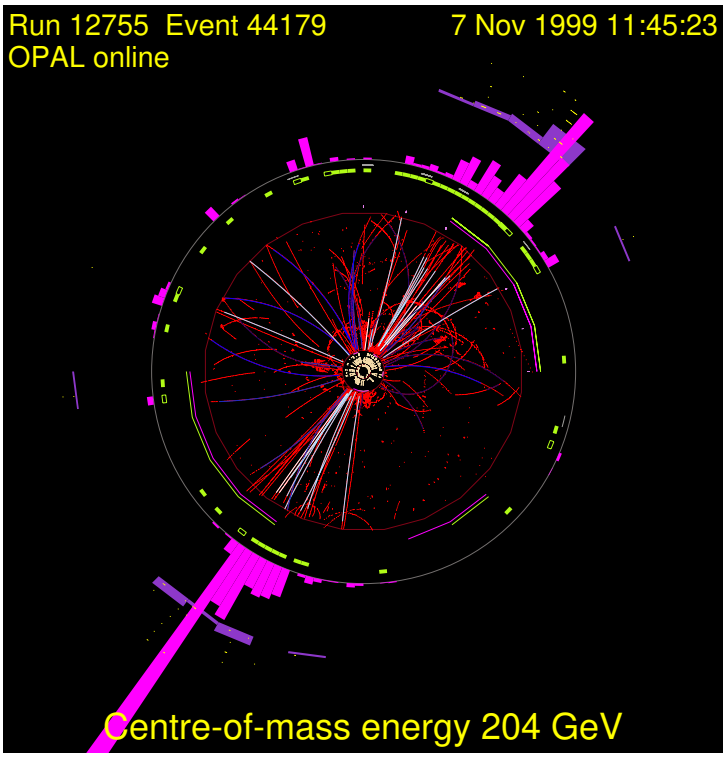
Electroweak Physics at LEP2



Particle Physics 2000
Edinburgh, 12 April

Dave Charlton

School of Physics and Astronomy
The University of Birmingham

Acknowledgements

Most of the averages presented here were made by the **LEP electroweak working group** and its **W mass, LEP2 ff̄** and **TGC** subgroups

Thanks to all of them for their help

Overview

The LEP2 Programme

Fermion Pair Production

W^+W^- Production & Decays

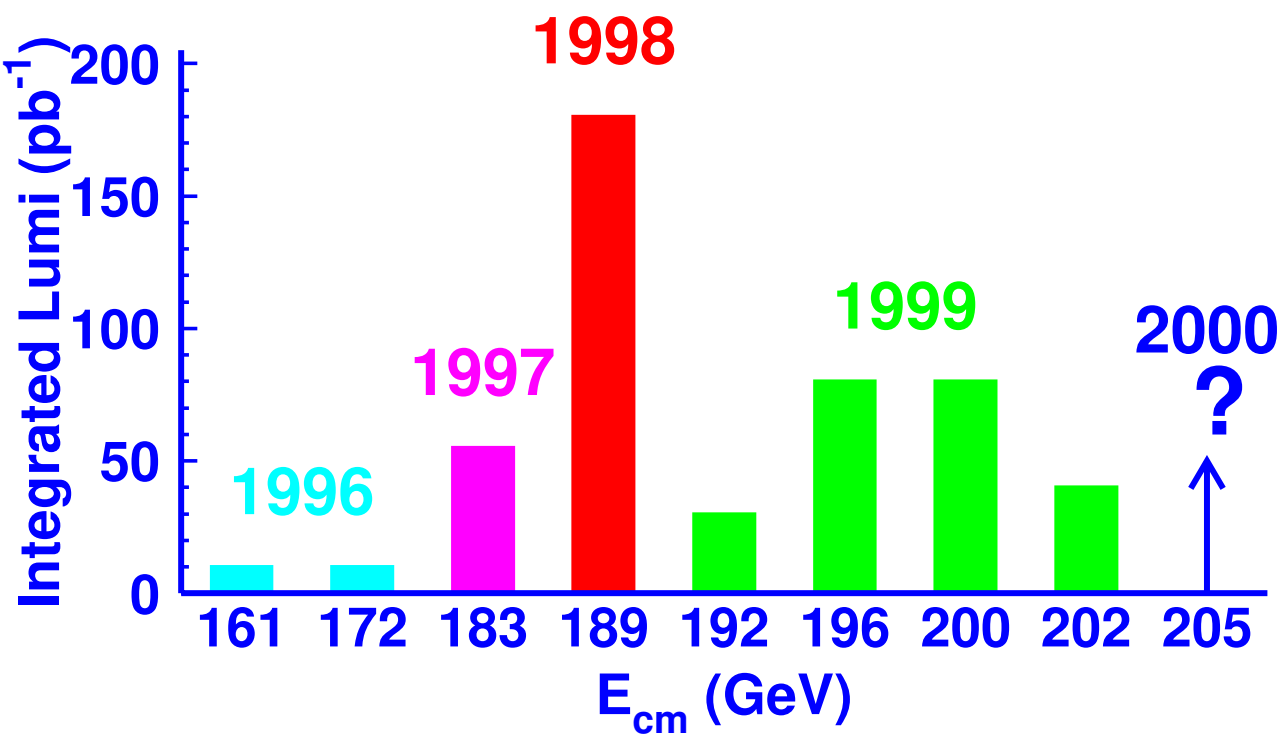
W Mass

Gauge Boson Self-Interactions

ZZ Production

Summary

The LEP2 Programme

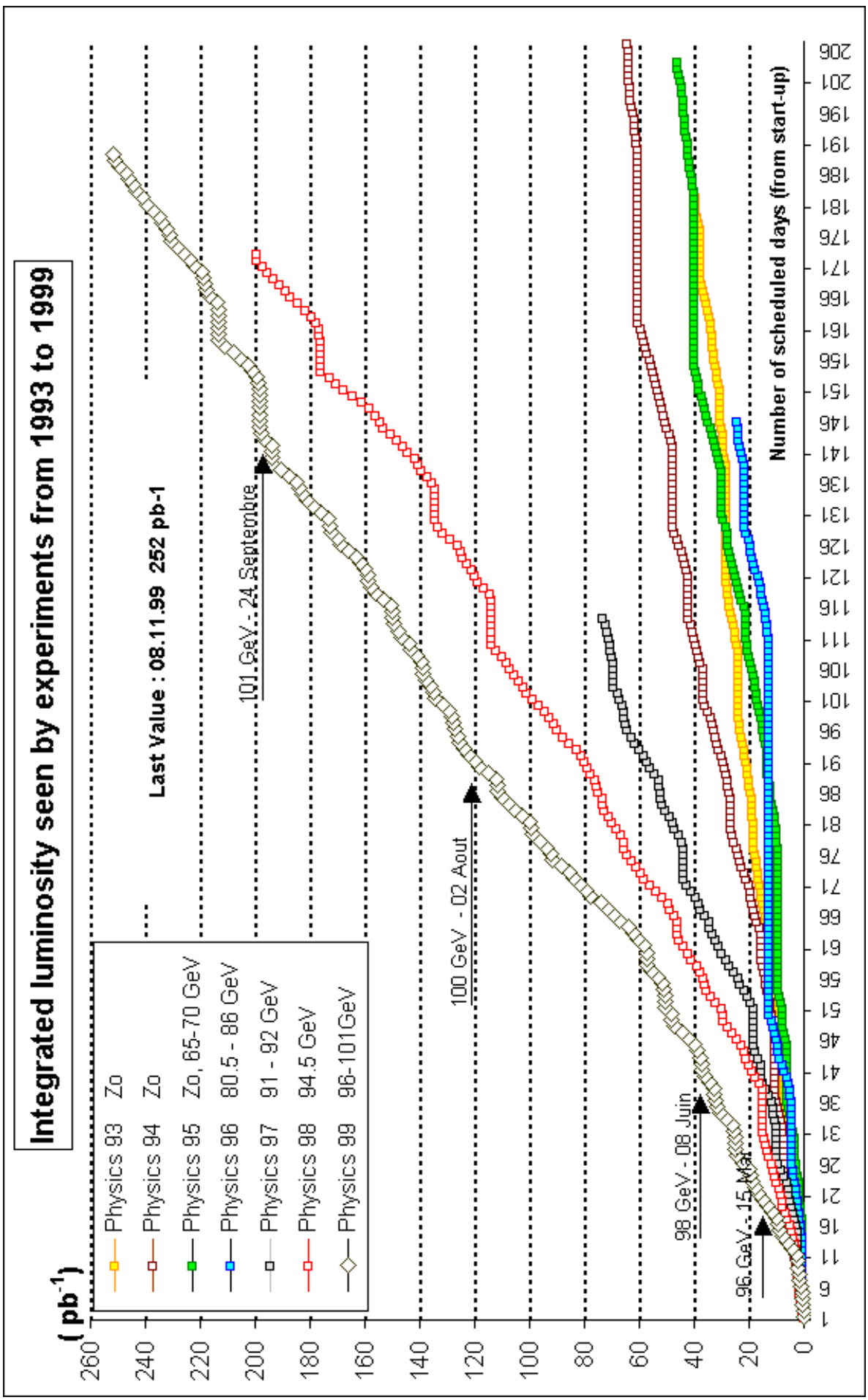


So far 490 pb^{-1} recorded per experiment at LEP2

Expect another ~150 pb^{-1} before end of LEP (late 2000)

LEP2 will comfortably exceed the canonical
500 pb^{-1}/expt (Aachen, 1986)

Almost all results are PRELIMINARY

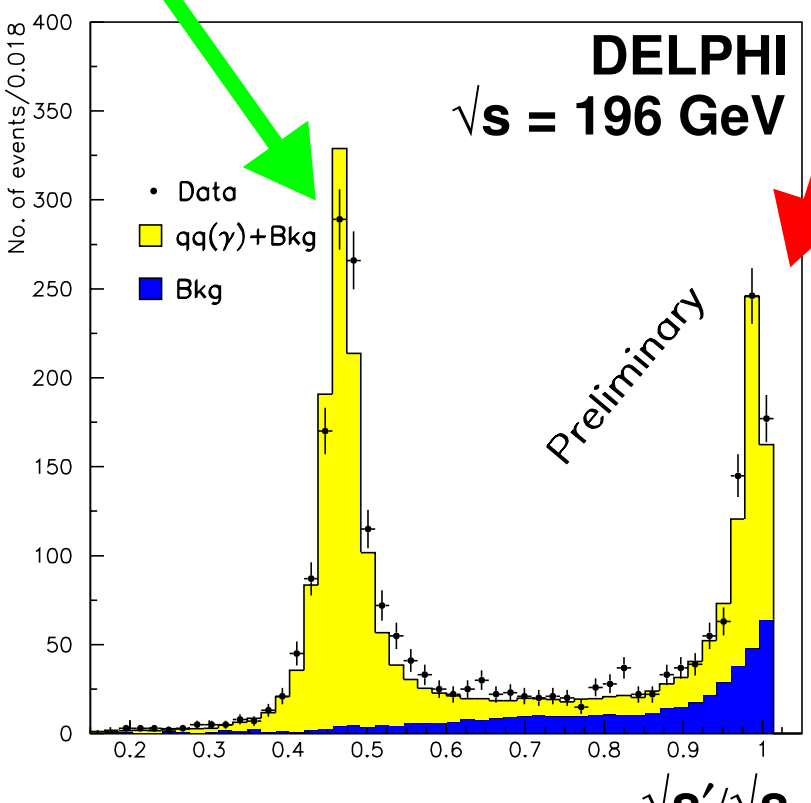

Integrated luminosity seen by experiments from 1993 to 1999
(pb-1)
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 96-101GeV
Last Value : 08.11.99 252 pb-1
101 GeV - 24 Septembre
100 GeV - 02 Aout
98 GeV - 08 Juin
96 GeV - 15 Mai
Number of scheduled days (from start-up)

