Electroweak Measurements

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Outline

Electroweak Standard Model

Measurements of Z and W Bosons

The Top Quark

The Higgs Boson

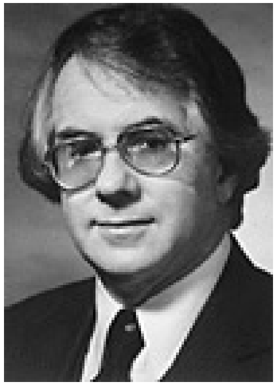
Rare electroweak processes

Summary and Outlook

Electroweak Standard Model

1960s: S.L.Glashow, A.Salam, S.Weinberg:

Integrated gauge theory of QED and weak interactions



Matter consists of fermions:

Left-handed weak-isospin doublets ($T_3 = \pm 1/2$)

Right-handed singlets

3 generations of fermions only?

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} 0 \\ -1 \end{matrix}$$

Increasing mass   *Charge* q_f

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} +2/3 \\ -1/3 \end{matrix}$$

Exchange particles are spin-1 bosons:

γ, Z, W^+, W^-

Mixing of neutral fields

Mixing angle Θ_W

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W^0 \end{pmatrix}$$

Exchange Particles

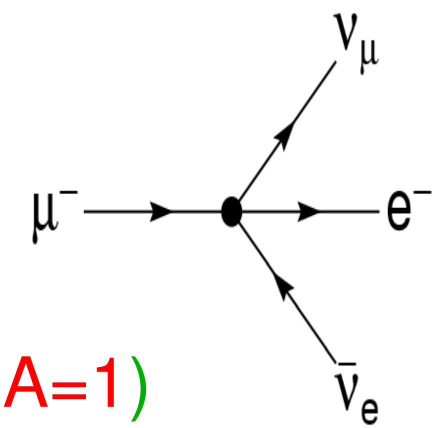
Weak interaction is of short range:

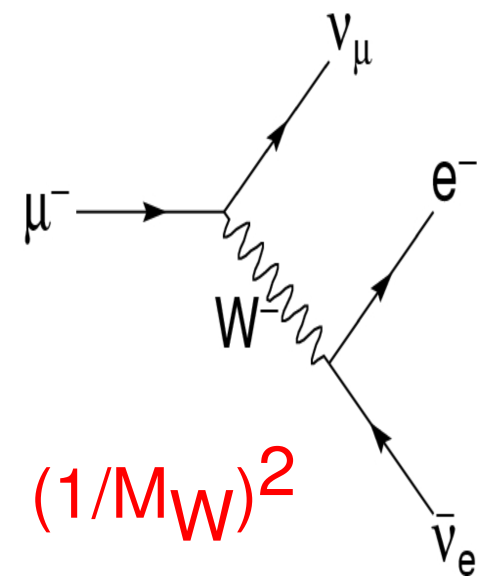
Massive exchange particles

Charged spin-1 bosons $W^{\pm}$

With universal couplings

$\gamma^{\alpha}\,(V - A\,\gamma^{5})$ to fermions $(V=A=1)$

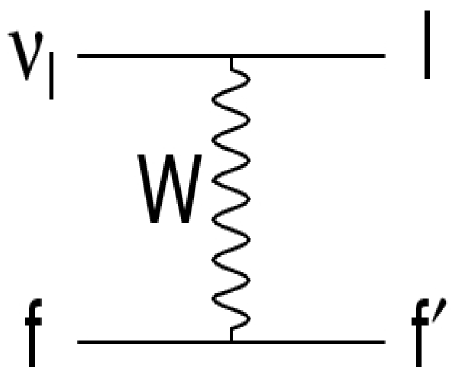


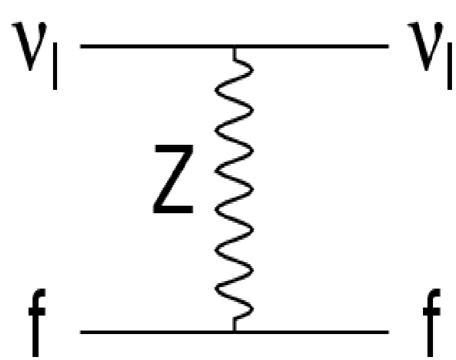


$G_F \propto (1/M_W)^2$

Neutral spin-1 boson Z ($\neq \gamma$!)

Necessary in gauge theory => Neutral weak current





Couplings g:

$\gamma^{\alpha}\,(g_{Vf} - g_{Af}\,\gamma^{5})$

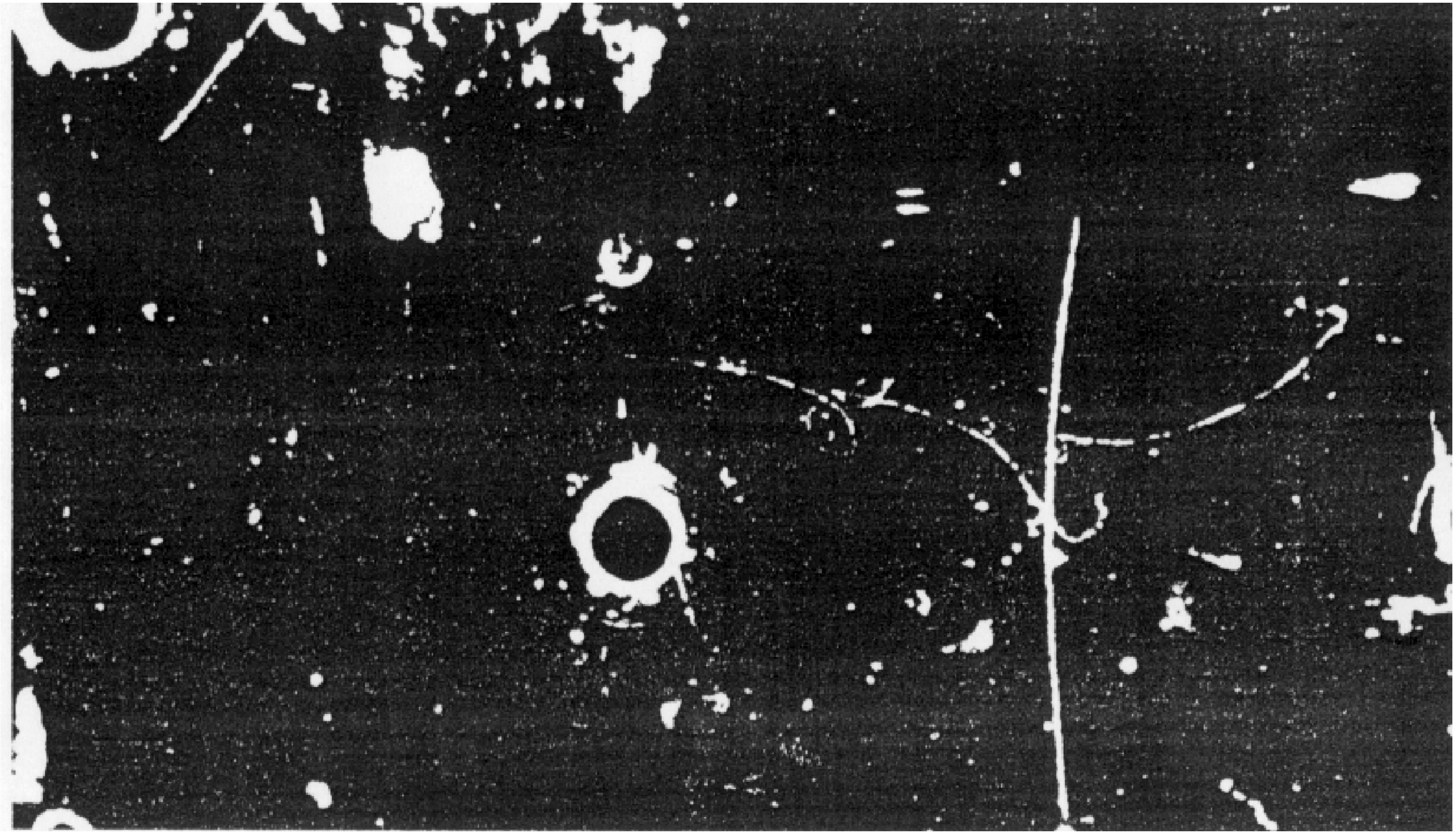
Parity violation?

Discovery of Neutral Weak Currents

1973: Gargamelle experiment at CERN, Geneva:

Reactions without charge exchange $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$

$\bar{\nu}_\mu \to$



Likewise: $\bar{\nu}_\mu N \to \bar{\nu}_\mu N$

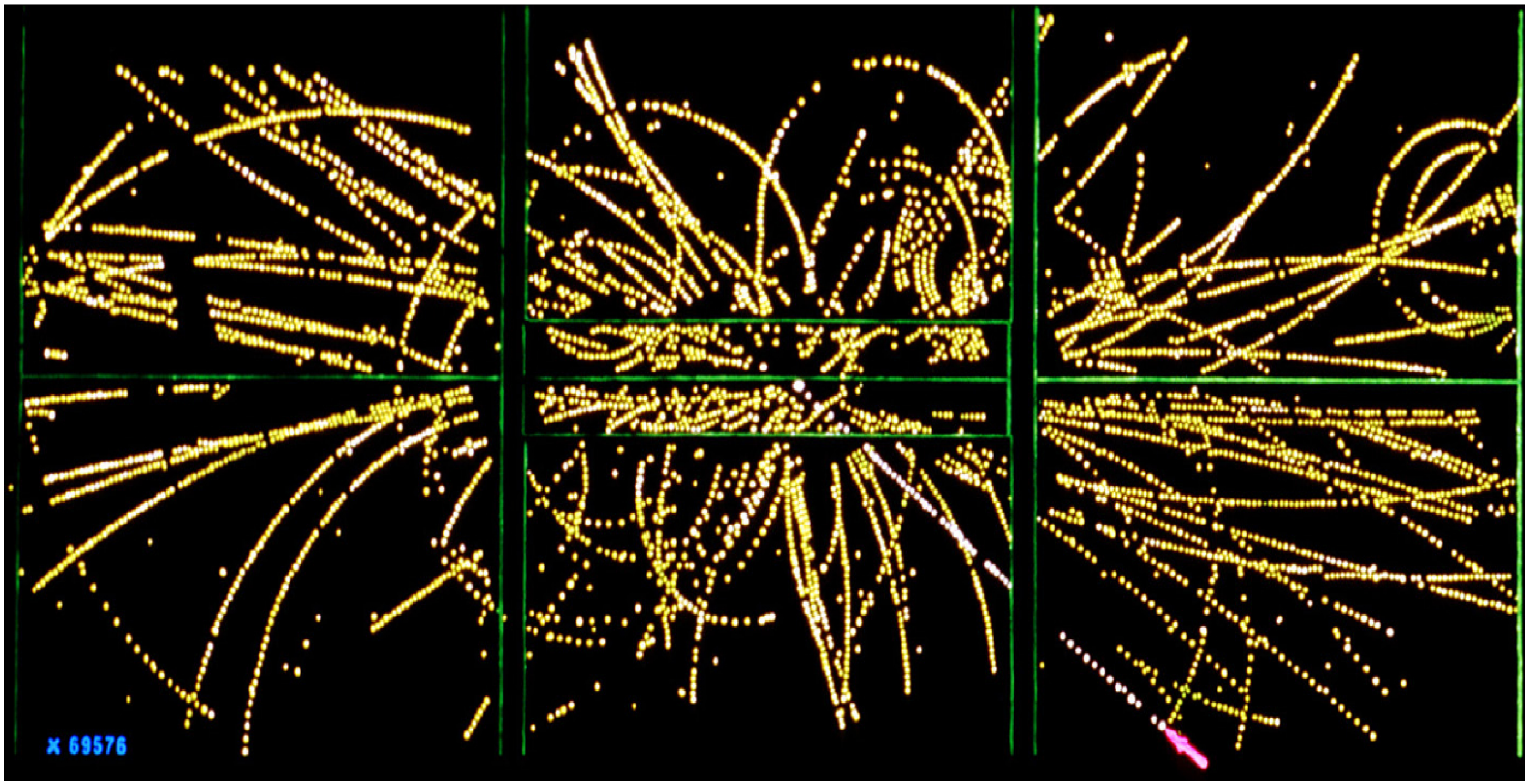
Mediated by Z exchange

2009 EPS HEP Prize to Gargamelle collaboration!

Discovery of W and Z Bosons

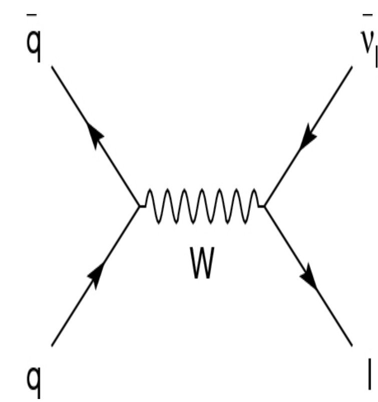
1983: UA1 experiment at CERN, Geneva

$$p\,\overline{p} \;\rightarrow\; (W^{\pm}\ or\ \ Z) \;+\; remainder$$



e

C.Rubbia



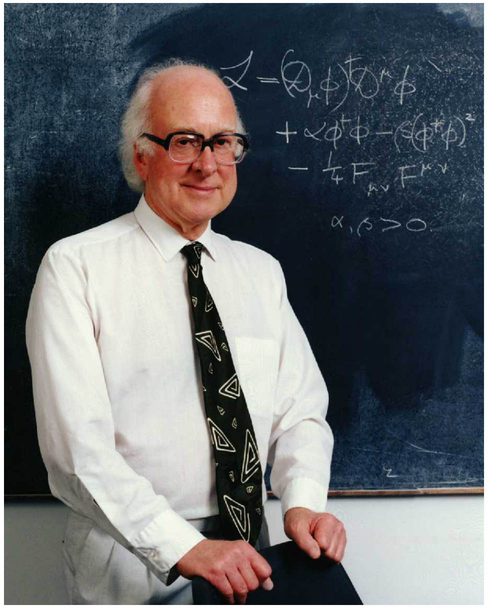
$$W^- \rightarrow e^- \nu_e, \qquad W^- \rightarrow \mu^- \nu_\mu$$

Likewise: $$Z \rightarrow e^+ e^-, \qquad Z \rightarrow \mu^+ \mu^-$$

$M_W \sim$ 80 GeV

$M_Z \sim$ 91 GeV

Electroweak Standard Model



P.Higgs

1964: Higgs-mechanism to generate masses:

- Need new spin-0 Higgs boson
- Theory to work: mass $M_H < 1000$ GeV

Predictions of the electroweak theory:

- Relation between W and Z mass:

$$1 - \frac{M_W^2}{M_Z^2} = \sin^2\theta_W$$

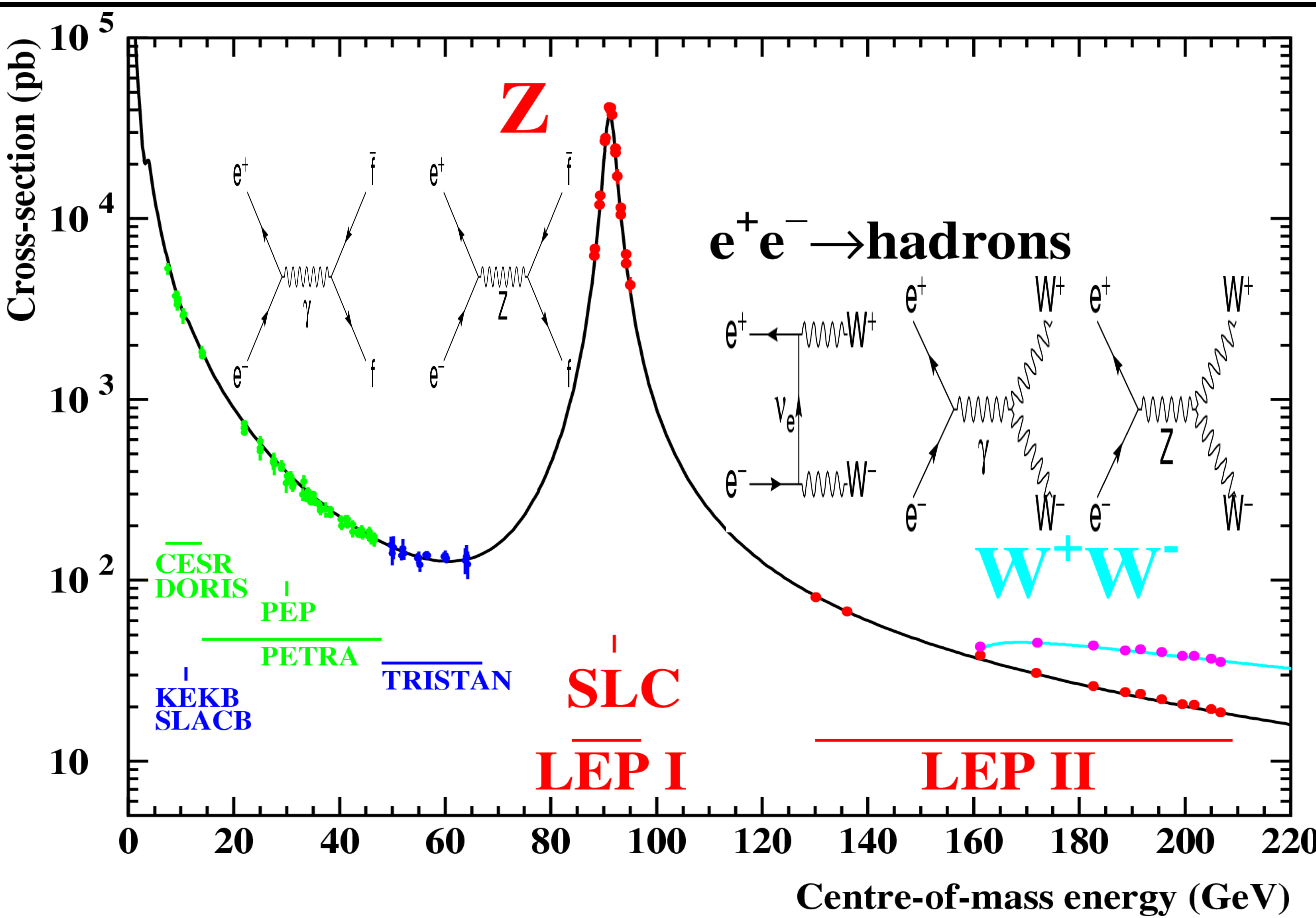
- Z-Fermion couplings:

$$g_{Vf} = T_3^f - 2q_f \sin^2\theta_W \qquad g_{Af} = T_3^f = \pm\frac{1}{2}$$

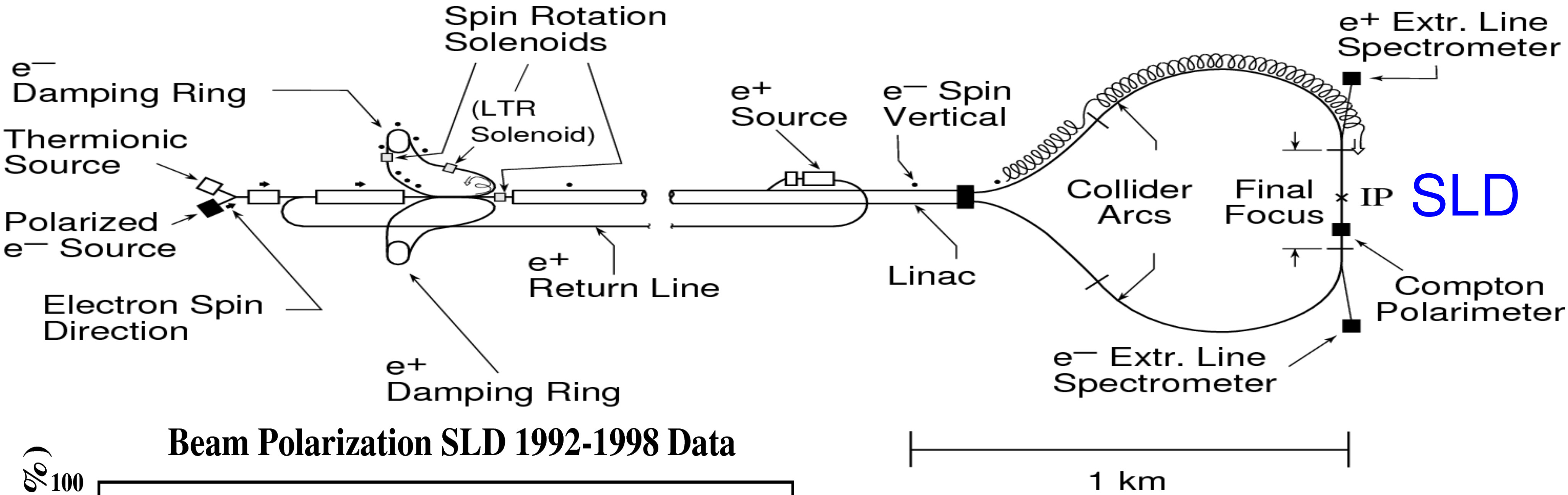
Definite experimental tests through measurements:

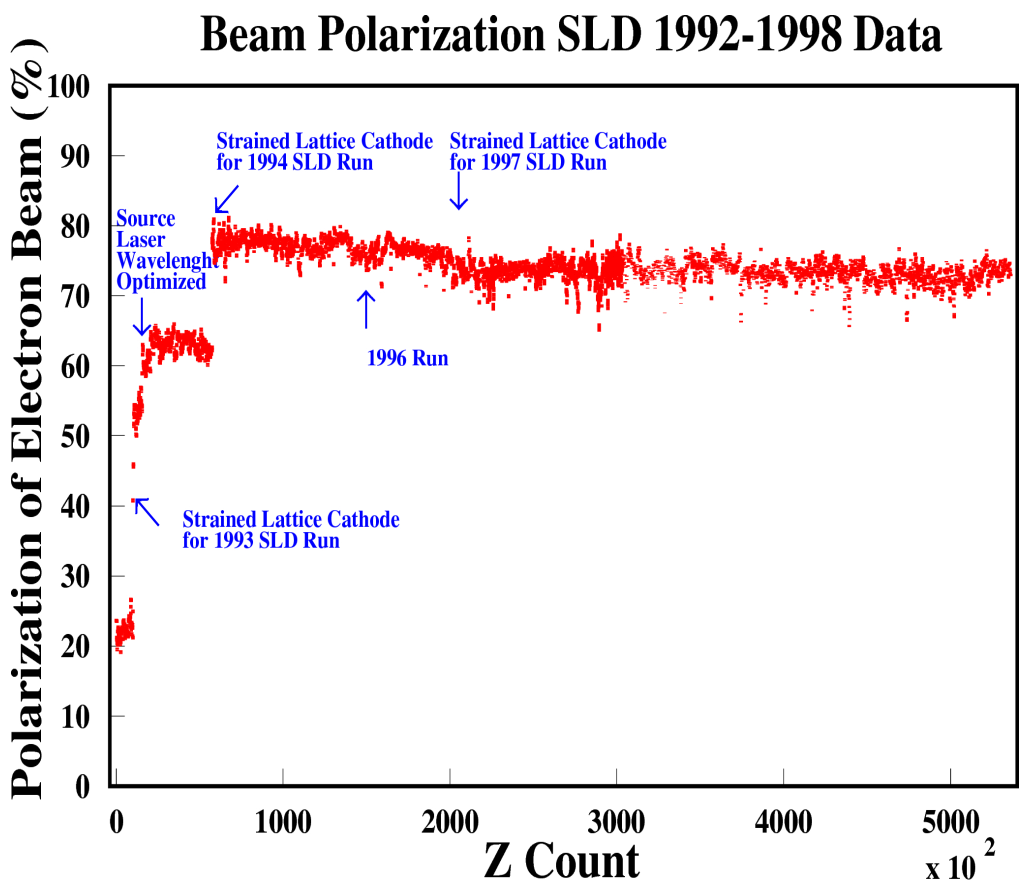
- Masses of W and Z, couplings g_{Vf} and g_{Af} (parity violation)
- Search for the Higgs boson, Boson self-coupling

e^+e^- Interactions



Stanford Linear Collider (SLC)

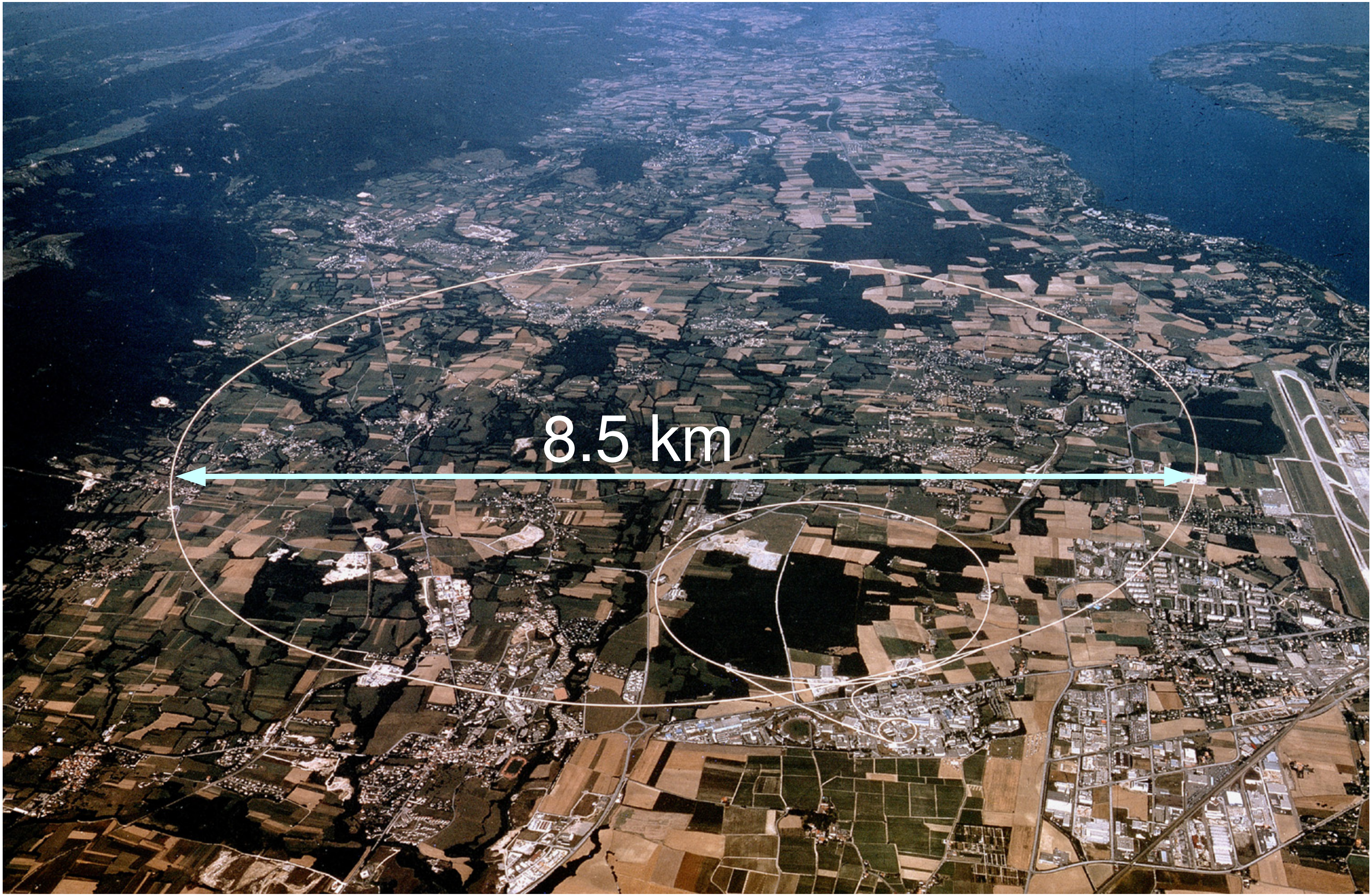




SLD at SLC:

- Data taking at peak cross section only to maximise number of events (statistical precision)
- 0.5 M events collected with high beam polarisation

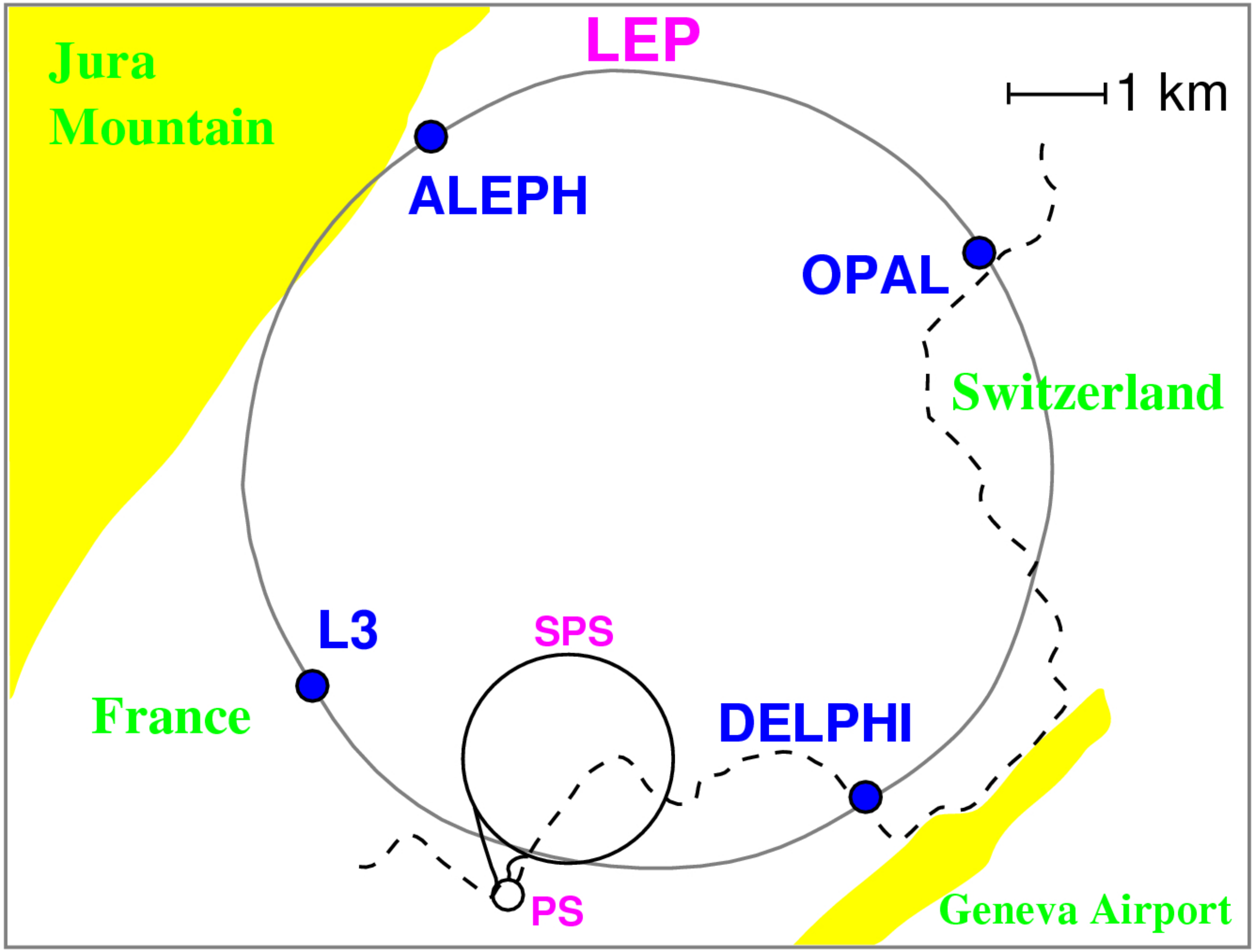
CERN Laboratory, Geneva, Switzerland



LEP

LEP: Large Electron Positron Accelerator

CERN, Geneva



e^+e^- interactions:

1989-1995 LEP-1

$e^+e^- \rightarrow Z$

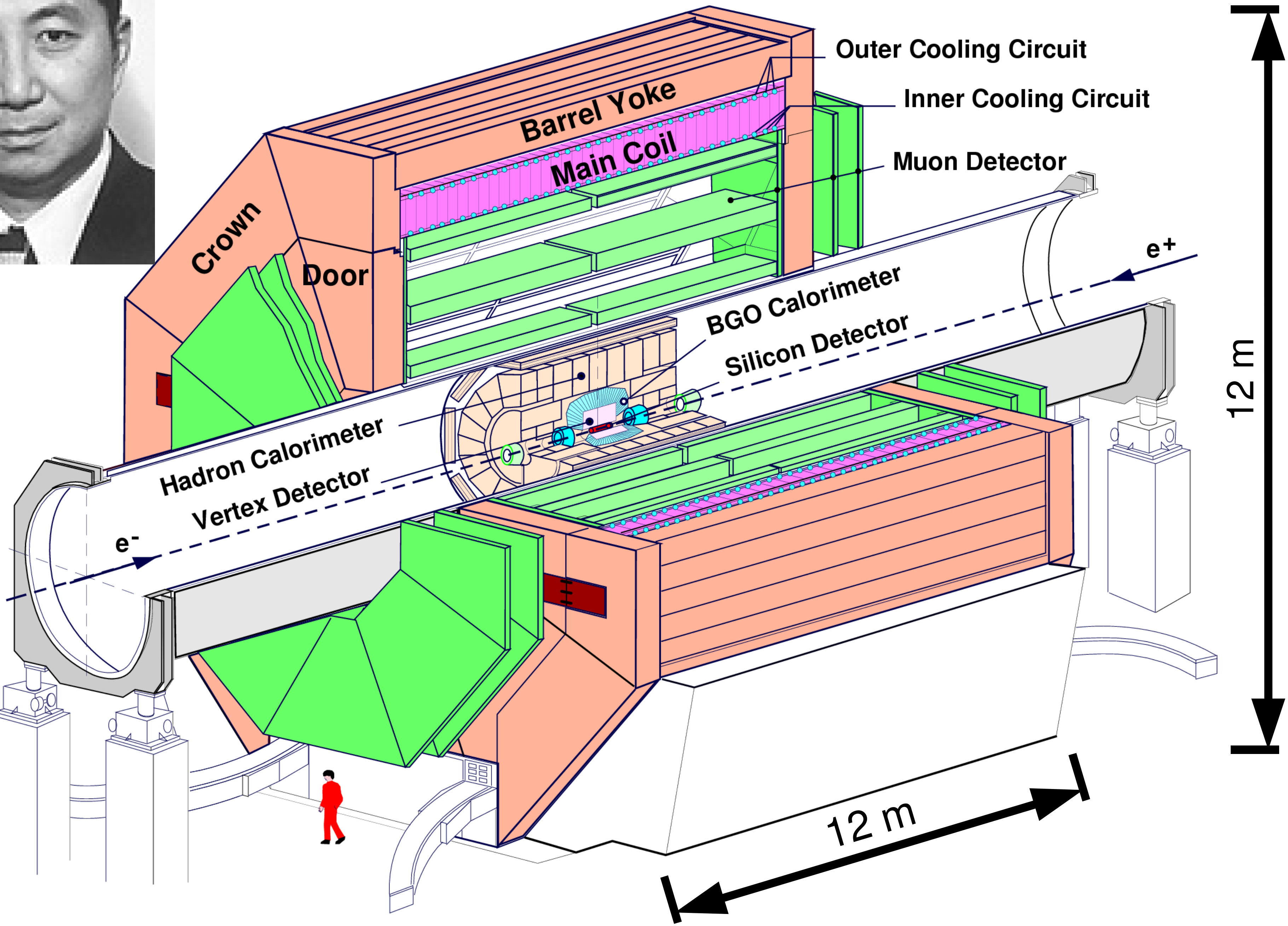
1996-2000 LEP-2

$e^+e^- \rightarrow W^+W^-$

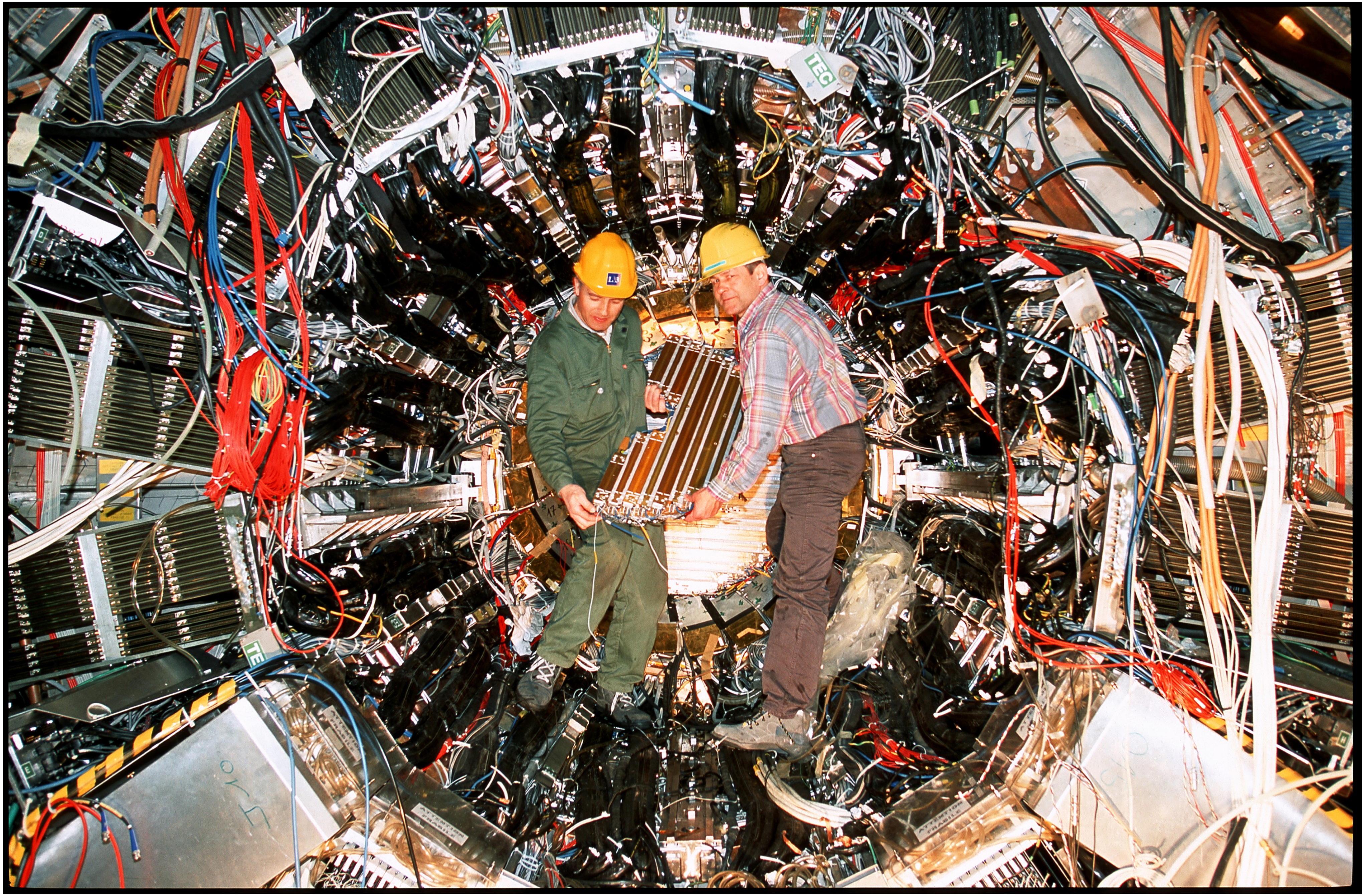
Search for new particles (especially the Higgs boson)

