Review of Final LEP Results

or

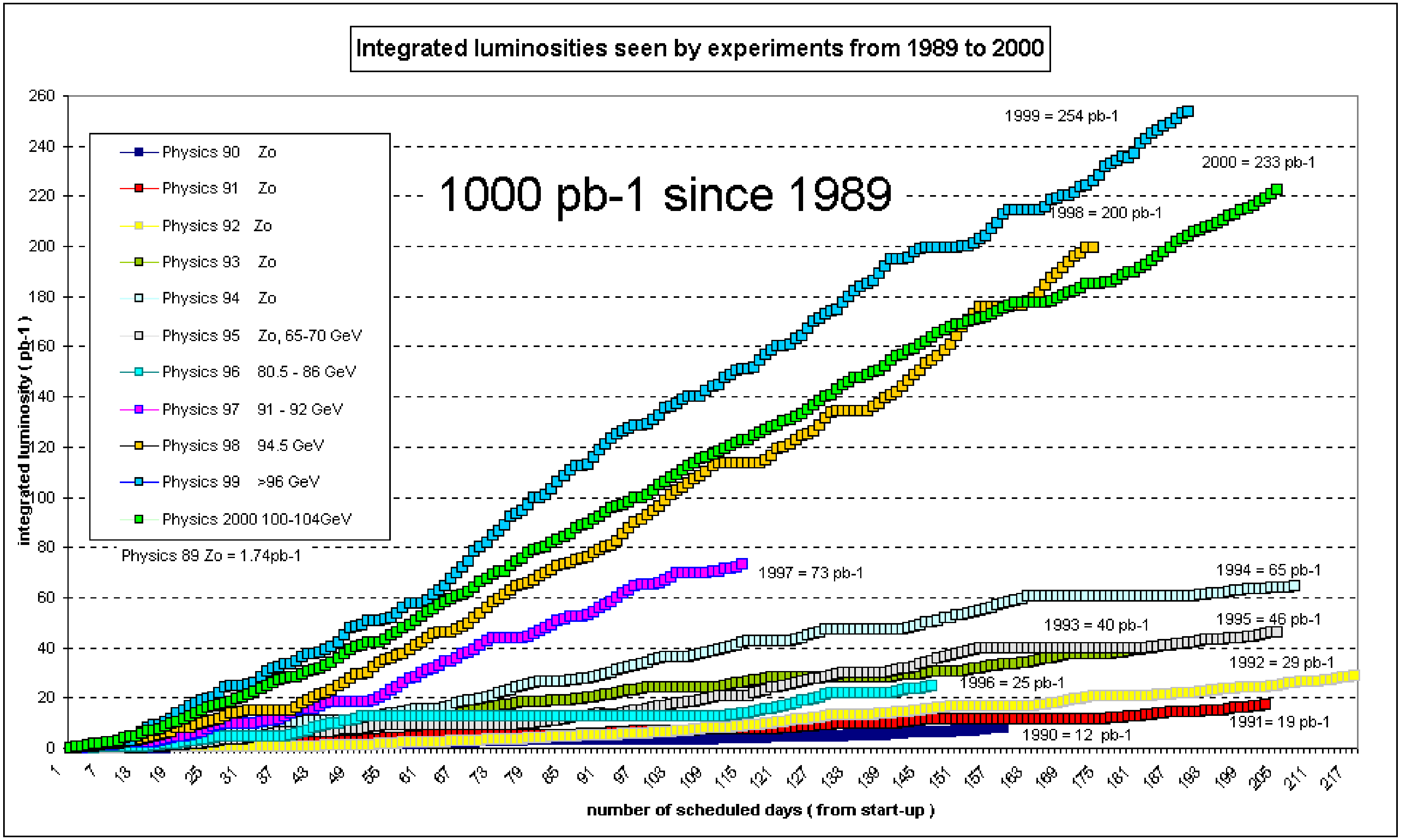
A Tribute to LEP

J. Drees

CERN / University Wuppertal

So far more than 1100 scientific papers, many analyses are still continuing. Main topics centre on the study of the properties of the gauge and scalar bosons, of heavy fermions and on searches for the Higgs and for new physics.

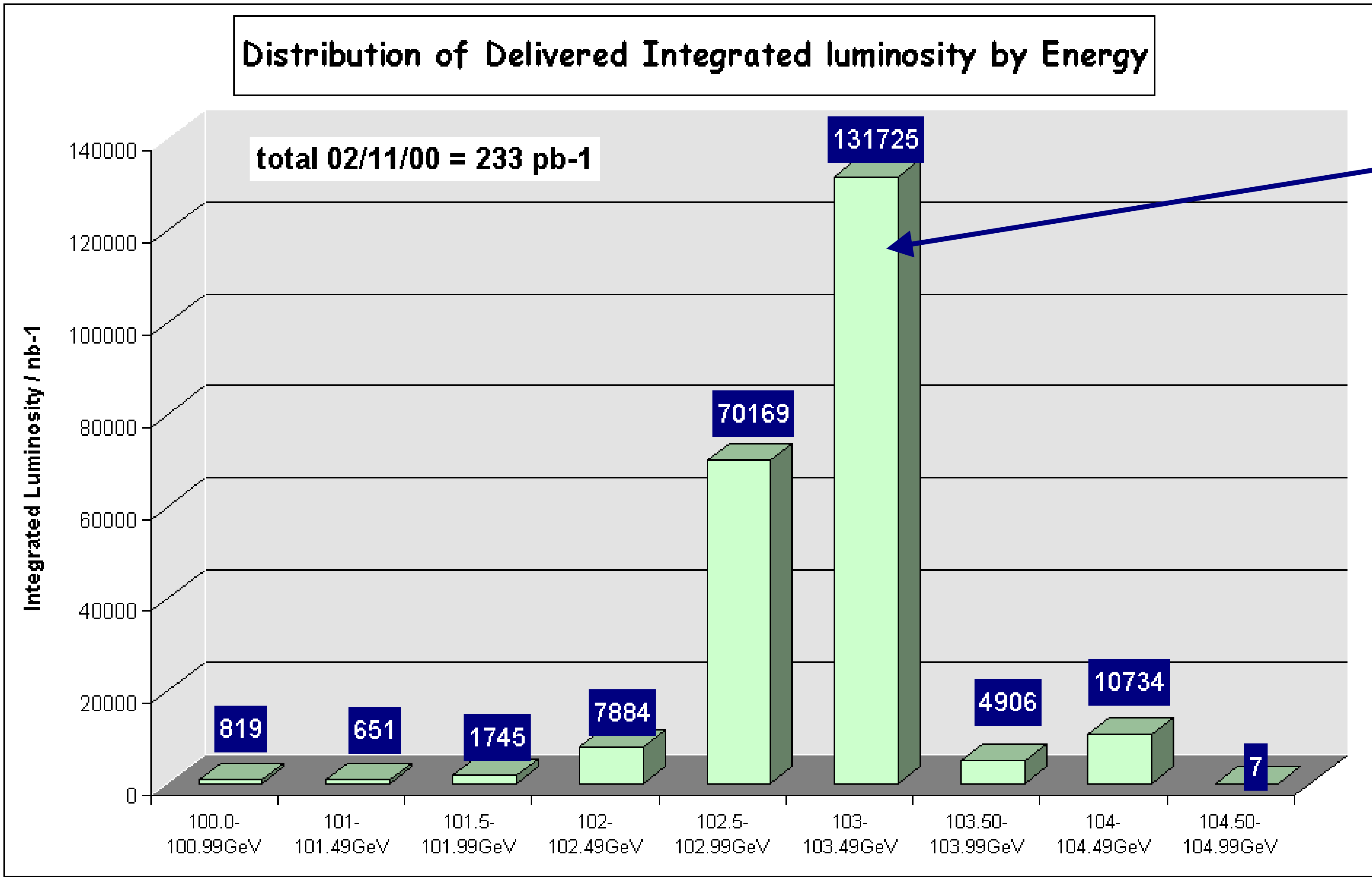
Performance of LEP during 12 years of operation



Total luminosity above WW threshold ~ 700 pb^{-1} per experiment.

LEP in 2000

Record beam energy 104.4 GeV, more than foreseen. 200 days of running, >130 pb^{-1} above 103 GeV, 100 pb^{-1} in last 110 days.



103 – 103.49 GeV

Superconducting cavities

Crucial for success of LEP2:

S. Myers: *For sc cavities the power needed is "only" proportional to the 4th power of energy. To operate LEP at 103 GeV with copper cavities ($P \propto E_{beam}^8$) would have needed 1280 cavities and 160 MW of power! Impossible for many reasons.*

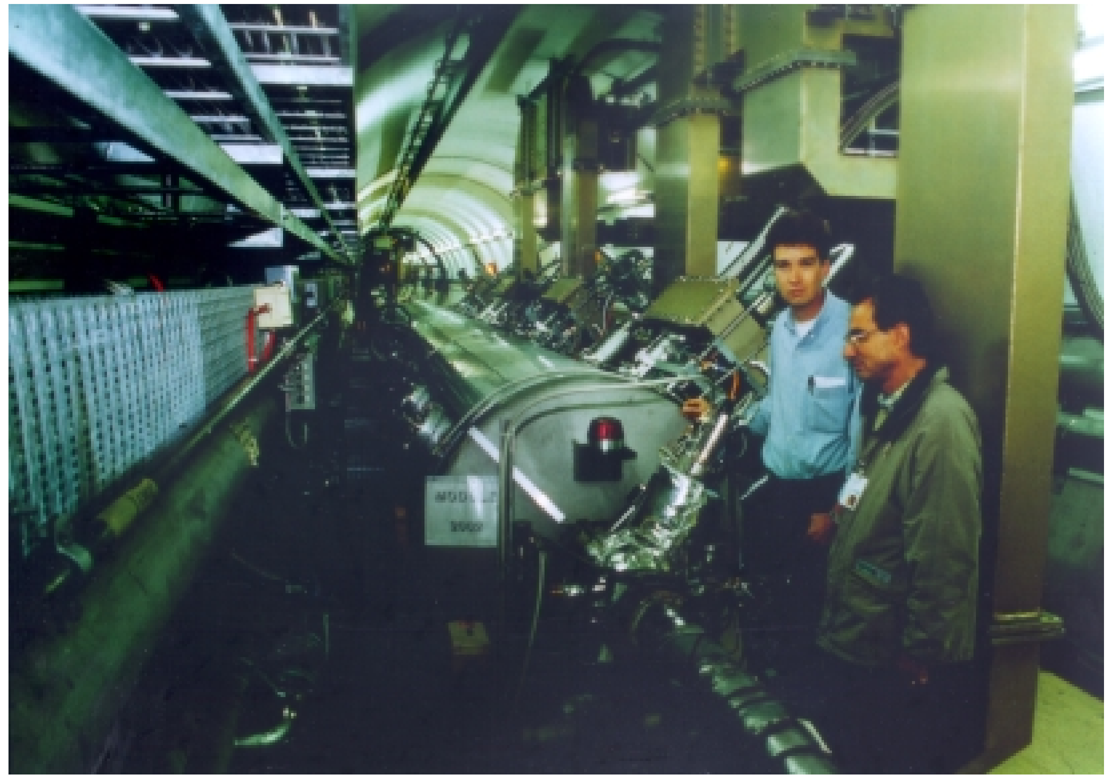
1980 development program for 350 MHz niobium coated copper cavities, goal thermal stability at reduced costs.

2000: 272 Nb film and 16 Nb bulk SC's.

Achieved:

Average accelerating field 7.5 MV/m, $Q > 3\times10^9$ at 4.5 K. Better than design value 6 MV/m. More than 80% of the Nb film SC's had $Q > 2.5\times10^9$ at 8 MV/m.

