"LEP II era/precision physics" (1994-2004),
CERN Auditorium, 25th July

YEARS/ANS CERN

The 1994-2004 years at LEP: precision physics

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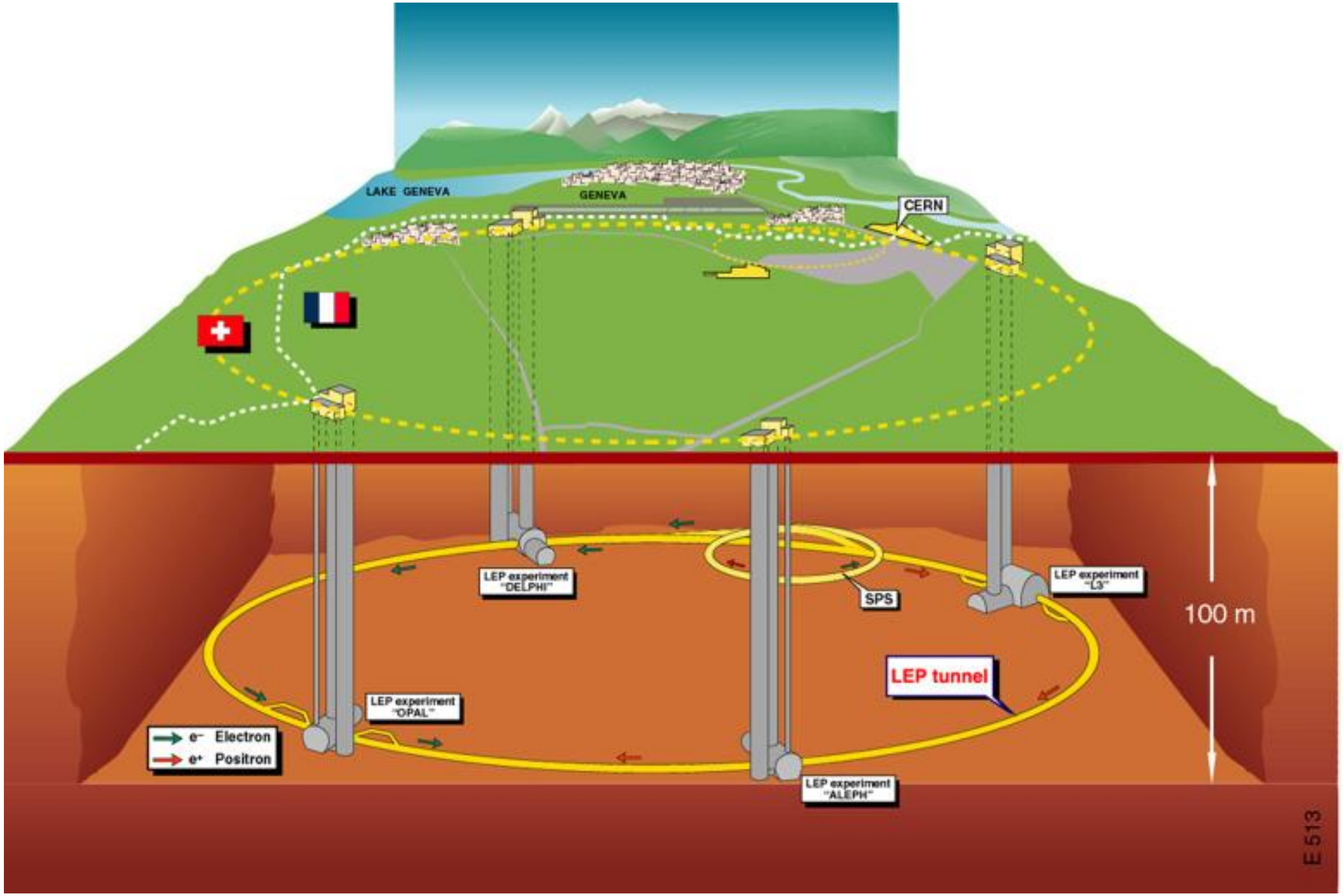
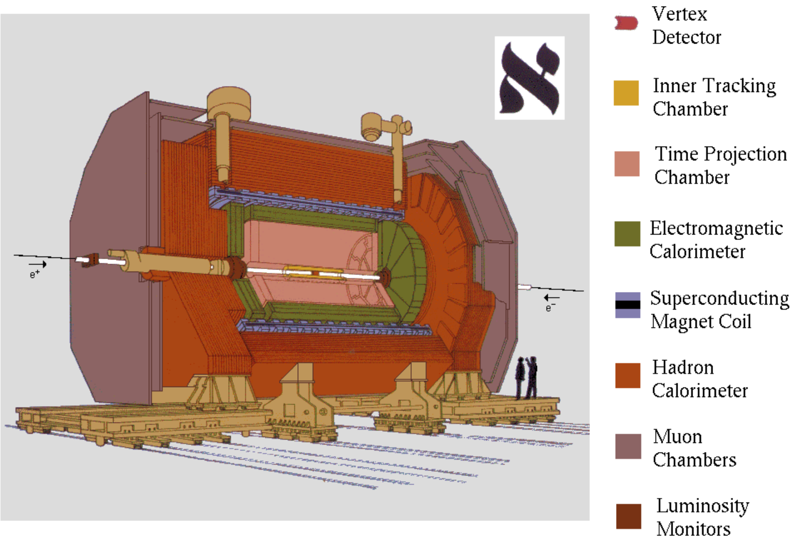
LEP and its experiments

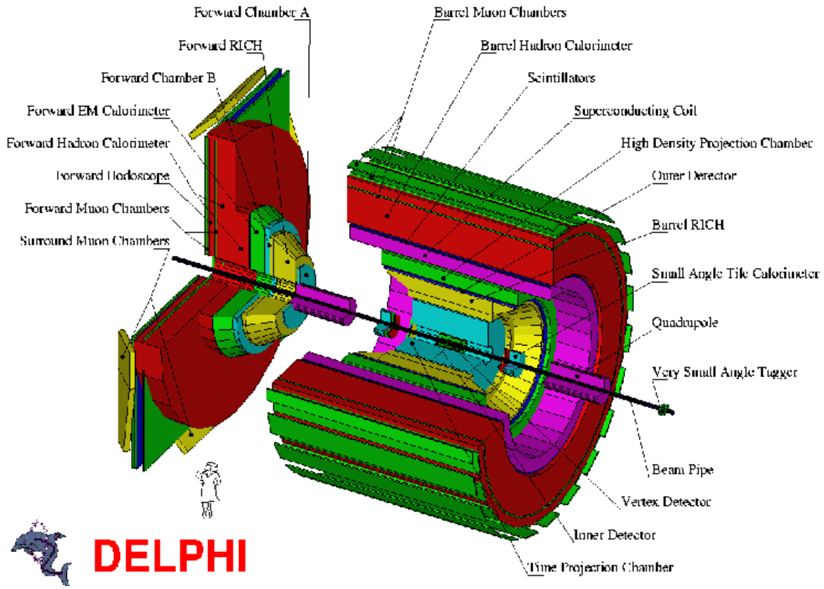


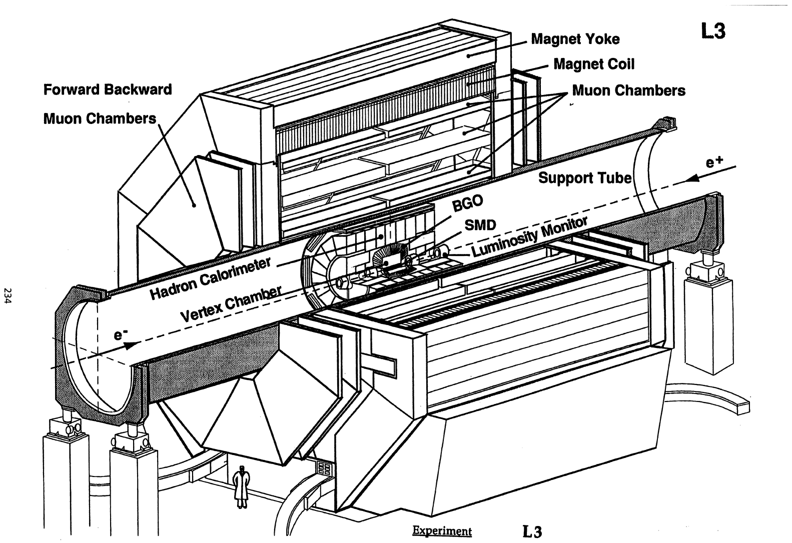
Providing e^+e^- collisions from the Z pole (~91 GeV) to 209 GeV centre-of-mass energy

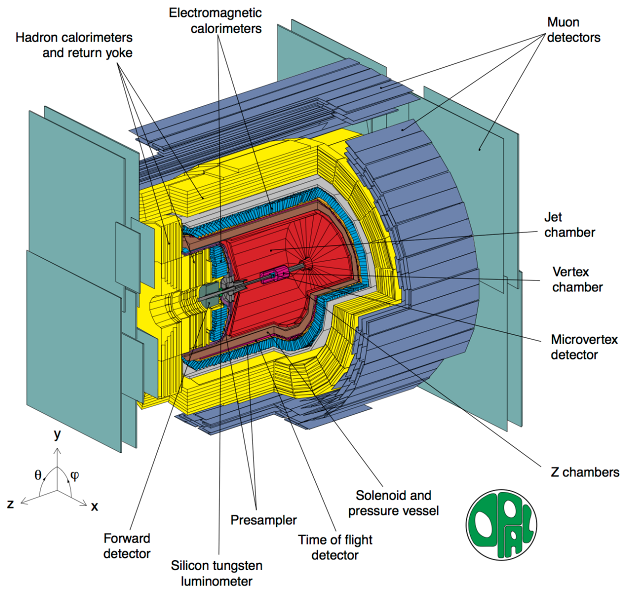
The four LEP experiments



The ALEPH Detector

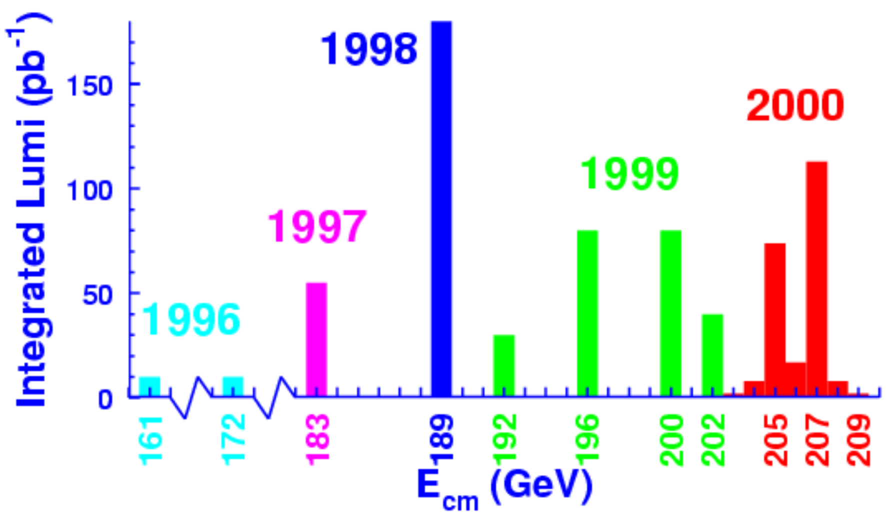


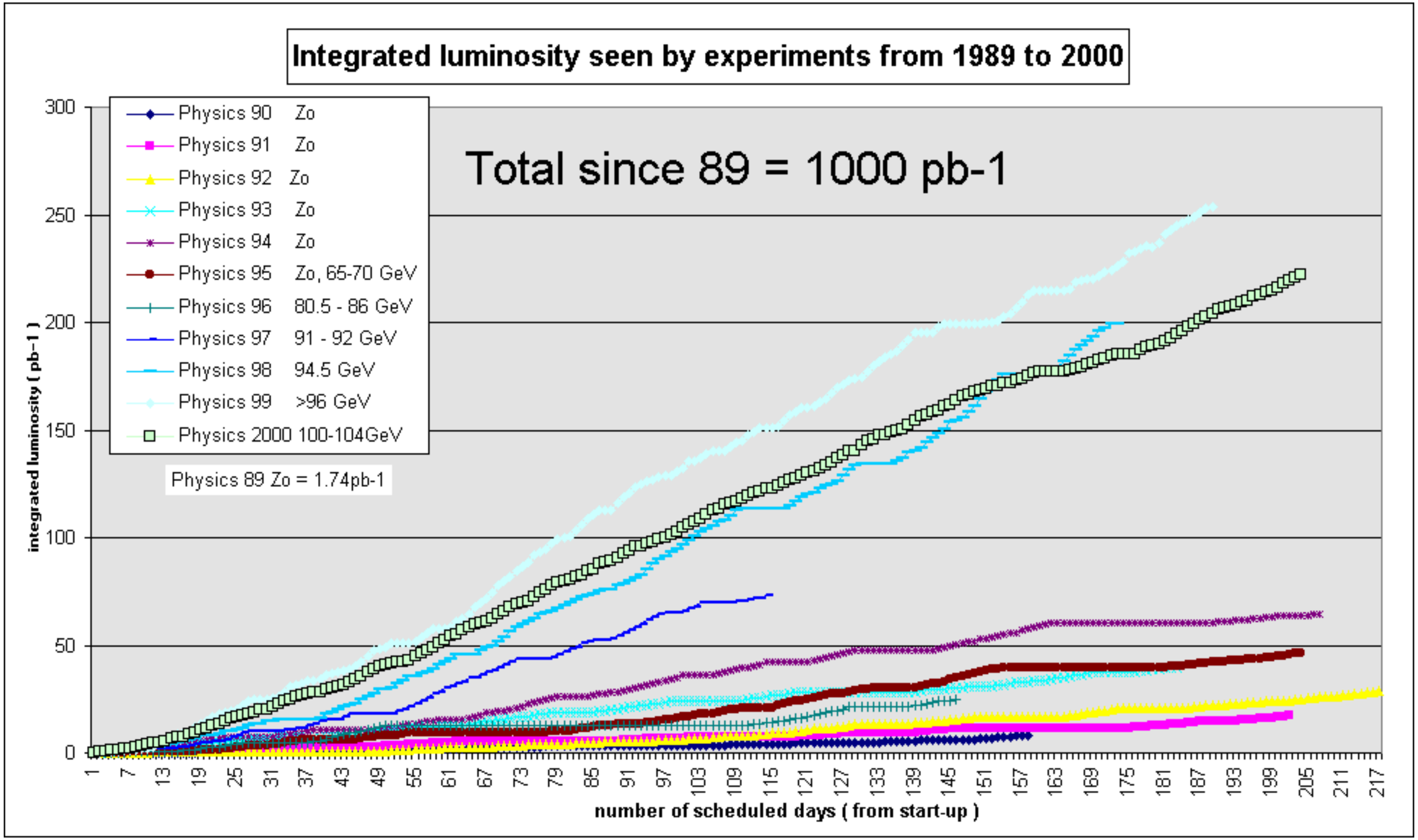




LEP Chronology

- **1980 -1989**: Detector Concepts and Construction
- **13th/14th Aug 1989**: First 15 Z recorded
- **Sept- Oct 1989** : first physics run
- **1990 - 1991** first Z pole scans
- **1992** about 20 pb^{-1} per exp at peak
- **1993** high luminosity Z scan (~ 30 pb^{-1} / exp)
- **1994** high luminosity at peak (~ 55 pb^{-1} /exp)
- **1995** high luminosity Z scan (~ 35 pb^{-1} / exp)
- **1996** 161 and 172 GeV c.o.m. energy
- **1997** 183 GeV c.o.m. energy
- **1998** 189 GeV c.o.m. energy
- **1999** 192 – 202 GeV c.o.m. energy
- **2000** reached 209 GeV
- **2001** → final publications





