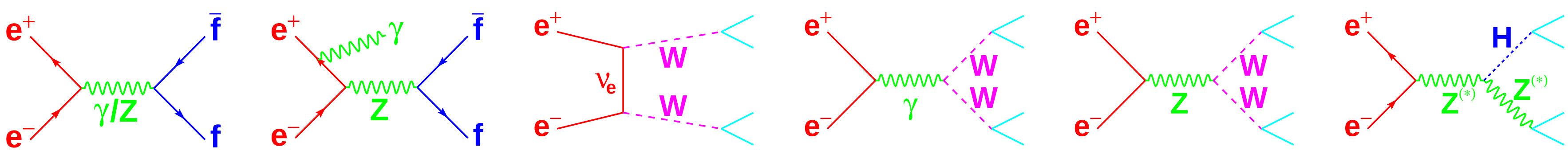
LEP, SLC and the Standard Model

Final - and not so final - electroweak results



Dave Charlton

The University of Birmingham

SLAC Summer Institute Topical Conference, August 2002

Most of the averages and plots shown were prepared by the LEP electroweak working group – particular thanks are due to them

High Energy e^+e^- Colliders

SLC 1989-1998

$\sqrt{s} \simeq M_Z$, $\sim$20 pb^{-1}

e^- polarisation $\sim$75%

LEP-1 1989-1995

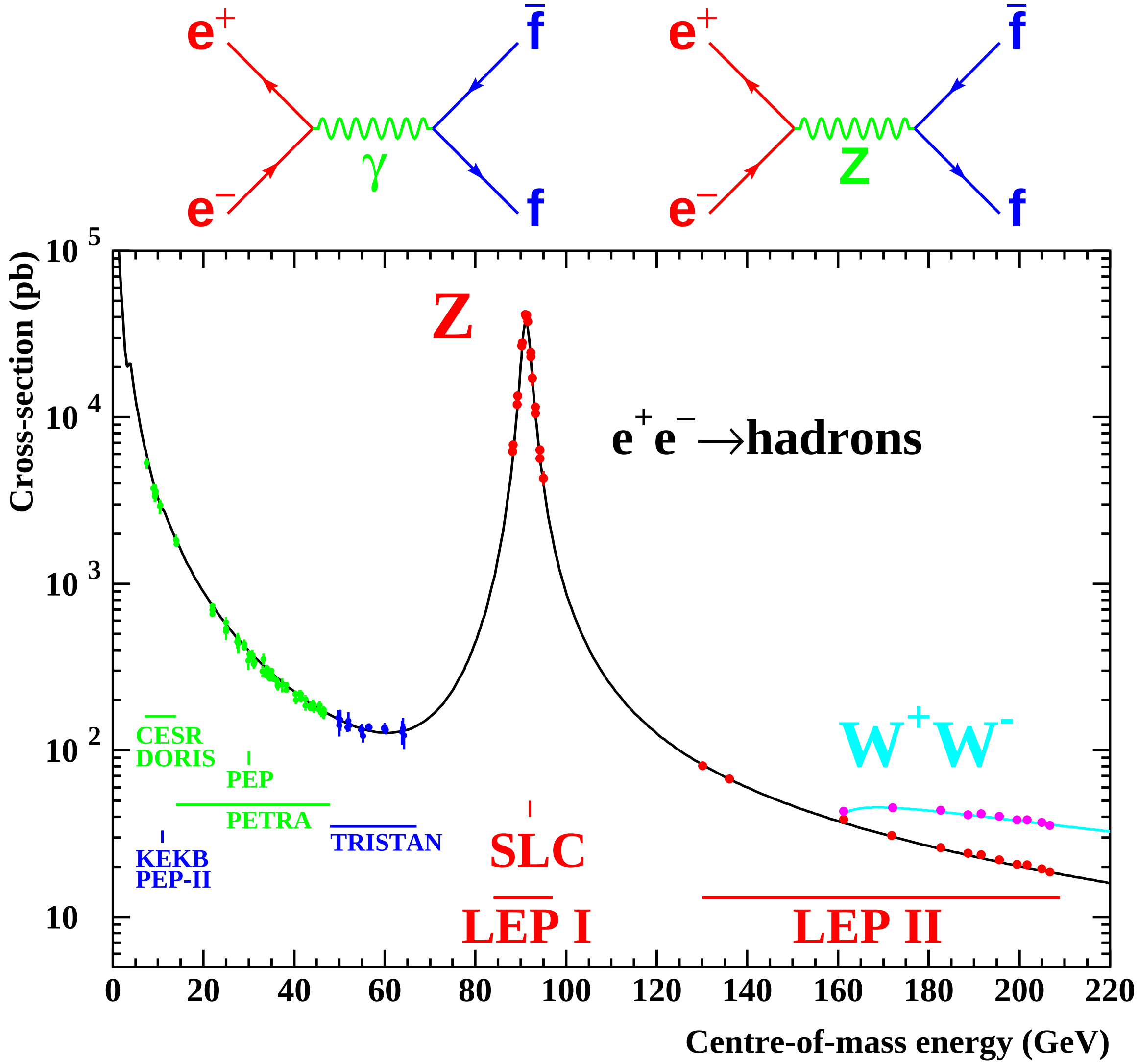
$88 < \sqrt{s} < 94$ GeV

$\sim$160 pb^{-1} $\times$ 4

LEP-2 1996-2000

$130 < \sqrt{s} < 209$ GeV

$\sim$700 pb^{-1} $\times$ 4



Millions of Z's, tens of thousands of W's

The Z Lineshape

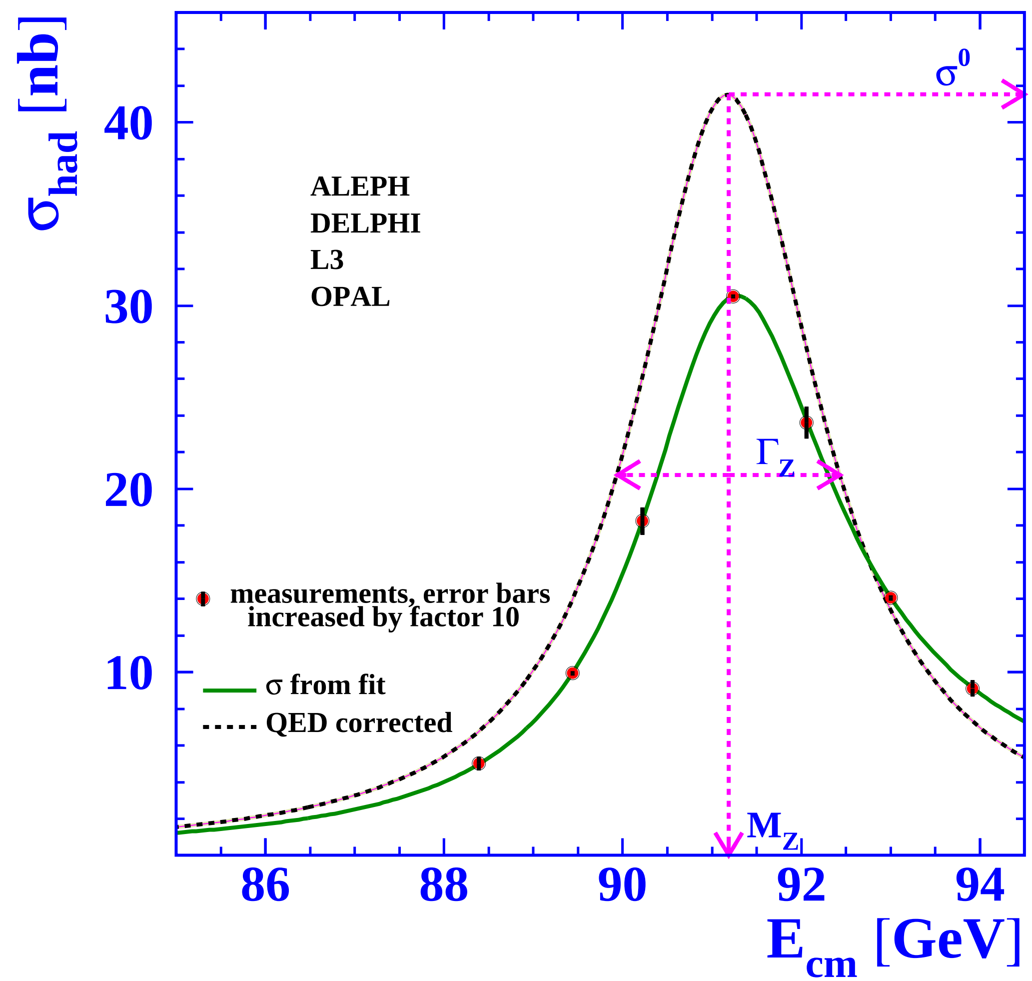
$\sigma(e^+e^- \to f\bar{f})$ measured over $M_Z \pm 3$ GeV

Initial-state radiation (ISR): big effect

$M_Z = 91.1875 \pm 0.0021$ GeV

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

$$\sigma^0(Z^0 \to f\bar{f}) = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$



