Four fermion production and limits on anomalous couplings at LEP-2

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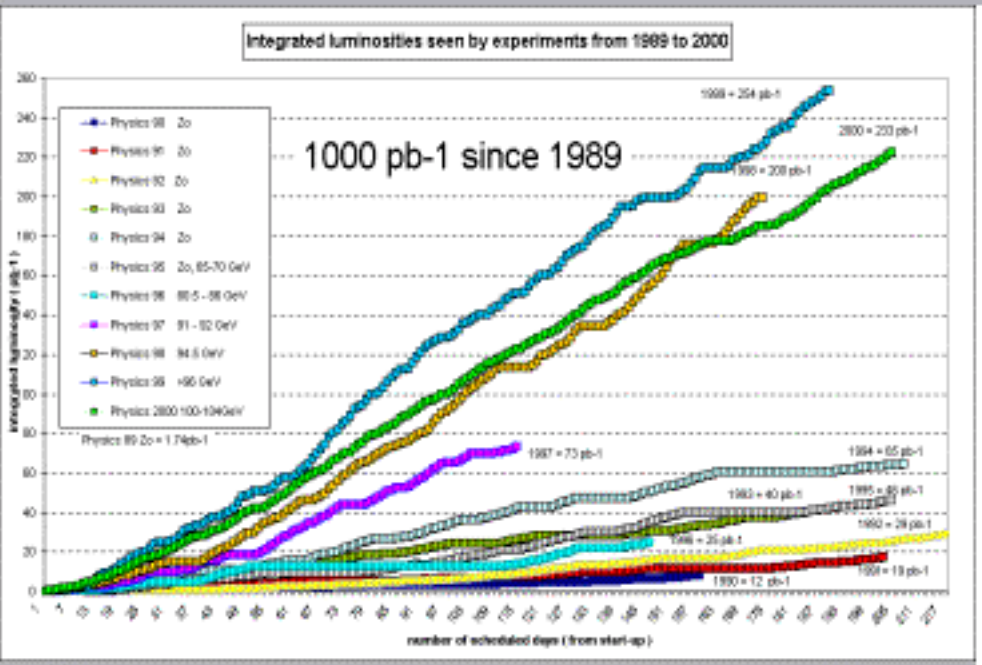
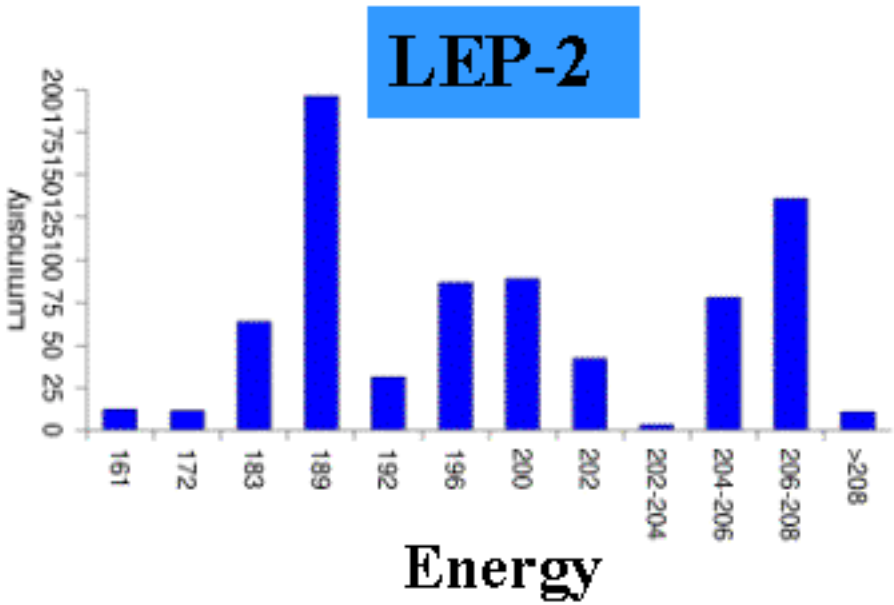
Les Rencontres de Physique de la Vallée d'Aoste
la Thuile, Italy, March 9-15, 2003

on behalf of the LEP collaborations and the EW Working Group

Special thanks to : R. Chierici, U. Parzefall, R. Sekulin

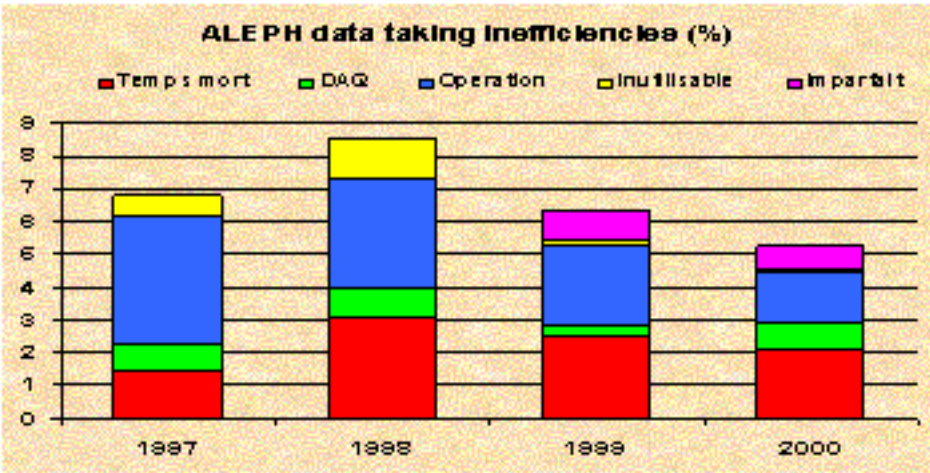
Accelerator and detector performances : excellent !





LEP-2 ~ 700 pb-1

(per experiment)



Outline

1. Four fermion production :

WW - ZZ/γ* - eeZ/γ* - eνW

2. Gauge boson self couplings :

Charged and neutral - Triple and quartic

→ *combined results*

Four fermion processes at LEP-2

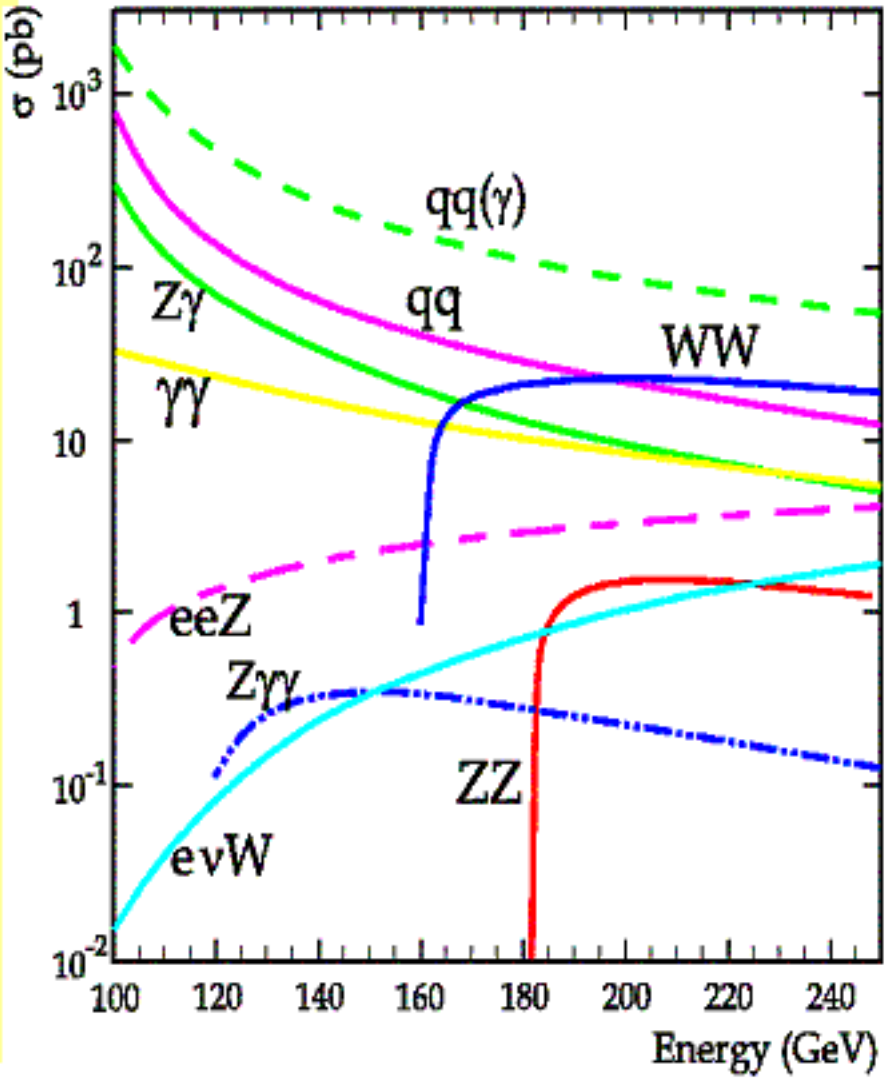
WW

ZZ

eeZ

eνW

~ picobarn



MOTIVATIONS:

Check SM :

- non Abelian structure (**WW**)
- precision calculations (radiation, choice of scale)

Search beyond SM :

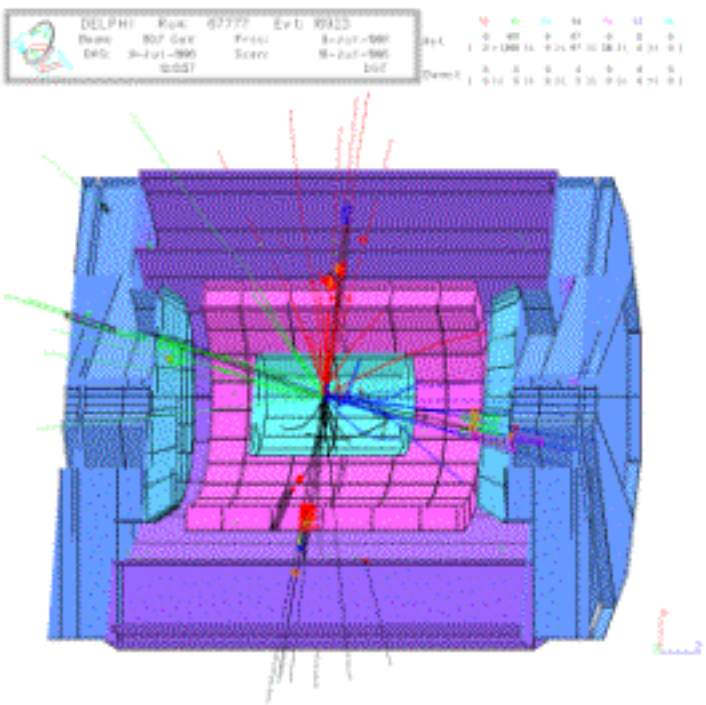
- Anomalous gauge couplings
- Backgrounds for new particle searches (**ZZ**...)

