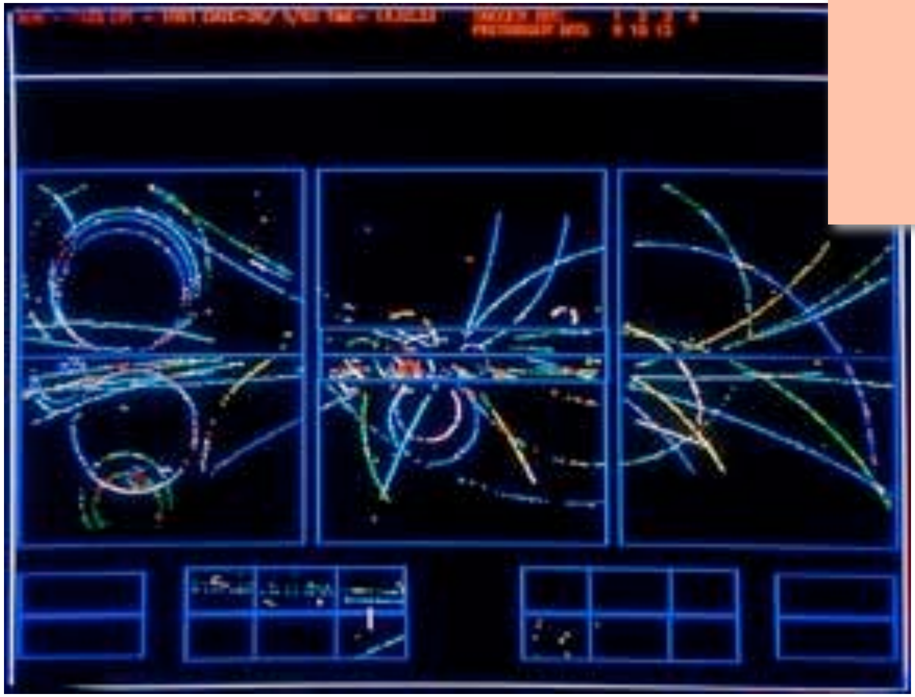

Tests of Electroweak theory

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Phenomenology of Particle Physics - FS2011

Lecture: 15/3/2011

Topics in this lecture

- Parameters of the Standard Model
- W and Z boson discovery, mass and width
- Forward/Backward asymmetries
- Higgs boson searches and constraints
  - Case study: Higgs searches into W boson pairs

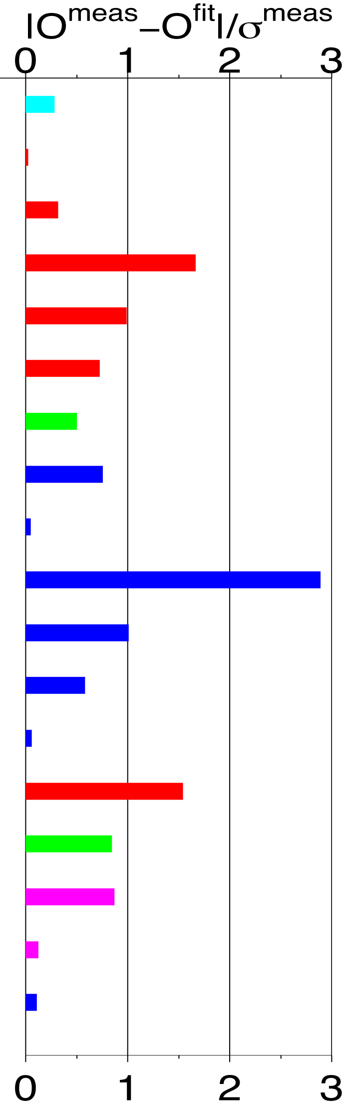
Parameters of the Standard Model

http://lepewwg.web.cern.ch

Most recent experimental values and global SM fit

Marked measurements discussed in this lecture

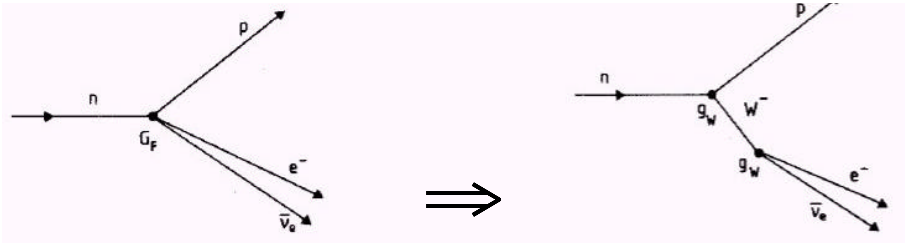
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



August 2009

Historical background

- 1960's: Glashow, Salam, Weinberg - Electroweak unification.
  - Consistent with observed charged current interactions (exchange of $W^{\pm}$ boson)
  - Theory predicted also **neutral current interactions** (exchange of γ, Z^0) which had never been observed...



- Until 1973 all observed weak interactions were consistent with only a charged boson.
- CERN, 1973: first neutral current interaction observed
  - ν_μ + *nucleus* $\rightarrow \nu_\mu + p + \pi^- + \pi^0$
  - suddenly very urgent to observe $W^{\pm}$, Z^0 bosons directly to test electroweak theory.

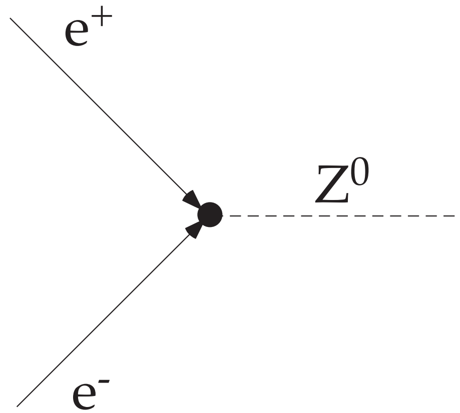
Sp$\bar{p}$S experiments

- Electroweak theory predicted $M(W^{\pm})\sim 83$ GeV and $M(Z^0)\sim 93$ GeV
  - Need particle collider capable of producing particles with mass ~ 100 GeV
  - ISR: $\sqrt{s}=61$ GeV. Too low.
  - SPS: 400 GeV proton beam against fixed target. Reminder: $\sqrt{s}=\sqrt{(2mE)}$ too low!
- **Solution**: SppS (Rubbia/Van der Meer)
  - proton-antiproton collider at $\sqrt{s}=540$ GeV
  - Luminosity ~ 5×10^{27} $cm^{-2}s^{-1}$
  - 3 against 3 bunches with $\sim10^{11}$ protons per bunch
  - First collisions in 1981

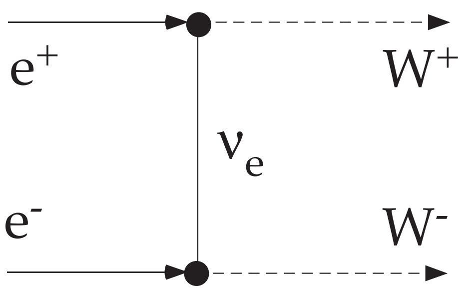
W and Z boson production

e+ e- collider

a)

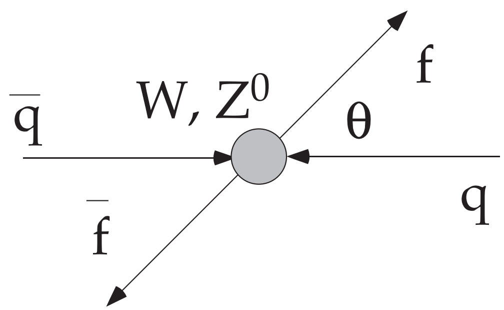


b)

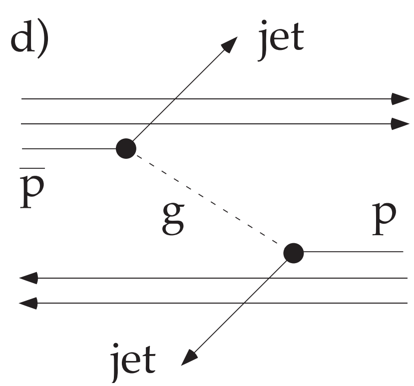


LEP I: √s=90 GeV
LEP II: √s=209 GeV

Hadron collider



$u\bar{d} \rightarrow W^{+}$
$d\bar{u} \rightarrow W^{-}$
$u\bar{u} \rightarrow Z^{0}$
$d\bar{d} \rightarrow Z^{0}$