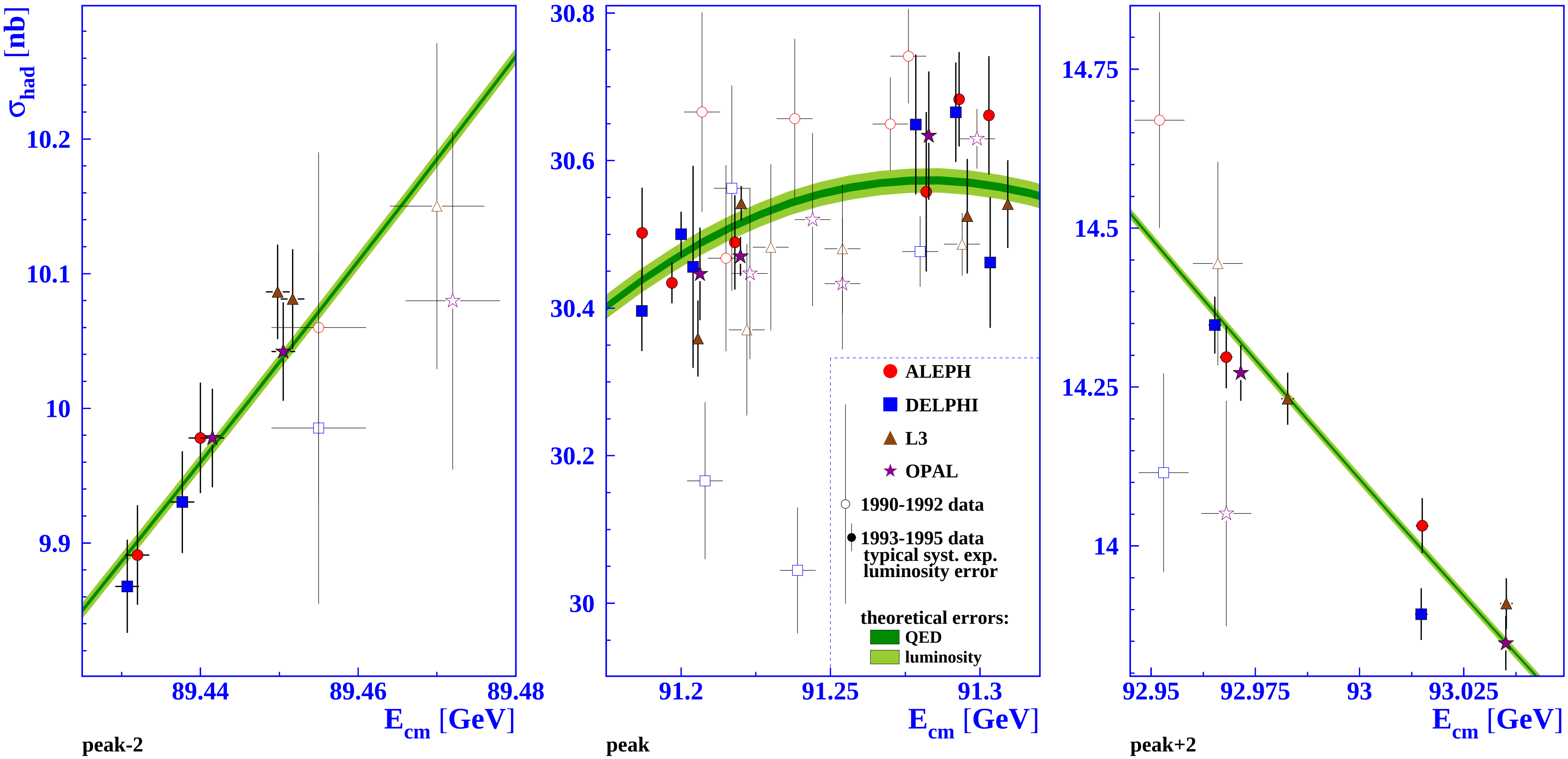
gives access to Γ_{invis} via

$$\Gamma_Z = \Sigma\Gamma(Z \to \text{vis}) + \Gamma_{\text{invis}}$$

Using $N_\nu = \Gamma_{\text{invis}}/\Gamma_{\nu\nu}(\text{SM})$ we find

$$N_\nu = 2.9841 \pm 0.0083$$

The Z Lineshape: High Statistics!



Z Decay Widths: Heavy Quarks

$$\Gamma_{f\overline{f}} \propto g^2_{Vf} + g^2_{Af}$$

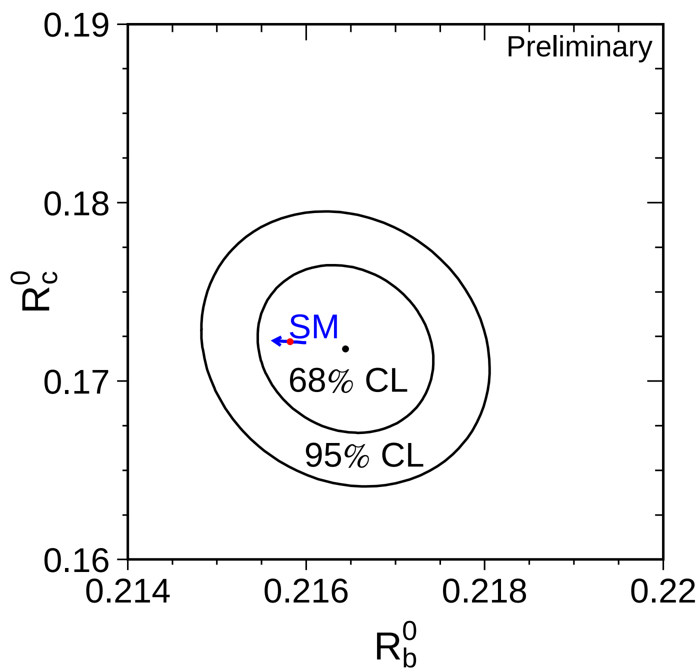
Z lineshape $\longrightarrow$ e,μ,τ,$\Sigma q\overline{q}$

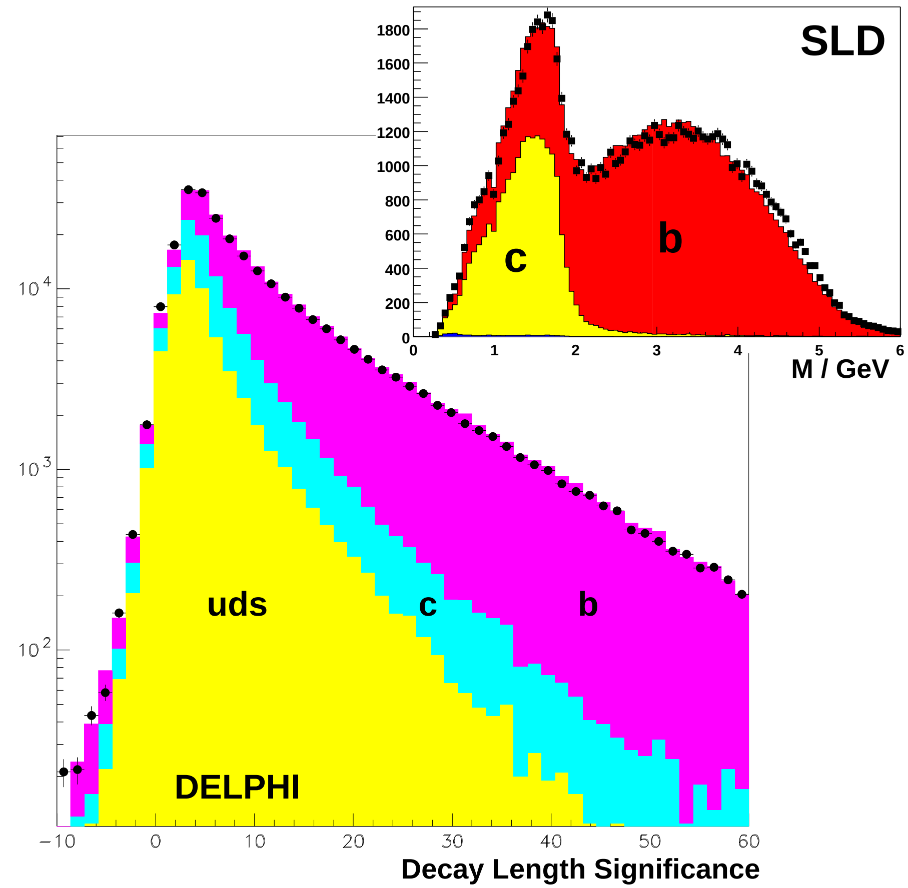
Also measure Z$\rightarrow$ $b\overline{b}$, Z$\rightarrow$ $c\overline{c}$

Main b tags: τ_B, M_B, $B \rightarrow \ell X$

High performance multivariate b tags:

ϵ from data – “double tag” method





By convention $R_Q \equiv \frac{\Gamma_{Q\overline{Q}}}{\Gamma_{\rm had}}$

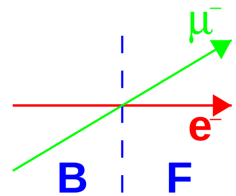
$$R_b = 0.21644 \pm 0.00065$$

Asymmetries at the Z

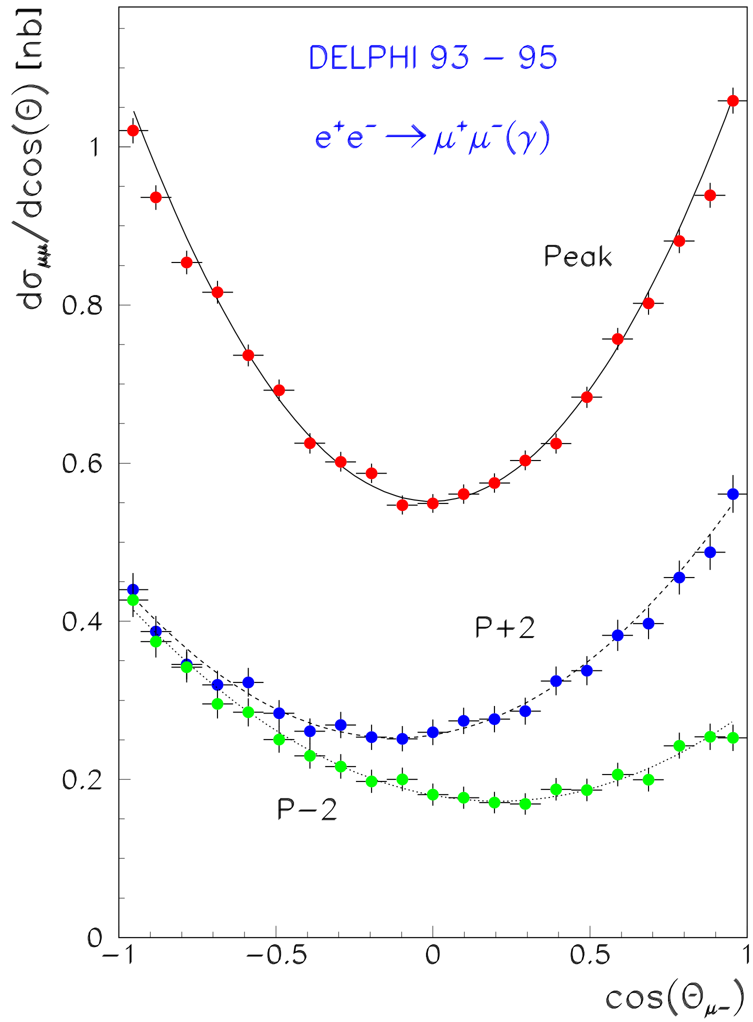
Asymmetry parameters $\mathcal{A}_f$

$$\mathcal{A}_f \equiv \frac{2 g_{Vf} g_{Af}}{(g_{Vf}^2 + g_{Af}^2)} = f\left(\frac{g_{Vf}}{g_{Af}}\right)$$

$$\frac{g_{Vf}}{g_{Af}} = 1 - 4|Q_f|\sin^2\theta_{\mathrm{eff}}^f$$



$$A_{FB} = \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)}$$



Various asymmetries:

- forward-backward $A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$
- tau polarisation P_τ, $\langle P_\tau \rangle = \mathcal{A}_\tau$
- left-right polarisation $A_{LR} = \mathcal{A}_e$
- forward-backward left-right

Superscript 0 denotes “Z-pole” quantities

A_{FB} measured for e,μ,τ, b and c

Left-Right Polarization Asymmetry

Measured by SLD, polarized e^- beam

Counting experiment:

$$A_{LR} = \frac{(N_L - N_R)}{(N_L + N_R)} \frac{1}{\langle P_e \rangle}$$

$\langle P_e \rangle$ mean polarization, three measurements

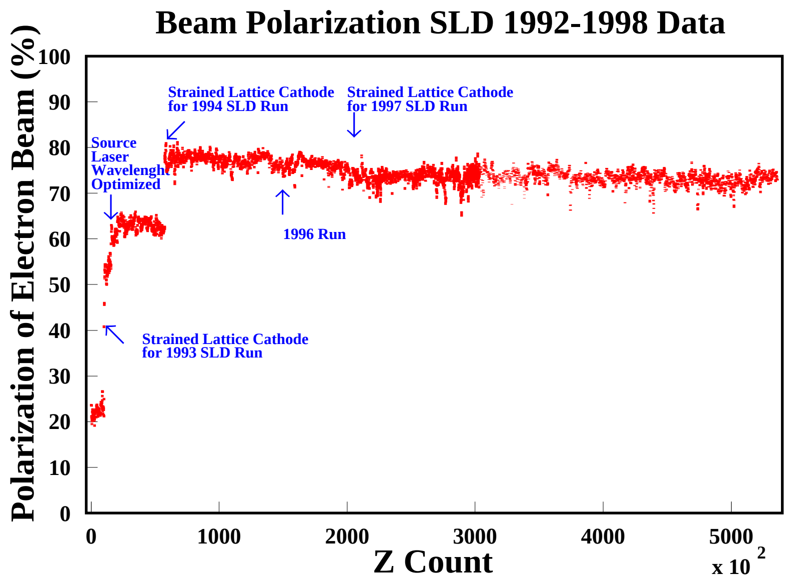
With $\langle \sqrt{s} \rangle$, convert to