LEP Experiment L3

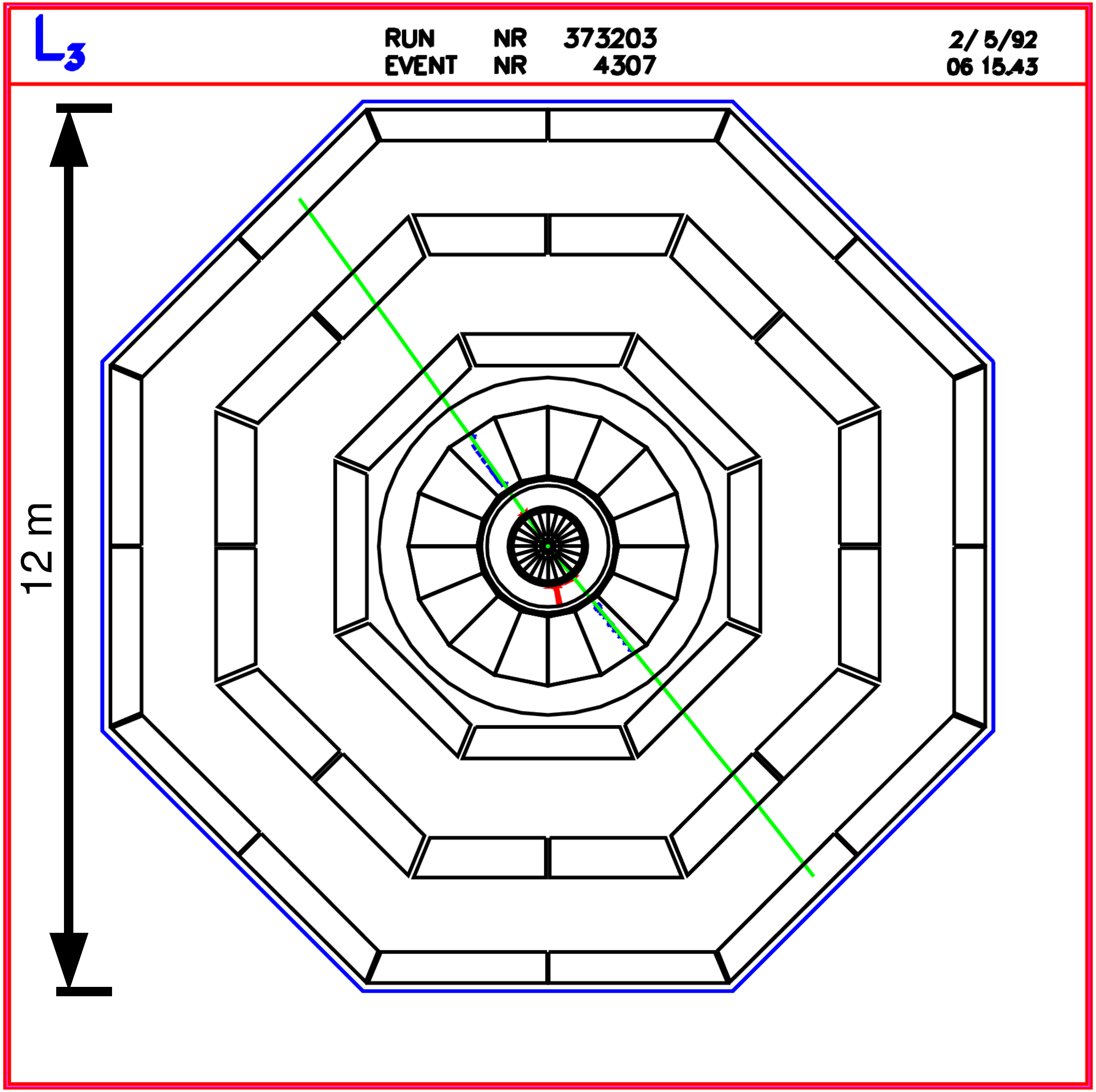
S.Ting



L3 Inner Detector



The Z Boson

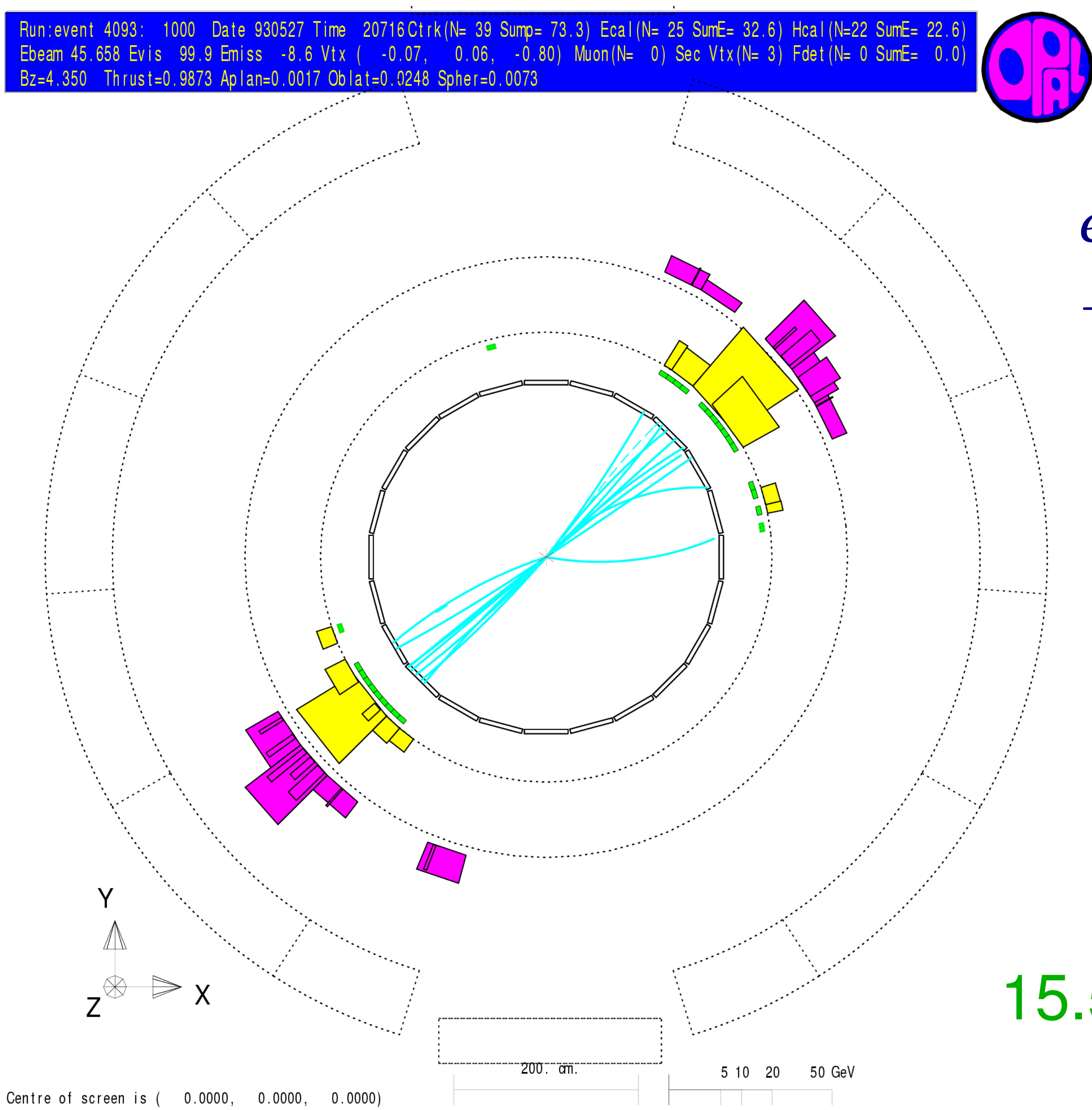


$$e^+ e^- \rightarrow Z \rightarrow l^+ l^-$$

$$here: \ \mu^+ \mu^-$$

$1.7 \cdot 10^6$ events at LEP

The Z Boson

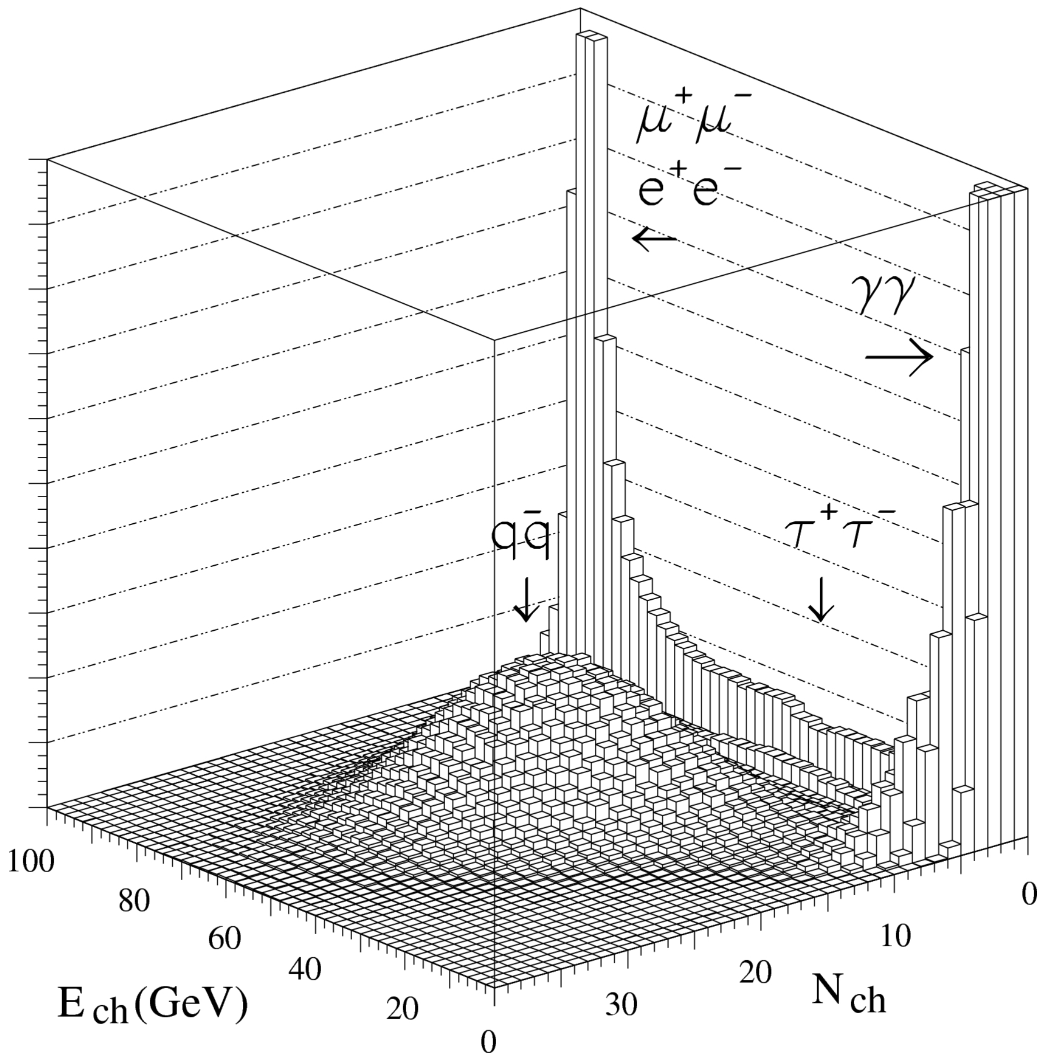


$e^+e^- \rightarrow Z \rightarrow q\bar{q}$

$\rightarrow$ *two hadronic jets*

$15.5 \cdot 10^6$ events at LEP

The Z Boson



Event selection:

Multiplicity:
- charged tracks
- calorimetric clusters

Energy:
- electromagnetic and hadronic calorimeters

Momentum:
- inner tracking chambers and muon chambers

Final states (ee / μμ / τ / qq→hadrons) are well separated!

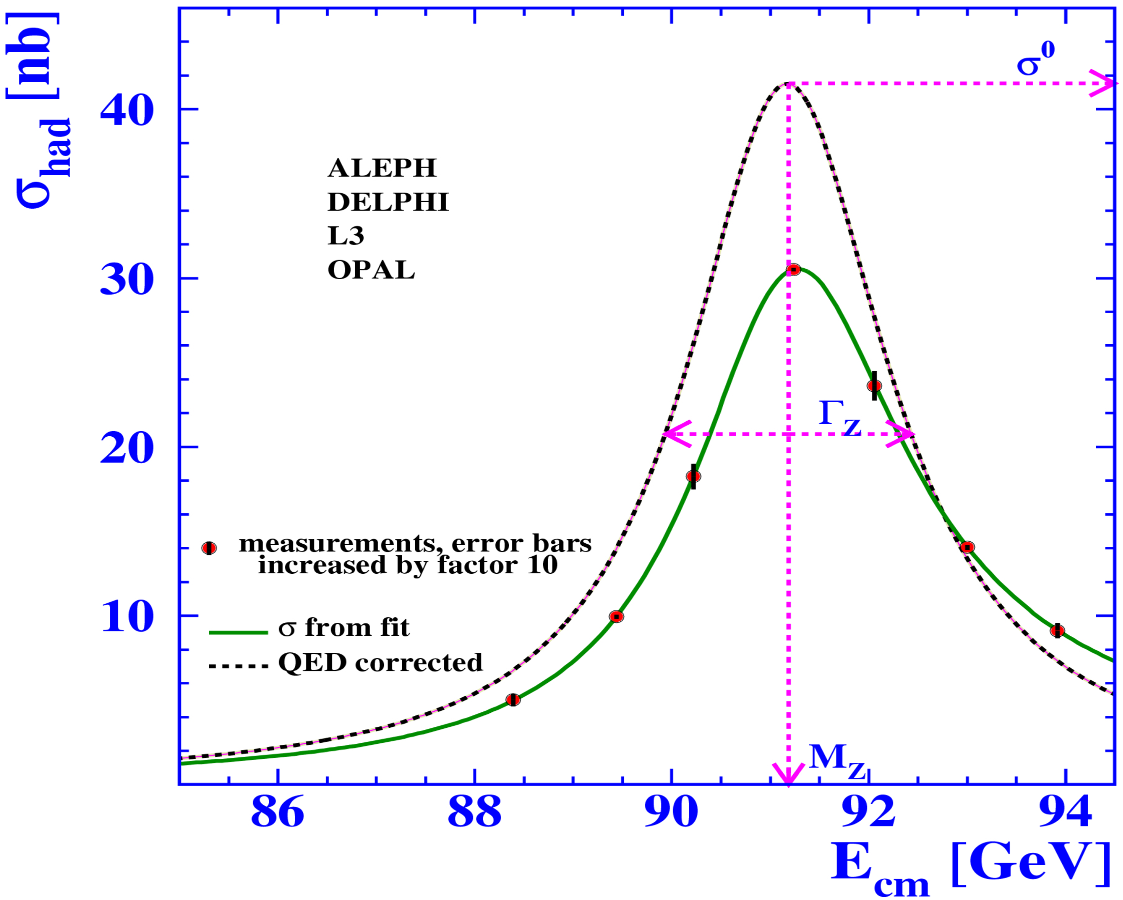
The Z Boson

Lowest order cross section for CM energies √s close to M_Z:

$$\sigma_Z^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z\Gamma_Z}\frac{s\Gamma_Z^2}{(s-M_Z^2)^2+s^2\Gamma_Z^2/M_Z^2}$$

$$\Gamma_f = \Gamma(Z\to f\bar{f})$$

partial decay width



Resonance curve:

Z parameters

Position: M_Z

Width: $\Gamma_Z = \sum_f \Gamma_f$

$\Gamma_f \propto g_{Vf}^2 + g_{Af}^2$

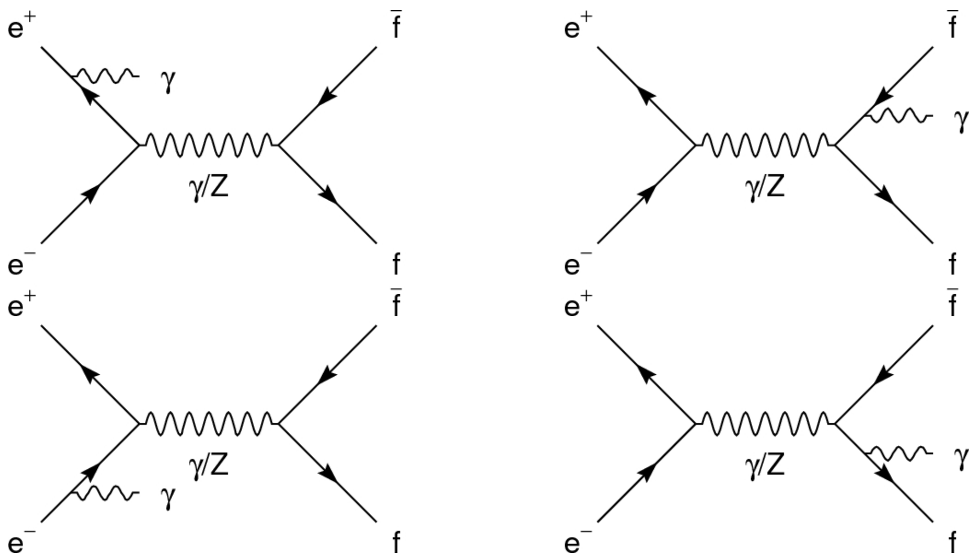
Height: $\sigma \propto \Gamma_e\Gamma_f$

Note large QED corrections

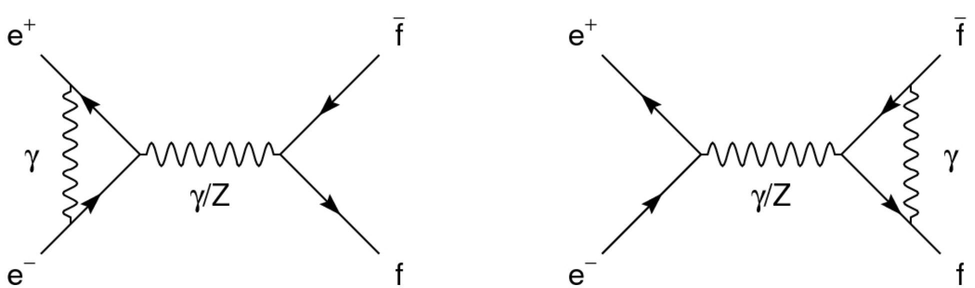
The Z Boson

QED corrections (photon radiation):

Initial-state & final-state radiation (and interference)



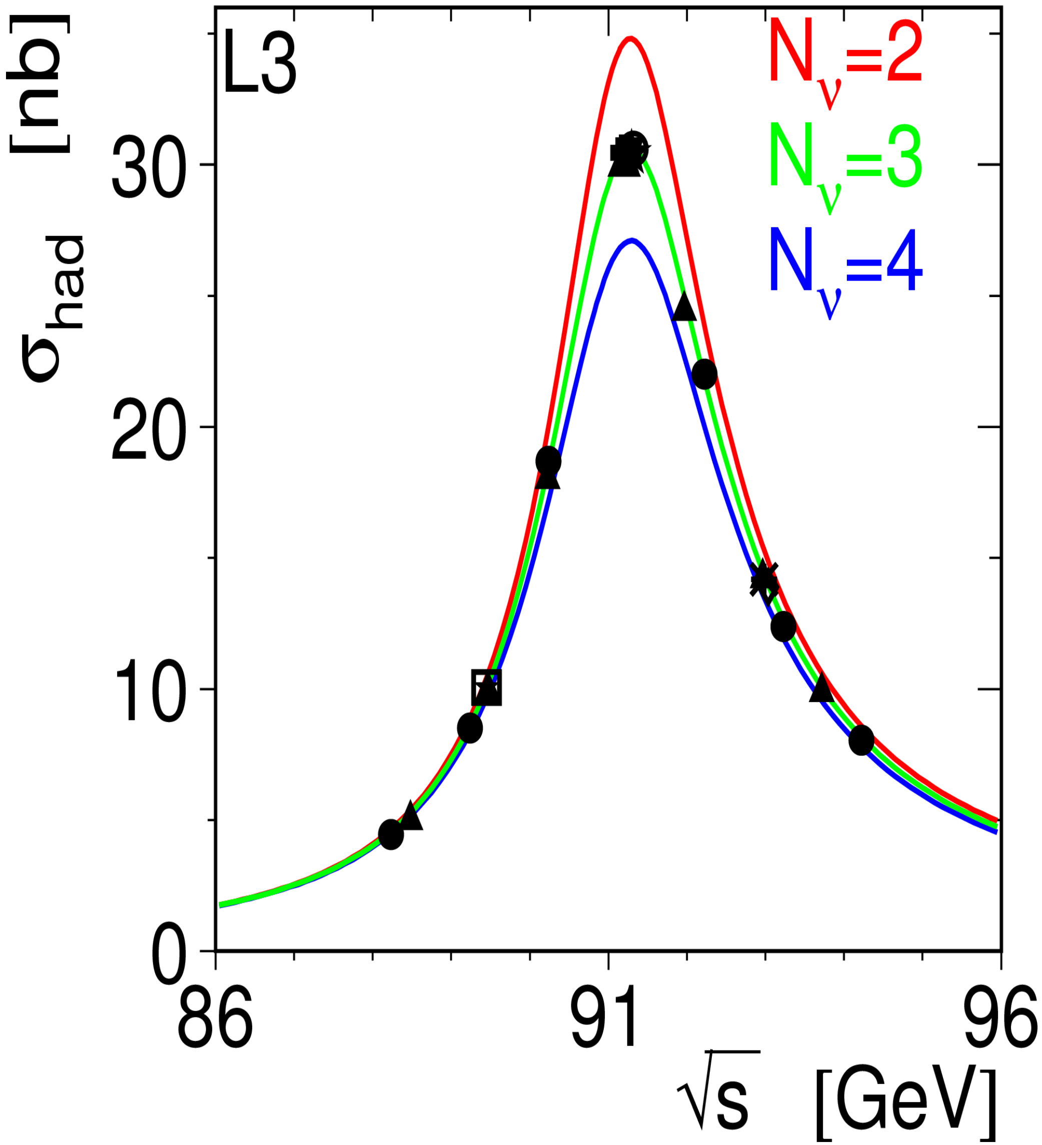
Vertex corrections



Need 3rd order QED calculations!

The Z Boson

Precise final LEP results:



$$M_Z = 91.1875 \pm 0.0021 \ GeV$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \ GeV$$

Total width: fermion counting

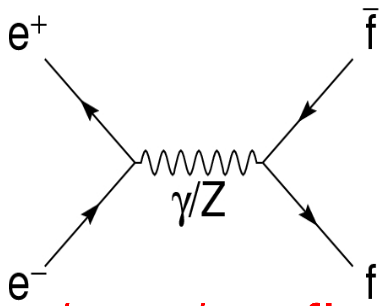
Number of light neutrino generations:

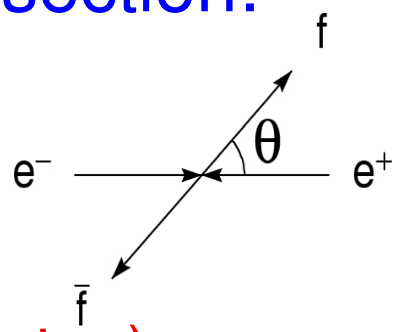
$$N_\nu = 2.9840 \pm 0.0082$$

There are three generations of fermions...
(... with light neutrinos)!

The Z Boson

Differential cross section:





(ee / μμ / τ final states)

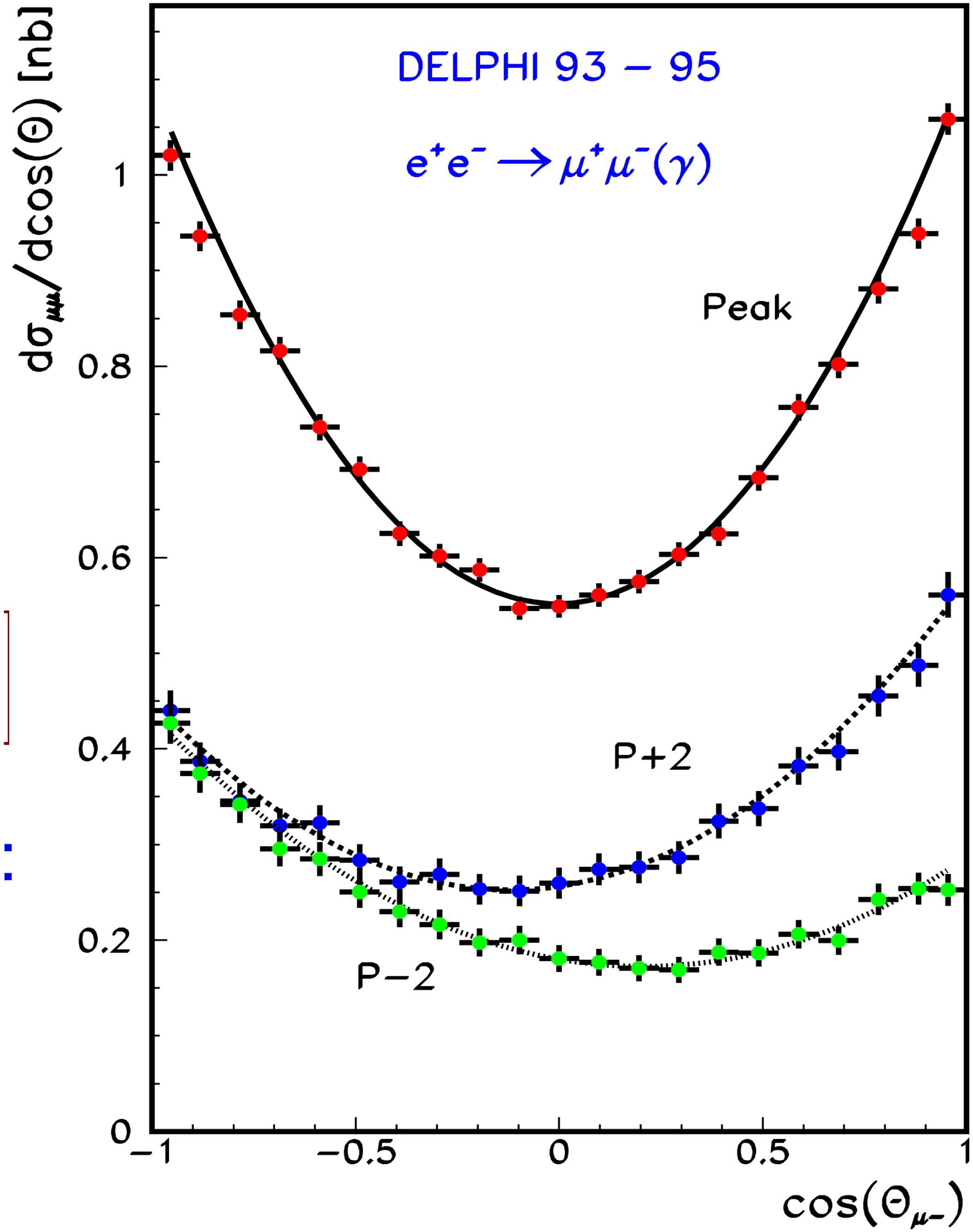
2nd order polynomial in cosθ:

$$\frac{d\sigma(s)}{d\cos\theta} = \sigma(s)\left[\frac{3}{8}(1+\cos^2\theta)+A_{FB}(s)\cos\theta\right]$$

Forward-backward asymmetry:

$$A_{FB}(s) = \frac{\sigma(\cos\theta>0)-\sigma(\cos\theta<0)}{\sigma}$$

$$= \frac{N_F-N_B}{N_F+N_B}$$



Easy to measure precisely – systematic uncertainties cancel

The Z Boson

Forward-backward asymmetry:

$$A_{FB}(s) = \frac{\sigma(s;\cos\theta>0)-\sigma(s;\cos\theta<0)}{\sigma(s)}$$

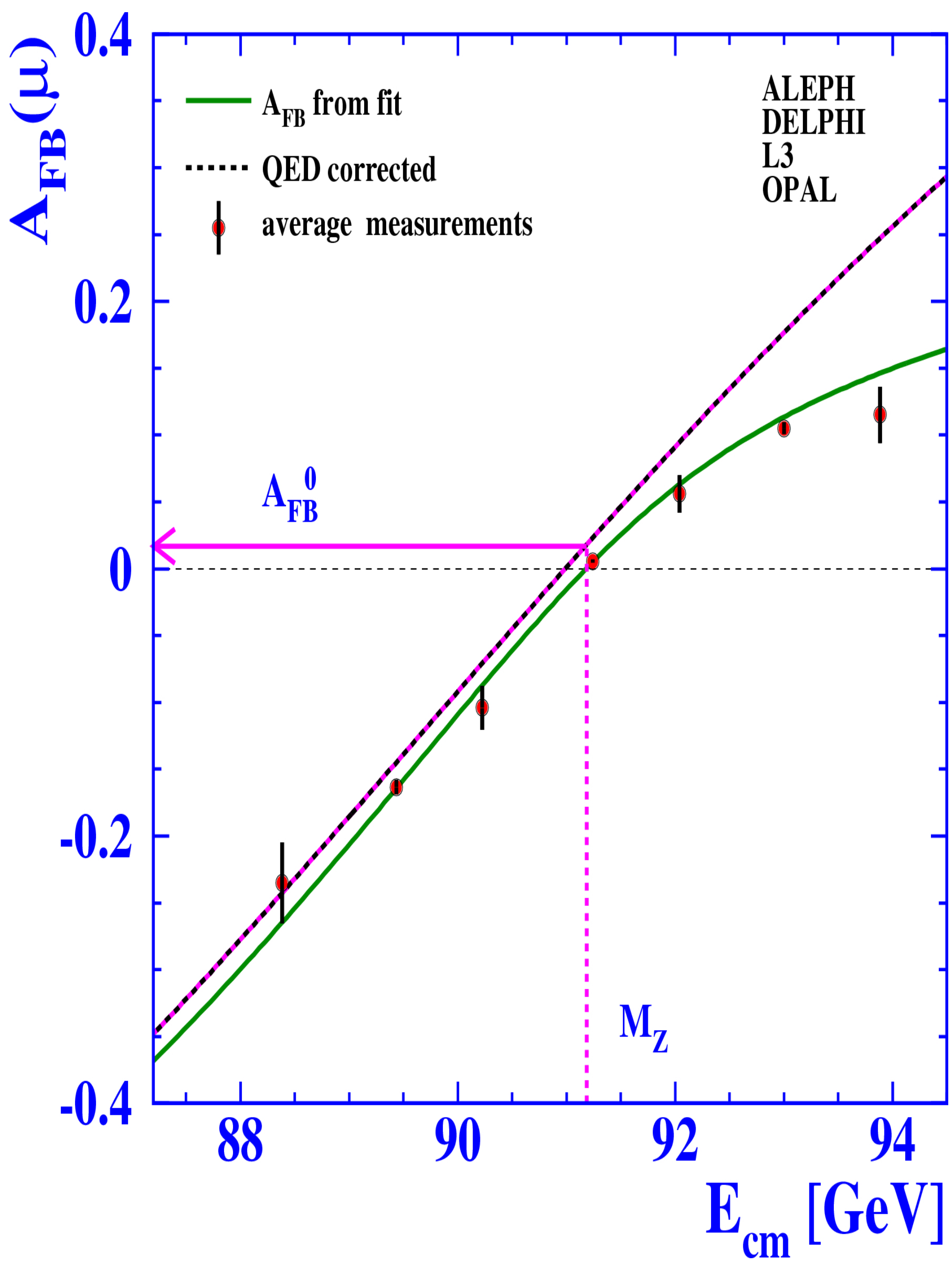
CM energy dependent

Special case at the Z-pole:

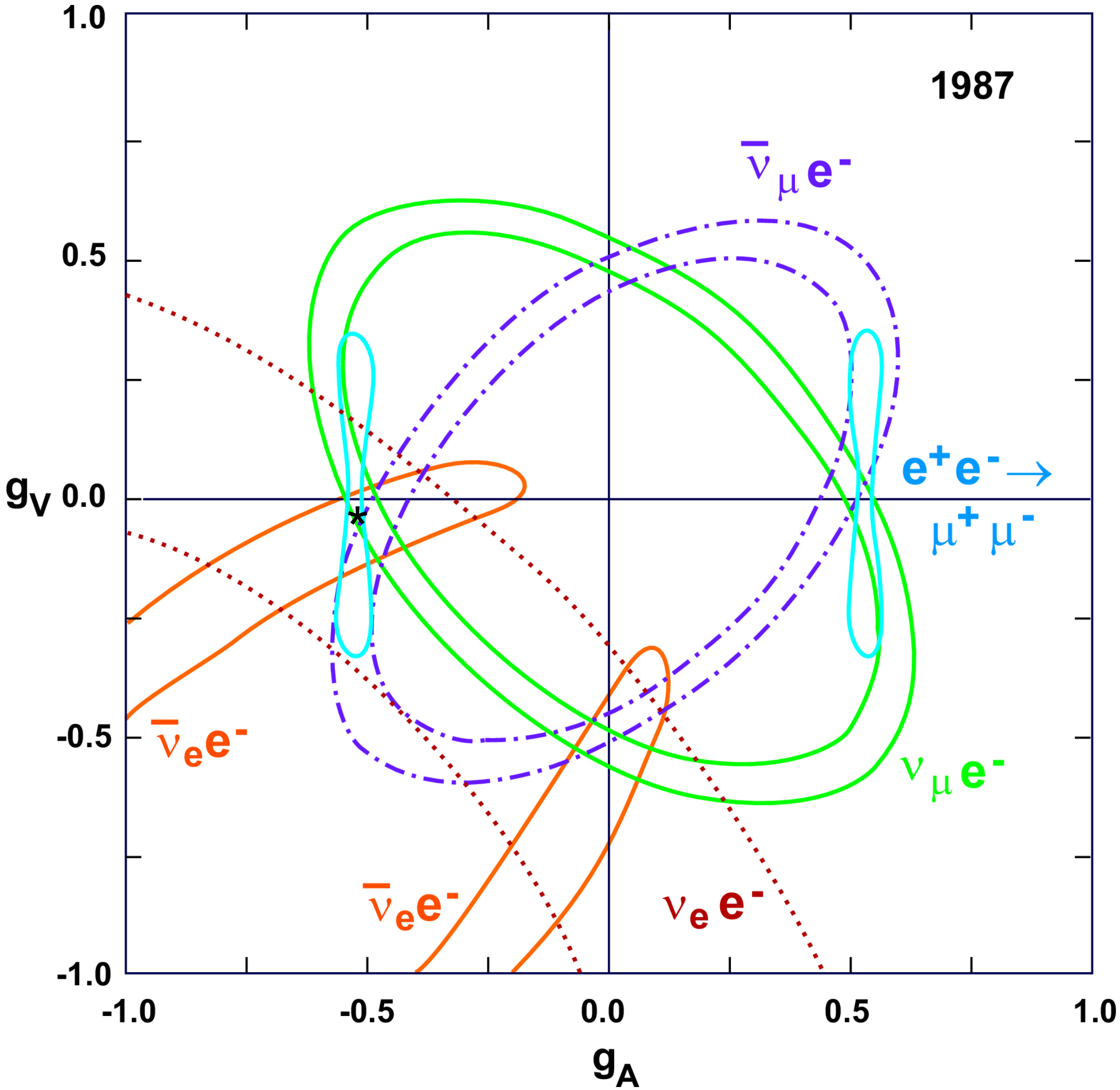
$$A_{FB}(s=M_Z^2) = A_{FB}^0 = \frac{3}{4} A_e A_f$$

$$A_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} \rightarrow \sin^2\theta_W$$

(plus QED radiative corrections)



The Z Boson



1987: Status before LEP

$g_{Vl} = 0$ still possible

Parity violation?

Final results for leptons:

Including other results

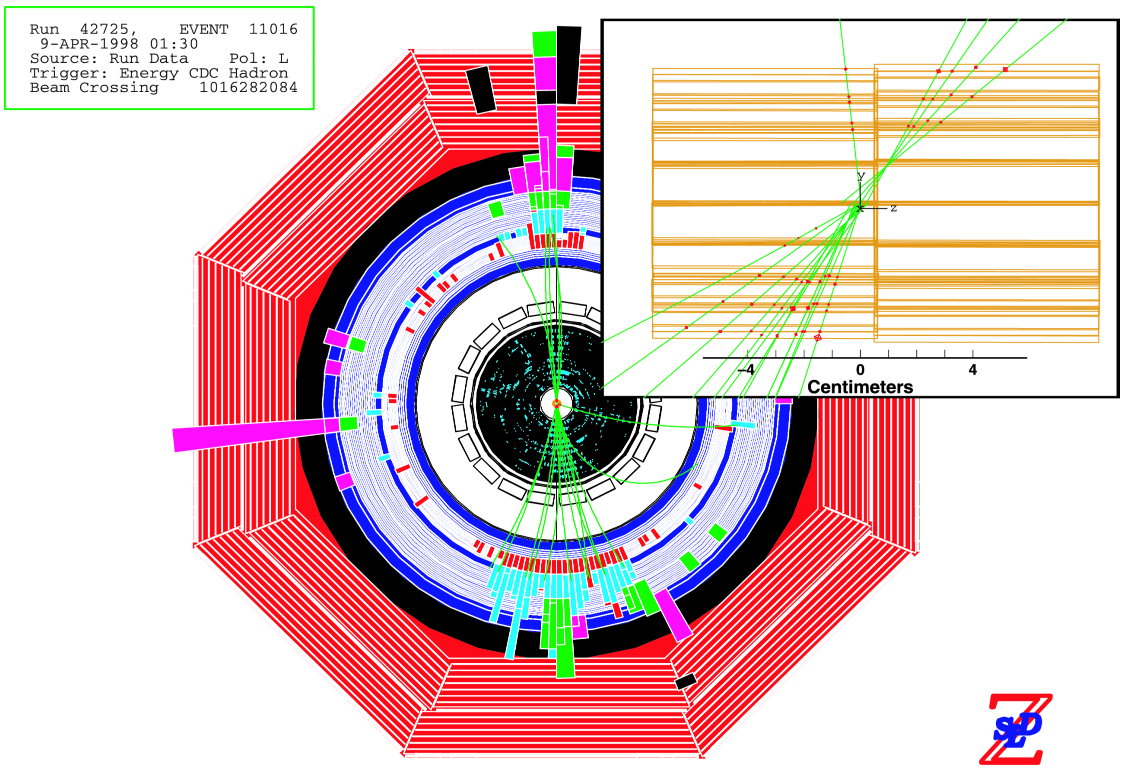
$g_{Vl} = -0.03783 \pm 0.00041 \quad \neq 0$! Parity violation also with Z!

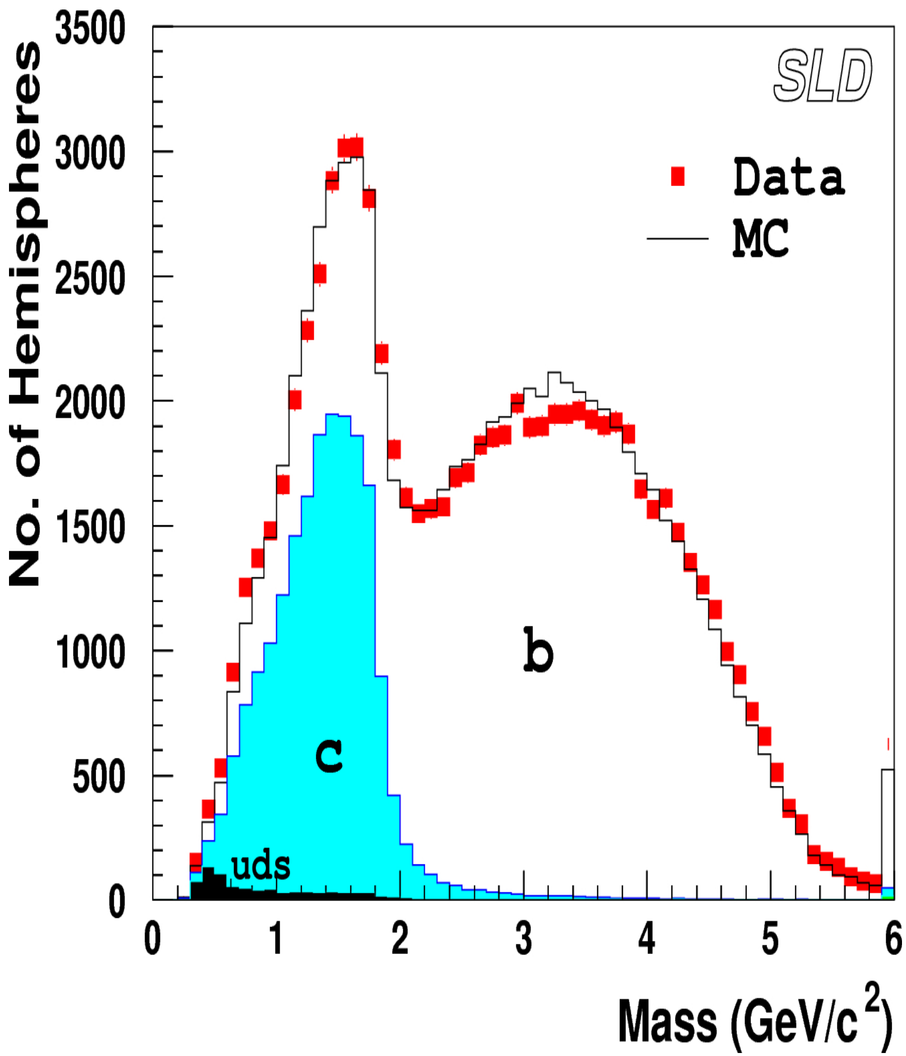
$g_{Al} = -0.50123 \pm 0.00026 \quad \neq -1/2$! A problem?

Heavy Flavour Results at the Z

Heavy quarks (b,c):

Long lifetime of b/c hadrons – secondary decay vertex

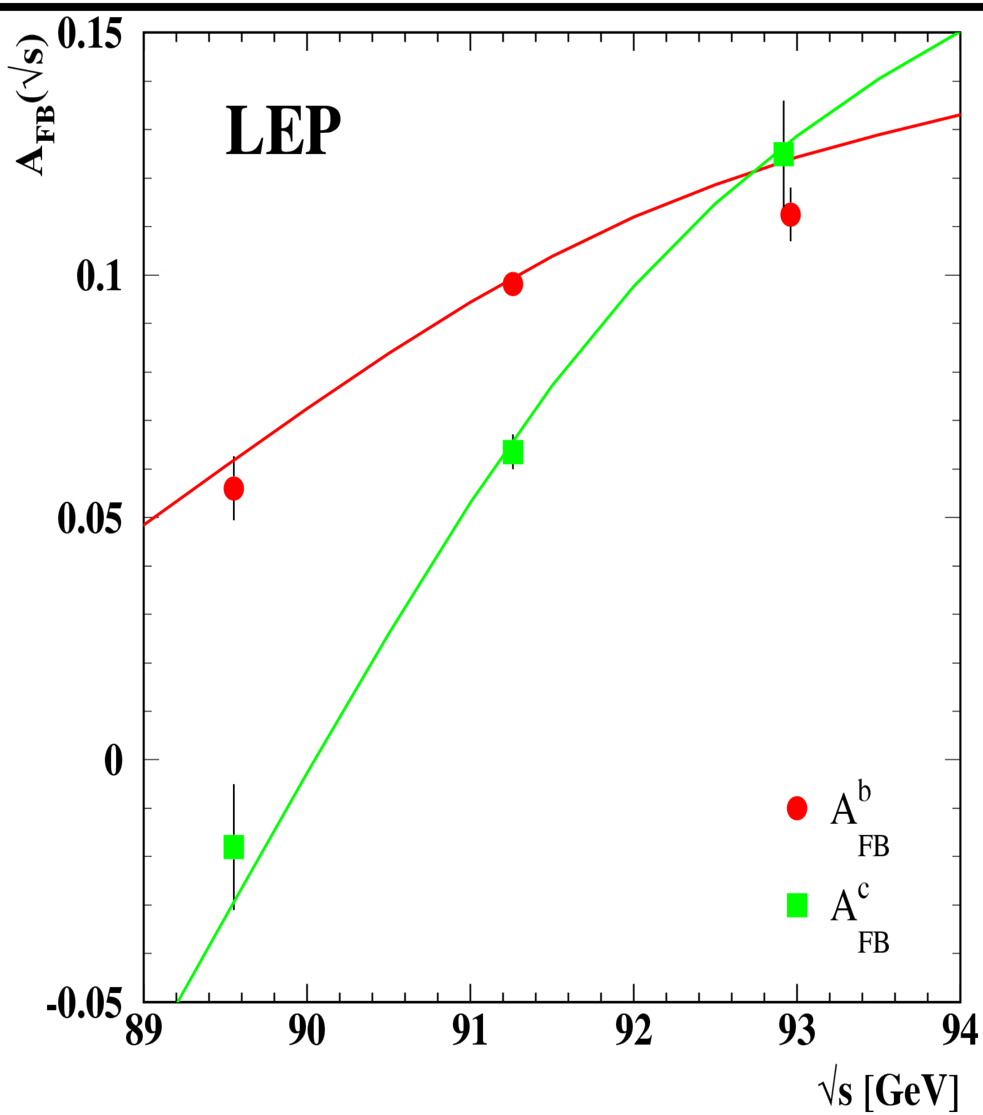


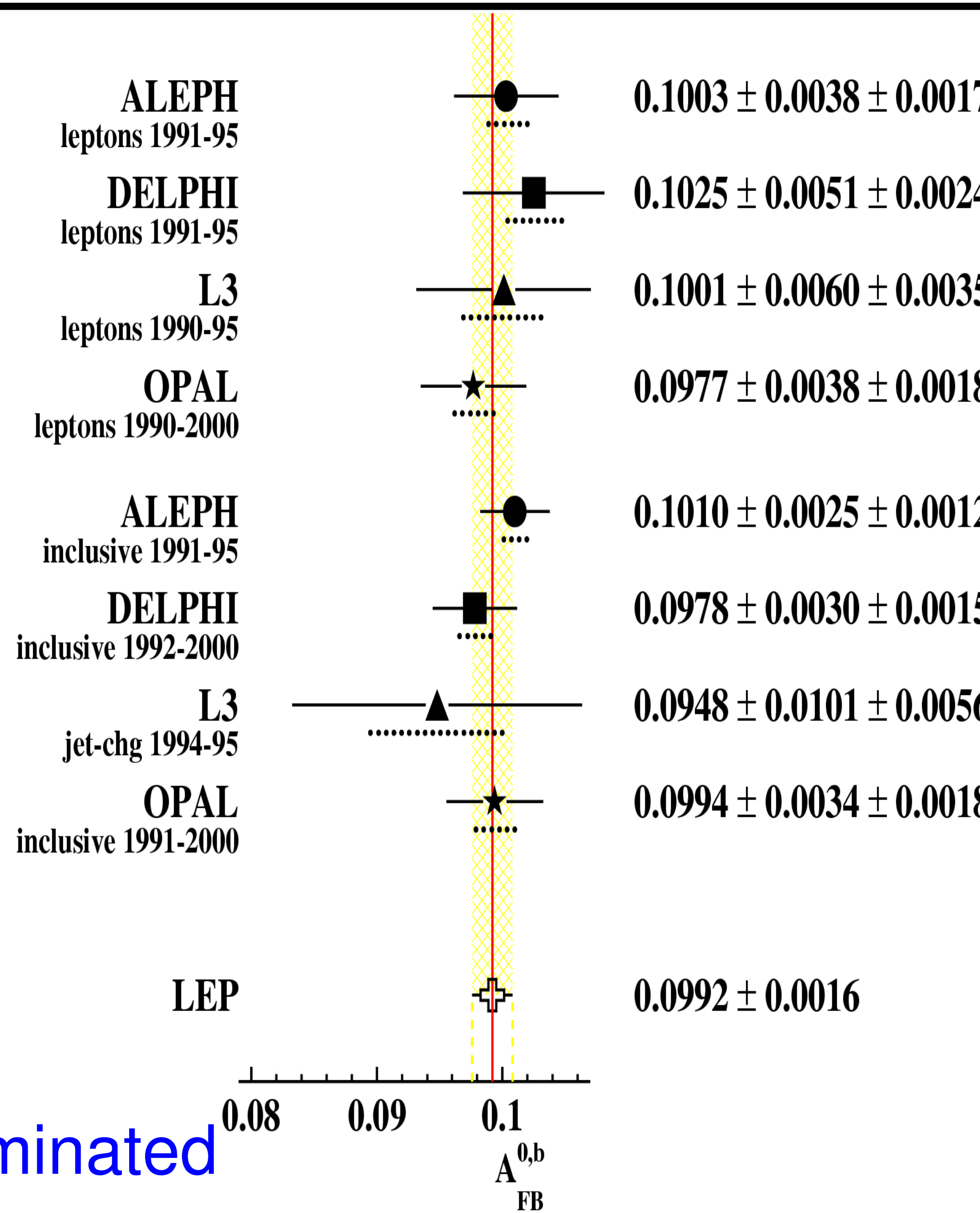


Vertex mass:

Mass of particles from decay vertex

Heavy Flavour Results at the Z





Asymmetries are statistics dominated

Central values very consistent

Heavy Flavour Results at the Z

Combined LEP1/SLD results:

Ratio of cross sections:

