VI. 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

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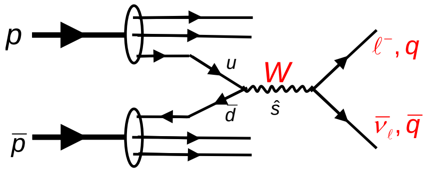
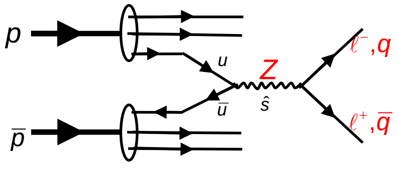
1. Discovery of the W and Z boson

1983 at CERN Sp$\bar{\text{p}}$S accelerator,
√s≈540 GeV, UA-1/2 experiments

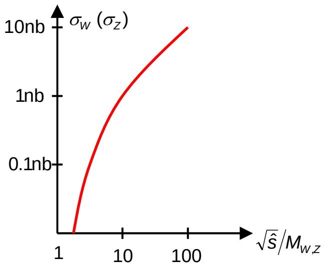
1.1 Boson production in p$\bar{\text{p}}$ interactions



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



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



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

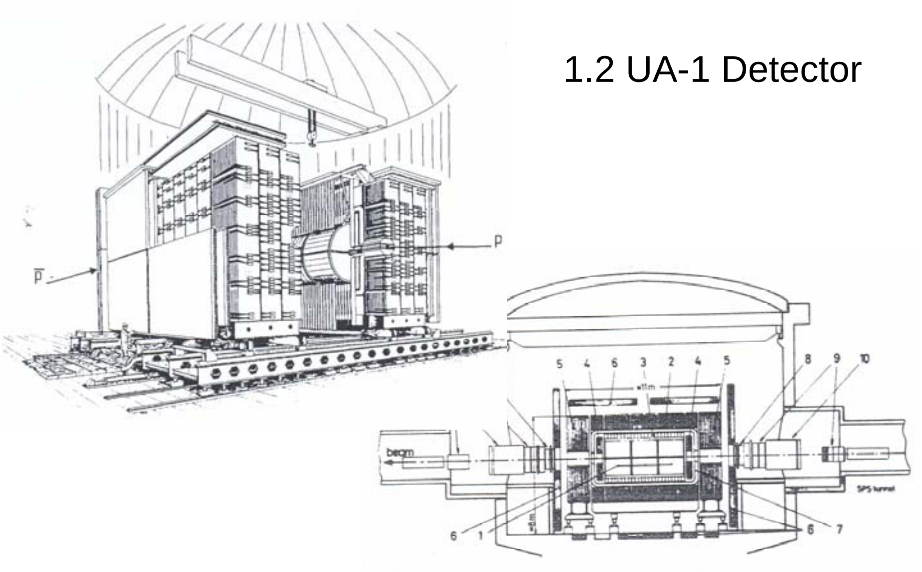
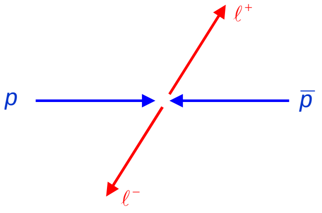


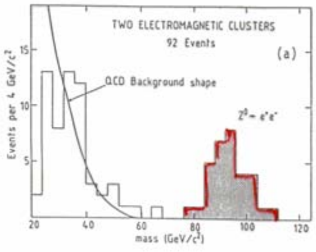
Fig.8.16: Seitenansicht des UA1-Detektors zum Nachweis von Proton-Antiproton-Wechselwirkungen bei 540 GeV Schwerpunktsenergie: 1. Zentraldetektor, 2. und 5. Hadron-Kalorimeter, 3. und 4. Elektron-Photon-Schauerzähler, 6. Myon-Detektor, 7. Spule für Dipolfeld, 8. und 9. Kleinwinkeldetektor mit Kammern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

