Electroweak physics at LEP

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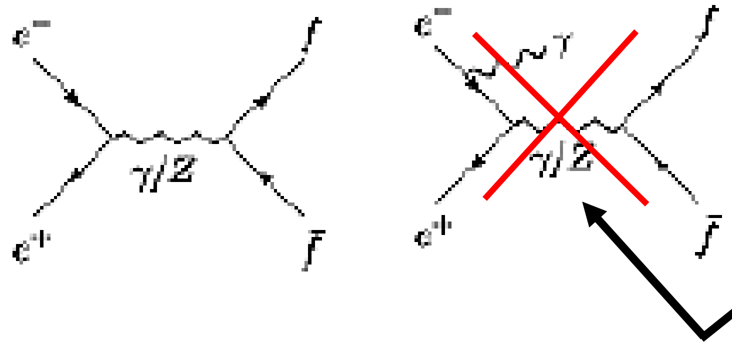
On behalf of the LEP Collaborations

Les Rencontres de Physique de la Vallée d'Aoste
February 29 – March 6, 2004 - La Thuile (Italy)

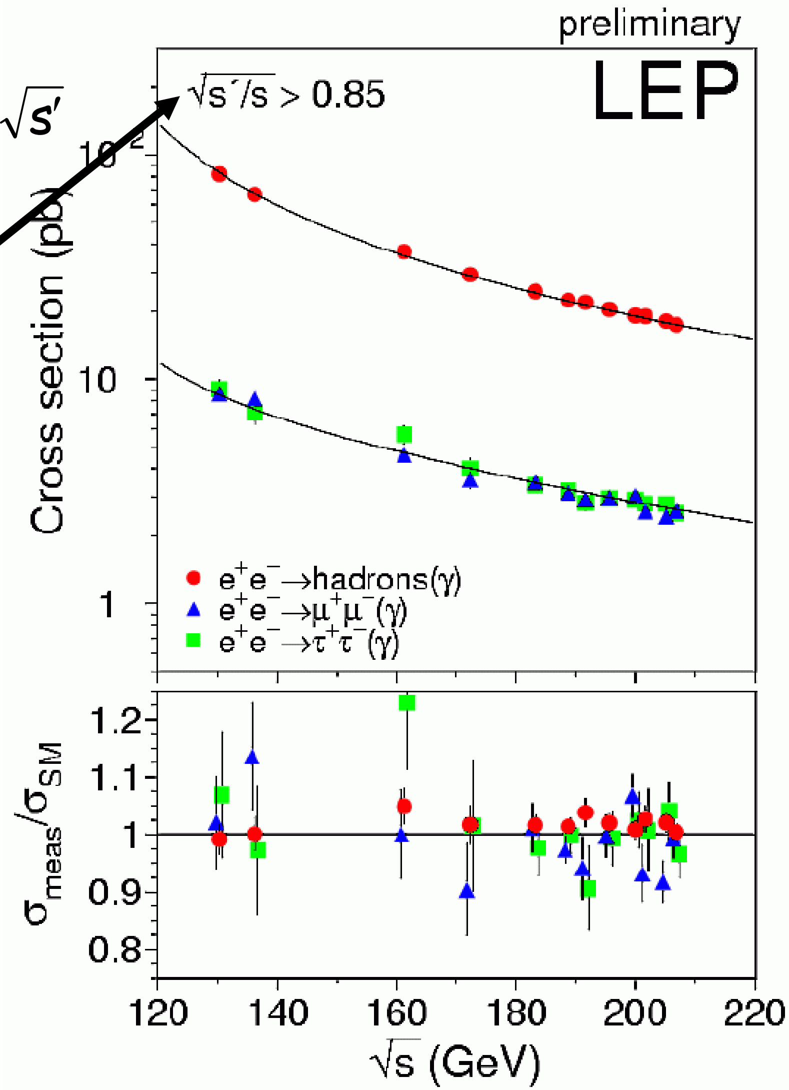
Outlook

- LEP1 (+ SLD): final results for a while, possibly except for b asymmetries (no new number since Summer 2003)
- LEP2:
  - 2 fermion production above the Z
  - 4 fermion production
  - Gauge Couplings
  - W mass and width
- Global electroweak fit: still the Summer 2003 one
- All the results are preliminary unless explicitly stated
- New results are explicitly marked

Fermion pair production at LEP2



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

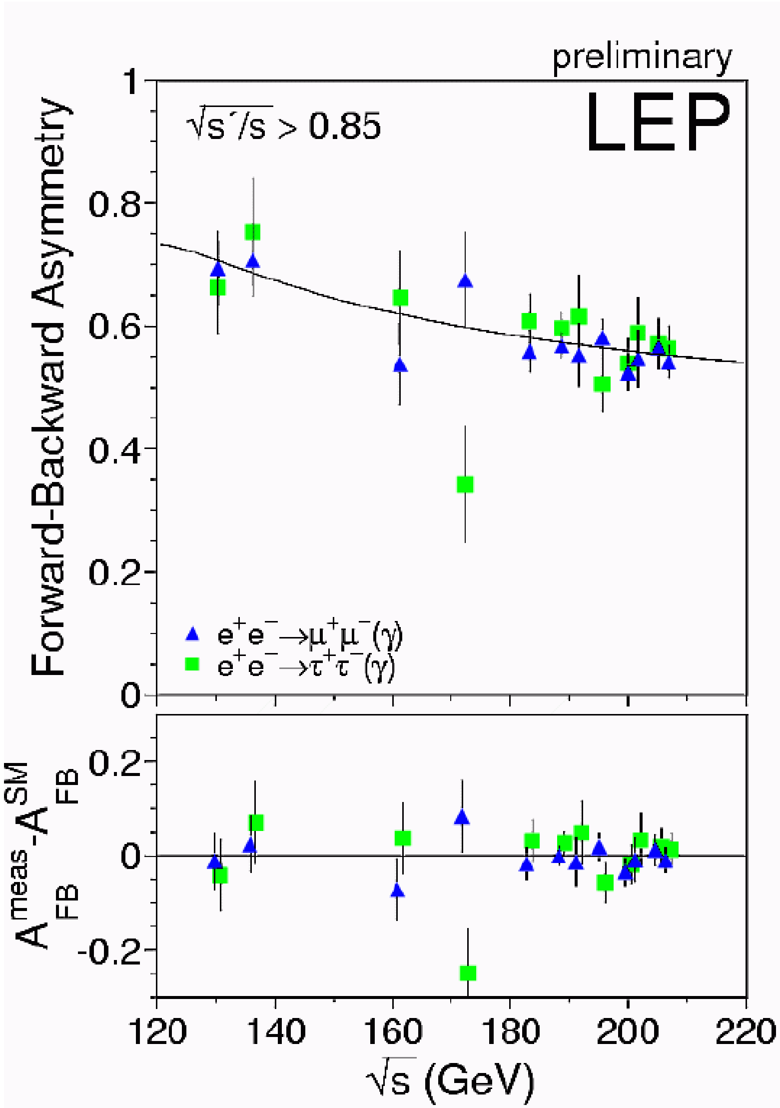


- Reject Z radiative return (ISR)
- $d\sigma/d\cos\theta$ (also ee), heavy flavour fractions and asymmetries
- Radiative Z return used for a cross check of LEP energy from a fit to the radiative return line shape, using LEP1 $\delta m_Z/m_Z \cong 10^{-5}$

δEb = -14 ± 21(stat.) ± 20(syst.) ± 20(LEP) MeV

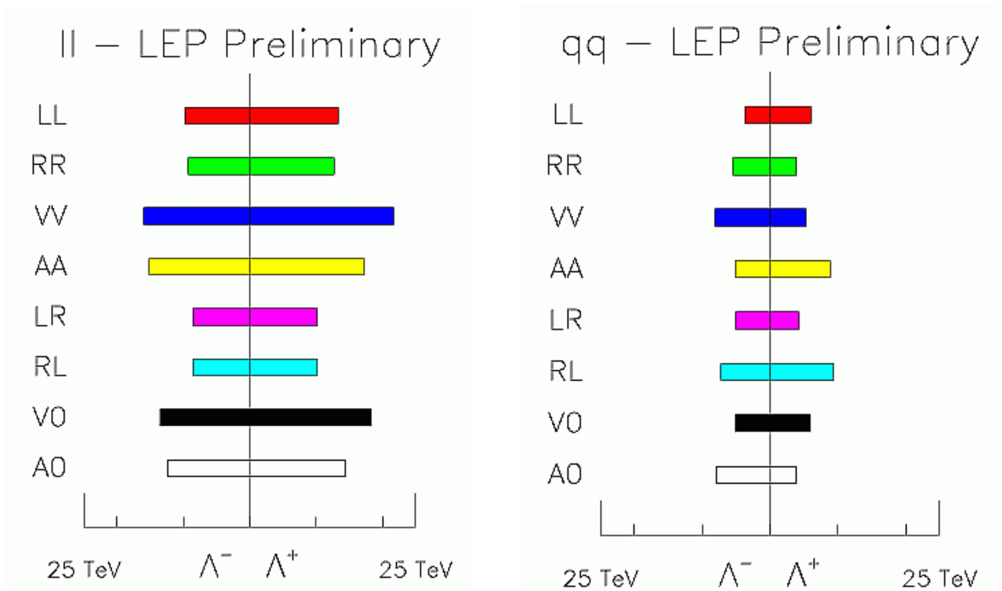
Final O results
Not in combination yet

Fermion pair production at LEP2



- Limits on new physics: contact interactions:

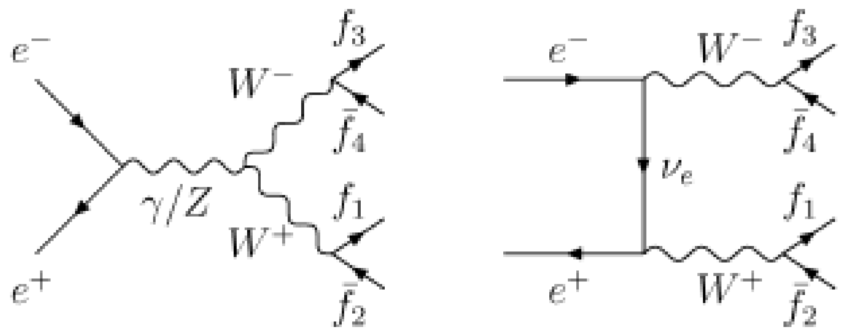
$$L_{eff} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

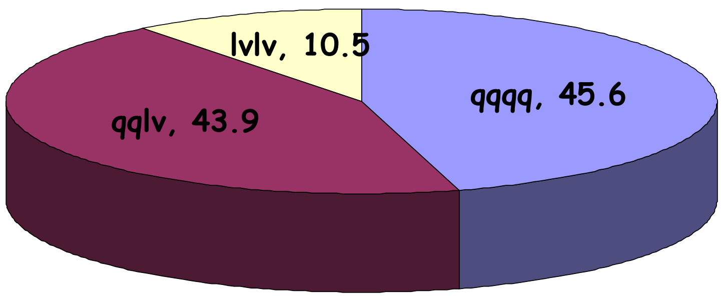


Scale lower limits for destructive (-) and constructive(+) interference with SM

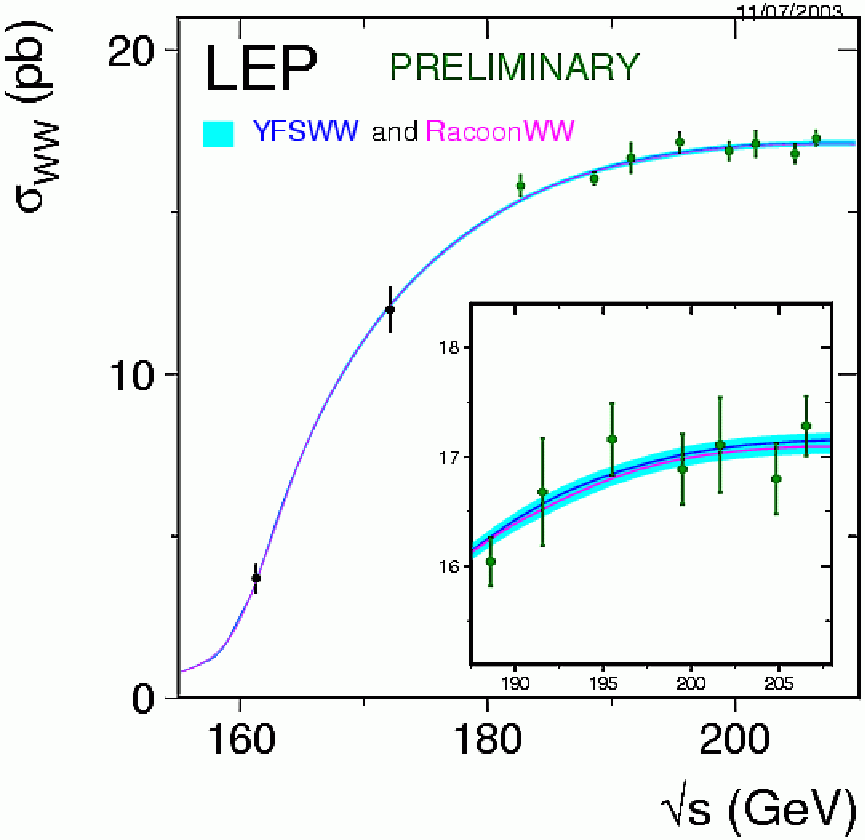
W pair production cross section

- CC03 diagrams:





Final results from D

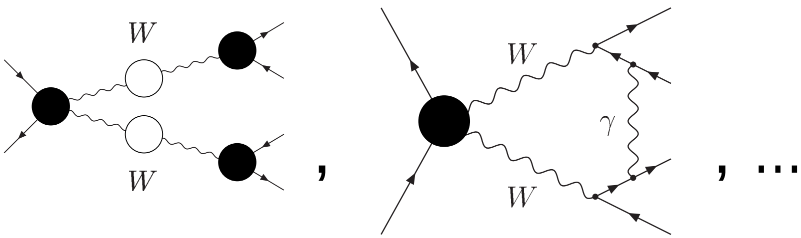


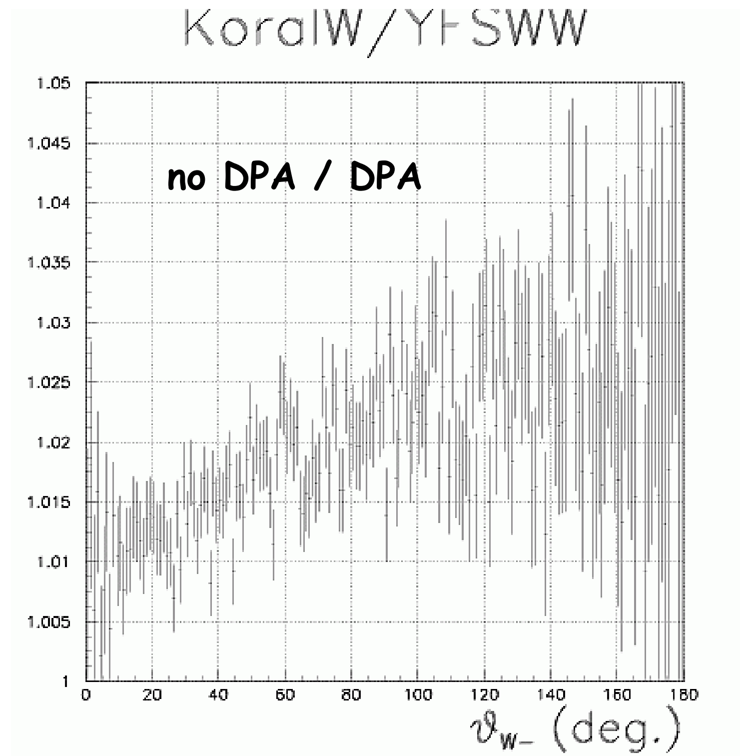
All energies combined →

$$\sigma_{WW}^{meas} / \sigma_{WW}^{YFSWW} = 0.997 \pm 0.007(\text{stat}) \pm 0.008(\text{syst})$$

$$\sigma_{WW}^{meas} / \sigma_{WW}^{RacoonWW} = 0.999 \pm 0.007(\text{stat}) \pm 0.008(\text{syst})$$

e+e- → WW: EW O(α) radiative corrections

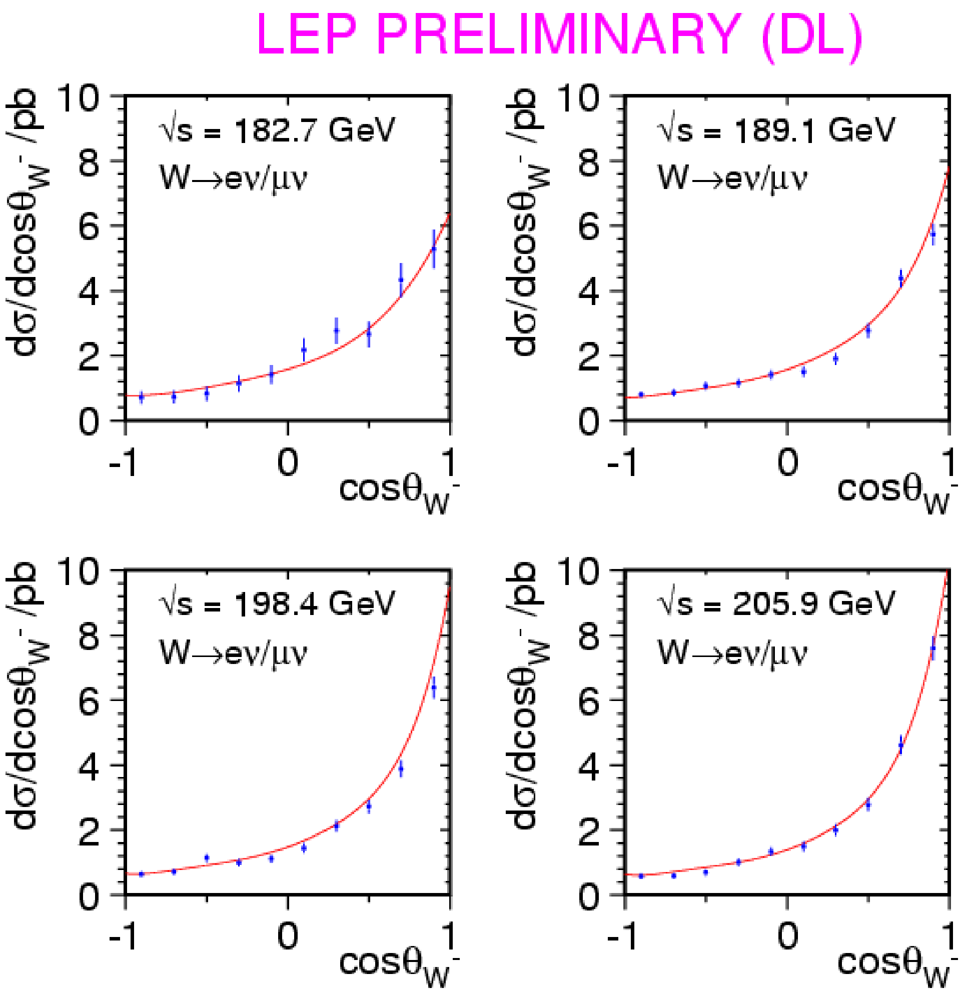




- Double Pole Approximation:
  - YFSWW
  - RacoonWW
- Effect on σ_{WW} : 1.5-3%
  - Theoretical precision: 0.4%
- Effect on W mass: O(10 MeV)
- Effect on W polar angle: cTGC
  - Effect on λ_γ g_1^Z ~ -0.015
  - Effect on κ_γ ~ -0.04
  - Same magnitude as total error

