Physics at Hadron Colliders

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Rathen
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Plan

Day 1:
1. Introduction ("Why?")
2. Hadron Collider basics
3. Colliders
4. Detectors

Day 2:

5. Data reconstruction + Analysis
6. Physics
   6.1 QCD + Electroweak
   6.2 Top Quark

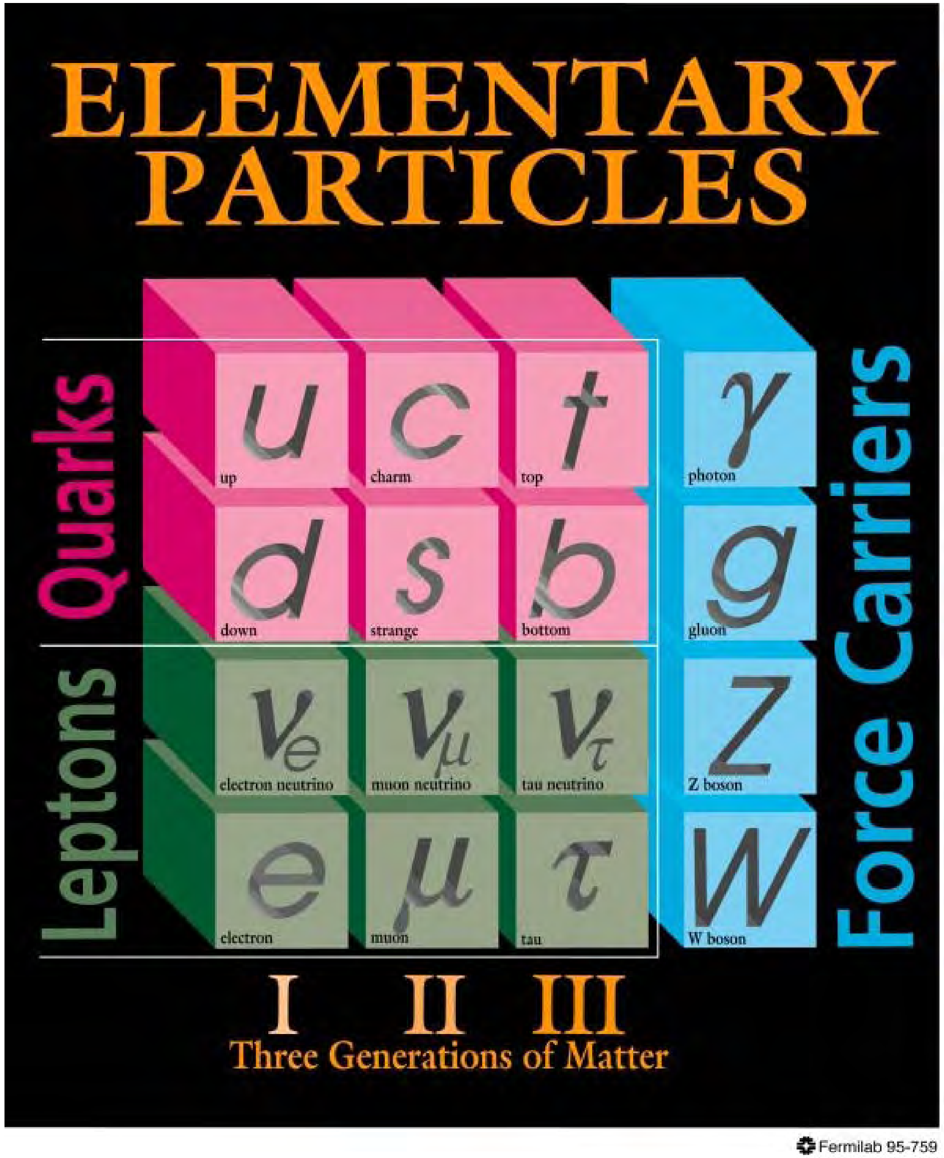
Day 3:

   6.3 Higgs Bosons
   6.4 Beyond SM Physics

- I'm happy to answer questions at any time
- Any selection of topics is biased – in these lectures as well…

1. Introduction

„Why?“

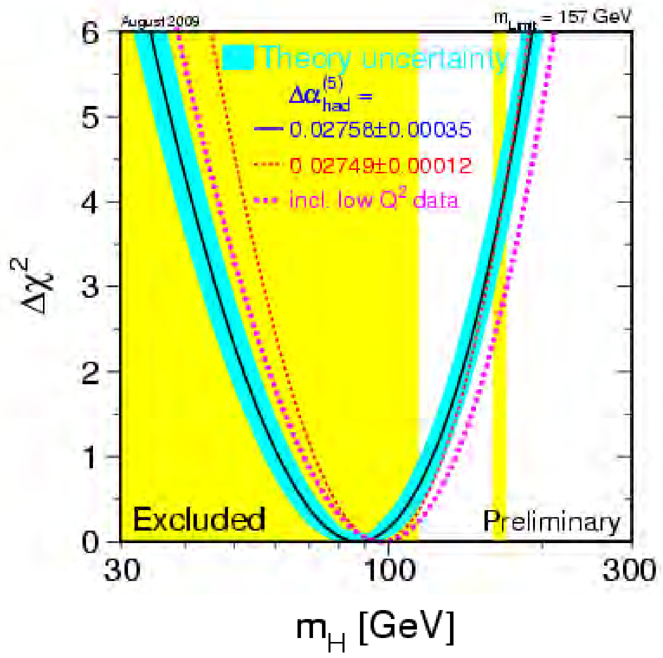


- Standard Model is extremely successful
- Experimental discovery of all of its matter constituents and force carriers
- Simple common approach to describe all (relevant) forces: QFT with a gauge principle
- Self-consistent at the level of quantum corrections

1st "but":

The SM's suggestion how to break electro-weak symmetry is not verified

Higgs mechanism (i.e. the SM approach) is a viable solution and evidence is compelling:



Experimental challenge #1:

Find this Higgs (or its relatives) or exclude it!

something in the loops mimics a light Higgs
or it is a light Higgs…

2nd 'but':

Even if we find a light Higgs:
why is it so light?

If there are no new phenomena which protect radiative corrections to the Higgs mass, it will receive un-naturally large (quadratic) corrections:

$m_H = m_{bare} - \delta m \approx (200\text{ GeV})$

$\delta m \sim \Lambda^2$ m_{bare} and δm are both $o(\Lambda^2)$ but almost equal!

'fine tuning'

We know this since so long that some of us are even willing to accept it (e.g. split SUSY, …)

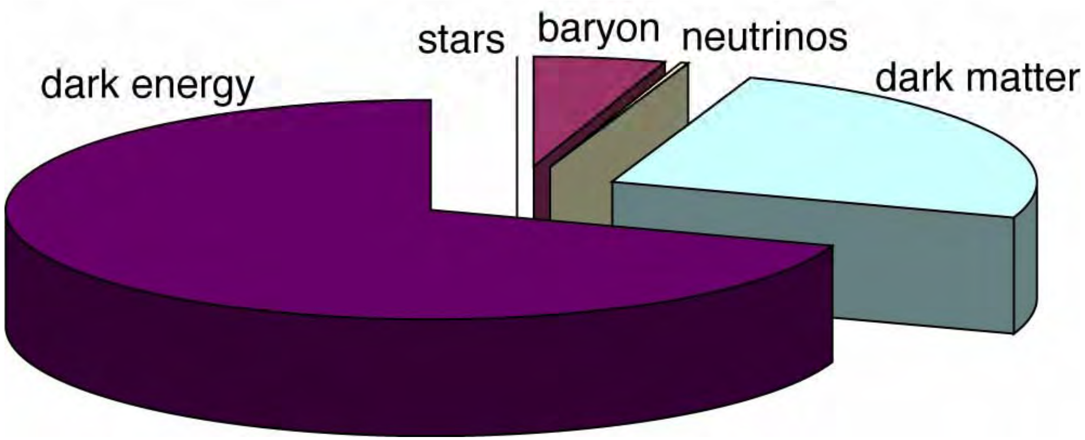
Nevertheless, there are very good ideas how to protect the Higgs mass

Experimental challenge #2:

Find out what protects the Higgs mass at the TeV scale

3rd 'but':

Our beloved SM contains only a tiny fraction of what's in our universe today! (how embarrassing)



The Universe:

5%   SM matter

25% dark matter

70% dark energy

Experimental challenge #3:

What is the microscopic nature of dark matter (and dark energy?)

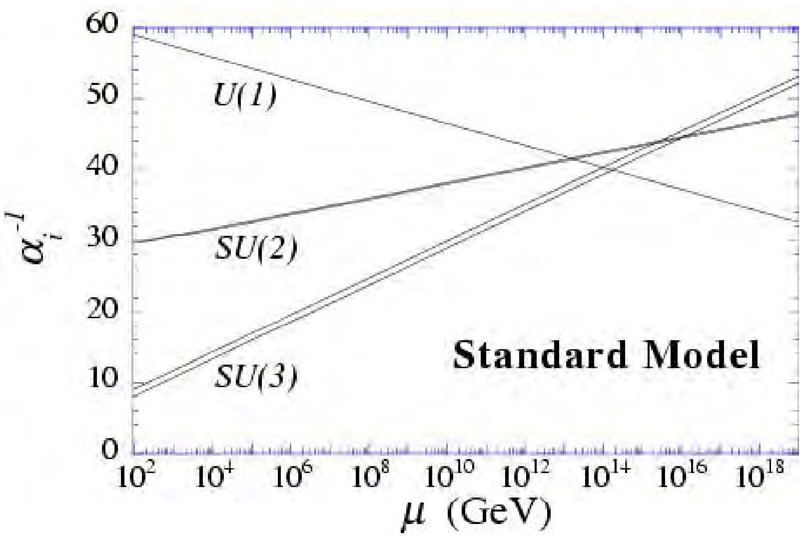
<u>4th 'but':</u>

We would probably not be happy with the answers to 'but's 1-3 unless they tell us something about physics at even higher energy scales!

a) unification of forces
b) connection between families (flavour physics)

We do have hints to very high scale physics

a) unification of forces ?



b) heavy neutrinos ?

$$m_N = \frac{m_D}{m_\nu^2} \approx \frac{1\mathrm{GeV}^2}{10^{-2}\mathrm{eV}^2} = 10^{11}\mathrm{GeV}\,??$$

Experimental challenge #4:

Can precise measurements at the TeV-scale yield information about unification at very high scales?

In a nutshell: the big questions of microscopic physics

The SM was to a large extent established at (hadron+lepton) colliders

The road ahead of us will need a broader set of exp. techniques:

- neutrino physics (from space + from accelerators/reactors)
- astro(particle)physics experiments (CMB, cosmic rays, DM searches, …)
- ultra-high precision at low energy (rare decays, g-2, …)

- but of course again colliders!

Which energy?

The TeV scale looks very interesting!

Why? →

In a nutshell: the big questions of microscopic physics

Why is the TeV scale interesting?

1. SM without Higgs violates unitarity (in $W_L W_L \rightarrow W_L W_L$) at 1.3 TeV!
   (something must happen!)
2. Higgs field vacuum expectation value v = 246 GeV
3. Evidence for light Higgs
4. Dark Matter consistent with (sub) TeV-scale WIMP (e.g. SUSY-LSP)
5. $2m_{top}$ = 350 GeV
6. “Fine tuning” can be mitigated with TeV-scale new physics (SUSY,…)

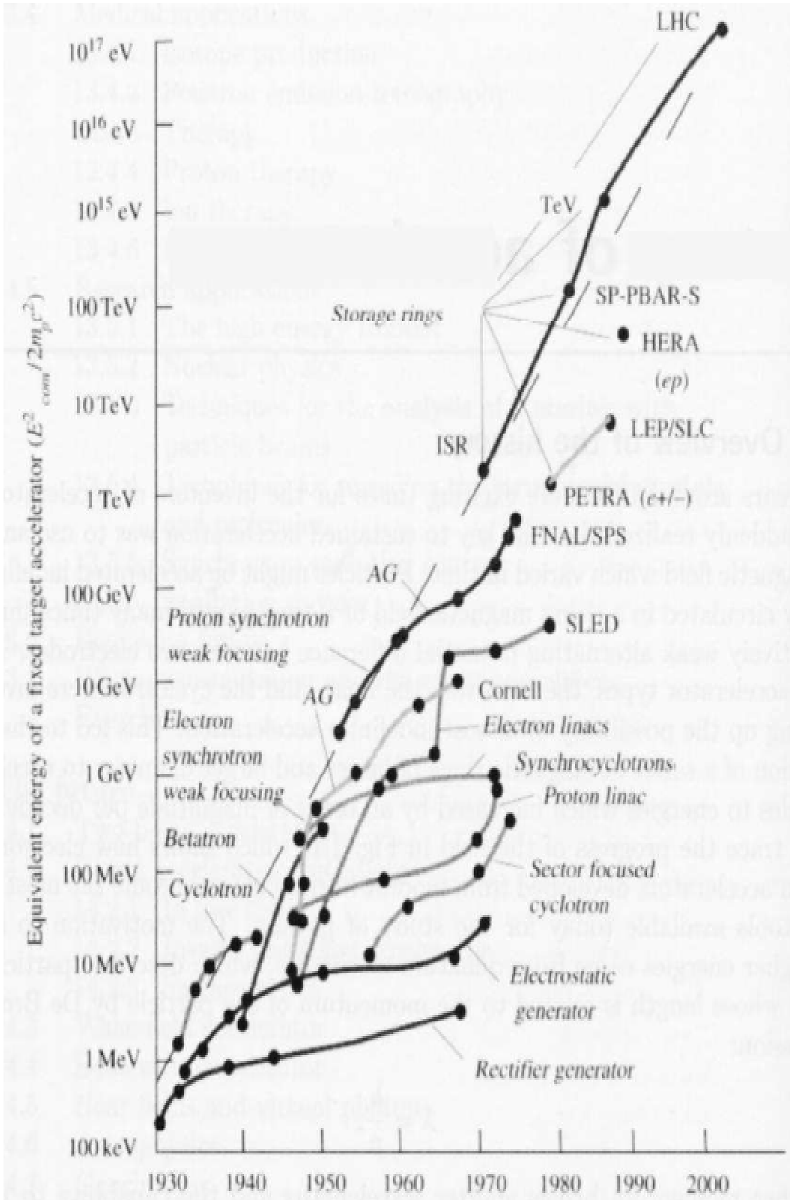
- $E = hc/\lambda$
  resolve small structures

- $E = mc^2$
  directly produce new particles

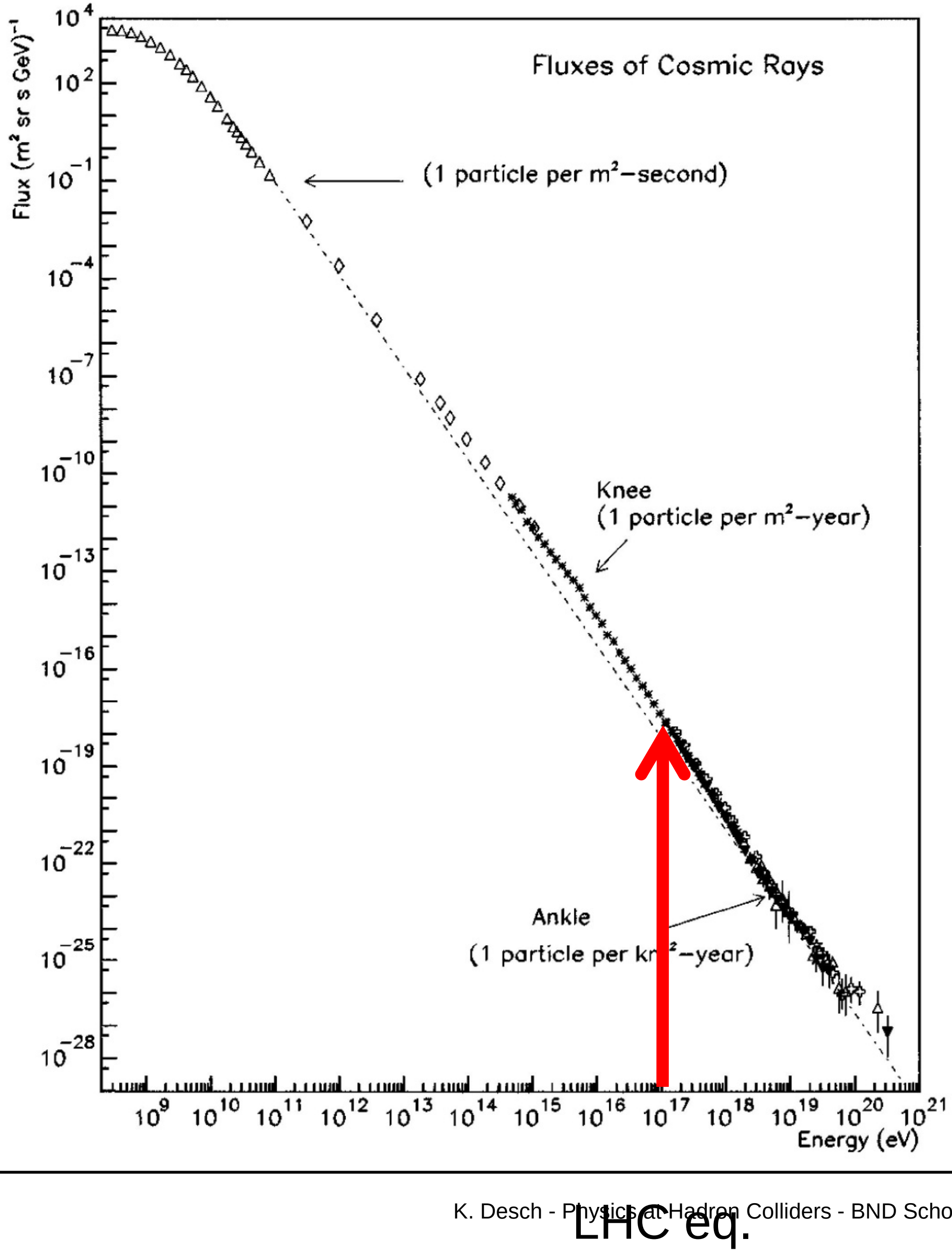
Relevant energy: centre-of-mass energy

→ colliders $E_{cm} = 2\ E_{beam}$

(fixed target: $E_{cm} = \sqrt{2(E_{beam}\ m_{target})}$)
would need 10^{17}eV (= 100000 TeV)
to have same c.m.s.
(+ cms system extremely boosted
in laboratory)



High energy accelerators vs. Cosmic Rays



Cosmics > 10^{17} eV:
o(10^{12}) particles / earth / year
~ 10 pb^{-1}

LHC:
10^{16} collisions / year

2. Basics

Rate of events for a given physics process with cross section σ:

$$N = L \cdot \sigma$$

units: $s^{-1} = cm^{-2}\, s^{-1} \cdot cm^2$

L = Luminosity

Luminosity depends on machine parameters:

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi\, \sigma_x\, \sigma_y}$$

#particles / bunch

repetition frequency
~ #colliding bunches

beam dimensions at IP

$L = 3.5 \cdot 10^{32}\ cm^{-2}\, s^{-1}$ peak luminosity reached at Tevatron Run II
$L = 10^{30} - 10^{32}\ cm^{-2}\, s^{-1}$ luminosity at LHC startup (1st year)
$L = 10^{33}\ cm^{-2}\, s^{-1}$ years 2-n of the LHC
$L = 10^{34}\ cm^{-2}\, s^{-1}$ LHC design luminosity (after n years)

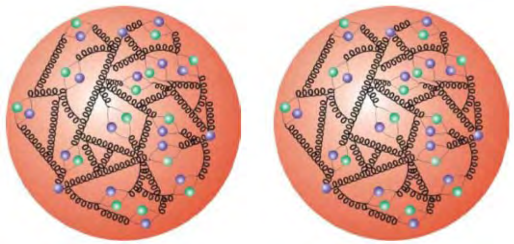
(1000 x larger than LEP-2, 30 x Tevatron Run II)

Integrated Luminosity per "year": $\int L dt = 10^7\ s * L$:

$L_{int/year} = L[cm^{-2}\, s^{-1}]/10^{32}\ fb^{-1}$

Experiments at high energy: Lepton vs. Hadron Collisions

Two complementary approaches

p  p

e^+ • • e^-

- easier to reach high energies

- p = composite particle
  unknown c.m.s. of initial system
  parasitic collisions

- p = strongly interacting
  huge SM backgrounds
  not possible to reconstruct all f.st.
  need highly selective trigger

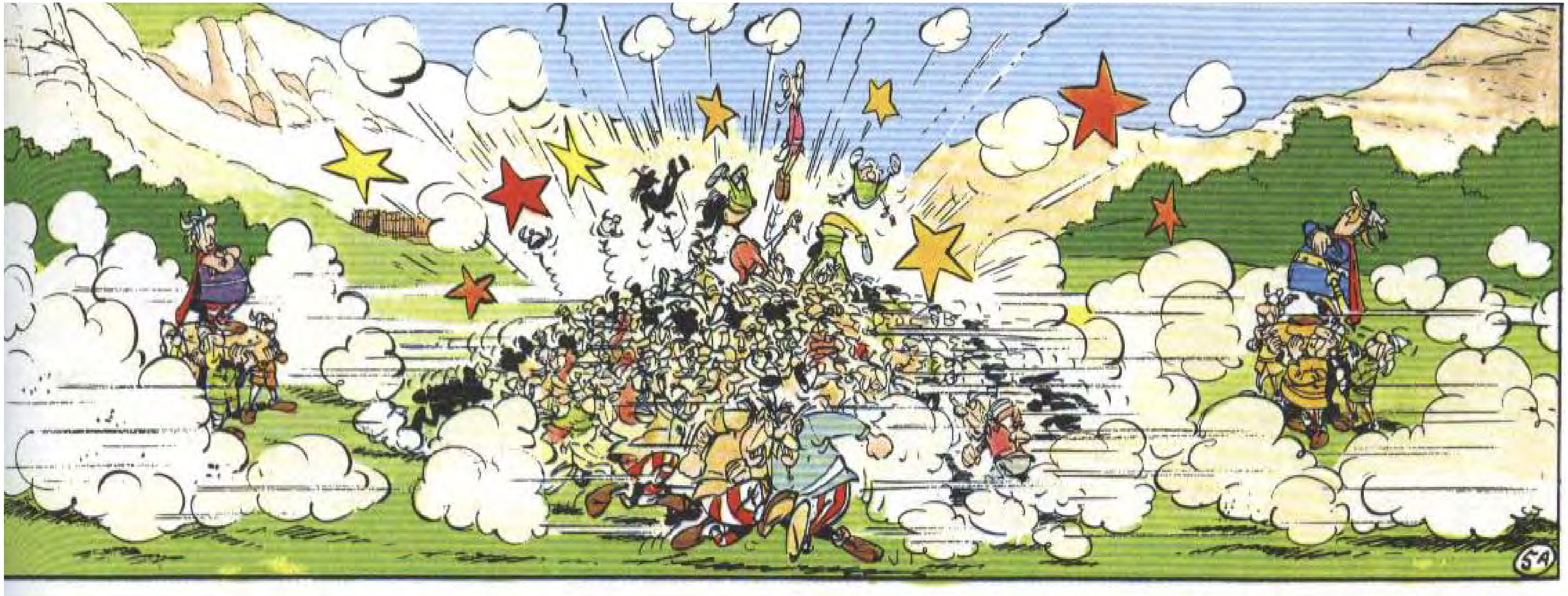
- difficult to reach high energies
  (synchrotron radiation)

- e = pointlike particle
  c.m.s. = lab system
  can use kinematic constraints

- e = electro-weakly interacting
  low SM backgrounds
  can reconstruct all final states
  no trigger needed!

2. Basics — Hadron – Hadron Collisions

Hadron Collisions are a big mess

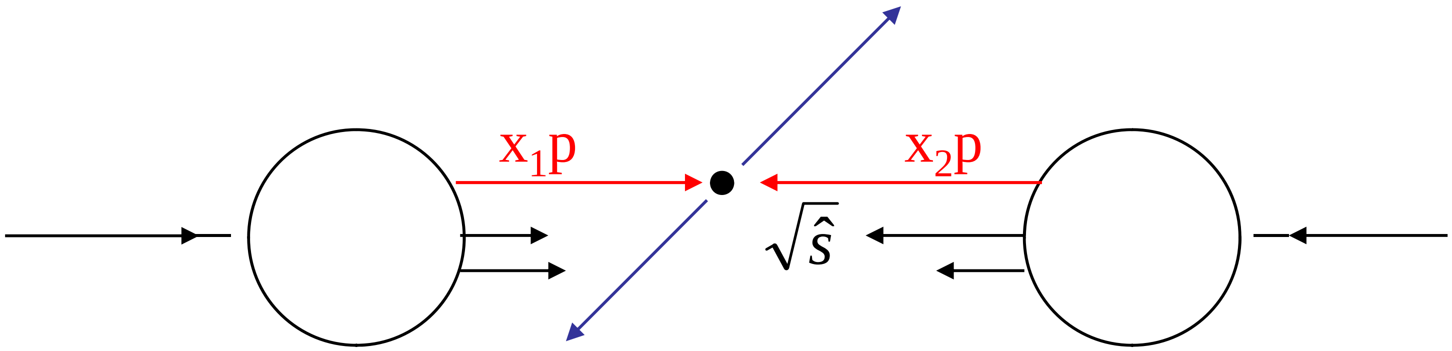


Idea stolen from K.Jakobs

why are we interested in that?

The (most) simplified view:

A fraction of the hadron-hadron-collisions contain a hard scattering process:



Collisions of two partons (with momentum fractions x_1, x_2) collide in a 2 → 2 (or 2→1, 2→3, …) scattering process at parton c.m.s. energy

If $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$ is large the partonic process

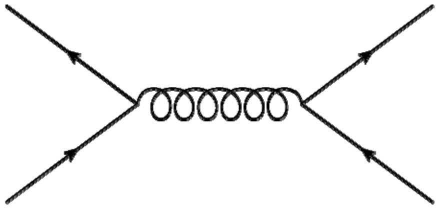
- can be calculated perturbatively
- dominates the observable final state
  (high p_T – process)

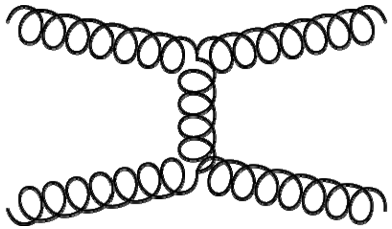
To produce a mass of:

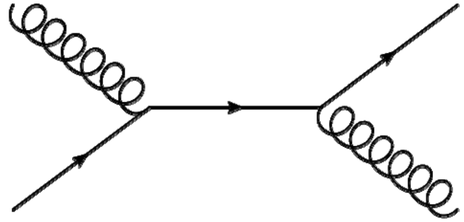
	LHC	Tevatron
100 GeV:	x ~ 0.007	0.05
5 TeV:	x ~ 0.36	--

Examples for hard scattering processes

QCD

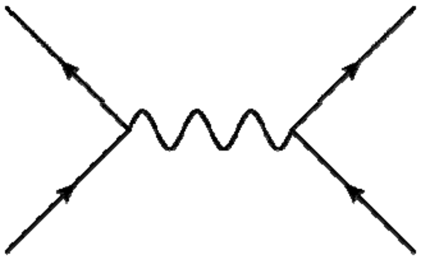


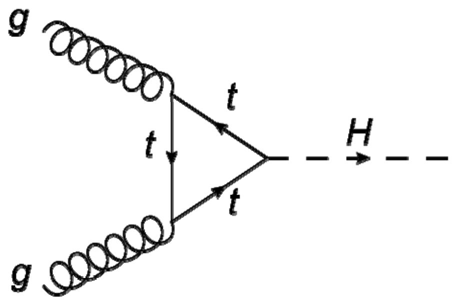




…

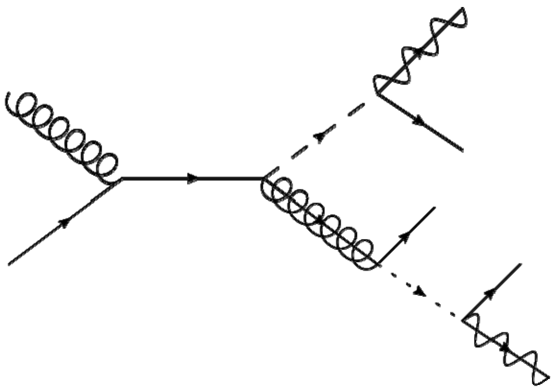
Electro-Weak





…

New Physics



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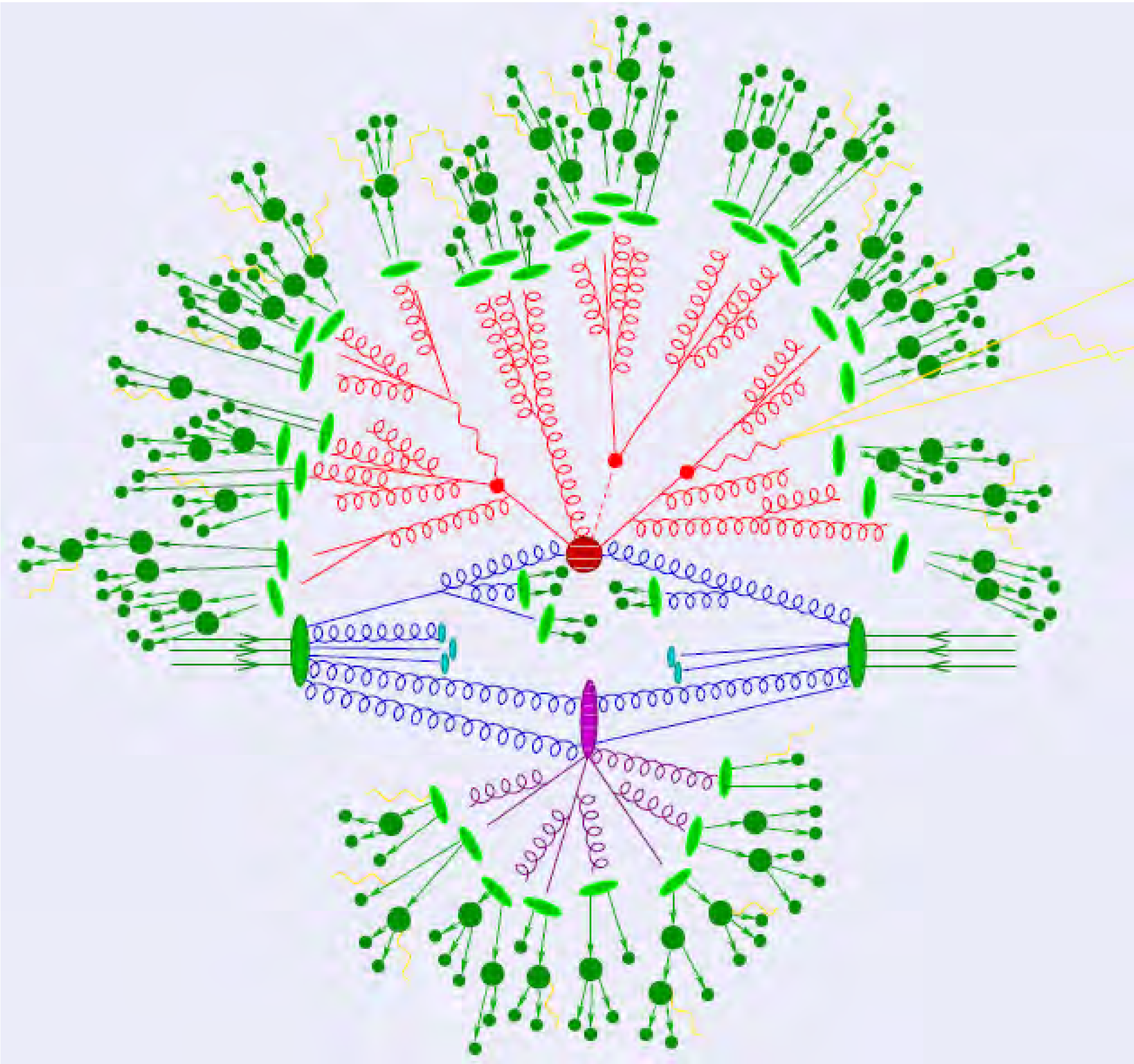


[Krauss]

Very complex process

Many approximations

→ MC Generators

→ data driven modelling

- hard scattering
- parton shower
- initial + final state rad.
- hadronisation
- hadron decays
- underlying event
  (multi-parton int.)

not shown:

virtual higher order correctionss

Higher orders are important (→ QFT)

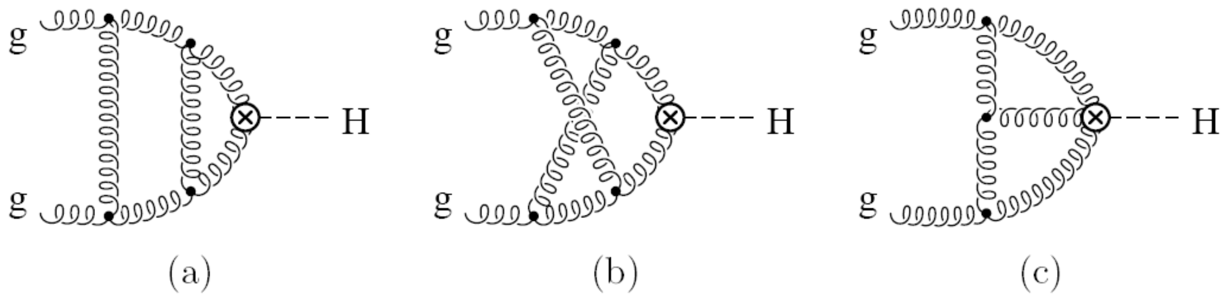
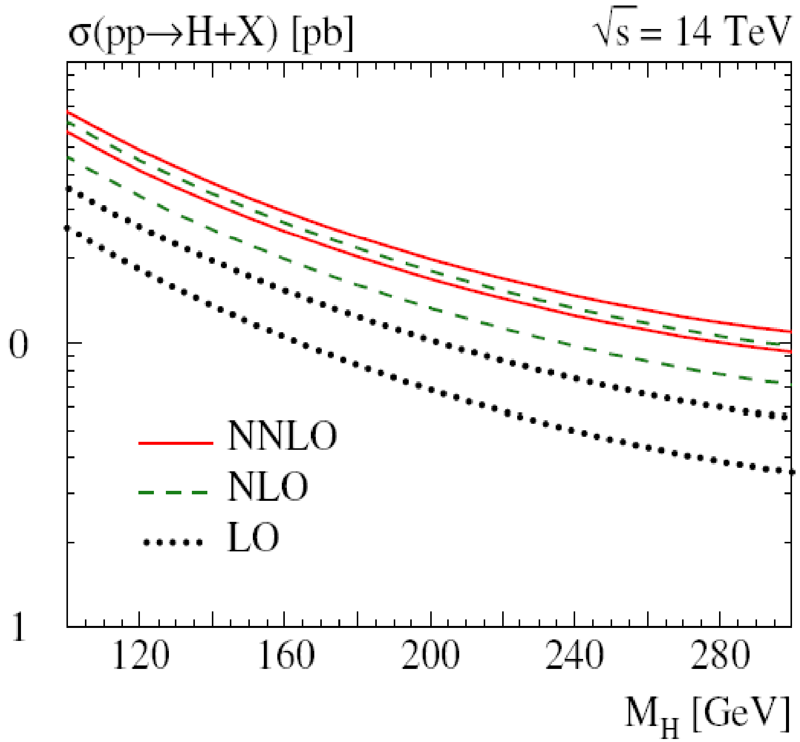
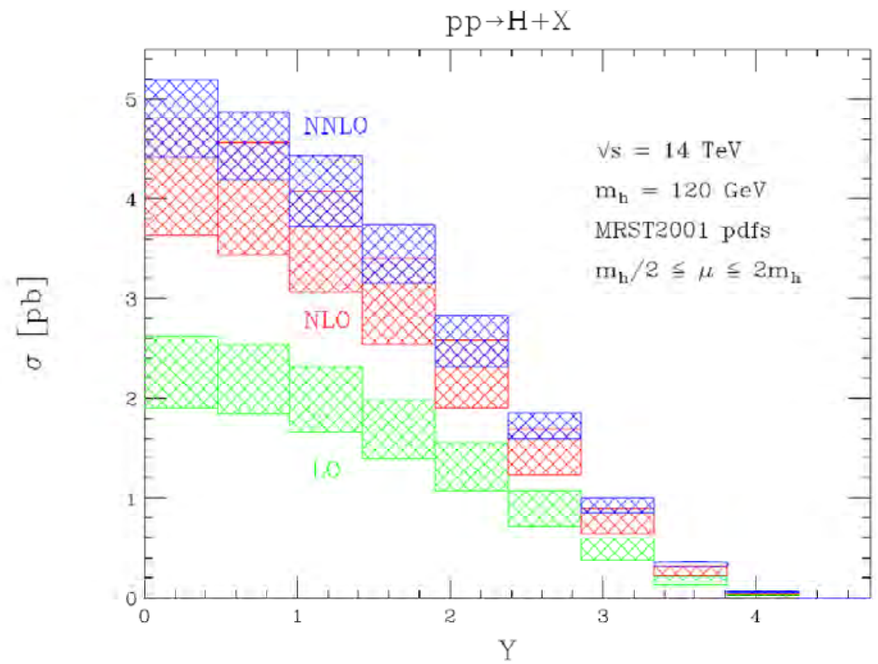


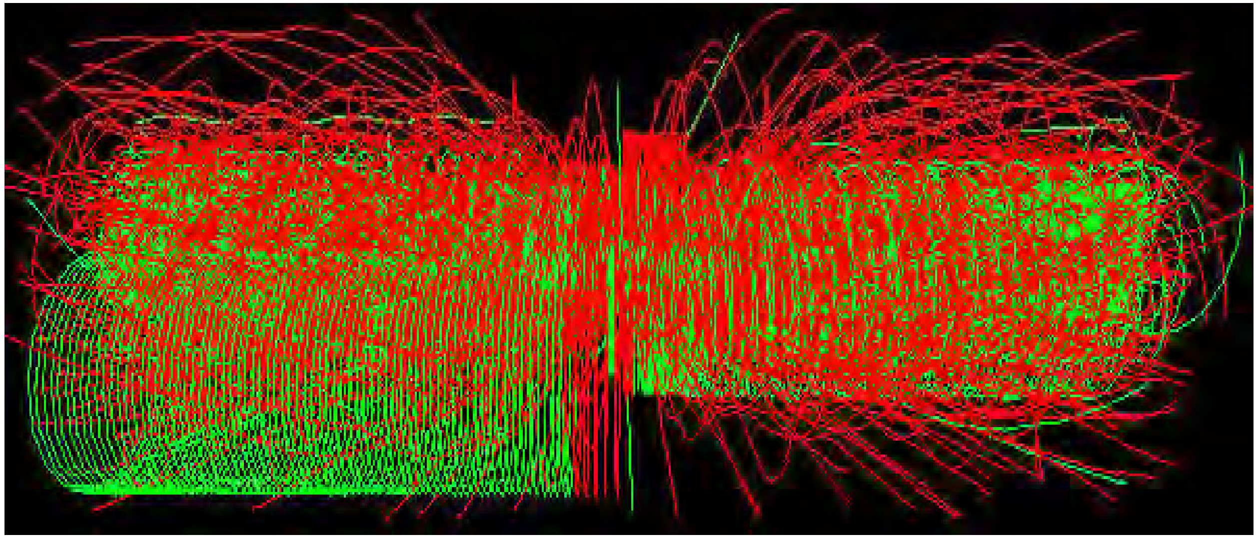
Figure 2: Sample two-loop diagrams contributing to the virtual corrections at NNLO.



