History of EM unification

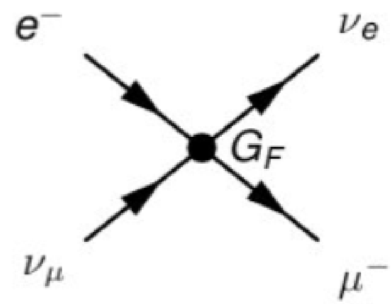
- 1934 Fermi-Theory: point-like interaction (no q^2 dependence)

$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} \left(\overline{\Psi}\gamma^\mu(1-\gamma^5)\Psi\right)\left(\overline{\Psi}\gamma^\nu(1-\gamma^5)\Psi\right)$$

approach still valid for q^2 < m(W)

However divergence of electron-neutrino cross section at high CME ($\sqrt{s}$)

$$\sigma \propto G_F^2 s$$

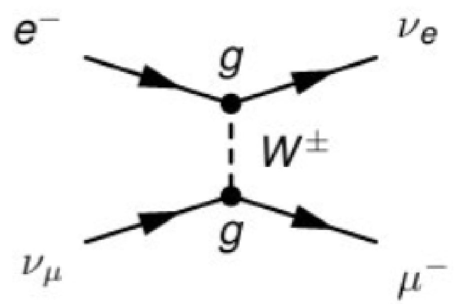


- Fix: exchange of massive boson $W^\pm$: V-A theory

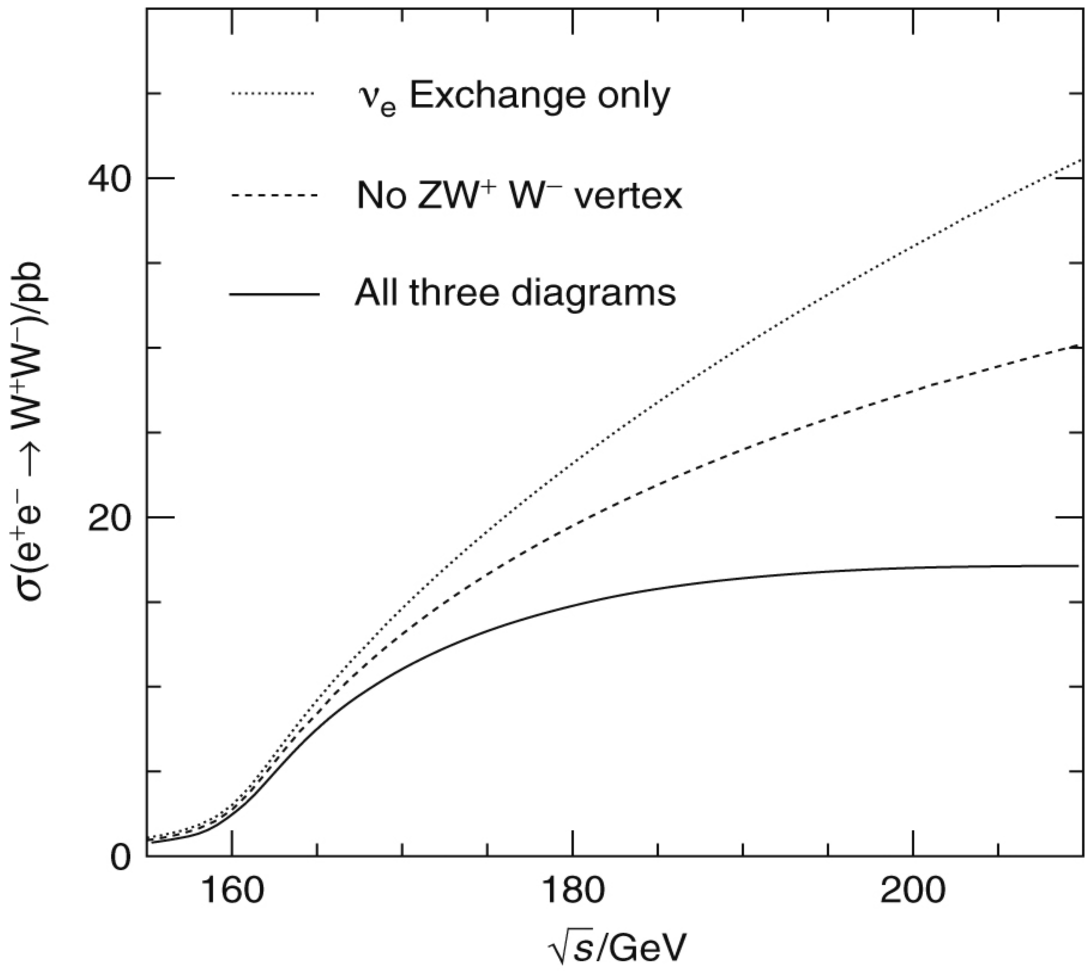
$$M_{fi} = \left(\frac{g_W}{\sqrt{2}}\overline{\Psi}\gamma^\mu\frac{1-\gamma^5}{2}\Psi\right)\frac{g_{\mu\nu}-q_\mu q_\nu/M_W^2}{q^2-M_W^2}\left(\frac{g_W}{\sqrt{2}}\overline{\Psi}\gamma^\nu\frac{1-\gamma^5}{2}\Psi\right)$$

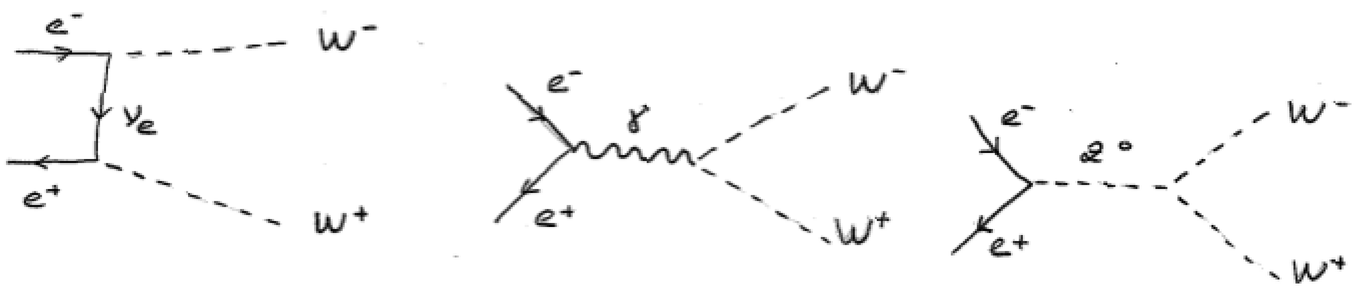
$$G_F = \frac{\sqrt{2}g_W^2}{8M_W^2}$$

$$\sigma \propto \frac{G_F^2 M_W^2}{s+M_W^2}s$$



Still remaining problem, divergence of W pair production cross-section





Standardmodel of particle physics → electroweak unification

Glashow, Salam and Weinberg (1967): Electroweak Unification

- in analogy to strong IA, introduce weak isospin

  left handed particles form isospin doublets, $T = \frac{1}{2}, T_3 = \pm\frac{1}{2}$

  right handed particle form isospin singlets $T = 0$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix} \begin{pmatrix} t_L \\ b_L \end{pmatrix}, u_R, d_R, c_R, s_R, t_R, b_R$$

$$\begin{pmatrix} \nu_{e,L} \\ e^-_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu,L} \\ \mu^-_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau,L} \\ \tau^-_L \end{pmatrix}, e^-_R, \mu^-_R, \tau^-_R$$

Electro-weak quantum numbers

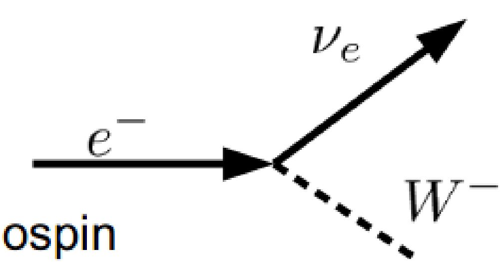
Leptons	T	T_3	Q	Y
ν_e	$1/2$	$+1/2$	0	−1
e_L	$1/2$	$-1/2$	−1	−1
e_R	0	0	−1	−2

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	$2/3$	$4/3$
d_R	0	0	$-1/3$	$-2/3$

W_1, W_2, W_3 generators of $SU(2)_{iso}$

$W^{\pm} = W_1 \mp iW_2$ ladder operators

W_3 eigenvalue: third component of weak isospin



$Y = 2[Q - T_3]$

Weak IA described by $SU_{iso}(2) \times U_Y(1)$

4 mass less gauge fields $W_1,\ W_2, W_3$ and B

couple to left handed particles only

couples to left and right handed particles

Glashow, Salam and Weinberg (1967): Electroweak Unification

$SU_{iso}(2) \times U_Y(1)$ contains subgroup $U_{em}(1)$

$B \neq A$ and $W_3 \neq A$ elm. IA does not couple to left handed neutrinos

Electro-weak 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	$2/3$	$4/3$
d_R	0	0	$-1/3$	$-2/3$

Solution: A is linear combination of W_3 and B

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

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

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

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

Weinberg angle θ_W defined by couplings of A and Z.

from experiment: $\sin^2\theta_W = 0.23143 \pm 0.00015$

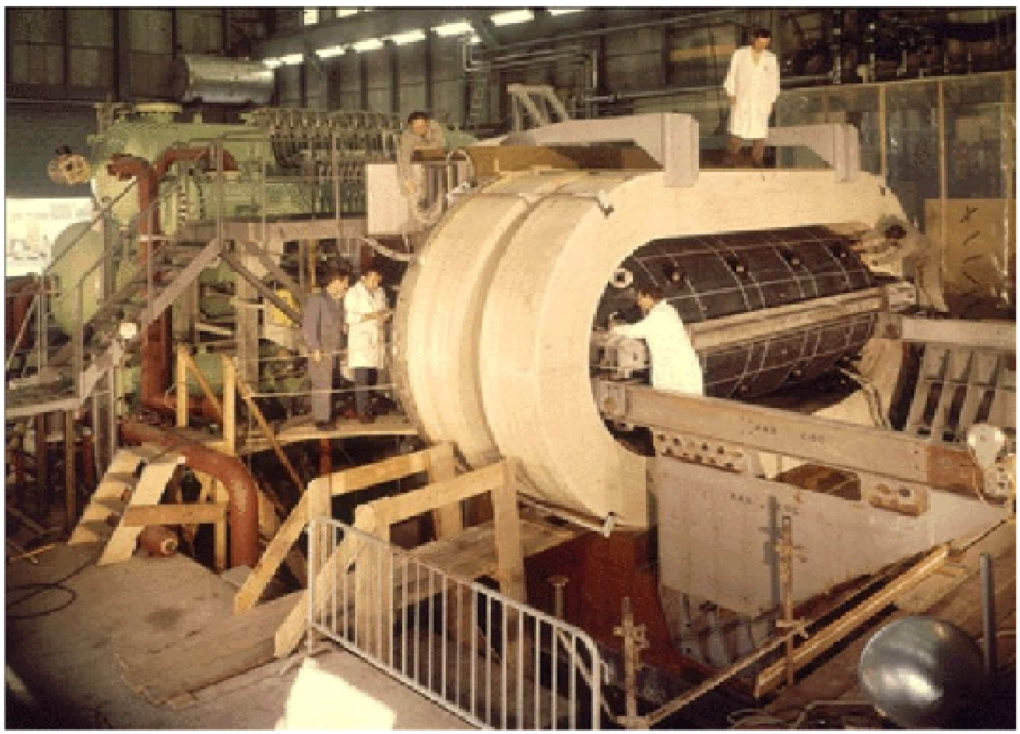
$$\cos\theta_W = \frac{M_W}{M_Z}$$

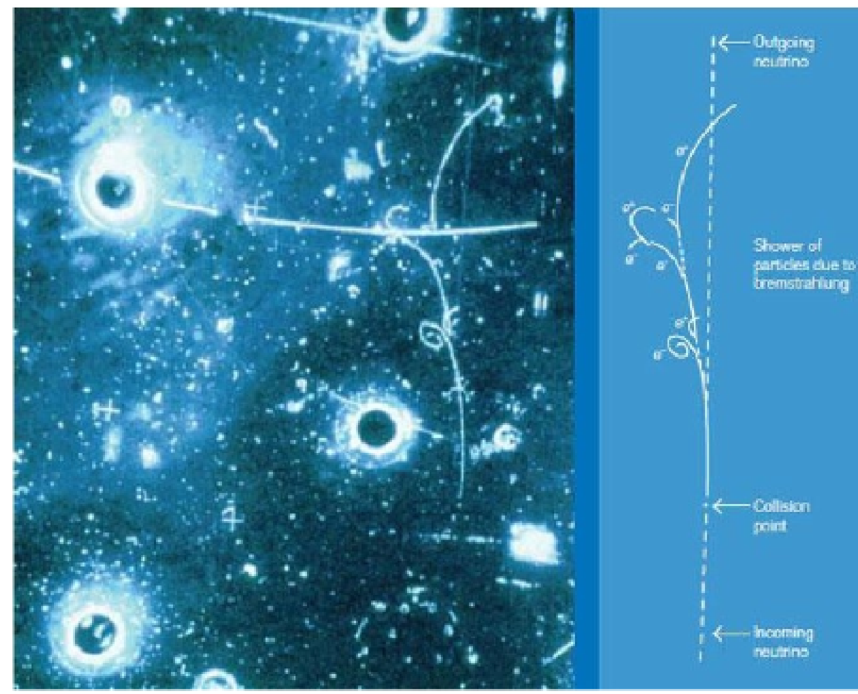
Problem, no mass term in Lagrangian (otherwise spoils gauge invariance, thus is not renormalizible)

→ require dedicated mechanism to create masses → HIGGS mechanism (introduced 1964)

Discovery of neutral current

NC was first theoretical introduced in GSW theory in 1969 and then discovered by the Gargamell experiment in 1973





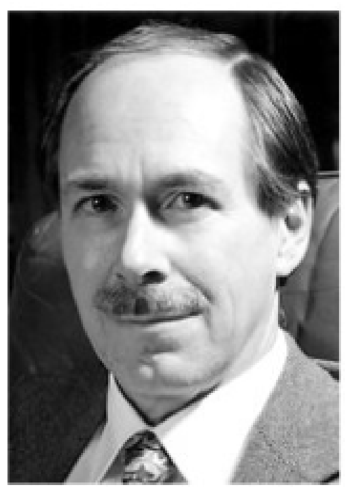
$$\overline{\nu}_\mu + e^- \rightarrow \overline{\nu}_\mu + e^-$$

Despite this experimental “proof” GSW model not widely accepted before 1977 t' Hooft and Veltmann demonstrated renormalization of this theory (all divergences cancel)

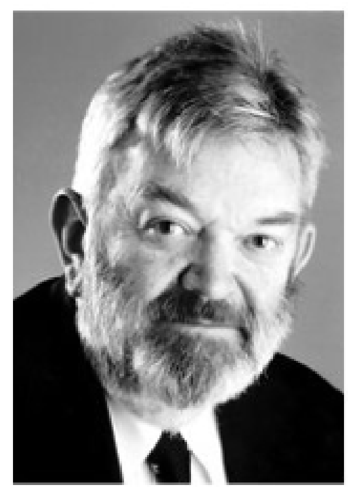
1979 Nobel prize for Glashow, Salam and Weinberg

