LEP 200 Physics

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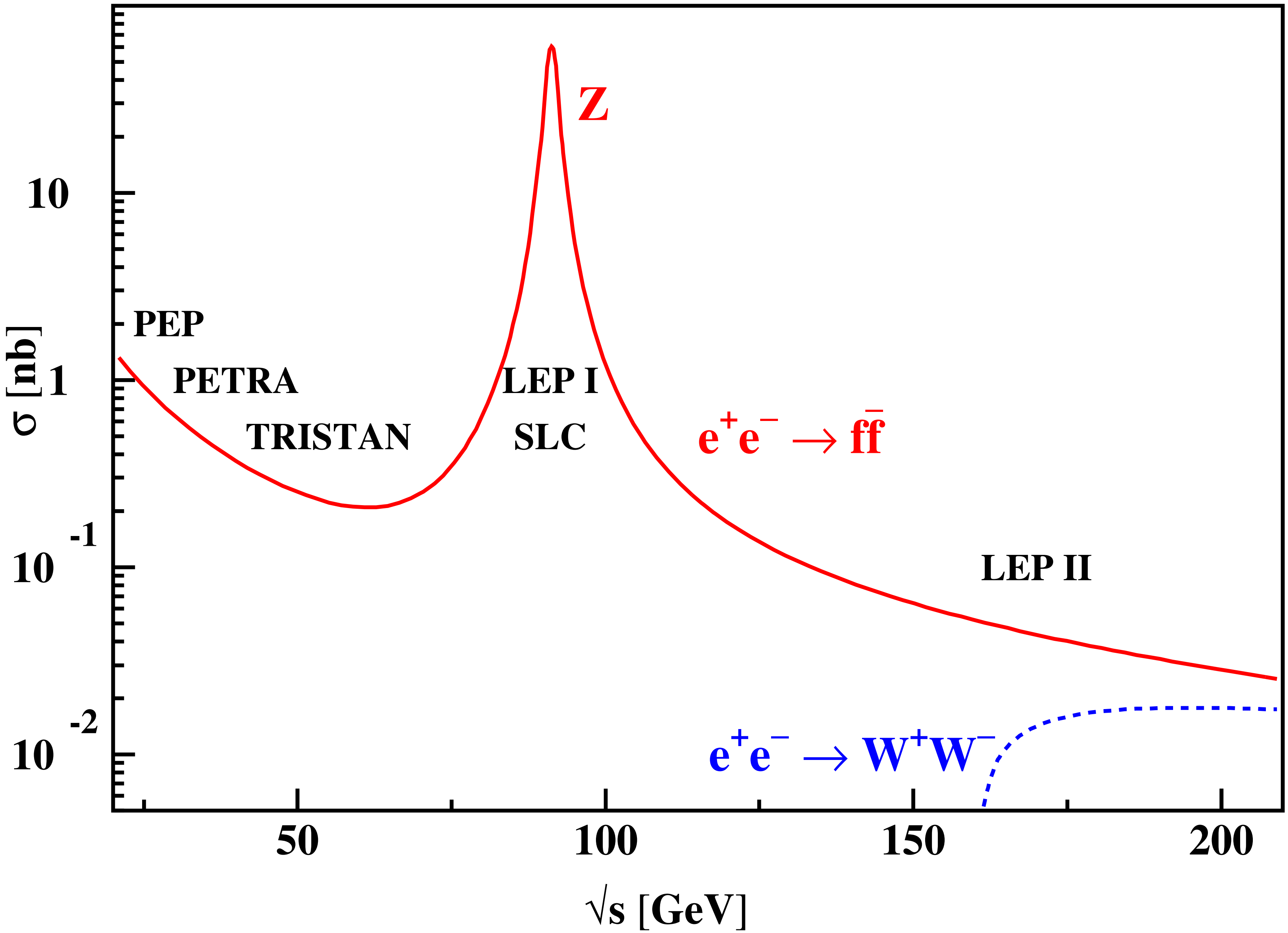
- Introduction
- The LEP collider
- Fermion-pair production above the Z
- Production of neutral bosons pairs $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow ZZ$ and the couplings of the neutral gauge bosons
- The properties of the $W^\pm$ boson
- Interpretation in the Standard Model
- Search for the Higgs boson
- Search for Supersummetry

New preliminary results from LEP up to $\sqrt{s} = 202$ GeV (1999 data)

LEP:
Large Electron-Positron Collider
located at CERN in Geneva

- e^+e^--storage ring
- 27 km circumference
- 8 straight sections, 4 equipped with detectors: ALEPH, DELPHI, L3, OPAL
- maximum centre-of-mass energy $\sqrt{s} > 200$ GeV
- in operation since 1989

- 4+4 oppositely circulating bunches of electrons and positrons (up to $16 + 16$ possible)
- fill LEP with 22 GeV electrons and positrons using older accelerators (PS, SPS)
- accelerate to maximum energy (100 GeV or more)
- collisions for about 4 hours, then refill



Z
PEP
PETRA
TRISTAN
LEP I
SLC
$e^+e^- \rightarrow f\bar{f}$
LEP II
$e^+e^- \rightarrow W^+W^-$
10
1
10^{-1}
10^{-2}
σ [nb]
50
100
150
200
√s [GeV]

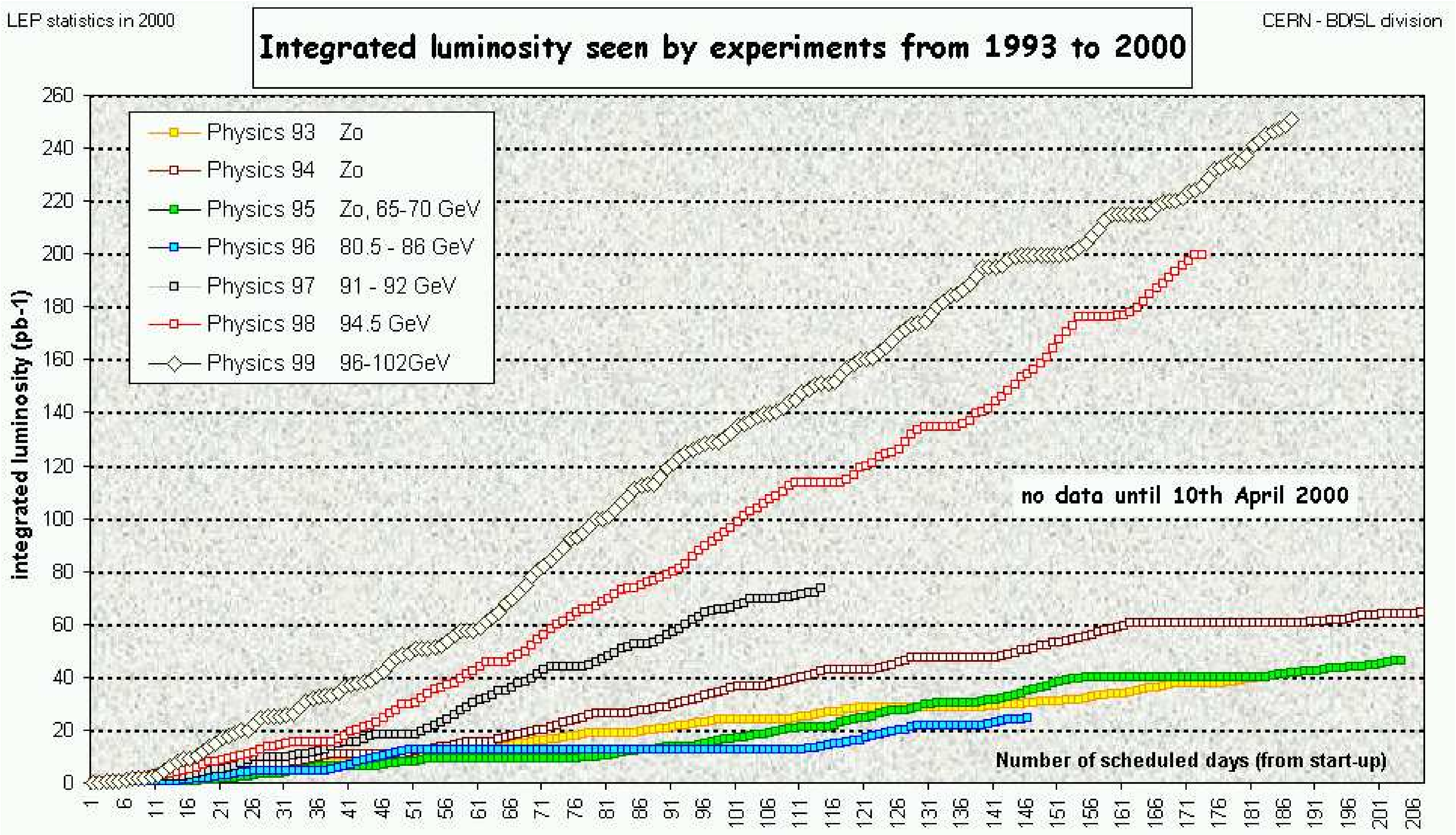
Two phases:

LEP I 1989-1995 $\sqrt{s} \approx m_{\mathrm{Z}} = 91$ GeV

- mass production of Z bosons
  ($\approx$ 17 million observed by the 4 experiments)
  - precise determination of Z parameters: mass widths, number of neutrino families
  - test of Standard Model predictions
- heavy quark physics (b and c), tau physics, QCD: measurement of α_{s}, ...
- search for new particles (Higgs, SUSY, ...)

LEP II 1995-2000 $2\,m_{\mathrm{W}} < \sqrt{s} \lesssim 200\ GeV$

- production of W bosons $\mathrm{e}^+\mathrm{e}^- \to W^+W^-$
  measurement of W mass and couplings
- search for the Higgs boson up to $m_{\mathrm{H}} \approx 110$ GeV
- search for SUSY particles
- other searches
- two-photon physics

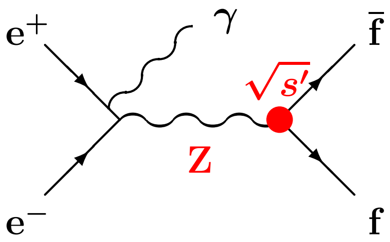


LEP statistics in 2000
CERN - BD/SL division
Integrated luminosity seen by experiments from 1993 to 2000
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 96-102GeV
no data until 10th April 2000
integrated luminosity (pb-1)
Number of scheduled days (from start-up)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
101
106
111
116
121
126
131
136
141
146
151
156
161
166
171
176
181
186
191
196
201
206

Centre-of-mass energies and approximate luminosities per experiment:

Year	$\sqrt{s}$	$\int \mathcal{L}\, dt$
1995	130 – 140 GeV	5 pb^{-1}
1996	161/172 GeV	21 pb^{-1}
1997	183 GeV	55 pb^{-1}
	130/136 GeV	7 pb^{-1}
1998	189 GeV	180 pb^{-1}
1999	192 – 202 GeV	240 pb^{-1}

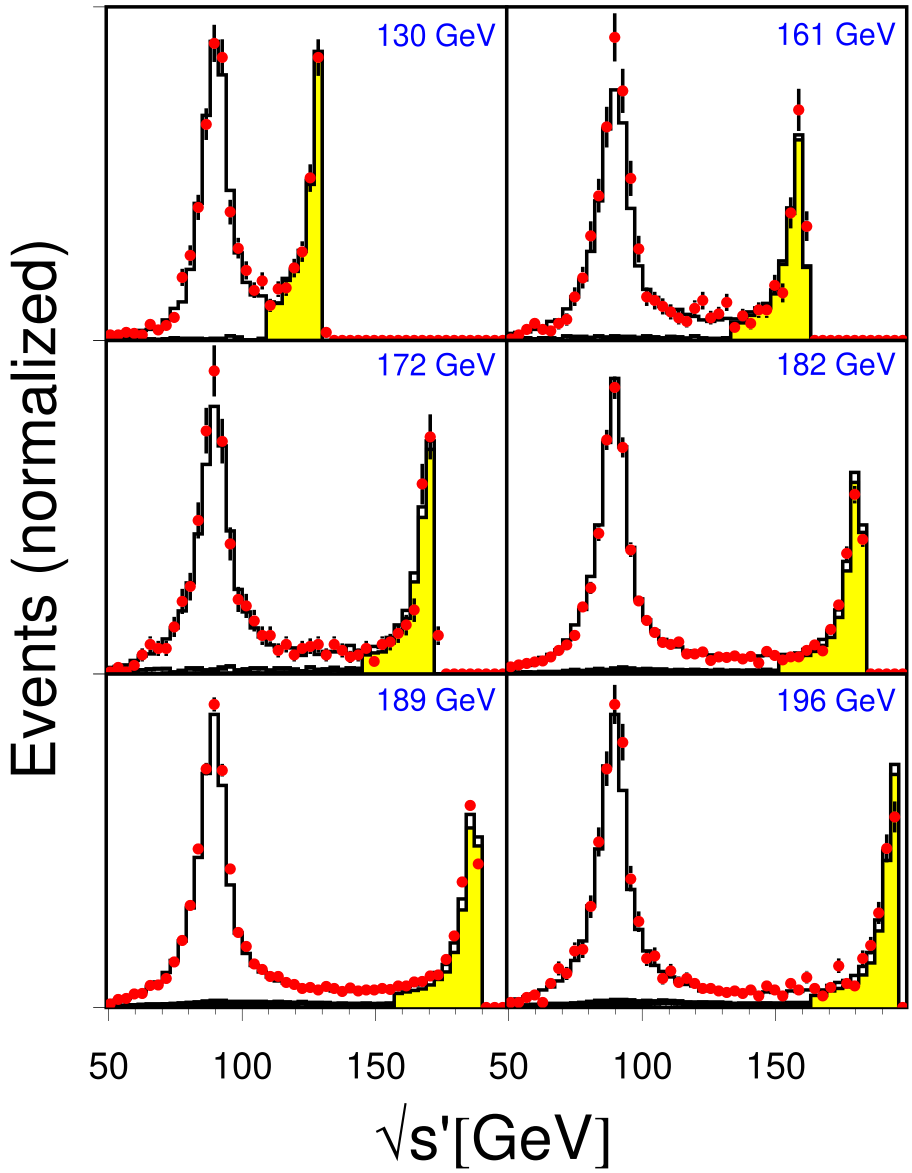
Important contribution from initial state radiation:



'Return-to-the-Z'

Effective cms energy $\sqrt{s'}$ in $e^+e^- \to \text{hadrons}(\gamma)$

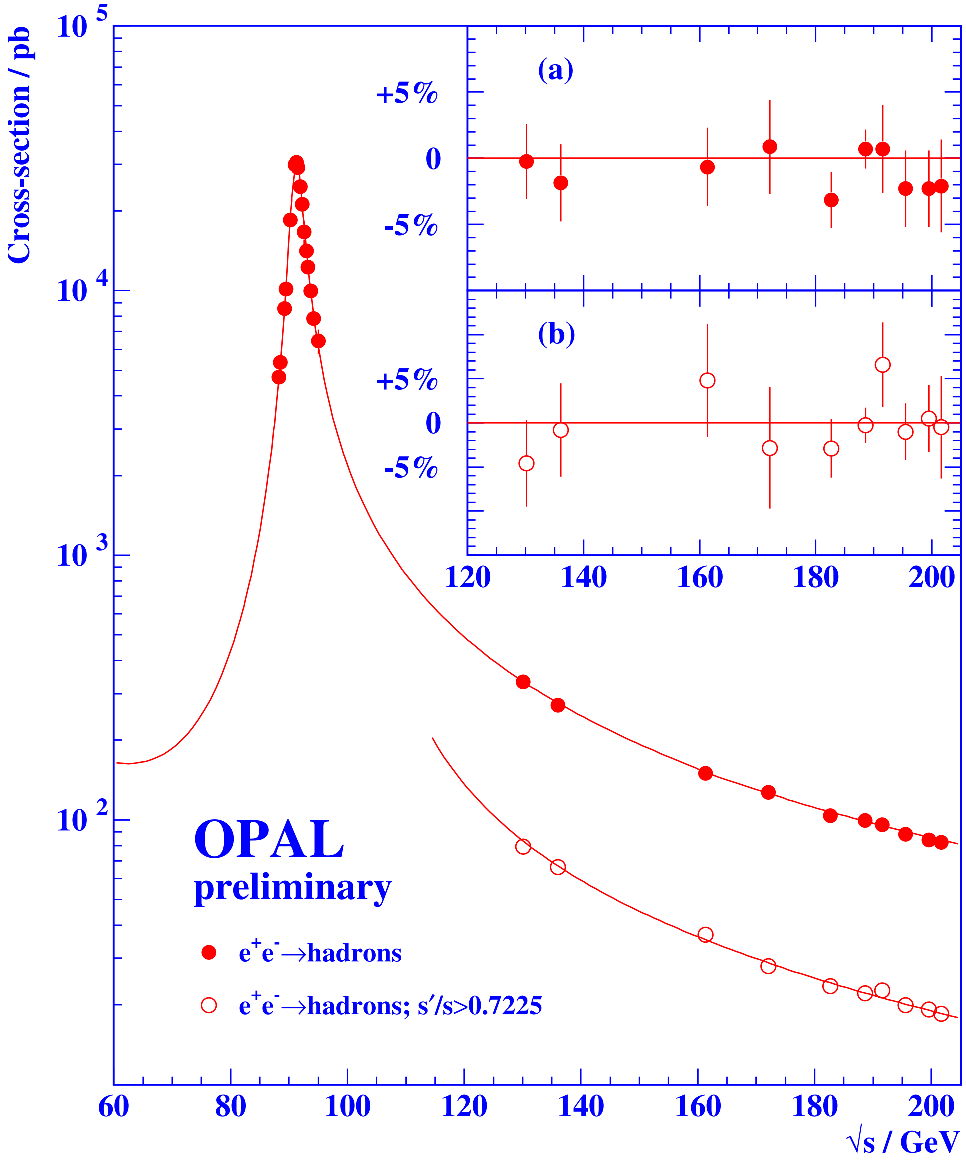
Data samples from $\sqrt{s} = 130$ GeV to $\sqrt{s} = 196$ GeV:



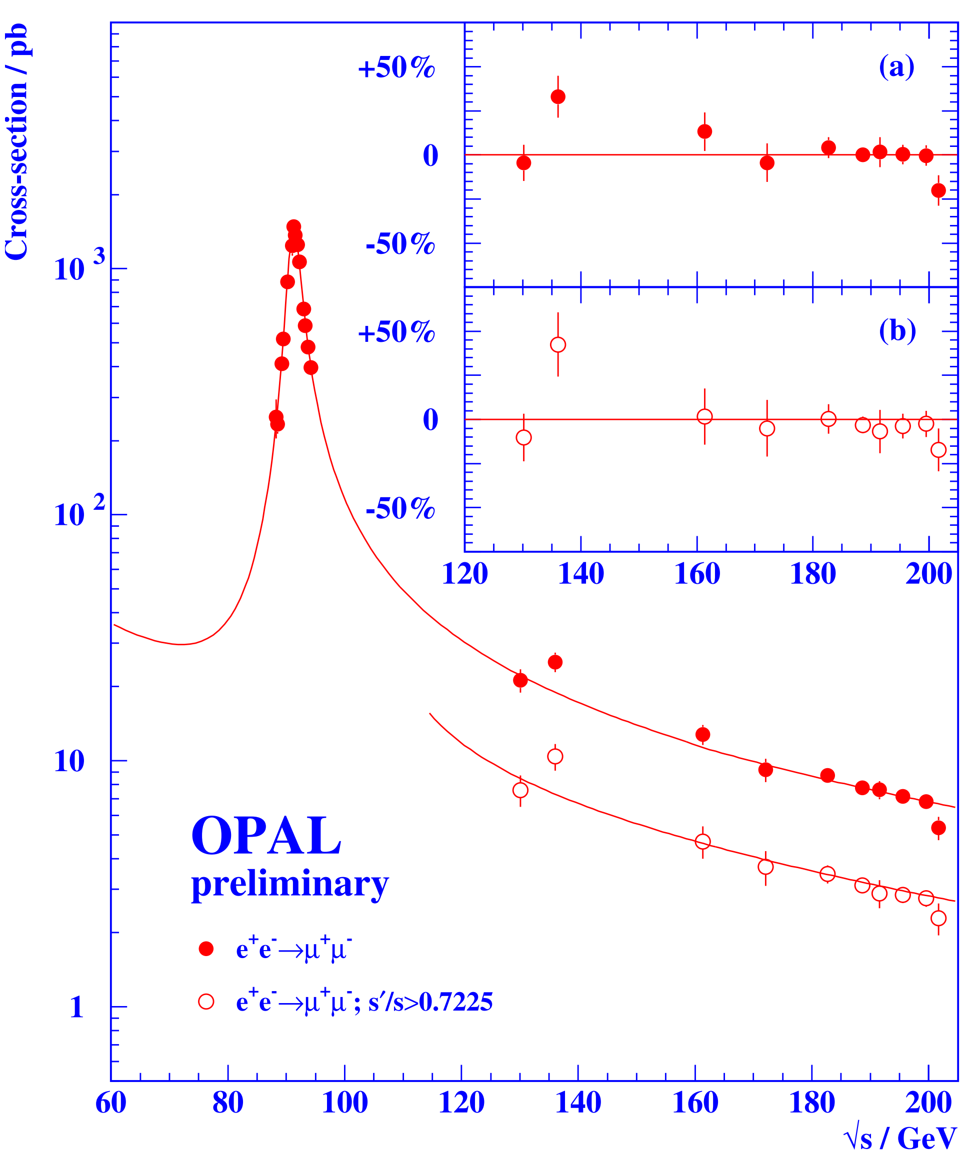
Measure cross sections and asymmetries for

