Experimental tests of the Standard Model

today

0. Standard Model in a Nutshell
1. Discovery of W and Z boson
2. Precision tests of the Z sector

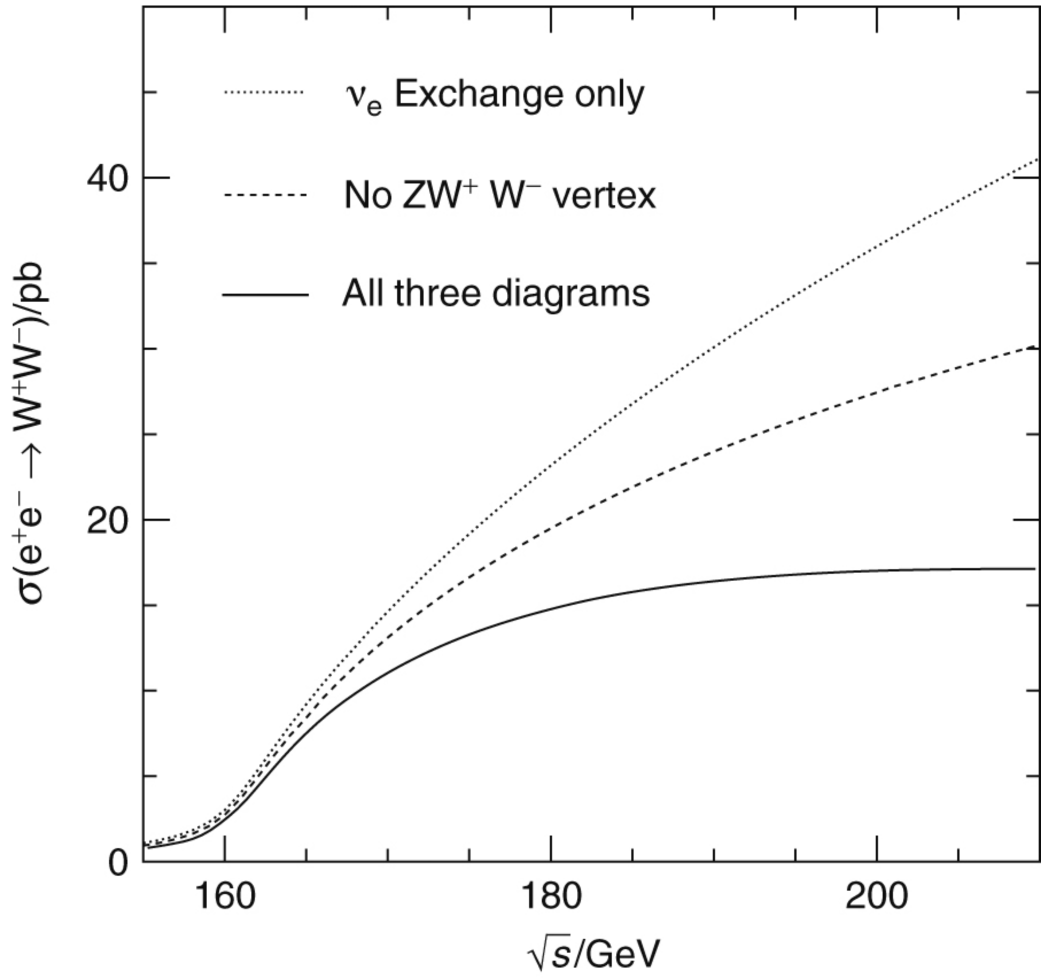
Friday

3. Precision test of the W sector
4. Radiative corrections and prediction of the Higgs mass

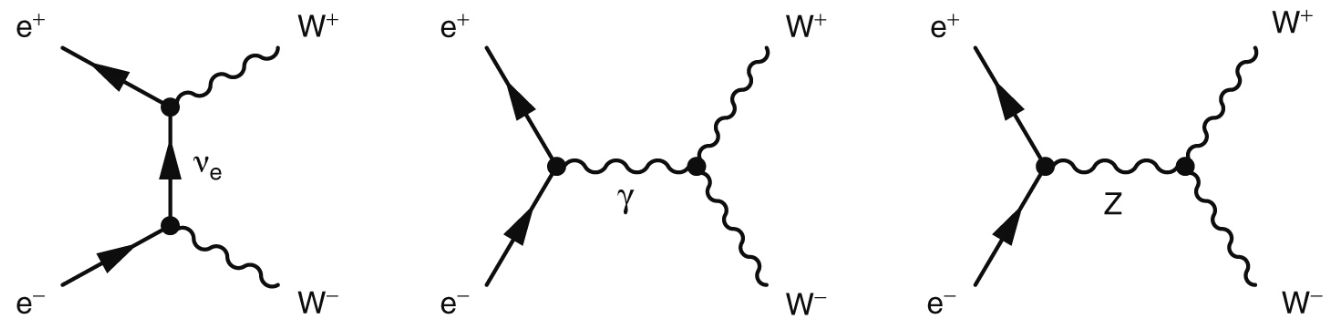
in two weeks

5. Higgs searches

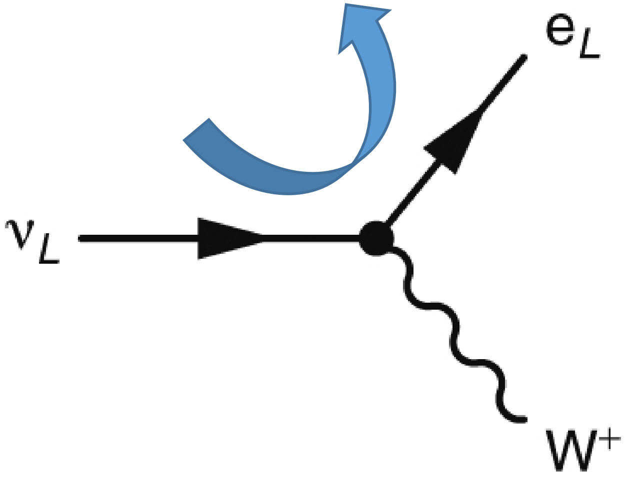
Why do we need electroweak unification?

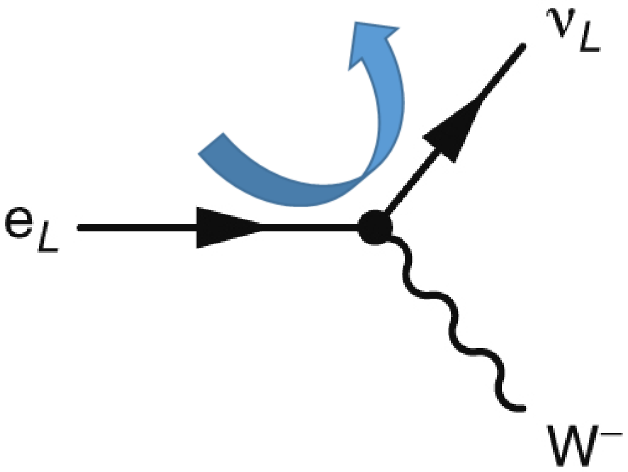


Divergence of the e+e- → WW cross-section acounting only for ν and γ exchange indicated the **existance of a further exchange boson**.



Isospin lowering and rising currents





$$\begin{aligned} j^\mu_+ &= \frac{1}{\sqrt{2}}(j^\mu_1 + i j^\mu_2) \\ &= \overline{\Psi}_L \gamma^\mu \frac{1}{2}(\sigma_1 + i\sigma_2)\Psi_L \\ &= \frac{1}{\sqrt{2}}(\overline{\nu}_L \quad \overline{e}_L)\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\ &= \frac{1}{\sqrt{2}}\overline{\nu}_L \gamma^\mu \frac{1}{2}(1-\gamma^5)e \end{aligned}$$

$$j^\mu_- = \frac{1}{\sqrt{2}}\overline{e}_L \gamma^\mu \frac{1}{2}(1-\gamma^5)\nu$$

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

$\updownarrow$ $W^\pm$

$$e_R^- \quad \mu_R^- \quad \tau_R^-$$

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:

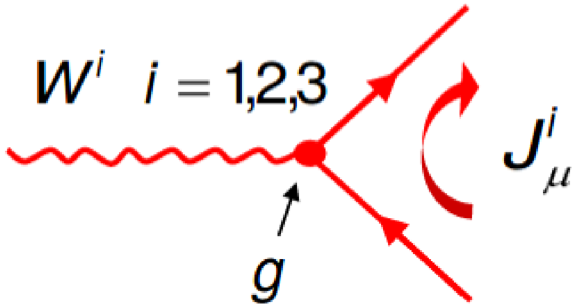
- Photon γ which couples to the LH and RH fermions with same strength.
- Z boson which couples to LH and RH fermions with different couplings g_L and g_R

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

$\Rightarrow$ Additional gauge field B

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

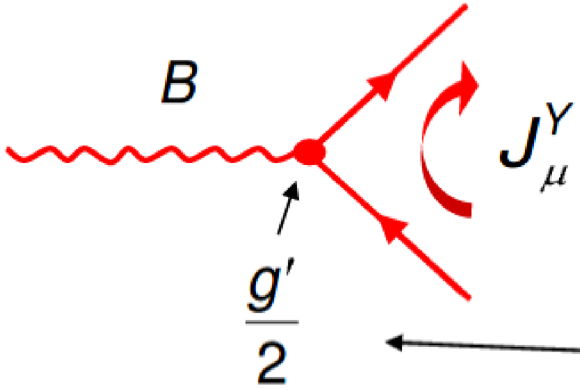
couples to LH and RH fermions



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

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

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



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

convention

g, g′ are coupling constants.