Fermion Pair Production

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

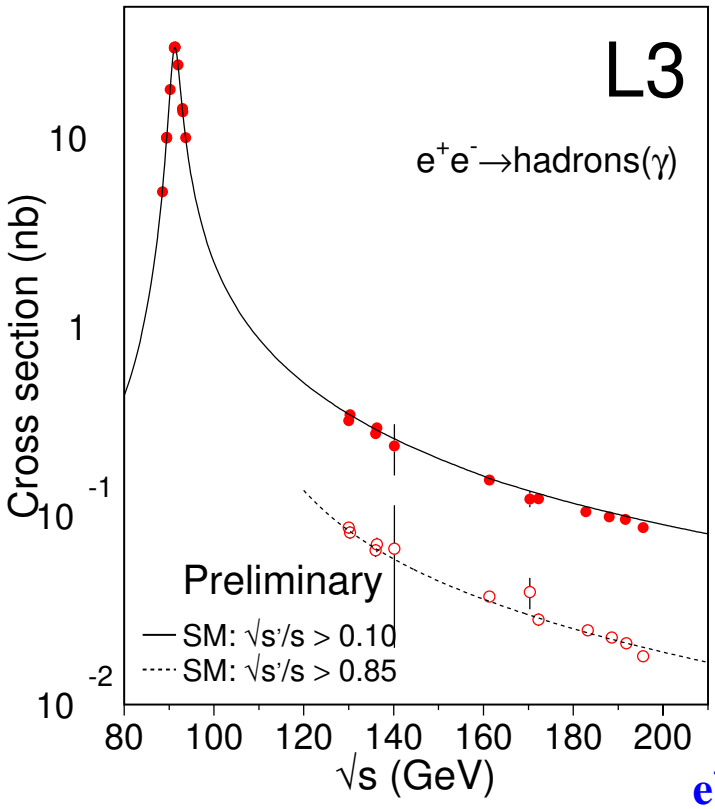
❶ Full energy events ($\sqrt{s'}\approx\sqrt{s}$)

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

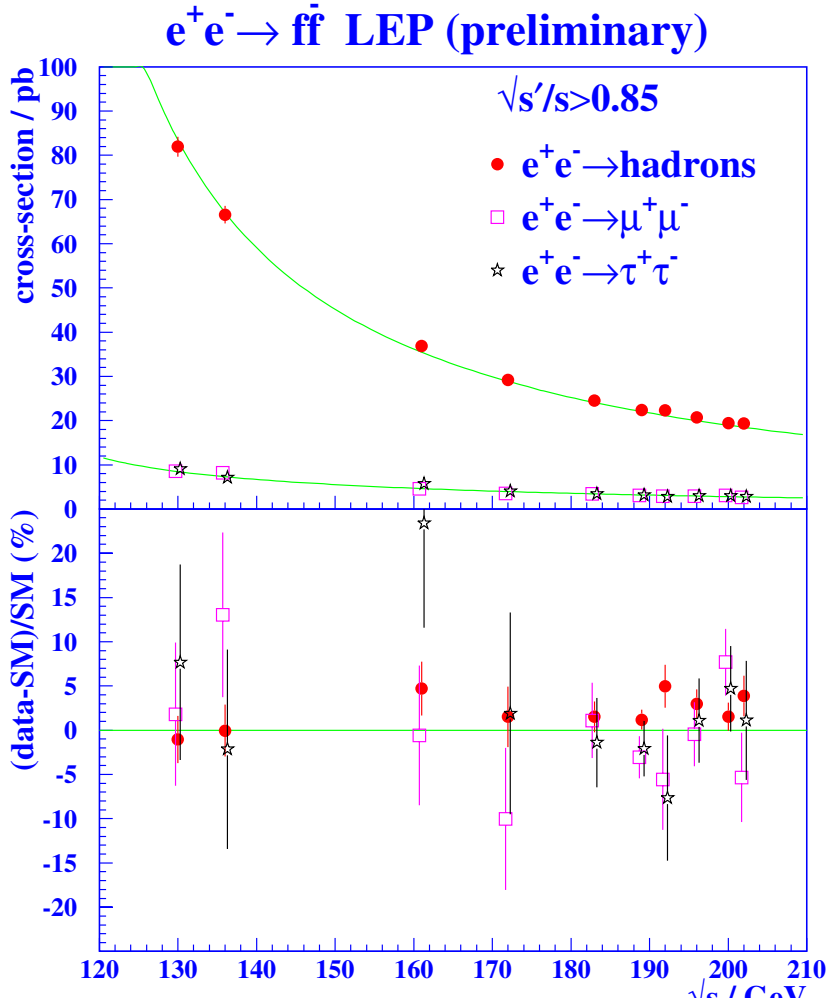


$e^+e^-\to q\bar{q}(\gamma)$

Fermion Pair Cross-Sections



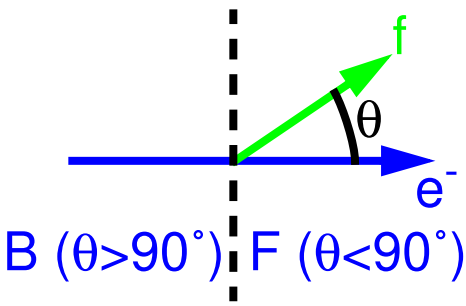
radiative return

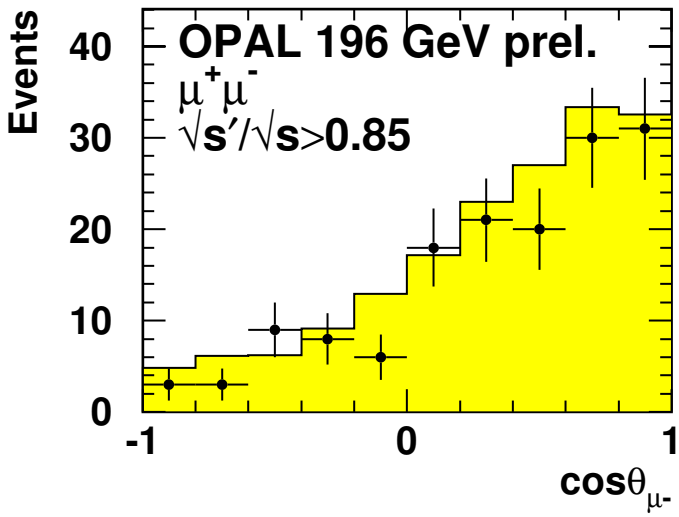


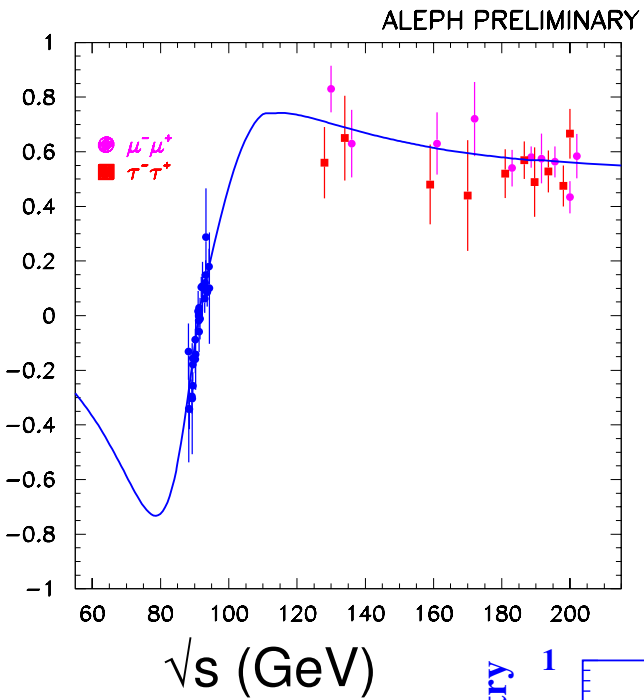
Comparison with SM expectation

Lepton Pair Asymmetries

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

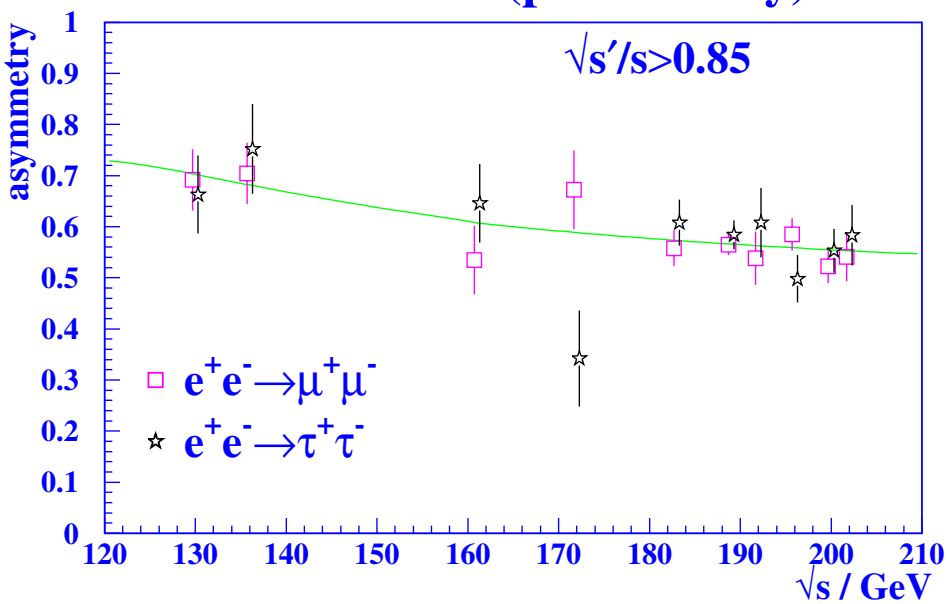






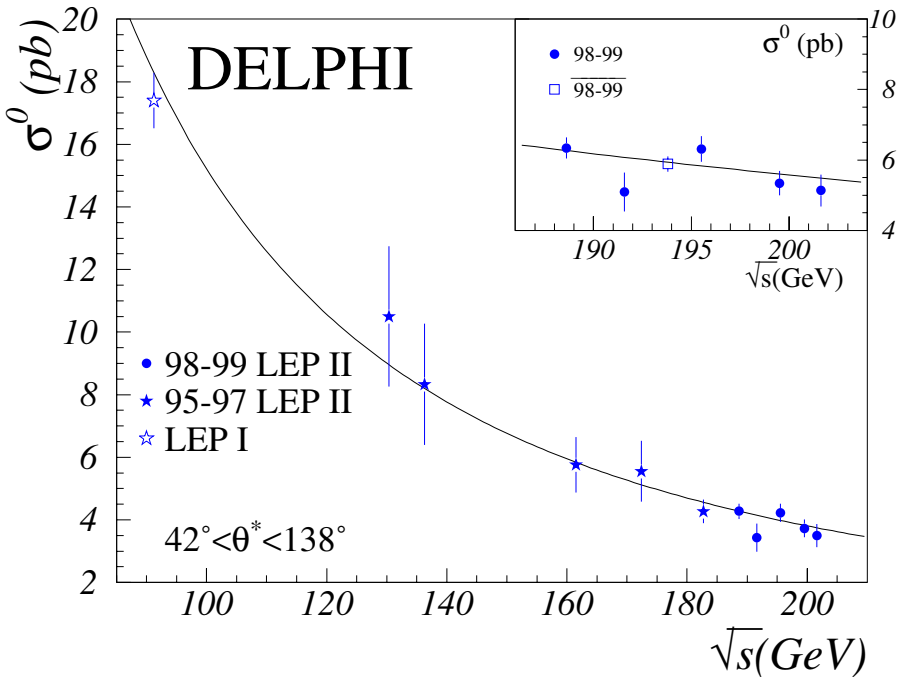
$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$

