Experimental tests of the Standard Model

- Discovery of the *W* and *Z* bosons
- Precision tests of the *Z* sector
- Precision tests of the *W* sector
- Electro-weak unification at HERA
- Radiative corrections and prediction of the top and Higgs mass
- Top discovery at the Tevatron
- Higgs searches at the LHC

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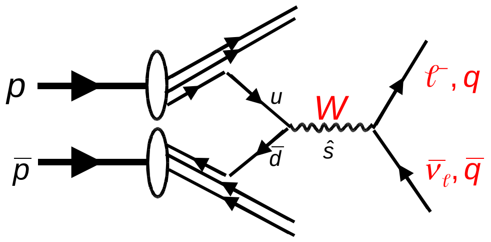
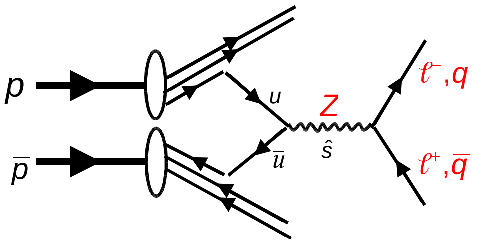
1. Discovery of the *W* and *Z* boson

1983 at CERN SppS accelerator,
√s≈540 GeV, UA-1/2 experiments

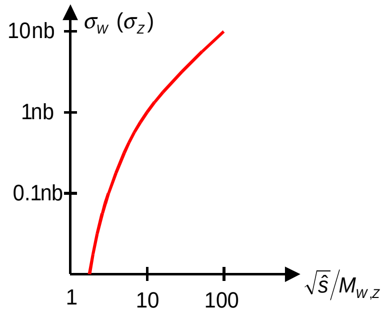
1.1 Boson production in *pp* interactions



$$p\bar p \to W \to \ell \bar\nu_\ell + X$$



$$p\bar p \to Z \to f\bar f + X$$

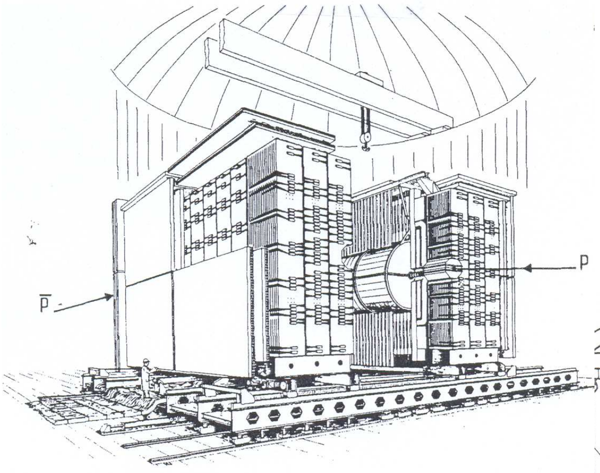


Similar to Drell-Yan: (photon instead of W)

$$\hat s = x_q x_{\bar q} s \quad \text{mit} \quad \langle x_q \rangle \approx 0.12$$

$$\hat s = \langle x_q \rangle^2 s \approx 0.014 s = (65\ \text{GeV})^2$$

→ Cross section is small !



1.2 UA-1 Detector

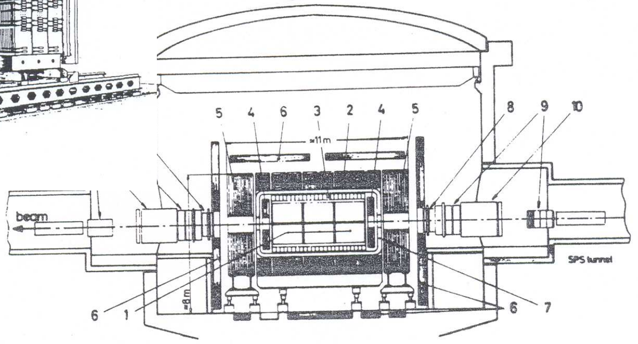
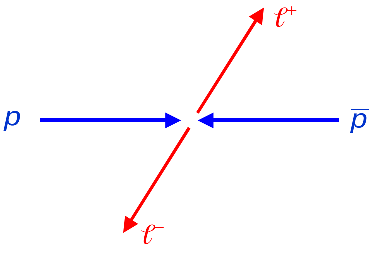


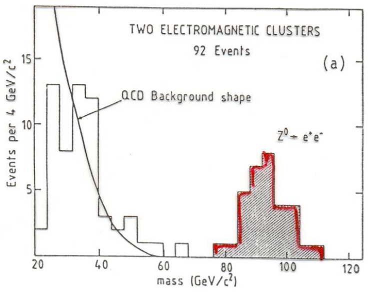
Fig.8.16: Seitenansicht des UA1-Detektors zum Nachweis von Proton-Antiproton-Wechselwirkungen bei 540 GeV Schwerpunktsenergie: 1. Zentraldetektor, 2. und 5. Hadron-Kalorimeter, 3. und 4. Elektron-Photon-Schauerzähler, 6. Myon-Detektor, 7. Spule für Dipolfeld, 8. und 9. Kleinwinkeldetektor mit Kammern und Kalorimetern, 10. Kompensator-Magnete [UA1].

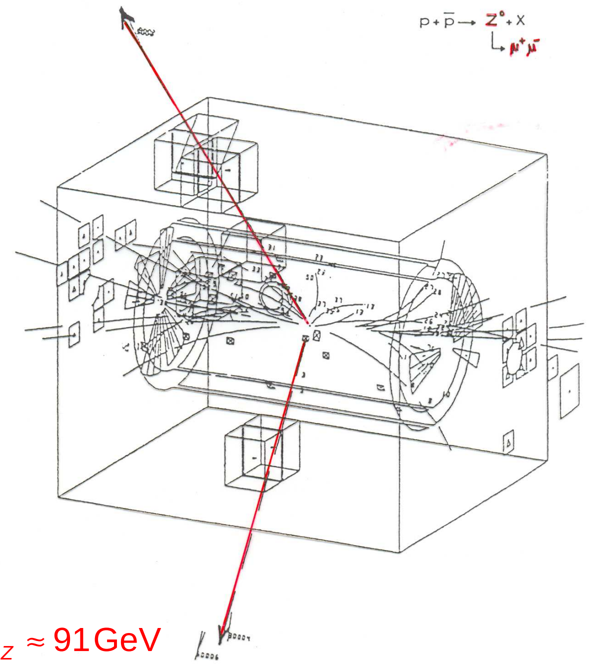
1.3 Event signature: $p\bar{p} \rightarrow Z \rightarrow f\bar{f} + X$



