Electroweak Results from LEP2

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Acknowledgements

The four LEP experiments
ALEPH **D**ELPHI **L**3 and **O**PAL
provided all the results presented

Most of the averages presented here were made by

The LEP electroweak working group and its
W mass, LEP2 $f\bar{f}$ and TGC subgroups

Thanks to all of them for their help

Outline

The LEP2 Programme

Fermion Pair Production

W^+W^- Production & Decays

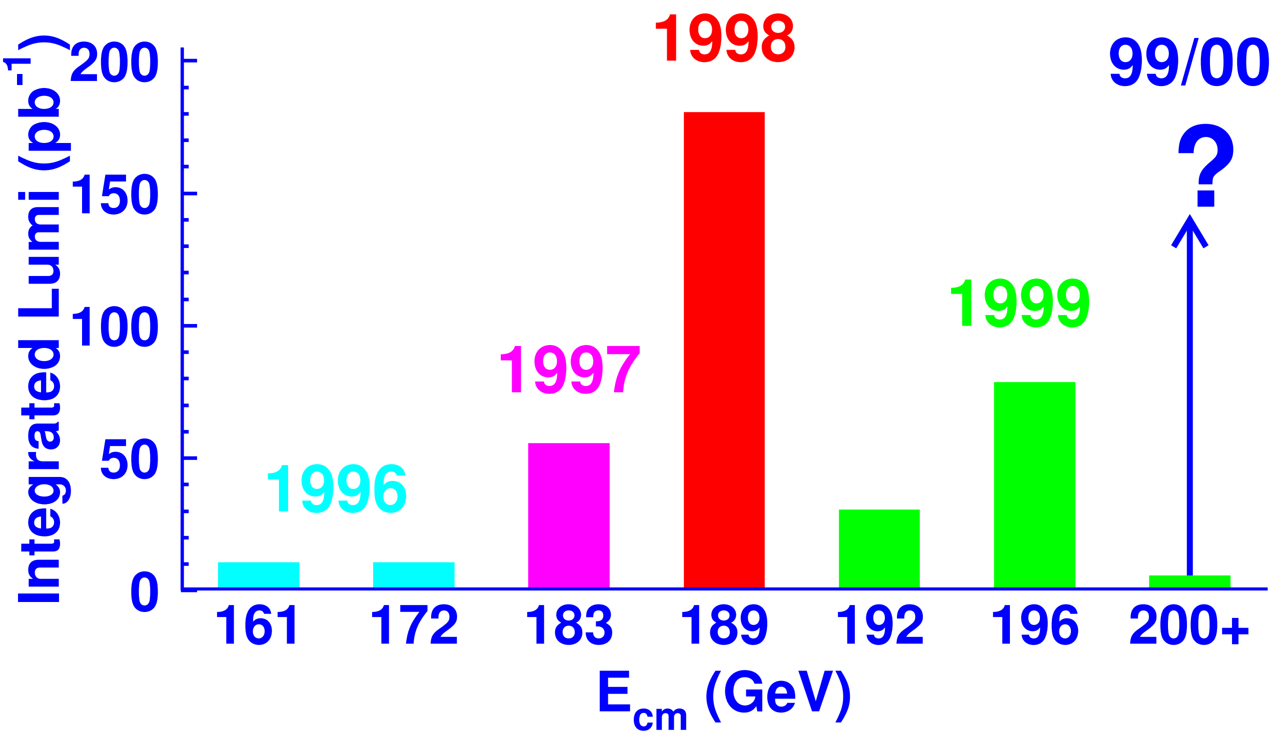
W Mass

Gauge Boson Self-Interactions

ZZ Production

Summary

The LEP2 Programme

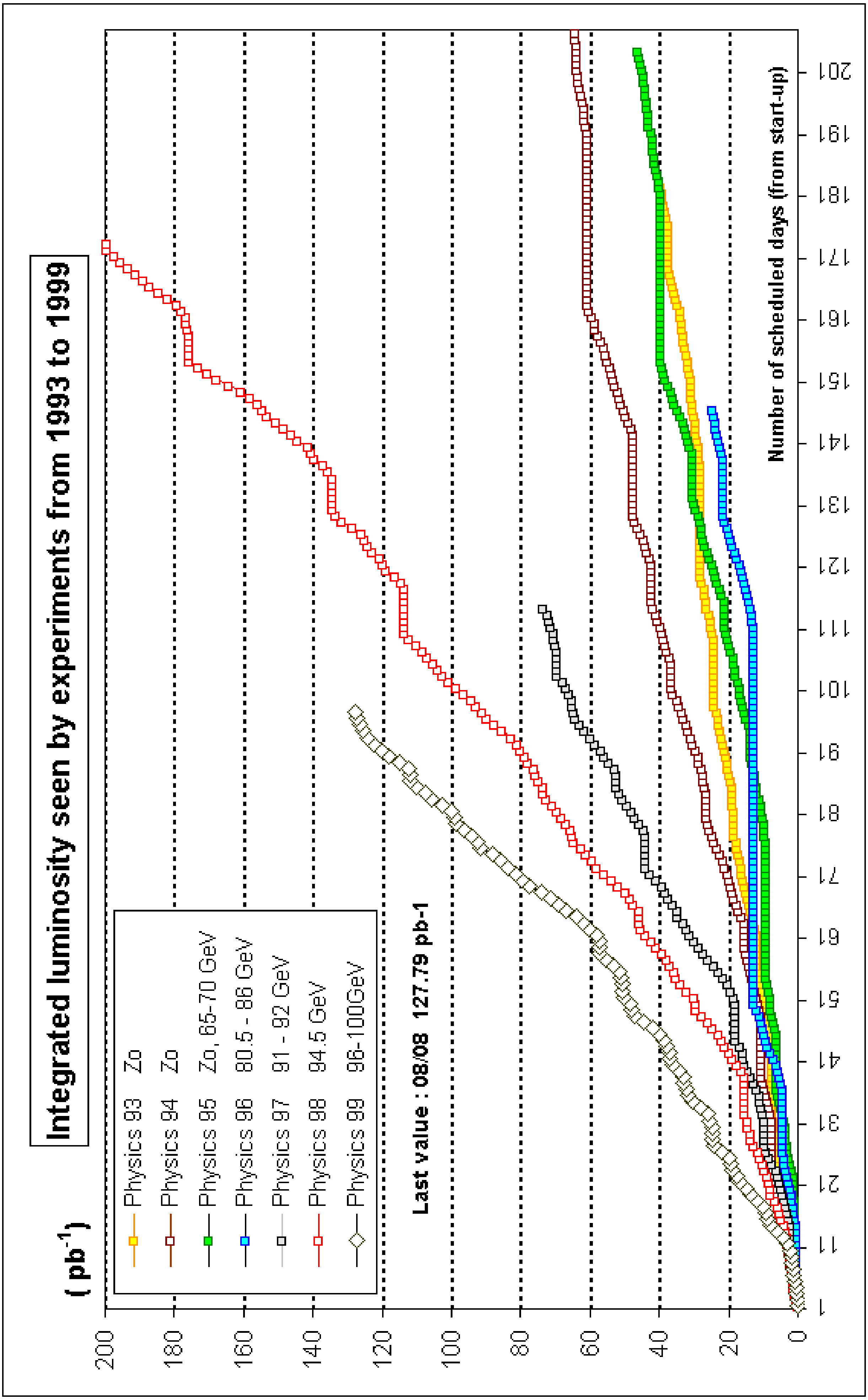


So far 375 pb^{-1} per experiment at LEP2

Expect another $\geq$200 pb^{-1} before end of LEP (late 2000)

Should surpass the canonical 500 pb^{-1}/expt

Almost all results are PRELIMINARY



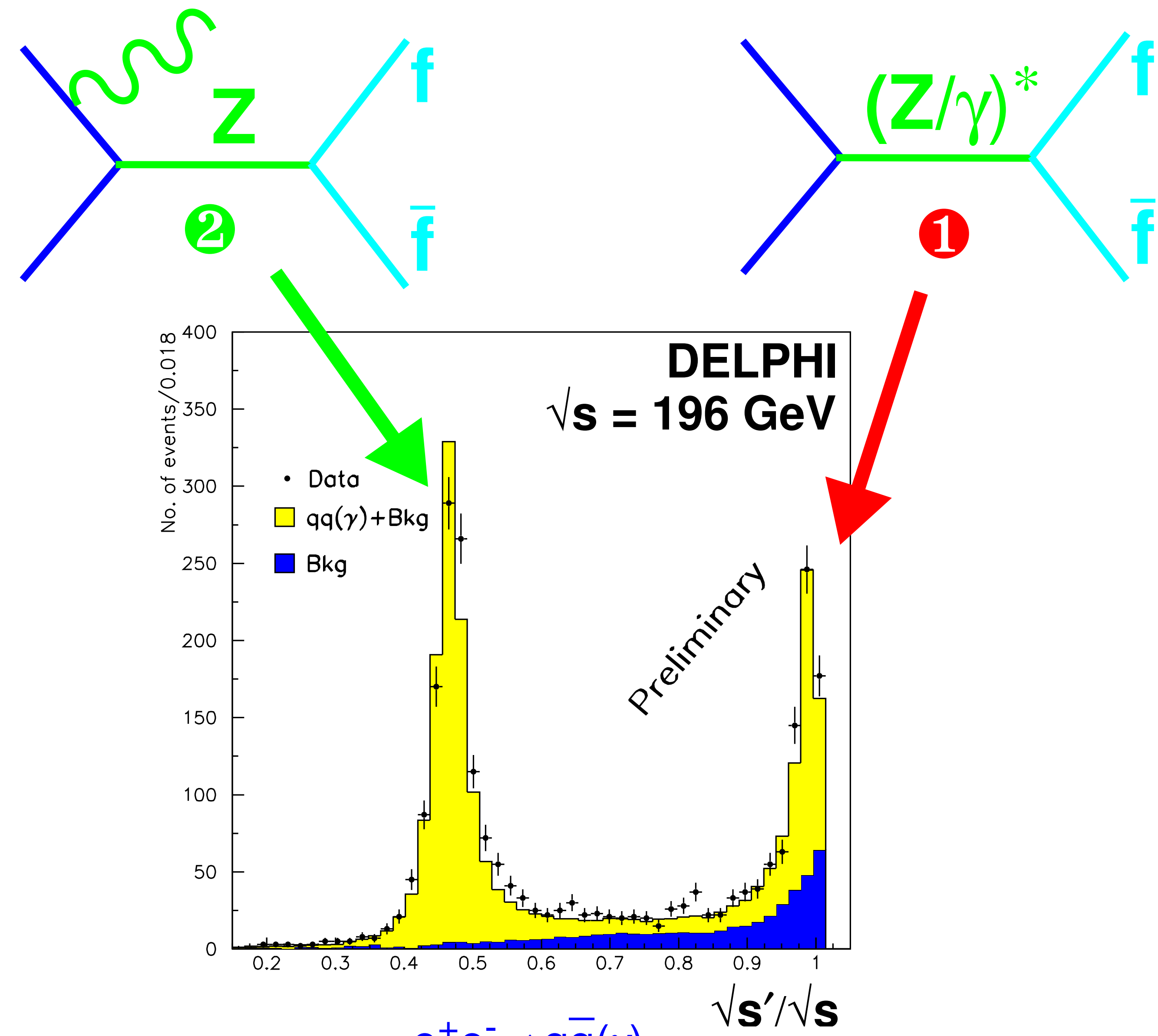
Integrated luminosity seen by experiments from 1993 to 1999
(pb-1)
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 96-100GeV
Last value : 08/08 127.79 pb-1
Number of scheduled days (from start-up)
0
20
40
60
80
100
120
140
160
180
200
1
11
21
31
41
51
61
71
81
91
101
111
121
131
141
151
161
171
181
191
201

