Overview of Standard Model Results from LEP and Tevatron

Advanced Studies Institute
Physics at the LHC
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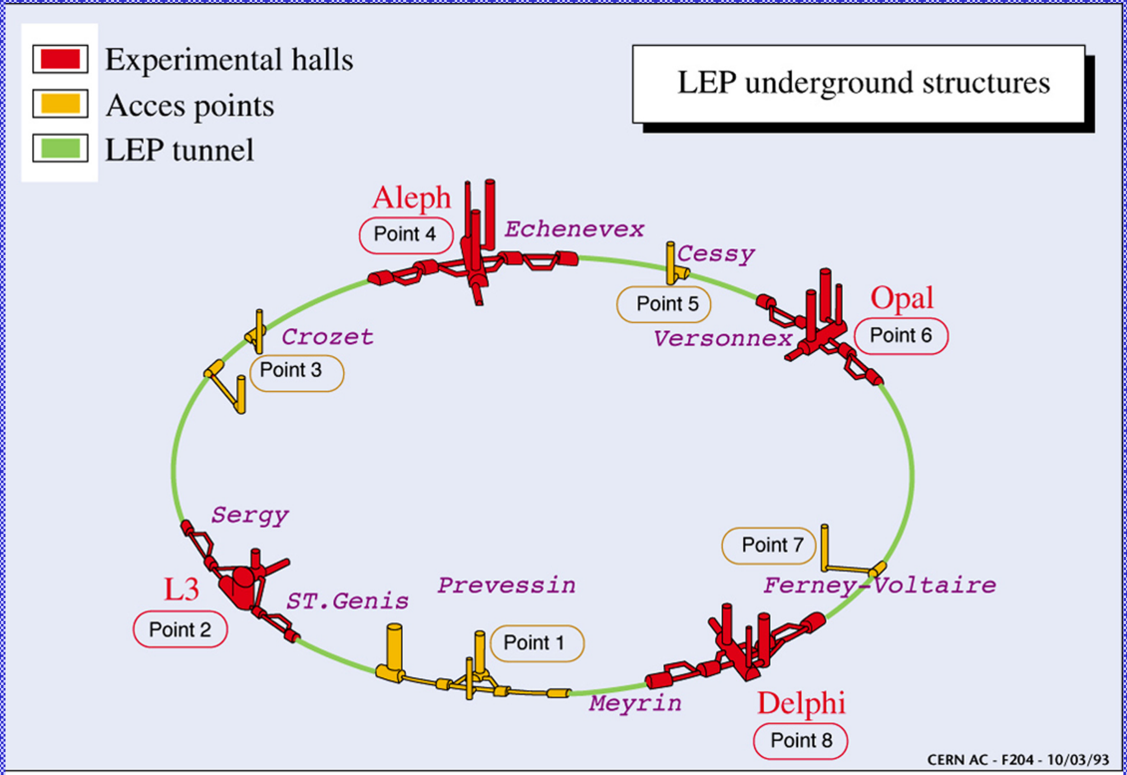
Outline:

- LEP I (1989 – 1995) The Z-Boson
  & SLD (1989 – 1998)
- LEP II (1996 – 2000) The W-Boson
- Tevatron (since 1992) The Top-Quark
  & the W-Boson
- Interpretation & SM Tests

LEP & the Experiments

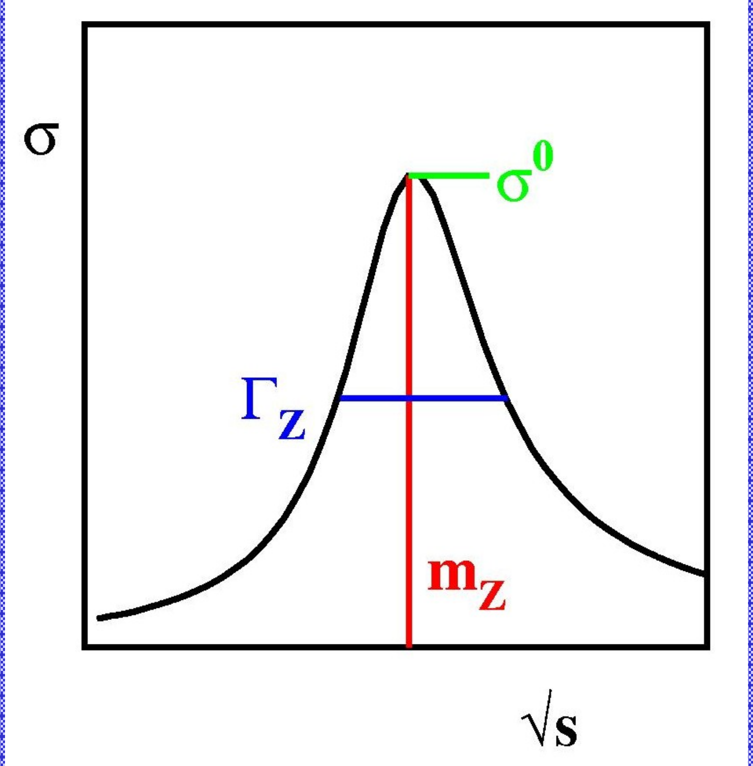

🟥 Experimental halls
🟨 Acces points
🟩 LEP tunnel
LEP underground structures
Aleph
Point 4
Echenevex
Cessy
Point 5
Opal
Point 6
Versonnex
Crozet
Point 3
Sergy
L3
Point 2
ST.Genis
Prevessin
Point 1
Point 7
Ferney-Voltaire
Meyrin
Delphi
Point 8
CERN AC - F204 - 10/03/93

ALEPH
DELPHI
L3
OPAL

- **High Luminosity:**
  approx. 1 fb^{-1}/experiment $\Rightarrow$
  $>4 \cdot 10^{6}$ Z decays & 10 k WW events
- **Precise beam energy calibration:**
  < ±1 MeV (LEP I) ≈ ±15 MeV (LEP II)

LEP I: The Z Lineshape and Asymmetries

Cross section measurements $e^+e^- \to f\,\bar{f}$ around the Z pole



➤ peak position	mass m_Z
➤ width	total width Γ_Z
➤ height	partial widths Γ_{had} , Γ_e , Γ_μ, Γ_τ

$$\sigma^0 = \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}$$

Large correlations between widths
⇒ use σ^0_{had} and $R_l = \Gamma_{had}/\Gamma_l$ for combination

Collaboration Theorists & Experiments

Higher order corrections are essential

o Theoretical calculations

ZFITTER D.Bardin et al.
TOPAZO G. Passarino et al.
ALIBABA W. Beenaker et al.

which include

o QED and QCD corrections

ISR: $O(\alpha^2)$, $O(\alpha^2 L^3)$ $L=\ln(s/m_e^2)$
FSR: $O(\alpha)$, $O(\alpha_s^3)$

o EW:

$O(G_F^2 m_t^4)$, $O(G_F^2 m_t^2 m_Z^2)$

o Mixed QCD×EW

$O(\alpha\alpha_s)$, leading $O(\alpha\alpha_s)$

o Essential contributions from

G. Degrassi et al.,
S. Jadach et al.,
D. Kniehl, J. Kühn et al.,
G. Montagna et al.

⇒ Small theoretical uncertainties, e.g.:

o QED corrections to lineshape

$$\Delta m_Z = \pm\, 0.3 \text{ MeV}$$
$$\Delta\Gamma_Z = \pm\, 0.5 \text{ MeV}$$
$$\Delta\sigma^0_{had}/\sigma^0_{had} = \pm\, 2\cdot 10^{-4}$$

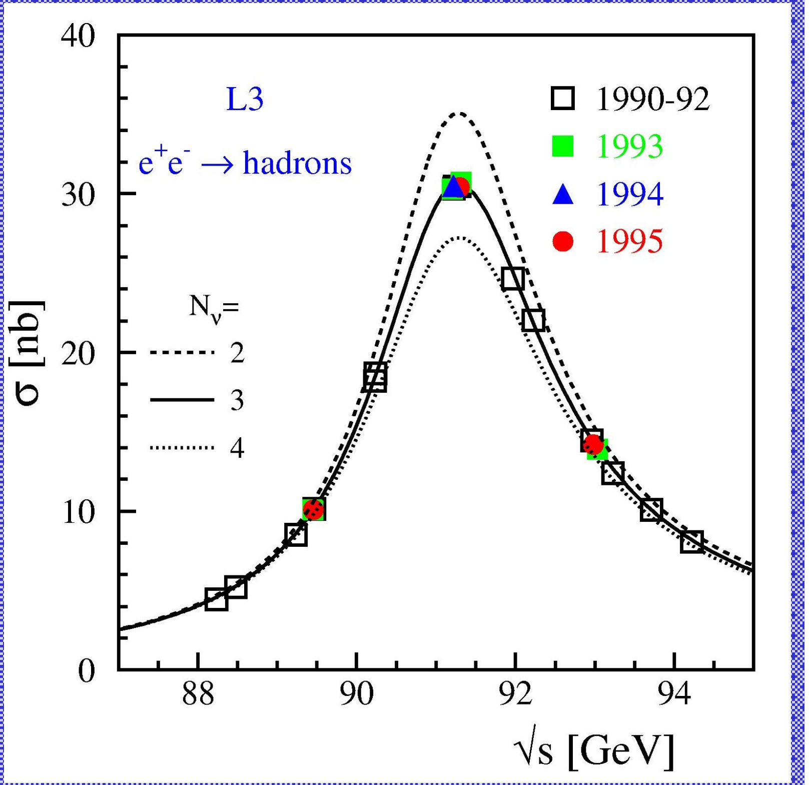
o agreement ZFITTER vs TOPAZO

$\leq 10^{-4}$ (peak) $\leq 3\cdot 10^{-4}$ (off-peak)

o luminosity measurement
(B. Ward et al.)

$$\leq 0.54 - 0.61\cdot 10^{-3}$$

The Z Lineshape



LEP results from Z lineshape
(incl. leptonic FB asymmetry)

m_Z = 91.1875 ± 0.0021 GeV

Γ_Z = 2.4952 ± 0.0023 GeV

σ^0_{had} = 41.540 ± 0.037 nb

R_l = 20.767 ± 0.025

A^0_{FB} = 0.0171 ± 0.0010

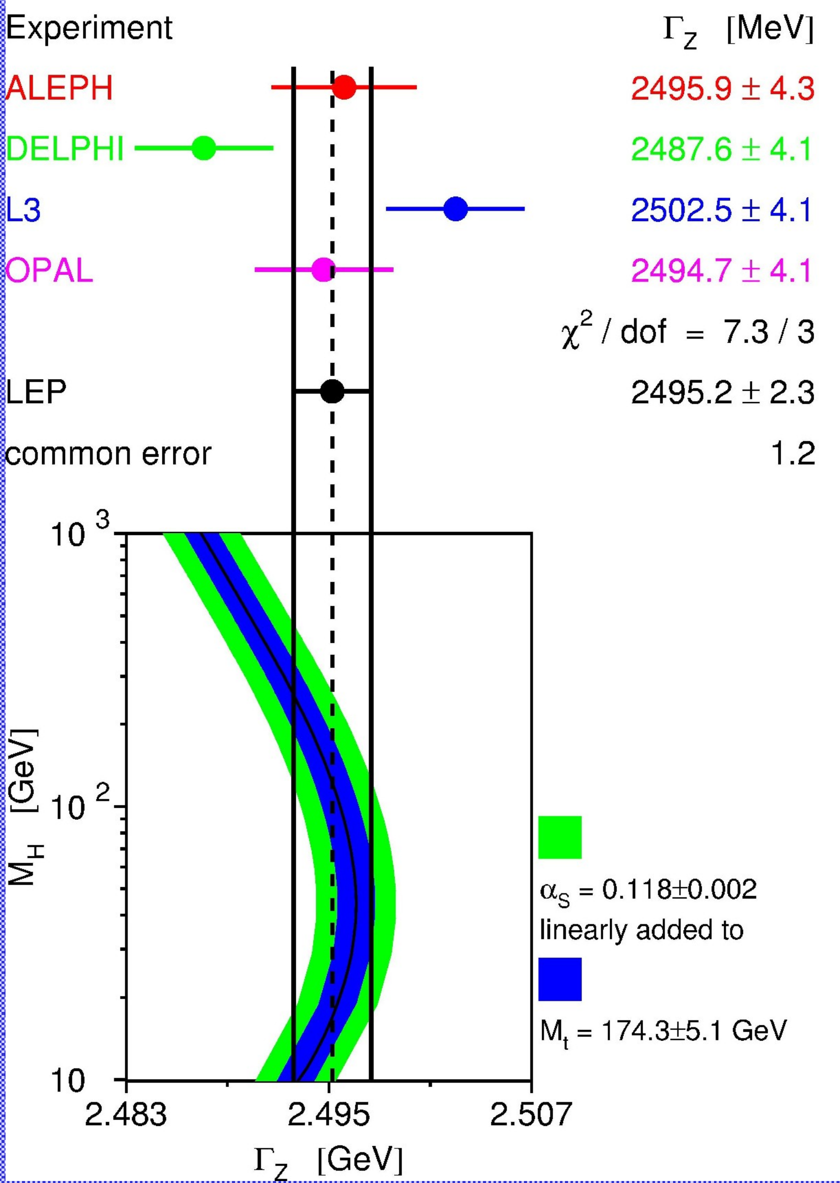
$$\boxed{\Delta m_Z / m_Z = \pm 2.3 \cdot 10^{-5}}$$

Number of neutrino families:

$N_\nu = 2.9841 \pm 0.0083$

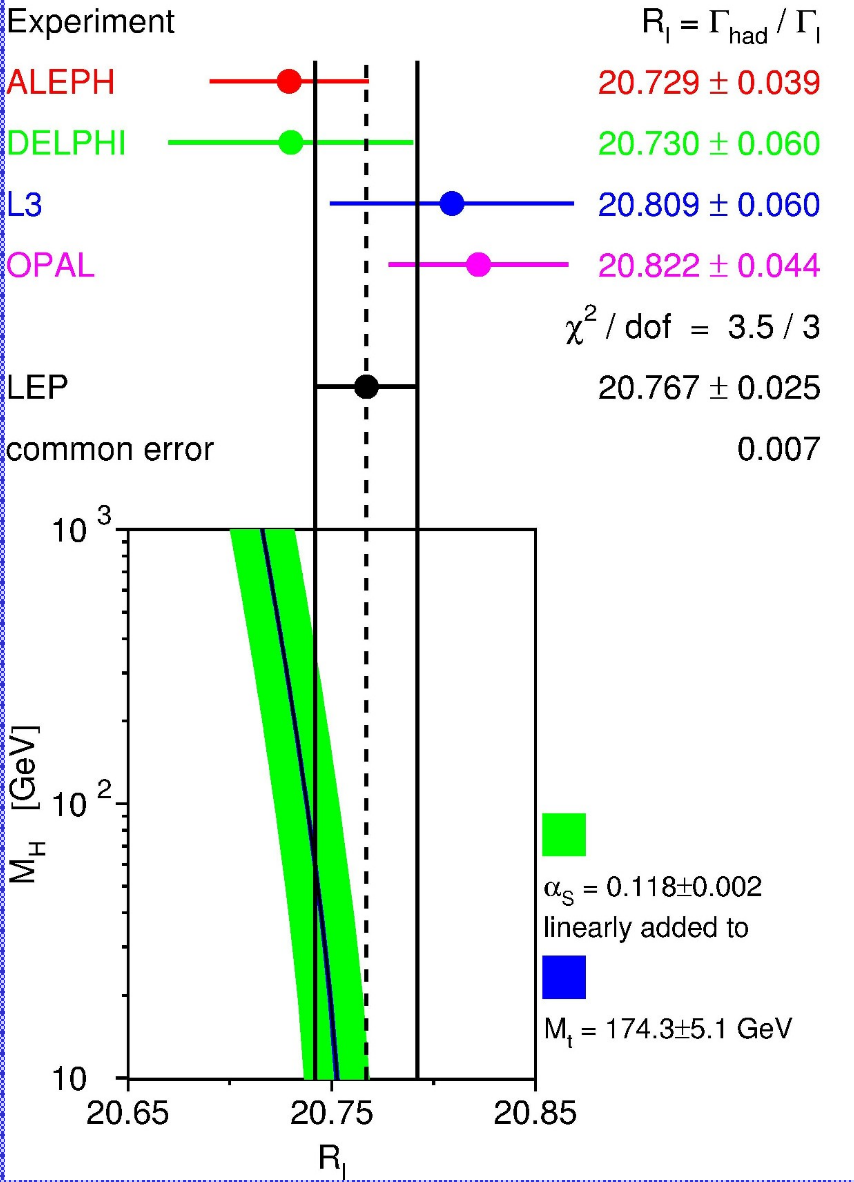
Comparison LEP Experiments

Total width Γ_Z



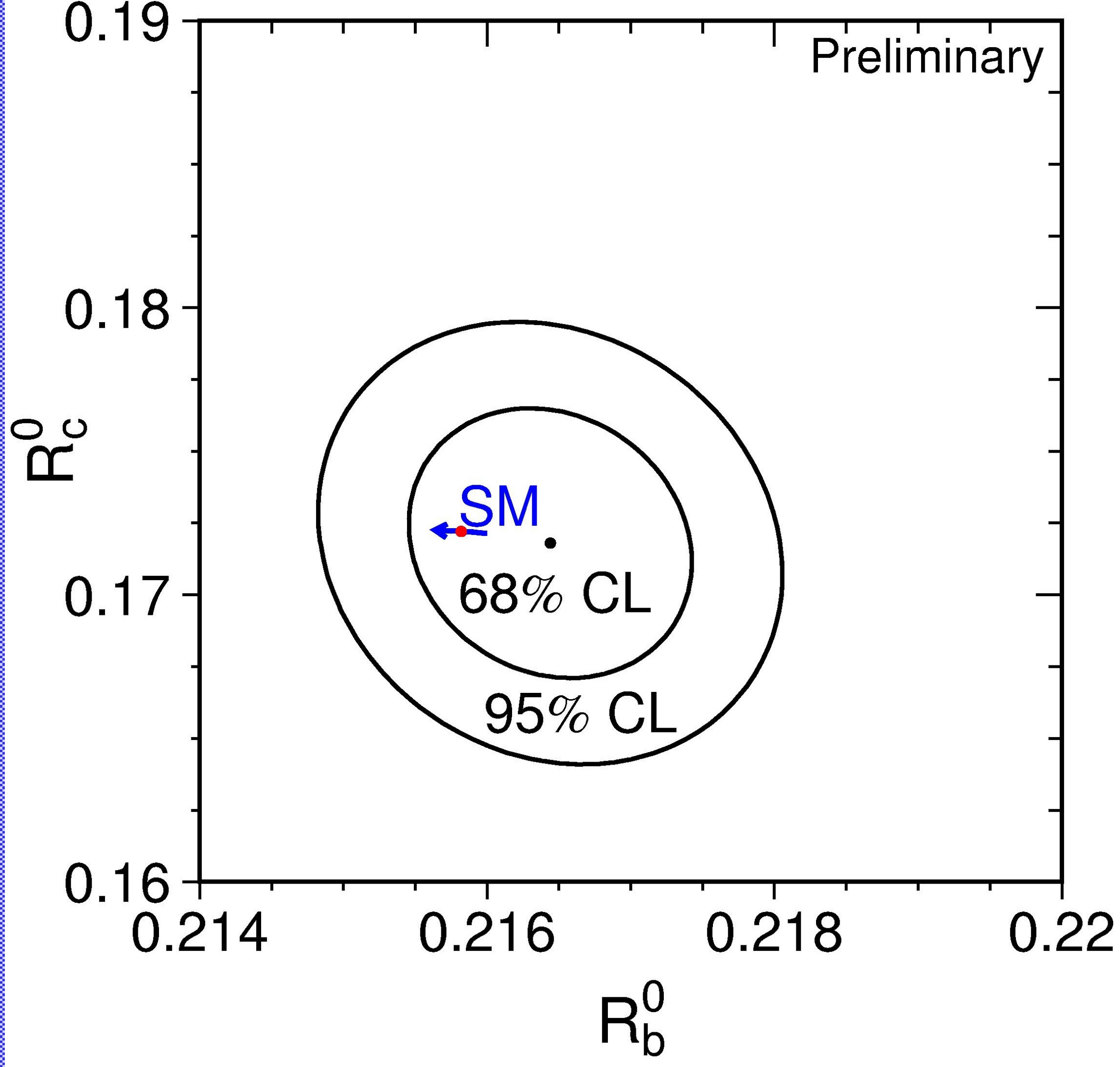
Experiment	Γ_Z [MeV]
ALEPH	2495.9 ± 4.3
DELPHI	2487.6 ± 4.1
L3	2502.5 ± 4.1
OPAL	2494.7 ± 4.1
	χ^2 / dof = 7.3 / 3
LEP	2495.2 ± 2.3
common error	1.2

