Experimental tests of the Standard Model

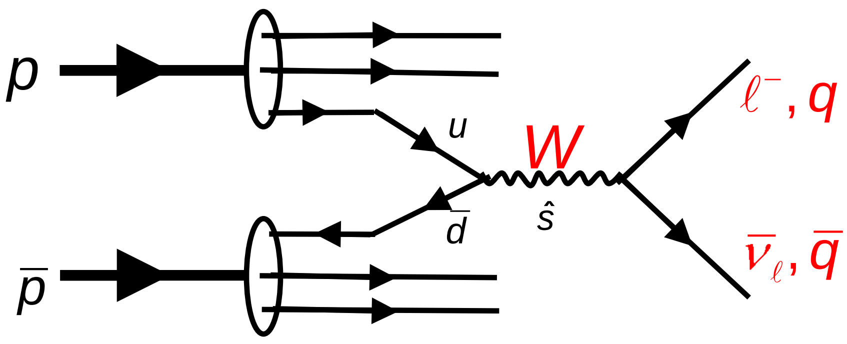
1. Discovery of W and Z boson
2. Precision tests of the Z sector
3. Precision test of the W sector
4. Radiative corrections and prediction of the Higgs mass
5. Higgs searches

Literature for (2):
Precision electroweak measurement on the Z resonance,
Phys. Rept. 427 (2006), hep-ex/0509008.
http://lepewwg.web.cern.ch/LEPEWWG/1/physrep.pdf

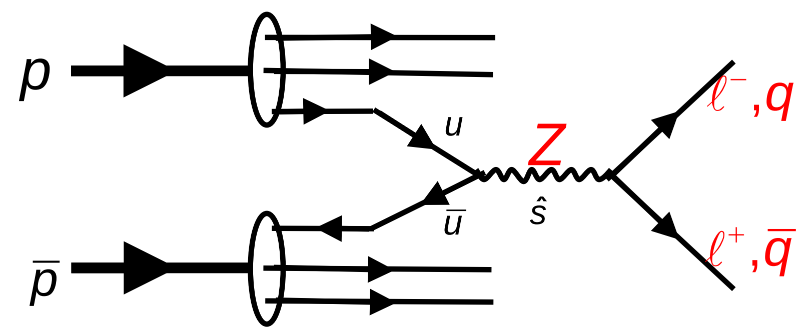
1. Discovery of the W and Z boson

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

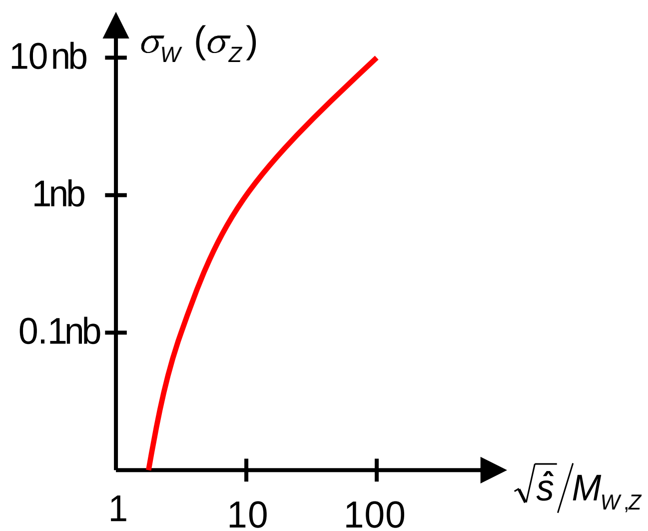
1.1 Boson production in p$\bar{p}$ interactions



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



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



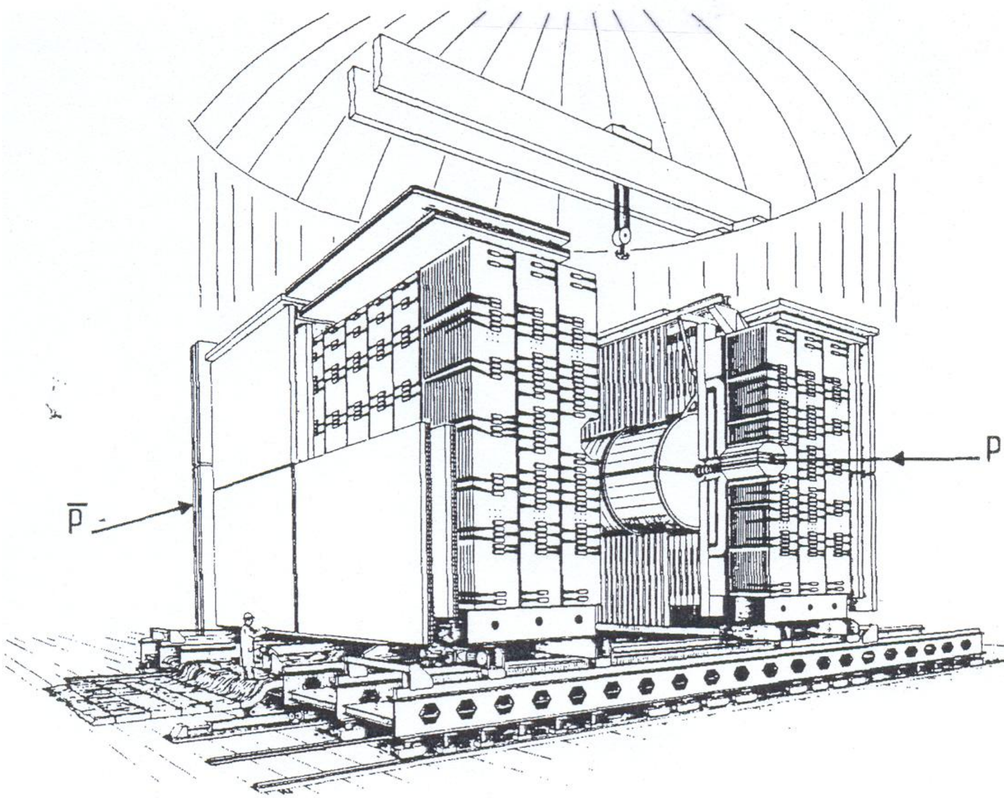
Similar to Drell-Yan: (photon instead of W)

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

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

$\rightarrow$ Cross section is small !

1.2 UA-1 Detector



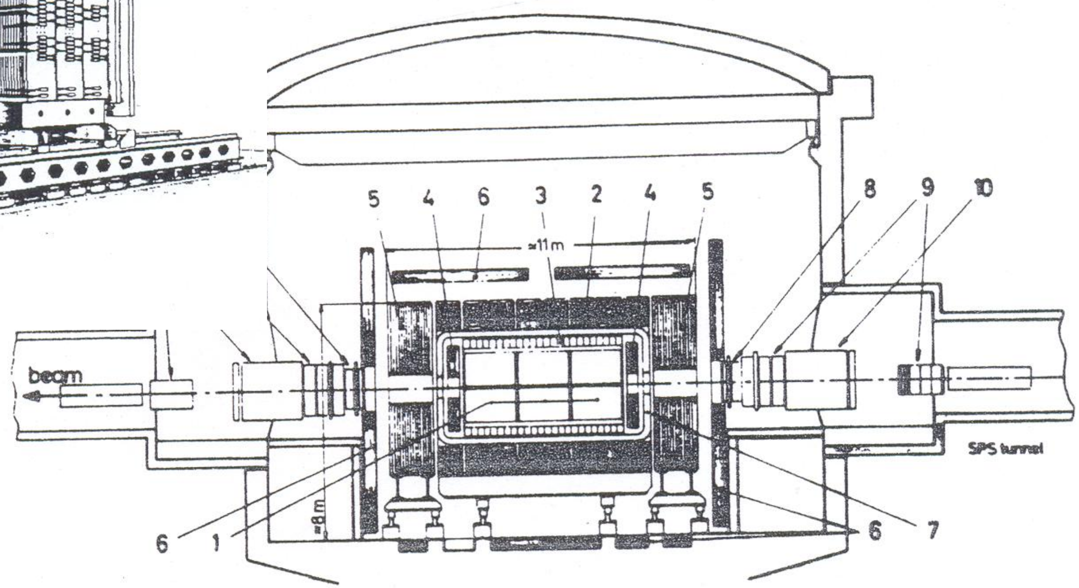
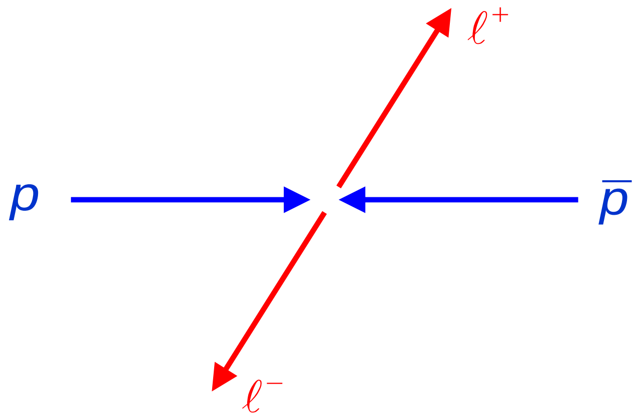