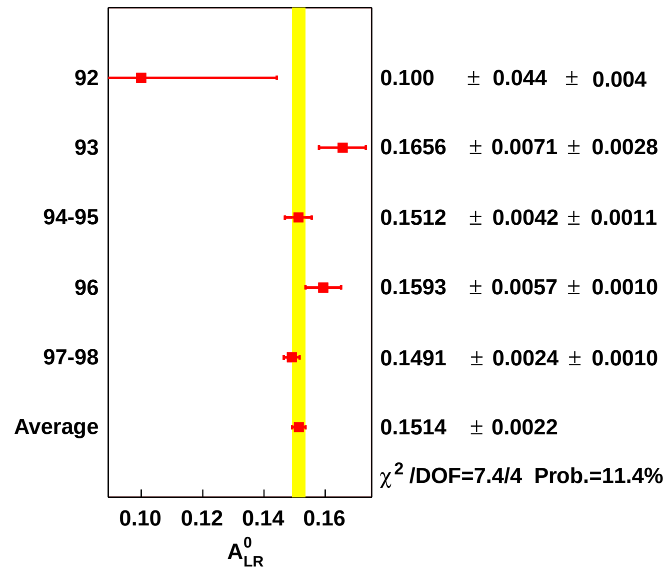
$$\mathbf{A^0_{LR} = 0.1514 \pm 0.0022}$$

Overall, SLD obtain

$$\sin^2 \theta^{\mathrm{lept}}_{\mathrm{eff}} = \mathbf{0.23098 \pm 0.00026}$$

Most precise measurement of $\sin^2 \theta_{\mathrm{eff}}$





Leptonic Couplings

Combining lepton asymmetry results

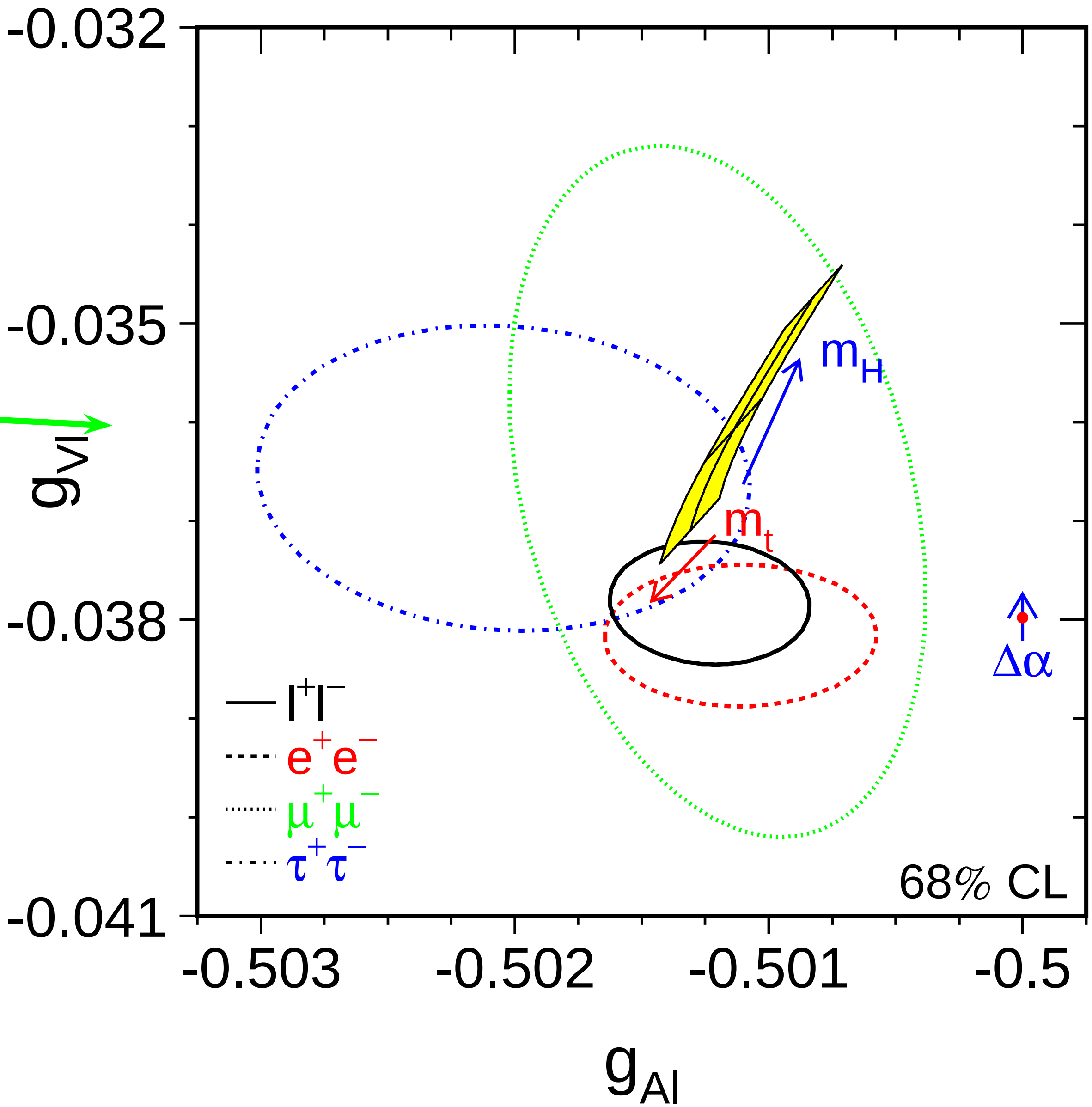
$\mathcal{A}_\ell = 0.1501 \pm 0.0016$

Combine also with leptonic partial widths

Test of NC lepton universality

Strong sensitivity to radiative corrections

Preference for small H mass in SM framework



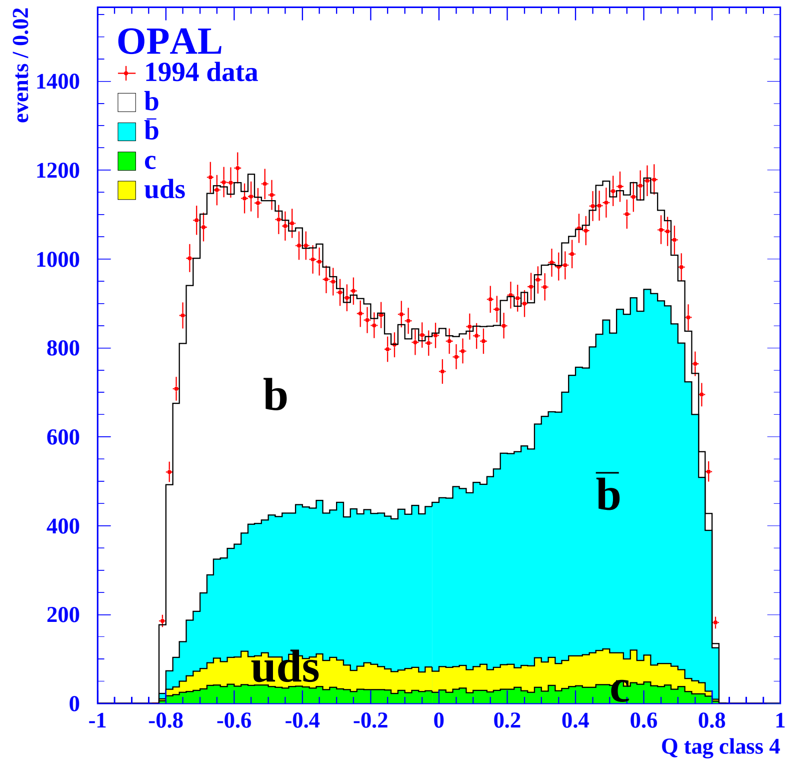
Heavy Quark Asymmetries

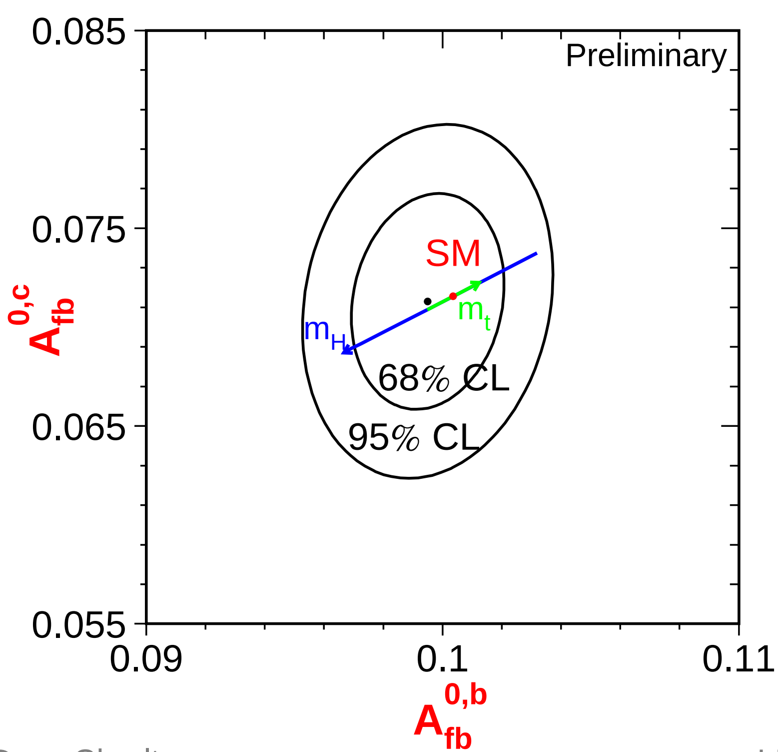
A^b_{FB} and A^c_{FB} measured at LEP/SLD

Needs good flavour and charge tagging

For A^b_{FB}, powerful lifetime tags need charge measure – multivariate techniques calibrated from data

Lepton tags probe b charge via $\ell^\pm$





For $A^{0,b}_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$, sensitivity to $\sin^2\theta_{\rm eff}$ mainly via $\mathcal{A}_e \longrightarrow \sin^2\theta^\ell_{\rm eff}$

