Four Fermion Processes at LEP II

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Valerio Verzi

Dip. di Fisica and INFN, Milano

DELPHI Collaboration

Outline of the talk:

- The data set
- WW production
- ZZ production
- $Z\gamma^{\star}$ production
- Single W production
- Conclusions

The Data Sample

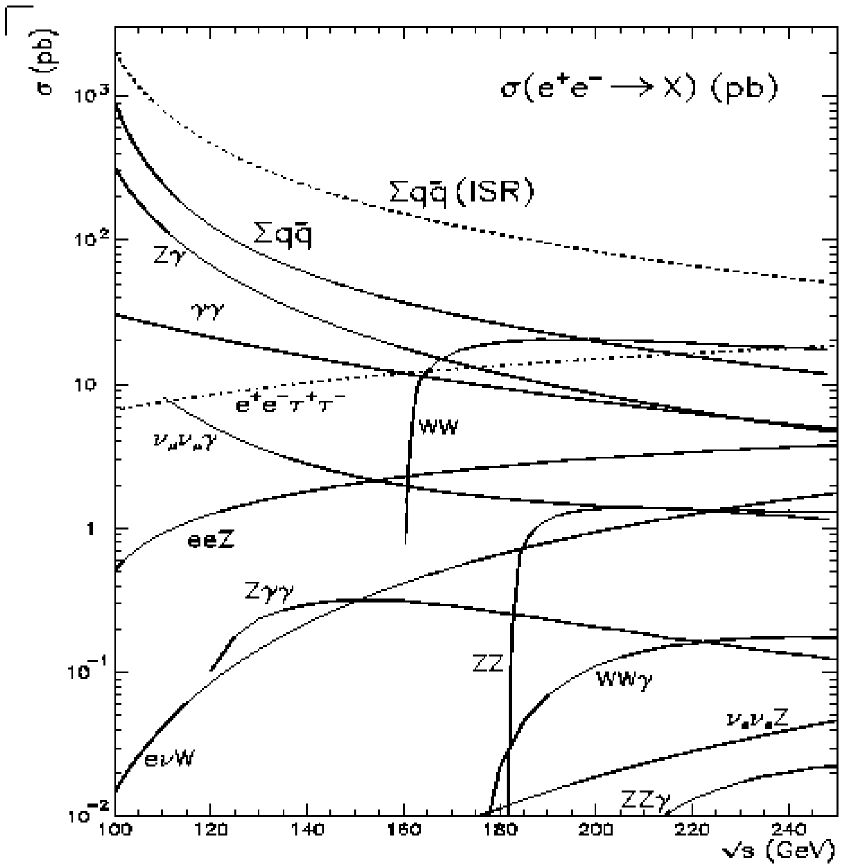
(Delphi luminosity)

Year	1996	1996	1997	1998	1999	1999
$\sqrt{s}$ (GeV)	161	172	183	189	192	196
L (pb^{-1})	10	10	55	160	25	75

Year	1999	1999	2000	2000	1996-2000
$\sqrt{s}$ (GeV)	200	202	205	207	161-209
L (pb^{-1})	85	40	85	140	685

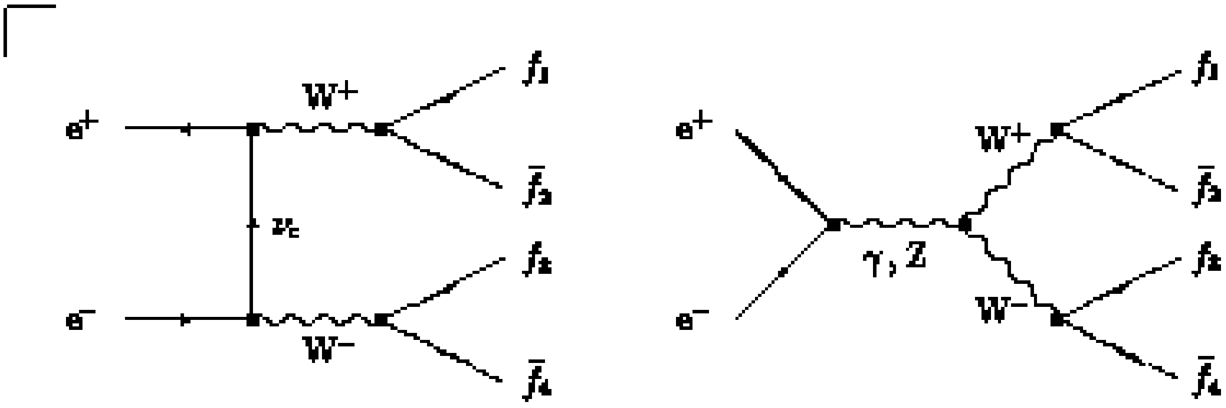
$\sigma_{WW} \sim 17$ pb
$N_{WW} \sim 4 \times 11000$

$\sigma_{ZZ} \sim 1$ pb
$N_{ZZ} \sim 4 \times 600$



WW Production

CC03 diagrams:



The study of the WW production provides the following measurements:

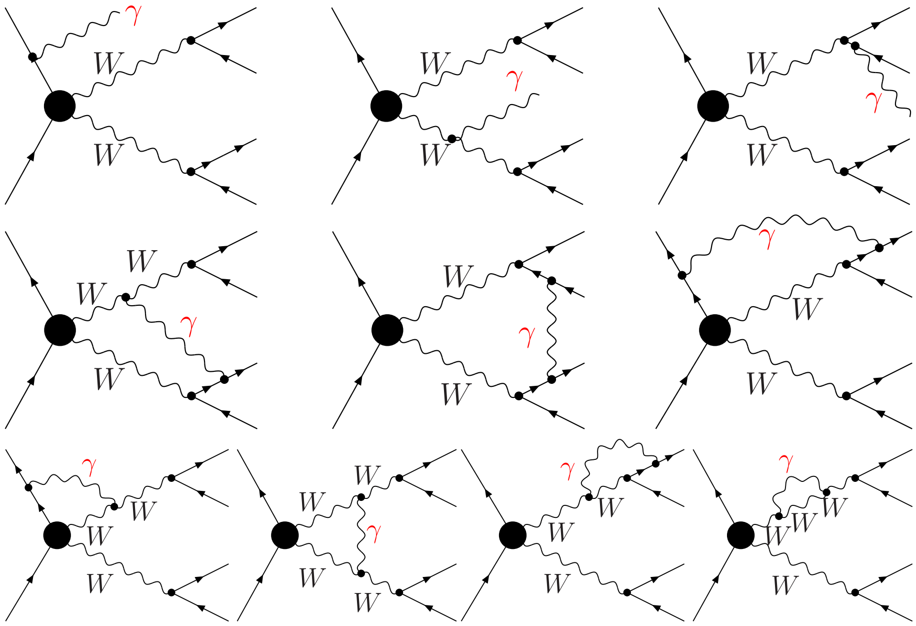
- **WW cross section**
- **W branching ratios**
- **WWZ and $WW\gamma$ couplings (TGC)**
- **W polarization in WW events**

and clearly the W mass (see N.Watson talk).

WW Production

Theory:

High accuracy on LEP WW measurements
$\Rightarrow$ knowledge of $\mathcal{O}(\alpha)$ radiative corrections:



The full calculation of $\mathcal{O}(\alpha)$ Electro-Weak corrections to 4-fermion is beyond the present possibilities for theory.

The problem can be solved considering only the $\mathcal{O}(\alpha)$ corrections enhanced by two resonant W bosons:
DPA "Double Pole Approximation"

- **Precision on $\sigma_{WW} \sim 0.5\%$.**
- **Effect of inctroducing DPA: up to 2% on differential distributions.**

WW Events Selection

$q\bar{q}q\bar{q}$ (hadronic channel)

- branching fraction is 46%
- four jets and no missing momentum
- $\epsilon \sim 80-90\%$ and $p \sim 75-80\%$
- main background: $q\bar{q}(\gamma)$

$q\bar{q}l\nu_l$ (semileptonic channel)

- branching fraction is 43%
- two jets plus an isolated lepton with missing momentum
- $\epsilon \sim 70-85\%$ and $p \sim 90\%$ (performance: "$\tau < e \sim \mu$")
- main background: $q\bar{q}(\gamma)$

$l\nu_l l\nu_l$ (fully leptonic channel)

- branching fraction is 11%
- two acoplanar and acollinear leptons plus missing momentum
- $\epsilon \sim 60-80\%$ and $p \sim 90\%$
- main background: $l^+l^-(\gamma)$, $\gamma\gamma$ and other 4-fermion processes.

WW Cross Section

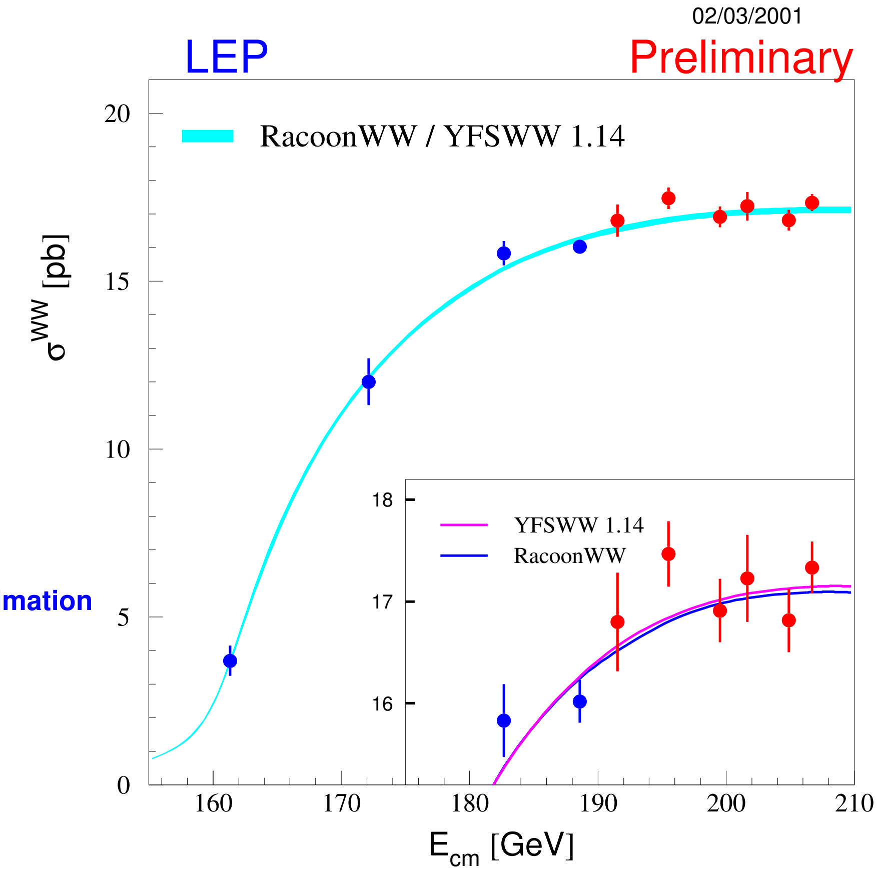
$\sqrt{s}$ (GeV)	$W\,W$ Cross section (pb)					
	ALEPH	DELPHI	L3	OPAL	LEP	RacoonWW
189	15.71±0.38	15.83±0.43	16.24±0.43	16.30±0.38	16.25±0.21	16.25
192	17.23±0.91	16.90±1.02	16.43±0.94	16.60±0.97	16.80±0.48	16.52
196	17.00±0.57	17.86±0.63	16.89±0.61	18.59±0.74	17.47±0.32	16.80
200	16.98±0.56	17.35±0.60	16.87±0.62	16.32±0.66	16.91±0.31	16.98
202	16.16±0.76	17.67±0.84	17.02±0.89	18.48±0.91	17.23±0.43	17.03
205	16.57±0.55	17.44±0.64	17.35±0.64	15.97±0.64	16.81±0.31	17.08
207	17.32±0.45	16.50±0.48	17.96±0.51	17.77±0.57	17.33±0.25	17.09

