# Loads of Electroweak Physics and the Standard Model

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Liverpool Seminar, 7 March 2002

A *brief* survey of the electroweak physics results from 12 years of data from LEP

The work of thousands of people
~ **ten thousand years** of effort!

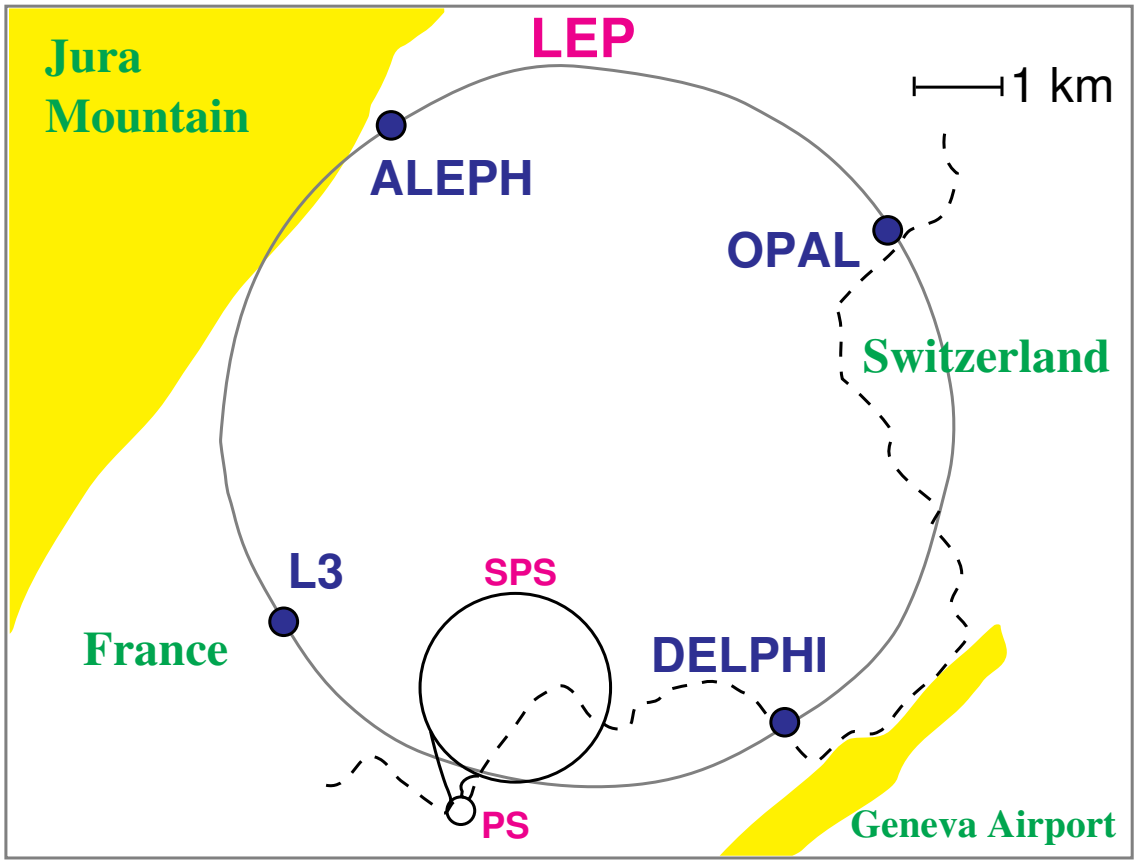
Only a small fraction of the physics output from LEP
(In total now >1000 published papers)

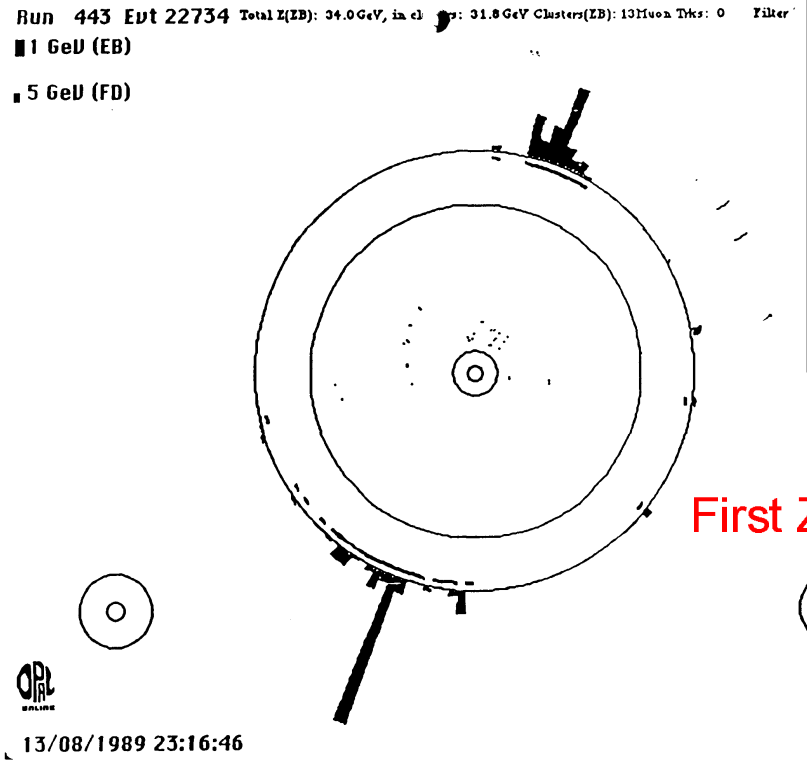
# LEP: The Large Electron-Positron Collider (RIP)

The LEP ring:
27km circumference

~100m underground in the "LHC" tunnel...

First collisions 13 Aug 1989



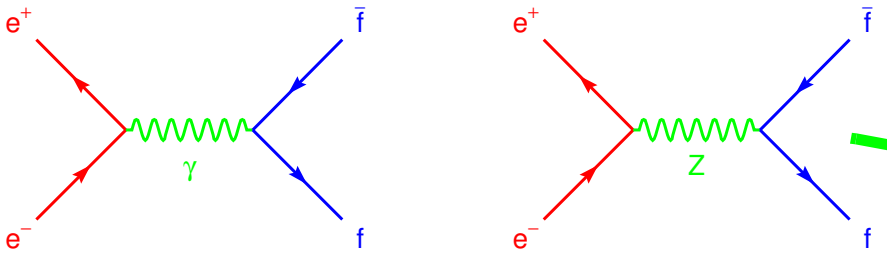




First $Z^0$ decay at LEP

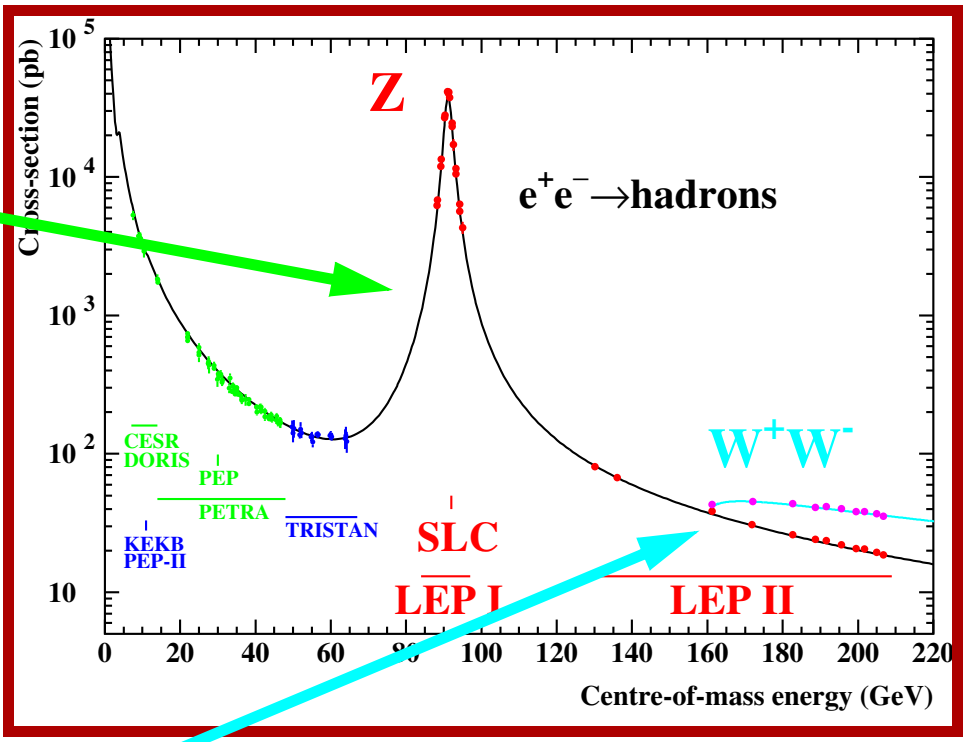
Final collisions: 2 Nov 2000

# LEP Data

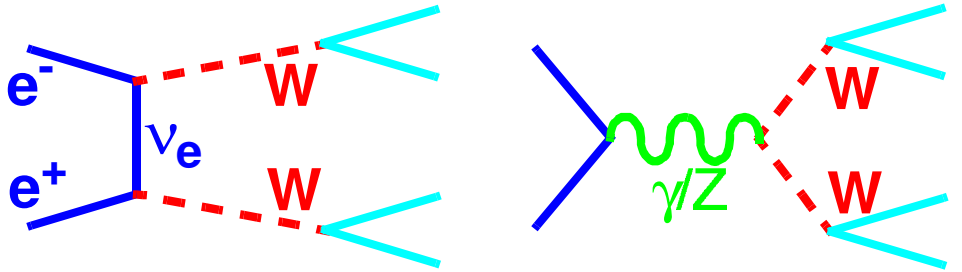
**LEP-1**: At the $Z^0$ peak 1989-1995




Total sample in excess of 16 million observed Z decays

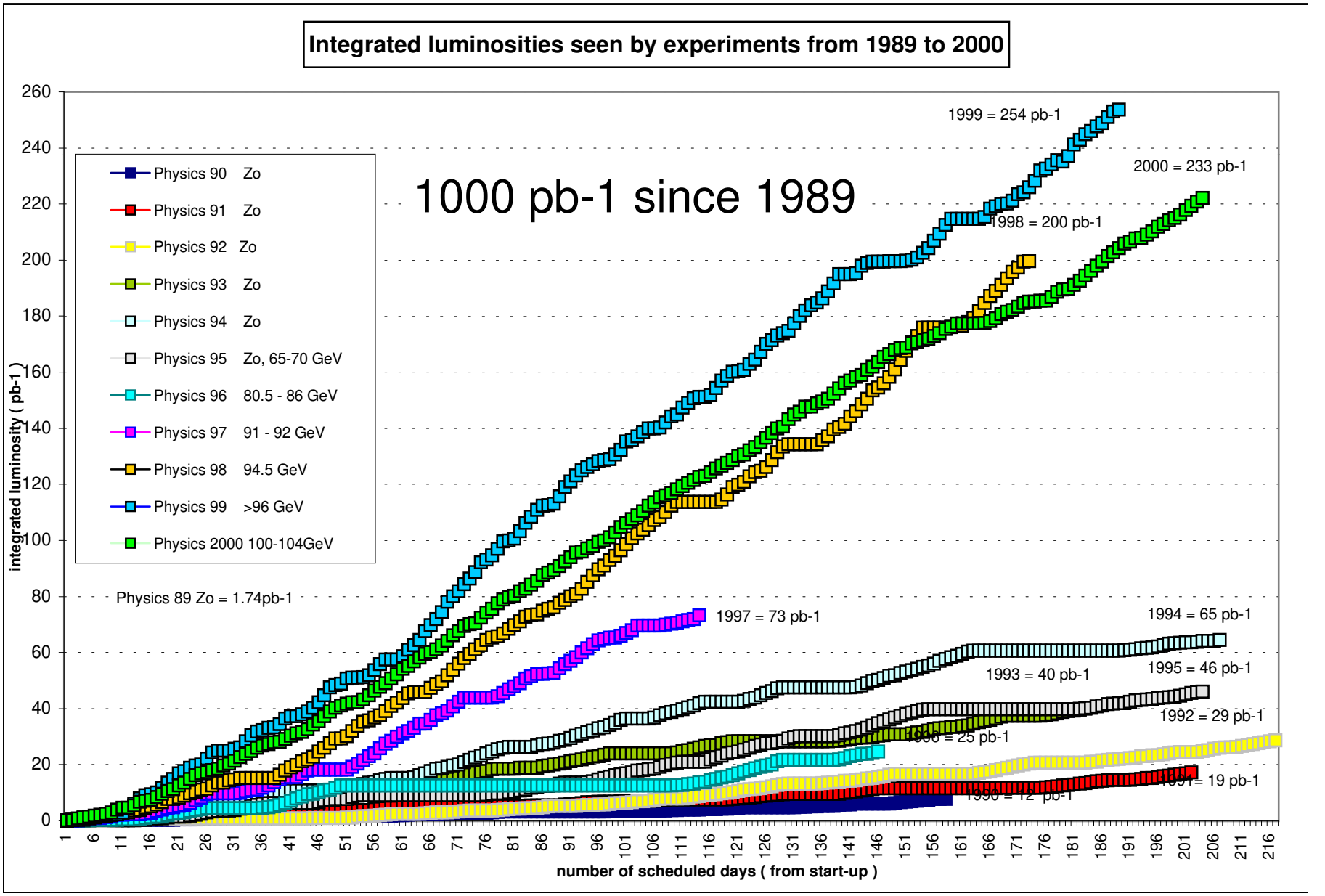



**LEP-2**: At and above the $W^+W^-$ threshold 1996-2000




Total sample in excess of 40 thousand $W^+W^-$ events

# LEP Luminosity



# The Standard Model: Tree-Level

The Standard Model describes the interactions of fermions via the exchange of gauge bosons

Gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow 8g, W^{\pm}, Z, \gamma$

- Wff vertex interaction is $g\,\bar{f}\gamma^{\mu}(1-\gamma^5)f$ $\qquad g^2=(4\sqrt{2})G_F M_W{}^2$
- Zff vertex interaction is $g'\,\bar{f}\gamma^{\mu}(g_V-g_A\gamma^5)f$

Electroweak unification $\rightarrow$ $\qquad G_F = \dfrac{\pi\alpha}{\sqrt{2}M_W^2\sin^2\theta_W}$ $\qquad g' = g\tan\theta_W$

and $\qquad g_V = T_3 - 2Q\sin^2\theta_W, \qquad g_A = T_3$

In SM, W/Z mass generation via single complex Higgs doublet $\rightarrow$

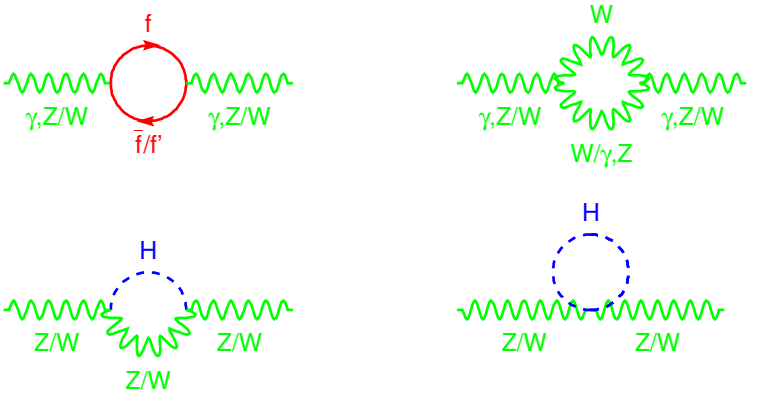
$$\rho \equiv \frac{M_W^2}{M_Z^2\cos^2\theta_W} = 1$$

# Radiative Corrections: Z Propagator

Main corrections affect the Z propagator, absorb via *effective*

$$\bar{\rho} = 1 + \Delta\rho$$
$$\sin^2\theta_{eff} = (1+\Delta\kappa)\sin^2\theta_W$$
$$g_V = \sqrt{\rho}(T_3 - 2Q\sin^2\theta_{eff})$$
$$g_A = \sqrt{\rho}T_3$$

(in principle complex)

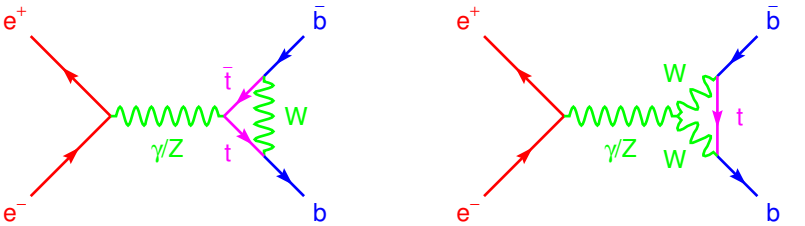



$\Delta\rho$ and $\Delta\kappa$ **probe $M_t$ and $M_H$** via loops...

$$\Delta\rho = \frac{3G_F M_t^2}{8\pi^2\sqrt{2}} - 3\frac{G_F M_W^2 \sin^2\theta_W}{8\pi^2\sqrt{2}\cos^2\theta_W}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots$$

$$\Delta\kappa = \frac{3G_F M_t^2 \cos^2\theta_W}{8\pi^2\sqrt{2}\sin^2\theta_W} - \frac{11}{3}\frac{G_F M_W^2}{8\pi^2\sqrt{2}}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots$$

Flavour dependence small, except for b quark - modified $M_t$ dependence



# Radiative Corrections: Running Couplings

In addition, radiative corrections modify $G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W} \frac{1}{(1-\Delta r)}$

where $\Delta r = \Delta\alpha + \Delta r_W$, and dominant part of $\Delta r_W = \cot^2\theta_W \, \Delta\rho$

$\Delta\alpha(s)$ — running electromagnetic coupling $\alpha(s) = \alpha / (1 - \Delta\alpha(s))$

$\Delta\alpha = 1 - \Delta\alpha_{e\mu\tau}(s) - \Delta\alpha_{had}(s) - \Delta\alpha_{top}(s)$

$\Delta\alpha_{had}(s)$ cannot be calculated from first principles

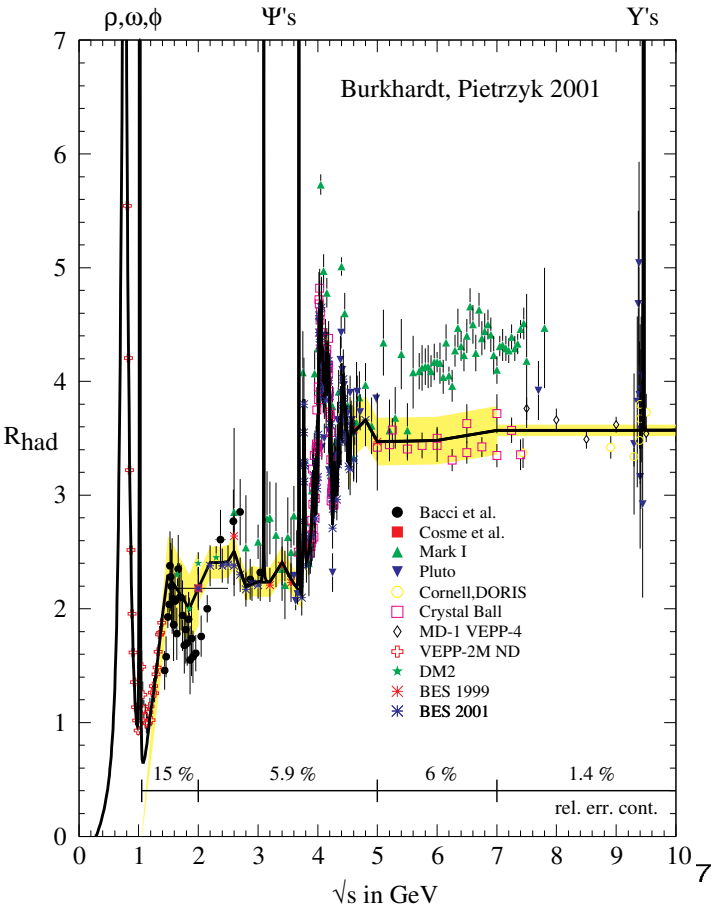
Can be found from data, via dispersion integral

$$\Delta\alpha_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi} Re \int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$

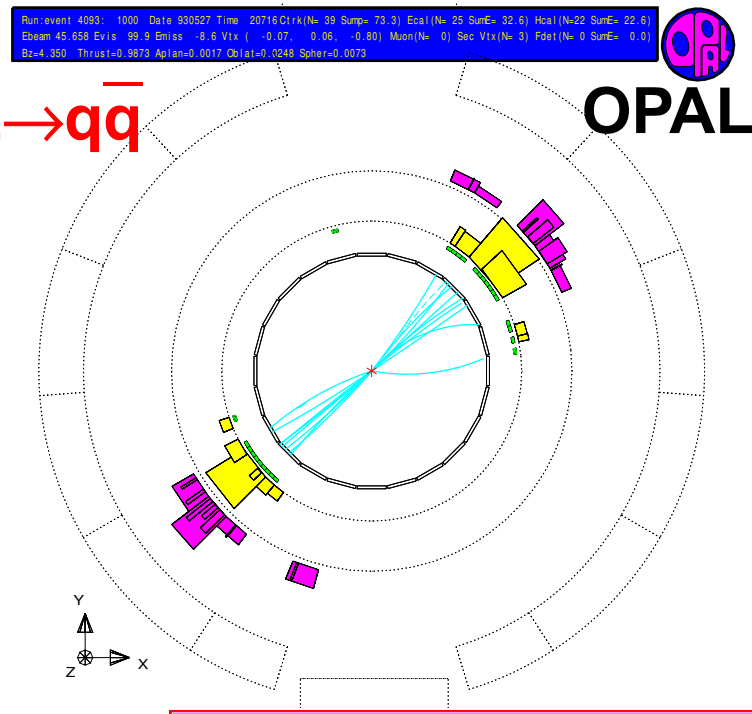
Data-driven update (Burkhardt,Pietrzyk 2001)