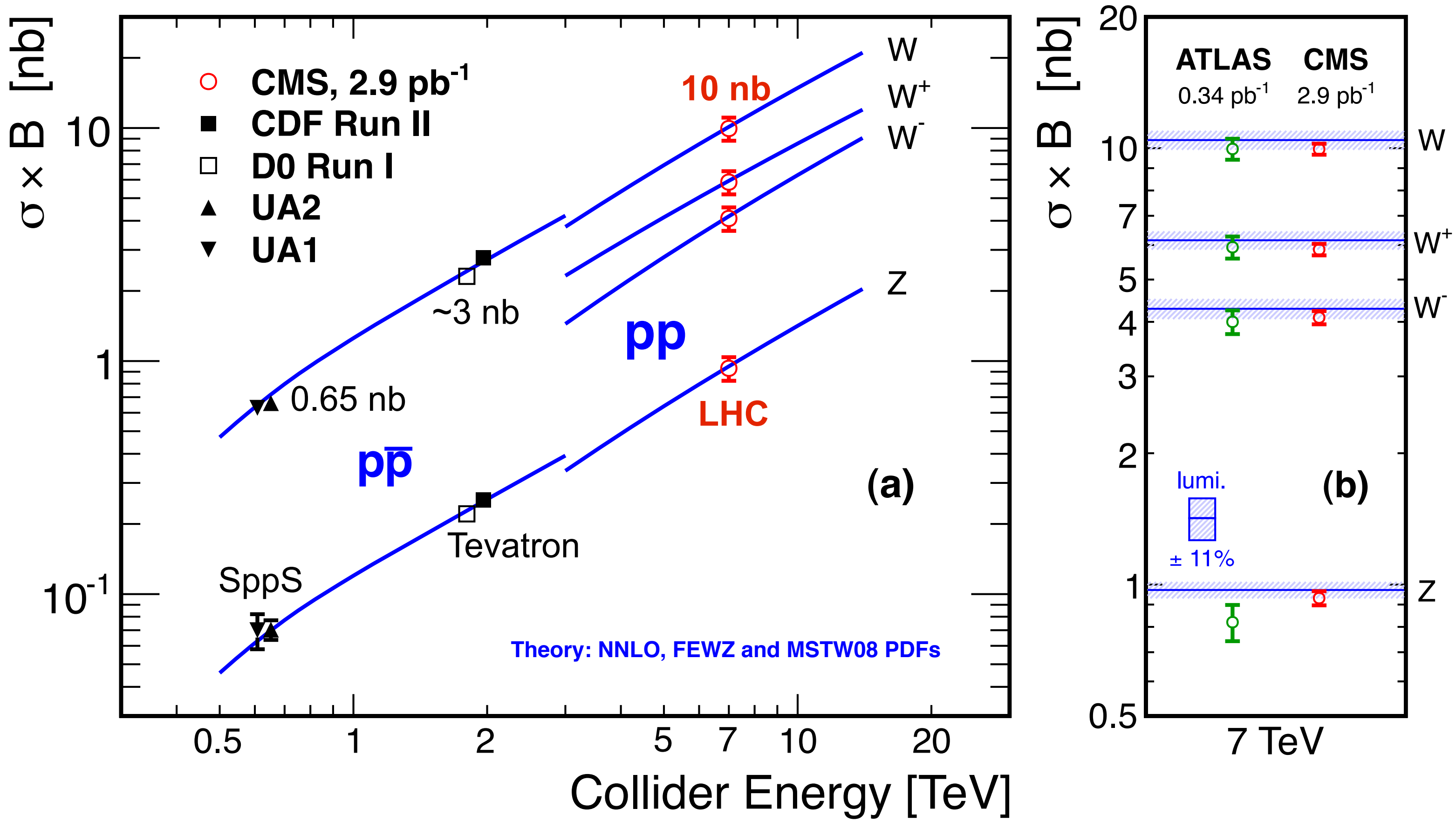


Dominant process

$$\frac{\sigma(\bar{p}p \rightarrow WX \rightarrow e\nu X)}{\sigma_T(\bar{p}p)} \approx 10^{-8}$$

W/Z decays into leptons preferred to decays into quarks!

Production cross section at hadron colliders



Source: arXiv:1012.2466

- Z^0 cross section ~10 times smaller than $W^\pm$ boson production
- W^+ cross section ~43% larger than W^- at LHC (pp collider!)

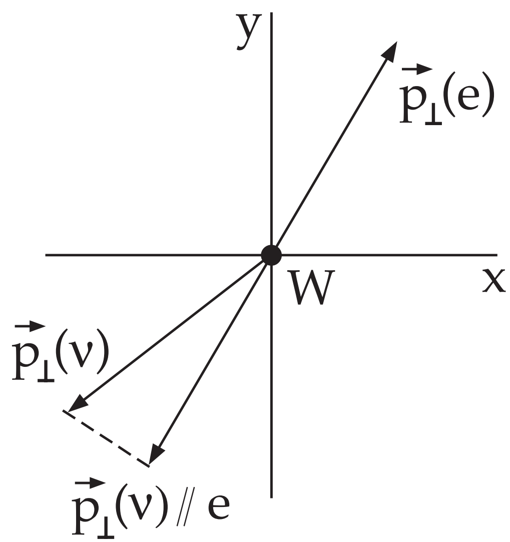
Searching for the W decay

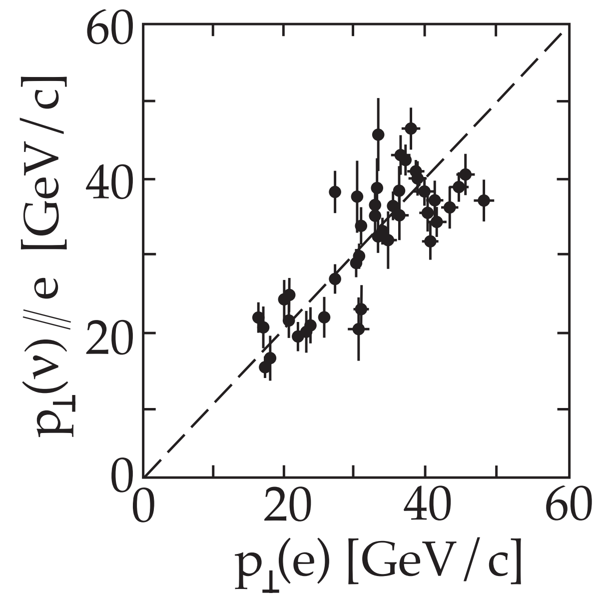
Hadrons

Electron

$$\vec{p}_\perp(\nu) = -\vec{p}_\perp(H) - \vec{p}_\perp(e).$$

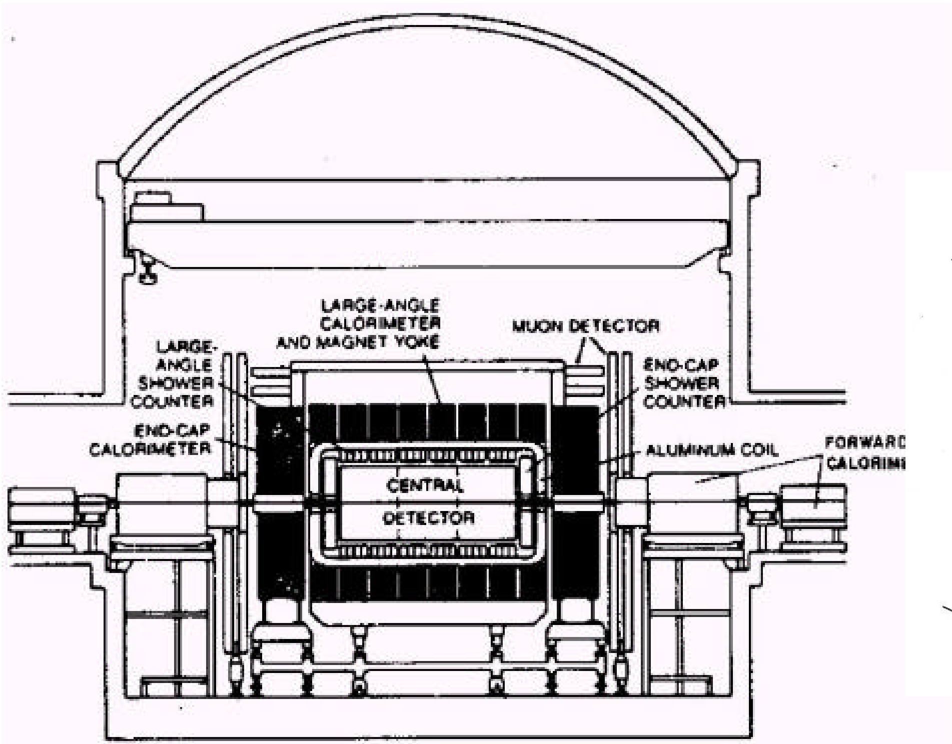
Neutrino (invisible)

