ZZ Production at LEP

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CERN

L3 COLLABORATION

EPS-HEP99, Tampere (Finland) 15-21 July 1999

OUTLINE

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INTRODUCTION

WW

FOUR FERMION PROCESSES AT LEP 2

$\gamma\gamma$

From $\sqrt{s} = 183$ GeV

also ZZ contribution

Small contribution

to the cross section.

Irreducible

backgrounds

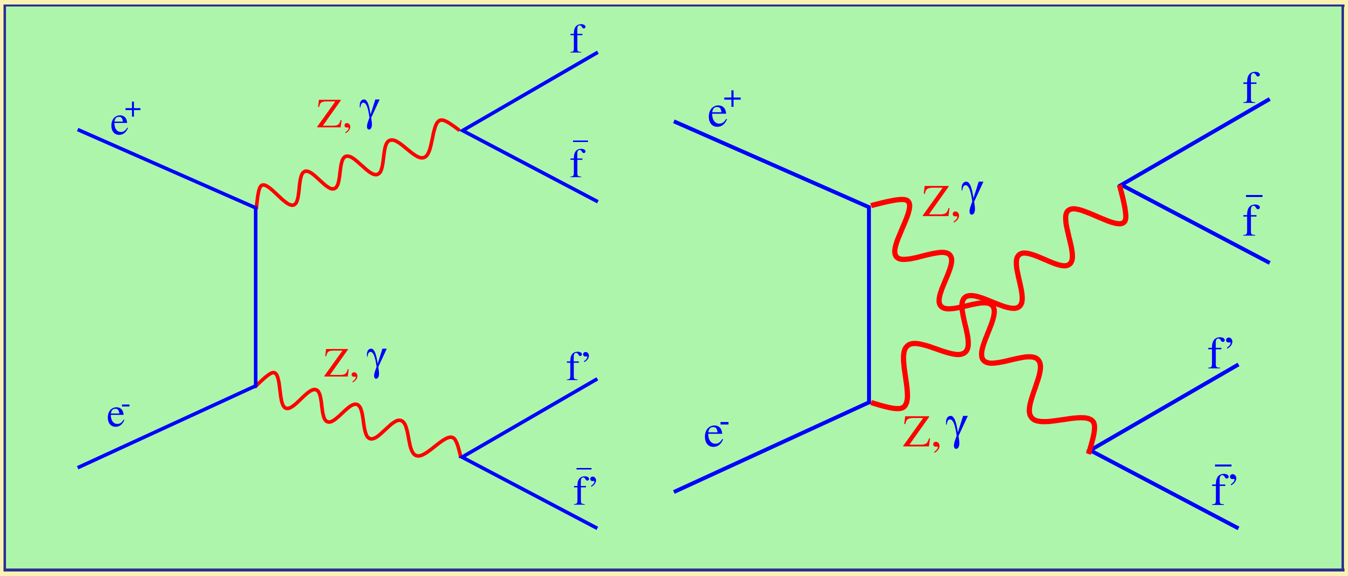
Necessary:

SIGNAL DEFINITION

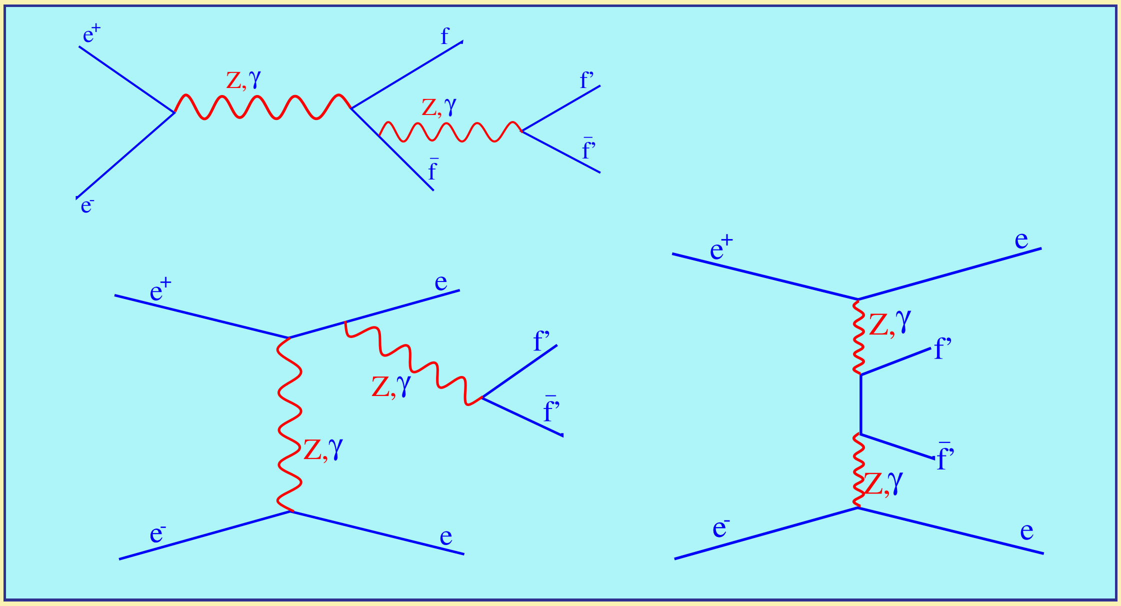
SIGNAL DEFINITION

CONVERSION DIAGRAMS (NC02):

This is the contribution we want to maximize with the selection.



SOME OTHER (NON-RESONANT) DIAGRAMS:



SIGNAL DEFINITION

The signal definition depends on the experiment

ALEPH

Quote NC02 cross section.

DELPHI

Quote NC02 but use in the analysis four fermion within cuts:
All 4f in $|M_{\rm Z} - M_{ff,f'f'}| < 10$ GeV
Channels in common with CC not analysed.

L3

Quote four fermion within cuts:
70 GeV $< M_{ff,f'f'} <$ 105 GeV
$E_f > 1$ GeV
$|\cos\theta_e| < 0.95$
Exclude 75 GeV $< M_{ff'} <$ 85 GeV
for channels in common with CC.

OPAL

Quote NC02 cross section.

◁ ● ▷ ◁ ● ▷ ◁ ● ▷ ◁ ● ▷ ◁ ● ▷ ◁ ● ▷ ◁ ● ▷ ◁ ●▷

ALL

For combinations use NC02 cross section for all the experiments.

Interest of ZZ

To change from 4f within cuts to NC02:

$$\sigma_{NC02} = \sigma^{MC}_{NC02} / \sigma^{MC}_{4f} \quad \sigma_{ZZ}$$

Interest of ZZ

Process produced for the first time at a e^+e^- collider.

Main background for Higgs search (if $M_H \sim M_Z$).

Low cross section, interesting to test searching algorithms.

