Tests of the Standard Model

W mass and WWZ couplings

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- Z^0 lineshape, lepton asymmetries; $Z^0 \to b\bar{b}/c\bar{c}$
- $e^+e^- \to f\bar{f}$ above the Z^0
- W Mass
- Global Electroweak fits: $\Rightarrow m_H, \alpha_s$
- W Width; branching ratios
- Triple gauge couplings
- Summary and outlook

n.b. Most of the results are averages of several experiments, and contain at least some preliminary data.

Data from LEP

- 1989-1995

  LEP I $\Rightarrow\sim 160$ pb^{-1}

  ($\sim 5 \cdot 10^6$ visible Z^0 decays) / experiment

  Precision scan of the Z peak in 1993, 1995; ~ 40 pb^{-1} of data $\pm$1.8 GeV off peak.

- November 1995

  LEP 1.5 – 130-136 GeV $\Rightarrow \sim 5$ pb^{-1} / experiment

- 1996 LEP2

  161 GeV $\Rightarrow \sim 10$ pb^{-1} / experiment

  172 GeV $\Rightarrow \sim 10$ pb^{-1} / experiment

- 1997

  LEP2 – now running at $\sim$183 GeV (~ 7 pb^{-1}/expt. by start of conference)

Data from SLC

- $\mathrm{e}^+\mathrm{e}^-$ on the Z peak

Up to 1996, ~ 5 pb^{-1}, with $\mathcal{P}_\mathrm{e}$ up to 80%.

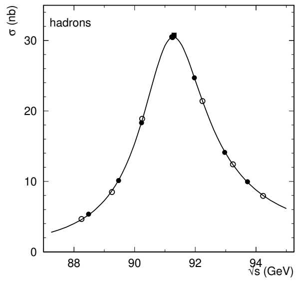
Data from FNAL

- $\overline{\mathrm{p}}\mathrm{p}$ at 1.8 TeV. Run IA+IB ~ 110 pb^{-1}.

Z^0 precision data - formalism

Principal measurements at LEP/SLC

- $\sigma(e^+e^- \to f\bar{f})$ vs. $\sqrt{s} \Rightarrow M_Z, \Gamma_Z$



- $\Gamma_f \equiv \Gamma(Z \to f\bar{f}) \sim (g_{Vf}^2 + g_{Af}^2)$ partial widths

or ratios $R_\ell = \Gamma_{had}/\Gamma_\ell$, $R_b = \Gamma_b/\Gamma_{had}$

- $A_{FB}^f \equiv \frac{\sigma_B - \sigma_F}{\sigma_B + \sigma_F} \sim \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$ Forward-backward asymmetry

  $\mathcal{A}_f = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2}$ Coupling Parameter

- $\mathcal{P}_\tau \sim -\mathcal{A}_\tau$ Average τ polarization

- $A_{FB}^{pol} \sim -\frac{3}{4}\mathcal{A}_e$ τ polarization FB asymmetry

And, specific to SLC, observables related to polarized beams:

- $A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim -\mathcal{A}_e$ Left-Right asymmetry

- $\tilde{A}_{LR}^f \sim -\frac{3}{4}\mathcal{A}_f$ Left-Right forward-backward asymmetry

In the “Improved Born Approximation”, many of the radiative corrections absorbed by using effective couplings in above formulæ, and running α_{em} to M_Z.

LEP Beam Energy

Represents a formidable amount of work.

- Basic method – resonant depolarization $\rightarrow$ average E_{beam}, governed by $\int B \mathrm{d}\ell$

- Length of ring – geophysical effects (tides etc.)

- 1995 – calibrations at beginning + end of fills, also NMR probes, $\Rightarrow$ increase in energy during fill
(parasitic currents, trains, thermal effects)

- Further measurements in 1996, including detailed study of thermal behaviour of magnets

- $\Rightarrow$ phenomenological model developed to describe E_{beam} as function of time of day, time since last magnet cycling, temperature. Applicable to 1993-4 data as well.

- Further corrections at each interaction point (RF status etc).

Almost final errors on E_{cm} (in MeV):

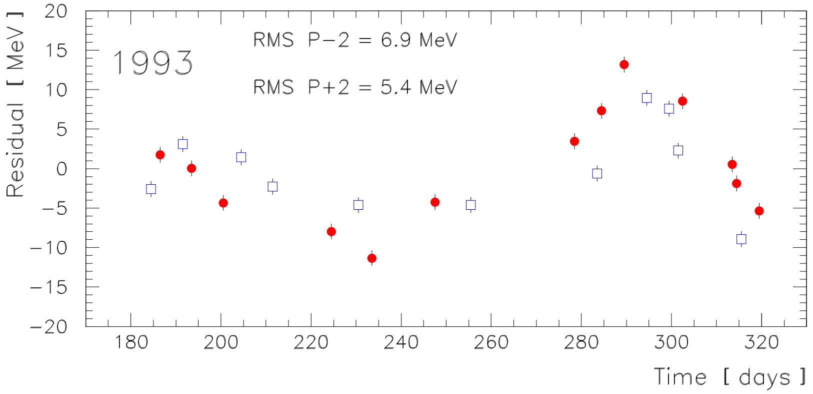
	peak$-$2	peak	peak+2
1993	3.5	6.7	3.0
1994		3.7	
1995	1.8	5.4	1.7

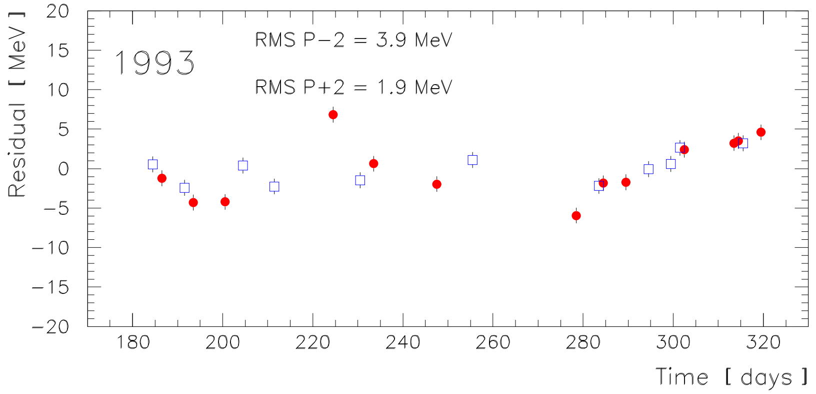
(+ correlations)

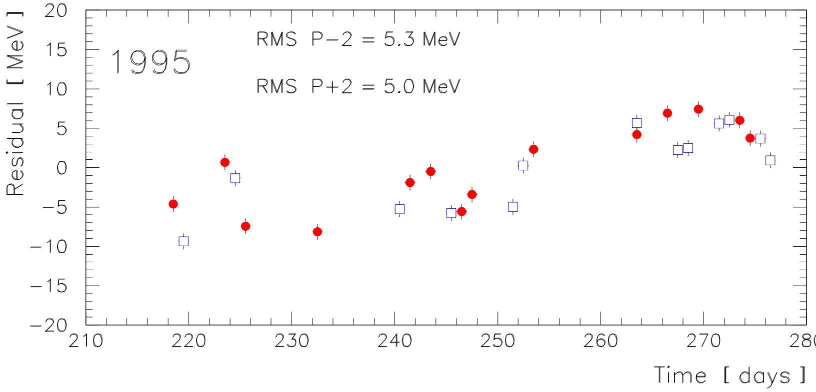
LEP Beam Energy

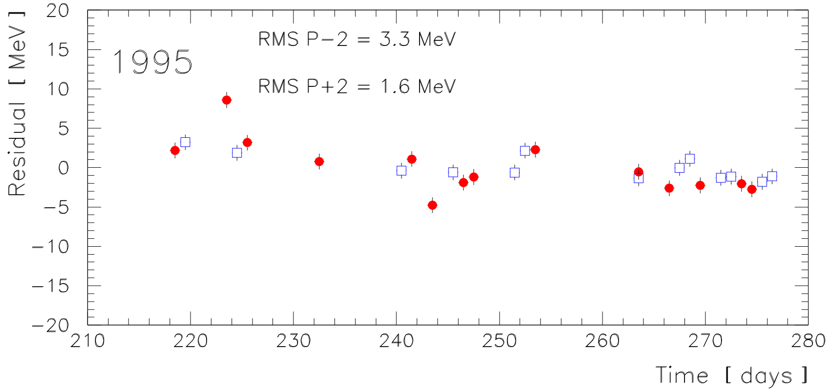
Residuals (for calibrated fills) before and after applying model correction

Before | **After**









Z^0 lineshape + lepton asymmetries

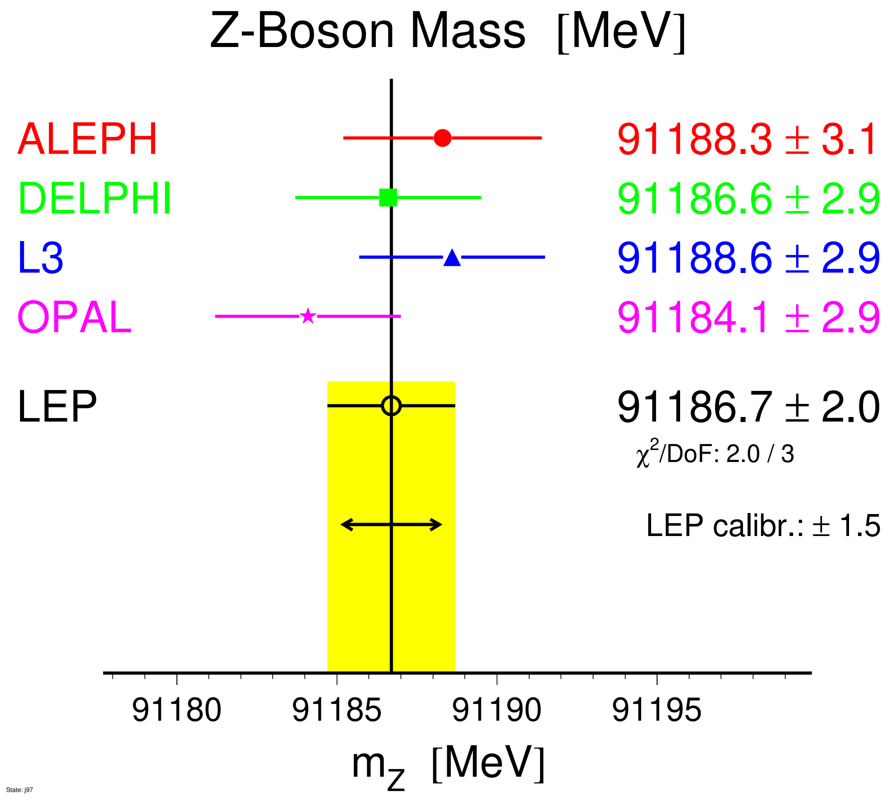
A brief summary of some of the main changes since last summer:

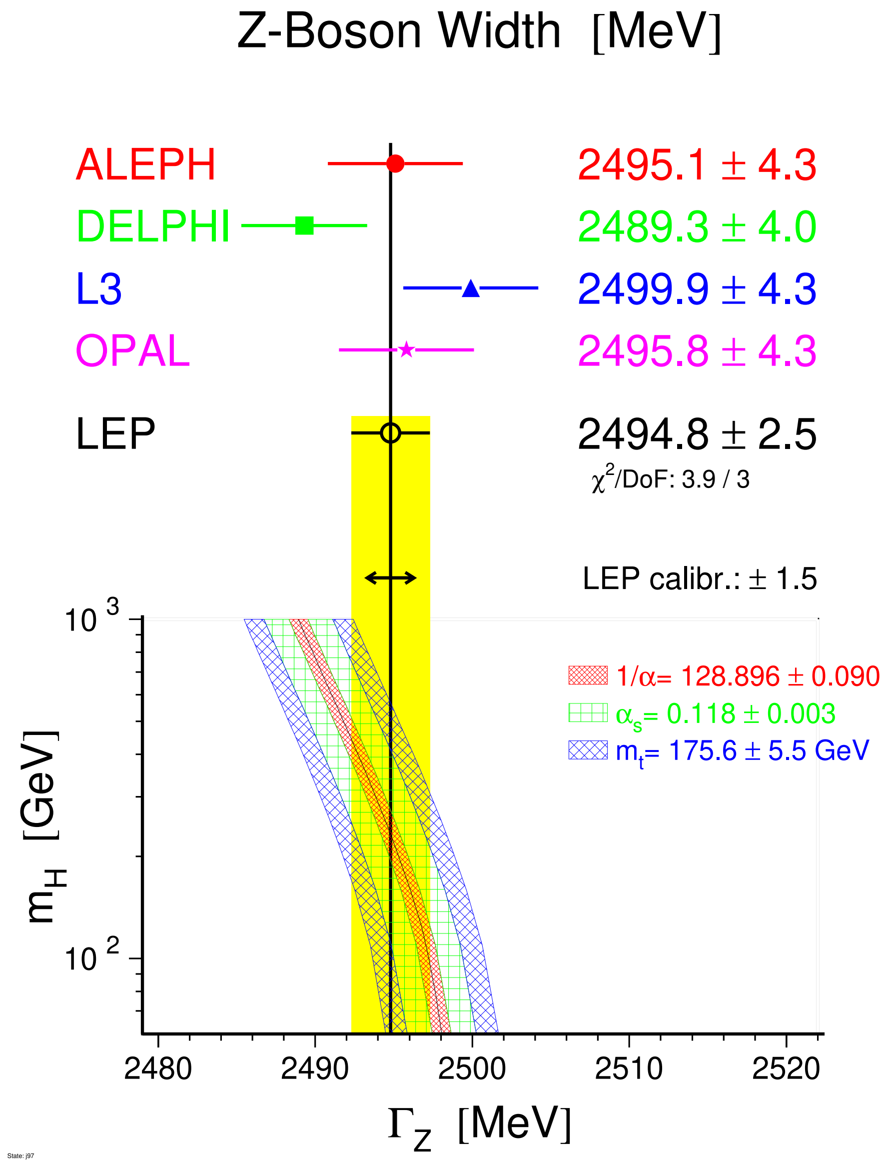
- LEP Beam energy Probably final beam energy + errors recently released. At present, used by ALEPH/DELPHI; not by OPAL/L3 (correction applied).
- Lineshape + $A_{\rm FB}^{\ell}$ Some 1995 data added (DO) Updates (especially $\Delta\sigma^0_{\rm had}$, $A_{\rm FB}^{0,\tau}$) (A)
  Final LEP I results awaiting definitive beam energy + errors $\Rightarrow$ PDG'98.
- τ polarization New result (inc. 1995 data) (L)
- $A_{\rm LR}$ (L-R asymmetry) 1996 result available (S)

Changes since last year quite small. Basic LEP measurements (assuming lepton universality):

$m_{\rm Z}$ /GeV	91.1867 ± 0.0020
$\Gamma_{\rm Z}$ /GeV	2.4948 ± 0.0025
$\sigma^0_{\rm h}$ /nb	41.486 ± 0.053
R_ℓ	20.775 ± 0.027
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010

χ^2/dof=22.7/31


Z-Boson Mass [MeV]
ALEPH 91188.3 ± 3.1
DELPHI 91186.6 ± 2.9
L3 91188.6 ± 2.9
OPAL 91184.1 ± 2.9
LEP 91186.7 ± 2.0
χ^2/DoF: 2.0 / 3
LEP calibr.: ± 1.5
91180
91185
91190
91195
m_Z [MeV]


Z-Boson Width [MeV]
ALEPH 2495.1 ± 4.3
DELPHI 2489.3 ± 4.0
L3 2499.9 ± 4.3
OPAL 2495.8 ± 4.3
LEP 2494.8 ± 2.5
χ^2/DoF: 3.9 / 3
LEP calibr.: ± 1.5
10^3
10^2
m_H [GeV]
$1/\alpha$= 128.896 ± 0.090
α_s= 0.118 ± 0.003
m_t= 175.6 ± 5.5 GeV
2480
2490
2500
2510
2520
Γ_Z [MeV]

