Recent ElectroWeak Results from LEP

Aspen 2001 Winter Conference

on Particle Physics

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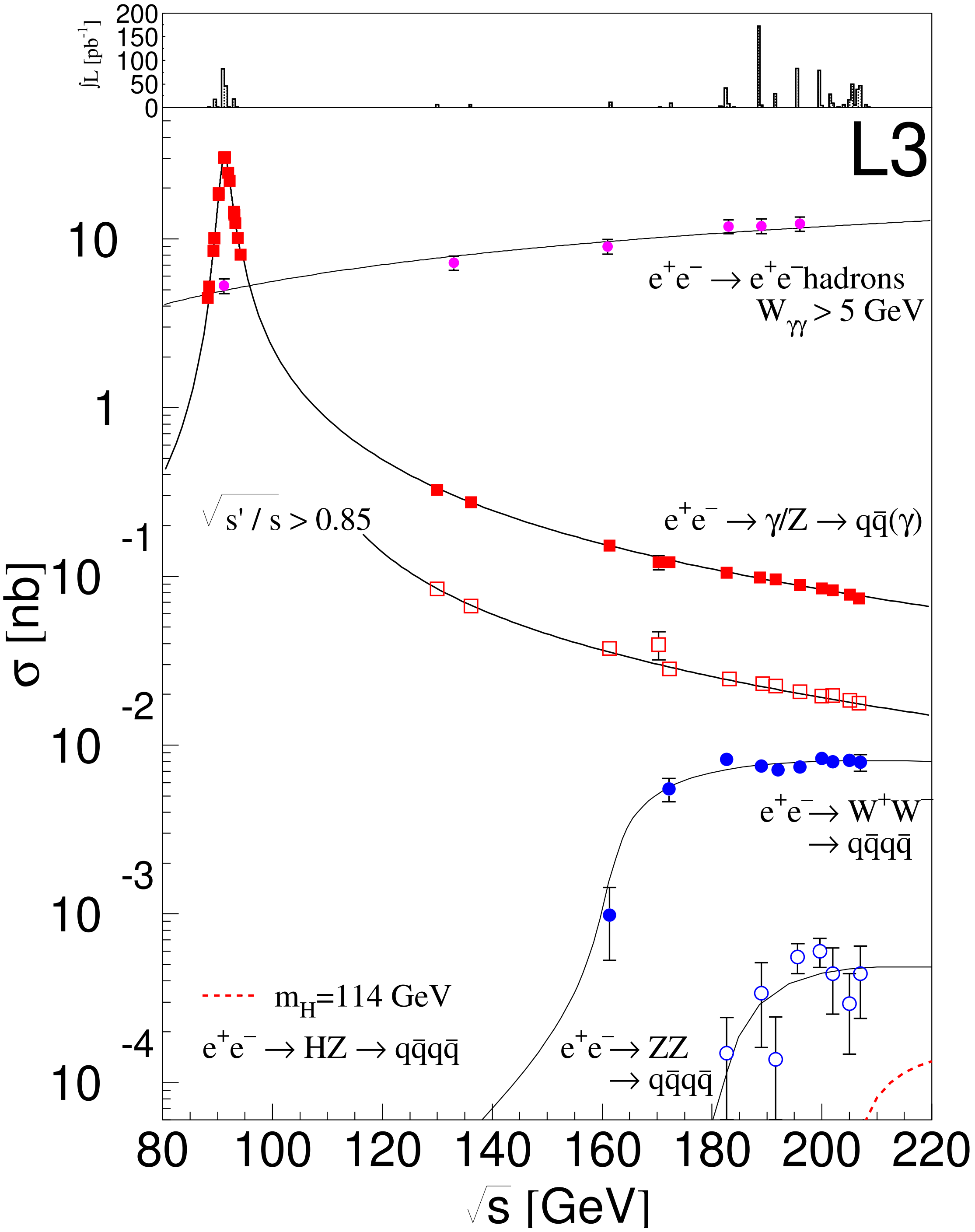
On behalf of ALEPH, DELPHI, L3, OPAL

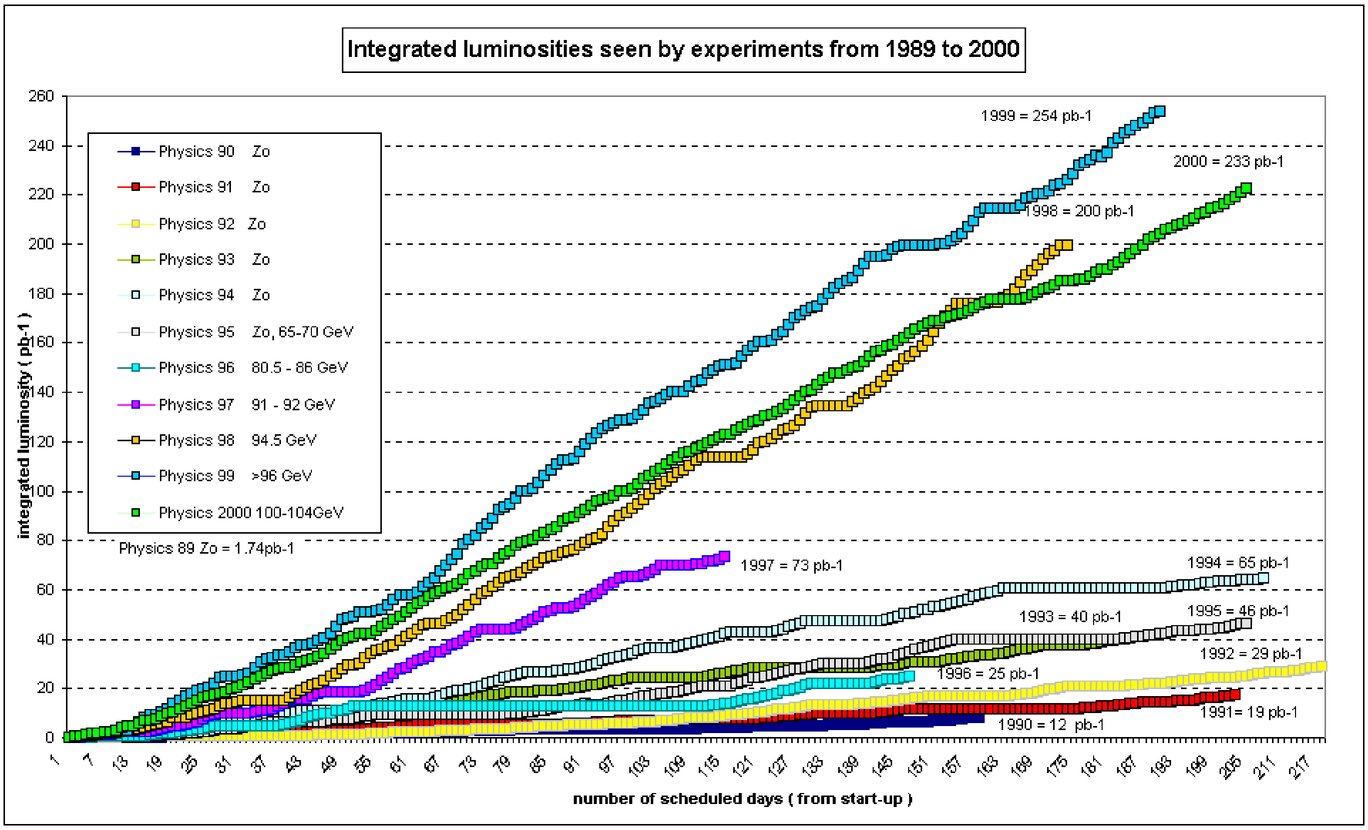
- **LEPII**
  - **Data recorded 1996–2000**
  - **Last $\sim$2 years results preliminary**
  - **Combined results from Summer 2000 ($\sim$60/30 pb^{-1} at 205/207 GeV).**
- **Last (?) word from LEPI & global fits**

Setting the scene

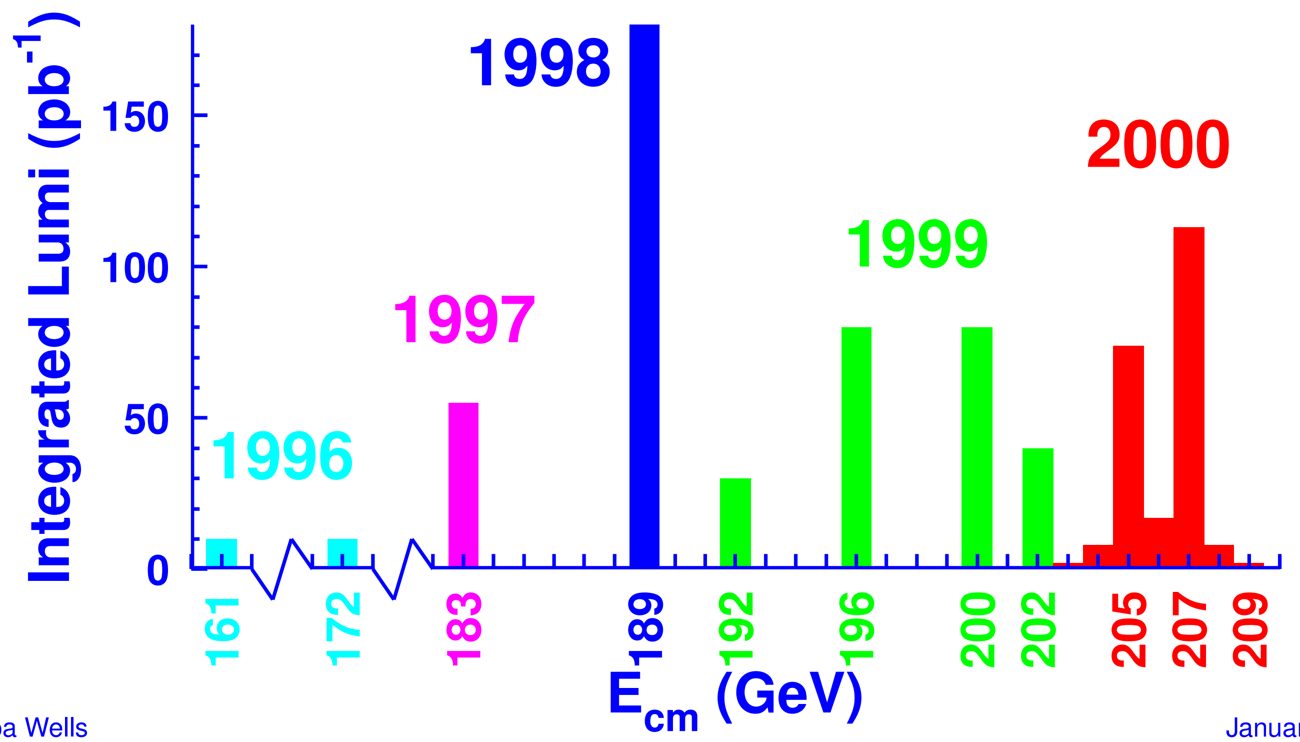
$$\sigma(\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{hadrons})$$



LEP luminosity performance



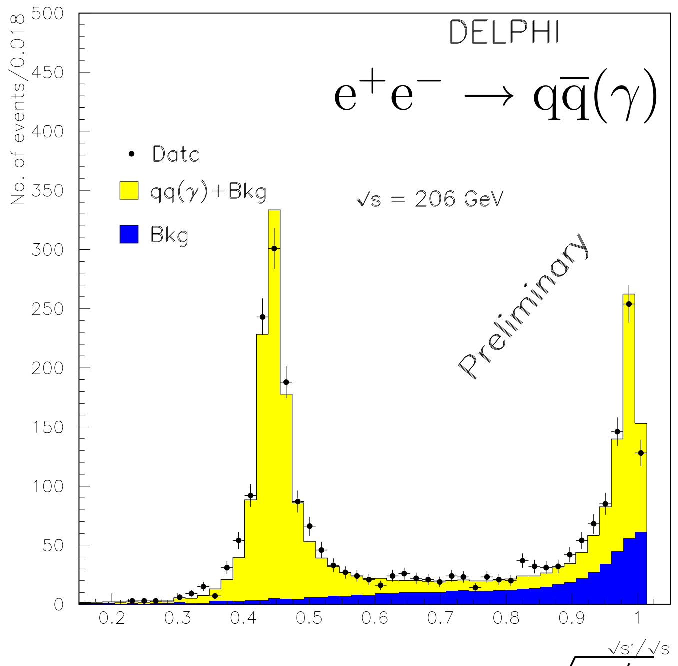
1989-2000 Total LEP luminosity 1000 pb^{-1}



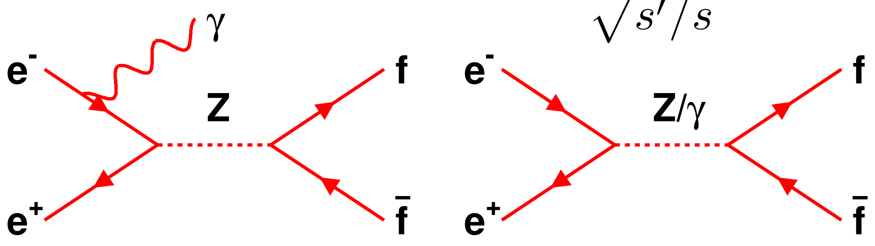
Fermion pair cross sections

$$\sigma(s) = \int \mathcal{R}_{\mathrm{QED}}(s', s)\sigma_{\mathrm{EW}}(s')\mathrm{d}s'$$