4 cell Nb/Cu cavity in the clean room



SC module installed in the LEP tunnel

The Collaborations

ALEPH, DELPHI, L3, OPAL

Major detector improvements during the years of data taking:

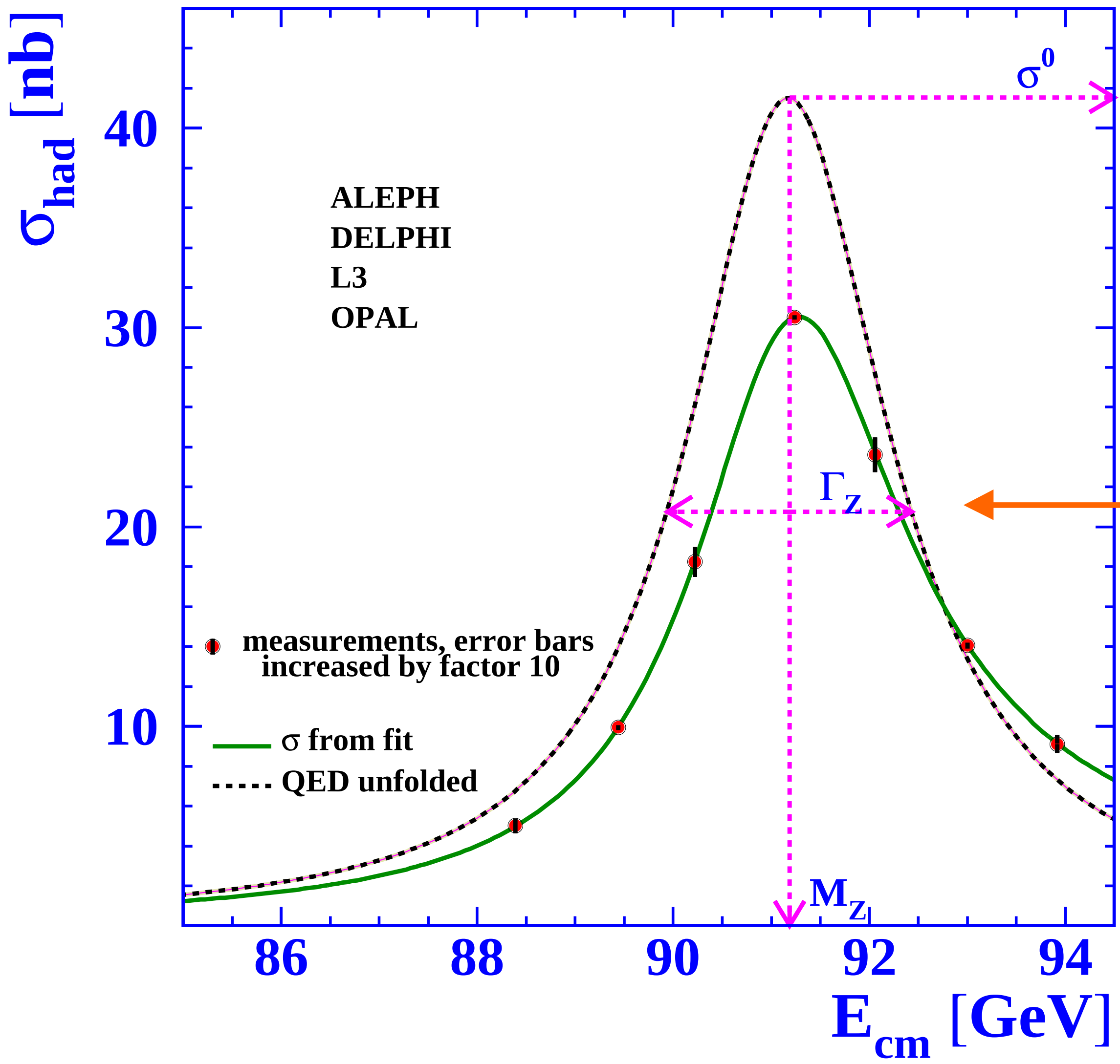
- Silicon micro vertex detectors for high resolution secondary vertex measurements,
- Exchange of first luminosity detectors by new high-precision detectors able to measure small angle Bhabha scattering at a level well below 1 $^{0}/_{00}$.

Creation of a new style of working together, the **LEP Working Groups**, e.g.

Electroweak Working Group (EWWG)

Combination of the results from all LEP collaborations and from **SLD** taking account of all systematic correlations between data.

Precision at the Z



The 4 exps. collected 15.5 million Z decays to quarks plus 1.7 million decays to charged leptons, integrated $L \cong 200\ pb^{-1}$ per exp.

The final hadronic cross section, measured and QED deconvoluted.

Radiative corrections large but v. well known.

The final result

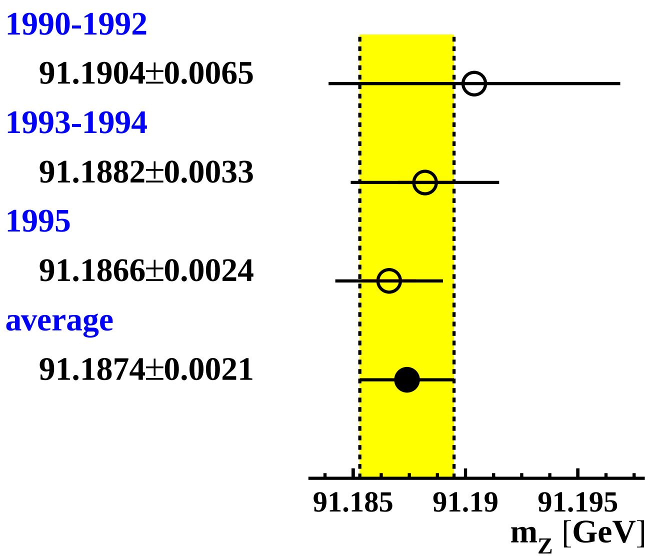
$2 \cdot 10^{-5}$ accuracy for one of the most fundamental constants:

$$m_Z = 91.1874 \pm \mathbf{0.0021}\ \text{GeV}$$

This cannot be exceeded with any one of the future machines, not even with a GigaZ Linear Collider!

Essential:

- Beam energy measurement using the technique of **resonant depolarisation** plus careful control of all machine parameters, still **dominant error of ±1.7 MeV,**
- Close cooperation with theory.



The full set

of nearly uncorrelated pseudo-observables from EWWG.

- Total Z width: $\Gamma_Z = 2.4952 \pm 0.0023$ GeV,
- Z peak cross section: $$\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2} \cdot \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2},$$
- Ratios $R_f^0 \equiv \Gamma_{had}/\Gamma_{ff}$ for f = e,μ,τ; also $R_q^0 \equiv \Gamma_{qq}/\Gamma_{had}$ for q = b,c,s,
- Forward backward asymmetries for f = e,μ,τ; b,c,s. At Z pole:

$$A_{FB}^{0,f} \equiv \frac{3}{4} A_e A_f \qquad A_f \equiv \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2},$$

- τ polarisation: $$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e\cos\theta}.$$

Number of light neutrinos N_ν

One of the questions asked by the **LEPC** before recommending approval of the experiments:

What is the expected accuracy for neutrino counting?

Best value from accurate measurement of Γ_{inv}/Γ_{ll} divided by $\Gamma_{\nu\nu}/\Gamma_{ll}$ from MSM; $\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - \Gamma_{ll}(3-\delta_\tau)$:

Average: $N_\nu = 2.9841 \pm 0.0083$ (2 σ below 3).

$$\Gamma_{inv}^{x} = -2.7^{+1.7}_{-1.5}\,MeV$$

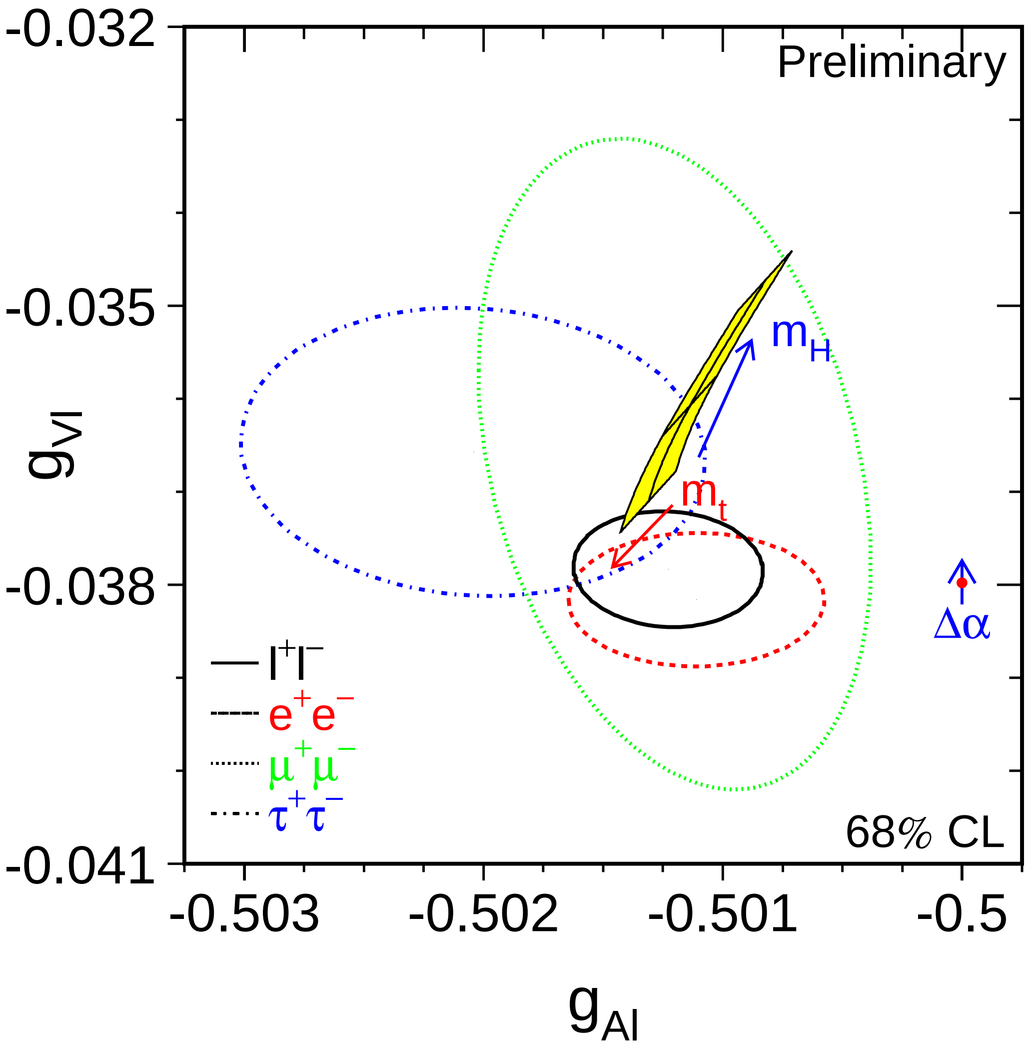
Veltman ρ-parameter

From leptonic width Γ_{ll}

$$\rho^{lept}{}_{eff} = 1.0050 \pm 0.0010$$

5 σ above tree-level value of 1, proves presence of genuine ew radiative corrections, agrees with SM.

Z couplings to e, μ, τ



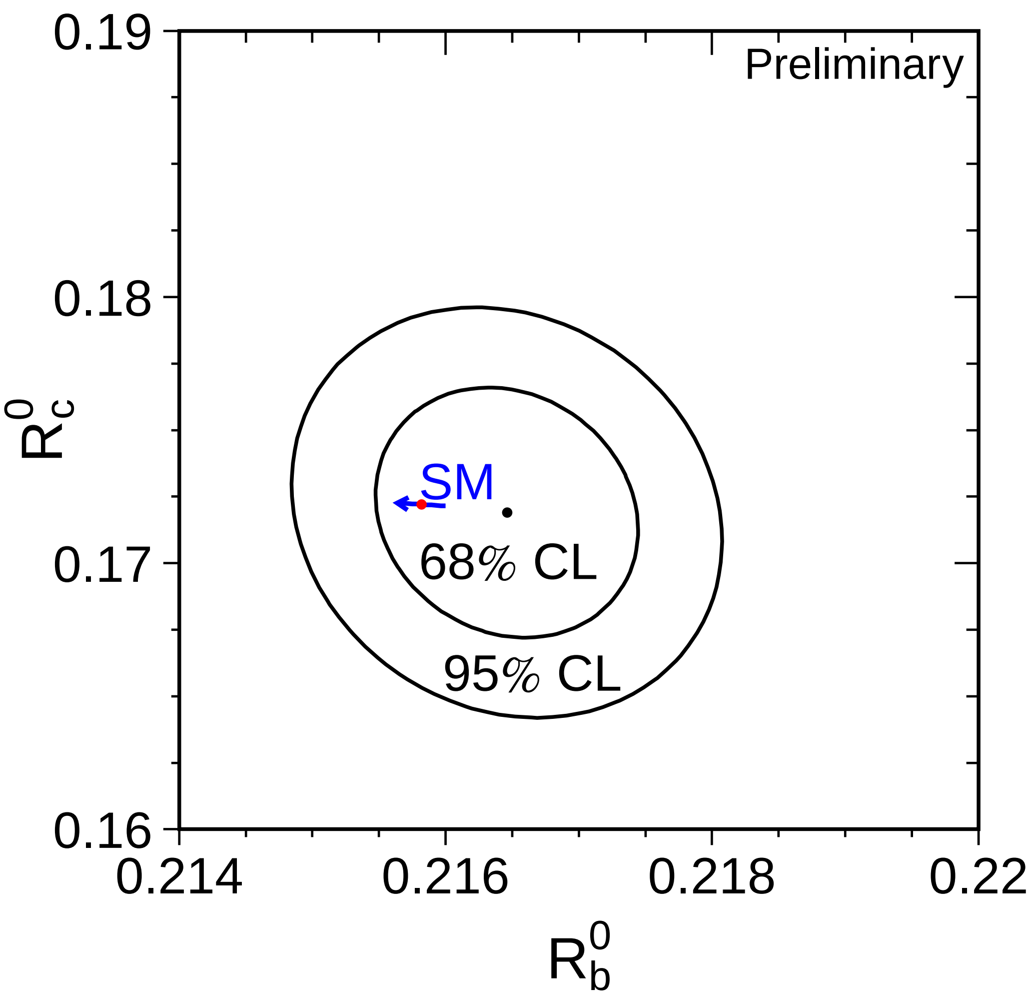
Contributions from LEP:

- A_{FB} at Z pole,
- Partial widths $\Gamma_{ff} \sim g_{Vf}^2 + g_{Af}^2$,
- Longitudinal τ polarisation: A_τ, A_e.