SLD also measure $\mathcal{A}_b$, $\mathcal{A}_c$ via polarized e^-

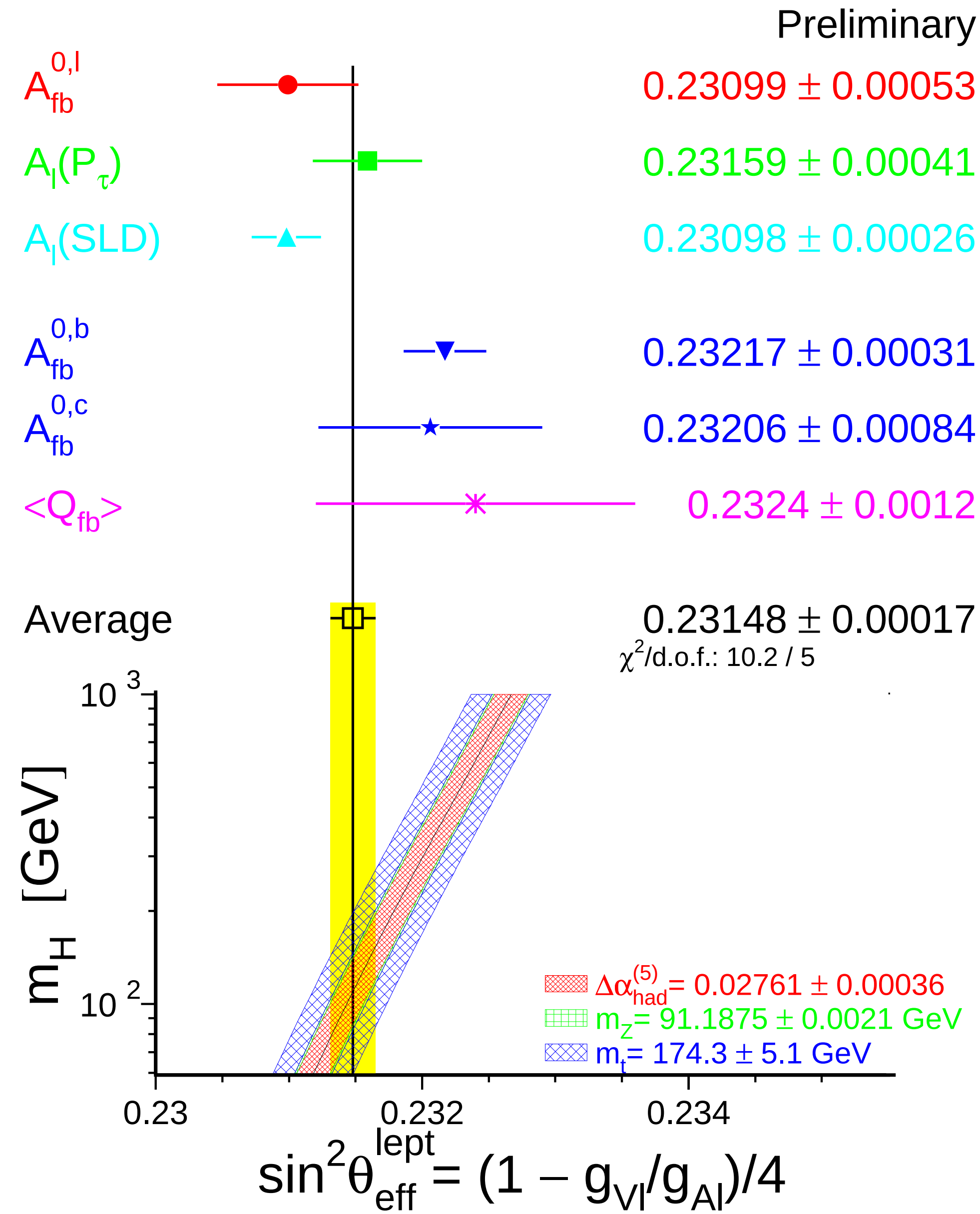
Effective Weak Mixing Angle

Asymmetries mostly measure
$\sin^2\theta_{\rm eff}^{\rm lept}$

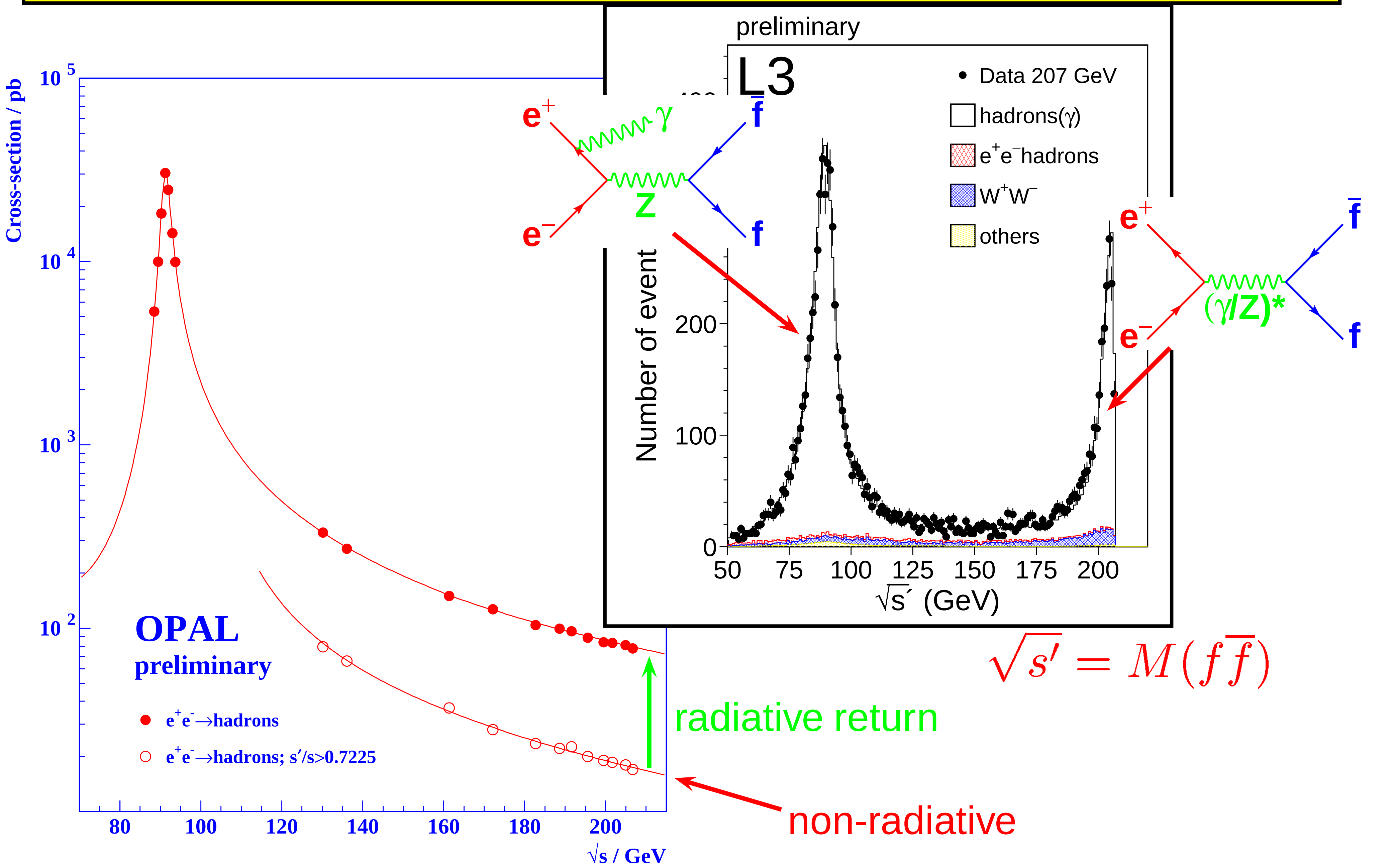
A posteriori, see that two most precise $\sin^2\theta_{\rm eff}^{\rm lept}$ measurements agree only at 2.9σ level

Old problem: discrepancy around 3σ for six years, though errors improved by factor 1.5

In context of SM: A_{FB}^b prefers $M_{\rm H} \sim$ 400 GeV — unlike most other observables which prefer low $M_{\rm H}$