High-energy lepton pair:

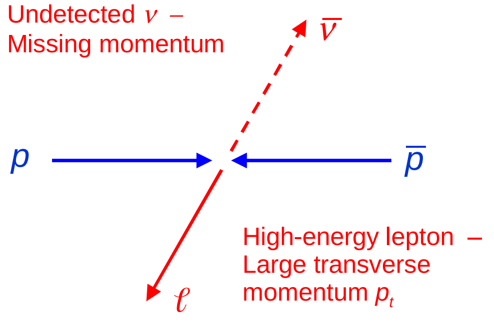
$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





$M_Z \approx 91\,\text{GeV}$

1.4 Event signature: $p\bar{p} \to W \to \ell \bar{\nu}_\ell + X$ $W^- \to e\,\bar{\nu}$



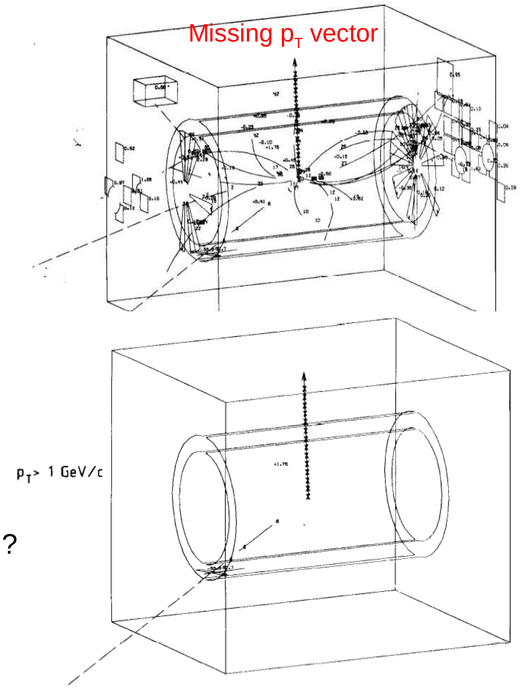
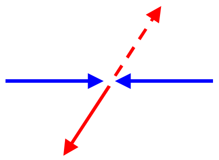


Fig. *16b*. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_t>1 GeV are shown.

How can the *W* mass be reconstructed ?

W mass measurement



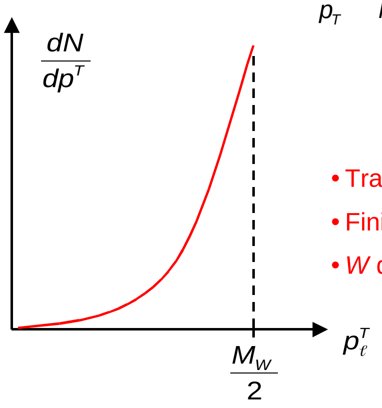
In the *W* rest frame:

- $|\vec{p}_\ell| = |\vec{p}_\nu| = \frac{M_W}{2}$
- $|p_\ell^T| \le \frac{M_W}{2}$

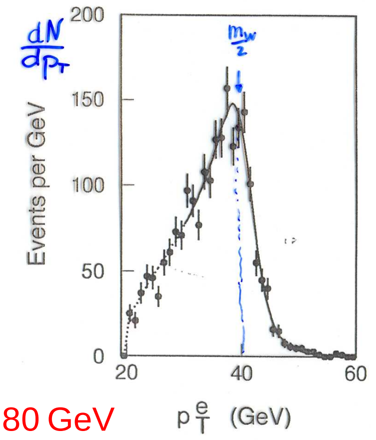
In the lab system:

- *W* system boosted only along *z* axis
- p_T distribution is conserved

Jacobian Peak: $\frac{dN}{p_T} \sim \frac{2p_T}{M_W} \cdot \left(\frac{M_W^2}{4} - p_T^2\right)^{-1/2}$



- Trans. Movement of the *W*
- Finite *W* decay width
- *W* decay is not isotropic



$M_W \approx 80$ GeV

The Nobel Prize in Physics 1984

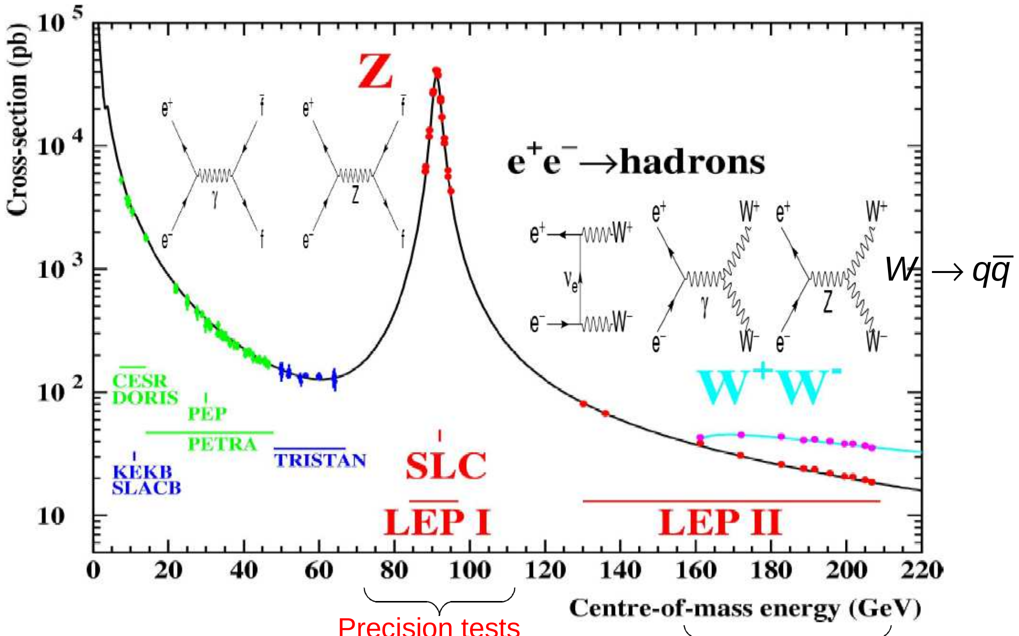
Carlo Rubbia	**Simon van der Meer**

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

S. van der Meer

One of the achievements to allow high-intensity p $\bar{p}$ collisions, is stochastic cooling of the $\bar{p}$ beams before inserting them into SPS.