Electroweak quantum numbers

Leptons	T	T_3	Q	Y
ν_e	1/2	+1/2	0	-1
e_L	1/2	-1/2	-1	-1
e_R	0	0	-1	-2

Quarks	T	T_3	Q	Y
u_L	1/2	+1/2	2/3	1/3
d'_L	1/2	-1/2	-1/3	1/3
u_R	0	0	-1	-2
d_R	0	0	-1/3	-2/3

$$Y = 2\,[Q - T_3]$$

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:

$$\boxed{\begin{aligned} A_\mu &= B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W \\ Z_\mu &= -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W \\ \\ B_\mu &= A_\mu \cos\theta_W - Z_\mu \sin\theta_W \\ W_\mu^3 &= A_\mu \sin\theta_W + Z_\mu \cos\theta_W \end{aligned}}$$

massless photon

massive Z boson

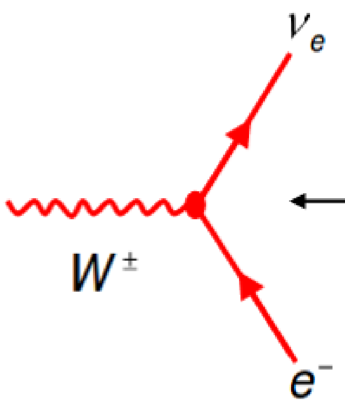
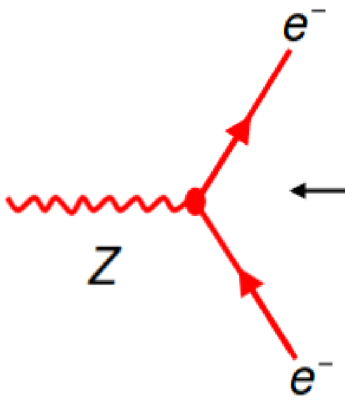
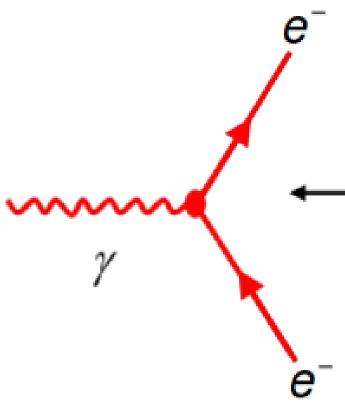
$$g_Z = \frac{g}{\cos\theta_W} \qquad g' = g\frac{\sin\theta_W}{\cos\theta_W}$$

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

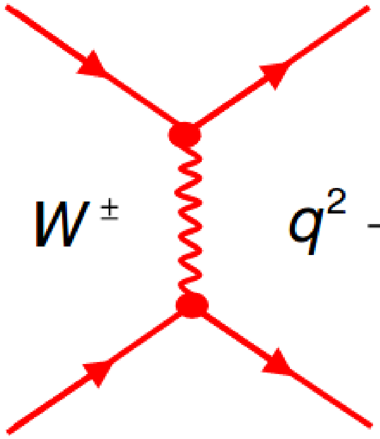
$$\boxed{g = \frac{e}{\sin\theta_W} \qquad g' = \frac{e}{\cos\theta_W}}$$

Coupling to the photon field ~e

Feynman rules

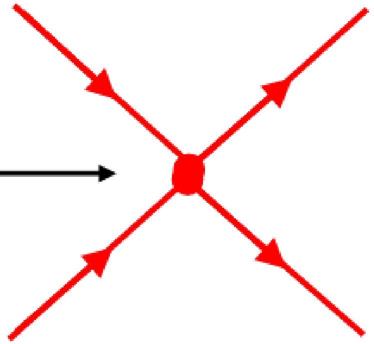
	Vertex factors	Propagator (unitary gauge)
	$-i\frac{g}{\sqrt{2}}\gamma_\mu\frac{1}{2}(1-\gamma^5)$	$\frac{g_{\mu\nu}-q_\mu q_\nu/M_W^2}{q^2-M_W^2}$
	$-i\frac{g}{\cos\theta_W}\gamma_\mu\frac{1}{2}(g_V-g_A\gamma^5)$	$\frac{g_{\mu\nu}-q_\mu q_\nu/M_Z^2}{q^2-M_Z^2}$
	$-ie\gamma_\mu$	$\frac{1}{q^2}$

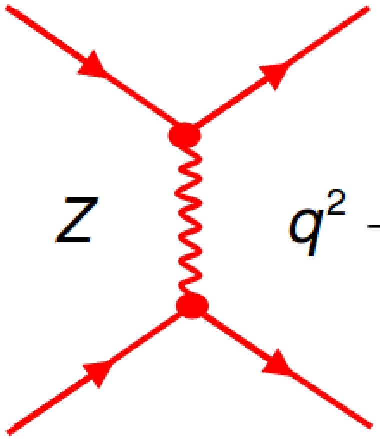
$$
\begin{aligned}
g_V &= I_3 - 2Q\sin^2\theta_w \\
g_A &= I_3
\end{aligned}
$$



$q^2 \to 0:$

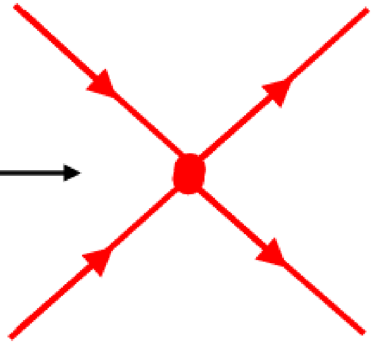
$$\boxed{\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}}$$





$q^2 \to 0:$

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



Assuming universality $\frac{G_F}{\sqrt{2}} \equiv \frac{G_{NC}}{\sqrt{2}}$ follows $\boxed{\cos^2\theta_W = \frac{M_W^2}{M_Z^2}}$

$\Delta\rho = 0$

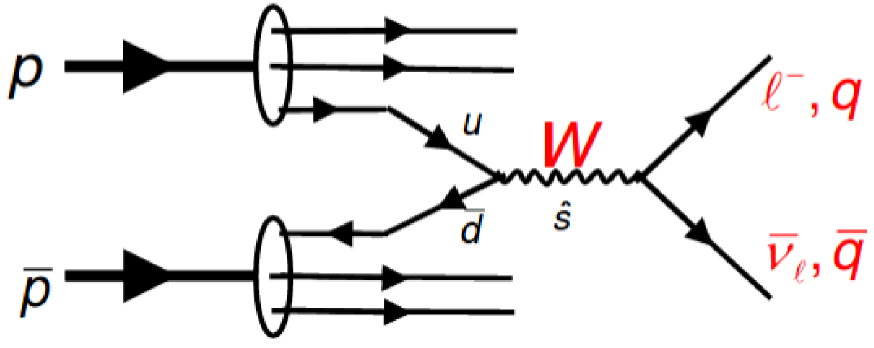
$\rho = 1 - \Delta\rho = 1$

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

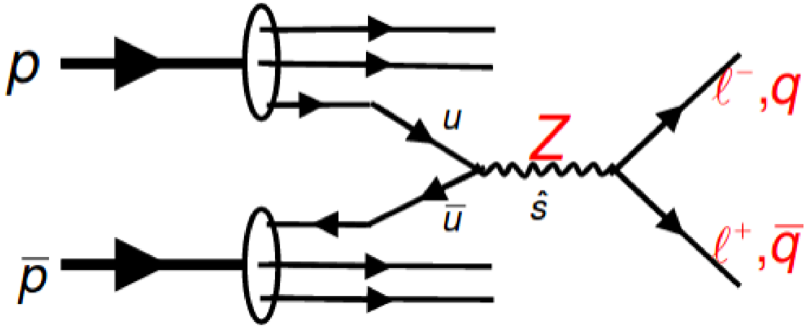
1. Discovery of the W and Z boson

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

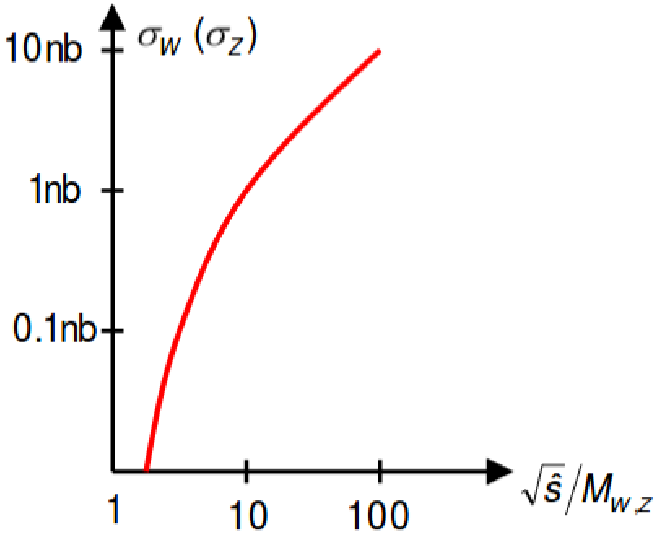
1.1 Boson production in p$\bar{p}$ interactions



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



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



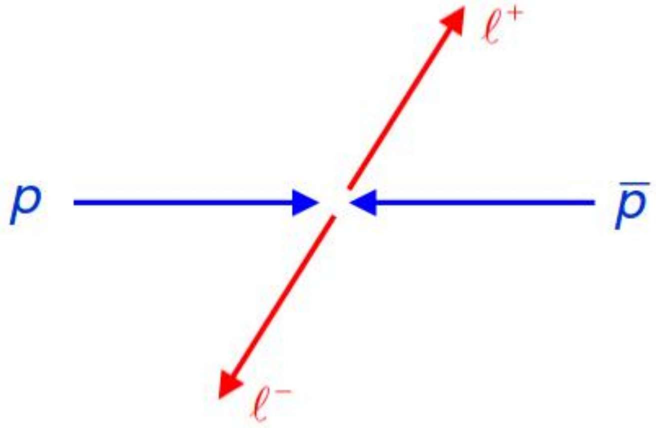
<u>Similar to Drell-Yan:</u> (photon instead of W)

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

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

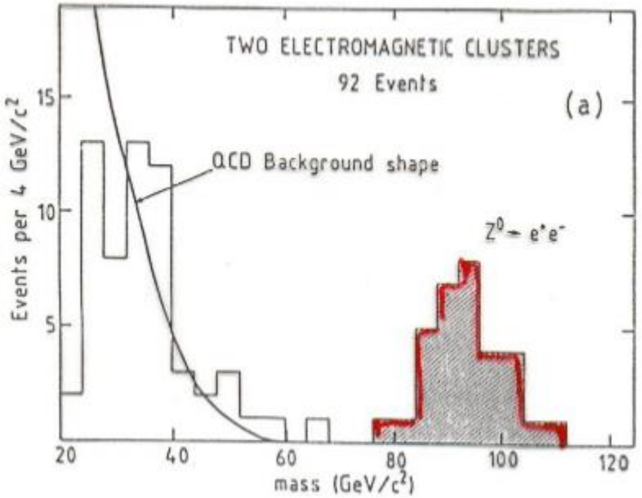
$\to$ Cross section is small !