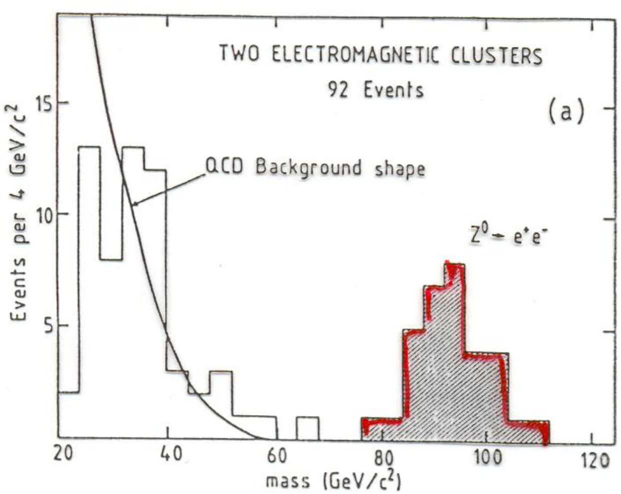
Fig.8.16: Seitenansicht des UA1-Detektors zum Nachweis von Proton-Antiproton-Wechselwirkungen bei 540 GeV Schwerpunktsenergie: 1. Zentraldetektor, 2. und 5. Hadron-Kalorimeter, 3. und 4. Elektron-Photon-Schauerzähler, 6. Myon-Detektor, 7. Spule für Dipolfeld, 8. und 9. Kleinwinkeldetektor mit Kammern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

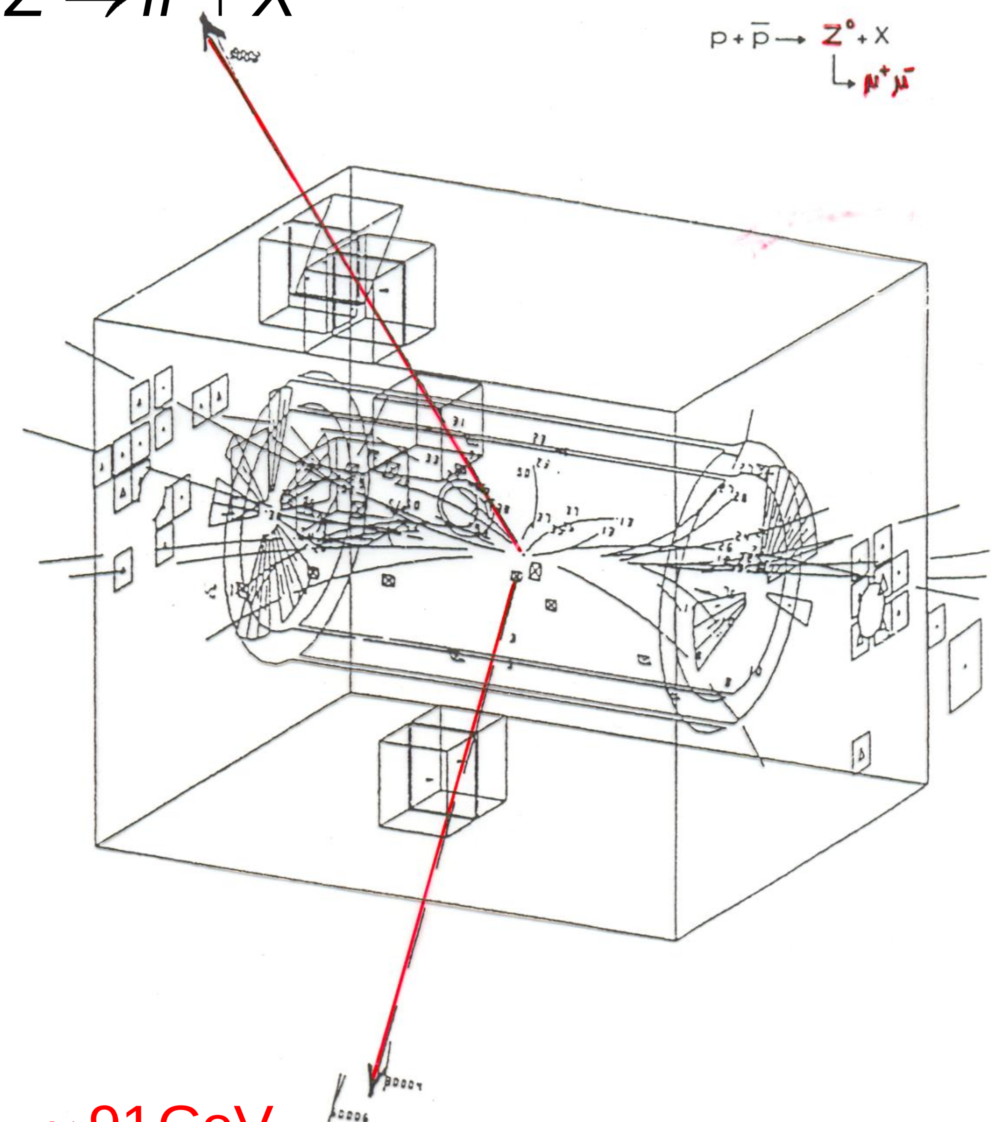
1.3 Event signature: $p\bar{p} \to Z \to f\bar{f} + X$



High-energy lepton pair:

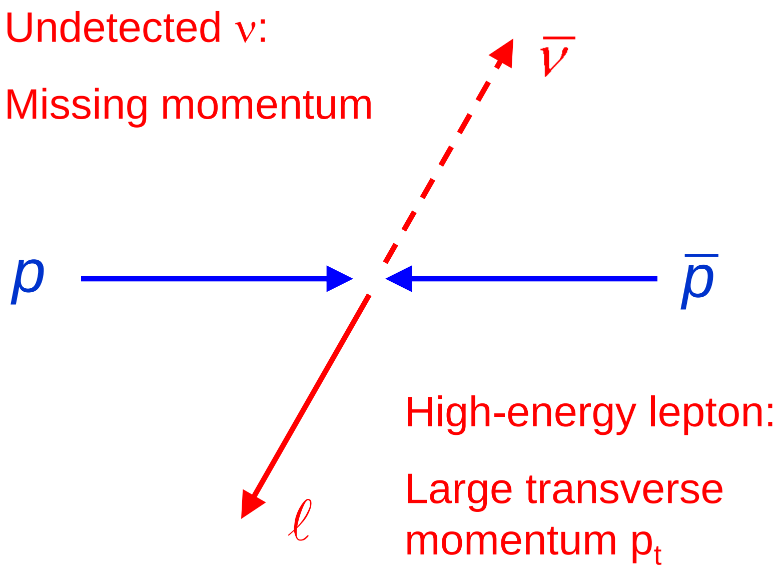
$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