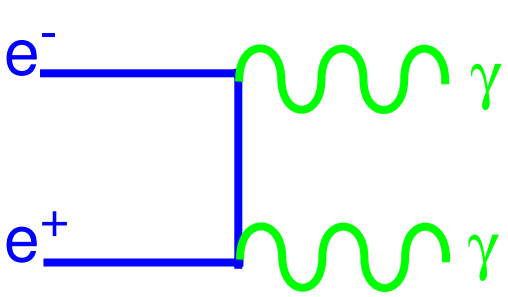
$e^+e^- \rightarrow f\bar{f}$ LEP (preliminary)



LEP at highest √s

QED Tests at High Energy

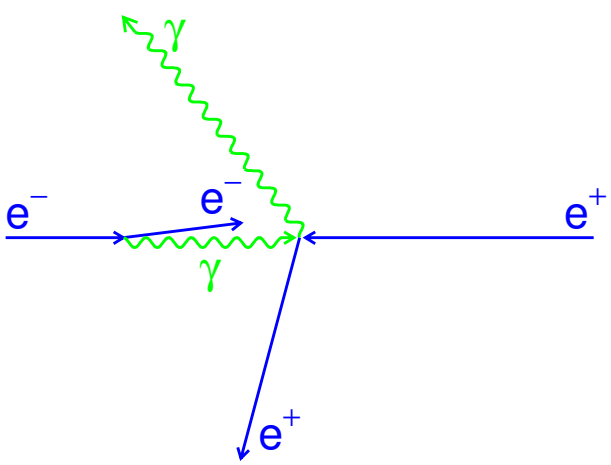




$e^+e^- \rightarrow \gamma\gamma(\gamma)$

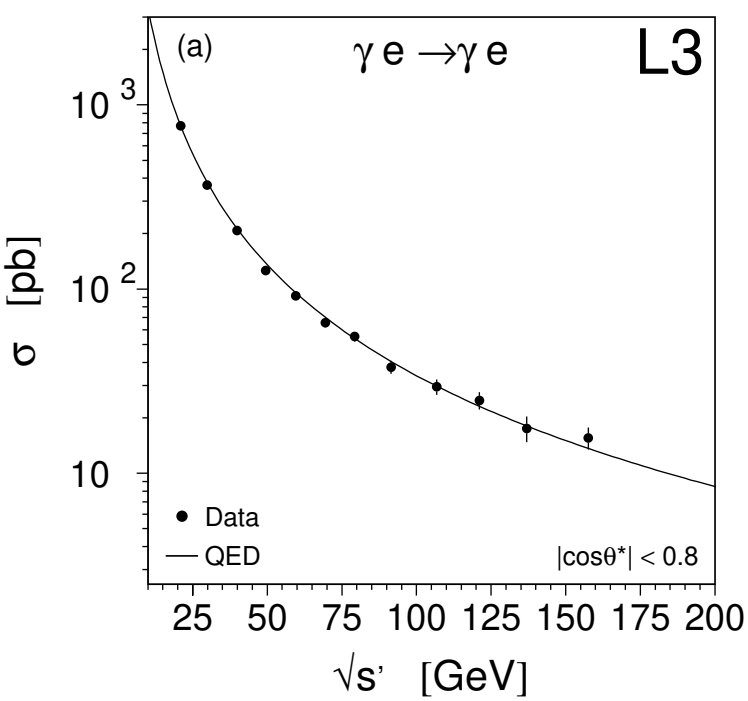
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Born} \pm \frac{\alpha^2 s}{2\Lambda_{\pm}^4}(1 + \cos^2\theta)$$

QED cut-off parameters $\Lambda_{\pm} > \sim 320$ GeV at 95% CL



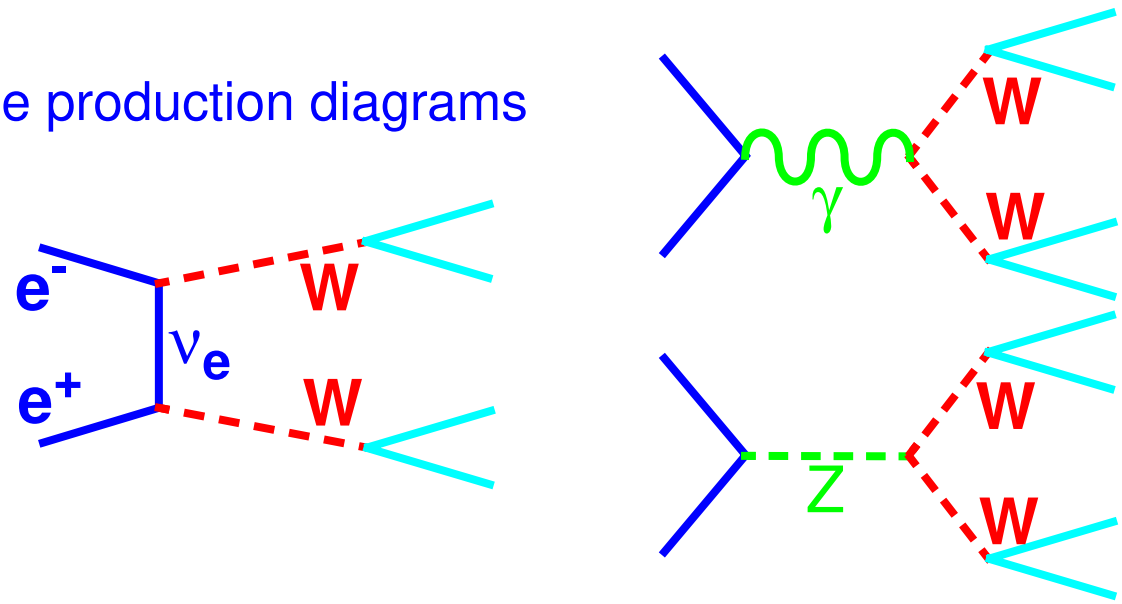
Compton scattering

$e\gamma \rightarrow e\gamma$



WW Production at LEP2

Three production diagrams



At $\sqrt{s}$=195 GeV, $\sigma_{WW} \approx 17$ pb

$\Rightarrow$ ~8500 W^+W^- / expt. for 500 pb^{-1}

$BR(W \to q\bar{q}) \approx {}^{2}/_{3}$

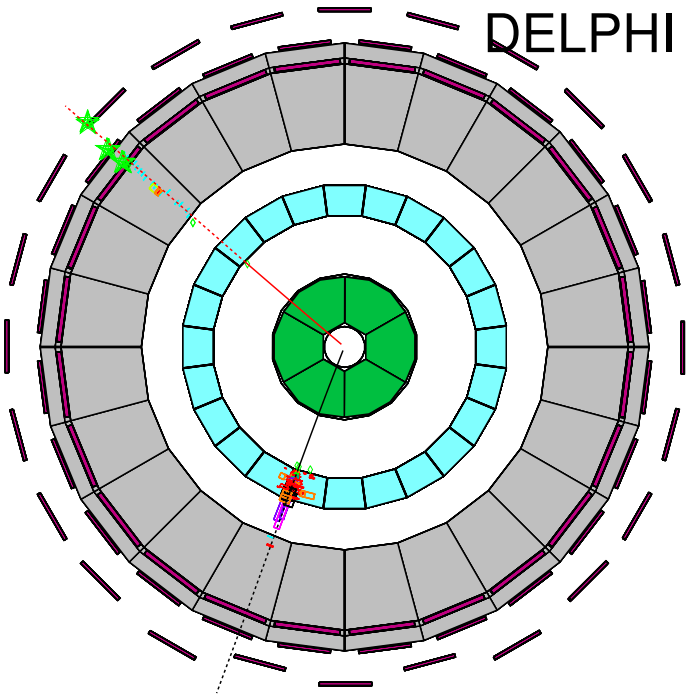
$BR(W \to e\nu, \mu\nu, \tau\nu) \approx {}^{1}/_{9}$ each

Observed events:

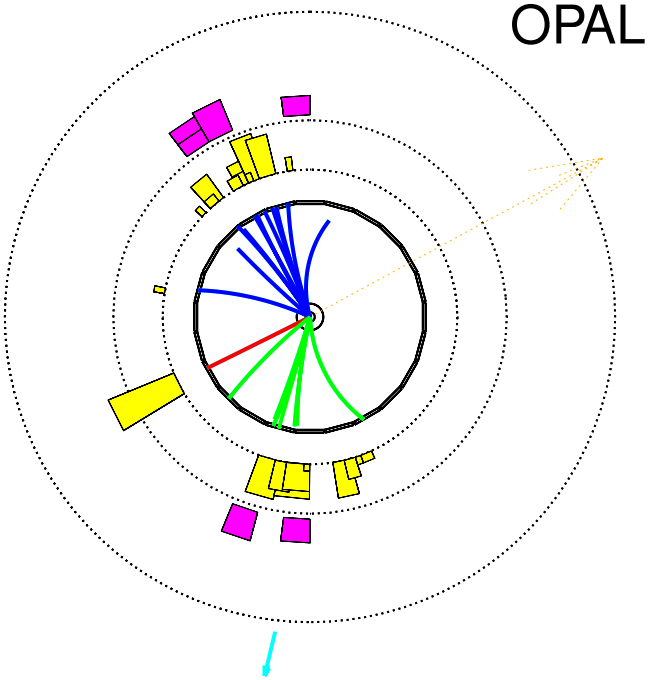
		for 500 pb^{-1}
$WW \to q\bar{q}q\bar{q}$	**46%**	~3900
	(≥)4-jet events	
$WW \to q\bar{q}l\nu$	**44%**	~3700
	2 jets, charged lepton, missing p	
$WW \to l\nu l\nu$	**10%**	~850
	2 energetic charged leptons	

