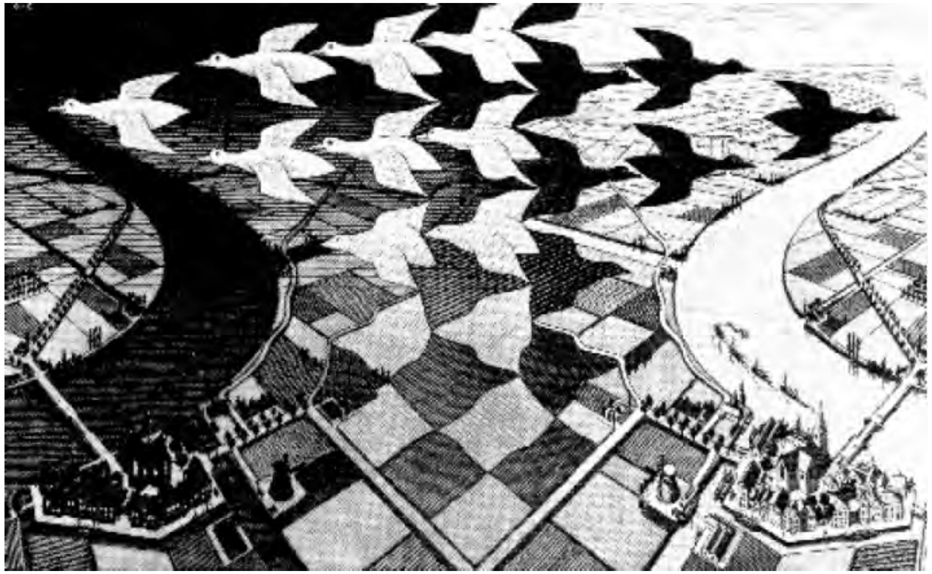
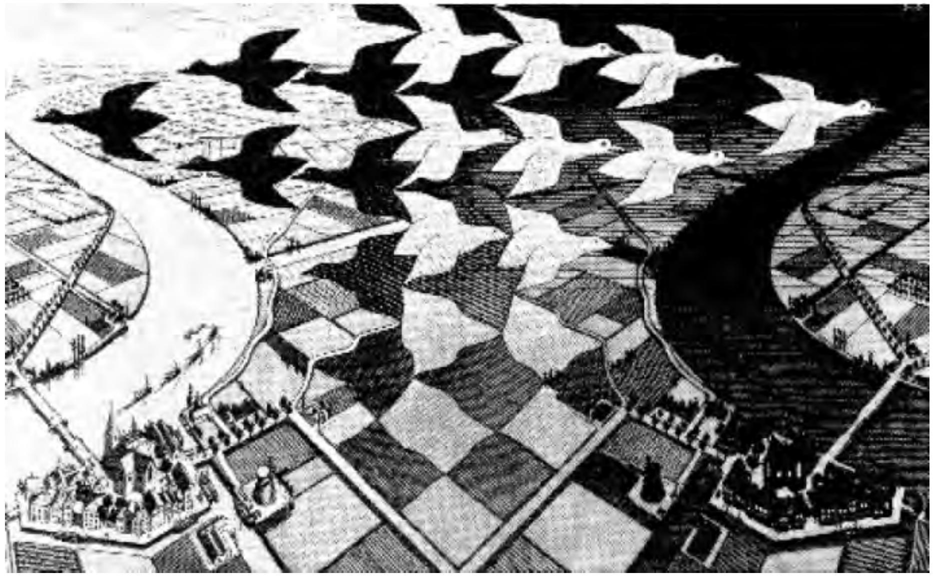
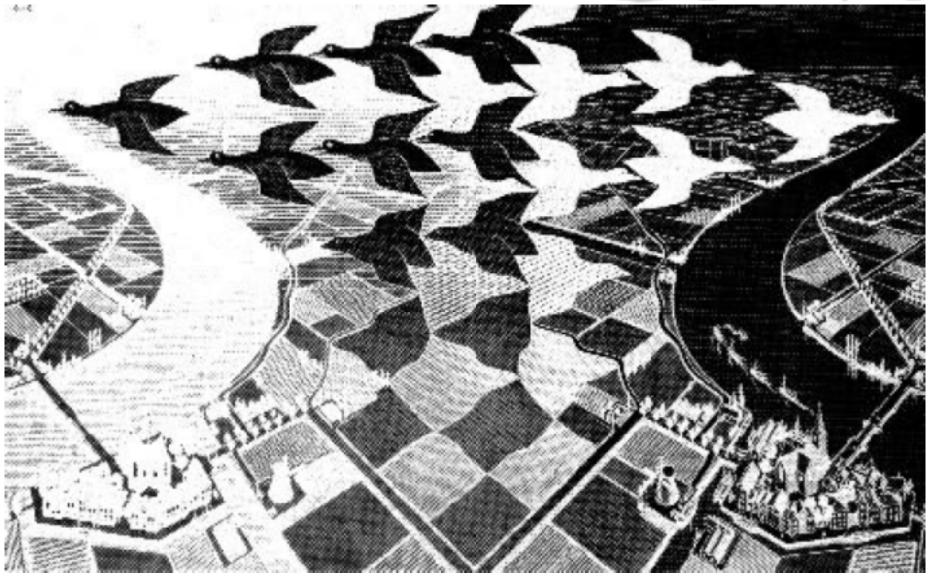
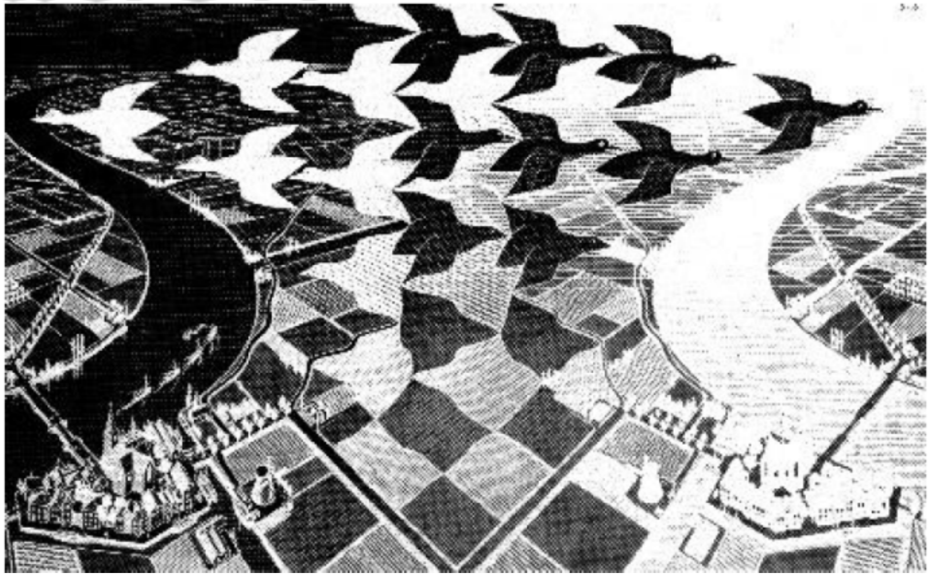




CP Violation





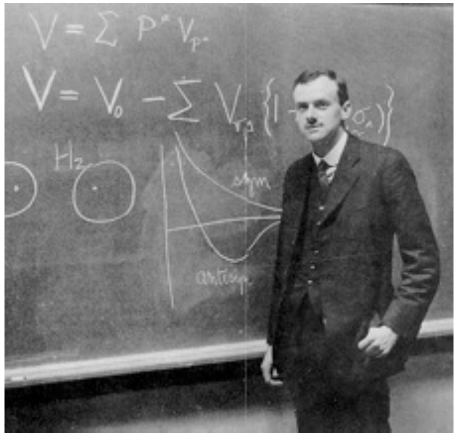
The asymmetry between Matter and AntiMatter

Gerhard Raven, Nikhef and Vrije Universiteit Amsterdam

Outline

1. Antimatter & Big Bang
2. Symmetries and the weak interactions
3. Discovery of CP violation
4. Describing CP violation and the weak interactions
5. CP violation and the Standard Model
6. Testing the Standard Model predictions of CP violation
7. Outlook for future measurements
8. Summary

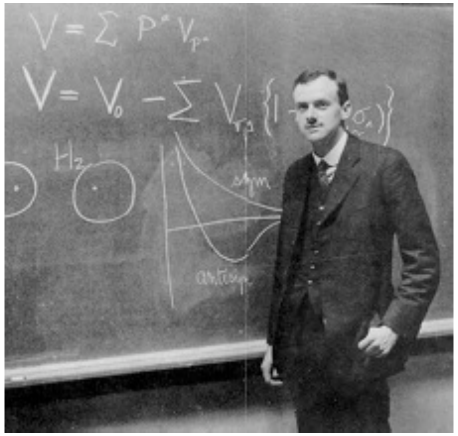
Antiparticles: Dirac's prediction



$$(i\gamma^\mu \partial_\mu - m)\, \psi(\vec{x}, t) = 0$$

$$E = \pm\sqrt{\vec{p}^{\,2} + m^2}$$

Antiparticles: Dirac's prediction



- Combining quantum mechanics with special relativity, and the wish to *linearize* ∂/∂t, leads Dirac to the equation

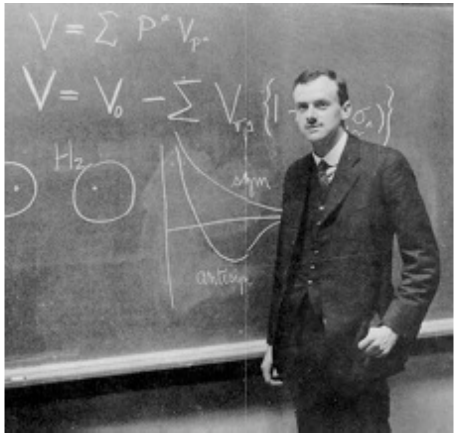
$$(i\gamma^\mu \partial_\mu - m)\,\psi(\vec{x}, t) = 0$$

- Solutions describe particles with spin = 1/2

- But half of the solutions have *negative energy*

$$E = \pm\sqrt{\vec{p}^{\,2} + m^2}$$

Antiparticles: Dirac's prediction



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- Solutions describe particles with spin = 1/2

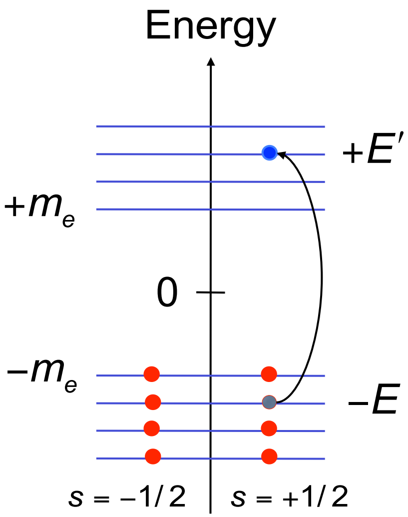
- But half of the solutions have *negative energy*

$$E = \pm\sqrt{\vec{p}^{\,2} + m^2}$$

- Vacuum represents a "sea" of such negative-energy particles (fully filled according to Pauli's principle)

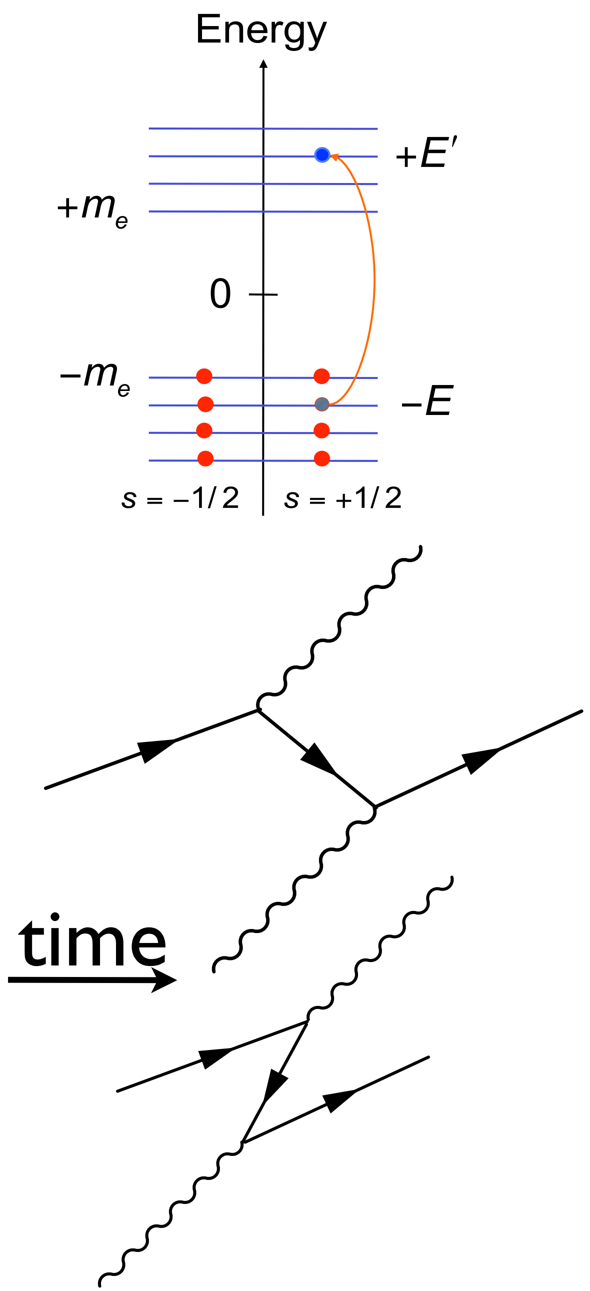
- Dirac identified holes in this sea as "antiparticles" with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought "positrons" would have been discovered already)

- An electron with energy E can fill this hole, emitting an energy 2E and leaving the vacuum (hence, the hole has effectively the charge +e and positive energy).



This picture fails for bosons !

Antiparticles: Stueckelberg/Feynman



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Stueckelberg/Feynman interpretation:

- consider the negative energy solution as *running backwards in time*

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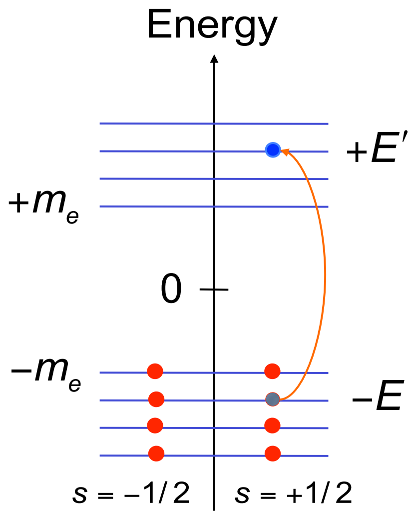
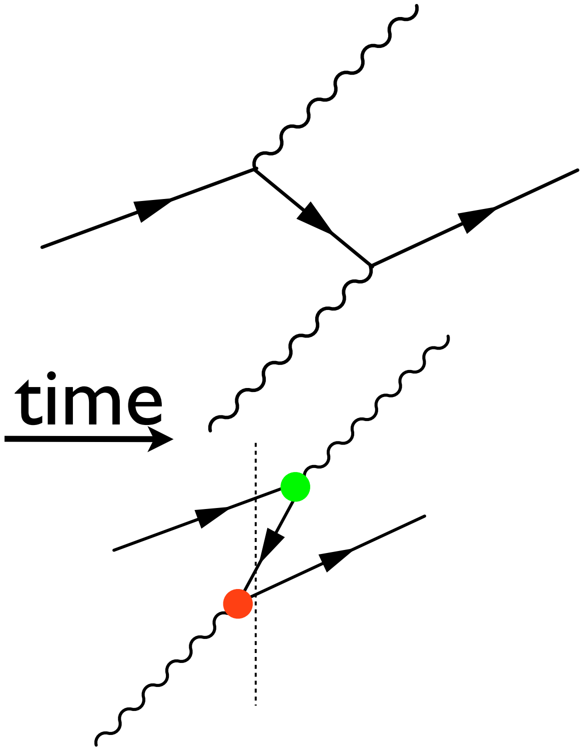


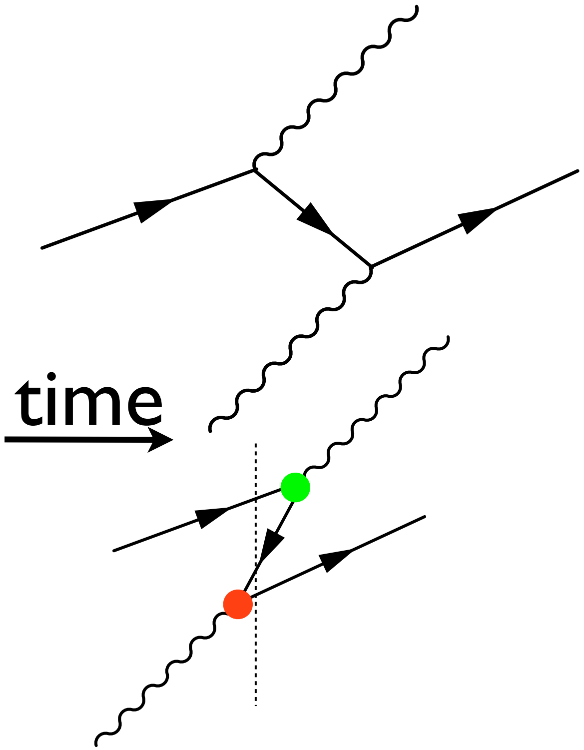


- An electron with energy E can fill this hole, emitting an energy 2E and leaving the vacuum (hence, the hole has effectively the charge +e and positive energy).

Stueckelberg/Feynman interpretation:

- consider the negative energy solution as *running backwards in time*
- and re-label it as *antiparticle*, with *positive* energy, going forward in time
- emission of E>0 antiparticle = absorption of particle E<0
- Naturally describes *creation* and *annihilation*...
- ... and that particles and antiparticles must have the same mass, spin, ... and opposite charges

Antiparticles: CPT



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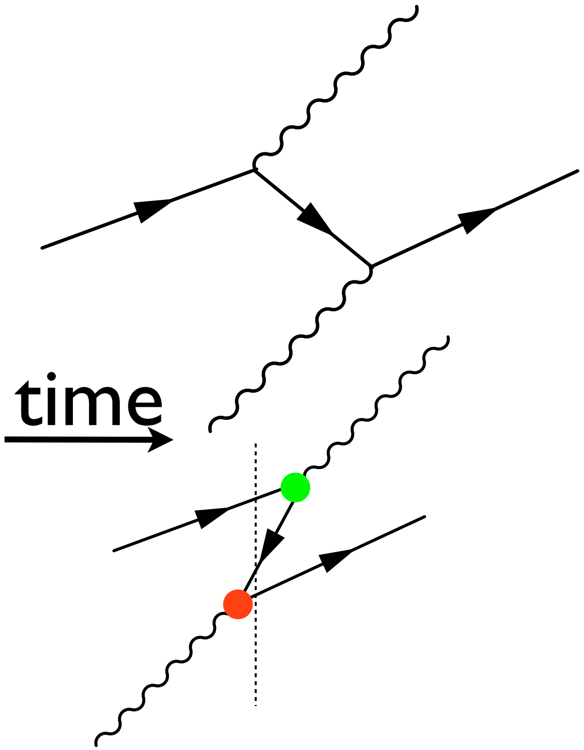

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Quantity		C	T	P
Time	t	t	$-t$	t
Space vector	$\mathbf{x}$	$\mathbf{x}$	$\mathbf{x}$	$-\mathbf{x}$
Momentum	$\mathbf{p}$	$\mathbf{p}$	$-\mathbf{p}$	$-\mathbf{p}$

This involves a *CPT* transformation:

- we have flipped Charge (C),
- flipped time (T),
- *and to prevent momentum* from being flipped, must *also* flip the space coordinates (P)

CPT theorem

"Any Lorentz-invariant local quantum field theory is invariant under the combined application of *C*, *P* and *T* "

G. Lüders, W. Pauli (1954); J. Schwinger (1951)

Assumptions:

1. Lorentz invariance
2. "principle of locality"
3. Causality
4. Vacuum lowest energy
5. Flat space-time
6. Point-like particles

Consequences:

1. Relation between spin and statistics: fields with integer spin commute and fields with half-numbered spin anticommute; Pauli exclusion principle
2. Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

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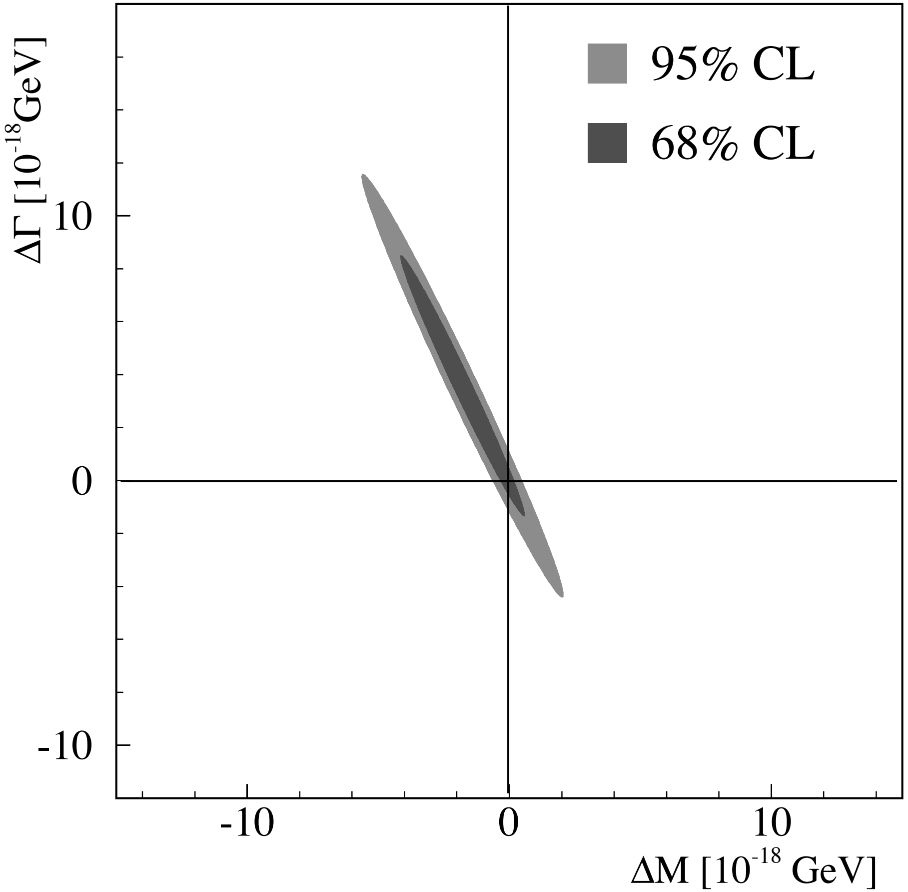


$$\frac{M(K^0) - M(\overline{K^0})}{\left(M(K^0) + M(\overline{K^0})\right)/2} < 10^{-17}(95\%CL)$$

Discovery of Antiparticles

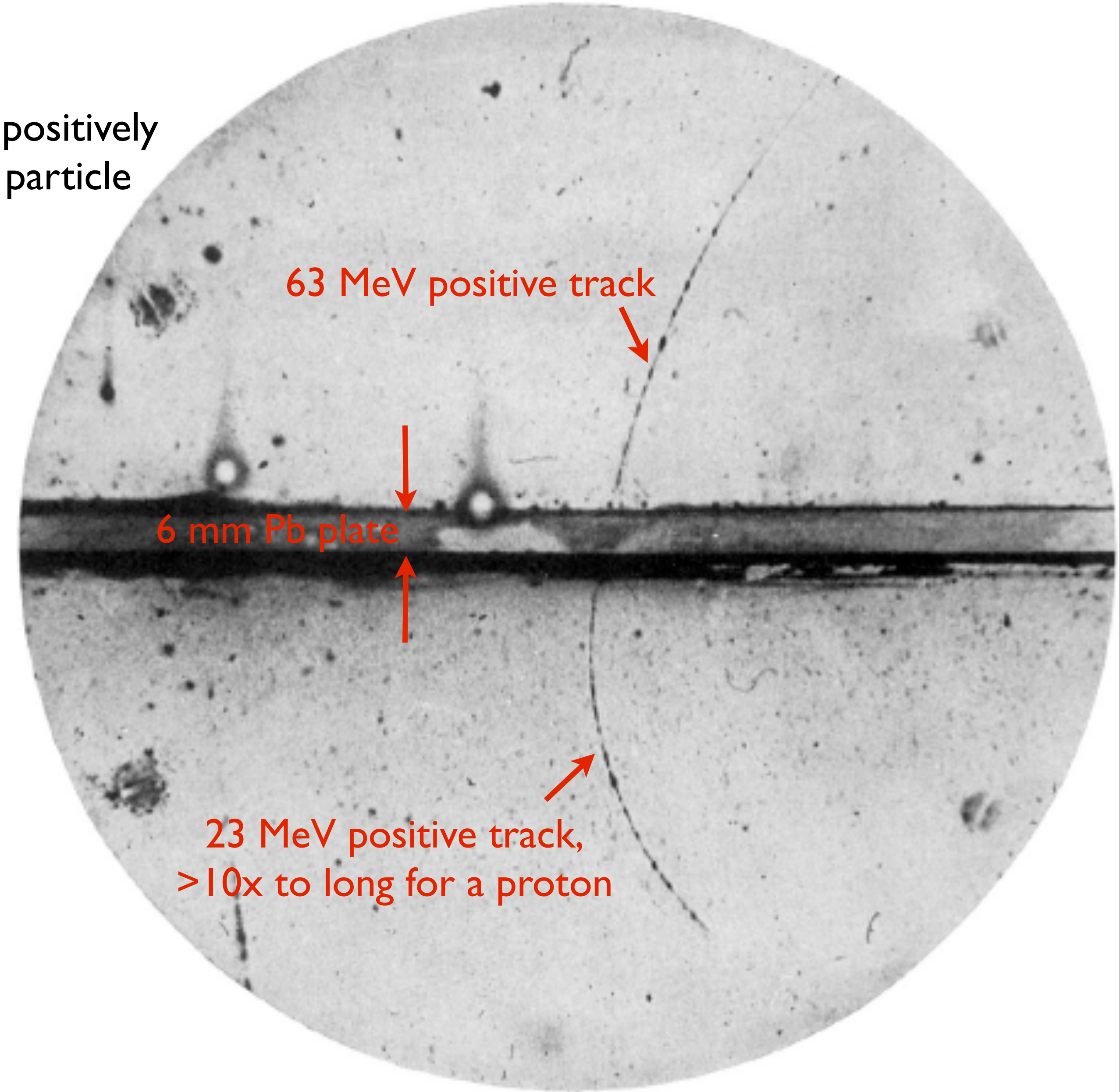
Back to experiment: does antimatter exists, and, if so, where is it?

Carl Anderson studies at cosmic rays on Pikes peak, using a Cloud chamber

Particles will show (temporarily) as condensation trail in gas volume (just like condensation trails of airplanes)

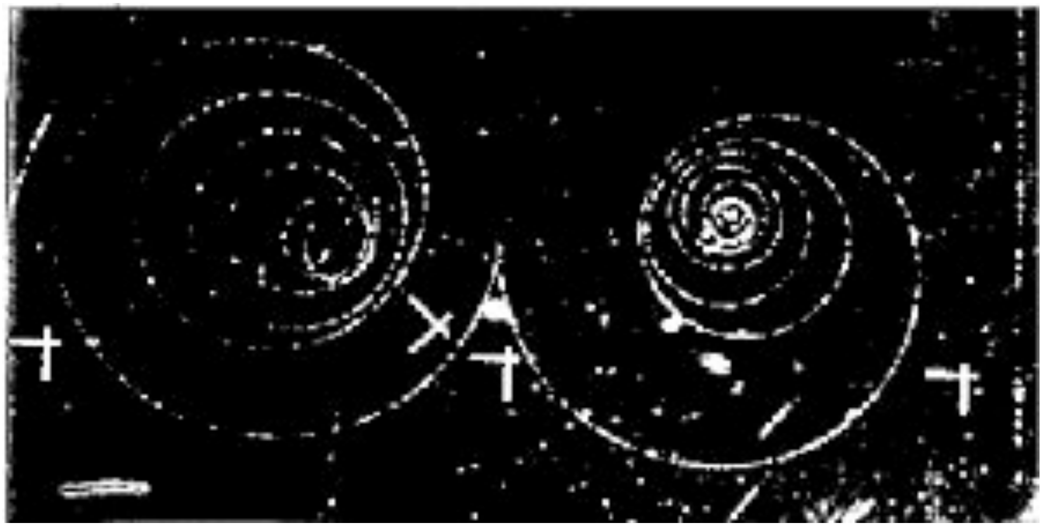
Antiparticles: Anderson's discovery

- Result: discovery of a positively charged, electron-like particle dubbed the 'positron'



Antiparticles: Anderson's discovery

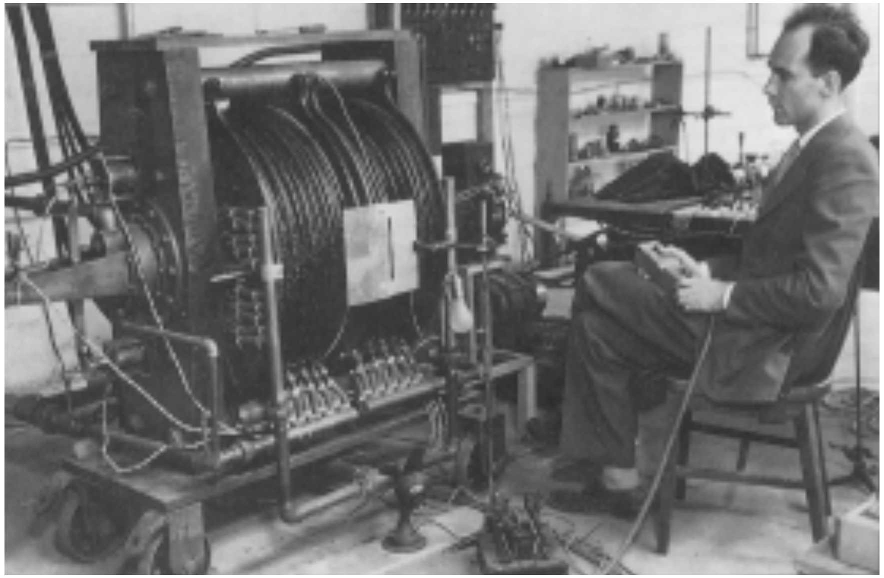
- Confirmed with $\gamma \rightarrow e^+e^-$

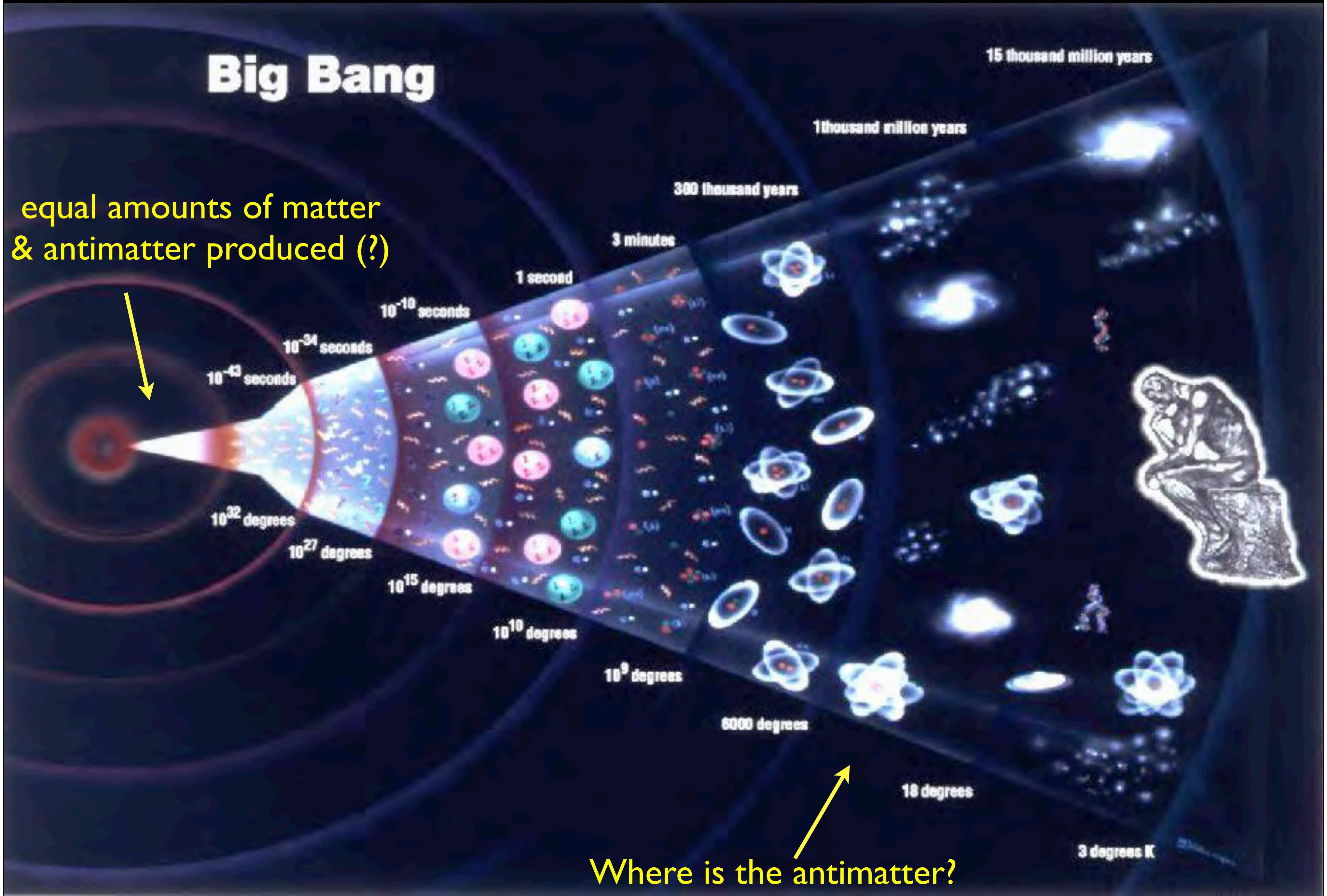


CARL D. ANDERSON

The production and properties of positrons

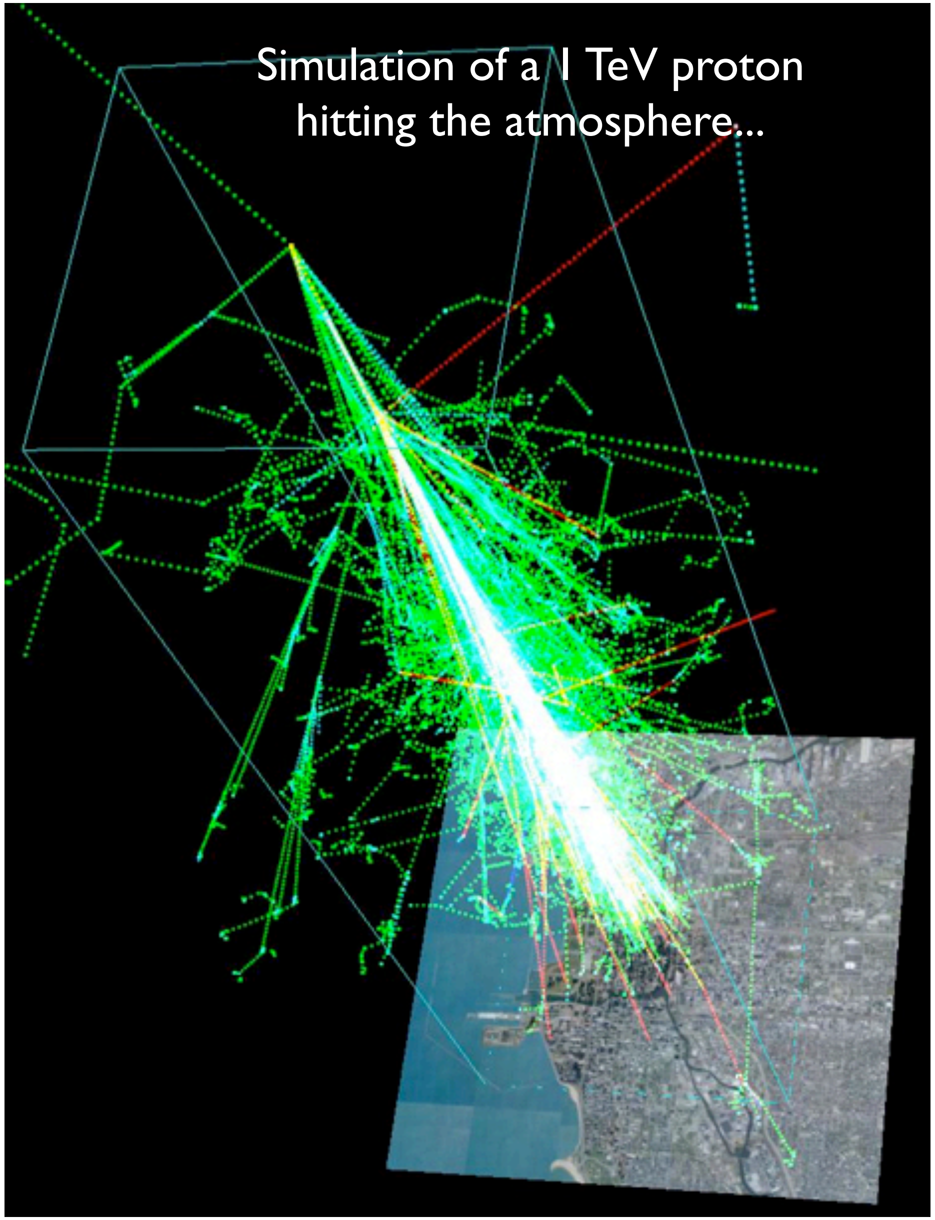
Nobel Lecture, December 12, 1936



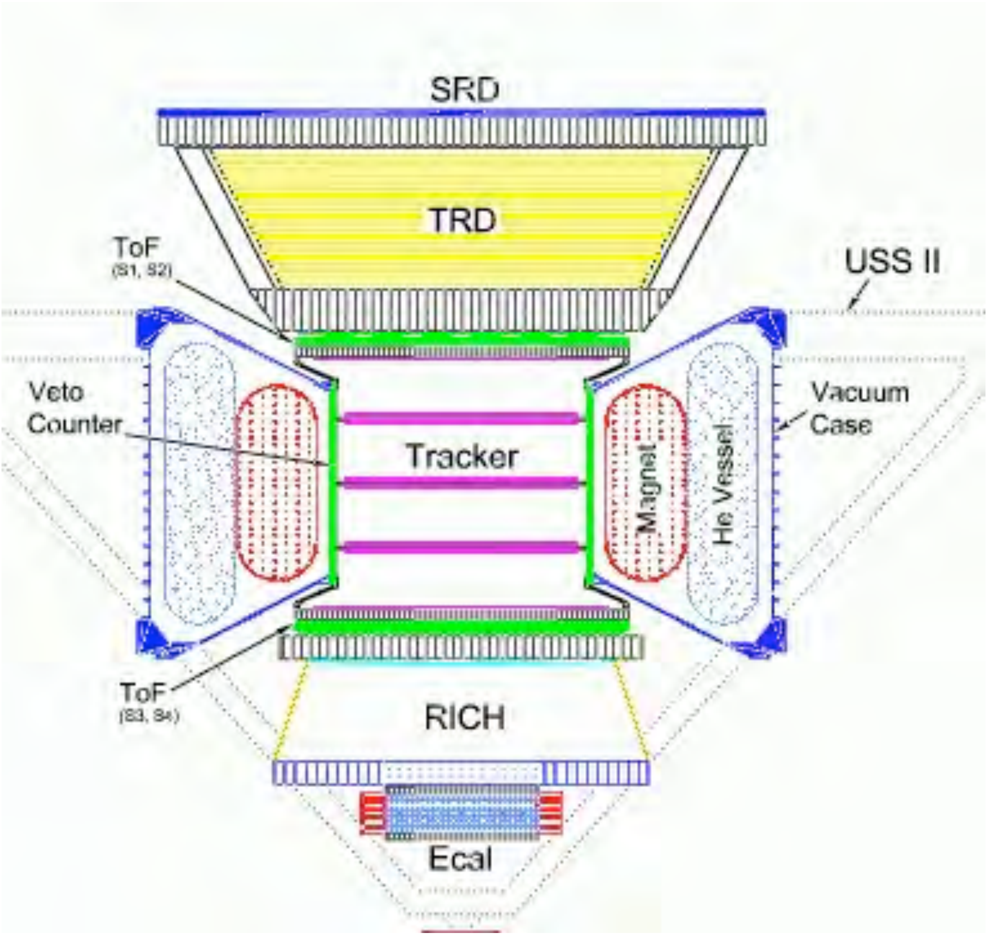

Big Bang
equal amounts of matter & antimatter produced (?)
10^-43 seconds
10^-34 seconds
10^-10 seconds
1 second
3 minutes
300 thousand years
1thousand million years
15 thousand million years
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
10^9 degrees
6000 degrees
18 degrees
3 degrees K
Where is the antimatter?

Cosmic Antimatter...

- Antiparticles appear in cosmic ray showers
- But what about the original incoming (anti?)particle
- Must measure before the shower starts, eg. above the atmosphere..



AntiMatter Searches: AMS



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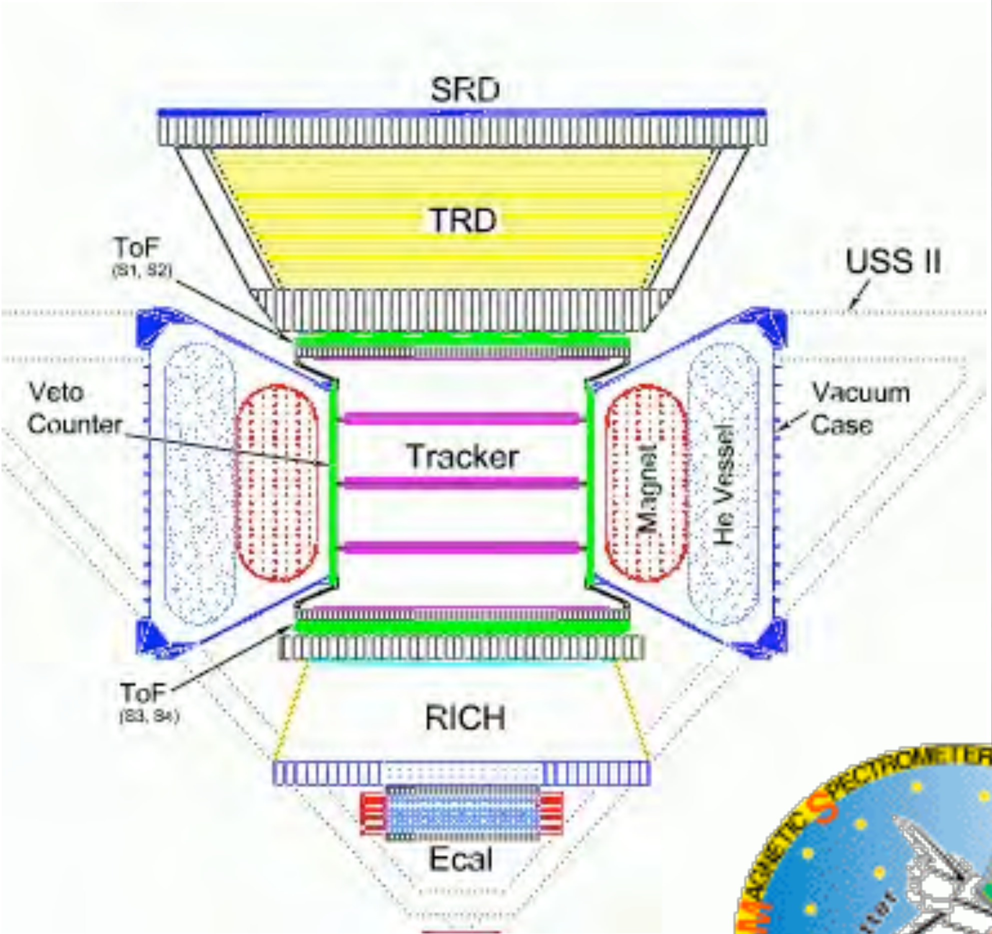


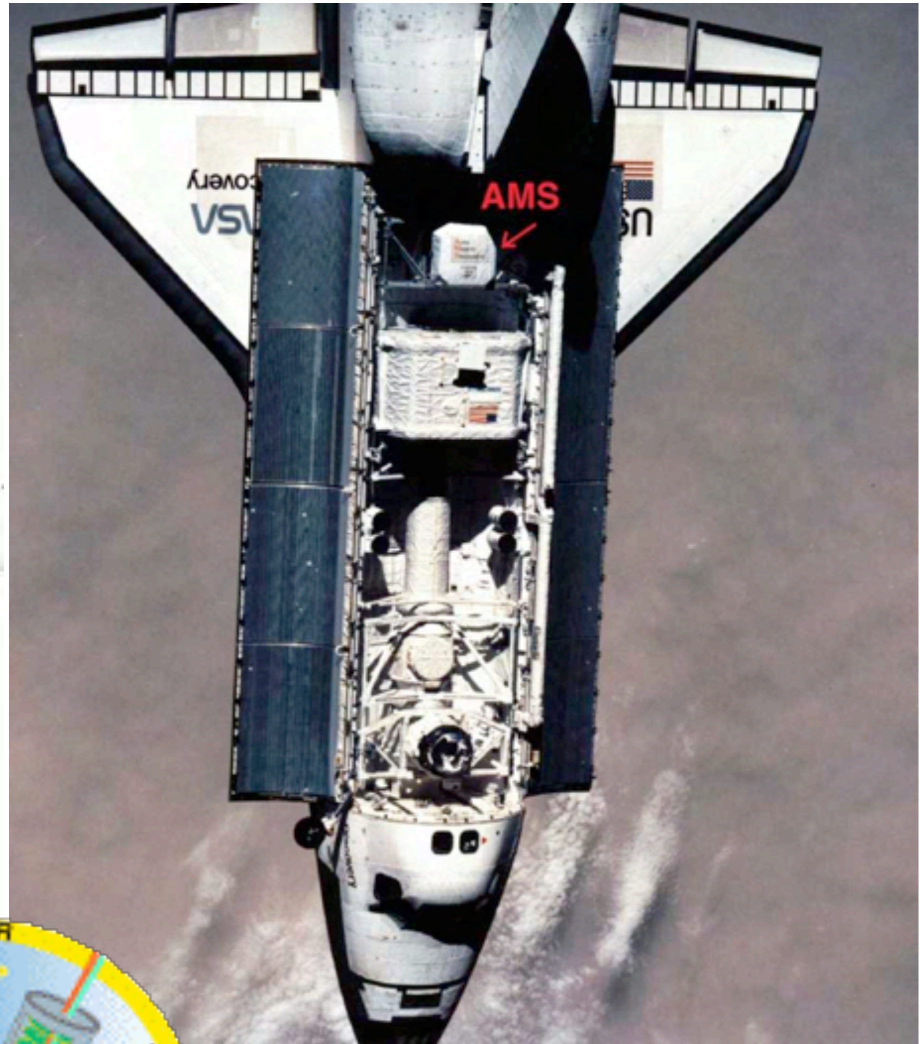
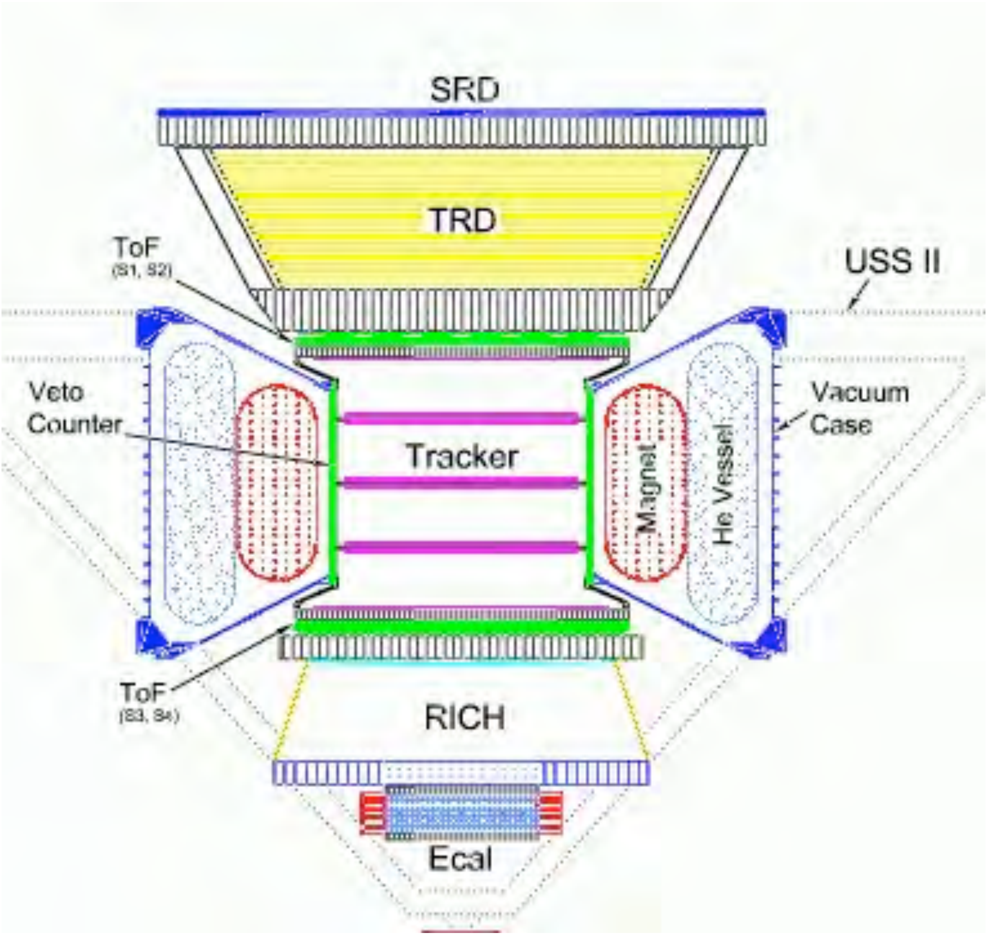
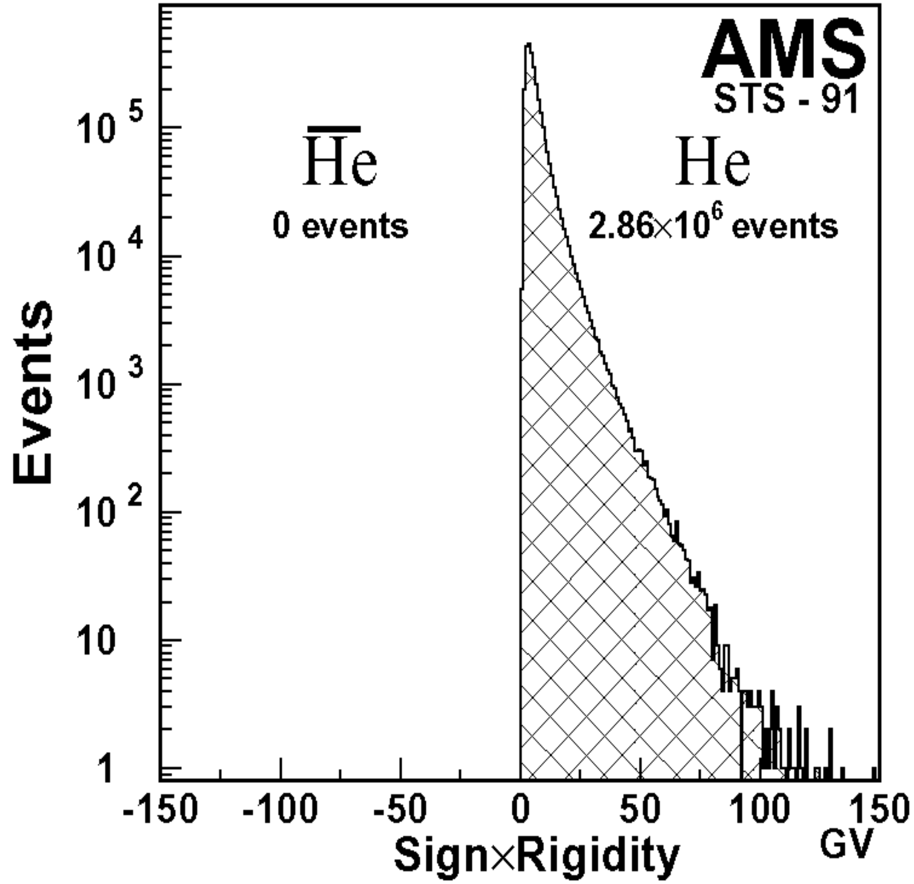


Photo taken from Mir (1998)

AntiMatter Searches: AMS



Look for anti-Helium: very unlikely to have been created as secondary product in collisions...



$$\frac{N_{\overline{\mathrm{He}}}}{N_{\mathrm{He}}} < 1.1 \cdot 10^{-6} \ @ \ 95\% CL$$

AMS-2 currently scheduled for STS-134 (either the last or last but one shuttle flight!) for delivery to the ISS..

Antimatter Searches: Summary

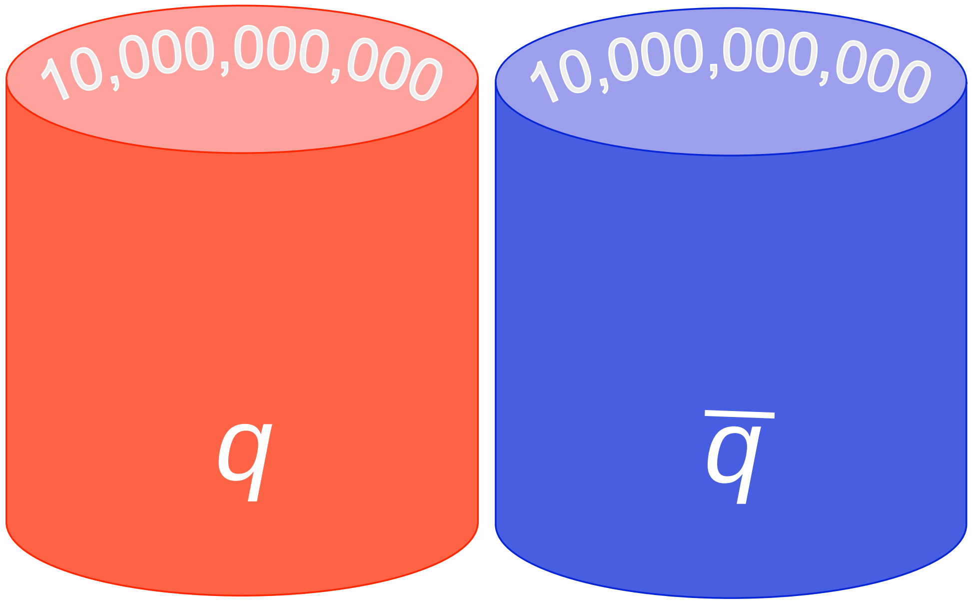
No evidence for the original, "primordial" cosmic antimatter:

- Absence of anti-nuclei amongst cosmic rays in our galaxy
- Absence of intense γ−ray emission due to annihilation of distant galaxies in collision with antimatter

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter

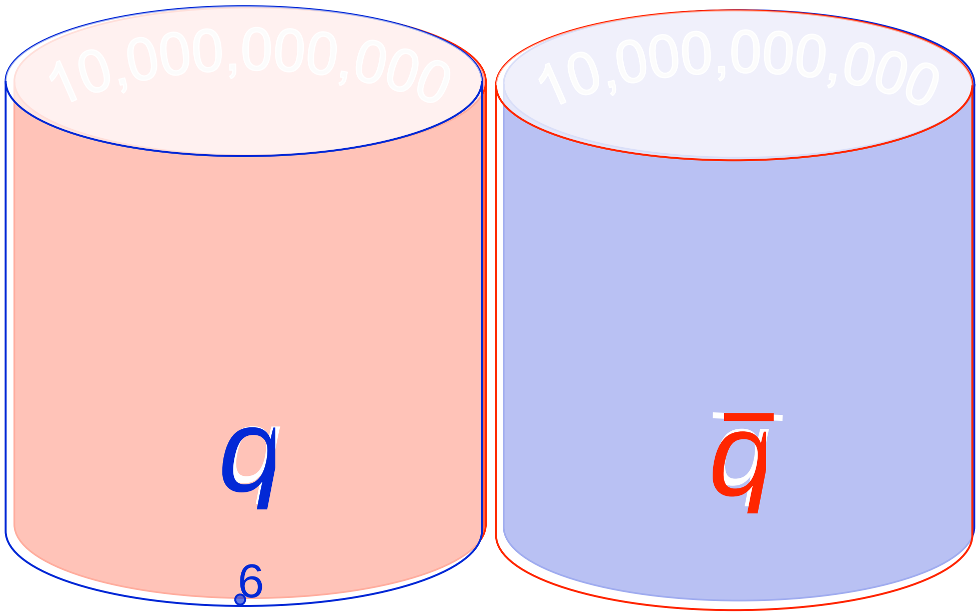


Early universe

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter
- Somewhere along the way, one (matter) is favored
- Final result : a bit of matter and *lots* of photons
  - $N_{baryons}/N_{photons} \cong 6\ 10^{-10}$



Current universe

Sakharov's conditions on the Big Bang

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Andrei Sakharov
"Father" of Soviet hydrogen bomb
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Three requirements for a universe with a baryon asymmetry:

1. A process that violates baryon number
2. C and CP violation, i.e. breaking of the C and CP *symmetries*
3. 1 & 2 should occur during a phase which is NOT in thermal equilibrium

These lectures will focus on 2.

Symmetries

Instructions by the VOC (Dutch East India Company) in Aug 1642:

"Since many rich mines and other treasures have been found in countries north of the equator between 15º and 40º latitude, there is no doubt that countries alike exist south of the equator. The provinces in Peru and Chili rich of gold and silver, all positioned south of the equator, are revealing proofs hereof."

Abel Tasman discovered Tasmania (Nov. 1642), New Zealand (Dec. 1642), Fiji (Jan 1643), ...

From the point of view of the VOC, this was a disappointment..

Abel Tasman

Symmetries & "Hidden Observables"

"The root to all symmetry principles lies in the assumption that it is impossible to observe certain basic quantities; the non-observables"

1. Space translation symmetry:
   Hidden observable: **Absolute position**
   Conserved quantity: momentum

2. Time shift symmetry:
   Hidden observable: **Absolute time**
   Conserved quantity: Energy

3. Rotation symmetry:
   Hidden observable: **Absolute orientation**
   Conserved quantity: Angular momentum

T.D. Lee

See Noether's theorem for more details

Discrete Symmetries

- Space, time translation & orientation symmetries are all *continuous* symmetries
  - Each symmetry operation associated with one ore more continuous parameter
- There are also *discrete* symmetries
  - Spatial sign flip (x,y,z → -x,-y,-z) : P
  - Charge sign flip (Q → -Q) : C
  - Time sign flip (t → -t) : T
- Are these discrete symmetries exact symmetries that are observed in nature?
  - Is the assignment of the label (anti) particle a convention or not?
  - Is there a fundamental difference between left-handed and right-handed?

Quantity		*P*	*C*	*T*
Space vector	$\mathbf{x}$	$-\mathbf{x}$	$\mathbf{x}$	$\mathbf{x}$
Time	t	t	t	$-t$
Momentum	$\mathbf{p}$	$-\mathbf{p}$	$\mathbf{p}$	$-\mathbf{p}$
Spin	$\mathbf{s}$	$\mathbf{s}$	$\mathbf{s}$	$-\mathbf{s}$
Electrical field	$\mathbf{E}$	$-\mathbf{E}$	$-\mathbf{E}$	$\mathbf{E}$
Magnetic field	$\mathbf{B}$	$\mathbf{B}$	$-\mathbf{B}$	$-\mathbf{B}$

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In particle physics:

$$P\left|e_L^-\right\rangle = \left|e_R^-\right\rangle$$

$$P\left|\pi^0\right\rangle = -\left|\pi^0\right\rangle$$

$$P\left|n\right\rangle = +\left|n\right\rangle$$

$$C\left|e_L^-\right\rangle = \left|e_L^+\right\rangle$$

$$C\left|u\right\rangle = \left|\bar{u}\right\rangle$$

$$C\left|d\right\rangle = \left|\bar{d}\right\rangle$$

$$C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$

note: the definition of a 'left handed' particle will follow in 'a few slides' time

Discrete Symmetries

- *No* evidence that electromagnetic & strong forces break C, P or T
- Example: π^0 decay into photons

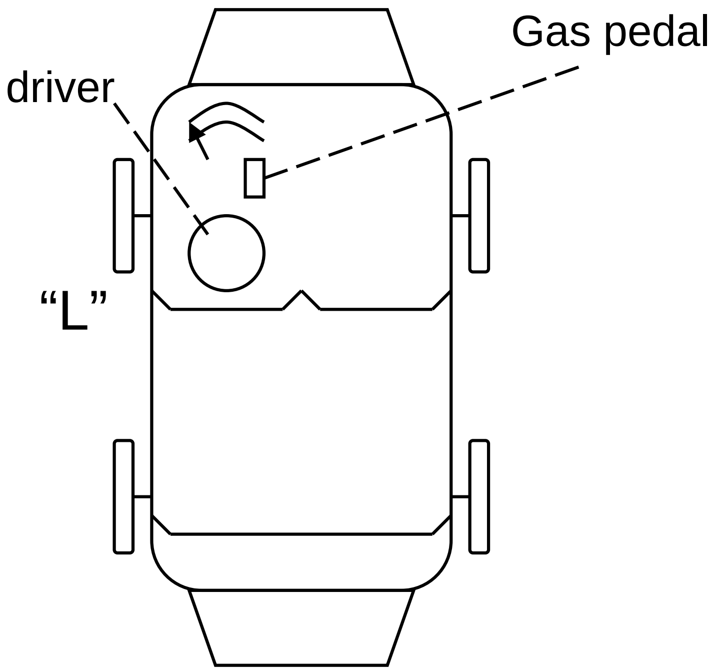
$$\pi^0 = \frac{1}{\sqrt{2}}\left[u\bar{u} - d\bar{d}\right]_{L=0,S=0} \quad \Rightarrow \quad C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$

$$C \cdot \vec{B} = -\vec{B}; C \cdot \vec{E} = -\vec{E} \quad \Rightarrow \quad C\left|\gamma\right\rangle = -\left|\gamma\right\rangle$$

- π^0 decays to two photons, but not three!
- Initial *and* final states are C even, thus C is conserved!
- Experimental test of P and C conservation in EM interaction:
  - C invariance: $Br(\pi^0 \rightarrow \gamma\gamma\gamma) < 3.1\ 10^{-5}$
  - P invariance: $Br(\eta \rightarrow \pi^0\pi^0\pi^0\pi^0) < 6.9\ 10^{-7}$
- Experimental test of C invariance in strong interaction:
  - compare rates of positive and negative particles in eg. $p\bar{p} \longrightarrow \pi^+\pi^- X, K^+K^- X, \ldots$

Parity

- Before 1956 physicists were *convinced* that the laws of nature were left-right symmetric. Strange?
  - A "gedanken" experiment:
    Consider two perfectly mirror symmetric cars:



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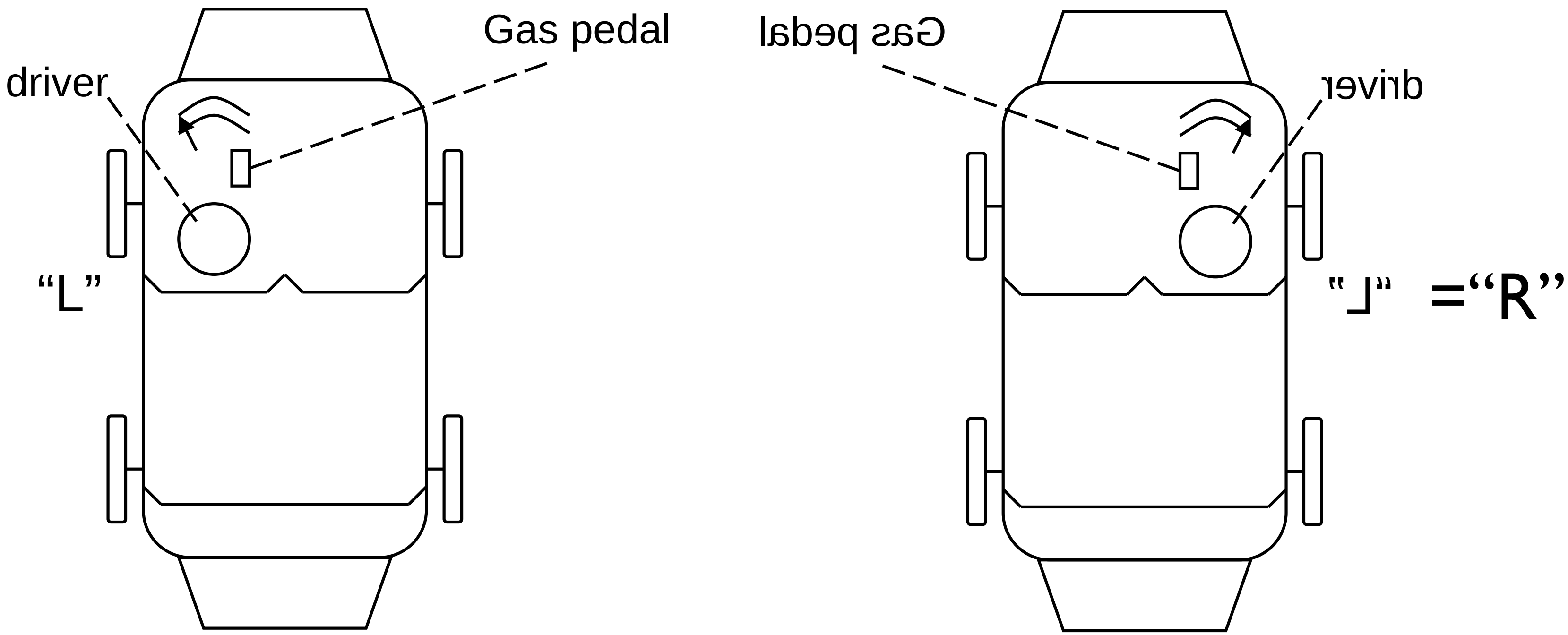

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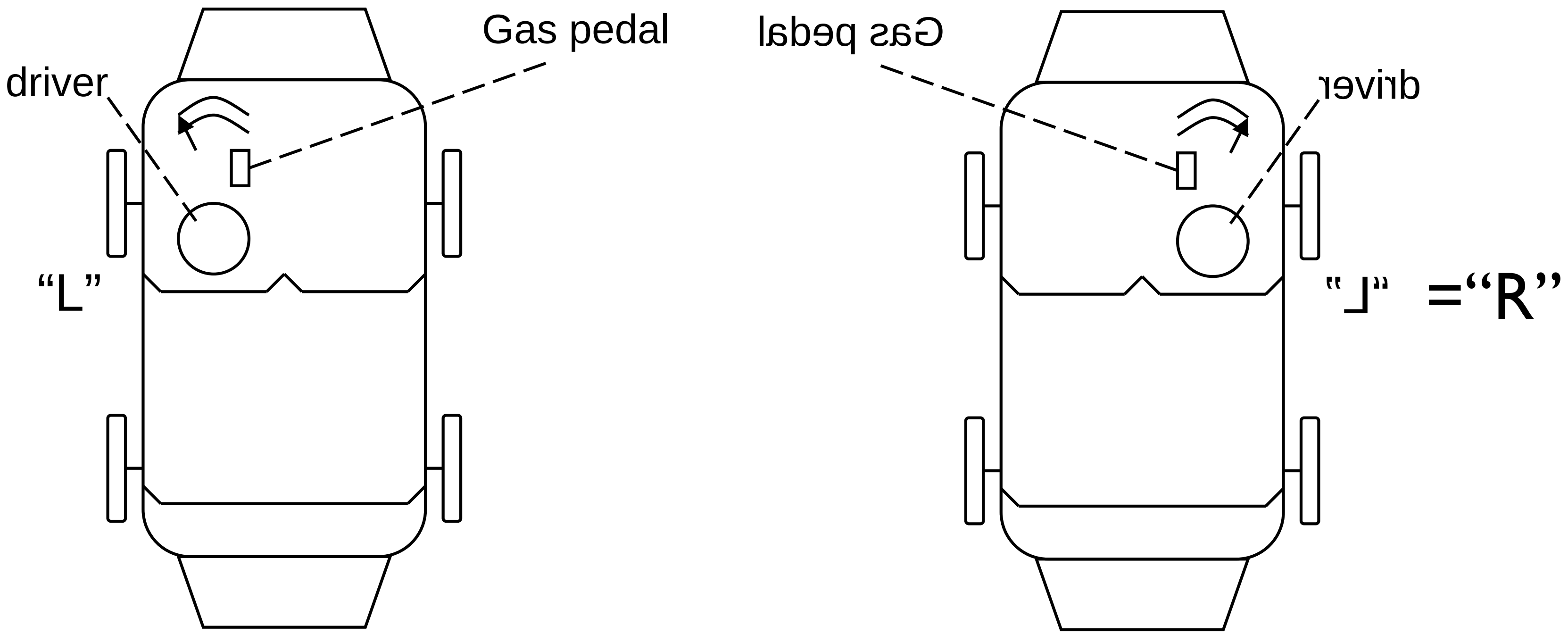


What would happen if the engine is powered by, say, ^{60}Co β decay?