Fermion Pairs at LEP-2

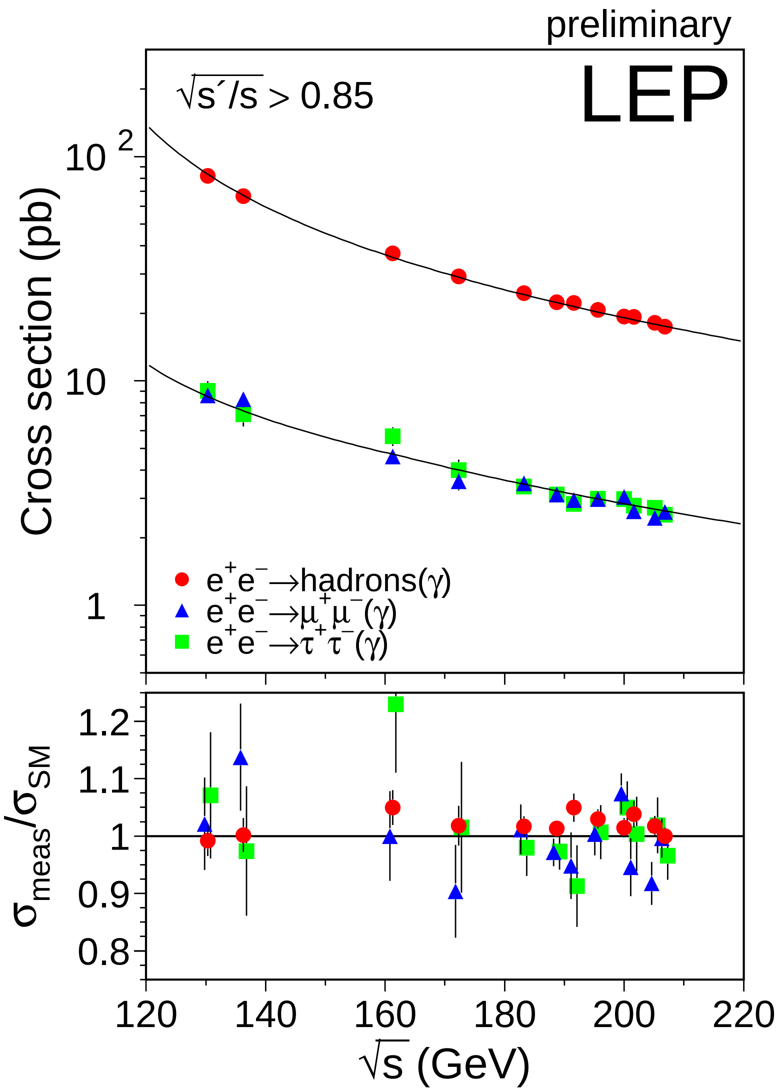


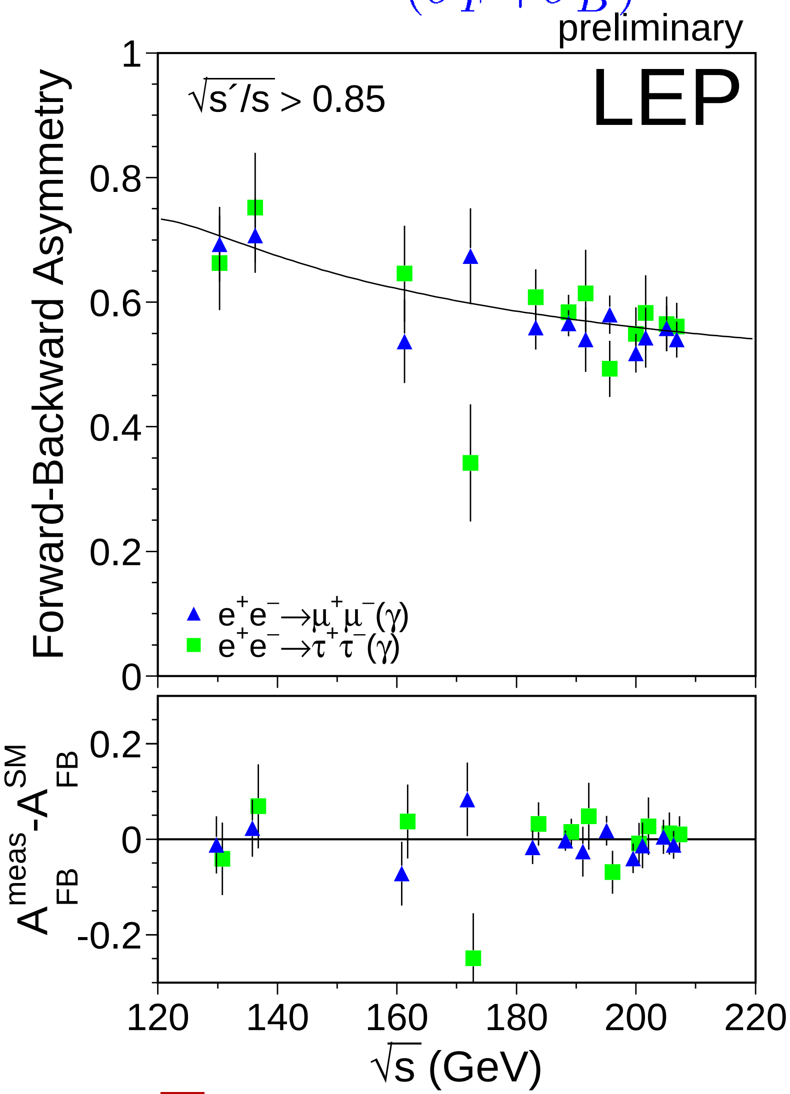
$$\sqrt{s'} = M(f\bar{f})$$

LEP-2 Fermion Pair Properties

Non-radiative events

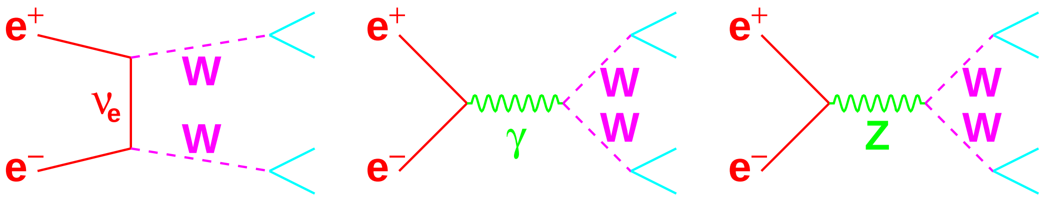
$$A_{FB} = \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)}$$

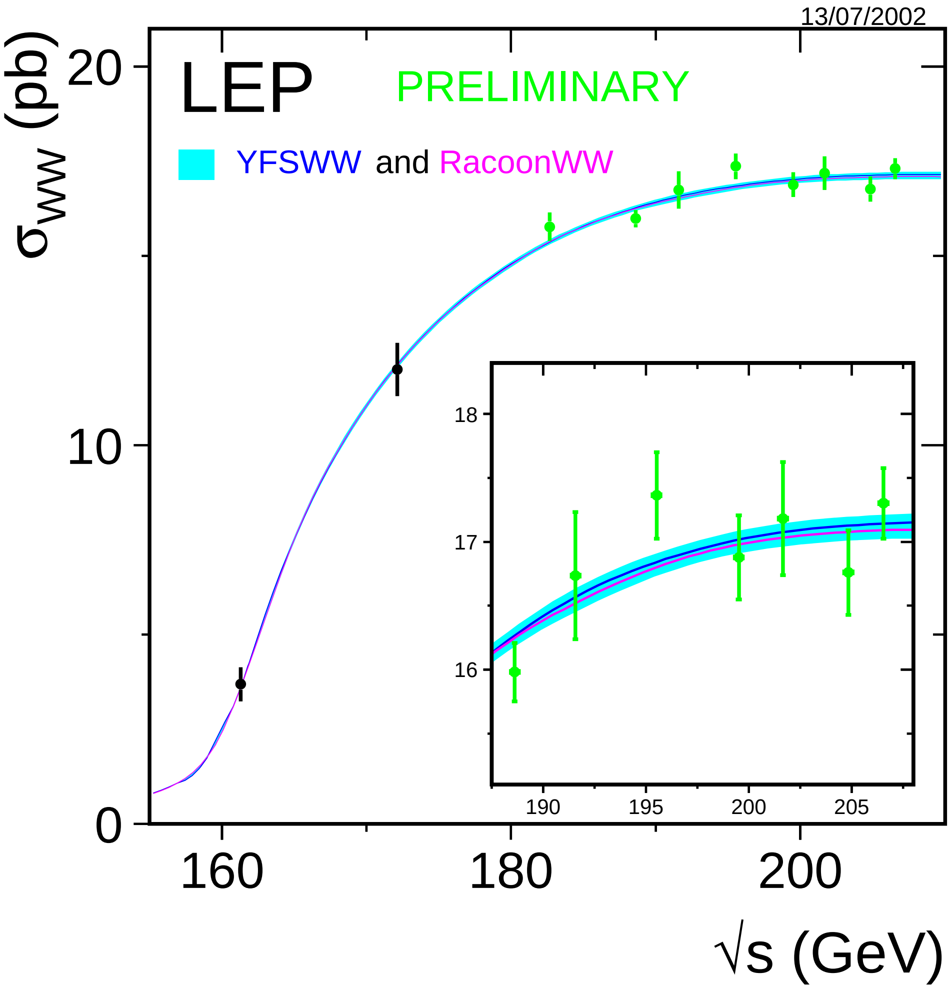




SM continues to describe $f\bar{f}$ at LEP-2

W Pair Production





Around 12000 WW / experiment

46% WW$\rightarrow$ qqqq

$\geq$4 jets

44% WW$\rightarrow$ qq$\ell\nu_\ell$

2 jets, charged lepton, missing p

10% WW$\rightarrow$ $\ell\nu_\ell\ell\nu_\ell$

2 leptons, missing p

Selection ϵ, π typically 80-90%

$\longrightarrow$ σ_{WW} to $\pm$1%

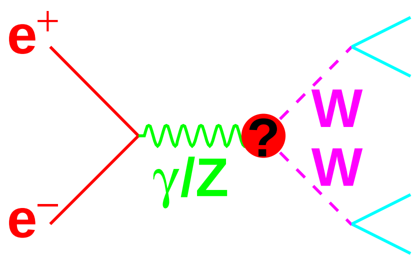
New O(α)-corrected predictions shift σ_{WW} by $-$2.5$\pm$0.5%

σ_{WW} well-described by O(α) calculations

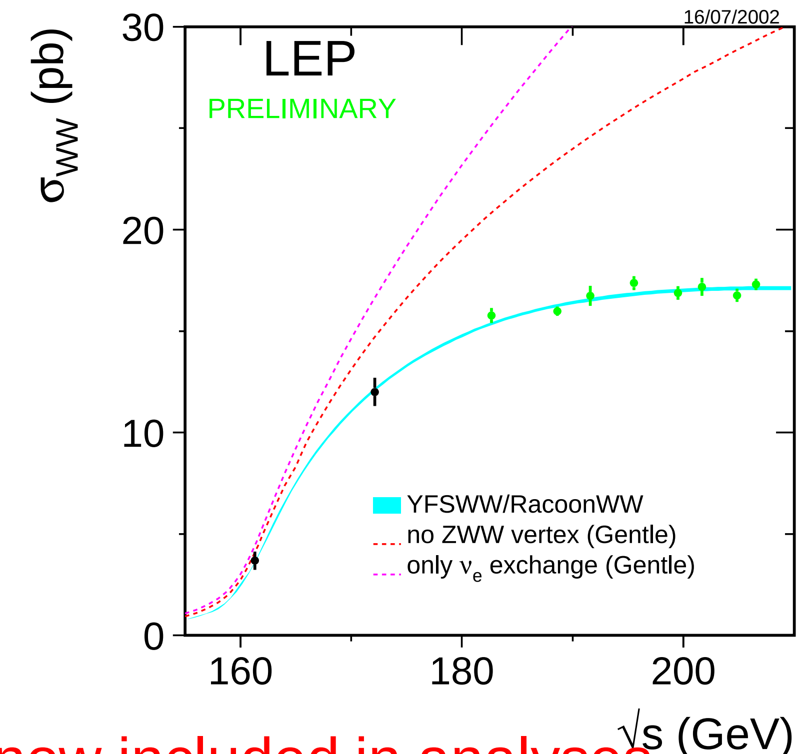
Gauge Boson Self-Couplings

Direct measurements possible at LEP-2

Several channels, WW is most powerful



Sensitivity via σ_{WW}, production polar angle, W polarisation



O(α) corrections $\sim$ current precision – now included in analyses

Vertex coupling parameters: (preliminary)

κ_γ	$=$	0.943 ± 0.055	SM: 1
λ_γ	$=$	-0.020 ± 0.024	0
g_Z^1	$=$	$0.998 \pm^{0.023}_{0.025}$	1

SM gauge structure of boson self-couplings demonstrated

W Mass from LEP-2

Primarily from WW$\rightarrow$ qqqq and $qq\ell\nu_\ell$

Reconstruct (jet,ℓ) angles and energies

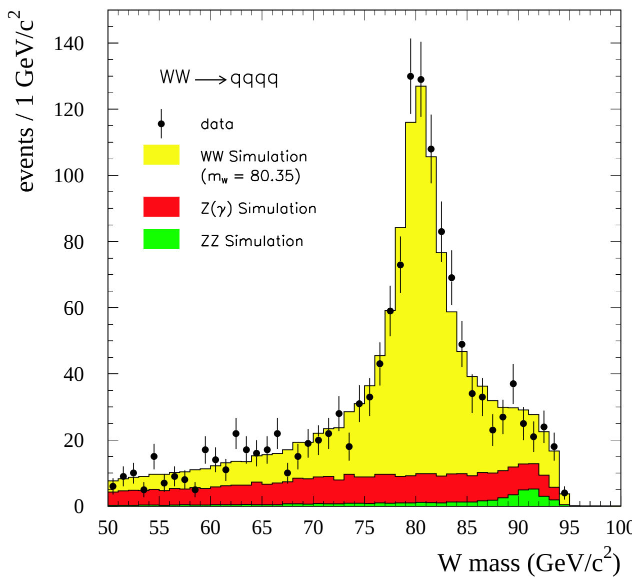
Kin. fit improves resolution:

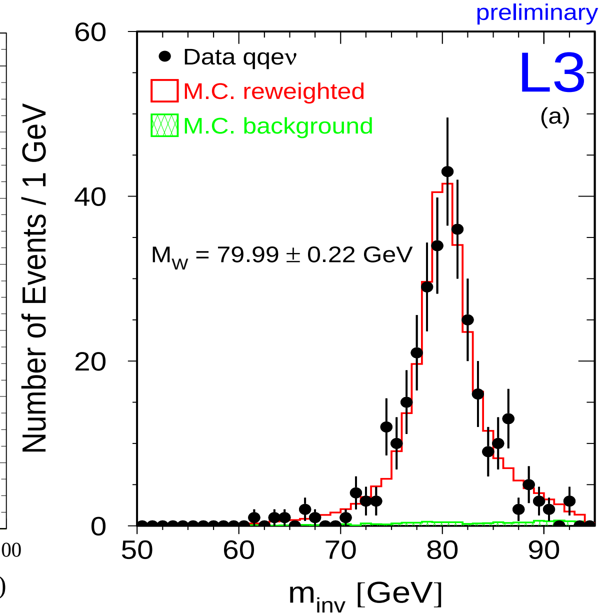
- (E,p)$_{\rm total} = (\sqrt{s}$,0)
- $M_{W+} = M_{W-}$