1.5 Production of *Z* and *W* bosons in e^+e^- annihilation



$W \to q\bar{q}$

Precision tests of the *Z* sector

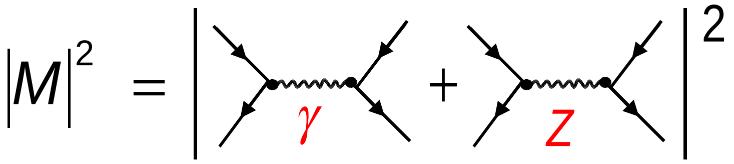
Tests of the *W* sector

2. Precision tests of the Z sector

(LEP and SLC)

~4.5M *Z* decays / experiment

2.1 Cross section for $e^+e^- \to \gamma/Z \to f\bar{f}$



for $e^+e^- \to \mu^+\mu^-$

$$M_\gamma = -e^2(\bar{\mu}\gamma_\mu\mu)\frac{1}{q^2}(\bar{e}\gamma^\mu e)$$

$$M_Z = -\frac{g^2}{\cos^2\theta_W}\left[\bar{\mu}\gamma^\nu\frac{1}{2}(g_V^\mu - g_A^\mu\gamma^5)\mu\right]\underbrace{\frac{g_{\nu\rho} - q_\nu q_\rho/M_Z^2}{(q^2 - M_Z^2) + iM_Z\Gamma_Z}}_{\text{Z propagator considering a finite Z width}}\left[\bar{e}\gamma^\rho\frac{1}{2}(g_V^e - g_A^e\gamma^5)e\right]$$

Differential cross section for $e^+e^- \to \mu^+\mu^-$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + \underbrace{F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}}_{\text{Vanishes at }\sqrt{s}\approx M_Z} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}\right]$$

γ $\qquad$ γ/Z interference $\qquad$ Z

with

$$F_\gamma(\cos\theta) = Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}\left[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta\right]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[(g_V^{e^2} + g_A^{e^2})(g_V^{\mu^2} + g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta\right]$$

At the *Z*-pole $\sqrt{s}\approx M_Z$ → *Z* contribution is dominant
→ interference vanishes

$$\sigma_{tot}\approx\sigma_Z=\frac{4\pi}{3s}\frac{\alpha^2}{16\sin^4\theta_w\cos^4\theta_w}\cdot\left[(g_V^e)^2+(g_A^e)^2\right]\left[(g_V^\mu)^2+(g_A^\mu)^2\right]\cdot\frac{s^2}{(s-M_Z^2)^2+(M_Z\Gamma_Z)^2}$$

$$\sigma(s)=12\pi\frac{\Gamma_e\Gamma_\mu}{M_Z^2}\cdot\frac{s}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

$$\sigma_Z\left(\sqrt{s}=M_Z\right)=\frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_\mu}{\Gamma_Z^2}$$

With partial and total widths:

$$\Gamma_f=\frac{\alpha M_Z}{12\sin^2\theta_w\cos^2\theta_w}\cdot\left[(g_V^f)^2+(g_A^f)^2\right]$$

$$\Gamma_Z=\sum_i\Gamma_i$$

Cross sections and widths can be calculated within the Standard Model if all parameters are known

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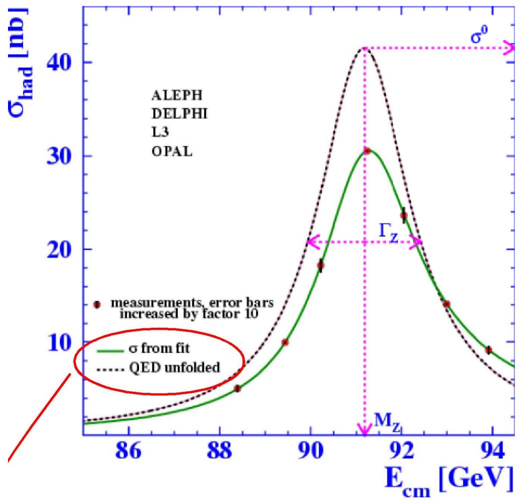
.2 Measurement of the *Z* lineshape



Z resonance curve:

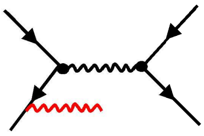
$$\sigma(s)=12\pi\frac{\Gamma_e\Gamma_\mu}{M_Z^2}\cdot\frac{s}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

Peak: $\sigma_0=\frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_\mu}{\Gamma_Z^2}$

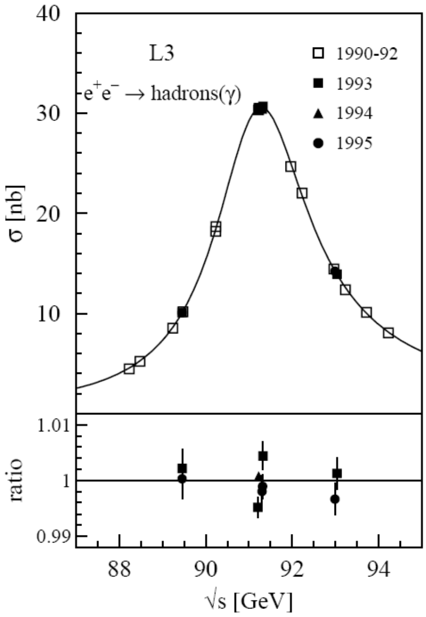
- Resonance position → M_Z
- Height → $\Gamma_e\Gamma_\mu$
- Width → Γ_Z

Initial state Bremsstrahlung corrections

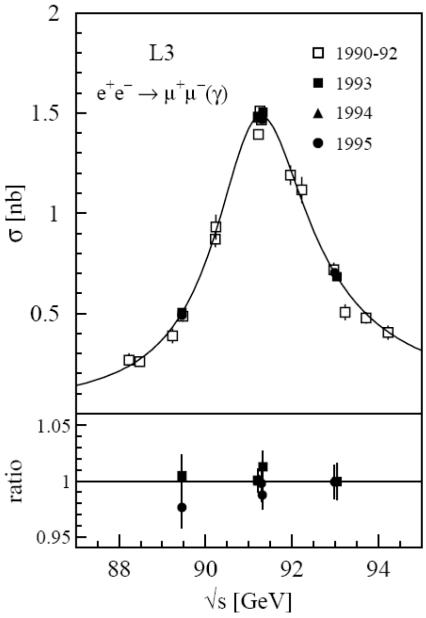
$$\sigma_{ff(\gamma)}=\int_{4m_f^2/s}^{1}G(z)\sigma_{ff}^{0}(zs)dz \qquad z=1-\frac{2E_\gamma}{\sqrt{s}}$$