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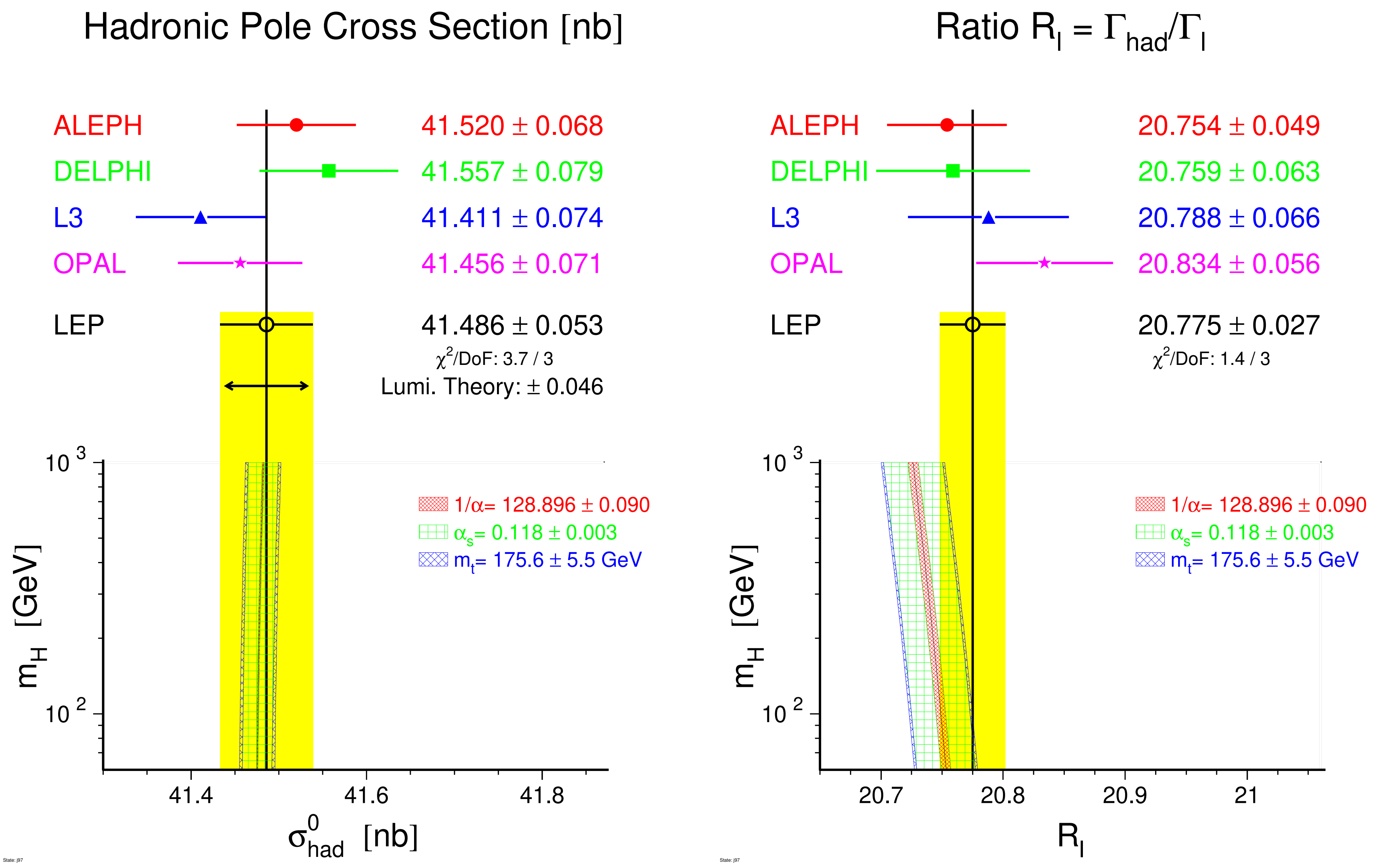

EPS Jerusalem 25 August 1997

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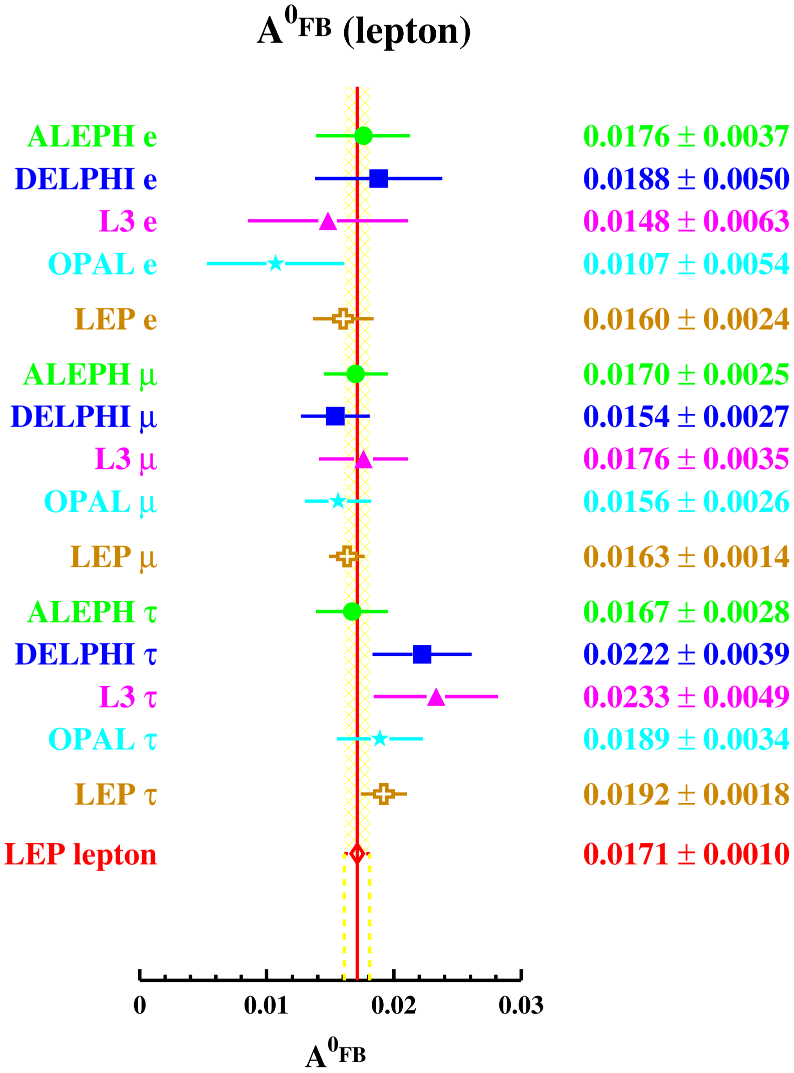

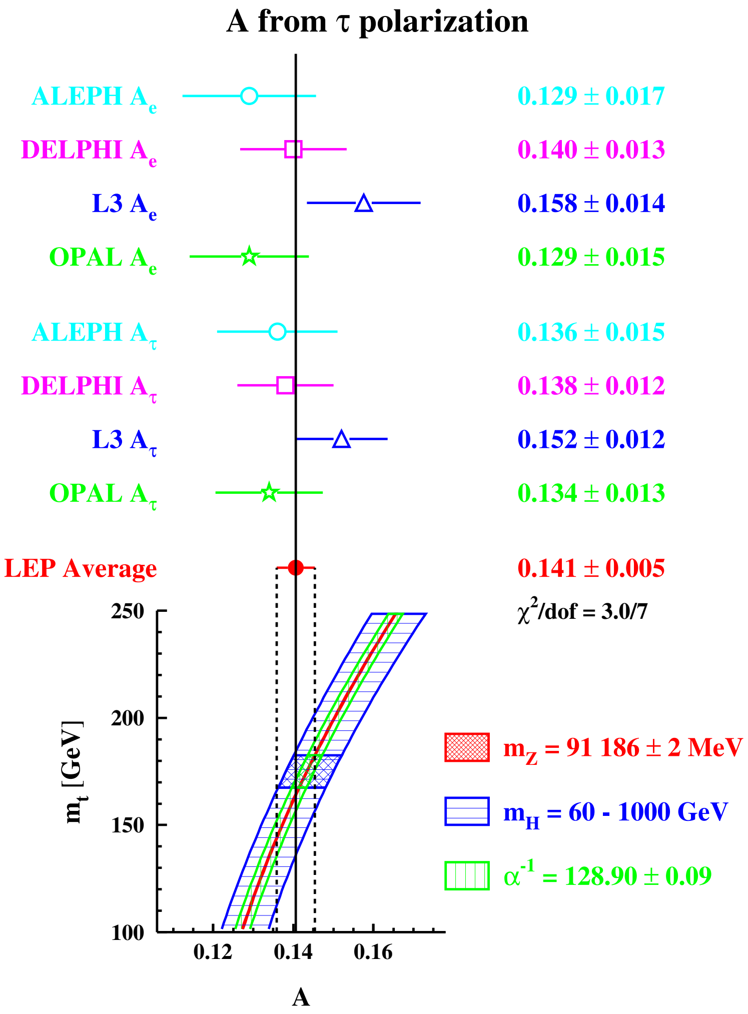

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Z^0 lineshape + lepton asymmetries

And the results without assuming lepton universality:

m_Z /GeV	91.1867 ± 0.0020
Γ_Z /GeV	2.4948 ± 0.0025
σ_h^0 /nb	41.486 ± 0.053
R_e	20.757 ± 0.056
R_μ	20.783 ± 0.037
R_τ	20.823 ± 0.050
$A_{FB}^{0,e}$	0.0160 ± 0.0024
$A_{FB}^{0,\mu}$	0.0163 ± 0.0014
$A_{FB}^{0,\tau}$	0.0192 ± 0.0018

χ^2/dof=20.5/27

Number of light neutrinos?

$$\Gamma_{inv} = 500.1 \pm 1.8 \text{ MeV}$$

$$N_\nu = 2.993 \pm 0.011$$

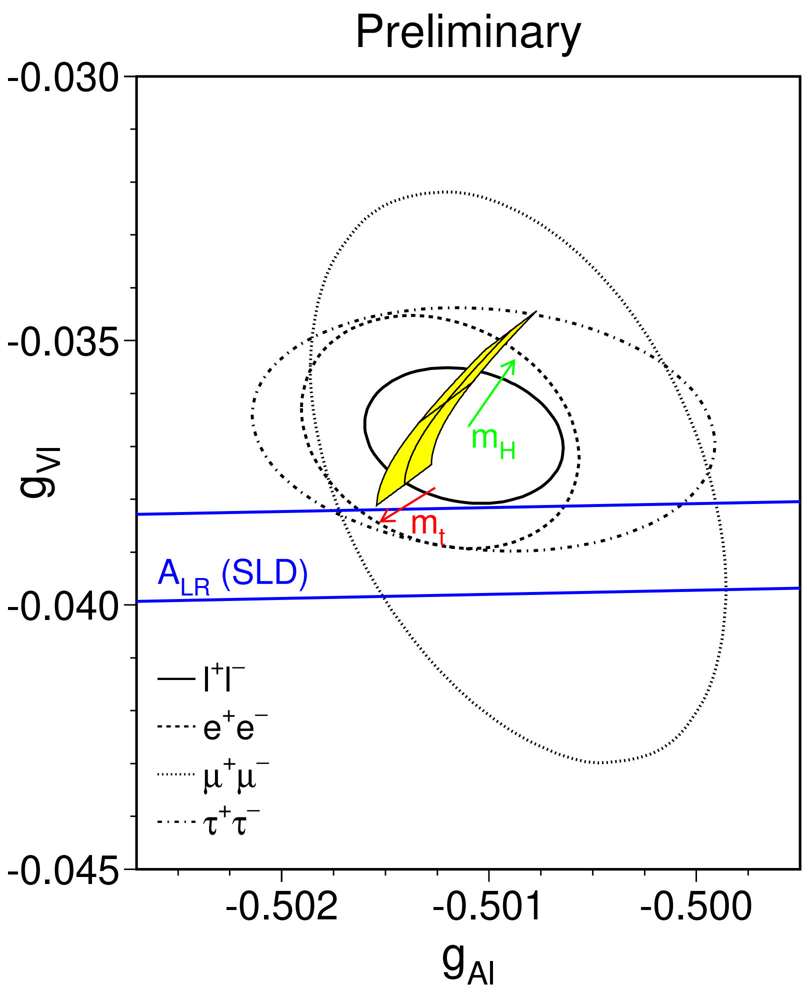
Additional invisible width?

$$\Delta\Gamma_{inv} = \Gamma_{inv} - 3\Gamma_\nu^{SM} = -1.2 \pm 1.8 \text{ MeV}$$

or $\Delta\Gamma_{inv} < 2.8$ MeV (95% c.l.)

Lepton universality

As well as leptonic Z^0 widths and asymmetries, include information from τ polarization to provide best constraints on lepton universality.



Tests universality at the 0.2% level for g_A, 5–10% for g_V.

Assuming universality:

	LEP	LEP+SLD
$g_{V\ell}$	-0.03681 ± 0.00085	-0.03793 ± 0.00058
$g_{A\ell}$	-0.50112 ± 0.00032	-0.50103 ± 0.00031
g_{ν}	$+0.50125 \pm 0.00092$	$+0.50125 \pm 0.00092$

Heavy Flavour Electroweak

A brief summary of some of the main changes since last summer:

- R_b Recent preliminary results published (AOS), new results (DLS)
- R_c Recent preliminary result published (O)New results (AS)
- A_FB^b New results (LO); withdrawn result (A)
- $\mathcal{A}_\mathrm{b}$, $\mathcal{A}_\mathrm{c}$ (L-R asymmetries) updated (S)

Summary of results (fit to all heavy flavour electroweak data):

R_b	0.2170 ± 0.0009
R_c	0.1734 ± 0.0048
$A_\mathrm{FB}^{0,\mathrm{b}}$	0.0984 ± 0.0024
$A_\mathrm{FB}^{0,\mathrm{c}}$	0.0741 ± 0.0048
$\mathcal{A}_\mathrm{b}$	0.900 ± 0.050
$\mathcal{A}_\mathrm{c}$	0.650 ± 0.058

Main improvements since last year are R_b, R_c, $\mathcal{A}_\mathrm{c}$.

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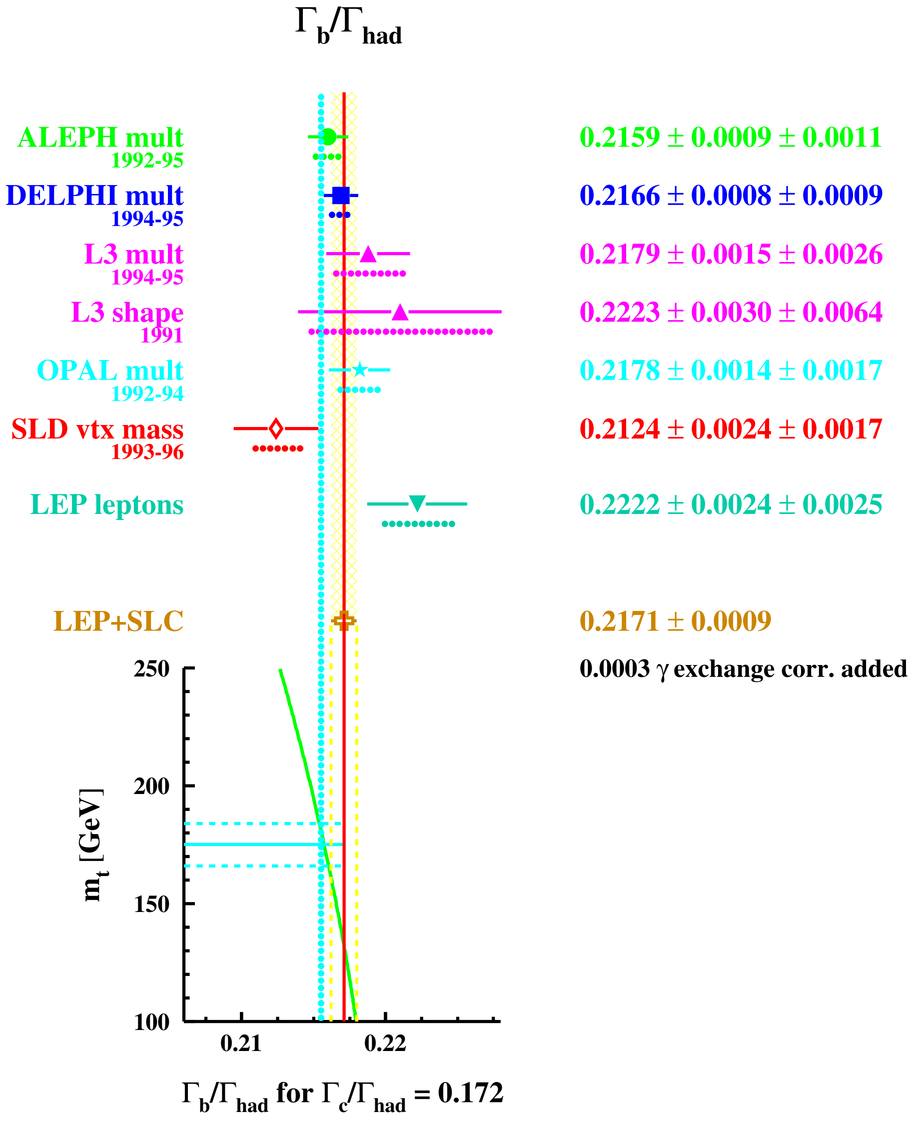
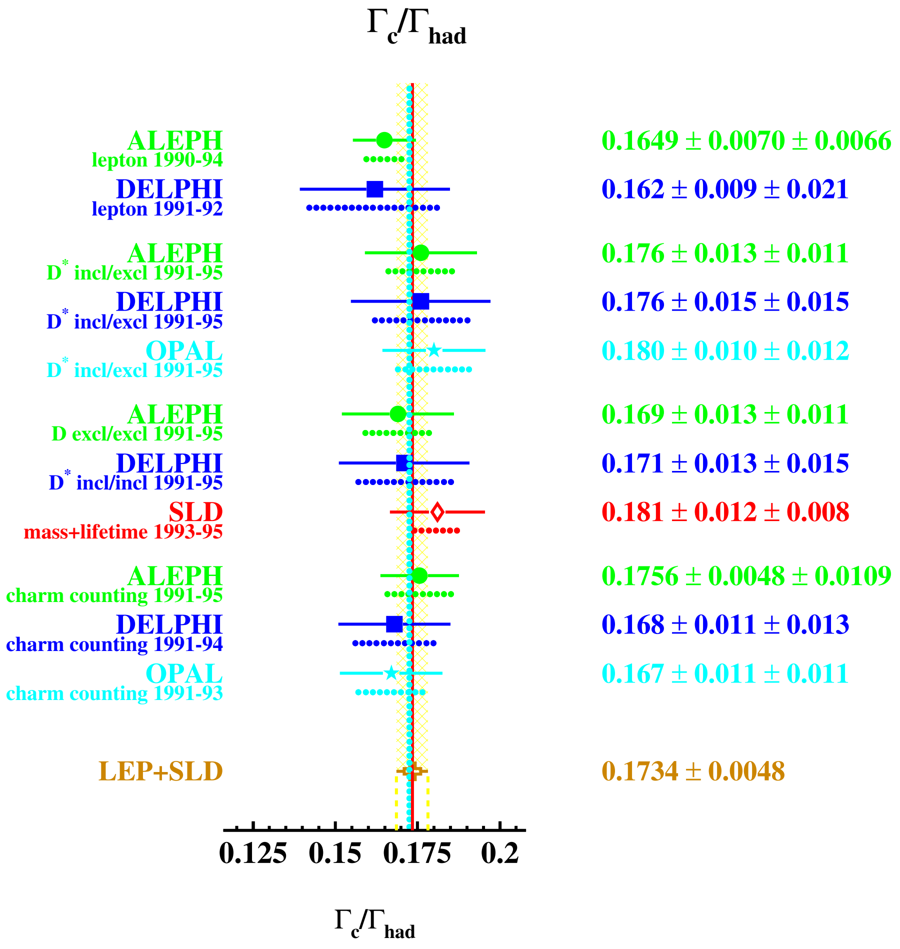
R_b and R_c





