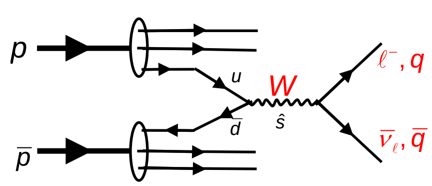
VIII. Experimental tests of the Standard Model

1. Discovery of W and Z boson
2. Precision tests of the Z sector
3. Precision test of the W sector
4. Radiative corrections and prediction of the Higgs mass
5. Higgs searches at the LHC

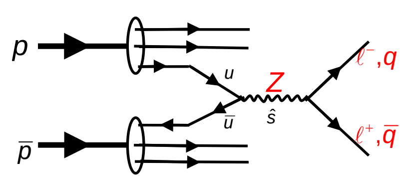
1. Discovery of the W and Z boson

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

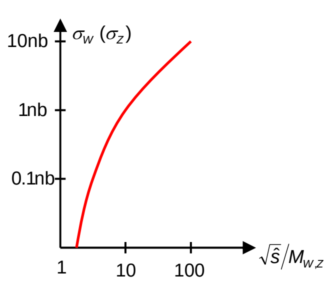
1.1 Boson production in pp interactions



$p\bar{p} \to W \to \ell \bar{\nu}_\ell + X$



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



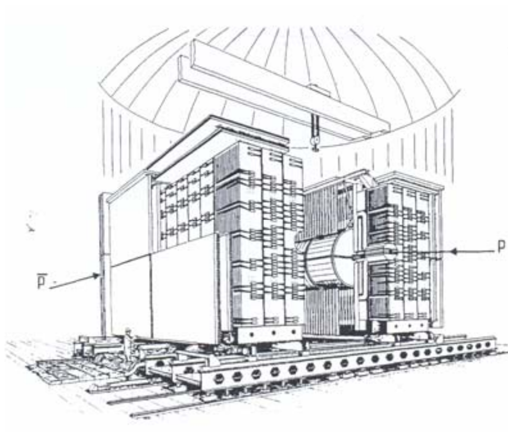
Similar to Drell-Yan: (photon instead of W)

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

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

→ Cross section is small !

1.2 UA-1 Detector



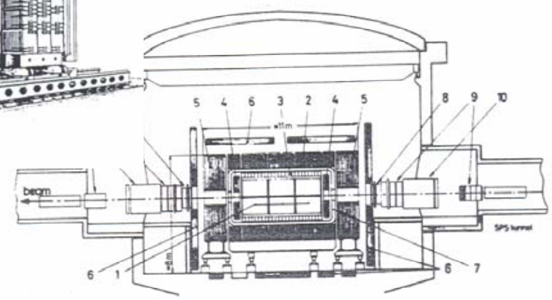
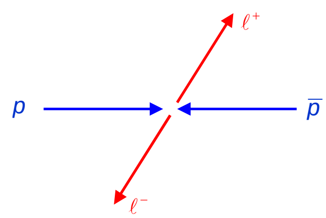


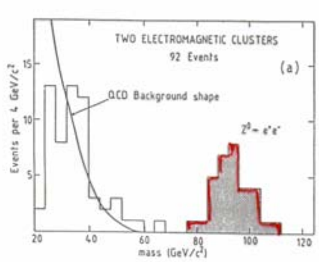
Fig.8.16: Seitenansicht des UA1-Detektors zum Nachweis von Proton-Antiproton-Wechselwirkungen bei 540 GeV Schwerpunktsenergie: 1. Zentraldetektor, 2. und 5. Hadron-Kalorimeter, 3. und 4. Elektron-Photon-Schauerzähler, 6. Myon-Detektor, 7. Spule für Dipolfeld, 8. und 9. Kleinwinkeldetektor mit Kammern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

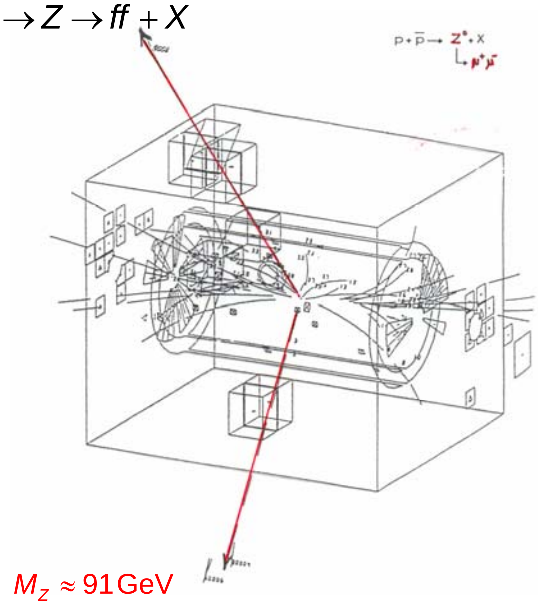
1.3 Event signature: $p\bar{p} \to Z \to f\bar{f} + X$



High-energy lepton pair:

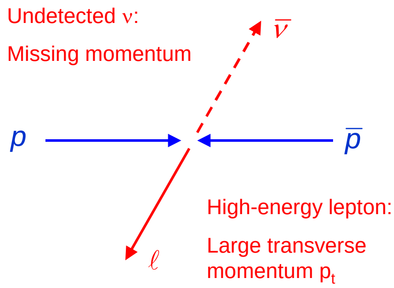
$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





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

1.4 Event signature: $p\bar{p} \rightarrow W \rightarrow \ell \bar{\nu}_\ell + X$



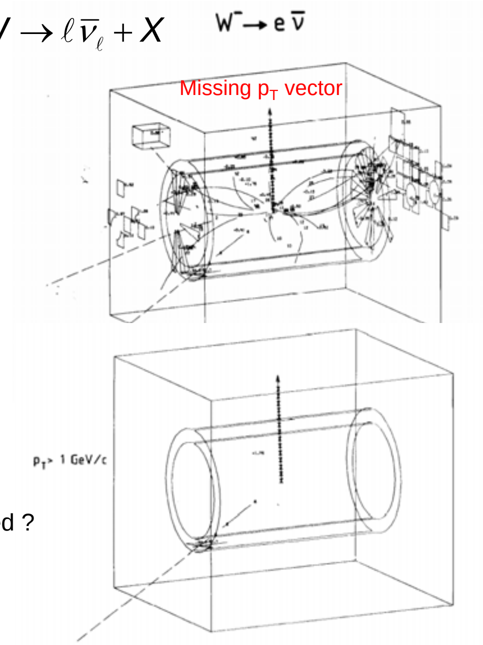
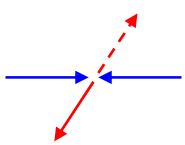


Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_t>1 GeV are shown.

How can the W mass be reconstructed ?

W mass measurement



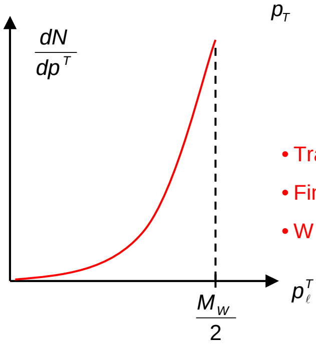
In the W rest frame:

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

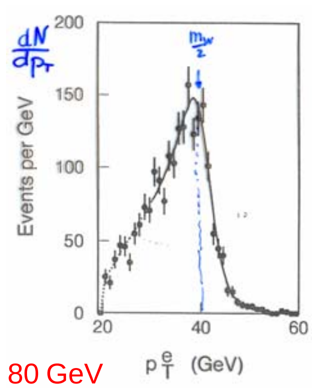
In the lab system:

- 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
- Finitte W decay width
- W decay not isotrop



$M_W \approx 80$ GeV

The Nobel Prize in Physics 1984

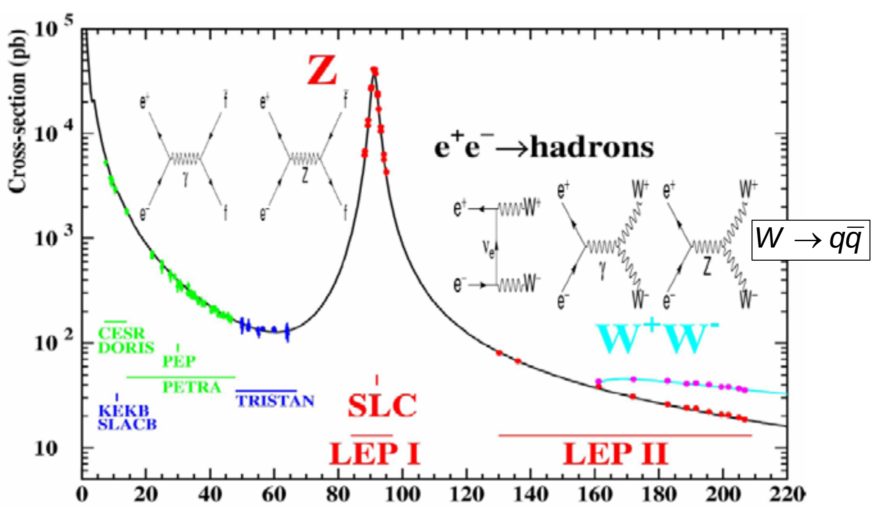
Carlo Rubbia	Simon van der Meer

"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



Precision tests of the Z sector

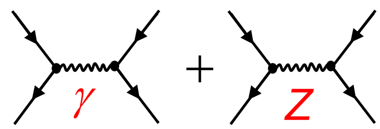
Tests of the W sector

2. Precision tests of the Z sector

(LEP and SLC)

~4.5M Z decays / experiment

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

$|M|^2 = \Big|$  $\Big|^2$

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

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

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

Z propagator considering a finite Z width

One finds for the differential cross section:

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

γ — γ/Z interference — Z

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

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

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

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[(g_V^{e2}+g_A^{e2})(g_V^{\mu2}+g_A^{\mu2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta\right]$$

Forward-backward asymmetry

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta \quad \text{with} \quad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

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

$$\sigma_{tot} \approx \sigma_Z = \frac{4\pi}{3s} \frac{\alpha^2}{16 \sin^4 \theta_w \cos^4 \theta_w} \cdot \left[g_V^{e2} + g_A^{e2} \right] \left[g_V^{\nu 2} + g_A^{\mu 2} \right] \cdot \underbrace{\frac{s^2}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2}}$$

