Testing the Standard Model at LEP

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Dave Charlton
University of Birmingham

- Z^0 Parameters & Couplings to Fermions
- High-Energy Fermion-Pair Production
- W Mass
- Other W Physics
- Combining the Above
- The Standard Model Higgs

Important Details

The measurements reported here are often preliminary – and may not reliably be noted as such

The LEP electroweak working group, together with the SLD electroweak and heavy flavour working groups, compiles and averages LEP/SLD electroweak data; Members of D0 also assist in preparation of averages with D0 triple-gauge coupling measurements

Without their work, the task of rapporteurs would be hugely more difficult

All the results and many of the plots shown here come from the LEPEWWG averages for Moriond 98 – plus additional material from D.Ward's talk in Jerusalem

Credit is due to them all

D. Abbaneo, J. Alcaraz, P. Antilogus, R. Batley, T. Behnke, G. Bella, B. Bertucci, J.J. Blaising, A. Blondel, D.G. Charlton, R. Clare, S. Dutta, M. Elsing, R. Faccini, D. Glenzinski, M.W. Grünewald, A. Gurtu, J.B. Hansen, R.W.L. Jones, P. de Jong, J. Jousset T. Kawamoto, N. Kjaer, M. Kobel, E. Lançon, W. Lohmann, C. Mariotti, M. Martinez, C. Matteuzzi, M.N. Minard, K. Mönig, P. Molnar, A. Nippe, S. Olshevski, Ch. Paus, M. Pepe-Altarelli, S. Petzold, B. Pietrzyk, G. Quast, D. Reid, P. Renton, J.M. Roney, P. Sherwood, D. Strom, R. Sekulin, R. Tenchini, F. Teubert, M.A. Thomson, J. Timmermans, H. Wahlen, N.K. Watson, P. Wells;

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LEP Data

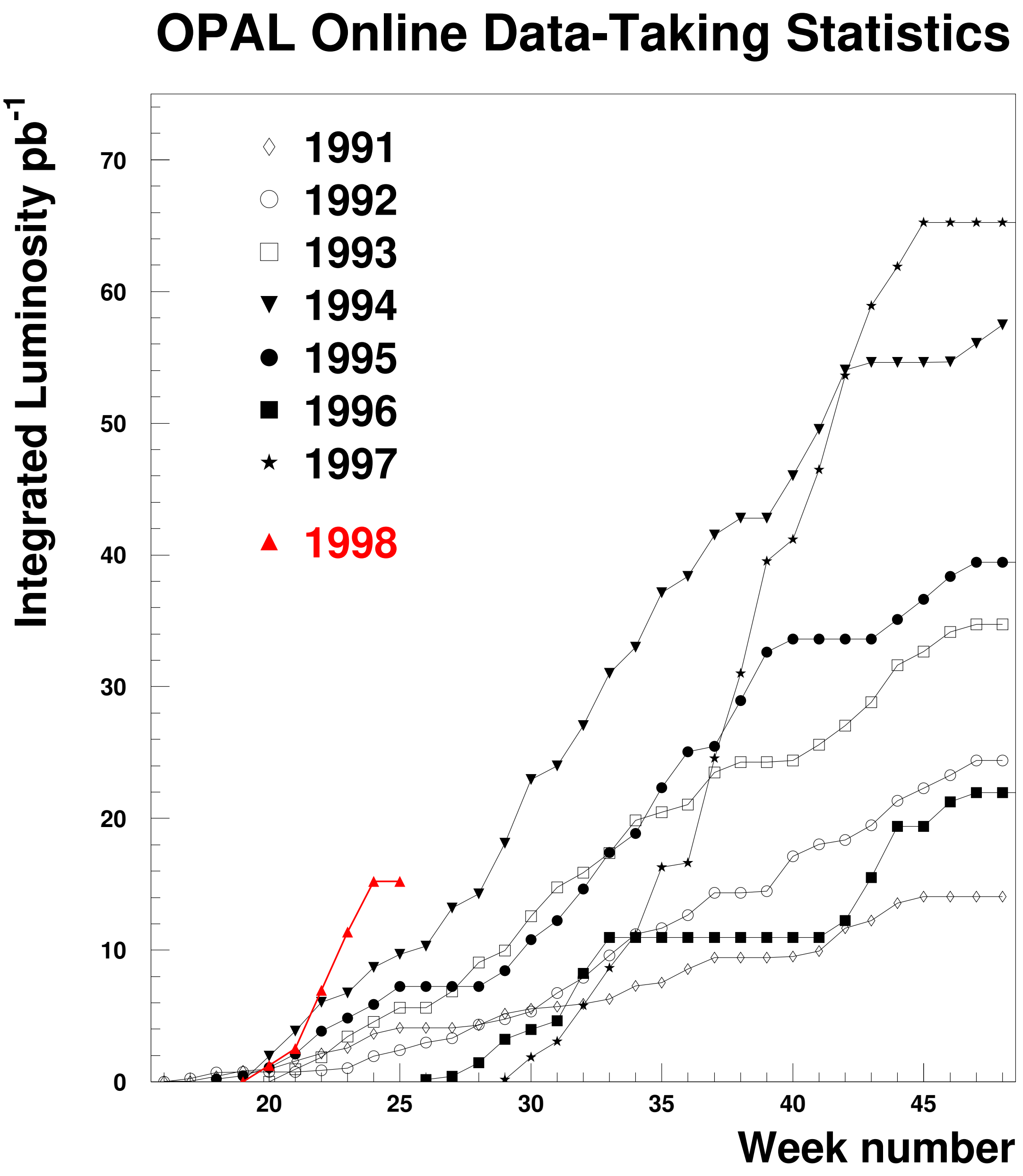
Two main phases of LEP operation:

- LEP-1 1989-1995: $\sim$5 million Z^0 per experiment
  - 160pb^{-1} of data, $\sim$40pb^{-1} taken at the sides of Z^0 peak

  Z physics at LEP is nearing completion

- LEP-2 1996-2000: $\sim$400-500 pb^{-1} per experiment
  - 10 pb^{-1} at $\sqrt{s} = 161$ GeV, 10 pb^{-1} at $\sqrt{s} = 171$ GeV
  - 60 pb^{-1} at $\sqrt{s} = 183$ GeV
  - 12 pb^{-1} at $\sqrt{s} = 189$ GeV, expect $\sim$150pb^{-1} during 1998

  W physics at LEP is maturing, still a long way to go


OPAL Online Data-Taking Statistics
Integrated Luminosity pb^{-1}
1991
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Week number

Precision Tests at the Z

- Inclusive fermion-pair cross-section vs $\sqrt{s} \implies m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}$
- Relative yields of different fermion-pair species f, Γ_f
- Asymmetry parameters, A_{FB}, $\mathcal{P}_\tau$

Simple relationships between observables and Z couplings at tree level:

$$\Gamma_f \sim ((g_V^f)^2 + (g_A^f)^2)$$

$$A_{\mathrm{FB}}^f \sim \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{f}};\, \mathcal{A}_{\mathrm{e}} = \frac{2 g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

Radiative corrections: modify these relationships, **but** the "Improved Born Approximation" (IBA) is a simple, and rather good approximation:

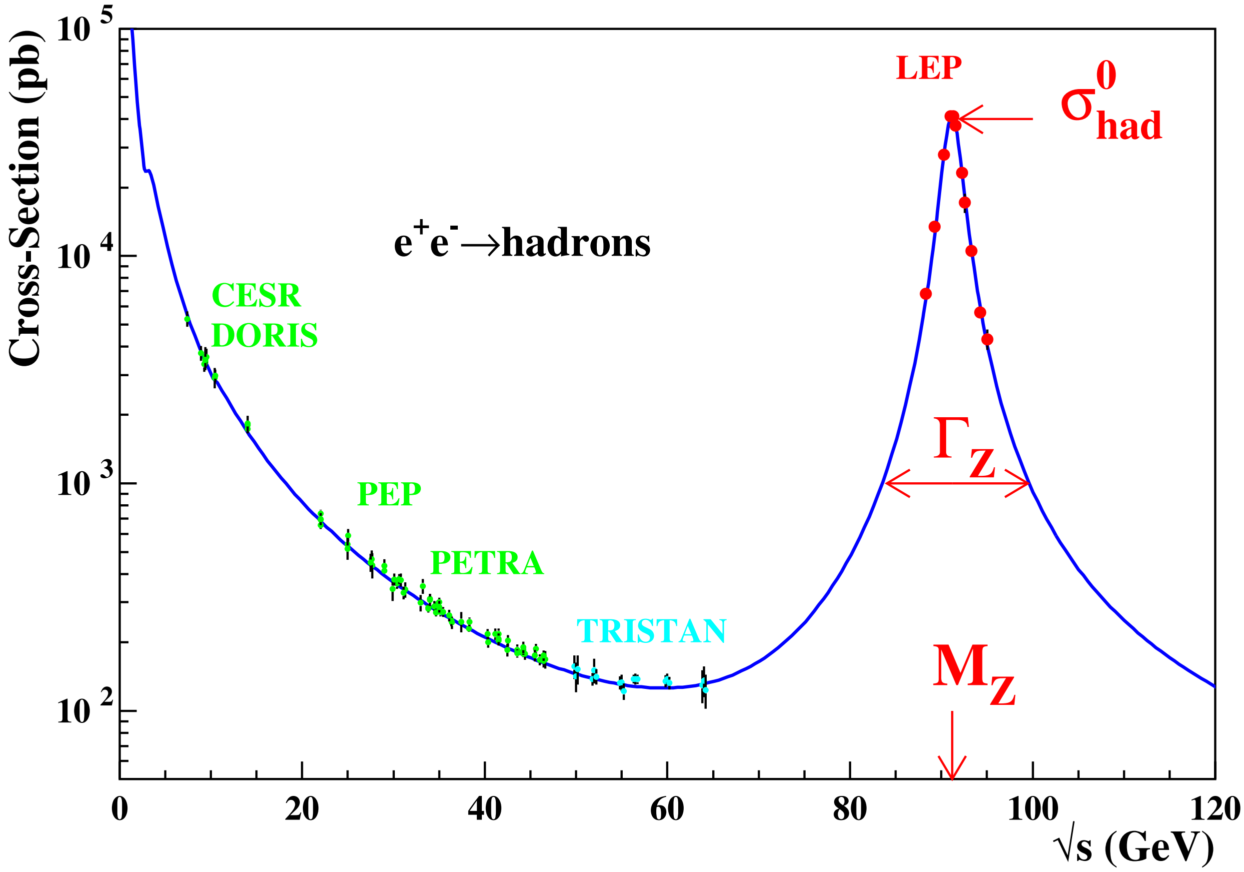
- Running α_{em}
- "Effective couplings" g in terms of $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\,f}$
- Running Z^0 width in propagator

Radiative corrections introduce dependence on m_{top}, m_{H}, different for different observables

LEP data sufficiently precise that IBA not really good enough!
For SM tests and fits need electroweak libraries (ZFITTER, TOPAZ0, BHM) including full structure of corrections

Even then, limited order of corrections – effect of missing higher orders quantified $\Longrightarrow$ see CERN 95-03

Z Mass and Width



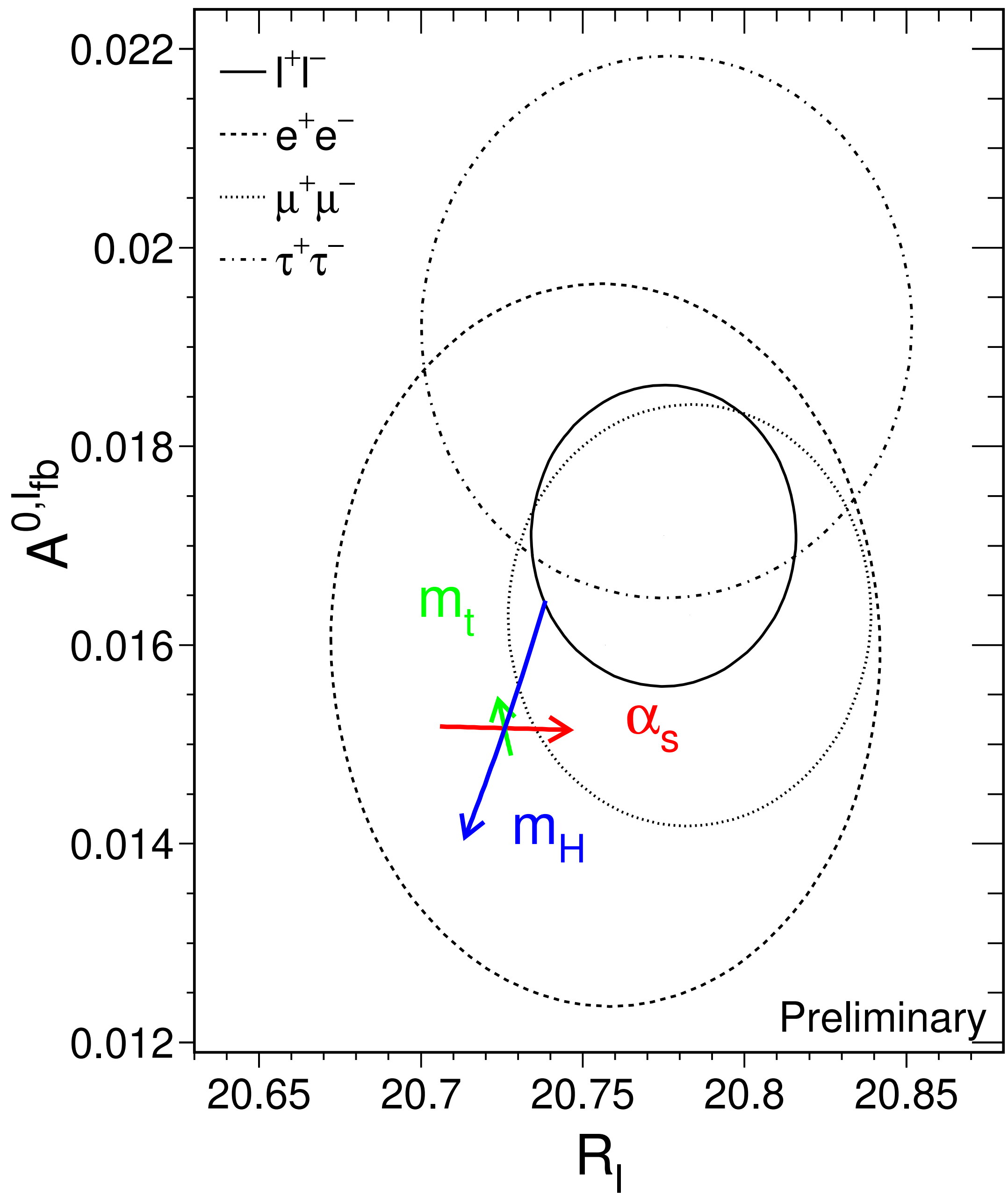
Critical issues:

- Off-peak statistics $\Longrightarrow$ Γ_Z error
- Uncertainty on luminosity for $\sigma^{\rm pole}_{\rm had}$
  – experimental and theoretical
- Detector acceptance understanding
- Absolute LEP energy scale for m_Z
- Relative LEP energy scale and beam energy spread for Γ_Z
  – big effort by LEP energy working group