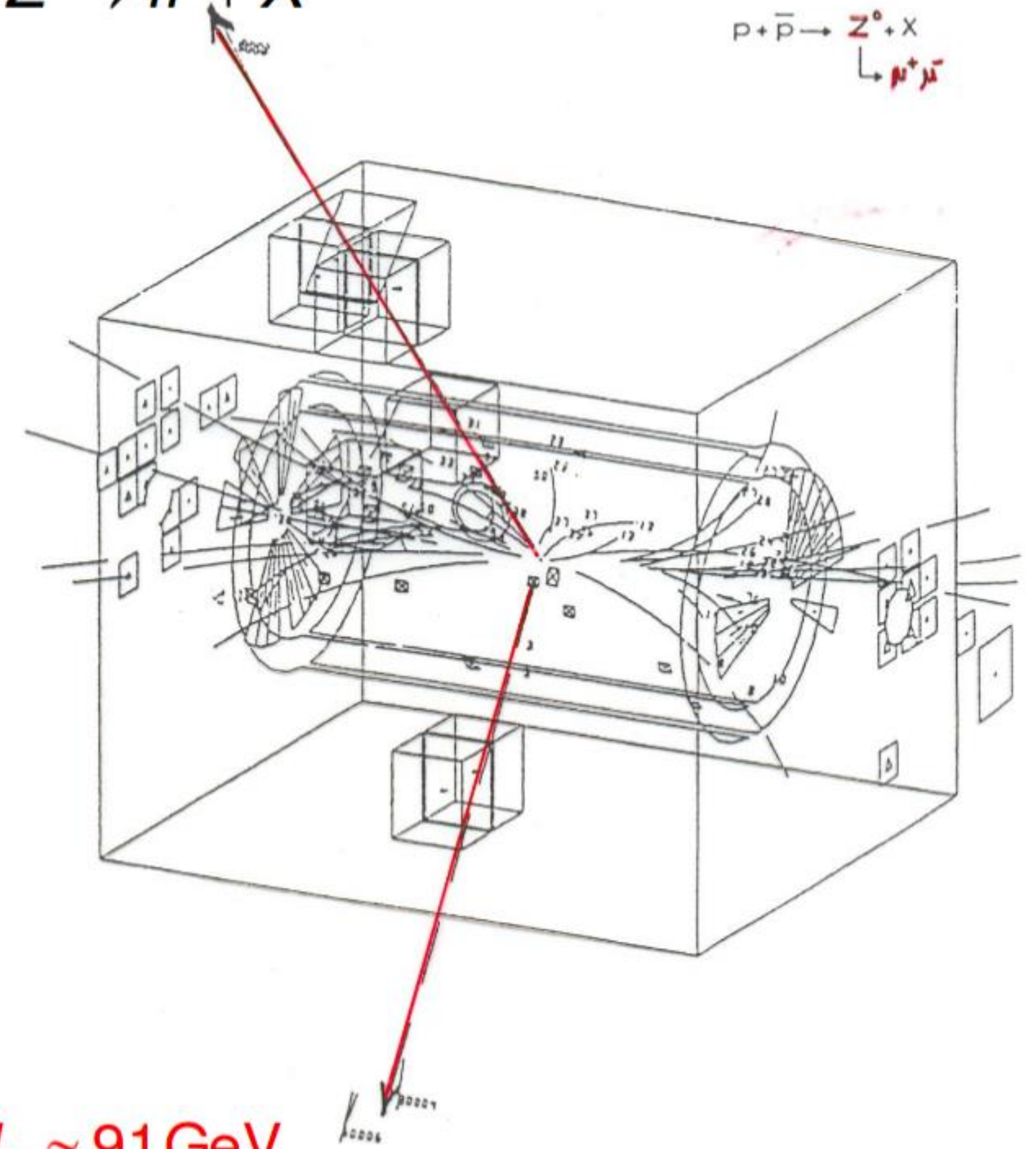
1.2 Event signature: $p\bar{p} \to Z \to f\bar{f} + X$



High-energy lepton pair:

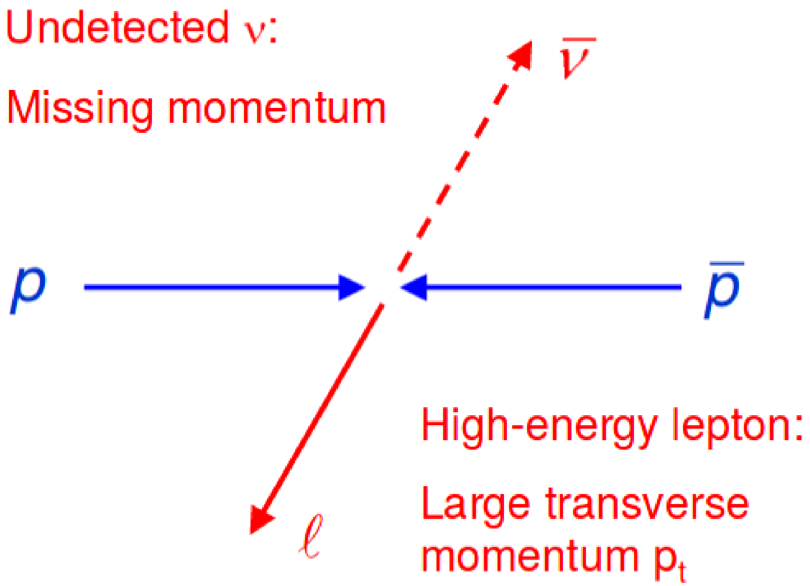
$$m_{\ell\ell}^2 = (p_{\ell^+} + p_{\ell^-})^2 = M_Z^2$$





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

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



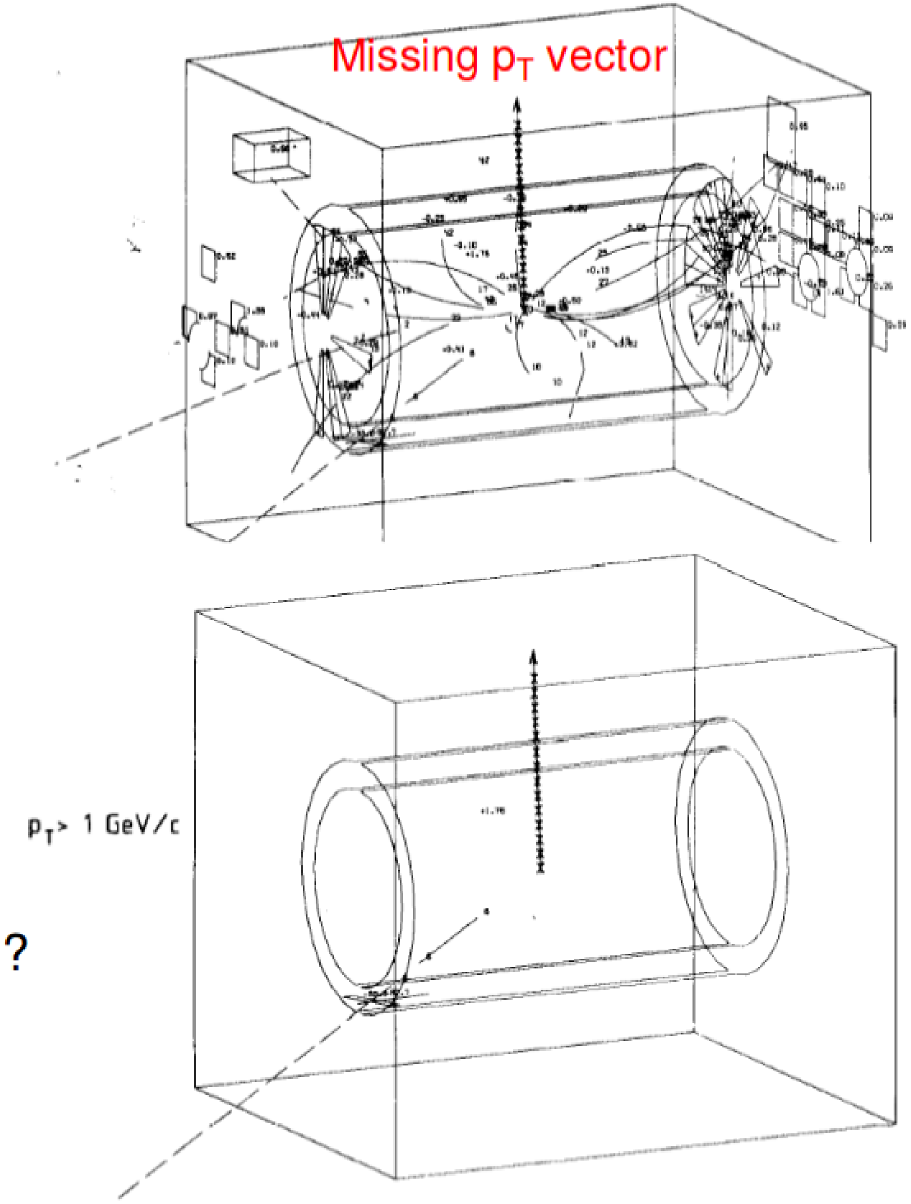
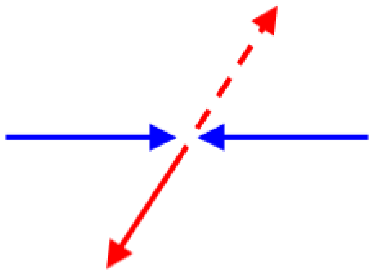


Fig. *16b*. The same as picture (a), except that now only particles with $p_T > 1$ GeV/c and calorimeters with $E_T > 1$ GeV are shown.