$R_l = \Gamma_{had}/\Gamma_l$



Experiment	$R_l = \Gamma_{had} / \Gamma_l$
ALEPH	20.729 ± 0.039
DELPHI	20.730 ± 0.060
L3	20.809 ± 0.060
OPAL	20.822 ± 0.044
	χ^2 / dof = 3.5 / 3
LEP	20.767 ± 0.025
common error	0.007

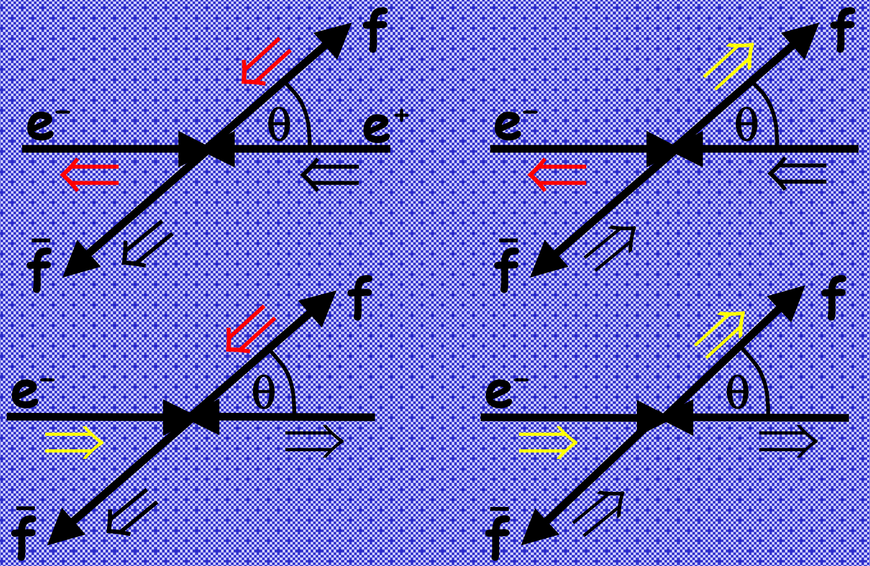
The Partial Widths Z → bb and Z → cc



$$R_{b,c} = \frac{\Gamma_{b,c}}{\Gamma_{had}}$$

Asymmetries in $e^+e^- \to f\,\bar{f}$

4 different helicity configurations contribute to cross section with different angular dependence



$$\frac{d\sigma_{ll}}{d\cos\Theta} \propto \left(g_L^e\right)^2\left(g_L^f\right)^2(1+\cos\Theta)^2$$

$$\frac{d\sigma_{lr}}{d\cos\Theta} \propto \left(g_L^e\right)^2\left(g_R^f\right)^2(1-\cos\Theta)^2$$

$$\frac{d\sigma_{rr}}{d\cos\Theta} \propto \left(g_R^e\right)^2\left(g_R^f\right)^2(1+\cos\Theta)^2$$

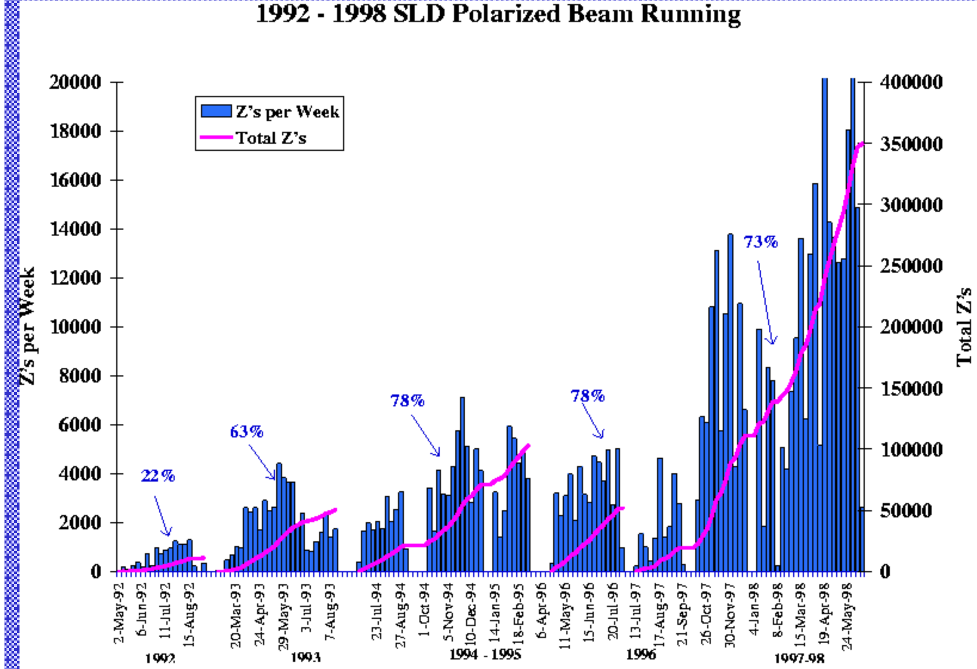
$$\frac{d\sigma_{rl}}{d\cos\Theta} \propto \left(g_R^e\right)^2\left(g_L^f\right)^2(1-\cos\Theta)^2$$

- o Transform to set of cross sections & asymmetries experimentally accessible
- o and identify left and right handed couplings with Z boson couplings g_V & g_A

Total cross section	$\sigma_{tot} \propto \left[\left(g_V^e\right)^2+\left(g_A^e\right)^2\right]\left[\left(g_V^f\right)^2+\left(g_A^f\right)^2\right]$	
Initial state pol.	$A_{LR} = \frac{\sigma_{ll}+\sigma_{lr}-\sigma_{rr}-\sigma_{rl}}{\sigma_{tot}}$	$= A_e$
Final state pol.	$P_f = -\frac{\sigma_{ll}-\sigma_{lr}-\sigma_{rr}+\sigma_{rl}}{\sigma_{tot}}$	$= -A_f$
Forward-backward	$A_{FB} = \frac{\sigma_{ll}-\sigma_{lr}+\sigma_{rr}-\sigma_{rl}}{\sigma_{tot}}$	$= \frac{3}{4}A_eA_f$

Initial State Polarization

SLD experiment at the Stanford Linear Collider

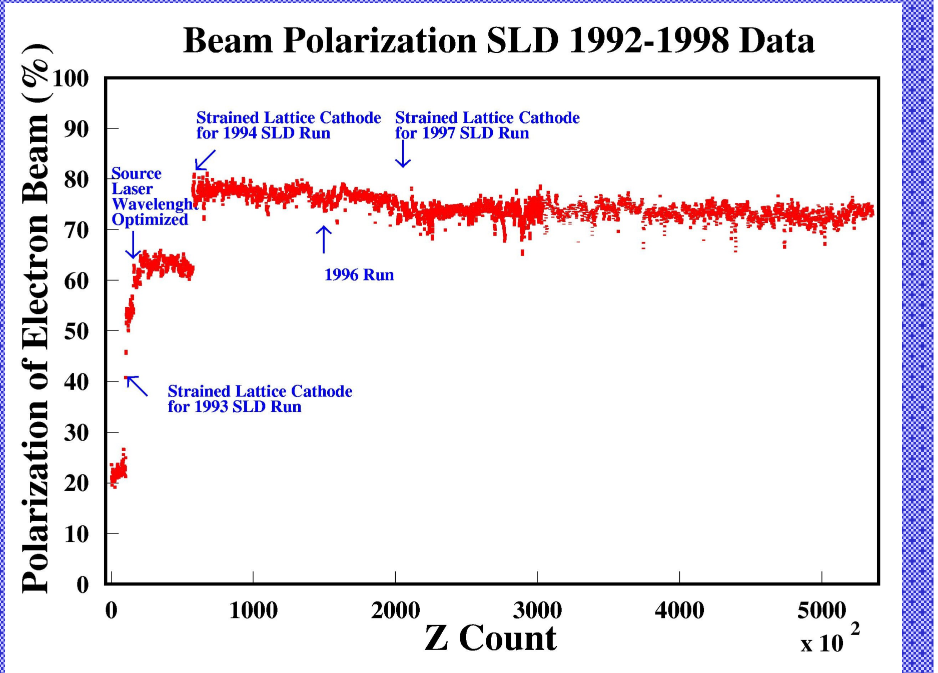


≈ 500 000 Z decays observed

≈ 1/10 of typical LEP experiment

BUT

≈ 75% long. electron polarisation



o measurement of left-right asymmetry

$A_{LR} = A_e/P_e$

⇒ electron couplings A_e

⇒ best measurement of $\sin^2\vartheta_W$

$$\sin^2\vartheta_W = 0.23098 \pm 0.00026$$

(with $g_V/g_A = 1 - 4\sin^2\vartheta_W$)

Angular Dependence of A_{LR}

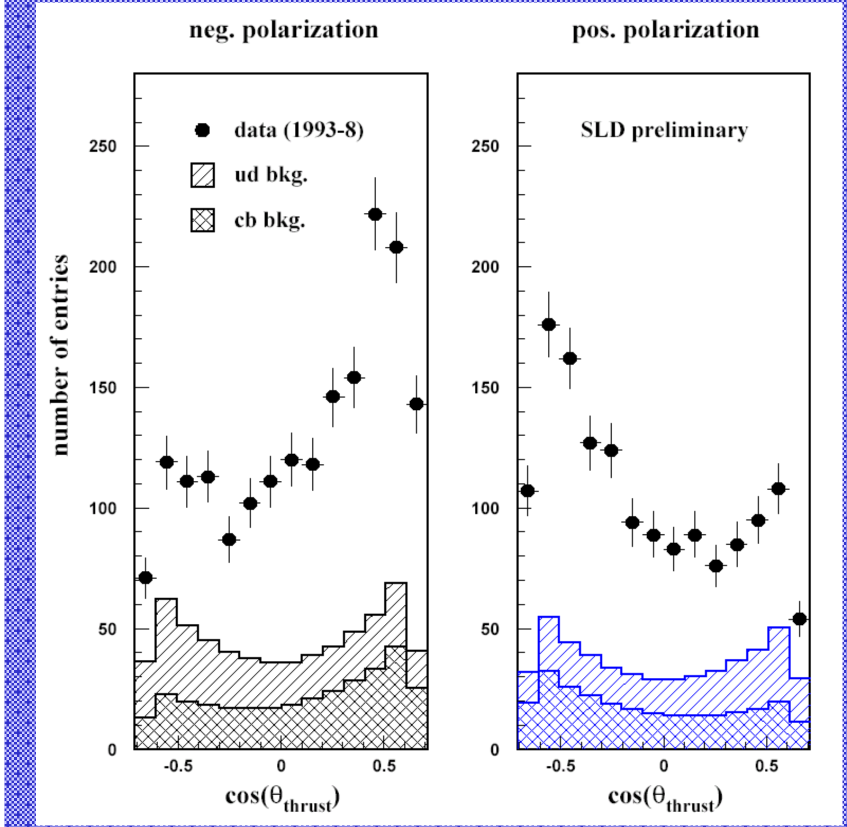
Forward-backward left-right asymmetry

$\Rightarrow$ Couplings of final state fermion

Example:

measurement of s-quark coulings A_s

tagged by high momentum K and Λ



SLD results on Z couplings:

Leptons:

A_e = 0.1516 ± 0.0021 (incl. A_{LR})

A_μ = 0.142 ± 0.015

A_τ = 0.136 ± 0.015

Quarks:

A_s = 0.85 ± 0.09

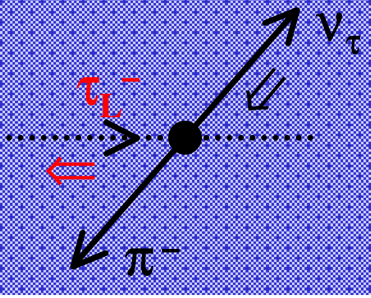
A_c = 0.922 ± 0.020

A_b = 0.670 ± 0.026

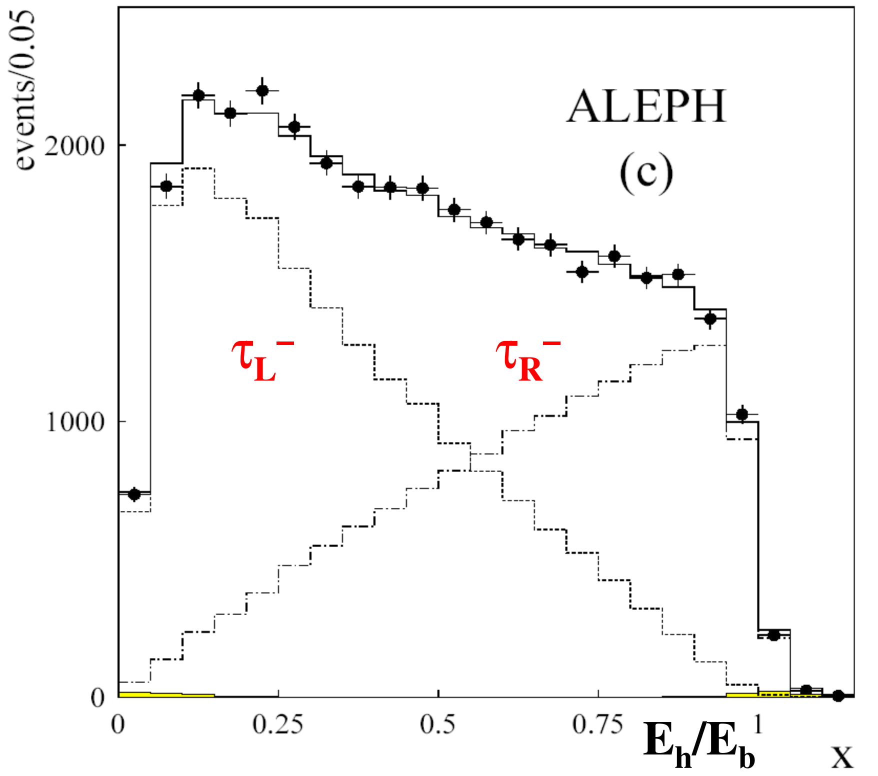
Final State Polarization

Measurable only in tau decays from decay spectra:

e.g. $\tau_L^- \rightarrow \pi^- \nu_\tau$


ν_τ
τ_L^-
$\Leftarrow$
$\Leftarrow$
π^-

Average polarization $\Rightarrow A_\tau$
Forward-backward $\Rightarrow A_e$

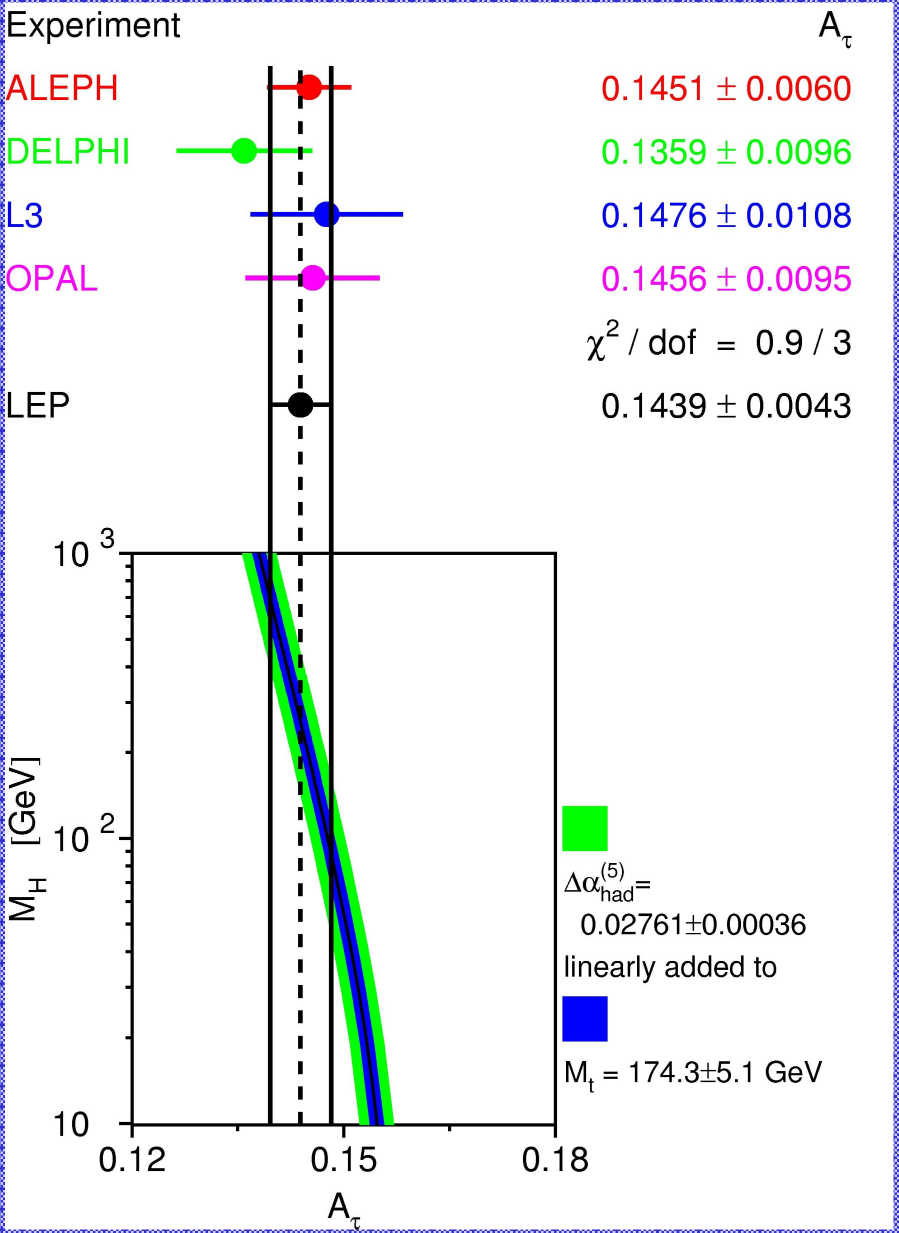


Results from LEP:

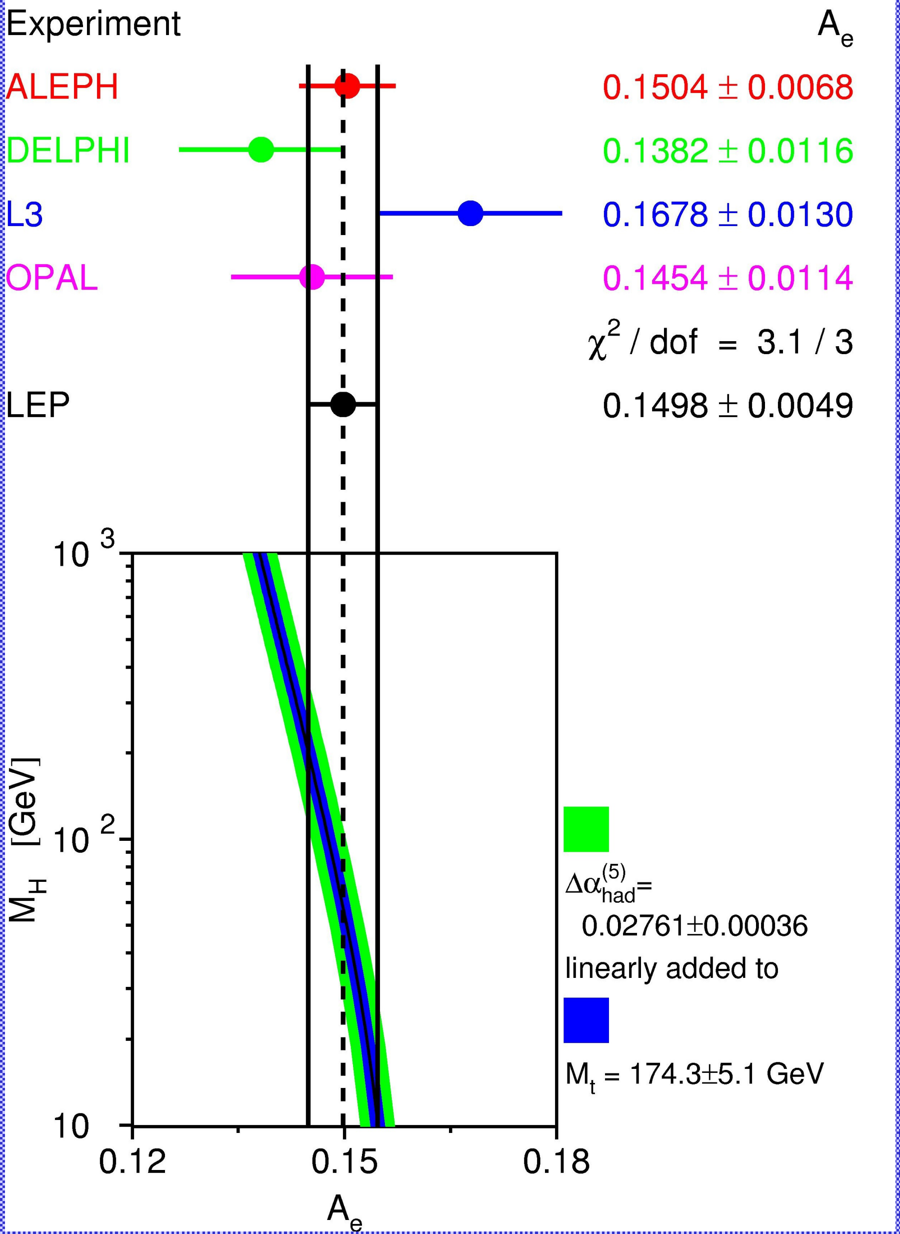
$A_\tau = 0.1439 \pm 0.0043$

$A_e = 0.1498 \pm 0.0049$

Average tau polarisation:

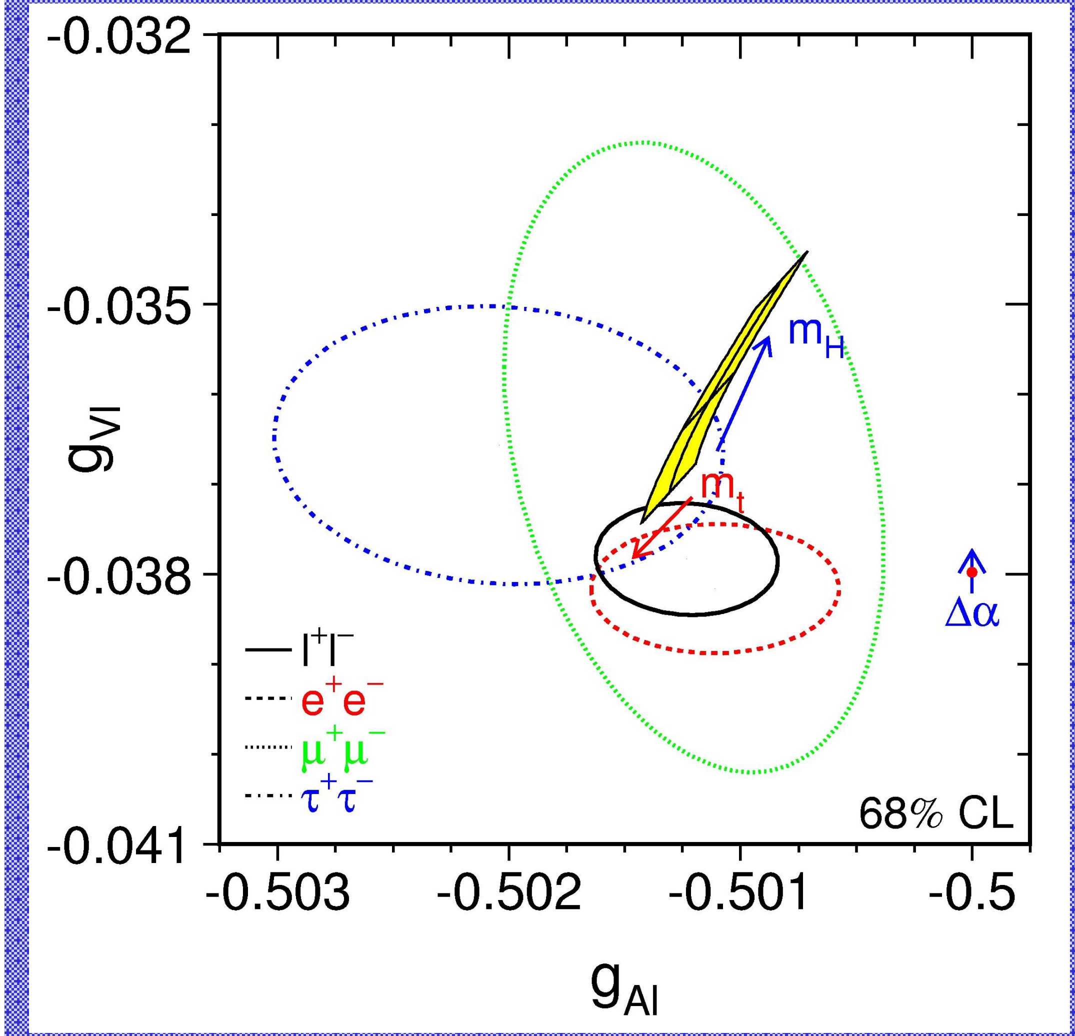


Forward-backward tau pol.:



Lepton Universality in Neutral Currents

From $A_l = 2g_A g_V/(g_A^2 + g_V^2)$
and $\Gamma_l \propto g_A^2 + g_V^2$:



Ratios of couplings:

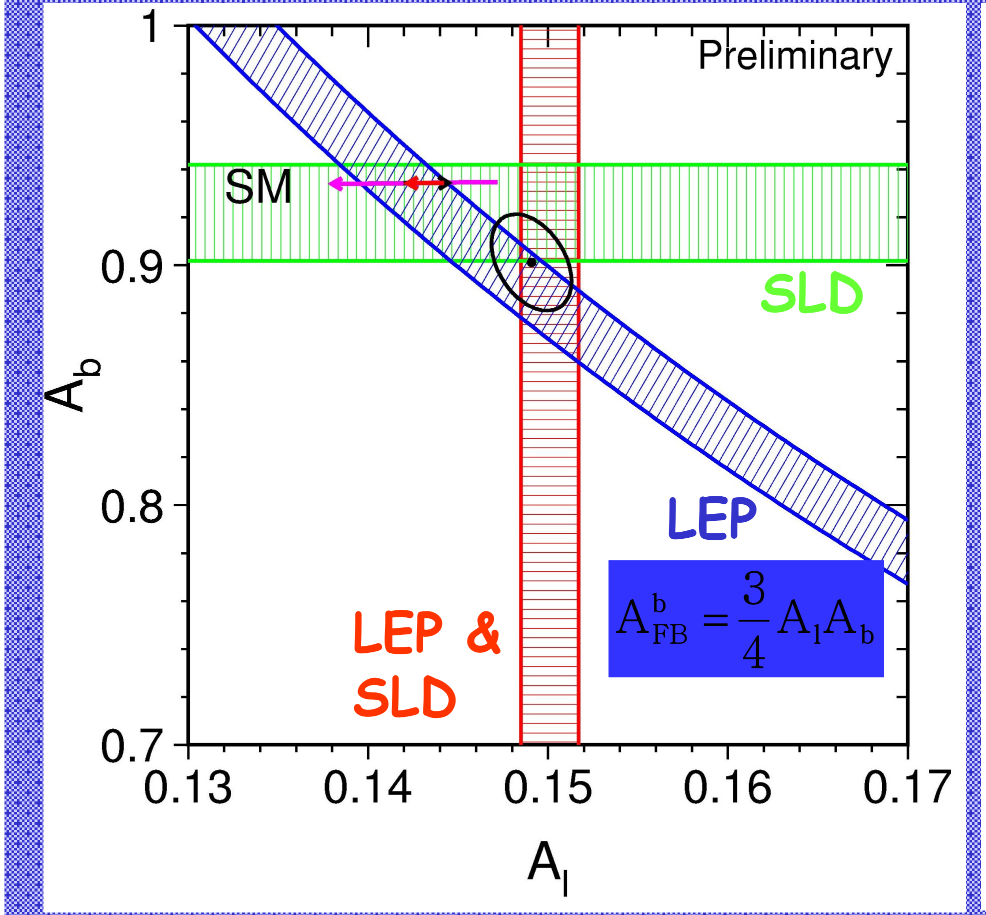
g_A^{μ}/g_A^{e} = 1.0002 ± 0.0014
g_A^{τ}/g_A^{e} = 1.0019 ± 0.0015
g_V^{μ}/g_V^{e} = 0.962 ± 0.063
g_V^{τ}/g_V^{e} = 0.958 ± 0.029

Lepton universality tested to 10^{-3} in g_A

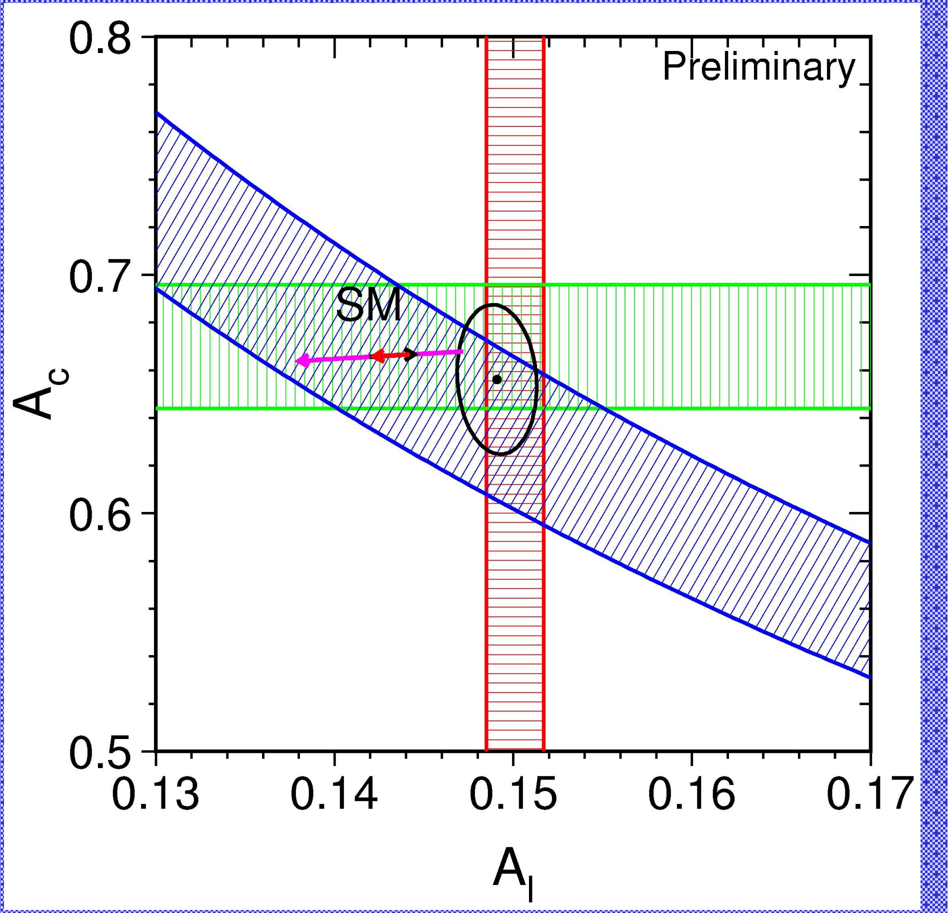
Neutral Current Couplings of Quarks:

Asymmetry parameter A_f of heavy quarks vs lepton

b-quark:

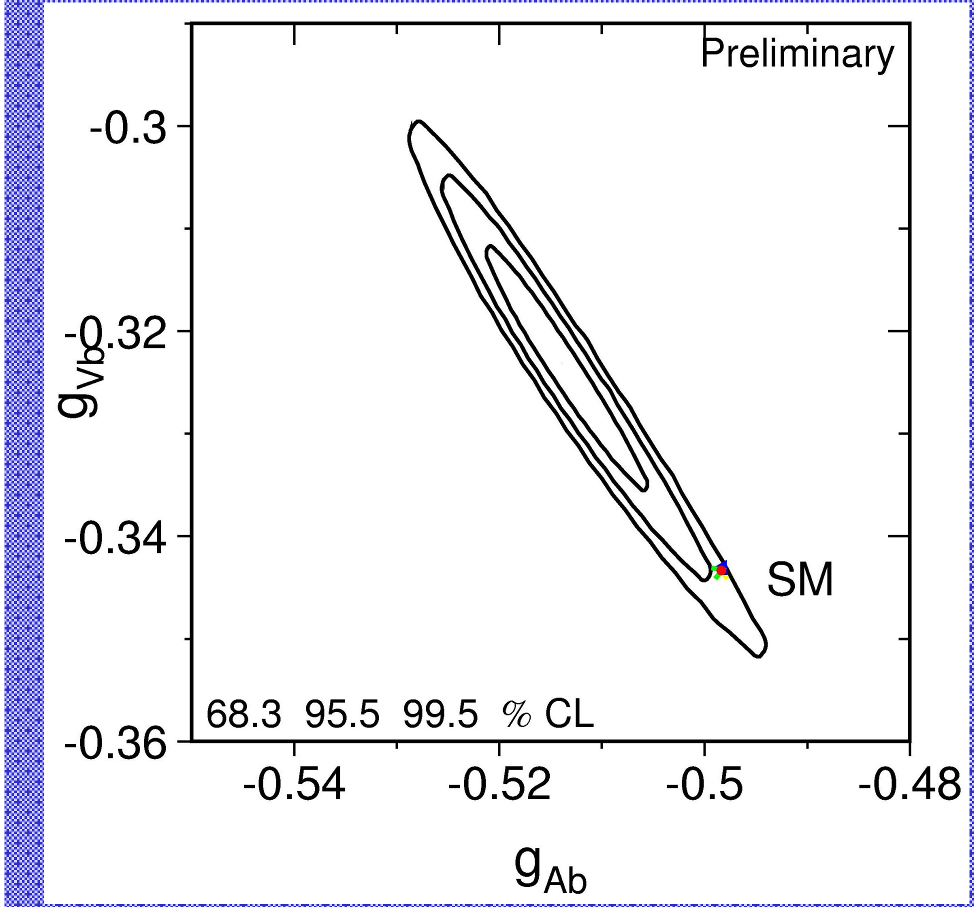


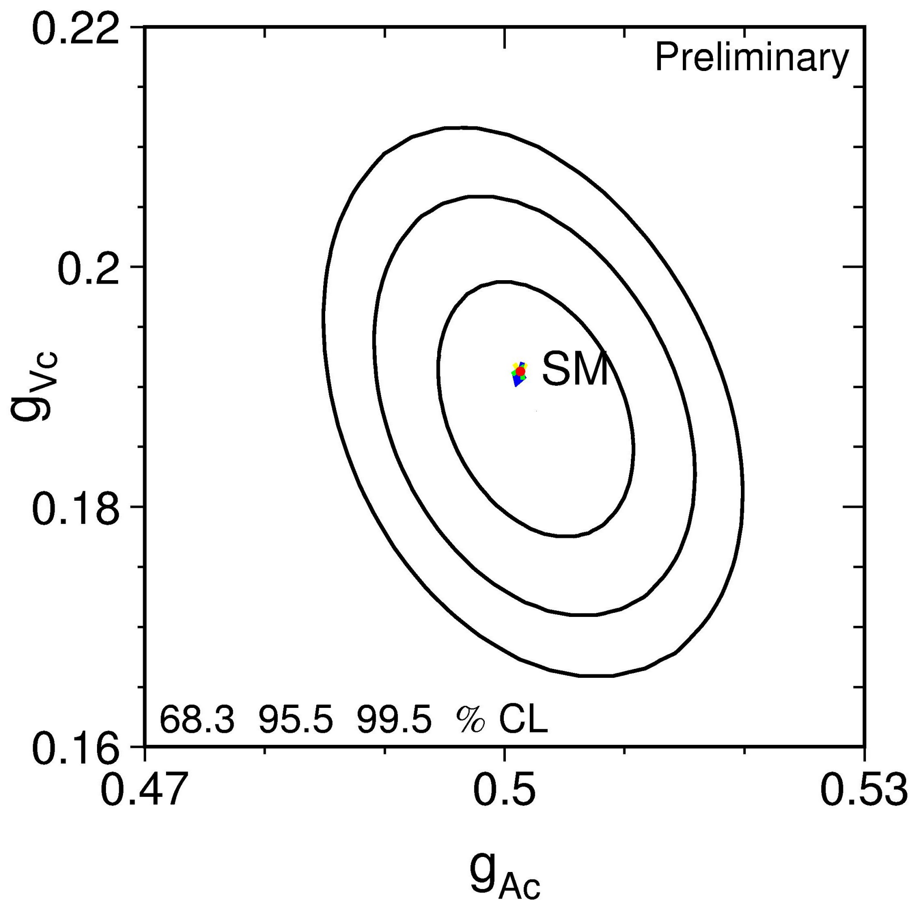
c-quark:



Neutral Current Couplings of Quarks:

b-quark: **c-quark:**





2σ deviation in b-couplings
„problem" can be cast into right-handed b-quark coupling

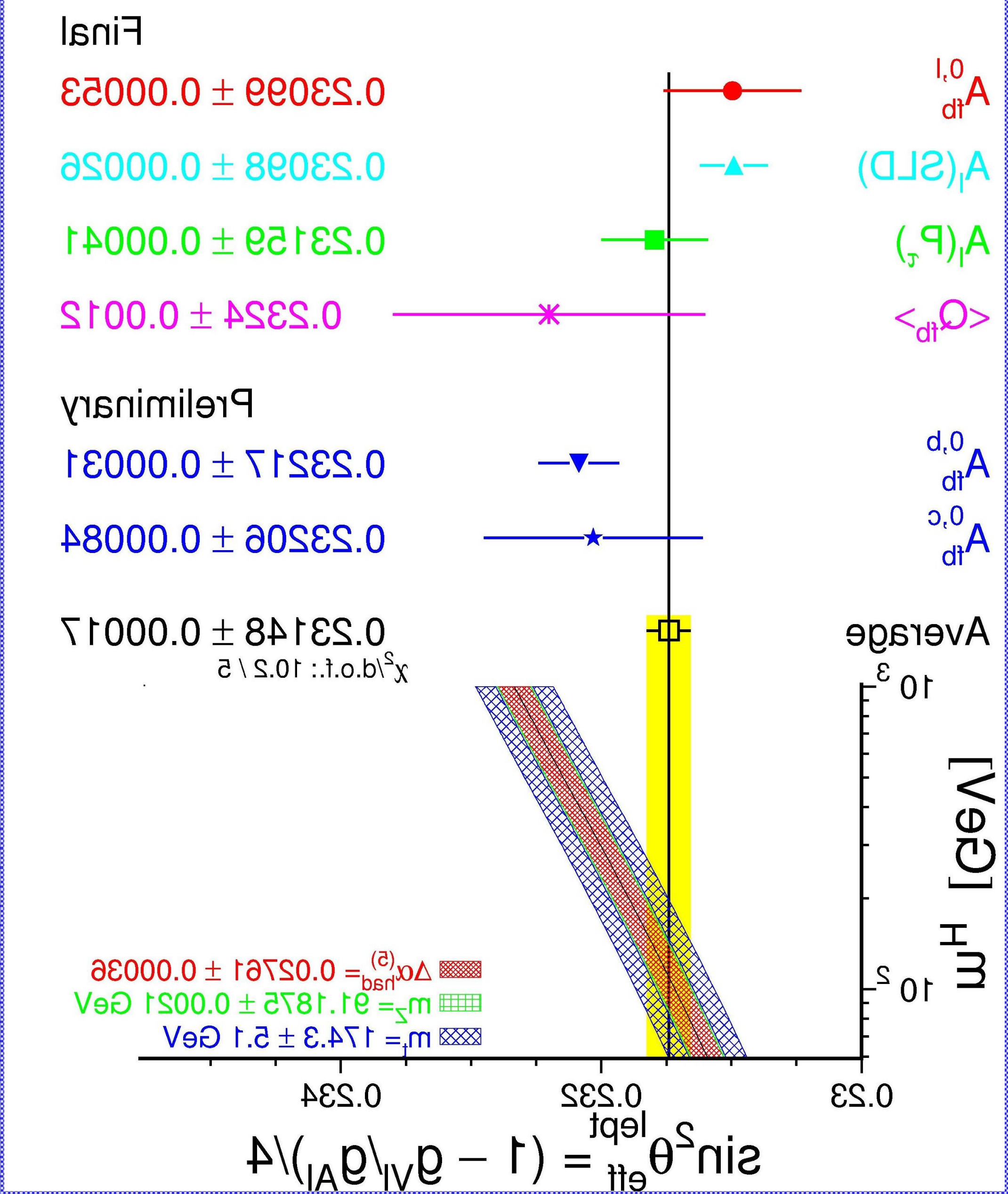
The (Effective) Weak Mixing Angle $\sin^2\vartheta_W$:

- Comparison of asymmetries in terms of $\sin^2\vartheta_W$
- Average value:

  $\sin^2\vartheta_W = 0.23148 \pm 0.00017$

- Comparison with SM:

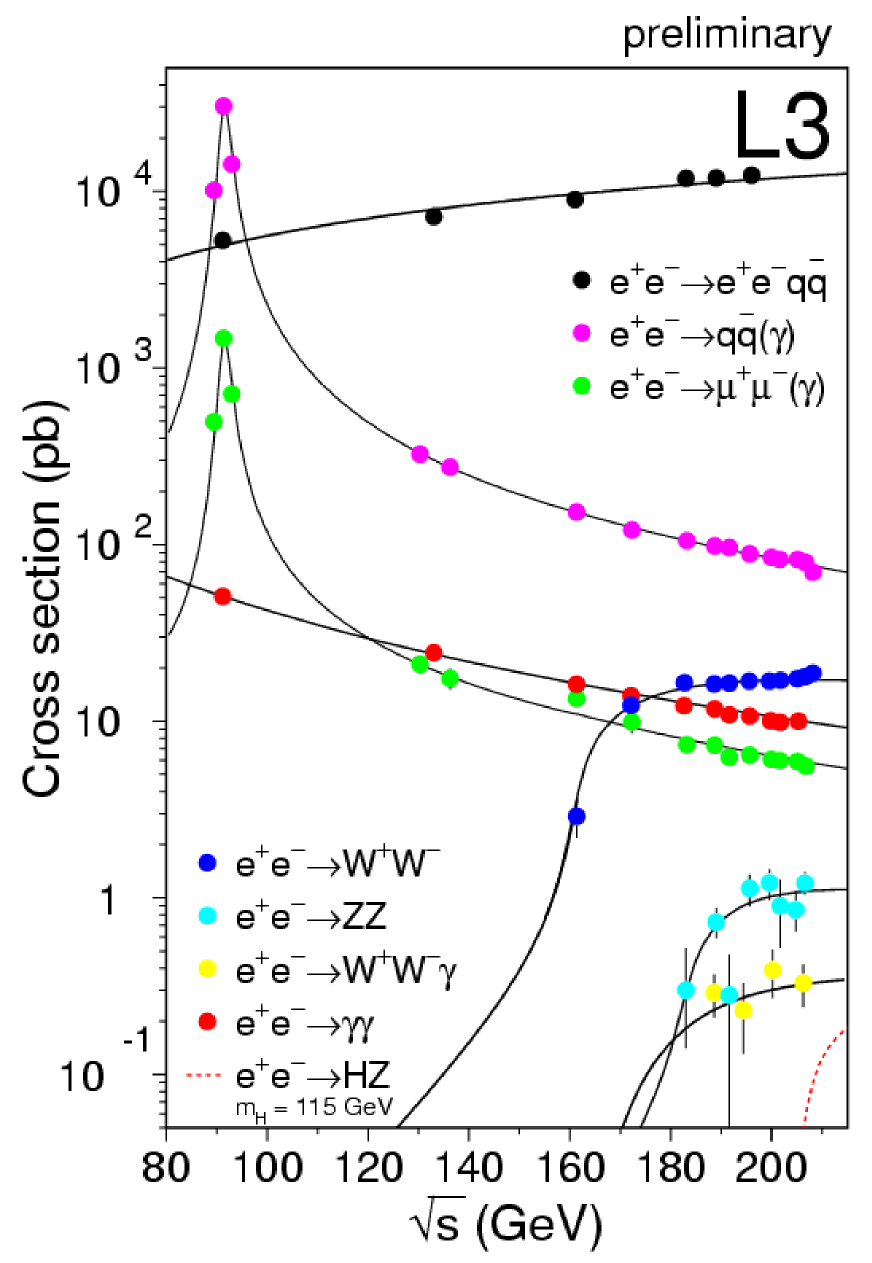
⇒ The Higgs is light



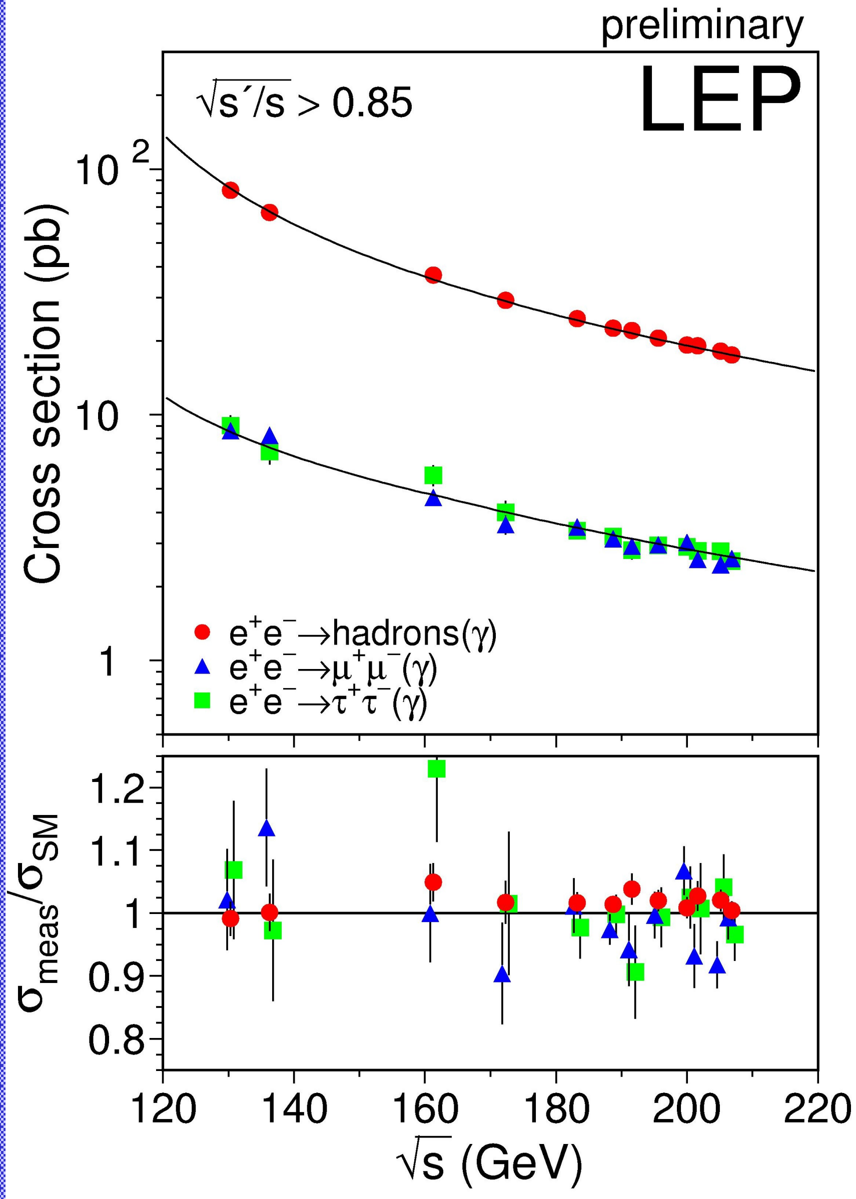
LEP II: e^+e^--Experiments up to 208 GeV

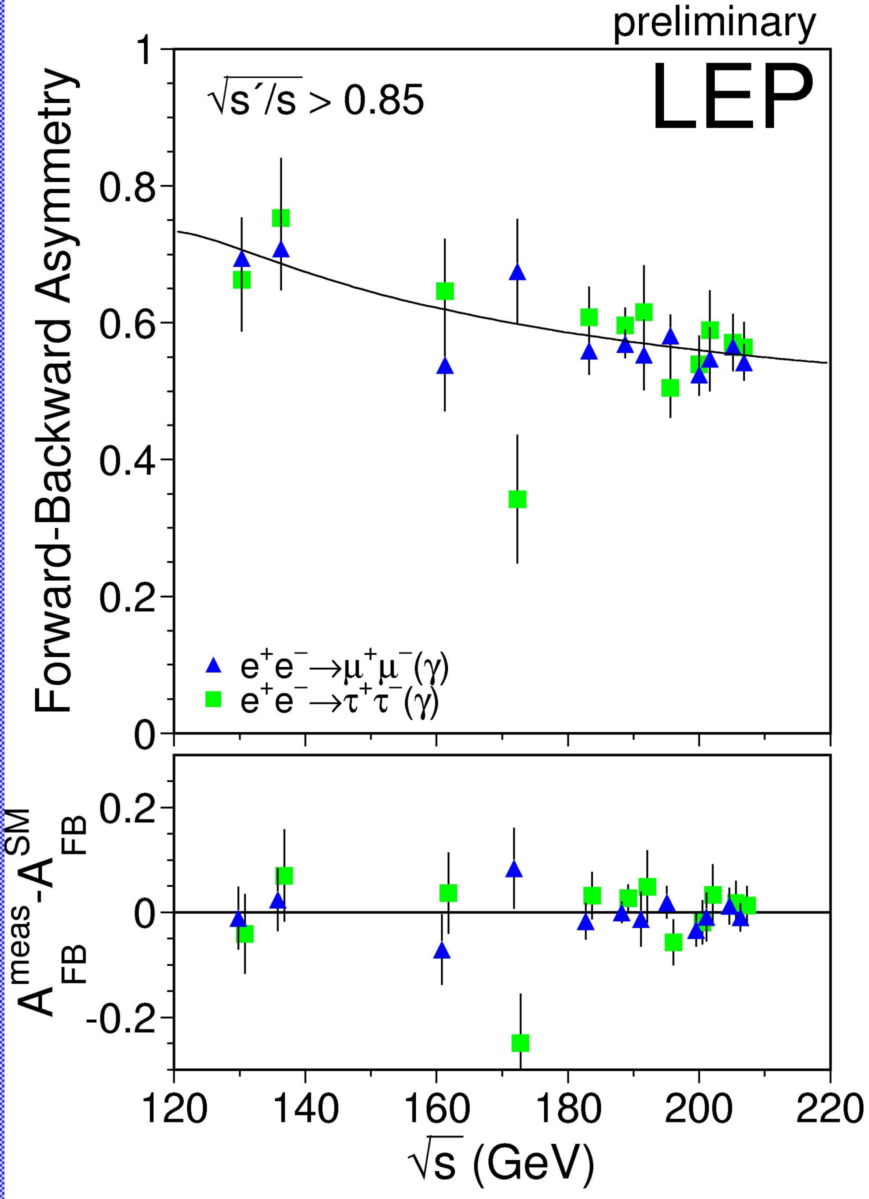
Comparison of various
SM cross sections

Experiments are in perfect agreement with SM predictions!