Integrated luminosity seen by experiments from 1989 to 2000
Total since 89 = 1000 pb-1
Physics 90 Zo
Physics 91 Zo
Physics 92 Zo
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 >96 GeV
Physics 2000 100-104GeV
Physics 89 Zo = 1.74pb-1
integrated luminosity (pb-1)
number of scheduled days (from start-up)

High Statistics years at the Z pole

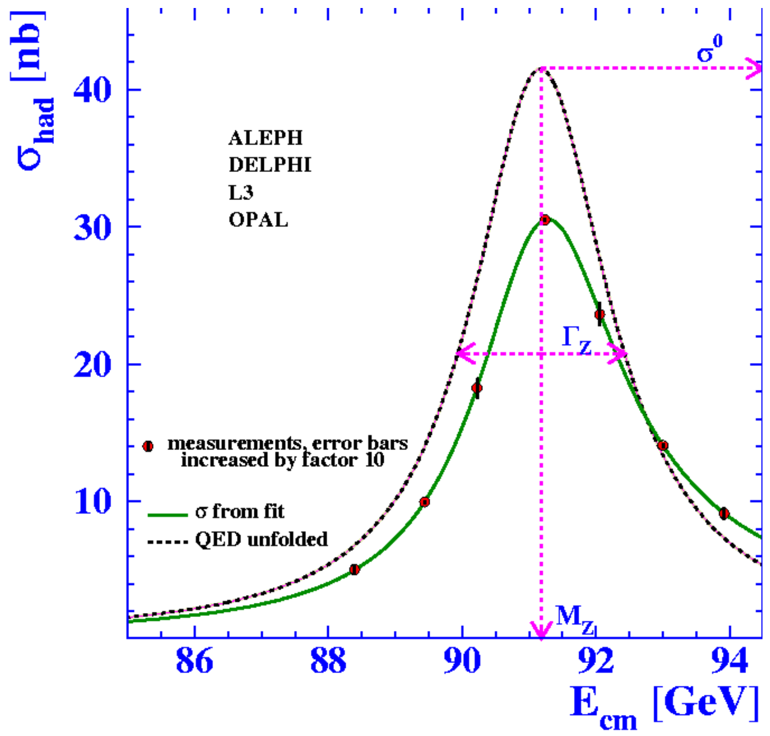
- Each of the four experiments collected about **150 pb^{-1}** (more than $1.5 \cdot 10^7$ hadronic and $1.7 \cdot 10^6$ leptonic Z decays)
- The precise knowledge of electroweak parameters at the **Z (mass, width, couplings)** it is a <u>fundamental input to thousands of physics papers</u>
- Data collected at the Z provided also many physics results and "first measurements" in other areas
  - QCD (e.g. measurement of α_s)
  - Heavy quarks (observation of time-dependent oscillations, discovery of Λ_b and B_s)
  - tau lepton physics (lifetime, couplings, BR's)
  - Higgs searches (mass below 65 GeV)
  - Physics Beyond the Standard Model (in many regions of the phase space limits are still from LEP)

The Z mass and lineshape

Final results of 4 LEP collaborations published in 2000 – 2001 (*)

The Z mass is known with a precision of 2 10^{-5}

Main error common uncertainty of +/- 1.5 MeV on the beam energy

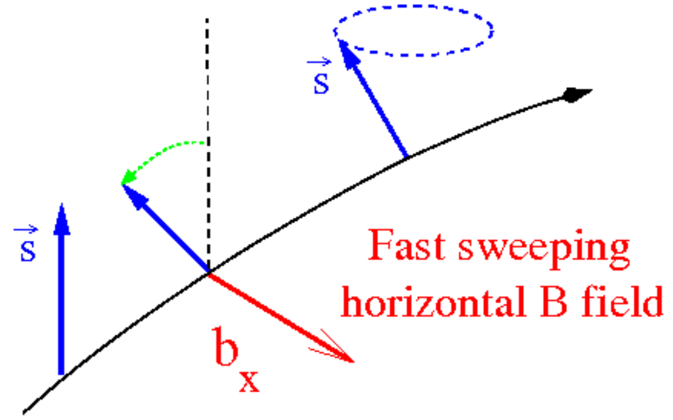


$$Mz = 91.1675 \pm 0.0021 \ \ GeV$$
$$\Gamma z = 2.4952 \pm 0.0023 \ \ GeV$$

(*) Combinations in Physics Report 427 (2006) 257

The key :E_{beam} calibration with resonant depolarization

• Vertical Polarization built up from synchrotron radiation
(Sokolov and Ternov, 1964)
• Thomas spin precession



(B vertical field)

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{e}{\gamma m}(1 + a\gamma)\vec{B}$$

Additional oscillating and resonant B' radial field with ν_0 spin tune has a depolarizing effect

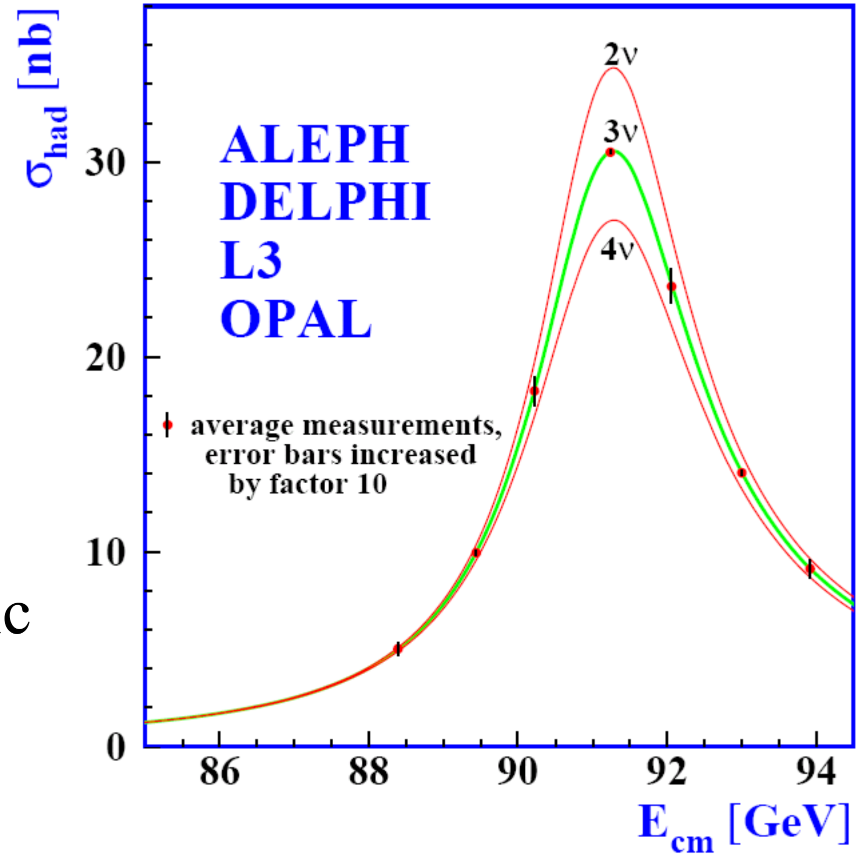
$$\nu_0 = a_e\gamma = \frac{a_e E}{m_e c^2} = \frac{E_{beam}}{440.6486(1)[MeV]}$$

(Works only up to 60 GeV beam energy … for W mass need extrapolation …..)

Number of light neutrinos and more

• From the lineshape fit, mostly from the hadronic peak cross section one gets

$$\boxed{N_\nu = 2.984 \pm 0.008}$$



• From the lineshape fit, mostly from the ratio of hadronic to leptonic Z decays

$$\boxed{\alpha_s\left(m^2{}_Z\right) = 0.1190 \pm 0.0027}$$

• From the comparison of the leptonic widths (e, μ, τ) one gets a test of lepton universality at the permil level

Z couplings and the electroweak mixing angle

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f$$

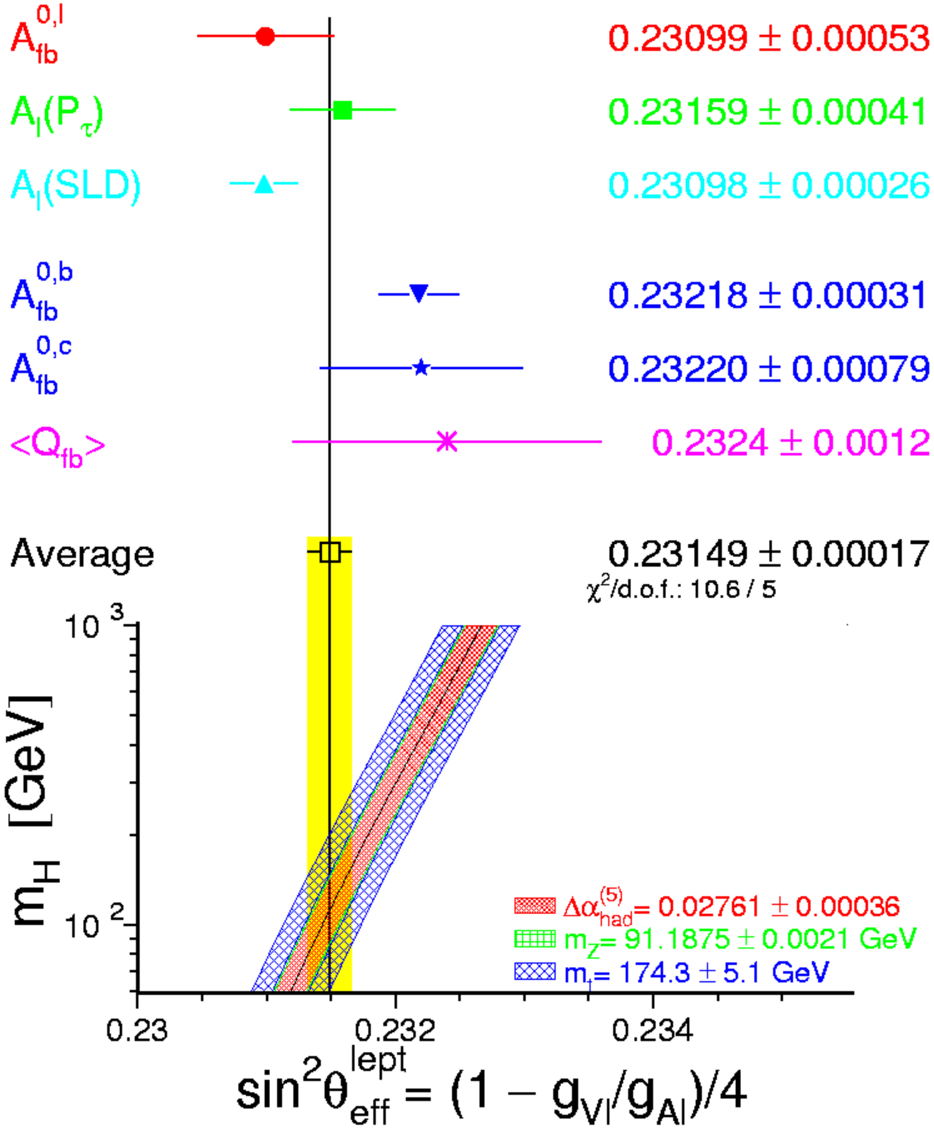
$$A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e$$

$$A_f = \frac{2 g_{Vf} g_{Af}}{(g_{Vf})^2 + (g_{Af})^2}$$

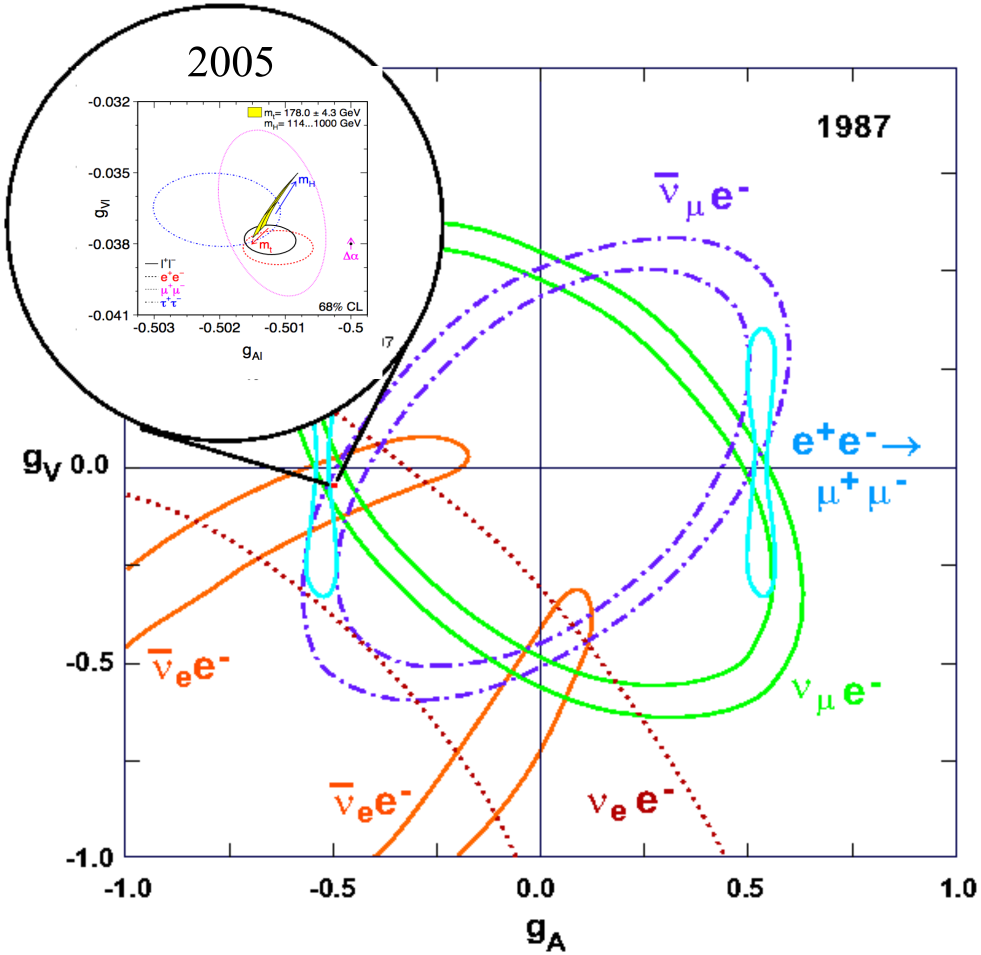
$$\sin^2 \theta_{eff}^{\,l} \equiv \frac{1}{4}\left(1 - \frac{g_{Vl}}{g_{Al}}\right)$$