Inclusive Leptonic Events

$\mathrm{Z}^0 \to \ell^+\ell^-$ cross-section, forward-backward cross-section asymmetry

$\Longrightarrow R_\ell = \Gamma_{\mathrm{had}}/\Gamma_\ell$, $A_{\mathrm{FB}}^{0,\ell}$ for $\ell = \mathrm{e}, \mu, \tau$



68% probability contours

Lepton universality test

Combined Lineshape Results

Combining hadron and lepton cross-sections and lepton asymmetries:

- Choose 9 variables with small correlations:

  $m_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}, \sigma^{\mathrm{pole}}_{\mathrm{had}},$
  $R_{\mathrm{e}}, R_{\mu}, R_{\tau},$
  $A^{0,\,\mathrm{e}}_{\mathrm{FB}}, A^{0,\,\mu}_{\mathrm{FB}}, A^{0,\,\tau}_{\mathrm{FB}}$

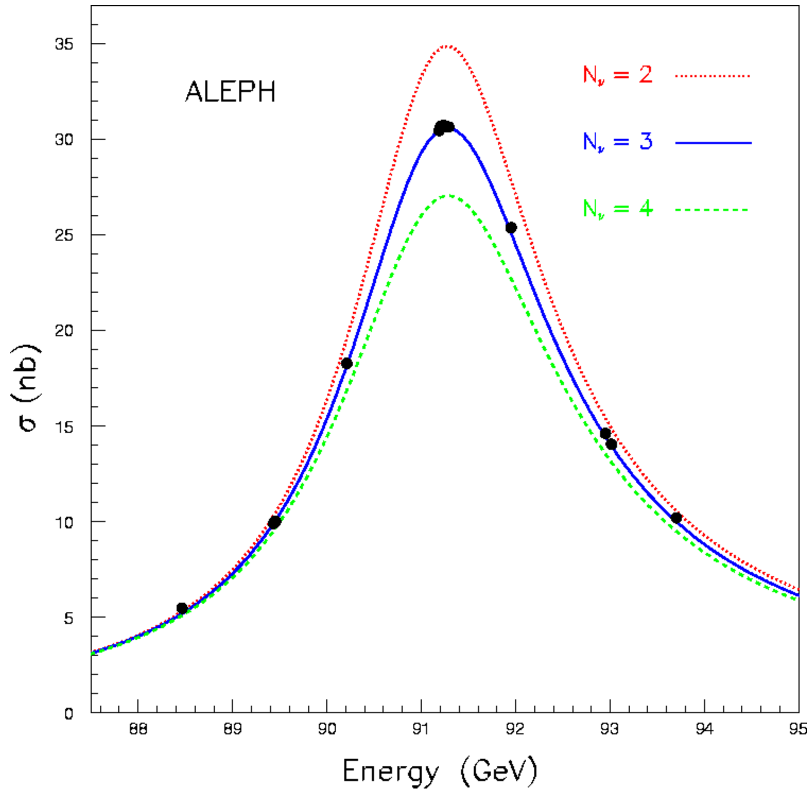
- Account for common errors (LEP energy, lumi. theory)

m_{Z} (GeV)	91.1867$\pm$0.0020
Γ_{Z} (GeV)	2.4948$\pm$0.0025
$\sigma^{\mathrm{pole}}_{\mathrm{had}}$ (nb)	41.486$\pm$0.053
R_{e}	20.757$\pm$0.056
R_{μ}	20.783$\pm$0.037
R_{τ}	20.823$\pm$0.050
$A^{0,\,\mathrm{e}}_{\mathrm{FB}}$	0.0160$\pm$0.0024
$A^{0,\,\mu}_{\mathrm{FB}}$	0.0163$\pm$0.0014
$A^{0,\,\tau}_{\mathrm{FB}}$	0.0192$\pm$0.0018

- Reduce to 5 variables by assuming L.U.

m_{Z} (GeV)	91.1867$\pm$0.0020
Γ_{Z} (GeV)	2.4948$\pm$0.0025
$\sigma^{\mathrm{pole}}_{\mathrm{had}}$ (nb)	41.486$\pm$0.053
R_{ℓ}	20.775$\pm$0.027
$A^{0,\ell}_{\mathrm{FB}}$	0.0171$\pm$0.0010

Invisible width: N_ν



Constrain number of light neutrino flavours:

- Extract $\Gamma_{\rm inv}/\Gamma_\ell = 5.960 \pm 0.022$
- Taking $(\Gamma_\nu/\Gamma_\ell)_{SM} = 1.991 \pm 0.001$
  $\Longrightarrow N_\nu = 2.993 \pm 0.011$

Alternatively, limit on additional invisible Z decay modes

- Assume $N_\nu = 3$, obtain $\Delta\Gamma_{\rm inv} < 2.9$ MeV at 95% CL.

Polarised Asymmetries

At LEP, polarised asymmetries accessible only in $Z^0 \to \tau^+\tau^-$:

$$\mathcal{P}_\tau = \frac{\sigma^L - \sigma^R}{\sigma^L + \sigma^R} = -\mathcal{A}_\tau$$

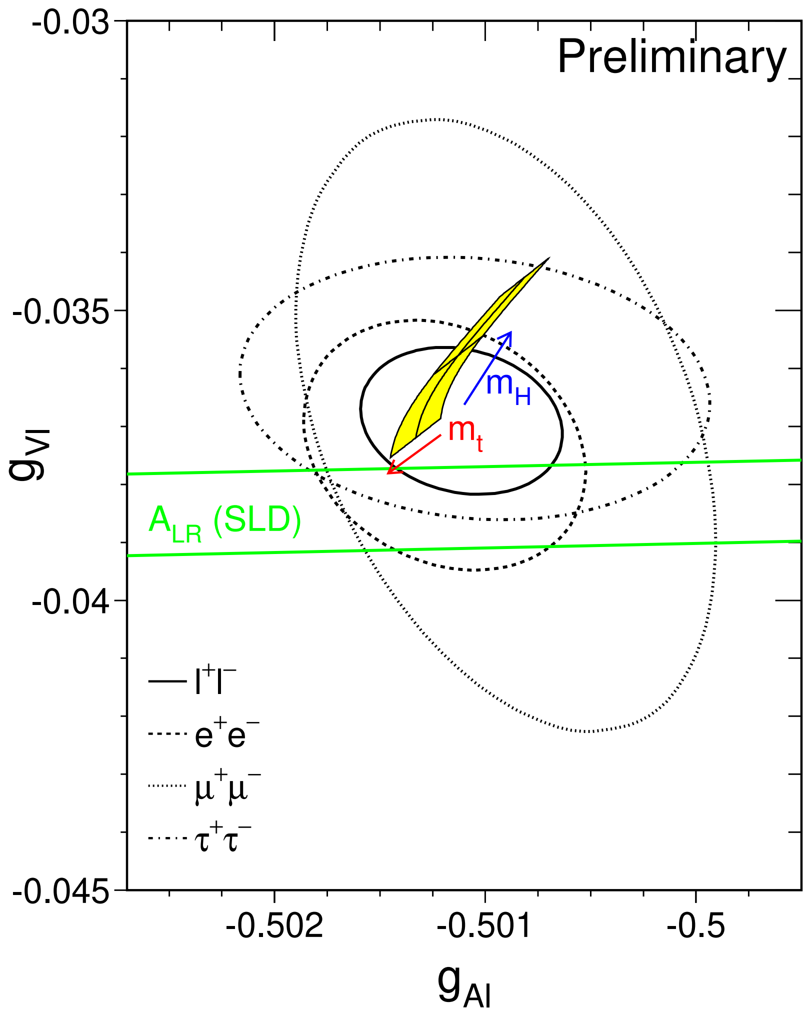
$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos\theta^2) + \mathcal{A}_e 2\cos\theta}{(1+\cos\theta^2) + \mathcal{A}_\tau\mathcal{A}_e 2\cos\theta}$$

At SLC, initial state e^- polarization is known

define $\sigma^L = \sigma(e^+e^-_L \to Z^0 \to X)$:

$$A_{LR} = \frac{\sigma^L - \sigma^R}{\sigma^L + \sigma^R} = \mathcal{A}_e$$

Observed $A_{LR} = \mathcal{P}_e\mathcal{A}_e$



68% probability contours

Z Decays to Heavy Quarks: I

Partial Z decay widths to $\mathrm{b\overline{b}}$ or $\mathrm{c\overline{c}}$ pairs:

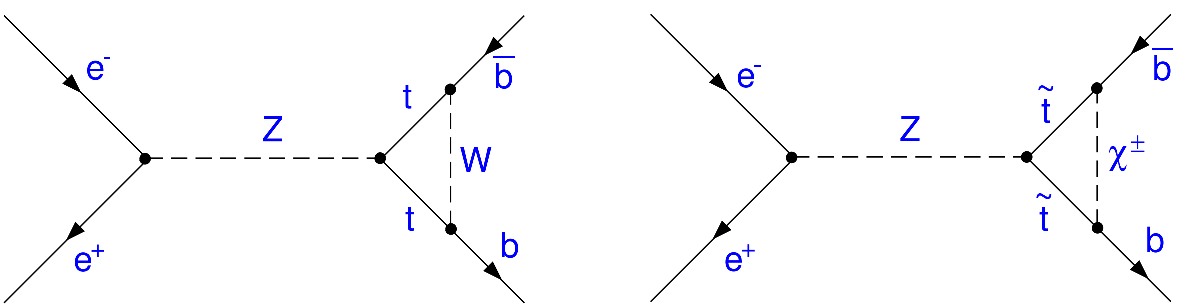
$$R_{\mathrm{Q}} = \frac{\sigma(\mathrm{e^+e^-} \to \mathrm{Q\overline{Q}})}{\sigma(\mathrm{e^+e^-} \to \mathrm{hadrons})} \simeq \frac{\Gamma(\mathrm{Z^0} \to \mathrm{Q\overline{Q}})}{\Gamma(\mathrm{Z^0} \to \mathrm{hadrons})}$$

(small corrections for γ and γ-$\mathrm{Z^0}$ interference)

Advantage of R_{Q}:

- Propagator and initial-state corrections cancel
- Sensitivity to vertex corrections

R_{b} case: “special” vertex corrections, SM or non-SM:



Z Decays to Heavy Quarks: II

Forward-backward asymmetries to heavy quarks:

$$A_{\mathrm{FB}}^{0,\mathrm{b}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{b}}$$

(similarly for c), and

$$\mathcal{A}_f = 2\frac{v_f a_f}{(v_f^2 + a_f^2)}$$

$$\frac{v_f}{a_f} = (1 - 4|Q_f|\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\,f})$$

SM expectation:

$$\begin{aligned}\mathcal{A}_{\mathrm{e}} &\approx 0.14\\ \mathcal{A}_{\mathrm{c}} &\approx 0.7\\ \mathcal{A}_{\mathrm{b}} &\approx 0.9\end{aligned}$$

($\Longrightarrow A_{\mathrm{FB}}^{\mathrm{b}}$ sensitive to $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\ell}$)

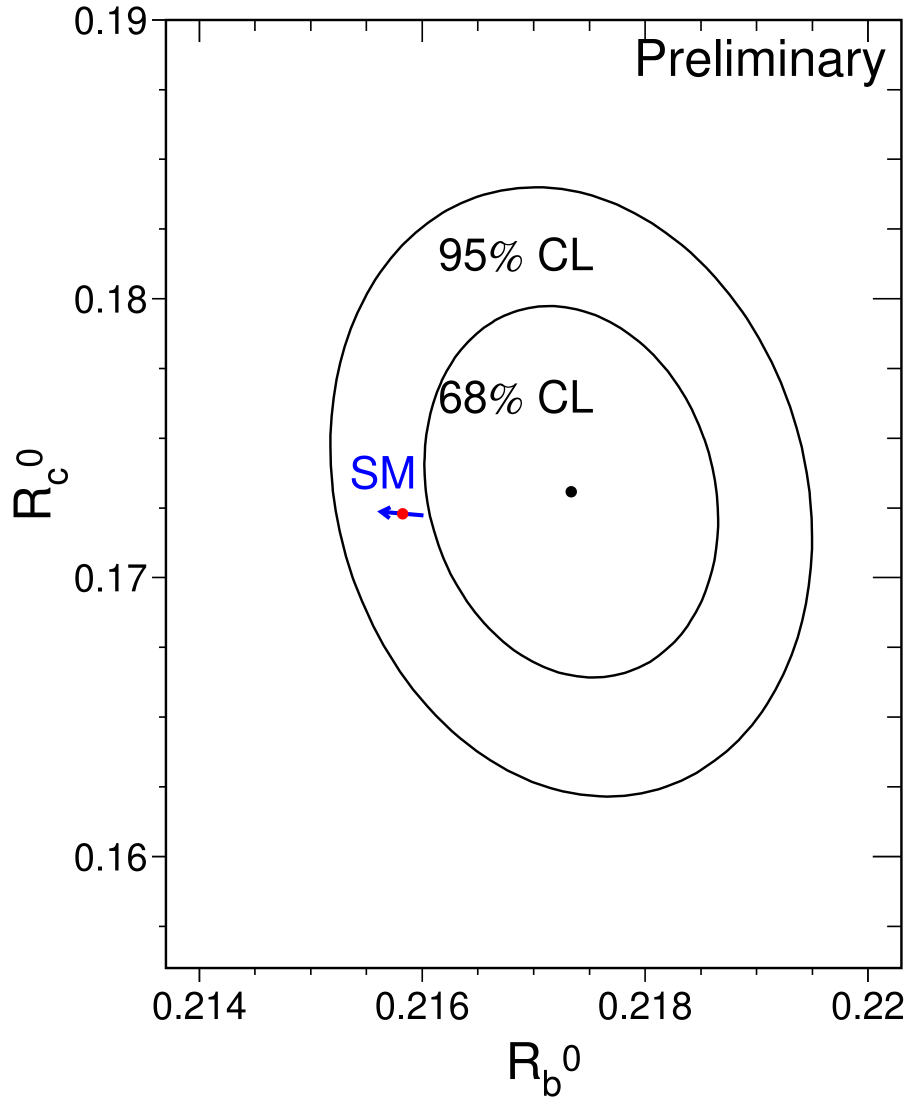
SLD measure also left-right forward-backward asymmetries

$\Longrightarrow$ $\mathcal{A}_{\mathrm{b}}$ and $\mathcal{A}_{\mathrm{c}}$ directly