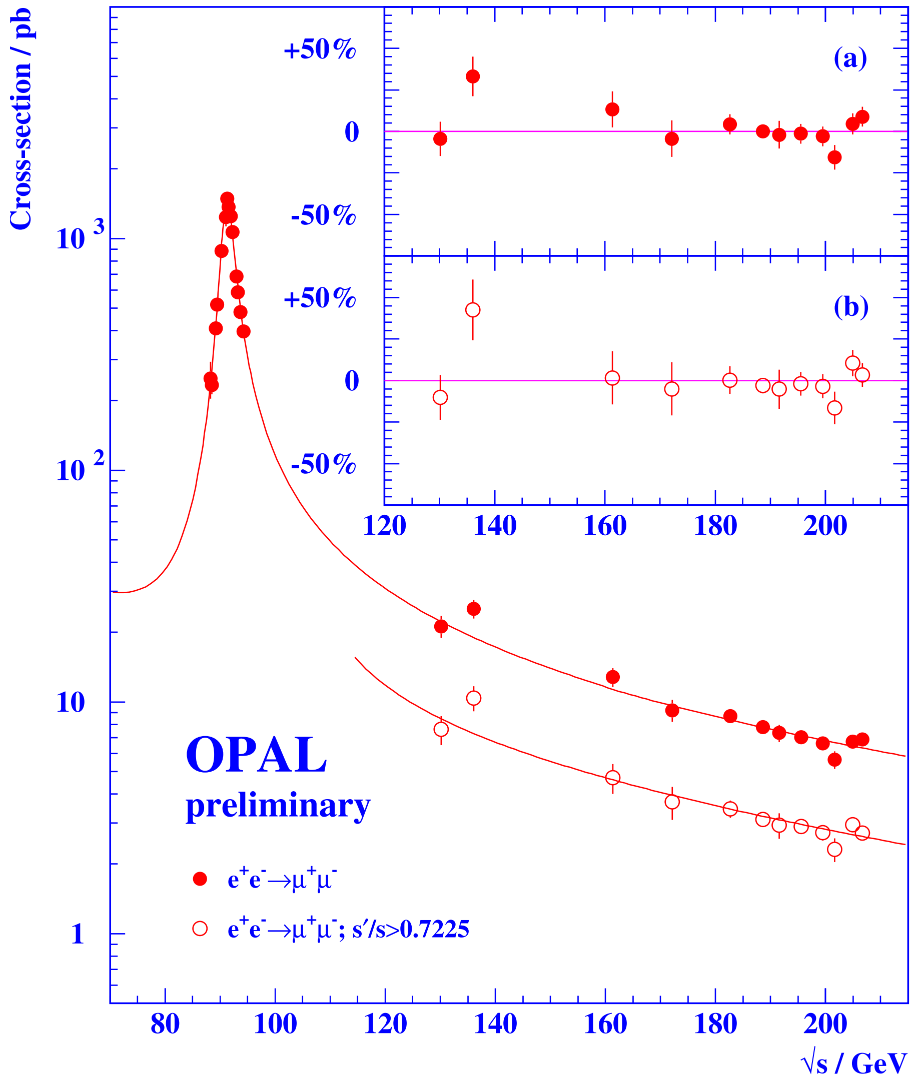
$\sqrt{s'}$ mass of fermion pair



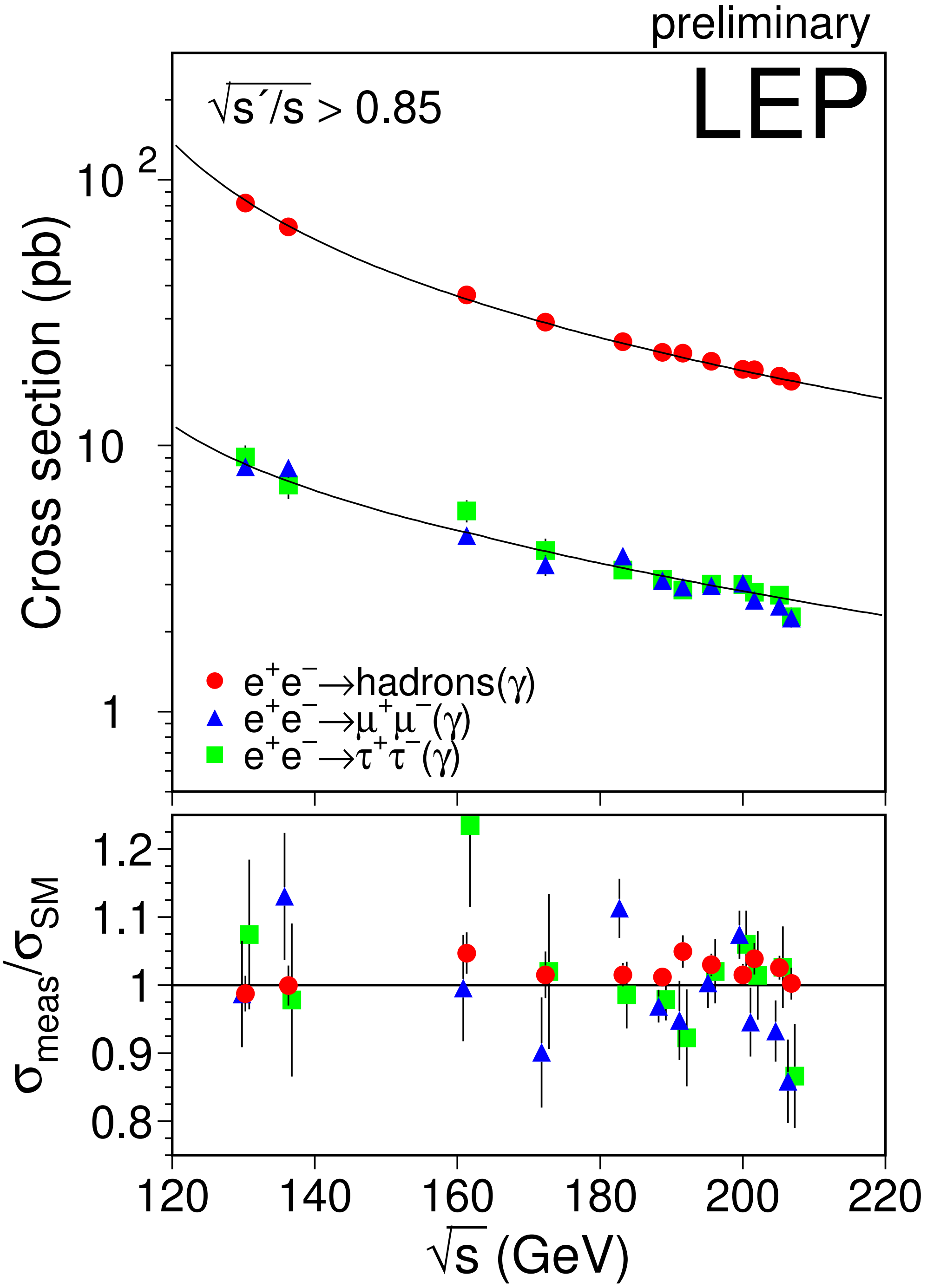
$\sqrt{s'/s}$



$e^+e^- \to \mu^+\mu^-(\gamma)$

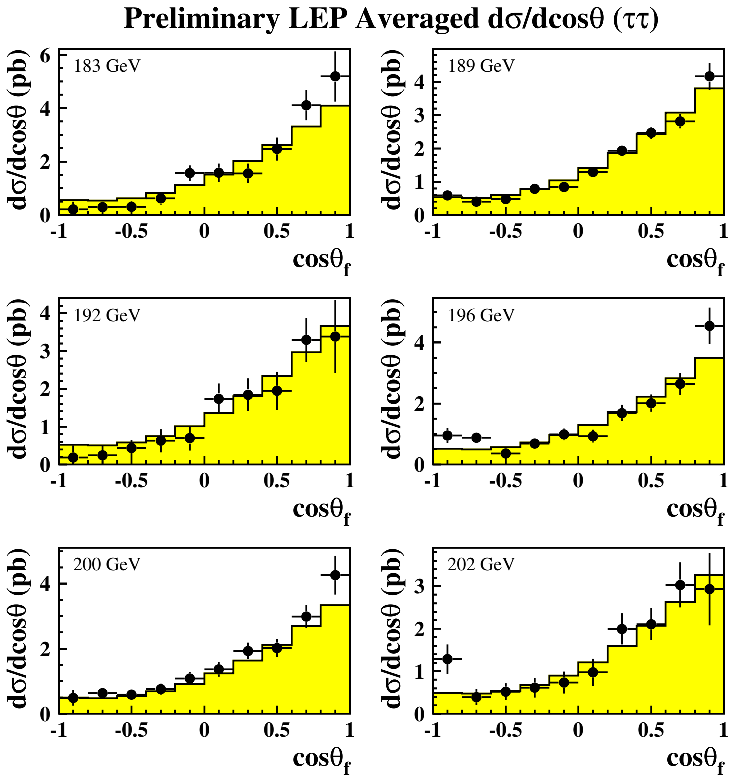


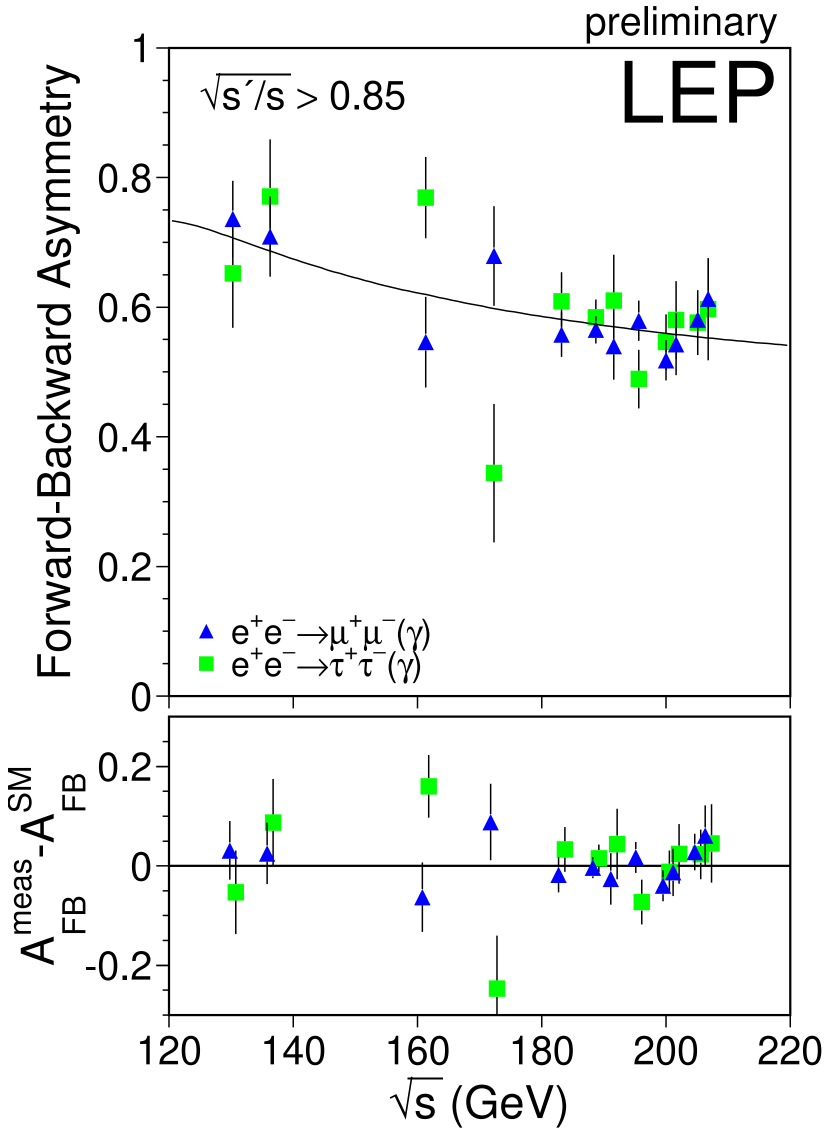
Fermion pair - LEP combined

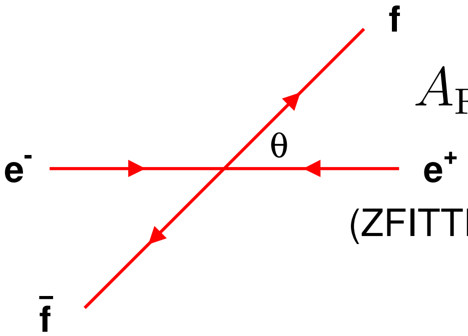


- Measured: hadrons, $\mathrm{b\overline{b}}$, $\mathrm{c\overline{c}}$, $\mathrm{e^+e^-}$, $\mu^+\mu^-$, $\tau^+\tau^-$
- ZFITTER curve – uncertainty $\sim$ 0.5%
- Average over all energies, $\mathrm{q\overline{q}}$ excess of 2.5σ

Lepton pair forward-backward asymmetry







$$A_{\rm FB} = \frac{\sigma(\theta<90^\circ)-\sigma(\theta>90^\circ)}{\sigma(\theta<90^\circ)+\sigma(\theta>90^\circ)}$$