Fermion Pair Production

Fermion-pair production at LEP2: $\sqrt{s'} = M(f\bar{f})$

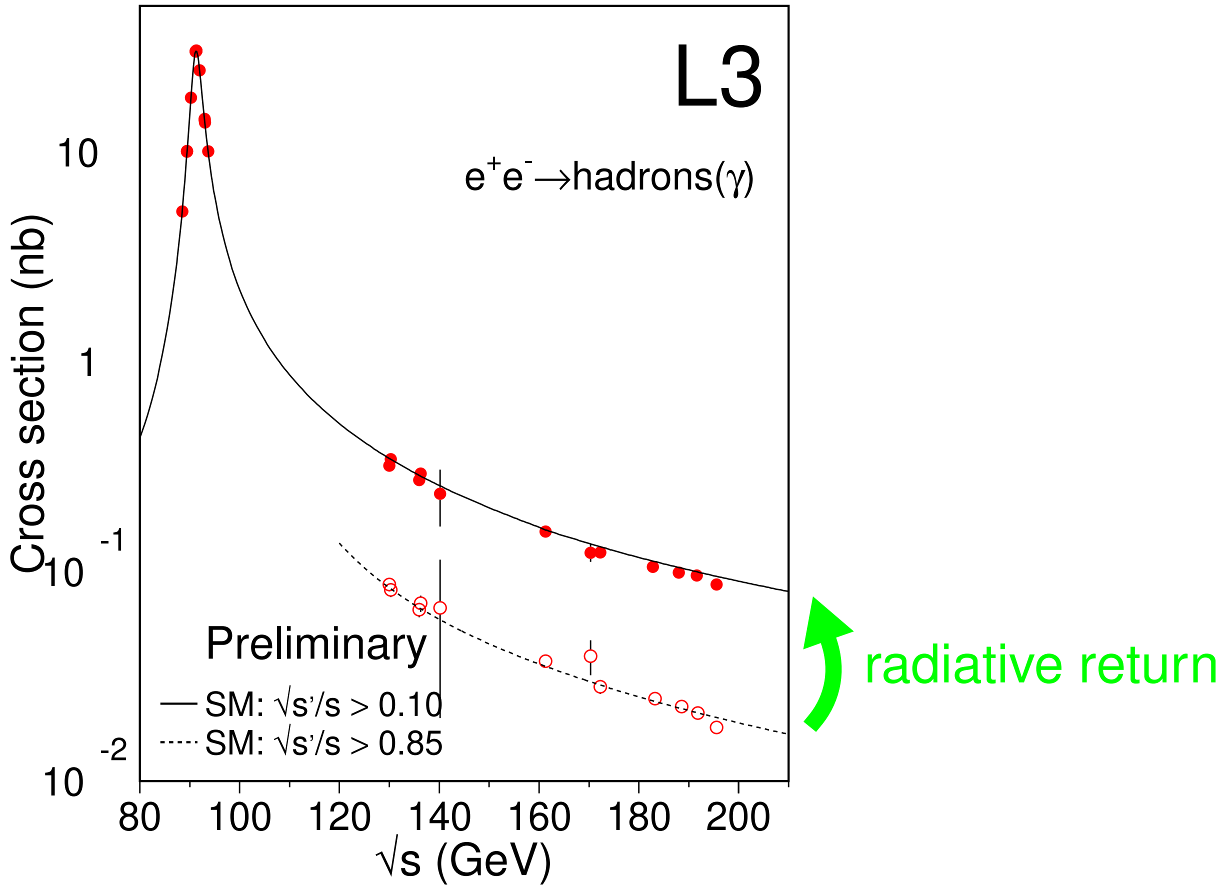
❶ Full energy events ($\sqrt{s'} \approx \sqrt{s}$)

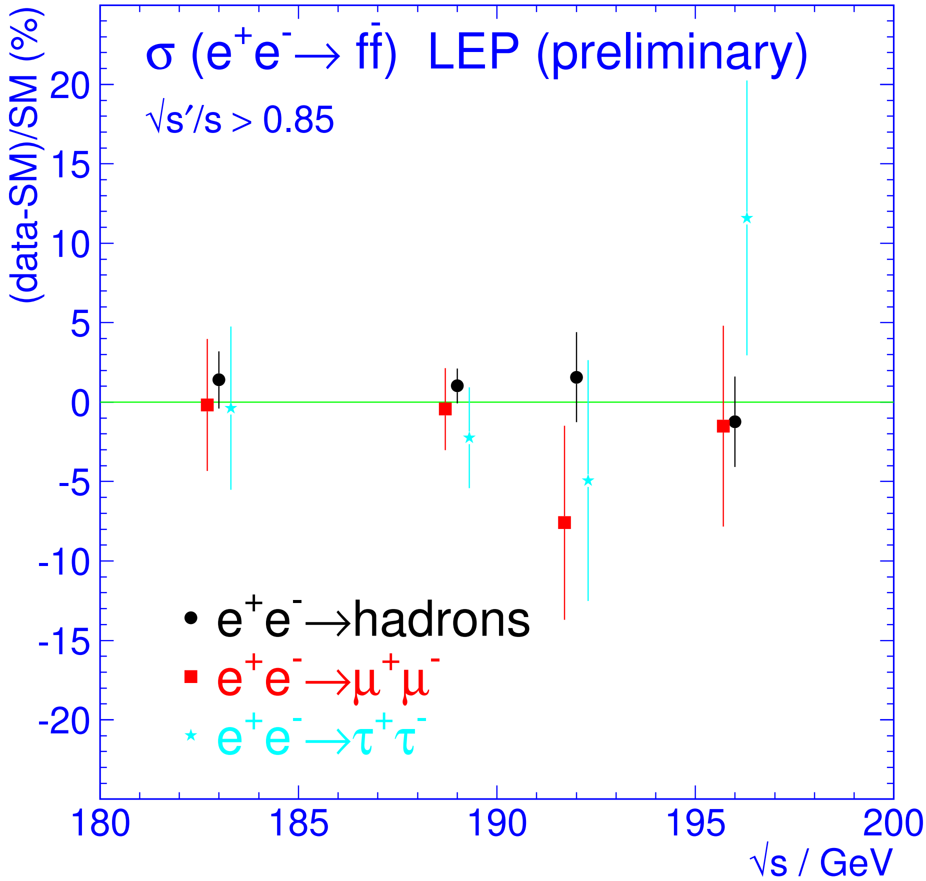
❷ "Radiative return" to the Z ($\sqrt{s'} \approx M_Z$)



$e^+e^- \to q\bar{q}(\gamma)$

Fermion Pair Cross-Sections

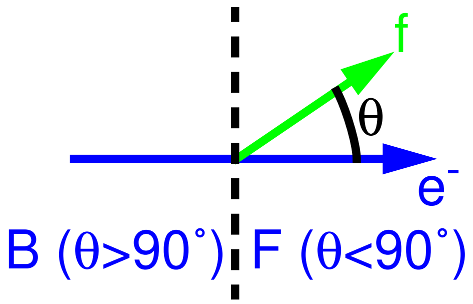


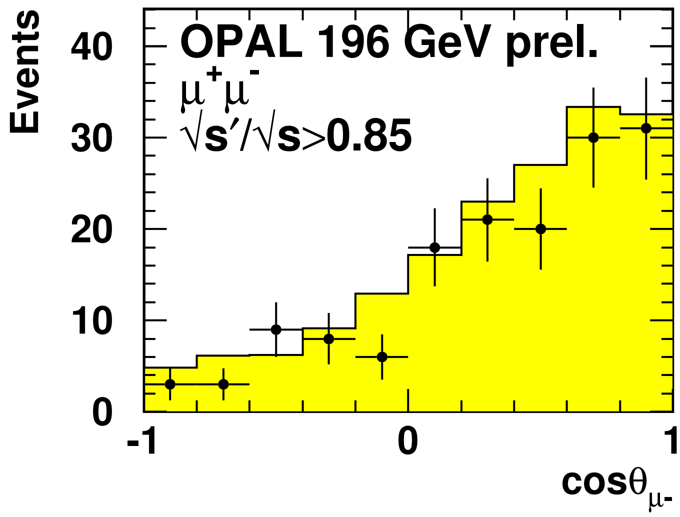


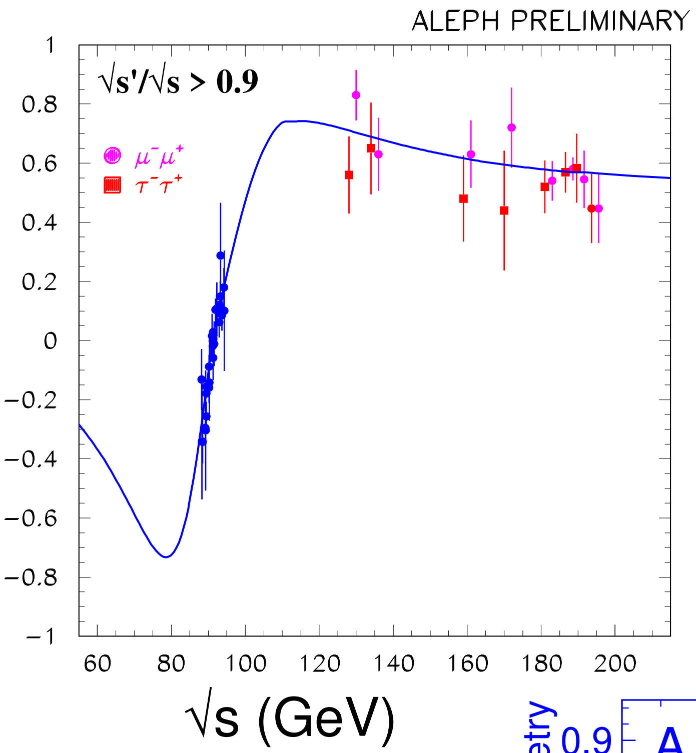
Comparison with SM expectation

Lepton Pair Asymmetries

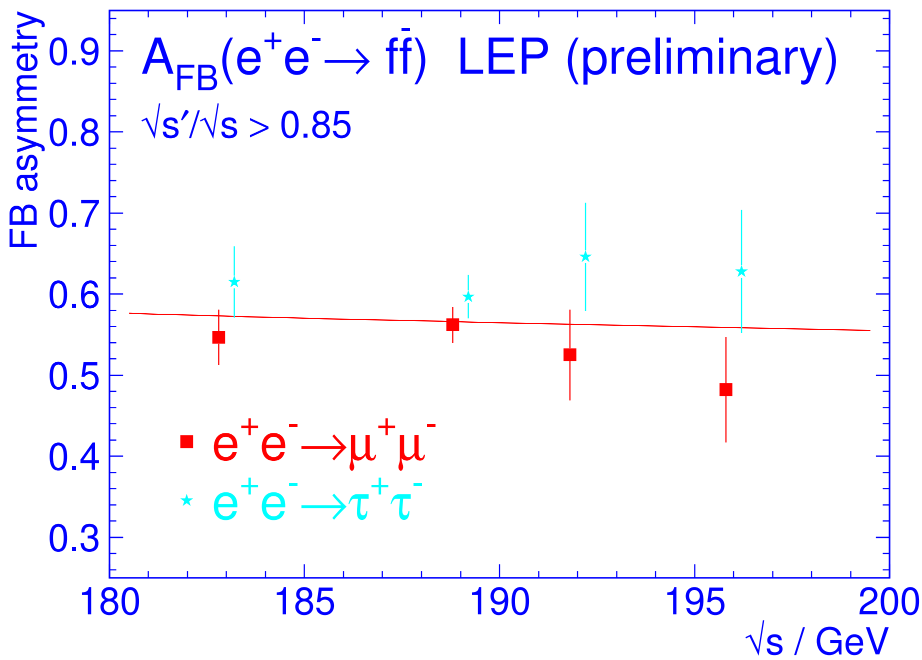
$A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B)$