The θ-τ puzzle

Observation of something(s) which decay to two pions and three pions, but whatever decays (now known as K^+), has, in both decays, the same lifetime, mass, spin=0...

In 1953, Dalitz argued that since the pion has parity of -1,

- two pions (*) would combine to produce a net parity of (-1)(-1) = +1,
- and three pions (*) would combine to have total parity of (-1)(-1)(-1) = -1.

Hence, if conservation of parity holds, there are two *distinct* particles with parity +1 (the 'θ') and parity -1 (the 'τ')(**).

But how to explain the fact that the mass and lifetime are the same?

$K^{\pm}$ $\qquad I(J^P) = \frac{1}{2}(0^-)$

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes		
Γ_9	$\pi^+\pi^0$	(21.13 ±0.14) %	S=1.1
Γ_{10}	$\pi^+\pi^0\pi^0$	(1.73 ±0.04) %	S=1.2
Γ_{11}	$\pi^+\pi^+\pi^-$	(5.576±0.031) %	S=1.1

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

(*) produced in the decay of a spin=0 mother
(**) Warning: do not confuse this 'τ' with what is now known as the τ lepton...

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

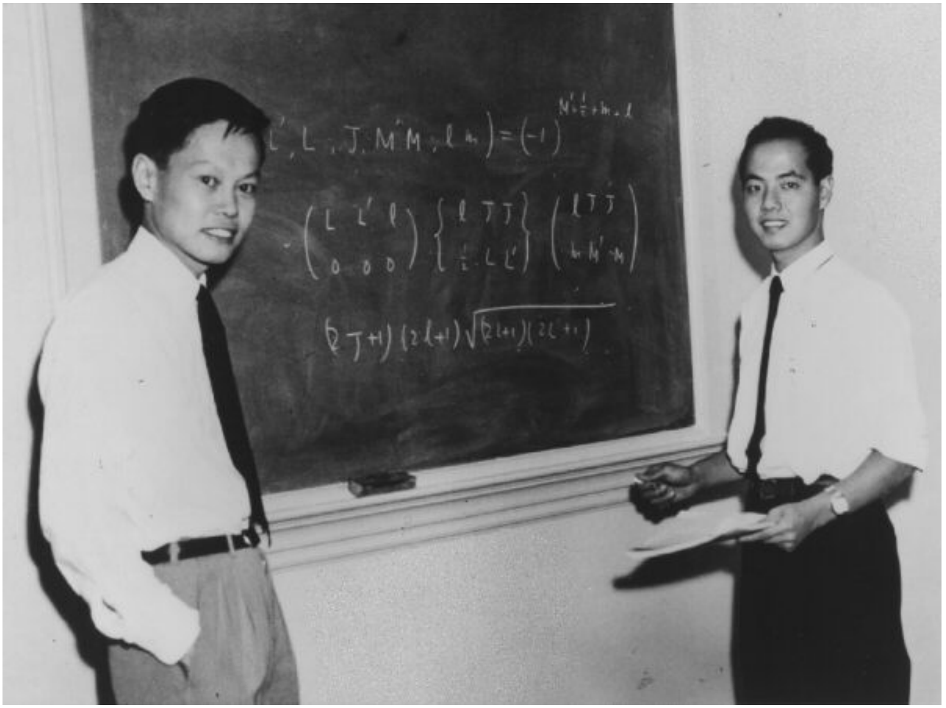
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi2}^+)$ and the $\tau^+(\equiv K_{\pi3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide



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T. D. LEE, *Columbia University, New York, New York*

AND

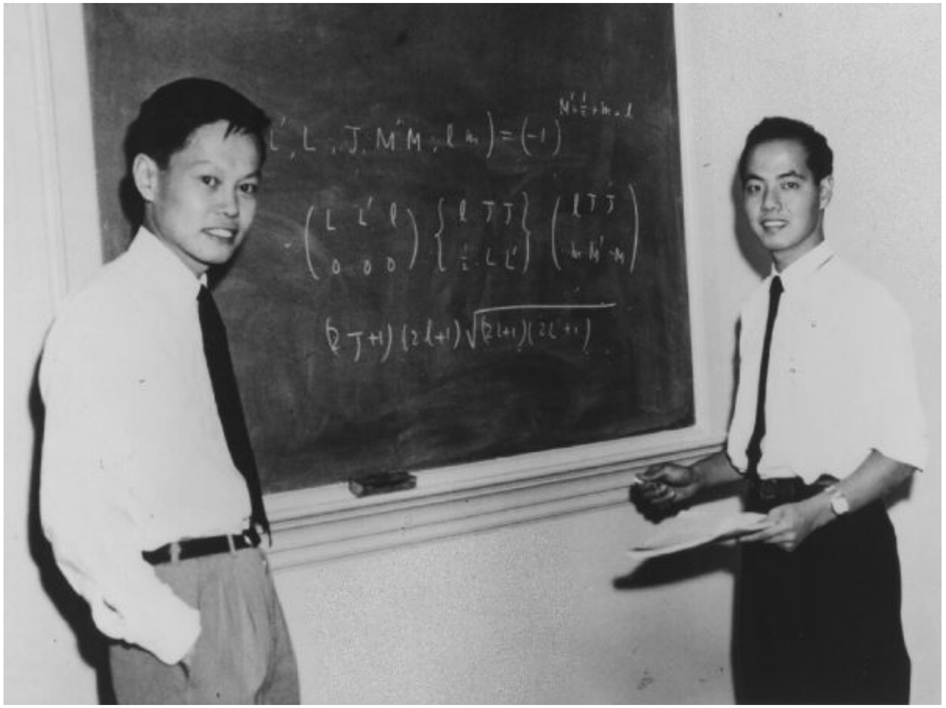
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide



The Nobel Prize in Physics 1957

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

The Exprimental (Re)Solution...

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

Idea for experiment in collaboration with Lee and Yang: *Look at spin of decay products of polarized radioactive nucleus*

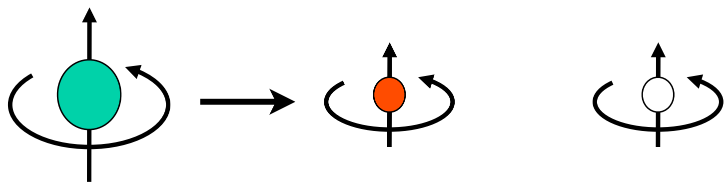
- Production mechanism involves exclusively weak interaction

Mme. Chien-Shiung Wu

Parity & Spin

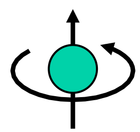
How does the decay of a particle with spin tell you something about parity?

Gedanken-experiment: decay of a spin-1 particle to two spin-½ particles



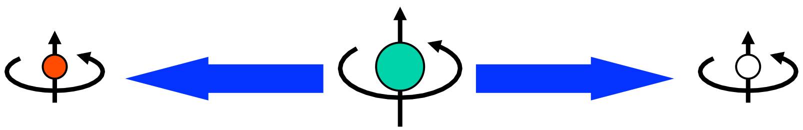
- Spin: |1,1> → |½, ½ > + |½, ½>
- It is important that initial state is *maximally polarized*: only then there is a single solution for the spin of the decay products. If not, e.g.
  - |1,0>→ |½, +½> + |½, -½>
  - |1,0> → |½, -½> + |½, +½>

Parity & Spin



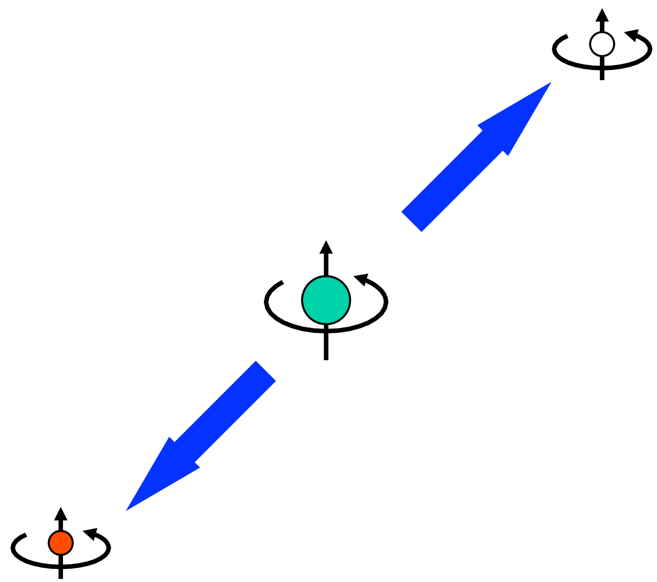
Parity & Spin

- A possible orientation



Parity & Spin

- A possible orientation
- And another...



Parity & Spin

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- And another...
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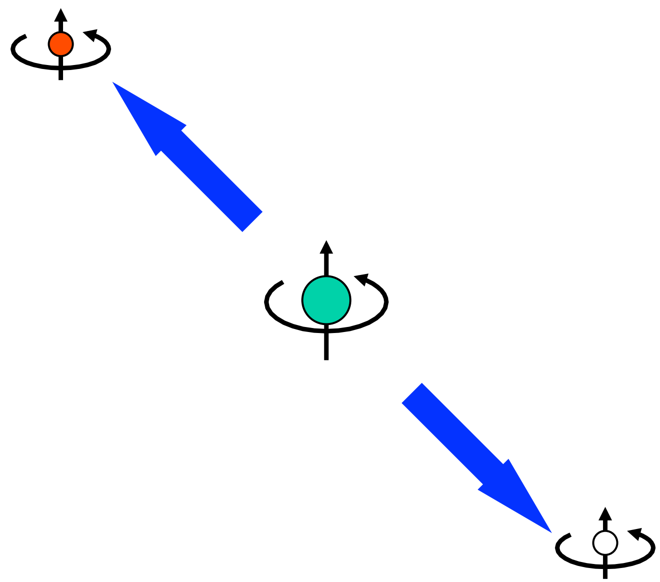

Parity & Spin

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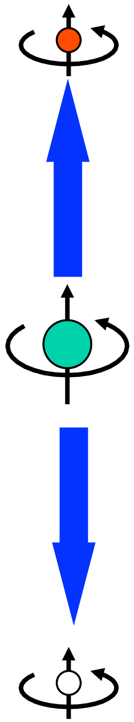


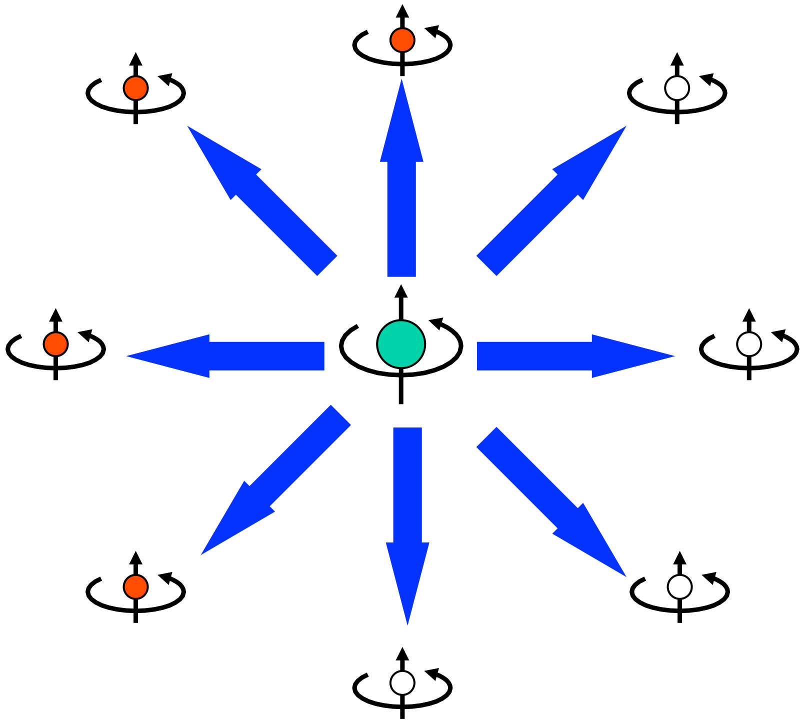
Parity & Spin: Helicity

- A possible orientation
- And another...
- And another...
- Introduce projection of spin on momentum, the helicity, to distinguish:

$$H = \frac{\vec{S}\cdot\vec{P}}{\left|\vec{S}\cdot\vec{P}\right|}$$

- Under parity transform H→-H
- If parity conserved, no reason to favour one value of H over another

$H = +1$ "Right Handed"

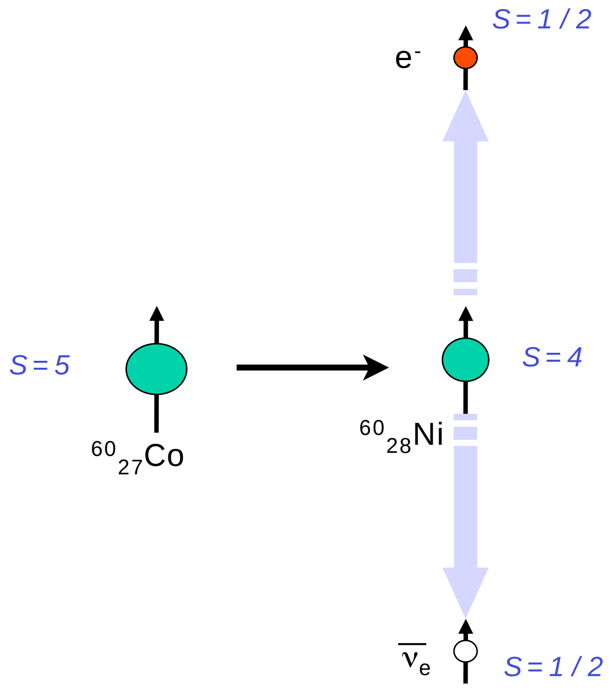


$H = -1$ "Left Handed"

warning:
helicity assignment is not Lorentz invariant for massive particles: an observer can boost 'past' such that p changes direction.

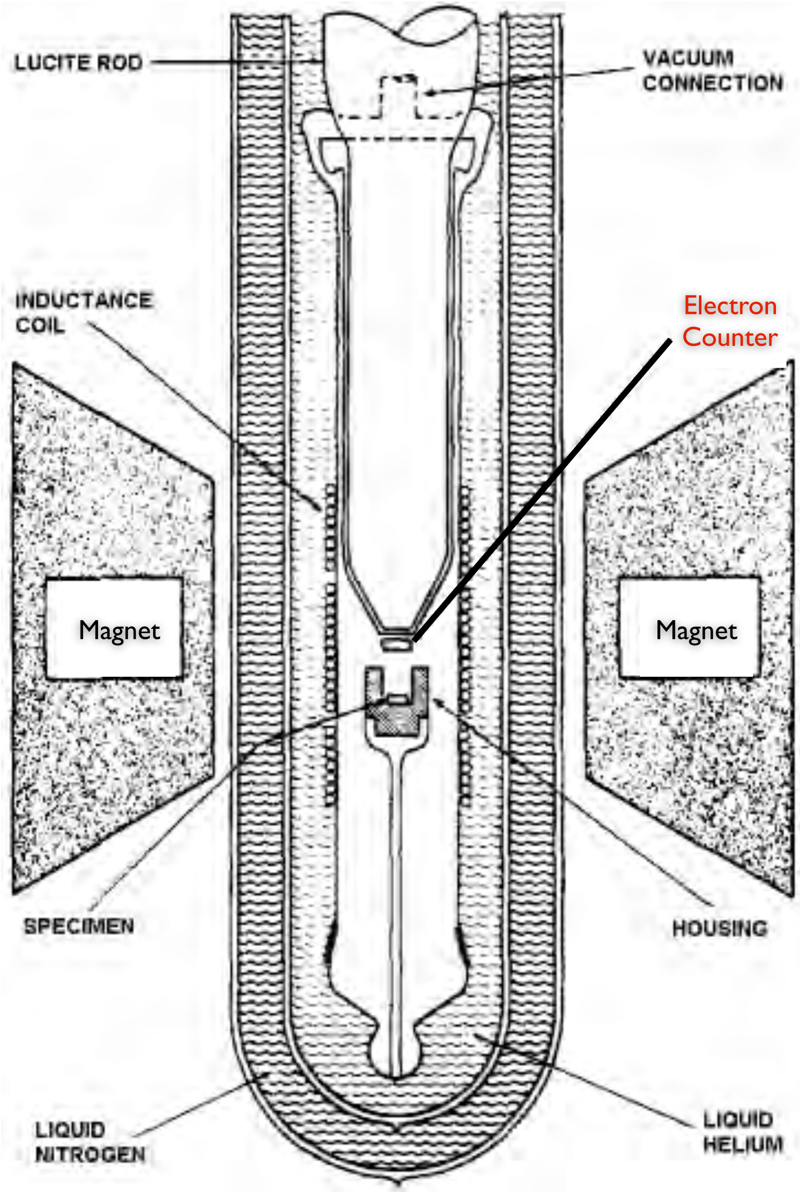
For more details, please check on the difference between 'chirality' and 'helicity'

Mme Wu's Experiment : setup



- How do you obtain a sample of ^{60}Co with spins aligned in one direction, and compare to non-aligned case?

- Adiabatic demagnitization of ^{60}Co in a magnetic field at very low temperatures (~0.01 K!). Extremely challenging in 1956!



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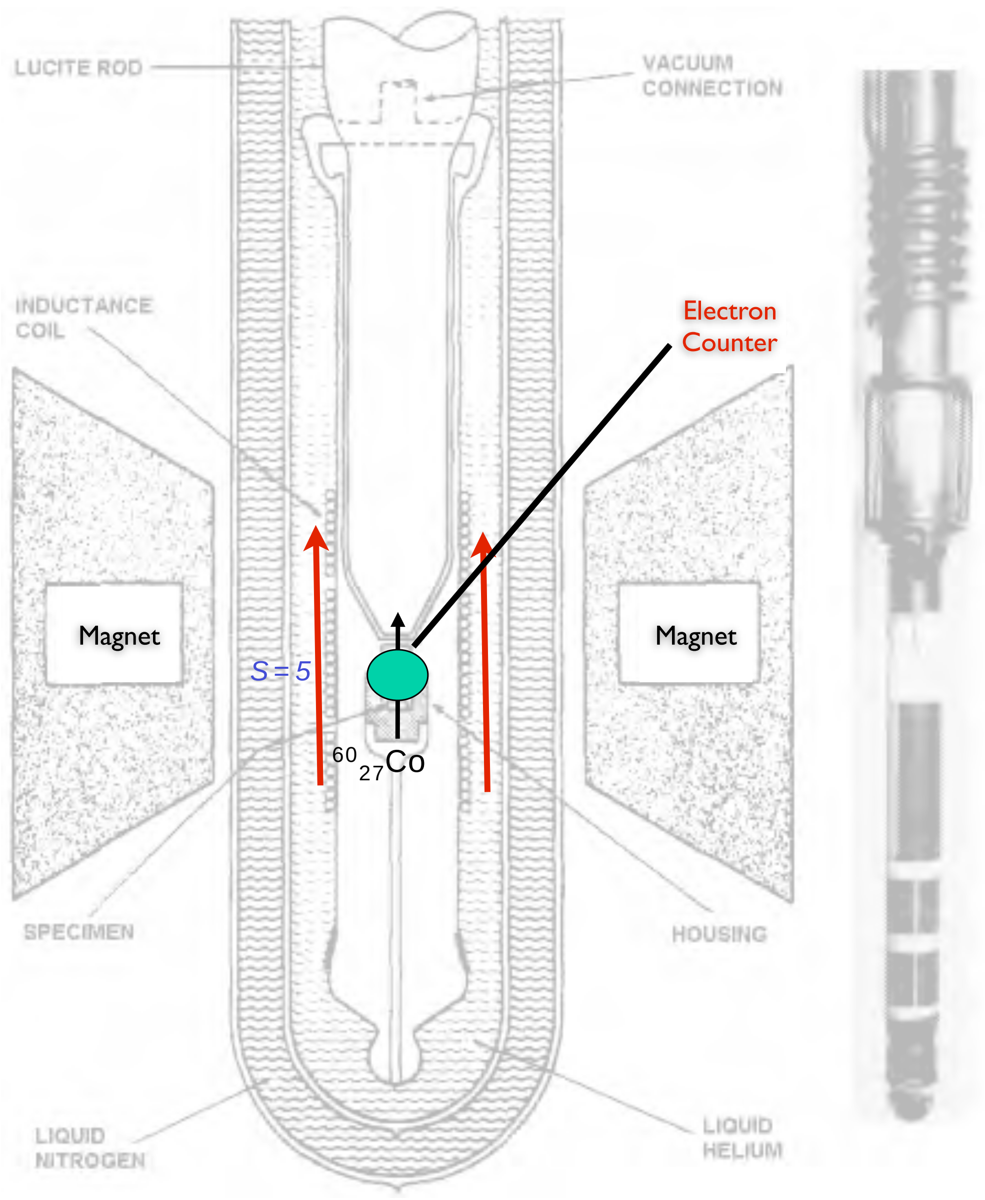

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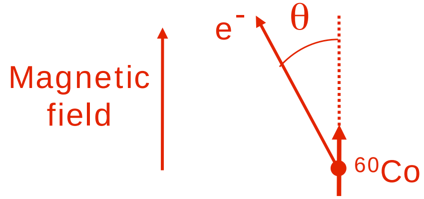

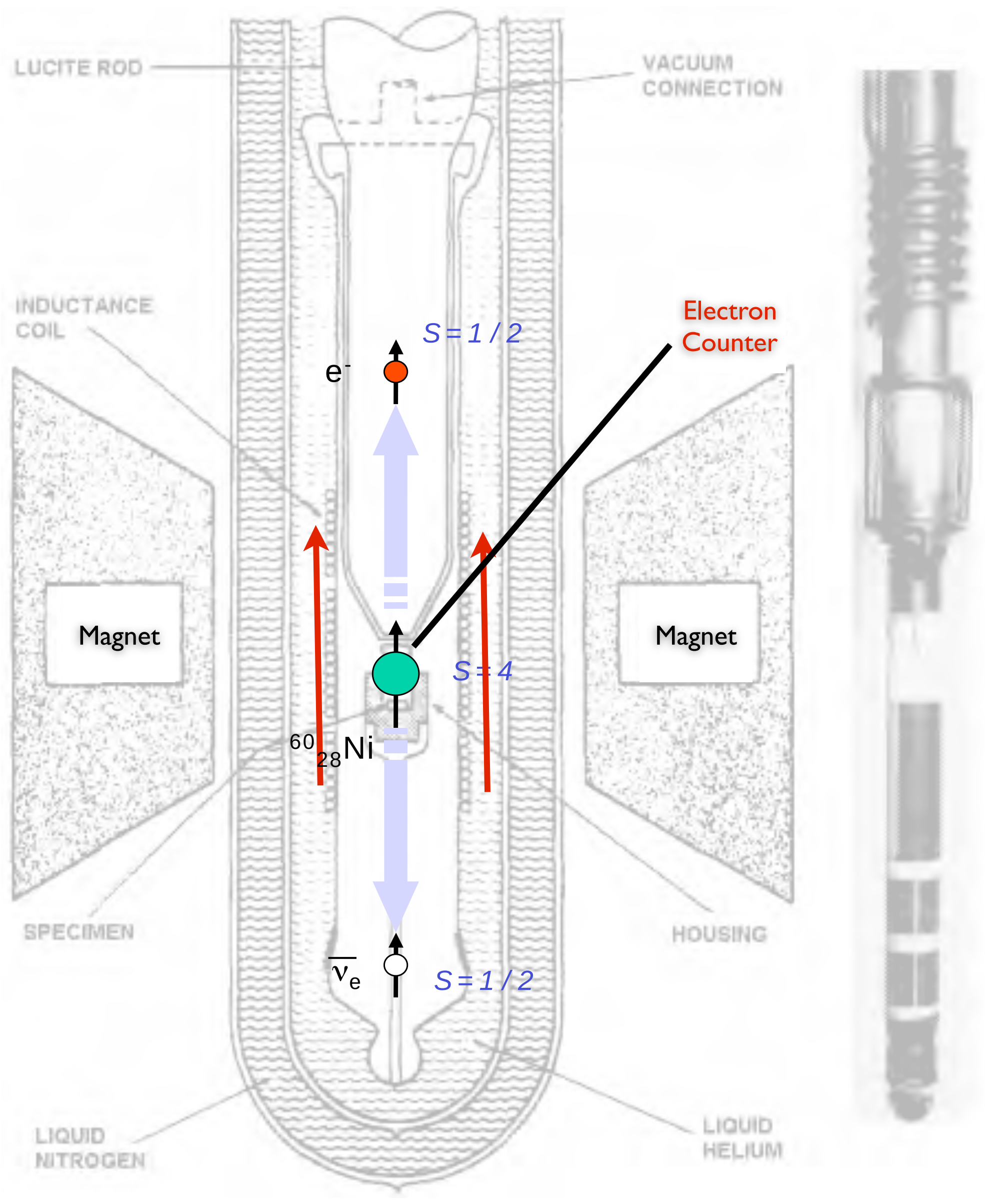

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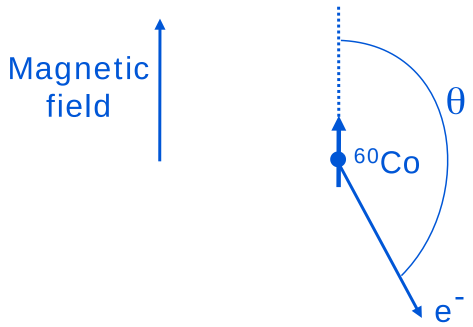

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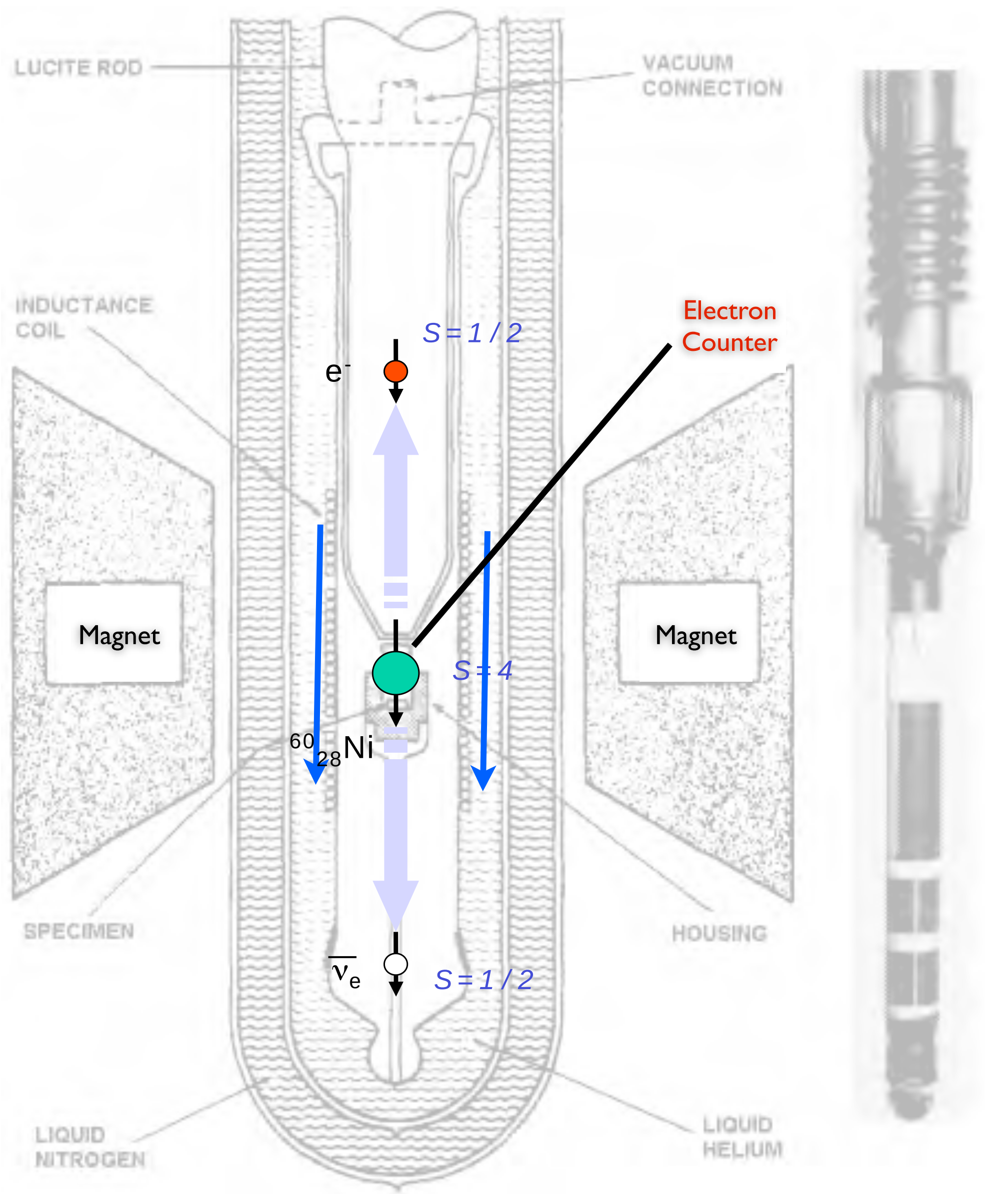
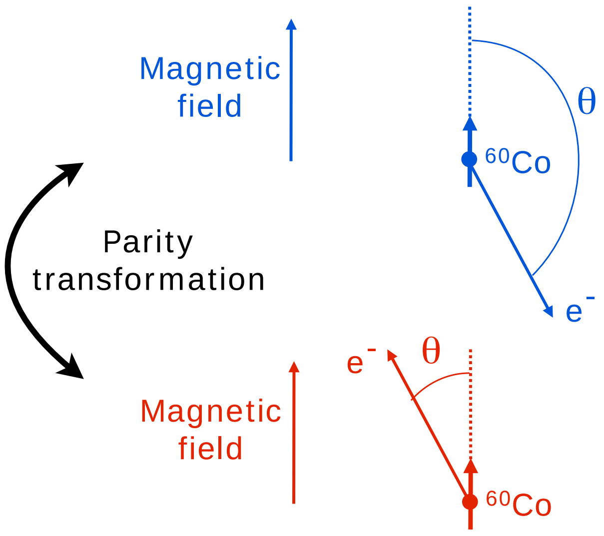
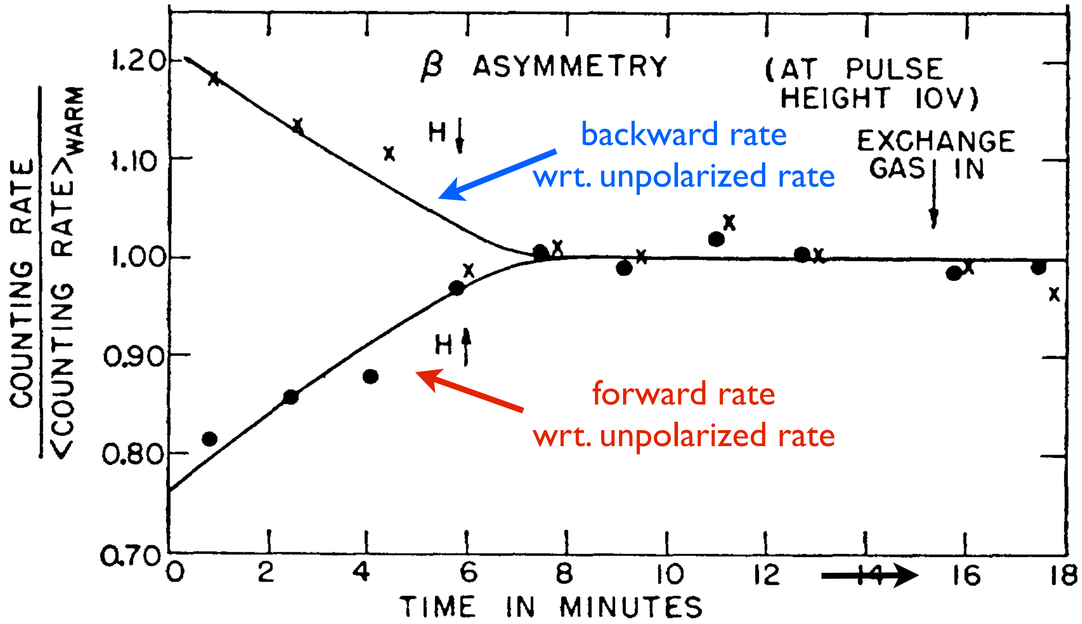


Mme Wu's Experiment : result

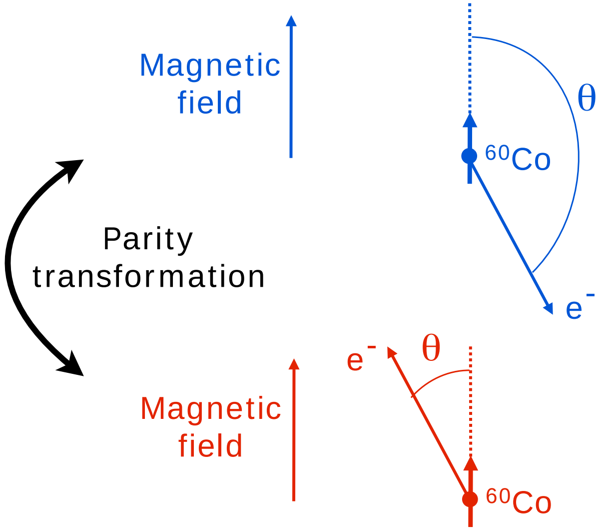


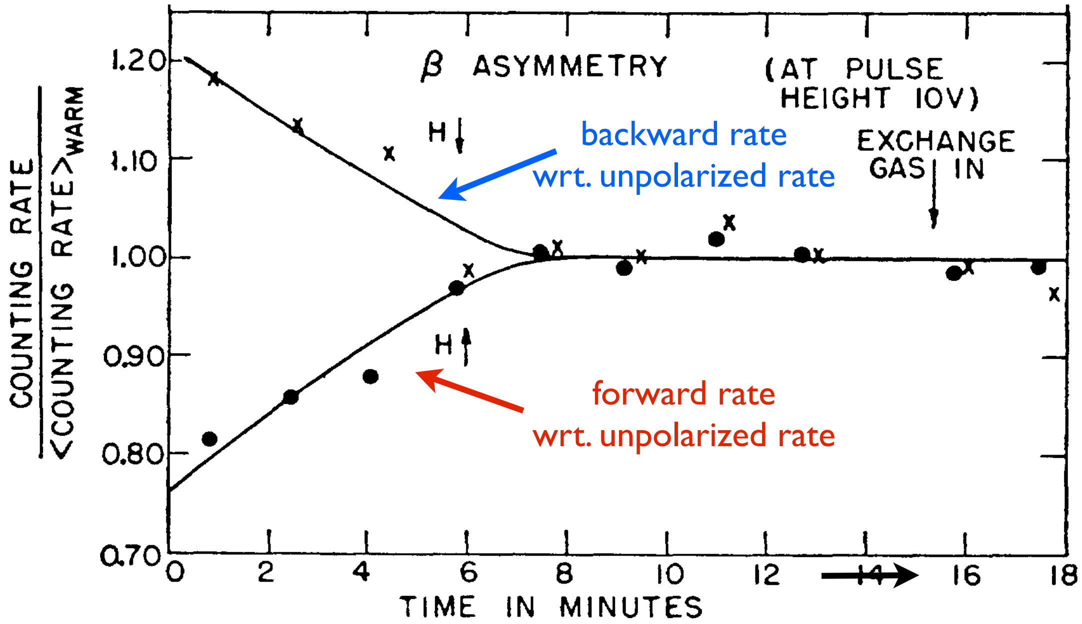


^{60}Co polarization decreases as a function of time as the temperature increases

- The counting rate in the polarized case is different from the unpolarized case
- Changing the direction of the B-field changes the counting rate!
- Electrons are preferentially emitted in the direction opposite the ^{60}Co spin!

Mme Wu's Experiment : conclusion





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- Electrons are preferentially emitted in the direction opposite the ^{60}Co spin!
- Analysis of the results shows that data consistent with the emission of only left-handed (i.e. H = -1) electrons ....
- ... and thus only *right-handed anti-neutrinos*

From P to C,P and CP

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

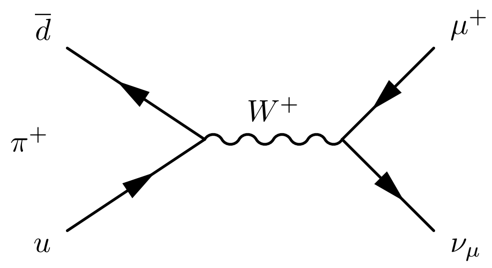
RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

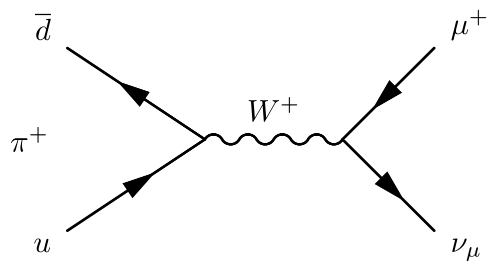
Leon M. Lederman

From P to C,P and CP



- Lederman et al.: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

From P to C,P and CP



- Lederman et al.: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

- Pion has spin 0; μ, ν_μ both have spin ½
  → spin of decay products must be *oppositely* aligned
  → Helicity of muon is the *same* as that of neutrino.

From P to C,P and CP

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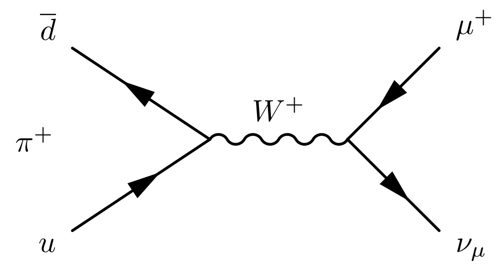
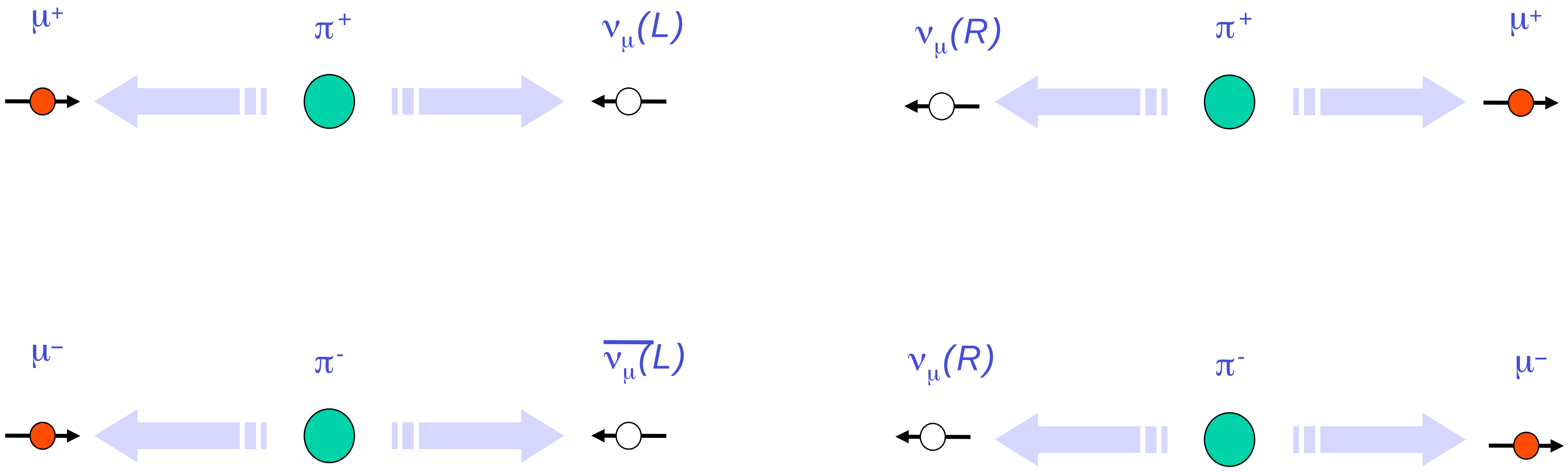
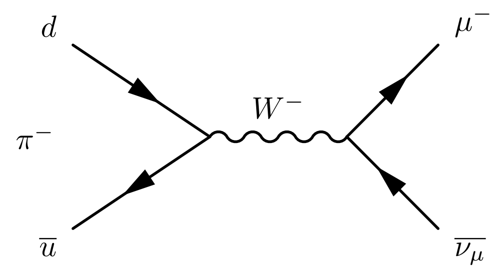


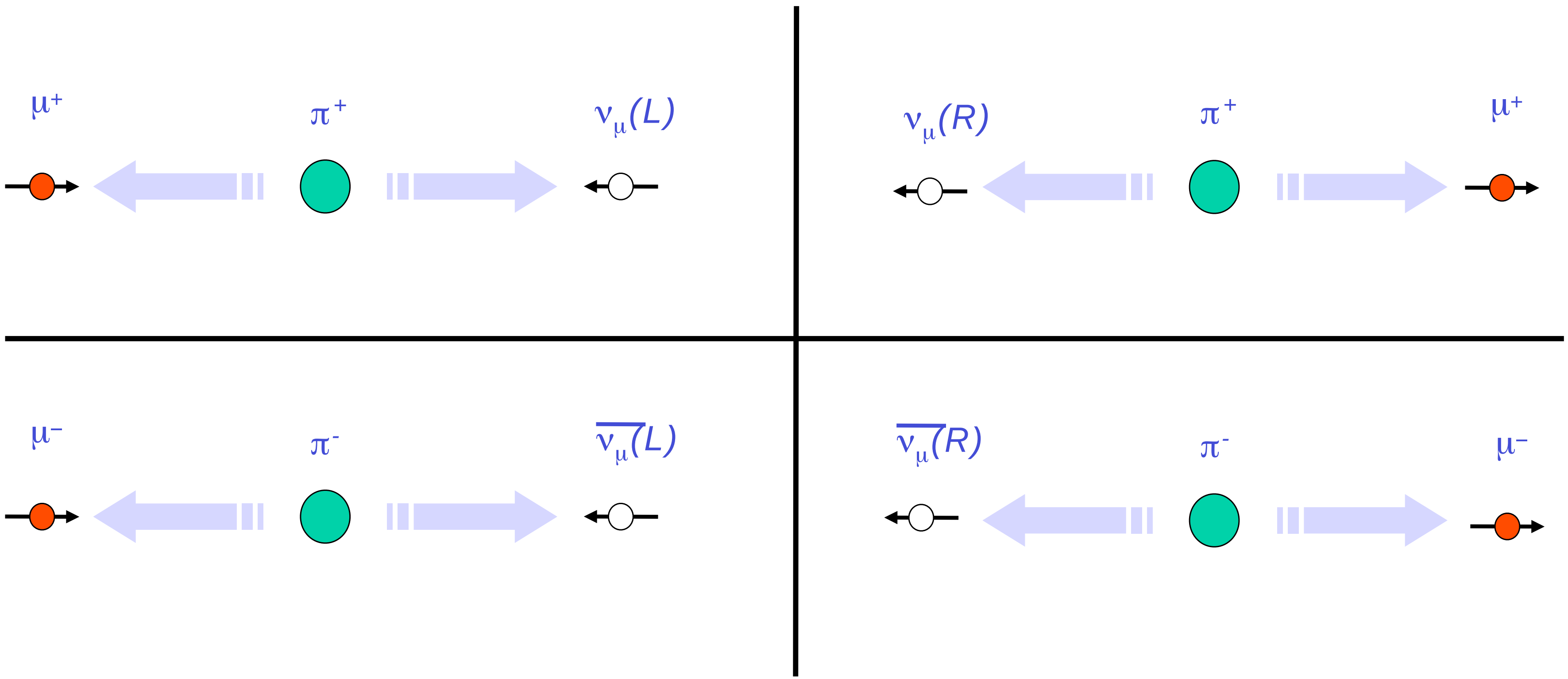


- Pion has spin 0; μ,ν_μ both have spin ½
  → spin of decay products must be *oppositely* aligned
  → Helicity of muon is the *same* as that of neutrino.

- Nice bonus: can also measure polarization of both neutrino (π^+ decay) and anti-neutrino (π^- decay)

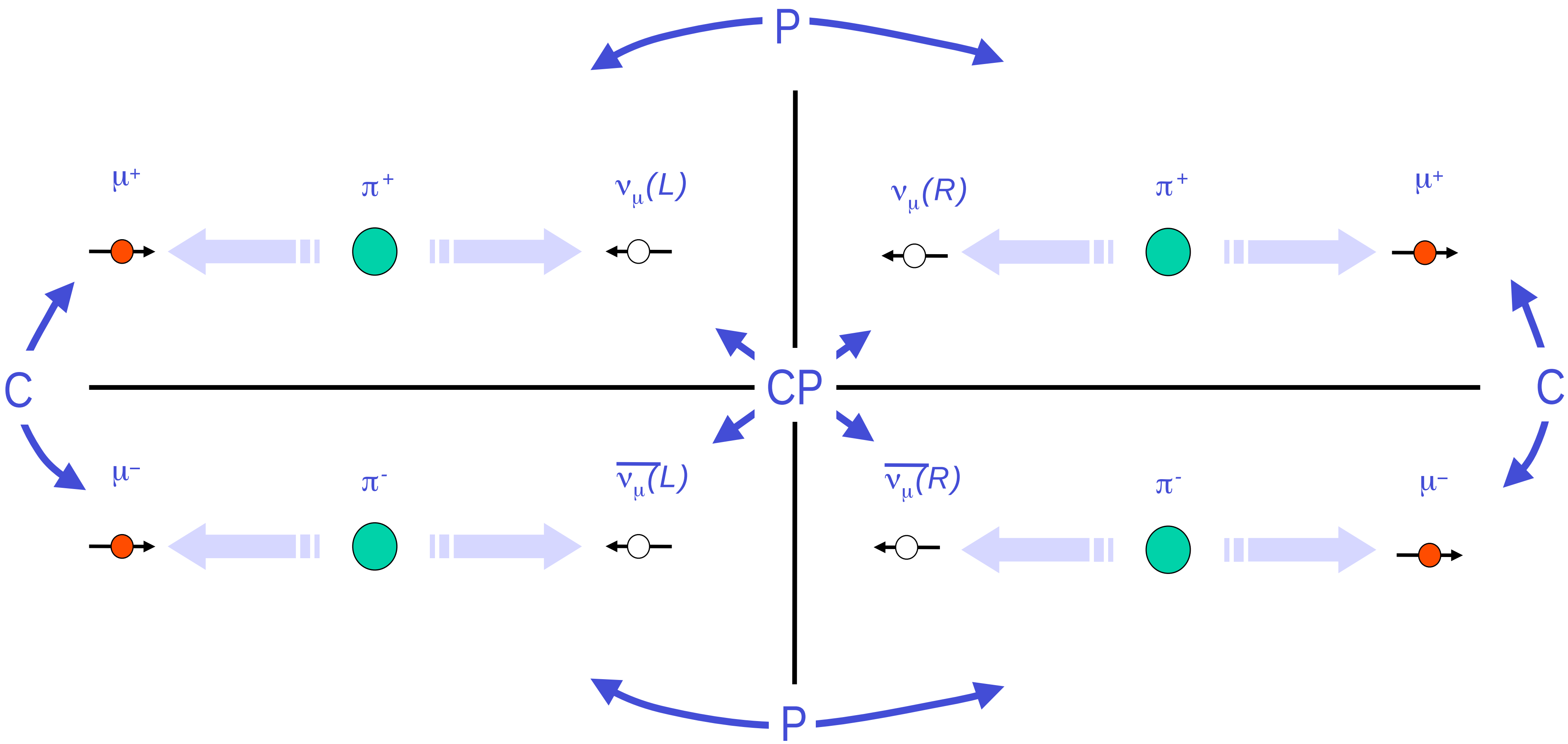


C,P and CP



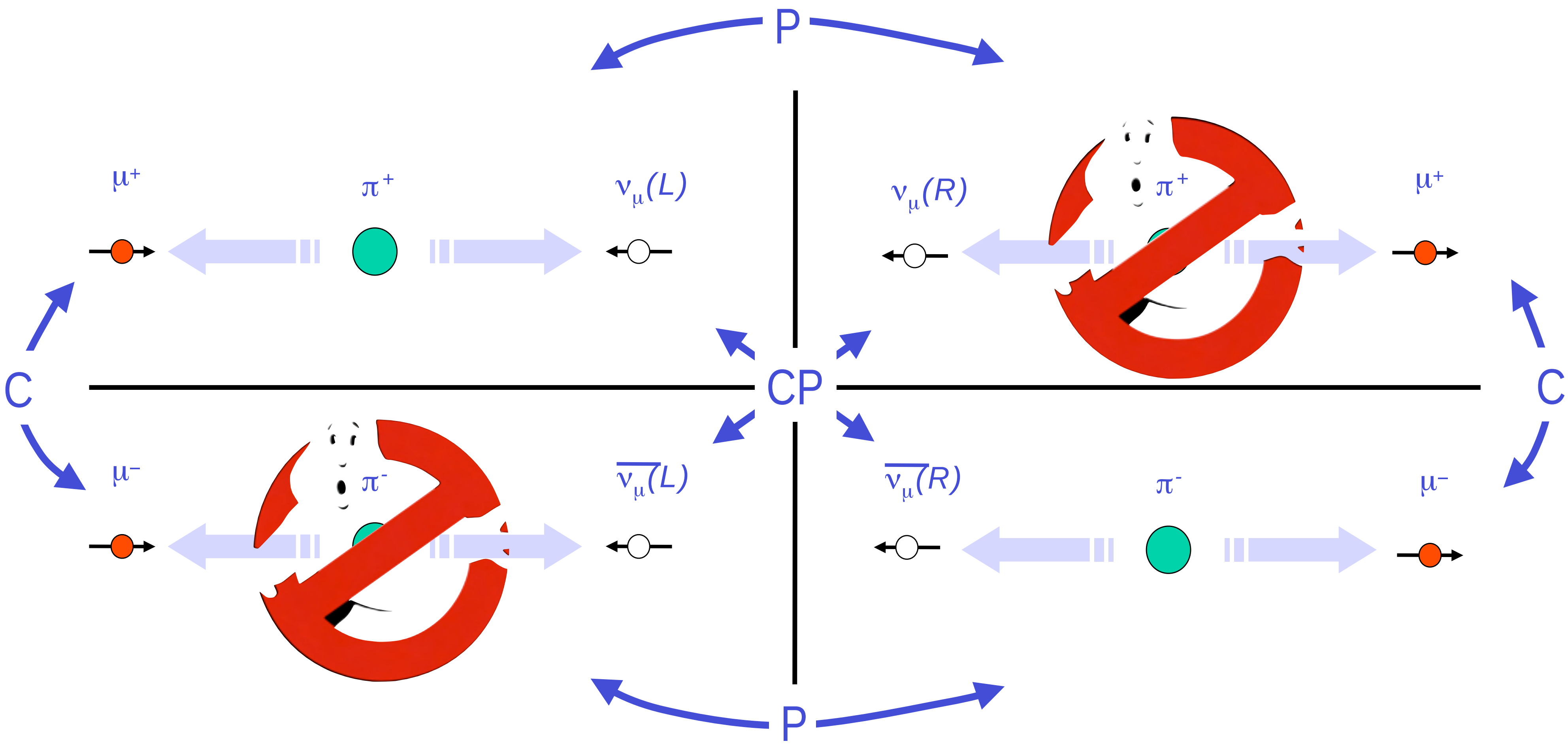
μ^+
π^+
$\nu_\mu(L)$
$\nu_\mu(R)$
π^+
μ^+
μ^-
π^-
$\overline{\nu_\mu}(L)$
$\overline{\nu_\mu}(R)$
π^-
μ^-

C,P and CP



P
μ^+
π^+
$\nu_\mu(L)$
$\nu_\mu(R)$
π^+
μ^+
C
CP
C
μ^-
π^-
$\overline{\nu_\mu}(L)$
$\overline{\nu_\mu}(R)$
π^-
μ^-
P

C,P and CP



C broken, P broken, but CP *appears* to be preserved in weak interaction!

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No 'primordial' antimatter observed
- Need something called 'CP' symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...

Kaons...

$m_K \sim 494$ MeV/c^2
No strange particles lighter than kaons exist
⇒Decay must violate "strangeness"

Strong force conserves "strangeness"
⇒Decay is a pure weak interaction

Isospin			
+1	$\overline{K^0}$ $(s\bar{d})$	K^+ $(\bar{s}u)$	
-1	K^- $(s\bar{u})$	K^0 $(\bar{s}d)$	
	-1	+1	"Strangeness"

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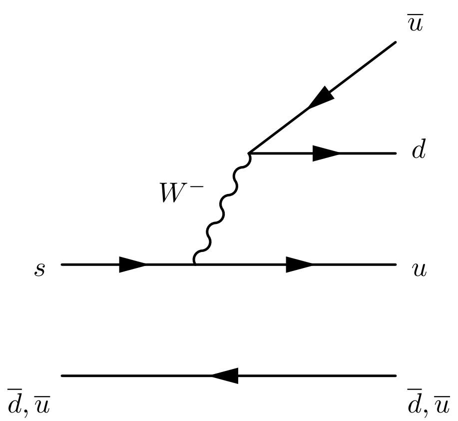

hadronic decays:

$$
\begin{aligned}
K^+ &\rightarrow \pi^+\pi^0,\ \pi^+\pi^-\pi^+,\ \pi^+\pi^0\pi^0 \\
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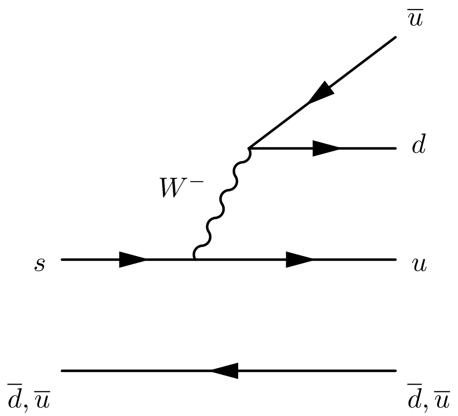

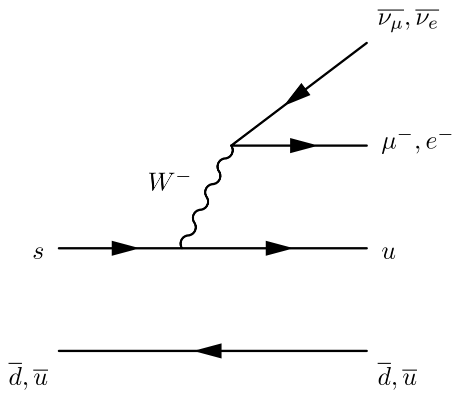

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semi-leptonic decays:

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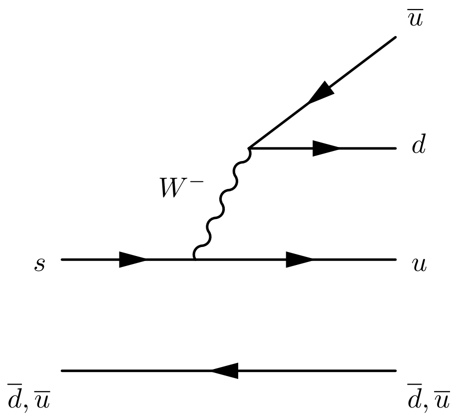

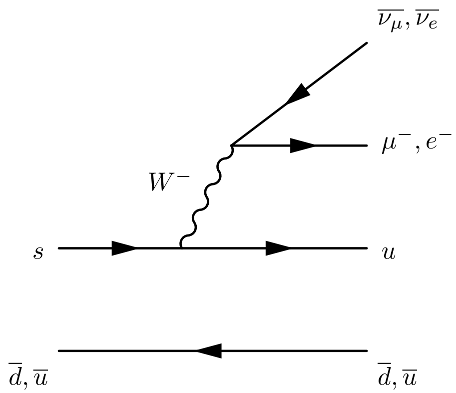

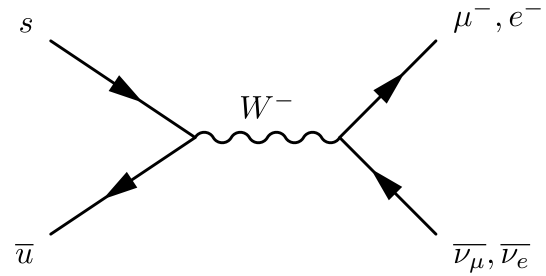

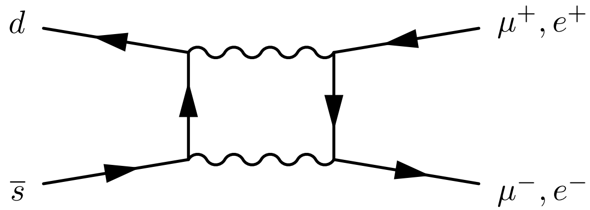

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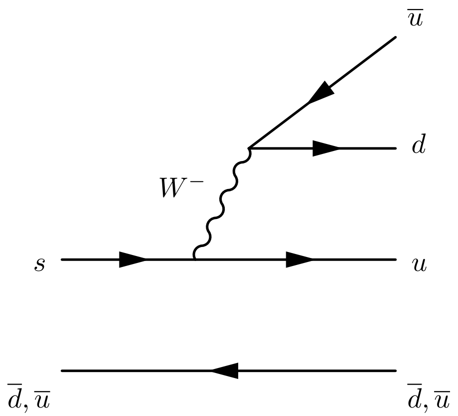

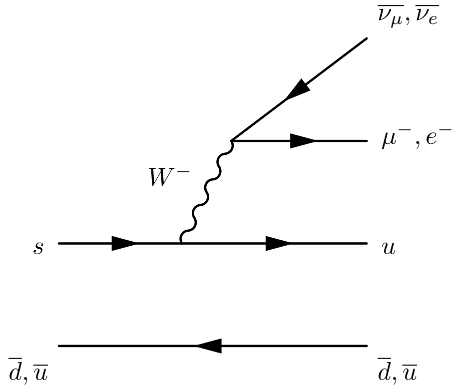

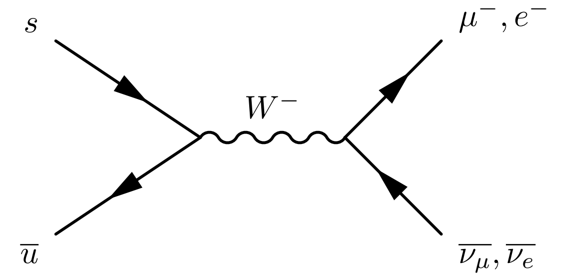

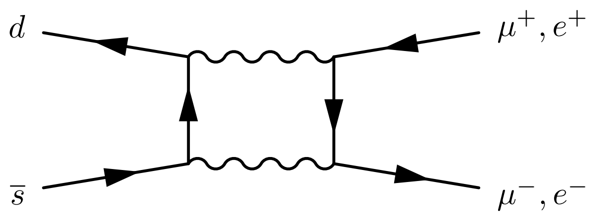

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leptonic decays:

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$$K^0 \rightarrow \mu^-\mu^+,\ e^-e^+$$
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Hadronic and leptonic decays:
particle and anti-particle behave the same

Kaons...

Isospin		
+1	$\overline{K^0}\ (s\overline{d})$	$K^+\ (\overline{s}u)$
-1	$K^-\ (s\overline{u})$	$K^0\ (\overline{s}d)$
	-1	+1 "Strangeness"

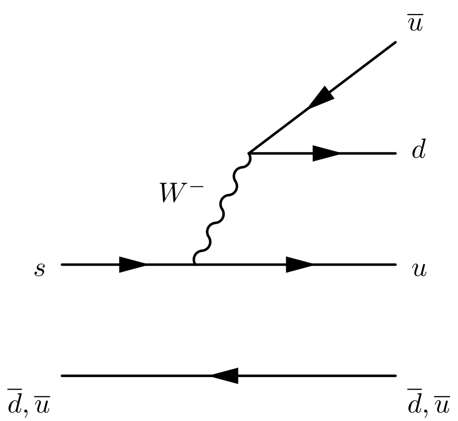
$m_K \sim 494$ MeV/c^2

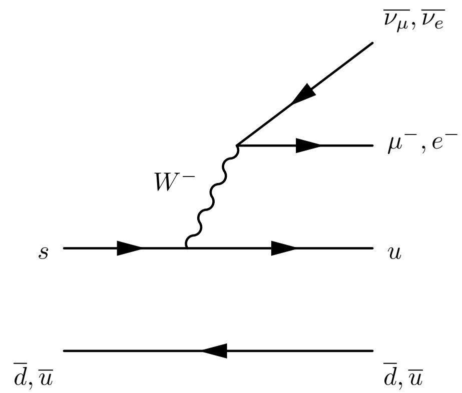
No strange particles lighter than kaons exist

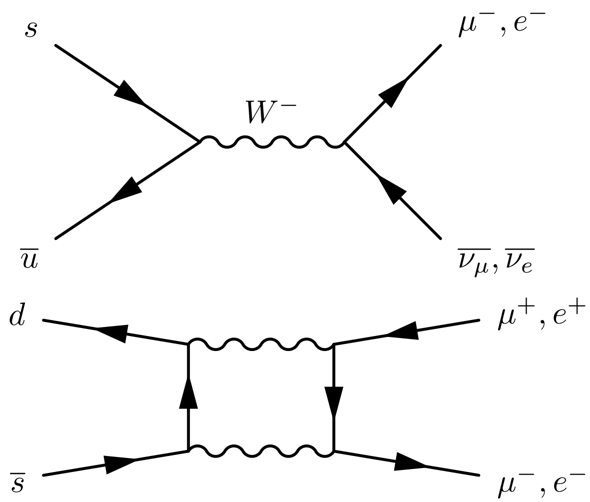
⇒Decay must violate "strangeness"

Strong force conserves "strangeness"

⇒Decay is a pure weak interaction







hadronic decays:

$$K^+ \rightarrow \pi^+\pi^0,\ \pi^+\pi^-\pi^+,\ \pi^+\pi^0\pi^0$$
$$K^- \rightarrow \pi^-\pi^0,\ \pi^-\pi^+\pi^-,\ \pi^-\pi^0\pi^0$$
$$K^0 \rightarrow \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0$$
$$\overline{K^0} \rightarrow \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0$$

semi-leptonic decays:

$$K^+ \rightarrow \pi^0\mu^+\nu_\mu,\ \pi^0 e^+\nu_e$$
$$K^- \rightarrow \pi^0\mu^-\overline{\nu_\mu},\ \pi^0 e^-\overline{\nu_e}$$
$$K^0 \rightarrow \pi^-\mu^+\nu_\mu,\ \pi^- e^+\nu_e$$
$$\overline{K^0} \rightarrow \pi^+\mu^-\overline{\nu_\mu},\ \pi^+ e^-\overline{\nu_e}$$

leptonic decays:

$$K^+ \rightarrow \mu^+\nu_\mu,\ e^+\nu_e$$
$$K^- \rightarrow \mu^-\overline{\nu_\mu},\ e^-\overline{\nu_e}$$
$$K^0 \rightarrow \mu^-\mu^+,\ e^-e^+$$
$$\overline{K^0} \rightarrow \mu^+\mu^-,\ e^+e^-$$

Hadronic and leptonic decays:
particle and anti-particle behave the same

Semi-leptonic decays:
particle and anti-particle are distinct!
"ΔQ=ΔS rule"

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

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Known:

-$K^0 \rightarrow \pi^+\pi^-$

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Known:

-$K^0 \rightarrow \pi^+ \pi^-$

Hypothesis:

-$\bar{K}^0$ is *not* equal to K^0

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Known:
- $K^0 \rightarrow \pi^+ \pi^-$

Hypothesis:
- $\bar{K}^0$ is *not* equal to K^0

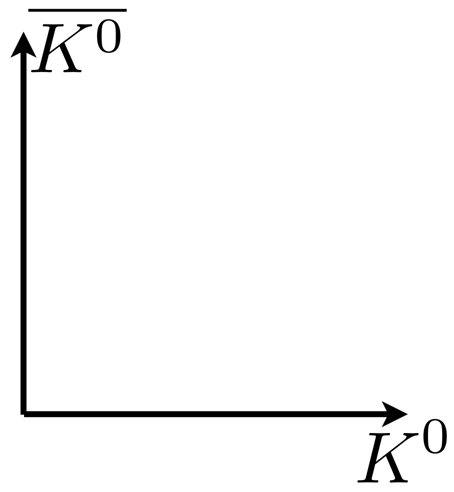
Use C (actually, CP) to deduce:
1. K^0 ($\bar{K}^0$) is an 'admixture' with two distinct lifetimes
2. Each lifetime associated to a distinct set of decay modes
3. No more than 50% of K^0 will decay to two pions...