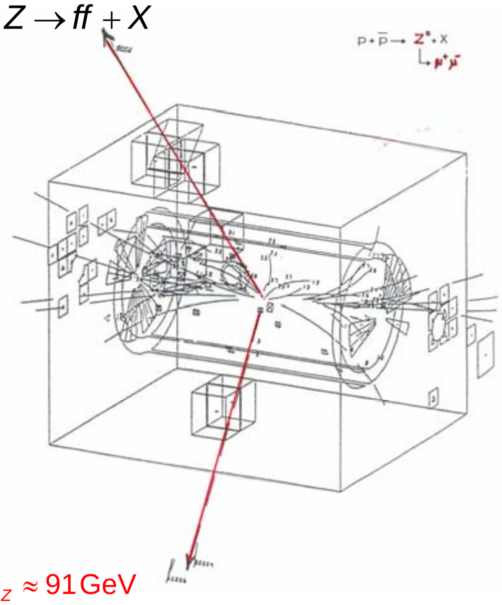
1.3 Event signature: $p\bar{p} \to Z \to f\bar{f} + X$



High-energy lepton pair:

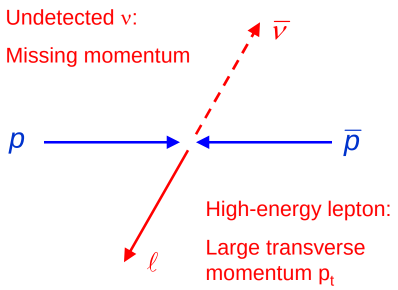
$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





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

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



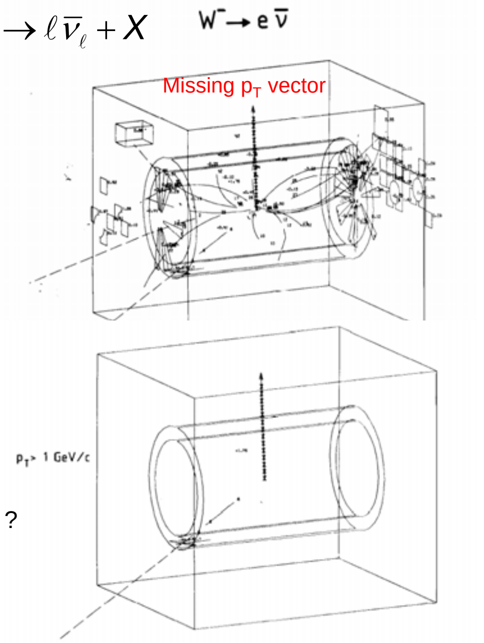
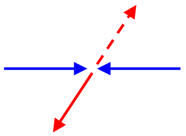


Fig. *16b*. The same as picture (a), except that now only particles with $p_T > 1$ GeV/c and calorimeters with $E_t > 1$ GeV are shown.

How can the W mass be reconstructed ?

W mass measurement



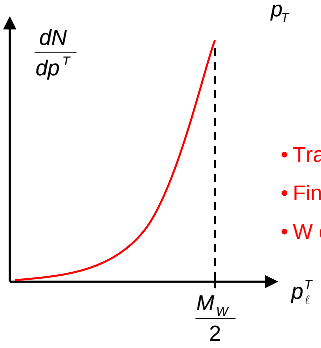
In the W rest frame:

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

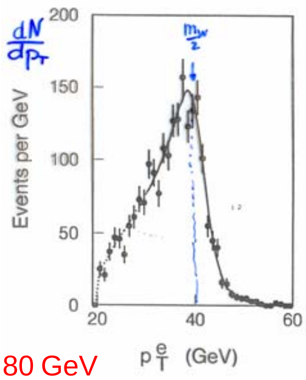
In the lab system:

- 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 not isotropic

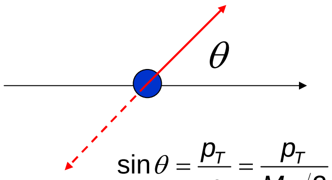


$M_W \approx 80$ GeV

Jacobian Peak

Assume isotropic decay of the W boson (not really correct) in its CM system:

$$\frac{dN}{d\cos\theta} = const.$$



Simplification: W boson has spin=1
→ decay is not isotropic!

$$\sin\theta = \frac{p_T}{p} = \frac{p_T}{M_w/2}$$

$$1-\cos^2\theta = \left(\frac{p_T}{M_w/2}\right)^2$$

$$d\cos\theta \sim \frac{p_T}{(M_w/2)^2}\,\frac{dp_T}{\cos\theta}$$

$$\frac{dN}{d\cos\theta} = \frac{dN}{dp_T} \sim \frac{2p_T}{M_W}\cdot\left(\frac{M_W^2}{4} - p_T^2\right)^{-1/2}$$