Sheldon Glashow, Abdus Salam, and Steven Weinberg sharing the Nobel Prize, 1979

1999 Nobel prize for 't Hooft and Veltman



Gerardus 't Hooft



Martinus J.G. Veltman

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

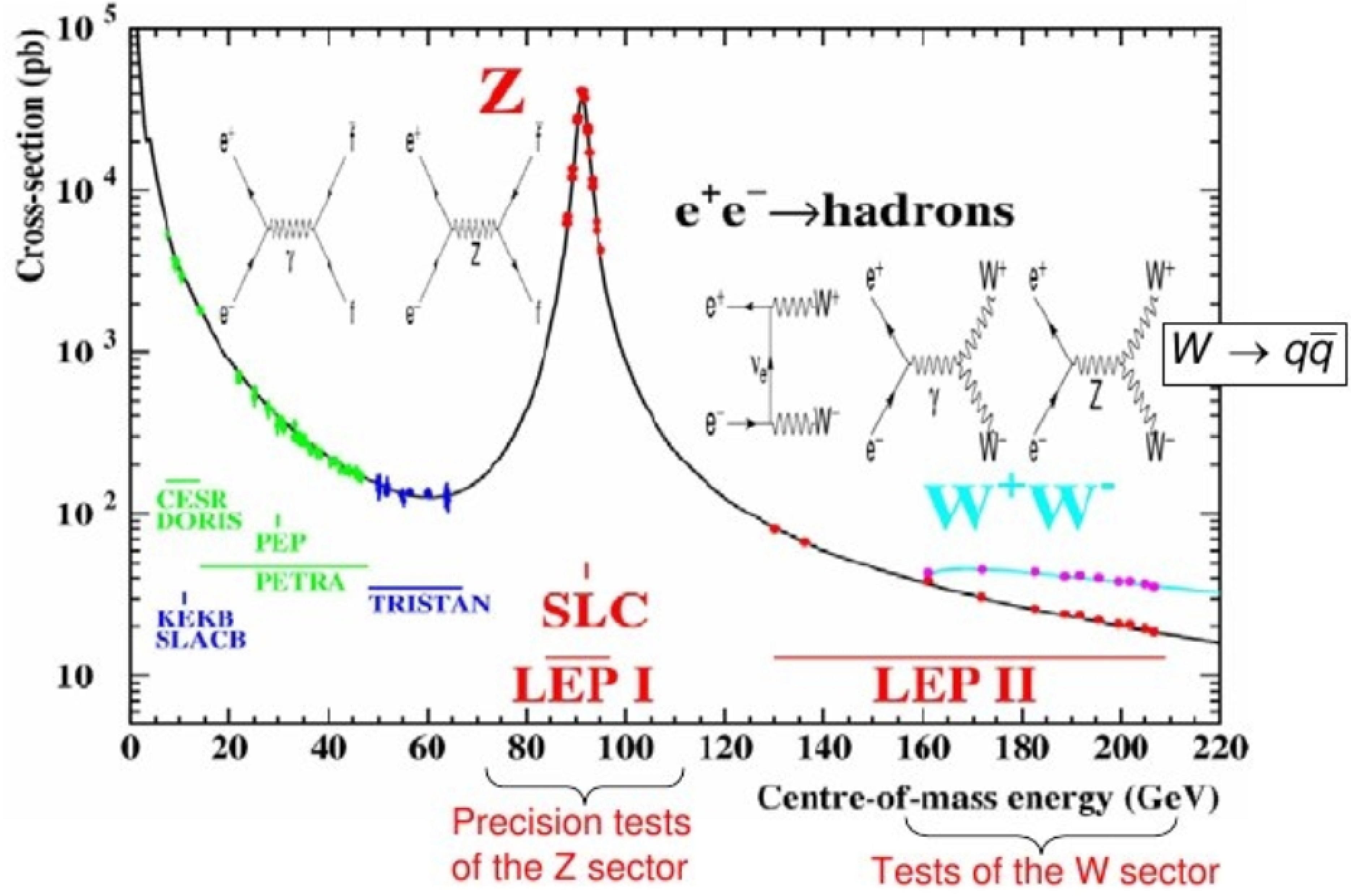
1984: Nobel Prize for the discovery of the Z and W boson

Carlo Rubbia

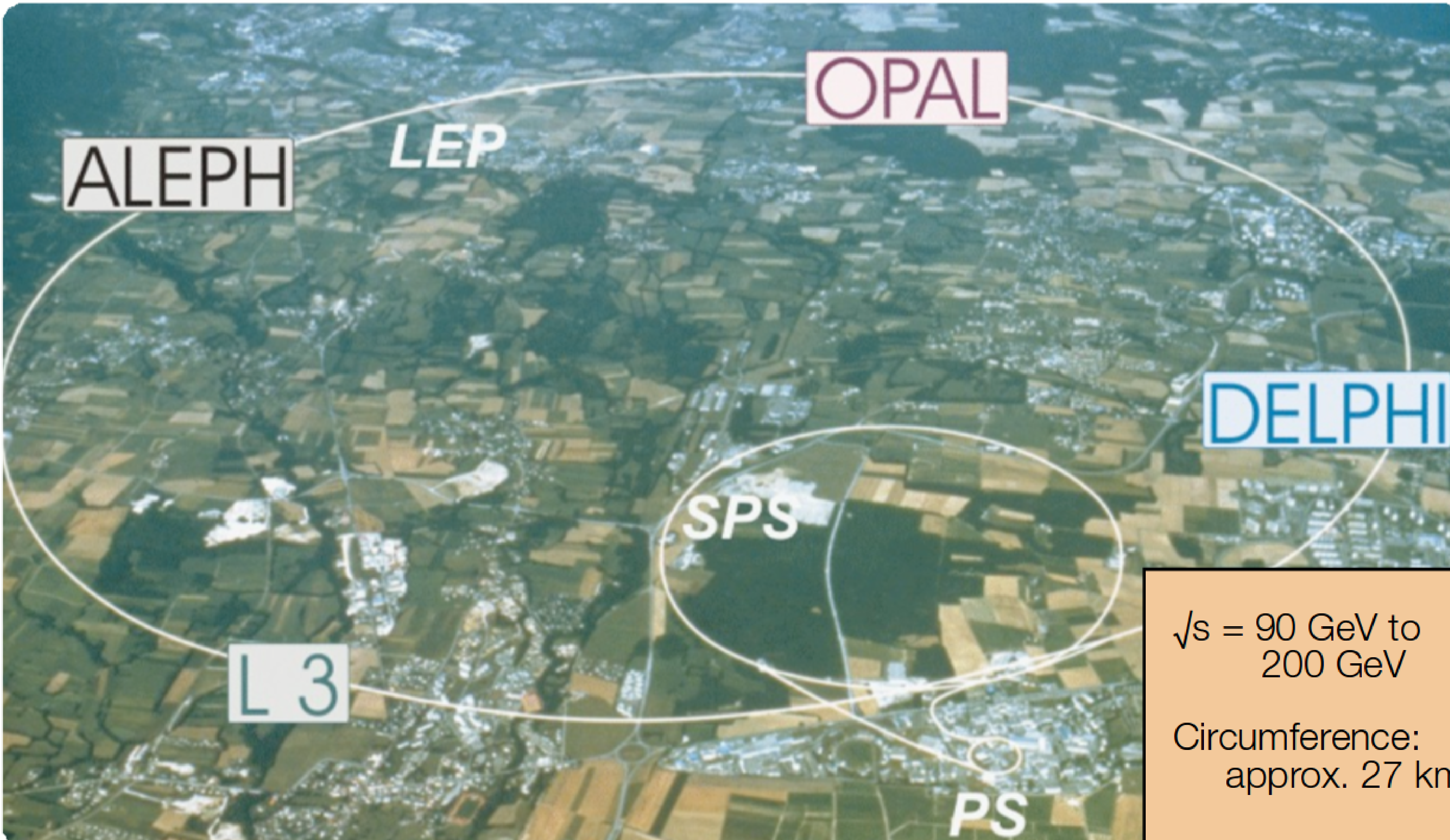
Simon van der Meer

The Nobel Prize in Physics 1984 was awarded jointly to Carlo Rubbia and 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"*

Precision Test of the Standard Model at LEP (e^+e^-)