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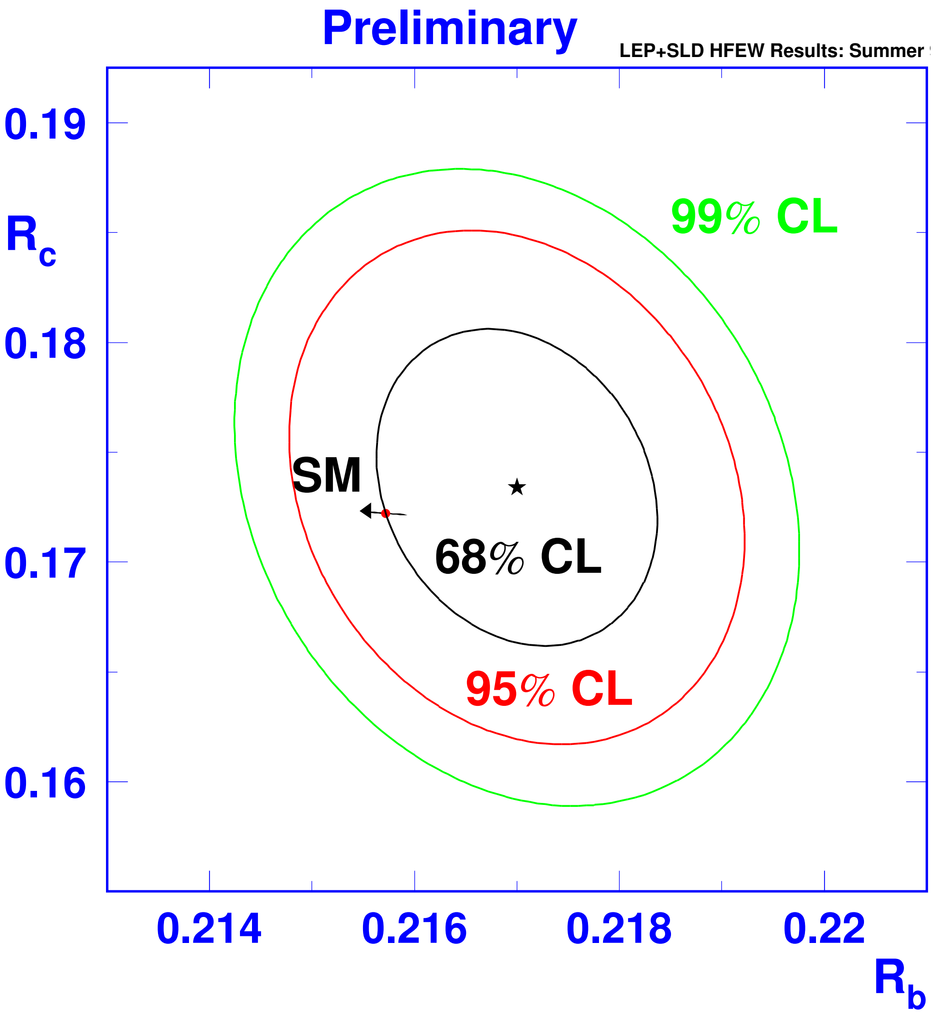
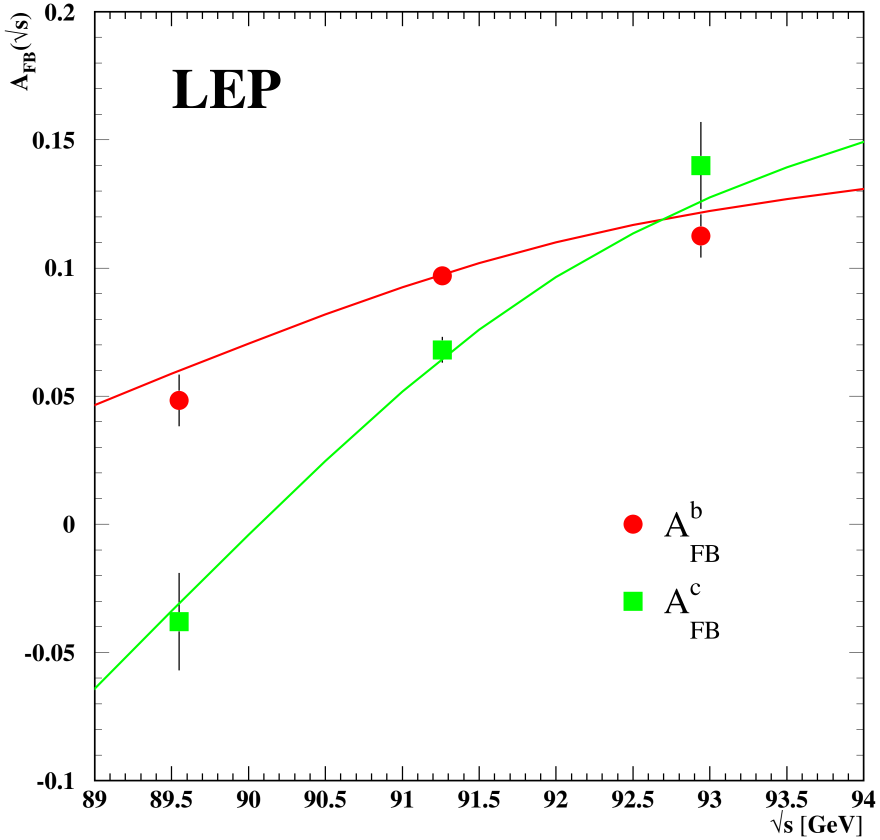
R_b vs. R_c



A_{FB}^{0b} and A_{FB}^{0c}

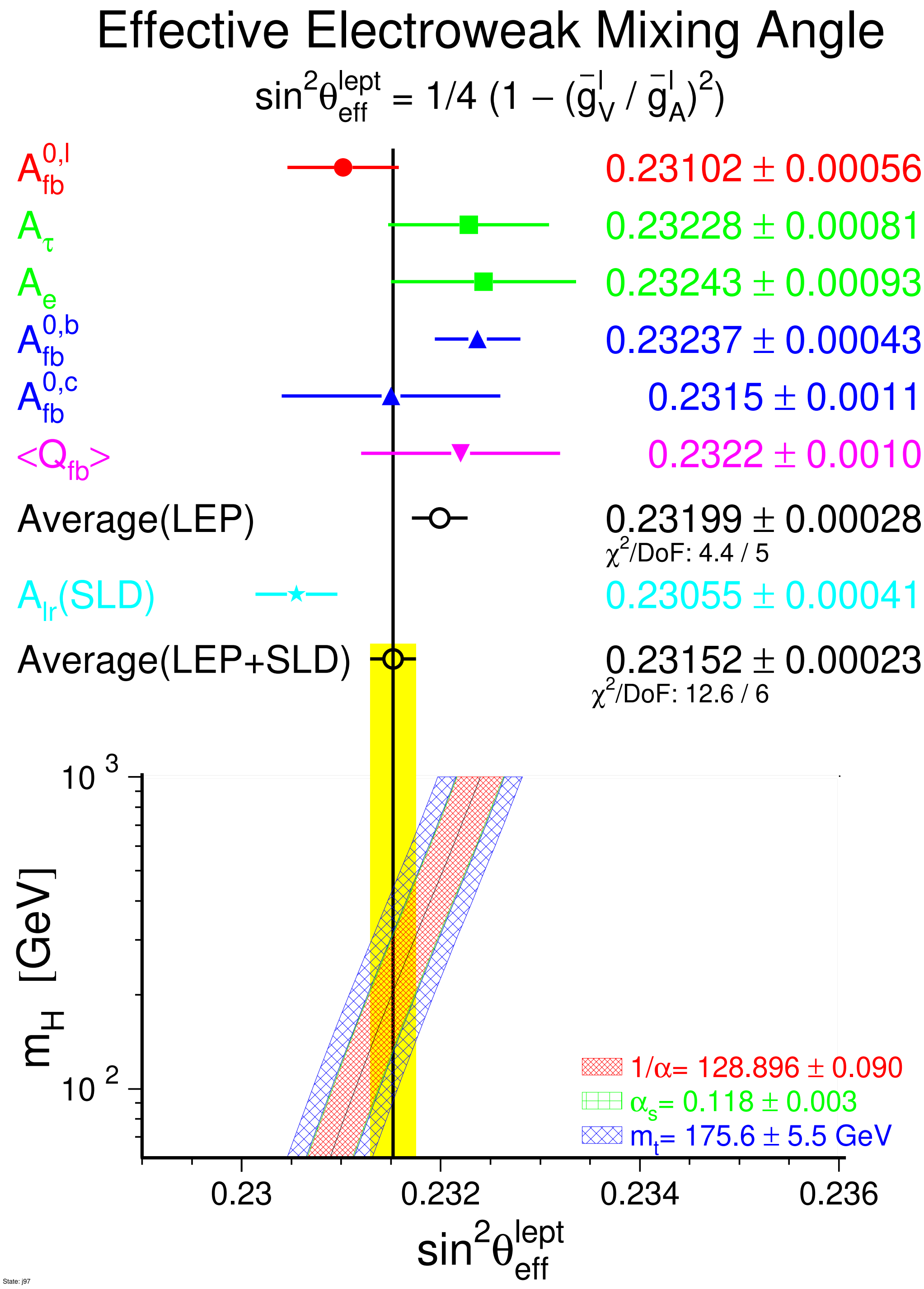


Errors improved by factor ~ 3 in the 4 years since EPS Marseille;

and R_b by factor ~ 2 since Brussels.

$\sin^2\theta_W^{\rm eff}$

The various asymmetry measurements all effectively measure $\sin^2\theta_W^{\rm eff}$ $\rightarrow$ check consistency.



Coupling parameters

- Leptons SM$\longrightarrow$ 0.1467 (from global fit)

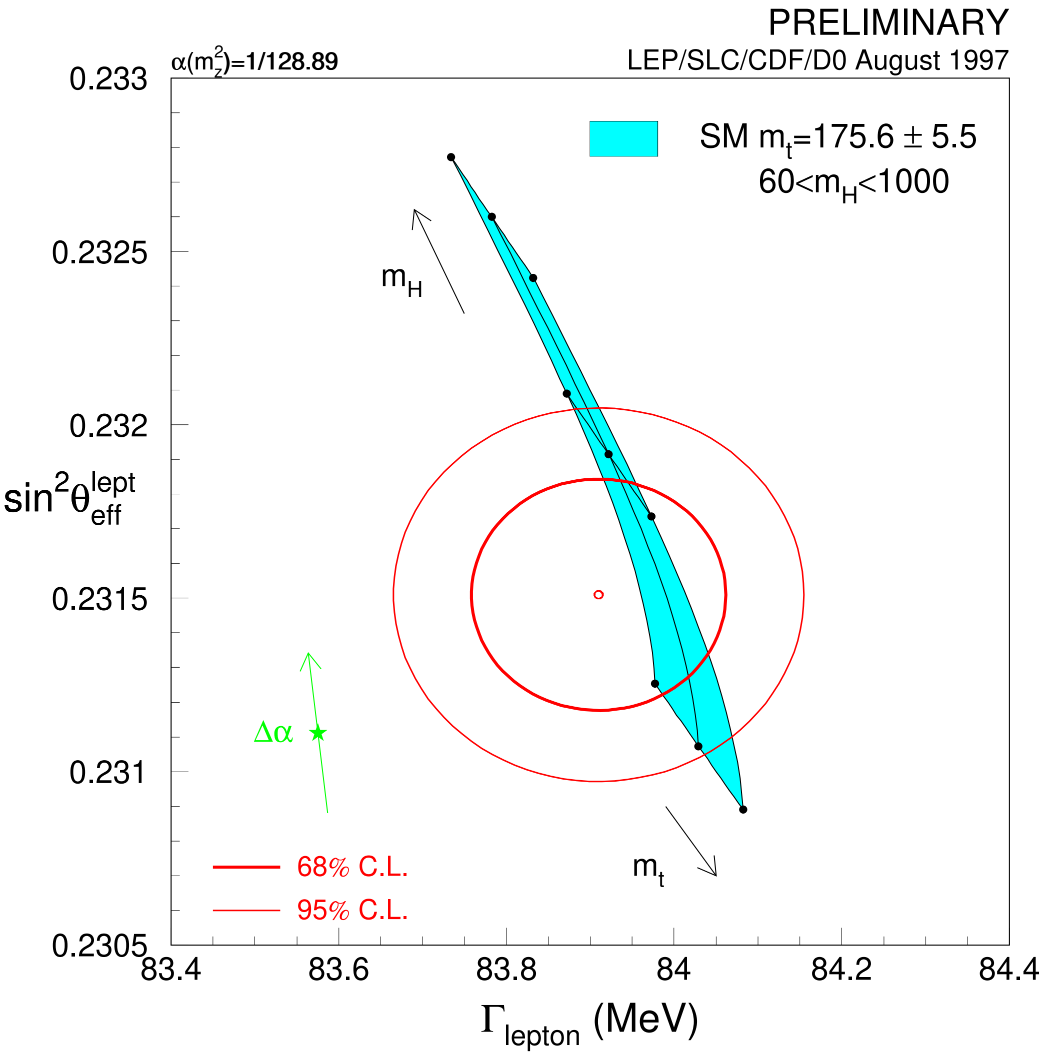
	$\mathcal{A}_\ell$	Cumulative average	χ^2/dof
$A_{\mathrm{FB}}^{0,\ell}$	0.1510 ± 0.0044		
$\mathcal{P}_\tau$	0.1406 ± 0.0048	0.1461 ± 0.0033	2.5/1
A_{LR} SLD	0.1547 ± 0.0032	0.1505 ± 0.0023	6.0/2

- Quarks SM$\Rightarrow$ $\mathcal{A}_\mathrm{b} = 0.935; \quad \mathcal{A}_\mathrm{c} = 0.668$

	$\mathcal{A}_\mathrm{b}$	$\mathcal{A}_\mathrm{c}$	($\mathcal{A}_\mathrm{e} =$)
LEP A_{FB}	0.897 ± 0.030	0.674 ± 0.046	(0.1461)
SLD	0.900 ± 0.050	0.647 ± 0.058	
LEP + SLD	0.877 ± 0.023	0.653 ± 0.037	(0.1505)

Appears to be some discrepancy in LEP+SLD $\mathcal{A}_\mathrm{b}$ w.r.t. SM, but includes effect of A_{LR}, which is also somewhat discrepant.

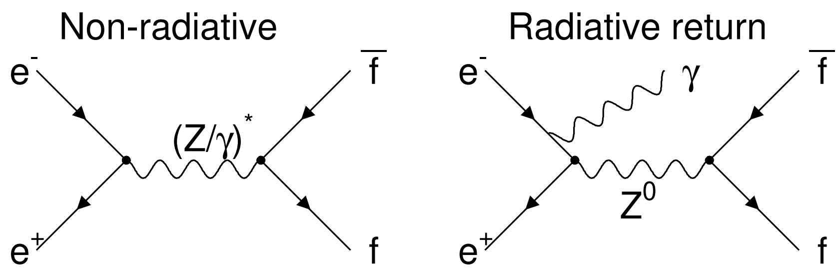
Electroweak radiative corrections



- The $\star$ shows SM expectation with only photon vacuum polarization corrections. $\Rightarrow$ electroweak corrections are needed
- n.b. The uncertainty in $\alpha(M_Z)$ is comparable with the experimental error on $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$.
- Can use the LEP/SLD/FNAL data to constrain Higgs mass...