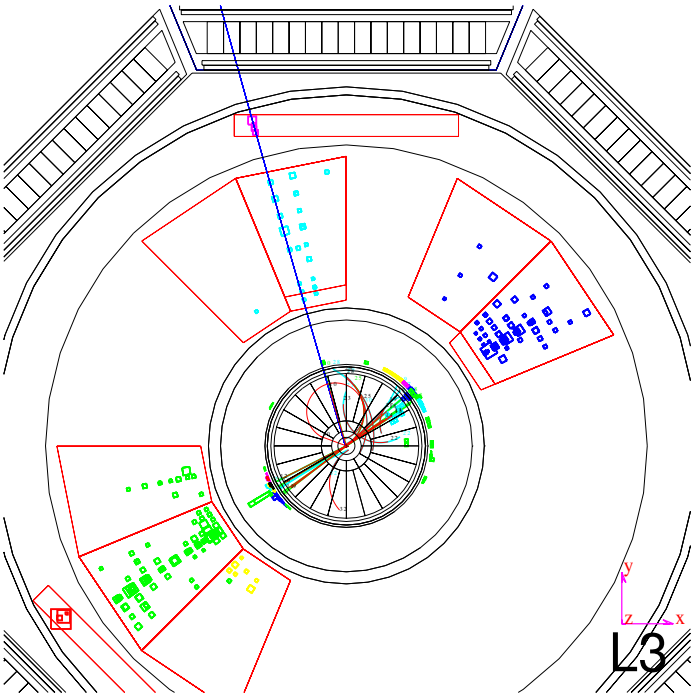
W^+W^- Events

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

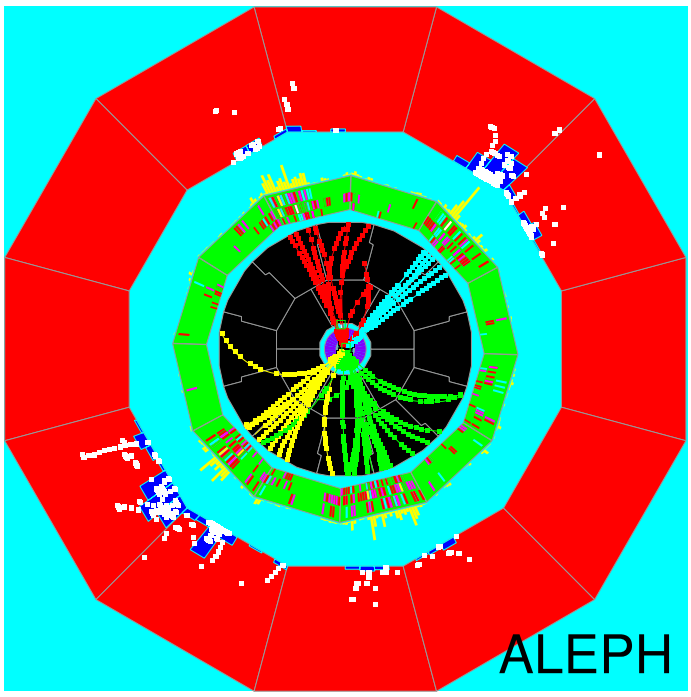


$WW \to q\bar{q}e\nu$





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



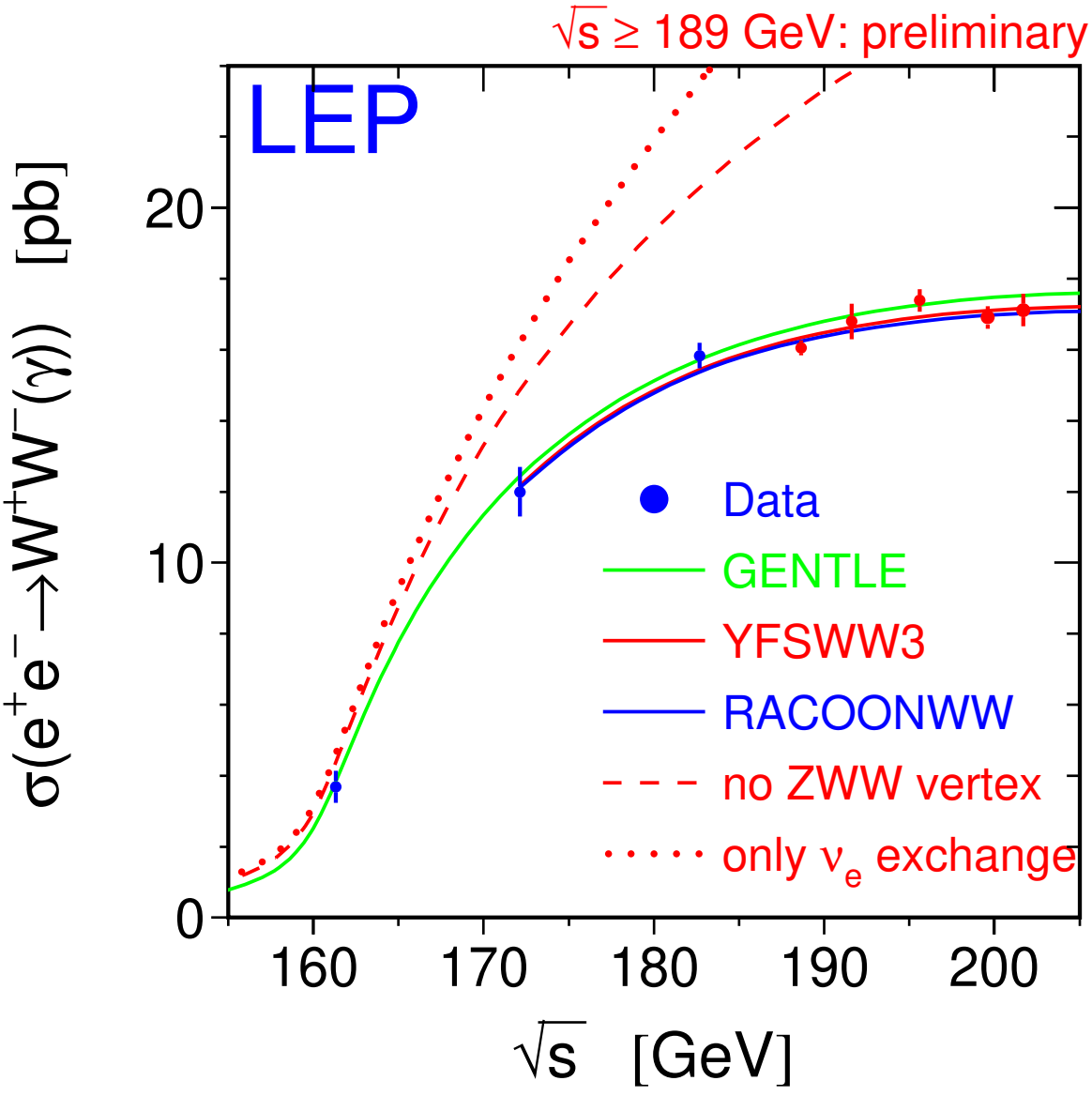
$WW \to q\bar{q}q\bar{q}$

W^+W^- Cross-Section

WW event selections: All final-states in all experiments

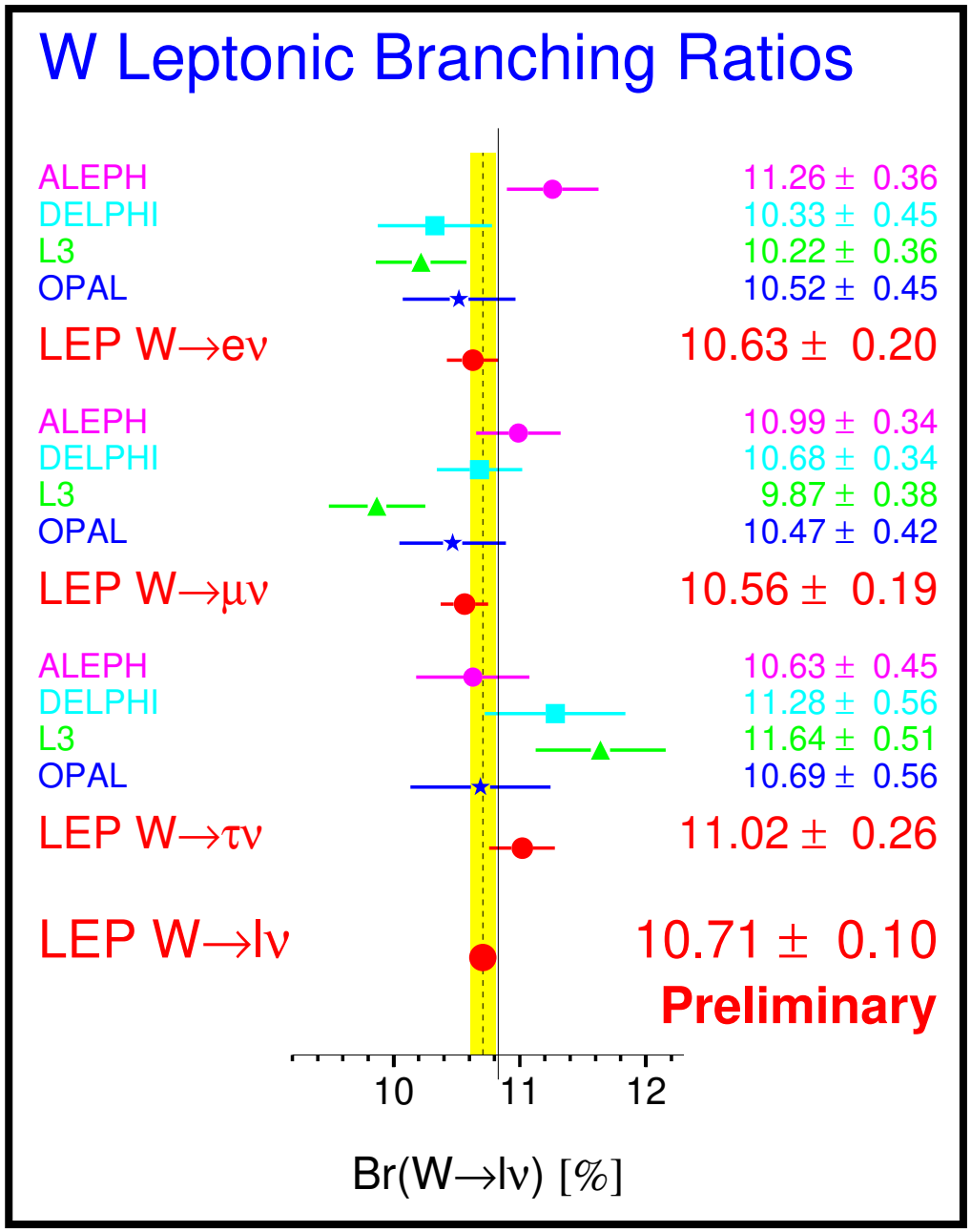
Multivariate discriminants give best selection performance

	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+DØ: BR(W→eν) = 10.45 ± 0.19 %

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

BR(W→$q\bar{q}$) = 67.85 ± 0.33 % (LEP combined)