$\Delta\alpha_{had}(M_Z^2) = 0.02761 \pm 0.00036$

Error may be as low as 0.00012 with extra theory-driven assumptions

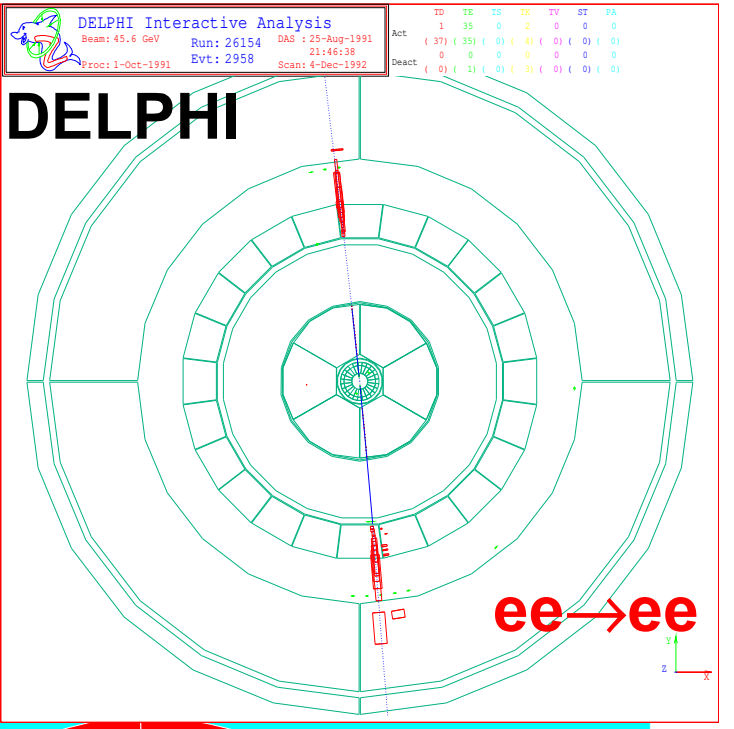


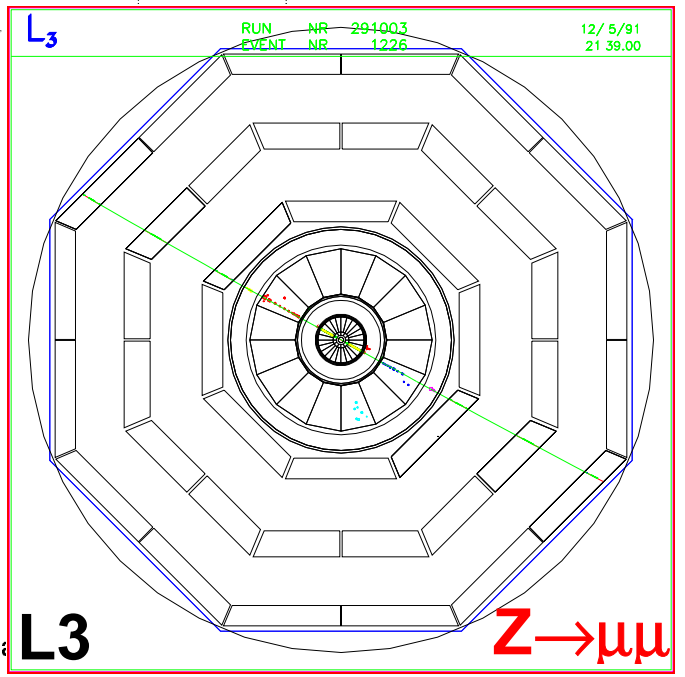
# Z Decay Events

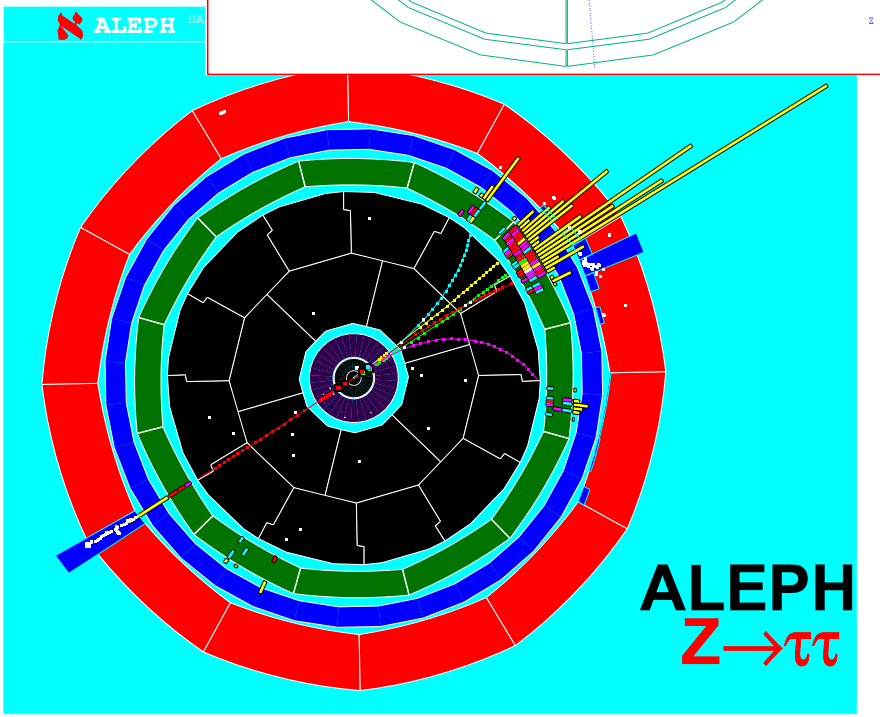



$Z \rightarrow q\bar{q}$

OPAL



# The Z Lineshape: $M_Z$ and $\Gamma_Z$

$\sigma(e^+e^- \to f\bar{f})$ measured within ±3 GeV of the Z mass

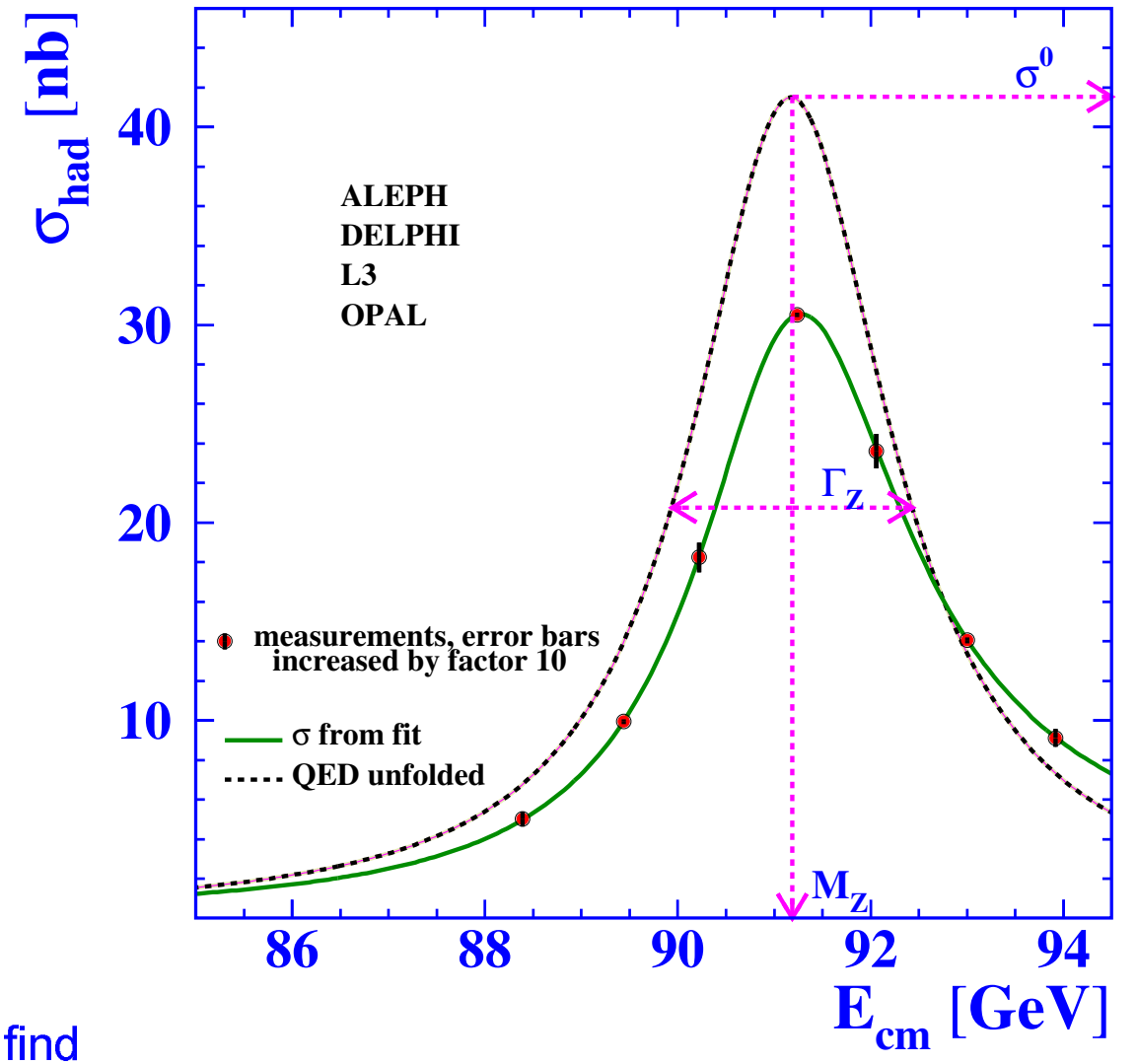
Initial-state radiation (ISR) has a big effect

**$M_Z$ = 91.1875±0.0021 GeV**

**$\Gamma_Z$ = 2.4952±0.0023 GeV**

(±0.12 and ±0.4 GeV before LEP)

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




allows deduction of $\Gamma(Z \to \text{invis.})$ from

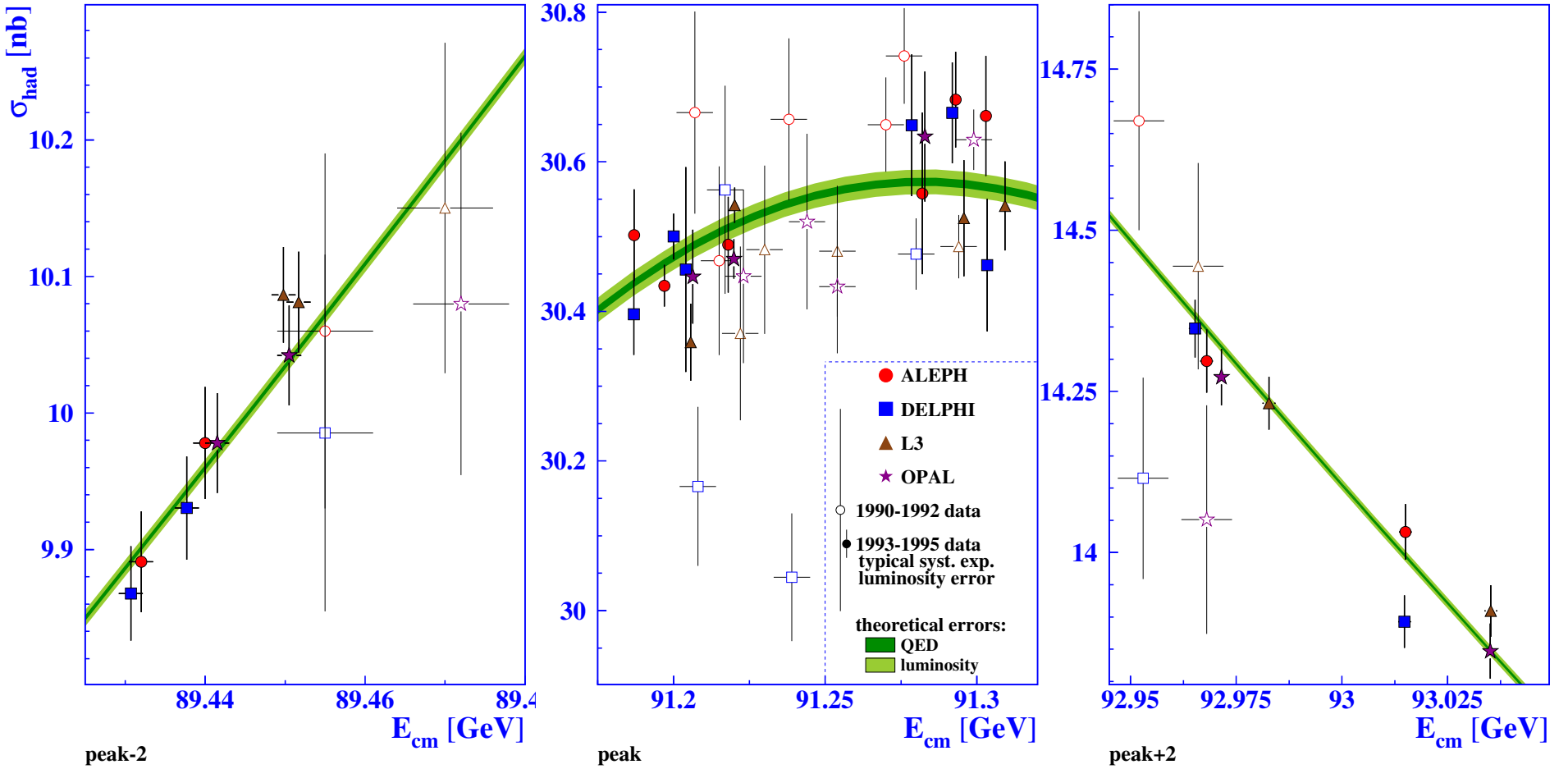
$\Gamma_Z = \Sigma\, \Gamma(Z \to \text{visible}) + \Gamma(Z \to \text{invis.})$

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

**$N_\nu$ = 2.9841±0.0083**

Before LEP, it was believed $N_\nu$ was no more than "about 4" !

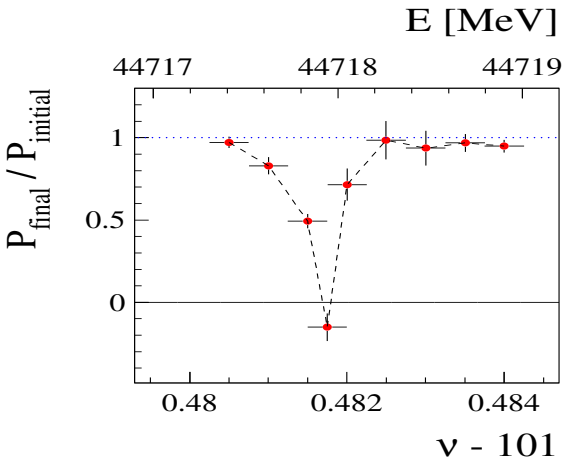
# Z Lineshape: High Statistics!

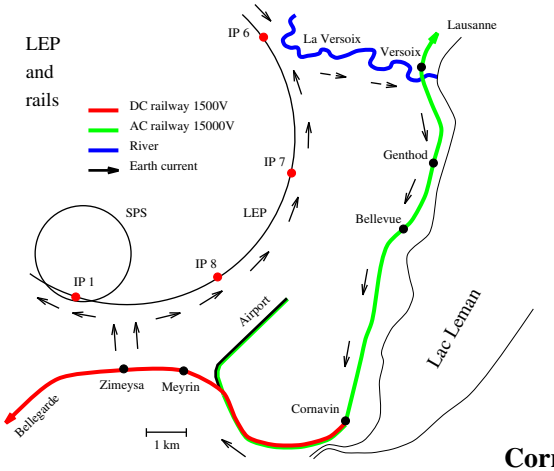


# The LEP Beam Energy

The main experimental uncertainty on $M_Z$ (1.7 of 2.1 MeV total error)

Precise measurement of beam energy by "resonant depolarisation" in special configuration of the machine



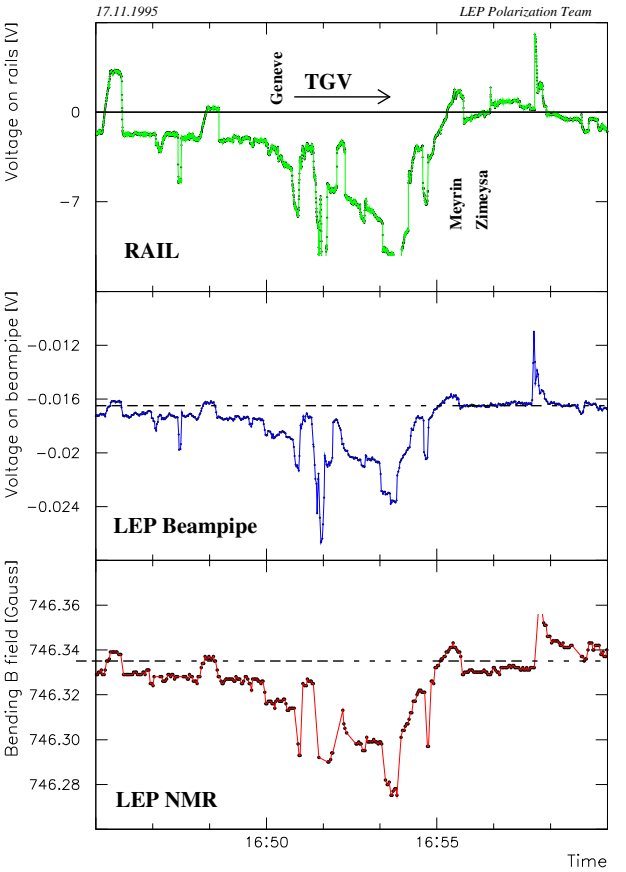




Sensitive to many effects:

- lunar/solar tides
- recent rainfall
- level of lake Geneva
- the French train timetable!

Major programme of work over many years led to the final very low error

**Correlation between trains and LEP**

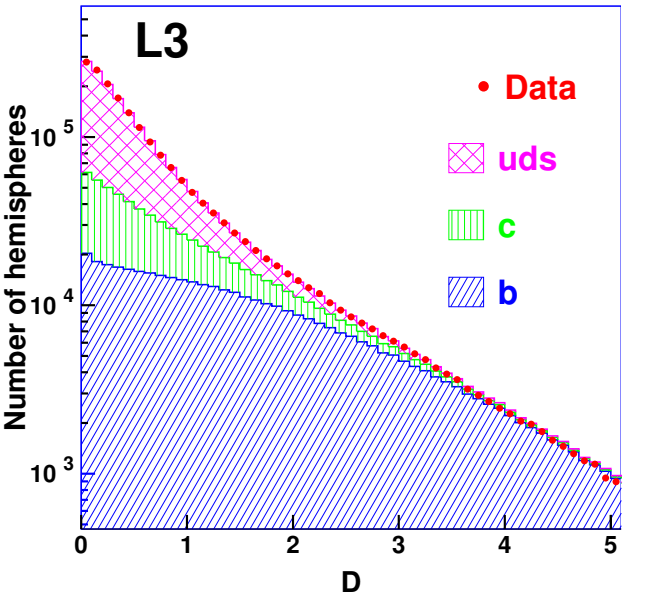


# $Z \rightarrow q\bar{q}$ Partial Widths

Only b and c can be identified well - many tags

lifetime,
lepton,
jet shape & structure,
event shape,
fast particles (kaons, pions),
transition pions, ...