(ZFITTER uncertainty $\sim$ 0.003 in $A_{\rm FB}$)

Constraints on new physics from ff

Combined LEP limits on M(Z')

Model	χ	ψ	η	L-R	SSM
Limit (GeV)	630	510	400	950	2260

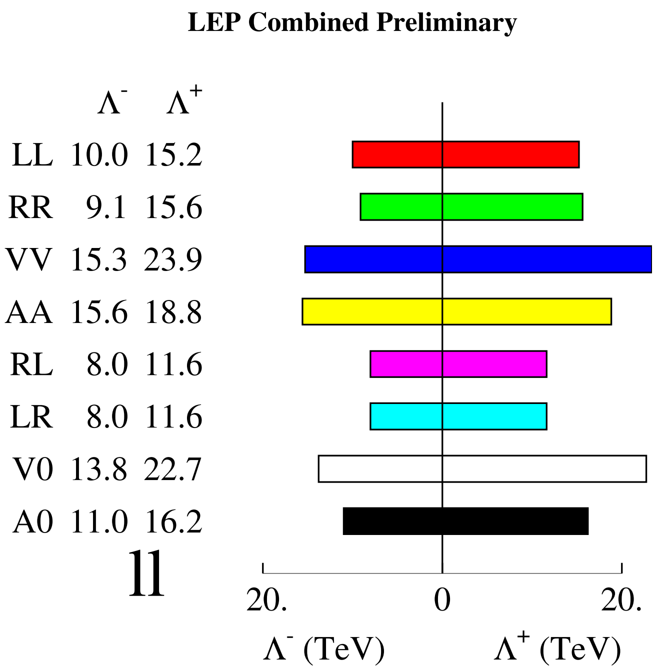
(Z/Z' mixing angle close to zero from LEP1)

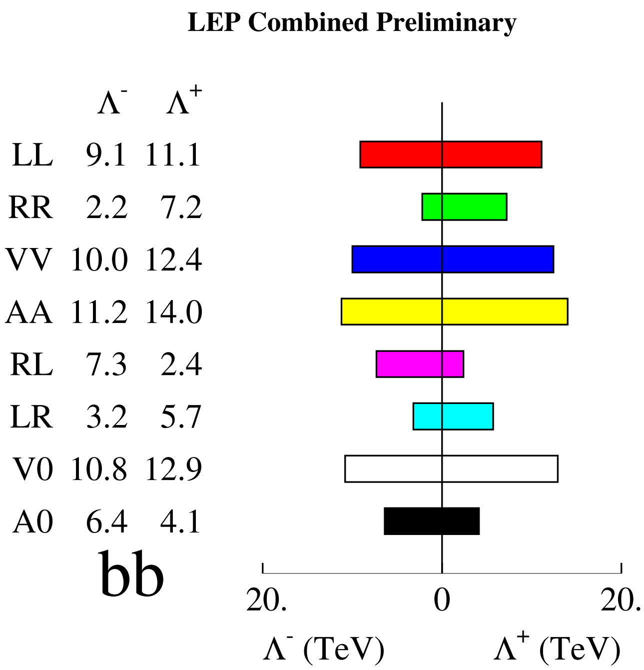
Contact interactions

$$\mathcal{L}^{\mathrm{contact}} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{i,j=\mathrm{L,R}} \eta_{ij} [\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i][\bar{\mathrm{f}}_j \gamma_\mu \mathrm{f}_j]$$

$g^2/4\pi = 1$; $\delta = 1$ for $\mathrm{f} = \mathrm{e}$, otherwise 0; models give $\eta_{ij} = \pm 1, 0$.

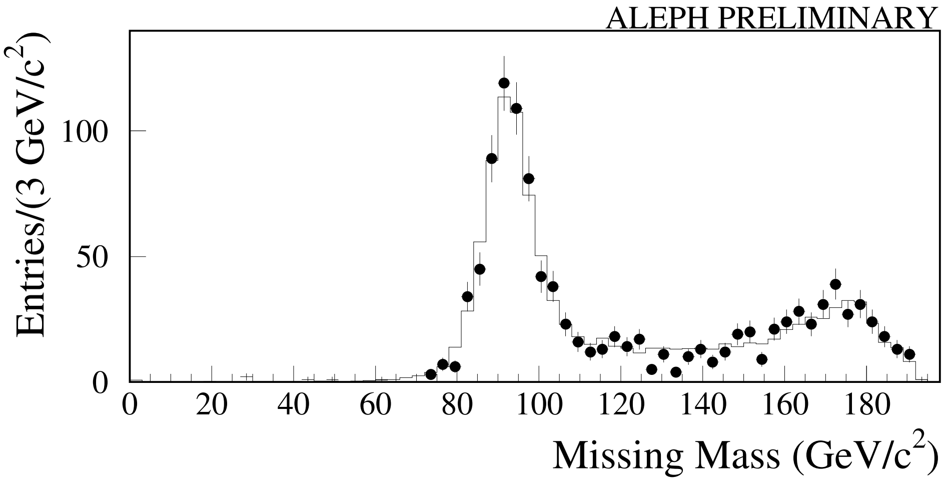
Limits o(10TeV)





Photons, QED tests...

- Rate of $\nu\bar{\nu}\gamma$ - check missing mass spectrum for radiative return to Z.



Limits eg. on $\mathrm{e}^+\mathrm{e}^- \to XY \to YY\gamma$, gravitino

- $\gamma\gamma(\gamma)$ - pure QED process at tree level.
  QED cutoff parameters $\gtrsim$ 320 GeV.

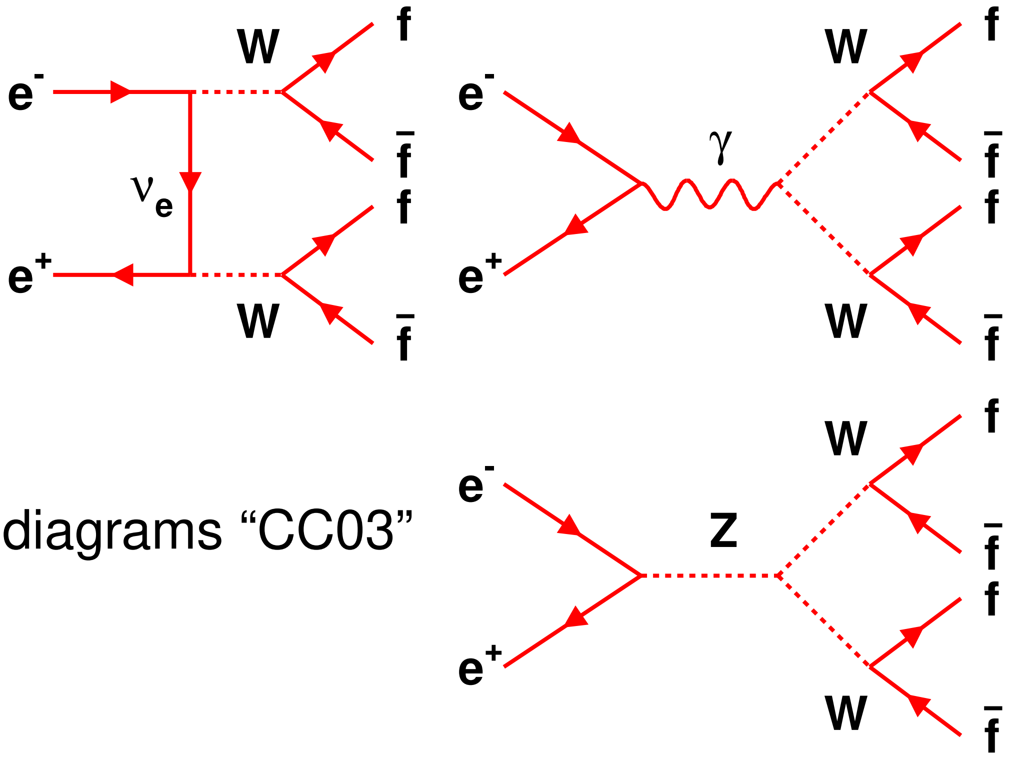
- $\gamma\gamma$ and missing energy - many searches, and also quartic gauge couplings (see later)

- Running of α_{em} from Bhabha scattering (L3) or two-fermion data (OPAL)

- Quasi-real compton scattering, $\gamma\mathrm{e} \to \gamma\mathrm{e}$ (L3,OPAL)

- No sign of new physics

$e^+e^- \longrightarrow W^+W^-$



3 diagrams “CC03”

W decays to 68% $\mathrm{q\bar{q}}$, 32% $\ell\nu$, so WW events are:

- 46% $\mathrm{q\bar{q}q\bar{q}}$ typically 4 jets

  effic/purity $\sim$ 90%/80%

- 44% $\mathrm{q\bar{q}}\ell\nu$ 2 jets, one charged lepton, missing p

  effic/purity $\sim$ 80%/90%

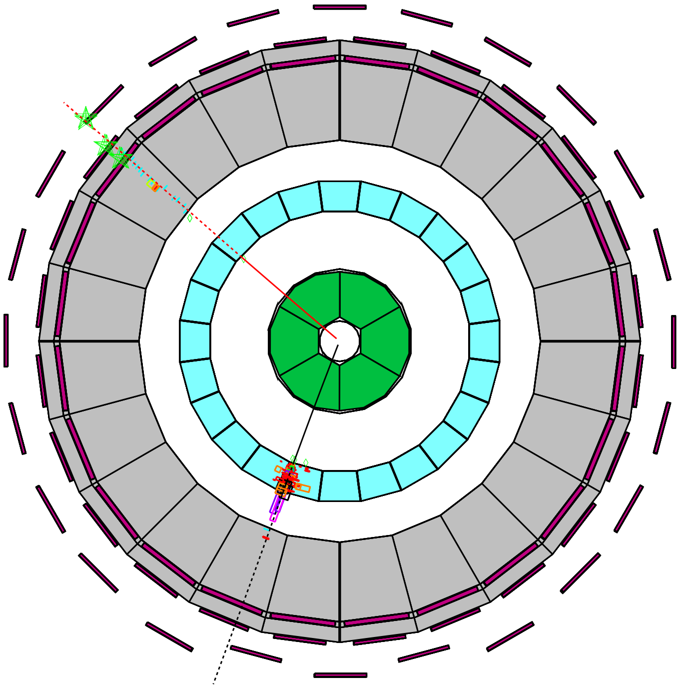
- 10% $\ell\nu\ell\nu$ two charged leptons, missing p

  effic/purity $\sim$ 60–80%/90%

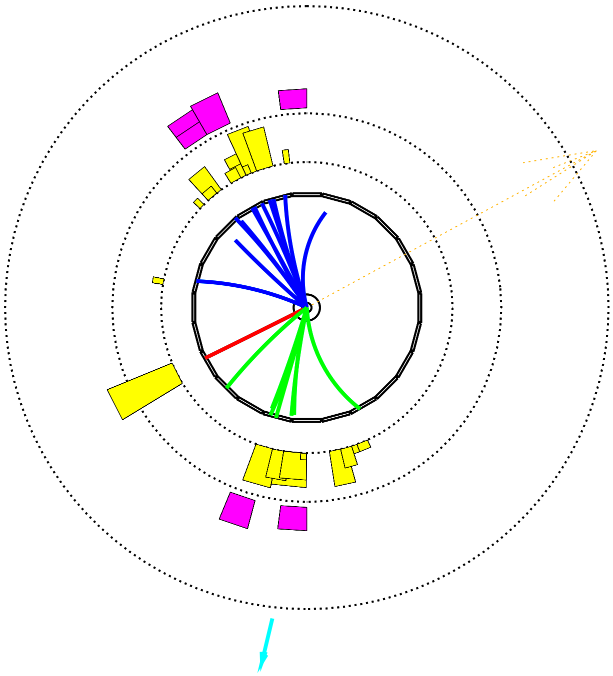
12 000 WW produced/experiment ($\sim$17 pb $\times$ 700 pb^{-1}).