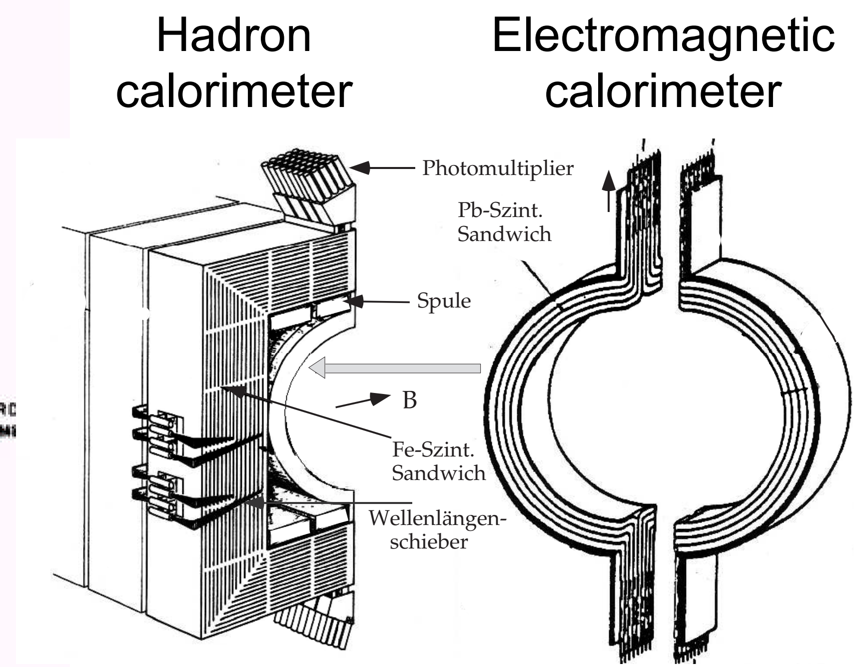




- Calculate sum of all hadron momenta in the **transverse plane** (to avoid leaks along the beam lines)
- **p_T**(ν) not exactly antiparallel to **p_T**(e)
  - W boson not always produced at rest, finite detector resolution

UA1 experiment





- **Hermetic particle detector optimized for the *$W^{\pm}\rightarrow e^{\pm}\nu$ measurement***
- Tracking: multi-wire chamber in magnetic field
- Electromagnetic calorimeter: Pb/scintillator sandwich
  - Resolution: 500 MeV for 40 GeV electrons (1%)
  - Electron angle determined from signal amplitudes in upper/lower photomultipliers
- Hadron calorimeter: Fe/scintillator sandwich

W boson: mass measurement

- Utilize **electron transverse momentum** spectrum assuming isotropic electron emission. Detector effects emulated with Monte Carlo simulation.

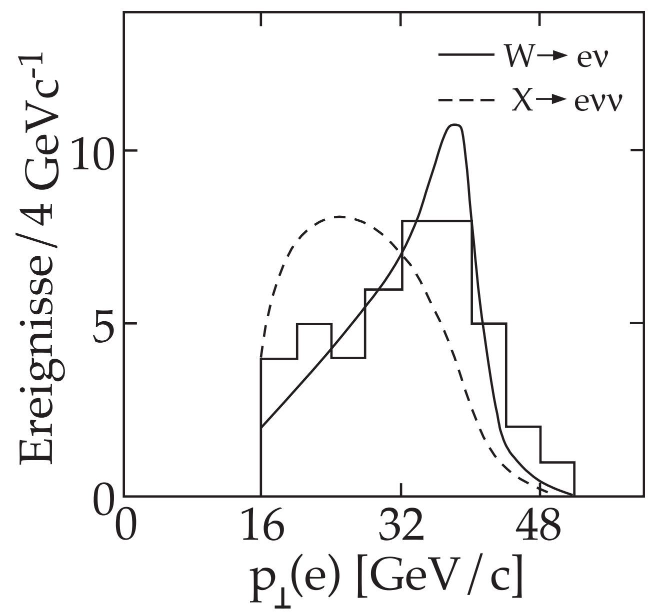
$$\frac{dN}{dp_\perp} = \frac{dN}{d\cos\theta}\frac{d\cos\theta}{dp_\perp} = \text{konst}\,\frac{d\cos\theta}{dp_\perp}$$

$$p_\perp = \frac{M_W}{2}\sin\theta = \frac{M_W}{2}\sqrt{1-\cos^2\theta}$$

$$\frac{dp_\perp}{d\cos\theta} = \frac{M_W}{2}\frac{\cos\theta}{\sin\theta} = \frac{M_W}{2}\frac{\sqrt{1-\sin^2\theta}}{\sin\theta} = \left(\frac{M_W}{2}\right)^2 \frac{\sqrt{1-\frac{4p_\perp^2}{M_W^2}}}{p_\perp},$$

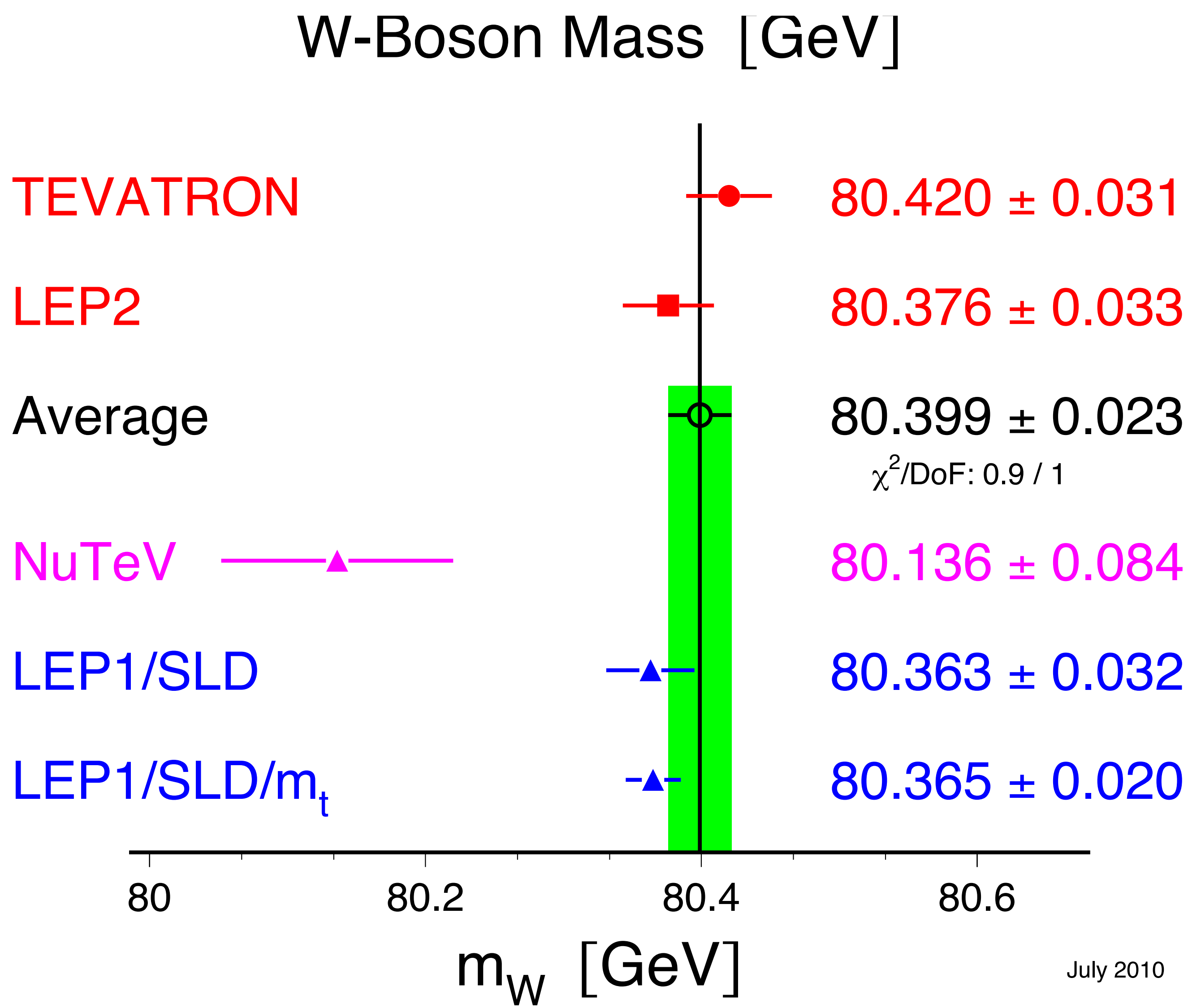
$$\frac{dN}{dp_\perp} \propto \frac{p_\perp}{\sqrt{M_W^2 - 4p_\perp^2}}.$$