Contributions from SLD:

- Asymmetry for left and right handed e^- polarisation: most precise A_e,
- A_{FB}^{LR}: A_e, A_μ, A_τ.

Z $\rightarrow$ quarks



Now R_b agrees with SM!

$$R_b^0 \equiv \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} \qquad R_c^0 \equiv \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$$

R_b contains higher order ew. contributions ~ m_t^2, nearly independent of QCD, QED or other ew. corr.

Measurement of R_b requires extremely high quality of b tagging.

$\rightarrow$ High resolution silicon microvertex detectors + multi-tag methods + control of hemisphere correlations …

New analyses of $A^{0,b}_{FB}$

ALEPH, inclusive B-decays

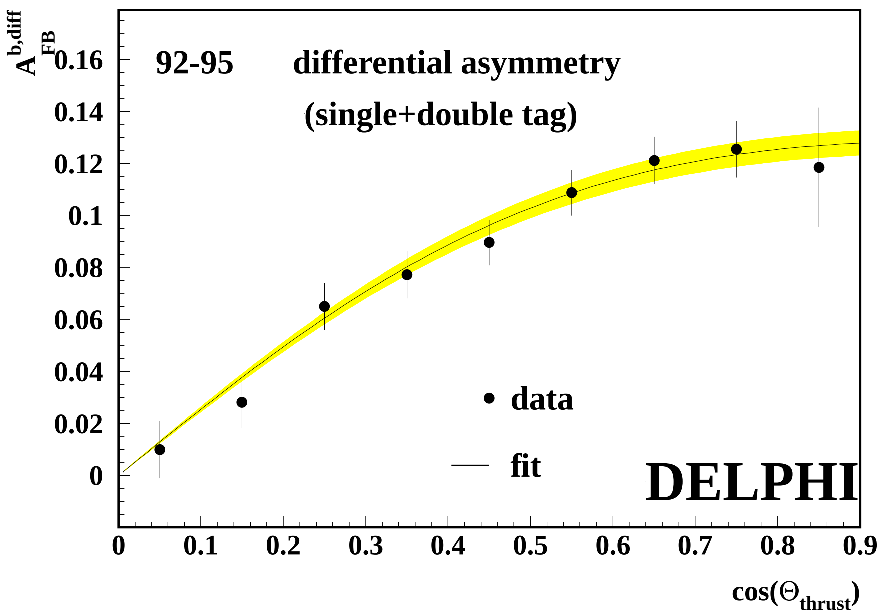
- 30% increase in data sample from neural network for b-tagging (b hemisphere charge estimated by optimal merge of information from primary and secondary vertex charge, leading kaons, and jet charge).

$$A^{0,b}_{FB} = 0.1009 \pm 0.0031$$

DELPHI, v. high purity b-sample

- Neural network (b hemisphere charge determined from vertex charge, jet charge, charge of leptons and kaons), self-calibration from double tagging.

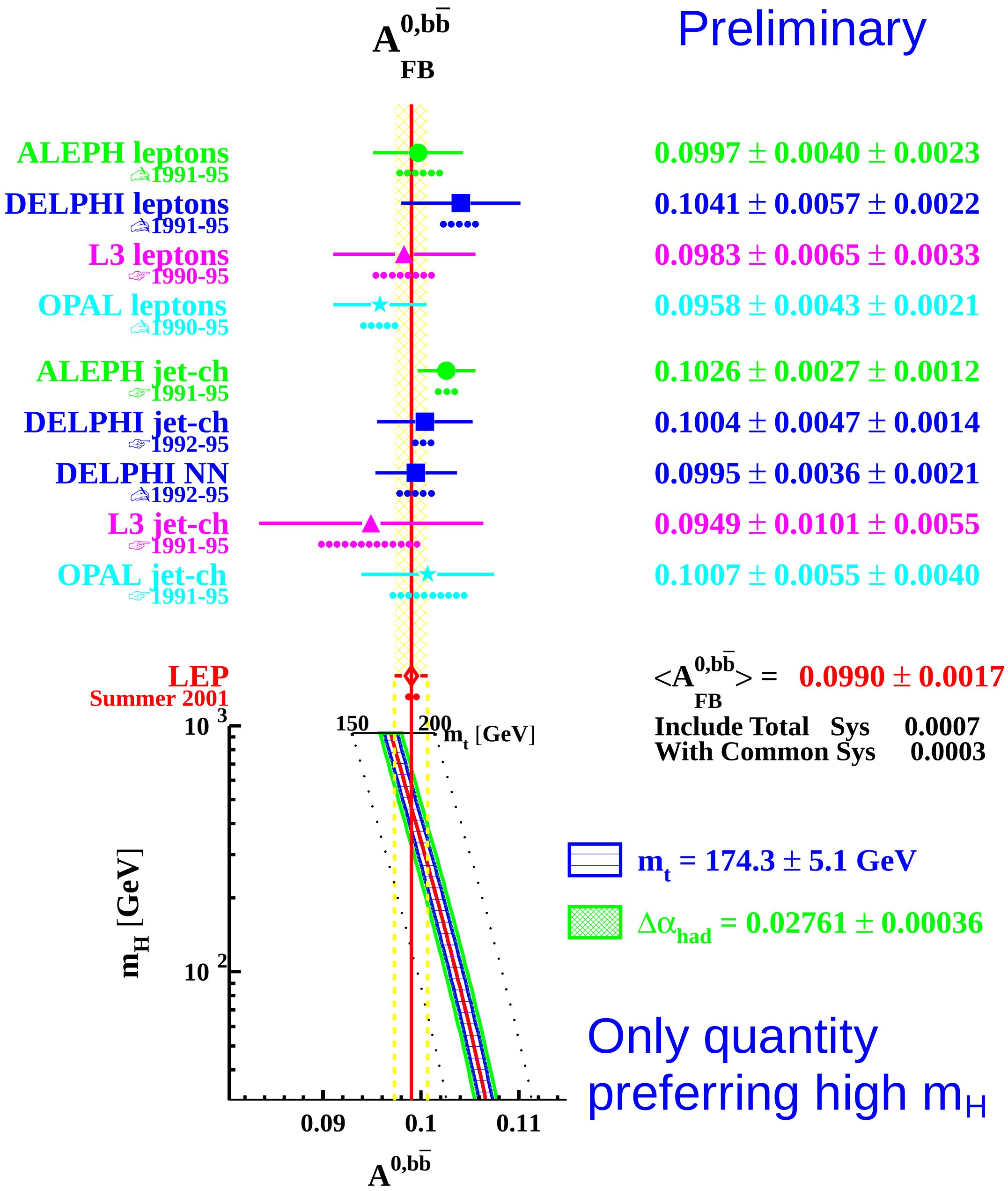
$$A^{0,b}_{FB} = 0.0997 \pm 0.0042$$



Significant improvement, still significant deviation?

The 3.3 σ discrepancy

$\sin^2\theta_{eff}$ from $A^{0,b}_{FB}$ versus A_l



Only quantity preferring high m_H

Q: Are LEP meas. consistent?
A: Yes!

Q: Are LEP and SLD results incompatible?

A_b(LEP only) = 0.891 ± 0.022
(last year 0.890 ± 0.024)

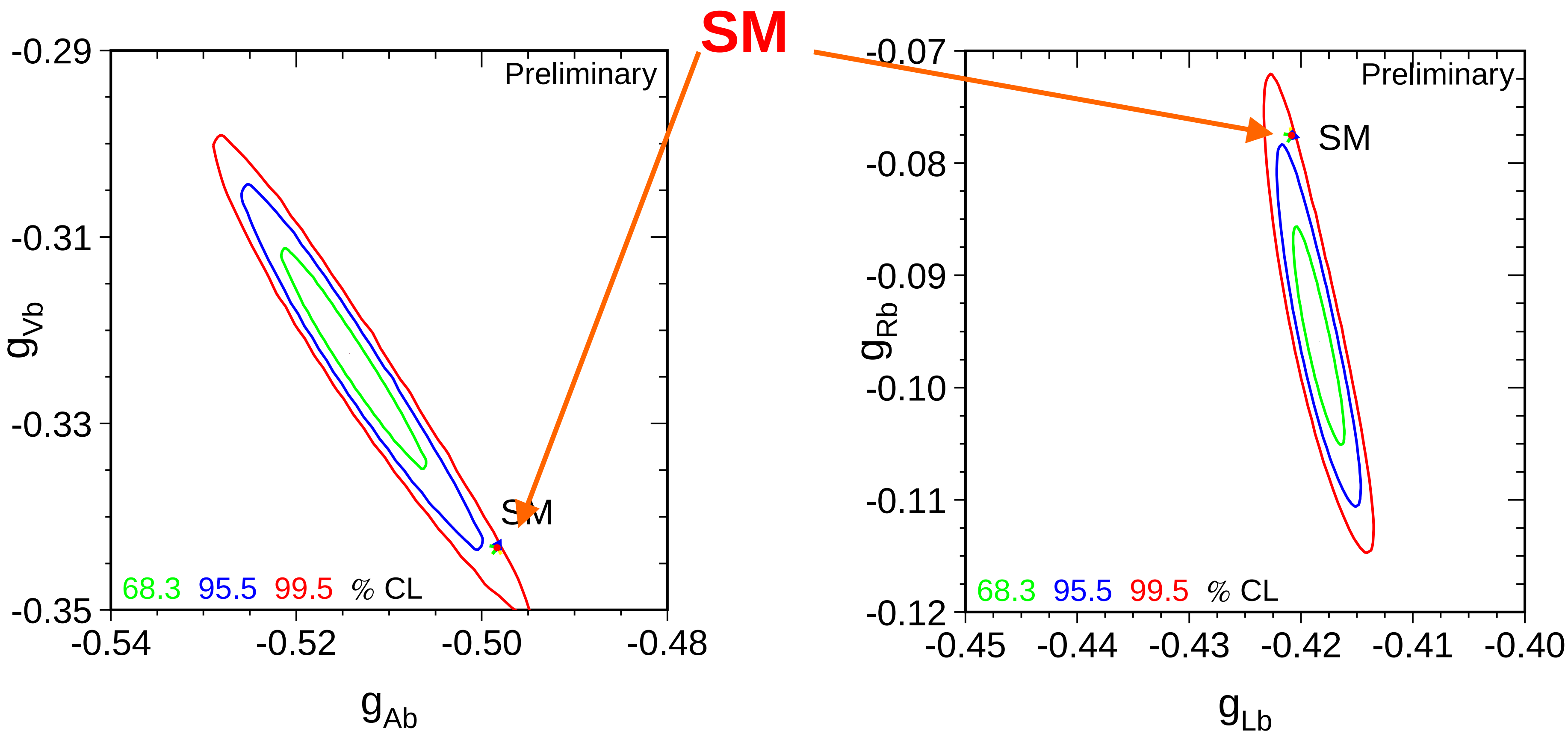
A_b(SLD) = 0.921 ± 0.020

Agree within 1.0 σ !