Theory:

$\mathcal{O}(\alpha)$ **in DPA**

Double Pole Approximation

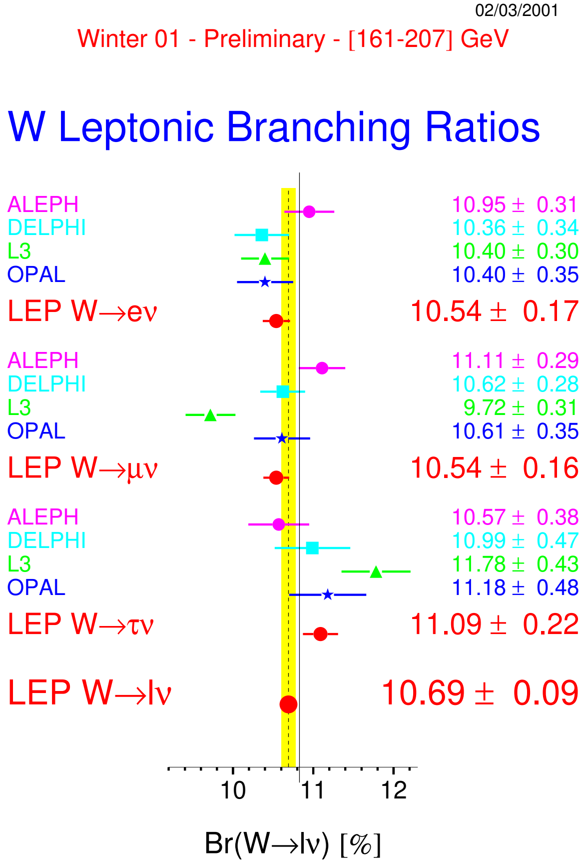
$\frac{\delta\sigma^{th}}{\sigma^{th}} \sim 0.5\%$

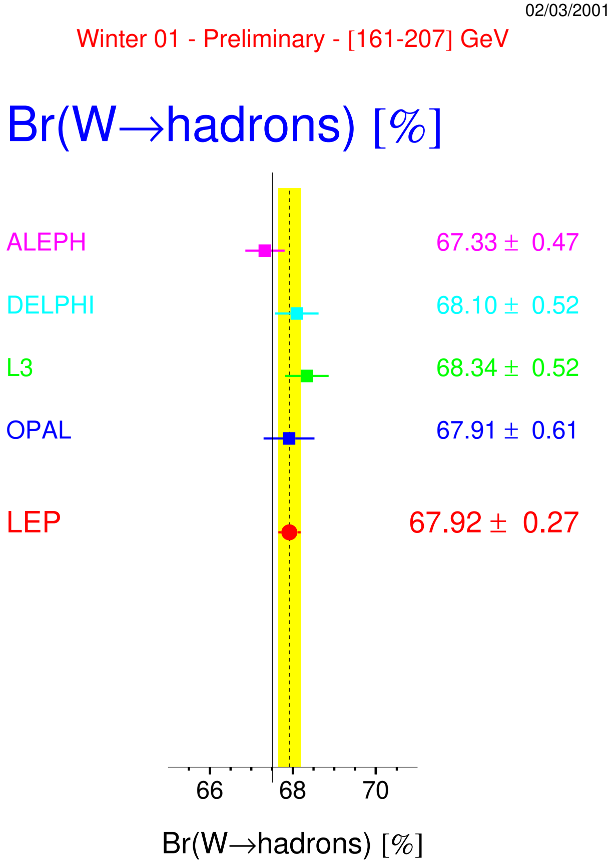


The error is dominated by statistics

. . . **having fixed the W branching fractions to their SM value**

W Branching Fractions





From $\mathbf{BR(W \rightarrow q\bar{q}')}$ **one obtaines:** $\quad |\mathbf{V_{cs}}| = \mathbf{0.996 \pm 0.013}$

Systematic error $\sim$ **Statistical error**

WWZ and WWγ couplings

SM: $SU(2)_L \otimes U(1)_Y$ **is non abelian** $\Rightarrow$ WWZ **and** $WW\gamma$ **vertices.**

Deviations from SM predictions can be searched considering the most general WWV **Lagrangian (**$2 \times 7 = 14$ **terms,** $V = Z, \gamma$**):**