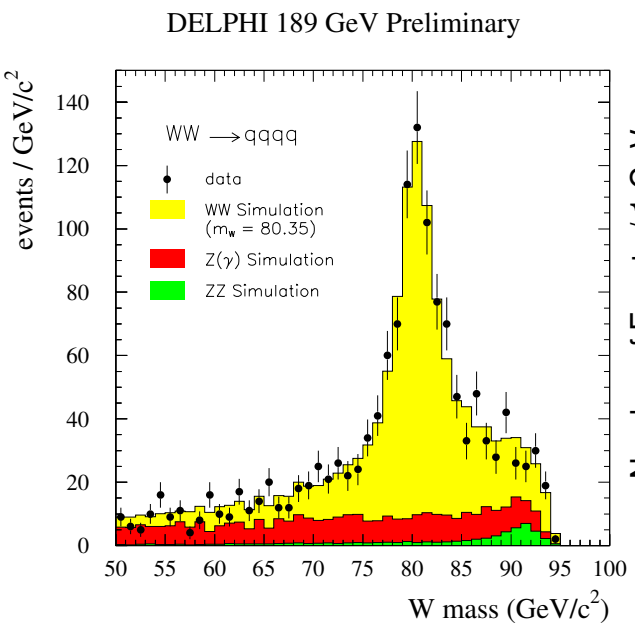
W Mass

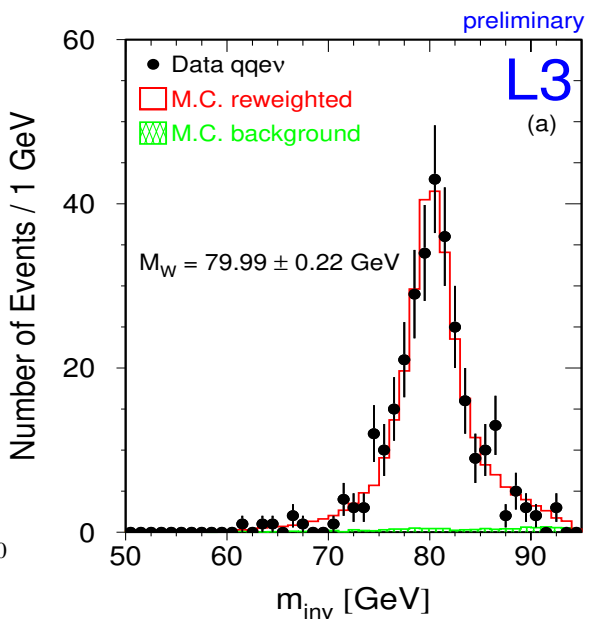
$WW \to q\bar{q}q\bar{q}$ and $WW \to q\bar{q}l\nu$ (**A** also $l\nu l\nu$)

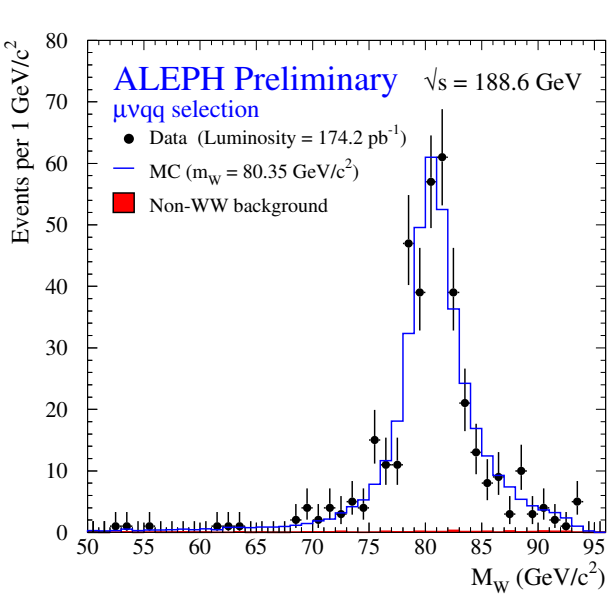
Excellent mass resolution comes from kinematic fit:

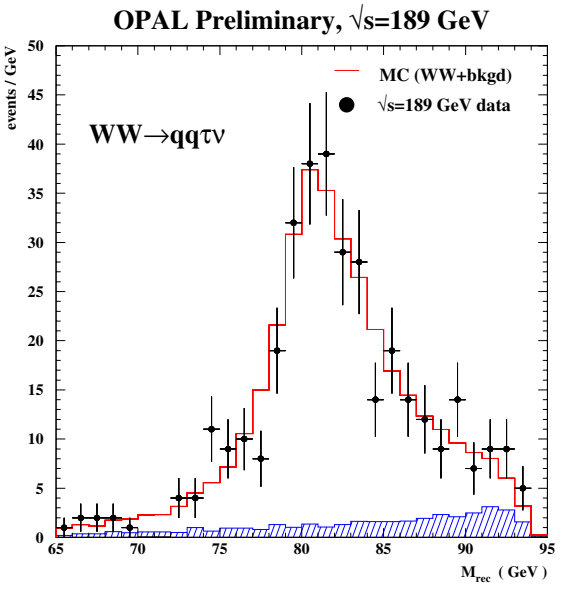
- Constrain total (E,**p**) to (√s,**0**) - needs E_{beam} from LEP

Reconstructed mass distributions

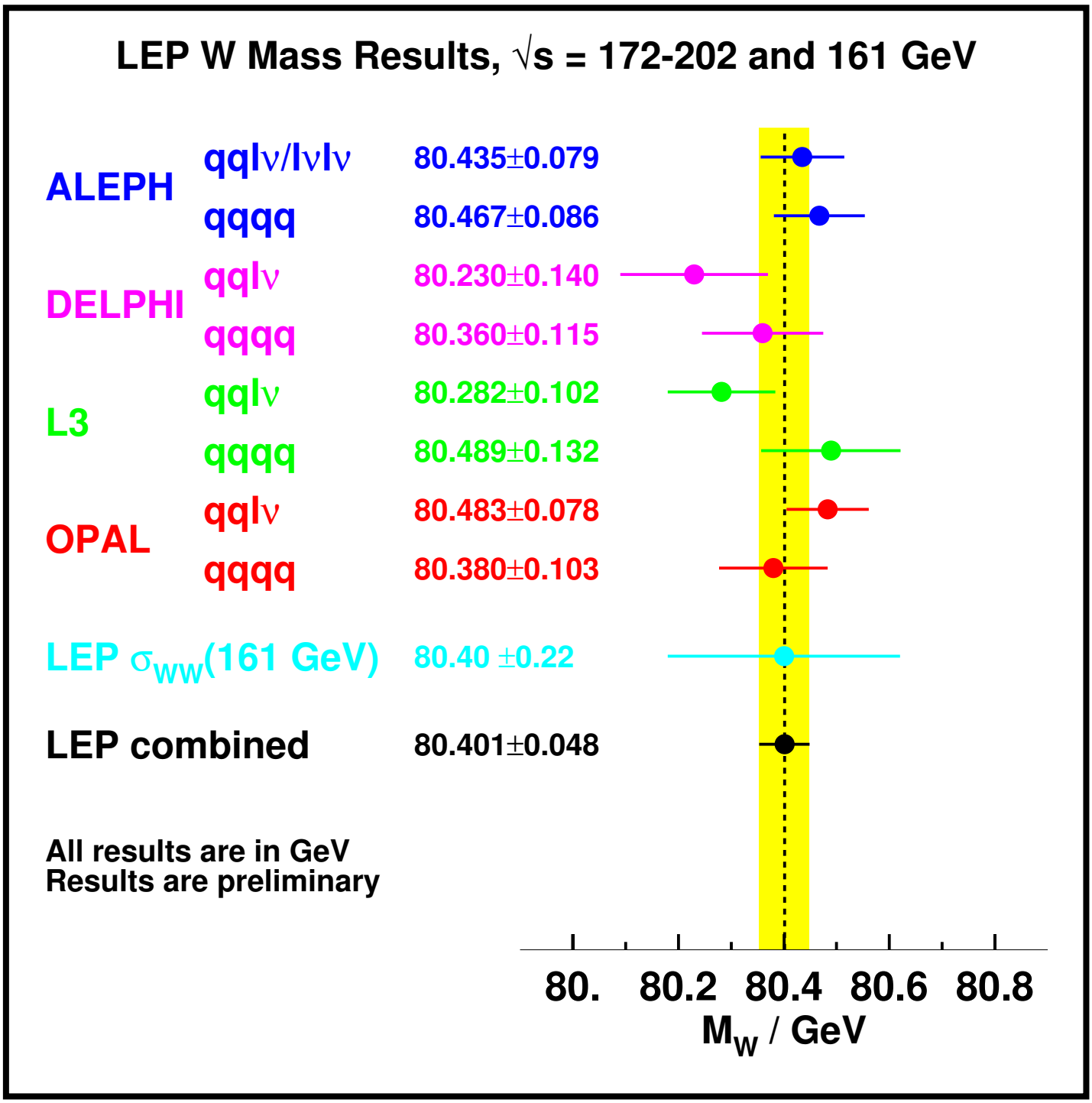








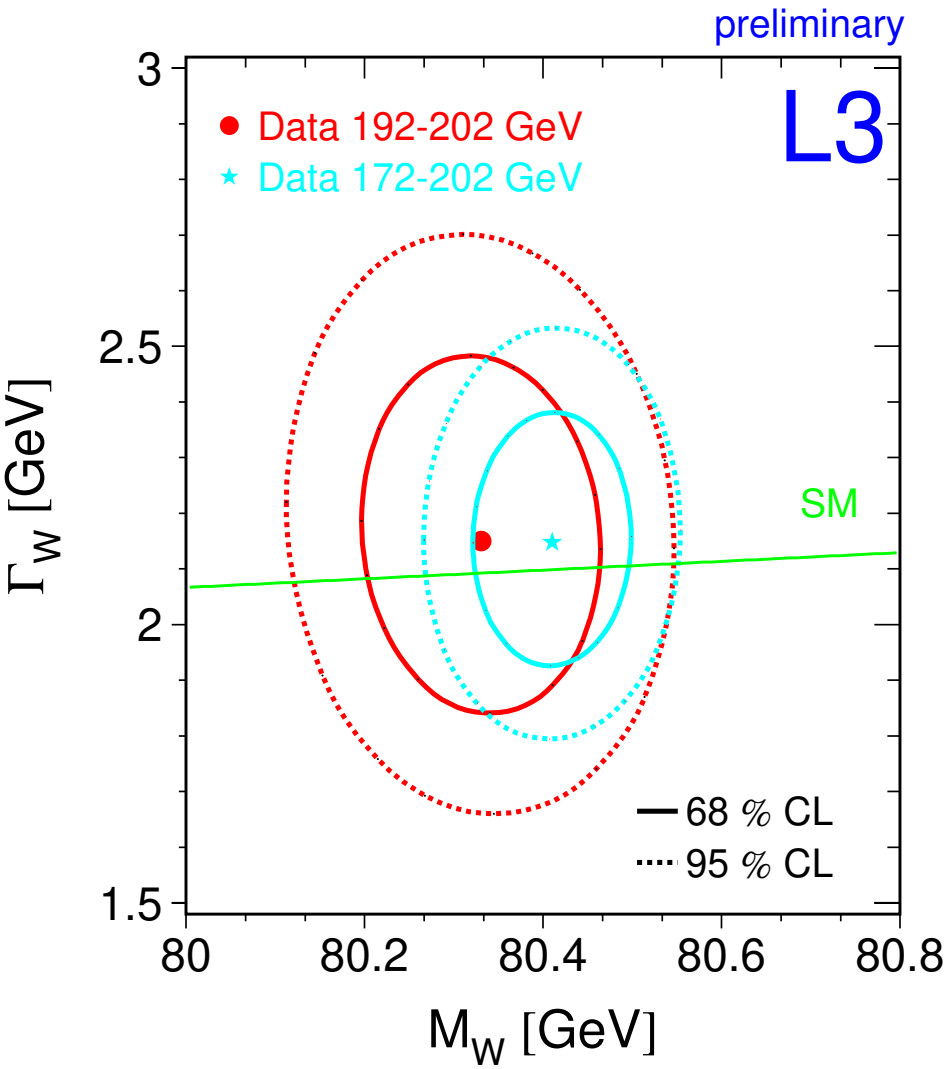
Standard fits: Γ_W constrained to SM relationship with M_W