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

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



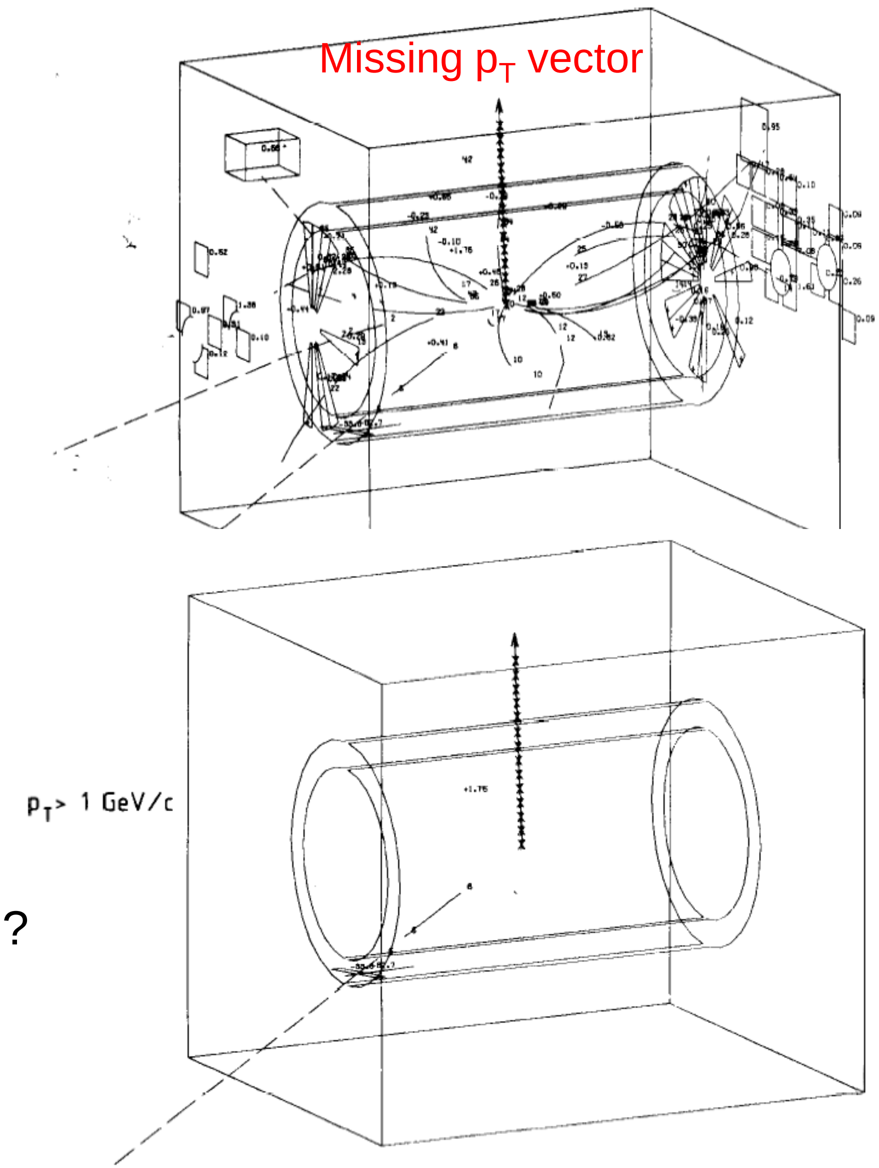
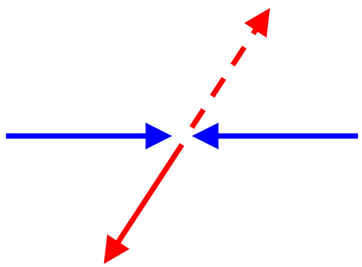


Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_T>1 GeV are shown.

How can the W mass be reconstructed ?

W mass measurement



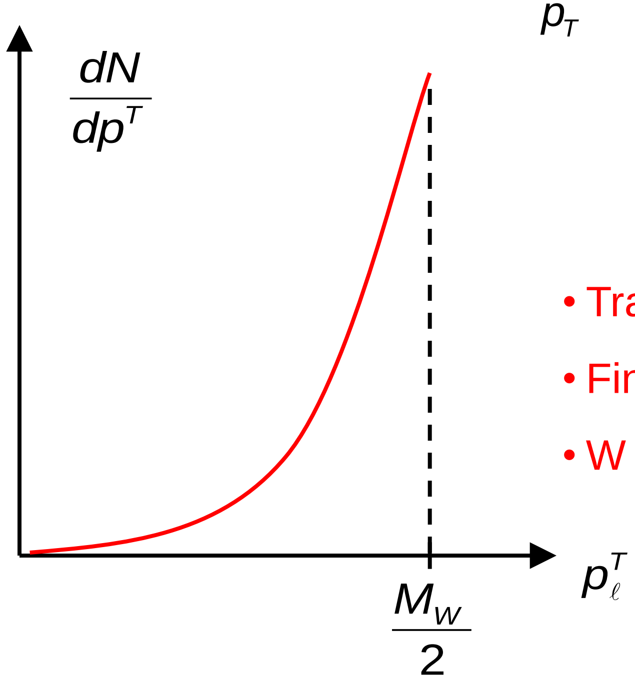
In the W rest frame:

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

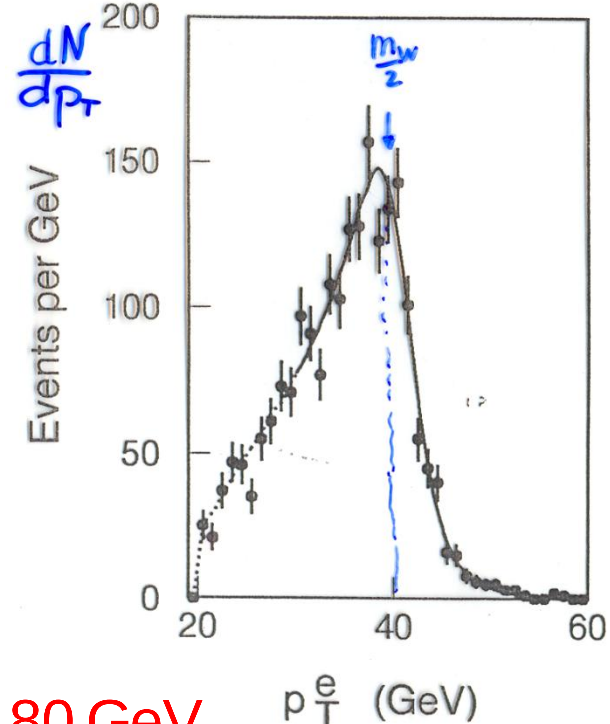
In the lab system:

- 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
- Finite W decay width
- W decay not isotropic



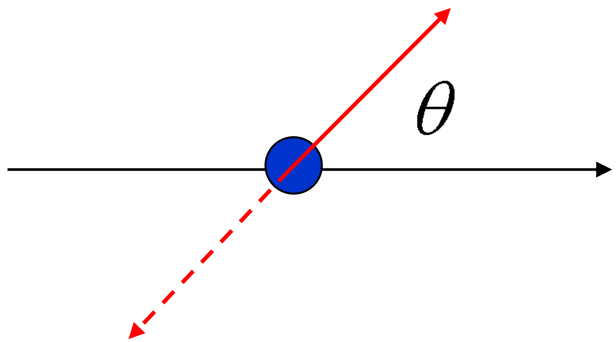
$M_W \approx 80$ GeV

Jacobian Peak

Assume isotropic decay of the W boson in its CM system:

(Not correct: W boson has spin=1 $\rightarrow$ decay is not isotropic!)