Pole at $M_W=2p_T$



M_W~80 GeV

W boson mass


W-Boson Mass [GeV]
TEVATRON
80.420 ± 0.031
LEP2
80.376 ± 0.033
Average
80.399 ± 0.023
χ²/DoF: 0.9 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.363 ± 0.032
LEP1/SLD/m_t
80.365 ± 0.020
80
80.2
80.4
80.6
m_W [GeV]
July 2010

W boson width

- Reminder: Partial width of a resonance with mass M_W

$$\frac{d\Gamma}{d\Omega} = \left[\frac{4k_1 E}{2M_W}\right]\frac{k_3}{64\pi^2 E^2 k_1}|F|^2.$$

$$k_3 = M_W/2 \qquad E = M_W$$

$$d\Gamma = \frac{|F|^2}{64\pi^2 M_W}\overbrace{d(2\pi\cos\theta)}^{d\Omega}$$

- Using the scattering matrix element and integrating

$$|F|^2 = \frac{g^2 M_W^2}{4}(1-\cos\theta)^2$$

$$G_F/\sqrt{2} = g^2/8M_W^2 \qquad M_W = 80\ \text{GeV}.$$

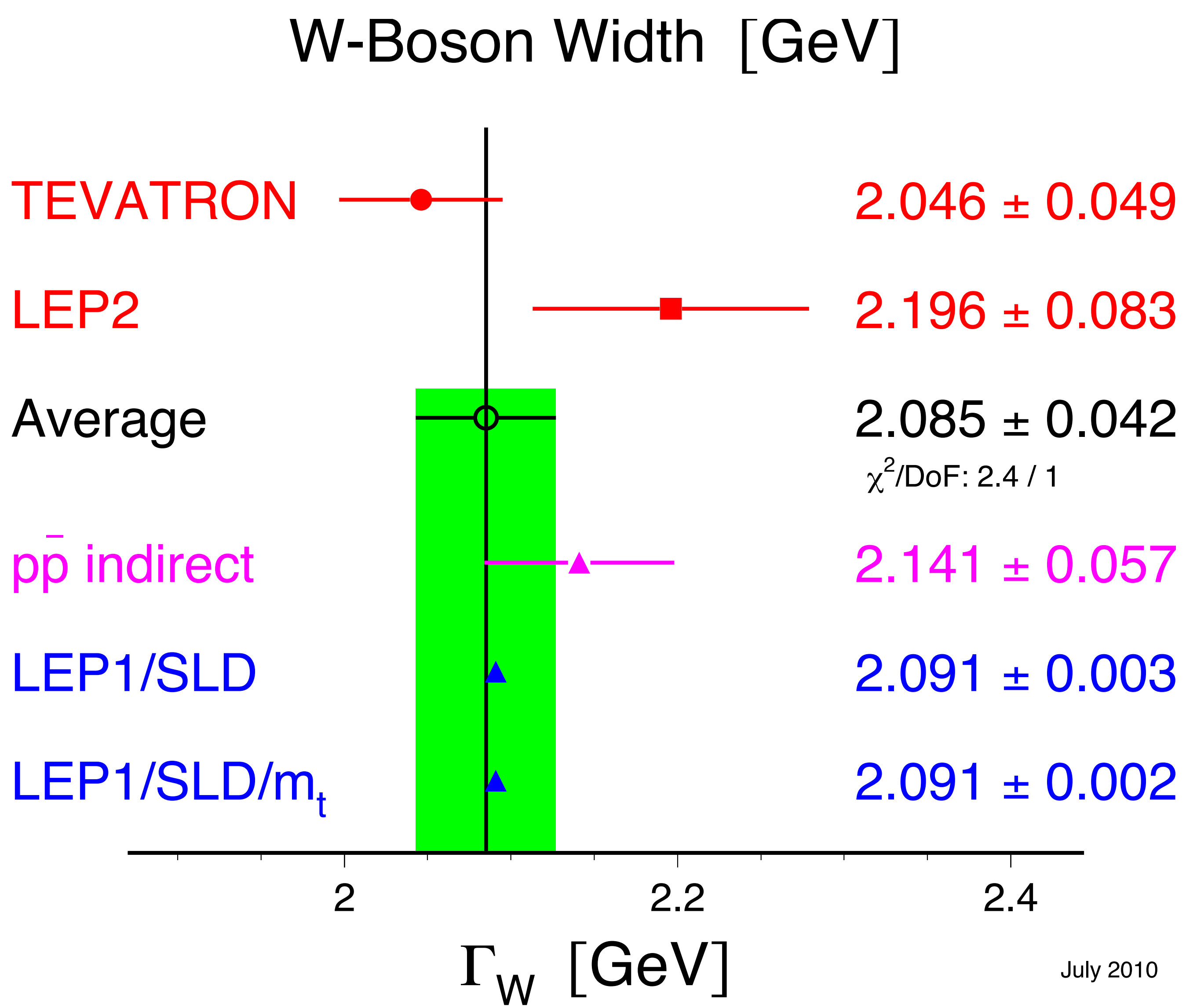
$$\Gamma(W \to e\nu) = \frac{g^2 M_W}{48\pi} = \frac{G_F}{\sqrt{2}}\frac{M_W^3}{6\pi} = 224\ \text{MeV}$$

- To obtain the total width (W^- case) we consider that:
  - All leptonic decays (e, μ, τ) have the same width
  - $\bar{u}d$ and $\bar{c}s$ are similar to leptonic channels ($\cos\theta_C \sim 1$)
  - other hadronic decays are Cabibbo-suppressed ($\bar{u}s$, $\bar{c}d$, $\bar{u}b$, $\bar{c}b$)

Total = 3 Lepton currents + (3 colors x 2 quark currents)

$$\Gamma_T(W) = 9 \times \Gamma(W \to e\nu) = 2.02\ \text{GeV}$$

W boson width



Z boson width

- The partial width of the Z boson (into neutrino's) can be obtained from the W boson case, with some substitutions

$$g \Rightarrow \frac{g\sqrt{2}}{\cos\theta_w} c_L(\nu)\,,\, M_W \Rightarrow M_{Z^0}$$

M_{Z^0} = 91 GeV.

$$\Gamma(Z^0 \to \nu\overline{\nu}) = \frac{g^2 M_{Z^0}}{96\pi \cos^2\theta_w}, = \frac{G_F}{\sqrt{2}}\frac{M_{Z^0}^3}{12\pi} = 165 \text{ MeV}$$

- For the total width we should sum up all possible decays into leptons and quarks

$$K \equiv 4[c_L(f)^2 + c_R(f)^2]$$

$f\overline{f}$	$K(a = \sin^2\theta_w = 0.23)$	=	n
$\nu\overline{\nu}$	1	1	3
e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$	$4[(-\frac{1}{2}+a)^2 + a^2]$	0.50	3
$u\overline{u}$, $c\overline{c}$	$4[(\frac{1}{2}-\frac{2}{3}a)^2 + \frac{4}{9}a^2]$	0.57	2 × 3 Farben
$d\overline{d}$, $s\overline{s}$, $b\overline{b}$	$4[(-\frac{1}{2}+\frac{1}{3}a)^2 + \frac{1}{9}a^2]$	0.74	3 × 3 Farben