The LEP Collider



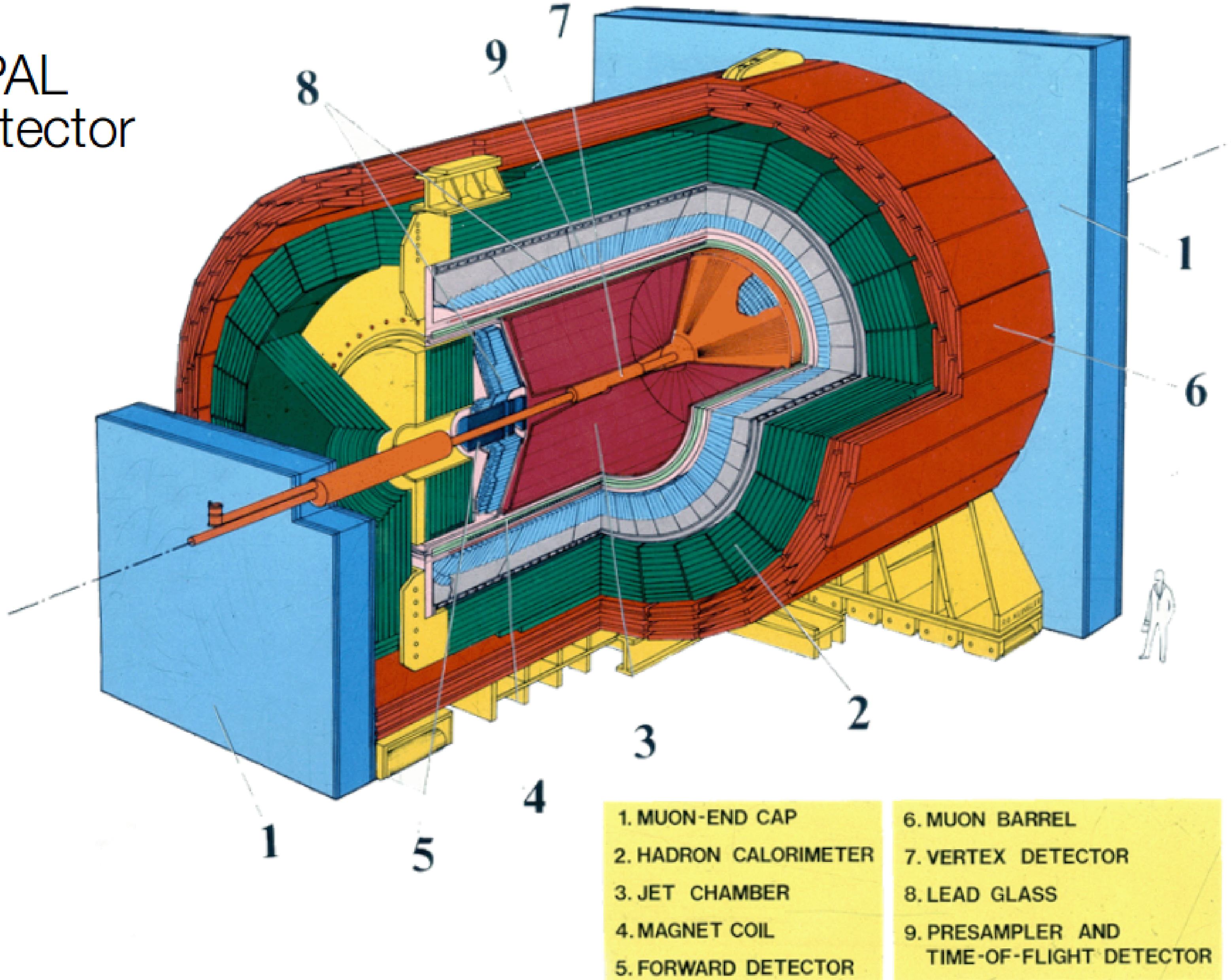
$\sqrt{s}$ = 90 GeV to 200 GeV

Circumference: approx. 27 km

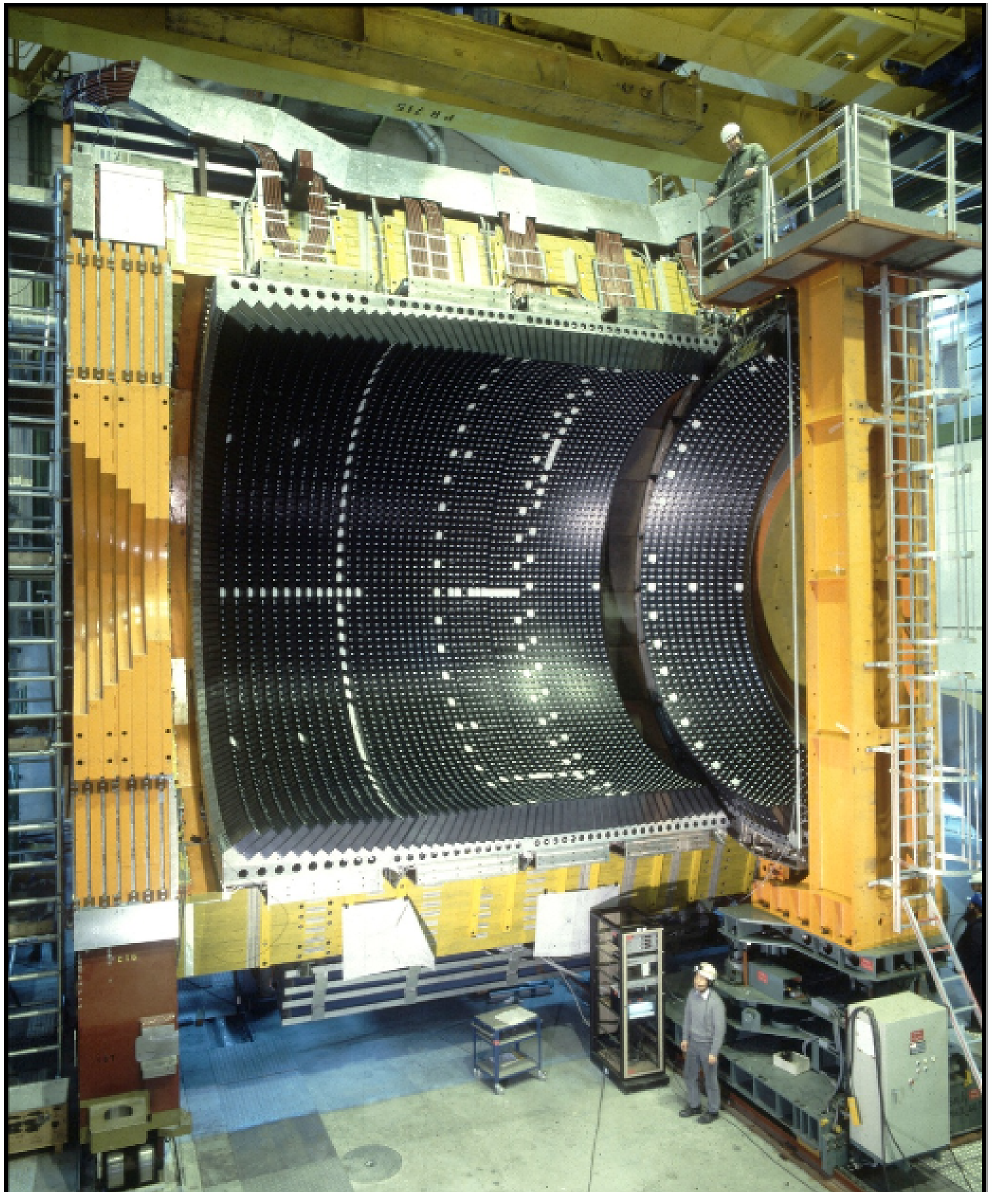
4 Experiments

The LEP Experiments - OPAL

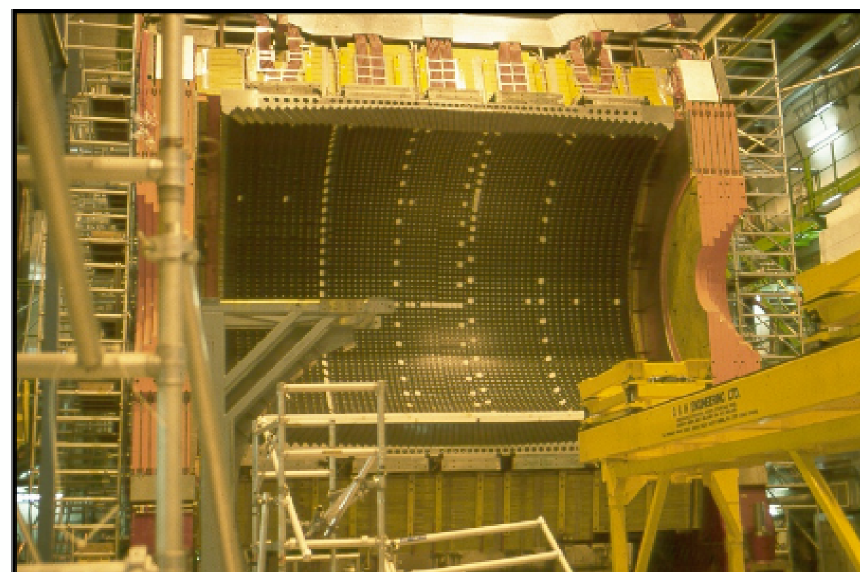
OPAL Detector



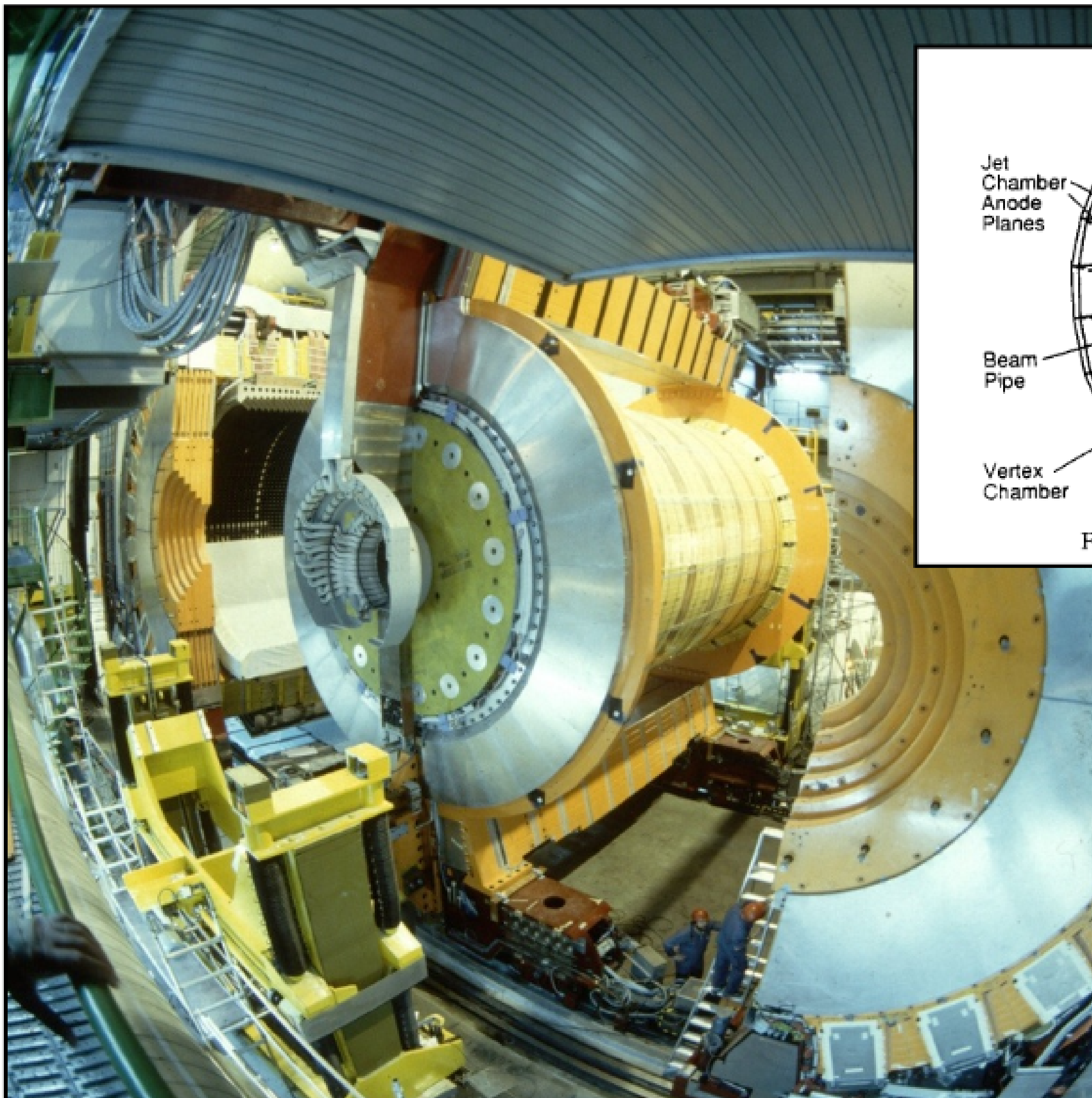
The LEP Experiments - OPAL



Opal Calorimeter



The LEP Experiments - OPAL



Opal Jet Chamber

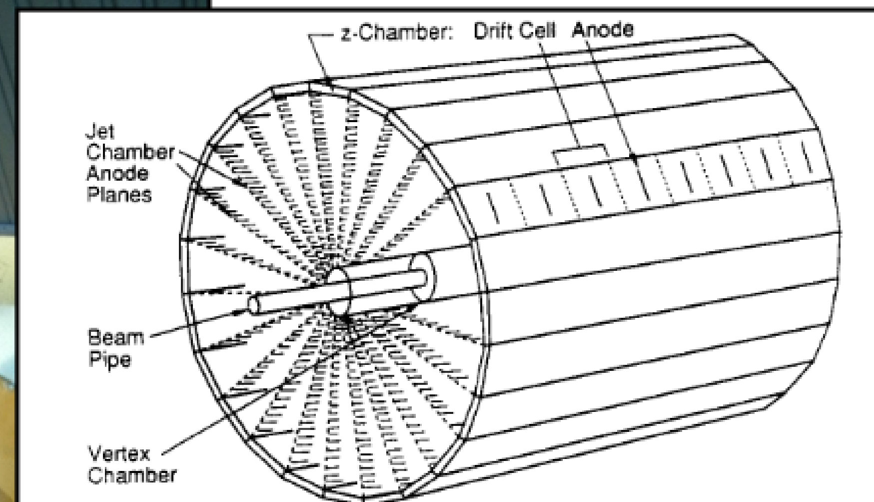
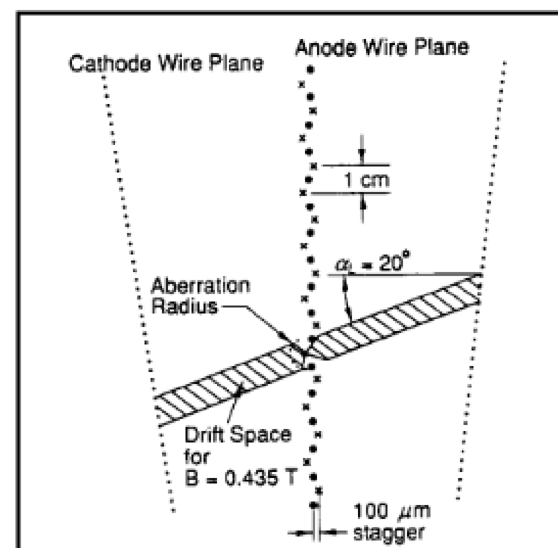


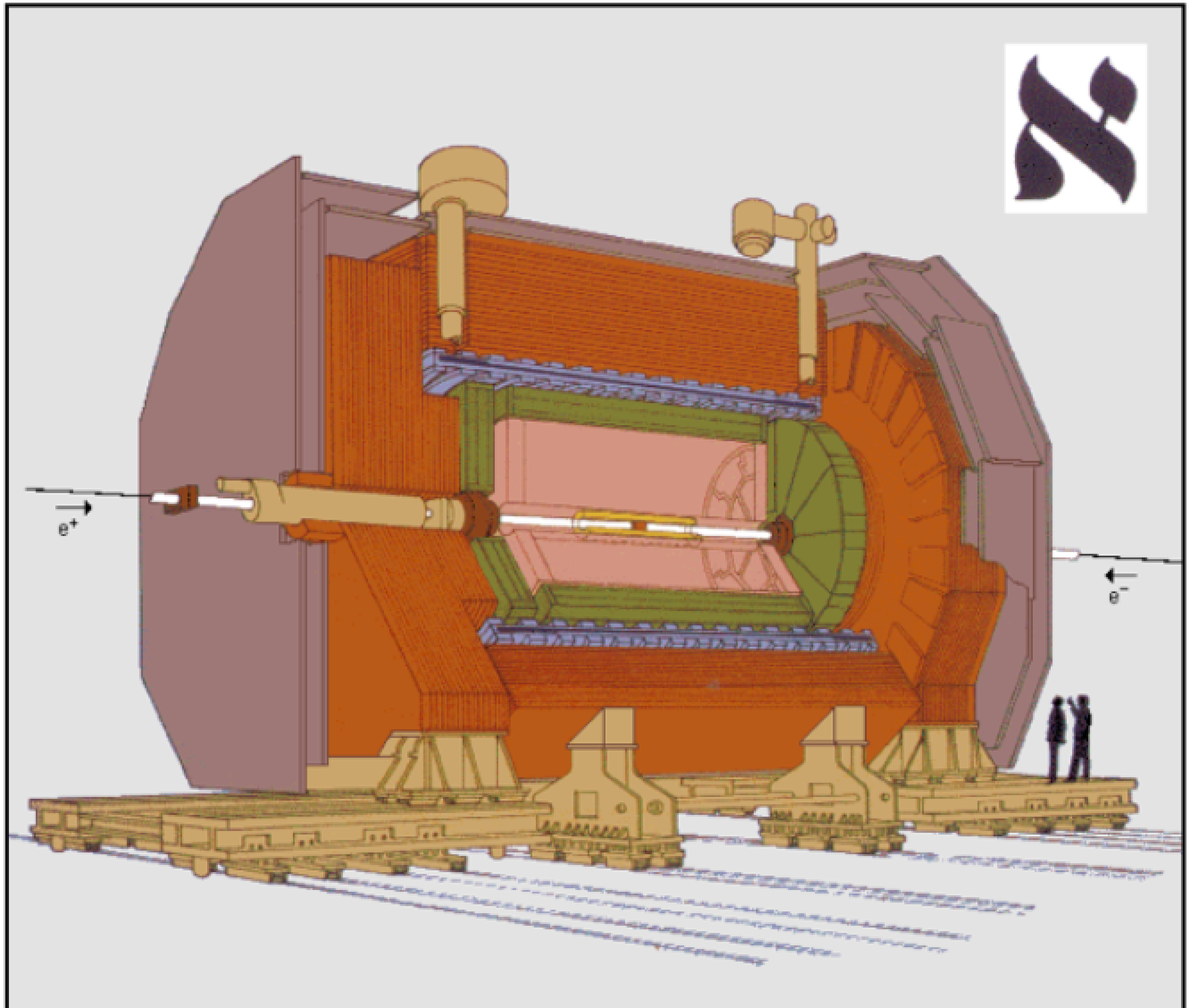
Fig. 1. Schematic view of the OPAL central detector.



