DESY, 12. September 2006

Precision Electroweak Measurements

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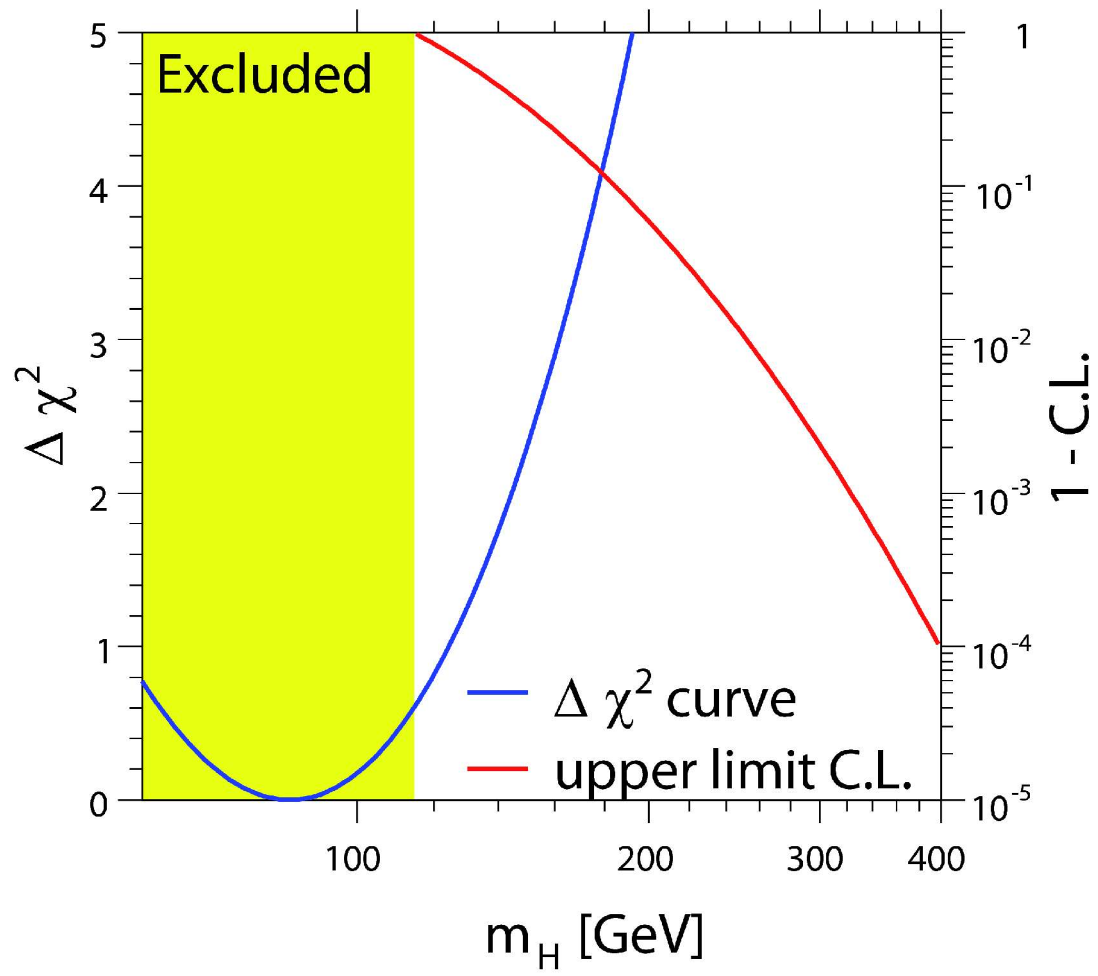
RWTH Aachen

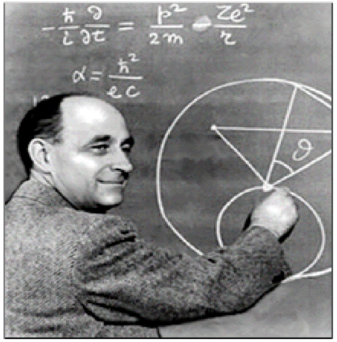


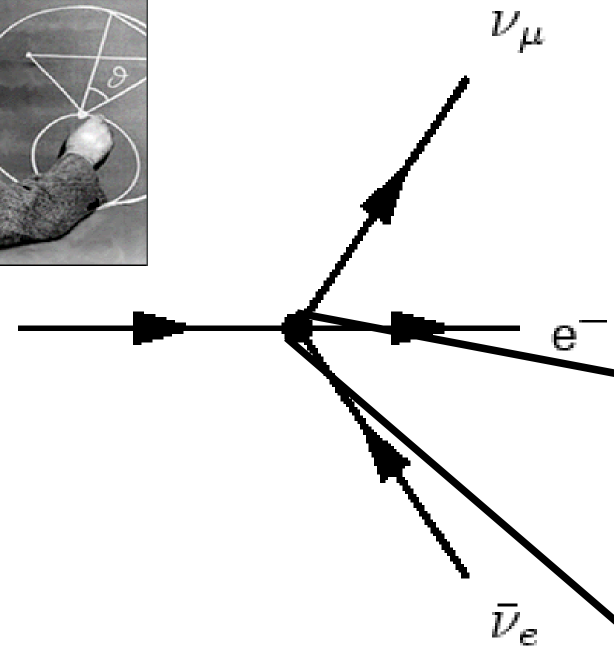
RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Outline

1. Theory of electroweak interaction
2. Precision measurements of electroweak processes
3. Global electroweak Fit
4. Conclusions

From Fermi to Glashow, Salam, Weinberg

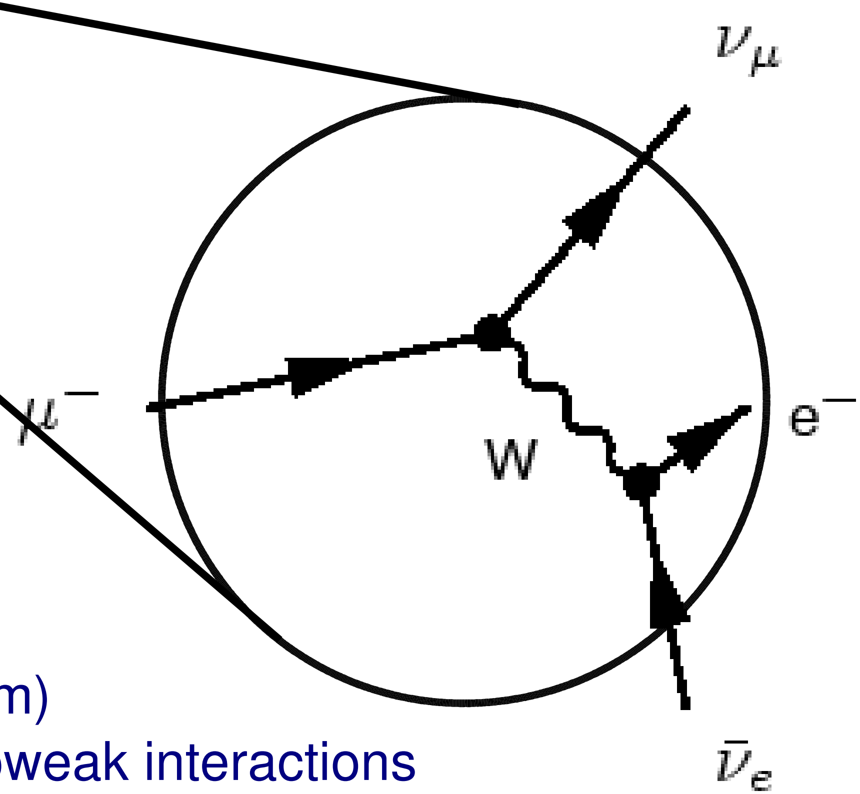




Fermi theory describes weak decay using four-fermion interaction

Coupling constant: $G_F = 1.6637 \cdot 10^{-5}\ \text{GeV}^{-2}$

Effective theory at low energies



High Energies:

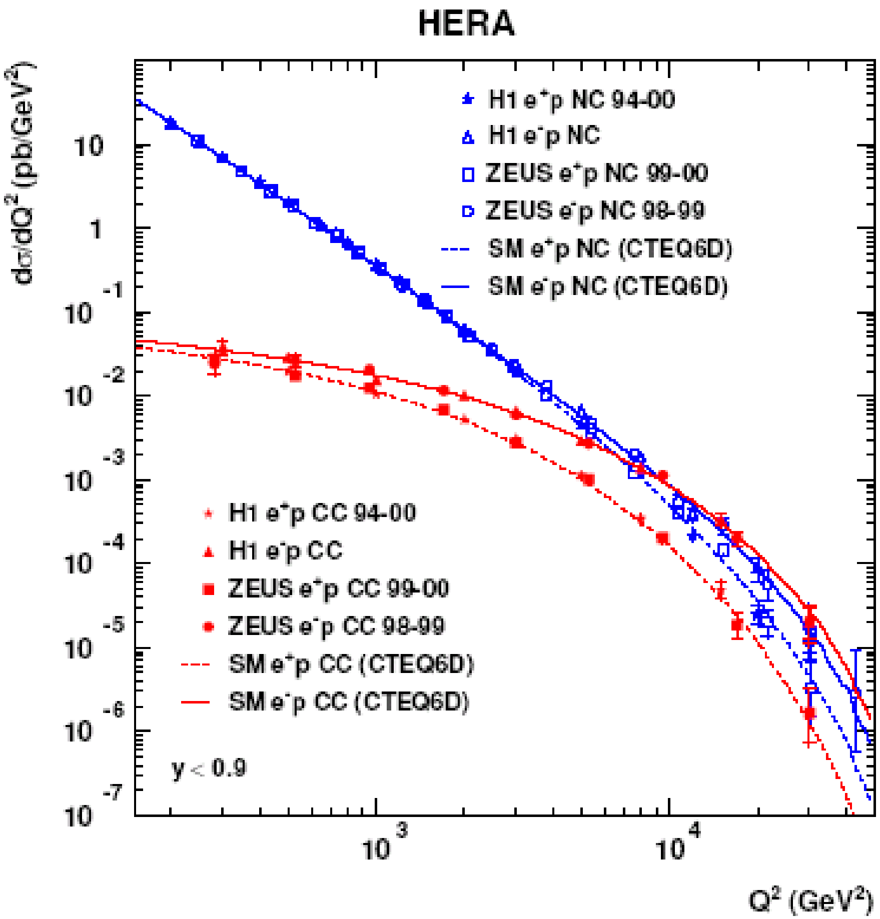
Exchange of weak gauge bosons

Interaction is small due to large mass of the W and Z bosons

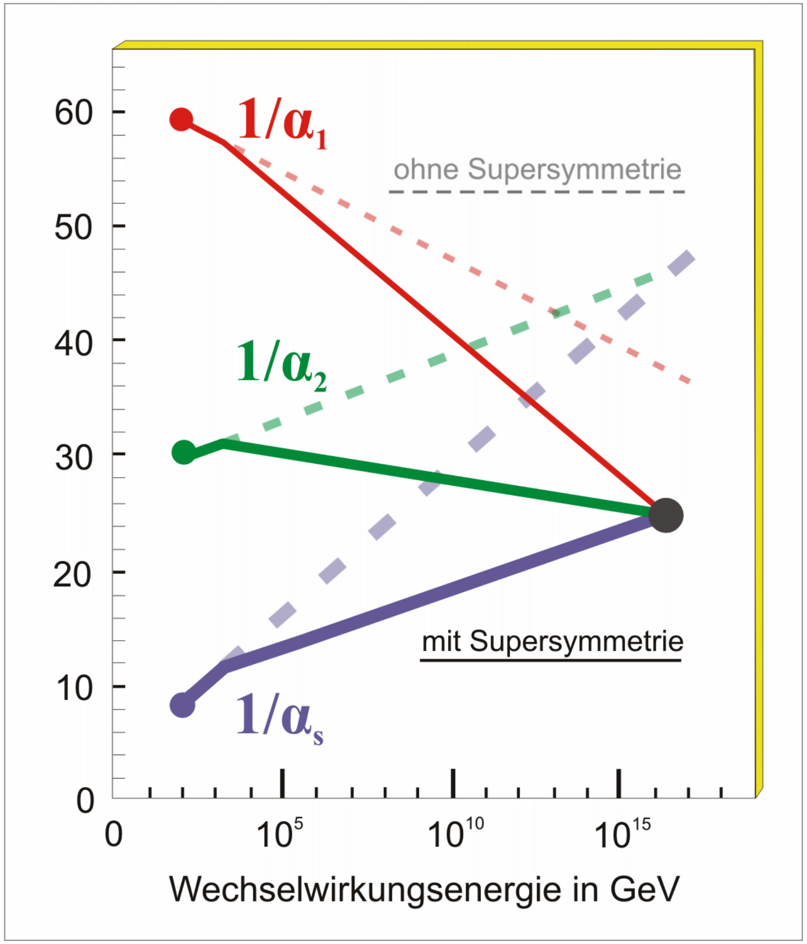
Together with photon (electromagnetism) decribed by the gauge theory of electroweak interactions

Glashow, Salam und Weinberg

Unification of Forces



Unification of electromagnetic and weak interactions is established at high energies.



Is it possible to include strong interaction?

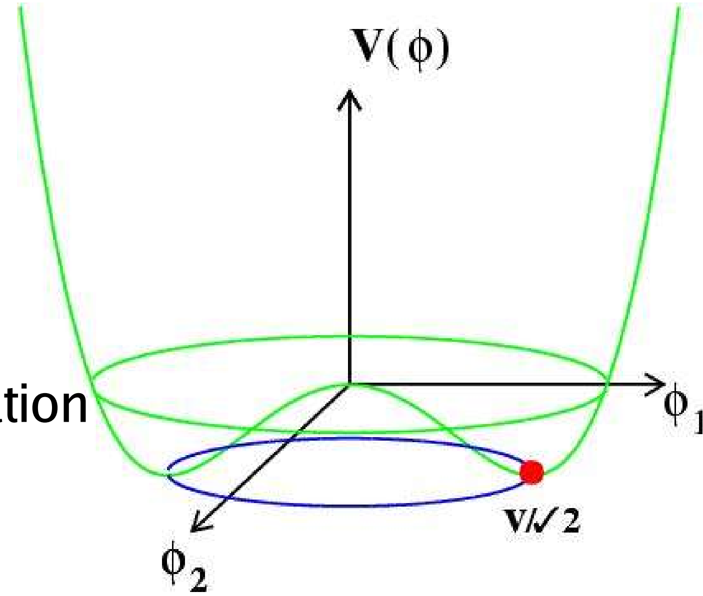
Mechanism: Supersymmetry?

Higgs Mechanism

Spontaneous symmetry breaking:

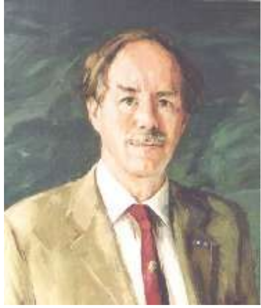
- Gauge theory of electroweak interactions
- Mass terms of gauge bosons are violating the gauge invariance of the theory !
- Scalar field Φ with electroweak coupling
- Potential $V(\Phi)$ with non-vanishing vacuum expectation value $v/\sqrt{2}$
- Theory stays gauge invariant, dynamical mass generation
- Coupling to Higgs field generates W and Z mass

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$



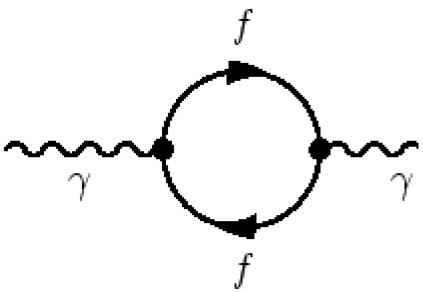
$$\left.\begin{aligned} m_{\mathrm{W}} &= \frac{1}{2} \frac{e}{\sin\theta_w} v \\ m_{\mathrm{Z}} &= \frac{1}{2} \frac{e}{\sin\theta_w \cos\theta_w} v \end{aligned}\right\} \quad \frac{m_{\mathrm{W}}}{m_{\mathrm{Z}}} = \cos\theta_w$$

Quantum Corrections

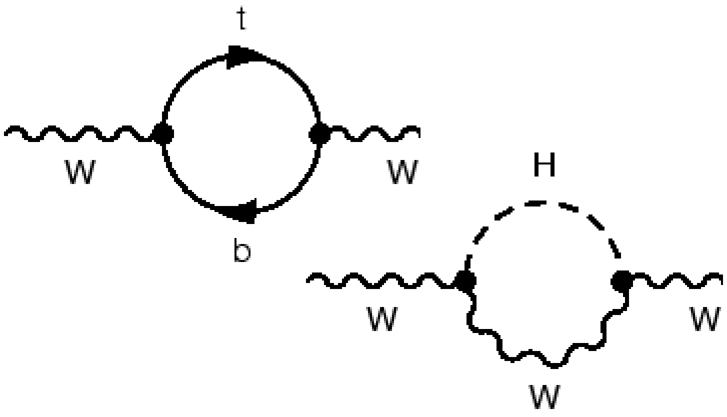


Veltman und `t Hooft:

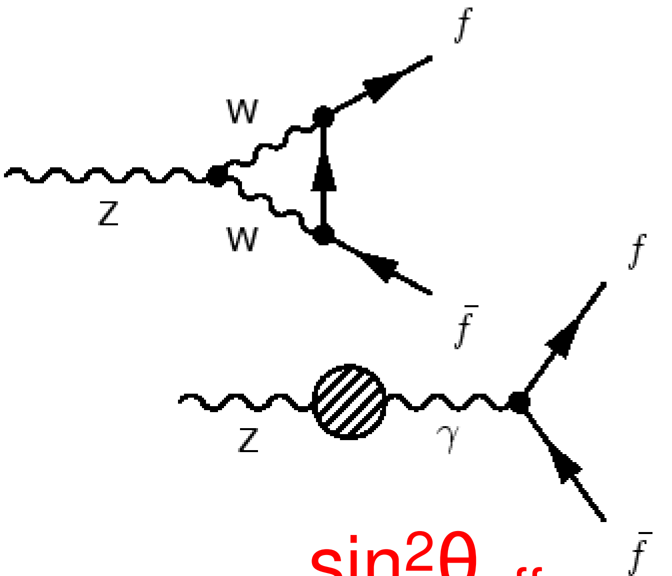
Electroweak theory is renormalisable gauge theory, i.e. higher orders in perturbation theory stay finite



$\Delta\alpha$



$\Delta\rho(m_t, m_H)$



$\sin^2\theta_{eff}$

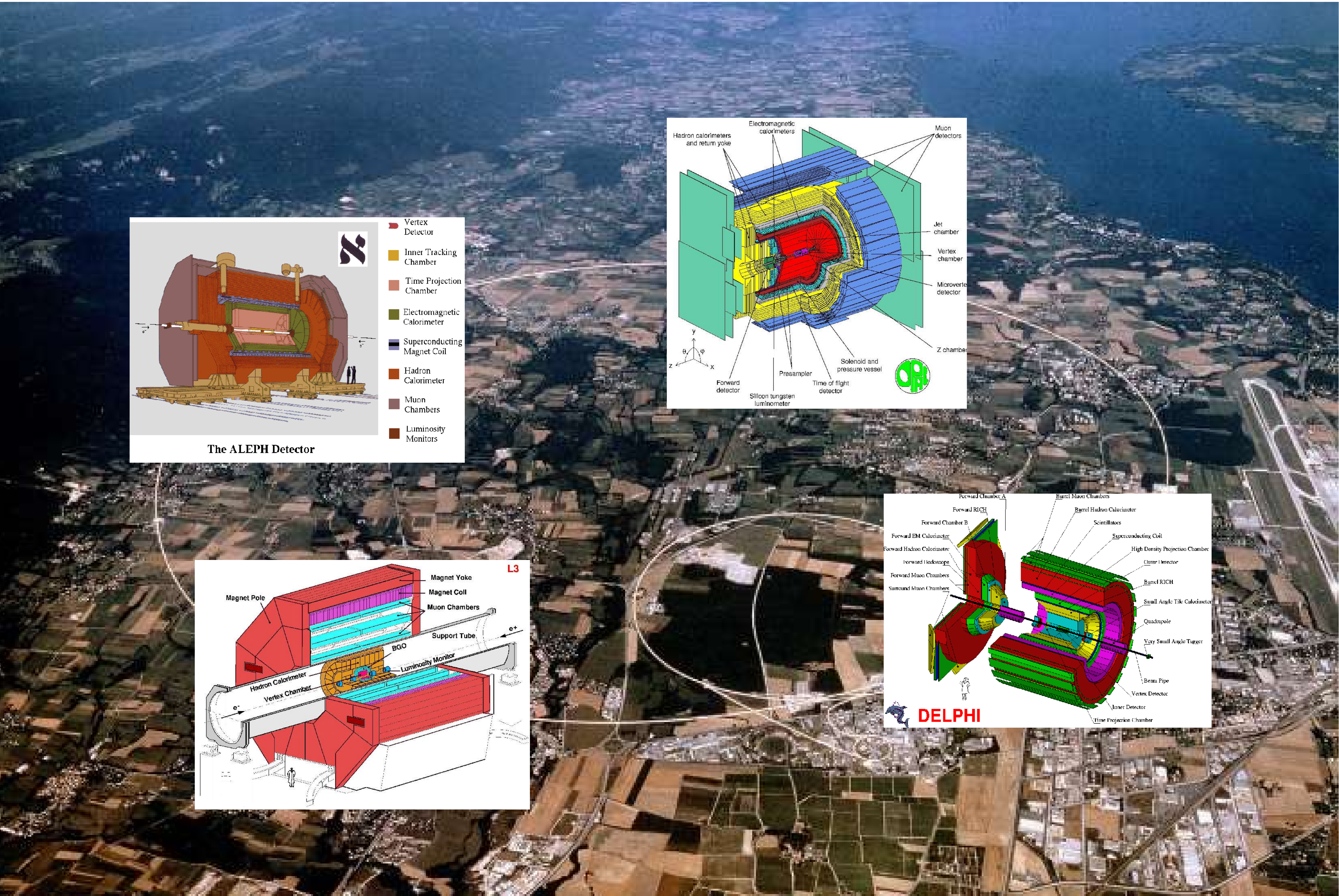
Measurements with sub-permille precision:

Quantum corrections uo to $O(\alpha^2)$ und leading terms of higher orders have to be calculated

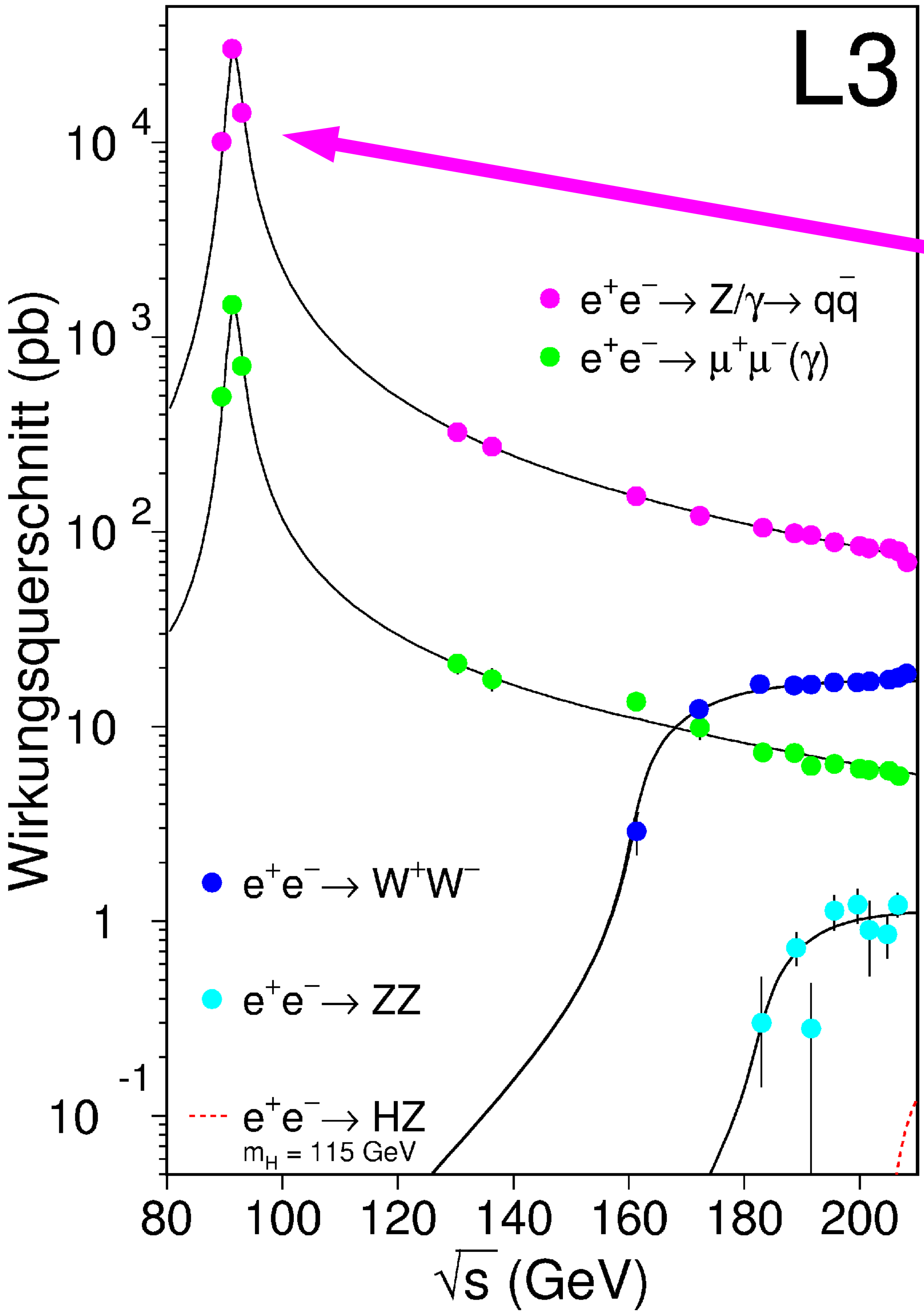
Contributions from loops:

Sensitivity to particles, which are too heavy to be directly produced in the experiment (top quark, Higgs boson)

Large Electron Positron Collider - LEP



Events at LEP



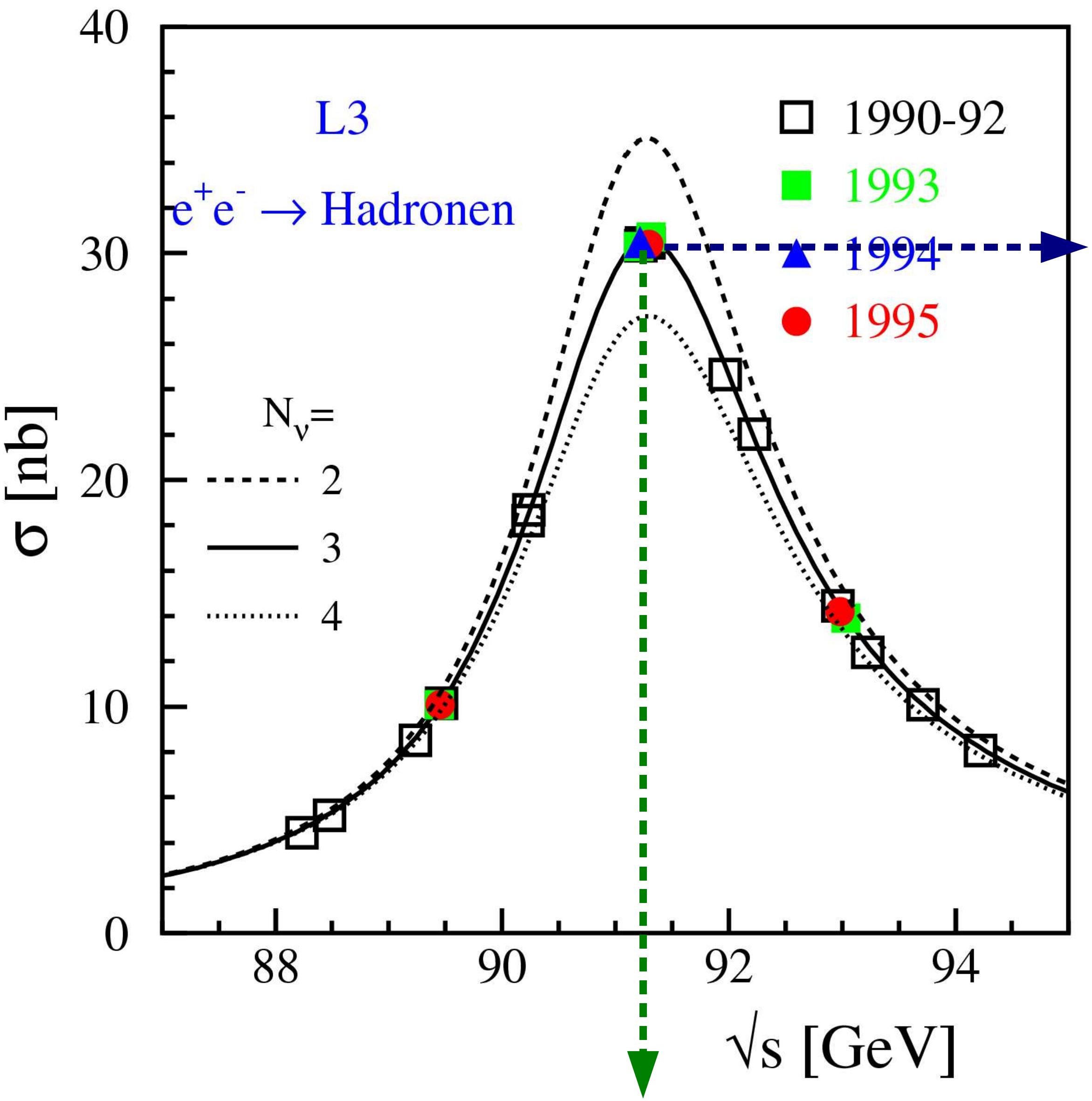
ca. 16 Mio. Z bosons

ca. 40 000 W bosons

ca. 0 Higgs bosons

(all 4 experiments together)

Measurement of Z resonance

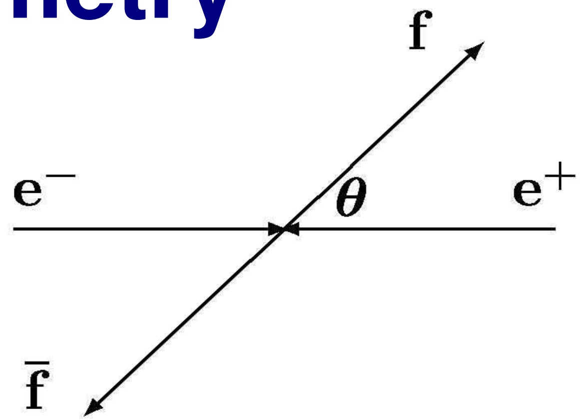


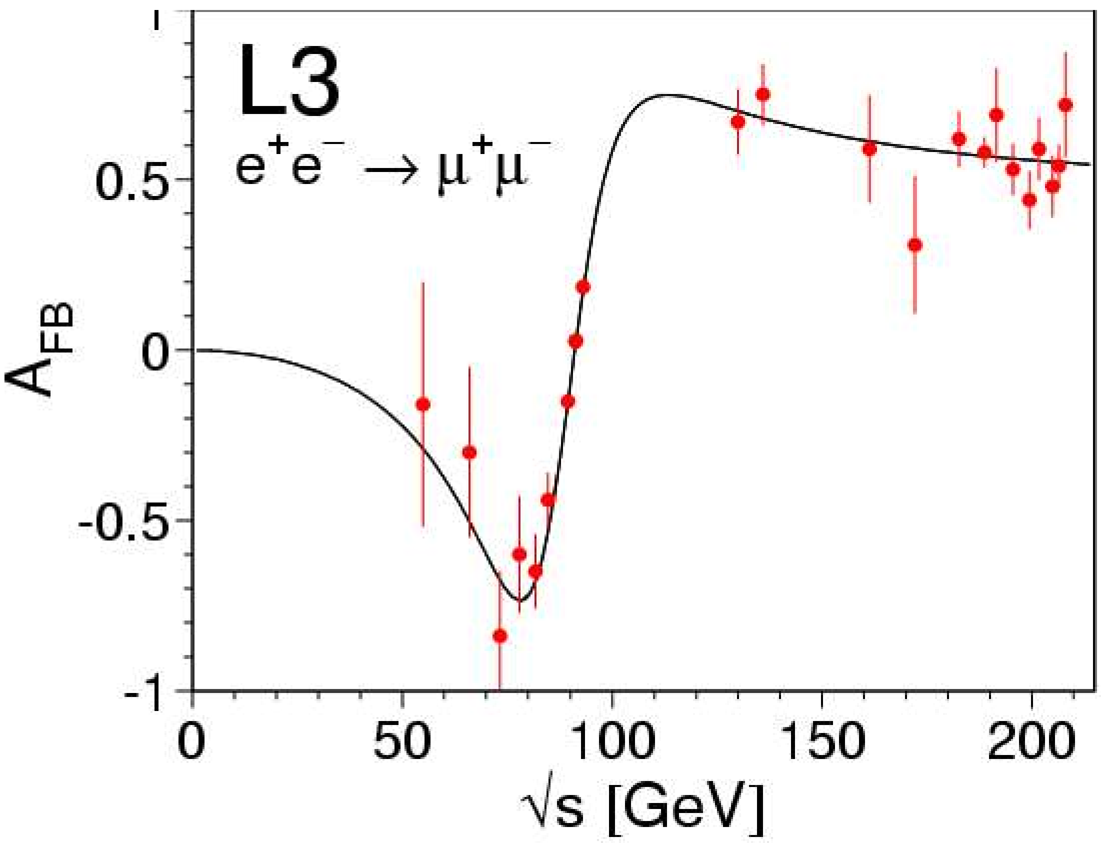
Number of neutrinos:
$N_\nu = 3 \times (0.9947 \pm 0.0028)$