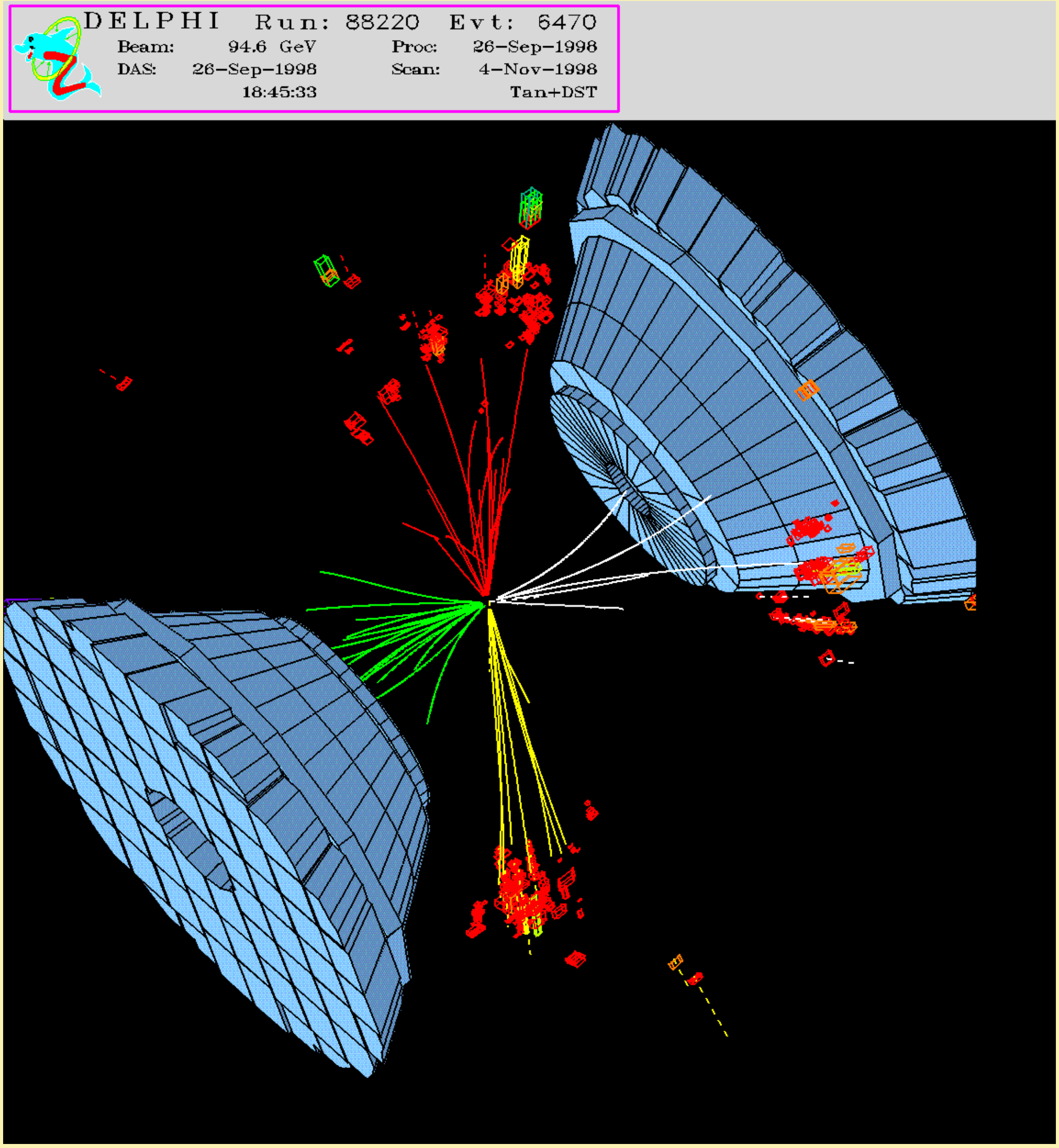
Test anomalous couplings among neutral bosons.