The LEP Experiments - OPAL

OPAL Jet Chamber installation

The LEP Experiments - ALEPH



Vertex Detector

Inner Tracking Chamber

Time Projectior Chamber

Electromagnetic Calorimeter

Superconductin Magnet Coil

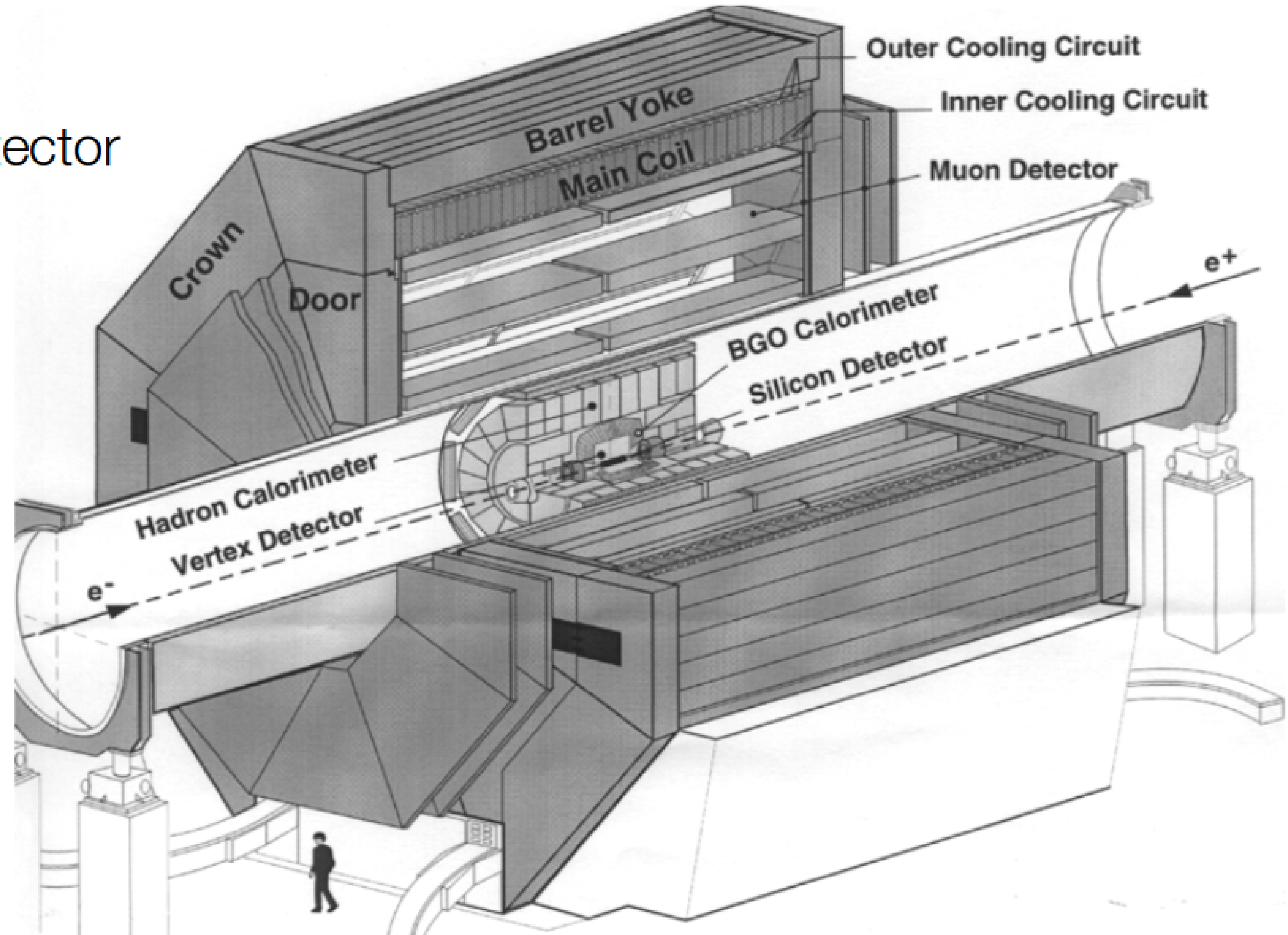
Hadron Calorimeter

Muon Chambers

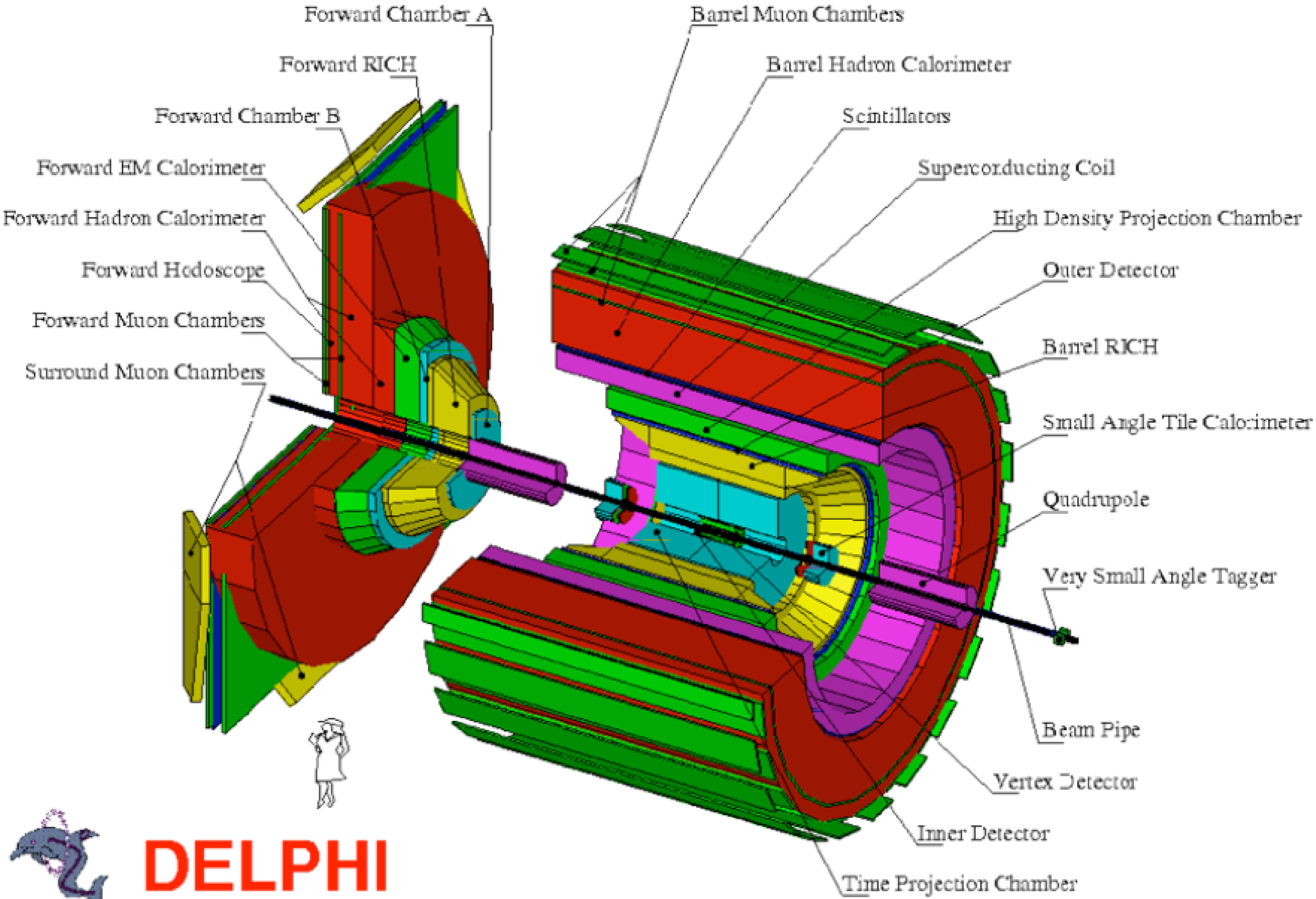
Luminosity Monitors

The LEP Experiments - L3

L3
Detector

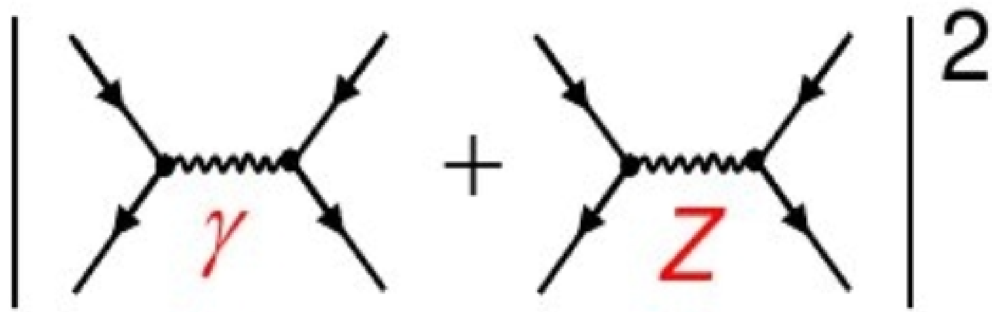


The LEP Experiments - DELPHI



Precision Test of the Z sector at LEP

$|M|^2 =$



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

s-channel only!

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

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

Z propagator considering
a finite Z width

One finds for the differential cross section:

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

γ — γ/Z interference — Z

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

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

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

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

Forward-backward asymmetry

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta \qquad \text{with} \qquad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

at Z pole ($\sqrt{s} = M_Z$):

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

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

$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at Z pole:

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

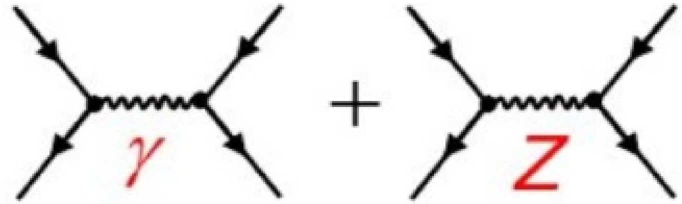
$$\sigma_z(\sqrt{s} = M_Z) = \frac{12\pi}{M_Z^2} \frac{\Gamma_e\Gamma_\mu}{\Gamma_Z^2}$$

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

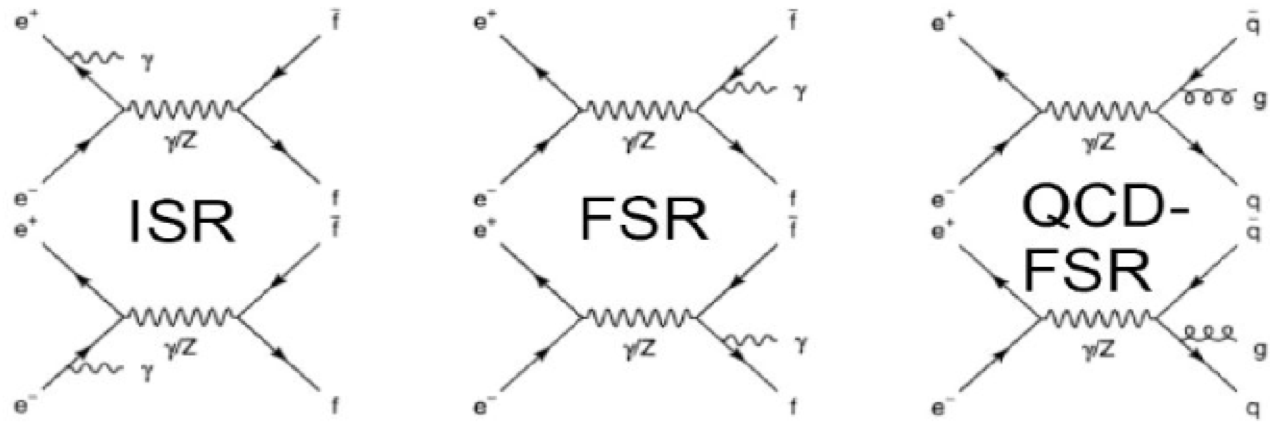
Cross sections and widths can be calculated within the Standard Model if all parameters are known

$$\Gamma_Z = \Sigma_f \Gamma_f$$

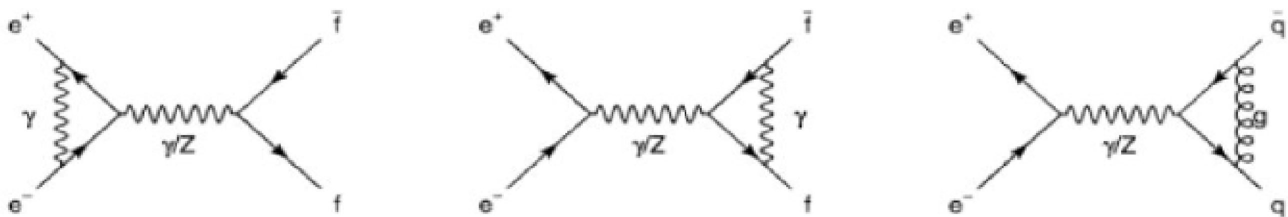
We like to measure:



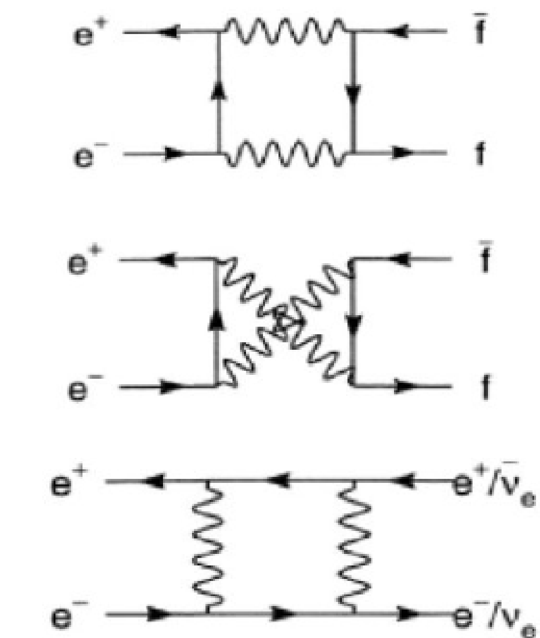
but there are many sizeable (but computable) higher order corrections:



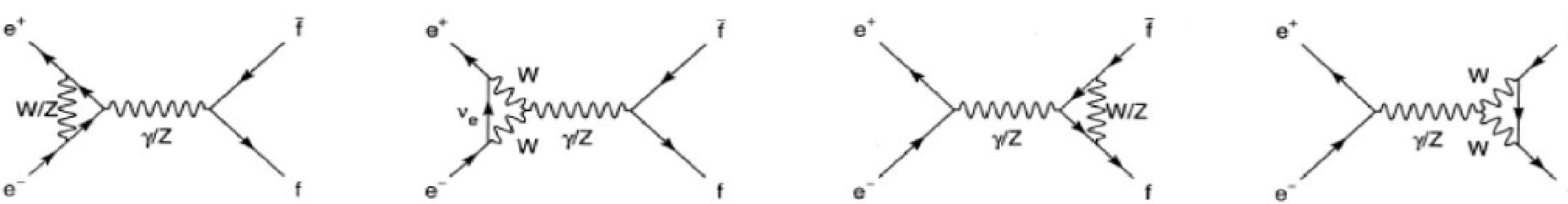
QED- und QCD-Vertex-Korrekturen



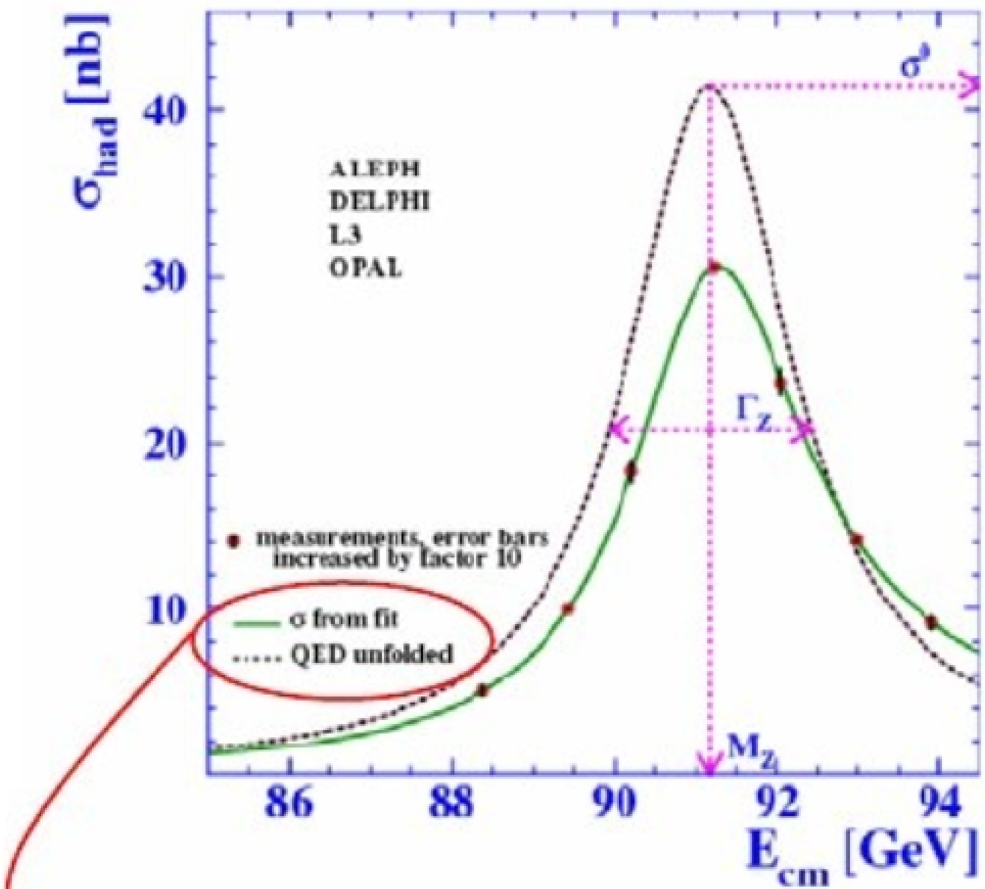
Box-Korrekturen



Elektroschwache Vertex-Korrekturen



Measurement of Z line shape



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

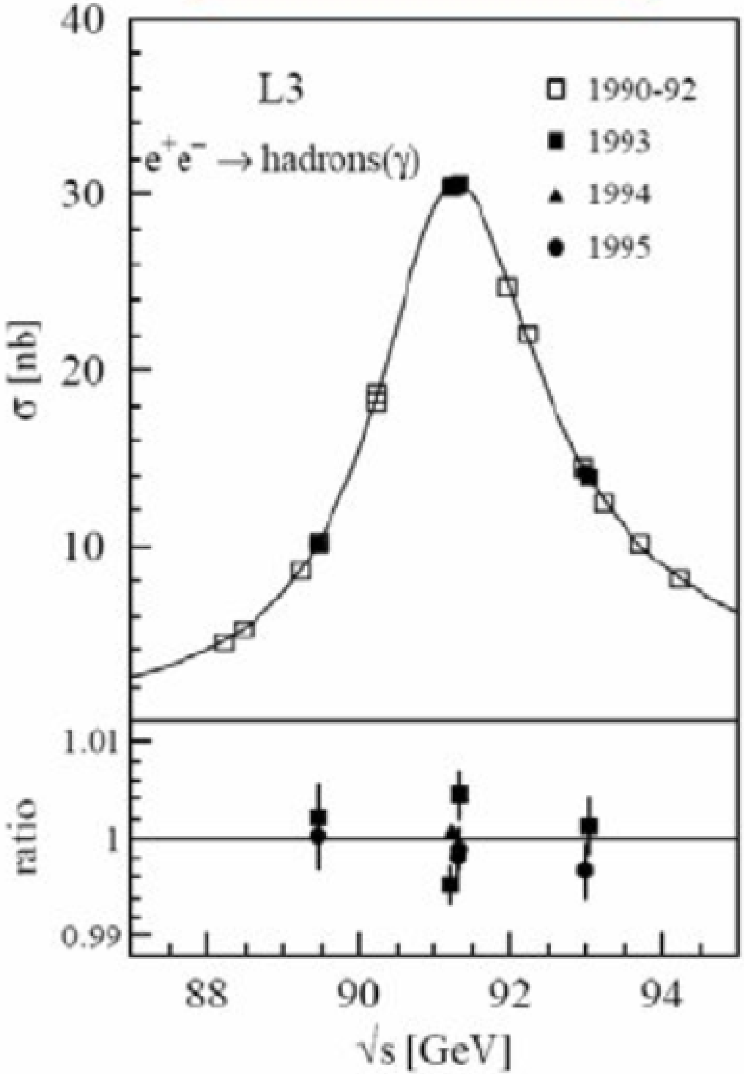
- Resonance position → M_Z
- Height → $\Gamma_e \Gamma_\mu$
- Width → Γ_Z

Initial state Bremsstrahlung corrections

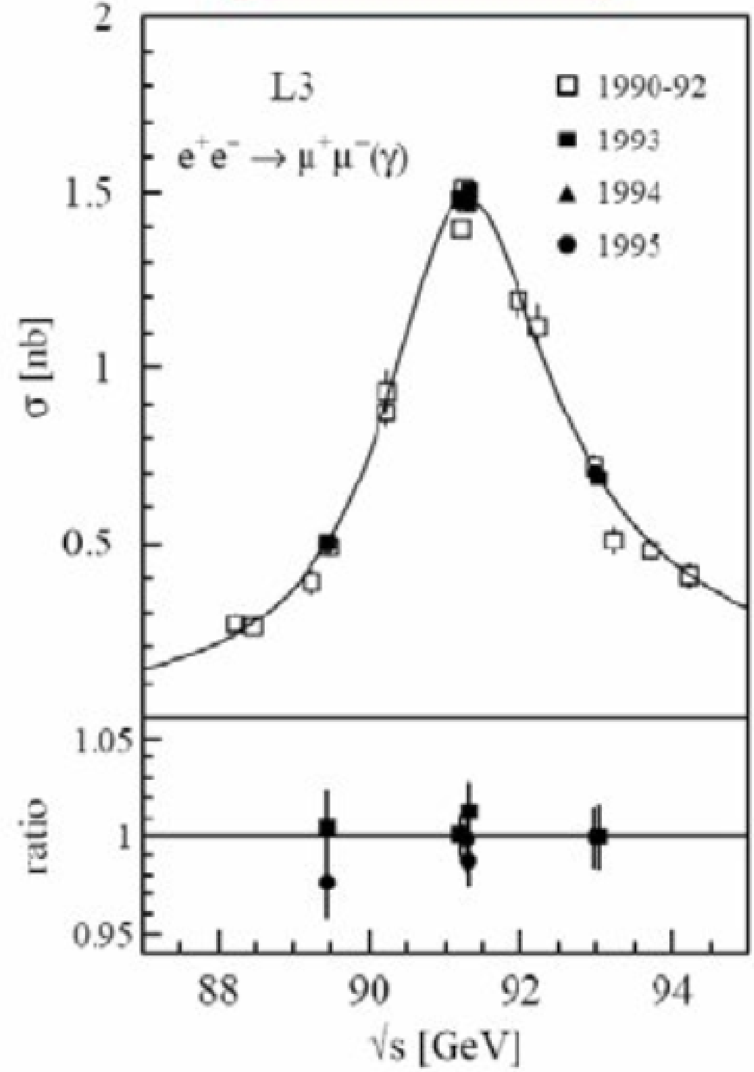
$$\sigma_{ff(\gamma)} = \int_{4m_f^2/s}^{1} G(z) \sigma_{ff}^0(zs)\, dz \qquad z = 1 - \frac{2E_\gamma}{\sqrt{s}}$$

Energy scan is more precise than reconstructed invariant mass, advantage of e^+e^-!

