Boson couplings and cross sections at LEP II

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OPAL Collaboration

Moriond, 11-18 Feb 2000

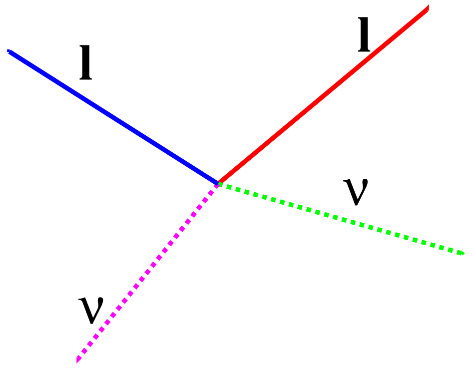
- W^+W^- cross section and W Branching ratios
- Z^0Z^0cross section
- Single W production
- Charged Triple Gauge Couplings: γWW, ZWW
- Neutral Triple Gauge Couplings: $ZZ\gamma$, ZZZ, $Z\gamma\gamma$
- Quartic Gauge Couplings

The Data Set

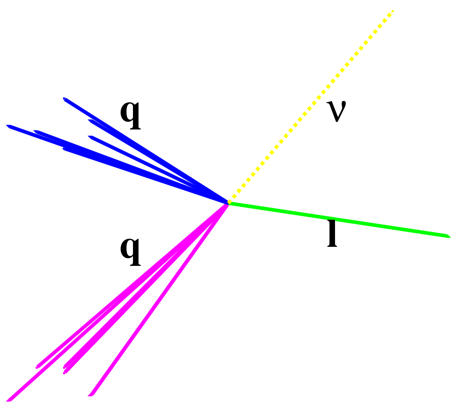
Year	E_{cm} (GeV)	$\mathcal{L}$ (pb^{-1})	σ_{WW}^{CC03} (pb)	W^+W^- events/exp	σ_{ZZ}^{NC2} (pb)	Z^0Z^0 events/exp
1996	161	10	3.47	35	-	-
1996	172	10	12.39	95	-	-
1997	183	55	15.71	700	0.26	5
1998	189	175	16.64	2350	0.65	45
1999	192	30	16.95	380	0.76	20
1999	196	75	17.25	1070	0.90	35
1999	200	80	17.45	1140	0.96	40
1999	202	40	17.52	550	1.00	25
Subtotal		**475**		**6320**		**170**
2000	?	?	?	?	?	?

All results at 192-202 GeV preliminary

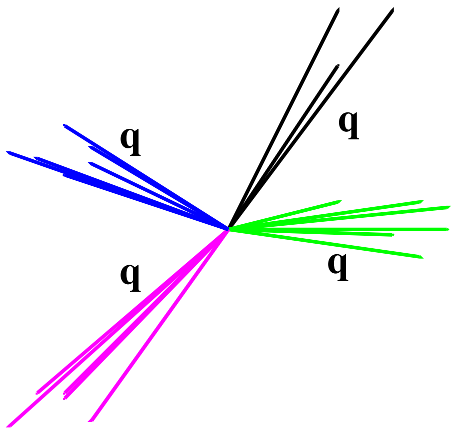
W pair event selection



BR= 11%
Two acoplanar leptons
Missing energy and momentum
$\mathcal{E} = 60-80\%$, $\mathcal{P} = 90\%$ (*)
main background:
CC56 diagrams and
$Z/\gamma \to \ell\ell\gamma$



BR= 43%
Two hadronic jets
One isolated energetic lepton
Missing energy and momentum
$\mathcal{E} = 70-80\%$, $\mathcal{P} = 90\%$ (*)
main background:
$e^+e^- \to Z^0/\gamma \to q\overline{q}(\gamma)$

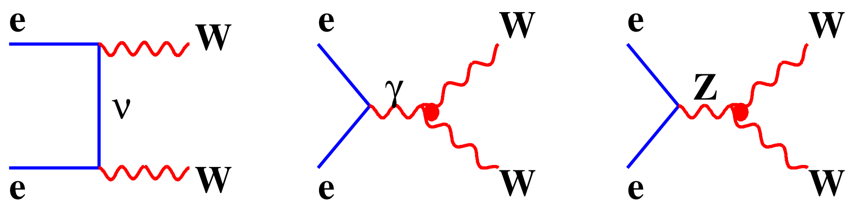


BR= 45%
Four hadronic jets
No missing energy
$\mathcal{E} = 90\%$, $\mathcal{P} = 80\%$
main background:
$e^+e^- \to Z^0/\gamma \to q\overline{q}(\gamma)$

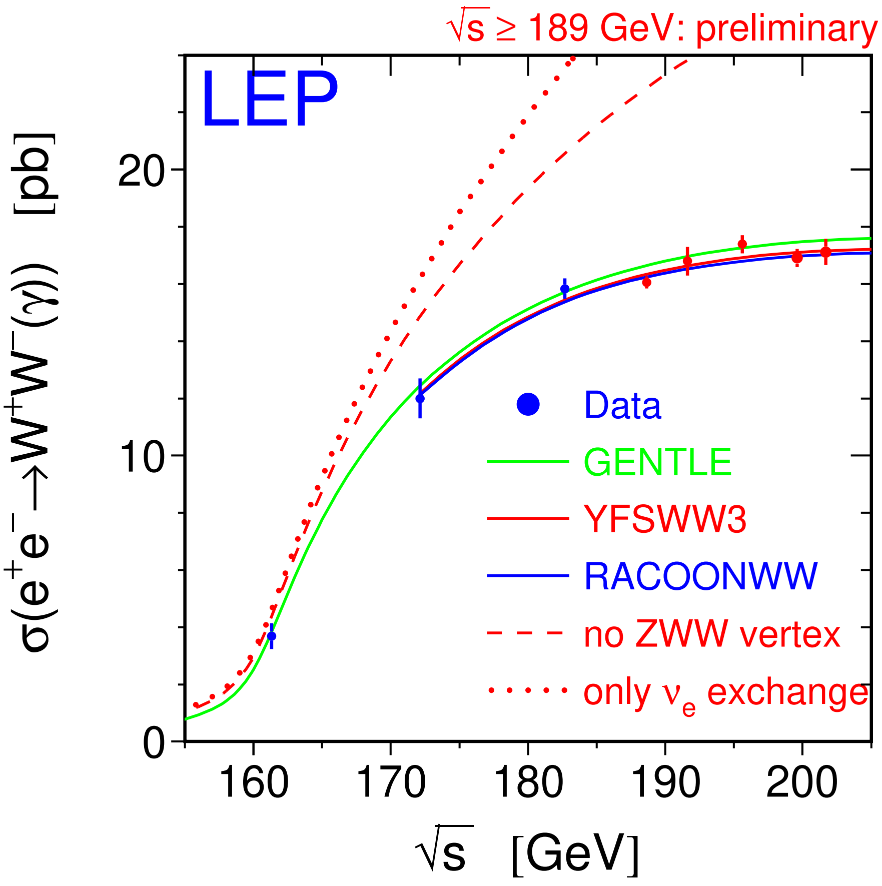
(*) worst performances when $\ell = \tau$

W pair cross section

Evidence for **ZWW**, γ**WW** vertices



Quote σ^{CC03}, correct for 4-fermion diagram interference



Experimental errors dominated by statistics.