Performance better for b than c

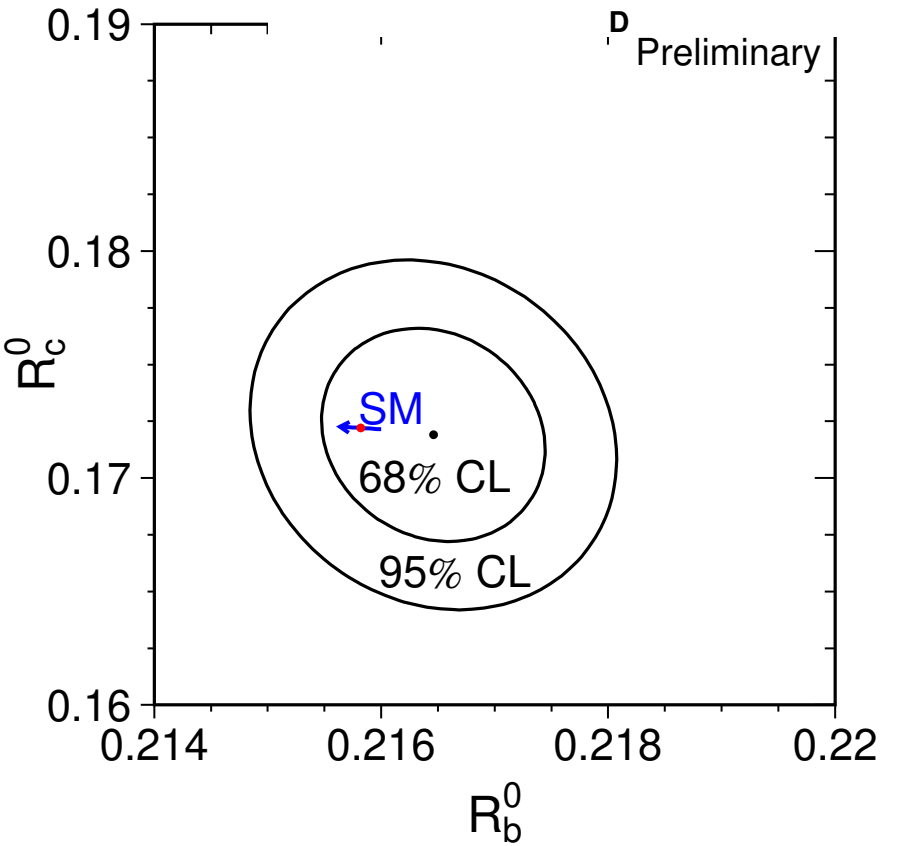



Measure

$R_Q = \Gamma(Z \rightarrow QQ) / \Gamma(Z \rightarrow \text{hadrons})$

$R_b = 0.21646 \pm 0.00065$
$R_c = 0.1719 \pm 0.0031$

in good agreement with SM expectations



# Asymmetries

Fermion-pair cross-sections at the Z give $\Gamma_{ff}$ via $\sigma^0(Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$

With $\Gamma_{ff} \approx N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi}(g_V^2 + g_A^2)\left(1 + \frac{\alpha_s}{\pi} + \ldots\right)$ can extract $(g_V^2 + g_A^2)$

**Asymmetries** give another handle on $g_V$ and $g_A$.

**Forward-backward asymmetry**

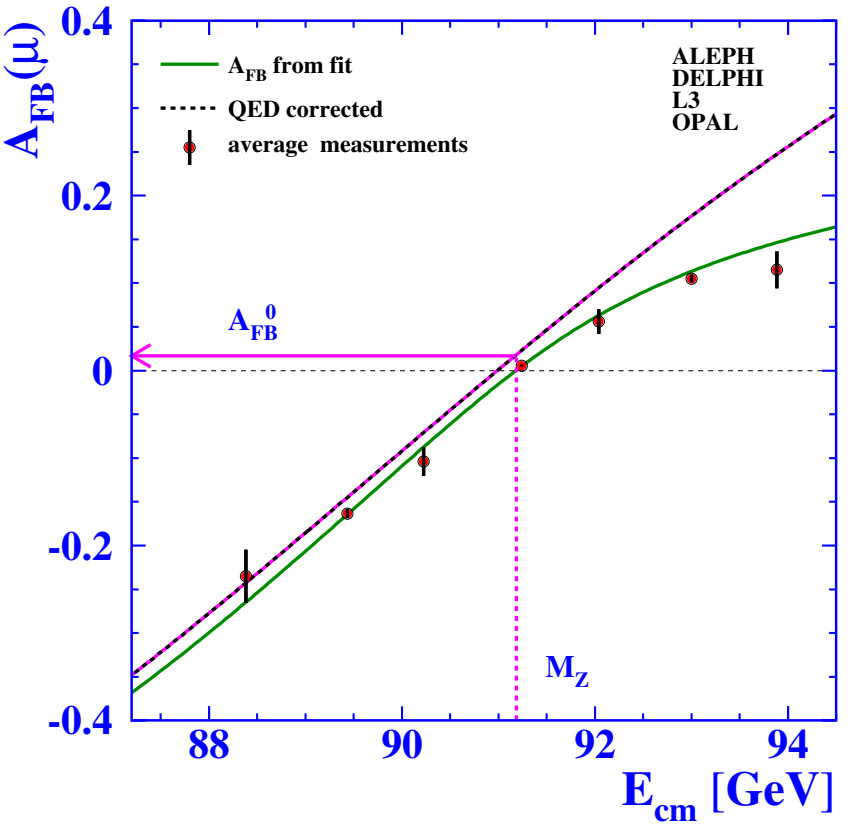
$A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B)$

varies with $\sqrt{s}$ from changing Z and $\gamma$ contributions

$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$

where

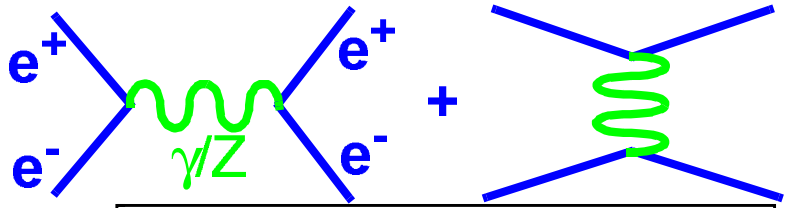
$A_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2} = f(g_V/g_A) = f(1\text{-}4|Q_f|\sin^2\theta_{eff})$

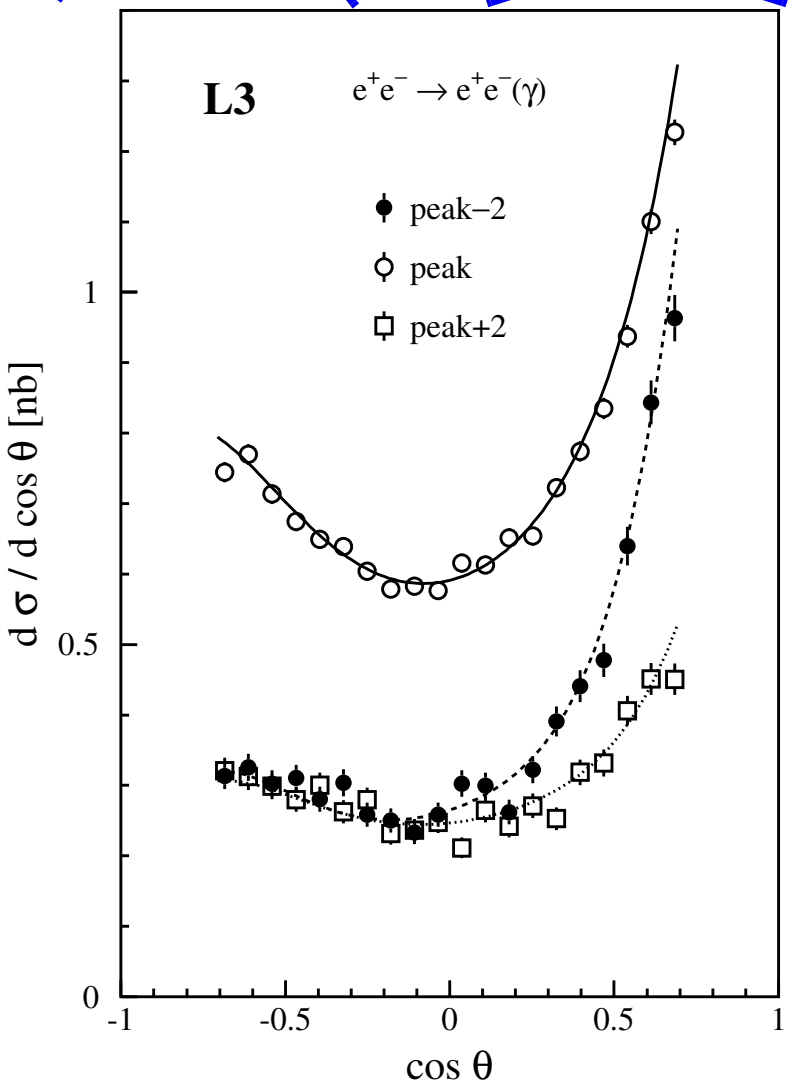


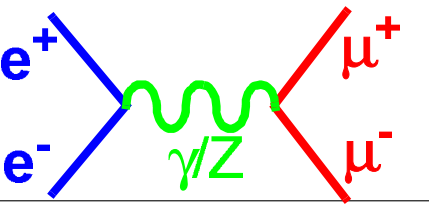

Also $\tau$ **polarisation** $A_{pol} = A_f = -P_f$

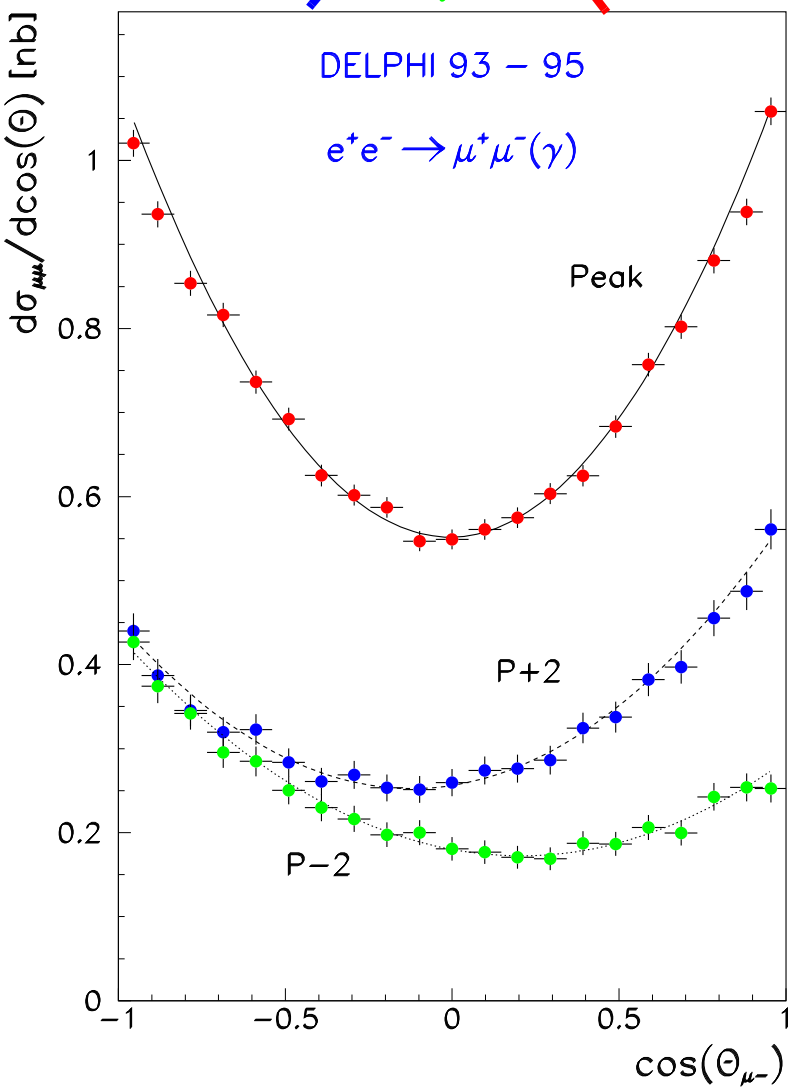
and polarised beam **left-right asymmetry** (SLD) $A_{LR} = A_e$

# Lepton Forward-Backward Asymmetry



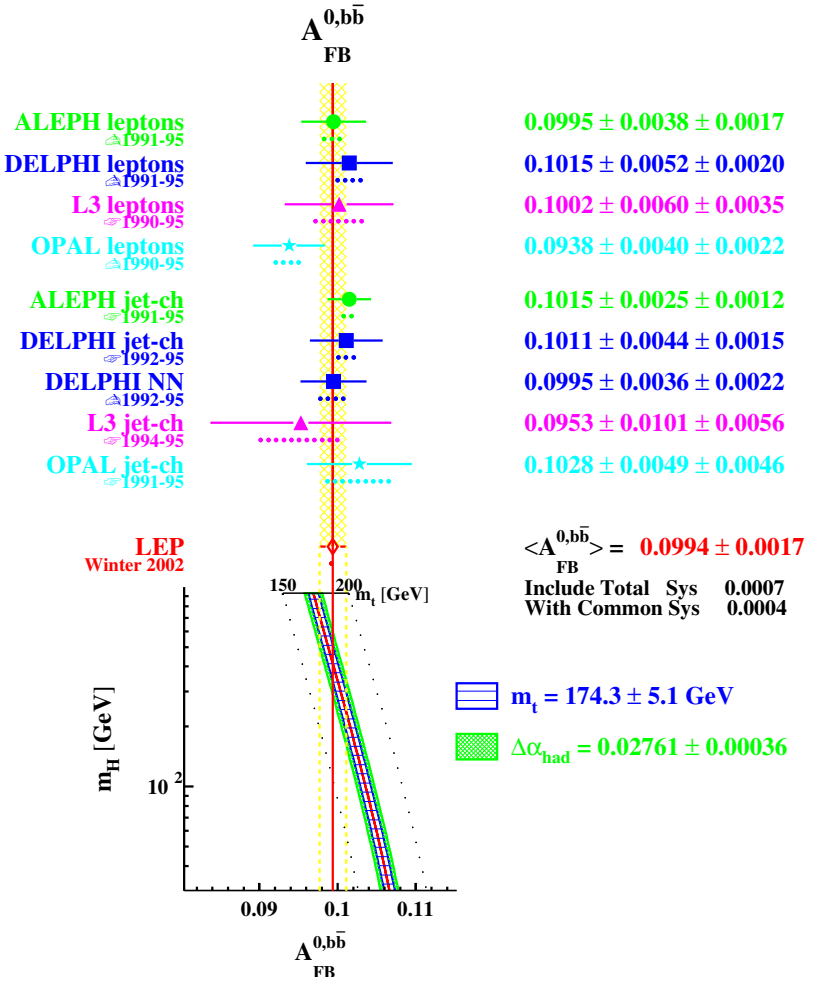



# Heavy Quark Forward-Backward Asymmetry

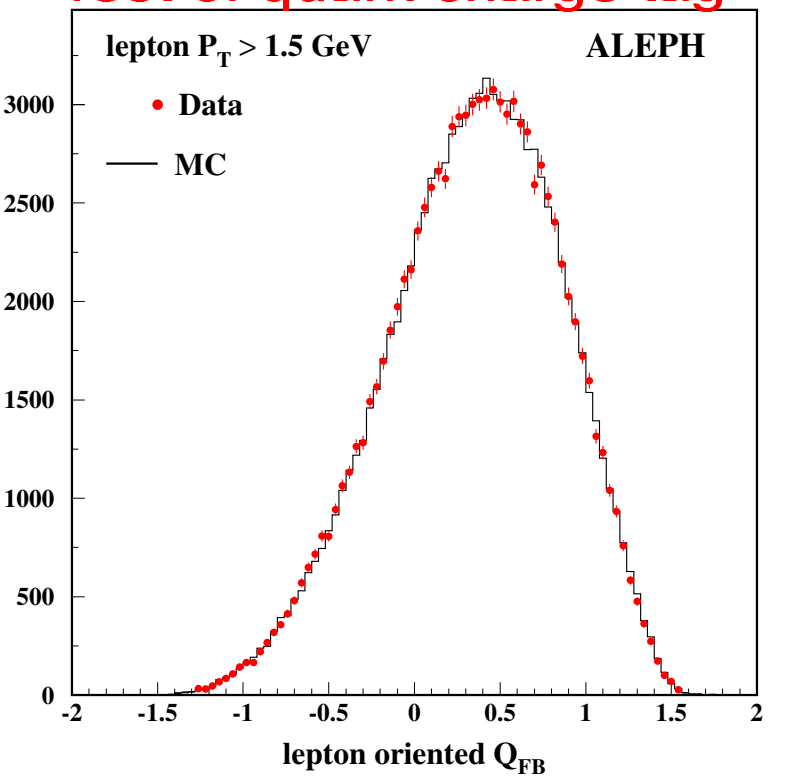
To measure $A_{FB}^{b/c}$: need to tag quark **flavour** and **charge**

For lifetime tags: *jet charge* and/or *vertex charge*

Most powerful analyses use combinations of flavour and charge tagging methods




## Test of quark charge tag




Substantial recent improvements compared to "old" LEP-1 analyses: *eg* ALEPH error reduced by 40% *cf* 1998 analysis

# Tau Polarisation

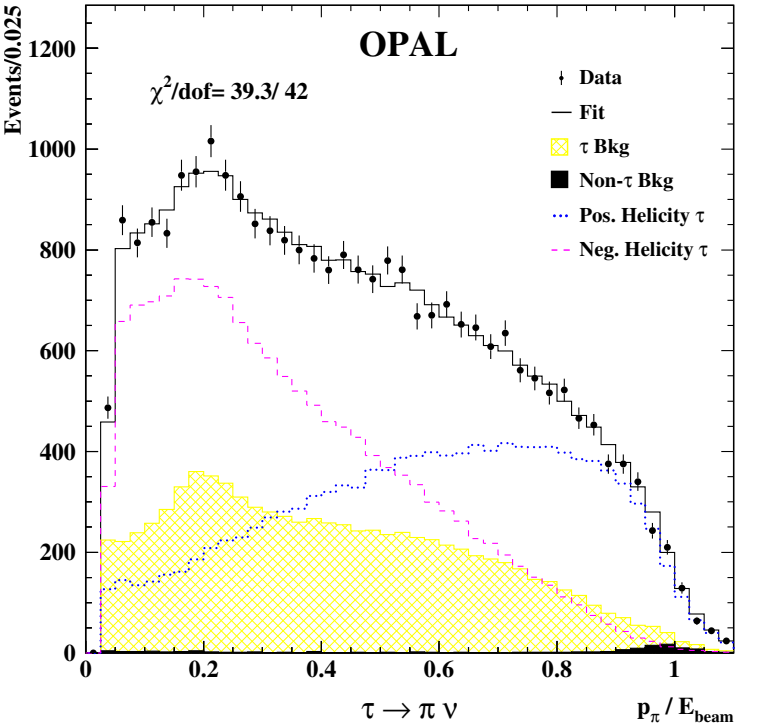
$Z \to \tau\tau$ : Distribution of $\tau$ decay products probes $\tau$ polarisation

*eg* $\tau \to \pi\nu_\tau$: $x_\pi = E_\pi / E_\tau$

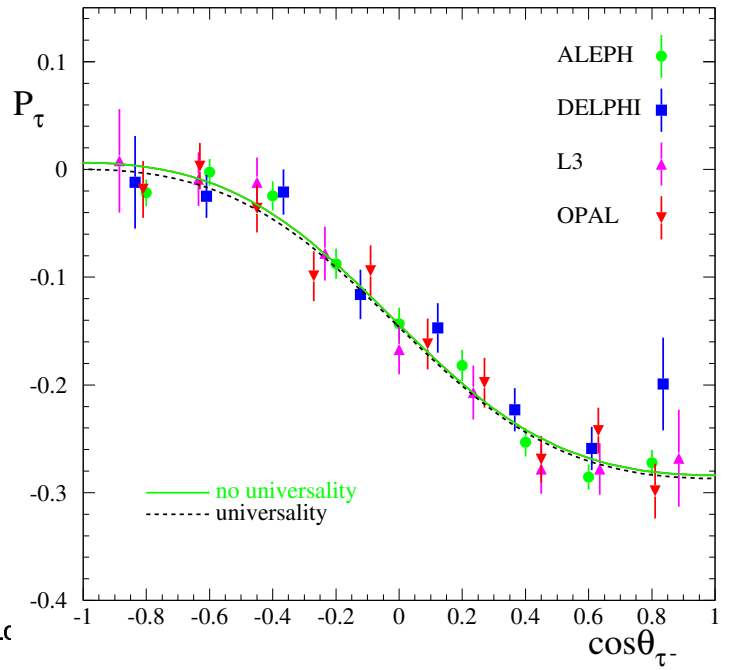
$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1 + P_\tau(2x_\pi - 1)$$

Polarisation varies with $e^- \to \tau^-$ scattering angle $\theta$:

$$P_\tau(\cos\theta) = \frac{-A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A_{FB}^\tau\cos\theta}$$