"Massive propagator" → 1 for $M_Z \to 0$

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

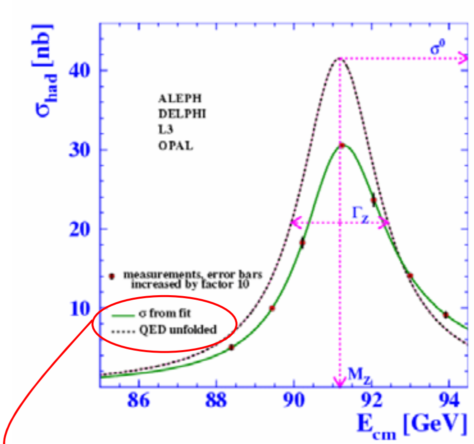
With partial and total widths:

$$\Gamma_f = \frac{\alpha M_Z}{4 \sin^2 \theta_w \cos^2 \theta_w} \cdot \left[g_V^{f\,2} + g_A^{f\,2} \right]$$

$$\Gamma_Z = \sum_i \Gamma_i$$

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

2.2 Measurement of the Z lineshape



Resonance curve:

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

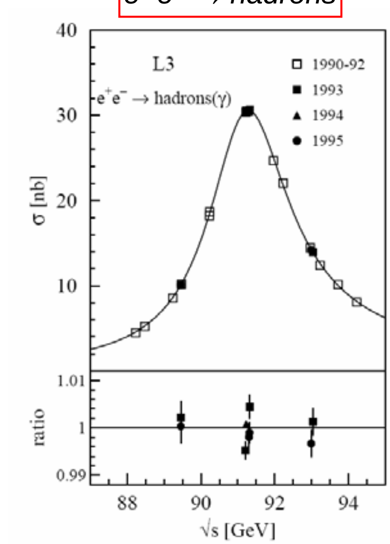
Peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

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

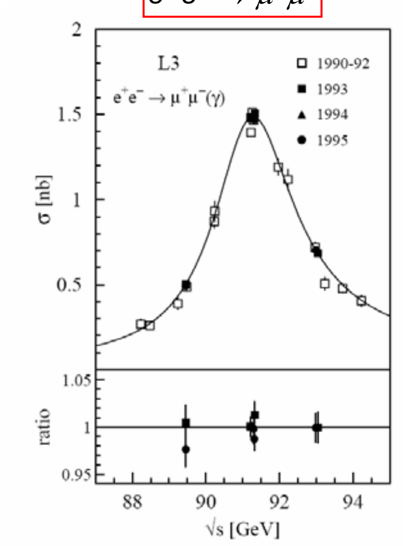
Initial state Bremsstrahlung corrections

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

$e^+e^- \to hadrons$

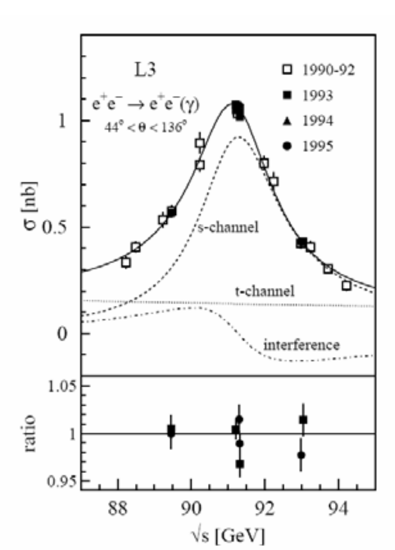


$e^+e^- \to \mu^+\mu^-$

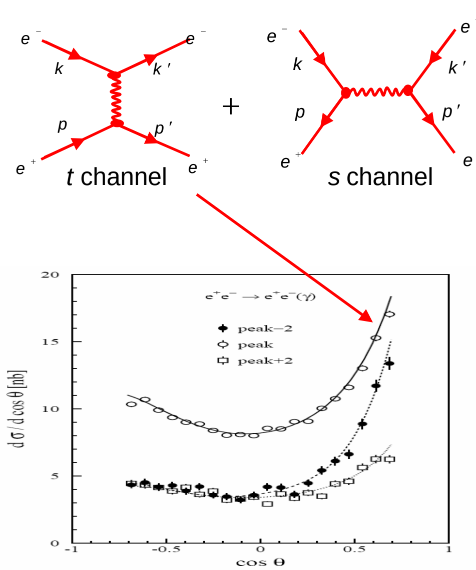


Resonance looks the same, independent of final state: Propagator the same

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



t channel contribution $\to$ forward peak



Z line shape parameters (LEP average)