$e^+e^- \to hadrons$



$e^+e^- \to \mu^+\mu^-$



Resonance looks the same, independent of final state: Propagator is the same

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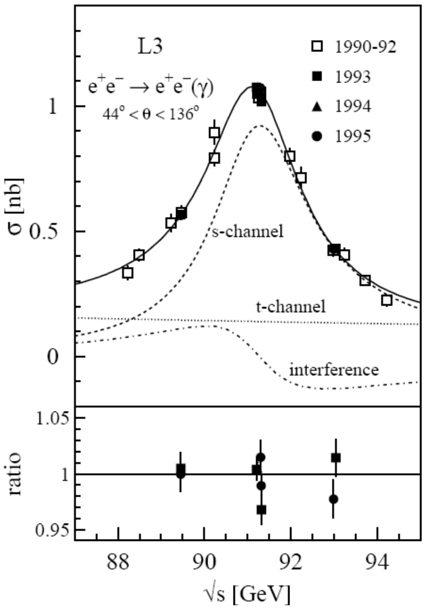
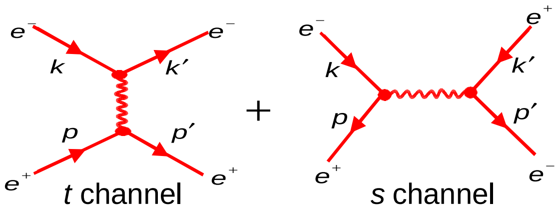
$e^+e^- \to e^+e^-$

t channel contribution → forward peak





Z line shape parameters (LEP average)

M_Z = 91.1876 ± 0.0021 GeV
= ±23 ppm (*)

Γ_Z = 2.4952 ± 0.0023 GeV
Γ_{had} = 1.7458 ± 0.0027 GeV
Γ_e = 0.08392 ± 0.00012 GeV
Γ_μ = 0.08399 ± 0.00018 GeV
Γ_τ = 0.08408 ± 0.00022 GeV

±0.09 %

3 leptons are treated independently

test of lepton universality

Γ_Z = 2.4952 ± 0.0023 GeV
Γ_{had} = 1.7444 ± 0.0022 GeV
Γ_e = 0.083985 ± 0.000086 GeV

Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$

*) error of the LEP energy determination: ±1.7 MeV (19 ppm)

http://lepewwg.web.cern.ch/ (Summer 2005)

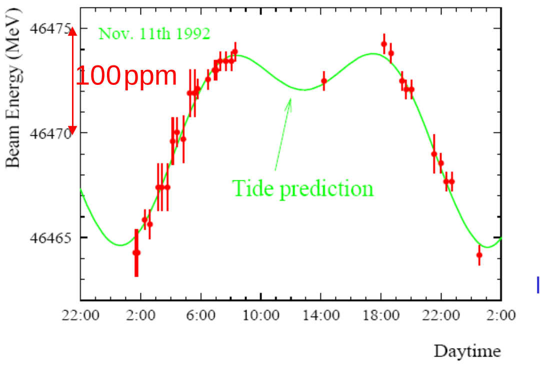
LEP energy calibration: Hunting for ppm effects

Changes of the circumference of the LEP ring changes the energy of the electrons:

- tide effects
- water level in lake Geneva

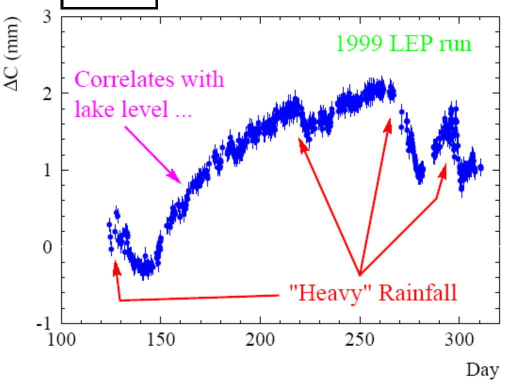
Changes of LEP circumference
ΔC=1…2 mm/27km (4…8x10^{-8})

1992 Effect of moon



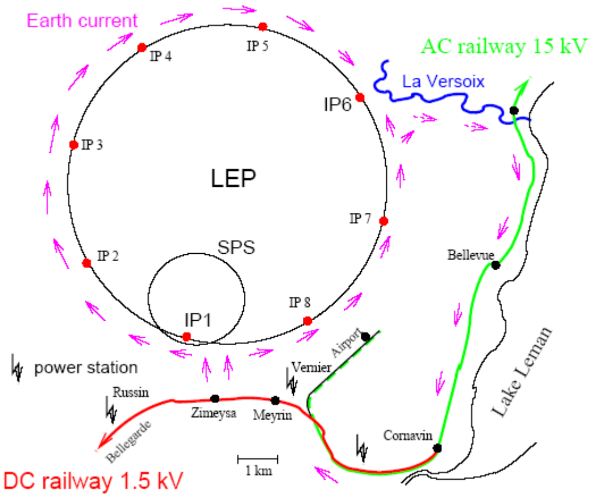
The total strain is 4 x 10^{-8} (ΔC = 1 mm)

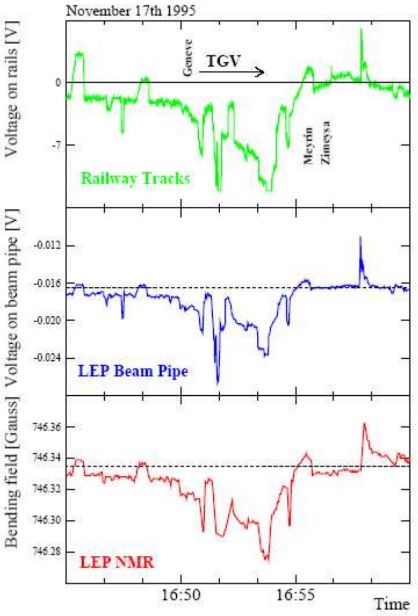
1993 Effect of lake



Effect of the French “Train a Grande Vitesse” (TGV)

Vagabonding currents (~1A) from trains





In conclusion: Measurements at the ppm level are difficult to perform. Many effects must be considered!