Coupling	Lagragian term ($\times i/g_{WWV}$)	Properties
g_1^V	$(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu})V^\mu$	C, P
k_V	$W^+_\mu W^-_\nu V^{\mu\nu}$	C, P
λ_V	$\frac{1}{m_W^2}V^{\mu\nu}W_\nu^{+\rho}W^-_{\rho\mu}$	C, P
g_5^V	$i\epsilon^{\mu\nu\rho\sigma}((\partial_\rho W^-_\mu)W^+_\nu - W^-_\mu(\partial_\rho W^+_\nu))V_\sigma$	$\not{C}$, $\not{P}$
g_4^V	$iW^-_\mu W^+_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$	$\not{CP}$
$\tilde{k}_V$	$-\frac{1}{2}\epsilon^{\mu\nu\rho\sigma}W^-_\mu W^+_\nu V_{\rho\sigma}$	$\not{CP}$
$\tilde{\lambda}_V$	$\frac{1}{2m_W^2}\epsilon^{\mu\nu\rho\sigma}W^-_{\mu\delta}W^{+\delta}{}_\nu V_{\rho\sigma}$	$\not{CP}$

Assuming C, P conserv., $U(1)_{em}$ and $SU(2)_L \otimes U(1)_Y$ invariance:

$$\Delta g_1^Z = g_1^Z - 1 \qquad \Delta k_\gamma = k_\gamma - 1 \qquad \lambda_\gamma \qquad \mathrm{all} = 0 \quad \mathrm{in} \quad \mathrm{SM}$$

$$k_Z = g_1^Z + (k_\gamma - 1)\tan^2\theta_W \qquad \lambda_Z = \lambda_\gamma$$

The couplings modify:

- W^- **production angle with respect to the beam axis.**
- W **polarization:** W **decay angles in its rest frame**
- **Total cross section**

But the event reconstruction is limited by:

- **Flavour and electric charge of jets is unknown**
- **Pairing of jets (**$\sim 80\%$**) and** $Q(W)$ **reconst. (**$\sim 80\%$**) in** $q\bar{q}q\bar{q}$
- **Two solutions for neutrinos in** $l\nu_l l\nu_l$

WWZ and WWγ couplings

Preliminary results from ALEPH including 2000 data (WW 183-207 GeV):

$$\Delta g_1^Z = 0.015 \pm 0.028\ (\mathrm{stat}) \pm 0.016\ (\mathrm{syst}) + 0.013\ (\mathcal{O}(\alpha))$$

$$\Delta k_\gamma = 0.018^{+0.100}_{-0.083}(\mathrm{stat}) \pm 0.084\ (\mathrm{syst}) + 0.037\ (\mathcal{O}(\alpha))$$

$$\lambda_\gamma = 0.006^{+0.028}_{-0.028}(\mathrm{stat}) \pm 0.015\ (\mathrm{syst}) + 0.015\ (\mathcal{O}(\alpha))$$

$\mathcal{O}(\alpha)$**: effect of DPA on the shape of distributions.**

They have used the method of "Optimal Observables":

Fit of $\mathcal{O}_{ij}$ averages where:

$$\mathcal{O}_{ij} = \frac{S_{ij}}{S_{00}} \qquad \text{“Optimal Observables''}$$

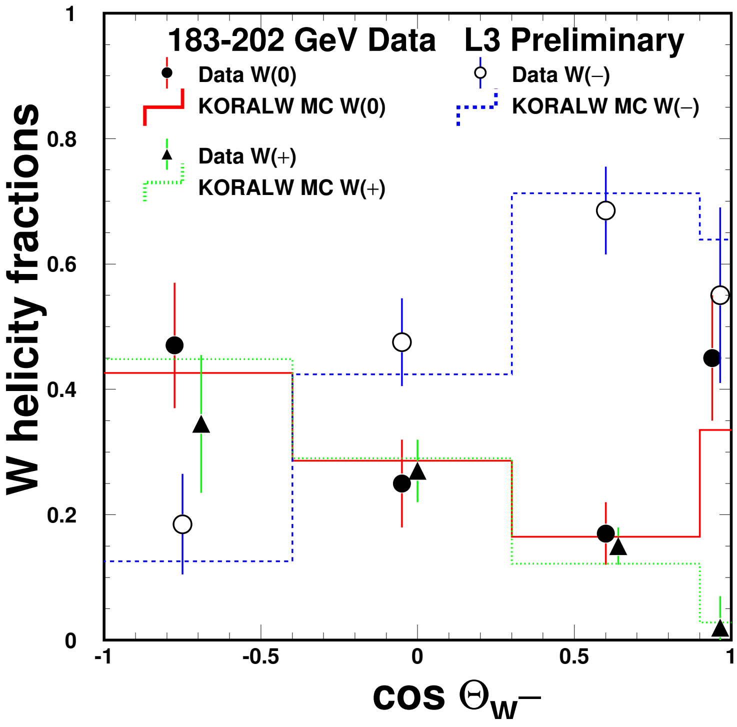
$$\frac{d\sigma(\Omega,\alpha)}{d\Omega} = S_{00}(\Omega) + \sum_i \alpha_i S_{i0}(\Omega) + \sum_{i \geq j} \alpha_i \alpha_j S_{ij}(\Omega)$$