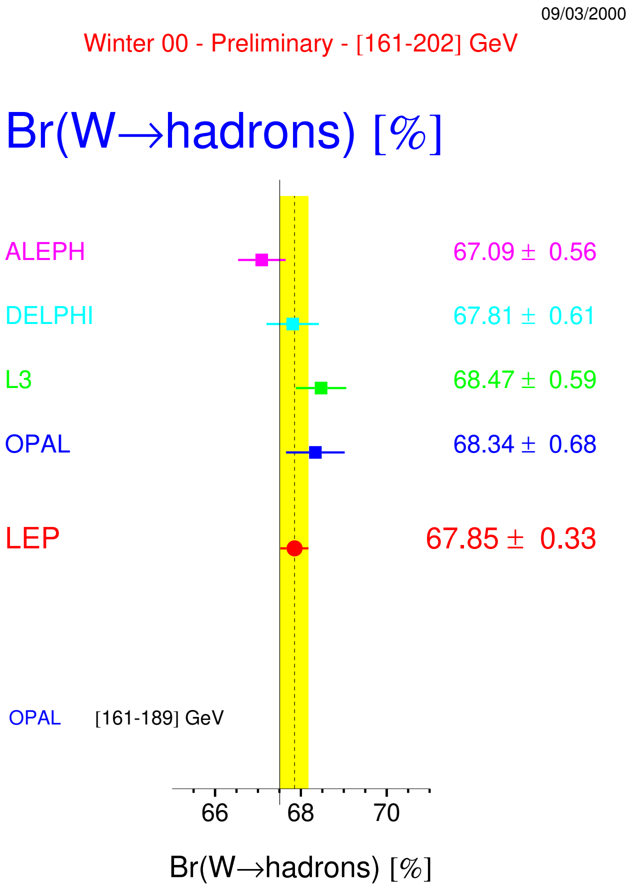
χ^2/dof(data-Gentle)=11.6/6

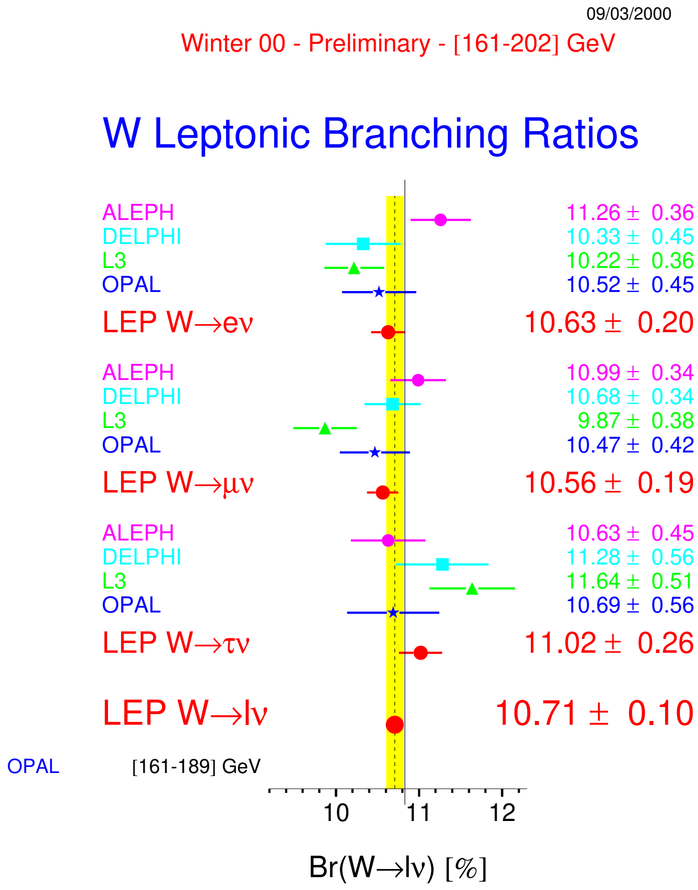
χ^2/dof(data-Racoonww)=5.6/6

W pair Cross section (pb)						
Exp	183 GeV	189 GeV	192 GeV	196 GeV	200 GeV	202 GeV
Aleph	$15.75 \pm .68$	$15.71 \pm .38$	$17.23 \pm .91$	$17.00 \pm .57$	$16.98 \pm .56$	$16.16 \pm .76$
Delphi	$15.86 \pm .74$	$15.83 \pm .43$	16.90 ± 1.02	$17.86 \pm .63$	$17.35 \pm .60$	$17.67 \pm .84$
L3	$16.53 \pm .72$	$16.20 \pm .46$	16.39 ± 0.93	16.67 ± 0.60	$16.94 \pm .62$	$16.95 \pm .88$
Opal	$15.43 \pm .66$	$16.55 \pm .40$	16.60 ± 1.08	$18.59 \pm .74$	$16.12 \pm .69$	19.99 ± 1.58
LEP	$15.83 \pm .36$	$16.05 \pm .22$	$16.80 \pm .50$	$17.39 \pm .32$	$16.91 \pm .32$	$17.11 \pm .46$
Gentle	$15.71 \pm .31$	$16.65 \pm .33$	$16.96 \pm .34$	$17.26 \pm .35$	$17.46 \pm .35$	$17.53 \pm .35$
YFSWW3	$15.43 \pm .01$	$16.34 \pm .01$	$16.63 \pm .01$	$16.92 \pm .01$	$17.11 \pm .01$	$17.16 \pm .01$
Racoon3	$15.37 \pm .01$	$16.24 \pm .01$	$16.52 \pm .01$	$16.79 \pm .01$	$16.97 \pm .01$	$17.03 \pm .01$