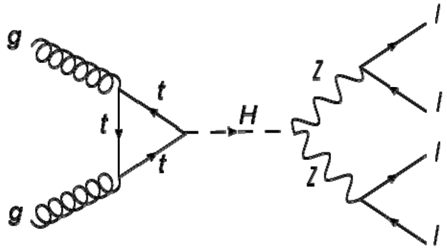


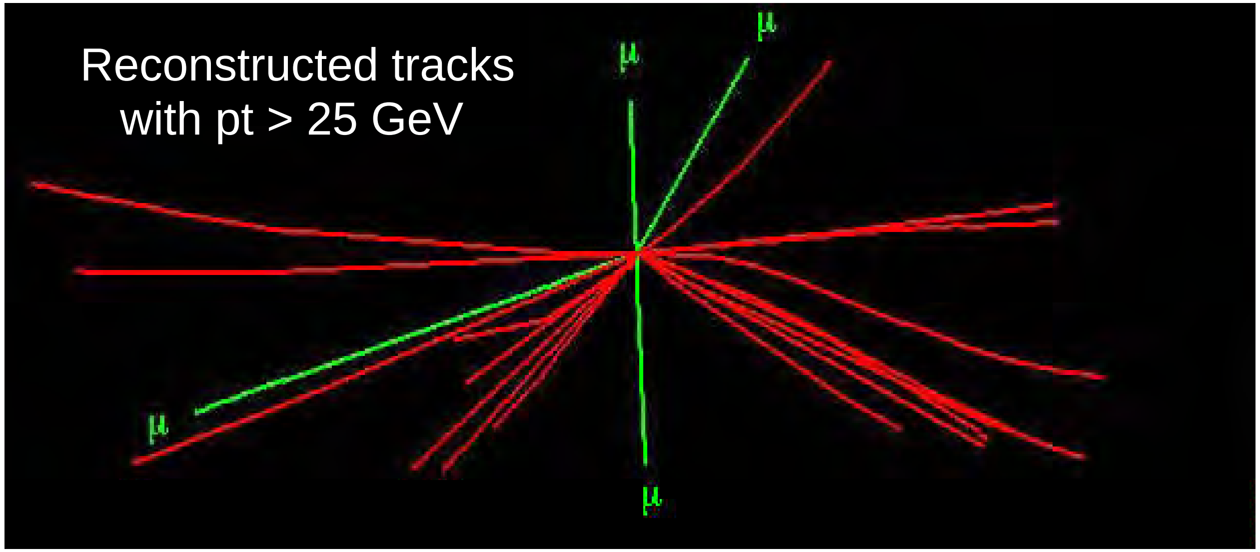
[Harlander,Kilgore]

A busy multi-particle event



can be revealed to be a „clean“





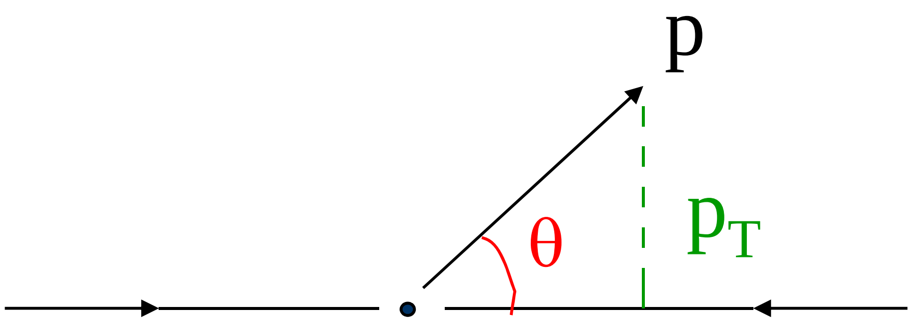
Higgs event after a p_T cut

note: it´s not always that simple…

c.m.s. of the hard scattering is unknown (even in the simple picture)
(x_1, x_2 unknown → unknown longitudinal momentum of parton system)

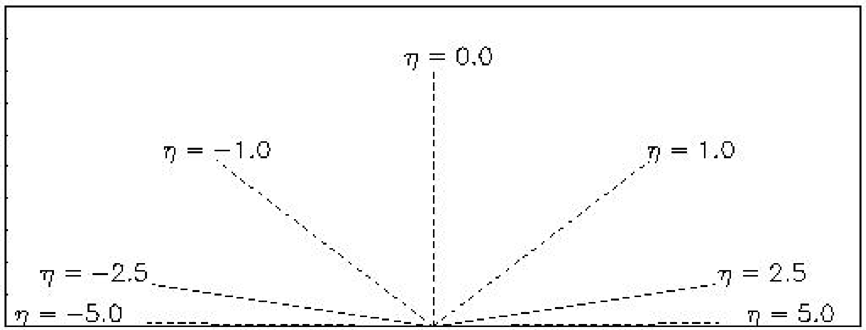
→ use variables which are insensitive to longitudinal boosts

Transverse momentum (invariant)



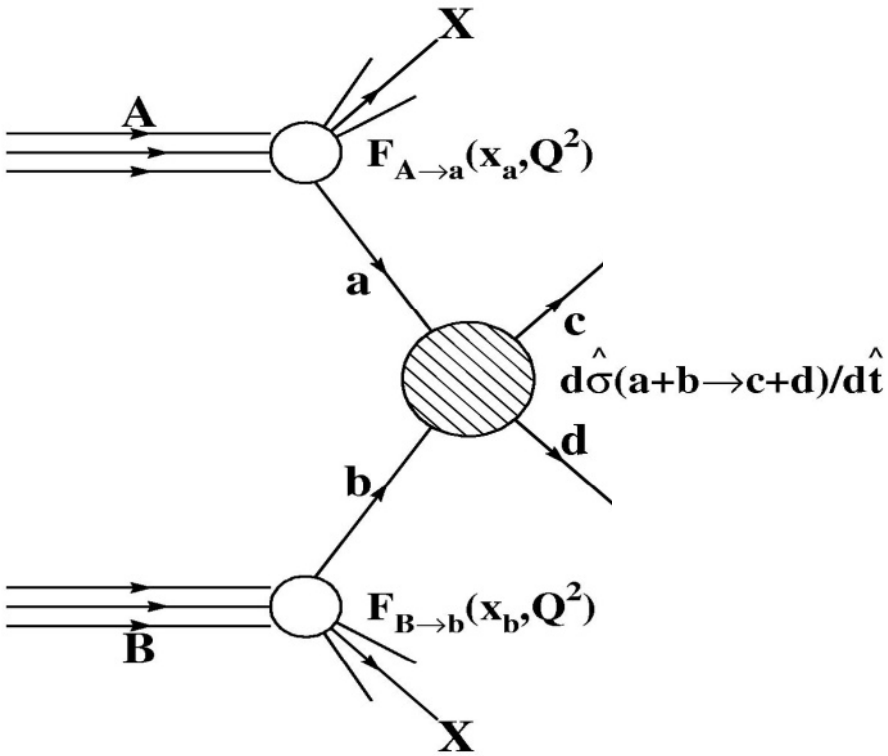
$$p_T = p \sin\theta$$

Pseudorapidity (differences are invariant)



$$\eta = -\ln \tan \theta/2$$

Cross section for hard processes



$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b) \, f_b(x_b, Q^2)$$

$\hat{\sigma}_{ab}(x_a, x_b)$: hard scattering (parton) cross section for $ab \to cd$

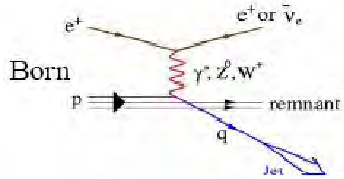
$f_a(x_a, Q^2), f_b(x_b, Q^2)$: parton density functions

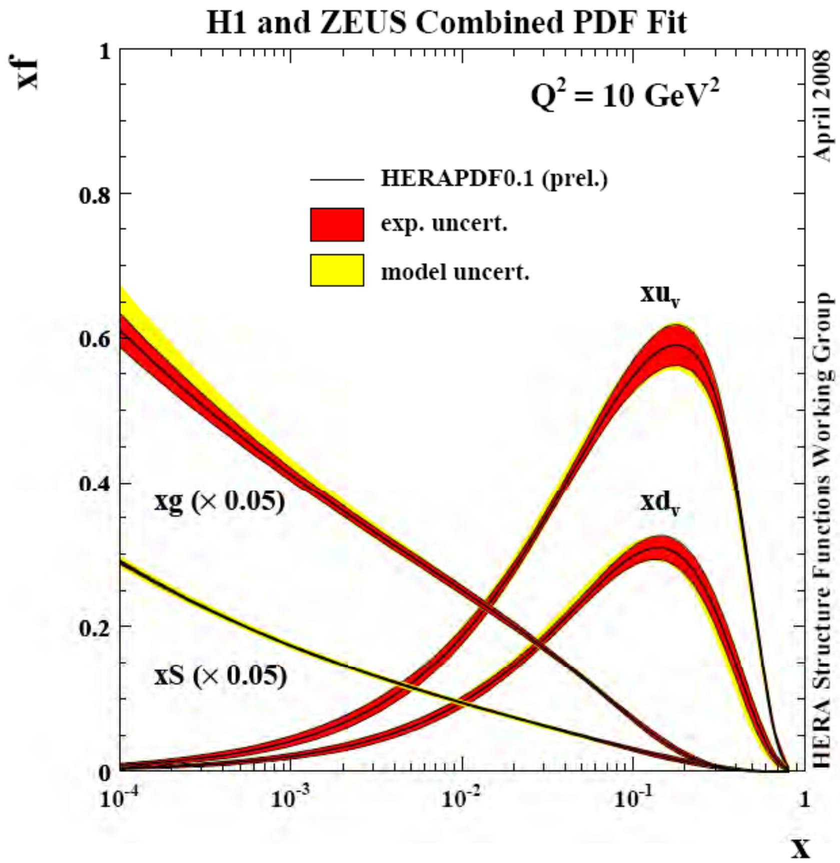
$a,b = q,\bar{q},g$

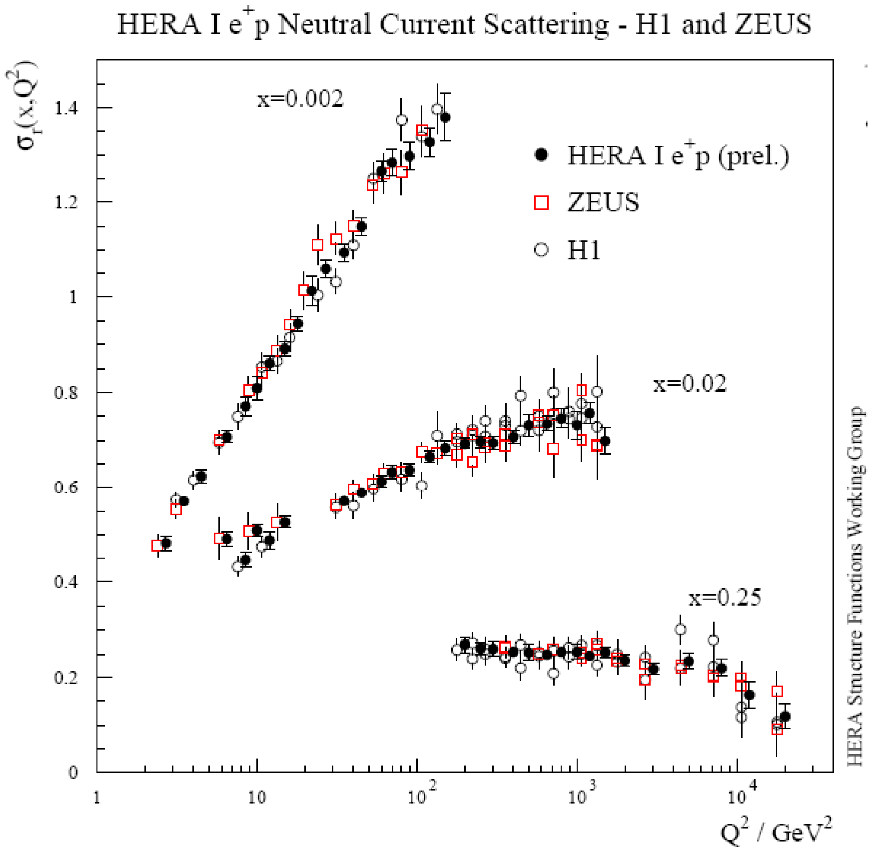
Q^2 : "energy scale" of hard process ($p_T, \hat{s}, \ldots$) not very well defined

2. Basics | Parton density functions

Have to be measured – mainly from deep inelastic scattering :
H1 & ZEUS at the HERA ep collider at DESY (1992-2007)







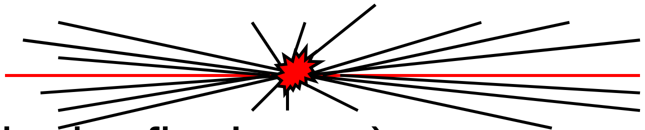
- Gluons dominate at low x
- Also (sea)quarks + antiquarks rise towards low-x for larger Q^2

Q^2 evolution follows DGLAP eqn.
→ can be extrapolated

Hard processes are only a tiny fraction of total cross section

Most interactions due to interactions at large distance between incom. protons

Small momentum transfer, particles in the final state have large longitudinal, but small transverse momentum



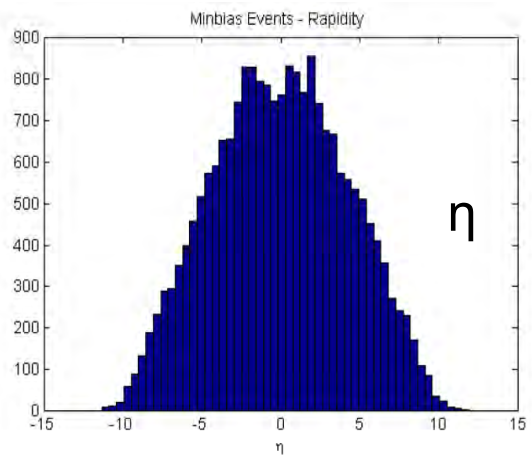
$$< p_T > \approx 600 \text{ MeV}$$ (of charged particles in the final state)

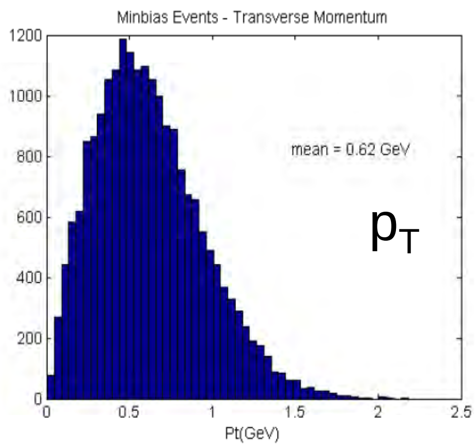
$$\frac{dN}{d\eta} \approx 7$$

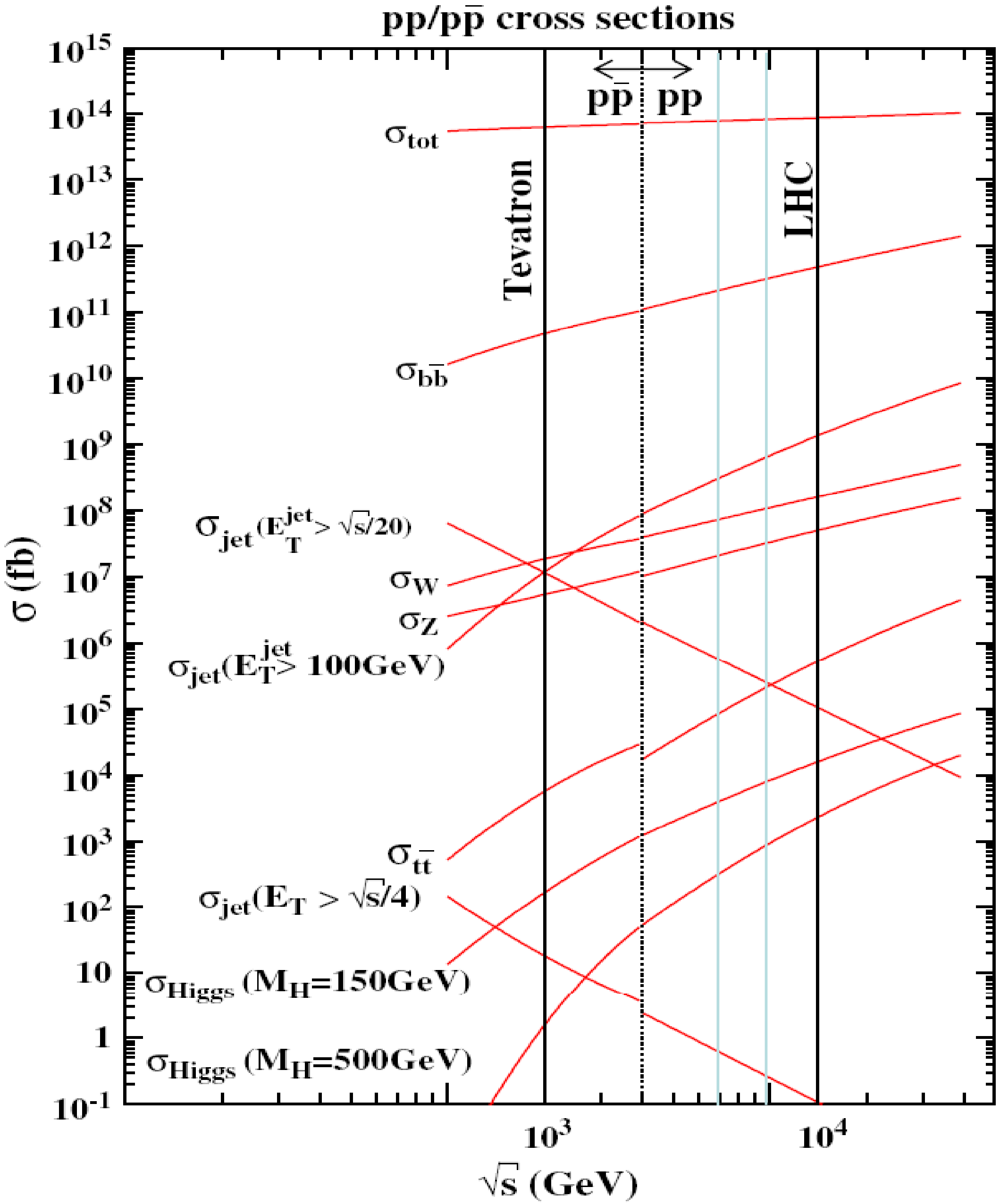
- about 7 charged particles per unit of pseudorapidity in the central region of the detector
- uniformly distributed in Φ

These events are called "Minimum-bias events"

They dominate the total rate
Their properties cannot be calculated from pQCD!
Need to be measured







„Interesting“ cross sections highly suppressed w.r.t. σ_{tot} or even σ_b

But huge rates:

- min. bias 10^9 Hz

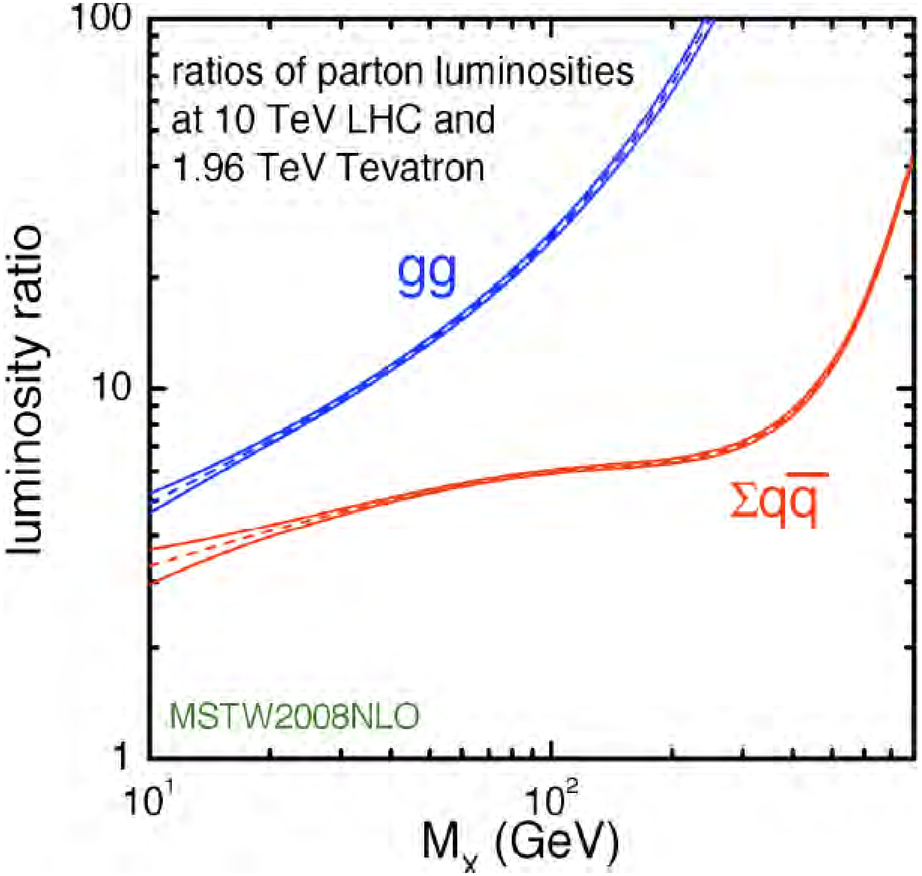
- bb pairs $5\ 10^6$ Hz
- tt pairs 8 Hz

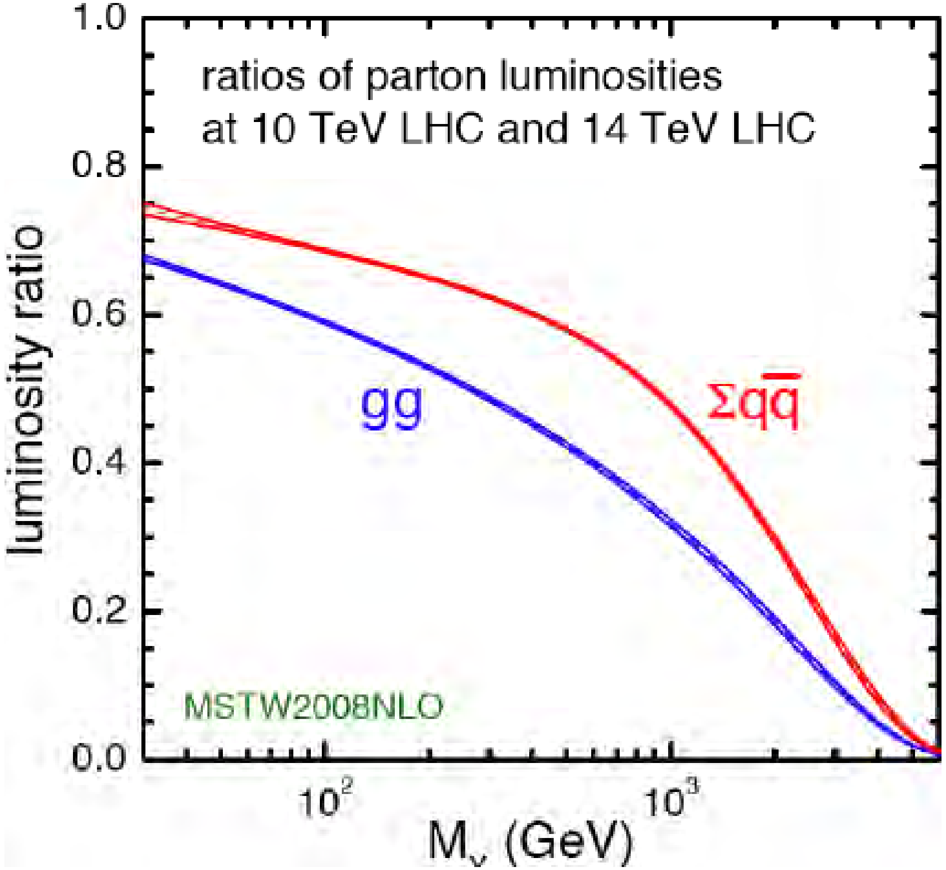
- W $\rightarrow$ e ν 150 Hz
- Z $\rightarrow$ e e 15 Hz

- Higgs (150 GeV) 0.2 Hz
- SUSY (1 TeV) 0.03 Hz

2. Basics

Parton Luminosities



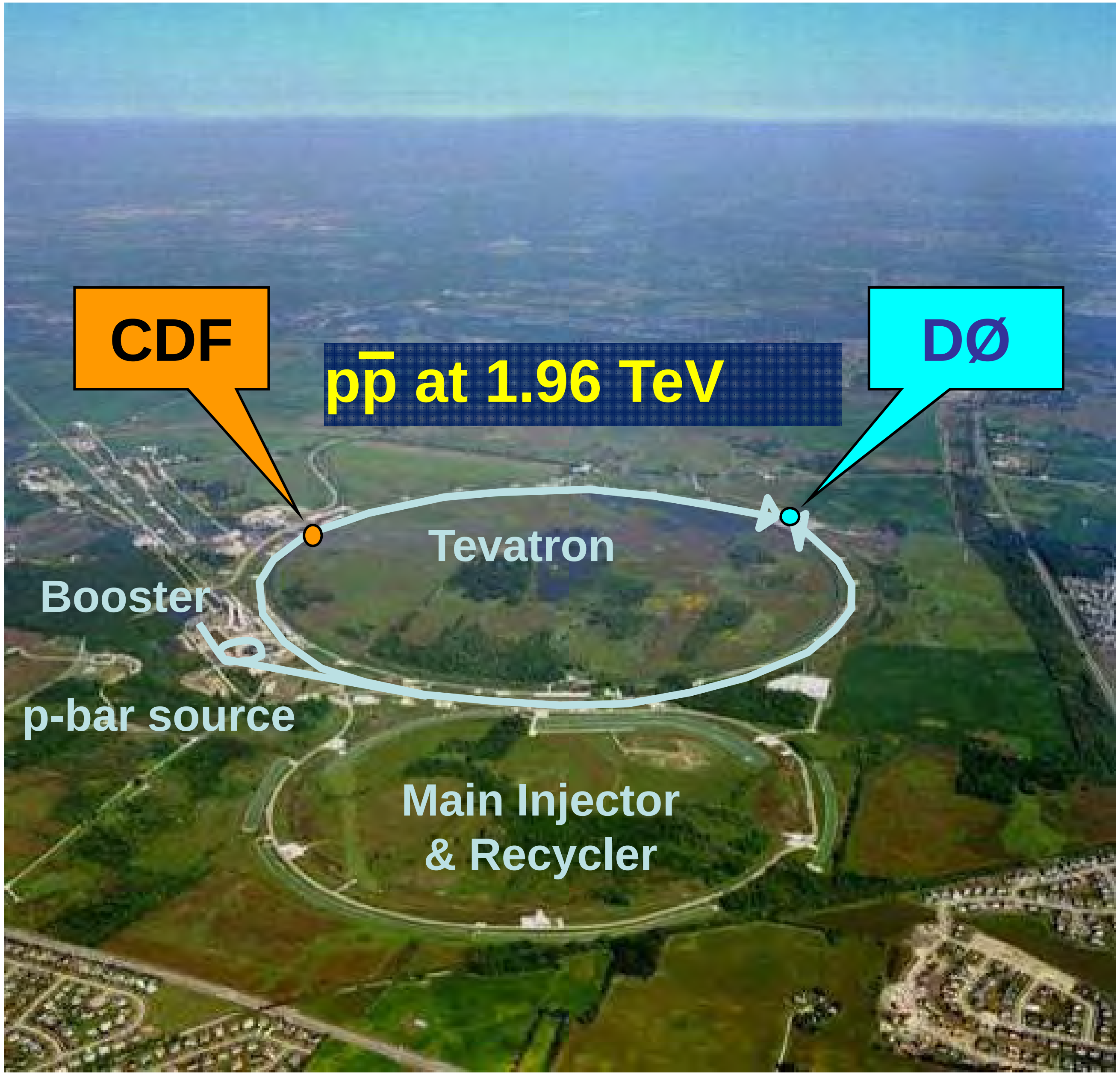


[Stirling]

End of Day1

3. Colliders

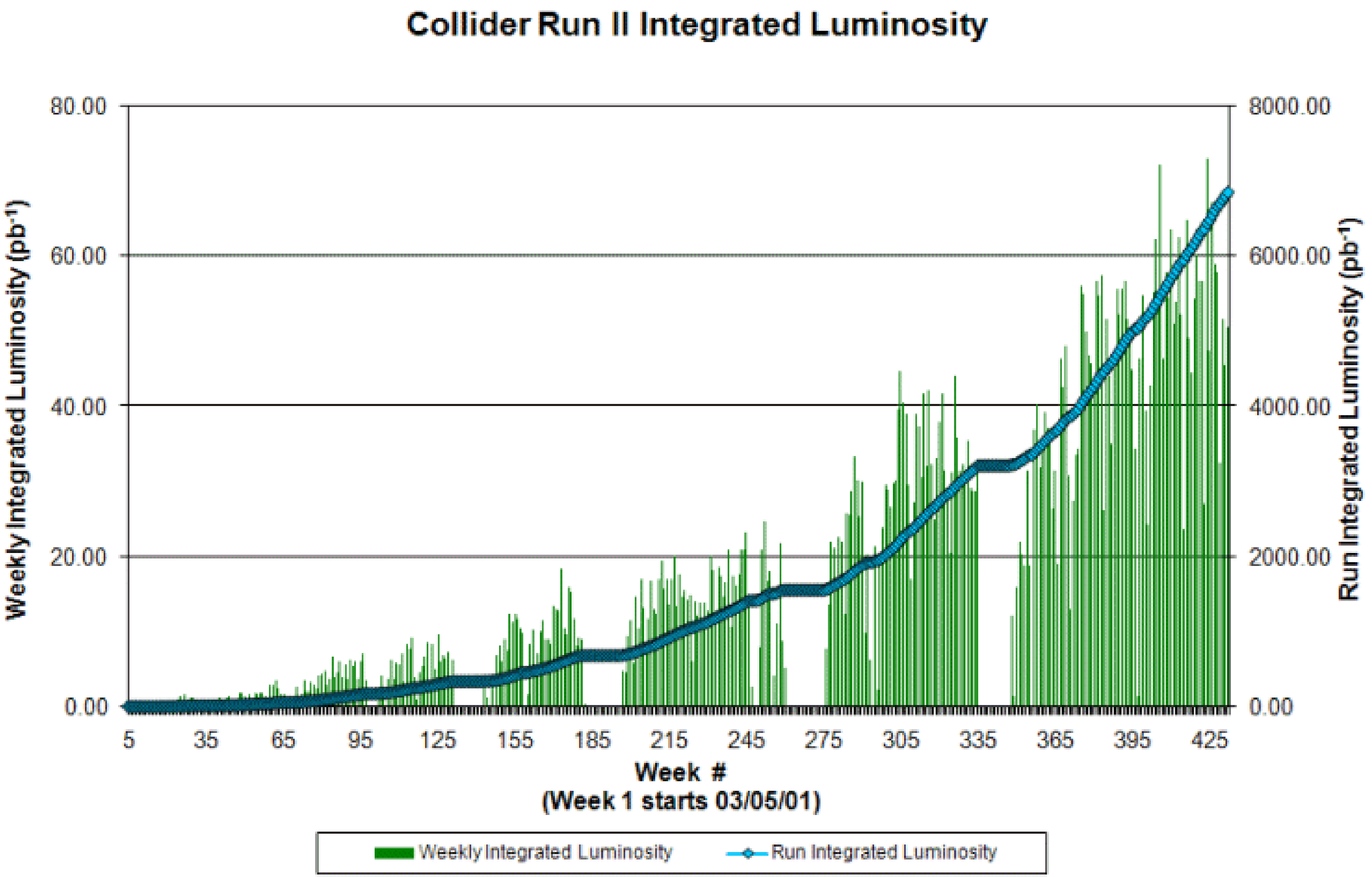
(very short)



- Proton-<u>Anti</u>proton

Pro:
Annihilation processes with valence quarks (high x → large $\sqrt{s'}$)
Con:
Antiproton production + recycling tedious (limits luminosity)

- 36x36 bunches
- bunch crossing 396 ns
- Run II started in March 2001



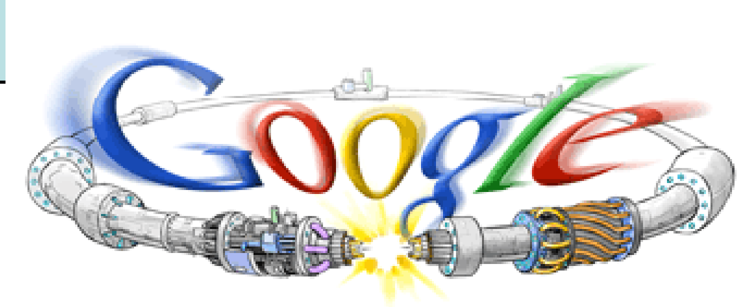
- Peak Luminosity: 3.5×10^{32} cm^{-2} s^{-1}
- Run II delivered: ~7 fb^{-1}

Run II Goal: 12 fb^{-1} by end of 2011

note: most analyses by now only use 50% or less of recorded data

The Large Hadron Collider LHC

Proton - Proton
Design beam energy 7 TeV
Design luminosity 10^{34} cm^{-2}s^{-1}
Bunch spacing 25 ns
Particles/Bunch 10^{11} x 2808 bunches
SC Dipoles 1232, 15 m, 8.33T
Stored Energy 350 MJ/Beam
Stored Energy (magnets) 10 GJ
(10 GJ melt 24 tons of Cu)



Sept 10, 2008: first beam day

Sept 10-12, 2008: very successful commissing - „feels like an old friend“ (L. Evans)

beam life times ~ hours!

Sept 19, 2008: electrical connection between two magnets („busbar“) in S34 had too high R (200 nΩ instead of 0.3 nΩ) produced too much heat → SC quench → more heat → melting connection → insulation vacuum damaged → LHe into vacuum → mechanical damage, 400 MJ dissipated, 6t He into tunnel

June 2, 2009 39 dipoles and 14 quadrupoles repaired/replaced, electrical connection finished

improved diagnostics, many measurements, add. pressure realease valves, improved mech. anchoring, enhanced quench protection system: avoid reoccurence!

[Burkhardt LP09]

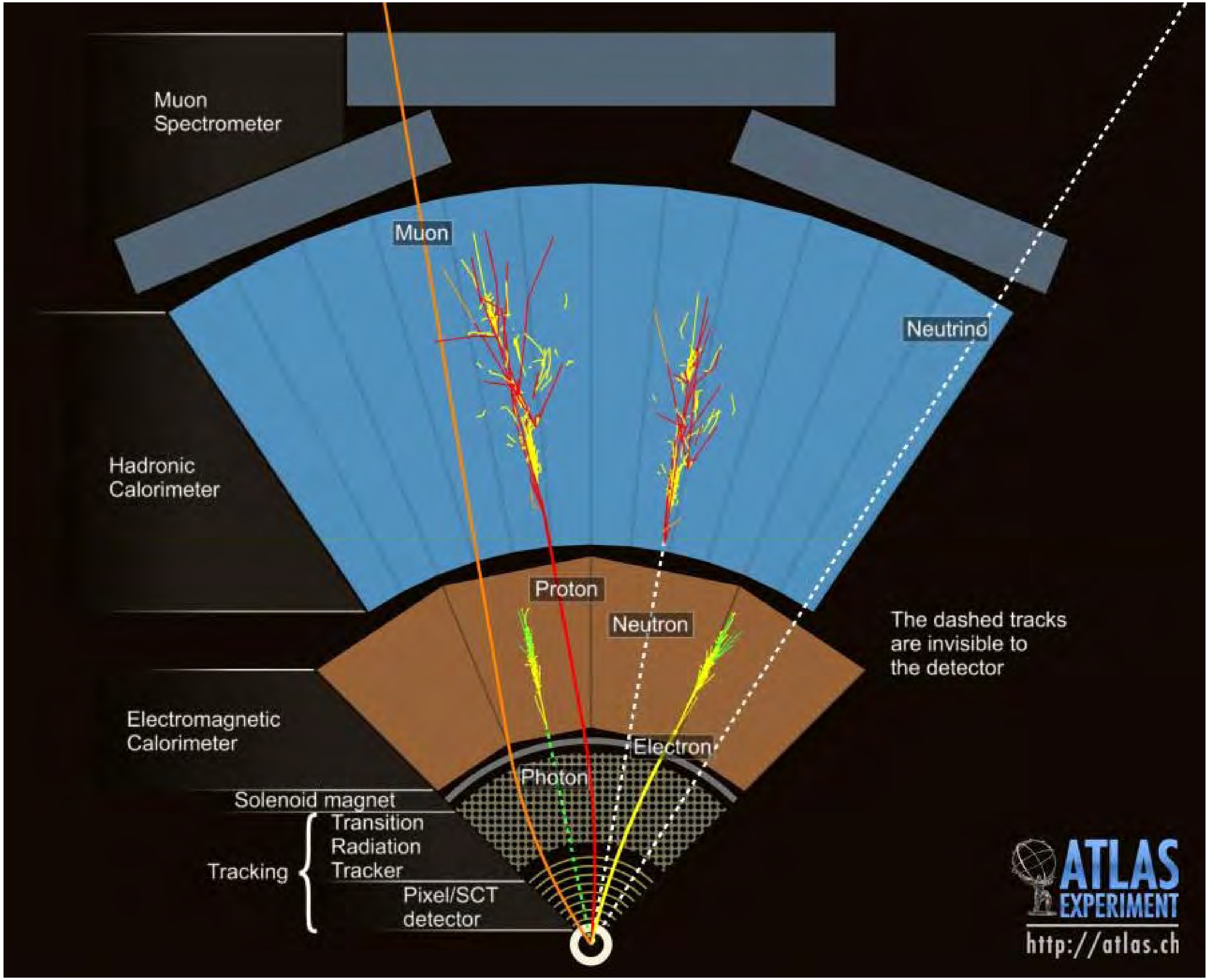
Restart with beam planned in mid-November (long run until end 2010)
Collisions at injection energy 2 × 0.45 TeV = 0.9 TeV
2. physics run at 2 × 3.5 TeV = 7 TeV
3. physics run at increased energy, max. 2 × 5 TeV = 10 TeV (H.Ions end 2010)
Luminosity?

		No crossing angle						Crossing angle				
Energy	TeV	0.45	0.45	3.50	3.50	3.50	3.50	3.50	3.50	4.00	5.00	7.00
Bunch intensity	1.E+10	1	4	4	4	4	9	9	9	9	9	11.5
Bunches		4	43	43	43	156	156	702	1404	2808	156	2808
Emittance	µm	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
β*	m	11	11	11	2	2	2	3	3	3	2	1
Luminosity	$cm^{-2} s^{-1}$	4.2E+26	7.2E+28	5.6E+29	3.1E+30	1.1E+31	5.6E+31	1.7E+32	3.3E+32	7.7E+32	8.0E+31	1.0E+34
Protons		4.0E+10	1.7E+12	1.7E+12	1.7E+12	6.2E+12	1.4E+13	6.3E+13	1.3E+14	2.5E+14	1.4E+13	3.2E+14
% nominal		0.0	0.5	0.5	0.5	1.9	4.3	19.6	39.1	78.3	4.3	100.0
Stored energy	MJ	0.0	0.1	1.0	1.0	3.5	7.9	35.4	70.8	161.7	11.2	361.7
Monthly (0.2)	pb-1	0.00	0.04	0.29	1.59	5.76	29.16	85.84	171.67	399.85	41.65	5231.88
Physics month				1	2	3	4	?	?	?	?	
Pile-up, σ_{in} = 75 mb				0.09	0.5	0.5	2.4					

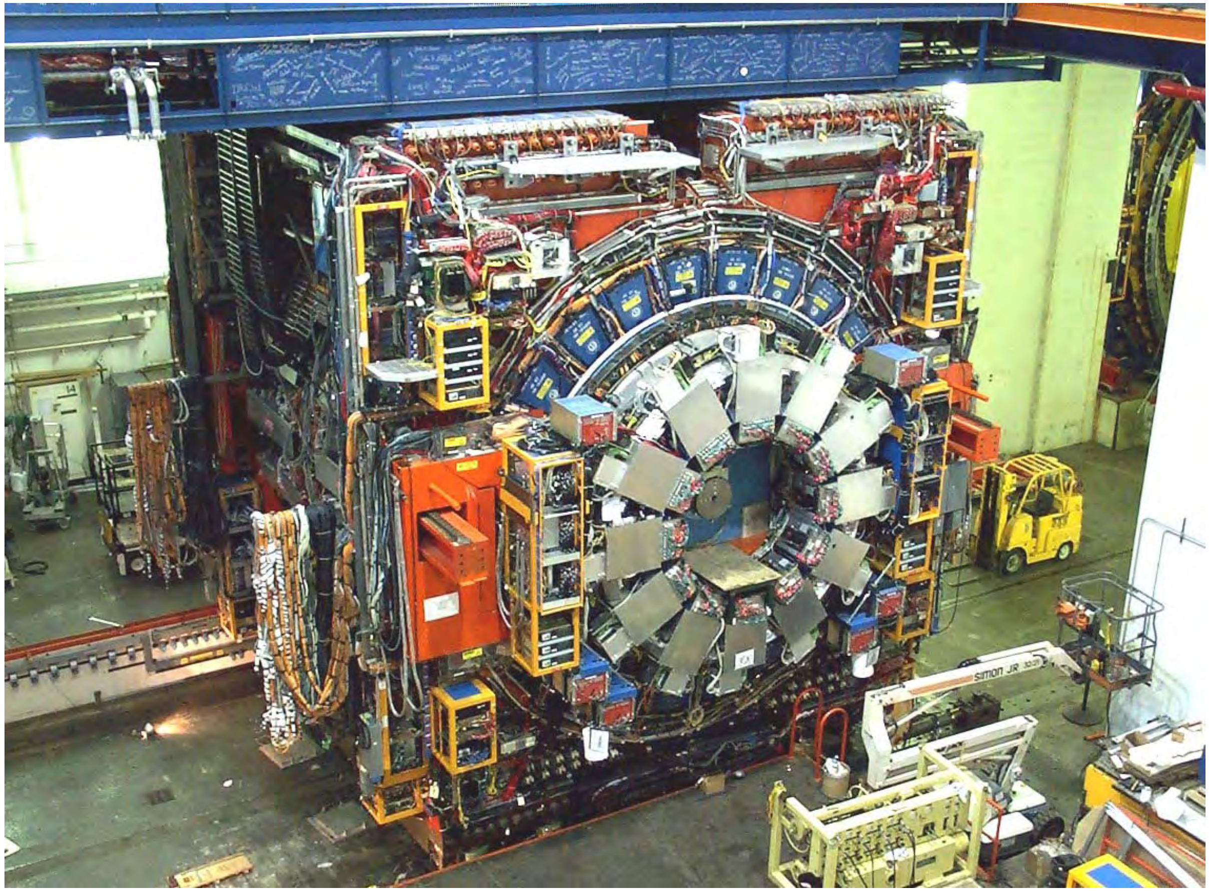
[Burkhardt LP09]

4. Detectors

Detection Principles



4. Detectors | CDF @ Tevatron



New in Run II :

Tracking system

Silicon vertex detector (SVXII)
Intermediate silicon layers
Central outer tracker (COT)

End plug calorimeter
Time of flight system

Front-end electronics
Trigger and DAQ systems

12 countries, 59 institutions
706 physicists

19 countries, 83 institutions

664 physicists

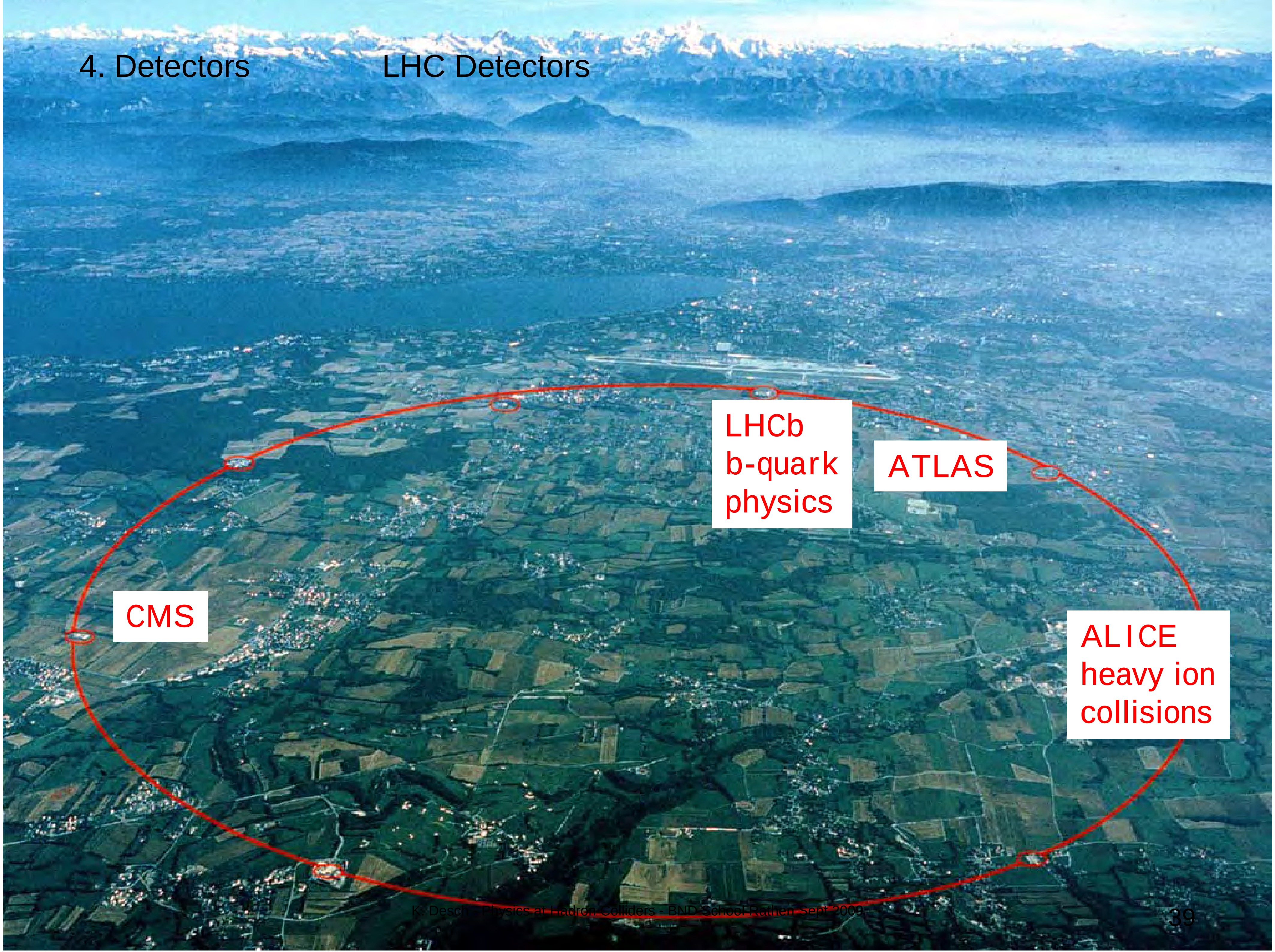
New for Run II

Inner detector
magnetic field added

Preshower detectors
Forward muon detector

Front-end electronics
Trigger and DAQ

LHC Detectors



Principles of particle detection + Overall structure similar to previous detectors (LEP, HERA, Tevatron) - BUT