M_Z	= 91.1876 ± 0.0021 GeV		±23 ppm (*)
Γ_Z	= 2.4952 ± 0.0023 GeV	±0.09 %	3 leptons are treated independently
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		
Γ_Z	= 2.4952 ± 0.0023 GeV		Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
Γ_{had}	= 1.7444 ± 0.0022 GeV		
Γ_e	= 0.083985 ± 0.000086 GeV		

test of lepton universality

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

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

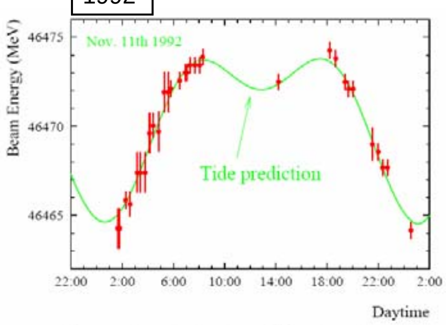
LEP energy calibration: Hunting for ppm effects

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

- tide effects
- water level in lake Geneva

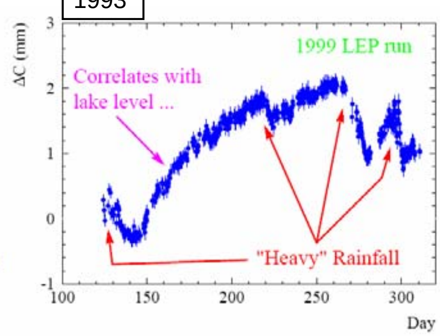
→ Changes of LEP circumference ΔC=1…2 mm/27km (4…8x10^{-8})

1992



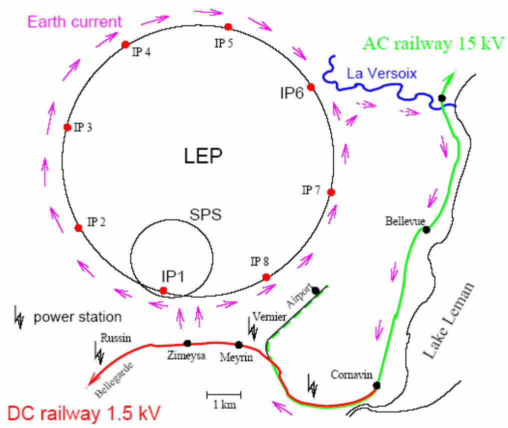
The total strain is 4 x 10^{-8} (ΔC = 1 mm)

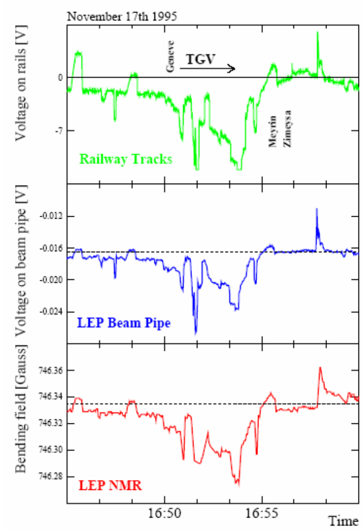
1993



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:

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

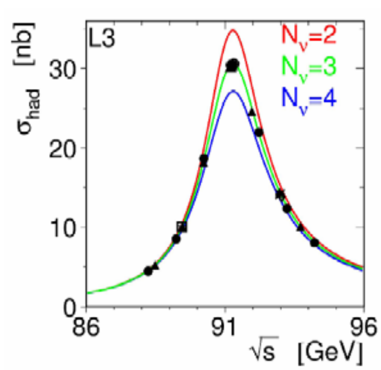
$$\Gamma_{inv} = 0.4990 \pm 0.0015\ \text{GeV}$$

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)

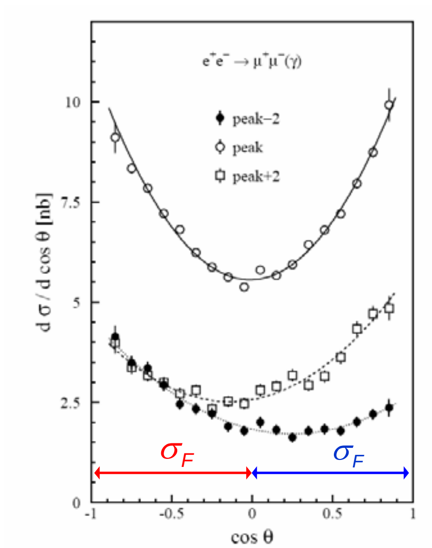
N_ν = 2.9840 ± 0.0082



No room for new physics: Z→new

2.4 Forward-backward asymmetry and fermion couplings to Z

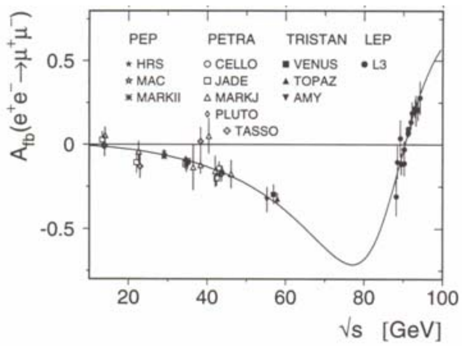
$$e^+ e^- \rightarrow Z \rightarrow \mu^+ \mu^-$$



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

with $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

$$\sigma_{F(B)} = \int_{0\,(-1)}^{1\,(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$