A_b(LEP+SLD) = 0.899 ± 0.013
(0.935 SM)

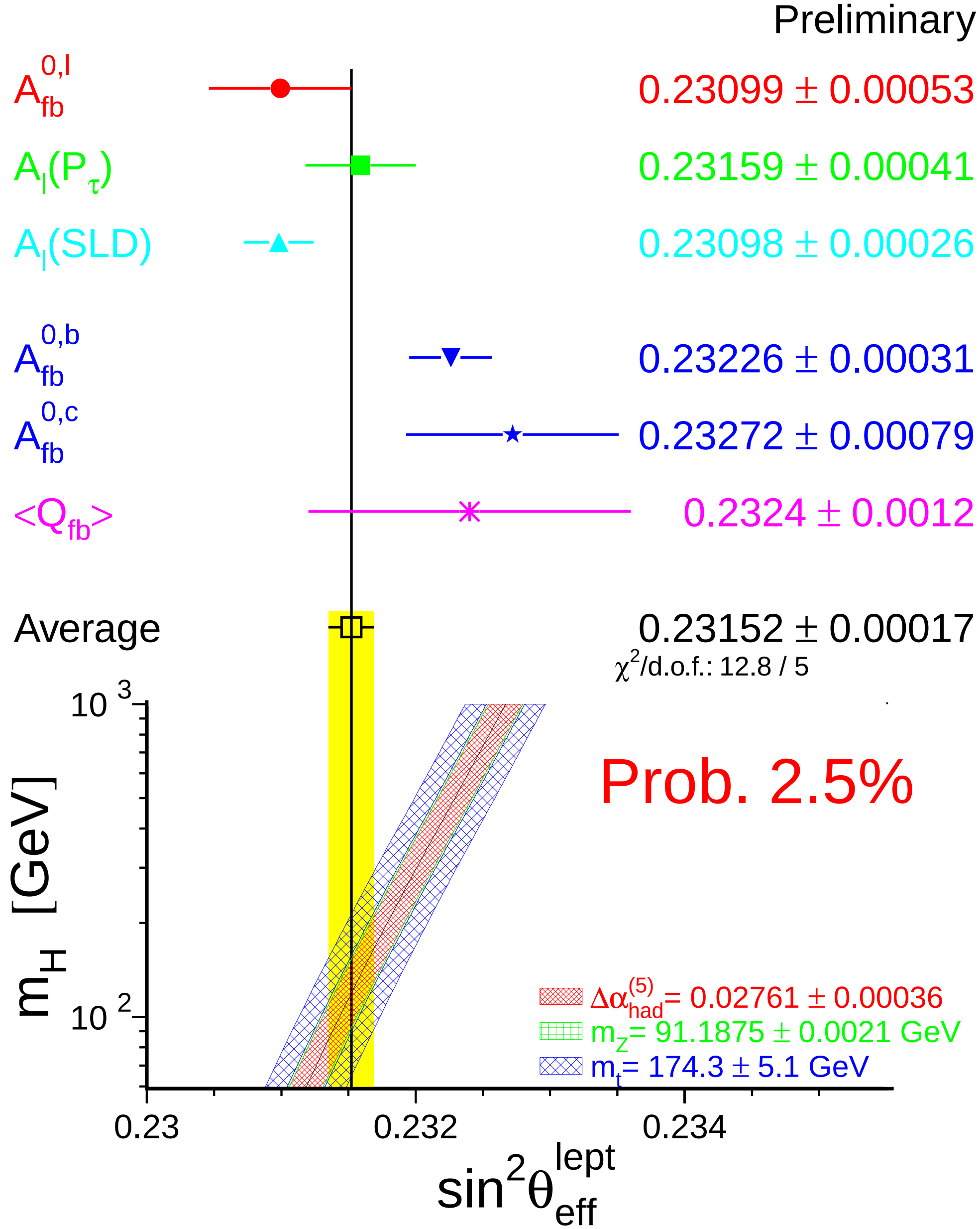
g_{Vb} versus g_{Ab}, g_{Rb} versus g_{Lb}

From R_b, $\mathcal{A}_b$, and A_{FB}^b, assuming lepton universality.



Strong anti-correlation of g_{Vb}, g_{Ab} due to constraint on sum of squares from precise R_b. Deviation from SM mainly for g_{Rb}.

Again $\sin^2\theta_{eff}$



$\sin^2\theta_{eff}^{lept}$ from only

leptons	.23113 ± .00021
hadrons	.23230 ± .00029

Either:

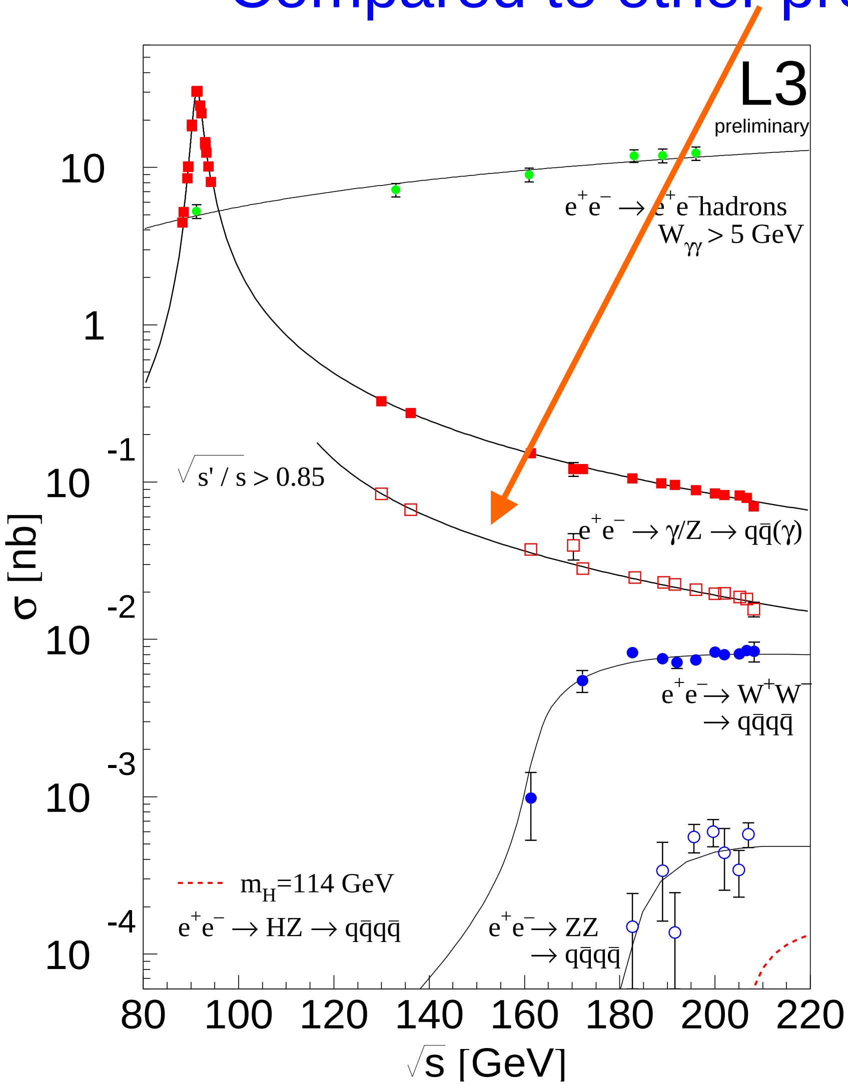
- Statistical fluctuation,
- unknown sources of systematic errors,
- or evidence for new physics.

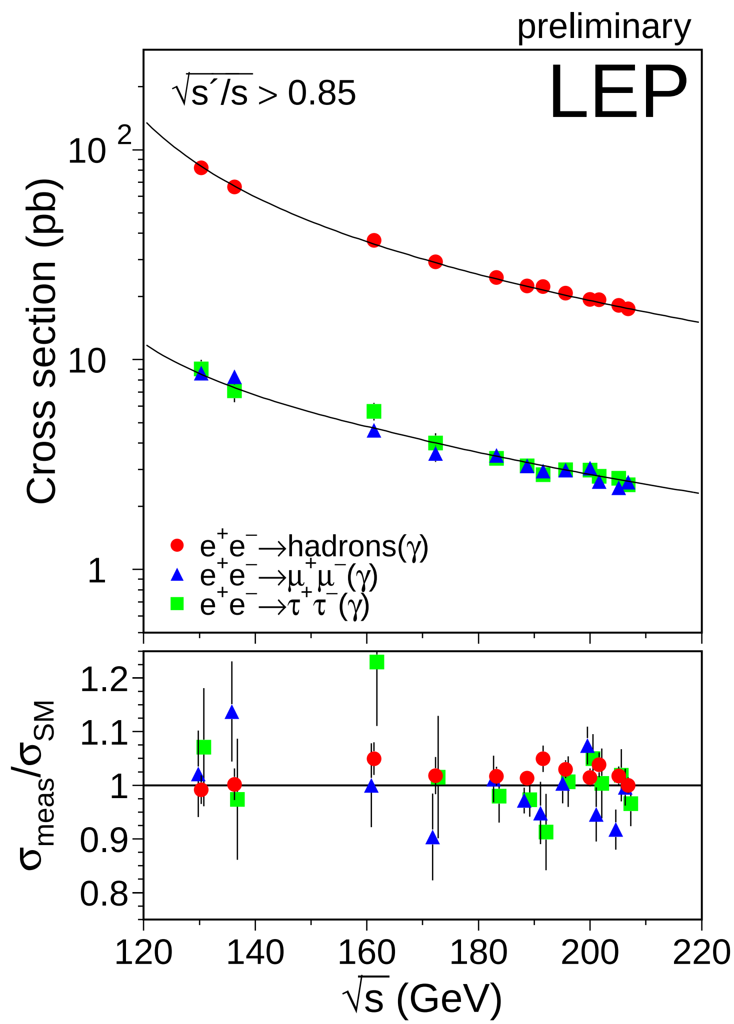
Note:

Only average $\sin^2\theta_{eff}$ consistent with m_H O(100 GeV) .

2 fermion production above Z

Compared to other processes cross-section still high.



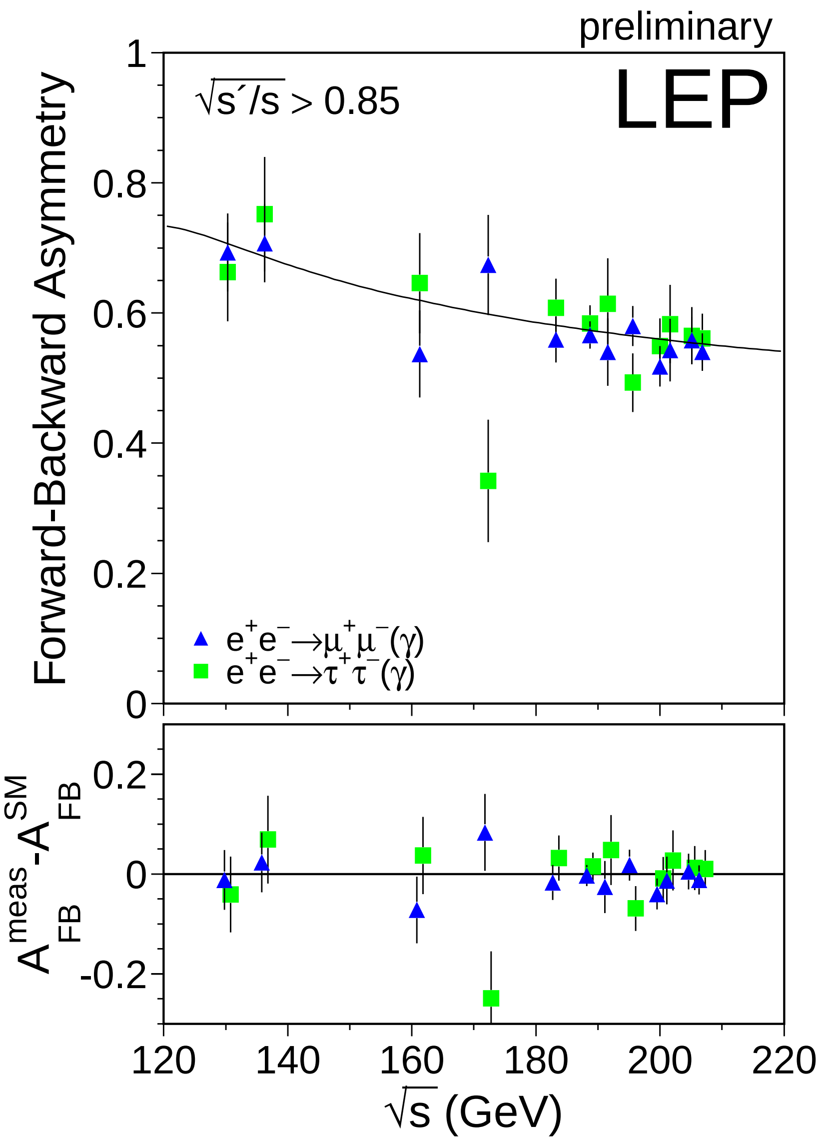


Cut on $\sqrt{s'/s}$ selects interesting events.

