Experimental tests of the Standard Model

0. Standard Model in a Nutshell
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

0. Standard Model in a Nutshell

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

LH weak iso-spin doublets

weak isospin: T, T_3

$W^\pm$ $\quad \tau^\pm = \frac{1}{2}(\tau^1 \pm i \cdot \tau^2)$

$$e^-_R \quad \mu^-_R \quad \tau^-_R$$

RH singlets

<u>Symmetry:</u>

Additional field W^3 which corresponds to the 3rd isospin operator τ^3.

W^3 only couples to the particles of the weak isospin doublet!

In addition we have two more fields:

- Photon γ which couples to the LH and RH fermions with same strength.
- Z boson which couples to LH and RH fermions with different couplings g_L and g_R

How can we associate the observed fields to W^3?

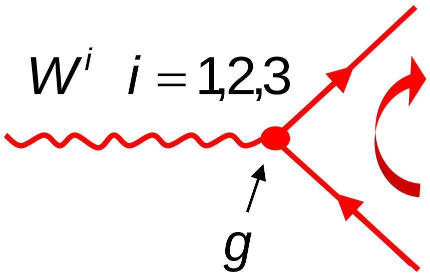
⇒ Additional gauge field B

Gauge field B couples to hyper-charge: $Y = 2\ [Q-T_3]$

couples to LH and RH fermions

T.Plehn

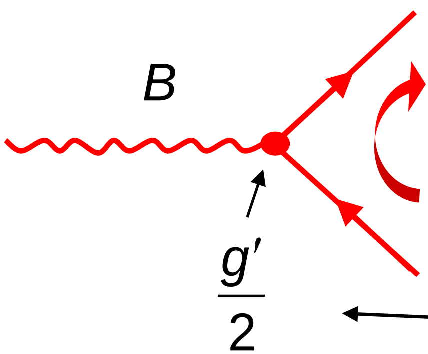
$$q \equiv \frac{y\mathbb{1} + \tau_3}{2}$$



$$J^i_\mu \qquad \sim -igJ^i_\mu \cdot W^{i,\mu}$$

Corresponding to $J^\pm$ and J^3 there are fields

$$W^\pm_\mu = \frac{1}{\sqrt{2}}(W^1_\mu \mp iW^2_\mu) \quad \text{and} \quad W^3_\mu$$



$$J^Y_\mu \qquad \sim -i\frac{g'}{2}J^Y_\mu \cdot B^\mu$$

convention

g, g′ are coupling constants.

While the charged boson fields $W^{\pm}$ correspond to the observed W bosons, the neutral fields B and W^3 only correspond to linear combinations of the observed photon and Z boson:

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$ ← massless photon

$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$ ← massive Z boson

$$B_\mu = A_\mu \cos\theta_W - Z_\mu \sin\theta_W$$

$$W_\mu^3 = A_\mu \sin\theta_W + Z_\mu \cos\theta_W$$

$$g_Z = \frac{g}{\cos\theta_W} \qquad g' = g\,\frac{\sin\theta_W}{\cos\theta_W}$$

The weak mixing angle θ_w (Weinberg angle) follows from coupling constants:

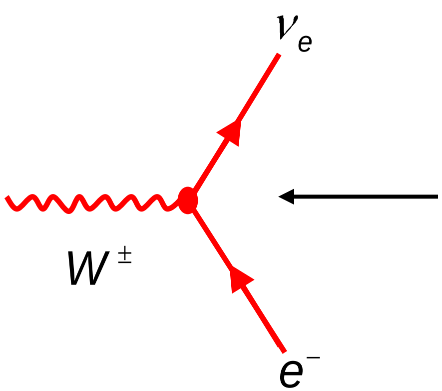
$$g = \frac{e}{\sin\theta_W} \qquad g' = \frac{e}{\cos\theta_W}$$

Coupling to the photon field ~e

Feynman rules

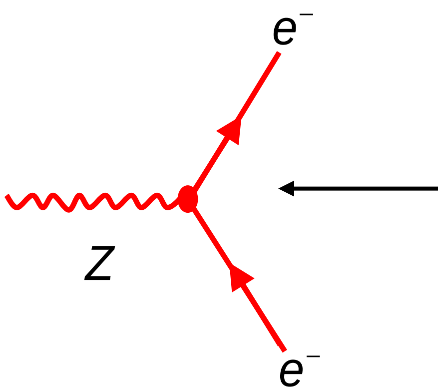
Vertex factors

Propagator
(unitary gauge)



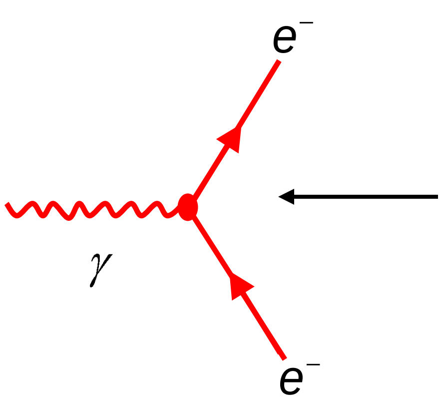
$$-i\frac{g}{\sqrt{2}}\gamma_\mu\frac{1}{2}(1-\gamma^5)$$

$$\frac{g_{\mu\nu}-q_\mu q_\nu/M_W^2}{q^2-M_W^2}$$



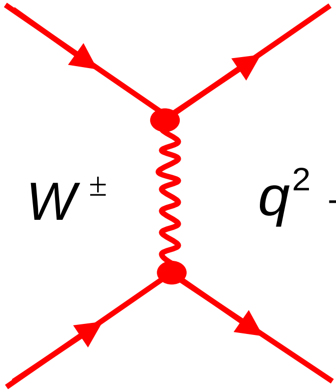
$$-i\frac{g}{\cos\theta_W}\gamma_\mu\frac{1}{2}(g_V-g_A\gamma^5)$$

$$\frac{g_{\mu\nu}-q_\mu q_\nu/M_Z^2}{q^2-M_Z^2}$$



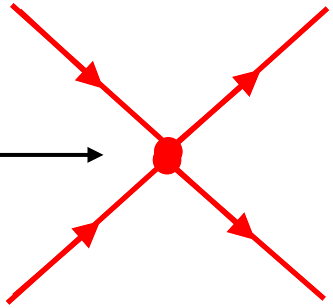
$$-ie\gamma_\mu$$

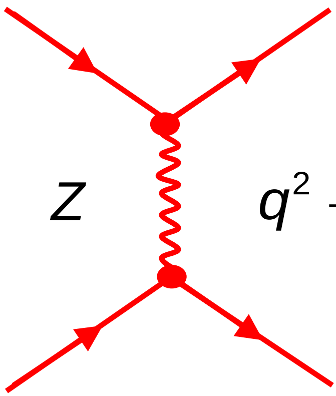
$$\frac{1}{q^2}$$



$q^2 \to 0:$

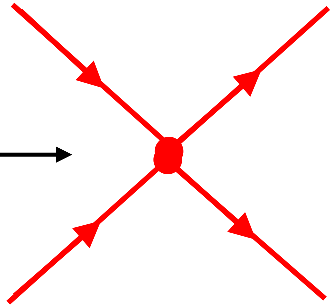
$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$$





$q^2 \to 0:$

$$\frac{g^2}{8\cos^2\theta_W M_Z^2} = \frac{G_{NC}}{\sqrt{2}}$$



Assuming universality $\frac{G_F}{\sqrt{2}} \equiv \frac{G_{NC}}{\sqrt{2}}$ follows