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



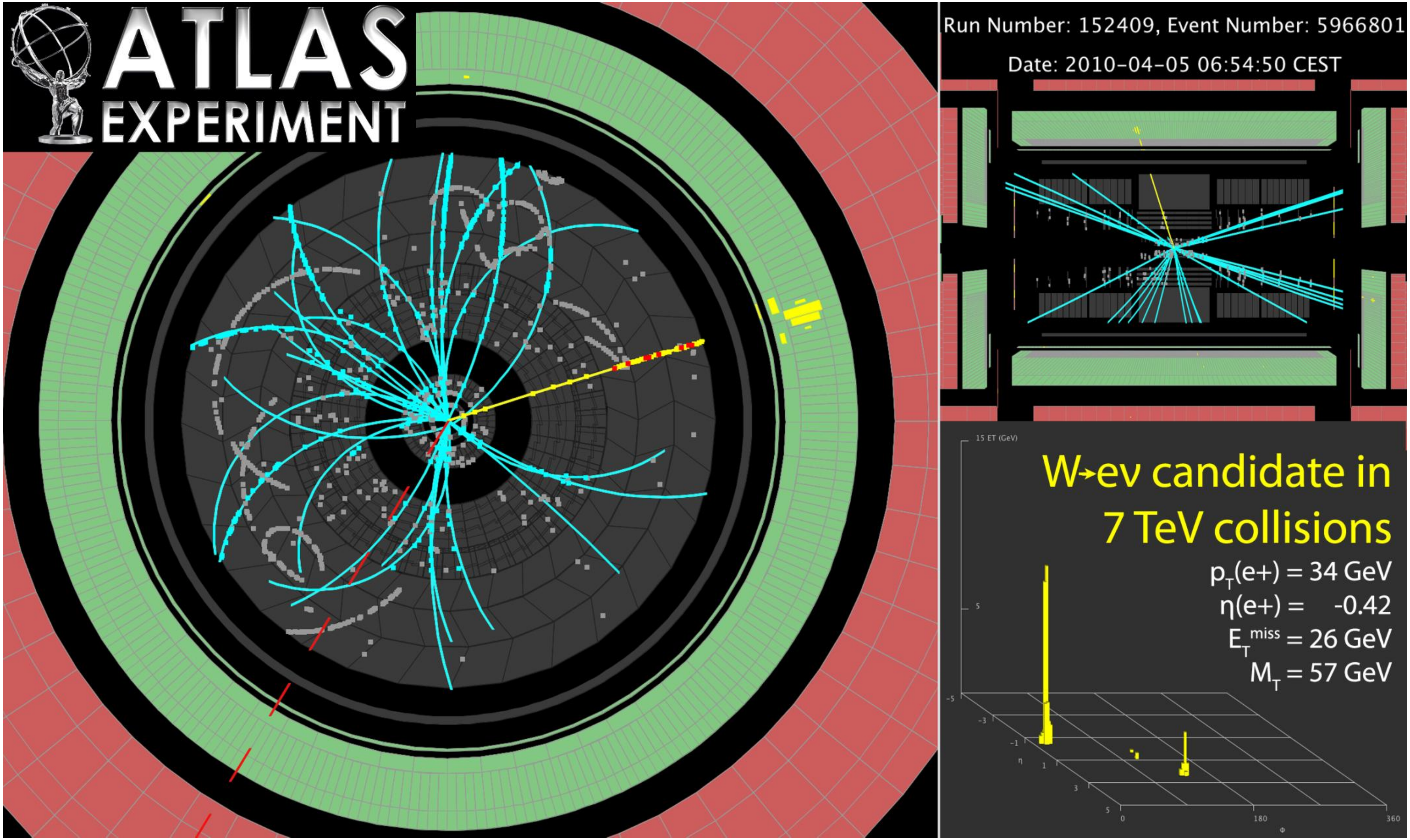
$$\sin\theta = \frac{p_T}{p} = \frac{p_T}{M_w/2}$$

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

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

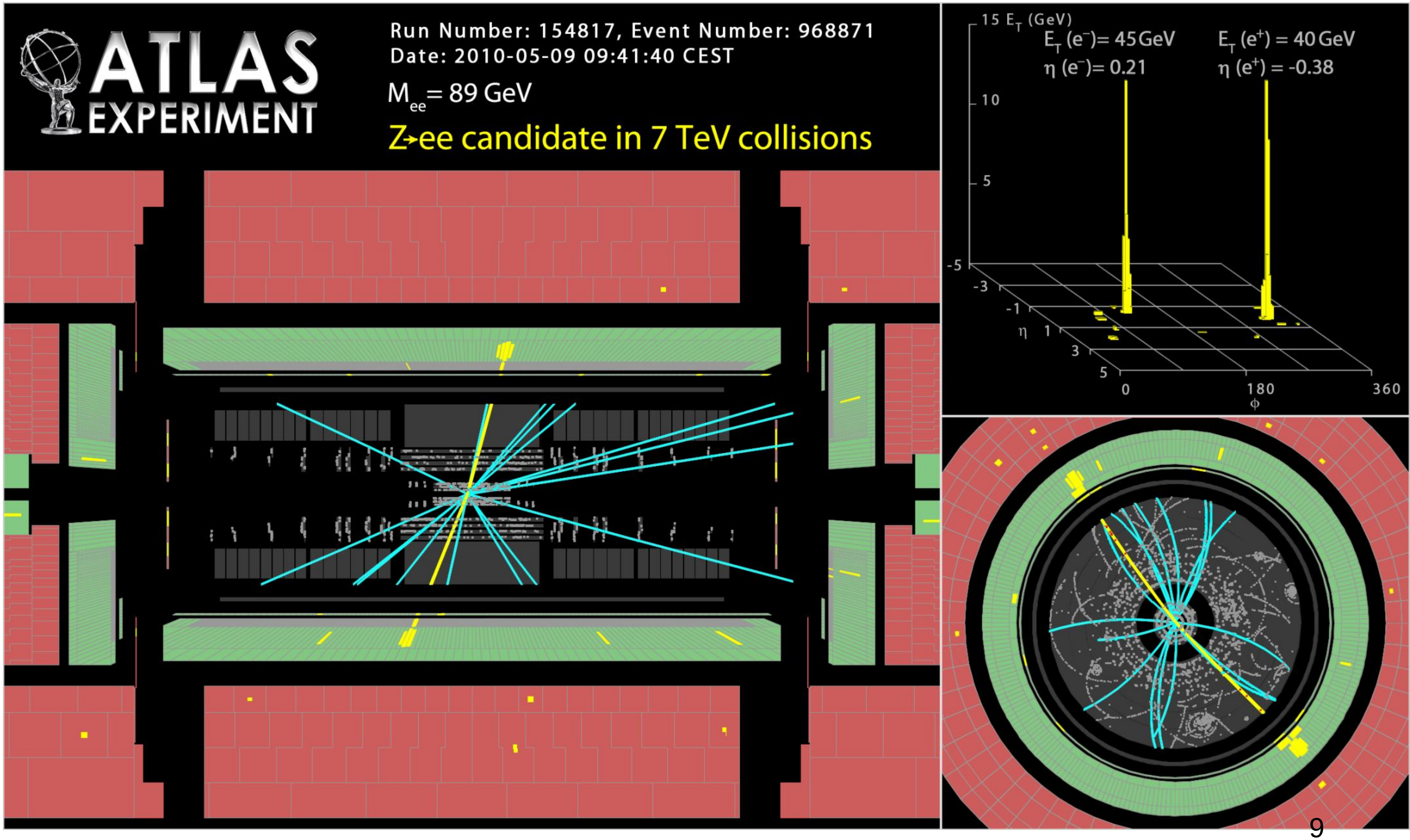
$$\frac{dN}{d\cos\theta} = \frac{dN}{dp_T} \sim \frac{2p_T}{M_W}\cdot\left(\frac{M_W^2}{4}-p_T^2\right)^{-1/2}$$

W candidate from the LHC – they still exist!