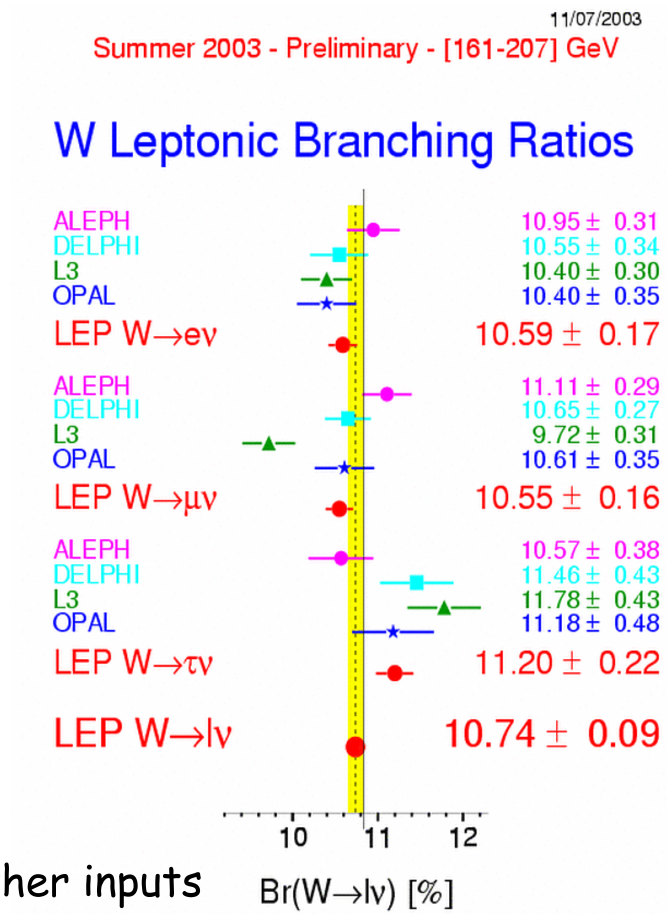
Study of effects and systematics needed in real analyses frame

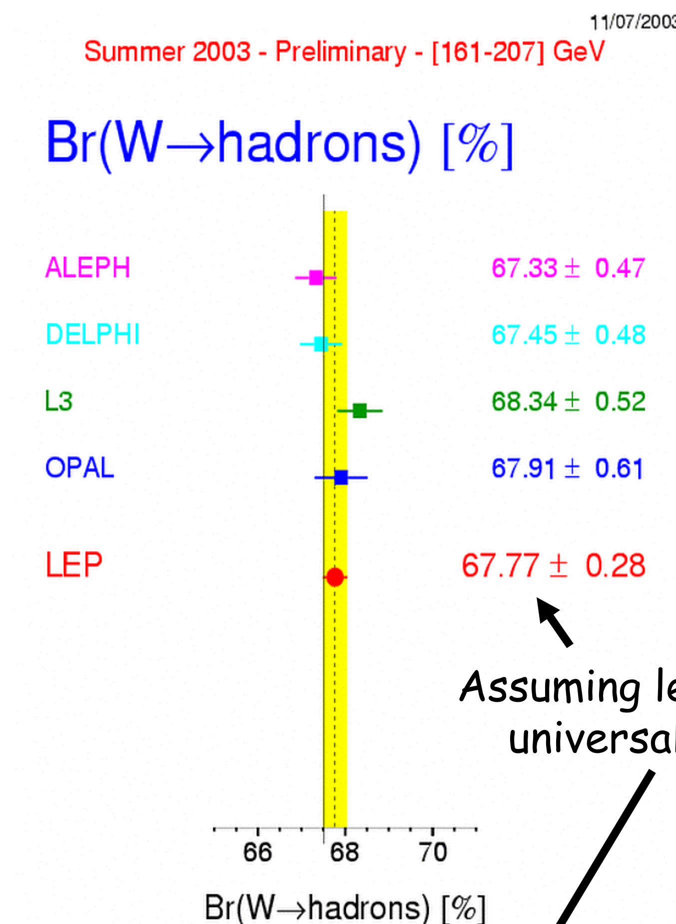
W angular distribution in CC03



- New LEP combination (DL)
- Very preliminary
- Use only semileptonic decays (e,μ)
- Tag the W sign with leptons
- Reconstruct the Ws with a constrained kinematic fit (E,p conservation)

W branching ratios and $|V_{cs}|$





Assuming lepton universality

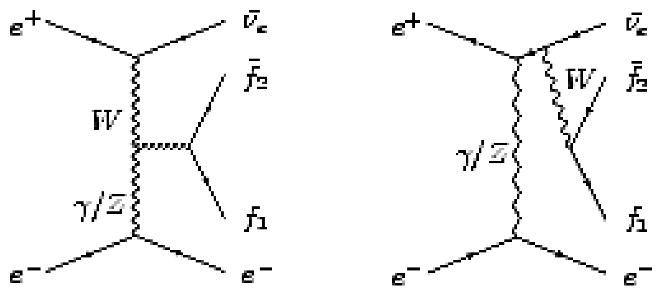
Using other inputs from PDG 2002

$$1/BR(W \to l\nu) = 3\left\{1 + \left[1 + \alpha_s(m_W^2)/\pi\right] \sum_{i=u,c} \sum_{j=d,s,b} |V_{ij}|^2\right\} \rightarrow$$

$|V_{cs}| = 0.989 \pm 0.014$

Single W production

- LEP definition: t-channel only

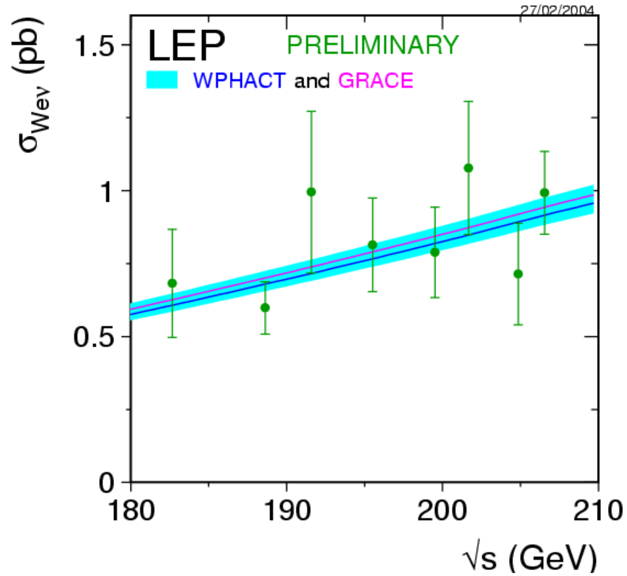


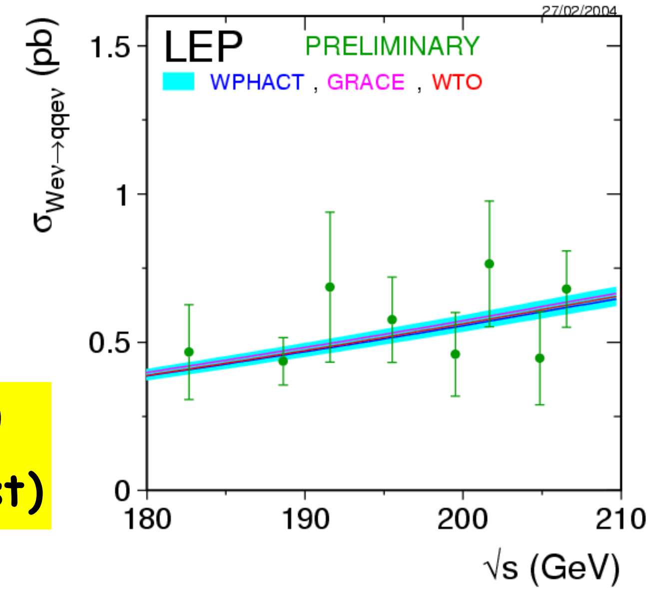
- $M(qq') > 45\ GeV/c^2$, $E_l > 20$ GeV
- If evev, $|\cos\theta_e| > 0.95$
- New LEP combination with final L results

All energies combined

$$\sigma^{meas}_{We\nu} / \sigma^{Grace}_{We\nu} = 0.958 \pm 0.067(stat) \pm 0.040(syst)$$

$$\sigma^{meas}_{We\nu} / \sigma^{WPHACT}_{We\nu} = 0.987 \pm 0.069(stat) \pm 0.042(syst)$$





Charged Triple Gauge Couplings

- In $SU(2)_L \otimes U(1)_Y$ 3 and 4 bosons vertices
- Anomalous couplings search $\Rightarrow$ new physics
- Lorentz invariant parameterization of the WWV part of the Lagrangian: 14 complex parameters
  - Electromagnetic gauge invariance
  - C,P conservation
  - Imaginary parts fixed at 0
  - Use gauge constraints and reduce to 3 independent parameters

- LEP combination:

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

$$\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W \quad , \quad \lambda_Z = \lambda_\gamma$$

- Directly linked to:
  - Magnetic dipole moment

$$\mu_W = \frac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

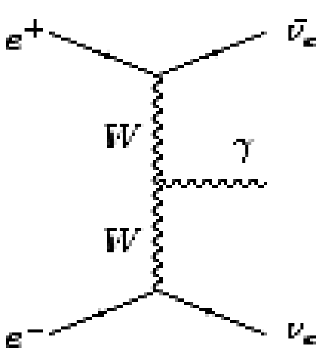
  - Electric quadrupole moment

$$Q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$

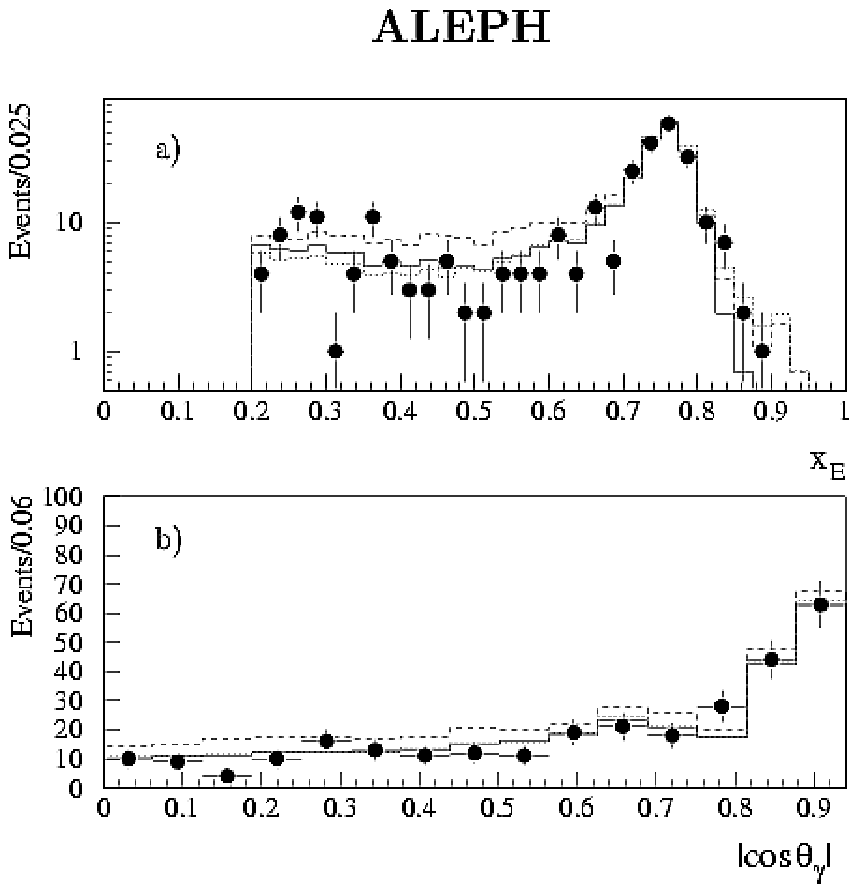
- No combination for limits on other parameters

Charged TGC measurement

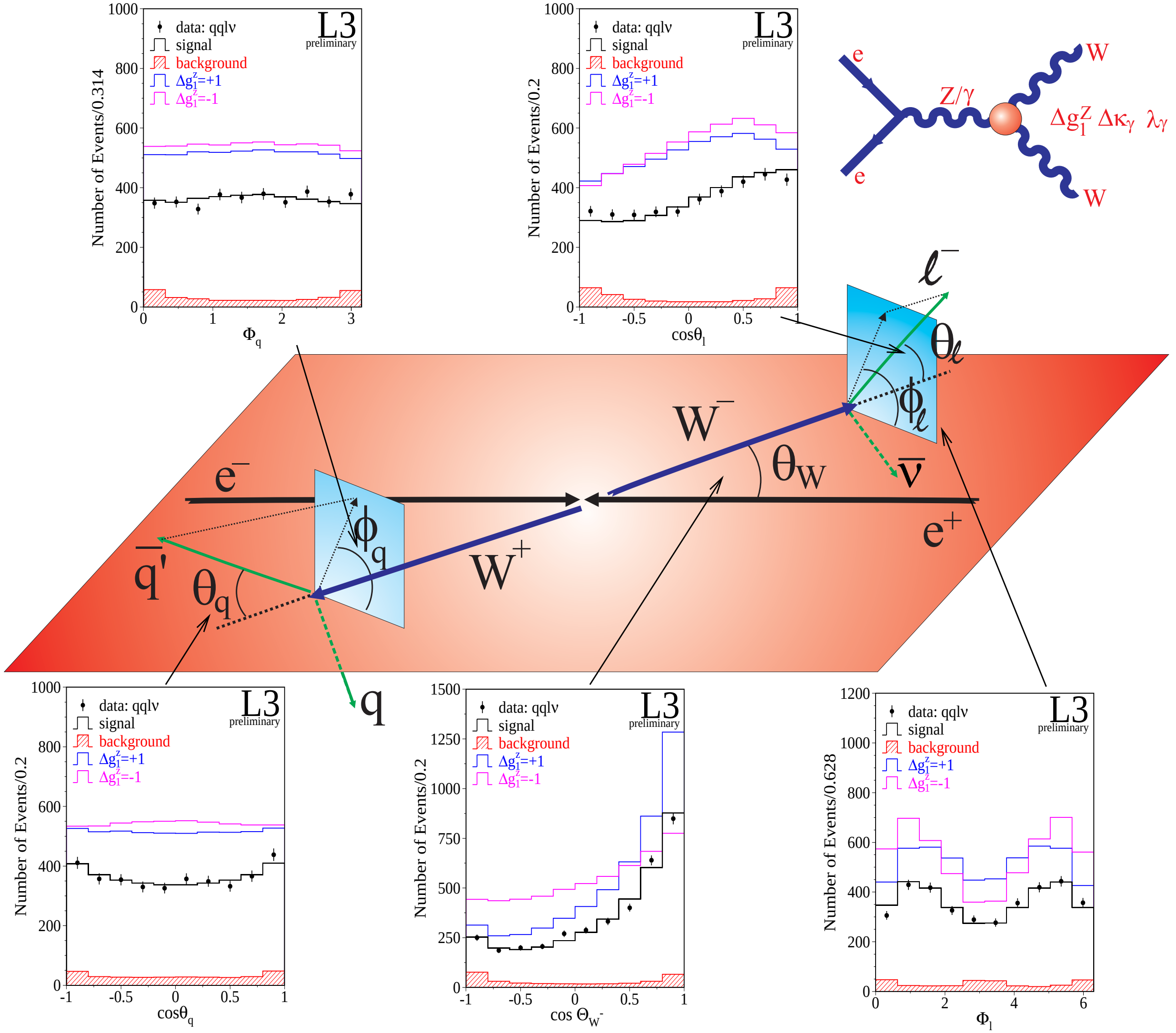
- WW cross section
- W helicities combinations affect decay angles
  - Maximum likelihood
  - Optimal observables
- Single W cross section (κ_γ)
- Single photon cross section (κ_γ λ_γ)