The other experiments have not released results:
work in progress on DPA effects

$\Rightarrow$ **No new LEP combination after ICHEP 2000**

W polarization in WW events

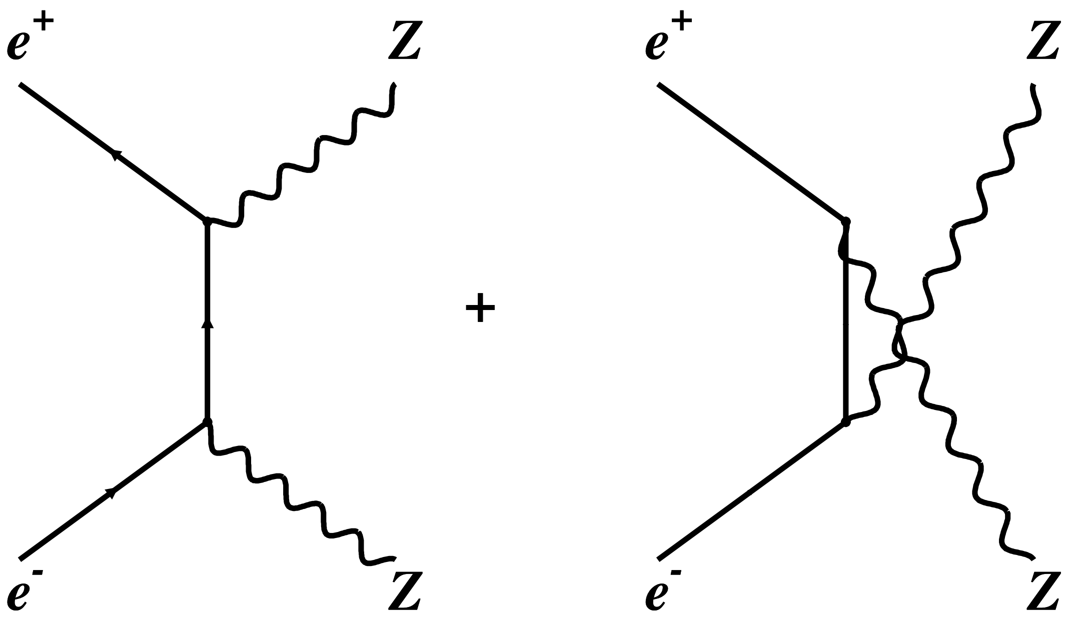
The W polarization is measured in different bins of $\cos\theta_W$ in $q\bar{q}l\nu_l$ events observing the distribution of the W decay angle in its rest frame:



	183-202 GeV		204-209 GeV	
Helicity	**L3 [%]**	**SM [%]**	**L3 [%]**	**SM [%]**
0	25.9 $\pm$ 3.5	24.8	21.6 $\pm$ 5.3	22.0
-1	56.2 $\pm$ 4.5	57.6	64.7 $\pm$ 6.6	62.3
$+1$	17.9 $\pm$ 2.3	17.6	13.7 $\pm$ 3.4	15.7

ZZ Production

NC02 diagrams:



Why it is important ?

- **Main background to Higgs searches ($M_H \sim M_Z$)**
- **Test of Standard Model: new Physics from ZZZ and $ZZ\gamma$ anomalous couplings**

Moreover:

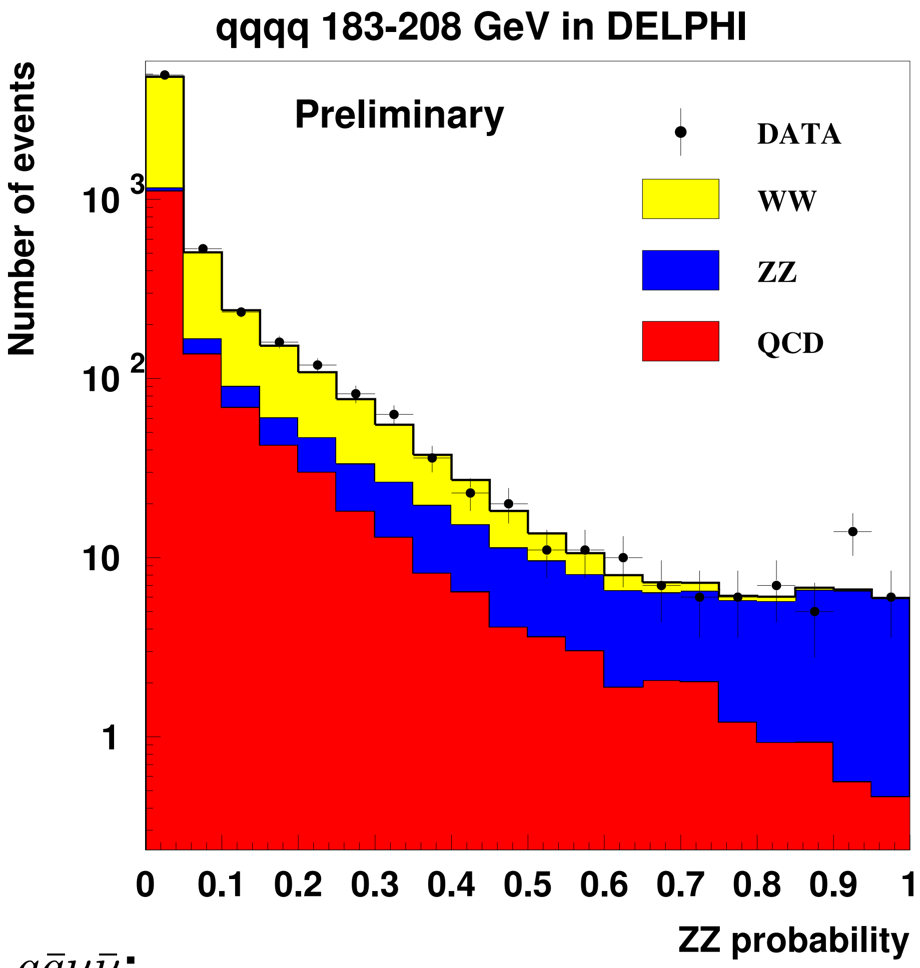
σ_{ZZ} **is small (~ 1 pb) $\Rightarrow$ high backgrounds**