Fermion couplings

Lowest order SM prediction:
$g_V = T_3 - 2q\sin^2\theta_W \quad g_A = T_3$

Forward-backward asymmetry

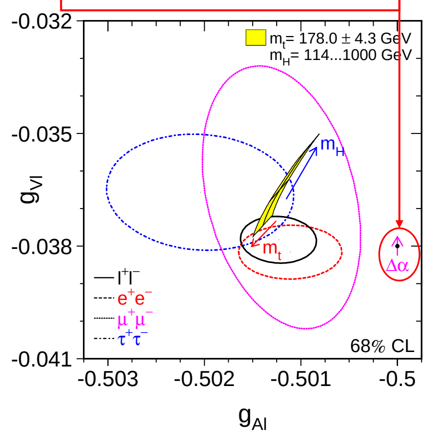
- Away from the resonance A_{FB} large
  → interference term dominates

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

- At the Z pole: Interference = 0

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

→ 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

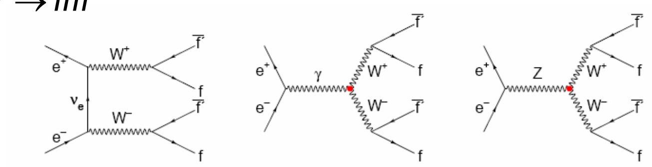
Confirms lepton universality

Higher order corrections seen

3. Precision tests of the W sector (LEP and Tevatron)

↑ ~10K WW events / experiment

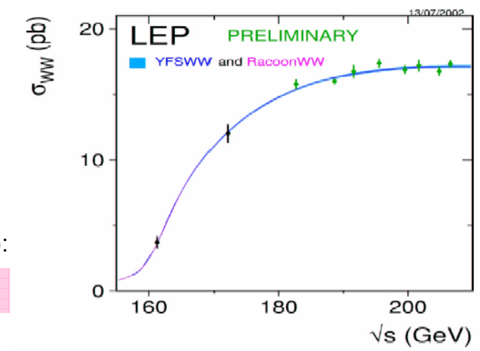
$e^+e^- \rightarrow WW \rightarrow f\bar{f}f\bar{f}$



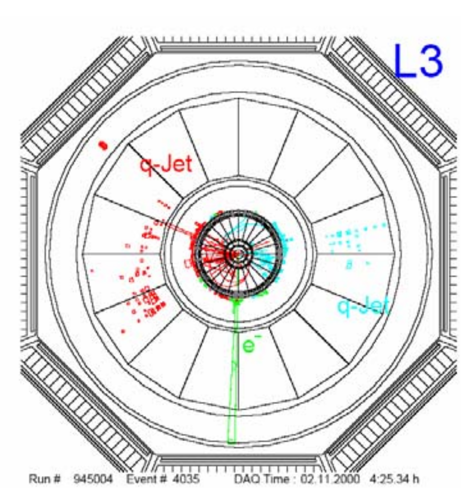
Threshold behavior of the cross section (phase space) for ee→WW production:

Phase space factor = f(M_W, √s):

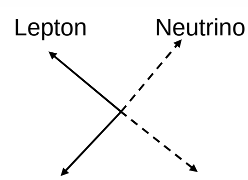
→ Allows determination of M_W

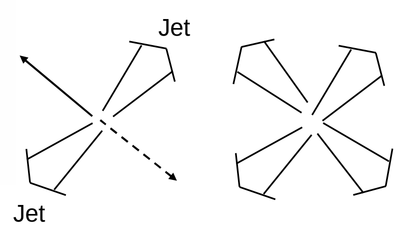


W decays

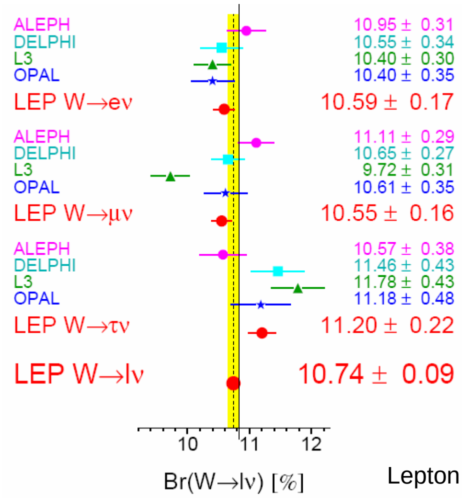


WW → { qqℓν 44%, qqqq 45%, ℓνℓν 11% }





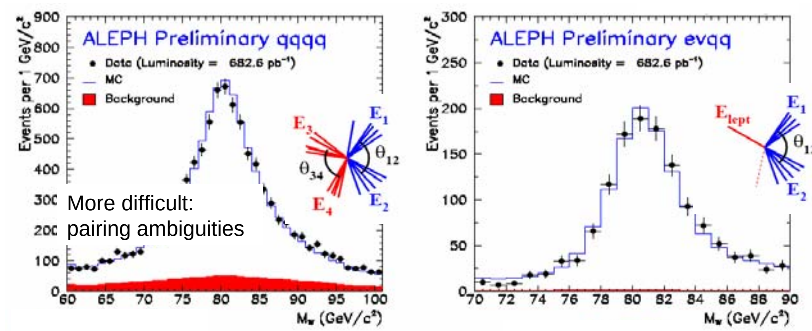
W branching ratios



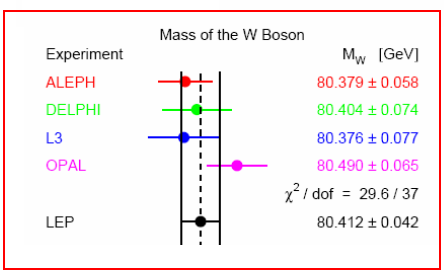
$Br(W \to q\bar{q}) = (67.77 \pm 0.28)\%$