Selection of the events

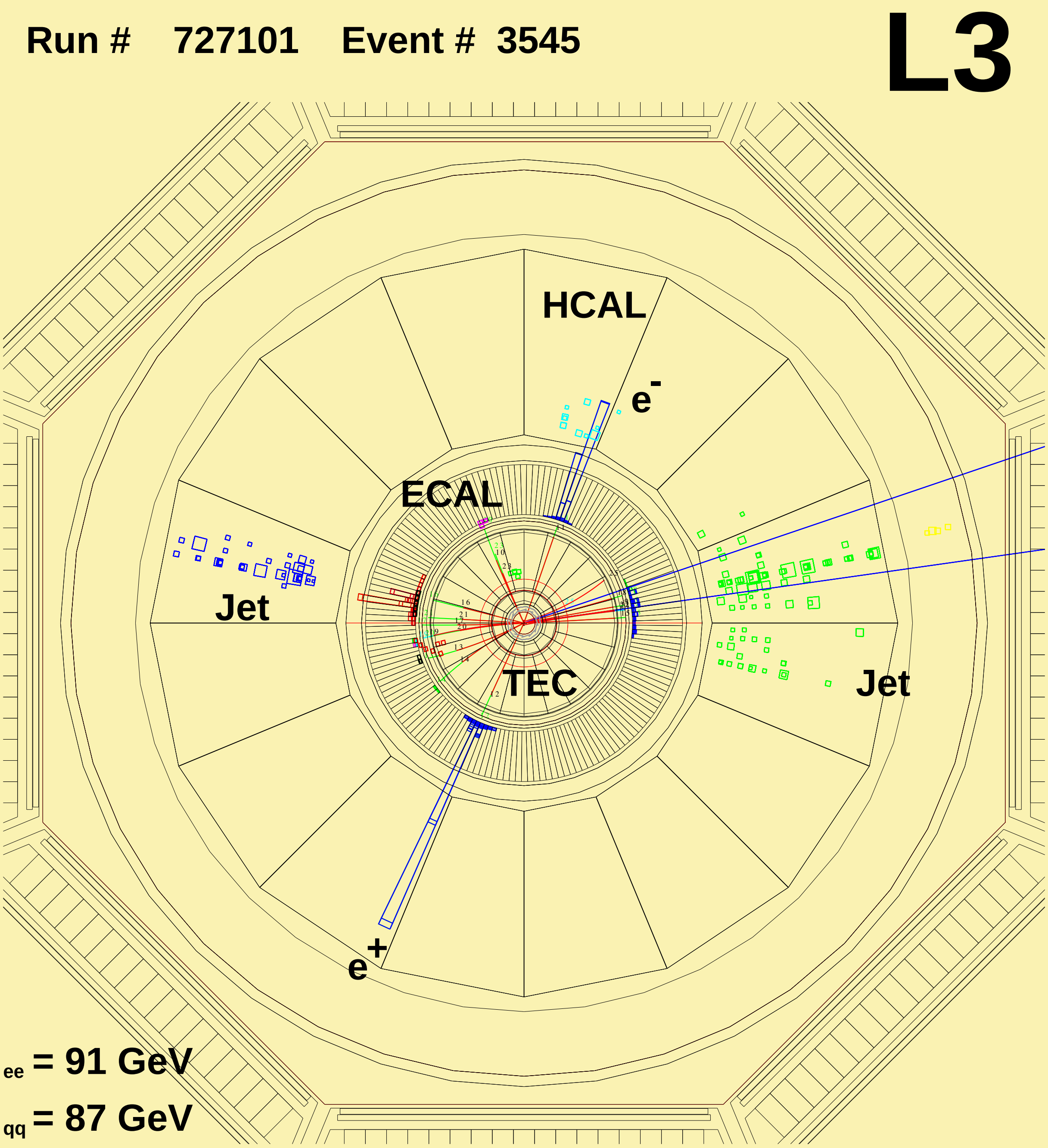
- FEATURES OF ZZ EVENTS

Channel	Br. Ratio	Experimental Signature	Background
$q_1\bar{q}_1q_2\bar{q}_2$	Large	4 hadronic jets	Large
$q\bar{q}\nu\bar{\nu}$	Large	2 jets + missing energy	Large
$q\bar{q}l^+l^-$	Medium	2 jets + 2 leptons	Low
$l^+l^-\nu\bar{\nu}$	Low	2 leptons + missing energy	Medium
$l_1^+l_1^-l_2^+l_2^-$	Low	4 leptons	Medium
$\nu_1\bar{\nu}_1\nu_2\bar{\nu}_2$		invisible!	