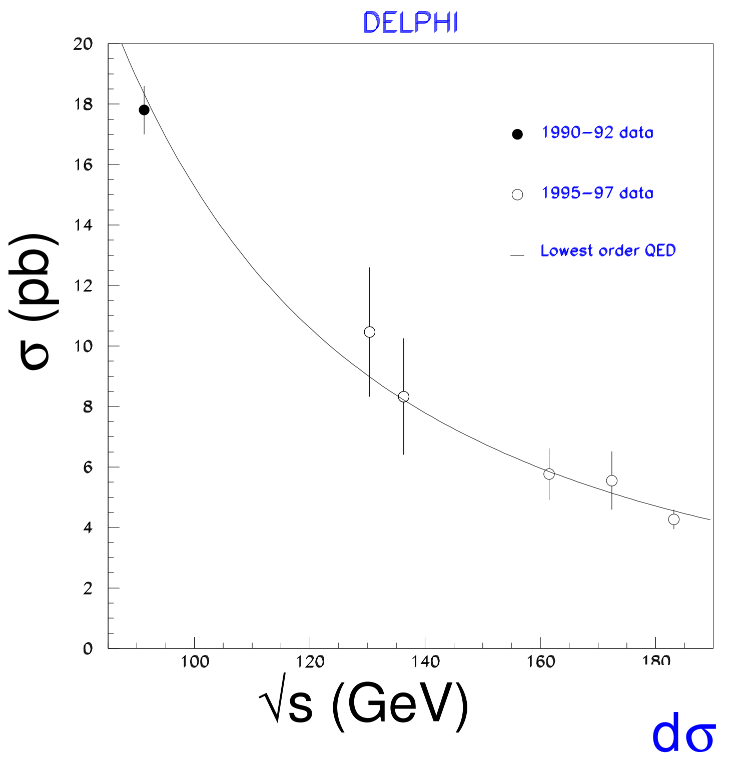


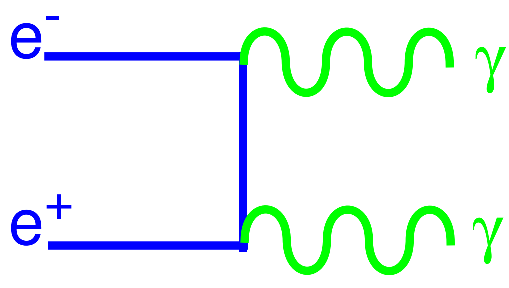
$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$



LEP at highest $\sqrt{s}$

QED Tests at High Energy



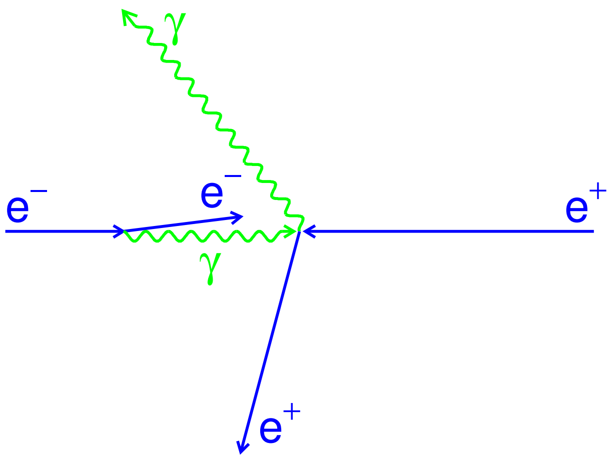


$e^+e^- \rightarrow \gamma\gamma(\gamma)$

QED cut-off parameters

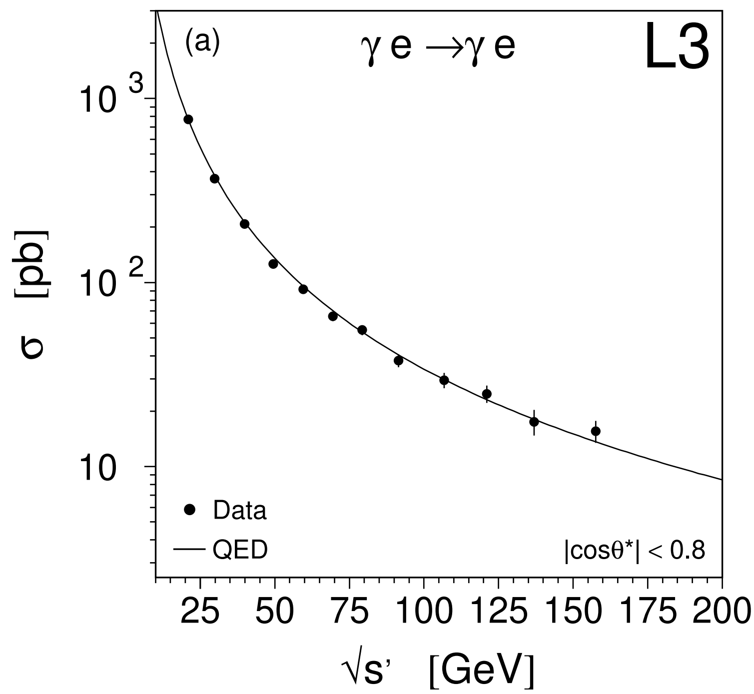
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Born}} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1 + \cos^2\theta)$$

$\Lambda_\pm >$ ~290 GeV at 95% CL



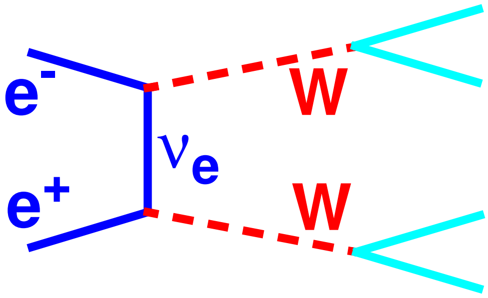
Compton scattering

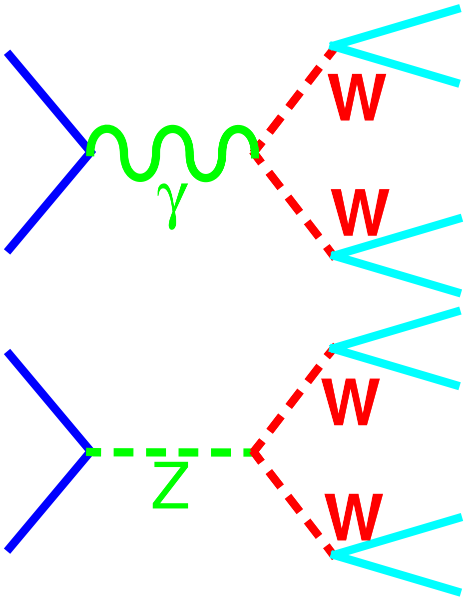
$e\gamma \rightarrow e\gamma$



WW Production at LEP2

Three production diagrams





At $\sqrt{s}$=189 GeV, $\sigma_{WW} \approx$ 16 pb

$\Rightarrow$ ~4000 W^+W^- / expt. for 250 pb^{-1}

BR($W \to q\bar{q}$) $\approx$ $^2/_3$

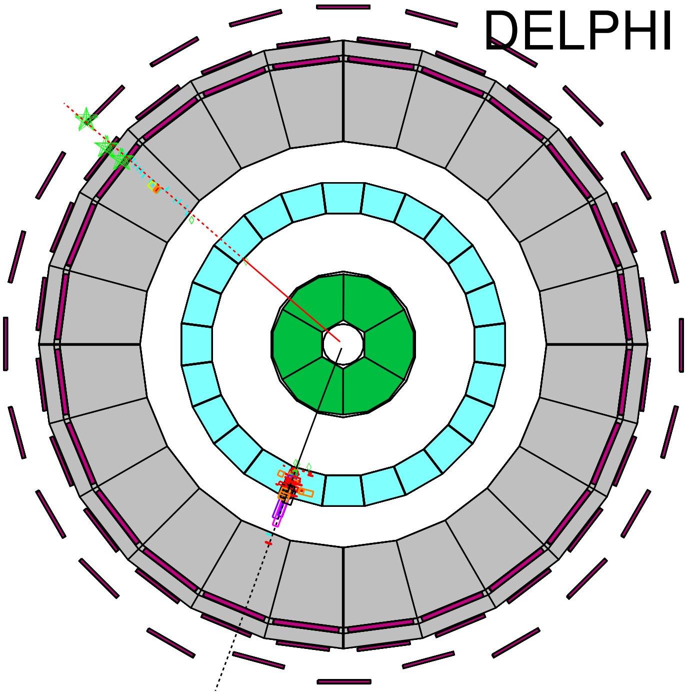
BR($W \to e\nu, \mu\nu, \tau\nu$) $\approx$ $^1/_9$ each

Observed events:

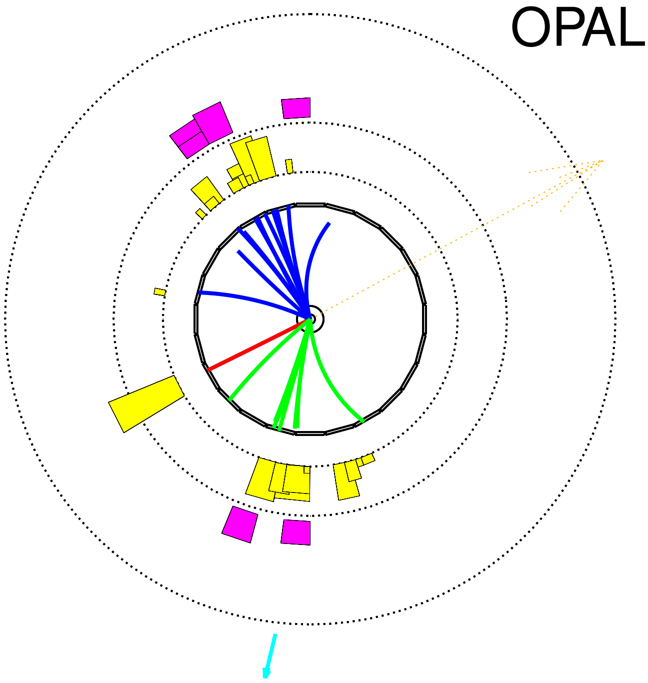
		for 250 pb^{-1}
$WW \to q\bar{q}q\bar{q}$	**46%**	~1800
	($\geq$)4-jet events	
$WW \to q\bar{q}l\nu$	**44%**	~1800
	2 jets, charged lepton, missing p	
$WW \to l\nu l\nu$	**10%**	~400
	2 energetic charged leptons	