- Obtained 10^{-4} precision, but consistency between A_{LR} (from SLC) and $A_{FB}(b)$ at 3 σ level

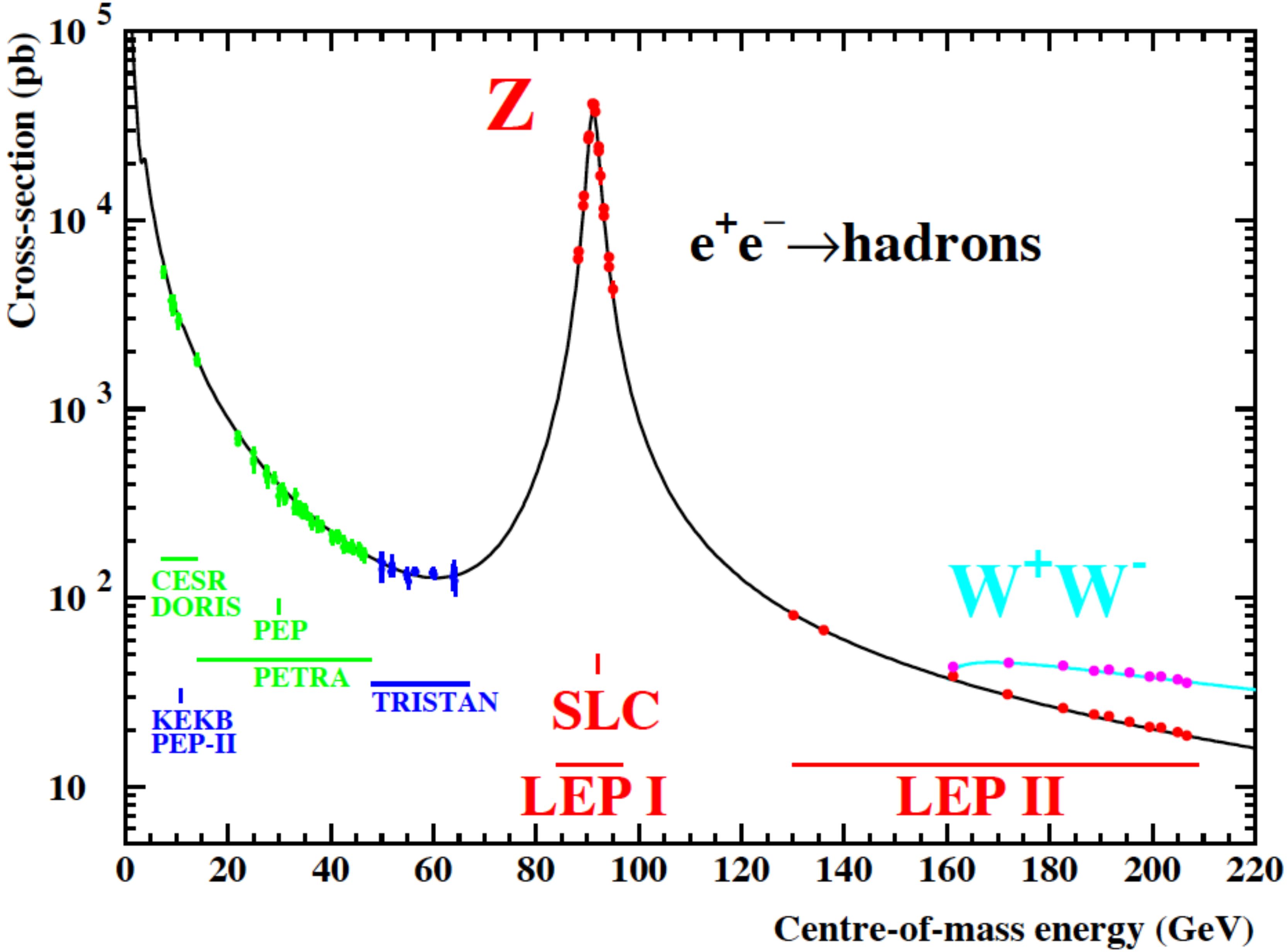
$\sin^2 \theta_{eff}^{\,l}$



Leptonic couplings before and after LEP-SLC

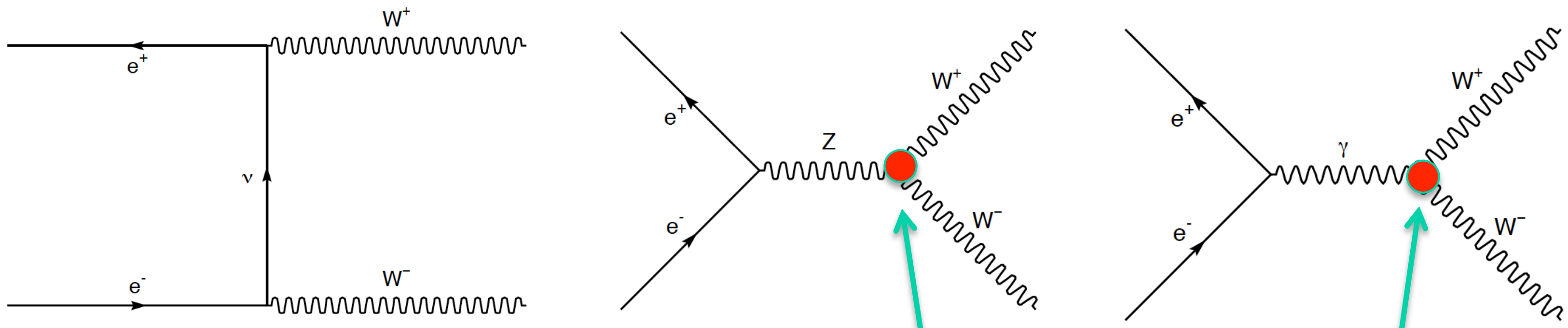


Moving to LEP 2 →



WW Production at LEP2

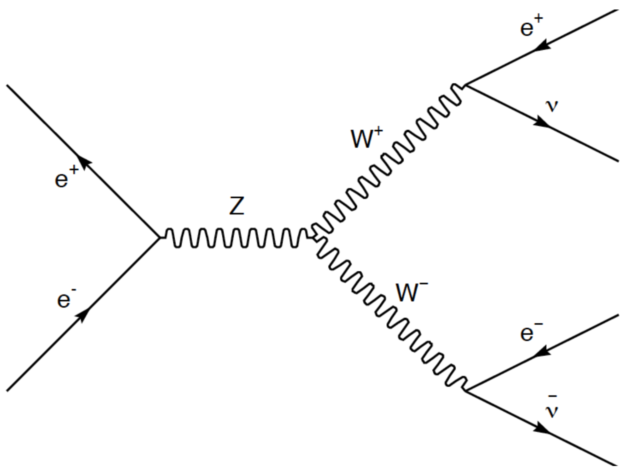
Three diagrams contribute at Born level (CC03 diagrams) :

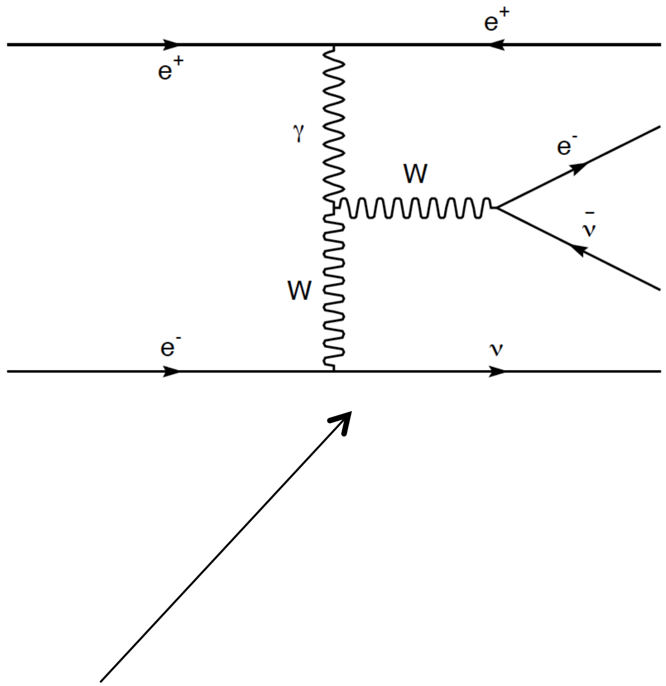


Dominant diagram at production threshold, alone it gives a cross section which violates unitarity

Triple Gauge Couplings

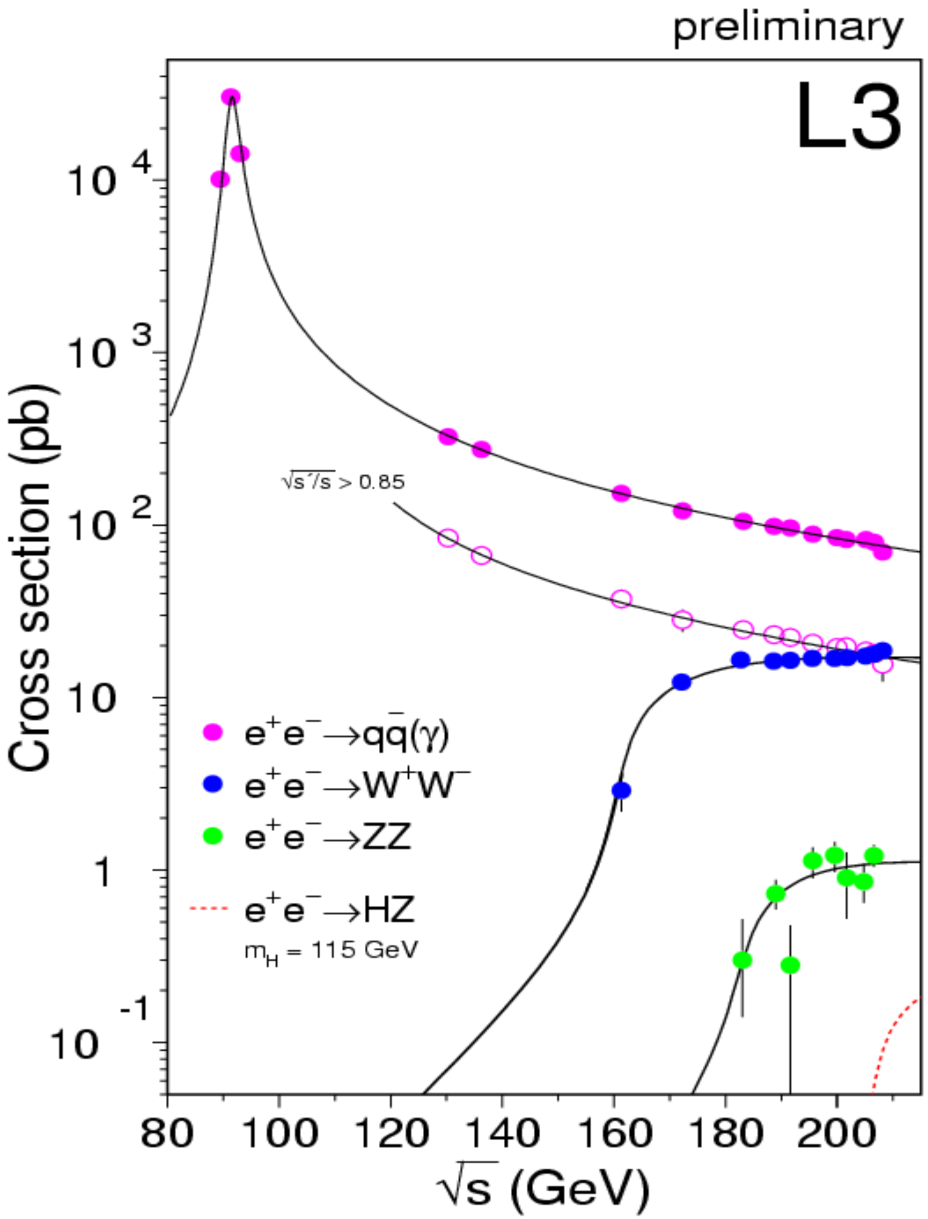
Four Fermion final states and interference