Measured $P_\tau$ vs $\cos\theta_{\tau^-}$




Find

$A_\tau = 0.1439 \pm 0.0043$

$A_e = 0.1498 \pm 0.0049$

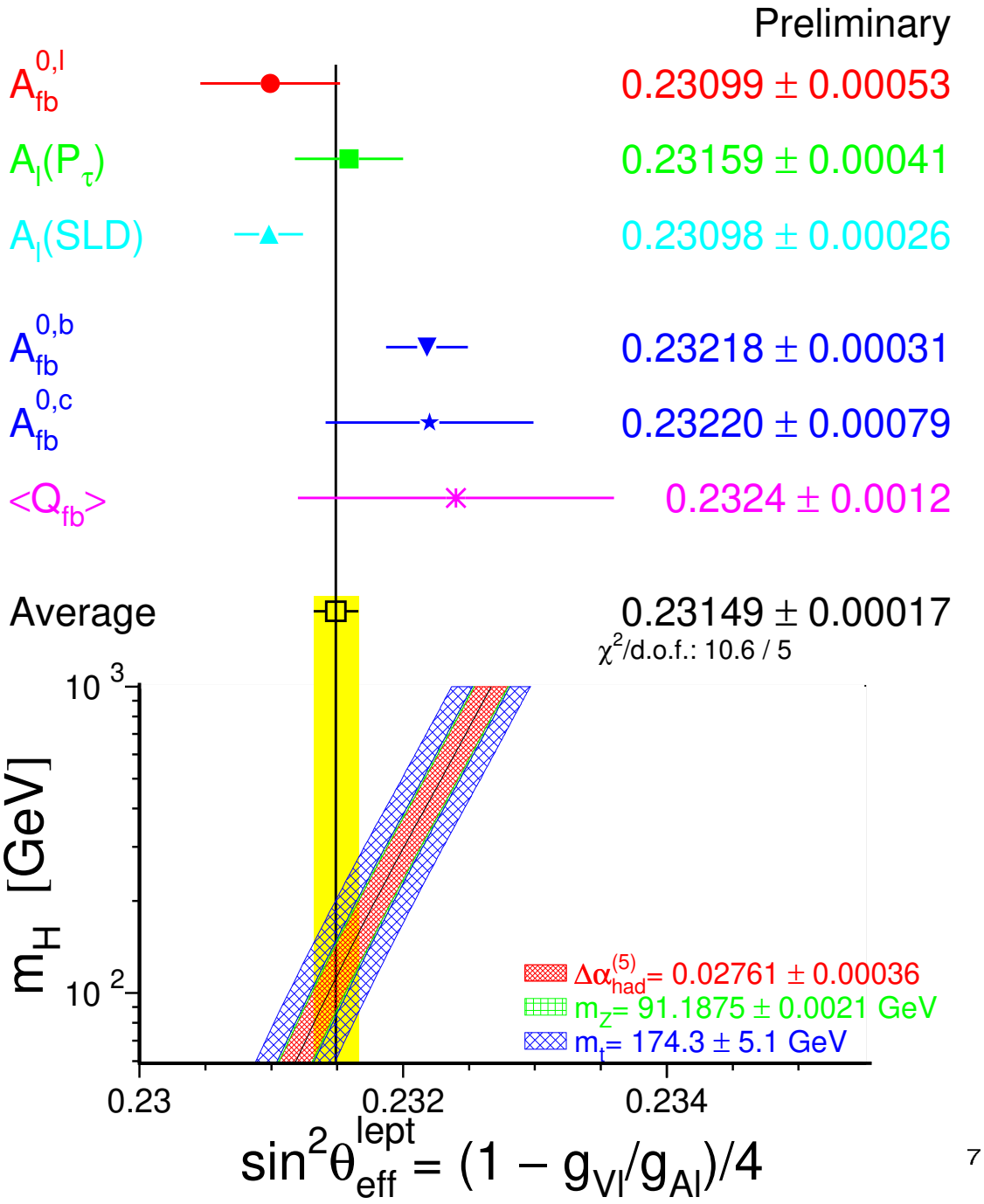
Combined from $\tau$ polarisation

$A_l = 0.1465 \pm 0.0033$

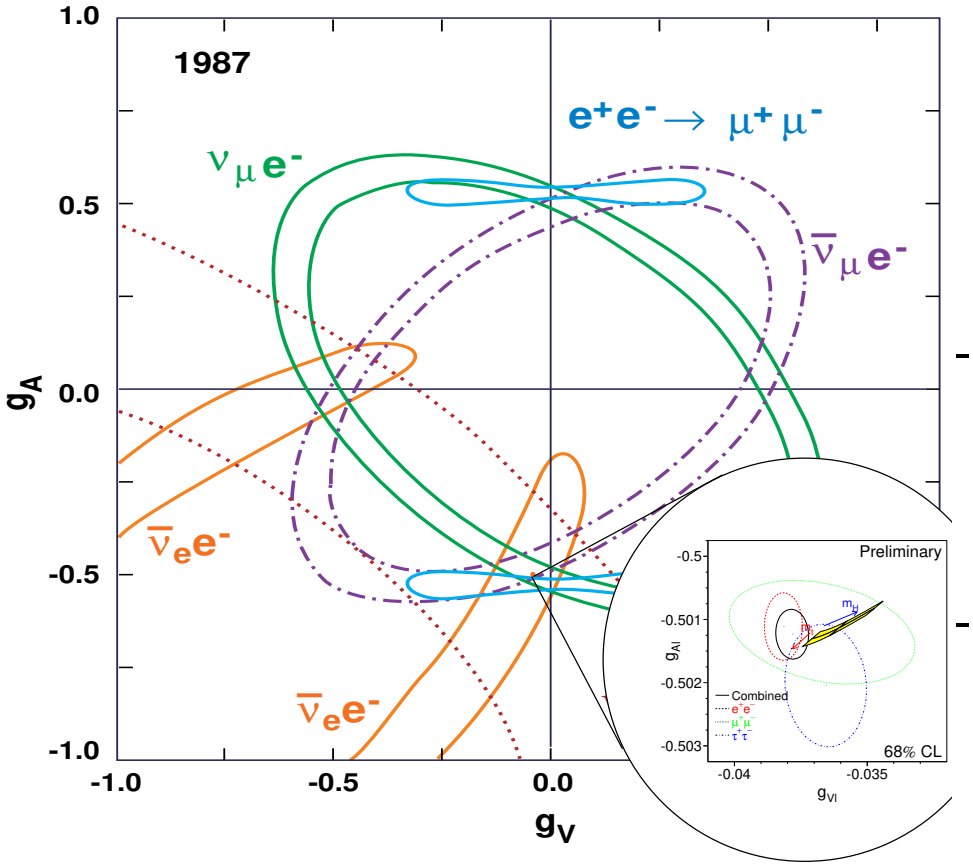
# Asymmetries at the Z: Measuring $\sin^2\theta^{lept}_{eff}$

Interpret various asymmetry measurements as measurements of $\sin^2\theta_{eff}$

**Consistency between values at 5.9% level**

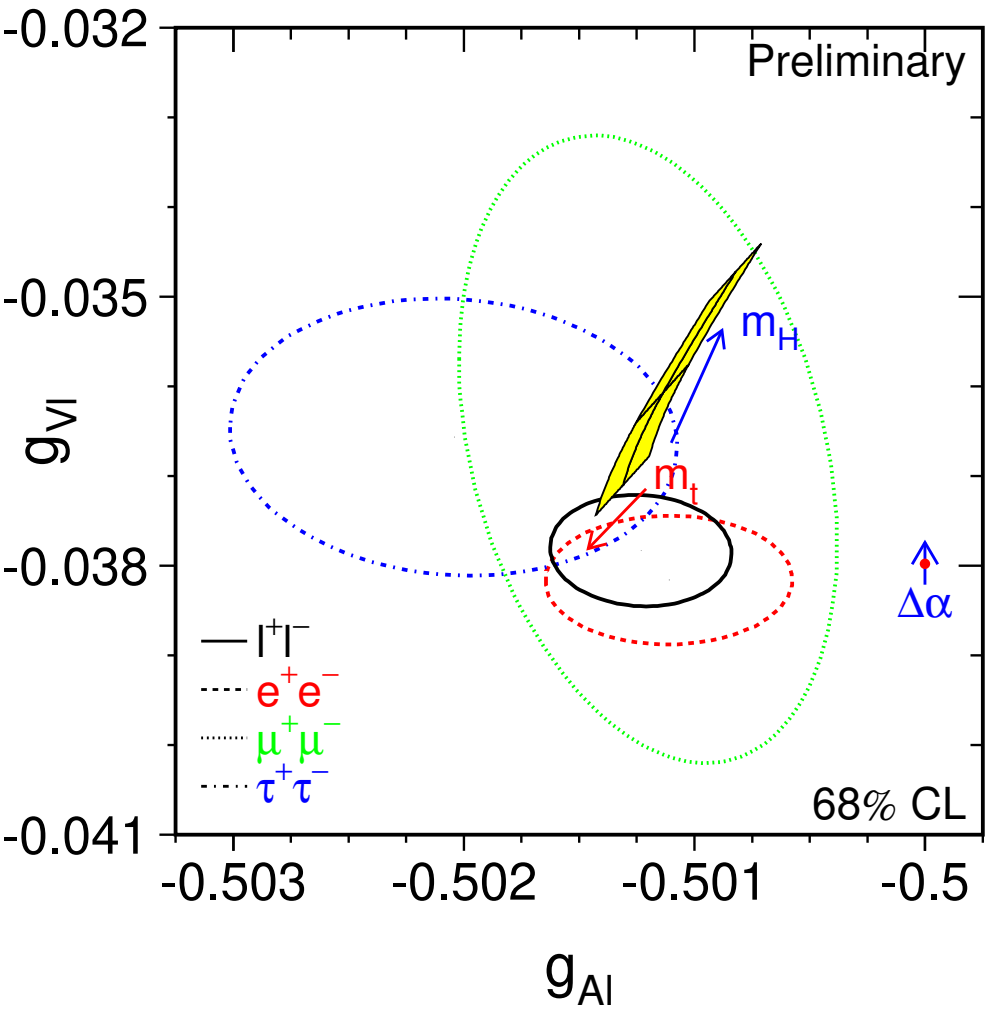


# Z Couplings to Leptons




Huge improvement from LEP-1 data

Sensitivity to $M_t$, $M_H$ via radiative corrections



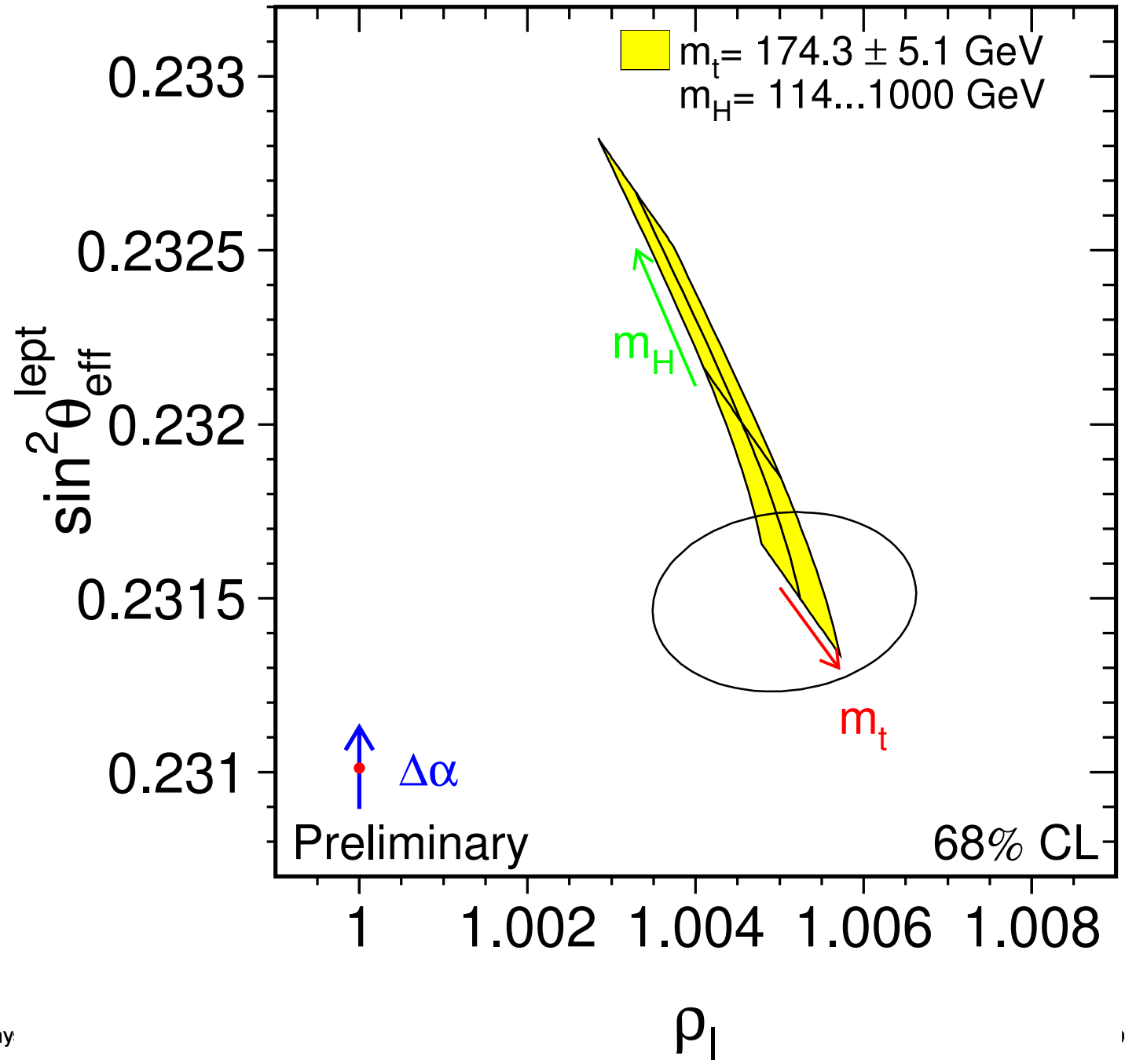

Tests lepton universality in weak neutral current

# The Evidence for Radiative Corrections

Data need **both** the running of $\alpha$ **and** the genuine electroweak corrections

Large sensitivity to $M_H$ and $M_t$

These data prefer **low $M_H$**



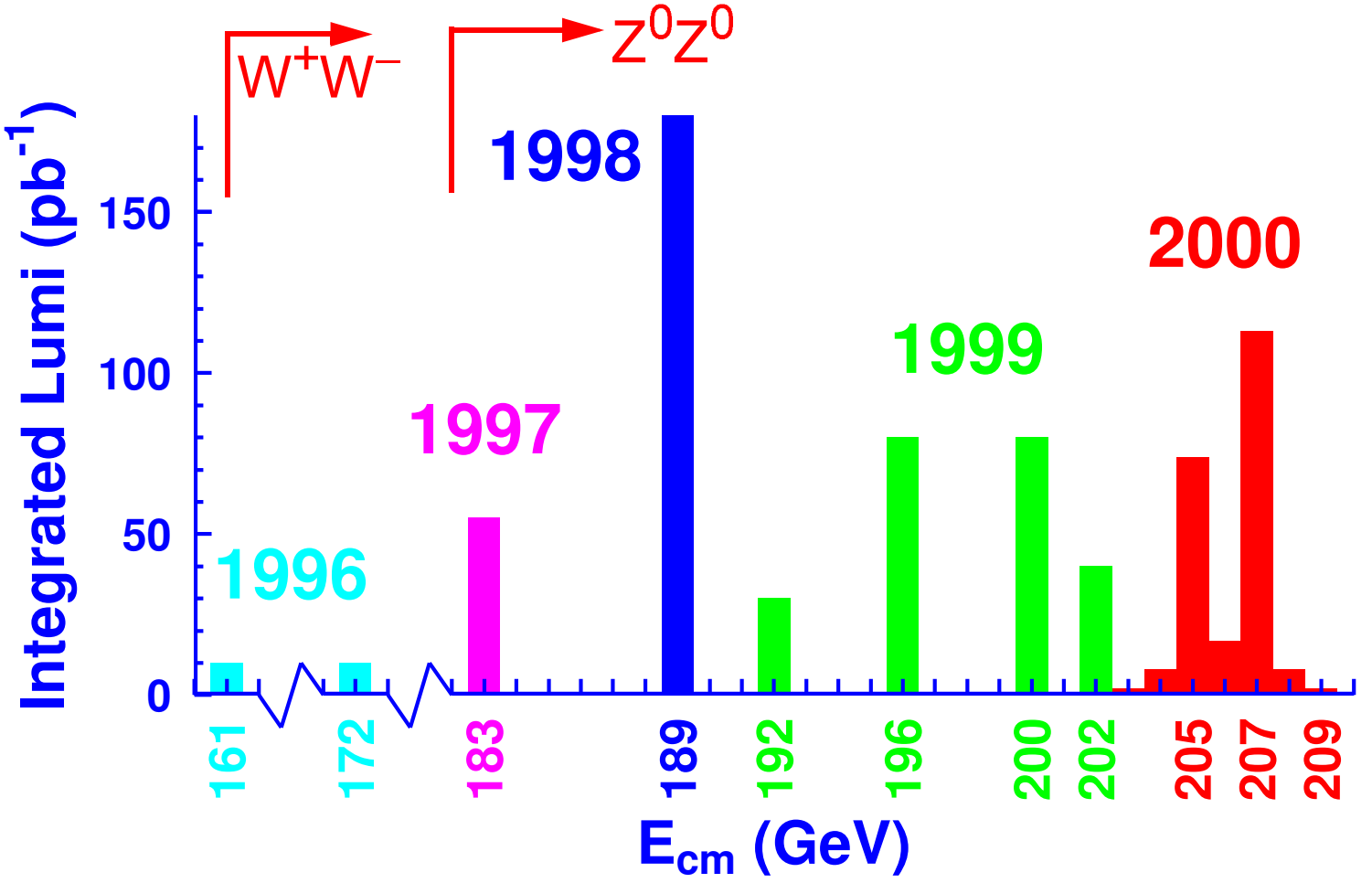

The evidence that led to the t'Hooft and Veltman Nobel prize?

# LEP-2 Data

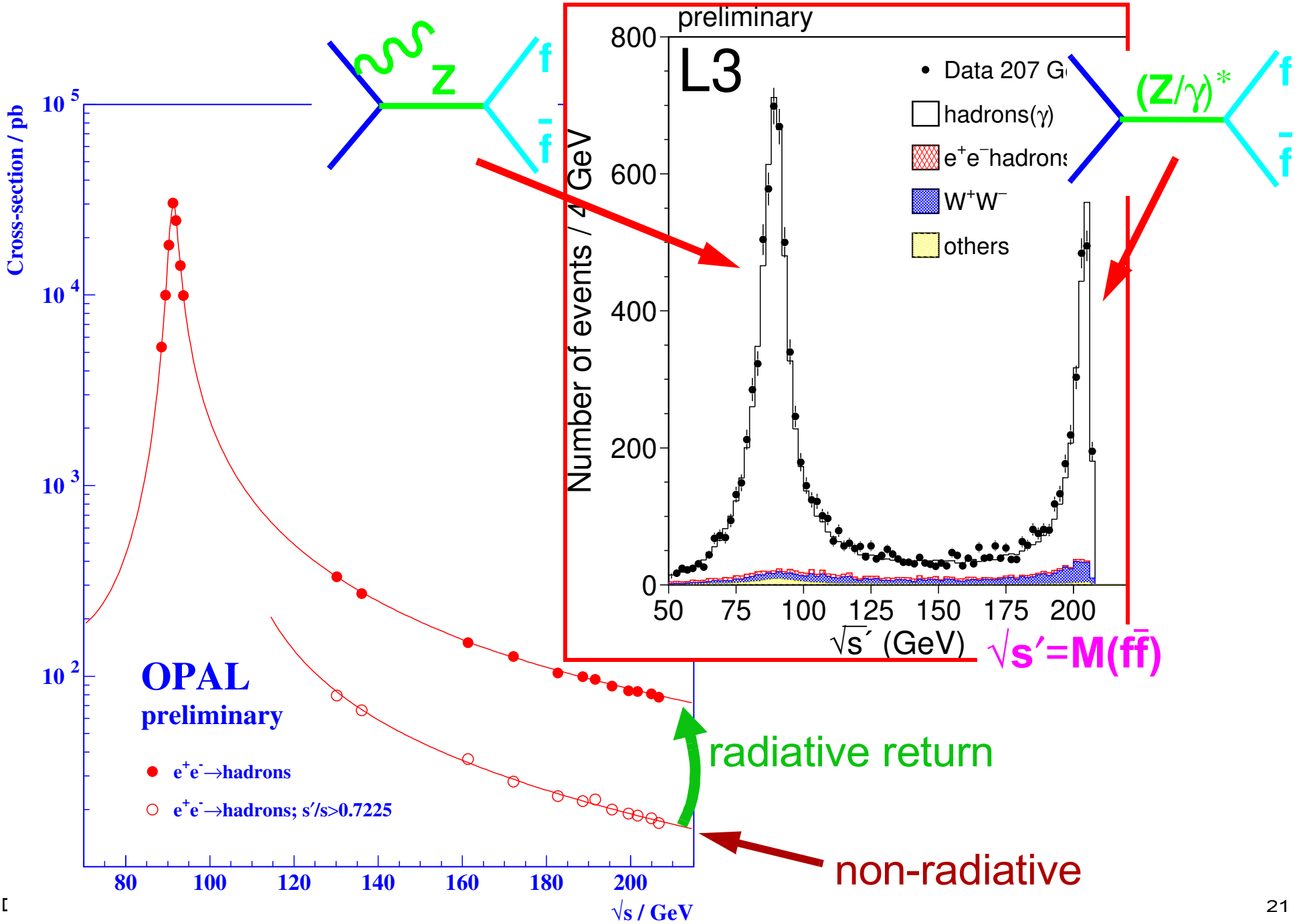
LEP-2 data-taking was completed 2nd Nov. 2000