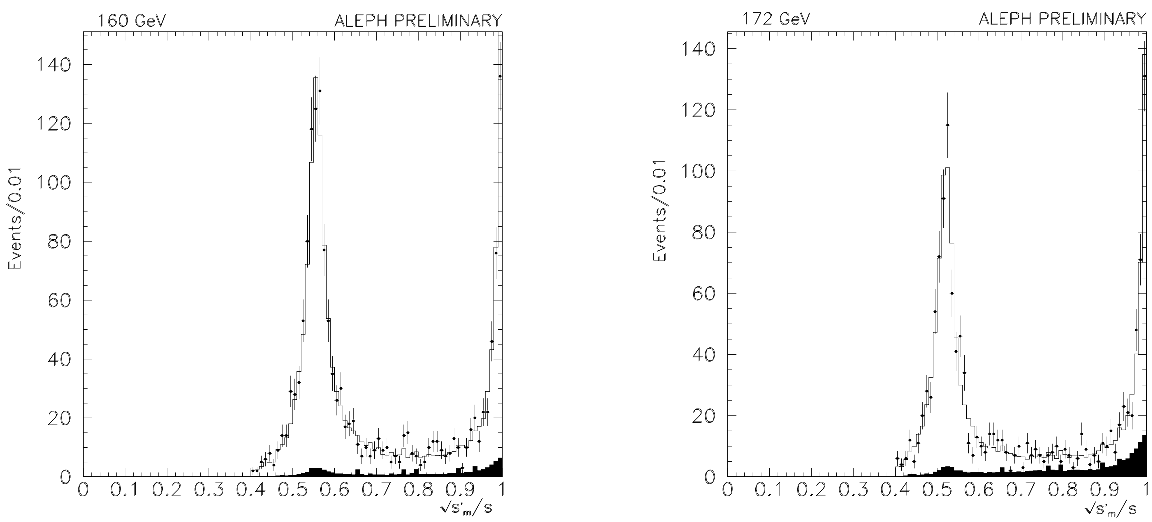
Two-fermion production at LEP2

- Initial state radiation very significant, especially radiative return to the Z pole:



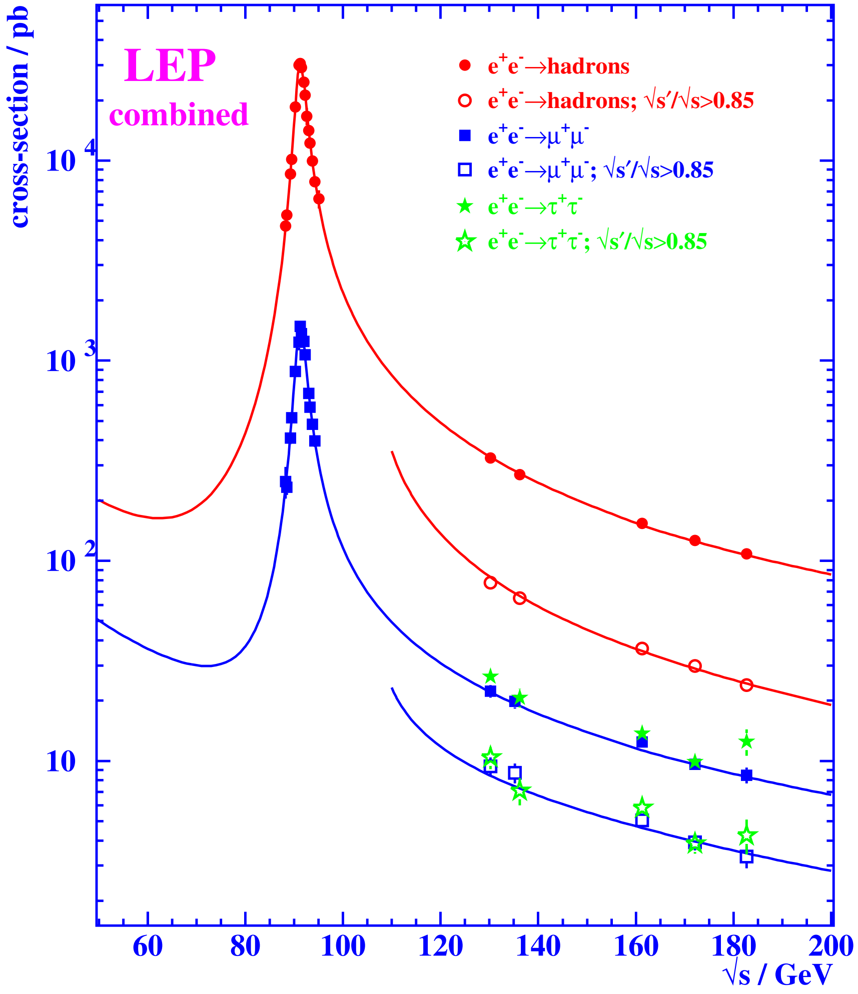
- Main interest is in the non-radiative sample, where new physics could show up.

- Define s' as the effective mass^2 of the $\mathrm{f\bar{f}}$ system after ISR.

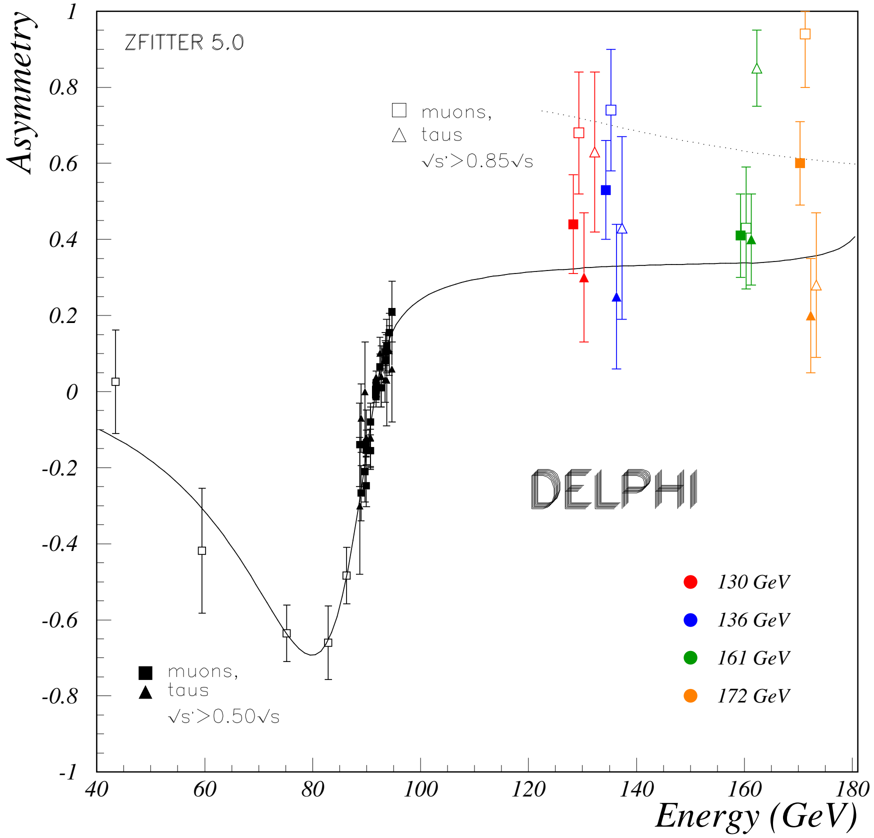


- Distributions of $\sqrt{s'/s}$ (measured from event kinematics).

Cross-sections



FB asymmetries



n.b. Preliminary data at 183 GeV included.

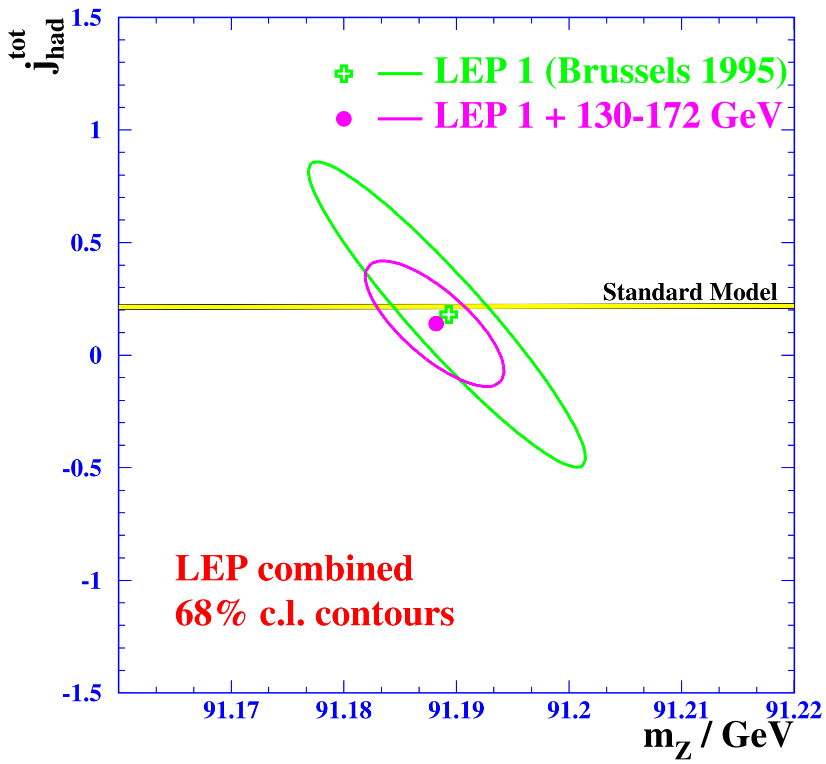
n.b. use of radiative Z events ($\Rightarrow \sqrt{s'} < M_Z$)

Two-fermion production at LEP2

- In standard (IBA) electroweak fits at the Z peak, γ-Z interference is not well constrained by the data $\Rightarrow$ fixed to SM expectation

- Above the Z peak, γ-Z interference sizeable, so data can be used to constrain it

- e.g. in the S-matrix formalism, $j_{\mathrm{had}}^{\mathrm{tot}}$ parametrizes the γ-Z interference in the hadronic cross-section.



LEP1+LEP2+TOPAZ$\Rightarrow$ $M_{\mathrm{Z}} = 91.1882 \pm 0.0029$

and $j_{\mathrm{had}}^{\mathrm{tot}} = 0.14 \pm 0.12$ (c.f. 0.22 in SM)

Two-fermion production at LEP2

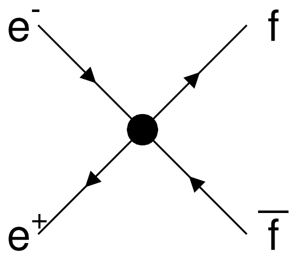
Alternatively, assume SM, except treat α_{em} as free parameter

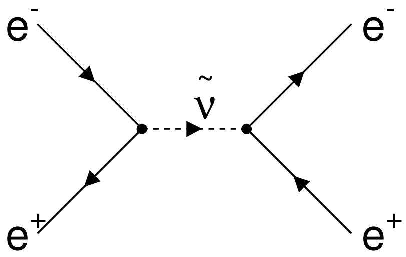
$\Rightarrow$ test running of α_{em}

e.g. OPAL$\Rightarrow$ $1/\alpha(157\mathrm{GeV}) = 119.9^{+6.6}_{-5.4}$

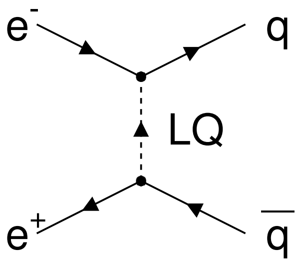
Place limits on new physics, e.g.

- Four-fermion contact interaction
- R-parity violating $\tilde{\nu}$

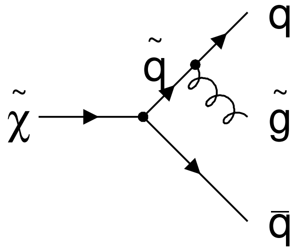




- Contribution of a virtual exchanged scalar (leptoquark?, RPV squark?) to $\mathrm{e^+e^-} \rightarrow \mathrm{q\overline{q}}$

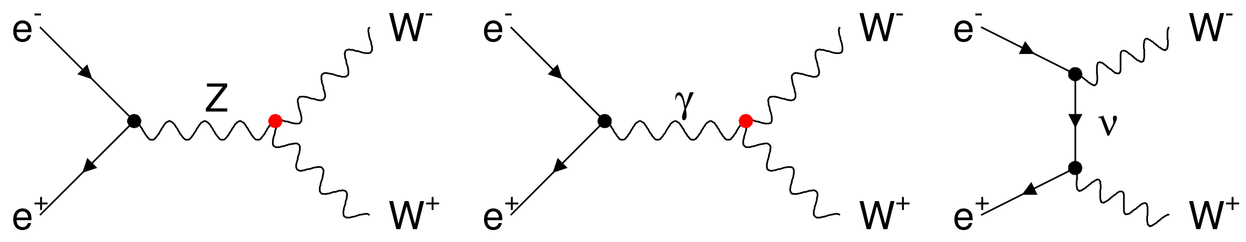


- Light gluino in $\tilde{\chi} \rightarrow \mathrm{q\overline{q}}\tilde{g}$
- Possible Z$'$



W^+W^- production at LEP2

Basic mechanisms:



Principal aims:

- W mass

  Indirect measurements from LEP I give M_W to about ± 40 MeV.

  Hence aim is to match this precision by direct measurement – test SM, constrain Higgs mass etc.

- Triple Gauge Couplings

  Search for any anomalies in the WWZ and WWγ couplings.

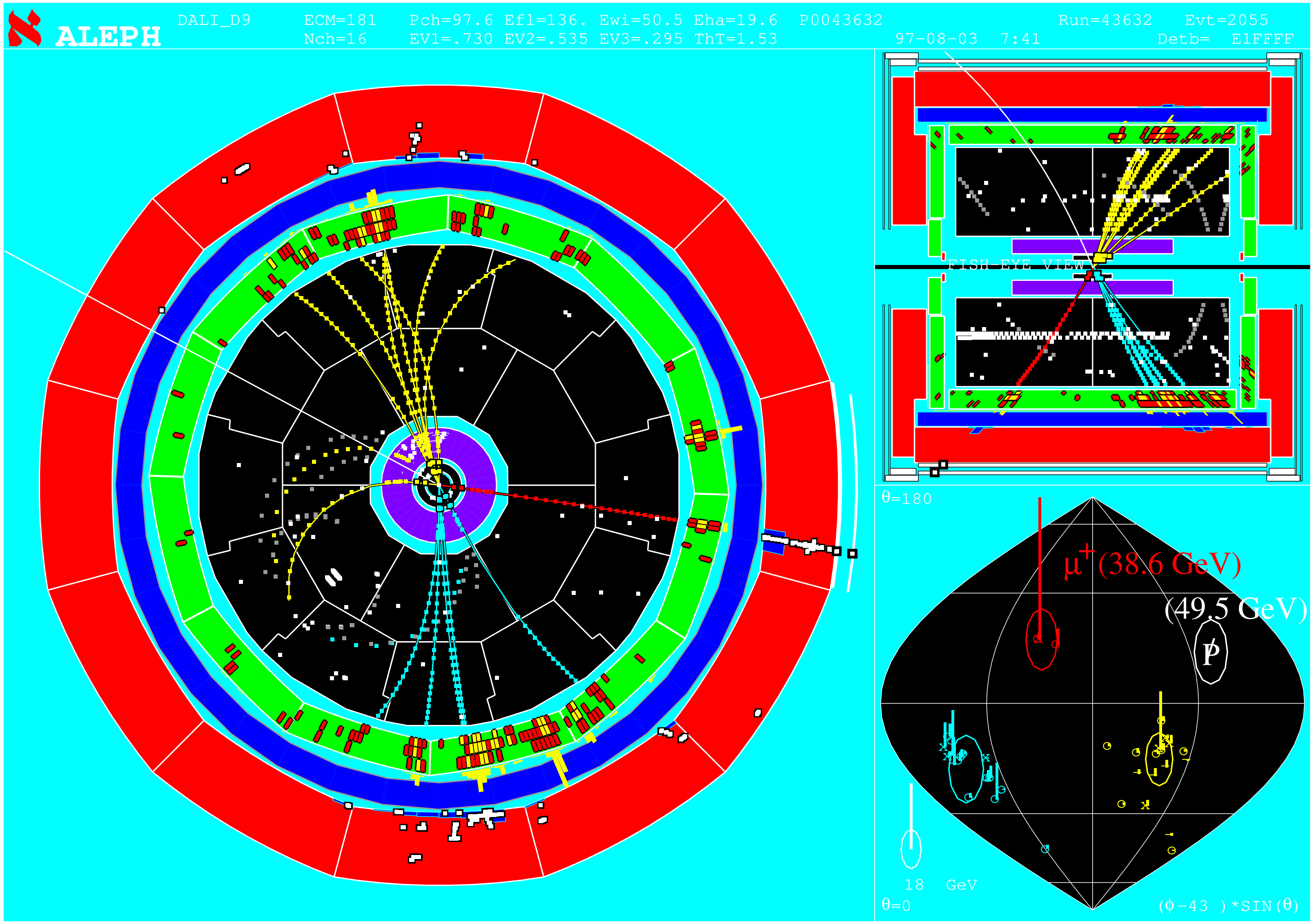
Events selected in the following channels:

$\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$ ($\sim 46\%$)

$\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ ($\sim 44\%$)