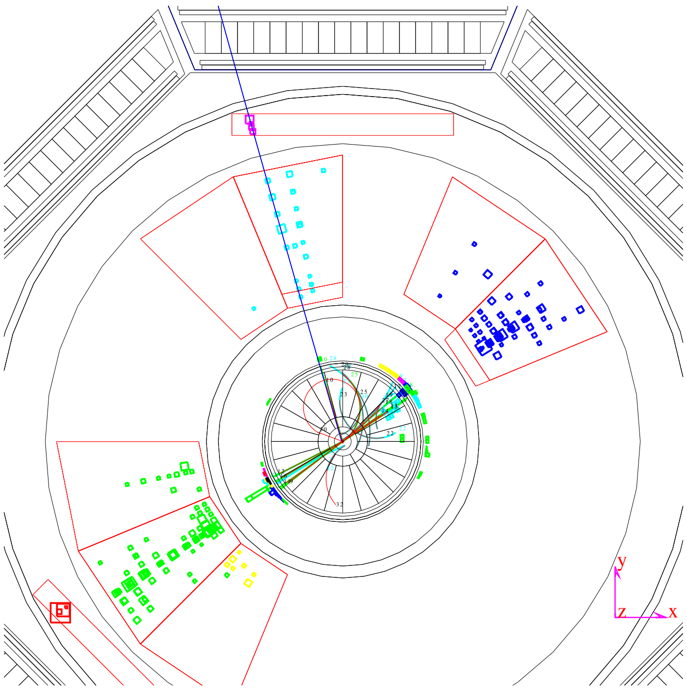
WW events

$W^+W^- \rightarrow \ell\nu\ell\nu$

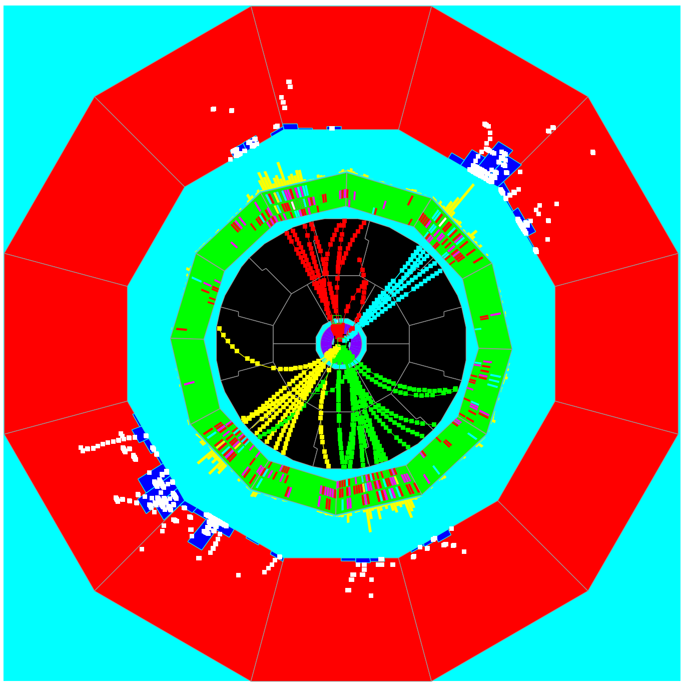


$W^+W^- \rightarrow q\bar{q}e\nu$



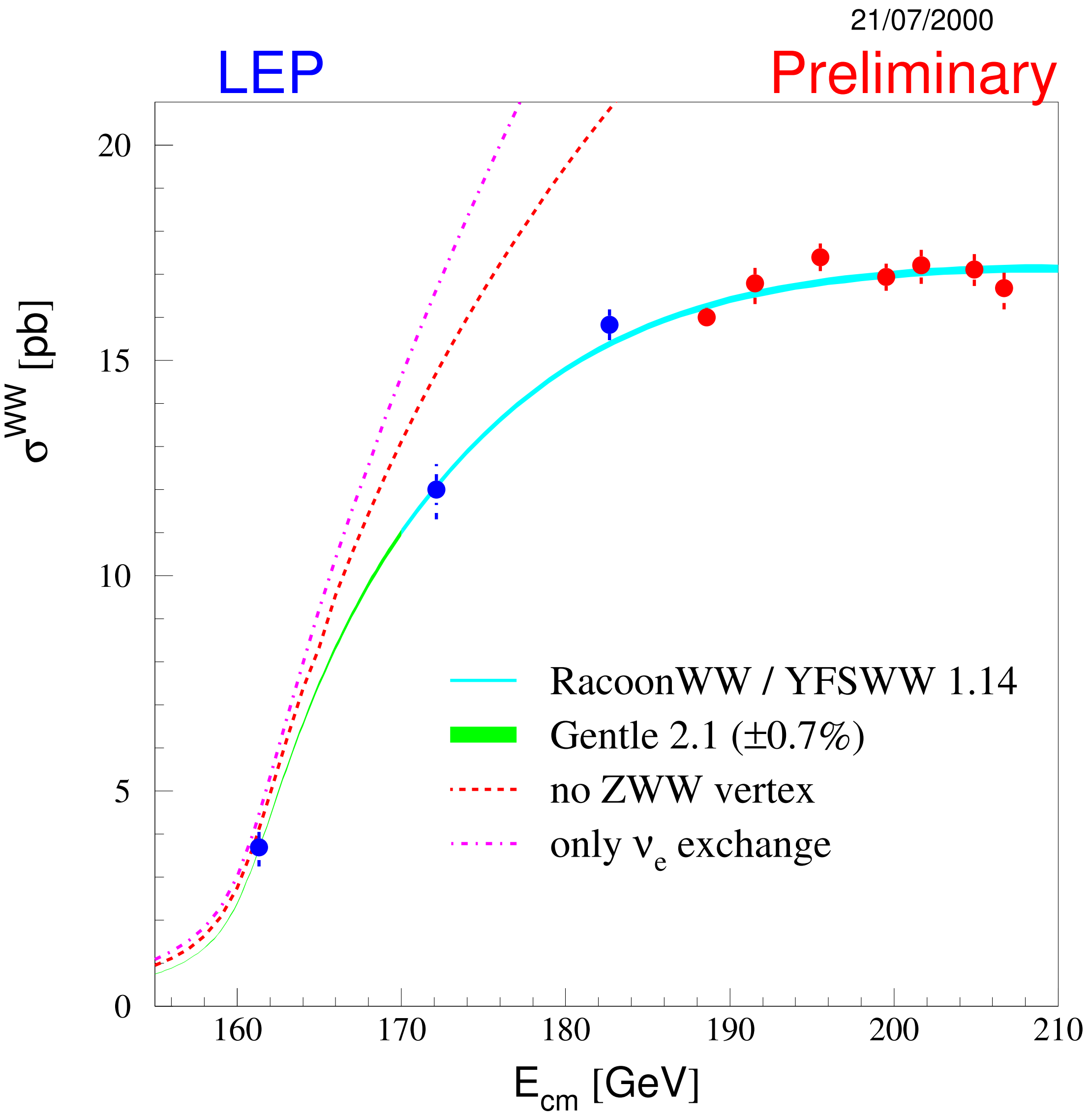


$W^+W^- \rightarrow q\bar{q}\mu\nu$



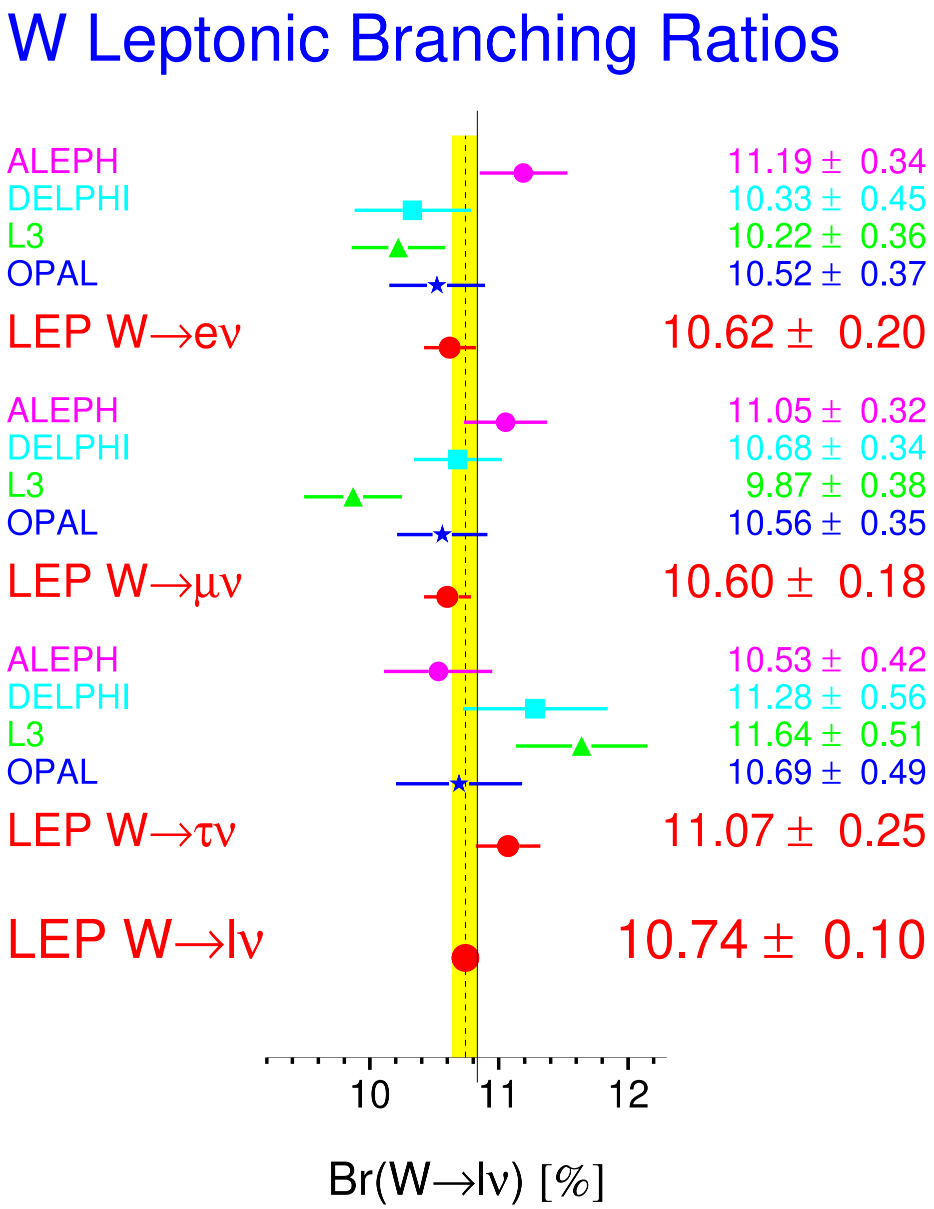
$W^+W^- \rightarrow q\bar{q}q\bar{q}$

W production cross section



- Sensitivity to mass at threshold (only 10 pb^{-1}).
- Sensitivity to gauge couplings - beautiful demonstration of non-abelian nature of electroweak theory.

W branching ratios



Test of lepton universality in W decay at 3.3% level.

Assuming lepton universality

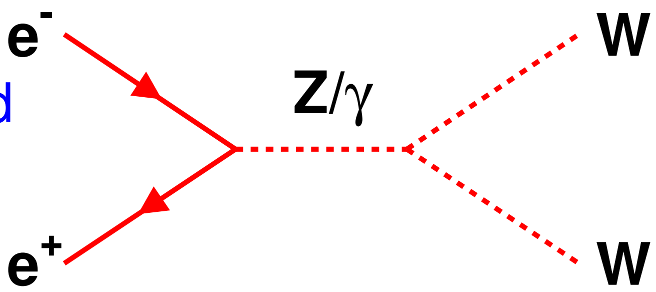
$$\mathrm{Br}(\mathrm{W} \to \mathrm{q}\overline{\mathrm{q}}) = (67.79 \pm 0.32)\%$$

Interpret as $|V_{\mathrm{cs}}| = 0.989 \pm 0.016$

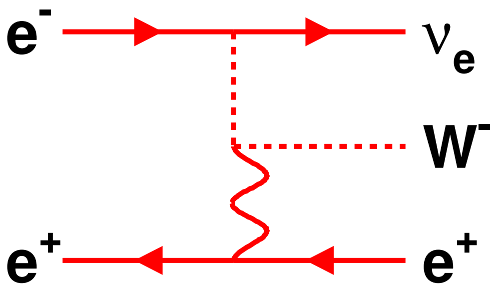
Triple gauge couplings

- 14 possible couplings for $\mathrm{WW}\gamma$ plus WWZ reduced to 6 by EM gauge invariance & CP conservation:
  g_1^{z}, κ_γ, κ_{z} (=1 in SM), λ_γ, λ_{z}, g_5^{z} (=0 in SM).
  (g_5^{z} violates C and P; assume couplings real).
- Plus SU(2)xU(1) relations and Z resonance constraints, leaves: $\Delta\kappa_\gamma$, Δg_1^{z}, λ_γ and g_5^{z}
  with $\Delta\kappa_{\mathrm{z}} = \Delta g_1^{\mathrm{z}} - \Delta\kappa_\gamma \tan^2\theta_W$ & $\lambda_{\mathrm{z}} = \lambda_\gamma$
- Sensitivity from:

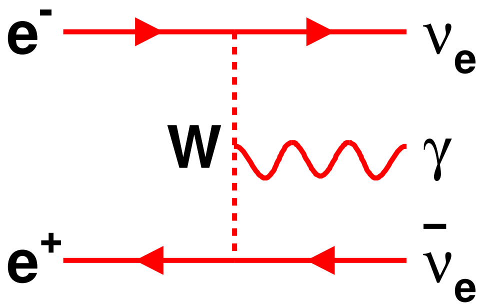
(a) WW cross section, and angular distributions