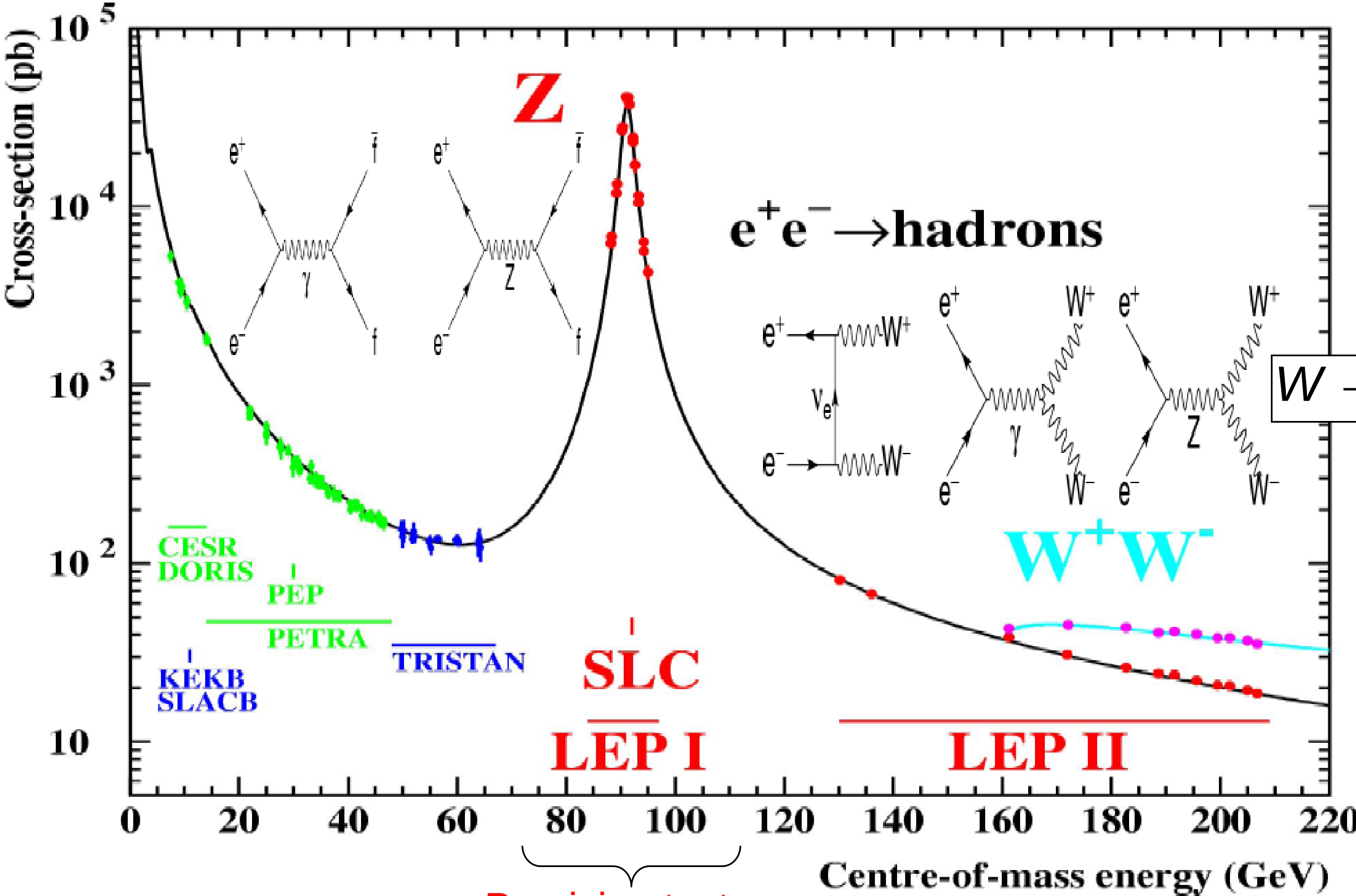


$u\,\bar{d} \rightarrow W^{+}$ or $\bar{u}\,d \rightarrow W^{-}$ Anti-quarks from the sea!

Z also exists at the LHC



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

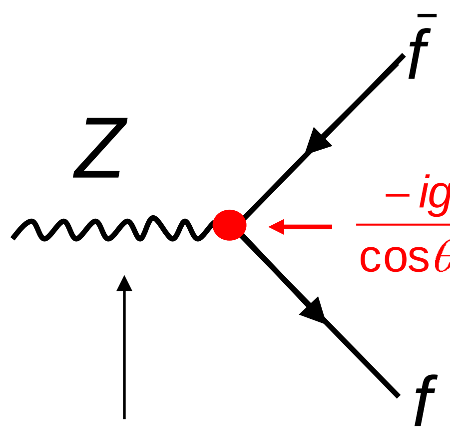


$W \to q\bar{q}$

Precision tests of the Z sector

Tests of the W sector

2. Precision tests of the Z sector (LEP and SLC)



$$\frac{-ig}{\cos\theta_W}\gamma^\mu \frac{1}{2}\left(g_V^f - g_A^f\gamma^5\right)$$

$$g = \frac{e}{\sin\theta_W}$$

$$\frac{-i\left(g_{\mu\nu} - q_\mu q_\nu / M^2\right)}{q^2 - M^2}$$

Standard Model

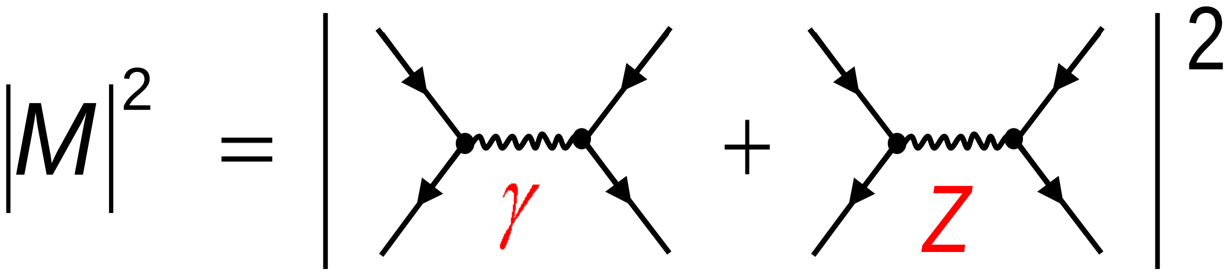
$$g_V = T_3 - 2Q\sin^2\theta_W \quad \text{and} \quad g_A = T_3$$

$$g_L = \frac{1}{2}(g_V + g_A) \qquad g_R = \frac{1}{2}(g_V - g_A)$$

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

	g_V	g_A
ν	$1/2$	$1/2$
ℓ^-	$-1/2 + 2\sin^2\theta_W$	$-1/2$
$u-quark$	$+1/2 - 4/3\sin^2\theta_W$	$1/2$
$d-quark$	$-1/2 + 2/3\sin^2\theta_W$	$-1/2$

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



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

$$M_\gamma = -ie^2(\bar{u}_\mu \gamma^\nu v_\mu)\frac{g_{\rho\nu}}{q^2}(\bar{v}_e \gamma^\rho u_e)$$

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

Z propagator considering a finite Z width

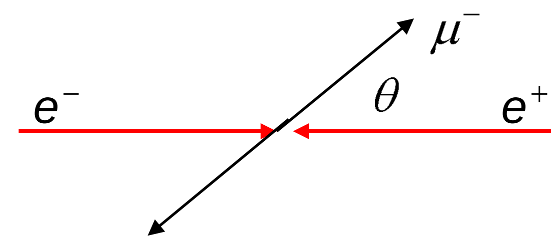
With a "little bit" of algebra similar as for M_γ ….

One finds for the differential cross section:

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

known γ γ/Z interference Z

Vanishes at √s≈M_Z



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

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

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

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

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

Forward-backward asymmetry

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

with

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

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

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

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

Breit-Wigner Resonans

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

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

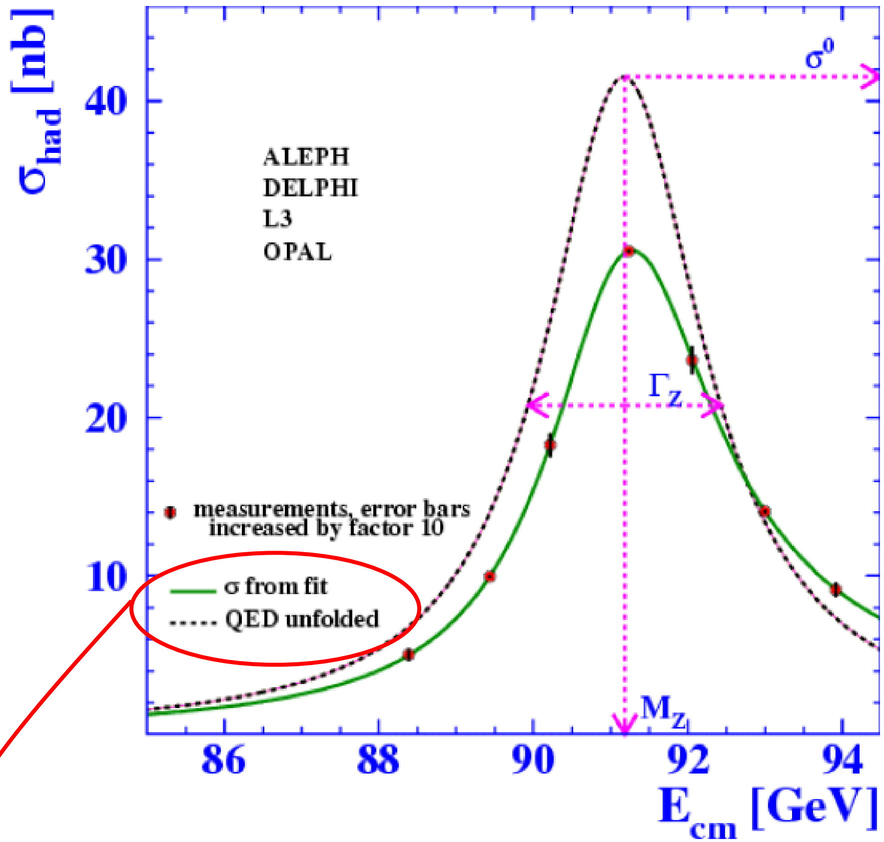
With partial and total widths:

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

$$\Gamma_Z = \sum_i \Gamma_i \qquad BR(Z\to ii)=\frac{\Gamma_i}{\Gamma_Z}$$

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:

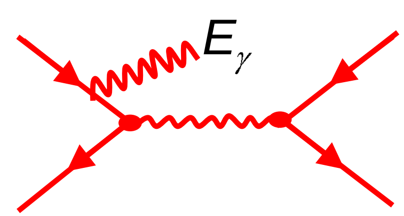
$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

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

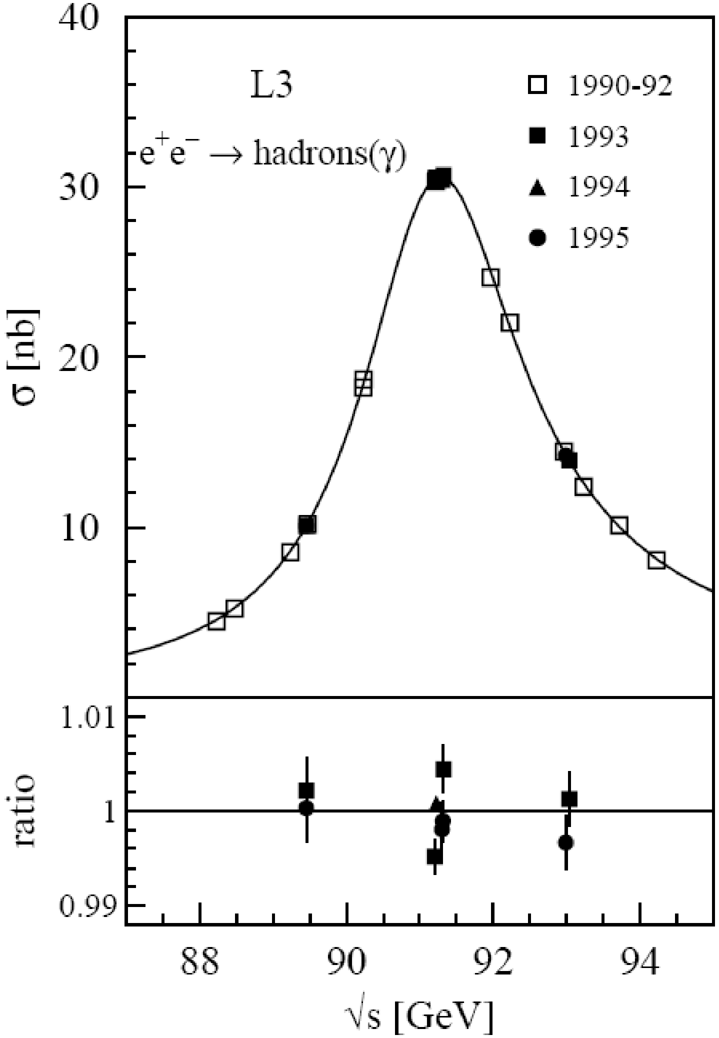
Initial state Bremsstrahlung corrections

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

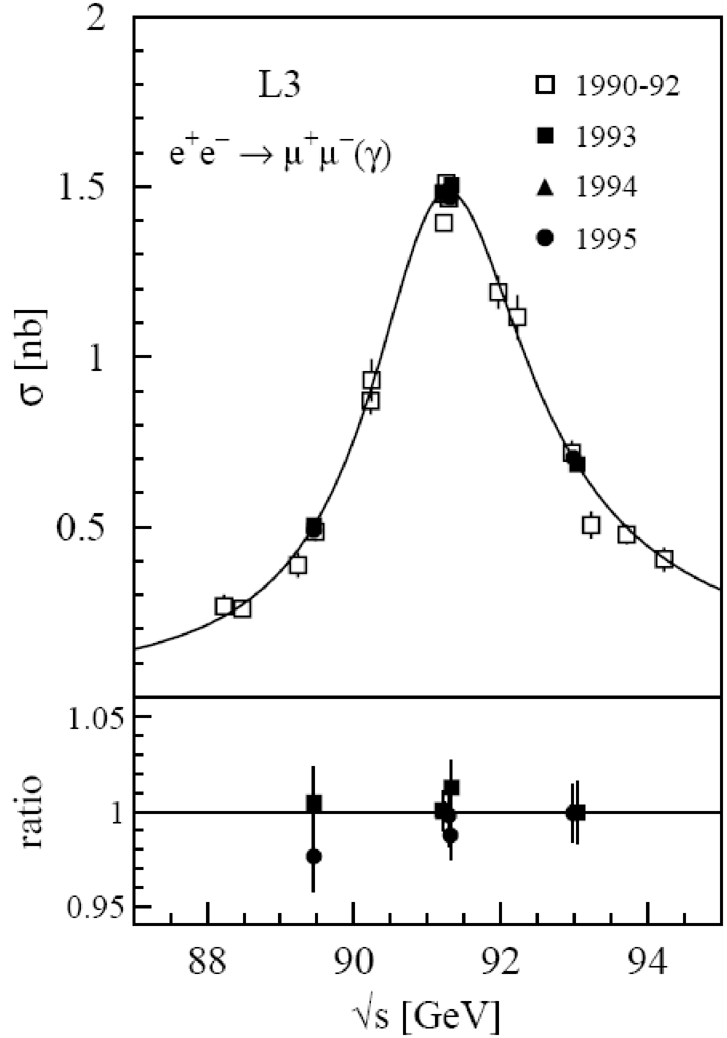


Leads to a deformation of the resonance: large (30%) effect !

$e^+e^- \rightarrow hadrons$

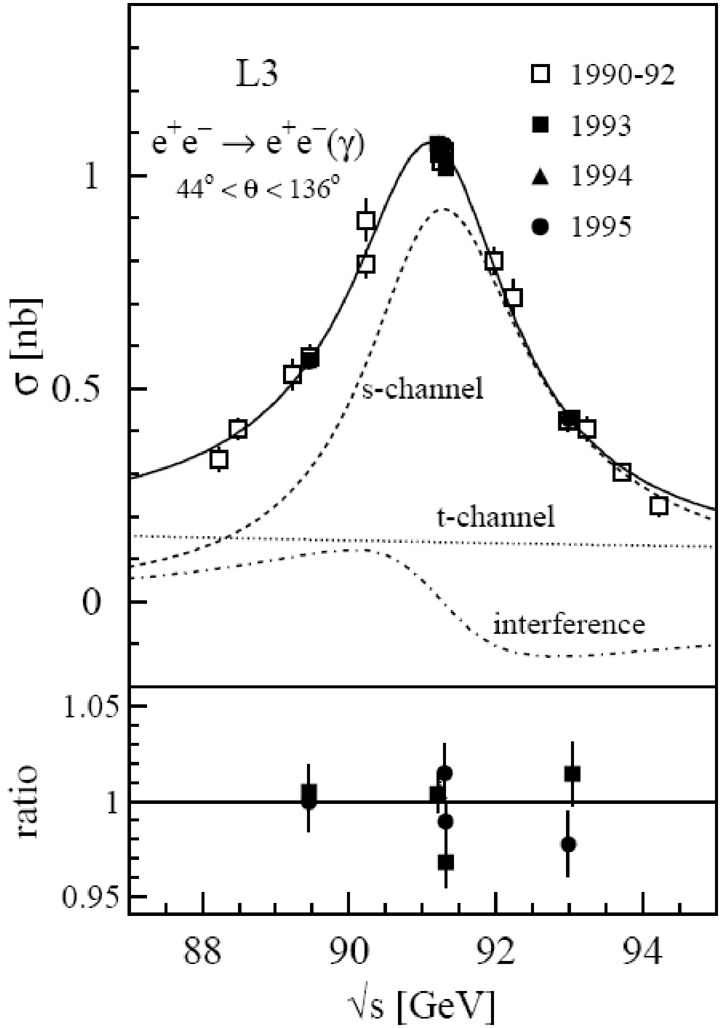


$e^+e^- \rightarrow \mu^+\mu^-$

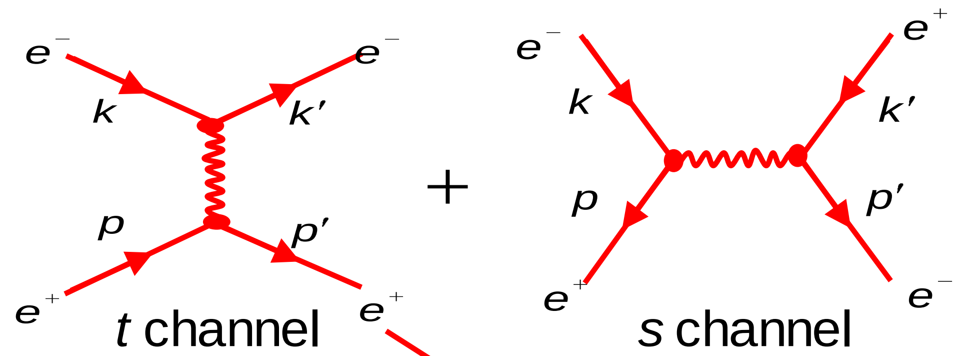


Resonance shape is the same, independent of final state: Propagator the same!