Neutral Meson Mixing

$$\Psi(t) = a(t)\left|K^0\right\rangle + b(t)\left|\overline{K^0}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

$$\hat{H} = \begin{pmatrix} M_K & 0 \\ 0 & M_K \end{pmatrix}$$



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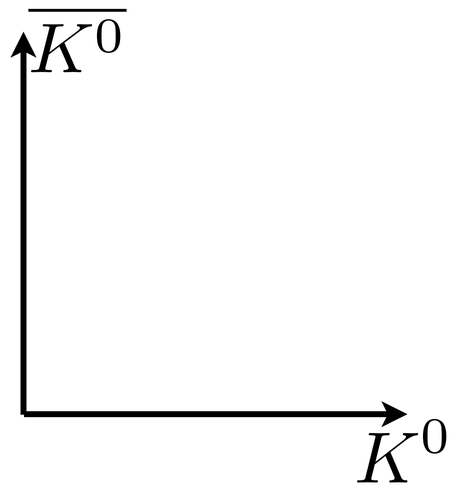

As (eventually) K^0 and $\overline{K^0}$ decay, add an *antihermitic* part to the Hamiltonian

$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & 0 \\ 0 & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$

$$\frac{d}{dt}\left(|a|^2 + |b|^2\right) = -\begin{pmatrix} a^* & b^* \end{pmatrix}\begin{pmatrix} \Gamma_K & 0 \\ 0 & \Gamma_K \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

Can identify Γ_K as the decay width ($=1/\tau_K$)

Neutral Meson Mixing

$$\Psi(t) = a(t)\left|K^0\right\rangle + b(t)\left|\overline{K^0}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

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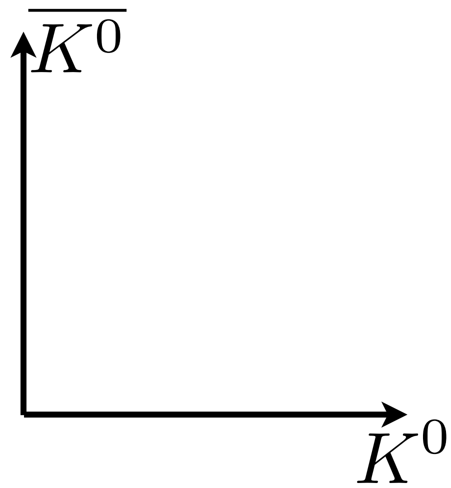

Neutral Meson Mixing

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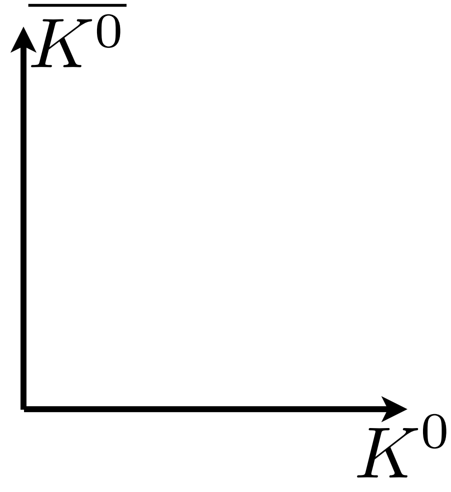


Now consider the effect of CP symmetry:

$$\text{CP}\quad \begin{array}{ccc} K^0 & \leftrightarrow & \pi^+\pi^- \\ \overline{K^0} & \leftrightarrow & \pi^+\pi^- \end{array} \quad \Leftrightarrow \quad K^0 \leftrightarrow \overline{K^0}$$

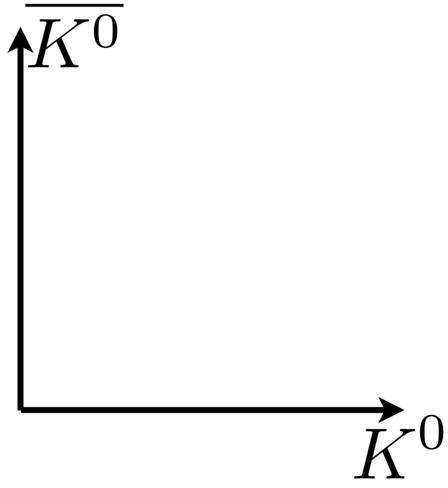
$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & \Delta \\ \Delta & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$

Neutral Meson Mixing

$$\Psi(t) = a(t)\left|K^0\right\rangle + b(t)\left|\overline{K^0}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

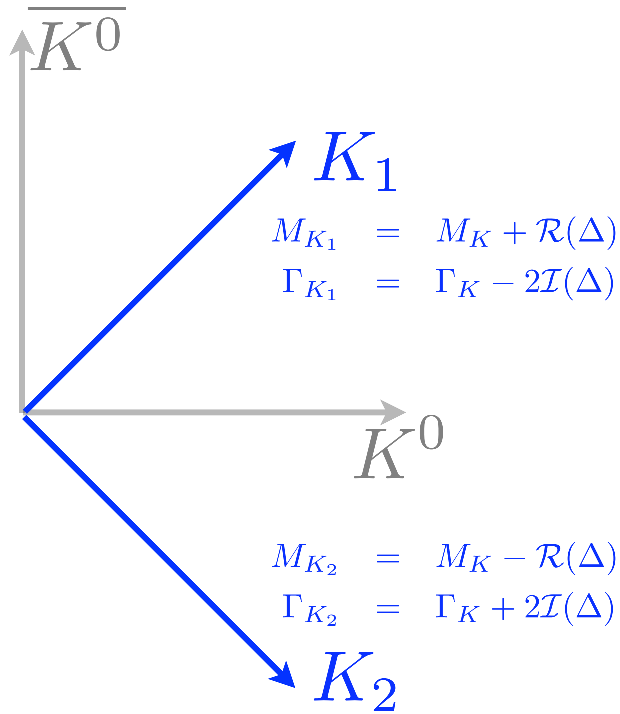
$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & 0 \\ 0 & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$



Now consider the effect of CP symmetry:

$$\mathrm{CP}\ \begin{matrix} K^0 & \leftrightarrow & \pi^+\pi^- \\ \overline{K^0} & \leftrightarrow & \pi^+\pi^- \end{matrix} \quad \Longleftrightarrow \quad K^0 \leftrightarrow \overline{K^0}$$

$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & \Delta \\ \Delta & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$



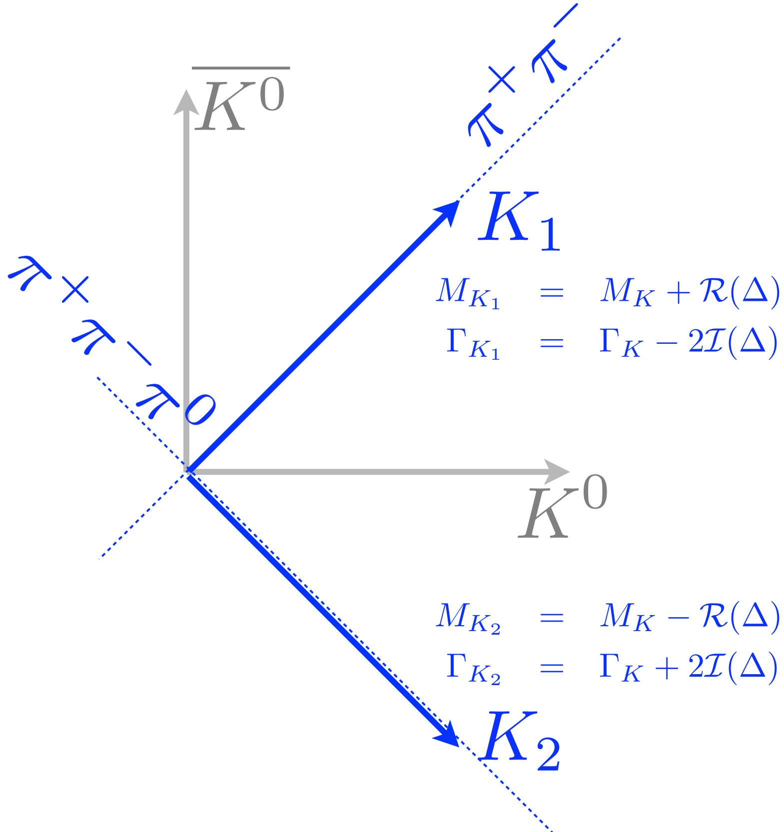
K^0 and $\overline{K^0}$ are *no longer* eigenstates of H
their *sum* (K_1) & *difference* (K_2) are eigenstates...
and K_1 and K_2 have *different* masses and lifetimes

Neutral Kaon Mixing

$$|K_1\rangle = \frac{|K^0\rangle + |\overline{K^0}\rangle}{\sqrt{2}}$$

$$|K_2\rangle = \frac{|K^0\rangle - |\overline{K^0}\rangle}{\sqrt{2}}$$

- K_1 and K_2 are their *own* antiparticle, but one is CP even, the other CP odd
- *Only* the CP even state can decay into 2 pions
  - $|K_1\rangle$ (CP=+1) → ππ (CP=-1 * -1 =+1)
- The CP odd state will decay into 3 pions instead
  - $|K_2\rangle$ (CP=-1) → ππ π (CP = -1*-1*-1 = -1)
- <u>There is a huge difference in available phasespace between the two (~600x!) → the CP *even* state will decay much faster</u>
  - Difference due to $M(K^0) \cong 3M(\pi)$
  - Δ has a large imaginary component!



Experimental confirmation...

Observation of Long-Lived Neutral V Particles*

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,
Columbia University, New York, New York

AND

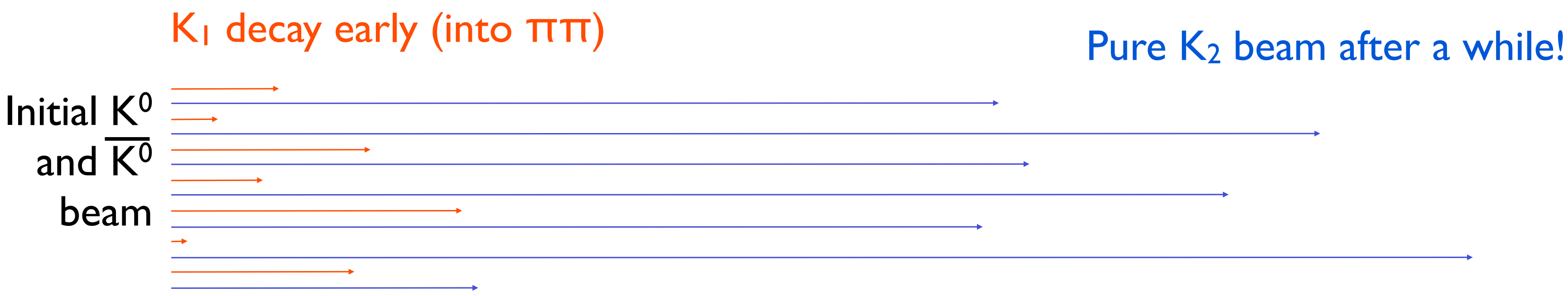
W. CHINOWSKY, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e \nu$ is probably prominent,[9] the mode $\pi\mu\nu$ and perhaps other combinations may exist but are more difficult to establish, and $\pi^+\pi^-\pi^0$ is relatively rare. Although the Gell-Mann-Pais predictions (I) and (II) have been confirmed, long lifetime and "anomalous" decay mode are not sufficient to identify the observed particle with $\theta_2{}^0$. In particular,

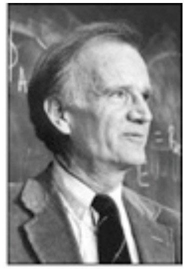
Designing a CP violation experiment

- How do you obtain a pure 'beam' of (CP-odd!) K_2 particles?
- Exploit that decay of K_1 into two pions is *much* faster than decay of K_2 into three pions
  - $\tau_1 = 0.89 \times 10^{-10}$ sec
  - $\tau_2 = 5.2 \times 10^{-8}$ sec (~600 times larger!)
- Beam of neutral Kaons automatically becomes beam of $|K_2\rangle$ as all $|K_1\rangle$ decay very early on…



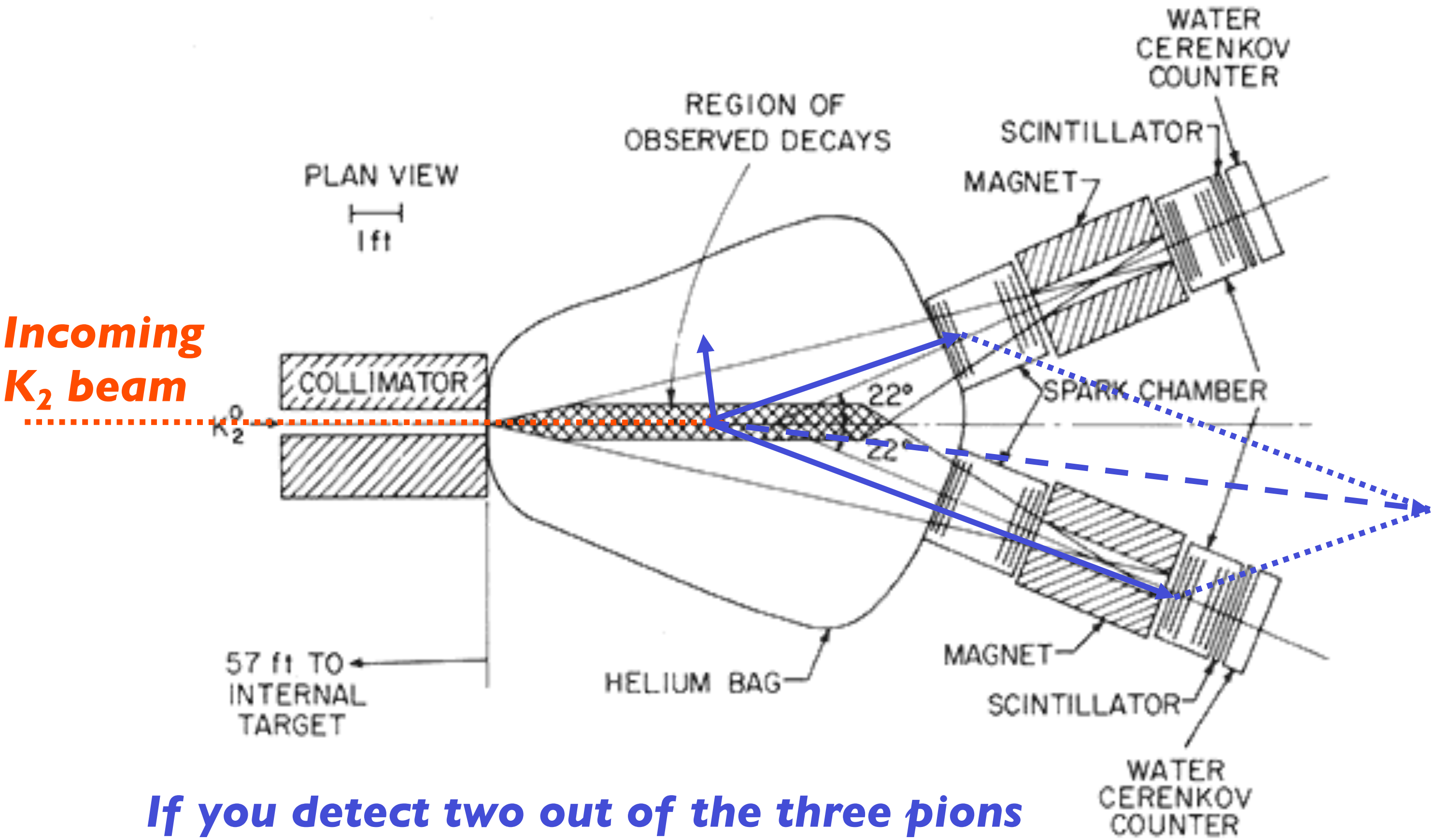
The Cronin & Fitch Experiment


James Cronin


Val Fitch

Essential idea: Look for (CP violating)
$K_2 \rightarrow \pi^+\pi^-$ decays 20 meters away from
K^0 production point

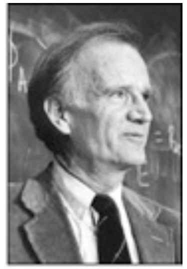
Decay of K_2 into 3 pions



If you detect two out of the three pions of a $K_2 \rightarrow \pi\pi\pi$ decay their combined momentum will generally not point along the beam line

The Cronin & Fitch Experiment


James Cronin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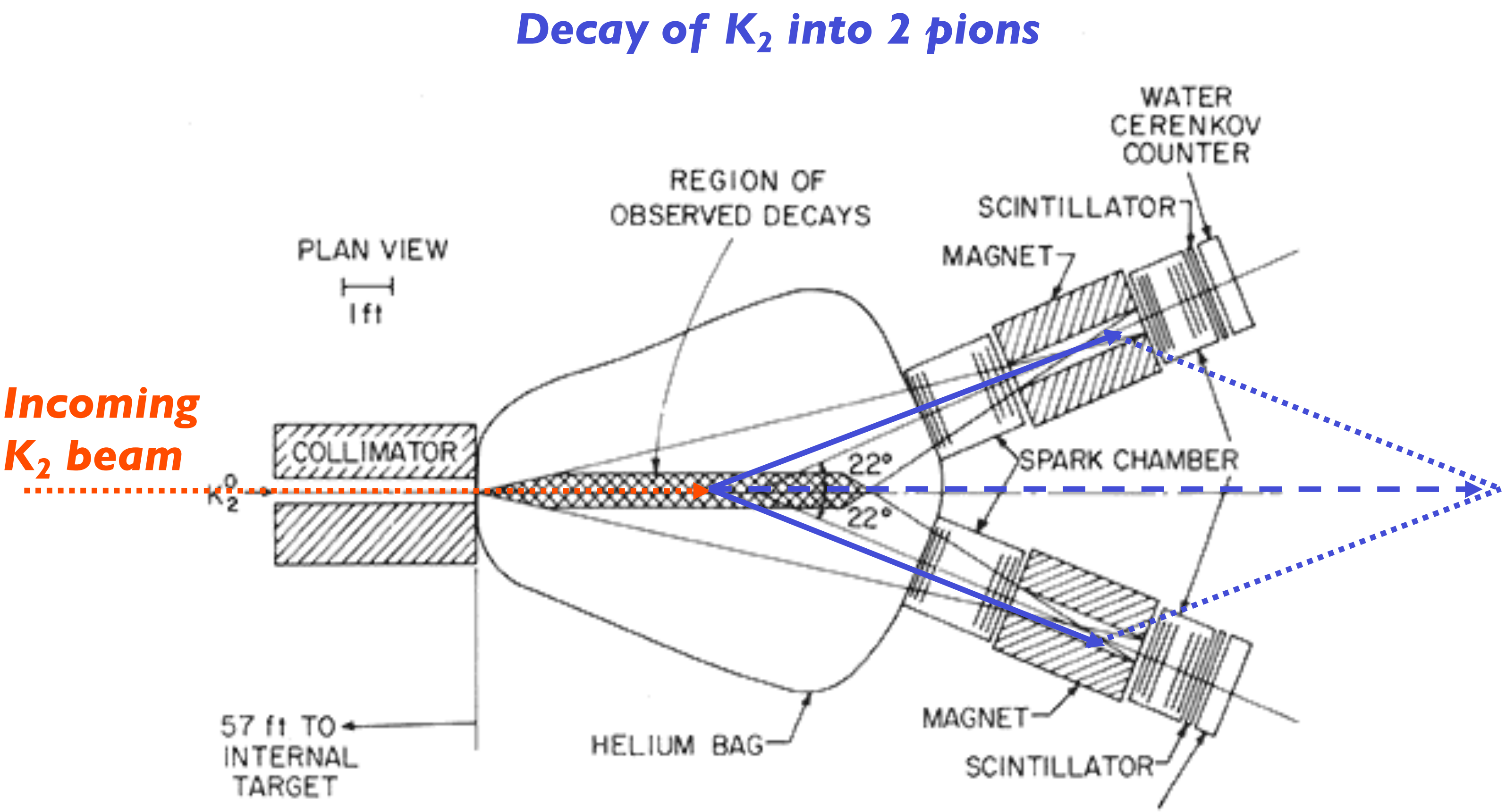

Plot the angle between the momentum direction of two pions and the beamline

The Cronin & Fitch Experiment

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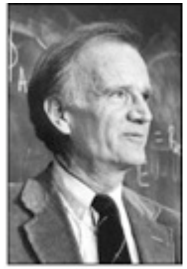

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Essential idea: Look for (CP violating)
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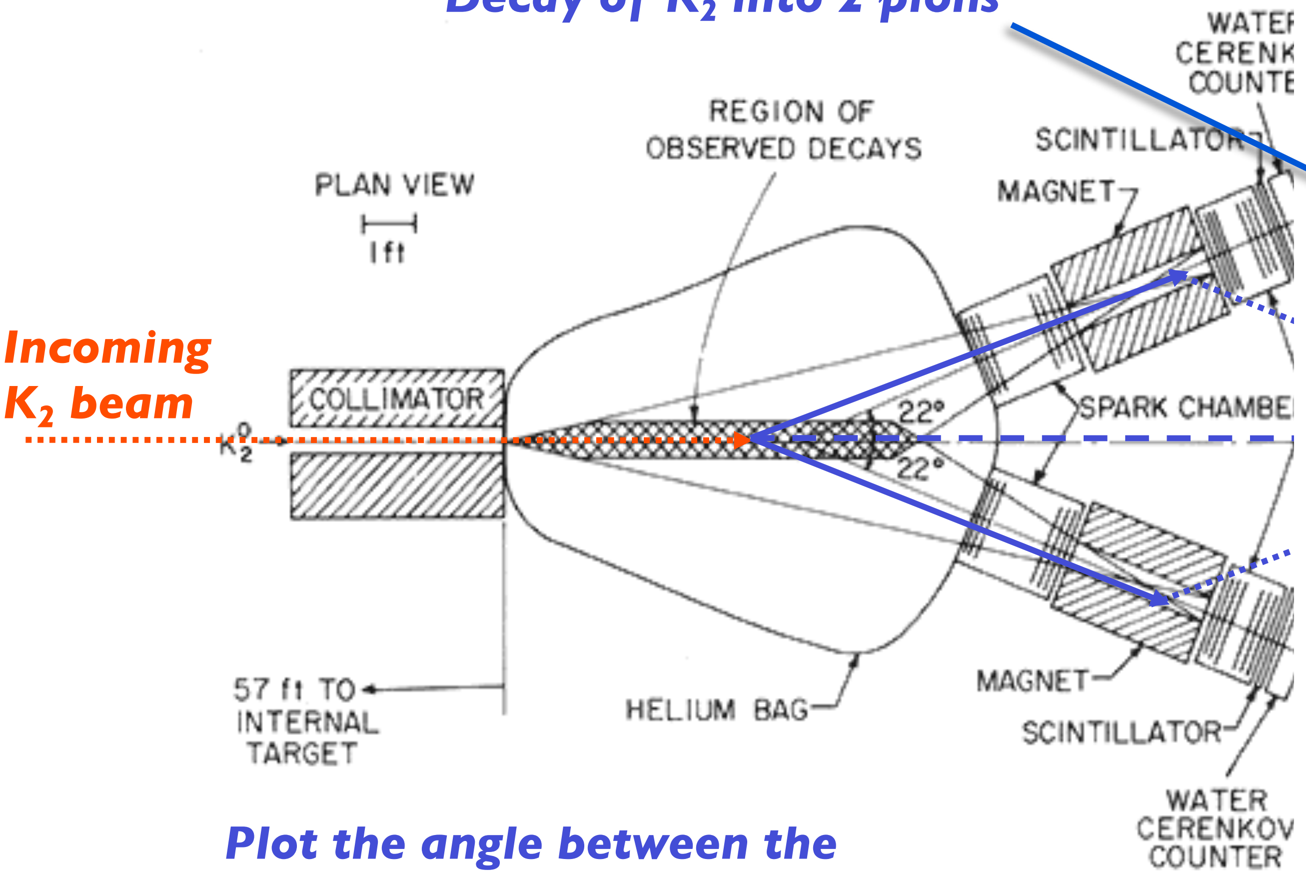
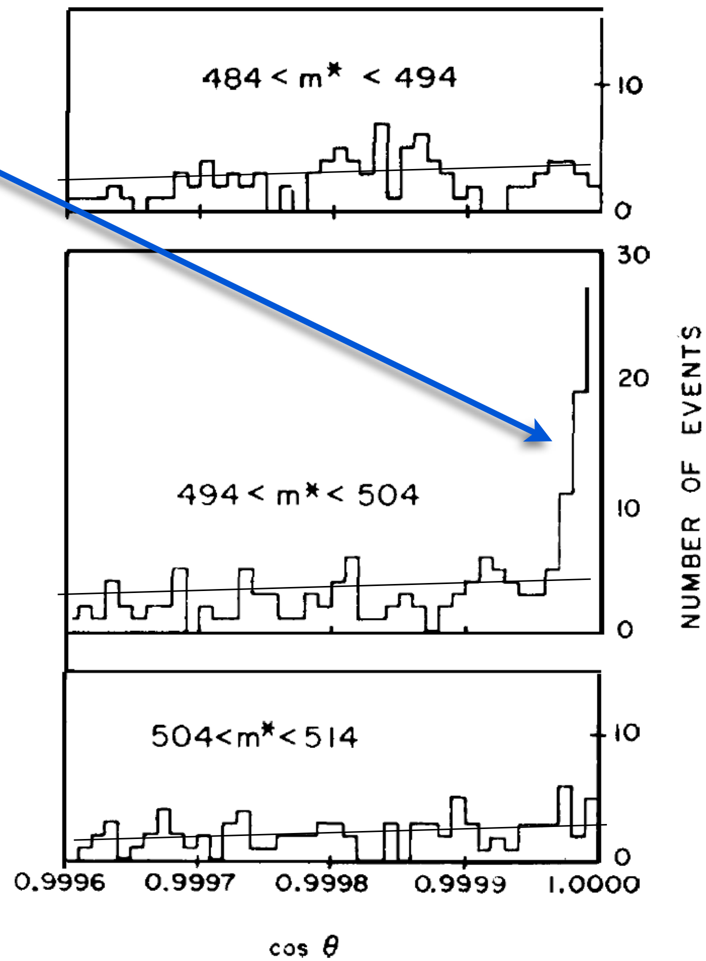
EVIDENCE FOR THE 2π DECAY OF THE $K_2{}^0$ MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

Decay of K_2 into 2 pions

Incoming K_2 beam



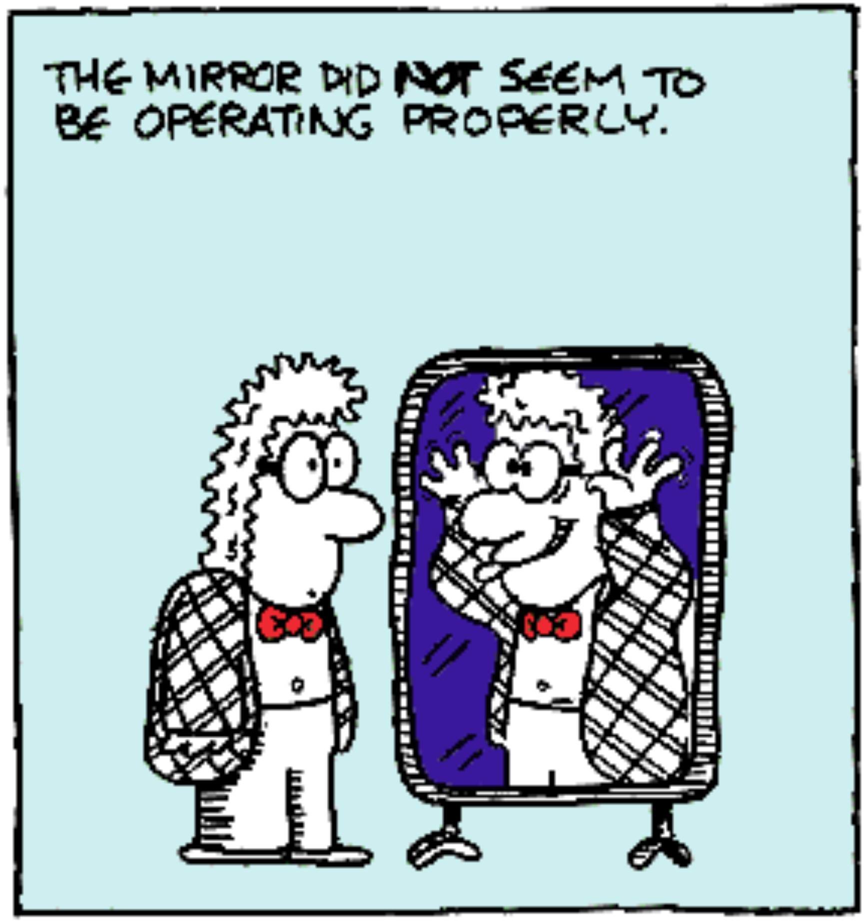


Plot the angle between the momentum direction of two pions and the beamline

CP is 'a bit' broken by weak interaction

Nobel prize 1980:

"The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments."



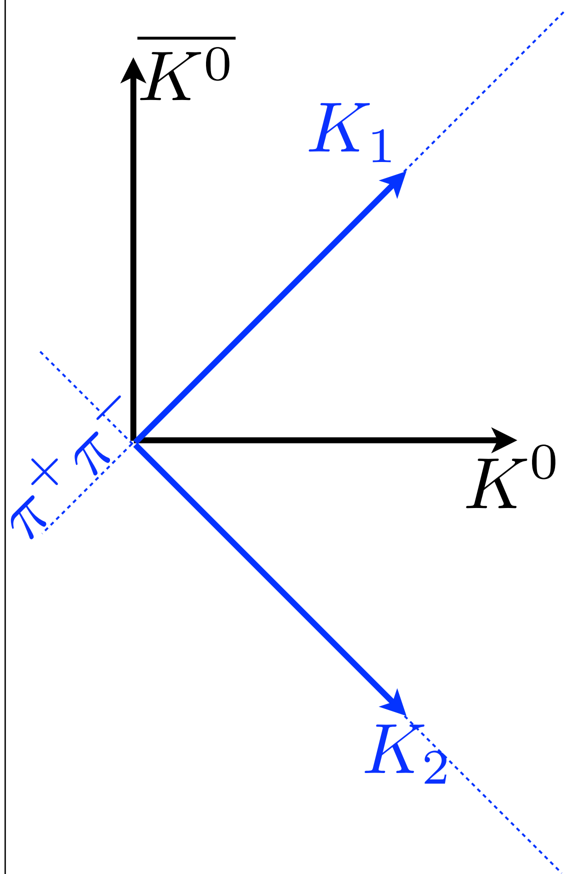
How to construct a physics law that violates a symmetry just a tiny bit?

- Only 0.2% of KL decays violate CP...
- Maximal (100%) violation of P symmetry "easily" interpretable/explained as absence of a right-handed neutrino...

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!

How to describe this?



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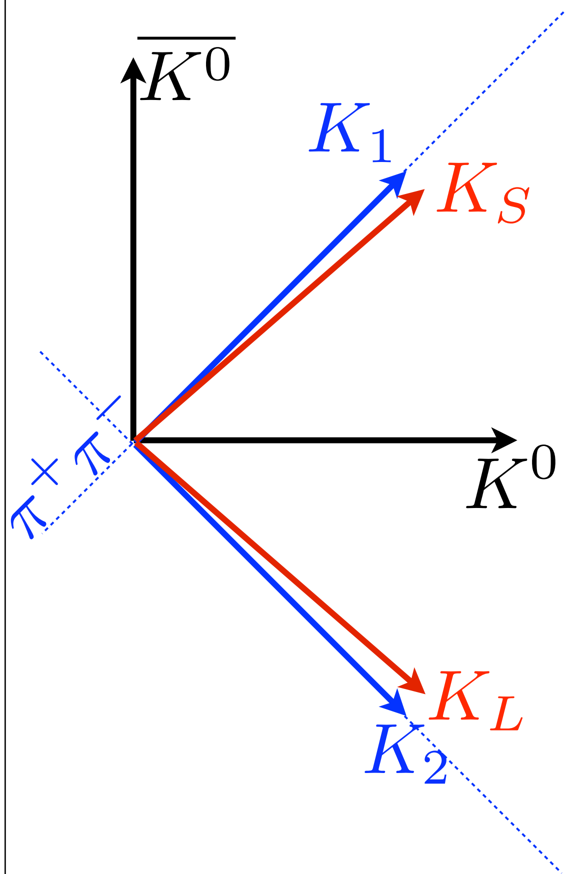

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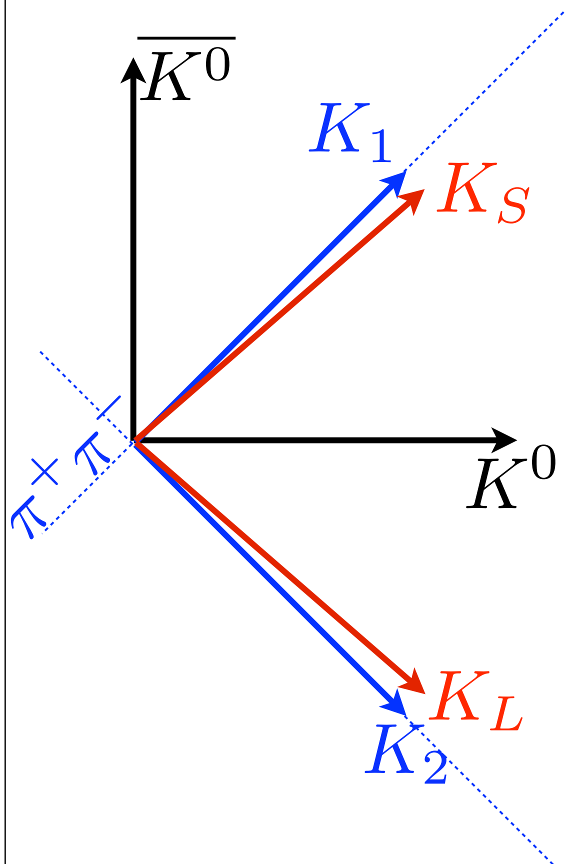
$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$

$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

$$\text{with } |\epsilon| << 1$$

How to describe this?



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$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

$$\text{with } |\epsilon| << 1$$

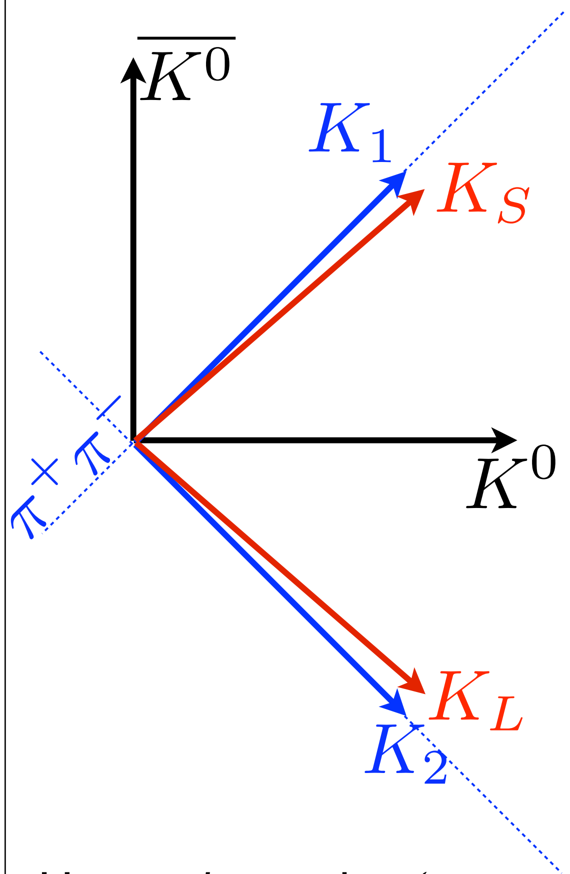
Have a *choice* when 'parameterizing' K_S and K_L:

1. in terms of K^0 and $\overline{K^0}$
2. in terms of K_1 and K_2

Historically, 'kaon physics' has chosen 2, but in in 'B physics' (next lectures!), the equivalent of 1 is very much dominant (as ε_B=0, but still q≠1 & p≠1...)

This tends to be *very* confusing...

How to describe this?



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$$|K_L\rangle = p\left|K^0\right\rangle - q\left|\overline{K^0}\right\rangle$$

$$|K_S\rangle = p\left|K^0\right\rangle + q\left|\overline{K^0}\right\rangle$$

Have a *choice* when 'parameterizing' K_S and K_L:

1. in terms of K^0 and $\overline{K^0}$
2. in terms of K_1 and K_2

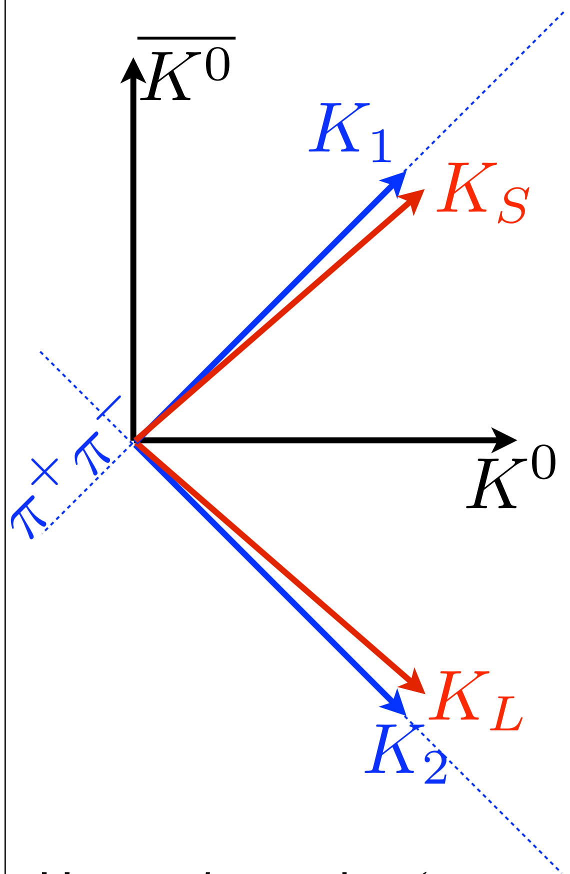
Historically, 'kaon physics' has chosen 2, but in in 'B physics' (next lectures!), the equivalent of 1 is very much dominant (as $\varepsilon_B=0$, but still $q \neq 1$ & $p \neq 1$...)

$$\langle K_L | K_L \rangle \equiv 1 \Rightarrow |q|^2 + |p|^2 = 1$$

eg. $$p = 1 + \epsilon \qquad q = 1 - \epsilon \qquad \text{with } |\epsilon| << 1$$

This tends to be *very* confusing...

How to describe this?



EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives and R_T is the branching ratio including decay to two π^0. Using $R_T = \frac{3}{2}R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3 \times 10^{-3}$.

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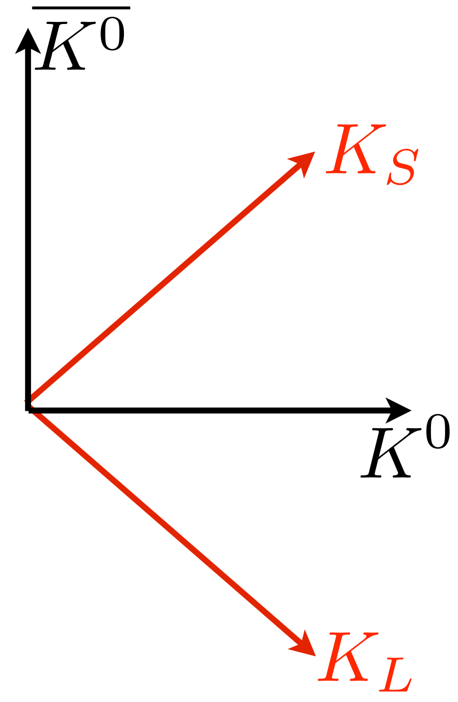
Historically, 'kaon physics' has chosen 2, but in in 'B physics' (next lectures!), the equivalent of 1 is very much dominant...

This tends to be *very* confusing...

Time Evolution of K^0 and $\overline{K^0}$...

$$\begin{pmatrix} K_S(0) \\ K_L(0) \end{pmatrix} = \begin{pmatrix} +q & +p \\ +q & -p \end{pmatrix}\begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix}$$

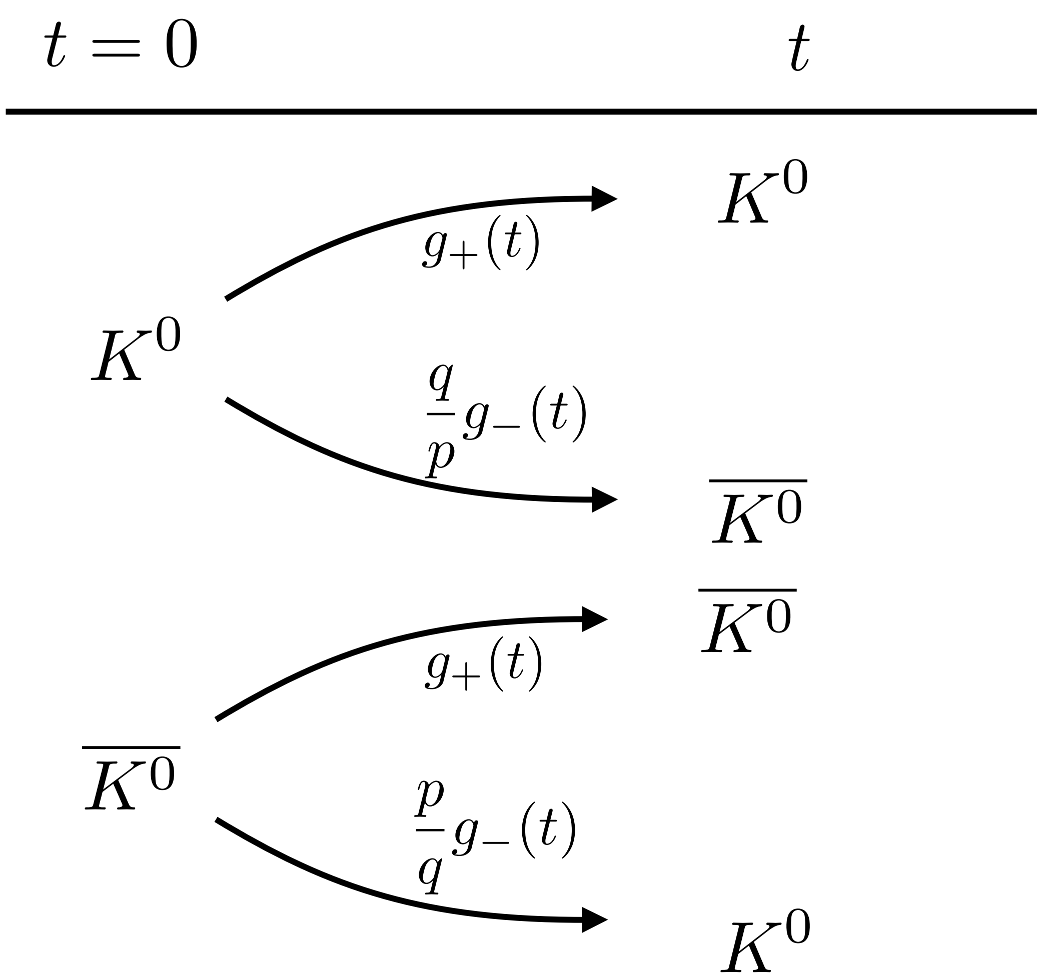


$$\begin{pmatrix} K_S(t) \\ K_T(t) \end{pmatrix} = \begin{pmatrix} e^{-i\omega_S t} & 0 \\ 0 & e^{-i\omega_L t} \end{pmatrix}\begin{pmatrix} K_S(0) \\ K_L(0) \end{pmatrix}$$

$$\begin{pmatrix} K^0(t) \\ \overline{K^0}(t) \end{pmatrix} = \begin{pmatrix} +1/2q & +1/2q \\ +1/2p & -1/2p \end{pmatrix}\begin{pmatrix} K_S(t) \\ K_L(t) \end{pmatrix}$$

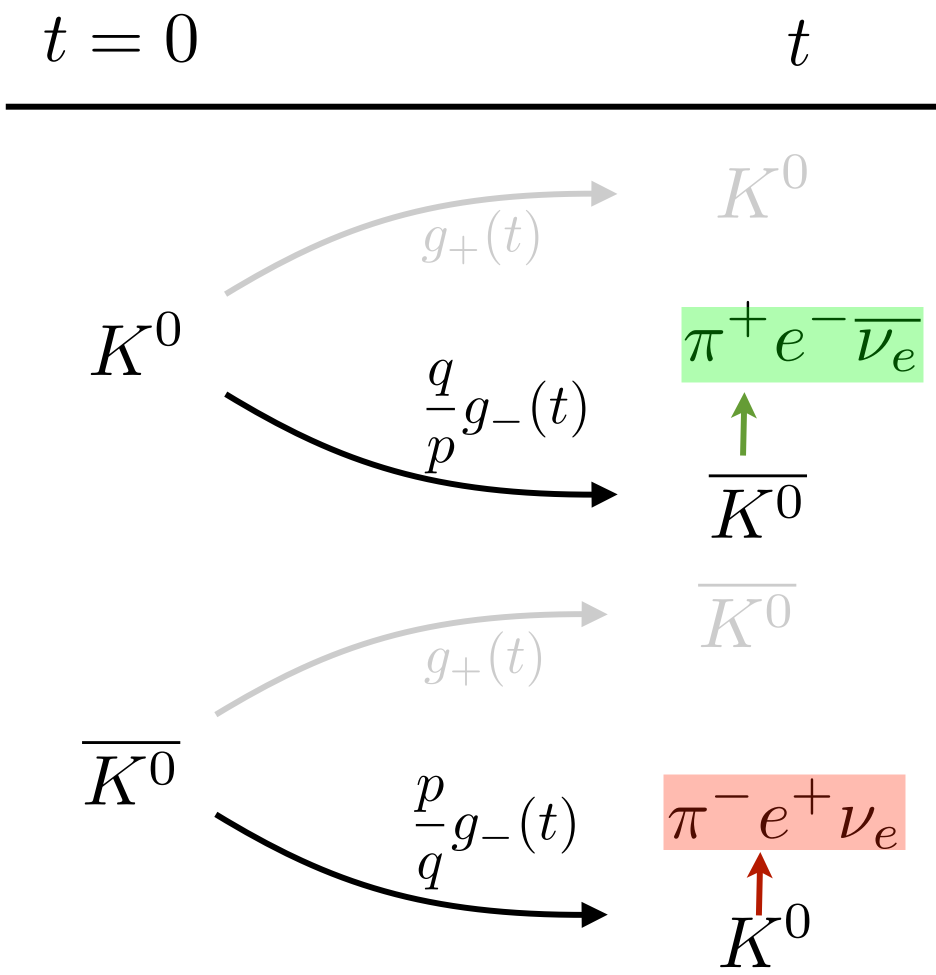
Time Evolution of K^0 and $\overline{K^0}$...

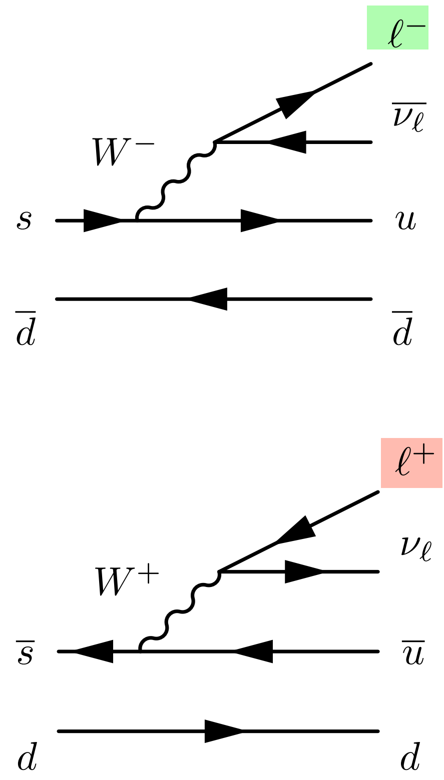
$$\begin{pmatrix} K^0(t) \\ \overline{K^0}(t) \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{p}{q} g_-(t) \\ \frac{q}{p} g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix} \qquad g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$



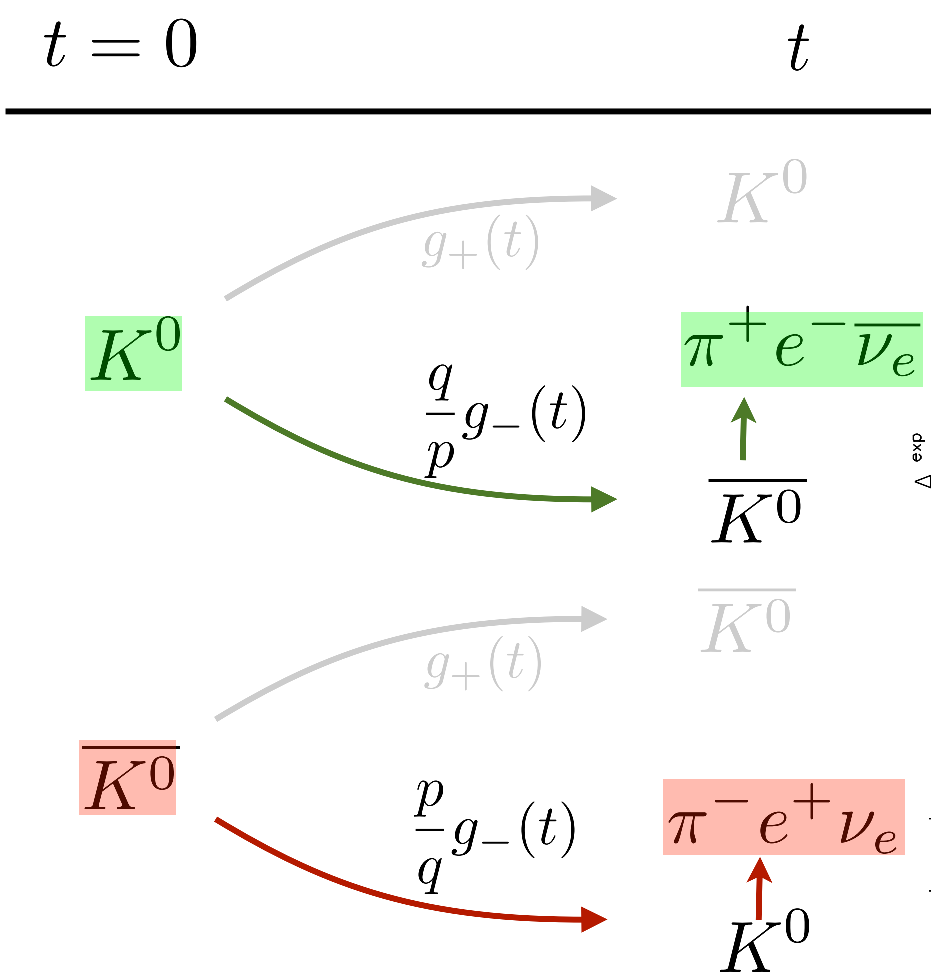
Time Evolution of K^0 and $\overline{K^0}$...

$$\begin{pmatrix} K^0(t) \\ \overline{K^0}(t) \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{p}{q} g_-(t) \\ \frac{q}{p} g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix} \qquad g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

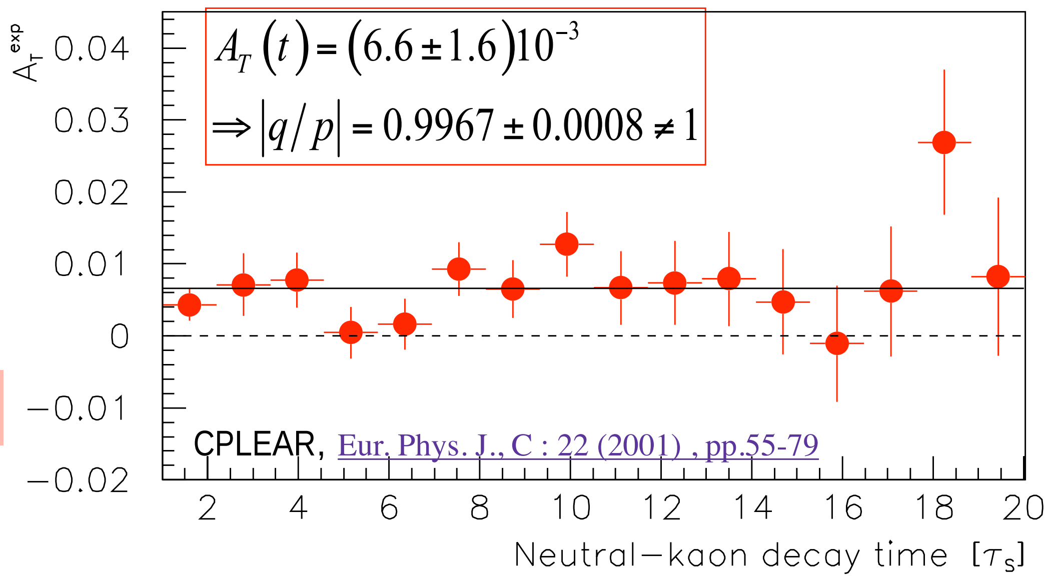




Time Evolution of K^0 and $\overline{K^0}$...



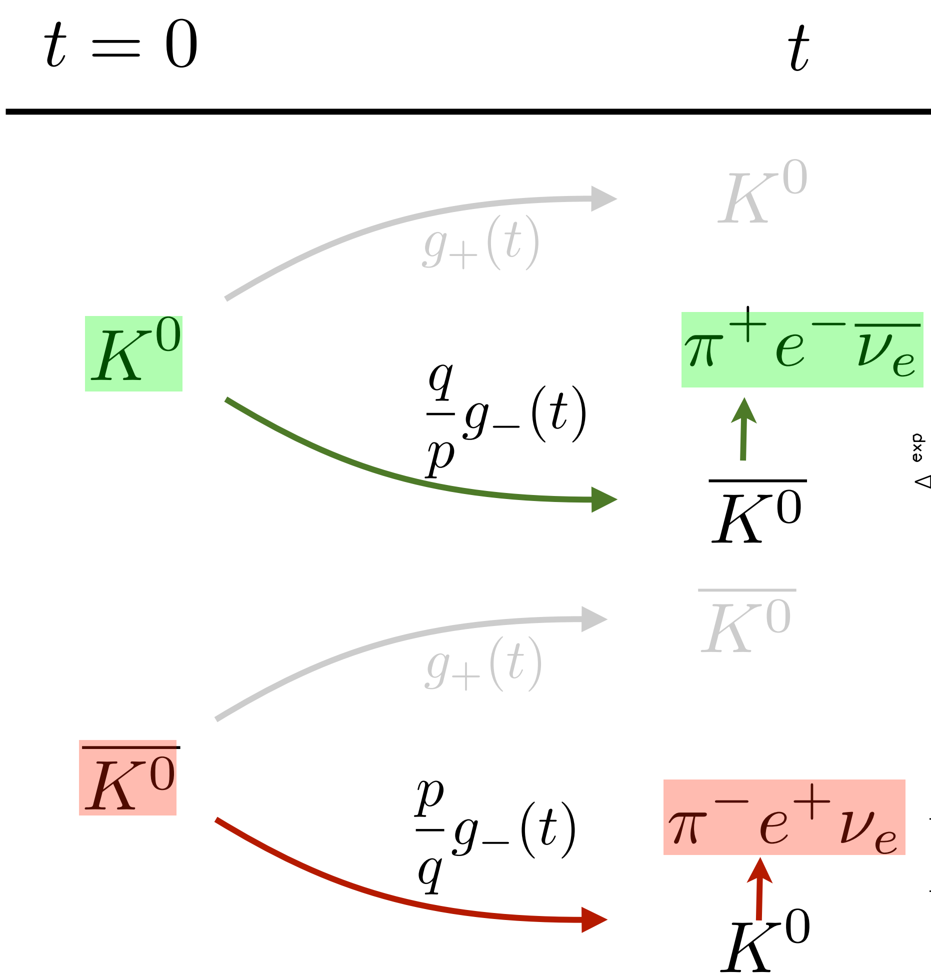
$$A_T(t) = \frac{\overline{I}_{\pi^- e^+ \nu}(t) - I_{\pi^+ e^- \overline{\nu}}(t)}{\overline{I}_{\pi^- e^+ \nu}(t) + I_{\pi^+ e^- \overline{\nu}}(t)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = 4\mathcal{R}\epsilon$$



Time Evolution of K^0 and $\overline{K^0}$...

This measurement allows one to make an *ABSOLUTE* distinction between matter and anti-matter

– *Positive charge is the charged carried by the lepton preferentially produced in the decay of the neutral K meson*



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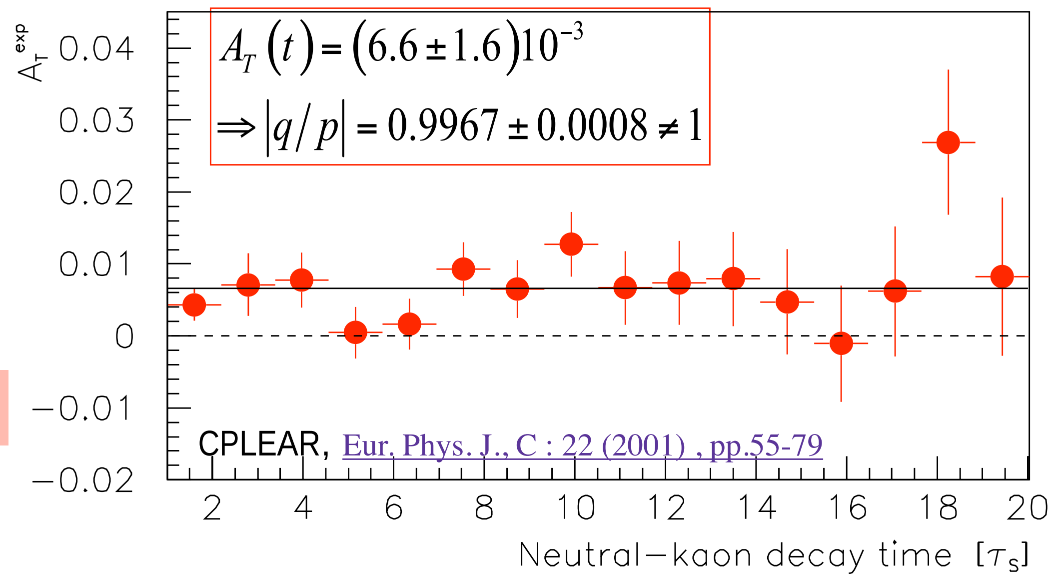

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter

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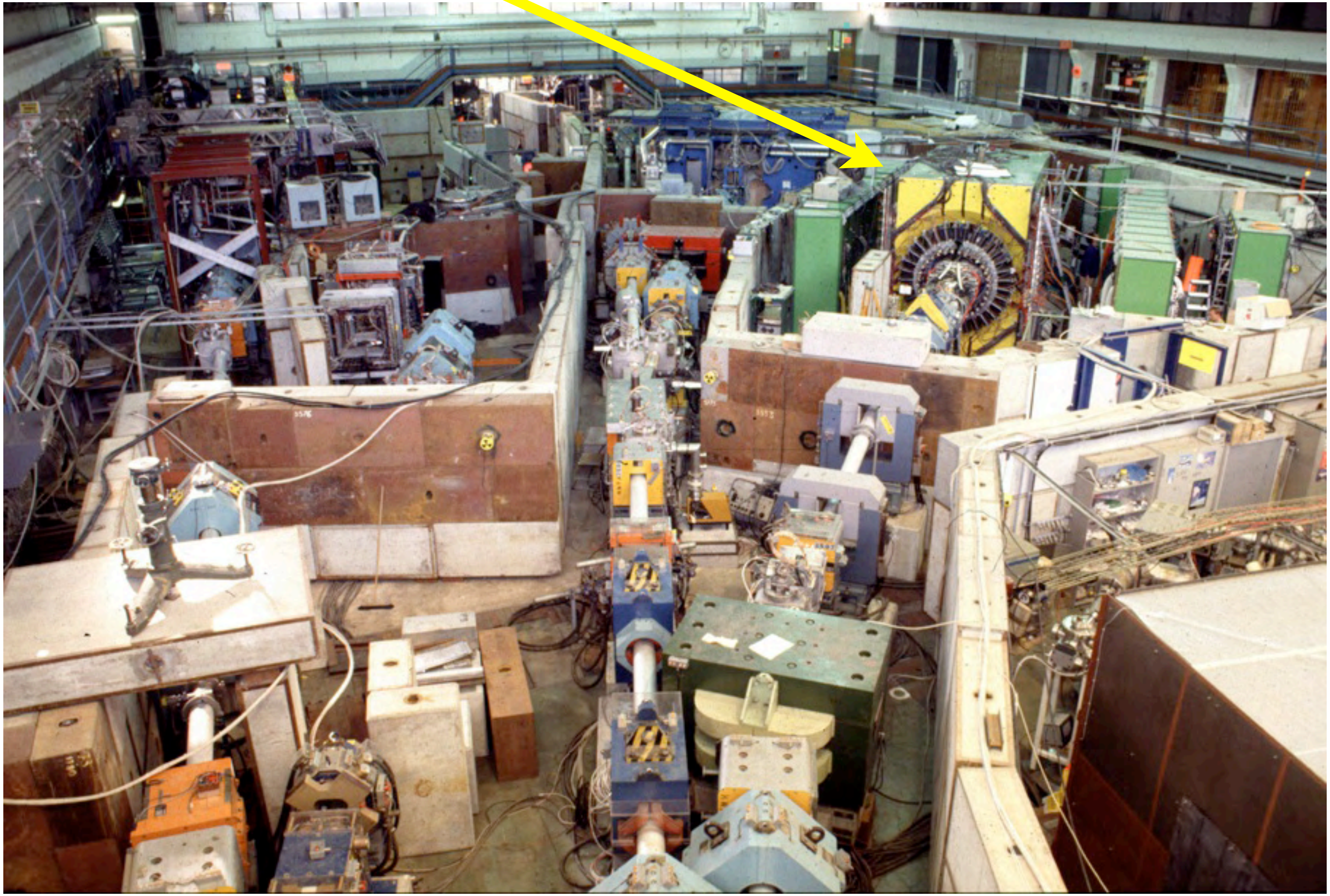

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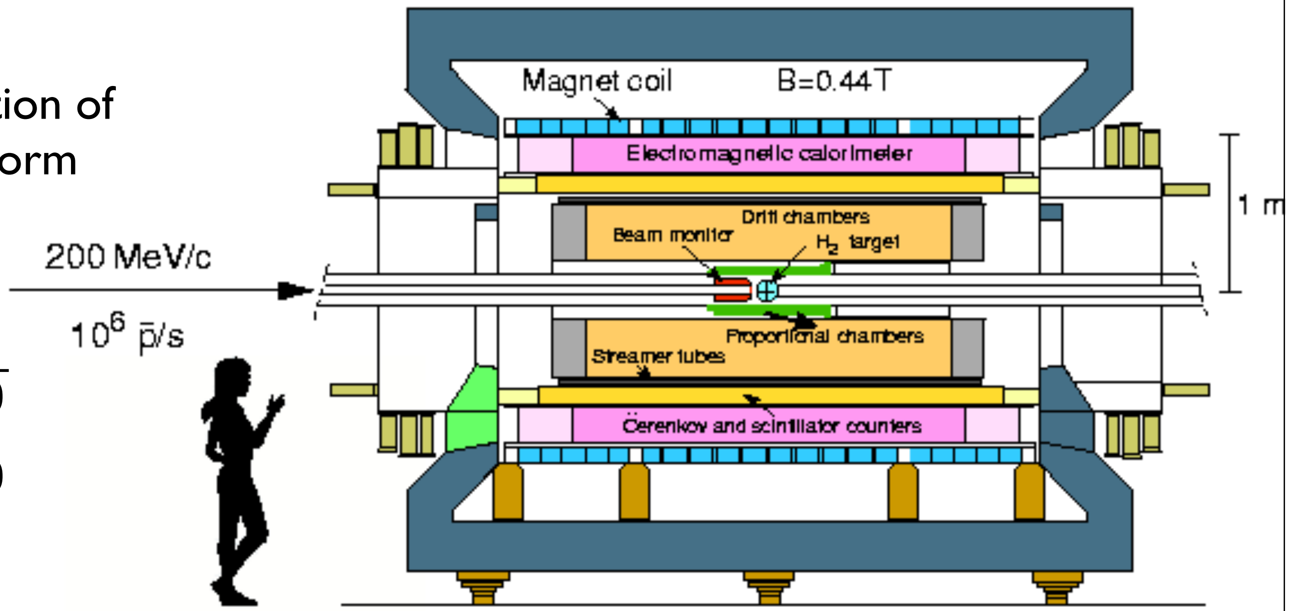
Use the strangeness conservation of the strong interactions to perform *tagged* K^0 and $\overline{K^0}$ production:

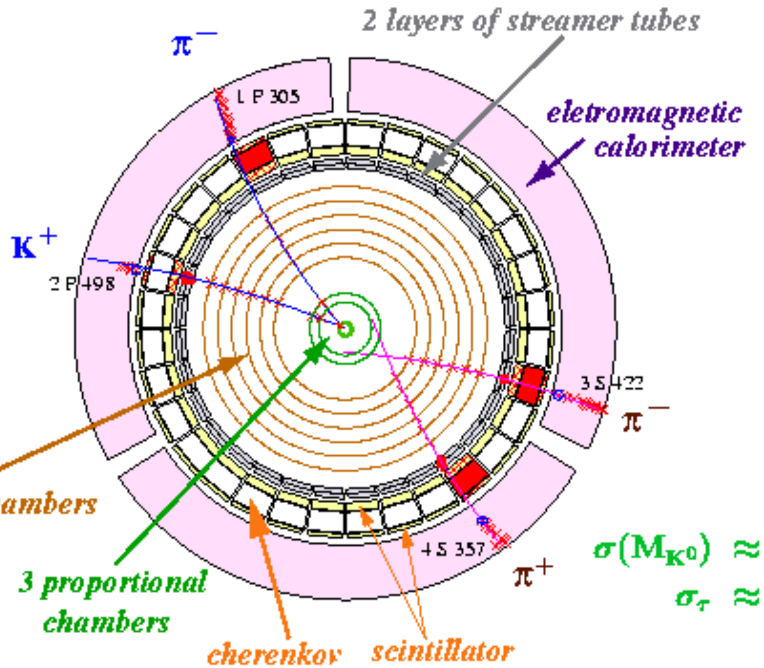


$$p\overline{p} \longrightarrow \begin{cases} \pi^- K^+ \overline{K^0} \\ \pi^+ K^- K^0 \end{cases}$$

At *t=0*, events with a

- K^+ 'tag' are a pure $\overline{K^0}$ sample
- K^- 'tag' are a pure K^0 sample

$$p\overline{p} \rightarrow \begin{cases} \pi^- K^+ \overline{K^0} & \rightarrow \pi^- K^+ \, \pi^+ \pi^- \\ \pi^+ K^- K^0 & \rightarrow \pi^+ K^- \, \pi^+ \pi^- \end{cases}$$

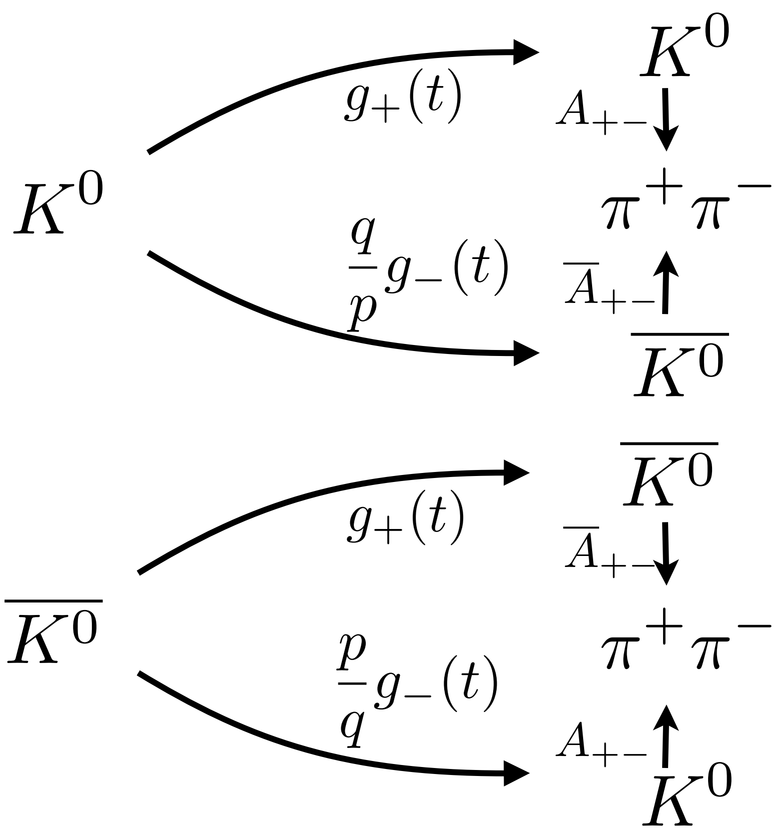


$$\sigma(M_{K^0}) \approx 13 \text{ MeV}/c^2$$
$$\sigma_\tau \approx (5-10) \text{ ps}$$

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \qquad \overline{A}_{+-} \equiv \langle \pi^+\pi^- | \overline{K^0} \rangle$$

$t = 0$	t	Amplitude



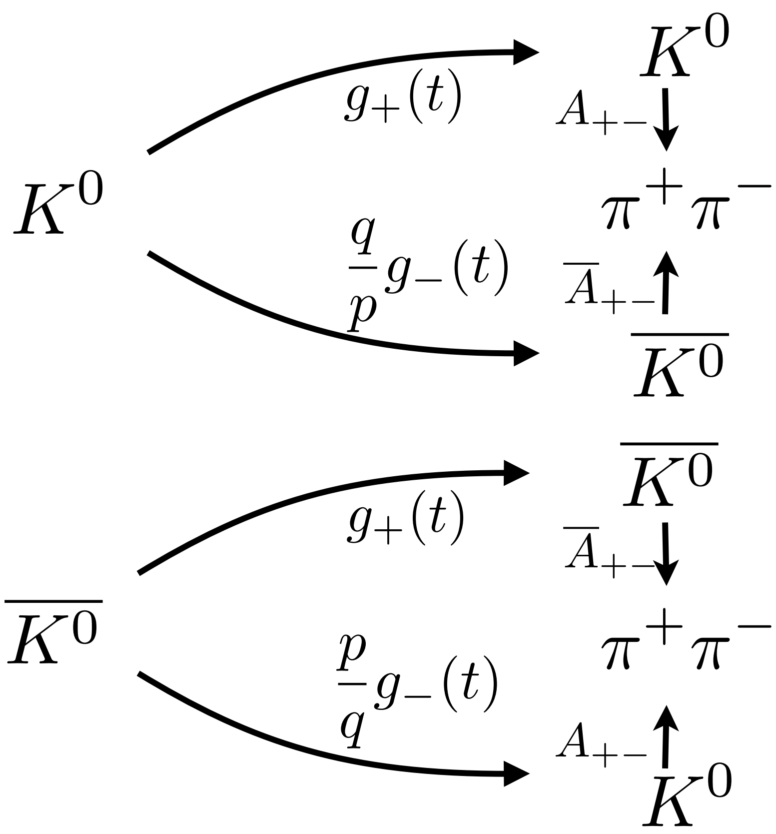
$$g_+(t) A_{+-} + \frac{q}{p} g_-(t) \overline{A}_{+-}$$

$$g_+(t) \overline{A}_{+-} + \frac{p}{q} g_-(t) A_{+-}$$

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \qquad \overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$t = 0$ | t | **Amplitude**



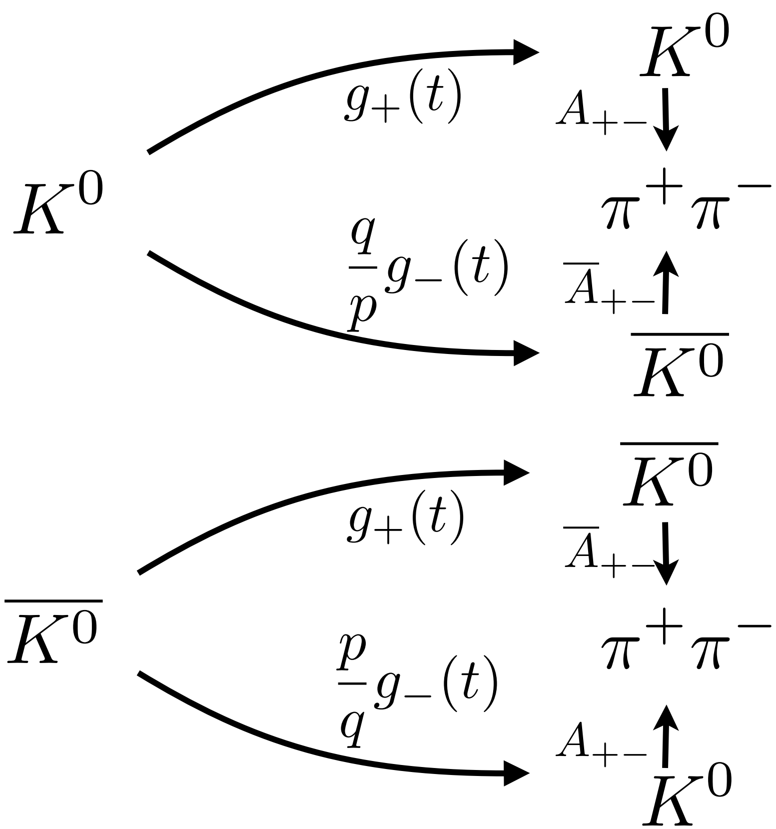
$$A_{+-}\left[\, g_+(t) + \lambda_{+-} g_-(t) \,\right]$$

$$\overline{A}_{+-}\left[g_+(t) + \frac{1}{\lambda_{+-}} g_-(t) \right]$$

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$
$$\overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle$$

$t = 0$	t	**Rate**



$$\propto \left| A_{+-} \left[\, g_+(t) + \lambda_{+-} g_-(t) \,\right] \right|^2$$

$$\propto \left| \overline{A}_{+-} \left[g_+(t) + \frac{1}{\lambda_{+-}} g_-(t) \right] \right|^2$$

Three ways to break CP...