qqqq Candidate

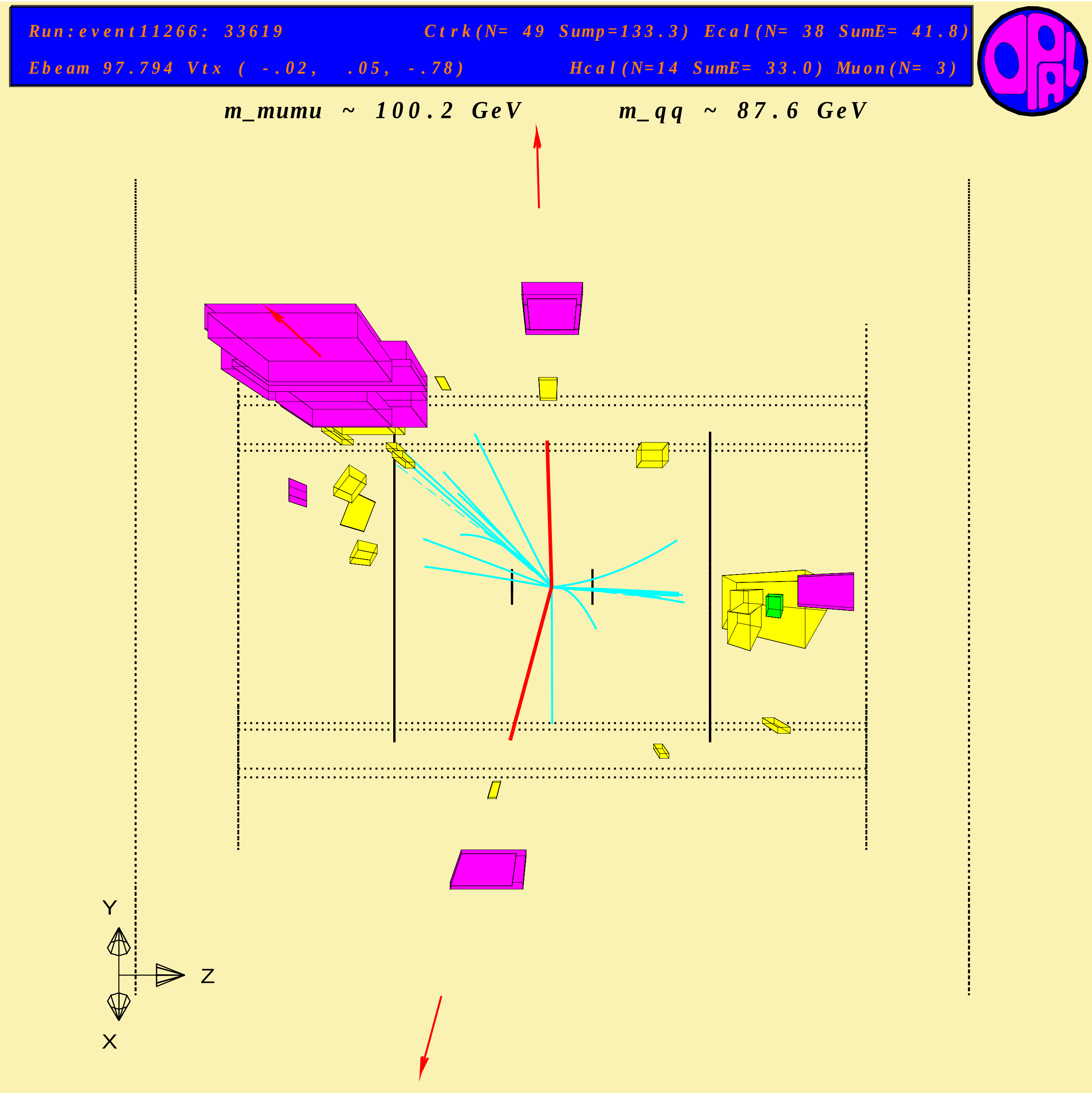


eeqq Candidate

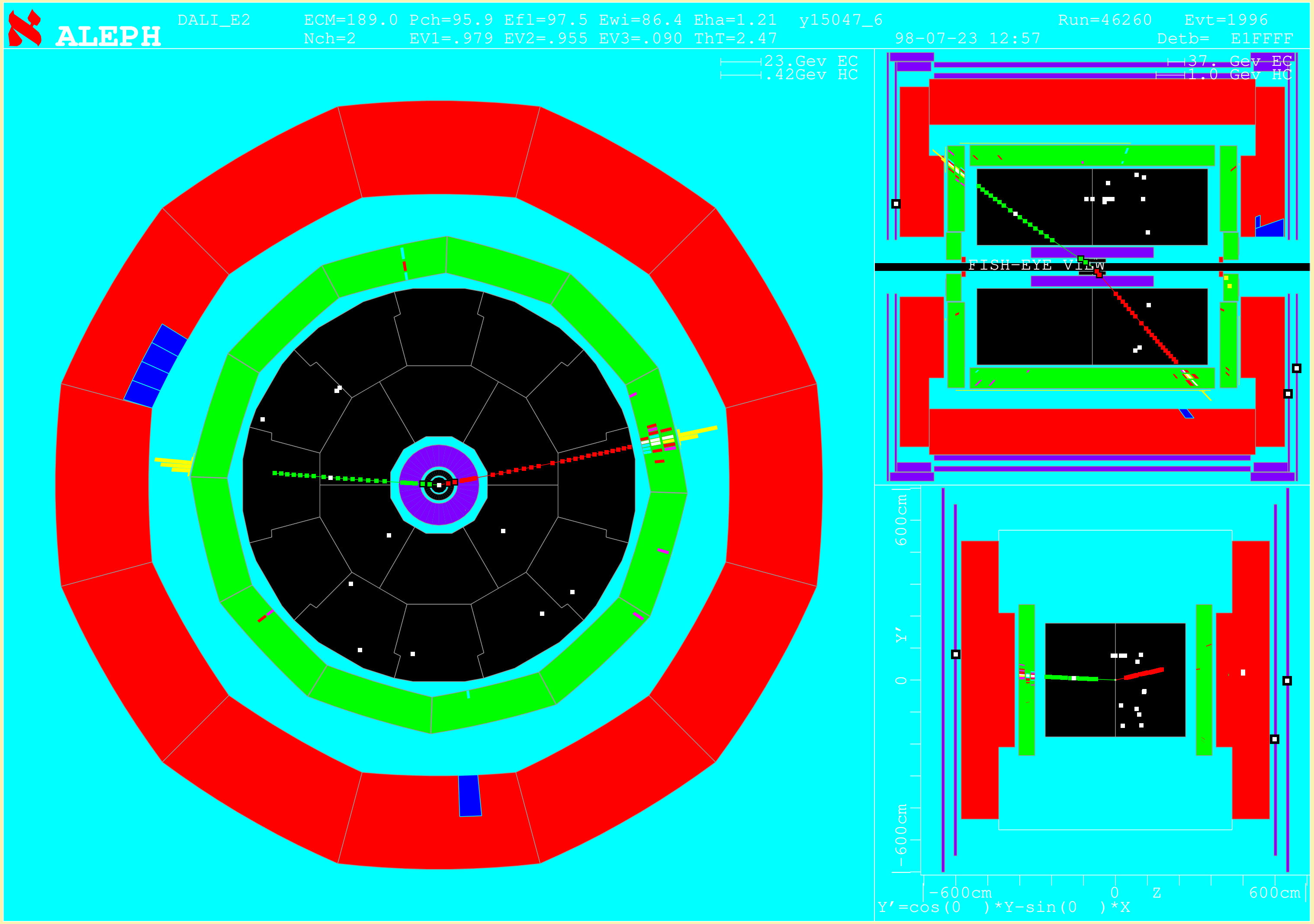


M_{ee} = 91 GeV
M_{qq} = 87 GeV
M_{5C} = 89 GeV

$\mu\mu$qq Candidate



$ll\nu\nu$ Candidate



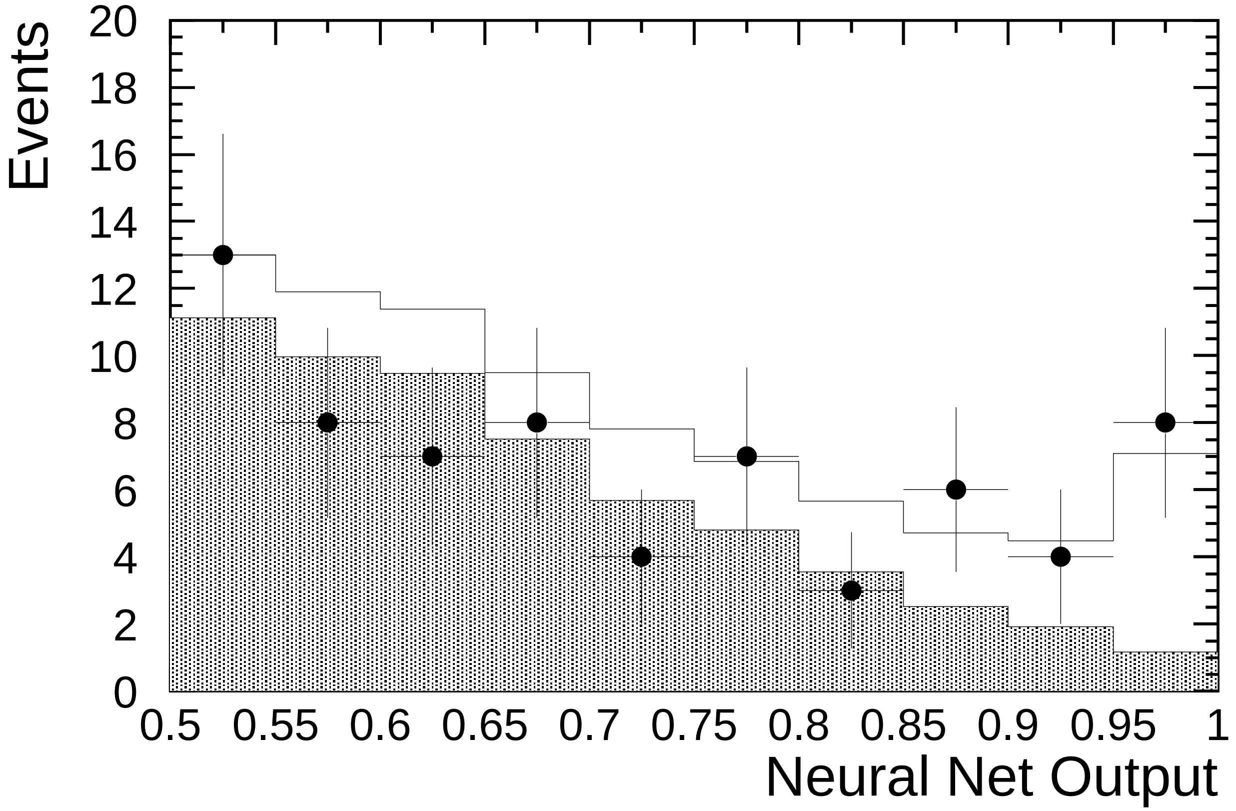
ALEPH RESULTS

$\sqrt{s} = 189$ GeV

	ϵ (%)	N_{bkg}	N_{ZZ}^{SM}	N_{obs}	σ (pb)