LEP-2 data sample: **700 pb$^{-1}$ / experiment**

Wide range of centre-of-mass energies

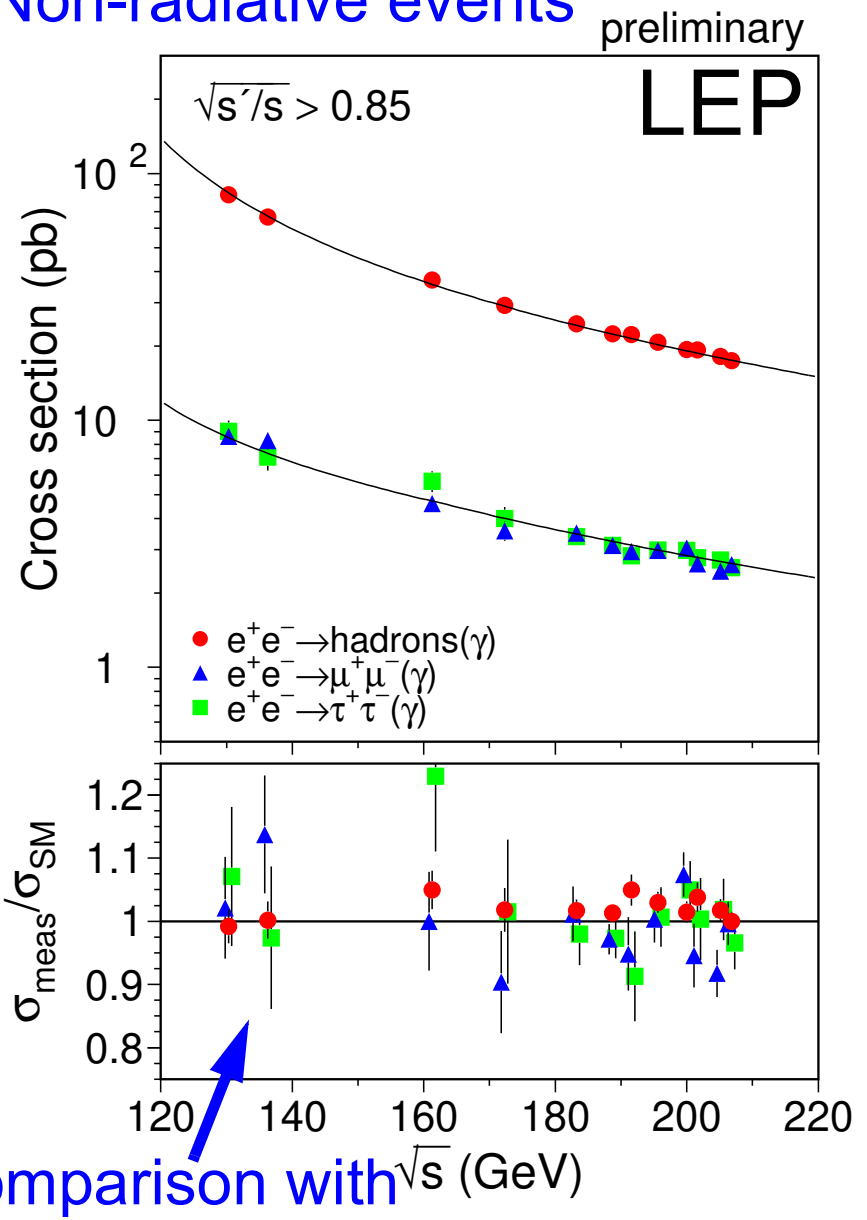


# LEP-2 Fermion Pair Production



# LEP-2 Fermion Pair Cross-Sections

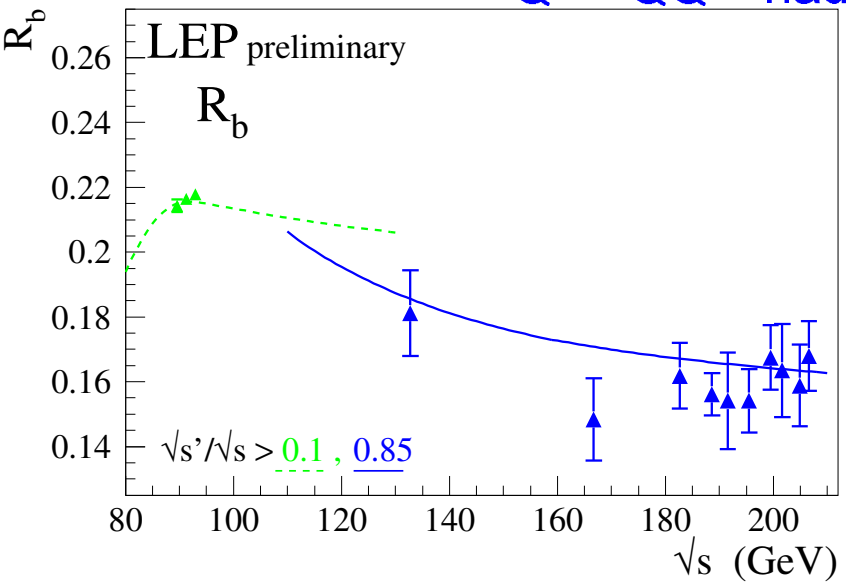
## Non-radiative events

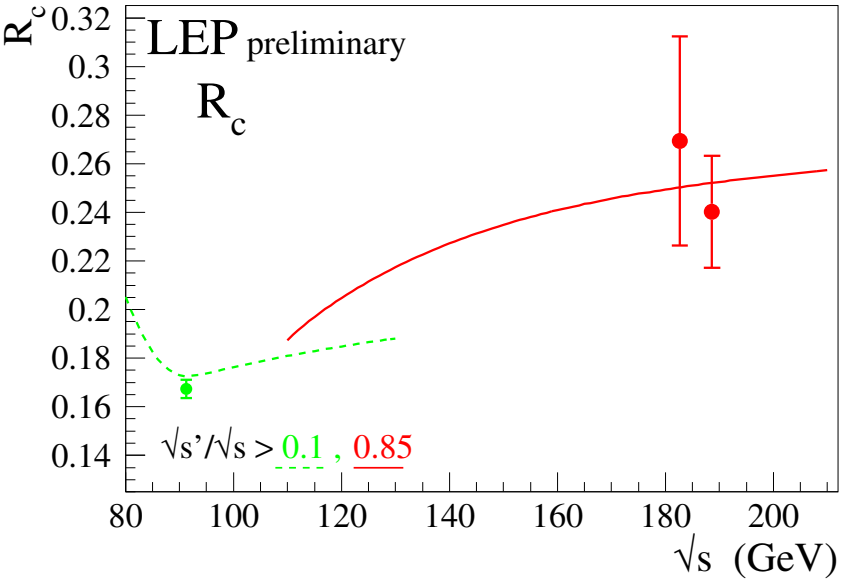



Comparison with SM expectation

## Heavy quark fractions

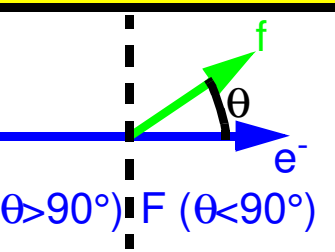
$R_Q = \sigma_{QQ}/\sigma_{had}$

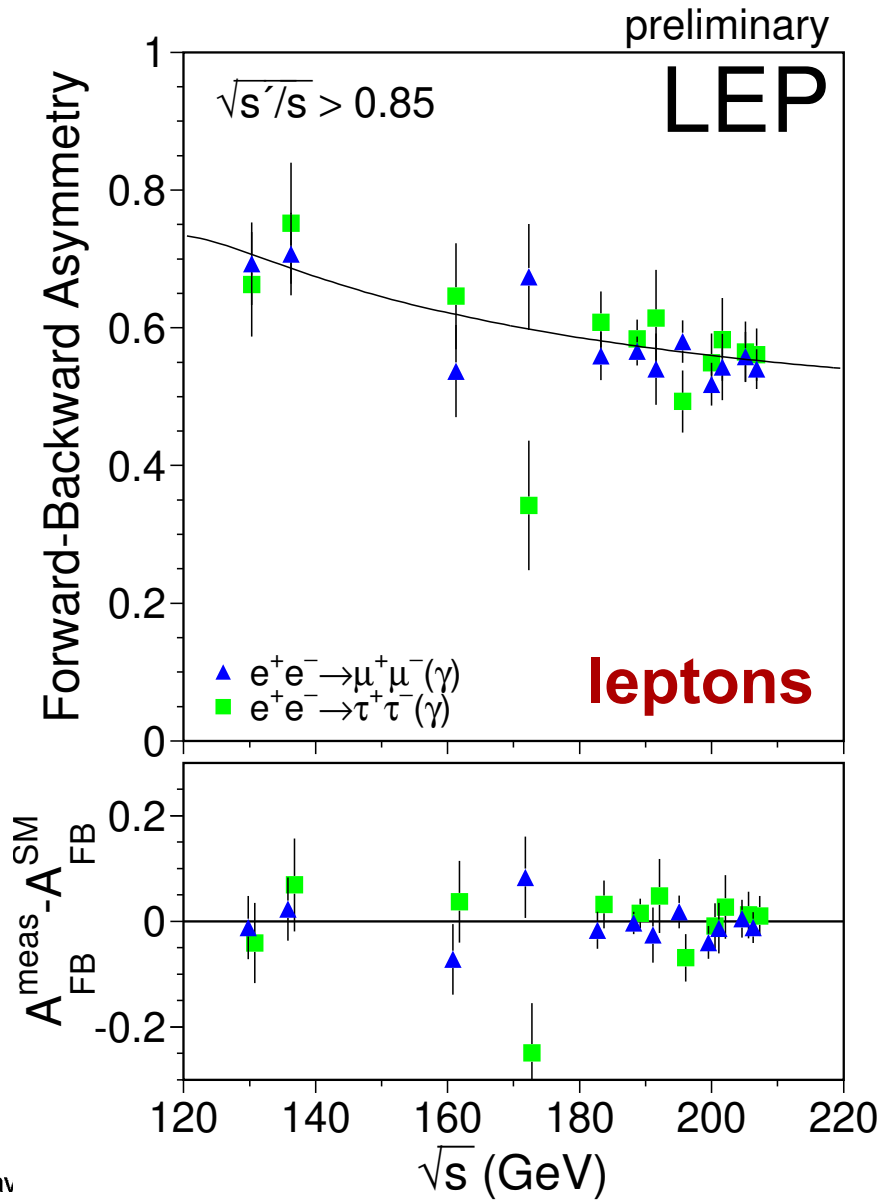


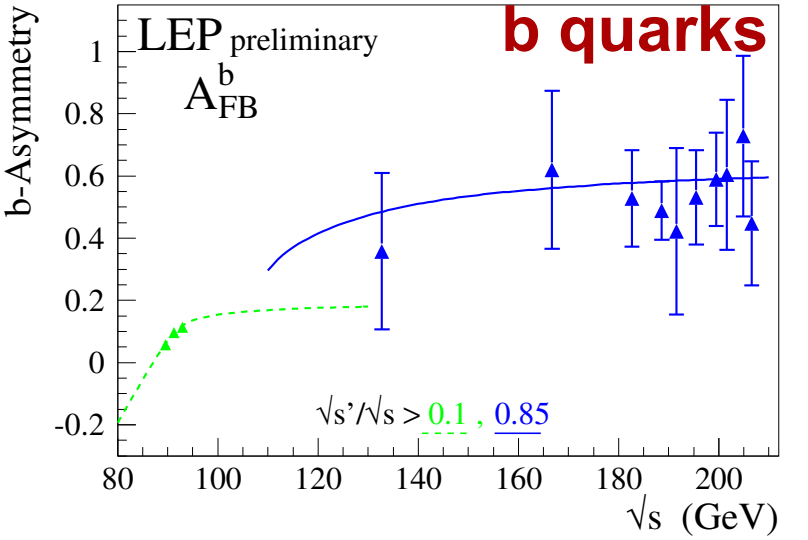



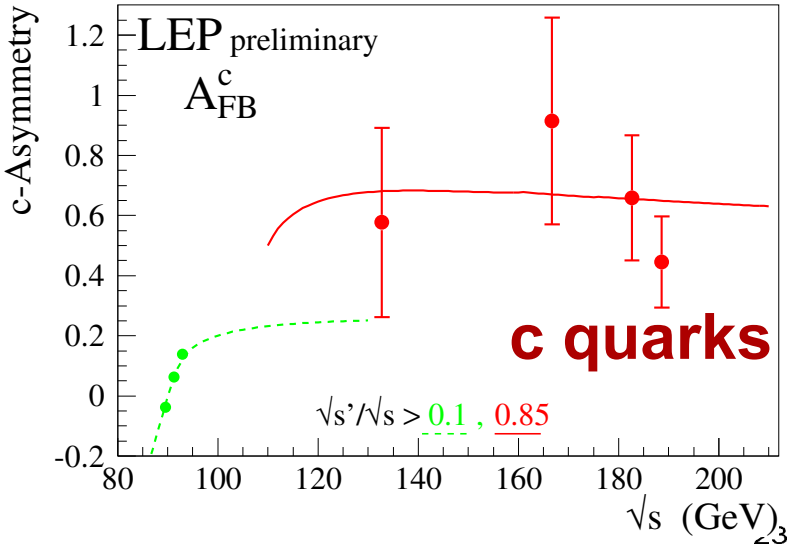
# LEP-2 Fermion Pair Asymmetries

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



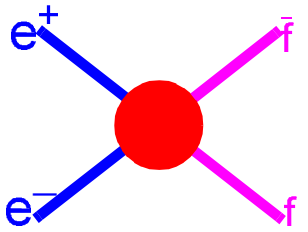



# New Physics Constraints from Fermion Pairs

LEP-2 $f\bar{f}$ results constrain new physics — examples...



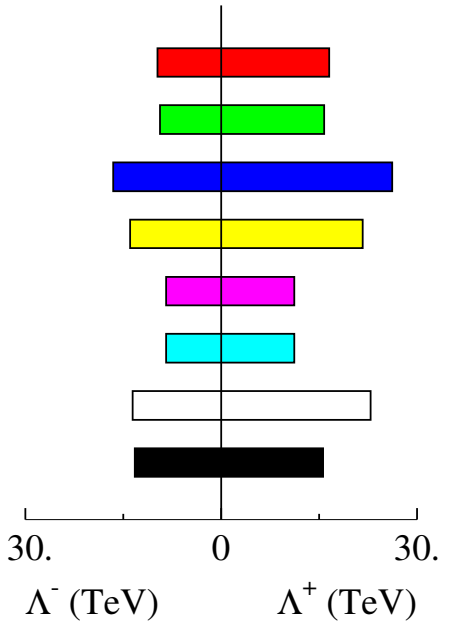

**4-f Contact Interactions**

$$L_{eff} = \frac{1}{1+\delta_{ef}} \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j)$$

**Preliminary LEP Combined**

$g^2=4\pi$

| | $\Lambda^-$ | $\Lambda^+$ |
|---|---|---|
| LL | 9.8 | 16.5 |
| RR | 9.4 | 15.7 |
| VV | 16.5 | 26.2 |
| AA | 14.0 | 21.7 |
| RL | 8.5 | 11.2 |
| LR | 8.5 | 11.2 |
| V0 | 13.5 | 22.8 |
| A0 | 13.2 | 15.6 |




$l^+l^-$

Possible new Z′ boson in $E_6$, L-R symmetric, or sequential models

Large mixing with Z excluded by LEP-1 data

LEP combined ($\theta_{ZZ'}=0$)

$M_{Z'}$ > 678 GeV ($\chi$)
463 GeV ($\psi$)
436 GeV ($\eta$)
800 GeV (LR)
1.89 TeV (SSM)

# W Pair Production at LEP-2

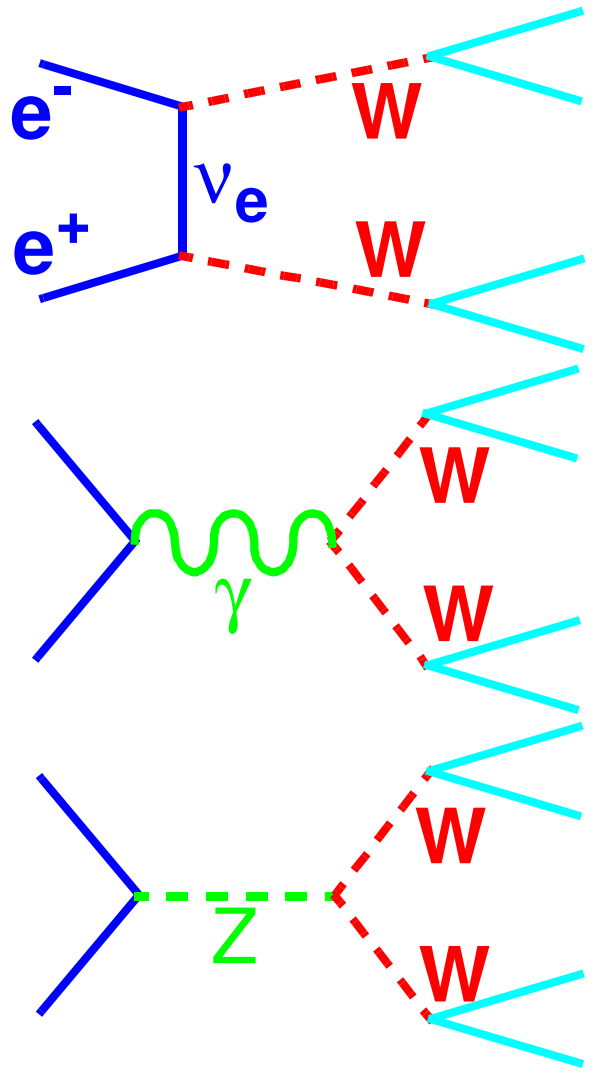
Three production diagrams dominate

At $\sqrt{s}$=200 GeV, $\sigma_{WW} \approx 17$ pb

$\Rightarrow$ ~12000 $W^+W^-$ / expt. for 700 $pb^{-1}$

BR(W$\rightarrow q\bar{q}$) $\approx$ $^2/_3$

BR(W$\rightarrow e\nu, \mu\nu, \tau\nu$) $\approx$ $^1/_9$ each




Observed events:

**WW$\rightarrow q\bar{q}q\bar{q}$** **46%**

*(≥)4-jet events*

**WW$\rightarrow q\bar{q}l\nu$** **44%**

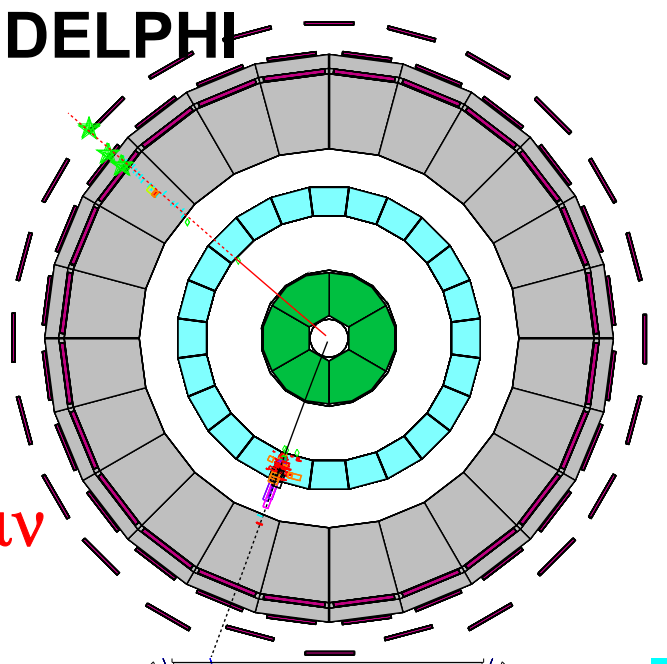
*2 jets, charged lepton, missing p*

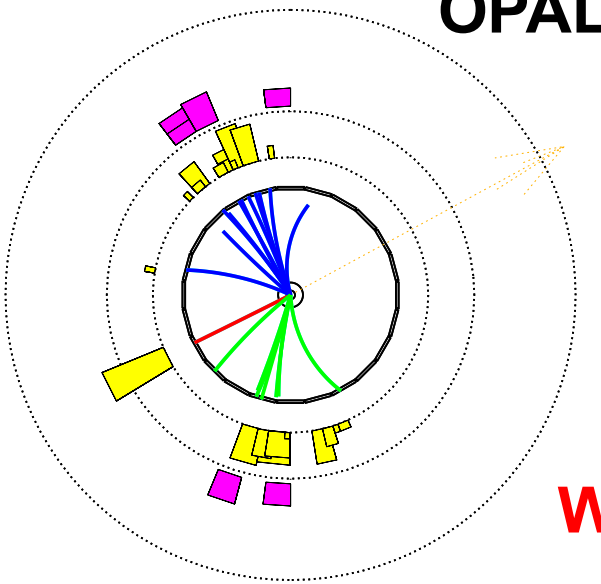
**WW$\rightarrow l\nu l\nu$** **10%**

*2 energetic charged leptons*

All final states selected by all experiments, mainly with high-performance multivariate methods