→ ***Linear Collider...***

WW production : analysis

First LEP candidate at 161 GeV

$e^+e^- \rightarrow WW \rightarrow$ four jets



DELPHI, July 9, 1996

1996 - 2000 $\rightarrow$ total $\sim 4 \times 10000$ events

topologies
- qqqq (1) 45.6 %
- qqlν (3) 43.8 %
- lνlν (6) 10.6 %

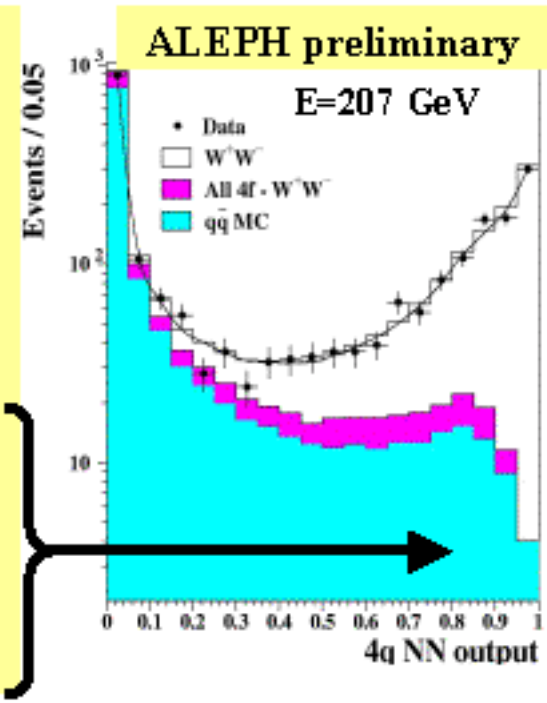
Four jets :

Main correlated error :

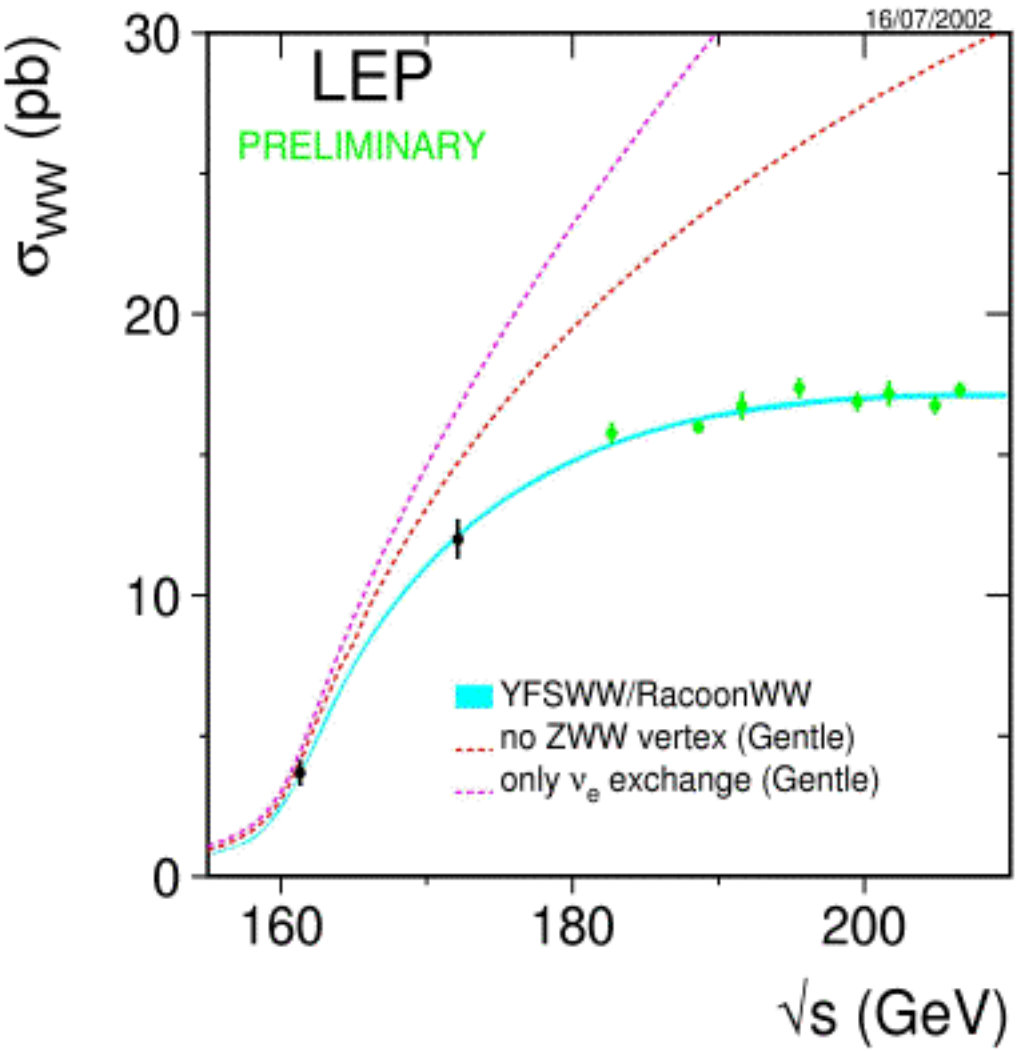
QCD fragmentation and hadronization models

- ***mass resolution***
- ***background***

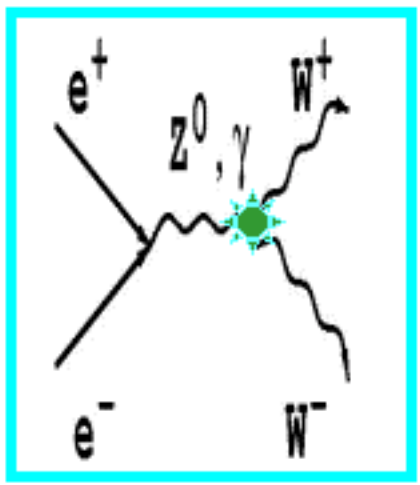
qqgg

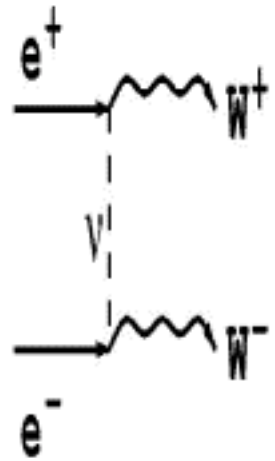


WW production : combined results (1)



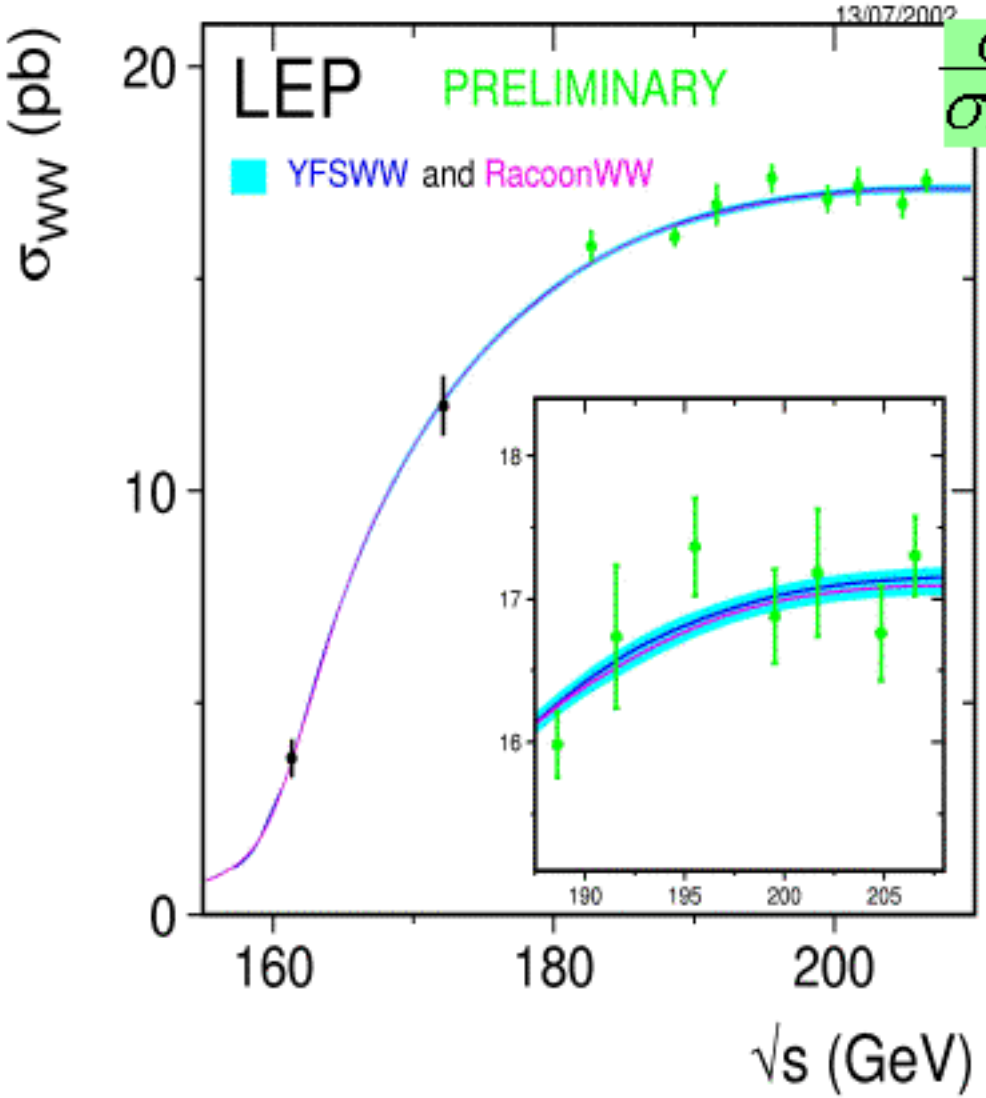
Clear evidence of SU(2) × U(1) gauge structure



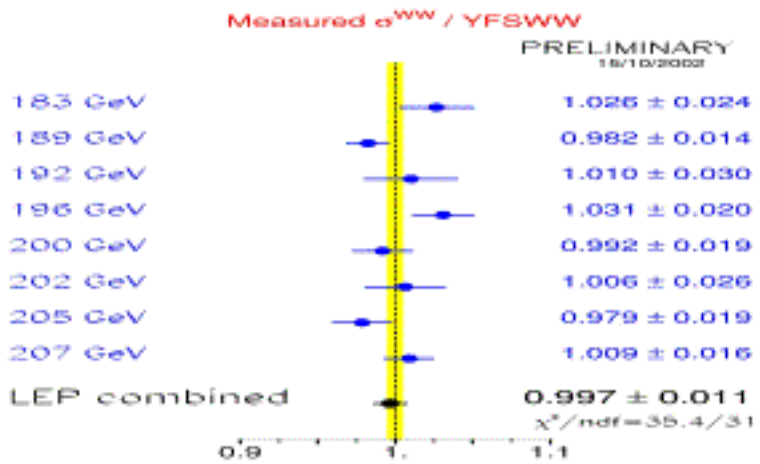


CC03 graphs

WW production : combined results (2)



$$\frac{\sigma_{WW}}{\sigma_{YFSWW}} = 0.997 \pm 0.007(\text{stat}) \pm 0.009(\text{syst})$$



Accurate predictions :