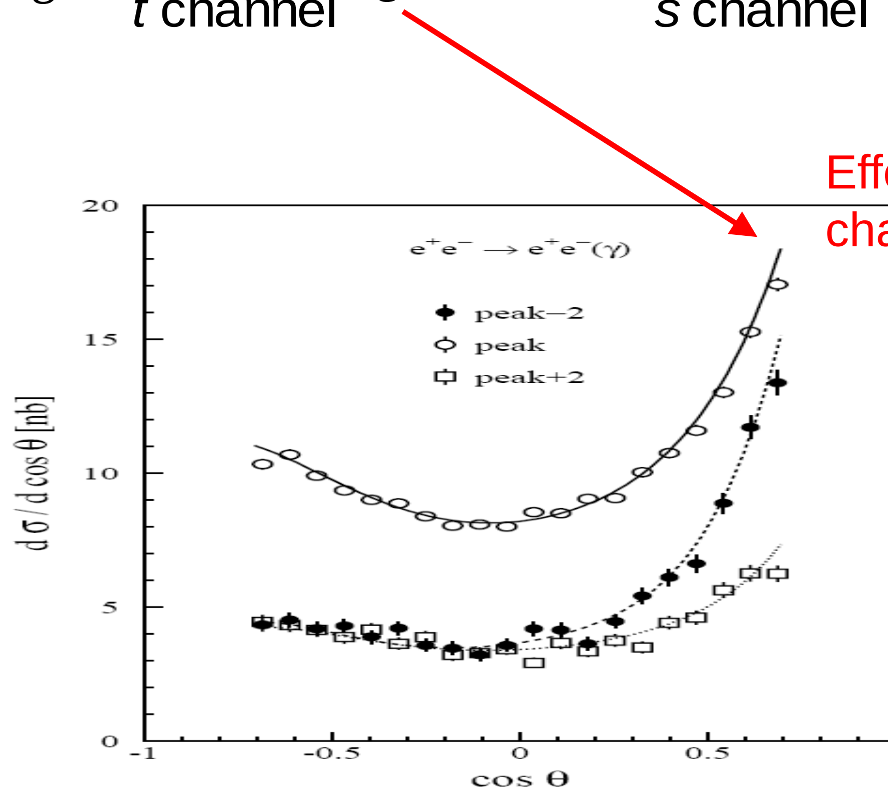
$e^+ e^- \to e^+ e^-$



t channel contribution → forward peak



Effect of t channel



s-channel contribution ~ $(\Gamma_e)^2$

Z line shape parameters (LEP average)

M_Z	$= 91.1876 \pm 0.0021$ GeV	± 23 ppm (*)

Γ_Z	$= 2.4952 \pm 0.0023$ GeV	± 0.09 %
Γ_{had}	$= 1.7458 \pm 0.0027$ GeV	
Γ_e	$= 0.08392 \pm 0.00012$ GeV	
Γ_μ	$= 0.08399 \pm 0.00018$ GeV	
Γ_τ	$= 0.08408 \pm 0.00022$ GeV	

3 leptons are treated independently

test of lepton universality

Γ_Z	$= 2.4952 \pm 0.0023$ GeV
Γ_{had}	$= 1.7444 \pm 0.0022$ GeV
Γ_e	$= 0.083985 \pm 0.000086$ GeV

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

(predicted by SM: g_A and g_V are the same)

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

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

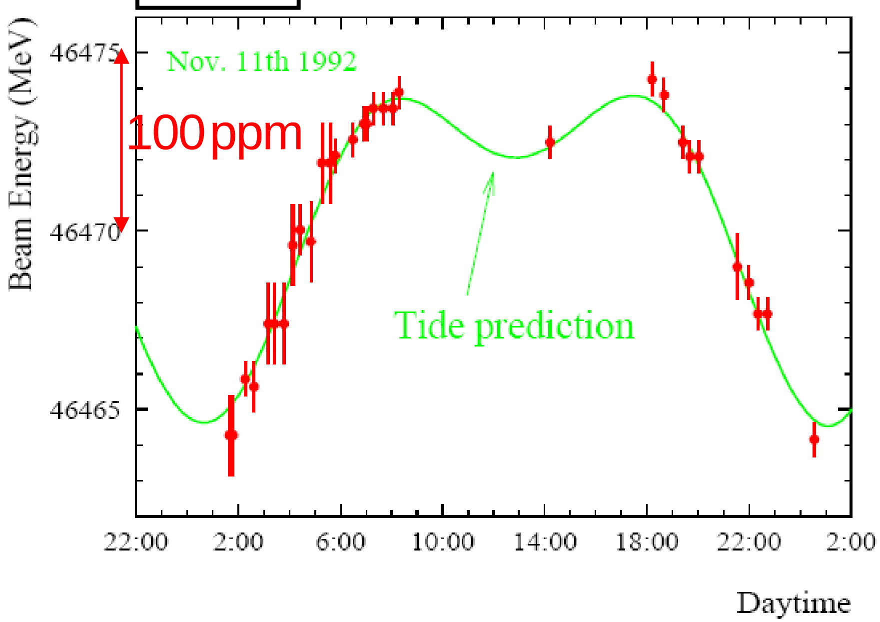
LEP energy calibration: Hunting for ppm effects

Changes of the circumference of the LEP ring changes the energy of the electrons and thus the CM energy (shifts M_Z) :

- tide effects
- water level in lake Geneva

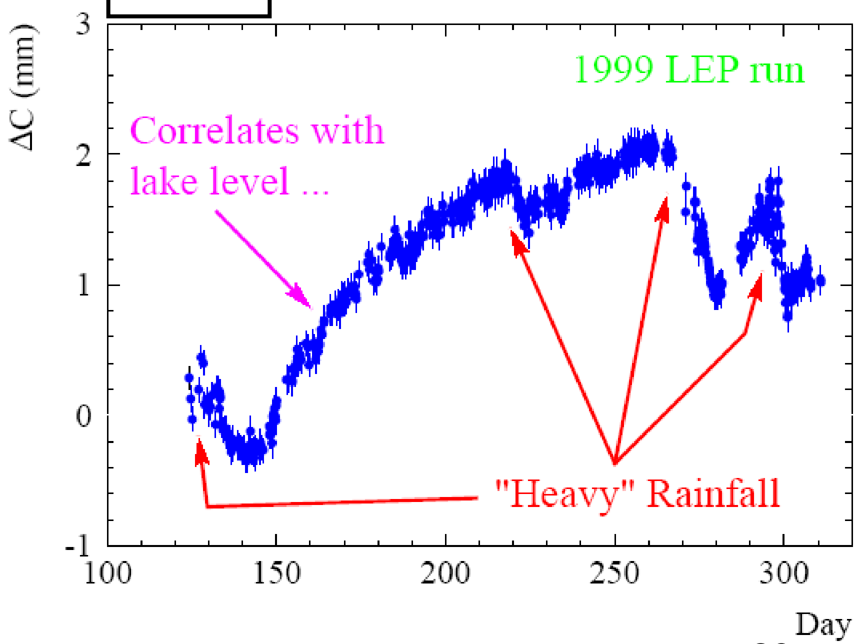
Changes of LEP circumference ΔC=1…2 mm/27km (4…8x10^{-8})