Combined LEP II Results on $e^+e^- \to f\bar{f}$



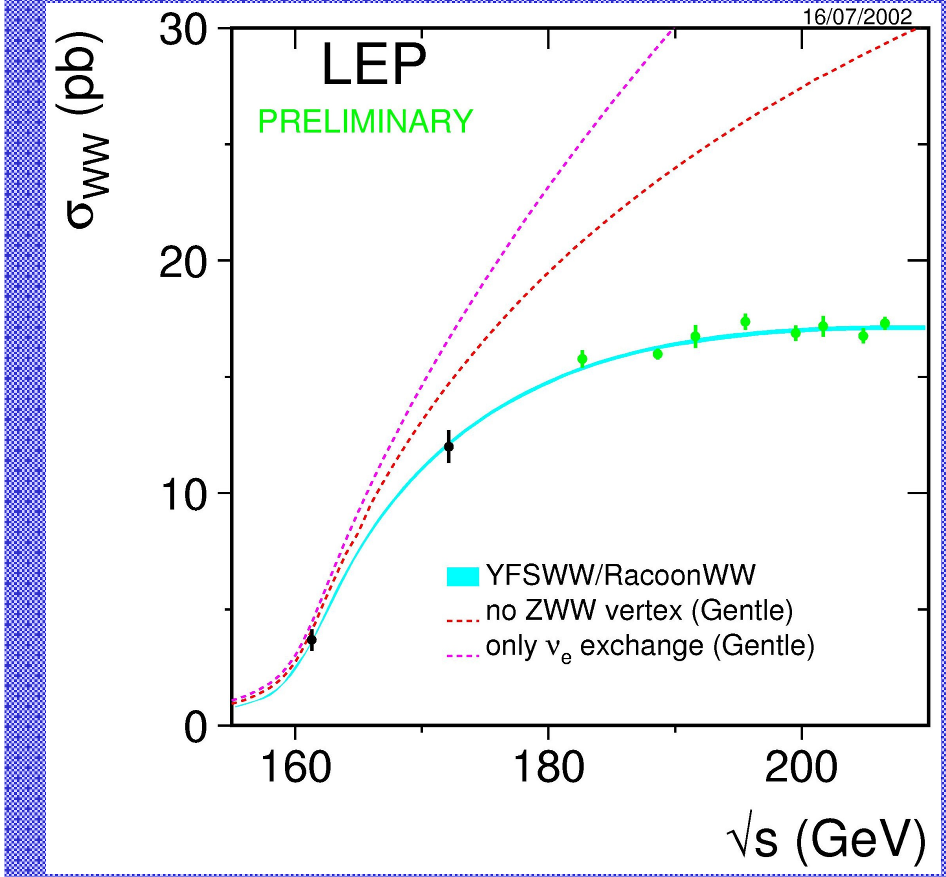


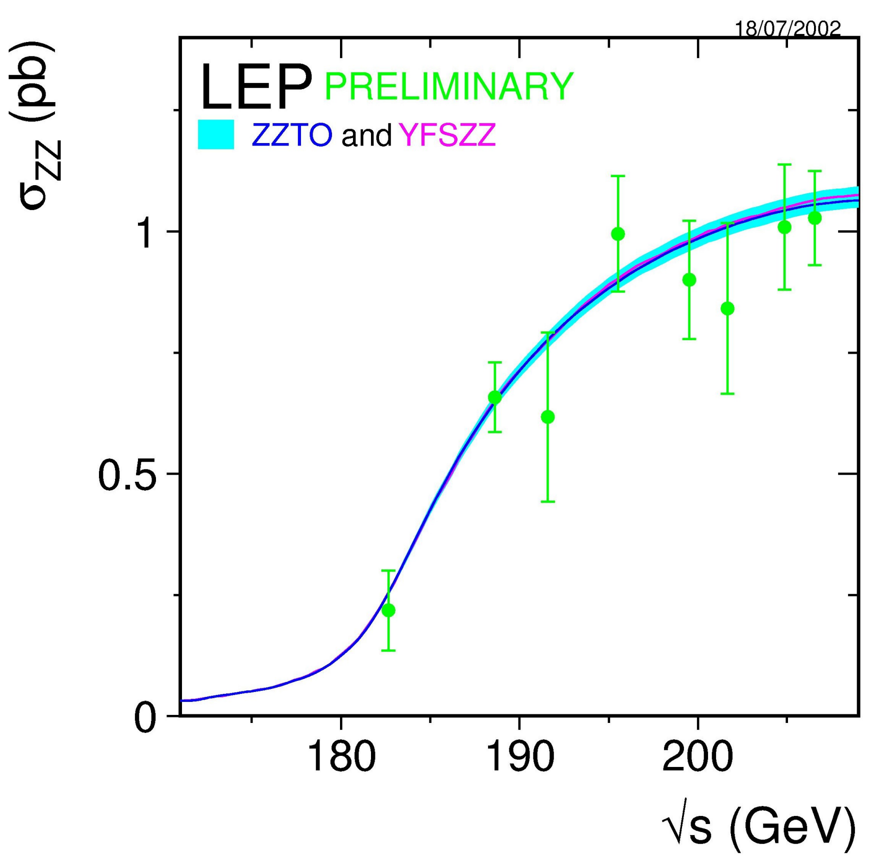
LEP II: Boson Pair Production

- Total cross sections

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

$e^+e^- \to ZZ$

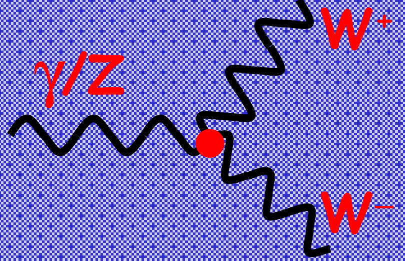


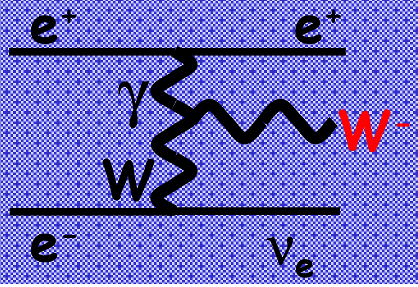


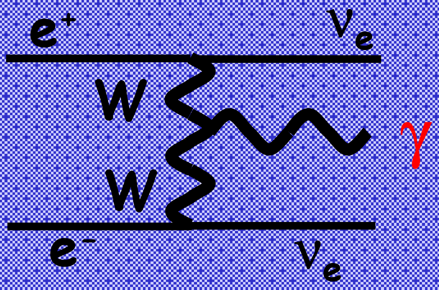
→ ZWW & γWW vertices exist → no ZZZ or γZZ vertex

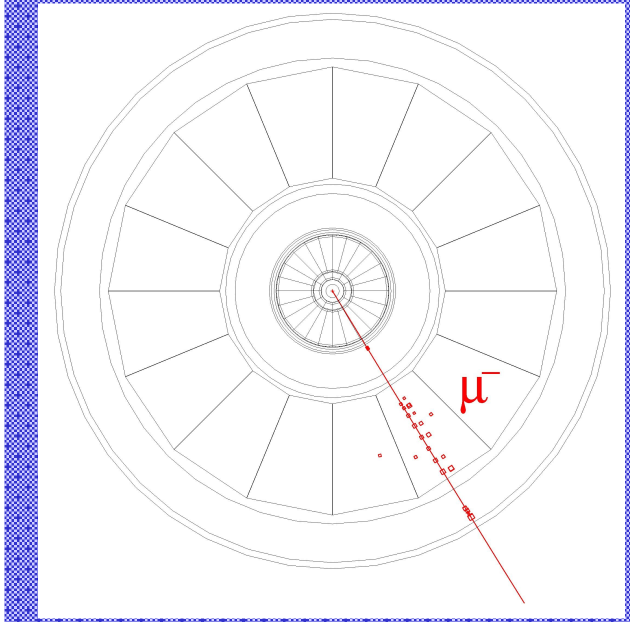
Measurement of ZWW & γWW Couplings:

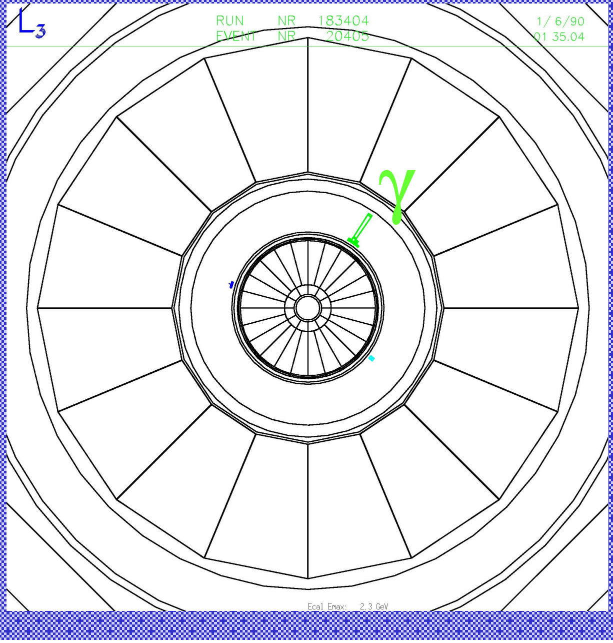
- o total WW cross section
- o differential WW cross sections
- o single W & photon events



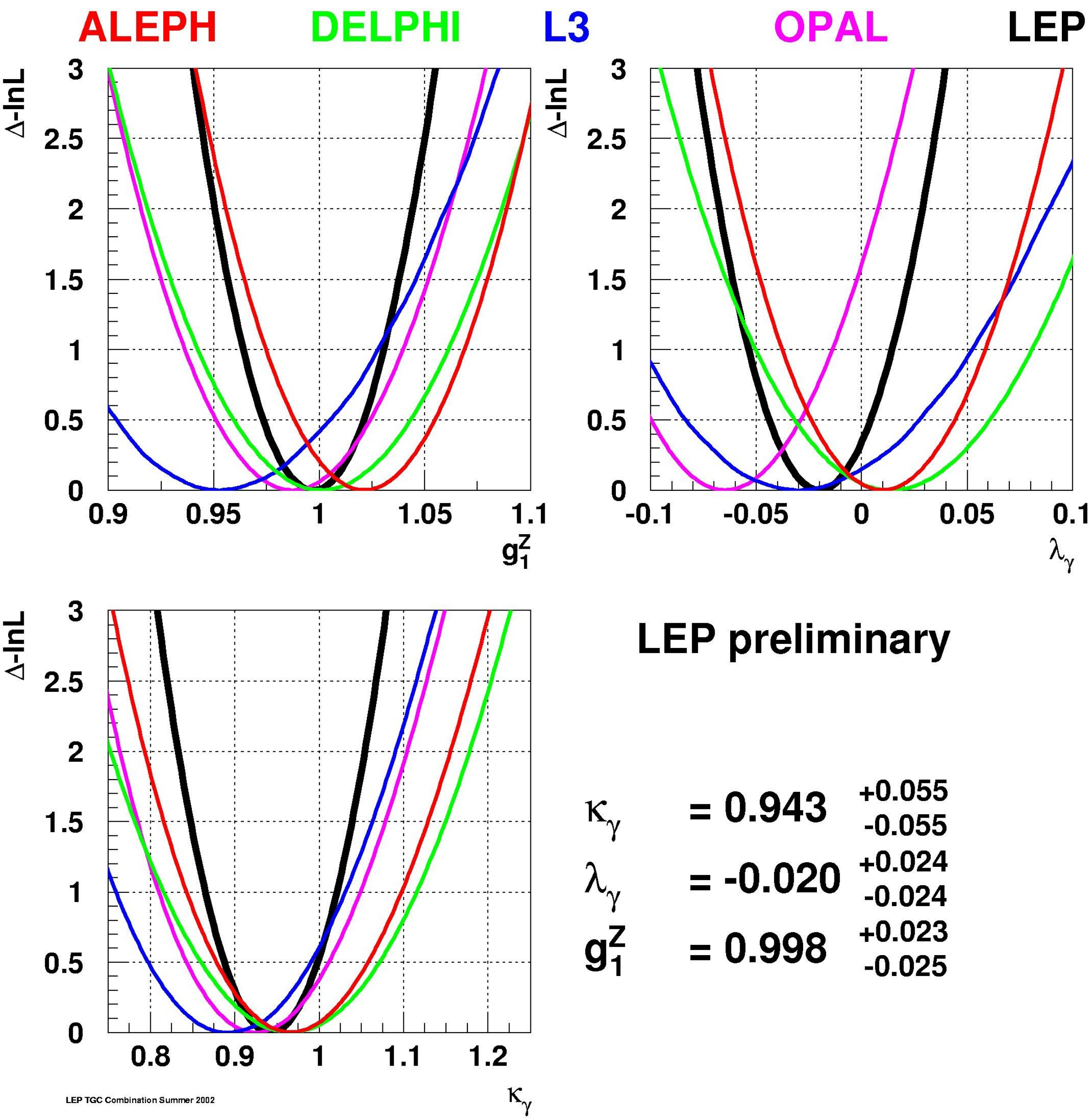



e^+
ν_e
W
γ
W
e^-
ν_e




L3
RUN NR 183404
EVENT NR 20405
1/ 6/90
01 35.04
γ
Ecal Emax: 2.3 GeV

Results on Triple Boson Couplings



LEP preliminary

$\kappa_\gamma = 0.943^{+0.055}_{-0.055}$

$\lambda_\gamma = -0.020^{+0.024}_{-0.024}$

$g_1^Z = 0.998^{+0.023}_{-0.025}$

SM values:

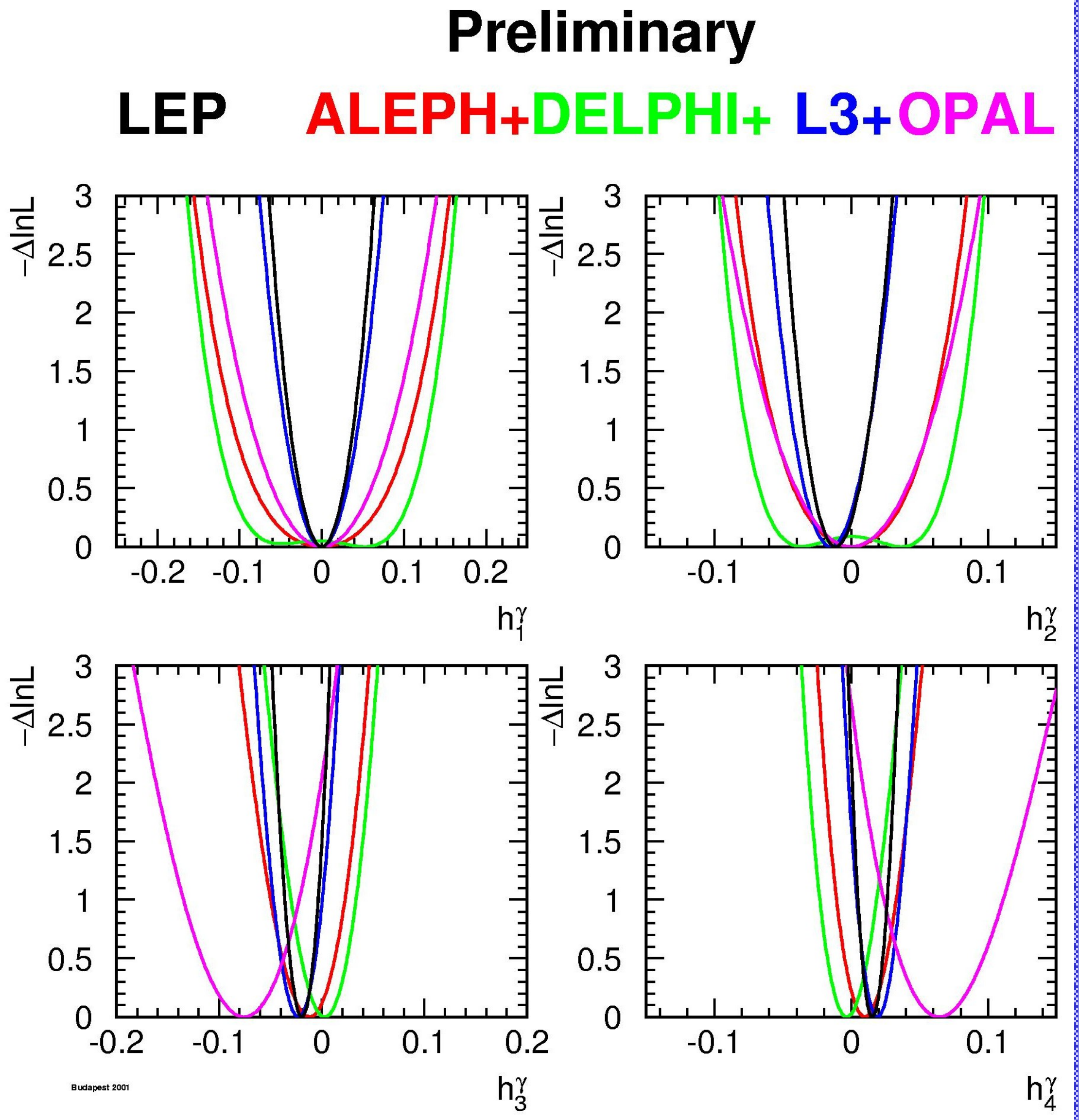
$\kappa_\gamma = 1$

$\lambda_\gamma = 0$

$g_1^Z = 1$

Measurement of TGCs involving the W to few %

Results on TGCs of neutral gauge bosons



SM: all 4 parameters vanish

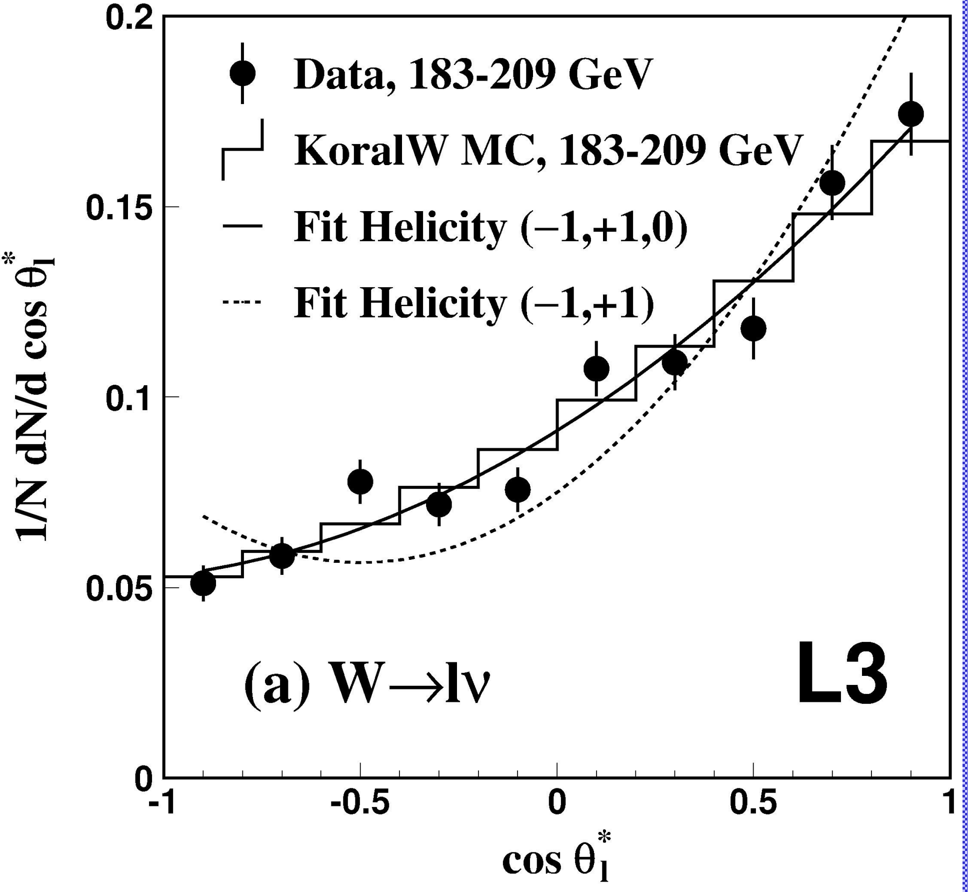
Experimentally confirmed on % level

W Polarization

Massive gauge bosons have three polarization states

Lepton (quark) decay angle in W rest frame θ^* :