Combined for hadrons, μμ, ττ, bb, cc by EWWG.

Agreement with SM, but hadronic cross-section 1.8 σ high.

LEP2 μ and τ asymmetries



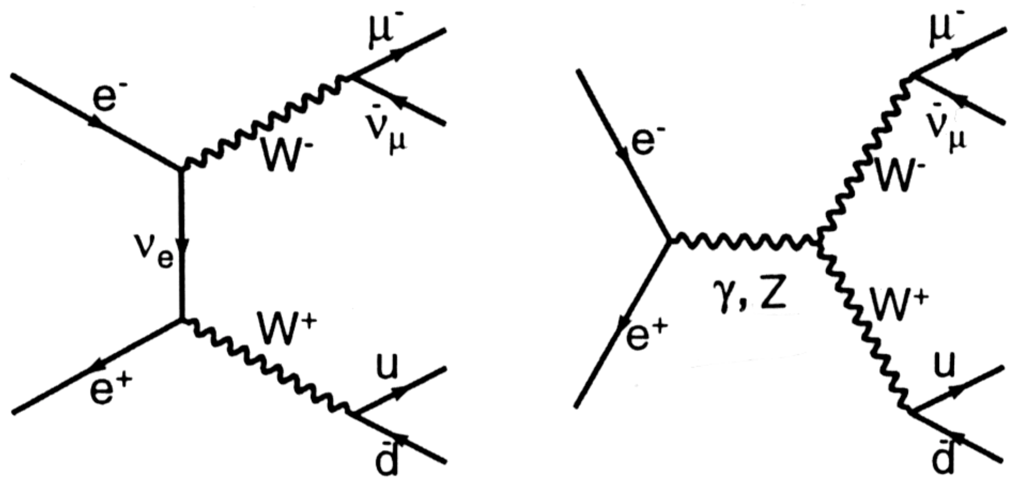
Test of models with combined data:

- Additional **Z′**, e.g. limit for $m_{Z'}$ (zero mixing) in
  - LR model 0.80 TeV (95% CL),
  - χ model 0.68 TeV,
- Constraints on contact interactions
  - between leptons: $\sqrt{4\pi}\Lambda/g$ > 8.5 to 26 TeV,
  - between leptons and heavy quarks. For eb: $\sqrt{4\pi}\Lambda/g$ > 2.2 to 15 TeV.

Low scale quantum gravity, including e^+e^- data: M_S > 1 TeV.

W^+W^- Production

Focus of SM tests at LEP2: Measurement of m_W, investigation of structure of triple boson couplings.

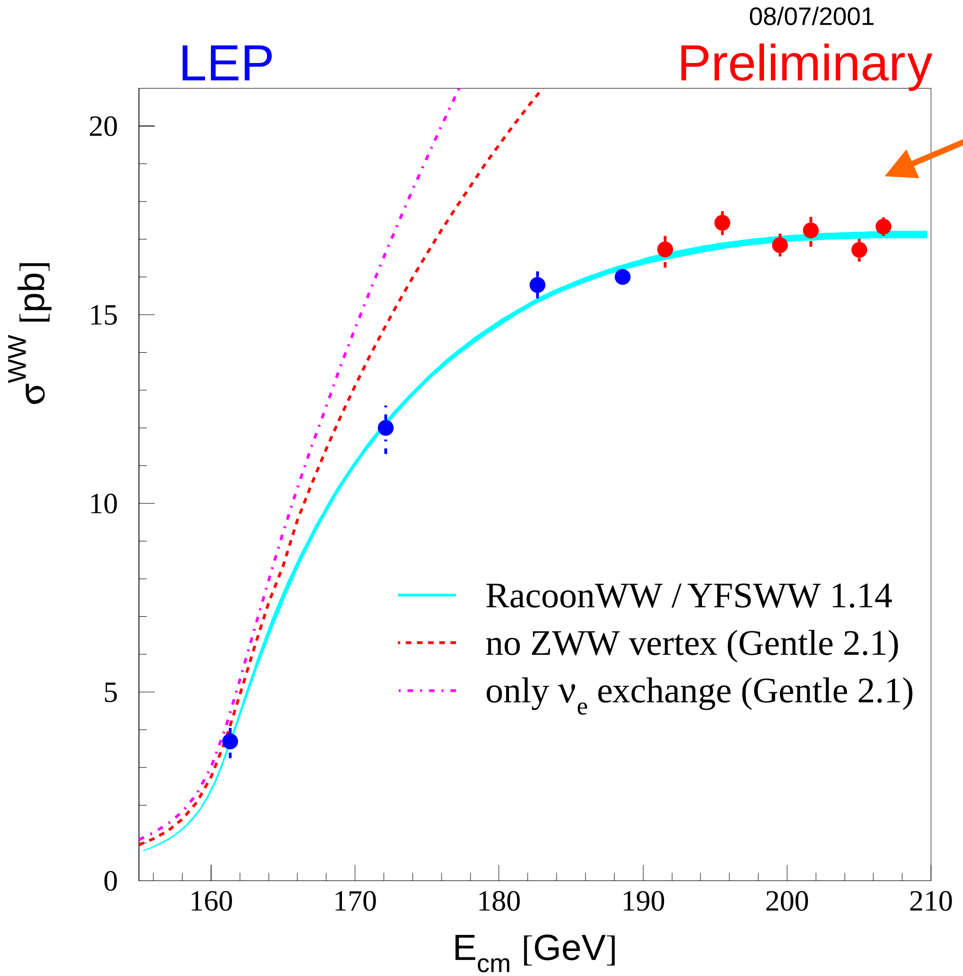


CC03 diagrams

Each LEP experiment has collected about 10000 W^+W^- events.
Five decay classes: Fully hadronic (45.6%), 3 semileptonic (each 14.6%), fully leptonic (10.6)%.

Powerful tools to separate four fermion events originating from W production from background, e.g. neural networks.
Typical efficiency for WW selection 85% at v. high purity.

$\sigma(e^+e^- \rightarrow W^+W^- \rightarrow 4$ fermions)



Combined results of the 4 collaborations

Obvious: All t- and s-channel contributions, needed to understand the data.

Subtle: Comparison with new MC generators with improved radiative corrections, DPA for virtual O(α) corrections in resonant W-pair production (plus all other QED corr.) needed for 0.5% accuracy.

$\sigma_{meas}/\sigma_{theory\ (RacoonWW)} = 1.000 \pm 0.009$ ($\sqrt{s} > 180$ GeV)

W mass

Before crossing W-pair threshold precise m_W value from Z data using SM relations. **Updated indirect value using measured m_t** :

$$\mathbf{m_W = 80.373 \pm 0.023\ GeV\ .}$$

Small error sets scale for direct mass measurements.

In SM m_W depends on m_t, m_H and $\Delta\alpha$ (complete 2-loop, Freitas et al.):

$$m_W = 80.3767 + 0.5235\left(\left(\frac{m_t}{174.3}\right)^2 - 1\right) - 0.05613\ln\left(\frac{m_H}{100}\right) - 1.081\left(\frac{\Delta\alpha}{0.05924} - 1\right) + - \ldots$$

Significant deviation of direct meas. from indirect value would indicate new physics and existence of new fundamental particles.

At LEP2 two independent methods:

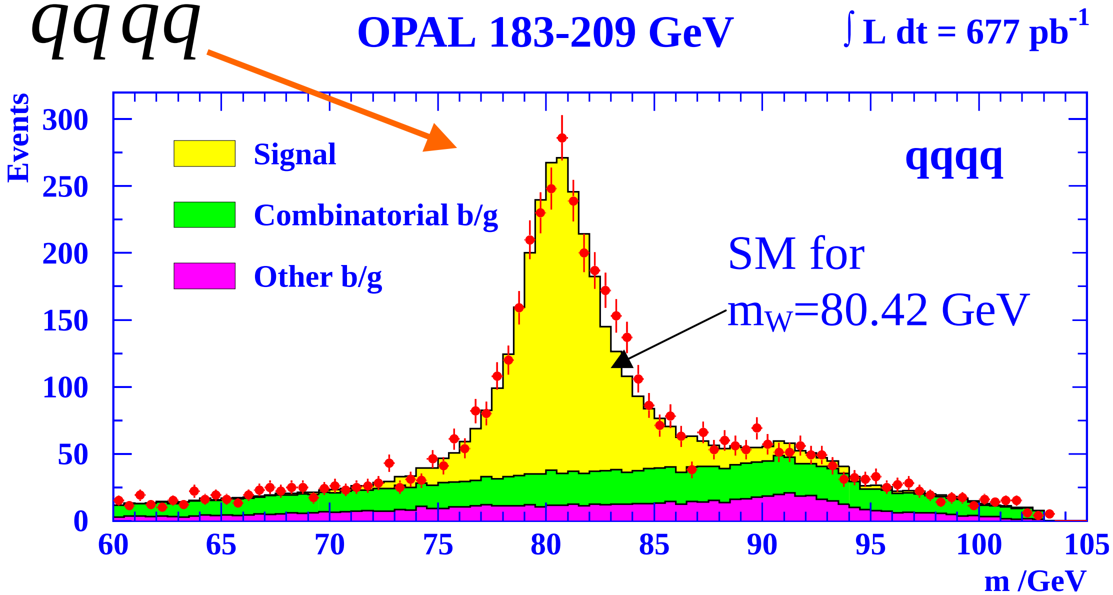
- Meas. of the total cross-section near threshold at E_{CM} = 161 GeV:

  $m_W = 80.40 \pm 0.21$ GeV. (Estimated error for GigaZ: $\Delta m_W = 0.006$ GeV)

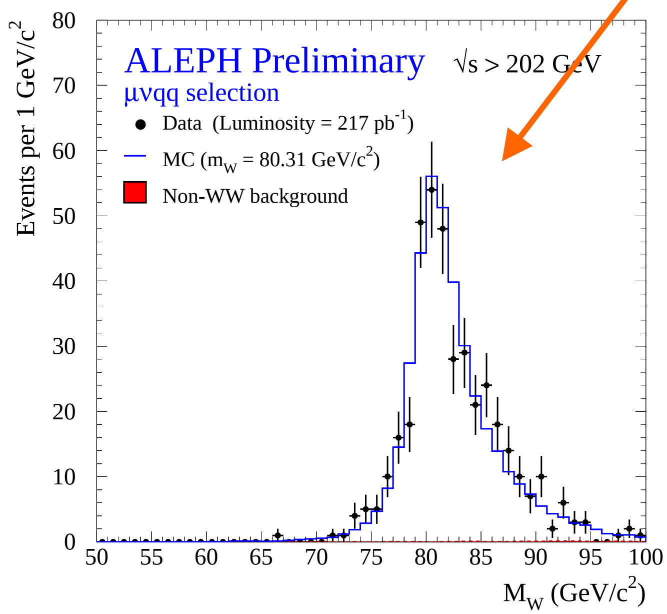
Direct m_W measurements

From invariant mass distribution of detected decay products (constrained by energy and momentum conservation):