$R_b = \Gamma_b/\Gamma_{had}$	0.21629	± 0.00066
$R_c = \Gamma_c/\Gamma_{had}$	0.1721	± 0.0031

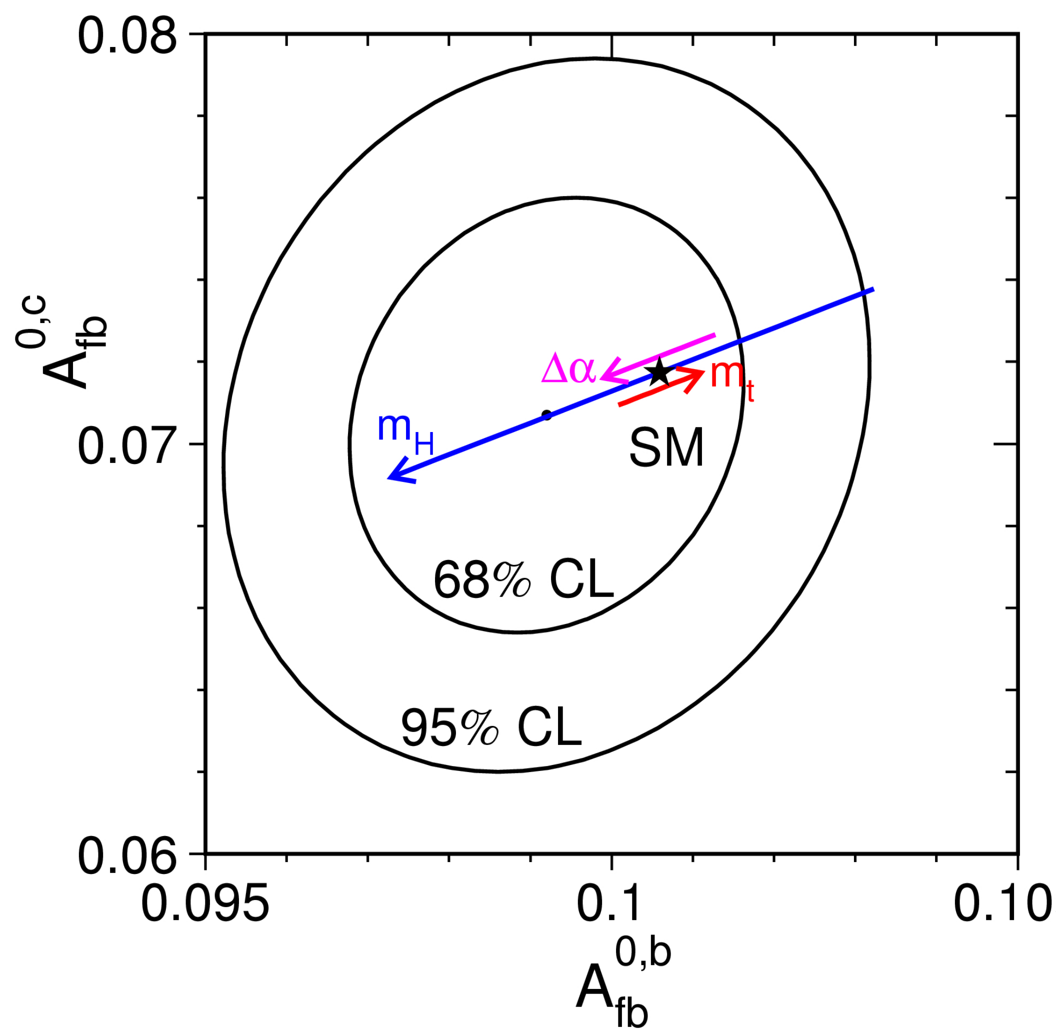
Forward-backward asymmetries:

$A_{fb}(b) = \frac{3}{4} A_e A_b$	0.0992	± 0.0016
$A_{fb}(c) = \frac{3}{4} A_e A_c$	0.0707	± 0.0035

Polarised asymmetries (SLD):

A_b	0.923	± 0.020
A_c	0.670	± 0.027

+ small correlations



SM comparison:
High Higgs-boson mass

Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

$\sin^2\Theta_{eff} = (1-g_{Vl}/g_{Al})/4$

$= 0.23153 \pm 0.00016$

$\chi^2/\text{ndof} = 11.8/5$ [3.8%]

A-posteriori observation:

0.23113±0.00021 leptons

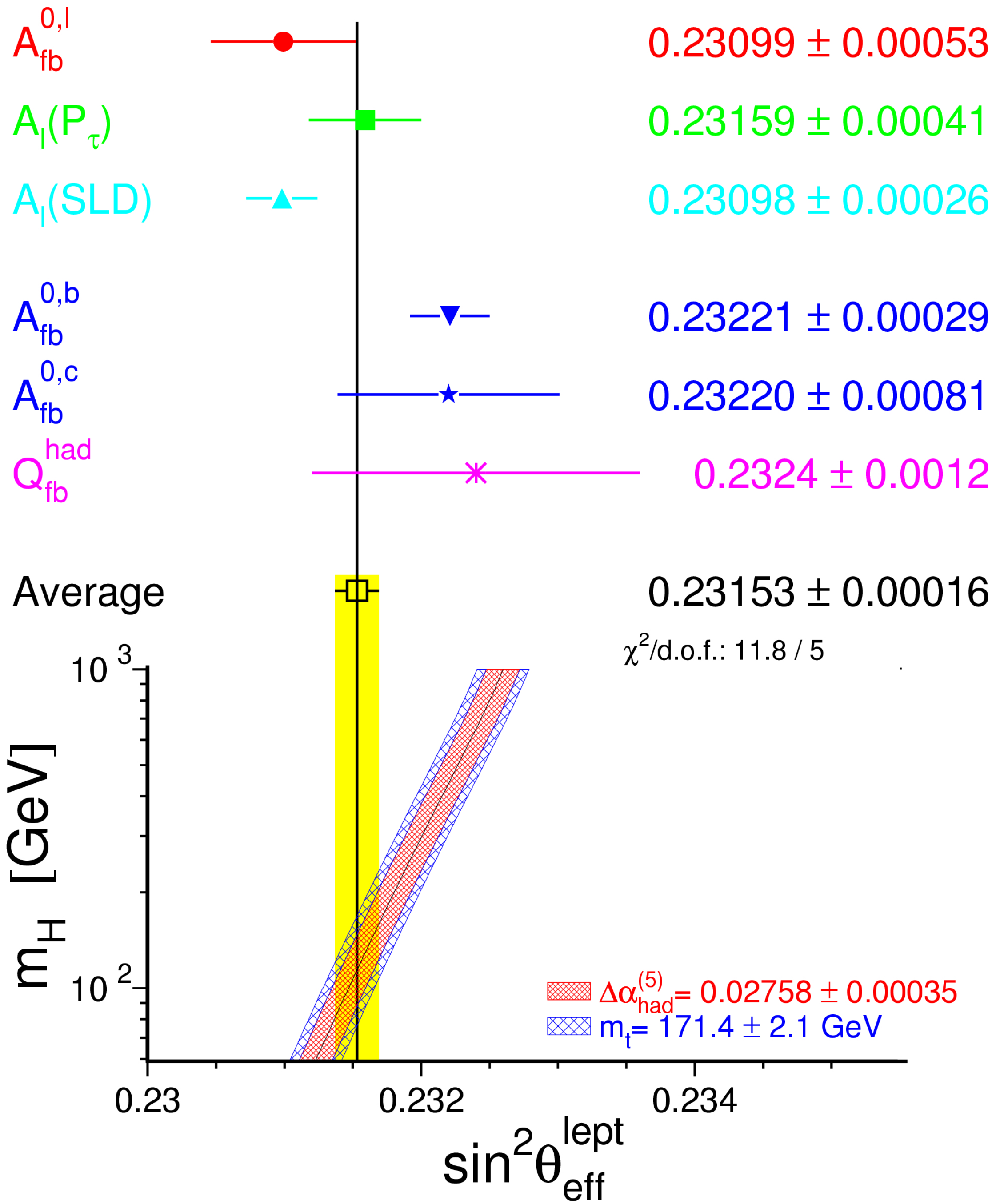
0.23222±0.00027 hadrons

3.2 σ difference

But is really:

A_l(SLD) vs. A_{fb}b(LEP)

3.2 σ difference

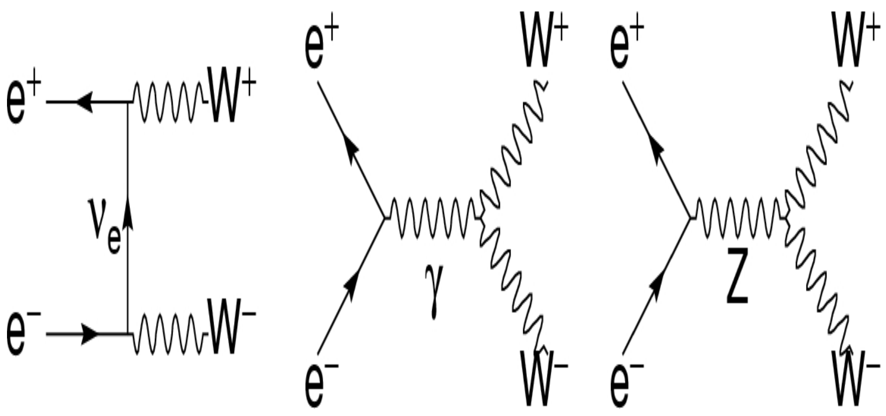


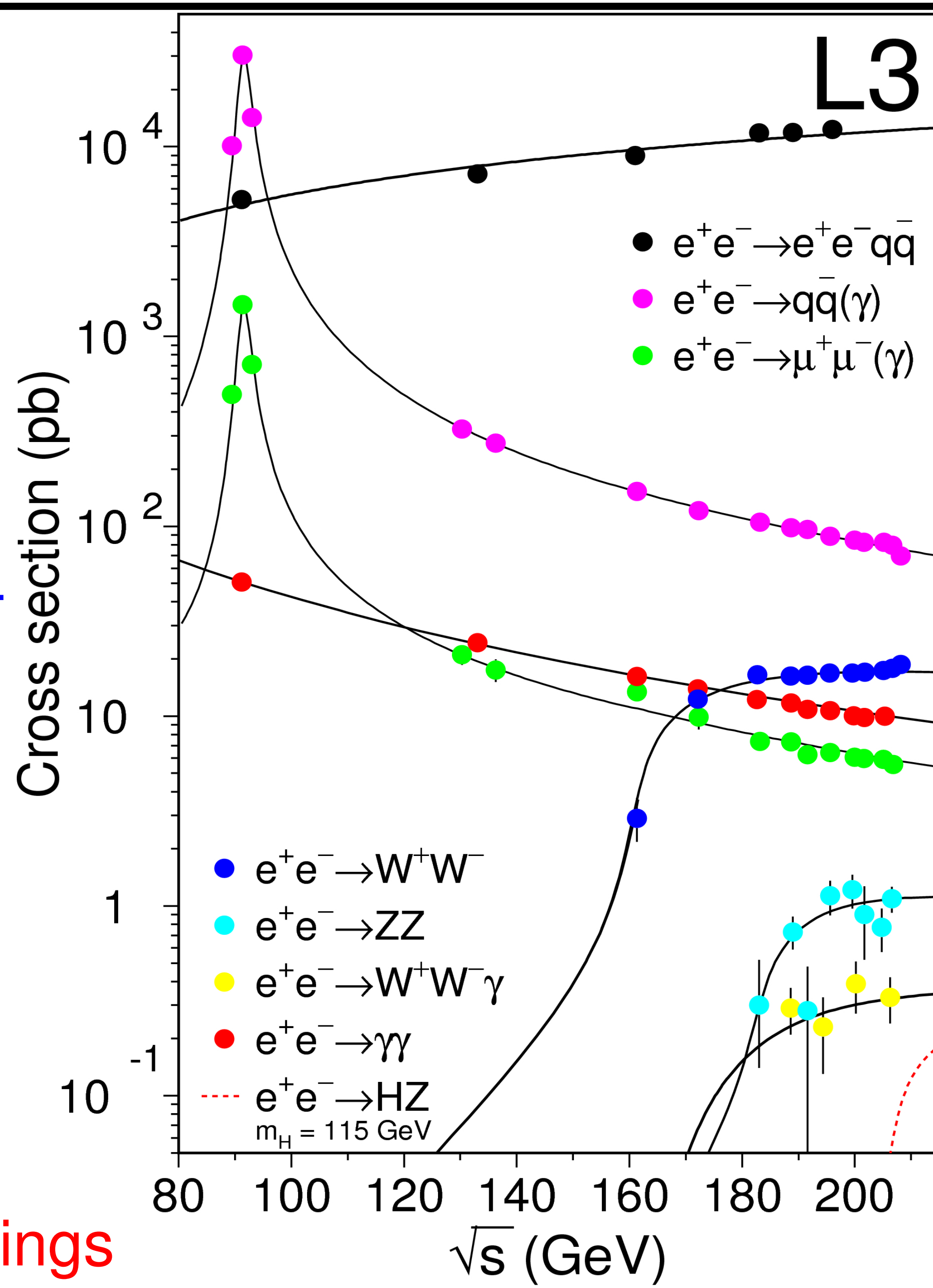
Electroweak Processes at LEP-2

Benchmark signatures
of electroweak physics

Di-Boson processes:
WW, WWγ
ZZ, Z$\boldsymbol{\gamma}$

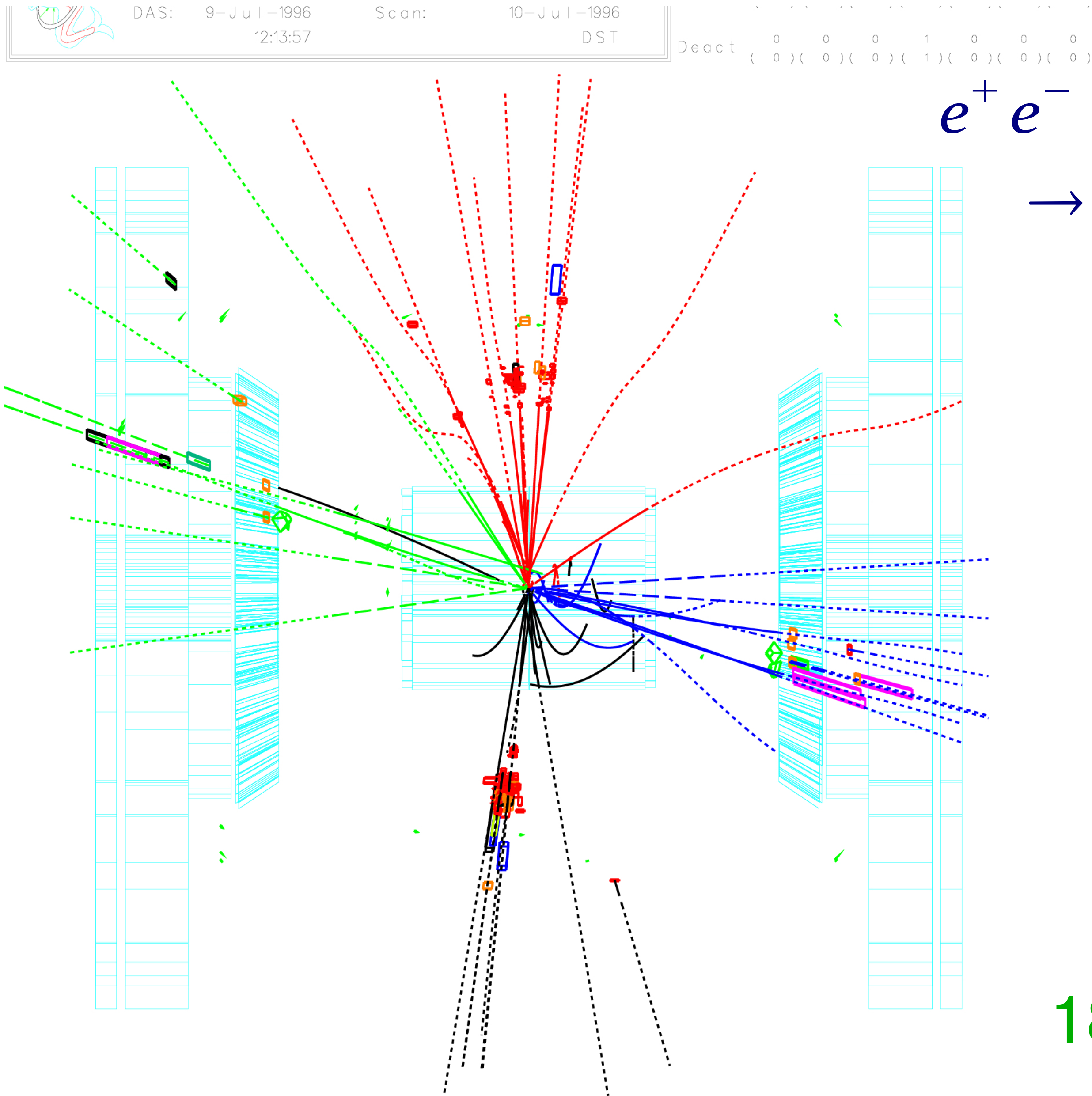
Top quark too heavy for ee→tT





W mass and triple gauge couplings

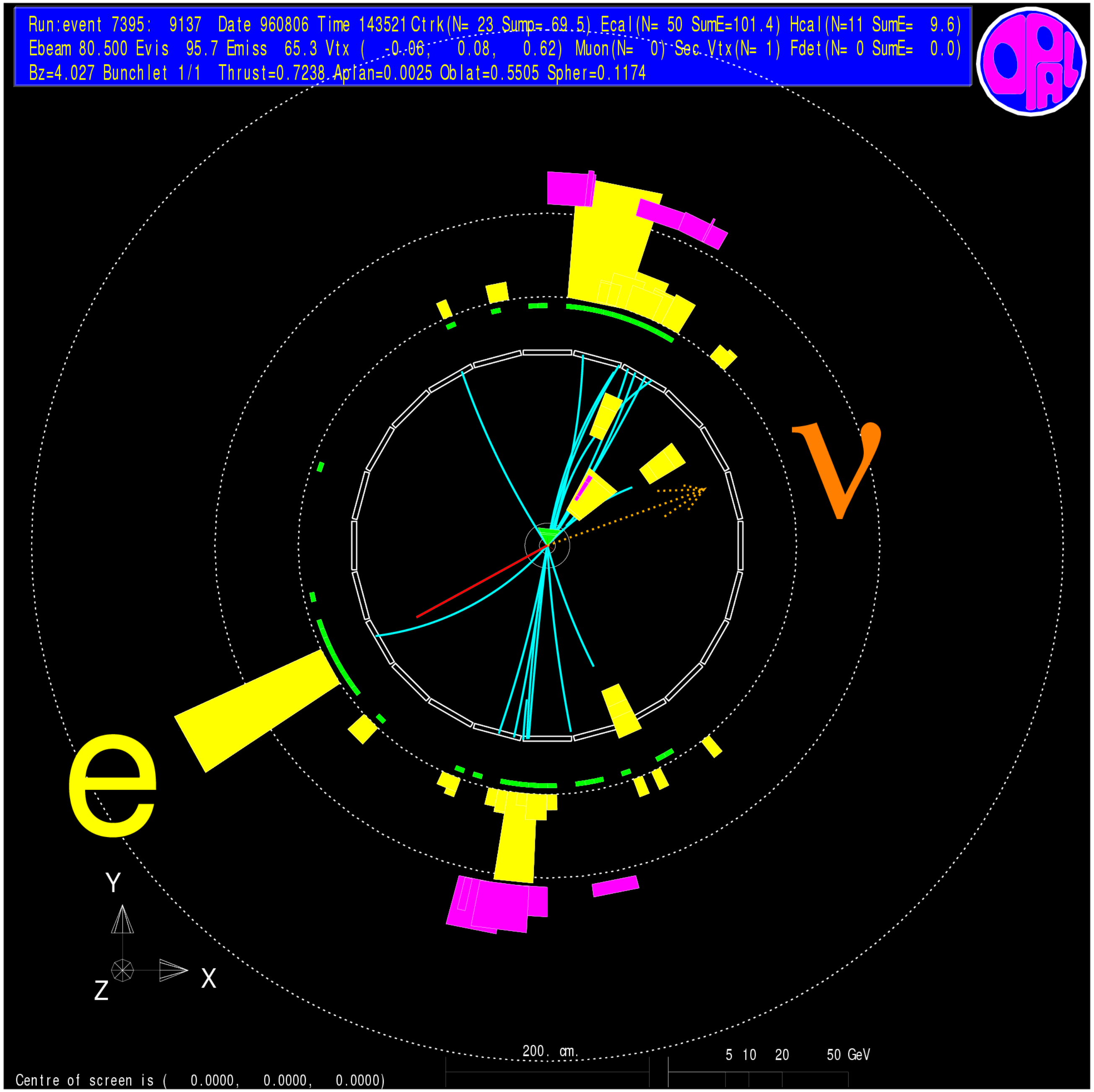
The W Boson



$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$
$$\rightarrow \textit{four hadronic jets}$$

18,000 events at LEP

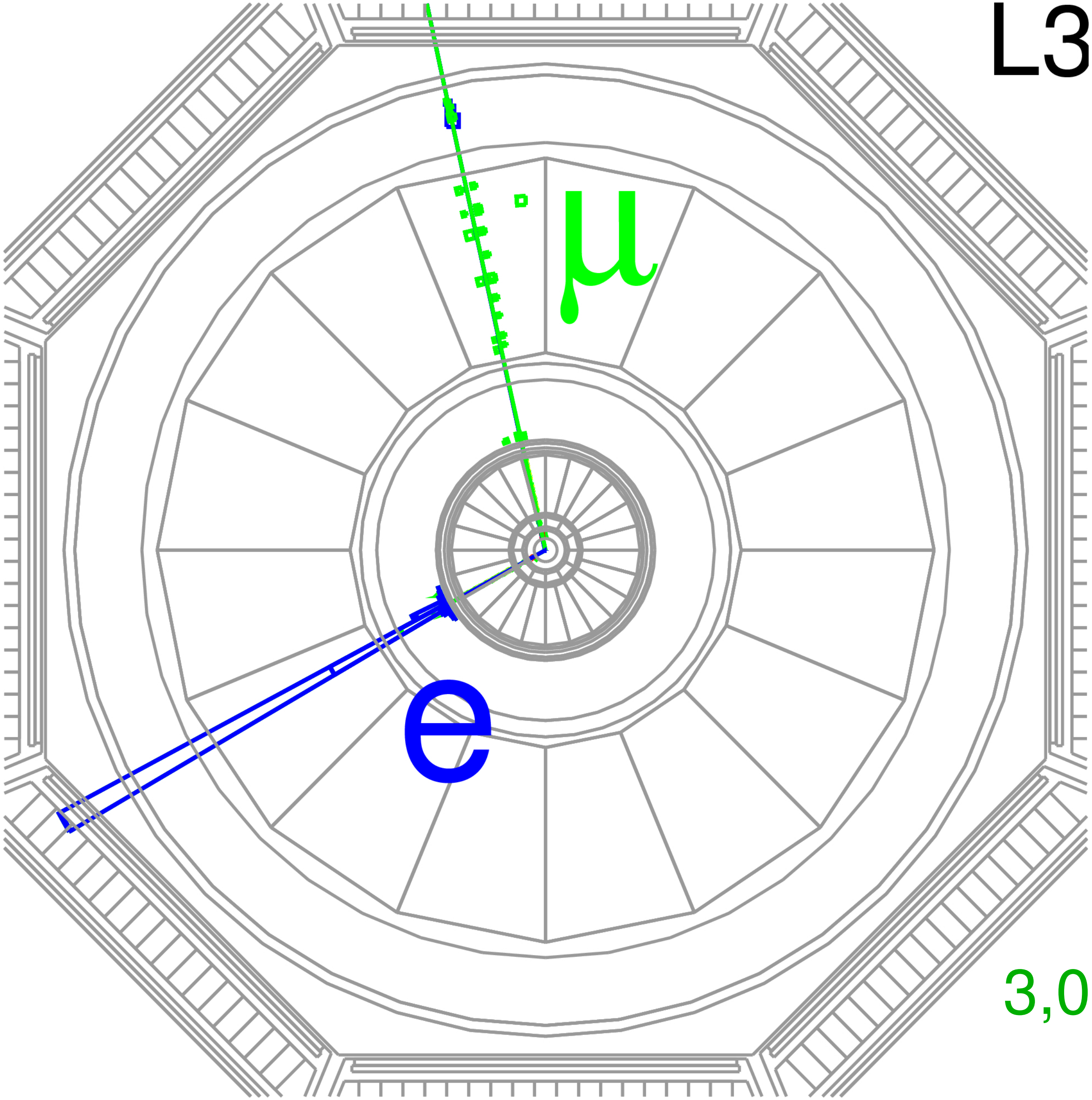
The W Boson



$$e^+ e^- \rightarrow W^+ W^-$$
$$\rightarrow q\bar{q} l \nu_l$$
$$\rightarrow two \quad jets \quad + l$$

15,000 events at LEP

The W Boson



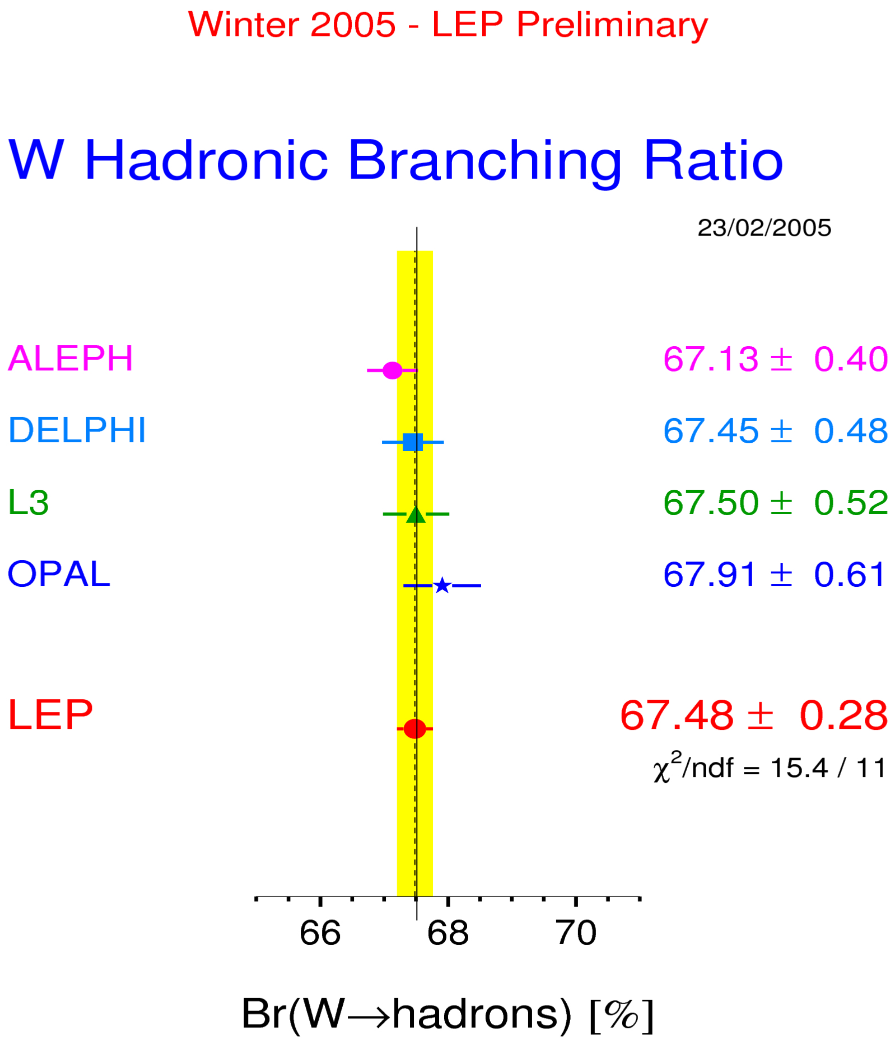
L3

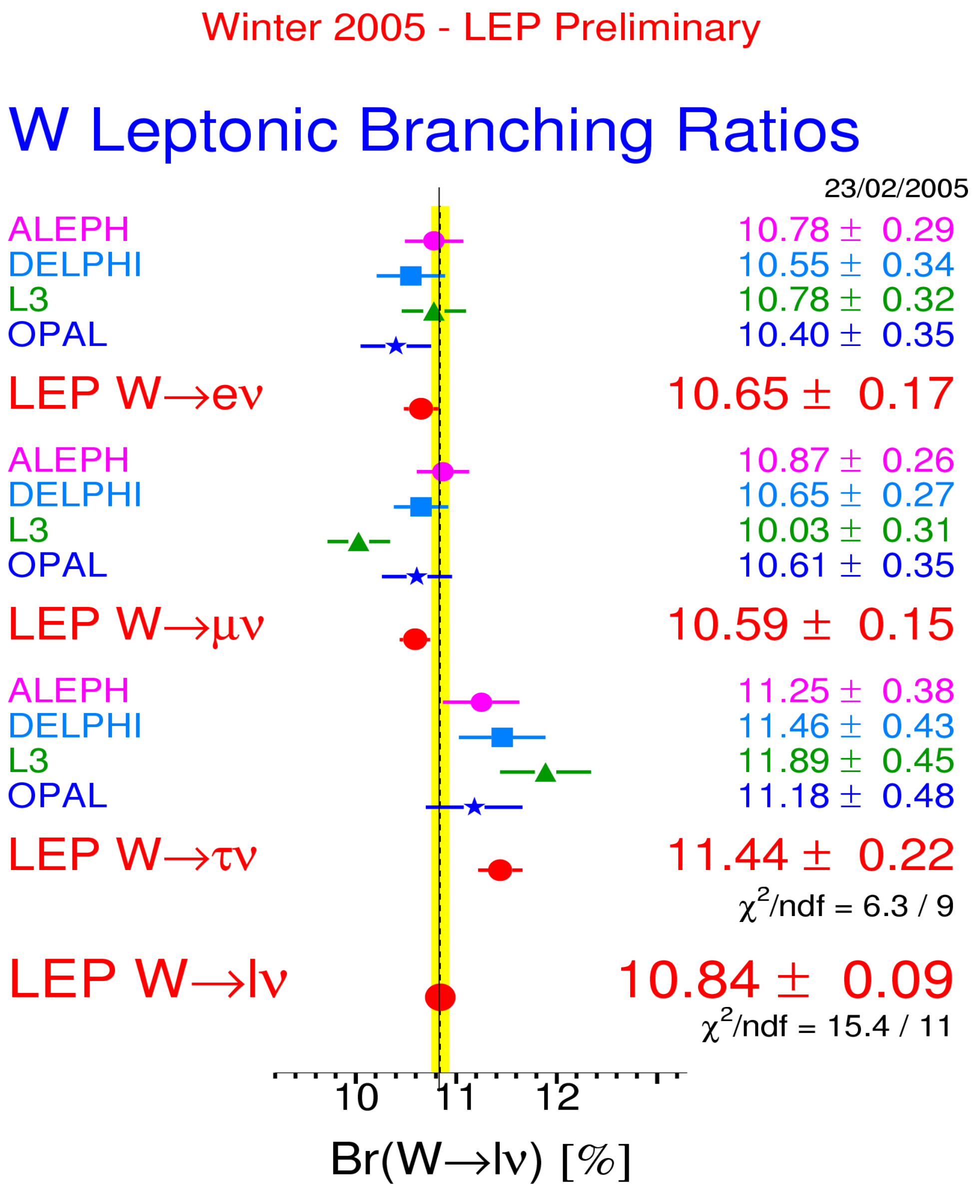
$$e^+ e^- \rightarrow W^+ W^-$$
$$\rightarrow l^+ \nu \, l^- \bar{\nu}$$

here: $e \nu \mu \nu$

3,000 events at LEP

The W Boson

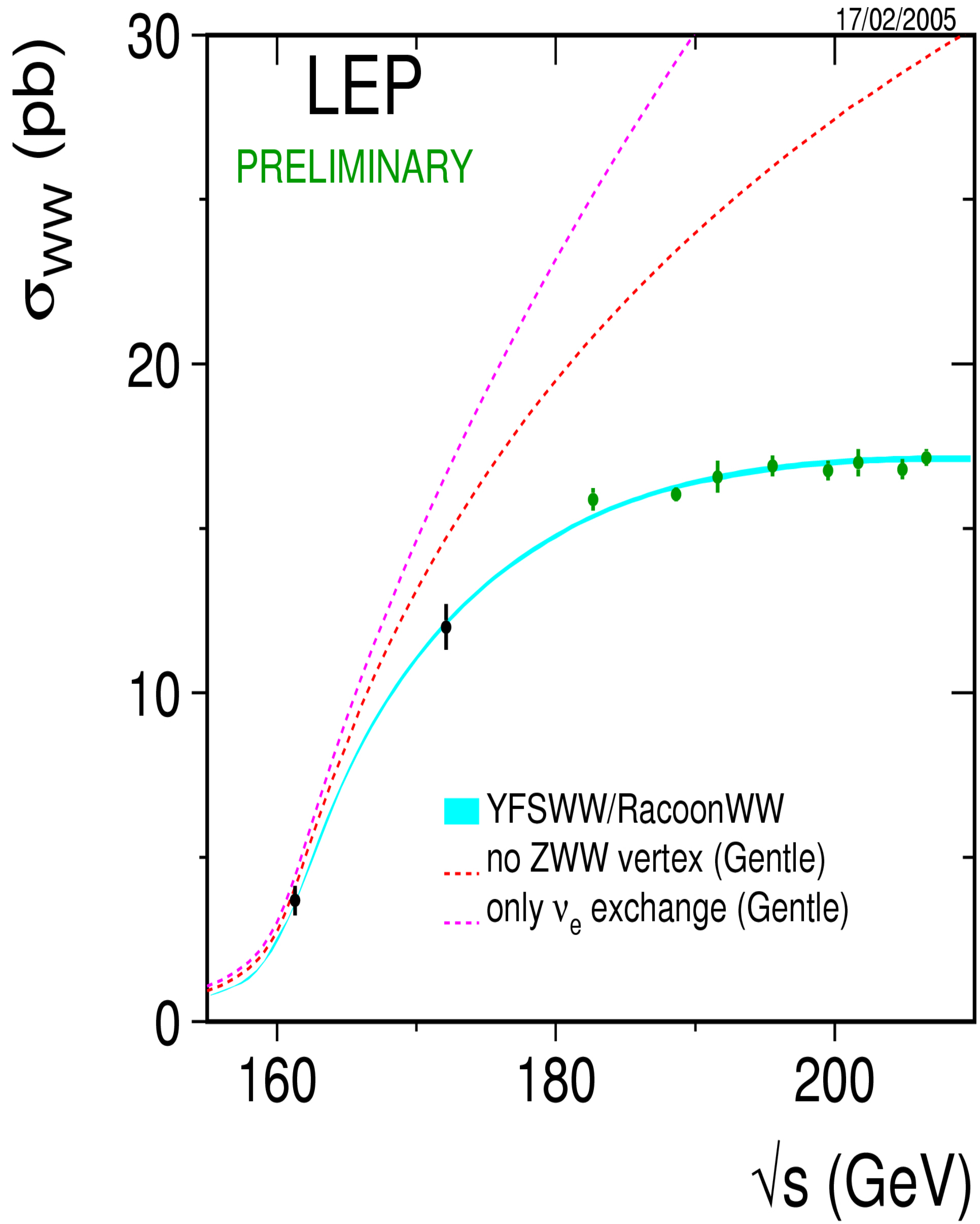




Branching fractions test universal W-ff coupling (V=A=1)

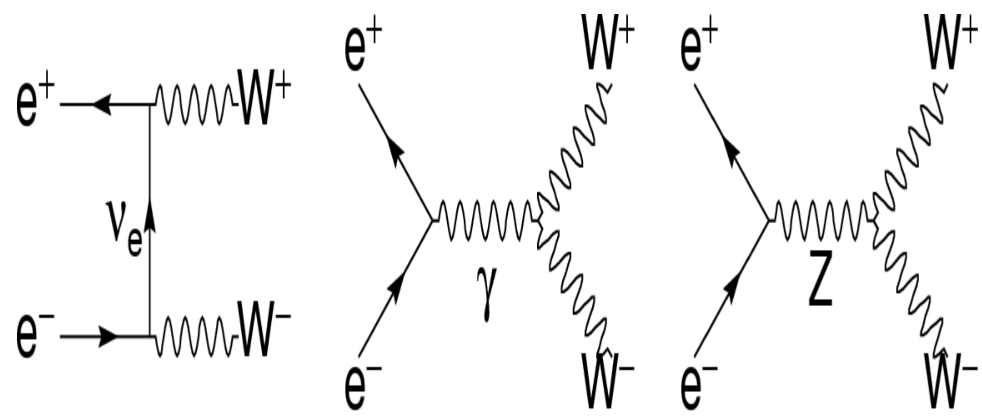
W-τ branching fraction ~2.8σ above W-e/μ average (a posteriori)

The W Boson



Triple-gauge boson coupling:

Self-coupling of gauge bosons



ν_e exchange	γWW vertex	ZWW vertex

Fundamental test of the SM

Unitarity at high energies

The W Boson

- effective Lagrangian, the C and P conserving part ($V=Z,\gamma$):

$$\frac{i\mathcal{L}_{\rm eff}}{g_{VWW}} = g_1^V V^\mu (W^-_{\mu\nu} W^{+\,\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^+_\nu W^-_\mu$$

- electric charge $\quad q_W = e g_1^\gamma$
- magnetic dipole moment $\quad \mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$
- electric quadrupole moment $\quad Q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$
- SU(2)×U(1): $g_1^\gamma = 1$

$$\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$$

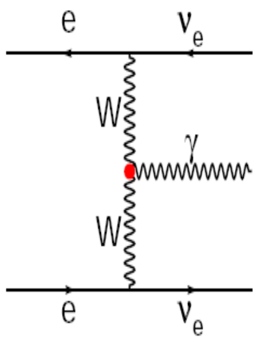
$$\lambda_\gamma = \lambda_Z$$

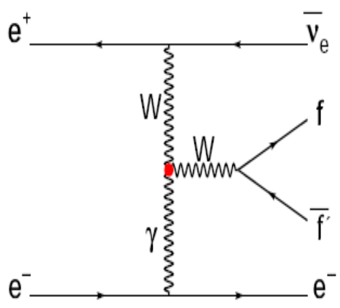
- SM values:

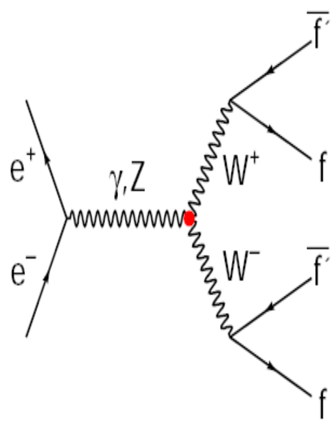
$$\kappa_\gamma = 1$$

$$g_1^Z = 1$$

$$\lambda_\gamma = 0$$

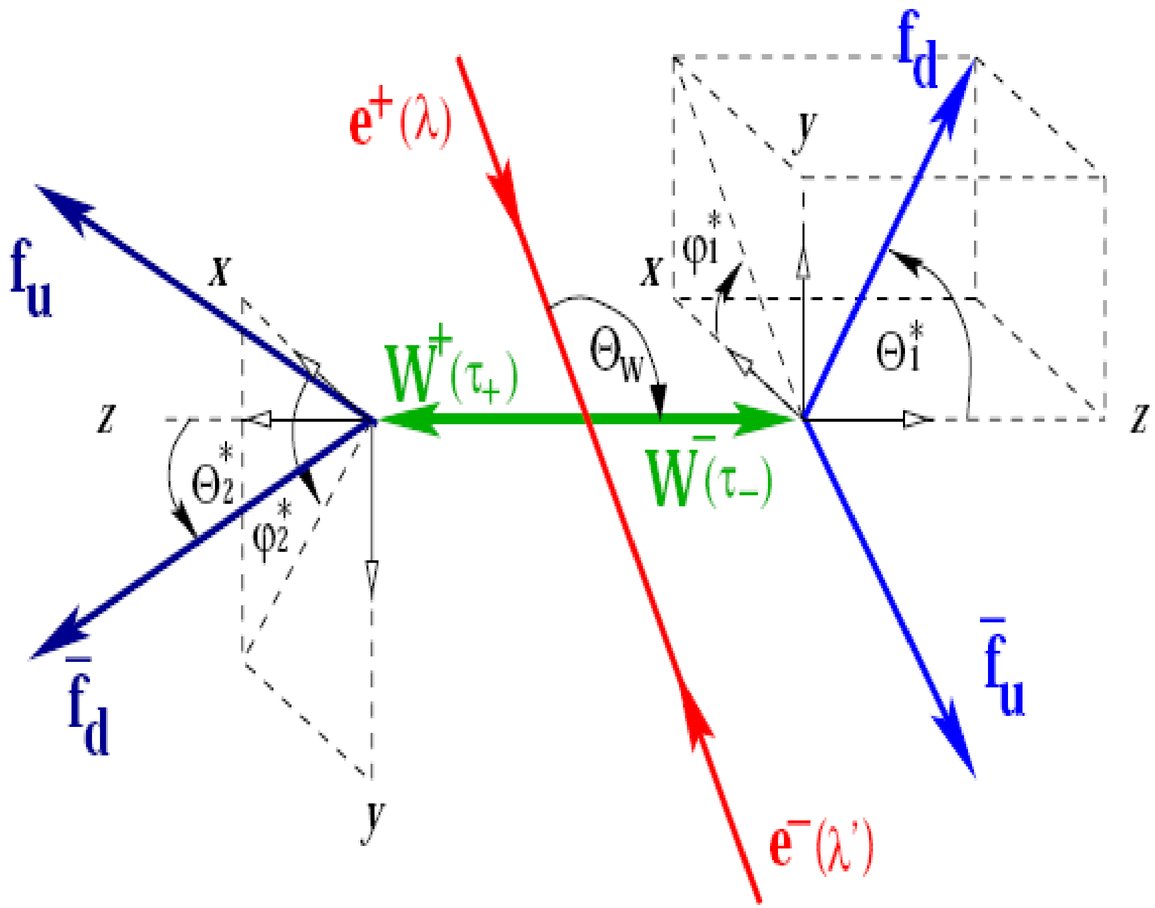


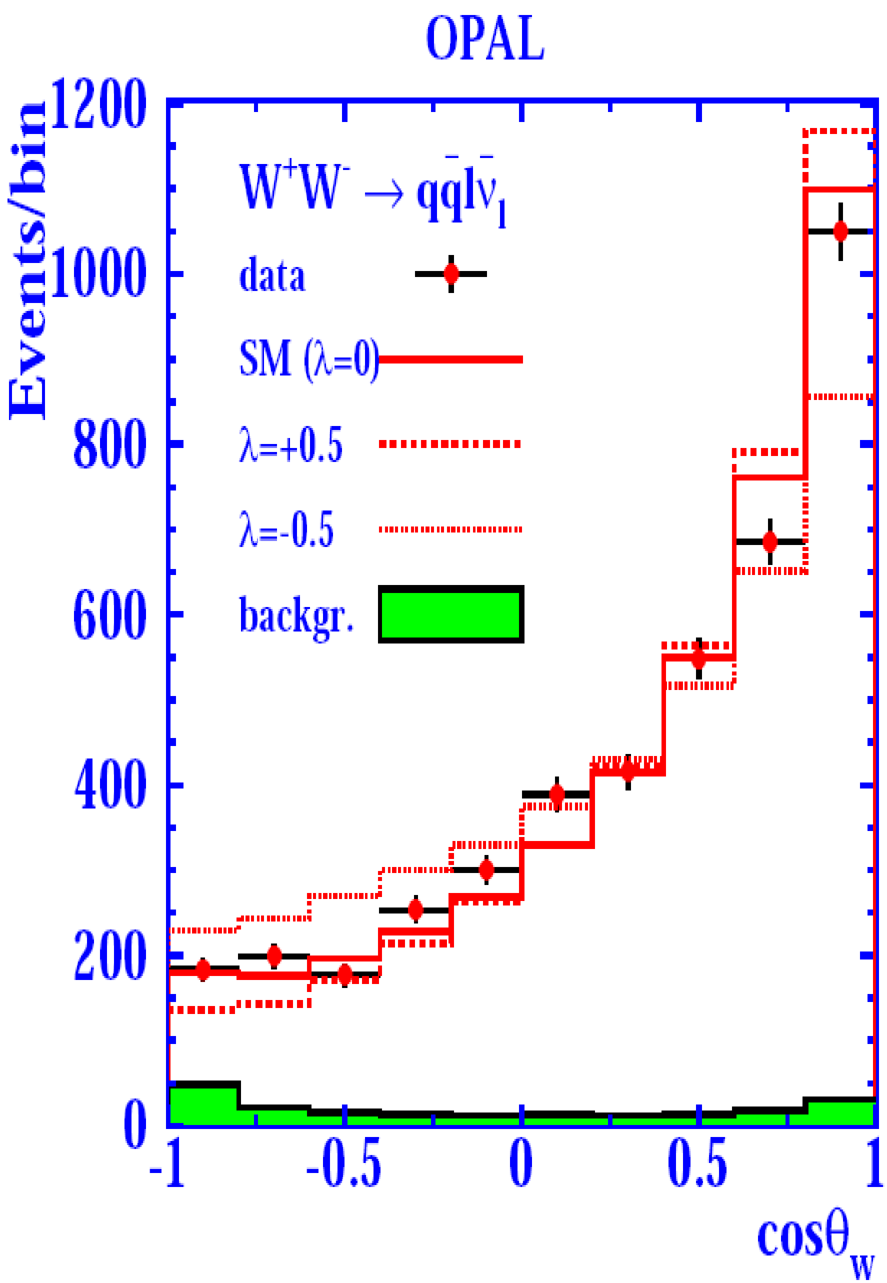




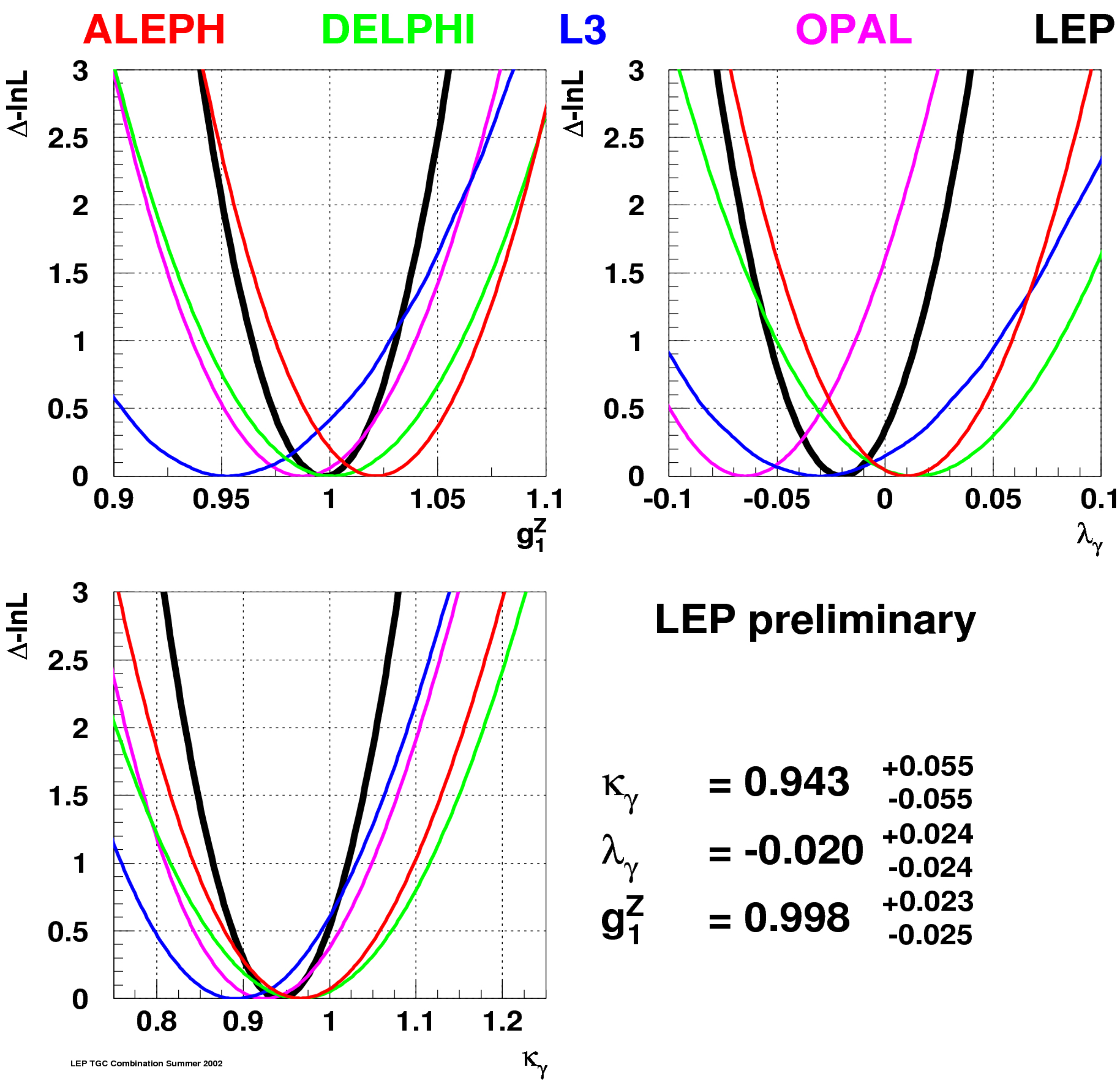
Triple-gauge boson coupling:

- Analysis of 5 phase-space variables
- W production angle
  - highest sensitivity





The W Boson



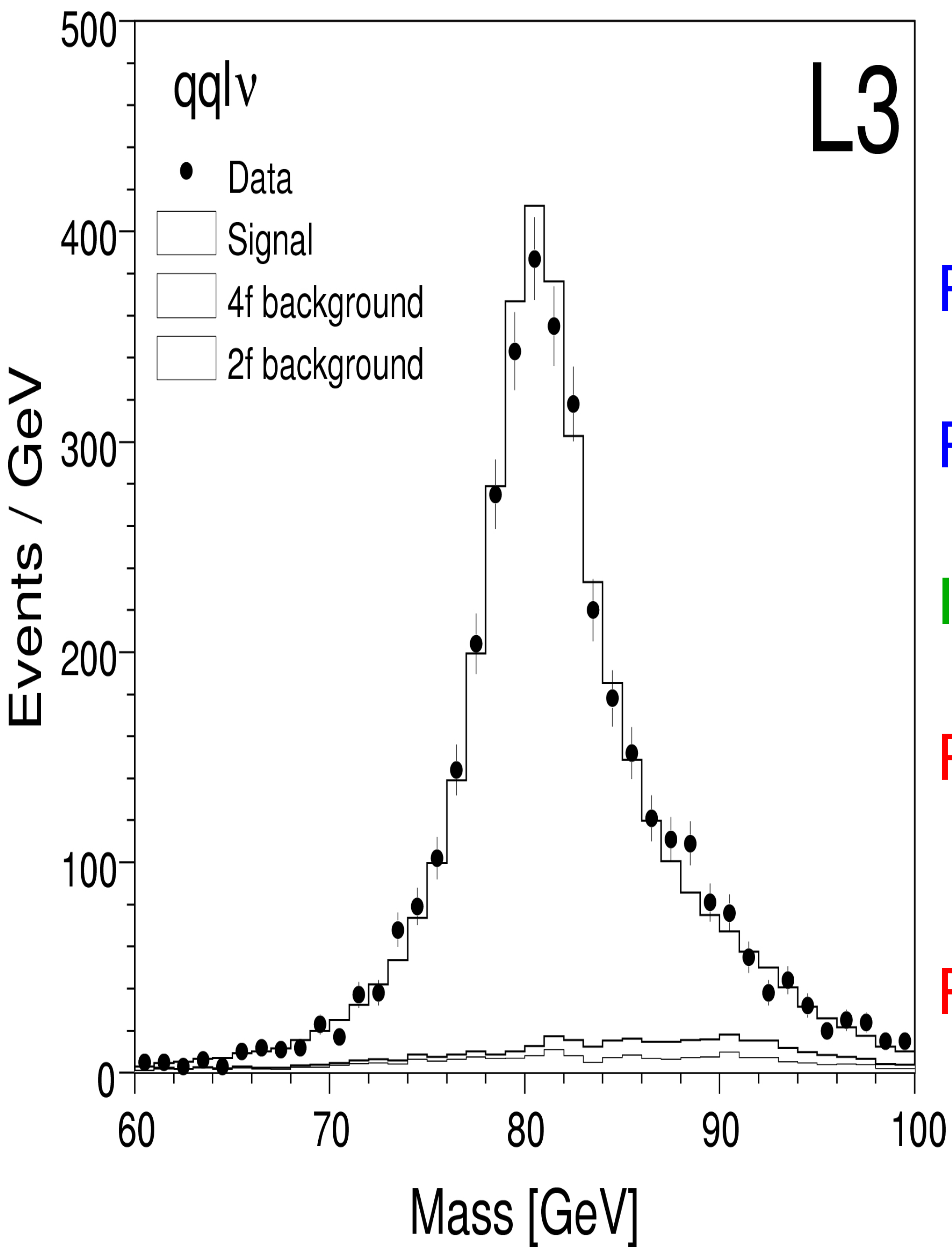
Standard-Model values:

1

0

1

The W Boson



$$e^+ e^- \rightarrow W^+ W^-$$

$$with \quad W \rightarrow f \bar{f}'$$

Reconstruction of 4 fermions

Pairing to form two W bosons

Invariant mass of decay products

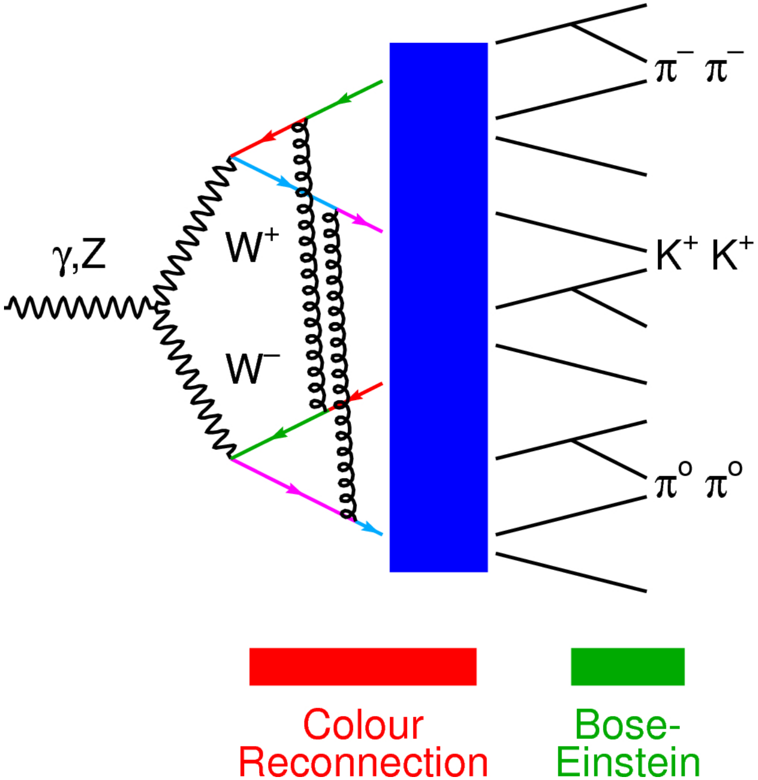
Peak position => W-boson mass

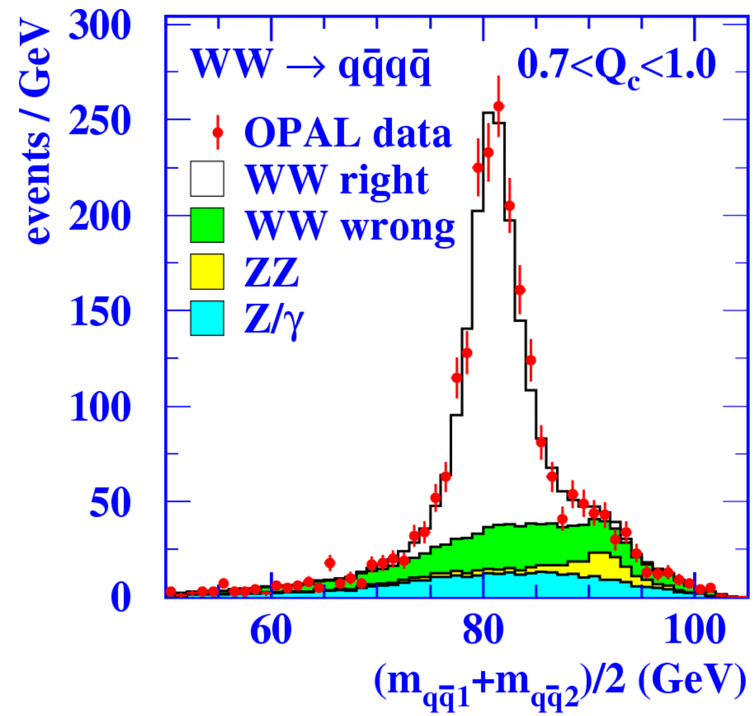
$$M_{inv}(f\bar{f}') = M_{inv}(W)$$

Peak width => W-decay width
(plus detector resolution)

The W Boson

LEP-2: $e^+e^- \rightarrow W^+W^- \rightarrow$ qqqq, qqlν, lνlν   Invariant mass M_{inv}(ff)





Potentially large FSI systematics (CR,BE) in the qqqq channel:

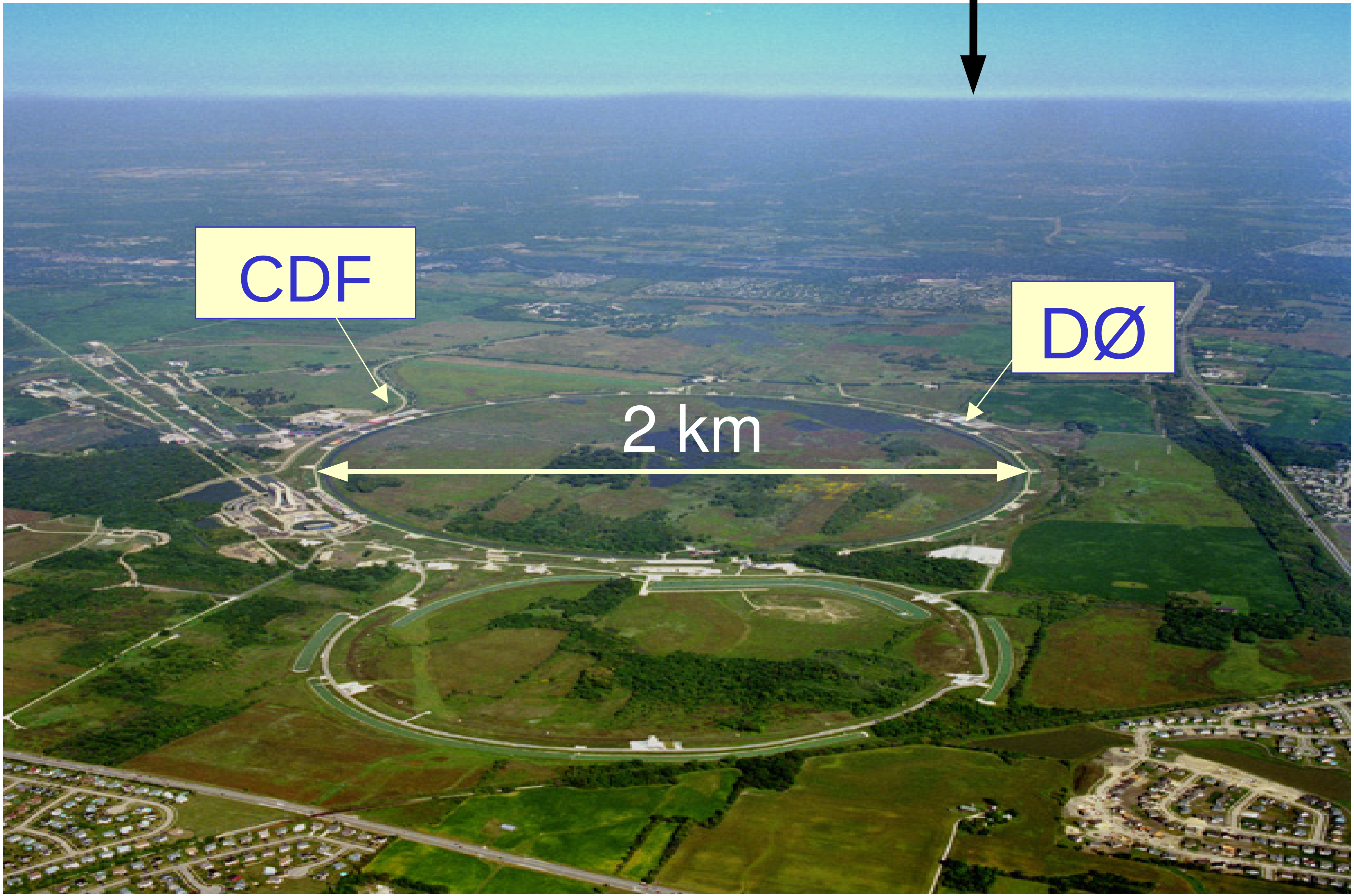
M_W average dominated by qqlν channel (qqlν: 78%, qqqq: 22%)

FSI test: mass difference (calculated without FSI uncertainties):

M_W(qqqq) – M_W(qqlν) = –12 ± 45 MeV

Need final CR limit from dedicated studies to limit CR error on M_W

Fermi National Laboratory, Chicago, USA



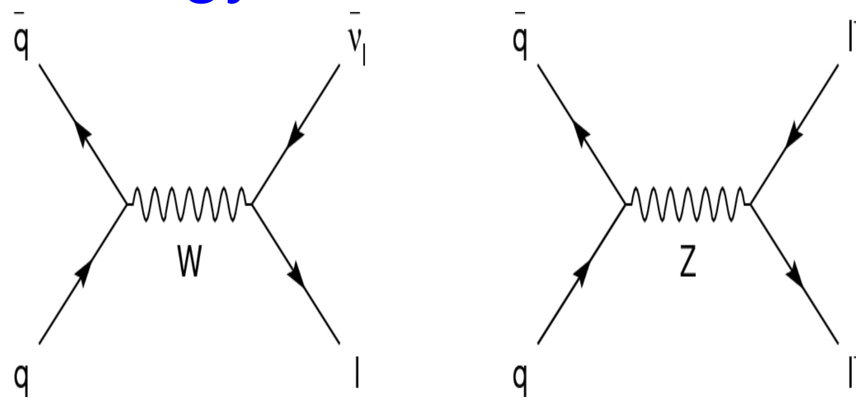
Event Signature

Tevatron (CDF, D∅): 1.8 – 2 TeV CM energy

Single-boson production

$p\bar{p} \rightarrow W$ + recoil/spectator quarks,

$d\bar{u} \rightarrow W \rightarrow e\nu, \mu\nu$

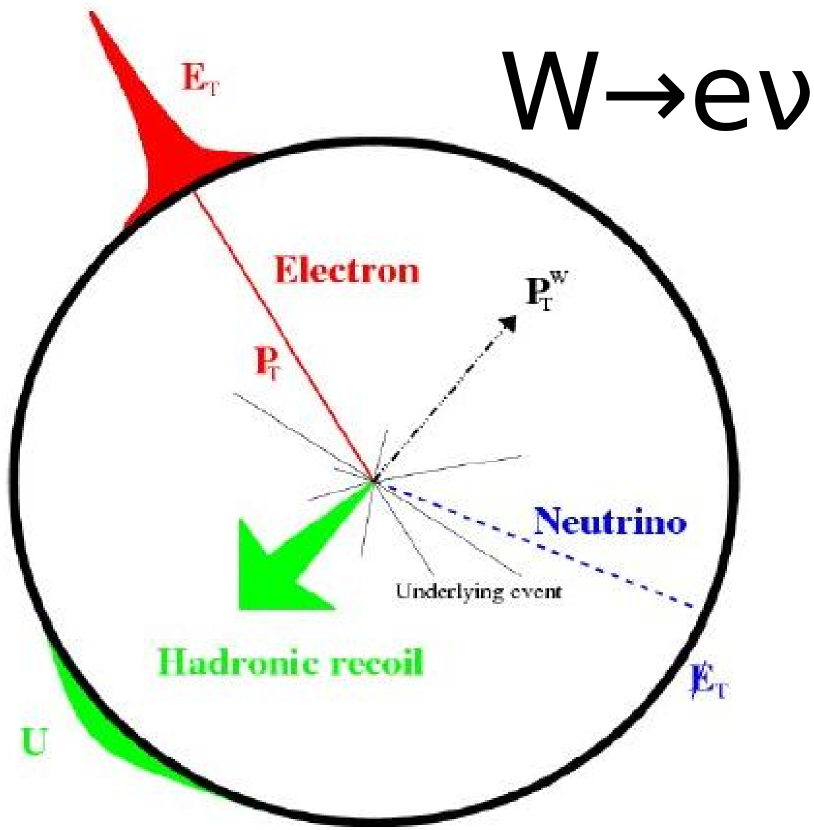


Inclusive $W \rightarrow l\nu$:

Single high-energy lepton (e, μ)

Missing (transverse) energy (ν)

Hadronic recoil, possibly jet(s)



Similar: Z production (calibration)

Use the transverse plane (only)

e.g., transverse mass:

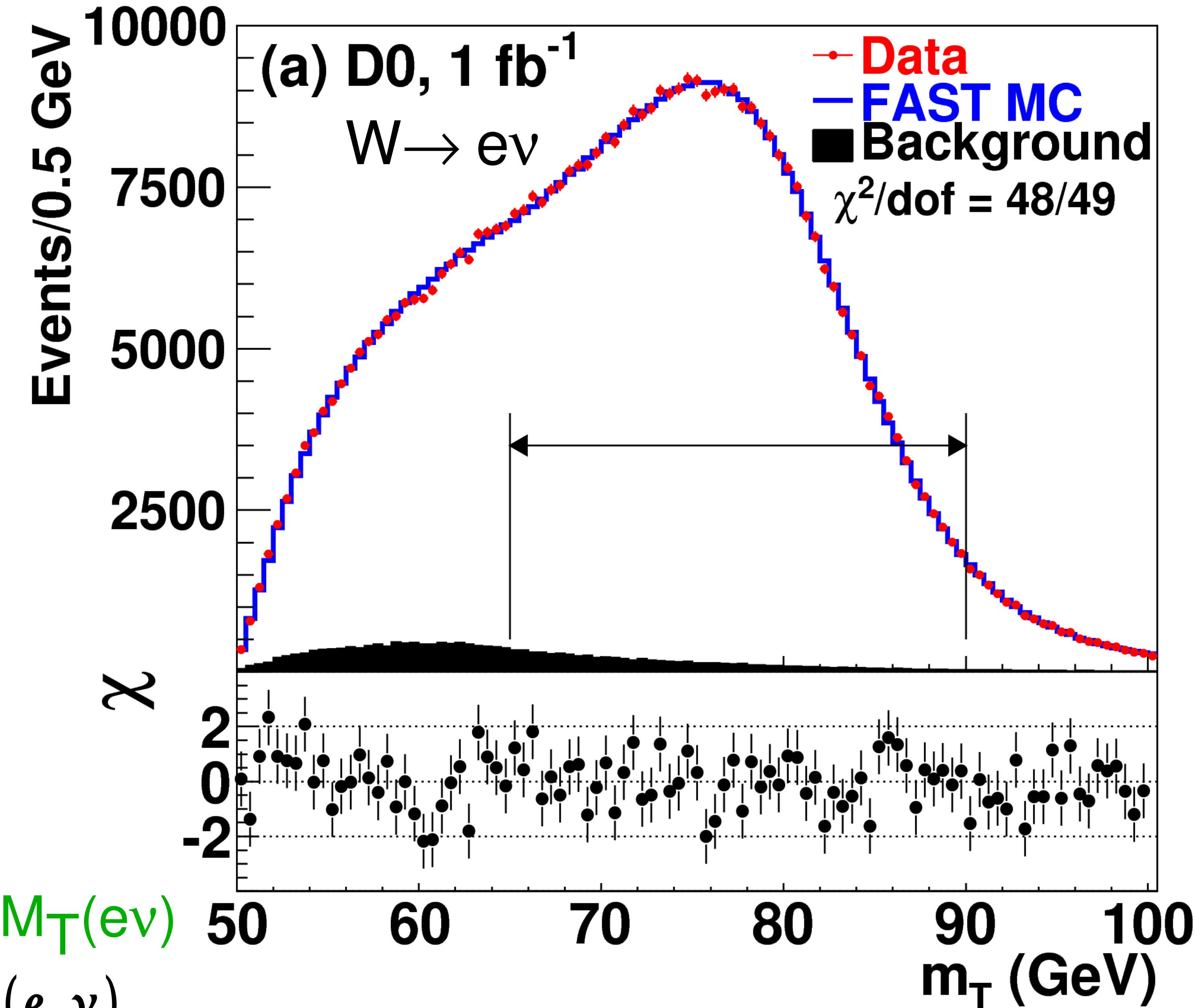
$$m_T^2 = 2 E_T^e E_T^\nu \cos\phi(e,\nu)$$

W Boson at the Tevatron

CDF, DØ:

$p\bar{p} \to WX$,

$W \to e\nu, \mu\nu$

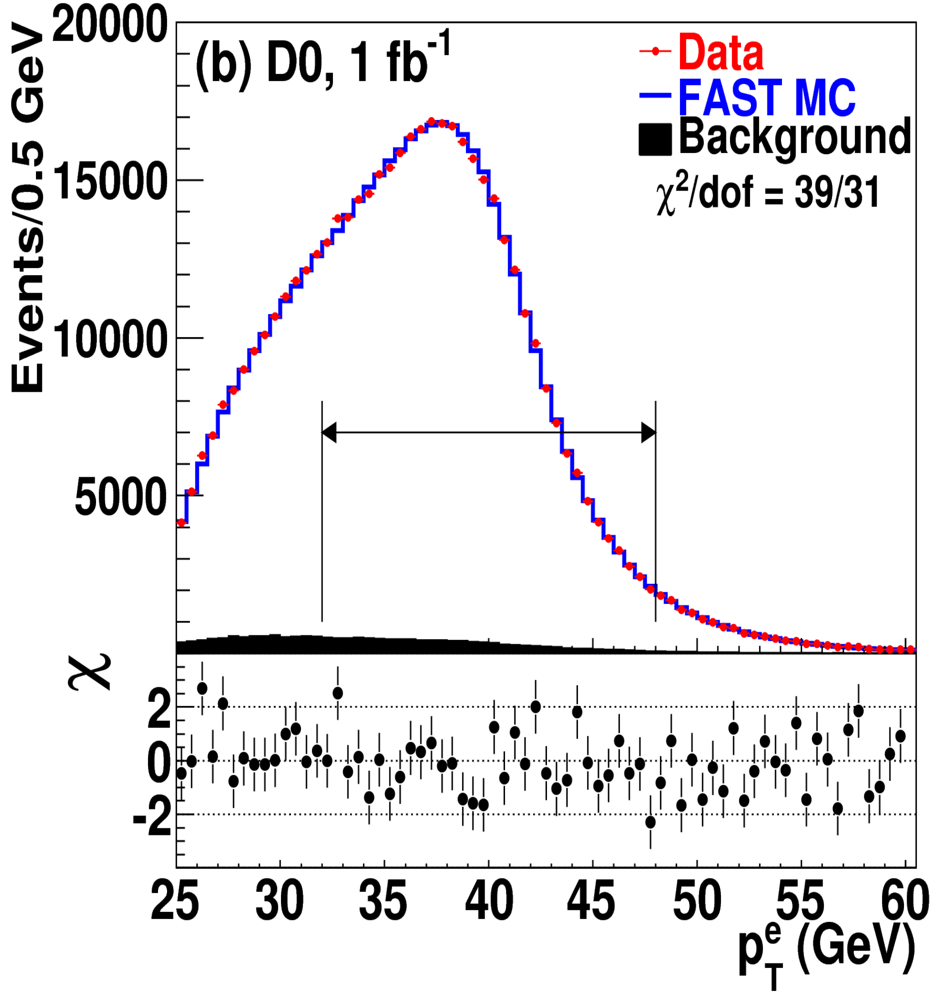


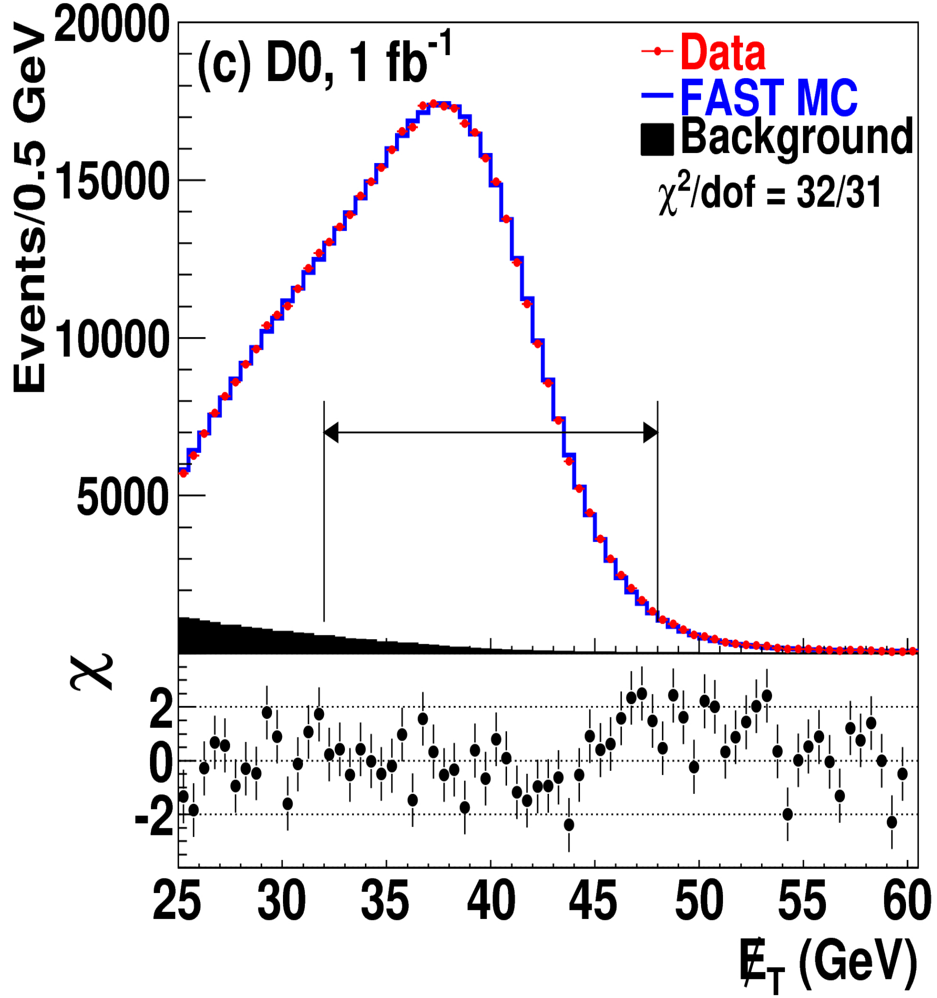
Transverse mass $M_T(e\nu)$

$$m_T^2 = 2E_T^e E_T^\nu \cos\phi(e,\nu)$$

W Boson at the Tevatron

CDF, DØ: $p\bar{p} \rightarrow WX$, $W \rightarrow e\nu, \mu\nu$





Transverse lepton energy

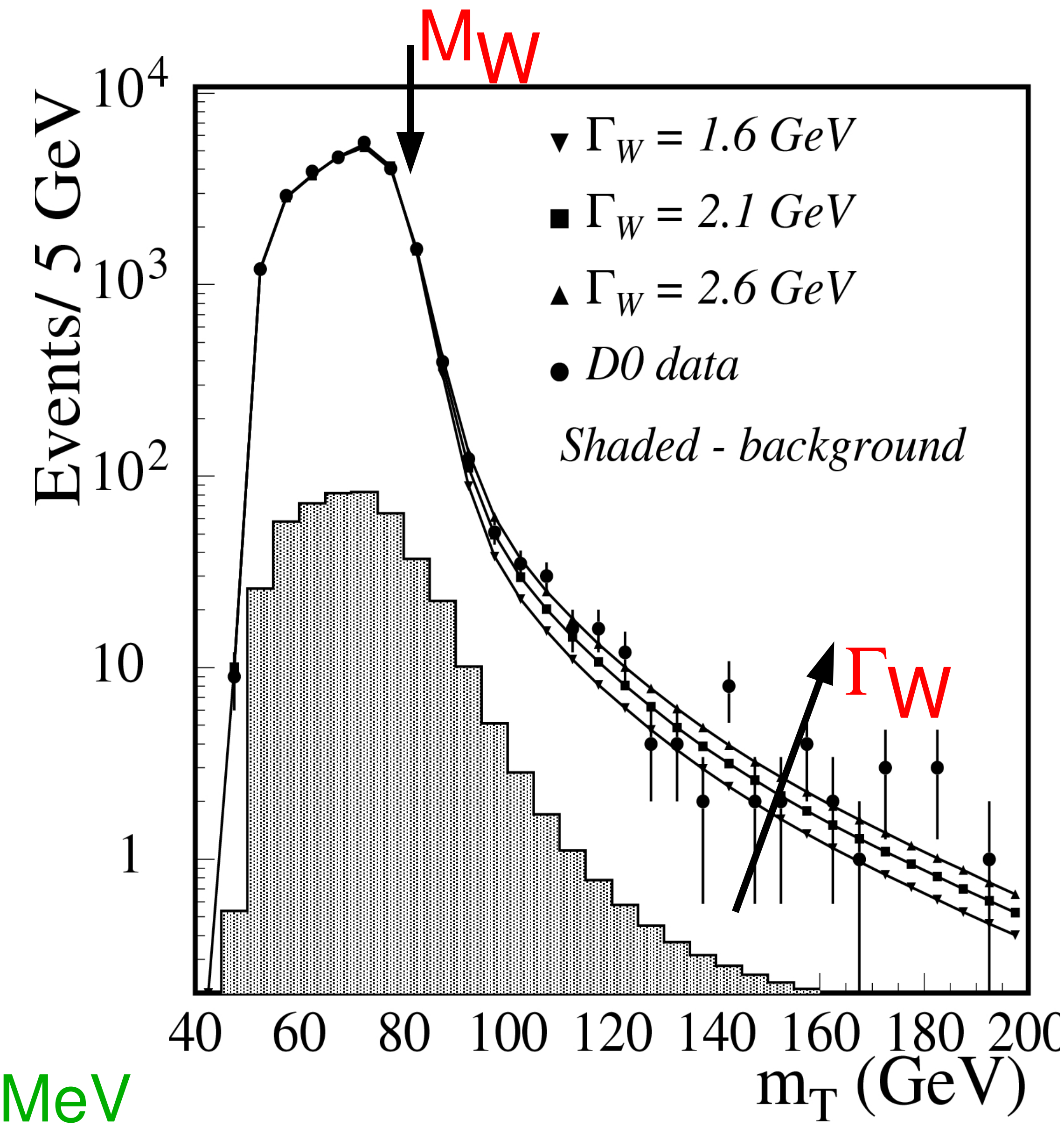
Transverse missing energy (ν)

W Boson at the Tevatron

CDF, DØ: $p\,\bar{p} \rightarrow$ WX, W $\rightarrow$ eν, μν

Transverse mass

$$m_T^2 = 2E_T^e E_T^\nu \cos\phi(e,\nu)$$



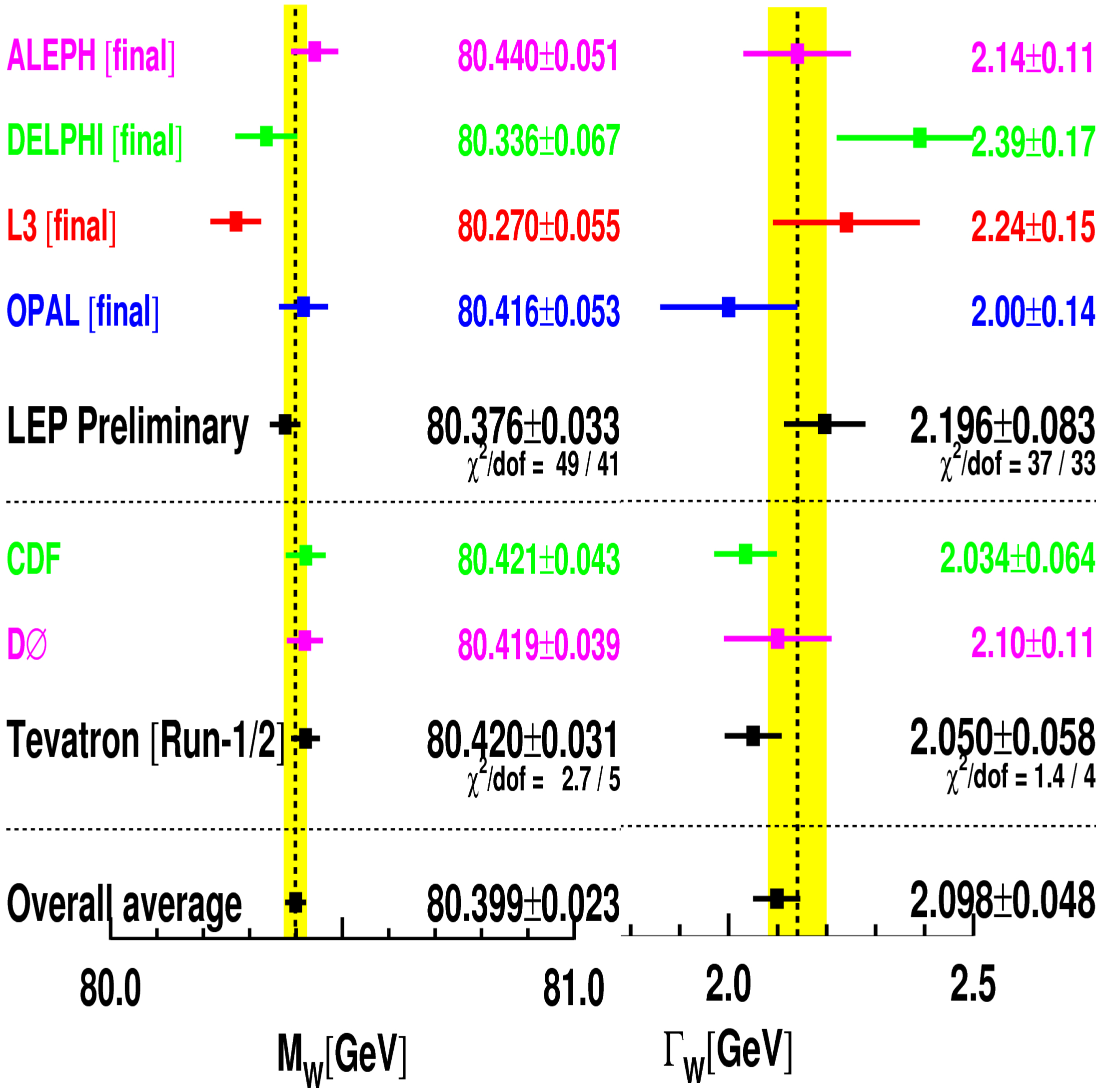
Uncertainties dominated by:

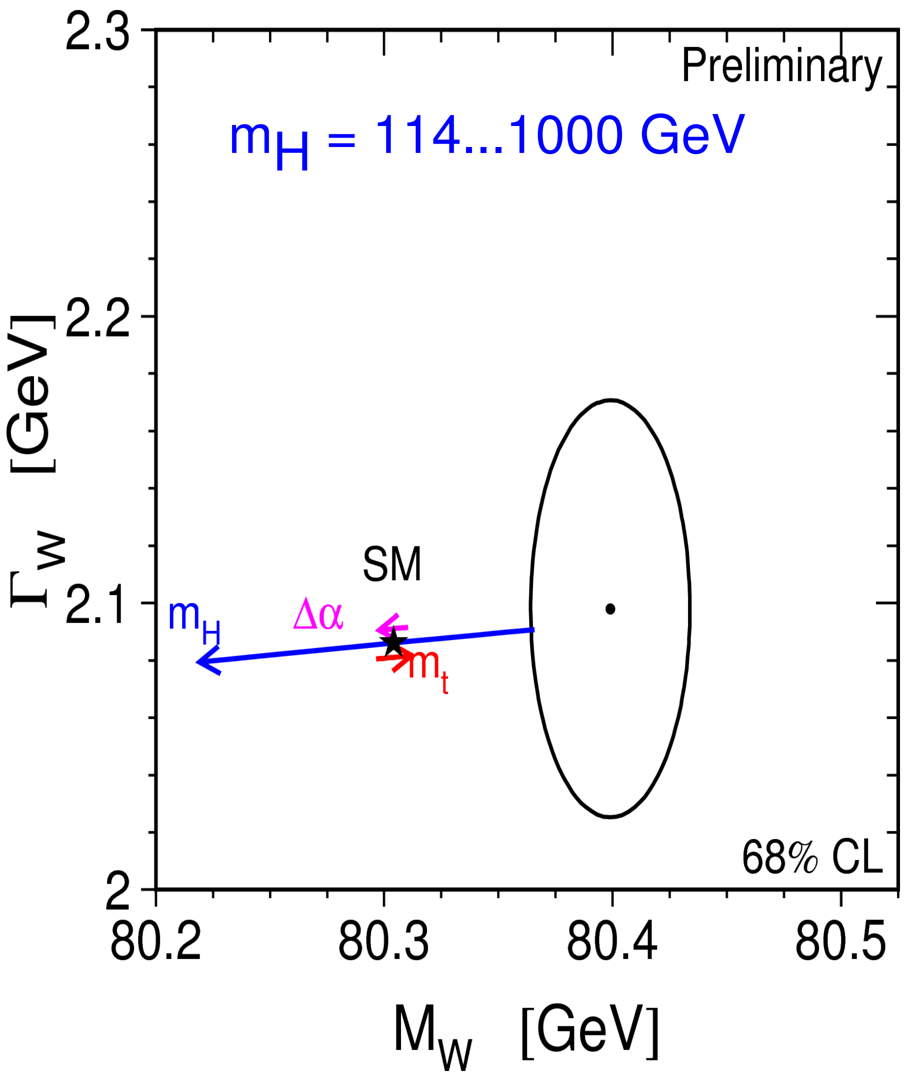
- Statistics
- Lepton energy scale - calibrated with Z events - will improve with more data
- Then: Signal model
  - PDFs, gluon radiation
  - QED corrections in W $\rightarrow$ lν

Run-II expectation: $\delta M_W < 25$ MeV

The W Boson

Good agreement between all six experiments:





SM comparison:

Small Higgs-boson mass

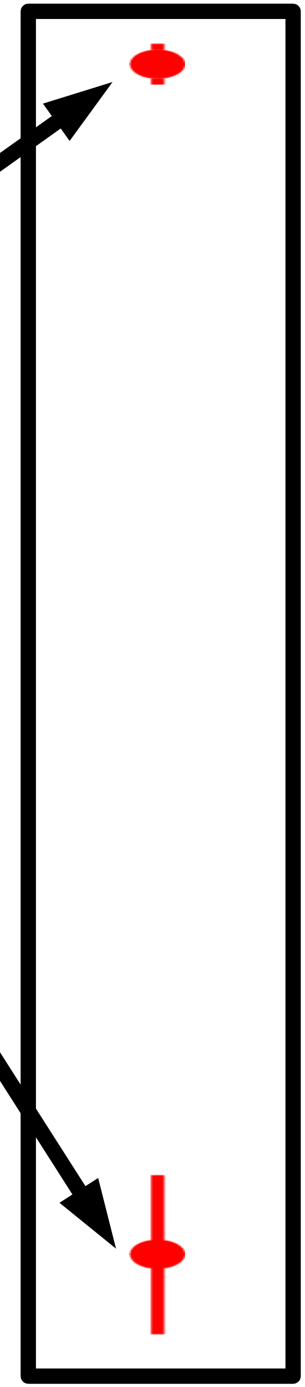
Comparison: Theory & Experiment

Z-fermion couplings:

$$\sin^2\theta_W = \frac{1}{4}\left(1 - \frac{g_{Vl}}{g_{Al}}\right) = 0.23153 \pm 0.00016$$

Masses of W and Z bosons:

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.22262 \pm 0.00045$$



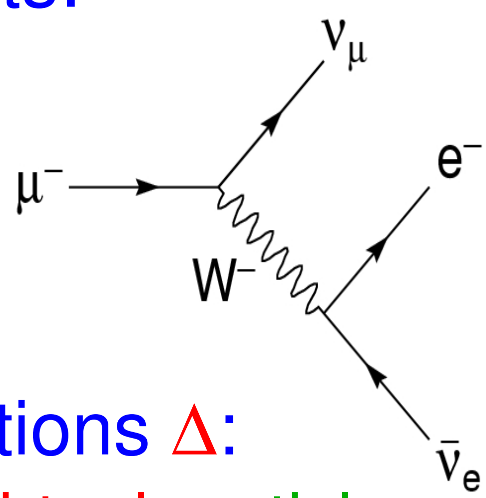
Comparison of the $\sin^2\Theta_W$ results:

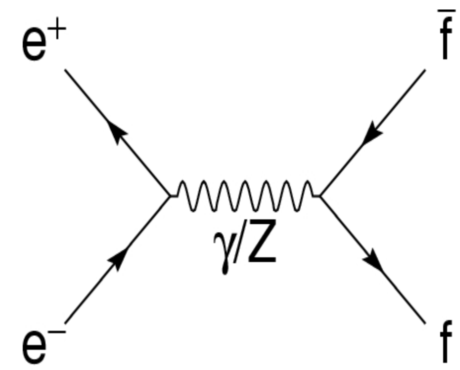
Qualitative: same order (about ¼)

Quantitative: ~20 std. dev. discrepancy!