- Inclusive sample
- High energy sample $\sqrt{s'} > 0.85\sqrt{s}$

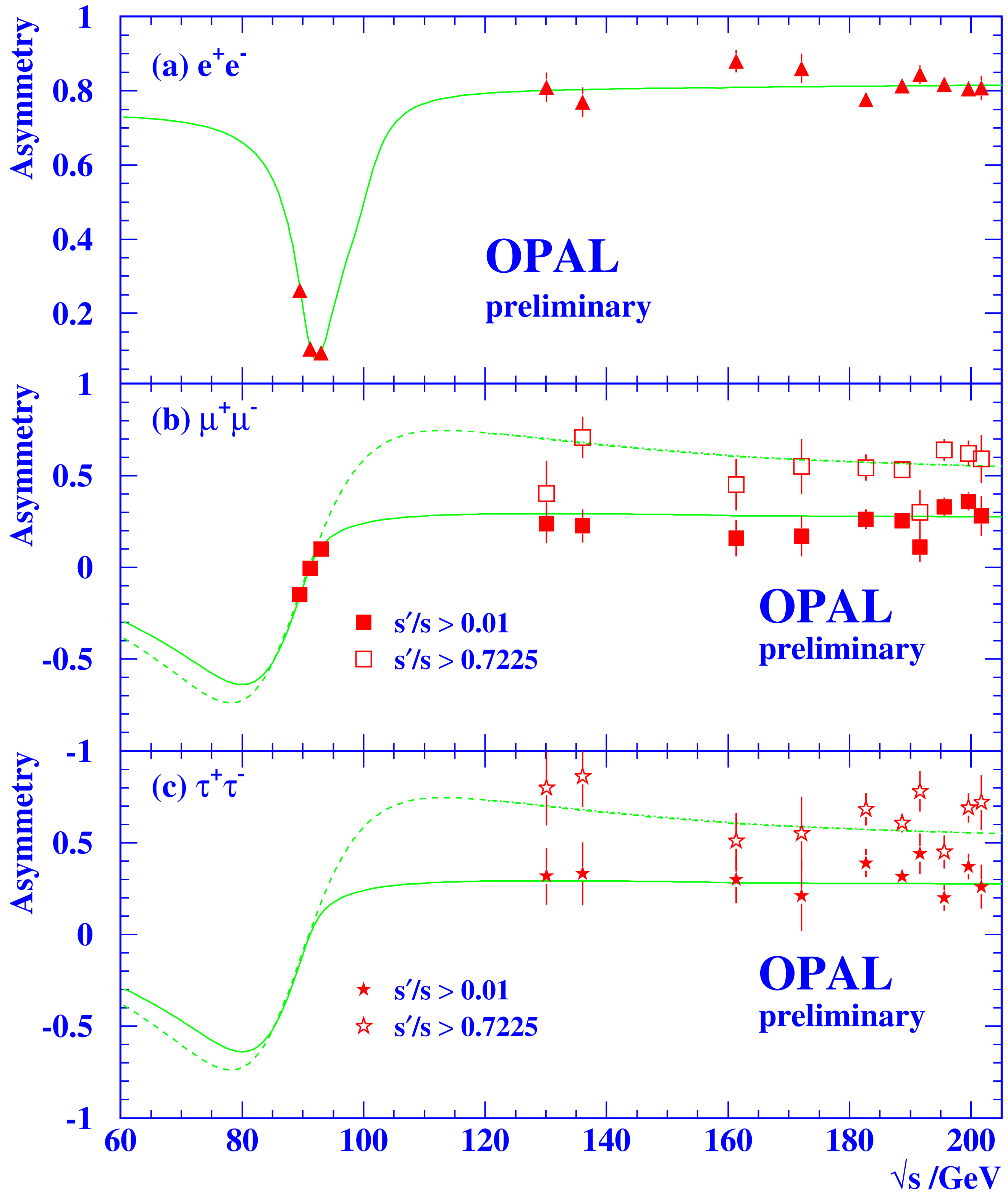
Hadrons

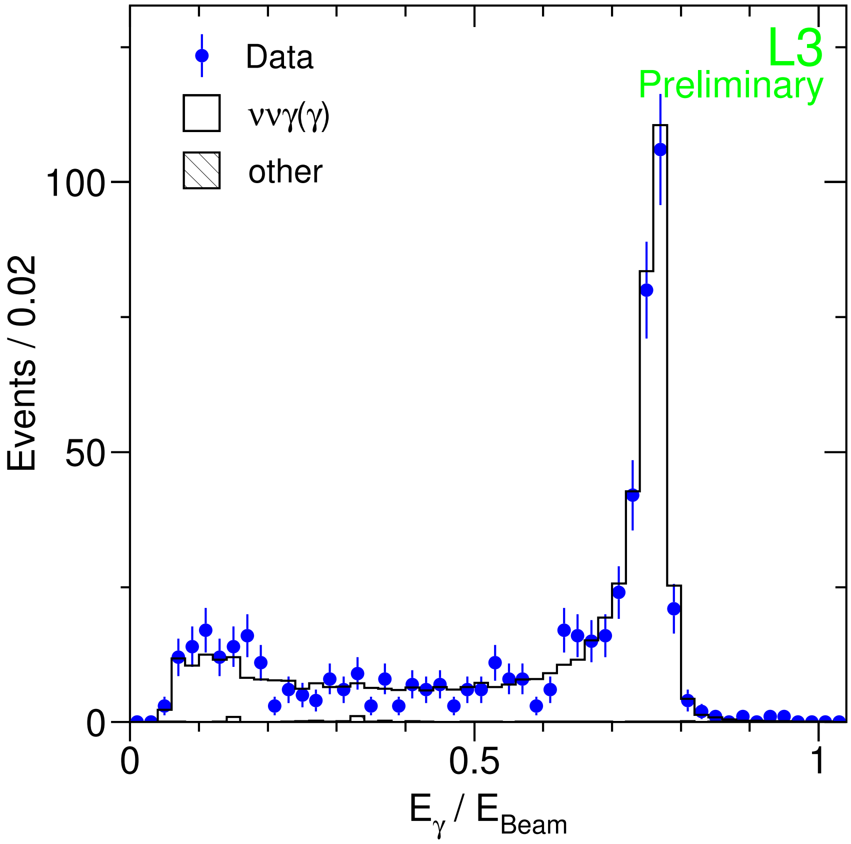


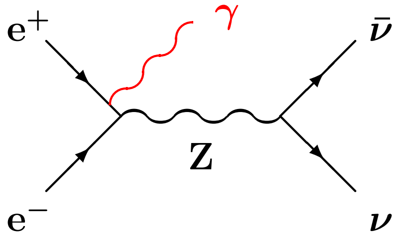
$\mu^+\mu^-$



Lepton-pair Asymmetries



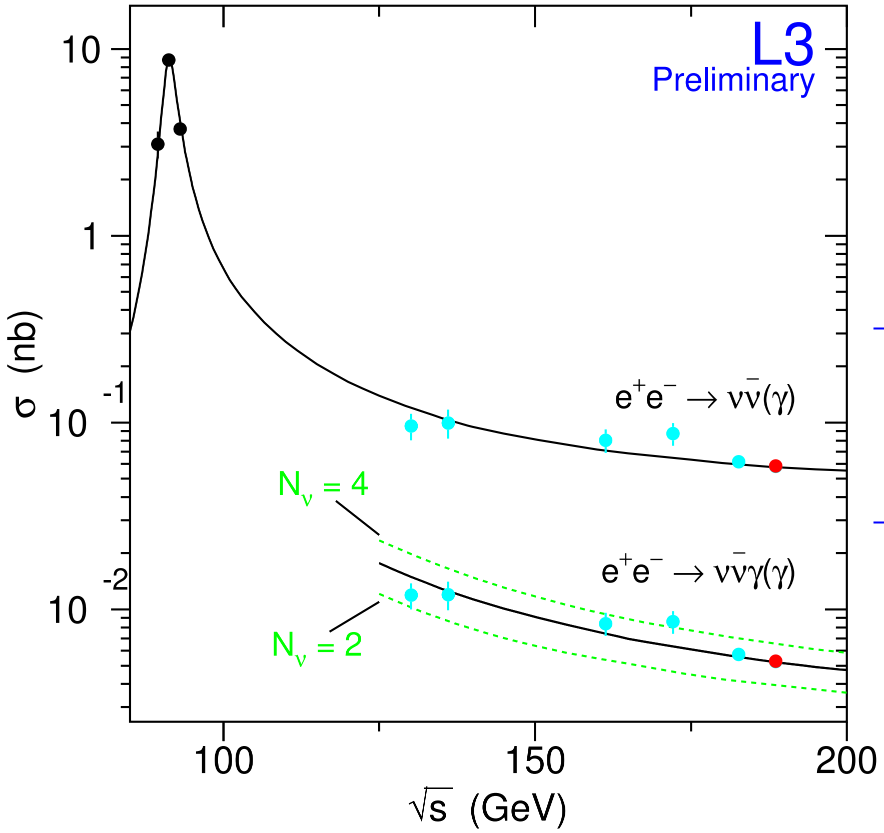




$\sqrt{s} = 189$ GeV

$\approx$ 500 events per expt.

	$\sigma^{meas}/\sigma^{SM}$
ALEPH	1.017 ± 0.053
DELPHI	0.965 ± 0.088
L3	0.994 ± 0.044
OPAL	0.908 ± 0.053

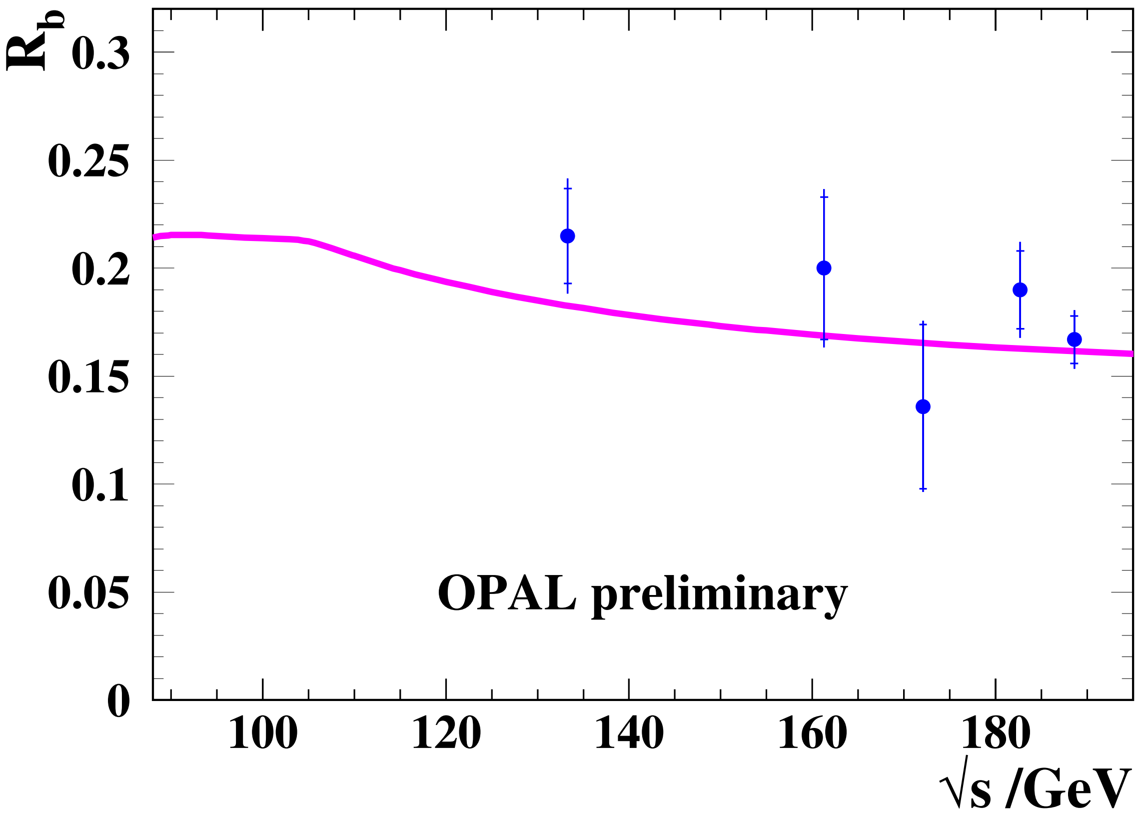


# of neutrino species

L3	3.05 ± 0.12
DELPHI	2.83 ± 0.19
LEP II	2.99 ± 0.10

LEP I	
single γ	3.00 ± 0.08
lineshape	2.9835 ± 0.0083

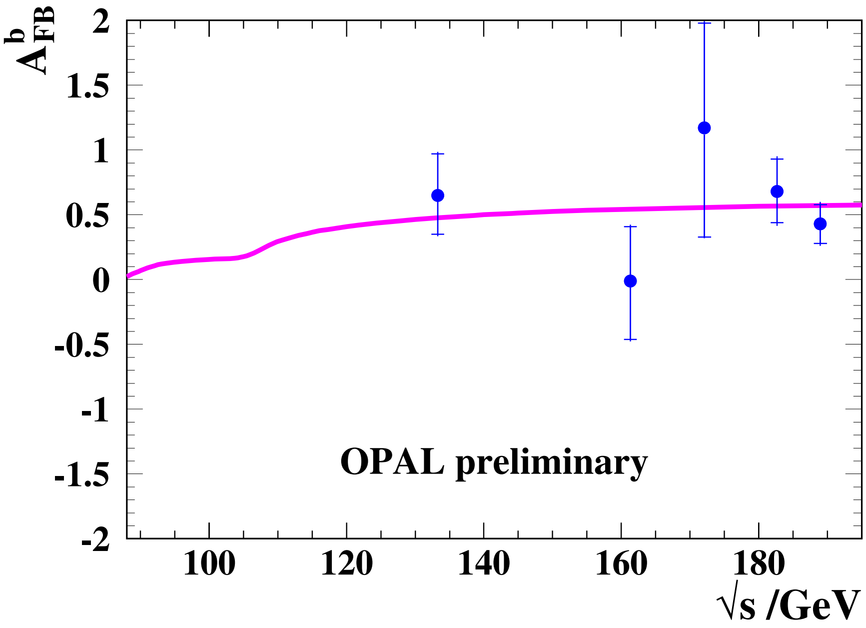
- Measurement of $R_\mathrm{b} = \sigma(\mathrm{e^+e^-} \to \mathrm{b\bar{b}})/\sigma(\mathrm{e^+e^-} \to \mathrm{q\bar{q}})$



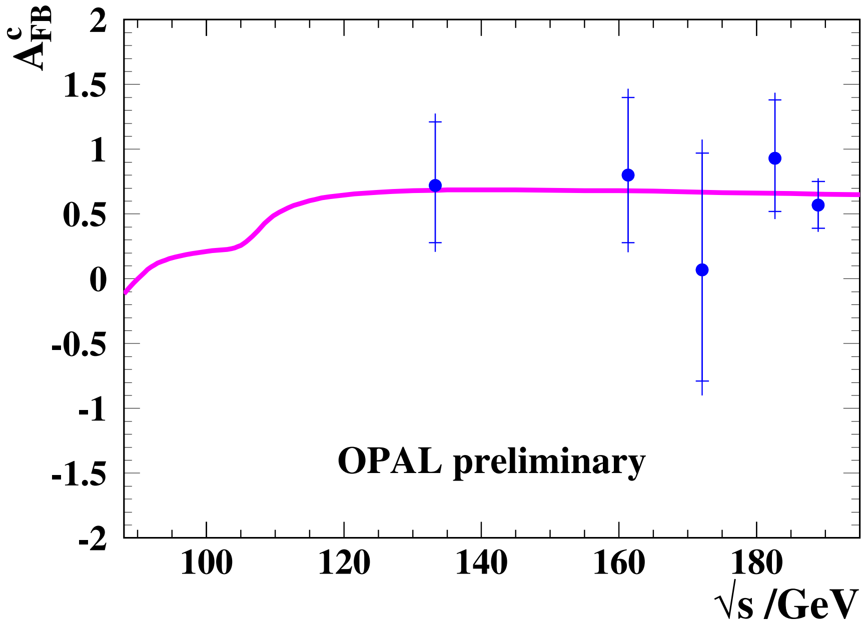
Compilation of measurements at $\sqrt{s} = 189$ GeV:

	R_b
ALEPH	$0.151 \pm 0.011\,^{+0.002}_{-0.004}$
DELPHI	0.167 ± 0.012
L3	$0.163 \pm 0.012 \pm 0.010$
OPAL	$0.167 \pm 0.011 \pm 0.008$
LEP	0.161 ± 0.007
SM	0.168

- Measurement of forward-backward asymmetries



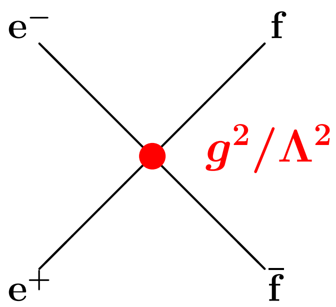
189 GeV	A_{FB}^{b}
ALEPH	$0.34 \pm 0.19 \pm 0.02$
L3	$0.66 \pm 0.23 \pm 0.08$
OPAL	$0.43 \pm 0.15 \pm 0.08$
LEP	0.44 ± 0.12
SM	0.58



189 GeV	A_{FB}^{c}
OPAL	$0.57 \pm 0.18 \pm 0.09$
SM	0.65

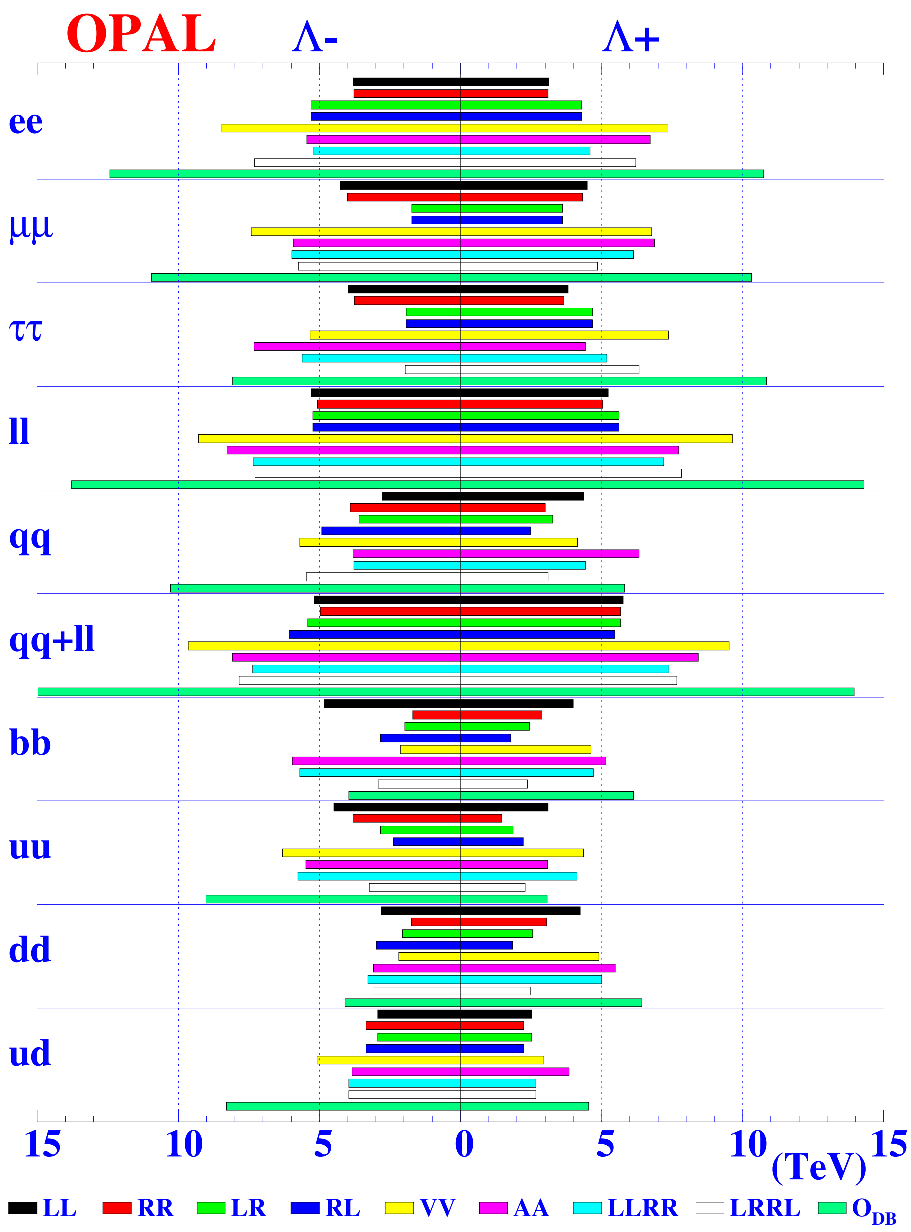
Limits on New Physics from $e^+e^- \to f\bar{f}(\gamma)$