Specific challenges at LHC

- Huge absolute collision rate (25 ns, up to 40 minimum bias events per BX)
  → fast detectors (identifiy each bunch crossing)
  → radiation hardness (tolerate up to 10^{17} n/cm^2 trackers: 10^{14} n/cm^2)
  → high granularity (handle pile-up)
  → trigger (suppress to 10^{-7} of input), DAQ, reconstruction, analysis

- Small Signal/Background ratio
  e.g. $\sigma_{Higgs}/\sigma_{tot} \sim 10^{-9}$ - visible σ_{Higgs} even smaller
  → very powerful object identification / jet background suppression needed
  → mass reconstruction of leptonic/photon (H,Z) and jet (top→bqq) objects

- Higher energies than previously
  → large B-Field (→ tracking up to 3-5 TeV)
  → larger calorimeters (→ containment of had. showers → muon ID)

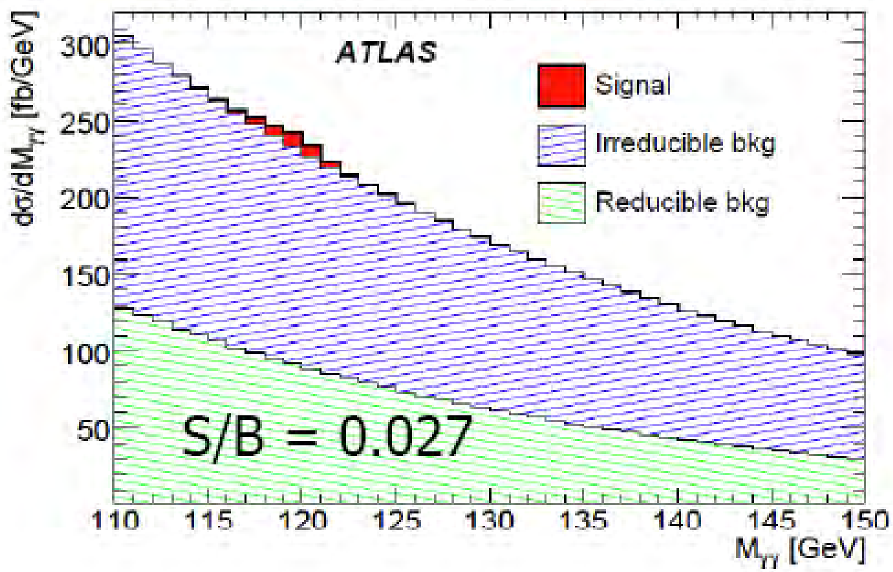
Physics object identification – suppression of QCD jets

Object	Efficiency	BG suppr.	Motivation
electrons	>70%	100000	Z,W,top,H→4ℓ,...
photons	80%	1000	H→γγ
muons	>97% for p_T>1GeV		H→4ℓ,...
tau leptons	50%	100	H/A→ττ, SUSY,…
b-jets	50%	100	top, H→bb,SUSY,…

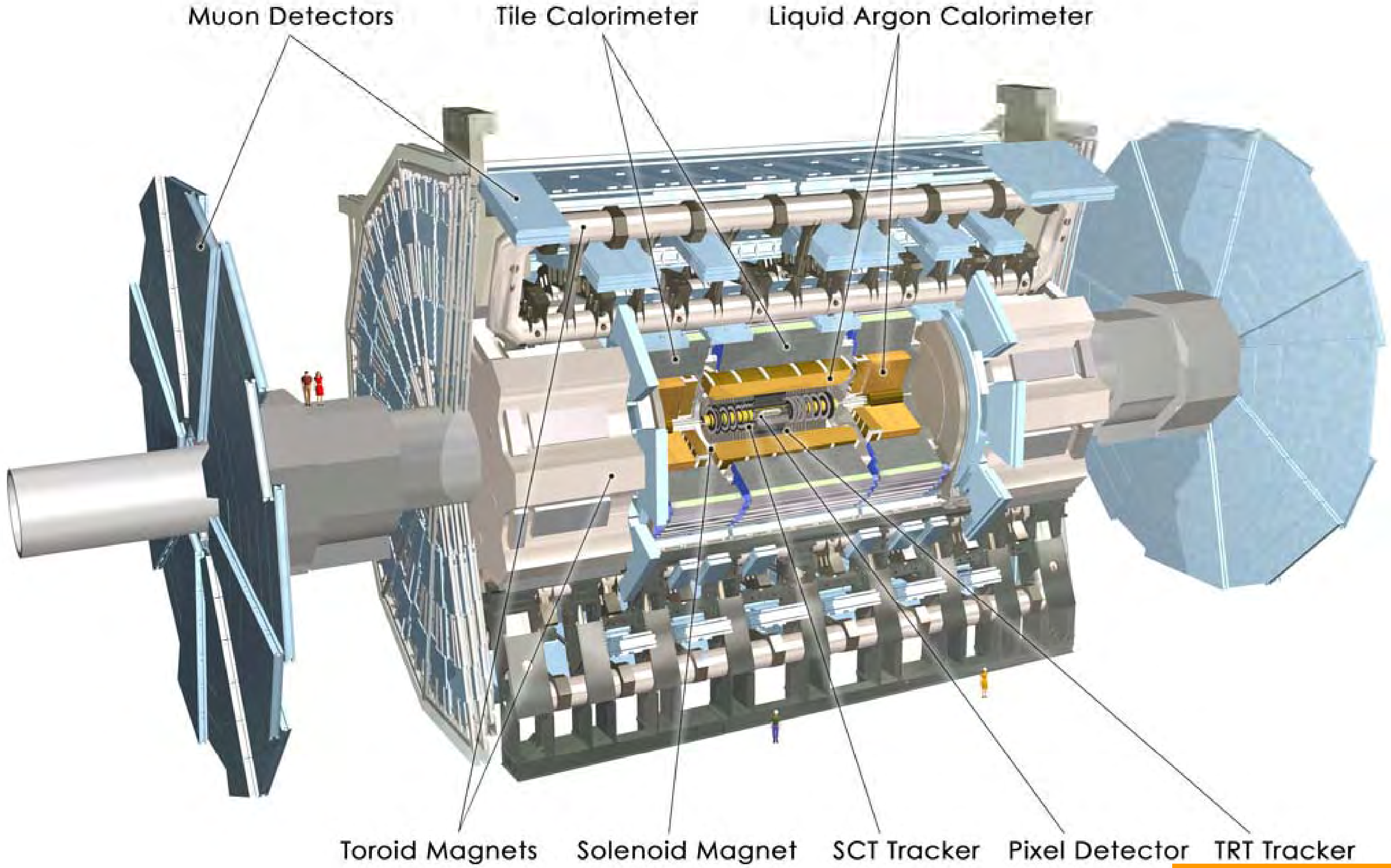
Mass resolution (calorimetric)
(to suppress ~flat backgrounds)

Photons, Electrons: 1%
(H→γγ, high mass resonances)

B-Jets, Jets: 10%
W, top, high mass resonances



The ATLAS Experiment

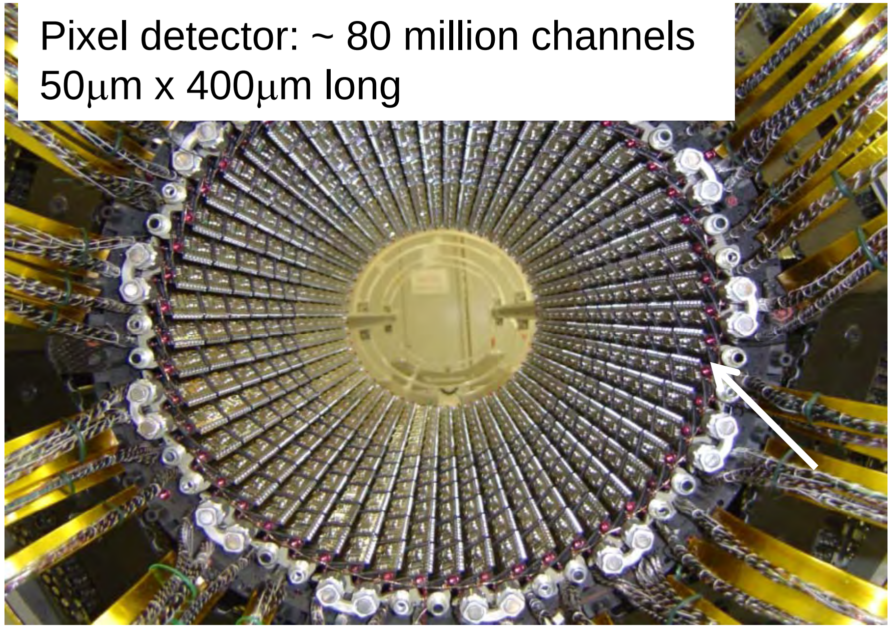


Diameter	25 m
Barrel toroid length	26 m
Total length	46 m
Overall weight	7000 t

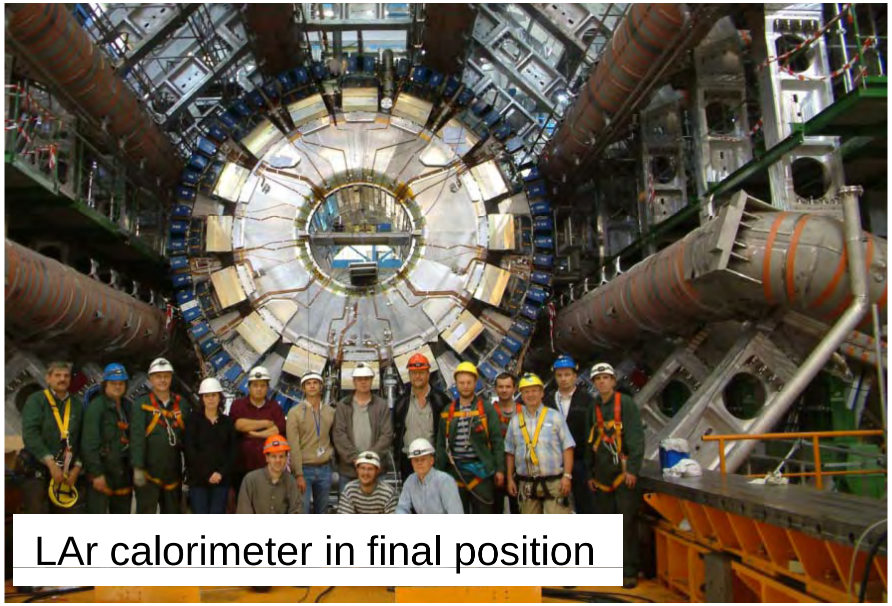
~2800 physicists
169 institutions
37 countries
5 continents

SC Toroid: installation of last coil

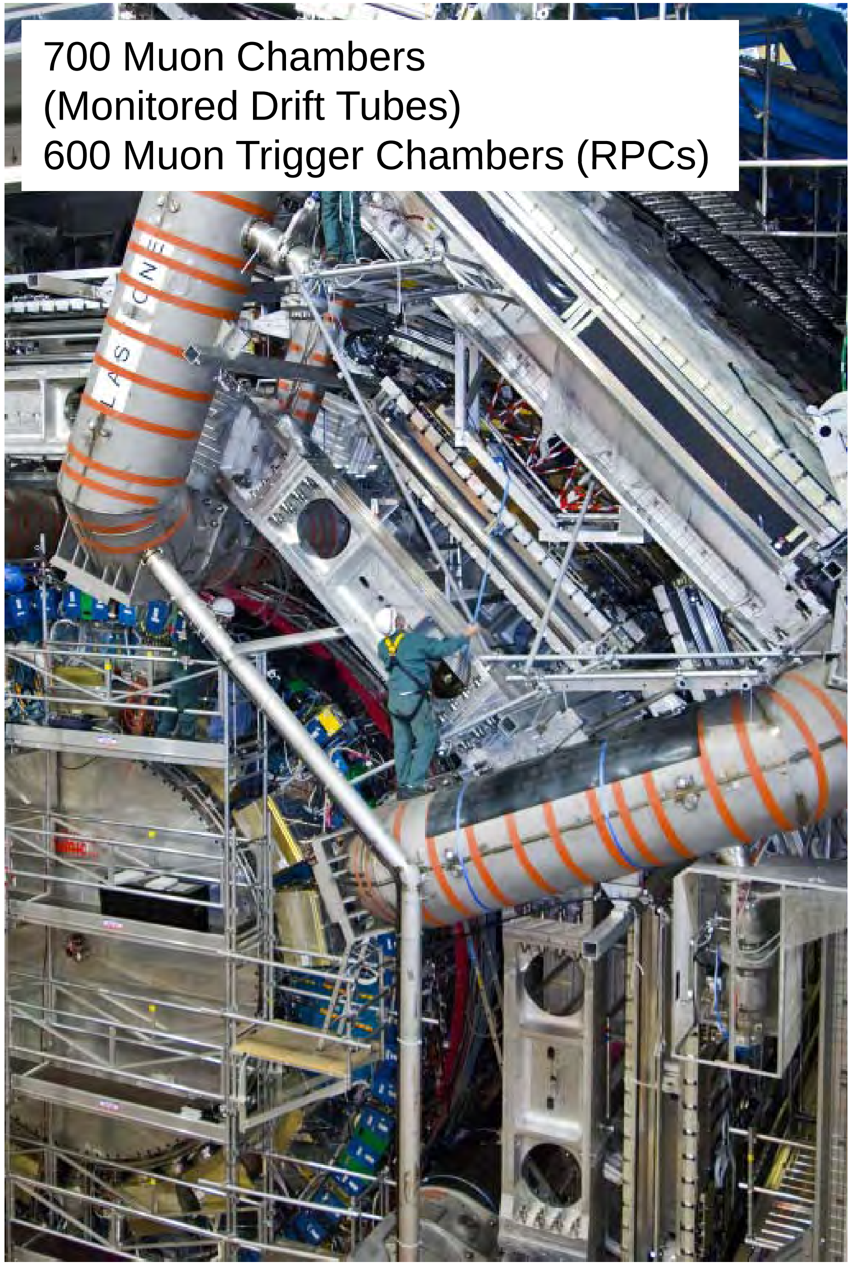
4. Detectors — The ATLAS Experiment



Pixel detector: ~ 80 million channels
50μm x 400μm long

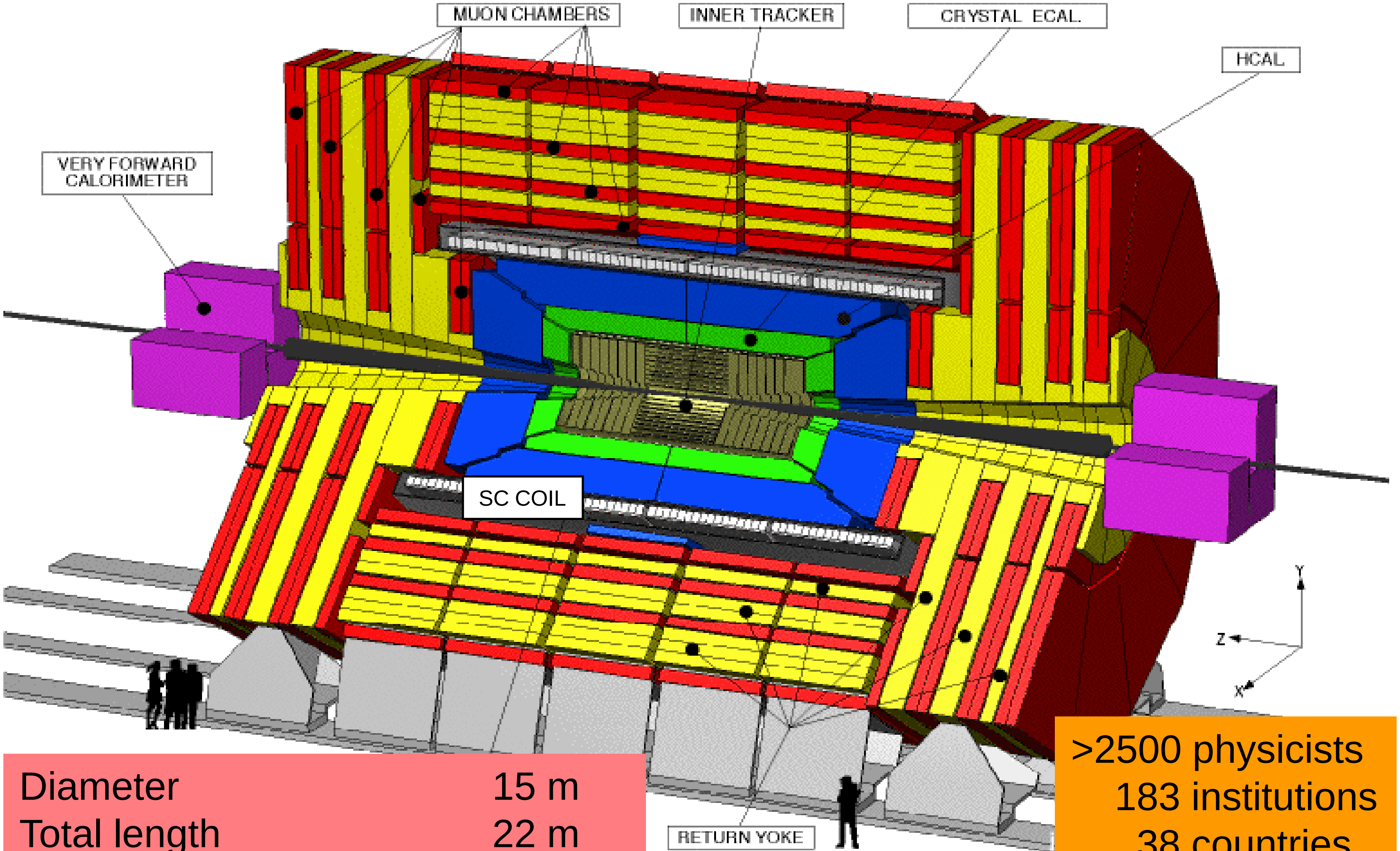


LAr calorimeter in final position



700 Muon Chambers
(Monitored Drift Tubes)
600 Muon Trigger Chambers (RPCs)

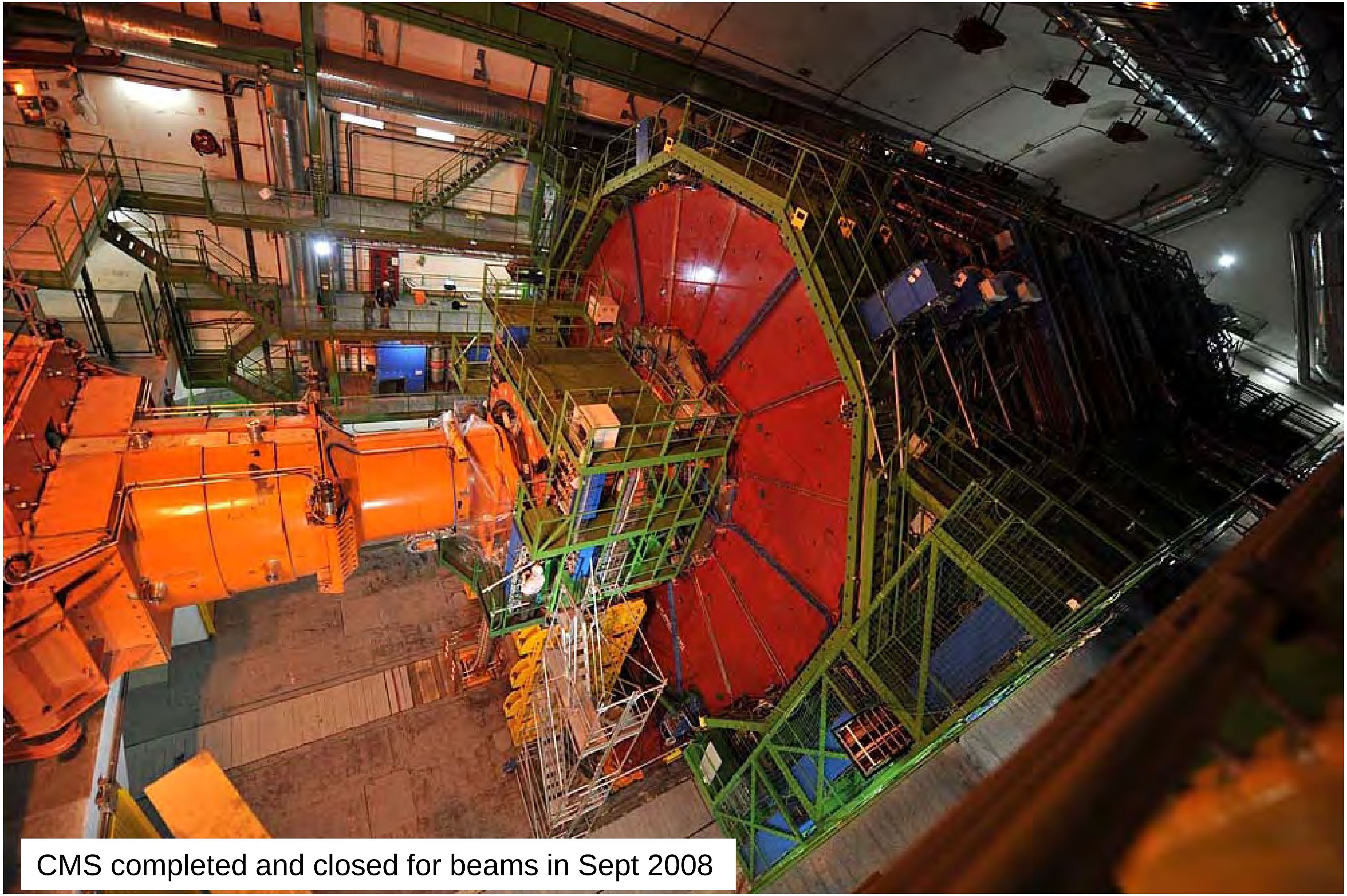
The CMS Experiment



Diameter	15 m
Total length	22 m
Overall weight	12500 t

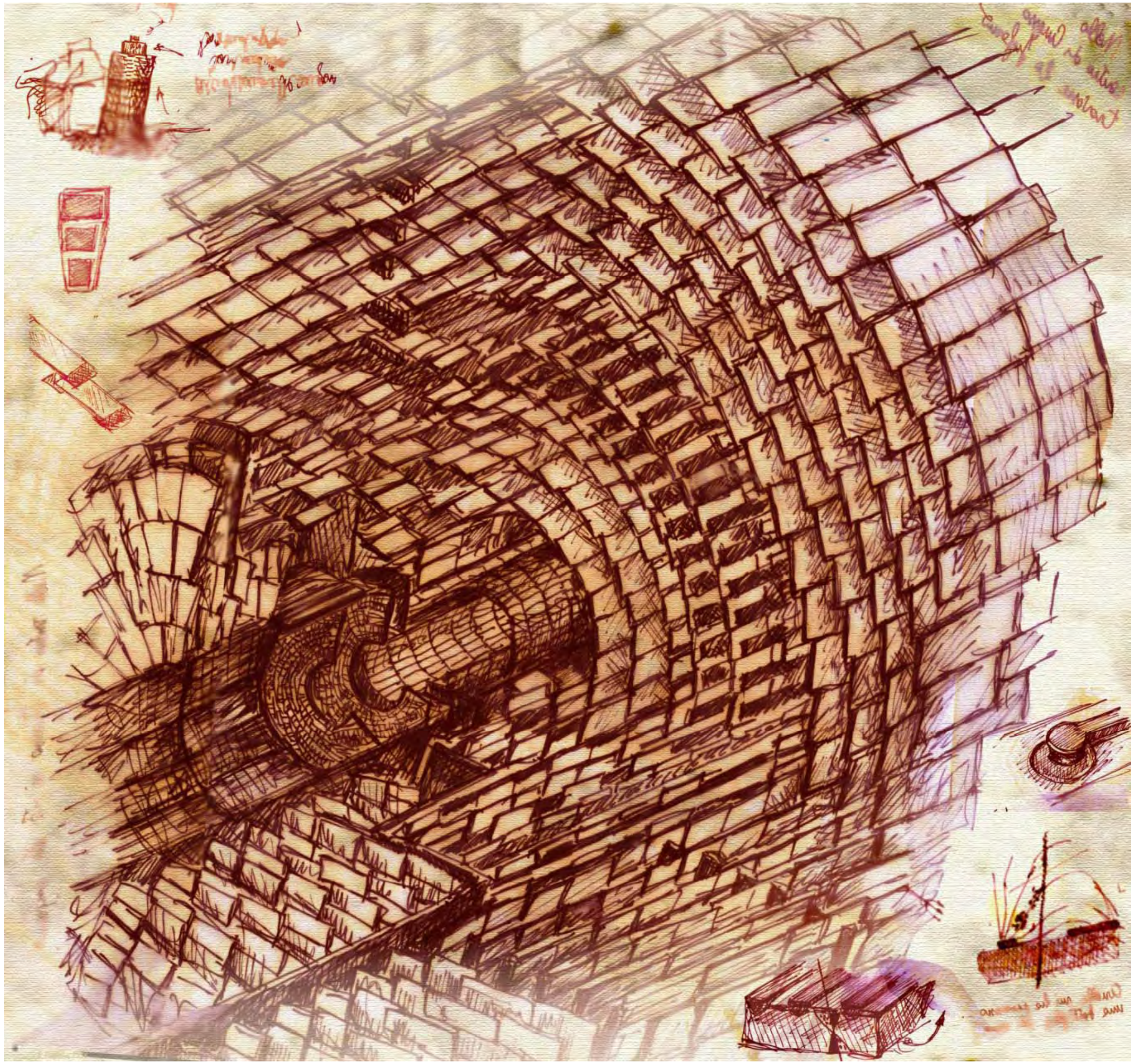
>2500 physicists
183 institutions
38 countries
4 continents

CMS

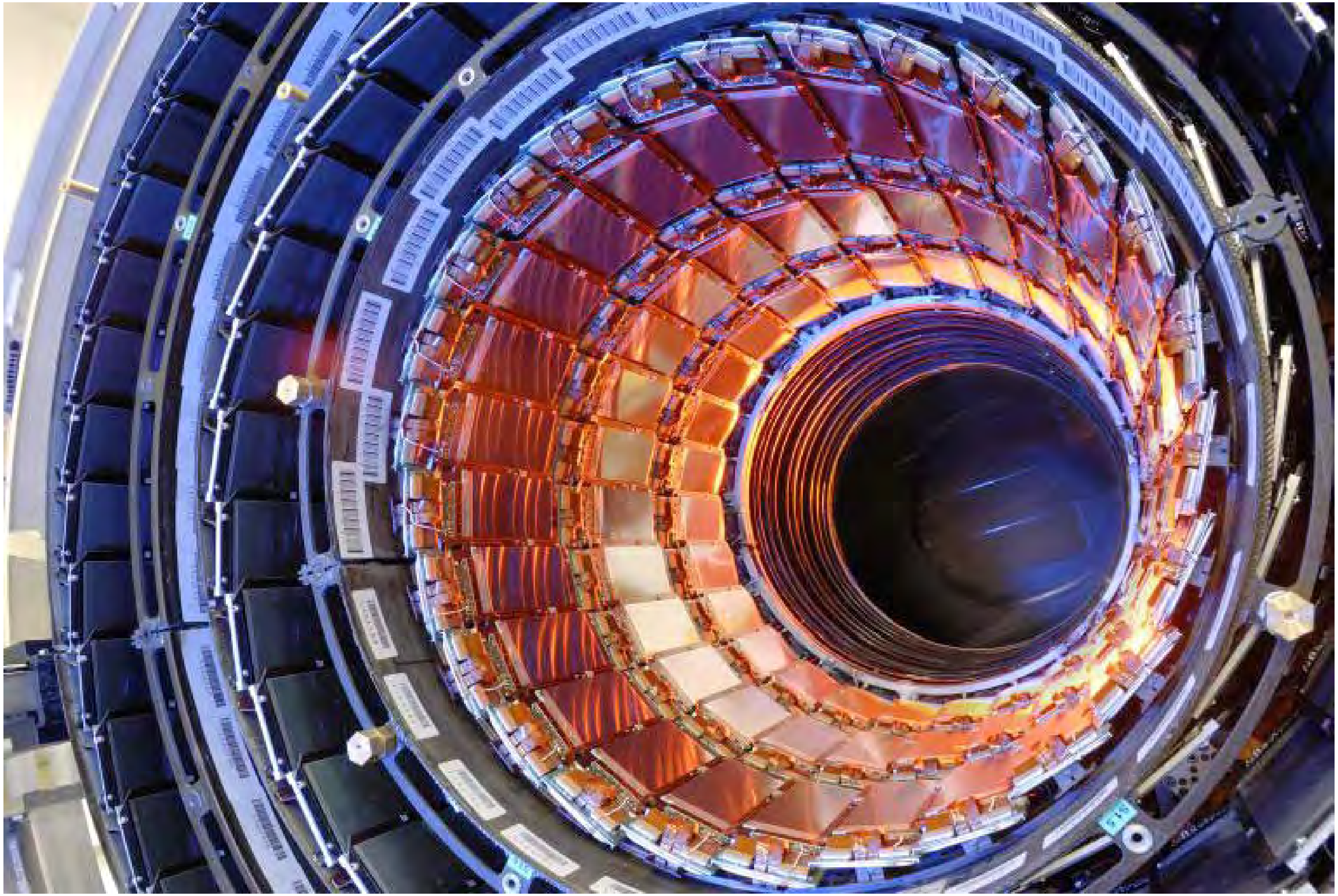


CMS completed and closed for beams in Sept 2008

CMS – Si tracker: from design…



CMS Si tracker - … to reality



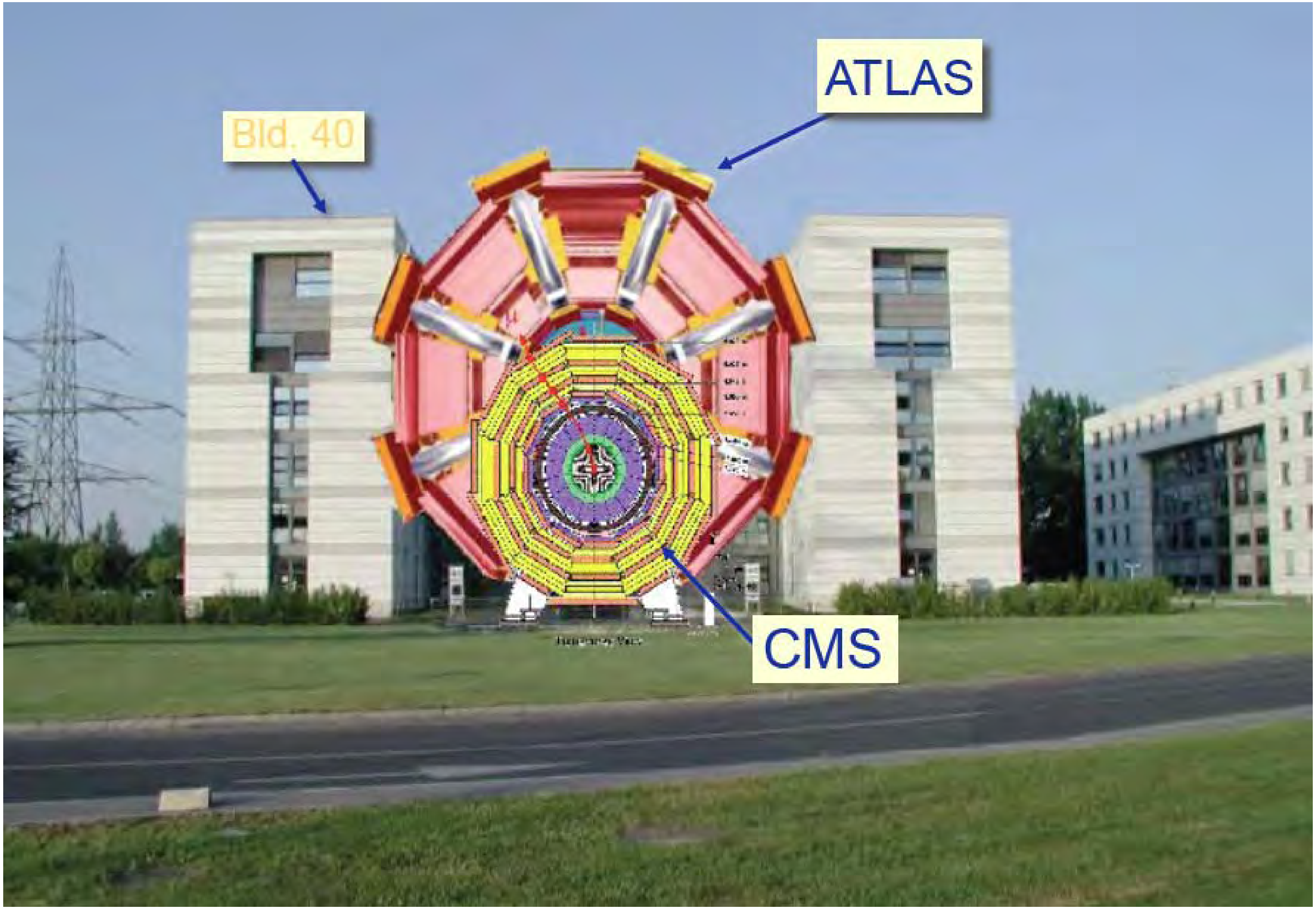
ATLAS vs. CMS – complementary technology choices

	ATLAS	CMS
Solenoidal B-Field	2T in front of ECAL	4T behind HCAL
Tracking	Si (Pixel+Strips)+Gas (TRT)	all Si (Pixel+Strips)
ECAL	L-Ar (high granularity)	$PbWO_4$ crytals (high E-resolution)
HCAL	Fe – Scintillator (10λ)	Brass – Scintillator (7λ)
Muons	SC air-core toroid (standalone)	Instrumented iron

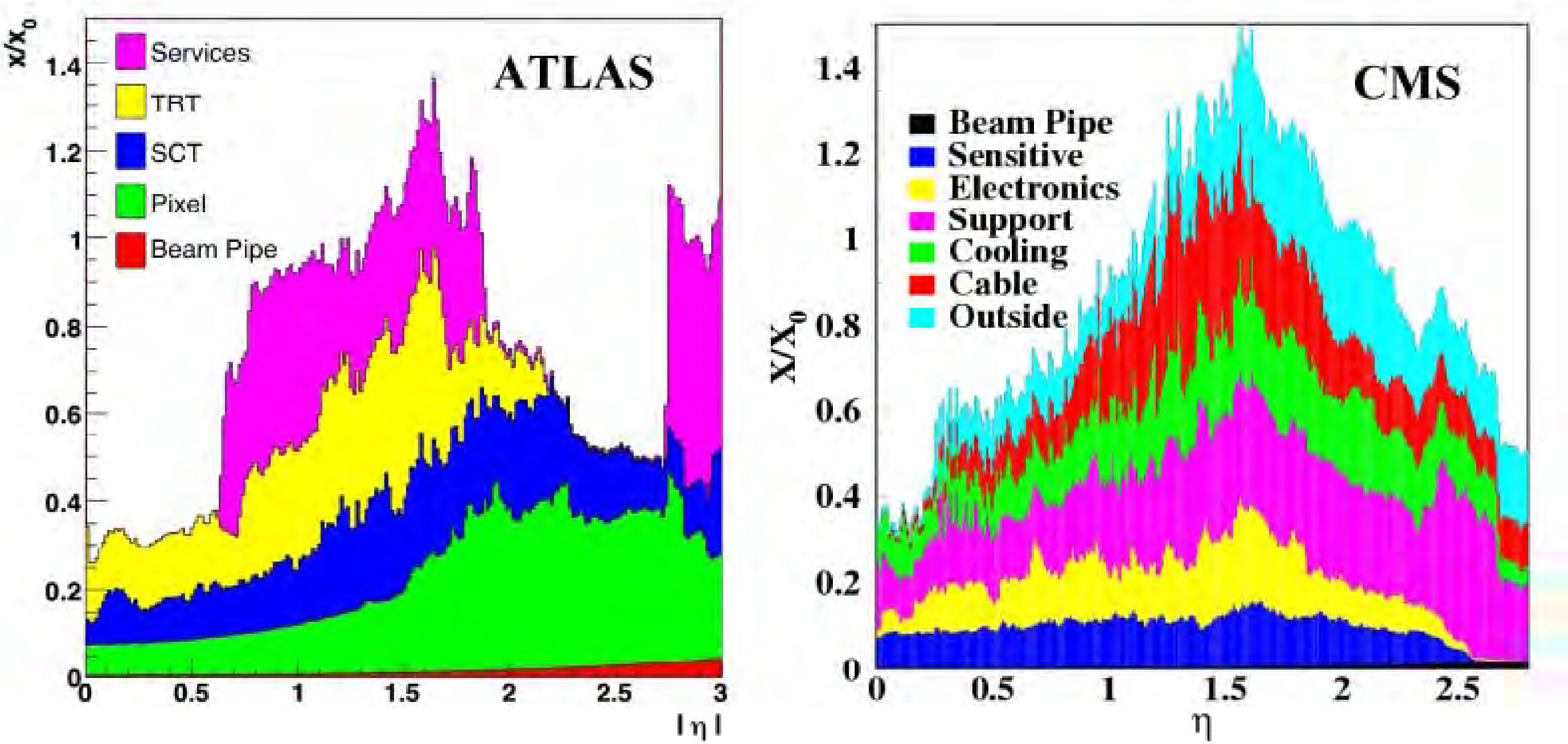
Suggested reading on comparison of ATLAS and CMS:

General-purpose detectors for the Large Hadron Collider.
D. Froidevaux, P. Sphicas, (CERN) . Nov 2006. 79pp.
Published in **Ann.Rev.Nucl.Part.Sci.56:375-440,2006**.

ATLAS vs. CMS – dimensions



Material – The need for “thin” detectors



- Active sensors and mechanics: only ~ 10% of material budget
- 70 kW power into tracker and to remove similar amount of heat
- complex layout of services

[Froidevaux]

Material – Design and Reality

TABLE 5 Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

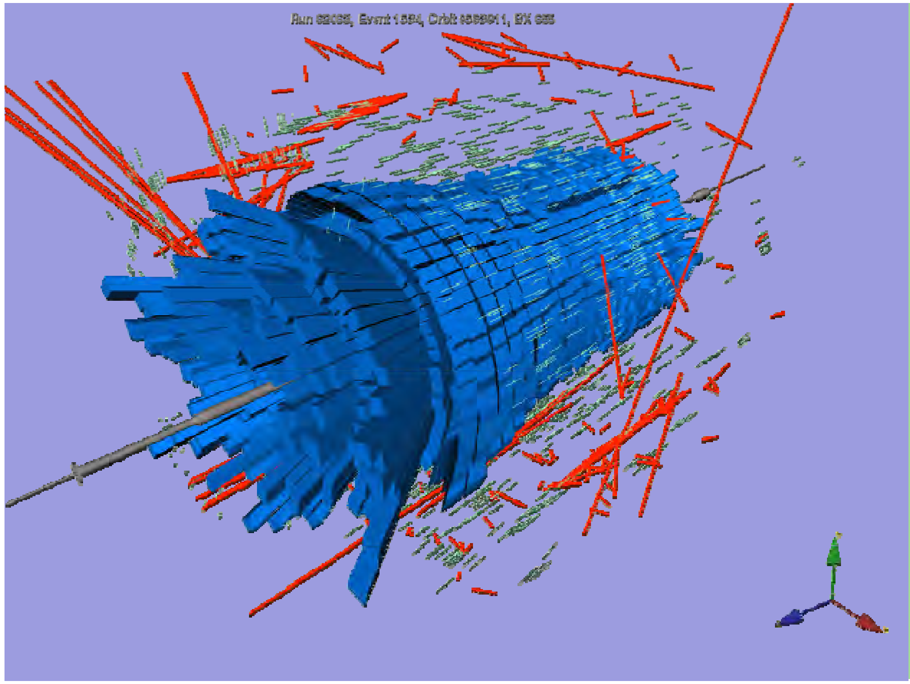
Date	ATLAS $\eta \approx 0$	$\eta \approx 1.7$	CMS $\eta \approx 0$	$\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50

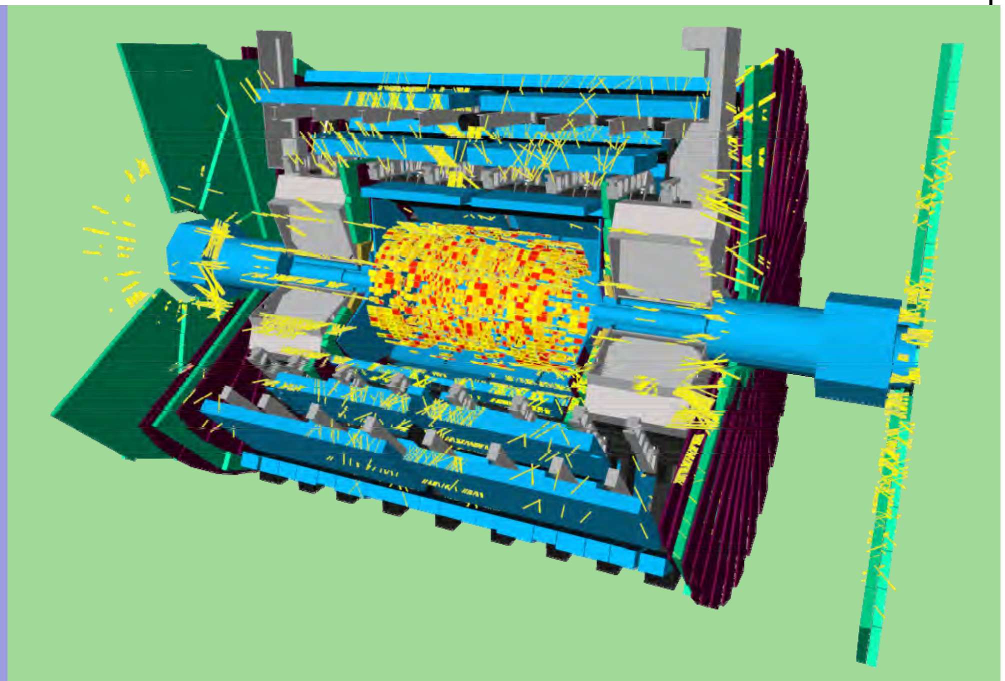
The numbers are given in fractions of radiation lengths (X/X_0). Note that for ATLAS, the reduction in material from 1997

- Material increased by ~ factor 2 from 1994 (approval) to now (end constr.)
- Electrons lose between 25% and 70% of their energy before reaching ECAL
- Between 20% and 65% of photons convert into e^+e^- pair before ECAL
- Need to know material to ~ 1% X_0 for precision measurement of m_W (< 10 MeV)

[Froidevaux]

- Both ATLAS and CMS were ready to take data in Sept 08 (and still are!)