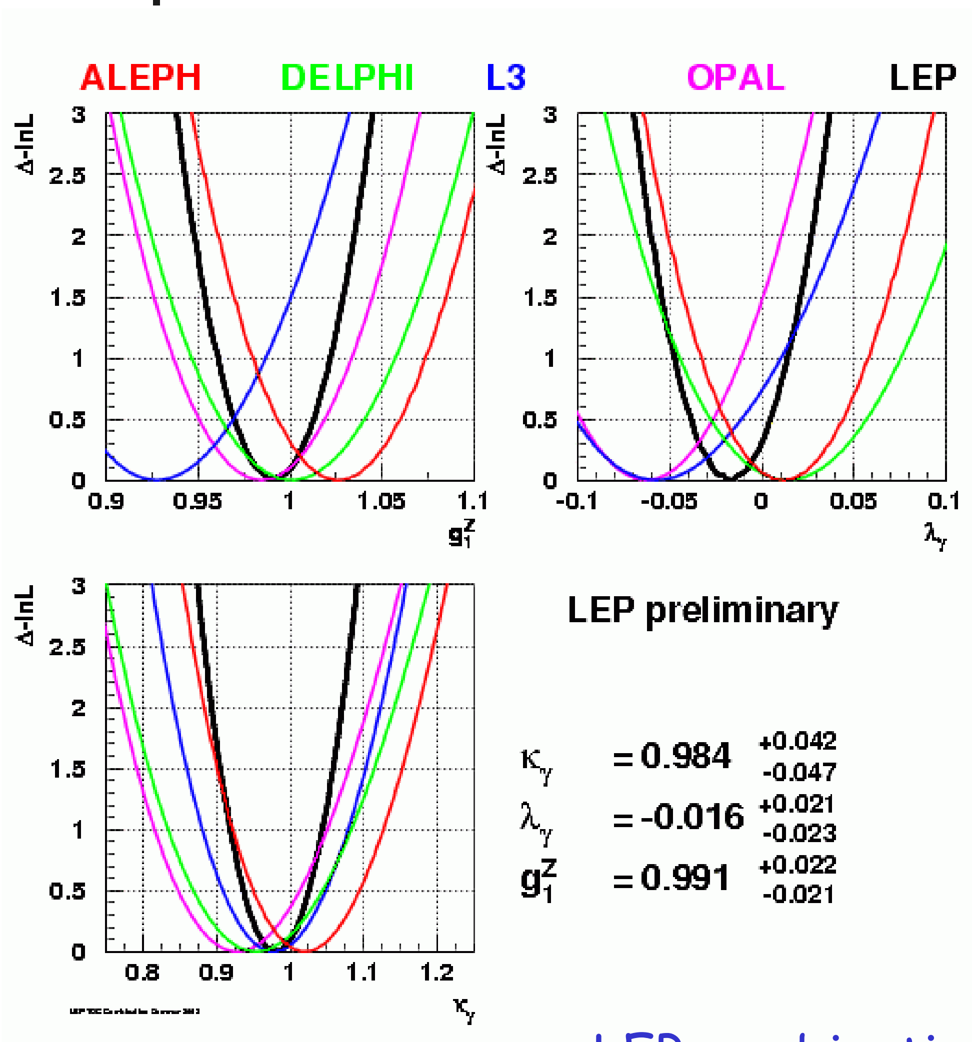
- Single photon energy and angle spectra

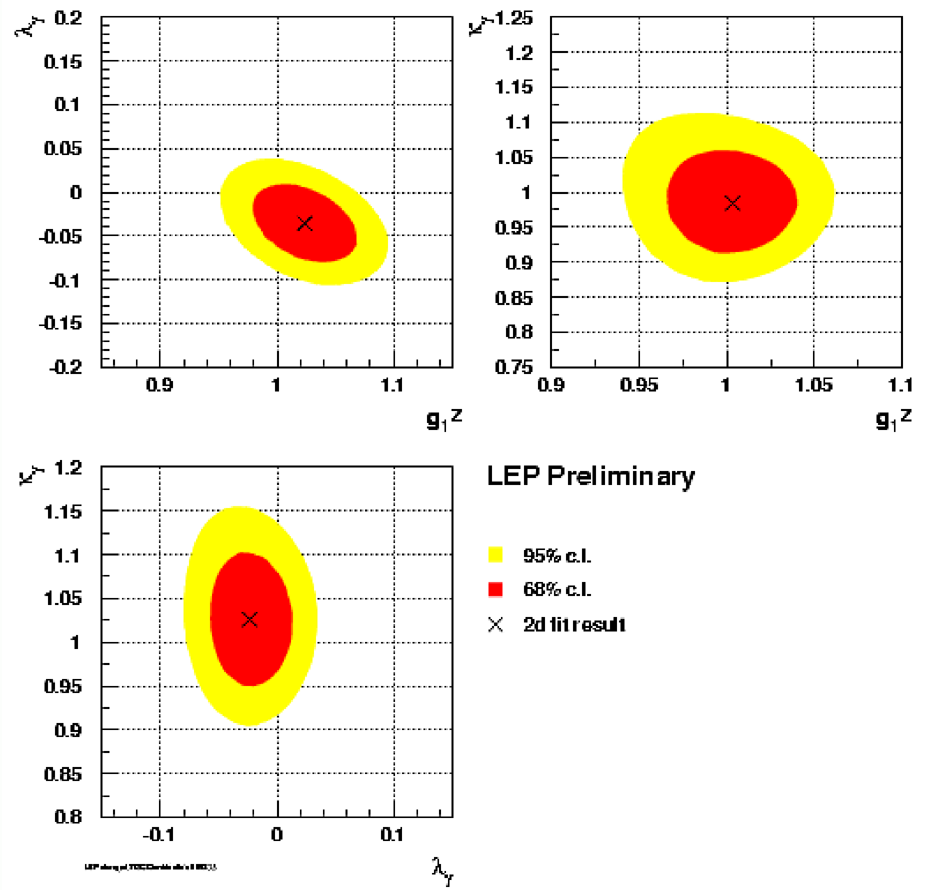


Charged TGC measurement



Charged TGC LEP combination





LEP combination not updated
LO new final results

W polarization

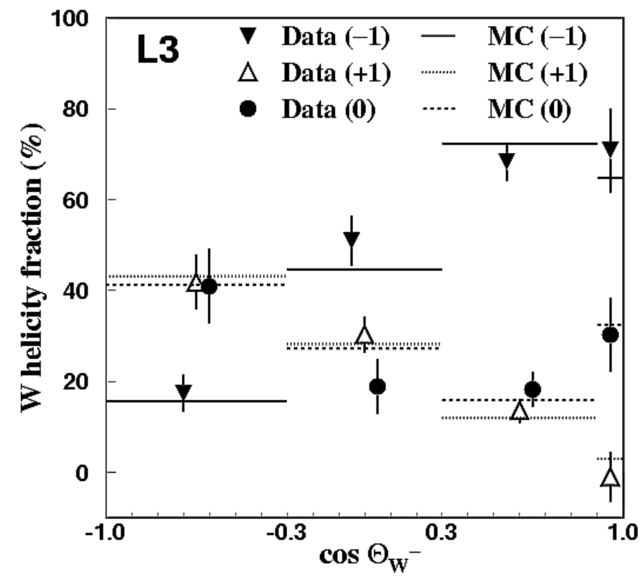
- Spin density matrix (DO)
  - Helicity states combinations
  - W boson longitudinal polarization in s channel

$$\sigma_L = \int \rho_{00} \left(d\sigma / d\cos\theta_W \right) \; d\cos\theta_W$$

- From off diagonal elements limits on CP/CPT odd observables (O final):

CP odd	CPT odd
$\sigma^{W^-}_{+-} - \sigma^{W^+}_{-+} = 0.33 \pm 0.17 \pm 0.06$	$\sigma^{W^-}_{+-} + \sigma^{W^+}_{-+} = -0.10 \pm 0.17 \pm 0.06$
$\sigma^{W^-}_{+0} - \sigma^{W^+}_{-0} = 0.09 \pm 0.11 \pm 0.04$	$\sigma^{W^-}_{+0} + \sigma^{W^+}_{-0} = -0.10 \pm 0.11 \pm 0.04$
$\sigma^{W^-}_{-0} - \sigma^{W^+}_{+0} = 0.02 \pm 0.15 \pm 0.06$	$\sigma^{W^-}_{-0} + \sigma^{W^+}_{+0} = 0.07 \pm 0.15 \pm 0.06$

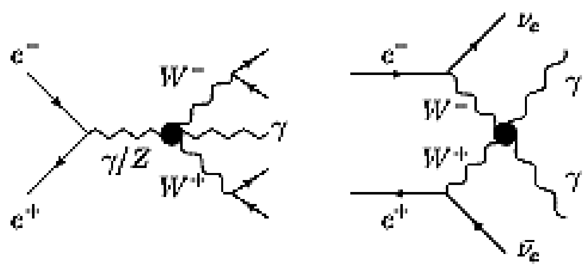
- Helicity components deconvolved from angular W distributions (L final)
  - Study of spin correlations



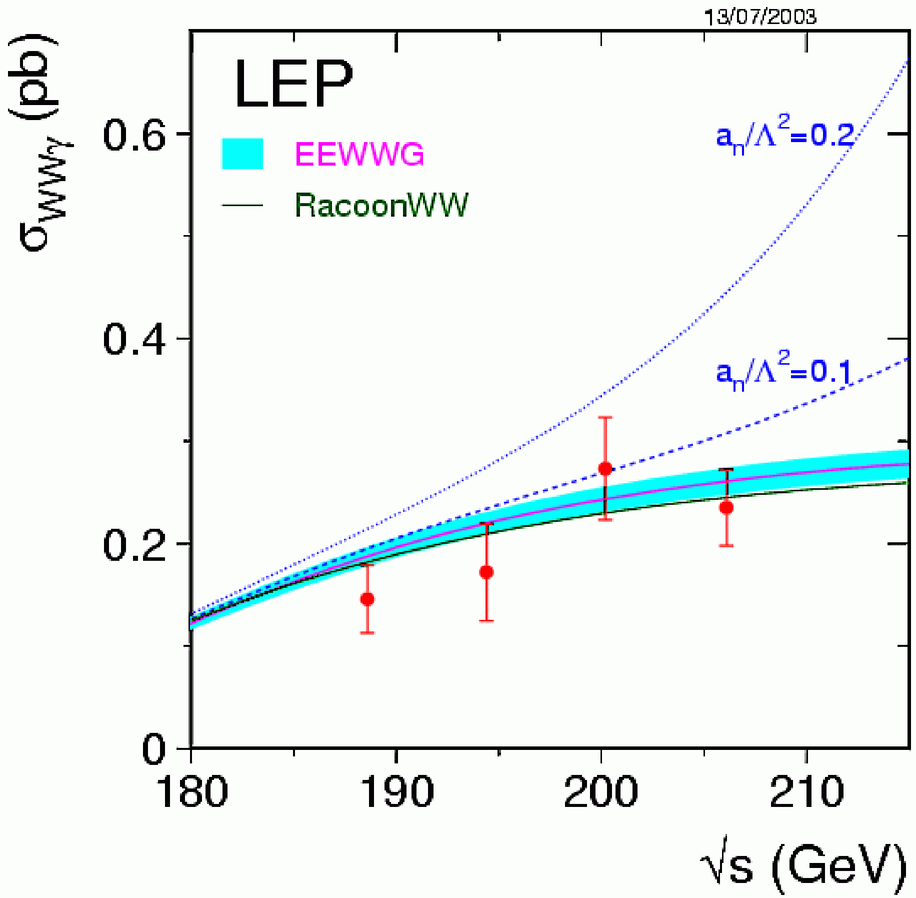
$\sigma_L / \sigma = 0.239 \pm 0.021 \pm 0.011$ (OPAL, SM = 0.239) final
$\sigma_L / \sigma = 0.218 \pm 0.027 \pm 0.016$ (L3, SM = 0.241) final
$\sigma_L / \sigma = 0.249 \pm 0.033$ (DELPHI, SM=0.240)

WWγ production

- Affected also by Quartic Gauge Couplings (but at LEP2 very small sensitivity):

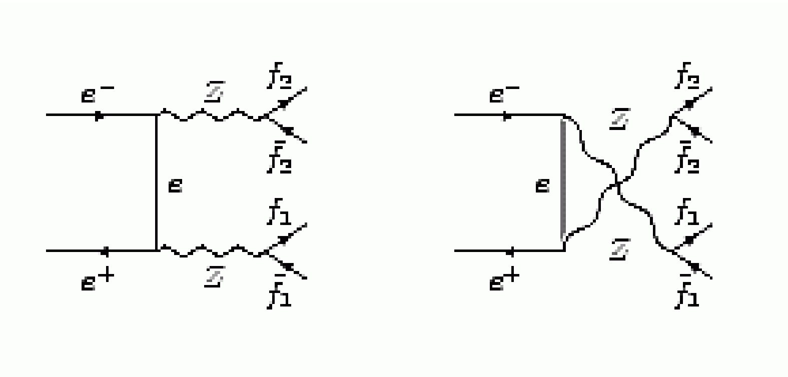


- Signal definition:
  - $E_\gamma > 5$ GeV
  - $|\cos\theta_\gamma| < 0.95$
  - $|\cos\theta_{\gamma,f}| < 0.90$
  - $m_W - 2\Gamma_W < m_{ff'} < m_W + 2\Gamma_W$
- Final LEP results (DLO)

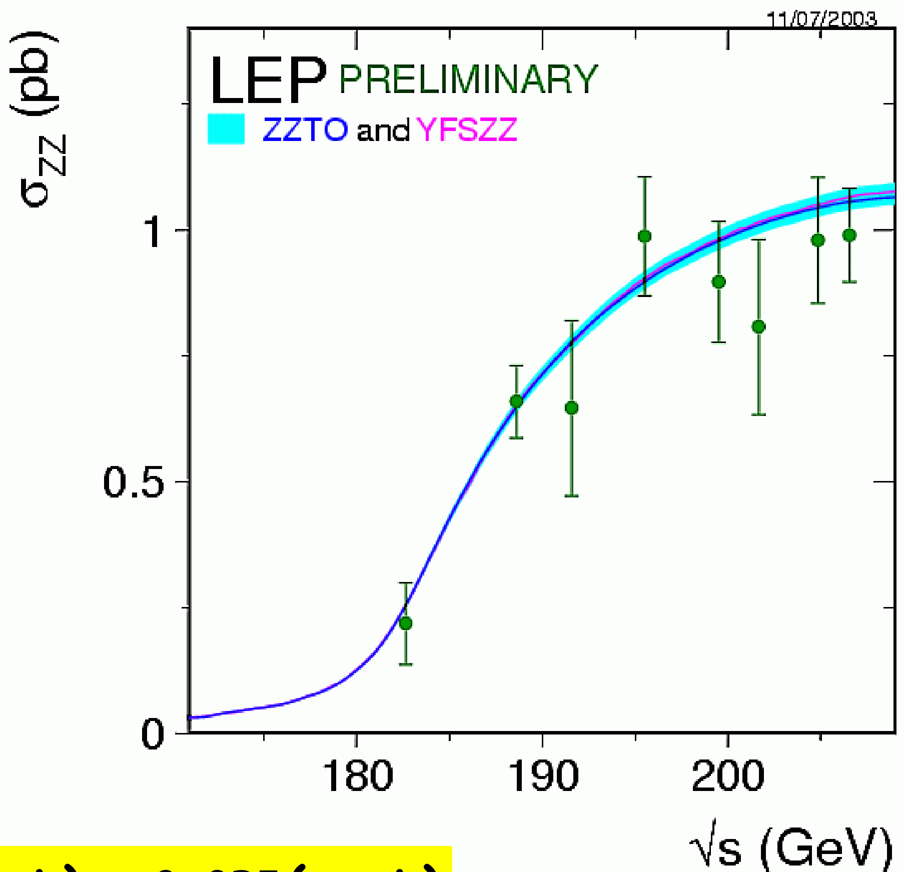


Z pair production cross section

- Defined as NC02 diagrams:



- qqqq,ννqq,eeqq,μμqq,ττqq,llll,ννll
- DLO final



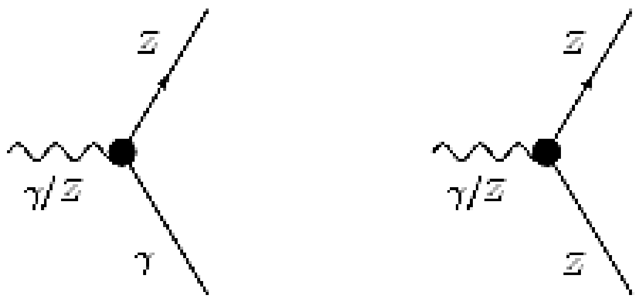
All energies combined

$$\sigma_{ZZ}^{meas} / \sigma_{ZZ}^{YFSZZ} = 0.945 \pm 0.045(stat) \pm 0.025(syst)$$

$$\sigma_{ZZ}^{meas} / \sigma_{ZZ}^{ZZTO} = 0.951 \pm 0.046(stat) \pm 0.025(syst)$$

Neutral Triple Gauge Couplings

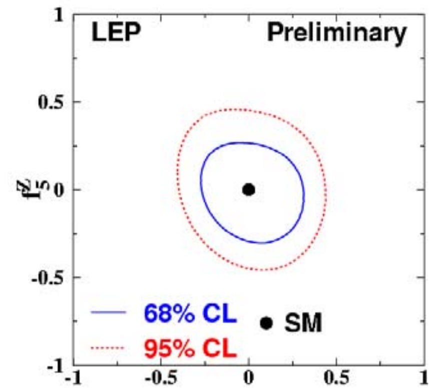
- In SM absent at tree level

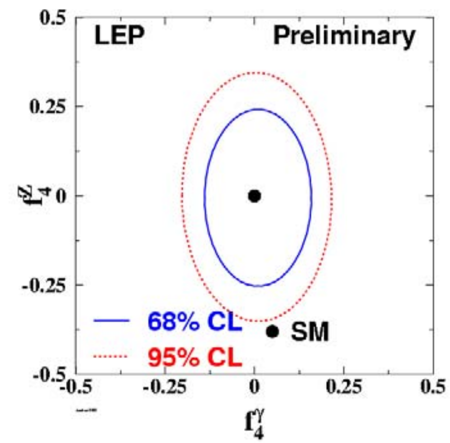


- 2 classes of nTGC:
  - $ZZ\gamma$, ZZZ in $e^+e^- \rightarrow ZZ$:

$$f_i^V \quad ,V = Z,\gamma, \quad i = 4,5$$

  - 4 conserved CP, 5 violated
  - ZZ cross section





$$f_4^\gamma \quad [-0.17 \ , \ 0.19], \quad f_4^Z \quad [-0.30 \ , \ 0.29]$$

$$f_5^\gamma \quad [-0.34 \ , \ 0.38], \quad f_5^Z \quad [-0.38 \ , \ 0.36]$$

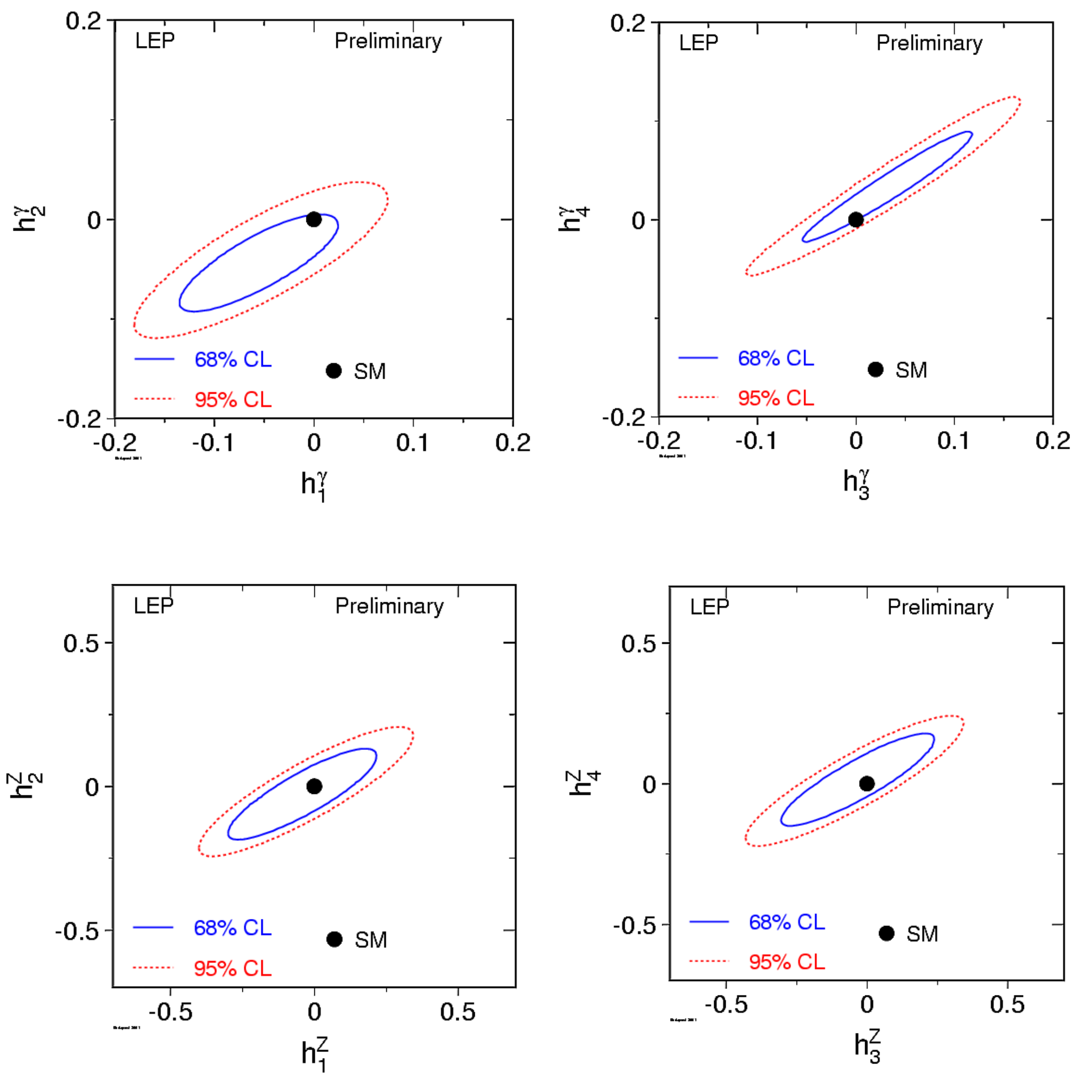
Neutral Triple Gauge Couplings

- $Z\gamma\gamma, ZZ\gamma$ in $e^+e^- \rightarrow Z\gamma$:

$$h_i^V, V = Z, \gamma, i = 1, \ldots, 4$$

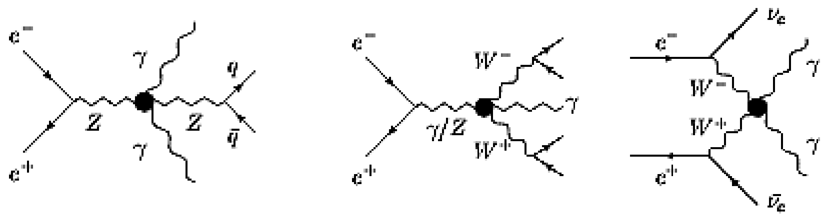
- 1,2 violated CP, 3,4 conserved
- Cross section and distributions in $\nu\nu\gamma$, $qq\gamma$

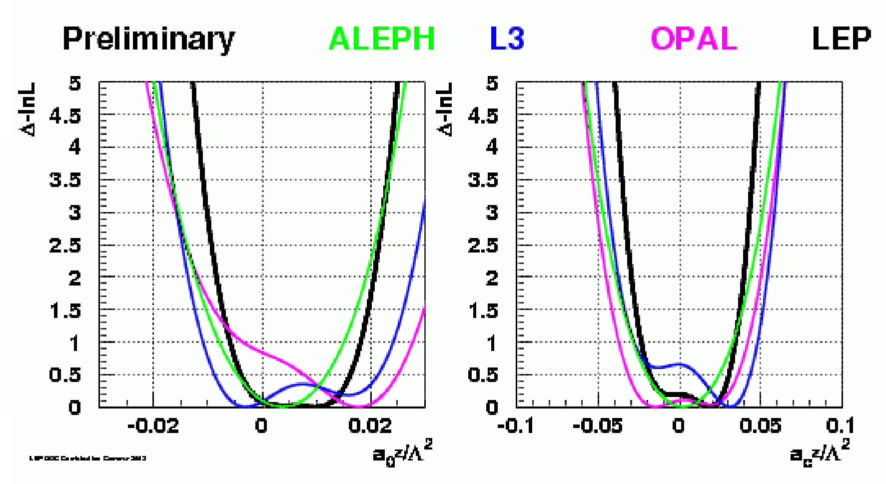
h_1^γ	$[-0.16\ ,\ 0.05]$		h_3^γ	$[-0.08\ ,\ 0.014]$
h_2^γ	$[-0.11\ ,\ 0.02]$		h_4^γ	$[-0.04\ ,\ 0.11]$
h_1^Z	$[-0.35\ ,\ 0.28]$		h_3^Z	$[-0.37\ ,\ 0.29]$
h_2^Z	$[-0.21\ ,\ 0.17]$		h_4^Z	$[-0.19\ ,\ 0.21]$



Neutral Quartic Gauge Couplings

- ZZγγ vertex forbidden in the SM





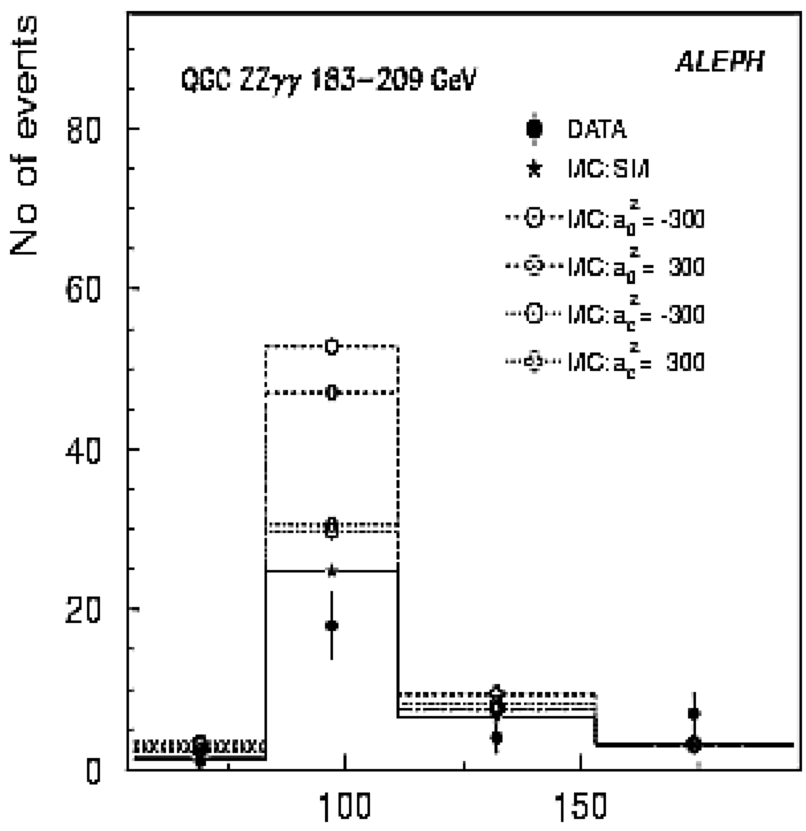
- Search for anomalous contributions in
  - qqγγ
  - ννγγ
  - Total cross section and differential distributions

a_c / Λ^2 $[-0.029, 0.039]$

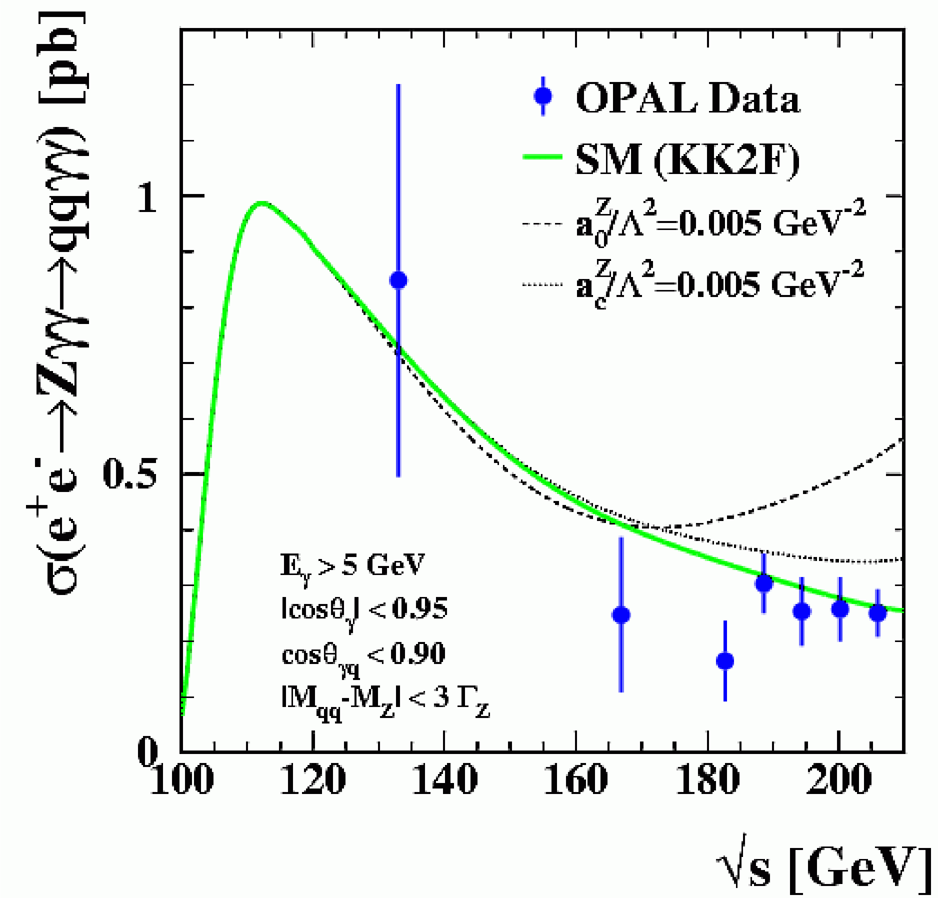
a_0 / Λ^2 $[-0.008, 0.021]$

Final results from L
LEP combination not updated
New final results from AO

Neutral Quartic Gauge Couplings

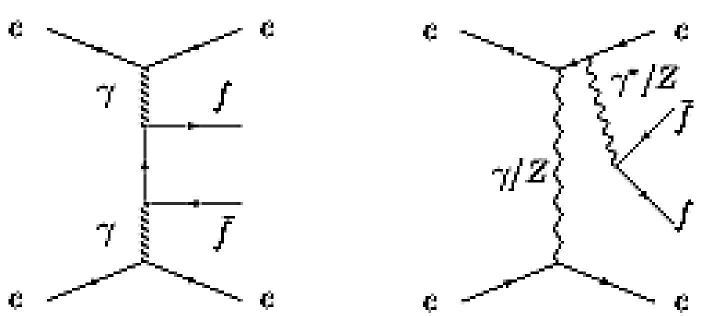


$\nu\nu\gamma\gamma$

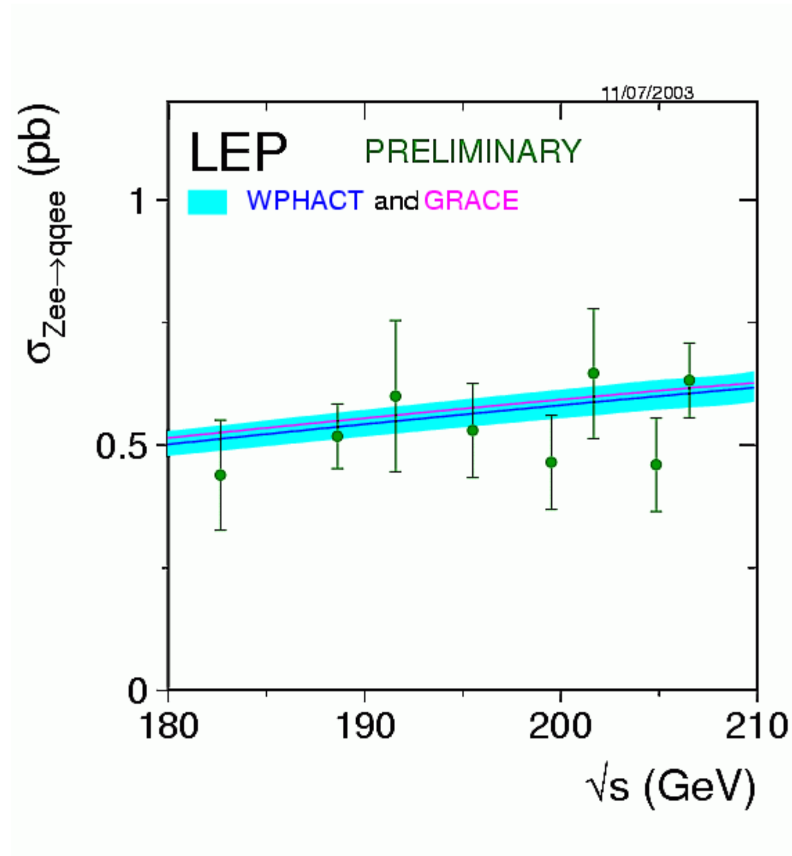


Single Z production

- LEP definition: NC48 diagrams set, search for 1 e scattered in the detector



- $M(ff) > 60$ GeV/c^2
- $\theta_{unscattered} < 3°$
- $12° < \theta_{scattered} < 168°$
- $E_{scattered} > 3$ GeV
- eeqq, eeμμ, eeττ considered
- Final eeqq results from L