The Nobel Prize in Physics 1984

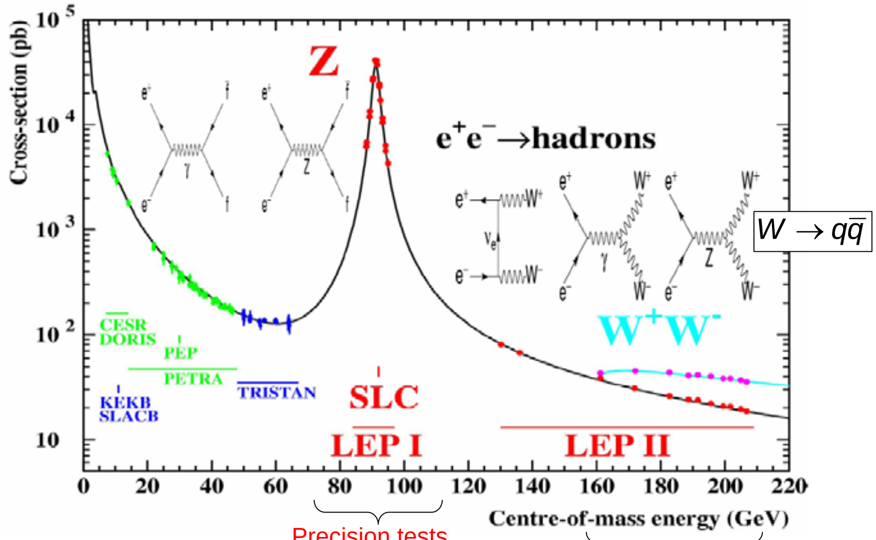
Carlo Rubbia	**Simon van der Meer**

"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

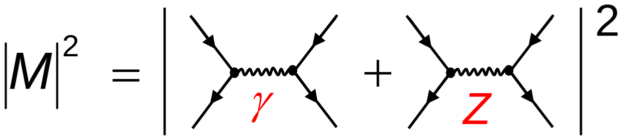
Tests of the W sector

2. Precision tests of the Z sector

(LEP and SLC)

~4.5M Z decays / experiment

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



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

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

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

Z propagator considering a
finite Z width at resonance

One finds for the differential cross section:

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

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

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

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

Forward-backward asymmetry

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta \qquad \text{with} \begin{cases} A_{FB} = \dfrac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} \\ \sigma_{F(B)} = \displaystyle\int_{0\,(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta}d\cos\theta \end{cases}$$

At the Z-pole √s≈M_Z → Z contribution is dominant
→ interference vanishes

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

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

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

→ interference vanishes

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

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

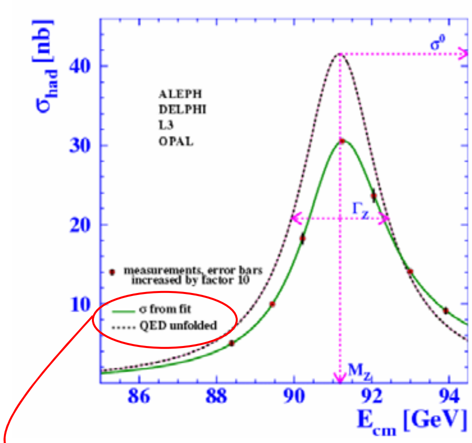
With partial and total widths:

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

$$\Gamma_Z=\sum_i\Gamma_i$$

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

2.2 Measurement of the Z lineshape



Z Resonance curve:

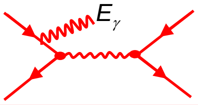
$$\sigma(s)=12\pi\frac{\Gamma_e\Gamma_\mu}{M_Z^2}\cdot\frac{s}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