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \quad \overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto |A_{+-}|^2 \left[|g_+(t)|^2 + |\lambda_{+-}|^2 |g_-(t)|^2 + 2\mathcal{R}\left(\lambda_{+-} g_+^*(t) g_-(t)\right) \right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) \propto |\overline{A}_{+-}|^2 \left[|g_+(t)|^2 + \frac{1}{|\lambda_{+-}|^2} |g_-(t)|^2 + \frac{2}{|\lambda_{+-}|^2}\mathcal{R}\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right) \right]$$

1. CP violation in decay $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$
2. CP violation in mixing: $\left|\frac{q}{p}\right| \neq 1$
3. CP violation in interference mixing/decay: $\mathcal{I}(\lambda_f) = \mathcal{I}\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0$

Write in terms of observables...

$$\eta_{+-} = \frac{1-\lambda}{1+\lambda} = \frac{pA - q\bar{A}}{pA + q\bar{A}} = \frac{\langle \pi^+\pi^- | K_L \rangle}{\langle \pi^+\pi^- | K_S \rangle} \qquad \eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\begin{aligned}
\Gamma\left(K^0 \to \pi^+\pi^-\right) &= N\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2e^{-\Gamma t}|\eta_{+-}|\cos\left(\Delta m t - \phi_{+-}\right)\right] \\
\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) &= \overline{N}\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} - 2e^{-\Gamma t}|\eta_{+-}|\cos\left(\Delta m t - \phi_{+-}\right)\right]
\end{aligned}$$

K_S $\quad$ K_L $\quad$ K_S-K_L interference

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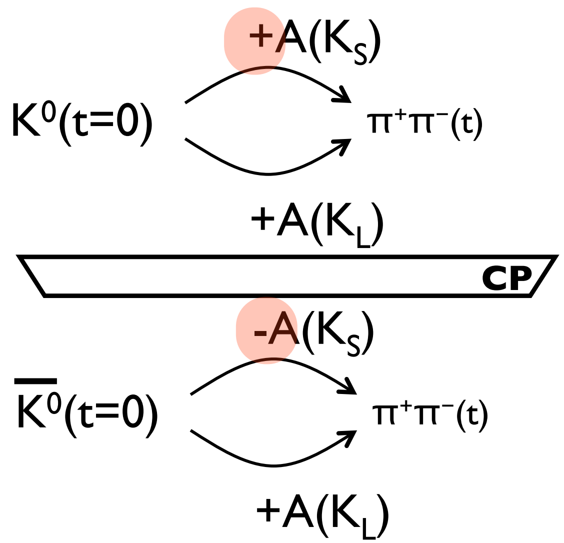
\end{aligned}$$

K_S $\quad$ K_L $\quad$ K_S-K_L interference

Interference term has a *sign difference* because:

$$\begin{aligned}
|K^0\rangle &= \frac{1}{2p}\left(|K_L\rangle + |K_S\rangle\right) \\
|\overline{K^0}\rangle &= \frac{1}{2q}\left(|K_L\rangle - |K_S\rangle\right)
\end{aligned}$$

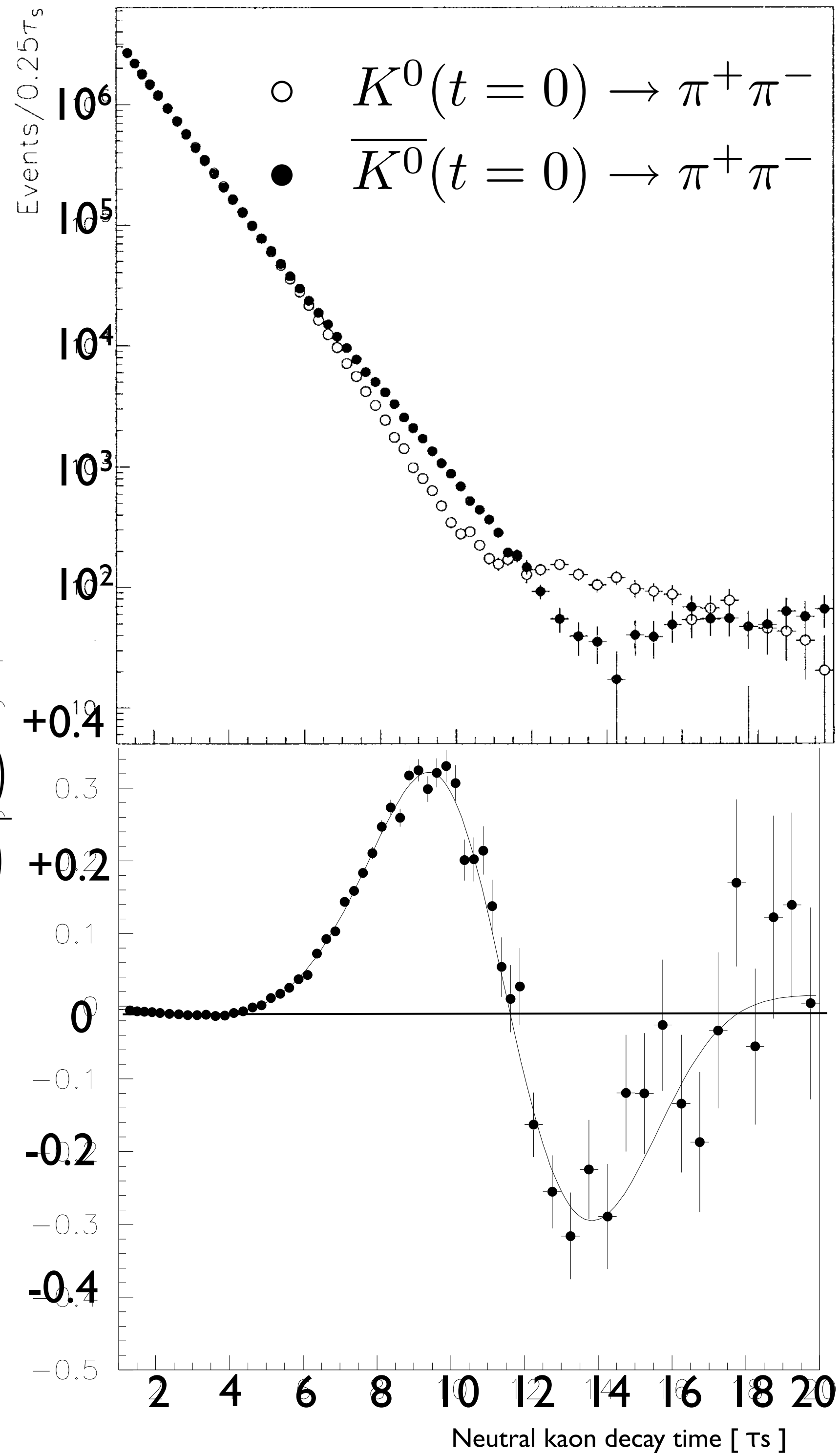


A determination of the CP violation parameter η_{+-} from the decay of strangeness-tagged neutral kaons

CPLEAR Collaboration

A. Apostolakis [a], E. Aslanides [k], G. Backenstoss [b], P. Bargassa [m], O. Behnke [q], A. Benelli [i], V. Bertin [k], F. Blanc [g,m], P. Bloch [d], P. Carlson [o], M. Carroll [i], E. Cawley [i], M.B. Chertok [c], M. Danielsson [o], M. Dejardin [n], J. Derre [n], A. Ealet [k], C. Eleftheriadis [p], W. Fetscher [q], M. Fidecaro [d], A. Filipčič [j], D. Francis [c], J. Fry [i], E. Gabathuler [i], R. Gamet [i], H.-J. Gerber [q], A. Go [o], A. Haselden [i], P.J. Hayman [i], F. Henry-Couannier [k], R.W. Hollander [f], K. Jon-And [o], P.-R. Kettle [m], P. Kokkas [d], R. Kreuger [f], R. Le Gac [k], F. Leimgruber [b], I. Mandić [j], N. Manthos [h], G. Marel [n], M. Mikuž [j], J. Miller [c], F. Montanet [k], A. Muller [n], T. Nakada [m], B. Pagels [q], I. Papadopoulos [p], P. Pavlopoulos [b], G. Polivka [b], R. Rickenbach [b], B.L. Roberts [c], T. Ruf [d], L. Sakeliou [a], M. Schäfer [q], L.A. Schaller [g], T. Schietinger [b], A. Schopper [d], L. Tauscher [b], C. Thibault [l], F. Touchard [k], C. Touramanis [i], C.W.E. Van Eijk [f], S. Vlachos [b], P. Weber [q], O. Wigger [m], M. Wolter [q], C. Yeche [n], D. Zavrtanik [j], D. Zimmerman [c]

$$\mathcal{A} = \frac{\Gamma\left(K^0 \to \pi + \pi -\right) - \Gamma\left(\overline{K^0} \to \pi + \pi -\right)}{\Gamma\left(K^0 \to \pi + \pi -\right) + \Gamma\left(\overline{K^0} \to \pi + \pi -\right)}$$



CP and the Standard Model

Sofar:

- seen that Weak Interaction breaks both C and P ‘completely’ and CP ‘a bit’
- described what happens in very generic terms...

Next:

1. towards the Standard Model description of the Weak Interaction
2. how CP violation is integrated into the Standard Model
3. how can we test the Standard Model description of CP violation?

Leptons & Quarks

In the sixties, it seemed that there were

- 4 types of lepton: e, ν_e, μ, ν_μ
- 3 types of quark: u, d, s
  - but many (most!) considered quarks a mathematical trick to explain the zoo of observed particles...

Let's sort them by their electrical charge:

0:	ν_e, ν_μ	$+\frac{2}{3}$:	u
-1:	e, μ	$-\frac{1}{3}$:	d, s

Leptons & Quarks

In the sixties, it seemed that there were

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- 3 types of quark: u, d, s
  - but many (most!) considered quarks a mathematical trick to explain the zoo of observed particles...

Let's sort them by their electrical charge:

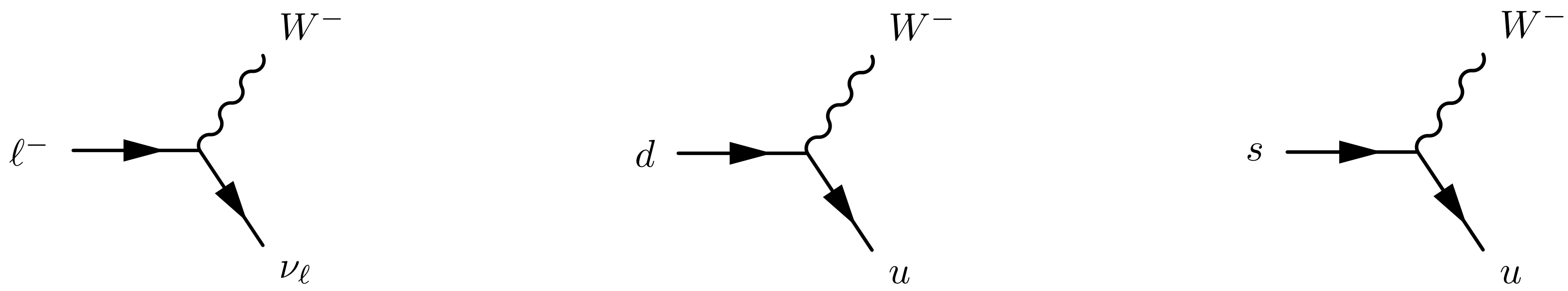
W^-

0:	ν_e, ν_μ	$+\frac{2}{3}$:	u
-1:	e, μ	$-\frac{1}{3}$:	d, s

W^+

Weak Interaction: Leptons vs Quarks

- Problem: using the measured muon lifetime, the *predicted* neutron lifetime is a bit too short -- and the *predicted* lifetime of strange particles way too short...



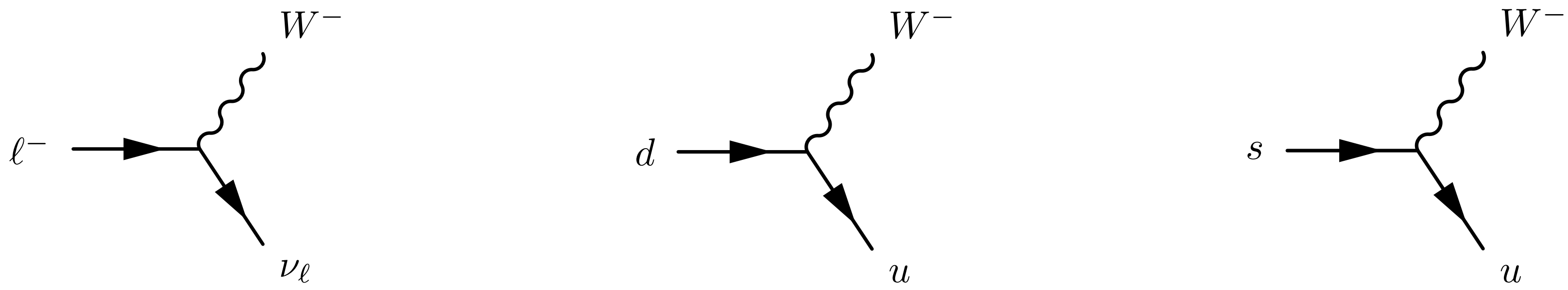
$$g \quad > \quad g' \quad >> \quad g''$$

- Conclusion: measured strength (coupling constant) of weak interaction is systematically (!) different when measured in different types of processes???

- Or maybe we just overlooked something?

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)



$$g \quad > \quad g\cos\theta_C \quad >> \quad g\sin\theta_C$$

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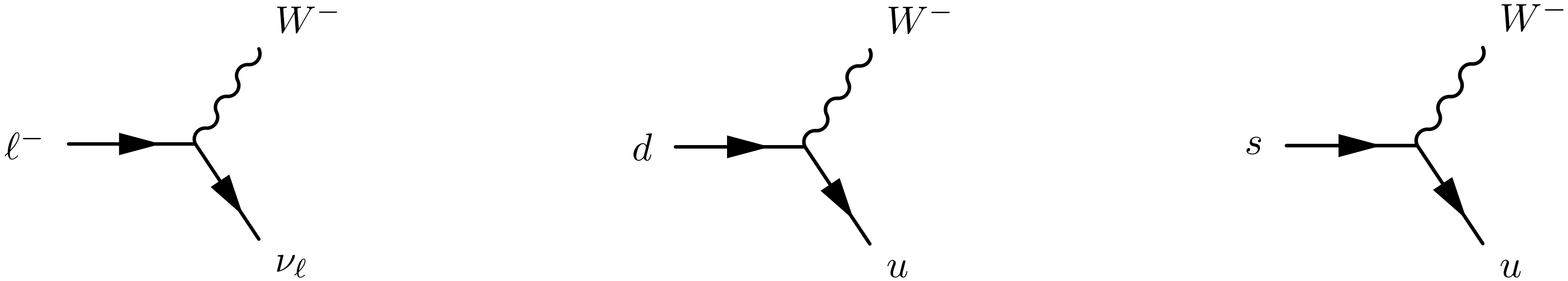


$$g \quad > \quad g\cos\theta_C \quad >> \quad g\sin\theta_C$$

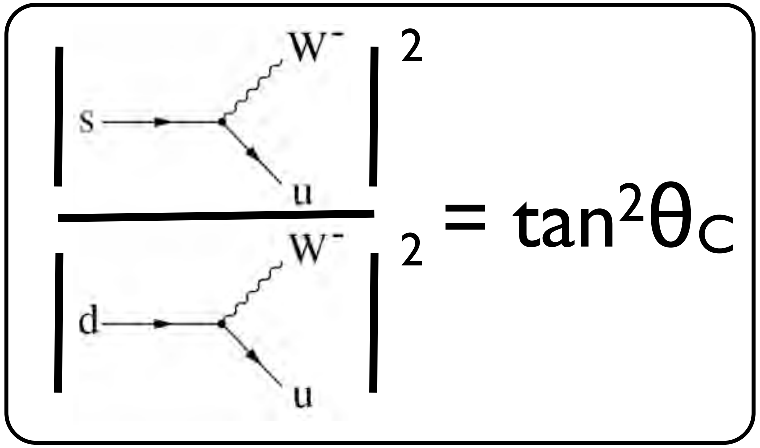
To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$

$$= \tan^2\theta M_K(1 - M_\mu{}^2/M_K{}^2)^2/M_\pi(1 - M_\mu{}^2/M_\pi{}^2)^2. \quad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$



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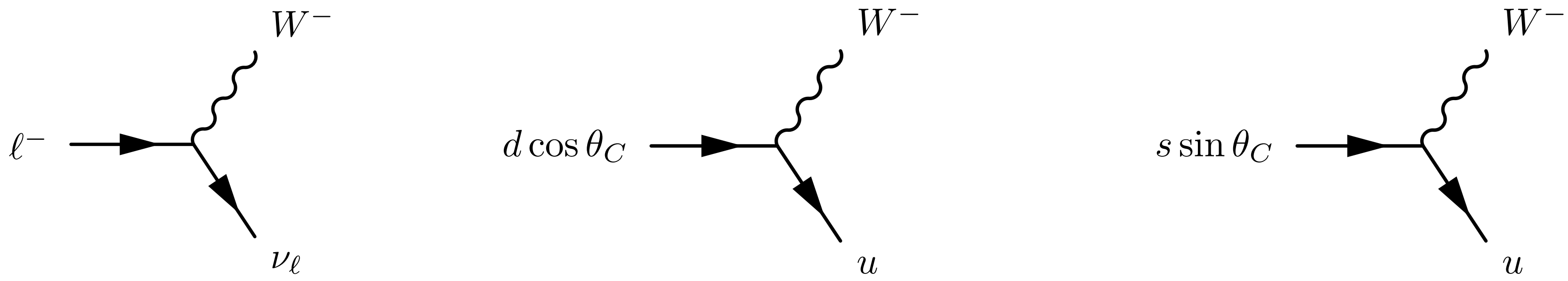

$$g \quad = \quad g \quad = \quad g$$

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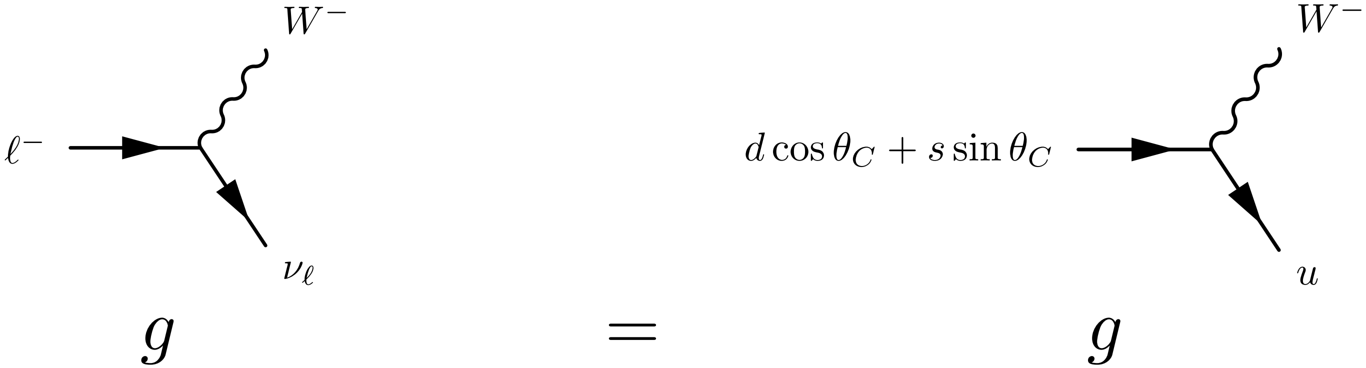
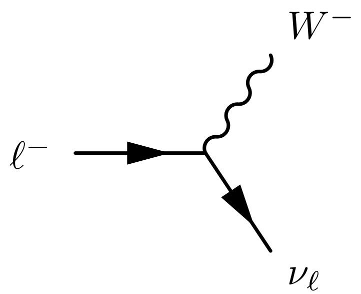
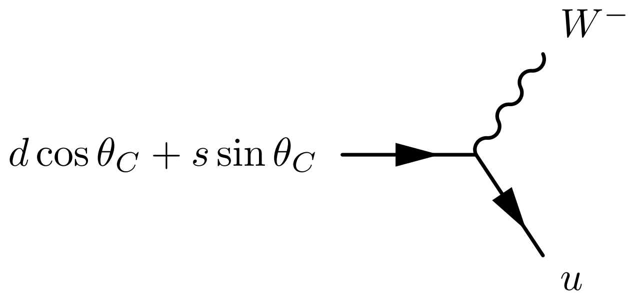


Weak Interaction: Universality



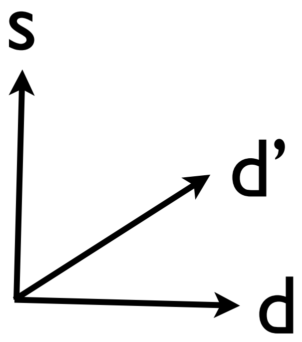
$$g = g$$



The d quark as 'seen' by the W, the *weak* eigenstate d',
is *not* same as the *mass* eigenstate (the d)...

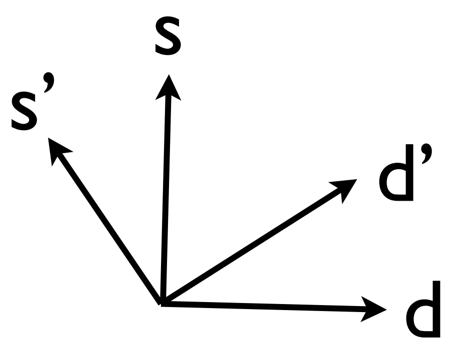
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}_L$$

Weak Interaction: Universality



The d' seen by the W is a *superposition* of the d and s...

Weak Interaction: Universality



$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

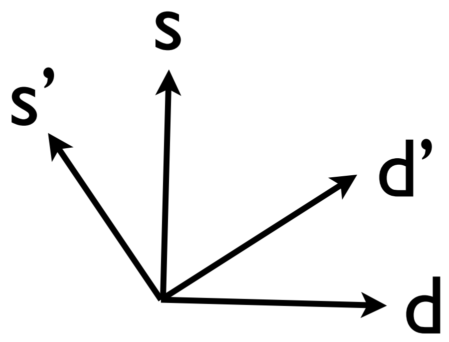
The d' seen by the W is a *superposition* of the d and s...

- If d' is a superposition of the d and s, shouldn't there be an s' as well? (*)

- If so, we can write d' and s' as *rotated* versions of d and s

(*) yes: coupling of Z to d' *without* matching s' causes a tree-level flavour changing neutral current, which is incompatible with eg. observed $Br(K_L \rightarrow \mu\mu)$

Weak Interaction: Universality



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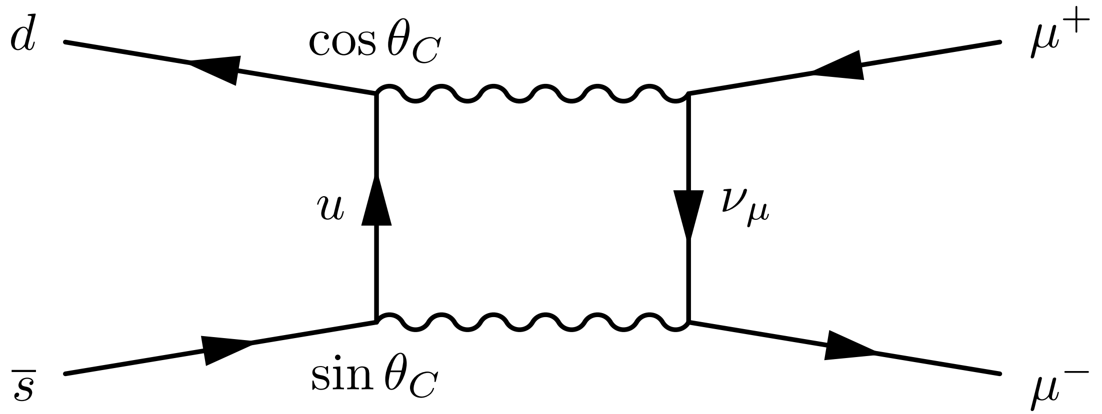
The d' seen by the W is a *superposition* of the d and s...

- If d' is a superposition of the d and s, shouldn't there be an s' as well? (*)
- If so, we can write d' and s' as *rotated* versions of d and s
- And if there is an s', why no u-like partner for it?

(*) yes: coupling of Z to d' *without* matching s' causes a tree-level flavour changing neutral current, which is incompatible with eg. observed $Br(K_L \to \mu\mu)$

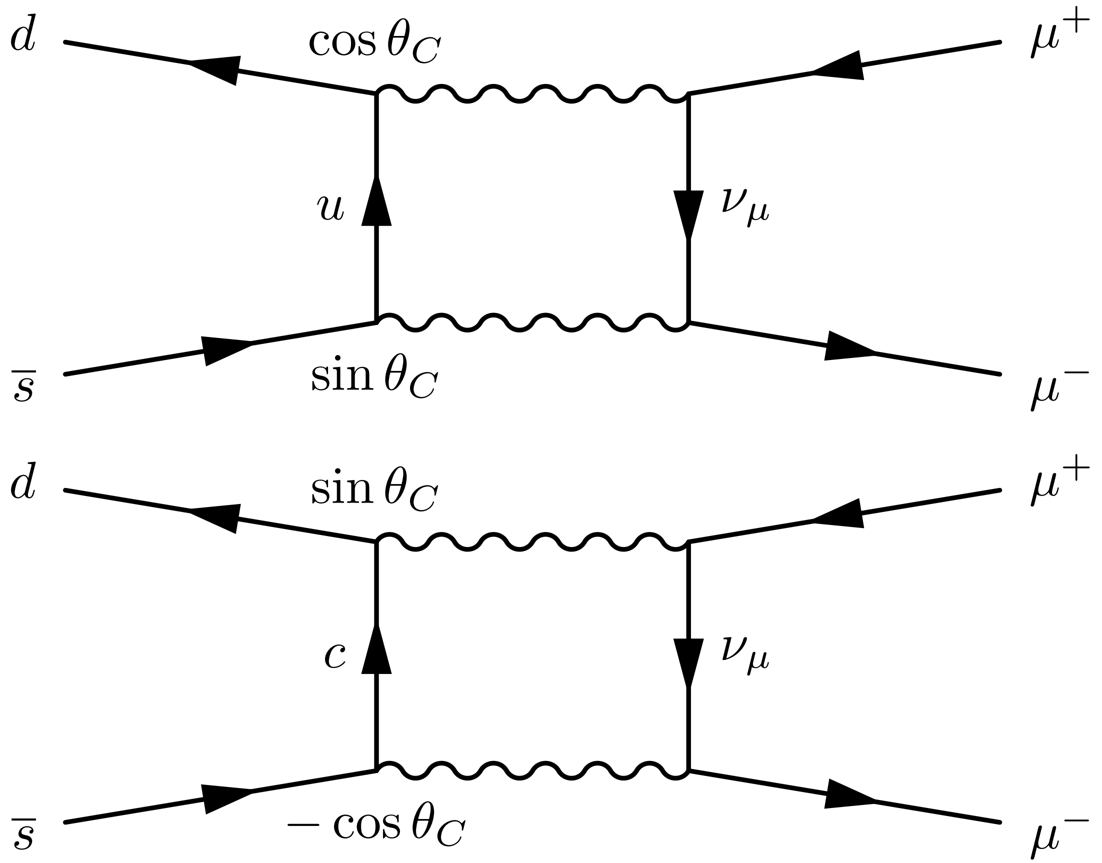
Cabibbo and the charm quark

- There was however one major exception which Cabibbo could not describe: $K^0 \to \mu^+ \mu^-$
  - Observed rate much lower than expected from Cabibbos rate correlations (expected rate $\propto g^8 \sin^2\theta_c \cos^2\theta_c$)



GIM and the charm quark

- How does it solve the $K^0 \rightarrow \mu{+}\mu{-}$ problem?
  - Second decay amplitude added that is almost identical to original one, but has relative minus sign ⇒ (Almost) fully destructive interference



  - Cancellation not perfect because u, c mass not quite the same...

Weak Interactions with Lepton-Hadron Symmetry*

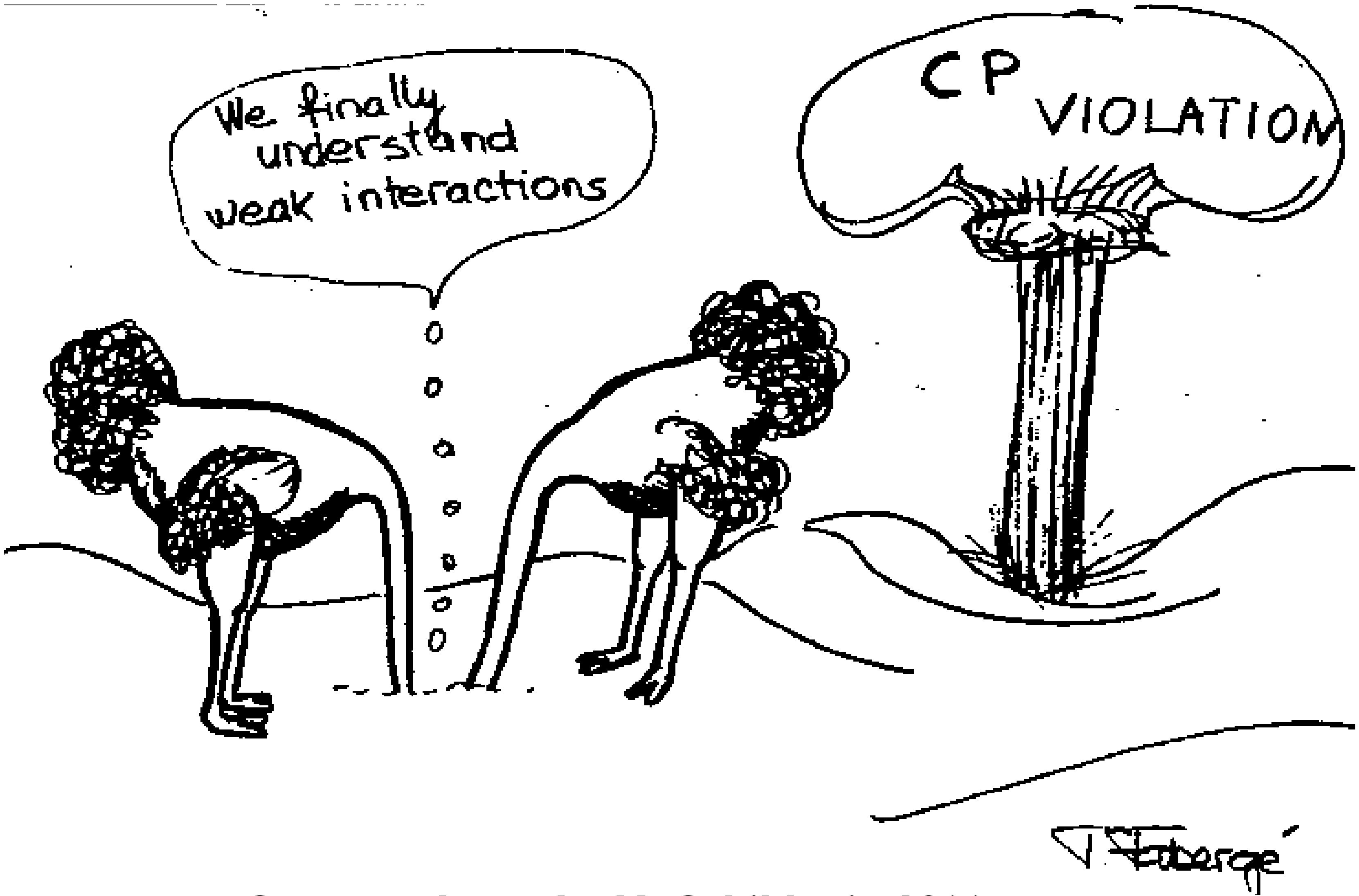
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$
$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

One 'tiny' problem: no experimental evidence for a fourth quark...

...until 1974: Ting, Richter (Nobel prize 1976)



Cartoon shown by N. Cabibbo in 1966…
since then, there was tremendous progress in the understanding (better: describing) *CP* violation

⇒ **next topic!**

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

The Nobel Prize winning part

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq 0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L \text{ with} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

How many ‘physical’ parameters in V_{CKM}?

- complex NxN matrix: $2N^2$ parameters
- must be unitary:
  - eg. t must decay to either b, s or d, so $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$
  - in general: $V^{*T} V = I \rightarrow N^2$ constraints
- freedom to change phase of quark fields $|q_j\rangle \longrightarrow e^{i\phi_j} |q_j\rangle$
  - 2N-1 phases are irrelevant:

$$\langle q_i | V_{ij} | q_j \rangle \longrightarrow \langle q_i | e^{-i\phi_i} V_{ij} e^{i\phi_j} | q_j \rangle$$

$$V_{ij} \longrightarrow e^{i(\phi_j - \phi_i)} V_{ij}$$

- number of ‘physical’ parameters = N^2-2N+1

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- number of ‘physical’ parameters = N^2-2N+1
- how many can be rotation angles? N(N-1)/2
- For N=2 : 1 parameter, with 1 rotation angle (Cabbibo!)
- For N=3: 4 parameters = 3 rotations + 1 *irreducible* complex phase!

Complex phases & CP

What does *CP* (or, equivalently *T*) conjugation do with the Hamiltonian *H* ?

$$[\hat{x}, \hat{p}] = i\hbar$$

$$T\,[\hat{x}, \hat{p}]\,T^{-1} = TiT^{-1}\hbar \xrightarrow{\begin{array}{rcl} T\hat{x} & = & \hat{x} \\ T\hat{p} & = & -\hat{p} \end{array}} TiT^{-1} = -i$$

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$$[\hat{x}, \hat{p}] = i\hbar$$

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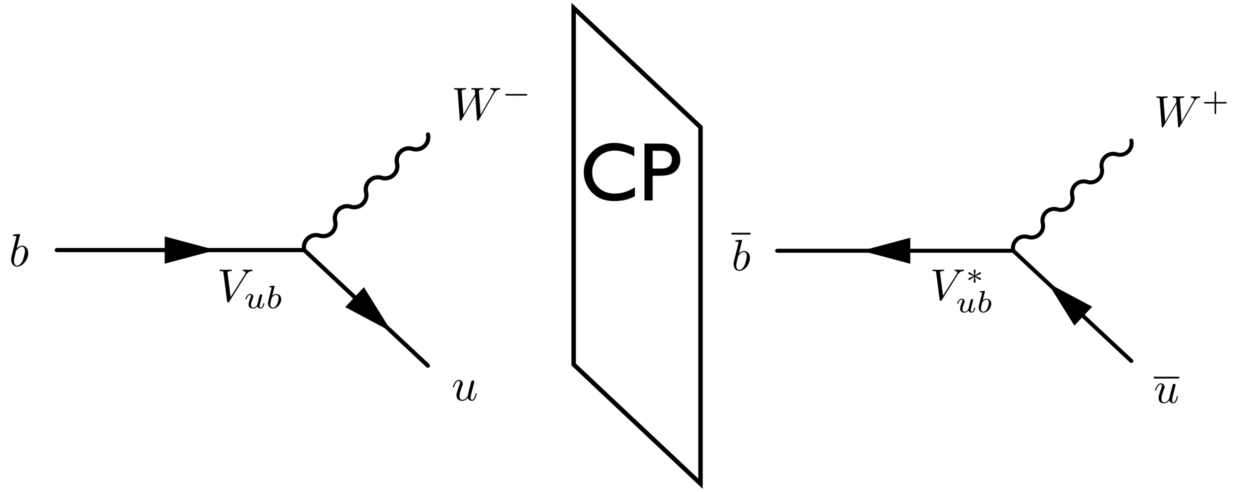
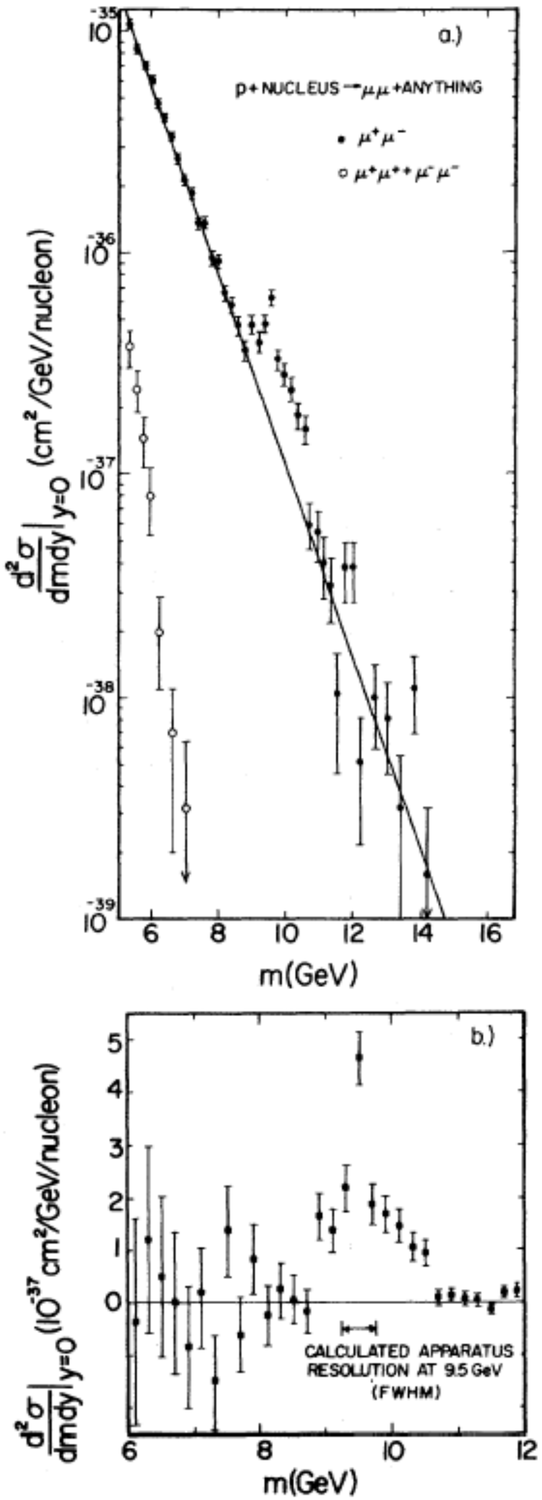
The *T* (and *CP*) operations must be **anti-unitary**,
which implies **complex conjugation** !



With 3 (or more) generations V_{CKM} can be complex
→ CP violation possible

Are there really 3 generations?

- Discovery of 5th quark in 1977
  - Named ‘b’ for beauty/bottom
  - Mass around 4.5 GeV
  - Start of the 3rd generation of quarks!



Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

(Received 1 July 1977)

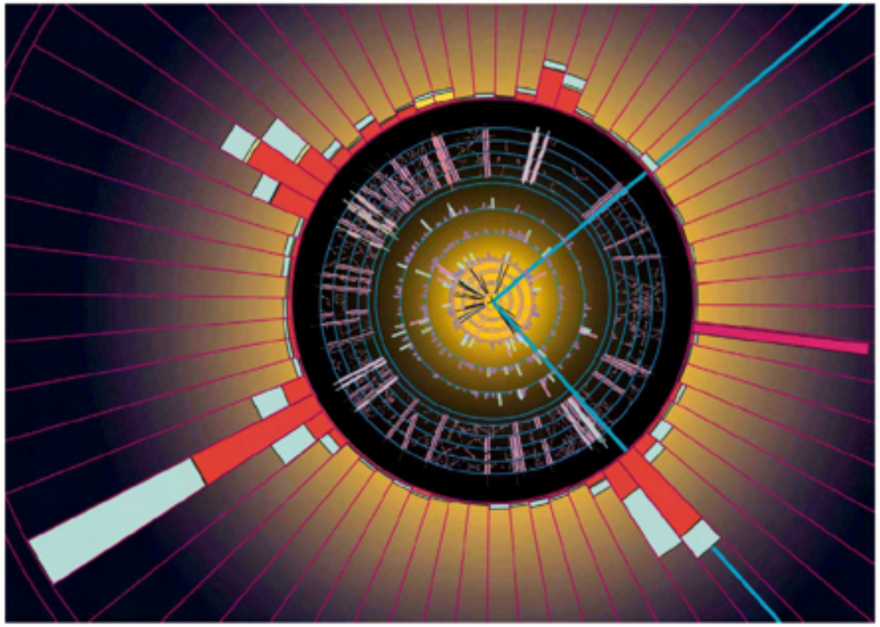
Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

Discovery of the 6th quark

- Discovery of top quark complete 3-generation picture
- Took a long time (1994) because t quark is *very* heavy: ~175 GeV/c^2!

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

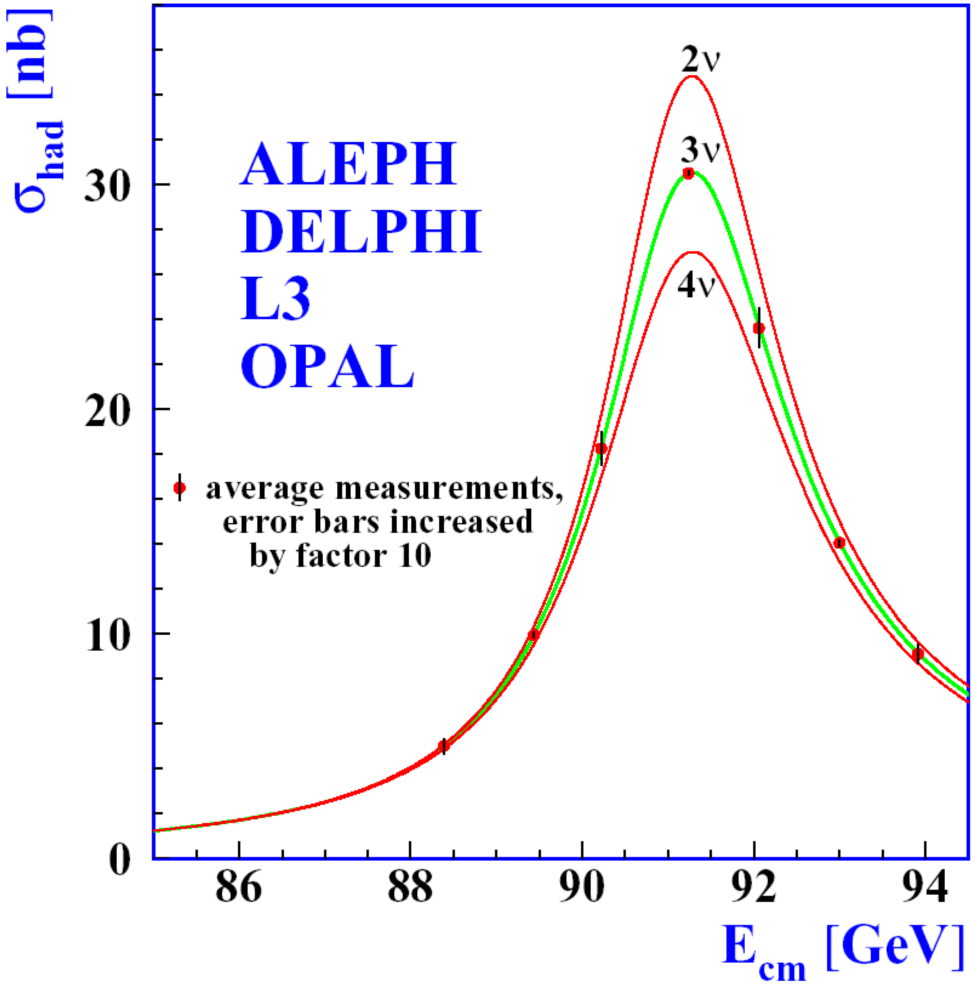


We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS numbers: 14.65.Ha, 13.85.Ni, 13.85.Qk

Are there *more* than three generations?

- Surprisingly, you can actually say something about that…
  - Measure decay rate of Z boson into all quarks, compare to total Z boson decay rate
  - Because Z can decay into $\nu\bar{\nu}$ each additional generation with a light neutrino increases the *fraction* of Z decaying to $\nu\bar{\nu}$, and thus decreases the *fraction* of hadronic decays....
  - Shows conclusively that there are only 3 generations (of neutrinos, of the type we know, with mass < $M_Z/2$)



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- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same... related by V_{CKM}
- with 3 or more families, one *can* have a complex phase(s) in V_{CKM} and thus CP violation is possible!

Three generations, four parameters...

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

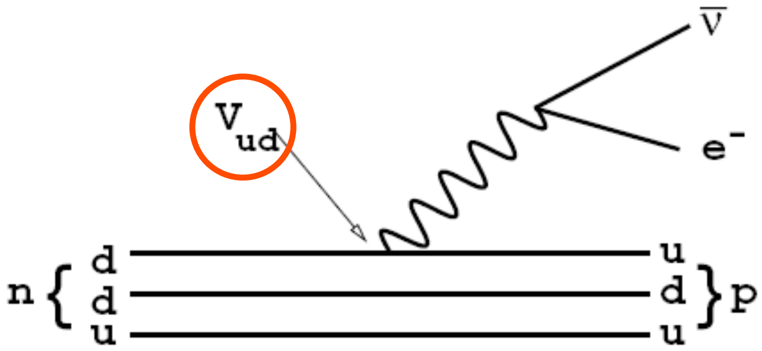
with $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$
so with four parameters $\theta_{12}, \theta_{23}, \theta_{13}, \delta$

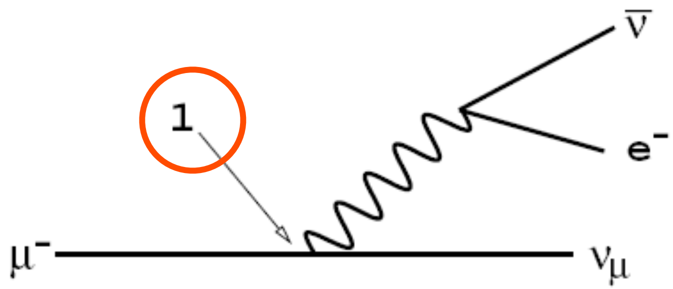
... and many more observables!

How do you measure those numbers?

- *Magnitudes* are typically determined from *ratio* of decay rates
- Example 1 – Measurement of $|V_{ud}|$
  - Compare decay rates of neutron decay and muon decay
  - Ratio proportional to $|V_{ud}|^2$
  - $|V_{ud}| = 0.9735 \pm 0.0008$
  - V_{ud} of order 1

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

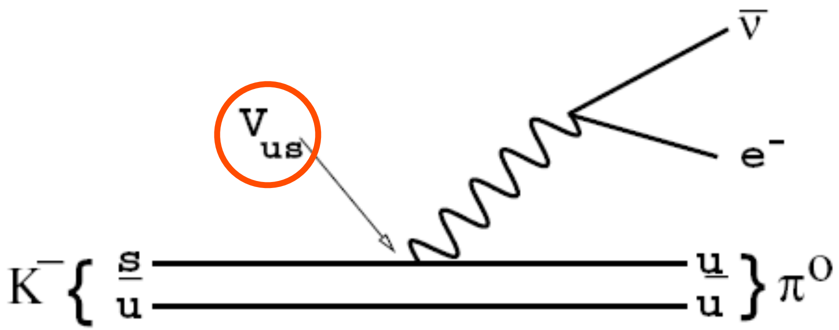


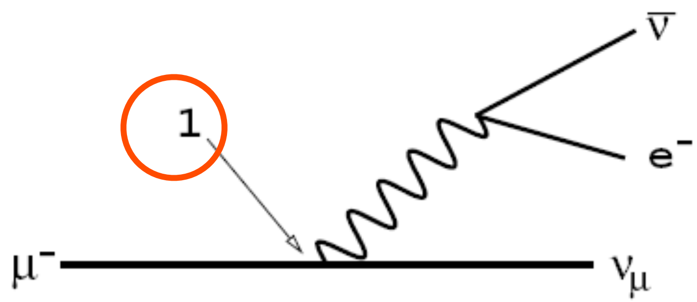


How do you measure those numbers?

- Example 2 – Measurement of $|V_{us}|$
  - Compare decay rates of semileptonic K^- decay and muon decay
  - Ratio proportional to $|V_{us}|^2$
  - $|V_{us}| = 0.2196 \pm 0.0023$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

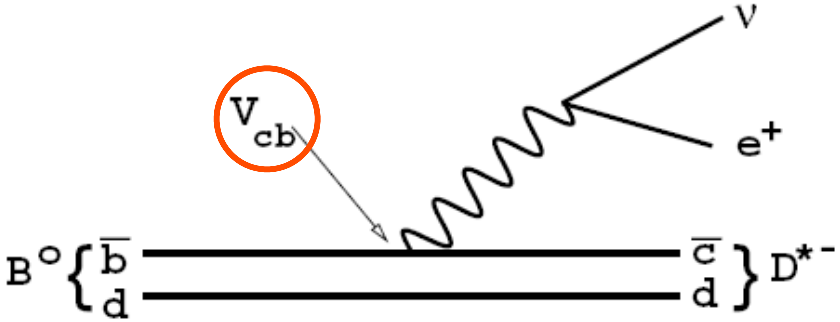


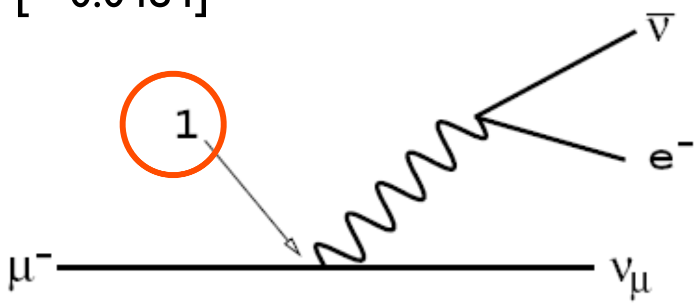


How do you measure those numbers?

- Example 3 – Measurement of V_{cb}
  - Compare decay rates of $B^0 \rightarrow D^{*-} l^+ \nu$ and muon decay
  - Ratio proportional to V_{cb}^2
  - $|V_{cb}| = 0.0402 \pm 0.0019$
  - $|V_{cb}|$ is almost (but not quite) equal to $\sin(\theta_c)^2$ [= 0.0484]

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

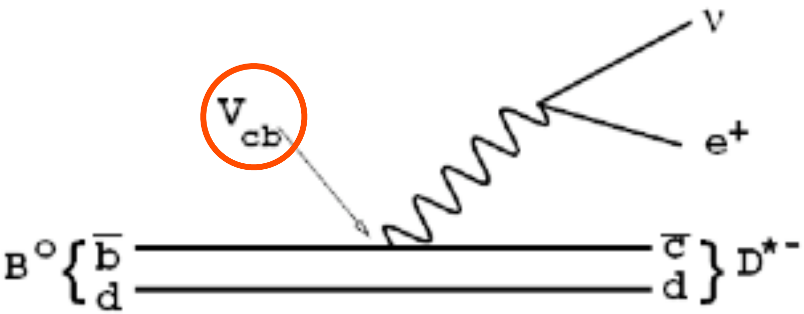


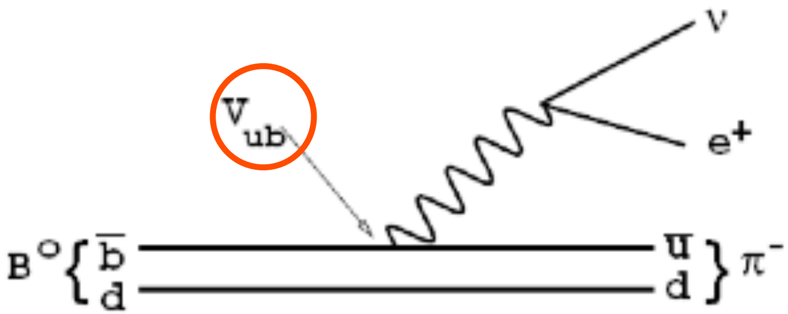


How do you measure those numbers?

- Example 4 – Measurement of V_{ub}
  - Compare decay rates of $B^0 \rightarrow D^{*-} l^+ \nu$ and $B^0 \rightarrow \pi^- l^+ \nu$
  - Ratio proportional to $(V_{ub}/V_{cb})^2$
  - $|V_{ub}/V_{cb}| = 0.090 \pm 0.025$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





Hierarchy...

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 22 August 1983)

The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured B lifetime. Two remaining parameters, including the CP-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the CP-nonconservation parameter and could rule out the hypothesis that the only source of CP nonconservation is the Kobayashi-Maskawa mechanism.

PACS numbers: 11.30.Er, 12.10.Ck, 13.25.+m

Hierarchy...

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$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda)$$

Hierarchy...

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$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & \lambda & 0 \\ -\lambda & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda^2)$$

Hierarchy...

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 22 August 1983)

The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured B lifetime. Two remaining parameters, including the CP-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the CP-nonconservation parameter and could rule out the hypothesis that the only source of CP nonconservation is the Kobayashi-Maskawa mechanism.

PACS numbers: 11.30.Er, 12.10.Ck, 13.25.+m

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & 0 \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ 0 & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^3)$$

Hierarchy...

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

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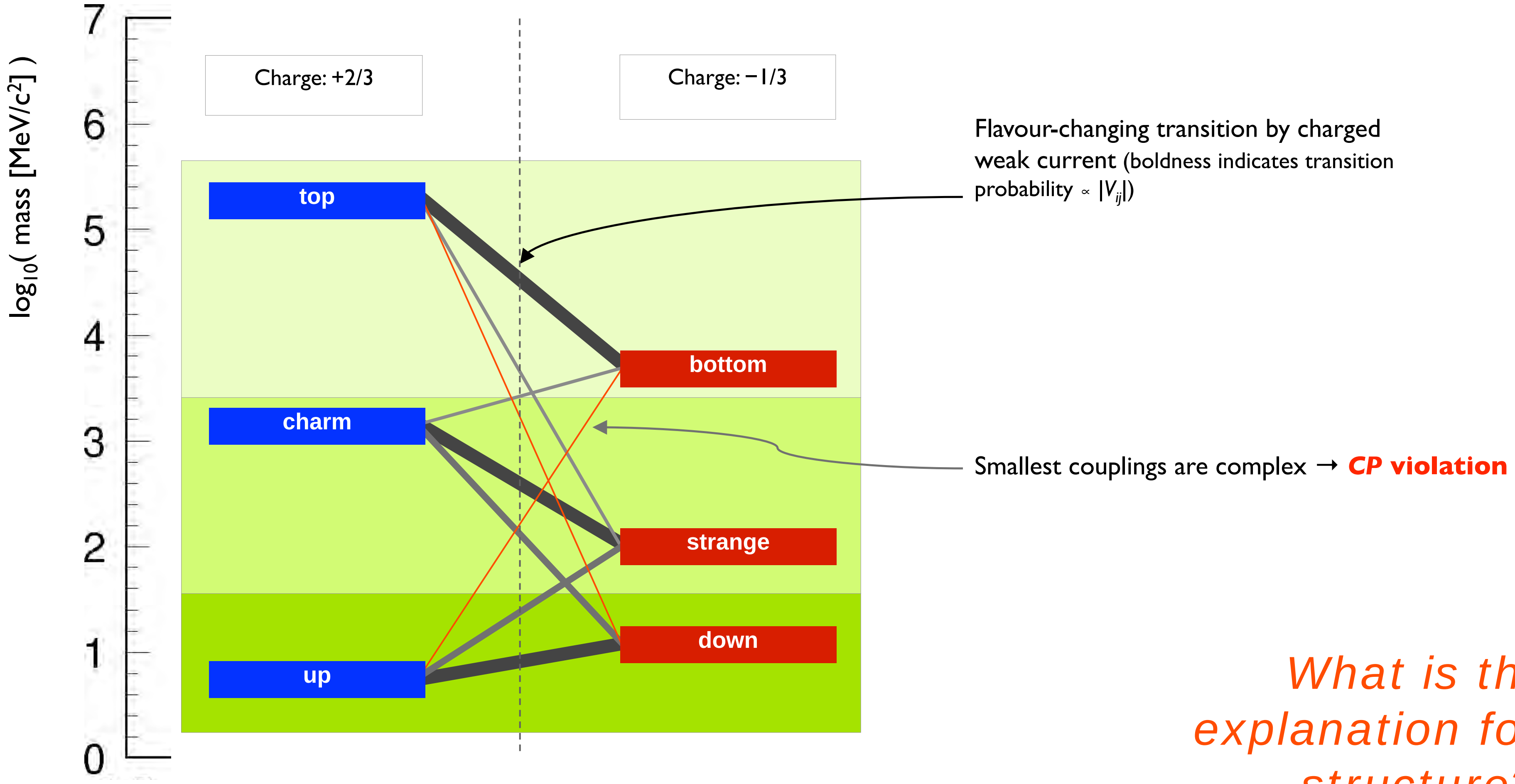
Hierarchy...



What is the explanation for this structure?
We don't know!

- Transition within generation favored
- Transition from 1st to 2nd generation suppressed by $\lambda=\sin(\theta_c)$
- Transition from 2nd to 3rd generation suppressed by $\lambda^2=\sin^2(\theta_c)$
- Transition from 1st to 3rd generation suppressed by $\lambda^3=\sin^3(\theta_c)$

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM

How to measure $|V_{td}|$ and $|V_{ts}|$?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Intermezzo: Neutral Meson Mixing

	u	c	t
$\overline{u}$	$\times$	D^0	$\diamond$
$\overline{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\overline{t}$	$\diamond$	$\diamond$	$\times$

	d	s	b
$\overline{d}$	$\times$	K^0	B^0
$\overline{s}$	$\overline{K^0}$	$\times$	B_s
$\overline{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

- Need to be neutral and have distinct anti-particle (x)
- Needs to have a non-zero lifetime
  - top is so heavy, it decays long before it can even form a meson ($\diamondsuit$)
- That leaves four distinct cases...

Note: for (much!) more detail, see eg. arXiv:hep-ex/0103016v1

Intermezzo: Describing Mixing…

Time evolution of B^0 and $\overline{B^0}$ can be described by an effective Hamiltonian:

$$i\frac{\partial}{\partial t}\Psi = H\Psi \qquad \Psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\overline{B}^0\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

what is the
difference between
M_{12} and Γ_{12}?

Intermezzo: Describing Mixing…

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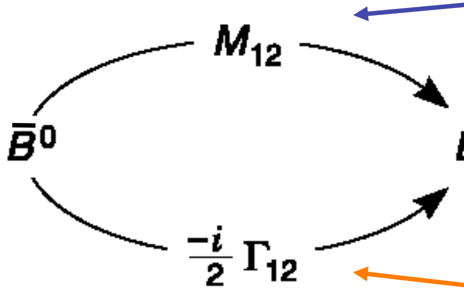
what is the *difference* between M_{12} and Γ_{12}?