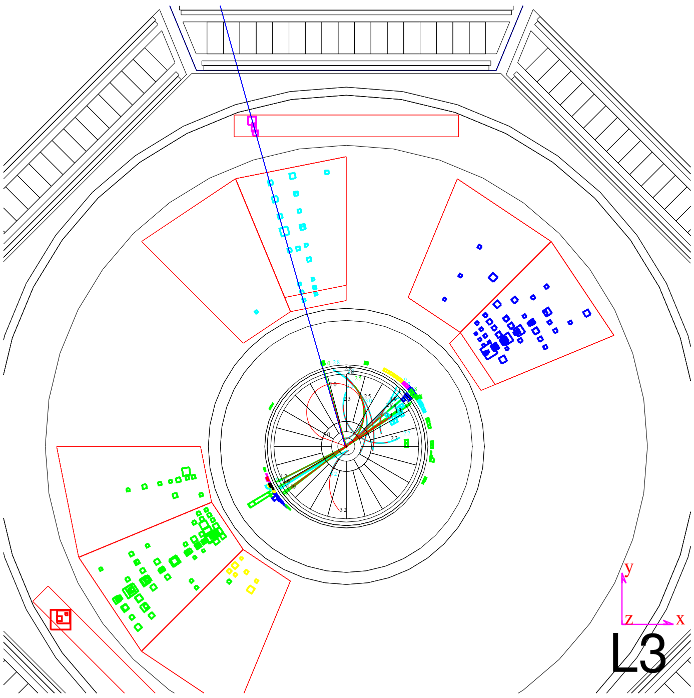
W^+W^- Events

$WW \to e\nu\mu\nu$

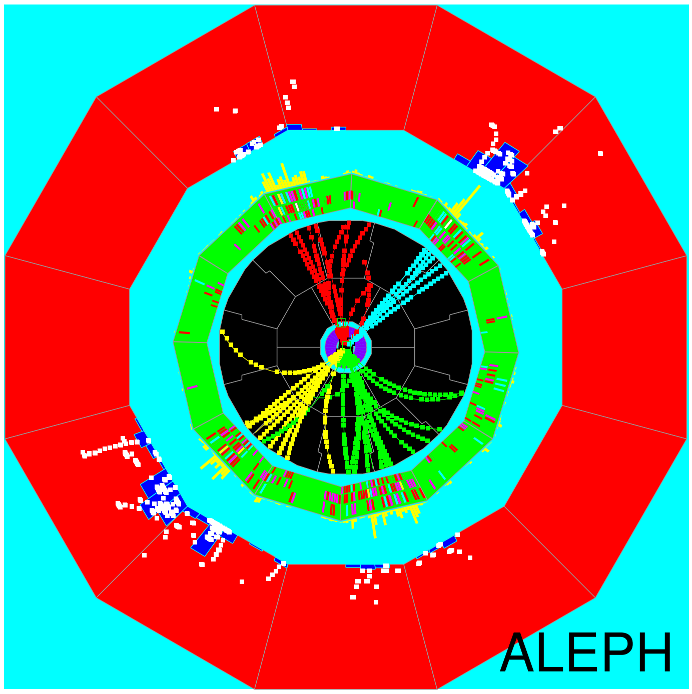


$WW \to q\bar{q}e\nu$





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



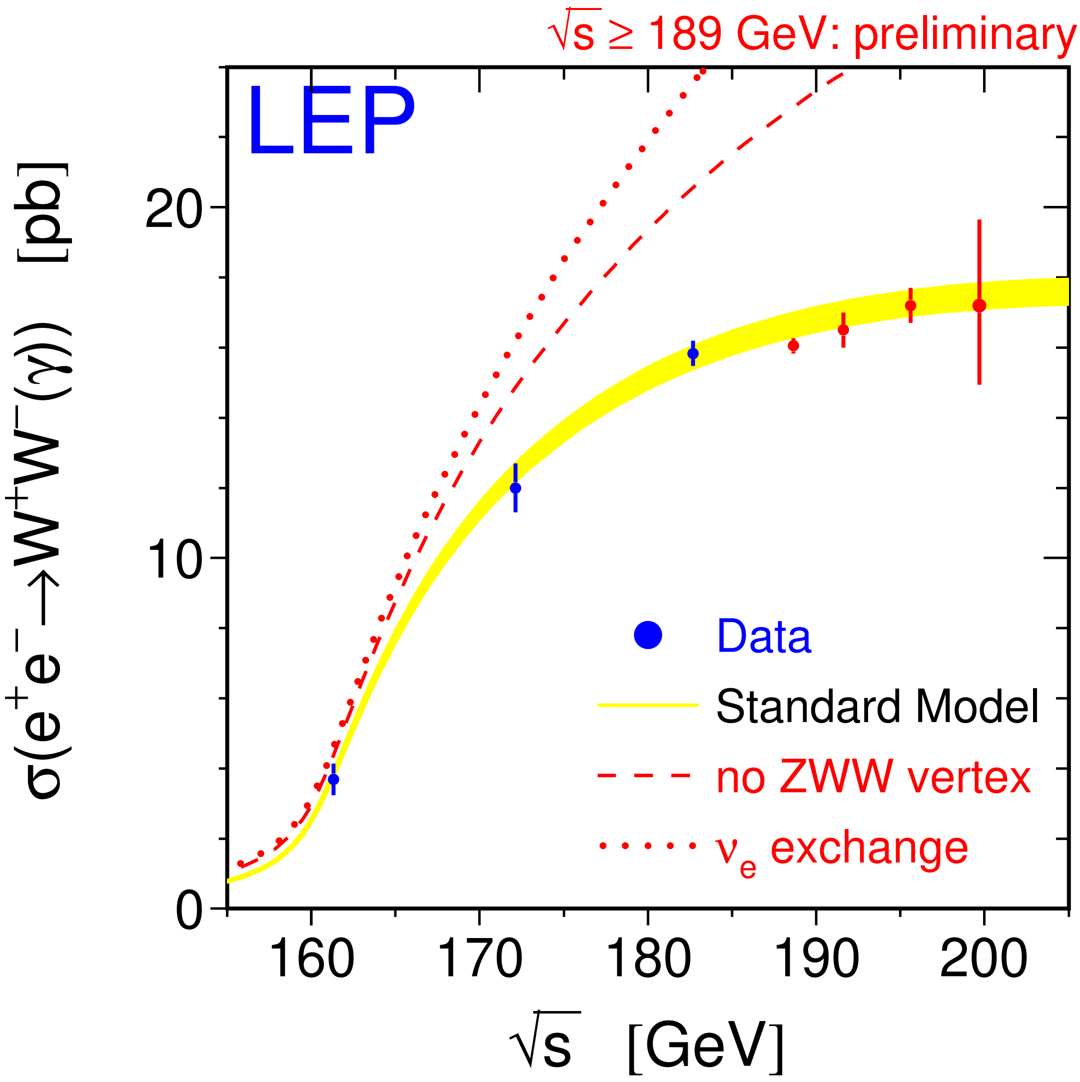
$WW \to q\bar{q}q\bar{q}$

W^+W^- Cross-Section

WW event selections: All final-states in all experiments

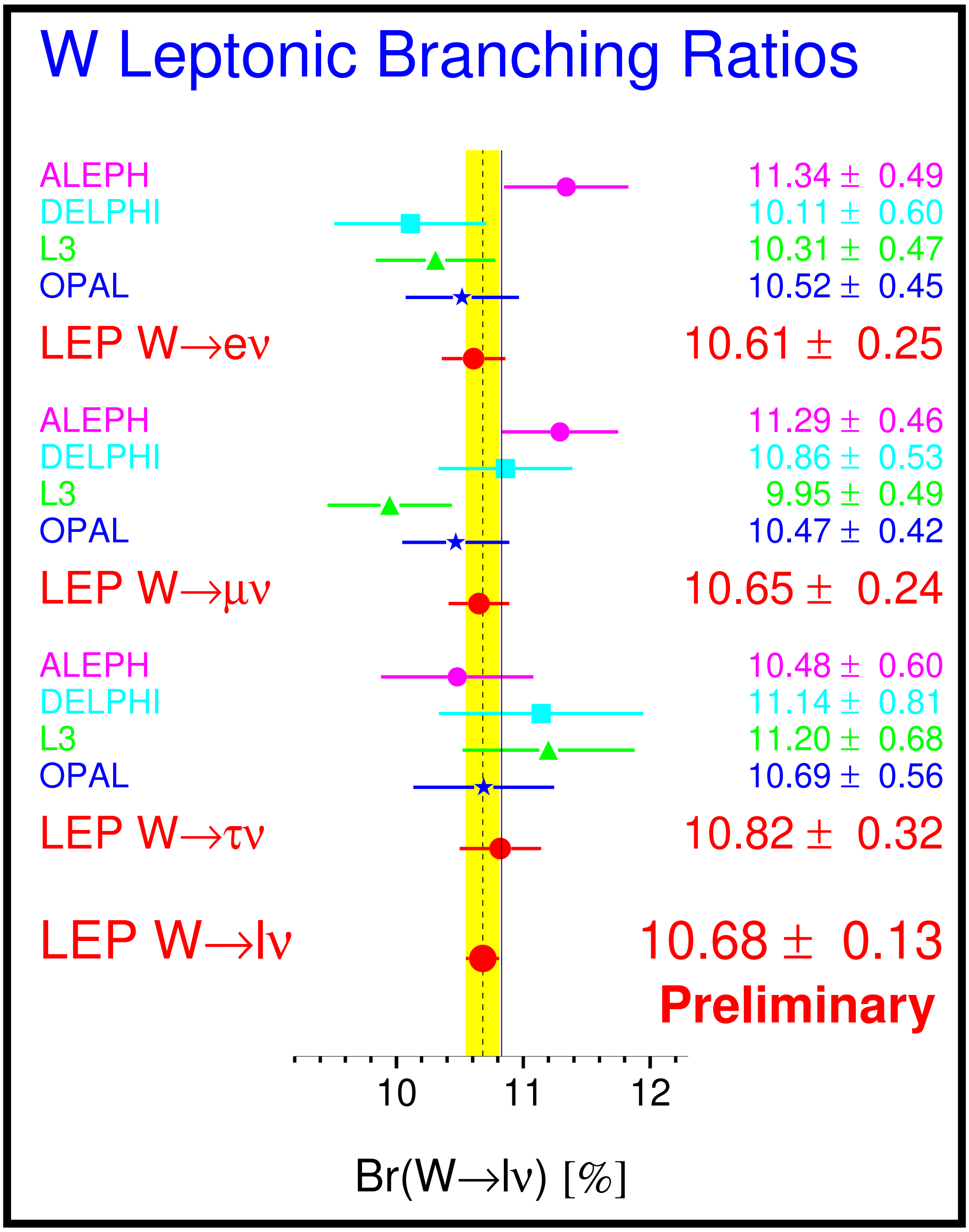
Multivariate discriminants give best selection performance

	ε	π
$WW \to q\bar{q}q\bar{q}$	90%	80%
$WW \to q\bar{q}l\nu$	82%	90%
$WW \to l\nu l\nu$	60-80%	90%



W Decay Branching Ratios

Test lepton universality in W decays SM: 10.8%



Cf: CDF+D∅: $BR(W\to e\nu) = 10.45 \pm 0.19$ %

Assuming lepton universality SM: 67.5% ($\alpha_s(M_W)=0.12$)

$BR(W\to q\bar{q}) = 67.96 \pm 0.41$ % (LEP combined)

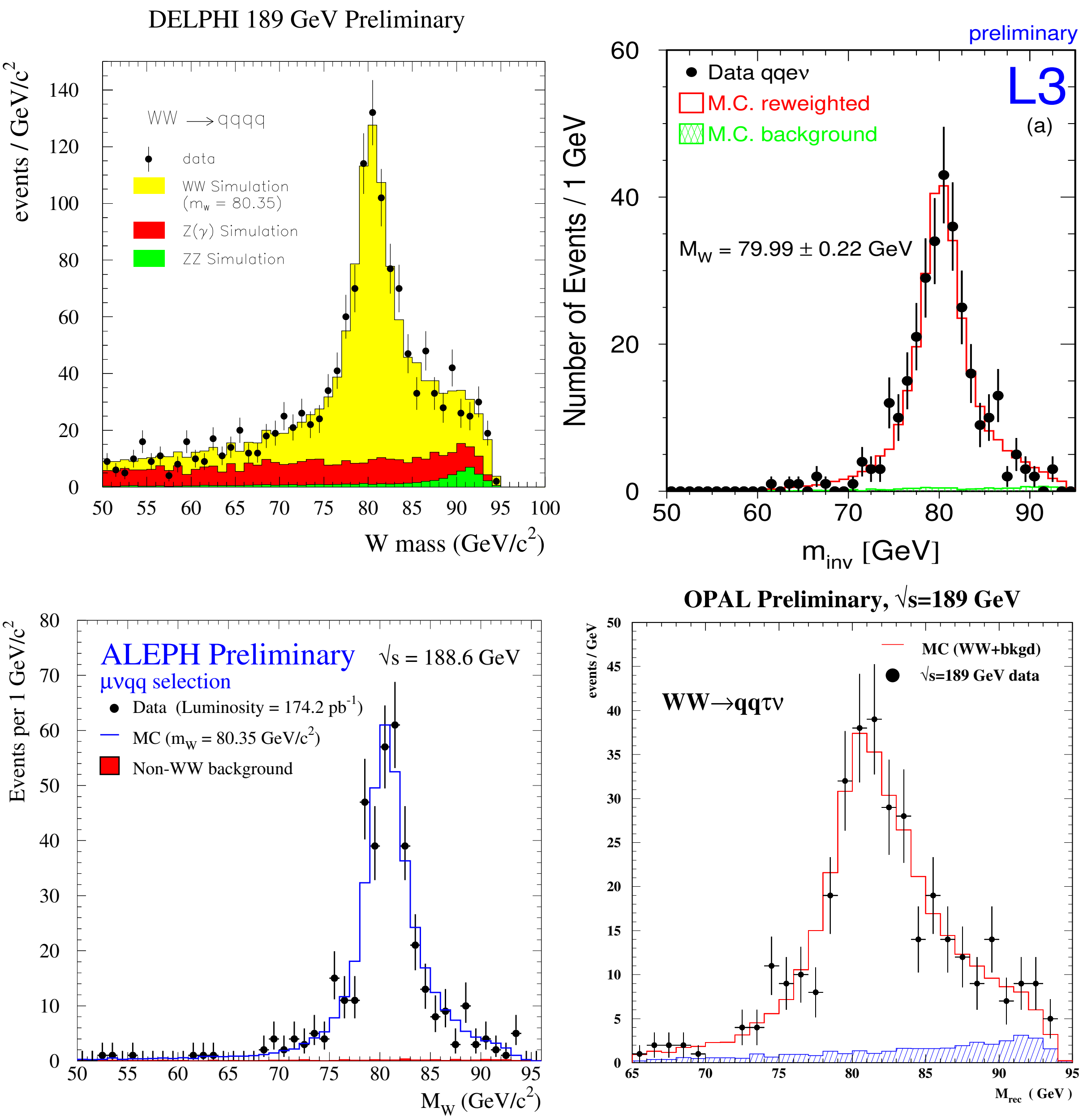
W Mass

WW→$q\bar{q}q\bar{q}$ and WW→$q\bar{q}l\nu$ (A also lνlν@183GeV)