Measurement of Z mass with 23 ppm: $m_Z = 91.1875 \pm 0.0021$ GeV

Forward Backward Asymmetry

$$\mathcal{A}_{\mathrm{FB}} = \frac{N(\theta > 90^\circ) - N(\theta < 90^\circ)}{N(\theta > 90^\circ) + N(\theta < 90^\circ)}$$





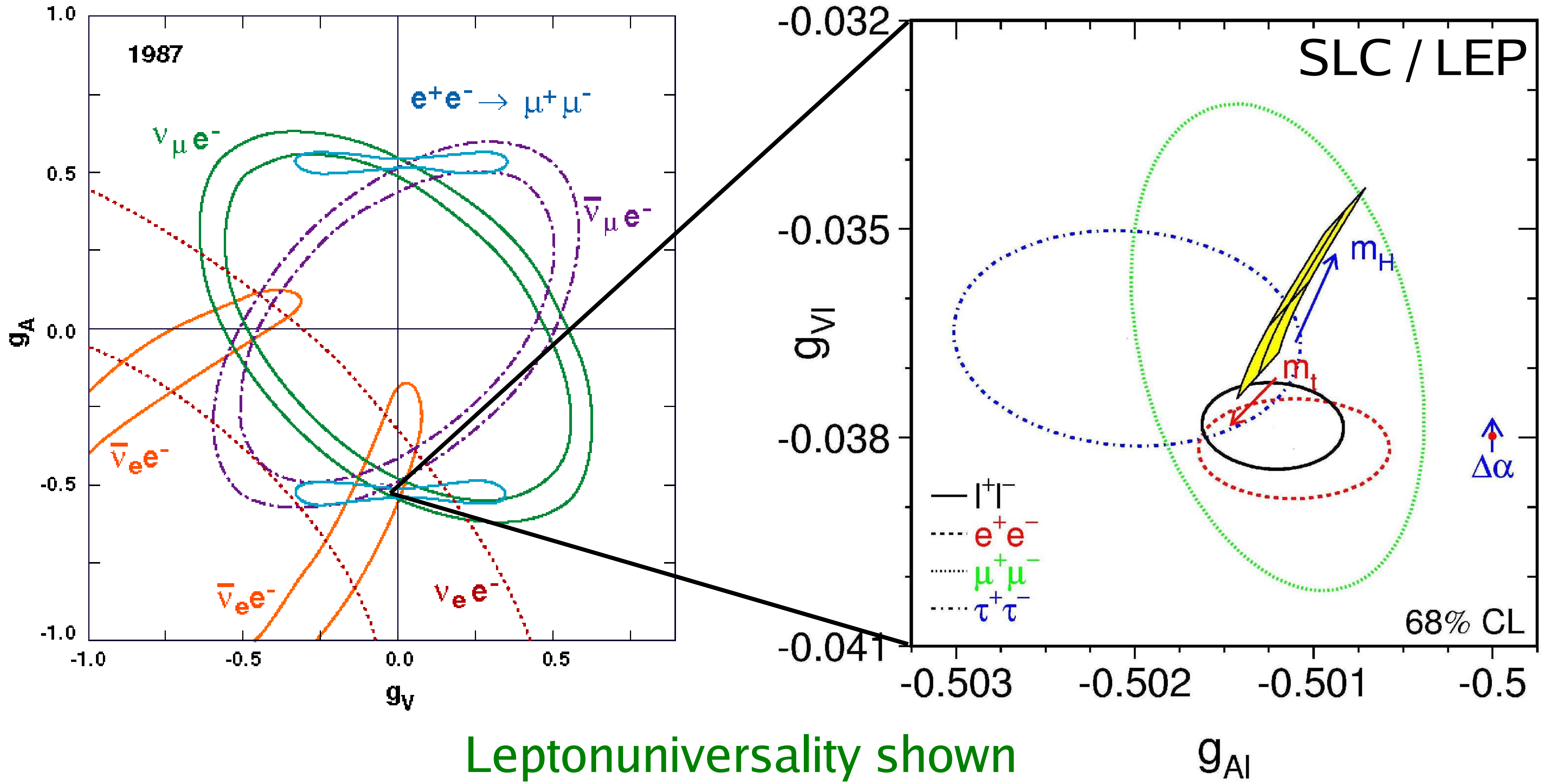
$A_{FB}(m_Z)$ measures

left g_L and right coupling g_R

of leptons to the Z

Coupling of Leptons to the Z

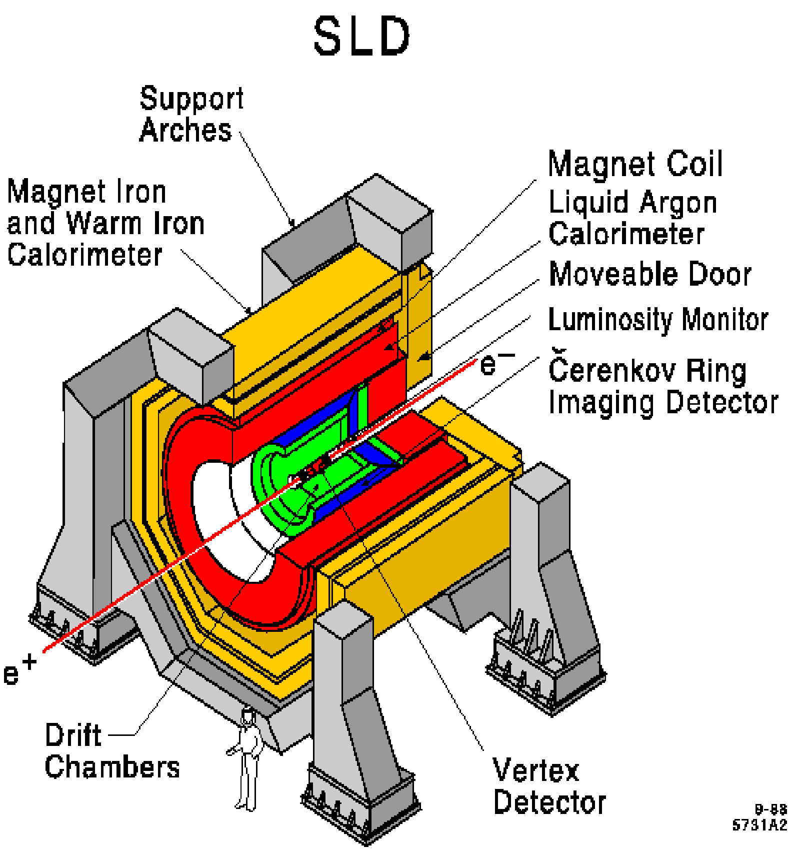
$g_V = g_L + g_R$ and $g_A = g_L - g_R$

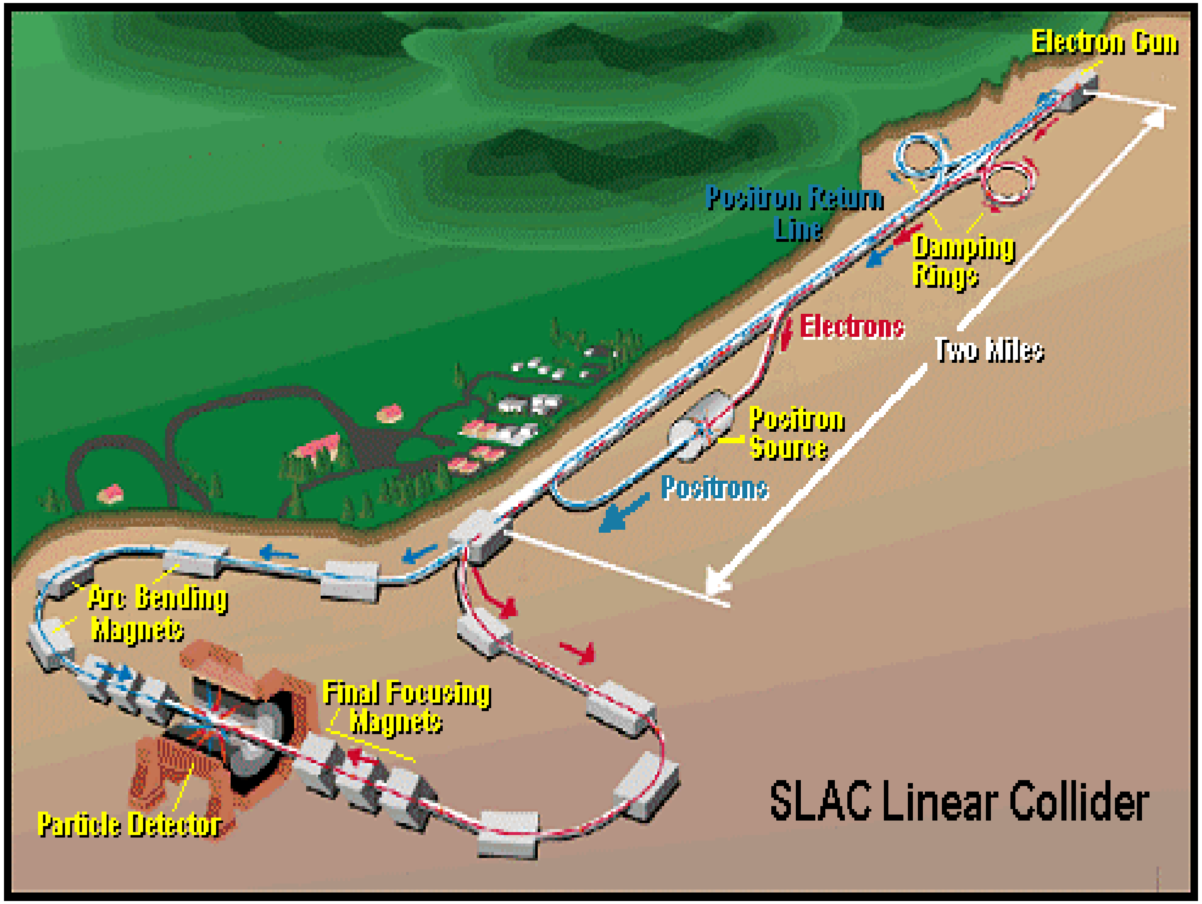


Leptonuniversality shown

Tendency for light Higgs

SLAC Linear Collider - SLC



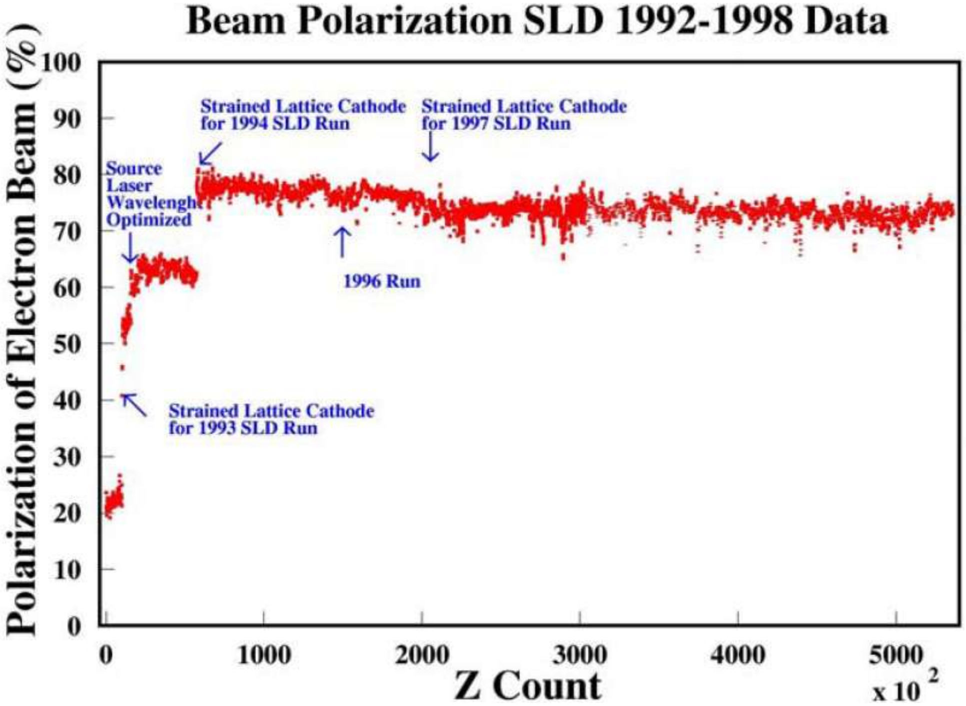


Left Right Asymmetry at SLC

Count Z events N_Z for both polarisations of electron beam:

$$\mathcal{A}_{\rm LR} = \frac{N_{\rm Z}(L) - N_{\rm Z}(R)}{N_{\rm Z}(L) + N_{\rm Z}(R)} = \mathcal{P}_e \, A_e$$

Measurement of couplings g_L and g_R of Electron to the Z :



Parity violation !

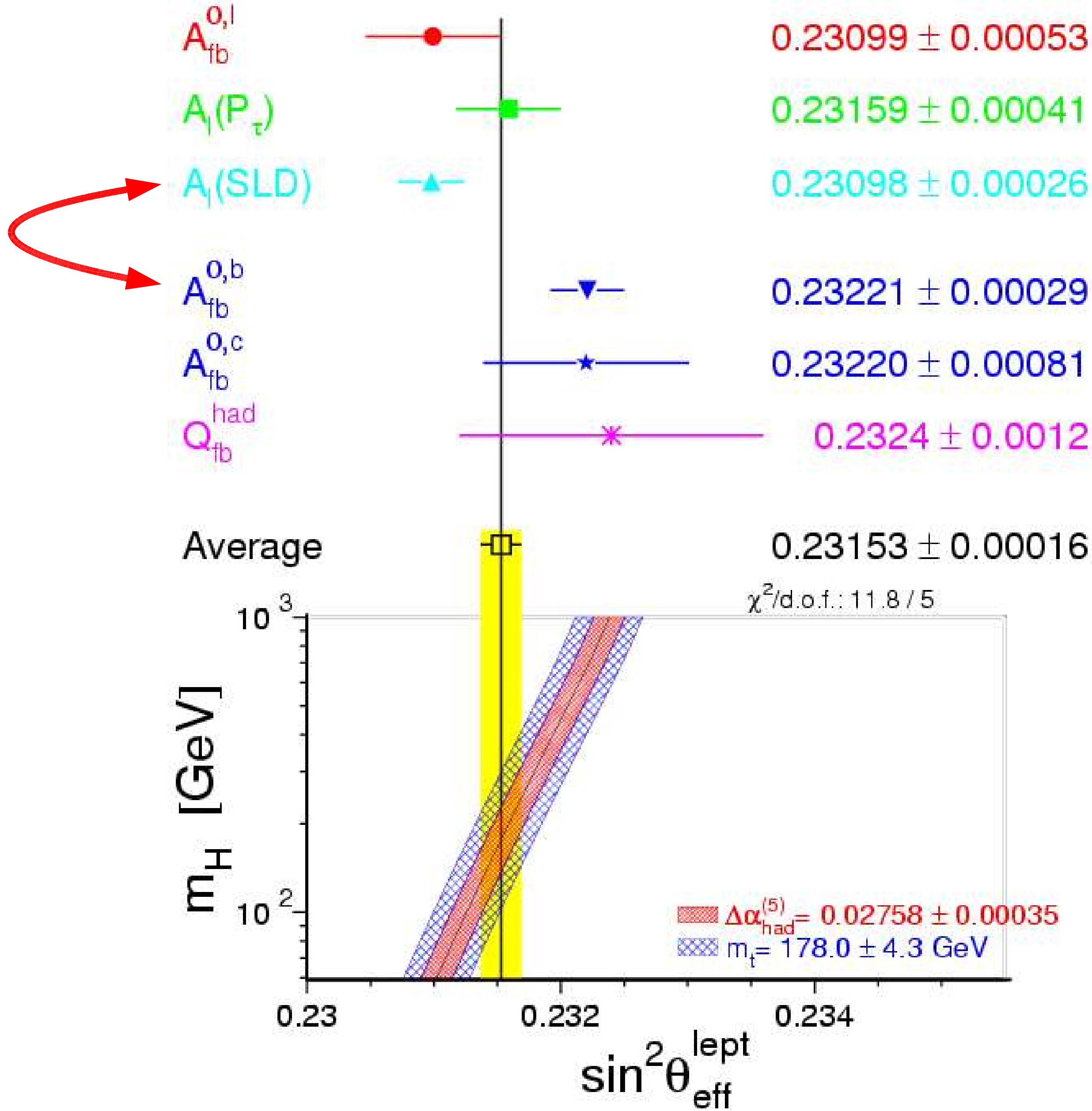
Important:
Precise Knowlegde of beam polarisation

High polarisation grade of 75% yields with only 500 000 Z decays:

$\sin^2 \theta_{\rm eff} = 0.23098 \pm 0.00026$

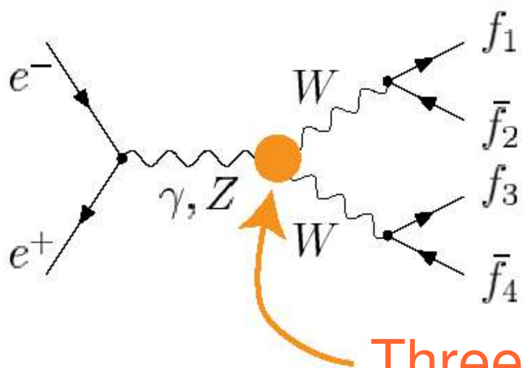
Weak Mixing Angle

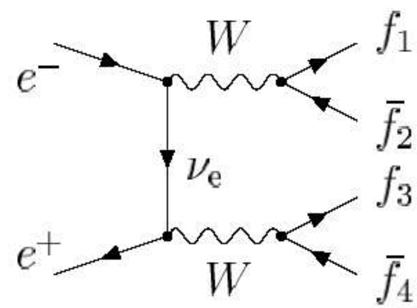
2.9 σ Deviation between both measurements



Light Higgs preferred

Production of W-Bosons at LEP



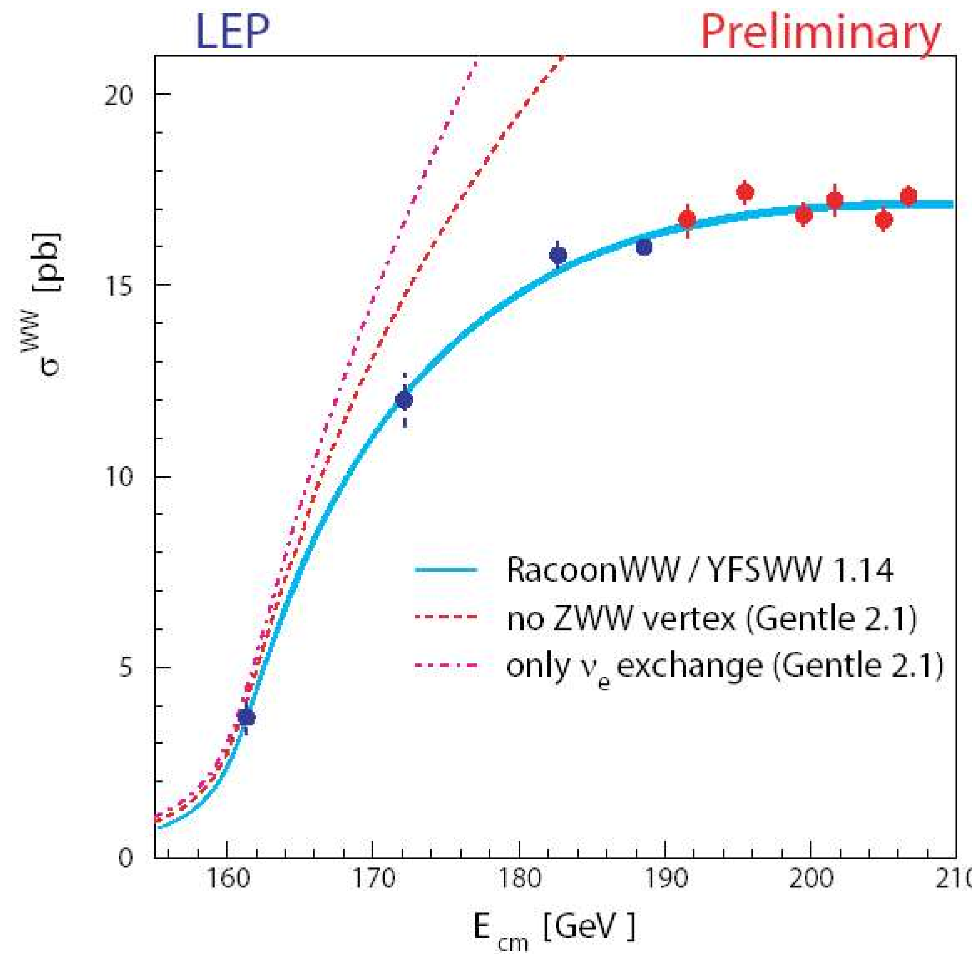


Three Boson Vertex

Contributions from
ν, γ and Z exchange
violate unitarity!

700 pb^{-1} per experiment
→ ca. 40.000 W-Pairs at LEP

Final states:
45% qqqq, 44% qlν, 11% lνlν



W-Pair Events

$e^+ e^- \rightarrow qq\,qq$

- 4 hadronic jets
- no missing momentum

Ratio 46 %
Efficiency ≈ 85 %
Putity ≈ 85 %

$e^+ e^- \rightarrow qq\,l\nu$

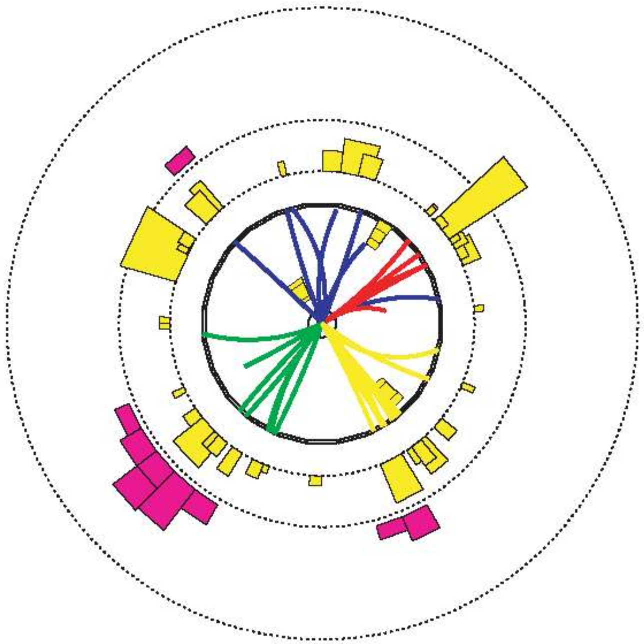
- 2 jets and 1 lepton
- missing energy

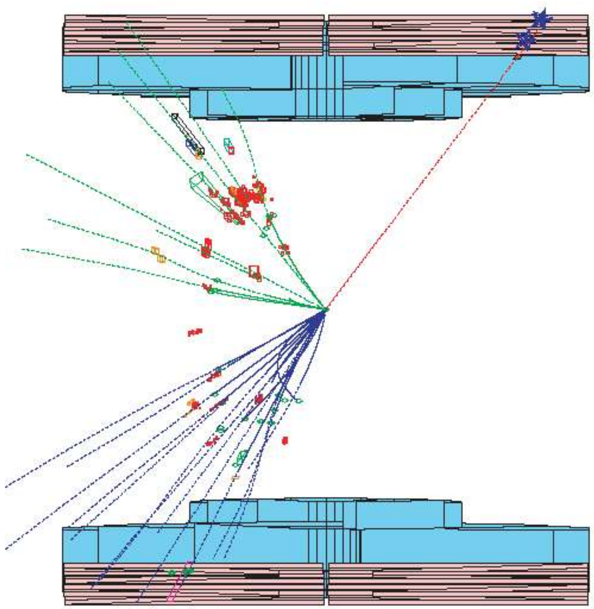
Ratio 44 %
Efficiency ≈ 70%
Purity ≈ 95 %

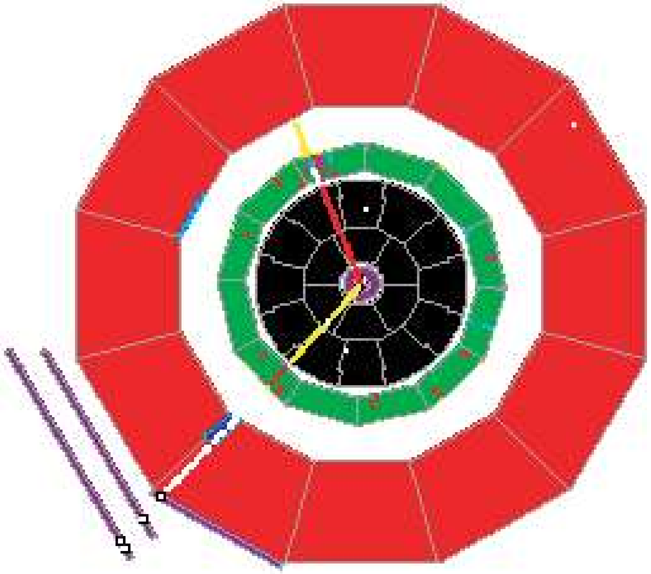
$e^+ e^- \rightarrow l\nu\,l\nu$

- 2 leptons
- missing energy

Ratio 10 %
Efficiency ≈ 50 %
Purity ≈ 90 %



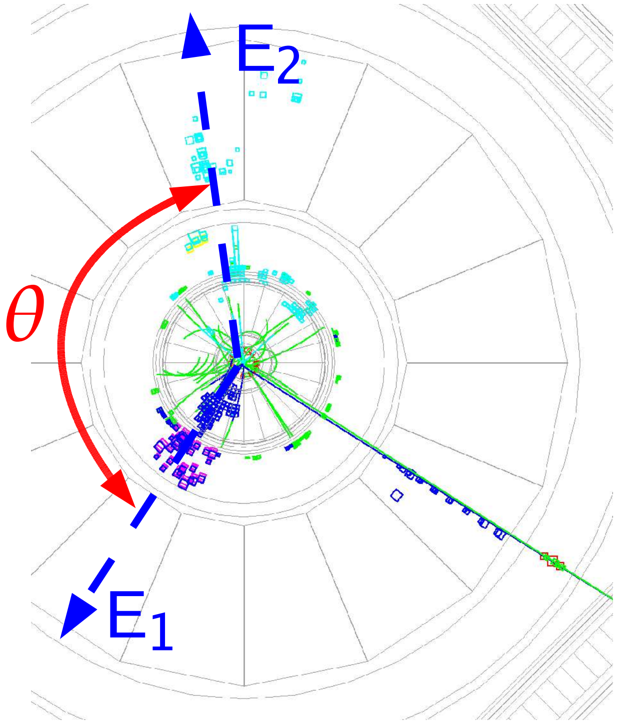




Reconstruction of W mass

- Invariant mass from decay products of W boson:
  q-Jets, e, μ, τ-Jets
- Precision of 30 – 40 MeV (0.5 ‰)
- Invariant mass from hadronic decaying W boson

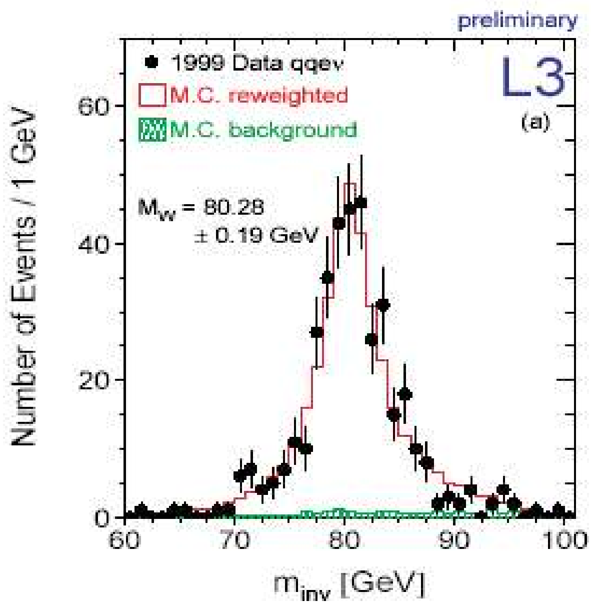
$$m_W = \sqrt{2\, E_1 E_2\, (1 - \cos\theta)}$$

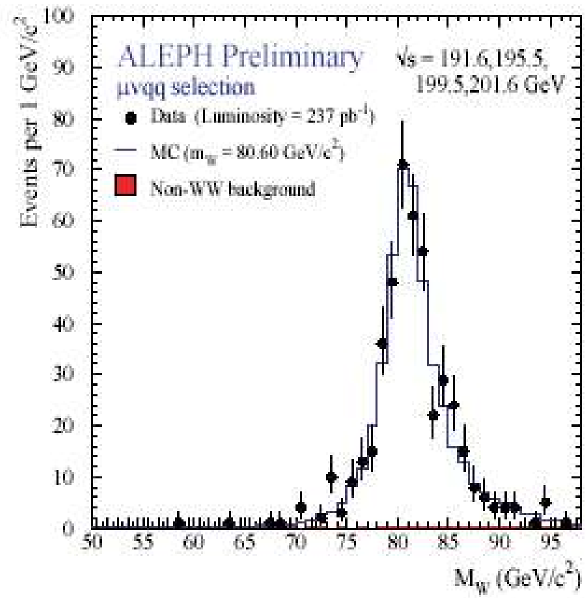


- Precision depends on energy scale and angular measurement
- Needed accuracy:
  - Angle 0.5 mrad
  - Jet energy scale 0.1 ‰
  - Fix E_{tot} to $\sqrt{s}$: kinematic fit

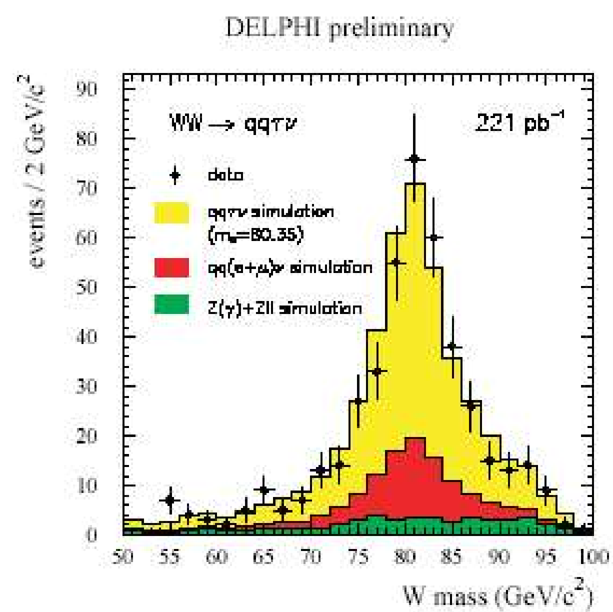
Mass Spectra

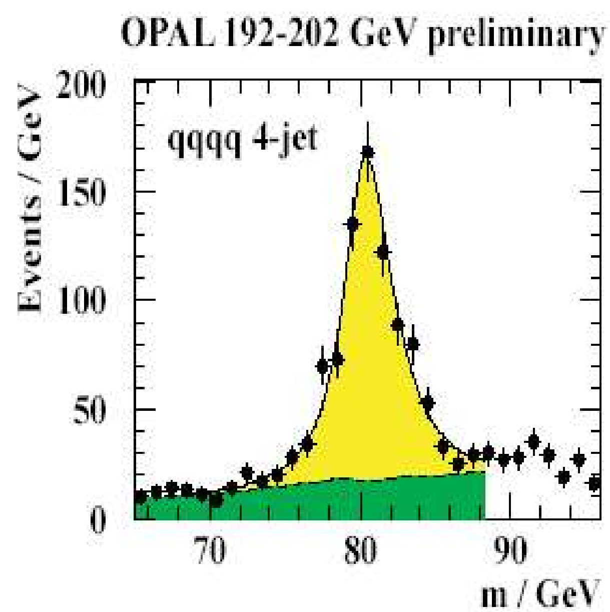
qq eν





qq $\mu\nu$





qq $\tau\nu$

qq qq

Status of W Mass from LEP

Final results from ALEPH, DELPHI, L3, OPAL

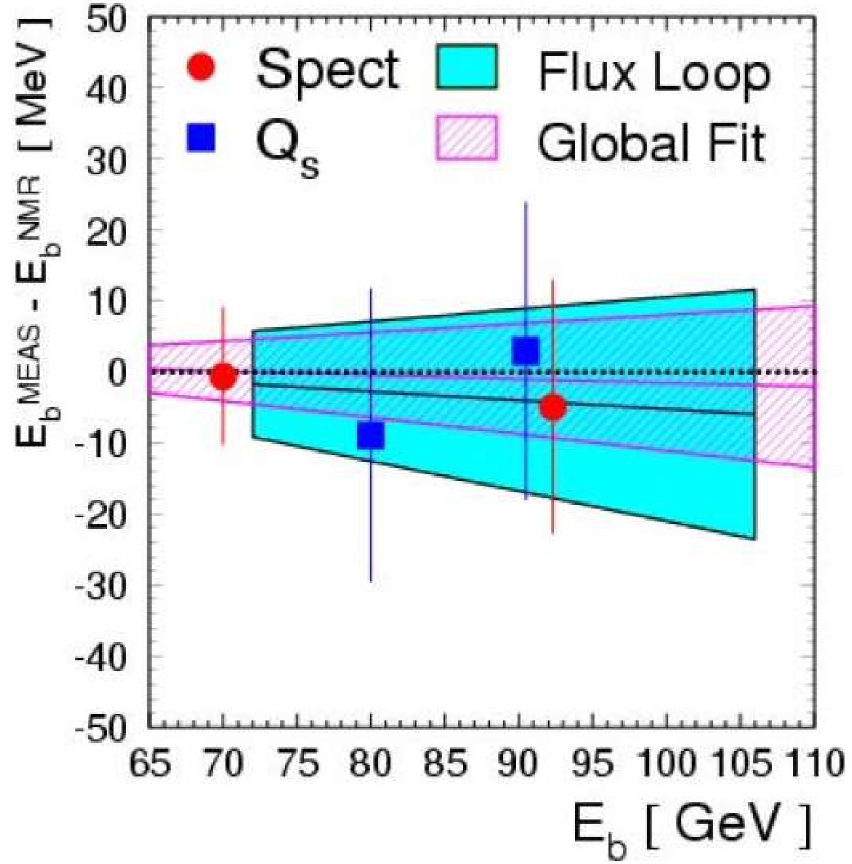
- Final calibration of LEP beam energy
- Final analysis of complete LEP2 data set
- Reduction of various systematic uncertainties
  - → Colour reconnection
  - → Bose-Einstein correlations