All energies combined

$$\sigma^{meas}_{Zee} / \sigma^{Grace}_{Zee} = 0.914 \pm 0.060(\mathrm{stat}) \pm 0.042(\mathrm{syst})$$

$$\sigma^{meas}_{Zee} / \sigma^{WPHACT}_{Zee} = 0.932 \pm 0.058(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

W mass at LEP2: method

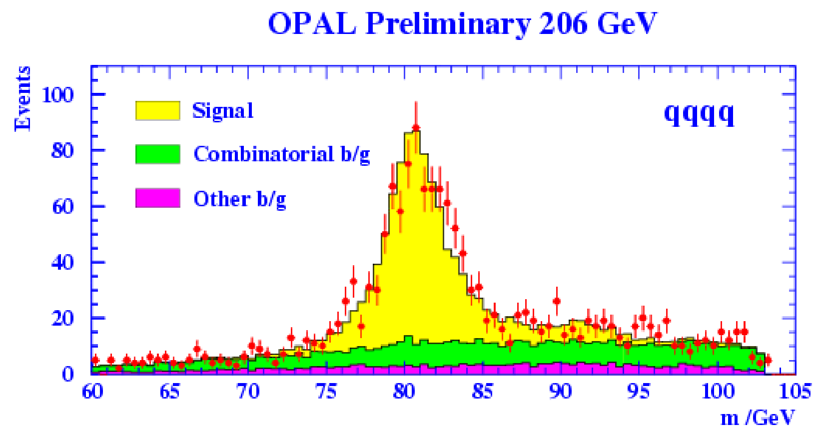
- Direct measurement of m_W:
  - Use W pair production (CC03)
  - ~ 35000 W pairs selected at LEP2
- At the WW production threshold from $d\sigma/dm_W$:

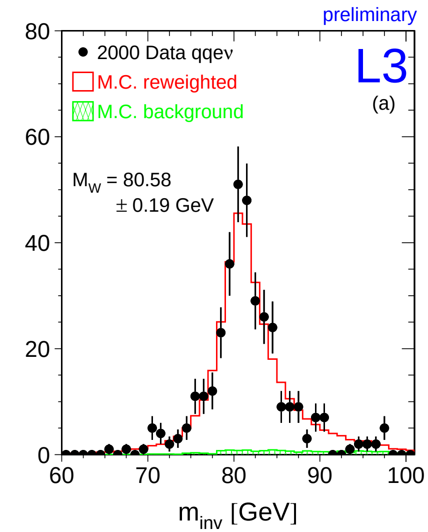
m_W = 80.40 $\pm$ 0.20 (stat) $\pm$ 0.07 (syst) $\pm$ 0.03 (LEP En.) GeV/c²

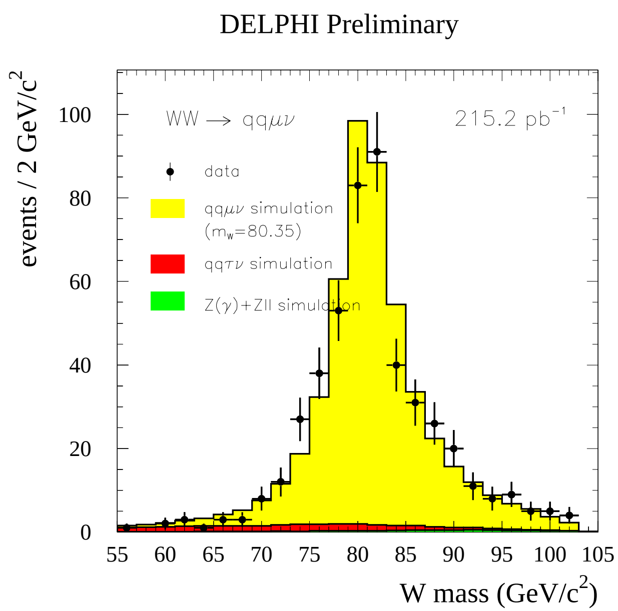
- At higher energies: direct kinematic reconstruction of m_W
  - qqqq (BR 46%)
  - qqlν (BR 44%)
  - lνlν (ALEPH E_l, OPAL E_l, pseudo mass), much smaller precision
- Improve mass resolution: constrained kinematic fit
  - $E_{tot} = \sqrt{s}, \quad \vec{p}_{tot} = \vec{0}$
  - Jet pairing ambiguities in qqqq: pair selection or pair weighting
  - $m_1=m_2$ or use both masses

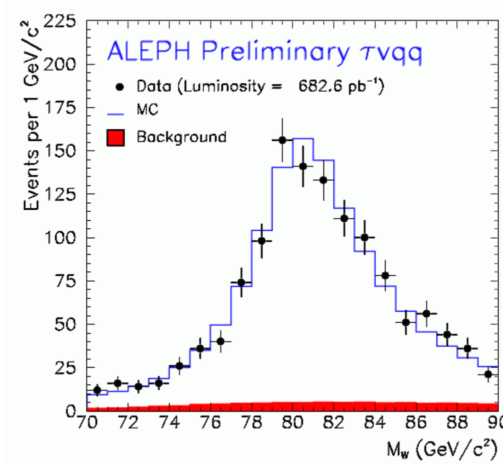
W mass at LEP2: method

- Extract m_W from the reconstructed mass distribution (also Γ_W, small correlation with m_W)
  - Likelihood fit based on simulation reweighting as a function of m_W
  - Likelihood fit based on the convolution of the m_W theoretical distribution with an experimental resolution function

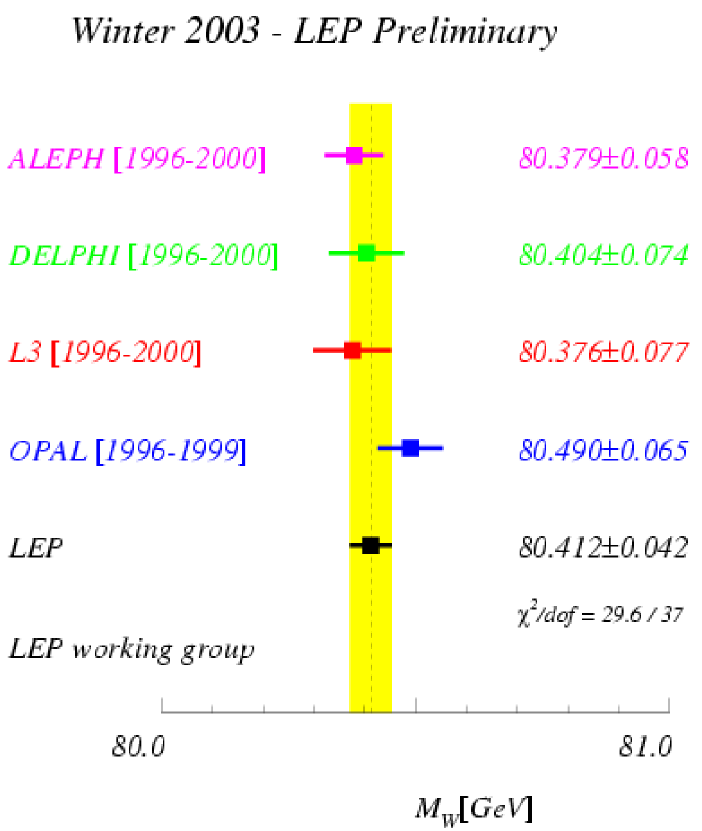


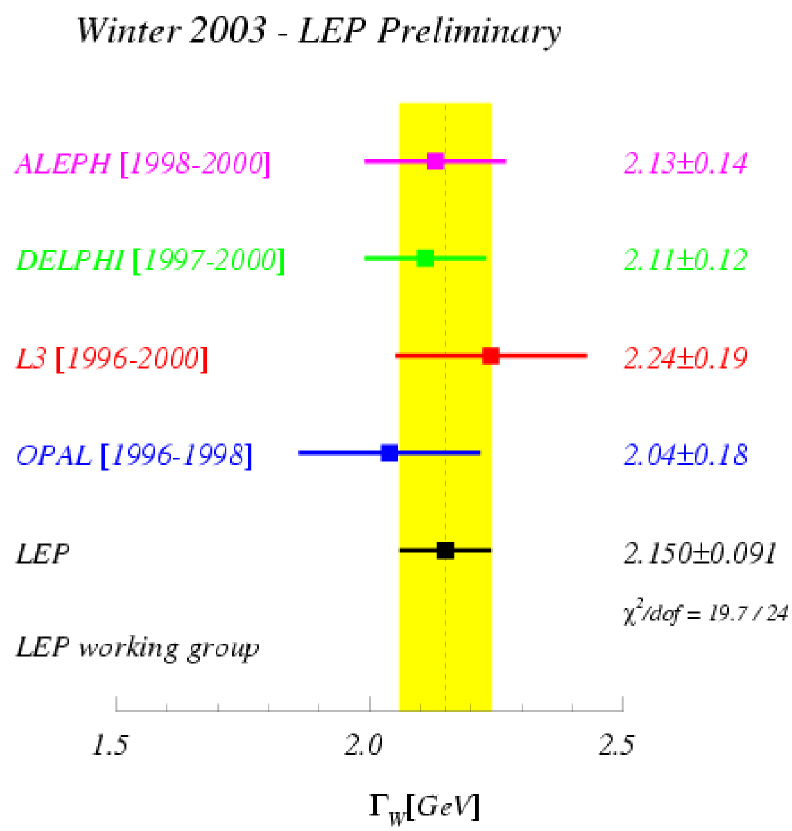






W mass and width at LEP2: results





Δm_W (qqqq – qqlν) = +22 $\pm$ 43 MeV

W mass at LEP2: uncertainties

- In the kinematic reconstruction direct measurement:

O(α) under study
YFSWW/RacoonWW
Full EW ≤ 10 MeV ?

Fragmentation models
Z peak data constraint

Calibration on real Z data, mainly at peak

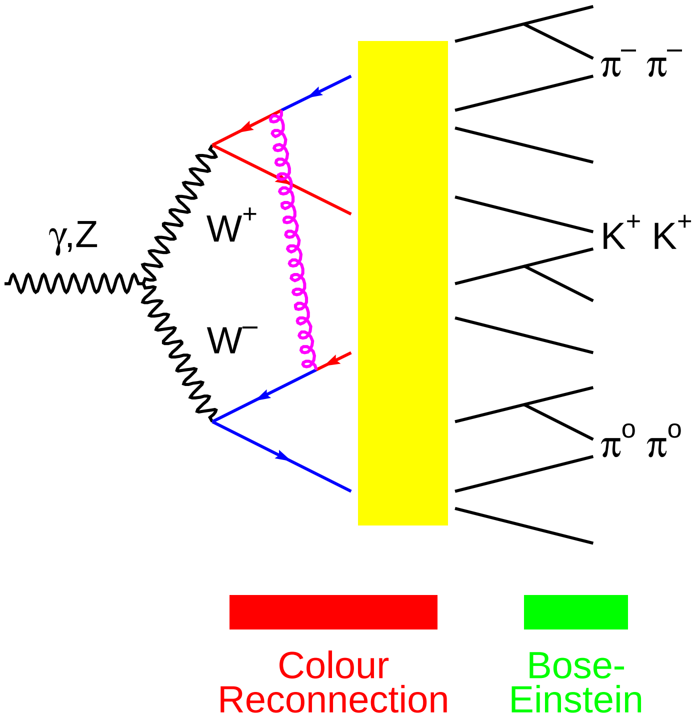
Final LEP energy:
δE~10-20 MeV
Cross check with Z radiative return

Source	Systematic Error on m_W (MeV) $q\bar{q}\ell\bar{\nu}_\ell$	$q\bar{q}q\bar{q}$	Combined
ISR/FSR	8	8	8
Hadronisation	19	18	18
Detector Systematics	14	10	14
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein Correlations	–	35	3
Other	4	5	4
Total Systematic	31	101	31
Statistical	32	35	29
Total	44	107	43
Statistical in absence of Systematics	32	28	21

- Main systematic problem: Final State Interactions in qqqq…
  - qqqq weight in the combined fit: 0.10

Final State Interactions between Ws

- Hadronisation scale: ~ 1 fm
- W lifetime/decay length very short: ~ 0.1 fm
- If both W → qq, independent hadronisation?



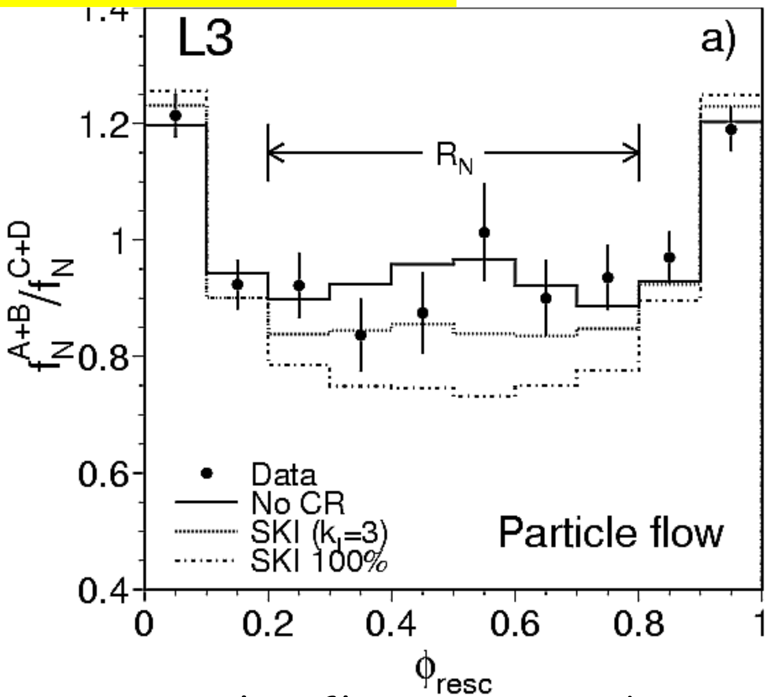
- Color reconnection: perturbative and non-perturbative cross talk between hadronising systems
- Bose Einstein correlations: between identical bosons from different Ws close in phase space

- Bias in reconstructed m_W ?
- At present their uncertainty is the limiting factor for LEP2 measurement

Color reconnection

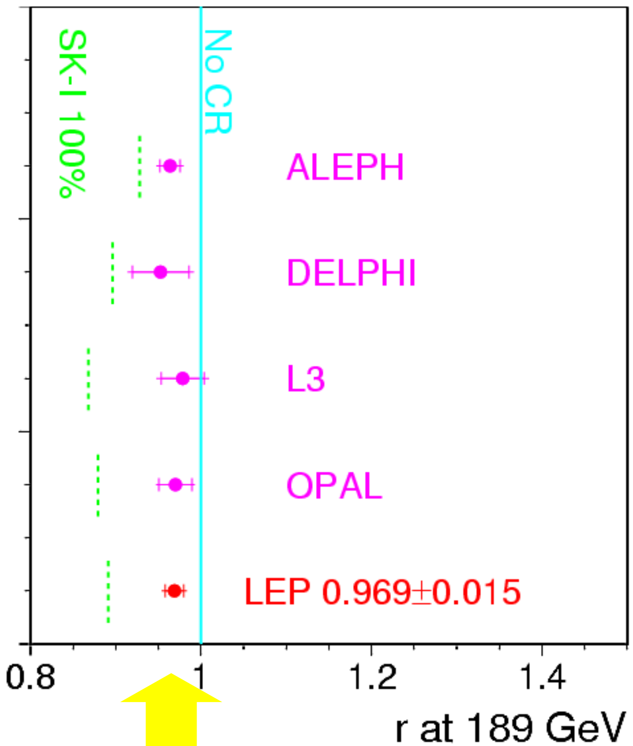
Possible sizable effects in the non perturbative regime

$$R = \frac{\int_{0.2}^{0.8} dn(intra-W)/d\phi}{\int_{0.2}^{0.8} dn(inter-W)/d\phi}$$



Inter-jet particles flux compared to phenomenological CR models

r=R(data)/R(no CR)