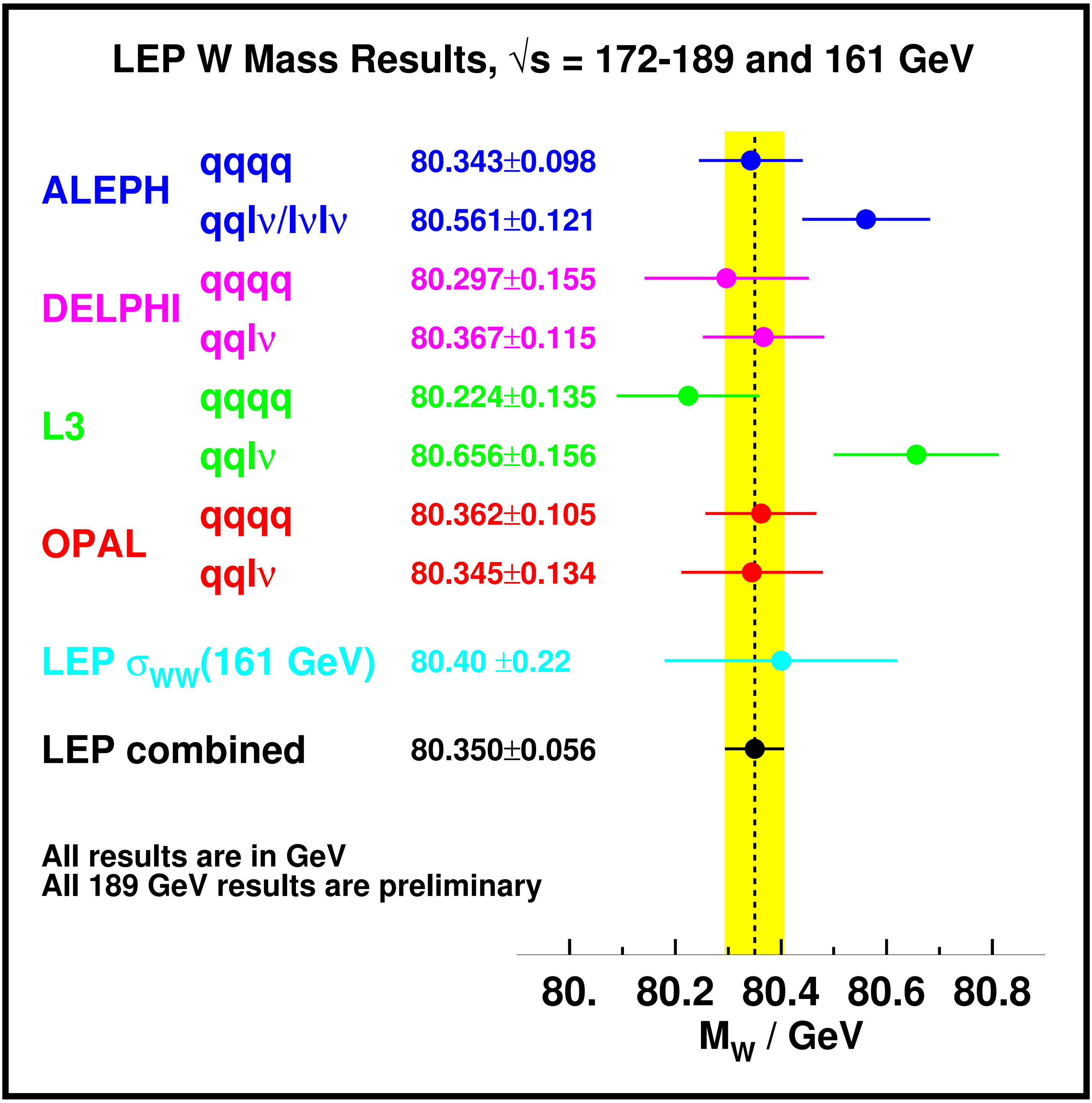
Excellent mass resolution comes from kinematic fit:

- Constrain total (E,**p**) to (√s,**0**) - needs E_{beam} from LEP

Reconstructed mass distributions



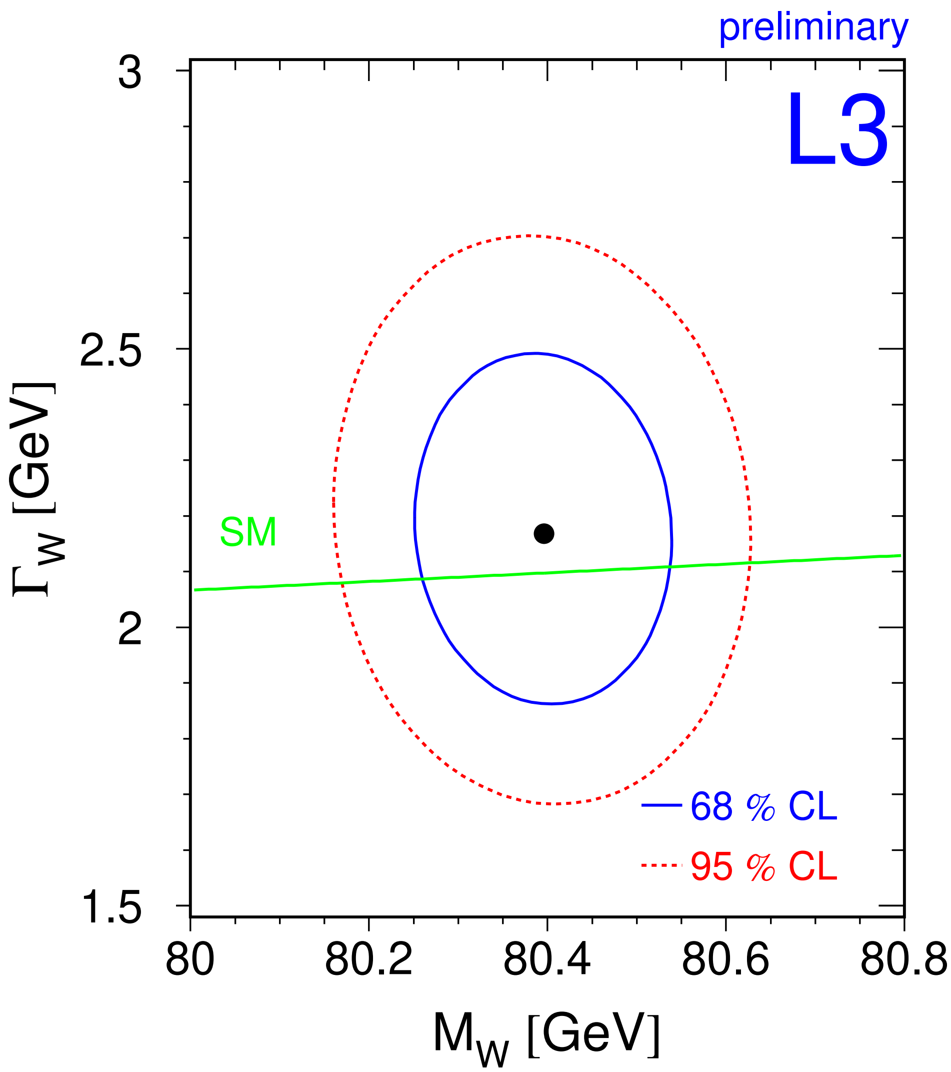
Standard fits: Γ_W constrained to SM relationship with M_W



W Width

May alternatively fit simultaneously Γ_W and M_W

→ direct measurement of Γ_W



Measurements by **D**@183, **L**@172-189, **O**@172-183 GeV

$\Gamma_W = 2.12 \pm 0.20$ GeV **(DLO combined)**

Cf. CDF direct: 2.055 ± 0.125 GeV

W Mass Uncertainties

At present: LEP2 M_W error: 56 MeV **preliminary**

statistics 36 MeV

systematics 43 MeV

$q\bar{q}q\bar{q}$ and $q\bar{q}l\nu$ channels ~ equal statistical power

Principal errors: (currently)

$q\bar{q}l\nu$ channel:

- Detector calibration 20-60 MeV/expt
- Errors dominated by MC statistics ~40 MeV

$\Rightarrow$ **likely to stay statistics limited**

$q\bar{q}q\bar{q}$ channel:

- Final-state interactions 50-90 MeV
- Others (fragmentation, background) also correlated between experiments 20-60 MeV

$\Rightarrow$ **systematic errors hard**

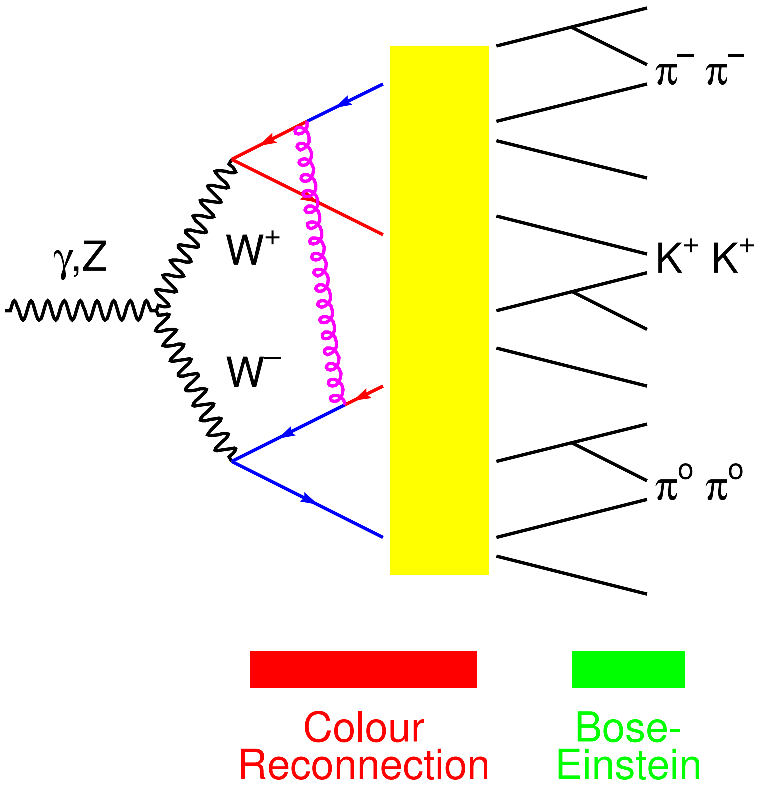
All channels:

- LEP beam energy 17 MeV

Overall, we are aiming for a ~30 MeV error from LEP2

Final-State Interactions

"Hadronisation" effects may not be independent between W's in $WW \to q\bar{q}q\bar{q}$ events



Need models of effects
- study with data

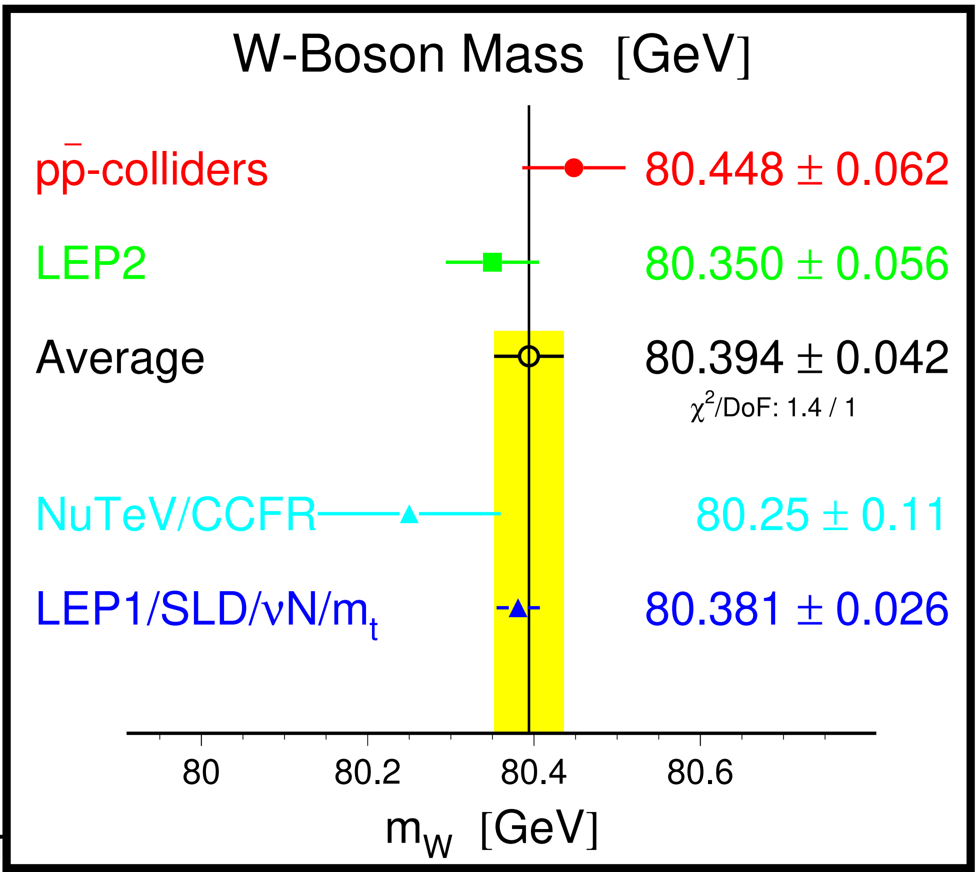
Current studies exclude some poorer models, but others will be difficult even with full LEP2 data sample

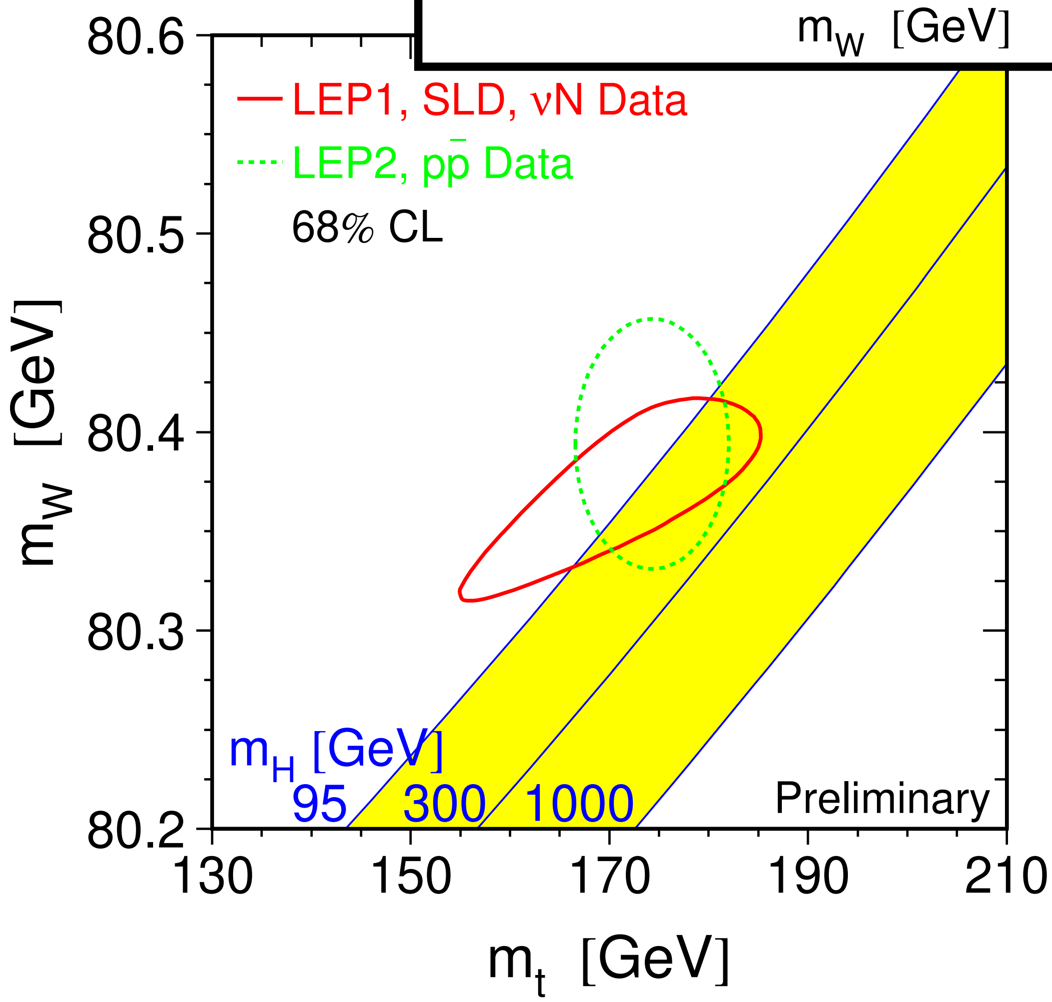
Estimates of effect on M_W from this channel
50-90 MeV (but with a MC statistics component)

Systematic error O(**30 MeV**) may be possible, ultimately

M_W average: effect deweights this channel

Impact of W Mass Measurement

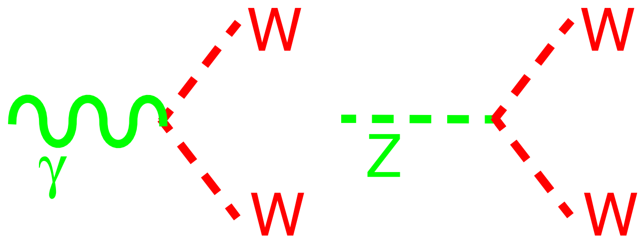




Standard Model looks OK at level of top and Higgs loops

Triple Gauge Couplings WWγ, WWZ

General WWγ and WWZ interaction: 14 parameters



Apply C and P invariance
& use low-energy constraints
$\rightarrow$ 3 parameters

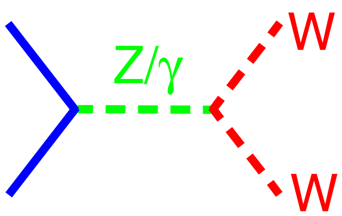
Conventionally κ_γ, g_1^Z and λ_γ, (1,1,0) in SM

Static W properties: $\mu_W = (e/2M_W)\,(1+\kappa_\gamma+\lambda_\gamma)$

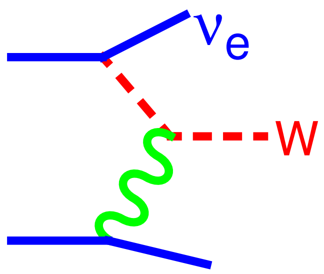
$q_W = (e/M_W^2)\,(\lambda_\gamma-\kappa_\gamma)$

Effects studied at LEP2 in

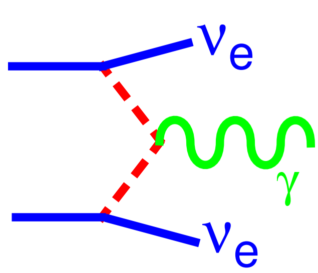
❶ WW production



❷ Single W production

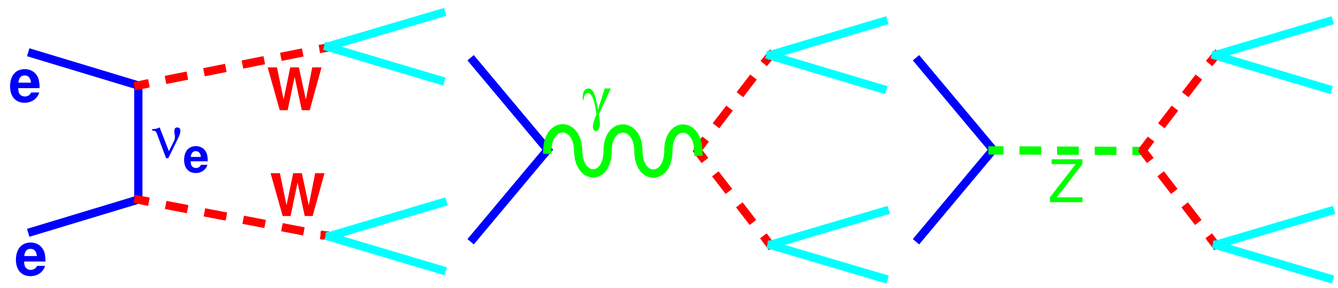


❸ Single photon production



❶ is most constraining, but ❷,❸ constrain primarily WWγ

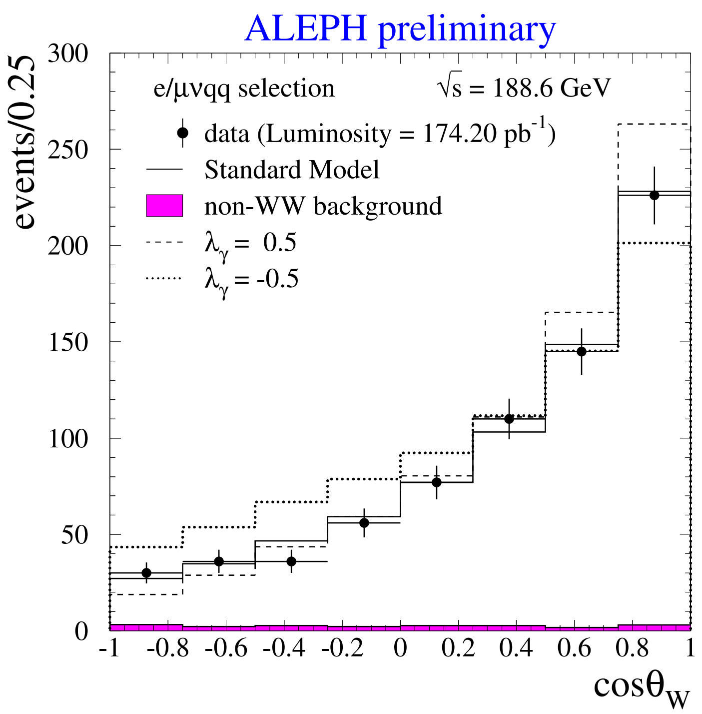
TGCs in $e^+e^- \rightarrow WW$



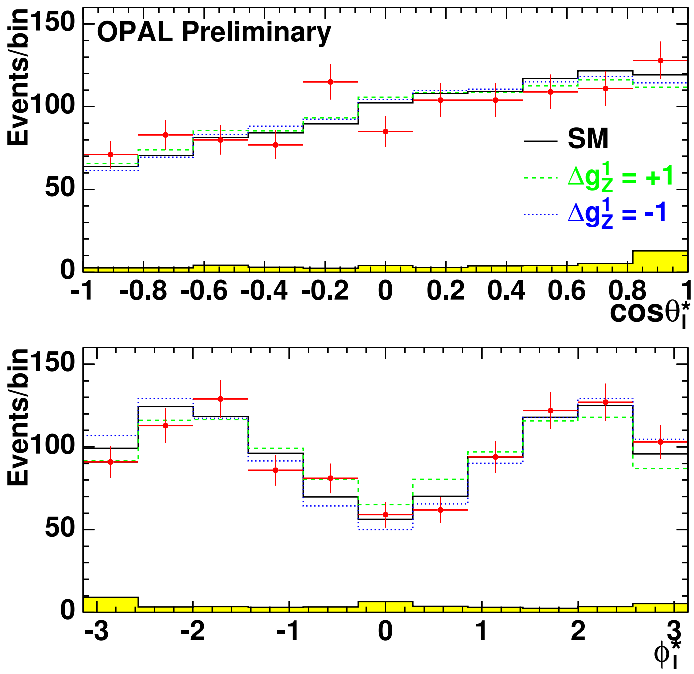
Triple gauge couplings affect

- ➔ total WW cross-section
- ➔ angular distribution of W^- production
- ➔ helicity mixture of W's: analyse via $W \rightarrow f$ decay angles