How can the W mass be reconstructed ?

W mass measurement



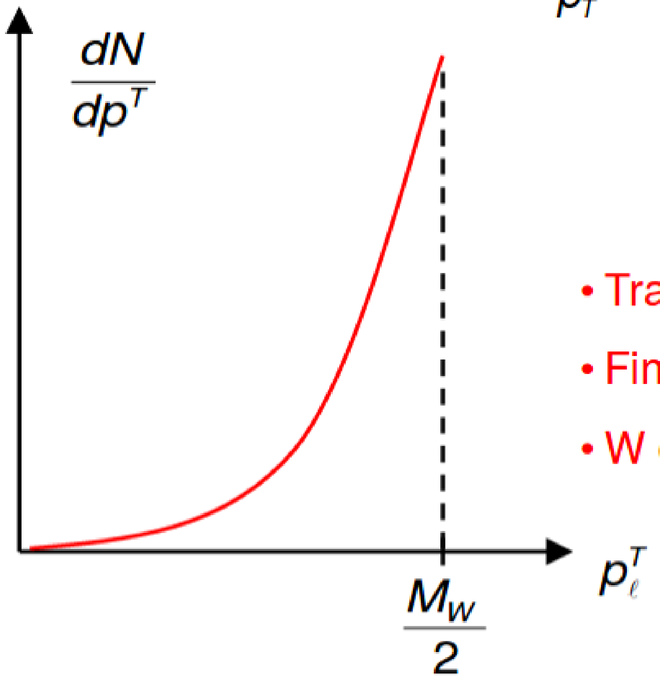
In the W rest frame:

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

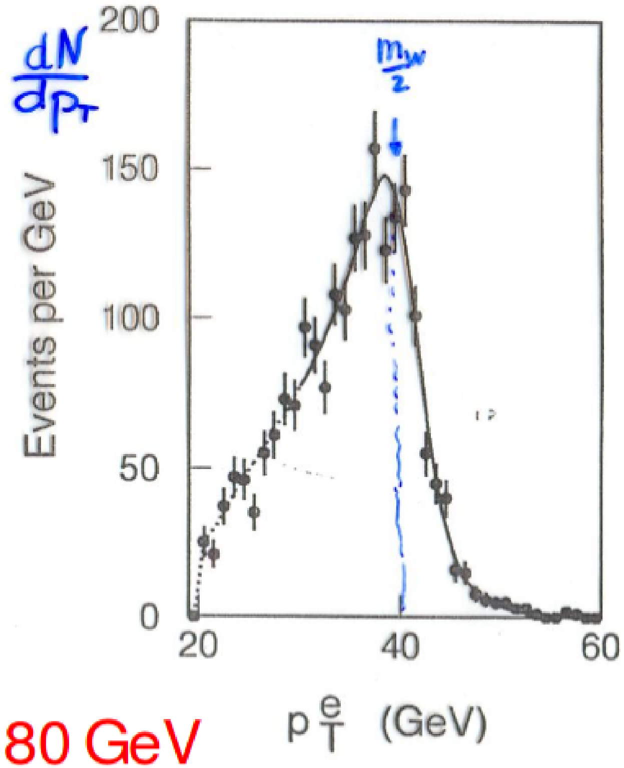
In the lab system:

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

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



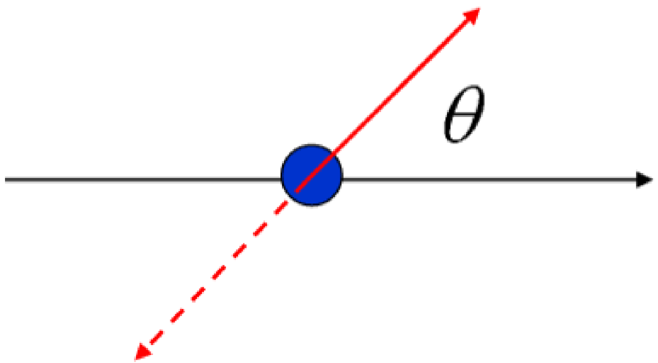
$M_W \approx 80$ GeV

Jacobian Peak

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

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

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



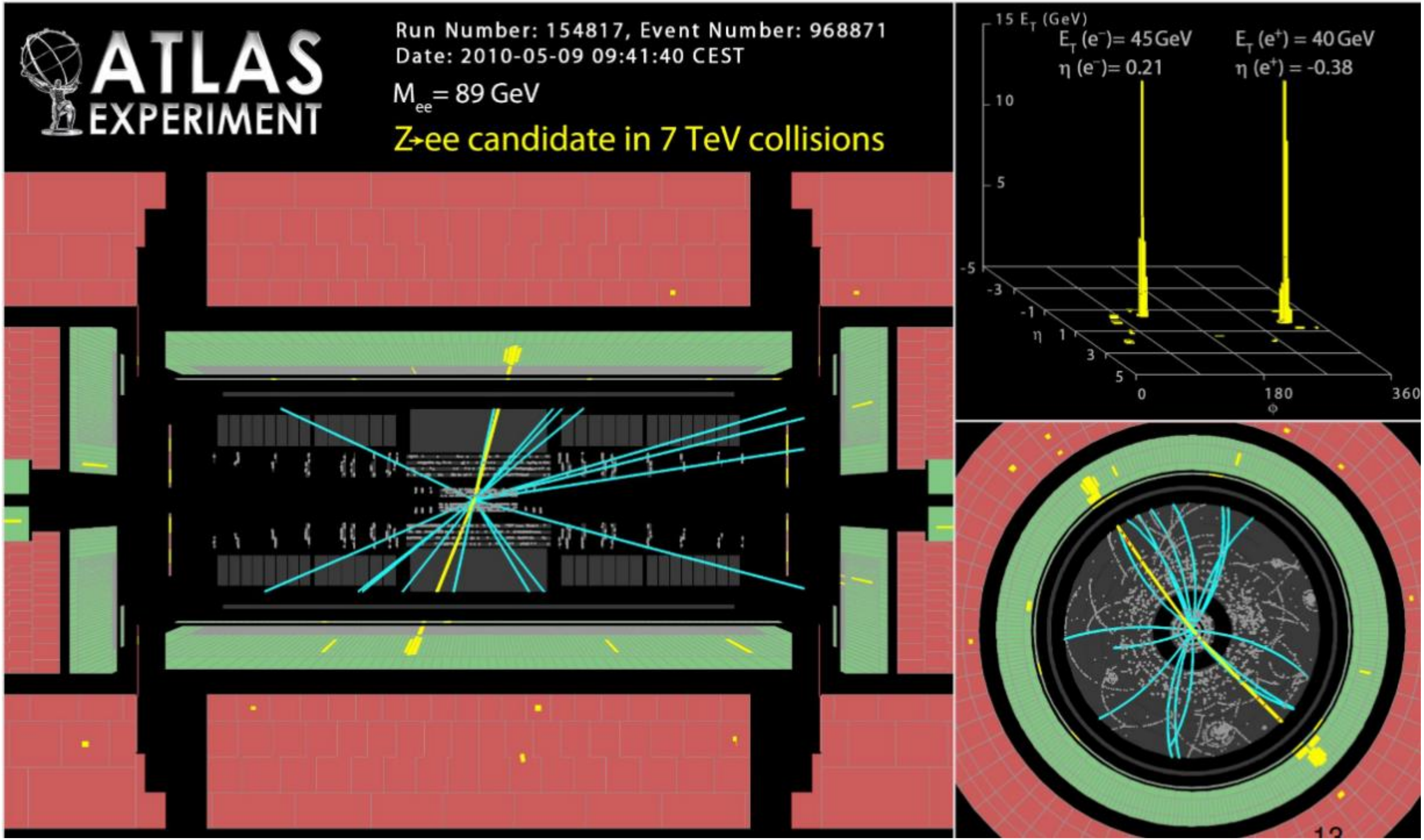
$$\sin\theta = \frac{p_T}{p} = \frac{p_T}{M_w/2}$$