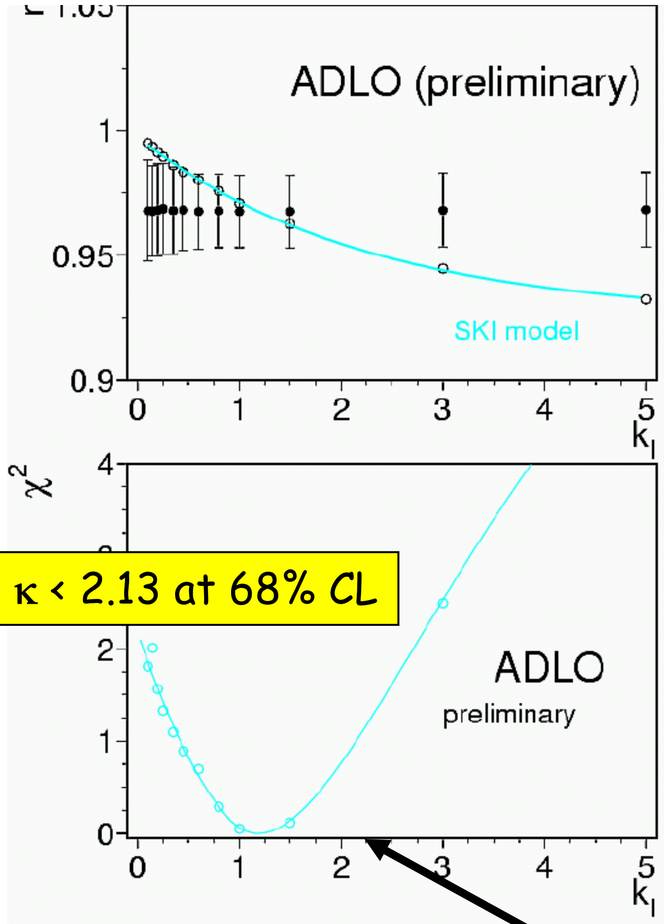


100% SKI CR model excluded at 5.2 σ

HERWIG,AR2 models: >3σ from no CR

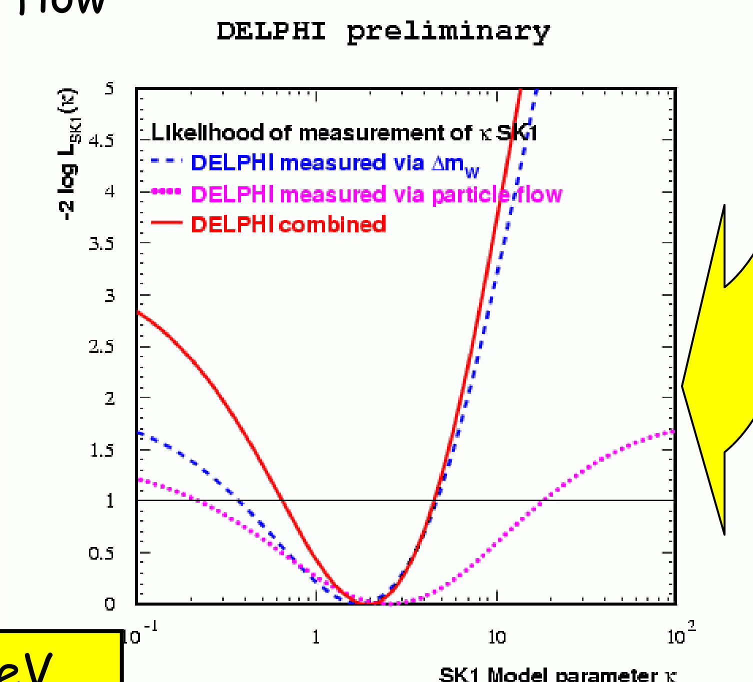
Color reconnection

Use r to tune the SKI parameter κ



0.39 < κ < 2.13 at 68% CL

- Idea: use in jets only particles in a cone or above a p cut
- Measure again m_W and compare with standard measurement: sensitivity to κ
- Uncorrelated with particle flow

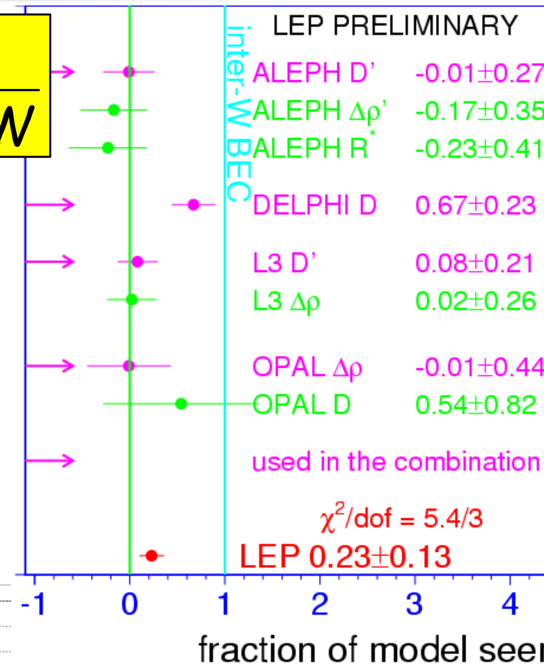


CR systematic δm_W = 90 MeV
Shift for SKI MC with κ= 2.13

Bose Einstein correlations

- BE systematic δm_W = 35 MeV LUBOEI model full interW-intraW
- Measurement of inter-W BE in data
- Reference sample from data: mix hadronic part of 2 $WW \to qql\nu$

$$\frac{data - intraW}{interW - intraW}$$

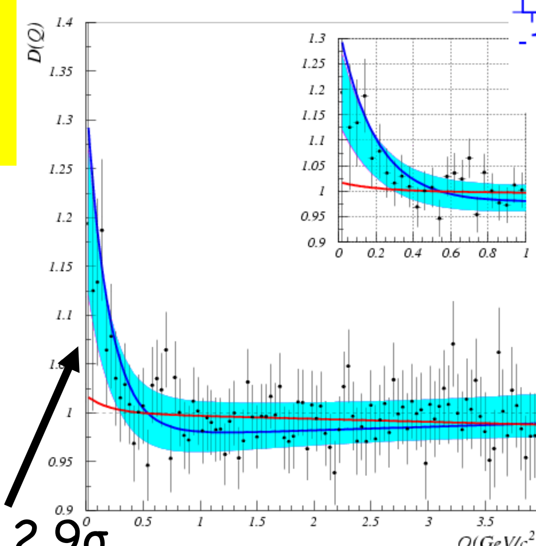


$$\Delta\rho(Q) = \rho^{WW} - 2\rho^{W} - 2\rho^{WW}_{mix}$$

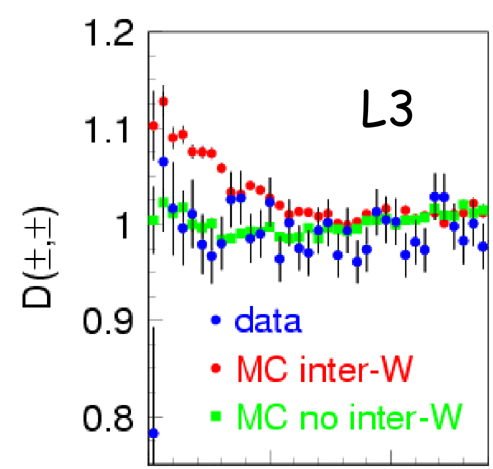
$$D(Q) = \frac{\rho^{WW}}{2\rho^{W} + 2\rho^{WW}_{mix}}$$

- If no inter-W BE: $\Delta\rho$=0 e D=1

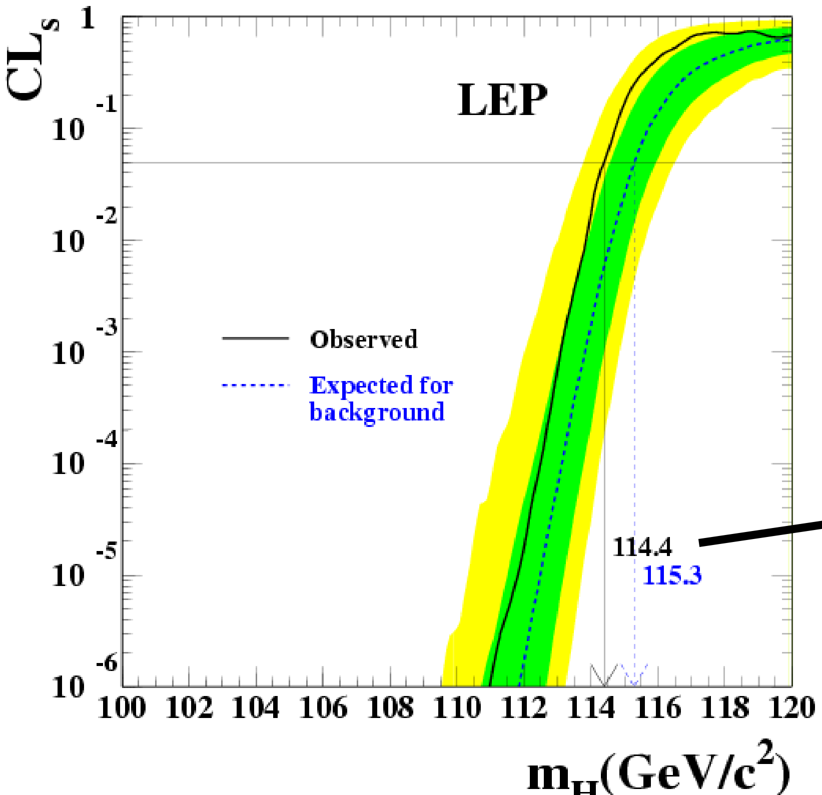
- If LEP combined fraction used $\delta m_W \sim O(10\ \text{MeV})$

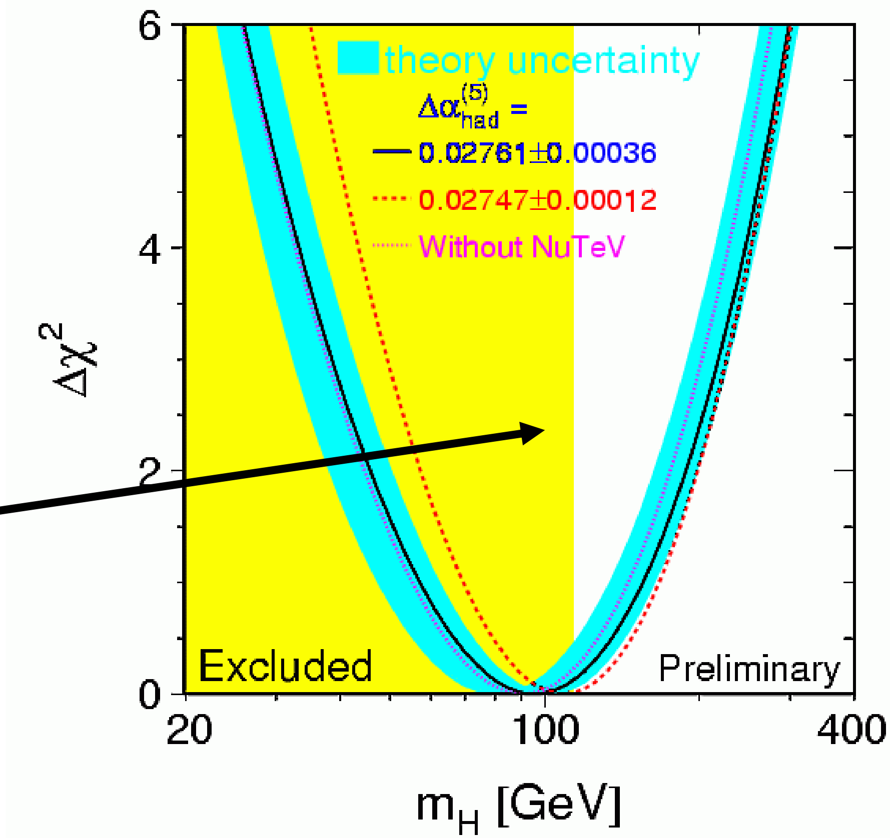


DELPHI: 2.9σ from no BE



SM Higgs: direct search vs EW fit result

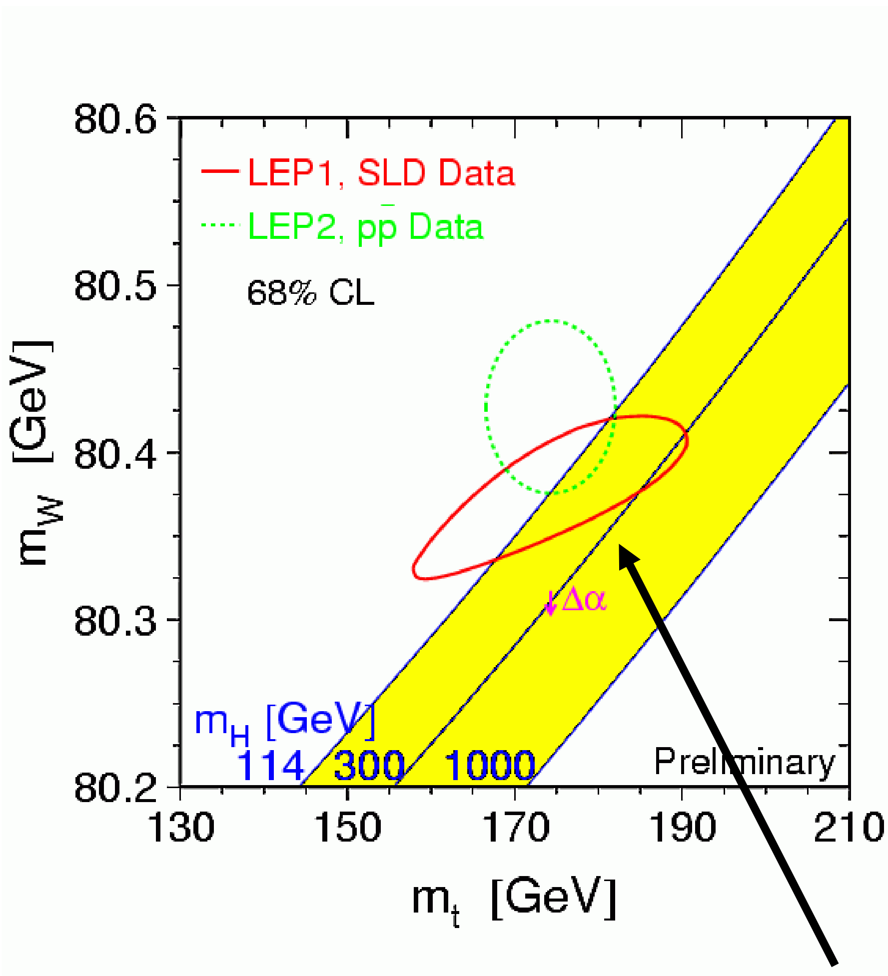


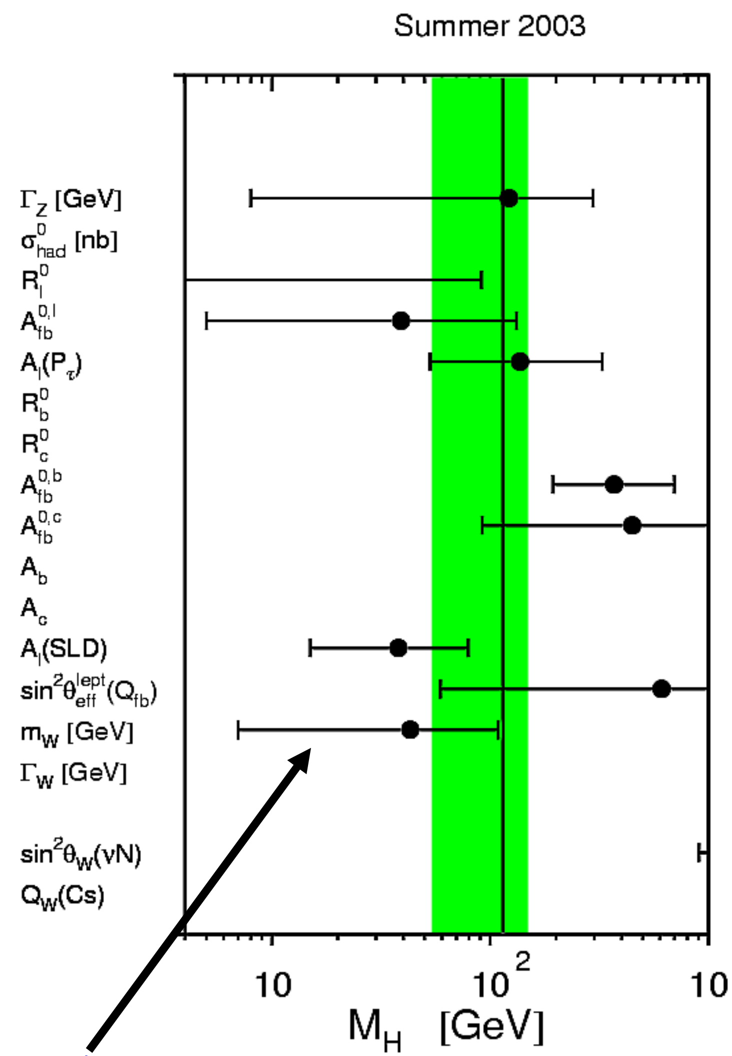


95% C.L.: 114.4 GeV/c^2
Direct search final LEP results

95% C.L. upper limit from fit: 219 GeV/c^2

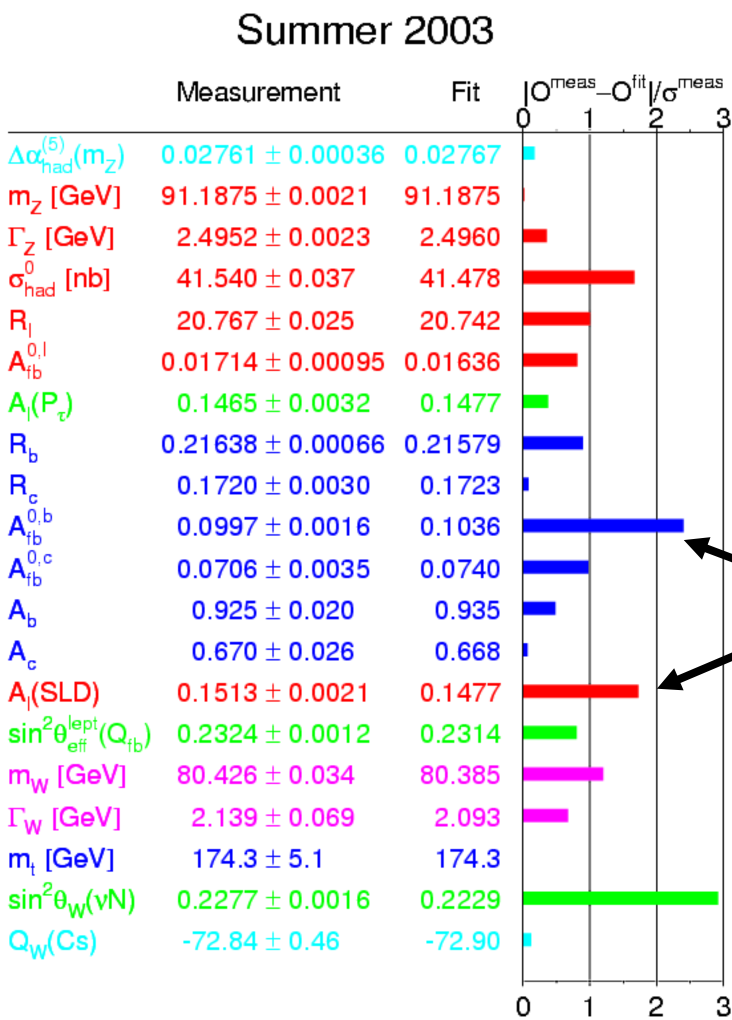
The global electroweak fit: constraints on SM Higgs