Remember: anti-hermitian part describes the 'leaking' out of (and into!) the (sub)space spanned by B^0 and $\overline{B^0}$

$$\frac{d}{dt}\left(|a|^2 + |b|^2\right) = -\begin{pmatrix} a^* & b^* \end{pmatrix}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

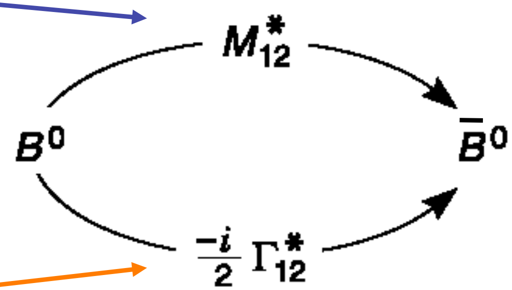


M_{12} describes $B^0 \leftrightarrow \overline{B^0}$

via *virtual* states

Γ_{12} describes $B^0 \leftrightarrow \overline{B^0}$

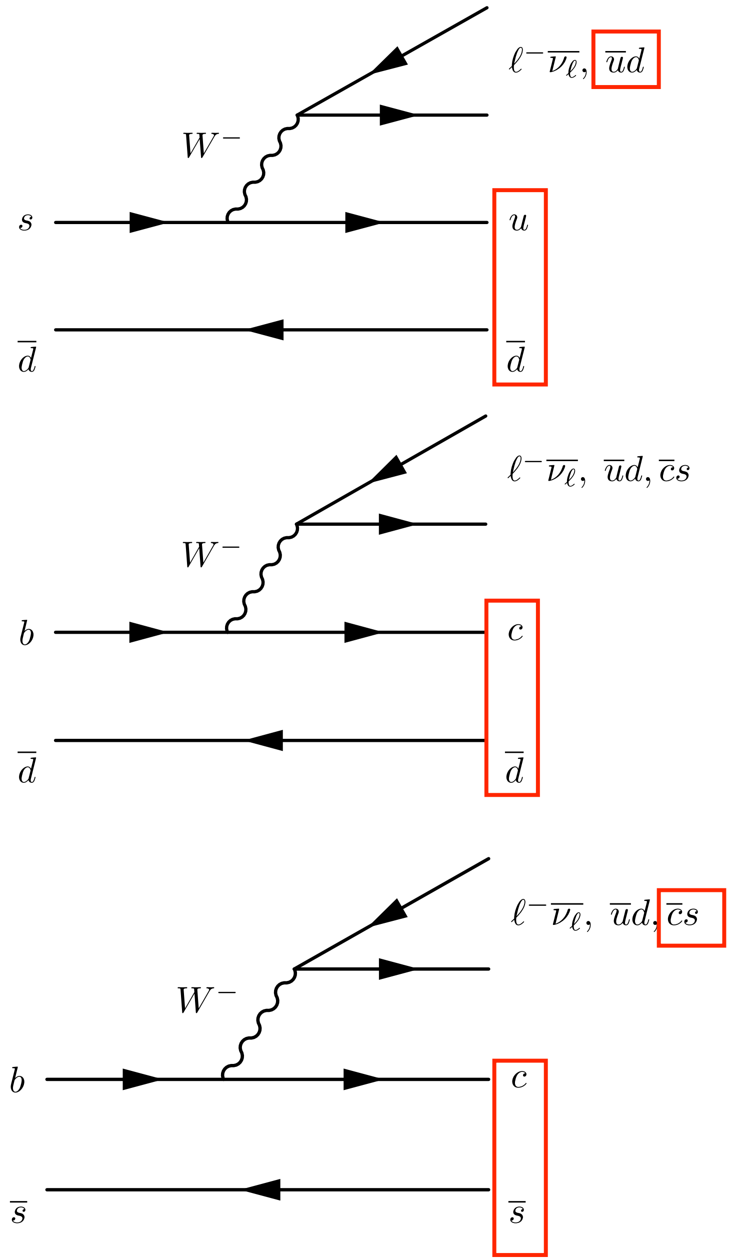
via *real* states, eg $\pi\pi$



For details, look up "Wigner-Weisskopf" approximation…

Mixing: Kaons vs. B mesons

- The difference between K mixing and 'the rest': Γ_{12}
- A *large* fraction of Kaon decays produce CP eigenstates:
  - all decays *without* leptons are CP eigenstates..
- the CP even ones have more phase-space
  - Hence the lifetime difference (large Γ_{12}!)
- For B^0, (and, to a somewhat lesser extent, B_s), the dominant decays are *not* CP eigenstates
  - hence $\Delta\Gamma$=0 (smallish), and Γ_{12} does *not* contribute to B^0 mixing
  - note: as a result labeling eigenstates as 'S'hort and 'L'ong doesn't make sense -- hence the 'H'eavy and 'L'ight



Dominant decay amplitudes

Solving the Schrödinger Equation

$$i\frac{\partial}{\partial t}\psi(t)=\begin{pmatrix} M-\frac{i}{2}\Gamma & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{12}^*-\frac{i}{2}\Gamma_{12}^* & M-\frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

Solution (in terms of eigenvectors):

$$\psi(t) = a\,|B_H(t)\rangle + b\,|B_L(t)\rangle$$

(a and b determined by initial conditions)

Eigenvectors:

$$|B_H\rangle = p|B\rangle + q|\overline{B}\rangle$$

$$|B_L\rangle = p|B\rangle - q|\overline{B}\rangle$$

Evolution of eigenvectors:

$$\begin{aligned} |B_H(t)\rangle &= |B_H\rangle\, e^{-i\left(M+\frac{1}{2}\Delta m-\frac{i}{2}(\Gamma-\Delta\Gamma)\right)t} \\ |B_L(t)\rangle &= |B_L\rangle\, e^{-i\left(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma)\right)t} \end{aligned}$$

From the eigenvector calculation:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

Δm and ΔΓ follow from the eigenvalues:

$$\Delta m + \frac{i}{2}\Delta\Gamma = 2\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

Solving the Schrödinger Equation

$$i\frac{\partial}{\partial t}\psi(t) = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

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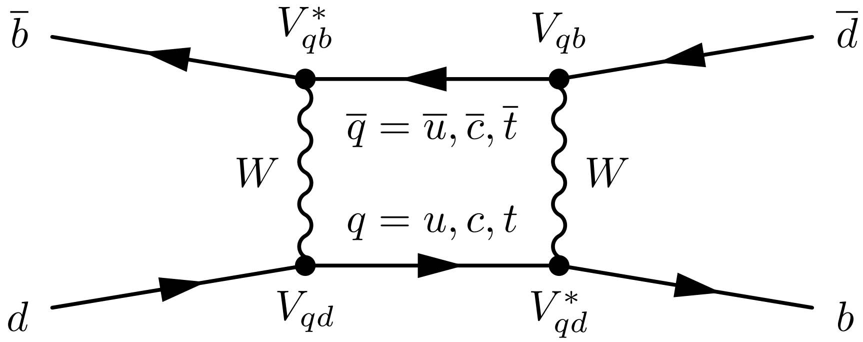
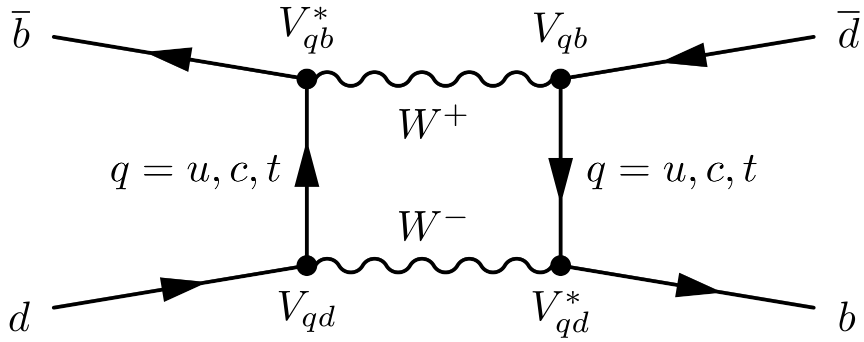
Δm and ΔΓ follow from the eigenvalues:

$$\Delta m + \frac{i}{2}\Delta\Gamma = 2\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

if: $\Gamma_{12} = 0 \Rightarrow \Delta\Gamma = 0, \left|\frac{q}{p}\right| = 1$

Mixing: Box Diagrams





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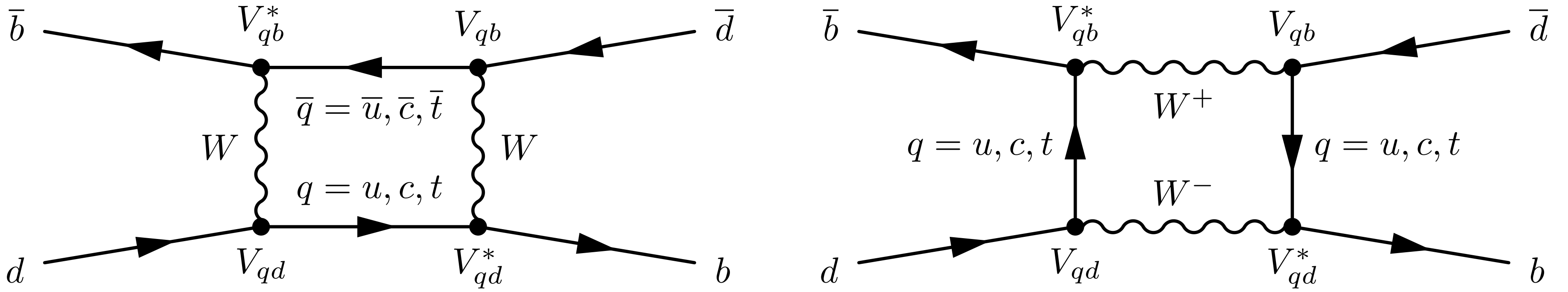
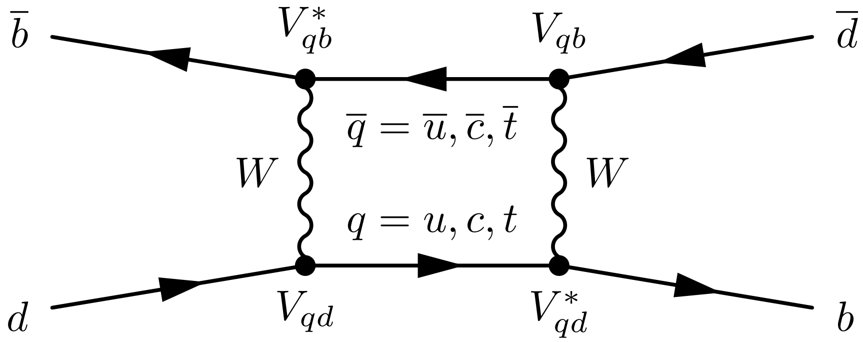
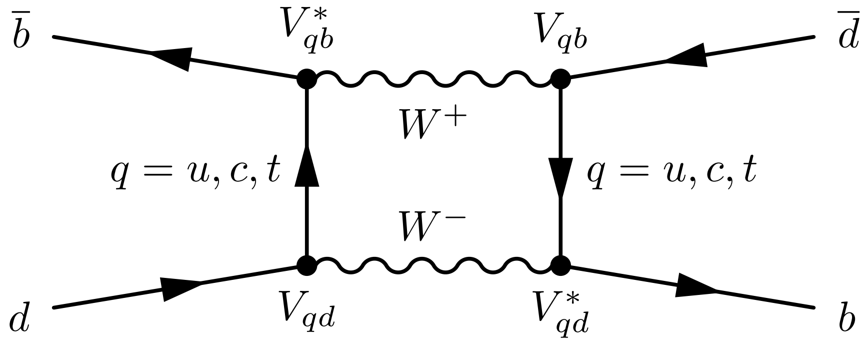


GIM(V_{CKM} unitarity):
if u,c,t same mass, everything
cancels *by construction*!

Mixing: Box Diagrams





$$t - \bar{t}: \quad \propto m_t^2 \left| V_{tb} V_{td}^* \right|^2 \quad \propto m_t^2 \lambda^6$$

$$c - \bar{c}: \quad \propto m_c^2 \left| V_{cb} V_{cd}^* \right|^2 \quad \propto m_c^2 \lambda^6$$

$$c - \bar{t}, \bar{c} - t: \quad \propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^* \propto m_c m_t \lambda^6$$

GIM(V_{CKM} unitarity):
if u,c,t same mass, everything cancels *by construction*!

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_w^2 \eta_B S_0(m_t^2 / m_W^2) m_{B_d} \boxed{|V_{td}|^2} B_{B_d} f_{B_d}^2$$

Dominated by top quark mass: $$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$$

reference: $\tau_B \sim 1.5$ ps

Before you decay, you've gotta ask yourself one question:

"do I feel like oscillating?"

well, do ya?

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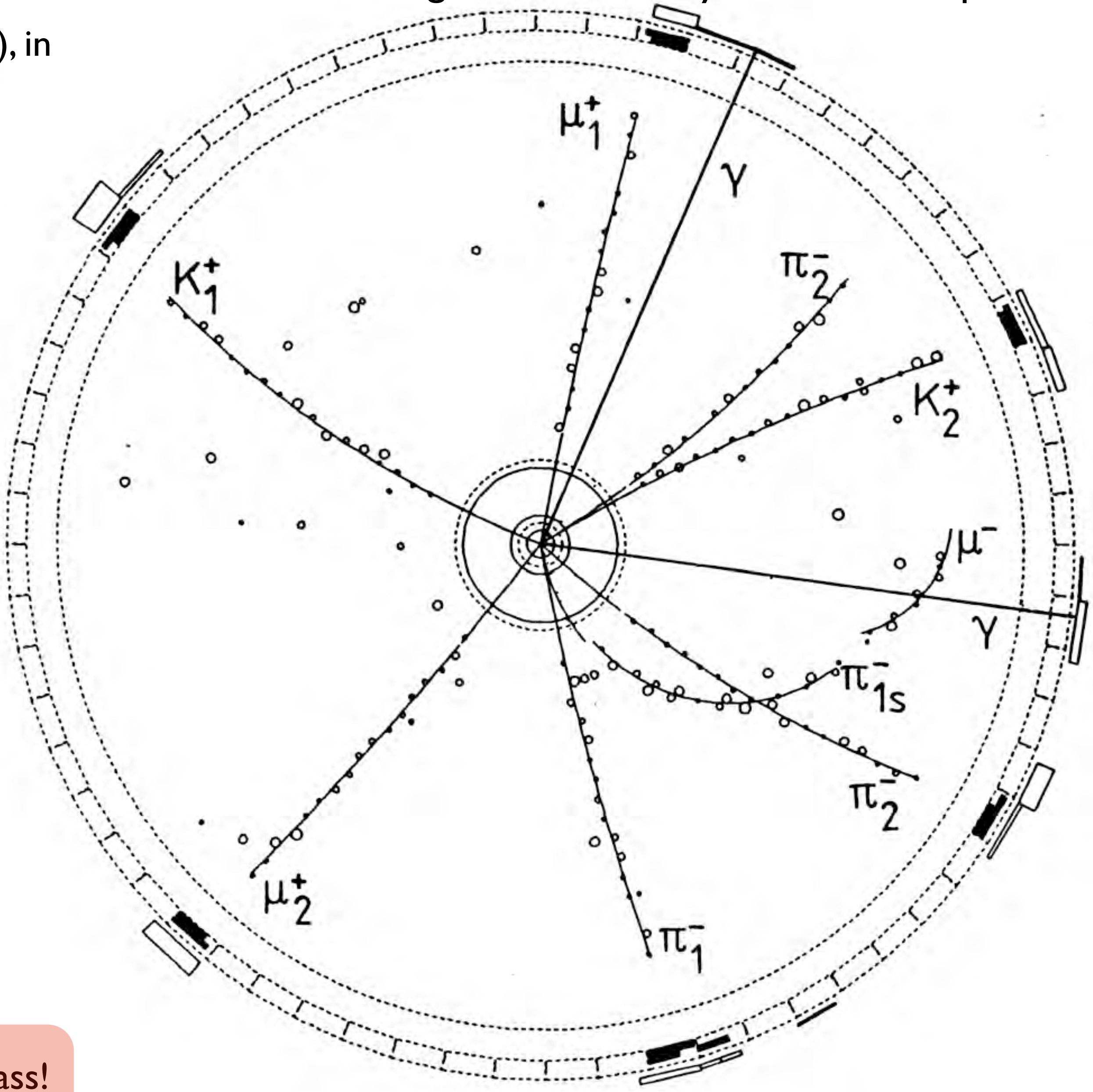
B^0 Mixing: ARGUS, 1987

- Produce an $b\overline{b}$ bound state, $\Upsilon(4S)$, in e^+e^- collisions:
    - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B^0}$
- and then observe:

$$
\begin{array}{llll}
B_1^0 \rightarrow & D_1^{*-}\mu_1^+\nu_1 & & \\
 & D_1^{*-} \rightarrow & \overline{D^0}\pi_{1s}^- & \\
 & & \overline{D^0} \rightarrow K_1^+\pi_1^- & \\
 & & & \\
B_2^0 \rightarrow & D_2^{*-}\mu_2^+\nu_2 & & \\
 & D_2^{*-} \rightarrow & D^-\pi^0 & \\
 & & D^- \rightarrow K_2^+\pi_2^-\pi_2^- & \\
 & & \pi^0 \rightarrow \gamma\gamma &
\end{array}
$$

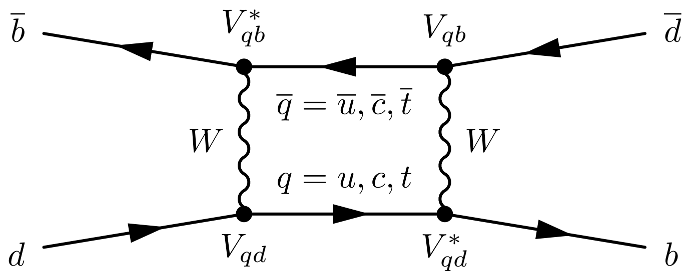
- measure that ~17% of B^0 and $\overline{B^0}$ mesons oscillate before they decay
    - $\tau_B \sim 1.5$ ps $\Rightarrow$ $\Delta m_d \sim 0.5$/ps,

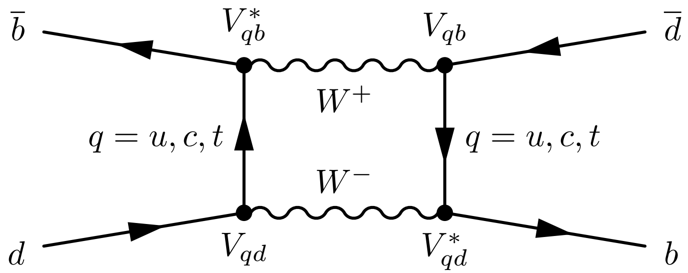
Integrated luminosity 1983-87: 103 pb-1



First evidence of a really large top mass!

B_s mixing:



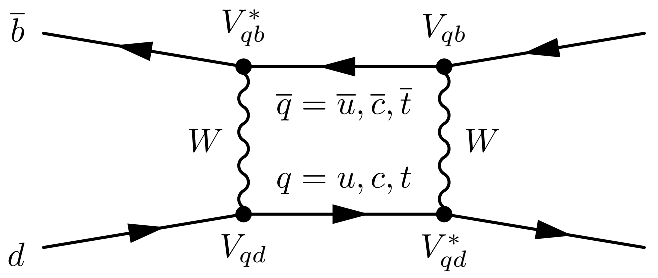


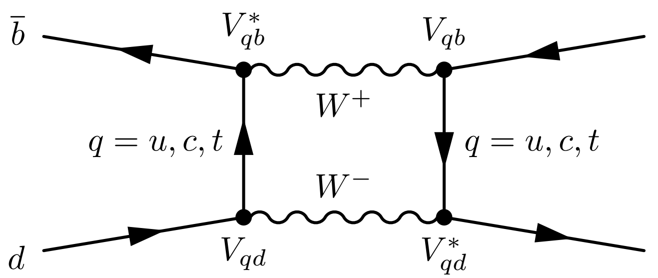
most important difference with B^0:
replace $V_{td} \rightarrow V_{ts}$

$$\left.\begin{array}{l} \dfrac{\Delta m_d}{\Delta m_s} \approx \dfrac{|V_{td}|^2}{|V_{ts}|^2} \approx \dfrac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04 \\ \Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1} \end{array}\right\} \Rightarrow \Delta m_s \approx 12 \text{ ps}^{-1}$$

A more complete calculation leads to the SM expectation of ~18/ps

B_s mixing: CDF, 2006





most important difference with B^0:
replace $V_{td} \to V_{ts}$

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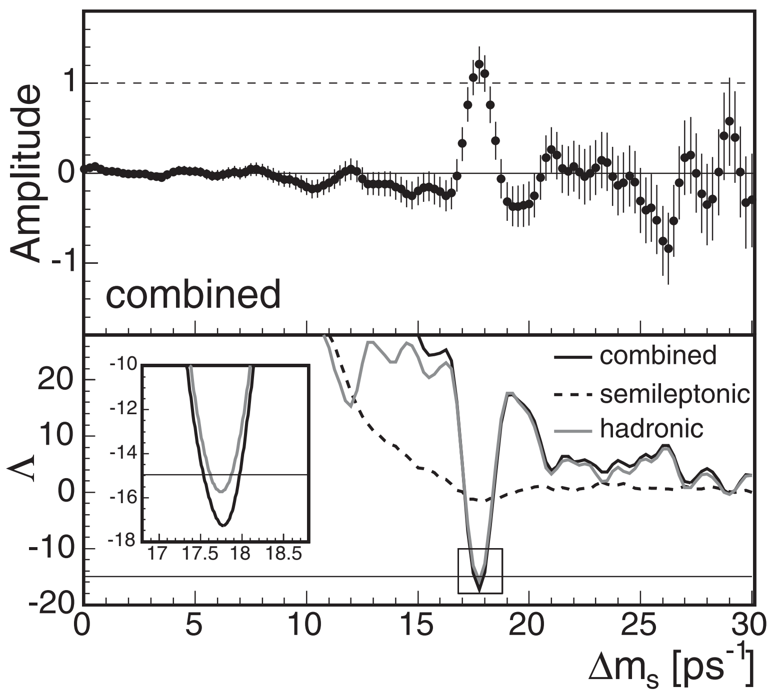
A more complete calculation leads to the SM expectation of ~18/ps

Observation of $B_s^0 - \bar{B}_s^0$ Oscillations



We report the observation of B_s^0-$\bar{B}_s^0$ oscillations from a time-dependent measurement of the B_s^0-$\bar{B}_s^0$ oscillation frequency Δm_s. Using a data sample of 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61 500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B_s^0-$\bar{B}_s^0$ oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8}, which exceeds 5σ significance. We measure $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ ps^{-1} and extract $|V_{td}/V_{ts}| = 0.2060 \pm 0.0007(\Delta m_s)^{+0.0081}_{-0.0060}(\Delta m_d + \text{theor})$.

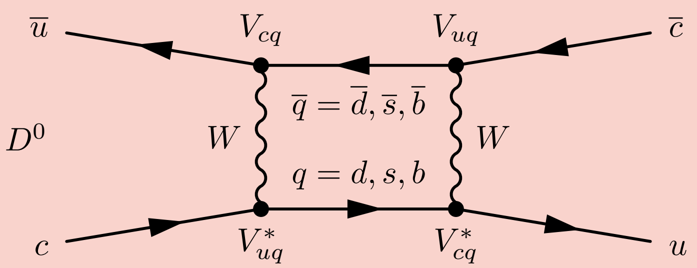
DOI: 10.1103/PhysRevLett.97.242003 PACS numbers: 14.40.Nd, 12.15.Ff, 12.15.Hh, 13.20.He

D^0 mixing

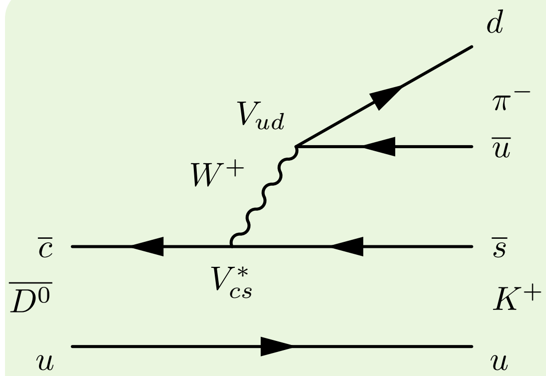
Look for 'wrong sign' D^0 decays

$$D^0 \longrightarrow K^+\pi^-$$

D⁰ mixing



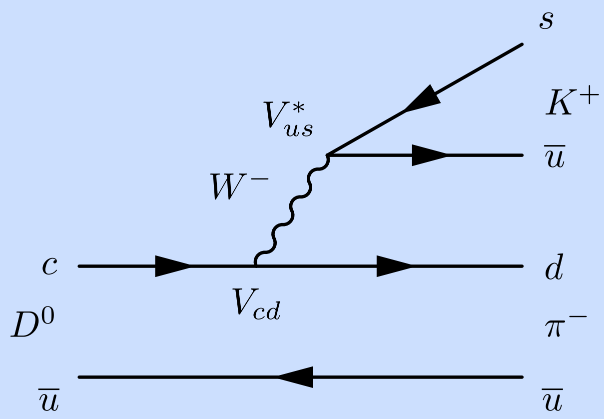
d,s,b 'in the loop' instead of u,c,t
⇒ GIM (almost) kills this amplitude...



$$|V^*_{cs} V_{ud}| = \mathcal{O}(1)$$

Look for 'wrong sign' D⁰ decays

$$D^0 \rightarrow \overline{D^0} \Rightarrow K^+\pi^-$$



$$|V_{cd} V^*_{us}| = \mathcal{O}(\lambda^2) \approx 0.04$$

D^0 mixing: BaBar, 2007

PRL **98,** 211802 (2007) PHYSICAL REVIEW LETTERS week ending 25 MAY 2007

Evidence for D^0-$\overline{D}^0$ Mixing

$$\boxed{D^0 \longrightarrow K^+\pi^-}$$

We present evidence for D^0-$\overline{D}^0$ mixing in $D^0 \to K^+\pi^-$ decays from 384 fb^{-1} of e^+e^- colliding-beam data recorded near $\sqrt{s} = 10.6$ GeV with the *BABAR* detector at the PEP-II storage rings at the Stanford Linear Accelerator Center. We find the mixing parameters $x'^2 = [-0.22 \pm 0.30(\text{stat}) \pm 0.21(\text{syst})] \times 10^{-3}$ and $y' = [9.7 \pm 4.4(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-3}$ and a correlation between them of -0.95. This result is inconsistent with the no-mixing hypothesis with a significance of 3.9 standard deviations. We measure R_D, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, to be $[0.303 \pm 0.016(\text{stat}) \pm 0.010(\text{syst})]\%$. We find no evidence for CP violation.

DOI: 10.1103/PhysRevLett.98.211802 PACS numbers: 13.25.Ft, 11.30.Er, 12.15.Ff, 14.40.Lb

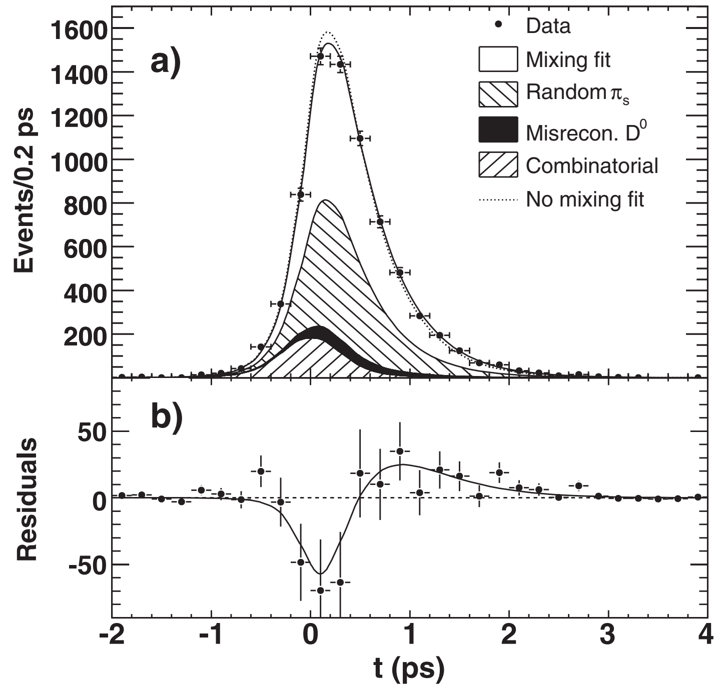
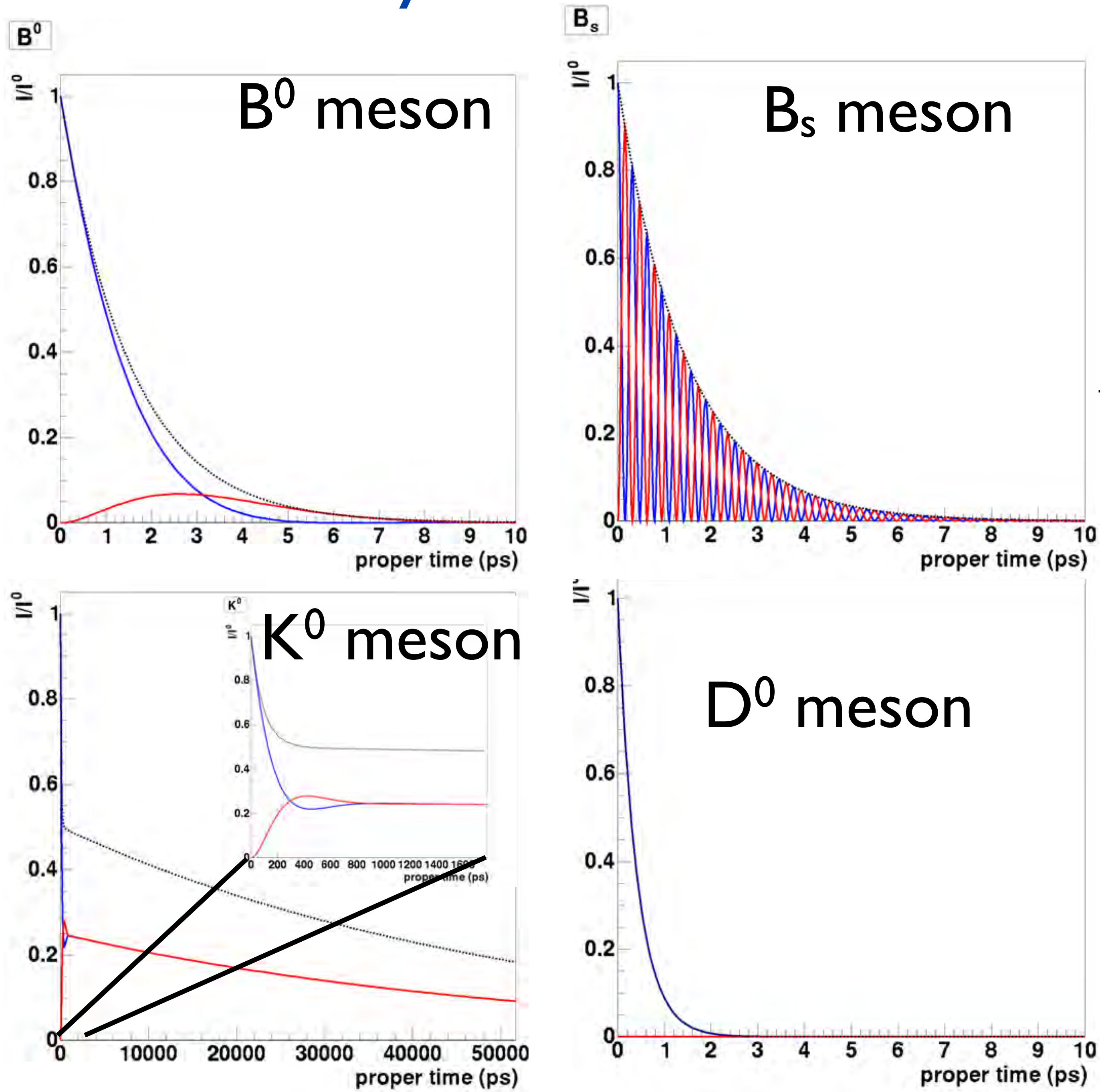


FIG. 2. (a) Projections of the proper-time distribution of combined D^0 and $\overline{D}^0$ WS candidates and fit result integrated over the signal region $1.843 < m_{K\pi} < 1.883$ GeV$/c^2$ and $0.1445 < \Delta m < 0.1465$ GeV$/c^2$. The result of the fit allowing (not allowing) mixing but not CP violation is overlaid as a solid (dashed) curve. (b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing.

Summary of Neutral Meson Mixing



	d	s	b
$\overline{d}$	$\times$	K^0	B^0
$\overline{s}$	$\overline{K^0}$	$\times$	B_s
$\overline{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

	u	c	t
$\overline{u}$	$\times$	D^0	$\diamond$
$\overline{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\overline{t}$	$\diamond$	$\diamond$	$\times$

Blue:
given a P^0, at t=0, the probability of finding a P^0 at t.

Red:
given a P^0, at t=0, the probability of finding a P^0bar at t.

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM
- All four neutral mesons can mix -- and do, but some faster(slower) than others...
- Heavy top quark needed for B mixing

How to put these measurements together?

- Many measurements, but in the end, V_{CKM} has only four parameters
- ...and only *one* of them is actually responsible for CP violation
- How to make a coherent/powerful/... test of the model?
- How to integrate CP measurements in this?

- V_{CKM} has *many* relations amongst its elements....

Use the unitarity constraint(s)!

The 9 unitarity conditions of the 3×3 generations CKM matrix:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Use the unitarity constraint(s)!

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The 6 complex "**Unitarity Triangles**" involve different physics processes

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The 6 complex "**Unitarity Triangles**" involve different physics processes

'sd' triangle: K^0

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0 \qquad \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0$$

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$$*$$

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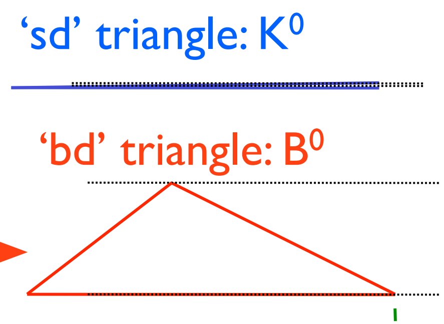

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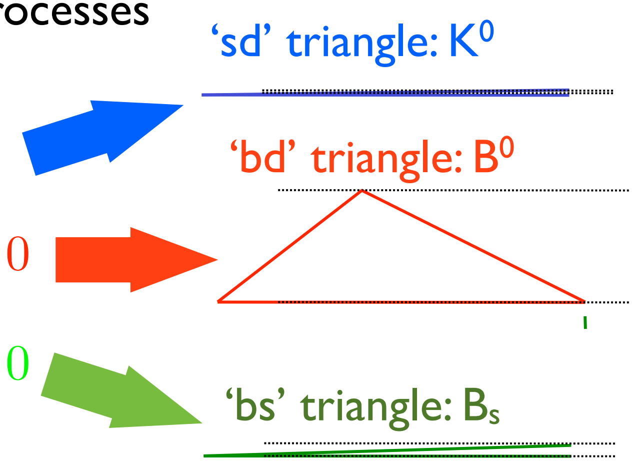

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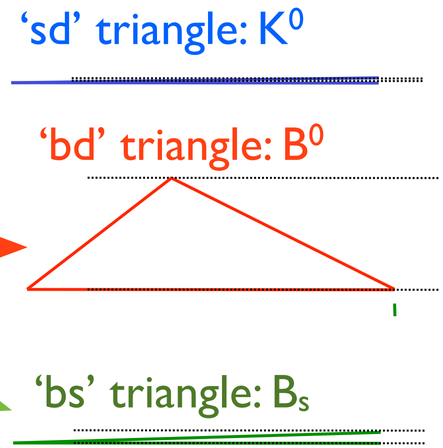

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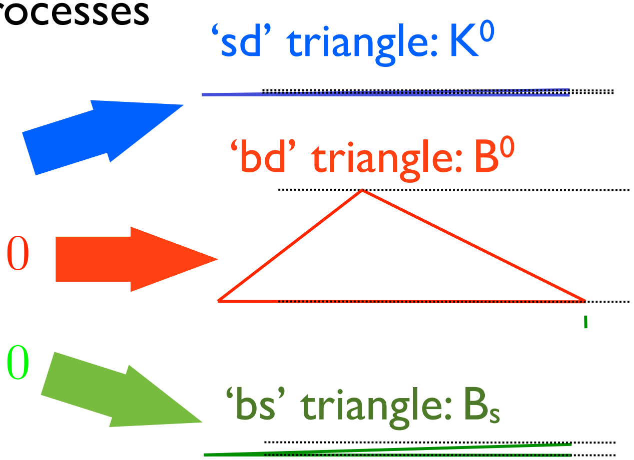

$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

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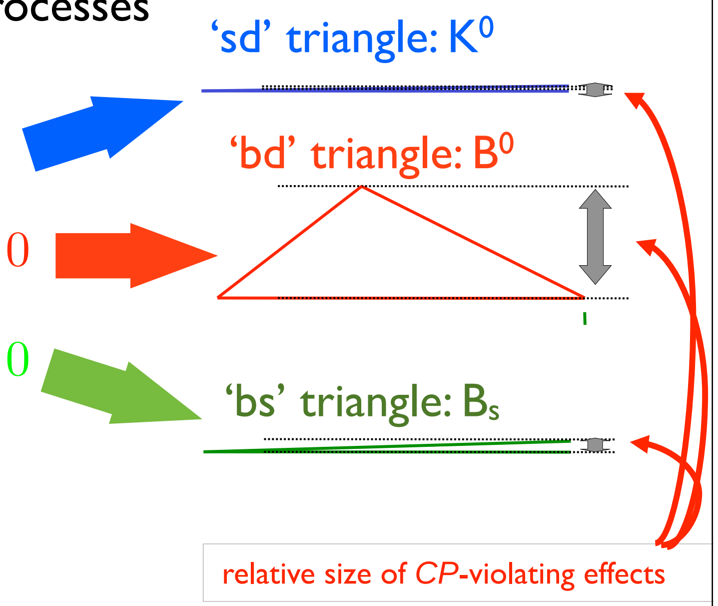

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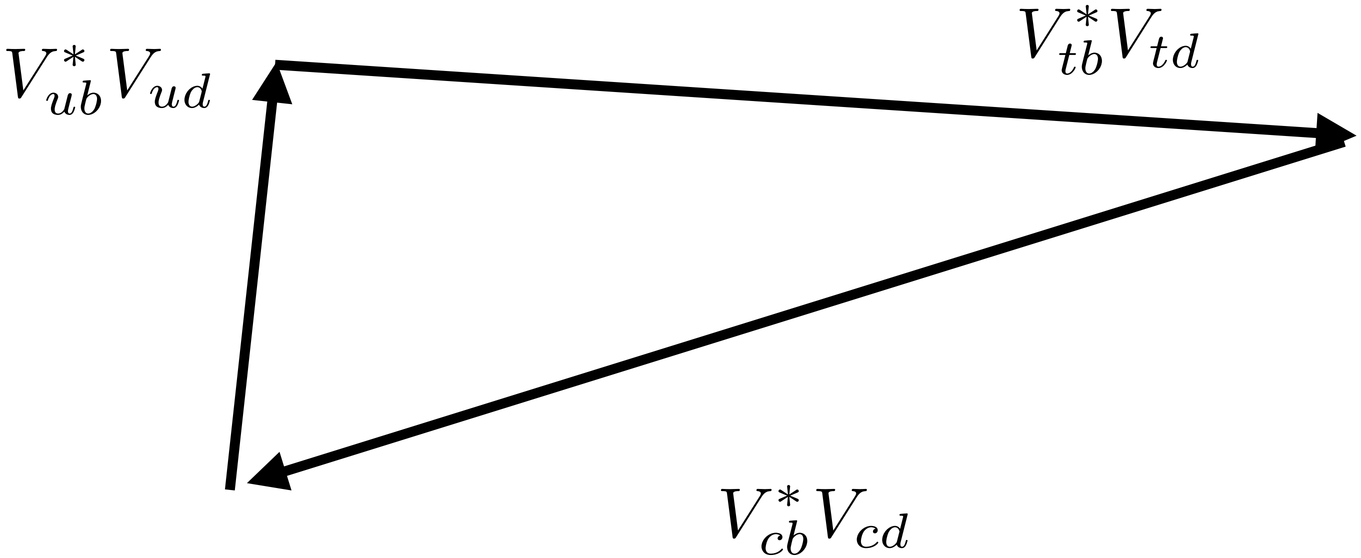
“The” Unitarity Triangle...

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



"The" Unitarity Triangle...

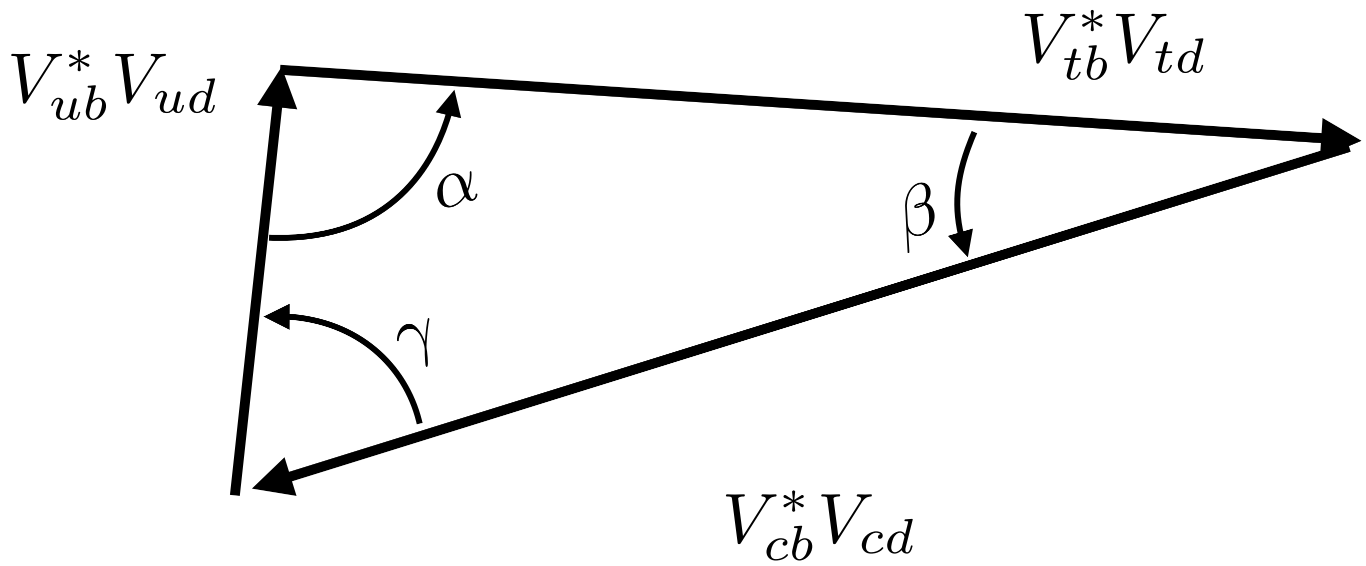
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- The internal angles are quark rephasing *independent* and *observable*

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



"The" Unitarity Triangle...

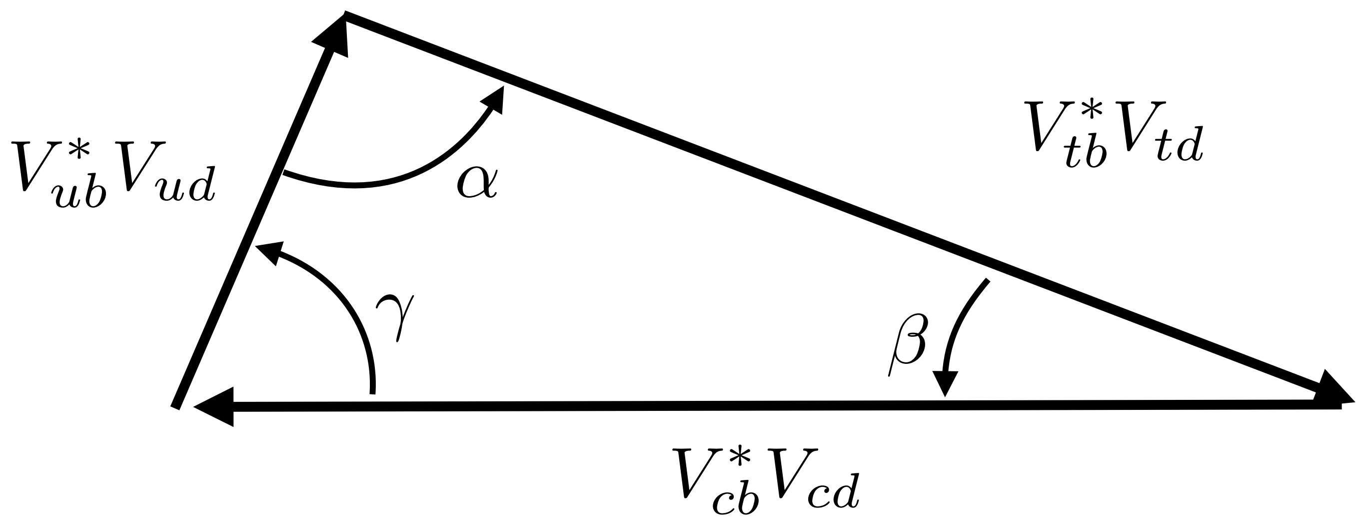
$$V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$$

- pick a quark phase convention such that $V_{cb}^*V_{cd}$ is real

$$\alpha = \arg\left(-\frac{V_{tb}^*V_{td}}{V_{ub}^*V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^*V_{cd}}{V_{tb}^*V_{td}}\right)$$



"The" Unitarity Triangle...

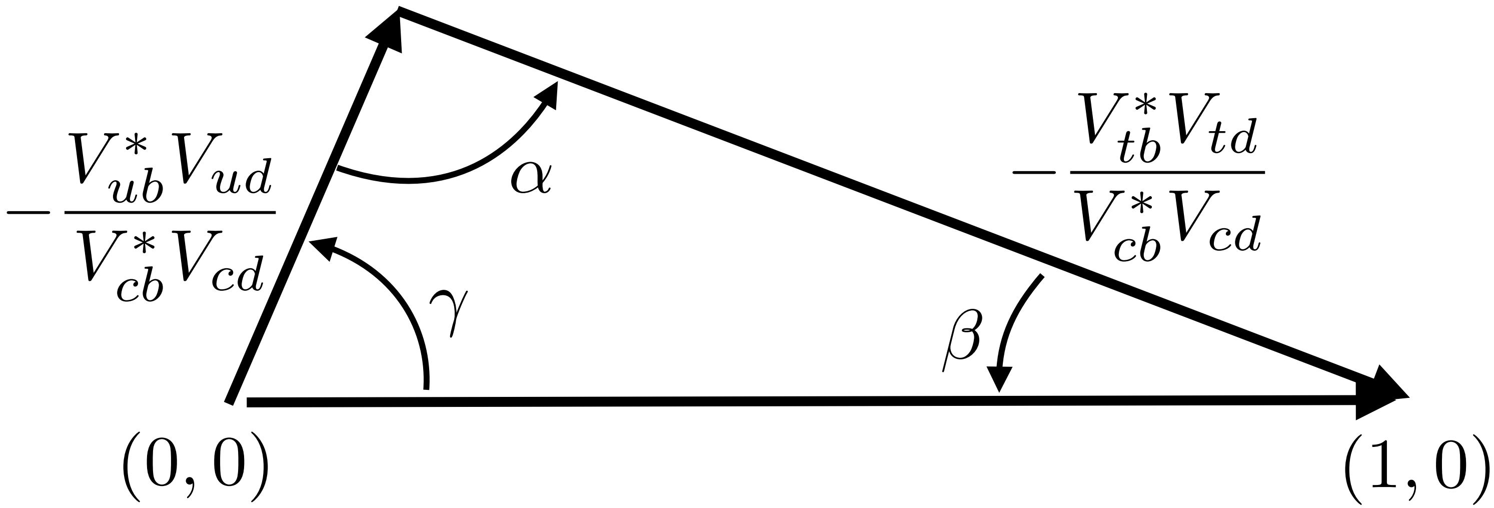
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- Normalize all sides by $-V_{cb}^* V_{cd}$

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



“The” Unitarity Triangle...

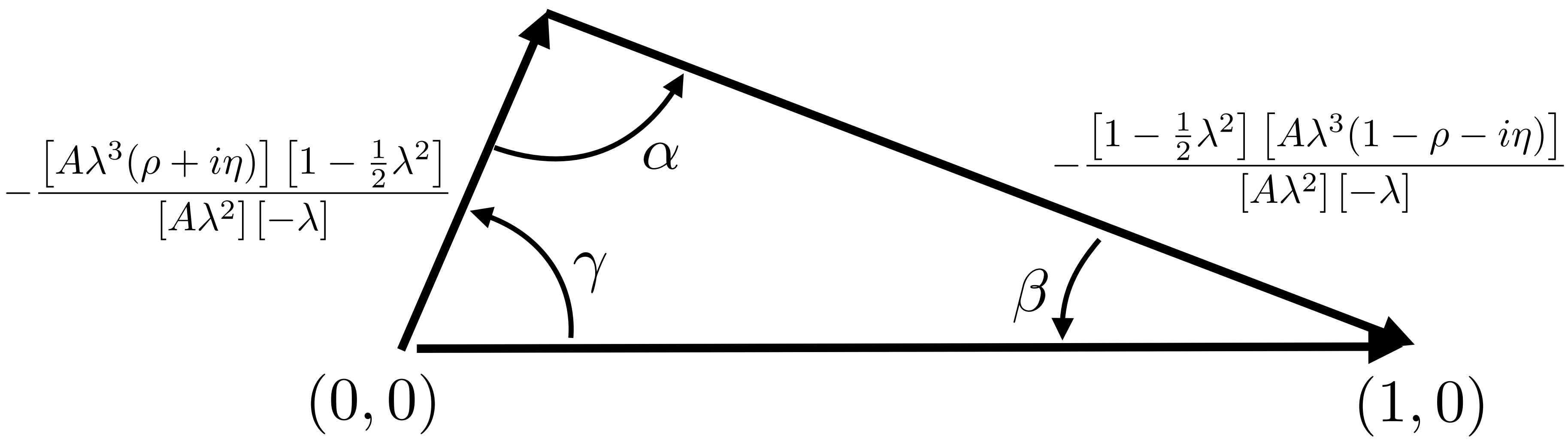
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- Put in the Wolfenstein parameterization of the V_{CKM} elements

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



“The” Unitarity Triangle...

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

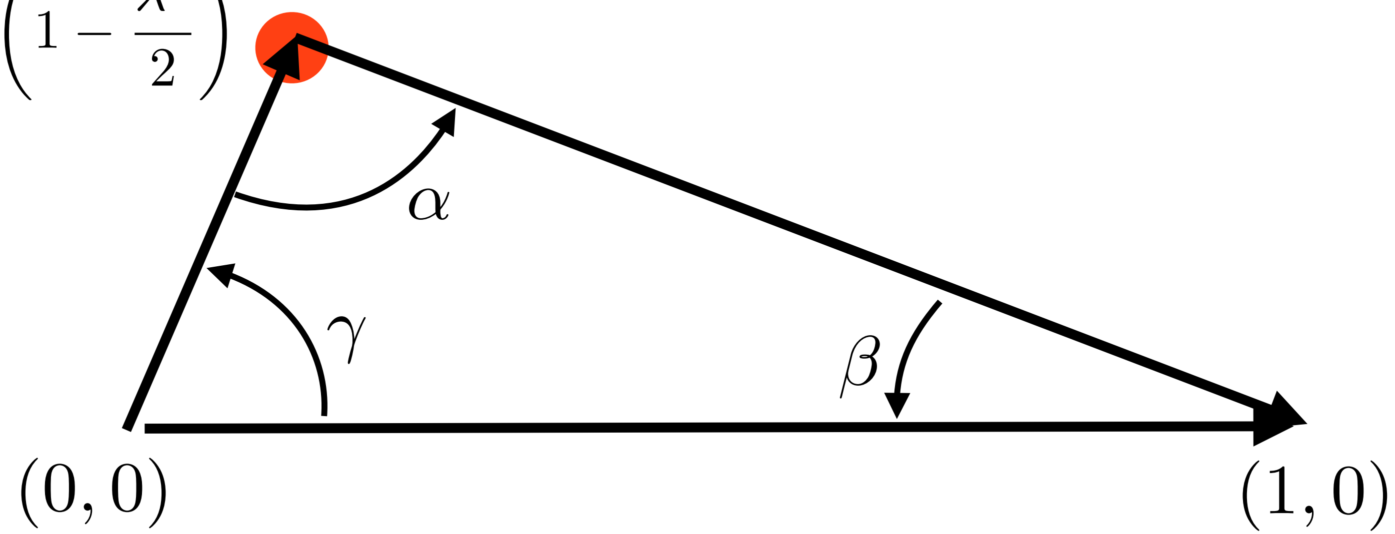
- And simplify...

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

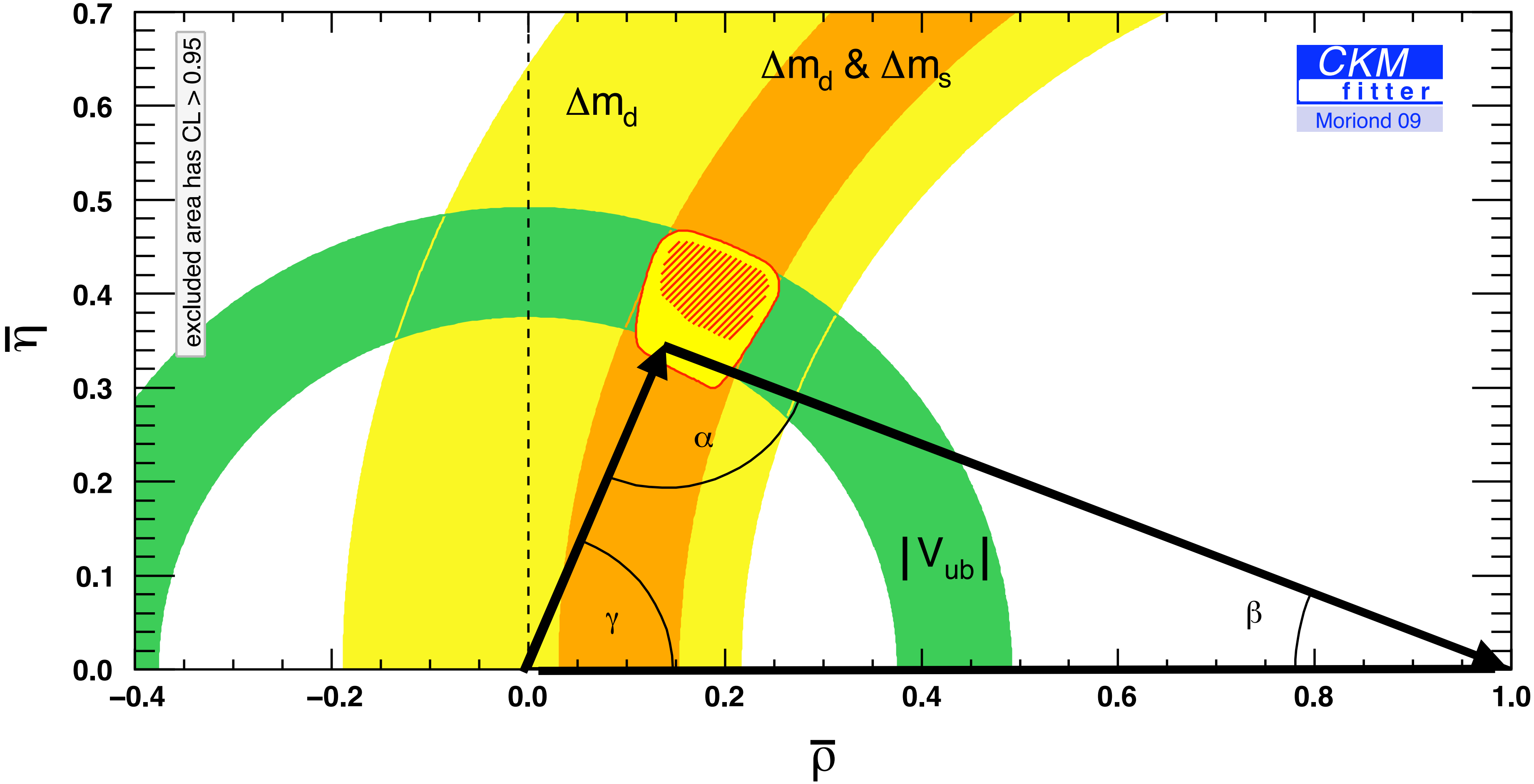
$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

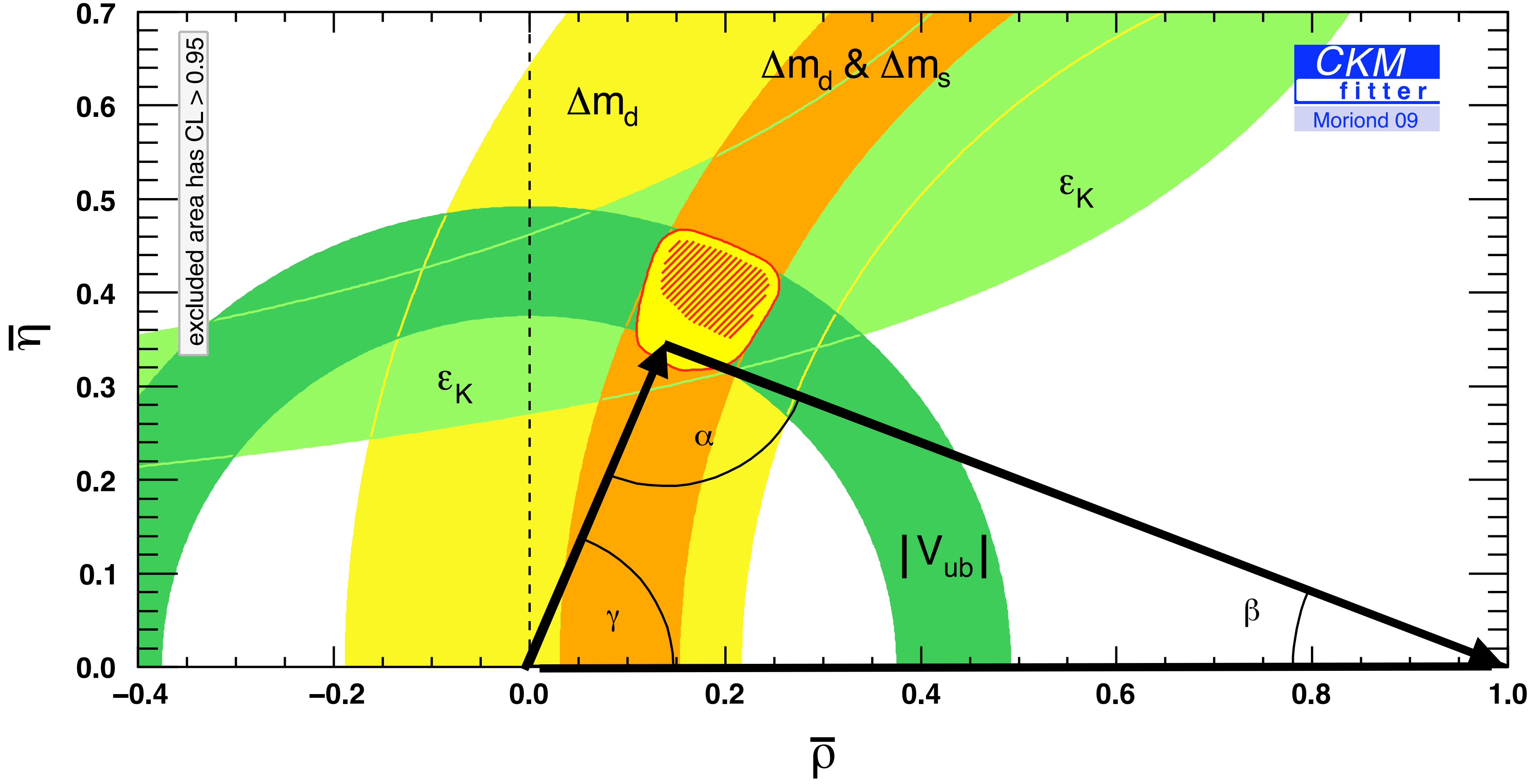
$$\overline{\rho} + i\overline{\eta} \equiv (\rho + i\eta)\left(1 - \frac{\lambda^2}{2}\right)$$



$(\bar\rho,\bar\eta)$: the magnitudes only...



$(\bar{\rho},\bar{\eta})$: the magnitudes and ε_K...



Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
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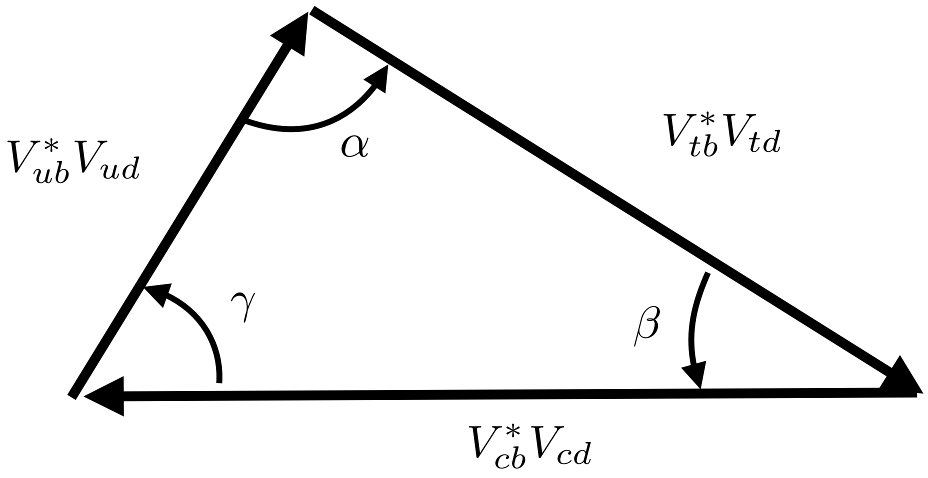
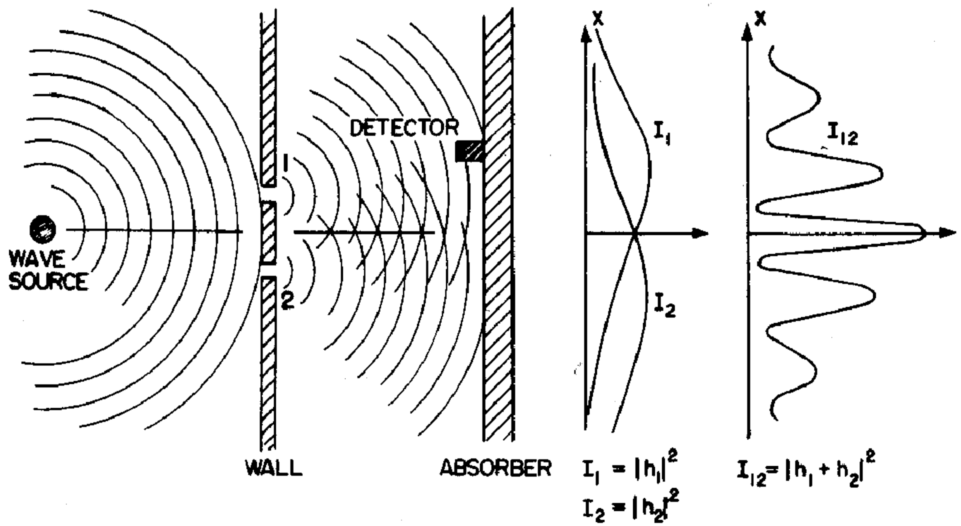
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM
- All four neutral mesons can mix -- and do, but some faster(slower) than others...
- Heavy top quark needed for B mixing
- Using the measured magnitudes of V_{CKM} elements, we can predict the weak phases!

Measuring the angles (phases!)..

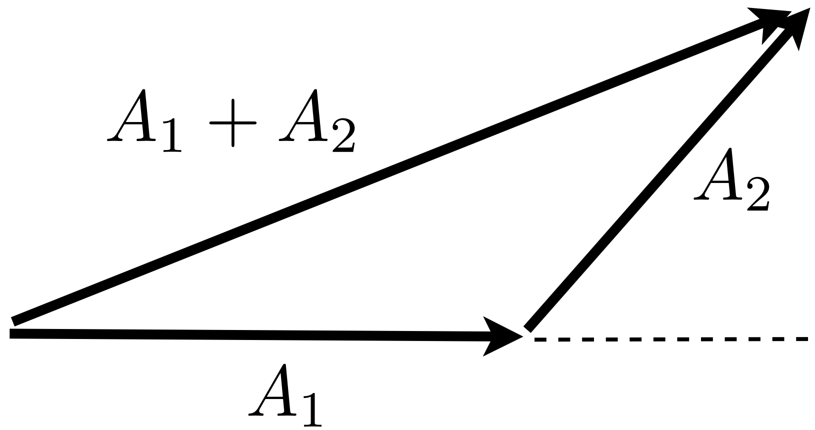


- We've measured the sides, and have predictions for the angles,
- But how to measure the angles, i.e. phases?
- Interference!



Amplitudes and Observables

$$\begin{aligned} A_j &= \langle \text{final} | H_j | \text{initial} \rangle \\ &= |A_j| e^{+i\phi_j^{\text{weak}}} \end{aligned}$$



$$P(i \to f) = |A_1 + A_2|^2$$

Amplitudes and Observables

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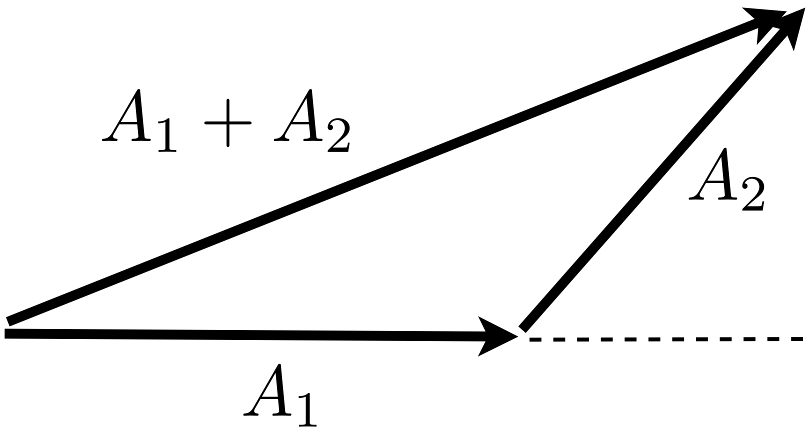
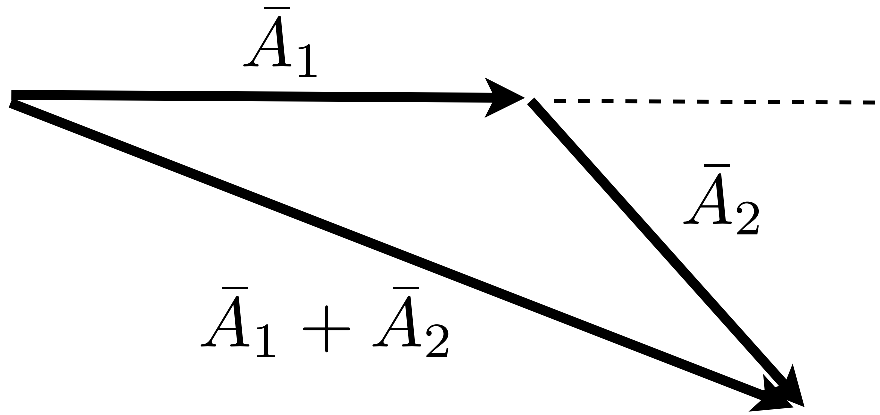
\end{aligned}
$$

CP

$$
\begin{aligned}
\bar{A}_j &= A_j^* \\
&= |A_j| e^{-i\phi_j^{\text{weak}}}
\end{aligned}
$$





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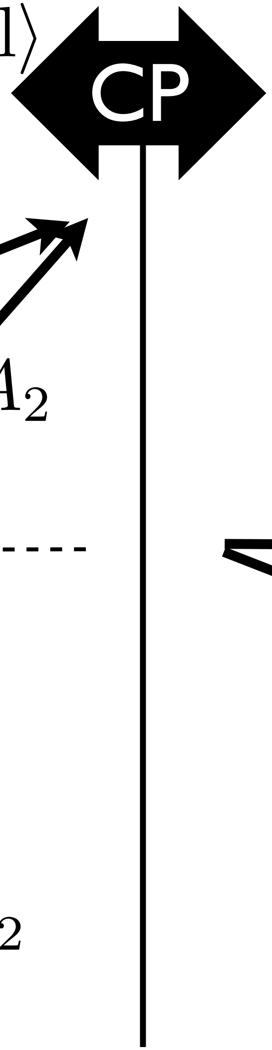

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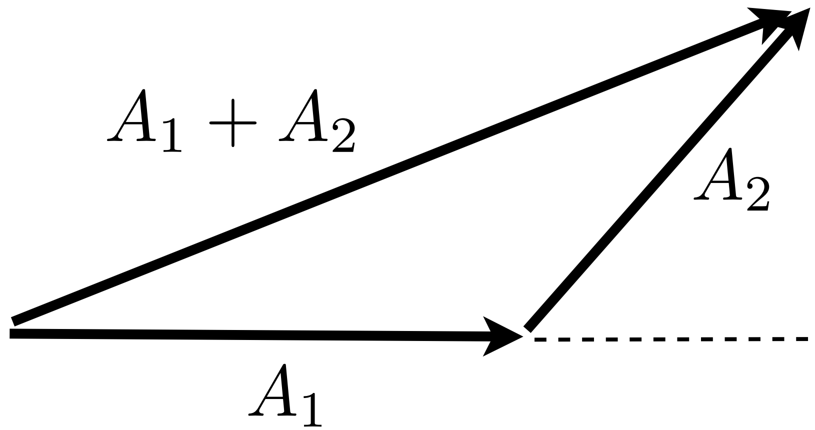
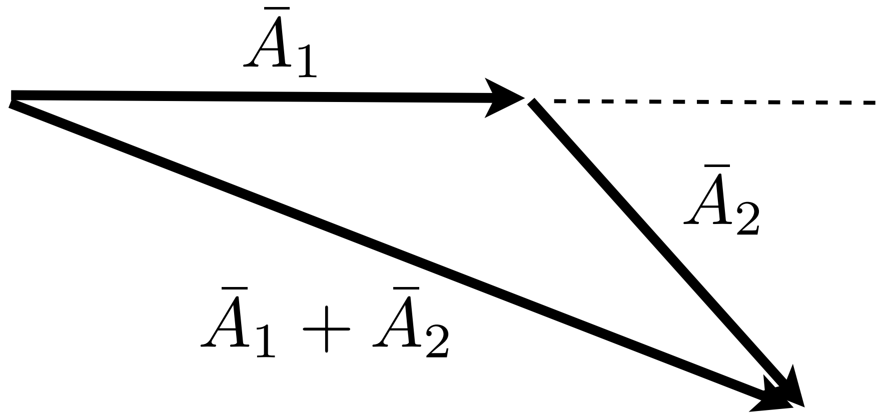


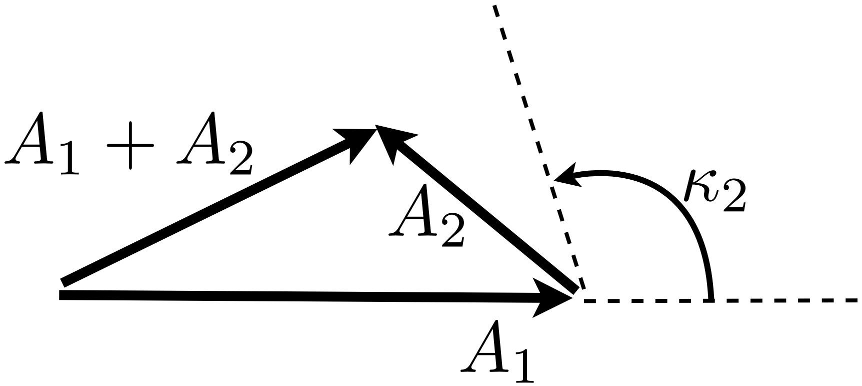


$$P(i \to f) = |A_1 + A_2|^2 \qquad P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$

$$= |A_1|^2 + 2|A_1||A_2|\cos\phi_2 + |A_2|^2$$

Amplitudes and Observables

$$A_j = |A_j| e^{i\left(\phi_j^{+\mathrm{weak}} + \kappa_j\right)}$$



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CP

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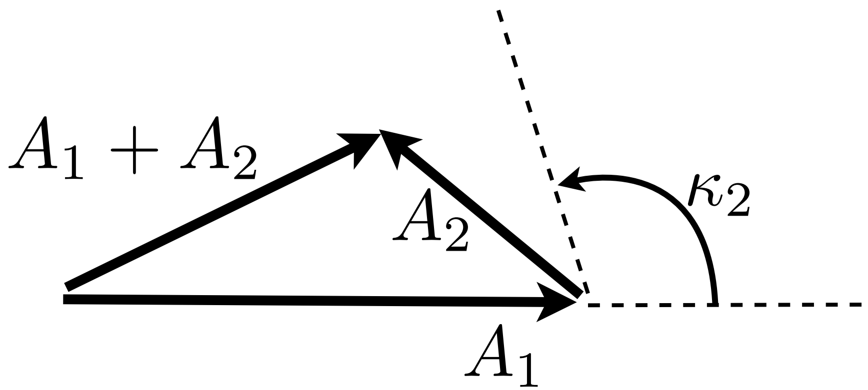

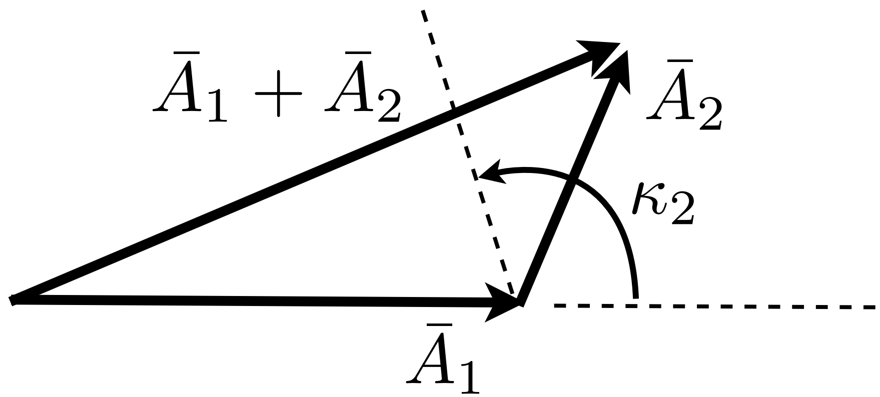

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Amplitudes and Observables

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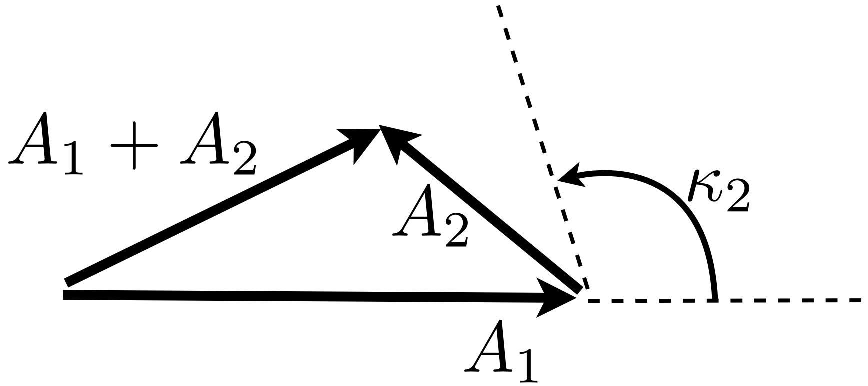
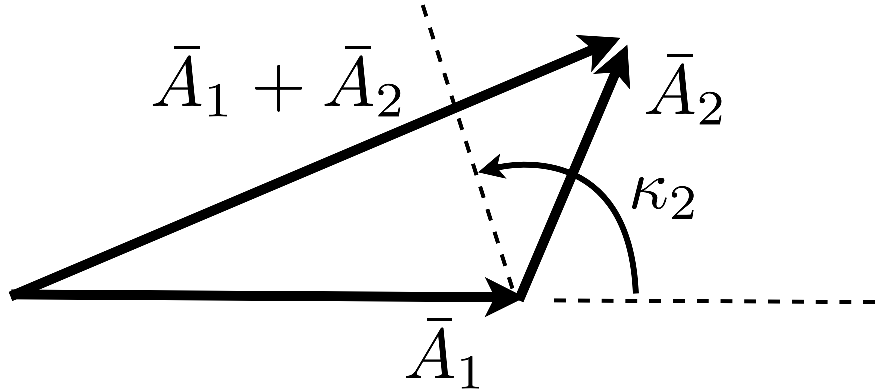
CP

$$\bar{A}_j = |A_j| e^{i\left(-\phi_j^{\text{weak}} + \kappa_j\right)}$$





$$P(i \to f) = |A_1 + A_2|^2$$

$$P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$

$$= |A_1|^2 + 2|A_1||A_2| \cos(\phi_2 \pm \kappa_2) + |A_2|^2$$

$$P(i \to f) - P(\bar{i} \to \bar{f}) = -4|A_1||A_2| \sin(\phi_2) \sin(\kappa_2)$$

(large) weak phases necessary but *not* sufficient for (large) CP violation...