ZZ Cross section (pb)						
Exp	183 GeV	189 GeV	192 GeV	196 GeV	200 GeV	202 GeV
Aleph	$.11 \pm .14$	$.67 \pm .14$	$.53 \pm .33$	$.69 \pm .23$	$.70 \pm .24$	$.70 \pm .35$
Delphi	$.38 \pm .18$	$.60 \pm .15$	$.55 \pm .34$	$1.17 \pm .29$	$1.08 \pm .26$	$.87 \pm .33$
L3	$.31 \pm .16$	$.73 \pm .15$	$.24 \pm .35$	$.94 \pm .23$	$1.16 \pm .25$	$1.03 \pm .35$
Opal	$.12 \pm .19$	$.80 \pm .15$	$1.13 \pm .38$	$1.28 \pm .27$	$1.01 \pm .26$	$1.09 \pm .38$
LEP	$.22 \pm .08$	$.70 \pm .07$	$.58 \pm .17$	$.97 \pm .13$	$.97 \pm .13$	$.91 \pm .18$
YFSZZ	.27	.66	.78	.90	.97	1.00

W branching fractions





Br$(W \rightarrow had)$ related to $\sum_{ij} |V_{ij}^{CKM}|^2$

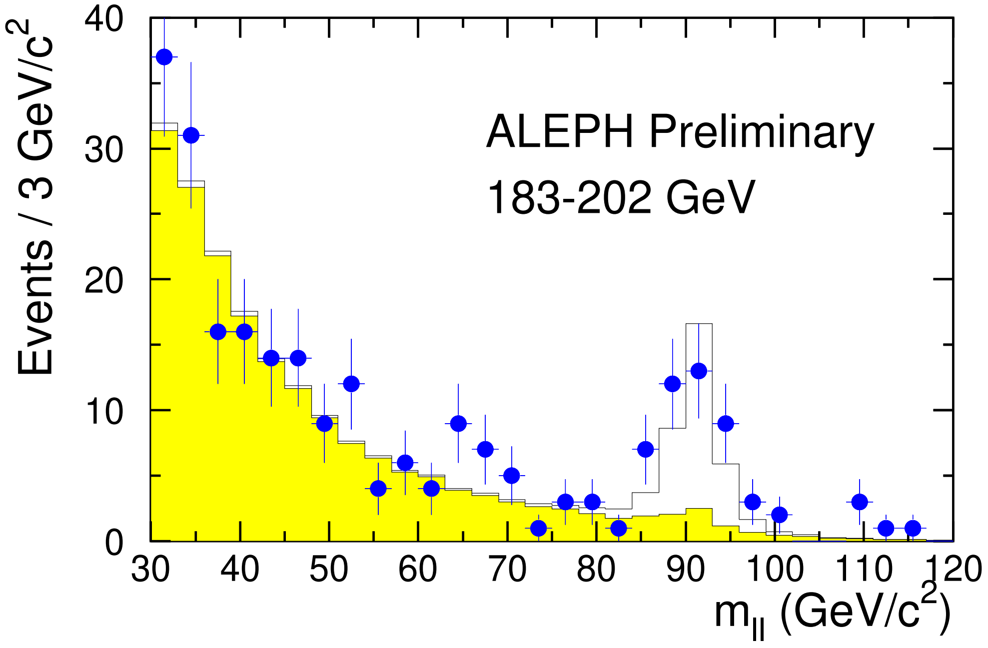
extract $|\mathrm{V}_{cs}| = .993 \pm .016$ without assuming unitarity of V^{CKM}

Carla Sbarra

Z pair event selection

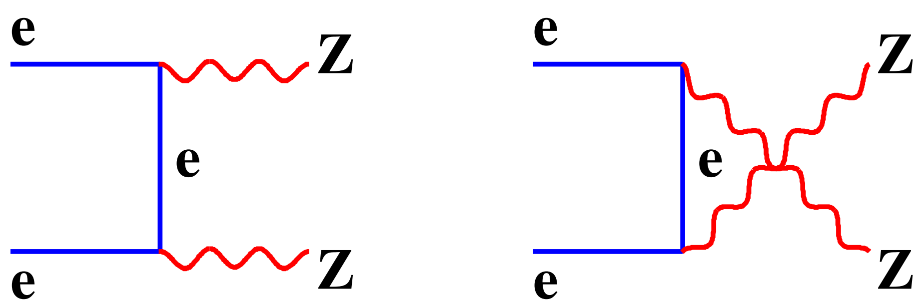
Decay channel	BR (%)	Signature	Main background
$q_1\bar{q}_1q_2\bar{q}_2$	49	4 hadronic jets	Very large $WW \to q\bar{q}q\bar{q} + q\bar{q}(n\gamma)$
$q_1\bar{q}_1l^+l^-$	14	2 jets + 2 leptons	Low $Z^0\gamma^* \to q\bar{q}\ell^+\ell^-$
$\ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1	4 energetic leptons	Medium non resonant $e^+e^-\ell^+\ell^-$
$q\bar{q}\nu\bar{\nu}$	28	2 jets + missing energy	Large $WW \to q\bar{q}\tau\nu + q\bar{q}(n\gamma)$
$\ell^+\ell^-\nu\nu$	4	2 leptons + missing energy	Medium $WW \to \ell\nu\ell\nu$
$\nu\bar{\nu}\nu\bar{\nu}$	4	invisible	

- dijet and dilepton invariant masse close to Z^0mass
- b tagging for jets to improve signal/noise