$\Rightarrow$ **challenging measurements**

ZZ Events Selection

$ZZ \to q\bar{q}q'\bar{q}'$:

- BR = 49%
- Four jets without missing energy
- Large background from WW and $q\bar{q}(\gamma)$
- b-tagging, "anti-QCD" variables, $M_{rec} \sim M_Z$



$ZZ \to q\bar{q}\nu\bar{\nu}$:

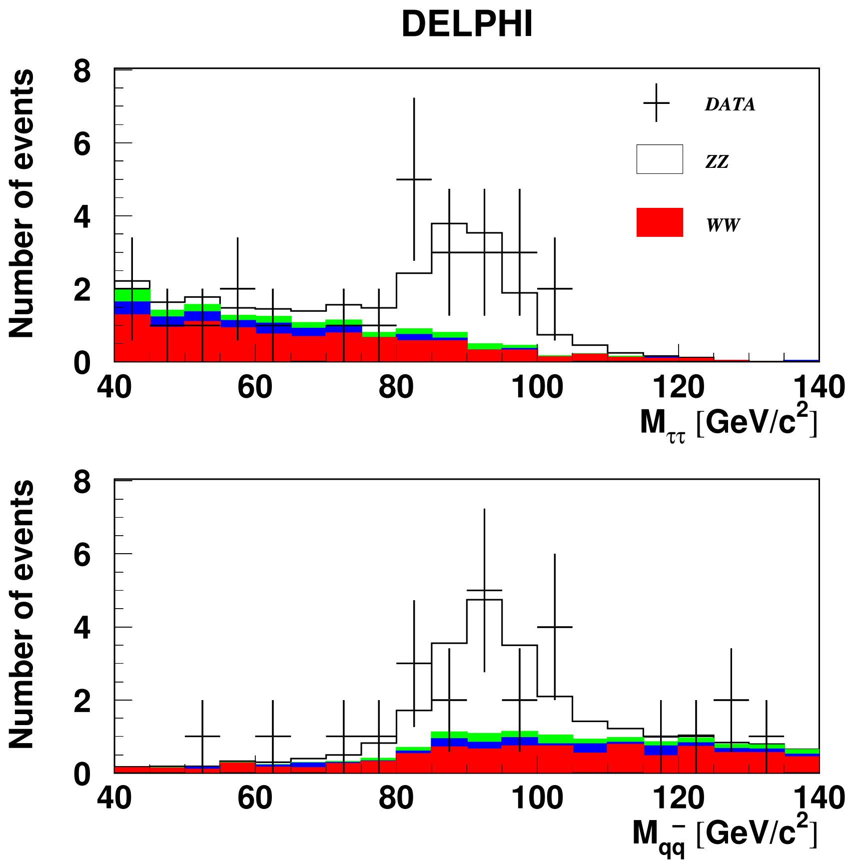
- BR = 28%
- Two jets acoplanar with the beam and with visible and recoil masses compatible with M_Z
- Large background from $We\nu_e$, $WW \to q\bar{q}\tau\nu_\tau$ and $q\bar{q}(\gamma)$

ZZ Events Selection

$ZZ \to q\bar{q}l^+l^-$:

- BR = 14%
- Two jets and two energetic and isolated leptons
- Background from $Z\gamma^\star \to q\bar{q}l^+l^-$ and WW in $q\bar{q}\tau^+\tau^-$

New $qq\tau\tau$ analysis in DELPHI (2000 data) Preliminary



$ZZ \to l^+l^-\nu\bar{\nu}$:

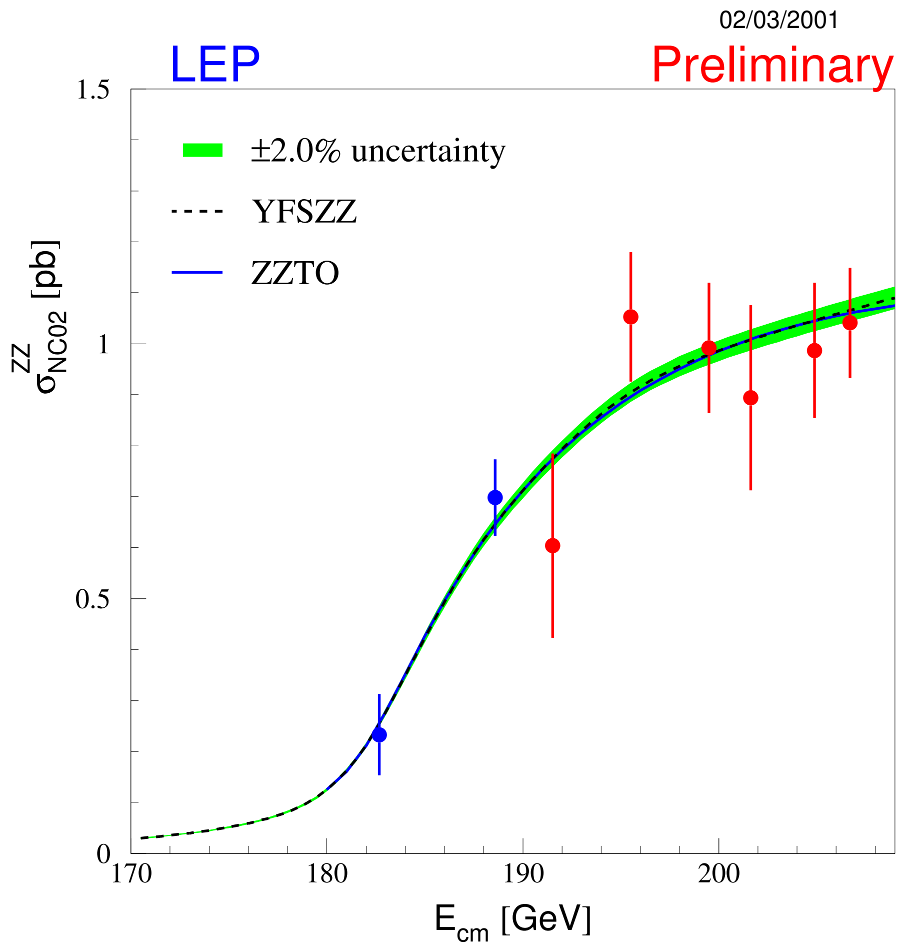
- BR = 4%
- Two acollinear leptons with visible and recoil masses compatible with M_Z
- Background from WW