Uncertainty of W mass:

42 MeV (Winter 2005) → 33 MeV (Summer 2006)

Calibration of LEP beam energy

Fit to event kinematics
uses LEP beam energy as constraint
for the determination of the W mass



Resonant depolarisation
up to 60 GeV beam energy

Extrapolation with NMR sensors

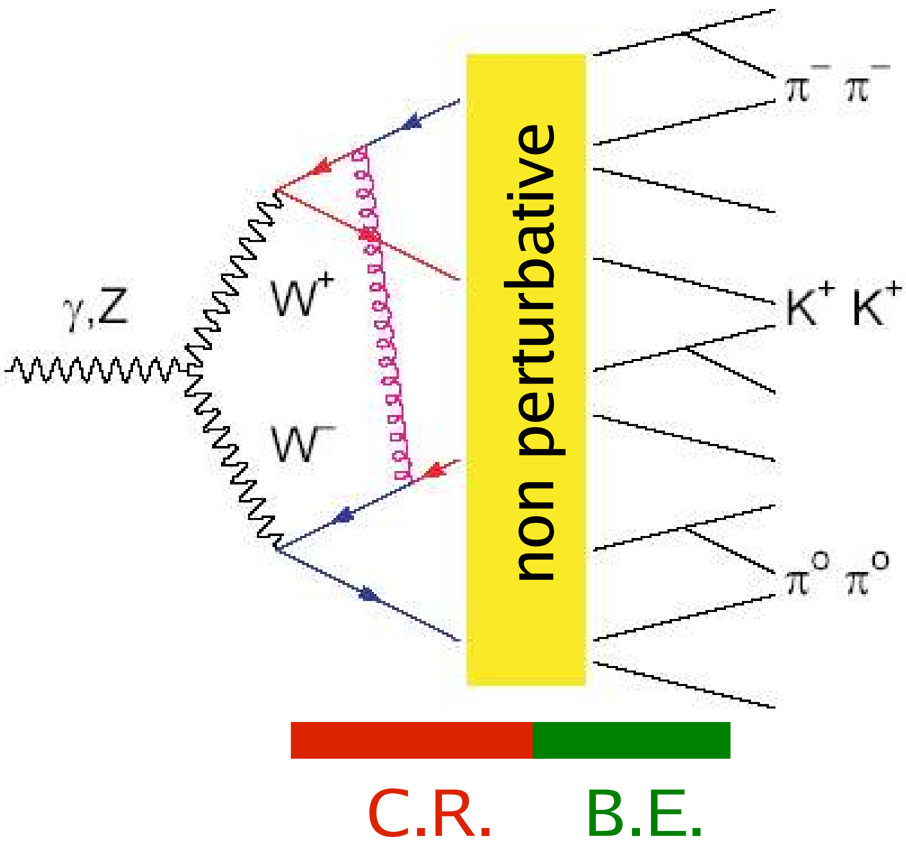
Comparison with
flux loop, synchrotron tunes,
magnetic spectrometer

Systematic uncertainties 10-20 MeV auf E_{beam}

Contribution to uncertainty in the W mass:
17 MeV (Winter 2005) → 9 MeV (Summer 2006)

Final State Interactions

Fully-hadronic final state



Hadronisation:

nont-perturbative phase
only empirical models
Extension 1 fm > 0.1 fm W decay length

Colour Reconnection:

Change of colour flow W's

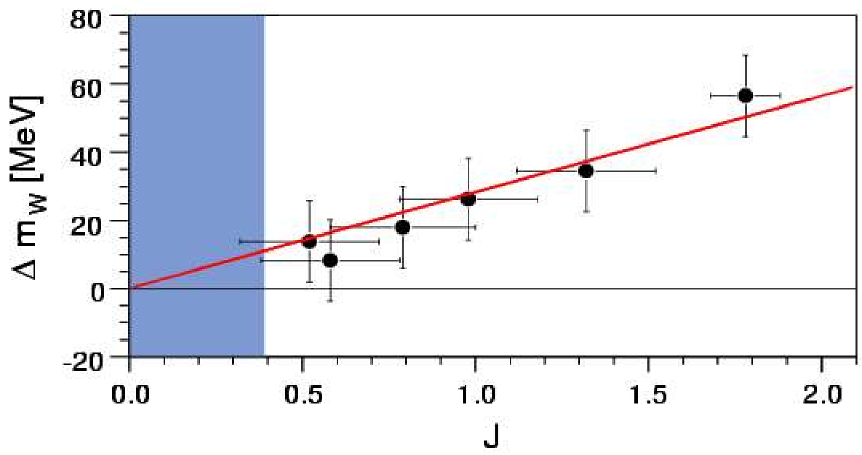
Bose-Einstein-Correlations:

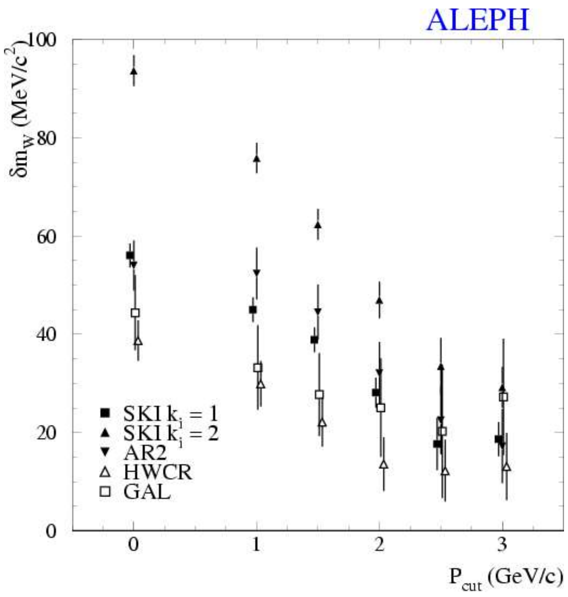
Identical bosons (e.g. π^0) prefer identical phase space region in final state

- FSI causes large shifts in reconstructed W mass
- up to 100 MeV for C.R. (SK I) and 35 MeV for B.E. (LUBOEI)
- Fully-hadronic final state contributes only with 9%

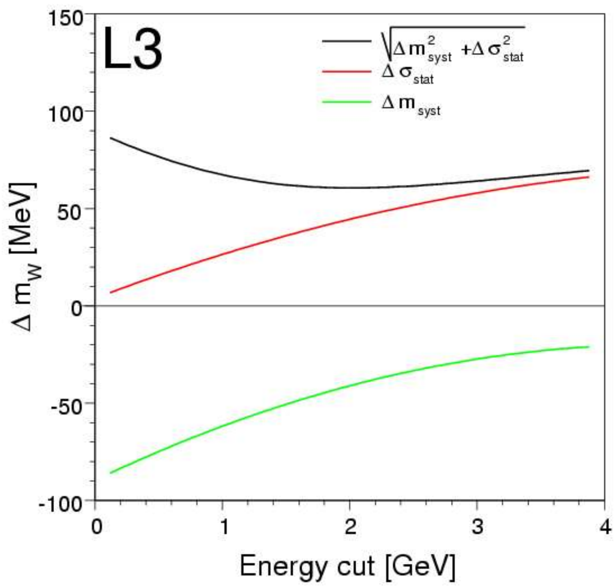
Reduction of B.E. and C.R.

Use the recorded data to set limits on the B.E. corrections
Determine effect on the W mass



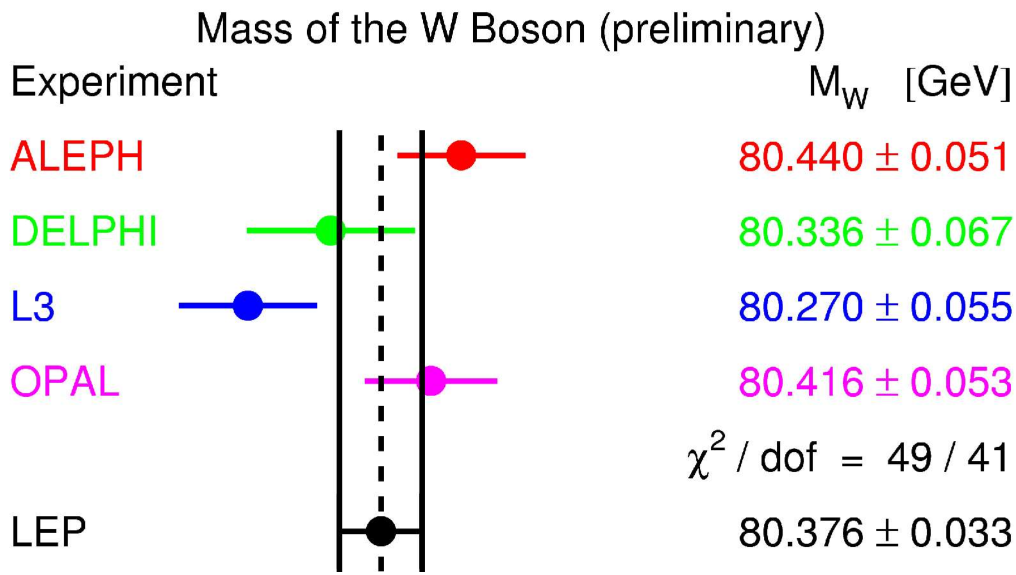


C.R. effects mostly:
"inter-jet" and "low-momentum"
Alternative jet algorithms:
PCUT or CONE
Compromise between:
reduced mass shift (syst.)
worse mass resolution (stat.)

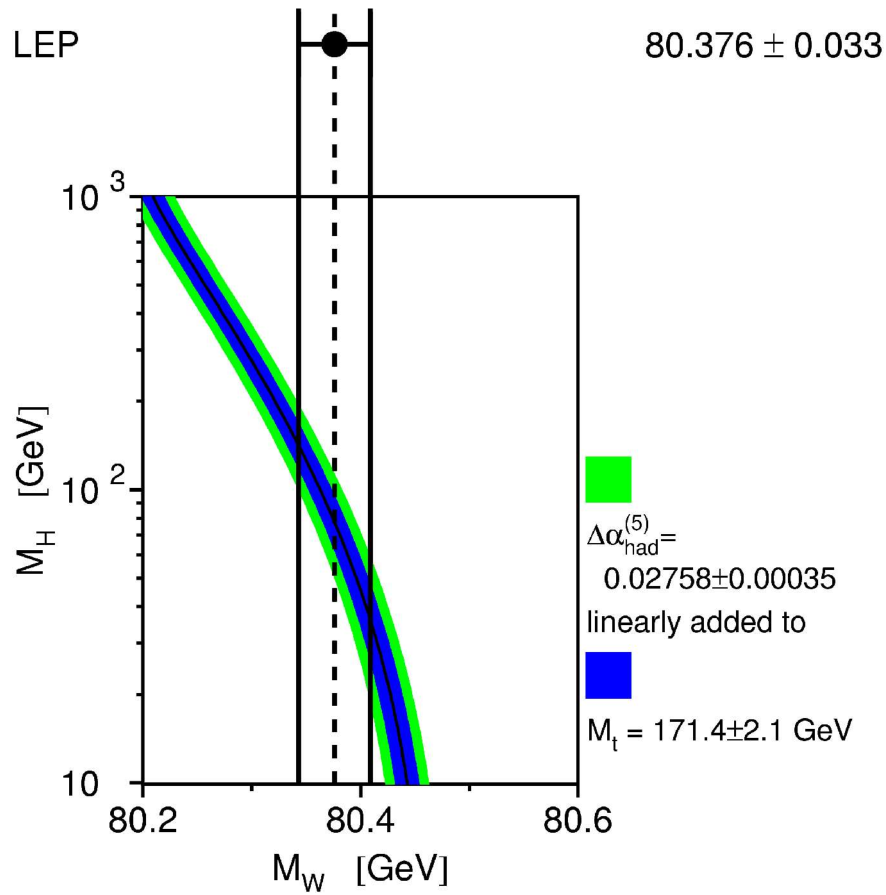


Contribution to the uncertainty of the W mass in fully hadronic channel:
B.E.: 35 MeV (Winter 2005) → 9 MeV (Summer 2006)
C.R.: 90 MeV (Winter 2005) → 35 MeV (Summer 2006)

W Mass from LEP



Light Higgs preferred



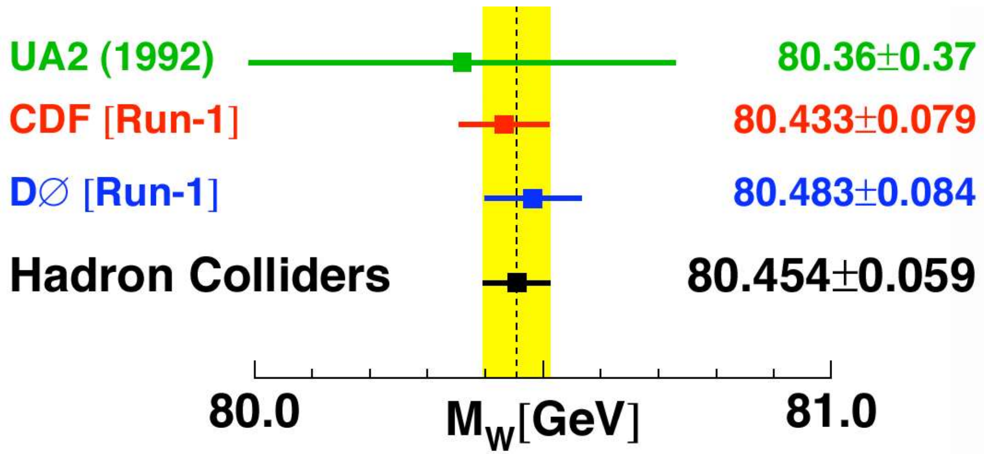
Combination of the four experiments

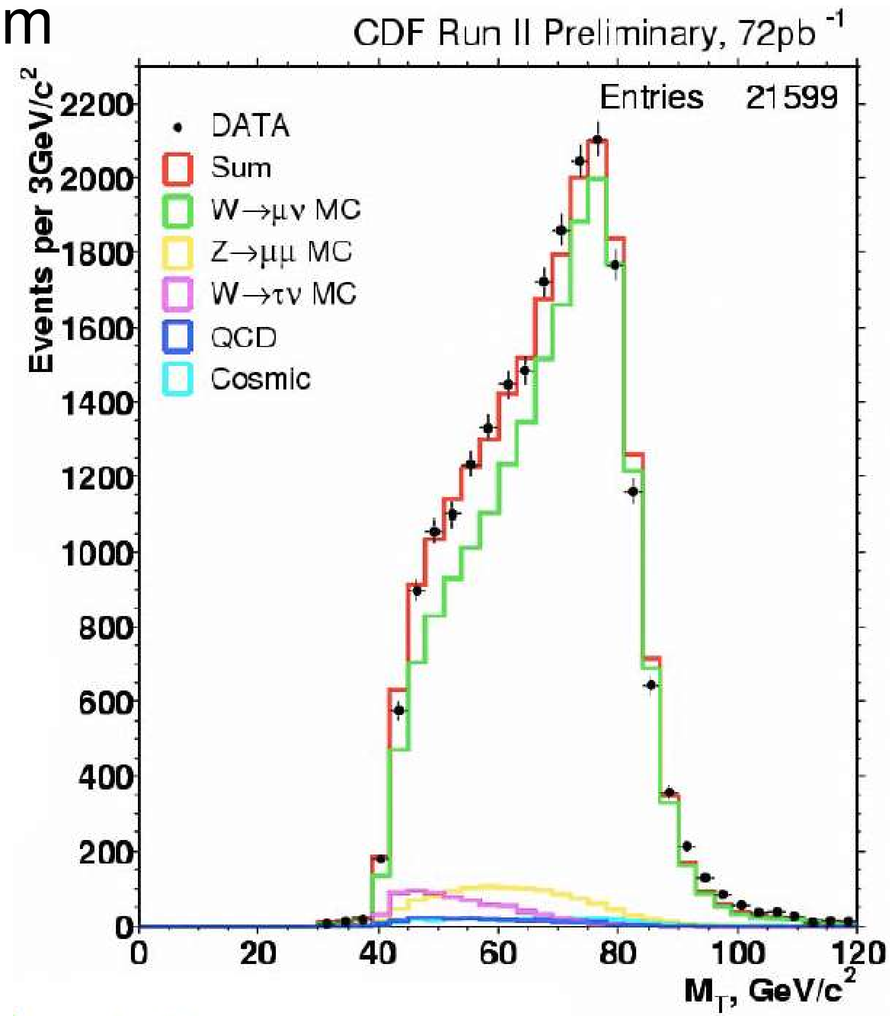
$m_W = 80.376 \pm 0.026(\text{stat}) \pm 0.024(\text{syst})$ GeV