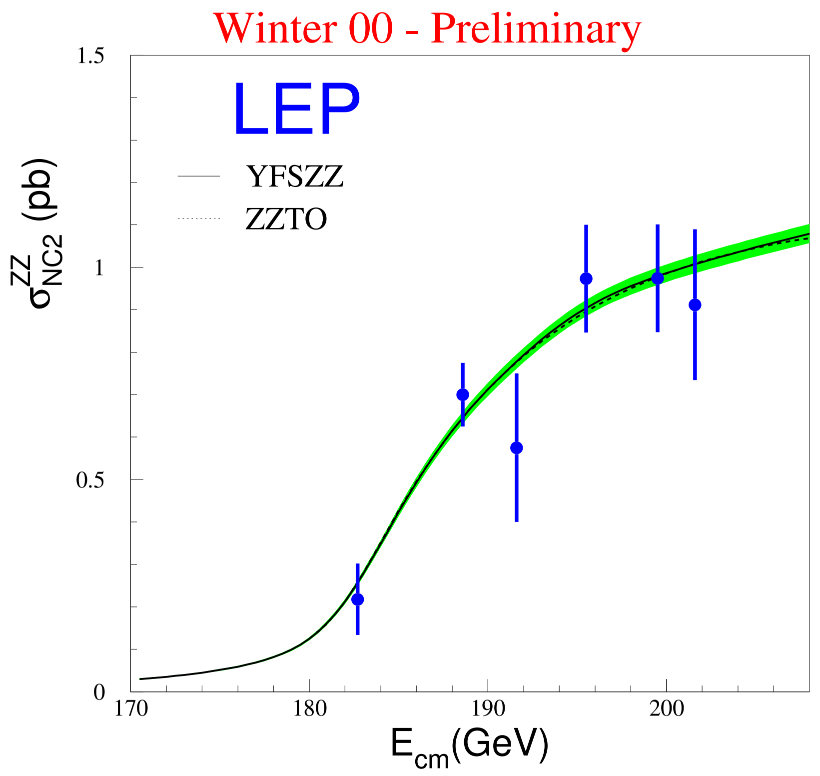


Z pair cross section

Main **background for Higgs searches** if $M_{Higgs} \simeq M_Z$
Test **anomalous couplings** among neutral bosons.

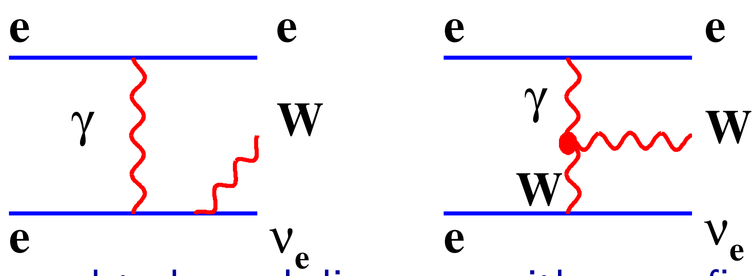


Quote σ^{NC2}, correct for 4-fermion diagram interference



Experimental errors dominated by statistics

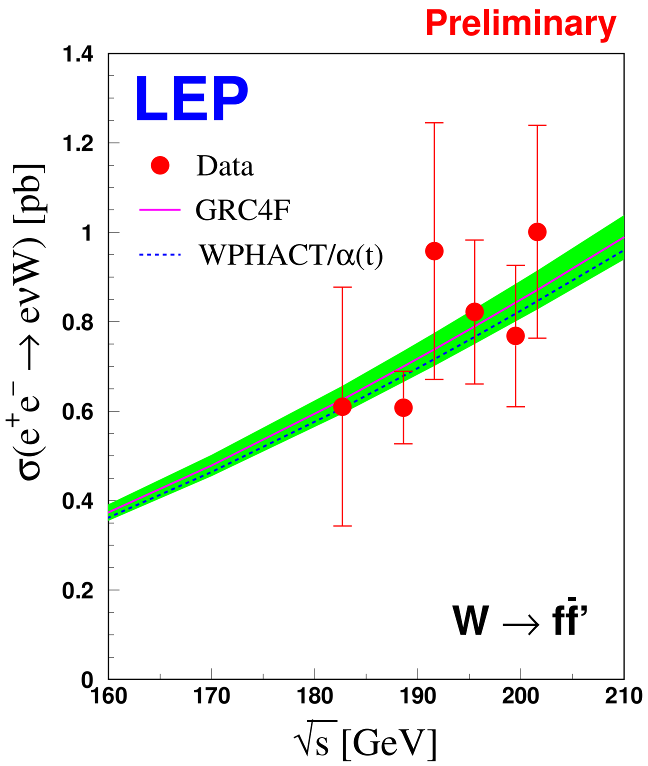
Single W production



plus many s- and t-channel diagrams with same final states

Lep signal definition:

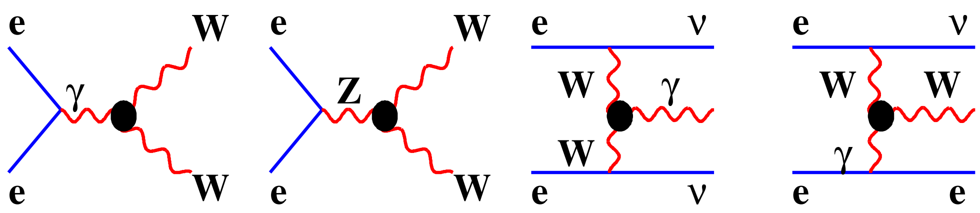
t-channel $e^+e^- \longrightarrow f\overline{f}' e\overline{\nu}_e$ process with $M_{q\overline{q}} > 45$ GeV/c^2, $E_\ell > 20$ GeV and, for $e^+\nu_e e^-\overline{\nu}_e$ final states: $\cos\theta_{e^+} < 0.95$, $\cos\theta_{e^-} > 0.95$ (or vice versa)



Aleph: 183-189 GeV ; Dephi-L3: 189-202 GeV ; Opal: 189 GeV

"Charged" Trilinear Gauge Couplings

Due to non abelian structure of $SU(2)_L \otimes U(1)_Y$ gauge theory.
Their strength mainly measured with W pair events.
Further information from single W and single γ events.