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

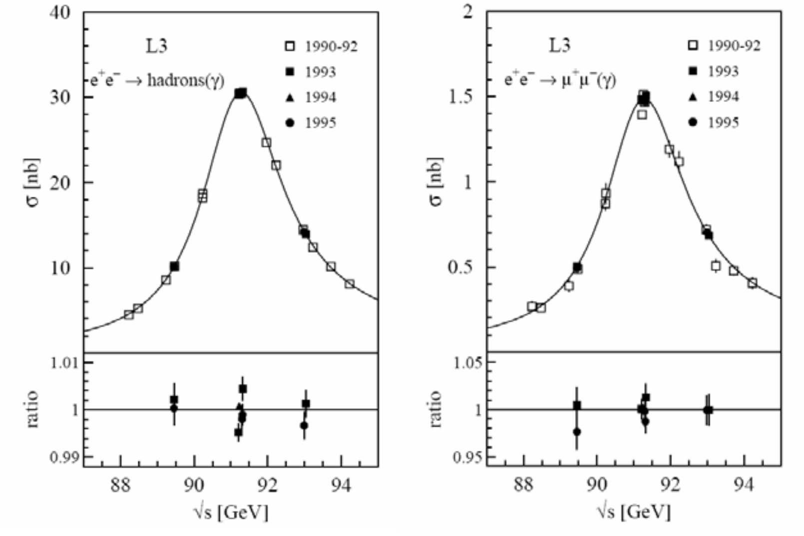
- Resonance position → M_Z
- Height → $\Gamma_e\Gamma_\mu$
- Width → Γ_Z

Initial state Bremsstrahlung corrections

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



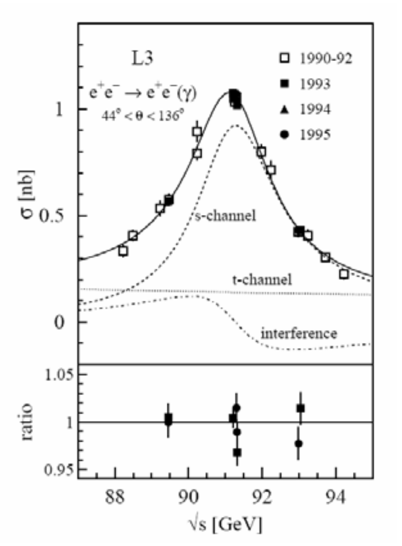
$e^+ e^- \to hadrons$ $e^+ e^- \to \mu^+ \mu^-$

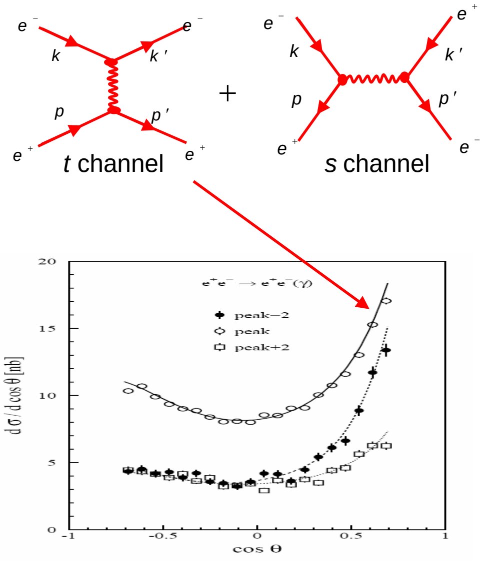


Resonance shape is the same, independent of final state: Propagator the same!

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

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)

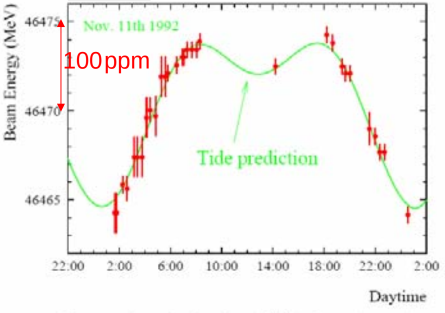
LEP energy calibration: Hunting for ppm effects

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

- tide effects
- water level in lake Geneva

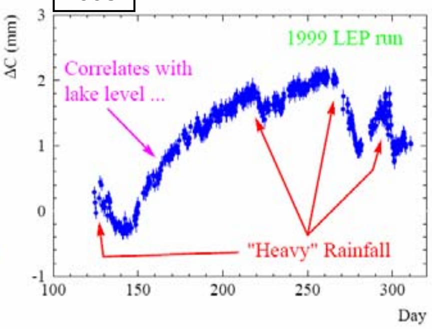
→ Changes of LEP circumference ΔC=1…2 mm/27km (4…8x10^{-8})