$$\cos^2\theta_W = \frac{M_W^2}{M_Z^2}$$

Δρ=0

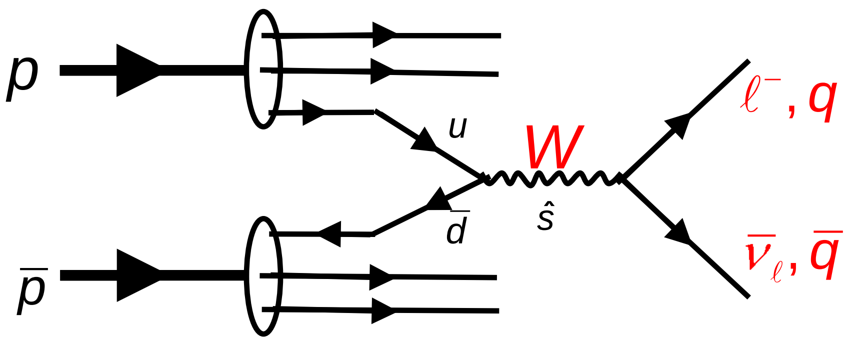
ρ= 1-Δρ =1

$$\rho\cos^2\theta_W = \frac{M_W^2}{M_Z^2}$$

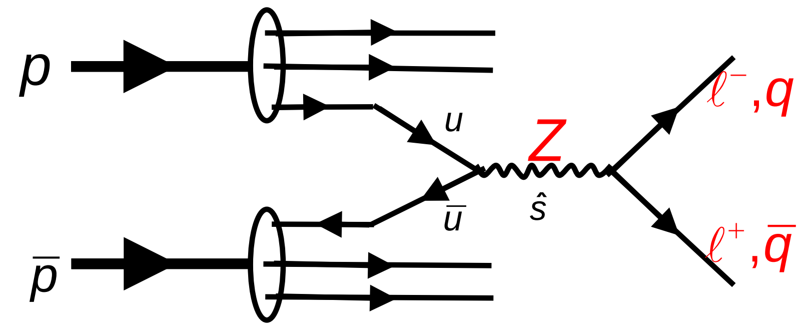
1. Discovery of the W and Z boson

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

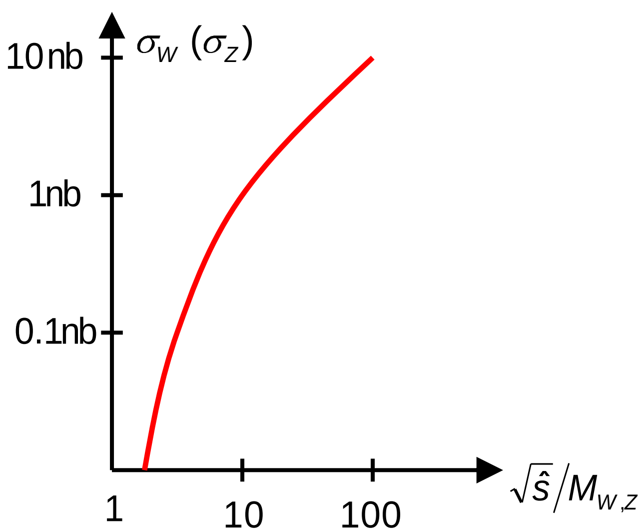
1.1 Boson production in p$\bar{p}$ interactions



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



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



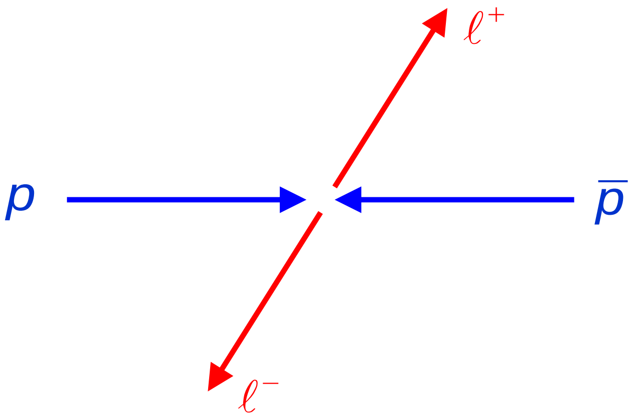
<u>Similar to Drell-Yan:</u> (photon instead of W)

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

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

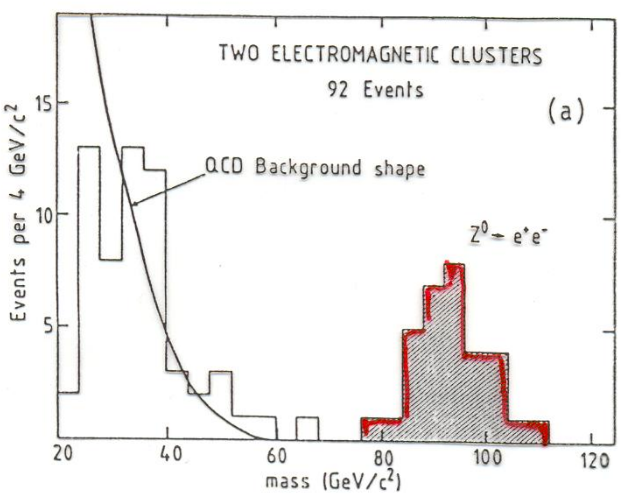
$\to$ Cross section is small !

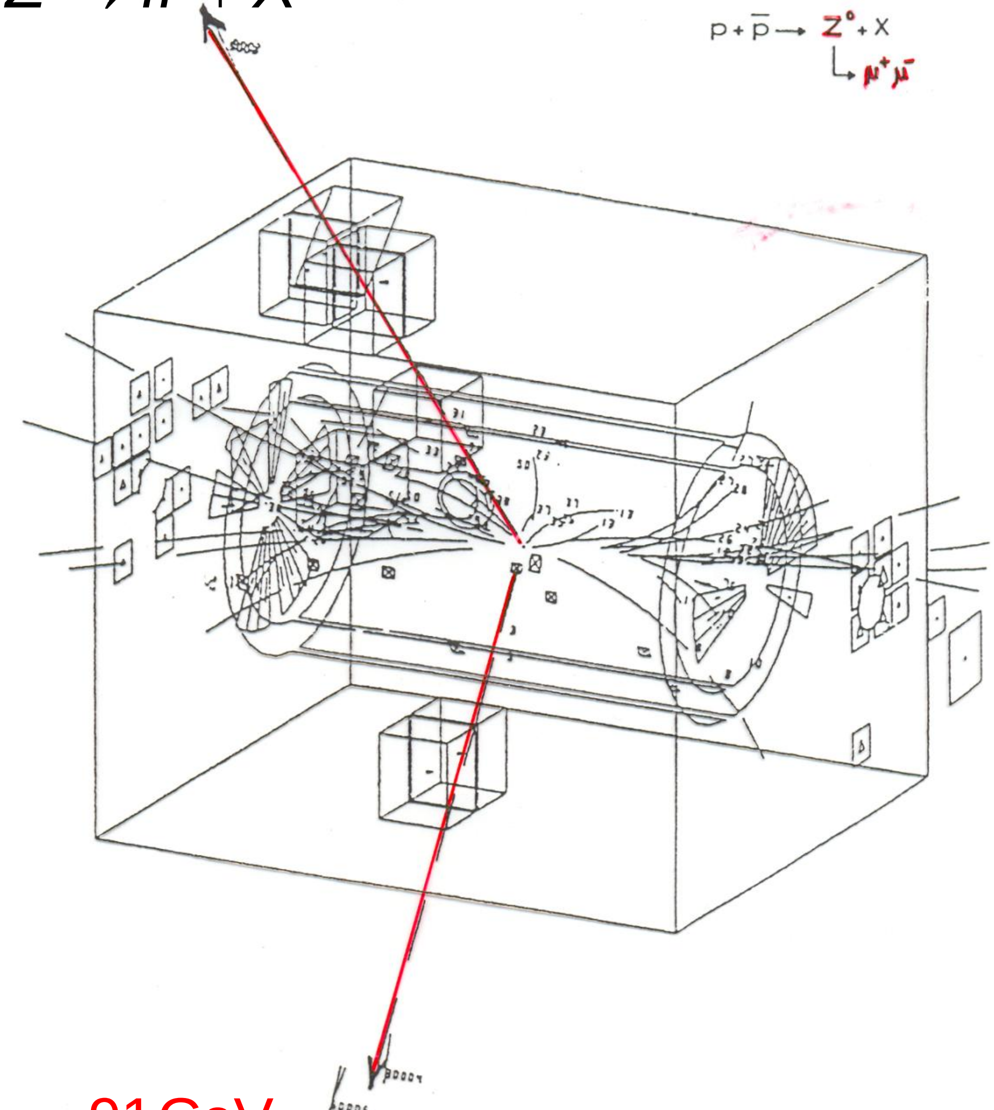
1.2 Event signature: $p\bar{p} \to Z \to f\bar{f} + X$



High-energy lepton pair:

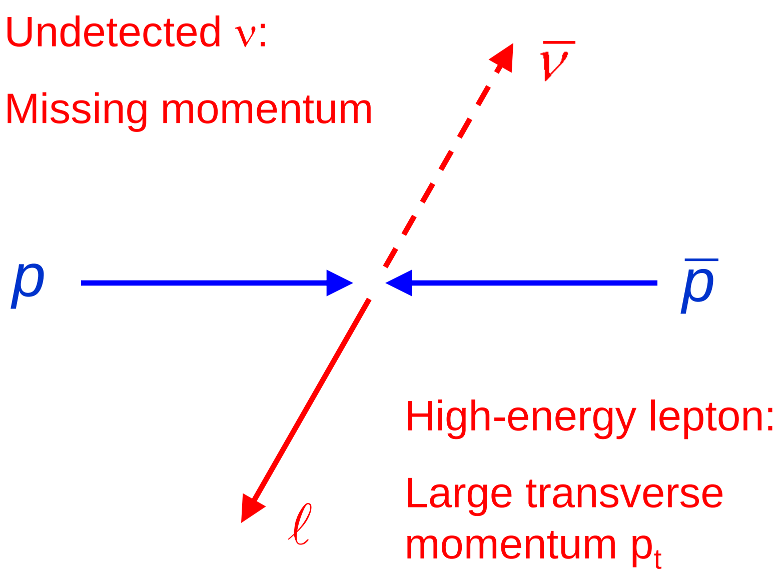
$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