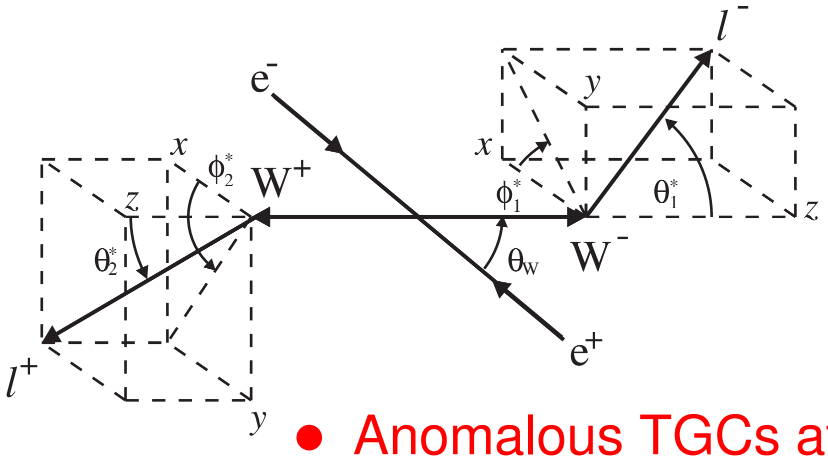
(b) $\mathrm{e}\nu\mathrm{W}$



(c) $\nu\nu\gamma$

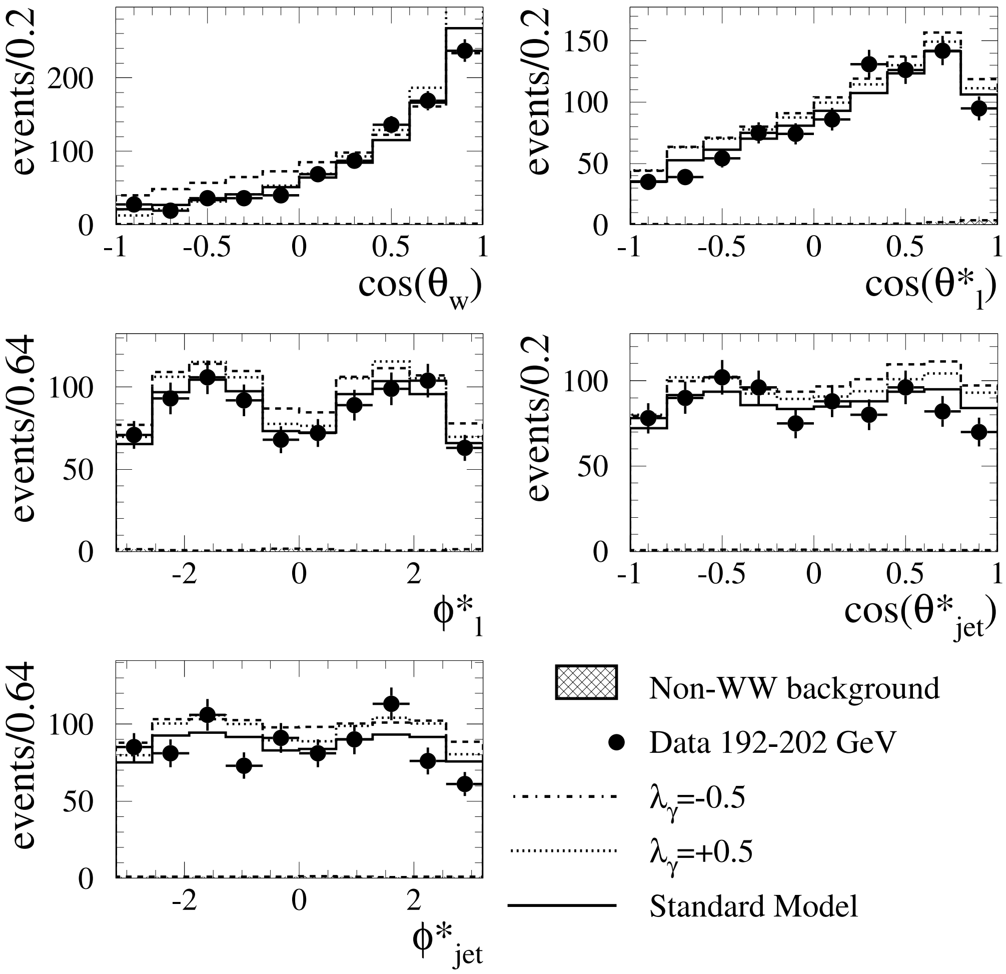


TGC angular variables



- Anomalous TGCs affect W helicities.
- Decay angles sensitive to polarisation.
- Accessible angles depend on final state.

ALEPH preliminary $q\bar{q}\ell\nu$

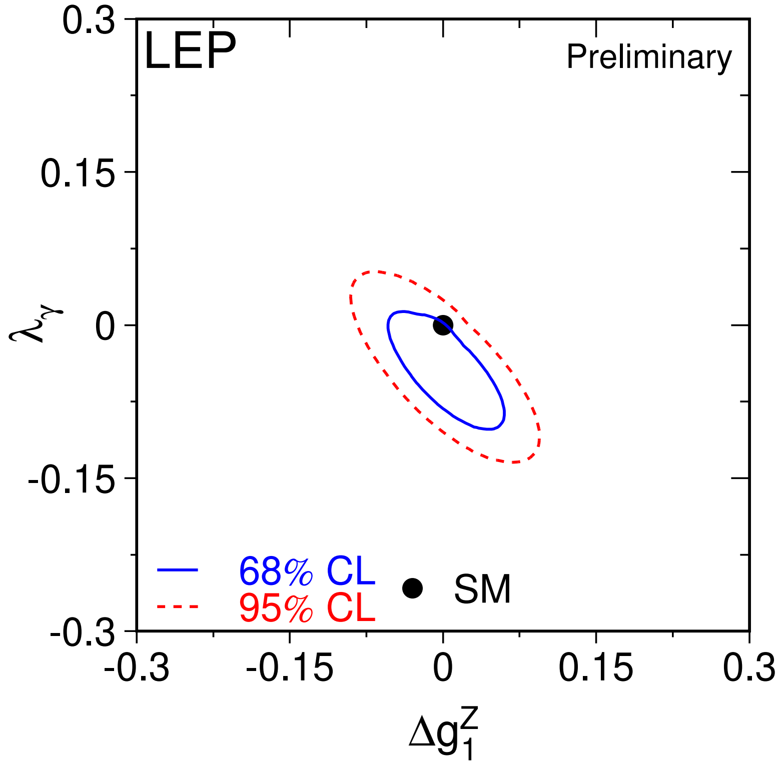


TGC results

1d fits (LEP combined)

g_5^Z	$0.05^{+0.16}_{-0.17}$
Δg_1^Z	$-0.025^{+0.026}_{-0.026}$
$\Delta\kappa_\gamma$	$-0.002^{+0.067}_{-0.065}$
λ_γ	$-0.036^{+0.028}_{-0.027}$

2d & 3d fits also made, eg.



Consistency with SM at few % level

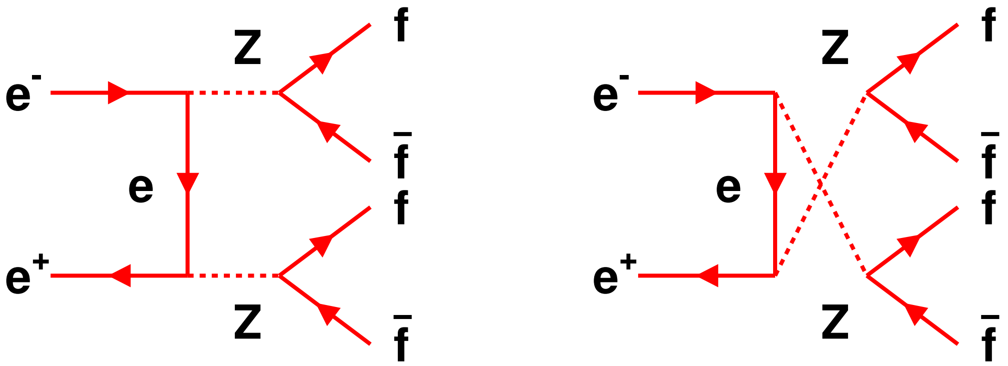
Alternatively analyse angular distributions in terms of spin states of W ($\ell\nu q\bar{q}$ events)

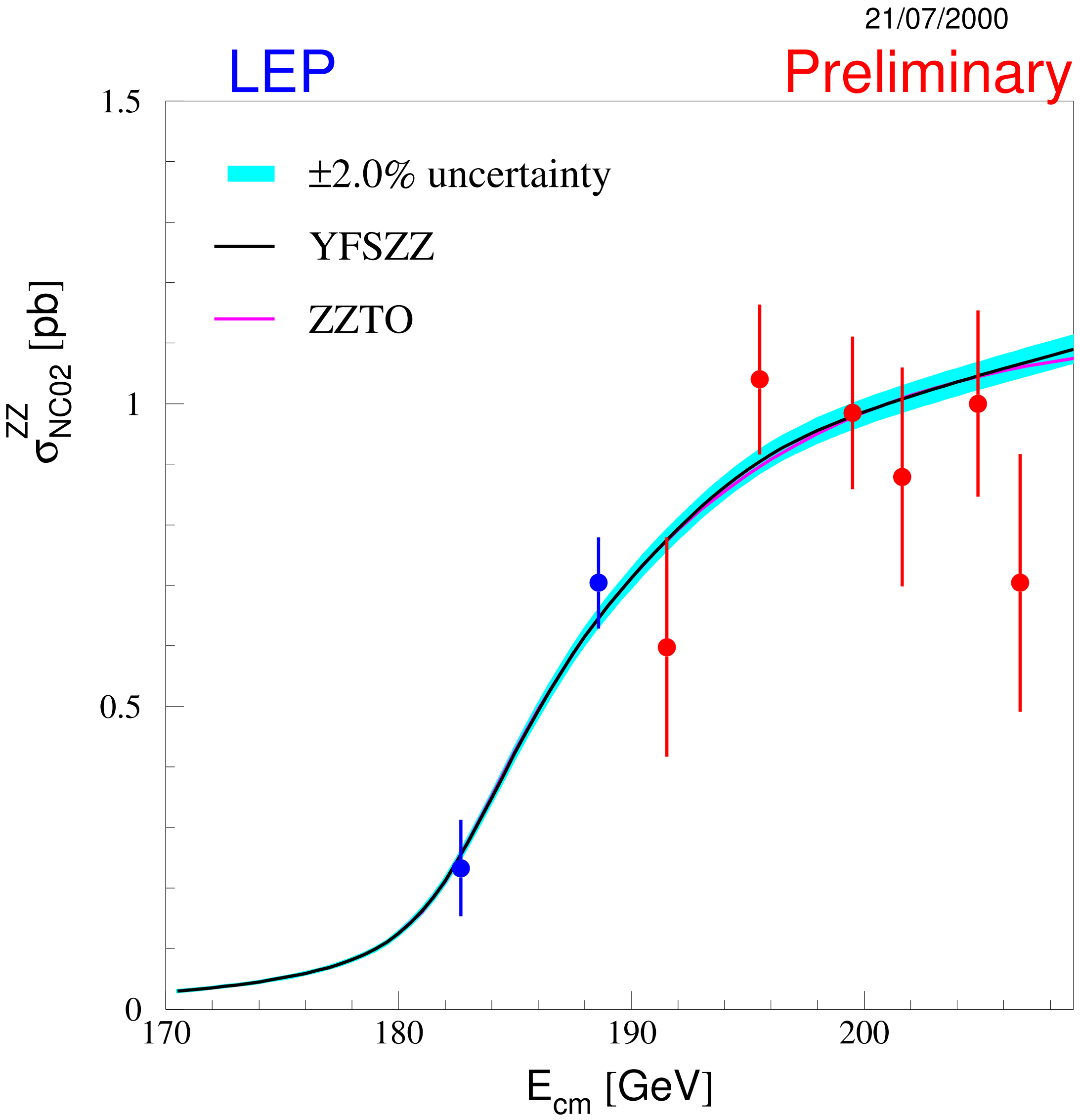
	σ_L/σ_{tot}
OPAL	$(21.0 \pm 3.3 \pm 1.6)\%$
L3	$(25.9 \pm 3.5)\%$

SM value 24.8%

$e^+e^- \rightarrow ZZ$

2 diagrams "NC02"

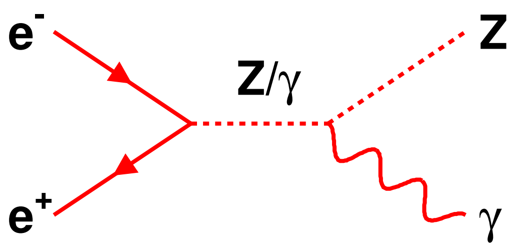




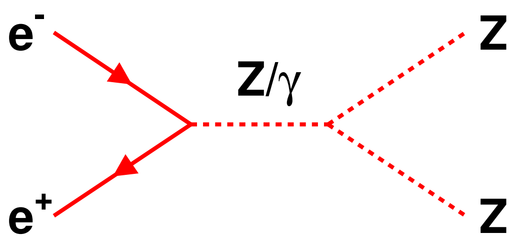
Irreducible bkd to ZH production, esp. in b-tagged events

Neutral TGC

- No neutral TGC in SM.
- Search for them via $Z\gamma$ and ZZ cross-sections and differential distributions.
- Parametrizations exist of two types of anomalous vertex (final state bosons on shell):
- (1) $Z\gamma\gamma$ and $ZZ\gamma$
  - From $e^+e^- \to Z\gamma$, $Z \to q\bar{q}$ or $\nu\bar{\nu}$.
  - Dominant background from ISR.
  - 8 couplings $|h| \lesssim 0.1$ (LEP combined 95% CL, 1d fits)

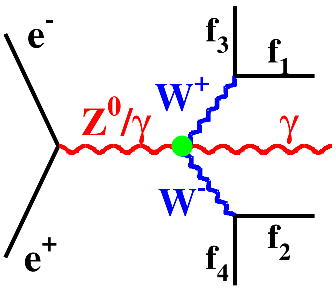


- (2) $ZZ\gamma$ and ZZZ
  - From $e^+e^- \to ZZ$
  - 4 couplings $|f| \lesssim 0.8$ (LEP combined, 95% CL, 1d fits)

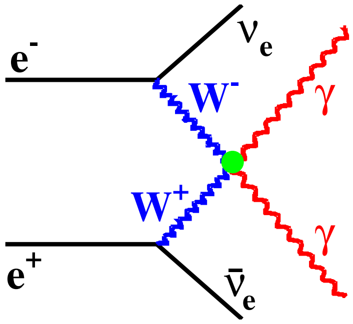


Quartic gauge coupling

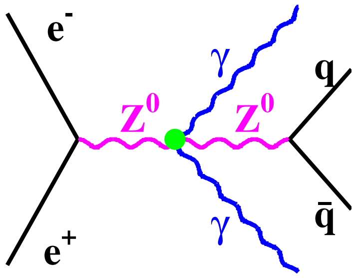
WWWW, WWZZ and WW$\gamma\gamma$ in SM, but small. Look for anomalous QGCs that respect TGCs.