Comparison: Theory & Experiment

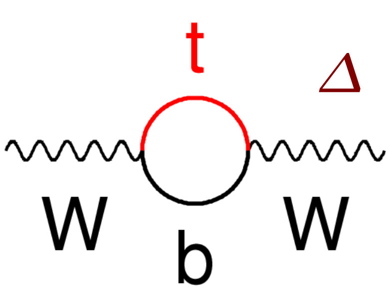
Highly precise measurements:



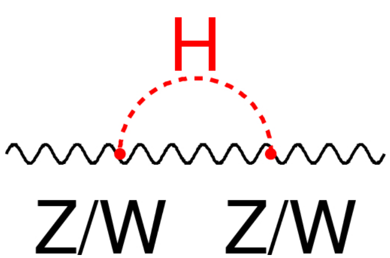


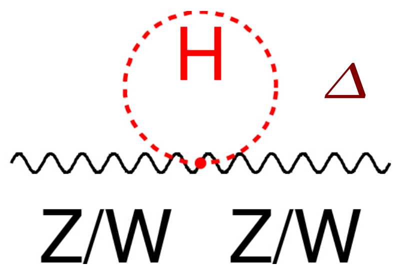
Sensitive to radiative corrections Δ:

~1% effect, e.g., loops with virtual particles



$$\Delta \propto M_{top}^2$$





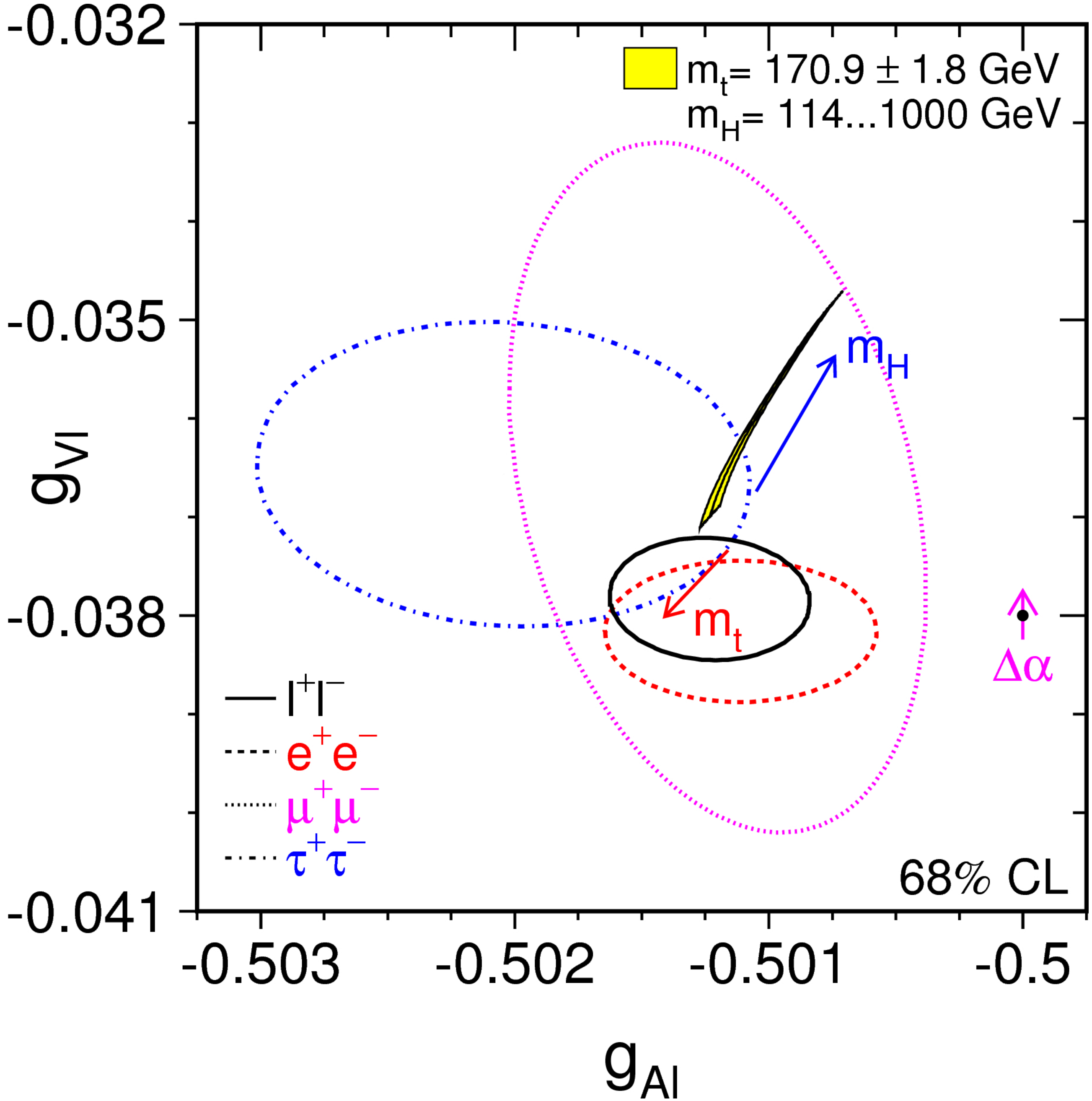
$$\Delta \propto \ln \frac{M_H}{M_W}$$

Couplings g_{Vf} and g_{Af} become effective couplings:

High sensitivity (quadratic) to M_{top}

Lower sensitivity (logarithmic) to M_H

Effective Couplings



For charged leptons:

- e
- μ
- τ

Lepton universality

Assume SM – allows to make predictions for top-quark and Higgs-boson mass

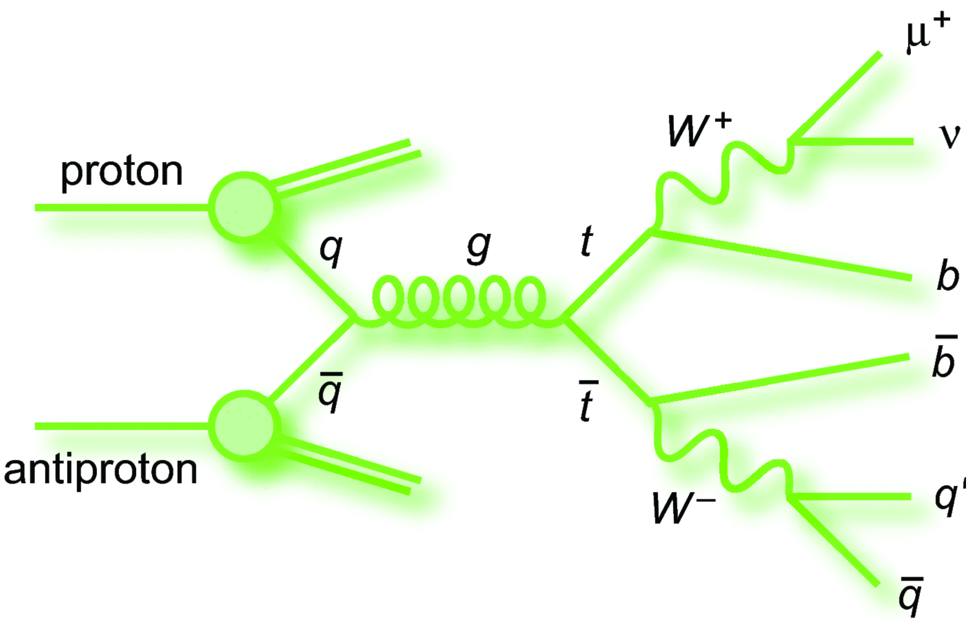
Top Physics

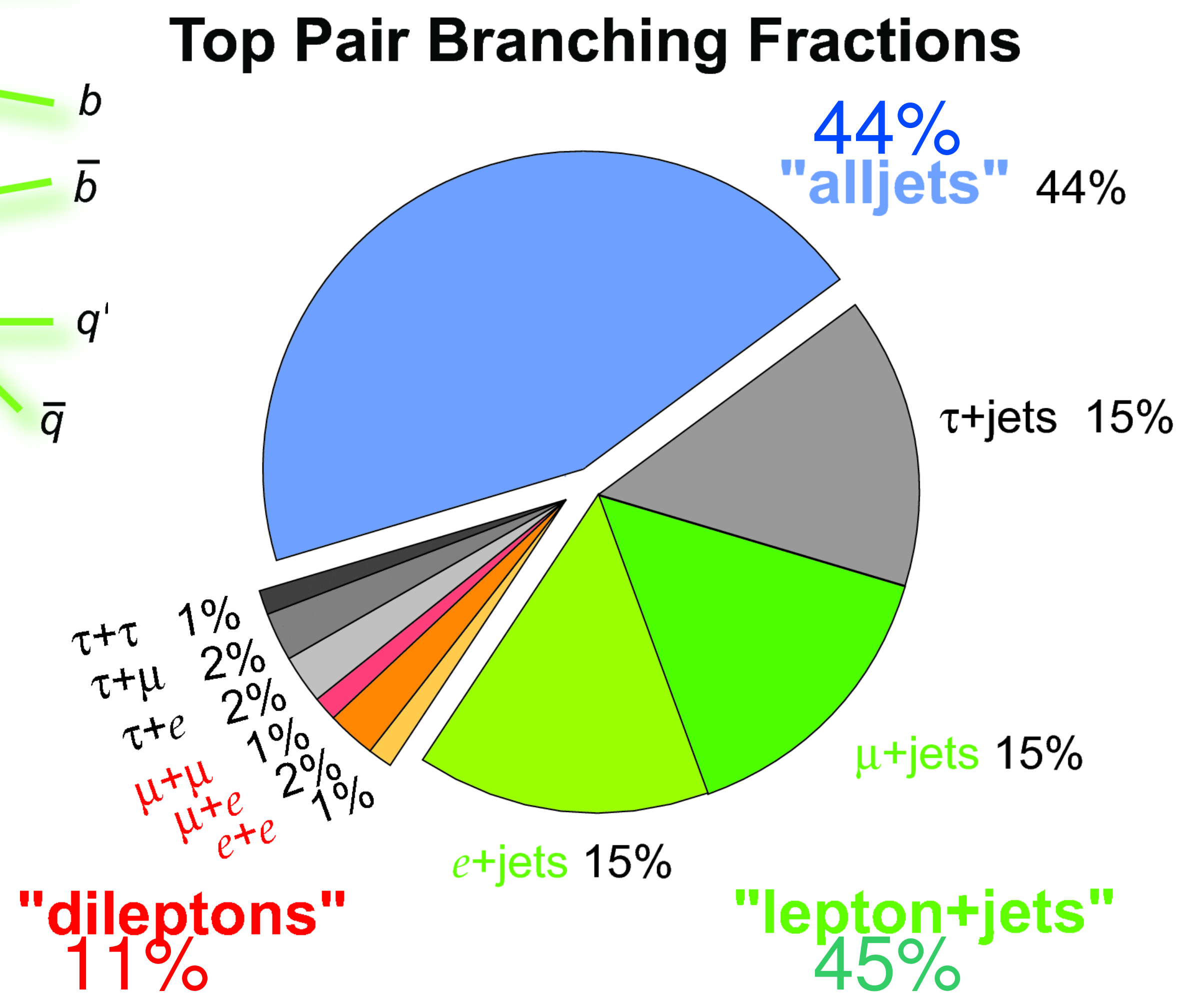
Tevatron (1.8 – 2 TeV): only source of top quarks in the world!

Mainly top-pair production

$$p\bar{p} \to t\bar{t}X,\quad t\bar{t} \to b\bar{b}W^+W^-$$

$$W^- \to q\bar{q},\, l^-\bar{\nu}$$





Total cross section: ~7.5 pb

Event signature given by W-pair decay modes

Top-Quark Mass

Separate final states:

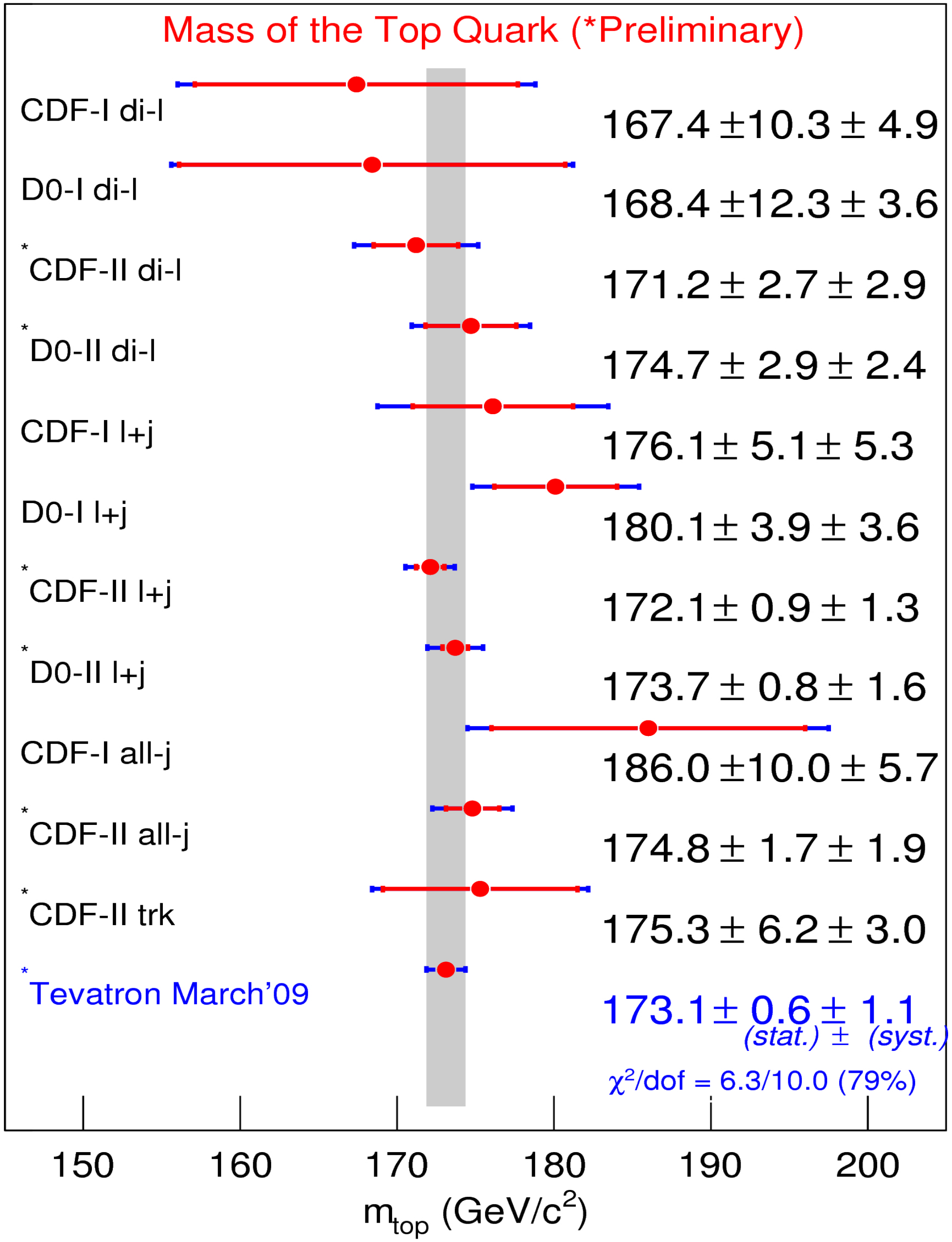
- 171.4 ± 2.7 GeV di-leptons
- 172.7 ± 1.3 GeV lepton+jets
- 175.1 ± 2.6 GeV all-jets

Reduction of JES systematics:

In-situ calibration using W-mass constraint

Systematic theory errors:

- Mass definition (in MC)
- Signal model
- Colour reconnection effects



Run-I+II preliminary: M_{top} = 173.1 ± 1.3 (total) GeV (0.75%!)

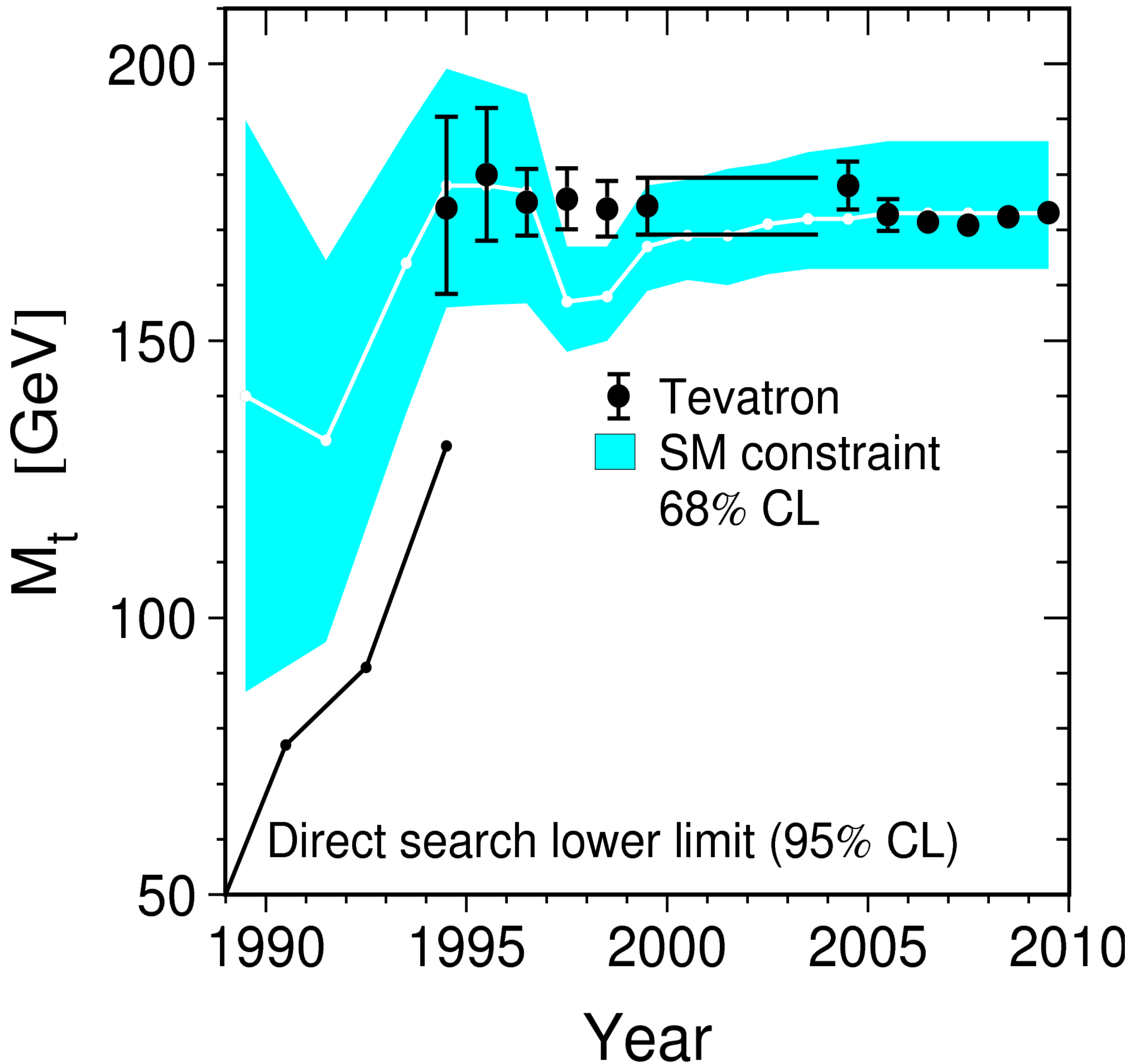
The Top Quark

Since 1990:

Prediction of the top quark mass

1995: Discovery

at the Tevatron CDF, DØ



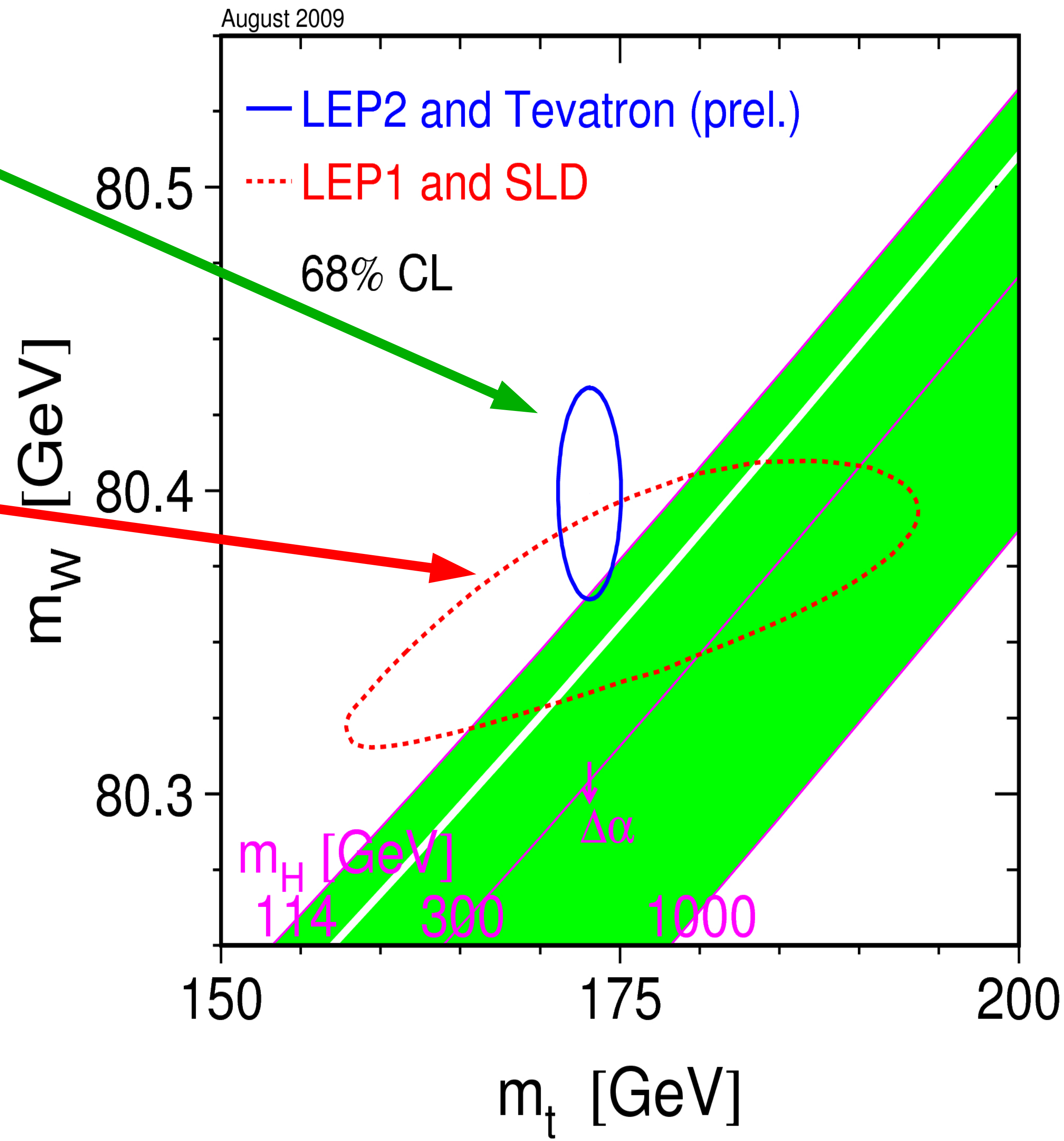
Heavy Particle Masses W and Top

Direct measurements:
- LEP2 and Tevatron

Z-Pole measurements:
- Constrain electroweak radiative corrections
- Allow to predict M_W and M_{top} within SM

Good agreement:
- Successful SM test at loop-level!

Both data sets prefer a light Higgs boson



Standard Model Analysis

Fit results:

$\Delta\alpha_{had}$	=	0.02768	$\pm$ 0.00033
$\alpha_s(M_Z)$	=	0.1185	$\pm$ 0.0026
M_Z	=	91.1874	$\pm$ 0.0021 GeV
M_{top}	=	173.2	$\pm$ 1.3 GeV
$\log_{10}M_H$	=	1.94	$\pm$ 0.15

$M_{Higgs} = 87^{+35}_{-26}$ GeV

$\Delta\alpha_{had}$ marginally improved

$\alpha_s(M_Z)$ one of the best

M_Z ~ unchanged

M_{top} error improved by few %

Correlations:

0.02			
-0.01	-0.02		
-0.02	0.03	-0.02	
-0.56	0.07	0.11	**0.32**

Strong correlations with:

fitted $\Delta\alpha_{had}$ - reduced to -0.23 with pQCD $\Delta\alpha_{had}$

fitted M_{top} - 15 % shift in M_{Higgs} for 2 GeV shift in meas. M_{top}

M_{top} measurement crucial!

Standard Model Analysis

$M_H = 87^{+35}_{-26}$ GeV

Incl. theory uncertainty:

M_H < 157 GeV (95%CL)

Direct search limit (LEP-2):

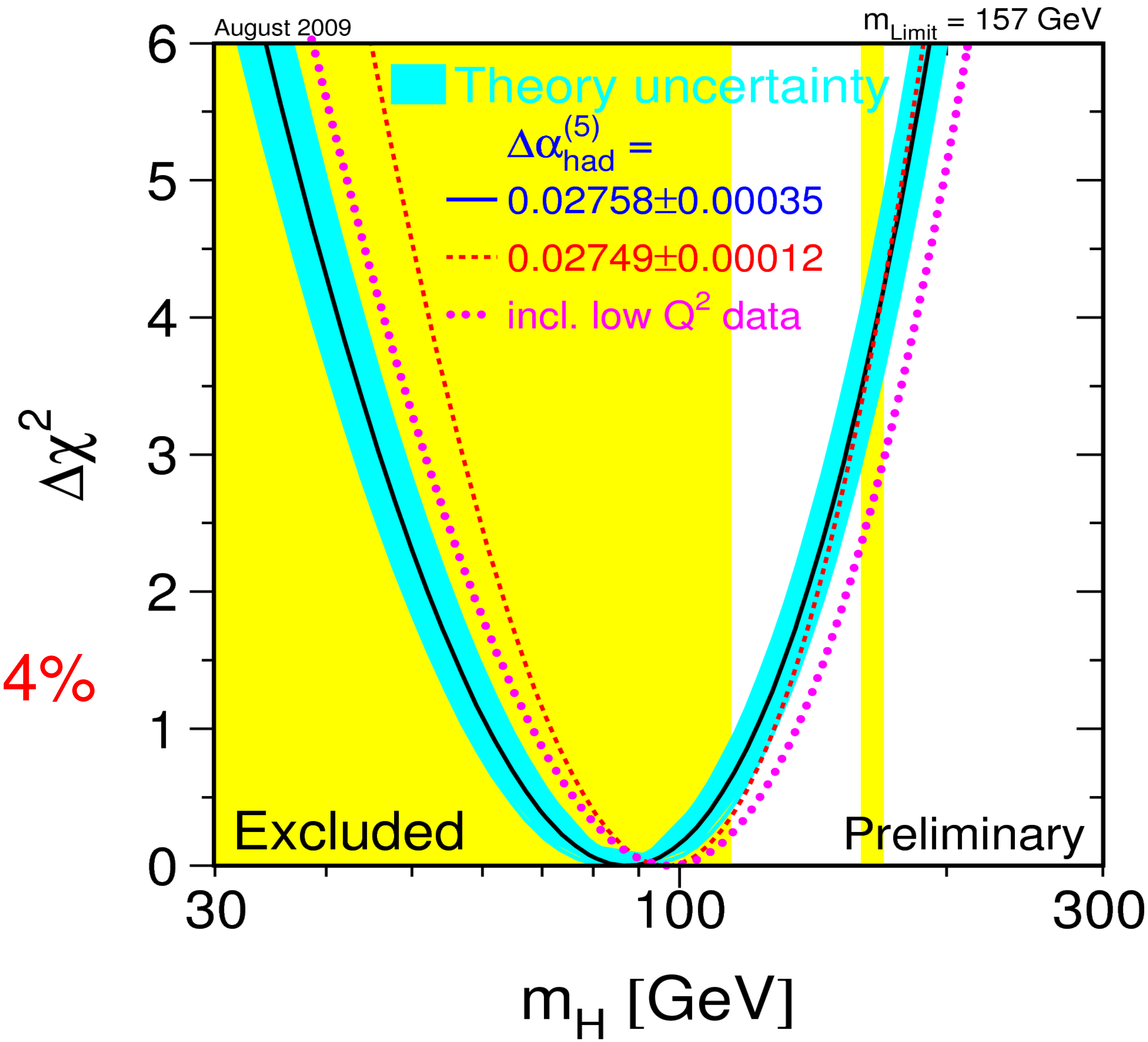
M_H > 114 GeV (95%CL)

Probability M_H>114 GeV: 24%

Renormalise probability

for M_H>114 GeV to 100%:

M_H < 186 GeV (95%CL)



Theory uncertainty:

Dominated by two-loop

calculations for $\sin^2\Theta_{eff}$

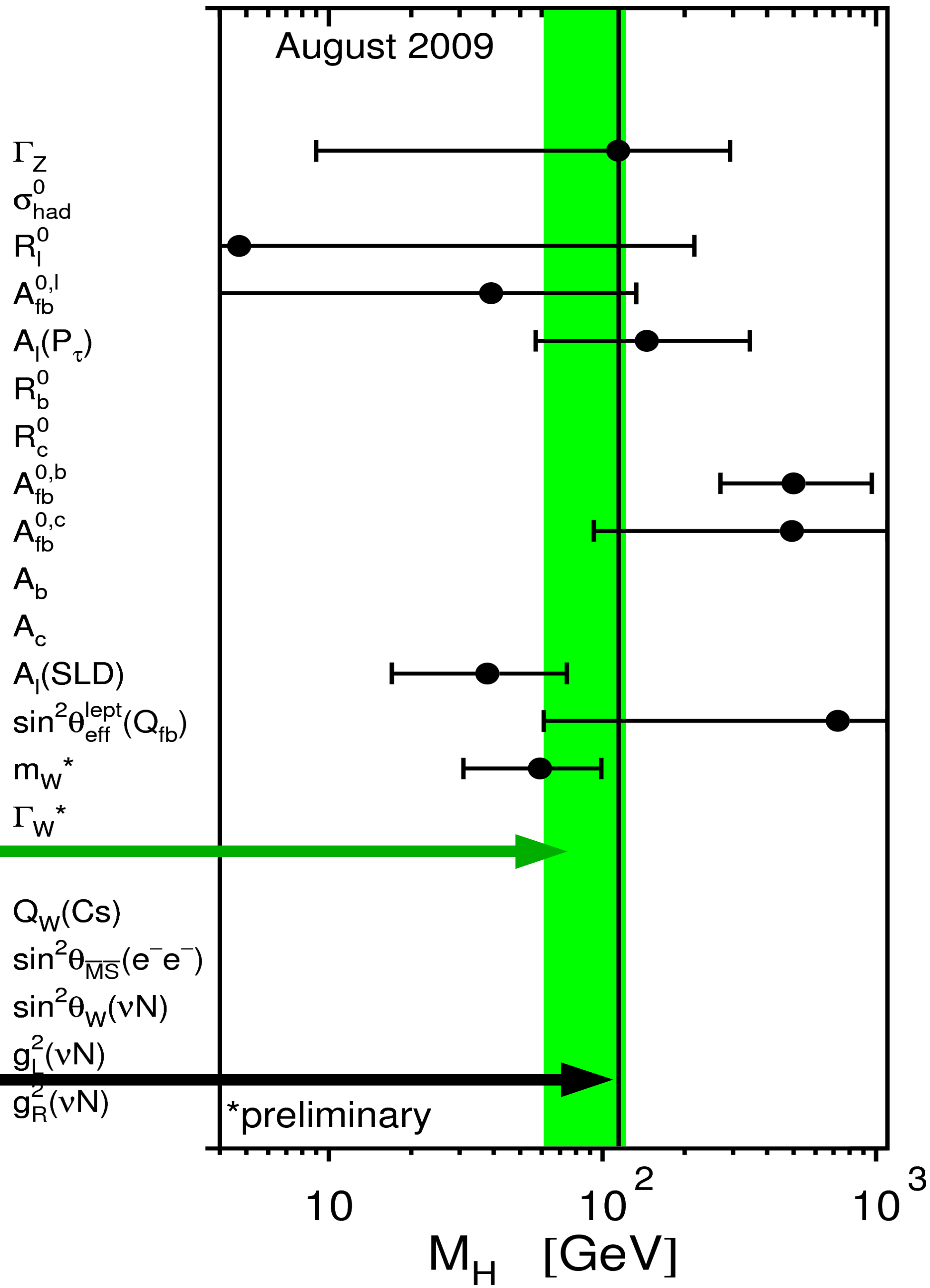
Higgs-Boson Constraints

Each observable yields a constraint on M_{Higgs}:

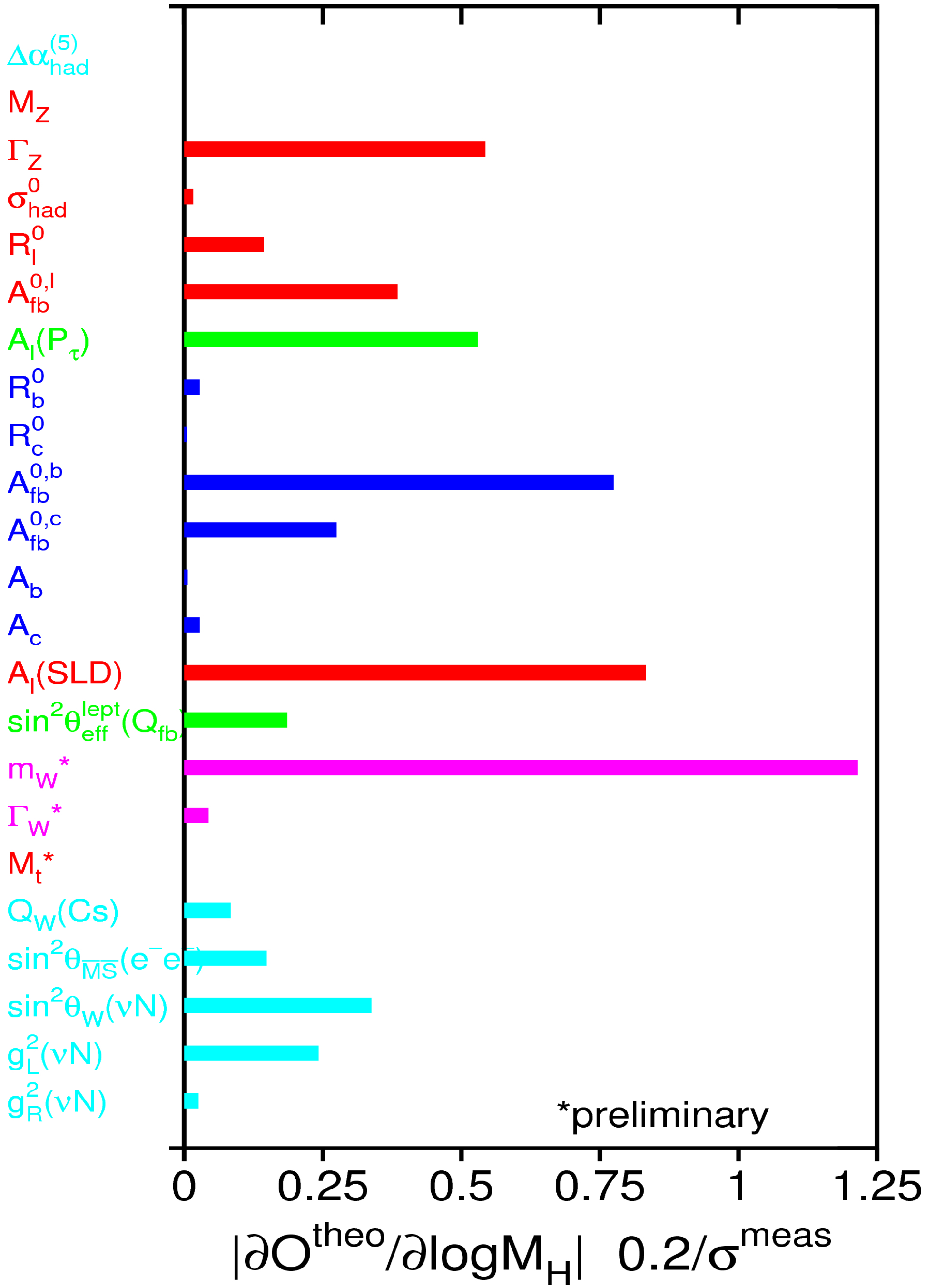
SM fit to observable, constraining the other 4 SM parameters:
$\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_{top},
to their measured results

Result from global fit:
$M_{Higgs} = 87^{+35}_{-26}$ GeV

Lower limit from Higgs search:
$M_{Higgs} > 114$ GeV



Higgs-Boson Sensitivity

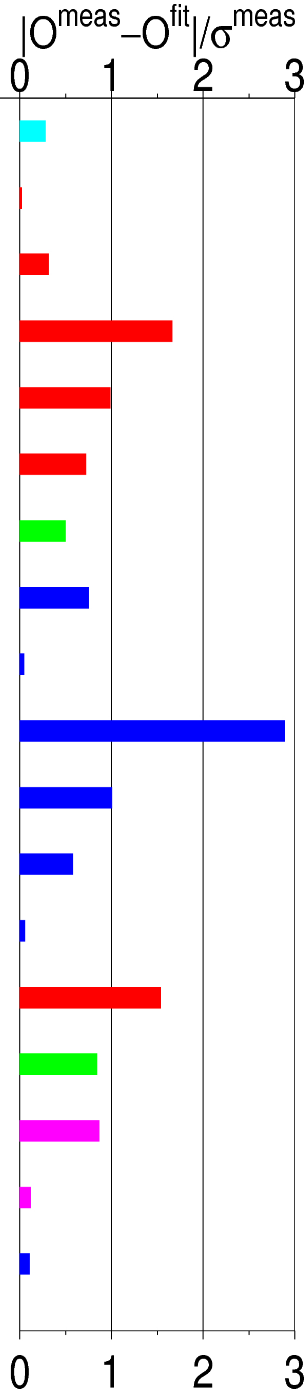


Relative Higgs Sensitivity:

Sensitivity of each observable (derivative) – divided by its measurement uncertainty

Global Standard Model Analysis

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



August 2009

Fit to all 17 observables
+ $\Delta\alpha_{had}$:
χ^2/ndof = 17.3/13 (17%)

Largest χ^2 contribution:
A_l(SLD) vs. A_{fb}b(LEP)
Decided in favour of "leptons" by M_W
Afb(b) has largest pull: 2.9σ

Predict observables measured in reactions with: $Q^2 \ll M_W^2$

Predictions for Low-Q^2 Measurements

Electron-nucleus atomic parity violation (APV) in atomic transitions:

Parity-violating t-channel contribution due to γ/Z interference

Weak charge Q_W of the nucleus (Z protons, N neutrons)

$$Q_W(Z,N) = -2 \left[(2Z+N)C_{1u} + (Z+2N)C_{1d} \right]$$

with $C_{1q} = 2g_{Ae}g_{Vq}$ at $Q^2 \to 0$ (q=u,d)

$Q_W(Cs) = -72.74 \pm 0.46$ SM fit: -72.91 ± 0.03 ✔

Møller scattering (e^-e^-) with polarised e^- beam (E-158 experiment):

Parity-violating t-channel contribution due to γ/Z interference

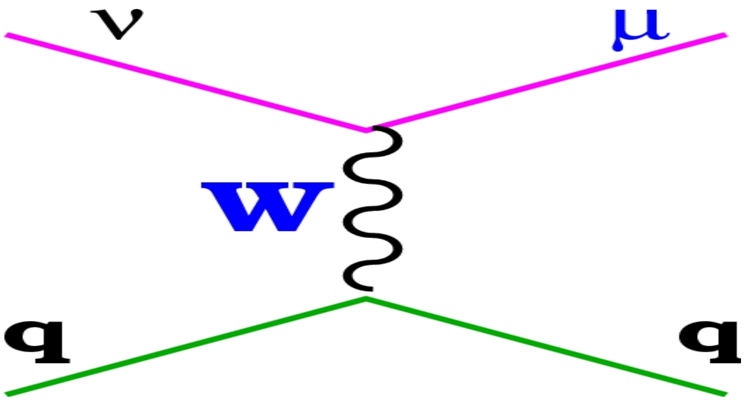
$A_{PV} = (\sigma_R-\sigma_L)/(\sigma_R+\sigma_L) \propto Q_W(e^-) = -4g_{Ae}g_{Ve}$ at $Q^2 \sim 0.03$ GeV^2

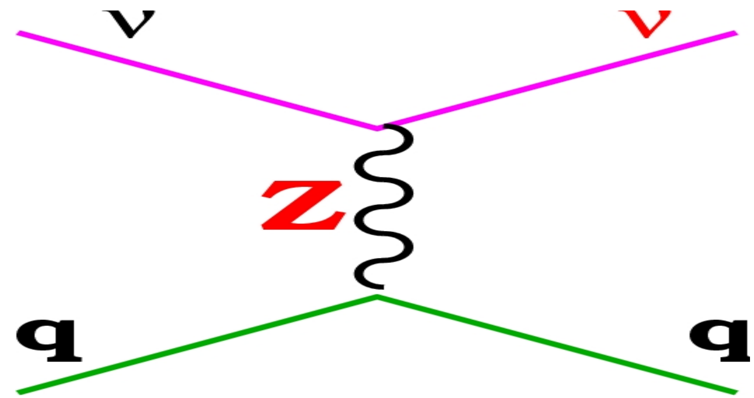
$\sin^2\Theta_{eff}(Q=M_Z) = 0.2333 \pm 0.0015$ SM fit: 0.2314 ± 0.0001 ✔

NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC) neutral current (NC)





Paschos-Wolfenstein relation (iso-scalar target):

$$R_{-} = \frac{\sigma_{NC}(\nu)-\sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu)-\sigma_{CC}(\bar{\nu})} = 4 g_{L\nu}^2 \sum_{q_\nu} \left[g_{Lq}^2 - g_{Rq}^2 \right] = \rho_\nu \rho_{ud} \left[\frac{1}{2} - \sin^2\theta_W^{(on-shell)} \right]$$

+ electroweak radiative corrections

Effective couplings: g_L, g_R at $\langle Q^2 \rangle \sim 20\ \mathrm{GeV}^2$

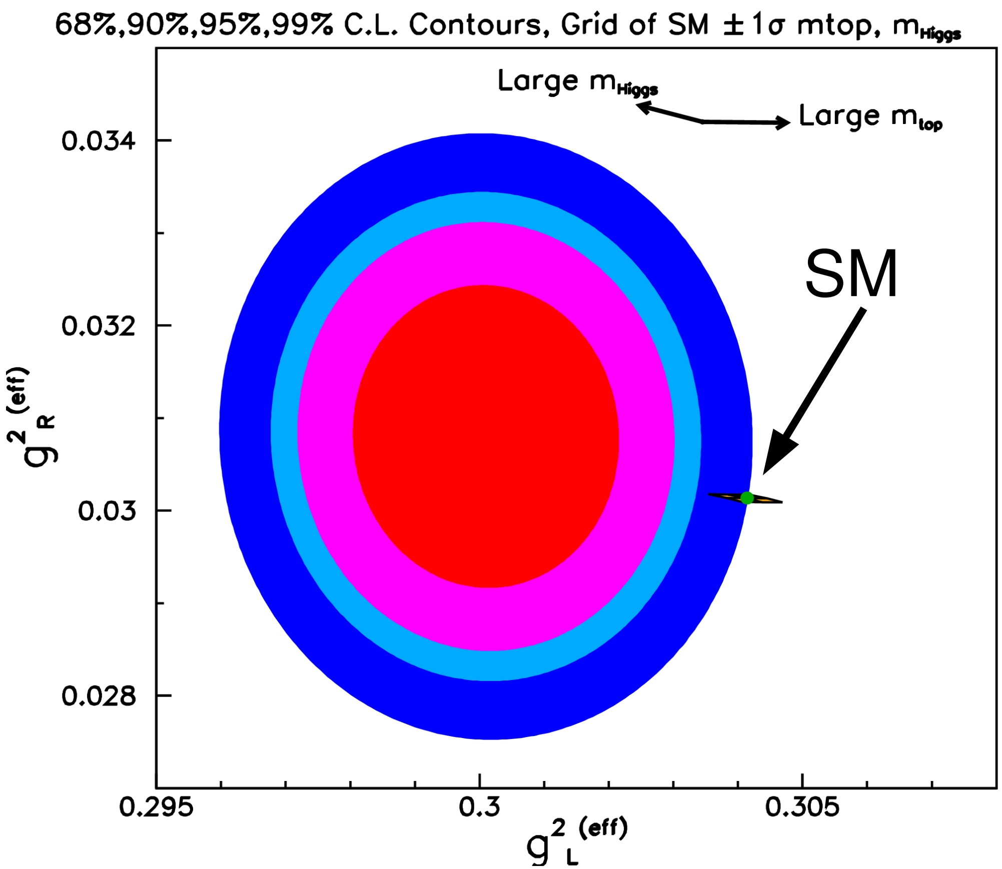
Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

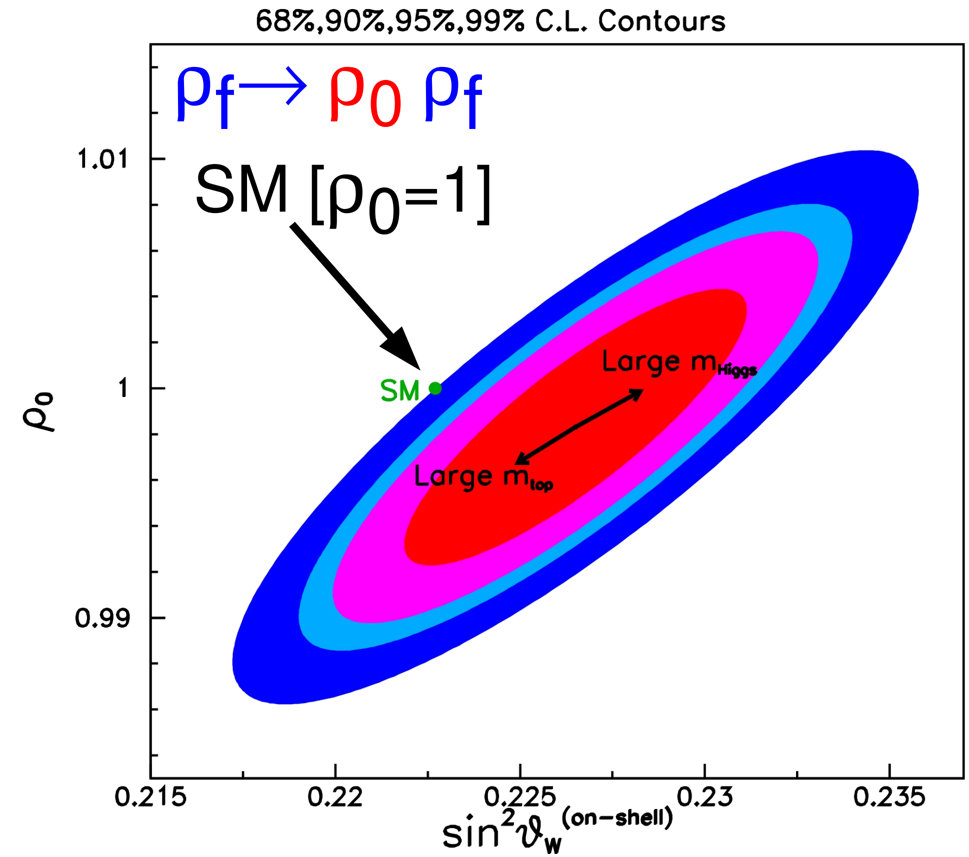
Factor two more precise than previous νN world average

NuTeV's Result

$$\sin^2\theta_W = 1-\frac{M_W^2}{M_Z^2} = 0.2277\pm0.0016 - 0.00022\frac{M_{top}^2-(175GeV)^2}{(50GeV)^2} + 0.00032\ln\frac{M_{Higgs}}{150GeV} \quad [\rho=\rho_{SM}]$$

SM fit: 0.2230 ± 0.0003 Difference of 2.9 σ!