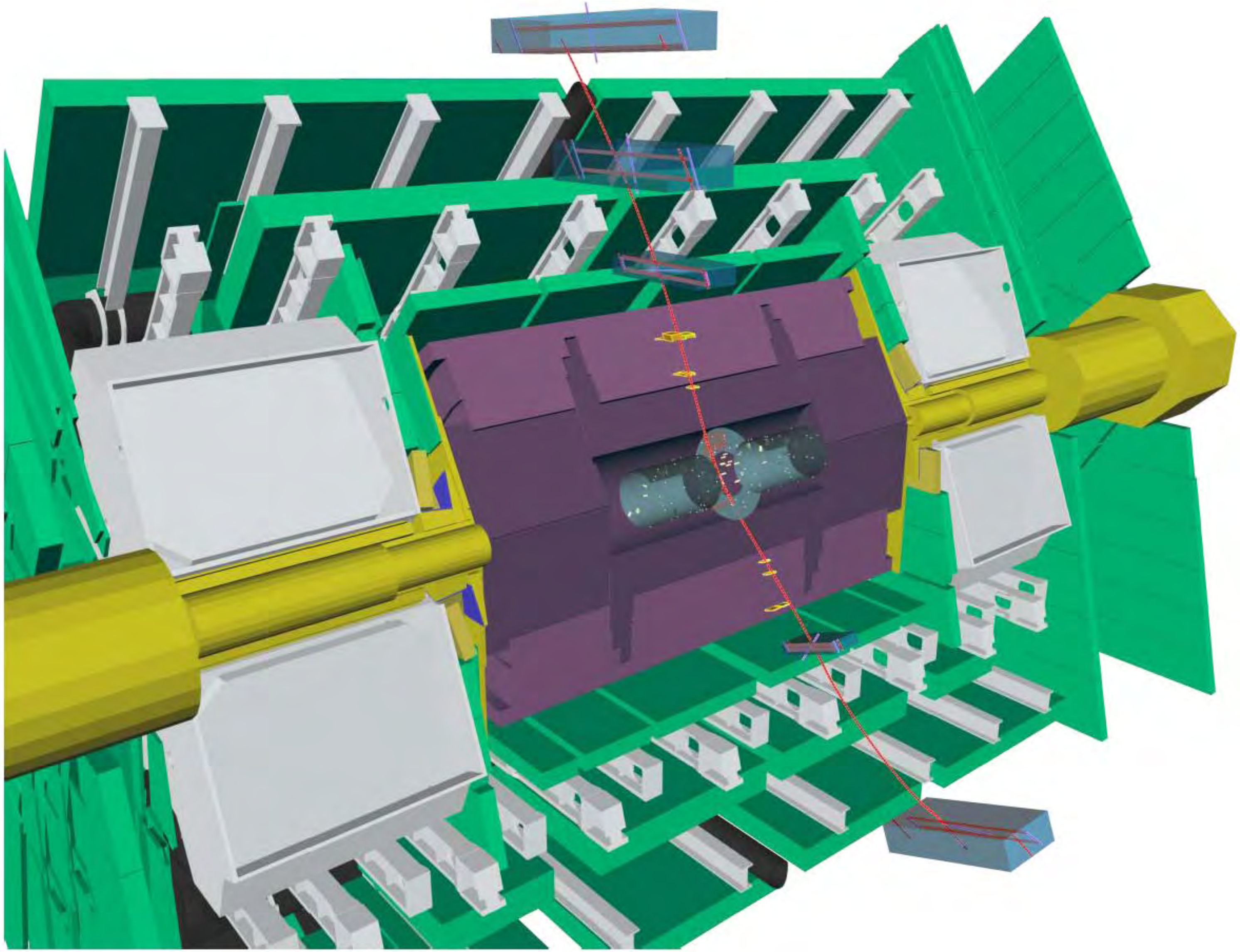


„Beam splash“ event (dump beam into close-by upstream collimator)
→1000s of muons seen in ATLAS and CMS

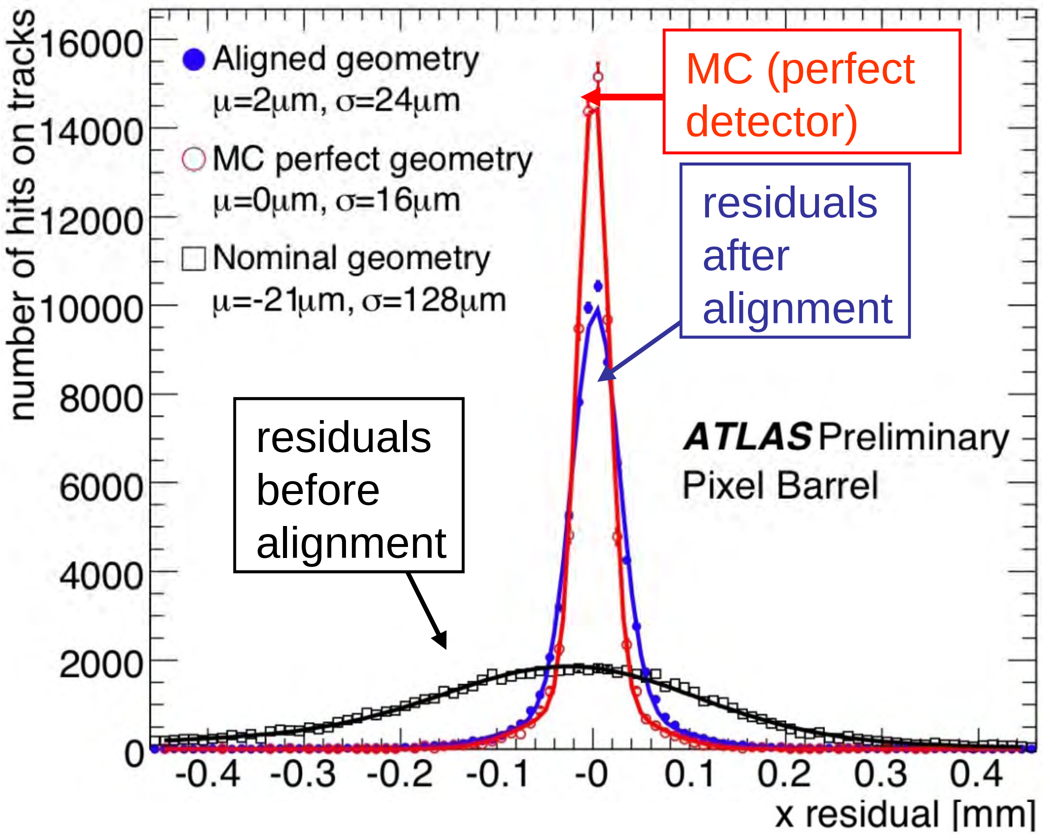
Example: ATLAS (CMS very similar)

Sub-detector	N. of channels	Fraction of working detector (%)
Pixels	$80x10^6$	98.5
Silicon strip detector (SCT)	$6x10^6$	~99.5
Transition Radiation Tracker (TRT)	$3.5x10^5$	98.2
LAr electromagnetic calorimeter	$1.7x10^5$	99.5
Fe/scintillator (Tilecal) calorimeter	9800	~99.5
Hadronic end-cap LAr calorimeter	5600	99.9
Forward LAr calorimeter	3500	100
Muon Drift Tube chambers (MDT)	$3.5x10^5$	99.3
Barrel muon trigger chambers (RPC)	$3.7x10^5$	~ 95.5 (aim: > 98.5 by first beams)
End-cap muon trigger chambers (TGC)	$3.2x10^5$	> 99.5

ATLAS recorded ~600 M of global cosmics (> 1PB of data) with full detector operational → commision detector for collisions



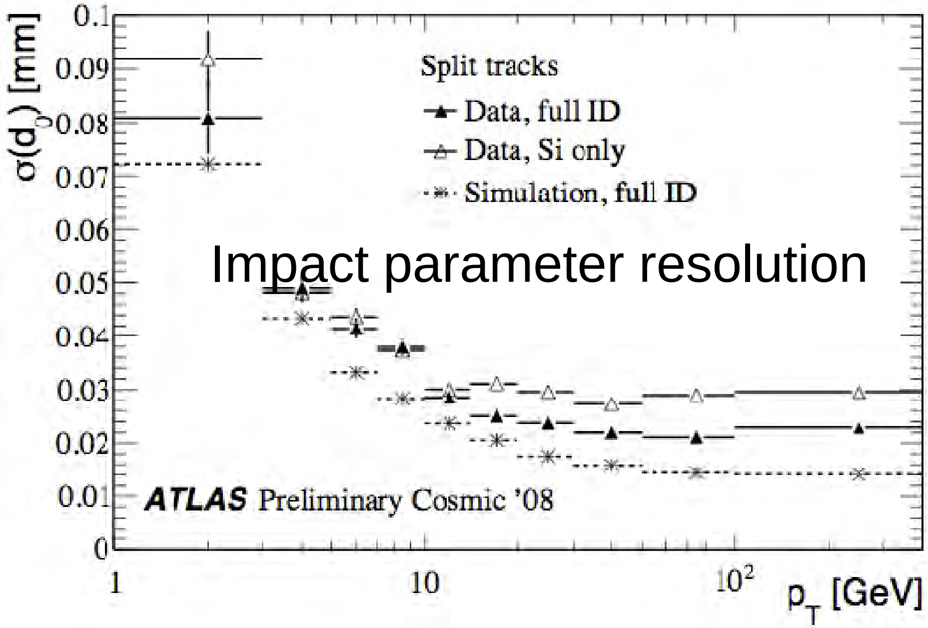
Cosmics calibration: example ATLAS pixels

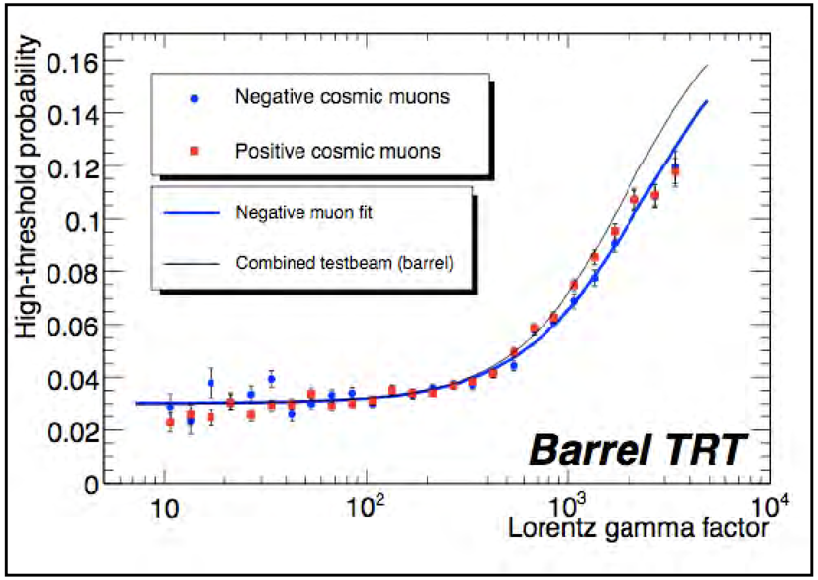


Pixels, SCT: achieved with cosmics:

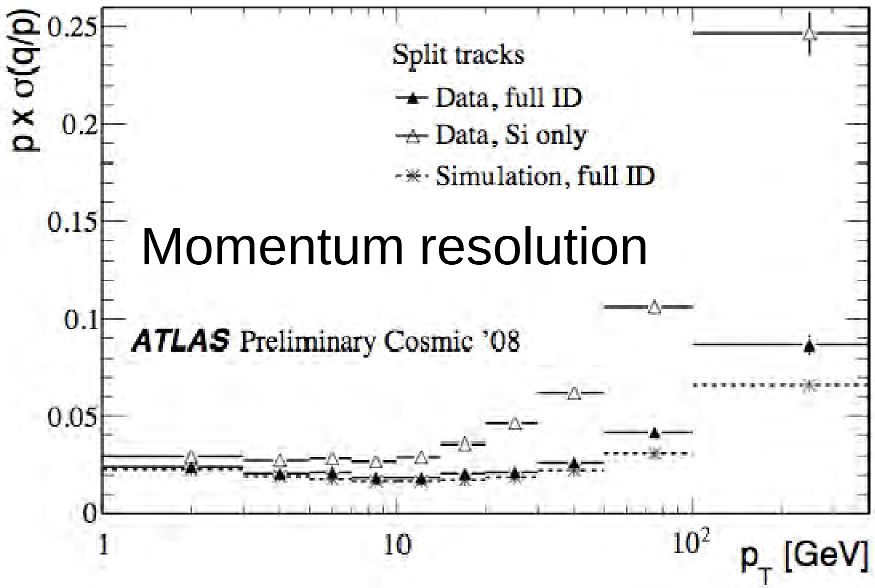
- alignment precision: ~ 20 μm (ultimate goal 5-10 μm)
- alignment stability Oct-2008-June-2009: few microns
- layer hit efficiency: > 99% ; occupancy: 10^{-10}

4. Detectors | Cosmics calibration: example ATLAS Tracker



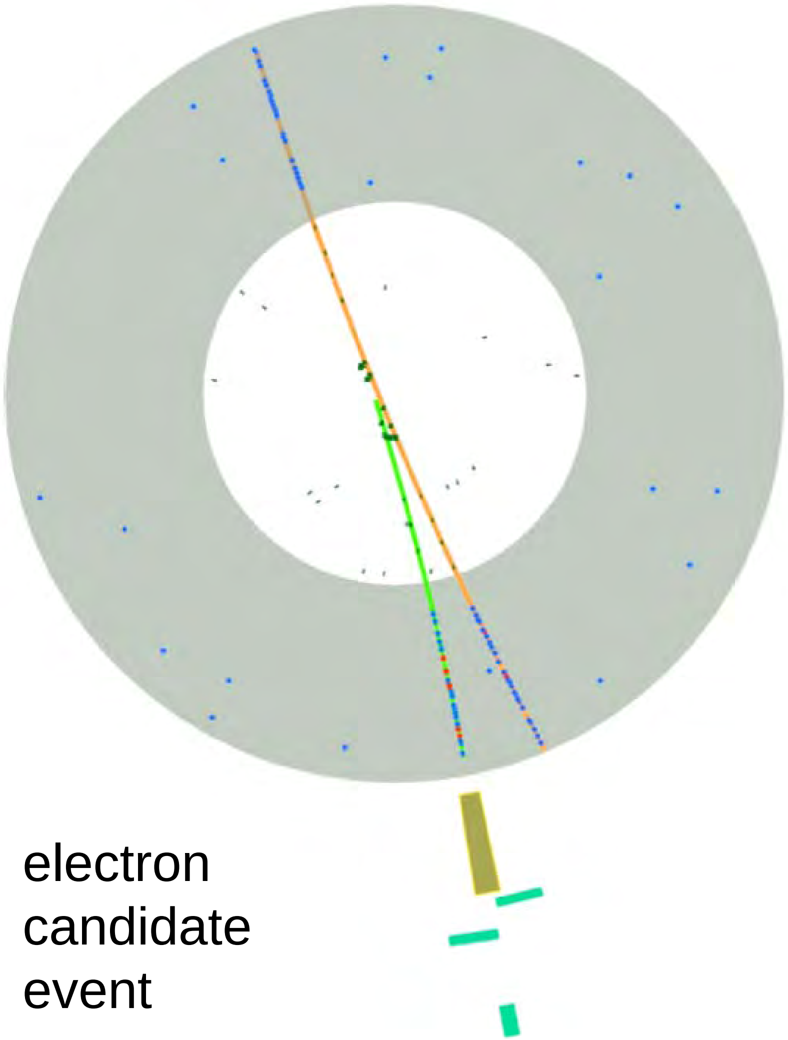


Transition radiation $\sim\gamma$
(E~100 GeV for muons)

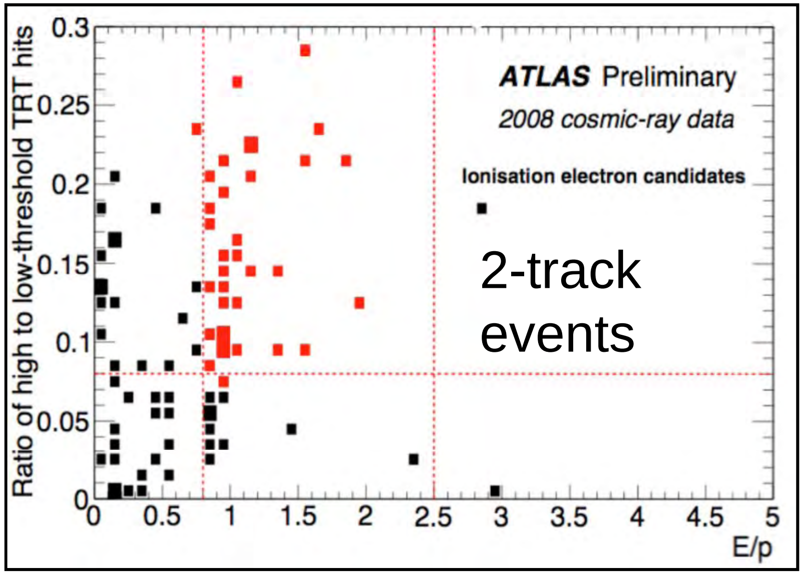


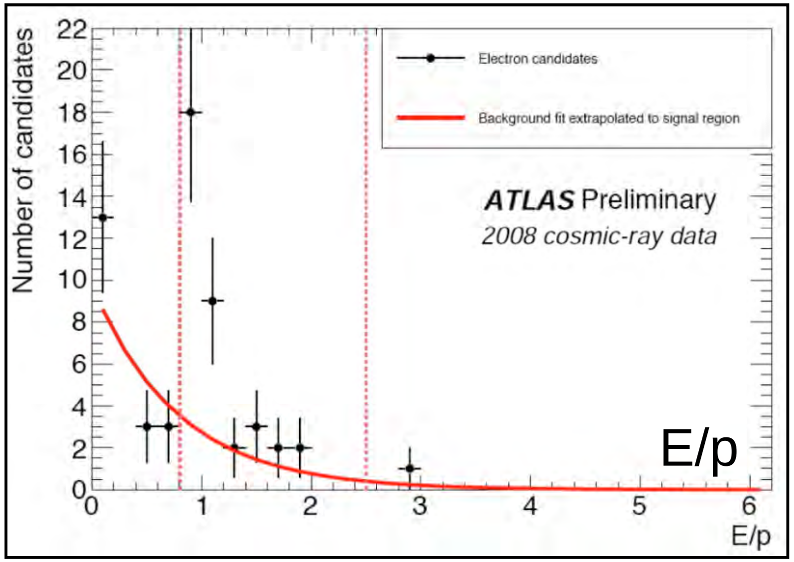
Cosmics calibration: example ATLAS TRT

Electron(!) candidates in ATLAS Transition Radiation Tracker (TRT) from δ-electrons from cosmic muons



electron candidate event





32/36 candidates have neg. charge!

5. Object reconstruction

(Combined) Reconstruction of high-p_T objects

Main objects to identify and reconstruct high-p_T events:

	Tracker	ECAL	HCAL	Muon-System	Vertex-Detector
Electrons	++	+++	+	-	-
Photons	+	+++	+	-	-
Muons	+(+)	+	+	+++	(+)
Taus	++	++	++	++	++
B-Jets	++	+	+	+	+++
Jets	+	+++	+++	(+)	-
Missing E_T	+	+++	+++	+	-

Most physics objects require many of the detector components to achieve the required/desired performance: <u>combined performance</u>

Targets (again)

Object	Efficiency	BG suppr.	Motivation
electrons	>70%	100000	Z,W,top,H→4ℓ,...
photons	80%	1000	H→γγ
muons	>97% for p_T>1GeV		H→4ℓ,...
tau leptons	50%	100	H/A→ττ, SUSY,…
b-jets	50%	100	top, H→bb,SUSY,…

Some examples (from ATLAS – sorry) how this is achieved…

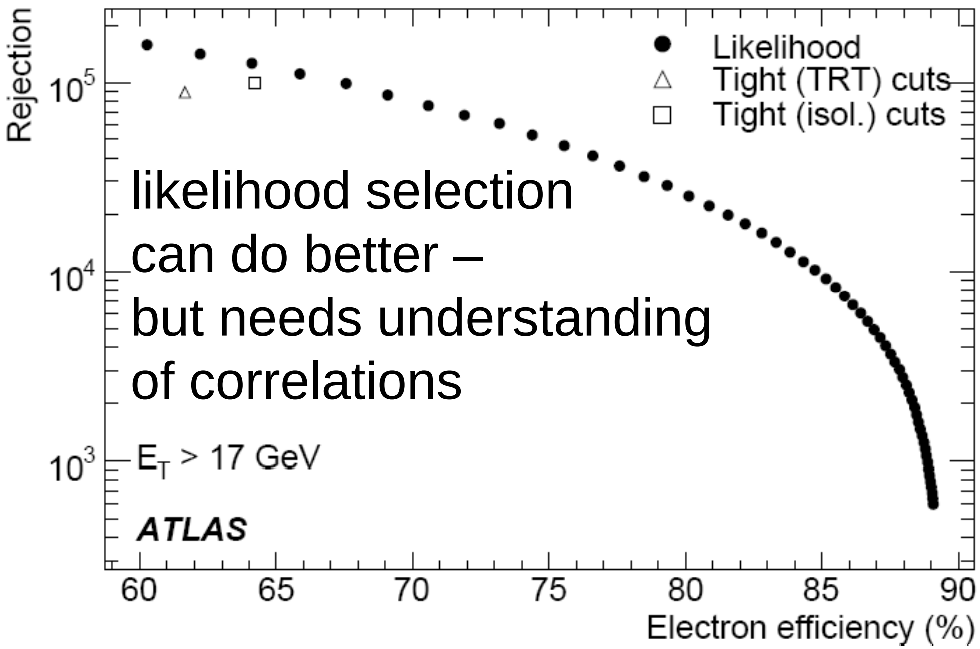
Electron candidates

- Calorimeter seeded → sliding window algorithm
- Matching track → exclude conversion tracks,
  → matching window 0.05x0.1 in $\Delta\eta \times \Delta\varphi$
- E/p < 10 (loose)

Cut-based selection („simple“) for loose-medium-tight „electrons“, e.g. track isolation, hadronic leakage, matching quality, TRT transition radiation,…

Cuts	$E_T > 17$ GeV		
	Efficiency (%)		Jet rejection
	$Z \to ee$	$b,c \to e$	
Loose	87.96 ± 0.07	50.8 ± 0.5	567 ± 1
Medium	77.29 ± 0.06	30.7 ± 0.5	2184 ± 13
Tight (TRT.)	61.66 ± 0.07	22.5 ± 0.4	$(8.9 \pm 0.3)10^4$
Tight (isol.)	64.22 ± 0.07	17.3 ± 0.4	$(9.8 \pm 0.4)10^4$

Cuts	$E_T > 8$ GeV		
	Efficiency (%)		Jet rejection
	Single electrons (E_T =10 GeV)	$b,c \to e$	
Loose	75.8 ± 0.1	55.8 ± 0.7	513 ± 2
Medium	64.8 ± 0.1	41.9 ± 0.7	1288 ± 10
Tight (TRT.)	46.2 ± 0.1	29.2 ± 0.6	$(6.5 \pm 0.3)10^4$
Tight (isol.)	48.5 ± 0.1	28.0 ± 0.6	$(5.8 \pm 0.3)10^4$



likelihood selection can do better – but needs understanding of correlations

$m = 1.78$ GeV, $c\tau \sim 90\ \mu m$

Branching ratios:

leptonic:

e/mu ~35%

hadronic:

1-prong ~48%

3-prong ~14%

others ~ 3%

where for 1-prong:

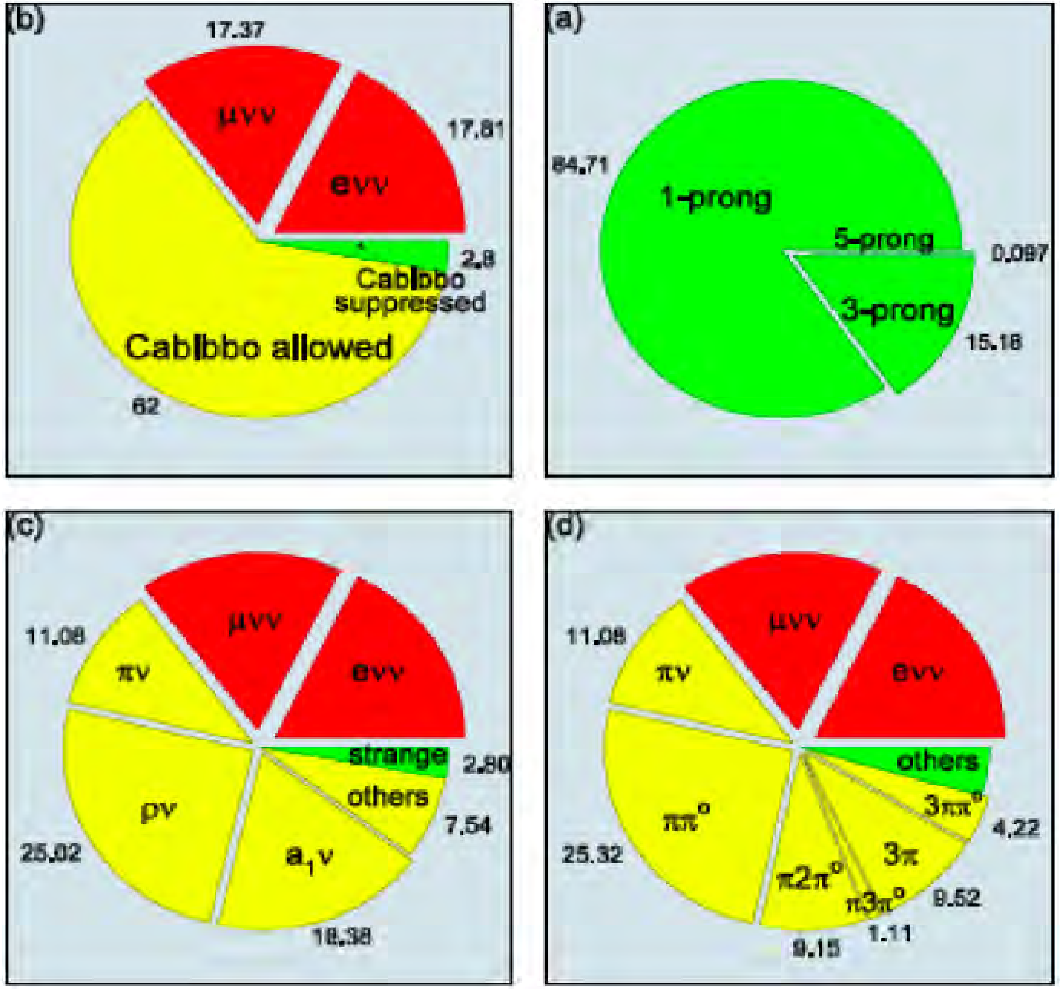
$\pi^{\pm}$ ~23%

$\pi^{\pm}\ n\pi^{0}$ ~74%

and for 3-prong:

$3\pi^{\pm}$ ~62%

$3\pi^{\pm}\ n\pi^{0}$ ~34%



Leptonic decay hard to distinguish from prompt lepton (except lifetime)

→ concentrate on hadronic tau´s

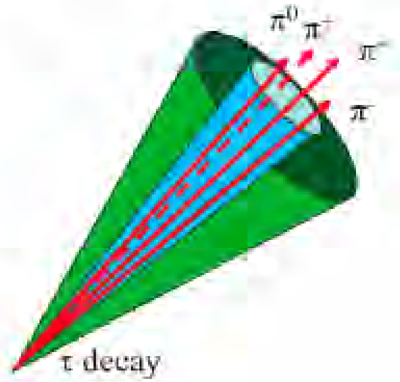
[M.Lehmacher]

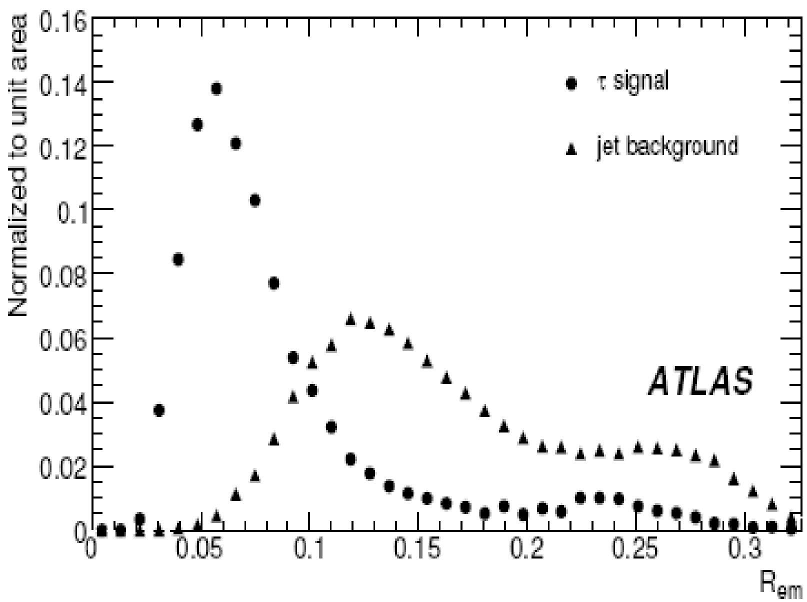
A hadronic tau is a narrow, low-multiplicity jet of hadrons („tau-jet“)
Main (serious!) background: QCD (quark,gluon) jets of low multiplicity

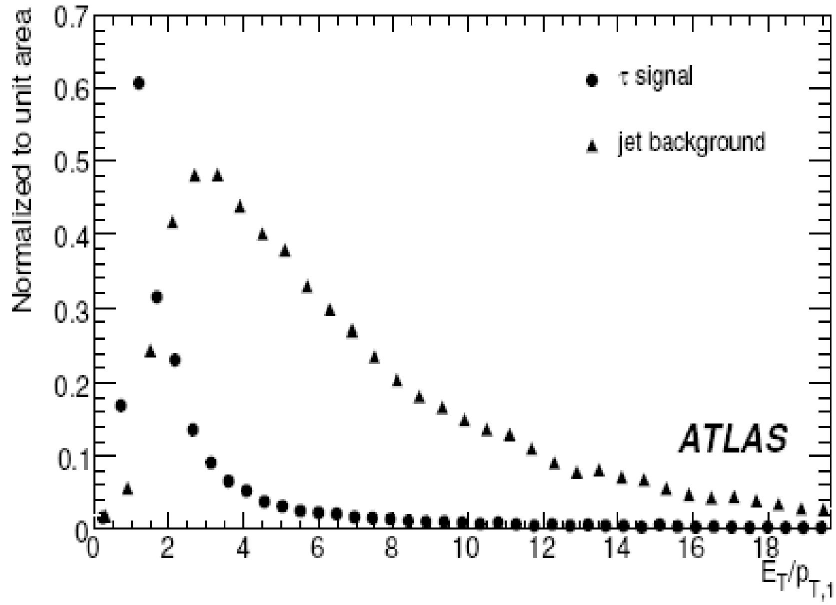
Seeding: Calorimeter-based or track-based (or from combined objects)

Discriminating varibles:

1. **emRadius**: radius of the cluster in the EM calorimeter,
2. **isolationFraction**: fraction of the transverse energy deposited in a hallow cone of $0.1 < \Delta R < 0.2$ around the tau cluster over the total energy in a cone of $\Delta R = 0.4$,
3. **ntrack**: number of associated tracks,
4. **charge**: absolute tau electric charge,
5. **numStripCells**: number of hits in the eta-strip with $E_T > 200$ MeV,
6. **stripWidth2**: energy weighted width in strips,
7. **ipSigLeadTrack**: lifetime signed impact parameter (2D) of the leading track,
8. **etOverPtLeadTrack**: ratio of the transverse energy of tau candidate to the transverse momentum of the leading track.







performance:

Selection	Efficiency	Rejection cuts	Rejection TMVA cuts	Rejection NN	Rejection PDRS
	E_T = 10-30 GeV				
one-prong	0.33	225 ± 10	435 ± 30	510 ± 40	460 ± 40
three-prong	0.28	360 ± 25	470 ± 40	740 ± 70	670 ± 60
	E_T = 30-60 GeV				
one-prong	0.42	140 ± 10	170 ± 10	440 ± 40	320 ± 30
three-prong	0.45	60 ± 2	9 0 ± 10	160 ± 10	130 ± 10

Particles which are neutral and interact only via weak interaction are invisible to the detector.
Their presence can be only inferred indirectly from „missing energy“ (E/p- conservation).
Since longitudinal momentum p_L cannot be measured at a hadron collider only transverse momentum conservation can be used:

$$0 = \sum_i p_{x,i} \quad 0 = \sum_i p_{y,i} \quad E_T^{miss} = \sqrt{\left(\sum_i p_{x,i}\right)^2 + \left(\sum_i p_{y,i}\right)^2}$$

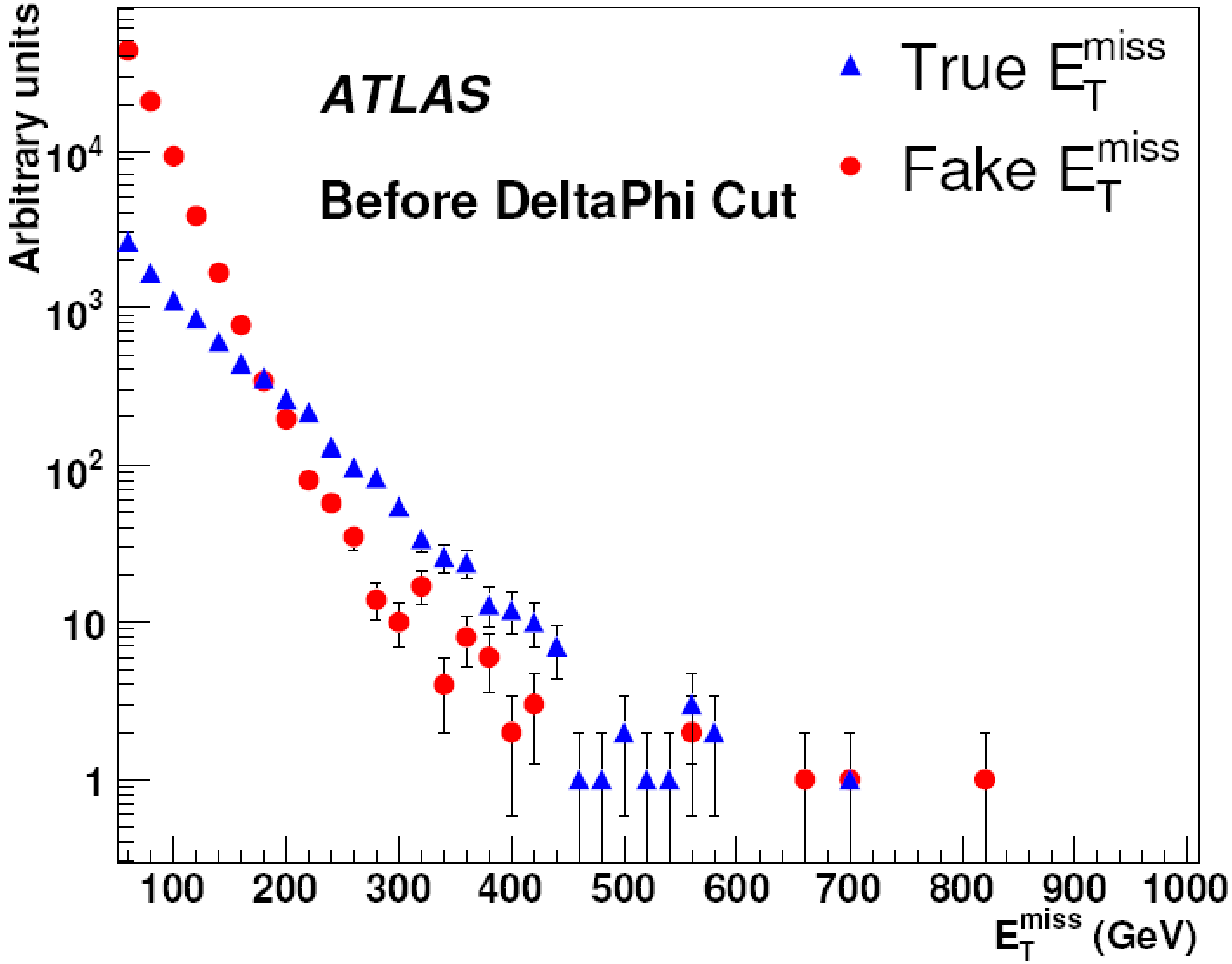
E_T^{miss} does not know why a particle was missed in the sum

- because it did not interact (neutrino, neutralino, …) : good

- because it escaped through a crack: bad
- because it escaped through the beampipe: bad (but low p_T)
- because it was misidentified (e.g. muon as hadron): bad
- because its energy was mismeasured (resolution,homogeneity):bad

fake E_T^{miss}

Example: QCD dijet events $560 < p_T < 1120$ GeV



Missing transverse energy: Algorithms

Calorimeter cell based:

$$E_T^{miss} = \sqrt{\left(\sum_{i=cell} p_{x,i}\right)^2 + \left(\sum_{i=cell} p_{y,i}\right)^2}$$

Advantage: no need to reconstruct particles, jets
Disadvantage: - have to calibrate calo response at the cell level (different for em and had showers)
- potentially sensitive to noise
- sensitive to min. bias pile-up
- correct for muons (which do not leave much E in calorimeter)
- correct for energy deposited in dead material (e.g. cryostat)

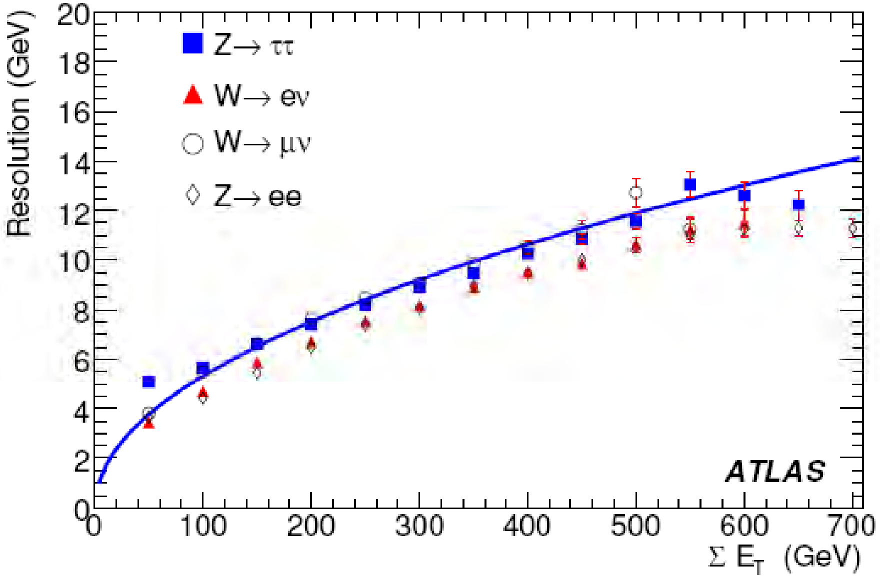
Object based:

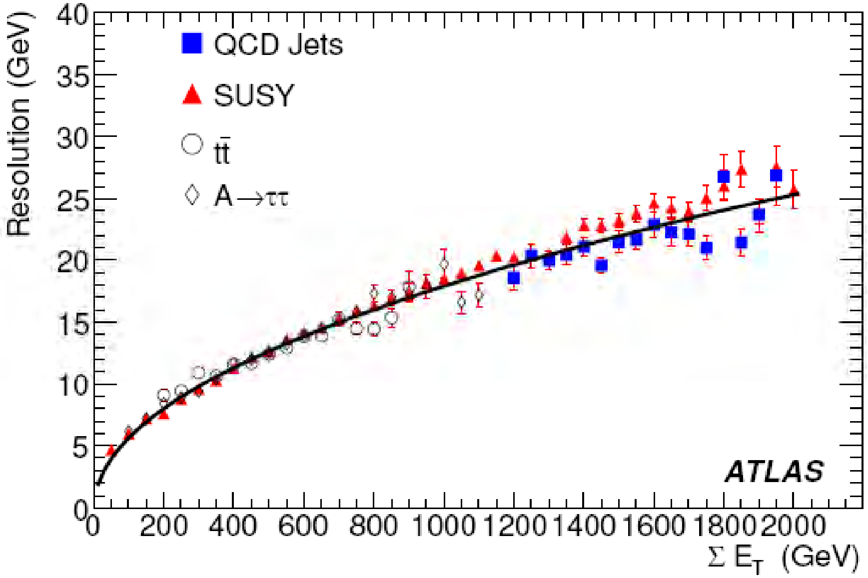
$$E_T^{miss} = \sqrt{\left(\sum_{i=objects} p_{x,i}\right)^2 + \left(\sum_{i=objects} p_{y,i}\right)^2}$$

Objects = Electrons, Photons, Muons, Taus, Jets, low-p_T objects
Advantage: can calibrate each object individually
Disadvantage: - E_T^{miss} depends on (many) object definitions, all have to be understood

Both algorithms perform very similarly on Monte Carlo
→ interesting to compare them with data…

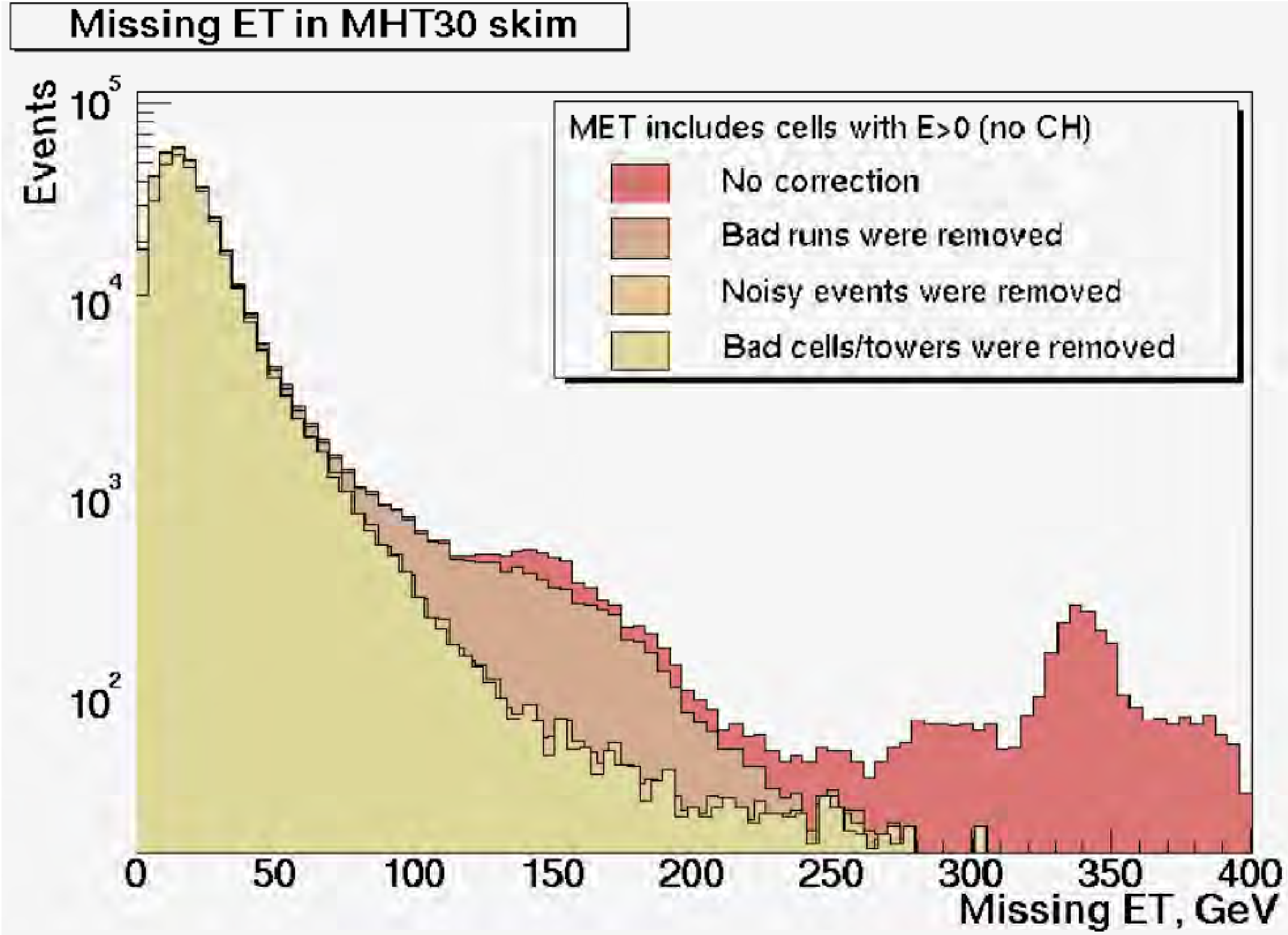
Resolution:





$$\frac{\Delta E_T^{miss}}{E_T^{miss}} = \frac{53-57\%}{\sqrt{E_T^{miss}\ /\ GeV}}$$

Missing Et: a word of warning



End of Day2

6. Physics

QCD

Electroweak

Top

Higgs

no time for BSM physics ☹

QCD & Electro-weak

LO cross sections in pb, inclusive

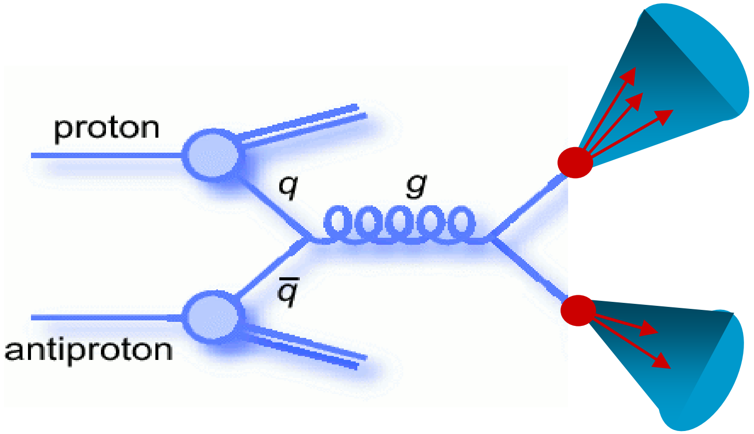
E_{cm} [TeV]/ Process	7	10	14	Evts (7 TeV) in 200/pb	Ratio 7/14
QCD pt>100 GeV	3.2E+05	6.8E+05	1.4E+06	6.4E+07	0.2
Z incl	2.5E+04	3.6E+04	5.7E+04	5.0E+06	0.4
W incl	9.5E+04	1.4E+05	2.1E+05	1.9E+07	0.5
ttbar	8.4E+01	2.2E+02	4.8E+02	1.7E+04	0.2
H(150 GeV)	4.0	8.2	16.0	8.0E+02	0.3

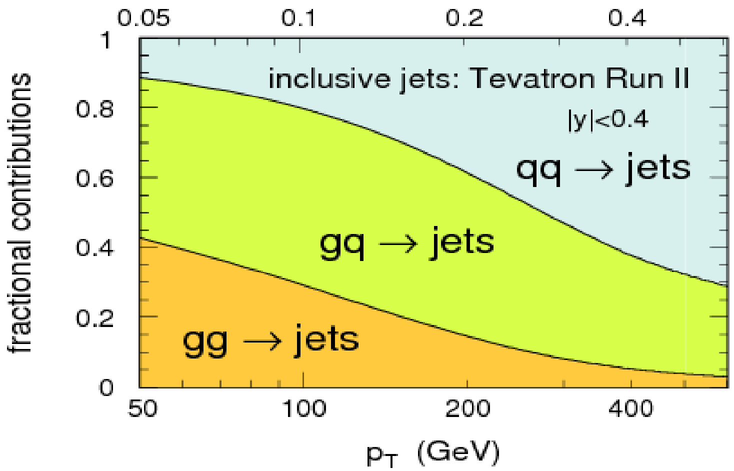
no branching ratios included !