$\mathrm{WW}\gamma$



$\nu\nu\gamma\gamma$

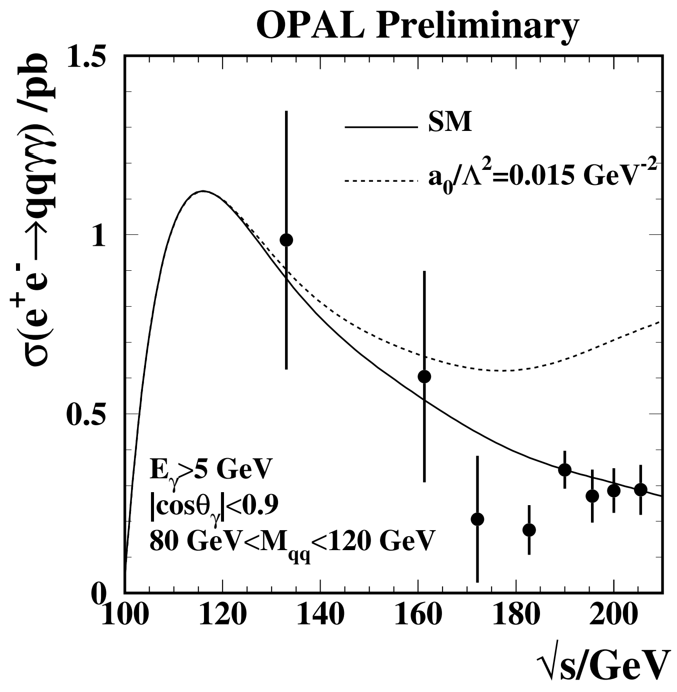


$\mathrm{Z}\gamma\gamma$

Main background: (double) ISR

Fit cross-section, photon E and angles to constrain QGC.

eg. $\sigma(\mathrm{q\bar{q}}\gamma\gamma)$

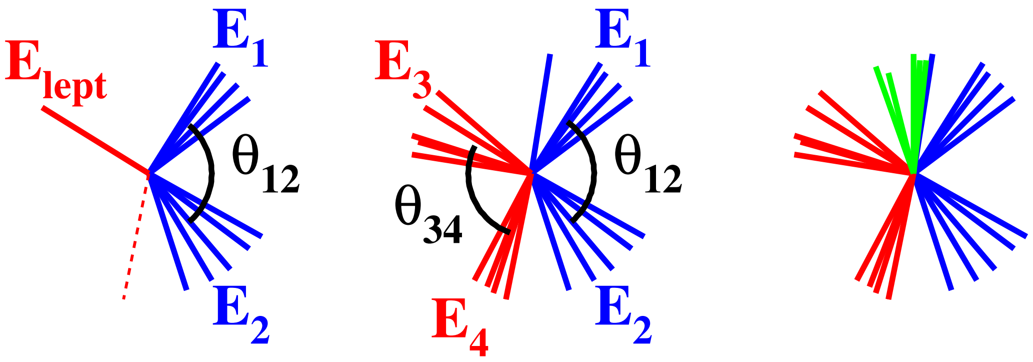


Strongest constraints (L+O, 95% CL) from $\mathrm{Z}\gamma\gamma$ [GeV^{-2}]

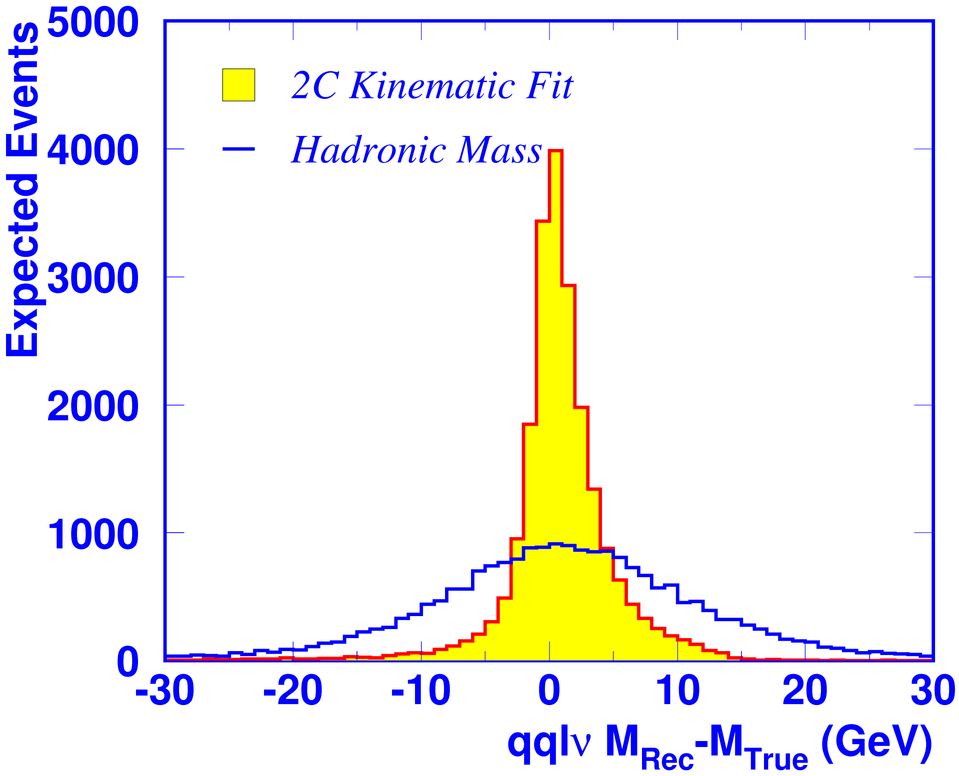
$$-0.0048 < a_0/\Lambda^2 < +0.0056$$
$$-0.0052 < a_c/\Lambda^2 < +0.0099$$

W mass measurement

- W mass from threshold cross section or from reconstructing final state W's.

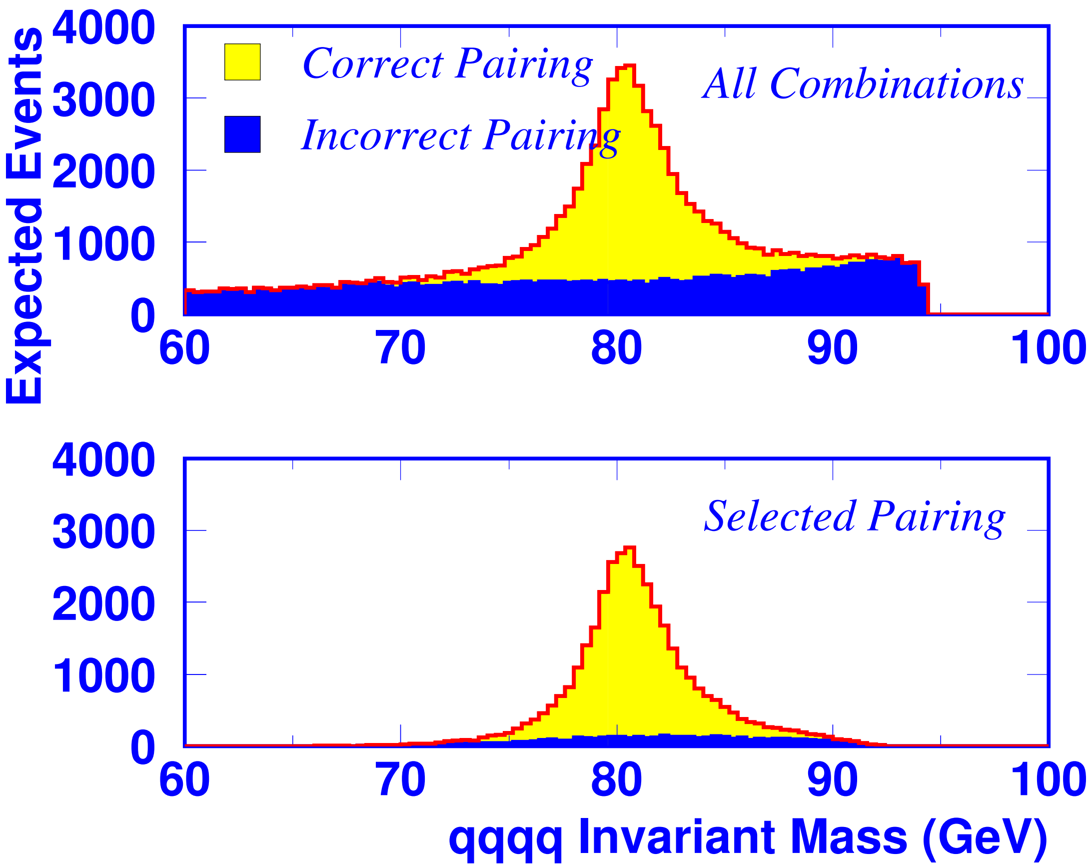


- $M_{12} = 2E_1E_2(1 - \cos\theta_{12})$
- Kinematic fit: conserve $E, \vec{p}$ & maybe $M_{12} = M_{34}$



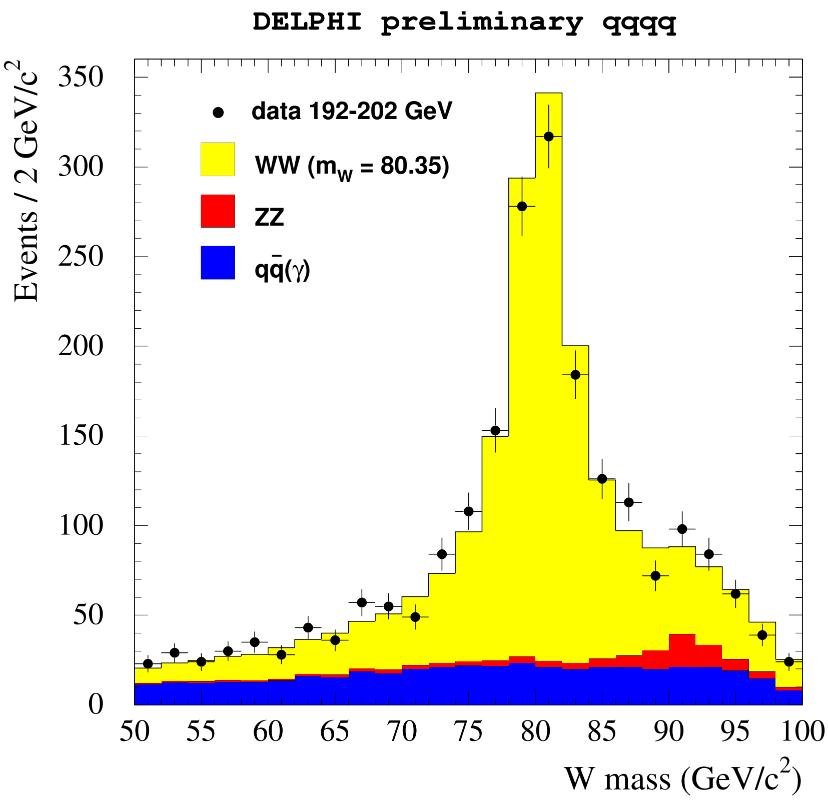
W mass measurement

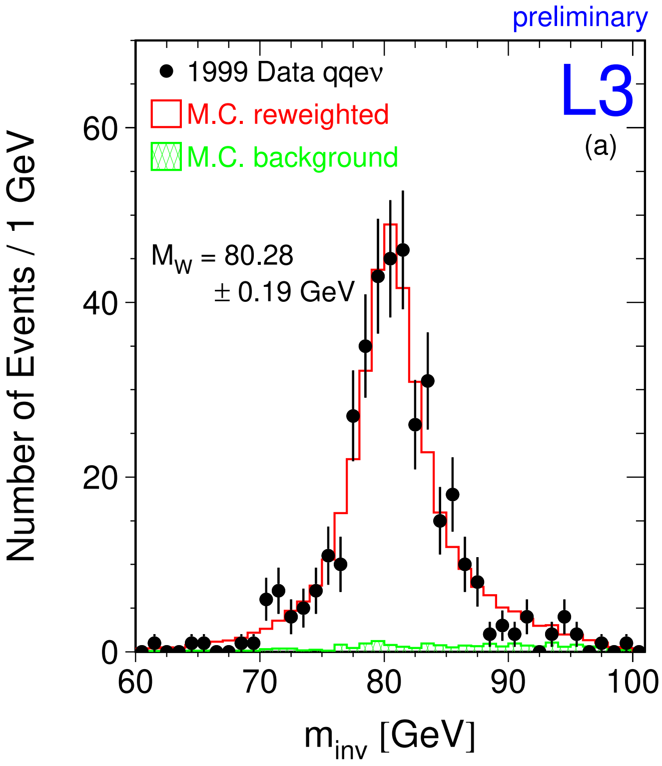
- For $q\overline{q}\ell\nu$ events, ν not measured, but no ambiguity.
- For $q\overline{q}q\overline{q}$ events, combinatorial background. Allow 4 or 5 jets in final state (gluon radiation)