$ZZ \to l^+l^-l^+l^-$:

- BR = 1%
- Four energetic leptons
- Background from non-resonant $e^+e^-l^+l^-$ production

ZZ Cross Section

$\sqrt{s}$ (GeV)	ZZ Cross section (pb)					
	ALEPH	DELPHI	L3	OPAL	LEP	YFSZZ
183	0.11 $\pm$ 0.14	0.38 $\pm$ 0.15	0.31 $\pm$ 0.16	0.12 $\pm$ 0.19	0.23 $\pm$ 0.08	0.25
189	0.67 $\pm$ 0.14	0.60 $\pm$ 0.15	0.73 $\pm$ 0.15	0.80 $\pm$ 0.15	0.70 $\pm$ 0.07	0.65
192	0.53 $\pm$ 0.33	0.55 $\pm$ 0.41	0.29 $\pm$ 0.34	1.13 $\pm$ 0.38	0.60 $\pm$ 0.18	0.66
196	0.69 $\pm$ 0.23	1.17 $\pm$ 0.26	1.18 $\pm$ 0.24	1.28 $\pm$ 0.27	1.05 $\pm$ 0.13	0.90
200	0.70 $\pm$ 0.23	1.08 $\pm$ 0.25	1.25 $\pm$ 0.26	1.01 $\pm$ 0.26	0.99 $\pm$ 0.13	0.99
202	0.70 $\pm$ 0.35	0.87 $\pm$ 0.35	0.95 $\pm$ 0.36	1.09 $\pm$ 0.38	0.89 $\pm$ 0.18	1.01
205	1.21 $\pm$ 0.27	1.05 $\pm$ 0.26	0.69 $\pm$ 0.24	1.08 $\pm$ 0.27	0.99 $\pm$ 0.13	1.05
207	1.01 $\pm$ 0.18	0.97 $\pm$ 0.22	1.17 $\pm$ 0.22	1.03 $\pm$ 0.22	1.04 $\pm$ 0.11	1.06



The error is dominated by statistics.

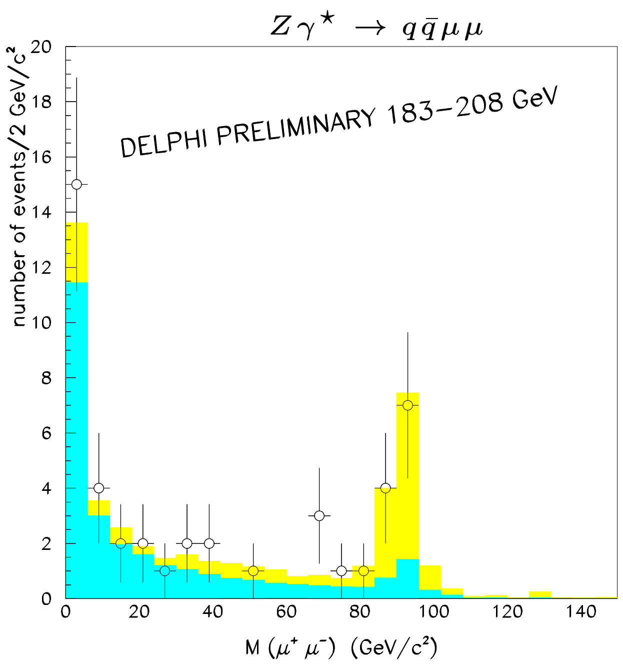
$Z\gamma^\star$ Production

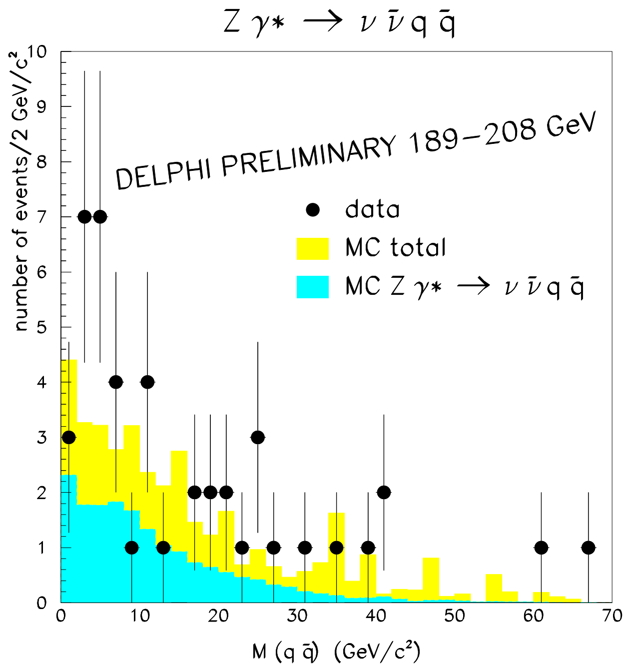
Why is the process $e^+e^- \rightarrow Z\gamma^\star \rightarrow f\bar{f}f'\bar{f}'$ interesting ?