Two approaches at LEP:

Model Dependent

- Introduce general Lorentz invariant Lagrangian for VWW verteces (V=γ,Z)
- Various assumptions to reduce the parameter space (7 for γWW + 7 for ZWW)

Model Independent

- Study W helicity structure

Model Dependent Approach

- Excluding **C**, **P**, and **CP** violating terms:

$$
\begin{aligned}
i\frac{\mathcal{L}^V_{TGC}}{g_{WWV}} &= g_1^V V_\mu (W^{-\mu\nu} W^+_\nu - W^{+\mu\nu} W^-_\nu) \\
&+ \kappa_V V^{\mu\nu} W^-_\mu W^+_\nu \\
&+ \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}
\end{aligned}
$$

$$g_{WW\gamma} = e \qquad\qquad g_{WWZ} = e \cot\theta_W$$

- Asking for **U(1)**$_{em}$ invariance:

$$Q_W = e g_1^\gamma \quad \Rightarrow \quad g_1^\gamma = 1$$

- We consider **deviations** from the Standard Model:

$$\Delta g_1^Z = g_1^Z - 1, \qquad \Delta k_\gamma = k_\gamma - 1, \qquad \lambda = 0$$

- Asking for $SU(2)_L \times U(1)_Y$ invariance:

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$$
$$\lambda_Z = \lambda_\gamma = \lambda$$

Three parameters left: $\Delta\kappa_\gamma$, Δg_1^Z, λ

W pair events

Tighter cuts than for the cross section measurement

Sensitivity to couplings in:

- total cross section σ_{tot}
- W^- scattering angle θ_W
- W polarisation $\longrightarrow$ angles of W decay fermions in the W rest frame: $\theta^*_{f(\overline{f})}$, $\phi^*_{f(\overline{f})}$

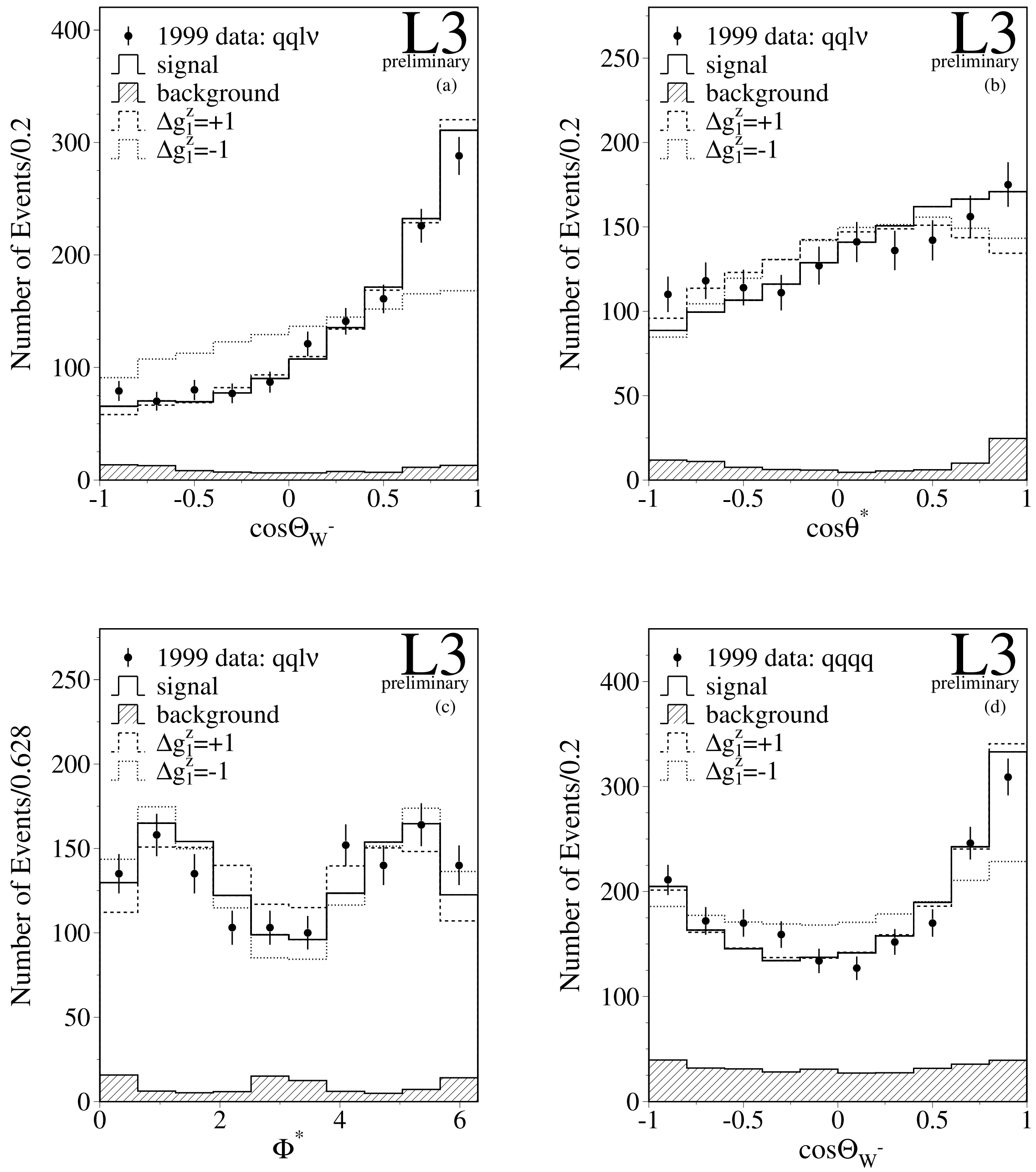
Accessibility of angles depends on the W decay channel

$W^+W^- \to q\overline{q}\ell^-\overline{\nu}_\ell$	Q_W from Q_ℓ, ambiguity in quark flavour $(\cos\theta^*_{jet}, \phi^*_{jet}) \leftrightarrow (-\cos\theta^*_{jet}, \phi^*_{jet}+\pi)$
$W^+W^- \to q\overline{q}q\overline{q}$	Unperfect jet pairing (75-85 %) and unperfect Q_W from Q_{jets} (70-80 %), ambiguity in quark flavour
$W^+W^- \to \ell^-\overline{\nu}_\ell\ell'^+\nu_{\ell'}$	Two-fold ambiguity in $(\cos\theta_W,\ \phi^*_1, \phi^*_2)$, both θ^*_1 and θ^*_2 measured

In terms of sensitivity (most of it from $d\sigma/d\Omega$):

$$\begin{array}{lcl} (\text{stat. error})^{qqqq} & \simeq & 2\cdot(\text{stat. error})^{qq\ell\nu} \\ (\text{stat. error})^{\ell\nu\ell\nu} & > & (\text{stat. error})^{qqqq} \end{array}$$

Examples of angular distributions



Extraction of couplings

Both σ^{tot} and $d\sigma/d\Omega$ depend quadratically on TGCs

Event rate:

Maximise Poisson probability (function of TGC parameters) to observe the number of events found in the data

Angular distributions:

- **Maximum likelihood fit** to 5 angle distributions
  Binned $\longrightarrow$ Loss of sensitivity
  Unbinned $\longrightarrow$ PDF from calculation + detector resolution function $\longrightarrow$ **all 14 TGCs** accessible
  Aleph in $qqe\nu$ and $qq\mu\nu$ events
  $\longrightarrow$ PDF from MC simulated events: L3

- **Optimal Observables** Aleph,Opal,Delphi
  project 5 kinematic variables onto 1(2) parameter per TGC coupling. Maximum sensitivity for couplings near the expansion point

$$d\sigma(\Omega,\alpha) = S^0(\Omega) + \sum_i \alpha_i \cdot S_i^1(\Omega) + \sum_{ij} \alpha_i\alpha_j \cdot S_{ij}^2(\Omega)$$
$$\mathcal{O}_i^1 = S_i^1(\Omega)/S_i^0(\Omega) \qquad \mathcal{O}_{ij}^2 = S_{ij}^2(\Omega)/S_i^0(\Omega)$$

- Binned maximum likelihood fit to $\mathcal{O}_i^1$ and $\mathcal{O}_{ij}^2$ shape
- χ^2 fit to $\mathcal{O}_i^1$ and $\mathcal{O}_{ij}^2$ averages
- χ^2 fit to $\mathcal{O}_i^1$ averages, iterative procedure to expand $d\sigma/d\Omega$ around the measured value

Single W and Single γ events

Clean access to the γWW vertex alone.
Sensitivity to the k_γ and λ_γ parameters

single W $(We\nu)$

Most of the information from the **event rate**
Fit also distributions like **E**$_\ell$, θ_ℓ, and θ_{jets}
Results from Aleph @ 161-189 GeV; Delphi @ 183-189 GeV;
Opal @ 189 GeV; L3 @ 131-202 GeV

single γ ($\nu\nu\gamma$)

Typical fits to **event rate**, θ_γ and E_γ.
Results from Aleph @ 189 GeV; Delphi @ 183-189 GeV;
L3 @ 161-183 GeV

Sensitivity compared to WW events:

$$(\text{error on } k_\gamma)^{We\nu} \simeq (\text{error on } k_\gamma)^{WW}$$

$$(\text{error on } \lambda_\gamma)^{We\nu} \simeq 10 \cdot (\text{error on } \lambda_\gamma)^{WW}$$

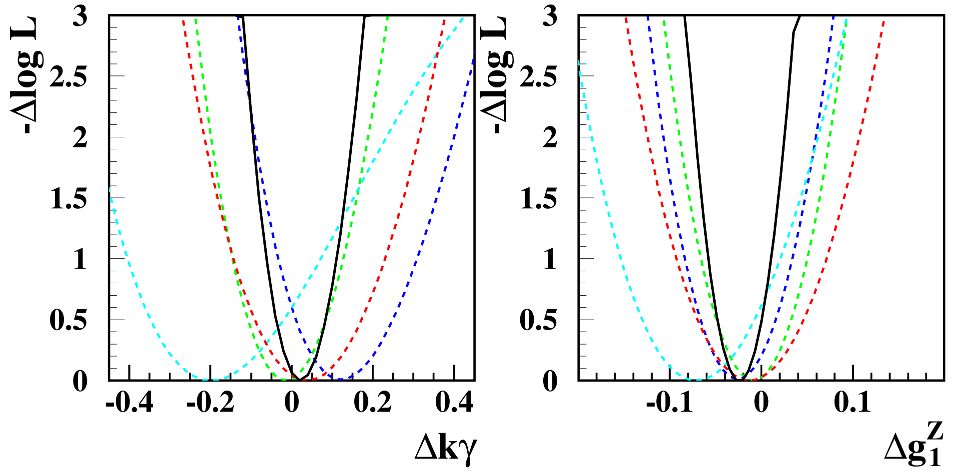
$$(\text{error on } k_\gamma)^{\nu\nu\gamma} \simeq 4 \cdot (\text{error on } k_\gamma)^{WW}$$

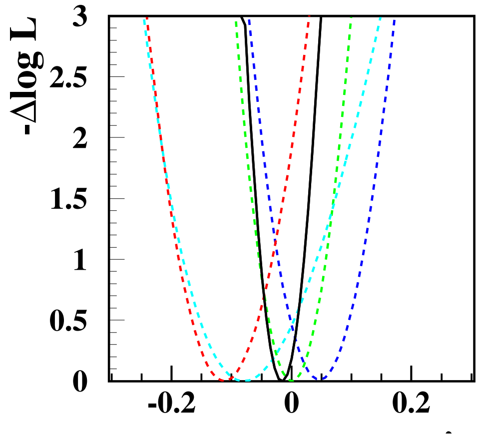
$$(\text{error on } \lambda_\gamma)^{\nu\nu\gamma} \simeq 10 \cdot (\text{error on } \lambda_\gamma)^{WW}$$

LEP Results on TGC parameters

One parameter fits - preliminary

ALEPH + DELPHI + L3 + OPAL





$\Delta k_\gamma = .021 ^{+0.063}_{-0.059}$

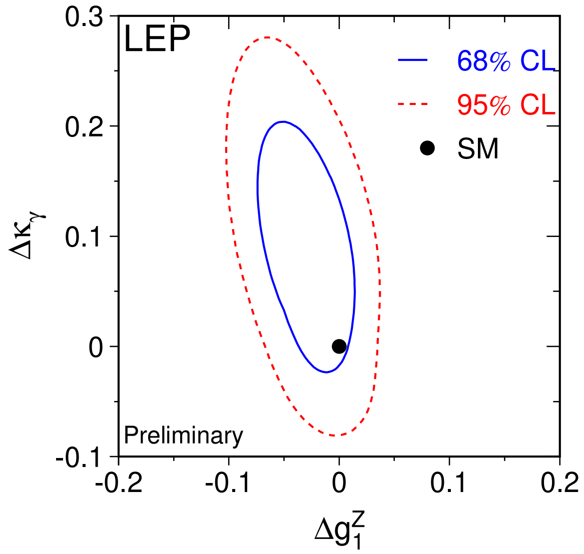
$\Delta g_1^Z = -.024 ^{+0.024}_{-0.024}$