Four-fermion contact interaction



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

$$\frac{d\sigma}{d\cos\Theta} = \frac{d\sigma^{SM}}{d\cos\Theta} + \frac{1}{\Lambda^2} c_{int}(s, \cos\Theta) + \frac{1}{\Lambda^4} c_{CI}(s, \cos\Theta)$$



$\Lambda > 2 - 10$ TeV

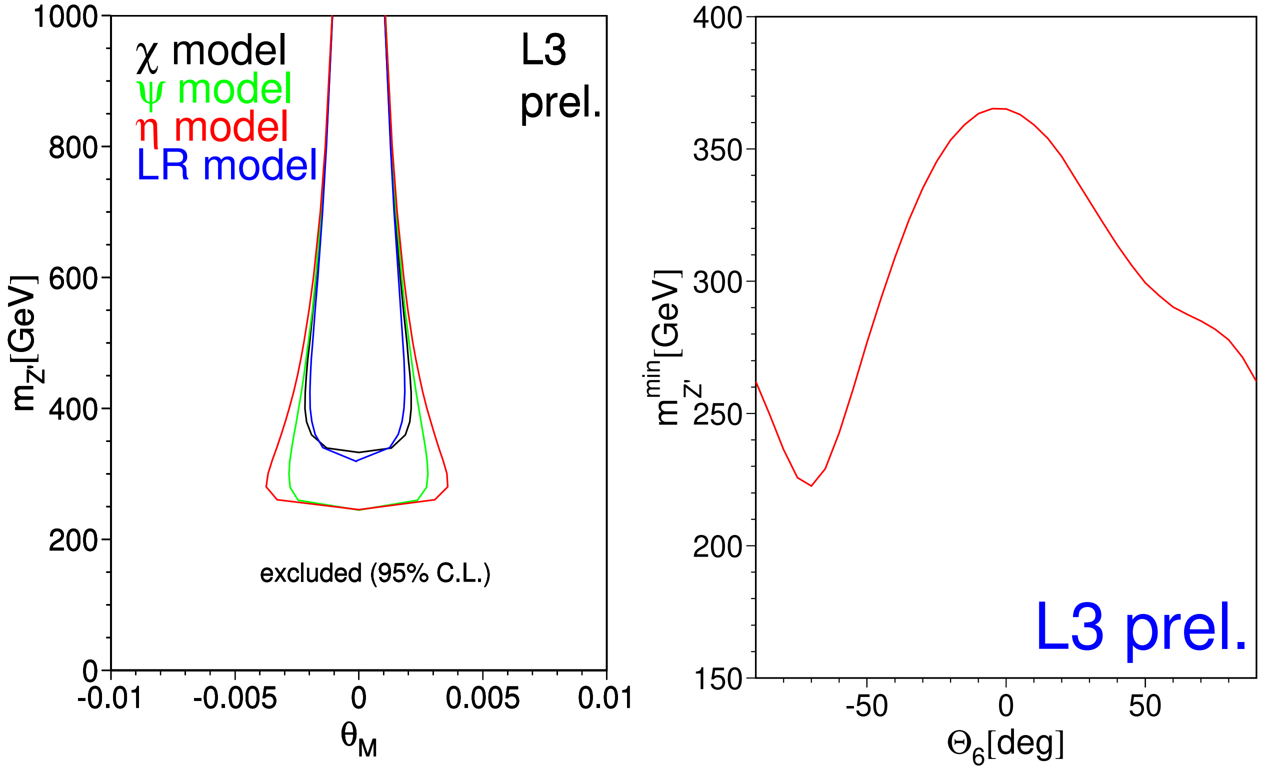
depending on helicity amplitudes and final state

Additional heavy boson Z':

- mass $m_{Z'}$
- Z' couplings
- $Z - Z'$ mixing Θ_M

Consider LR and E_6 models:

$\chi, \psi, \eta:\quad \Theta_6 = 0,\ \frac{\pi}{2},\ -\arctan\sqrt{\frac{5}{3}}$

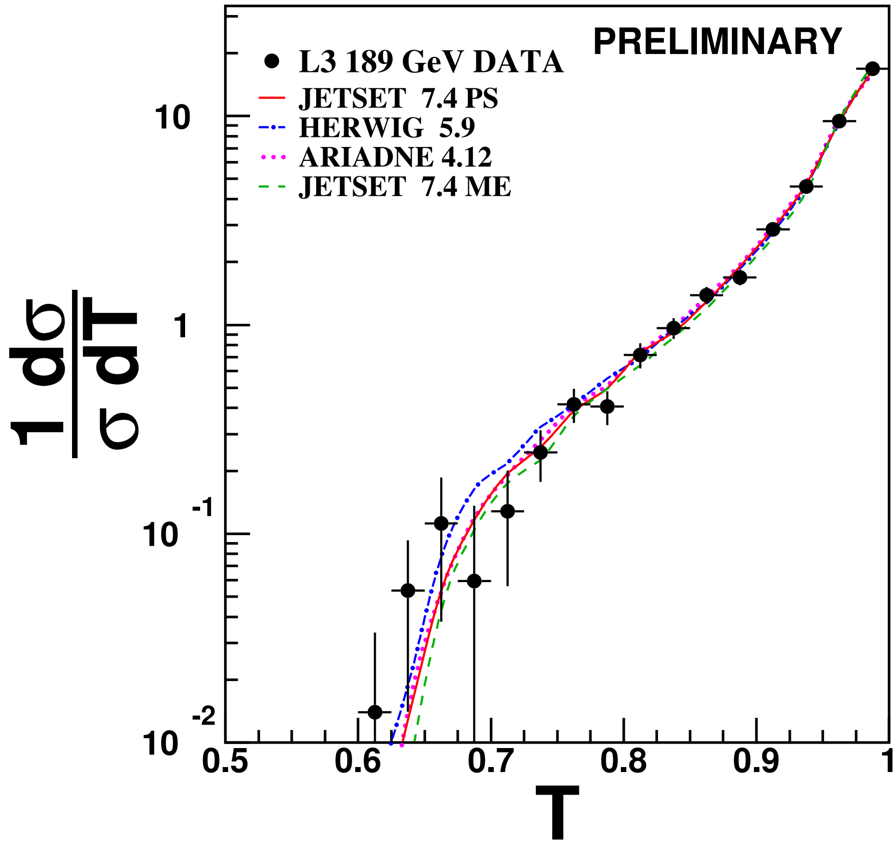


Sequential Standard Model
($\Theta_M = 0$, SM couplings)

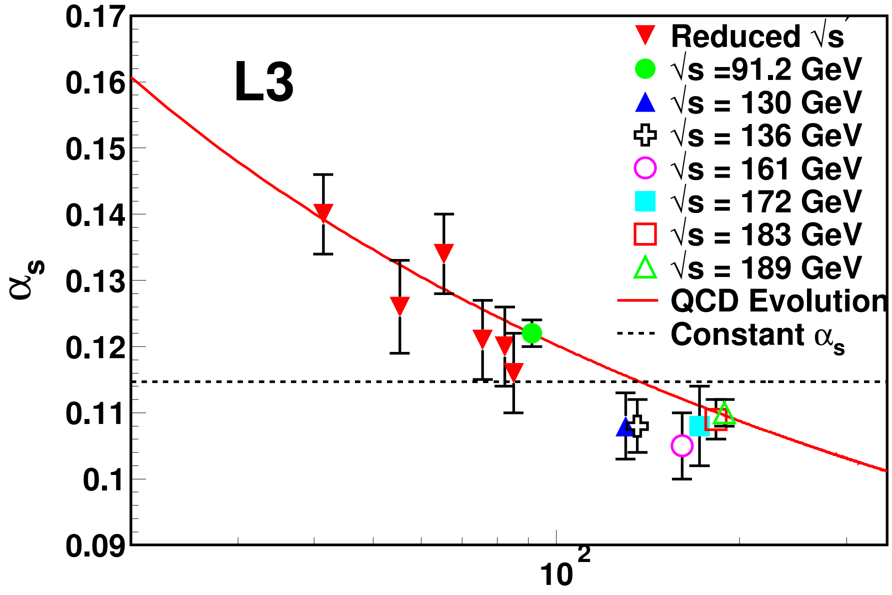
$$m_{Z'} > 950 \text{ GeV} \quad (95\% \text{ CL})$$

Study hadronic event shape variables, e.g. thrust

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |p_i|}$$

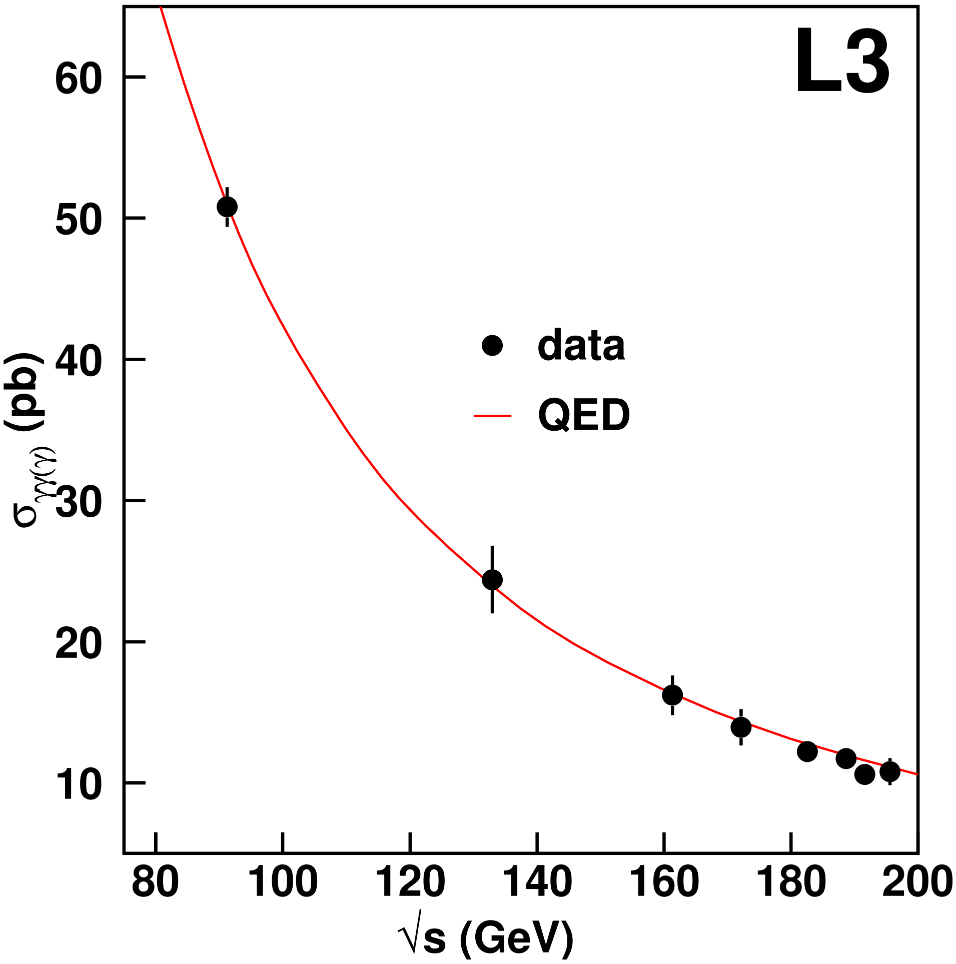


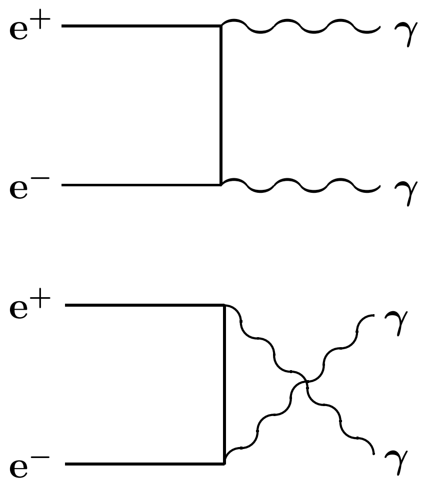
Measurement of α_s as function of $\sqrt{s}$ using same method
only experimental errors matter



$$\alpha_s(m_Z) = 0.1106 \pm 0.0036 \pm 0.0040$$

- Test of QED in $e^+e^- \rightarrow \gamma\gamma(\gamma)$





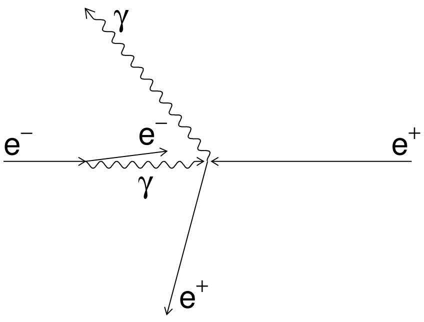
Lower limits on QED cut-off parameter

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Born}} + \frac{\alpha^2 s}{2\,\Lambda_\pm^4}\left(1+\cos^2\theta\right)$$

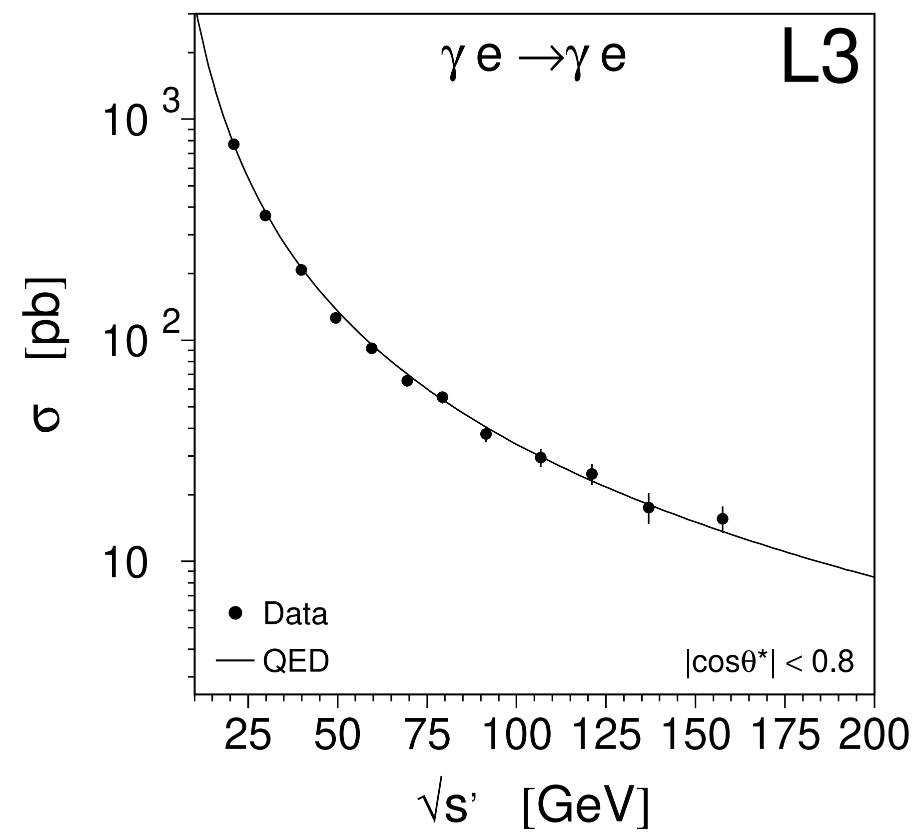
and mass of excited electrons m_{e^*} for equal $e^*e\gamma$ and $ee\gamma$ couplings (189 GeV data)

	Λ_+	Λ_-	m_{e^*} [GeV]
ALEPH	309	269	335
DELPHI	284	278	262
L3	289	291	292
OPAL	304	295	306

- Compton scattering $e^{\pm}\gamma \to e^{\pm}\gamma$



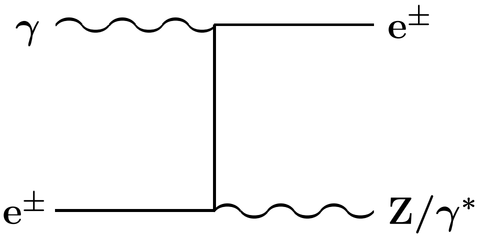
$91\,\mathrm{GeV} \leq \sqrt{s} \leq 189$ GeV



6000 events

$\sqrt{s'} \leq 160$ GeV

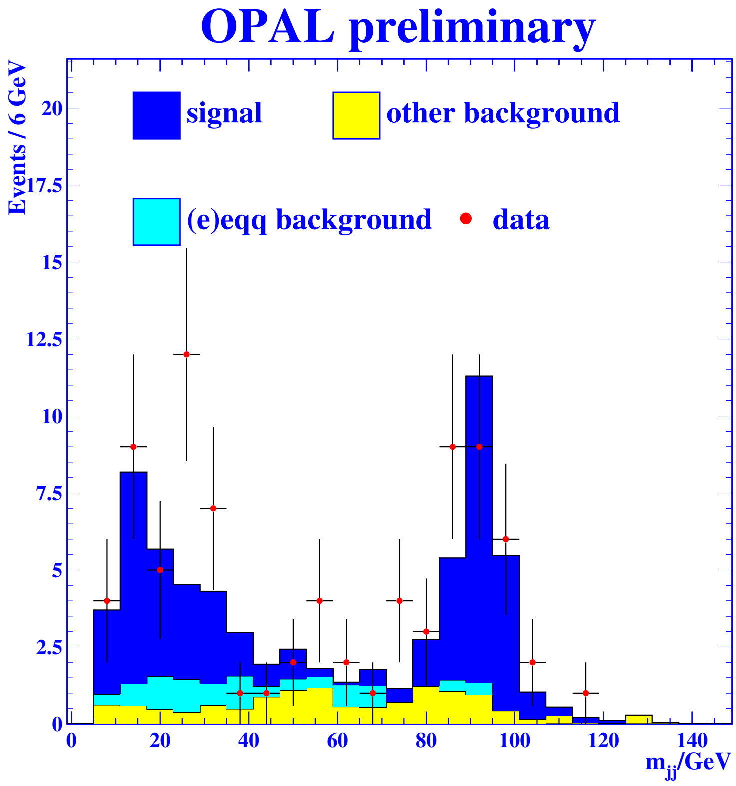
- Electroweak Compton scattering $e^{\pm}\gamma \to e^{\pm}\, Z/\gamma^*$