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

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



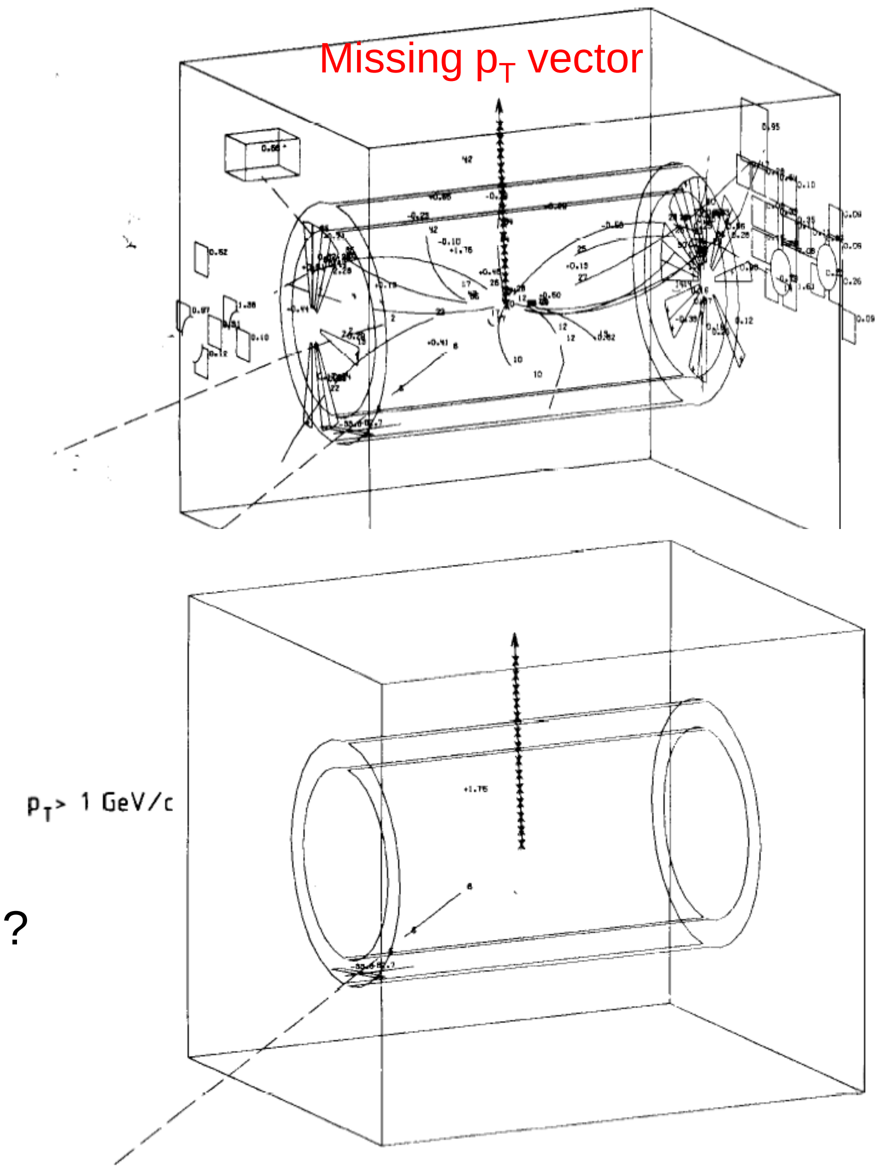
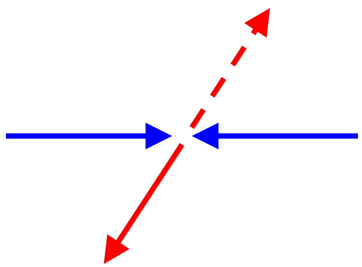


Fig. 16b. The same as picture (a), except that now only particles with p_T>1 GeV/c and calorimeters with E_T>1 GeV are shown.

How can the W mass be reconstructed ?

W mass measurement



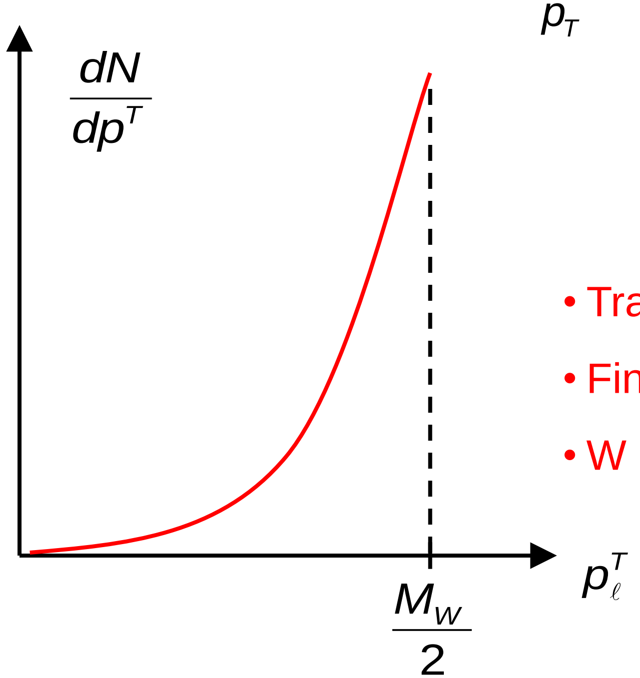
In the W rest frame:

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

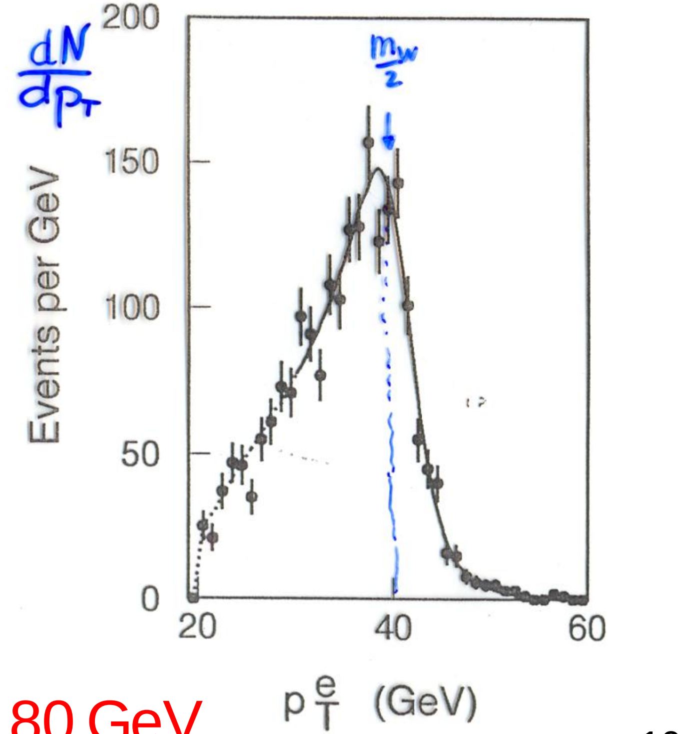
In the lab system:

- W system boosted only along z axis
- p_T distribution is conserved: maximum $p_T = M_W / 2$