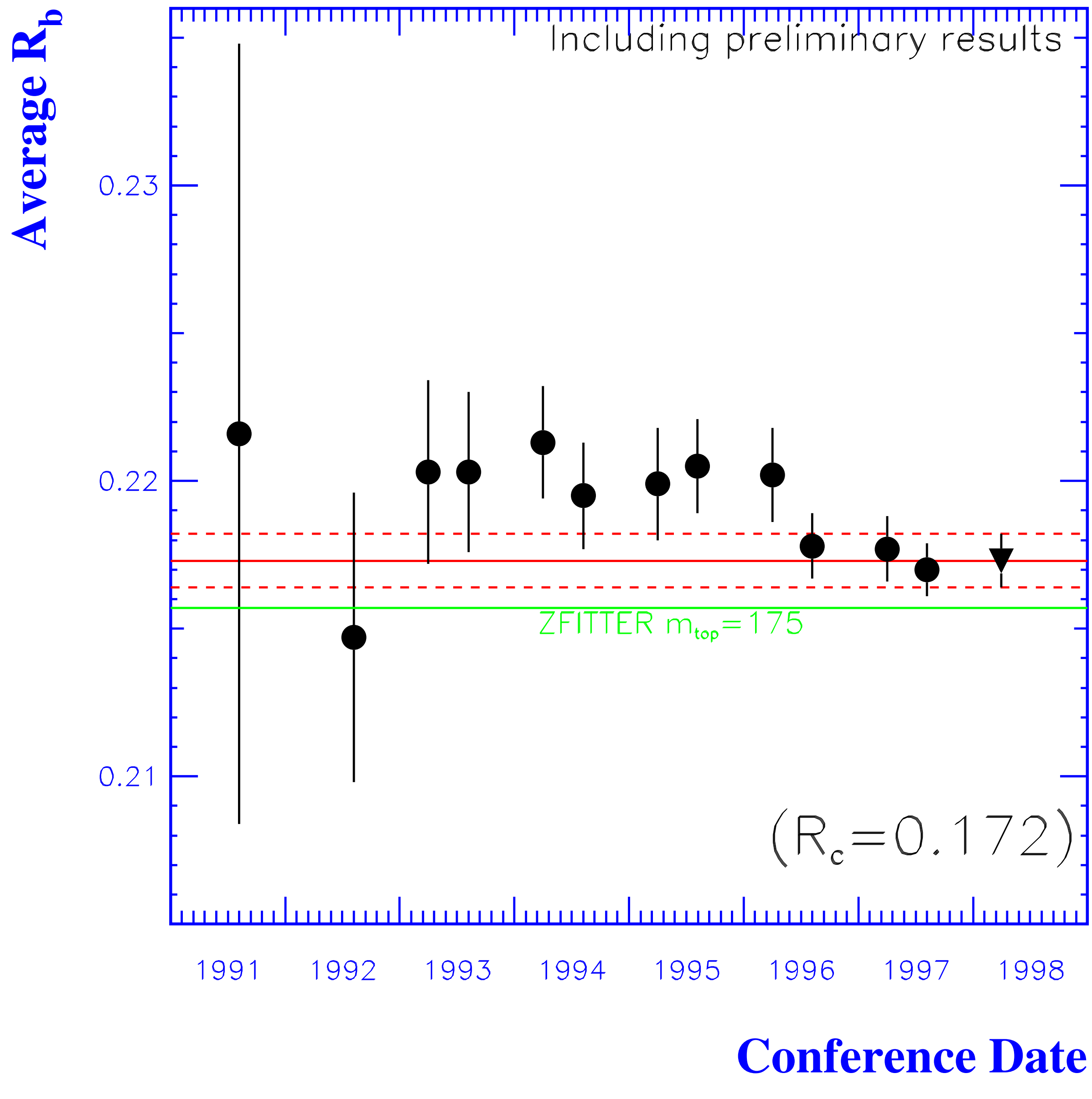
Combined LEP/SLD Heavy Quark Results

Combination procedure takes account of correlations, etc.

R_{b}	0.21732±0.00087
R_{c}	0.1731±0.0044
$A_{\mathrm{FB}}^{0,\mathrm{b}}$	0.0998±0.0022
$A_{\mathrm{FB}}^{0,\mathrm{c}}$	0.0735±0.0045
$\mathcal{A}_{\mathrm{b}}$	0.899±0.049
$\mathcal{A}_{\mathrm{c}}$	0.660±0.045



Time Evolution of World Average R_{b}



Z^0 Couplings to Fermions

Can measure $\mathcal{A}_\ell$ in several channels (assuming L.U.):

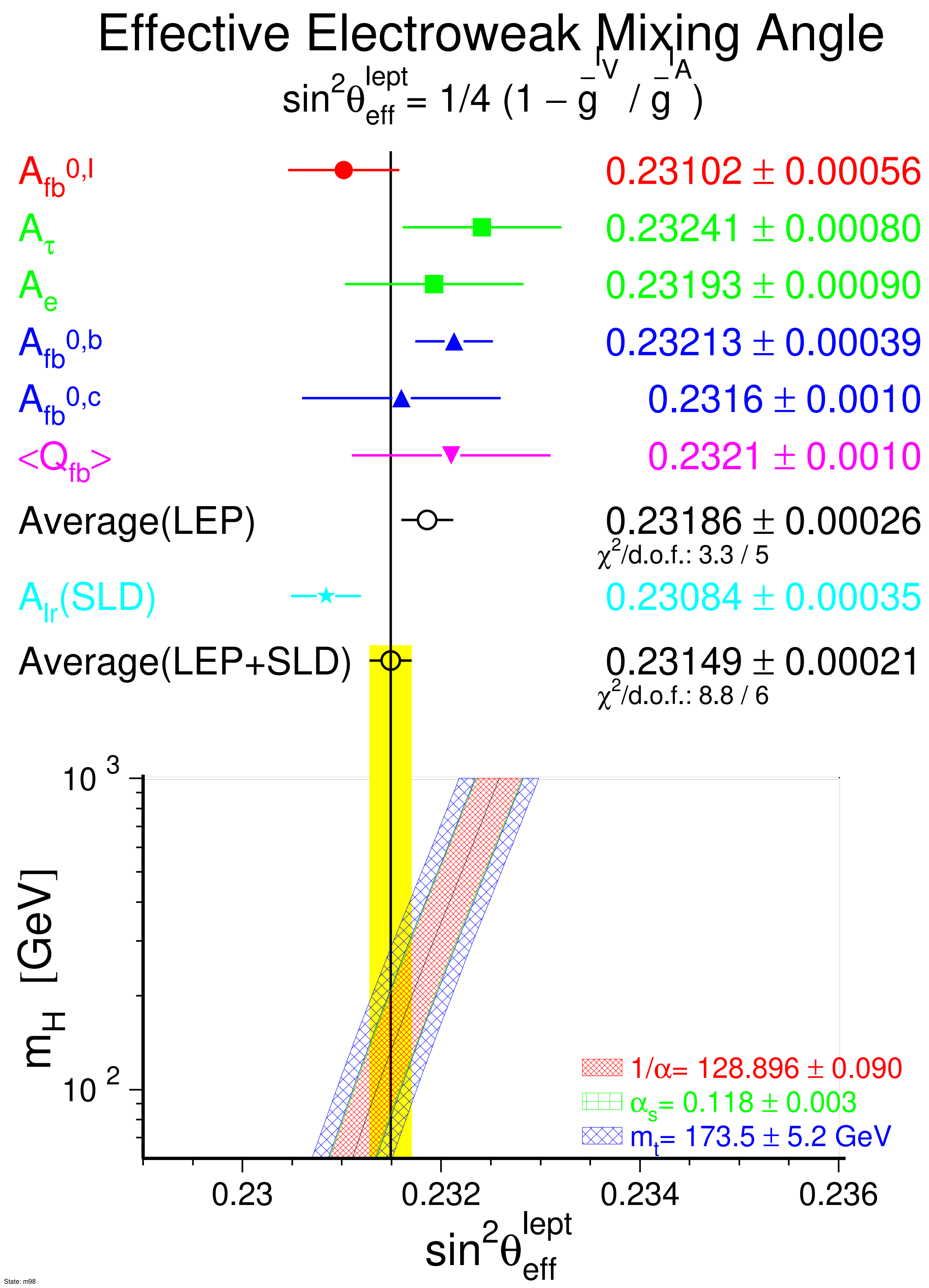
	$\mathcal{A}_\ell$	Cumulative Average	χ^2/d.o.f.
$A_{FB}^{0,\ell}$	0.1510 ± 0.0044		
$\mathcal{P}_\tau(\cos\theta)$	0.1417 ± 0.0047	0.1465 ± 0.0033	$2.1/1$
A_{LR}^0 (SLD)	0.1525 ± 0.0029	0.1499 ± 0.0021	$3.9/2$

Can also derive $\mathcal{A}_b$, $\mathcal{A}_c$ in different ways:

	LEP ($\mathcal{A}_\ell = 0.1465(33)$)	SLD	LEP+SLD ($\mathcal{A}_\ell = 0.1499(21)$)
$\mathcal{A}_b$	0.907 ± 0.029	0.899 ± 0.049	0.890 ± 0.021
$\mathcal{A}_c$	0.667 ± 0.044	0.660 ± 0.045	0.657 ± 0.031

Combined $\mathcal{A}_b$ ($\mathcal{A}_c$) result is 2.1 (0.4) sigma below SM 0.935 (0.668)

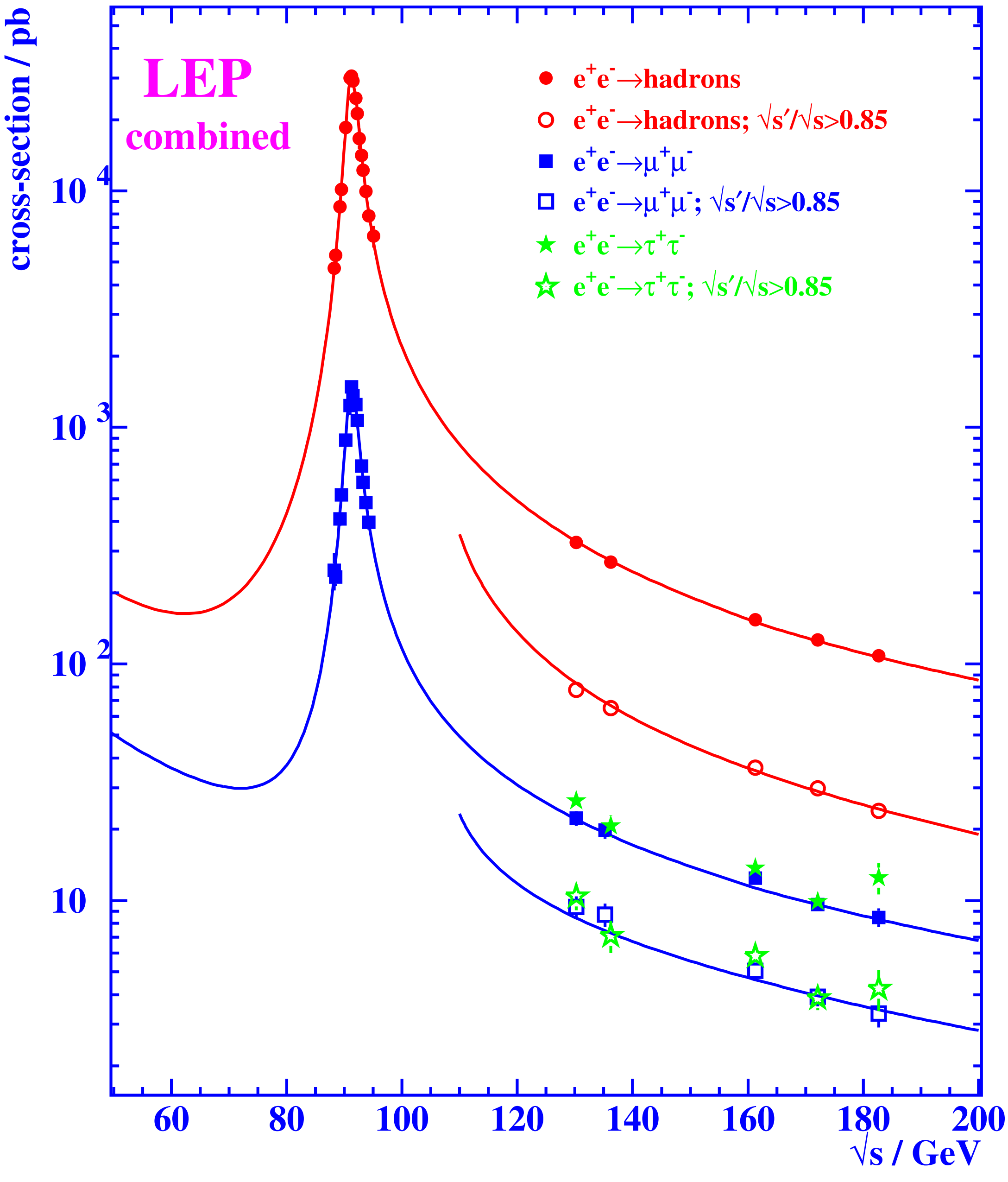
In terms of $\sin^2\theta_W^{\mathrm{eff},\ell}$ ...



Fermion Pair Production at LEP-2

Dominant feature is “radiative return” to Z pole

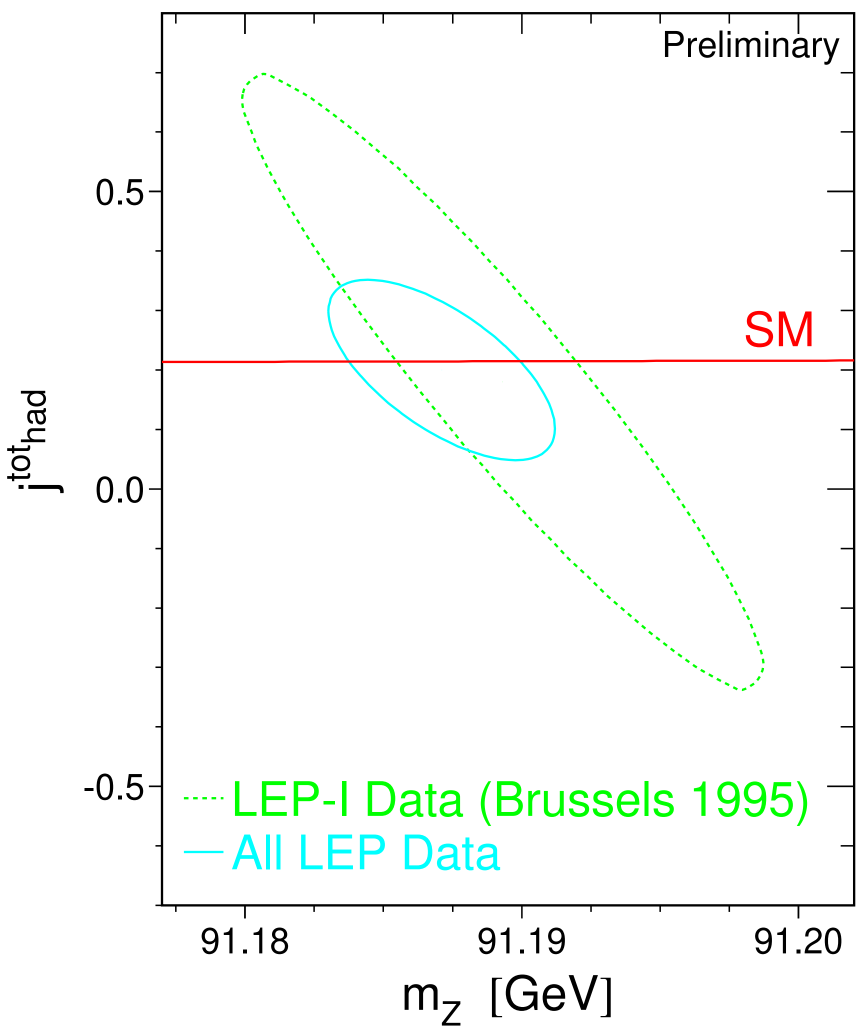
D.R.Ward, EPS Jerusalem 1997



(183 GeV data are not the full statistics)