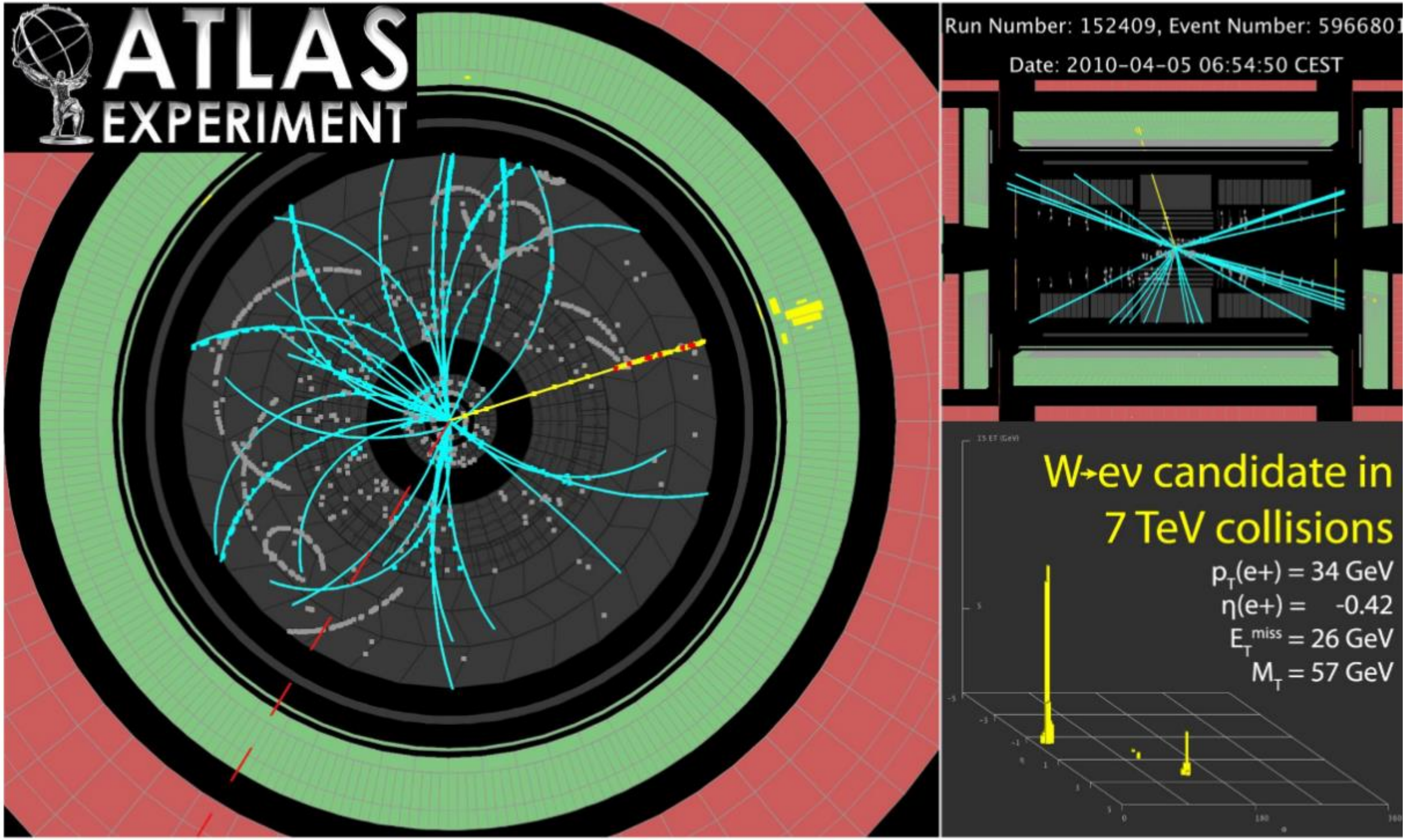
$$1-\cos^2\theta = \left(\frac{p_T}{M_w/2}\right)^2$$

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

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

Jacobian

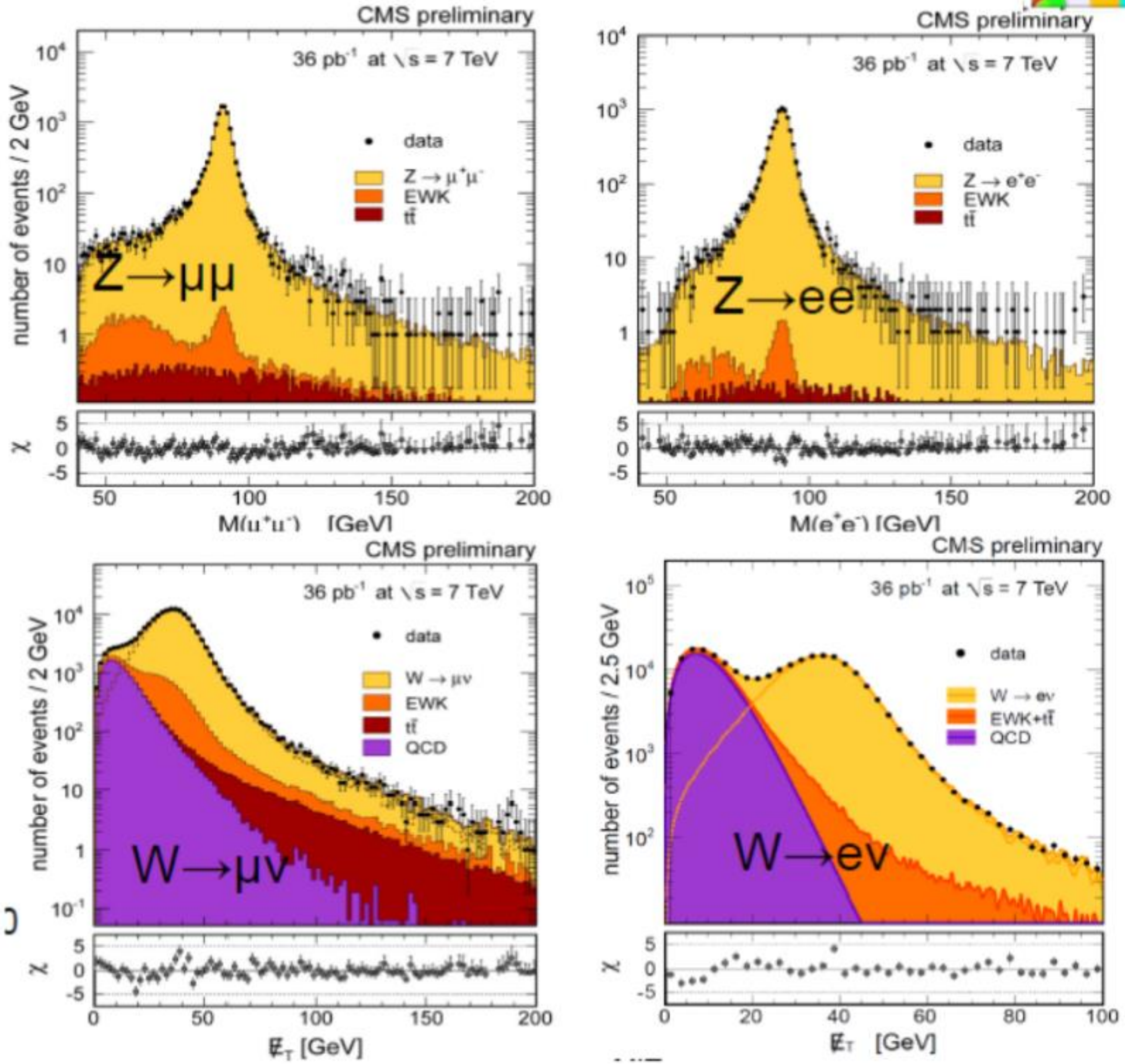

ATLAS
EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_ee = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e⁻)= 45GeV
η (e⁻)= 0.21
E_T (e⁺) = 40GeV
η (e⁺) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ



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

Anti-quarks from the sea!

Z and W production at LHC



Moriond 2011

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

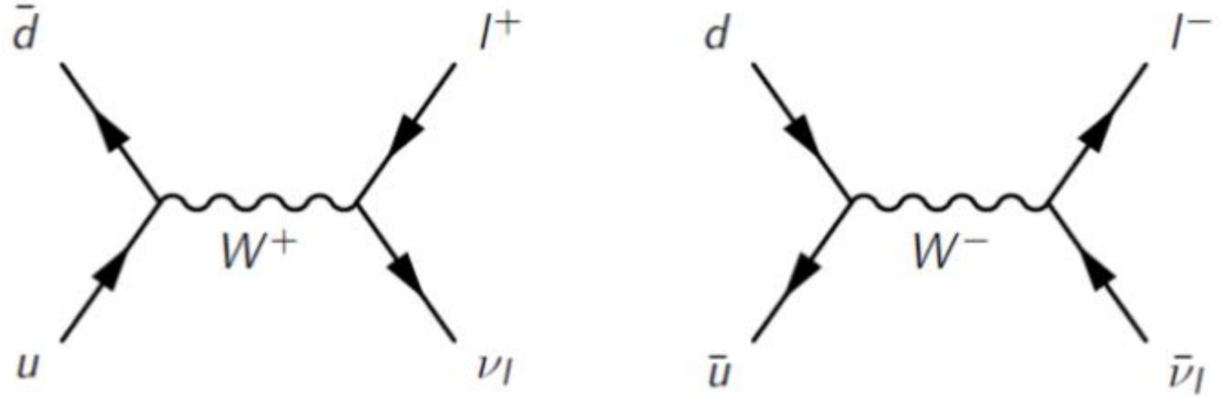
Are more W^+ or W^- produced at the LHC (pp)?

Are more W^+ or W^- produced at the Tevatron ($p\bar{p}$)?

Are more W^+ or W^- produced at LEP (e^+e^-)?