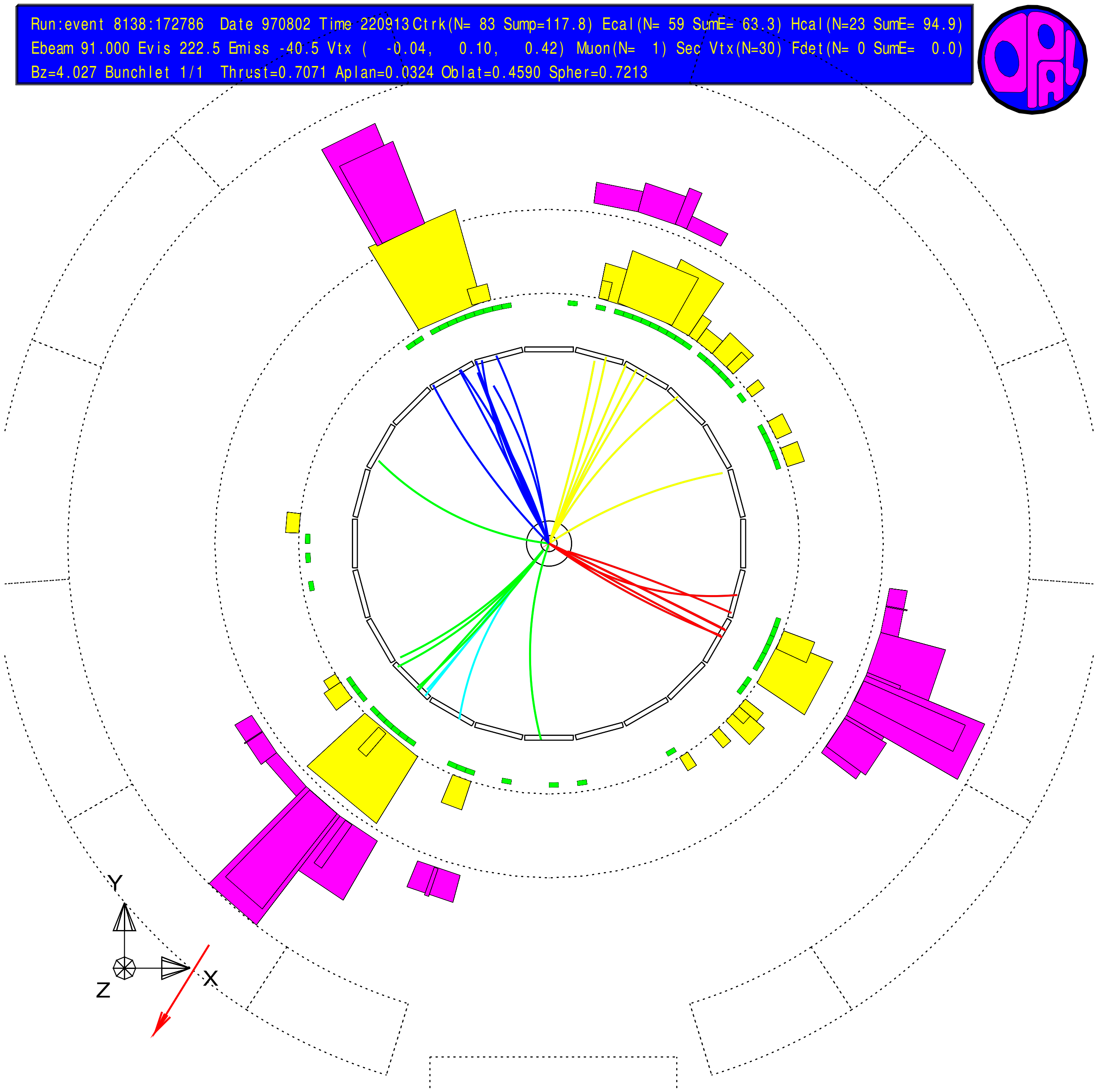
$\mathrm{W^+W^-} \rightarrow \ell\overline{\nu}_\ell\ell\nu_\ell$ ($\sim 10\%$)

$e^+e^- \to W^+W^- \to q\bar{q}\mu\nu$ at 181 GeV



Two jets; lepton (often isolated); missing energy and p_{T}

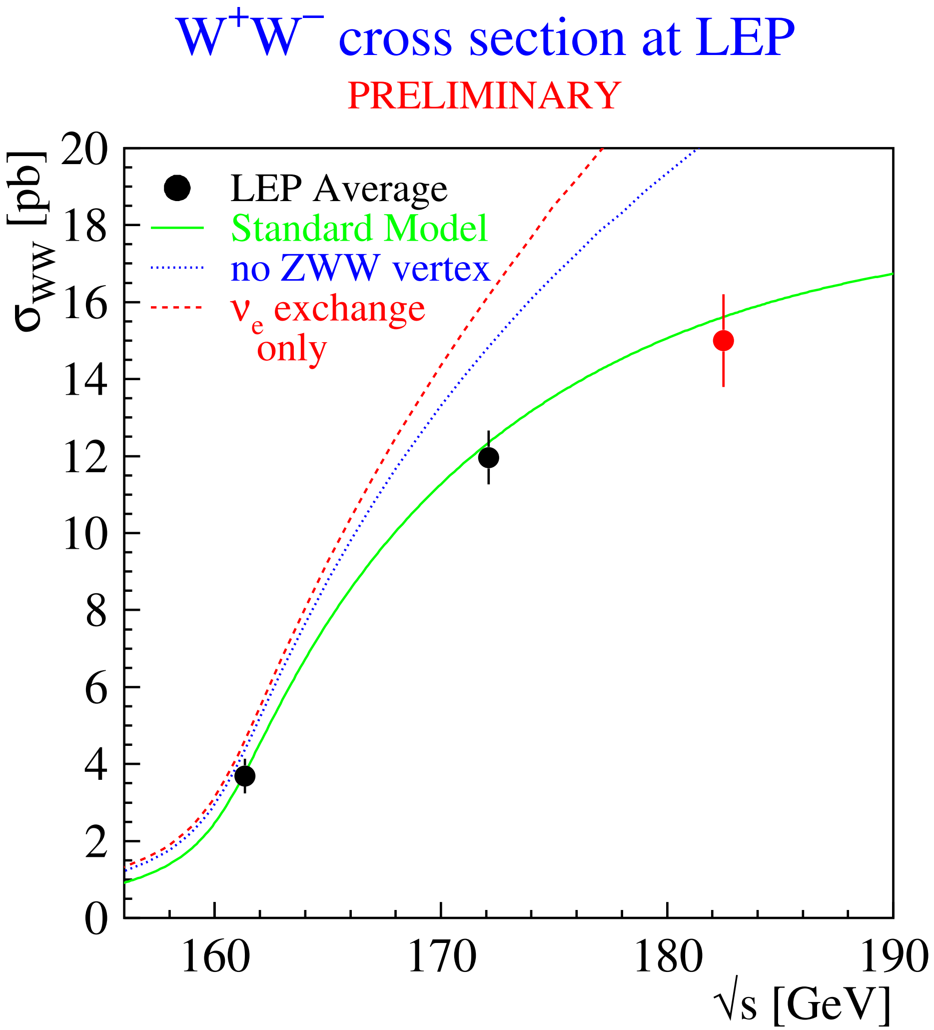
$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$ at 182 GeV

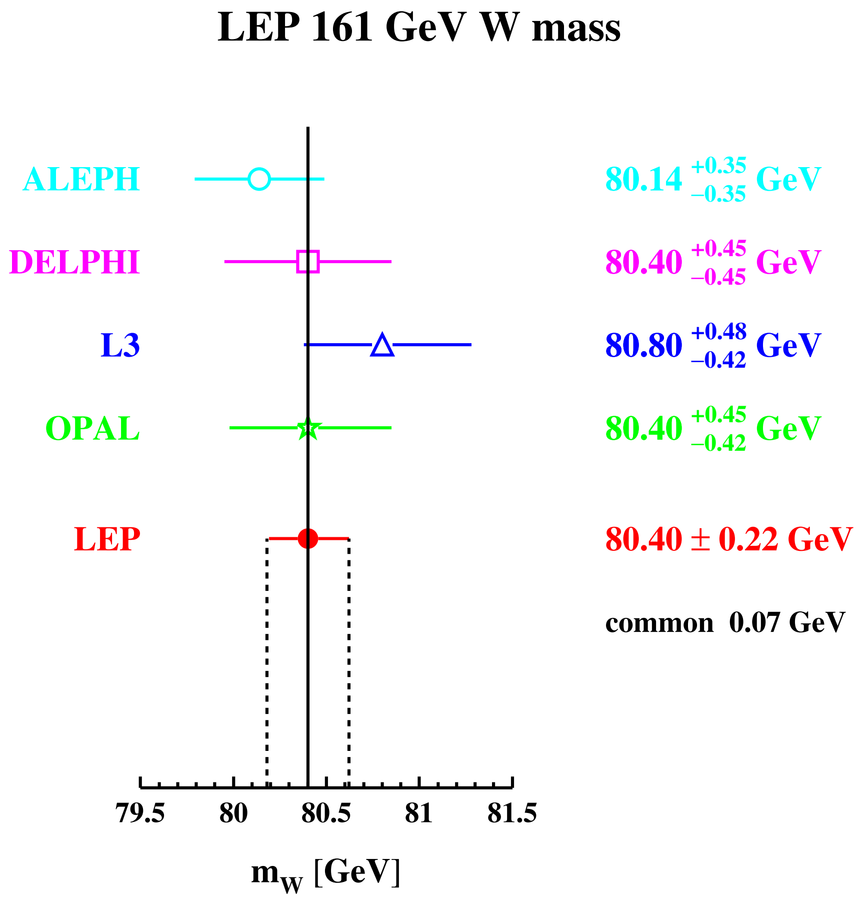


Four (or more) jets

W Mass at threshold (LEP)

At 161 GeV, just above W^+W^- threshold, $\sigma(W^+W^-)$ is very sensitive to M_W.



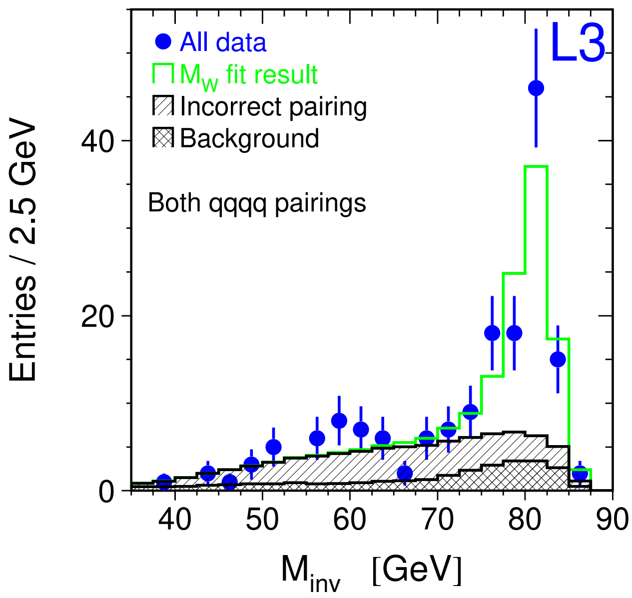


n.b. 183 GeV data highly preliminary

The errors are predominantly statistical.

W Mass by direct reconstruction (LEP)

- At higher energies, M_{W} is obtained by direct reconstruction of jet-jet invariant masses. Kinematic fit techniques are used to improve resolution. A typical mass spectrum:



- Combined result at 172 GeV: (errors predominantly statistical)

$$M_{\mathrm{W}} = 80.53 \pm 0.18 \text{ GeV (LEP 172 GeV; prelim.)}$$

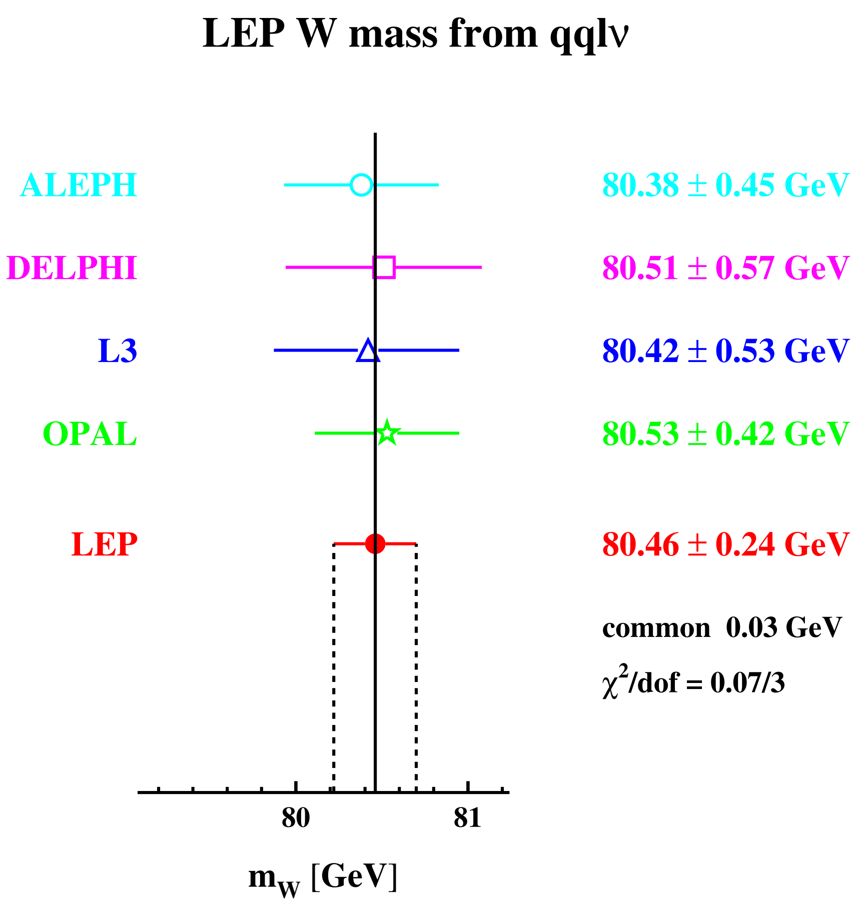
- Statistical power of direct reconstruction technique comparable to threshold method; systematics largely independent. Combine with LEP result at 161 GeV:

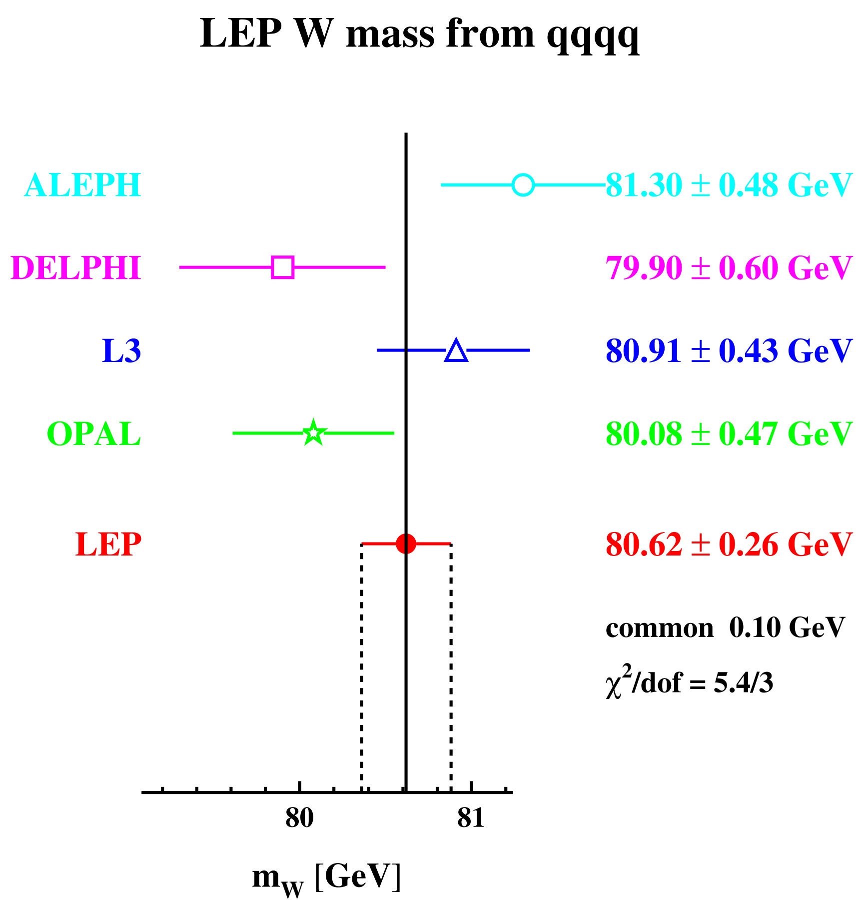
$$\boxed{M_{\mathrm{W}} = 80.48 \pm 0.14 \text{ GeV}} \text{ (LEP 1996)}$$

- $\mathrm{q\bar{q}q\bar{q}}$ channel potentially more problematic than $\mathrm{q\bar{q}}\ell\nu$: more background and colour reconnection + Bose-Einstein – estimated to contribute ~ 50 MeV error to combined 172 GeV result.

W Mass by direct reconstruction (LEP)

Good consistency between experiments, and between $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\nu$ channels.





Colour reconnection

- Important to try to measure such effects in data, e.g. comparing $q\bar{q}q\bar{q}$ with $q\bar{q}\ell\nu$.