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



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



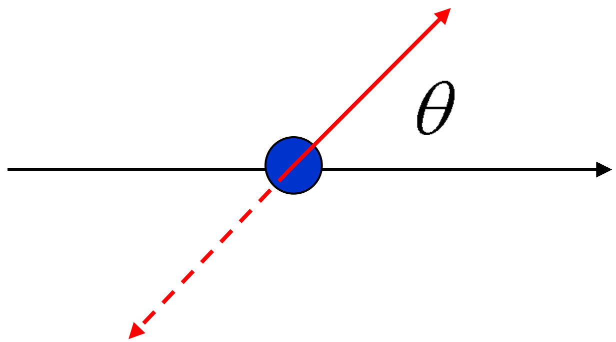
$M_W \approx 80$ GeV

Jacobian Peak

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

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

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



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

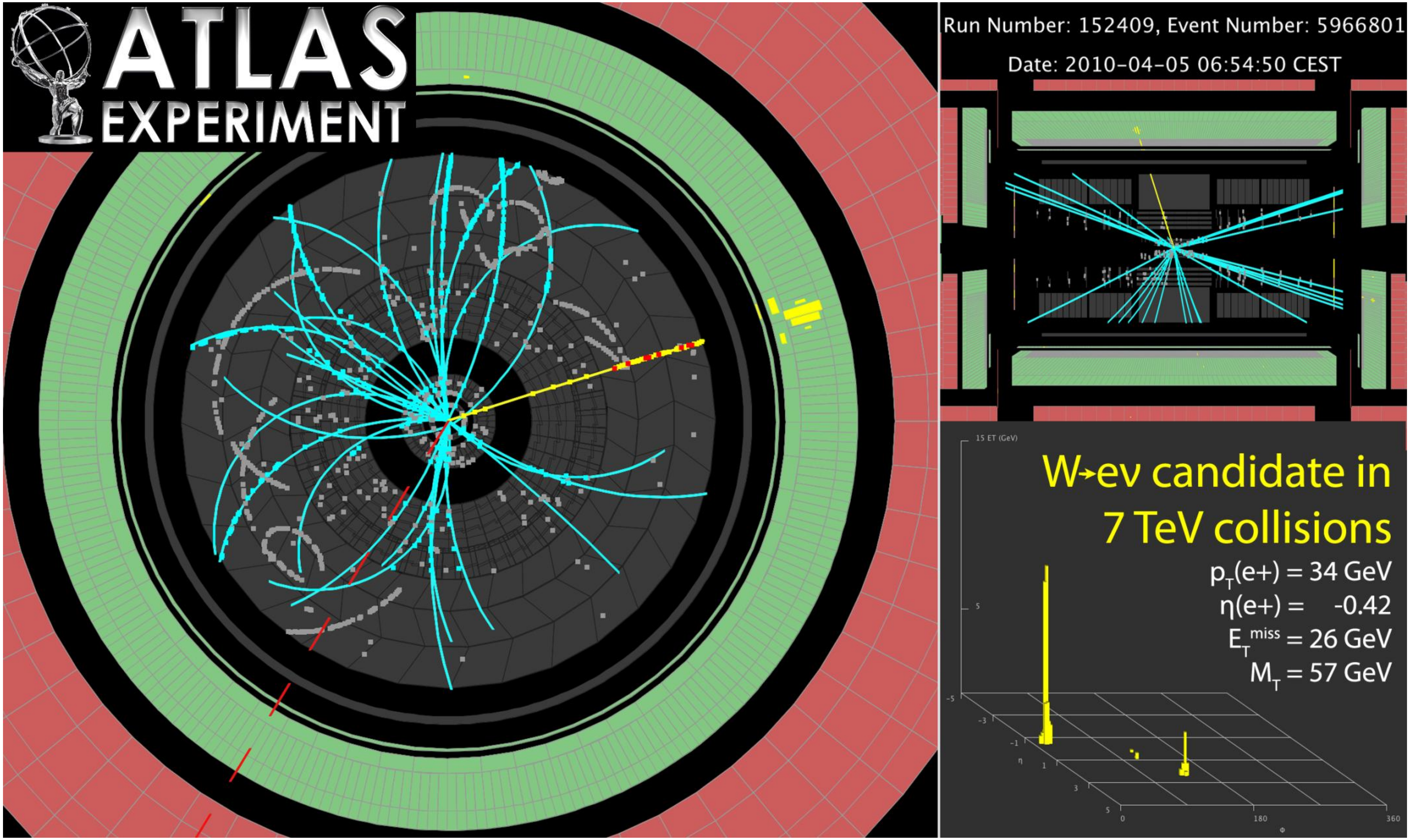
$$1-\cos^2\theta = \left(\frac{p_T}{M_w/2}\right)^2$$

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

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

Jacobian

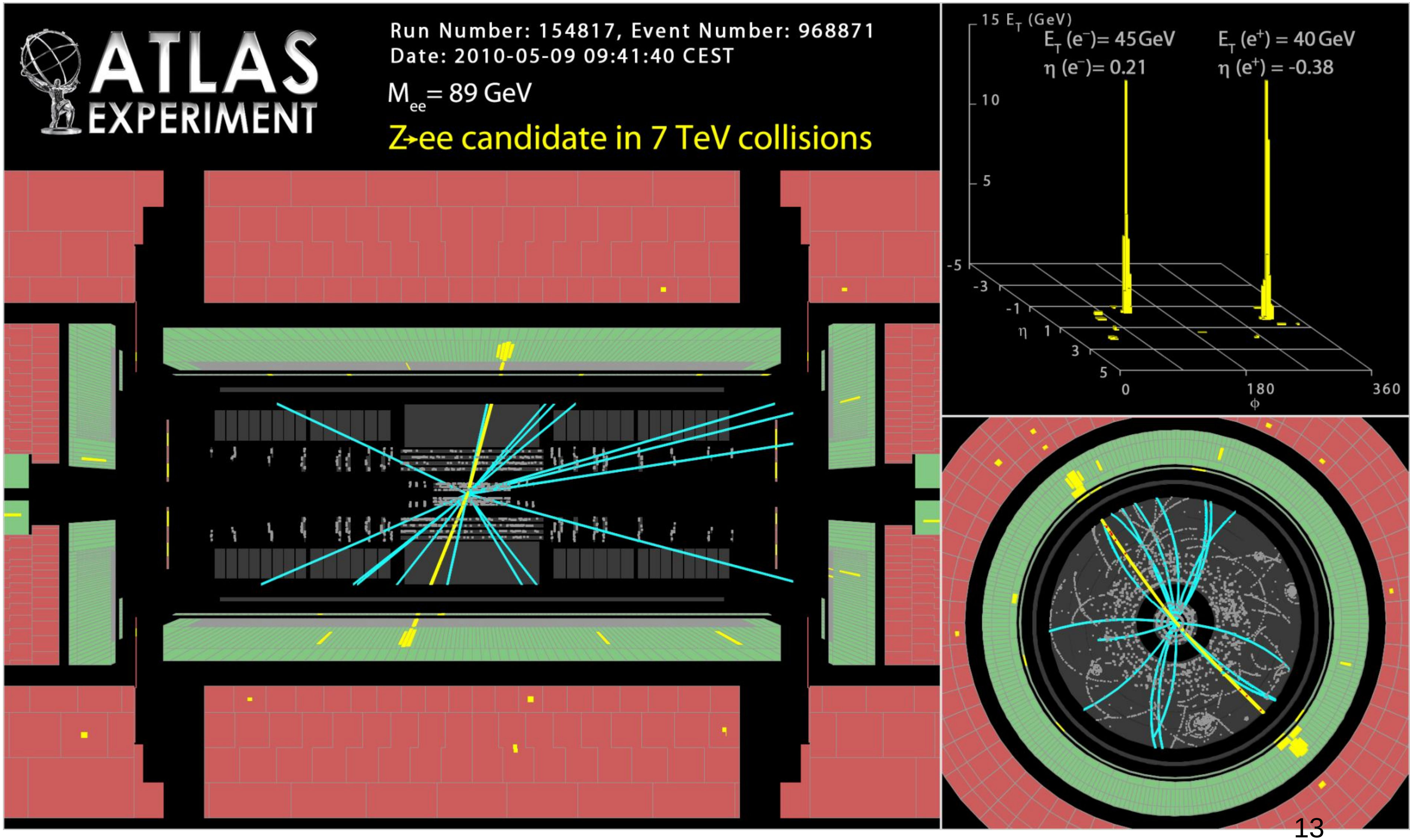
W candidate from the LHC – they still exist!