Study W production and decay angle distributions



W production angle



W decay angles

Combined WWγ, WWZ TGC Results

One-parameter fits
(preliminary)

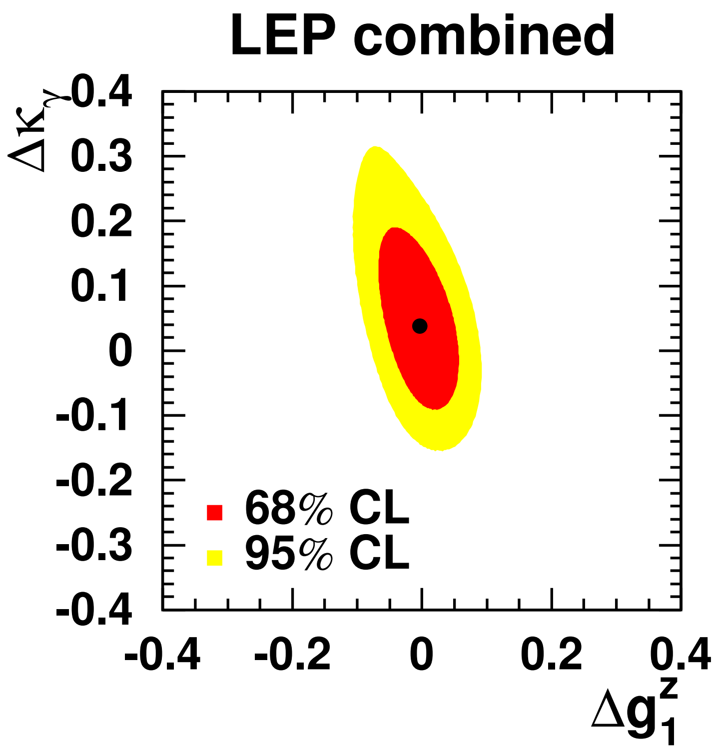
$\kappa_\gamma = 1.04 \pm 0.08$

$g_1^Z = 0.99 \pm 0.03$

$\lambda_\gamma = -0.04 \pm 0.04$

(LEP combined)

Two-parameter fits



Alternatively, in terms of W_L/W_T production (L,O)

f (W_L in $e^+e^- \rightarrow W^+W^-$) = 24.4 ± 4.8 ± 3 % (**L3** 189 GeV)

SM: 26%

Evidence for W_L production now at 5σ level

First unambiguous observation of longitudinally polarized W's

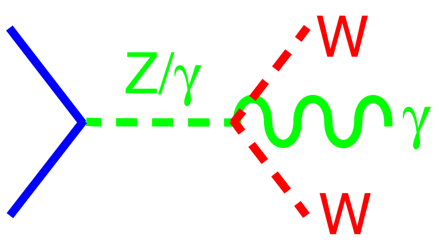
Quartic Gauge Couplings

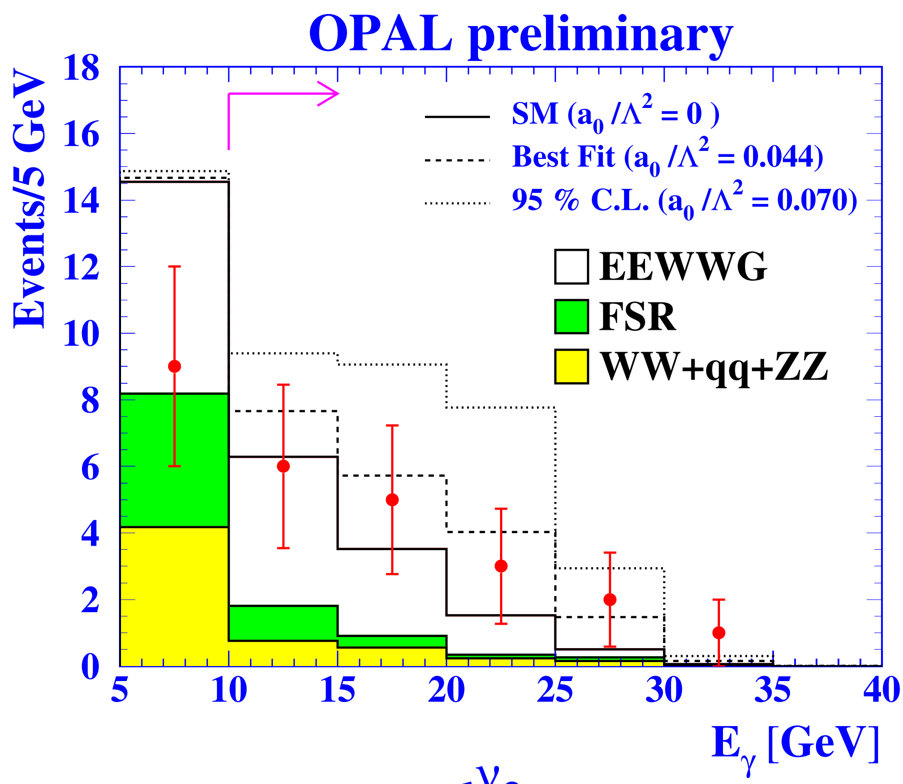
First direct constraints on $WW\gamma\gamma$, $WWZ\gamma$ (OPAL)

In SM: the couplings exist, but too small to see at LEP

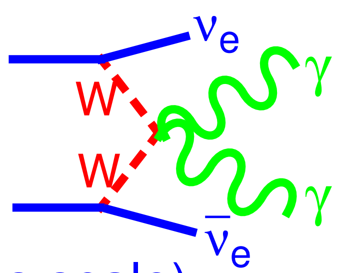
Anomalous QGCs a_0, a_c and a_n studied

With $WW\gamma$ events:





Combine with analysis of
$\nu_e\bar{\nu}_e\gamma\gamma$ final state



Obtain at 95% CL (Λ new physics scale)

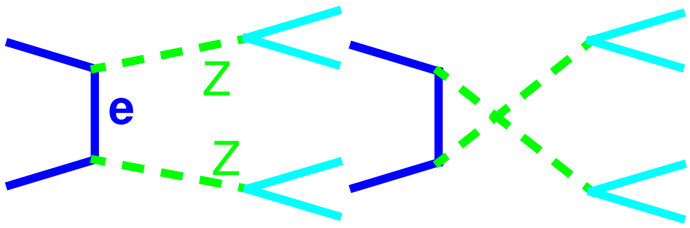
$-0.065\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.065\ \mathrm{GeV}^{-2}$

$-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.17\ \mathrm{GeV}^{-2}$ (OPAL)

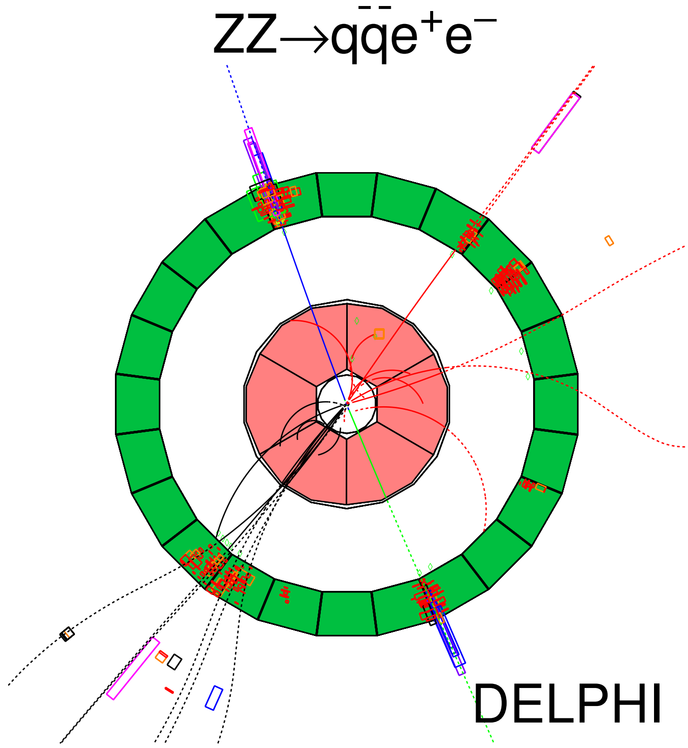
$-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < 0.57\ \mathrm{GeV}^{-2}$

ZZ Production

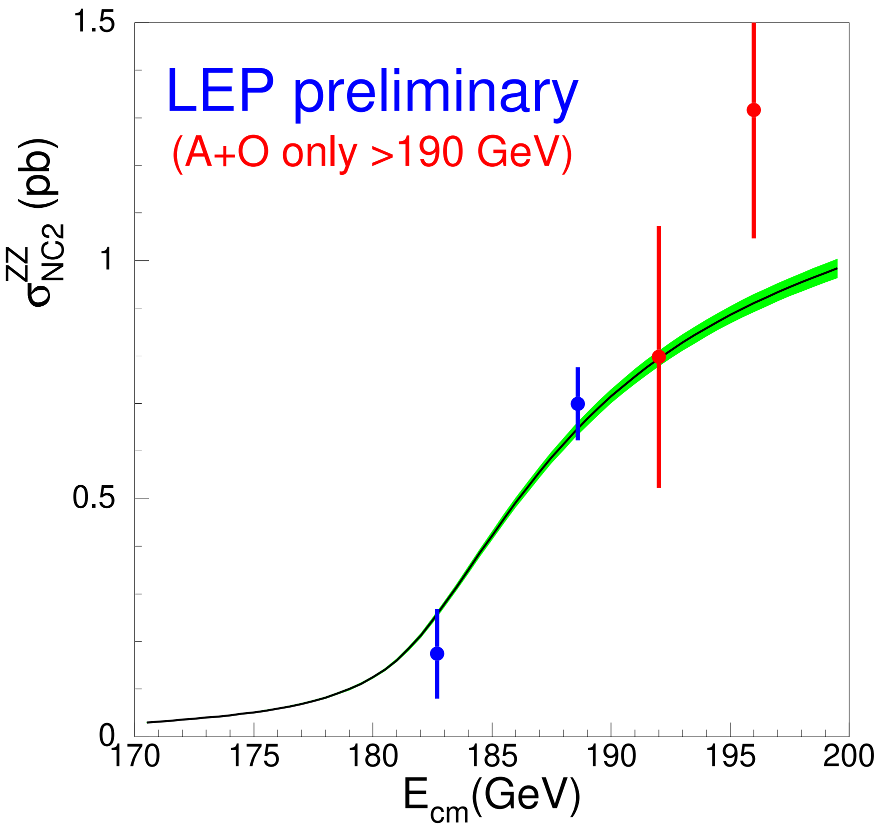
ZZ production in SM



Cross-section much lower than WW: Zee ~ $(1-4\sin^2\theta_W)$



Cross-section vs. $\sqrt{s}$
(ADLO)



Background to possible ZH production...?