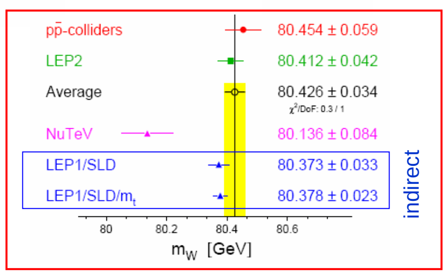
Lepton universality tested to 2%

Invariant W mass recontruction



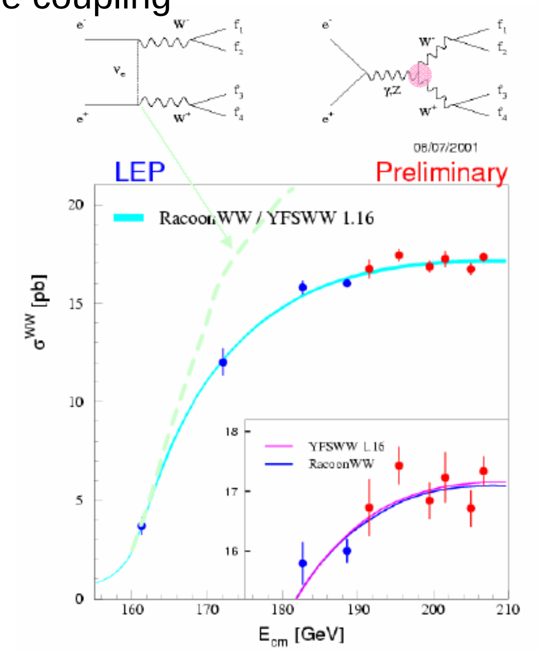
More difficult:
pairing ambiguities





Effect of triple gauge coupling

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



4. Higher order corrections and the Higgs mass

Lowest order SM predictions

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

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

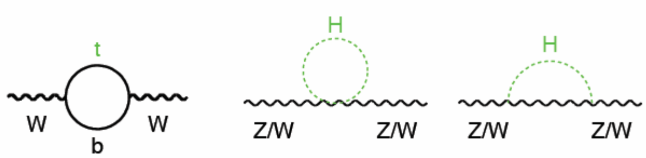
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

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

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

Including radiative corrections

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



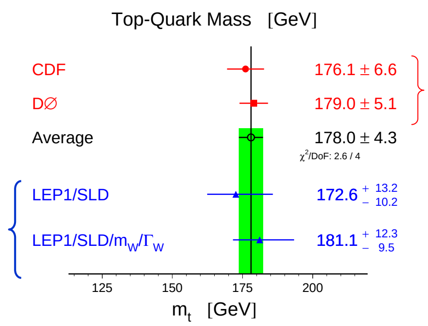
Top mass prediction from radiative corrections

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 the indirect determination of the unknown parameters m_t and M_H.



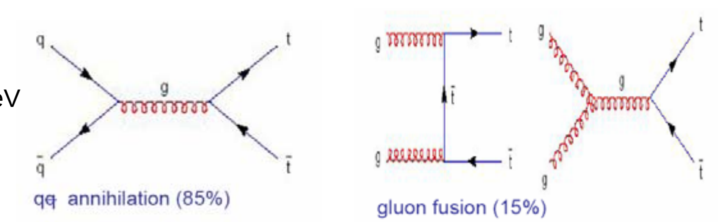
Direct measurement of m_t

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

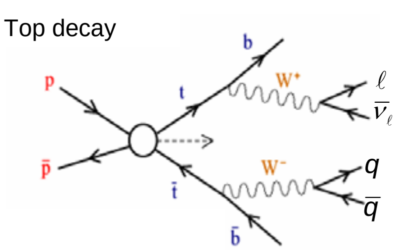
Good agreement between the indirect prediction of m_t and the value obtained in direct measurements confirm the radiative corrections of the SM

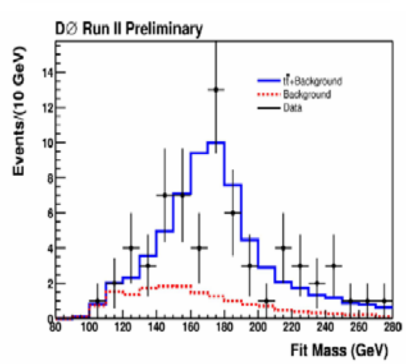
Observation of the top quark at TEVATRON (1995)