2.3 Number of light neutrino generations

In the Standard Model:

$$\Gamma_Z = \Gamma_{\text{had}} + 3\cdot\Gamma_\ell + \underbrace{N_\nu\cdot\Gamma_\nu}_{\text{invisible}:\,\Gamma_{inv}} \rightarrow \left\{ \begin{array}{l} e^+e^- \rightarrow Z \rightarrow \nu_e\bar{\nu}_e \\ e^+e^- \rightarrow Z \rightarrow \nu_\mu\bar{\nu}_\mu \\ e^+e^- \rightarrow Z \rightarrow \nu_\tau\bar{\nu}_\tau \end{array} \right.$$

$$\Gamma_{inv} = 0.4990 \pm 0.0015\,\text{GeV}$$

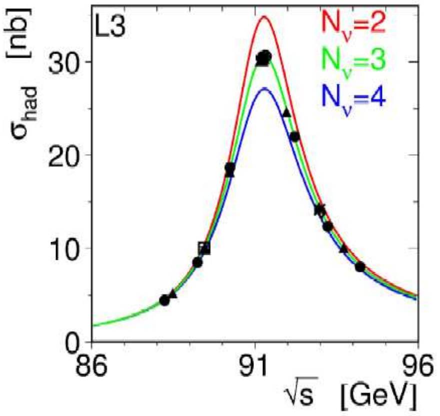
To determine the number of light neutrino generations:

$$N_\nu = \underbrace{\left(\frac{\Gamma_{inv}}{\Gamma_\ell}\right)_{\exp}}_{5.9431\pm0.0163} \cdot \underbrace{\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}}_{=1.991\pm0.001}$$

5.9431±0.0163 =1.991±0.001 (small theo. uncertainties from m_{top} M_{H})

$$\boxed{N_\nu = 2.9840 \pm 0.0082}$$

No room for new physics: $Z \rightarrow$ new



4 Forward-backward asymmetry and fermion couplings to Z

erential cross section

$$\frac{\sigma}{\mathrm{os}\,\theta} = \frac{\pi\alpha^2}{2s}\left[\underbrace{F_\gamma(\cos\theta)}_{\gamma} + \underbrace{F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}_{\gamma/Z\ \text{interference}} + \underbrace{F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}_{Z}\right]$$

Vanishes at $\sqrt{s} \approx M_Z$

$${}_{\gamma}(\cos\theta) = Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$${}_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}\left[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta\right]$$

$${}_{Z}(\cos\theta) = \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[({g_V^e}^2 + {g_A^e}^2)({g_V^\mu}^2 + {g_A^\mu}^2)(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta\right]$$

Forward-backward asymmetry

Forward-backward asymmetry

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta$$

$$\text{with}\quad \begin{cases} A_{FB} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \\ \sigma_{F(B)} = \displaystyle\int_{0\,(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta}\,d\cos\theta \end{cases}$$

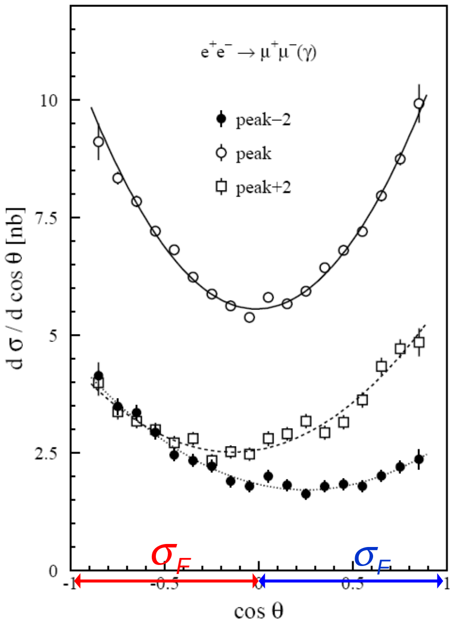
At the Z-pole $\sqrt{s} \approx M_Z$

→ Z contribution is dominant

→ interference vanishes

$$A_{FB} = 3\cdot\frac{g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2}\cdot\frac{g_V^\mu g_A^\mu}{(g_V^\mu)^2 + (g_A^\mu)^2}$$

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



Forward-backward asymmetry

- Away from the resonance A_{FB} is large
  $\rightarrow$ interference term dominates

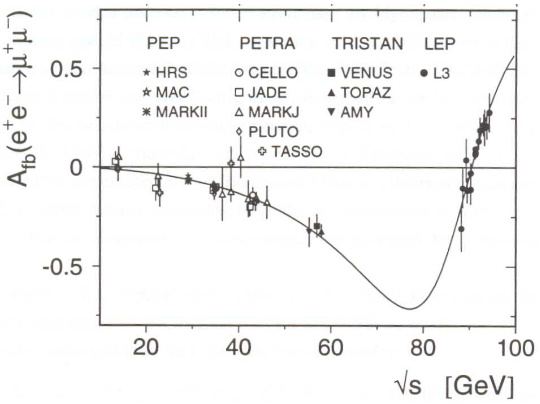
$$A_{FB} \sim g_A^e g_A^f \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}$$

- At the Z pole: Interference = 0

$$A_{FB} \sim g_A^e g_V^e g_A^f g_V^f$$

$\rightarrow$ very small because g_V^l small in SM

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



Fermion couplings

- Away from the resonance A_{FB} is large
  $\rightarrow$ interference term dominates

$$A_{FB} \sim g_A^e g_A^f \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}$$

- At the Z pole: Interference = 0

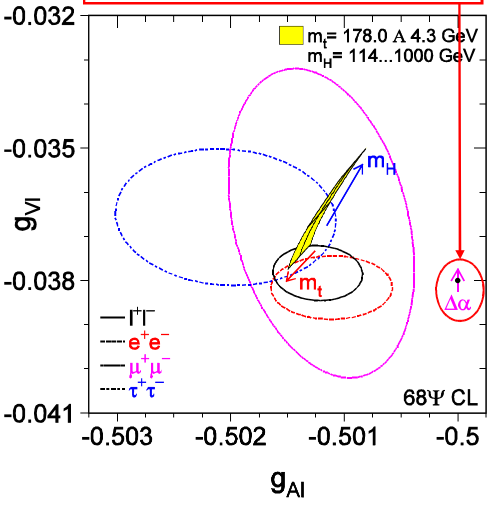
$$A_{FB} \sim g_A^e g_V^e g_A^f g_V^f$$

$\rightarrow$ very small because g_V^l small in SM

Asymmetries together with cross sections allow the determination of the fermion couplings g_A and g_V