# LEP-2 WW Events

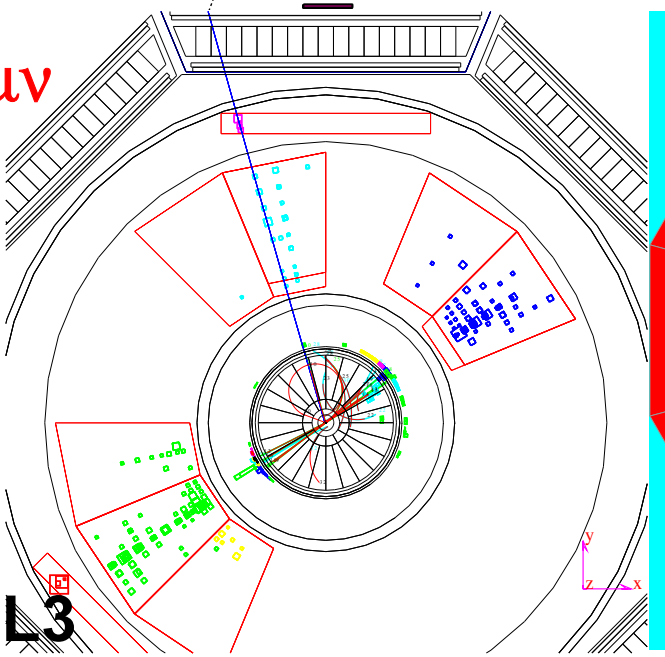


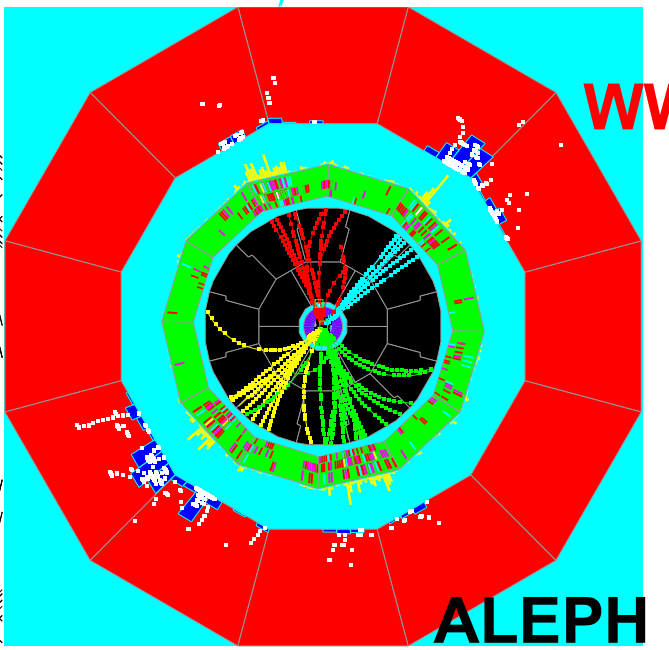

$WW \rightarrow e\nu\mu\nu$

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

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




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



# WW Cross-Section

WW selection performance

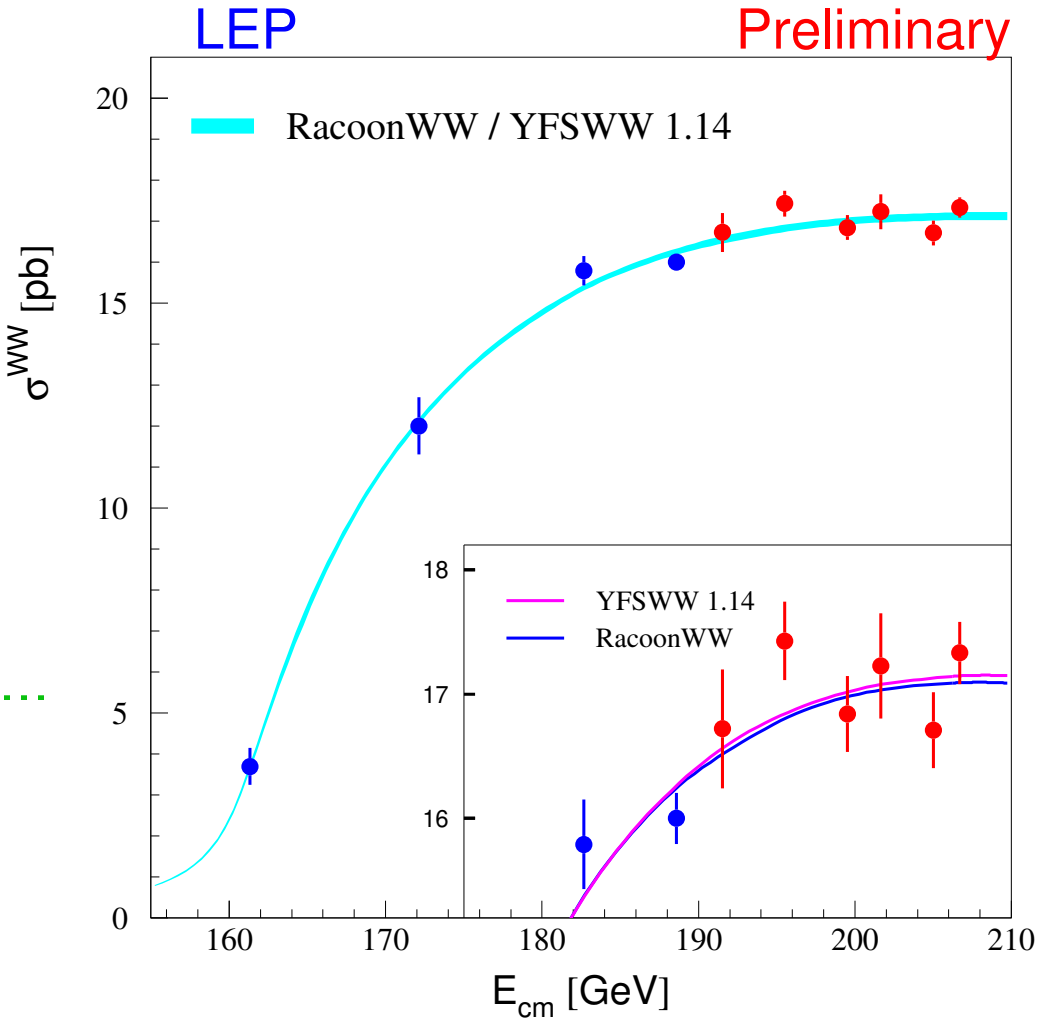
| | ε | π |
|---|---|---|
| WW→qq̄qq̄ | 87% | 80% |
| WW→qq̄lν | 85% | 90% |
| WW→lνlν | 50-80% | 90% |

Recently, theoretical progress on O(α) corrections to WW production diagrams
→ $\sigma^{WW}$, $\cos\theta_W$ etc
YFSWW,Racoon,...

Compare overall normalisation for
$\sqrt{s}$>180 GeV with predictions
$R_{WW}=\sigma(exp)/\sigma(th)$:

| | |
|---|---|
| Gentle | 0.973 |
| KoralW | 0.979 |
| YFSWW | 0.998 |
| RacoonWW | 1.000 |

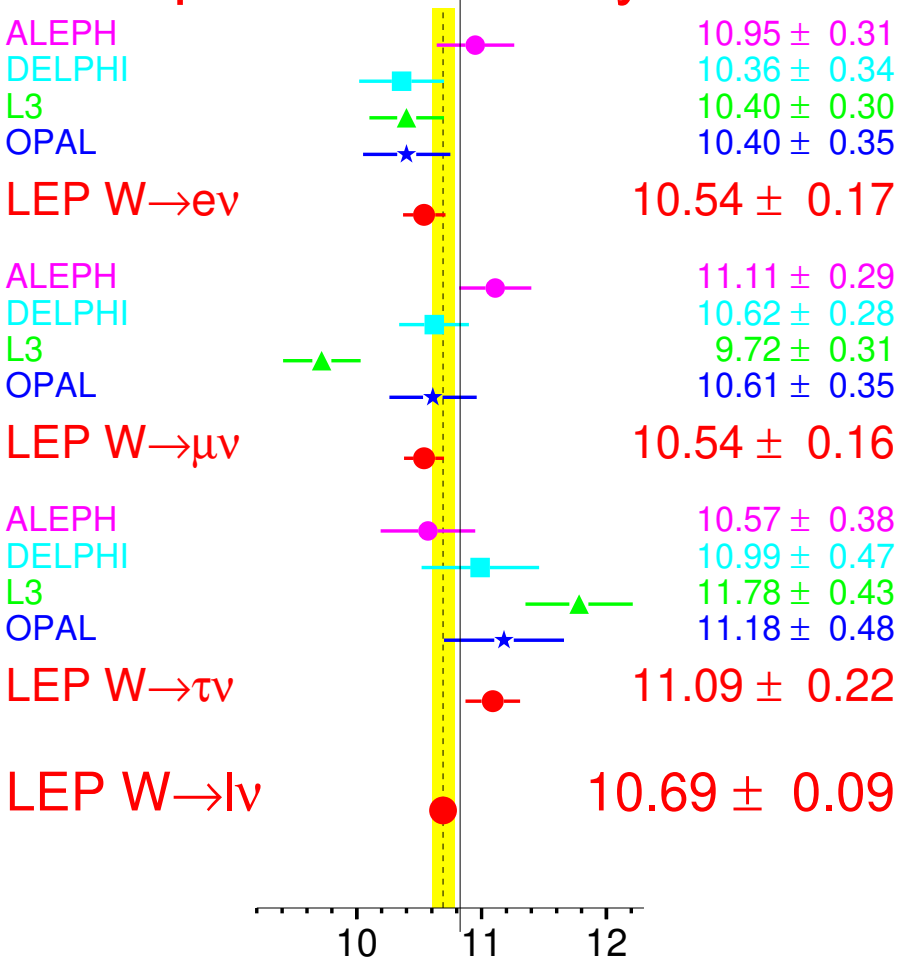
±0.009 (exp) for each



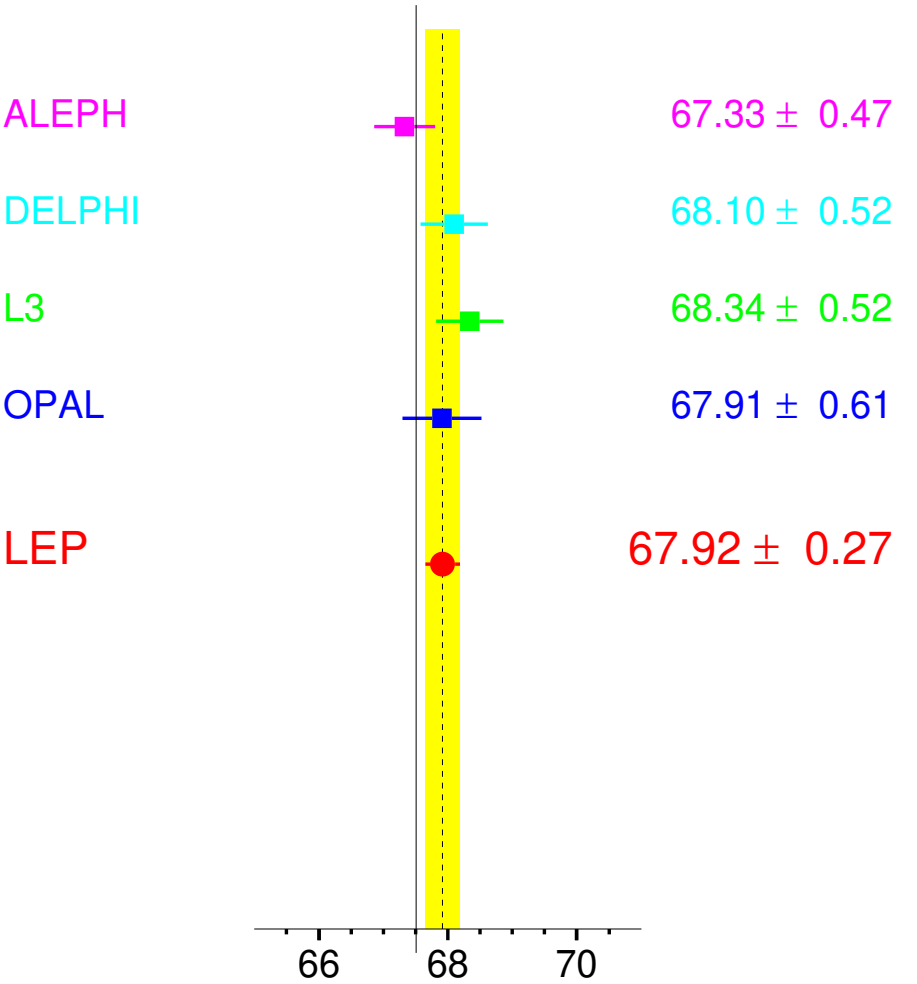

Full O(α) corrections needed for W cross-section prediction!

# W Decay Branching Ratios

## W Leptonic Branching Ratios
## Lepton Universality Test




## W Hadronic Branching Ratio




CDF+DØ: B(W→lν)=10.43±0.25%

# W Mass from LEP-2

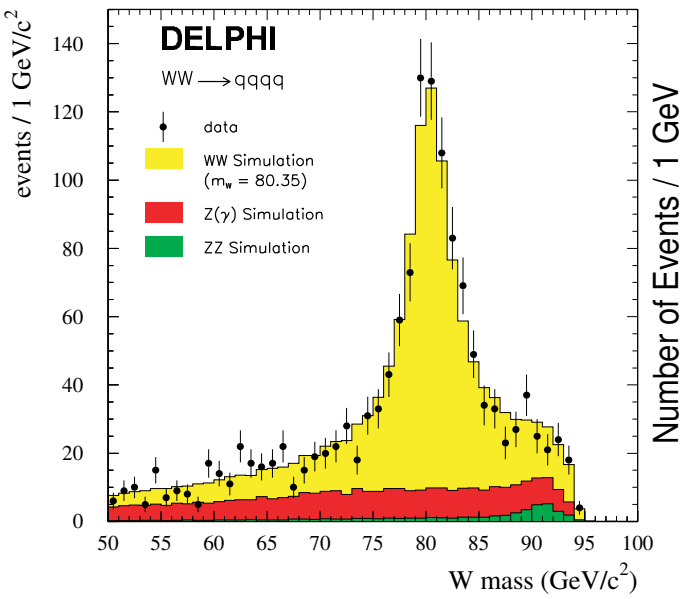
Primarily
**WW→qq̄qq̄ & qq̄lν**

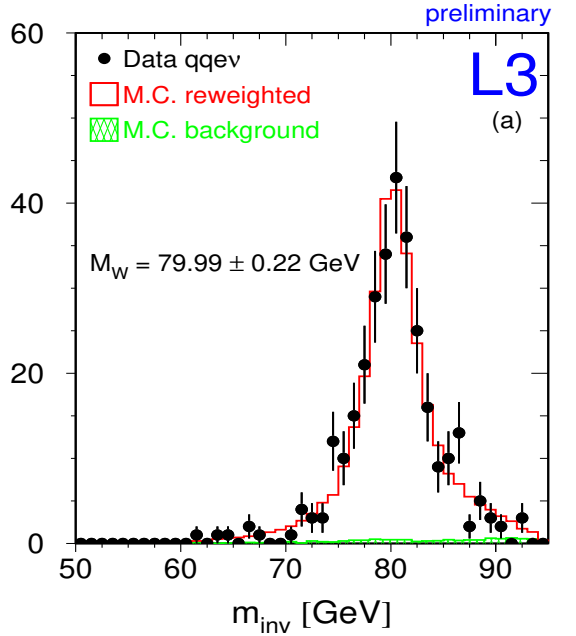
Mass resolution improved by kinematic fit:

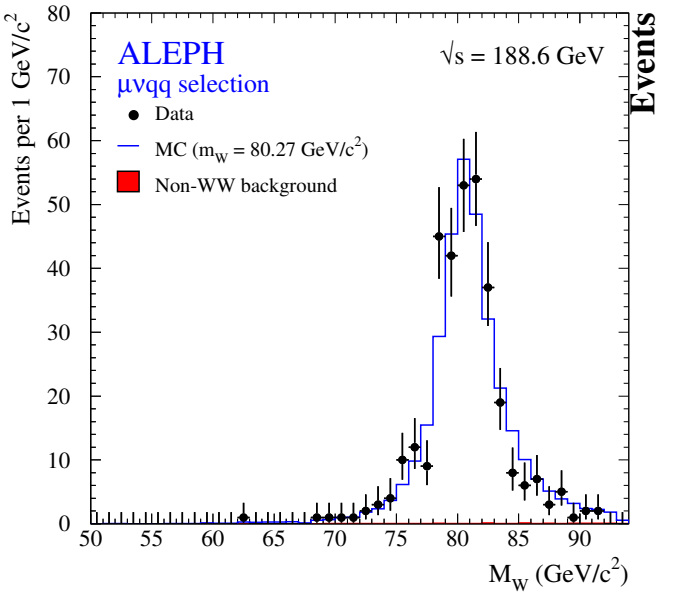
- $(E,\mathbf{p})_{total} = (\sqrt{s},\mathbf{0})$
  - needs $E_{beam}$
- $M_{W+} = M_{W-}$

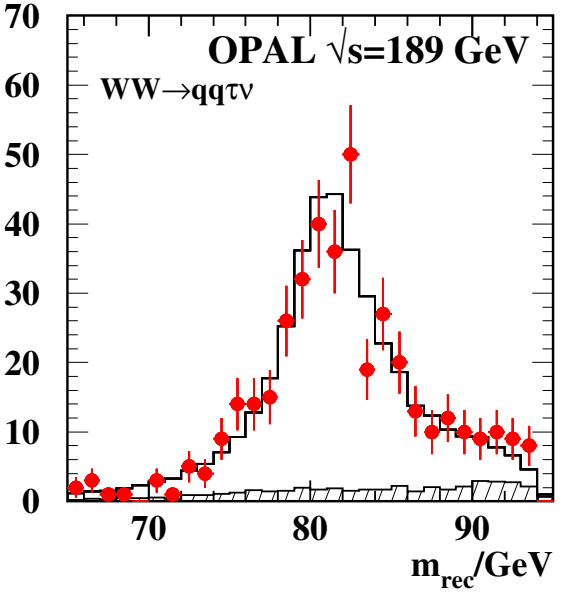
Fit either for $M_W$, or for $M_W$ and $\Gamma_W$

Various methods to extract $M_W$ ($+\Gamma_W$)



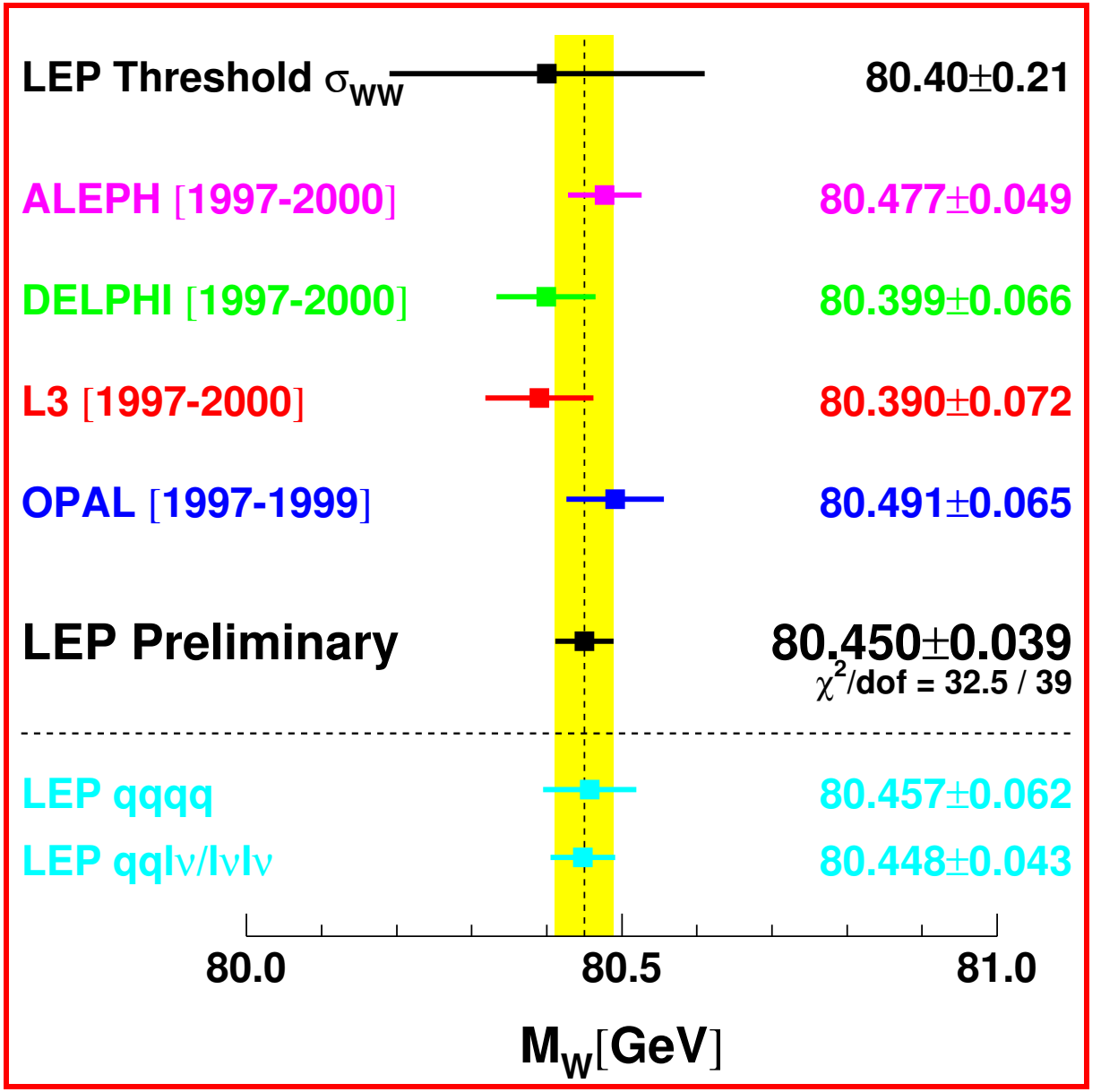



# LEP-2 W Mass

Analyses now dominated by systematic errors

Many detailed studies in progress, often across LEP expts

| Error sources / MeV | |
|---|---|
| Statistics | 26 |
| Systematics | 30 |
| Detector-related | 11 |
| Fragmentation | 17 |
| Phot. corrections | 8 |
| "FSI" | 13 |
| LEP $E_{beam}$ | 17 |



# LEP W Mass — Final State Interactions

Two systems from $W \to q\bar{q}$ decays may not hadronise independently

W decay separation << 1 fm

Have to rely on models:

- Bose-Einstein correlations in formation of hadrons
- Colour reconnection in hadronic shower phase

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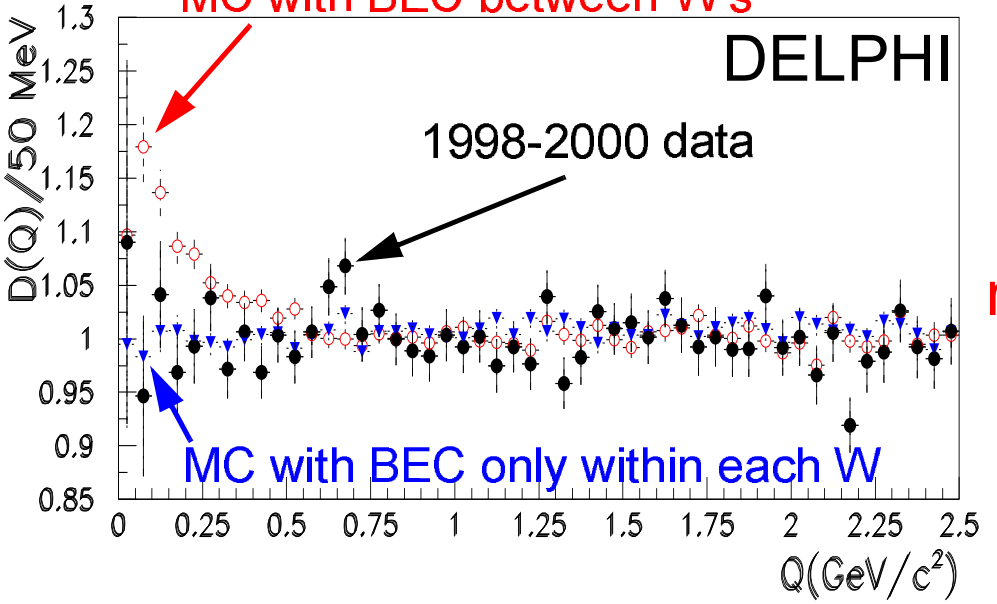
Bose-Einstein correlations (BEC) between like particle pairs

Clearly established between $\pi^{\pm}$ from same W – but between W's?