Example of another 4-fermion diagram which interferes with the signal

LEP2: 4 fermion vs 2 fermion final states



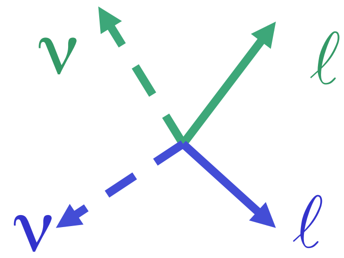
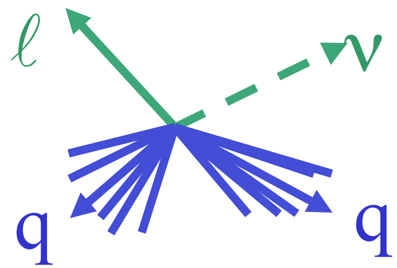
2 fermion production at LEP II was much higher than 4 fermion (WW or ZZ) however it was mostly due to Z radiative returns

$$\boxed{e^+e^- \to Z\gamma}$$

where a γ of fixed energy was emitted

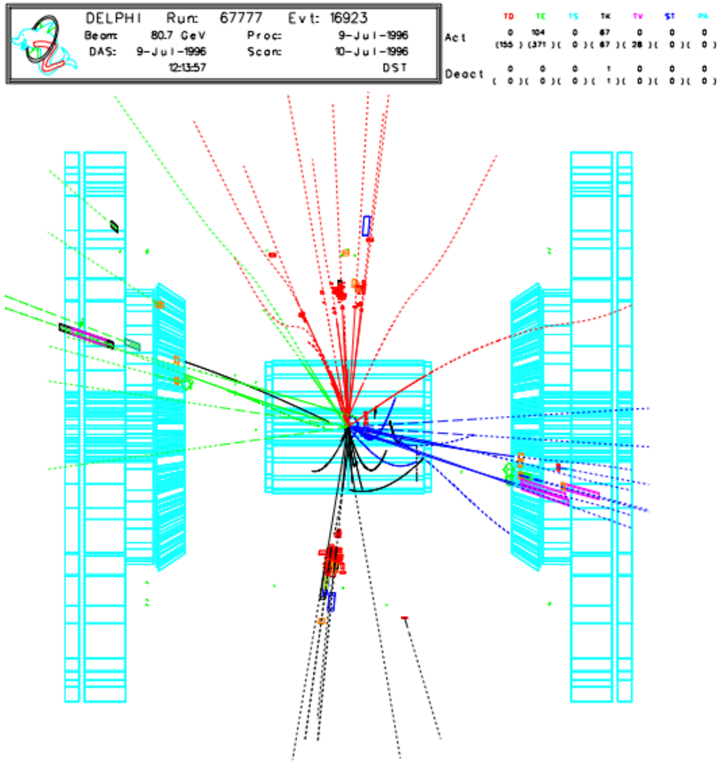
$$\boxed{E_\gamma = \frac{s - M_Z^2}{2\sqrt{s}}}$$

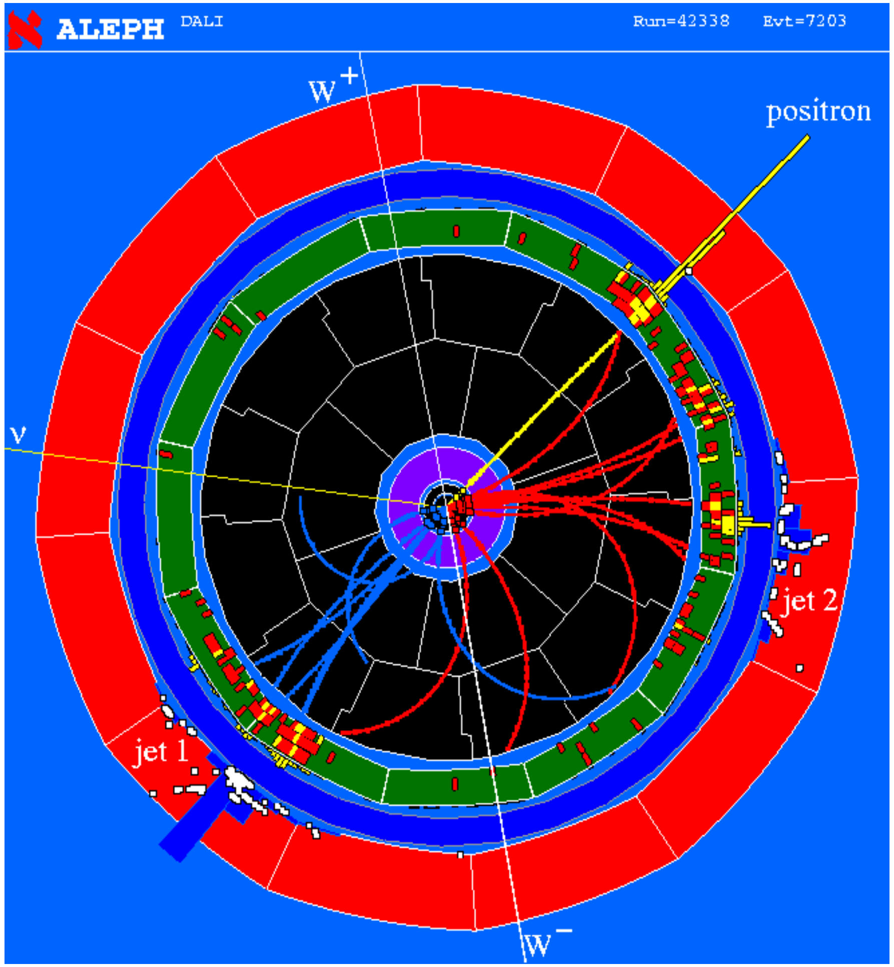
WW Event selection

	Leptonic 	*Semileptonic (qqlν)* 	*Hadronic (4q)* 
BR	11%	44%	45%
Signatures	- 2 energetic, aco-planar leptons - large missing E, p	- 2 hadronic jets - missing E & p - isolated lepton	- 4 hadronic jets - low missing E, p
Backgrounds	ZZ, Zee, Z^{γ}	We^{ν}, qq(γ)	qq(γ)
Efficiency	~50%	~70%	~85%
Purity	~90%	~94-99%	~85%

Selection of W pairs

- 161 – 209 GeV centre of mass energy
- ~600 pb^{-1} by each experiments
- ~4500 qqqq , ~4000 lνqq events for each exp's.



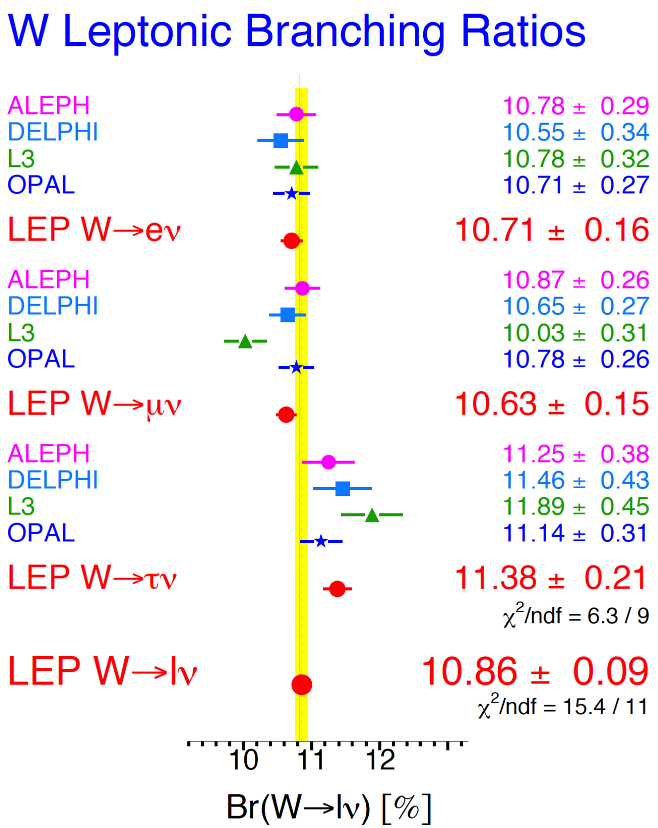


Hadronic event

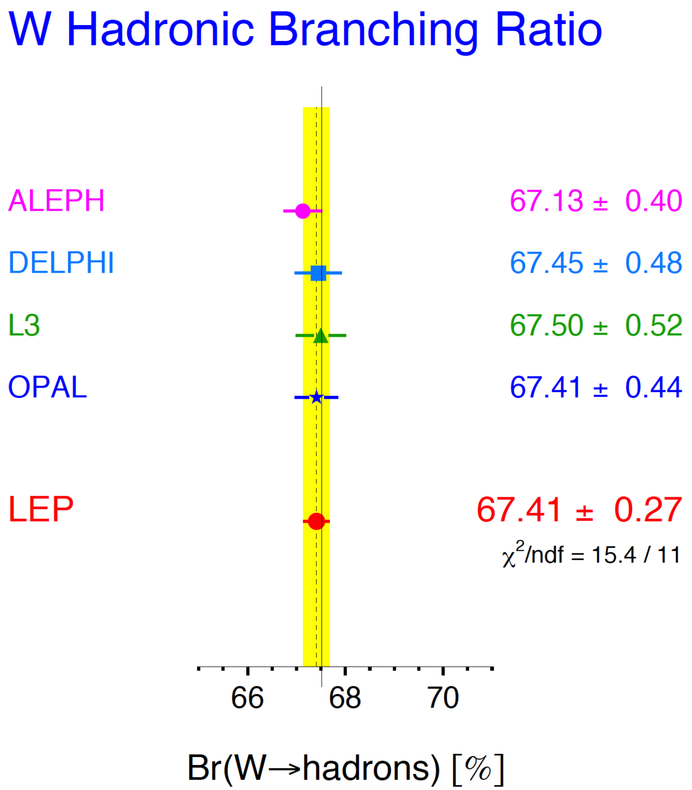
Semileptonic event

W decays : Branching Ratios

Standard Model : 10.8%



Standard Model : 67.5%



Test of lepton universality: tension with taus (2.8 σ)

BR_{had} can be related to CKM elements

$$\frac{B_h}{1-B_h} = \sum_{i=u,c\ j=d,s,b,} |V_{i,j}|^2 \left(1+\frac{\alpha_s}{\pi}\right) \qquad \boxed{|V_{CS}| = 0.969 \pm 0.013}$$

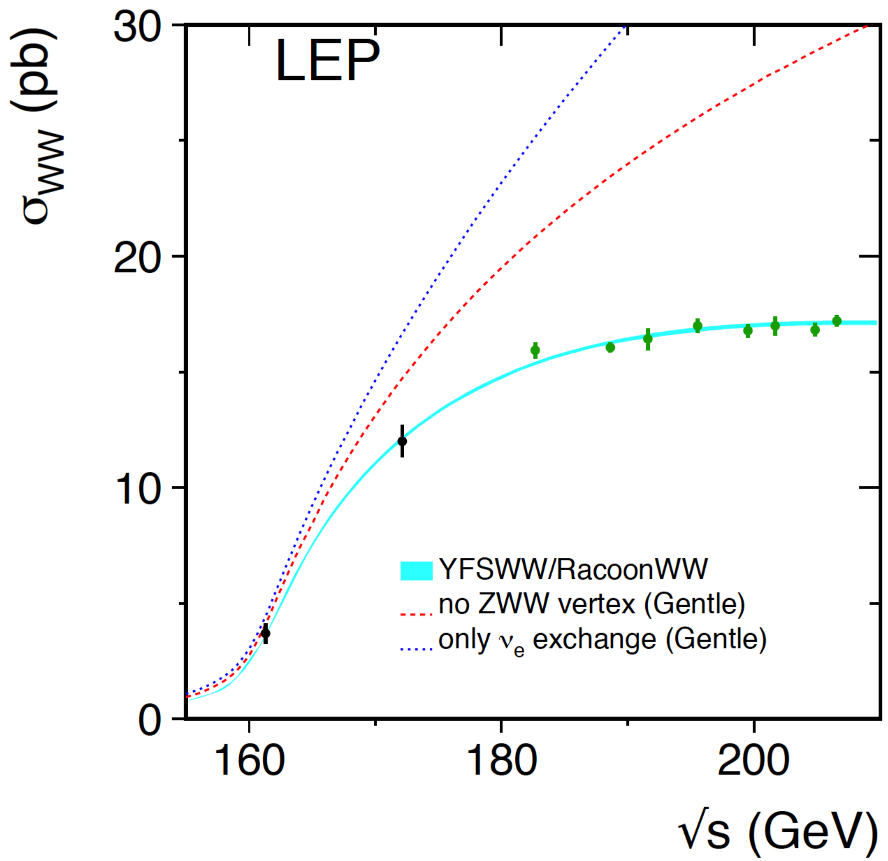
Total WW Cross Section

Strong evidence of Triple Gauge Couplings

- Precision reached by LEP experiments a challenge to theoretical predictions
  - Predictions with non-leading O(α) radiative corrections were needed !

$$R_{\text{with } O(\alpha)} = \frac{\sigma(\text{LEP})}{\sigma(\text{Theory : YFSWW})} = 99.32 \pm 0.89$$

$$R_{\text{without } O(\alpha)} = \frac{\sigma(\text{LEP})}{\sigma(\text{Theory : KORALW})} = 97.42 \pm 0.87$$



Probing Triple Gauge Couplings

- Triple gauge boson vertices (WWγ , WWZ) : probing the non-Abelian structure of the Standard Model. Search for anomalous couplings.
- The most general Lorentz invariant Lagrangian involves 14 couplings (7 for WWγ and 7 for WWZ)
- Assuming electromagnetic gauge invariance, C and P conservation, leaves 5 parameters

$$\left\{ g_1^z, \kappa_Z, \kappa_\gamma, \lambda_Z, \lambda_\gamma \right\}$$

W anomalous magnetic moment $\quad \mu_W = \frac{e}{2m_W}(1 + k_\gamma + \lambda_\lambda)$

W anomalous electric quadrupole moment $\quad Q_w = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$

Triple Gauge Couplings

Precise LEP1 measurements motivated SU(2)xU(1) constraints

TGC contributes via loops

$$\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_Z^1$$

$$\lambda_Z = \lambda_\gamma$$

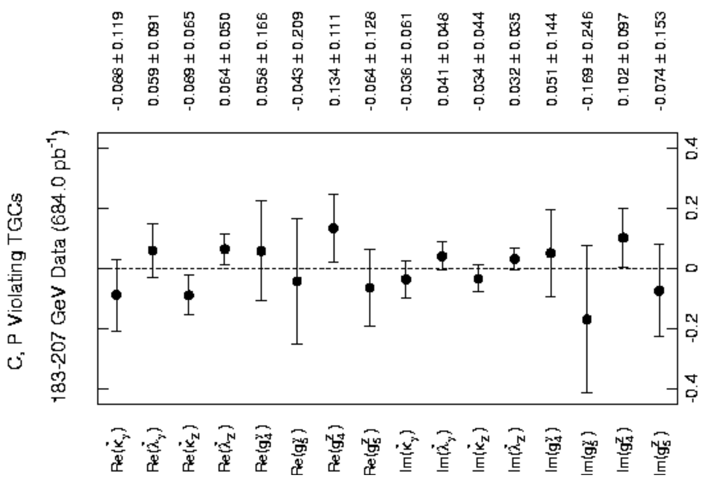
Δ is deviation from SM

Within Standard Model

Typical analyses (and LEP combinations) in terms of three couplings.

$$\left\{\Delta g_Z^1, \Delta\kappa_\gamma, \lambda_\gamma\right\} \equiv \left\{0,0,0\right\}$$

However more general constraints of C, P and CP violating couplings were published: all 14 couplings were probed !!