Lowest order SM prediction:

$$g_V = T_3 - 2q\sin^2\theta_W \quad g_A = T_3$$



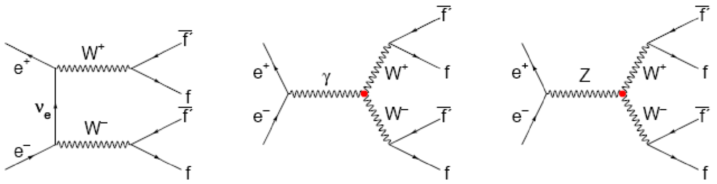
Confirms lepton universality

Higher order corrections seen

. Precision tests of the W sector (LEP2 and Tevatron)

~10K WW events / experiment

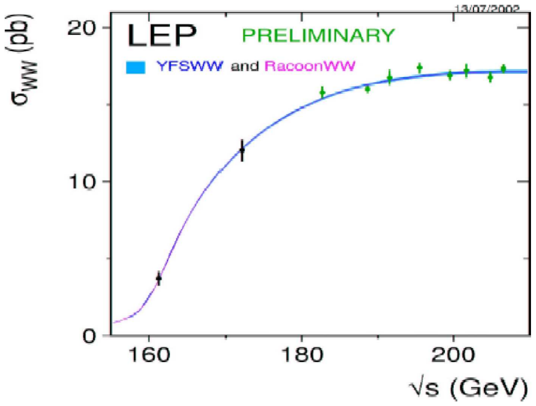
$e^+e^- \rightarrow WW \rightarrow f\bar{f}f\bar{f}$



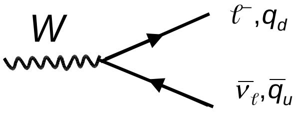
hreshold behavior of the
ross section (phase space)
r ee→WW production:

hase space factor = f(M_W, $\sqrt{s}$):

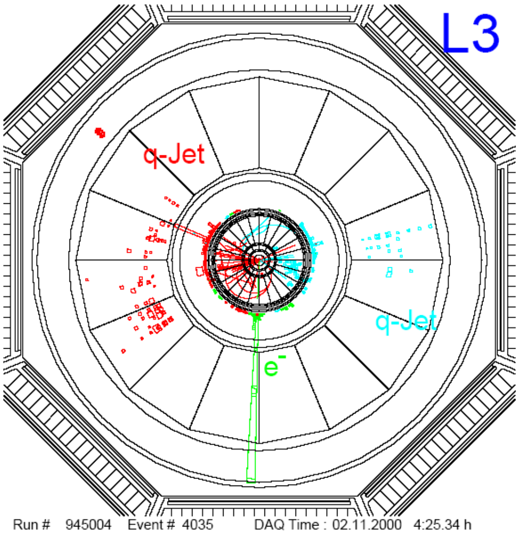
Allows determination of M_W

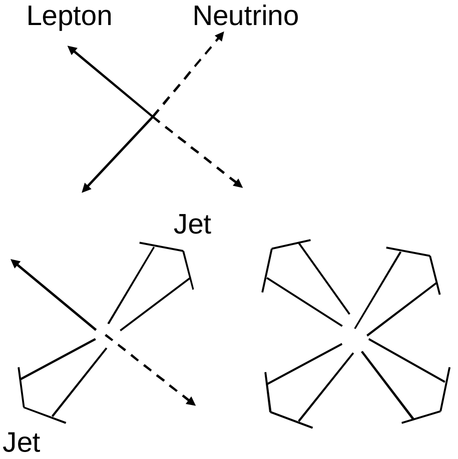


W decays

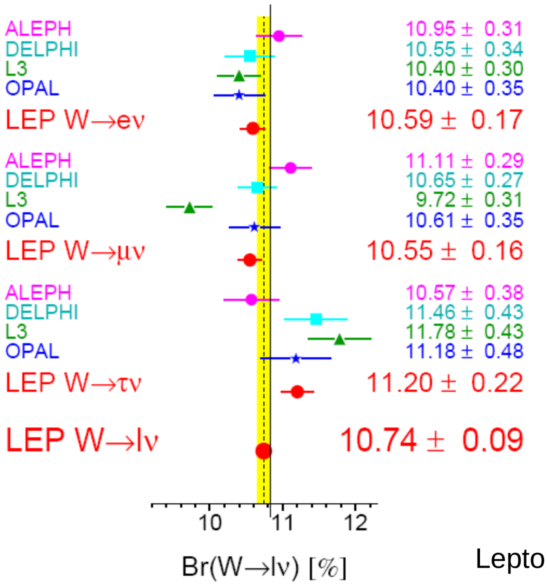


$$WW \rightarrow \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$





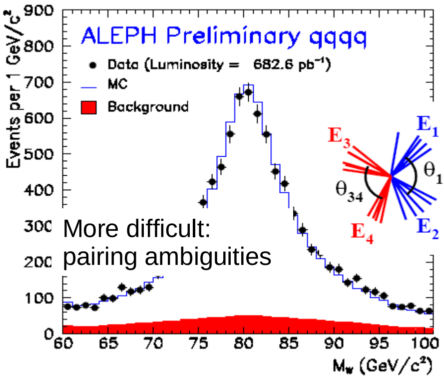
W branching ratios



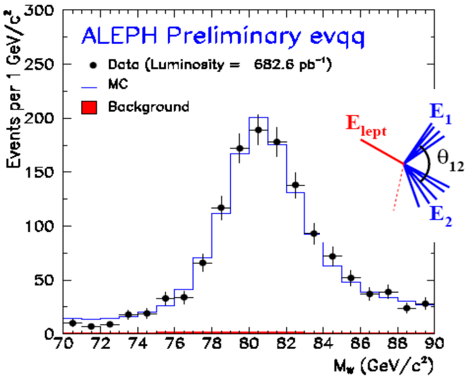
$Br(W \to q\overline{q}) = (67.77 \pm 0.28)\%$