- o $(1 \pm \cos\theta^*)^2$ transverse
- o $\sin^2\theta^*$ longitudinal



Fraction of long. W in $e^+e^- \to W^+W^-$

$F_0 = 0.218 \pm 0.031$

(SM pred.: 0.24)

Tevatron (CDF):
Long. W in top decays

$F_0 = 0.91 \pm 0.52$

(SM pred.: 0.7)

LEPII: The Mass of the W

$e^+e^- \rightarrow W^+W^-$ events:

- o use invariant mass spectra
- o and kinematic constraints

$$\sum \vec{p} = 0 \qquad \sum E = \sqrt{s}$$

$\Rightarrow$ fully hadronic & semi-leptonic channels useable

$e^+e^- \rightarrow W^+W^- \rightarrow qqqq$

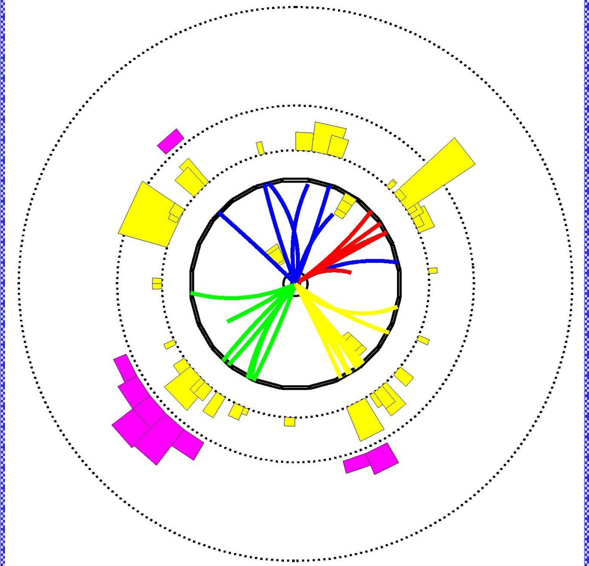
$\rightarrow ql\nu \quad (l = e, \mu, \tau)$

≈ 10 k events/expt.

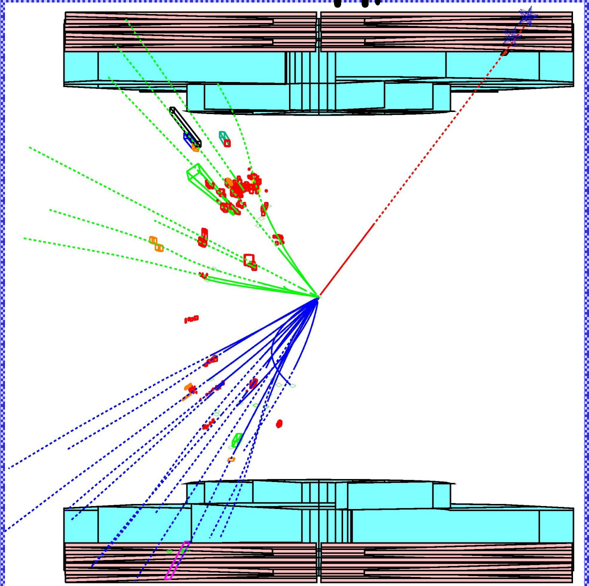
- o Absolute energy scale given by LEP beam energy

$\Delta E_b \approx \pm$ 17 MeV

$e^+e^- \rightarrow qqqq$

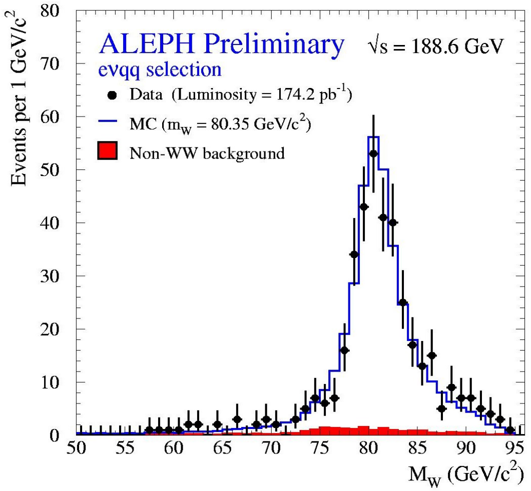


$e^+e^- \rightarrow qq\mu\nu$

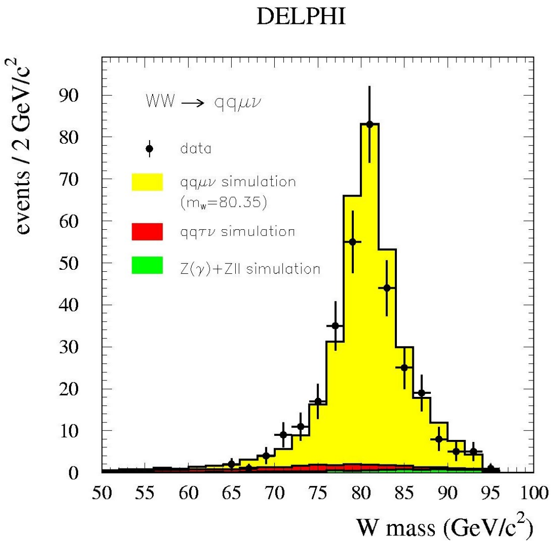


Sample spectra:

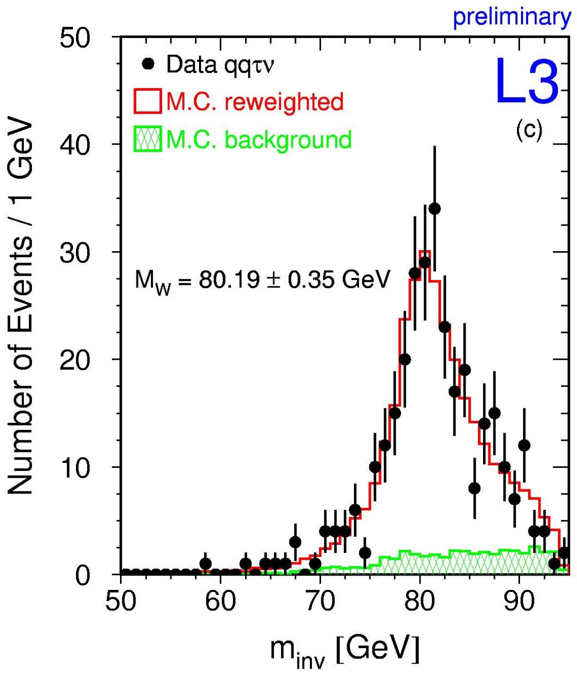
$WW \rightarrow q\bar{q}\, e\nu$



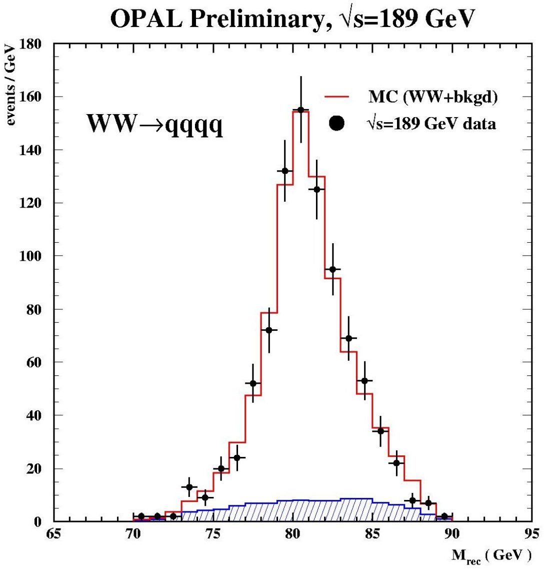
$WW \rightarrow q\bar{q}\, \mu\nu$



$WW \rightarrow q\bar{q}\, \tau\nu$



$WW \rightarrow q\bar{q}\, q\bar{q}$



m_W Result from LEPII

Problems in $W^+W^- \rightarrow qqqq$

- *Colour reconnection*
- *Bose-Einstein correlations*

o **no experimental evidence**

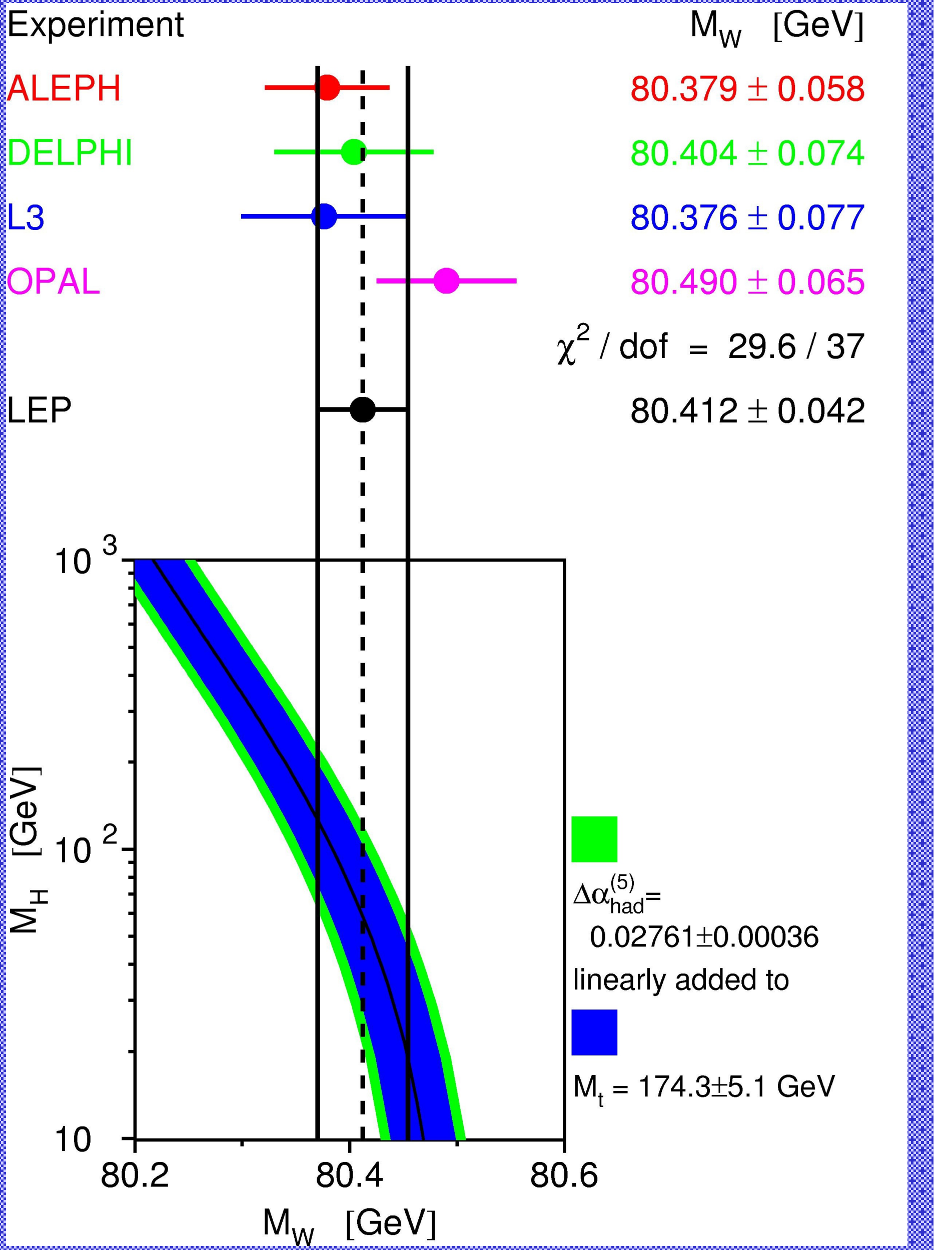
$\Delta m_W(qqqq\text{-}qql\nu) = 22 \pm 43$ MeV

o **but dominant sys. error in qqqq channel** *O(100 MeV)*

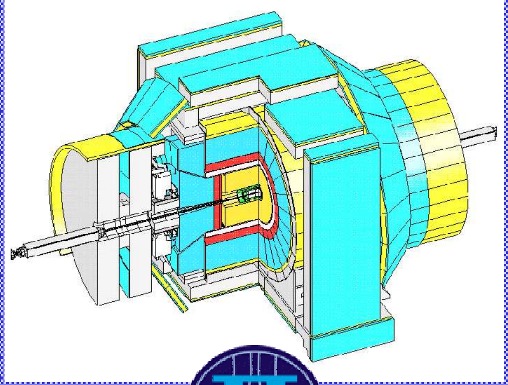
Combined LEP result (prelim.):

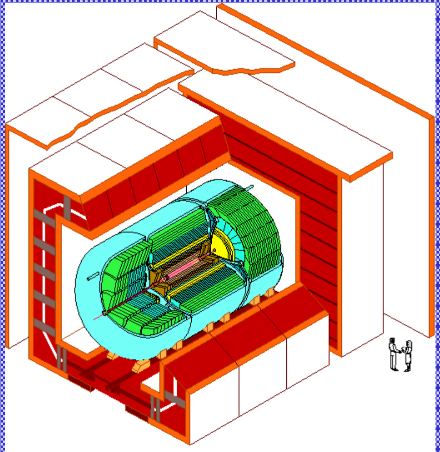
$m_W = 80.412 \pm 0.042$ *GeV*

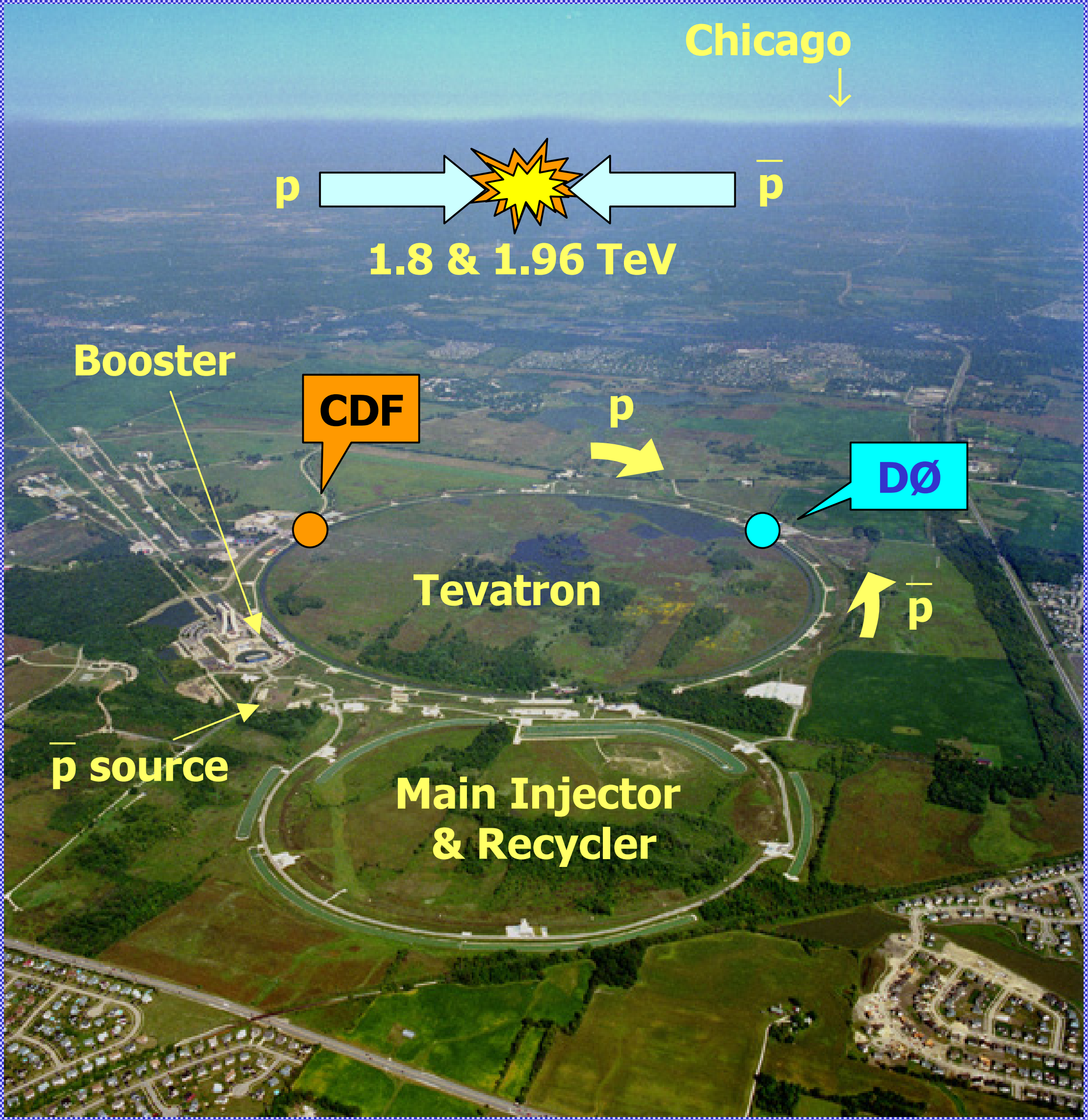
$\Gamma_W = 2.150 \pm 0.091$ *GeV*



SM Results from the Tevatron Experiments





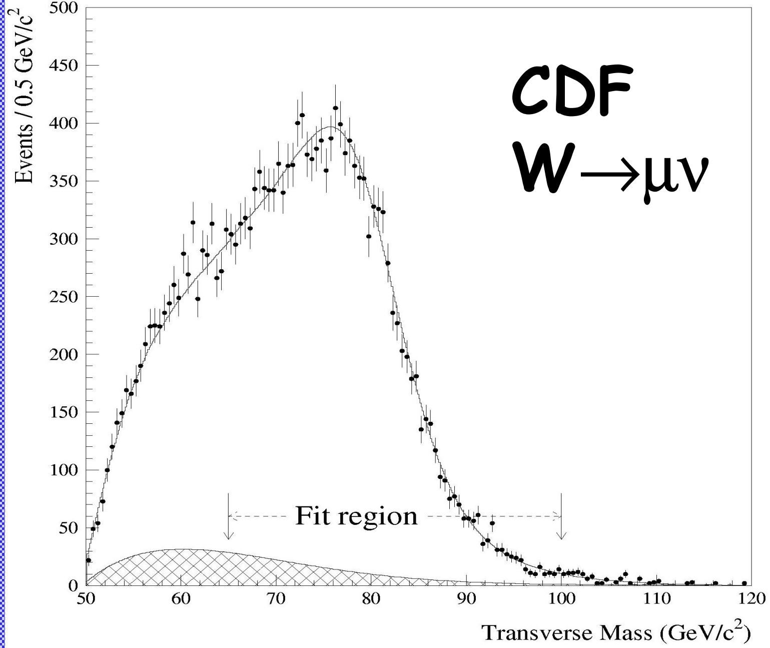

Chicago
p
$\bar{p}$
1.8 & 1.96 TeV
Booster
CDF
p
DØ
Tevatron
$\bar{p}$
$\bar{p}$ source
Main Injector
& Recycler