$e^+ e^- \to hadrons$

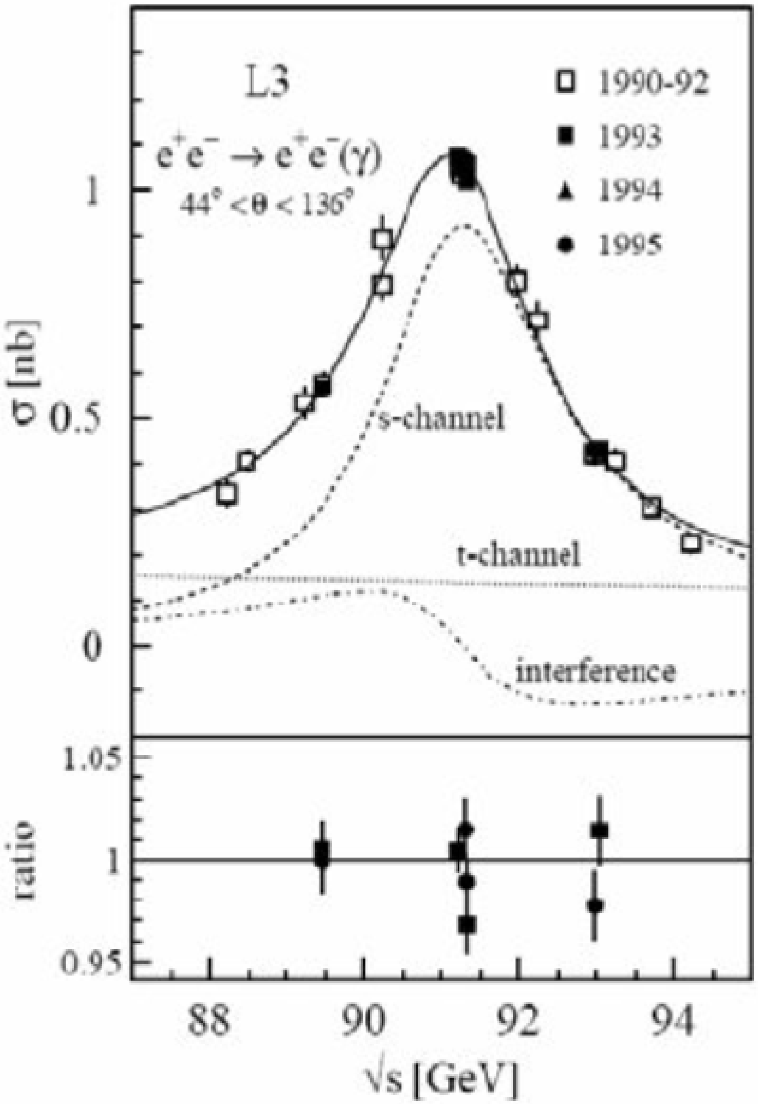


$e^+ e^- \to \mu^+ \mu^-$

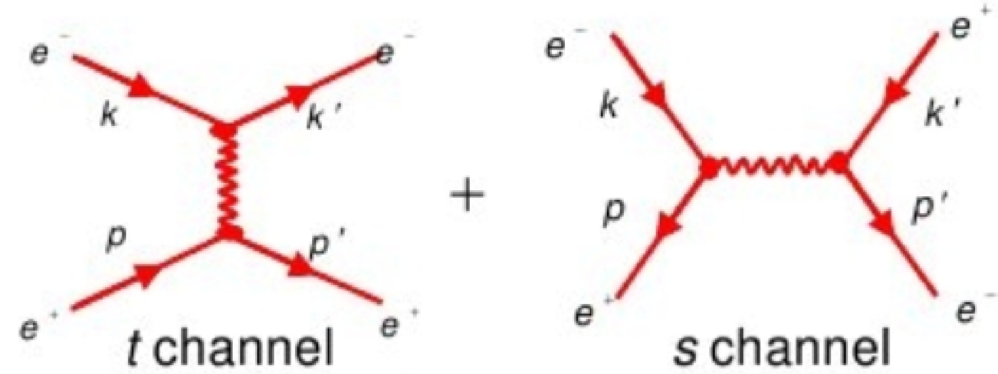


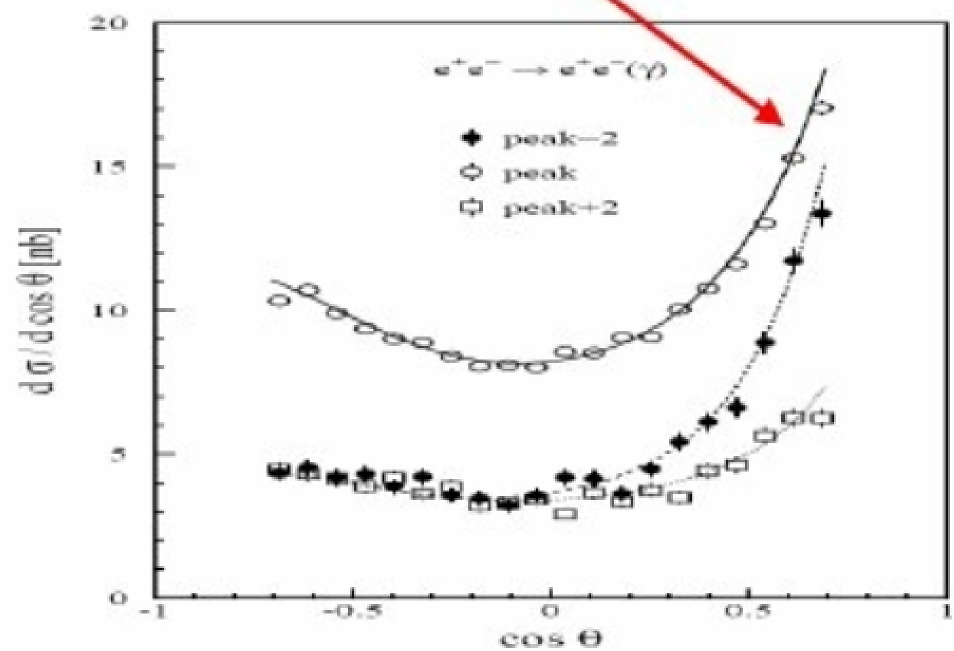
Resonances look the same, independent of the final state: propagator is the same!

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



t channel contribution → forward peak





Phase shift around the pole of Breit-Wigner of s-channel process, explains the shape of the interference term.

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)

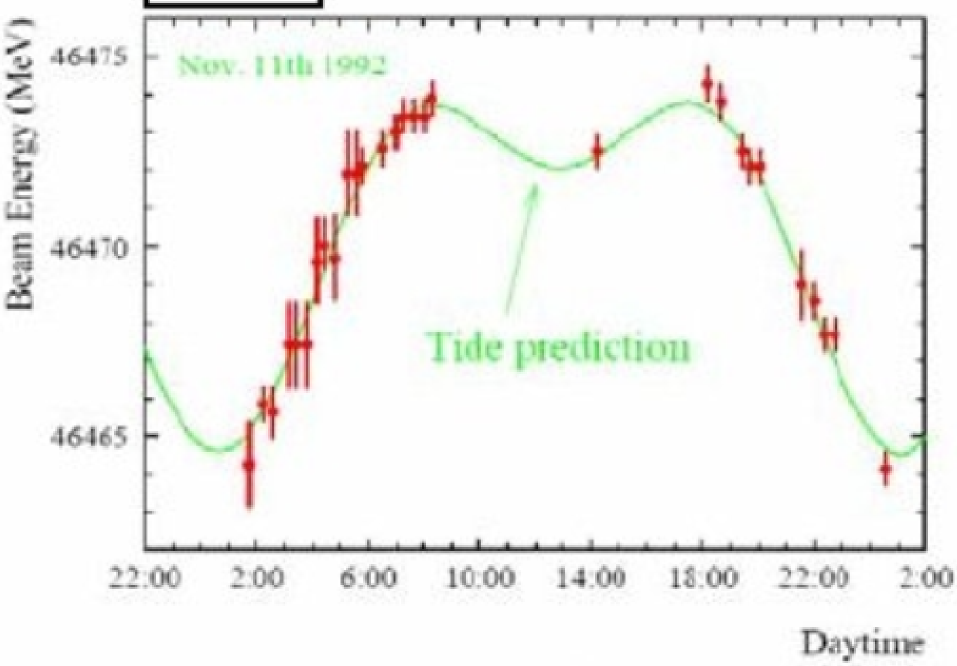
LEP energy calibration: Hunting for ppm effects

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

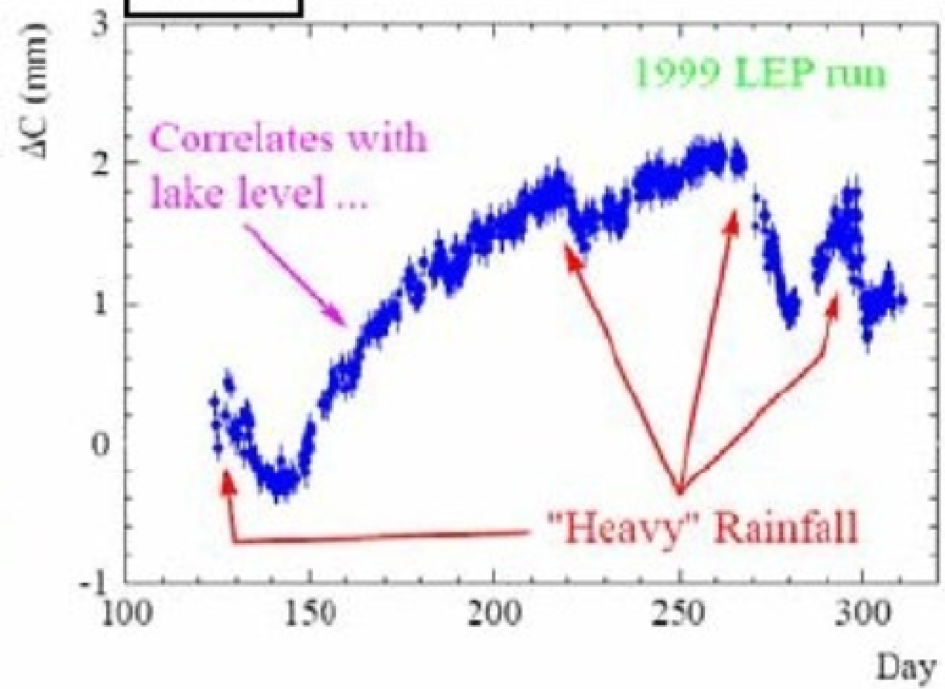
- tide effects
- water level in lake Geneva

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

1992

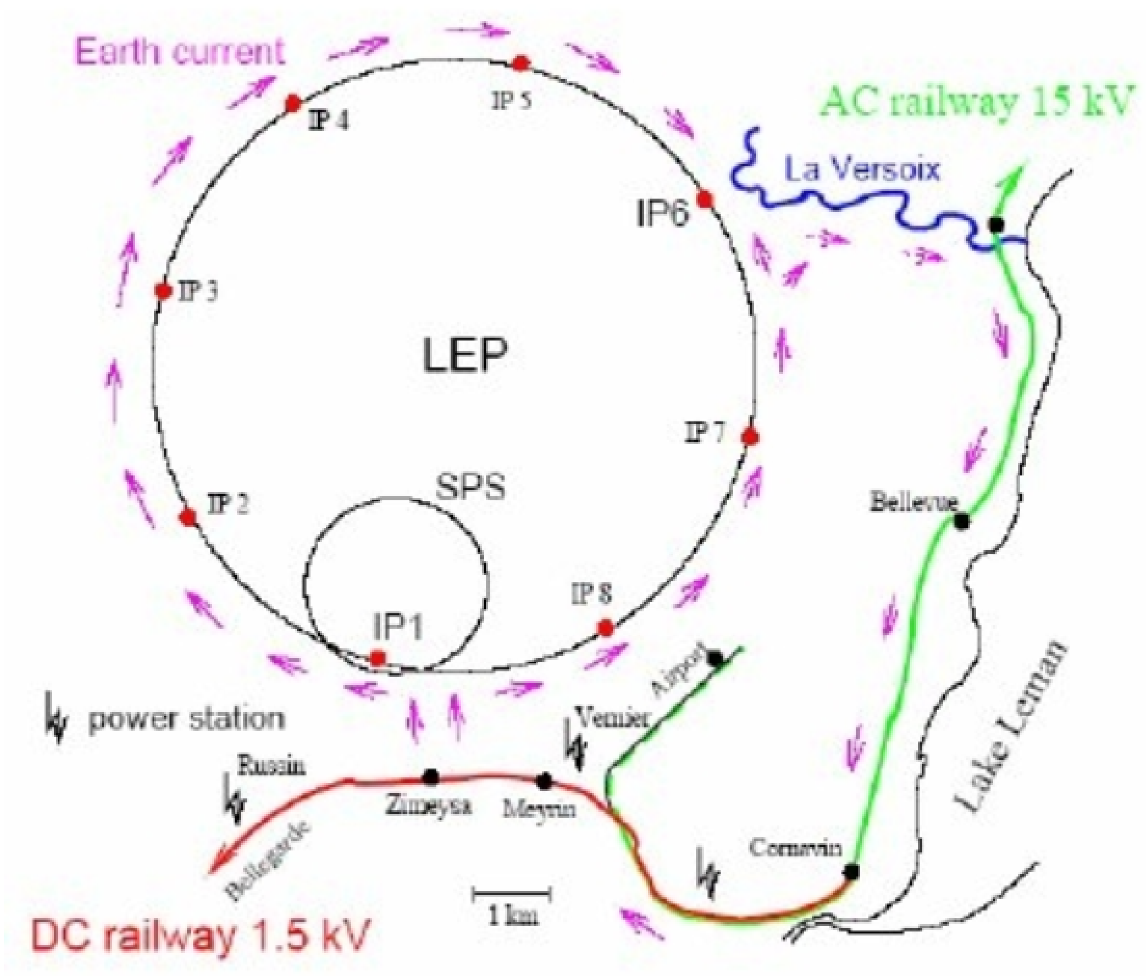


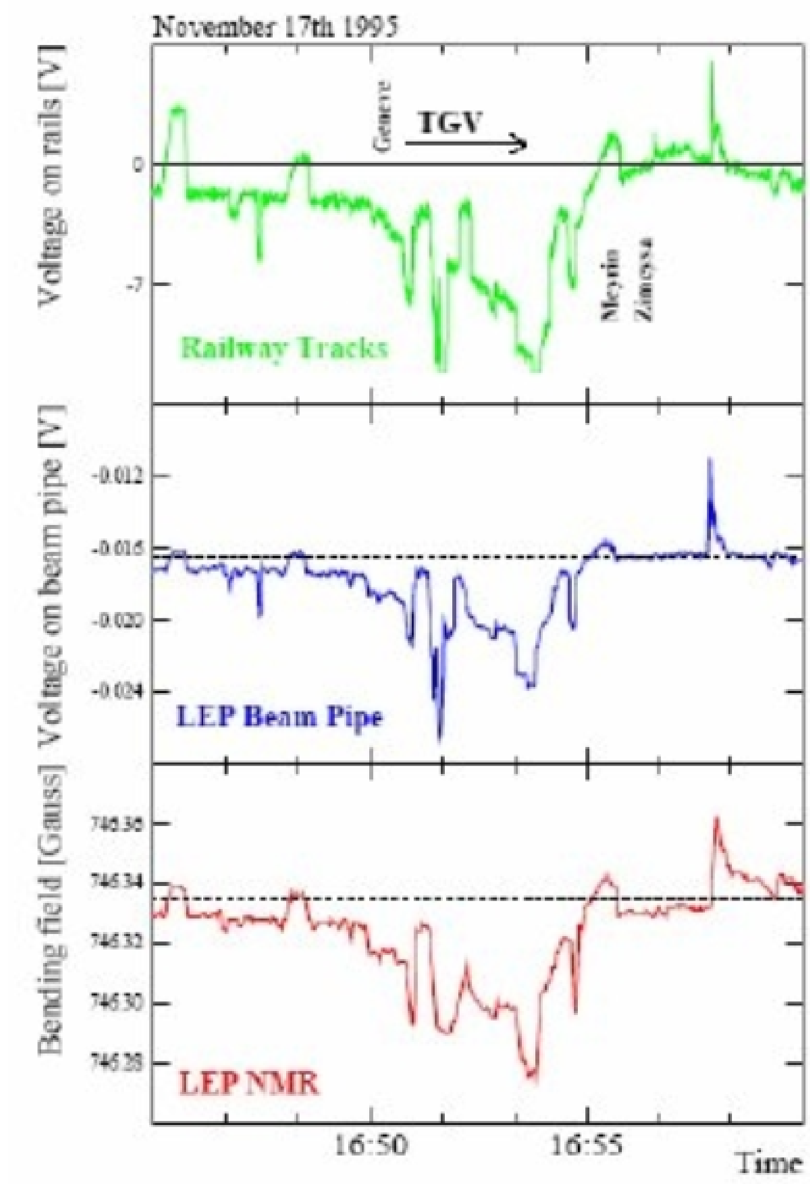
1993



Effect of the French “Train a Grande Vitesse” (TGV)