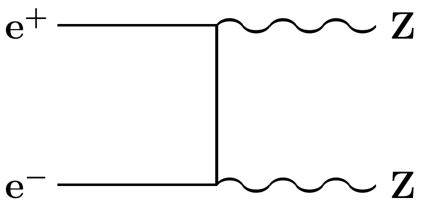


OPAL: $Z/\gamma^* \to$ hadrons

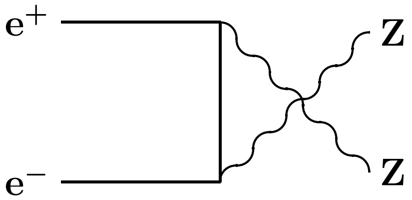
2 jets and isolated electron

m_{jj} [GeV]	5 – 60	> 60
	γ^*e	Ze
data	52	38
σ [pb]	4.6 ± 0.9	1.5 ± 0.3
σ^{SM} [pb]	3.06	1.19

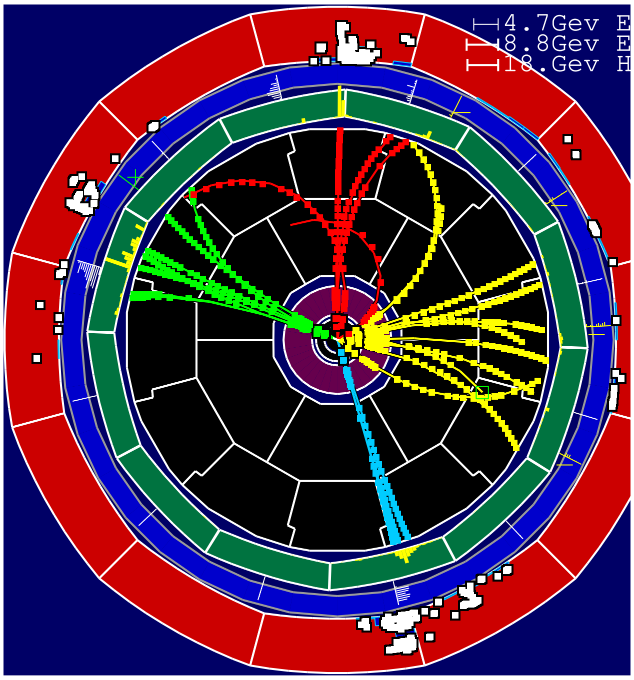




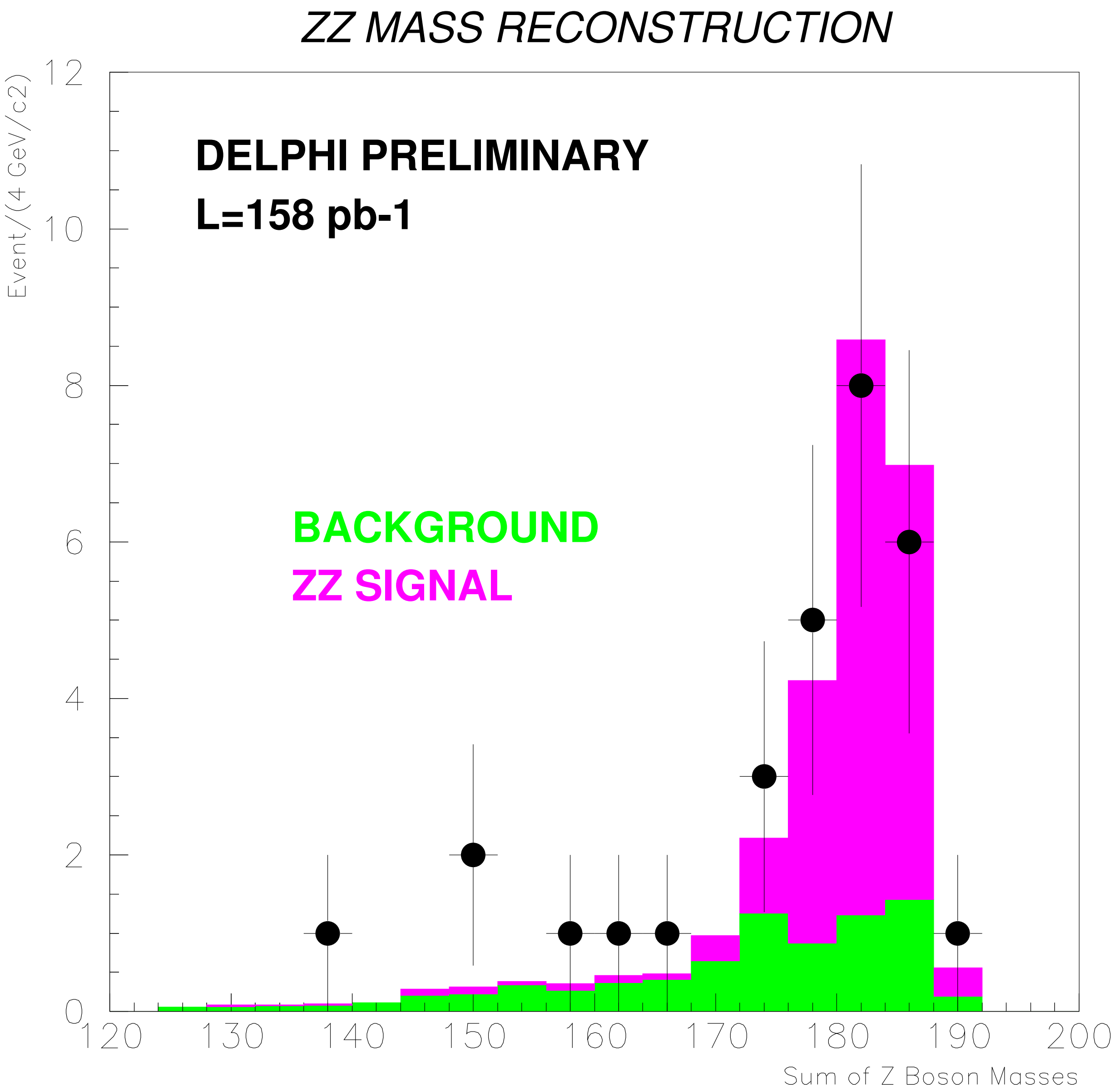
e^+
Z
e^-
Z



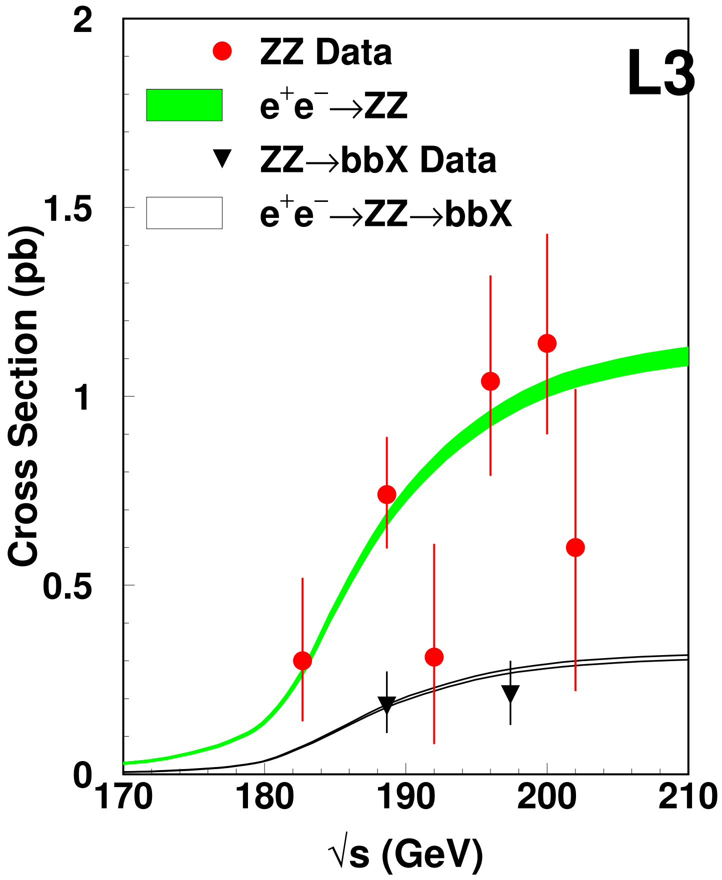
e^+
Z
e^-
Z



4.7Gev E
8.8Gev E
18.Gev H

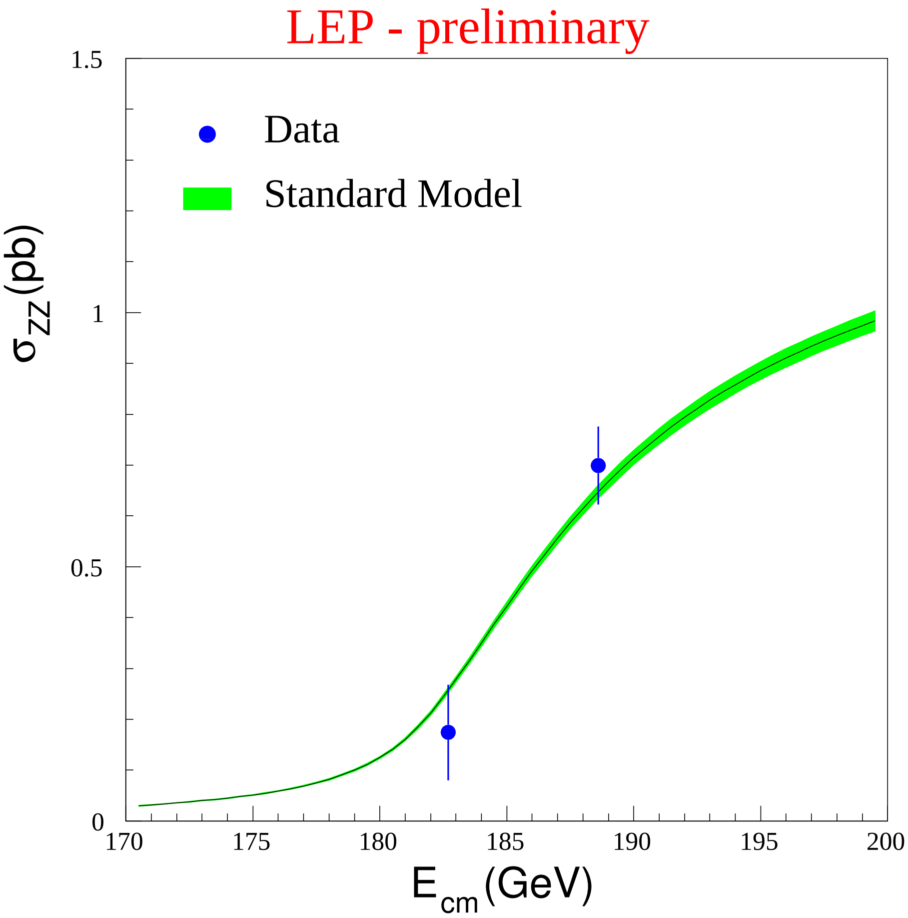


ZZ MASS RECONSTRUCTION
DELPHI PRELIMINARY
L=158 pb-1
BACKGROUND
ZZ SIGNAL
Event/(4 GeV/c2)
0
2
4
6
8
10
12
120
130
140
150
160
170
180
190
200
Sum of Z Boson Masses



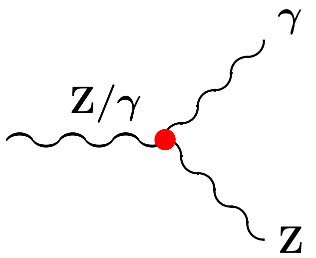
Cross section measurement up to $\sqrt{s} = 202$ GeV

- Combined LEP cross sections



$e^+e^- \to ZZ$ probes ZZZ and $ZZ\gamma$ vertices

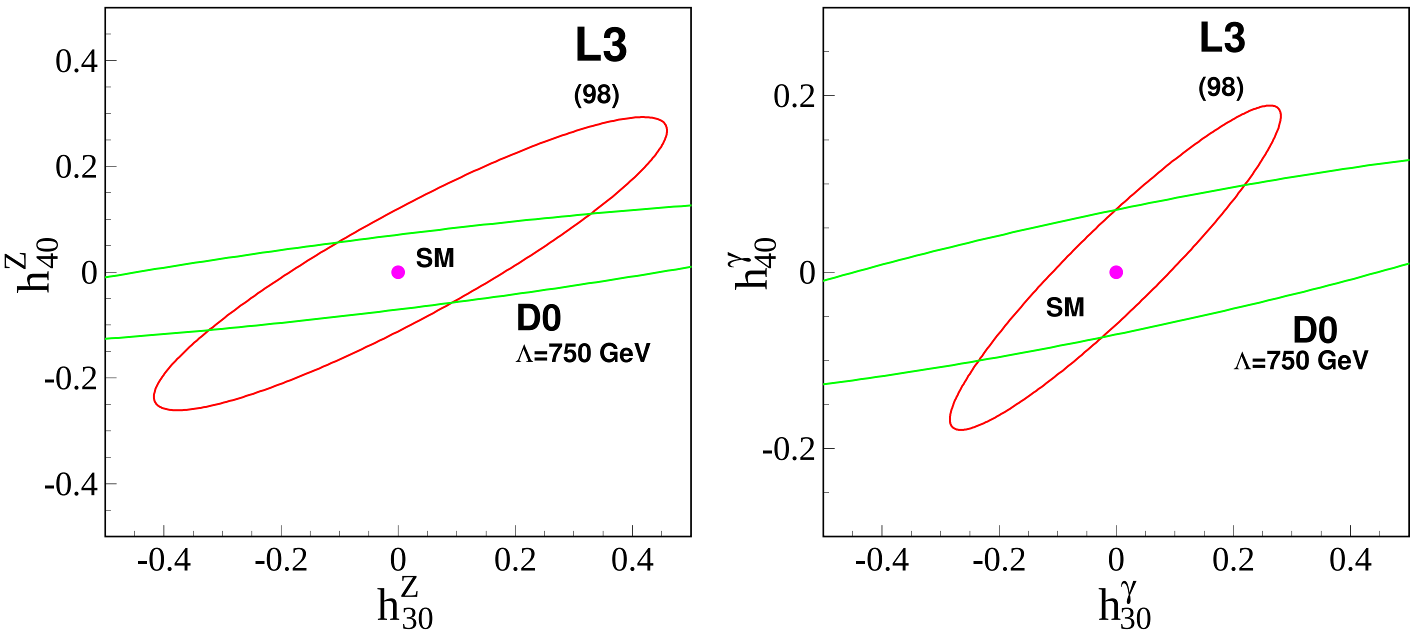
- $\mathrm{e^+e^-} \rightarrow \mathrm{Z}/\gamma \rightarrow \mathrm{f\bar{f}}\gamma$ probes $\mathrm{ZZ}\gamma$ and $\mathrm{Z}\gamma\gamma$ vertices



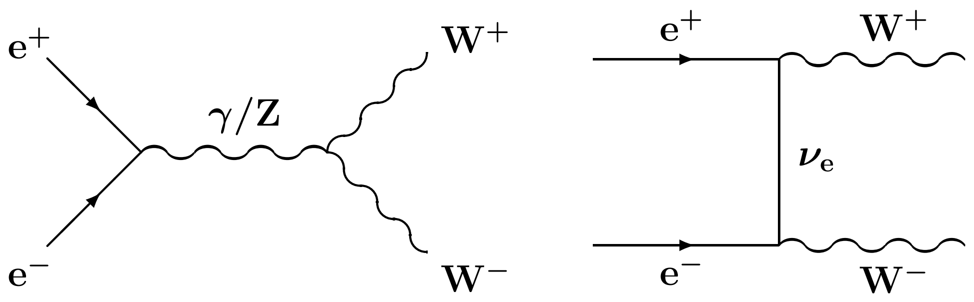
8 coupling parameter h_i^V; $V = \gamma, \mathrm{Z}$
$i = 1, 2$ CP violating
$i = 3, 4$ CP conserving

Study of rate and differential distributions in $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}}\gamma$ and $\mathrm{e^+e^-} \rightarrow \nu\bar{\nu}\gamma$ events

- $\mathrm{Z}\gamma$ production at the Tevatron:
study of $\mathrm{p\bar{p}} \rightarrow \mathrm{e^+e^-}\gamma,\ \mu^+\mu^-\gamma$ events (DØ)



In lowest order 3 Feynman diagrams contribute:



Important:

Individual contributions from ν_e, γ and Z exchange are divergent!

e.g. ν_e exchange:

$$\sigma_\nu = \frac{\pi\alpha^2 s}{96 \sin^4\vartheta_W m_W^4} \to s \quad \text{for } s \gg m_W^2$$

In the SM couplings are such that divergencies cancel:

$$\begin{aligned}\sigma = & \frac{\pi\alpha^2\beta}{2\sin^4\vartheta_W s}\left\{\left[1+\frac{2m_W^2}{s}+\frac{2m_W^4}{s^2}\right]\frac{1}{\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)-\frac{4}{5}\right.\\ & +\frac{m_Z^2(1-2\sin^2\theta_W)}{s-m_Z^2}\left[2\left(2\frac{m_W^2}{s}+\frac{m_W^4}{s^2}\right)\frac{1}{\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)-\frac{s}{12m_W^2}-\frac{5}{3}-\frac{m_W^2}{s}\right]\\ & \left.+\frac{m_Z^4\left(8\sin^4\vartheta_W-4\sin^2\theta_W+1\right)\beta^2}{48\left(s-m_Z^2\right)^2}\left[\frac{s^2}{m_W^4}+20\frac{s}{m_W^2}+12\right]\right\}\end{aligned}$$

$$\sigma_{SM} = \frac{\pi\alpha^2}{2\sin^4\vartheta_W}\frac{1}{s}\ln\frac{s}{m_W^2} \quad \text{for } s \gg m_W^2$$

Requires existence of triple gauge boson couplings γWW and ZWW

Event samples (per experiment):

$161~\text{GeV} \le \sqrt{s} \le 189~\text{GeV} \approx 3500$
$192~\text{GeV} \le \sqrt{s} \le 202~\text{GeV} \approx 3400$

Most results based on $161~\text{GeV} \le \sqrt{s} \le 189~\text{GeV}$ data

Three different event topologies:

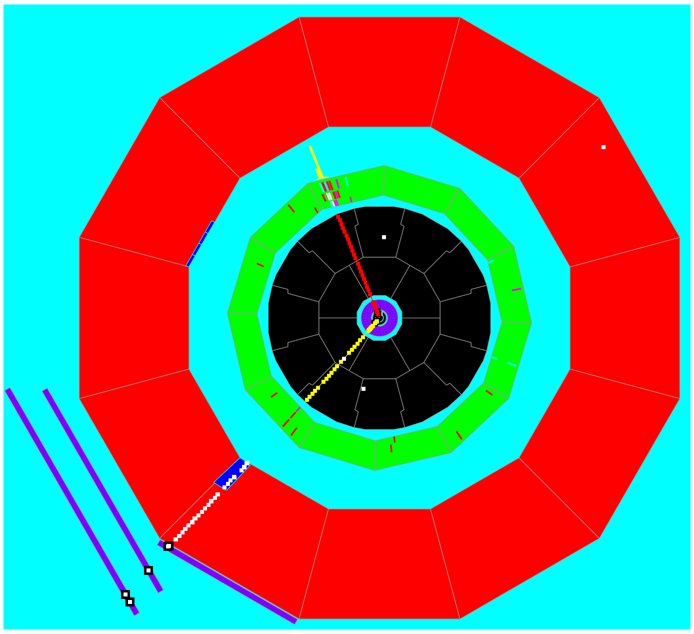
- $W^+W^- \to \ell\nu\ell\nu,\ \ell = e, \mu, \tau \quad (\approx 11\%)$
  two energetic, acoplanar leptons, missing energy
- $W^+W^- \to q\bar{q}\ell\nu \quad (\approx 44\%)$
  two jets plus isolated energetic lepton
  or jet for $W^+W^- \to q\bar{q}\tau\nu$, missing energy
- $W^+W^- \to q\bar{q}q\bar{q} \quad (\approx 46\%)$
  four jets of similar energy
  severe background from QCD: $e^+e^- \to q\bar{q} +$ gluons

$$\sigma(e^+e^- \to q\bar{q}) \approx 100~\text{pb}$$
$$\sigma(e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}) \approx 8~\text{pb}$$