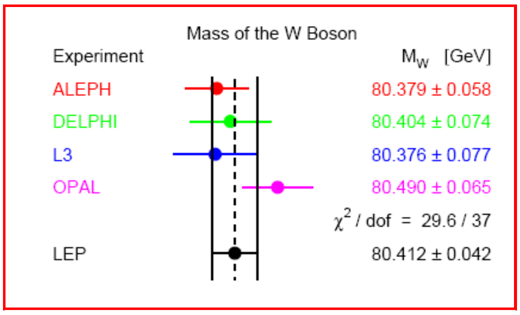
Lepton universality tested to 2%

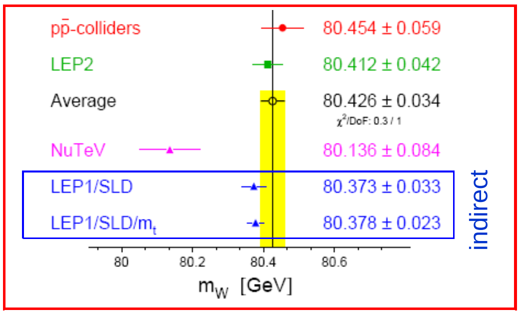
Invariant *W* mass recontruction



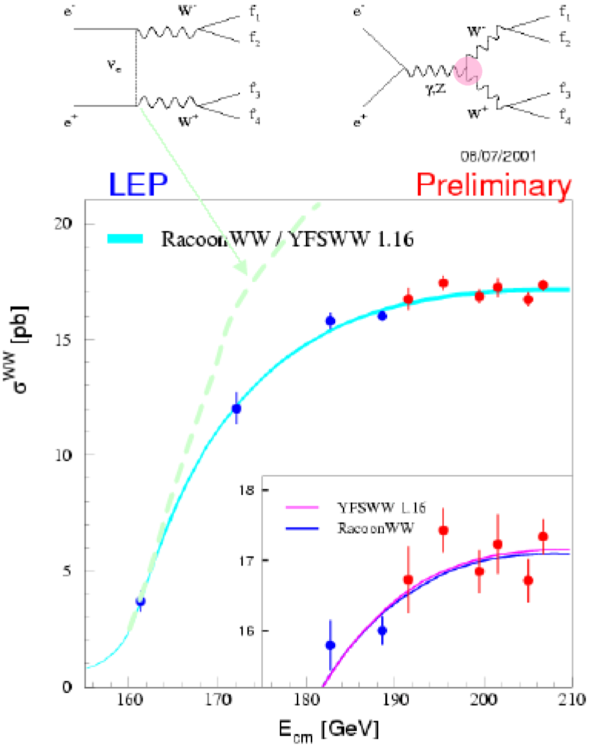
More difficult:
pairing ambiguities







Effect of triple gauge coupling



Data confirms the existence of the γ/ZWW triple gauge boson vertex

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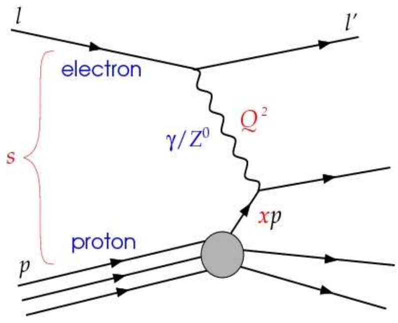
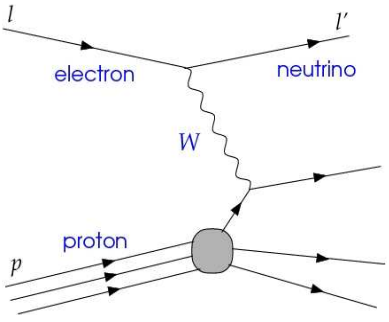
4. Electro-weak unification, as visible at HERA

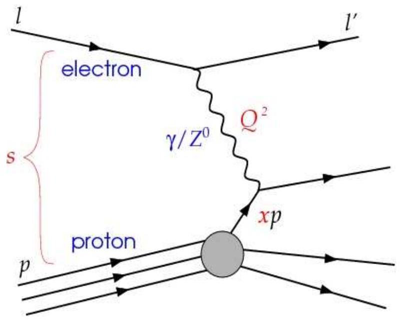


$$\frac{d\sigma_{NC}}{dQ^2} \sim \underbrace{\frac{1}{(Q^2)^2}}_{\gamma} + \dots \underbrace{\frac{1}{Q^2(Q^2+M_Z^2)}}_{\gamma/Z} + \dots \underbrace{\frac{1}{(Q^2+M_Z^2)^2}}_{Z}$$

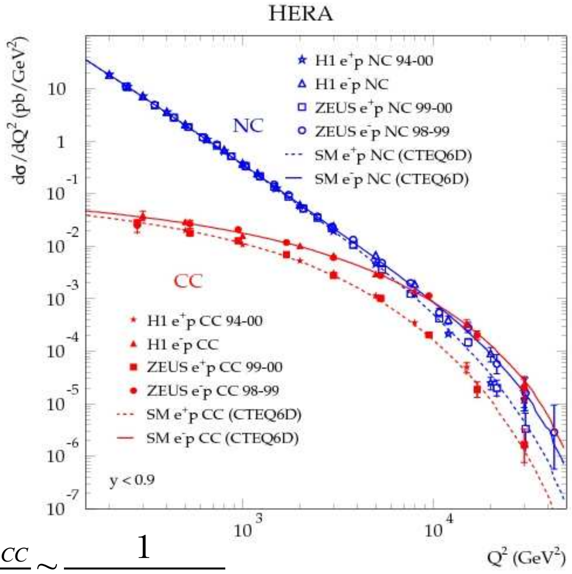


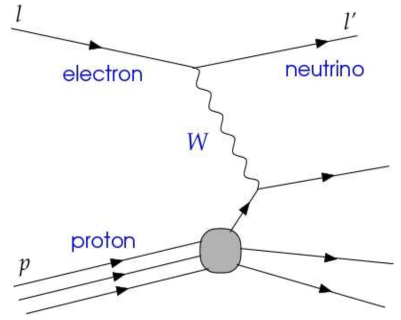
$$\frac{d\sigma_{CC}}{dQ^2} \sim \frac{1}{(Q^2+M_W^2)^2}$$