1992 Effect of moon



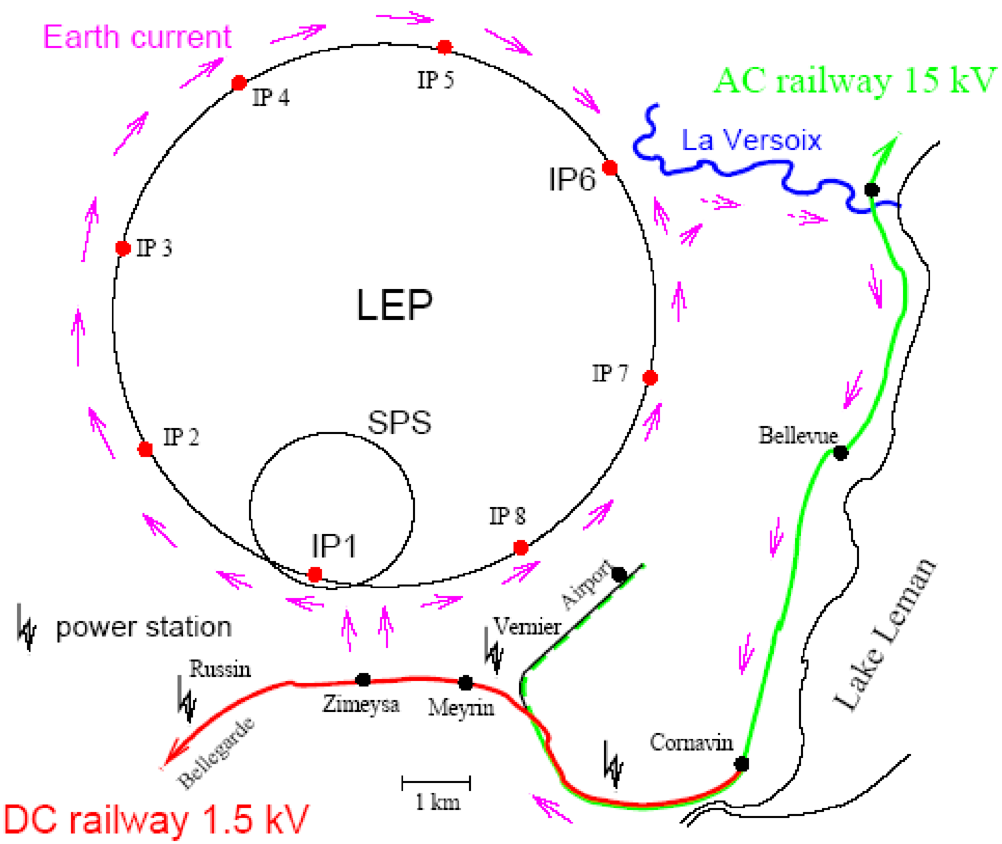
The total strain is 4 x 10^{-8} (ΔC = 1 mm)

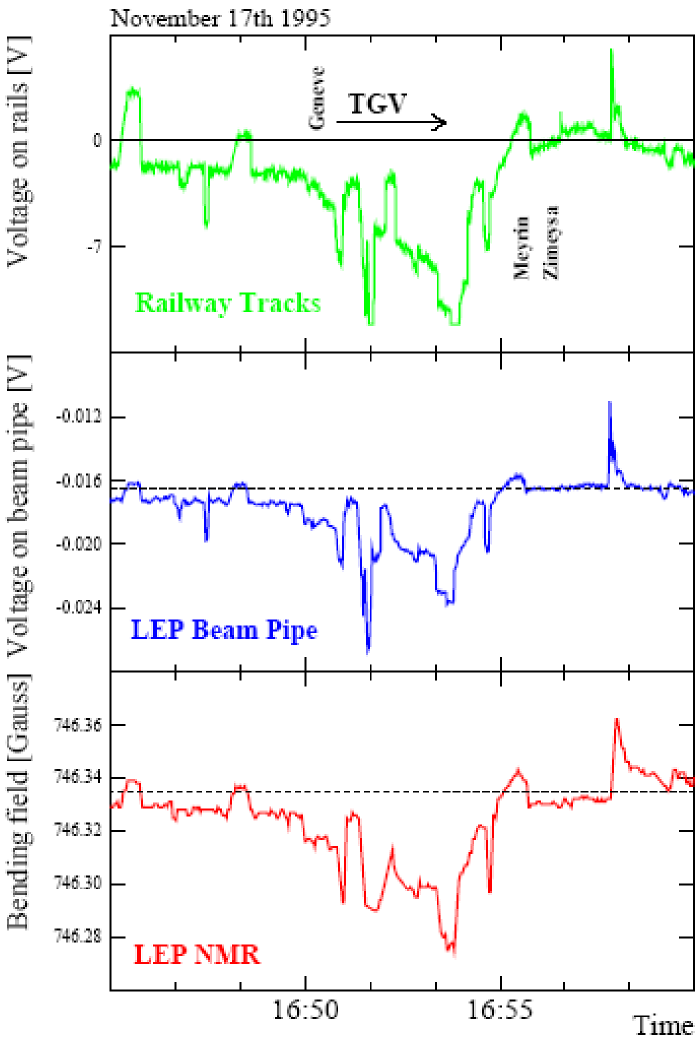
1993 Effect of lake



Effect of the French "Train a Grande Vitesse" (TGV)

Vagabonding currents 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:

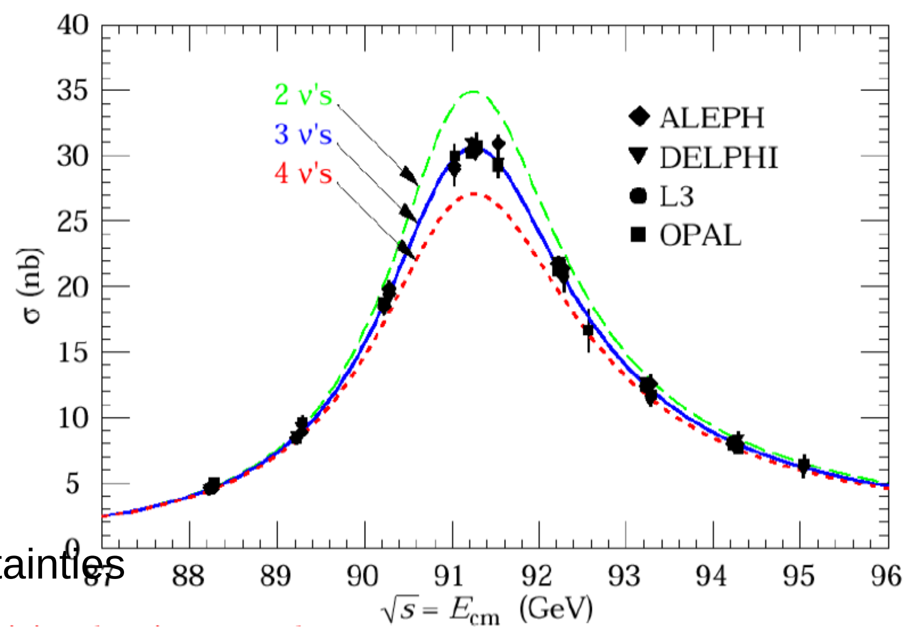
$$\Gamma_Z = \Gamma_{had} + 3 \cdot \Gamma_\ell + \underbrace{N_\nu \cdot \Gamma_\nu}_{\text{invisible } : \Gamma_{inv}} \rightarrow \begin{cases} e^+e^- \rightarrow Z \rightarrow \nu_e \bar{\nu}_e \\ e^+e^- \rightarrow Z \rightarrow \nu_\mu \bar{\nu}_\mu \\ e^+e^- \rightarrow Z \rightarrow \nu_\tau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

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

To determine the number of light neutrino generations:

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\nu,SM}} = \underbrace{\left(\frac{\Gamma_{inv}}{\Gamma_\ell}\right)_{exp}}_{5.9431 \pm 0.0163} \cdot \underbrace{\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}}_{=1/1.991 \pm 0.001}$$

(small theo. uncertainties from m_{top} M_H)



$N_\nu = 2.9840 \pm 0.0082$

No room for new physics: Z→new