W-boson production at LHC

Valence quark +
sea quark

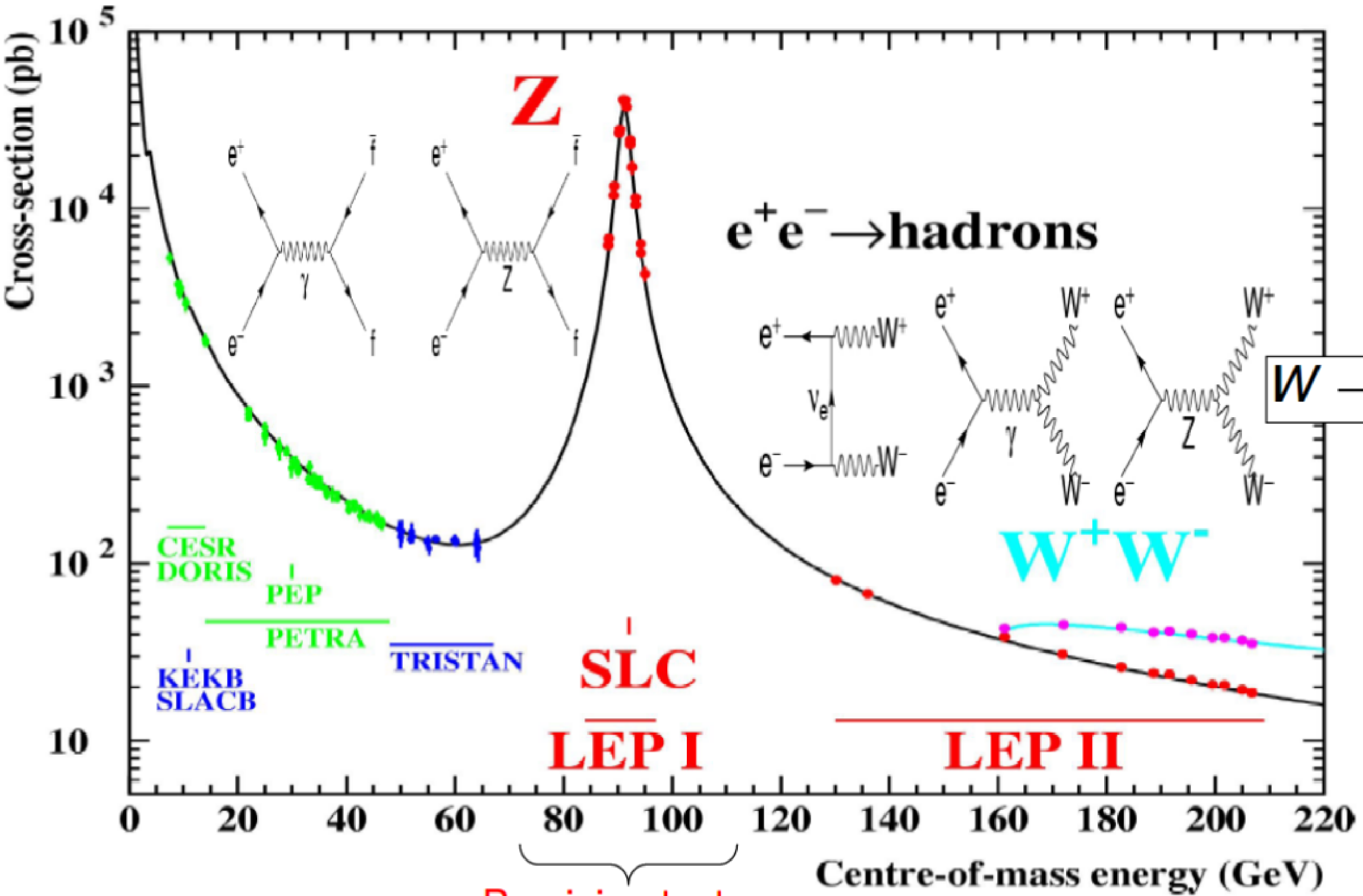


valence quark ratio u/d = 2 $\Rightarrow$ more W^+ than W^-

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

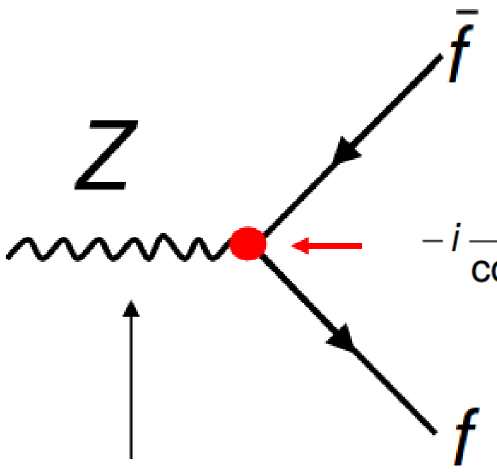


$W \to q\bar{q}$

Precision tests of the Z sector

Tests of the W sector

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



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

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

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

$$\sin^2\theta_w = 1 - \frac{M_w^2}{M_Z^2}$$

Standard Model

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

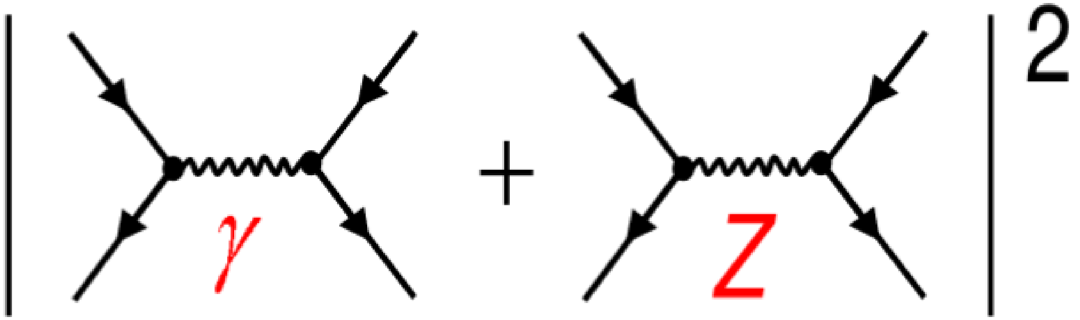
$$g_L = \frac{1}{2}(g_V + g_A) \qquad g_R = \frac{1}{2}(g_V - g_A)$$

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

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

$|M|^2 =$

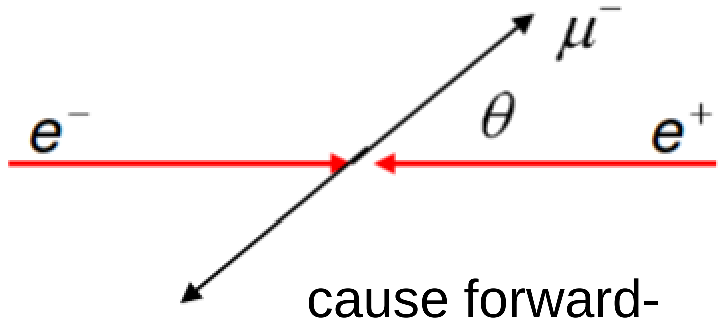


$\boxed{\text{for} \quad e^+e^- \rightarrow \mu^+\mu^-}$

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

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

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



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

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

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

cause forward-backward asymmetry vanish for total cross-section

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

$\rightarrow$ interference vanishes

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

Forward-backward asymmetry

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

with

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

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

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

Breit-Wigner Resonance is very general described:

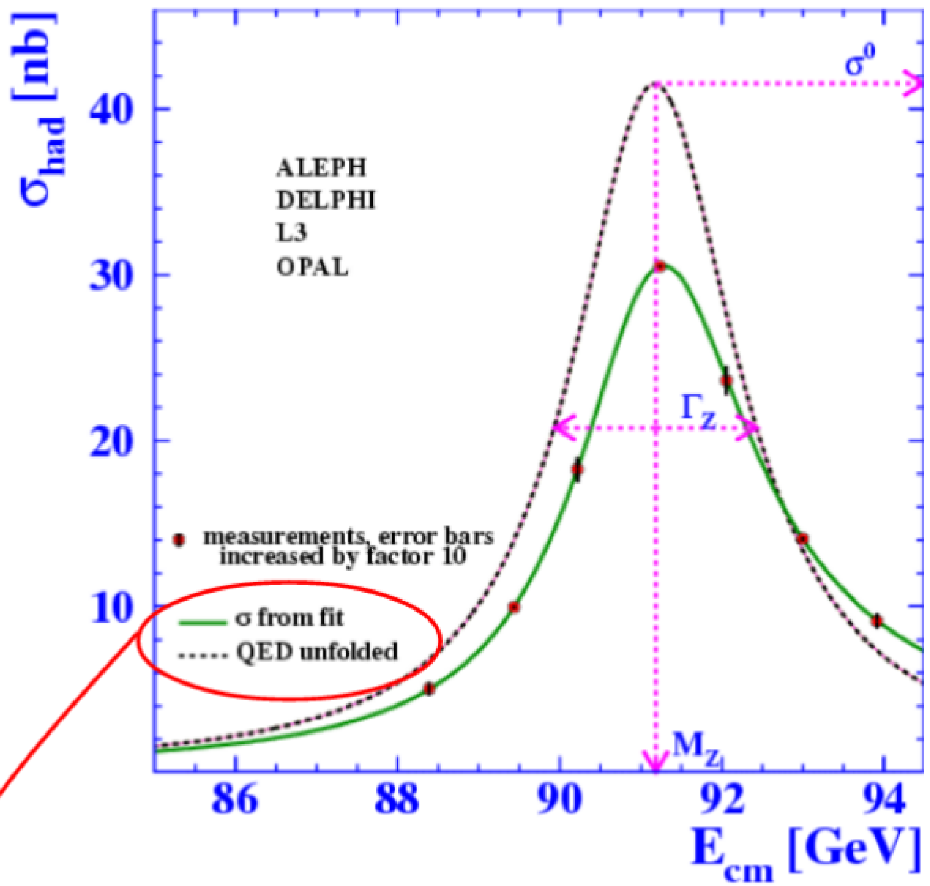
$$\sigma(s) = 12\pi\frac{\Gamma_e\Gamma_\mu}{M_Z^2}\frac{s}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

Cross sections and width can be calculated within the Standard Model, if all parameters are known:

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

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

2.2 Measurement of the Z lineshape



Z Resonance curve:

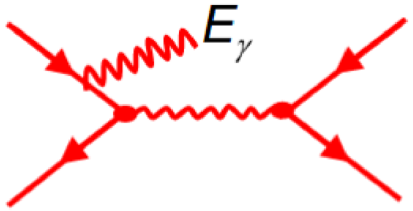
$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