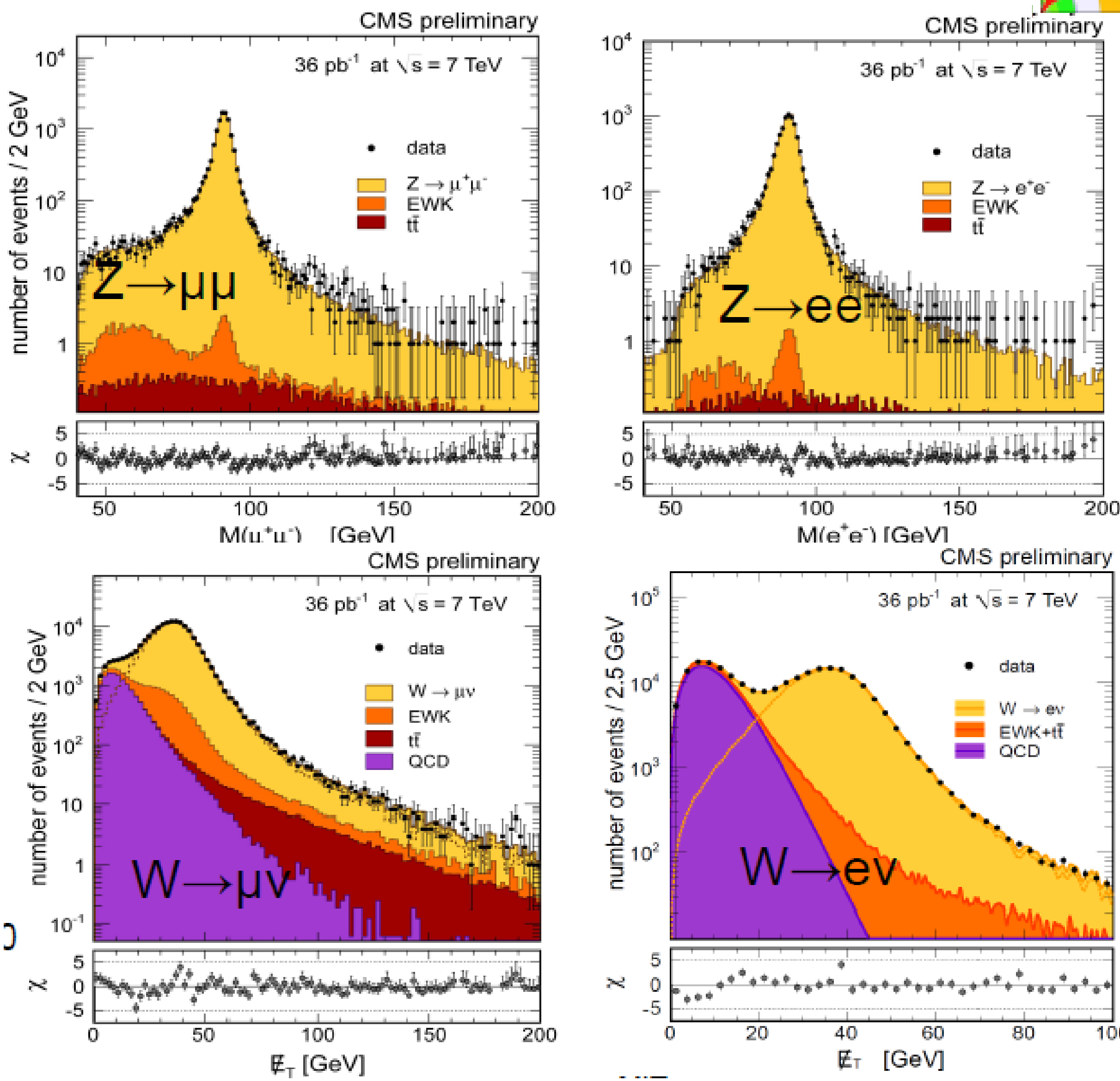
$$u\,\bar{d} \rightarrow W^{+} \rightarrow e^{+}\,\nu_{e}$$

Anti-quarks from the sea!

Z bosons are alos produced at the LHC



Z and W production at LHC

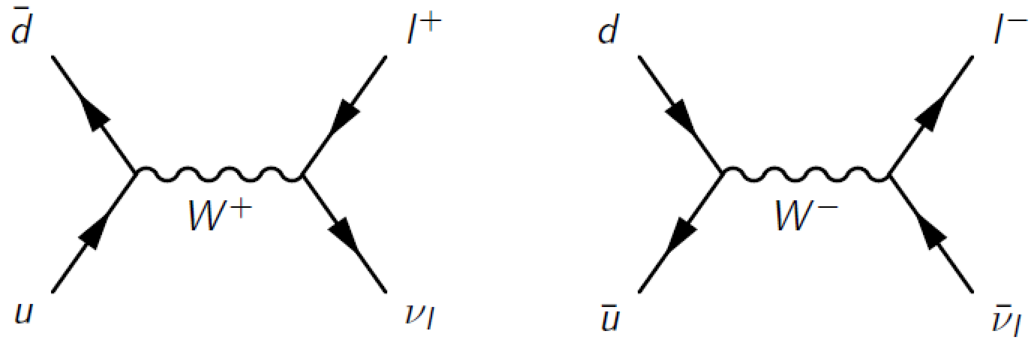


P.Harris, Moriond 2011

Instead of E_{eT} use E_T (i.e. $E_{\upsilon T}$)

W-boson production at LHC

Valence quark +
sea quark

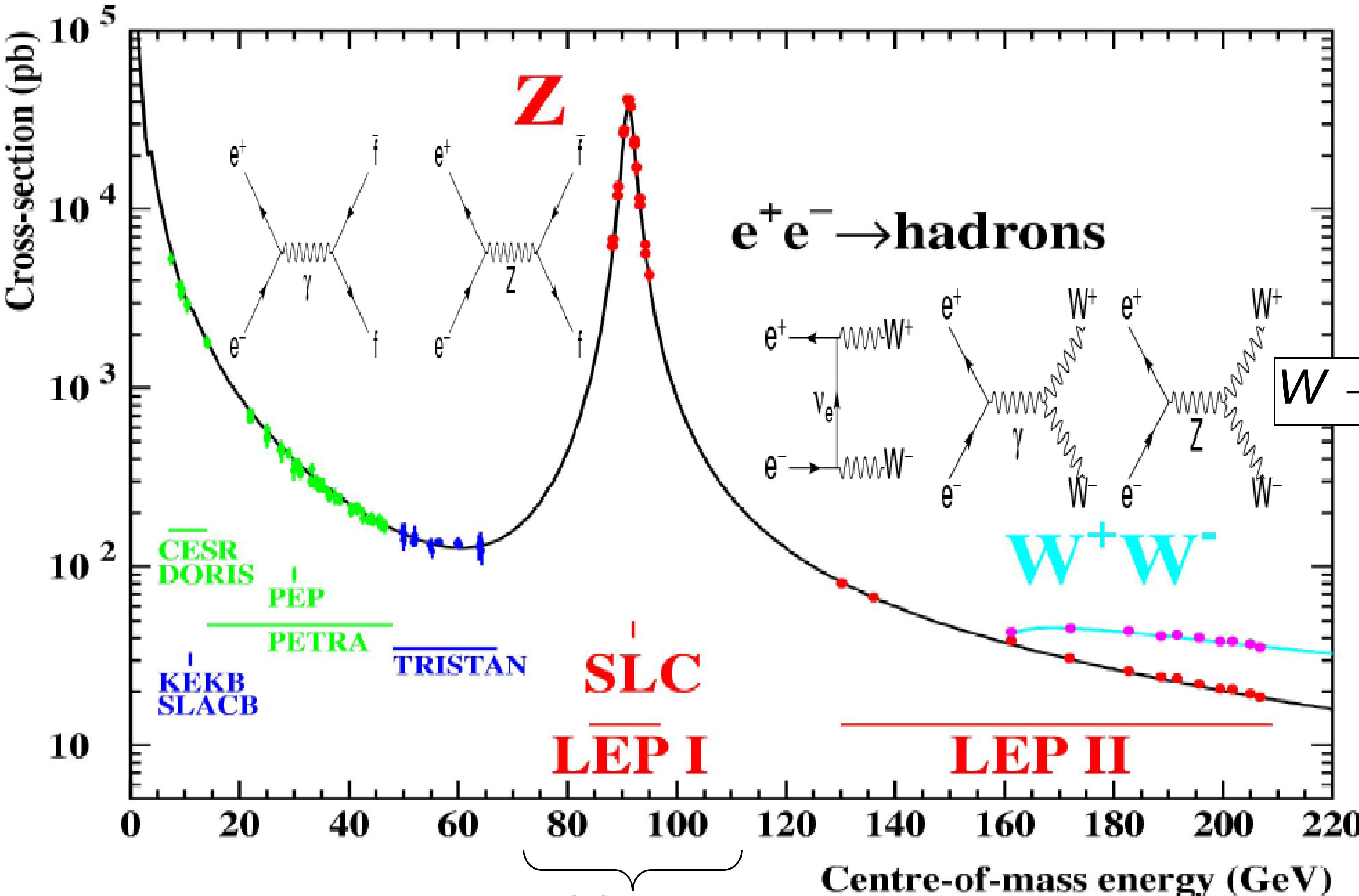


valence quark ratio u/d = 2 $\Rightarrow$ more W^+ than W^-

ATLAS 2010:

[nb]	Data
W^+	6.257±0.017(sta)±0.152(sys)±0.213(lum)±0.188(acc)
W^-	4.149±0.014(sta)±0.102(sys)±0.141(lum)±0.124(acc)
W	10.391±0.022(sta)±0.238(sys)±0.353(lum)±0.312(acc)

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

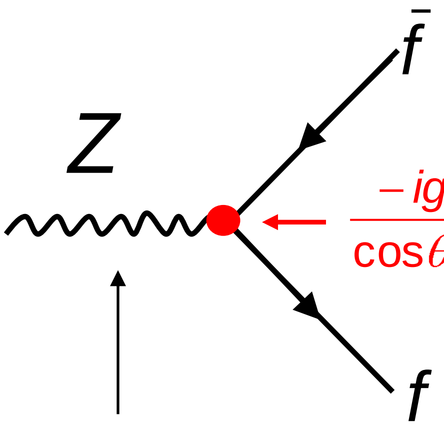


$W \rightarrow q\bar{q}$

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

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

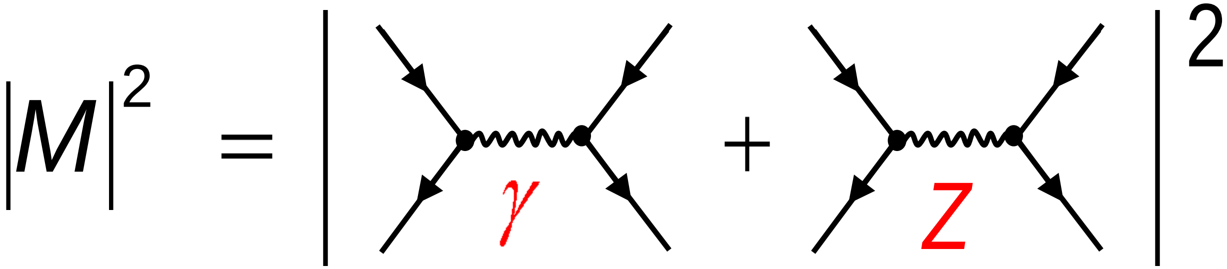
$$g_L = \frac{1}{2}(g_V + g_A) \qquad g_R = \frac{1}{2}(g_V - g_A)$$

$$\frac{g_V}{g_A} = 1 - 2\frac{Q}{T_3}\sin^2\theta_W = 1 - 4|Q|\sin^2\theta_W$$

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

	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 $e^+e^- \rightarrow \gamma / Z \rightarrow f\bar{f}$



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

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

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

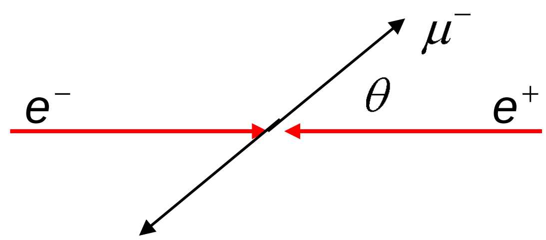
Z propagator considering a finite Z width (real particle)

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

One finds for the differential cross section:

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

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



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

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

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

At the Z-pole $\sqrt{s} \approx M_Z$ $\rightarrow$ 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 Resonance:
BW description is very general

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

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

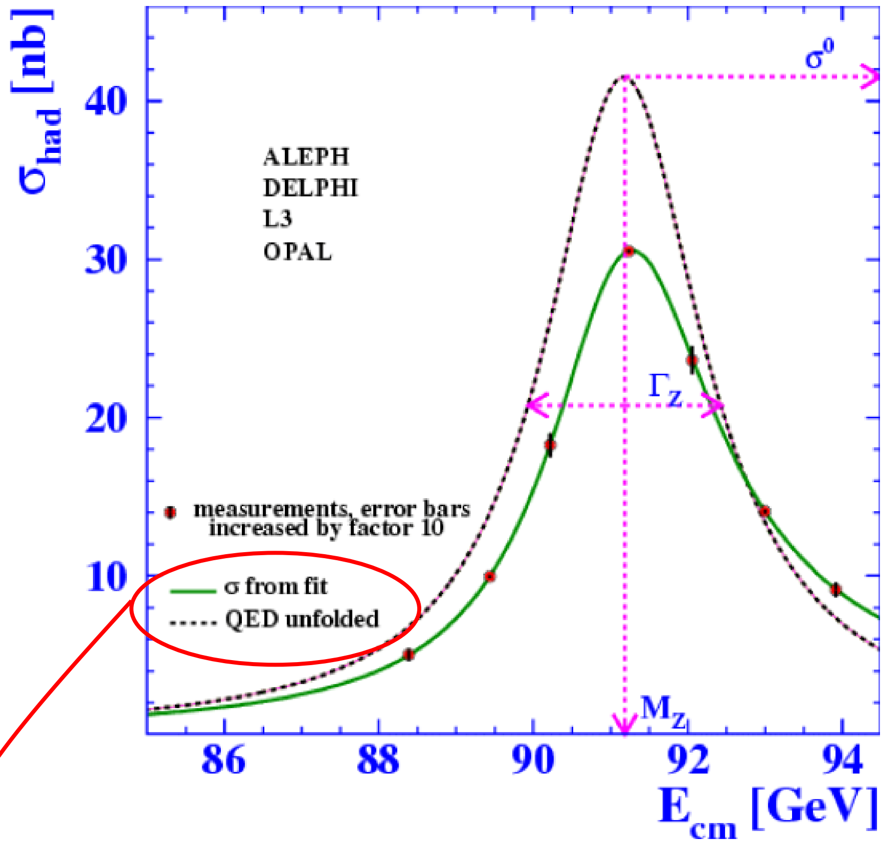
With partial and total widths:

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

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

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:

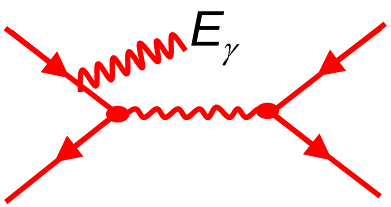
$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

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

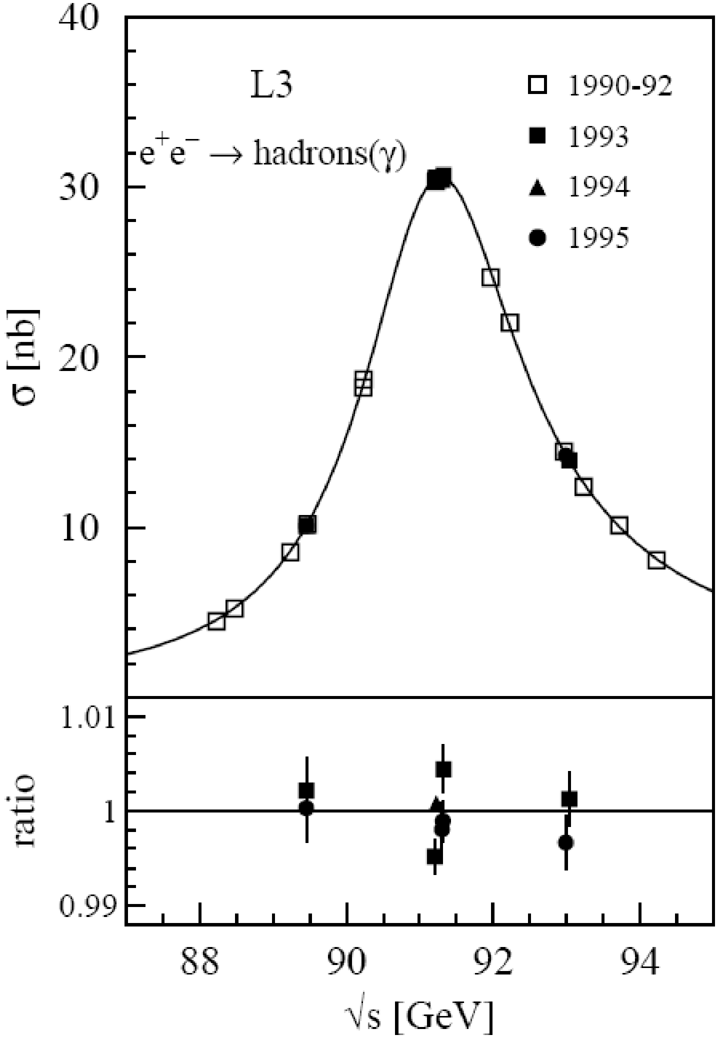
Initial state Bremsstrahlung corrections