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

$t=0$	t	Amplitude

$$\begin{tikzcd} & B^0 \arrow[d, "A_f"] \\ B^0 \arrow[ur, bend left, "g_+(t)"] \arrow[dr, bend right, "\frac{q}{p}g_-(t)"'] & f_{CP} \\ & \overline{B^0} \arrow[u, "\overline{A}_f"'] \end{tikzcd} \qquad g_+(t)A_{f_{CP}} + \frac{q}{p}g_-(t)\overline{A}_{f_{CP}}$$

$$\begin{tikzcd} & \overline{B^0} \arrow[d, "\overline{A}_f"] \\ \overline{B^0} \arrow[ur, bend left, "g_+(t)"] \arrow[dr, bend right, "\frac{p}{q}g_-(t)"'] & f_{CP} \\ & B^0 \arrow[u, "A_f"'] \end{tikzcd} \qquad g_+(t)\overline{A}_{f_{CP}} + \frac{p}{q}g_-(t)A_{f_{CP}}$$

Interference!

$$g_{\pm}(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

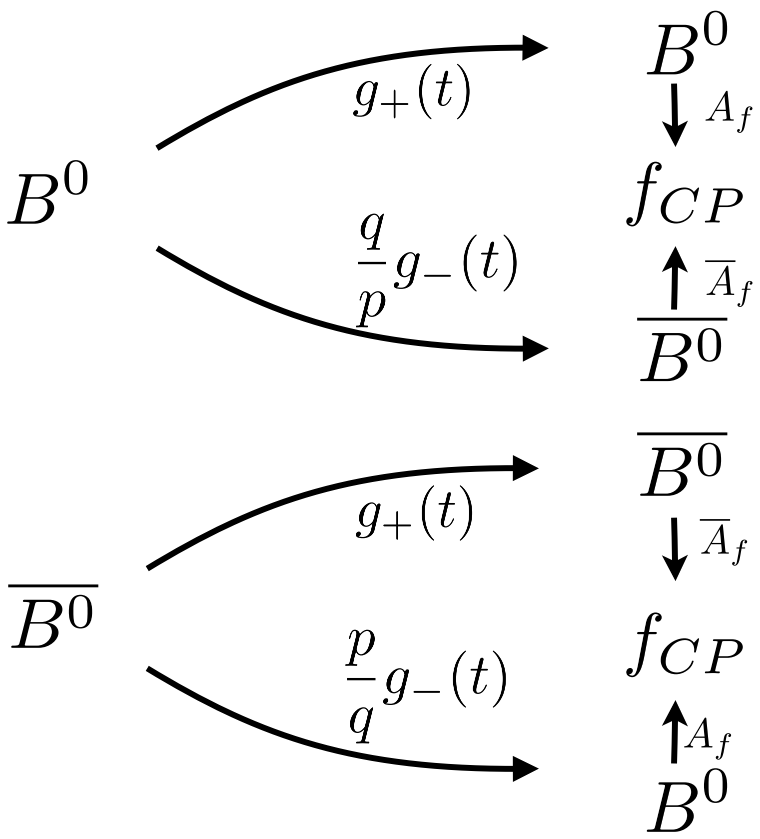
For neutral B mesons, g_- has a 90° phase difference wrt. g_+

$$g_+(t) = e^{-imt} e^{-\Gamma t/2} \cos\frac{\Delta m t}{2}$$

$$g_-(t) = e^{-imt} e^{-\Gamma t/2} i \sin\frac{\Delta m t}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$t=0$	t	Amplitude



$$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2} \left(\cos\frac{\Delta m t}{2} + \lambda_{f_{CP}} i \sin\frac{\Delta m t}{2} \right)$$

$$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2} \left(\cos\frac{\Delta m t}{2} + \frac{1}{\lambda_{f_{CP}}} i \sin\frac{\Delta m t}{2} \right)$$

Interference!

Assume $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$

$t=0$	t	Amplitude
$B^0 \longrightarrow$	f_{CP}	$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2} \left(\cos\frac{\Delta m t}{2} + \lambda_{f_{CP}} i \sin\frac{\Delta m t}{2} \right)$
$\overline{B^0} \longrightarrow$	f_{CP}	$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2} \left(\cos\frac{\Delta m t}{2} + \frac{1}{\lambda_{f_{CP}}} i \sin\frac{\Delta m t}{2} \right)$

Interference!

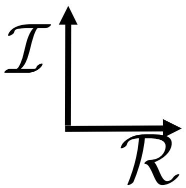
Assume $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$

$t=0$	t	Amplitude
$B^0 \longrightarrow$	f_{CP}	$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + \lambda_{f_{CP}} i \sin\frac{\Delta mt}{2}\right)$
$\overline{B^0} \longrightarrow$	f_{CP}	$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + \frac{1}{\lambda_{f_{CP}}} i \sin\frac{\Delta mt}{2}\right)$

$B^0 \longrightarrow f_{CP}$

$\overline{B^0} \longrightarrow f_{CP}$

Δmt/2=0



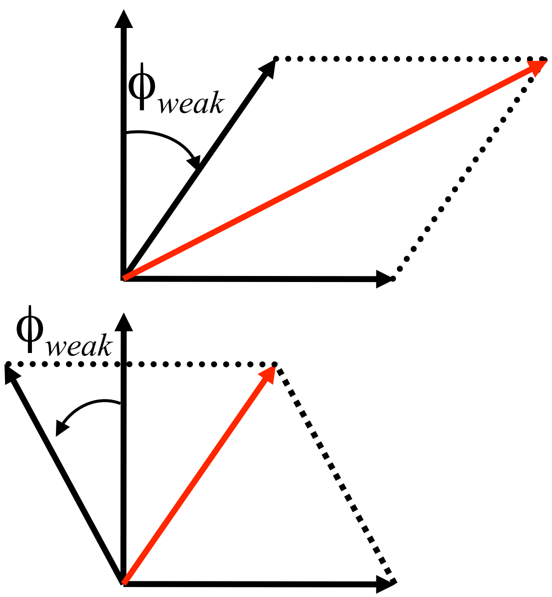
Interference!

Assume $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$

$t=0$	t	Amplitude
$B^0 \longrightarrow$	f_{CP}	$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + \lambda_{f_{CP}} i \sin\frac{\Delta mt}{2}\right)$
$\overline{B^0} \longrightarrow$	f_{CP}	$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + \frac{1}{\lambda_{f_{CP}}} i \sin\frac{\Delta mt}{2}\right)$

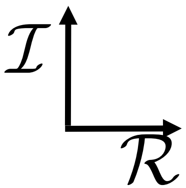
$B^0 \longrightarrow f_{CP}$

$\overline{B^0} \longrightarrow f_{CP}$



Δmt/2=0

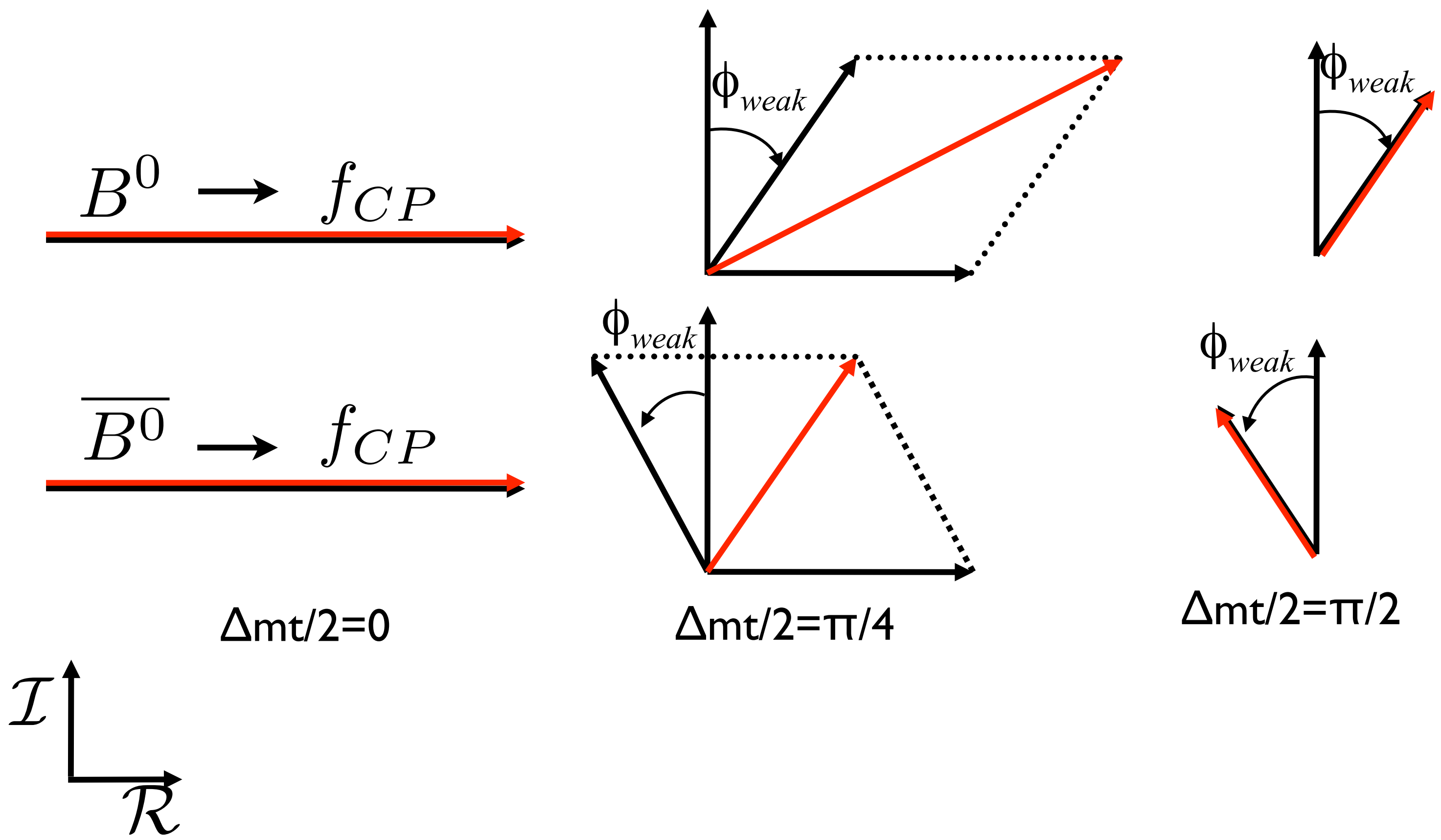
Δmt/2=π/4



Interference!

Assume $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$

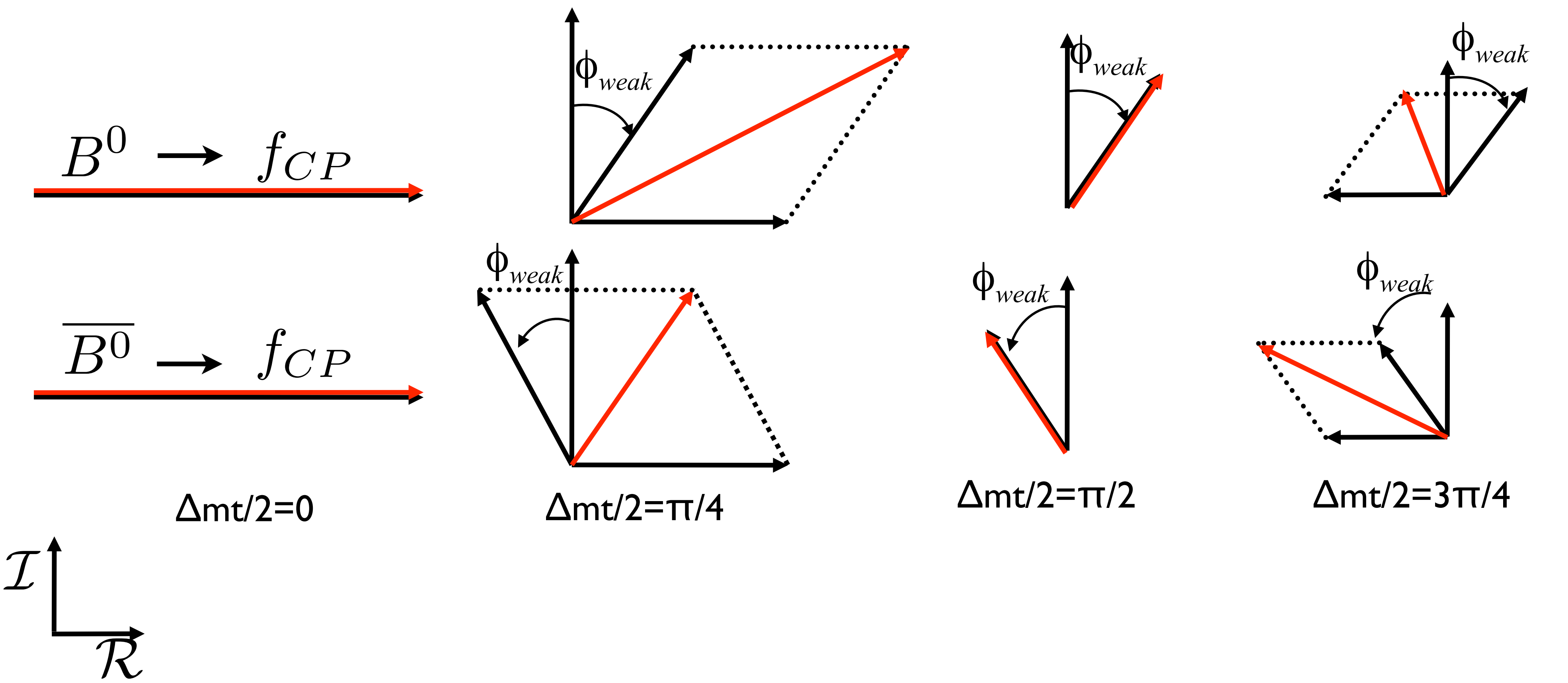
$t=0$	t	Amplitude
B^0	$\longrightarrow f_{CP}$	$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + \lambda_{f_{CP}}\, i \sin\frac{\Delta m t}{2}\right)$
$\overline{B^0}$	$\longrightarrow f_{CP}$	$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + \frac{1}{\lambda_{f_{CP}}}\, i \sin\frac{\Delta m t}{2}\right)$



Interference!

Assume $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$

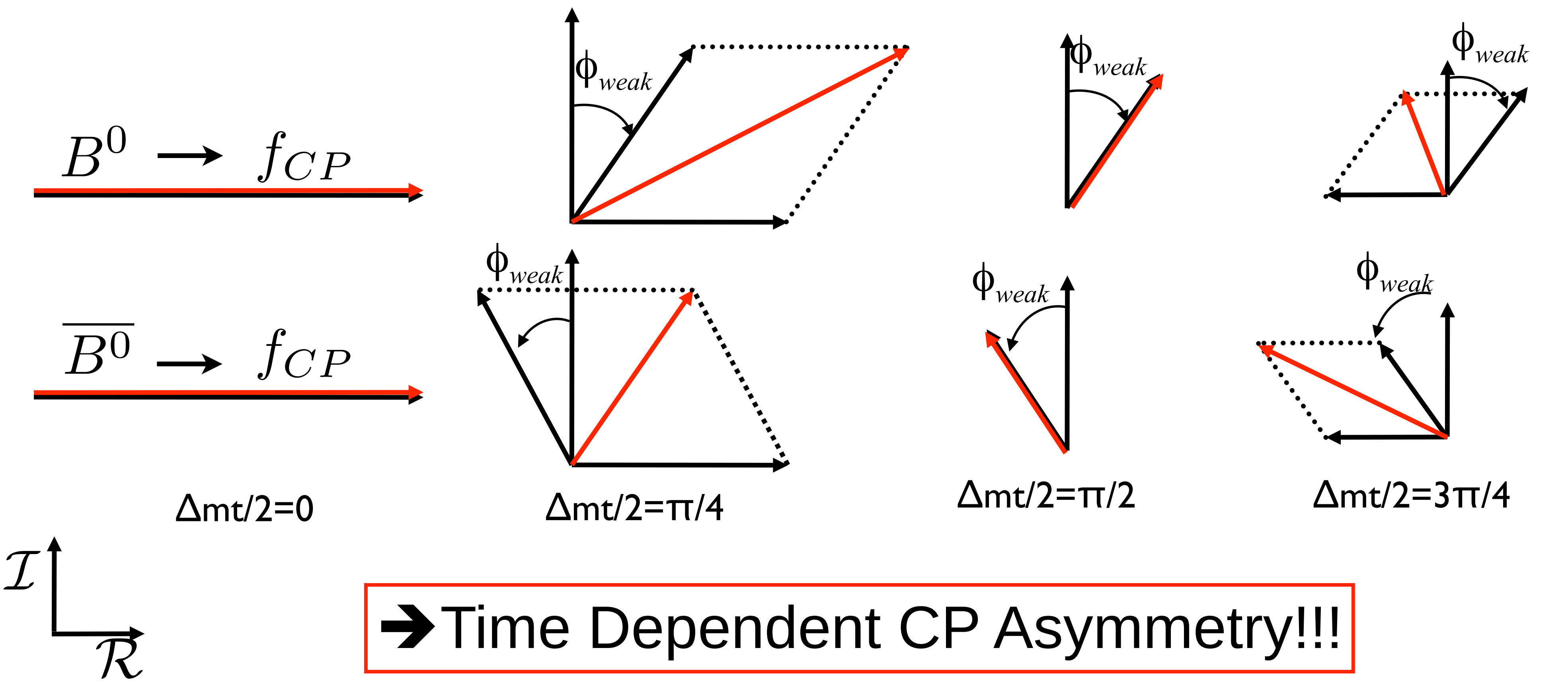
$t=0$	t	Amplitude
B^0	$\longrightarrow f_{CP}$	$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + \lambda_{f_{CP}} i \sin\frac{\Delta m t}{2}\right)$
$\overline{B^0}$	$\longrightarrow f_{CP}$	$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + \frac{1}{\lambda_{f_{CP}}} i \sin\frac{\Delta m t}{2}\right)$



Interference!

Assume $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$

$t=0$	t	Amplitude
B^0	$\longrightarrow f_{CP}$	$A_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + \lambda_{f_{CP}}\, i \sin\frac{\Delta mt}{2}\right)$
$\overline{B^0}$	$\longrightarrow f_{CP}$	$\overline{A}_{f_{CP}} e^{-imt} e^{-\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + \frac{1}{\lambda_{f_{CP}}}\, i \sin\frac{\Delta mt}{2}\right)$

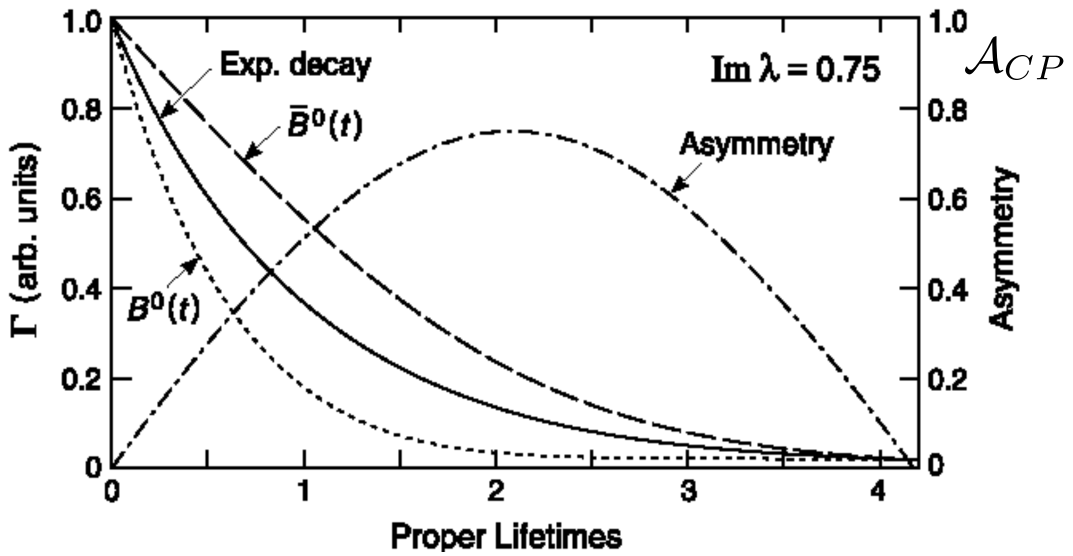


➔Time Dependent CP Asymmetry!!!

Interference!

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$t=0$	t	Rate
B^0 $\longrightarrow$	f_{CP}	$\frac{1}{2}e^{-\Gamma t}\left[1+\left(\frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}\right)\cos(\Delta m t)-\left(\frac{2\mathcal{I}(\lambda)}{1+\lvert\lambda\rvert^2}\right)\sin(\Delta m t)\right]$
$\overline{B^0}$ $\longrightarrow$	f_{CP}	$\frac{1}{2}e^{-\Gamma t}\left[1-\left(\frac{1-\lvert\lambda\rvert^2}{1+\lvert\lambda\rvert^2}\right)\cos(\Delta m t)+\left(\frac{2\mathcal{I}(\lambda)}{1+\lvert\lambda\rvert^2}\right)\sin(\Delta m t)\right]$



$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\overline{B^0}\to f_{CP})-\Gamma(B^0\to f_{CP})}{\Gamma(\overline{B^0}\to f_{CP})+\Gamma(B^0\to f_{CP})}$$

$$= -C_{f_{CP}}\cos(\Delta m t)+S_{f_{CP}}\sin(\Delta m t)$$

CP in decay

CP in interference between decay and mixing

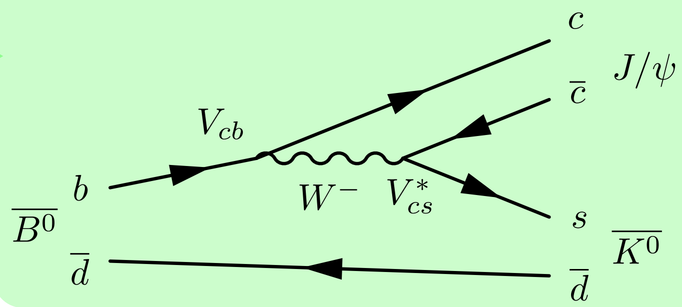
Next: find the right f_{CP}...

B→ J/ψKs

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

B→ J/ψKs

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

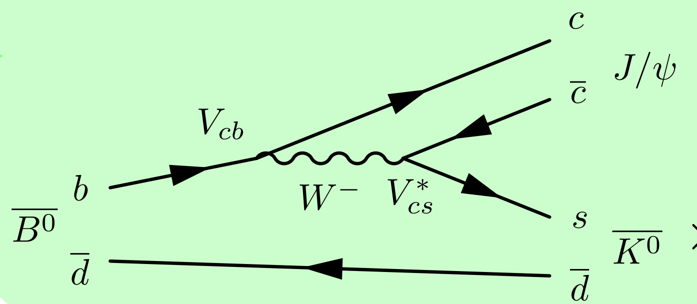


$$\times \left\langle K_s | \overline{K^0} \right\rangle$$

B→ J/ψKs

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0\to K_S}}$$

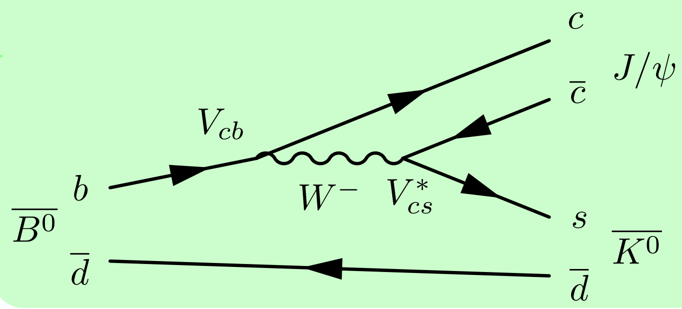


$$\times \left\langle K_s \middle| \overline{K^0} \right\rangle$$

$B \to J/\psi K_S$

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$



$$\times \left\langle K_s | \overline{K^0} \right\rangle$$

$$\overline{A}_f = \eta_{CP}\overline{A}_{\overline{f}}$$

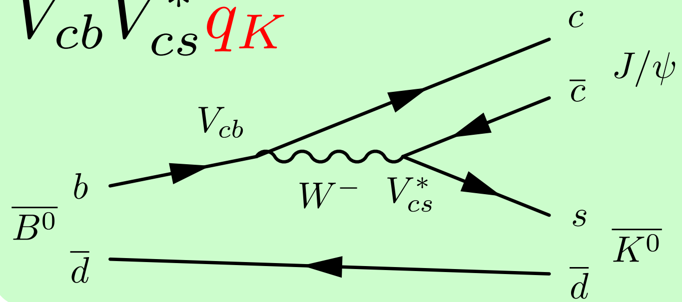
$$\begin{aligned} CP\,|J/\psi K_S\rangle &= \left(-1^1\right)\left[CP\,|J/\psi\rangle\right]\left[CP\,|K_S\rangle\right] \\ &= \left(-1^1\right)\left[(-1^1)(-)\,|J/\psi\rangle\right]\left[(+)\,|K_S\rangle\right] \\ &= -\,|J/\psi K_S\rangle \end{aligned}$$

$B \to J/\psi K_S$

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

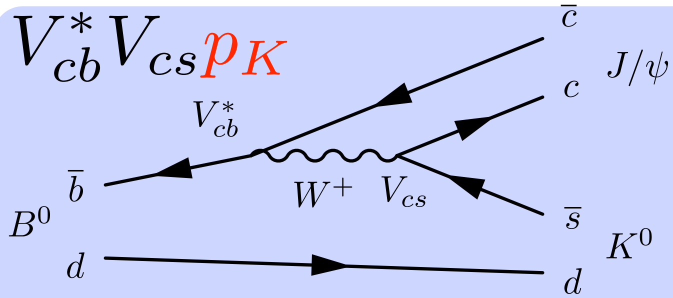
$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0} \to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$

$V_{cb}V_{cs}^{*}q_K$



$\times \left\langle K_s | \overline{K^0} \right\rangle$

$V_{cb}^{*}V_{cs}p_K$

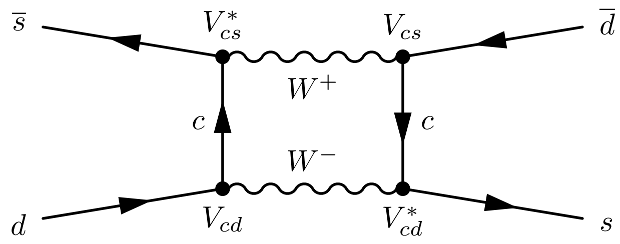


$\times \left\langle K_s | K^0 \right\rangle$

$$|K_s\rangle = p_K \left|K^0\right\rangle + q_K \left|\overline{K^0}\right\rangle$$

$B \to J/\psi K_S$

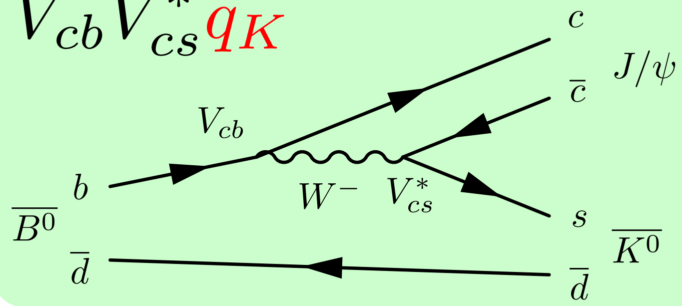
$$\frac{q_K}{p_K} \approx \frac{V_{cs}^* V_{cd}}{V_{cs} V_{cd}^*}$$



$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

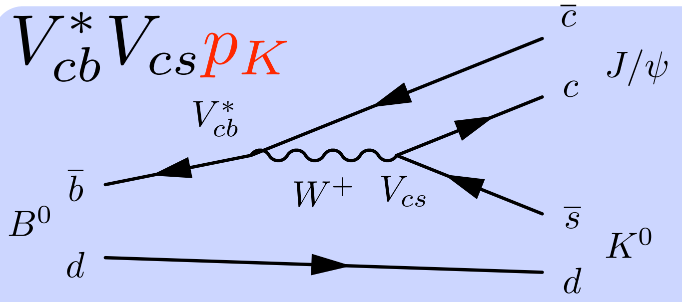
$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0} \to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$

$$V_{cb} V_{cs}^* q_K$$



$$\overline{K^0} \times \left\langle K_s | \overline{K^0} \right\rangle$$

$$V_{cb}^* V_{cs} p_K$$

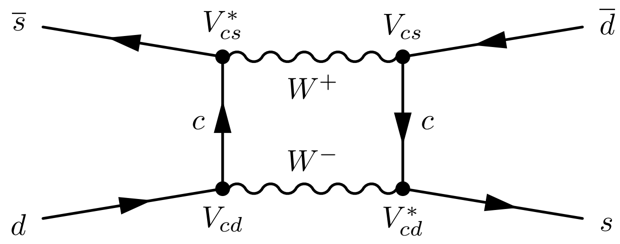


$$K^0 \times \left\langle K_s | K^0 \right\rangle$$

$$|K_s\rangle = p_K \left|K^0\right\rangle + q_K \left|\overline{K^0}\right\rangle$$

B→ J/ψKs

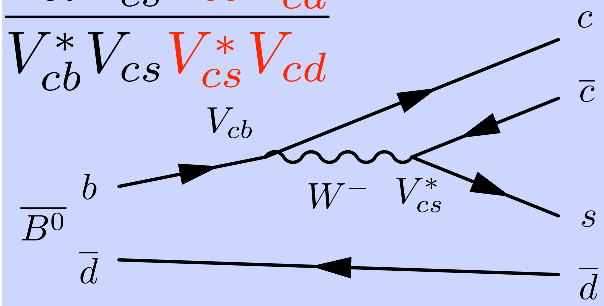
$$\frac{q_K}{p_K} \approx \frac{V_{cs}^* V_{cd}}{V_{cs} V_{cd}^*}$$



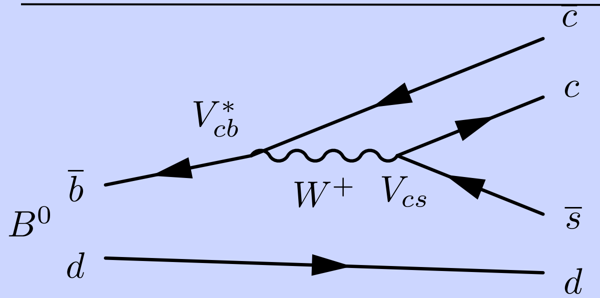
$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0\to K_S}}$$

$$\frac{V_{cb}V_{cs}^* V_{cs} V_{cd}^*}{V_{cb}^* V_{cs} V_{cs}^* V_{cd}}$$



$$\overline{K^0} \times \left\langle K_s | \overline{K^0} \right\rangle$$



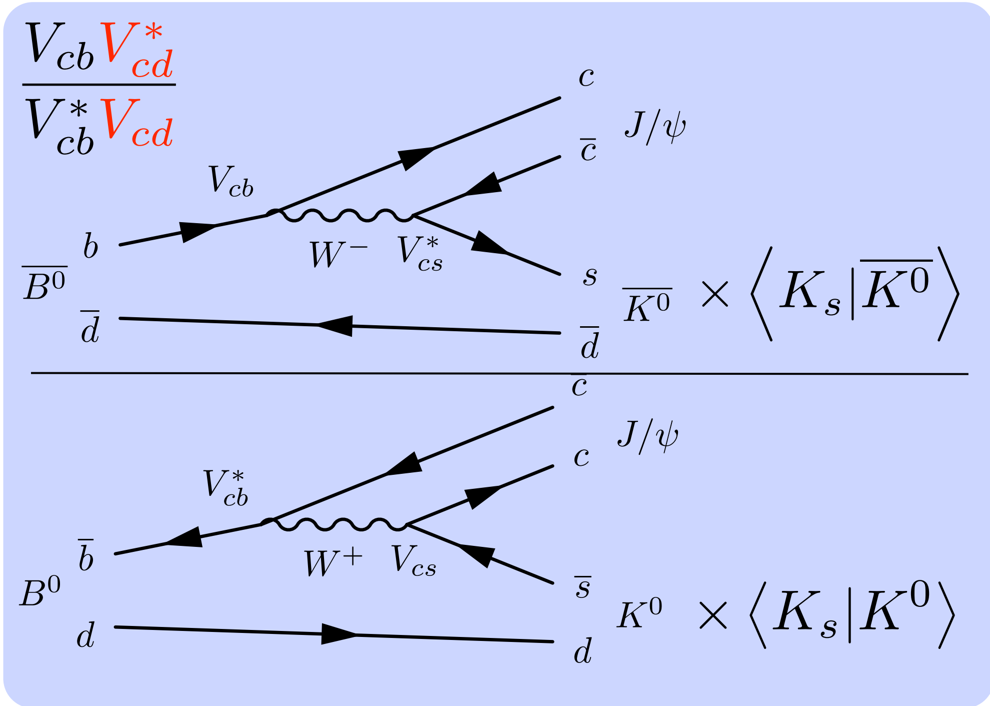
$$K^0 \times \left\langle K_s | K^0 \right\rangle$$

$$|K_s\rangle = p_K \left|K^0\right\rangle + q_K \left|\overline{K^0}\right\rangle$$

$B \to J/\psi K_S$

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0\to K_S}}$$

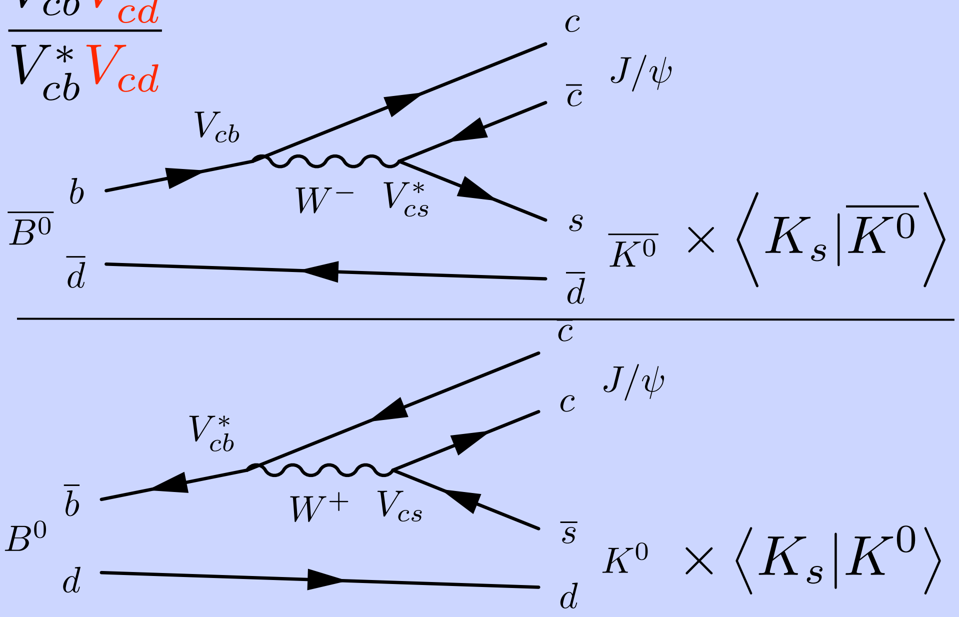


B→ J/ψKs

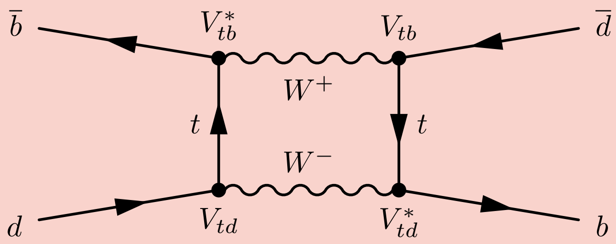
$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\rightarrow K_S}}{A_{J/\psi K^0, K^0\rightarrow K_S}}$$

$$\frac{V_{cb}V_{cd}^*}{V_{cb}^*V_{cd}}$$



$$\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}$$



$B \to J/\psi K_S$

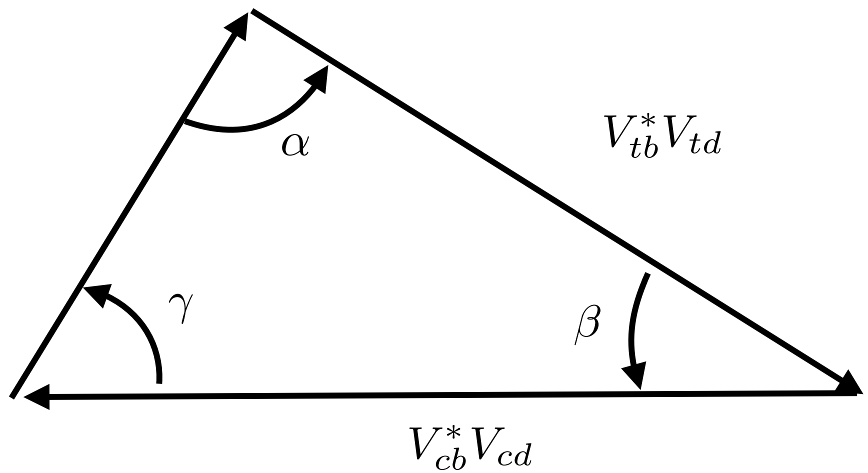
$$\begin{aligned}
\lambda_{J/\psi K_S} &\equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}} \\
&= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0} \to K_S}}{A_{J/\psi K^0, K^0 \to K_S}} \\
&= -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}}{V_{cb}^* V_{cd}}
\end{aligned}$$

$B \to J/\psi K_S$

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

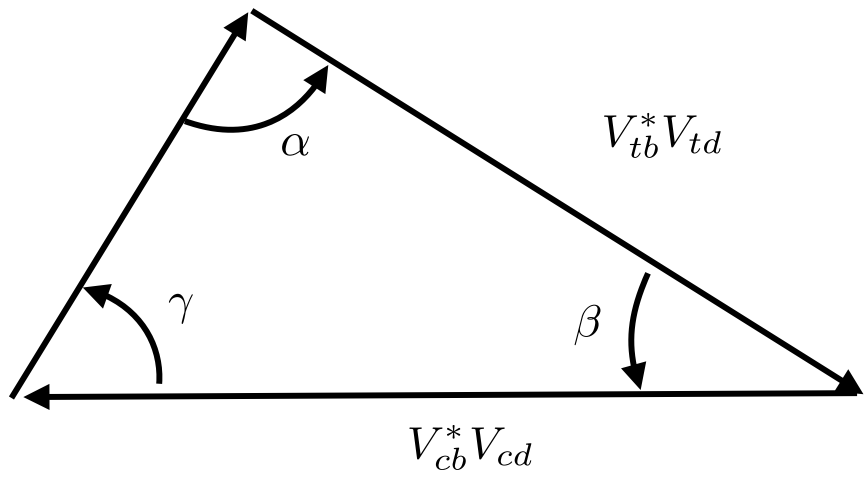
$$= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0} \to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$

$$= -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}}{V_{cb}^* V_{cd}}$$



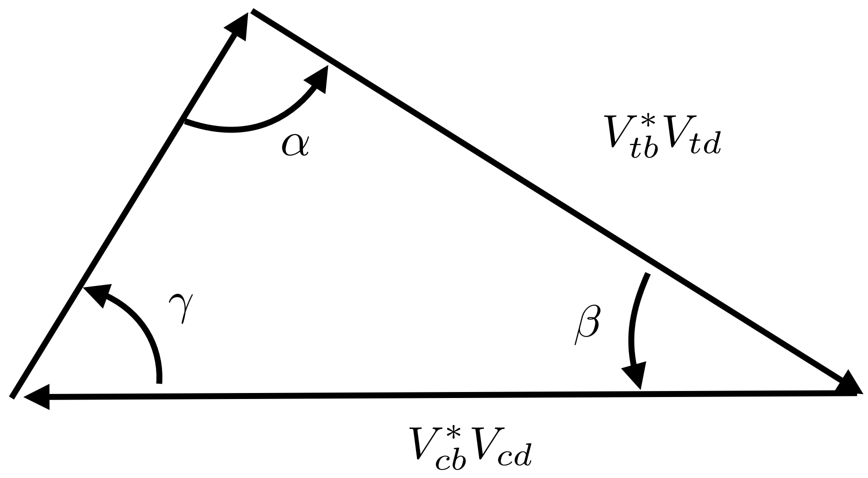
B→ J/ψKs

$$
\begin{aligned}
\lambda_{J/\psi K_S} &\equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}} \\
&= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0} \to K_S}}{A_{J/\psi K^0, K^0 \to K_S}} \\
&= -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}}{V_{cb}^* V_{cd}} \\
&= -e^{-2i\beta}
\end{aligned}
$$

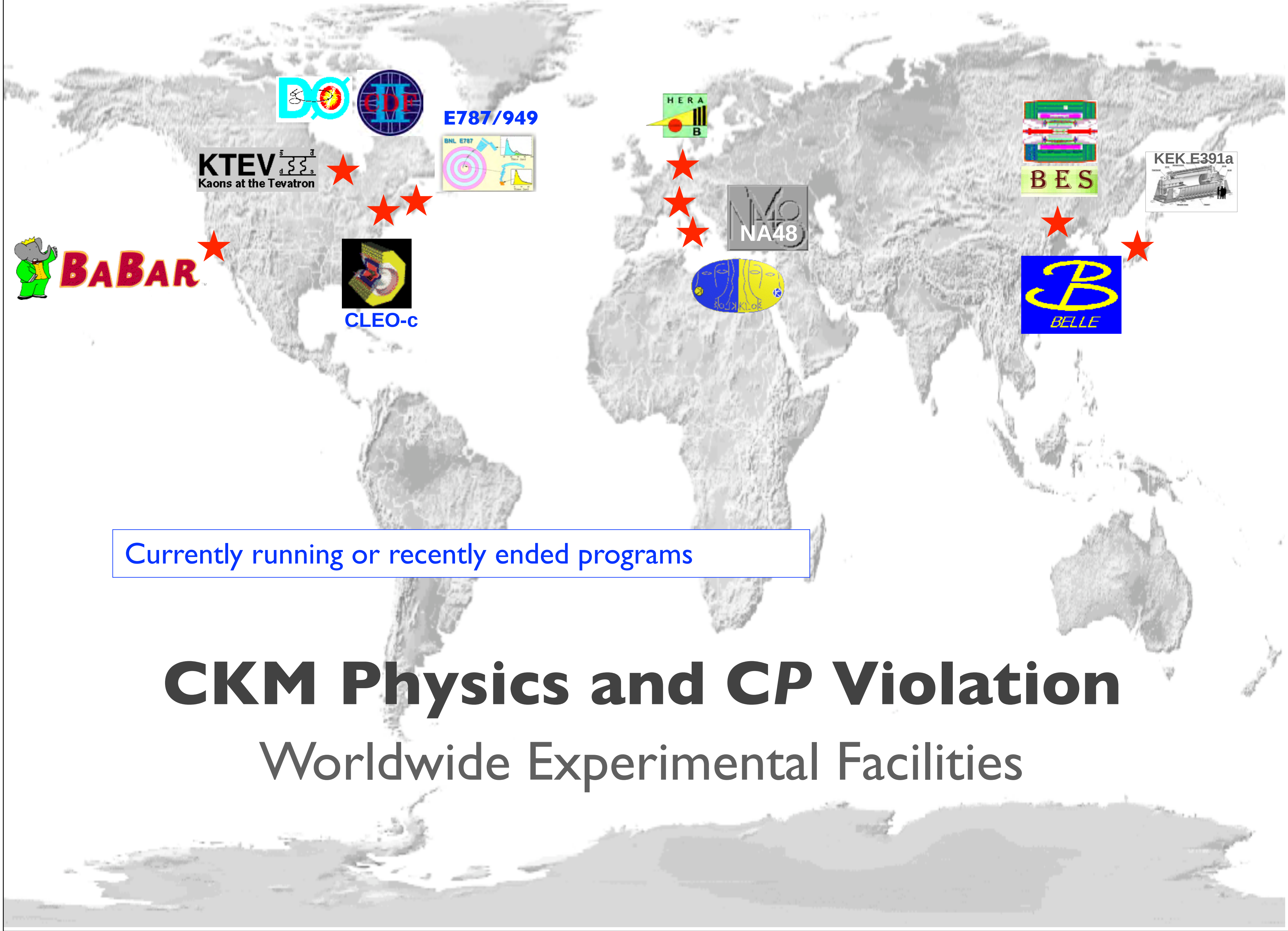


$B \to J/\psi K_S$

$$
\begin{aligned}
\lambda_{J/\psi K_S} &\equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}} \\
&= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0\to K_S}} \\
&= -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}}{V_{cb}^* V_{cd}} \\
&= -e^{-2i\beta}
\end{aligned}
$$



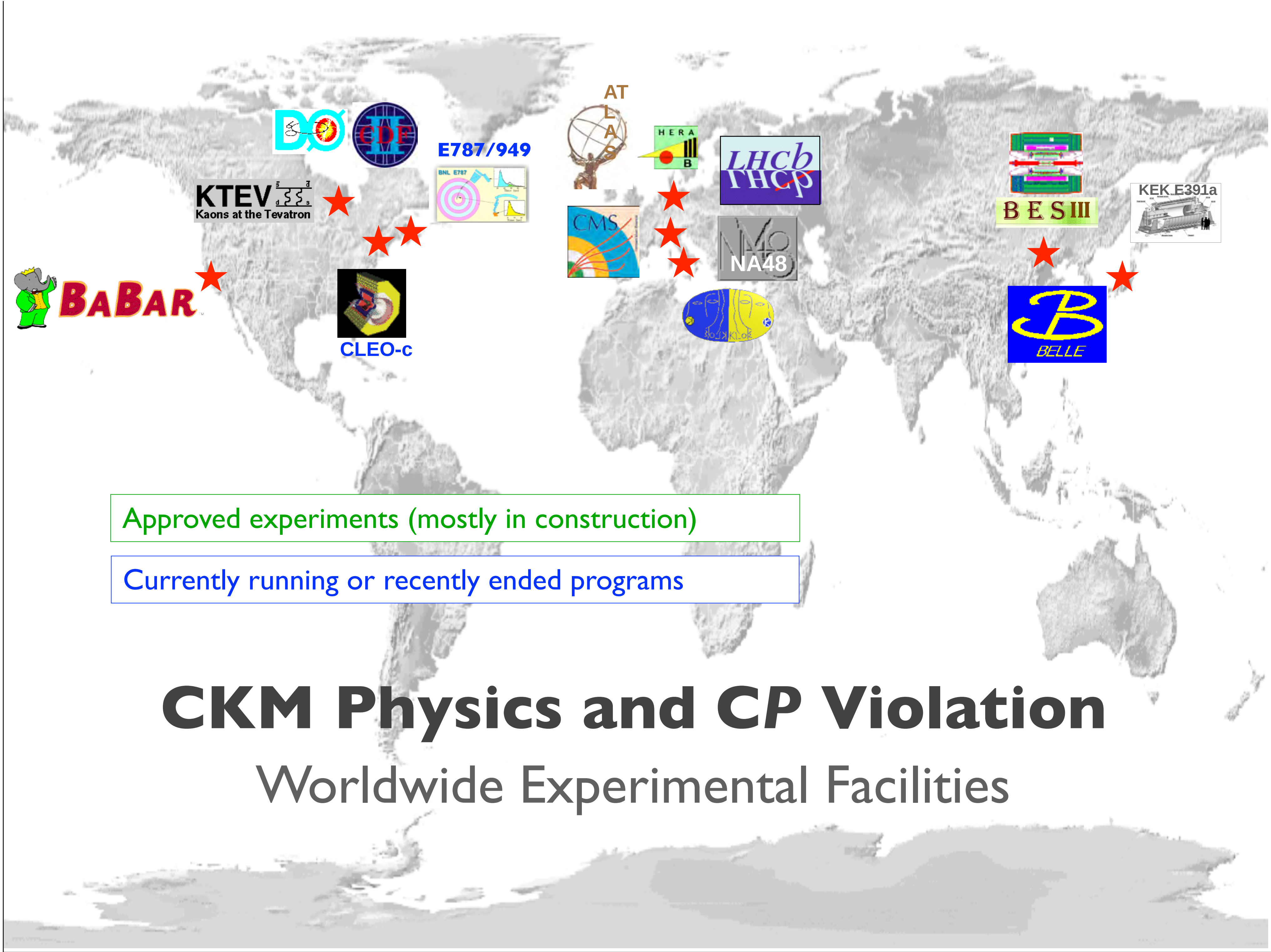
$$
\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B^0} \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)
$$



Currently running or recently ended programs

CKM Physics and C*P* Violation

Worldwide Experimental Facilities

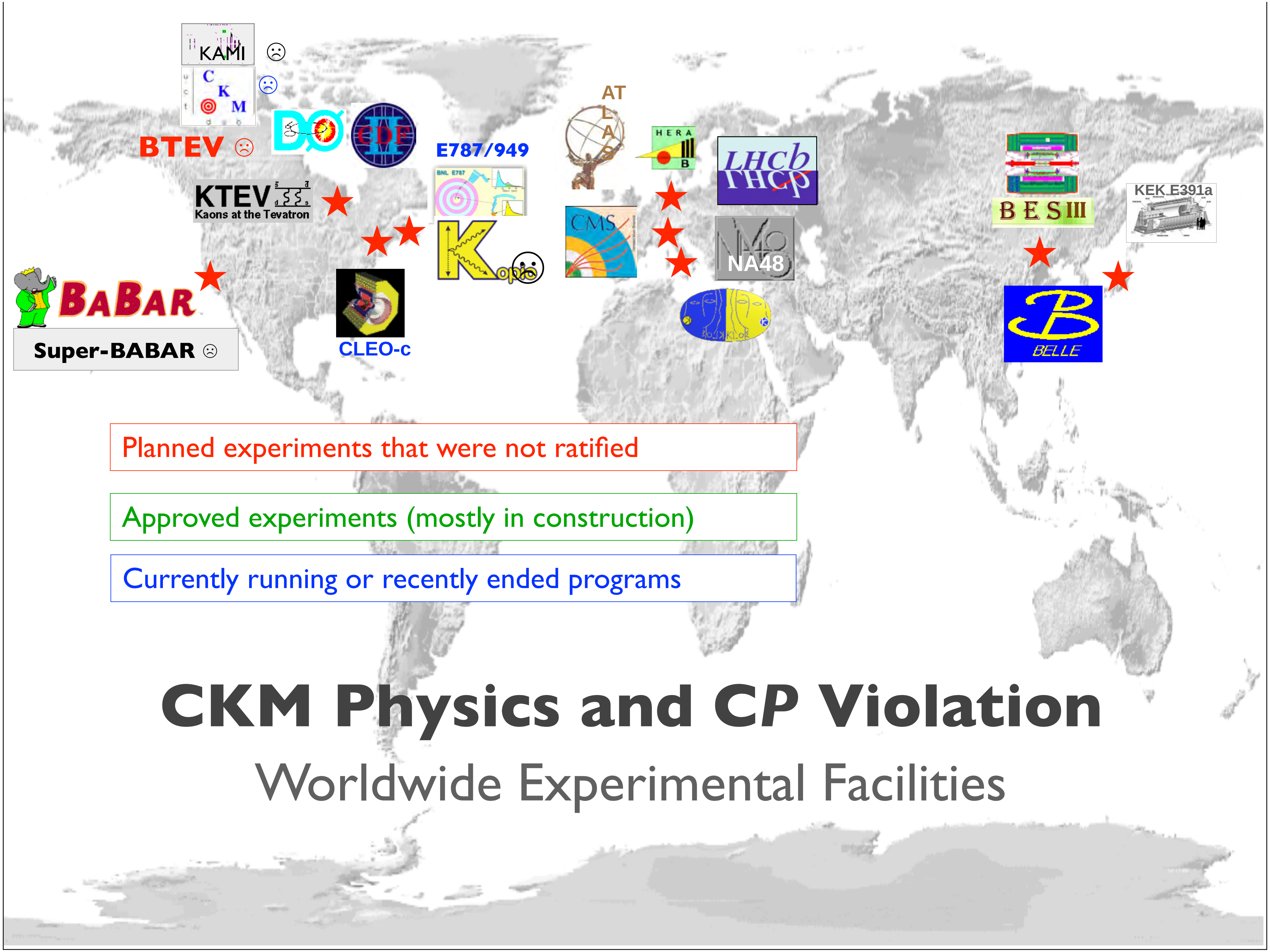


Approved experiments (mostly in construction)

Currently running or recently ended programs

CKM Physics and C*P* Violation

Worldwide Experimental Facilities



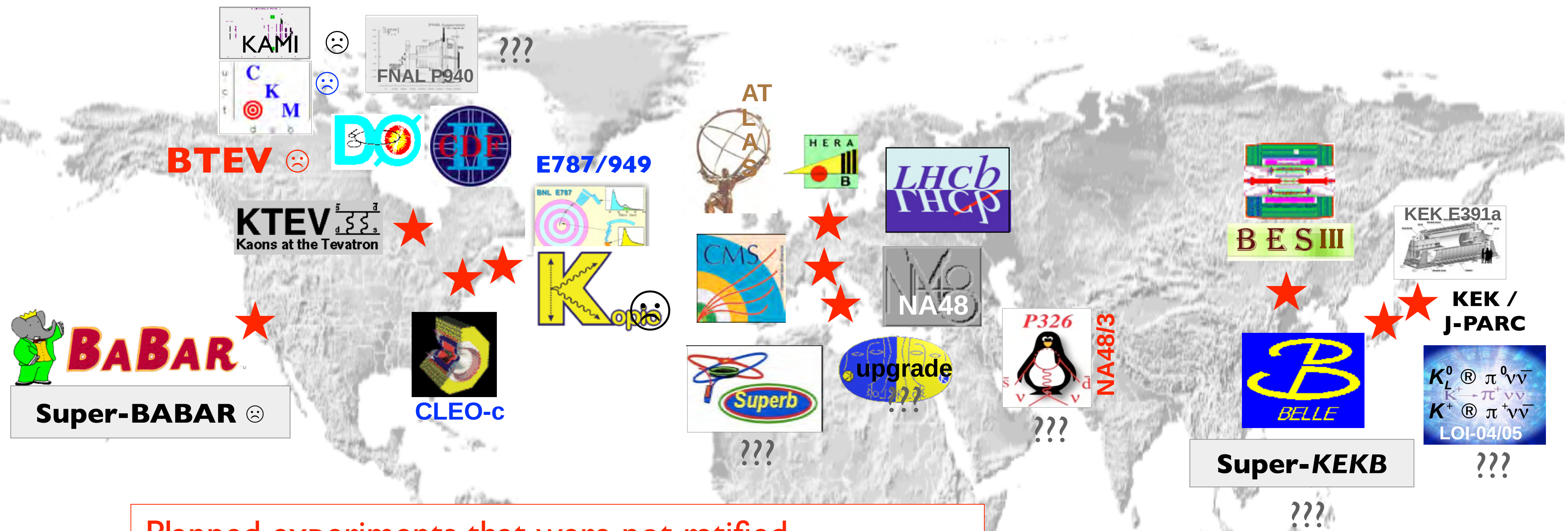
Planned experiments that were not ratified

Approved experiments (mostly in construction)

Currently running or recently ended programs

CKM Physics and *CP* Violation

Worldwide Experimental Facilities



Planned experiments that were not ratified

Approved experiments (mostly in construction)

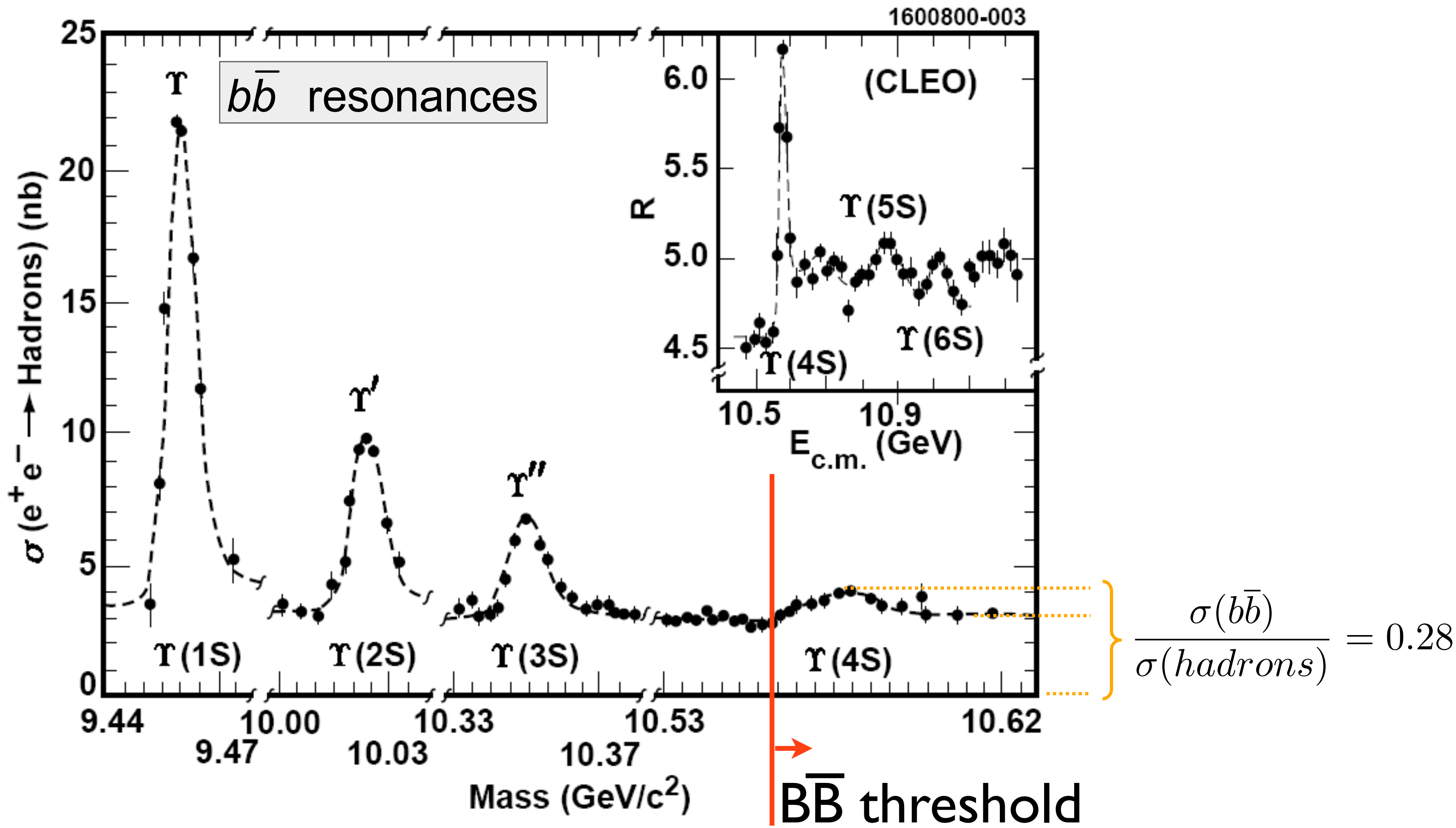
New proposals

Currently running or recently ended programs

CKM Physics and C*P* Violation

Worldwide Experimental Facilities

B factories: $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$



Very clean environment!

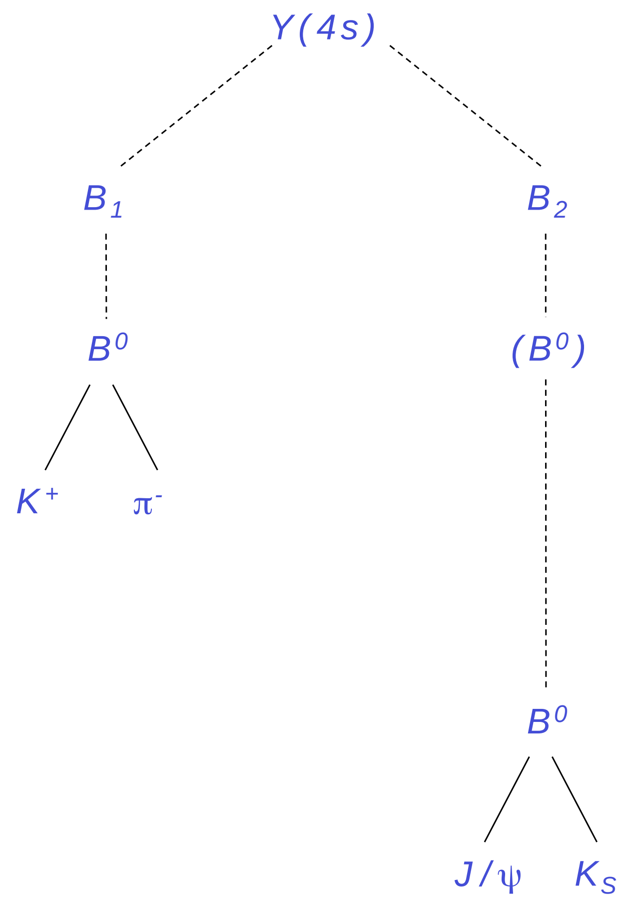
Measuring $A_{CP}(t)$ in $B^0 \rightarrow J/\psi\ K_S$

- Times evolution of $\Upsilon(4s)$ decay
  - t=0: Decay of $\Upsilon(4s)$ into 2 B mesons

    Neither B is in a specific eigenstate,
    but B_1B_2 system evolves *coherently*,
    i.e. flavor anti-correlation preserved in evolution
  - $t=t_1$ One of the two mesons (B_1) decays.