1992 Effect of moon



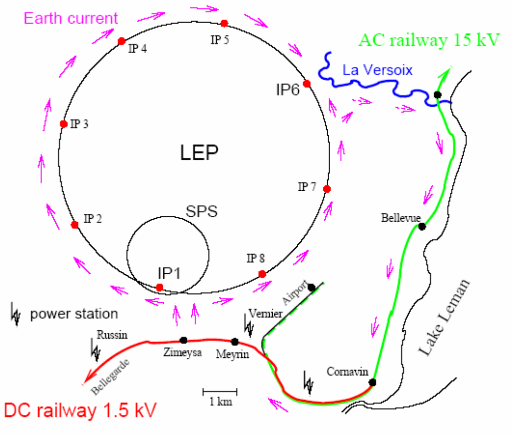
The total strain is 4 x 10^{-8} (ΔC = 1 mm)

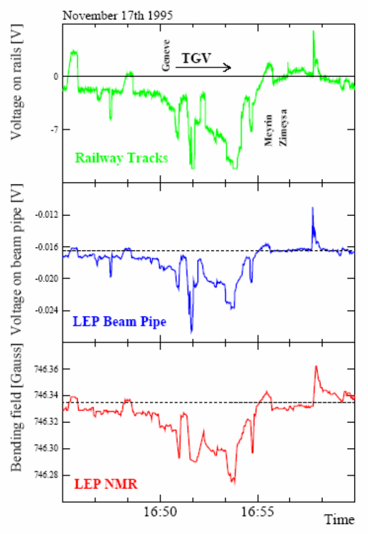
1993 Effect of lake



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:

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

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

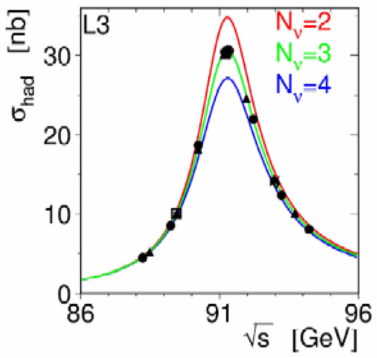
To determine the number of light neutrino generations:

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

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→new

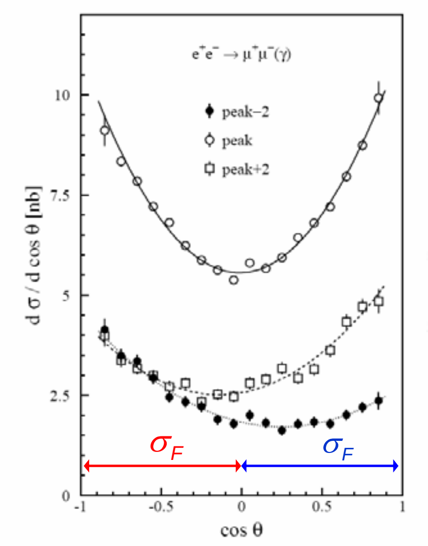
2.4 Forward-backward asymmetry and fermion couplings to Z

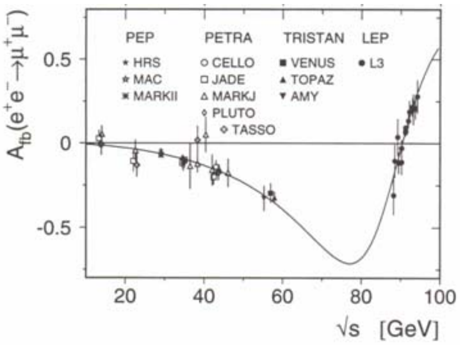
$e^+e^- \to Z \to \mu^+\mu^-$

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

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

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

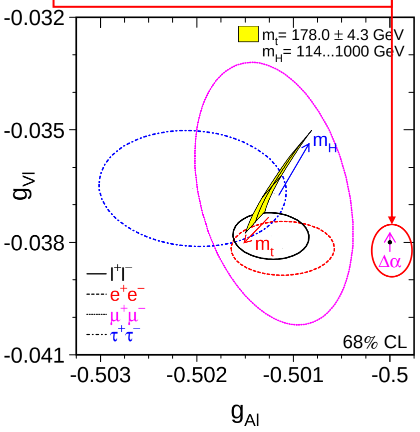
$$A_{FB} \sim g_A^e g_V^e g_A^f g_V^f$$

→ 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

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