Low Higgs mass values preferred
(apart b quark A_{FB} at LEP)

The global electroweak fit: problems



- When all available data (LEP + SLD + Tevatron + NuTev + APV) are included:

X^2/dof = 25.4/15 (prob. 4.5%)

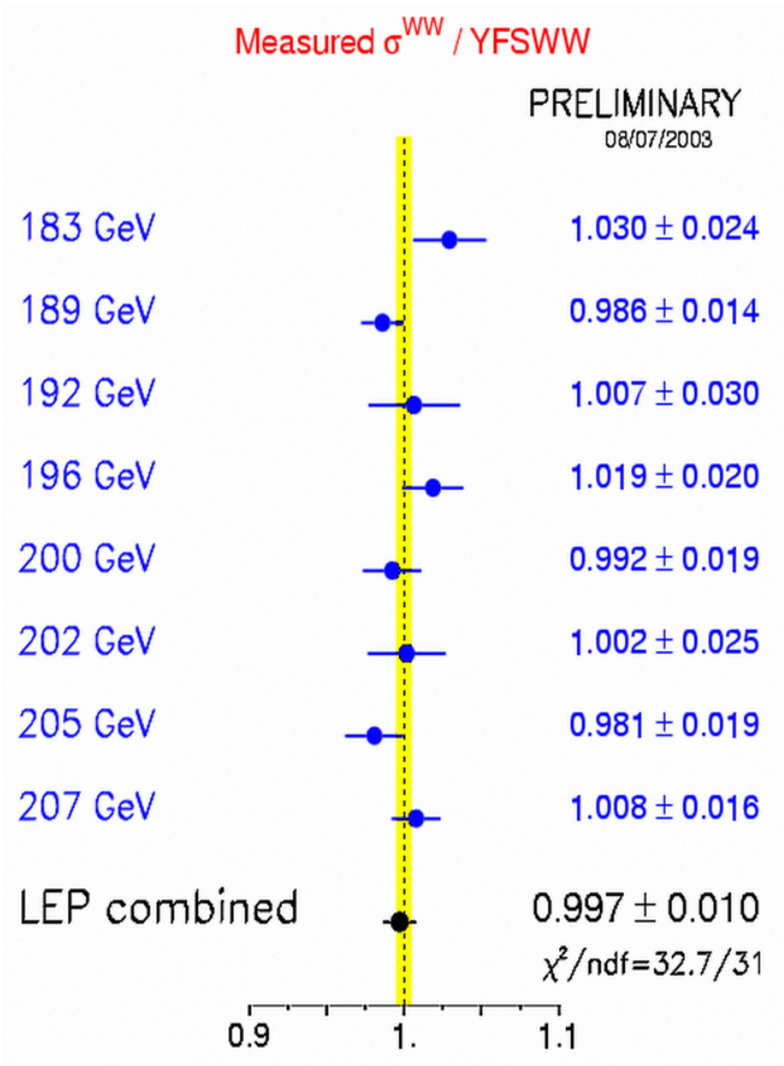
- A^b_{FB}(LEP) vs A_{LR}(SLD) : a long standing unresolved problem ($\Delta\sin^2\theta^{eff}_W$ ~2.9 σ)
- NuTev $\sin^2\theta_W$:big impact on the X^2 (16.7/14 if excluded) but a negligible influence on the Higgs mass

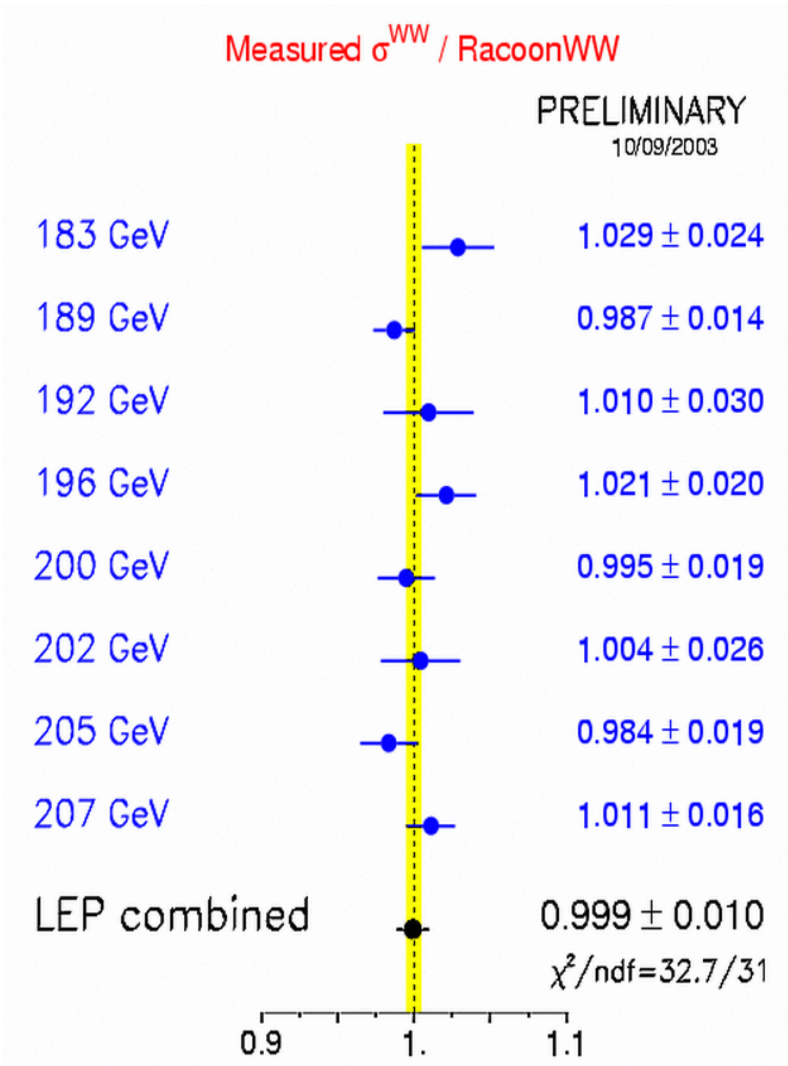
Conclusions

- LEP1 electroweak physics (almost) closed
- LEP2 has still to provide lots of final numbers
  - But the overall picture looks defined
- No news in the global electroweak fits
  - the problems are known
- Although LEP has not yet said its final word, the moment is approaching for Tevatron to take over in feeding new results into the electroweak fit!