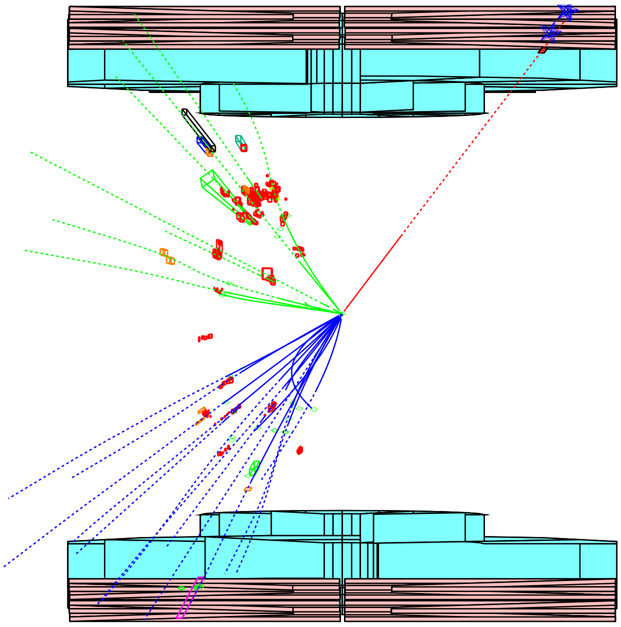
neural networks, likelihood analyses

$e^+e^- \to W^+W^-$ candidates at $\sqrt{s} = 189$ GeV

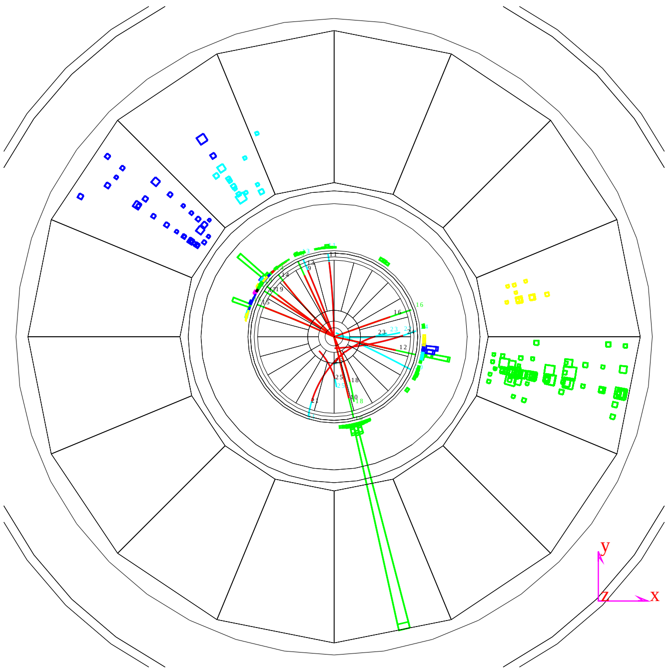
$e^+e^- \to \ell\nu\ell\nu$



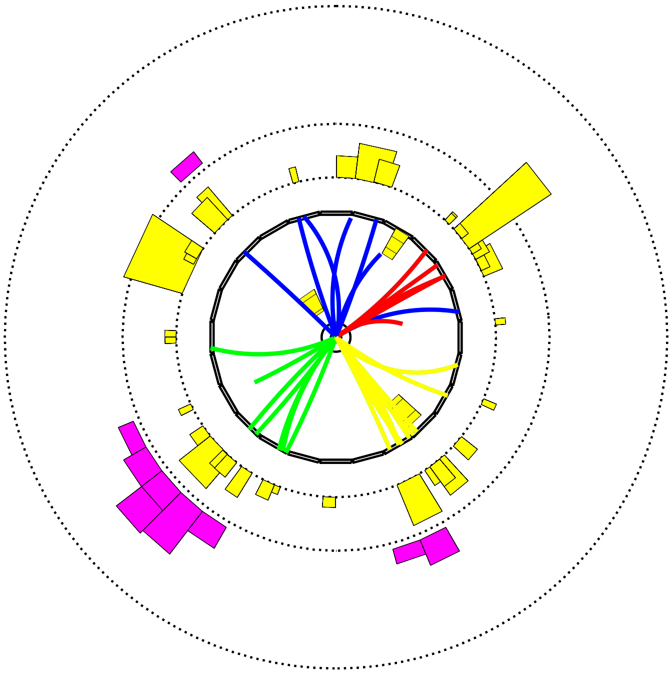
$e^+e^- \to q\bar{q}\mu\nu$



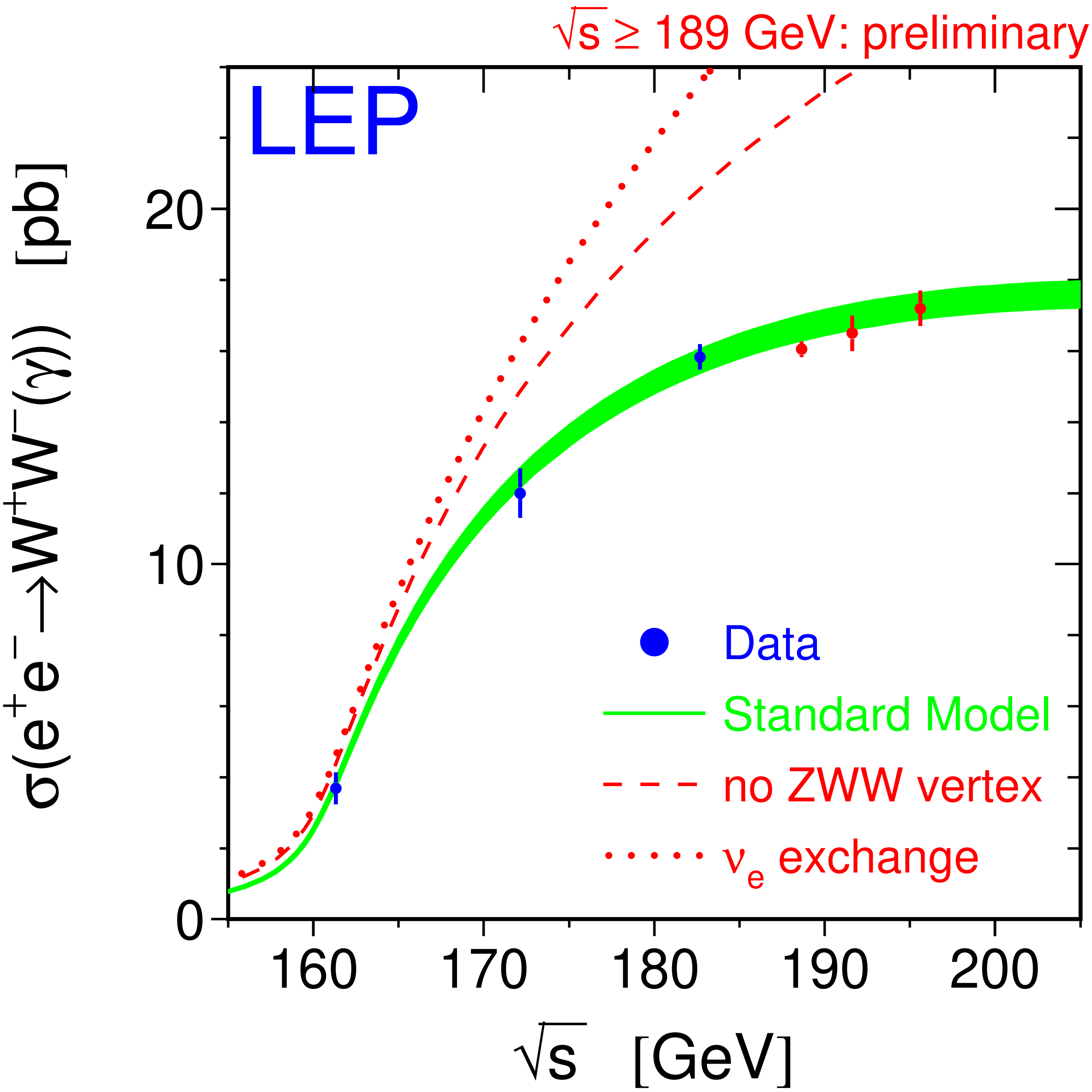
$e^+e^- \to q\bar{q}e\nu$



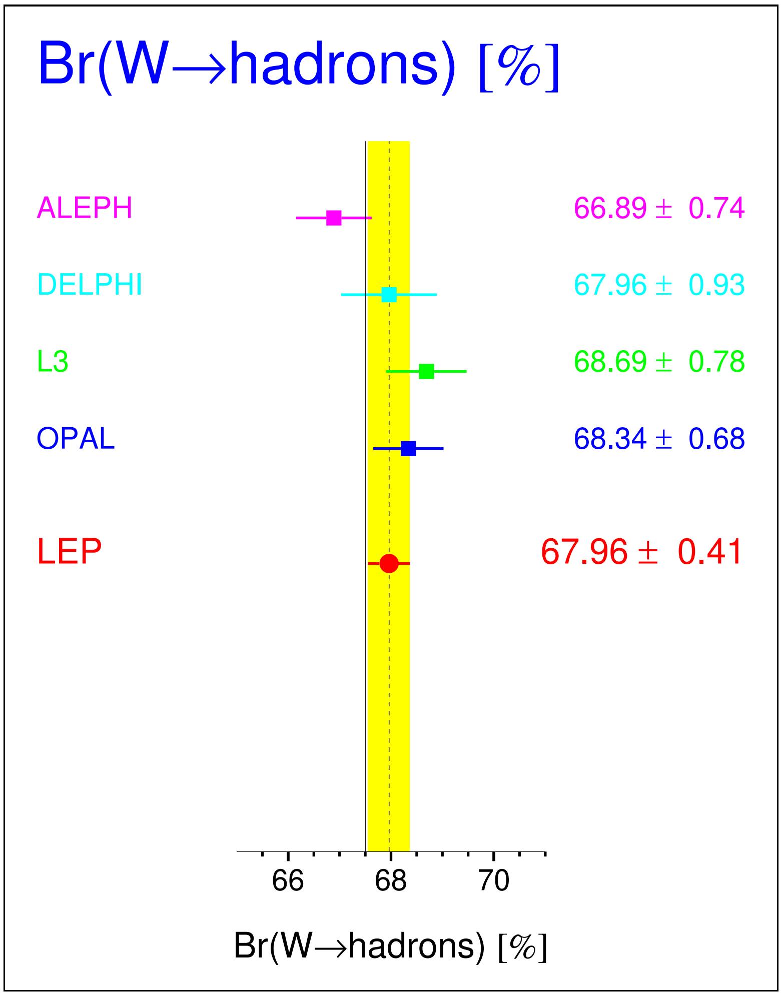
$e^+e^- \to q\bar{q}q\bar{q}$



Combined LEP cross section measurement $e^+e^- \to WW$ for 161 GeV $\leq \sqrt{s} \leq$ 196 GeV



- Very good agreement with SM
  2% theoretical error
- ZWW vertex exists



Determination of $|V_{\mathrm{cs}}|$

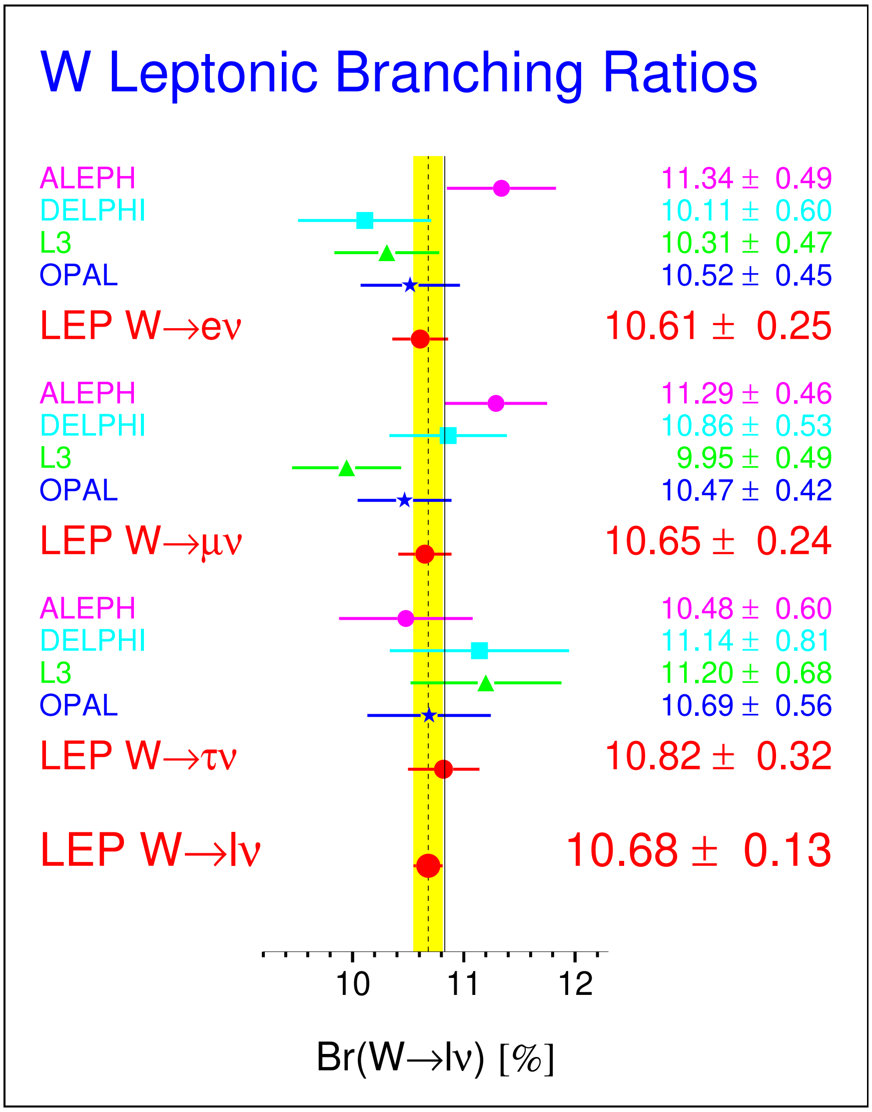
- indirectly from hadronic branching ratio

$$\frac{BR_{\mathrm{had}}}{1 - BR_{\mathrm{had}}} = \sum_{\substack{i=\mathrm{u,c} \\ j=\mathrm{d,s,b}}} |V_{ij}^2| \left(1 + \frac{\alpha_{\mathrm{s}}}{\pi}\right)$$

LEP: $|V_{\mathrm{cs}}| = 0.997 \pm 0.020$

- directly by charm tagging (189 GeV)

	$\Gamma(\mathrm{W} \to \mathrm{cX})/\Gamma(\mathrm{W} \to \mathrm{had})$	$\lvert V_{\mathrm{cs}}\rvert$
ALEPH	$0.51 \pm 0.05 \pm 0.03$	$1.00 \pm 0.11 \pm 0.07$
OPAL	$0.47 \pm 0.04 \pm 0.06$	$0.91 \pm 0.07 \pm 0.11$



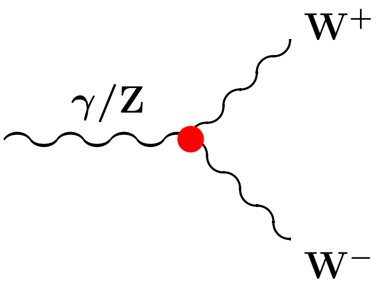
Charged current lepton universality ($Q^2 = m_W^2$):

$$g_\mu/g_e = 1.001 \pm 0.016$$
$$g_\tau/g_e = 1.010 \pm 0.022$$
$$g_\tau/g_\mu = 1.008 \pm 0.021$$

$$\text{CDF}: BR(\mathrm{W} \to e\nu) = 0.1037 \pm 0.0022$$
$$\text{DØ}: BR(\mathrm{W} \to e\nu) = 0.1080 \pm 0.0030$$

$$\text{DØ}: g_\tau/g_e = 0.98 \pm 0.03$$

Triple gauge boson vertices γWW and ZWW



Most general Lorentz invariant ansatz:
2×7 complex couplings

Assume real couplings,
C-, P- and CP invariance,
charge of $\mathrm{W}^{\pm}$ $(= \pm e)$
no change of tree-level boson propagators

$\Rightarrow$ 3 coupling parameter to be studied:

$$g_1^{\mathrm{Z}}, \; \kappa_\gamma, \; \lambda_\gamma$$

Related to static moments of the W boson

$$\mu_{\mathrm{W}} = \frac{e}{2m_{\mathrm{W}}}(2 + \Delta\kappa_\gamma + \lambda_\gamma) \quad \text{magnetic dipole moment}$$

$$Q_{\mathrm{W}} = -\frac{e}{m_{\mathrm{W}}^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma) \quad \text{electric quadupole moment}$$

SM values:

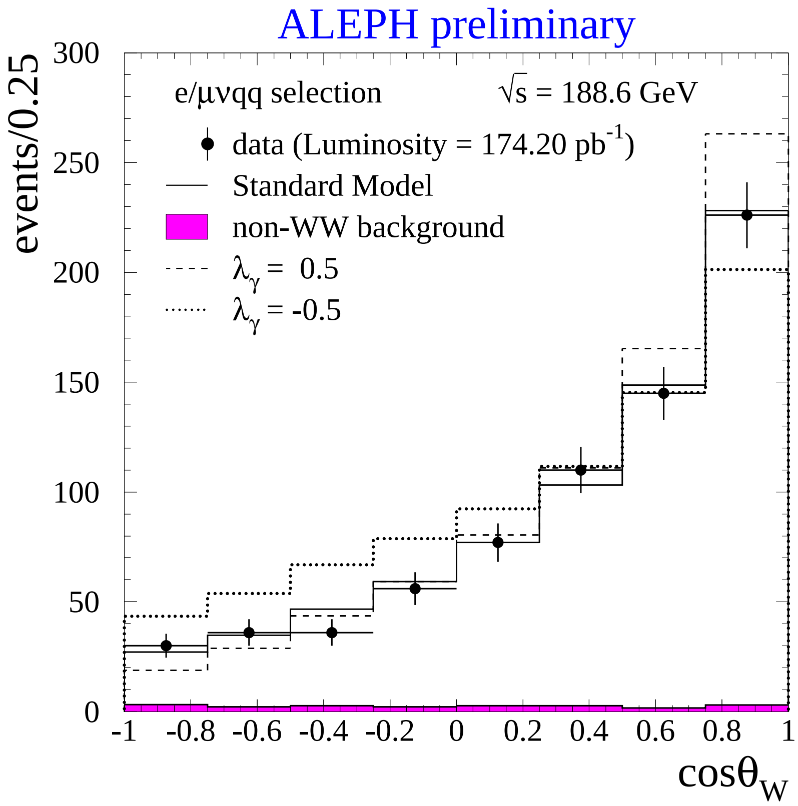
$$g_1^{\mathrm{Z}} = 1, \quad \kappa_\gamma = 1, \quad \lambda_\gamma = 0$$

Deviations from Standard Model would

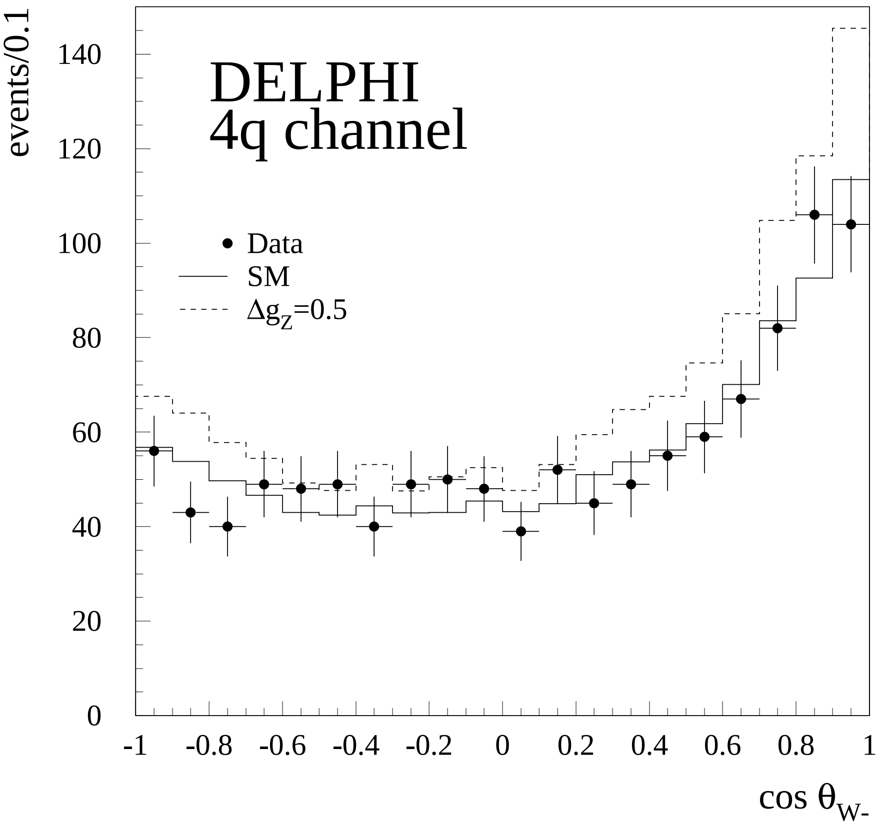
- increase $\mathrm{e^+e^-} \rightarrow \mathrm{WW}$ cross section
- modify W production angles
- modify W polarization