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

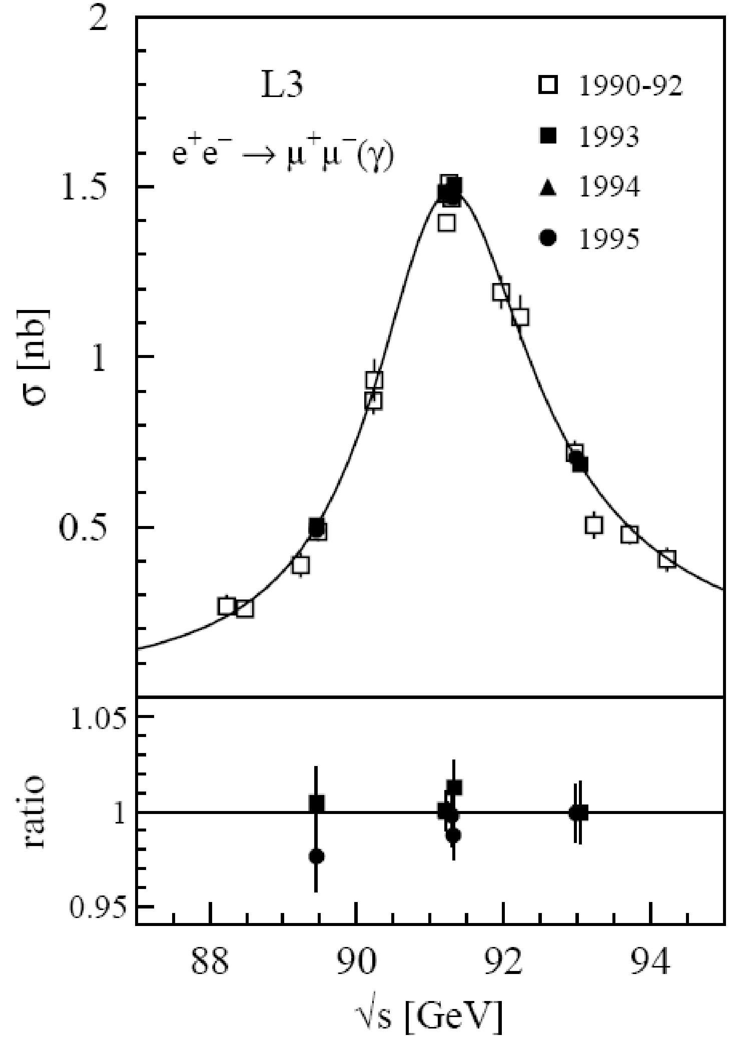


Leads to a deformation of the resonance: large (30%) effect !

$e^+ e^- \to hadrons$



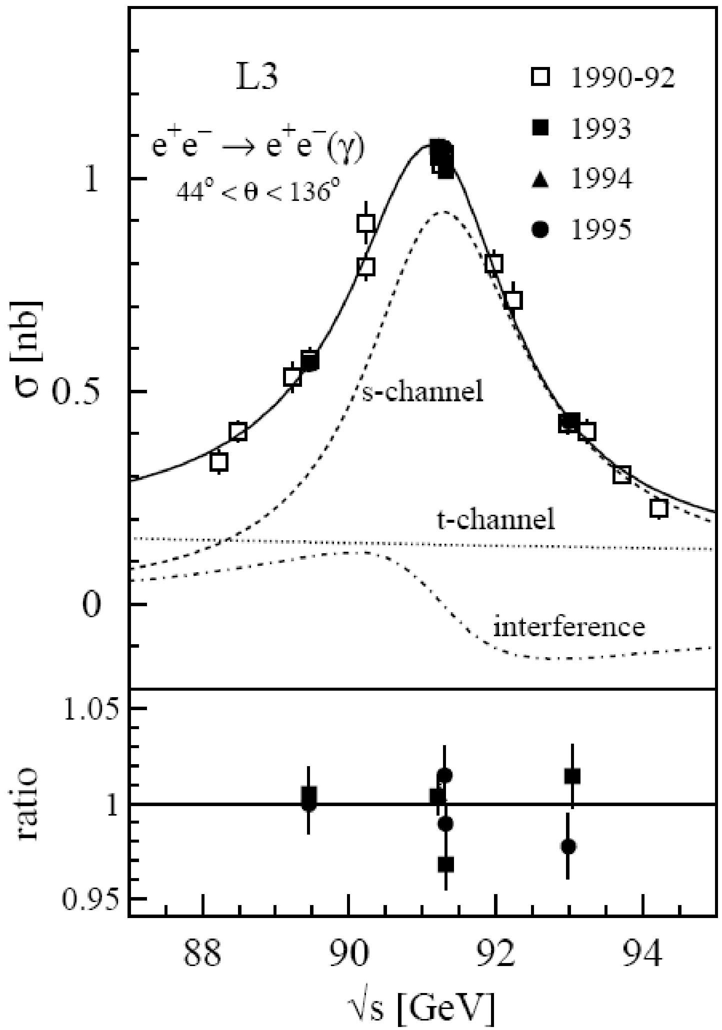
$e^+ e^- \to \mu^+ \mu^-$

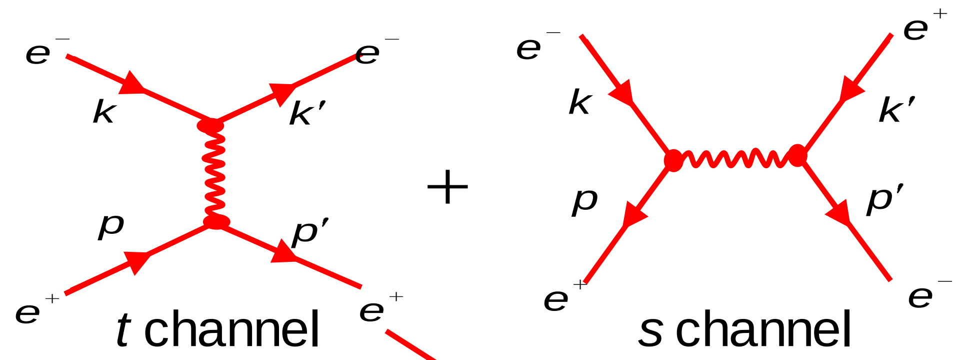


Resonance shape is the same, independent of final state: Propagator the same!

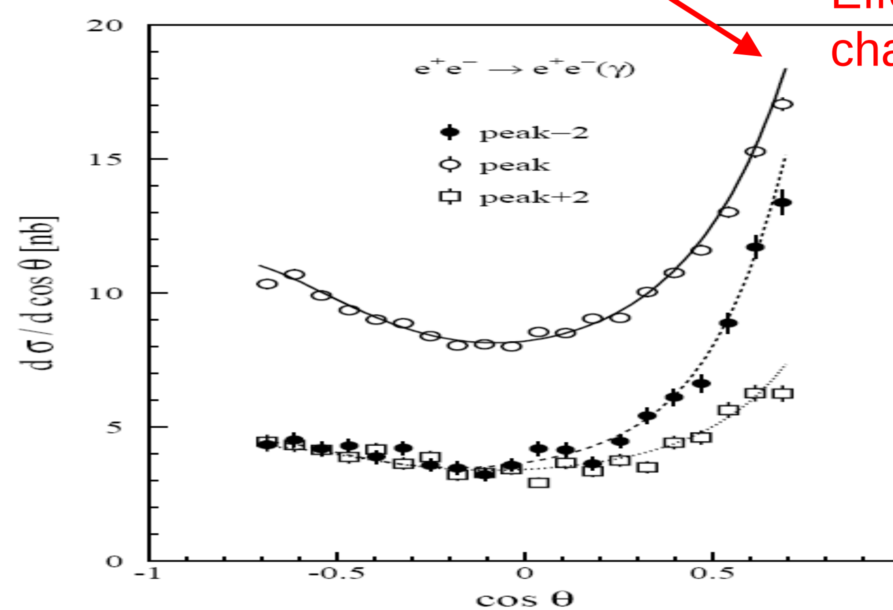
$e^+e^- \to e^+e^-$

t channel contribution → forward peak





Effect of t channel



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

Z line shape parameters (LEP average)

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

Γ_Z = 2.4952 $\pm$ 0.0023 GeV
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

$\pm$0.09 %

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: $\pm$1.7 MeV (19 ppm)