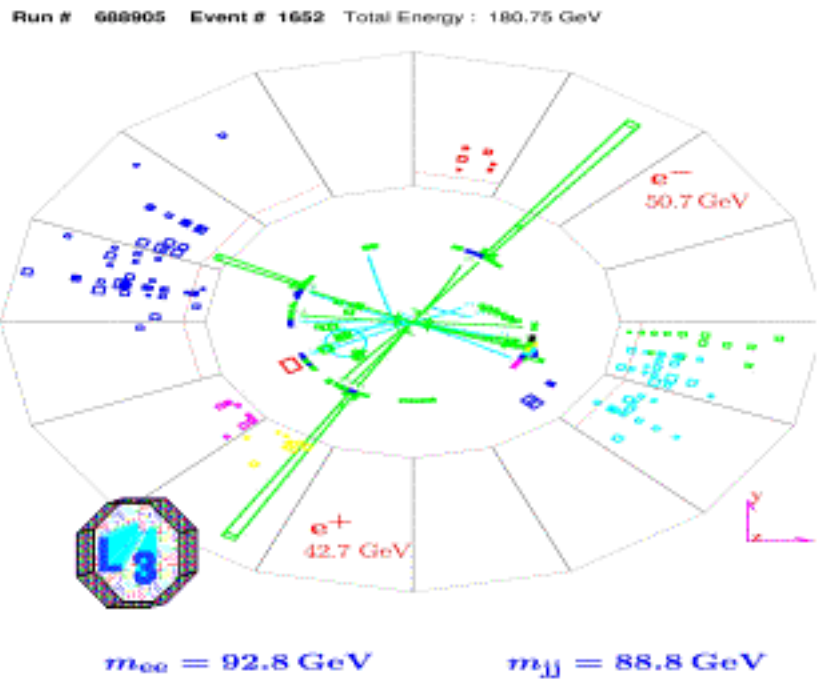
YFSWW and RacoonWW

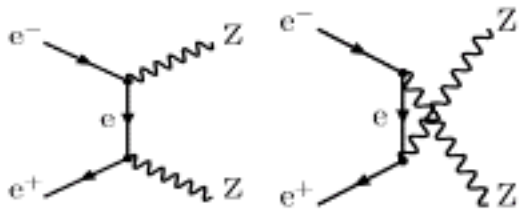
- **Full non leading, non factorizable O(α) EW radiative corrections : LPA / DPA**
- **Precision ~ 0.5%**
- **NEEDED ! old calculations ~ 2% too high**

ZZ production : analysis (1)

Best L3 candidate at 183 GeV

$e^+e^- \rightarrow ZZ \rightarrow qqee$



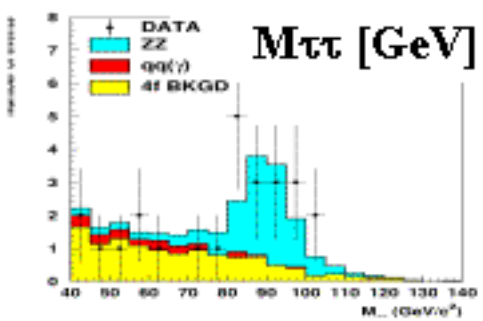


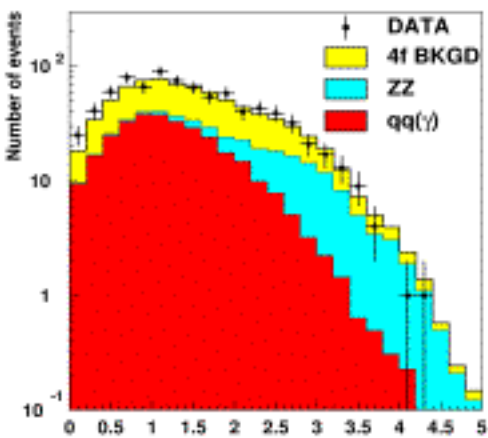
NC02 graphs

qqqq	(1)	49.0 %
qqυυ	(1)	28.0 %
qqll	(3)	14.0 %
llll	(6)	1.0 %
llυυ	(3)	4.0 %

DELPHI : CERN-EP/2003-009

$ZZ \rightarrow qq\tau\tau$ **$ZZ \rightarrow qq\upsilon\upsilon$**





1. Small cross sections → refined selection methods
2. Similar to SM Higgs search → useful benchmark

ZZ production : analysis (2)

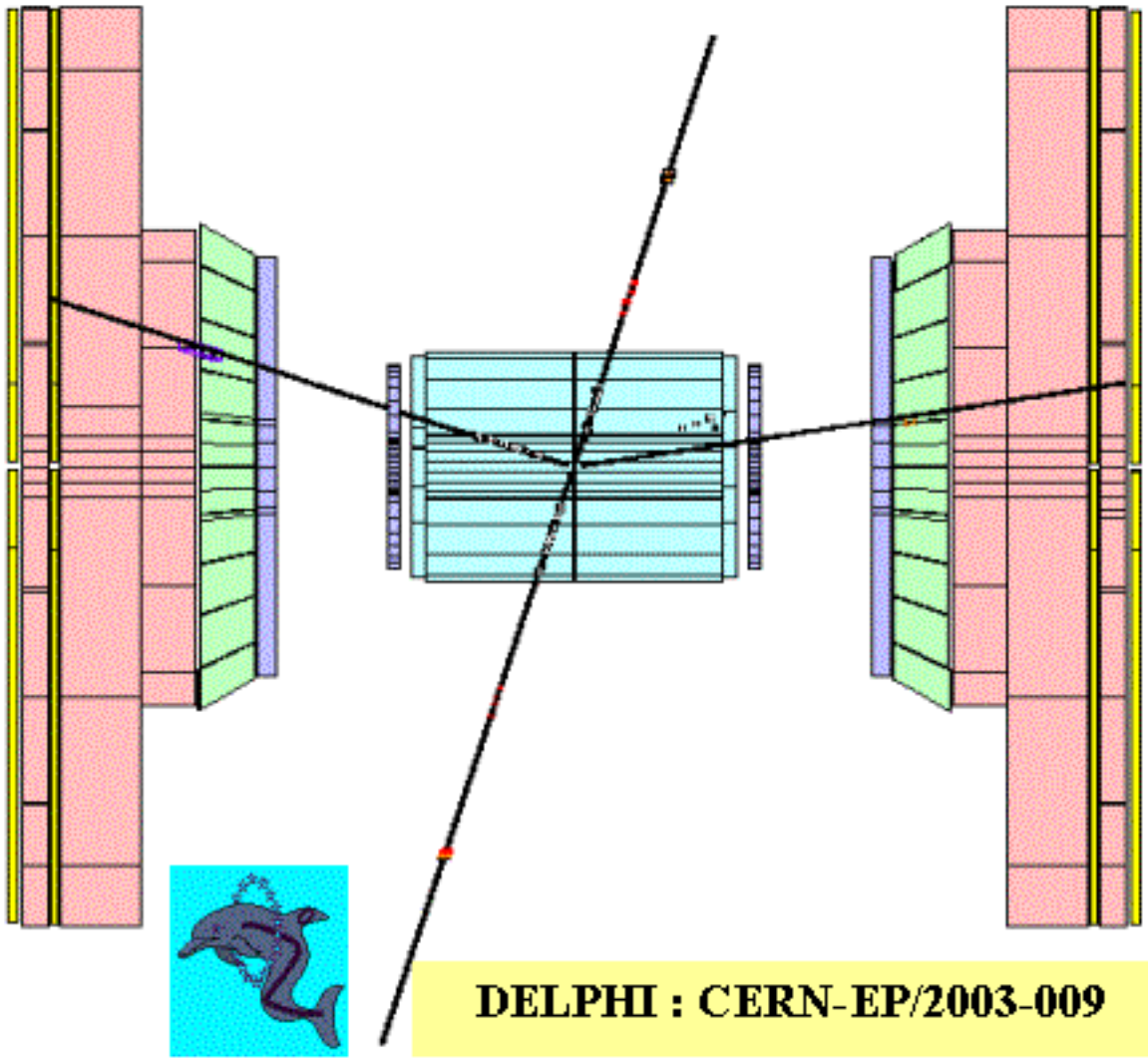
$ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$