    If it decays into a flavor eigenstate, flavor conservation in the coherent B_1B_2 requires that also B_2 *goes into a flavor eigenstate, even though it has not decayed yet*!
  - $t=t_2$ The other B meson decays

    This meson can decay into any kind of state, eg. a $\overline{B^0}$ or B^0 flavor eigenstate. The latter means that mixing took place between t_1 and t_2.
    It can also decay into a CP eigenstate (either directly or after a mixing)

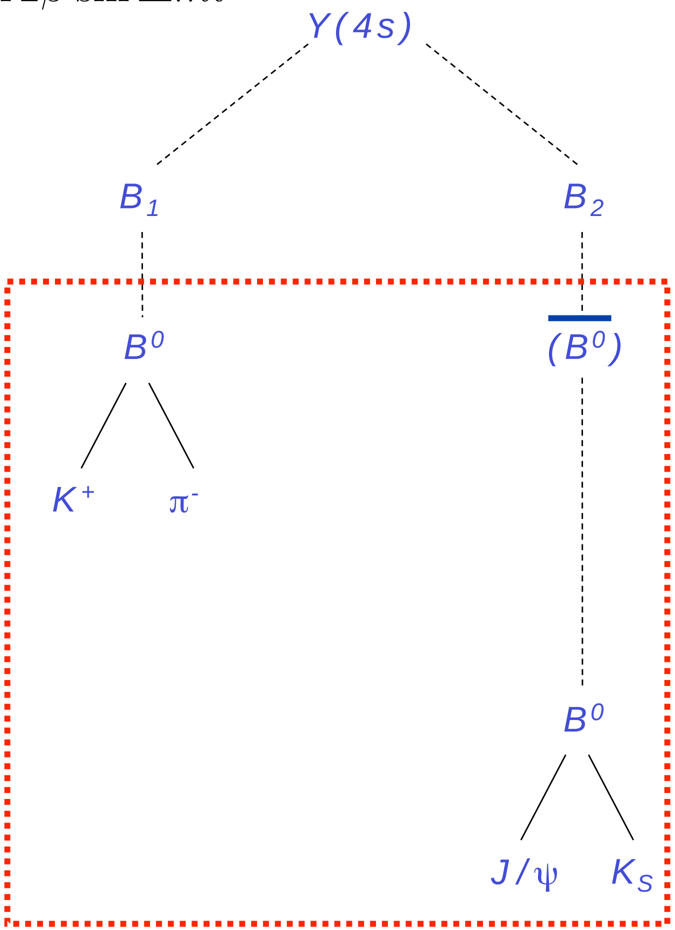


Measuring $A_{CP}(t)$ in $B^0 \rightarrow J/\psi\, K_S$

- We can use this process to measure $A_{CP}(t)$

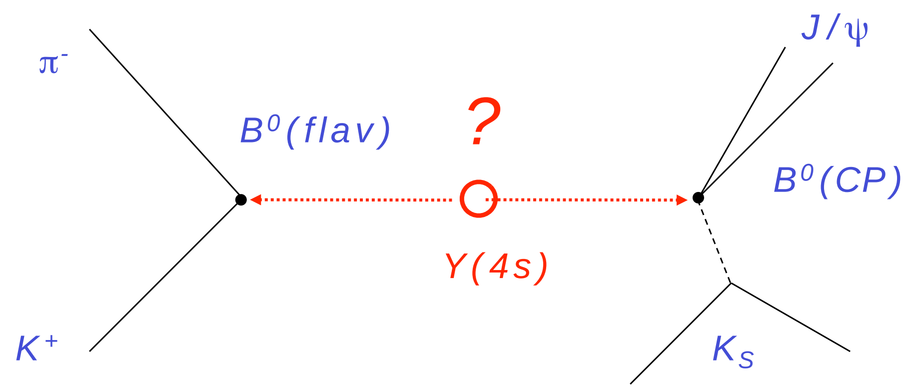
$$\mathcal{A}_{CP}(t) = \frac{N(\overline{B^0}(t) \to J/\psi K_s) - N(B^0(t) \to J/\psi K_s)}{N(\overline{B^0}(t) \to J/\psi K_s) + N(B^0(t) \to J/\psi K_s)} = \sin 2\beta \sin \Delta m t$$

- More precise reading of A_{CP}:
  - We don't necessarily need to *produce* B^0 mesons in a flavor eigenstate, we just need to measure the decay into CP eigenstate after a known time *t* since it was (through whatever means) in a flavor eigenstate
- Bottom line
  - Look for $\Upsilon(4s) \rightarrow B^0\overline{B^0}$ where '1st' B^0 decays in to flavor eigenstate and '2nd' B^0 decays into CP eigenstate and interpret t_2-t_1 as the correct time for the $A_{CP}(t)$ formula
  - Note: formalism also works when $\Delta t<0$!



Measuring $A_{CP}(t)$ in $B^0 \to J/\psi\ K_S$

- The last little catch: How do you measure a decay time *difference*?
  - Naïve solution: measure both decay times
  - Impossible in practice because you measure decay times from flight distances, but nothing marks the decay point of the Υ(4s)
  - And even if you knew the decay point, the produced B are almost at rest in the Υ(4S) frame...

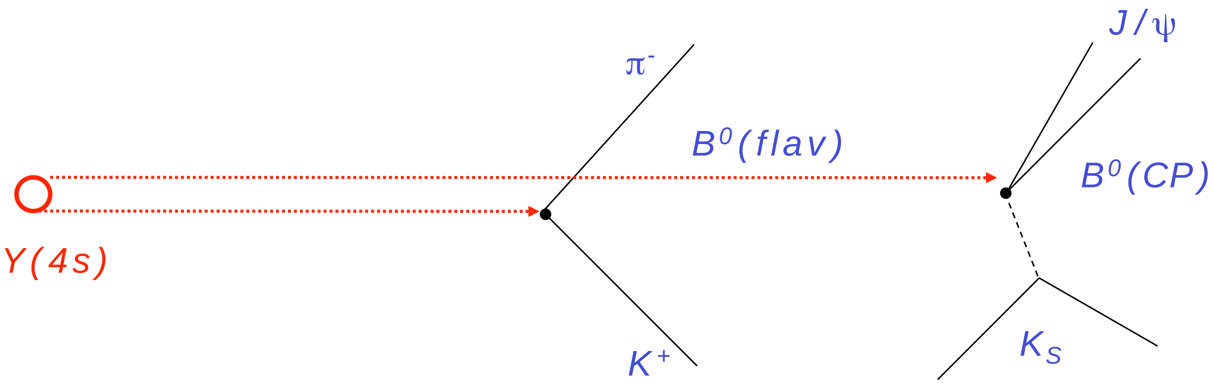


  - m(Υ(4s)) = 10.58 GeV
  - $m(B^0) = 5.28$ GeV → $p^*_B = 340$ MeV/c → $(\beta\gamma)^* = 0.064$ → 30 um for $\tau = 1.5$ ps

Measuring $A_{CP}(t)$ in $B^0 \to J/\psi\ K_S$

Pier Oddone,LBL
(now: FNAL)

- Solution: Make the $\Upsilon(4s)$ fly!
- Both B^0 mesons practically at rest *in $\Upsilon(4s)$ rest frame*
  - If $\Upsilon(4s)$ moves in lab frame at modest speed no B^0's will be emitted 'backwards' as speed of $\Upsilon(4s)$ in lab is always larger than maximum backward speed of B^0 w.r.t the $\Upsilon(4s)$



- Result: spacing between vertices $\propto$ *difference* in decay time!

The B Factories: PEP-2 (SLAC, USA) and KEK-B (KEK, Japan)

SLAC

Stanford Linear Accelerator Center

The B Factories: PEP-2 (SLAC, USA) and KEK-B (KEK, Japan)

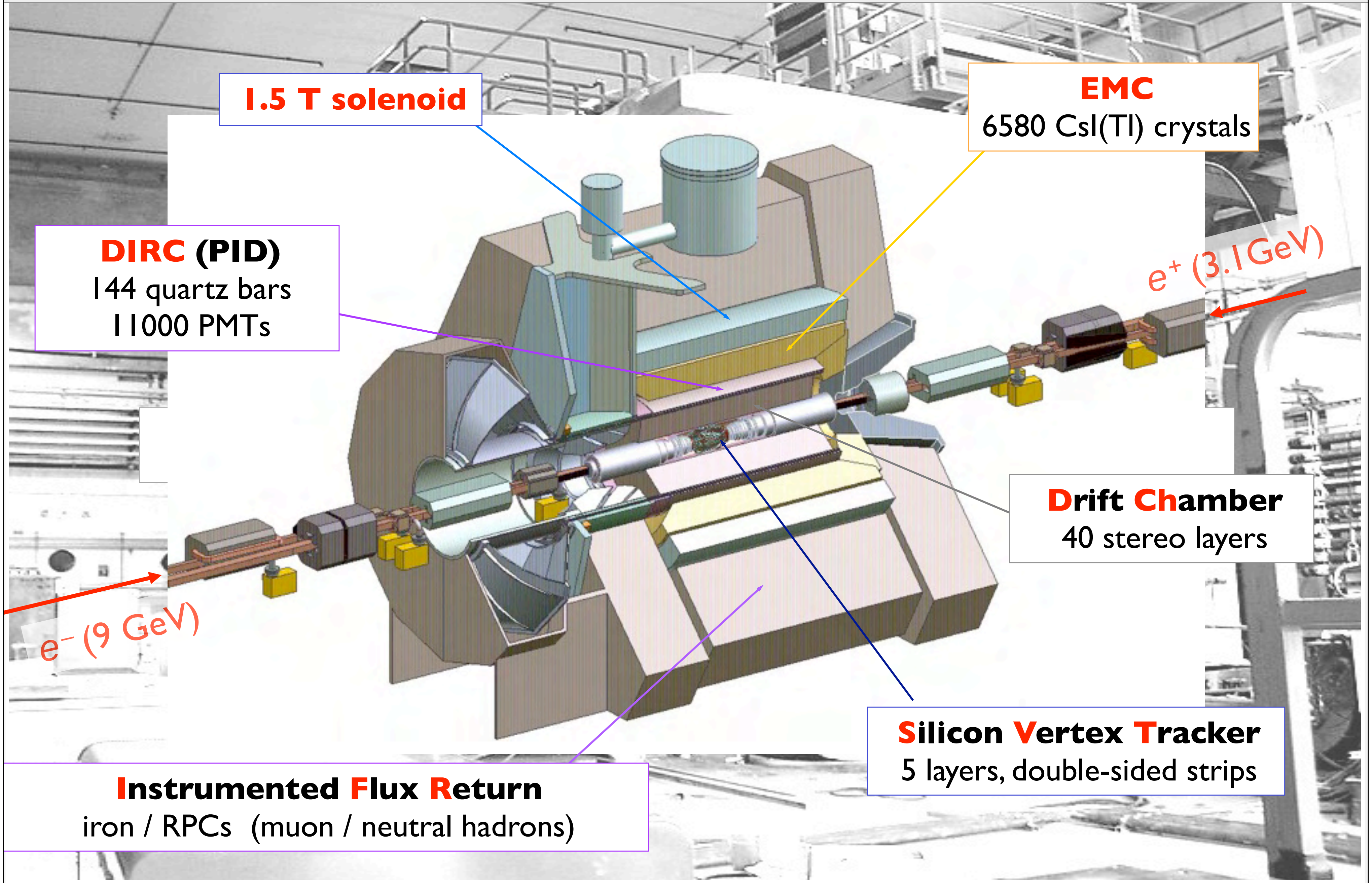
SLAC

Stanford Linear Accelerator Center

KEKB delivered $\int L$ = 950 fb^{-1}
Peak record: 2.1 10^{34} cm^{-2}s^{-1}

PEP-II delivered $\int L$ = 557 fb^{-1}
Peak record: 1.2 10^{34} cm^{-2}s^{-1}
switched off: april 7th, 2008

The BABAR Detector



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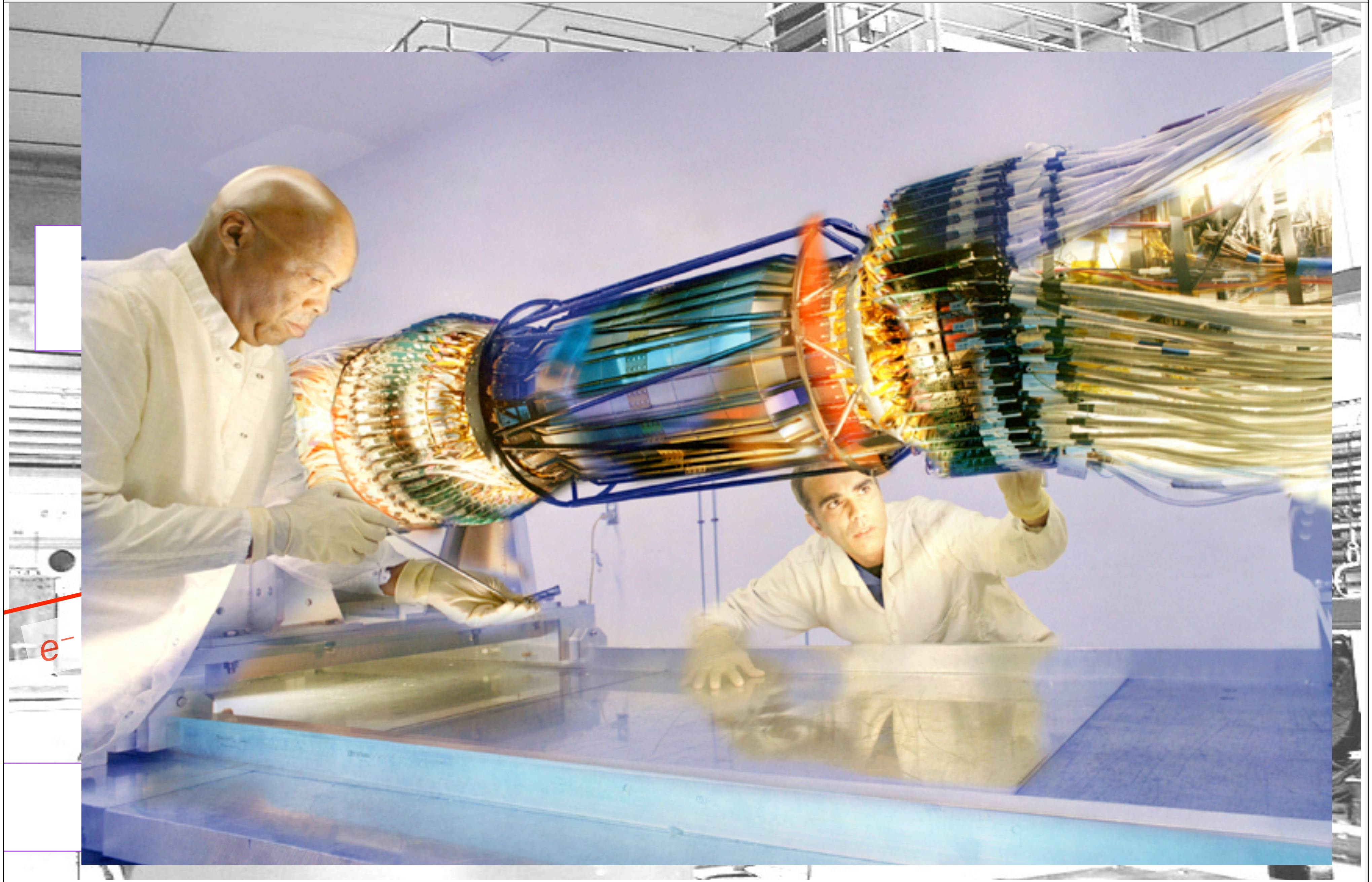

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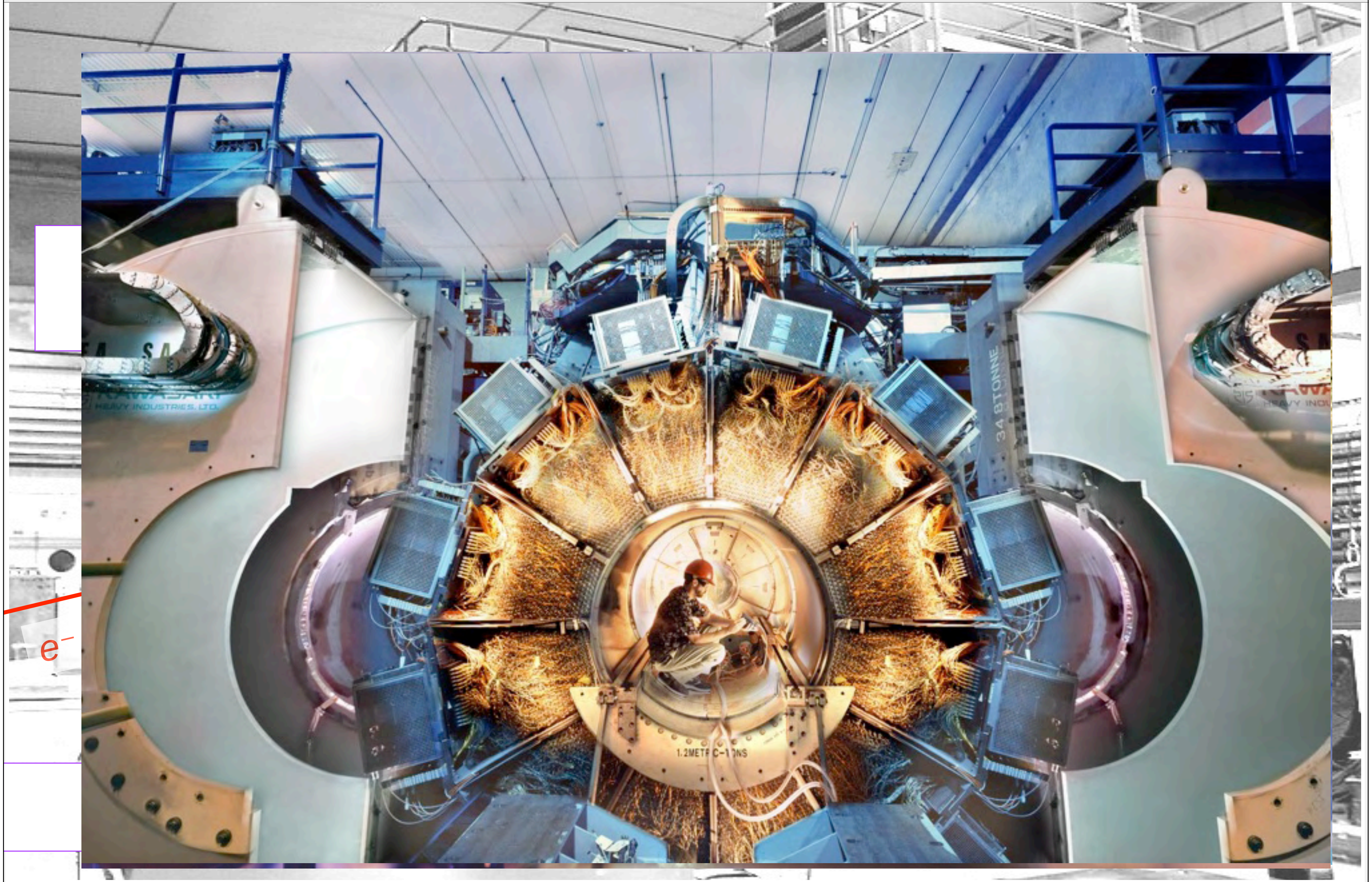

Ingredients of the measurements

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PEP-2 (SLAC)

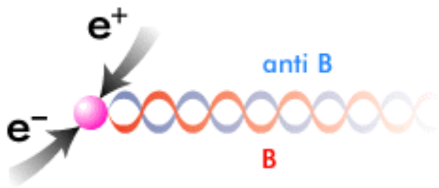
$$E_{e^-} = 9\,\mathrm{GeV} \qquad E_{e^+} = 3.1\,\mathrm{GeV}$$

$$\sqrt{s} = 10.58\,\mathrm{GeV}$$

$$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.56$$

$$\Upsilon(4S)$$

$$e^- \longrightarrow \longleftarrow e^+$$



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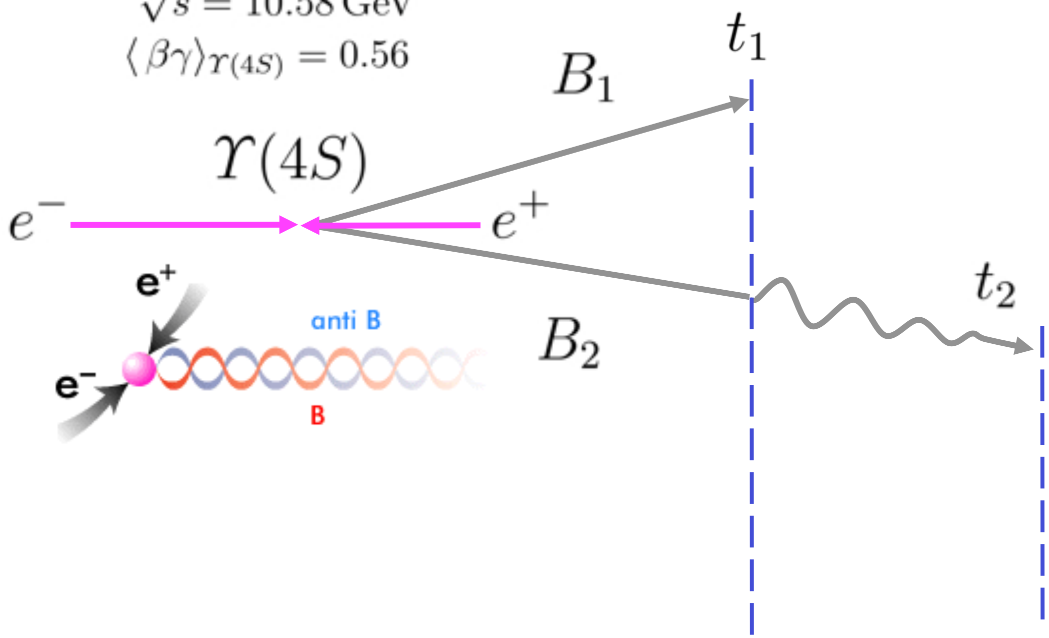

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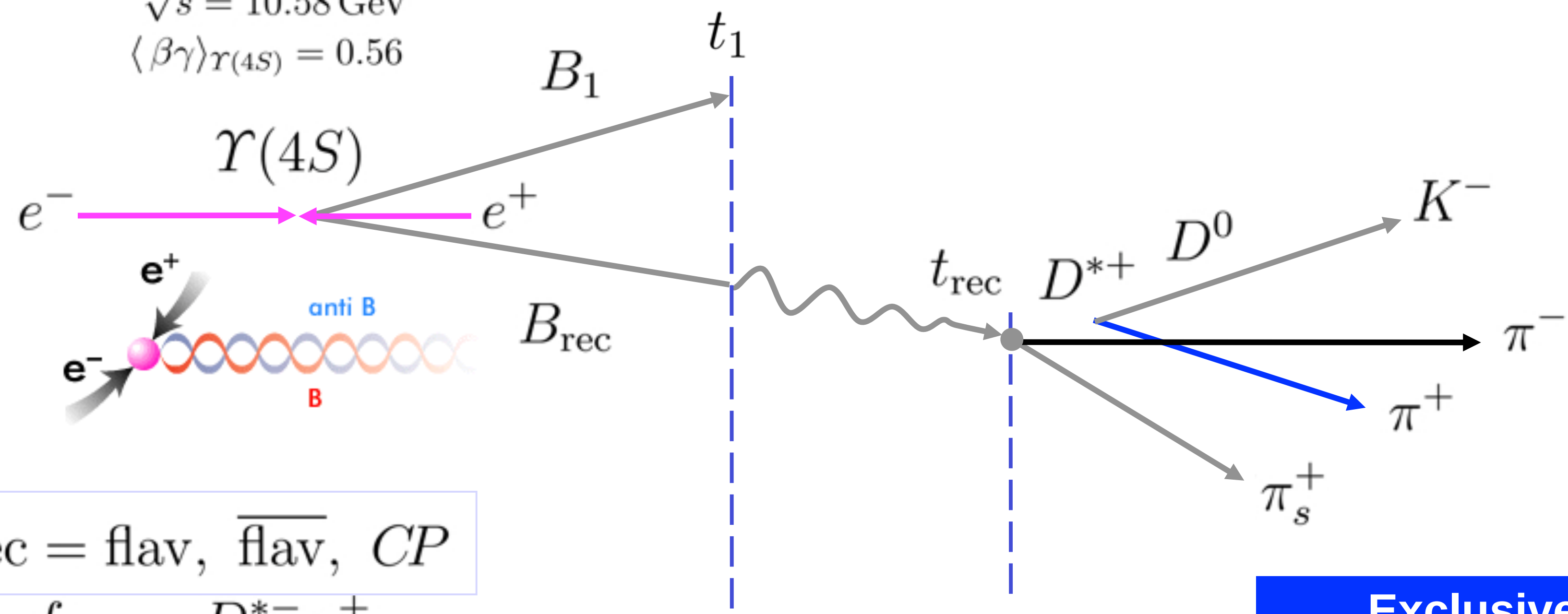

$\mathrm{rec} = \mathrm{flav},\ \overline{\mathrm{flav}},\ CP$

$f_{\mathrm{flav}} = D^{*-}\pi^+, \ldots$

$f_{CP} = J/\psi\, K_S^0,\ J/\psi\, K_L^0, \ldots$

Exclusive B Meson Reconstruction

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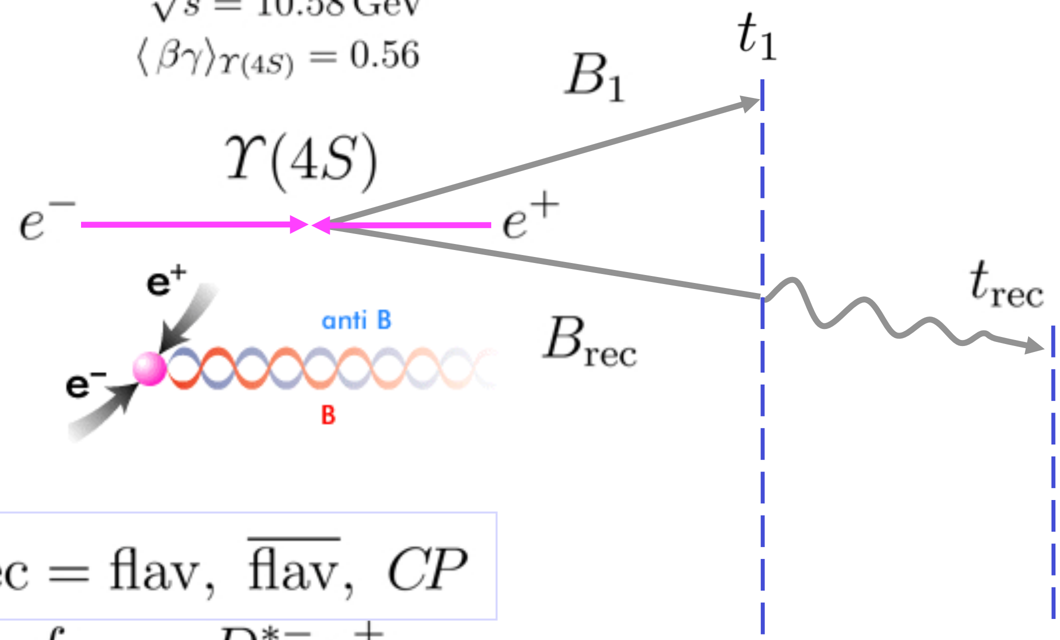

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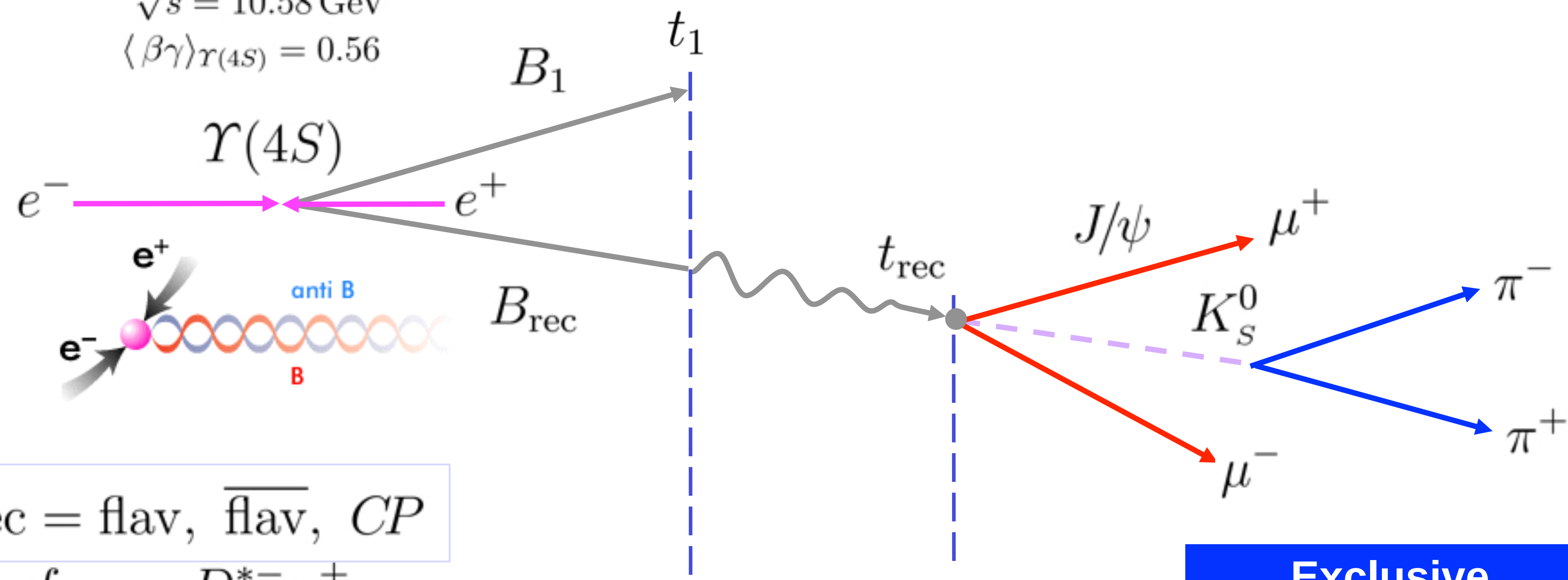

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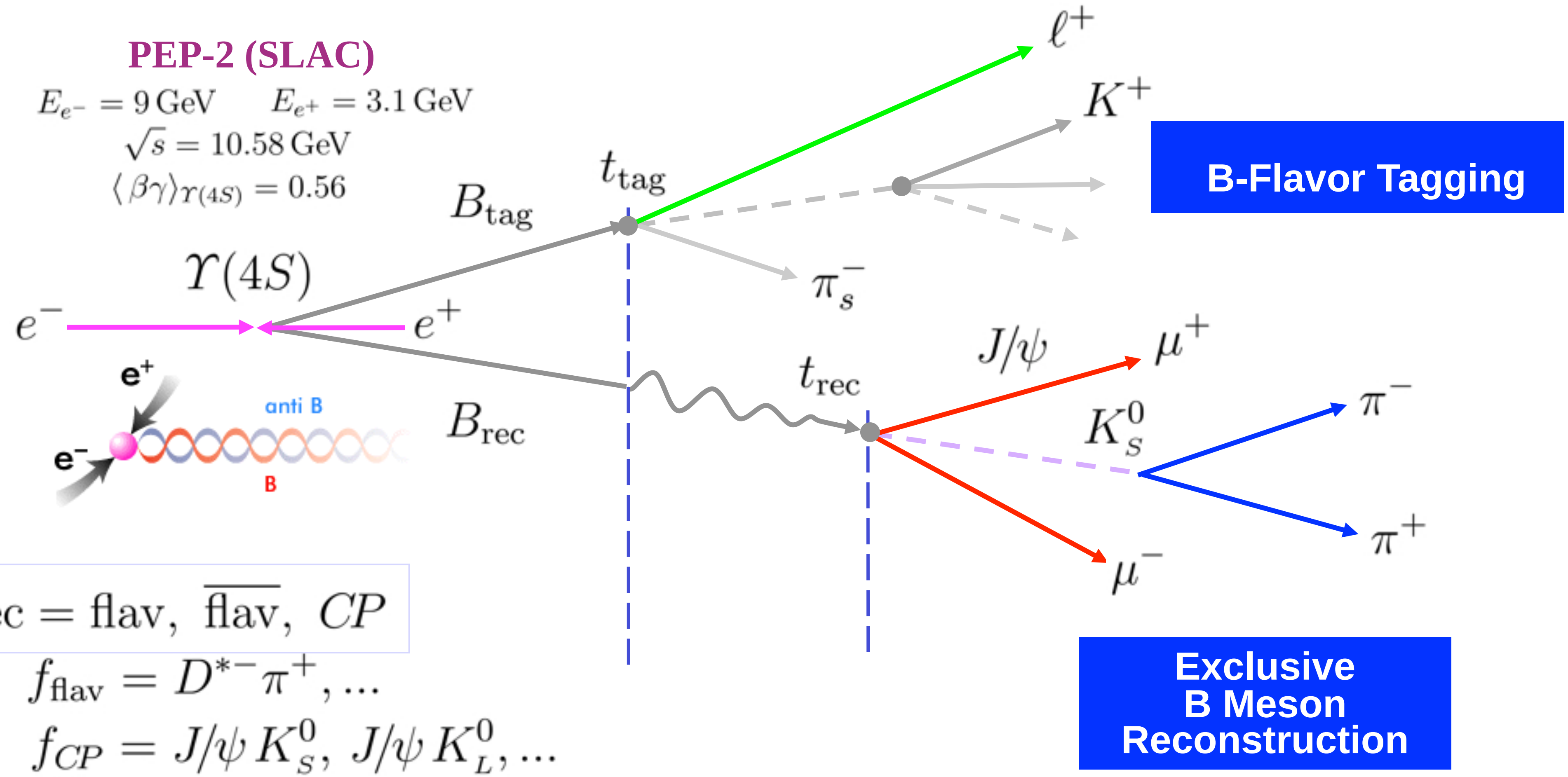

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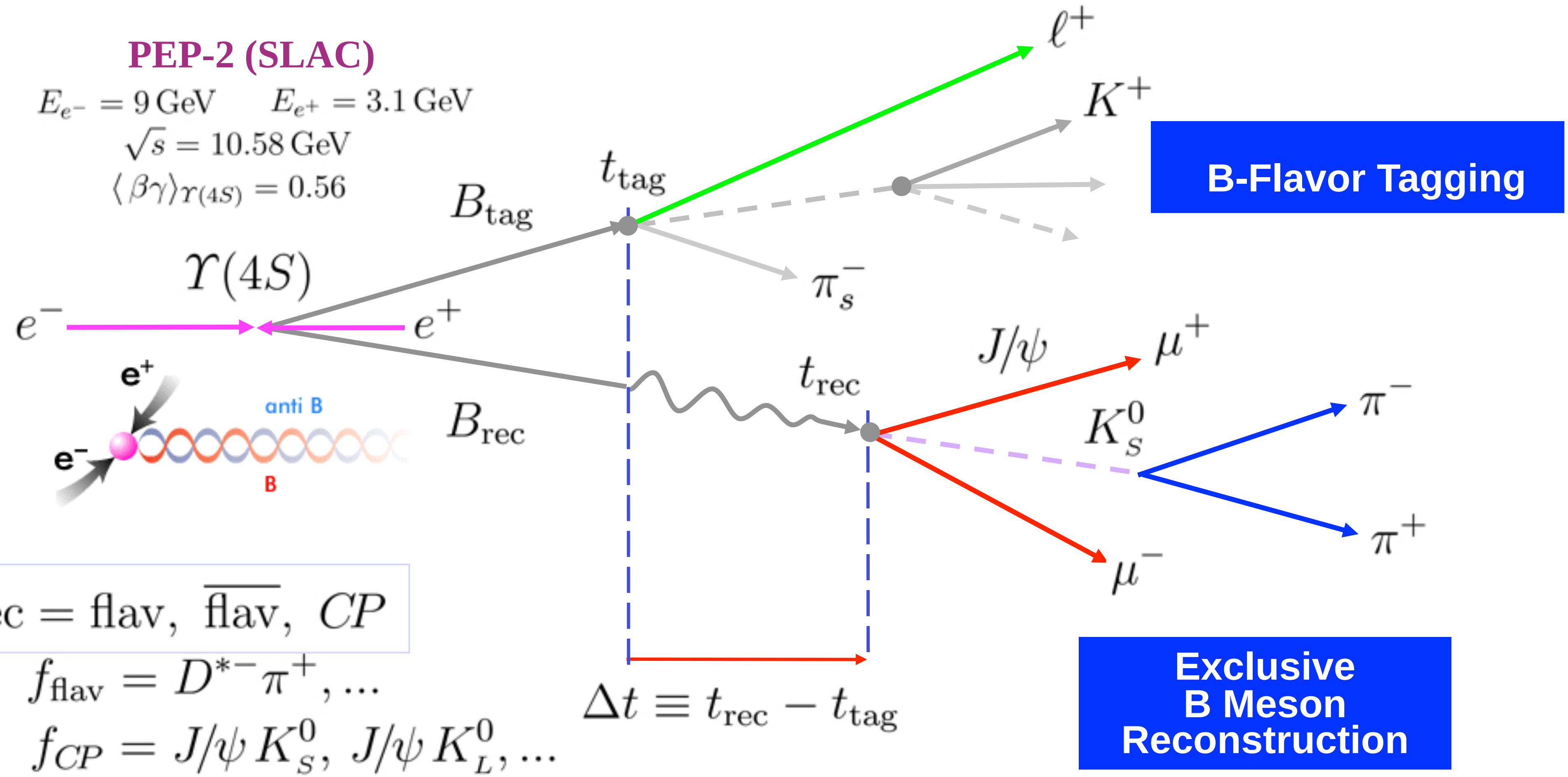

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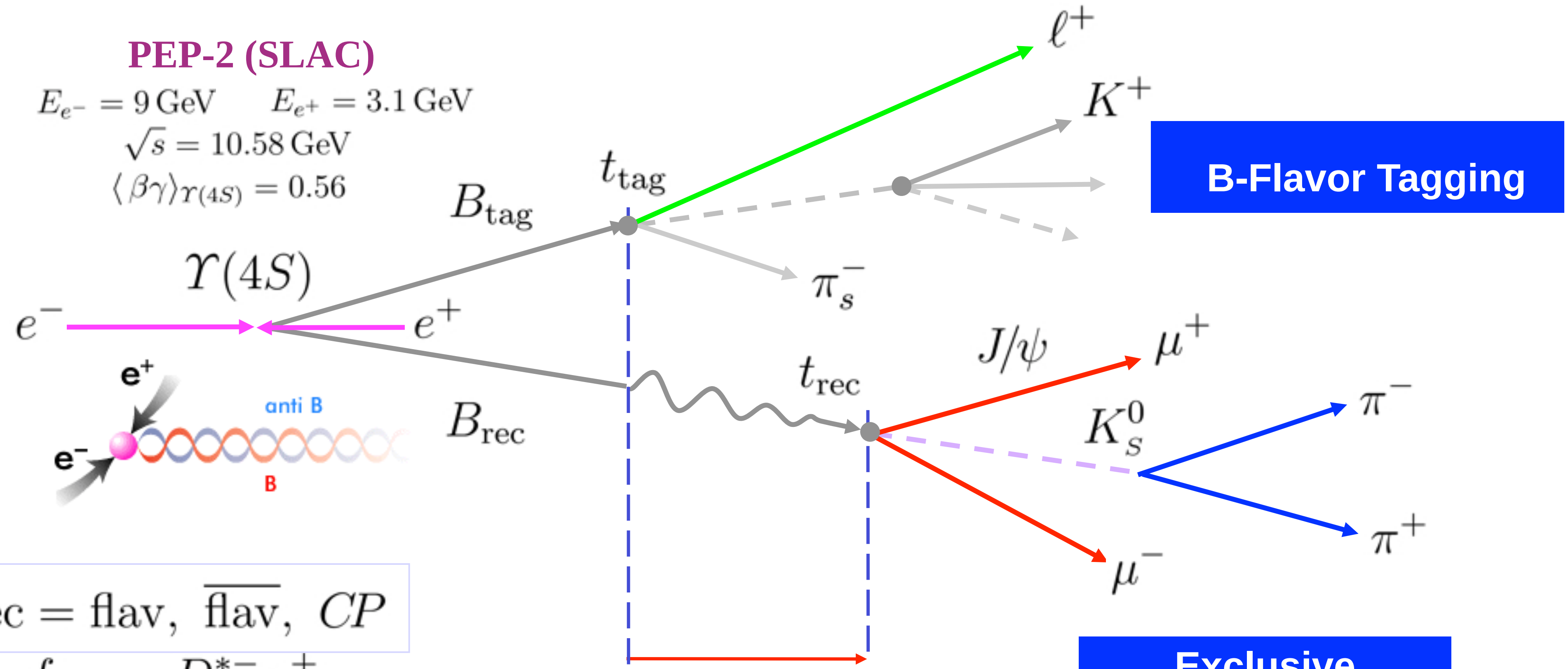

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$f_{B^0} = X\ell^+\nu,\ XK^+,\ X\pi_s^-, \ldots$

$\Delta t \equiv t_{\mathrm{rec}} - t_{\mathrm{tag}}$

Vertexing & Time Difference Determination

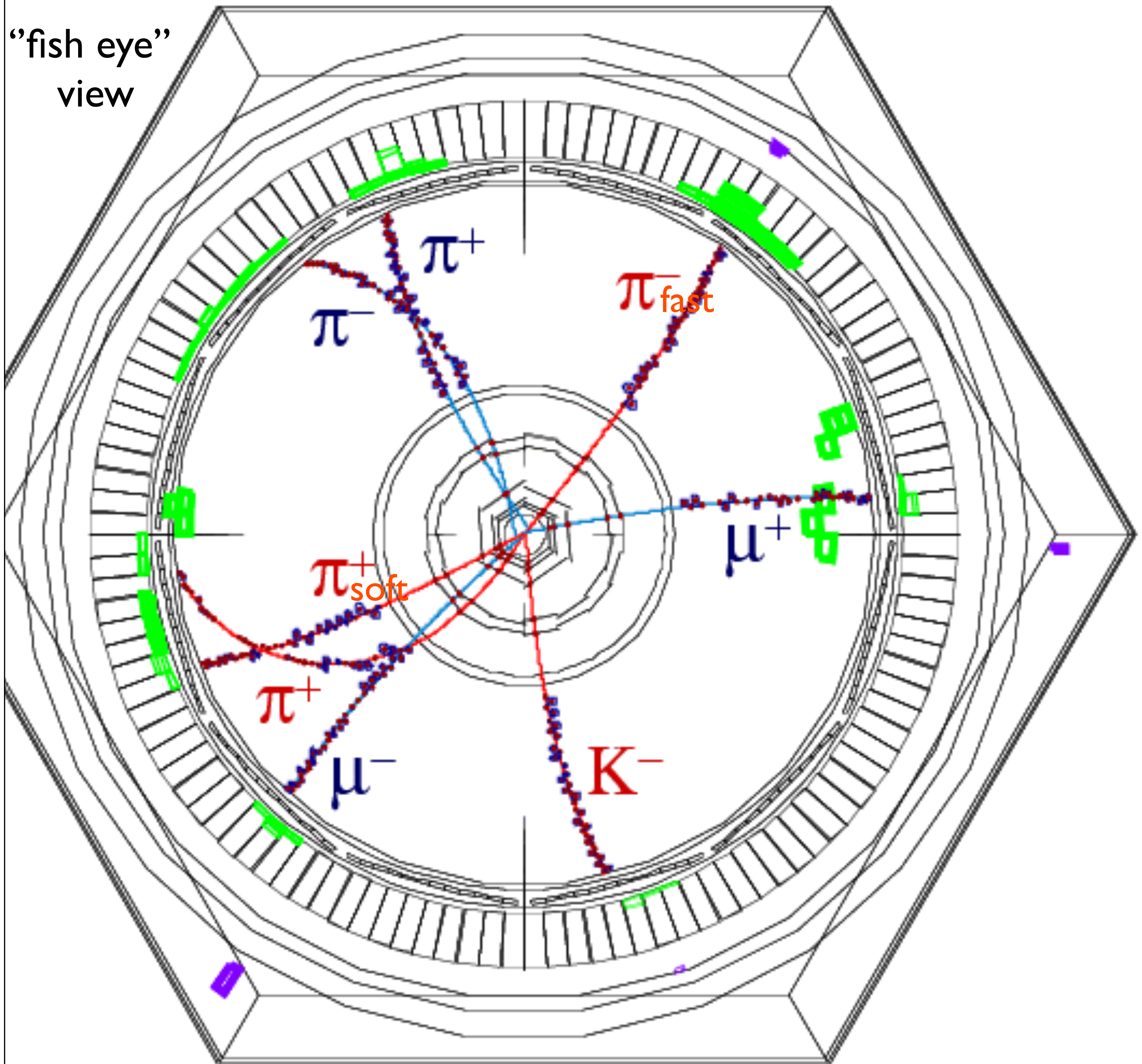
Exclusive B Meson Reconstruction

$\Delta t \approx \Delta z / c\,\langle \beta\gamma \rangle_{\Upsilon(4S)}$

$\langle \Delta z \rangle_{B\overline{B}} \approx 260\,\mu\mathrm{m}$

Example of fully reco'd BaBar event

"fish eye" view



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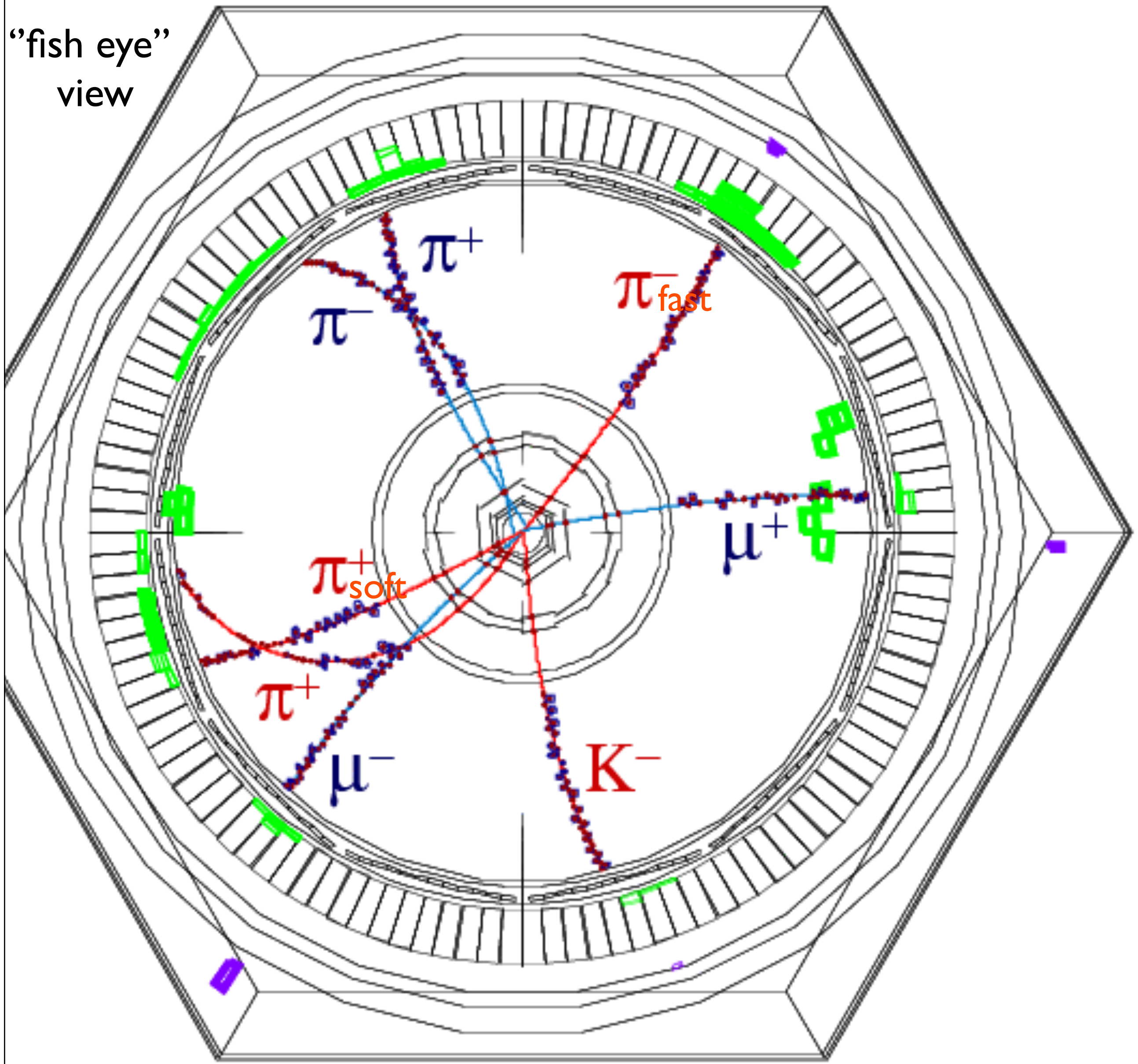

$$\overline{B}^0 \rightarrow D^{*+}\,\pi^-_{fast}$$

$$D^{*+} \rightarrow D^0\,\pi^+_{soft}$$

$$D^0 \rightarrow K^-\pi^+$$

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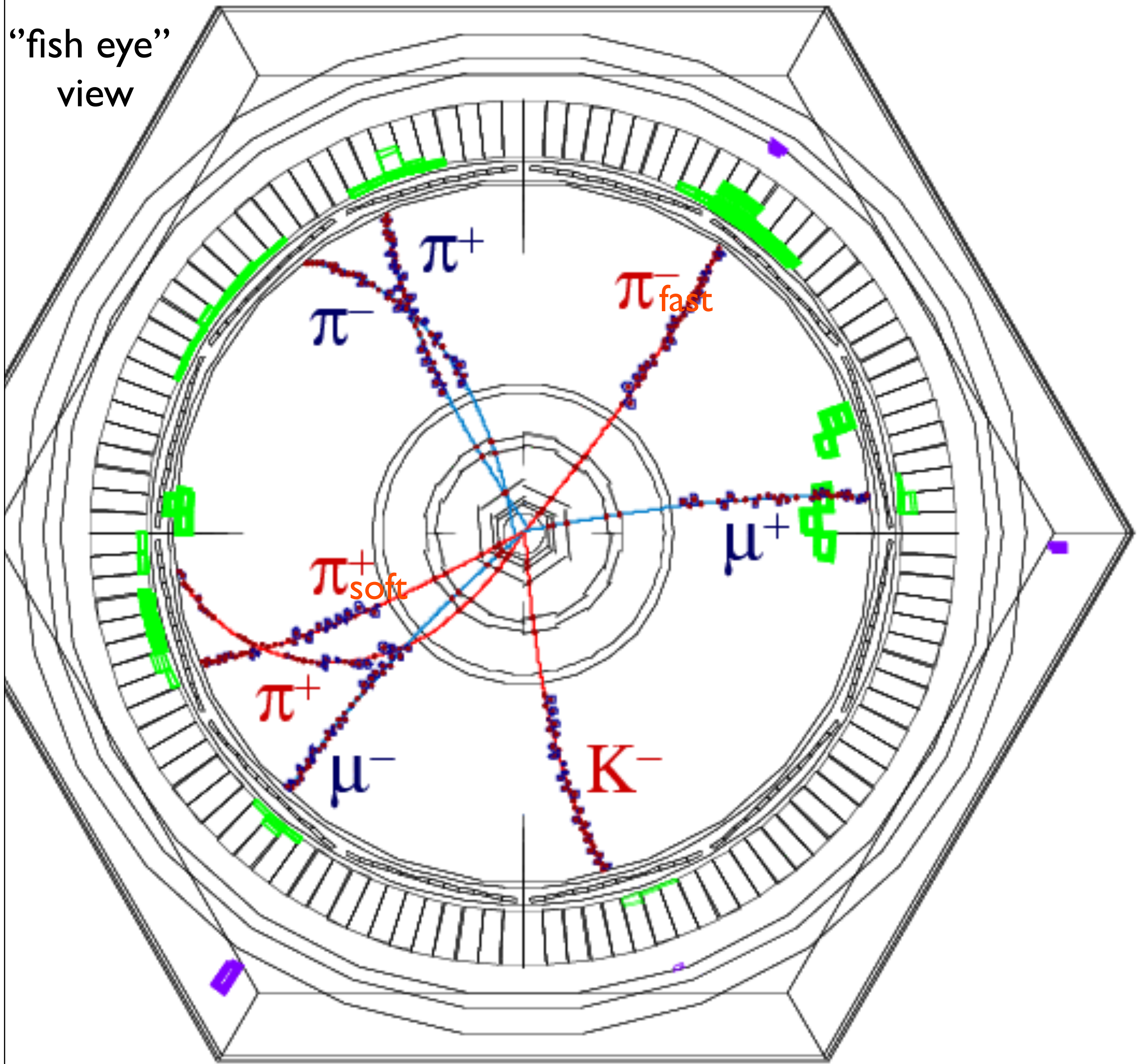

$\overline{B^0} \rightarrow D^{*+}\ \pi^-_{fast}$

$\hookrightarrow D^0 \pi^+_{soft}$

$\hookrightarrow K^- \pi^+$

$B^0(\Delta t) \rightarrow \psi(2S)\ K_s$

$\hookrightarrow \mu^+\mu^-$ $\hookrightarrow \pi^+\pi^-$

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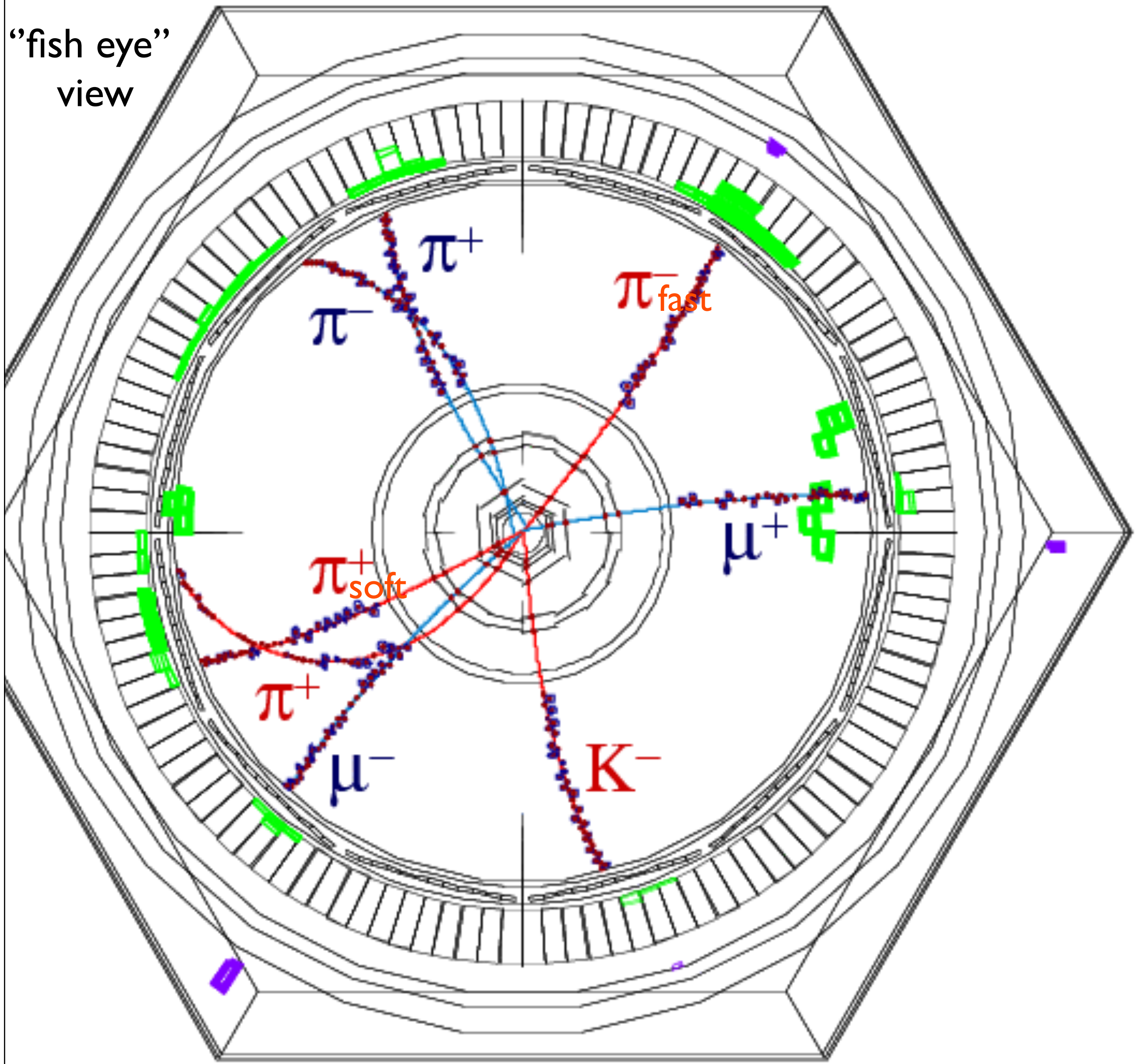


$\overline{B^0} \rightarrow D^{*+}\, \pi^-_{fast}$

$\quad D^{*+} \rightarrow D^0 \pi^+_{soft}$

$\quad\quad D^0 \rightarrow K^- \pi^+$

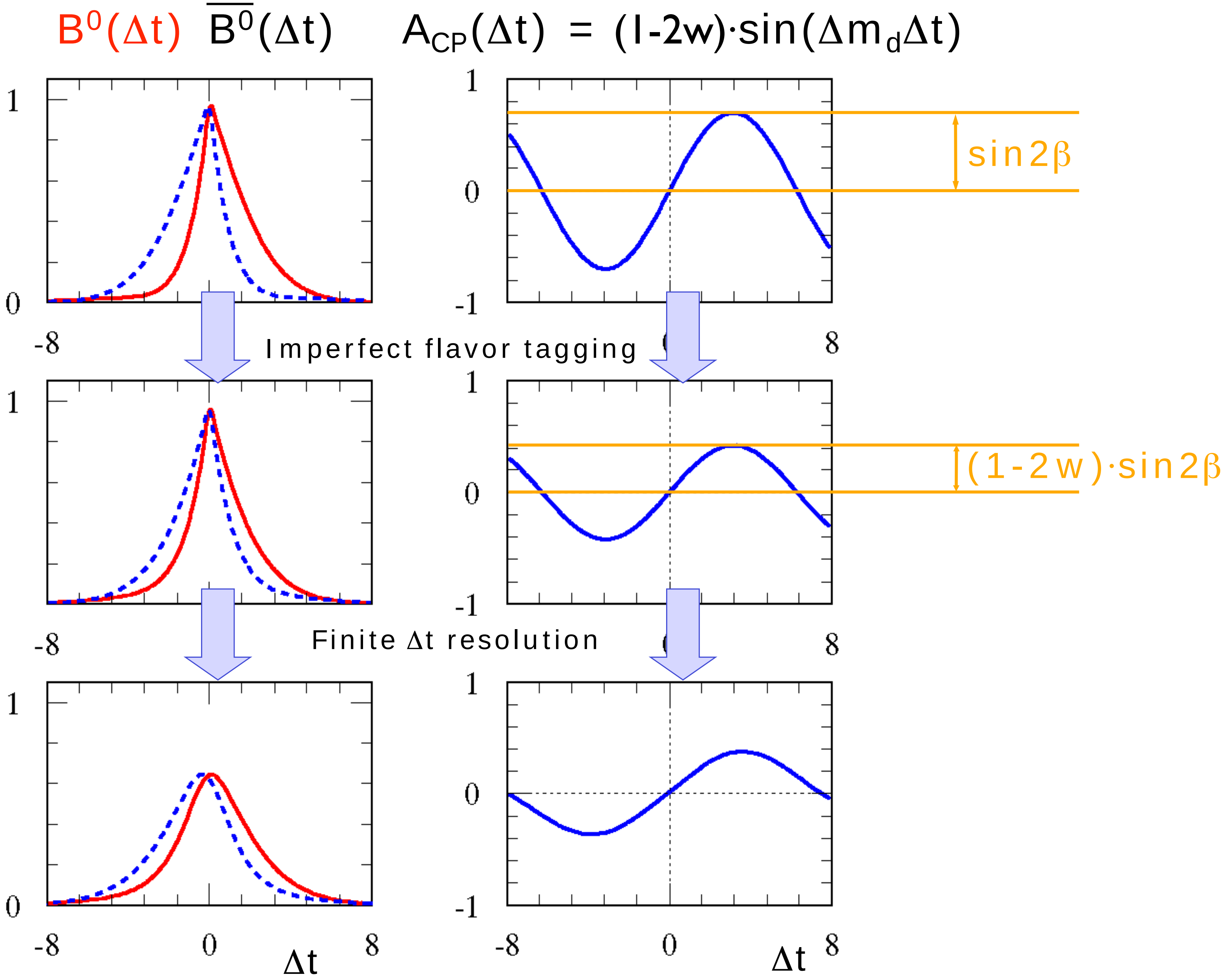
$\Updownarrow$

$B^0(\Delta t) \rightarrow \psi(2S)\, K_s$

$\quad \psi(2S) \rightarrow \mu^+\mu^-$, $\quad K_s \rightarrow \pi^+\pi^-$

At Δt=0 (i.e. when the $D^*\pi$ decay happened), the 'CP' B was/would have been a B^0

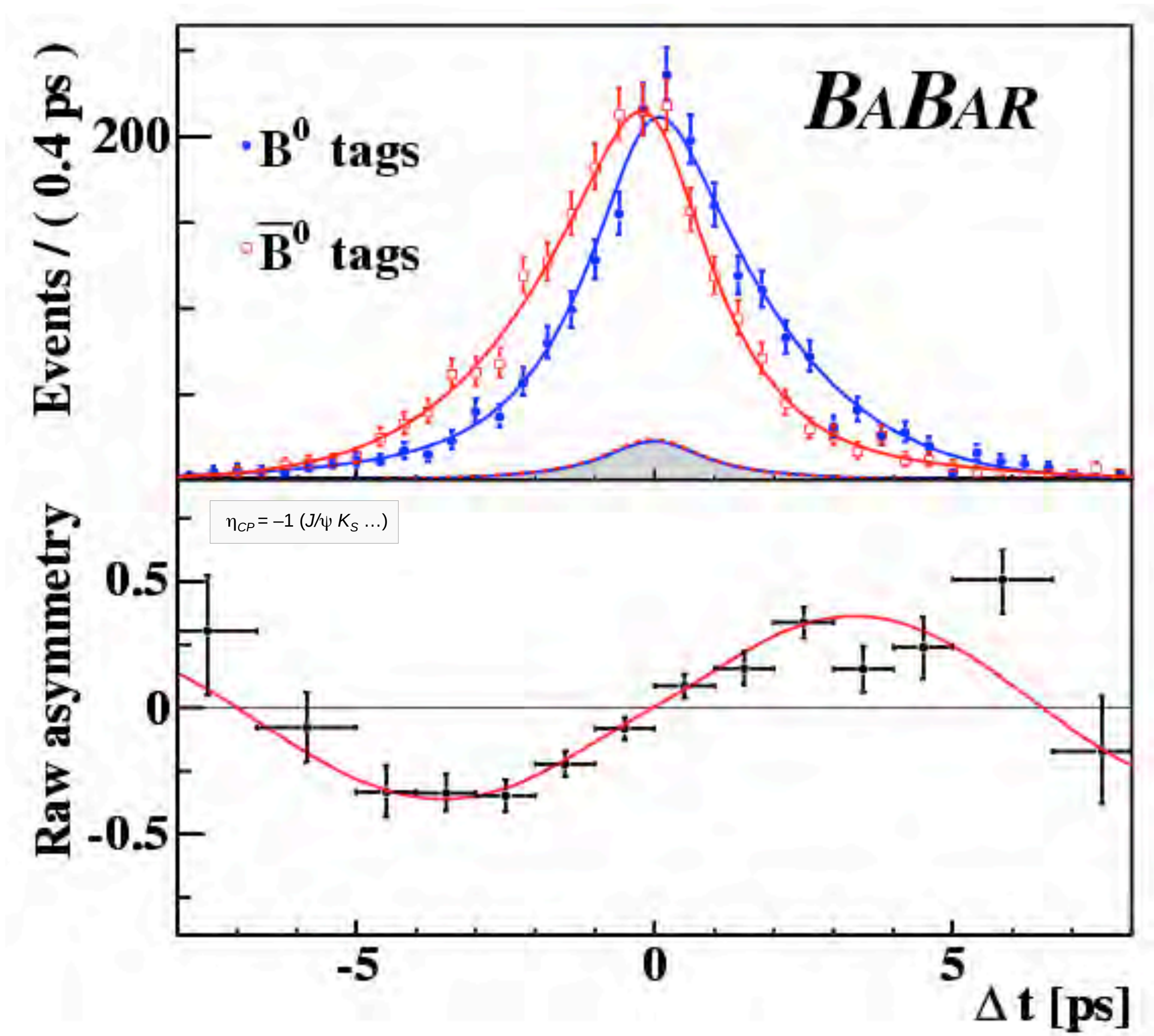
Putting it all together:



CP violation in B system!

$$e^+e^- \to \Upsilon(4S) \to B_{\rm rec}B_{\rm tag}$$

$$\begin{array}{rl} B_{\rm rec} \to & J/\psi K_S \\ B_{\rm tag} \to & \ell^\pm X, K^\pm X, \pi^\mp_{soft}, \pi^\pm_{fast}X, \ldots \end{array}$$



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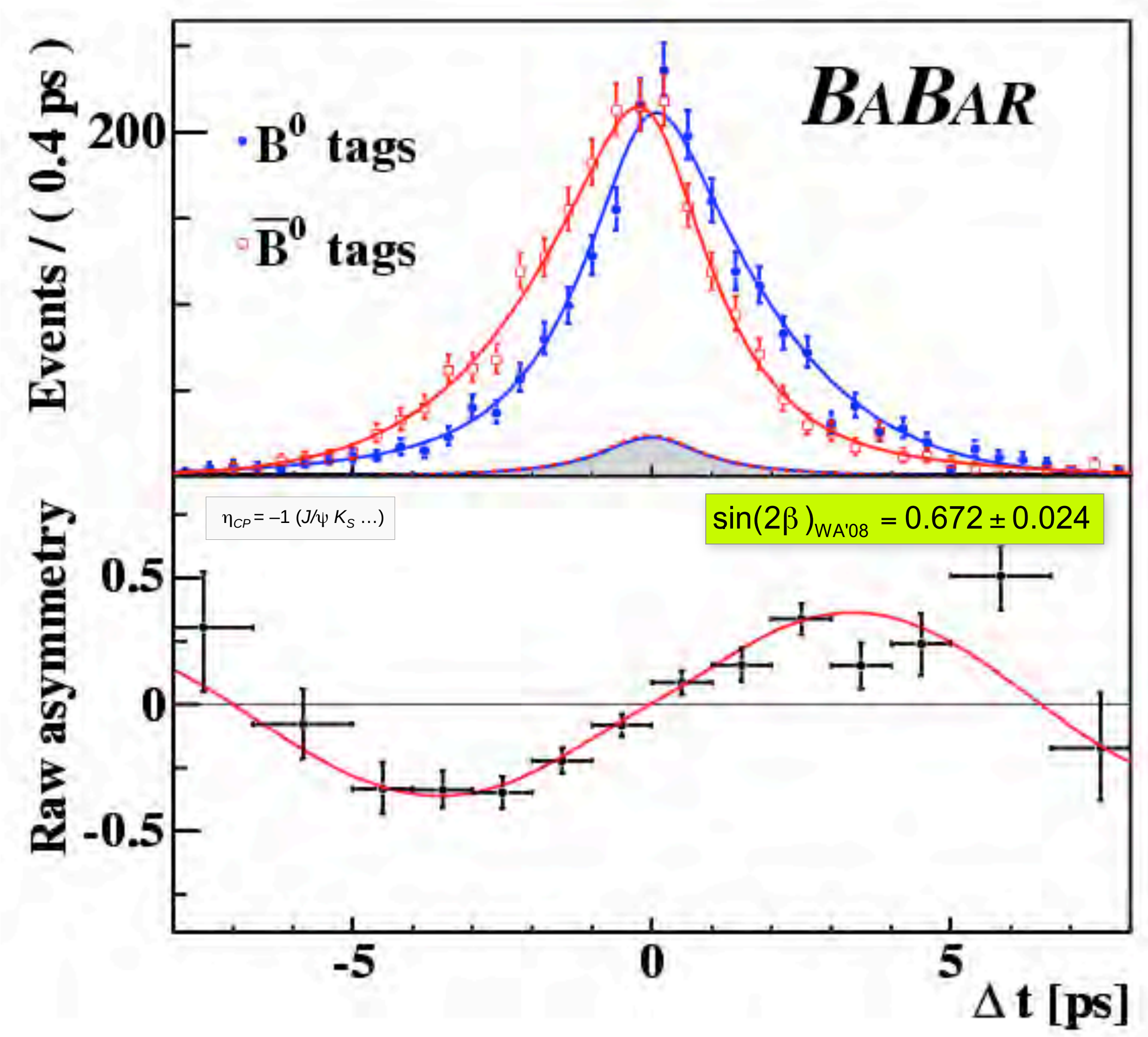

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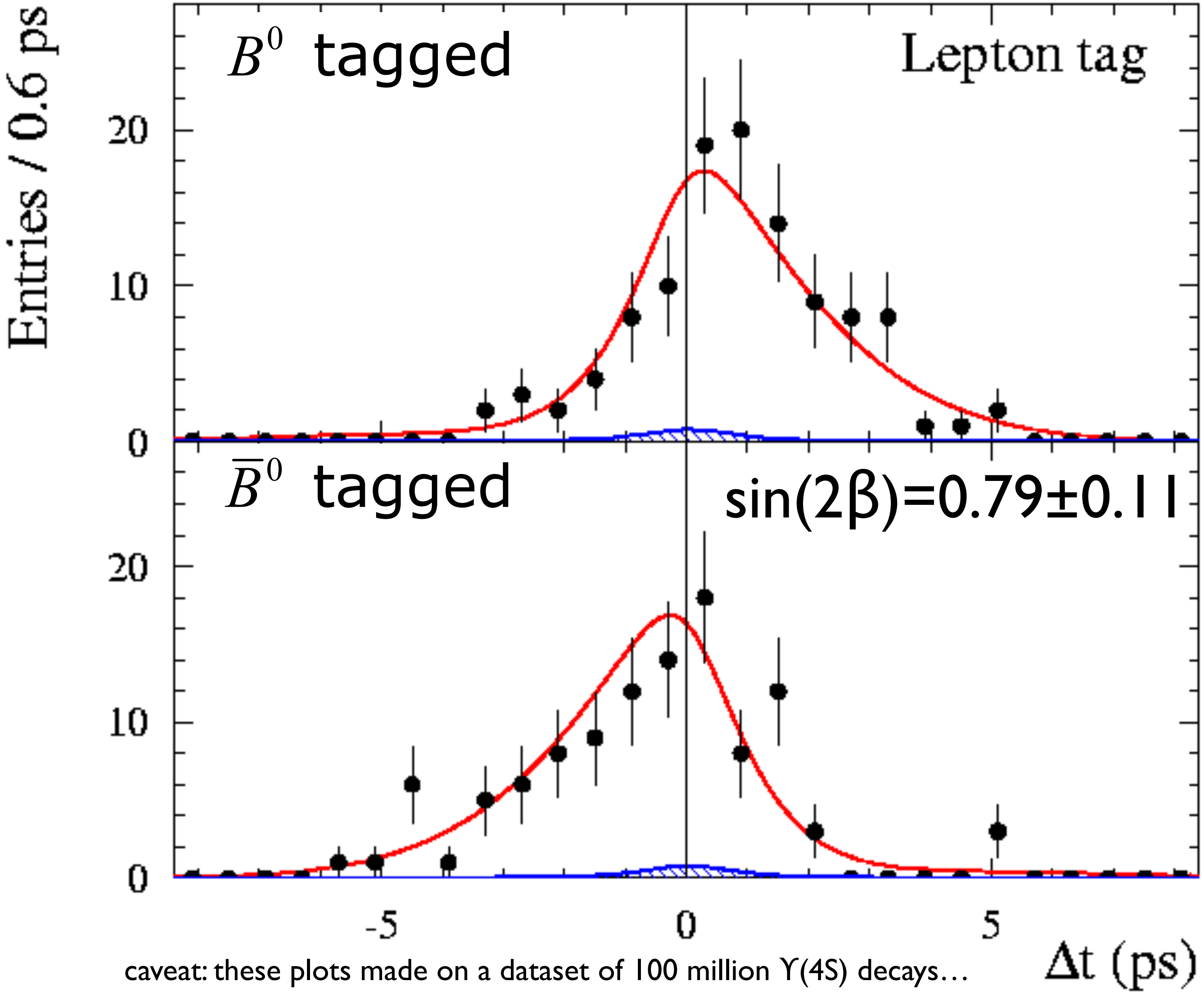
$$e^+e^- \to \Upsilon(4S) \to B_{\rm rec}B_{\rm tag} \qquad \begin{array}{rcl} B_{\rm rec} & \to & J/\psi K_S \\ B_{\rm tag} & \to & \ell^\pm X \end{array}$$

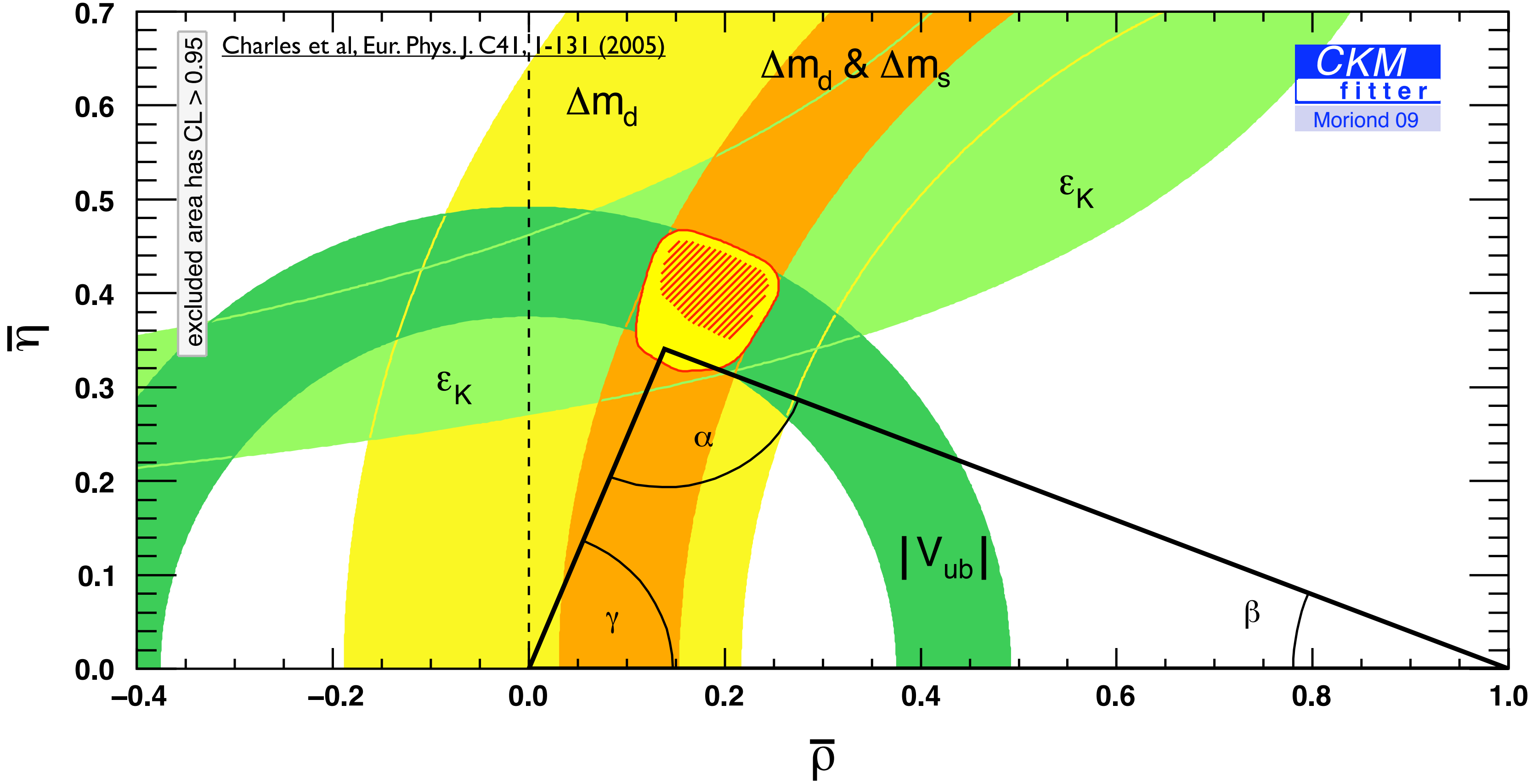


220 events

98% signal purity!
3.3% mistag rate!
20% better Δt resolution!

caveat: these plots made on a dataset of 100 million ϒ(4S) decays…

Putting it all together...