$p\bar{p}$ @ 2 TeV



Top decay

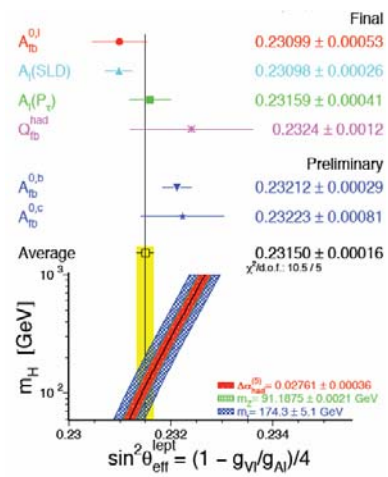


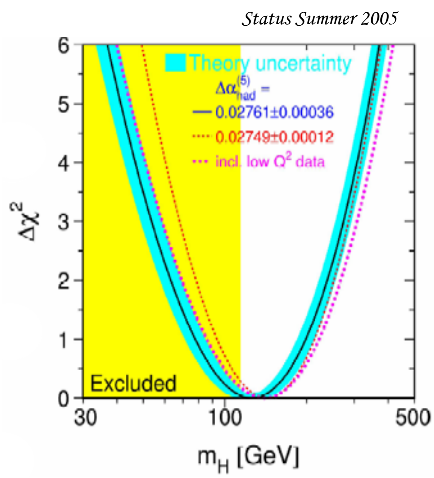


Channel used for mass reconstruction:

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

Higgs mass prediction from radiative corrections





Awaiting the discovery of the Higss at LHC

M_H > 114 GeV (from direct searches)

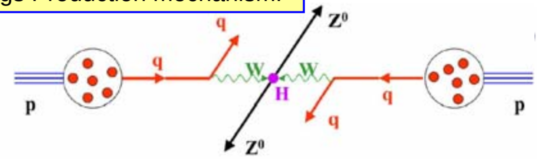
M_H < 300 GeV @ 95 % C.L.

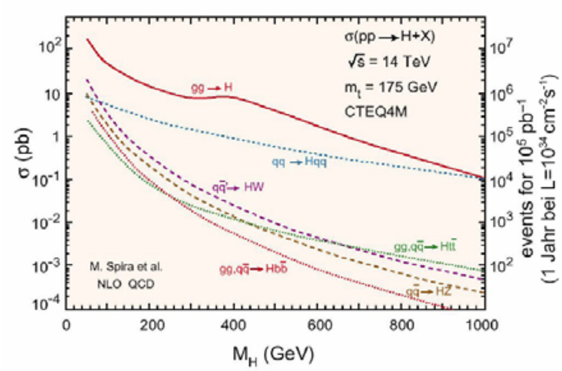
5. Higgs searches at the LHC (pp collider @ 14 TeV)

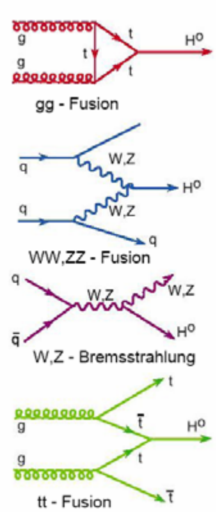
Only missing ingredient of the Standard Model: Higgs-Boson

→ Huge effort to find it

Higgs Production mechanism:







Higgs decay channels

At LEP: Searches were done using

$H \rightarrow b\bar{b}$ $M_H > 114$ GeV

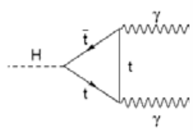
("golden" Higgs decay channel at LEP energies because of large b mass →too much background at LHC)

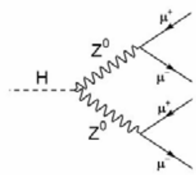
At LHC:

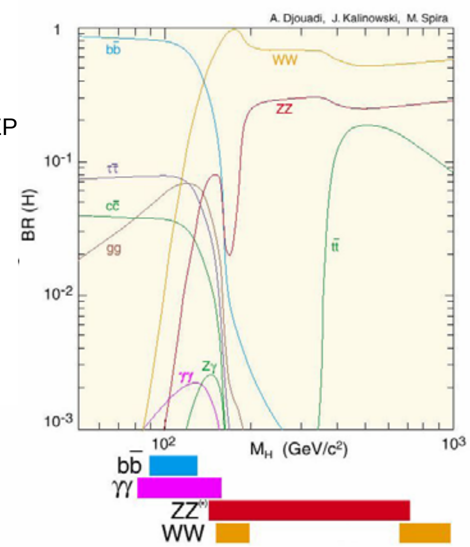
- $m_H < 150$ GeV: $H \rightarrow \gamma\gamma$
- 150 GeV < m_H < 1 TeV