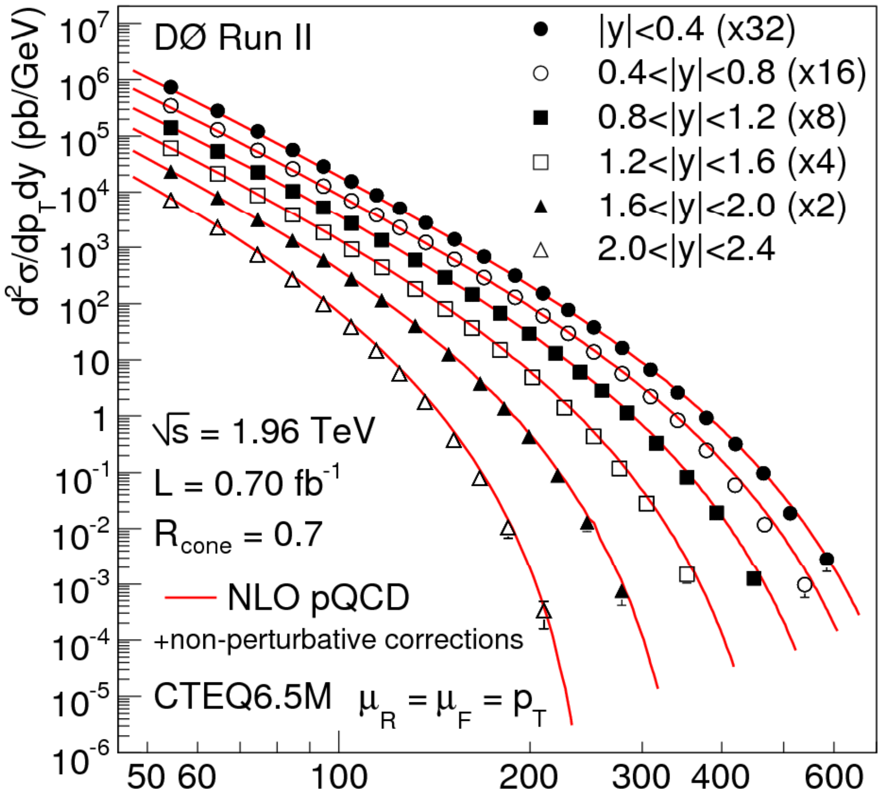
[Dissertori]

QCD jet production: largest (hard) cross section at a hadron collider

- highest p_T reach
- test of pQCD – sensitivity to pdf´s
- sensitivity to new physics (new particles → jets, compositeness, extra dim…)







[Wobisch LP09]

excellent desciption by NLO QCD
cross section varies over 10^{10}

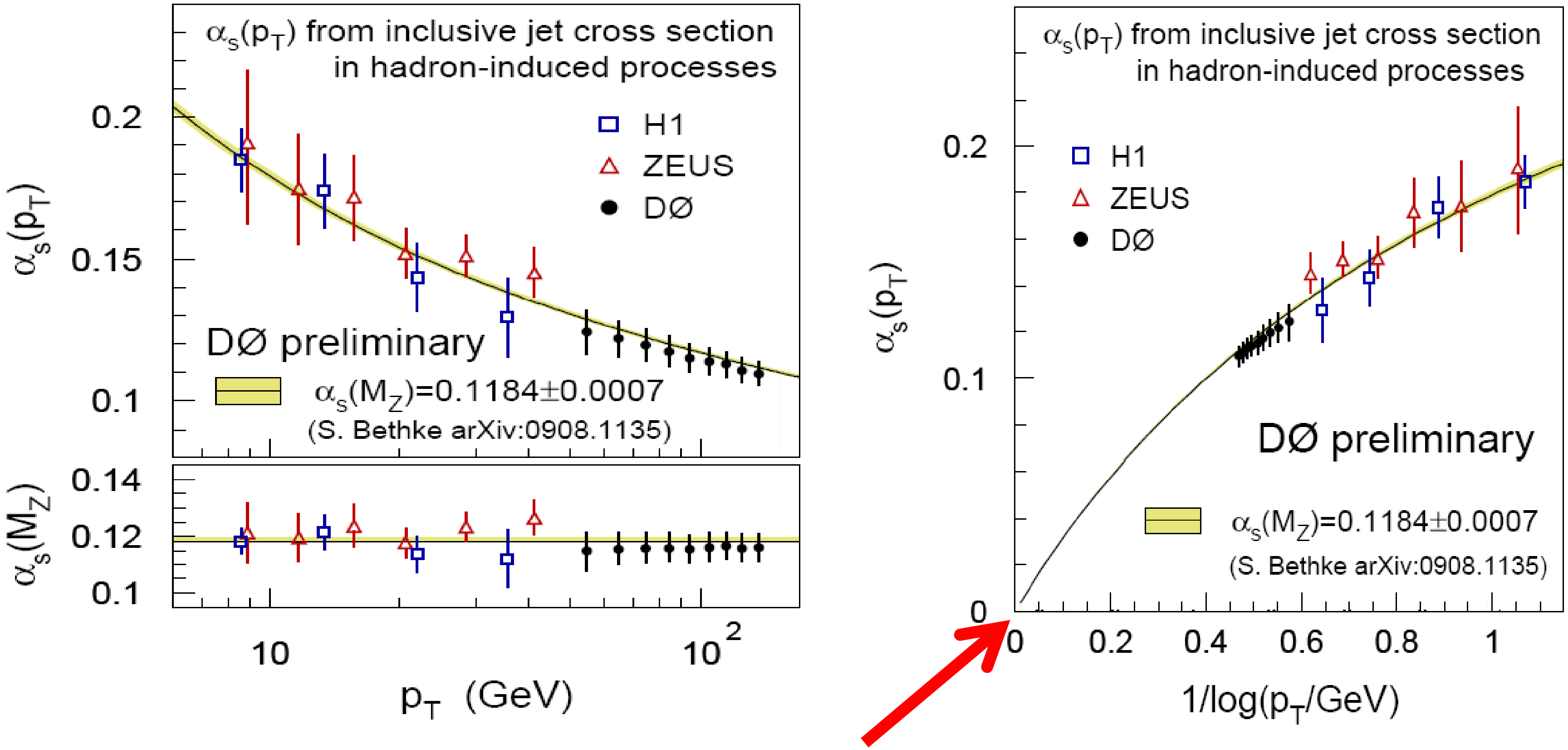
QCD – Jet production: strong coupling constant

Compare inclusive jet cross section with NLO + 2-loop threshold corrections

→ sensitivity to strong coupling constant

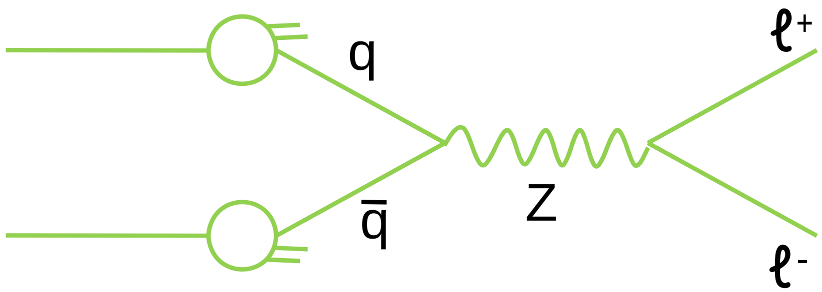
→ observe running of α_s

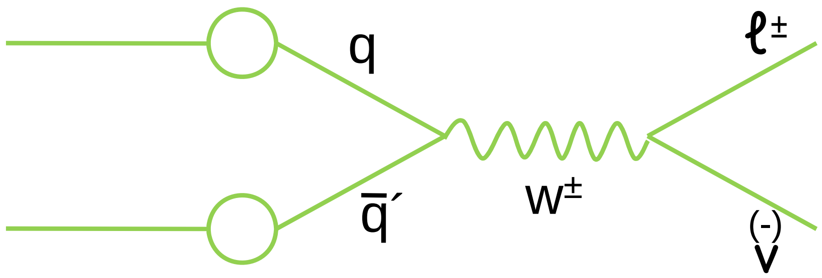
→ demonstration of asymptotic freedom

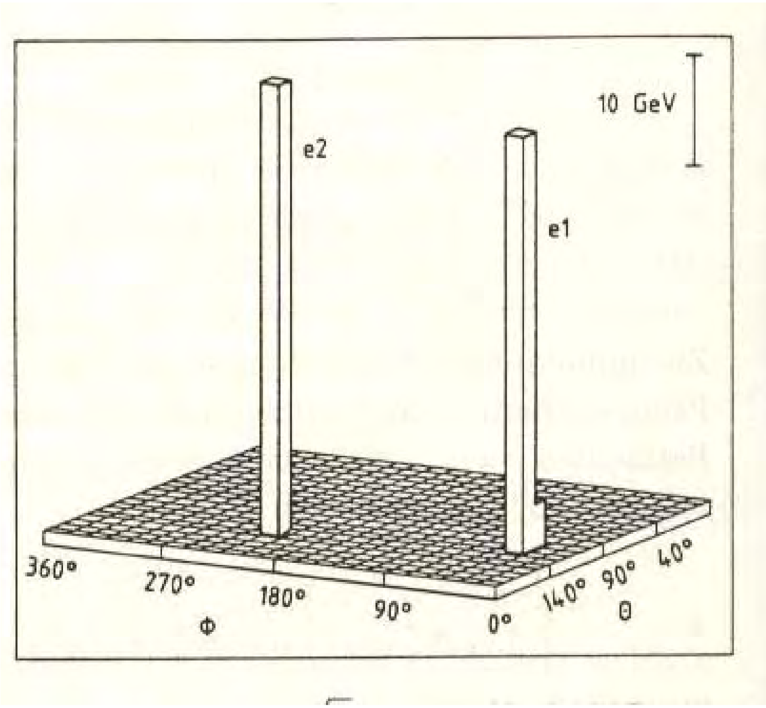


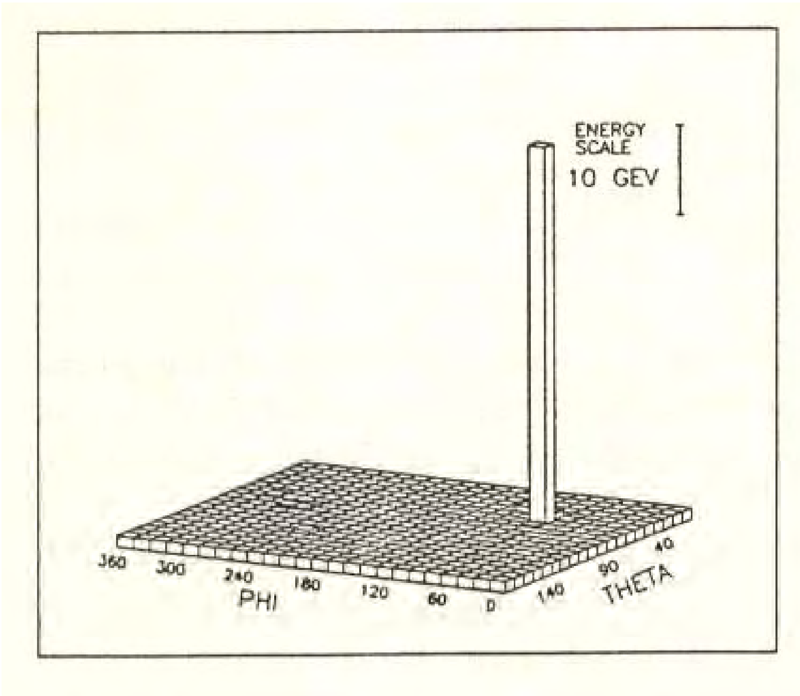
asymptotic freedom !

Electro-weak gauge bosons





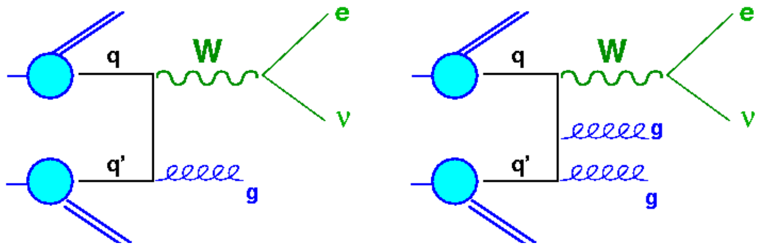




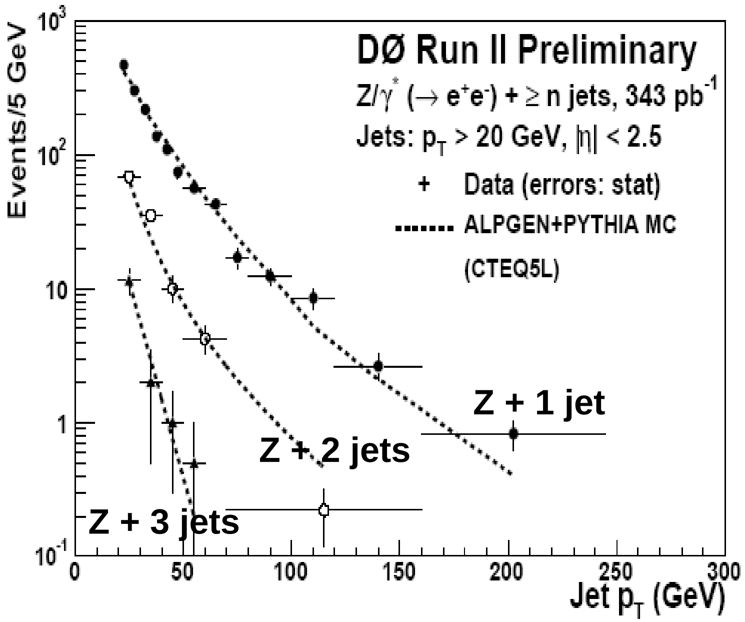
Z/W discovery by UA1 and UA2 (1983/84) at the CERN Sp$\bar{p}$S ($\sqrt{s}$ = 900 GeV)

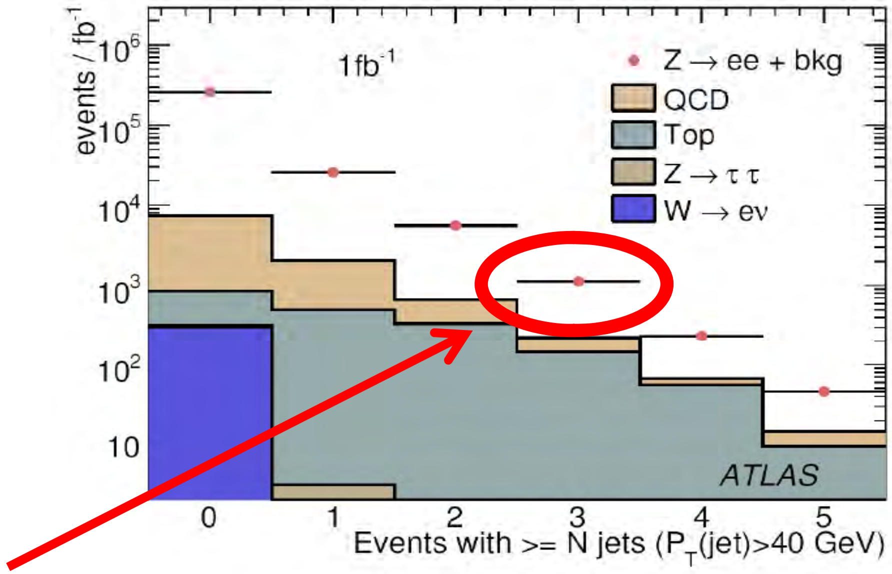
At Tevatron and LHC W/Z production is/will be

- a major tool for detector calibration & alignment
- a tool to measure luminosity
- an important background
- a process for QCD studies



W/Z+jets(!)

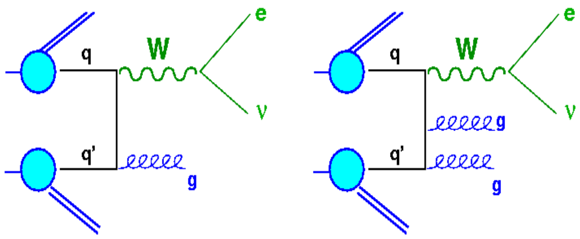




Keep in mind: at LHC(14) for $1fb^{-1}$ you expect 1000 events with Z+3 jets(pt>40)

„Yesterday´s discovery is todays calibration and tomorrows background…“

Modelling of extra jets

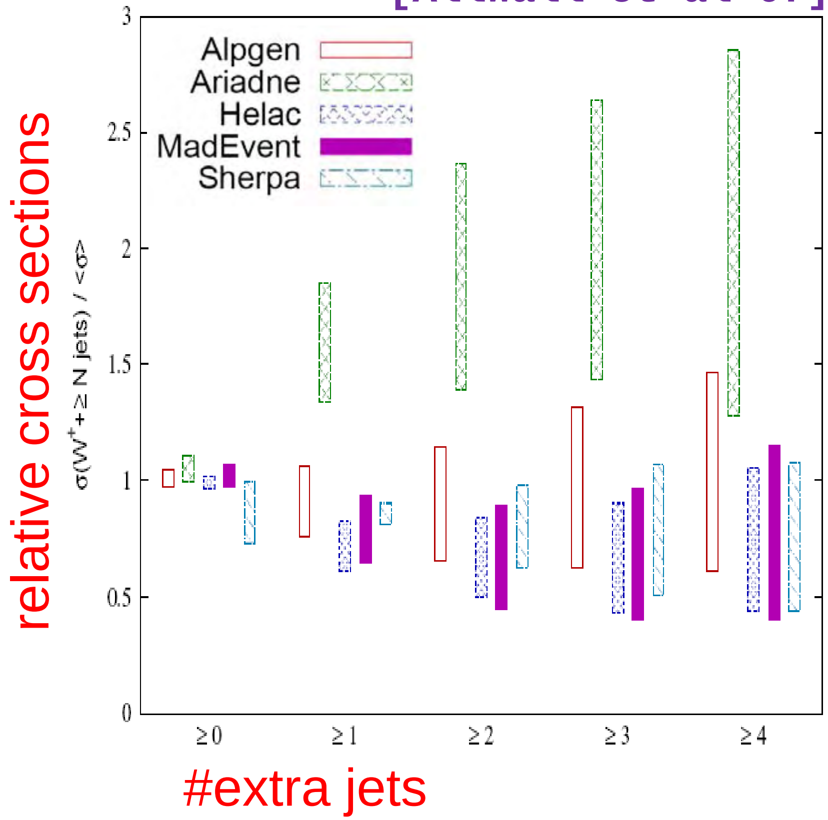


- 2→2 process at LO + parton shower (PS) (e.g. PYTHIA) fails at high jet multiplicities + large emission angles/p_t´s

- 2→n process at LO („Matrix element“) + PS (e.g. ALPGEN, SHERPA,…) needs careful „matching“ algorithms „CKKW“, „MLM“, … (avoid double counting of partons from ME and PS)

- 2→3 processes at NLO (MC@NLO,...) + PS („correct“ for W+1jet, Z+1jet, … but similar problem as LO + PS for higher jet multiplicities good for total cross section („K-factor“)

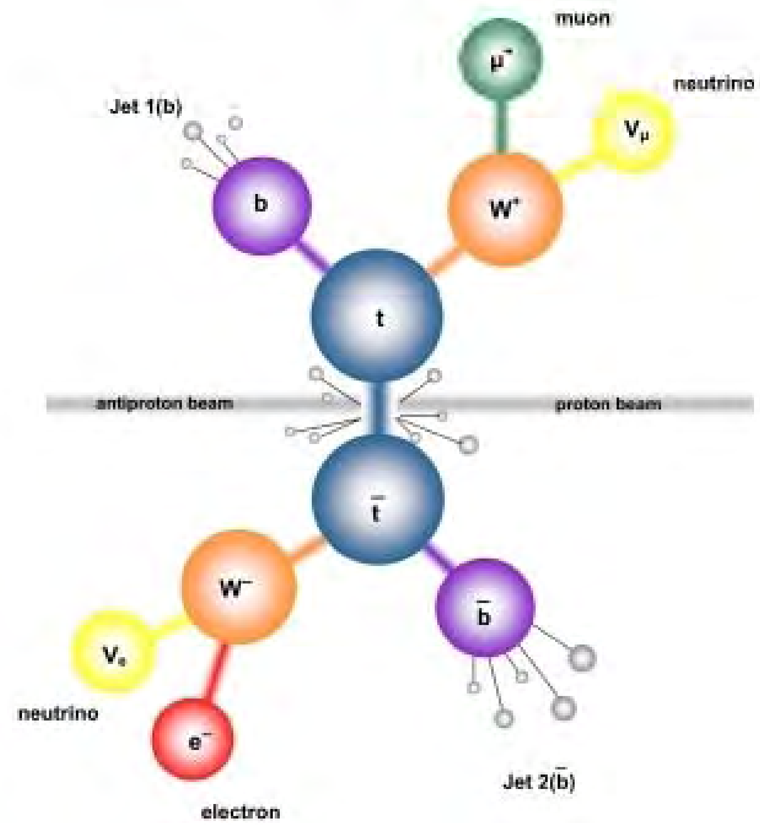
[Allwall et al 07]

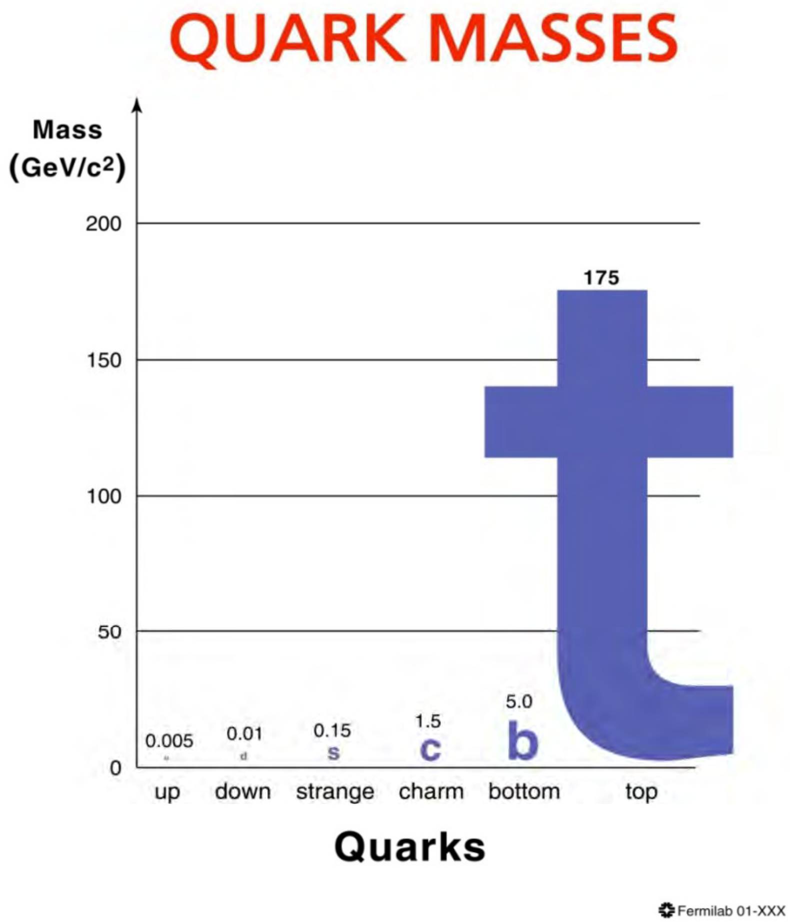


→ even „state-of-the-art“ Monte Carlo programs have large uncertainties

→ prepare to measure these cross sections with data

Top Quark

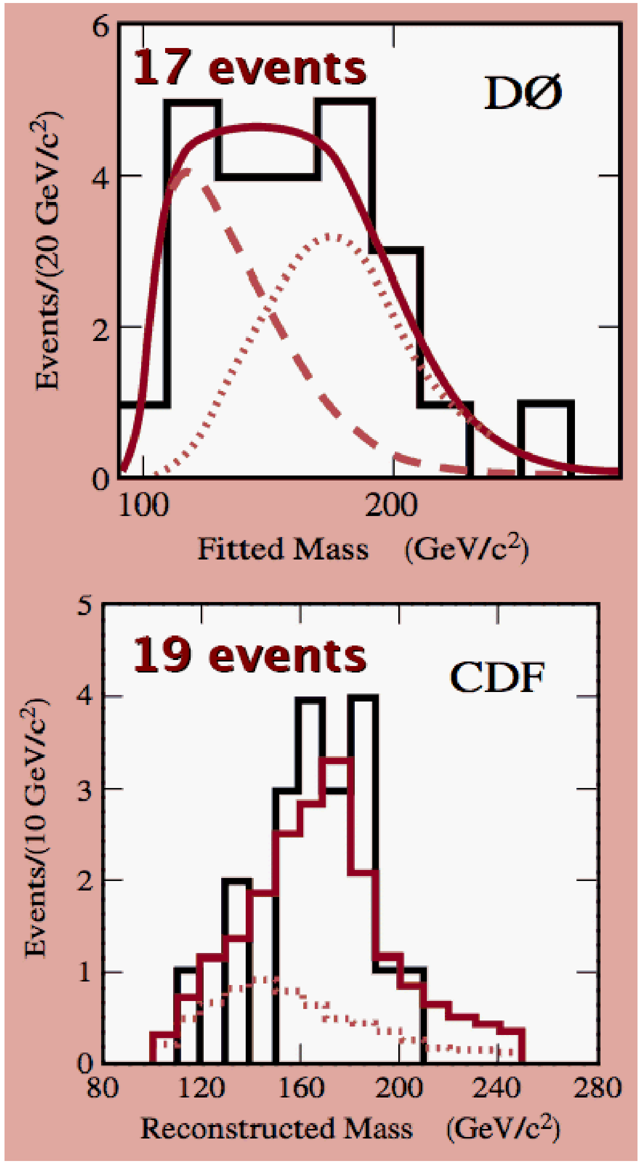




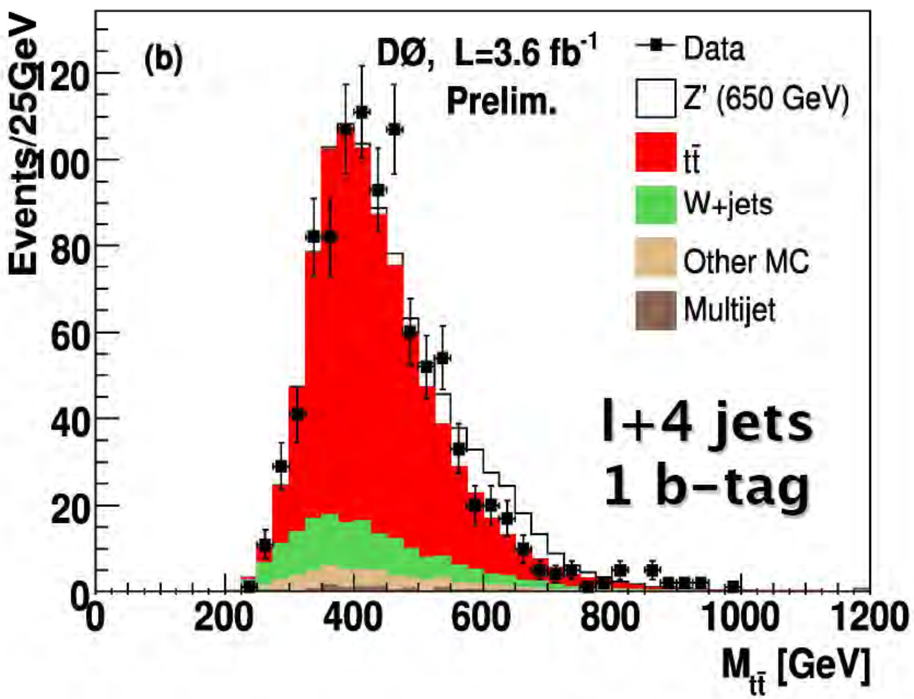
- Heaviest quark
- Discovered at Tevatron Run-I in 1995
- Tevatron Run-II measurements so far consistent with SM but: top is a „gate to new physics“

Top Quark at Tevatron

At discovery (1995)



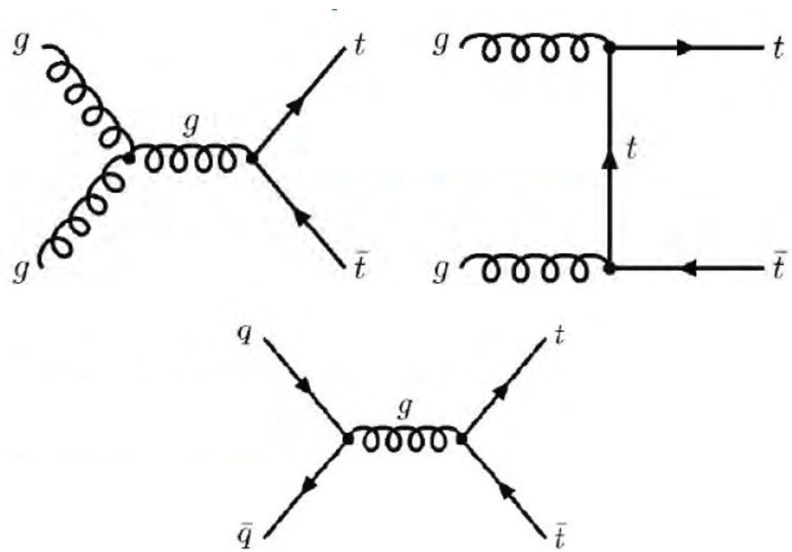
Today: ~ 1000 tt pairs



LHC: 1 top pair /second

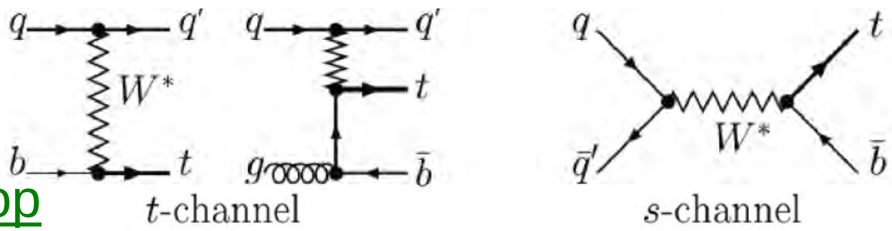
Top – processes and cross sections

top pair production (strong)

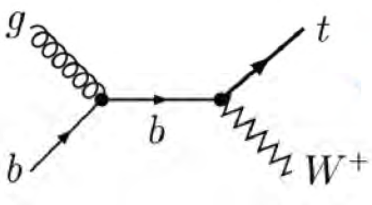


	Tevatron	LHC (14 TeV)
qq gg	85% 15%	5% 95%
σ	7 pb	600 pb

single top production (electro-weak)

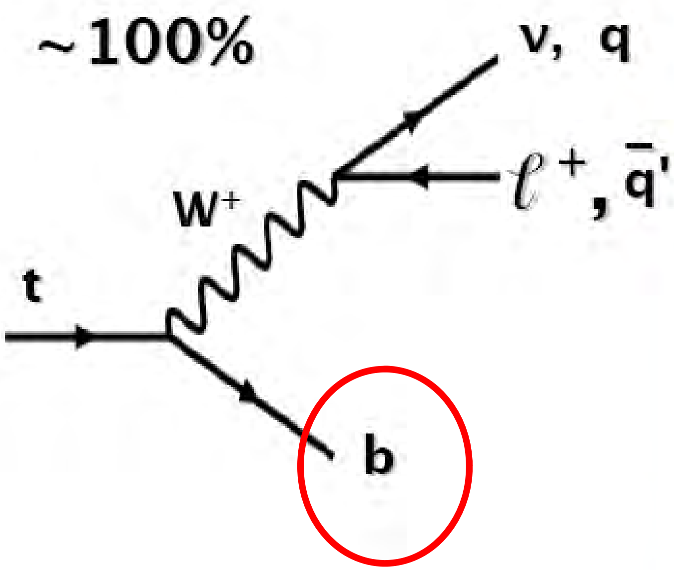


tW-channel

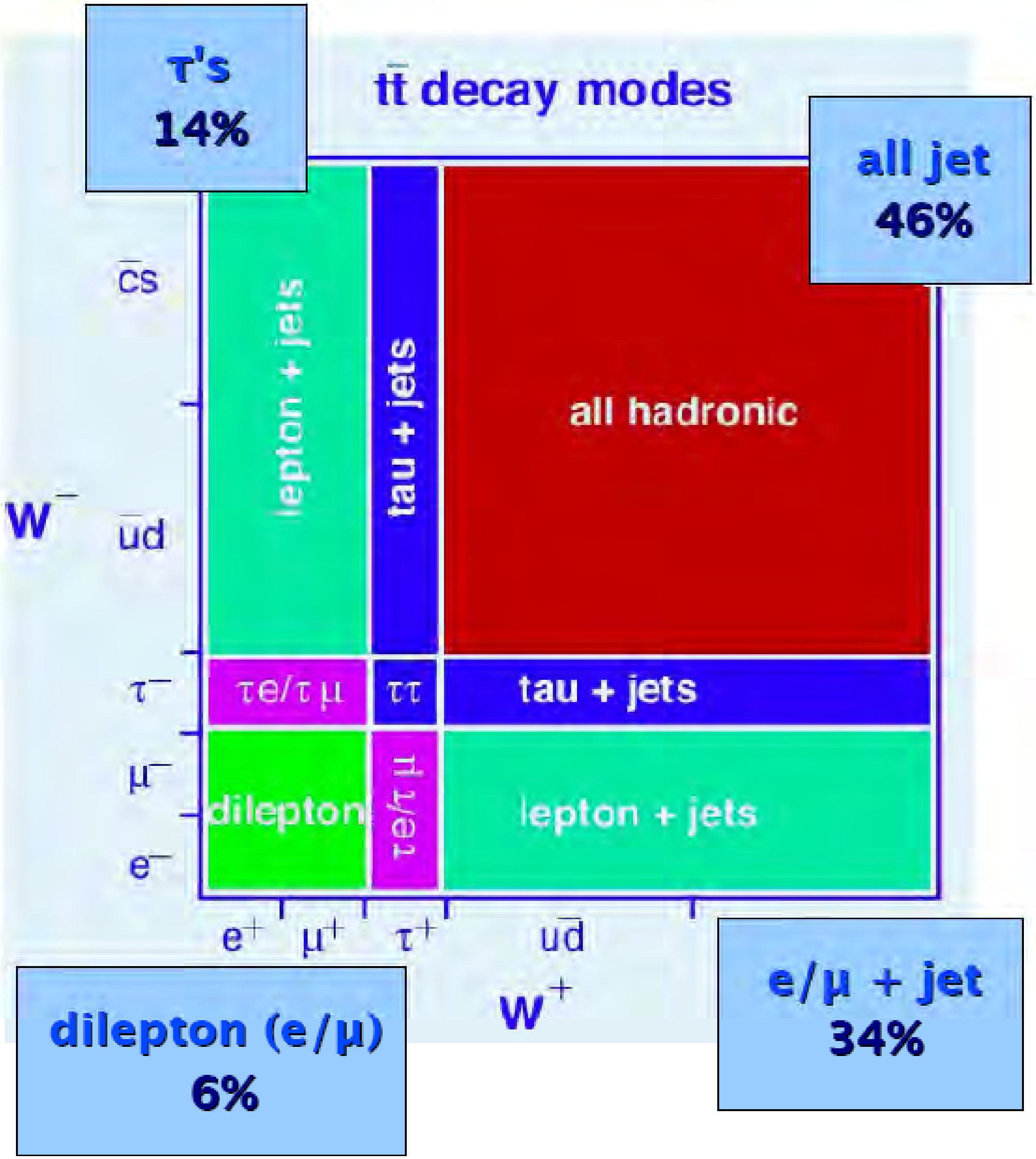


	Tevatron	LHC (14 TeV)
σ (s) (pb)	0.9	10
σ (t) (pb)	2.4	250
σ (tW) (pb)	0.1	60

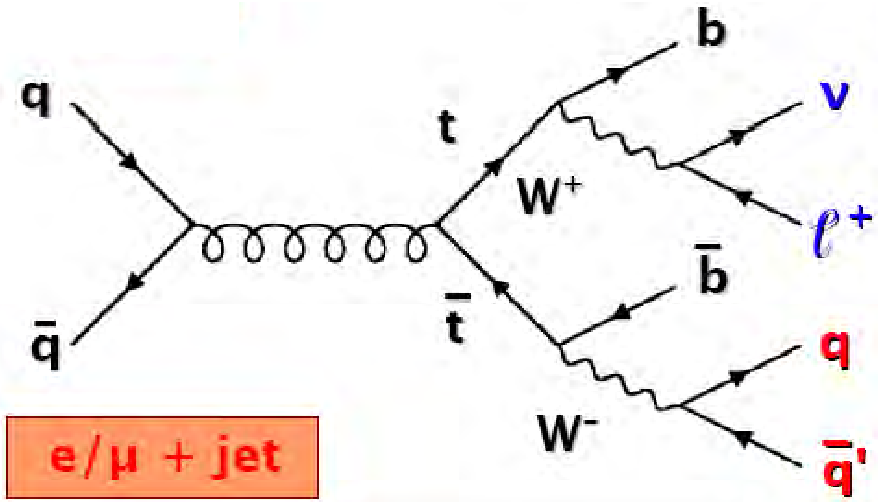
top decay:

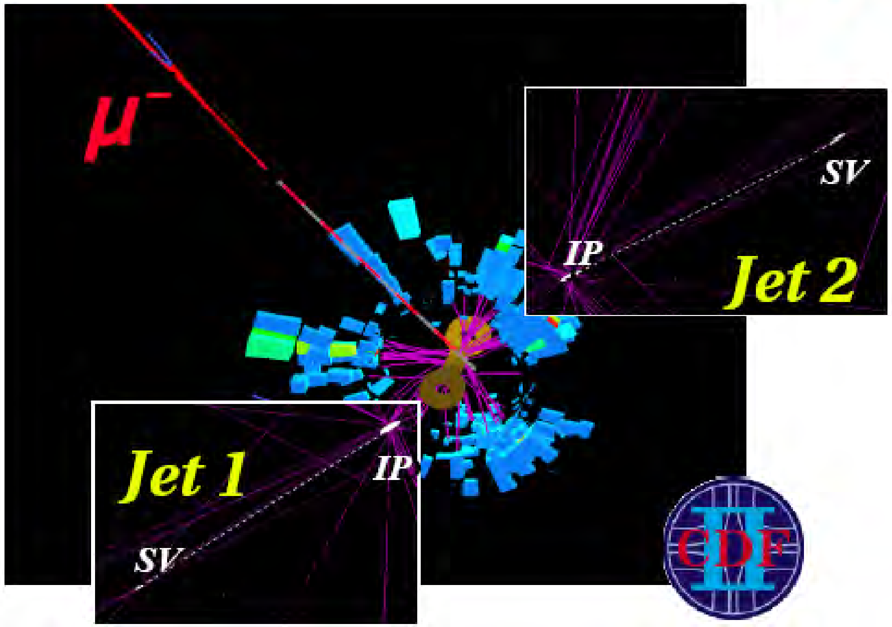


b-tagging important

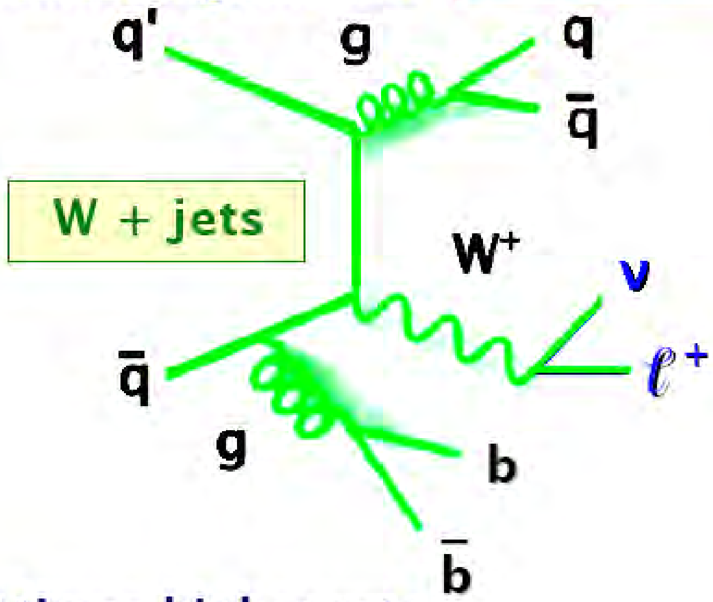


[Schwanenberger]

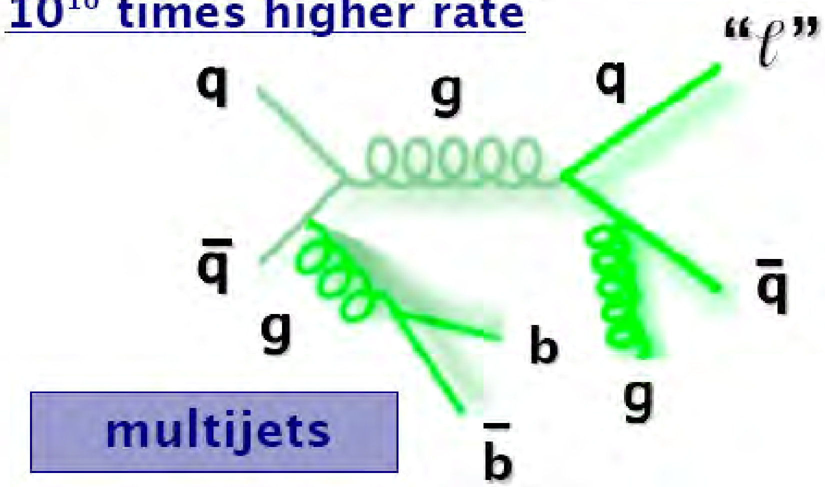




3000 times higher rate

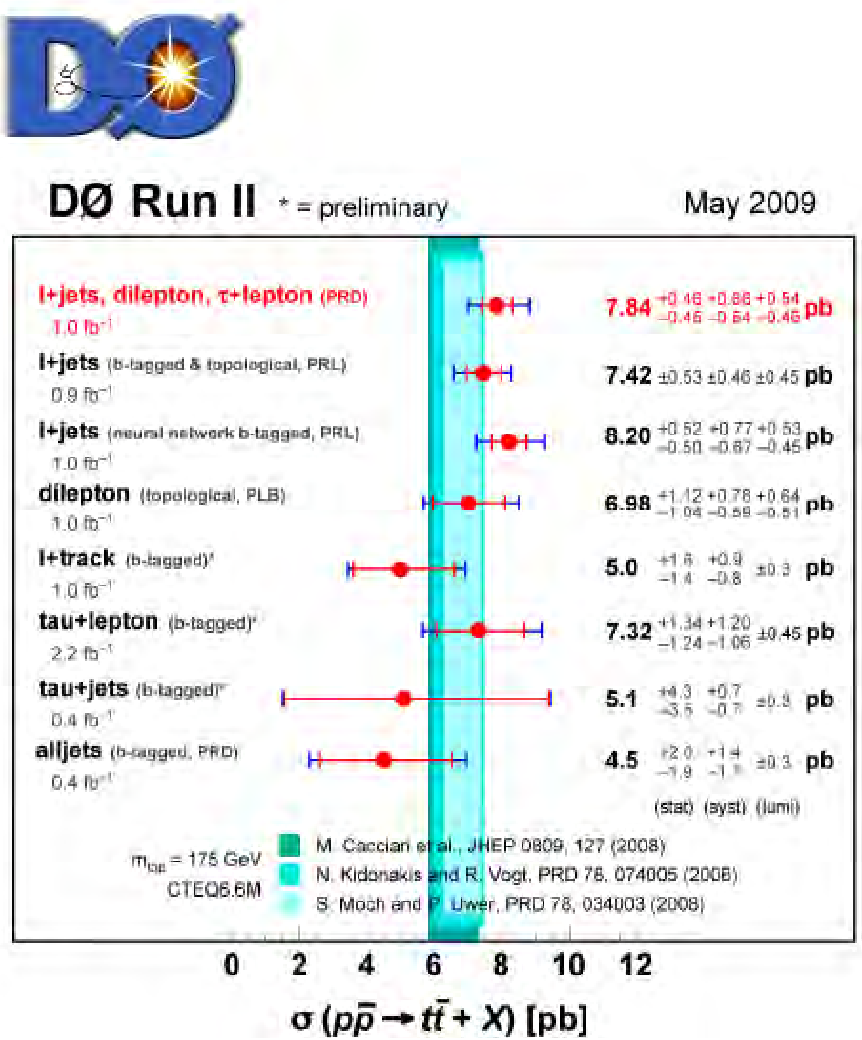


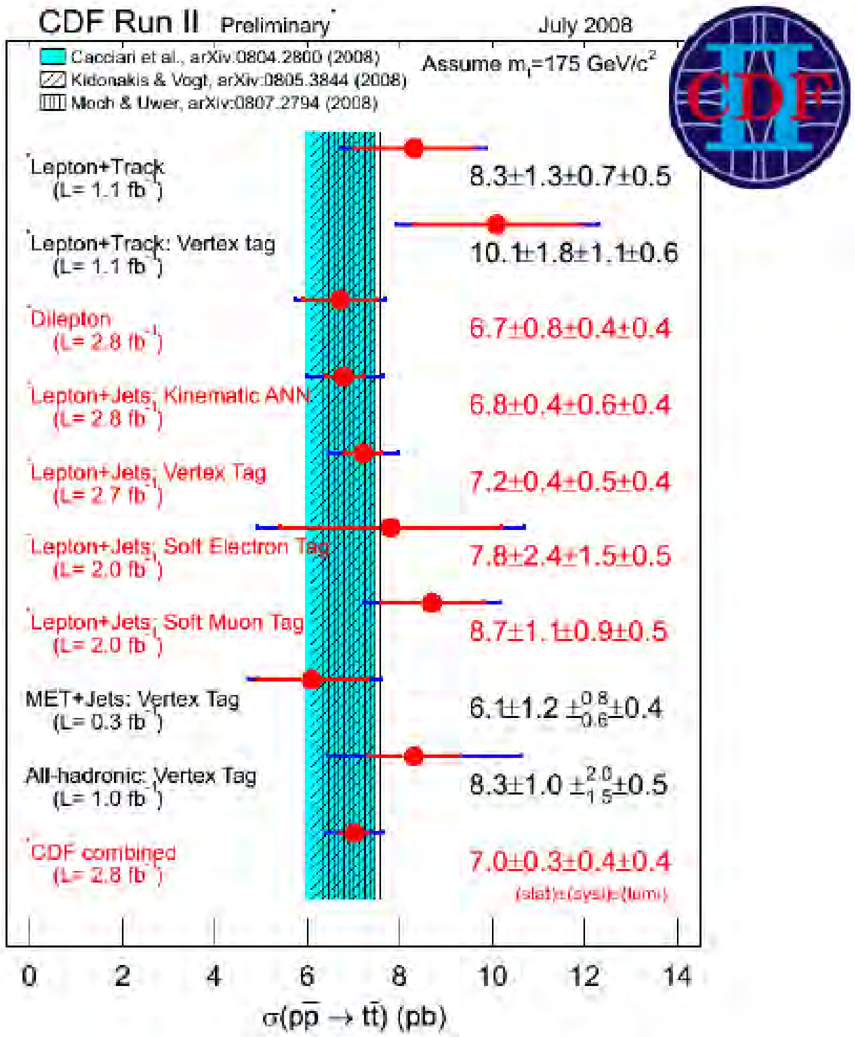
10^{10} times higher rate



[Schwanenberger]

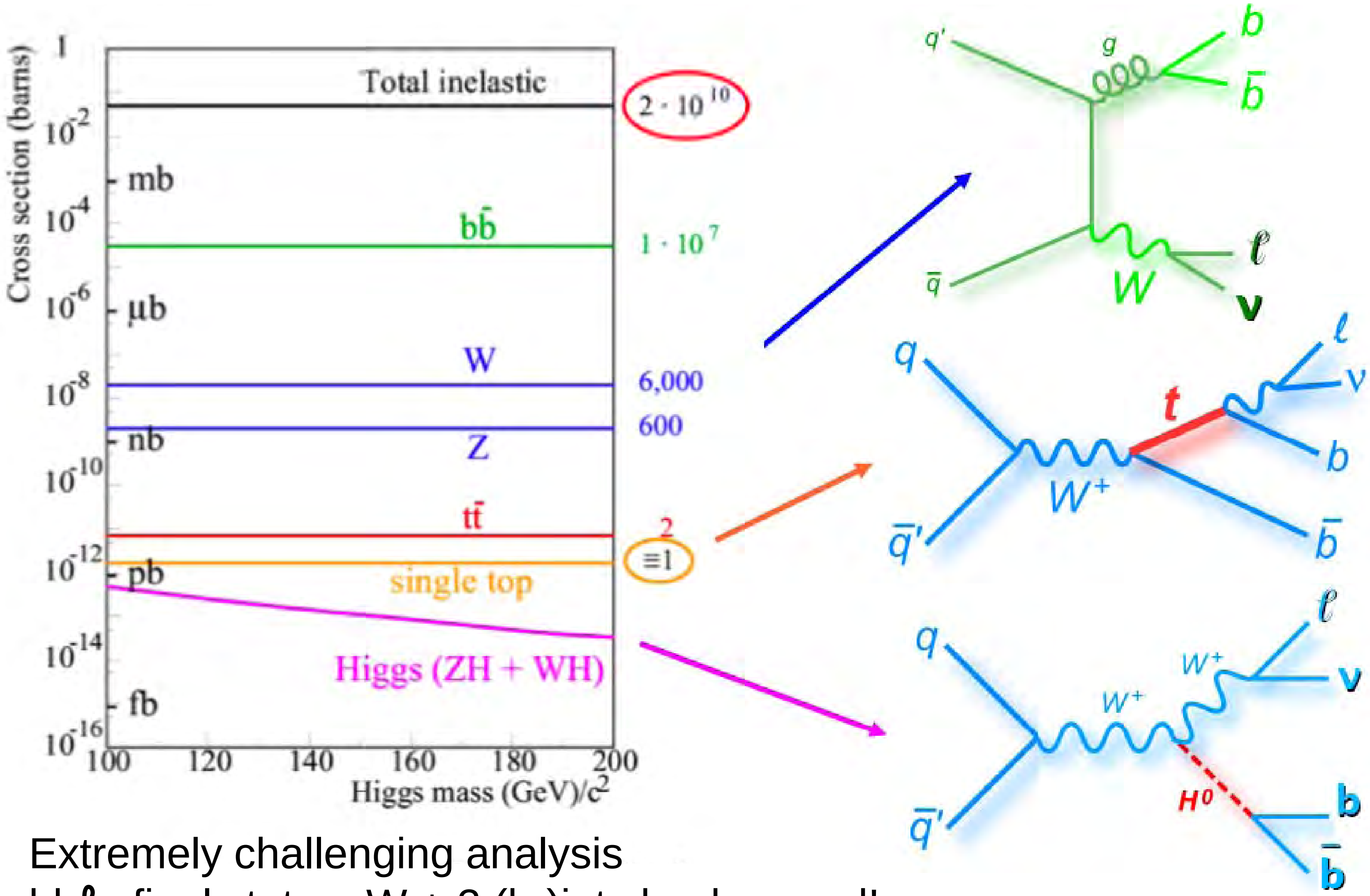
Top-Antitop cross section





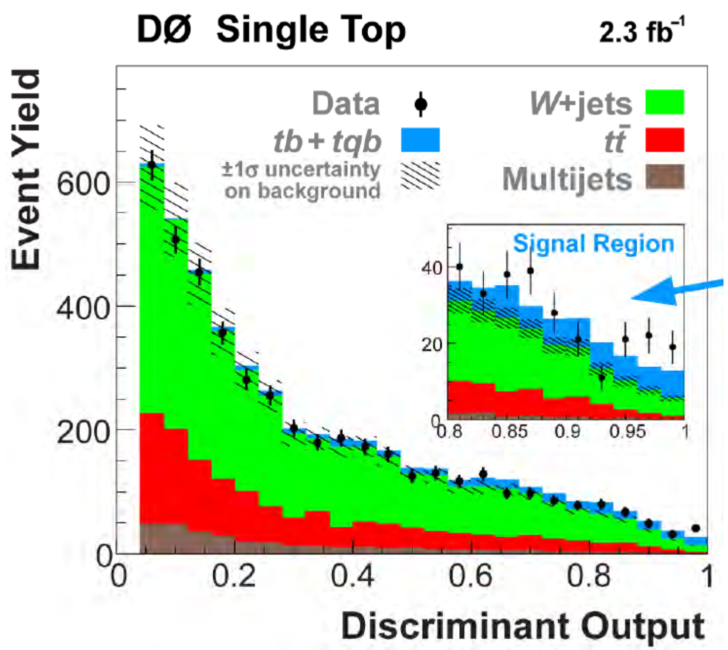
Measurements performed in ll, l(incl τ)+jets, all-jets channels

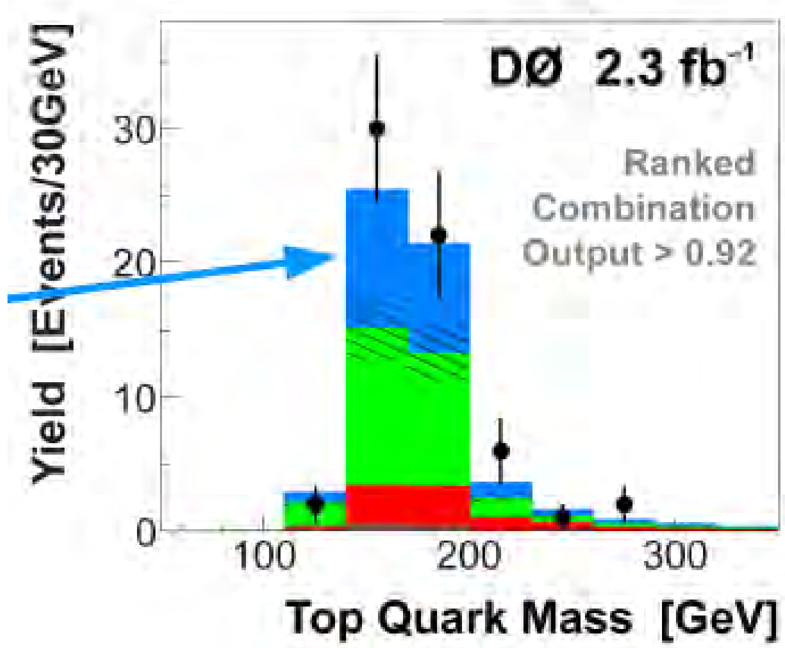
Good agreement with NLO-QCD



Extremely challenging analysis
bbℓν final state – W + 2 (b-)jets background!
complex multivariate analysis needed
important benchmark/milestone for (light) Higgs search

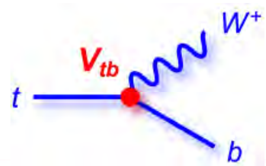
Single top production





Single Top Cross Section	Signal Significance Expected	Signal Significance Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
$2.3^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

assume SM production → observed rate ~ $|V_{tb}|^2$



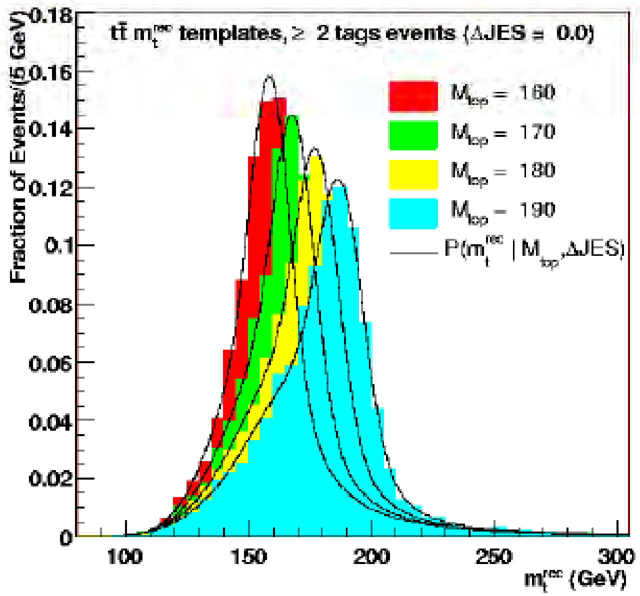
DØ: $|V_{tb}| = 1.07 \pm 0.12$

CDF: $|V_{tb}| = 0.91 \pm 0.13$

template method:

- reconstruct m_{top}
- compare data to MC with different m_{top} hypotheses

all hadronic



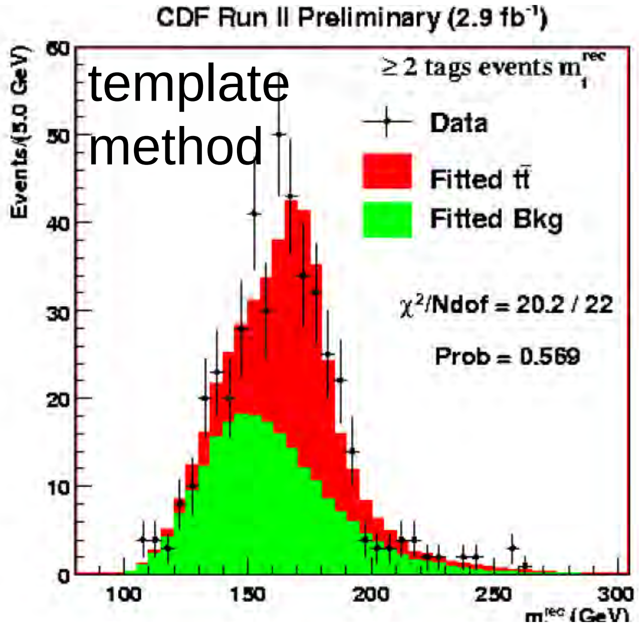
matrix element method:

- probability densities for every event as function of m_{top}

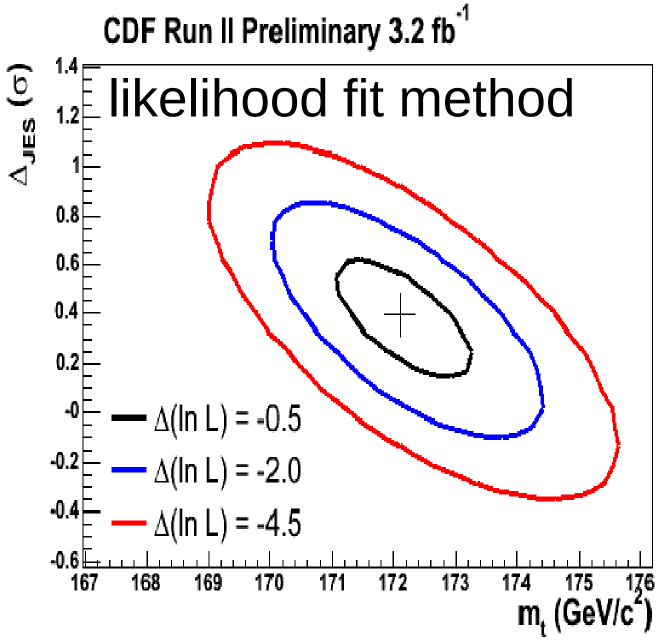
$$P_{sig}(x; m_{top}, JES) = \underbrace{Acc(x)}_{\text{Acceptance (selection, trigger,...)}} \times \frac{1}{\sigma} \int d^n \underbrace{\sigma(y; m_{top})}_{\text{LO-Matrix element x phase space}} \underbrace{dq_1\, dq_2\, f(q_1)\, f(q_2)}_{\text{PDF's}} \underbrace{W(x, y; JES)}_{\text{Transfer Functions (Probability to measure x when y was produced)}}$$

[Schwanenberger]

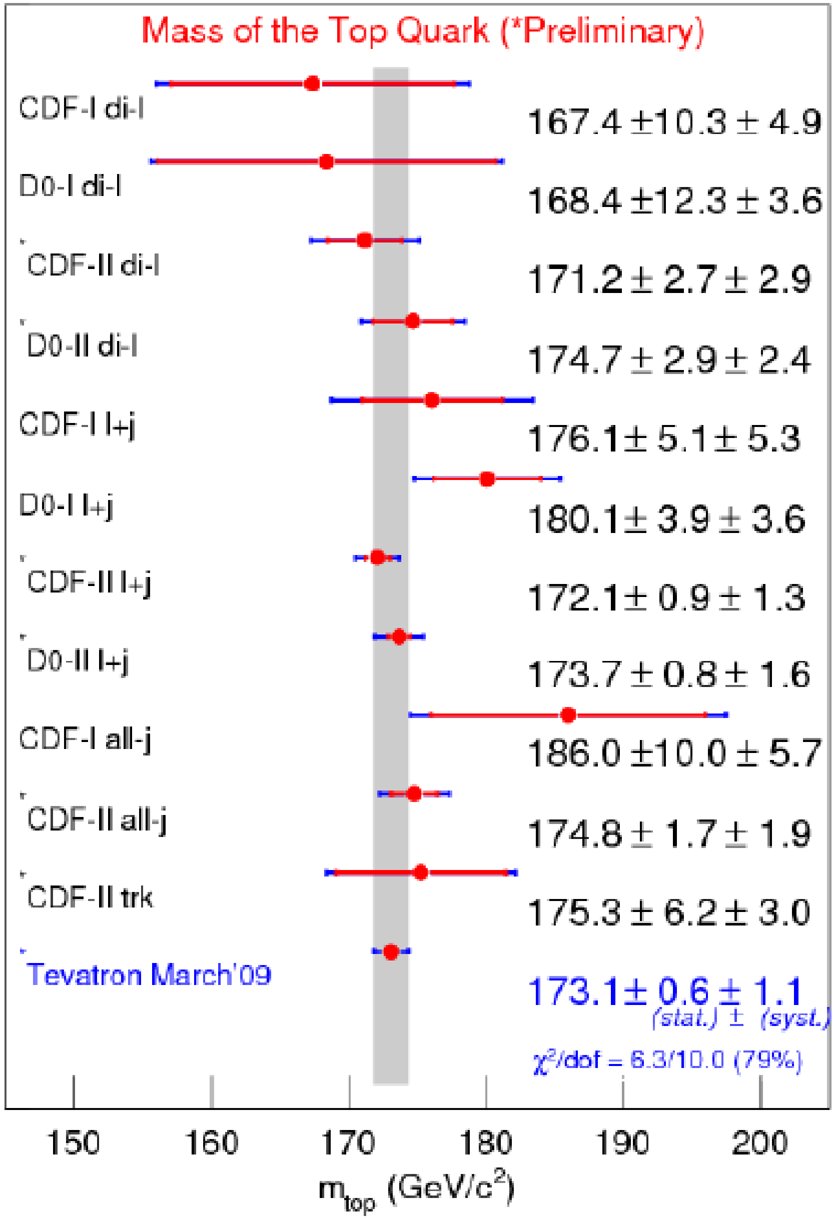
Top mass



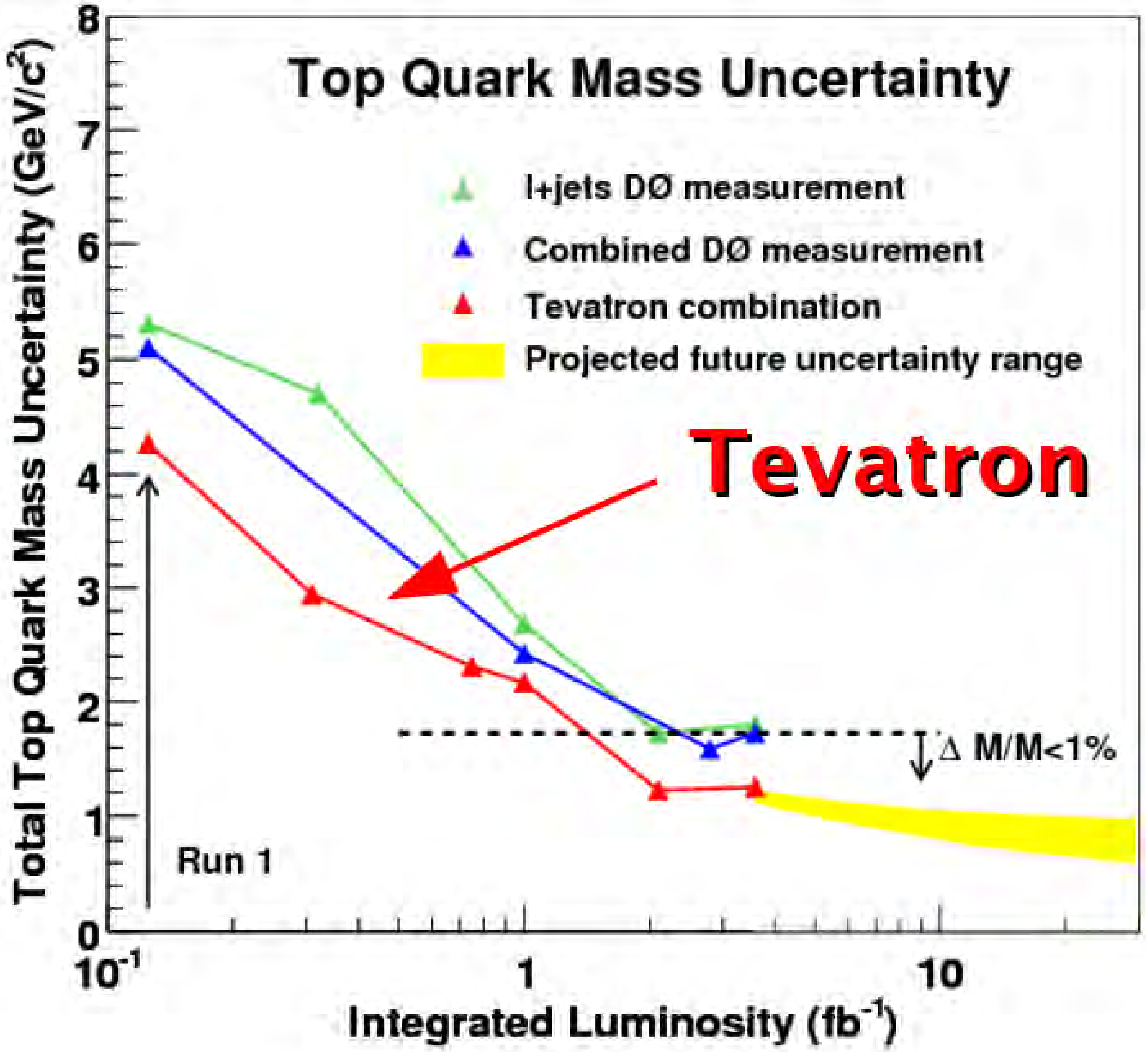
CDF Run II Preliminary (2.9 fb^{-1})
template method
≥ 2 tags events m_t^{rec}
Data
Fitted $t\bar{t}$
Fitted Bkg
χ^2/Ndof = 20.2 / 22
Prob = 0.569
Events/(5.0 GeV)
m_t^{rec} (GeV)



CDF Run II Preliminary 3.2 fb^{-1}
likelihood fit method
$\Delta(\ln L) = -0.5$
$\Delta(\ln L) = -2.0$
$\Delta(\ln L) = -4.5$
Δ_{JES} (σ)
m_t (GeV/c^2)



Mass of the Top Quark (*Preliminary)
CDF-I di-l 167.4 ±10.3 ± 4.9
D0-I di-l 168.4 ±12.3 ± 3.6
CDF-II di-l 171.2 ± 2.7 ± 2.9
D0-II di-l 174.7 ± 2.9 ± 2.4
CDF-I l+j 176.1 ± 5.1 ± 5.3
D0-I l+j 180.1 ± 3.9 ± 3.6
CDF-II l+j 172.1 ± 0.9 ± 1.3
D0-II l+j 173.7 ± 0.8 ± 1.6
CDF-I all-j 186.0 ±10.0 ± 5.7
CDF-II all-j 174.8 ± 1.7 ± 1.9
CDF-II trk 175.3 ± 6.2 ± 3.0
Tevatron March'09 173.1 ± 0.6 ± 1.1
(stat.) ± (syst.)
χ^2/dof = 6.3/10.0 (79%)
m_{top} (GeV/c^2)

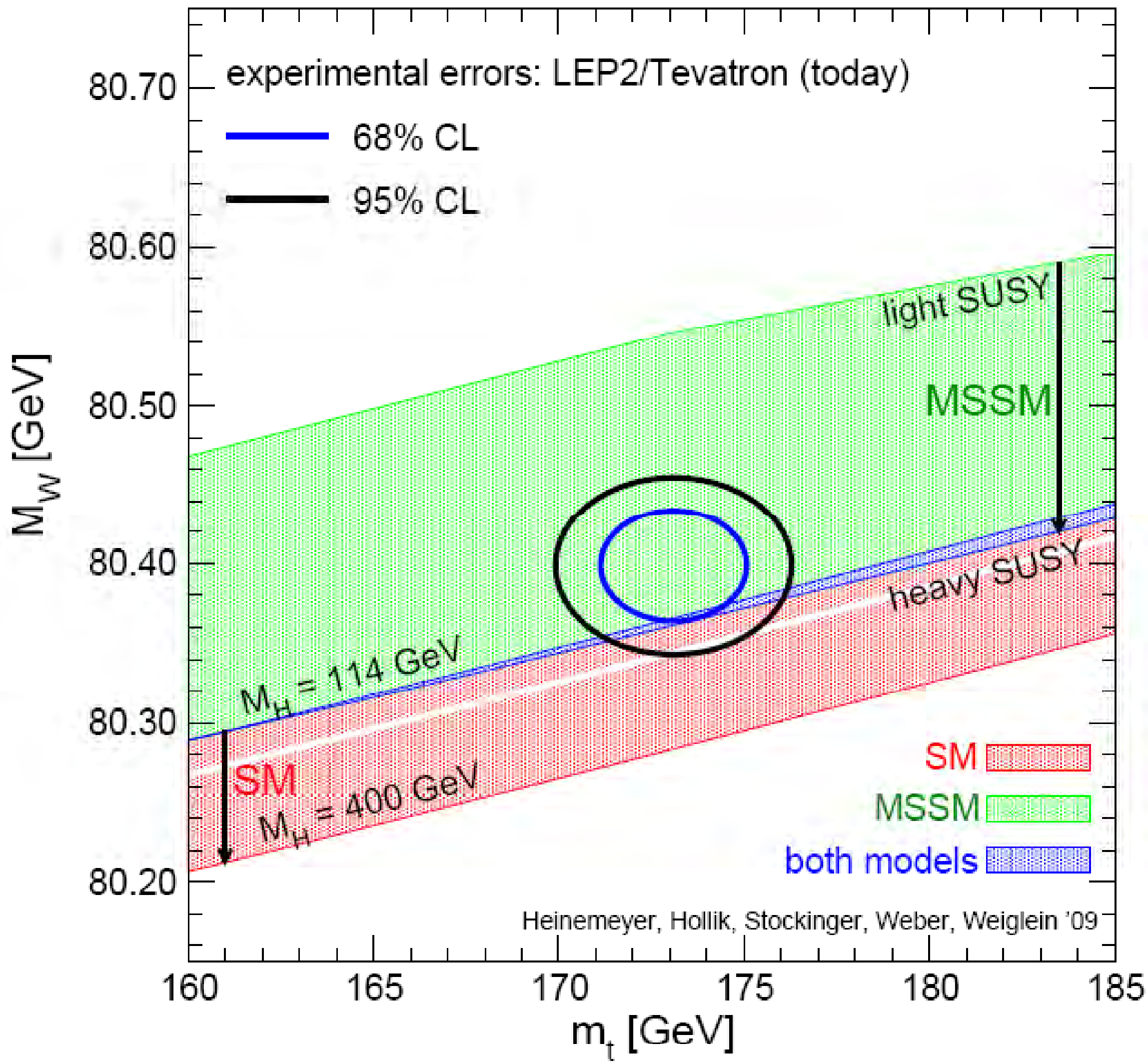


systematic limit reached

further improvement
will be slow

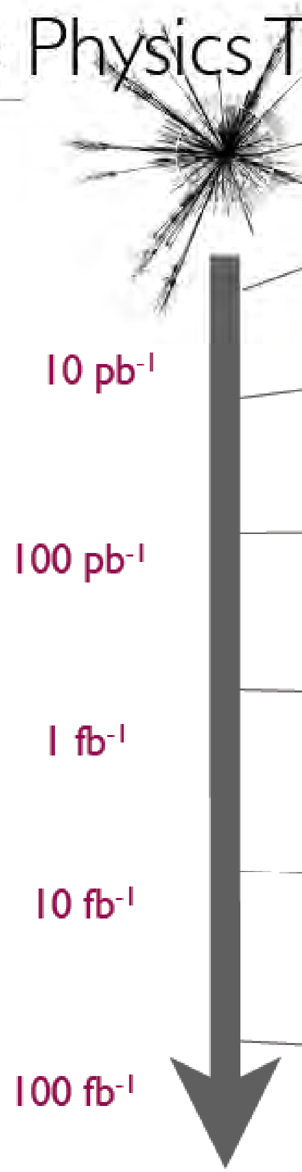
M_{top} vs. M_W: the SM health indicator

The SM (with G_F, m_Z, $\sin^2\theta_W$ as input) can predict m_W vs. m_{top} from quantum corrections



→ lectures by M.Grünewald

Top Physics Timeline at the LHC



Top for commissioning:
The first observation of the top quark is a landmark event for the initial detector commissioning.

Early Measurements:
tT cross section will be among the first top physics measurements to be made.

Top for calibration:
The top mass and the tT topology are strong tool for understanding the detector.

Top as background:
Good understanding of the top is crucial to the discovery of new physics.

Precision measurements:
Precision-measurement of top properties and single top can be performed with accumulated data.

Discovery through top:
Study of the top quark may itself lead to the discovery of new physics.

HCPS2008 - May 27, 2008 akira.shibata@nyu.edu

Top-physics topics of interest

tT cross section :
- tT semileptonic (lepton + jets)
- tT dileptonic
- tT fully hadronic

Top mass:
- tT semileptonic (using hadronic jets)
- tT dileptonic (using leptons)

Top property:
- top charge
- top width
- tT spin correlation
- W helicity
- Yukawa coupling
- anomalous coupling
- resonance production

Single top measurement:
- s-, t-, Wt cross section
- Vtb measurement
- top polarization

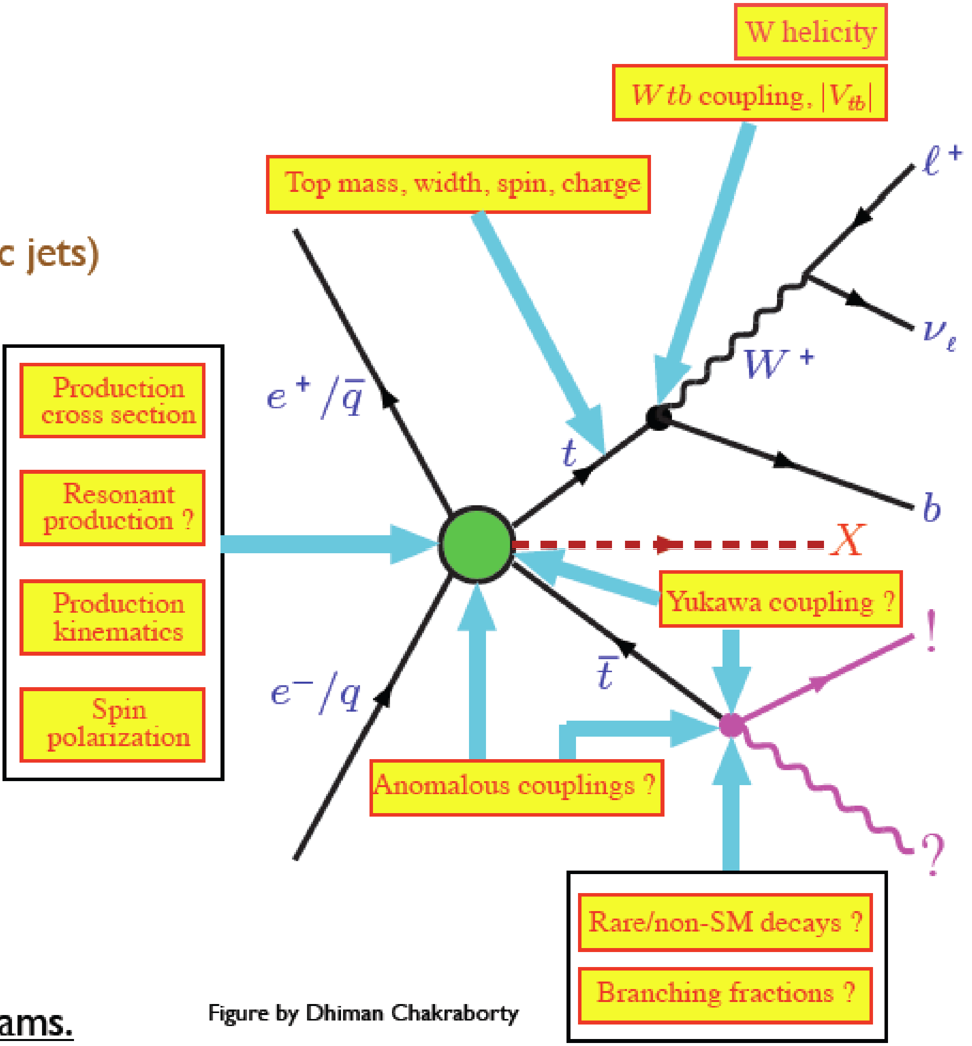


Figure by Dhiman Chakraborty

A rich collection of physics programs.