$$Kn = 3 \times 1 + 3 \times 0.5 + 6 \times 0.57 + 9 \times 0.74 = 14.6$$

$$\Gamma_T(Z^0) = Kn\Gamma(Z^0 \to \nu\overline{\nu}) = 2.41 \text{ GeV}$$

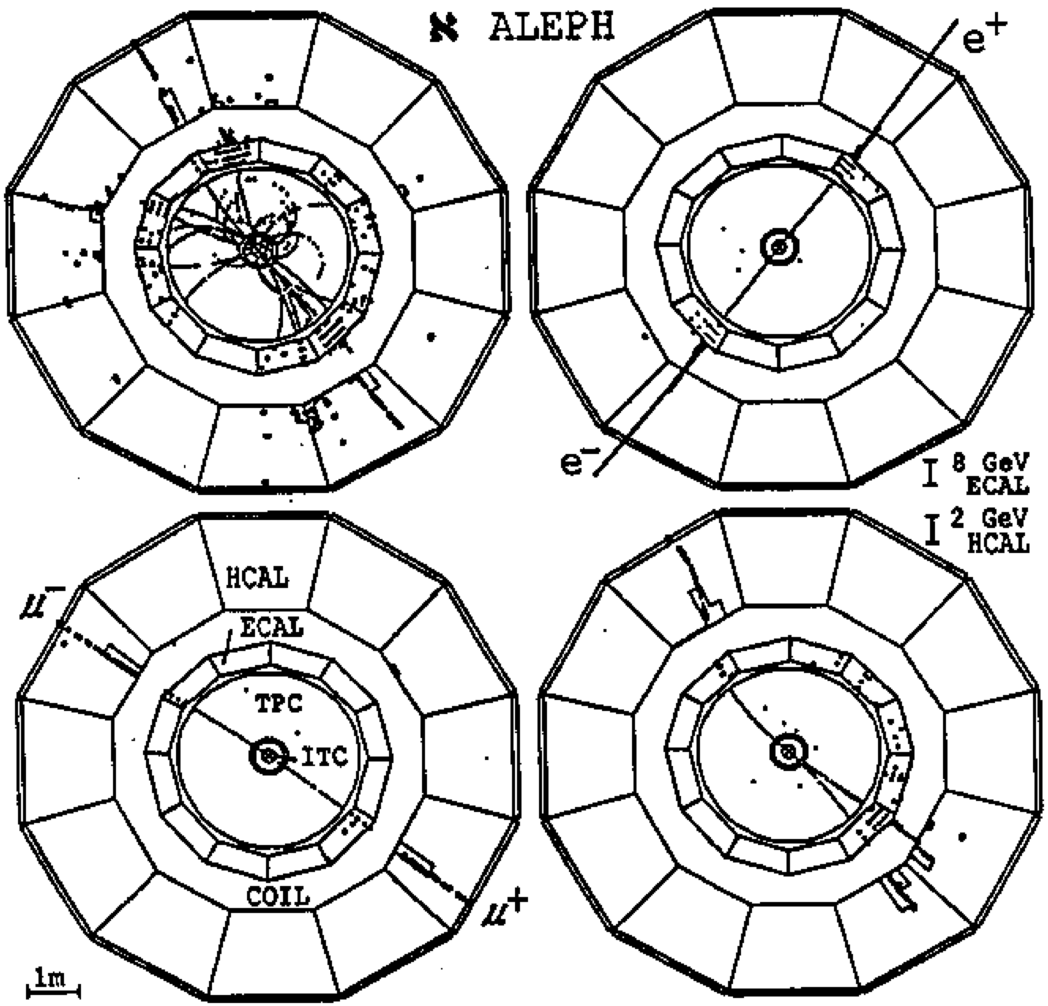
e+e- annihilation: final states

Hadronic

e+e-

μ+μ-

τ+τ-



Z boson width from hadrons

J=1

$$\sigma = \frac{4\pi}{s}\left[\frac{2J+1}{(2S+1)^2}\right]\frac{\Gamma(e^+e^-)\Gamma(f\bar{f})}{(\sqrt{s}-M_{Z^0})^2+\Gamma_T^2(Z^0)/4}.$$

S=1/2

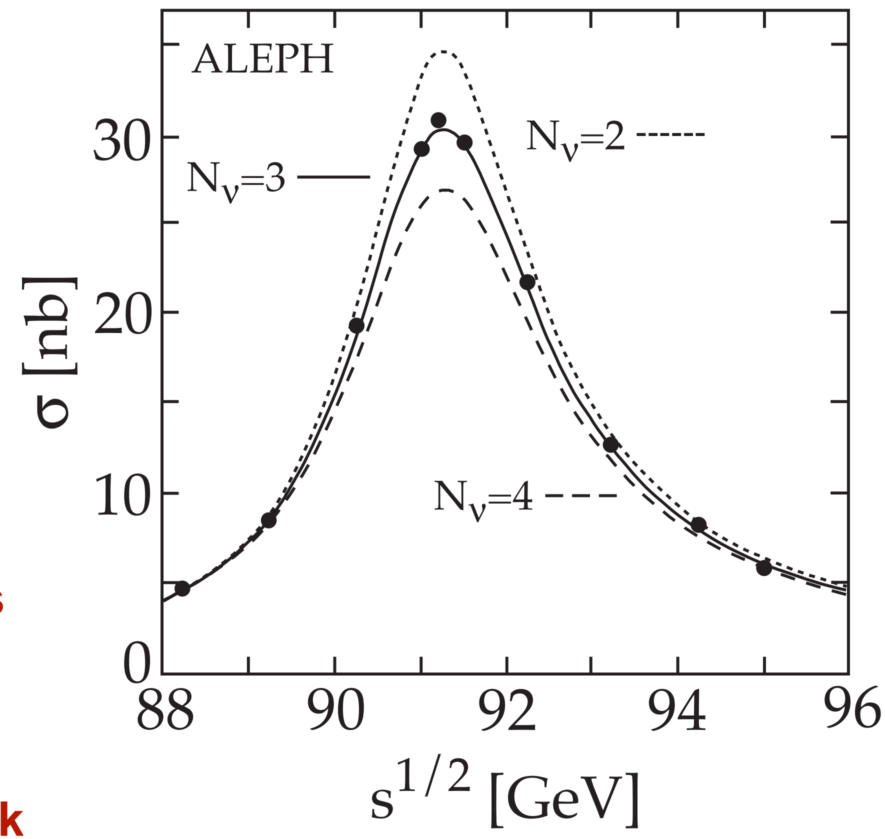
- Experimental ingredients:
  - Trigger and its efficiency
  - Selection of hadronic events (with tracks or calorimeter)
  - Luminosity measurement

Constrains number of neutrino families

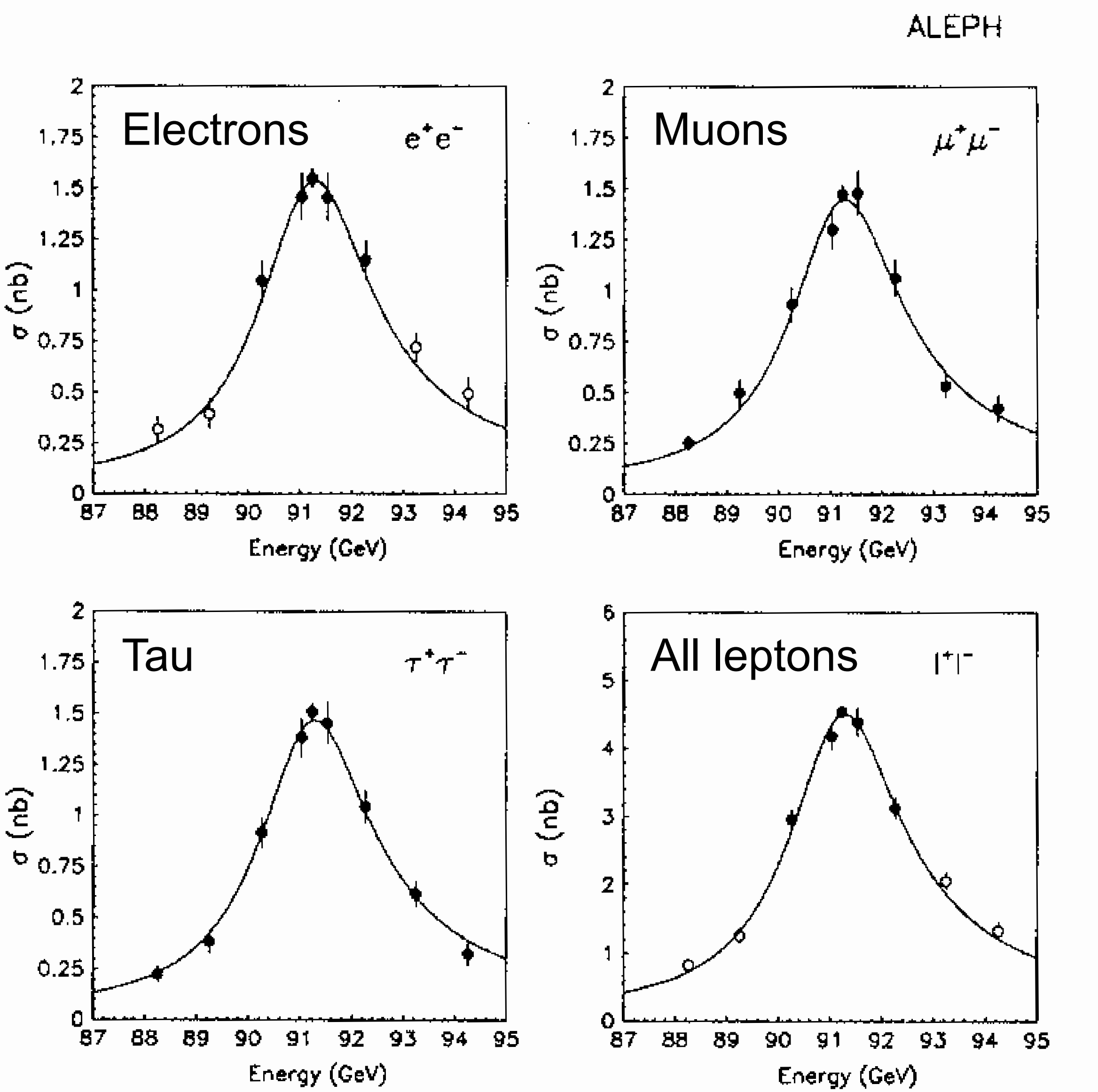
$$N_\nu = 2.994 \pm 0.012$$

But, existence of heavy (>45 GeV) quark and neutrino families *not* excluded!