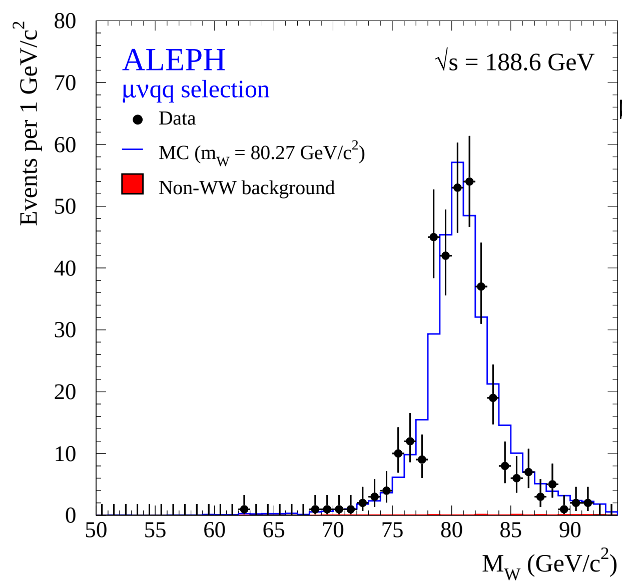
Fit to extract M_W (+Γ_W)

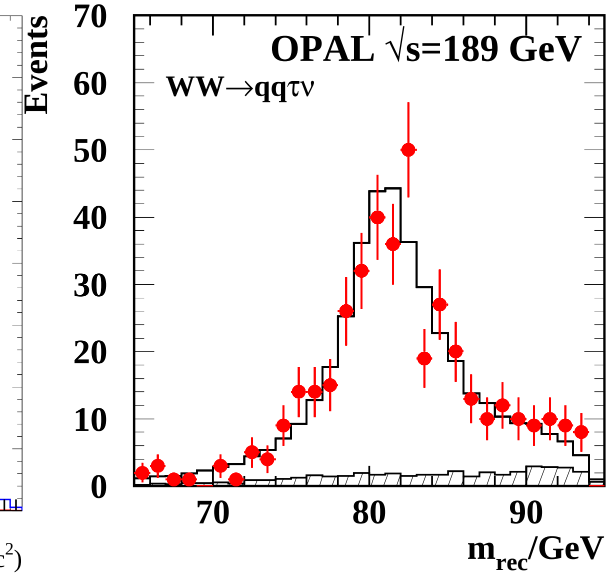
Statistical power: $qqqq \simeq qq\ell\nu_\ell$

Systematic errors significant







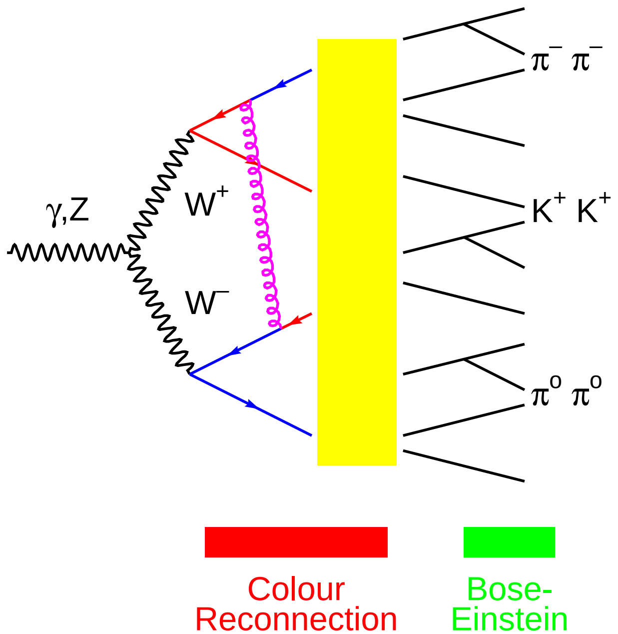


Final-State Interactions

WW$\rightarrow$ qqqq may suffer from "final-state interactions": if the two hadronic W decays don't develop independently

Non-perturbative hadronisation process: needs models

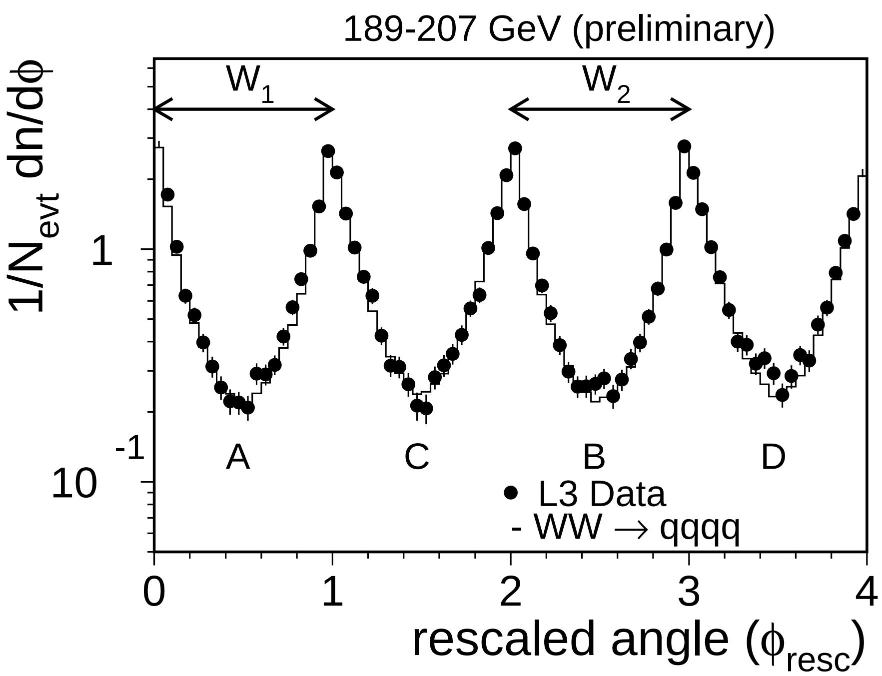
Models of two types: "colour reconnection" (CR) and Bose-Einstein correlations (BE)

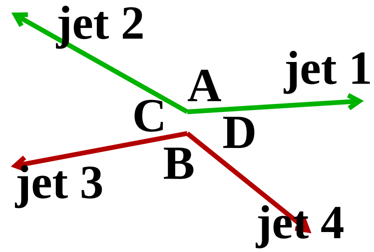


Ongoing work to compare models with data:

- BE between W decay hadrons small, so give low M_{W} shift
- CR studies focus mainly on particle flow - but several models give quite different effects

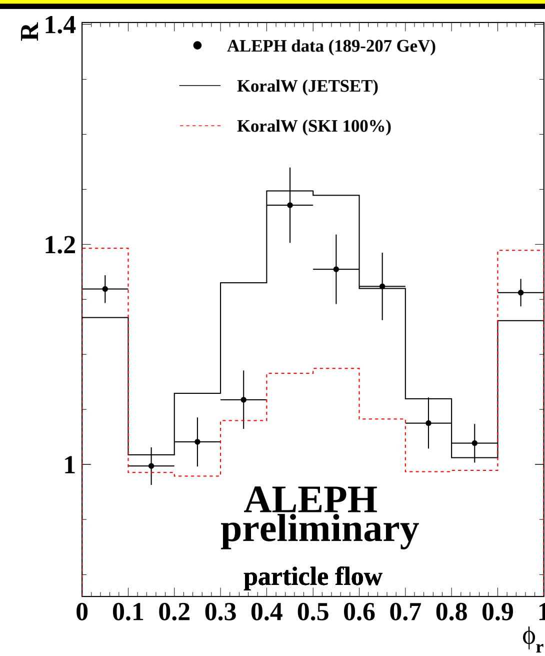
Particle Flow & Colour Reconnection



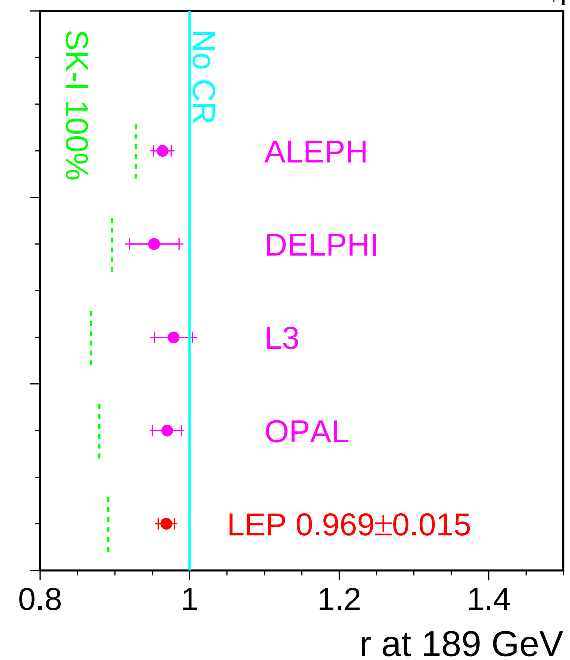


$$\frac{\mathbf{A+B}}{\mathbf{C+D}}$$

$$\frac{\mathrm{Within W}}{\mathrm{between W's}}$$



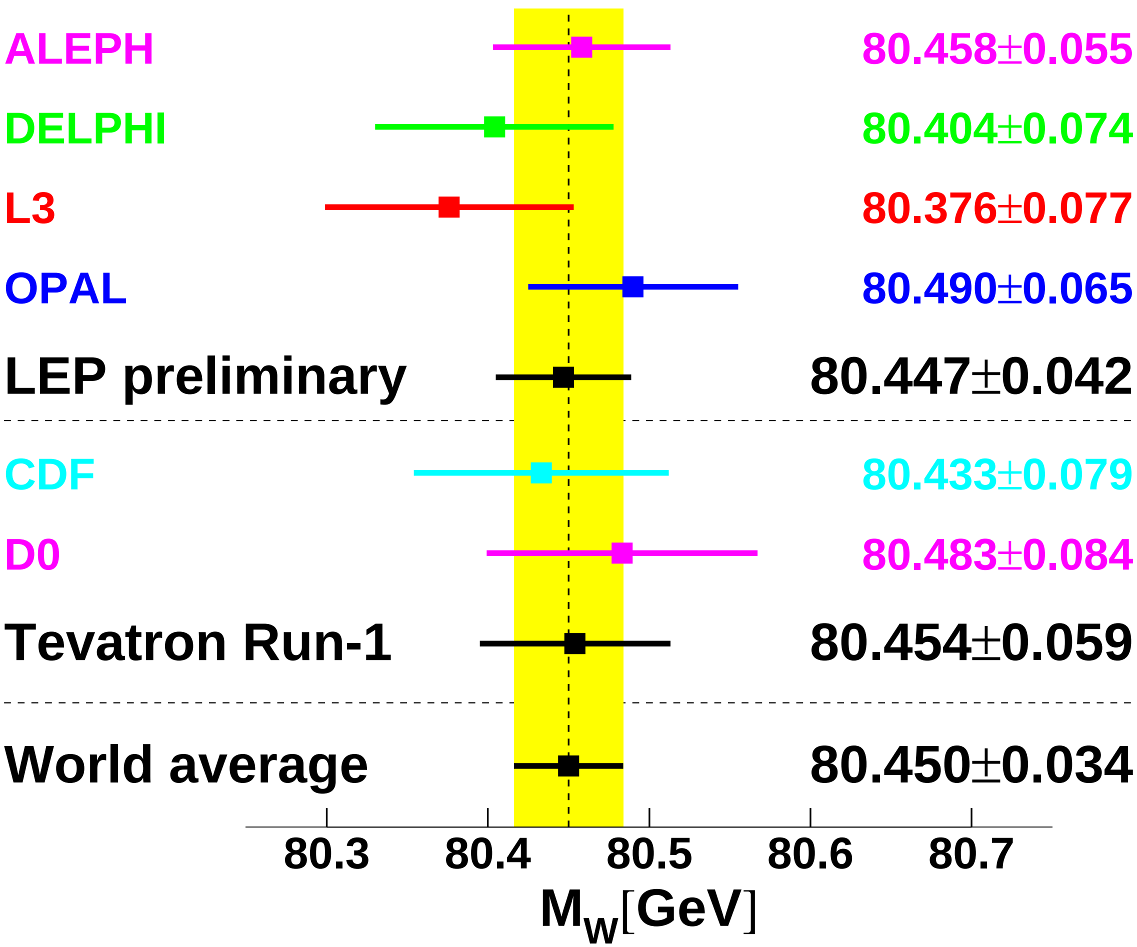
$$R_N \equiv \frac{\int_{0.2}^{0.8} \frac{dn}{d\phi}(\mathrm{inter-W})d\phi_r}{\int_{0.2}^{0.8} \frac{dn}{d\phi}(\mathrm{intra-W})d\phi_r}, \quad r \equiv \frac{R_N^{\mathrm{data}}}{R_N^{(\mathrm{no-CR})}}$$