W Width

May alternatively fit simultaneously Γ_W and M_W

→ direct measurement of Γ_W



Measurements by **ADLO** (preliminary, not all data)

Γ_W = **2.188 ± 0.147 GeV** **(LEP combined)**

Cf. CDF direct: 2.055 ± 0.125 GeV

W Mass Uncertainties

Latest analyses → estimate **final** LEP M_W precision

for 650 pb^{-1} per experiment

Final **statistical** error: ~20 MeV

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

Key **systematic** errors:

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

- Detector calibration etc.	10-20 MeV/expt
- Hadronisation	20-40 MeV

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

- Final-state interactions	40-90 MeV
- Hadronisation	~30 MeV

All channels:

- LEP beam energy	17 MeV

Cross-LEP effort in progress to address these key errors

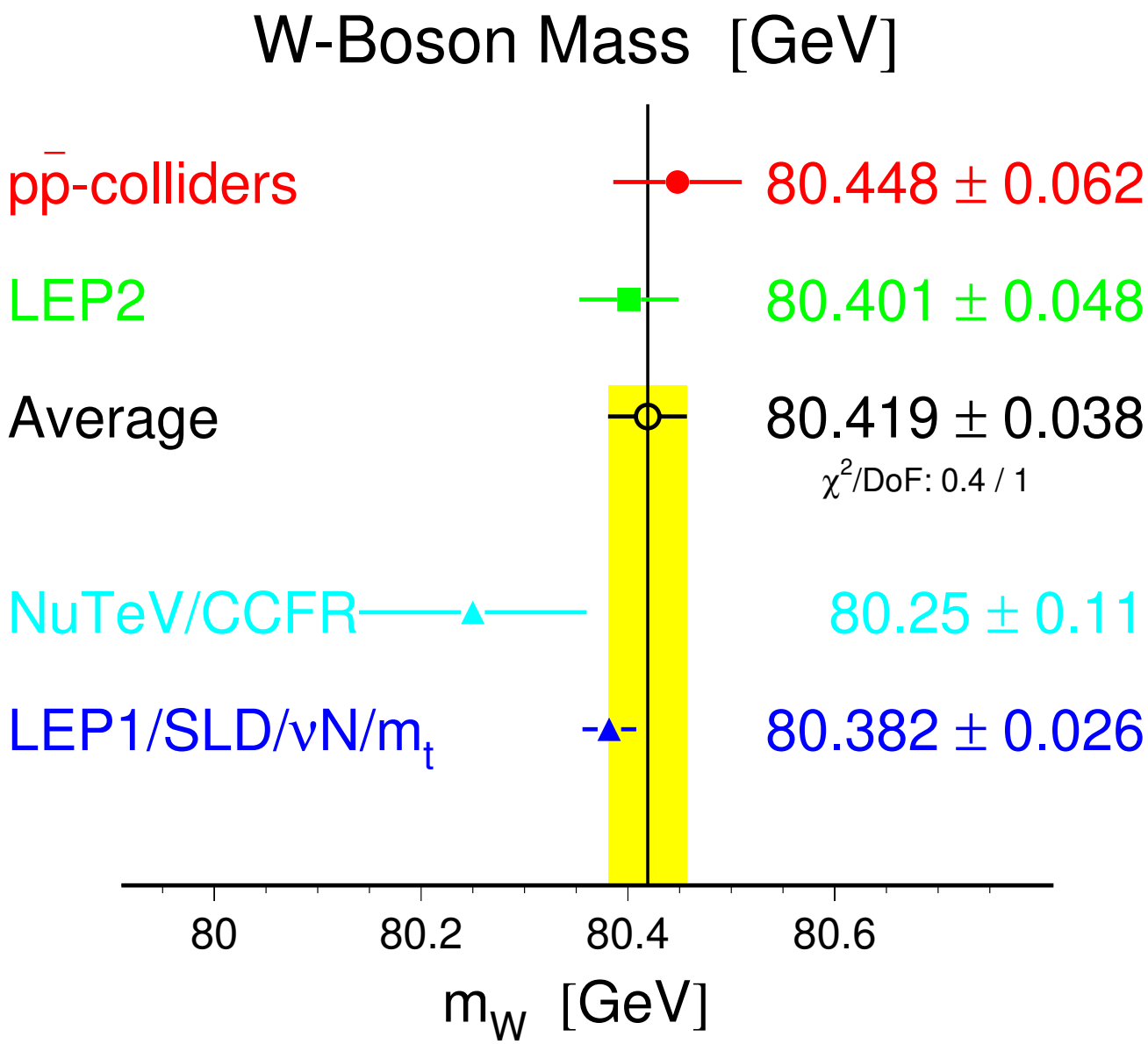
Series of workshops: Crete, CERN, Lisbon