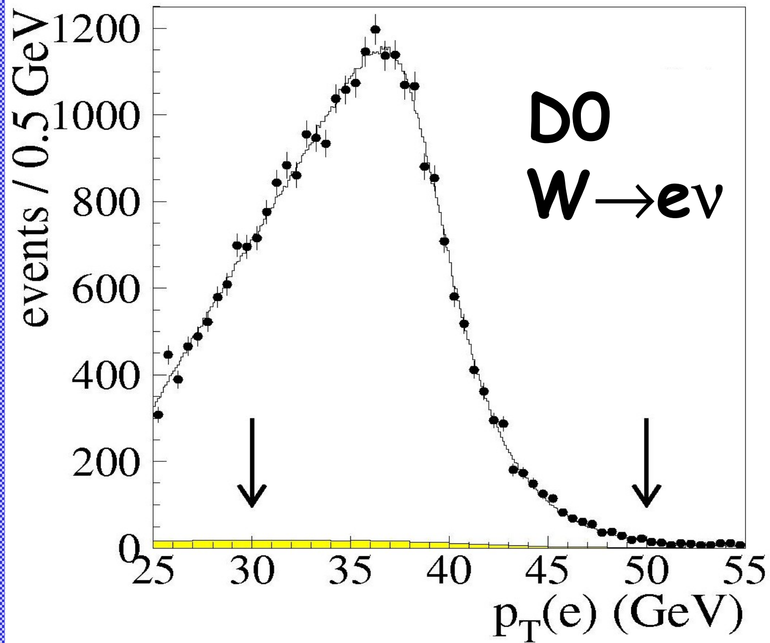
Tevatron Part I: The W-Boson

- Run I:
  ≈ 50k events/expt.
- W mass from fits to p_T, m_T spectra
- lepton energy scale from Z decays

Combined Tevatron result:

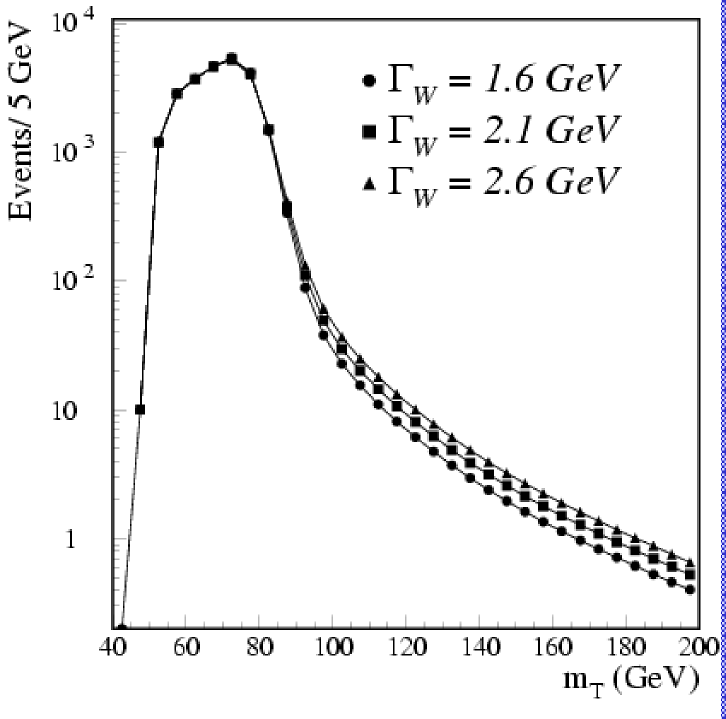
$m_W = 80.454 \pm 0.059$ GeV

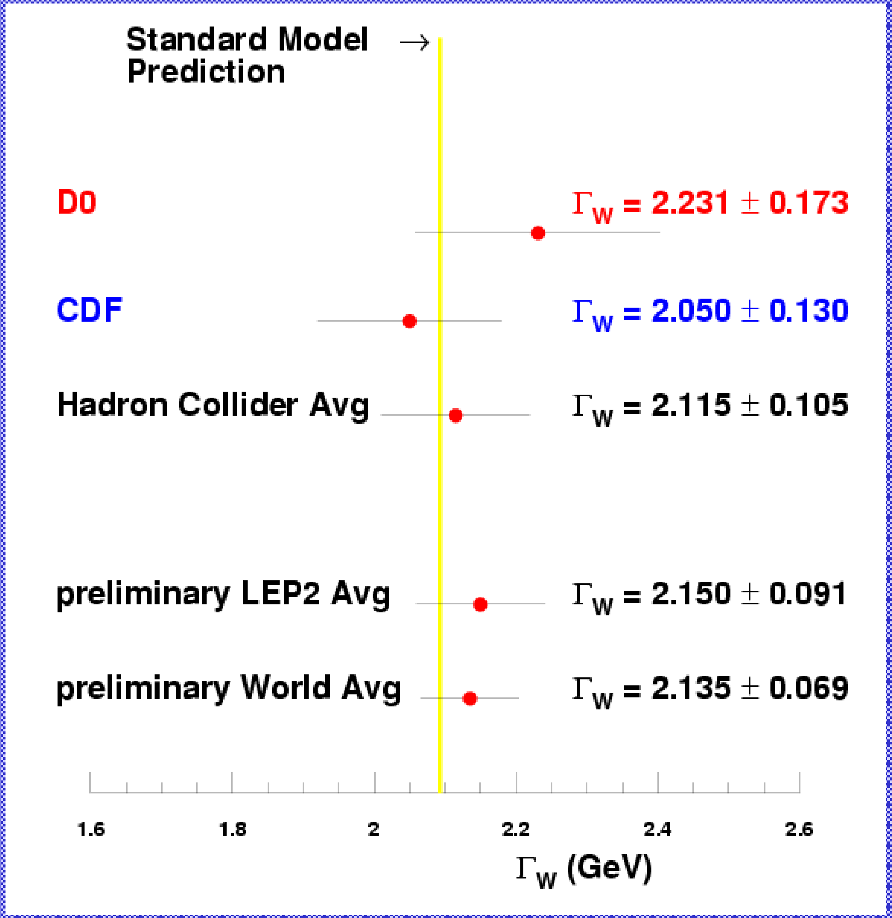




The Width of the W

- direct measurement from m_T spectra:





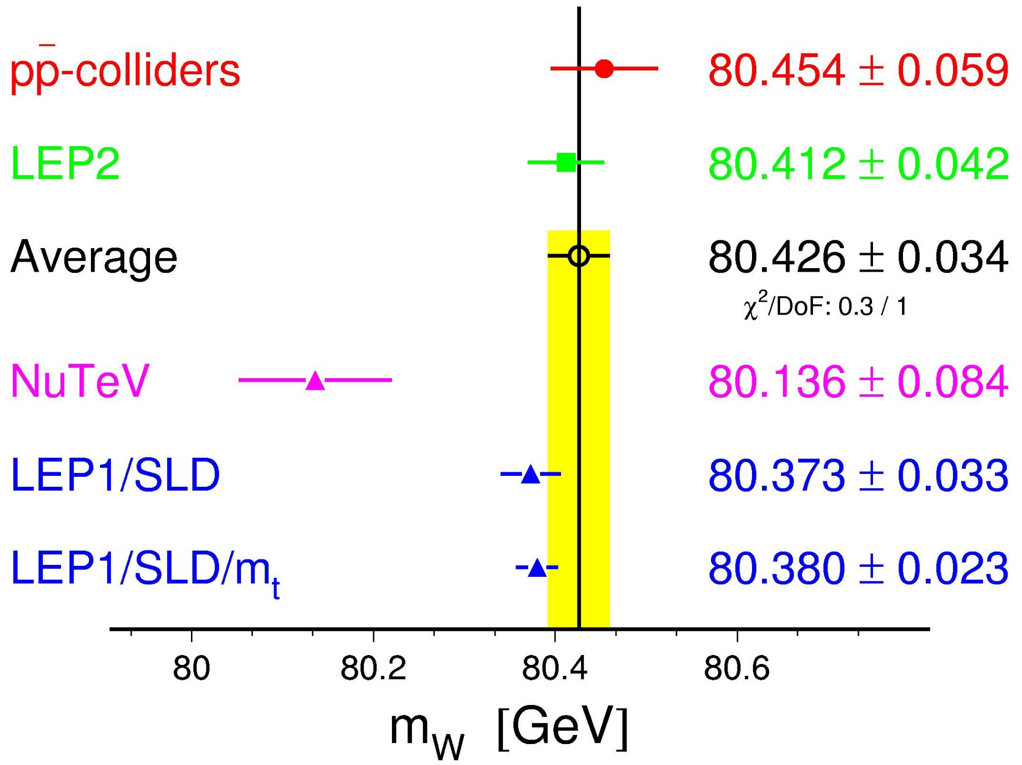
- indirect measurement:

$$R = \frac{\sigma(p\bar{p} \rightarrow W + X) \times BR(W \rightarrow l\upsilon)}{\sigma(p\bar{p} \rightarrow Z + X) \times BR(W \rightarrow ll)}$$

$$= \frac{\sigma(W)}{\sigma(Z)} \times \frac{\Gamma_Z}{\Gamma_{Z \rightarrow ll}} \times \frac{\Gamma(W \rightarrow l\upsilon)}{\Gamma_W}$$

⇒ $\Gamma_W = 2.171 \pm 0.051\ GeV$

Comparison W Mass at LEP & Tevatron



- o *good agreement of direct W mass measurements in pp- and e^+e^--collisions*

- o indirect measurement at LEP I & SLD through couplings:

$$\sin^2\vartheta_W = 1 - m_W^2 / m_Z^2$$

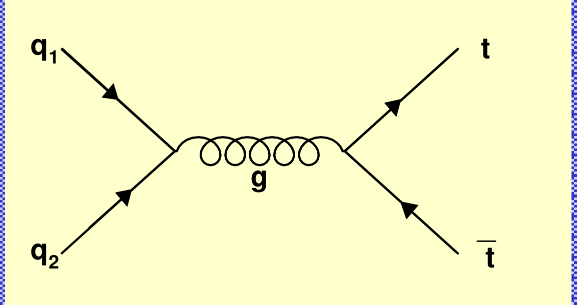
→ SM is correct at tree-level

or: ρ = 1 + rad. corr.

Tevatron Part II: The Top-Quark

o Production

qq → tt (90%)

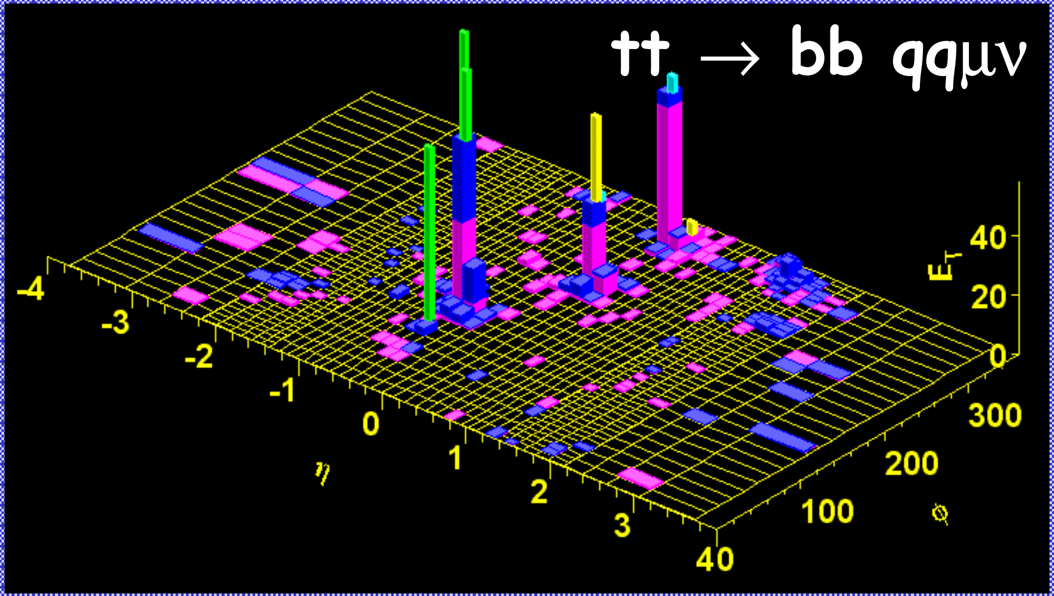


o Decay

t → Wb (100%)

Signature depends on W decays:

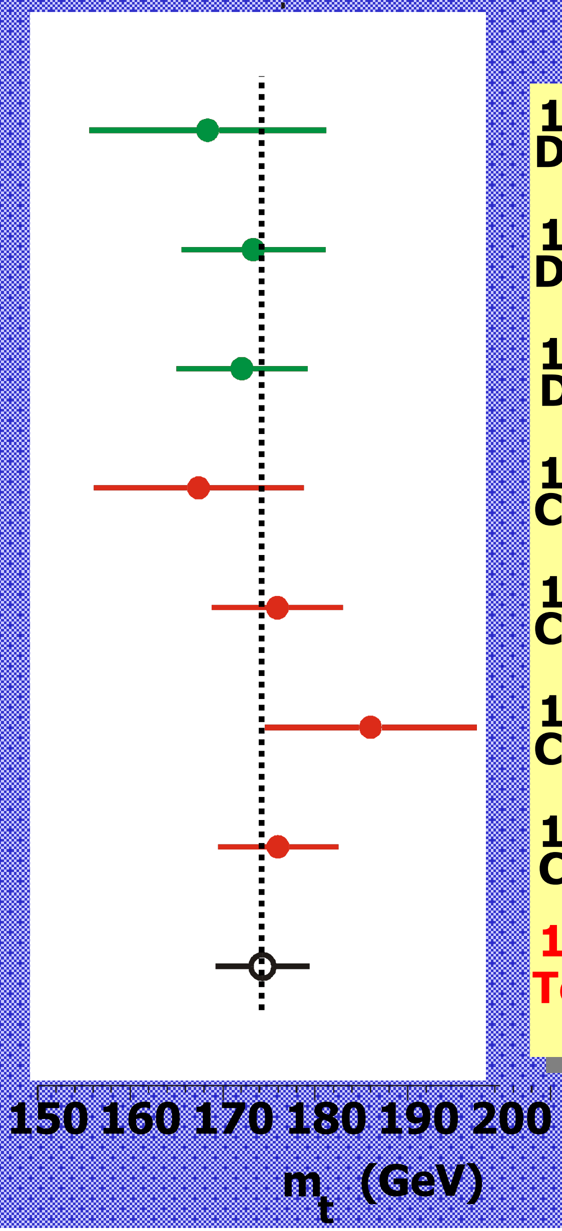
WW → qq qq
→ qq lν
→ lν lν


tt → bb qqμν

Run I: ≈ 100 events/expt.