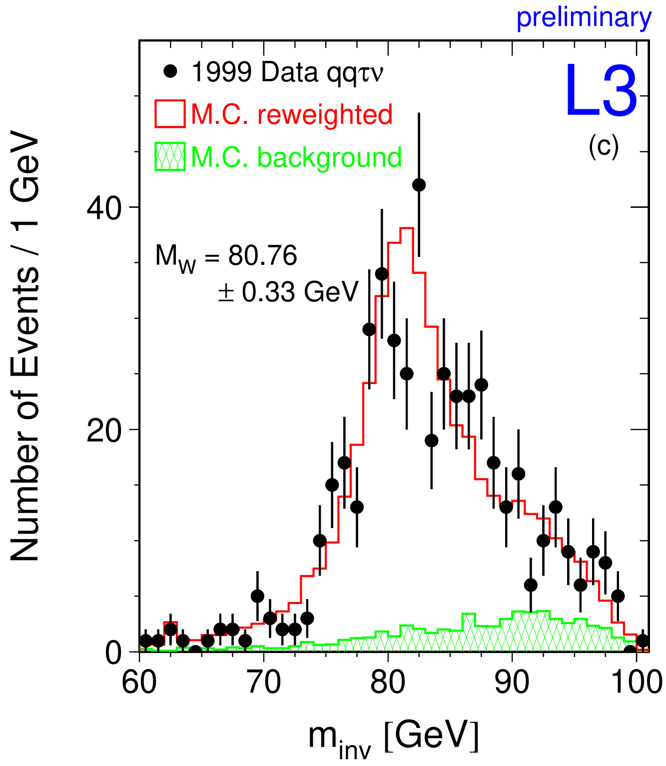


- Fit to E_ℓ and other kinematic variables for $\ell\nu\ell\nu$ events (ALEPH, OPAL). $\sim 10\times$ larger stat. error than other channels.

W mass - examples



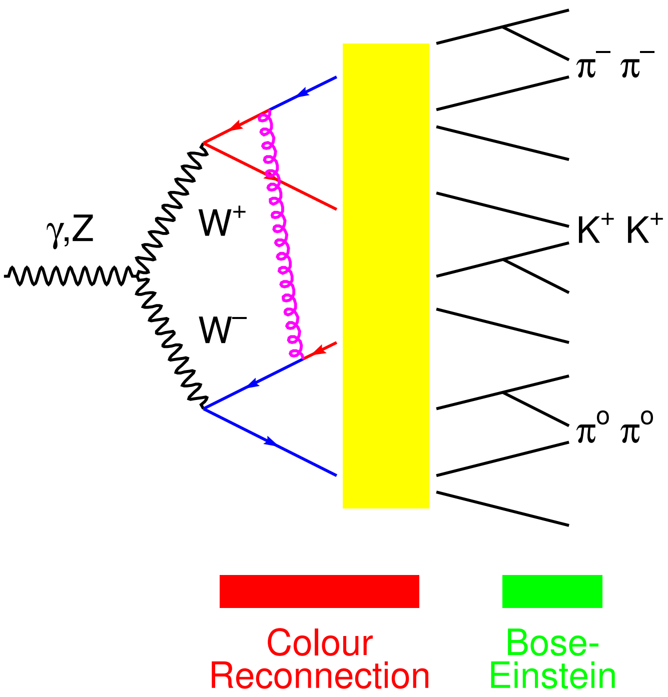




W mass systematics

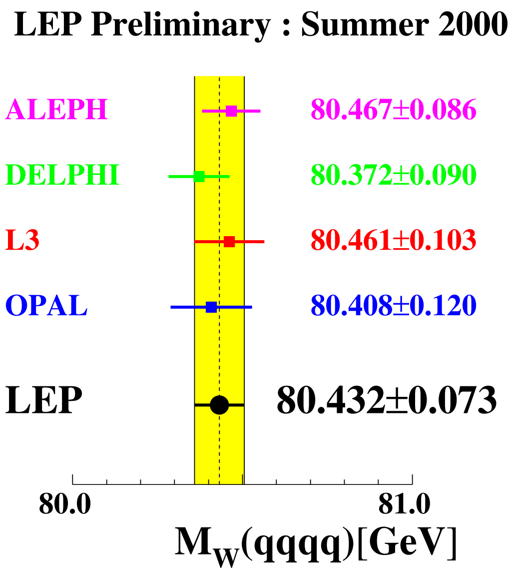
Dominant errors (MeV)

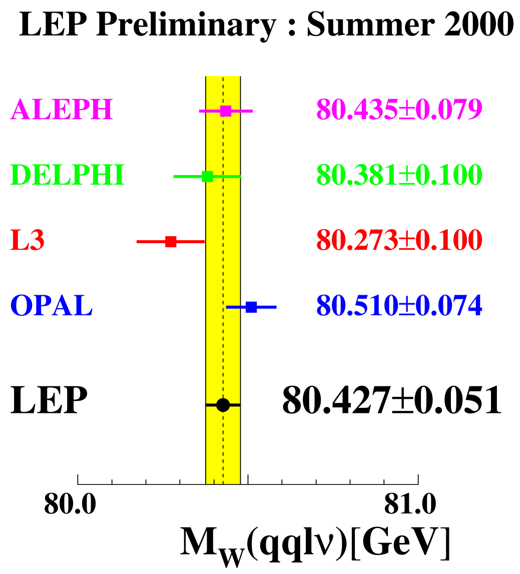
	$q\bar{q}\ell\nu$	$q\bar{q}q\bar{q}$	Combined
ISR/FSR	8	10	8
Hadronisation	26	23	24
LEP Beam Energy	17	17	17
Colour Reconnection	–	50	13
Bose-Einstein	–	25	7
Total Systematic	35	64	36
Statistical	38	34	30

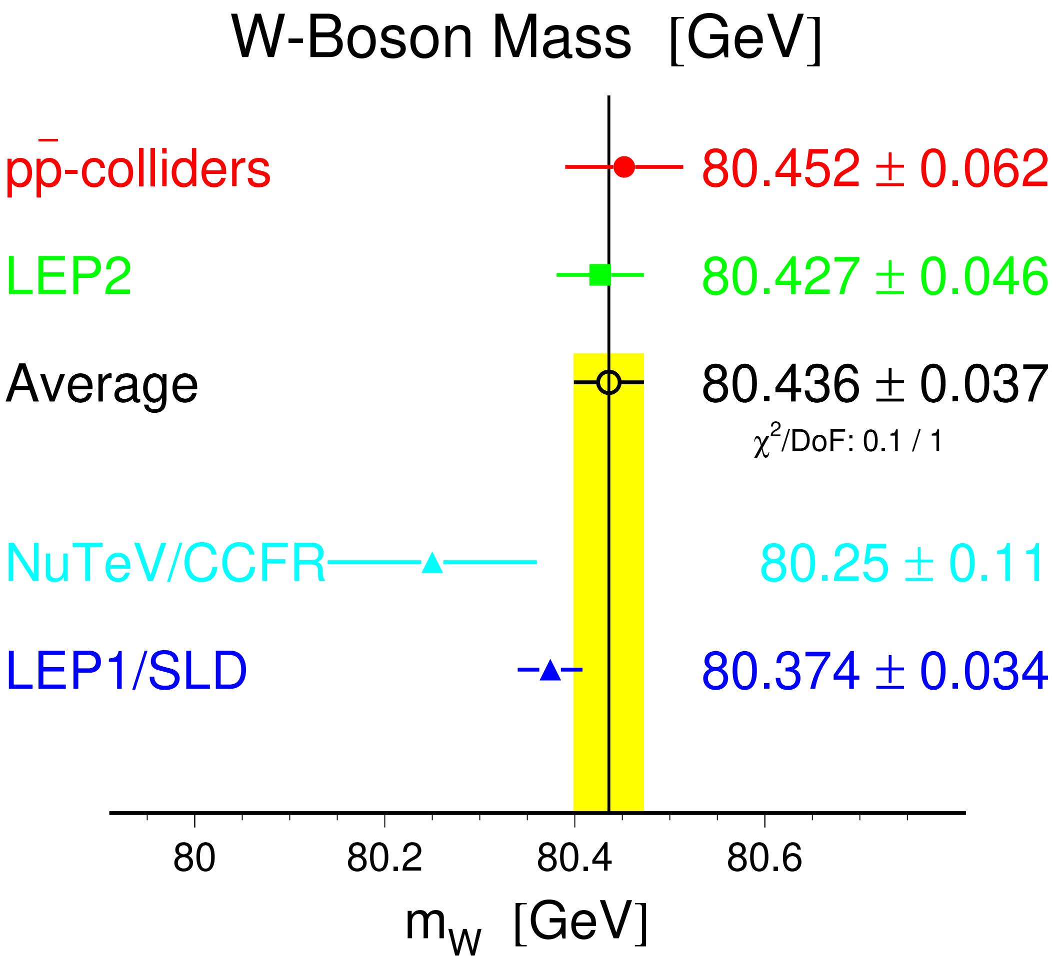


W mass results

Cross check $\Delta M_{\mathrm{W}}(\mathrm{q\bar{q}q\bar{q}} - \mathrm{q\bar{q}}\ell\nu) = +5 \pm 51$ MeV

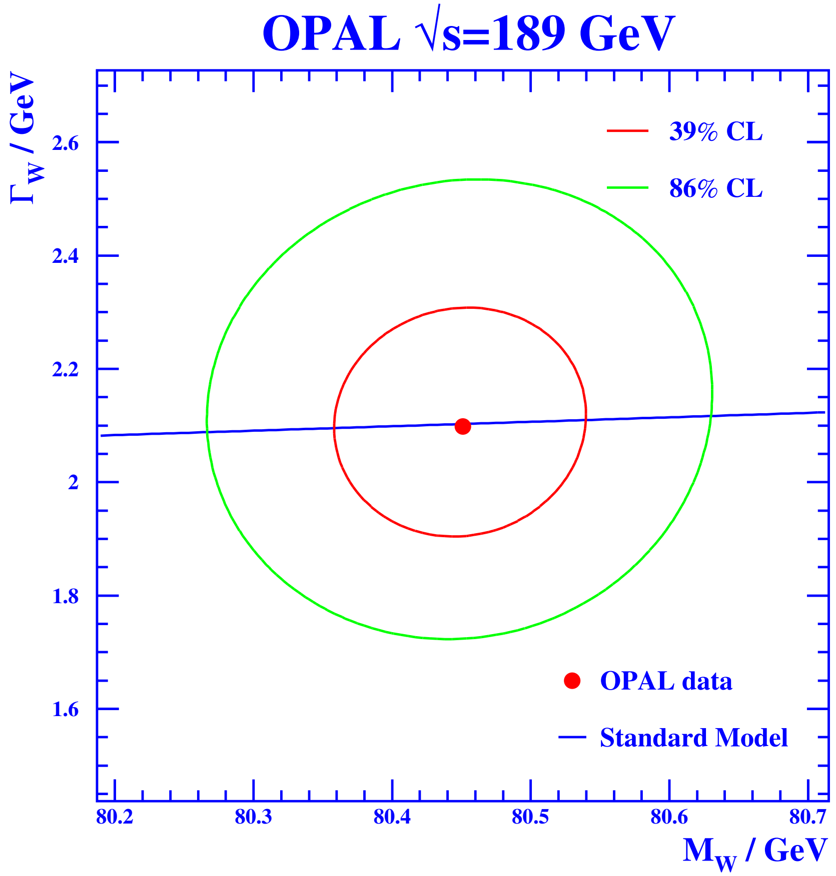


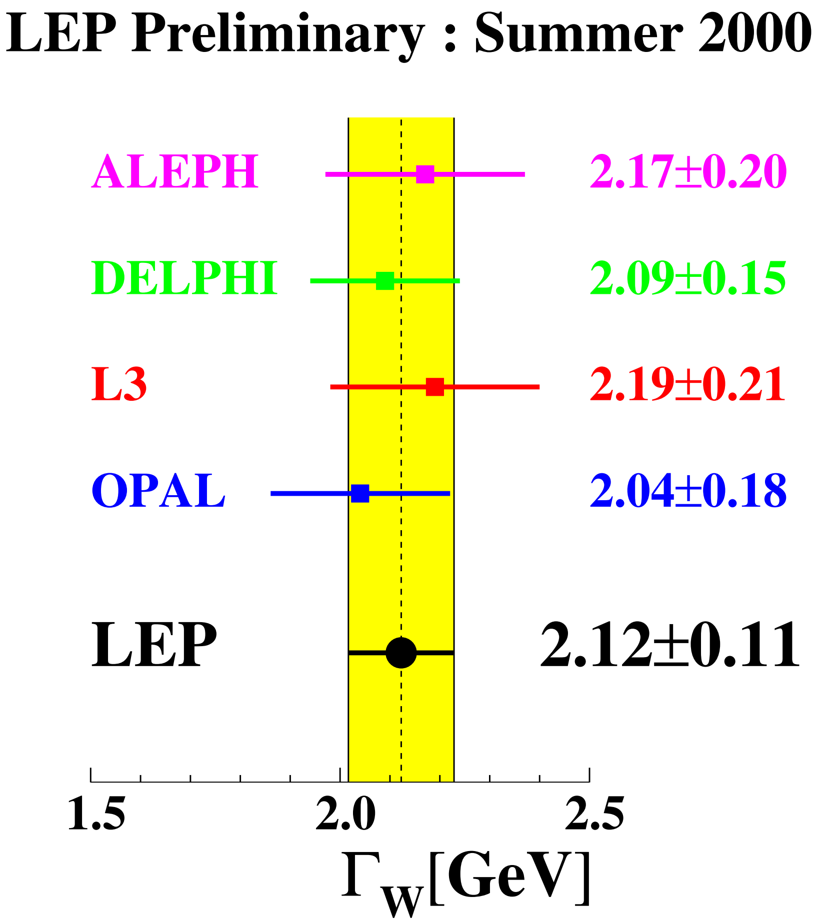




W width

Fit mass and width together. SM predicts mass-width relation.