$H \rightarrow ZZ^{(*)}$

$H \rightarrow W^+W^-$

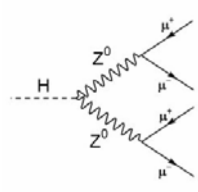


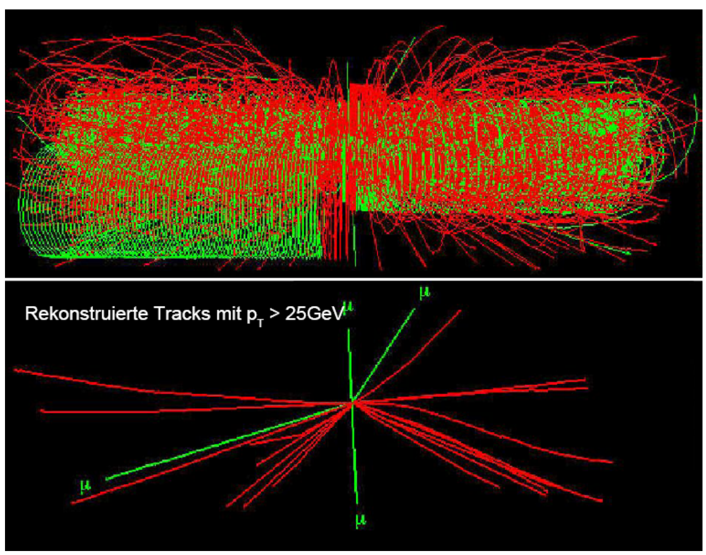




Simulated H→ZZ→4μ event at LHC

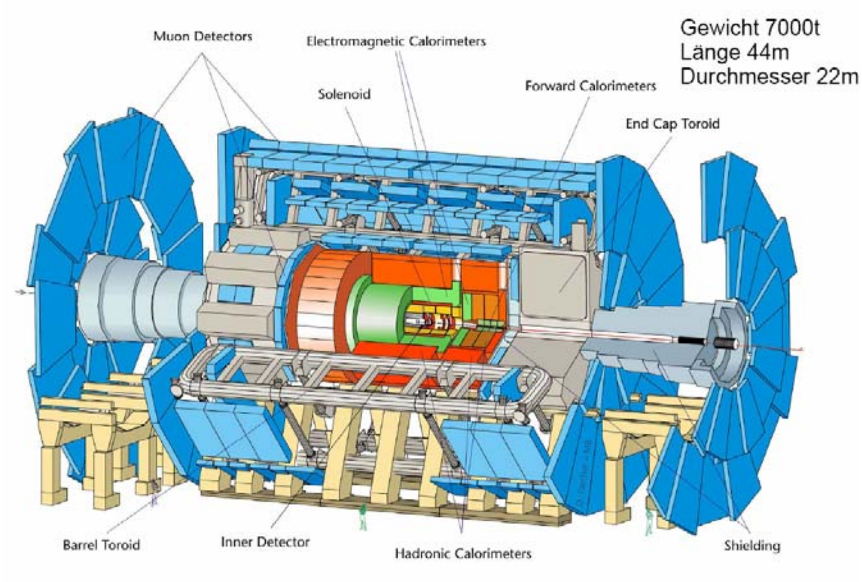
- 20 pp interaction / event
- Large number of particles



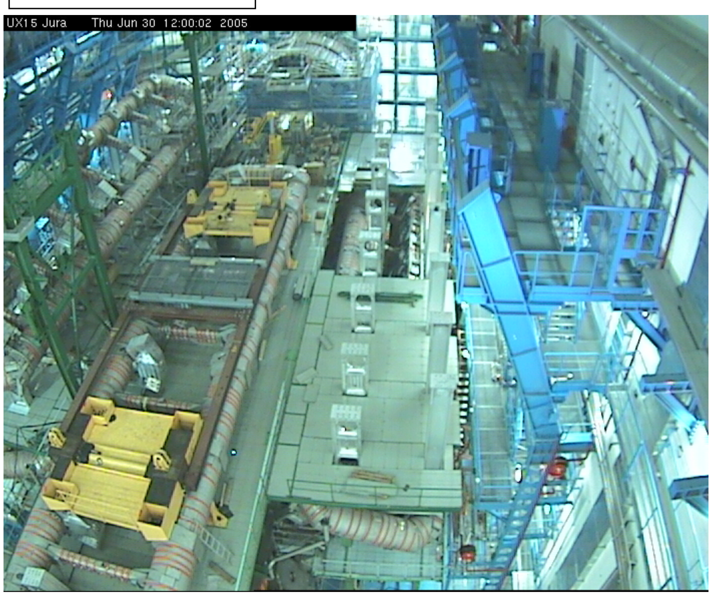


To trigger and to reconstruct these events is an exp. challenge.

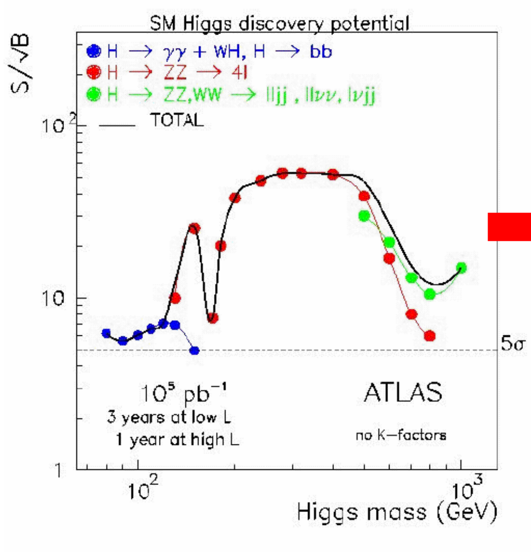
The ATLAS Experiment at LHC



ATLAS Construction



Higgs discovery potential (ATLAS experiment)



If the Higgs Boson exists, it will be found at LHC

LHC start is foresen for the end of 2007.