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

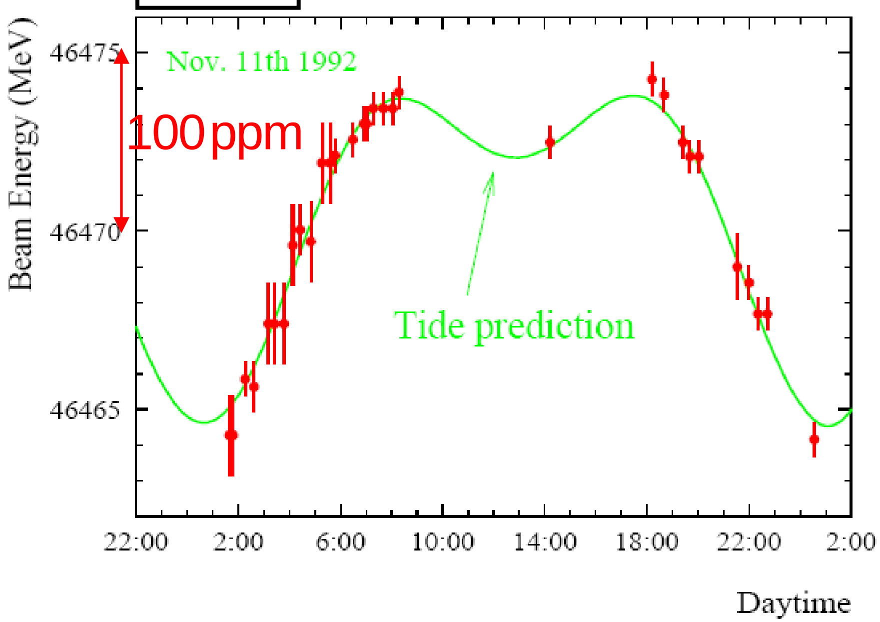
LEP energy calibration: Hunting for ppm effects

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

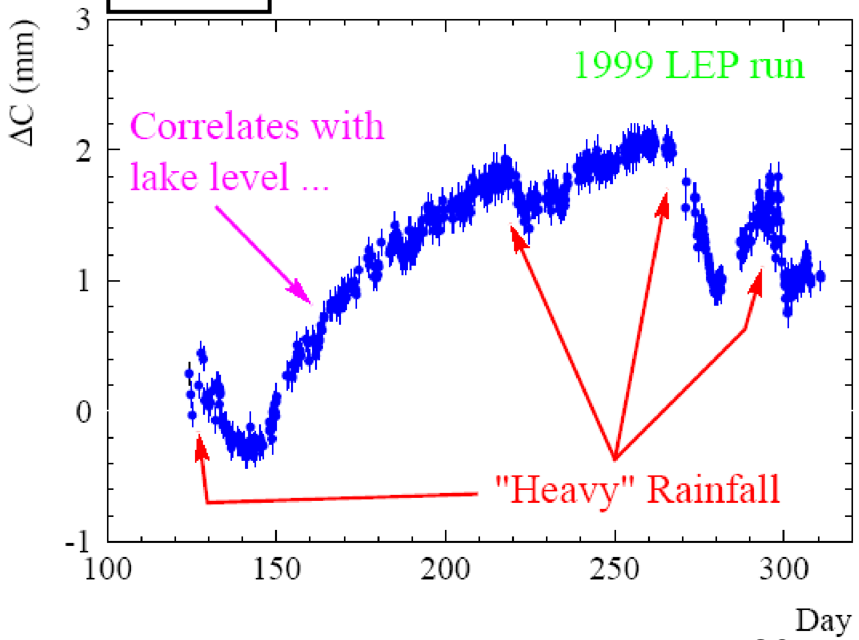
Changes of LEP circumference ΔC=1…2 mm/27km (4…8x10^{-8})

1992 Effect of moon



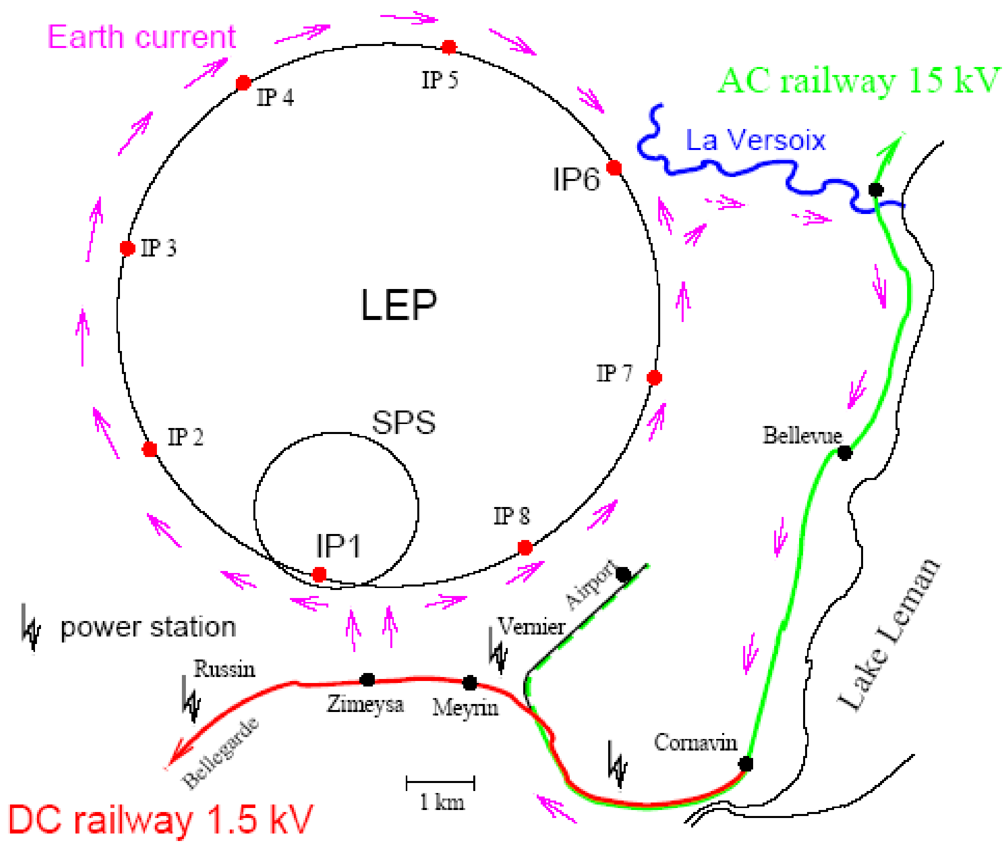
The total strain is 4 x 10^{-8} (ΔC = 1 mm)

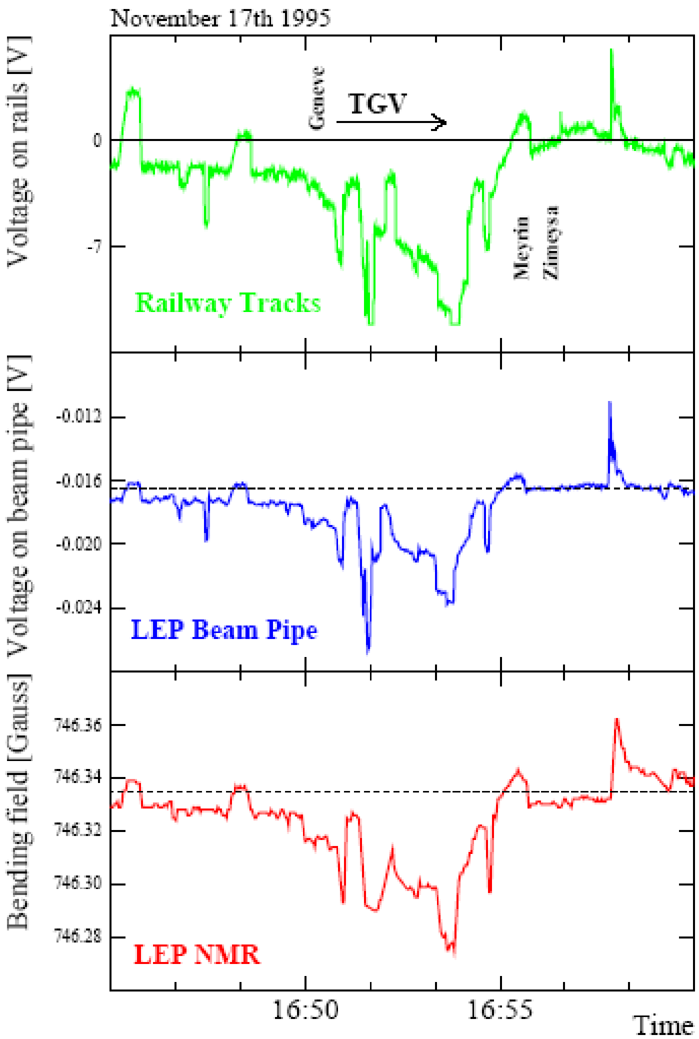
1993 Effect of lake



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!