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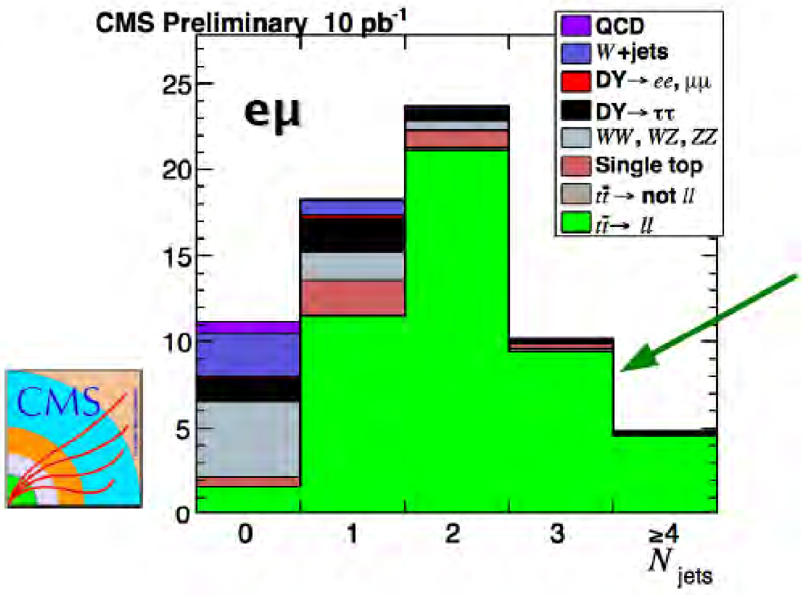
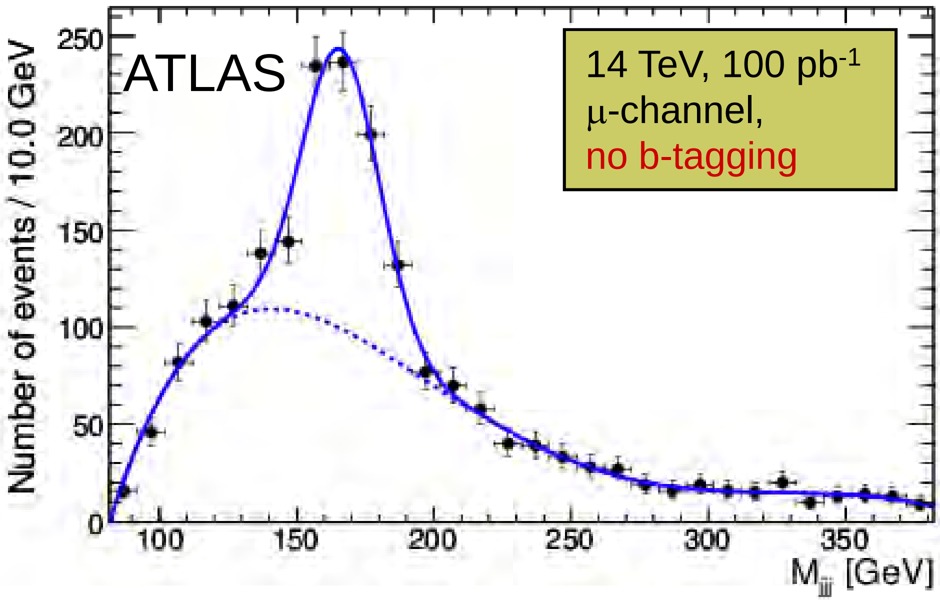
6. Physics	LHC: The first top quarks to be seen in Europe



Rediscovery possible with $10\ pb^{-1}$ at 10 TeV

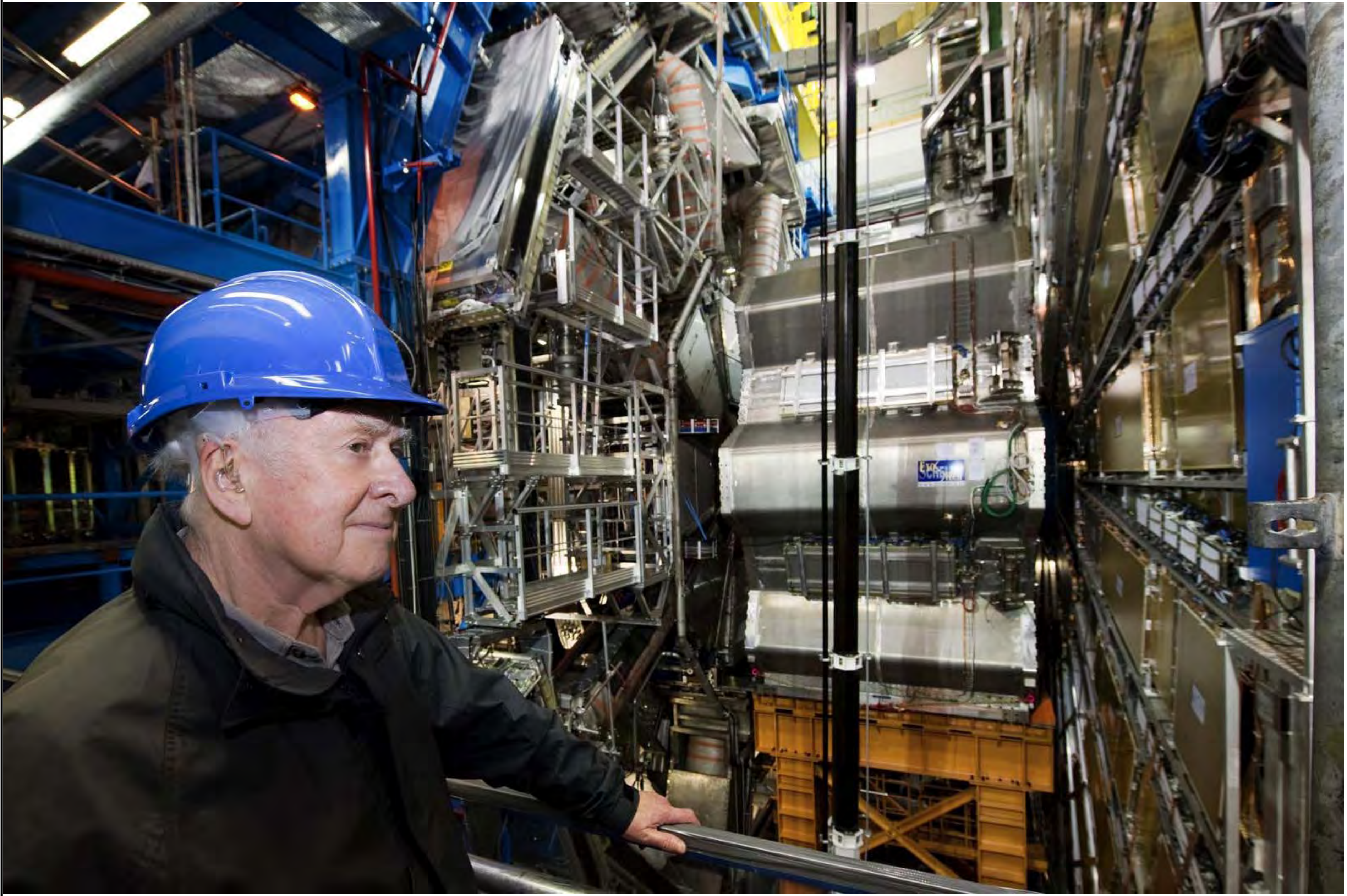


$\sqrt{s}$ = 10 TeV, after cuts:
~ 15 l=e,μ events per pb^{-1}
but ~ 3x less at $\sqrt{s}$ = 7 TeV

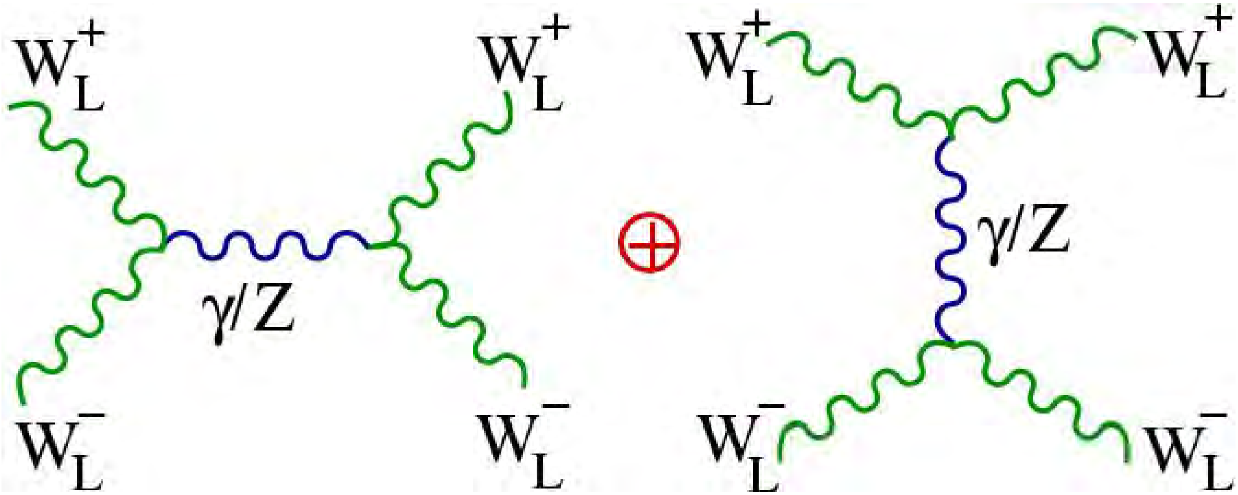
Ideal calibration source for most physics objects:
e,μ,τ,jets,b-jets,miss.-E

Higgs Bosons

Higgs Bosons



Quantum field theory with massive exchange particles fails at high energies:



cross section:
$\sigma \sim s^2$
violates unitarity at
$\sqrt{s} \sim 1.3$ TeV

(if forces remain weak)

"if nothing happens, something must happen..."

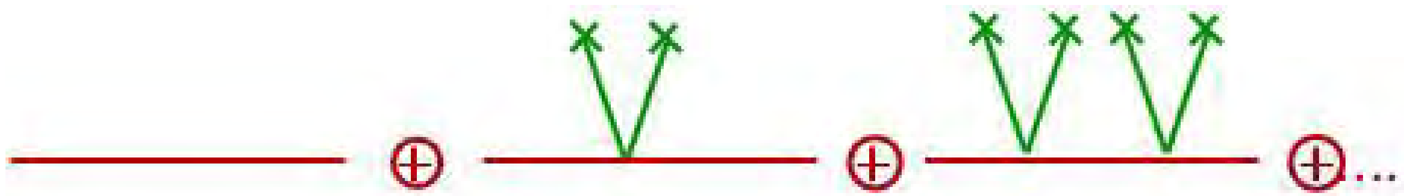
<u>The Standard Model Solution:</u>
(rescue plan for the gauge principle)
Introduction of a new scalar field with non-vanishing field strength in the vacuum: the Higgs field.

Paradigm:

All (elementary) particles are massless

⇨ gauge principle works
⇨ renormalizable theory (finite cross sections)

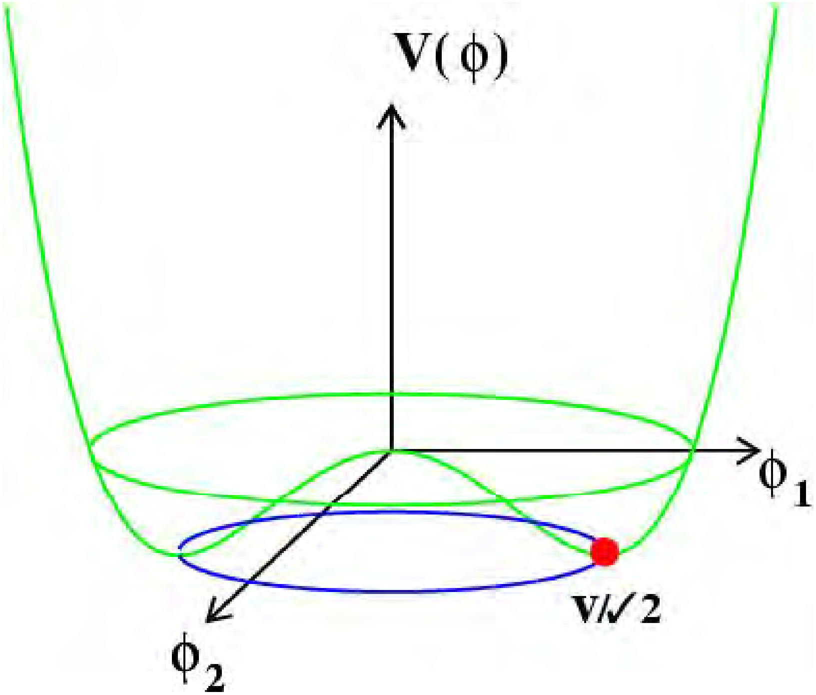
permanent interaction with the Higgs field acts, as if the particles had a mass (effective mass)



$$\left(\frac{1}{q^2}\right) \oplus \left(\frac{gv}{\sqrt{2}}\right)^2\left(\frac{1}{q^2}\right) \oplus \left(\frac{gv}{\sqrt{2}}\right)^4\left(\frac{1}{q^2}\right)^2 \oplus \ldots$$

$$= \quad \frac{1}{q^2 - M^2} \quad with\ M^2 = g^2\frac{v^2}{2}$$

How to add such a field in a gauge invariant way?



"Mexican hat-Potential"

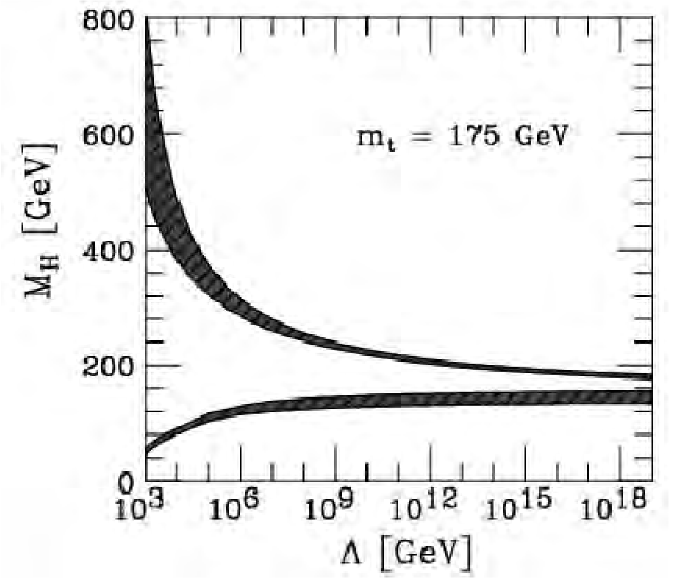
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

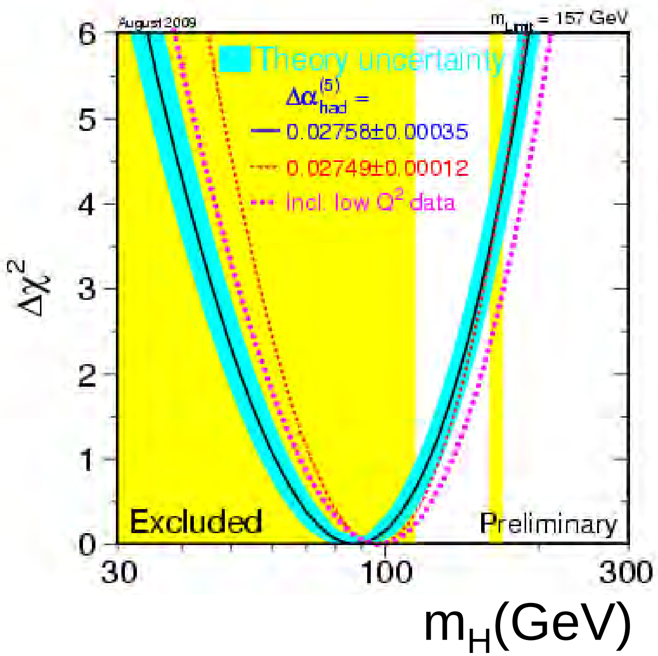
most simple case: Φ =complex doublet of weak isospin (=SM)

but this is a pure guess
many more possibilities, e.g.:
2 doublets (minimal SUSY),
triplets,…

models with "true" and "effective" mass are not equivalent:

formulation with the help of Higgs mechanism:
- is gauge invariant
- postulates at least 1 scalar, massive Higgs boson





Theory:

Upper bound: perturbativity (l<1)
Lower bound: vacuum stability
Models: minimal SUSY: m<135 GeV
GUT's : m<180 GeV

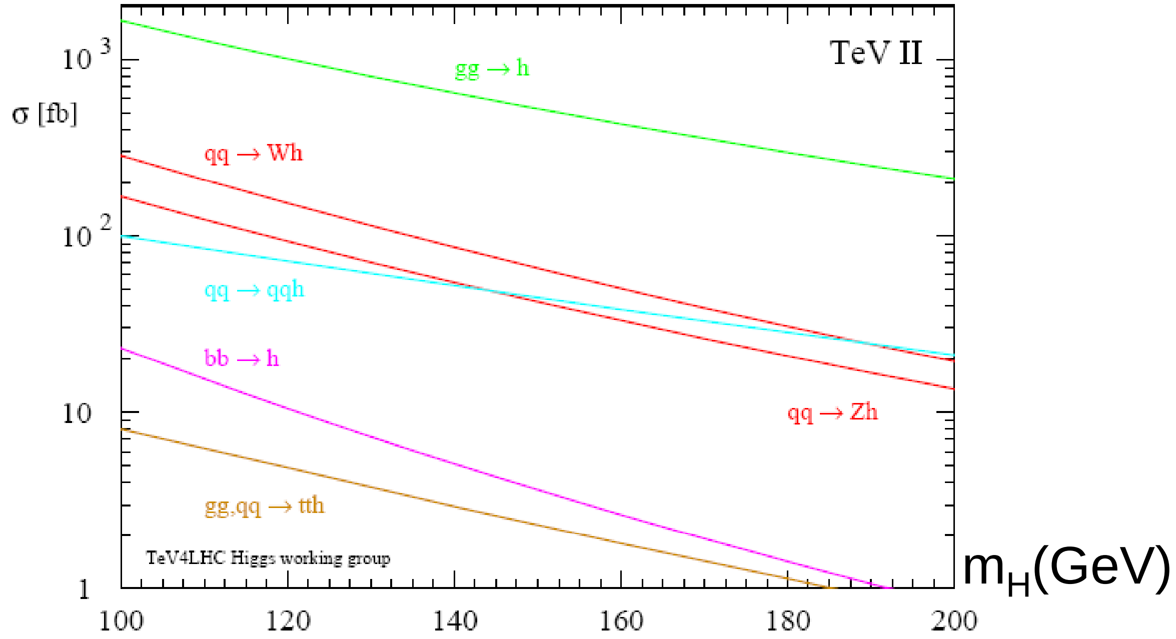
Experiment:

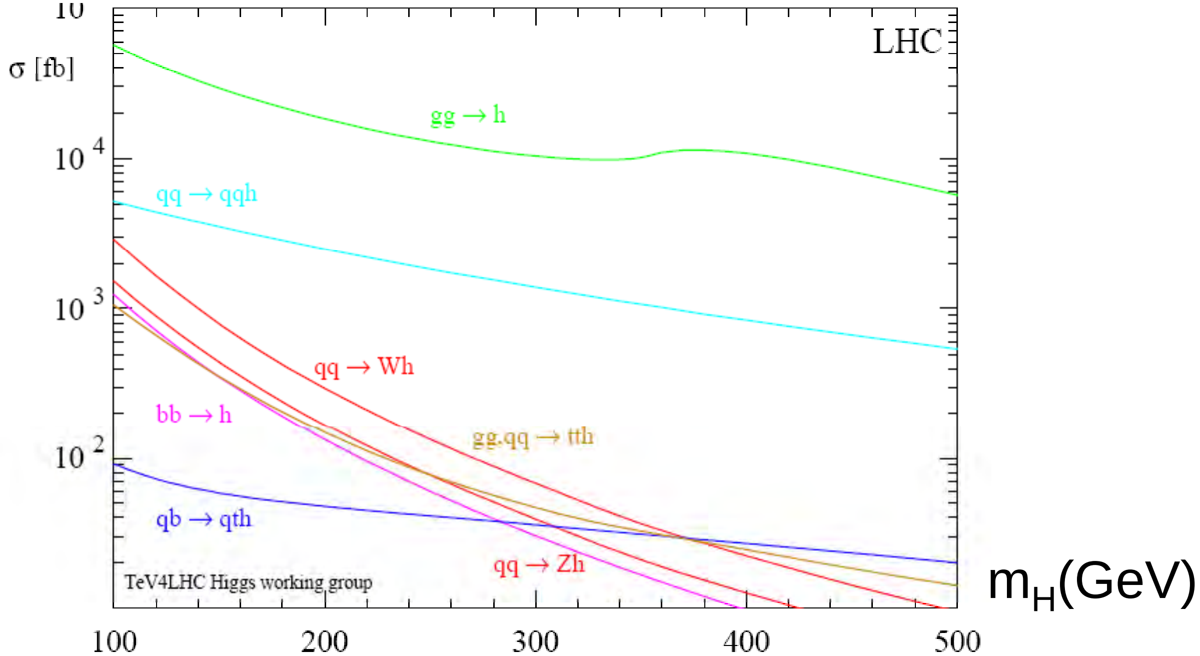
Precision measurements (LEP,SLC,Tevatron) are sensitive to virtual corrections:

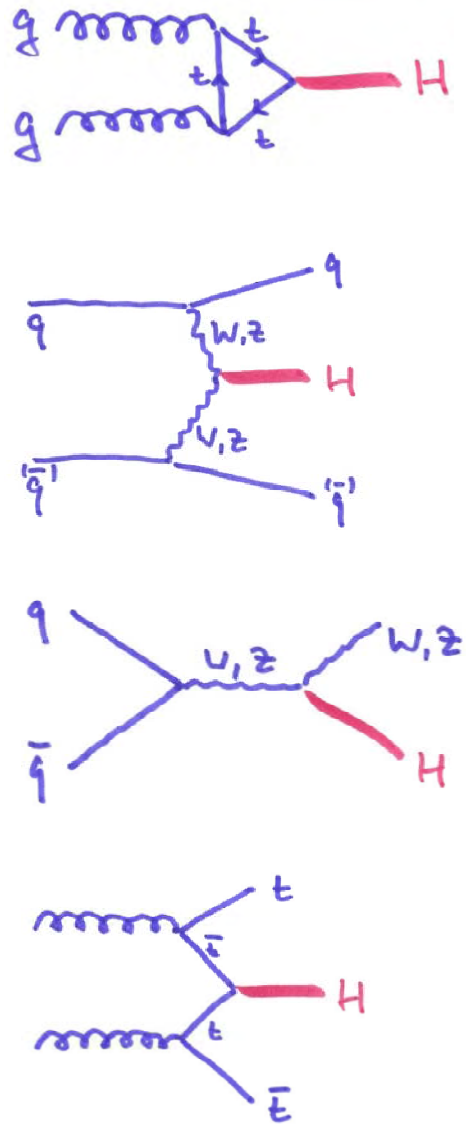
m<250 GeV (95% CL) within SM

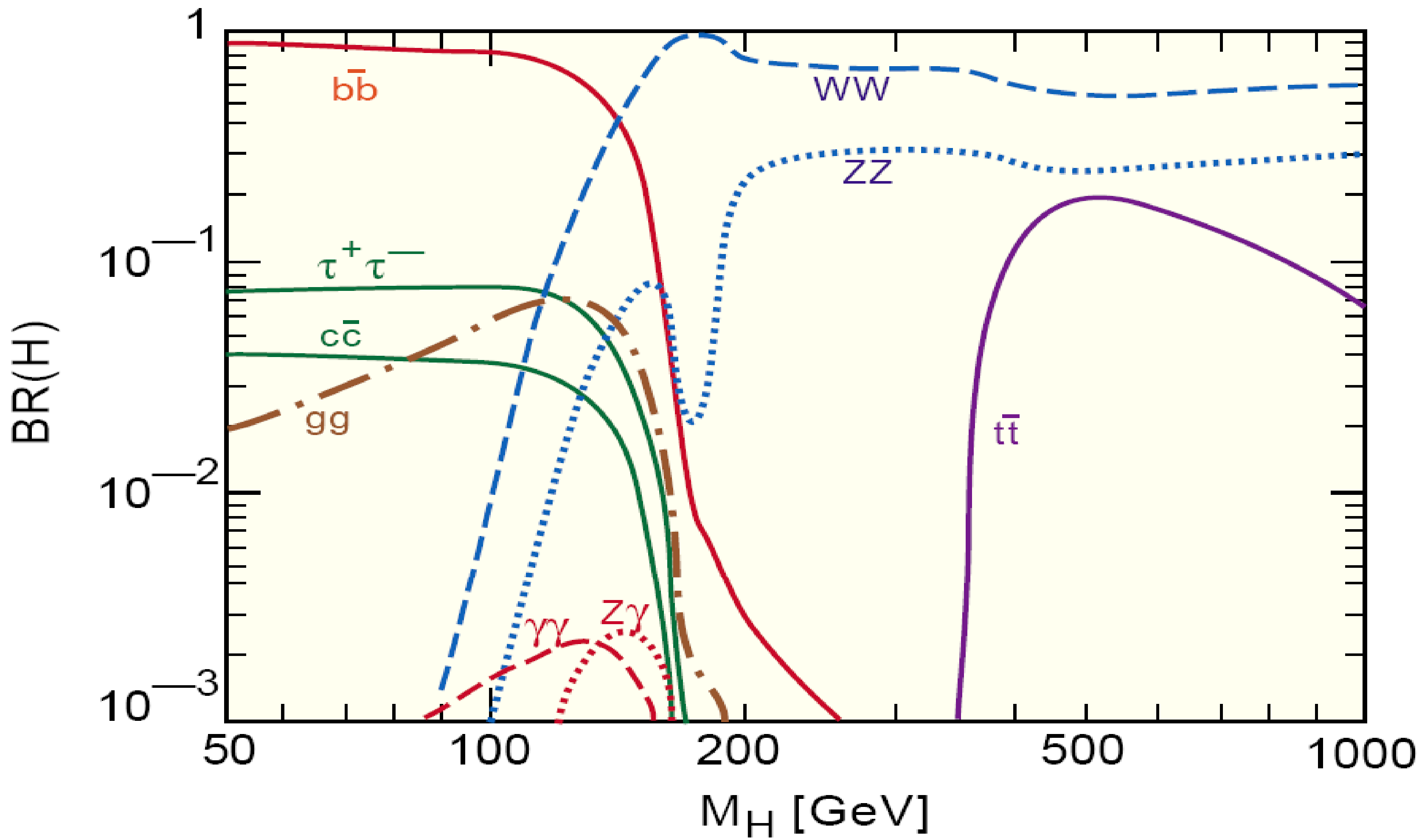
The Higgs boson is probably "light"!

Higgs production at hadron colliders







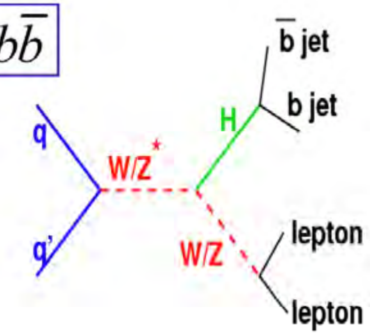


Only few combinations of production and decay can be used at hadron colliders
„good" signatures (γγ, ℓℓℓℓ) have small BR´s
for light (<130 GeV) Higgs, bb-mode can only be used in assoc. production

6. Higgs search | at Tevatron: main search channels

at low mass (<135 GeV)

$\boxed{H \to b\bar{b}}$



$WH \to \ell \nu b\bar{b}$

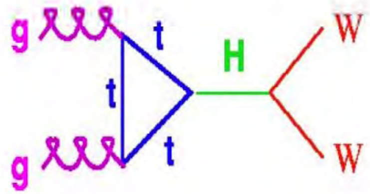
$ZH \to \ell^+ \ell^- b\bar{b}$

$ZH \to \nu\bar{\nu} b\bar{b}$

at high mass (>135 GeV)

$\boxed{H \to WW^{(*)}}$

$WW \to \ell \nu \ell' \nu'$



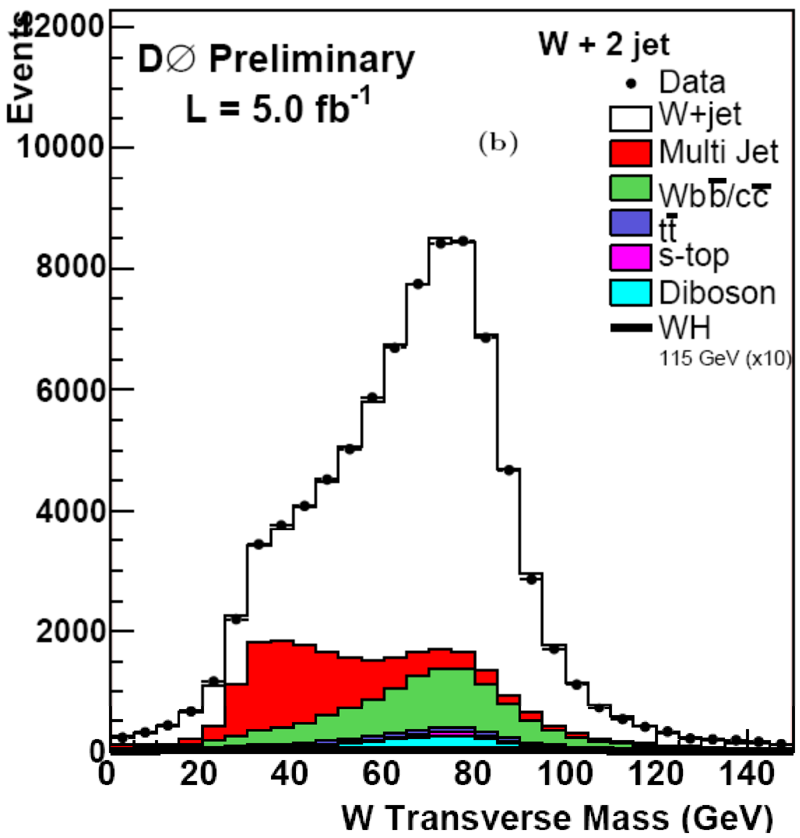
critical experimental issues:

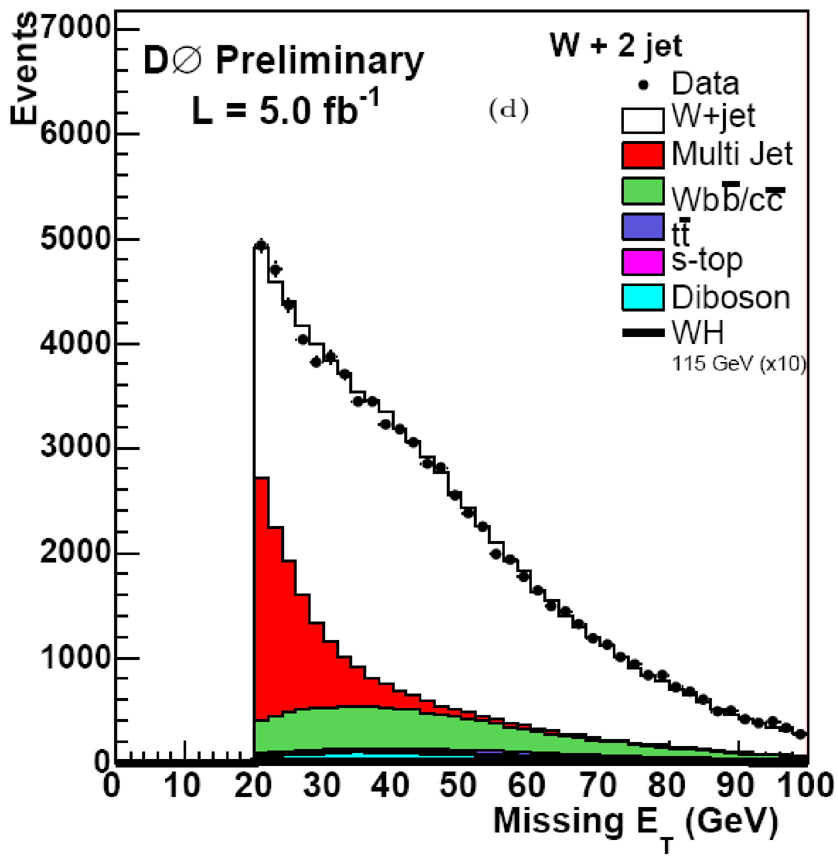
low mass: b-tagging, jet-energy resolution (di-jet mass = m_H)

high mass: missing transverse energy, background modelling

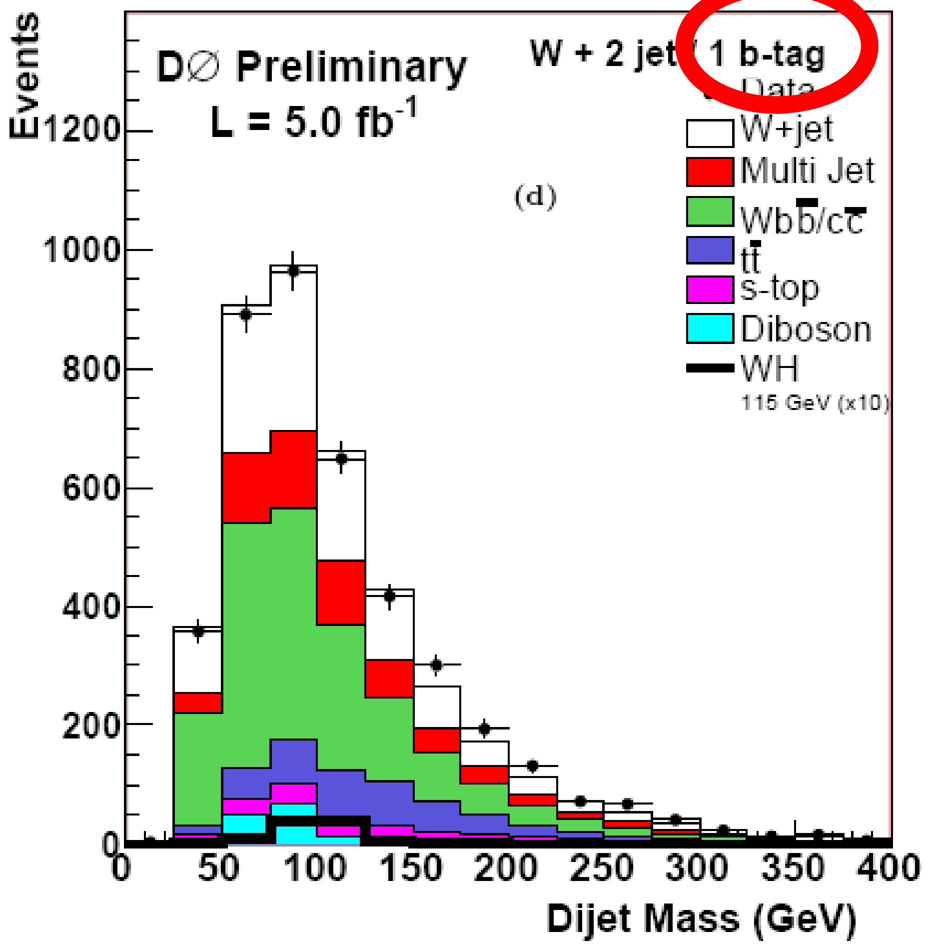
Starting point: W(→ ℓν)+2jet events:

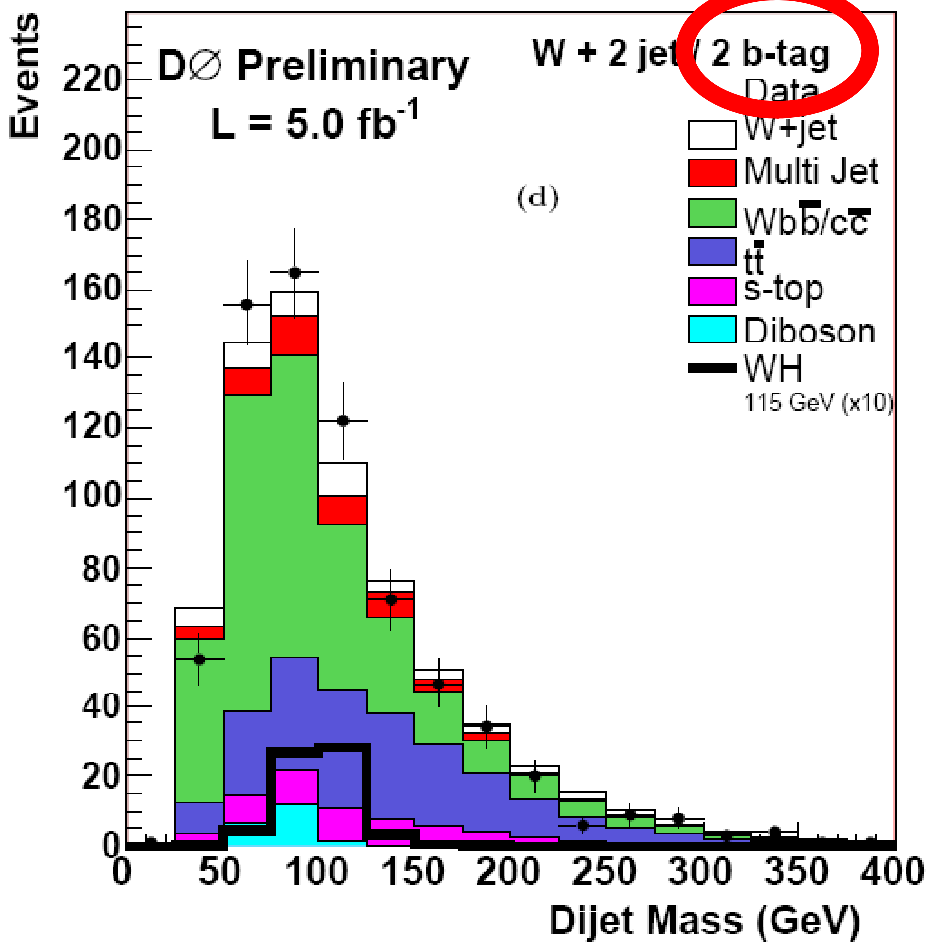
look at many observables and make sure, they are modelled correctly (Higgs negligible at this stage)





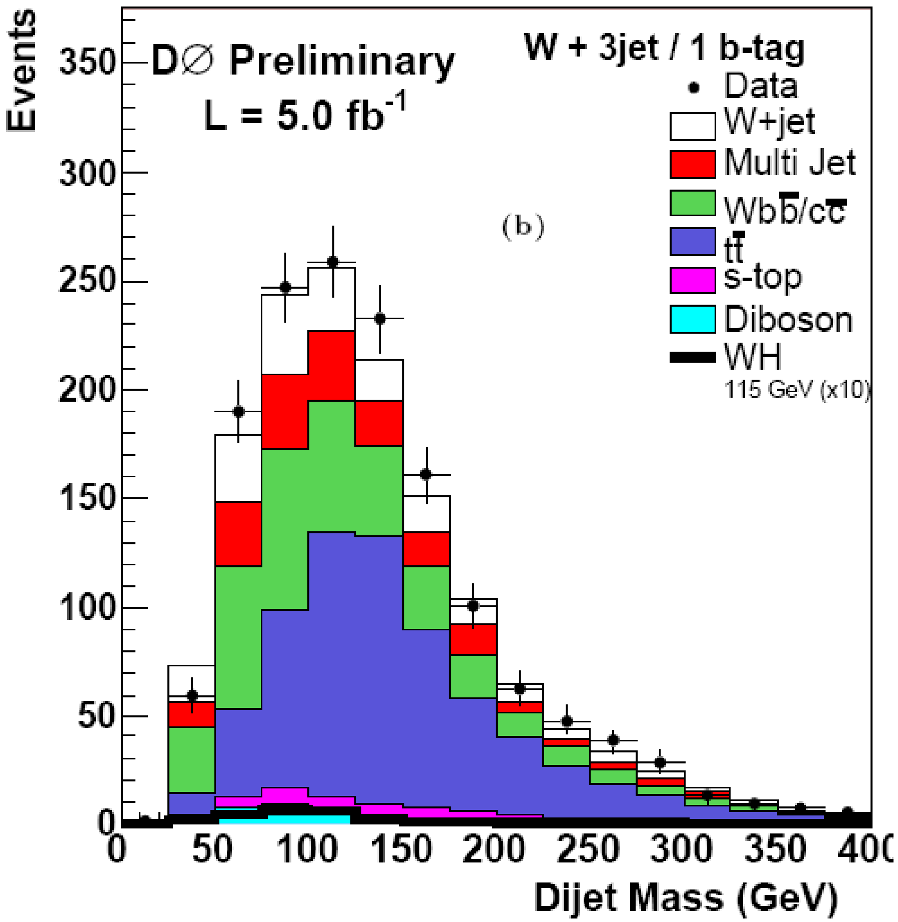
Next: apply b-tagging (2 categories: 1 b-tag, 2 b-tags)

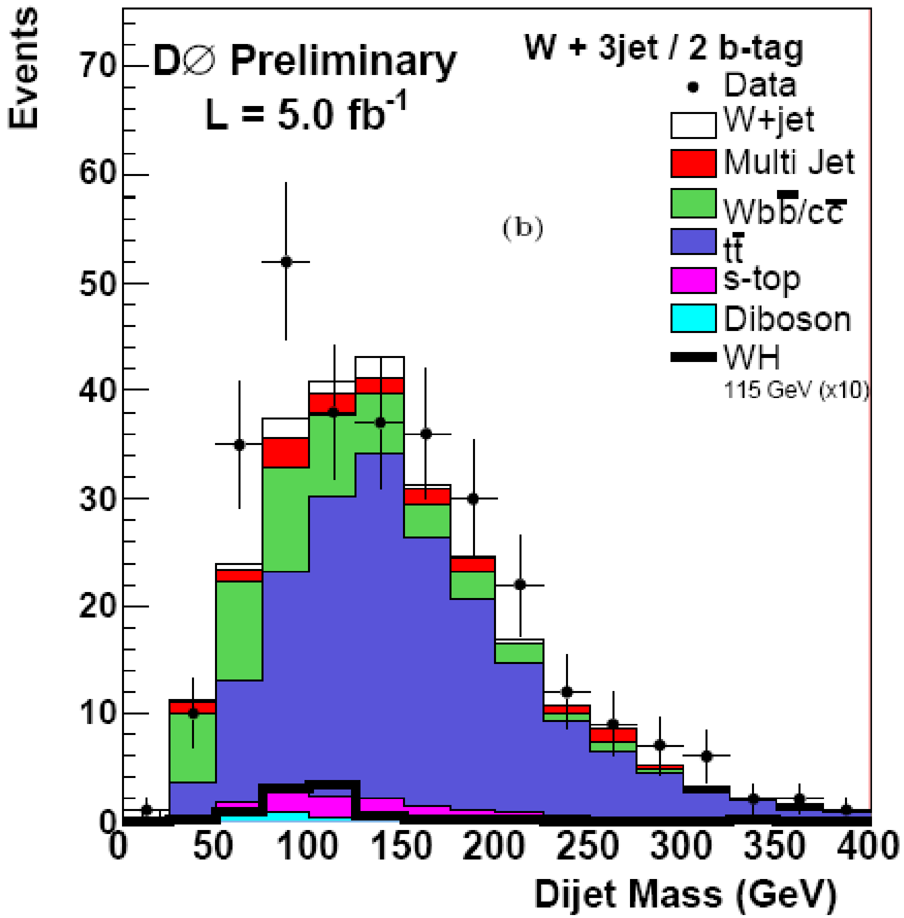




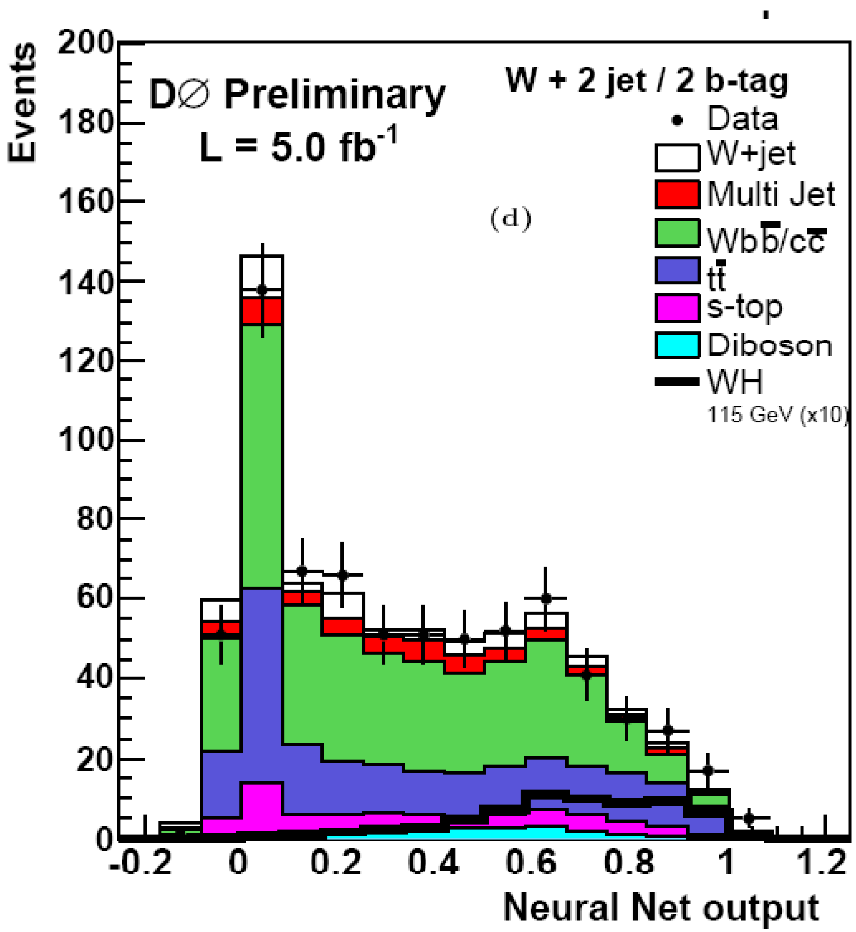
→ Higgs x10 becomes visible

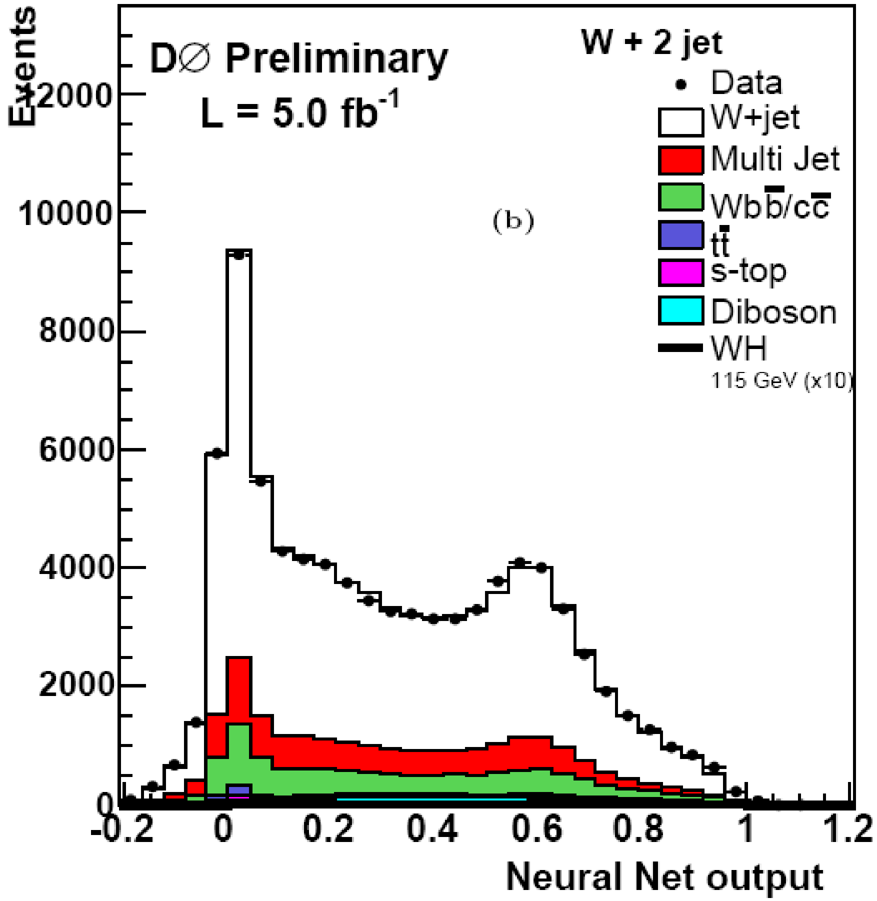
in addition look at W+3jets (different BG composition…)