4. Electro-weak unification, as visible at HERA



$$\frac{d\sigma_{NC}}{dQ^2} \sim \frac{1}{(Q^2)^2} + \dots \frac{1}{Q^2(Q^2+M_Z^2)} + \dots \frac{1}{(Q^2+M_Z^2)^2}$$





$$\frac{d\sigma_{CC}}{dQ^2} \sim \frac{1}{(Q^2+M_W^2)^2}$$

5. Higher order corrections and the Higgs mass

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

Including radiative corrections

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\text{eff}} = (1 + \Delta\kappa)\sin^2\theta_W$$

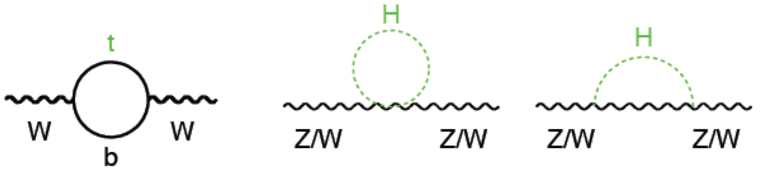
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

Lowest order SM predictions

with : $\Delta\alpha = \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{top}} + \Delta\alpha_{\text{had}}^{(5)}$

$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t{}^2, \log(m_H), \dots\right)$$



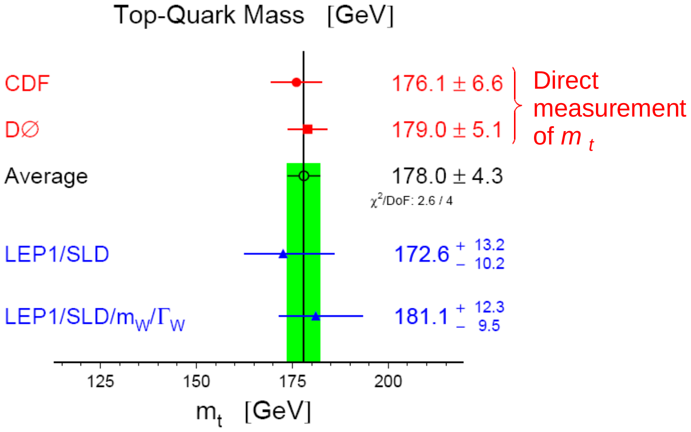
Top mass prediction from radiative corrections

The measurement of the radiative corrections:

$$\sin^2\theta_{eff} \equiv \frac{1}{4}(1 - \bar{g}_V / \bar{g}_A)$$

$$\sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_w$$

allows an indirect determination of the unknown parameters m_t and $M_{H.}$

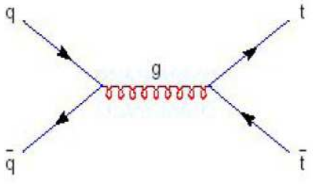


Prediction of m_t by LEP before the discovery of the top at TEVATRON.

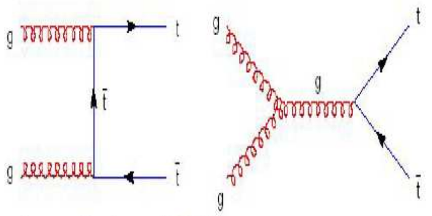
Good agreement between the indirect prediction of m_t and the value obtained in direct measurements confirm the radiative corrections of the SM

Observation of the top quark at TEVATRON (1995)

$p\bar{p}$ @ 2 TeV

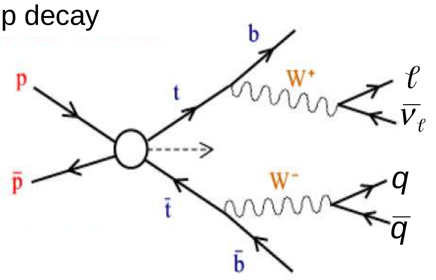


$q\bar{q}$ annihilation (85%)



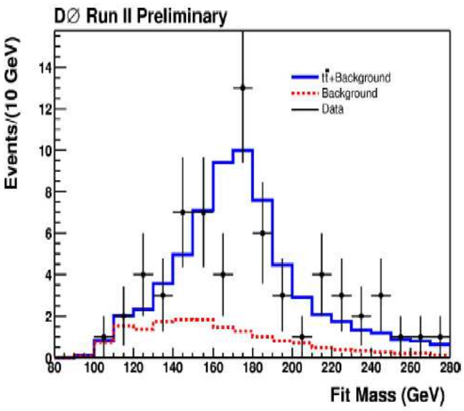
gluon fusion (15%)

Top decay

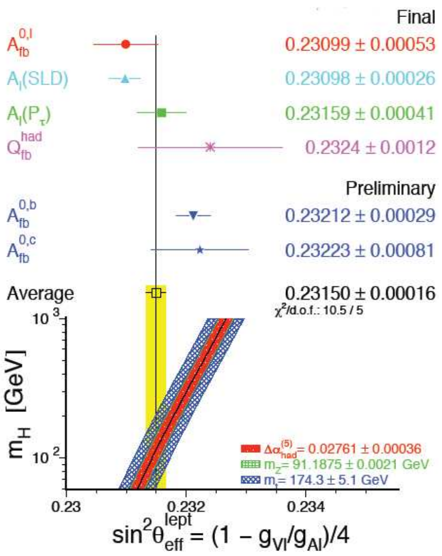


Channel used for mass reconstruction:

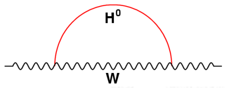
$$m_t = m_{inv}(b - jet, W \to jet + jet)$$

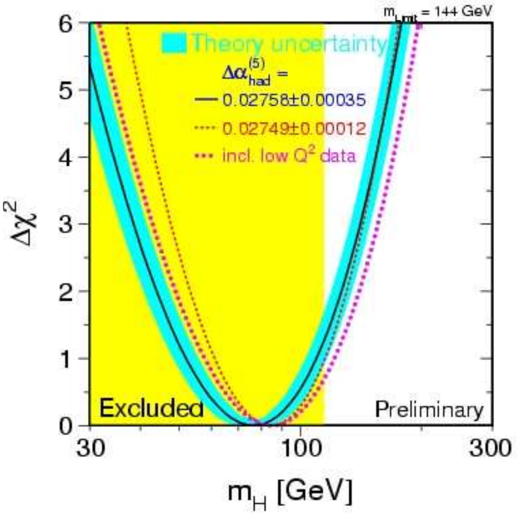


Higgs mass prediction from radiative corrections



Status end of 2007





M_H > 114 GeV (from direct searches)

M_H < 144 GeV (from EW fits)

Awaiting the discovery
of the Higgs at the LHC