"S-Matrix" Formalism

- Standard Model predicts size of $\gamma - \mathrm{Z}^0$ interference term
- With LEP-1 data cannot float this term separately – constraints are very poor (three energy point Z^0 lineshape scans)
- High energy fermion-pair data provides a good constraint



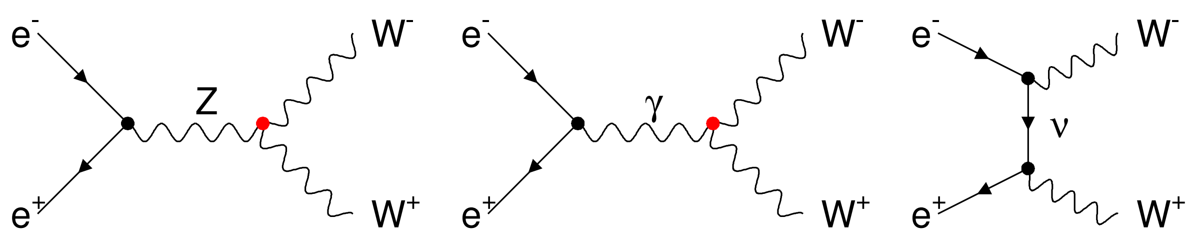
j^{tot}_{had} parameterises the $\gamma - \mathrm{Z}^0$ interference in the hadronic cross-section, and is 0.22 in the SM

W Pair Production at LEP-2

Principal physics goals:

- W mass
  - Target set by precision of SM prediction from SM fits
    $\Longrightarrow\ \sim 35$ MeV
  - Main measurement: "direct reconstruction", $\sqrt{s} > 170$ GeV
  - also first measurement at LEP-2 from WW threshold cross-section

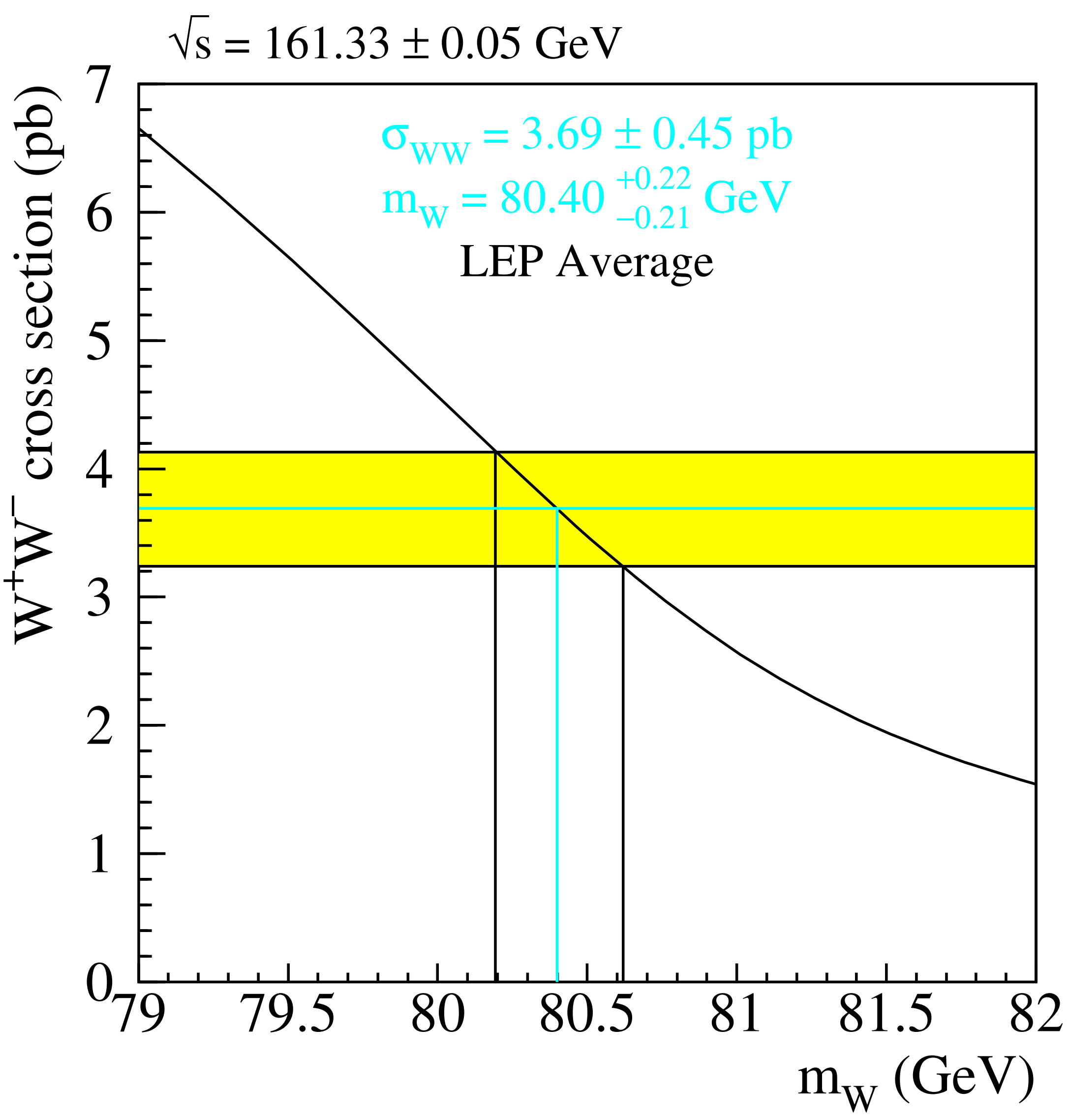
- Vector-boson self-couplings: "Triple-Gauge Couplings" (TGC)



W Mass from Threshold Cross-Section

Idea:

- At threshold, σ_{WW} depends strongly on m_{W}
- Measure σ_{WW}, infer m_{W}
- Need to understand effects on σ_{WW} (Coulomb correction...)



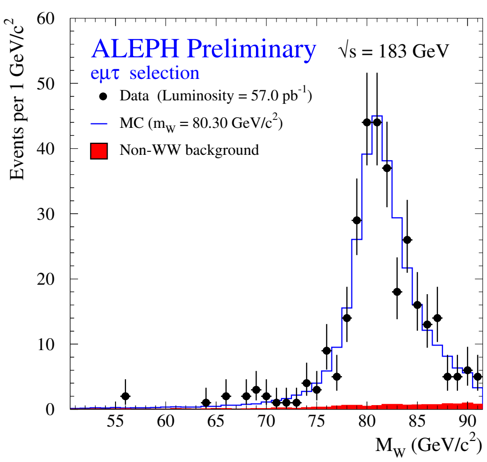
Very low statistics obtained (10 pb^{-1} per expt)

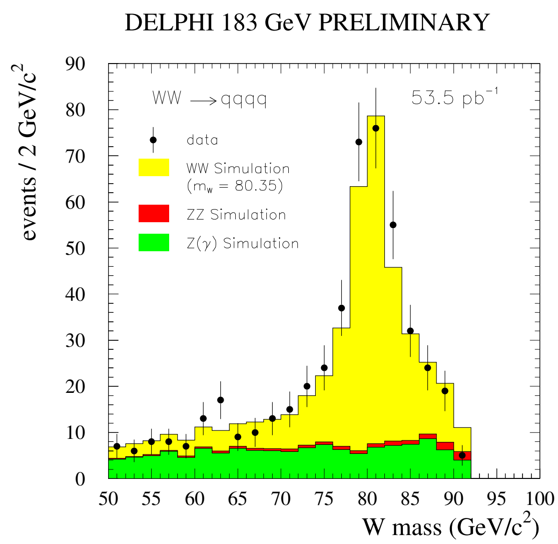
W Mass Reconstruction from Decay Products

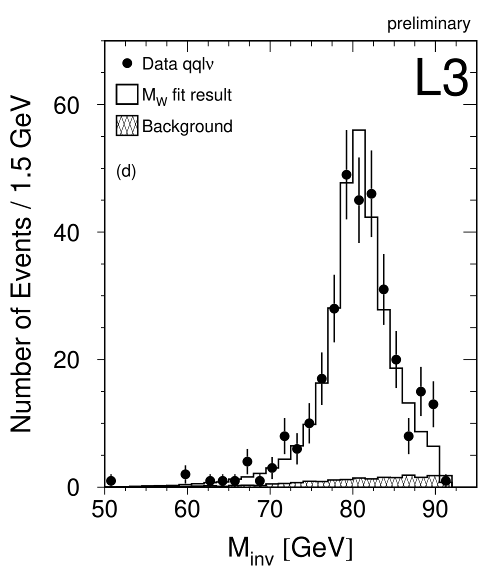
Idea:

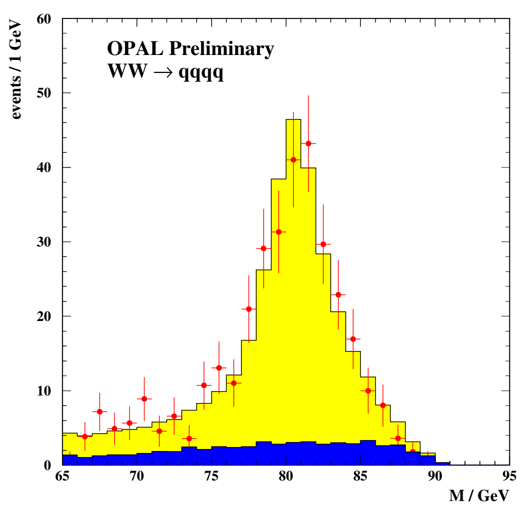
- reconstruct W mass from observed decay products: leptons, jets, missing momentum
- use energy-momentum constraints to improve resolution

$\longrightarrow$ the “direct reconstruction” method









Issues in Direct Reconstruction Method

To measure with high precision $\sim 30 - 40$ MeV, need to understand many effects well:

- LEP beam energy calibration
- Initial-state photon radiation
- Other four-fermion diagrams (incl. interference)
- Detector calibration, fit techniques
- Physical effects may distort decay product distributions:
  - (Intermediate and) Final-state photon radiation
  - Colour reconnection in $\mathrm{q\overline{q}q\overline{q}}$ final state
  - Bose-Einstein correlations in $\mathrm{q\overline{q}q\overline{q}}$ final state (?)

Colour Reconnection

W^+–W^- decay separation $\ll$ typical hadronisation scales

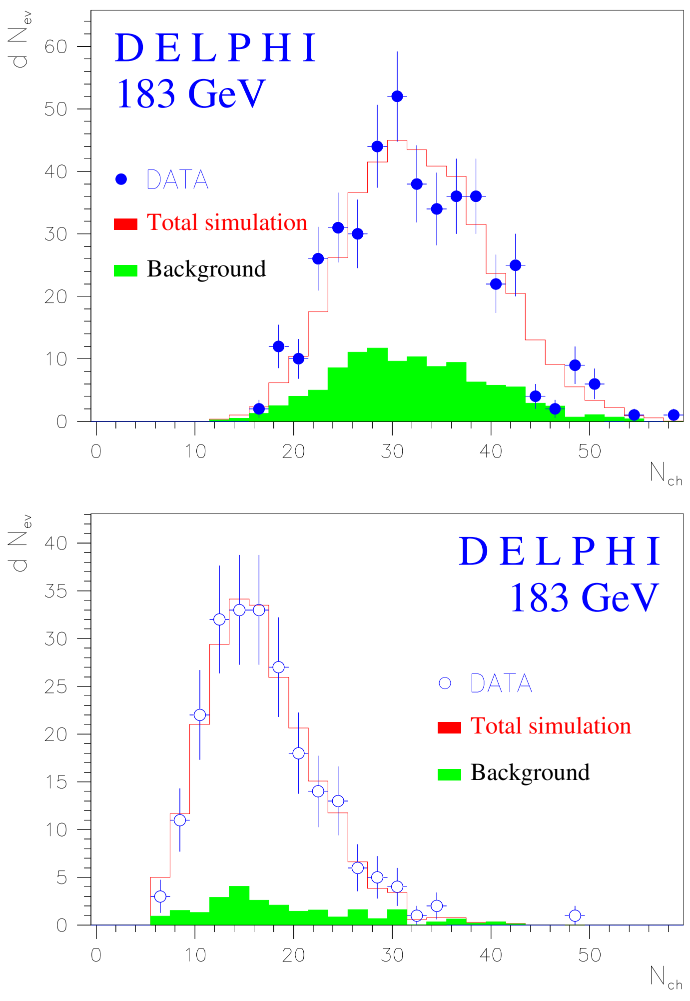
Many phenomenological studies of this effect:

- Mass shifts: 0-100 MeV in either direction
- Effects on soft particles might be measurable (y, N_{chg},...)
  $\rightarrow$ possible experimental tests of models
- Models of event selections, mass fits of varying realism

Work in progress in experiments to understand effect at level of “real analysis”, and to cross-check with data

Tests of Colour Reconnection

E.g. compare charged multiplicity in $W^+W^- \to q\bar{q}q\bar{q}$ and $W^+W^- \to q\bar{q}\ell\nu$ events