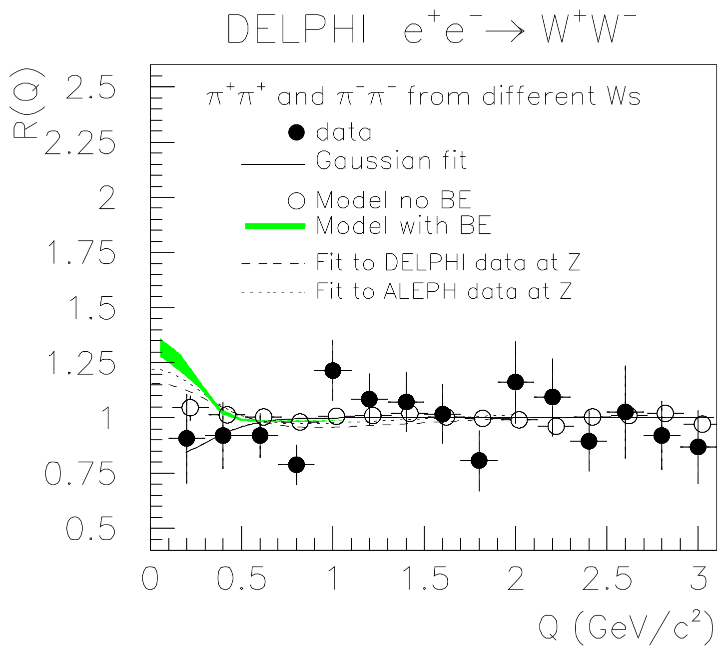
$$M_{\rm W}(q\bar{q}q\bar{q}) - M_{\rm W}(q\bar{q}\ell\nu_\ell) = 0.16 \pm 0.35 \text{ GeV}$$

- Models which predict large CR effects on $M_{\rm W}$ (e.g. Ellis/Geiger) predict other effects, e.g. decrease of up to 10% in $\langle n \rangle$ for $q\bar{q}q\bar{q}$.
- Data (DELPHI/L3/OPAL) give:

$$\frac{\langle n \rangle (q\bar{q}q\bar{q})}{2\langle n \rangle (q\bar{q}\ell\nu_\ell)} = 1.04 \pm 0.03$$

Bose-Einstein

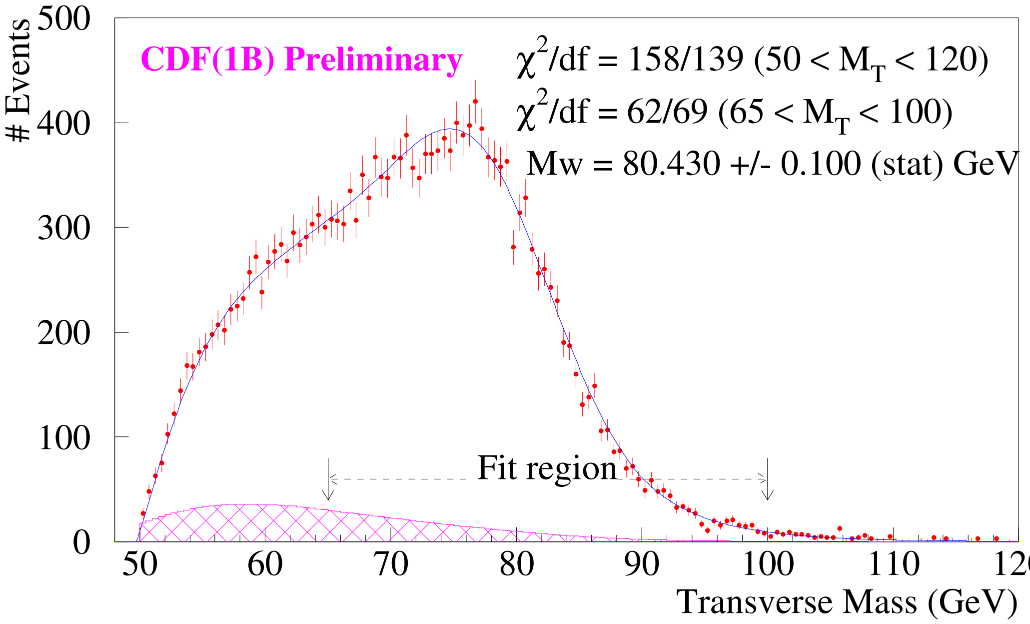
Experimental studies so far (DELPHI, ALEPH) show no evidence yet for BEC between different W bosons.



Recent theoretical studies suggest BEC may not be too serious.

W Mass from Tevatron

- Process studied is $q\bar{q}' \to \mathrm{W} \to \ell\nu$ ($\ell = \mathrm{e}/\mu$); detect neutrino from missing momentum; determine M_W from transverse mass distribution of $\ell\nu$:



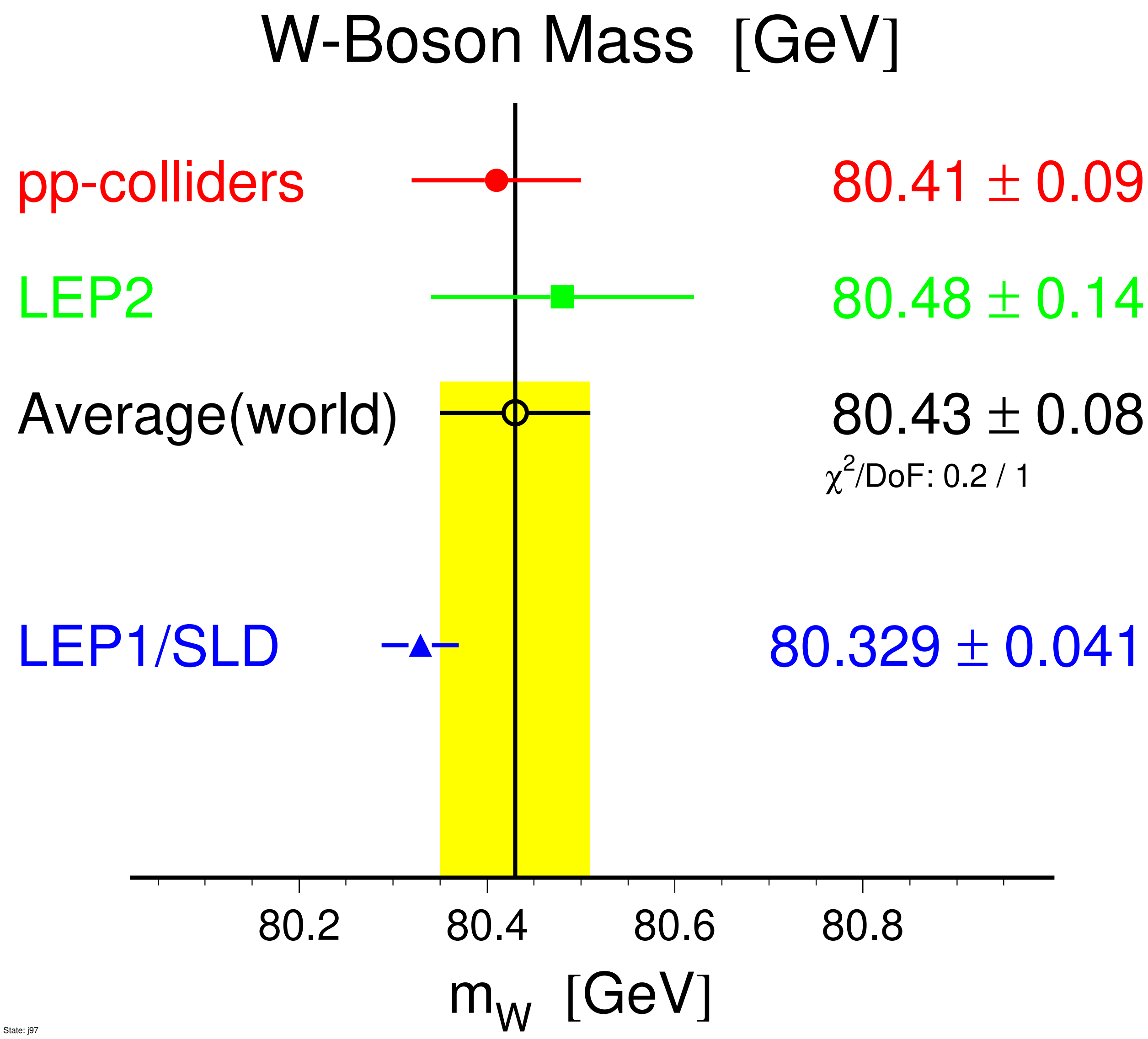
- Use Z^0, J/ψ for calibration of energy scale.
- Statistical and systematic errors comparable.

	m_W /GeV
CDF	80.375 ± 0.120
D0	80.44 ± 0.11

Combine with UA2 $\to$

$\boxed{M_\mathrm{W} = 80.41 \pm 0.09 \text{ GeV}}$ (hadron colliders)

W Mass – world compilation



- If LEP delivers 50 pb^{-1}/experiment in 1997, the LEP error should reduce to about 0.08 GeV.

- By the end of LEP2 and Tevatron Run 2, both expect to achieve error on M_{W} around 0.03–0.04 GeV.

SM fit to LEP/SLD/$\mathrm{p\overline{p}}/\nu\mathrm{p}$ data

Perform global electroweak fits to the SM using as inputs:

- Z^0 measurements from LEP/SLC
- M_W from LEP 2/Tevatron
- $m_\mathrm{t} = 175.6 \pm 5.5$ GeV CDF/D0
- $1 - M_\mathrm{W}^2/M_\mathrm{Z}^2 = 0.2254 \pm 0.0037$ from $\nu\mathrm{N}$ scattering

(includes new result from CCFR)

- $1/\alpha(M_\mathrm{Z}) = 128.894 \pm 0.090$

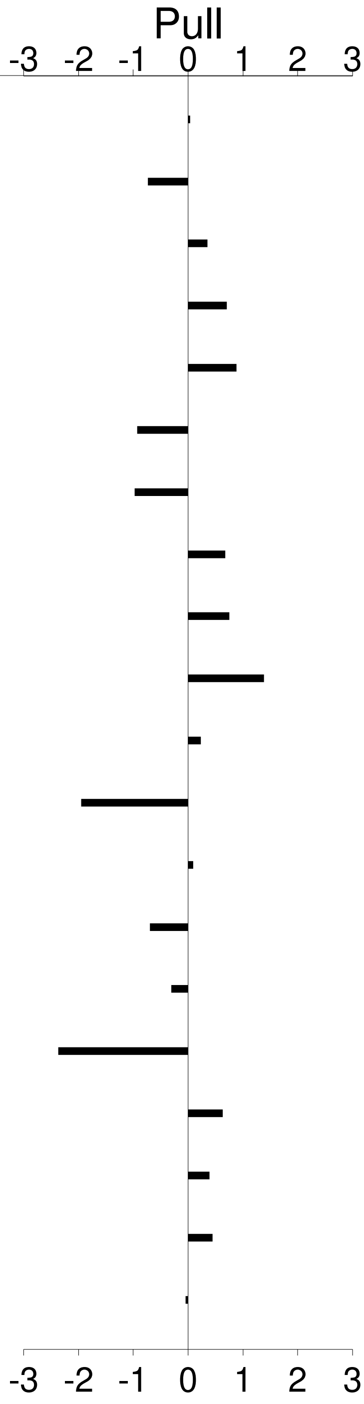
Treating m_H, $\alpha_\mathrm{s}(M_\mathrm{Z})$ and optionally m_t, M_W, as free parameters.

	LEP (inc. M_W)	All but M_W, m_t	All data
m_t / GeV	158^{+14}_{-11}	157^{+10}_{-9}	173.1 ± 5.4
m_H / GeV	83^{+168}_{-49}	41^{+64}_{-21}	115^{+116}_{-66}
$\log m_\mathrm{H}$	$1.92^{+0.48}_{-0.39}$	$1.62^{+0.41}_{-0.31}$	$2.06^{+0.30}_{-0.37}$
$\alpha_\mathrm{s}(M_\mathrm{Z})$	0.121±0.003	0.120±0.003	0.120±0.003
χ^2/dof	8/9	14/12	17/15
m_W / GeV	80.298±0.043	80.329±0.041	80.375±0.030

SM fit to LEP/SLD/$p\bar{p}$/νp data

Jerusalem 1997

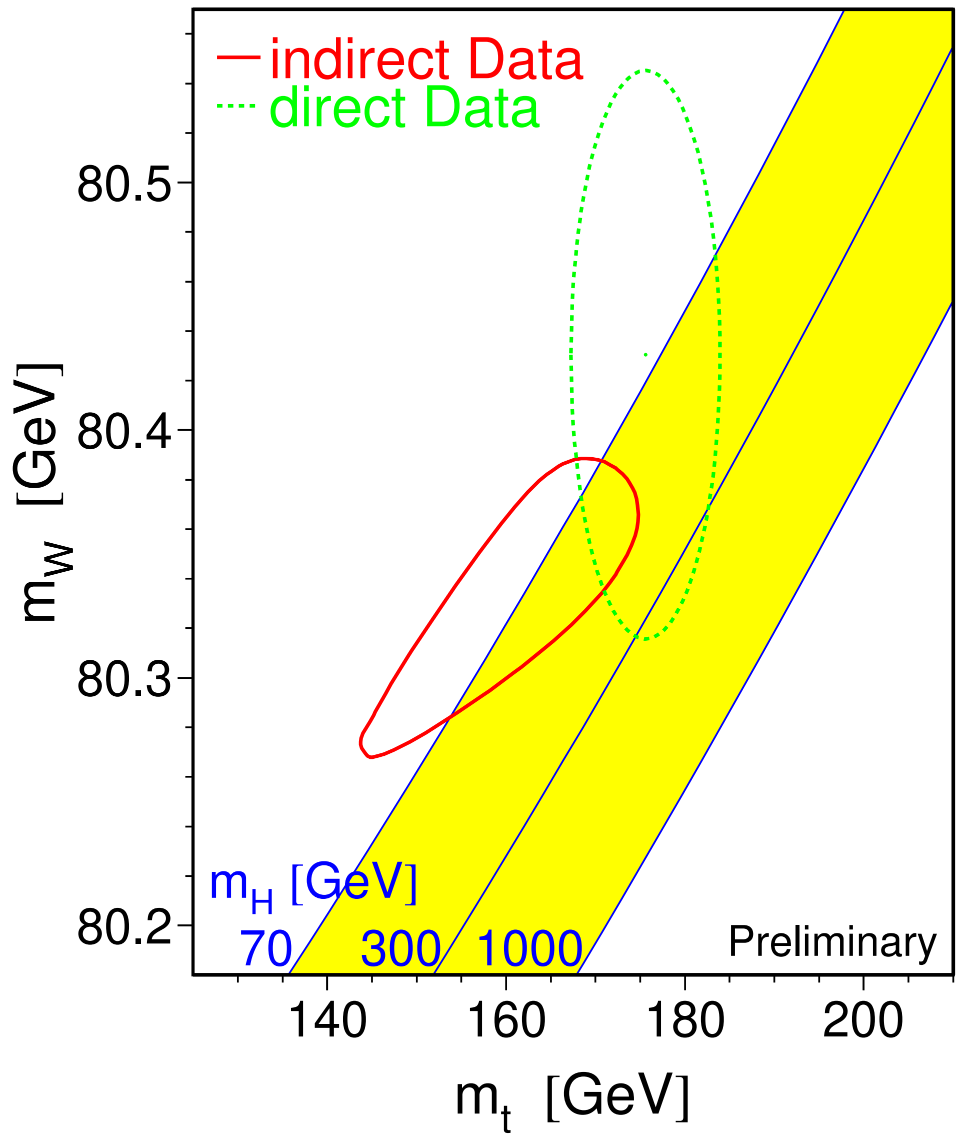
	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0020	.04
Γ_Z [GeV]	2.4948 ± 0.0025	-.73
σ^0_{hadr} [nb]	41.486 ± 0.053	.36
R_l	20.775 ± 0.027	.71
$A^{0,l}_{fb}$	0.0171 ± 0.0010	.89
A_τ	0.1411 ± 0.0064	-.93
A_e	0.1399 ± 0.0073	-.98
$\sin^2\theta^{lept}_{eff}$	0.2322 ± 0.0010	.68
m_W [GeV]	80.48 ± 0.14	.75
R_b	0.2170 ± 0.0009	1.38
R_c	0.1734 ± 0.0048	.24
$A^{0,b}_{fb}$	0.0984 ± 0.0024	-1.95
$A^{0,c}_{fb}$	0.0741 ± 0.0048	.09
A_b	0.900 ± 0.050	-.69
A_c	0.650 ± 0.058	-.31
$\sin^2\theta^{lept}_{eff}$	0.23055 ± 0.00041	-2.37
$1-m^2_W/m^2_Z$	0.2254 ± 0.0037	.63
m_W [GeV]	80.41 ± 0.09	.39
m_t [GeV]	175.6 ± 5.5	.45
$1/\alpha$	128.896 ± 0.090	-.05



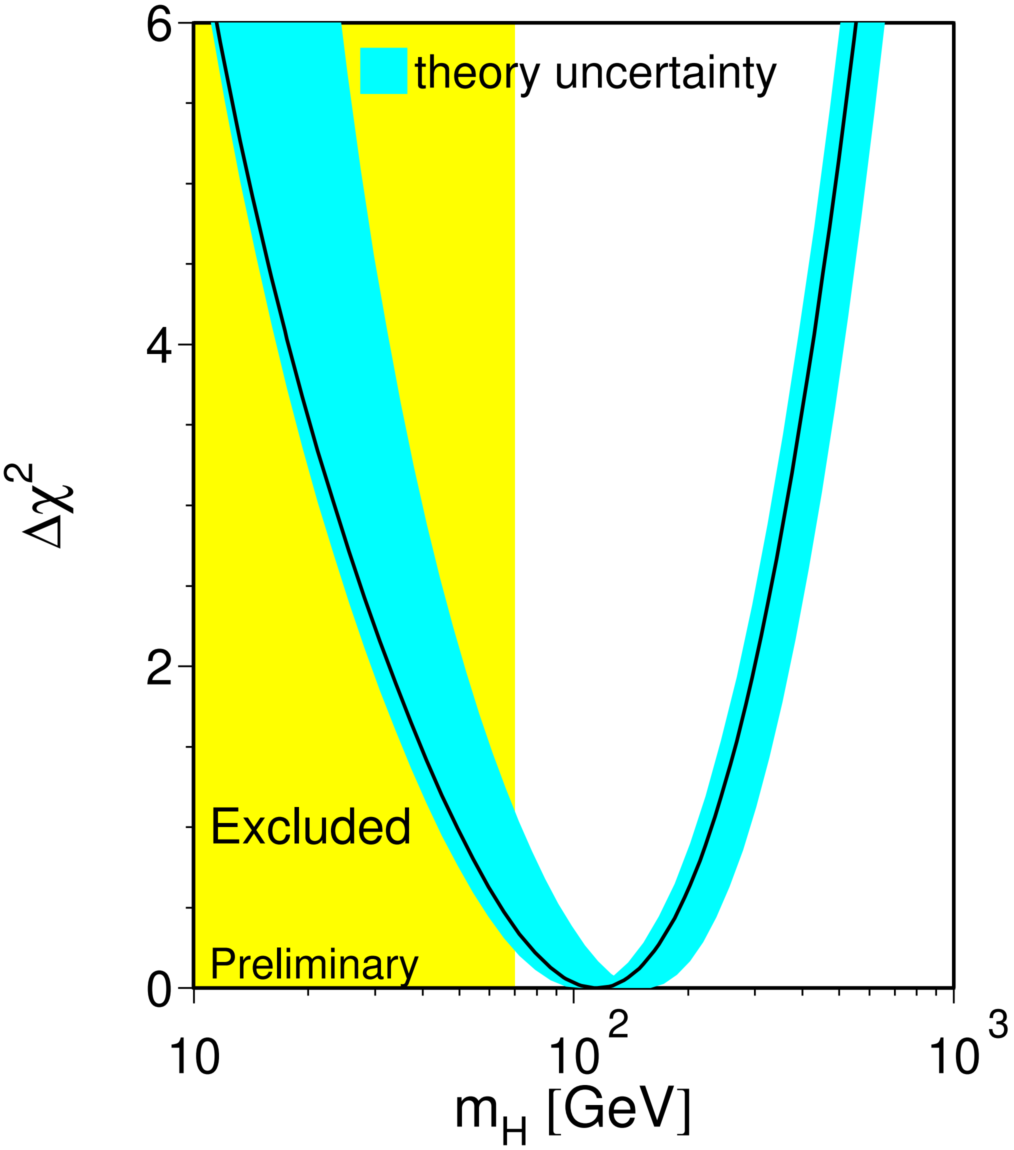
Fit SM to all data $\Rightarrow$ χ^2/dof = 17/15.