Examples for W^- production angle $\cos\Theta_W$:

- $\cos\Theta_W$ in $WW \to q\bar{q}e\nu,\ q\bar{q}\mu\nu$

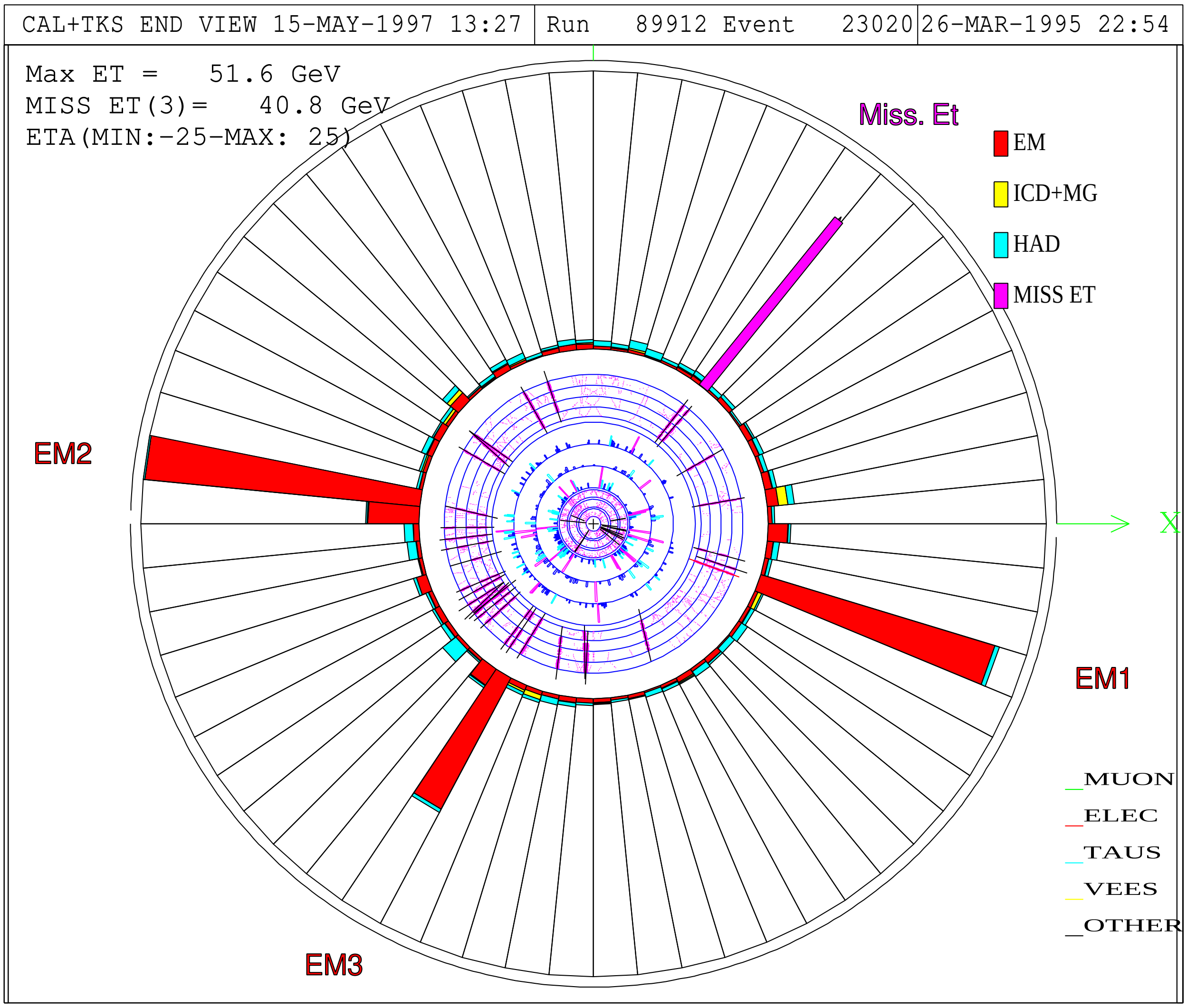


- $\cos\Theta_W$ in $WW \to q\bar{q}q\bar{q}$ events



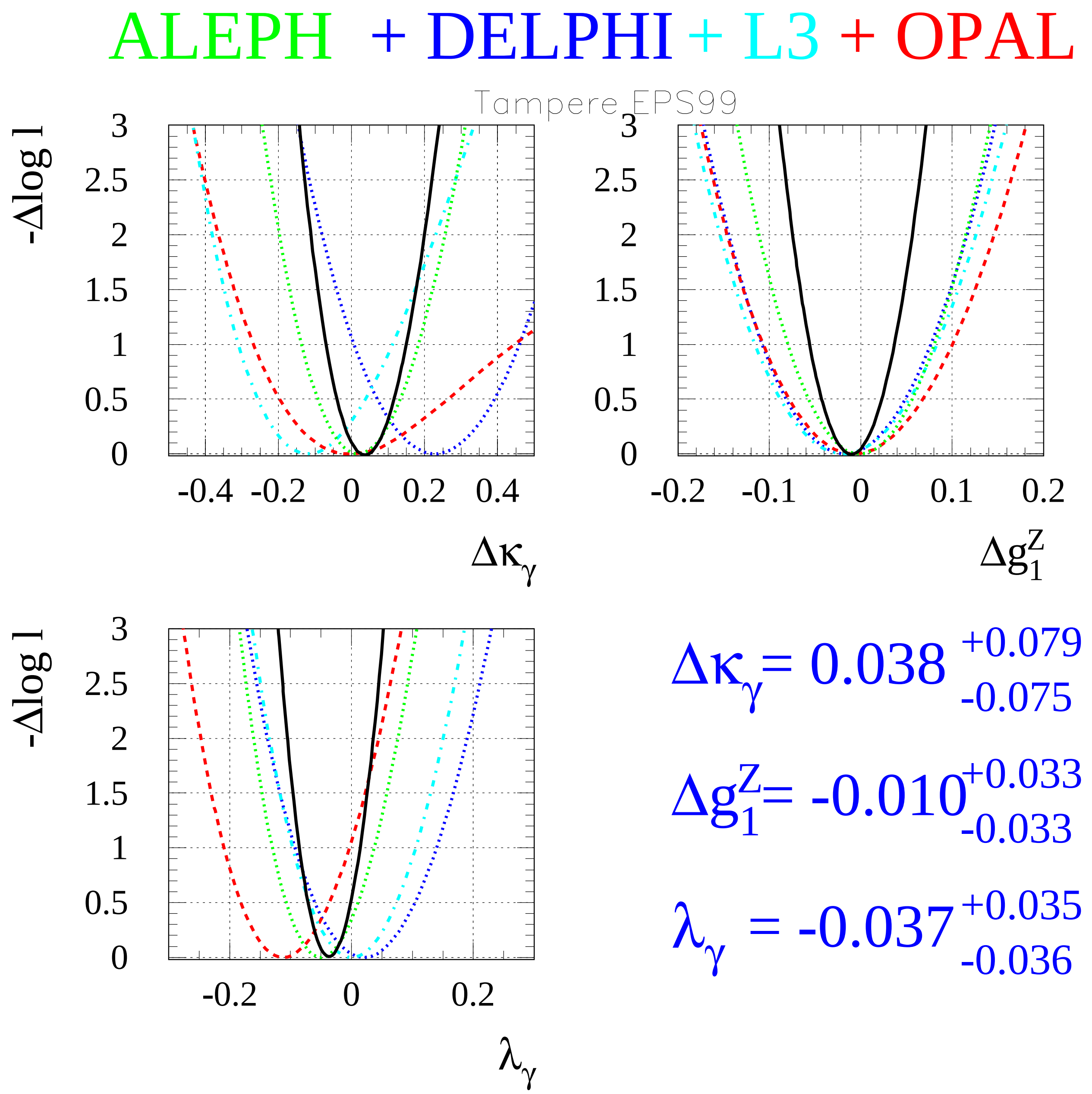
Anomalous W couplings would lead to enhanced boson pair production $W\gamma$, WW, WZ in $p\bar{p}$

DØ candidate event ZW $\rightarrow ee e\nu$



$M_T(2)$=74.7 GeV M_{13}=93.6 GeV

- **LEP combination ($e^+e^- \rightarrow WW$ up to 189 GeV)**



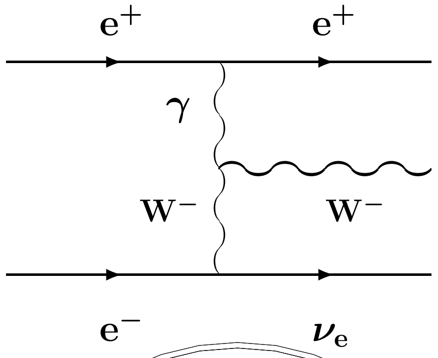
Result from DØ:

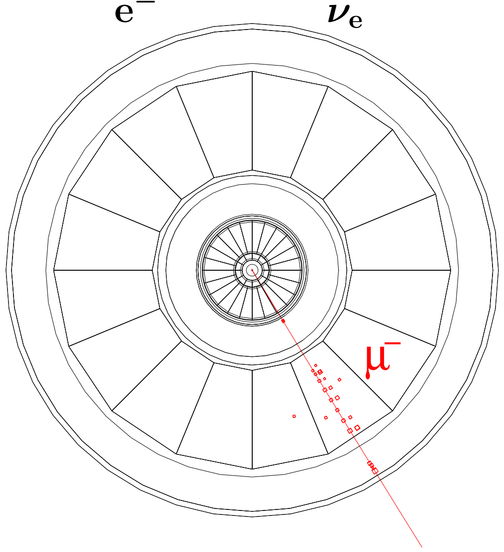
$$\begin{aligned} \Delta\kappa_\gamma &= -0.08 \pm 0.34 \\ \lambda_\gamma &= 0.00\,^{+0.10}_{-0.09} \end{aligned}$$

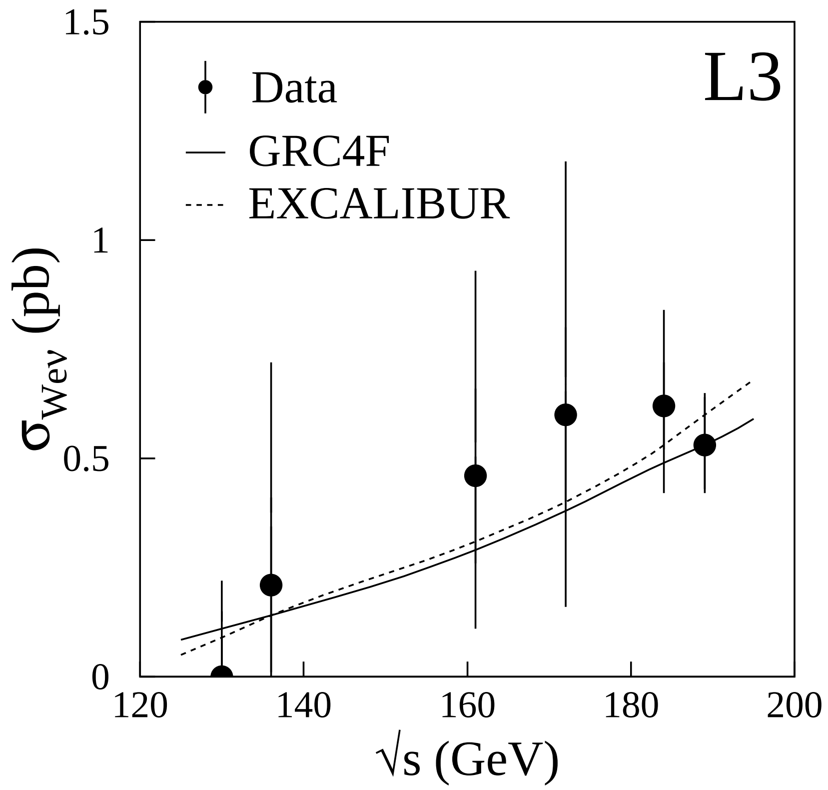
(Δ denotes deviation from SM value)

Single W production at LEP

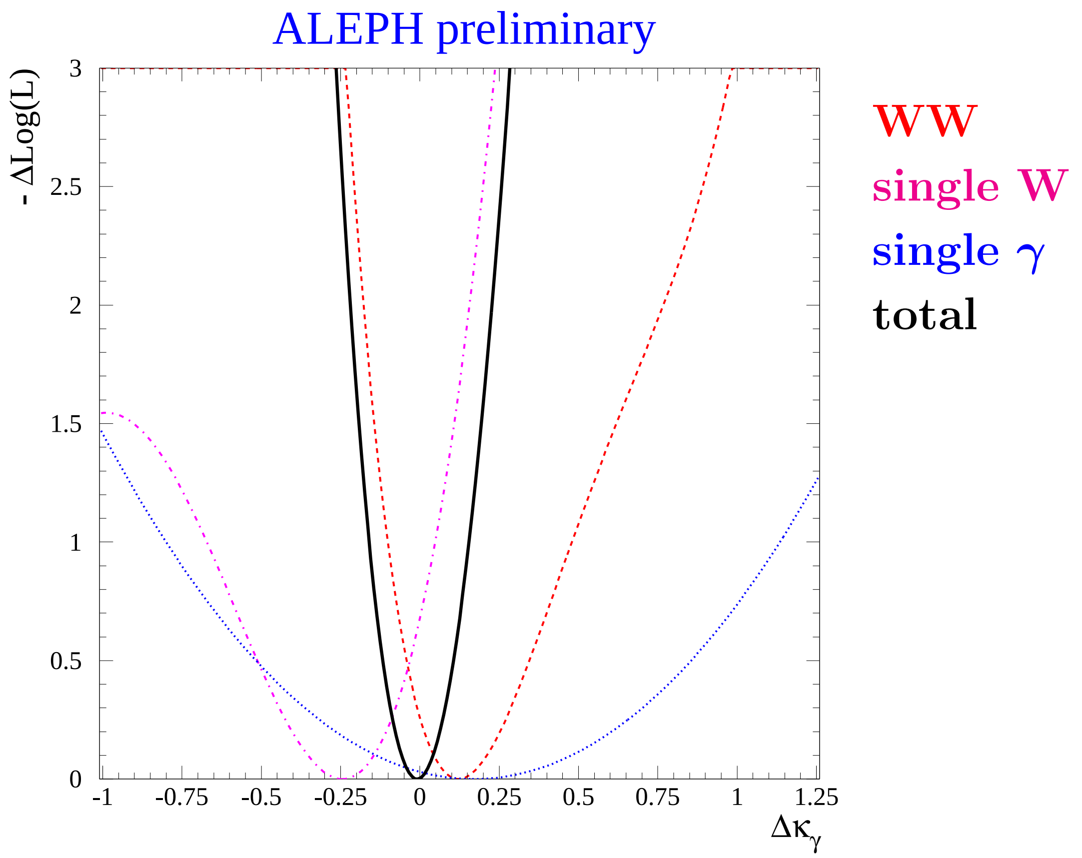
- More information on γWW vertex from single W events:



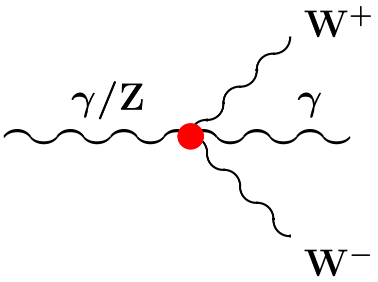




- and from single photon events



- $e^+e^- \to WW\gamma$ probes quartic boson vertices $WW\gamma\gamma$ and $WWZ\gamma$



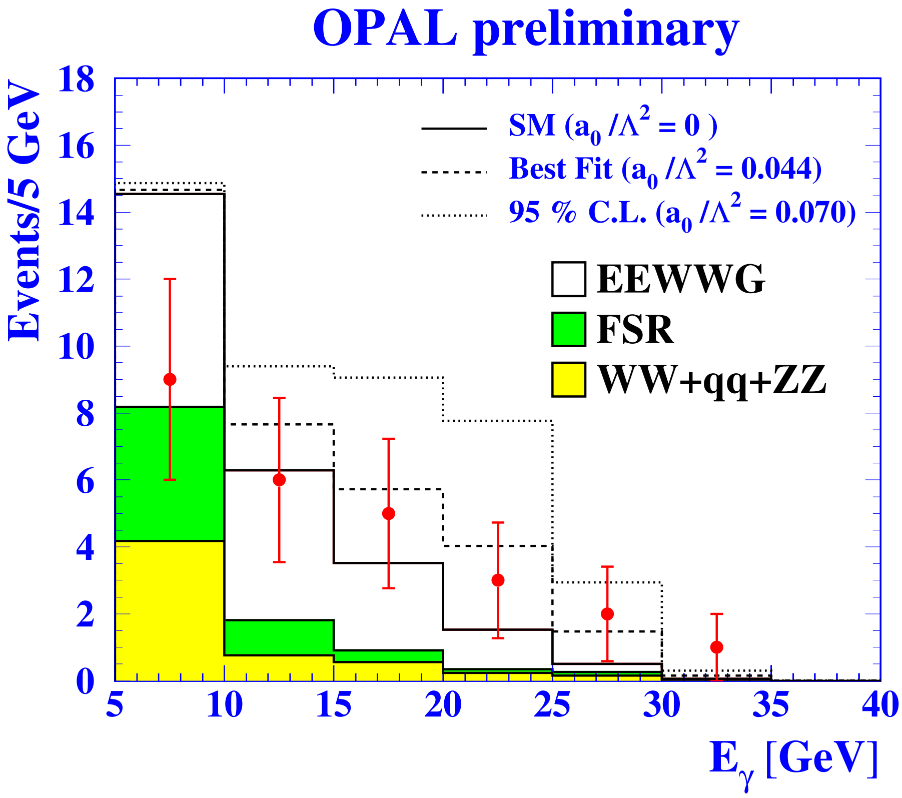
Genuine quartic gauge boson couplings:

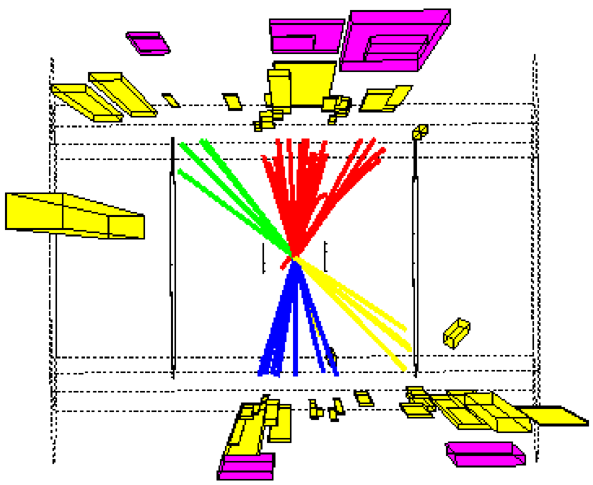
6 dimensional operators

$a_0/\Lambda^2,\ a_c/\Lambda^2,\ a_n/\Lambda^2$

OPAL: 17 candidates with $E_\gamma \geq 10$ GeV

$\sigma_{WW\gamma} = 136 \pm 37 \pm 8$ fb $\qquad \sigma^{SM}_{WW\gamma} = 85 - 105$ fb





Combine with $e^+e^- \to \nu\bar{\nu}\gamma\gamma$:

$$-0.065\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < +0.065\ \mathrm{GeV}^{-2} \qquad WW\gamma\gamma$$

$$-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < +0.17\ \mathrm{GeV}^{-2} \qquad WW\gamma\gamma$$

$$-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < +0.57\ \mathrm{GeV}^{-2} \qquad WWZ\gamma$$

(More stringent indirect limits exist on a_0 and a_c)