Chekanov, de Wolf & Kittel

$$\rho_2^{WW}(Q) = 2\rho_2^{W}(Q) + \rho_{mix}^{WW}(Q)$$

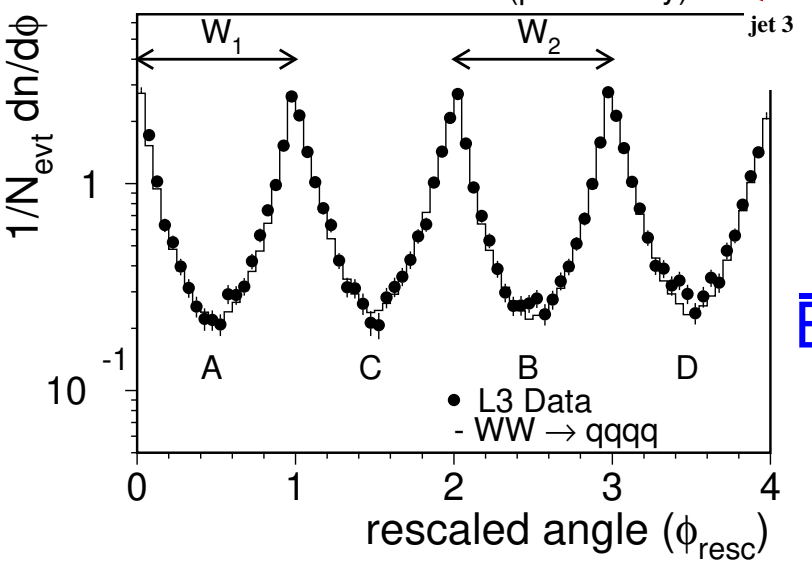
$$D(Q) = \frac{\rho_2^{WW}(Q)}{2\rho_2^{W}(Q) + \rho_{mix}^{WW}(Q)}$$

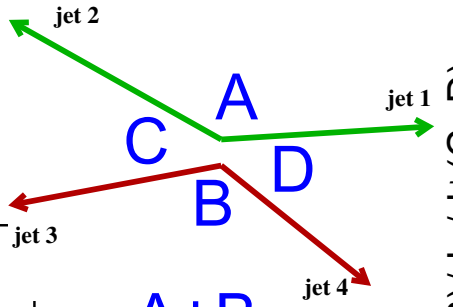
measurable from $q\bar{q}q\bar{q}/q\bar{q}l\nu$ data

No evidence for BEC of $\pi$ from different W's

# LEP-2 W Mass – FSI (continued)

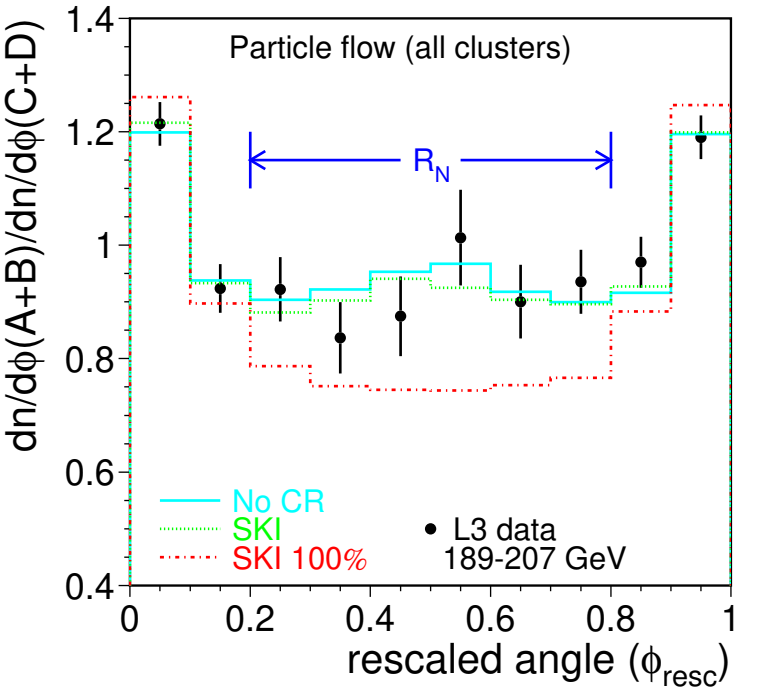
## Colour reconnection (CR)




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

$$\frac{\text{Within W}}{\text{Between W's}}$$




Sensitive to CR models: work ongoing to constrain from LEP data

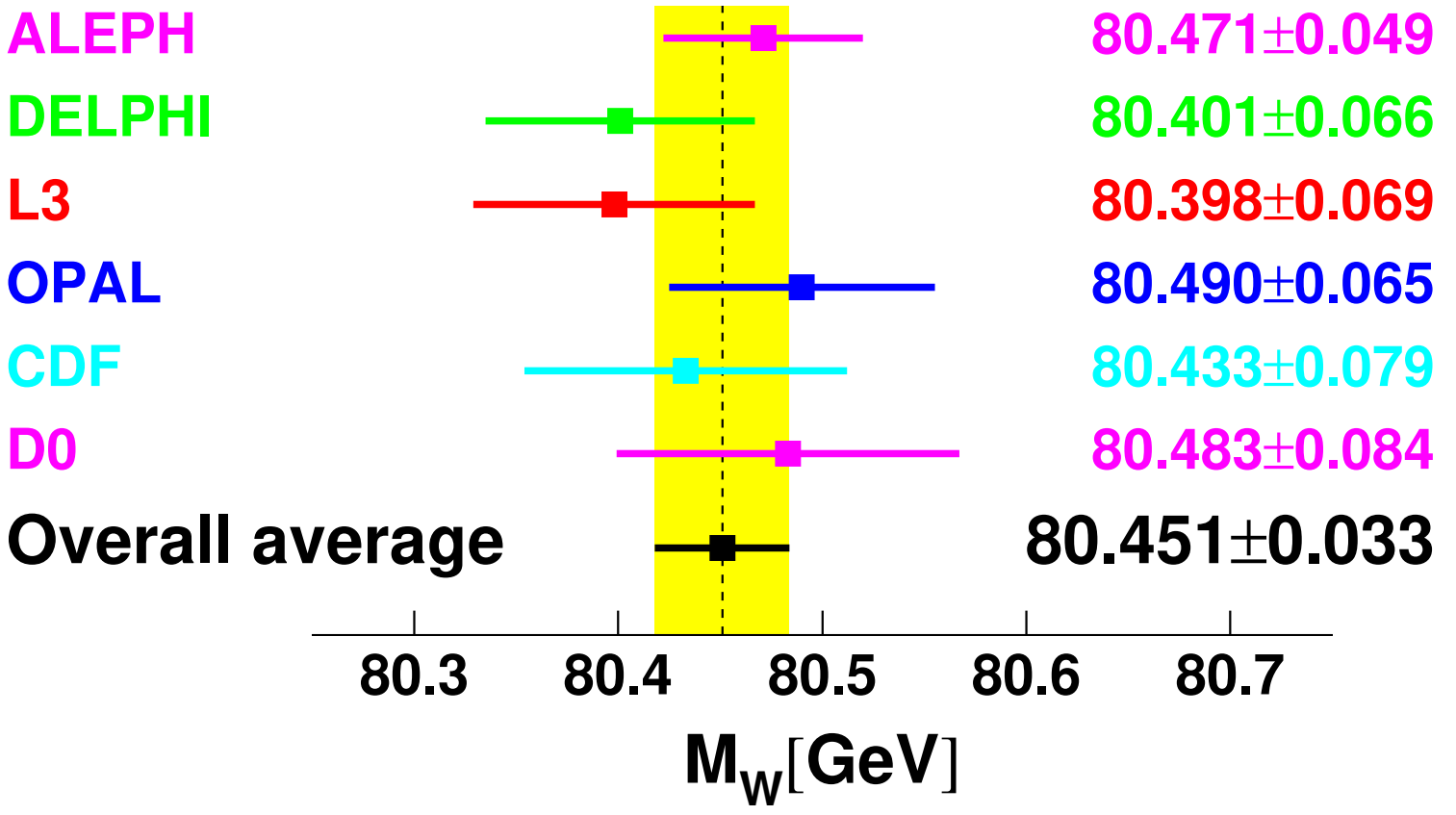
---

Current errors from FSI on the $q\bar{q}q\bar{q}$ channel: CR 40 MeV
(common to all 4 experiments) BEC 25 MeV
Diluted in average – lowers weight of $q\bar{q}q\bar{q}$ channel to 27%

These studies of visible effects should lead to a reduced $M_W$ error

# W Mass: World Average

Precision from LEP and Tevatron similar: gain a lot by combining



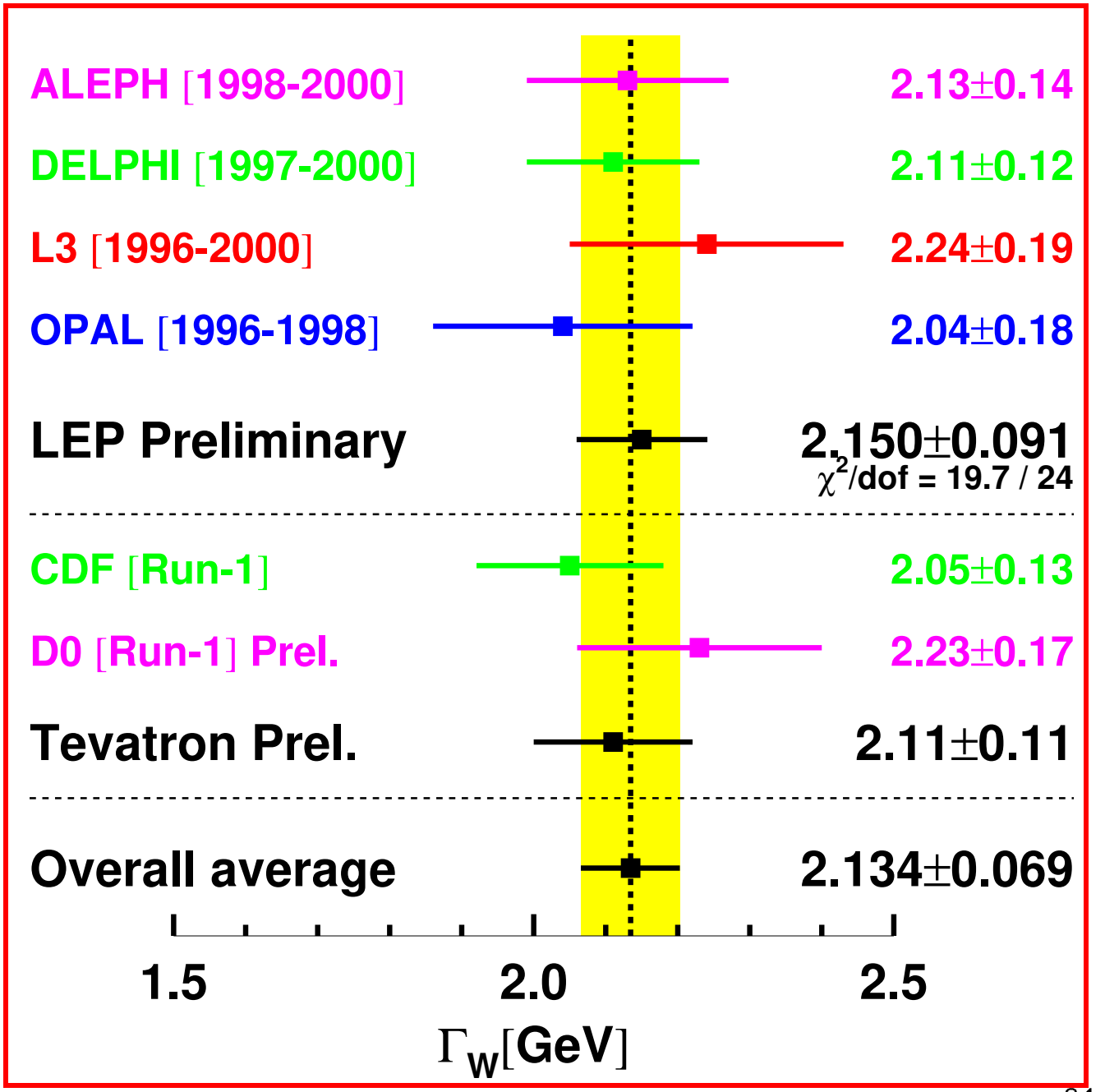

Final LEP-2 $M_W$ precision: 39 MeV $\rightarrow$ 30-35 MeV, with completion of systematic studies and beam energy work

# W Width

At LEP from width of W mass distribution

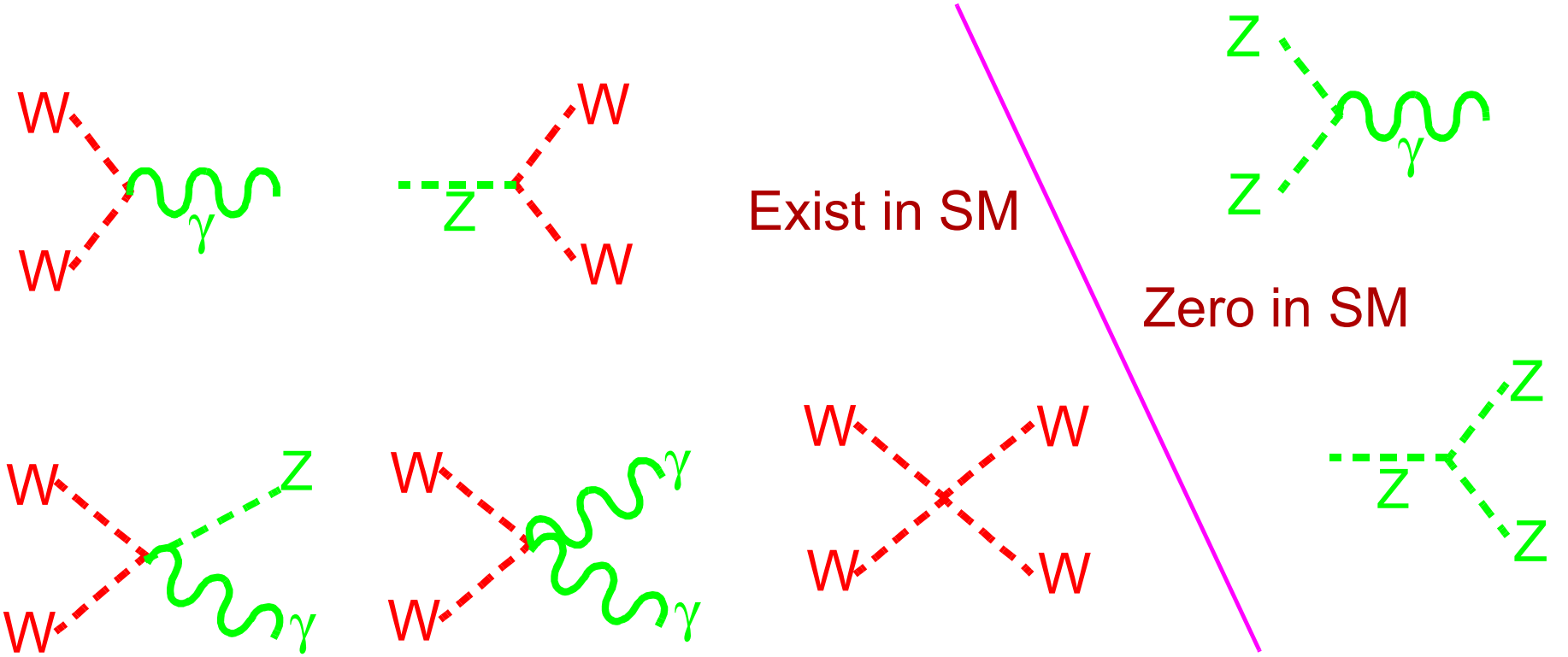
At Tevatron from high tail of lepton $p_t$ (or transverse mass) distribution

SM: $\Gamma_W \approx 2.095$ GeV



# Vector Boson Self-Interactions

Gauge structure of electroweak model specifies precisely triple and quartic gauge boson couplings




Measured at both LEP and the Tevatron – currently LEP constraints are more stringent

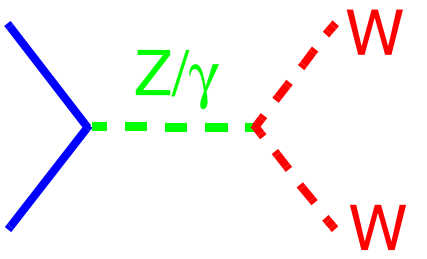
# LEP-2 Triple Gauge Couplings WWγ and WWZ

Up to 14 parameters, but usual to consider (at least)

$(\kappa_\gamma, g_1^Z, \lambda_\gamma) = (1,1,0)$ in Standard Model

Main sensitivity at LEP-2 in $W^+W^-$ production, affecting

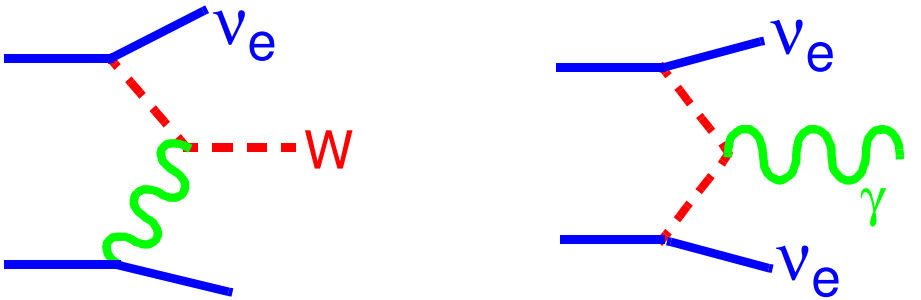
- $W^+W^-$ cross-section
- angular distribution of $W^-$
- helicity mixture of W's: analyse $W^\pm$ decay angles




**O(α) corrections** comparable to current precision – under study

**No new LEP average in 2001**

Other channels (single-W, single-γ) not affected, but less precise




Osaka 2000

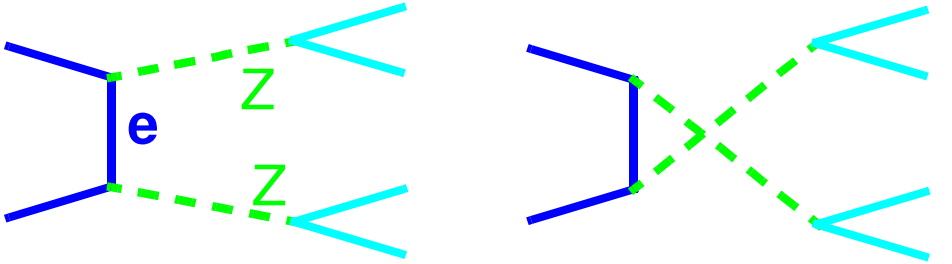
$\kappa_\gamma = 0.998^{+0.067}_{-0.065}$

$g_z^1 = 0.975 \pm 0.026$

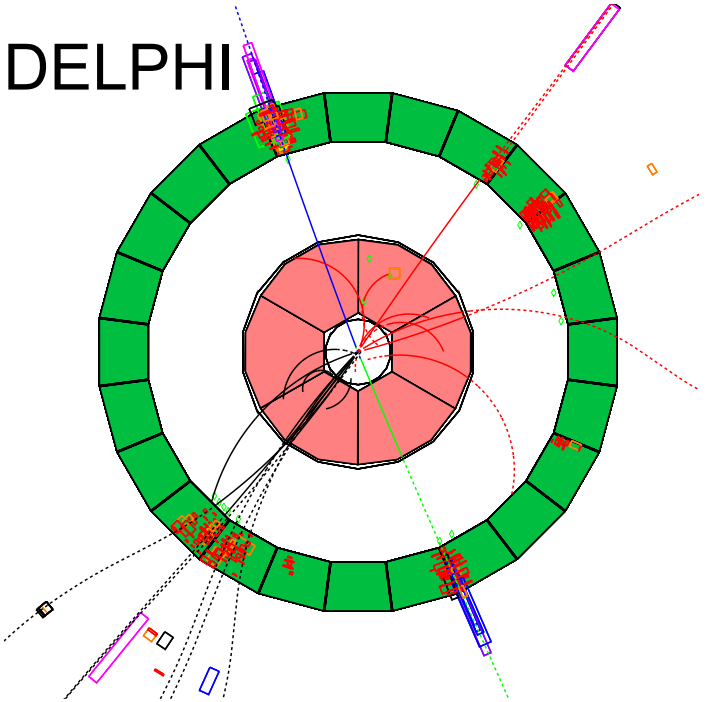
$\lambda_\gamma = -0.036^{+0.028}_{-0.027}$