Ecms = 199.5 GeV

M_{5C} = 90.8 GeV

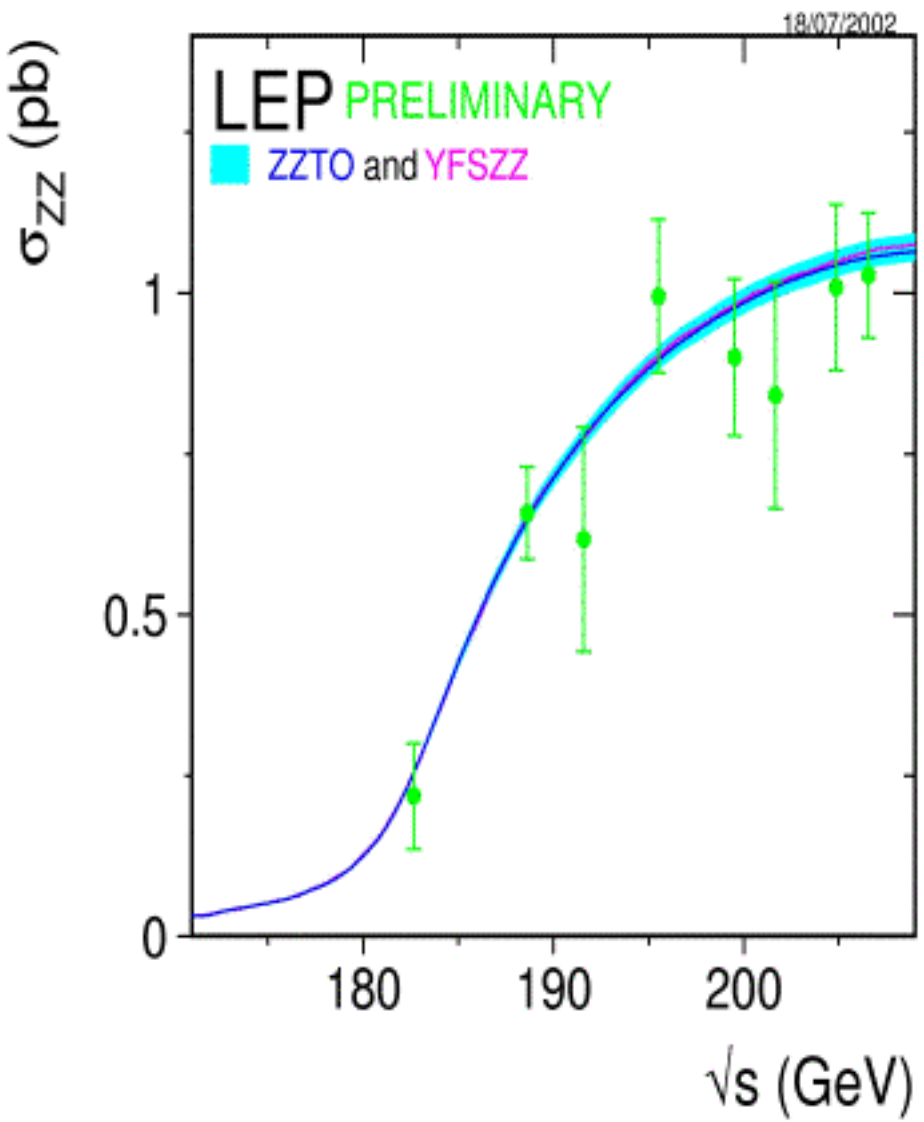
cross section ~ 1 fb

expect ~ 3 in full LEP data set

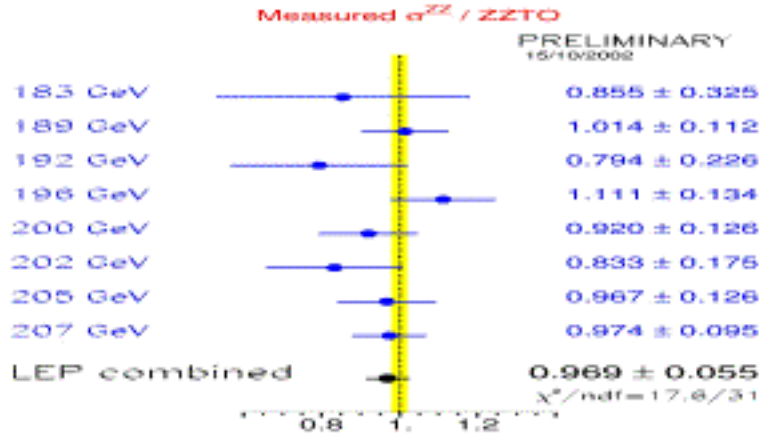


DELPHI : CERN-EP/2003-009

ZZ production : combined results



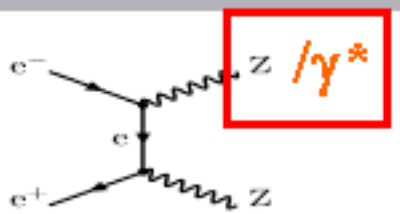
$$\frac{\sigma_{ZZ}}{\sigma_{ZZTO}} = 0.969 \pm 0.047(\text{stat}) \pm 0.028(\text{syst})$$



- **Statistics limited**
- **Accuracy of prediction ~ 2.0 %**
  (*sufficient*)
- **Main correlated systematics :**
  background modeling

Zγ* production : analysis

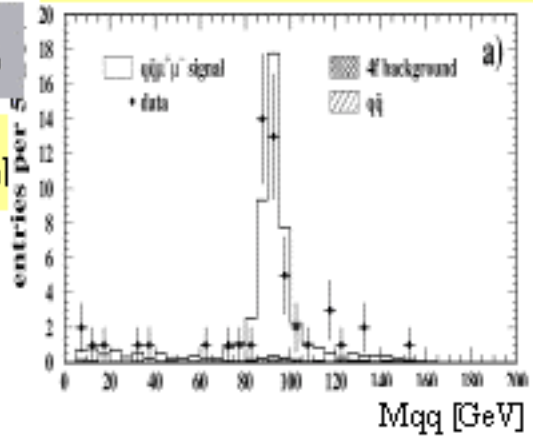
DELPHI analyses :
qqμμ, qqee
qqυυ (monojet), llll
qqqq (low mass)

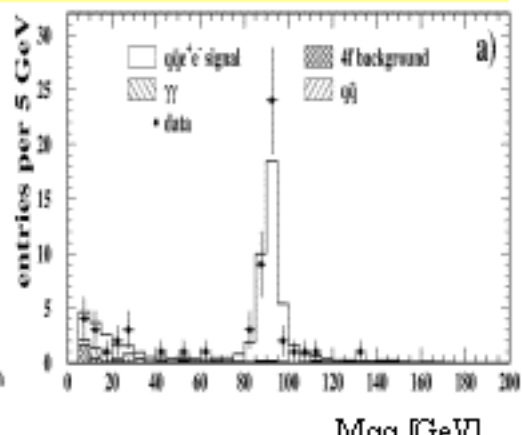


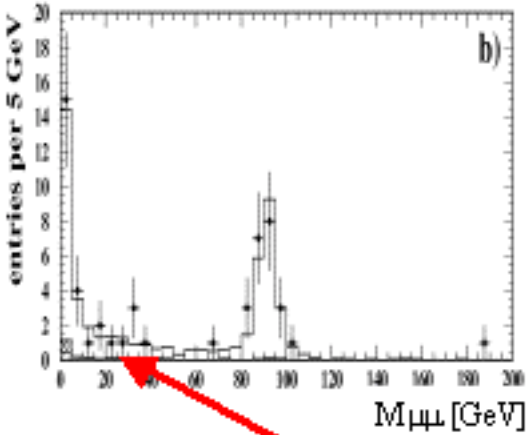
NC08 graphs

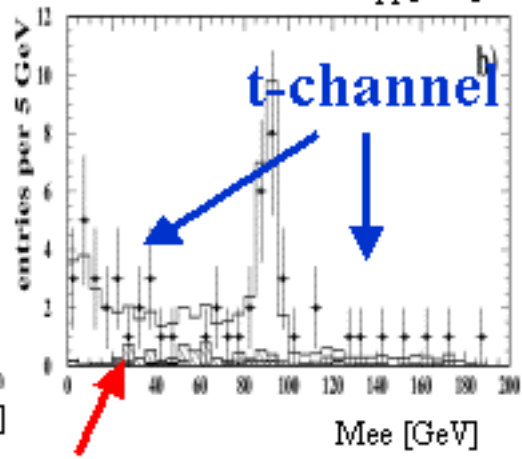
OPAL : Phys. Lett. B544 (2002) 259

$Z(Z/\gamma^*) \rightarrow qq\mu\mu$ $Z(Z/\gamma^*) \rightarrow qqee$

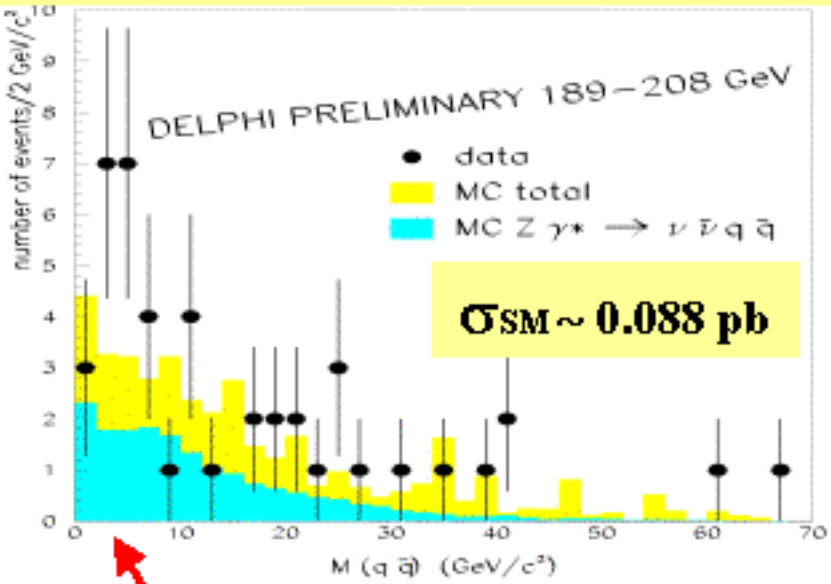








$\sigma_{monojet} = 0.129 \pm 0.035\ (stat) \pm 0.015\ (syst)$ pb



$\sigma_{SM} \sim 0.088$ pb

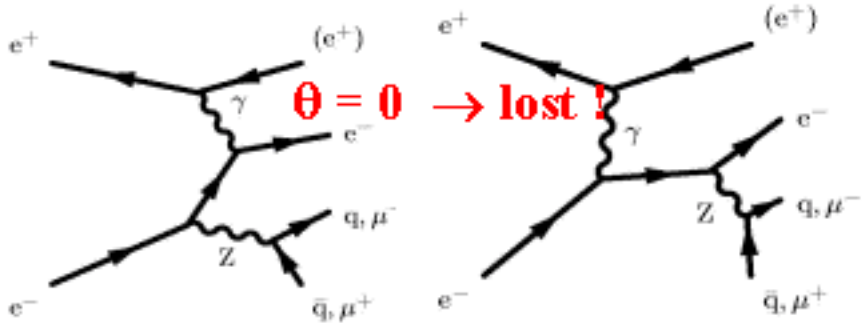
hadronization

scale for α_{em}

eeZ/γ* production : analysis

(e)eqq

(e)eμμ



Signal definition (all graphs)

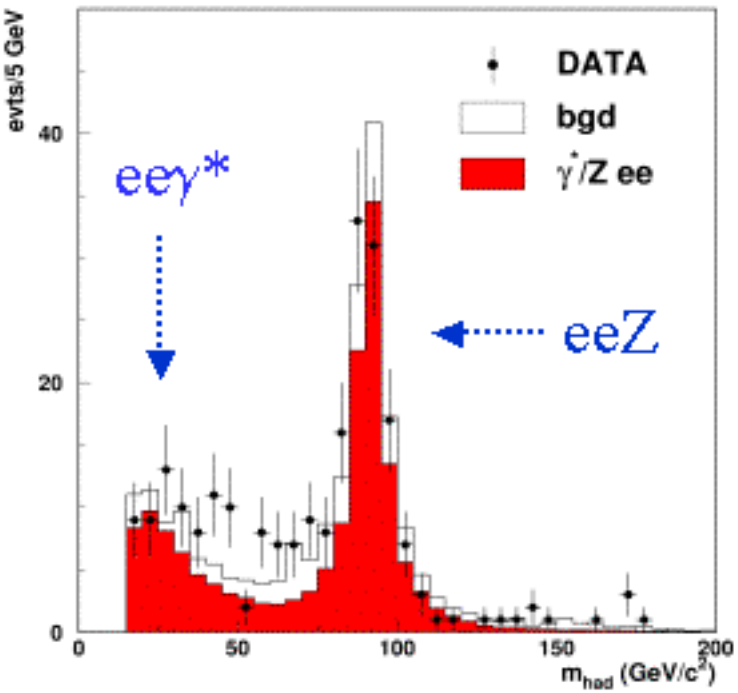
Mff > 60 GeV

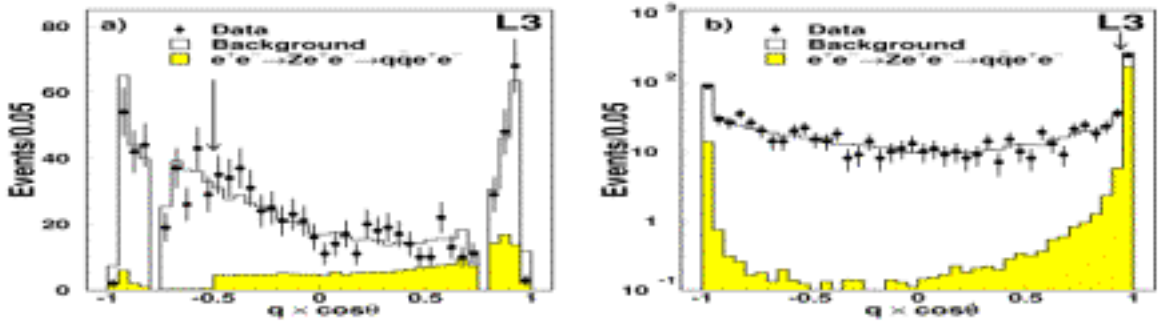
12 > θe− > 120 degrees (*visible*)