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

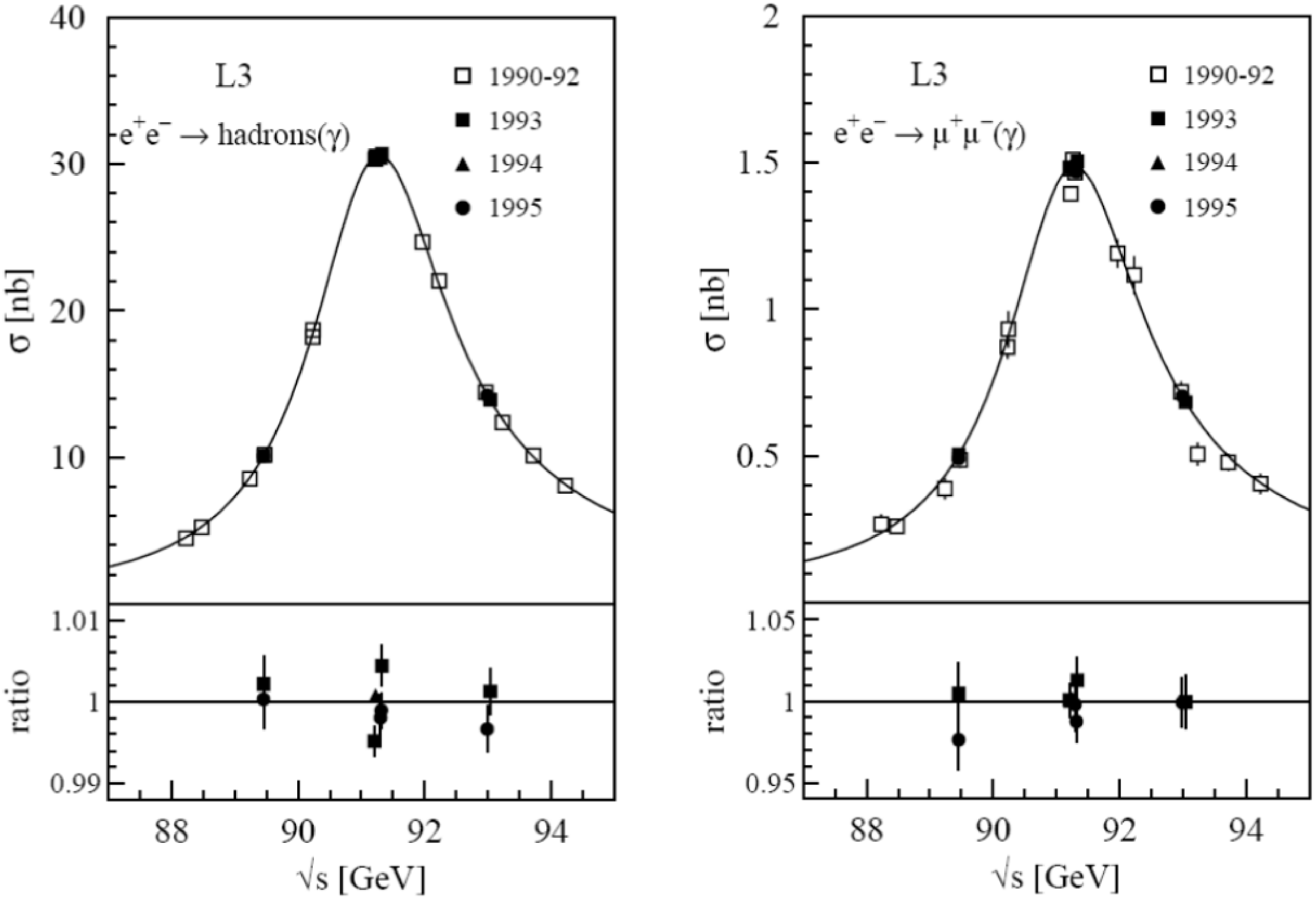
Initial state Bremsstrahlung corrections

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



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

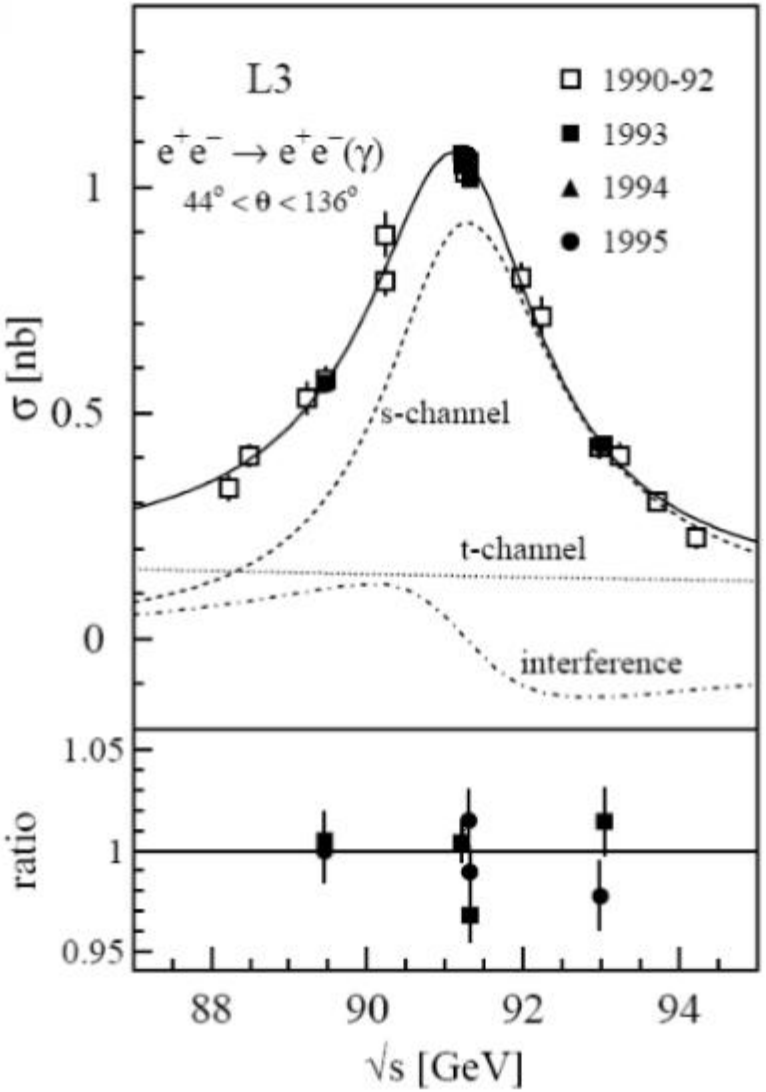
$e^+e^- \to hadrons$ $e^+e^- \to \mu^+\mu^-$

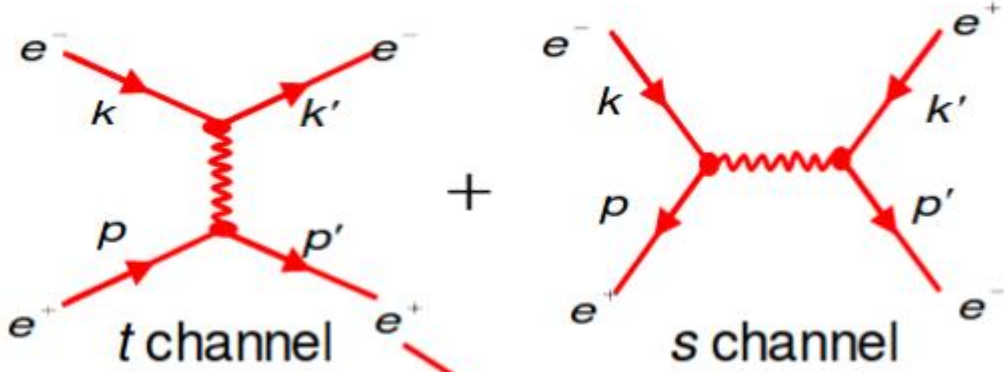


Resonance shape is the same, independent of final state: Propagator the same!

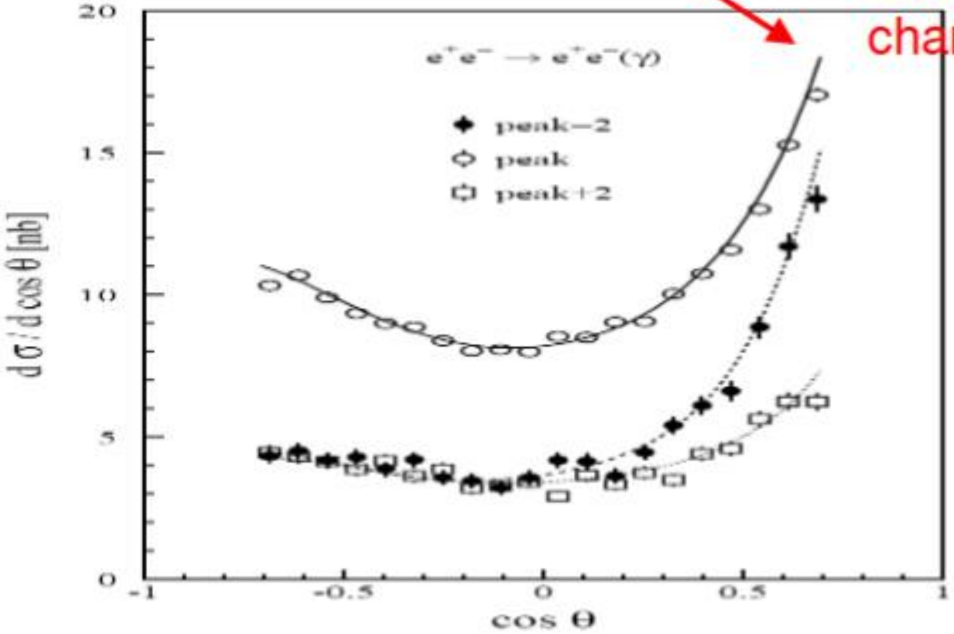
$e^+ e^- \to e^+ e^-$

t channel contribution $\to$ 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 (*)

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

$\Gamma_{had} = 1.7458 \pm 0.0027$ GeV

$\Gamma_e = 0.08392 \pm 0.00012$ GeV

$\Gamma_\mu = 0.08399 \pm 0.00018$ GeV

$\Gamma_\tau = 0.08408 \pm 0.00022$ GeV

± 0.09 %

3 leptons are treated independently

test of lepton universality

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

$\Gamma_{had} = 1.7444 \pm 0.0022$ GeV

$\Gamma_e = 0.083985 \pm 0.000086$ 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)