$e^+e^- \to \bar{q}q$



Z resonance from lepton decays



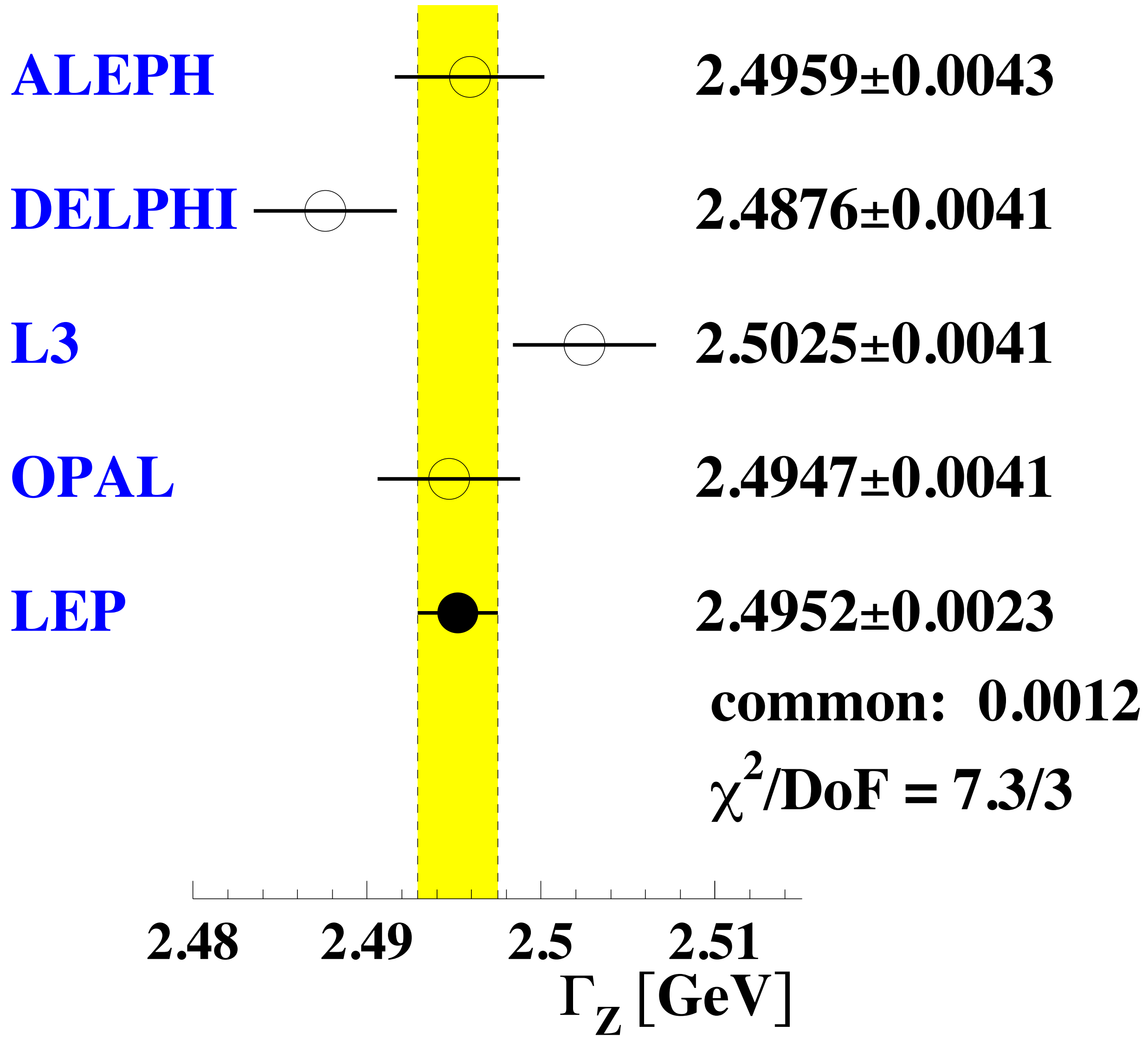
From slide 12:

$$\frac{\Gamma(\mu^+\mu^-)}{\Gamma_T} = \frac{0.5}{14.6} = 3.4\%,$$

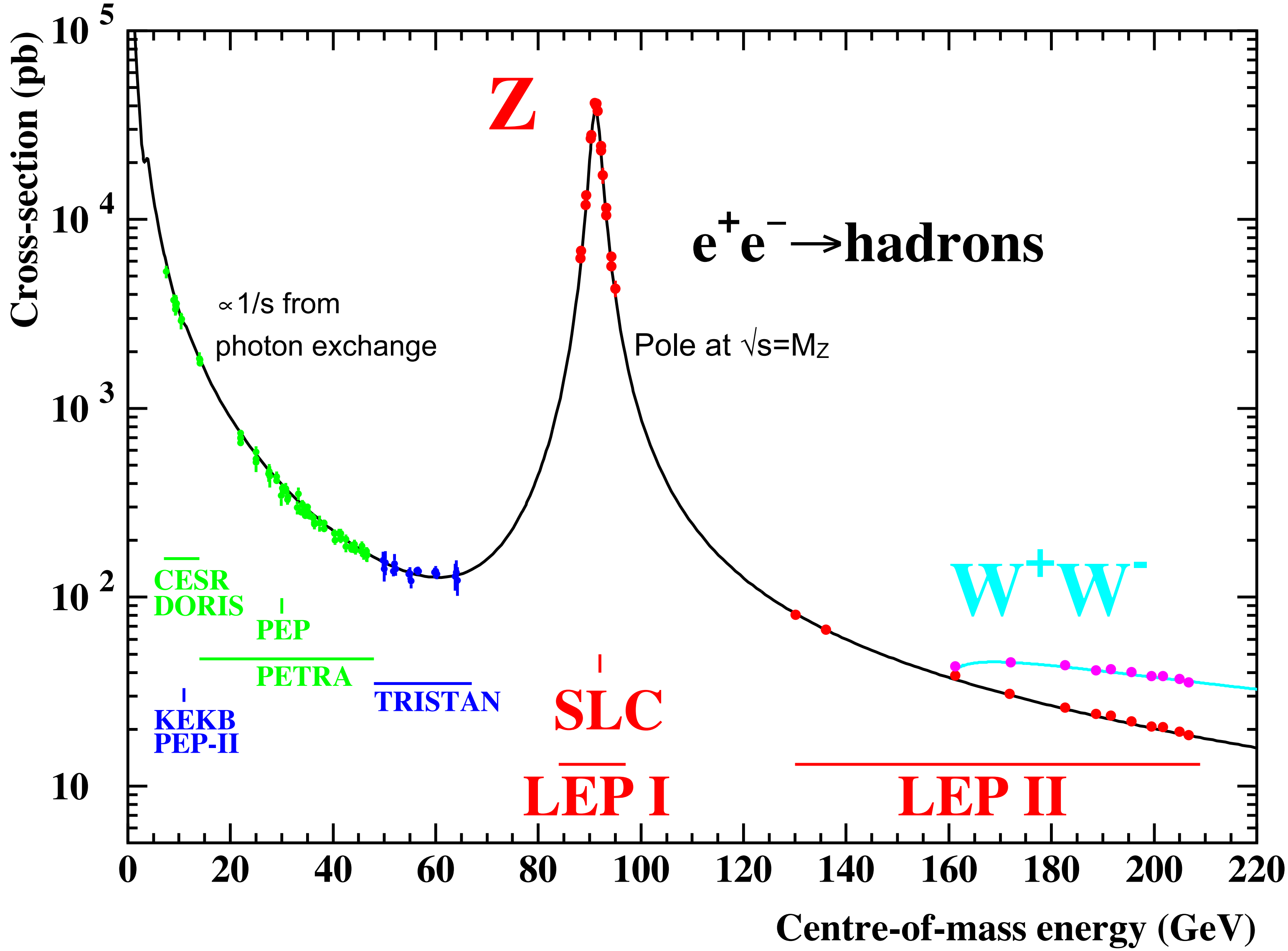
Experiment:

$$(3.366 \pm 0.007)\%$$

Z width: LEP summary



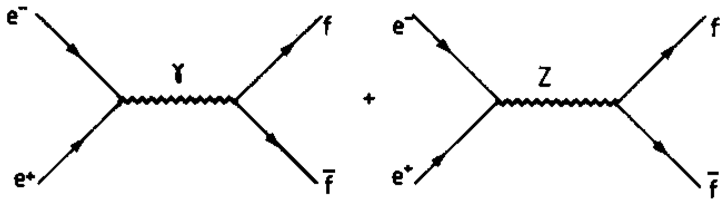
Z lineshape: world summary



Angular differential cross section

- The differential e+e- cross section can be written as:

$$\frac{d\sigma_f}{d\Omega} = \frac{\alpha^2 N_c^f}{4s} \left[F_1(s)\,(1+\cos^2\theta) + 2(F_2(s)\cos\theta\right]$$