θe+ < 12 degrees (*lost*)

Ee - > 3 GeV (also e - ↔ e+)

DELPHI preliminary





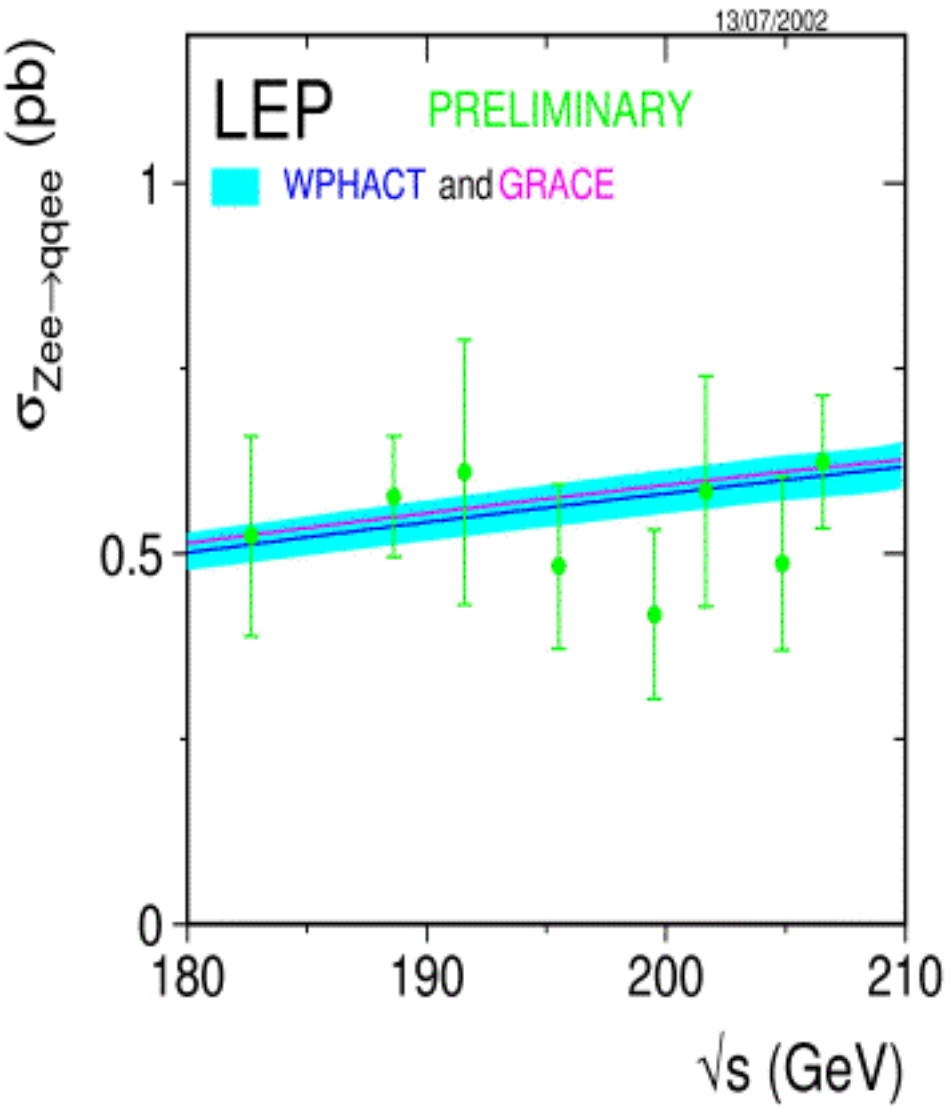
L3 : CERN-EP/2002-103

Issues in calculation :

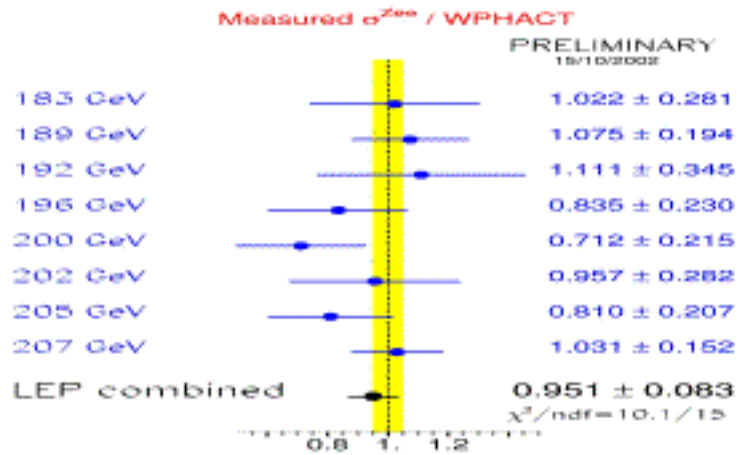
Collinear singularity → masses in calc.

Scale for α_{em} and for QED radiation

eeZ/γ* production : combined results (ADL)



$$\frac{\sigma_{eeZ}}{\sigma_{WPHACT}} = 0.951 \pm 0.068(stat) \pm 0.048(syst)$$



- **Statistics limited**
- **Accuracy of prediction ~ 5.0 %**
  (*just matches*…)
- **Main correlated systematics :**
  detector + background models

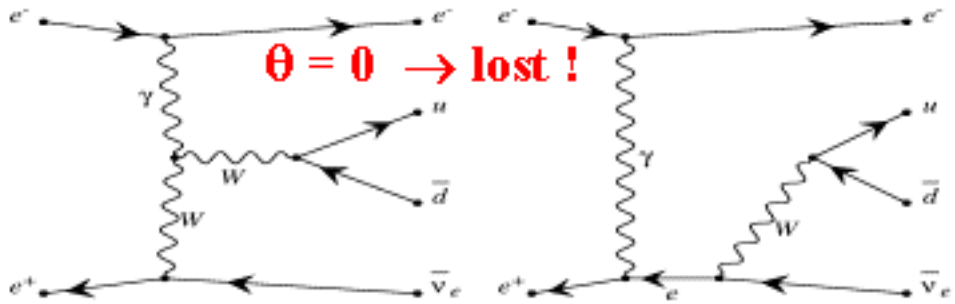
eυW production : analysis

(e)υqq

(e)υμυ

(e)υτυ

(e)υeυ



ALSO : s-channel and multiperipheral graphs

Signal definition

(t-channel → gauge inv.)

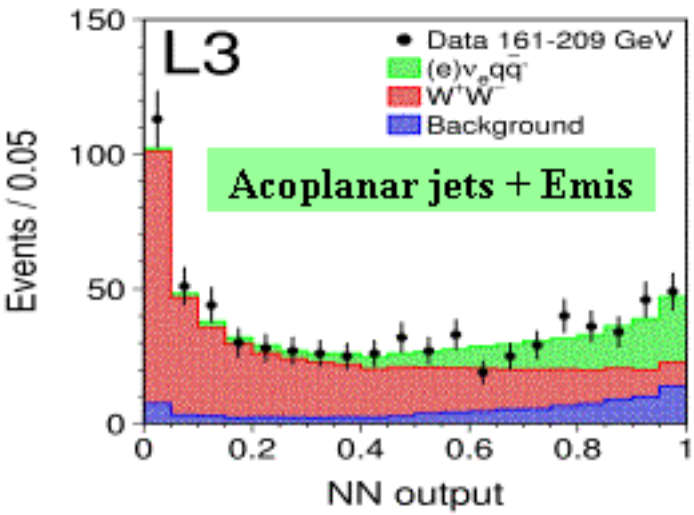
M_{qq} > 45 GeV (qq)

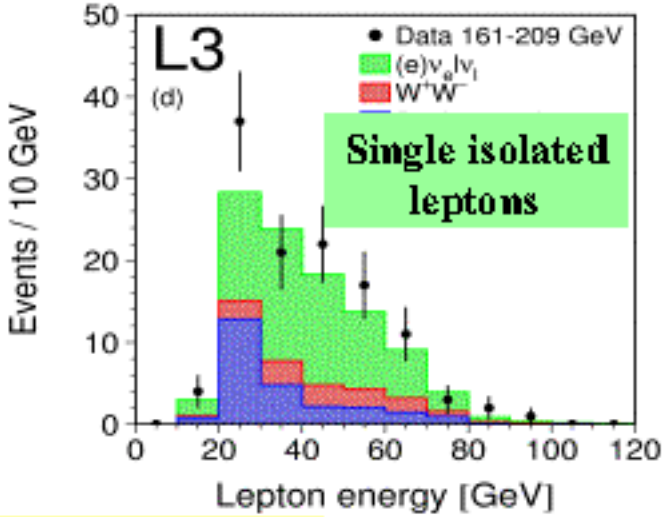
$E_{\mu,\tau}$ > 20 GeV (μ, τ)

|cos(θ e−)| > 0.95 (e)

|cos(θ e+)| < 0.95

E e+ > 20 GeV





L3 : CERN-EP/2002-064

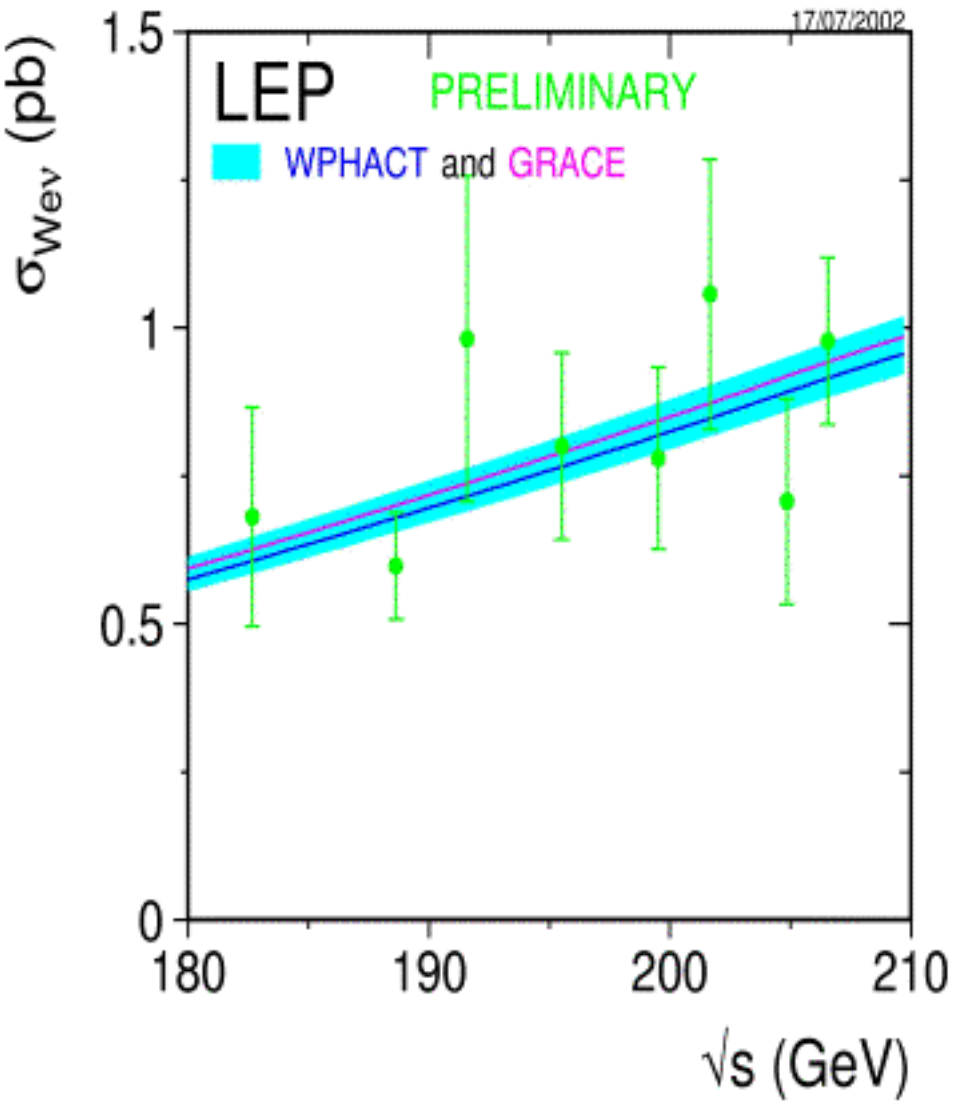
***Issues in calculation* :**

(as for eeZ/γ*)