Consistency of $M_{\mathrm{W}}, m_{\mathrm{t}}$?

Compare the indirect determination with direct measurements.



Implications for M_{H}?



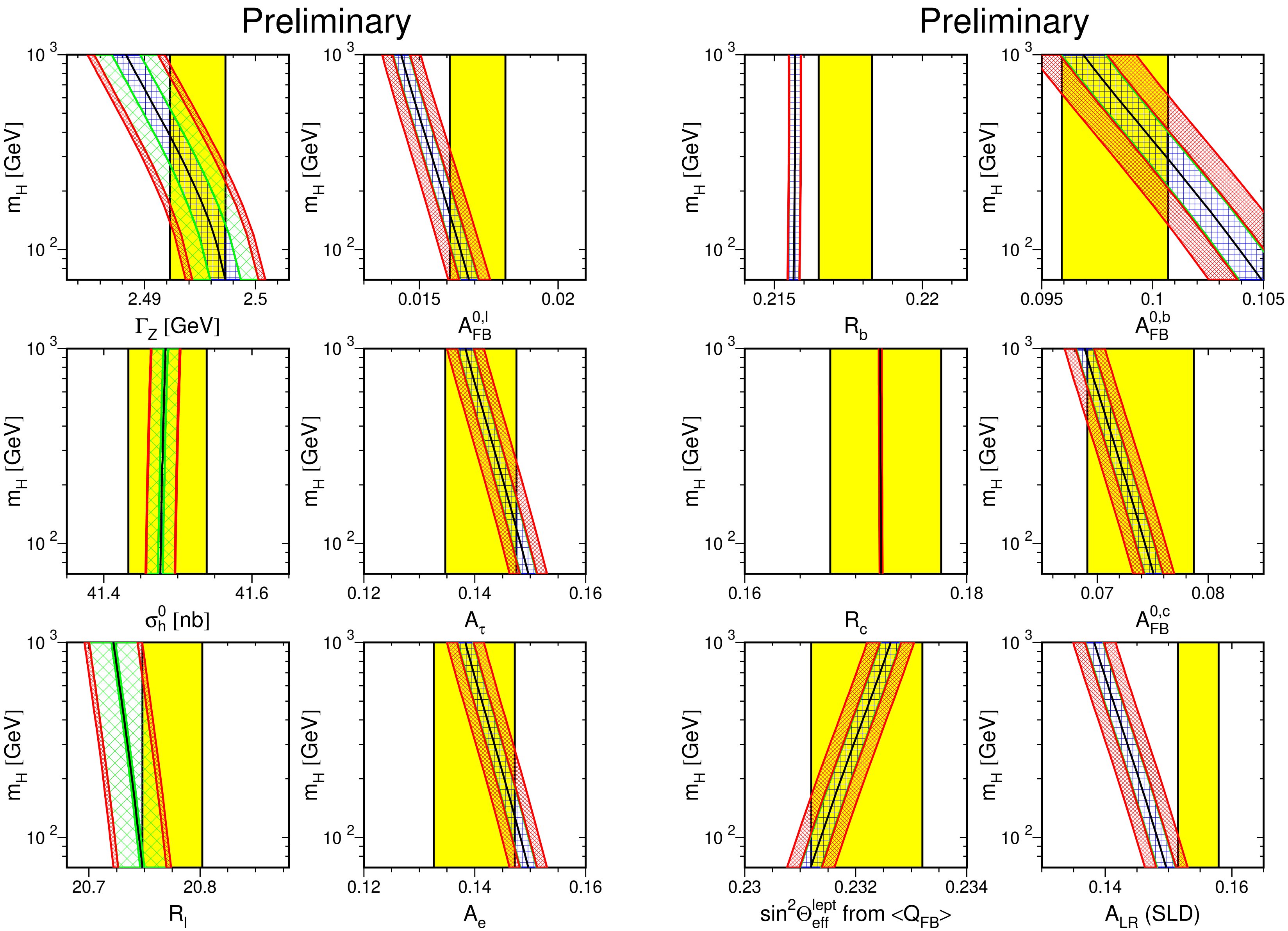
$\Rightarrow M_{\mathrm{H}} = 115^{+116}_{-66}$ GeV

$M_{\mathrm{H}} < 420$ GeV (95% c.l.)

Direct search results not taken into account in 95% c.l. limit.

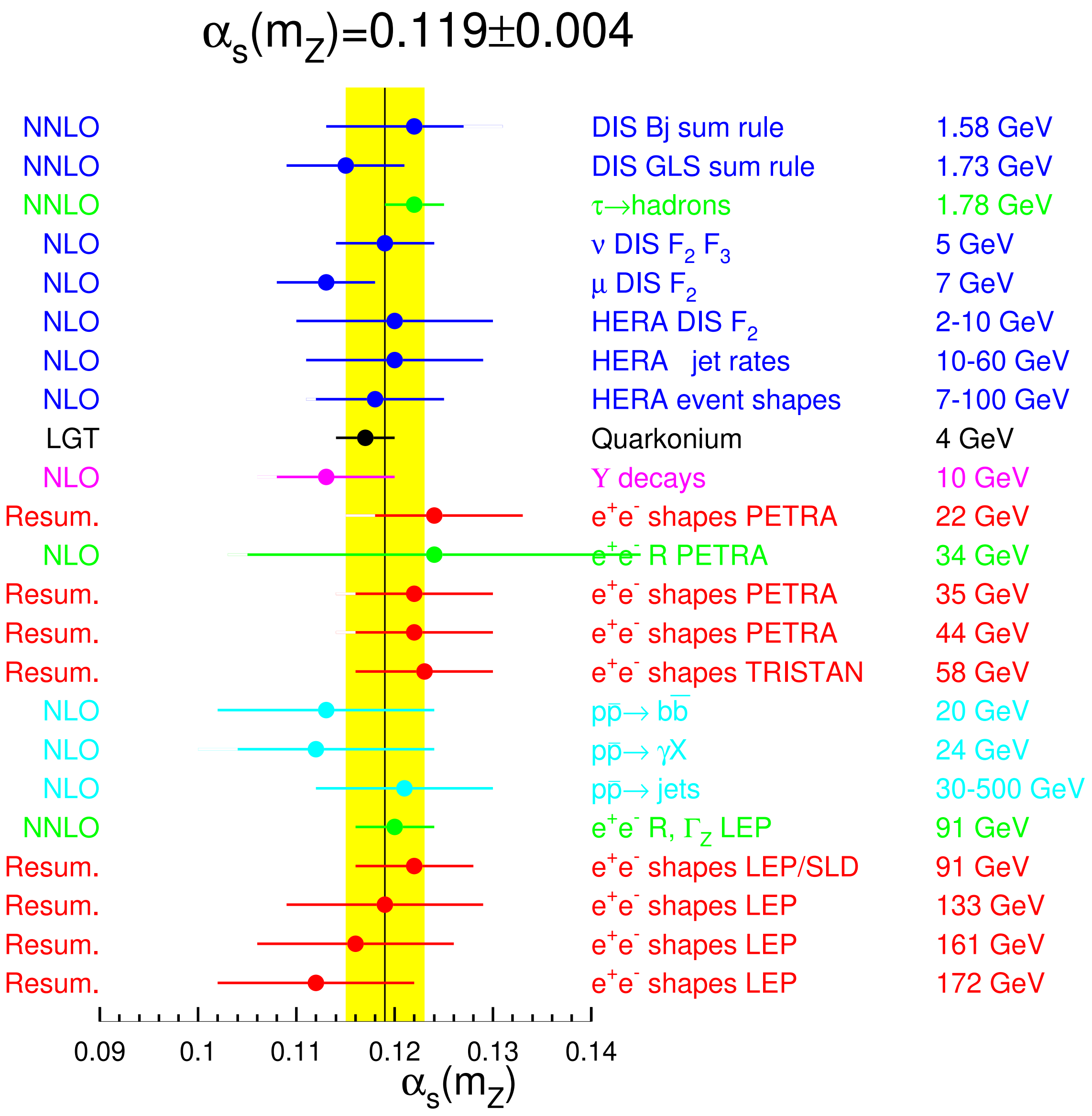
Theory uncertainty has been allowed for.

Sensitivity of observables to M_{H}?



α_s

- Electroweak fits $\Rightarrow$ $\alpha_s = 0.120 \pm 0.003$ (experimental error, including m_H, but no QCD errors, $\sim \pm 0.002$).
- Compilation of the main measurements of α_s.



- Measurements are *much* more consistent than 2 years ago.
- Central value 0.119 is rather independent of how average is formed.
- e.g. the simple r.m.s. of all the above is 0.004 – seems a reasonable error to quote.

W width

- Most precise (but indirect) value from Tevatron

$$\frac{\sigma_{\mathrm{W}} \cdot \mathrm{BR}(\mathrm{W} \to \ell\nu)}{\sigma_{\mathrm{Z}} \cdot \mathrm{BR}(\mathrm{Z} \to \ell\ell)} = \frac{\sigma_{\mathrm{W}} \cdot \Gamma(\mathrm{W} \to \ell\nu) \cdot \Gamma_{\mathrm{Z}}}{\sigma_{\mathrm{Z}} \cdot \Gamma(\mathrm{Z} \to \ell\ell) \cdot \Gamma_{\mathrm{W}}}$$

Need σs from QCD; Z data from LEP, $\mathrm{BR}(\mathrm{W} \to \ell\nu)$ from SM. $\Rightarrow$

$$\Gamma_{\mathrm{W}} = 2.06 \pm 0.06 \text{ GeV. (CDF+D0)}$$

c.f. SM $\Rightarrow 2.077 \pm 0.014$

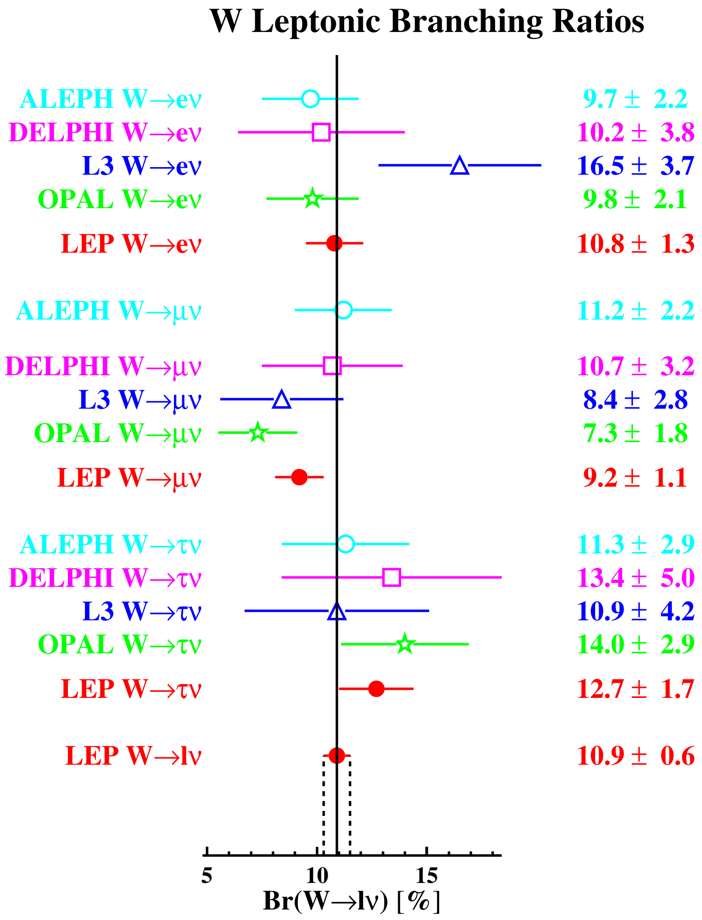
- Γ_{W} affects tail of Tevatron M_T distribution. Fit $\Rightarrow$

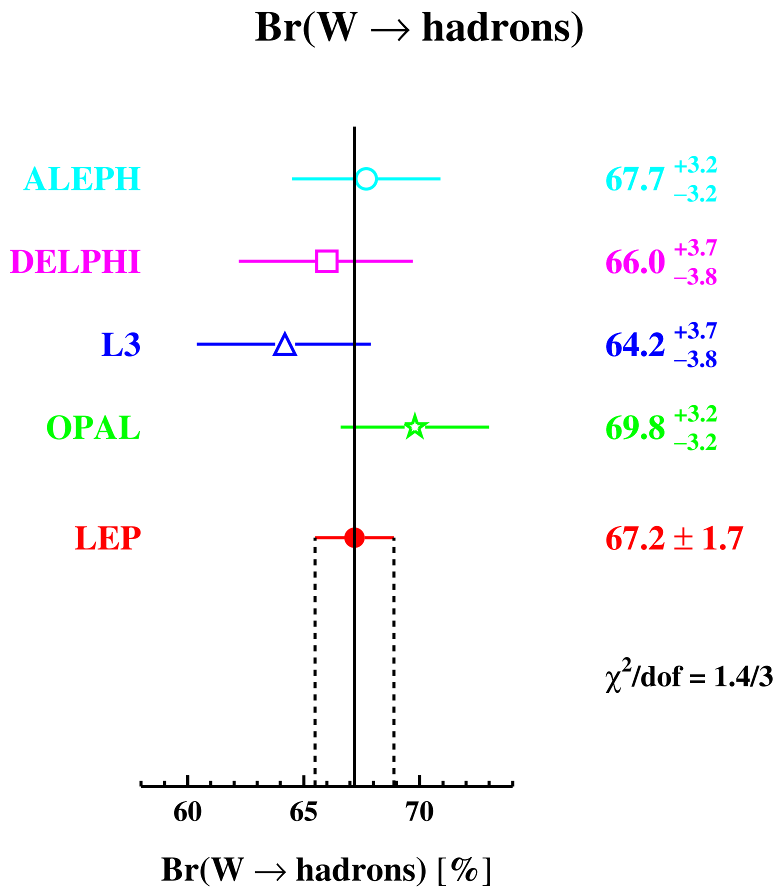
$$\Gamma_{\mathrm{W}} = 2.11 \pm 0.17 \pm 0.09 \text{ GeV. (CDF – this conference)}$$

- Analyses of M_{W} at LEP using direct reconstruction can infer a value for Γ_{W}:

	Γ_{W}/GeV
L3	$1.74^{+0.88}_{-0.78}$(stat.)± 0.25(syst.)
OPAL	$1.30^{+0.62}_{-0.55}$(stat.)± 0.18(syst.)

W branching ratios





Competitive with Tevatron values

based on cross-section ratio.

V_{cs}

$$B_h \equiv \mathrm{BR}(\mathrm{W} \to \mathrm{hadrons}) = 0.672 \pm 0.017$$

can be related to CKM elements:

$$\frac{B_h}{1 - B_h} = \sum_{i=\mathrm{u,c}; j=\mathrm{d,s,b}} |V_{ij}|^2 \left(1 + \frac{\alpha_s}{\pi}\right)$$

Among these CKM elements, V_{cs} is least well measured by far V_{cs}=1.01±0.18 from D meson decays. Taking the others from PDG, $\Rightarrow$

$$\boxed{|V_{\mathrm{cs}}| = 0.96 \pm 0.08}$$ (LEP average)

- Direct measurements of $\mathrm{W} \to \mathrm{c}$ using charm tagging give:

	$\lvert V_{\mathrm{cs}} \rvert$
ALEPH	1.13 ± 0.43(stat.)± 0.03(syst.)
DELPHI	$0.87^{+0.26}_{-0.22}$(stat.)± 0.11(syst.)

Triple gauge couplings

WWZ and $\mathrm{WW}\gamma$ couplings:

- Effective Lagrangian of the form:

$$g_{WWV}\Big[g_1^V V^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu})$$

$$+ \quad \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} \cdots \Big]$$

(V=Z or γ; $g_{WW\gamma} = e$; $g_{WWZ} = e\cot\theta_W$).