- where:

$$F_1(s) = Q_f^2 - 2\, v_e\, v_f\, Q_f\, R_e\,\chi + (v_e^2 + a_e^2)\,(v_f^2 + a_f^2)\,|\chi|^2$$

$$F_2(s) = -2\, a_e\, a_f\, Q_f\, R_e\,\chi + 4\, v_e\, a_e\, v_f\, a_f\,|\chi|^2$$

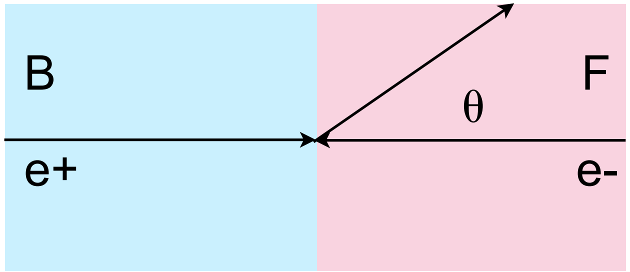
$$\chi = \frac{s}{s - m_Z^2 + i\, m_Z\, \Gamma_Z}$$ ***Breit-Wigner resonant denominator***

$$v_f = \frac{I_3^f - 2Q_f \sin^2\theta_W}{2\sin\theta_W \cos\theta_W}$$ ***Weak vector coupling***

$$a_f = \frac{I_3^f}{2\sin\theta_W\cos\theta_W}$$ ***Weak axial coupling***

Asymmetries

$$A_{FB} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}$$



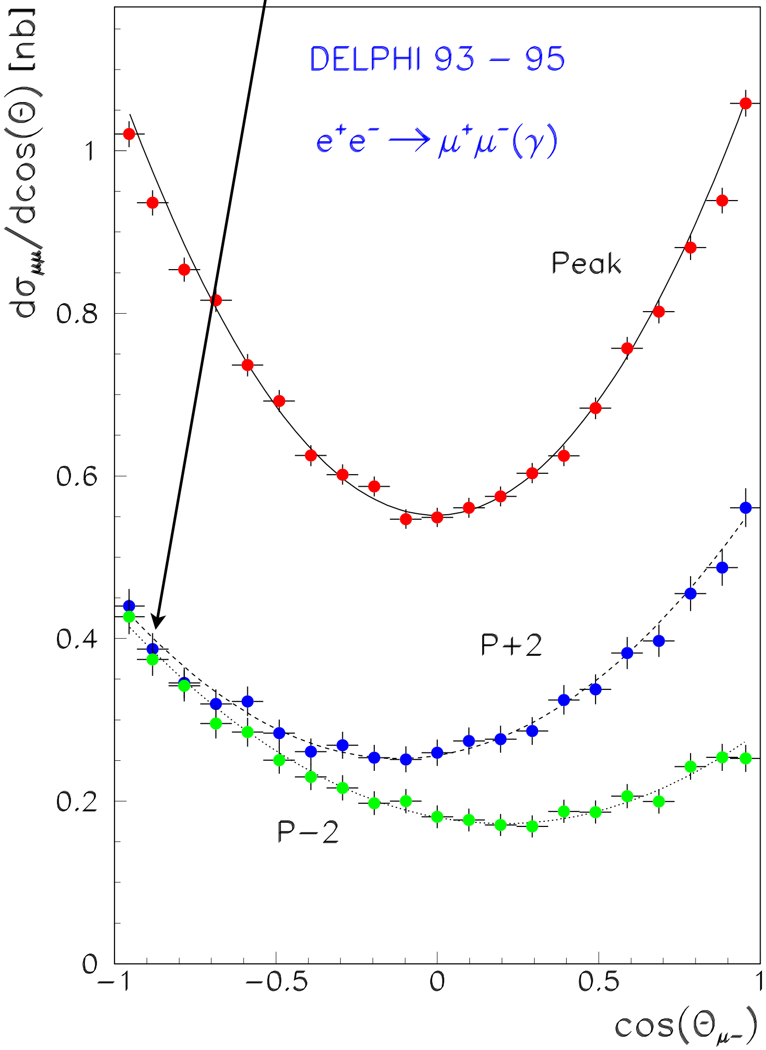
$$A_{FB} = \frac{3}{4} F_2/F_1 = 3\, v_e a_e v_f a_f \,/\, (v_e^2 + a_e^2) \cdot (v_f^2 + a_f^2).$$

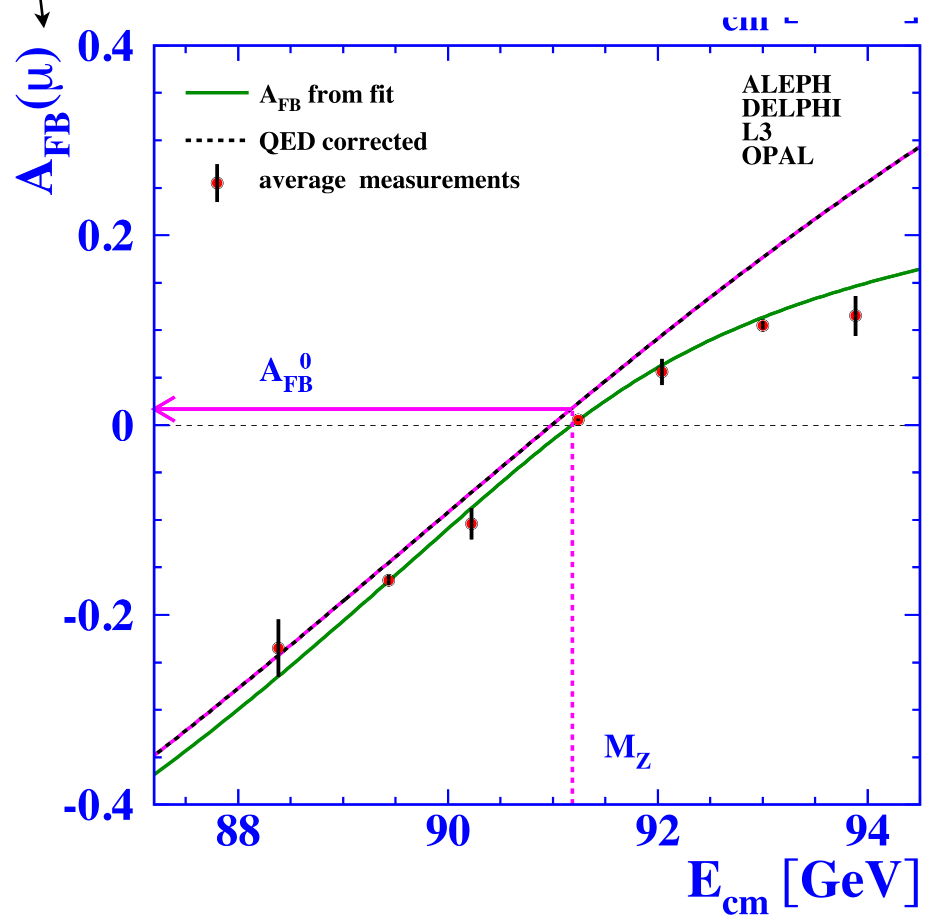
- At the Z-peak the asymmetry is sensitive to the vector/axial coupling ratio
- In the electroweak theory the v/a ratio is proportional to $\sin^2\theta_W$