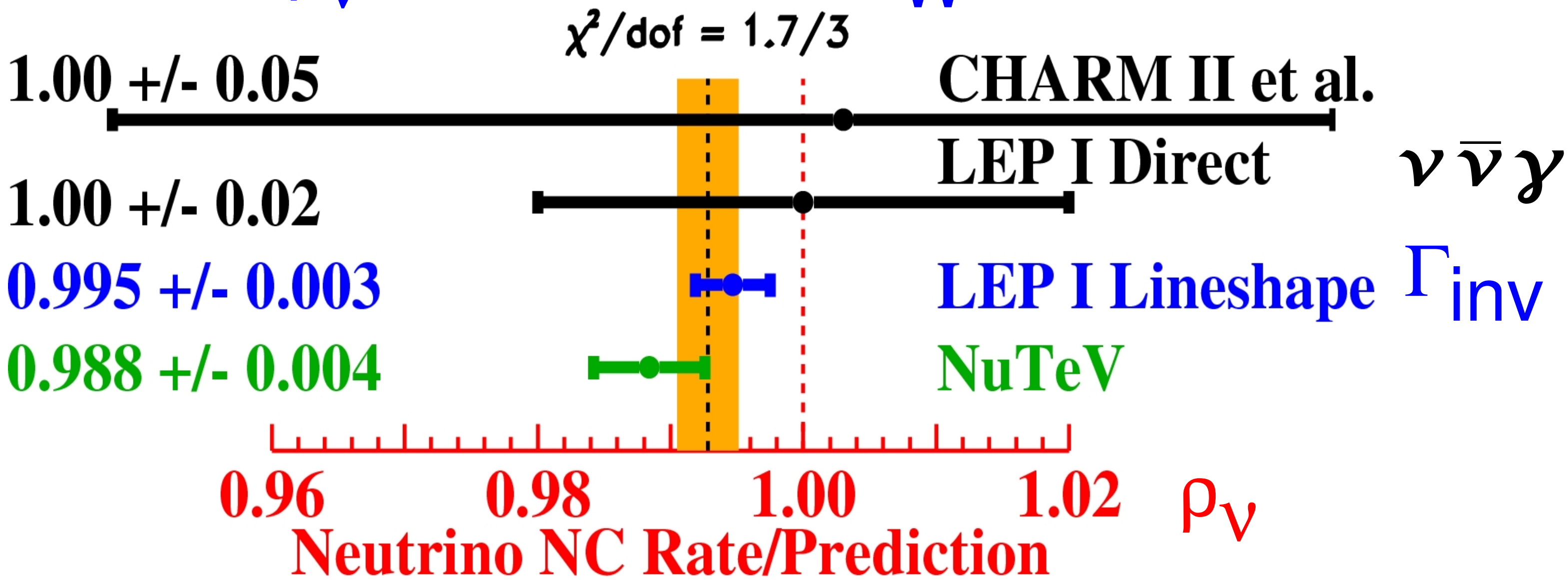




Quote result in terms of effective couplings, not $\sin^2\Theta_W$ nor M_W!

NuTeV's Result

Strength of ν coupling ρ_ν (assuming $\sin^2\Theta_W$ ok):



Various explanations:

New physics:

Z', contact interactions, lepto-quarks, new fermions, neutrino oscillations, . . .

But likely rather old physics:

Theory uncertainty (QED, LO PDFs)

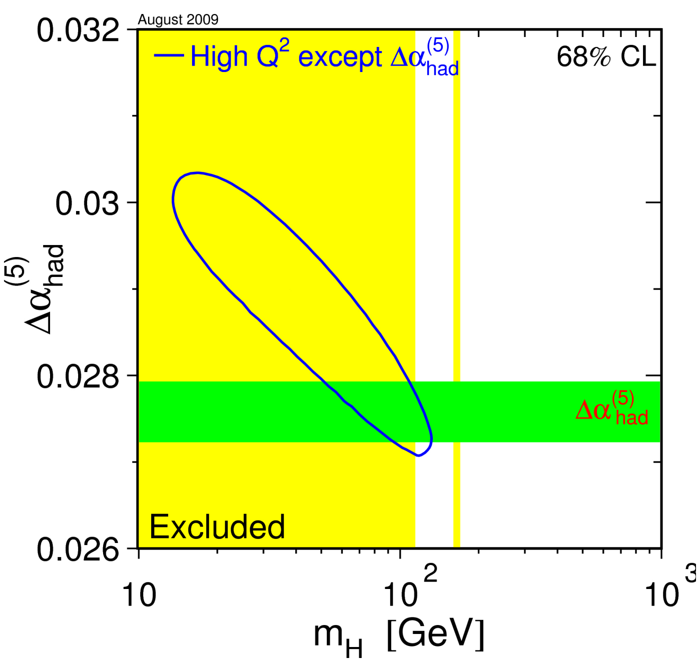
Isospin violating PDFs, sea asymmetry

Collective nuclear effects

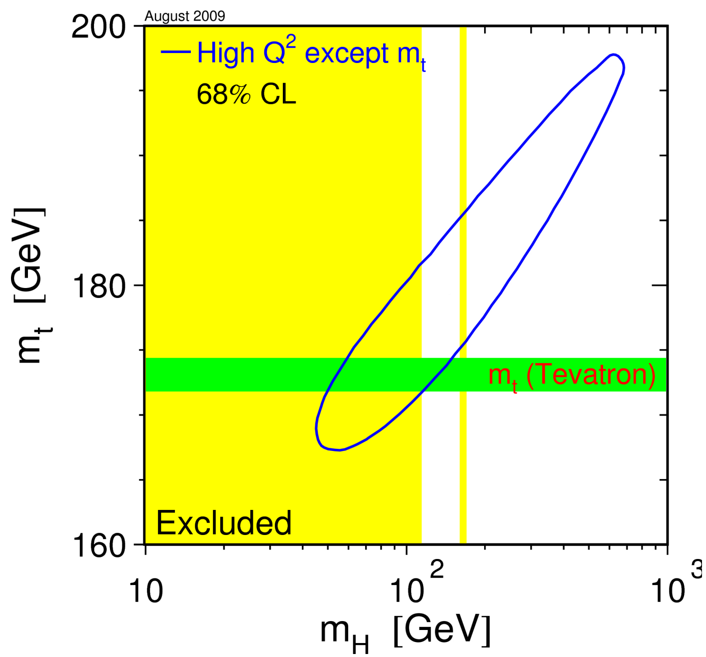
Crucial Observables

Fit to all measurements but excluding either:

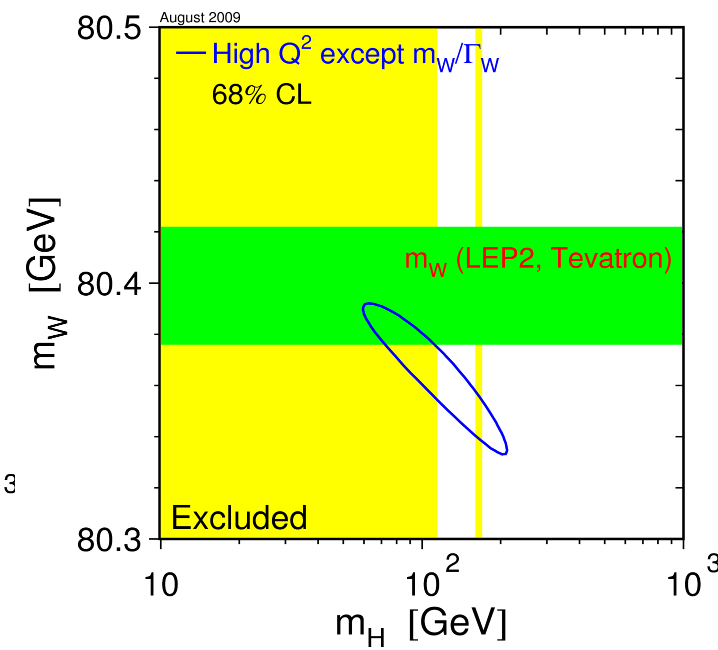
$\Delta\alpha_{had}(M_Z)$



M_{top}



M_W



Future constraints with increased precision:

- Tevatron/LHC
- ILC/GigaZ

Future Prospects

2009:

M_{Higgs} constrained to 37%

Tevatron/LHC:

M_W to 15 MeV

M_{top} to 1.0 GeV

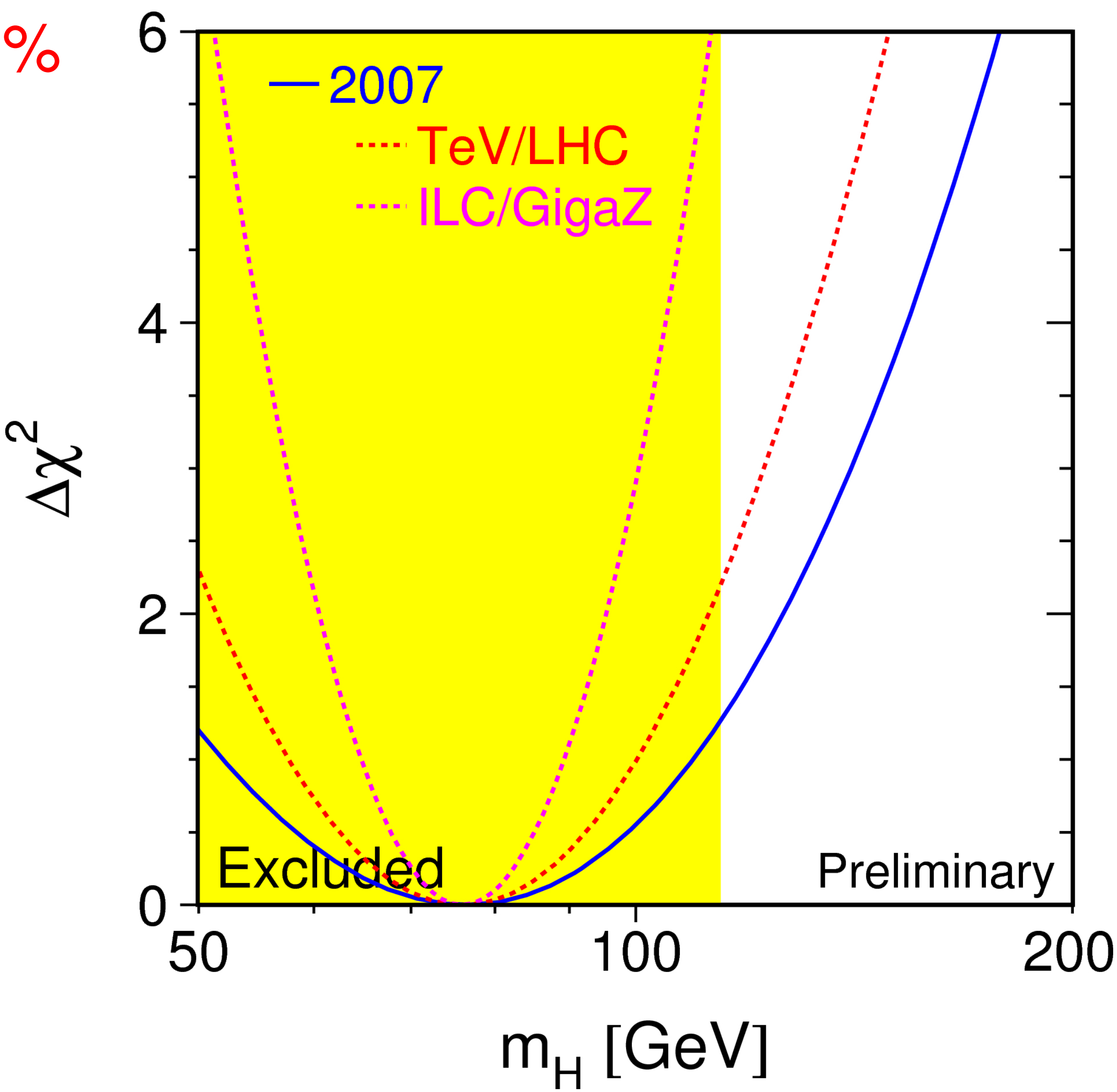
=> M_{Higgs} to 28%

ILC/GigaZ:

M_W to 7 MeV

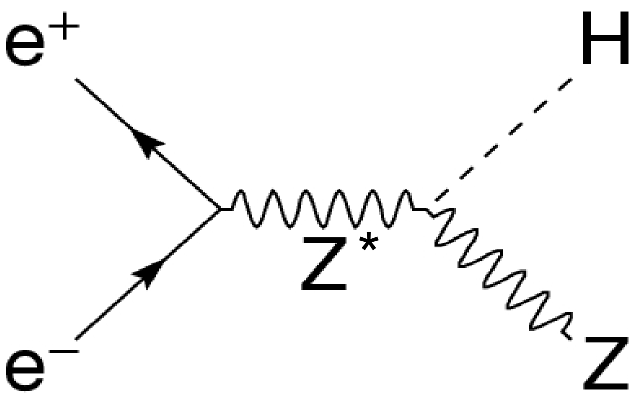
M_{top} to 0.1 GeV

=> M_{Higgs} to 16%



Direct M_{Higgs} measurement at discovery: ~ 1% accuracy

Previous Searches for the Higgs Boson



Higgs production at LEP:

$e^+e^- \rightarrow HZ$

Kinematic mass reach: $M_H \rightarrow \sqrt{s} - M_Z$

Need highest possible collision energies!

Direct search for the Higgs boson ($\sqrt{s} \rightarrow$ 209 GeV):

$H \rightarrow b\bar{b}$ dominant Higgs decay mode in this mass range

$Z \rightarrow f\bar{f}$

Lower limit for its mass: M_H > 114.4 GeV (95% CL)

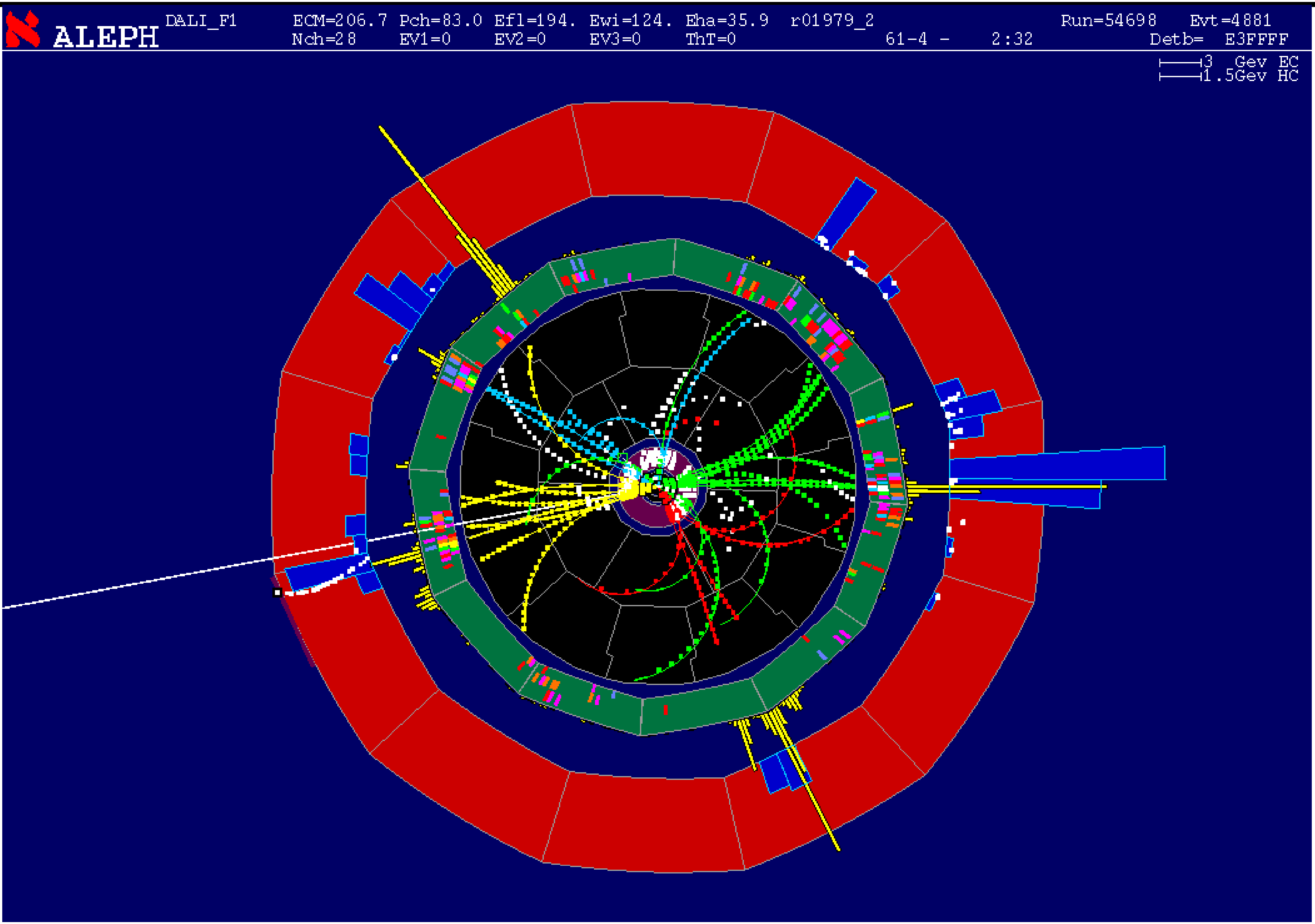
In 2000, at the end of LEP-2 data taking:

Few events found, compatible with M_H of 115 GeV

$e^+e^- \rightarrow HZ \rightarrow b\bar{b}q\bar{q}$ (ALEPH) $e^+e^- \rightarrow HZ \rightarrow b\bar{b}\nu\bar{\nu}$ (L3)

However: statistically not significant (background compatible!)

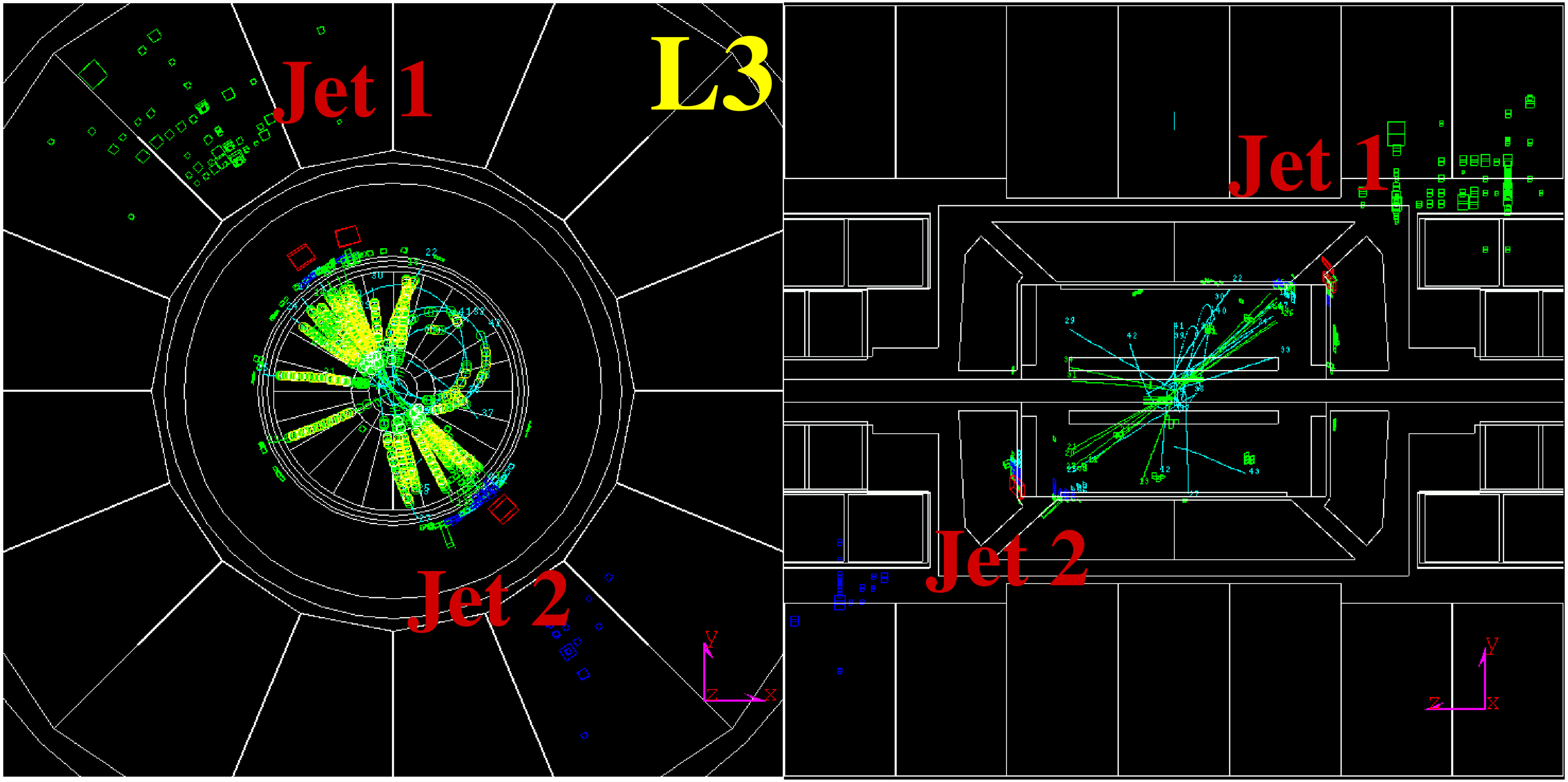
Higgs Boson Candidate Event



Higgs Boson Candidate Event

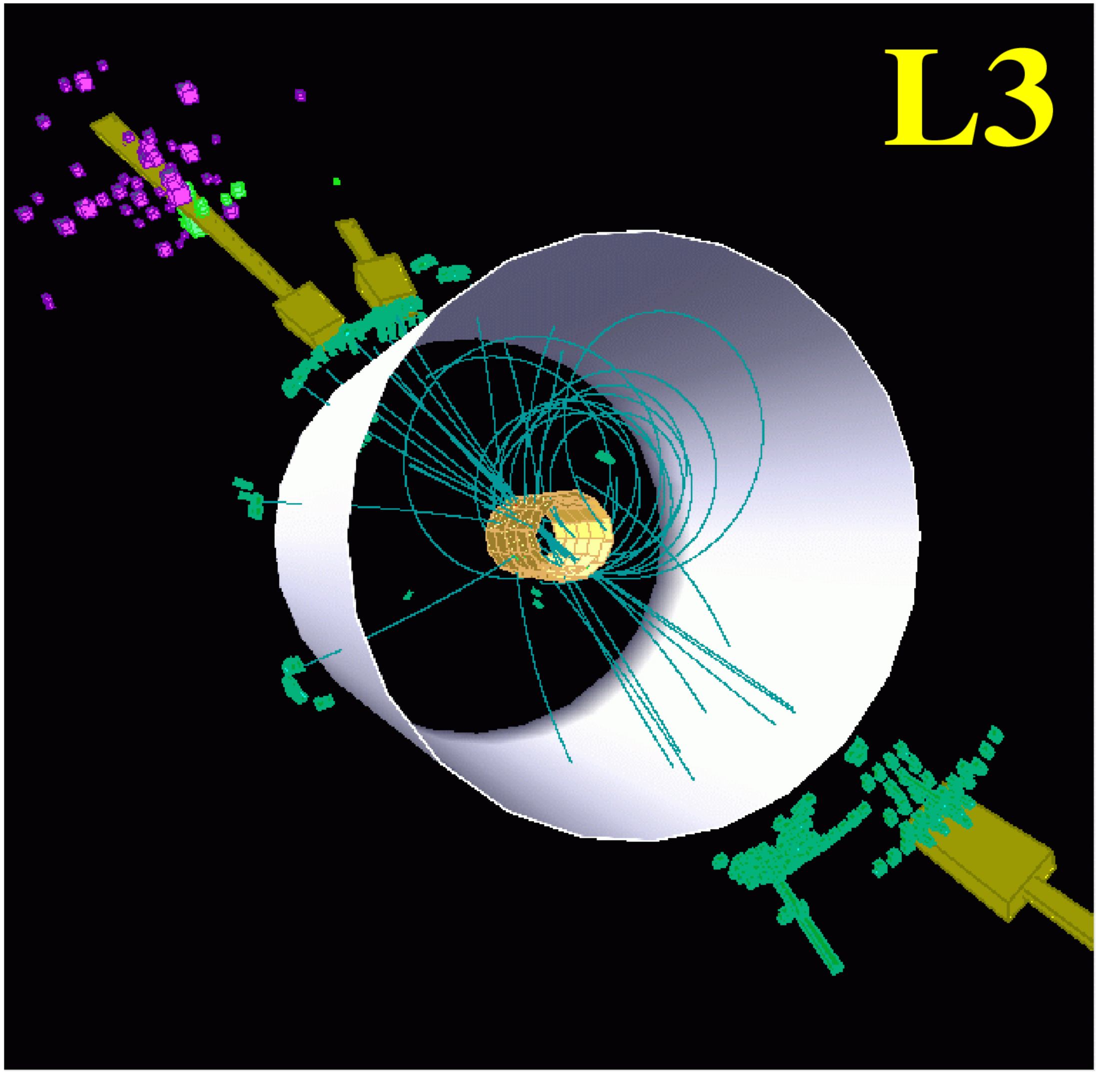
candidate for

$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow$ 2 jets + missing energy



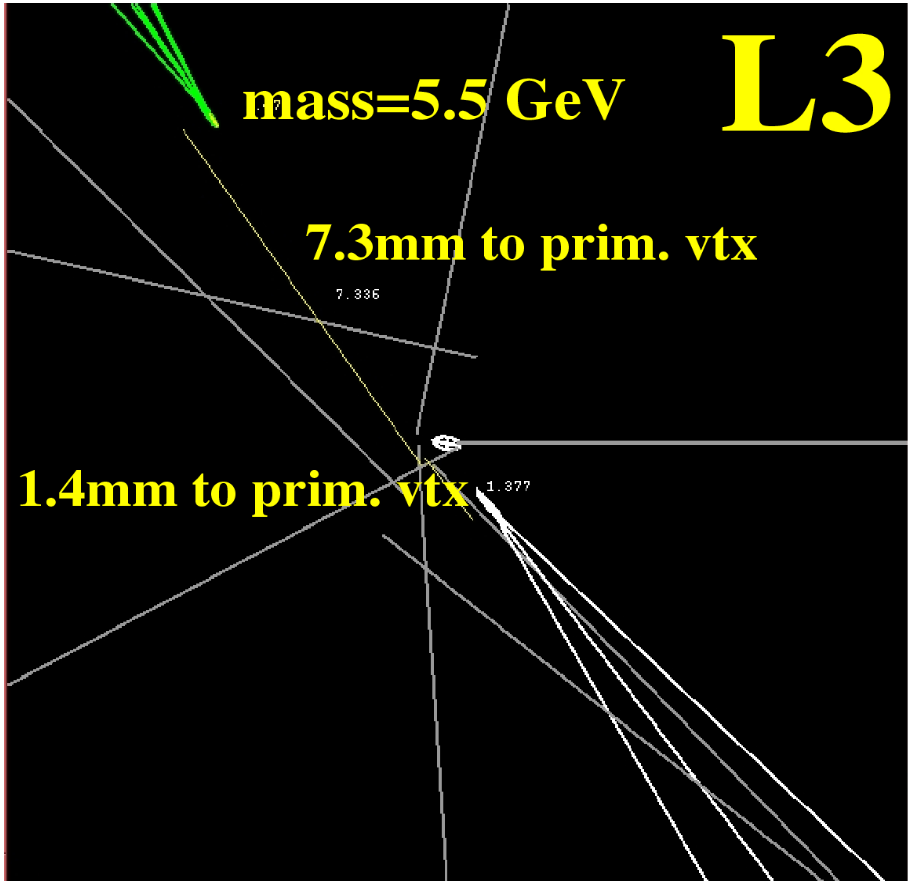
Higgs Boson Candidate Event

most significant Hνν candidate



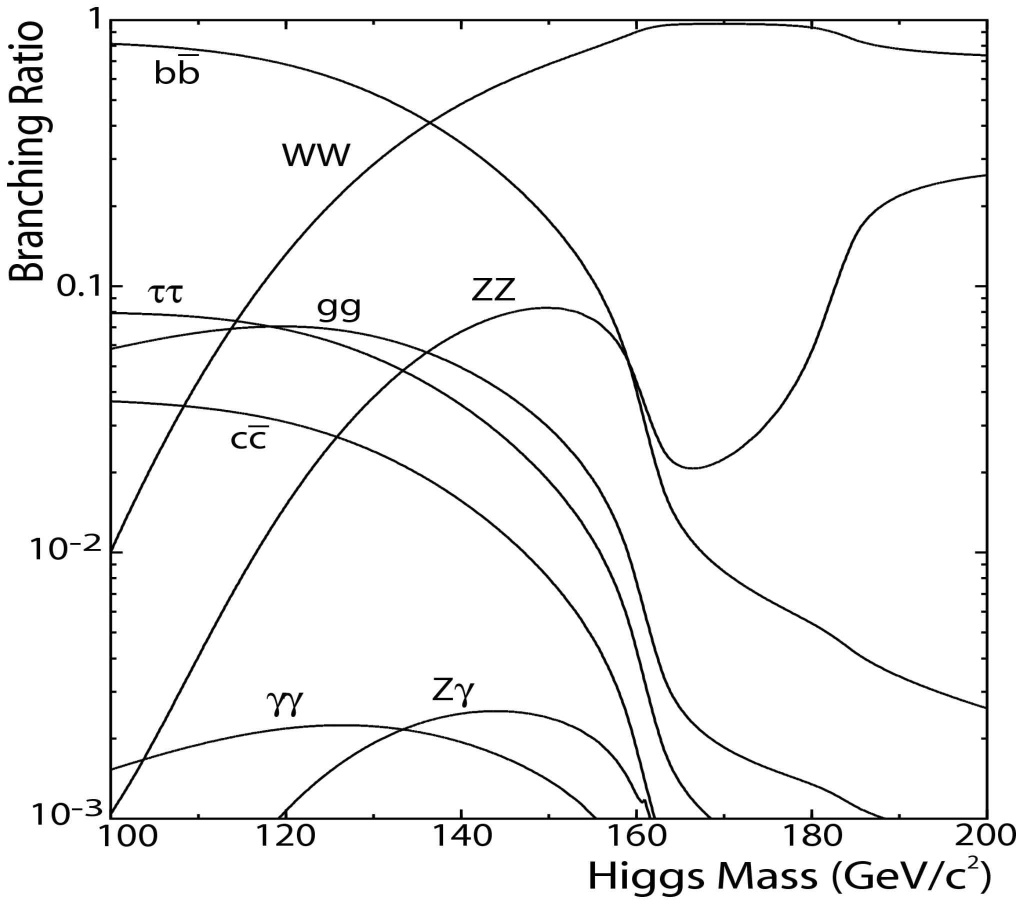
measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view

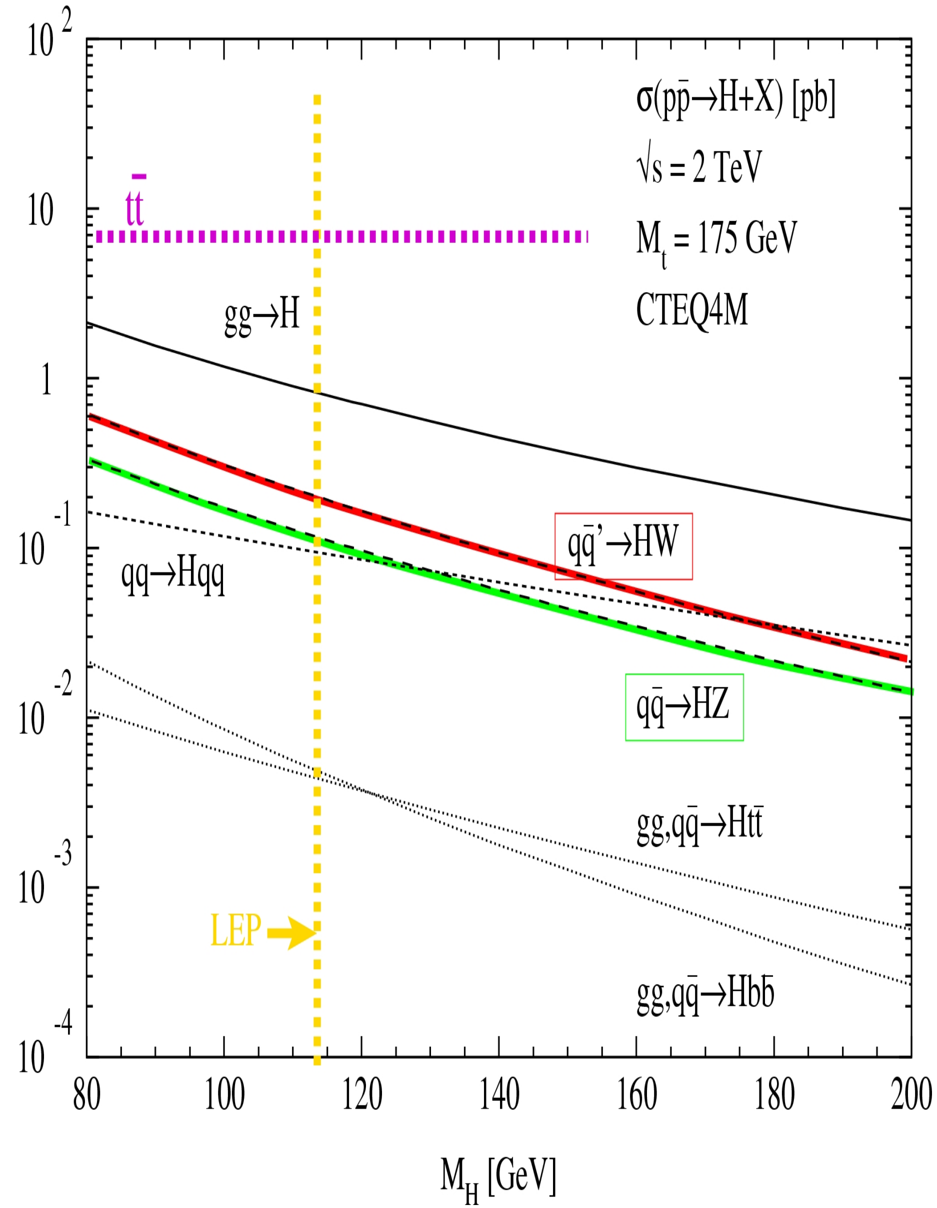


Current Searches for the Higgs Boson

Higgs decay modes



Production cross section @ Tevatron



Low Higgs-boson mass:

H+W/Z assoc. production

High Higgs-boson mass:

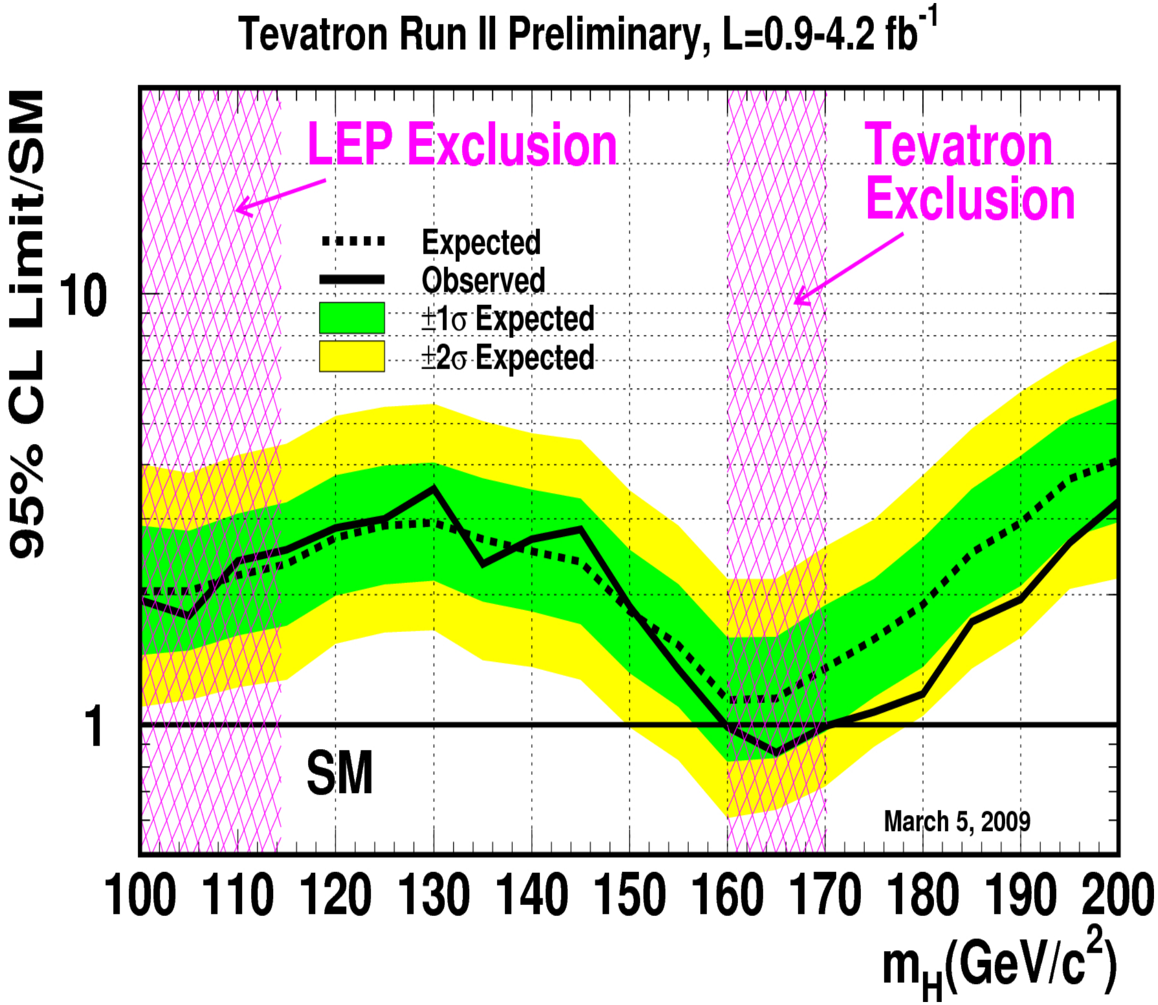
H→WW→lνlν decay mode

Current Searches for the Higgs Boson

Run-II of Tevatron (2001-20011?):

Proton-antiproton collisions at 2 TeV CM energy

Relative cross section limit $\sigma_{Limit}/\sigma_{SM}$ on SM Higgs production:



Combined CDF+DØ results using up to 4.2/fb/analysis

SM Higgs boson with mass between 160 and 170 GeV excluded (at least 95% CL)