Vagabonding currents (~1A) from trains





3 “light” neutrino species!

In the Standard Model:

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

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

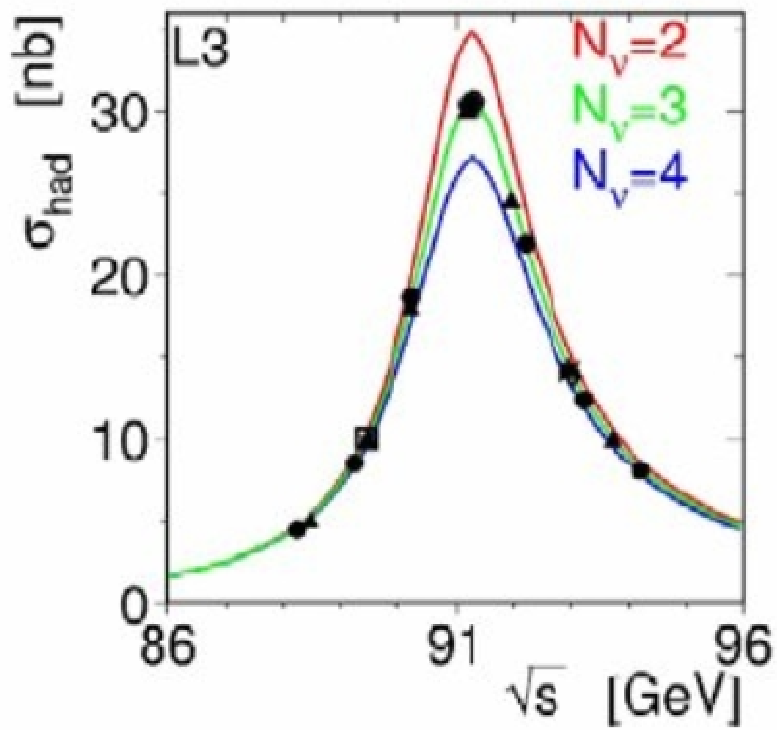
To determine the number of light neutrino generations:

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

5.9431±0.0163 =1.991±0.001 (small theo. uncertainties from m_{top} M_H)

$$N_\nu = 2.9840 \pm 0.0082$$

No room for new physics: $Z\rightarrow$new



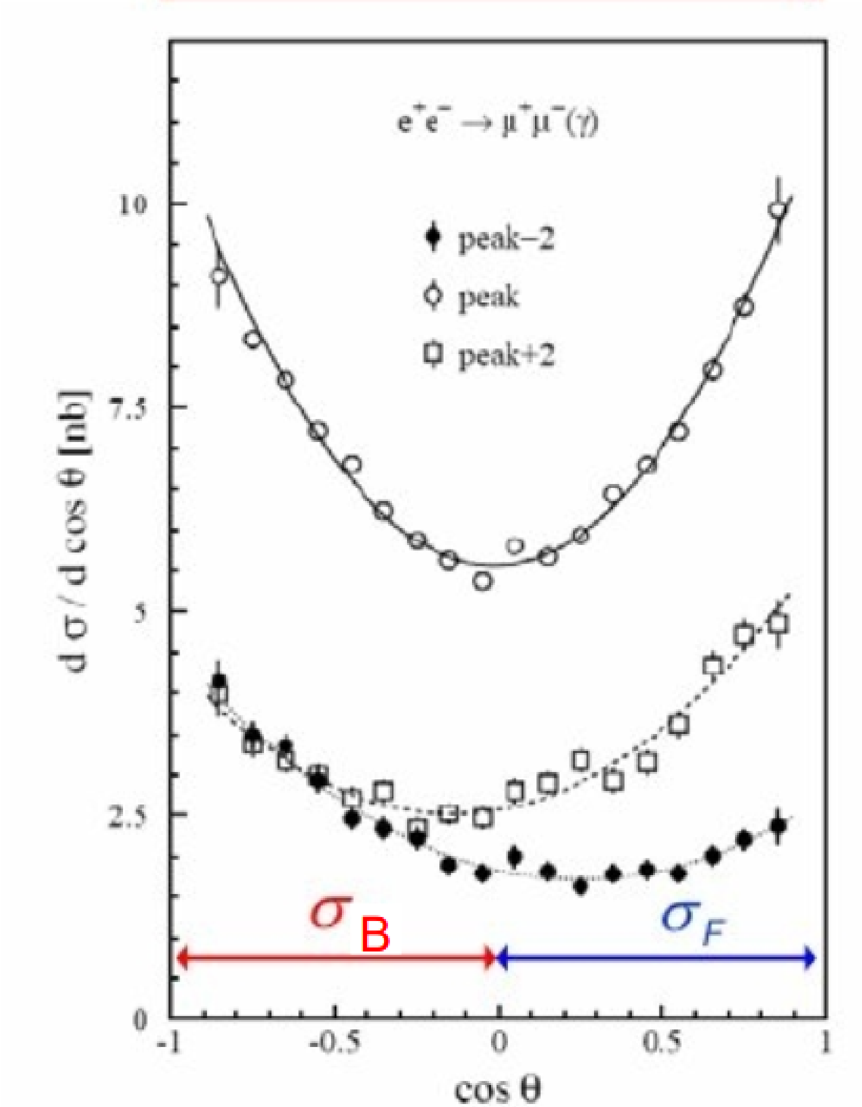
Forward-backward asymmetry and fermion couplings to Z

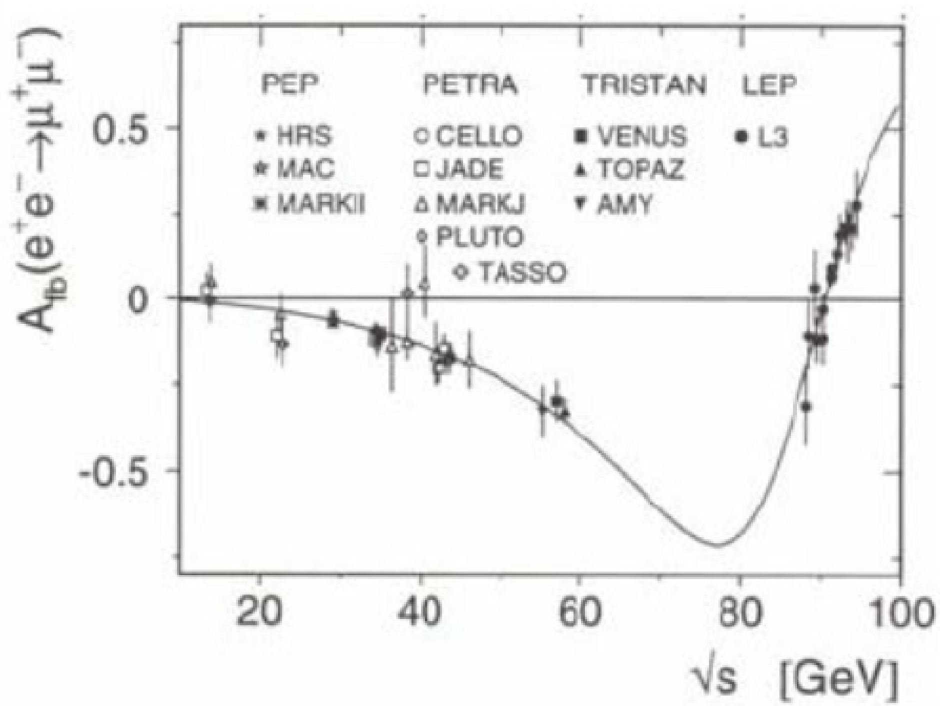
$$e^+ e^- \rightarrow Z \rightarrow \mu^+ \mu^-$$

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

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

Lowest order SM prediction:

$$g_V = T_3 - 2q\sin^2\theta_W \quad g_A = T_3$$

Forward-backward asymmetry

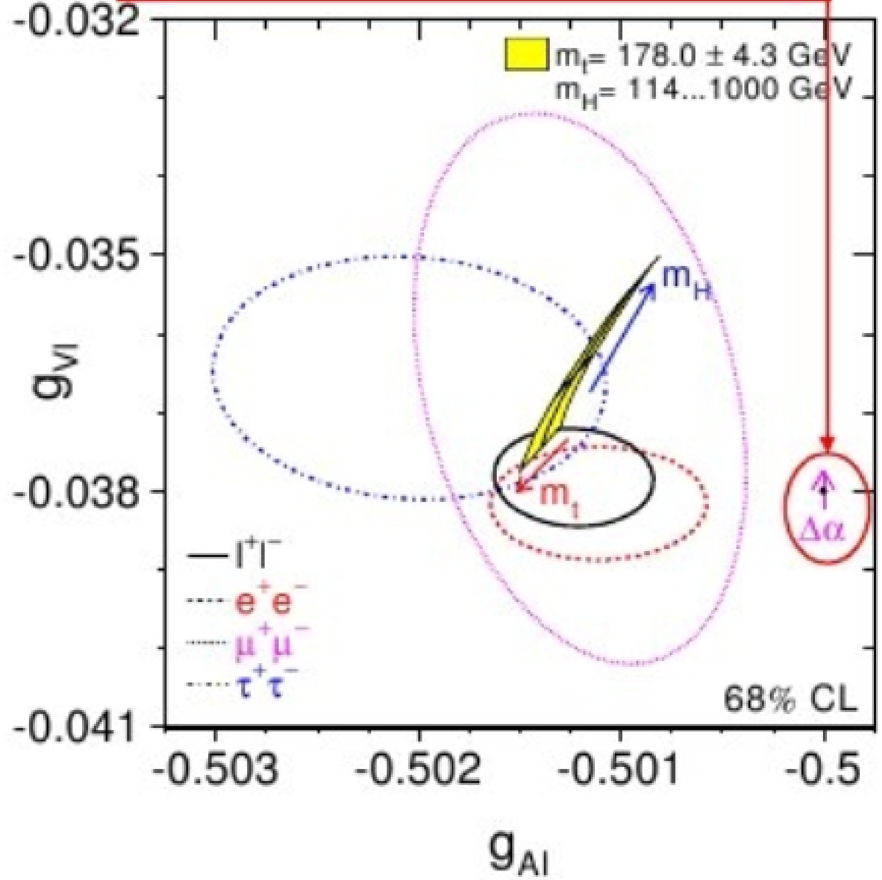
- Away from the resonance A_{FB} large
  → interference term dominates

$$A_{FB} \sim g_A^e g_A^f \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2}$$

- 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

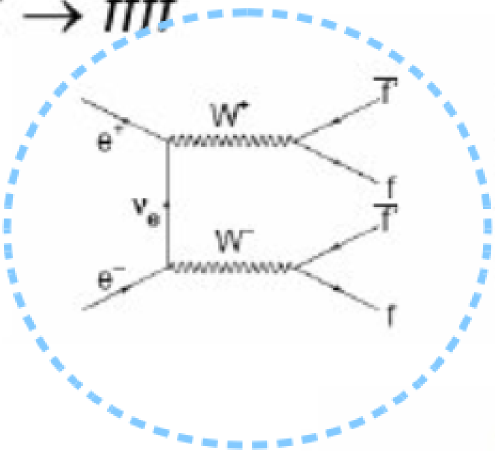
Confirms lepton universality

Higher order corrections seen

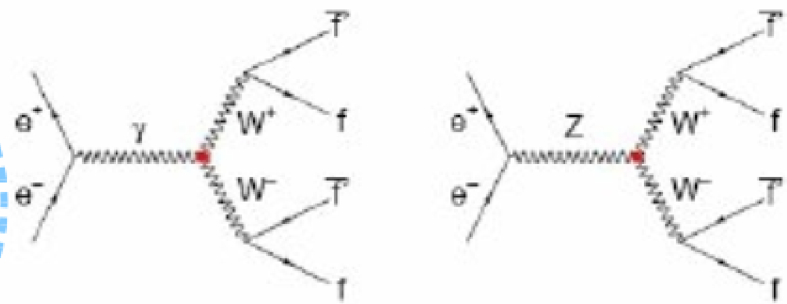
Precision measurements of W branching ratio at LEP (~10K WW events):

$e^+e^- \rightarrow WW \rightarrow ffff$

V-A theory:



additional SM vertices, triple gauge boson coupling

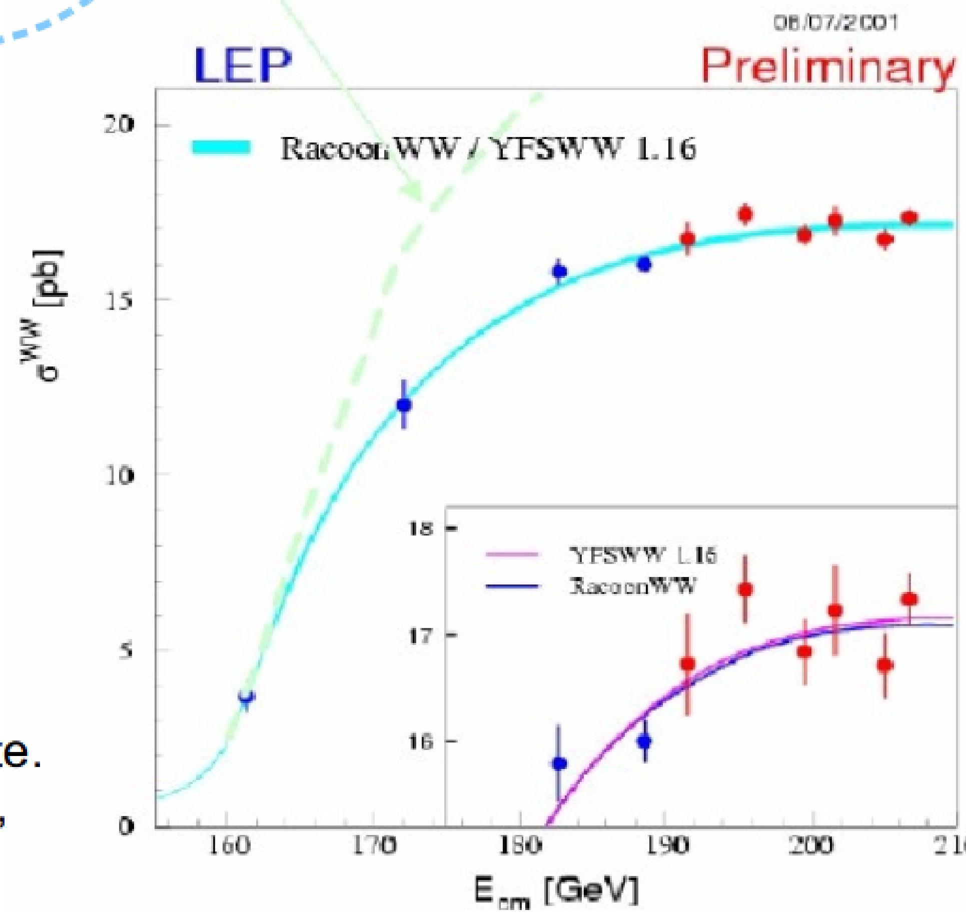


"Ugly" fine tuning!