- **$Z\gamma^\star$ is an important part of NC08 ($ZZ+Z\gamma^\star+\gamma^\star\gamma^\star$) cross section (when no electrons are in the final state).**
- **Test of the SM: $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings**

DELPHI @ $183-208$ GeV

Channel	$<\sigma^{meas.}_{Z\gamma^\star\rightarrow f\bar{f}q\bar{q}}>$ (pb)	$\sigma^{exp.}_{Z\gamma^\star\rightarrow f\bar{f}q\bar{q}}$ (pb)
$\mathbf{q\bar{q}}\mu\mu$	0.123 ± 0.025	0.098
$\nu\bar{\nu}\mathbf{q\bar{q}}$	0.129 ± 0.038	$0.092 - 0.084$
$\mathbf{q\bar{q}q\bar{q}}$	0.074 ± 0.045	0.082



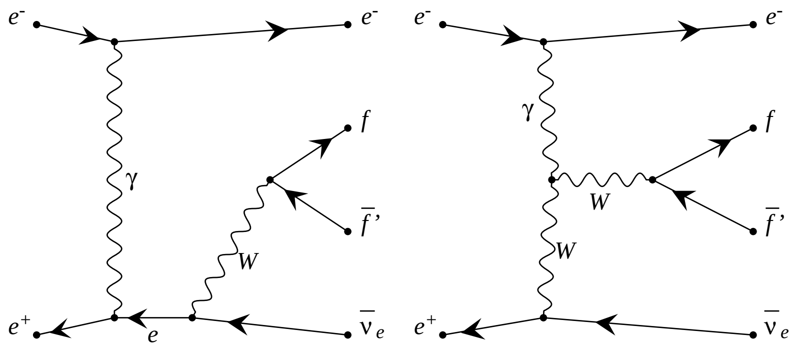


Work in progress: combine the measurements for the different channels and include new channels.

Single W production

One of the dominant t-diagrams for single W production includes $WW\gamma$ vertex

$\Rightarrow$ **test of SM**

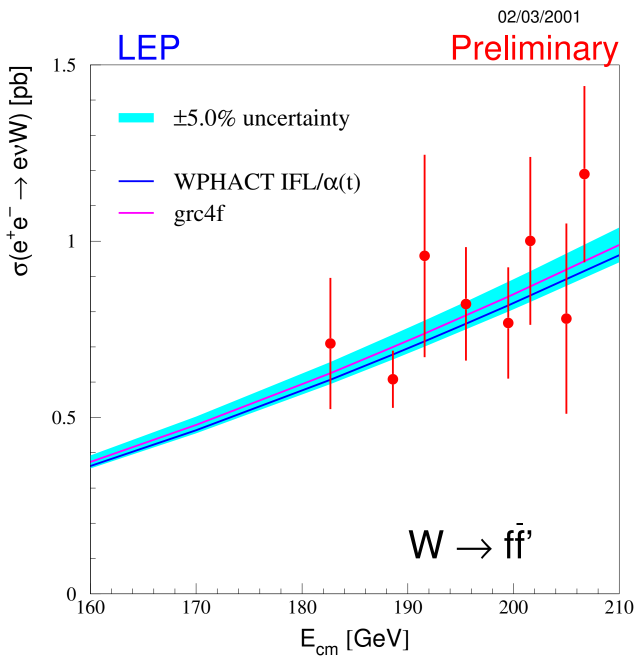


Signal definition:

Process	diagrams	cuts
$e^- \bar{\nu}_e e^+ \nu_e$	t-channel only	$E_{e^+} > 20$ GeV, $\mid\cos\theta_{e^+}\mid < 0.95$ $\mid\cos\theta_{e^-}\mid > 0.95$
$e^- \bar{\nu}_e l^+ \nu_l$ ($l = \mu, \tau$)	t-channel only	$E_{l^+} > 20$ GeV
$e^- \bar{\nu}_e q\bar{q}'$	t-channel only	$M_{q\bar{q}'} > 45$ GeV

(Charge conjugation is implied)

ALEPH @ 183-208 GeV
DELPHI @ 189-202 GeV
L3 @ 189-202 GeV
OPAL @ 189 GeV



Conclusions

- Preliminary measurements using all LEP2 data for:
  - WW cross section and W branching ratios
  - ZZ cross section
- $WW\gamma$ and WWZ anomalous couplings measurements need attention in the estimation of $\mathcal{O}(\alpha)$ corrections. Preliminary results only from ALEPH.
- Preliminary measurements also for:
  - W polarization in WW events
  - $Z\gamma^{\star}$ cross section
  - $We\nu_e$ cross section
- No evidence of deviations from the Standard Model expectations have been observed
- Work in progress towards LEP final results.