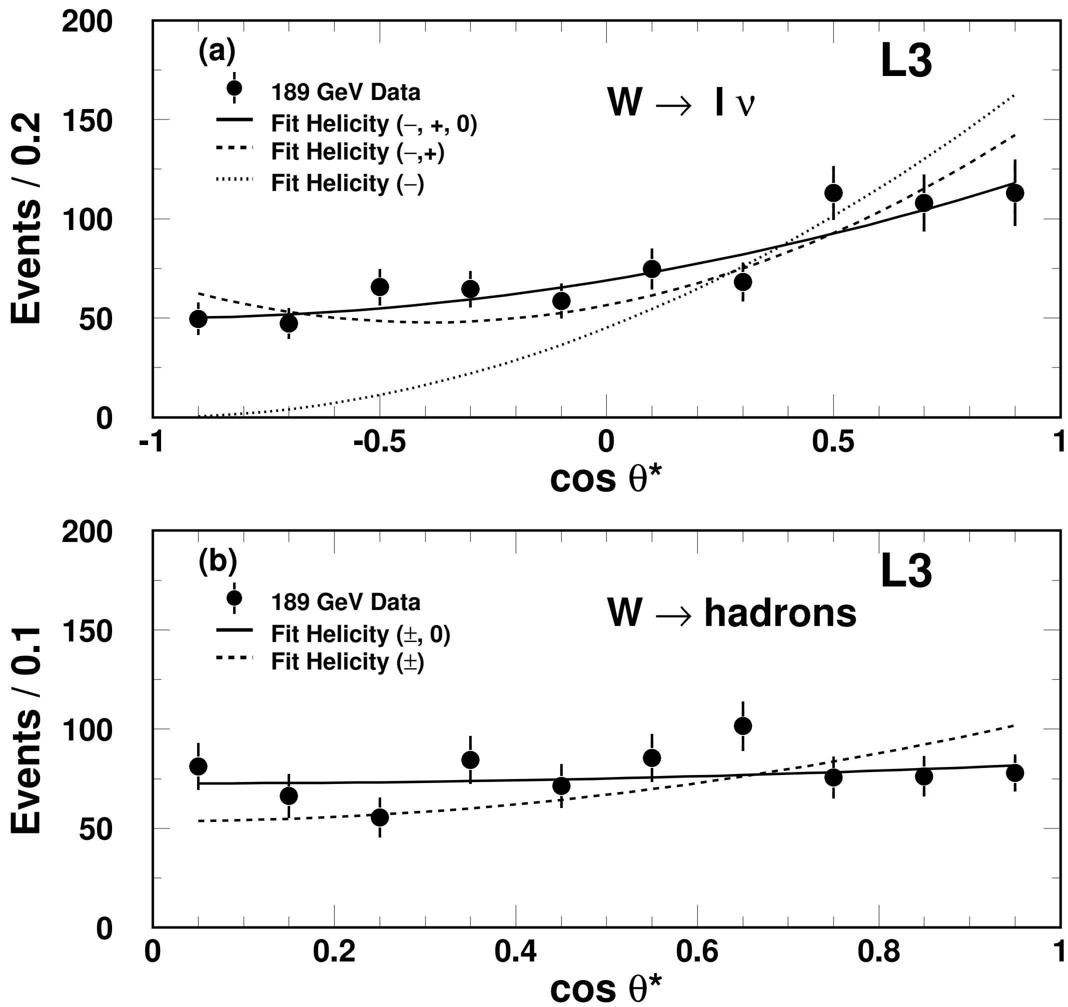
Massive gauge bosons have three polarization states

- transverse $(-\,+)$ • longitudinal (0)

Lepton (quark) angle in W rest frame θ^*:

$\propto (1 \pm \cos\theta^*)^2$ transverse W

$\propto \sin^2\theta^*$ longitudinal W



Measured fraction of longitudinally polarized W bosons:

L3 : $0.261 \pm 0.051 \pm 0.016$

SM 0.26

Top quark decay:

CDF : $0.91 \pm 0.37 \pm 0.12$

SM 0.70

Reconstruction of W decay products
invariant masses $m_{q\bar{q}}$, $m_{\ell\nu}$ provide m_W

Improve mass resolution by kinematic fit with 5 constraints

$$\begin{aligned} \sum \vec{p}_i &= 0 \\ \sum E_i &= \sqrt{s} \\ m_W^1 &= m_W^2 \text{or } |m_W^1 - m_W^2| \approx \Gamma_W \end{aligned}$$

- $\vec{p}_\nu$ is not measured in $W^+W^- \to q\bar{q}e\nu$ and $W^+W^- \to q\bar{q}\mu\nu$ events
  $\Rightarrow$ 2 constraints
- for $W^+W^- \to q\bar{q}\tau\nu$ also E_τ is not measured
  $\Rightarrow$ 1 constraint
- $W^+W^- \to \ell\nu\ell\nu$ events not useable

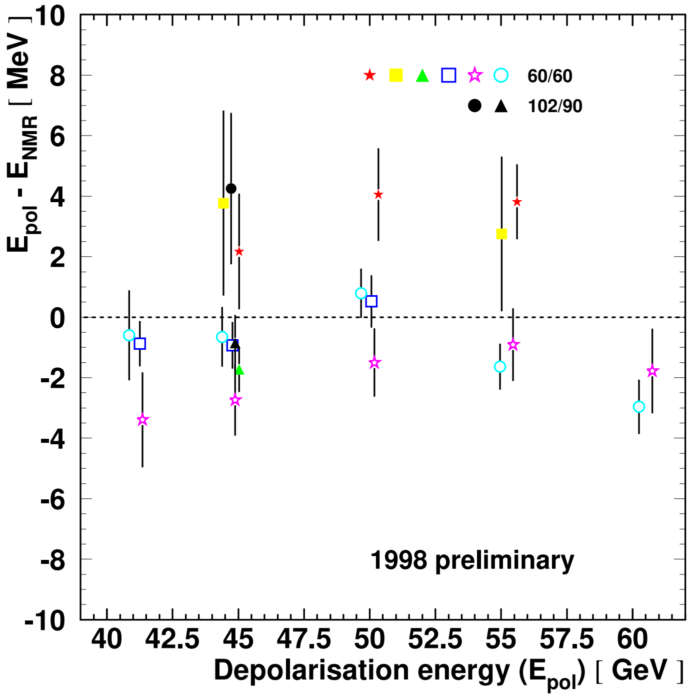
Precise knowledge of LEP beam energy is mandatory

$$\frac{\Delta E_b}{E_b} = \frac{\Delta m_W}{m_W}$$

Absolute scale of m_W is determined by LEP beam energy

Problems in fully hadronic channel $e^+e^- \to qqqq(\gamma)$

- 3 possible jet pairings
  best pair selected by χ^2, Δm_W
- Final state interactions

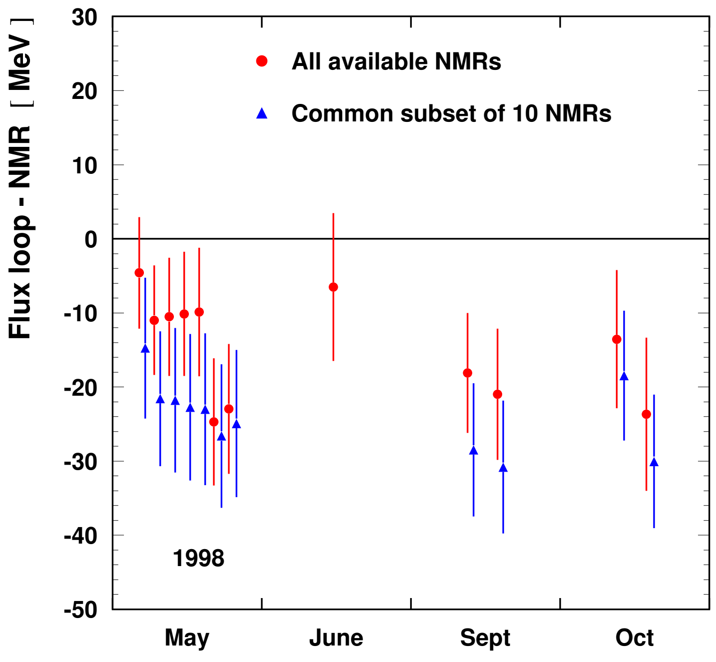


Resonant depolarisation
$E_b \lesssim 61$ GeV

Precison $\mathcal{O}(1\ \mathrm{MeV})$

Used to measure m_Z, Γ_Z (LEP I)

But no polarization possible at high energy!



Extrapolate to $E_b = 94.5$ GeV using magnetic measurements: NMR probes, flux loop

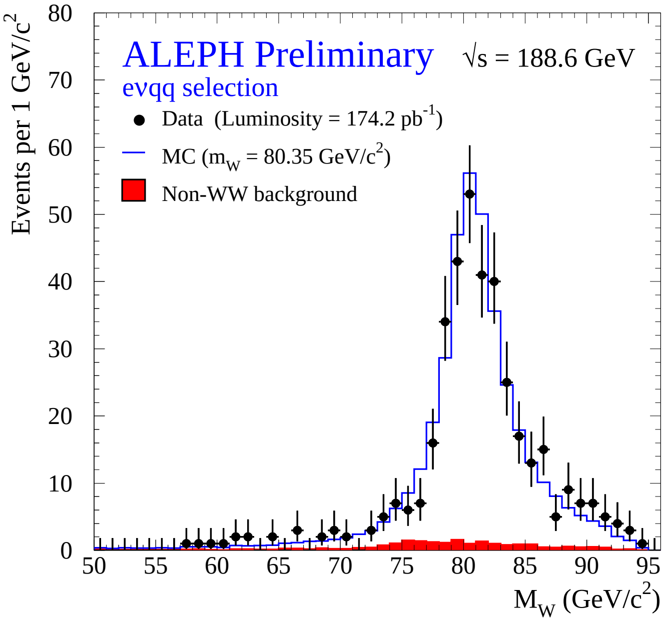
Difference determines error on E_b

$\Longrightarrow \Delta E_b = \pm 20$ MeV at $E_b = 94.5$ GeV

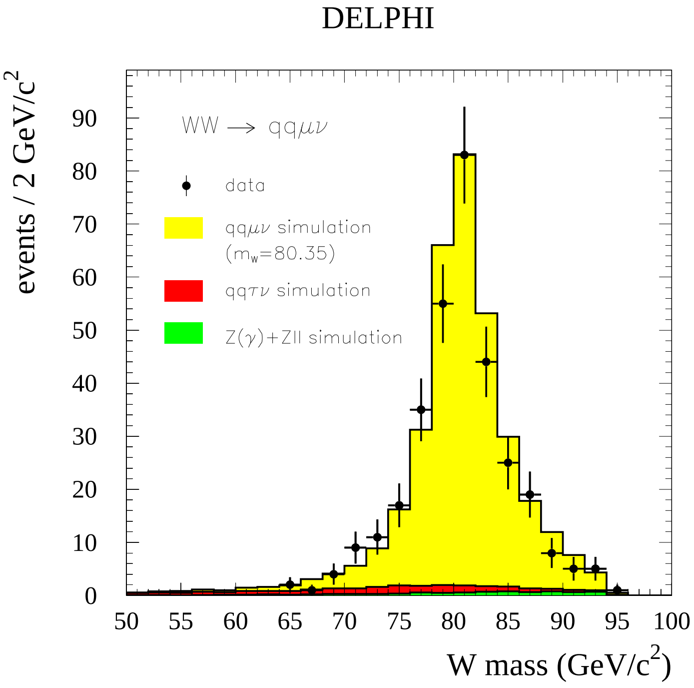
Invariant mass distributions after kinematic fit

Data at $\sqrt{s} = 189$ GeV:

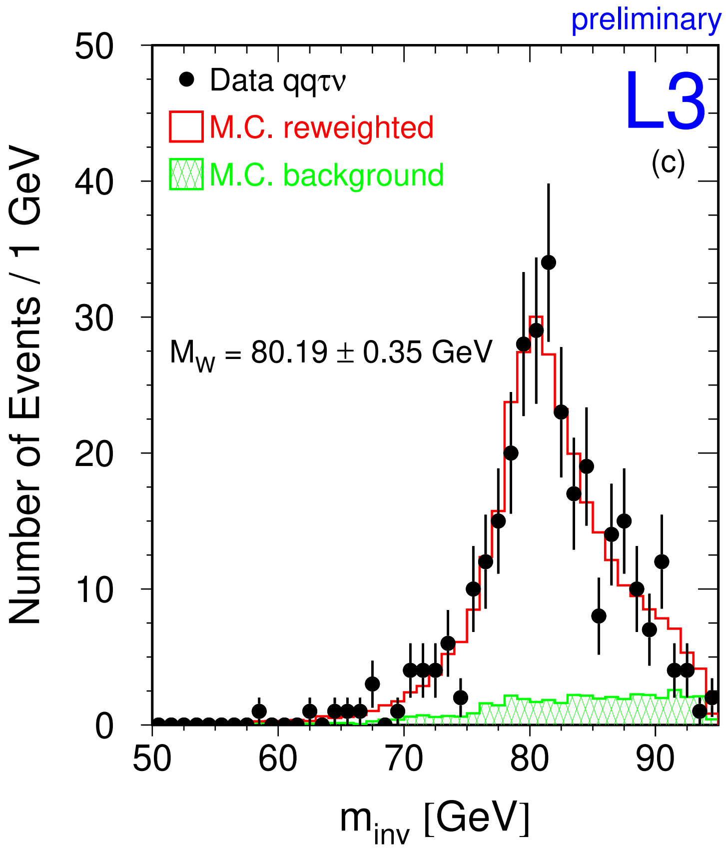
$\mathrm{WW} \rightarrow \mathrm{q\bar{q}}\, e\nu$



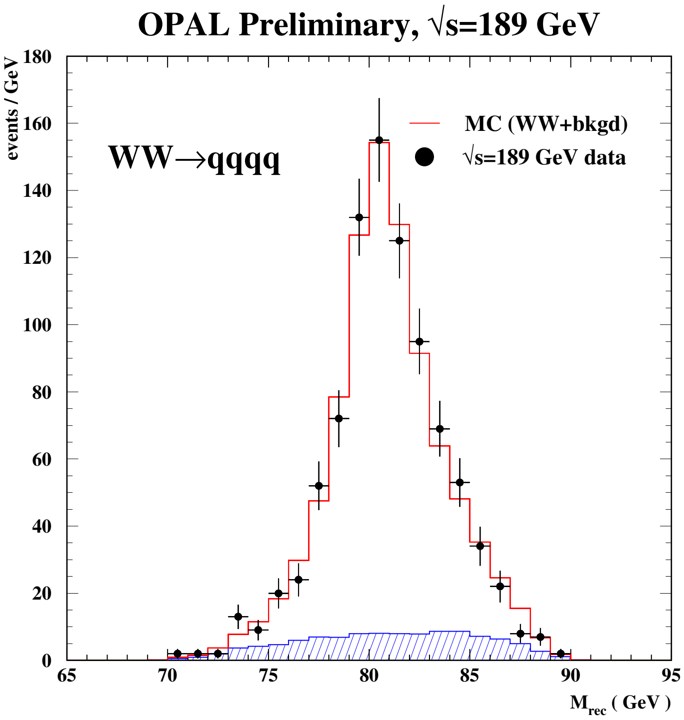
$\mathrm{WW} \rightarrow \mathrm{q\bar{q}}\, \mu\nu$



$\mathrm{WW} \rightarrow \mathrm{q\bar{q}}\, \tau\nu$

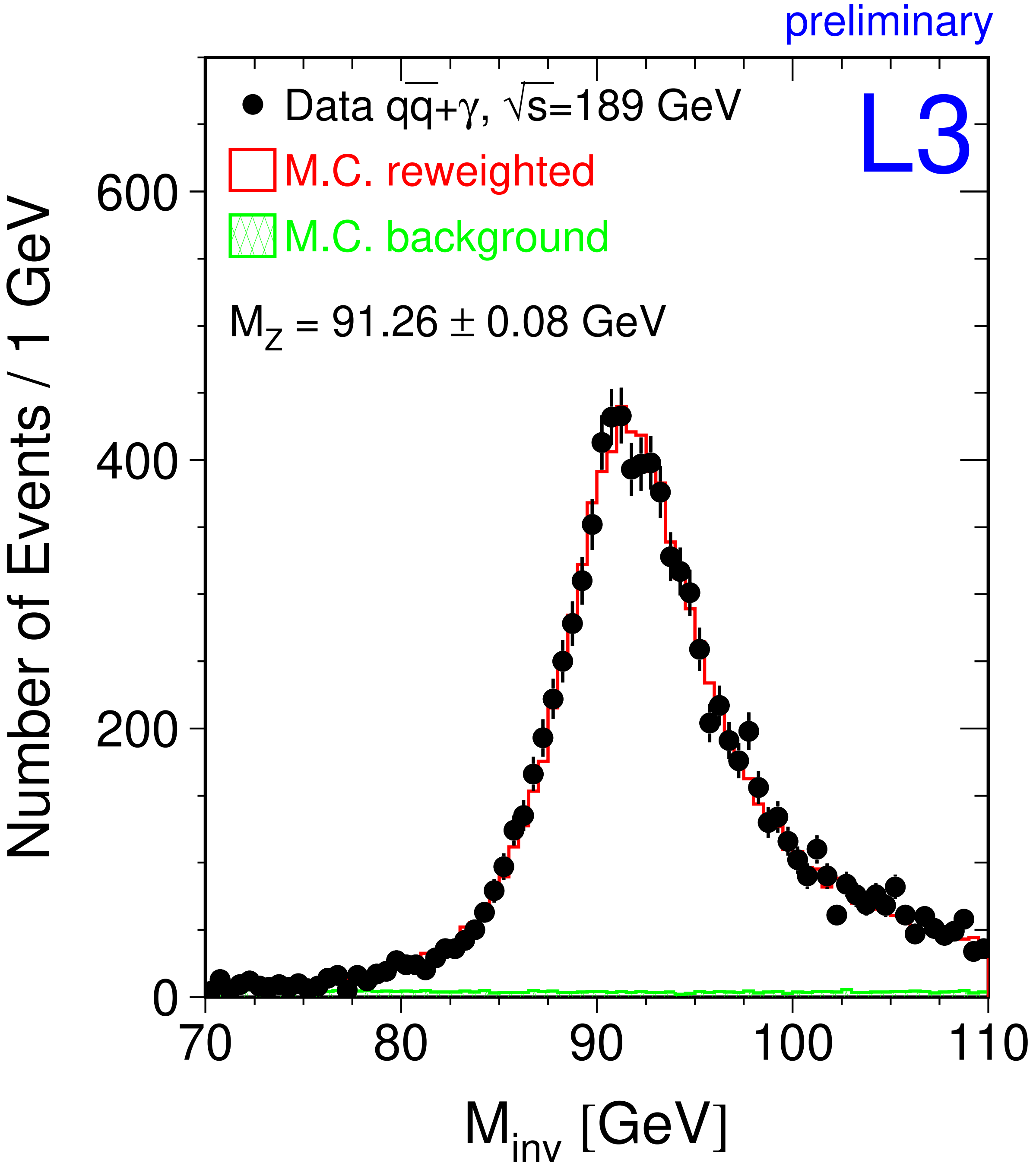


$\mathrm{WW} \rightarrow \mathrm{q\bar{q}}\, \mathrm{q\bar{q}}$



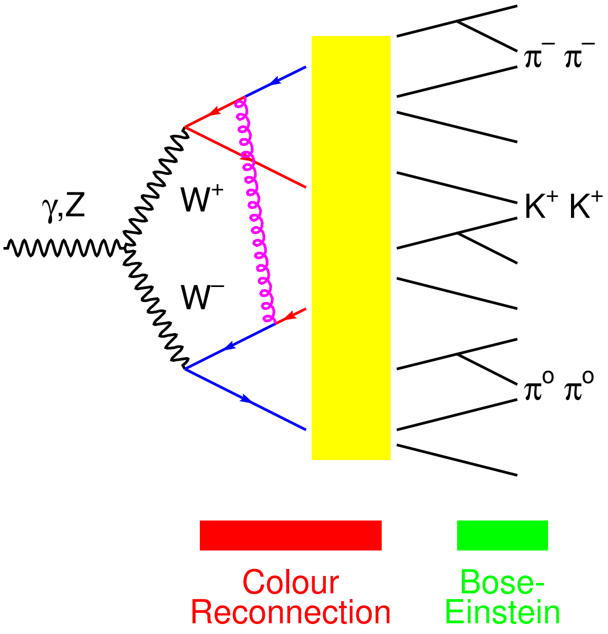
Determine m_Z from hadronic 'Return-to-the-Z' events to check