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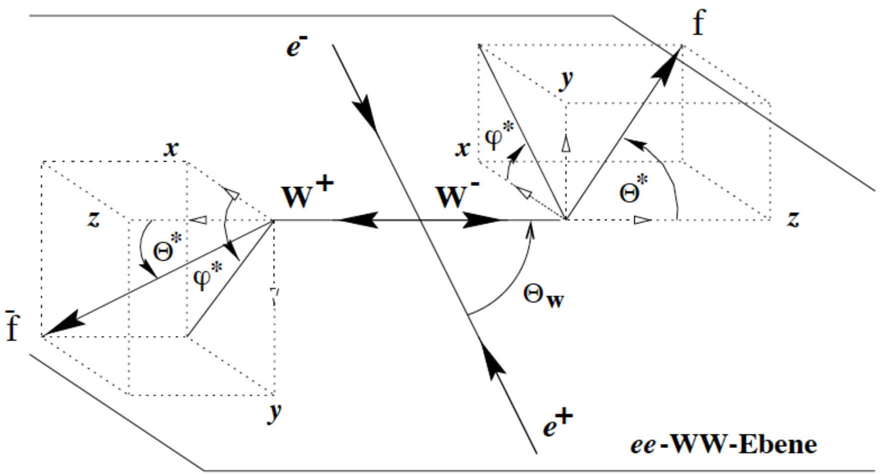
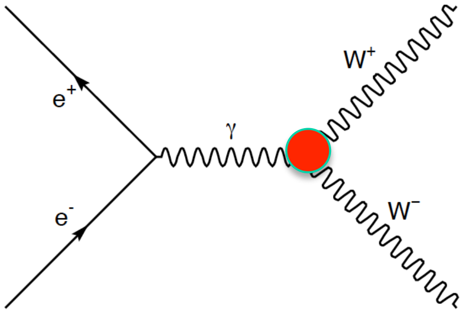
Triple Gauge Couplings at LEP

- Anomalous couplings affect W helicity states
- Modify total cross section and angular distribution
- Ignoring width and ISR production and decay of W's described by 5 angles



Physics processes: WW and single W

- $e^+e^- \to W^+W^-$ (CC03)

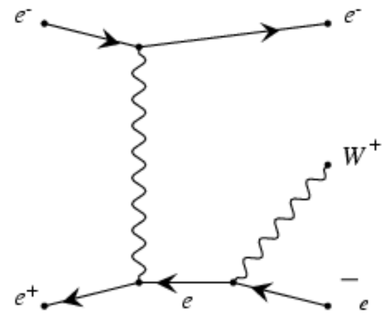


188.6 GeV

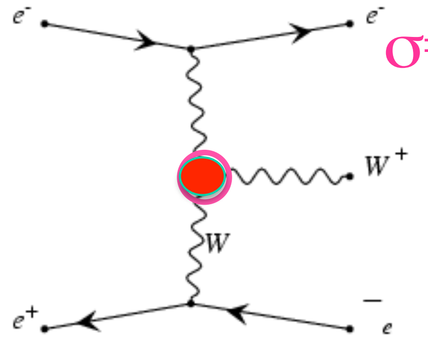
σ=15.98±0.23 pb

g_1^Z, κ_γ and λ_γ

- $e^+e^- \to We\nu_e$



188.6 GeV



σ=0.60±0.09 pb

κ_γ and λ_γ

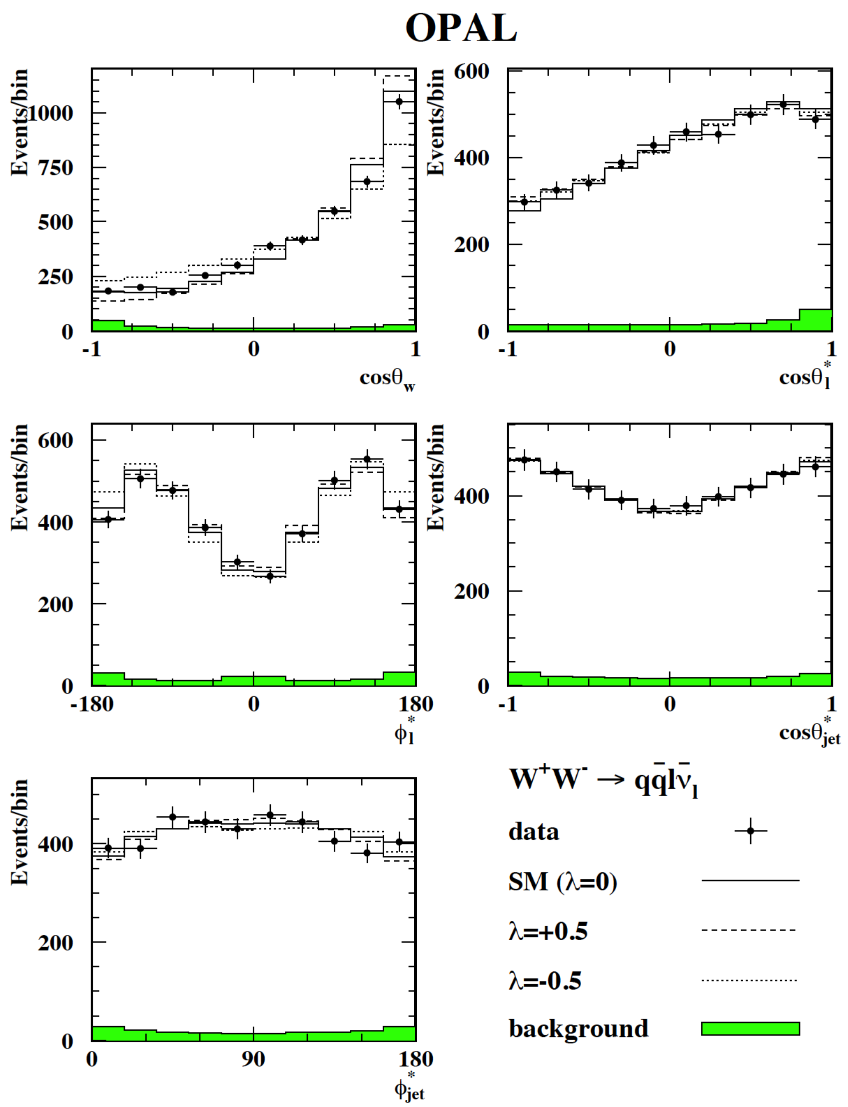
- $e^+e^- \to \gamma\nu_e\bar{\nu}_e$

$e^+e^- \to W^+W^-$

Kinematic :

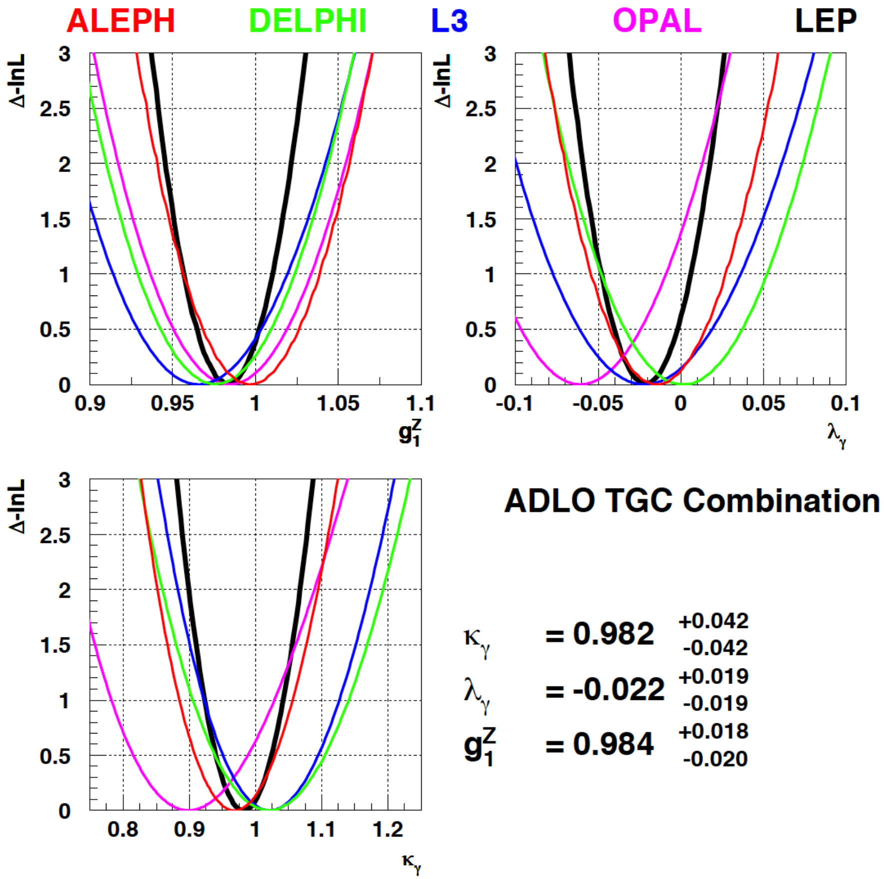
the 5 angles

- most of the information in θ_W
- no flavour tagging
- W charge tagging in $W^+W^- \to qqqq$ channel



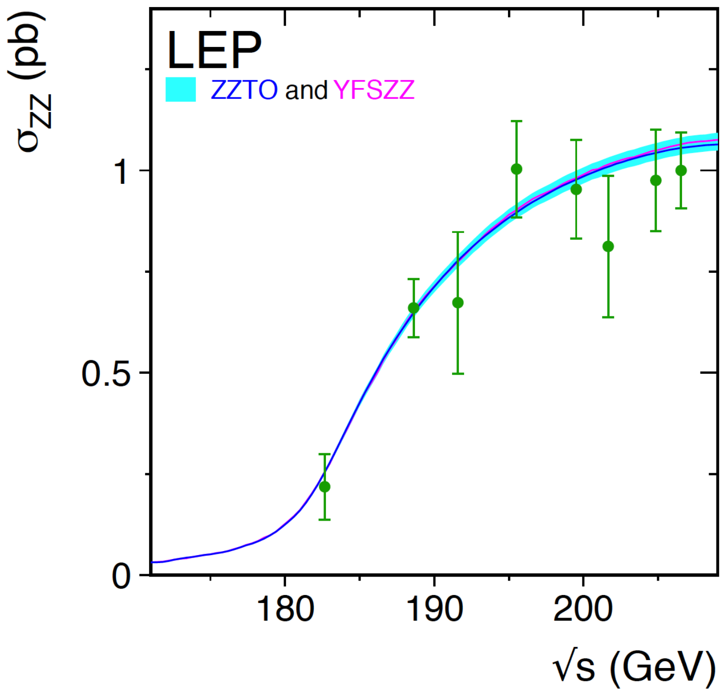
TGC results

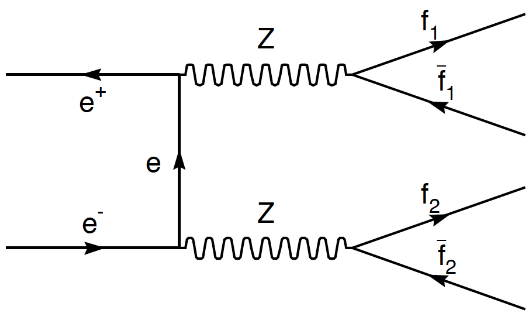
- 1-parameter fit, The other two couplings are set to their SM value
- 2- and 3- parameter fits were also published

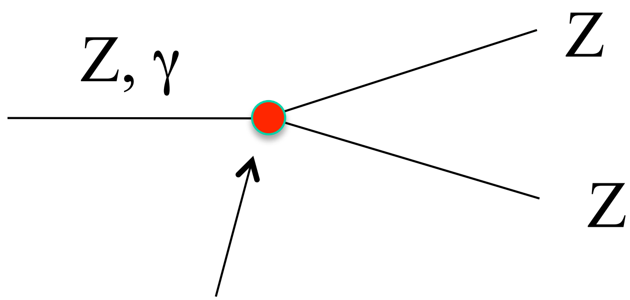


- ➢ Existence of triple gauge couplings was proven.
- ➢ Compatible with the Standard Model expectations.
- ➢ Sensitive to radiative corrections ($\approx 10^{-2}$)

The ZZ production cross section



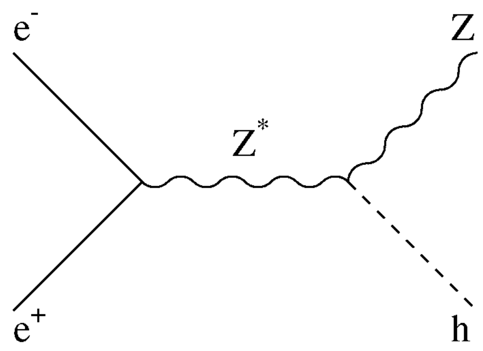




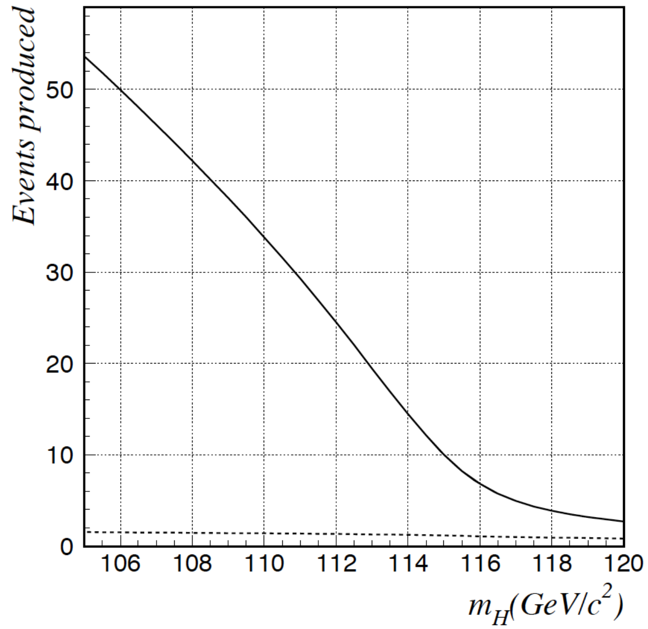
Forbidden in the SM at tree level, set limits to anomalous neutral vector boson couplings

Search for ZH production at LEP
(in a nutshell ...)