W-Mass from Tevatron

Measurement of transverse mass spectrum

Energy scale calibrated with Z decays
→ Implicit usage of high precision
Z mass from LEP

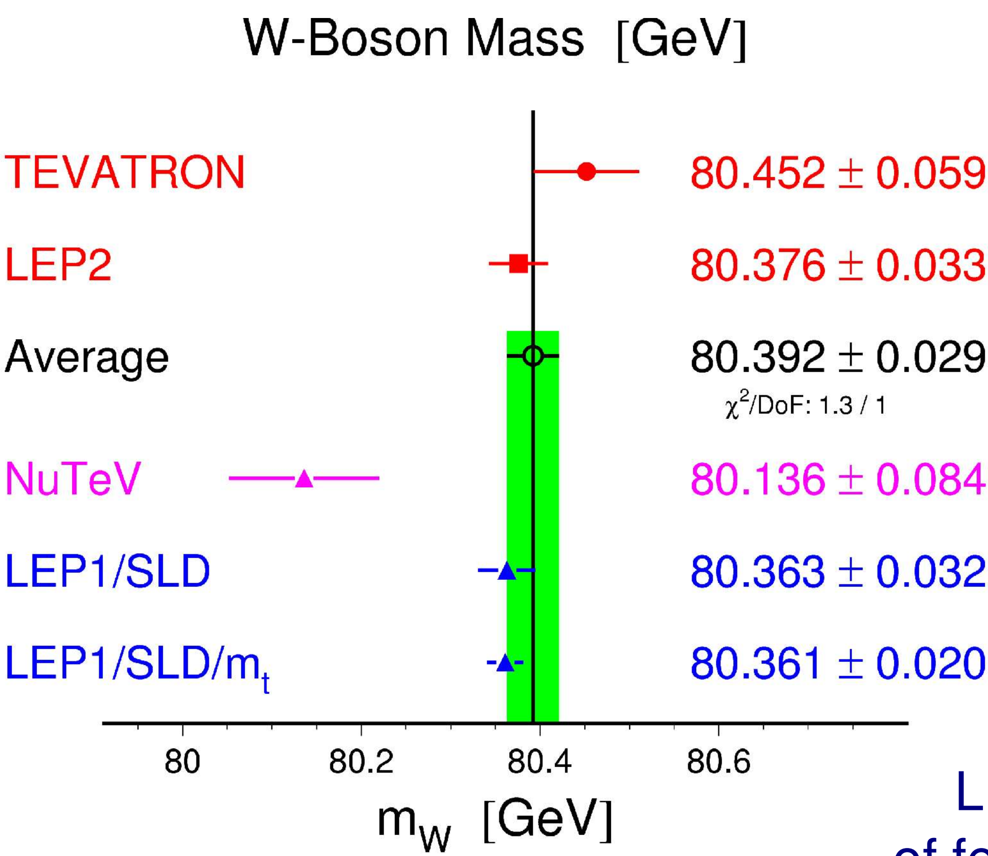




Combination of CDF und D0 (Run-I):

$m_W = 80.452 \pm 0.059$ GeV

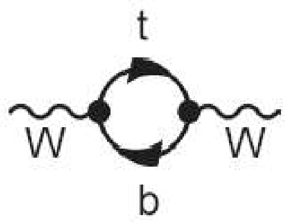
World Average of W mass



LEP1: Couplings of fermions to the Z $\sin^2\theta_w$

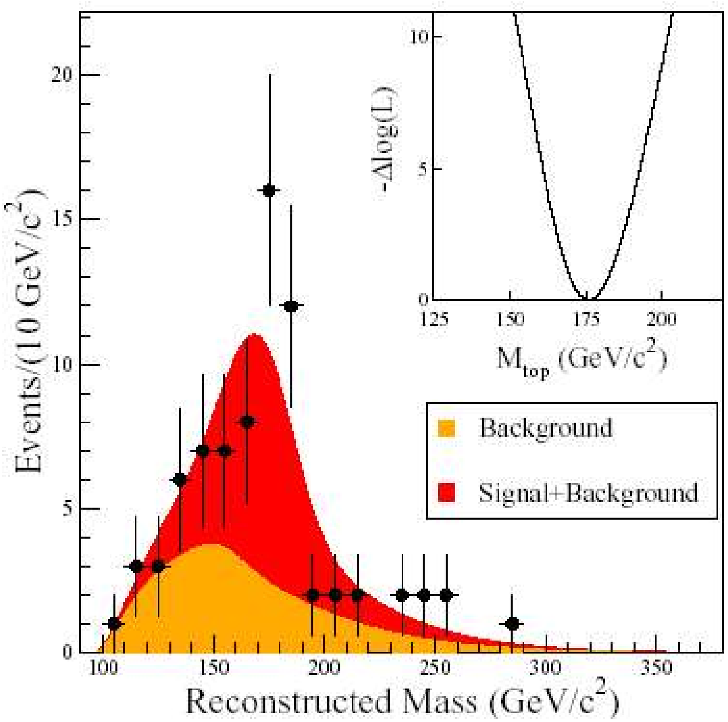
Relation between masses of gauge bosons via the Higgs mechanism $m_W = m_Z \cos\theta_w$

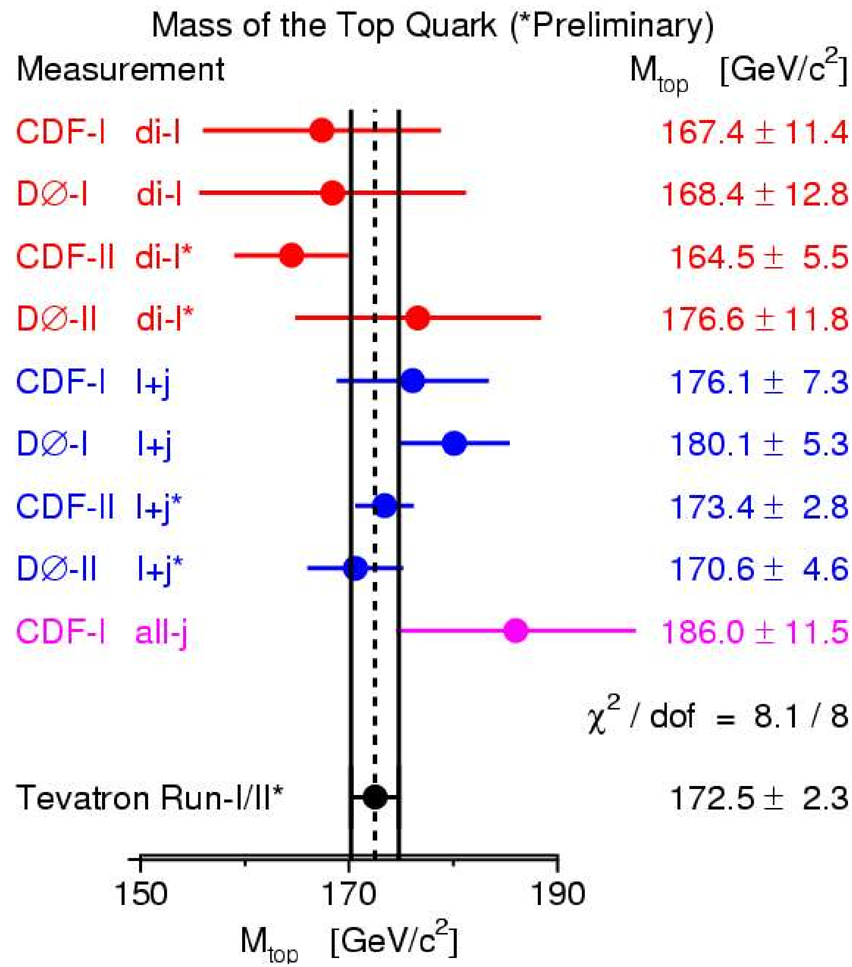
Additional dependency on the top mass via radiative corrections



Measurement of top mass

Tevatron (CDF,D0): $p\bar{p} \to t\bar{t}X, \;\; t\bar{t} \to b\bar{b}WW$

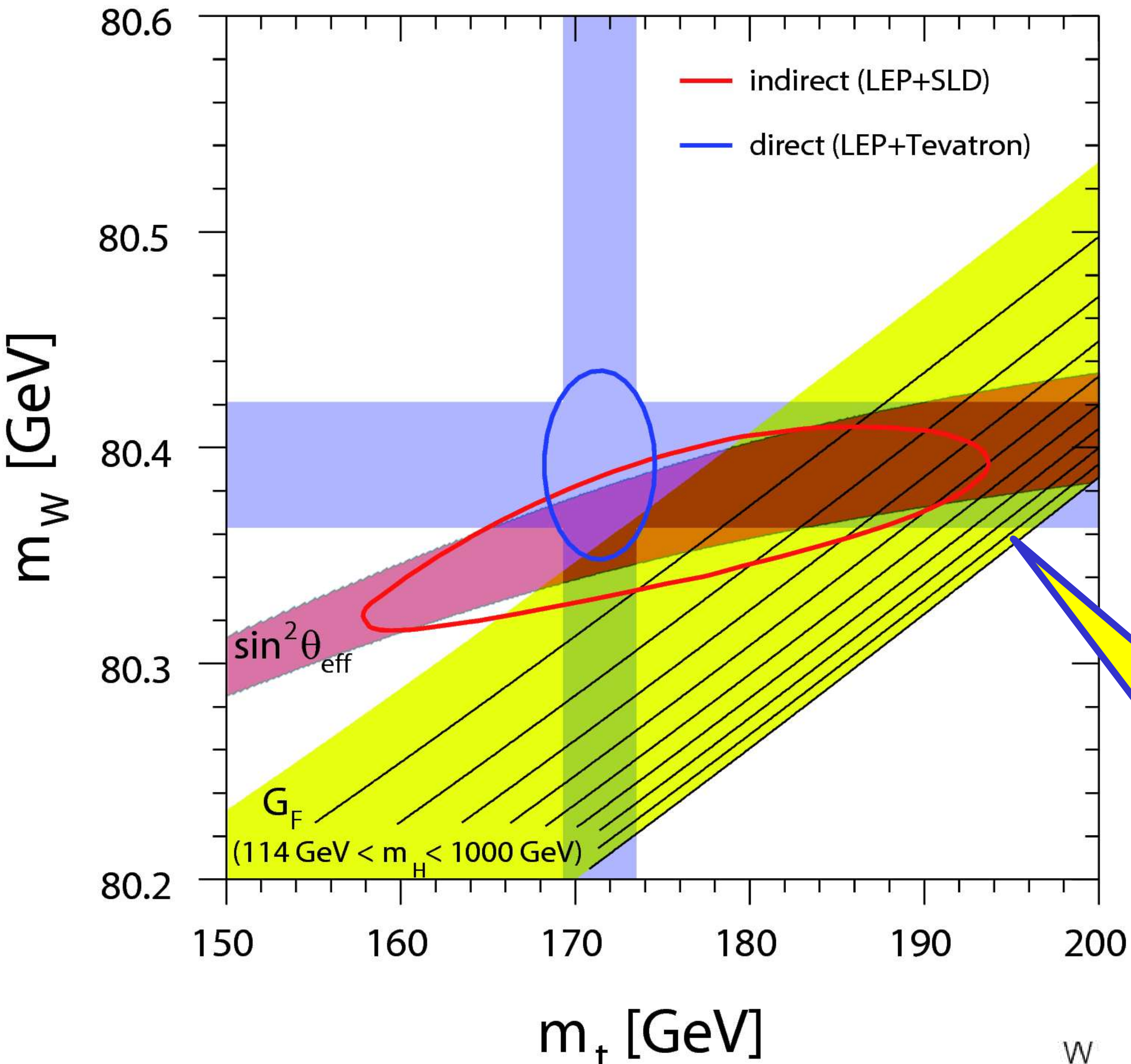




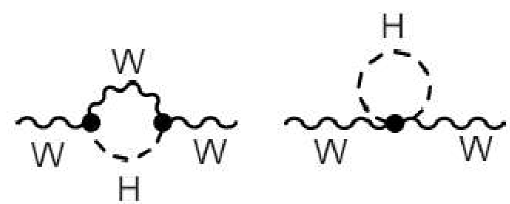
Most recent number (incl. Run-II):

$m_t = 171.4 \pm 2.1$ GeV

W Mass and Top Mass

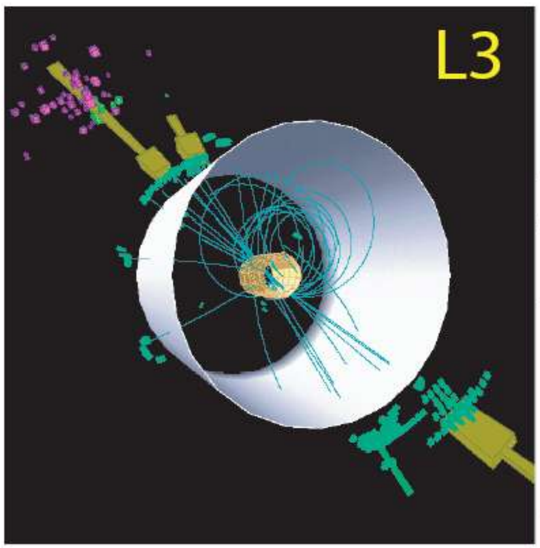


$$\frac{G_F}{\sqrt{2}} = \frac{\pi\,\alpha}{2}\,\frac{1}{m_W^2\,\sin^2\upsilon_W}\,\frac{1}{1-\Delta r}$$

Dependency of Δr on the Higgs mass:  ~ $\log(m_H/m_W)$

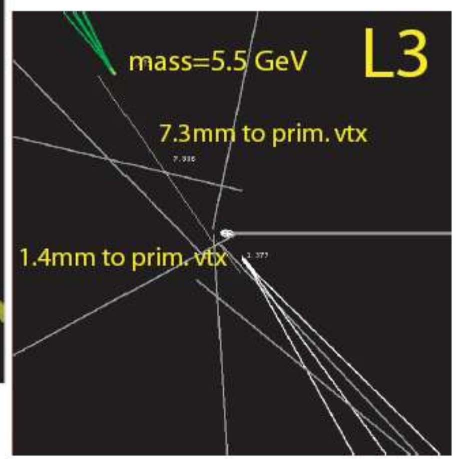
Higgs search at LEP

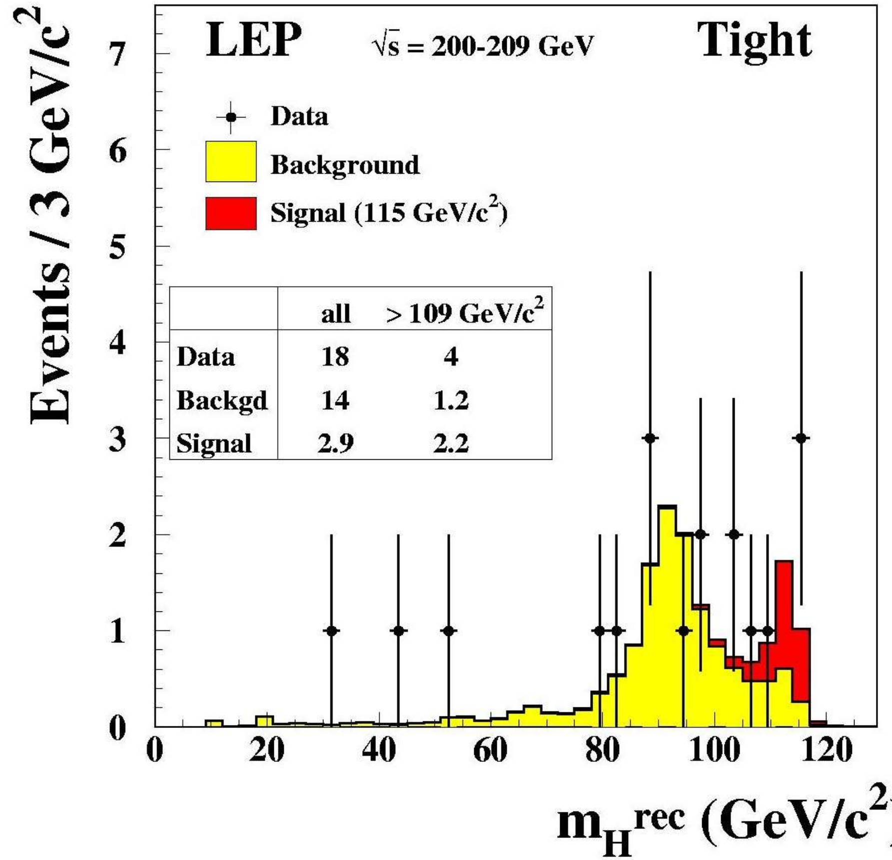
Candidate: $e^+e^- \rightarrow HZ \rightarrow b\bar{b}\,\nu\bar{\nu}$



measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view

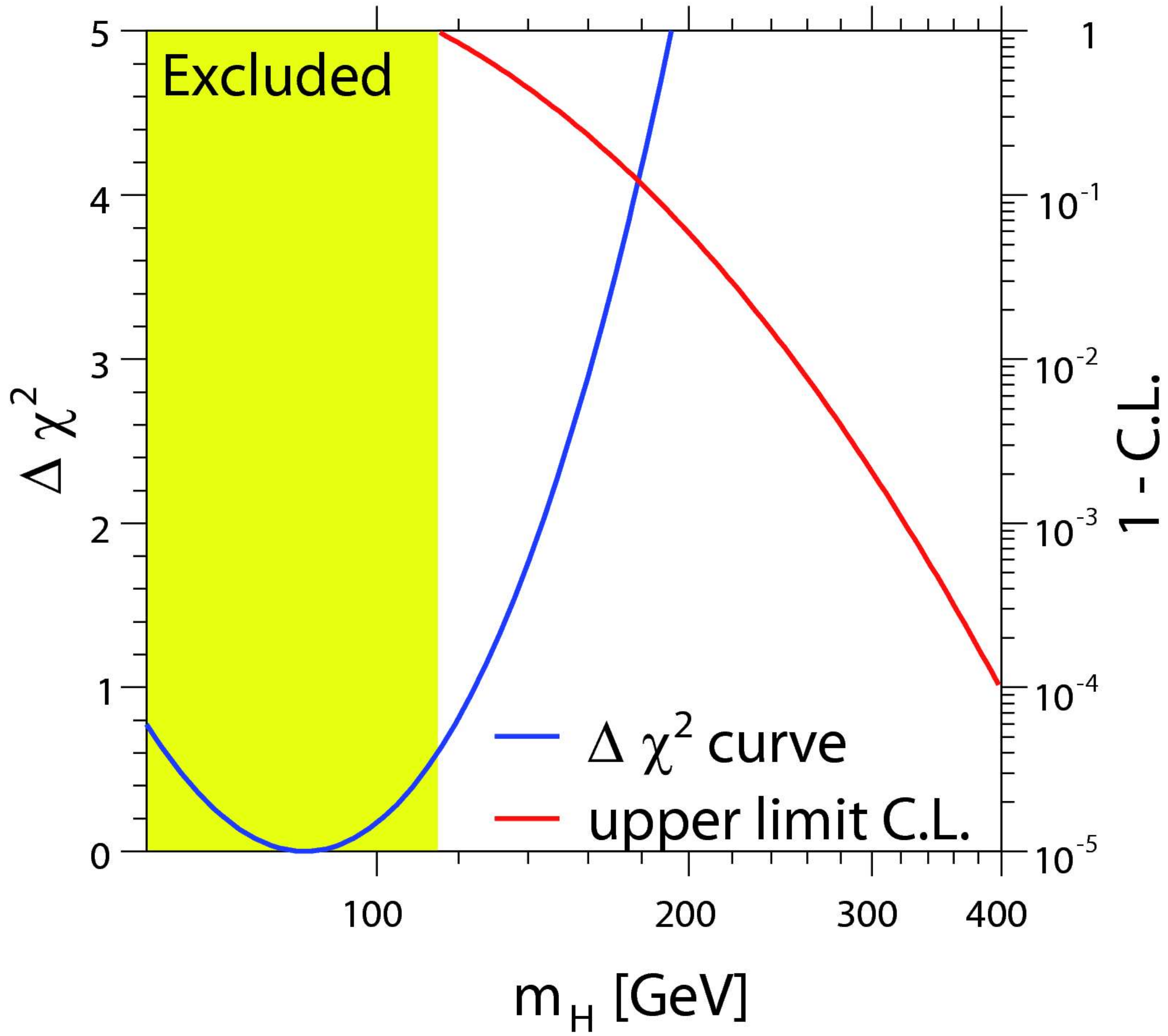




Number of candidates not significant above background.

lower mass limit : m_H > 114 GeV at 95% C.L.

Higgs Mass



Direct search: $m_H > 114$ GeV

Precision data: $m_H < 199$ GeV (bei 95% C.L.)

Summary

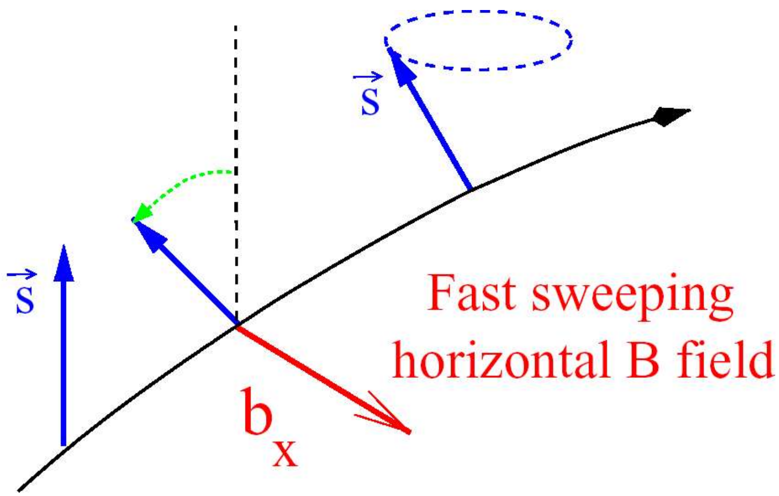
- The study of e^+e^- collisions at LEP and SLC allowed precision tests of the elecroweak theory
- Comparison of direct W mass from LEP2/Tevatron with indirect W mass from precision data confirms Standard Model including its quantum corrections
- Quantum corrections depend on mass of top quark and Higgs boson
- Global electroweak fit using all electroweak data yields information to the last unknown parameter of the Standard Model m_H

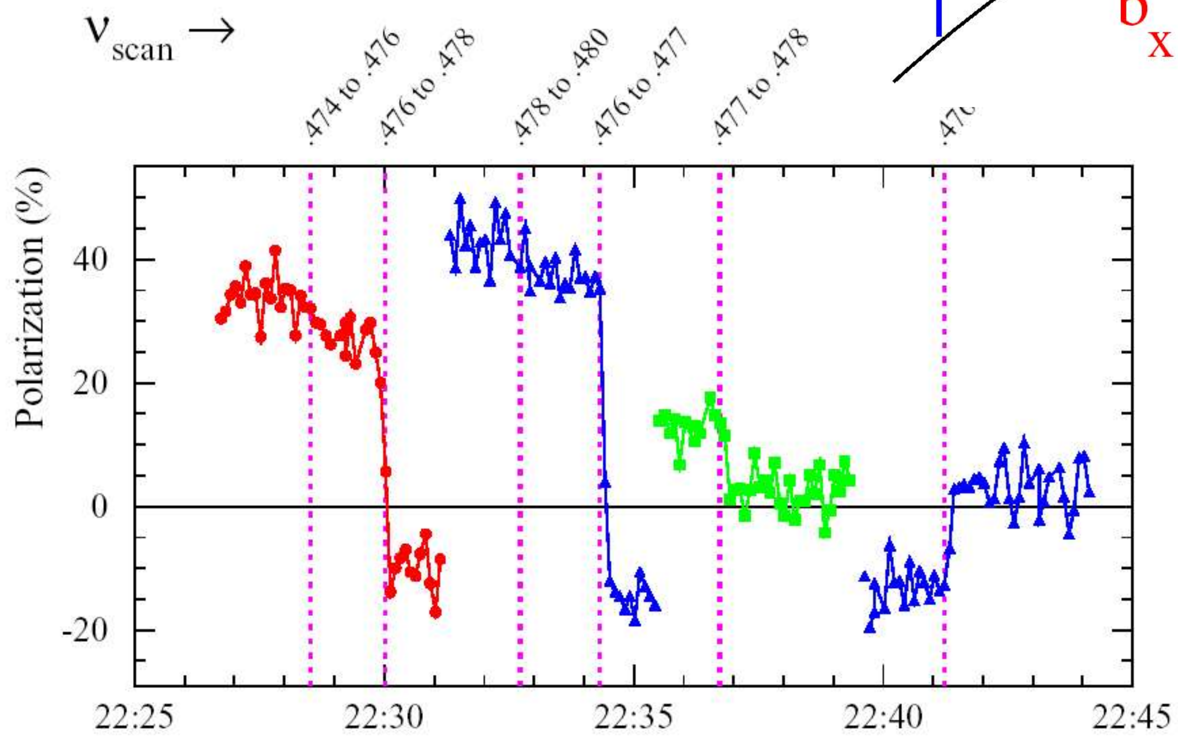

BACKUP
follows

Resonant Deoplarisation

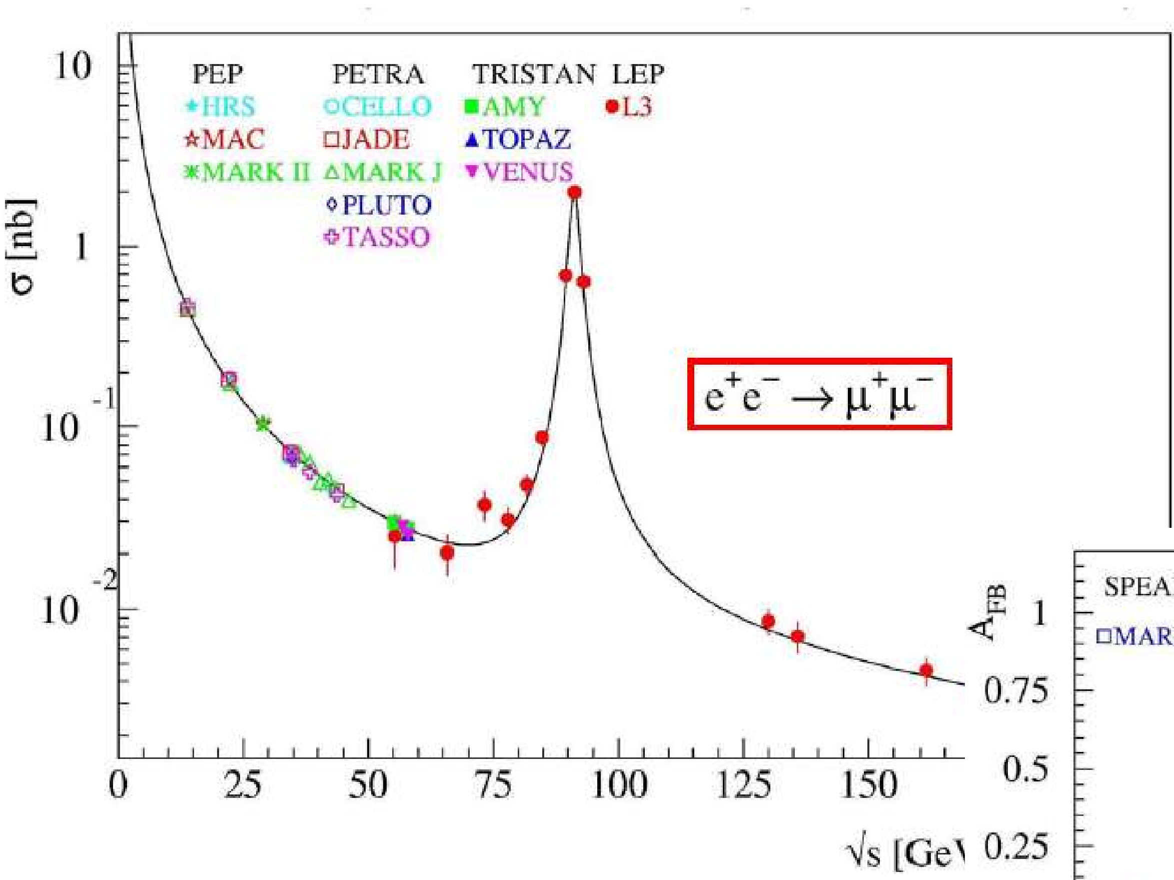
- Transverse beam polarisation builds up in magnet dipoles
- Spin of electron is precessing with frequency ν_s
- Depolarisation with external field

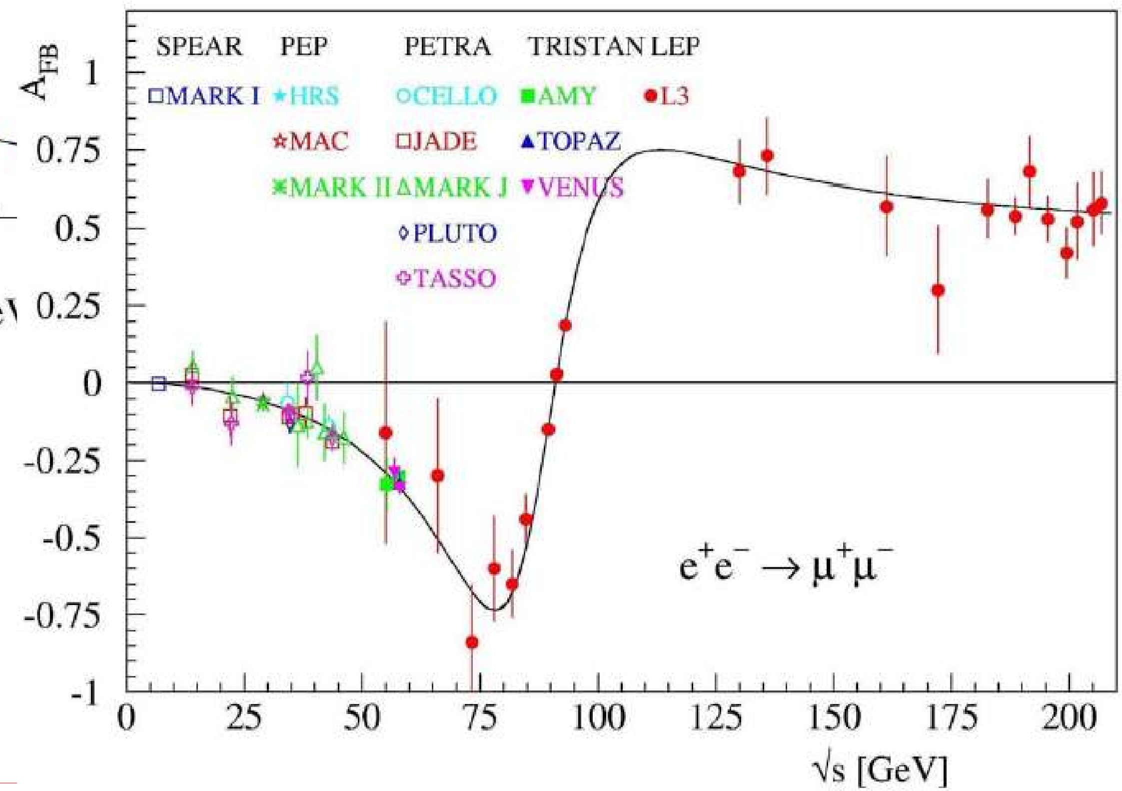
$$\nu_s = \frac{g_e - 2}{2} \frac{e}{2\pi m_e} \oint B \cdot \mathrm{d}\ell = \frac{g_e - 2}{2} \frac{E_{\mathrm{beam}}}{m_e}$$