Top Mass Results from Tevatron

RunI: CDF & D0



168.4 ± 12.8 GeV
D0 ll PRL 80, 2063 (1998)

173.3 ± 7.8 GeV
D0 lj PRD 58, 52001 (1998)

172.1 ± 7.1 GeV
D0 combined

167.4 ± 11.4 GeV
CDF ll PRL 82, 271 (1999)

176.1 ± 7.4 GeV
CDF lj PRL 80 2767 (1998)

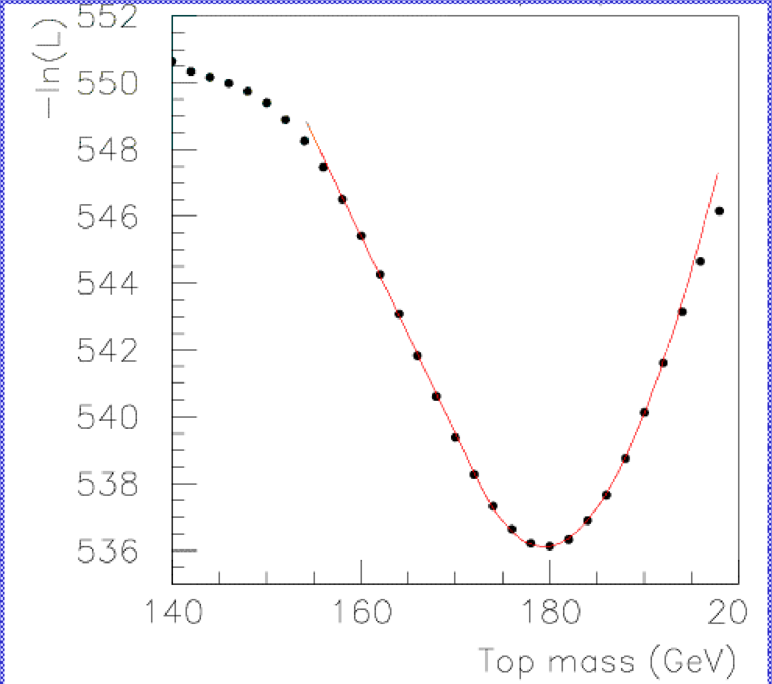
186.0 ± 11.5 GeV
CDF jj PRL 79, 1992 (1997)

176.1 ± 6.6 GeV
CDF combined

174.3 ± 5.1 GeV
Tevatron FERMILAB-TM-2084

Future improvements on m_t

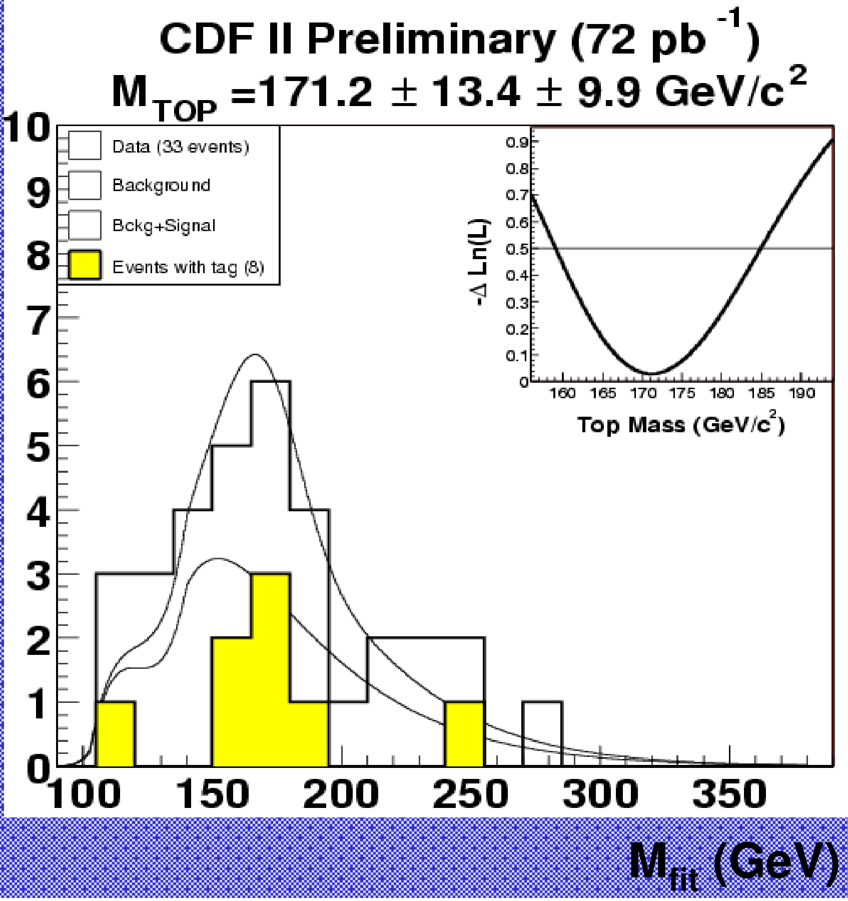
- Improved analysis, e.g. D0 run I data:



$m_t = 179.9 \pm 3.6(\text{stat})$ GeV

- Run IIa data (2 fb^{-1}): 4000 events/expt. ⇒ 2-3 GeV/expt.

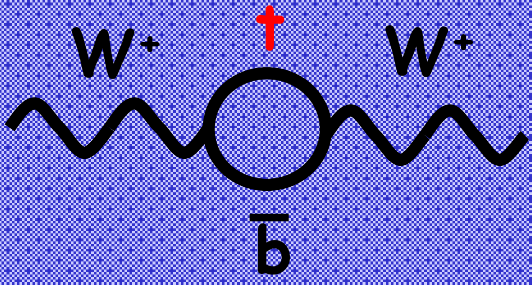
First run II data:


CDF II Preliminary (72 pb^{-1})

$M_{TOP} = 171.2 \pm 13.4 \pm 9.9$ GeV/c^2

Comparison Top Mass at LEP & Tevatron

- Indirect measurement of m_t at LEP & SLD leading contribution to weak rad. corrections:



$\Delta r_W \propto (m_t^2 - m_b^2)$

From precision Z observables:

$$m_t = 171^{+11}_{-9}\ \mathrm{GeV}$$

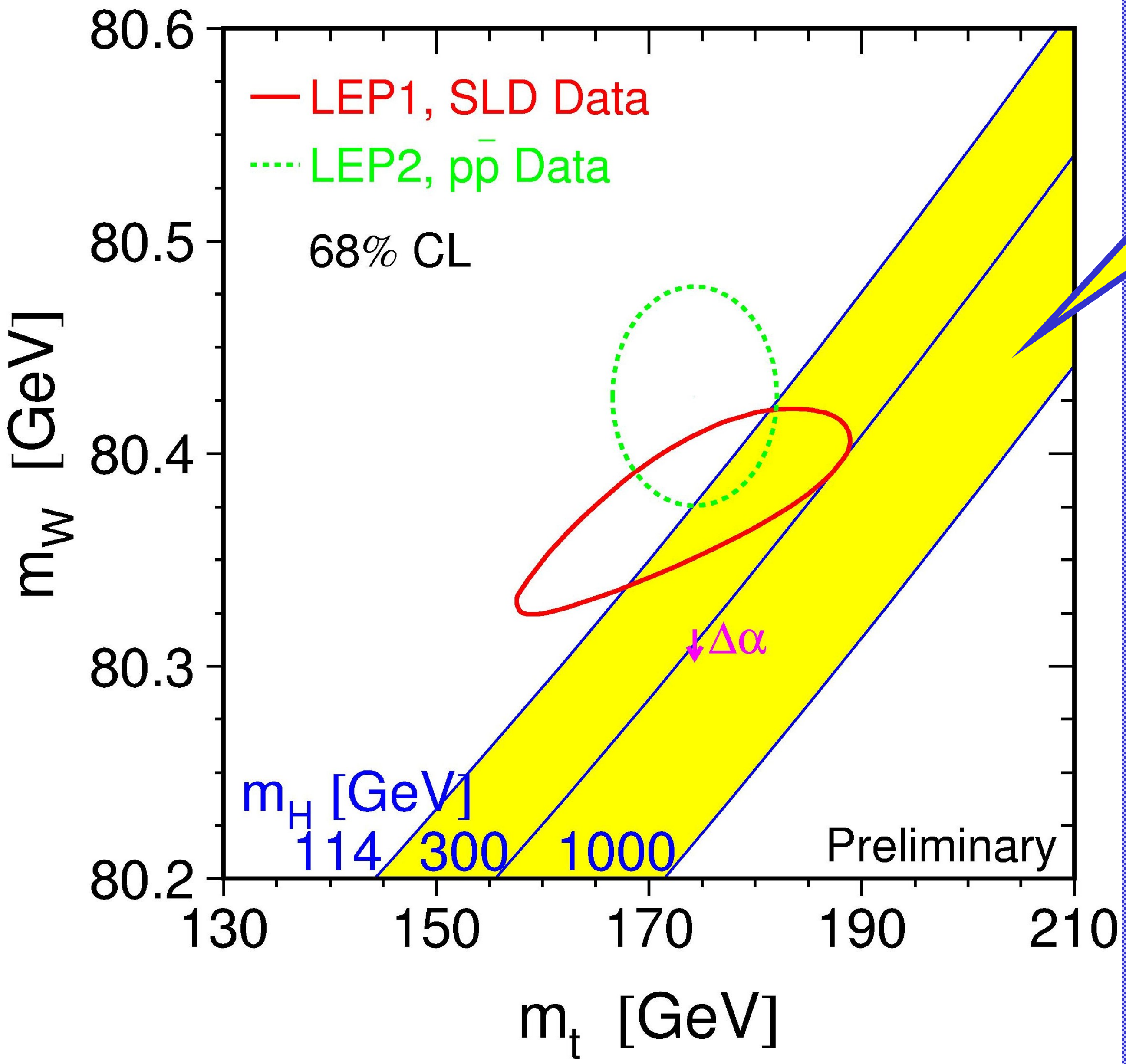
- Compare to direct measurement:

$$m_t = 174.3 \pm 5.1\ \mathrm{GeV}$$

→ SM is correct at one-loop-level

This is the DISCOVERY of LEP & SLD

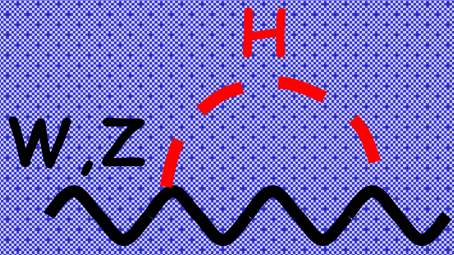
Comparison direct & indirect mass measurements:



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

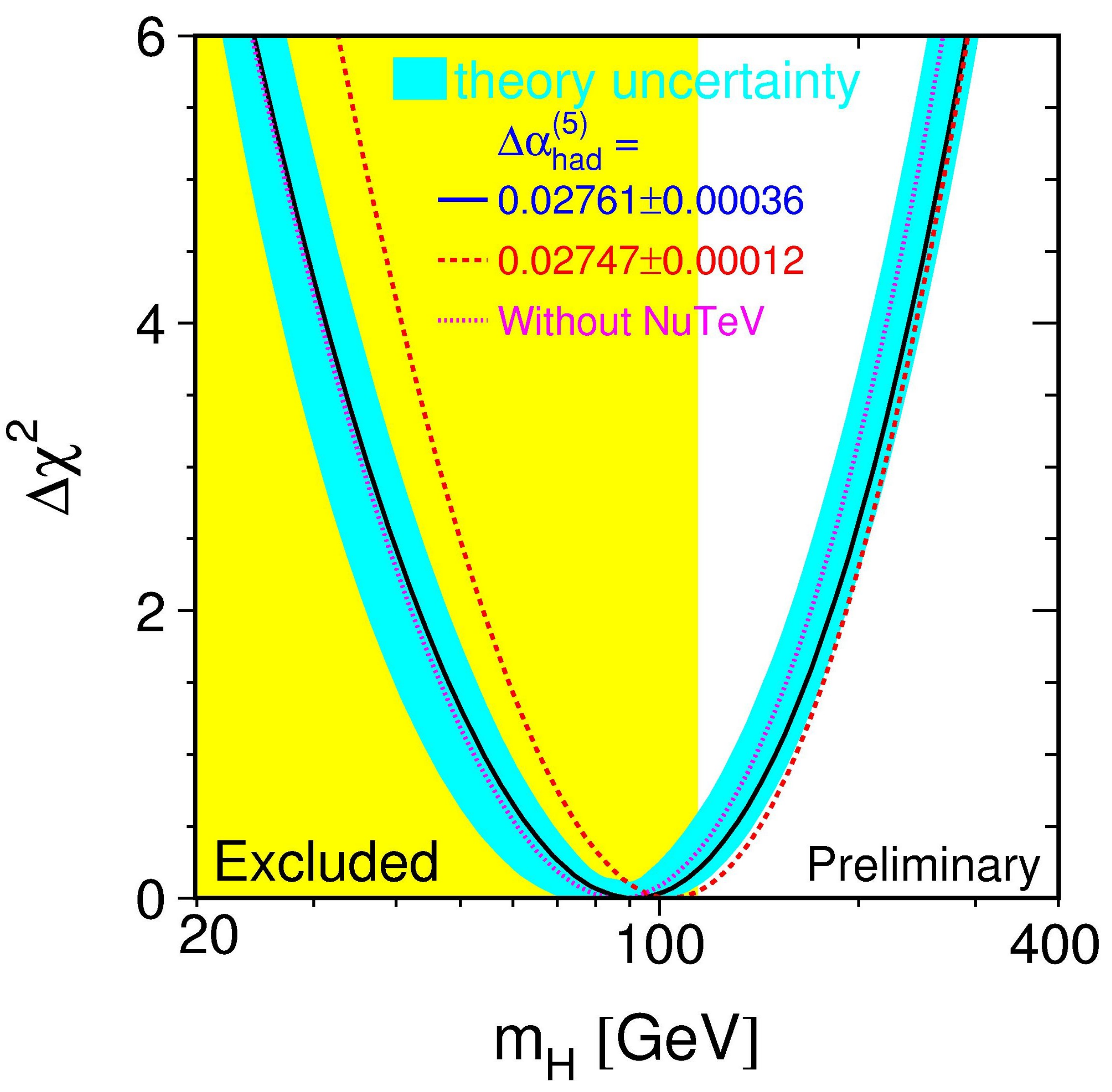
$1-\Delta r \approx$
$(1-\Delta\alpha)(1-\Delta r_W)$

Sub-leading contribution to Δr_W:



$\propto \log m_H$

The Higgs Mass from Weak Radiative Corrections:



$$\log m_H/\mathrm{GeV} = 1.96^{+0.21}_{-0.23}$$

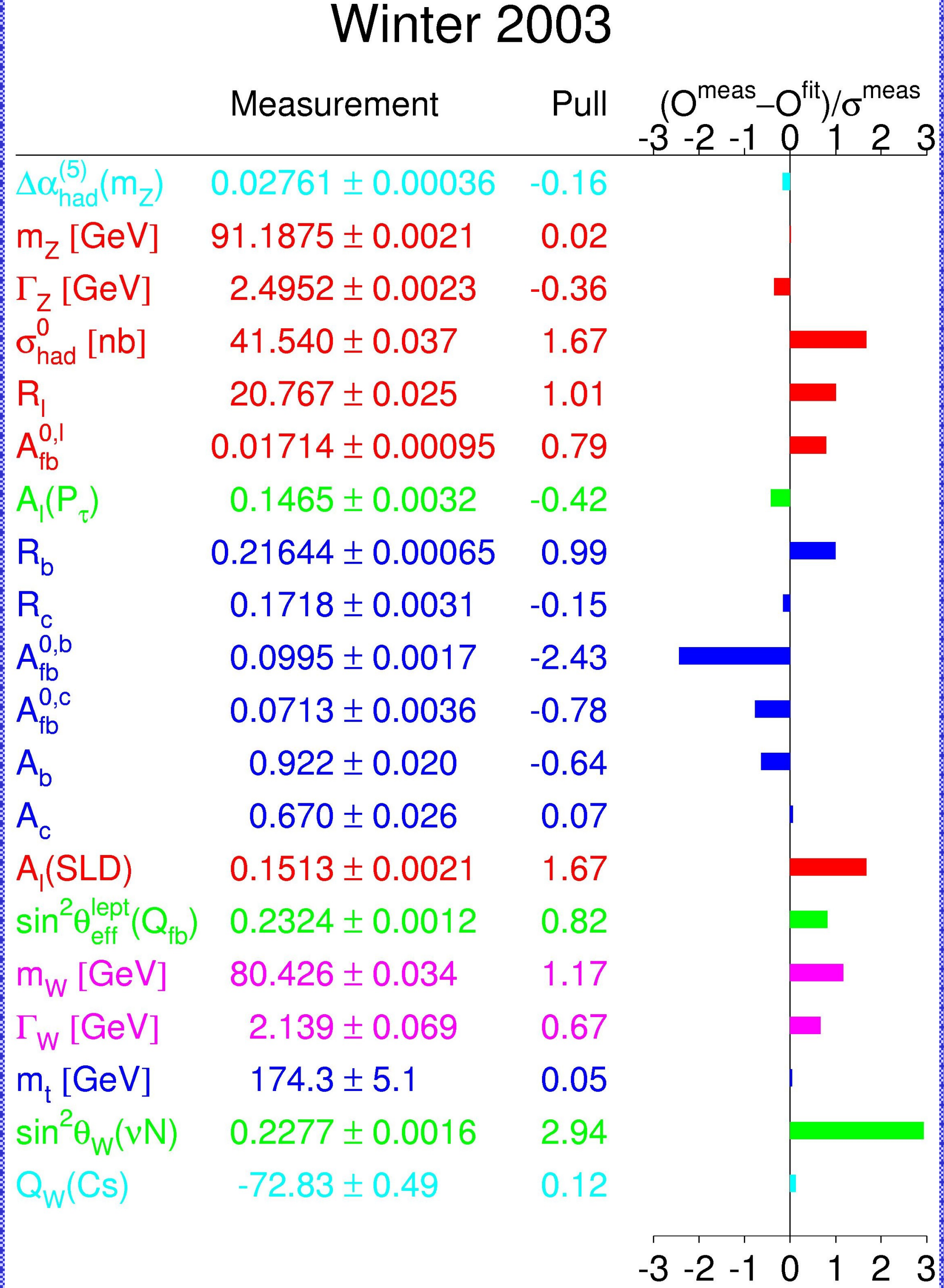
$$m_H = 91^{+58}_{-37}\ \mathrm{GeV}$$

95% *CL* upper limit

m_H < 211 GeV

Details of the Fit:

$\chi^2/\mathrm{dof} = 25.5/15$



Winter 2003

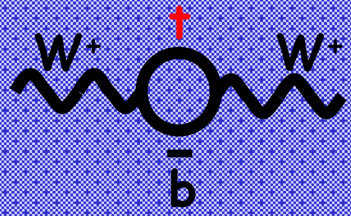
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
Q_W(Cs)	-72.83 ± 0.49	0.12

Conclusions & Outlook:

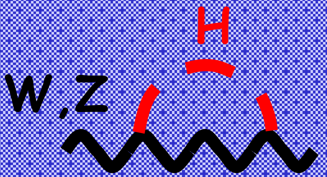
The 1990ies: the decade of precision EW physics

LEP, SLD, Tevatron

o SM correct to one-loop-level



⇒ prediction for Higgs mass



$m_H < 211$ GeV

After final LEP II analysis and Tevatron run II (2 fb^{-1}):

o improved W mass $\Delta m_W \approx \pm$ 15 - 20 MeV
o improved top mass $\Delta m_t \approx \pm$ 2 GeV