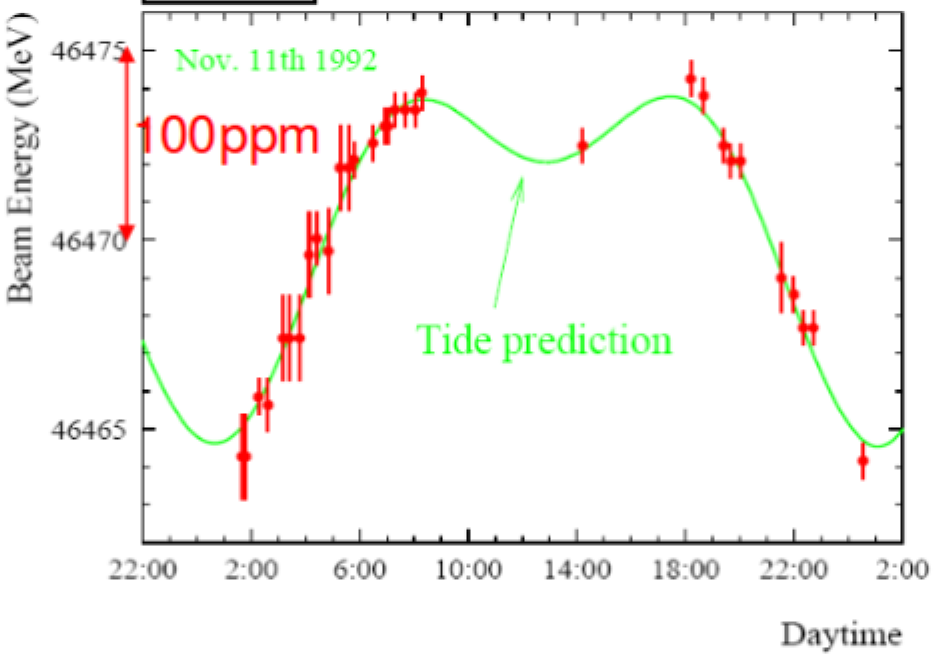
LEP energy calibration: Hunting for ppm effects

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

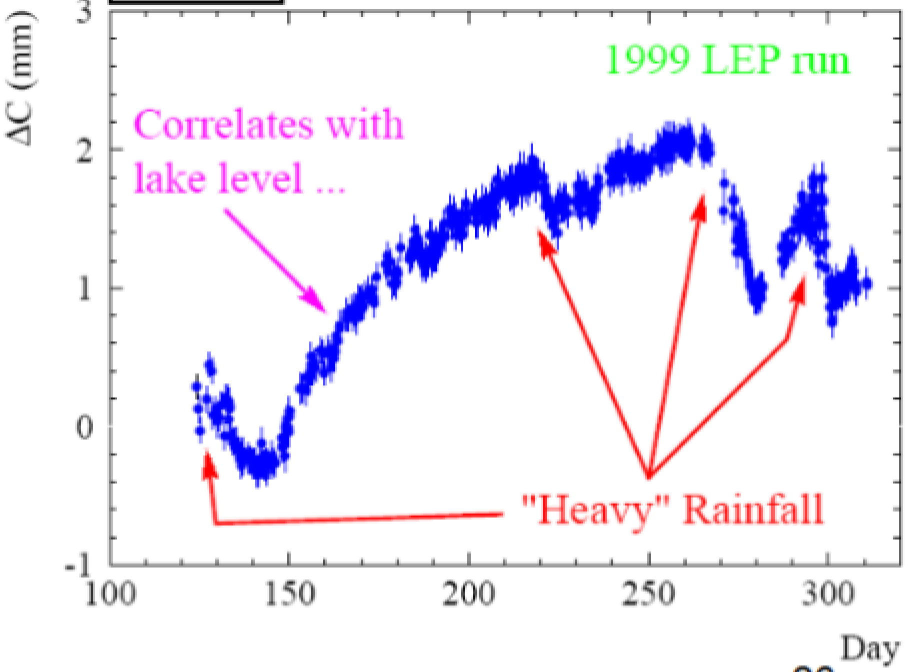
→ Changes of LEP circumference ΔC=1…2 mm/27km (4…8x10^{-8})

1992 Effect of moon



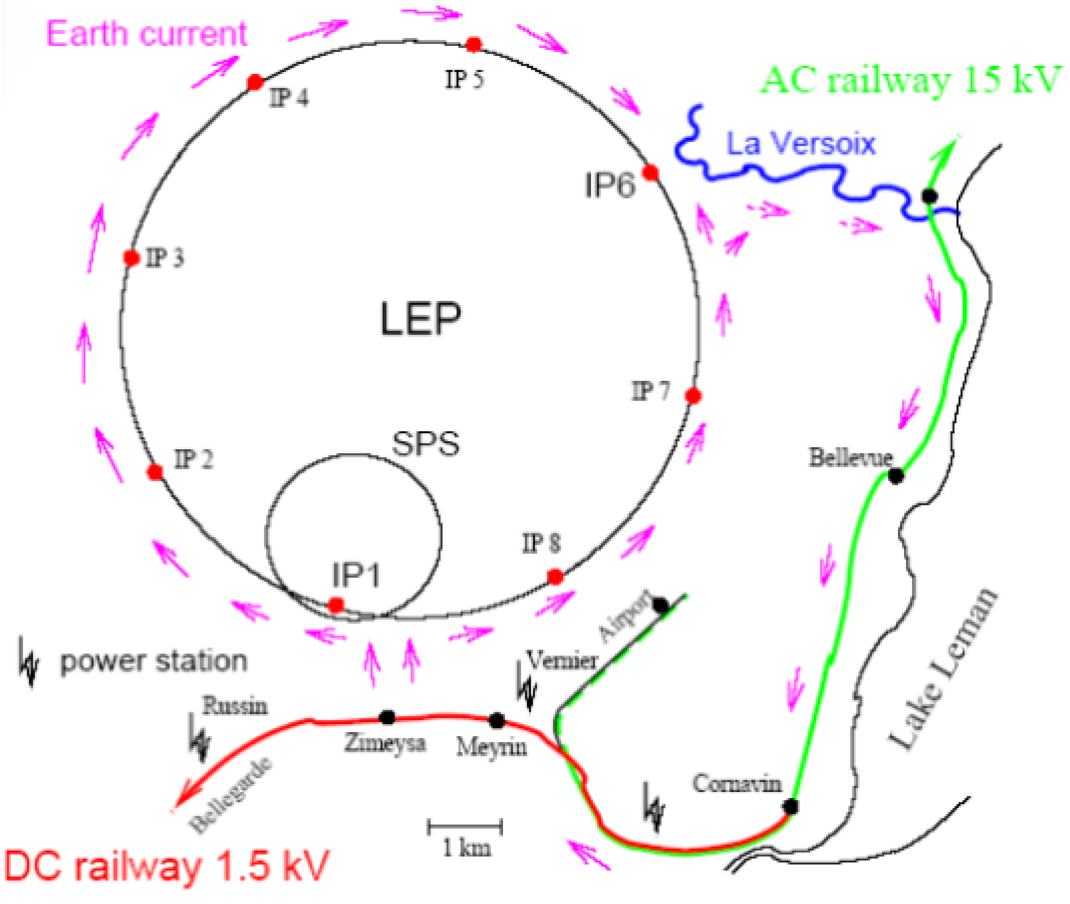
The total strain is 4 x 10^{-8} (ΔC = 1 mm)

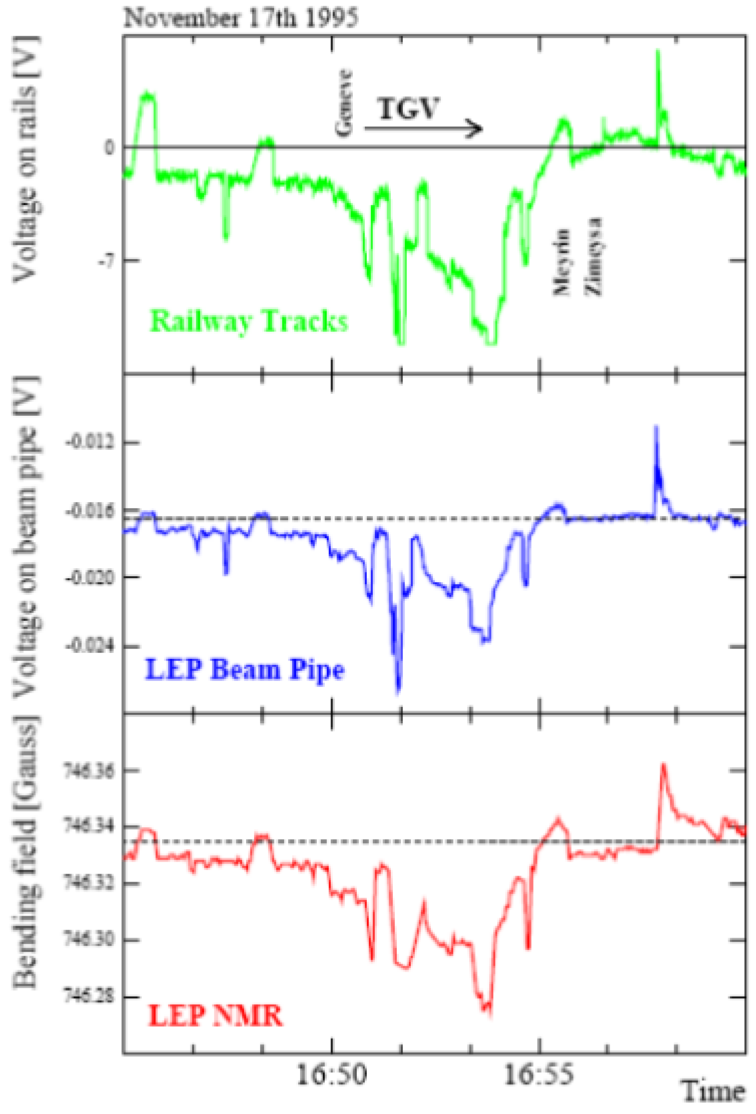
1993 Effect of lake



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!