Then apply m_H-dependent neural network to check for compatibility with HW production

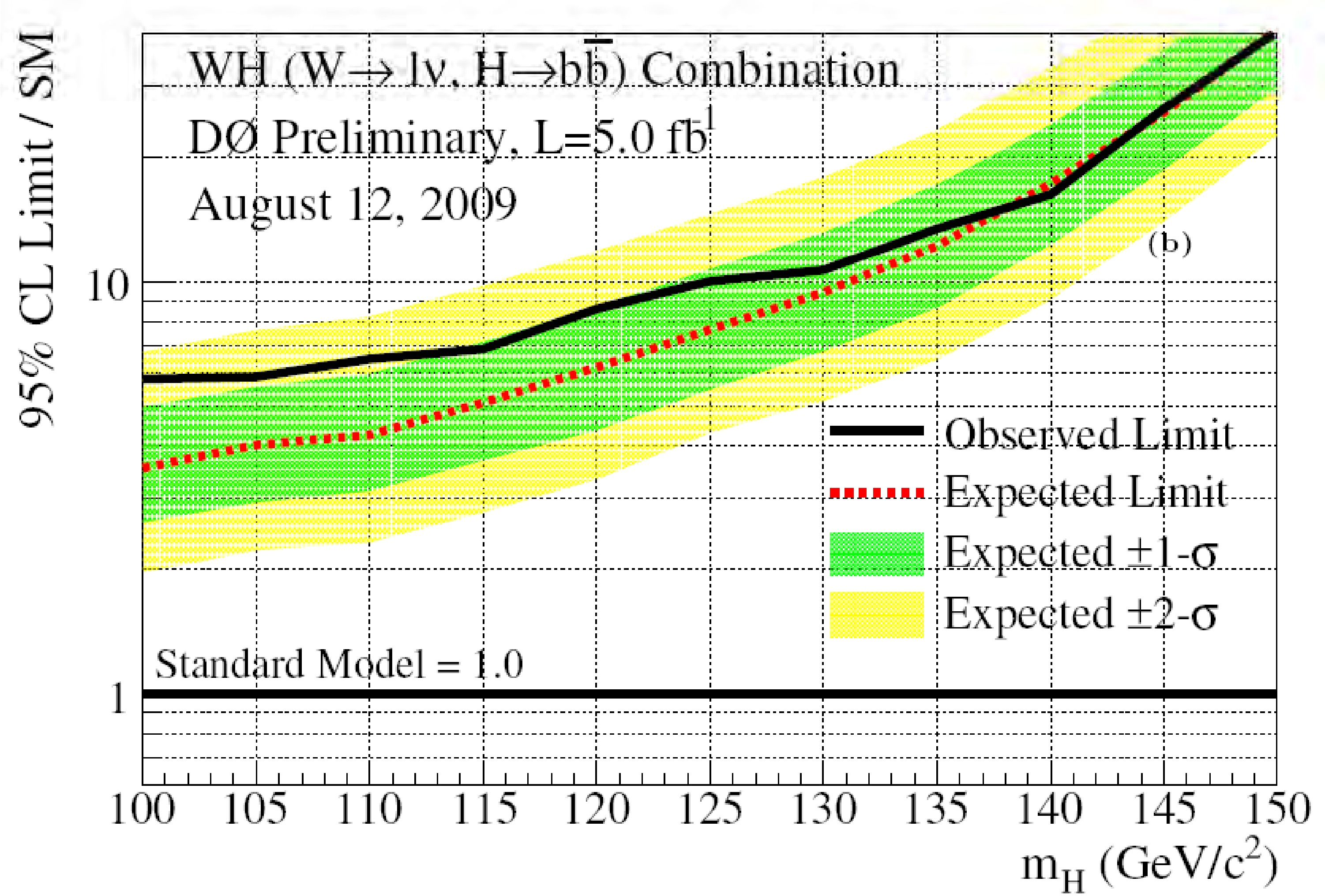




check that the NN does what it should on the sample before b-tagging

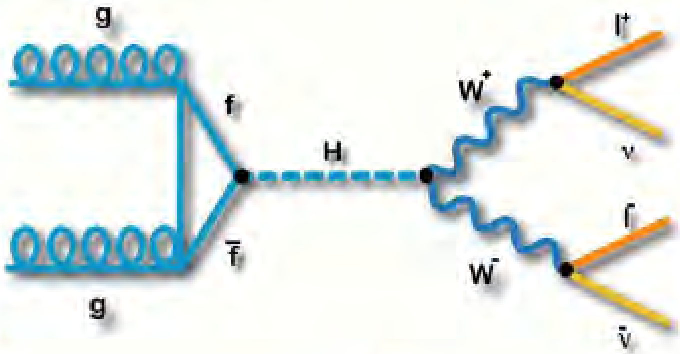
at Tevatron: example WH → bbℓν @ D0

no significant excess at high NN-outputs
→ calculate CL for exclusion in this channel with log-likelihood ration
using poisson-statistics (+bg-systematics in each bin of the NN output)



Main mode: gg → H →WW* → lν l′ν′ (l, l′=e,μ)

- two high p_T isolated leptons, missing E_T
- three main channels (ee, eμ, μμ)
- start probing other channels (μτ)



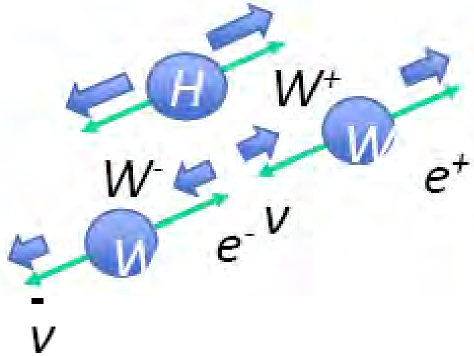
No direct reconstruction of the Higgs mass (ν's)

Main background:

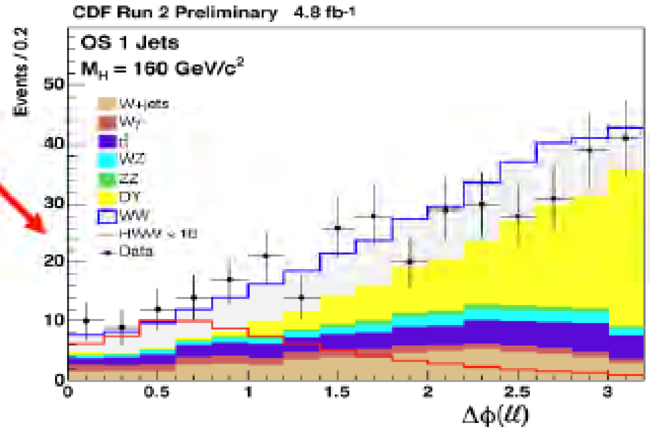
Dibosons

WW separated from the signal based on angular correlation Δφ(l,l′)

Higgs is a scalar!



→ Δϕ best background discriminant , used as one of the input variables to the NN



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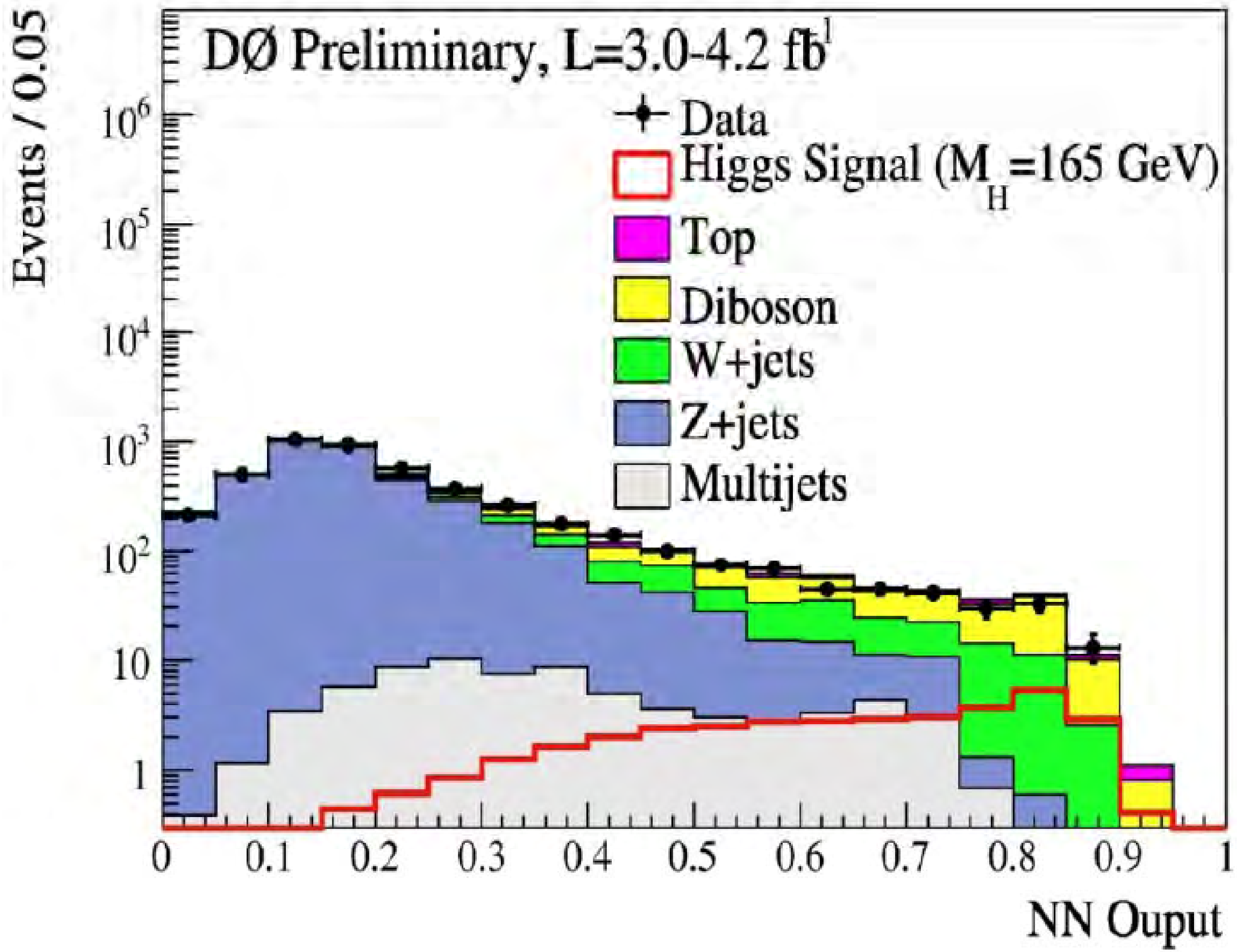
Other Backgrounds:

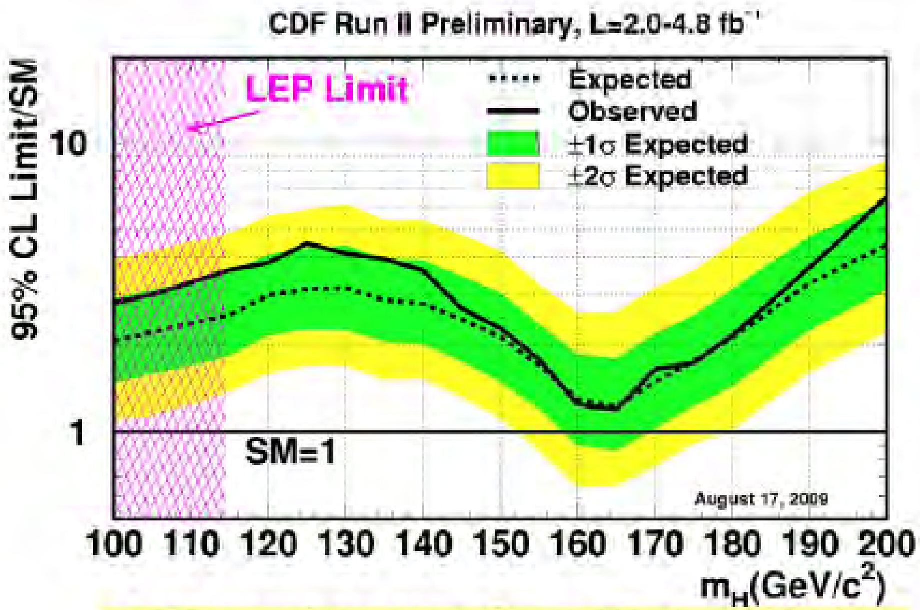
W+jets and multijets

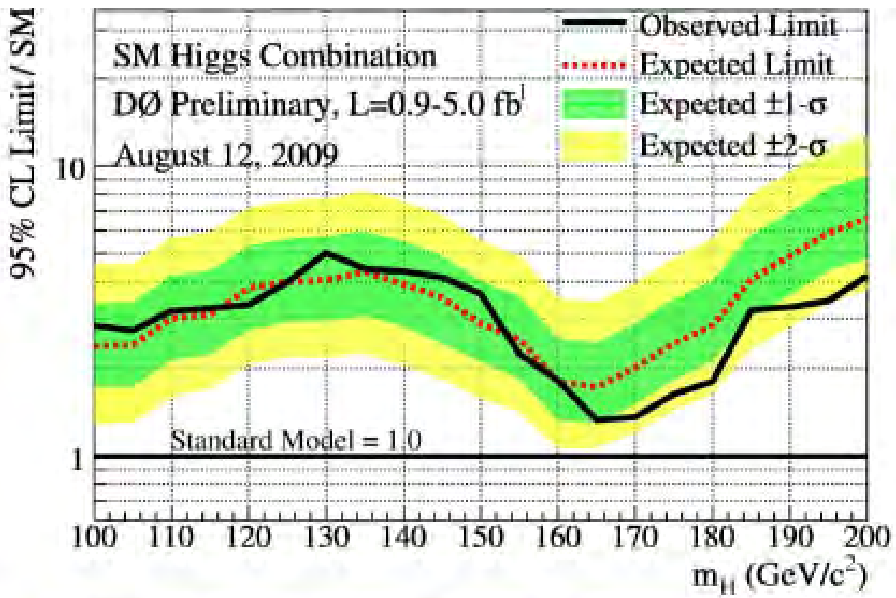
need good lepton identification

Z→ττ : specific for eμ channel and channels involving taus



note: Higgs signal x1 (!!)





CDF combination from Winter 2009 →Summer 2009

M_H=115 GeV
- Expected limit 3.2 σ_{SM} → 2.5σ_{SM}
- Observed limit 3.8 σ_{SM} → 3.6 σ_{SM}

M_H=165 GeV
- Expected limit 1.7 σ_{SM} →1.2 σ_{SM}
- Observed limit 1.6 σ_{SM} →1.2 σ_{SM}

DØ combination from Winter 2009 →Summer 2009

M_H=115 GeV
- Expected limit 3.6 σ_{SM} → 3.1 σ_{SM}
- Observed limit 3.7 σ_{SM} → 3.2 σ_{SM}

M_H=165 GeV
- Expected limit 1.7 σ_{SM}
- Observed limit 1.3 σ_{SM}

most CDF/DØ low mass updates finalized only last week, DØ still analyzing extended dataset at high mass (5.4 fb^{-1}) → all finalized analyses are included in the combinations above but NO update of Tevatron combination

[Bernardi LP09]

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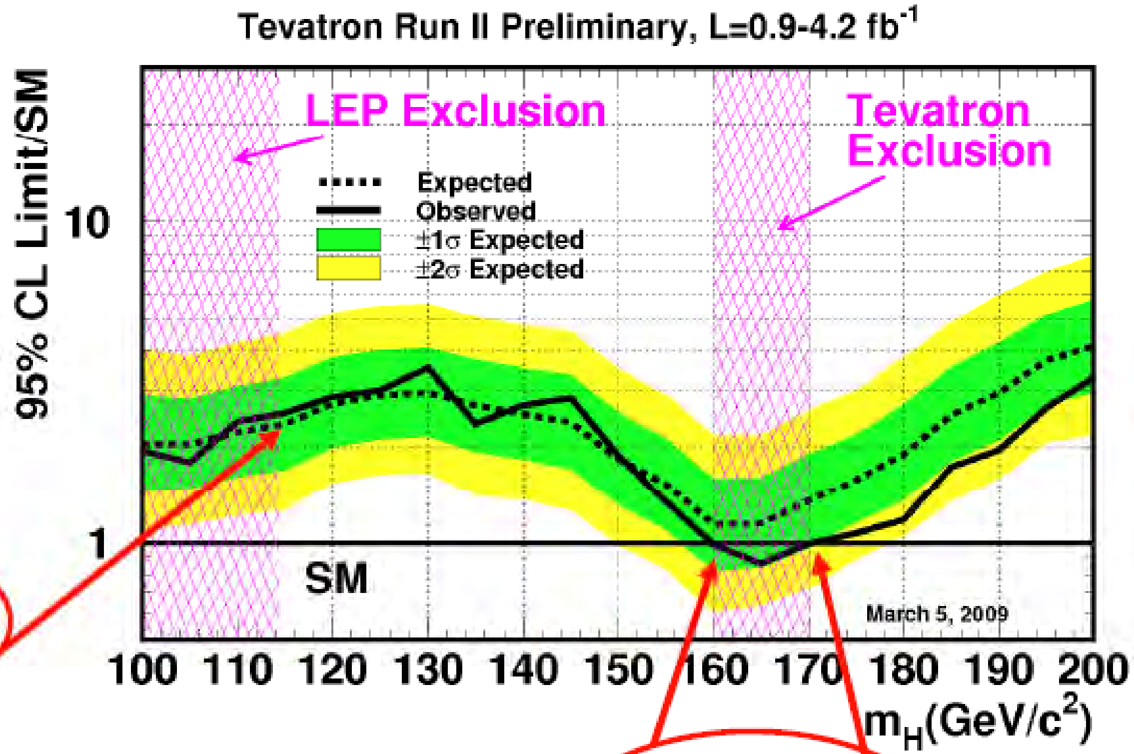
6. Higgs search at Tevatron: status winter 2009



Low Mass analyses:
$L = 0.9 - 2.7 fb^{-1}$

(results with more luminosity as presented before are **NOT** yet included in this combination)

@ $M_H=115$
Observed → $2.5x\sigma_{SM}$
Expected → $2.4x\sigma_{SM}$

High Mass analyses:
Higgs cross sections use most recent theoretical inputs including MSTW 2008 NNLO PDF set

Bayesian	150	155	160	165	170	175	180	185
Expected	1.8	1.5	1.1	1.1	1.4	1.6	1.9	2.2
Observed	1.9	1.4	0.99	0.86	0.99	1.1	1.2	1.7

We exclude the SM Higgs from 160 to 170 GeV at 95% C.L.

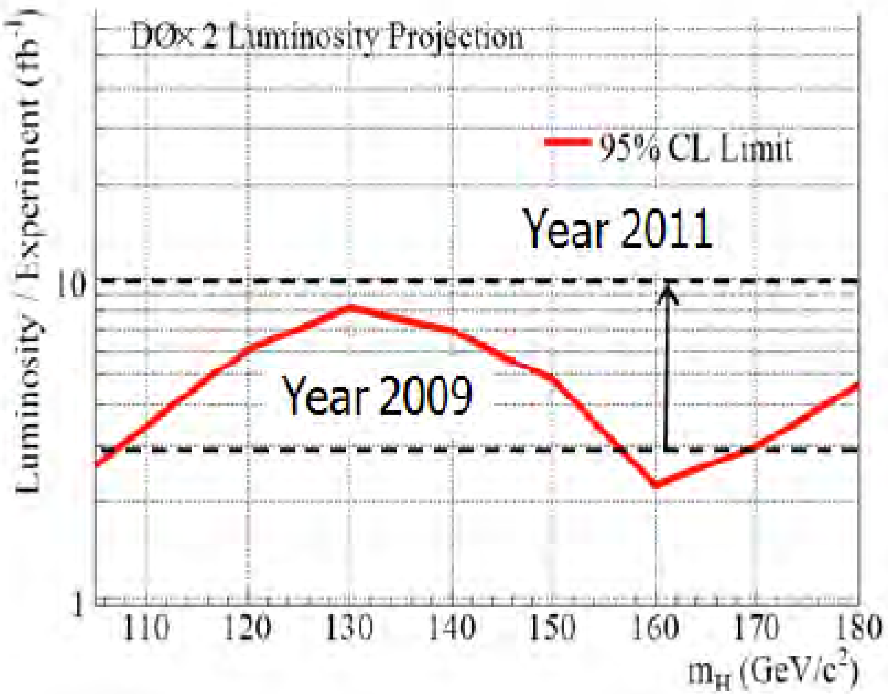
These Moriond '09 CDF-DØ combined limits are obtained with an "effective" luminosity of 2.5/4.0 fb^{-1} at low/high mass

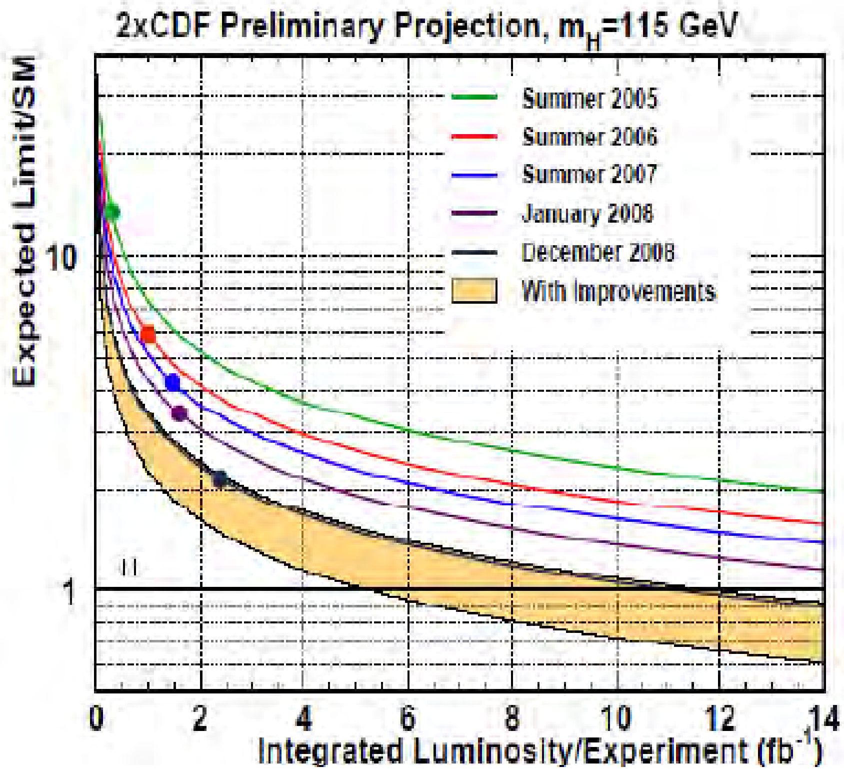
Gregorio Bernardi / LPNHE-Paris 19

[Bernardi LP09]

6. Higgs search at Tevatron: projection

assume CDF+DØ, and projected improvements:





2009: precision EW measurements + Tevatron ➔ SM Higgs 115 – 160 GeV

2010: with Tevatron luminosity, expects upper limit to go down to ~145 GeV

≥2011: @ Tevatron, direct exclusion from 115 to 185 GeV, or first evidence?

@ LHC requires several fb^{-1} to have evidence for the low mass Higgs

➔ LHC/Tevatron complementarity H→ $\gamma\gamma$ vs H→ bb

[Bernardi LP09]

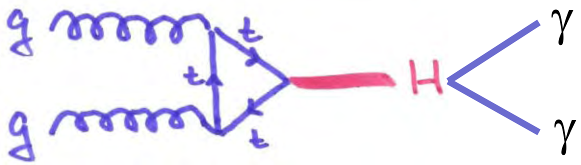
The race is on…

Cross section for Higgs (120 GeV) ~ xx x larger than at Tevatron
- can exploit other (cleaner) channels.

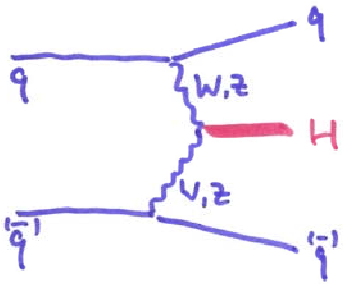
But Higgs – due to large backgrounds – Higgs search is not „early LHC physics“

Low mass (<~ 135 GeV):

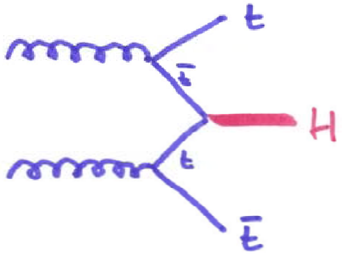
- $H \rightarrow \gamma\gamma$ (inlcusive)



- Vector boson fusion ($H\rightarrow\tau\tau$, $H\rightarrow\gamma\gamma$, $H\rightarrow W^+W^-$)

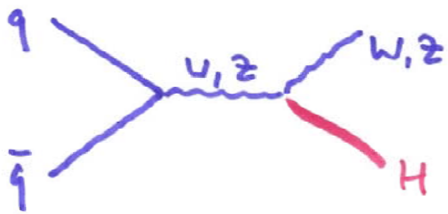


- ttH associated production



→ no longer considered „discovery channel“

- new idea: WH,ZH at high $p_T(H)$



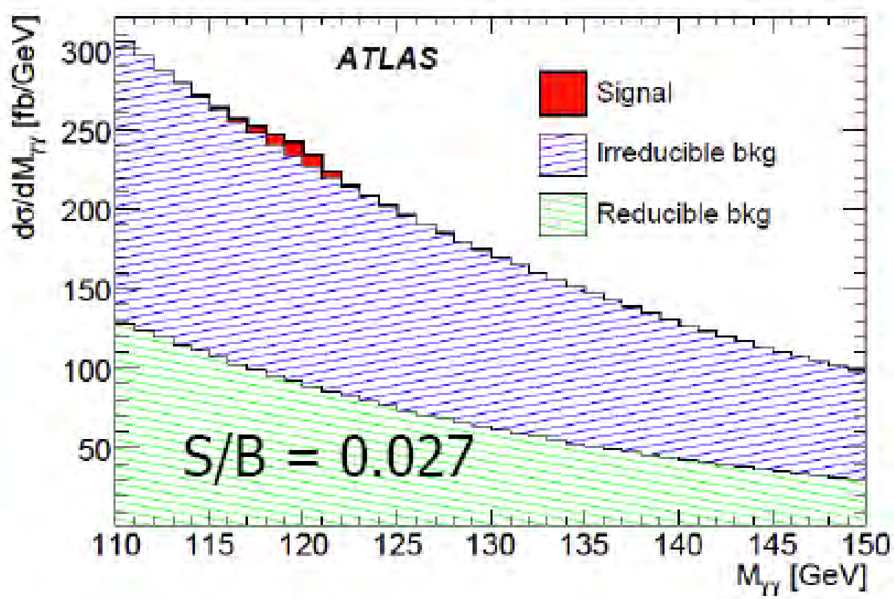
BR(H→γγ) = 0.2%, narrow peak
huge, but smooth background
→ mass resolution is the key

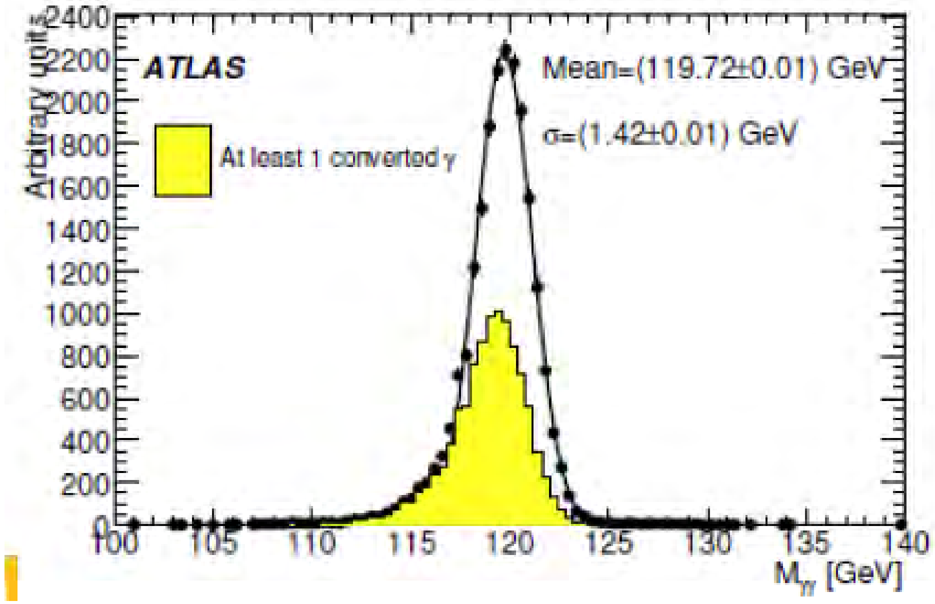
- Photon energy resolution & calibration
- Photon direction → granularity

Mass resolution (ATLAS): 1.4 GeV

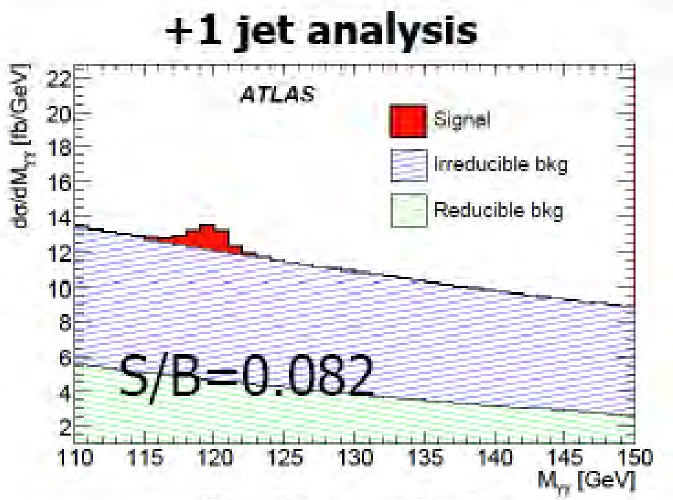
Problem:
60% of H→γγ events have at least one conversion

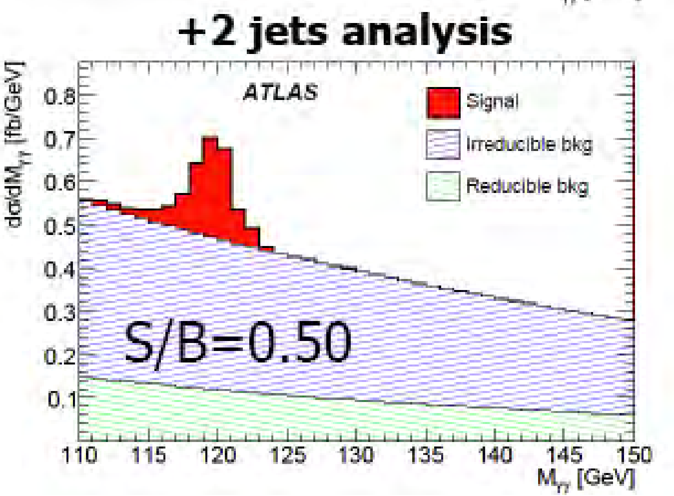
need to be identified
tail in resolution
need precise knowledge of material to obtain reliable simulation of signal & bg

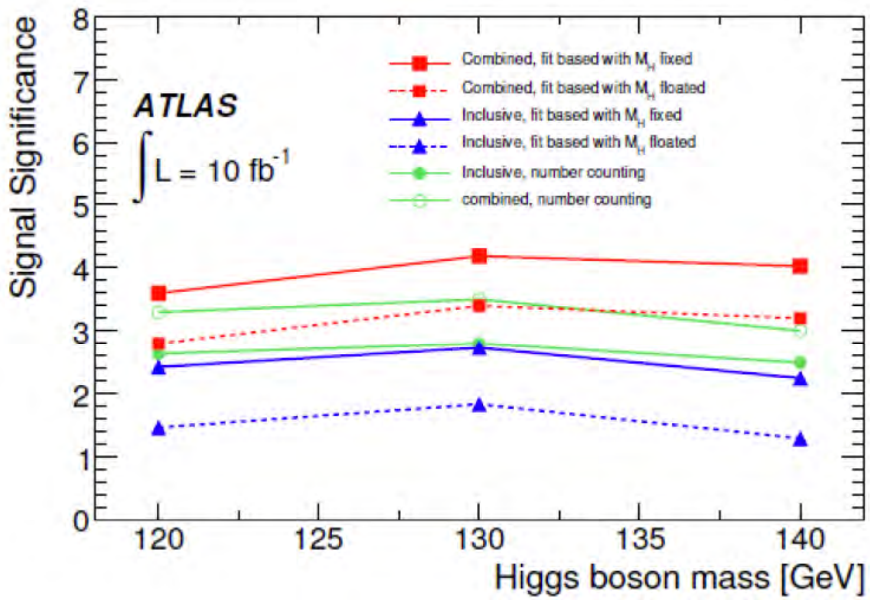


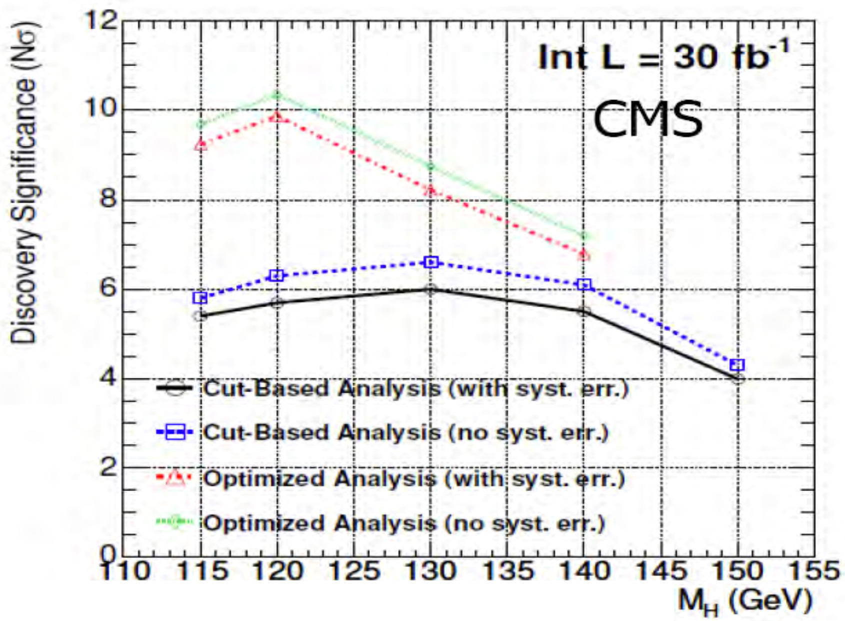


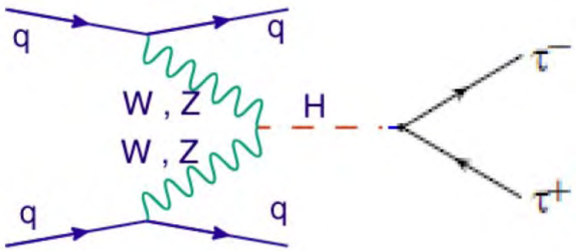
additional get better S/B
(but lower rate)





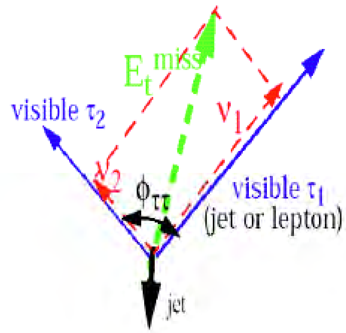






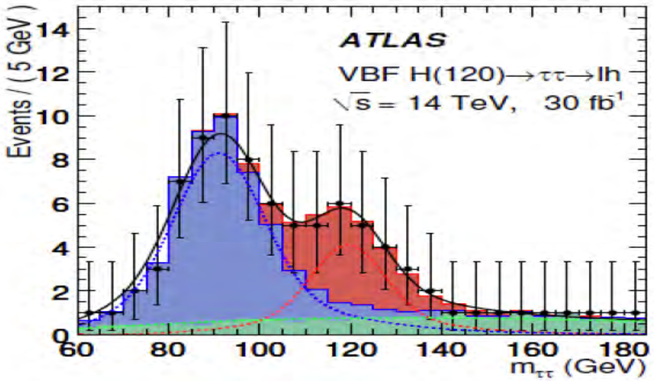
smaller rate than inclusive production
but forward „tagging jets“ + rapidity gap
can be used to improve S/B

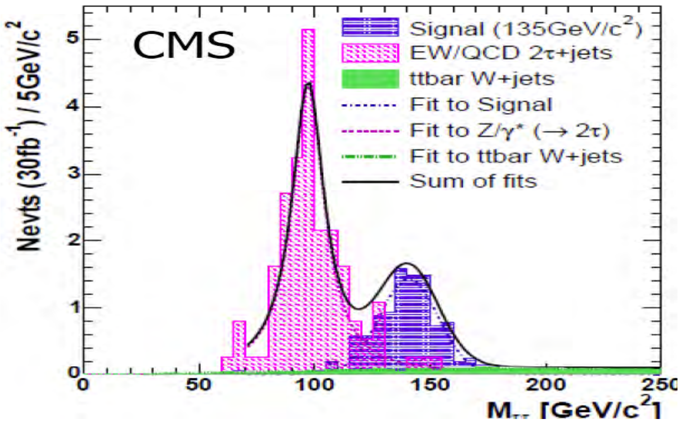
$m_{\tau\tau}$ can be reconstructed in
collinear approximation

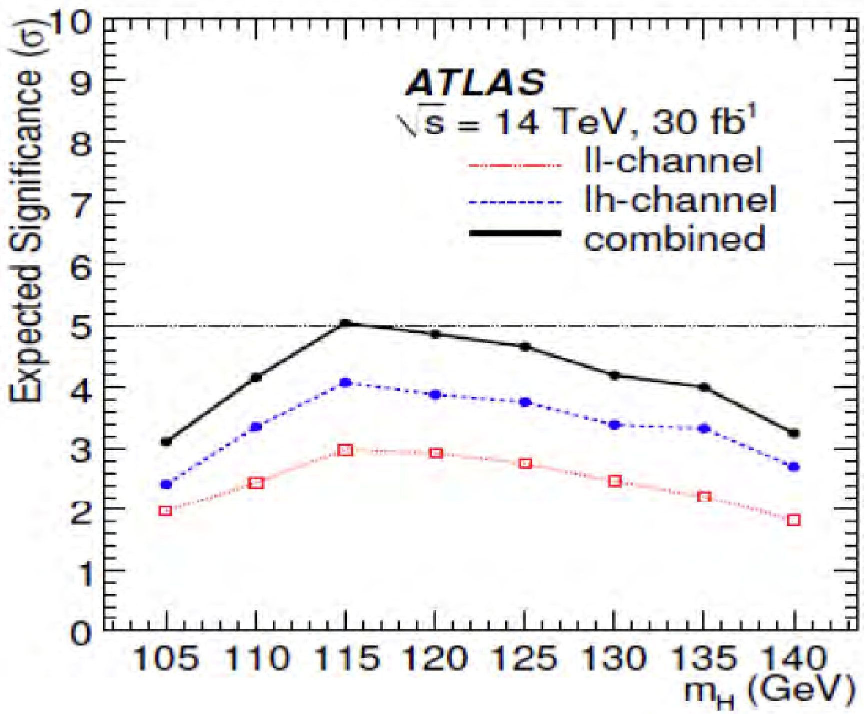


important discovery channel

$$\tau^+\tau^- \rightarrow h\nu_\tau \ell \nu_\tau \nu_\ell$$

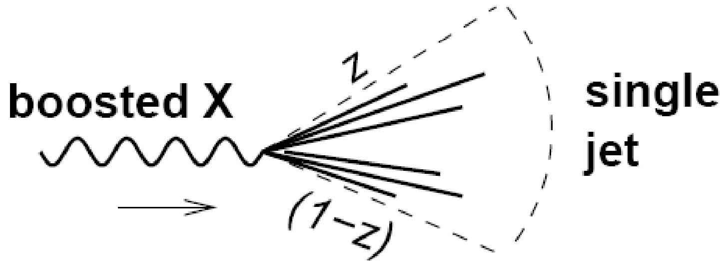




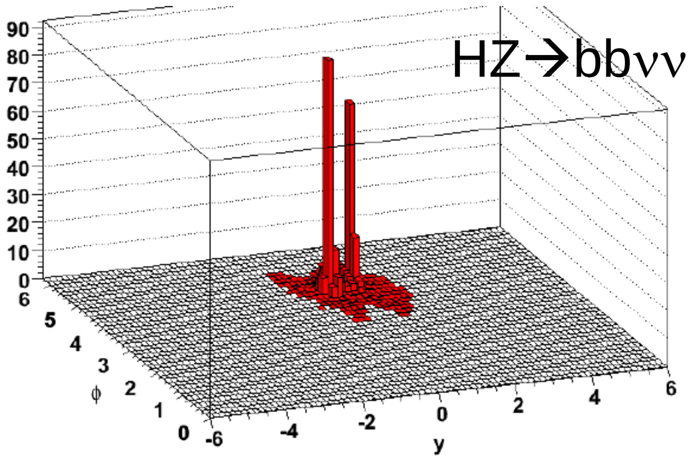


HW, HZ production was considered not a discovery channel for a long time
Very recent new investigation: H+W/Z production at high $p_T(H)$

2 b-quarks from Higgs decay will be reconstructed in single jet



Look at „jet –substructure“



ATLAS (prel.) sensitivity for 30 fb^{-1}
(m_H = 120 GeV)

Channel	signal	t_i	w_i	z_i	$S/\sqrt{B}$
$llb\bar{b}$	5.34	0.98	0.0	11.2	1.5
$l\nu b\bar{b}$	13.5	7.02	12.5	0.78	3.0
$\nu\nu b\bar{b}$	16.3	45.2	27.4	31.6	1.6
Combined					3.7

[Butterworth et al,arXiv:0810.0409; ATL-PHYS-PUB-2009-088]

Combined discovery prospects