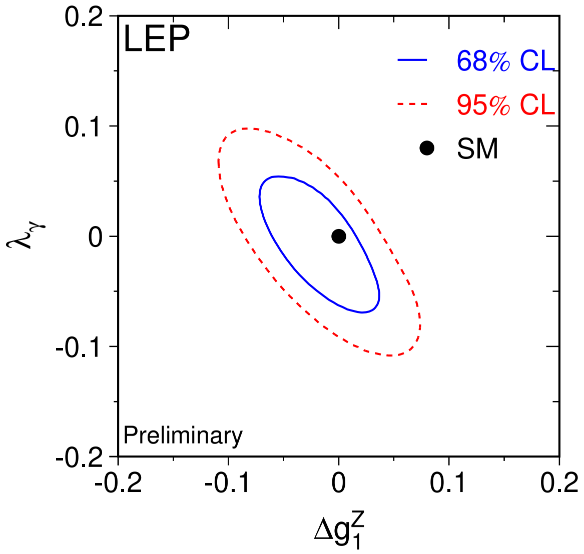
$\lambda_\gamma = -.016 ^{+0.026}_{-0.026}$

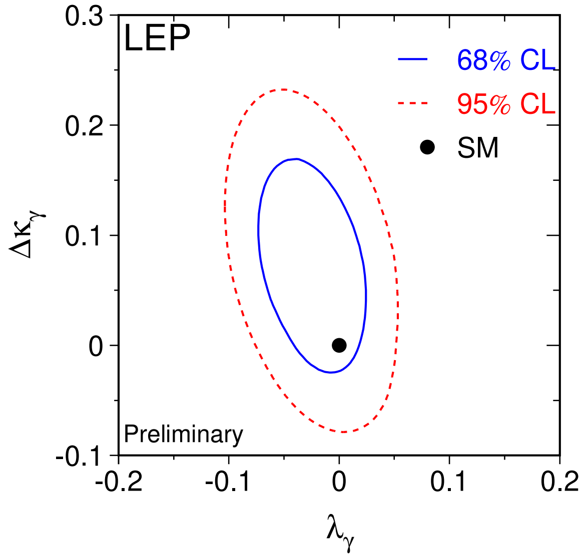
Tampere		
Δk_γ	Δg_1^Z	λ_γ
$.04 \pm 0.08$	-0.01 ± 0.03	-0.04 ± 0.04

No single W at 192-202 GeV
No 192-202 GeV data from OPAL
Not all W decay channels for ALEPH at 192-202 GeV

Two parameter fits - preliminary







C, P and CP violating couplings

1 parameter fits, no constraints among the 14 couplings.

Coupling	Result	95% C.L.
$Re(\tilde{k}_\gamma)$	$-.112^{+.169}_{-.153}$	[-.394, .218]
$Re(\tilde{\lambda}_\gamma)$	$.145^{+.113}_{-.129}$	[-.117, .353]
$Re(\tilde{k}_Z)$	$-.034^{+.096}_{-.094}$	[-.213, .151]
$Re(\tilde{\lambda}_Z)$	$.062^{+.072}_{-.076}$	[-.088, .198]
$Re(g_4^\gamma)$	$.106^{+.234}_{-.238}$	[-.358, .557]
$Re(g_5^\gamma)$	$.143^{+.326}_{-.328}$	[-.401, .879]
$Re(g_4^Z)$	$.095^{+.159}_{-.161}$	[-.220, .402]
$Re(g_5^Z)$	$.126^{+.207}_{-.206}$	[-.277, .532]
$Im(\tilde{k}_\gamma)$	$.029^{+.090}_{-.089}$	[-.146, .205]
$Im(\tilde{\lambda}_\gamma)$	$-.013^{+.070}_{-.070}$	[-.150, .123]
$Im(\tilde{k}_Z)$	$-.011^{+.059}_{-.059}$	[-.126, .105]
$Im(\tilde{\lambda}_Z)$	$.014^{+.047}_{-.047}$	[-.077, .105]
$Im(g_4^\gamma)$	$.425^{+.194}_{-.197}$	[-.037, .803]
$Im(g_5^\gamma)$	$-.061^{+.372}_{-.369}$	[-.777, .668]
$Im(g_4^Z)$	$.240^{+.135}_{-.137}$	[-.031, .503]
$Im(g_5^Z)$	$-.015^{+.226}_{-.225}$	[-.454, .428]

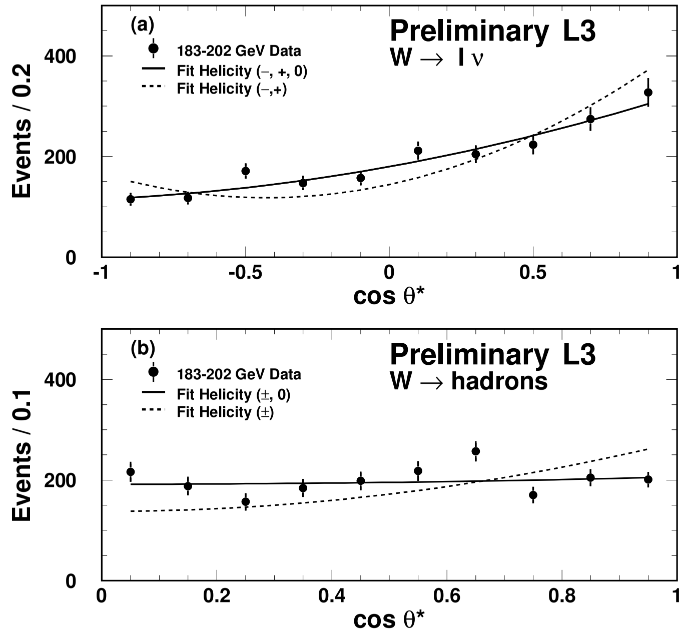
ALEPH @ 183-202 GeV, $q\bar{q}e\nu$ and $q\bar{q}\mu\nu$ final states.

Model Independent analysis

Use W decay products to analyse W polarisation vs $\cos\theta_W$.