LEP combination now available, full LEP-2 data

Hints of CR effects, data-driven error on M_W(qqqq channel) from CR ±90 MeV

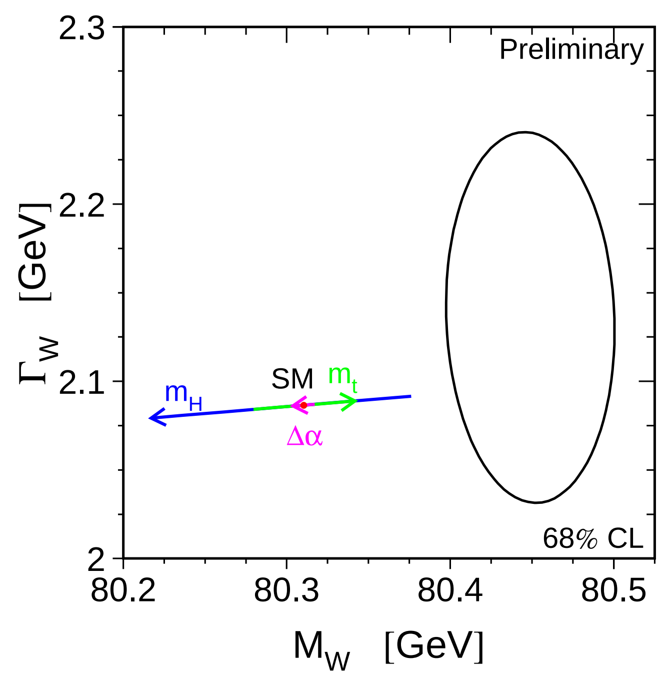
W Mass Results



In LEP M_{W} average, weight of qqqq channel just 9%

Also find

$$\Gamma_{\mathrm{W}}^{\mathrm{LEP}} = 2.150 \pm 0.091$$
$$\Gamma_{\mathrm{W}}^{\mathrm{Tev}} = 2.115 \pm 0.105$$
$$\Gamma_{\mathrm{W}} = 2.135 \pm 0.069 \text{ GeV}$$



Good agreement LEP-Tevatron, comparable precision per experiment

Global Electroweak Tests

Use precise LEP/SLD and Tevatron EW data to probe SM

(other inputs from NuTeV and atomic parity violation)

SM predictions from ZFITTER and TOPAZ0 electroweak libraries

Parameters:

$M_{\rm Z}$	measured precisely by LEP-1 Z data
$\alpha_s(M_{\rm Z}^2)$	measured precisely by LEP-1 Z data
$\alpha_{em}(M_{\rm Z}^2)$	calculated from low-energy measurements
$M_{\rm W}, M_{\rm t}$	may be either predicted, or put in as measured
$M_{\rm H}$	may be predicted in this framework

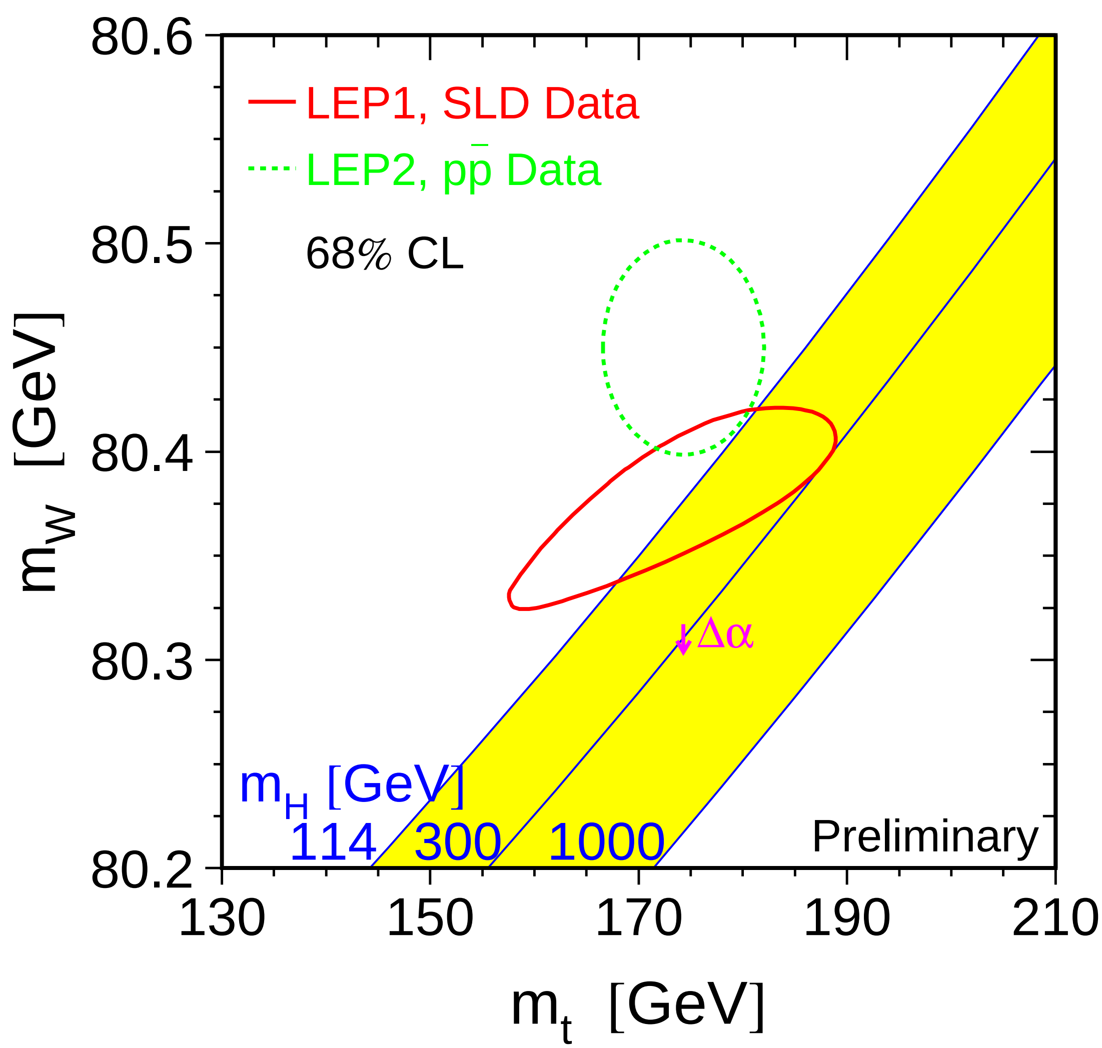
Predicting M_{W} and M_{t}

LEP-1/SLD Z data, $\alpha_{em}(M_{\mathrm{Z}}^2)$, NuTeV and APV results used to predict $M_{\mathrm{W}}, M_{\mathrm{t}}$

Compare with direct measurements (Tev/LEP-2), and with SM relation between $M_{\mathrm{W}}, M_{\mathrm{t}}, M_{\mathrm{H}}$

Electroweak fit correctly predicts the masses of the heavy particles (W,top)

Both sets of data prefer a light Higgs in the SM framework



Fit to all Electroweak Data

Full electroweak fit of all results, including M_W and M_t

Overall consistency χ^2/dof is 29.7/15 (**1.3%** probability)

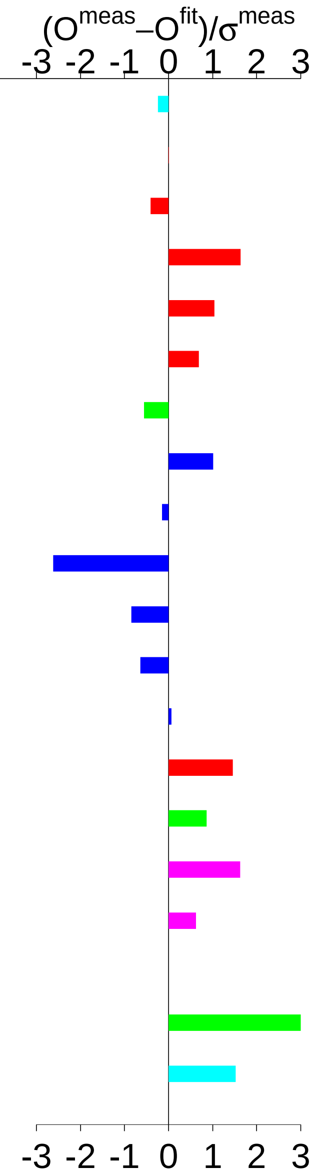
Large χ^2 contribution from NuTeV, without it fit probability is **11%**