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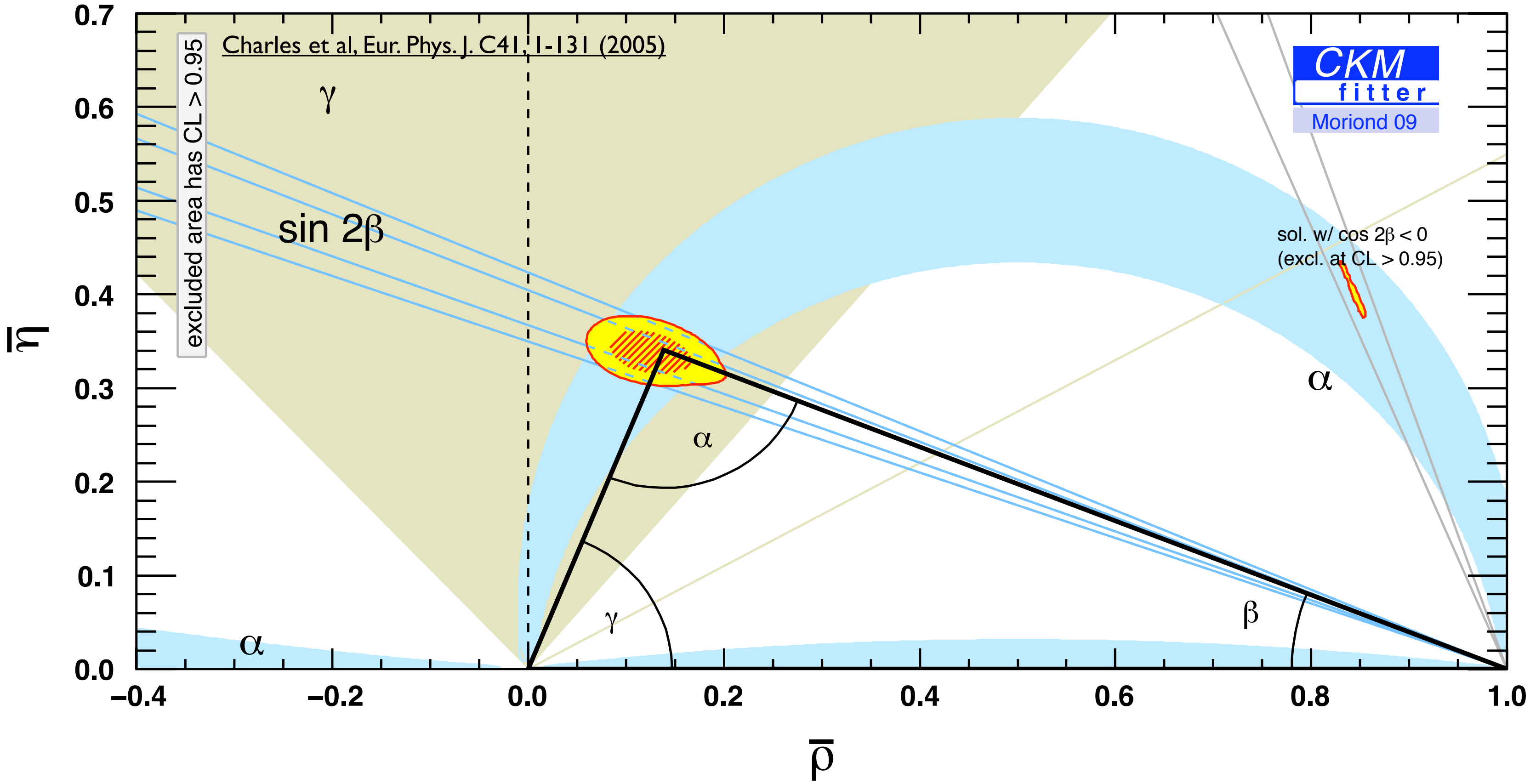

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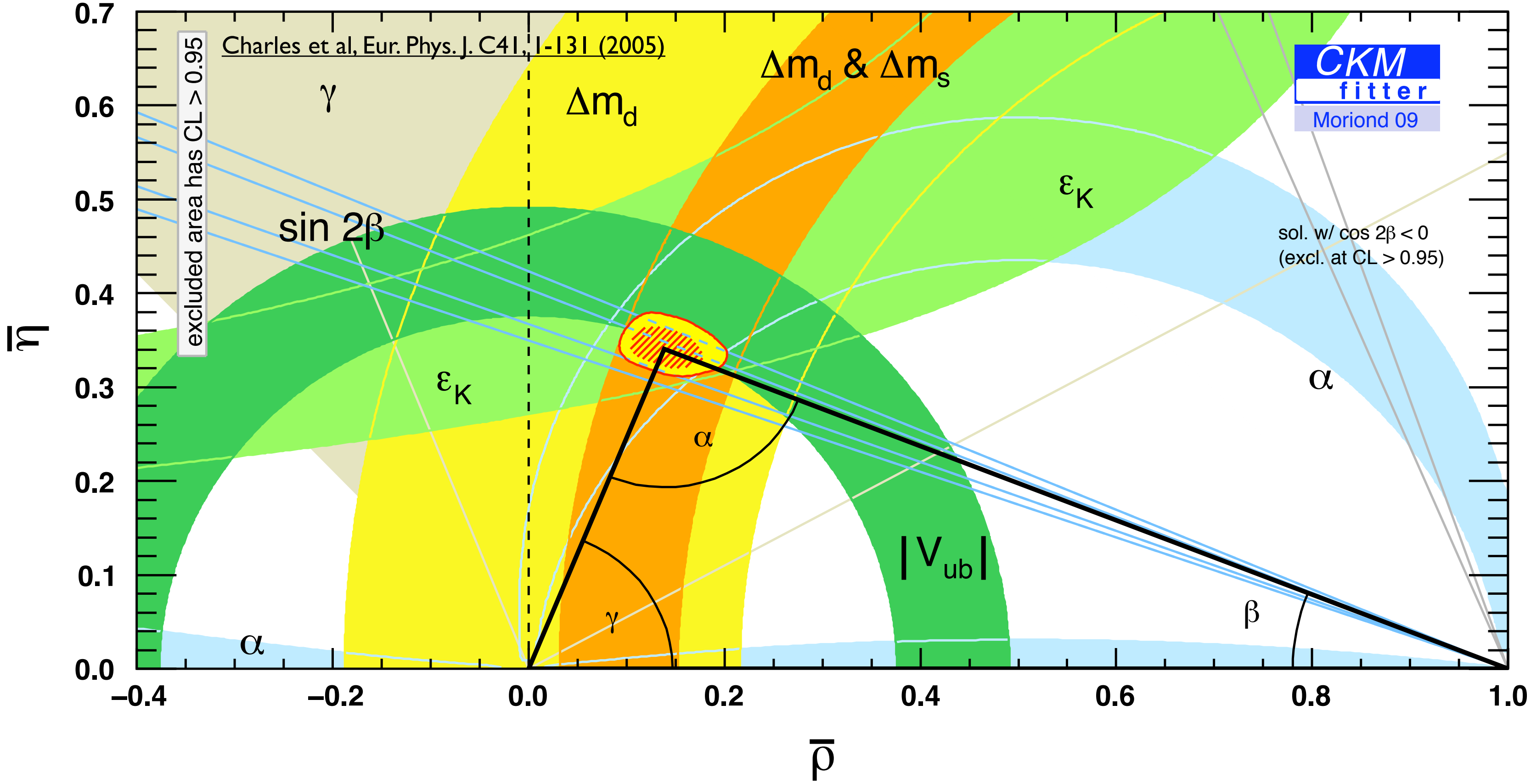

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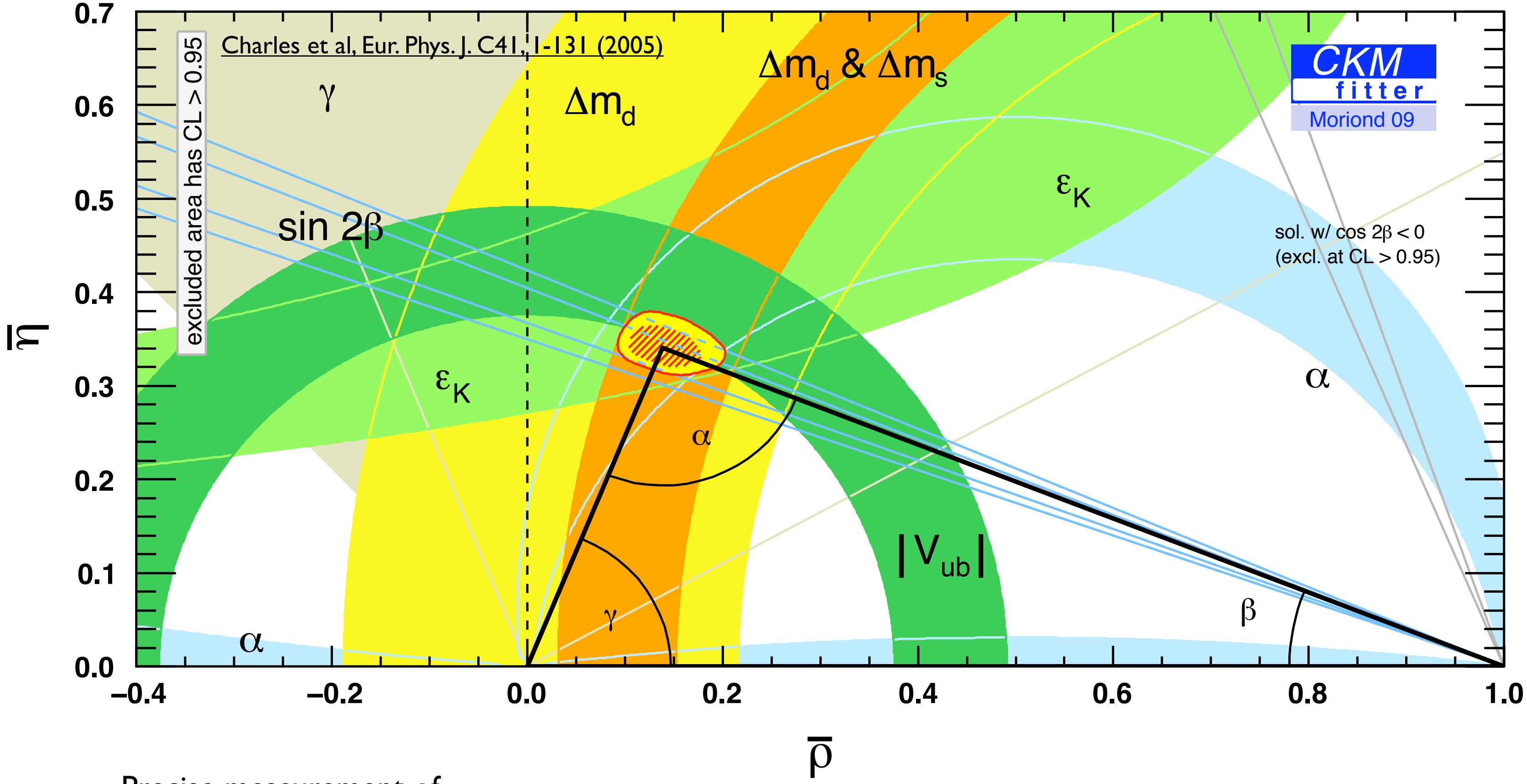
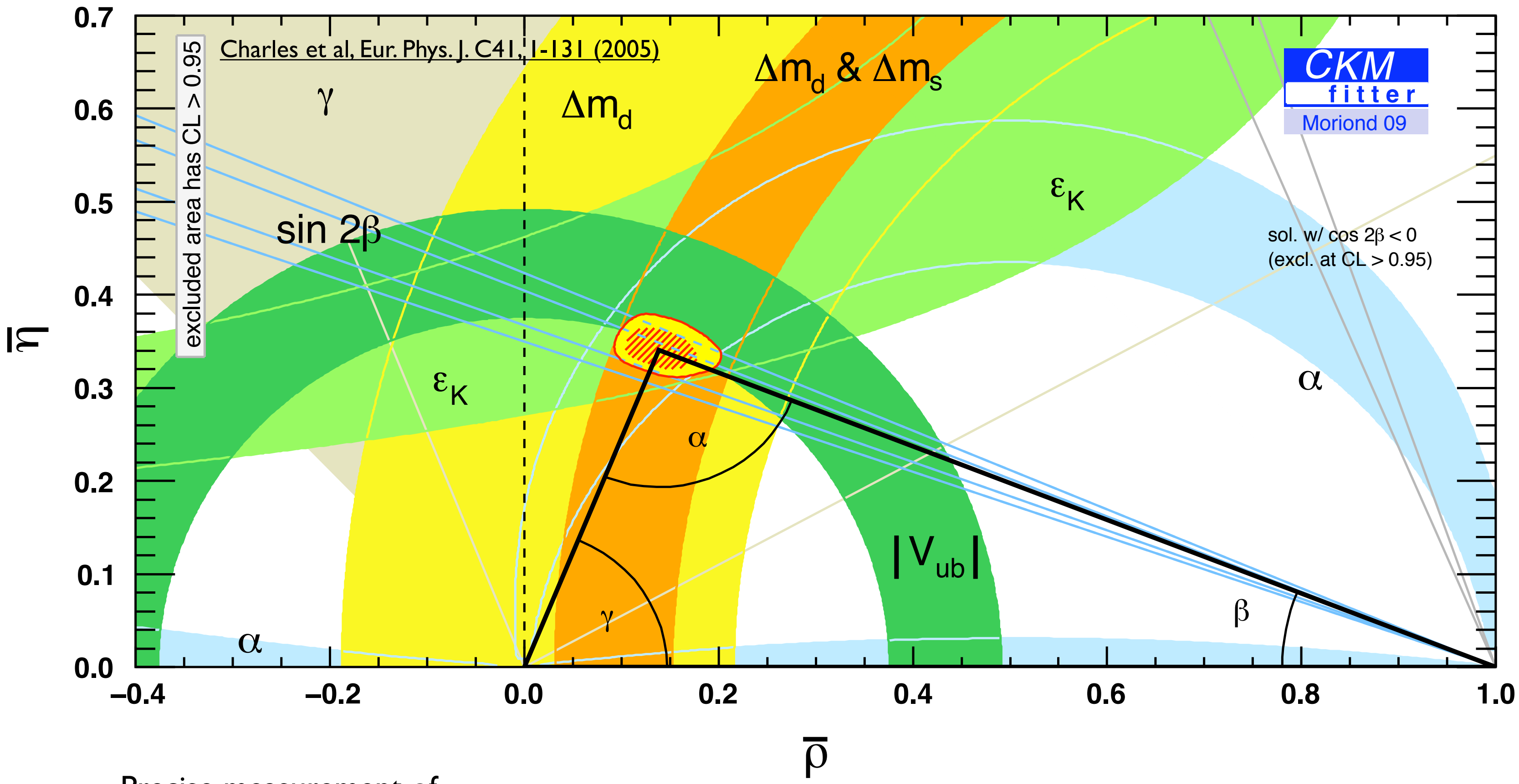


Precise measurement of sin(2β) agrees perfectly with other measurements and CKM assumptions

There is a solution of ρ,η consistent with all measurements

Putting it all together...



Precise measurement of sin(2β) agrees perfectly with other measurements and CKM assumptions

There is a solution of ρ,η consistent with all measurements

☺ The CKM model of CP violation has successfully been confirmed!

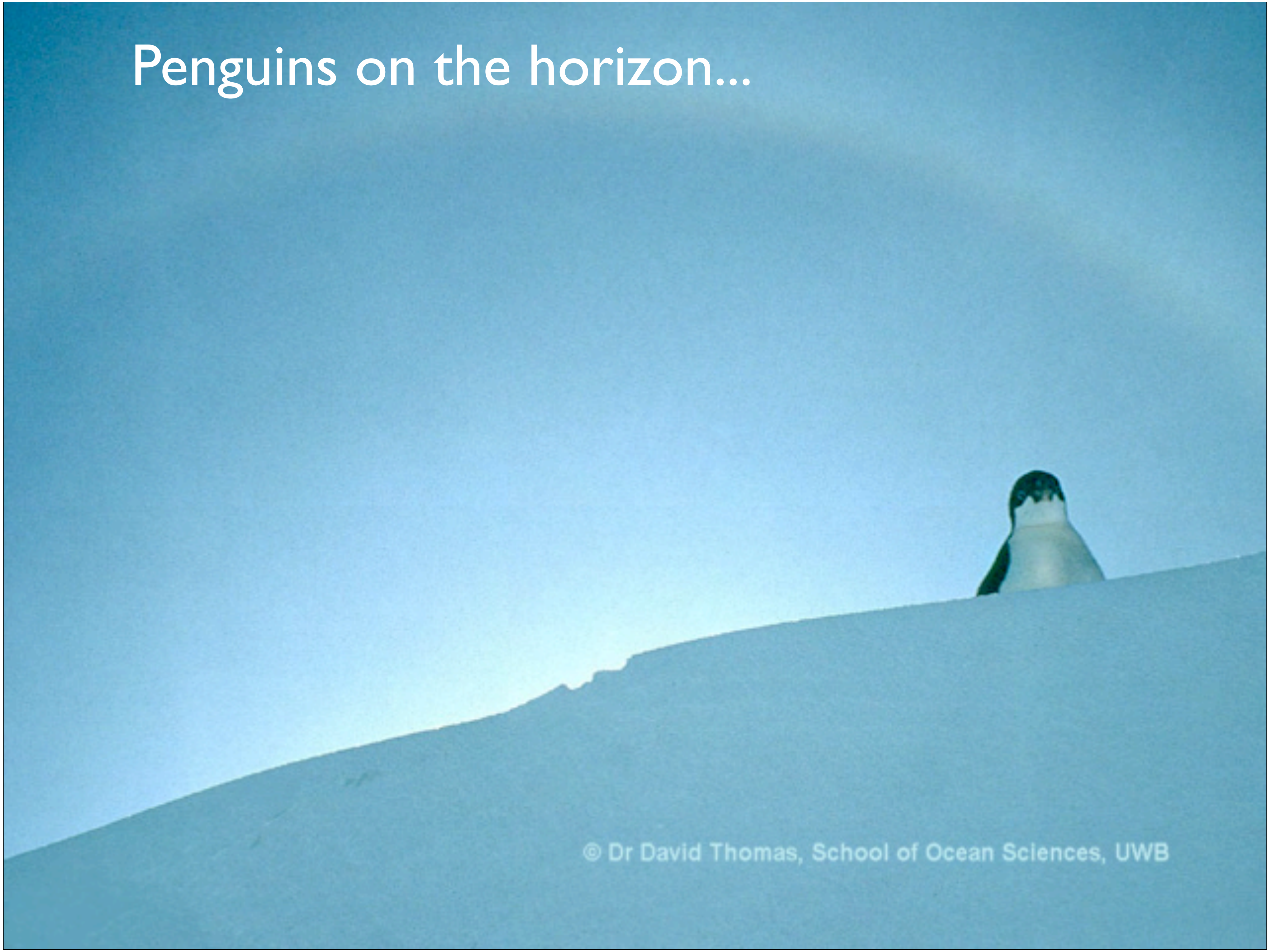
At the scale of electroweak interaction, CKM is *dominates CP* violation

☹ No need (at current level of precision!) for physics beyond the Standard Model to explain observed CP violation

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No 'primordial' antimatter observed
- Need something called 'CP' symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can 'mix' (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM
- All four neutral mesons can mix -- and do, but some faster(slower) than others...
- Heavy top quark needed for B mixing
- Using the measured magnitudes of V_{CKM} elements, we can predict the weak phases!
- And the measurements agree with the predictions...

Penguins on the horizon...

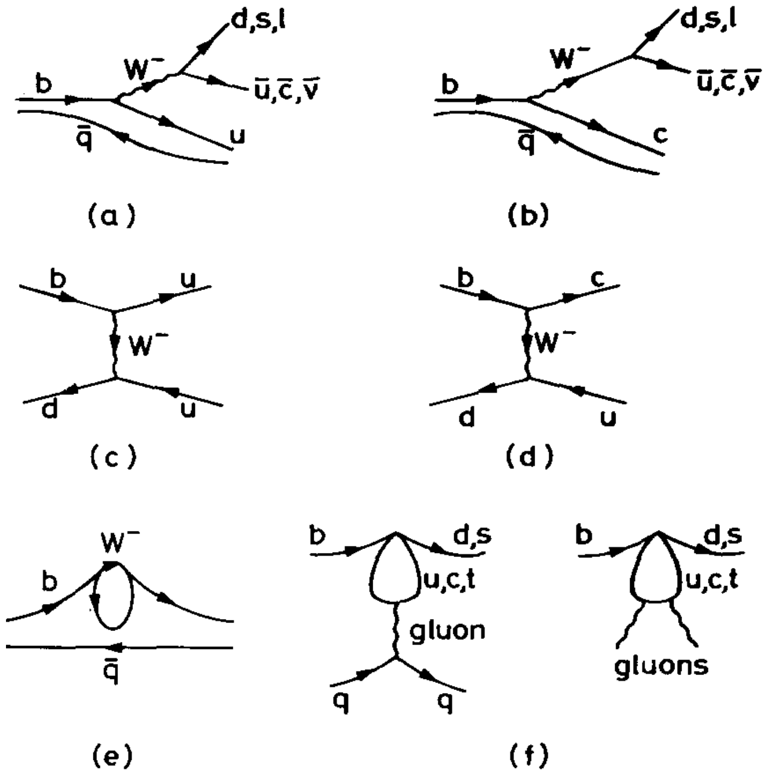


Left-handed quarks, penguins and darts...

THE PHENOMENOLOGY OF THE NEXT LEFT-HANDED QUARKS

J. ELLIS, M.K. GAILLARD *, D.V. NANOPOULOS ** and S. RUDAZ ***
CERN, Geneva

Received 14 July 1977



We now turn to the "penguin" diagrams of figs. 2e and 2f.

Nucl. Phys. B131:285 1977

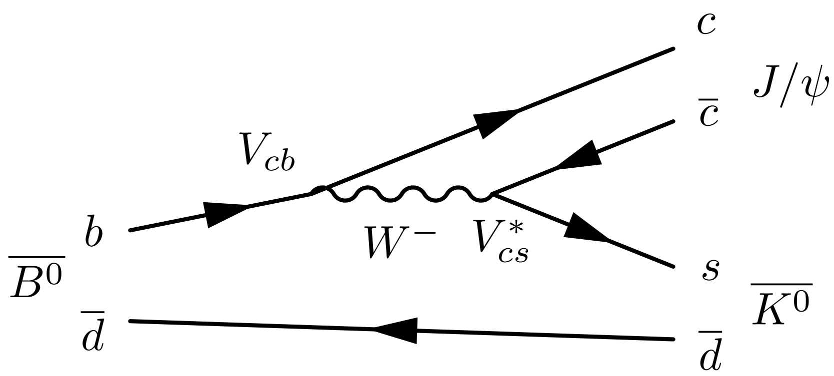
"In the spring of 1977, Mike Chanowitz, Mary K. and I wrote a paper on GUTs [Grand Unified Theories] predicting the b quark mass before it was found. When it was found a few weeks later, Mary K., Dimitri, Serge Rudaz and I immediately started working on its phenomenology.

That summer, there was a student at CERN, Melissa Franklin, who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time…. Later…I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."

John Ellis in Mikhail Shifman's "ITEP Lectures in Particle Physics and Field Theory", hep-ph/9510397

Are we sure that $A_{CP}(J/\psi K_S) = \sin(2\beta)$?



$$A_{\overline{B^0}\to J/\psi \overline{K^0}} = V_{cb} V_{cs}^* T$$

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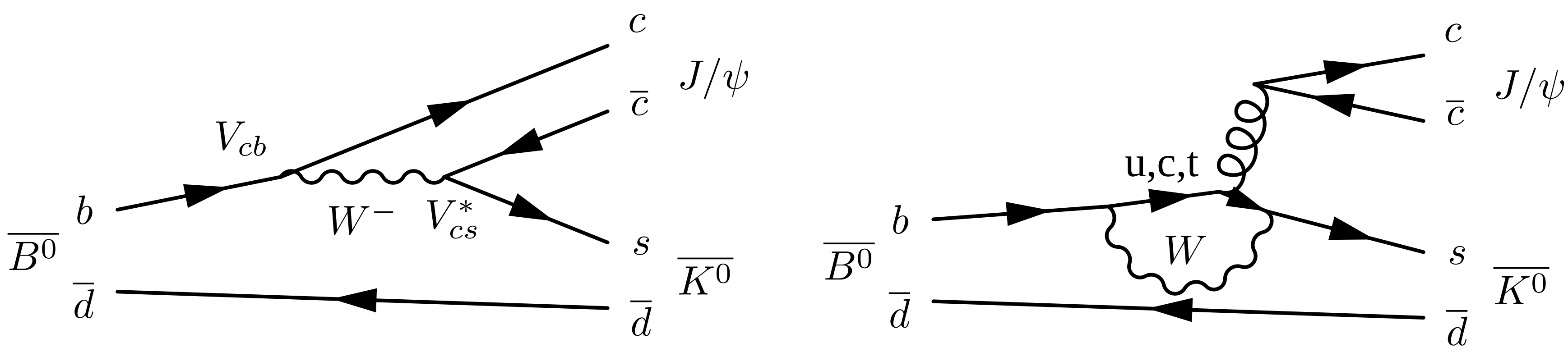

$$A_{\overline{B^0}\to J/\psi \overline{K^0}} = V_{cb}V^*_{cs}T + V_{tb}V^*_{ts}P_t + V_{cb}V^*_{cs}P_c + V_{ub}V^*_{us}P_u$$

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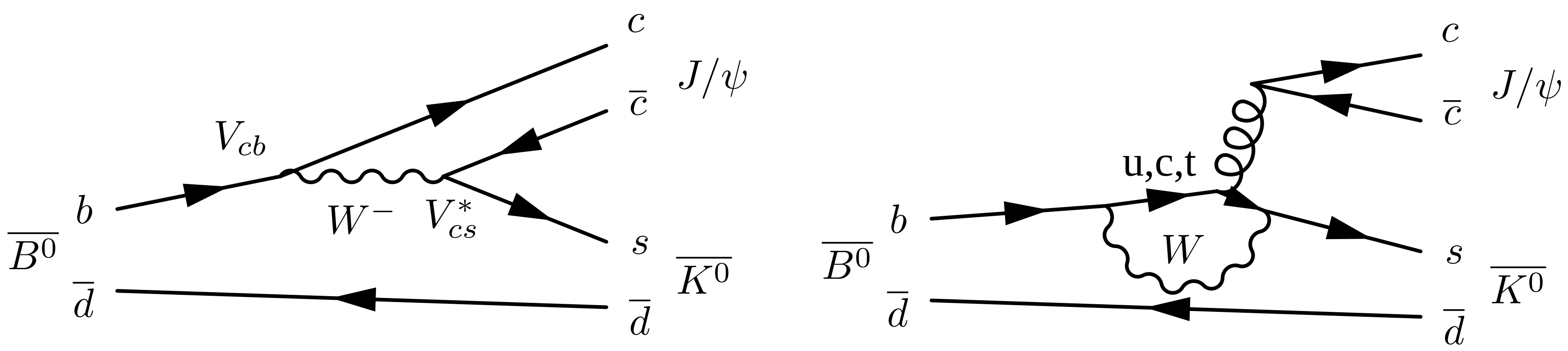

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Use the 'bs' unitarity triangle relation: $V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{tb}V_{ts}^* = 0$

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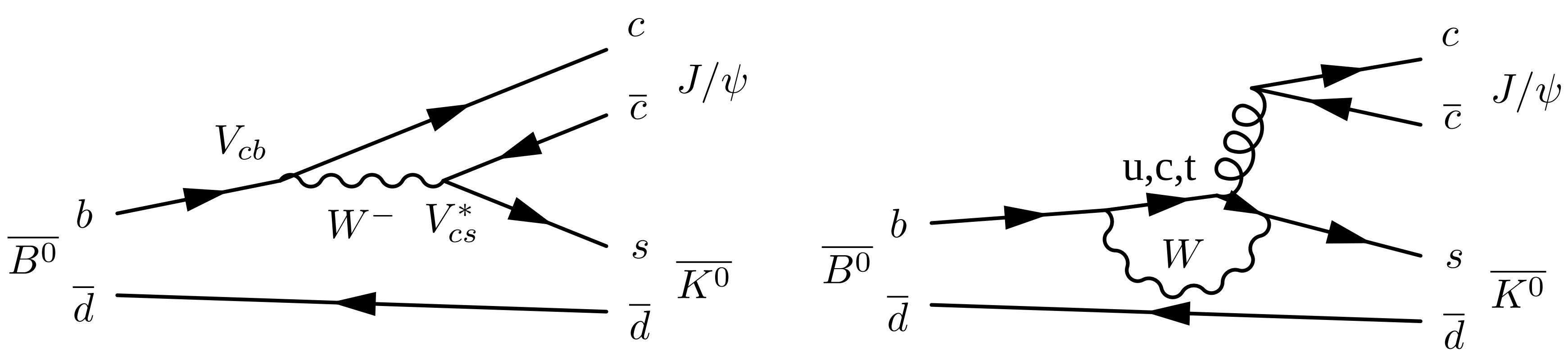

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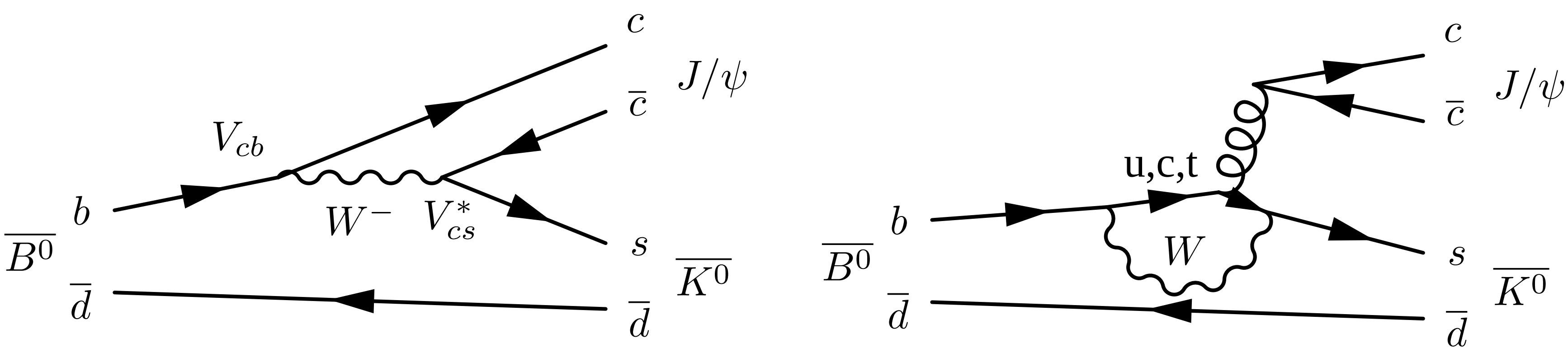
$$A_{\overline{B^0}\to J/\psi\overline{K^0}} = V_{cb}V_{cs}^*(T + P_c - P_t) + V_{ub}V_{us}^*(P_u - P_t)$$

relative phase: γ

Are we sure that $A_{CP}(J/\psi K_S) = \sin(2\beta)$?



$$A_{\overline{B^0}\to J/\psi \overline{K^0}} = V_{cb}V_{cs}^* T + V_{tb}V_{ts}^* P_t + V_{cb}V_{cs}^* P_c + V_{ub}V_{us}^* P_u$$

Use the 'bs' unitarity triangle relation: $V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{tb}V_{ts}^* = 0$

$$A_{\overline{B^0}\to J/\psi \overline{K^0}} = V_{cb}V_{cs}^*(T + P_c - P_t) + V_{ub}V_{us}^*(P_u - P_t)$$

$= \mathcal{O}(\lambda^2)$ relative phase: γ $= \mathcal{O}(\lambda^4)$

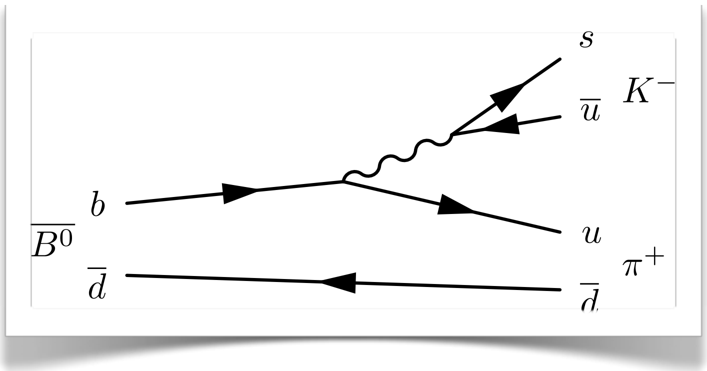
$$\boxed{\begin{array}{c}\text{Penguin contribution with different weak phase suppressed by an extra factor } \lambda^2\text{:}\\ \text{Extraction of } \sin(2\beta) \text{ from } J/\psi K_S \text{ is "theoretically clean"}\end{array}}$$

Direct CP violation: $\Gamma(B^0 \rightarrow f) \neq \Gamma(\overline{B}^0 \rightarrow \overline{f})$

CP violation if $\Gamma(B^0 \rightarrow f) \neq \Gamma(\overline{B}^0 \rightarrow \overline{f})$

But: need (at least) 2 amplitudes for interference

Amplitude 1



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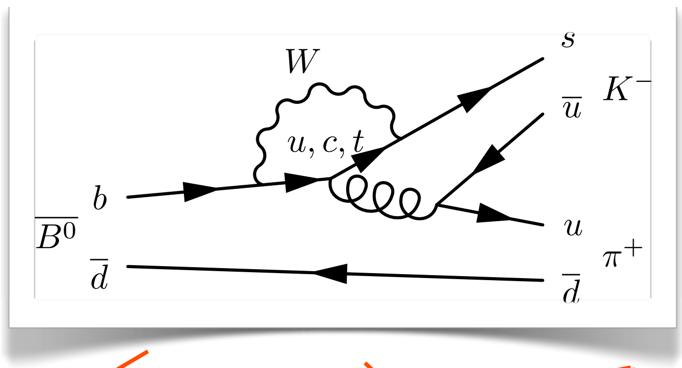
Amplitudes 2,3 and 4...



$$A_{\overline{B^0}\rightarrow K^-\pi^+} = V_{ub}V_{us}^*(T + P_u - P_t) + V_{cb}V_{cs}^*(P_c - P_t)$$

Direct CP violation: $\Gamma(B^0 \rightarrow f) \neq \Gamma(\overline{B}^0 \rightarrow \overline{f})$

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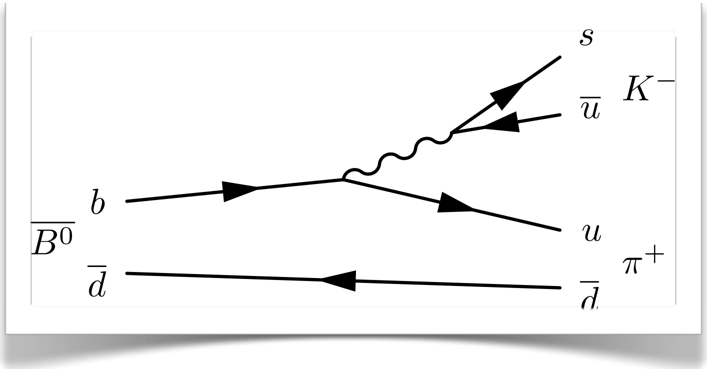

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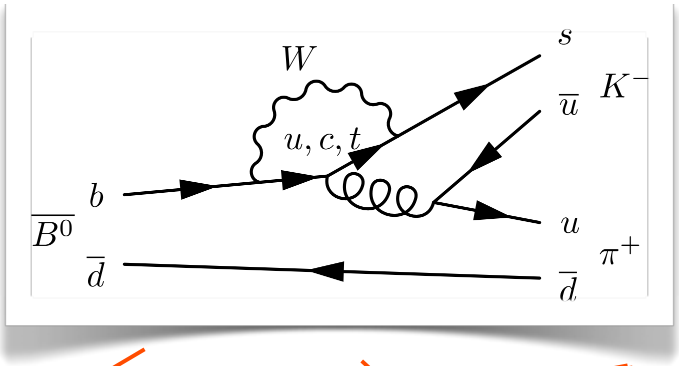
Amplitudes 2,3 and 4...



$$A_{\overline{B^0}\rightarrow K^-\pi^+} = V_{ub}V^*_{us}(T + P_u - P_t) + V_{cb}V^*_{cs}(P_c - P_t)$$

$$= \mathcal{O}(\lambda^4) \qquad\qquad = \mathcal{O}(\lambda^2)$$

relative phase: γ

Direct CP violation: $\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f})$

CP violation if $\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f})$

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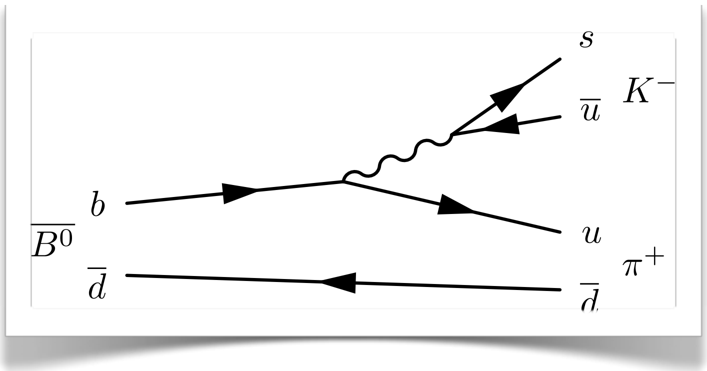

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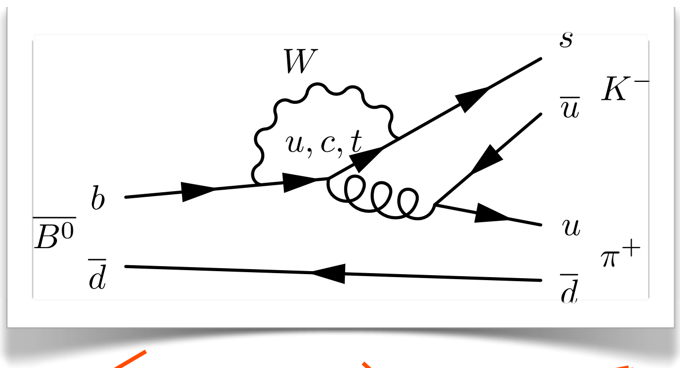
Amplitudes 2,3 and 4...



$$A_{\overline{B^0}\to K^-\pi^+} = \underbrace{V_{ub}V_{us}^*}_{=\mathcal{O}(\lambda^4)}(T + P_u - P_t) + \underbrace{V_{cb}V_{cs}^*}_{=\mathcal{O}(\lambda^2)}(P_c - P_t)$$

relative phase: γ

Now the otherwise dominant tree diagram is suppressed by λ^2!

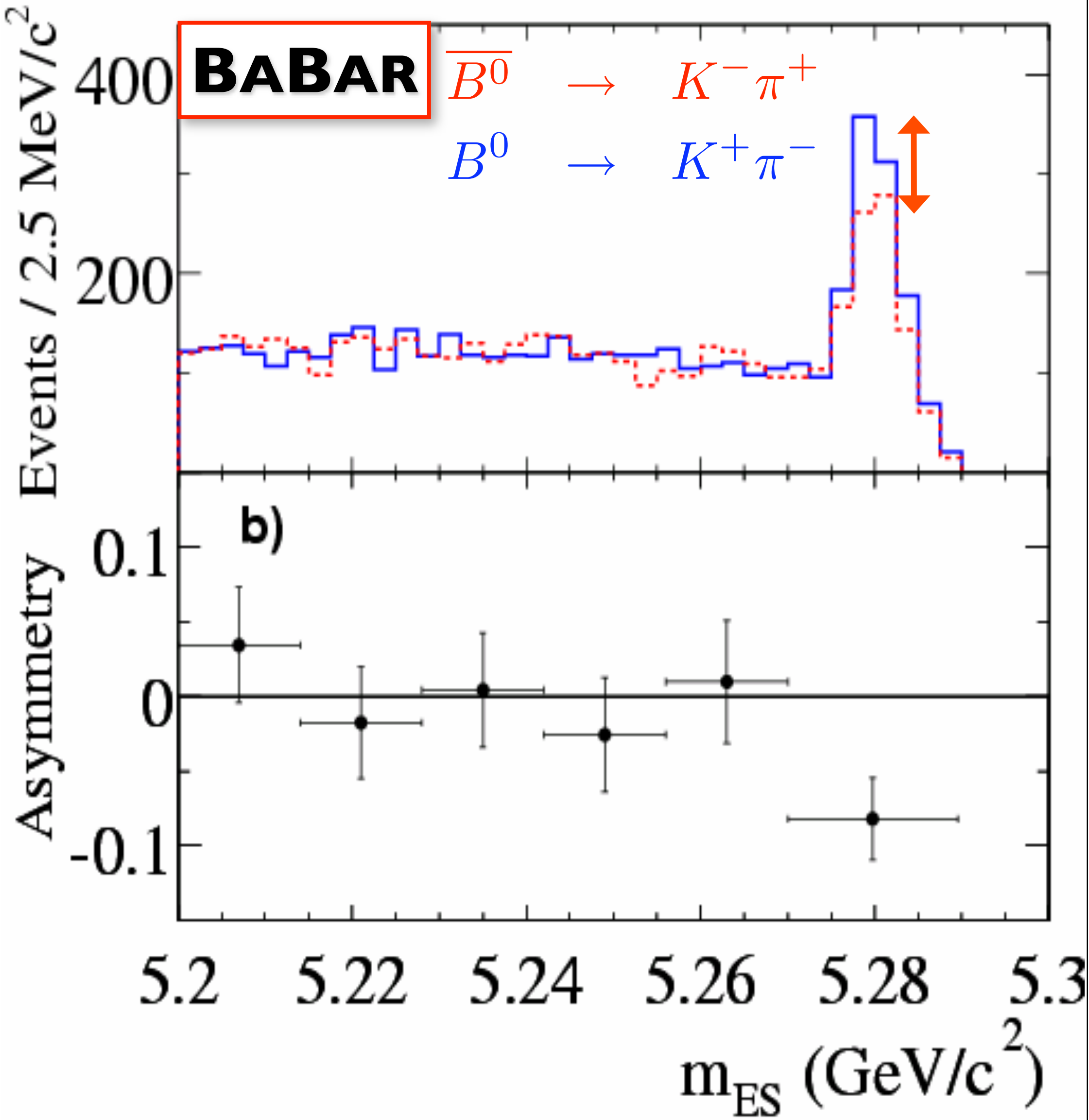
potentially ~equal amplitudes with *both* different strong and weak phases !

$\Rightarrow$ $\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f})$

Direct CP violation: $\Gamma(B^0 \to f) \neq \Gamma(\overline{B}^0 \to \overline{f})$

First observation of Direct CPV in B decays (2004):

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B^0} \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$



BABAR

hep-ex/0407057
Phys.Rev.Lett.93:131801,2004

$A_{CP} = -0.133 \pm 0.030 \pm 0.009$ **4.2σ**

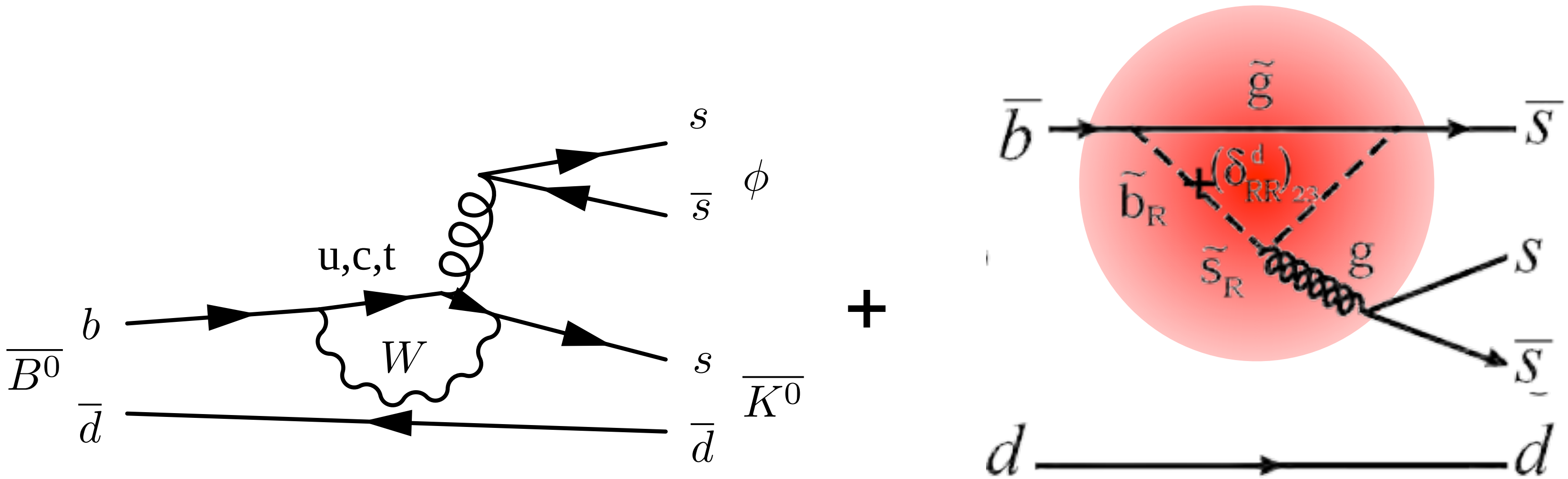
BaBar+Belle:

$A_{CP} = -0.114 \pm 0.020$

Peaking around the corner

Why are loop dominated decay processes very perceptible to ‘new’ particles?

- You can simply replace an ‘internal quark line’ (the circle) with ‘new’ particles without affecting the initial and final state of the decay



- Momentum flowing through loop should be integrated to “infinity”
  → Potential high masses of virtual particles don’t kill their contribution…

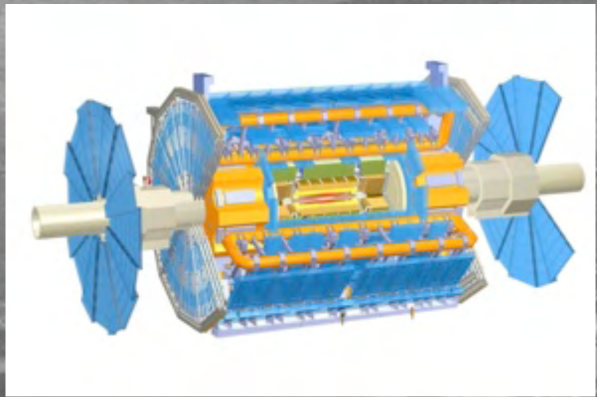
- No tree-level diagrams: less ‘competition’ from boring Standard Model amplitudes..

Summary

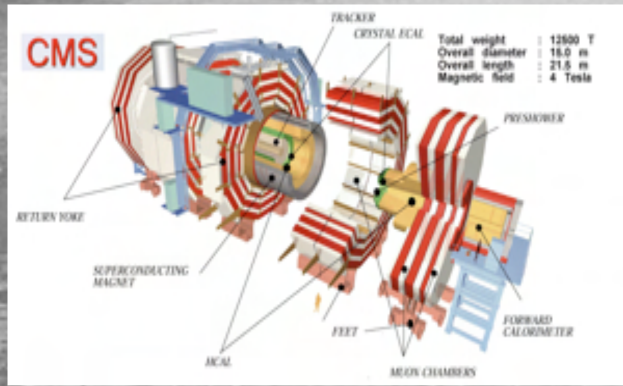
- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No 'primordial' antimatter observed
- Need something called 'CP' symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can 'mix' (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM
- All four neutral mesons can mix -- and do, but some faster(slower) than others...
- Heavy top quark needed for B mixing
- Using the measured magnitudes of V_{CKM} elements, we can predict the weak phases!
- And the measurements agree with the predictions...
- Penguins and rare decays *could* provide hints of physics beyond the Standard Model

The Future of B physics & CP violation at the LHC

ATLAS



CMS



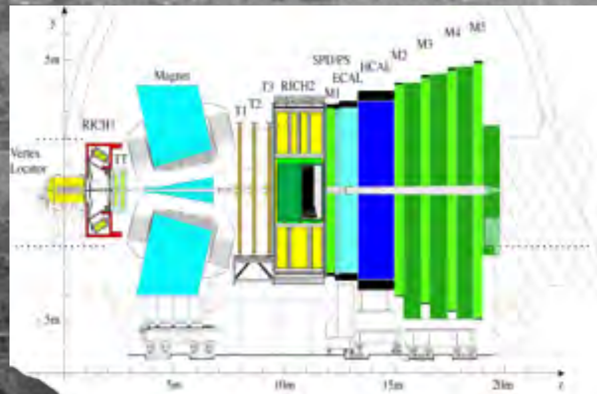
ATLAS and CMS concentrate on "high-p_T" discovery physics.

Their *B*-physics potential relies on the low-p_T performance of the Trigger systems.

LHCb is **not** a fixed-target experiment (but does look like one). It concentrates on *B* physics.

Virtues over ATLAS & CMS: Low-pT track trigger, particle ID & better mass resolution

LHCb

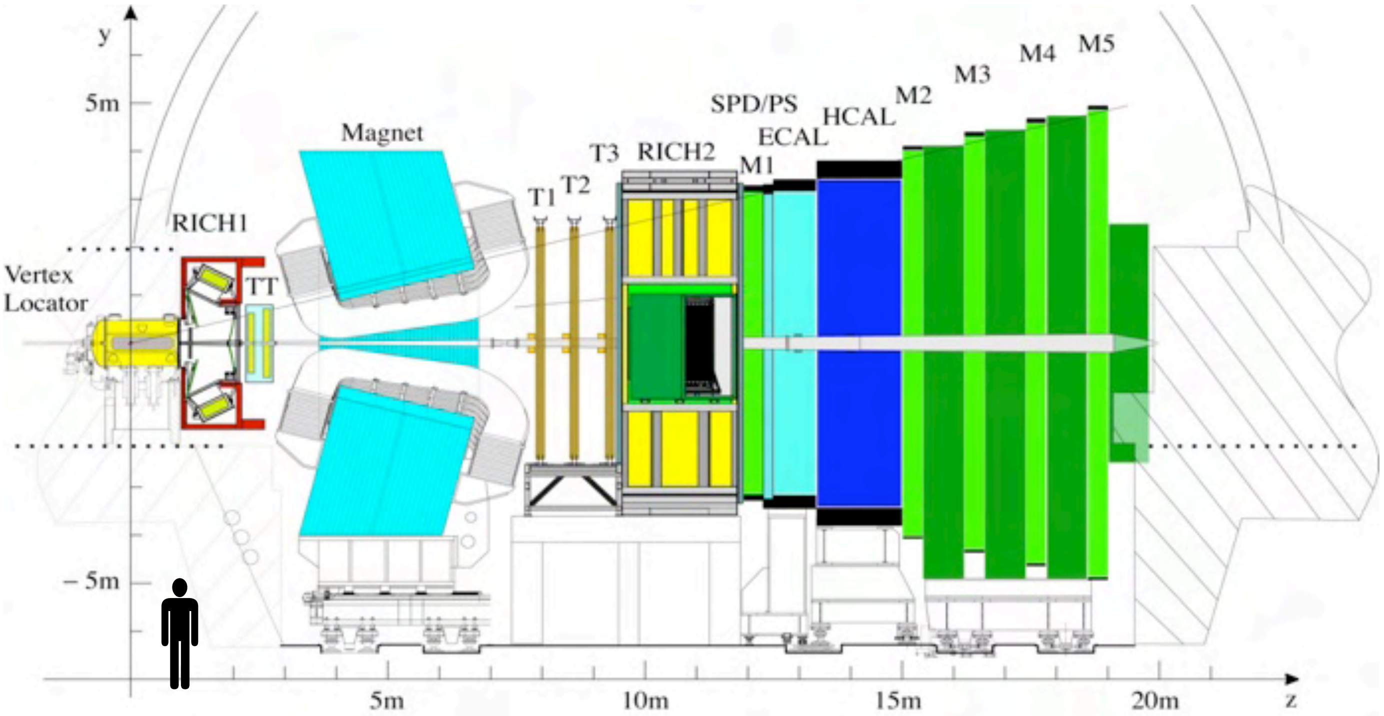


B Physics at Tevatron and LHC

B physics at hadron colliders is complementary to the e^+e^- *B* factories.

Strengths: High statistics: LHC will *produce* 10^{12} bb/year at $2\text{x}10^{32}$ $cm^{-2}s^{-1}$; accesses the B_s;sensitive to very rare modes, if clean signature; production of *b* baryons and B_c mesons

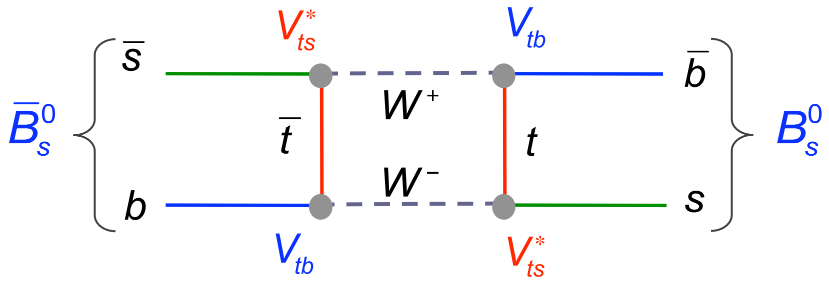
Weaknesses: Worse tagging (no quantum coherence) and background; no rare modes with neutrinos can be reconstructed; less efficient for π^0;

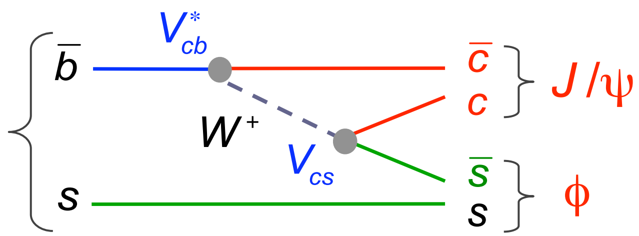


B physics at the Tevatron & LHC

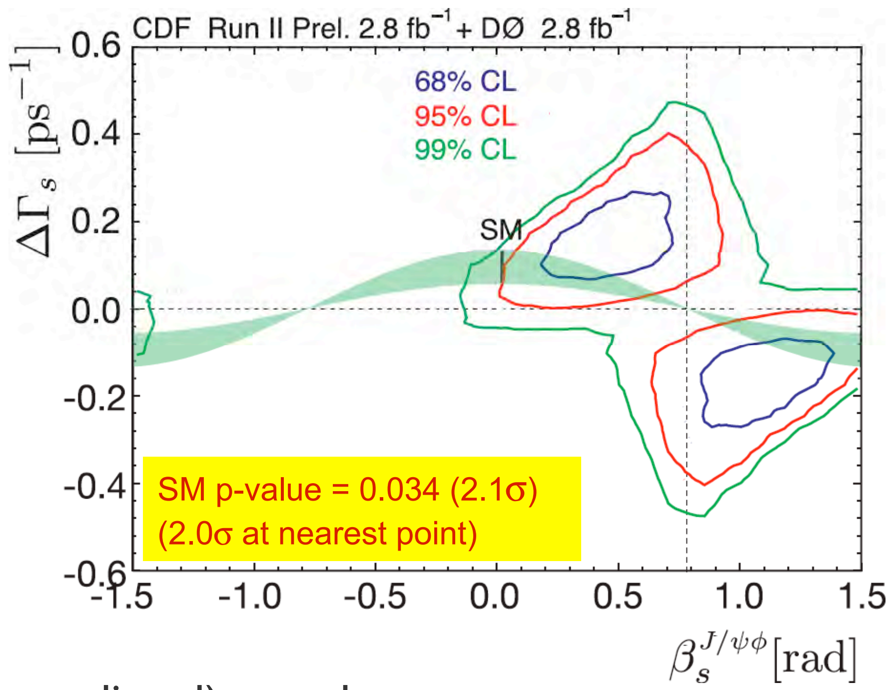
Prime Measurements: (**many, many** more interesting measurements to be done!)

- B_s mixing phase: very small in SM , excellent probe for new physics: $2\beta_s \approx -2\arg V_{ts} V_{tb}^*$





new result
shown at EPS 16-22 July
2009



- $B_s \rightarrow \mu^+\mu^-$: FCNC (box & EW-penguin-mediated) rare decay
- SM BR ~ 3 · 10^{-9}; current limit (CDF) < 5.8 · 10^{-8} at 95% CL
- in MSSM, BR enhanced by $\tan(\beta)^6$ (note: β = ratio of VEVs, not 'sin(2β)')

CKM phase and the universe

See, e.g.,
W. Bernreuther,
Lect. Notes Phys. 591 (2002) 237-293

- **could the CKM phase generate the observed baryon asymmetry ?**

- KM *CP*-violating asymmetries, d_{CP}, must be proportional to the Jarlskog invariant J

$$d_{CP} = J \times \tilde{F}_U \times \tilde{F}_D$$

where: $J = \mathrm{Im}\left(V_{ud}V_{cs}V_{us}^{*}V_{cd}^{*}\right) \simeq A^2\lambda^6\eta$ and: $\tilde{F}_U = \left(m_t^2 - m_c^2\right)\cdot\left(m_t^2 - m_u^2\right)\cdot\left(m_c^2 - m_u^2\right)$

Area of every unitarity triangle!

$= (3.1 \pm 0.2) \times 10^{-5}$ $\qquad \tilde{F}_D = \left(m_b^2 - m_s^2\right)\cdot\left(m_b^2 - m_d^2\right)\cdot\left(m_s^2 - m_d^2\right)$

  - If any two up- or down- type masses equal, can *redefine* mass eigenstates, 'effectively' reducing the CKM from 3x3 to 2x2

- Since non-zero quark masses are required, *CP* symmetry can only be broken where the Higgs field has acquired a vacuum expectation value → T_{EW}
- (But with M(Higgs)>70 GeV, insufficient deviation from thermal equilibrium...)
- To make d_{CP} dimensionless, we divide by dimensioned parameter $D = T_c$ at the EW scale ($T_c = T_{EW} \sim 100$ GeV), with $[D] = \text{GeV}^{12}$

$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \approx 10^{-19} \ll \eta \approx O\left(10^{-10}\right)$$

KM *CP* violation seems *irrelevant* for baryogenesis !

What about neutrinos?

- However, we now know that neutrinos also have flavour oscillations
  - thus they must have a (very small) mass...
  - ... and thus there is the equivalent of a CKM matrix for them:
    - *the Pontecorvo-Maki-Nakagawa-Sakata matrix*

$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu 1}|^2 & |U_{\mu 2}|^2 & |U_{\mu 3}|^2 \\ |U_{\tau 1}|^2 & |U_{\tau 2}|^2 & |U_{\tau 3}|^2 \end{pmatrix} \approx \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{pmatrix}$$

  - which has a completely different hierarchy!
  - and, because neutrinos have no electric charge, you can do things you cannot do with quarks...
  - there are scenarios (leptogenesis) where CP violation in the neutrino sector would generate (eventually) baryogenesis...

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No 'primordial' antimatter observed, need CP violation (amongst others!)
- CP broken by the charged weak interaction
- The weak and mass eigenstates of quarks are *different*, and this difference is *described* by the CKM matrix (but not explained!)
- There is a clear (and unexplained!) hierarchical structure to the CKM matrix...
- With 3 (or more) families, one can have a complex phase(s) in the CKM matrix, and this *allows* for CP violation!
- Measurements show that CKM describes the dominant (only?) source of CP violation (at the EW scale).
- But it doesn't explain the matter -- antimatter asymmetry of the universe..

➡ *There is plenty left to be explored!*

Symmetries

Instructions by the VOC (Dutch East India Company) in Aug 1642:

"Since many rich mines and other treasures have been found in countries north of the equator between 15° and 40° latitude, there is no doubt that countries alike exist south of the equator. The provinces in Peru and Chili rich of gold and silver, all positioned south of the equator, are revealing proofs hereof."

Abel Tasman discovered Tasmania (Nov. 1642), New Zealand (Dec. 1642), Fiji (Jan 1643), ...

From the point of view of the VOC, this was a disappointment..

Abel Tasman


I'd be happy to discover Fiji instead!