$$v/a = 1 - 4|Q|\sin^2\theta_W(m_Z^2)$$

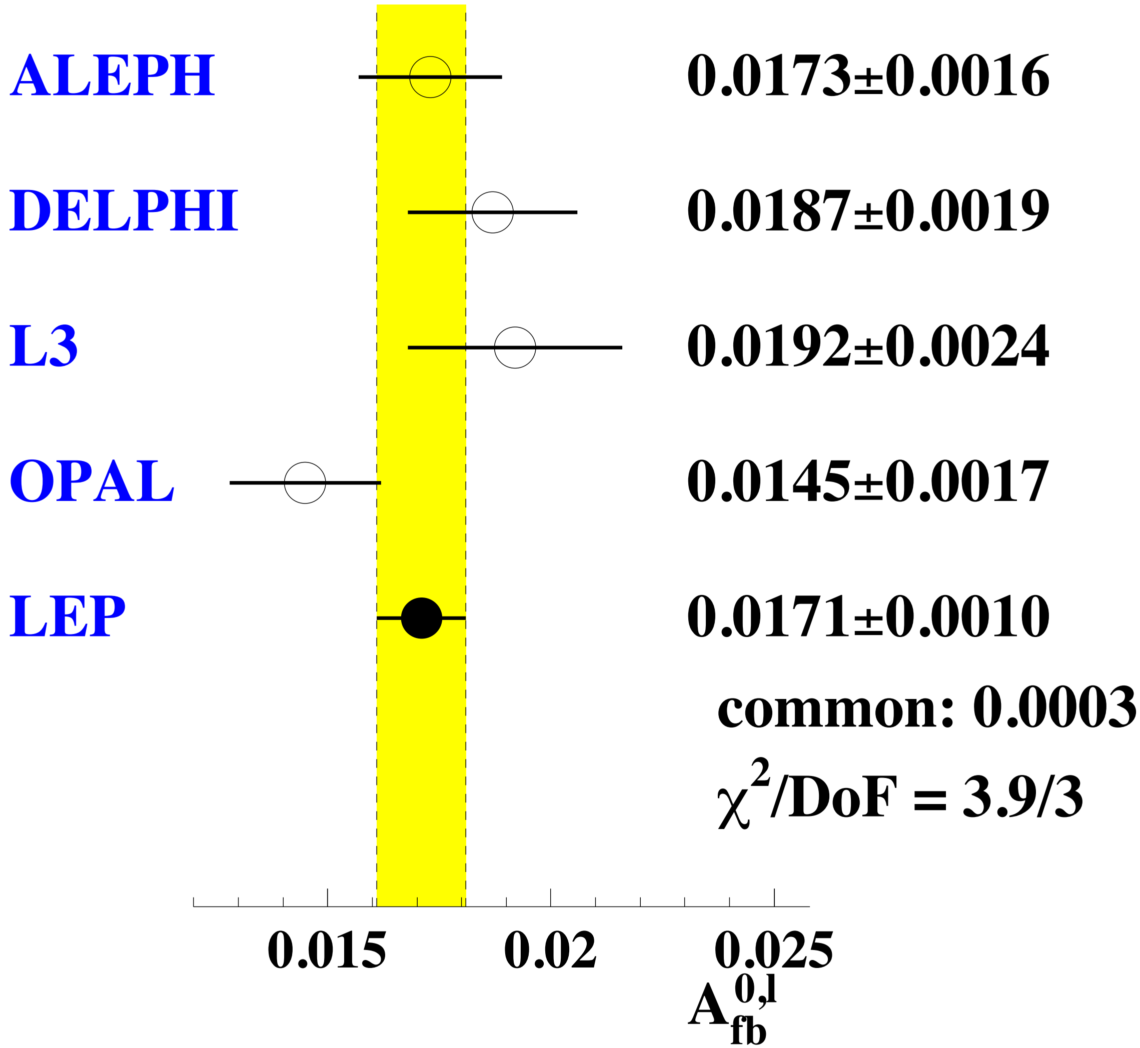
F-B asymmetries (into muons)

$$d\sigma/d\cos\theta \propto 1+\cos^2\theta + 8/3\cdot A_{FB}\cos\theta.$$





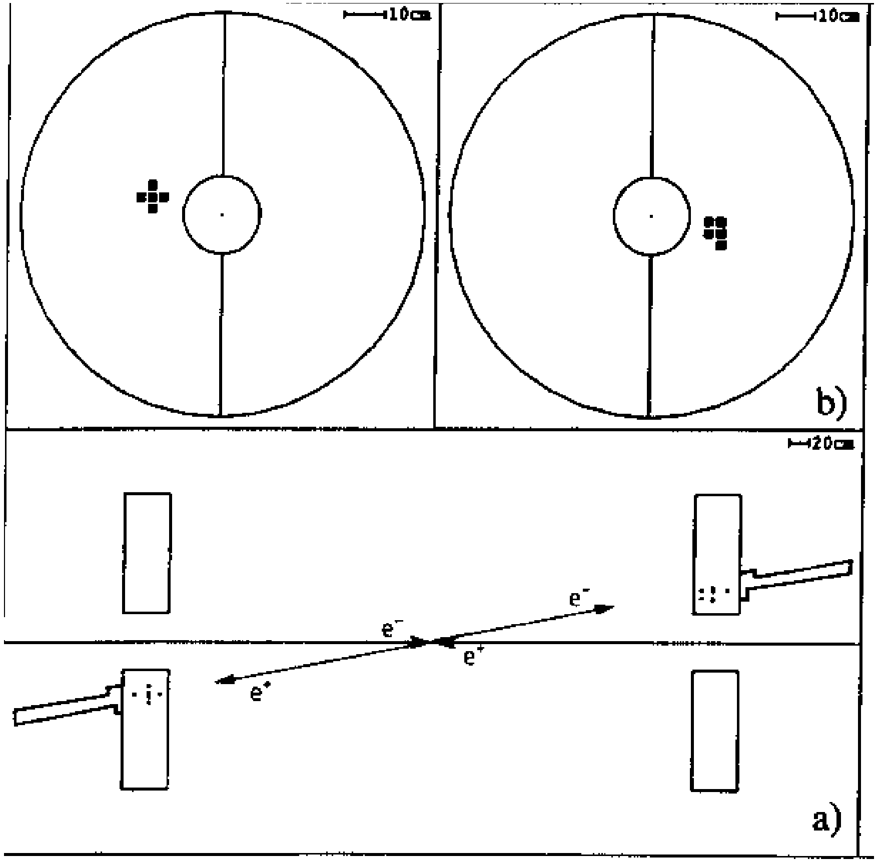
F-B asymmetries (all leptons)

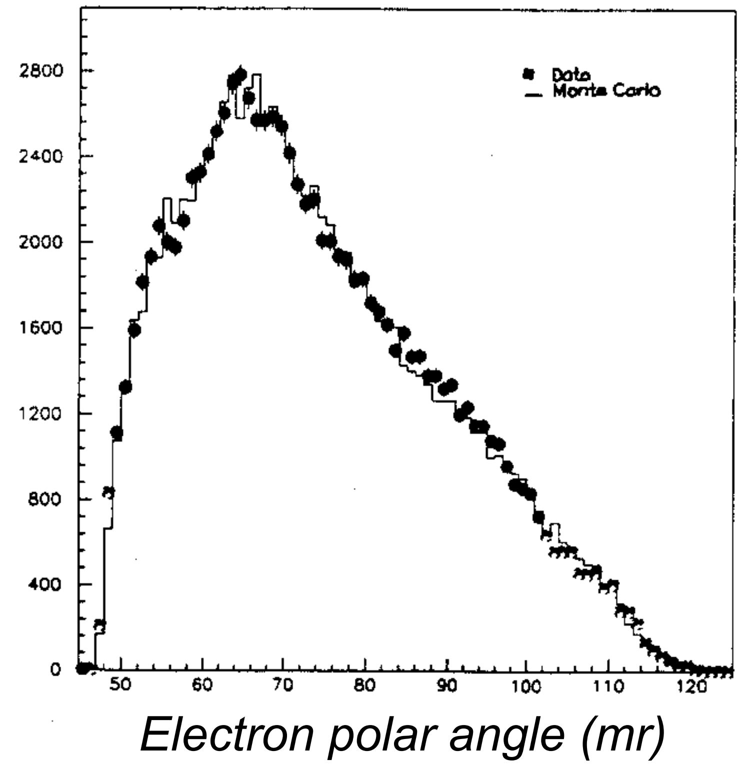


References

- C.Amsler, *Kern- und Teilchenphysik, UTB. Chapter 17.*
- *J.Steinberger, First results at the LEP e+e- collider, CERN, 1991*
  - *PDF available at: http://ccdb4fs.kek.jp/cgi-bin/img/allpdf?199012067*
- *LEP Electroweak working group et al., Precision Electroweak measurements on the Z resonance, CERN-PH-EP/2005-041, 2005*
- *LEP Standard Model global fits:* http://lepewwg.web.cern.ch

Luminosity measurement





- Measure rate of Bhabha scattering.
- Final precision ~3%