Currently: 6/fb/exp on tape

Expect 12/fb at end of 2011

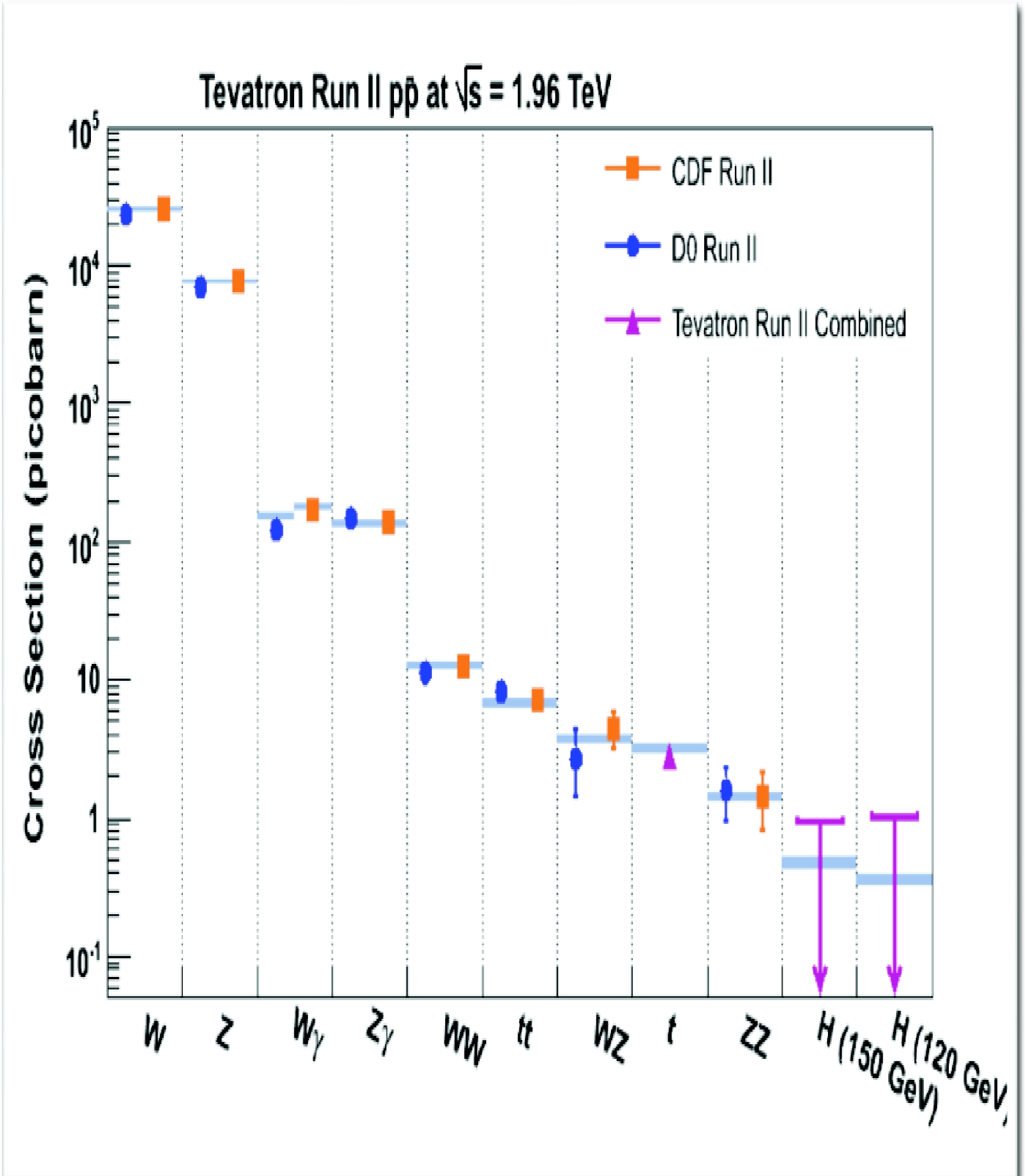
Rare EW Processes at the Tevatron

Benchmark signatures
of electroweak physics

W and Z bosons
Di-Boson
Top-Quark pairs
Single-Top
Higgs boson

definite processes, with decreasing cross section, and final states similar to Higgs production

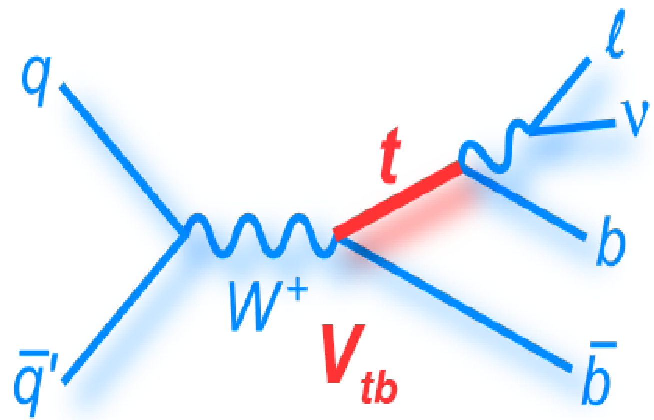
Challenge to experiments



Single-top Production

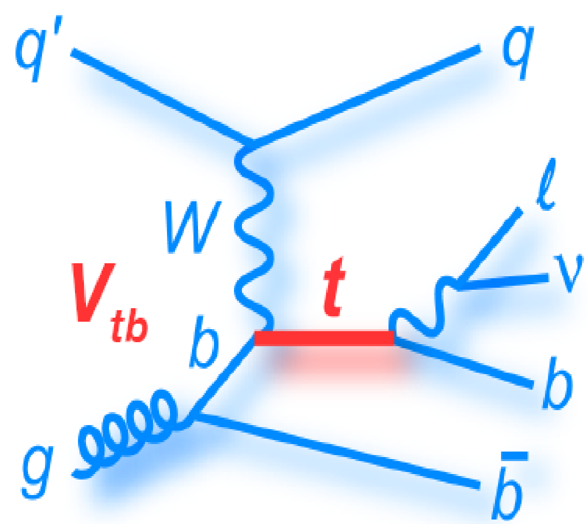
s-channel: σ_{tb} = 1.04 ± 0.04 pb

NNNLO$_{approx}$, m_{top} = 172.5 GeV



t-channel: σ_{tb} = 2.26 ± 0.12 pb

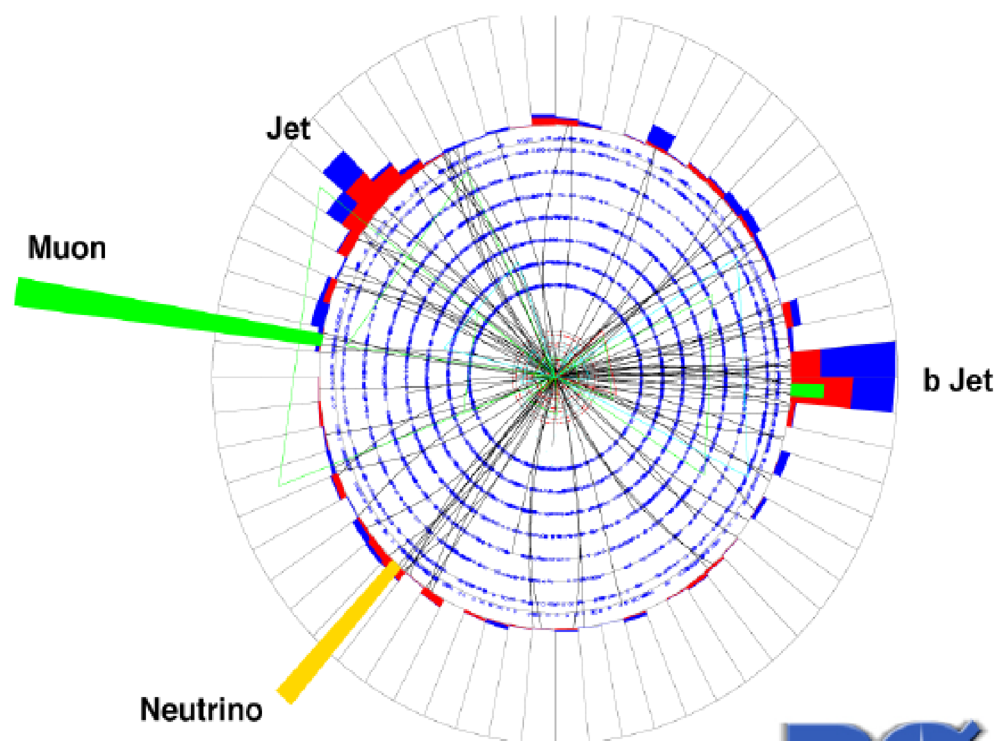
NNNLO$_{approx}$, m_{top} = 172.5 GeV



- jets
- lepton
- missing E_T
- b-jets

W→ tb decay vertex

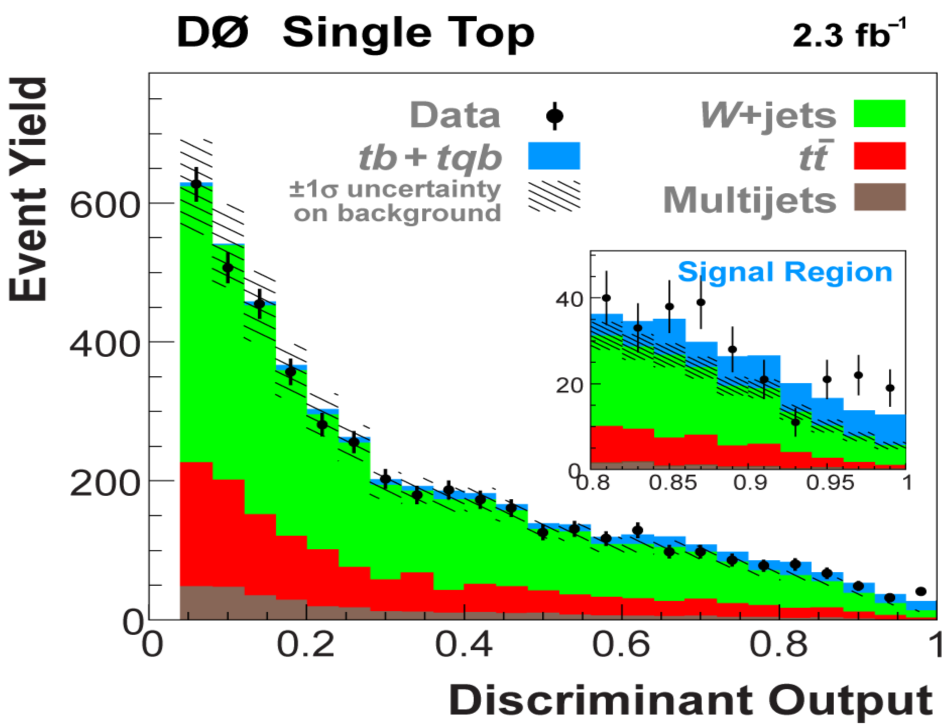
$|V_{tb}|$ determination

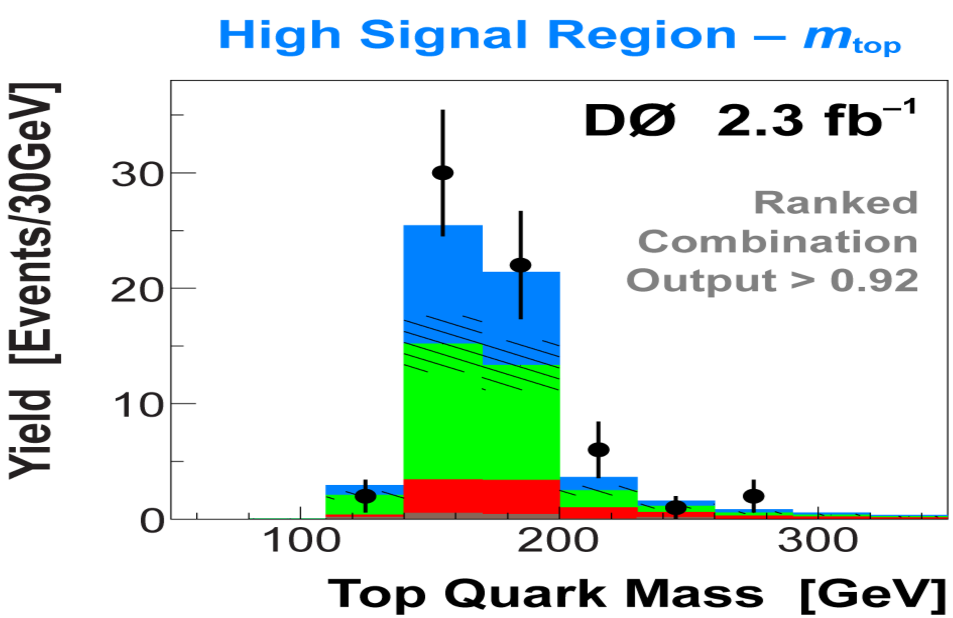


Signal << Backgound:

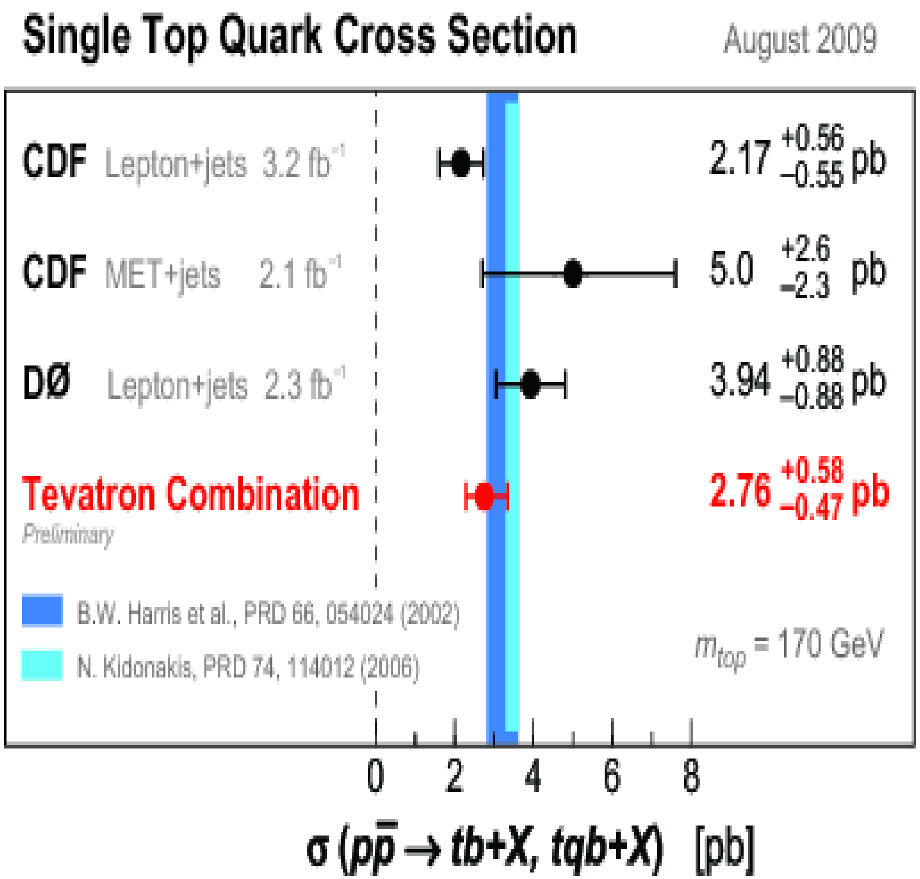
Multivariate techniques

Single-top Production





> 5 std. dev. significance



Result: $|V_{tb}| = 0.88 \pm 0.07$

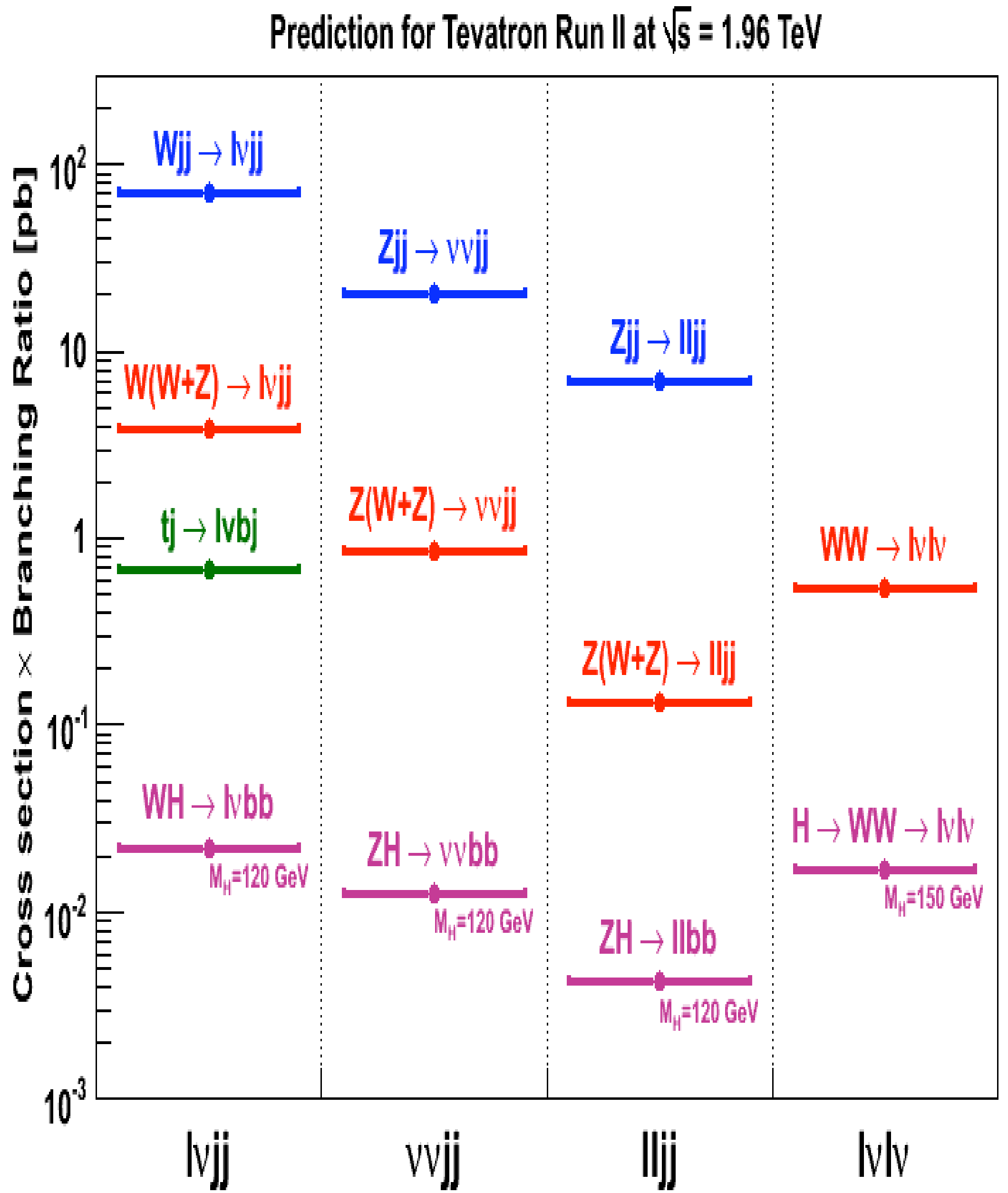
WW/WZ/ZZ Production

WW/WZ/ZZ decay modes with jets or neutrinos

Same final states as in most Higgs search channels

Last steps before finding the Higgs boson

H→WW or ZZ: best channel to search for heavy Higgs bosons



ZZ Production

ZZ→ llll:

Striking event signature

Selection:

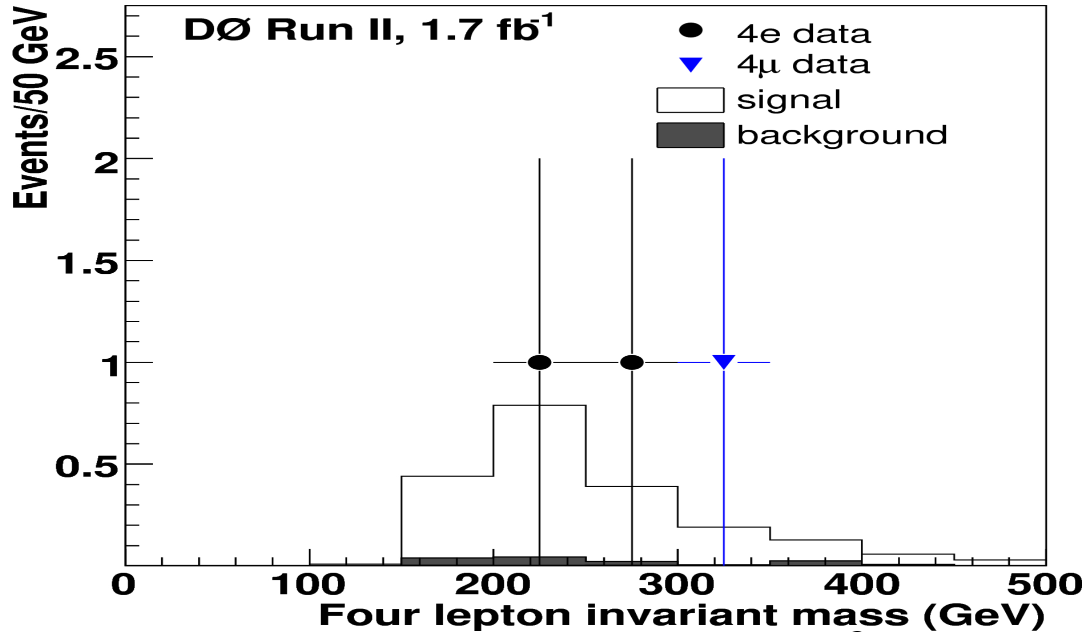
2 high-mass pairs of leptons

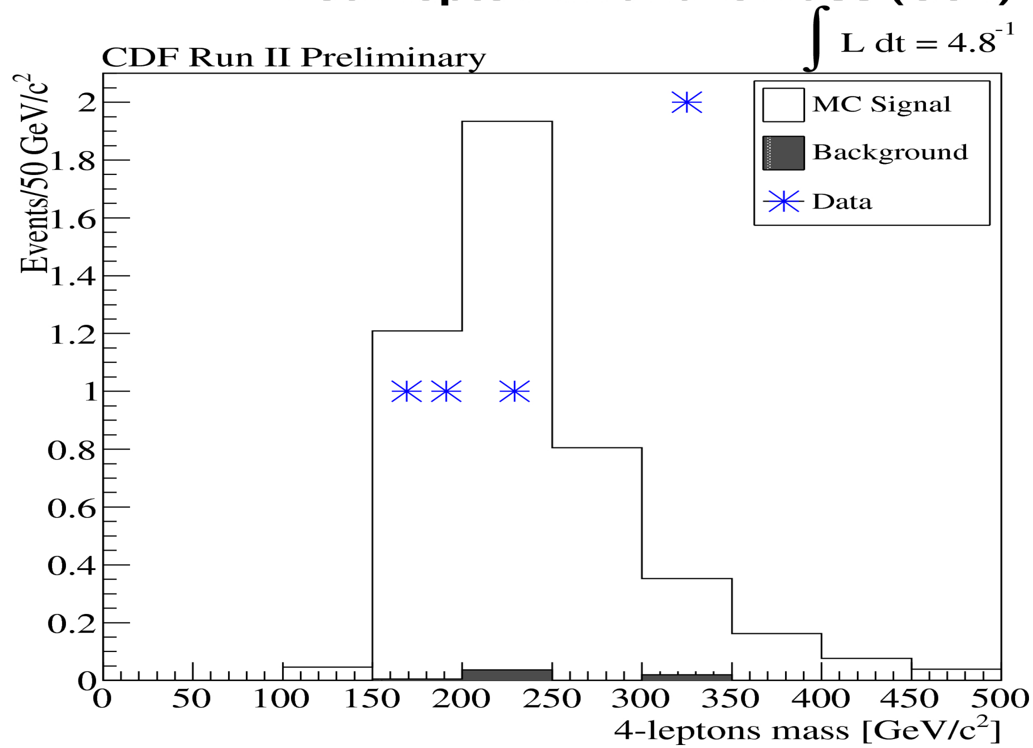
D0 2008: 1.7/fb – 3 events

CDF 2009: 4.8/fb – 5 events

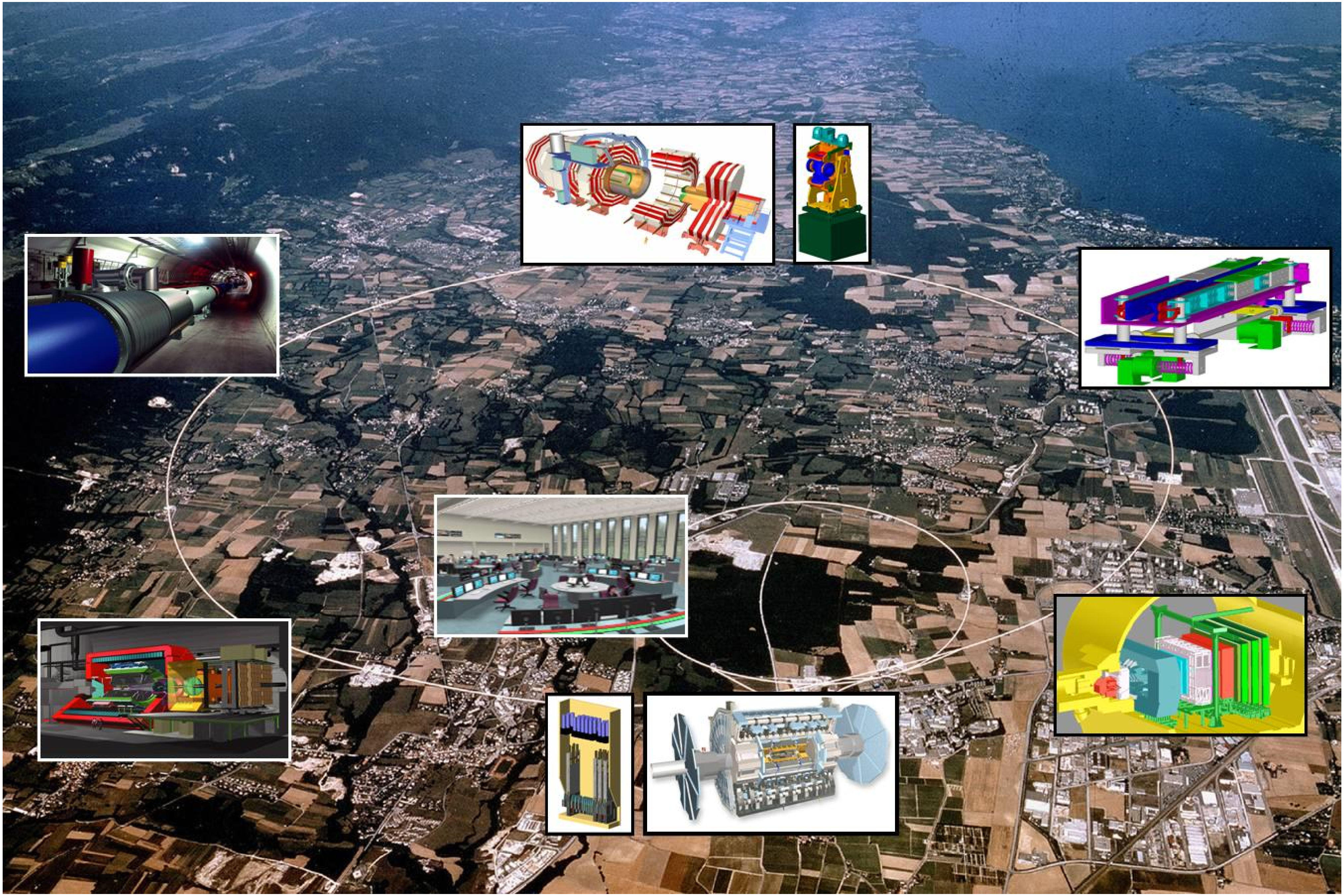
Process observed:

Significance of 5.7 std. dev. in each case



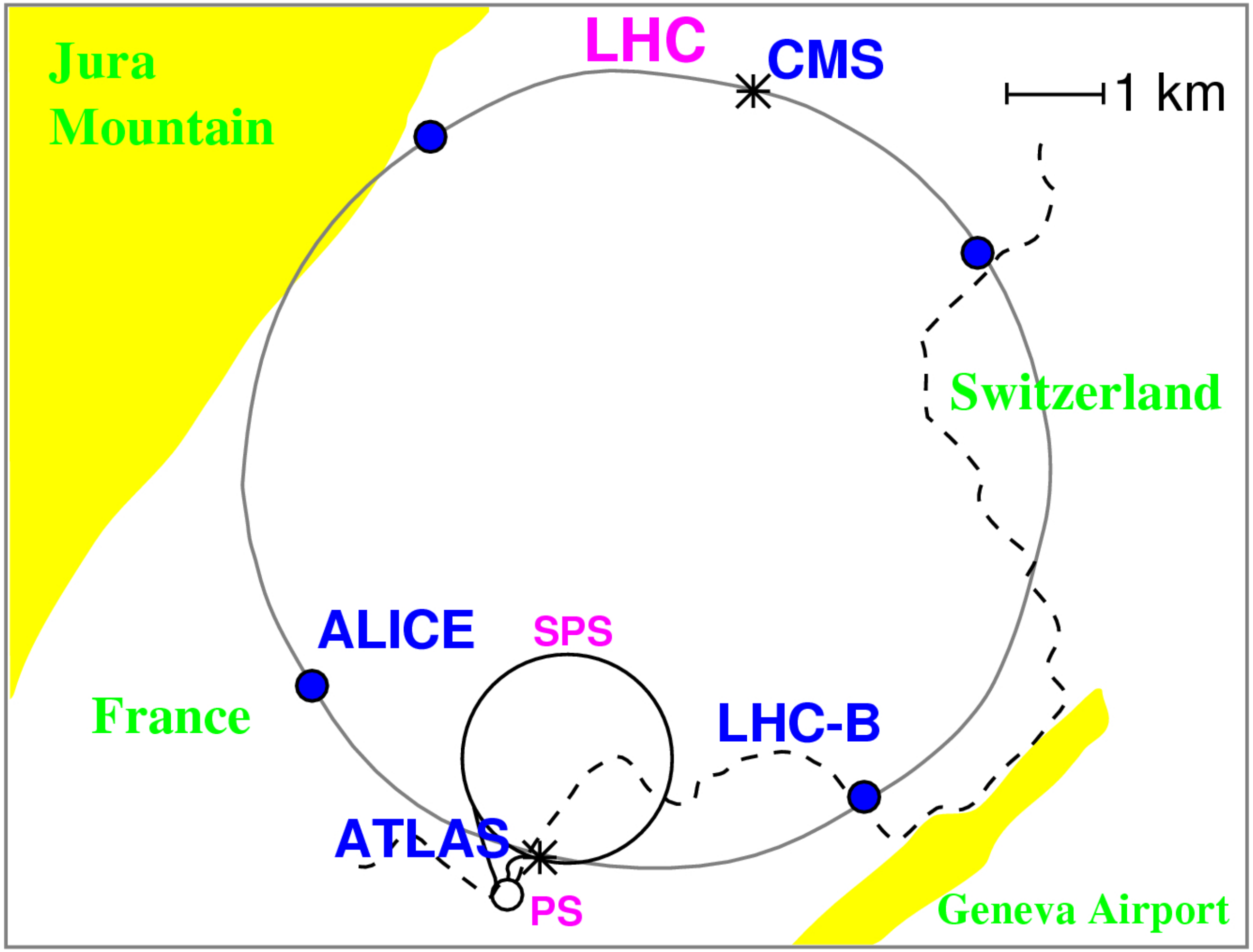


Future: Large Hadron Collider



Future: Large Hadron Collider

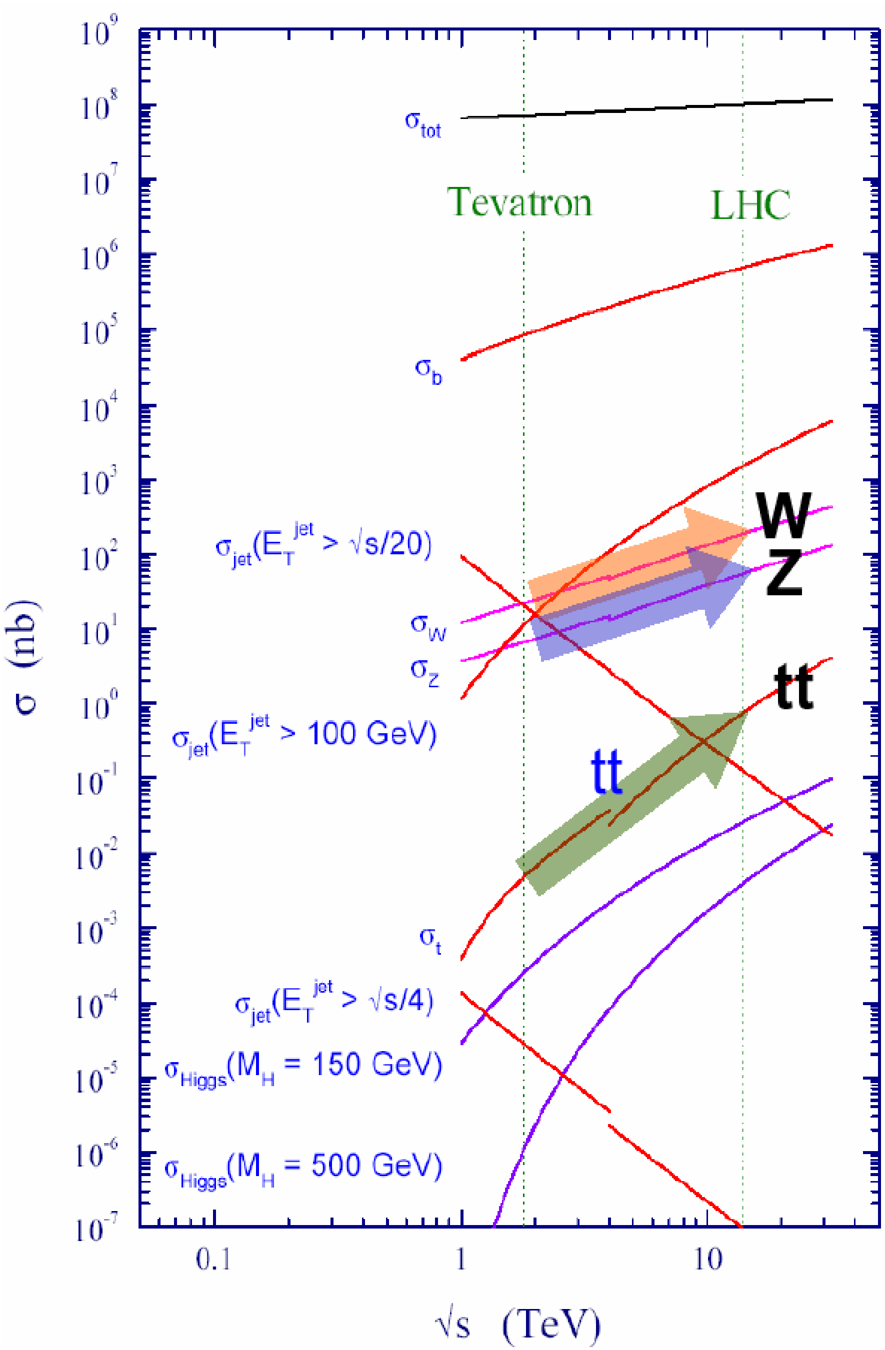
2009+: ATLAS and CMS at the Large Hadron Collider (LHC):



Proton-proton collisions up to 14,000 GeV CM energy:

Successful search for the Higgs boson and/or other new physics in the full mass range

Expected cross sections



Fermilab Tevatron: 2 TeV

LHC: 7 TeV (November 2009) to
14 TeV (2011+) CM energy

LHC at 1E33 luminosity:
- 150 Hz W
- 50 Hz Z
- 1 Hz tT

In 10/pb of luminosity (2009 startup):
- 150k W→eν
- 15k Z→ee
- 10k tT

Event samples are LARGE!

The CMS Detector

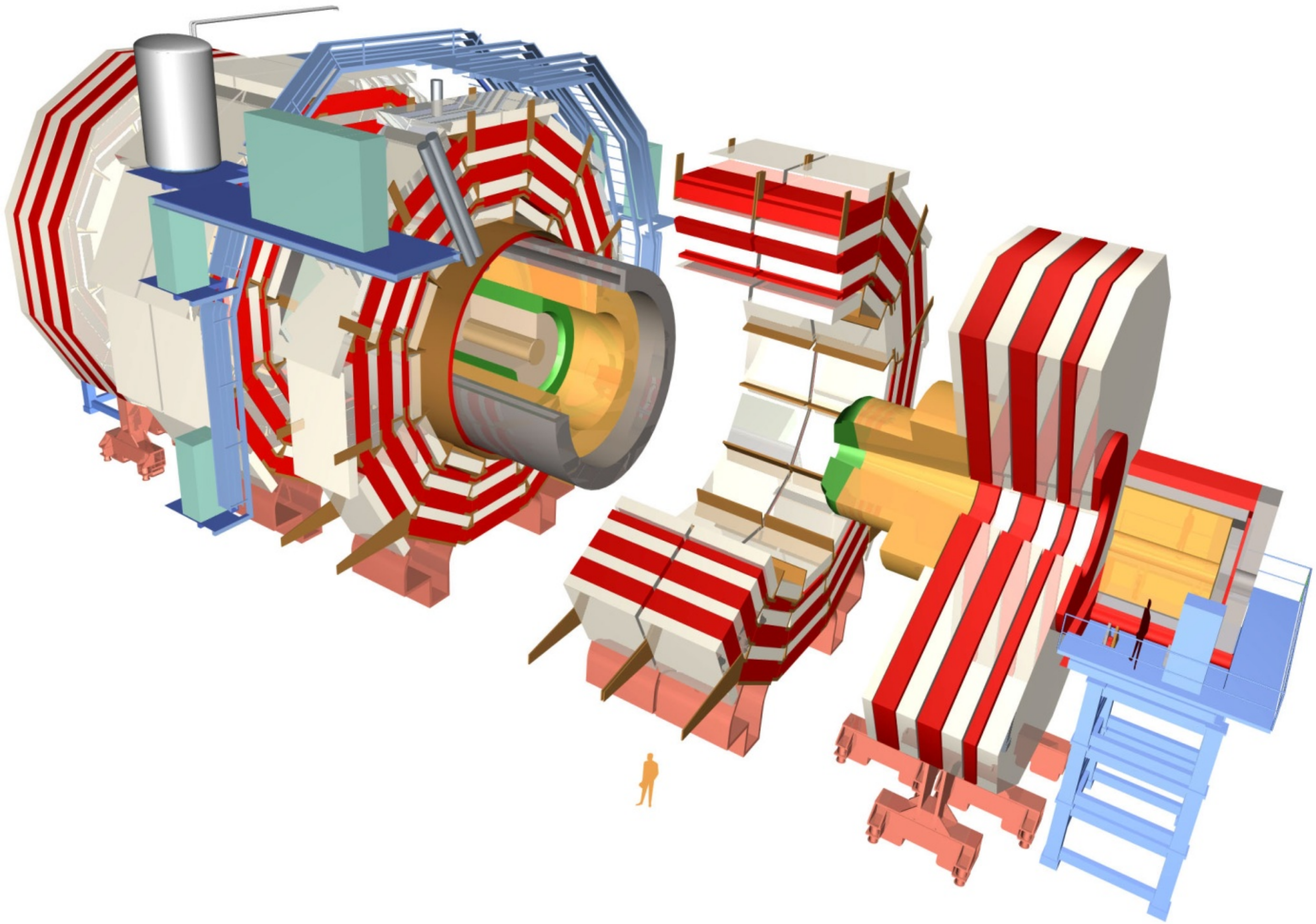
Compact
Muon
Solenoid

Detector to measure particle collisions

> 36 countries

> 180 institutes

> 3000 physicists and engineers

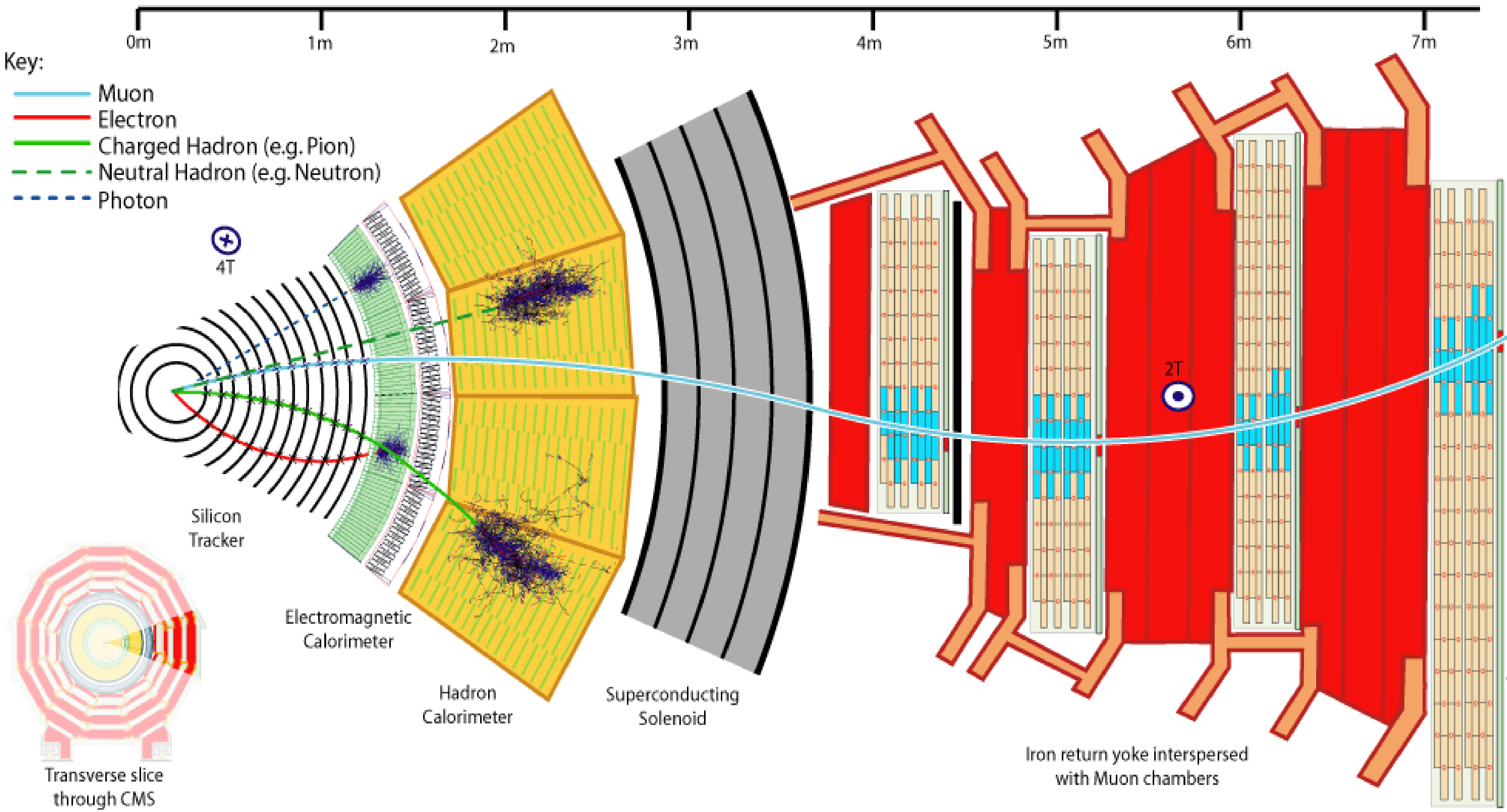


Total weight	12500 tonnes
Diameter	15m
Length	21.6m
Magnetic field	4 Tesla

As much iron as the Eiffel Tower

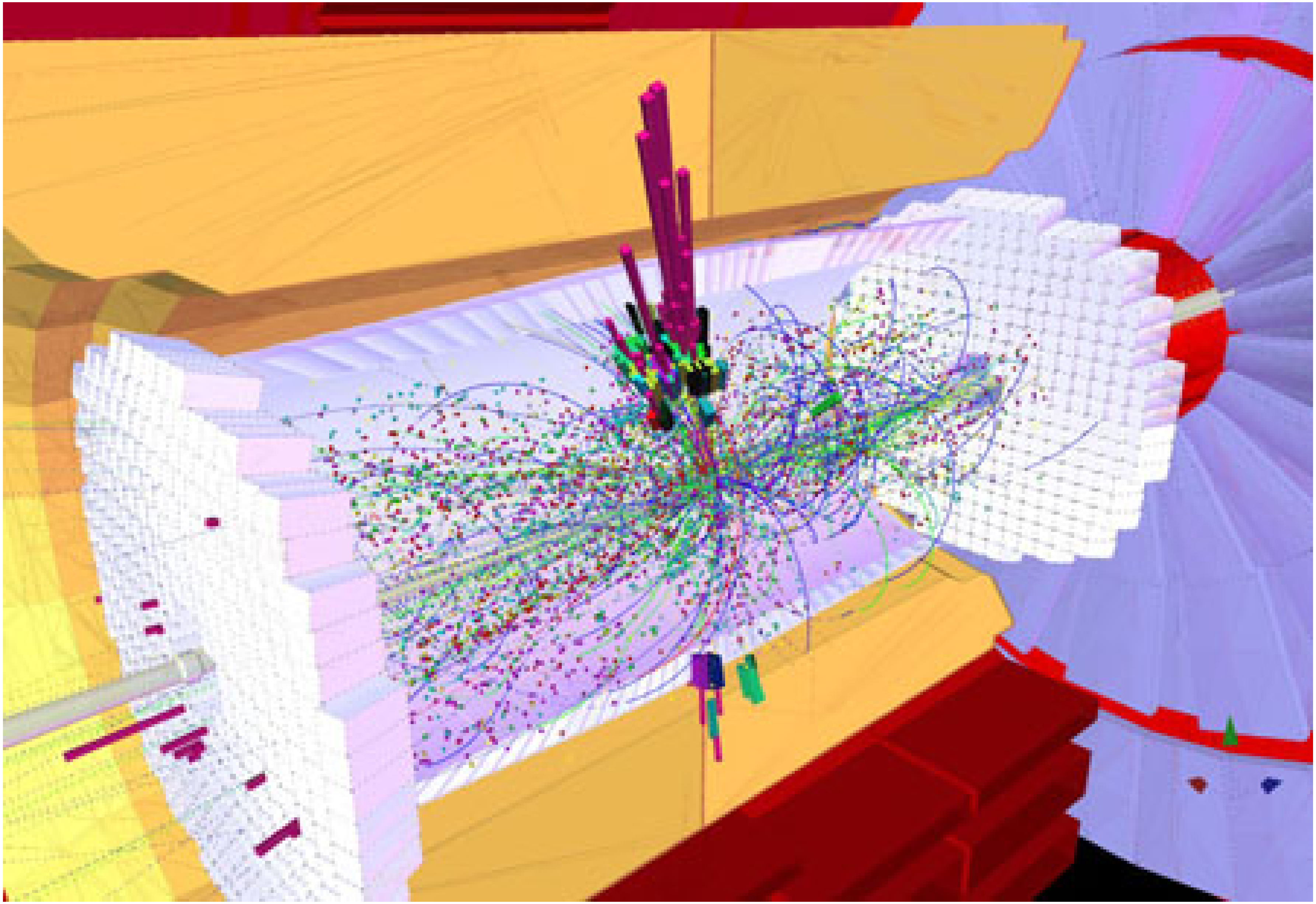
Cost: 380 MEuro

The CMS Detector



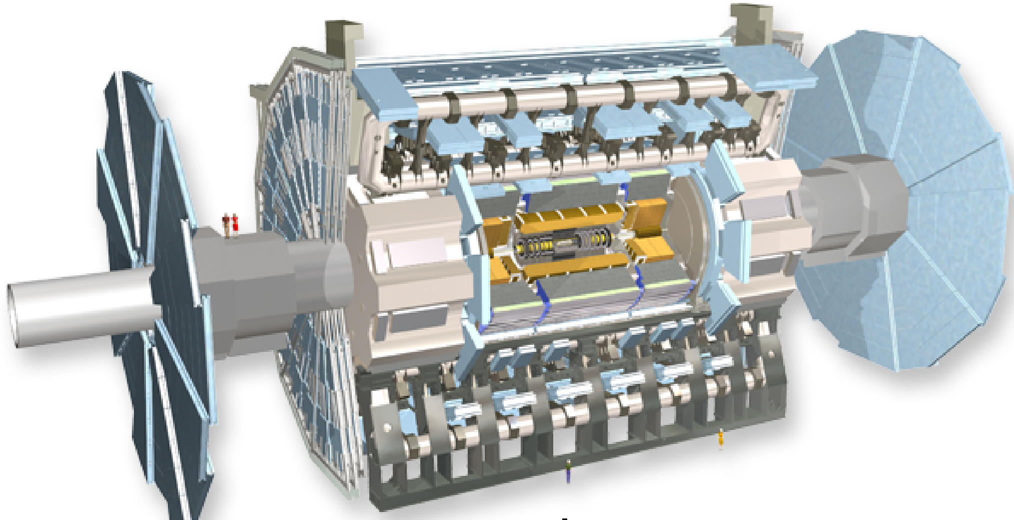
Charged Particles | Electrons Photons | Hadrons | 3.8 Tesla Solenoid | Iron yoke (return flux) Muons