Myon Pair Production



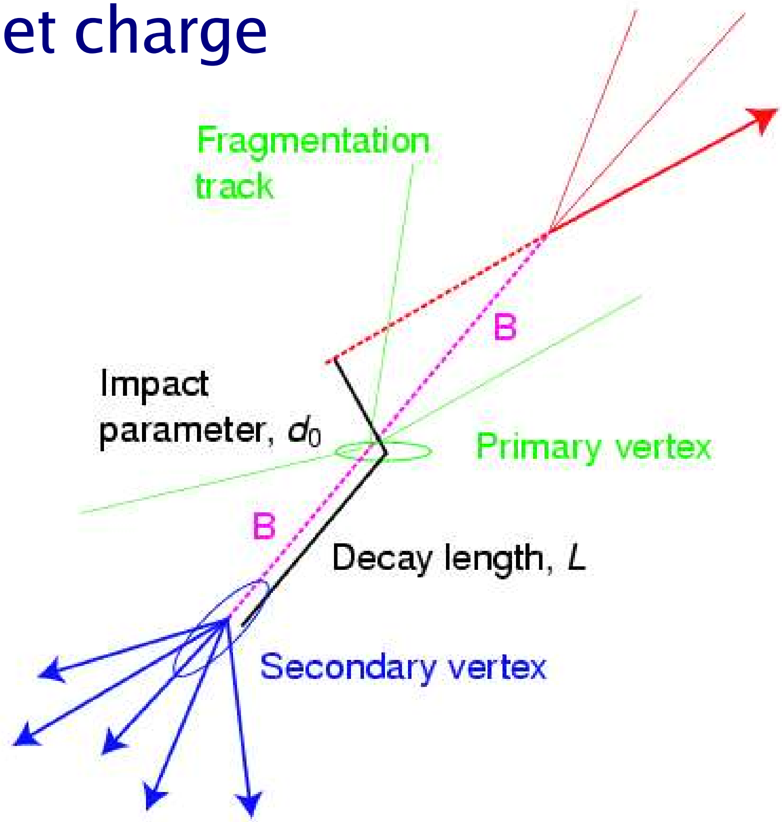


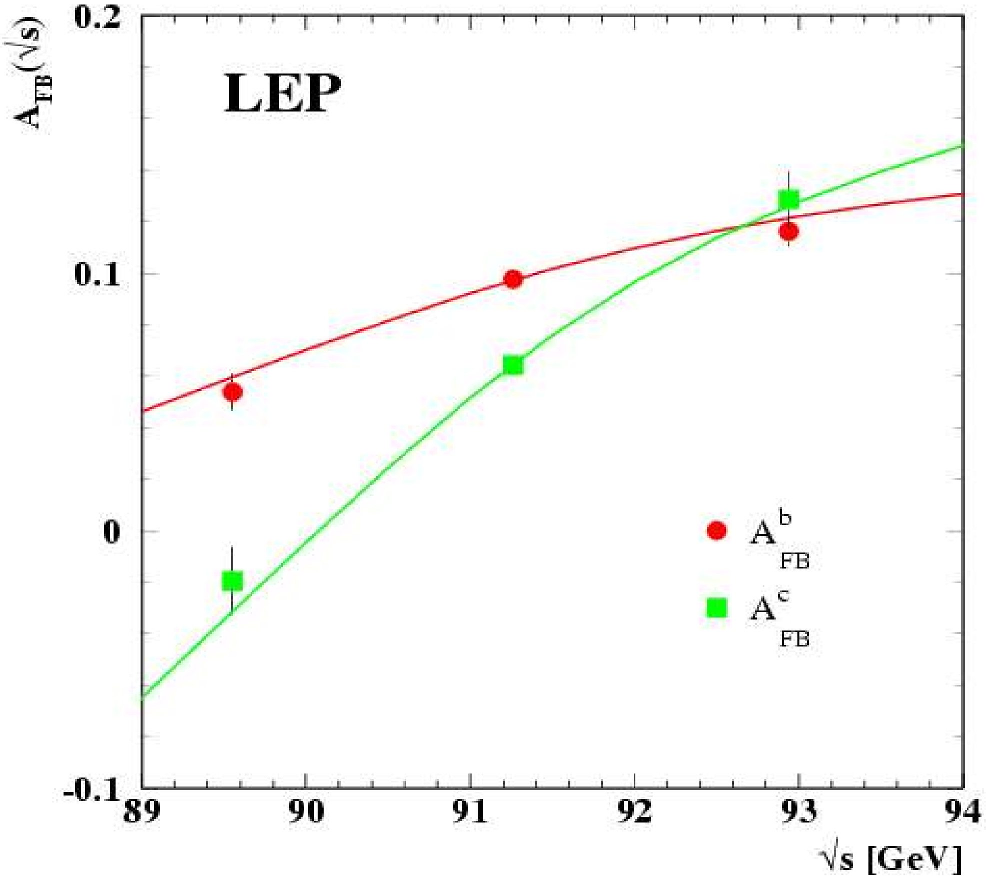
A_{FB} for b Quarks

jet direction

B tagging

jet charge





$A_{FB}(b)$ measurement translated into weak mixing angle:

$$\sin^2 \theta_{eff} = 0.23212 \pm 0.00029$$

Rho Parameter

$$m_W = m_Z \cdot \cos\theta_w$$

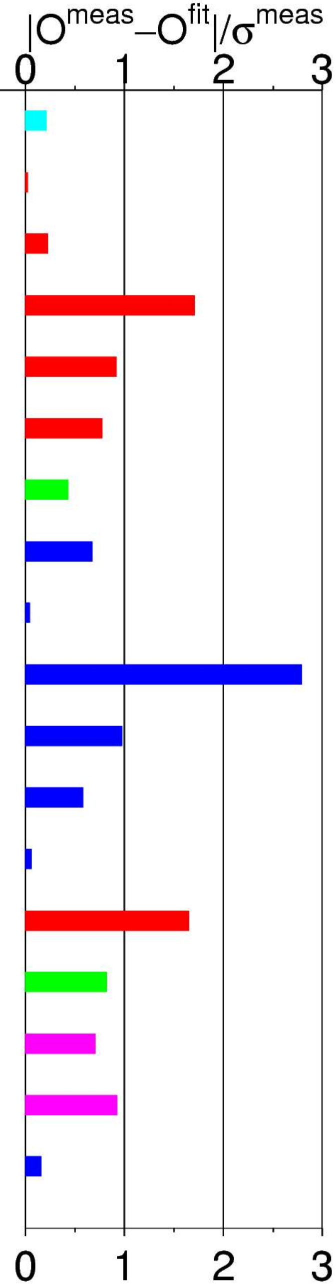
LEP 1 :	m_Z =	91.1875 ± 0.0021	[$2.3 \cdot 10^{-5}$]
LEP 2 / Tevatron :	m_W =	80.392 ± 0.029	[$3.7 \cdot 10^{-4}$]
LEP 1 / SLD :	$\sin^2\theta_{eff}$ =	0.23147 ± 0.00017	[$7.3 \cdot 10^{-4}$]
$\sin^2\theta_{eff}$ / m_t :	$\sin^2\theta_w$ =	0.22332 ± 0.00041	[$1.8 \cdot 10^{-3}$]
m_W / m_Z :	$1 - (m_W/m_Z)^2$ =	0.22276 ± 0.00058	[$2.6 \cdot 10^{-3}$]

$$\rho = \left(\frac{m_W}{m_Z \cdot \cos\theta_w}\right)^2 = 1.0008 \pm 0.0009$$

(Quantum corrections $\Delta\rho$ removed)

Standard Model Fit

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7

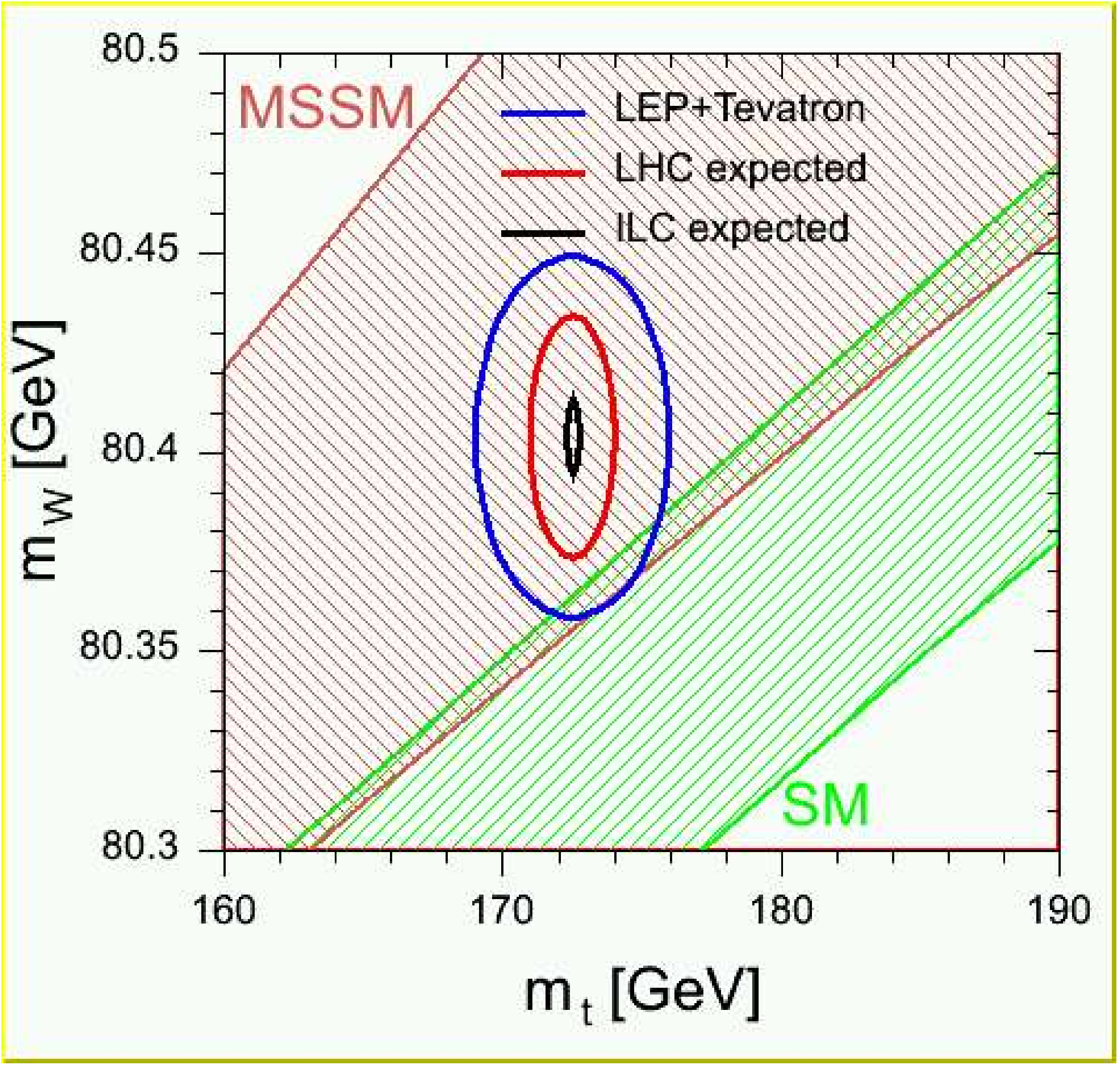


Fit quality :

χ^2 / d.o.f. = 17.8 / 13

Prob(χ^2) = 17 %

W Mass, Top Mass and SUSY



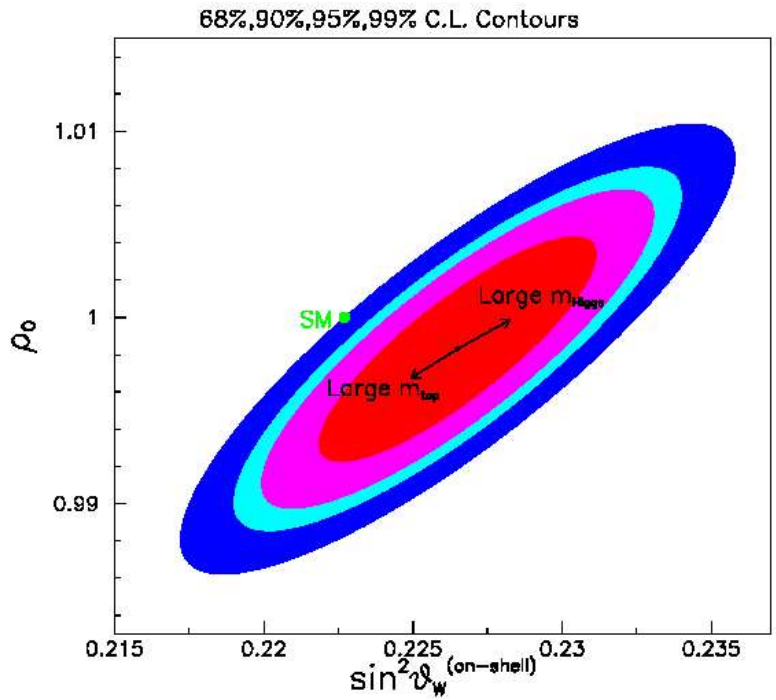
Heinemeyer, Hollik, Weiglein
in hep-ph/0412214 :

Quantum corrections in
Standard Model (SM)
and in
Minimal Supersymmetric
Standard Model (MSSM)

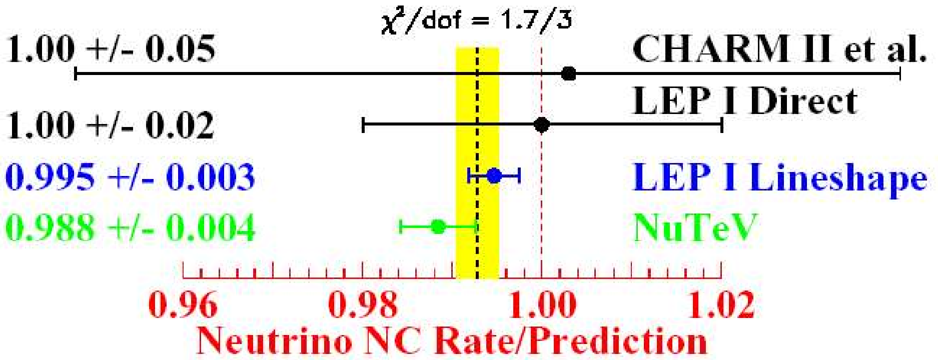
Comparison with measurments of
W mass and top mass shows
slight prefernce for MSSM

If SUSY will be discovered
this test will check the consistency
of the MSSM

NuTeV Result



$$= \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W \right)$$



LEP Lineshape: $N_\nu = 3 \times (0.9947 \pm 0.0028)$

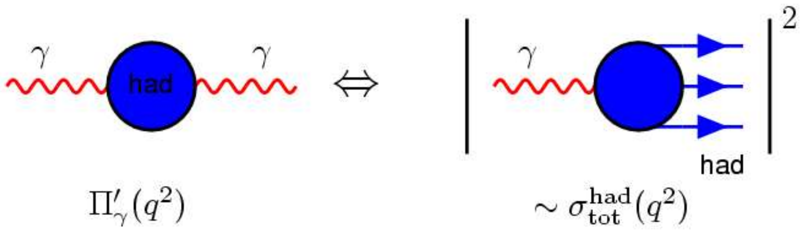
Other explanations:

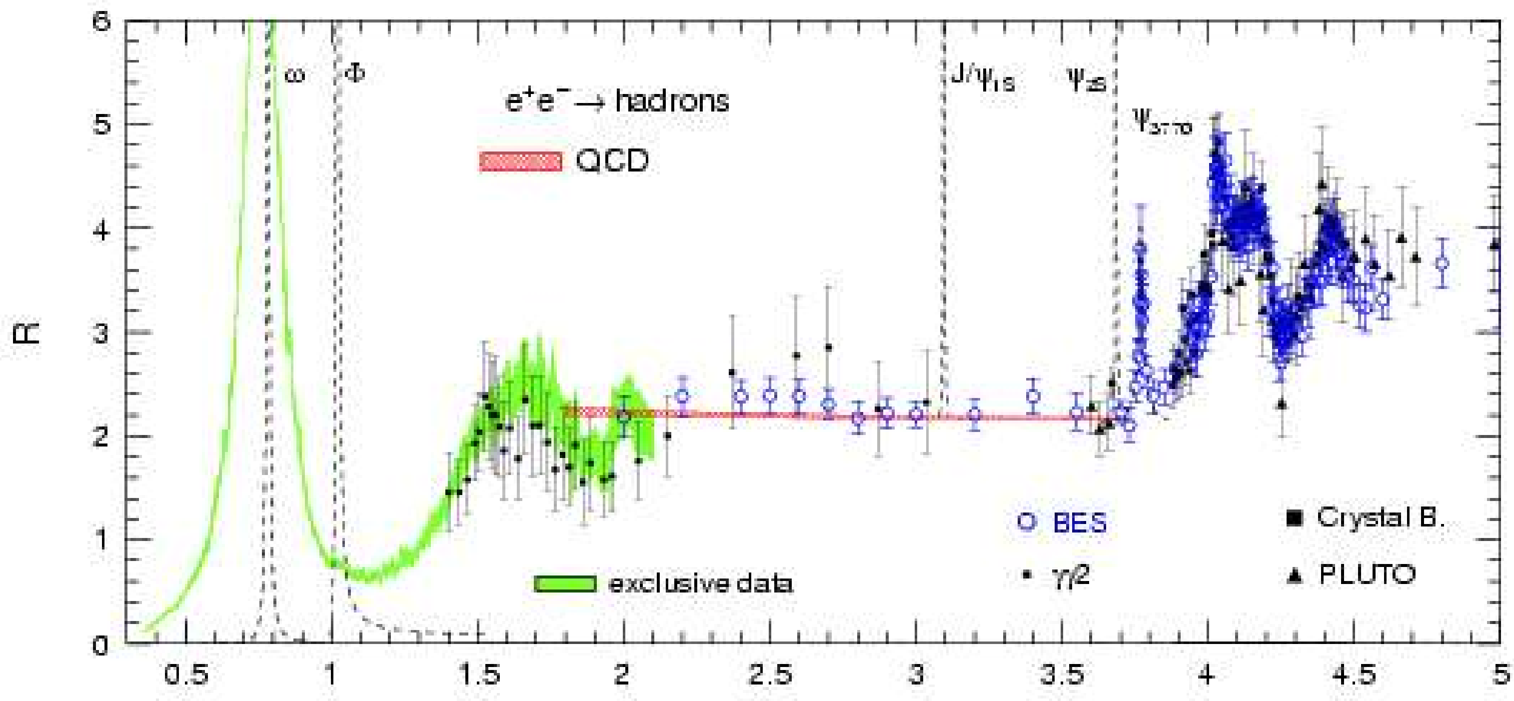
- Experimental effects: ν_e background
- QCD effects: wrong PDF's, non-isoscalar contributions, asymetry in strange-sea

Calculation of $\alpha(m_Z)$

Uncertainty in $\alpha(m_Z)$ dominated by hadronic vacuum polarisation

Measurement of $e^+e^- \rightarrow$ hadrons





Most recent CMD-2 result yields

$\alpha(m_Z) = 0.02768 \pm 0.00036$ (Burkhard and Pietrzyk)