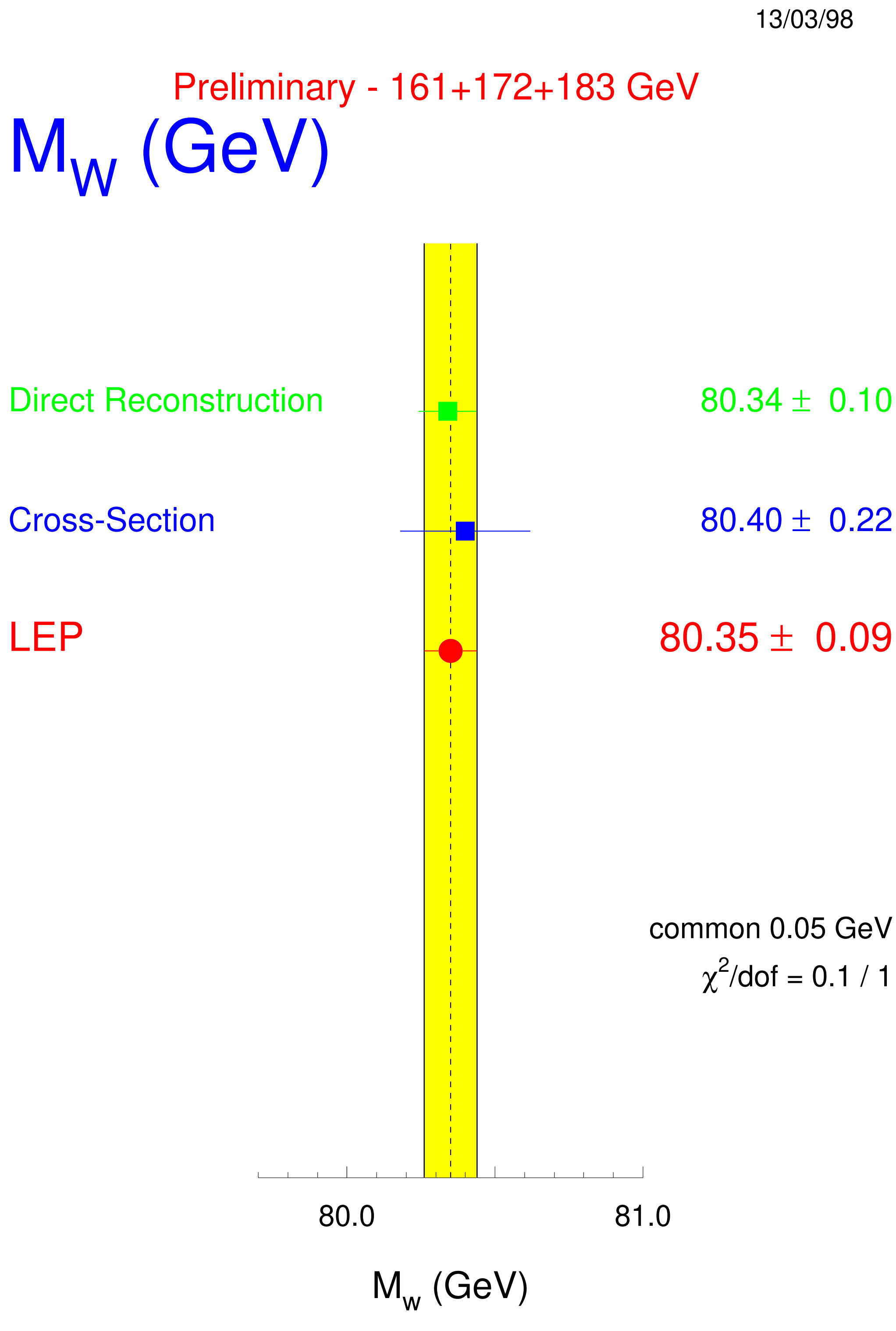
Crude check also from consistency of channels

m_W $W^+W^- \to q\bar{q}\ell\nu$ 80.27±0.10 GeV

m_W $W^+W^- \to q\bar{q}q\bar{q}$ 80.40±0.10 GeV

(plus ±0.030(LEP) and ±0.10(F.S.I. on $q\bar{q}q\bar{q}$) errors)

Summary of Measurements of m_{W}



W Decay Branching Ratios

From relative rates of $\mathrm{W^+W^-}$ to different final states:

Br(W$\to$eν)	11.0 ± 0.5 %
Br(W$\to \mu\nu$)	10.3 ± 0.5 %
Br(W$\to \tau\nu$)	10.0 ± 0.6 %
Br(W$\to$hadrons) (assume LU)	68.6 ± 0.8 %

SM expectation: Br(W$\to$hadrons) $\simeq$ 67.8%

Can interpret Br(W$\to$hadrons) as a measure of $|V_{cs}|$, if don't require CKM unitarity

$$|V_{cs}| = 1.03 \pm 0.04$$

Direct measurements of Br(W$\to \mathrm{c}X$), Br(W$\to \mathrm{c\bar{s}}$) also starting to be made

Vector Boson Self Interactions

Effective lagrangian for ZWW vertex (similar for γ):

$$e \cot\theta_W \quad [\quad (1+\Delta g_1^Z) Z^\mu (W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}) +$$
$$(1+\Delta\kappa_Z) W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} Z^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + \ldots \;]$$

Anomalous coupling parameters **"TGC's"**, all 0 in SM:

$$\Delta g_1^Z, \Delta\kappa_\gamma, \Delta\kappa_Z, \lambda_\gamma, \lambda_Z$$

plus additional C,P,CP violating terms

Static electromagnetic properties of W:

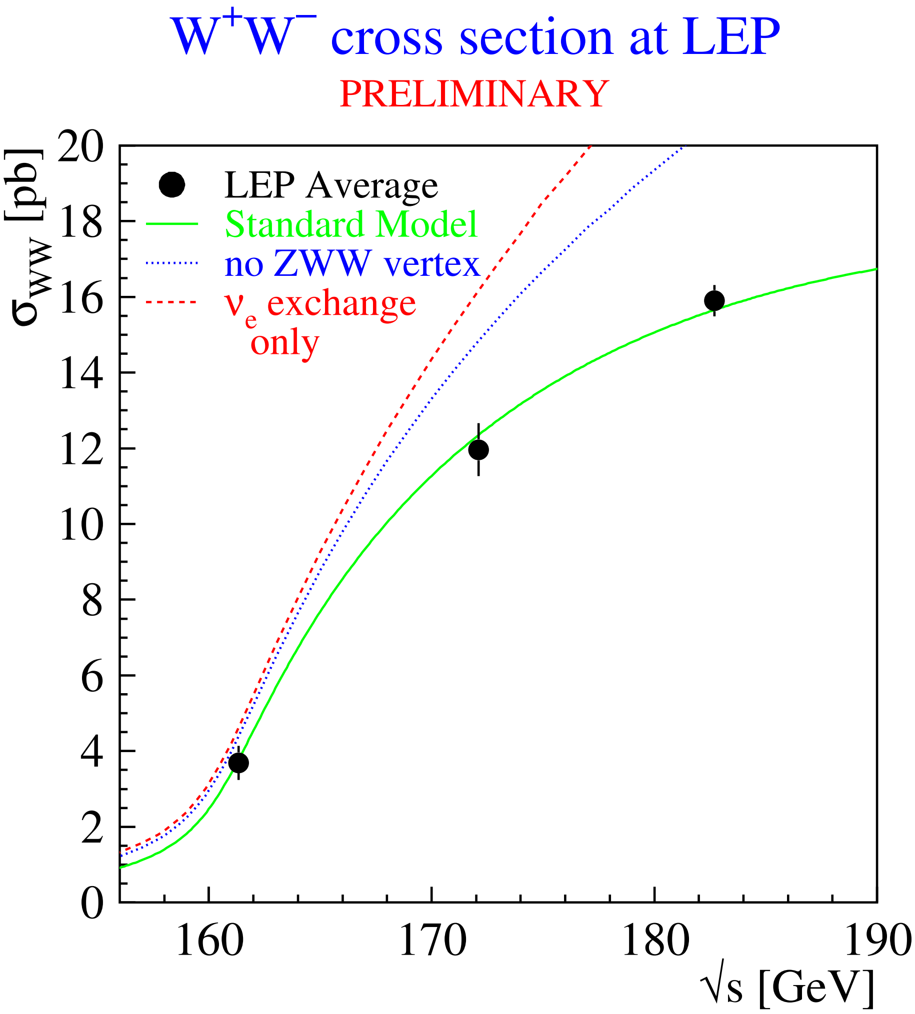
- Electric charge: $Q_W = e$
- Magnetic dipole moment: $\mu_W = \frac{e}{2m_\mathrm{W}}(2+\Delta\kappa_\gamma+\lambda_\gamma)$
- Electric quadrupole moment: $q_W = \frac{-e}{m_\mathrm{W}^2}(1+\Delta\kappa_\gamma-\lambda_\gamma)$

Common LEP-2 parameterisation, motivated by operators not already constrained by LEP-1:

- $\alpha_{W\phi} = \Delta g_1^Z \cos^2\theta_W$
- $\alpha_{B\phi} = \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$
- $\alpha_W = \lambda_\gamma = \lambda_Z$

with $\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_1^Z$

Measuring the Triple-Gauge Couplings



Fit to total WW cross-section and W production, decay angles:

- Needs W charge identification: main analysing power from $q\overline{q}\ell\nu$
- Experimental challenge to reconstruct W decay angles

Analyses now employ several channels:

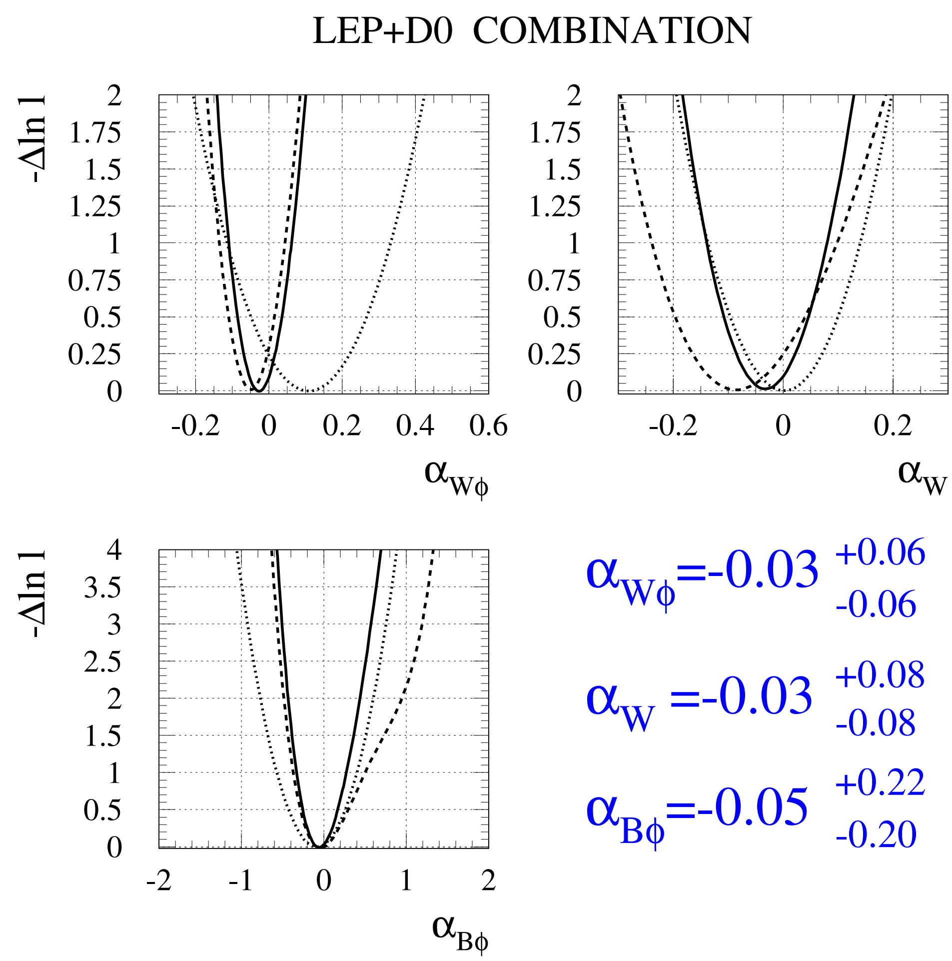
$$W^+W^- \to q\overline{q}q\overline{q},\ W^+W^- \to q\overline{q}\ell\nu,\ W^+W^- \to \ell\nu\ell\nu$$

Triple-Gauge Coupling Measurements

Results so far with $\frac{3}{4}$ of 183 GeV data statistics

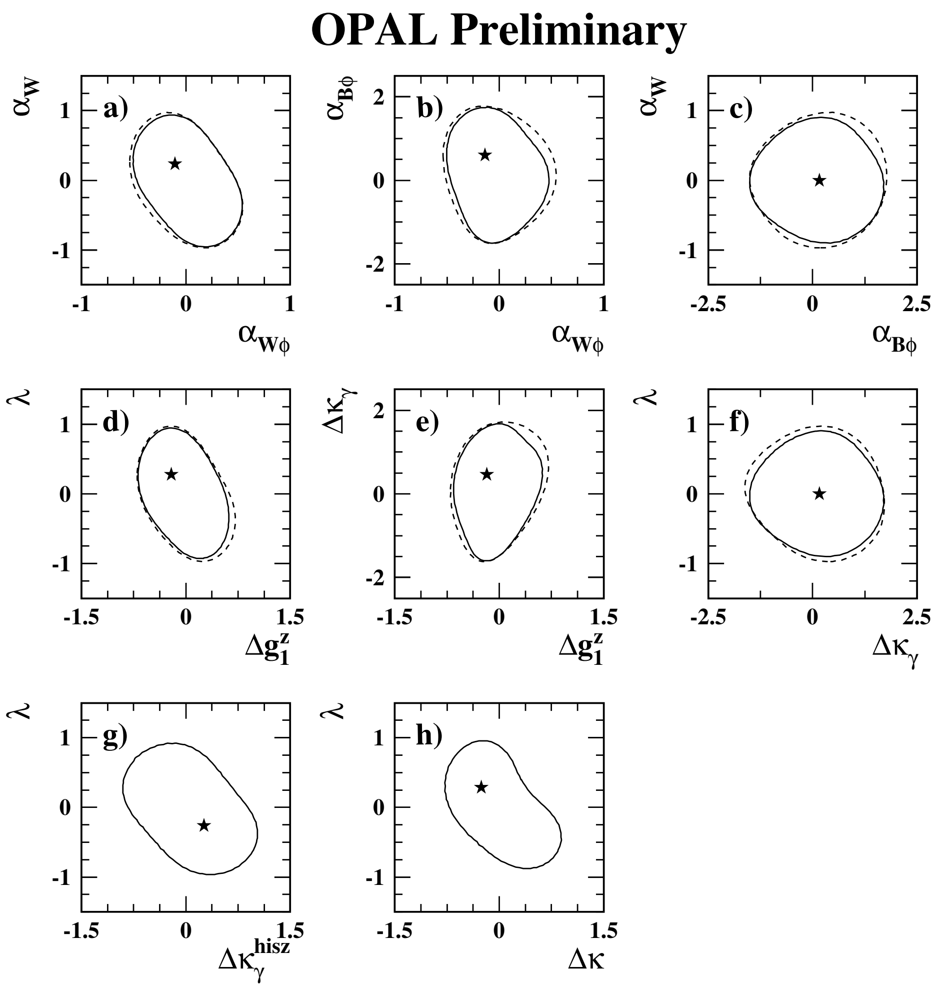
One-dimensional fits (only one α parameter non-zero at a time):

	$\alpha_{W\phi}$	α_W	$\alpha_{B\phi}$
LEP	$-0.05^{+0.06}_{-0.06}$	$-0.09^{+0.13}_{-0.11}$	$-0.04^{+0.33}_{-0.24}$
DØ	$0.11^{+0.16}_{-0.16}$	$0.00^{+0.10}_{-0.10}$	$-0.08^{+0.34}_{-0.34}$
LEP-DØ 1σ	$-0.03^{+0.06}_{-0.06}$	$-0.03^{+0.08}_{-0.08}$	$-0.05^{+0.22}_{-0.20}$
LEP-DØ 95% CL	$[-0.14,\ 0.10]$	$[-0.18,\ 0.13]$	$[-0.42,\ 0.43]$



Other TGC Measurements

First two and three-dimensional fits taking place...



Also: Other vector-boson self-coupling analyses at LEP-2:

- Sensitivity to $\mathrm{ZZ}\gamma$, $\mathrm{Z}\gamma\gamma$ couplings
- Sensitivity to C,P and CP-violating couplings
- Single-W production $\Longrightarrow$ $\mathrm{WW}\gamma$-couplings

Standard Model Fits

- **Check validity and consistency of SM**
- Infer information on $m_{\rm top}$, $m_{\rm H}$ through loop corrections
- Use directly measured $m_{\rm top}$ $\Longrightarrow m_{\rm H}$ constraints?

Limitations on precision from "well-known" inputs?