$q\bar{q}q\bar{q}$



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



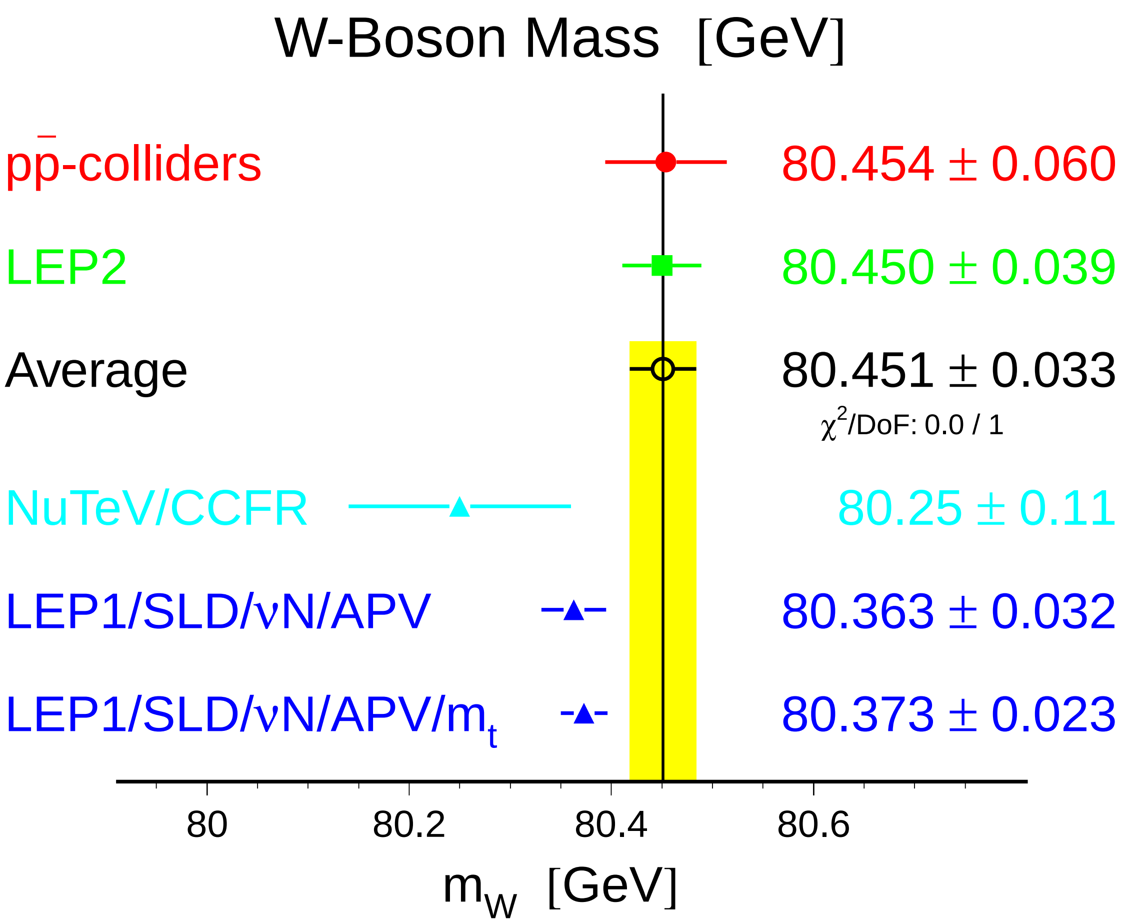
Systematic uncertainties of m_W:

- 29 MeV for semileptonic, (fragmentation, beam energy, detector systematic, initial and final state photon radiation, …)
- 54 MeV for fully hadronic, (colour reconnection, BE).

Consistency: $$\Delta m_W(q\bar{q}q\bar{q} - q\bar{q}l\bar{\nu}) = +9 \pm 44 MeV$$

Results

LEP: m_W = 80.450 ± 0.026 ± 0.030 GeV, weight of 4q channel 26%.

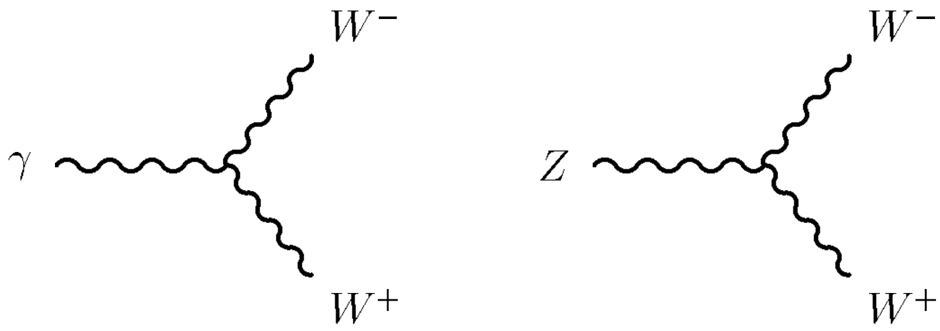


Still agreement between indirect and direct measurements within 1.9 σ.

Final LEP:
$\Delta m_W \cong$ 35 MeV

Γ_W from direct reconstruction:
Γ_W = 2.150 ± 0.091 GeV
agrees with SM.

Charged gauge couplings



W^+ electromagnetic moments:

Magnetic dipole moment
$\mu_W = (e/2m_W)\,(1 + \kappa_\gamma + \lambda_\gamma)$,

Electric quadrupole moment
$q_W = -(e/m_W^2)\,(\kappa_\gamma - \lambda_\gamma)$.

- Tools: σ^{WW}, $\cos\theta_{W^-}$ distribution, $W^\pm$ helicities analysed via fermion decay angles, $e^+e^- \rightarrow e\nu W$ and $\bar{\nu}\nu\gamma$ production.

C and P conservation plus constraints from low energy data leaves:

$$g_1^Z,\ \kappa_\gamma,\ \lambda_\gamma\ \ (1,1,0 \text{ within SM}).$$

One parameter fit precision:

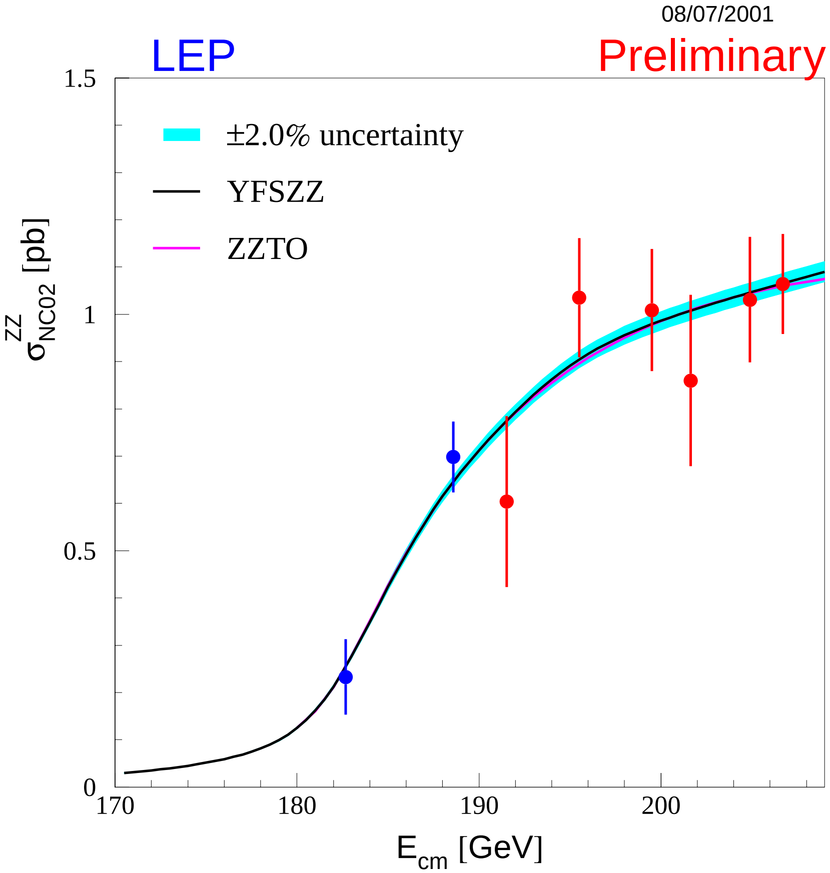
$$\delta g_1^Z = \pm\, 0.026,\ \delta\kappa_\gamma = \pm\, 0.066,\ \delta\lambda_\gamma = \pm\, 0.028.$$

CP violating couplings studied by ALEPH, OPAL. Within errors no deviation from SM. Quartic gauge couplings (ALEPH, L3, OPAL): limits available.

No evidence for any anomalous W boson coupling!

ZZ production

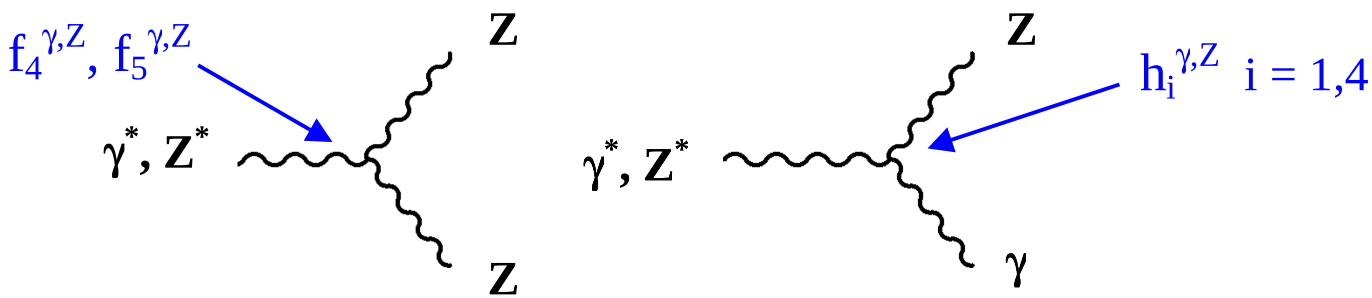
- New test of SM. Search for existence of anomalous neutral gauge boson couplings (ZZZ, ZZγ).



Combined results (NC02, only t- and u-channel exchange).

All experiments analyse ZZ $\rightarrow$ qqqq (4 jets), qq$\nu\nu$ (2jets + missing energy), qql^+l^- (2jets + 2 isolated leptons),
4 lepton final states;
statistic v. limited.

Anomalous neutral gauge couplings

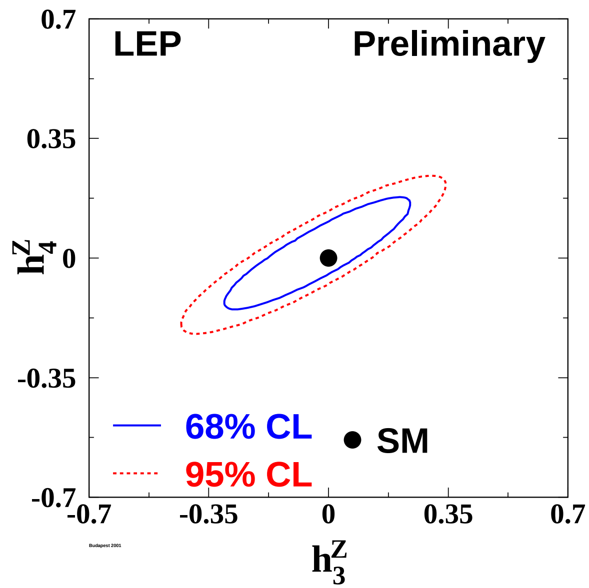


- SM tree level $\rightarrow$ **no** neutral TGCs,
- Tools to search for anomalous neutral TGCs:
  - Total cross section for ZZ and γZ (increase?),
  - cos $\theta_{Z,}$ cos θ_{γ}, and E_{γ} distributions (deviations at large θ?).