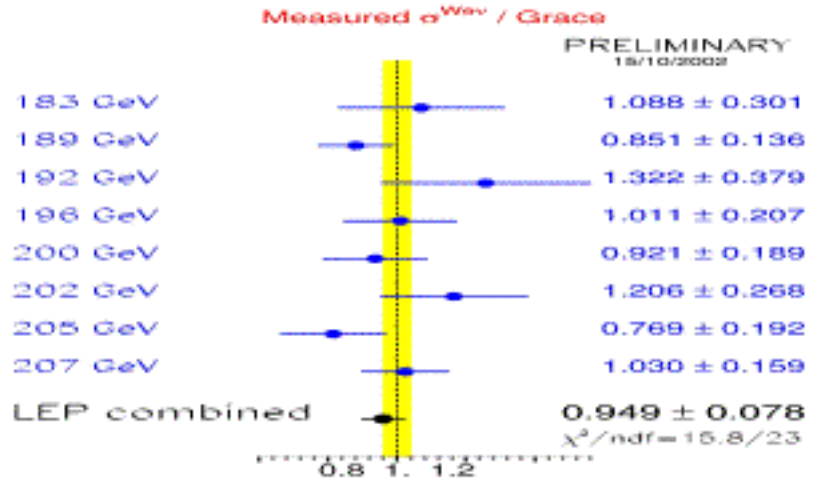
Collinear singularity → masses in calc.

Scale for α_{em} and for QED radiation

eνW production : combined results



$$\frac{\sigma_{e\nu W}}{\sigma_{GRACE}} = 0.949 \pm 0.067(stat) \pm 0.040(syst)$$



- **Statistics limited**
- **Accuracy of prediction ~ 5.0 %**
  (*just matches…*)
- **Main correlated systematics :**
  detector + background model

Four fermion production - Summary

	EXPERIMENTAL RESULTS	THEORY
★	$\sigma_{WW}/\sigma_{YFSWW} = 0.997 \pm 0.007\ (stat) \pm 0.009\ (syst)$	~ 0.005
	• Confirms SU(2) × U(1) gauge structure	
	• Probes SM calculation at loop level	
★	$\sigma_{ZZ}/\sigma_{ZZTO} = 0.969 \pm 0.047\ (stat) \pm 0.028\ (syst)$	~ 0.02
	• Experimental cross-check for Higgs search	
★	$\sigma_{eeZ}/\sigma_{WPHACT} = 0.951 \pm 0.068\ (stat) \pm 0.048\ (syst)$	~ 0.05
★	$\sigma_{e\upsilon W}/\sigma_{GRACE} = 0.949 \pm 0.067\ (stat) \pm 0.040\ (syst)$	~ 0.05
	• Tests predictions in several unexplored regions	

★ also : $d\sigma/d\cos\theta_W$, BR_W, $Z\gamma^*$, $WW\gamma$, $Z\gamma\gamma$ results ⇒ LEP combination

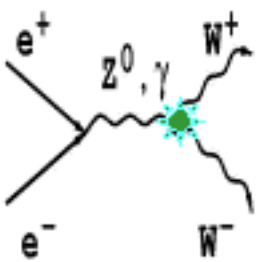
Successful program - Solid basis for new physics searches

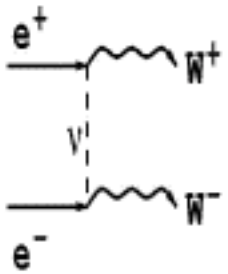
Charged triple gauge couplings : analysis

- VWW vertex (V=Z,γ) : general Lorentz invariant Lagrangian → 14 parameters
- Models with symmetries as in SM : C and P, $U(1)_{em}$, $SU(2)_L \times U(1)_Y$

→ 3 independent couplings : g^1_Z (=1) , κ_γ (=1) , λ_γ (=0)

related to W weak charge, magnetic dipole and electric quadrupole moments



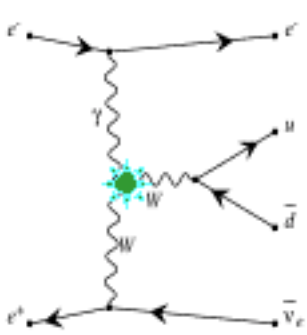


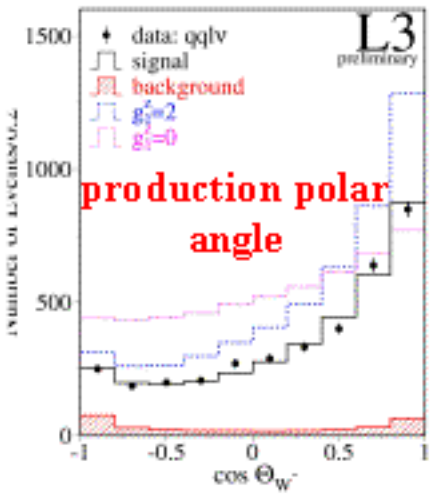
Effects from deviations in the couplings :
Total cross sections - Boson production polar angles - Polar and azimuthal decay angles – Aver. polarisation

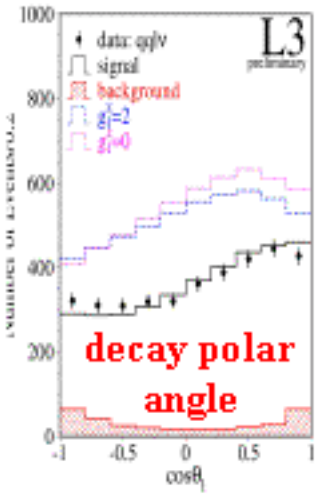
WW: g^1_Z λ_γ (κ_γ)

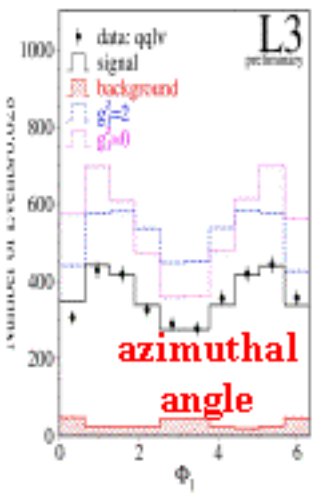
Wεν: κ_γ (λ_γ)

γνν via WW fusion (less sensitive)



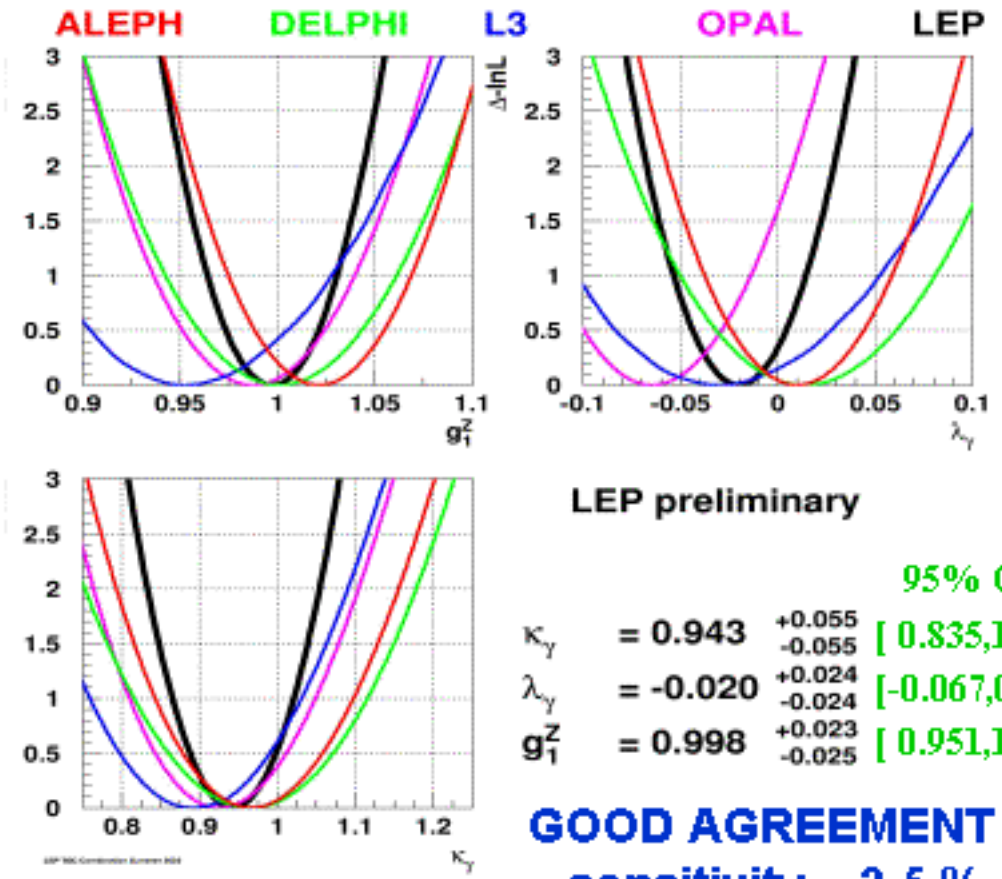






Charged triple gauge couplings : combined results

(single-parameter analysis)



95% C.L.