- Before LEP only a tiny m_H region was excluded in a model independent way ($m_e<m_H<52$ MeV), even the case $m_H=0$ had to be investigated at LEP
- The region $m_H<65.6$ GeV was excluded at LEP1 investigating several topologies (with virtual Z in the final state)
- At LEP2 the expected Higgs production mechanism was Higgs-strahlung (with a small contribution from VV fusion) and the Higgs was searched in the bb and ττ final states



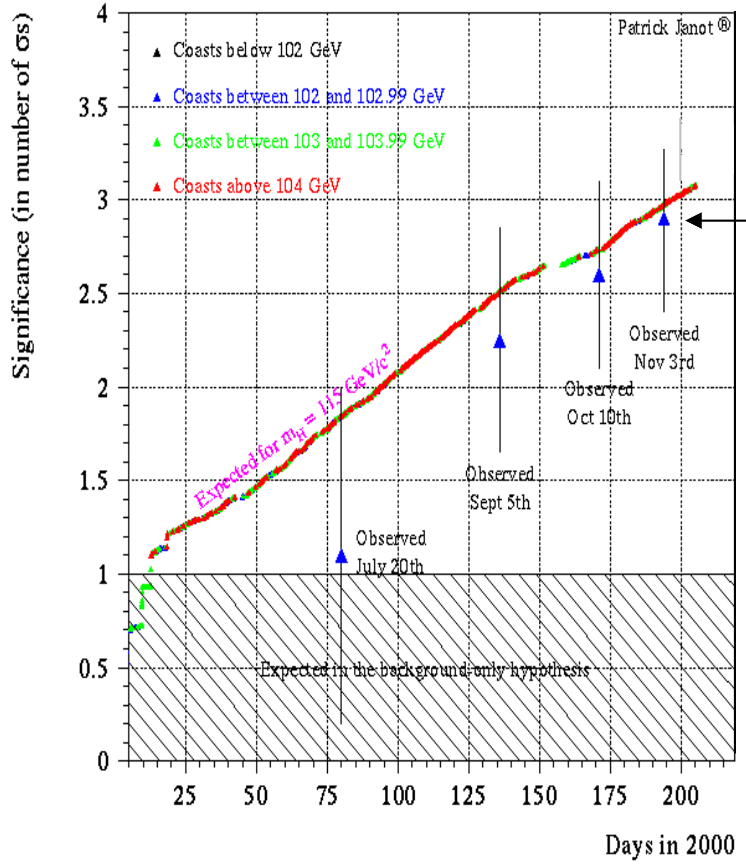
expected events produced at 206 GeV and with 200 pb^{-1}



Exciting hunting ... and now we know the beast was not hidden there, but closeby ...

- Year 2000 has been a very exciting ... a few interesting high-purity events showed up
- picture consistent with 115 GeV Higgs boson ...
- The run was extended by a few weeks, then LEP was closed
- Final LEP result **m_H>114.4 GeV**

Significance for m_H =115 GeV



Nov. 3rd

LEPC: 2.9 σ

in the final comb. (2003)

1.7 σ

W Mass from direct reconstruction in WW events

• The WW threshold position is very sensitive to the W mass value, however we did not have enough statistics for a precise measurements, LEP combination gives

$$m_W = 80.42 \pm 0.20 \pm 0.03(E_{LEP})\ \text{GeV}$$

•Above threshold the W mass was measured from direct reconstruction of the jet-jet invariant mass in the fully hadronic and semileptonic channels

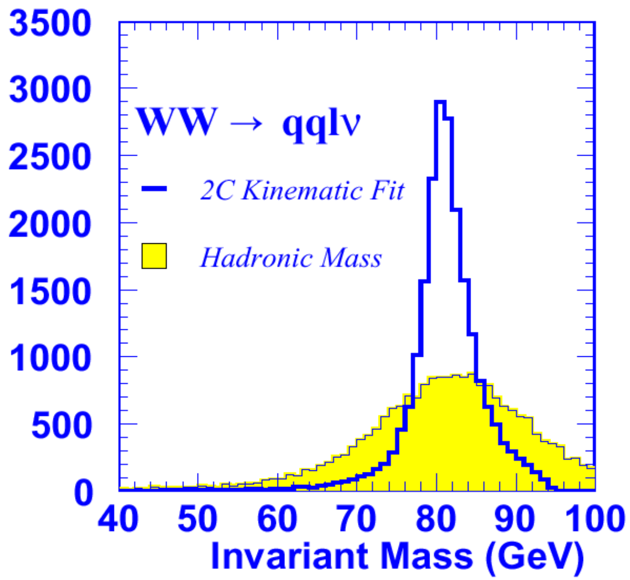
• Event reconstructed as 2 (semileptonic candidate) or 4 (hadronic candidate) jets with iterative procedure

• In the hadronic channel 3 jet-jet combinations from 4 jet

• Kinematic fit used to improve the reconstructed four momenta, need to know the beam energy

Systematics:

LEP2 Energy



- Kinematic fit imposing energy-momentum conservation ⇒

$$\frac{\delta M_W}{M_W} \approx \frac{\delta E_{Beam}}{E_{Beam}}$$

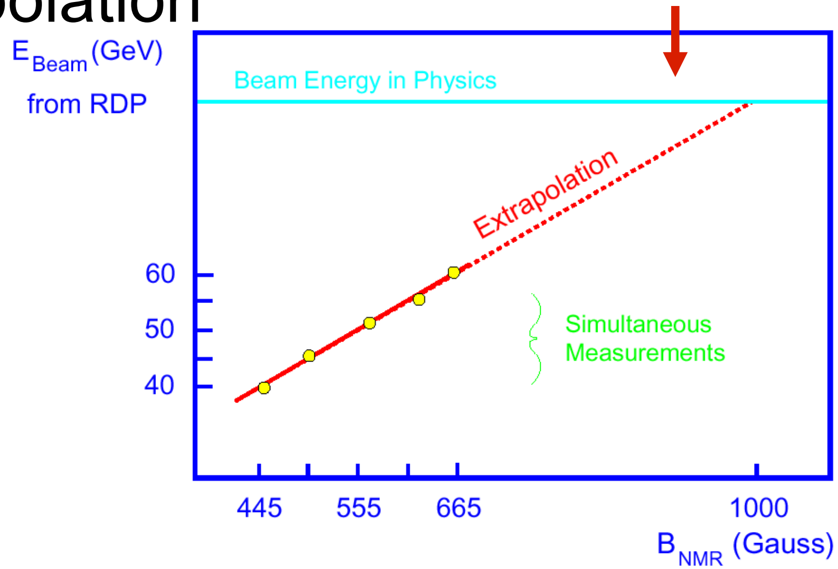
Resonant depolarization:

– only works up to 60GeV ⇒ extrapolation

- At LEP2:
  – $\delta E_{beam} \sim 20$MeV ($\delta E/E \sim 10^{-4}$) ⇒

$\delta m_W \sim 17$MeV

  – Error coming mainly from extrapolation.



Systematics:

LEP Energy

- three independent methods used to cross-check extrapolation:

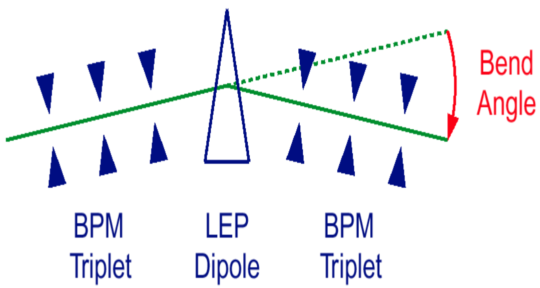
Energy loss

Based on the frequency of the field provided to beam to compensate from syncroton radiation.

$$Q_s^2 = \left(\frac{\alpha_c h}{2\pi E}\right)\sqrt{e^2 V_{RF}^2 - U_0^2}$$

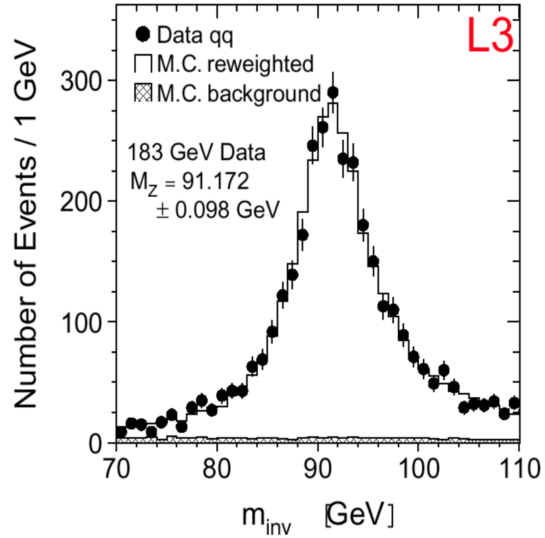
E loss by sync.

Spectrometer

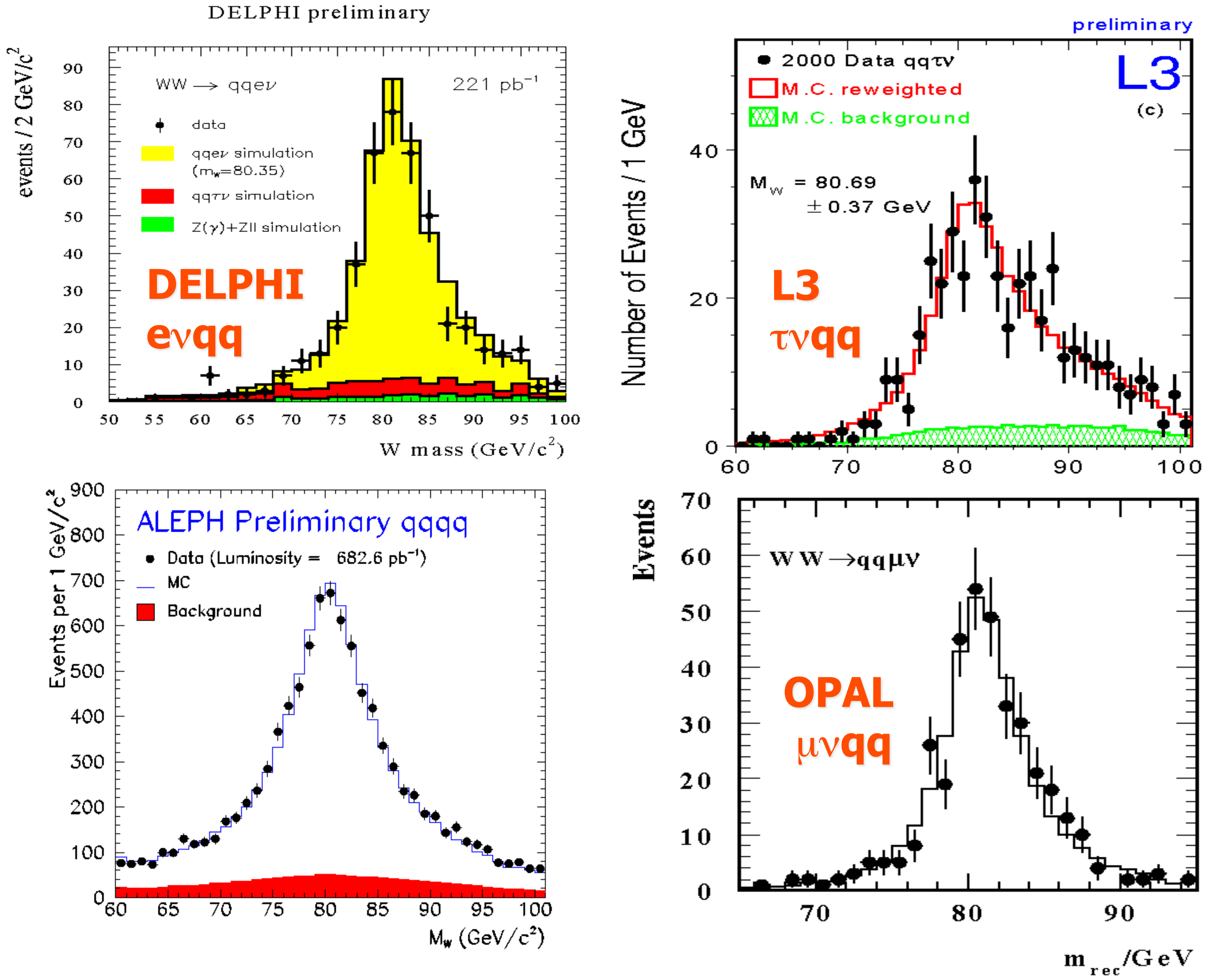


Based on measurement of lepton bending angle

Radiative return



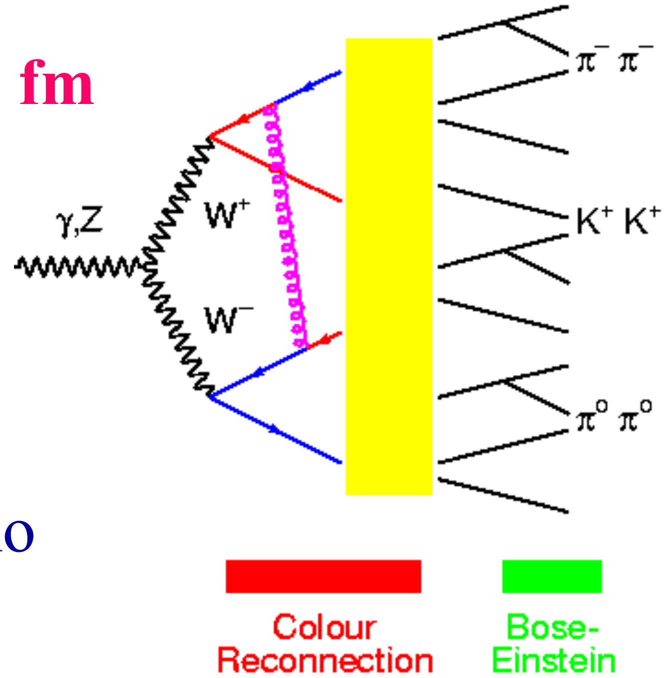
Reconstructed M_W



Final State Interactions (4q channel)

Separation of W decays vertex at LEP2 ~0.1 fm
$\Rightarrow$ small with respect
to the hadronization scale ~1fm

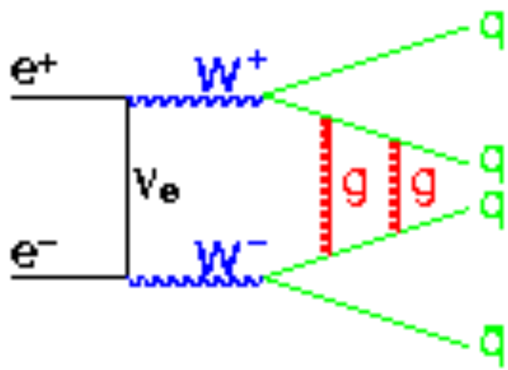
$(\Gamma_W \approx 10\Lambda_{QCD})$



Interconnection phenomena : Final State is no longer factorized into two separated W's