$\ell^+\ell^-XX$ cut+NN	76.7 ± 0.5	1.1	8.8	12	$0.80^{+0.28}_{-0.23}$
$q\bar{q}q'\bar{q}'$ (b) cut	14.6 ± 0.2	3.8	8.3	14	$0.80^{+0.32}_{-0.27}$
$q\bar{q}q'\bar{q}'$ (non-b) cut	27.4 ± 0.2	60.0	16.0	69	$0.36^{+0.35}_{-0.32}$
$q\bar{q}q'\bar{q}'$ NN	$15.2 \pm 0.6^*$	19.7	17.2	32	$0.58^{+0.22}_{-0.19}$
$q\bar{q}\nu\bar{\nu}$ cut	47.2 ± 0.3	13.0	15.0	30	$0.74^{+0.25}_{-0.22}$
$q\bar{q}\nu\bar{\nu}$ NN	$22.3 \pm 0.2^*$	65.0	25.3	88	$0.65^{+0.22}_{-0.20}$
$\ell^+\ell^-\nu\bar{\nu}$ cut+NN	50.3 ± 1.5	1.5	1.4	1	$-0.26^{+0.66}_{-0.30}$
$\tau\tau q\bar{q}$ NN	$1.96 \pm 0.06^*$	1.5	2.2	3	$0.44^{+0.62}_{-0.41}$
Total cut		20.9	35.7	60	