- Need 2×7 parameters to describe most general Lorentz invariant WWV vertices.
- C, P, e.m. gauge invariance ($\Rightarrow g_1^\gamma = 1$) reduces to 5: $\lambda_\gamma, \lambda_Z$ (=0 in SM) $\kappa_\gamma, \kappa_Z, g_1^Z$ (=1 in SM)
- Related to static moments of the W^+:

Charge	$Q_W = e g_1^\gamma$
Magnetic dipole moment	$\mu_W = (e/2m_W)(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$
Electric Quadrupole moment	$q_W = -(e/m_W^2)(\kappa_\gamma - \lambda_\gamma)$

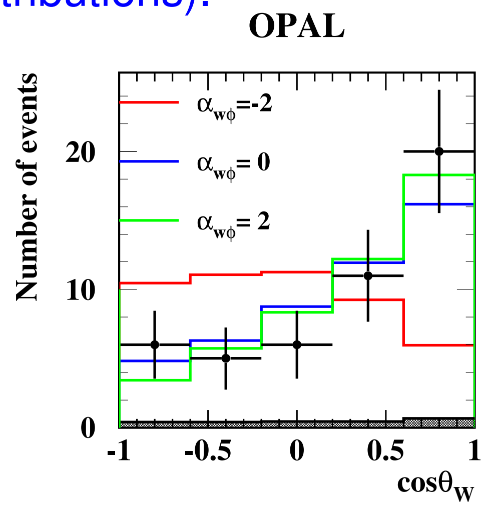
$\mathrm{Z}\gamma\gamma$ and $\mathrm{ZZ}\gamma$ couplings:

- Dimensionless couplings h_i^V; V=Z or γ, $i = 1,2$ CP-violating, $i = 3,4$ CP-conserving $\times(1+\hat{s}/\Lambda^2)^{-n}$ (form factor); $n = 3$ ($i = 1,3$) or $n = 4$ ($i = 2,4$).
- All zero in SM (at tree level).

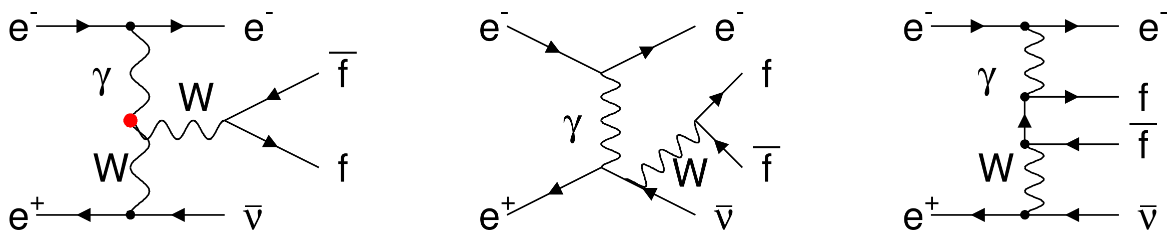
Triple gauge couplings (LEP)

Methods:

- W^+W^- Anomalous couplings generally increase the W^+W^- cross-section, change the angular distribution of produced W bosons, and affect their helicity states (⇒ different decay angular distributions).



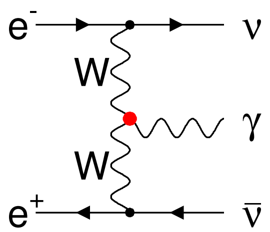
- $We\nu$ Important diagrams contributing to "single W" production



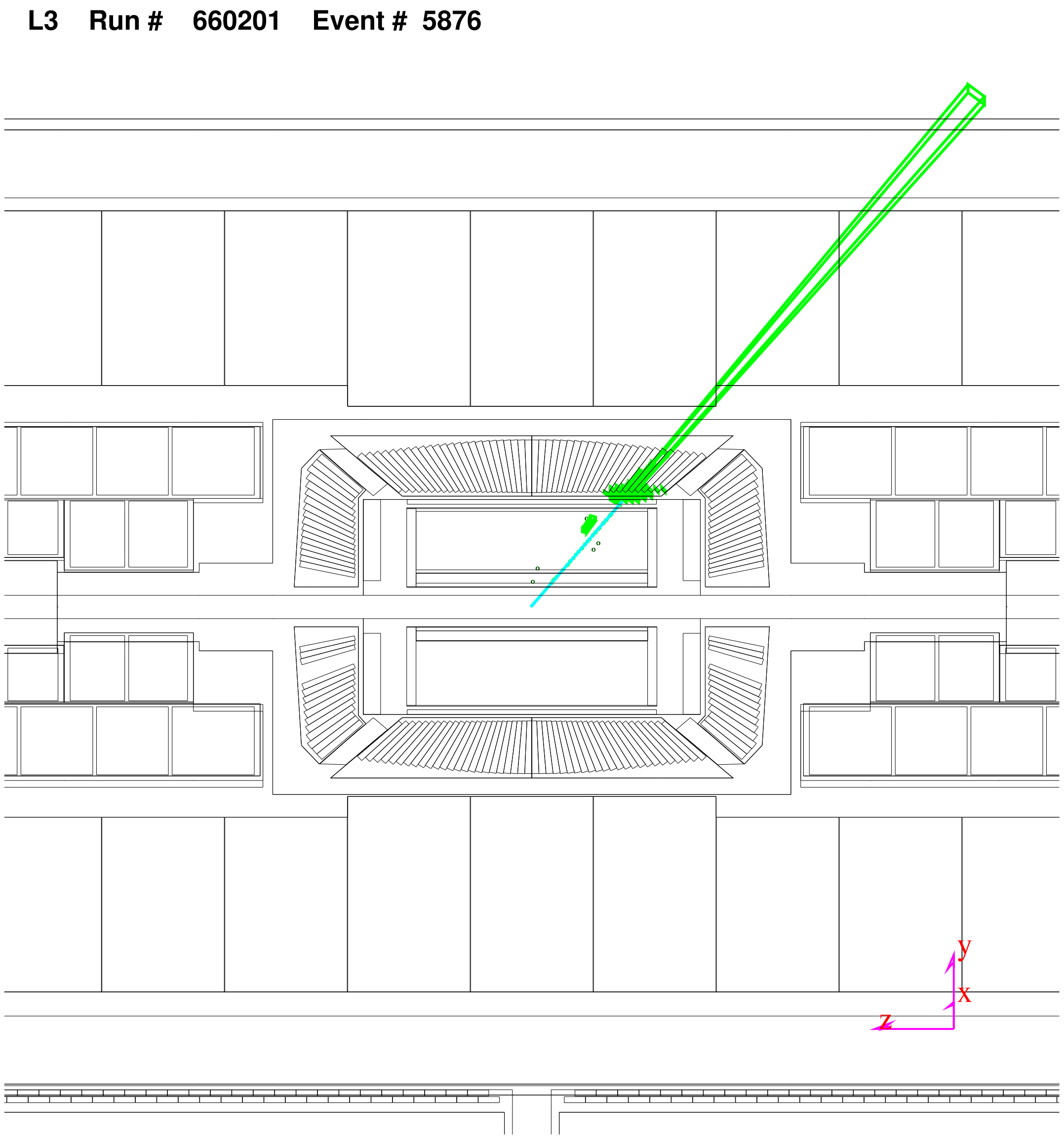
Typically electron along beam pipe, so signatures are a single energetic lepton, or two acoplanar jets with missing $\not{E}_T$.

Sensitive to WWγ vertex, and hence complementary to W^+W^-.

- $\nu\bar{\nu}\gamma$ also sensitive to $WW\gamma$ coupling:



Single W production



This event from L3 has a 40 GeV electron.

Triple gauge couplings (LEP)

- Precision Z^0 data constrains possible anomalous couplings.

LEP analyses focus on three combinations which do not affect gauge boson propagators at tree level:

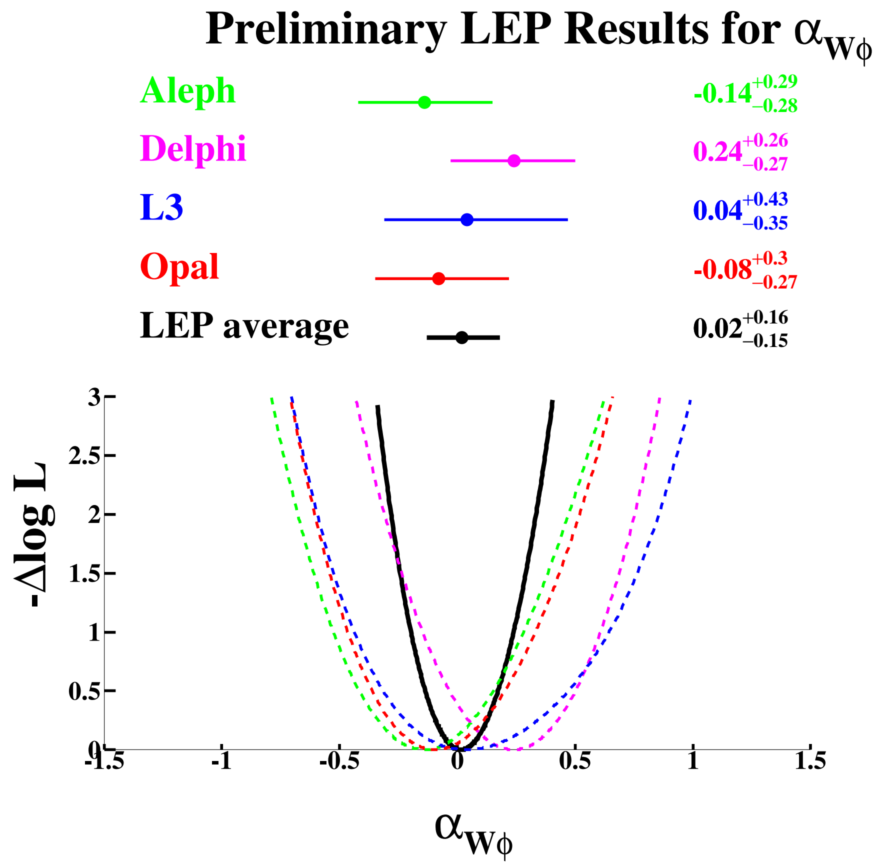
$$\begin{aligned}\Delta\kappa_\gamma - \Delta g_1^{\mathrm{Z}}\cos^2\theta_W &= \alpha_{B\phi} \\ \Delta g_1^{\mathrm{Z}}\cos^2\theta_W &= \alpha_{W\phi} \\ \lambda_{\mathrm{Z}} = \lambda_\gamma &= \alpha_W\end{aligned}$$

with the constraint $\Delta\kappa_{\mathrm{Z}} = \Delta g_1^{\mathrm{Z}} - \Delta\kappa_\gamma \tan^2\theta_W$. All zero according to the Standard Model.

- Strongest information comes from $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ (unambiguous charge assignment).
- $\mathrm{q\overline{q}q\overline{q}}$ and $\ell\overline{\nu}_\ell\overline{\ell}\nu_\ell$ also used for cross-section and (sometimes) angular information.
- Single W production (L3/DELPHI/OPAL) also studied. Less powerful on its own, but can be combined with WW (DELPHI).
- Single γ production (ALEPH) gives weaker limits.

Triple gauge couplings (LEP)

Combine results from four LEP experiments by adding likelihood curves.



	α	95% c.l. limits
$\alpha_{W\phi}$	$0.02\pm^{0.16}_{0.15}$	$-0.28 < \alpha < 0.33$
α_W	$0.15\pm^{0.27}_{0.27}$	$-0.37 < \alpha < 0.68$
$\alpha_{B\phi}$	$0.45\pm^{0.56}_{0.67}$	$-0.81 < \alpha < 1.50$

i.e. no discrepancy with the Standard Model.

Results on several other couplings; correlations etc. from individual LEP experiments.

Triple gauge couplings (CDF/D0)

Information from two sources:

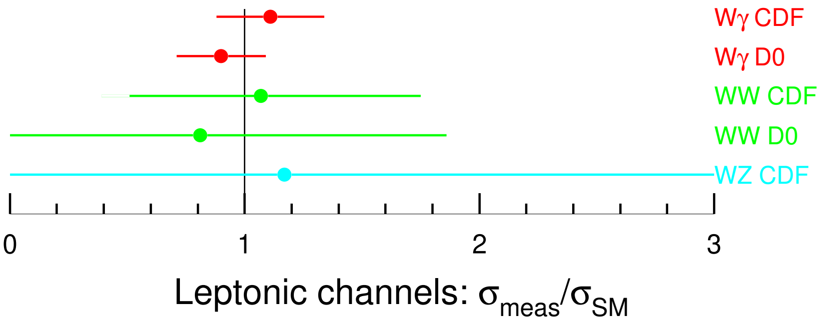
- $W\gamma$ production; especially high p_T photons.

Sensitive to WWγ coupling.

95% c.l. limits on anomalous couplings:

	$\lambda_\gamma = 0$	$\Delta\kappa_\gamma = 0$
D0	$-0.93 < \Delta\kappa_\gamma < 0.94$	$-0.31 < \lambda_\gamma < 0.29$
CDF	$-1.8 < \Delta\kappa_\gamma < 2.0$	$-0.7 < \lambda_\gamma < 0.6$

- WW/WZ pair production. $\ell\nu\ell\overline{\nu}$; $\ell\nu jj$:

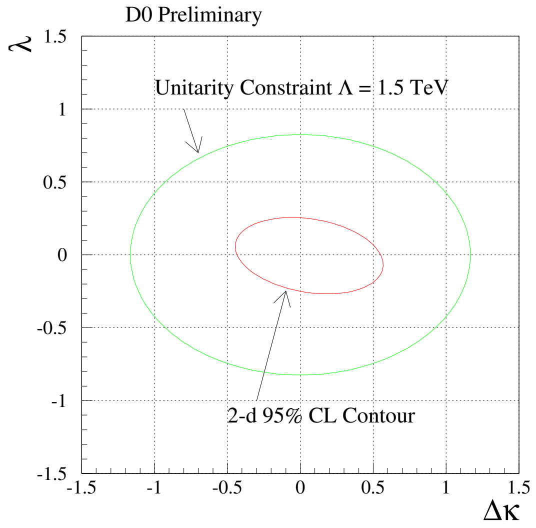


- D0 Combined fit to provide best limits:

$$-0.33 < \Delta\kappa < 0.45$$

$$-0.20 < \lambda < 0.20$$

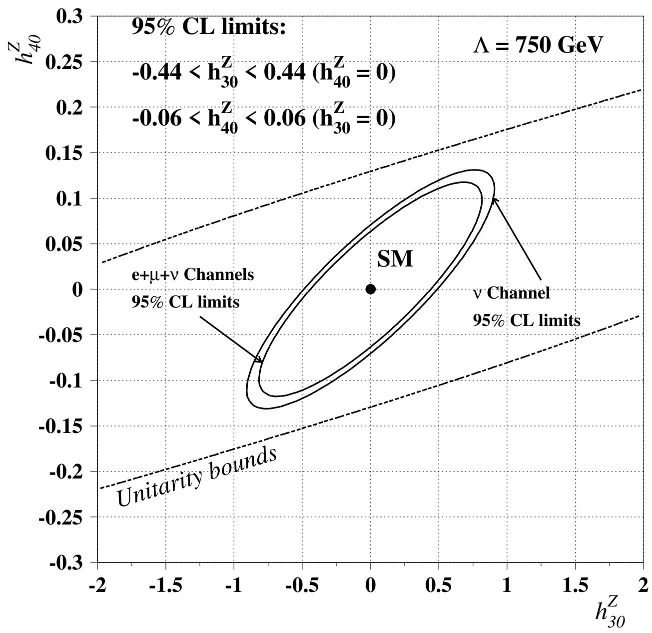
assuming equal WWZ and WWγ couplings.



- Tevatron limits more stringent than LEP at present, factor ~ 2.5 for λ ($\equiv \alpha_W$),~ 1.5 for κ (based on OPAL/L3 $\div\sqrt{2}$)

ZZγ and Z$\gamma\gamma$ couplings

- Zγ production. (CDF/D0) $ee\gamma$, $\mu\mu\gamma$, $\nu\overline{\nu}\gamma$



Most stringent limits from D0 $Z\gamma \to \nu\overline{\nu}\gamma$

$|h^Z_{30}| < 0.44$, $|h^\gamma_{30}| < 0.45$, $|h^Z_{40}| < 0.06$, $|h^\gamma_{40}| < 0.06$.

all at 95% c.l., for Λ=750 GeV.

- Single photon (i.e. $\nu\overline{\nu}\gamma$) production. (DELPHI)

$|h^Z_{30}| < 0.9$, $|h^\gamma_{30}| < 0.5$ at 95% c.l., for Λ=500 GeV. Not competitive for h_{40} couplings.

Summary and Outlook

- Precision Z^0 measurements at LEP1 nearing completion. SM still in good shape
- No significant anomalies in heavy flavour sector
- Distinctive contribution from SLC (polarization) set to continue
- W physics – progress from both LEP2 and Tevatron. Just starting – both expect factor ~ 20 more data in future runs
- e.g. $M_\mathrm{W} = 80.43 \pm 0.08$ GeV from LEP2+$\mathrm{p\overline{p}}$
- TGC - no deviations from SM yet
- M_W and m_t help to constrain $m_\mathrm{H} < 420\, GeV$ (electroweak radiative corrections), c.f. $m_\mathrm{H} < 77\, GeV$ from direct searches at LEP2

Acknowledgements

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Apologies to all those whose contributions (150 submitted to this session) were not mentioned owing to lack of time.