New results from all LEP collaborations, examples of averages (95% CL):

f_5^Z [-0.36, +0.38]

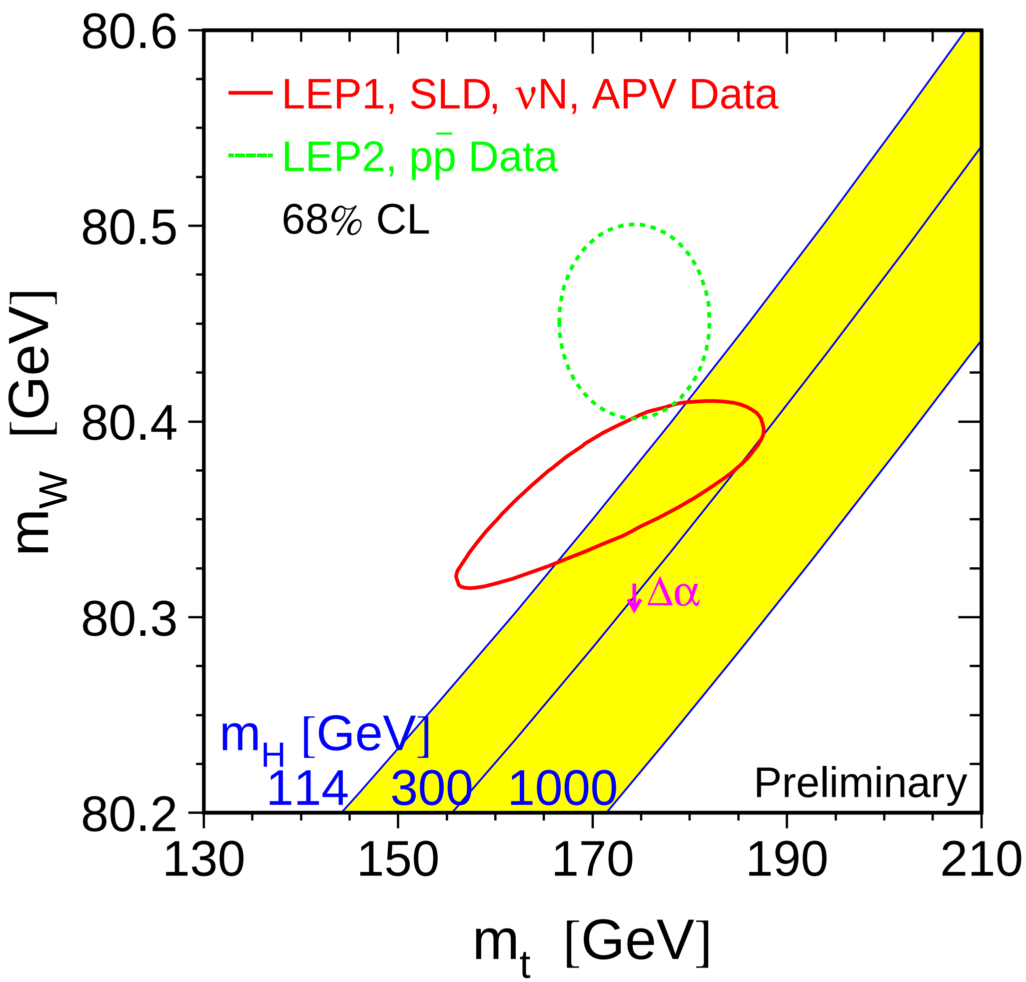
h_3^{γ} [-0.08, +0.14]



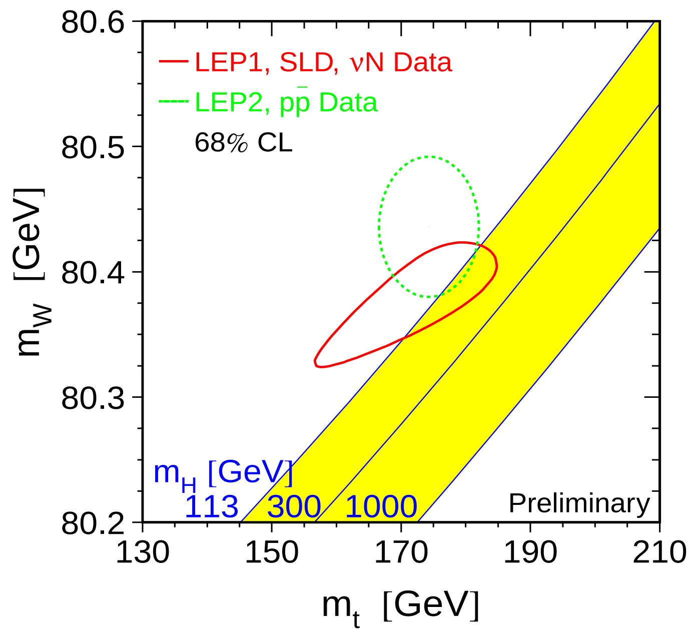
No evidence for any anomalous boson coupling!

Consistency test of SM

m_W from LEP and Fermilab versus m_t from Fermilab



Indirect and direct measurements favour low m_H !



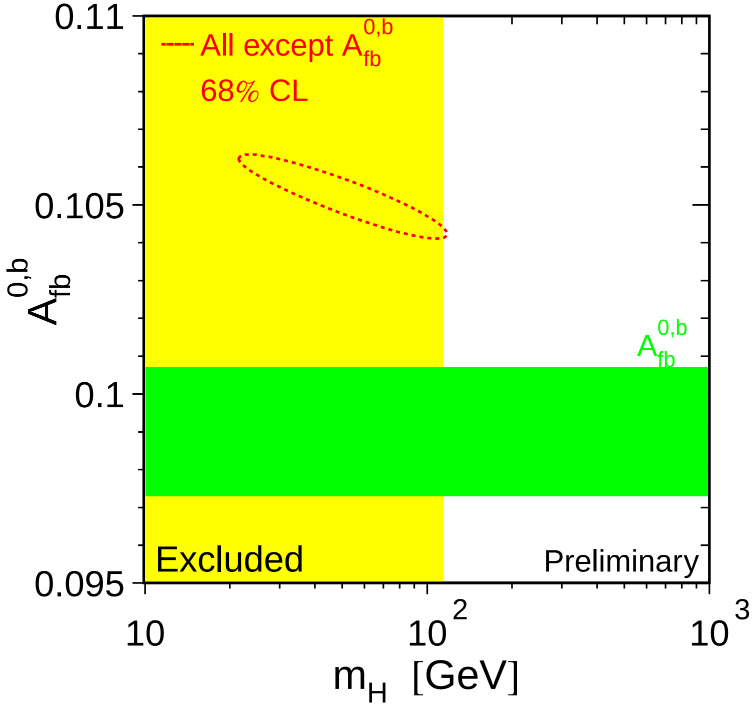
Status summer 2000

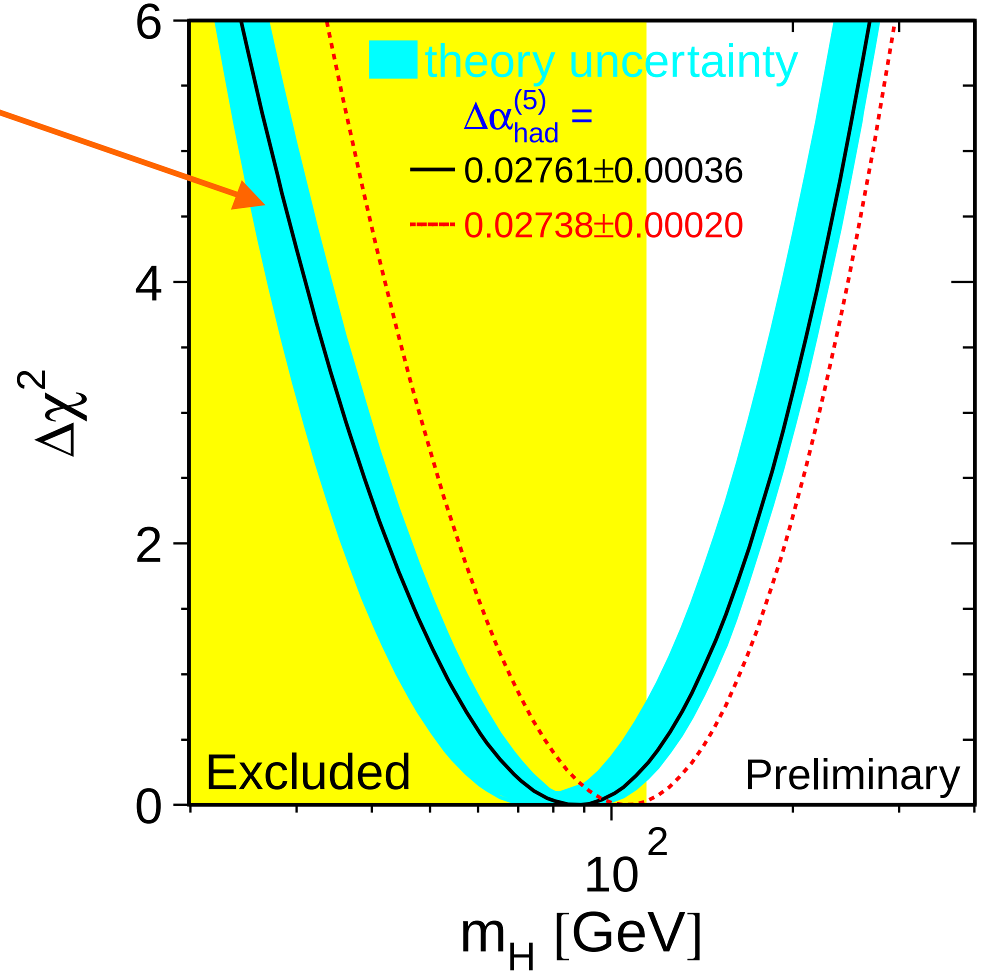
Predicting m_H

MSM fit to

- all data from LEP1 and SLD,
- m_t , $m_{W,}$
- $\sin^2\theta_W$ from CCFR, NUTEV,
- APV.

Information from $A^{0,b}_{FB}$:





$m_H <$ 196 GeV (95% CL)

Contributions to CKM

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Many tools available at LEP:

- W branching ratios,
- High Z $\rightarrow$ $\bar{b}b$ statistics,
  $\sim$ 4 M events,
  - Fast moving B-hadrons,
  - B decay particles well separated from QCD rest,
  - Particle identification,
  - Full reconstruction of B^0_s,
  - Experience of 12 years.

Few examples:

$|V_{cs}|$ from Br(W→lν)

$$\frac{1}{3 \cdot Br(W \rightarrow l\nu)} = 1 + (1 + \frac{\alpha_s}{\pi}) \sum_{i=u,c} |V_{ij}|^2$$

Results:

$$\sum |V_{ij}|^2 = 2.039 \pm 0.025$$

unitarity not needed,

$$|V_{cs}| = 0.996 \pm 0.013$$

assuming world average for other V_{ij}.

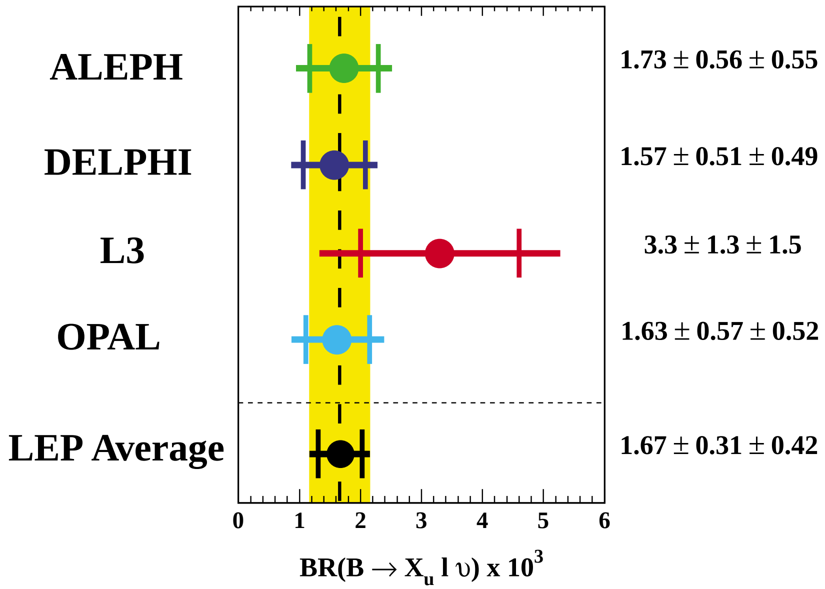
$|V_{ub}|$

Strategy: Inclusive reconstruction of $b \to ul\nu$ fraction:

$$|V_{ub}|^2 = BR(B \to X_u l \nu) / \tau_b \gamma_b$$

γ_b uncertainty known.

V. difficult to separate charmless b decays from dominant $b \to c$ background. In a new analysis **OPAL** uses 7 kinematic variables as NN input to enrich $B \to X_u$ sample.



LEP average from $|V_{ub}|$ WG:

$$BR(b \to X_u l^- \overline{\nu}_l) = (1.67 \pm 0.52) \times 10^{-3}$$

with world average B hadron lifetime $\tau_b = (1.564 \pm 0.014)$ ps:

$$|V_{ub}| = (4.04^{+0.59}_{-0.69}) \times 10^{-3}$$

incl. theoretical uncertainties (QCD, m_b).