- $\alpha_{em} = 1/(128.896 \pm 0.090) \Longrightarrow \Delta \sin^2\theta_{\rm W}^{\rm eff,\ell} = 0.00023$, $\Delta m_{\rm top} = 1$ GeV, $\Delta \log m_{\rm H} = 0.2$
- $G_F = (1.16639 \pm 0.00002) \times 10^{-5}$ GeV^{-2} now has relative error similar to $m_{\rm Z}$, but not a big problem

Theoretical precision?

Effect of missing higher-order corrections and interplay with QCD corrections investigated in:

CERN 95-03: "Precision Calculations for the Z Resonance"

Since then, more higher-order corrections calculated – uncertainties on SM fit parameters still under study

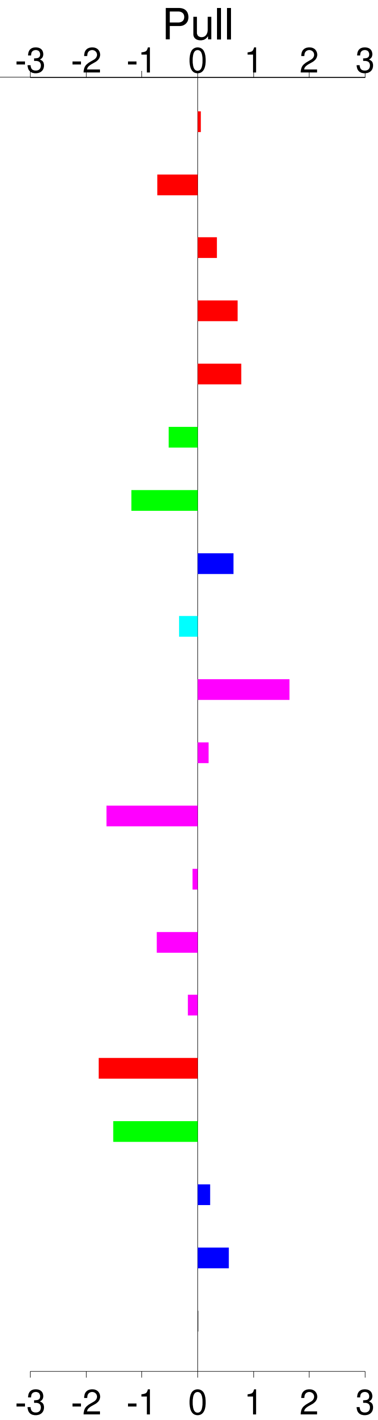
Summary of Measurements

	Measurement	SM Fit	Pull
$\alpha(m_Z^2)^{-1}$	128.896 ± 0.090	128.895	0.0
LEP			
line-shape/lepton asy			
m_Z [GeV]	91.1867 ± 0.0020	91.1866	0.1
Γ_Z [GeV]	2.4948 ± 0.0025	2.4966	-0.7
$\sigma_{\rm had}^{\rm pole}$ [nb]	41.486 ± 0.053	41.468	0.3
R_ℓ	20.775 ± 0.027	20.756	0.7
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0163	0.8
τ polarization			
$\mathcal{A}_\tau$	0.1400 ± 0.0063	0.1475	-1.2
$\mathcal{A}_{\rm e}$	0.1438 ± 0.0071	0.1475	-0.5
$\rm q\overline{q}$ charge asymmetry			
$\sin^2\theta_{\rm W}^{\rm eff,\ell}$ ($\langle Q_{FB}\rangle$)	0.2321 ± 0.0010	0.23146	0.6
m_W [GeV]	80.35 ± 0.09	80.380	-0.3
SLD			
$\sin^2\theta_{\rm W}^{\rm eff,\ell}$ ($A_{\rm LR}$)	0.23084 ± 0.00035	0.23146	-1.8
b and c quark results			
$R_{\rm b}$	0.2173 ± 0.0009	0.2159	1.6
$R_{\rm c}$	0.1731 ± 0.0044	0.1723	0.2
$A_{\rm FB}^{0,\rm b}$	0.0998 ± 0.0022	0.1034	-1.6
$A_{\rm FB}^{0,\rm c}$	0.0735 ± 0.0045	0.0739	-0.1
$\mathcal{A}_{\rm b}$	0.899 ± 0.049	0.935	-0.7
$\mathcal{A}_{\rm c}$	0.660 ± 0.045	0.668	-0.2
$\rm p\overline{p}$ and νN			
m_W [GeV] ($\rm p\overline{p}$)	80.41 ± 0.09	80.380	0.2
$1 - m_W^2/m_Z^2$ (νN)	0.2197 ± 0.0021	0.2230	-1.6
$m_{\rm top}$ [GeV] ($\rm p\overline{p}$)	174.1 ± 5.4	171.1	0.6

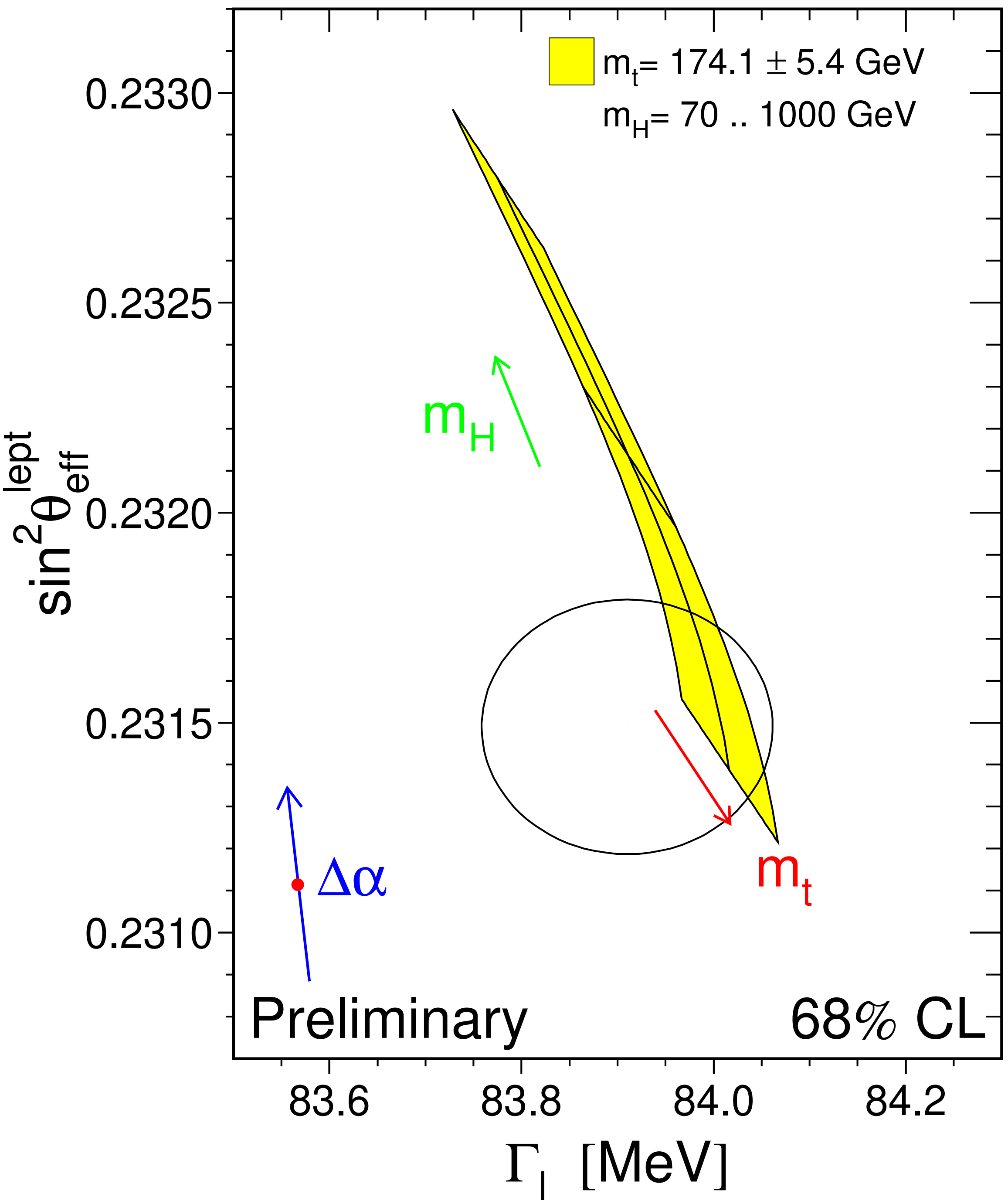
Standard Model predictions from fit to all data, $m_{\rm H} = 300$ GeV.

Moriond 1998

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0020	.05
Γ_Z [GeV]	2.4948 ± 0.0025	-.73
σ^0_{hadr} [nb]	41.486 ± 0.053	.34
R_e	20.775 ± 0.027	.72
$A^{0,e}_{fb}$	0.0171 ± 0.0010	.78
A_e	0.1438 ± 0.0071	-.52
A_τ	0.1400 ± 0.0063	-1.19
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.64
m_W [GeV]	80.350 ± 0.090	-.34
R_b	0.21732 ± 0.00087	1.64
R_c	0.1731 ± 0.0044	.19
$A^{0,b}_{fb}$	0.0998 ± 0.0022	-1.64
$A^{0,c}_{fb}$	0.0735 ± 0.0045	-.09
A_b	0.899 ± 0.049	-.73
A_c	0.660 ± 0.045	-.18
$\sin^2\theta^{lept}_{eff}$	0.23084 ± 0.00035	-1.78
$\sin^2\theta_W$	0.2198 ± 0.0021	-1.51
m_W [GeV]	80.400 ± 0.090	.22
m_t [GeV]	174.1 ± 5.4	.56
$1/\alpha$	128.894 ± 0.090	.01



The Need for Electroweak Corrections



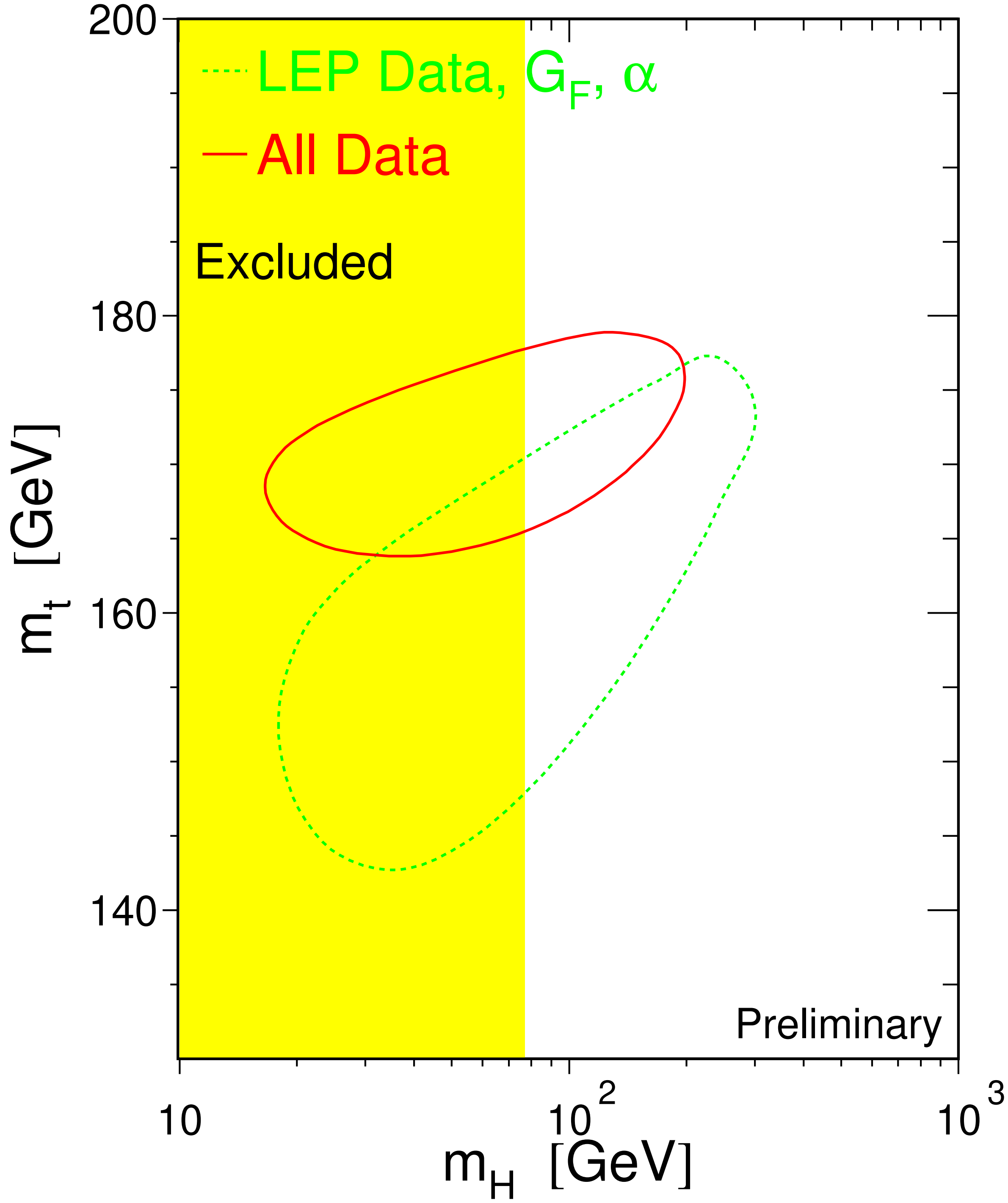
Results of Standard Model Fits

- No external constraint on α_s, but cf: $\alpha_s(m_Z^2) = 0.118 \pm 0.003$
- Constraint $\alpha_{em} = 1/(128.896 \pm 0.090)$