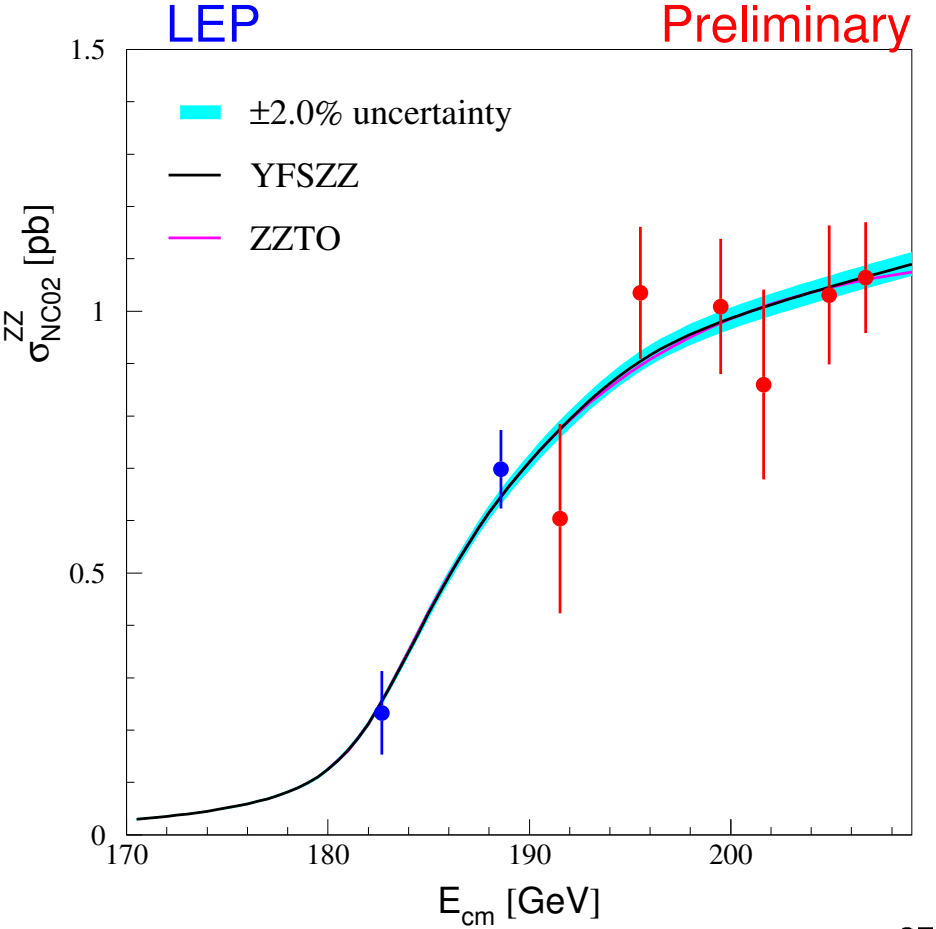
# LEP-2 ZZ Production

Two doubly-resonant production diagrams in SM




Cross-section much lower than WW: Zee ~ $(1–4\sin^2\theta_W)$




**Would be the background to ZH production**

# Global Electroweak Tests

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

Other inputs: $\sin^2\theta_W$ from $\nu$N scattering (**NuTeV**);
atomic parity violation of Cs ("APV")

SM predictions from ZFITTER 6.36 and TOPAZ0 4.4 electroweak libraries

Parameters

| | |
|---|---|
| $M_Z$ | measured precisely by LEP-1 Z data |
| $\alpha_s(M_Z)$ | measured precisely by LEP-1 Z data |
| $\alpha_{em}(M_Z)$ | requires use of R(low E) for hadronic corrections |
| $M_W$, $M_{top}$ | measured at LEP-2 and Tevatron, but may predict from other EW measurements<br>"prediction precision" ~ measurement precision |
| $M_H$ | may be predicted in this framework...<br>"*the last free parameter*" |

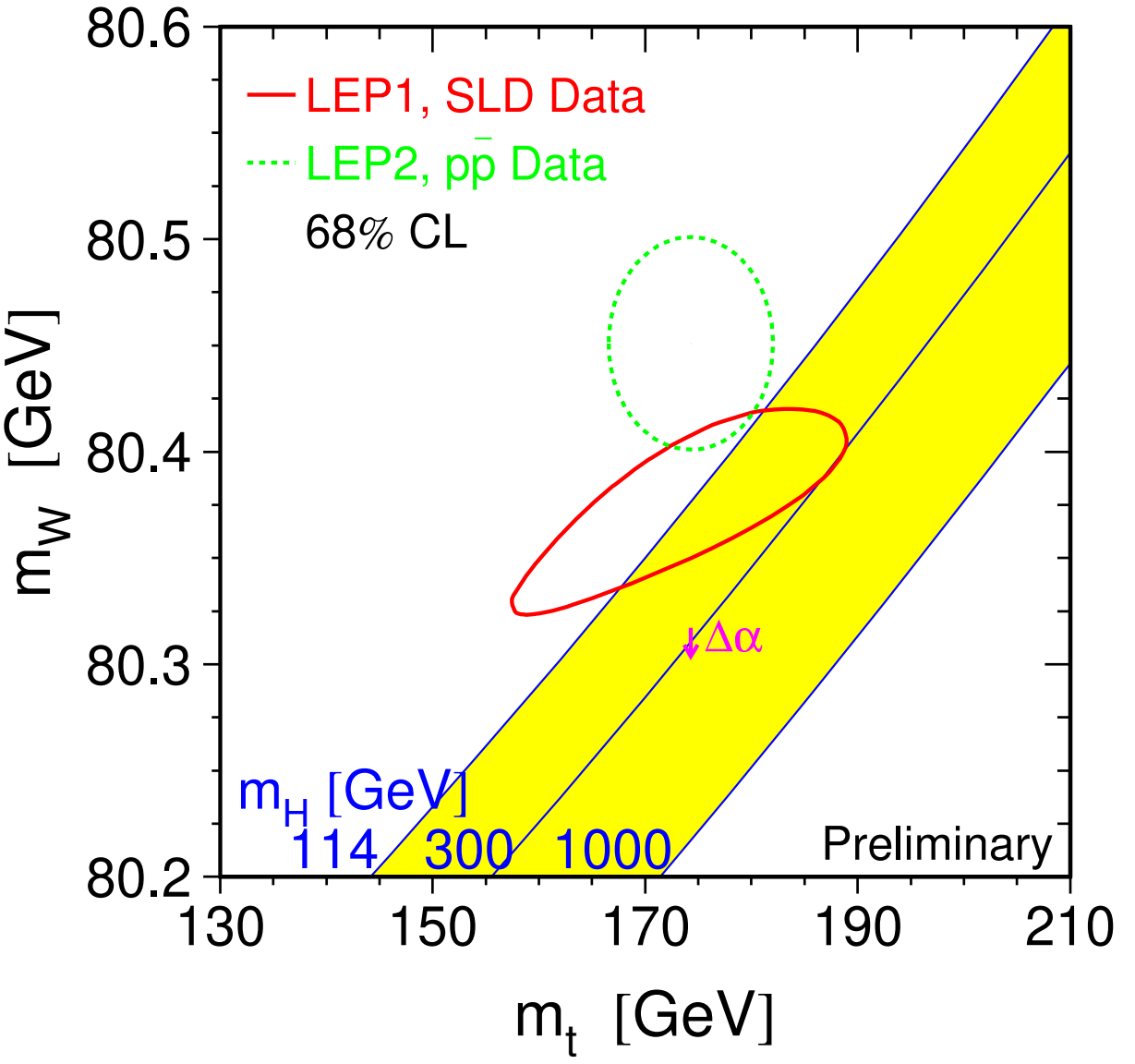
# Predicting $M_W$ and $M_{top}$

Use LEP-1/SLD Z data, $\alpha_{em}(M_Z)$, $\nu$N, APV results to predict $M_W$ and $M_{top}$

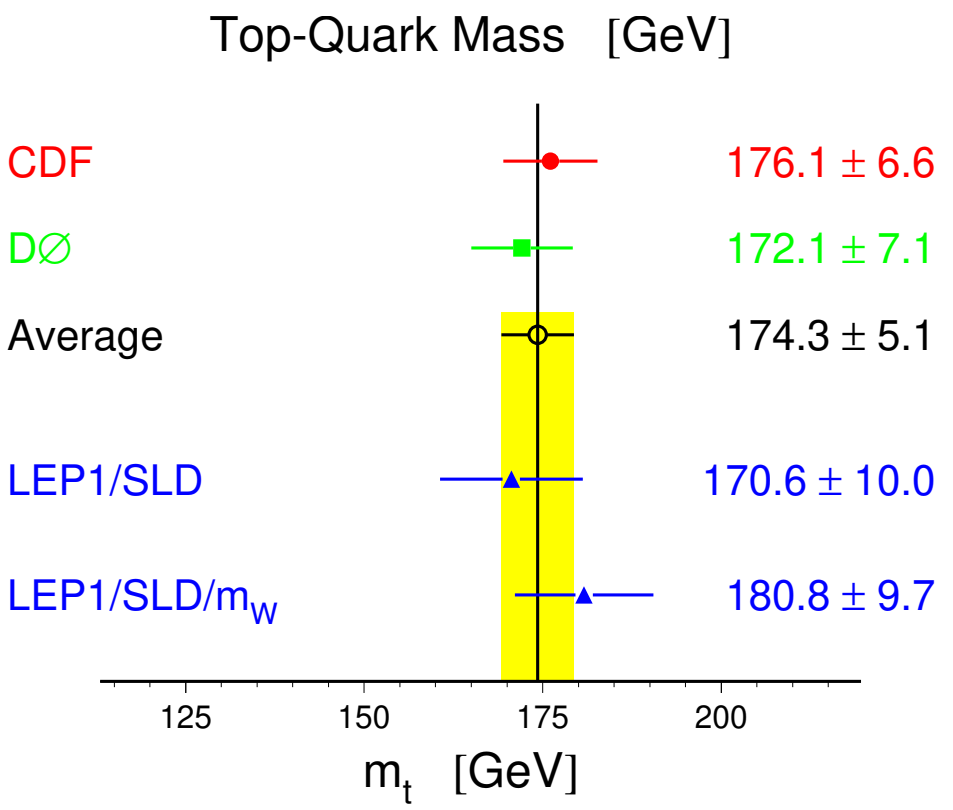
Compare with direct Tevatron/LEP-2 results, and with SM relation between $M_W$, $M_{top}$, $M_H$

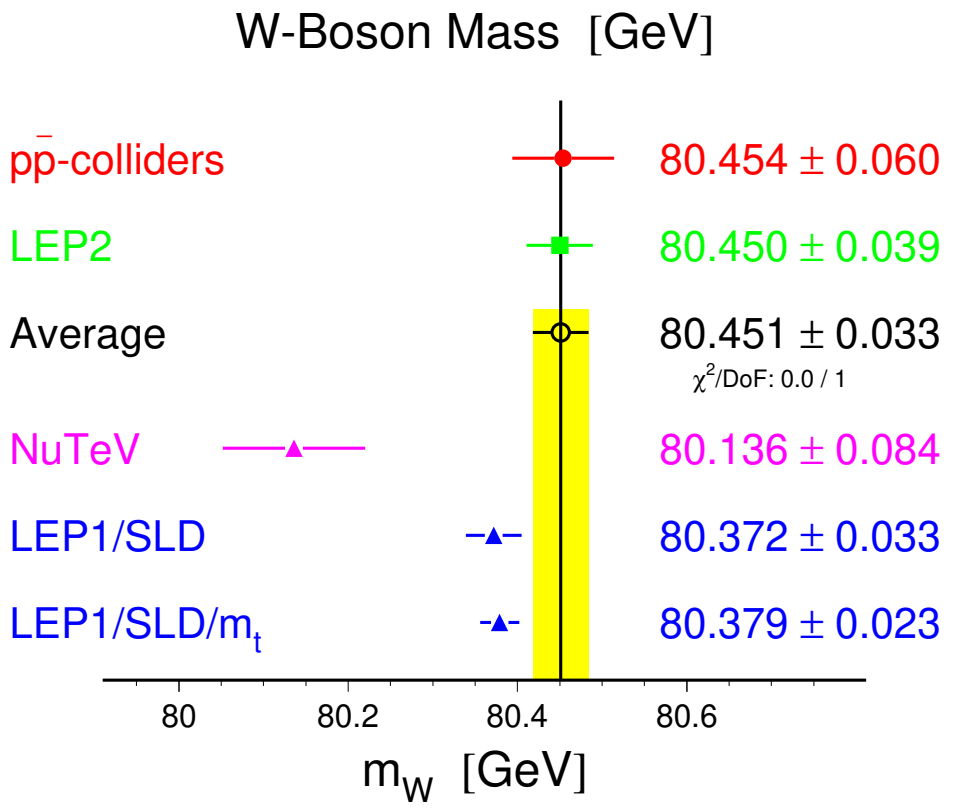
**Electroweak fit correctly predicts the masses of heavy particles (W,top)**

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



# Top and W Mass: Prediction vs. Data




Predicted $M_{top}$ agrees very well with measurement
Measured $M_{top}$ from Tevatron twice as precise as prediction

Predicted $M_W$ within $2\sigma$ of that measured
$M_W$ now ~ matches precision of LEP1/SLD prediction

# Fit to all Electroweak Data

Full electroweak fit of all measurements, including $M_W$ and $M_{top}$

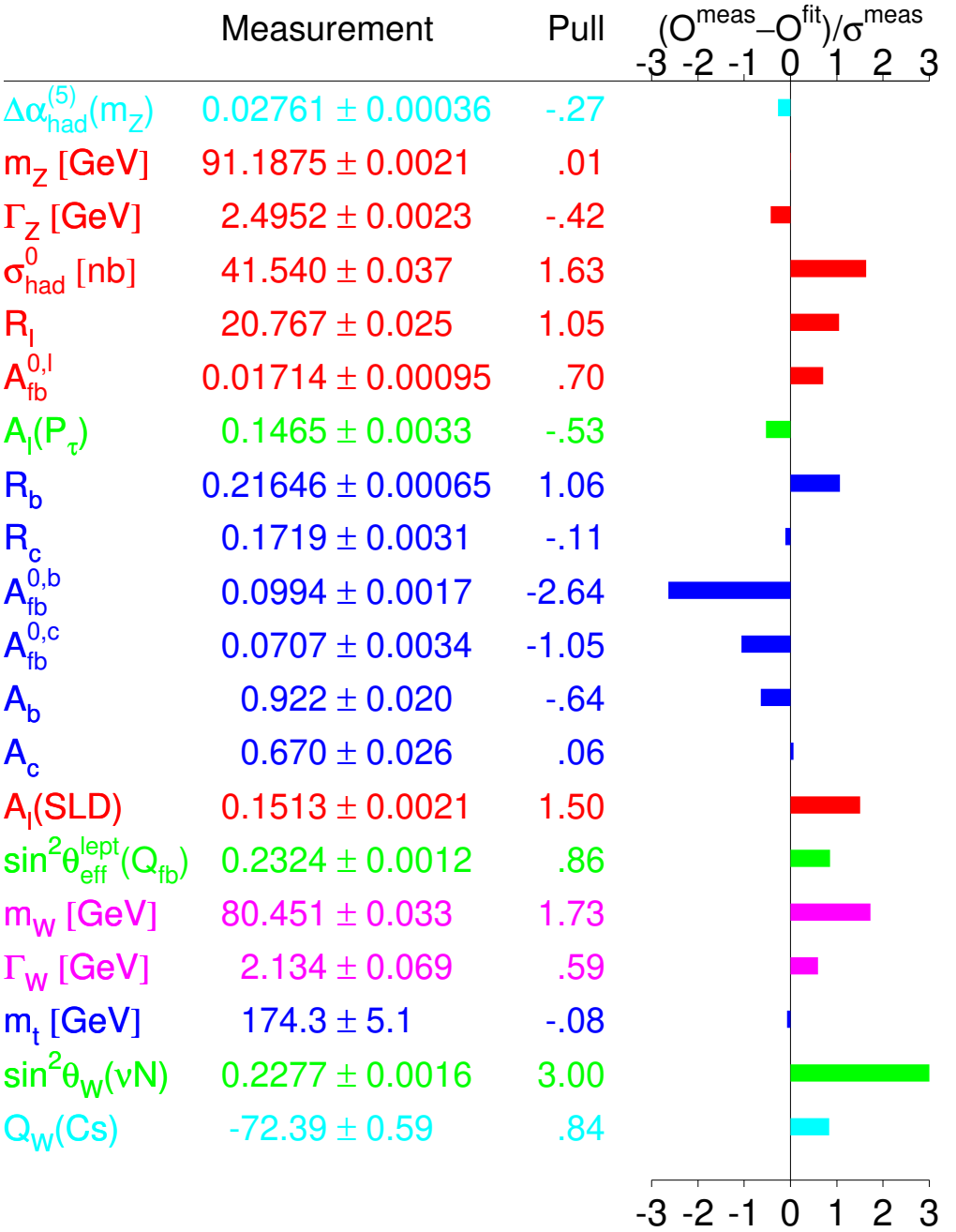
Overall consistency $\chi^2$/d.o.f is 28.8/15 (**1.7%** probability)

Large contribution to $\chi^2$ comes from new NuTeV result: without it, fit probability is **14%**

Standard Model parameters ($M_H$ etc) little affected by NuTeV result

Because NuTeV pulls results little go on to see what fit says about $M_H$

Winter 2002



# Constraining the SM Higgs?

Fit to all electroweak data in Standard Model framework

Freitas, Hollik, Walter, Weiglein

Theory uncertainty includes effect of complete fermionic two-loop $M_W$: small effect for $M_W$, controversial problem for

$$\sin^2\theta^{lept}_{eff} = \kappa_W \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

Need equivalent calculations for Z widths and effective mixing angle

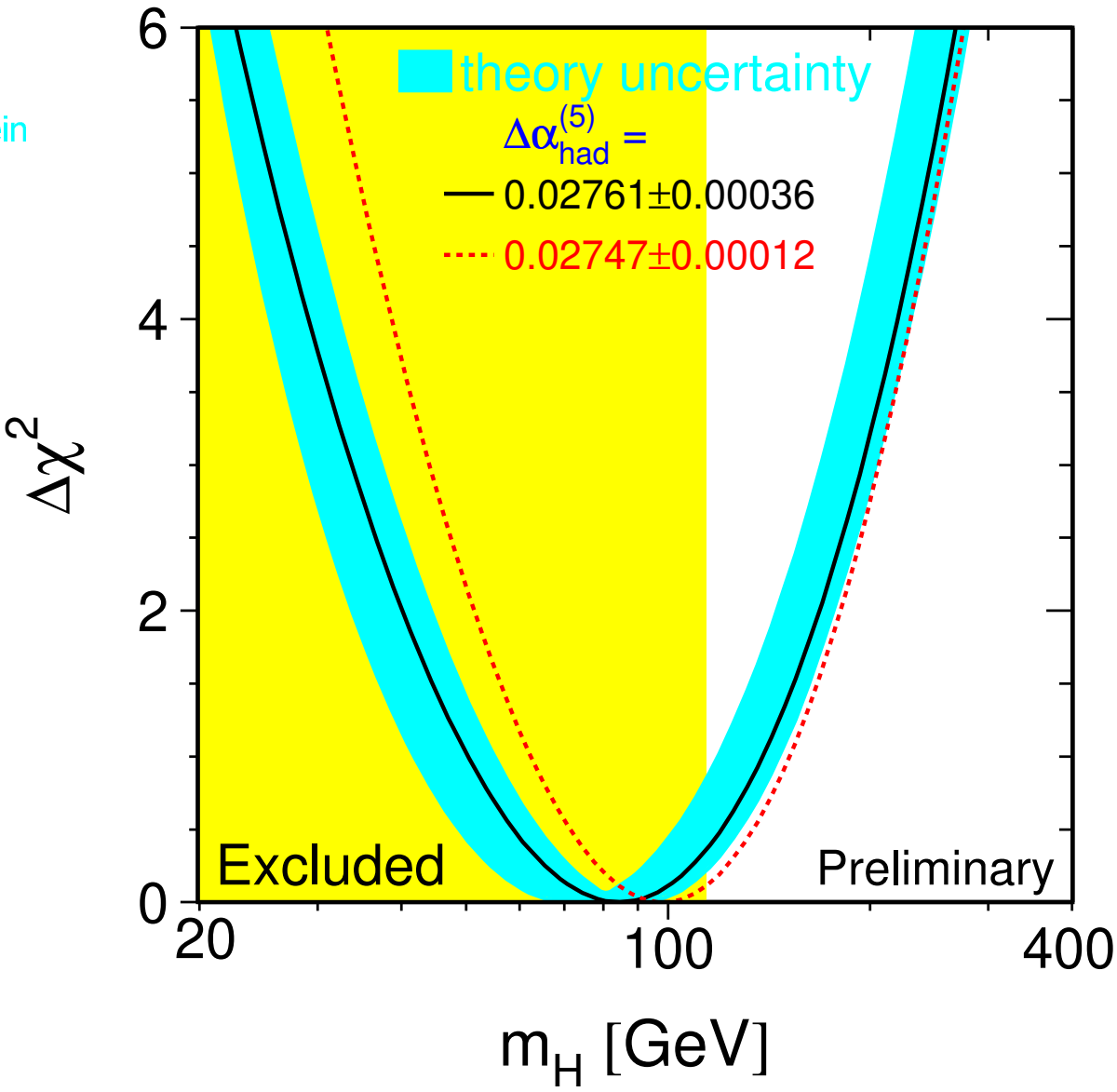
From EW fit, obtain

$M_H = 85^{+54}_{-34}$ GeV

$M_H < 196$ GeV (95% CL)

(without NuTeV: $81^{+49}_{-32}$ GeV)

If use alternative theory-driven $\Delta\alpha_{had}$=0.02747±0.00012 limit moves to 199 GeV



# LEP Electroweak Physics Summary

With 12 years of data (1 $fb^{-1}$):

The performance of the LEP accelerator was outstanding
Larger than expected Z and W statistics

**$M_Z$ = 91.1875±0.0021 GeV**
**$\Gamma_Z$ = 2.4952±0.0023 GeV**
**$N_\nu$ = 2.9841±0.0083**
**$M_W$ = 80.450±0.039 GeV**

**114 < $M_H$ < 196 GeV at 95% CL (only in SM framework!)**

A wealth of high-precision tests of the electroweak sector, with convincing demonstrations of the effects of loop corrections

Two loop calculations are now essential to make the most of the precision data