B^0_s - $\overline{B}^0_s$ oscillations

Main interest:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

ξ^2 of O(1) known to 5-6%. Analysis technique amplitude method (ALEPH):

$$P(B_s^0 \to \overline{B}_s^0) = \frac{1}{2}(1 - A\cos(\Delta m_s t))e^{-t/\tau_{B_s^0}}$$

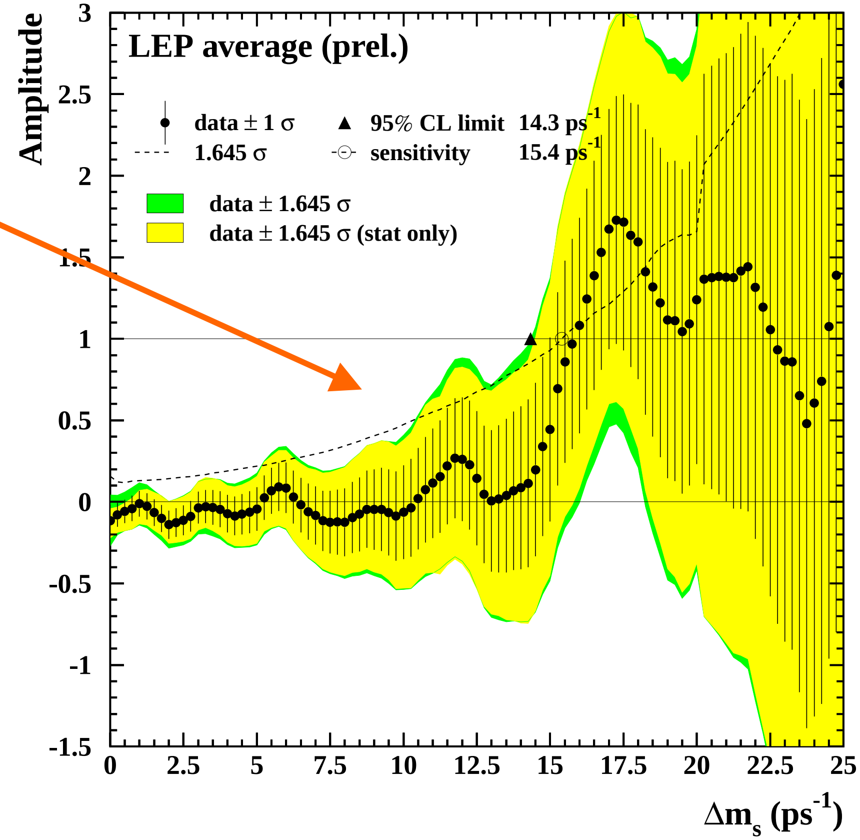
Amplitude A fitted to data for various Δm_s.

Present **world** limit, including **SLD** and **CDF** and new data from **DELPHI**

$\Delta m_s > 14.6\ ps^{-1}$ (95% CL)

$\longrightarrow$ $|V_{td}| / |V_{ts}| < 0.22$

LEP only



Contributions to QCD

Clean environment, hadronic cm. energy well defined, well collimated jets, enough statistics to investigate even rare topologies.

Typical early topics:
- Tests of QCD, measurements of α_s, understanding of fragmentation,

Later: Global studies (up to which level can the accurate data be described).

Ew precision quantities depend on α_s:

$$R_{lept} = \frac{\Gamma(Z \to hadrons)}{\Gamma(Z \to leptons)} = 19.934 \cdot \left(1 + 1.045\frac{\alpha_s}{\pi} + 0.94\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3 \right)$$

With final $R_{lept} = 20.767 \pm 0.025$:

$$\alpha_s(m_Z) = 0.124 \pm 0.004(\exp.) \pm 0.002(m_H, m_t)^{+0.003}_{-0.001}(QCD)$$

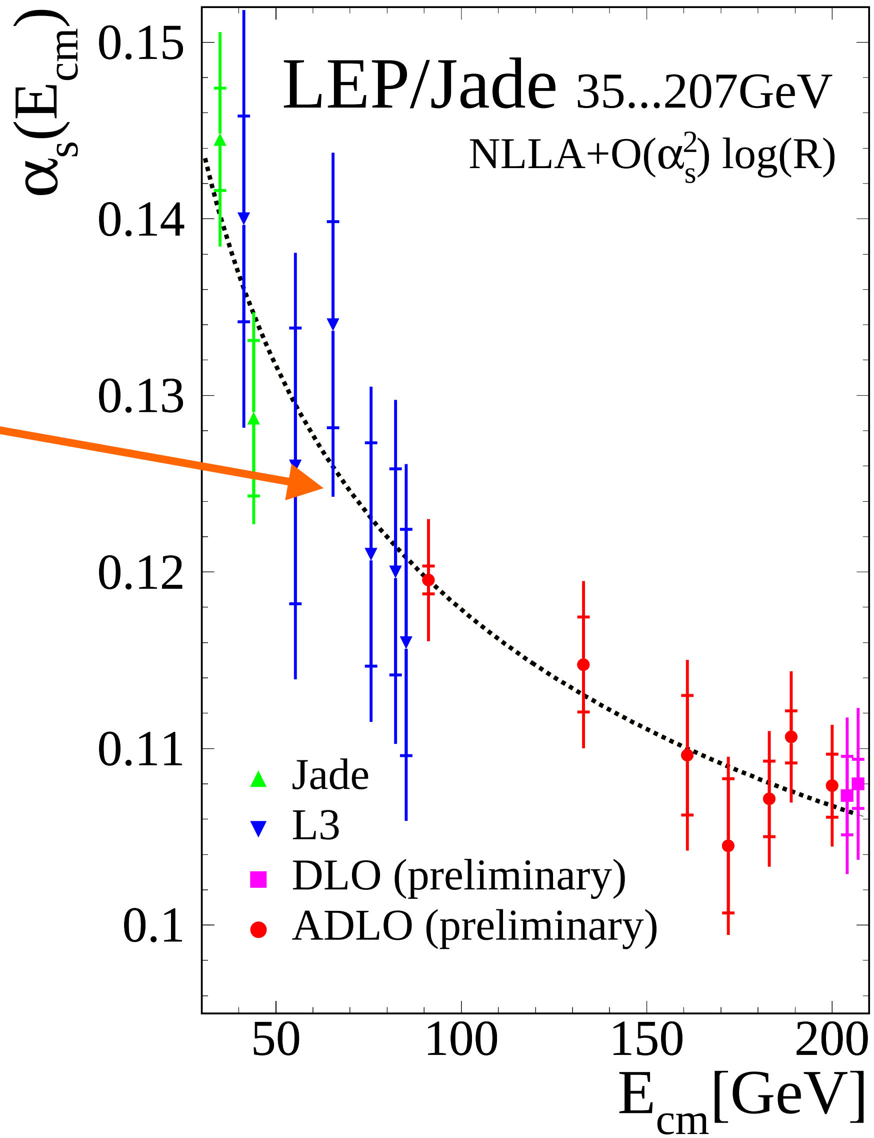
Best measurement?

- Relies on electroweak sector of MSM,
- Convergence, at m_Z α_s^3-term $\cong$ 63% of α_s^2-term.

α_s

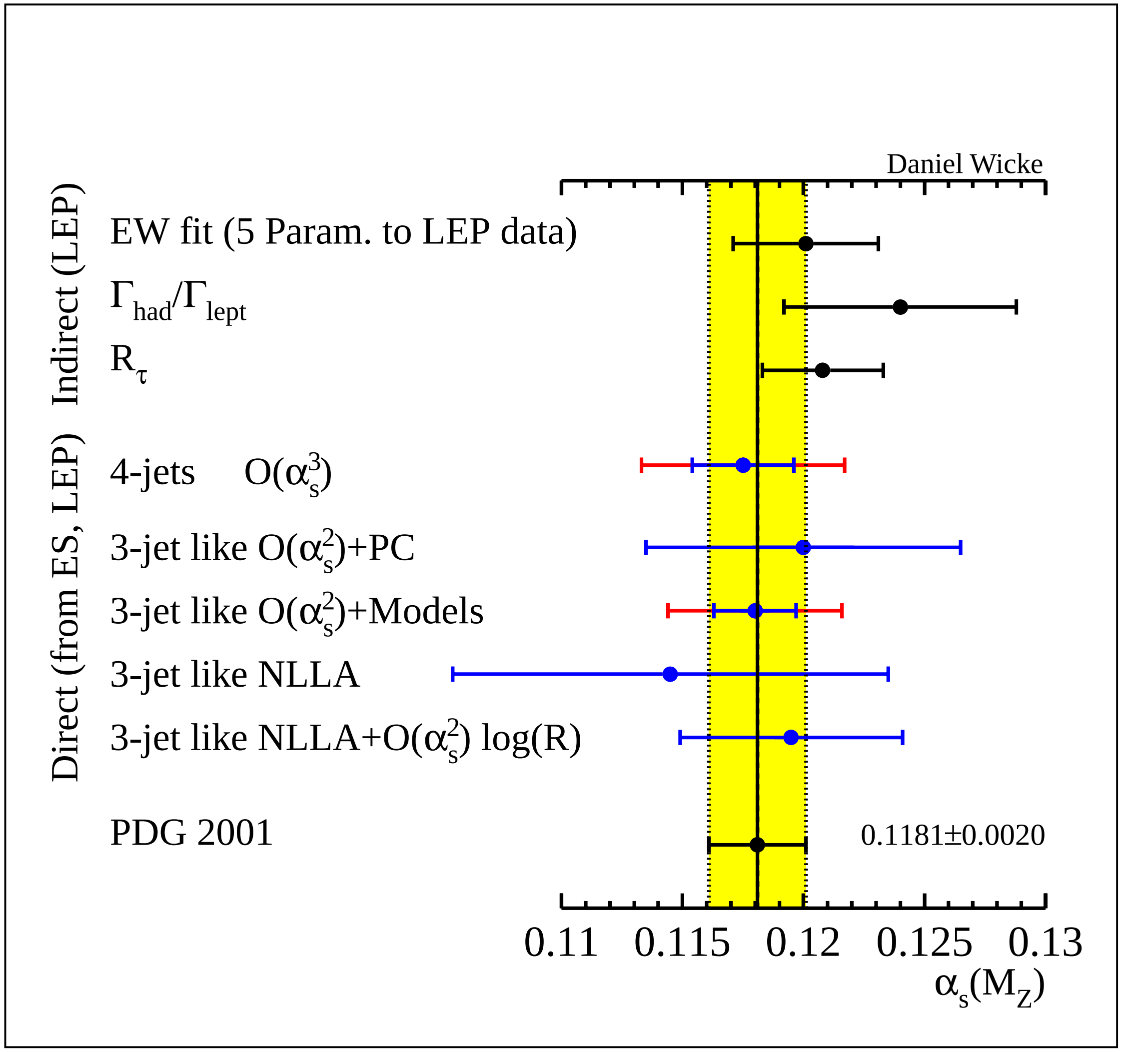
- Need to measure α_s from infrared safe shape variables like jet rates, thrust, etc. not depending on Z couplings to quarks.

From event shapes
(LEP QCD Working Group)



But all these quantities are calculated in O(α_s^2) matched with NLLA
$\rightarrow$ renormalisation scale uncertainty.

All LEP α_s measurements



Studies of

- gauge structure of QCD,
- running b-quark mass,
- colour coherence,
- hadronisation models,
- power corrections as alternatives to hadronisation models,
- differences between quark and gluon jets,

are all consistent with QCD predictions.

For this fig.: Theoretical uncertainties for all α_s from event shapes evaluated from change in renormalisation scale μ by factor 2.

Before LEP

What was known or expected in summer 1989 before start of LEP (G. Altarelli; LP, Stanford and R. Barbieri; EPS, Madrid):

$m_Z = 91.12 \pm 0.16$ GeV $\quad m_W = 80.0 \pm 0.36$ GeV

$\sin^2\theta_W = 0.227 \pm 0.006 \quad N_\nu = 3.0 \pm 0.9$

Quantity	Expected error	Achieved
m_Z	50 to 20 MeV	**2.1 MeV**
m_W	100 MeV	**39 MeV**
N_ν	0.3	**0.008**
$A^{0,\mu}_{FB}$	0.0035	**0.0013**
$A^{0,b}_{FB}$	0.0050	**0.0017**
A_τ	0.0110	**0.0043**

In the end, all measurements are much more precise. SM continues to be in good shape.

Why was LEP so successful?

- Dedicated machine group, excellent performance of LEP, low background,
- Good performance of detectors from beginning until end of data taking,
- Effective division of work between CERN and outside laboratories,
- Close cooperation
  - between the 4 collaborations and also between LEP and SLD (without avoiding competition),
  - with the machine group,
  - with theory groups.

Many analyses continuing, still more to be expected.