30-35 MeV should be achievable

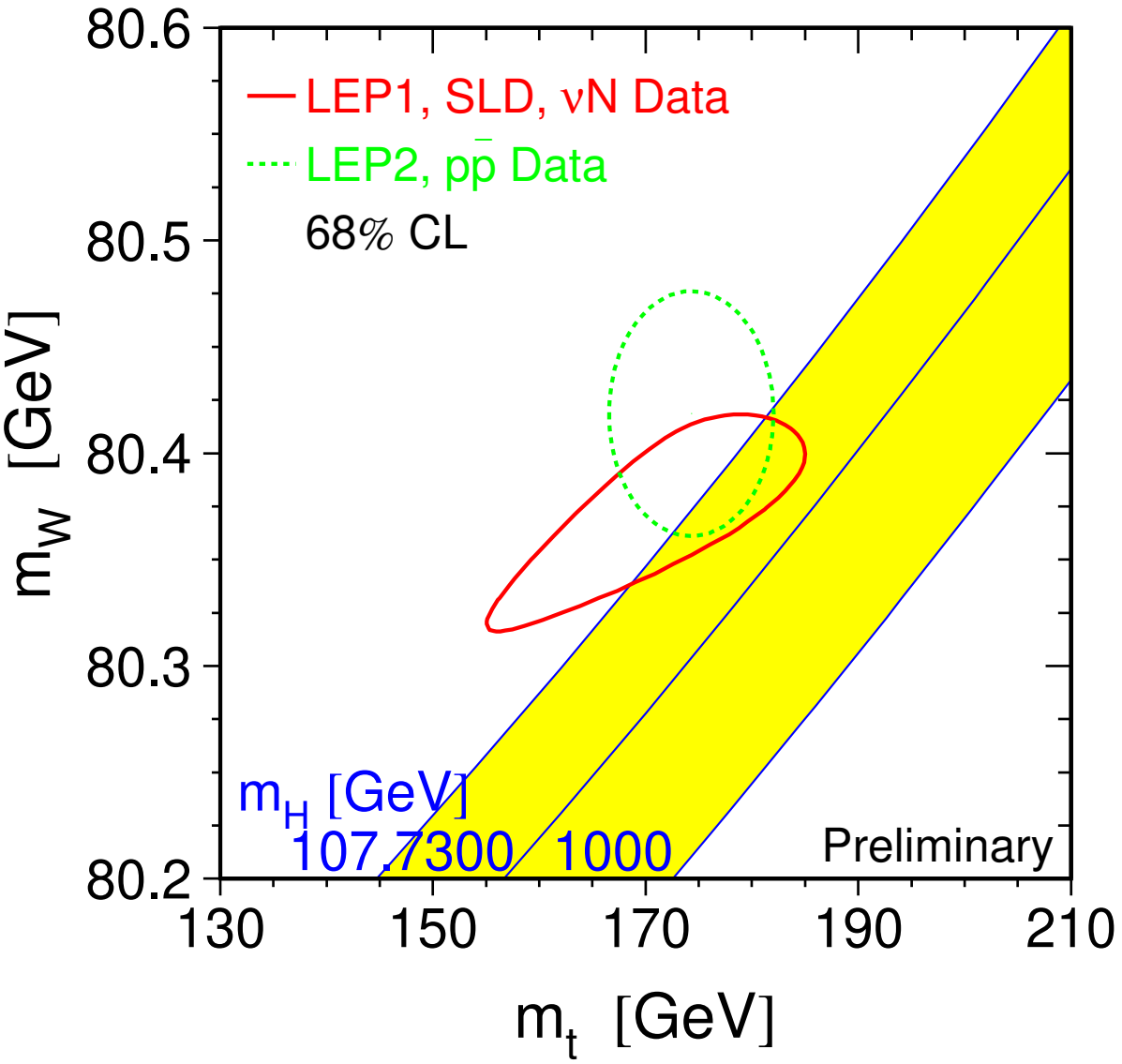
World Average W Mass

LEP and Tevatron M_W precisions similar
Experimental errors very different

$\rightarrow$ Major gain by combining



Impact of W Mass Measurement

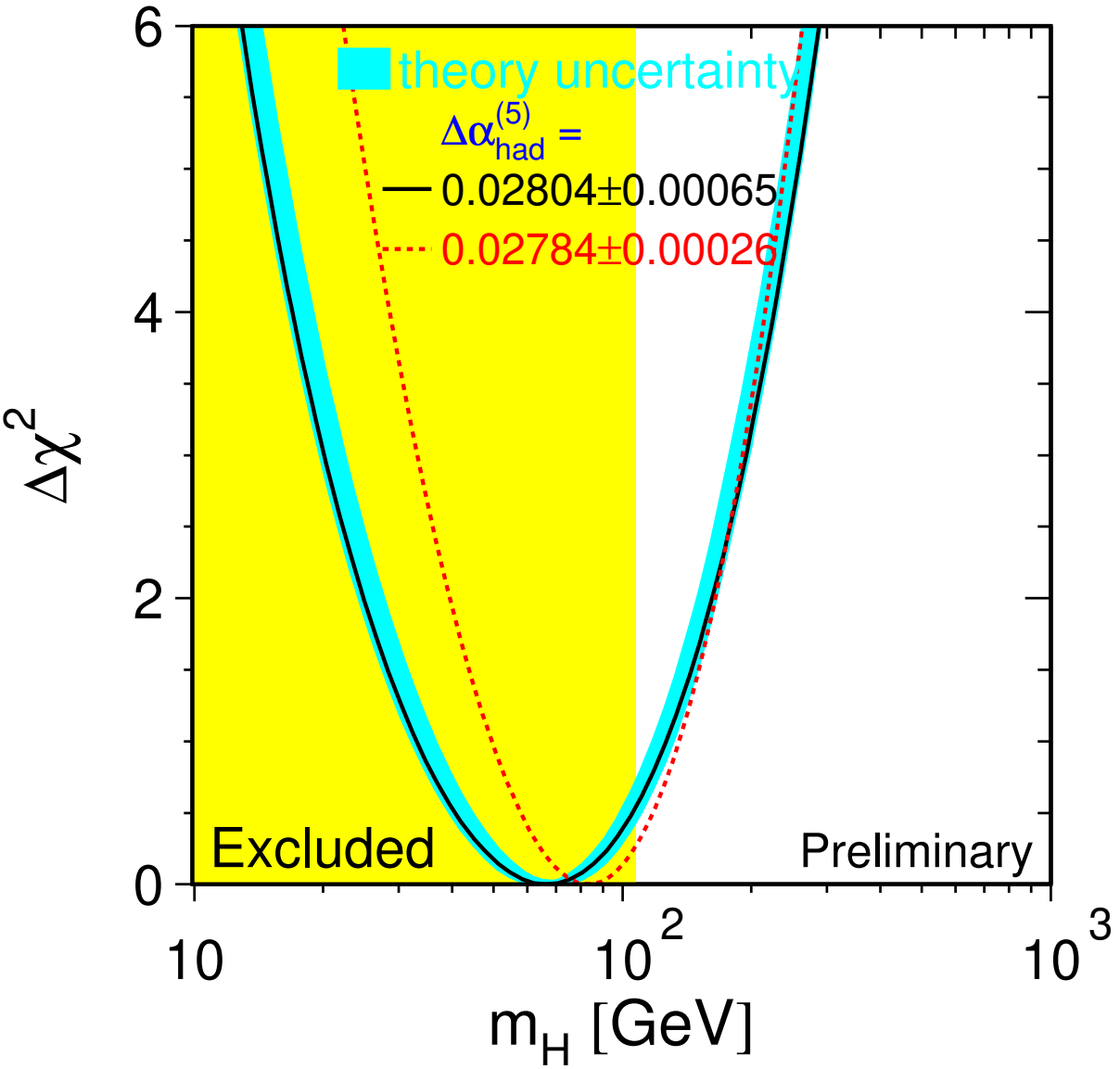


Two experimentally independent SM tests:
Consistent
Both suggest low M_H

Standard Model still OK at level of top and Higgs loops

SM Fit for the Higgs Mass

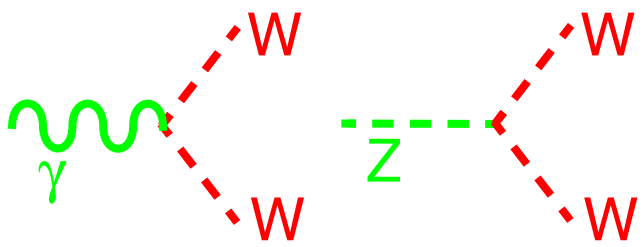
Health warning: Full SM radiative correction structure



Without using direct search results, obtain
$M_H < 188$ GeV at 95% CL

Triple Gauge Couplings WWγ, WWZ

General WWγ and WWZ interaction: 14 parameters



Apply C and P invariance
& use low-energy constraints
→ 3 parameters

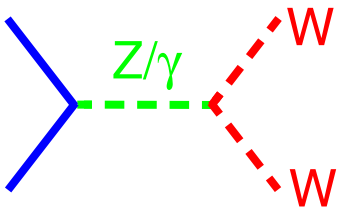
Conventionally κ_γ, g_1^Z and λ_γ, (1,1,0) in SM

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

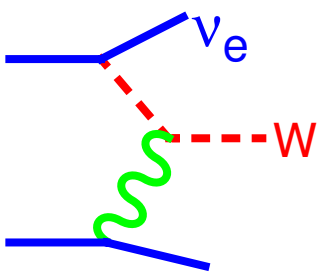
$q_W = (e/M_W^2)\,(\lambda_\gamma-\kappa_\gamma)$

Effects studied at LEP2 in

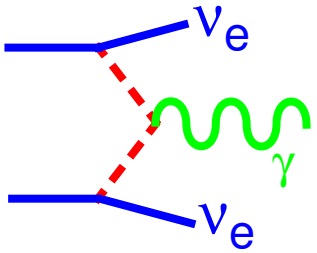
❶ WW production



❷ Single W production

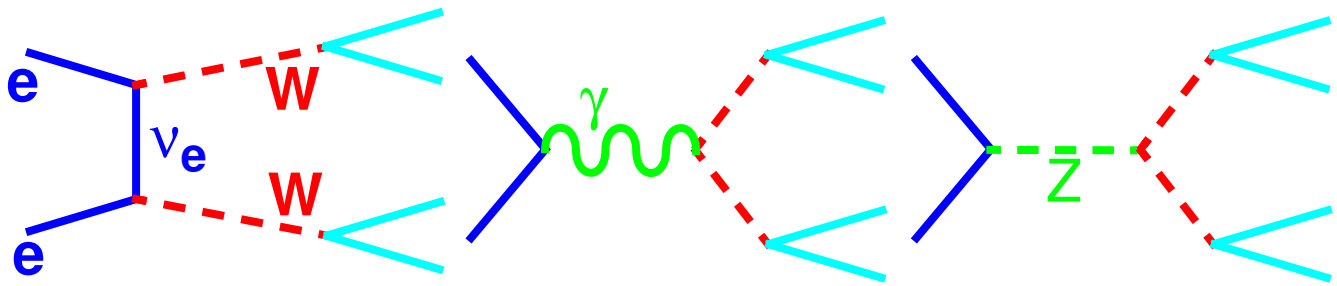


❸ Single photon production



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

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



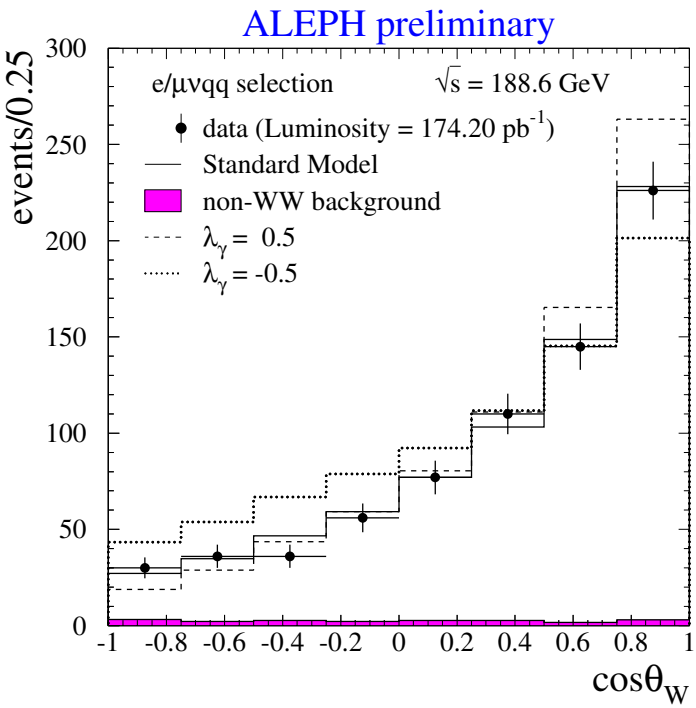
Triple gauge couplings affect

➔ total WW cross-section

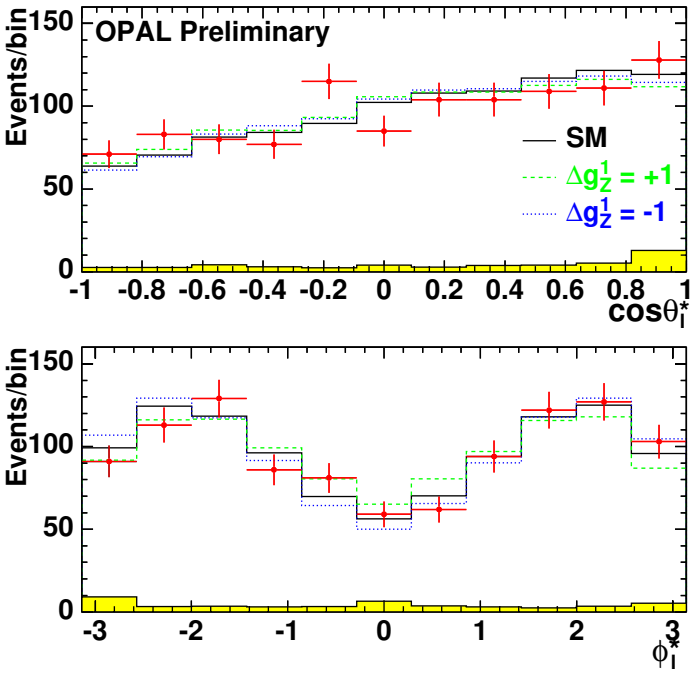
➔ angular distribution of W^- production

➔ helicity mixture of W's: analyse via W→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)

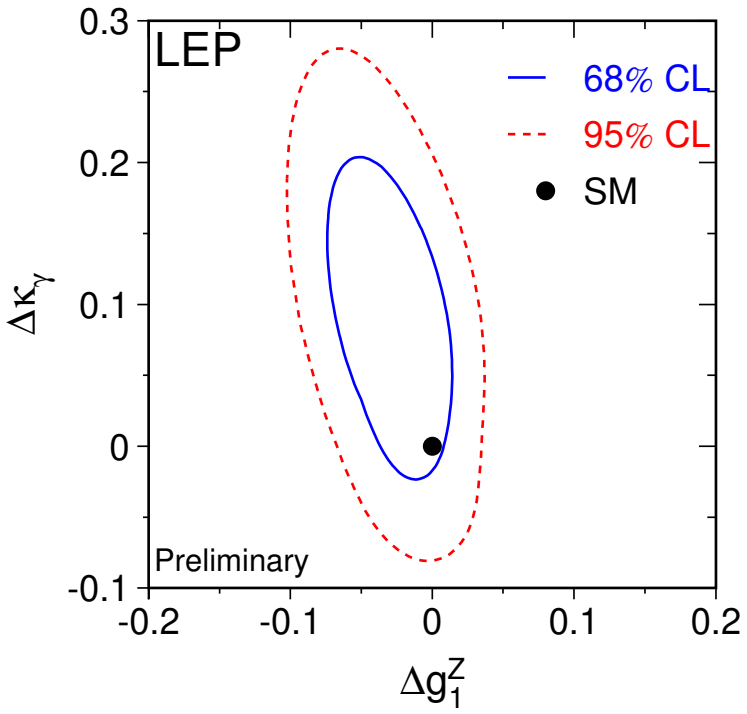
$\kappa_\gamma = 1.02 \pm 0.06$

$g_1^Z = 0.976 \pm 0.024$

$\lambda_\gamma = -0.016 \pm 0.026$

(LEP combined)