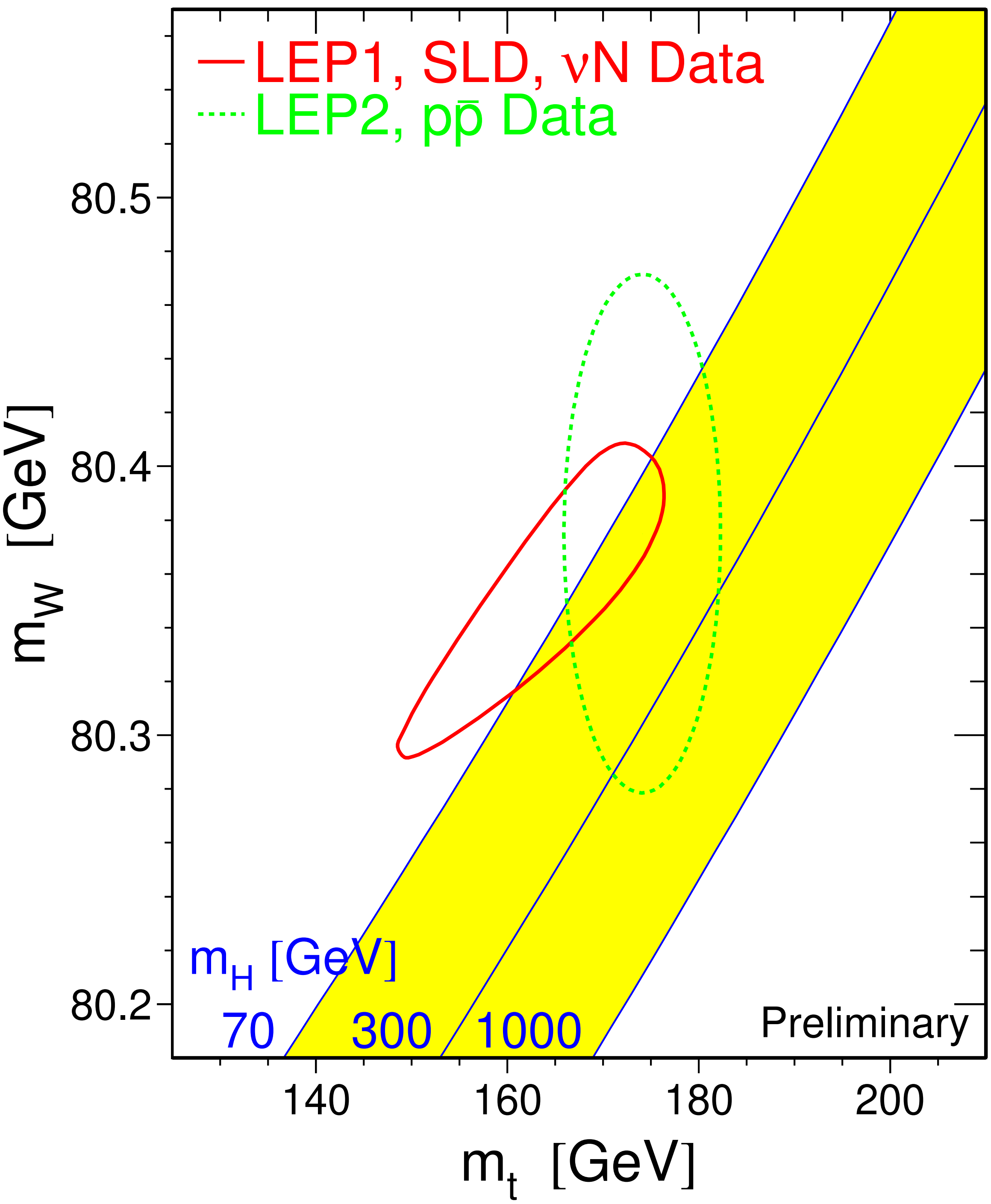
	LEP (incl. m_W)	all data except m_{top},m_W
m_{top} [GeV]	$157\ ^{+12}_{-10}$	$161\ ^{+9}_{-8}$
m_H [GeV]	$56\ ^{+101}_{-31}$	$33\ ^{+45}_{-17}$
$\log(m_H$/GeV)	$1.75\ ^{+0.45}_{-0.35}$	$1.53\ ^{+0.37}_{-0.29}$
α_s	0.122 ± 0.003	0.121 ± 0.003
χ^2/d.o.f.	$6/9$	$14/12$
$\sin^2\theta_W^{\mathrm{eff},\ell}$	0.23183 ± 0.00025	0.23145 ± 0.00021
$1 - m_W^2/m_Z^2$	0.2245 ± 0.0008	0.2235 ± 0.0008
m_W [GeV]	80.302 ± 0.040	80.351 ± 0.040

	all data
m_{top} [GeV]	171.1 ± 5.5
m_H [GeV]	$66\ ^{+74}_{-39}$
$\log(m_H$/GeV)	$1.82\ ^{+0.33}_{-0.40}$
α_s	0.120 ± 0.003
χ^2/d.o.f.	$16/15$
$\sin^2\theta_W^{\mathrm{eff},\ell}$	0.23146 ± 0.00022
$1 - m_W^2/m_Z^2$	0.2230 ± 0.0005
m_W [GeV]	80.380 ± 0.027

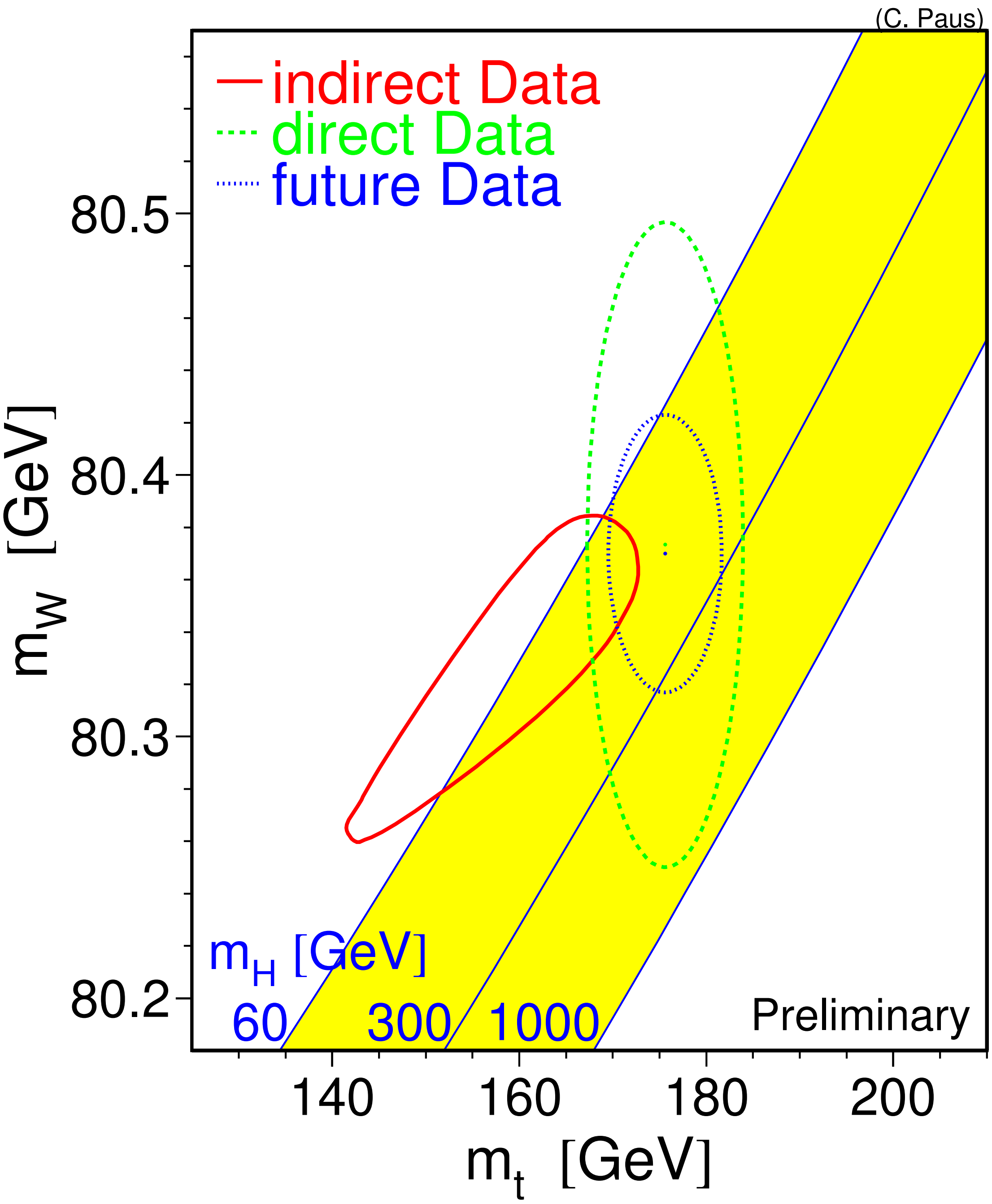
A Handle on m_{H} from LEP data alone?



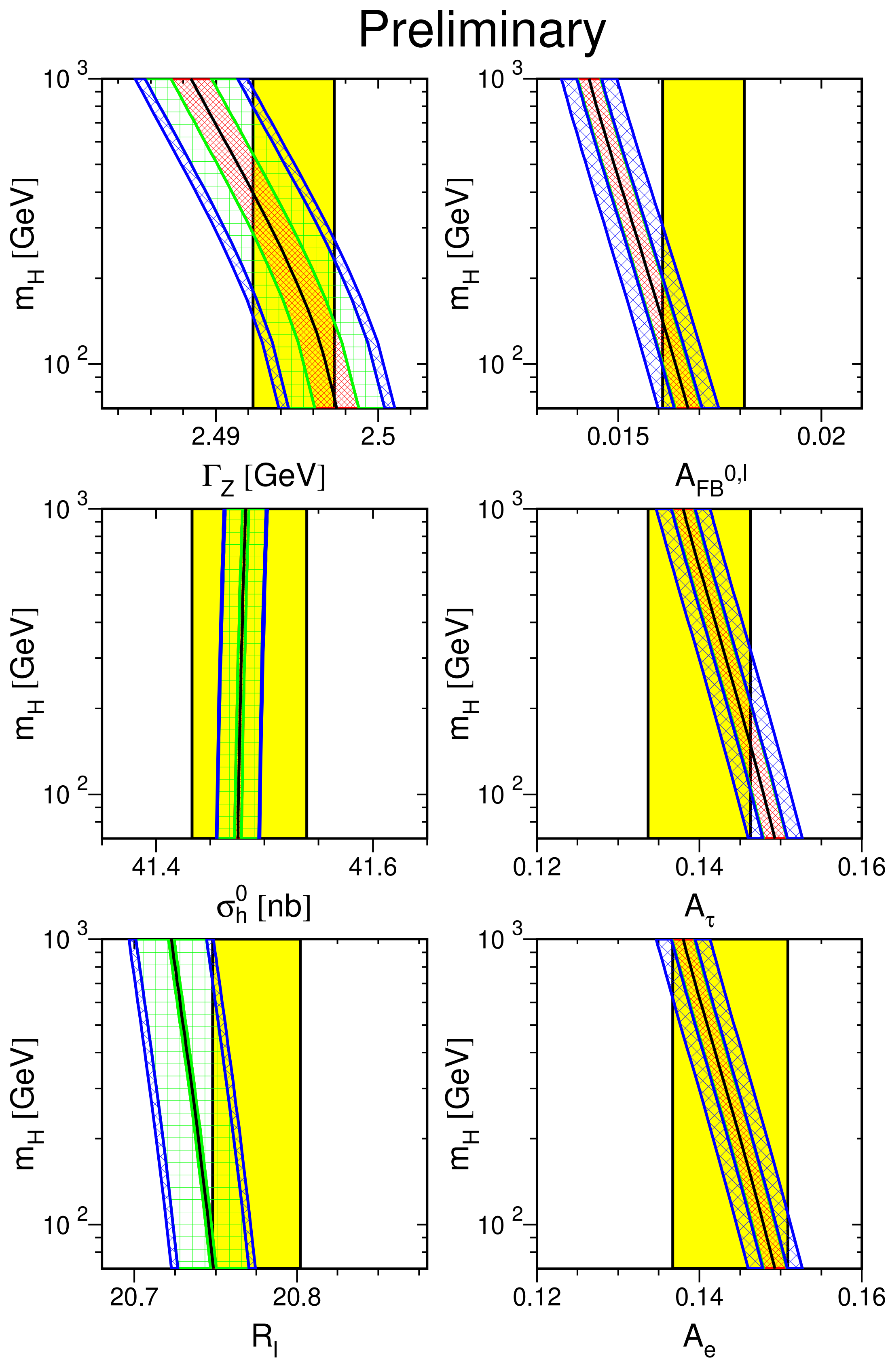
Testing the Standard Model with m_{W}

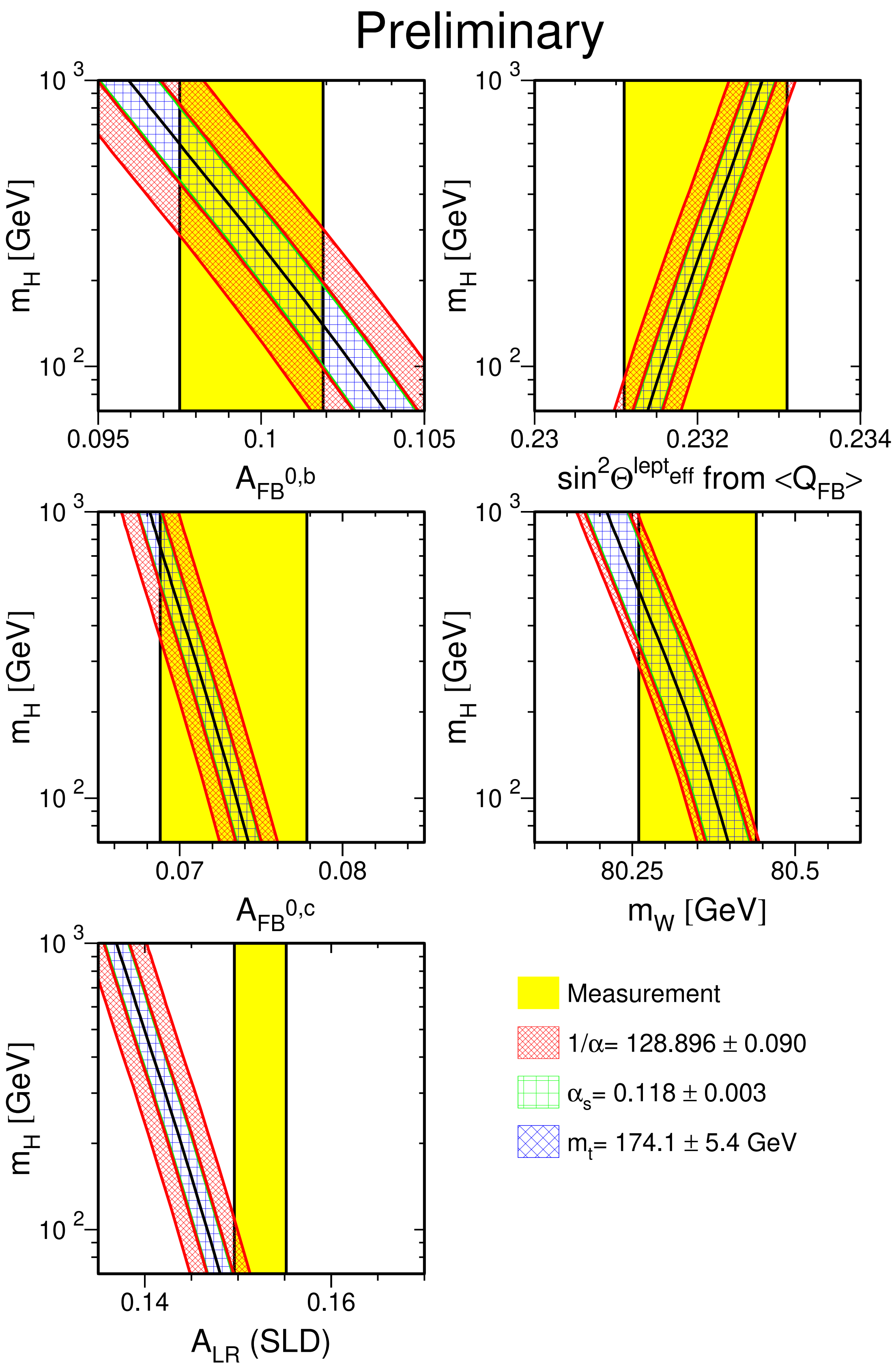


If Δm_{W}=35 MeV and Δm_{top}=4 GeV (68% CL contours):