- kinematic fit
- detector calibration



$$m_Z = 91.263 \pm 0.054(stat.) \pm 0.056(sys.)\ \text{GeV}$$

Statistical error smaller than on m_W



- **Colour reconnection**
  - Hadronisation scale $\mathcal{O}(1\ \text{fm})$ much larger than W decay length $\mathcal{O}(0.1\ \text{fm})$
  - Gluons carry momentum between quarks from different W bosons
  - Impact on reconstructed m_W

- **Investigate charge multiplicity:**

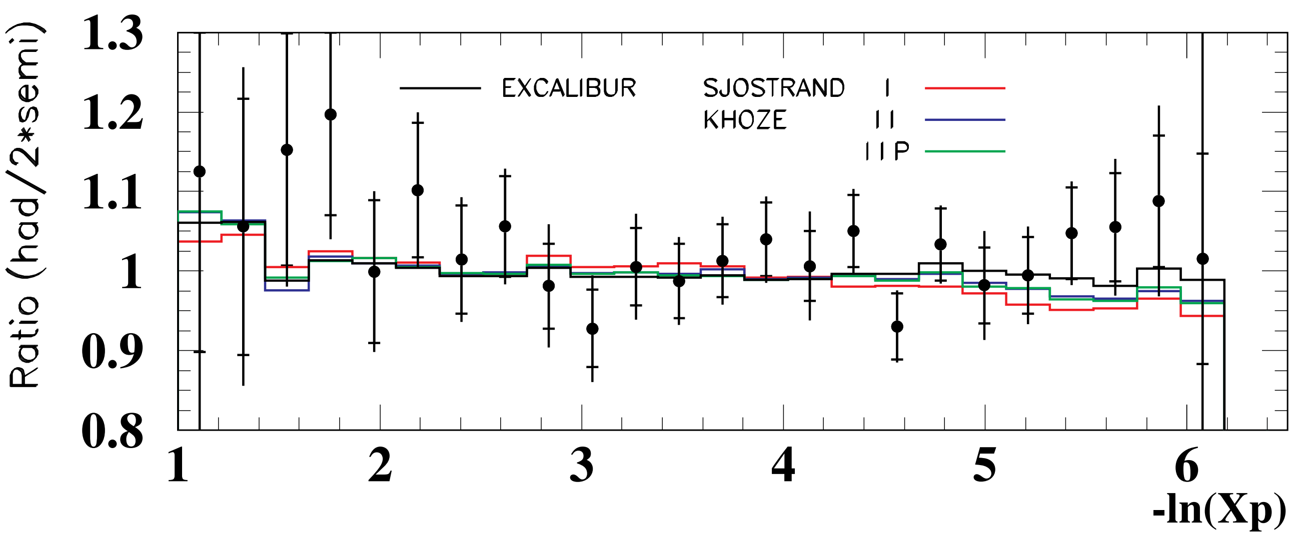
$$\Delta n_{ch} = \langle n_{ch}^{qqqq} \rangle - 2 \langle n_{ch}^{qq\ell\nu} \rangle \qquad r_{ch} = \frac{\langle n_{ch}^{qqqq} \rangle}{2 \langle n_{ch}^{qq\ell\nu} \rangle}$$

ALEPH	Δn_{ch}	$+0.52 \pm 0.52$
DELPHI	r_{ch}	$+0.977 \pm 0.017 \pm 0.027$
L3	Δn_{ch}	$-0.23 \pm 0.40 \pm 0.52$
OPAL*	Δn_{ch}	$+0.7 \pm 0.8 \pm 0.6$

* 183 GeV

- **compatible with no or small effect**

e.g. ALEPH result for scaled momentum x_p:



Estimated systematic error on m_W: 25 – 70 MeV

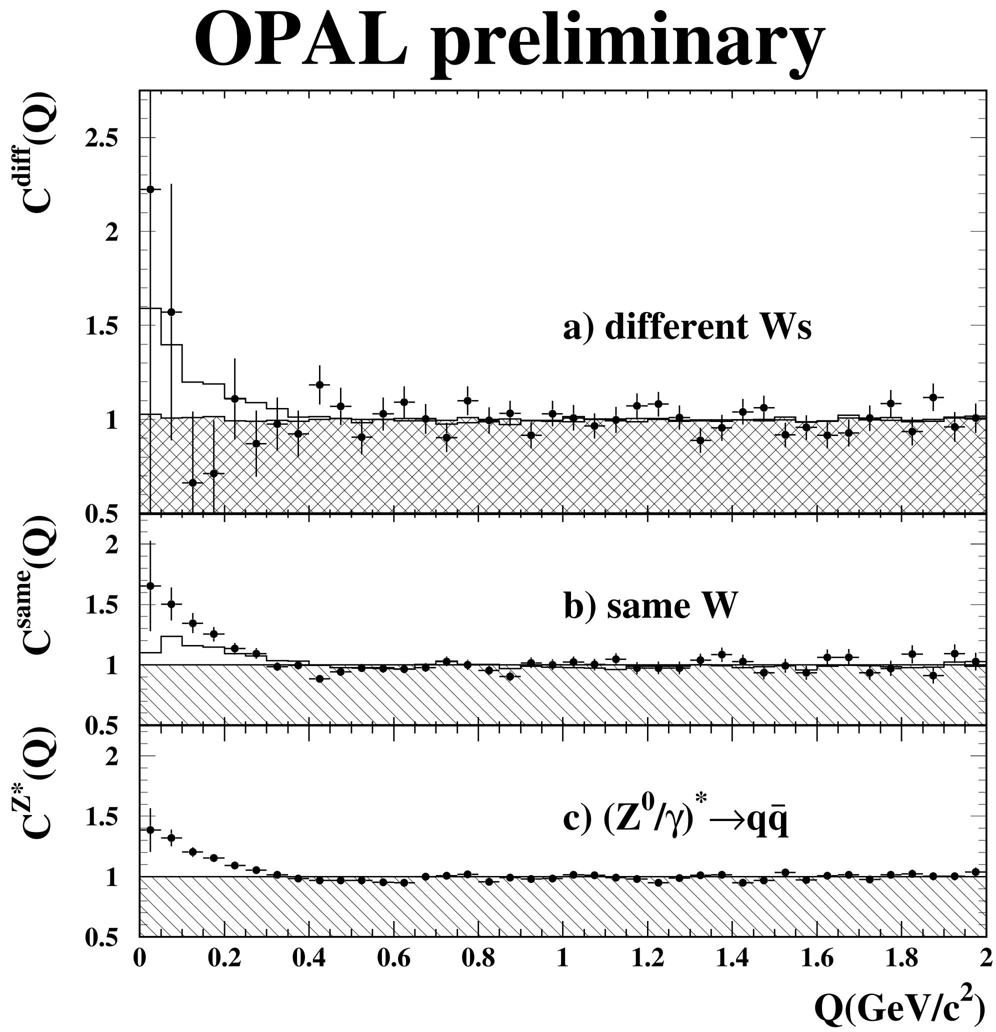
- Bose-Einstein correlation of decay hadrons

  may lead to momentum transfer between decay products of different W bosons

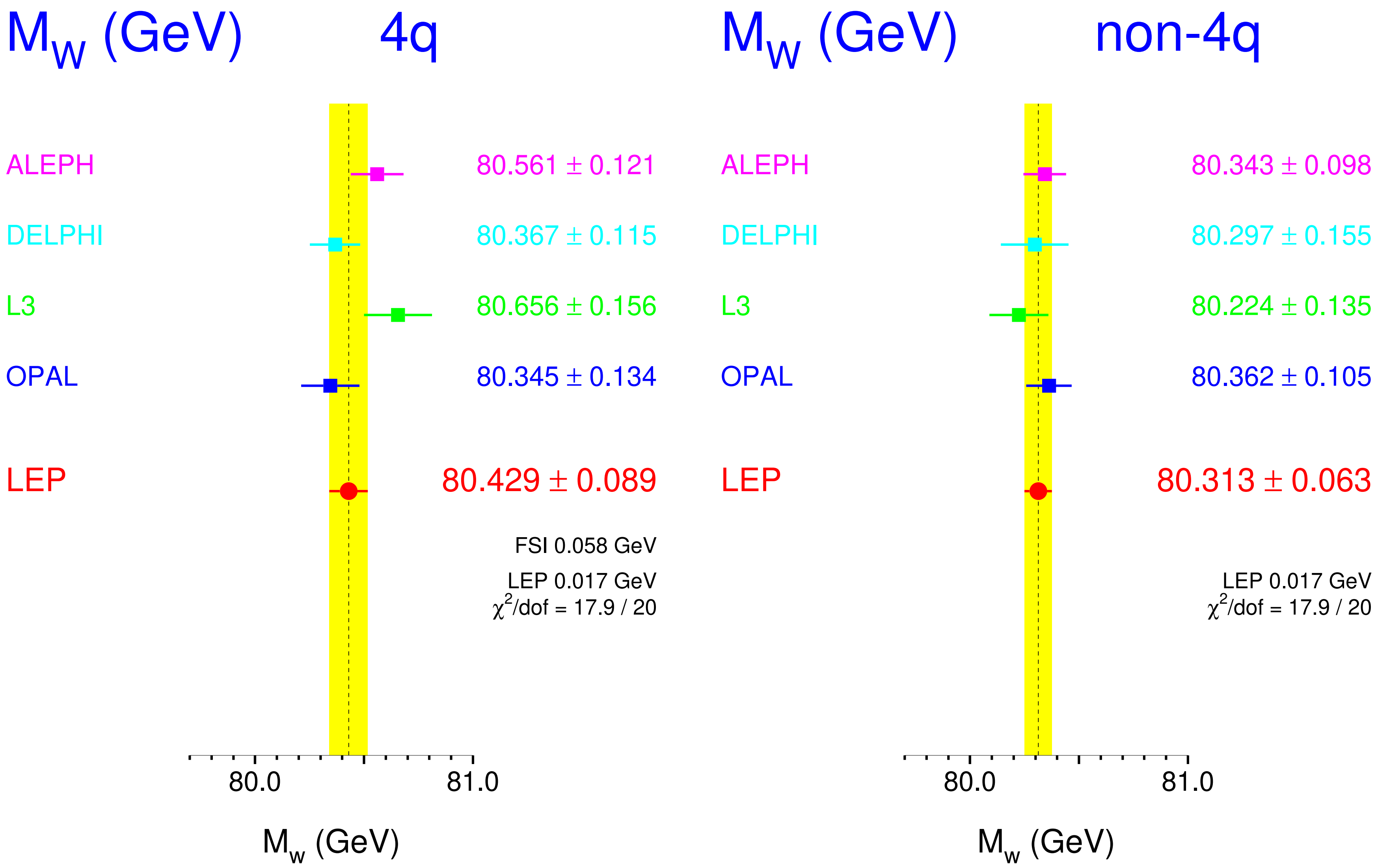
Study correlation function:

$$C(Q) = N\left[1 + \lambda \exp\left(-Q^2R^2\right)\right] \qquad Q^2 = -\left(p_1 - p_2\right)^2$$

Correlations established in hadronic Z decays and in decays of the same W

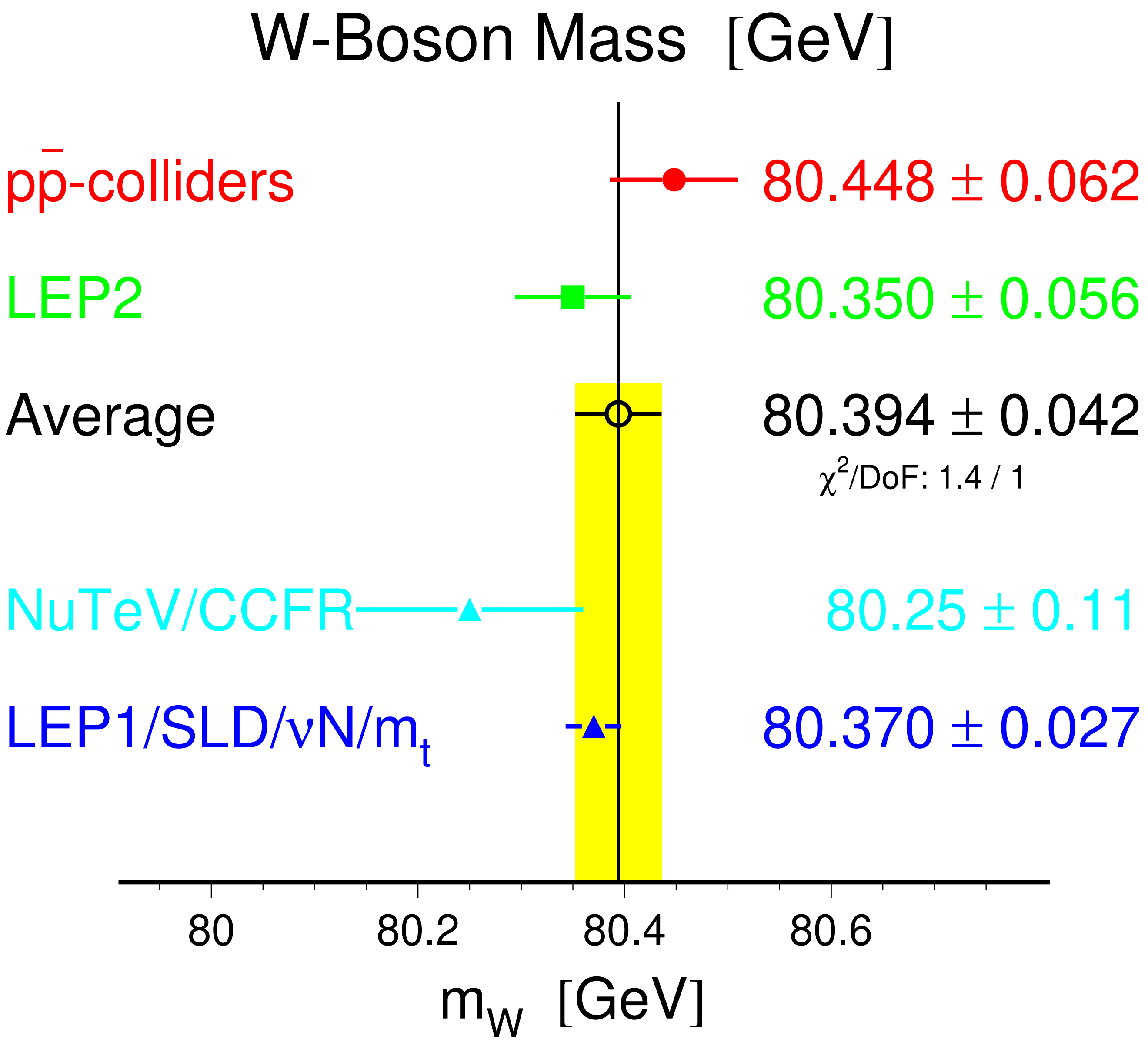


Estimated systematic error on m_W: $20 - 60$ MeV



Combined LEP W mass measurement including 189 GeV data:

$$m_W = 80.350 \pm 0.056 \text{ GeV}$$

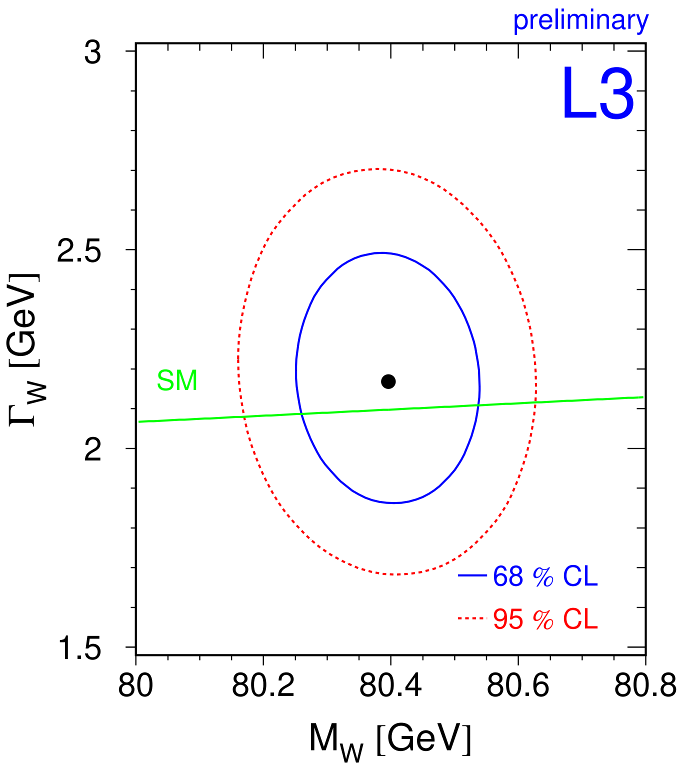

W-Boson Mass [GeV]
pp̄-colliders
80.448 ± 0.062
LEP2
80.350 ± 0.056
Average
80.394 ± 0.042
χ²/DoF: 1.4 / 1
NuTeV/CCFR
80.25 ± 0.11
LEP1/SLD/νN/m_t
80.370 ± 0.027
80
80.2
80.4
80.6
m_W [GeV]

- Direct determination

  - LEP: fit to invariant mass distributions:

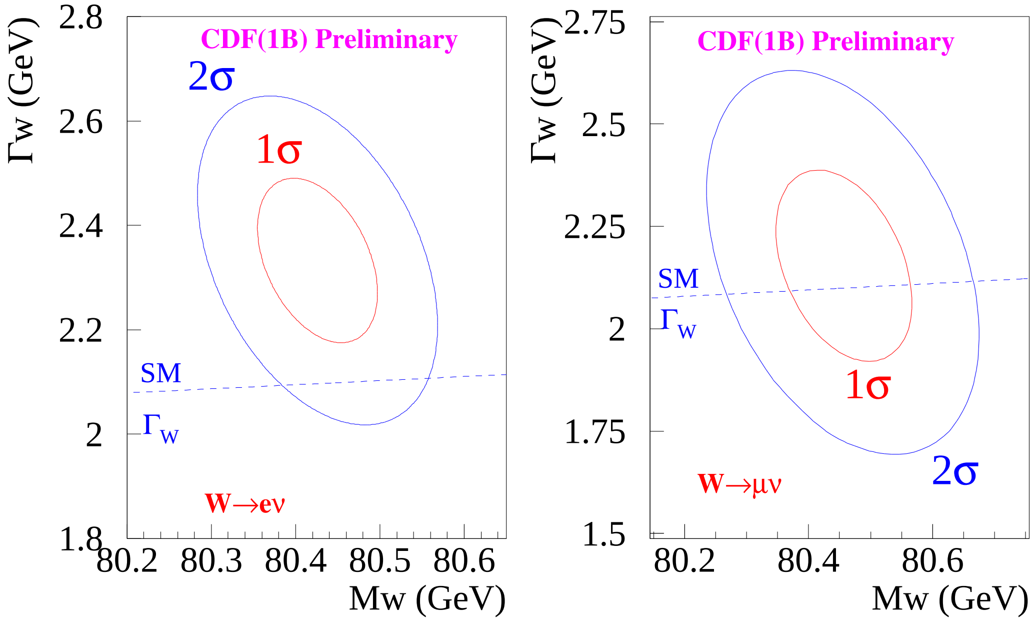
	Γ_W[GeV]
DELPHI*	2.48 ± 0.41
L3	2.12 ± 0.25
OPAL*	1.84 ± 0.38
SM	2.08

* 183 GeV data



  - CDF: high end of transverse mass distributions

$$\Gamma_W = 2.055 \pm 0.125 \text{GeV}$$



- Indirect measurement from

$$\frac{\sigma(p\bar{p} \to W + X)\, BR(W \to \ell\nu)}{\sigma(p\bar{p} \to Z + X)\, BR(W \to \ell\ell)} = \left(\frac{\sigma_W}{\sigma_Z}\right)^{SM} \left(\frac{\Gamma_Z}{\Gamma_{Z\to\ell\ell}}\right)^{LEP} \frac{\Gamma^{SM}_{W\to\ell\nu}}{\Gamma_W}$$

$$\text{CDF}: \Gamma_W = 2.179 \pm 0.046 \text{ GeV}$$

$$\text{DØ}: \Gamma_W = 2.107 \pm 0.054 \text{ GeV}$$