Two-parameter fits



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

f (W_L in $e^+e^- \to W^+W^-$) = 26.1 ± 5.1 ± 1.6 % **L3** 183/9 GeV

SM: 26%

Evidence for W_L production now at 5σ level

First unambiguous observation of longitudinally polarized W's

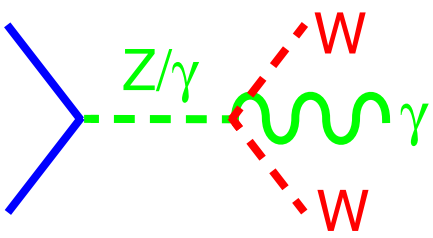
Quartic Gauge Couplings

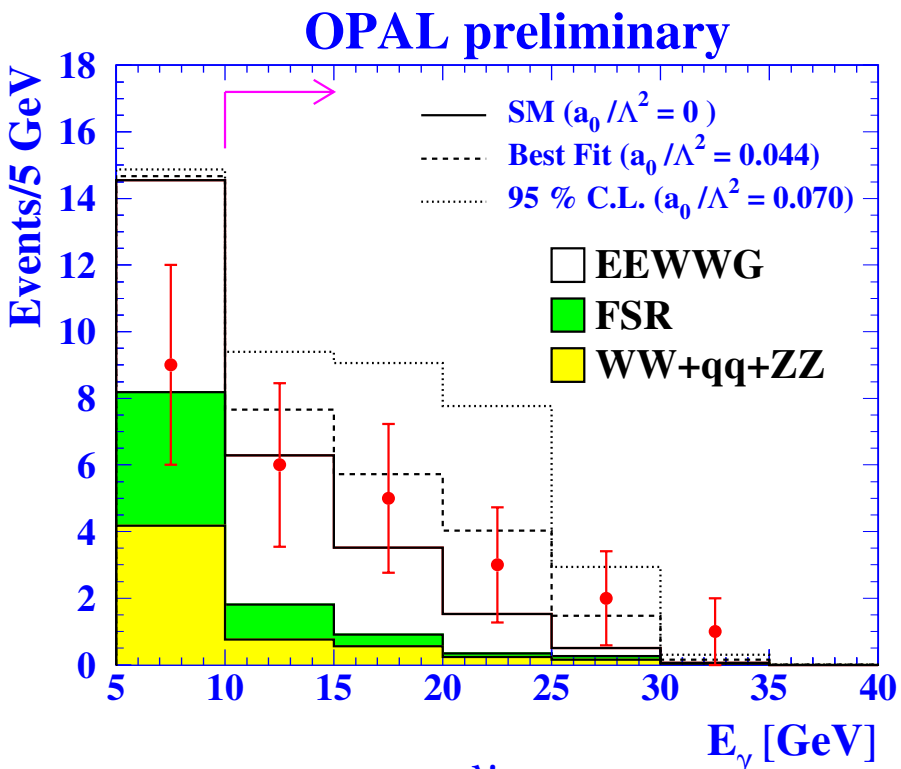
First direct constraints on WWγγ, WWZγ (OPAL)

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

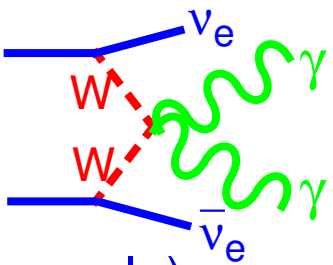
Anomalous QGCs a_0, a_c and a_n studied

With WWγ events:





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



Obtain at 95% CL (Λ new physics scale)

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

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

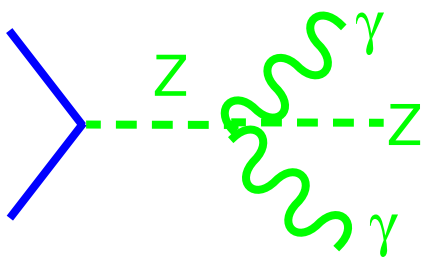
$-0.61\ \text{GeV}^{-2} < a_n/\Lambda^2 < 0.57\ \text{GeV}^{-2}$

Quartic Gauge Couplings ZZγγ

New analysis from **L3**

In the SM, ZZγγ coupling is zero

Analyse Zγγ final state (hadronic Z decays)

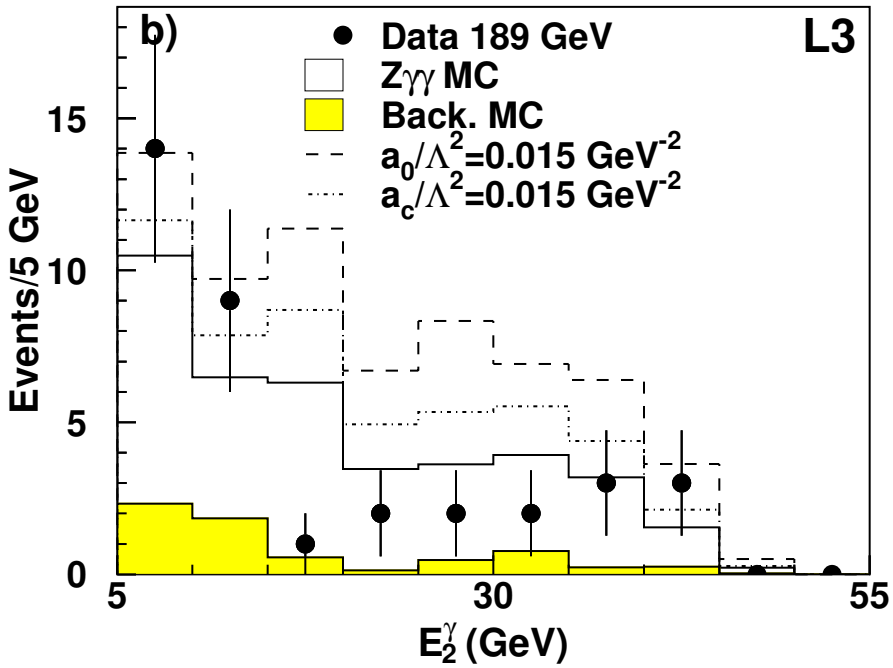


Signal region:

$E_\gamma > 5$ GeV

$|\cos\theta_\gamma| < 0.97$

$M_{q\bar{q}}$ within $2\Gamma_Z$ of M_Z

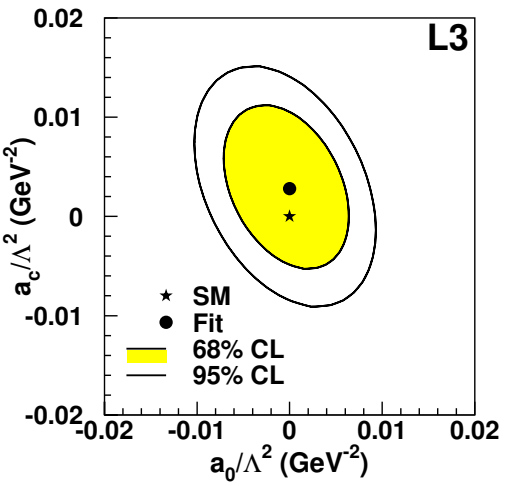


Obtain at 95% CL (Λ new physics scale)

-0.009 GeV$^{-2} < a_0/\Lambda^2 < 0.008$ GeV^{-2}

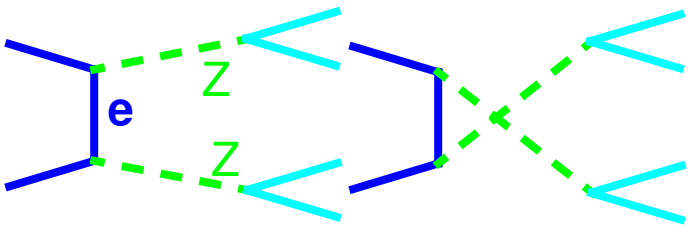
-0.007 GeV$^{-2} < a_c/\Lambda^2 < 0.013$ GeV^{-2}

(**L3**)

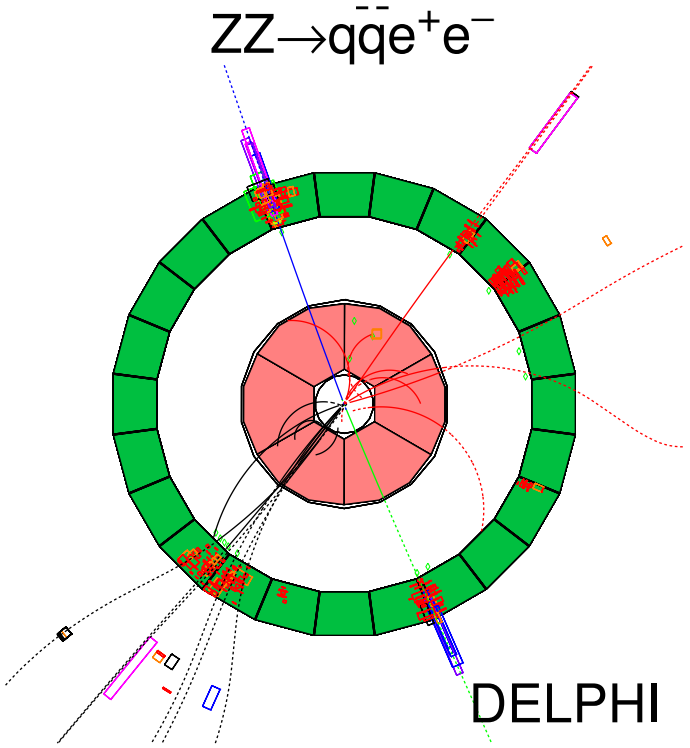


ZZ Production

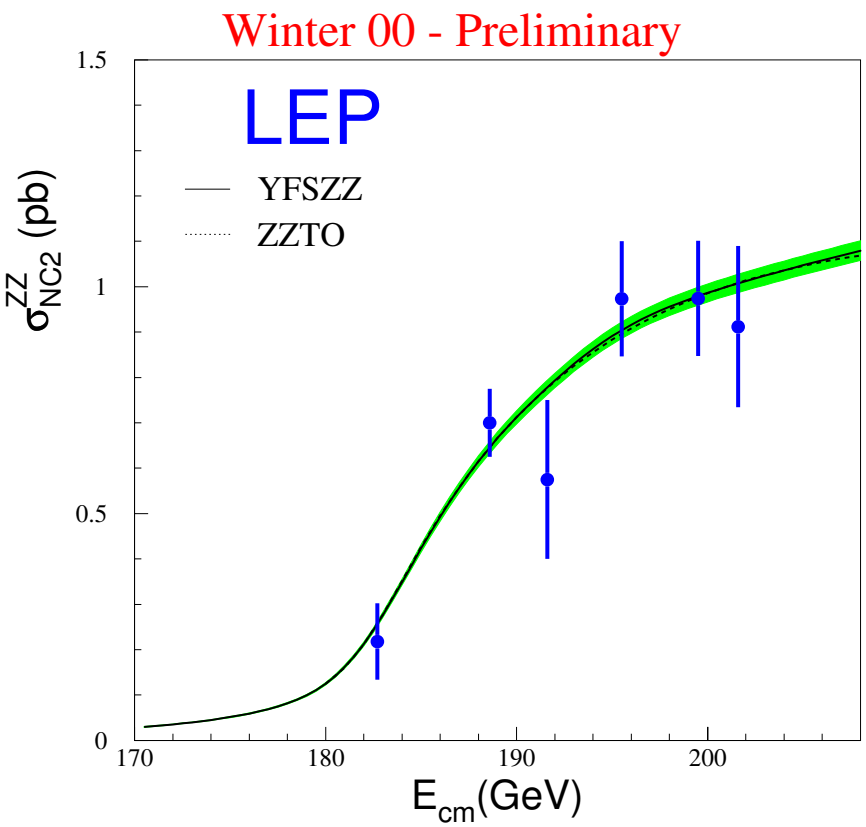
ZZ production in SM



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



Cross-section vs. √s **(ADLO)**



Background to possible ZH production...?

Summary and Outlook

LEP2 is working superbly at high energy
design energy, luminosity **have been** passed

Wealth of electroweak processes measured
SM describes all with flying colours
...so far

LEP2 W mass measurement

$M_W = 80.401 \pm 0.048$ GeV (Preliminary)

now dominates world average
Scope for a final error close to 30 MeV

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

WWZ and WWγ couplings measured at few percent level

Year 2000 high-energy running starts this week:
the highest LEP energies are still to come!