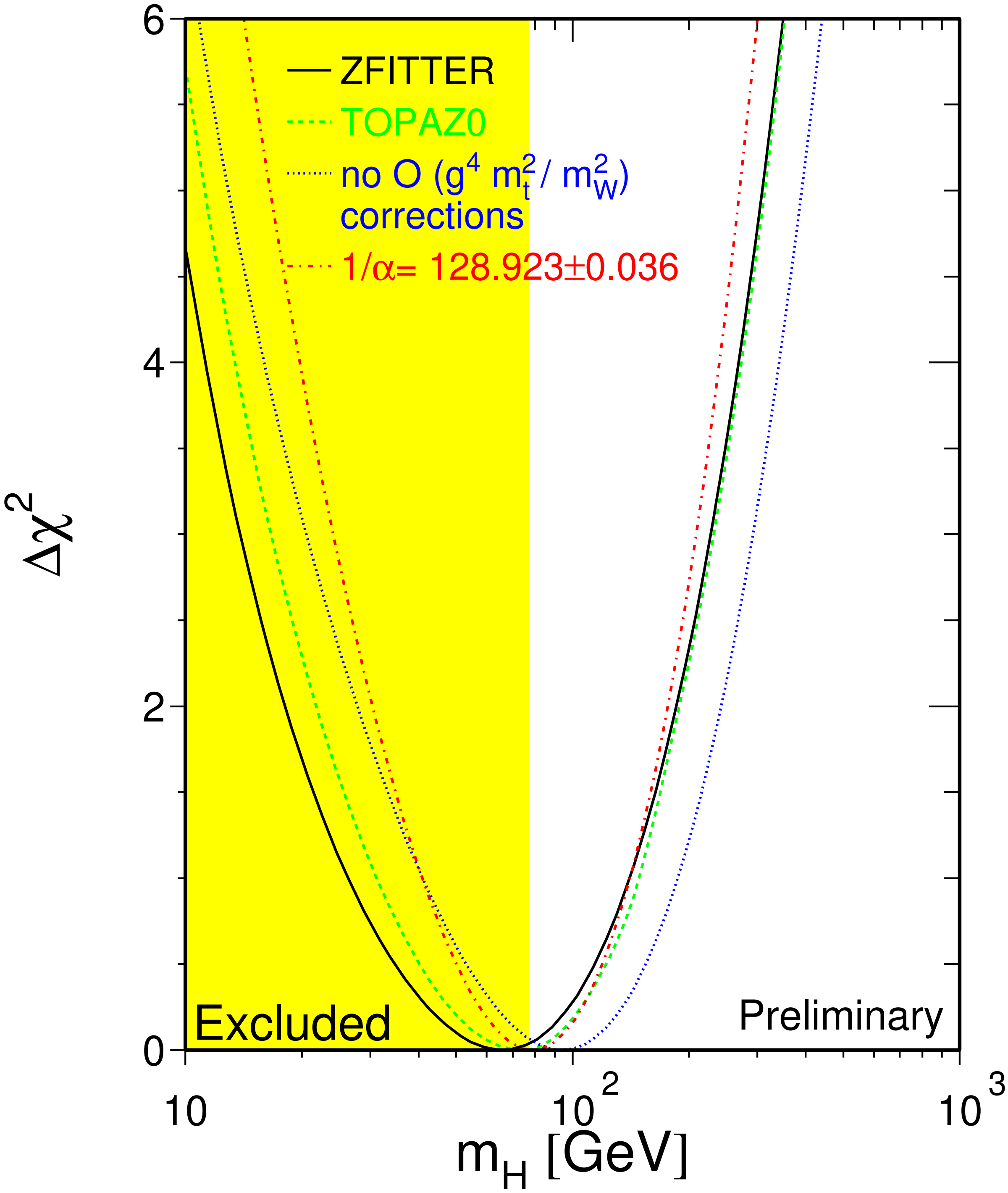


Sensitivities to m_{H} of Observables



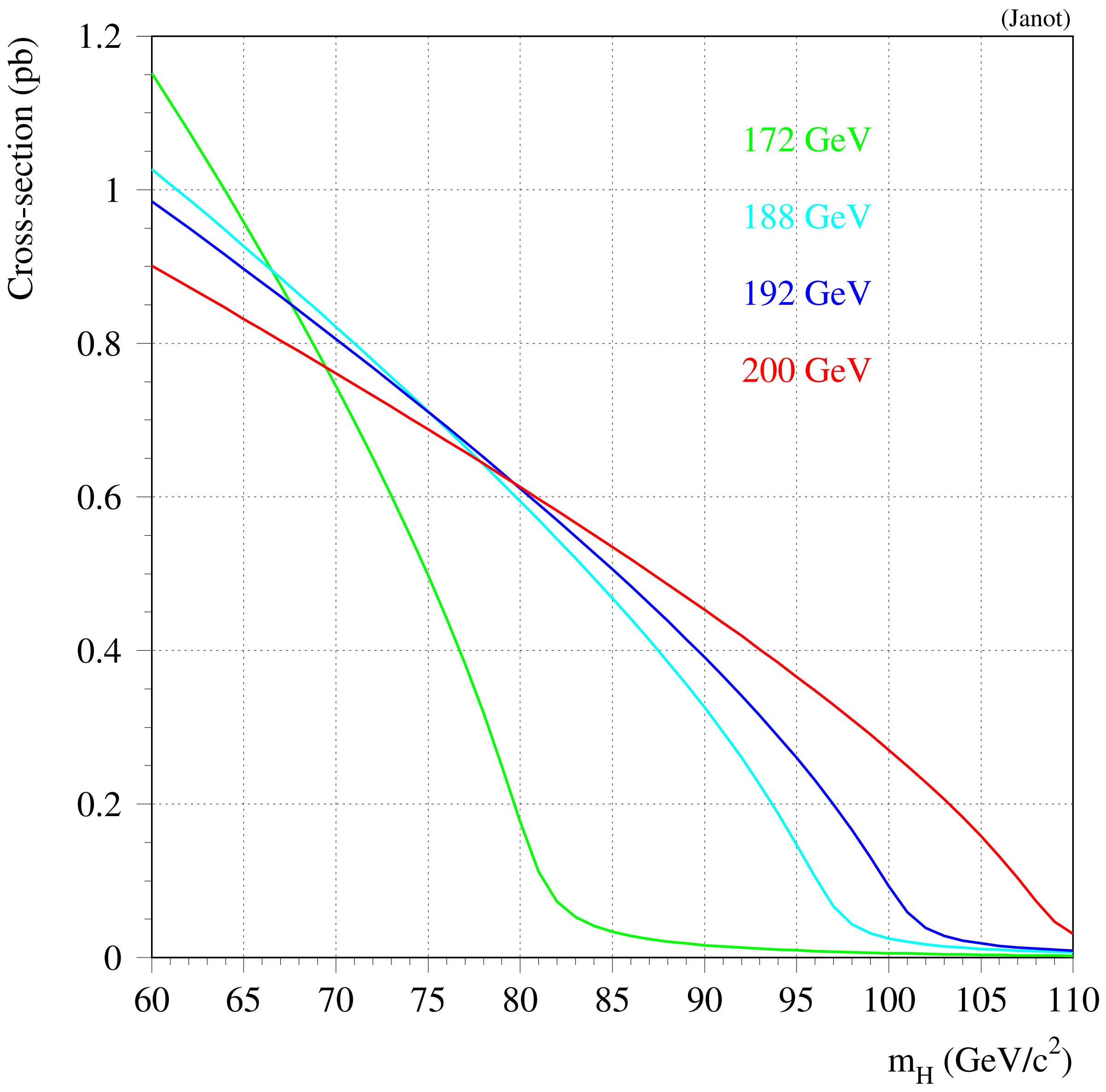

Preliminary
m_H [GeV]
10^3
10^2
0.095
0.1
0.105
$A_{FB}^{0,b}$
0.23
0.232
0.234
$\sin^2\Theta^{lept}_{eff}$ from <Q_{FB}>
0.07
0.08
$A_{FB}^{0,c}$
80.25
80.5
m_W [GeV]
0.14
0.16
A_{LR} (SLD)
Measurement
$1/\alpha = 128.896 \pm 0.090$
$\alpha_s = 0.118 \pm 0.003$
$m_t = 174.1 \pm 5.4$ GeV

m_{H} with all data



Direct Higgs Search at LEP-2

Expected H production cross-section (ZH plus boson fusion):

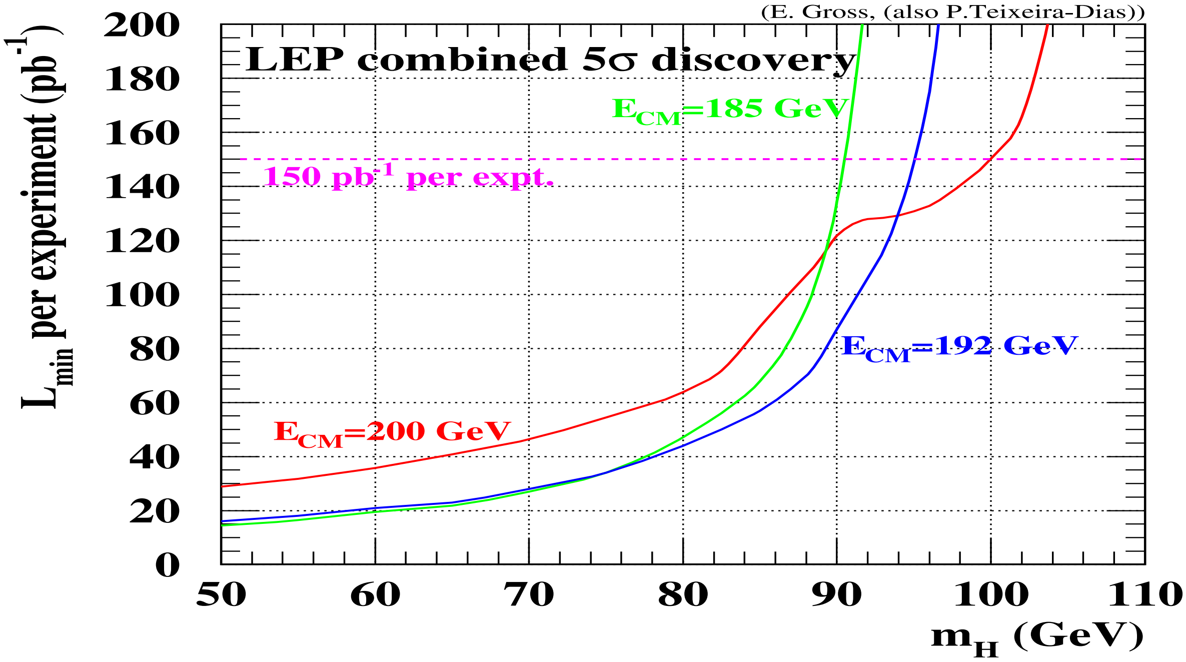


- ZH production dominates over boson fusion process at LEP-2 energies
- ZZ background becomes significant at high E_{CM}, $m_{\rm H} \simeq m_{\rm Z}$:
  $\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{ZZ} \to \mathrm{b\bar{b}}X) \simeq 0.24$ pb at 200 GeV

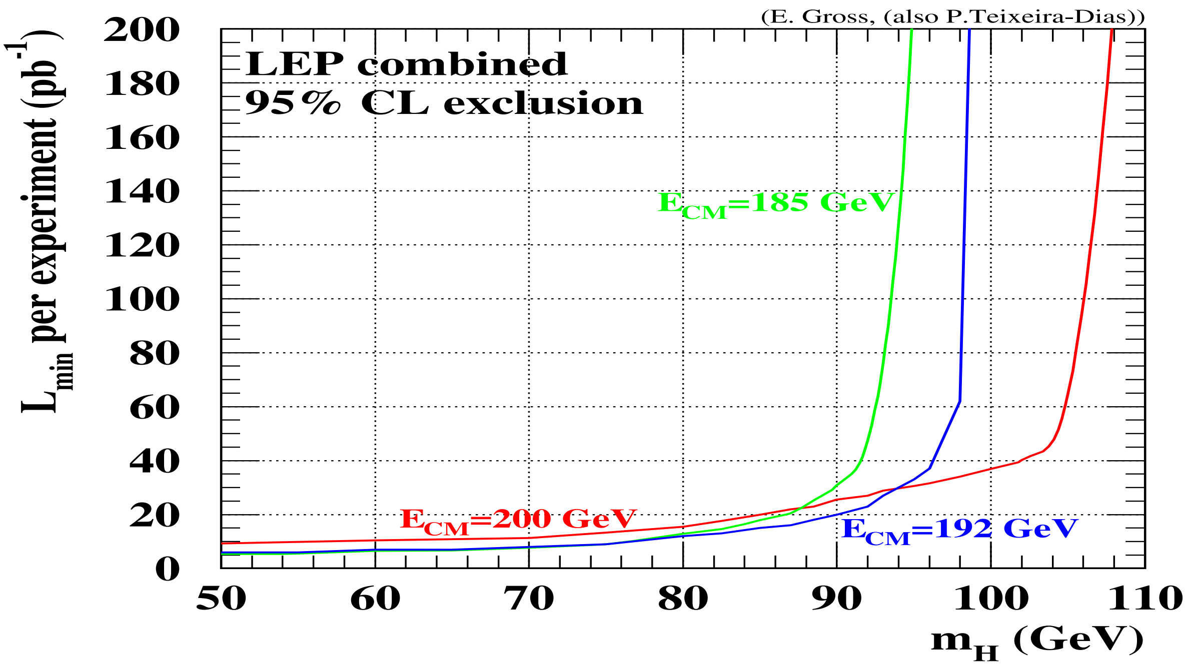
Standard Model Higgs Mass Reach

Sensitivity studied during the LEP workshop, as reported in the yellow book

5σ case : “Solid” discovery potential



95% CL limit case : relatively weak exclusion potential



Caveat:

Sensitivity at 200 GeV has not been studied in detail: limits here rely on extrapolation from 205 GeV

SM Higgs Mass Reach: Summary

Mass reaches for LEP combined, integrated luminosity per expt:

Sample	95% CL exclusion	5σ discovery
50 pb^{-1} at 184 GeV	91 GeV	80 GeV
200 pb^{-1} at 192 GeV	99 GeV	96 GeV
100 pb^{-1} at 200 GeV	106 GeV	87 GeV
150 pb^{-1} at 200 GeV	106 GeV	100 GeV
***) 150 pb^{-1} at 200 GeV	109 GeV	106 GeV

***) new study by Gross, Read and Lellouch

- For 95% CL exclusion, 50-70 pb^{-1} per experiment is enough for limit close to sensitivity "wall"
- This level of sensitivity could also give a first hint if there is a signal
- But, for 5σ discovery at high energy, need substantial ($\gtrsim$ 150 pb^{-1}) luminosity

Summary and Prospects

The Standard Model has been extensively probed at LEP and SLD via Z^0 precision measurements

Conclusive evidence of electroweak corrections

Excellent agreement with Standard Model

In *framework of SM* **and including other data, suggestion that a SM Higgs would be light**

Further tests in W sector to come – new Standard Model tests

Window to discover the SM Higgs at LEP-2 up to $\sim$100-106(?) GeV