Decay angle method

W polarisation extracted in bins of $\cos\theta_W$ from the θ^* distribution in $q\bar{q}\ell\nu$ events by L3 @ 183-202 GeV



$$f(\tau=0) = (25.9 \pm 3.5)\%$$

$f(\tau=0) = 24.8\%$ in the SM

Spin density matrix elements

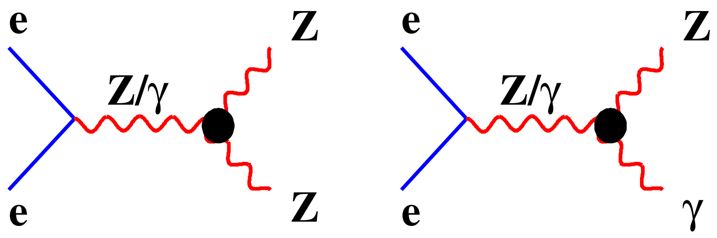
Directly related to the W polarisation. Also used to extract $d\sigma_L/d\cos\theta$ and $d\sigma_T/d\cos\theta$ by OPAL @ 183 GeV.

$$f(\tau=0) = (24.2 \pm 9.1 \pm 2.3)\%$$

$f(\tau=0) = 27\%$ in the SM

"Neutral" Trilinear Gauge Couplings

Forbidden at tree level in the Standard Model



Effective couplings (due to high mass particle loops or compositness) would increase the $e^+e^- \to ZZ$ and $e^+e^- \to Z\gamma$ cross section and affect Z polarisation

ZZ final state

Anomalous vertices parametrised by 4 couplings:

$$f_4^\gamma,\ f_5^\gamma, f_4^Z,\ f_5^Z$$

f_4^V $\not{P}$, $C\not{P}$

f_5^V $\not{P}$, $\not{C}$, CP conserving

Zγ final state

Anomalous vertices parametrised by 8 couplings

$$h_1^\gamma,\ h_2^\gamma, h_1^Z,\ h_2^Z$$
$$h_3^\gamma,\ h_4^\gamma, h_3^Z,\ h_3^Z$$

h_1^V, h_2^V CP violating

h_3^V, h_4^V CP conserving

Combined limits on neutral TGCs

ZZ final state

Delphi and L3 up to 189 GeV

Opal up to 202 GeV

Coupling	68% error	95% C.L.
f_4^γ	$+.29^{+.11}_{-.21}$	$[-.49,\ +.49]$
f_4^Z	$+.49^{+.19}_{-.31}$	$[-.82,\ +.82]$
f_5^γ	$-0.6^{+1.4}_{-0.3}$	$[-1.1,\ +1.1]$
f_5^Z	$-.01^{+.56}_{-.57}$	$[-1.1,\ +1.1]$

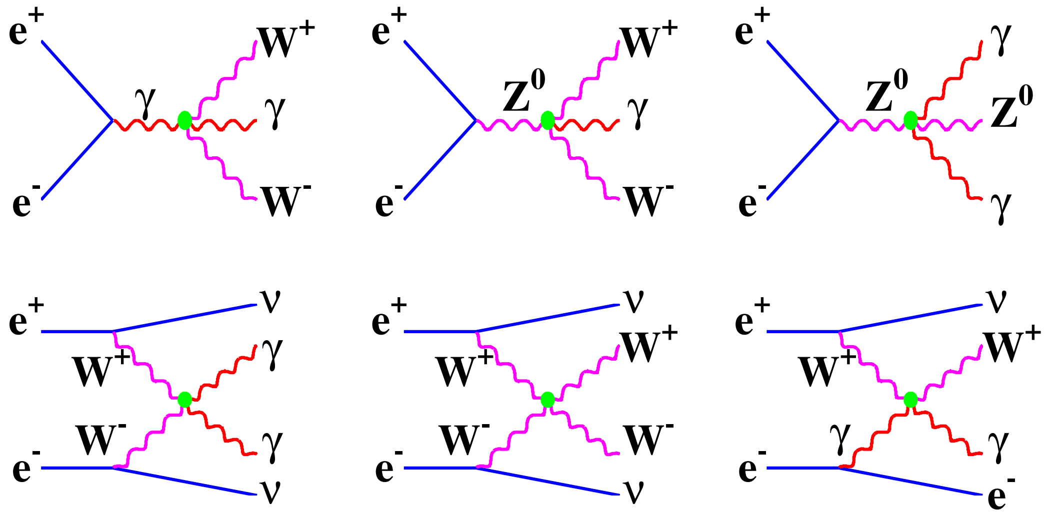
Zγ final state

Delphi and L3 up to 189 GeV

Coupling	68% error	95% C.L.
h_1^γ	$-.10^{+.06}_{-.04}$	$[-.17,\ +.08]$
h_2^γ	$-.05^{+.12}_{-.04}$	$[-.11,\ +.10]$
h_1^Z	$-.13^{+.10}_{-.07}$	$[-.26,\ +.09]$
h_2^Z	$+.07^{+.05}_{-.09}$	$[-.11,\ +.16]$
h_3^γ	$+.01^{+.02}_{-.02}$	$[-.03,\ +.04]$
h_4^γ	$0.00^{+.01}_{-.01}$	$[-.03,\ +.02]$
h_3^Z	$+.07^{+.08}_{-.15}$	$[-.29,\ +.21]$
h_4^Z	$+.08^{+.07}_{-.16}$	$[-.12,\ +.20]$

Quartic Gauge Couplings

Accessible at LEP II:



Predicted contribution of WWVV vertices NEGLIGIBLE
Predicted contribution of ZZ$\gamma\gamma$ vertex ZERO

Limits on genuine QGC parameters (not already constrained by TGC limits) @ 95% C.L.(all limits in GeV^{-2} units):

Final state	a_0/Λ^2	a_c/Λ^2
WWγ	$[-.070, .070]$	$[-.13, .19]$
	$[-.042, .045]$	$[-.072, .148]$
$\nu\nu\gamma\gamma$	$[-.086, .085]$	$[-.23, .23]$
$Z^0\gamma\gamma$	$[-.009, .008]$	$[-.007, .013]$

OPAL @ 189 GeV   L3 @ 183+189 GeV

Indirect limits (LEP I,SLD):
-0.0007$<a_0/\Lambda^2 < 0.0001$ -0.002 $<a_c/\Lambda^2 < 0.0009$

Conclusions

- **Preliminary** analysis of data collected between **192** and **202 GeV** available

- Measured W pair production cross section **supports** most **recent Monte Carlo** generators

- Good **agreement** between data and Monte Carlo for ZZ and single W production cross section

- Final analysis of data up to 202 GeV will measure the g_1^Z,λ_γ and k_γ parameters at a level better than 2%, 2% and 5% respectively

- First LEP combined limits on neutral TGCs, new limits on Quartic Gauge Couplings

- No deviations from the Standard Model expectations yet

- Eagerly waiting for **more data at higher energies** this summer