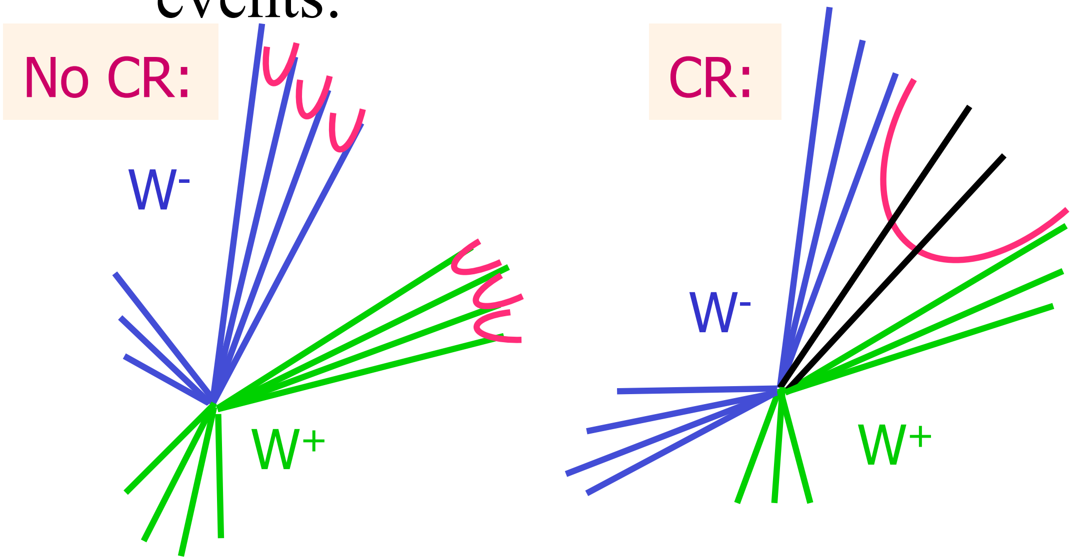
$\Rightarrow$ can bias the W mass in the fully hadronic channel

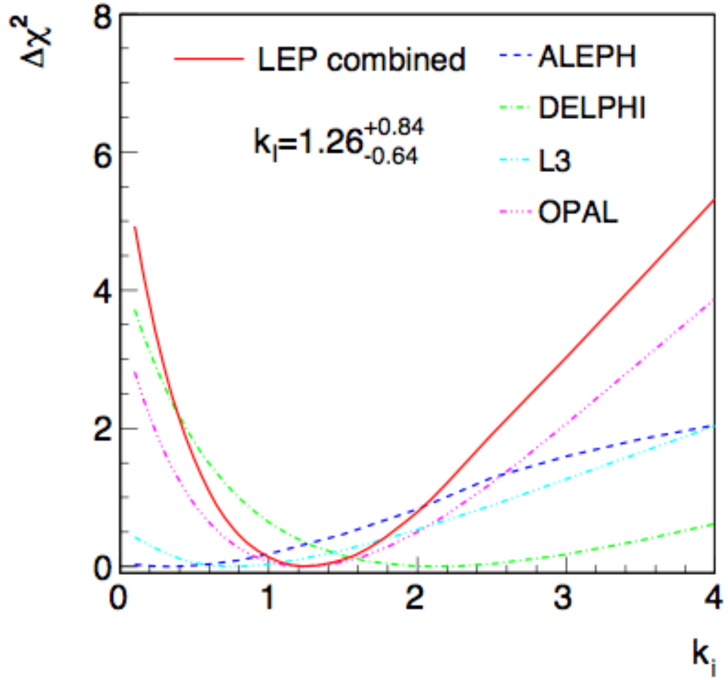
- **Colour Reconnection**
- **Bose-Einstein correlations**



Setting constraints to Colour Reconnection

1. Most CR models predict a modified particle flow in W^+W^- events:

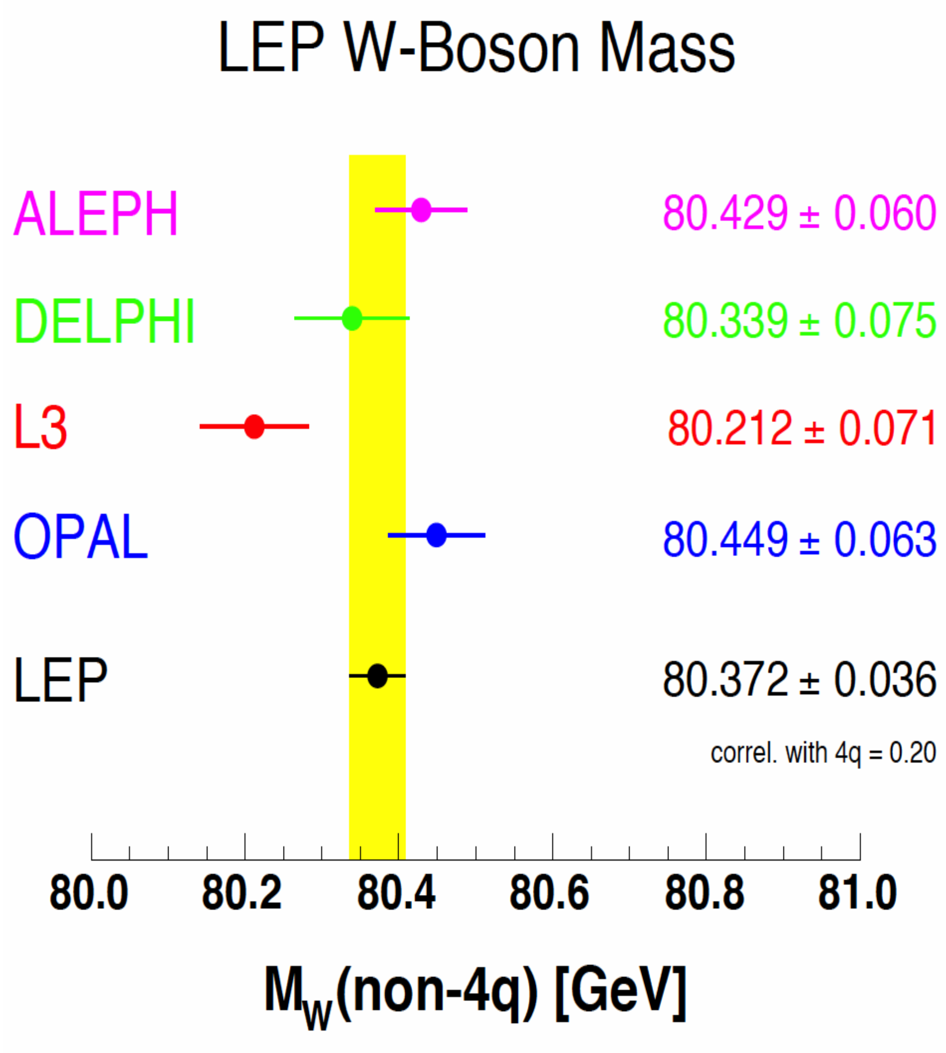


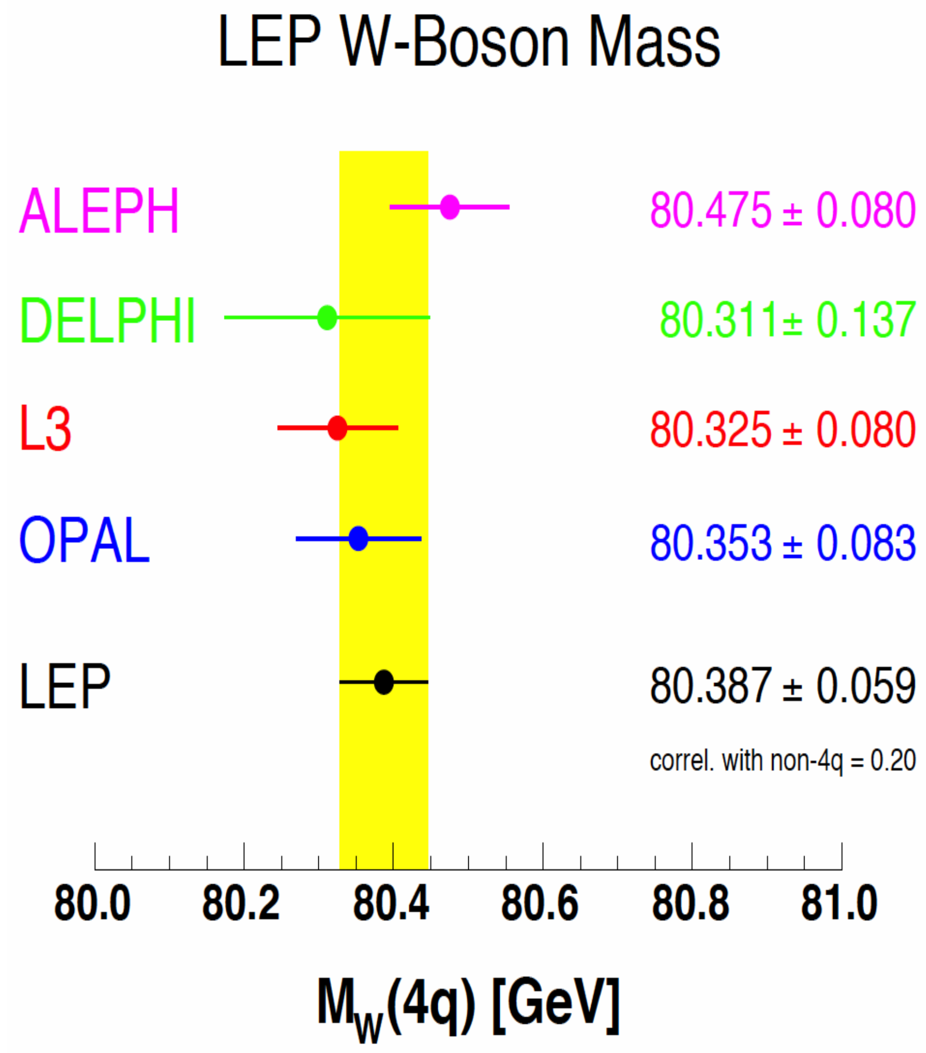


Example of limits set on parameter (k_i) of a particular model

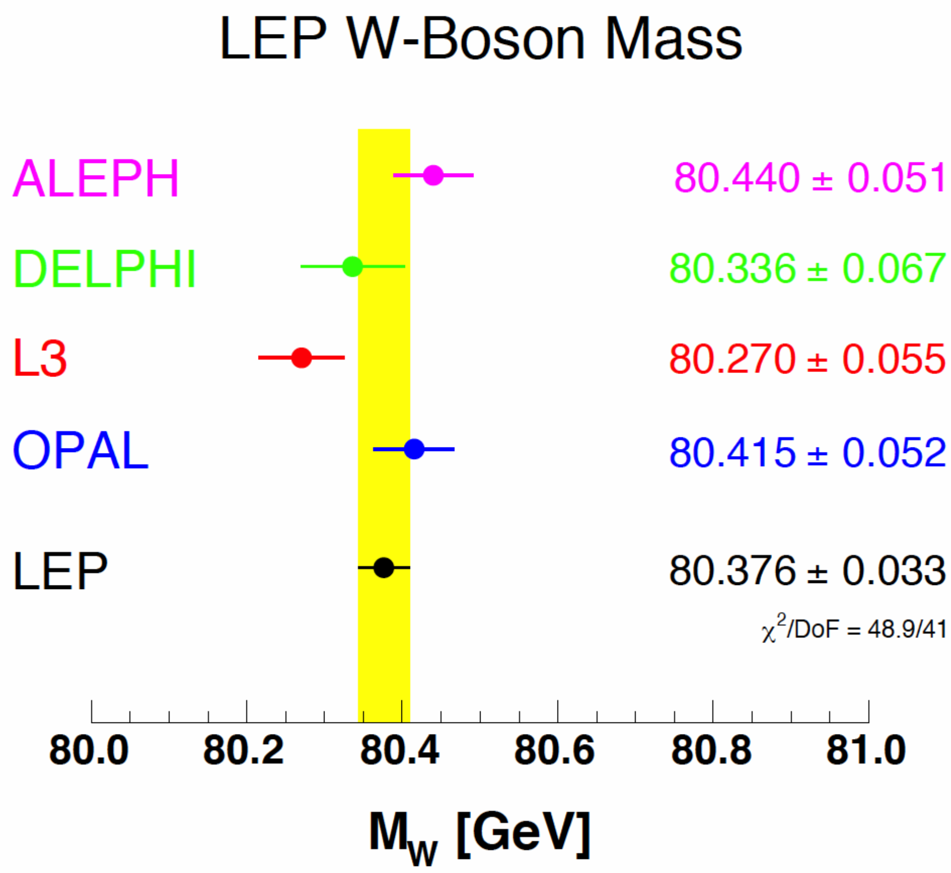
2. Studied W mass variation as a function of softness of particles used for jet reconstruction