The final word from LEP1

- 4.5 million Z's per experiment from 1989 to 1995 at a few $\sqrt{s}$ values (majority on peak & $\pm$1.8 GeV)
- Many measurements, Results close to final, eg.
- Number of neutrinos $N_\nu = 2.984 \pm 0.008$
- Coupling parameters $\mathcal{A} = 2g_v g_a/(g_v^2 + g_a^2)$

	LEP+SLD	SM fit	Pull
$\mathcal{A}_\ell$	0.1500 ± 0.0016	0.1472	$+1.8\sigma$
$\mathcal{A}_\mathrm{b}$	0.898 ± 0.015	0.935	-2.5σ
$\mathcal{A}_\mathrm{c}$	0.623 ± 0.020	0.668	-2.3σ

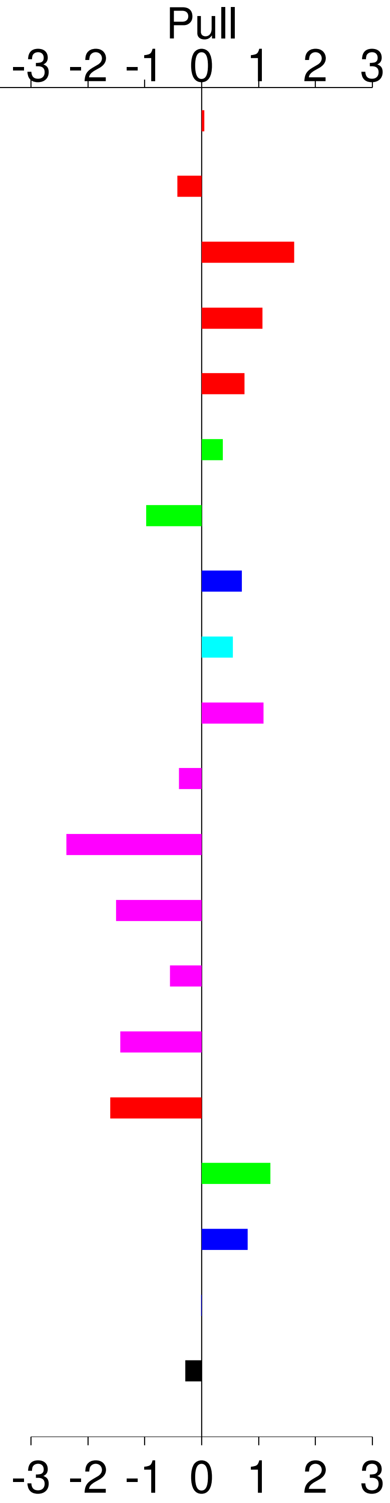
(Including 600 thousand Z's at SLD with electron beam up to 77% polarised)

Results of global electroweak fits

Fit to data from LEP, SLD, Tevatron, νN scattering.

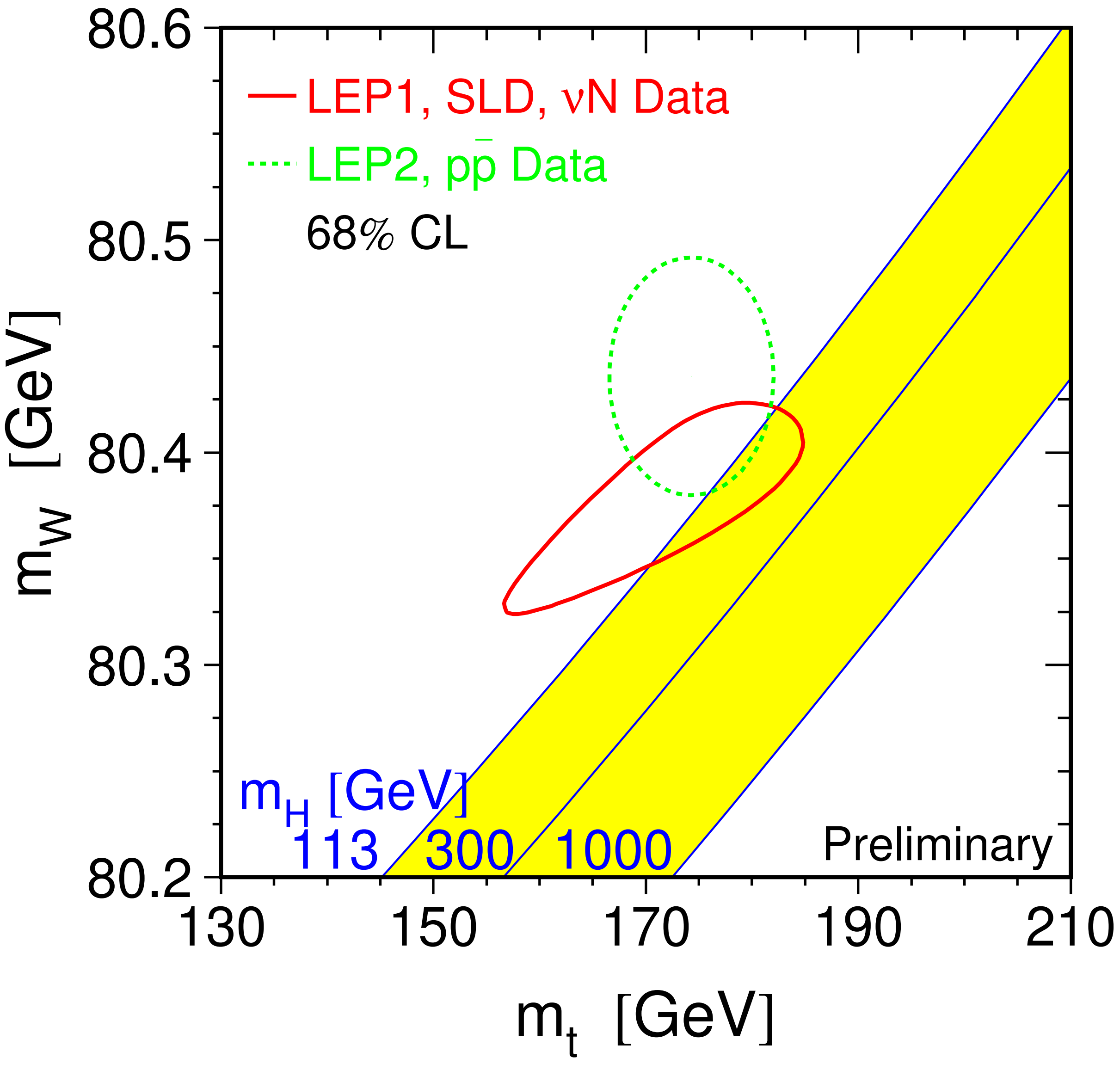
Osaka 2000

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.05
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.07
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.75
A_e	0.1498 ± 0.0048	.38
A_τ	0.1439 ± 0.0042	-.97
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.70
m_W [GeV]	80.427 ± 0.046	.55
R_b	0.21653 ± 0.00069	1.09
R_c	0.1709 ± 0.0034	-.40
$A^{0,b}_{fb}$	0.0990 ± 0.0020	-2.38
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.51
A_b	0.922 ± 0.023	-.55
A_c	0.631 ± 0.026	-1.43
$\sin^2\theta^{lept}_{eff}$	0.23098 ± 0.00026	-1.61
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.81
m_t [GeV]	174.3 ± 5.1	-.01
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.29



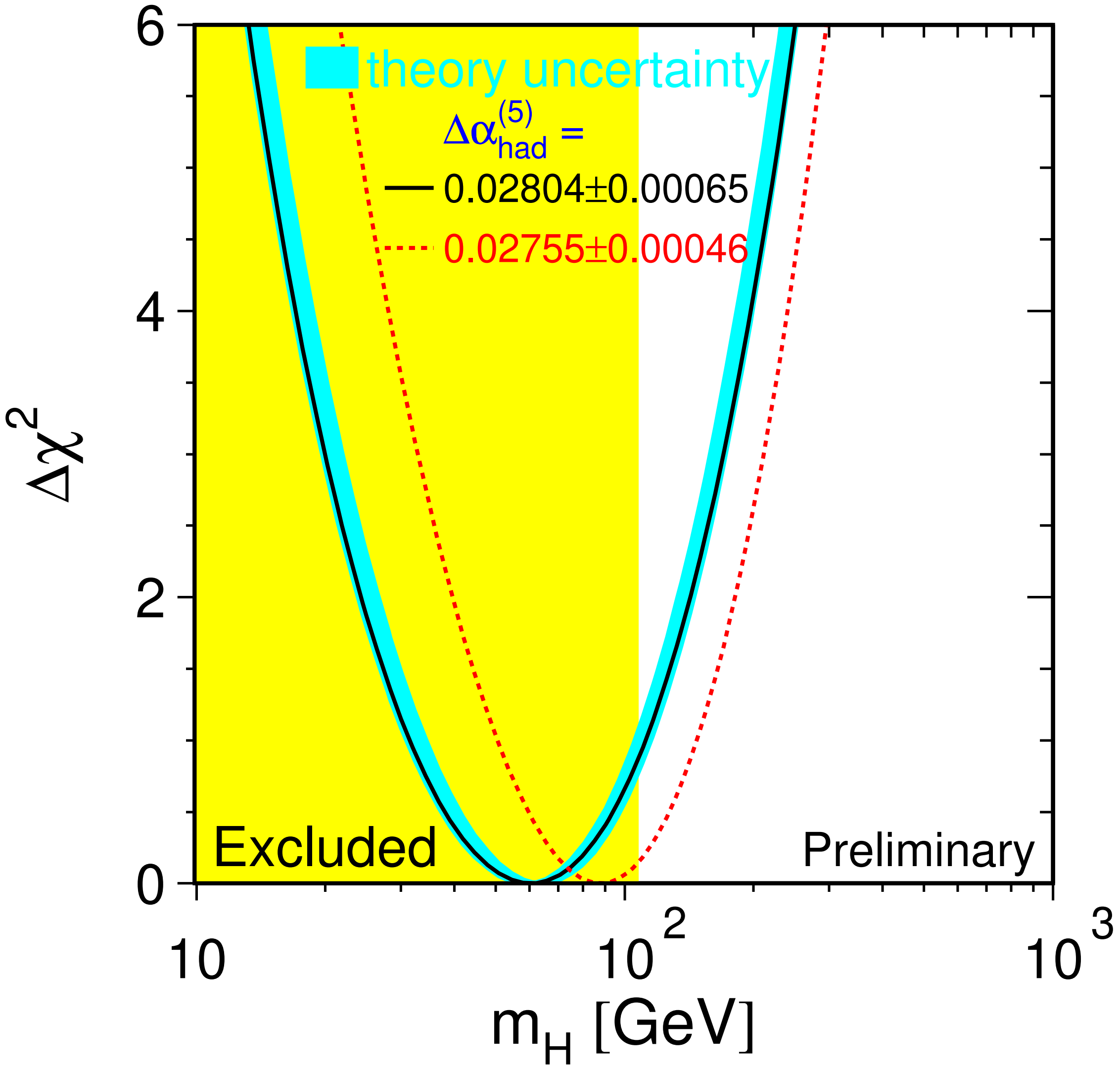
Top and W mass

- Consistency between predicted top and W mass from radiative corrections and direct measurements.
- Preference for low Higgs mass.



The missing piece

- Without accounting for limit from direct searches, global fits give $M_{\text{Higgs}} < 165$ GeV at 95% CL
- α with latest BES data gives limit of 206 GeV.



- Electroweak Standard Model gives a complete description of diverse data at LEP energies.
- The next big question - Where is the Higgs?