κ_γ = 0.943 $^{+0.055}_{-0.055}$ [0.835,1.052]

λ_γ = -0.020 $^{+0.024}_{-0.024}$ [-0.067,0.028]

g_1^Z = 0.998 $^{+0.023}_{-0.025}$ [0.951,1.043]

GOOD AGREEMENT !

sensitivity ~ 2-5 %

- **Combine likelihood func. from each experiment**
- **Careful treatment of correlated systematic errors**

Systematic effects (*correlated*) :

Source	g_1^Z	λ_γ	κ_γ
$O(\alpha_{em})$ correction	0.015	0.015	0.039
σ_{WW} prediction	0.003	0.005	0.014
Hadronisation	0.004	0.002	0.004
Bose-Einstein Correlation	0.005	0.004	0.009
Colour Reconnection	0.005	0.004	0.010
$\sigma_{singleW}$ prediction	-	-	0.011

O(α) EW corrections { **total rates** **angles**

largest error : reduce factor 3 ?

without O(α) EW corrections

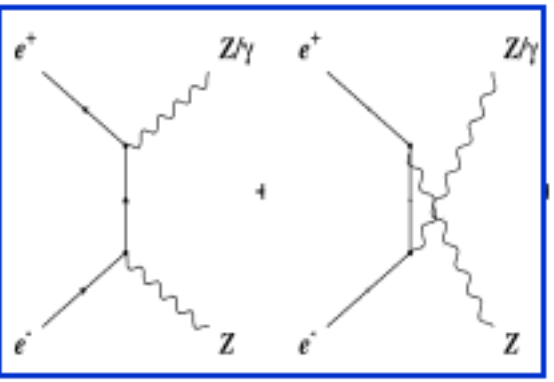
$\kappa_\gamma \approx 0.982$ $\lambda_\gamma \approx -0.005$ $g^1_Z \approx 1.013$

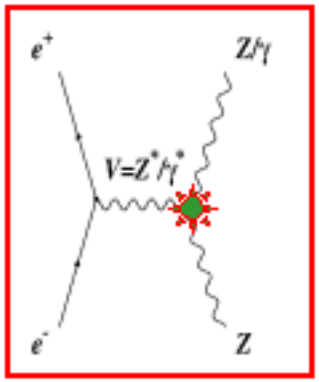
(also good agreement)

Neutral triple gauge couplings : analysis

- **SM → no tree level couplings between neutral gauge bosons**
- **Lorentz and U(1)em invariance + Bose symmetry for id. bosons → 12 couplings**

  CP-conserving : $h_{3,4}^{Z/\gamma}$ $f_5^{Z/\gamma}$ **CP violating :** $h_{1,2}^{Z/\gamma}$ $f_4^{Z/\gamma}$
- **SU(2)L × U(1)Y symmetry links Zγ + ZZ terms (*for some operators*) → fewer couplings**
- **New parameterizations allow bosons to be off-shell**





Standard Model

Zγ (radiative return)

ZZ (on-shell)

Zγ*(off-shell)

Anomalous

$h_{1,2,3,4}^{Z/\gamma}$

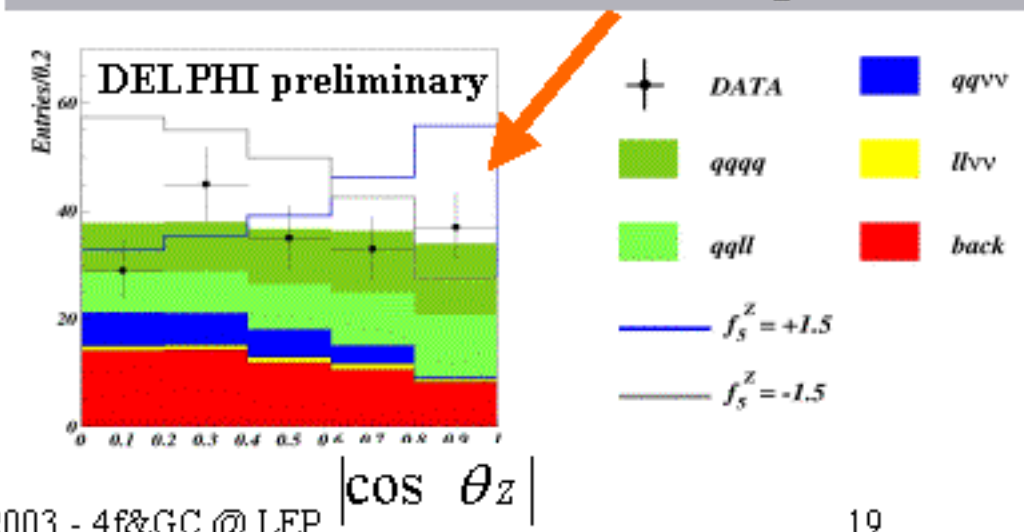
$f_{4,5}^{Z/\gamma}$

$l_i^3\ V\ \tilde{l}_i^3\ V$

Effects from deviations :

Zγ : photon energy - production angle - angle/jet

ZZ : Total cross section - Z Polar angle - Polar.



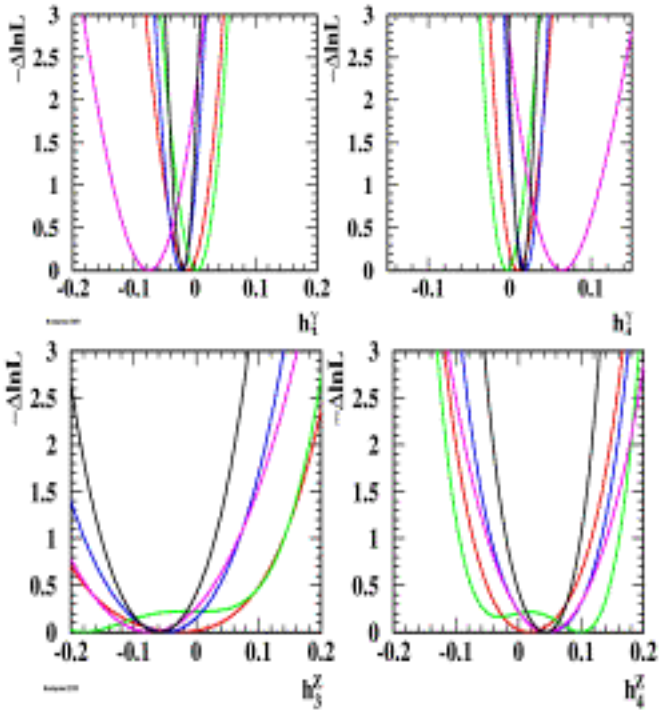
Neutral triple gauge couplings : combined results

(Zγ single-parameter analysis)

Parameter	95% C.L.
h_1^γ	$[-0.056, +0.055]$
h_2^γ	$[-0.045, +0.025]$
h_3^γ	$[-0.049, -0.008]$
h_4^γ	$[-0.002, +0.034]$
h_1^Z	$[-0.13, +0.13]$
h_2^Z	$[-0.078, +0.071]$
h_3^Z	$[-0.20, +0.07]$
h_4^Z	$[-0.05, +0.12]$

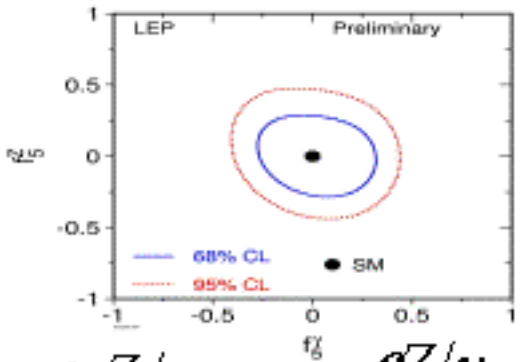
Preliminary

LEP ALEPH+DELPHI+ L3+OPAL



(ZZ two-parameter analysis)

Parameter	95% C.L.
f_4^γ	$[-0.17, +0.19]$
f_4^Z	$[-0.30, +0.28]$
f_5^γ	$[-0.34, +0.38]$
f_5^Z	$[-0.36, +0.38]$

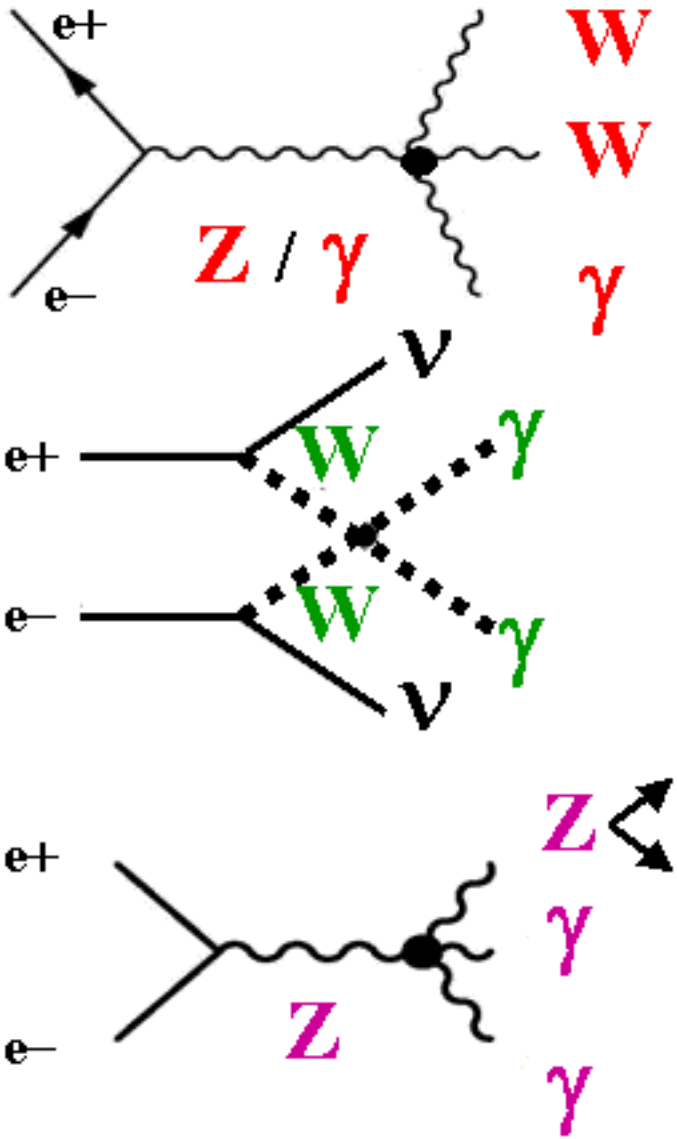


Zγ and ZZ : CP-conserving terms $h_{3,4}^{Z/\gamma}$ **and** $f_5^{Z/\gamma}$

- **Separate Zγ and ZZ treatments - Future : also $SU(2)_L \times U(1)_Y$ constraints**
- **Statistics dominated - Only correlated error from cross sections ~ 1 - 2%**

NO DEVIATIONS ! Sensitivity ~ 0.05 – 0.30 ***(not as good as charged couplings)***

Quartic gauge couplings : analysis



- **Tree level quartic couplings in SM very small**
- **New physics in scalar sector may yield anomalous quartic contributions without affecting triple gauge couplings – *Lagrangians* :**

$$\mathcal{L}_0 = -\frac{e^2}{16}\frac{a_0^{W,Z}}{\Lambda^2} F^{\mu\nu}F_{\mu\nu}\vec{W}^{\alpha}\vec{W}_{\alpha} \qquad WW\gamma\gamma, ZZ\gamma\gamma$$

$$\mathcal{L}_c = -\frac{e^2}{16}\frac{a_c^{W,Z}}{\Lambda^2} F^{\mu\alpha}F_{\mu\beta}\vec{W}^{\beta}\vec{W}_{\alpha} \qquad WW\gamma\gamma, ZZ\gamma\gamma$$

$$\mathcal{L}_n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2}\vec{W}_{\mu\alpha}\cdot(\vec{W}_{\nu}\times\vec{W}^{\alpha})F^{\mu\nu} \qquad WWZ\gamma \text{ (CP-odd)}$$

Λ = new physics scale

Effects from deviations :