Summary and Outlook

LEP is working superbly at high energy
design energy, luminosity will be reached / passed

Many processes measured
SM describes them all with flying colours
...so far

From around half the LEP2 data

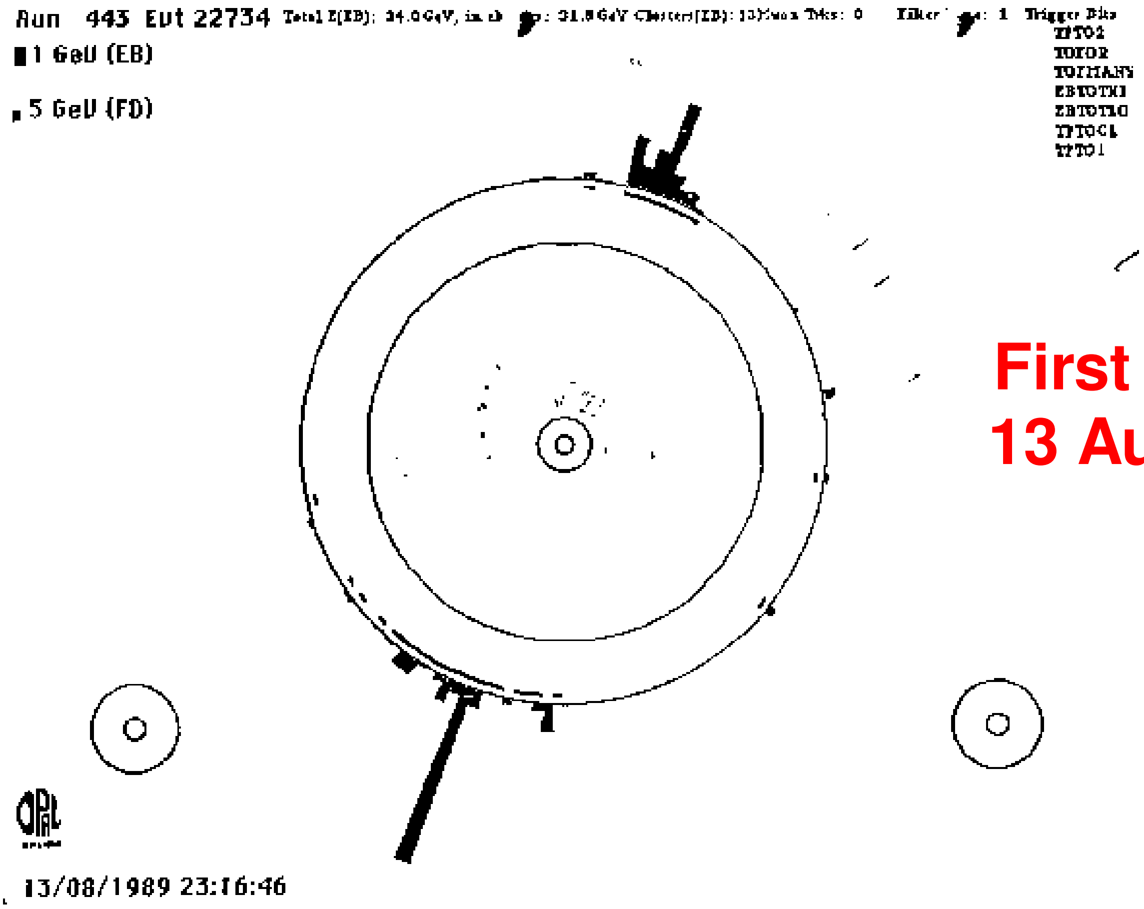
$M_W = 80.350 \pm 0.056$ GeV (Preliminary)

with scope for a final error close to 30 MeV

Precision M_W gives another probe of SM loop corrections
the SM passes again

WWZ and WWγ couplings measured at few percent level

Plenty more data and results yet to come
from LEP2 electroweak physics



First LEP Z^0
13 Aug 1989

Ten years on...

```
111     CERN SL
LEP Run 6032    data of:02-08-99    13:10:15
   -** STABLE BEAMS **-

E = 100.010 GeV/c Beam    In Coast:   1.8
Beams              e+             e-
I(t)    uA      1550.8         1834.7
tau(t)  h        7.24           7.26

LUMINOSITIES      L3     ALEPH     OPAL   DELPHI
L(t) cm-2*s-1    34.9     31.5     34.4     32.2
/L(t) nb-1      285.1    265.1    291.3    262.9
Bkg 1            0.53     0.38     0.85     0.61
Bkg 2            0.52     0.36     0.68     1.46

 COMMENTS   02-08-99 12:14
 COLLIMATORS AT PHYSICS SETTINGS

FIRST PHYSICS AT 100 GEV...
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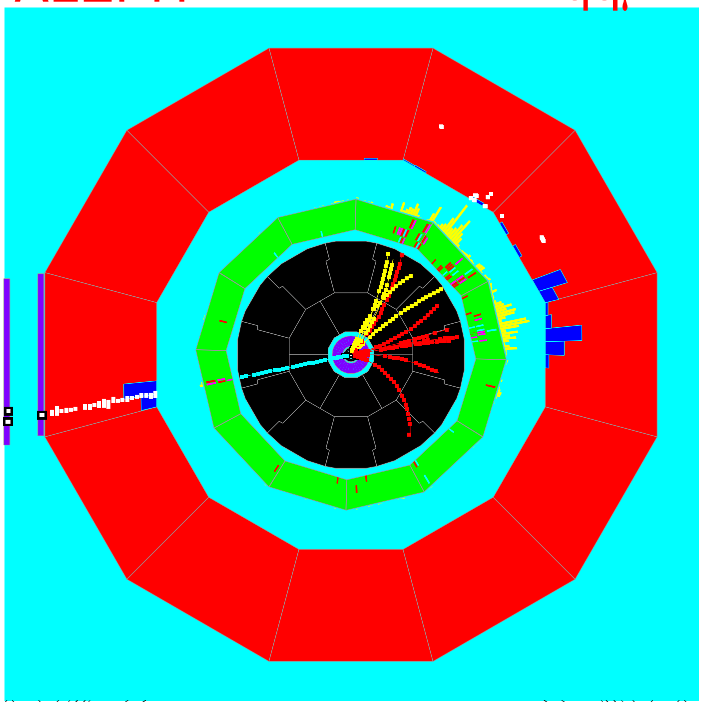
(E_{beam})

e^+e^- physics at 200 GeV

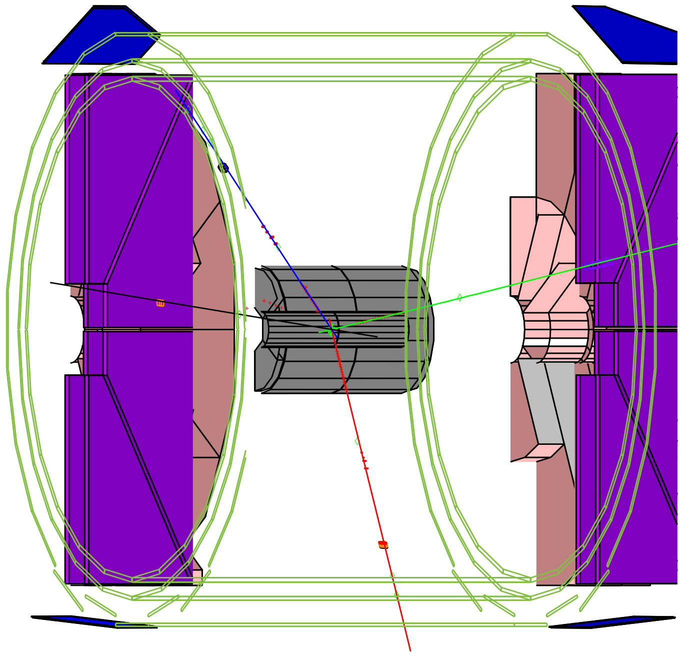
Events at E_{cm} = 200 GeV

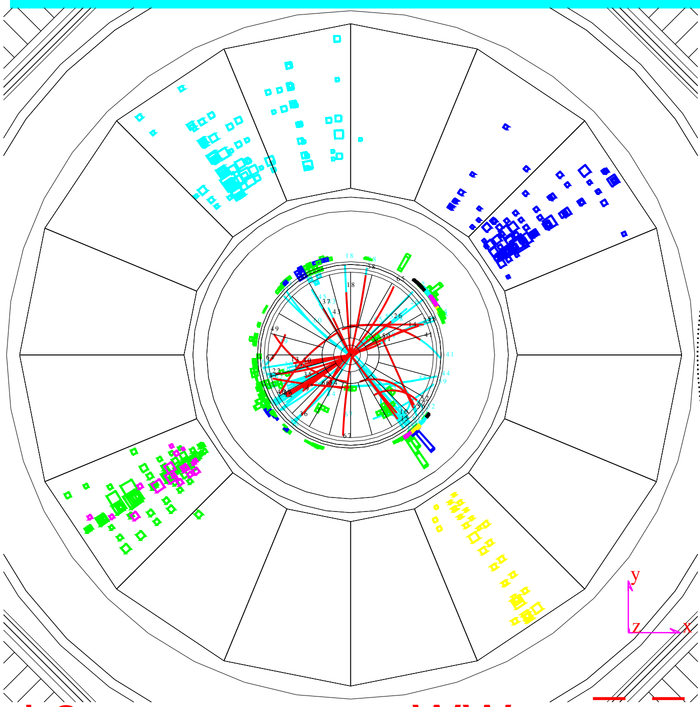
LEP has been taking data at $\sqrt{s}$=200 GeV since 2 August

ALEPH $WW \to q\bar{q}\mu\nu$

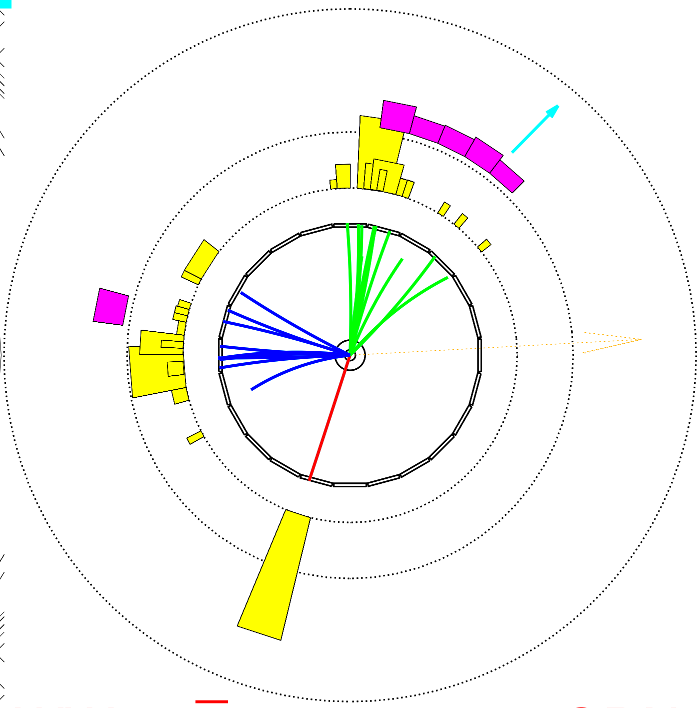


$ZZ \to \mu\mu\mu\mu$ DELPHI





L3 $WW \to q\bar{q}q\bar{q}$



$WW \to q\bar{q}e\nu$ OPAL