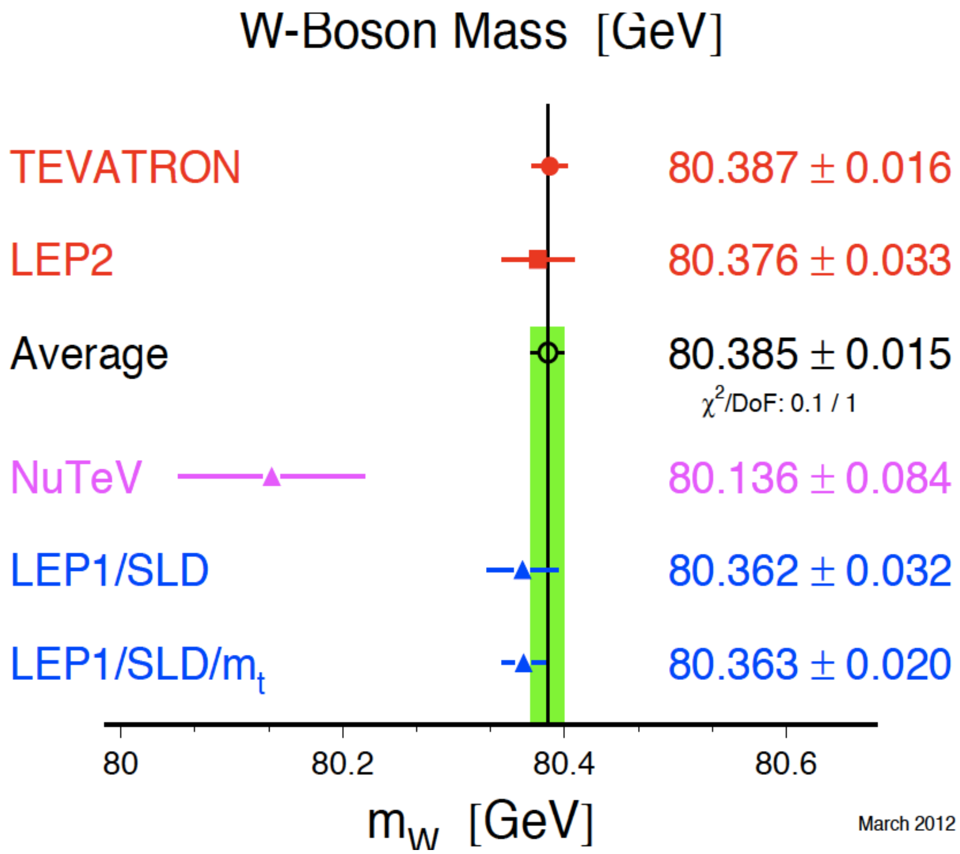
M_W at LEP : 4q and lνqq



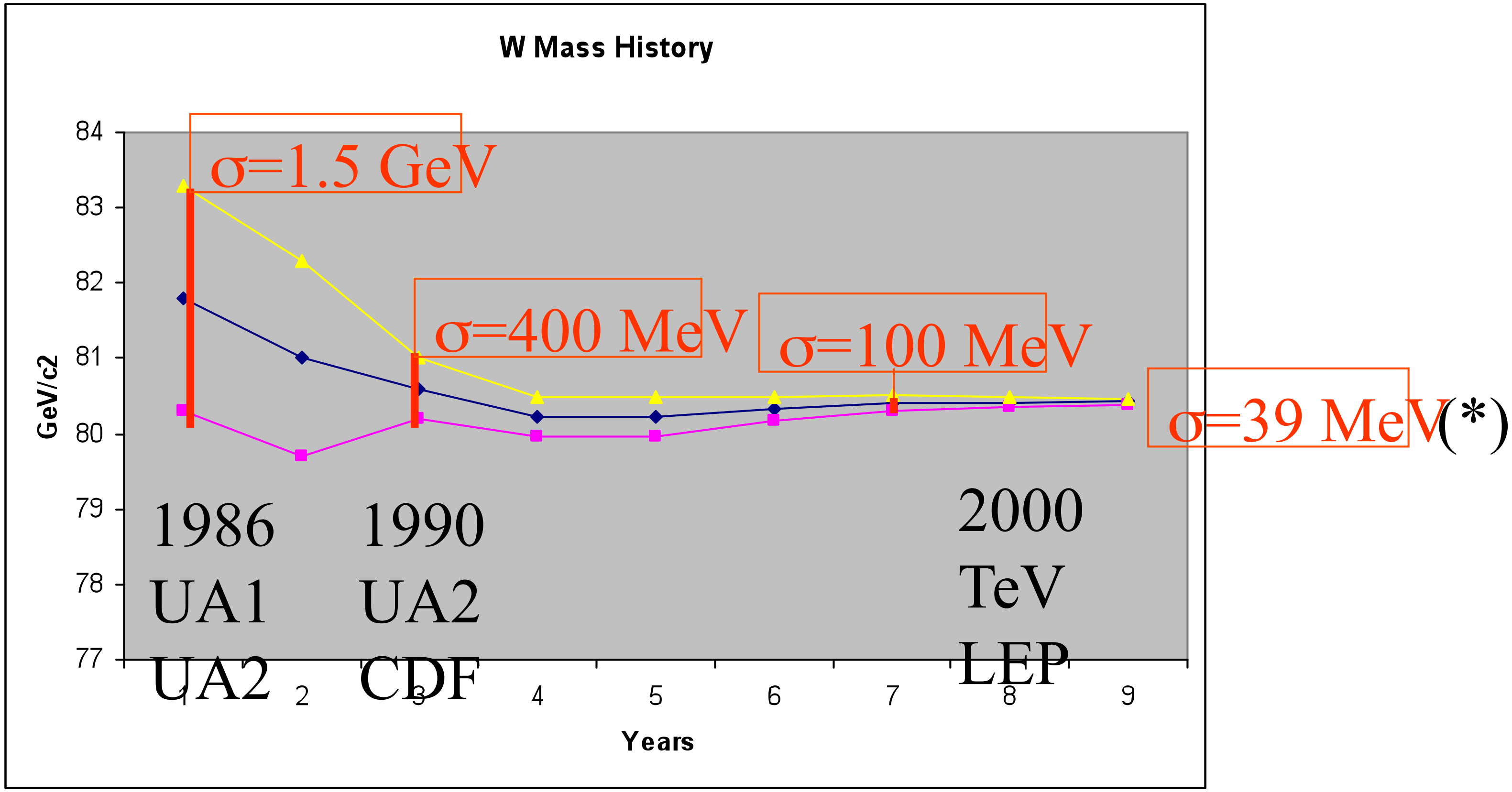


Present M_W at LEP and TeVatron





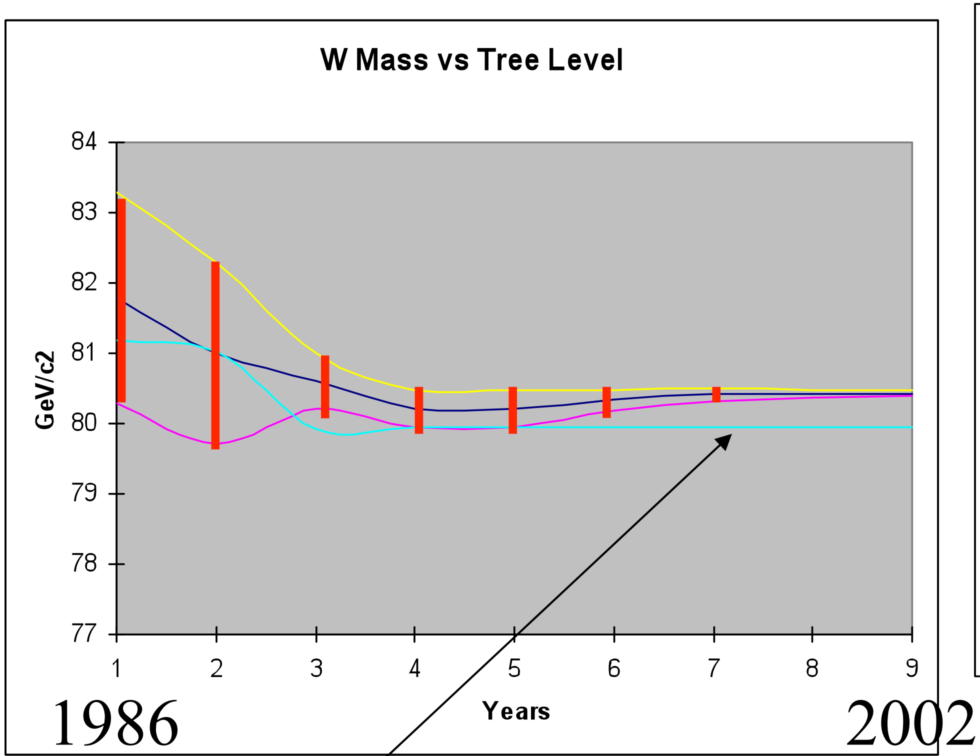
W mass precision from 1986 to 2004

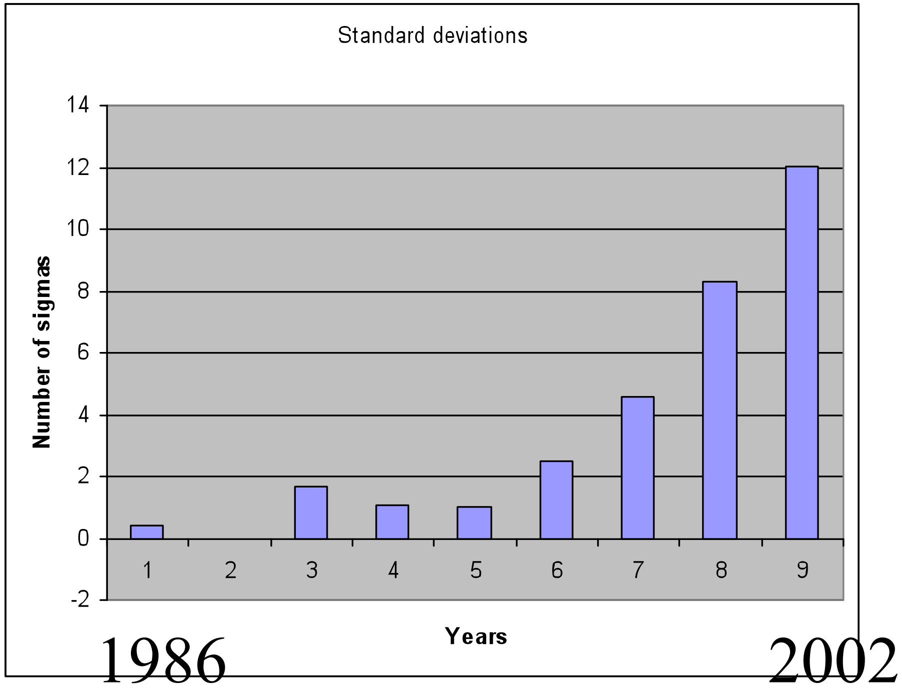


Only Published Results

(*) Preliminary w.a. 2004 : σ=34 MeV, weight of LEP 2/3, Tevatron 1/3

Strong Evidence of electroweak radiative corrections from Z and W mass





Strong Evidence of pure E.W. Higher Order Corrections

E.W. Tree level SM relation

(with running α QED)

$$M_W^{\;2}\left(1-\frac{M_W^{\;2}}{M_Z^{\;2}}\right)=\frac{\pi\alpha(M_Z)}{\sqrt{2}}\frac{1}{G_F}$$

$$\alpha(\sqrt{s}=\mathrm{M}_Z)=\frac{1}{128.936\pm 0.046}$$

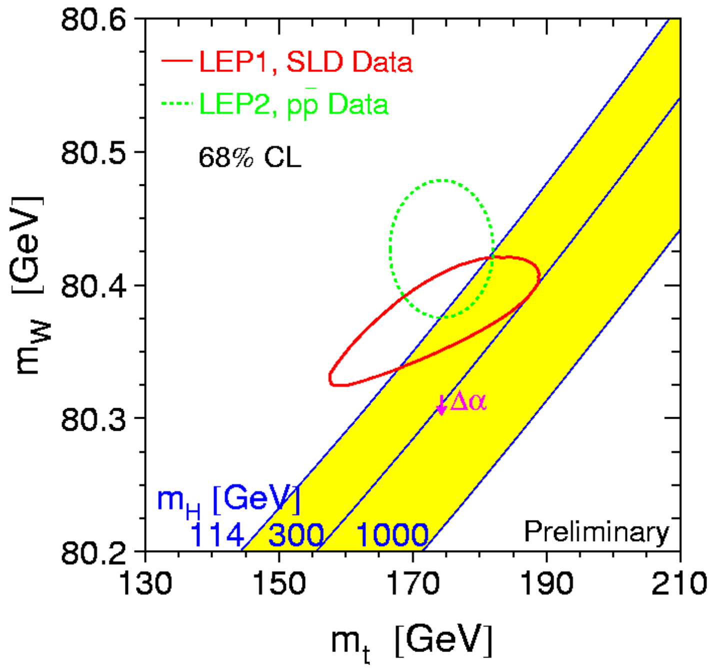
ElectroWeak fit results (slide from 2004)

- Electroweak theory tested at one loop level
- Indications for a light Higgs

$$M_{top} = 174.3 \pm 5.1\ \mathrm{GeV/c^2}$$

$$M_{Higgs} \leq 219\ \mathrm{GeV/c^2}$$

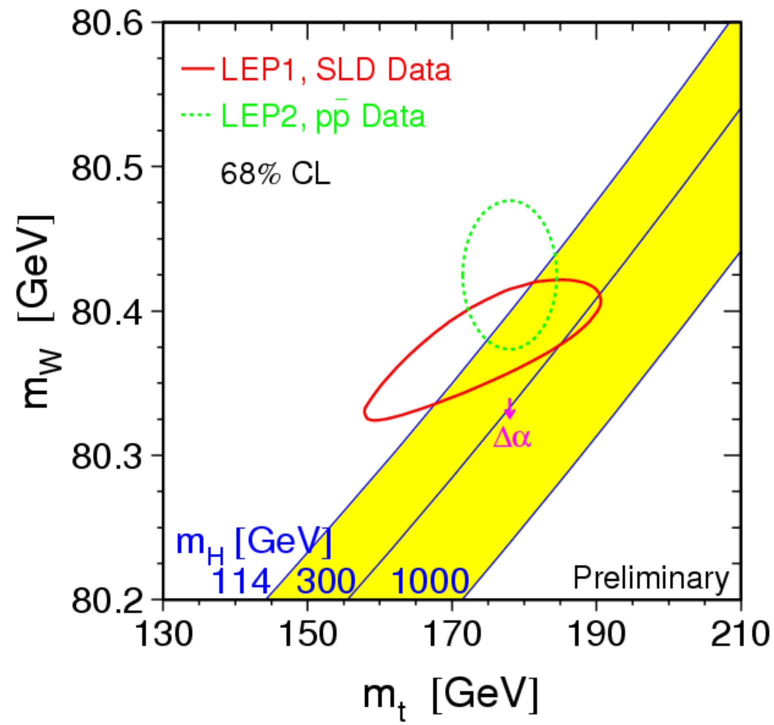
Summer 2003



$$M_{top} = 178.0 \pm 4.3\ \mathrm{GeV/c^2}$$

$$M_{Higgs} \leq 251\ \mathrm{GeV/c^2}$$

Winter 2004



Summary of main LEP2 electroweak measurements

$$m_W = 80.376 \pm 0.033 \text{ GeV}$$

$$\Gamma_W = 2.195 \pm 0.083 \text{ GeV}$$

$$B(W \rightarrow \text{had}) = 67.41 \pm 0.27 \ \%$$

$$g_Z^1 = 0.984^{0.018}_{0.020}$$

$$\kappa_\gamma = 0.982 \pm 0.042$$

$$\lambda_\gamma = -0.022 \pm 0.019$$

$m_H \geq 114.4$ GeV from direct searches

$m_H \leq 152$ GeV from electroweak fits (*)

(*) including other inputs most noticeably m_Z from LEP 1 and m_t from Tevatron

(find more in: Aleph, Delphi, L3, Opal, Physics Report 532 (2013) 119 and references therein)

Acknowledgements

- **All authors appearing in**
  - **LEP1 final EWK paper: Physics Report 427 (2006) 257**
  - **LEP2 final EWK paper: Physics Report 532 (2013) 119**
- **Physicists and engineers from the CERN accelerator divisions over the successful LEP years**
- **Many physicists from the theory community**