- **WWγ rate + γ spectrum :** $a_{0,c}^{W}, a_n$
- **Zγγ rate + 2nd γ spectrum :** $a_{0,c}^{Z}$
- **ννγγ (fusion) rate + recoil mass** $a_{0,c}^{W}$

Quartic gauge couplings : results

WWγ signal definition :

$|M_{ff'} - M_W| < 2\Gamma_W$

$|\cos\theta_{\gamma,f}| < 0.90$, $|\cos\theta_\gamma| < 0.95$

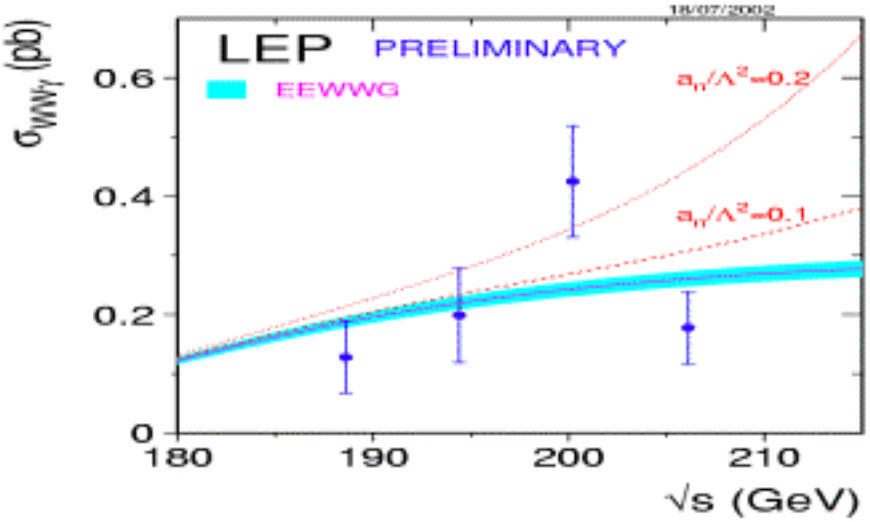
$E_\gamma > 5$ GeV

Rate combination for WWγ with

channels (D+L)	
WWγ → qqqqγ	
WWγ → qqνlγ	

L3 Phys.Lett. B527/1-2 (2000) 29

+ DELPHI 2002-059 (preliminary)



WWγ results from DELPHI, OPAL, L3 : (95%CL)

(single-parameter analyses)

$|a^W_{0,c}/\Lambda^2| \cdot \mathrm{GeV}^2 \lesssim$ 0.02-0.05

$|a_n/\Lambda^2| \cdot \mathrm{GeV}^2 \lesssim$ 0.14

Zγγ results from L3, OPAL - νννγγ results from OPAL → no anomalies

Prelim. LEP (L+O) comb. for : $|a^Z_{0,c}/\Lambda^2| \cdot \mathrm{GeV}^2 \lesssim$ 0.03 - 0.05

Gauge boson self couplings - Summary

★ **Charged couplings agree with SM within…** **~ 2 - 5 %**

- SM loops ~ 0.001 SUSY loops → a few 0.001
- Excludes new physics giving anom. contributions O(few %) → Z'… ?
- *Future* : Tevatron(10 fb-1) → λ_γ ~ 0.003
  LHC(100 fb-1) → λ_γ ~ 0.0003 κ_γ ~ 0.02
  TESLA(500 fb-1) → λ_γ, κ_γ, g^1_Z ~ 0.0005
- Main systematics : O(α) EW cor. ⇒ factor 3 reduction feasible

★ **Neutral couplings ~ zero, but errors….** **~ 0.05 – 0.30**

- Less precise & sensitive to new physics → < 0.0001
  (*operators of higher order*) - No unexpected effects

★ **Quartic couplings ~ zero within….** **~ 0.01 – 0.14**

- Expected "natural" size (*Belanger et al. hep-ph 9908254*) : a/Λ^2 ~ 10^{-7}
- First look at LEP-2 !

Conclusions

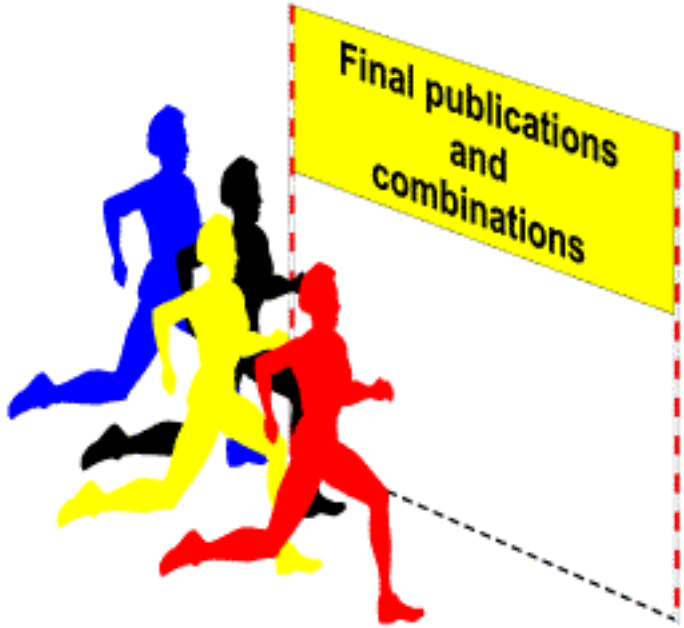
All final exp. results + LEP combinations expected summer 2003

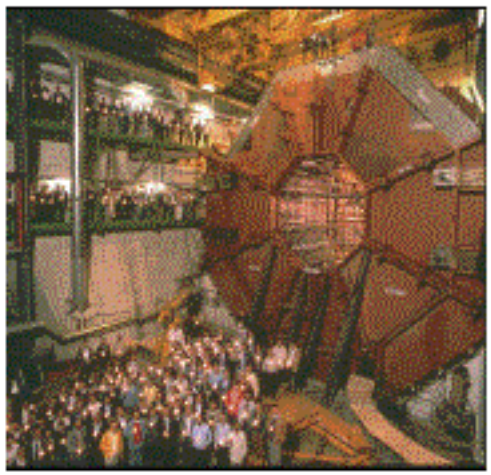
LEP W.G. → *CO-OPETION*

Final so far (*CERN-EP*)
- **DELPHI : ZZ**
- **L3 : eeZ, eυW, all quartic couplings**
- **OPAL : Zγ***

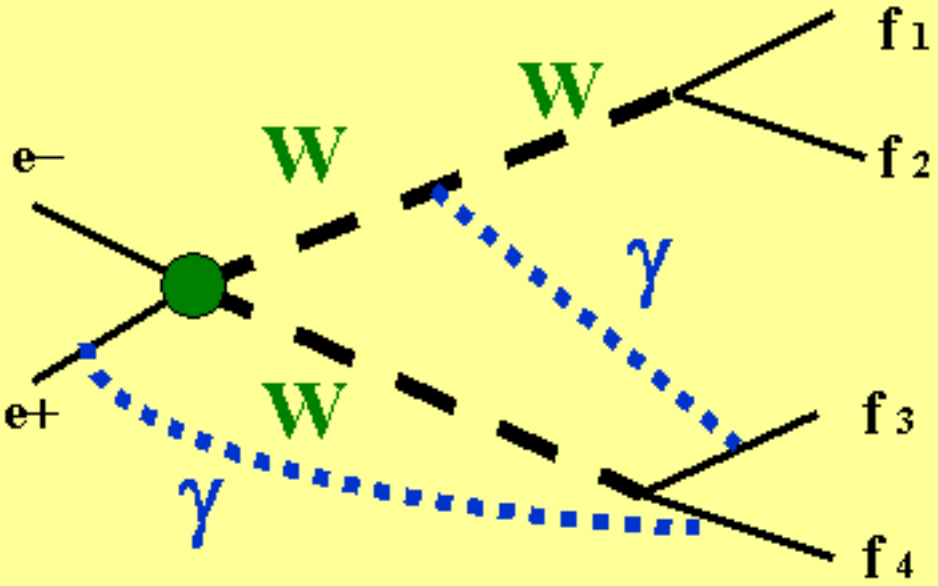
Measurements of 4 fermion production and gauge boson self couplings :

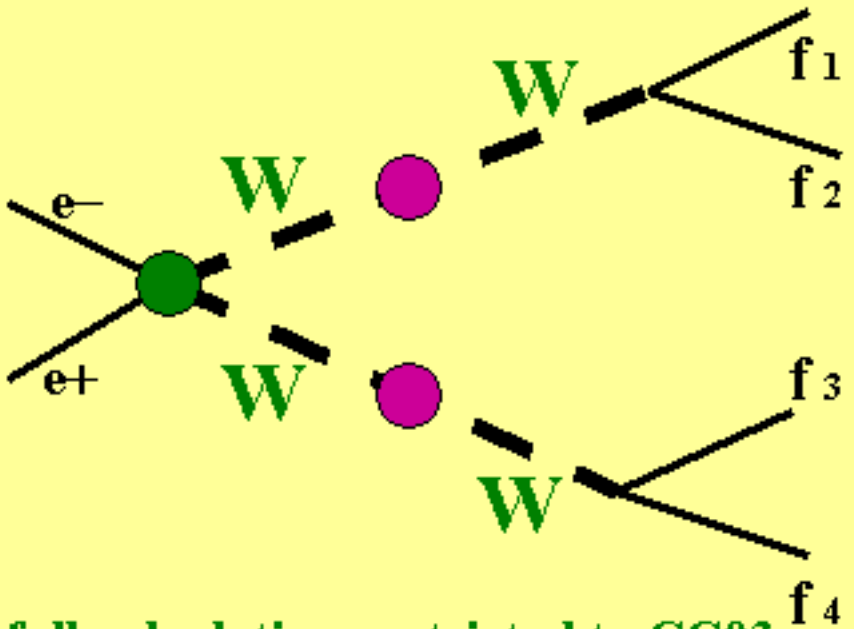
→ **important part of LEP legacy**





Add. 1 : O(α) corrections - Four fermion simulation





Non-leading non-factorizable contributions important at 1-2 % precision level

full calculation restricted to CC03 expansion about W-pole : LPA, DPA

RacoonWW: full virtual O(α) in DPA, exact real single γ correction,…

YFSWW: O(α) in LPA, multi γ corrections,…

Agreement : O(0.002)

Need full 4-f phase space for WW + other topics → include O(α) correction from YFSWW by reweighting matrix elements in "complete" generators :

1. Koralw (built on GRACE,…), 2. Wphact (match to generation of γγ process,…)

Add. 2 : Treatment of correlated errors in combinations

Four fermion cross section : χ min.

- 8×4 measured values
- 8×4 measured statistical (or expected) errors
- systematic errors grouped in 4 classes (100% correlated among experiments and/or energies, or not) :

$\rightarrow 32 \times 32$ cov. matrix $\rightarrow$ χ^2 minimized via matrix algebra

Gauge couplings : $\Sigma \log(\mathcal{L})$

- QGC $\rightarrow$ correlated errors neglected
- neutral TGC $\rightarrow$ global rescaling of $\Sigma \log(\mathcal{L})$
- charged TGC $\rightarrow$ $\Sigma \log(\mathcal{L})$ expressed w.r.t. the gauge coupling and free parameters accounting for 5 correlated errors (each weighted by sensitivities of each experiment) $\rightarrow$ **simultaneous minimization**