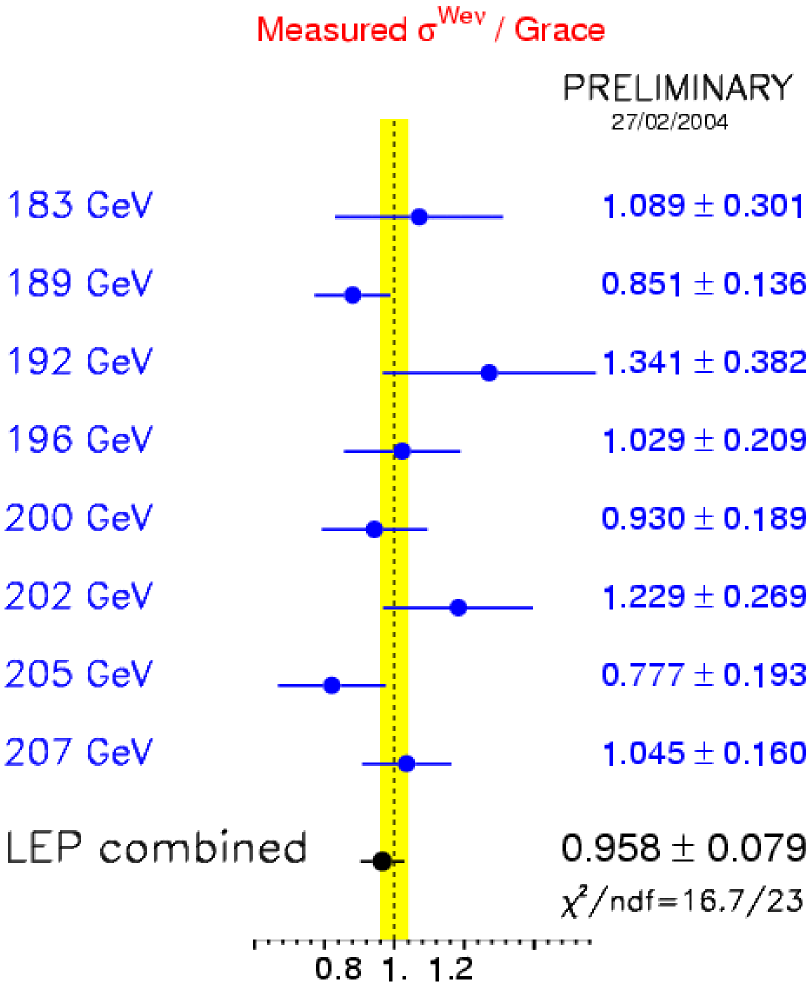
BACKUP TRANSPARENCIES

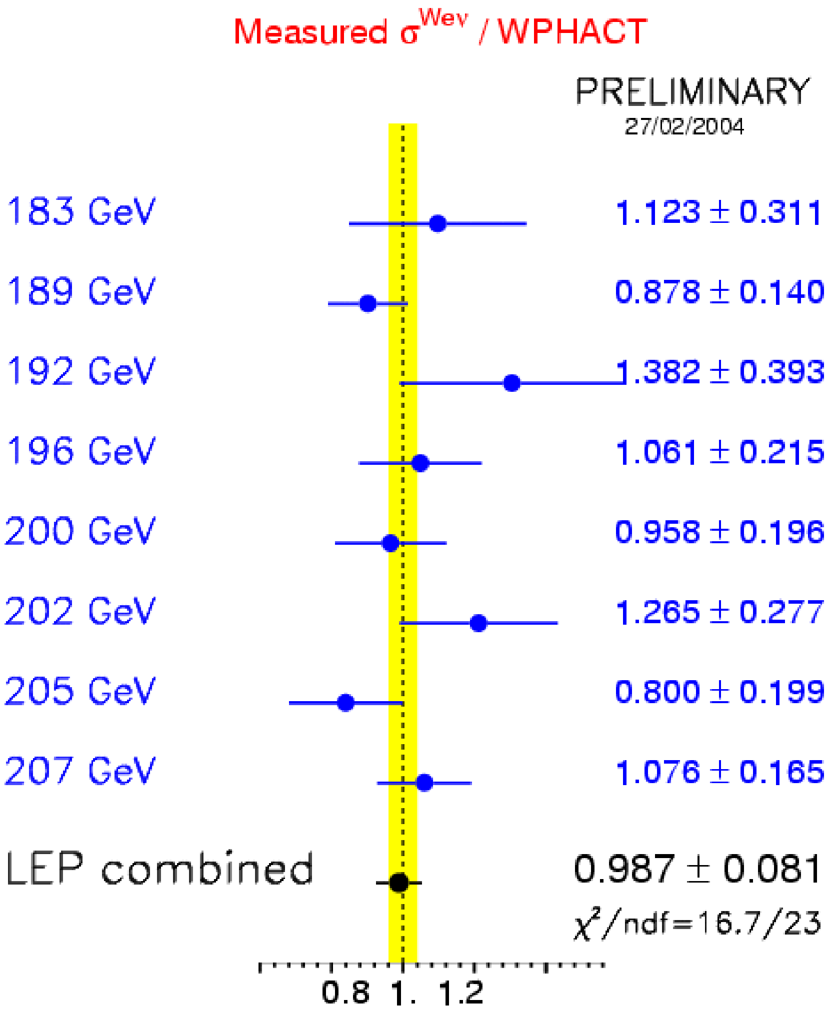
W pair production cross section



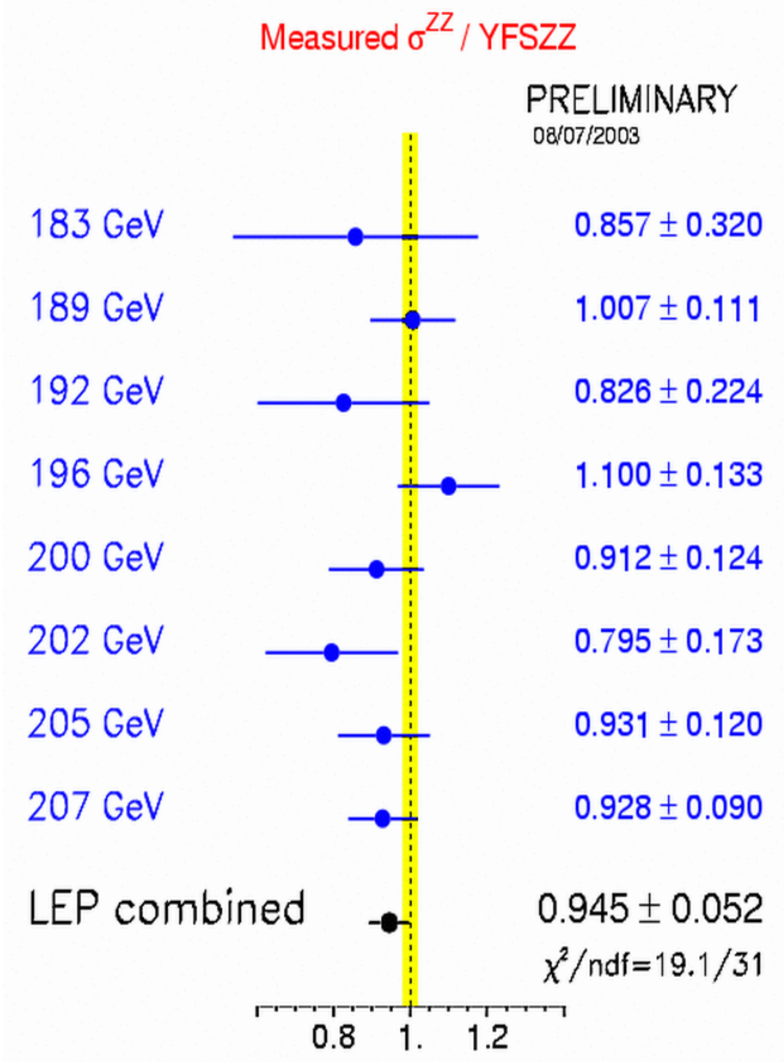


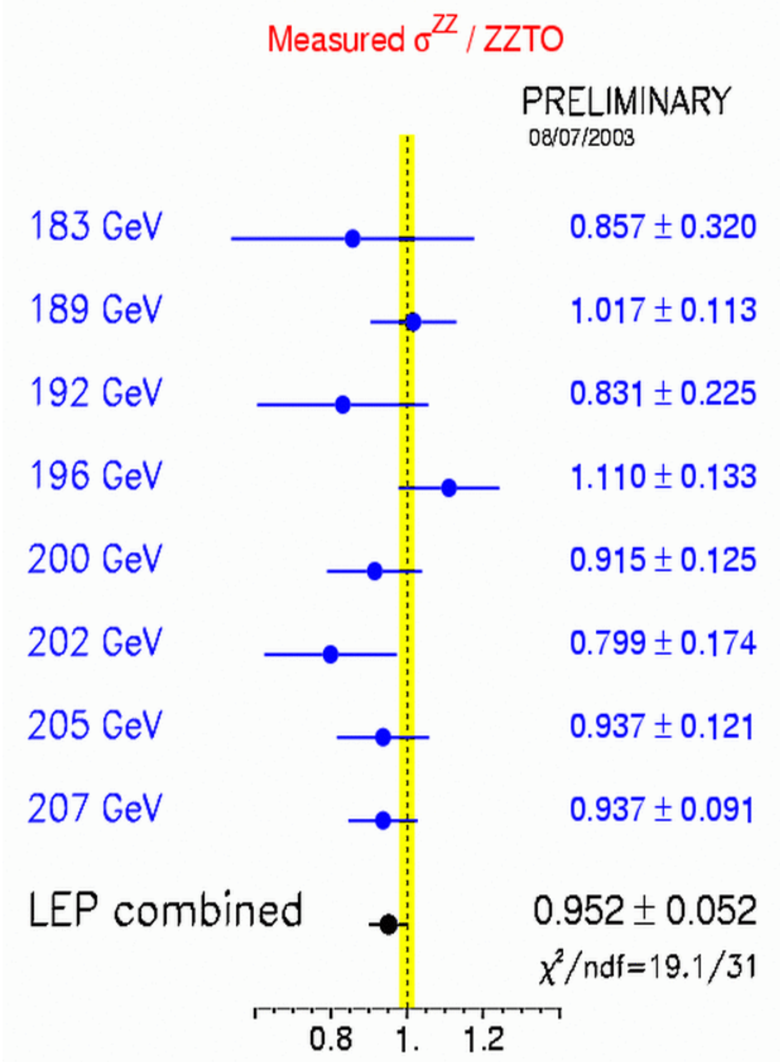
Single W production



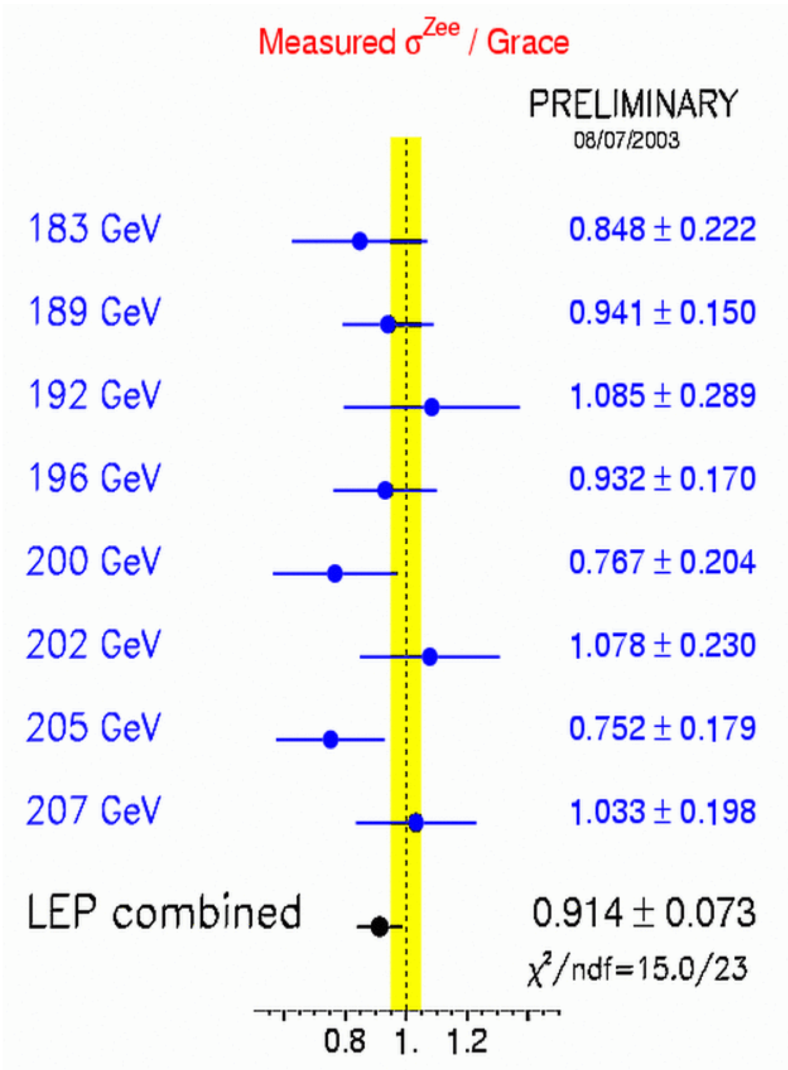


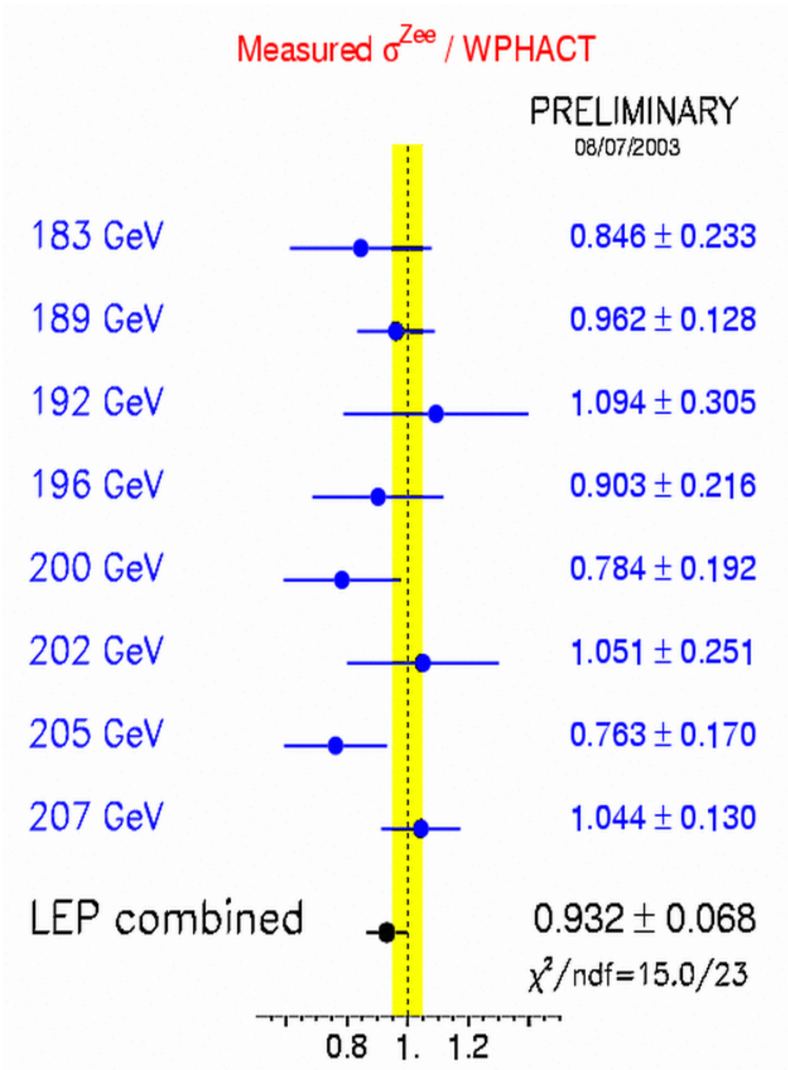
Z pair production cross section





Single Z production





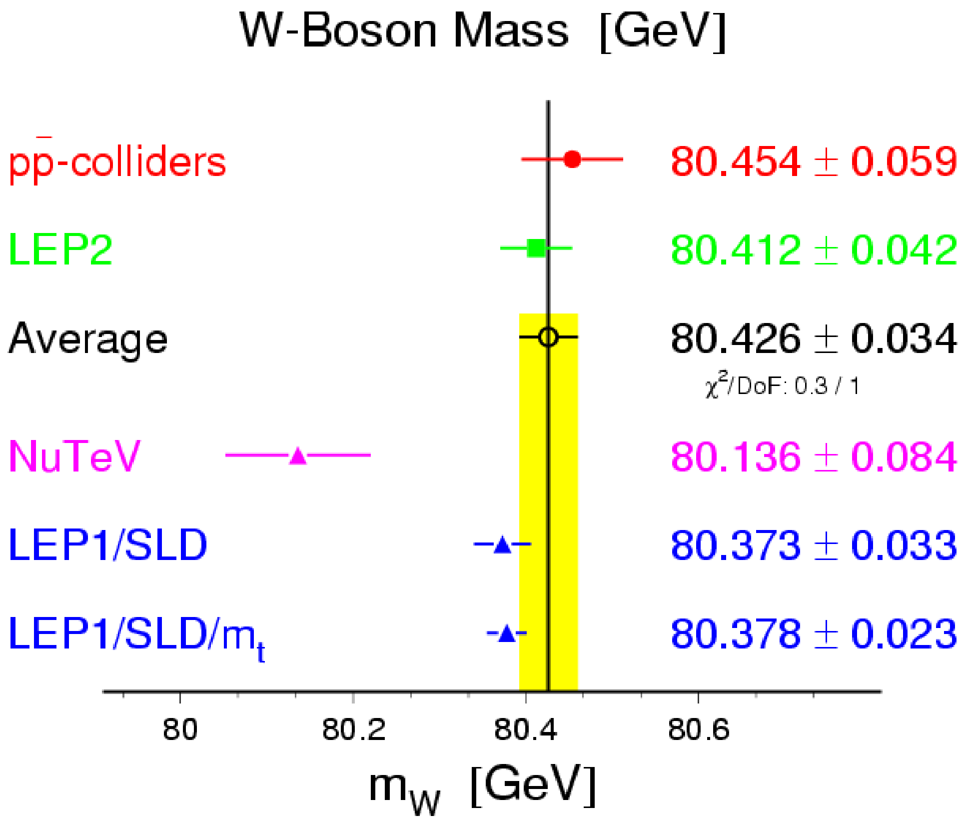
W mass: why do we measure it?

- In the Standard Model (SM):

$$m_W^2 = \frac{\alpha\pi}{\sqrt{2}s_W^2 G_F}\frac{1}{1-\Delta r(m_t, m_H)}$$

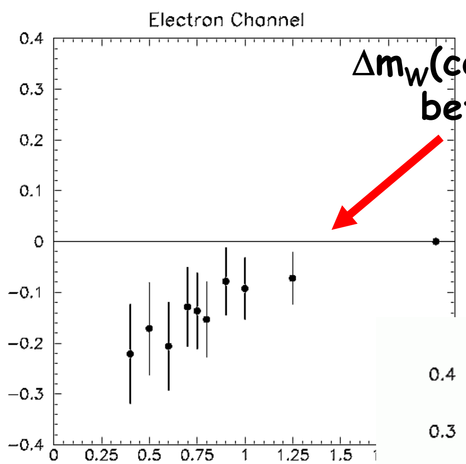
$$s_W^2 = 1 - m_W^2/m_Z^2$$

- W mass direct measurement:
  - Comparison with the indirect determination from other measurements in (e+e- $\rightarrow$ Z, νN) $\Rightarrow$ SM test
  - Higgs boson limits from electroweak fits



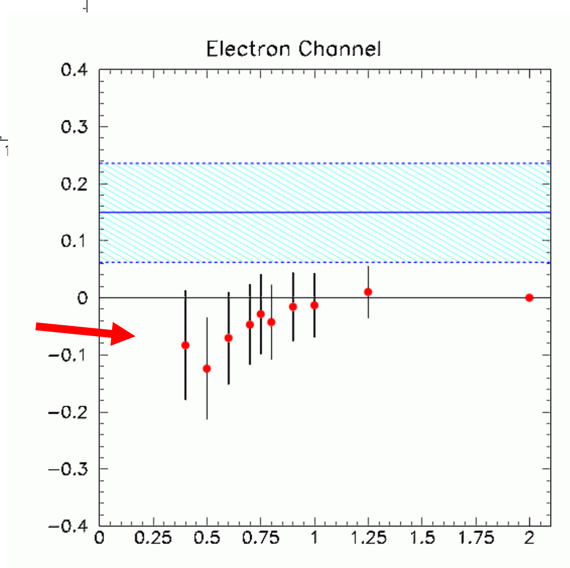
New ALEPH m_W result

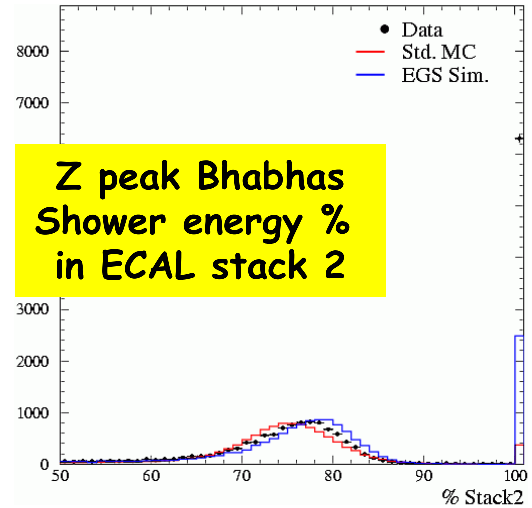
- Detector (ECAL) studies because of instabilities in m_W with p or cone cuts in jets



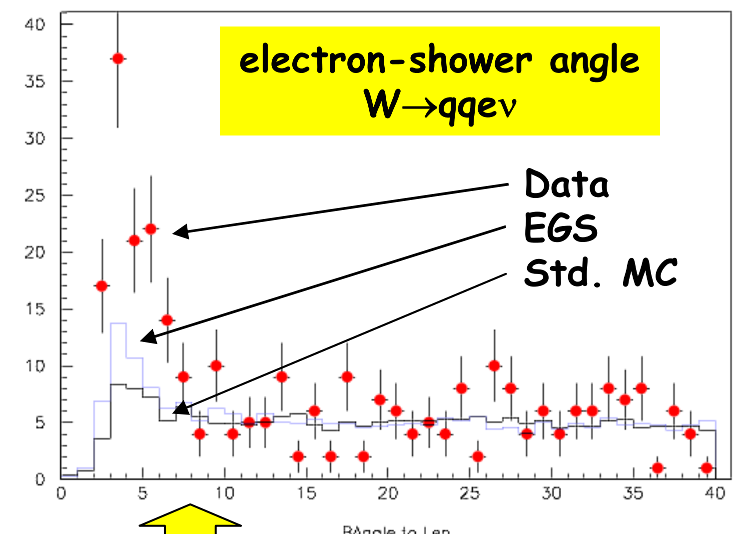
Δm_W(cone – std) in $W \to qqe\nu$ before EGS/cleaning

After EGS/cleaning





- Improve ECAL simulation (EGS)
- Clean residual single stack showers



Cut here

m_W systematics at LEP2: LEP energy

- Constrained kinematic fit:

$$\Delta\sqrt{s}/s = \Delta m_W / m_W$$

- Main method:
  - Resonant depolarisation up to 60 GeV
  - NMR probes give local field in dipoles $\Rightarrow$ extrapolate with $E_{beam} = a + bB_{NMR}$
  - Cross check integrated field with "Flux loop"

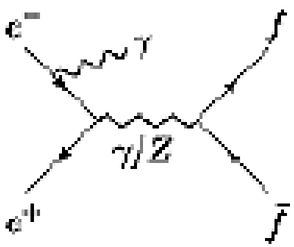
$\delta E_b \cong 15$ MeV

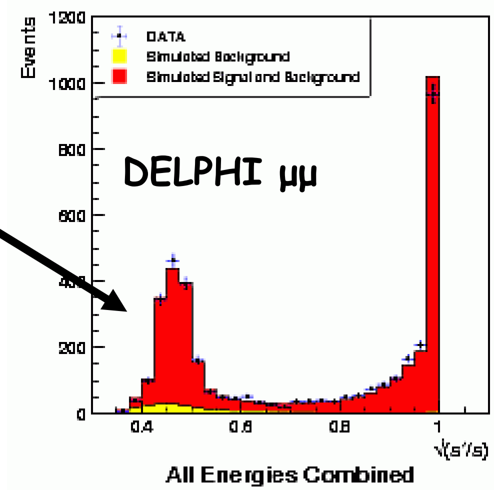
- Synchrotron tune Q_S vs V_{RF} :
  $\delta E_b \cong 20$ MeV

- LEP Spectrometer (1999-2000)
  - Energy from beam curvature in a known magnetic field at 0.001%
    $\delta E_b \cong 20$ MeV

- Radiative return to Z peak in e+e- $\rightarrow$ ffγ

$$\delta m_Z / m_Z \cong 10^{-5}$$





- δE_b = -14 ± 21(stat.) ± 20(syst.) ± 20(LEP) MeV

m_W systematics at LEP2: hadronisation

- m_W kinematic reconstruction:
  - Jet characteristics
  - Particle assignment
- Hadronisation models tuned in $Z \to qq$ on peak
  - High statistics
  - Detailed studies
- Compare JETSET/ARIADNE/HERWIG
- Different tunings/models imply differences at 10-50 MeV
  - Baryon/kaon rates relevant due to pion/γ mass assignment in analysis!
  - But when same tuning/model reasonable consistency between experiments

- Data/MC comparison
  - Exploit mainly Z on peak data
  - Check jets characteristics not well described by tunings
  - Both hadronisation and detector effects

- Mixed Lorentz Boosted Z (DELPHI):
  - Pseudo WW events from 2 Z peak hadronic events mixed and boosted
  - Constrained fit data/MC comparison (high statistics)
  - Result interpretation? (both hadronisation and detector effects)