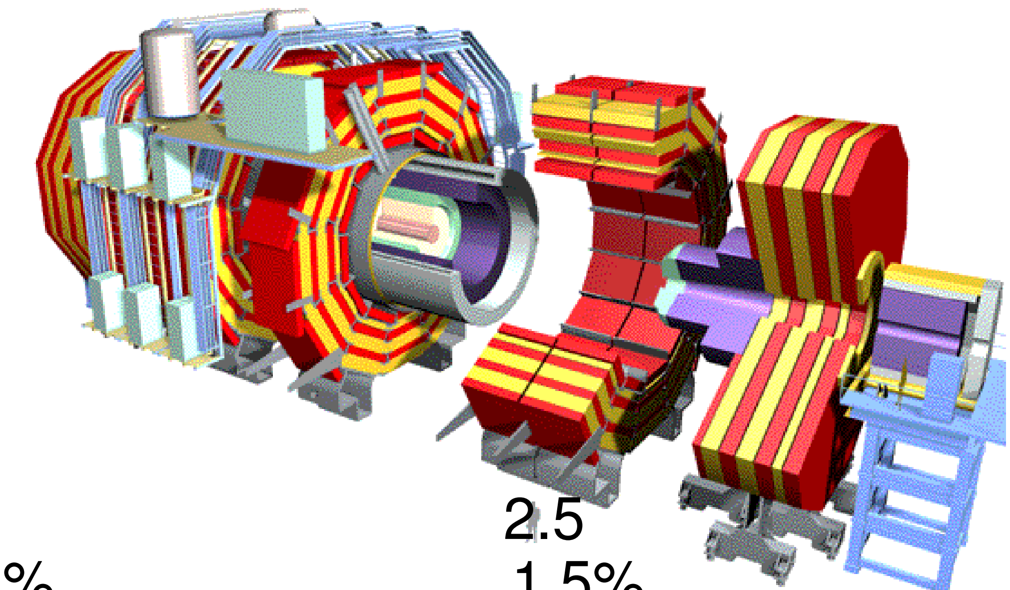
Simulated Collision Event in CMS



ATLAS and CMS Detectors

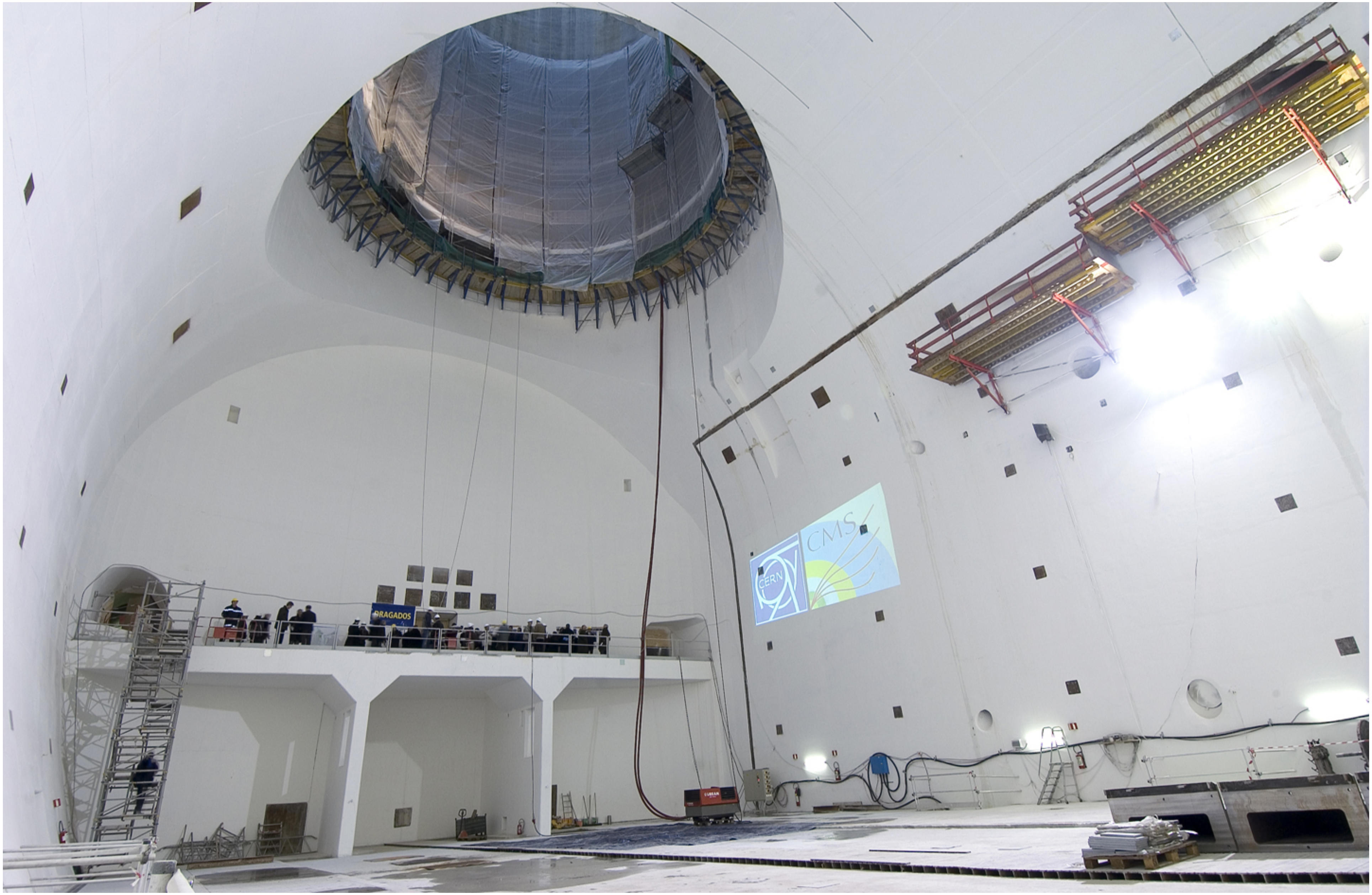
B field:		2.6 T (Solenoid), 4 T (Toroid)	3.8 T (Solenoid)





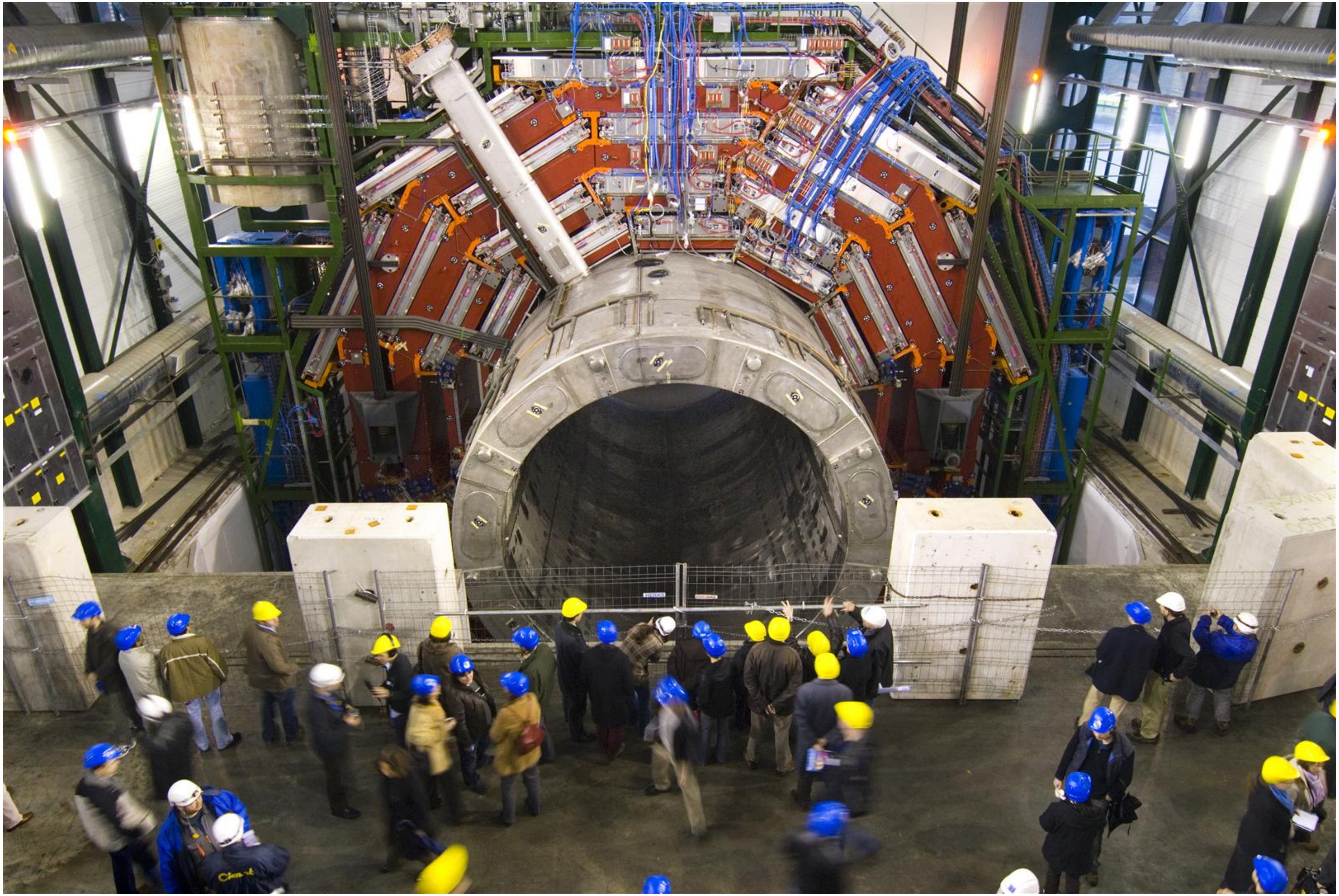
Inner tracker:	$\lvert\eta\rvert$ coverage	2.5	2.5
$\sigma(p_T)/p_T$ at p_T=100 GeV		3.8%	1.5%
EM calorimeter:	$\lvert\eta\rvert$ coverage	3.2	3.0
$\sigma(E)/E$		$9\%/\sqrt{E} + 0.5\%$	$3\%/\sqrt{E} + 0.25\%$
HAD calorimeter:	$\lvert\eta\rvert$ coverage	4.9	5.2
$\sigma(E)/E$ (EM+HAD combined)		$70\%/\sqrt{E} + 3.3\%$	$70\%/\sqrt{E} + 8\%$
Muon system:	$\lvert\eta\rvert$ coverage	2.7	2.4
$\sigma(p_T)/p_T$ at p_T=1 TeV		7%	5%

CMS Cavern (2004)



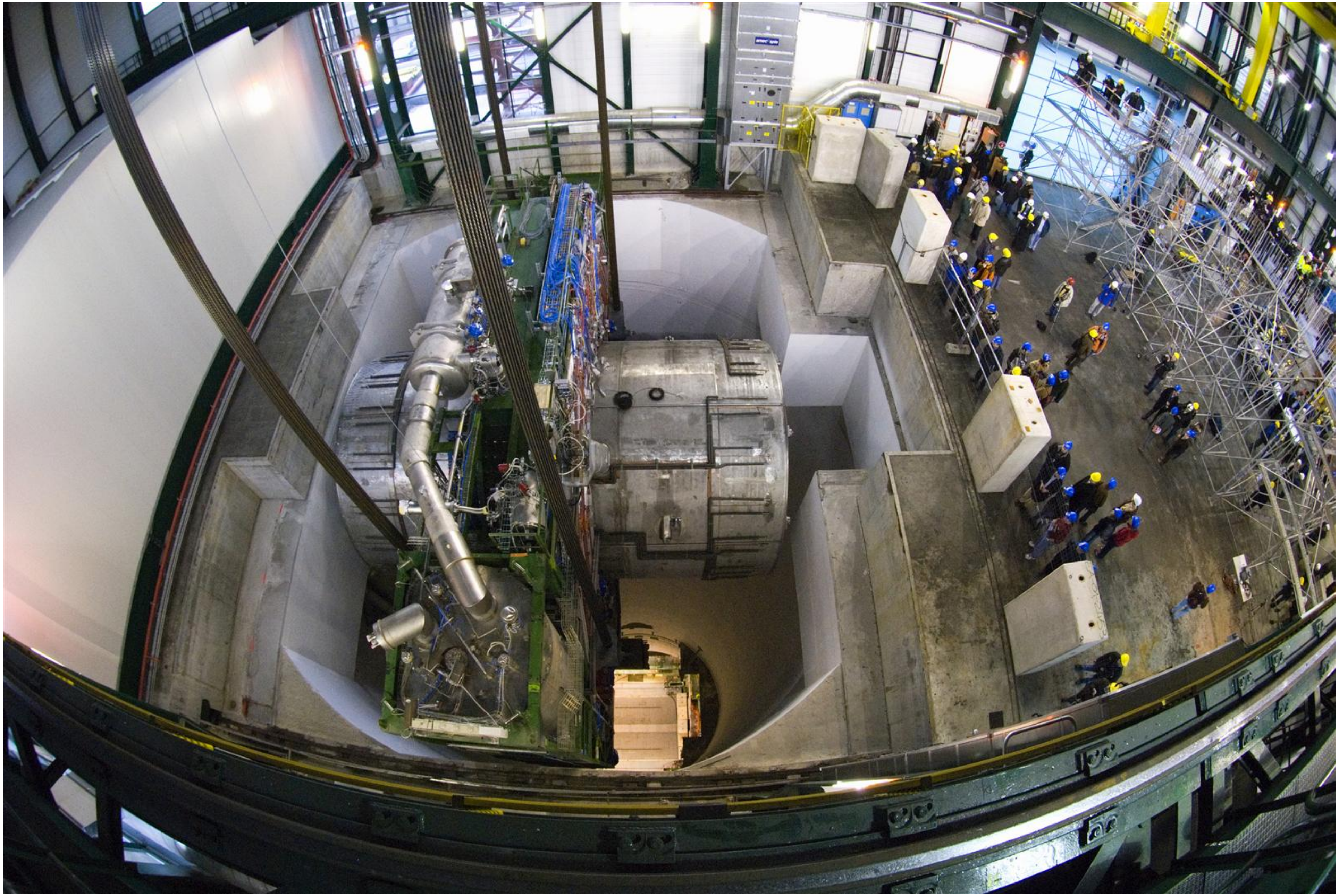
Length: 53m, width: 27 m, height: 24m

The CMS Detector



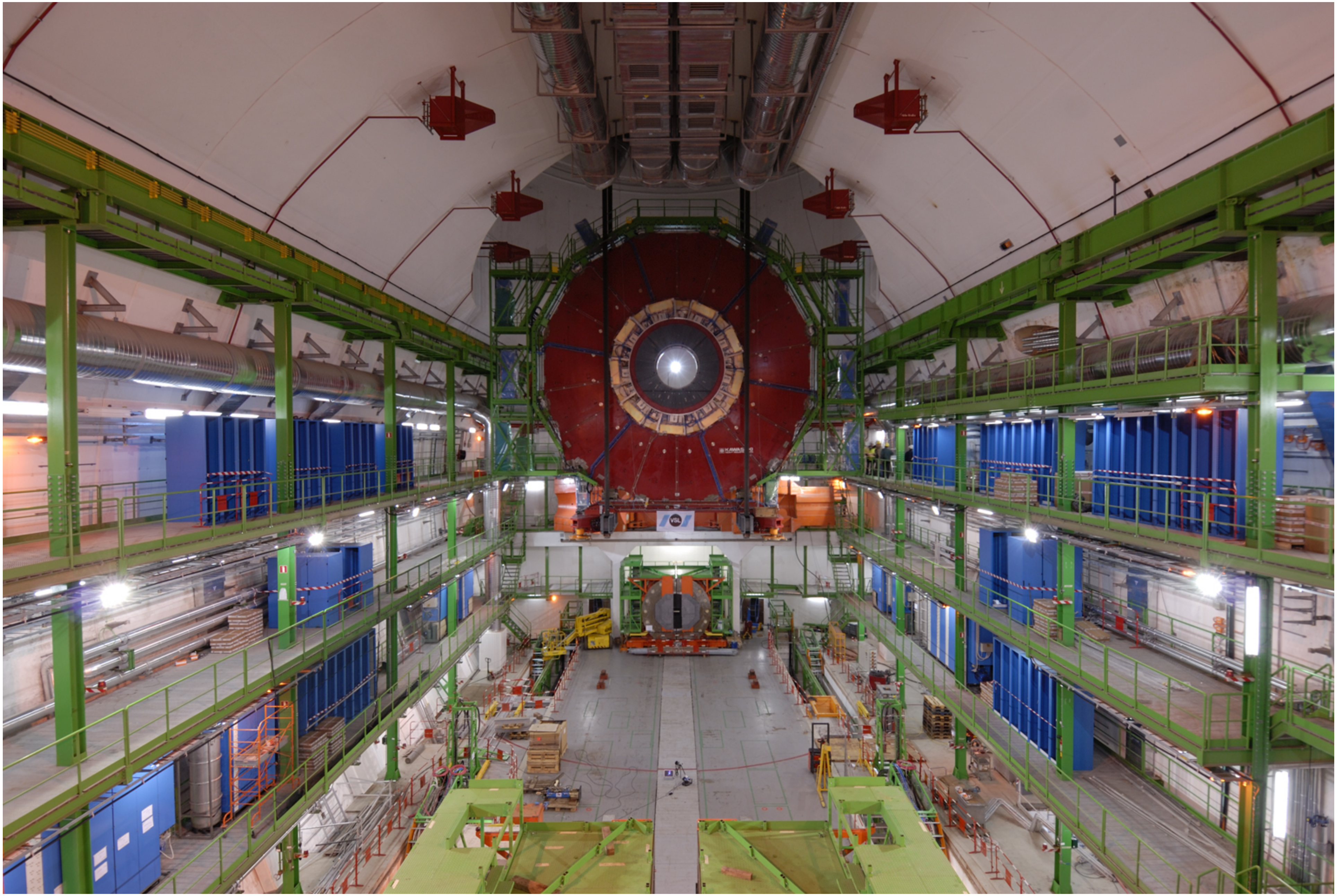
Lowering pre-assembled CMS parts of up to 2000 tons weight ...

The CMS Detector



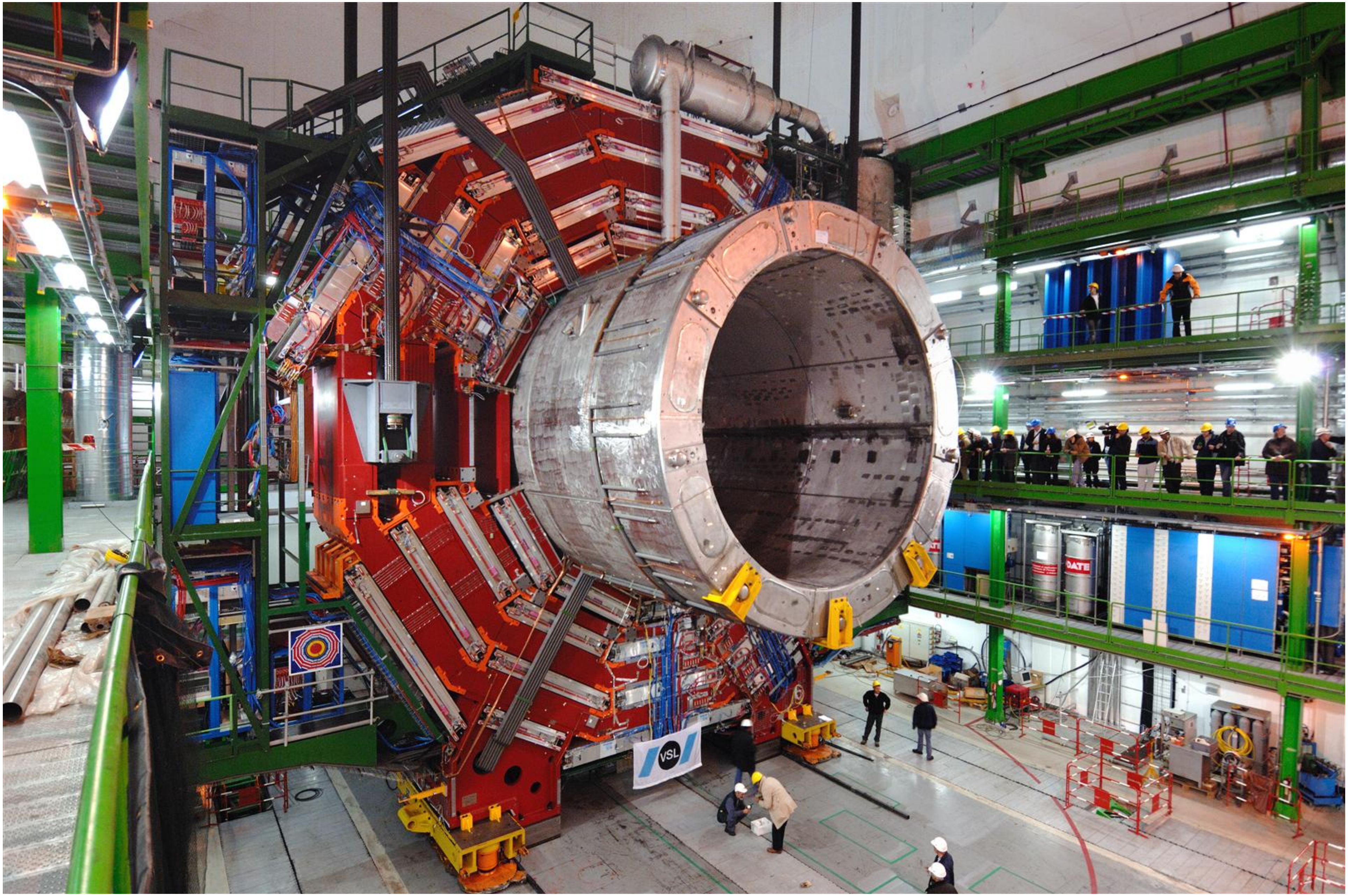
... with only a few centimeters to spare

The CMS Detector



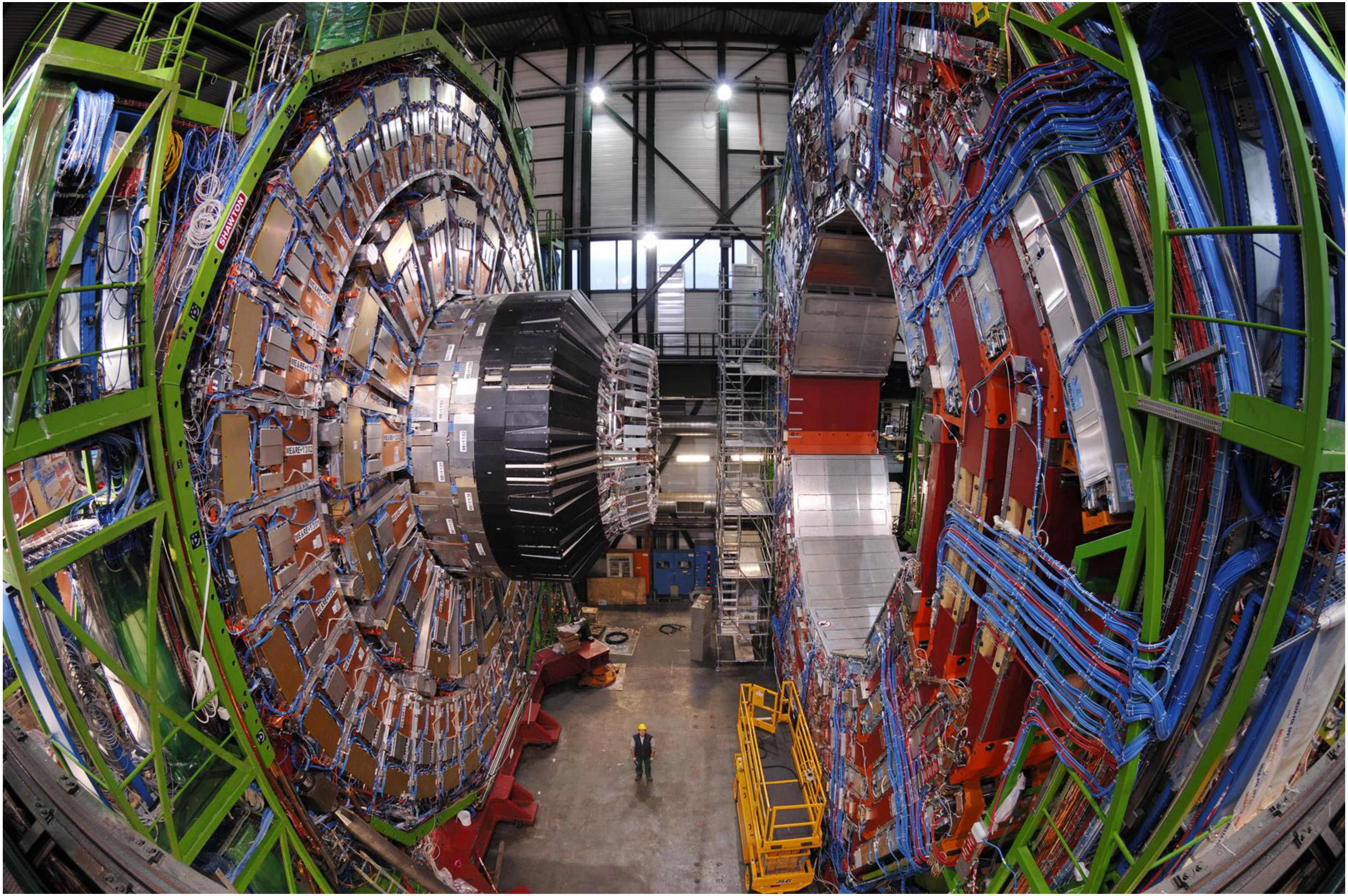
... with only a few centimeters to spare

The CMS Detector



Superconducting coil: 2700 MJ – (heat and melt 13 tons of gold)

The CMS Detector

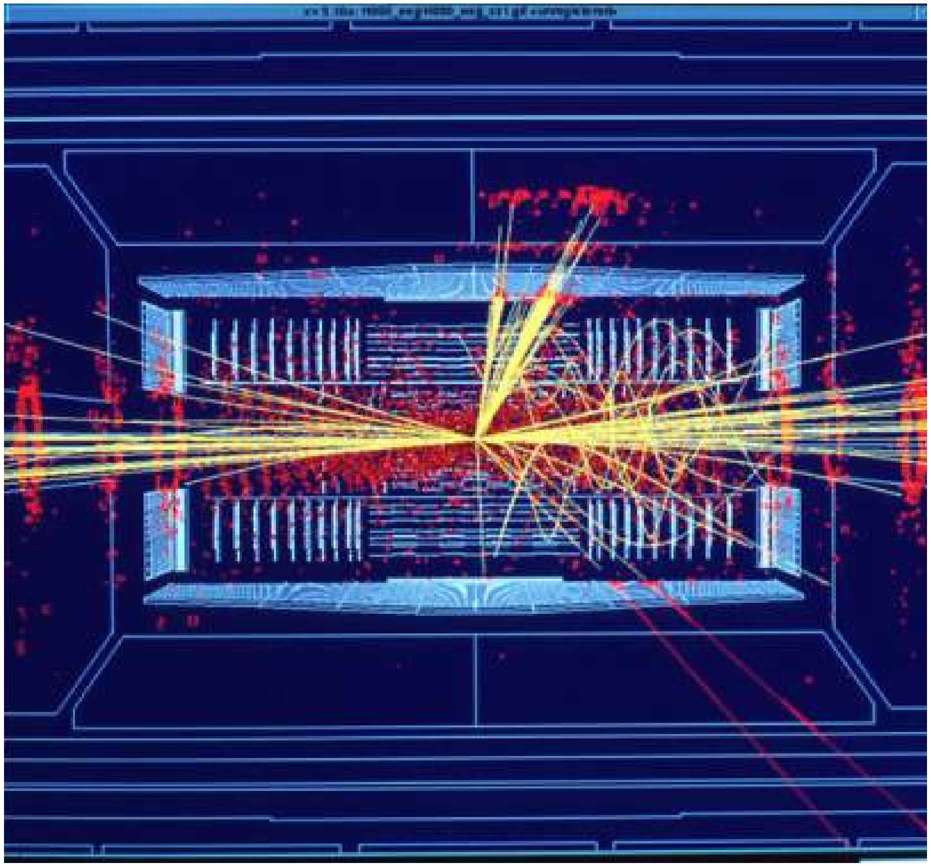


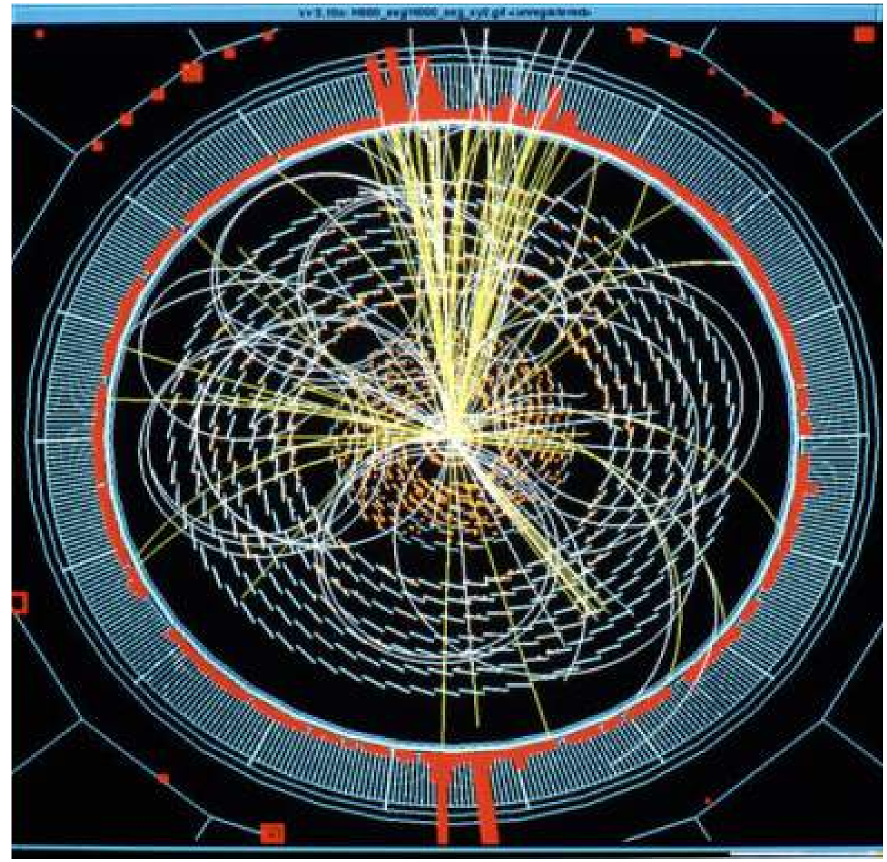
The CMS Detector

-z Endcap before closure

Simulated Collision Event in CMS

Production and decay of a Higgs boson in the CMS detector



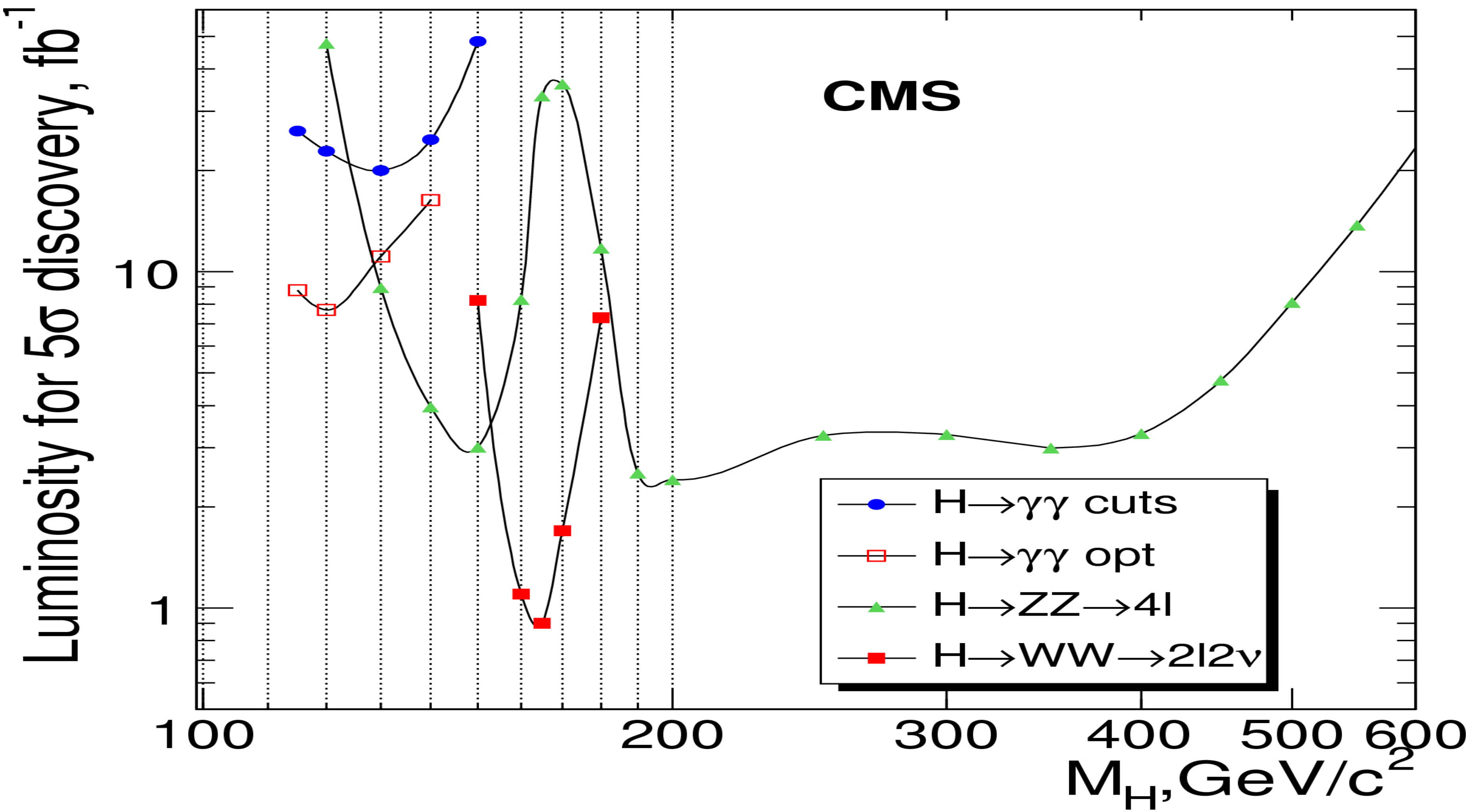


Analysis of collision event by computer (the “GRID”):

- Reconstruct each event
- Search for the interesting events (1 in 1 billion)

Future Searches for the Higgs Boson

Luminosity needed for discovery: 1/fb – 10/fb



Measurement of the Higgs-boson mass:

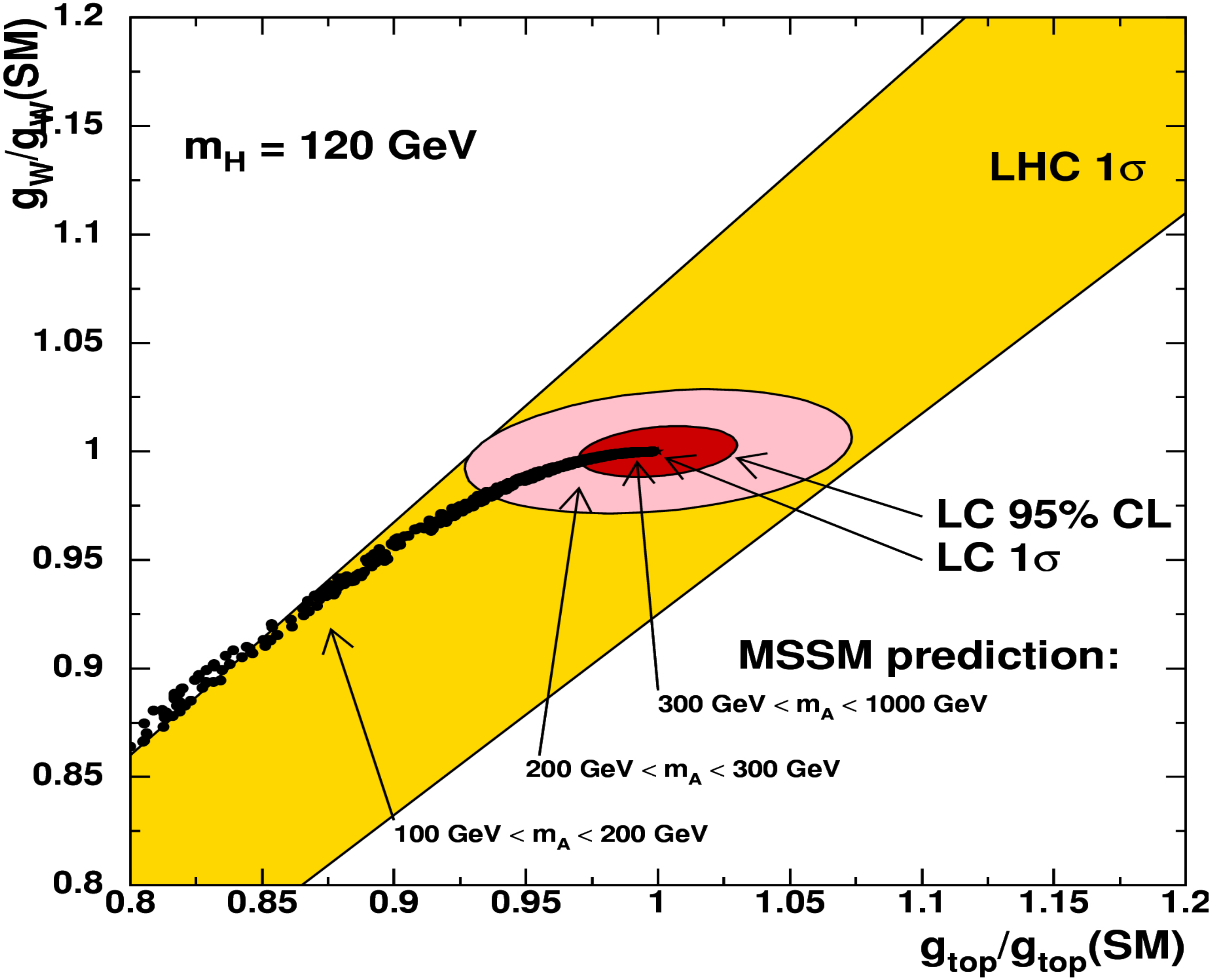
0.1% – 1% accuracy expected for 30/fb

Precision Higgs-Boson Physics

Electron-positron linear collider: ~500 - 1000 GeV (ILC)

Higgs-boson mass and decay width, quantum numbers, ...

Couplings to
fermions and
bosons



Summary

Electro-Weak Standard Model:

From radioactivity to the electroweak interaction

Mathematically consistent description:

Gauge theory with massive gauge bosons Z and W

Precise experimental tests of the electroweak theory:

Accuracy per-mille and better

Determination of masses and couplings

Analysis of radiative corrections including loops

Theory passes tests successfully

Many “rare” processes observed

Higgs boson as fundamental ingredient:

Not yet found in direct search!

Hints in direct search at LEP-2 - but not significant!

Outlook

Search & discovery of the Higgs at the Tevatron(?) & LHC

Which type of Higgs boson? How many?

Detailed measurements at LHC & ILC

Stringent tests of theory: heavy particles and Higgs boson

Open questions of the Standard Model

Why are there three fermion families?

Calculation of all particle masses?

Unification with strong interaction (QCD)?

Unification with gravity?

Extended theories:

Supersymmetry, superstrings, extra dimensions?, ...

Final judgment by experiment

Search for and find(!) such new phenomena at LHC and ILC