Threshold behavior of the cross section (phase space) for ee→WW production:

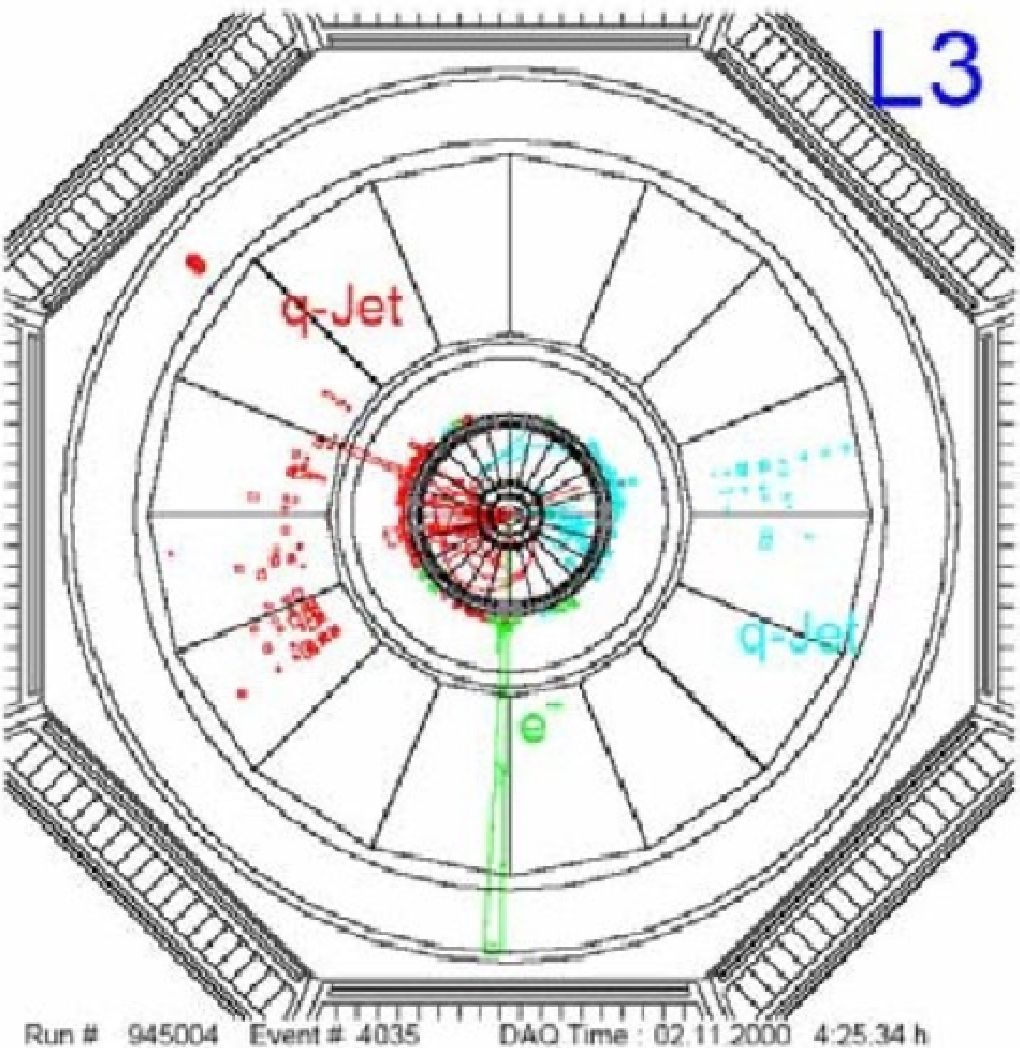
Phase space factor = f(M_W, √s):

→ Allows determination of M_W

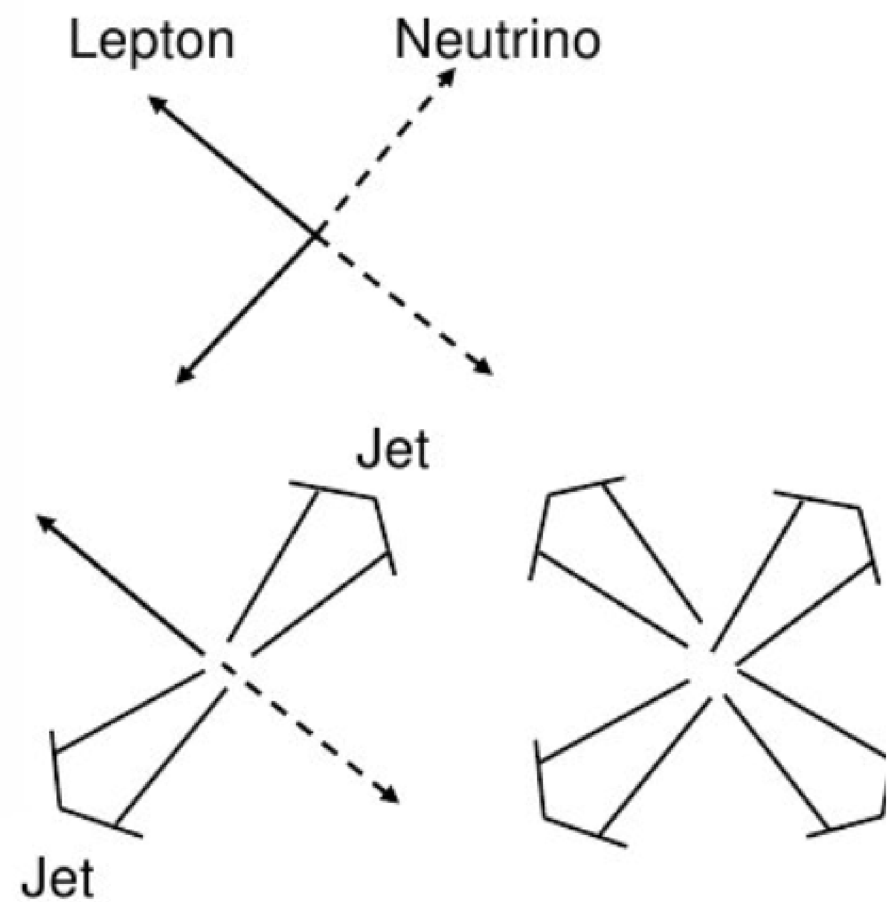


Jets and/or neutrinos in the final state.
Not easy to compute invariant mass,
but exploit that CME known in e^+e^-

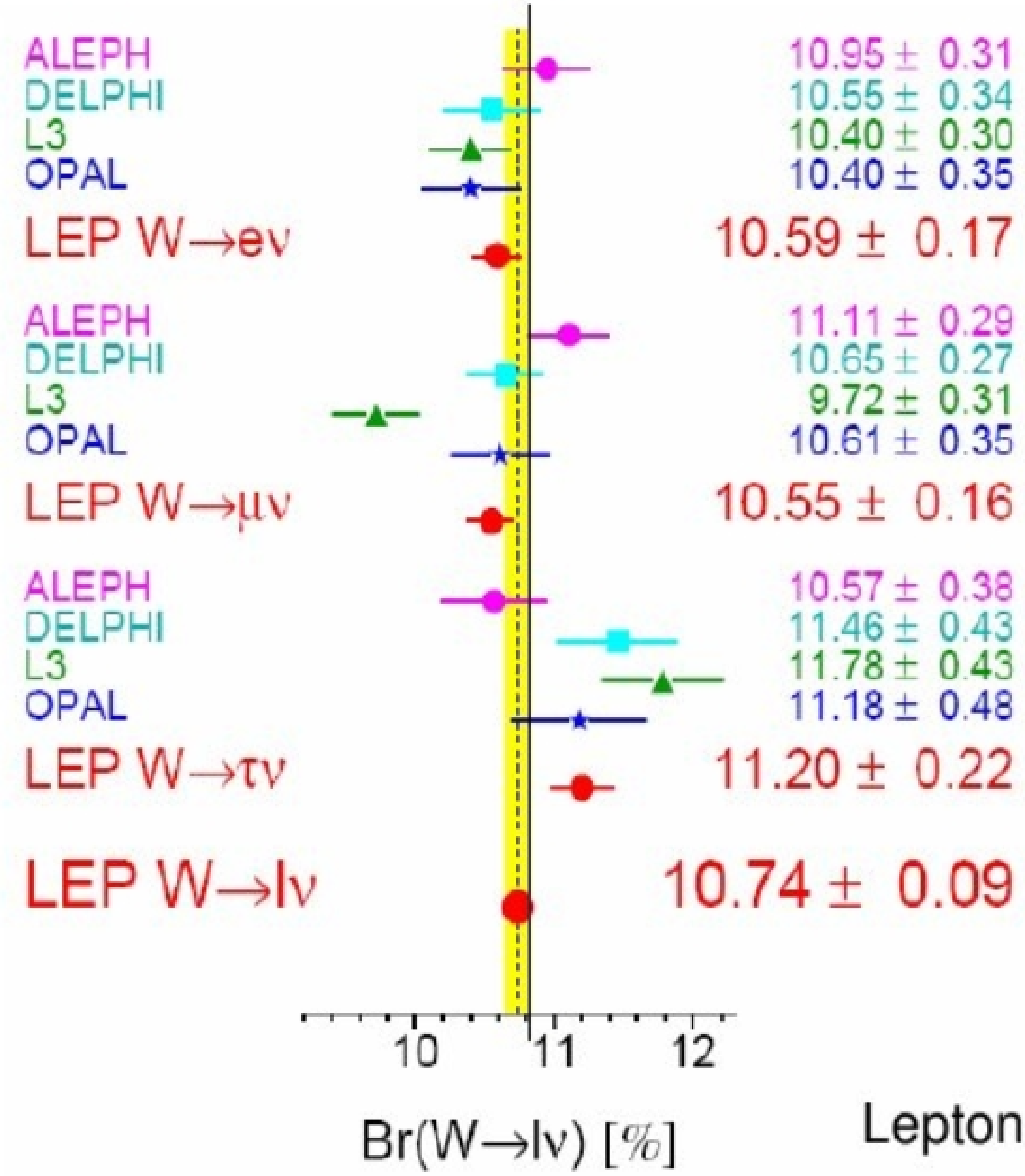
W decays



$$WW \rightarrow \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$



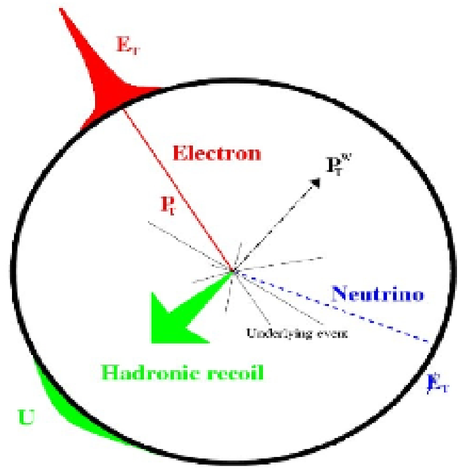
W Branching ratio at LEP

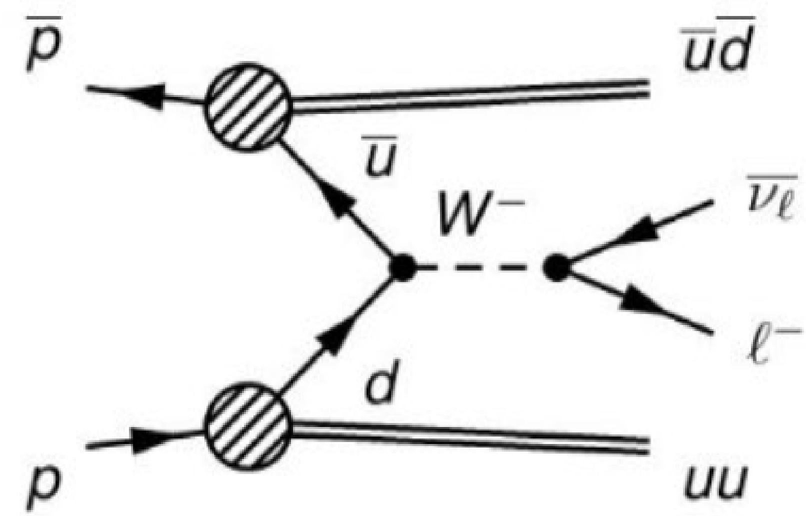


$$Br(W \to q\bar{q}) = (67.77 \pm 0.28)\%$$

Lepton universality tested to 2%

W Mass measurement at Tevatron:





Method of transverse mass:

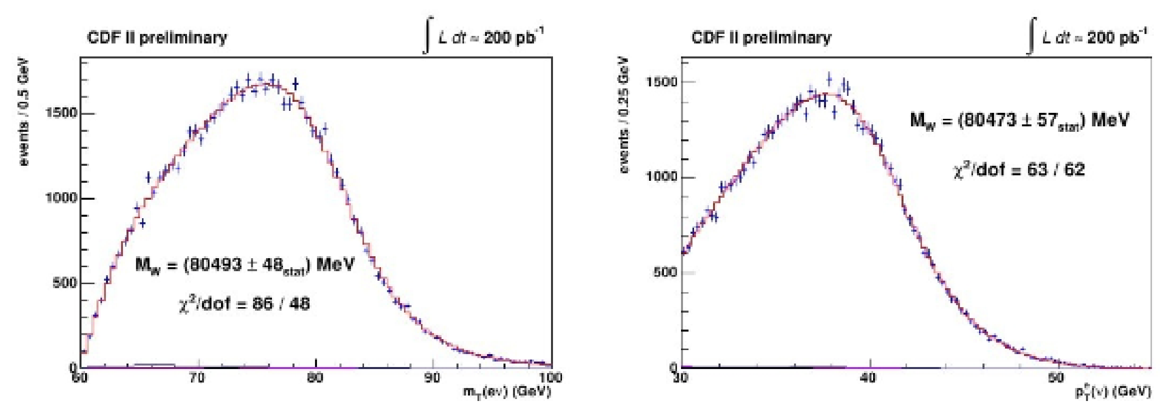
Idea: $\sum p_T = 0$

p_T^ℓ and p_T^{had} are measurable

$$p_T^\nu = -p_T^\ell - p_T^{had}$$

$$M_T^W = \sqrt{2 p_T^\ell p_T^\nu - 2 \vec{p_T}^\ell \vec{p_T}^\nu}$$

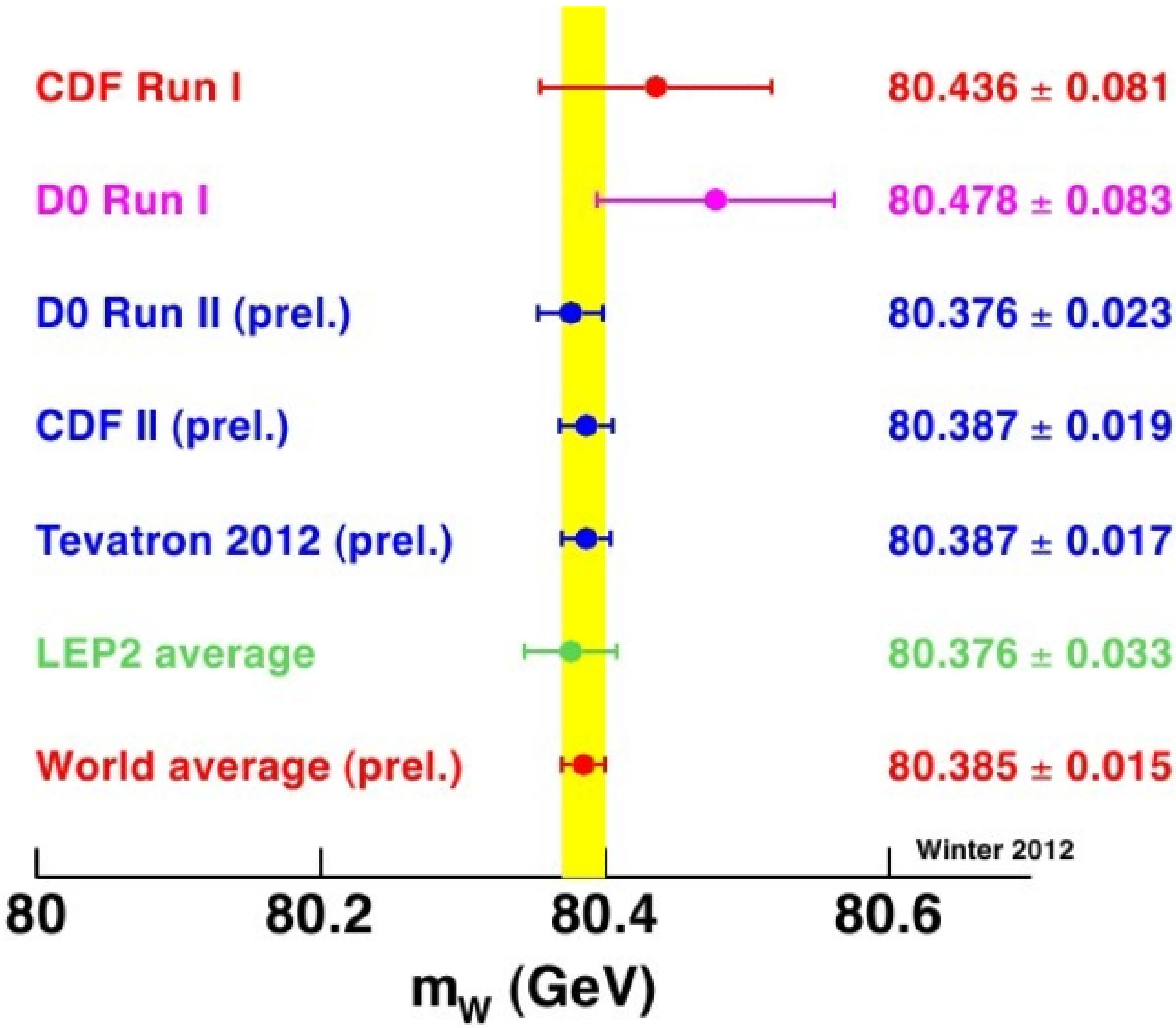
or method of p_T^ℓ, similar to UA1



Spectra not analytically computable;
both methods rely on templates from MC

main challenge: calibration of calorimeter

Precision measurement of W mass:



Mass measurements are completely systematically dominated:
calorimeter calibration, uncertainties on input from simulation …

Many different methods with different source of systematics performed to get the uncertainties smaller.

Higher order corrections + the Higgs

Lowest order SM predictions

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad\Longrightarrow\quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad\Longrightarrow\quad \sin^2\theta_{\text{eff}} = (1 + \Delta\kappa)\sin^2\theta_W$$

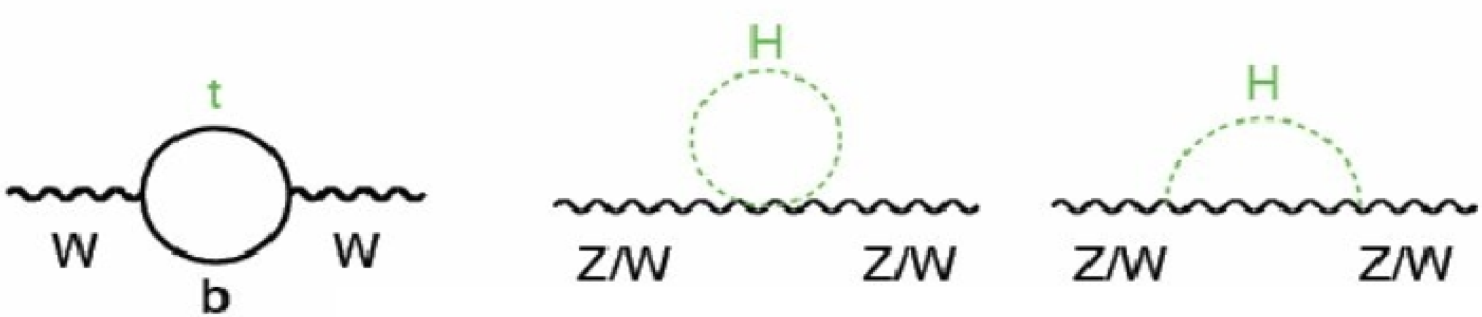
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad\Longrightarrow\quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

$$\alpha(0) \quad\Longrightarrow\quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

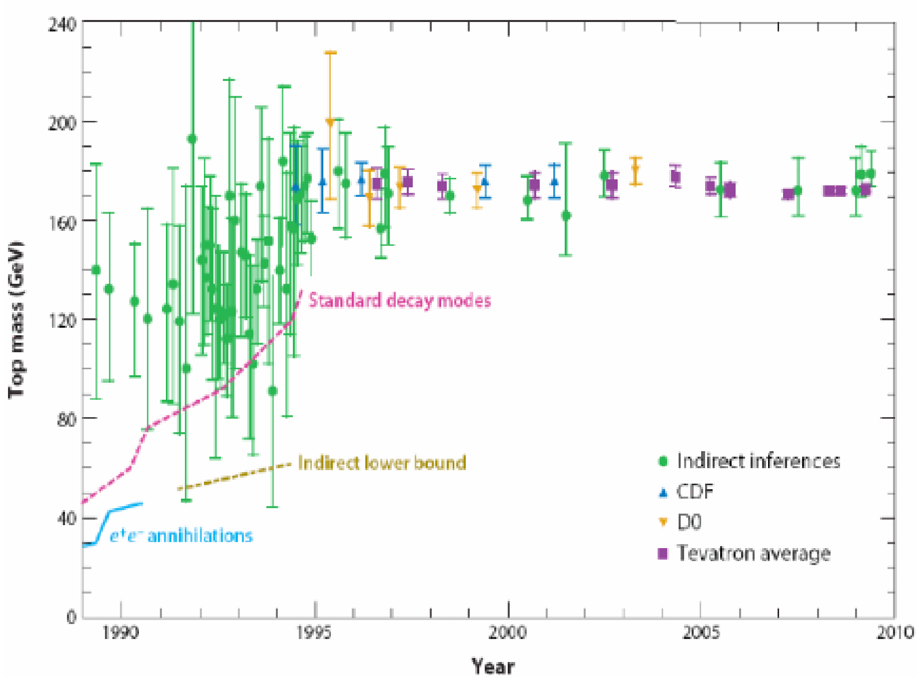
Including radiative corrections

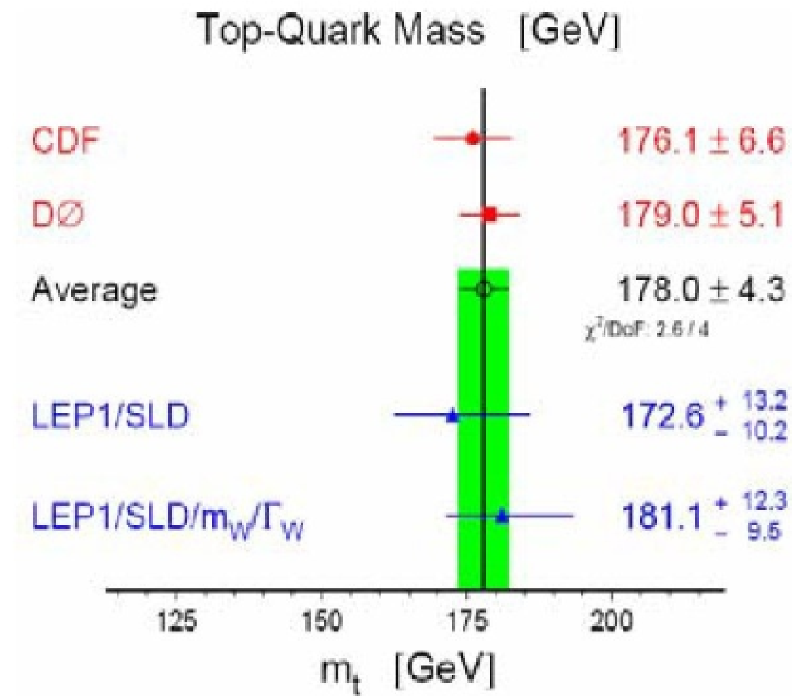
with : $\Delta\alpha = \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{top}} + \Delta\alpha^{(5)}_{\text{had}}$

$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t^2, \log(m_H), \ldots\right)$$



Prediction of the Top-Quark Mass





Direct measurement of m_t

Todays best value:

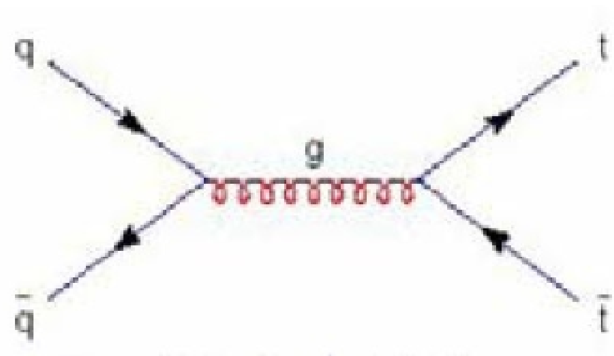
m(top) = 173.2 +/- 0.9 GeV

Prediction of m_t by LEP before the discovery of the top at TEVATRON.

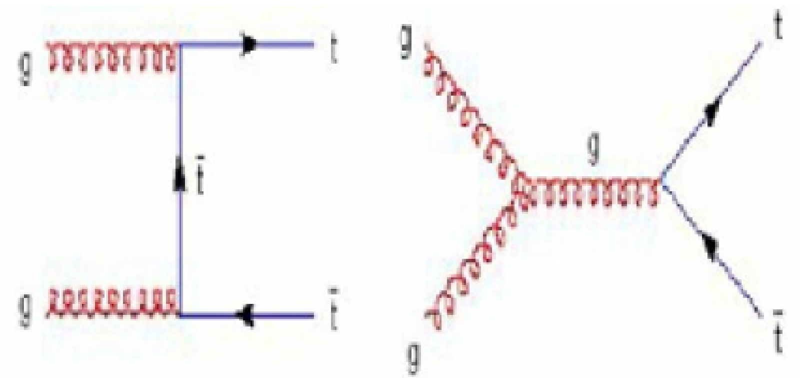
Very impressive proof of Standard Model predictive power!

Top discovery at the Tevatron 1995

$p\bar{p}$ @ 2 TeV

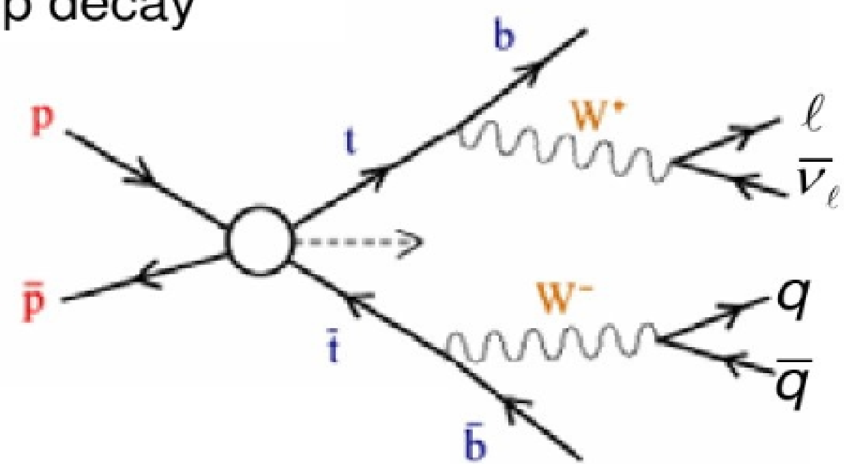


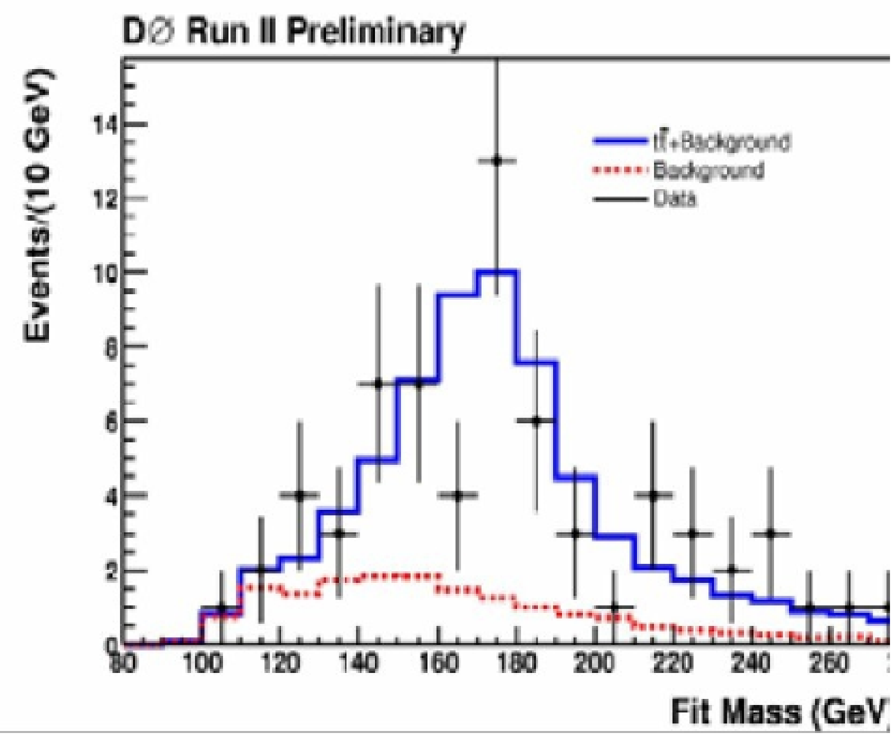
$q\bar{q}$ annihilation (85%)



gluon fusion (15%)

Top decay



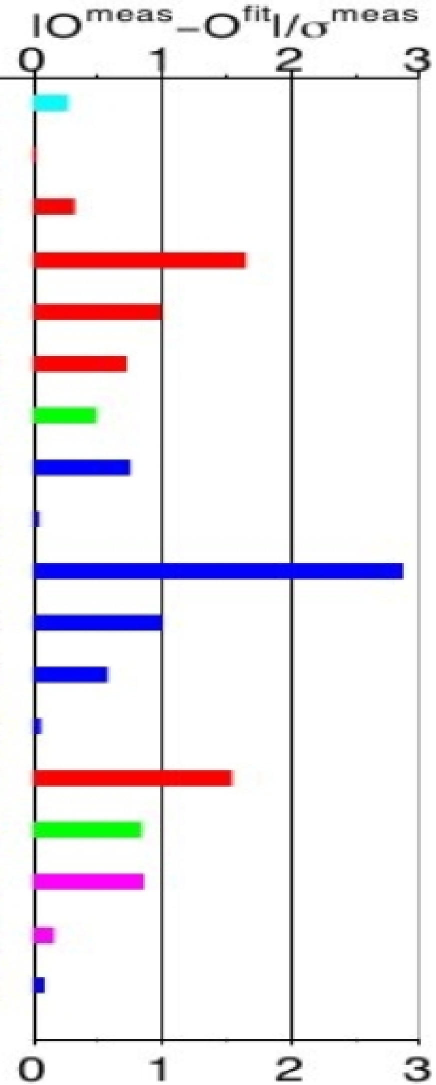


Channel used for mass reconstruction:

$$m_t = m_{inv}(b - jet, W \rightarrow jet + jet)$$

Standard Modell precisely tested .....

	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	41.479
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]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



July 2010

Everything is very consistent … however Higgs boson is still missing.