Standard Model parameters (M_H etc) **little affected** by NuTeV

Go on to see what the SM fit says about M_H

Summer 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.18 ± 0.46	1.52



Constraining the SM Higgs

Fit to all electroweak data in Standard Model framework

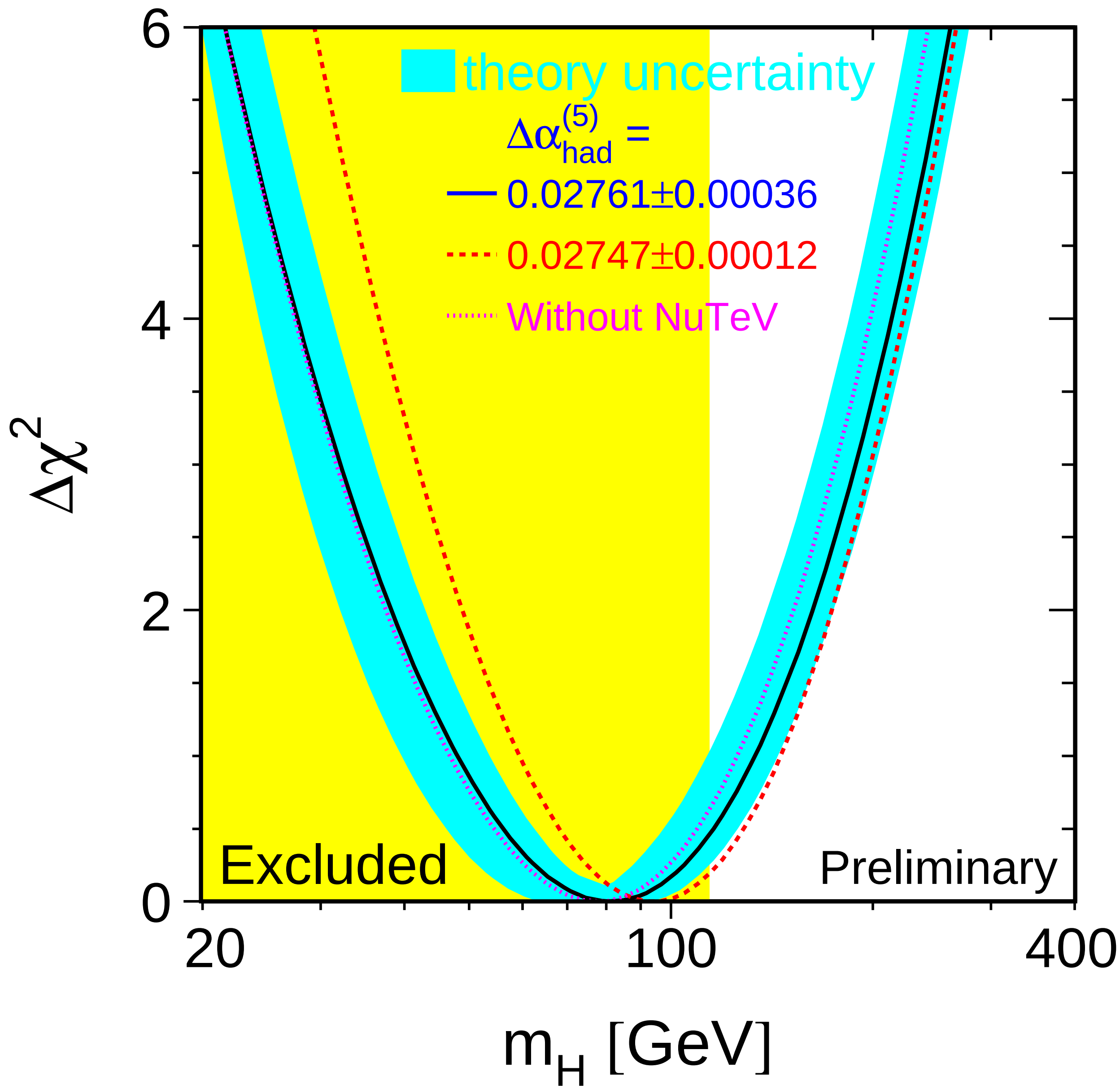
Theory uncertainty includes ZFITTER/TOPAZ0 options, partial two-loop calculations

NuTeV has little impact on M_{H} results, but may affect whether to believe the SM fit...

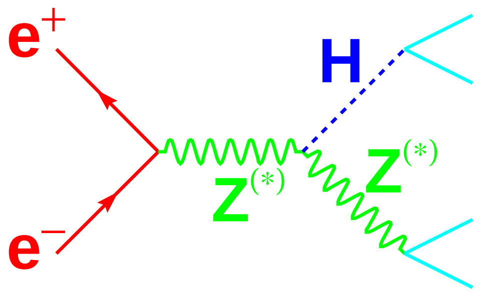
From the fit, obtain

$$M_{\mathrm{H}} = 81^{+52}_{-33}\ \mathrm{GeV}$$

$M_{\mathrm{H}} < 193$ GeV at 95% CL



A Hint of the Higgs?

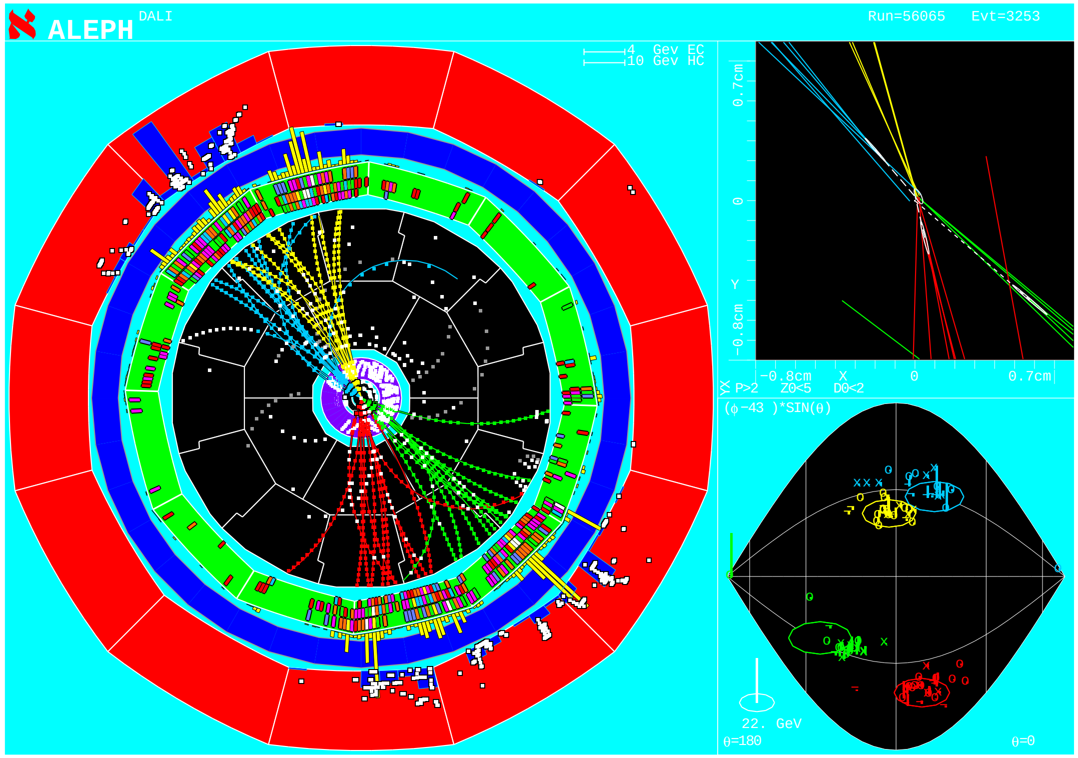


At LEP-2, main process is $e^+e^- \rightarrow ZH \rightarrow f\bar{f}b\bar{b}$

Rely on good b tagging and mass reconstruction

In September 2000, ALEPH reported an excess (3 events) in the $q\bar{q}b\bar{b}$ channel consistent in mass with a 115 GeV H

LEP run extended for 1 month...



LEP Higgs Search: Final Results

Final data, analyses and calibrations:

- no confirmation of ALEPH $q\bar{q}b\bar{b}$ excess
- no significant excess in final combined sample ($P = 8\%$)

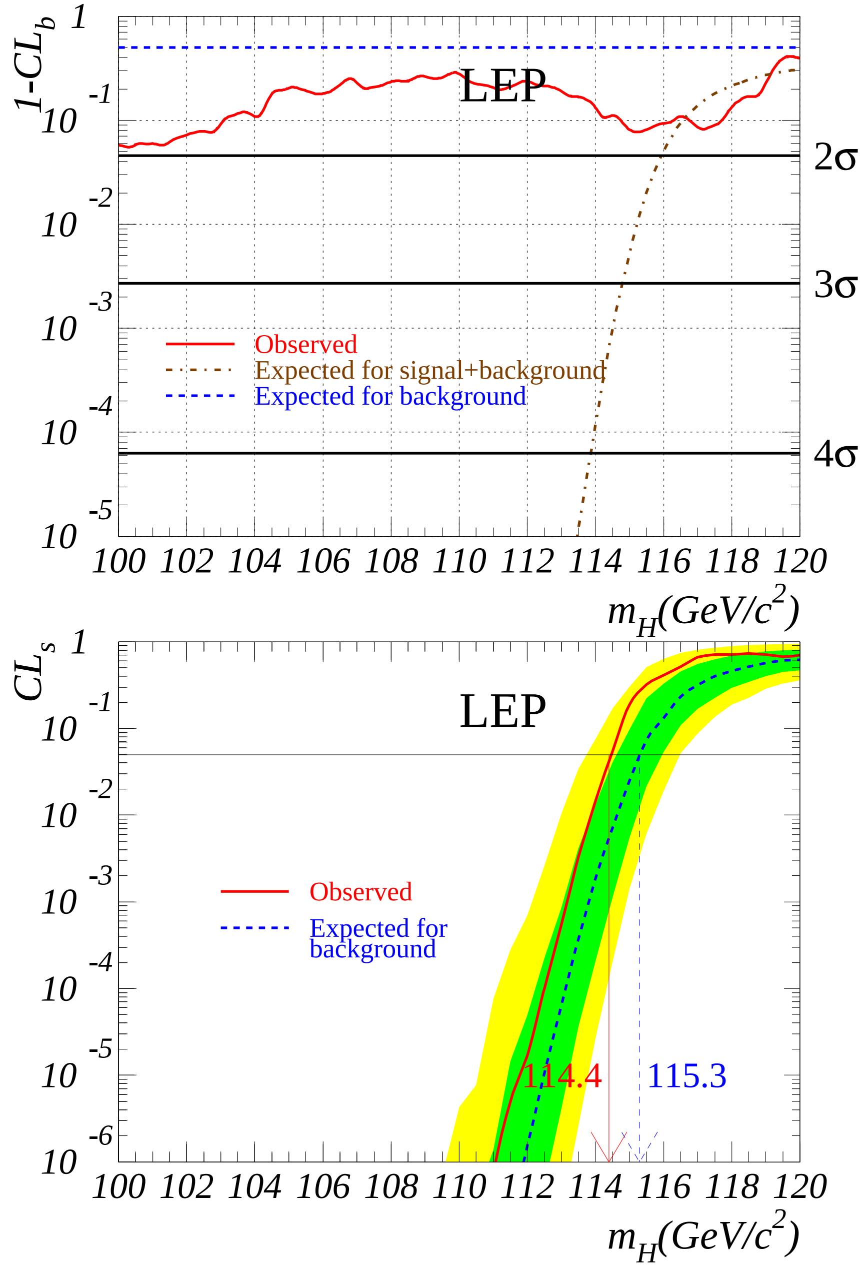
but extra statistics too limited to exclude a 115 GeV SM Higgs

Sophisticated statistical combination of channels/experiments

Final direct search result:

$M_{\rm H} >$ **114.4 GeV (95% CL)**

(expected limit 115.3 GeV)



Highlights

Wealth of precise electroweak measurements from LEP and SLD

(and the Tevatron)

Amongst hundreds of other results, LEP/SLD have:

- shown there are **three light neutrino species**
- demonstrated **radiative loop corrections**
- predicted the **top quark mass**
- verified SM triple **gauge couplings**
- put many **strong constraints on physics beyond the SM**
- indicated where to look for the **SM Higgs** (and ”nearly” found it)...

LEP and SLD have provided a huge step forward for the Standard Model

– *but* the Higgs sector waits for another day