* : Respect to the complete ZZ sample

ALEPH RESULTS



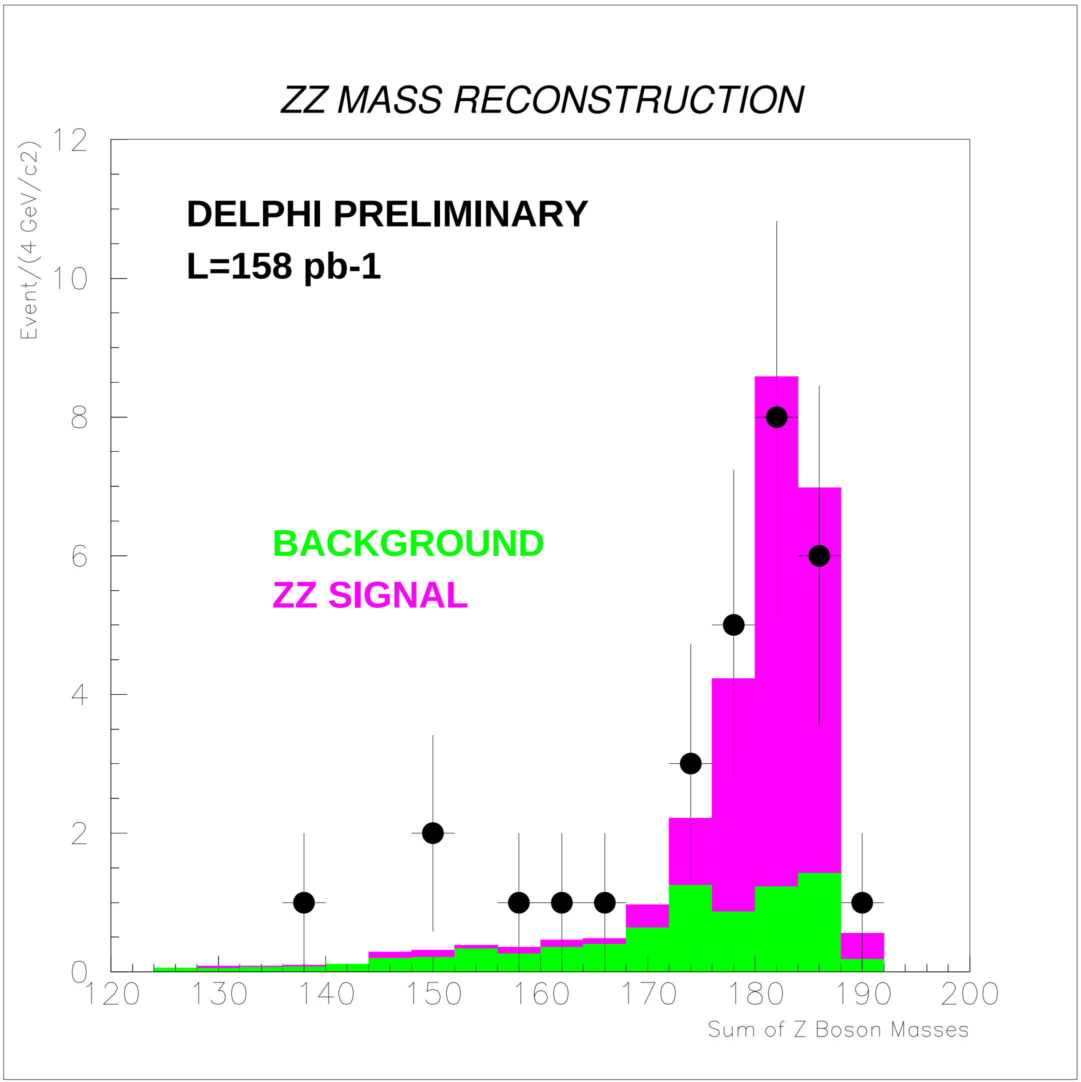
Neural Network output
for qqqq events

DELPHI RESULTS

$\sqrt{s} = 189$ GeV

Channel	N_{obs}	$N_{expected}$	N_{signal}	N_{bkg}	R
$\ell^+\ell^-\ell'^+\ell'^-$	1	0.9	0.6	0.3	-
$e^+e^-q\bar{q}$	2	4.5 ± 0.4	3.7 ± 0.4	0.8 ± 0.2	0.88
$\mu^+\mu^-q\bar{q}$	6	4.5 ± 0.4	4.0 ± 0.5	0.5 ± 0.2	1.05
$q\bar{q}\nu\bar{\nu}$	6	7.7 ± 0.5	5.7 ± 0.3	2.0 ± 0.4	1.05
$b\bar{b}q\bar{q}$	6	4.9	3.5	1.4	1.14
Total	21	22.5	17.5	5.0	-

DELPHI RESULTS



Sum of the Z boson Masses

L3 RESULTS

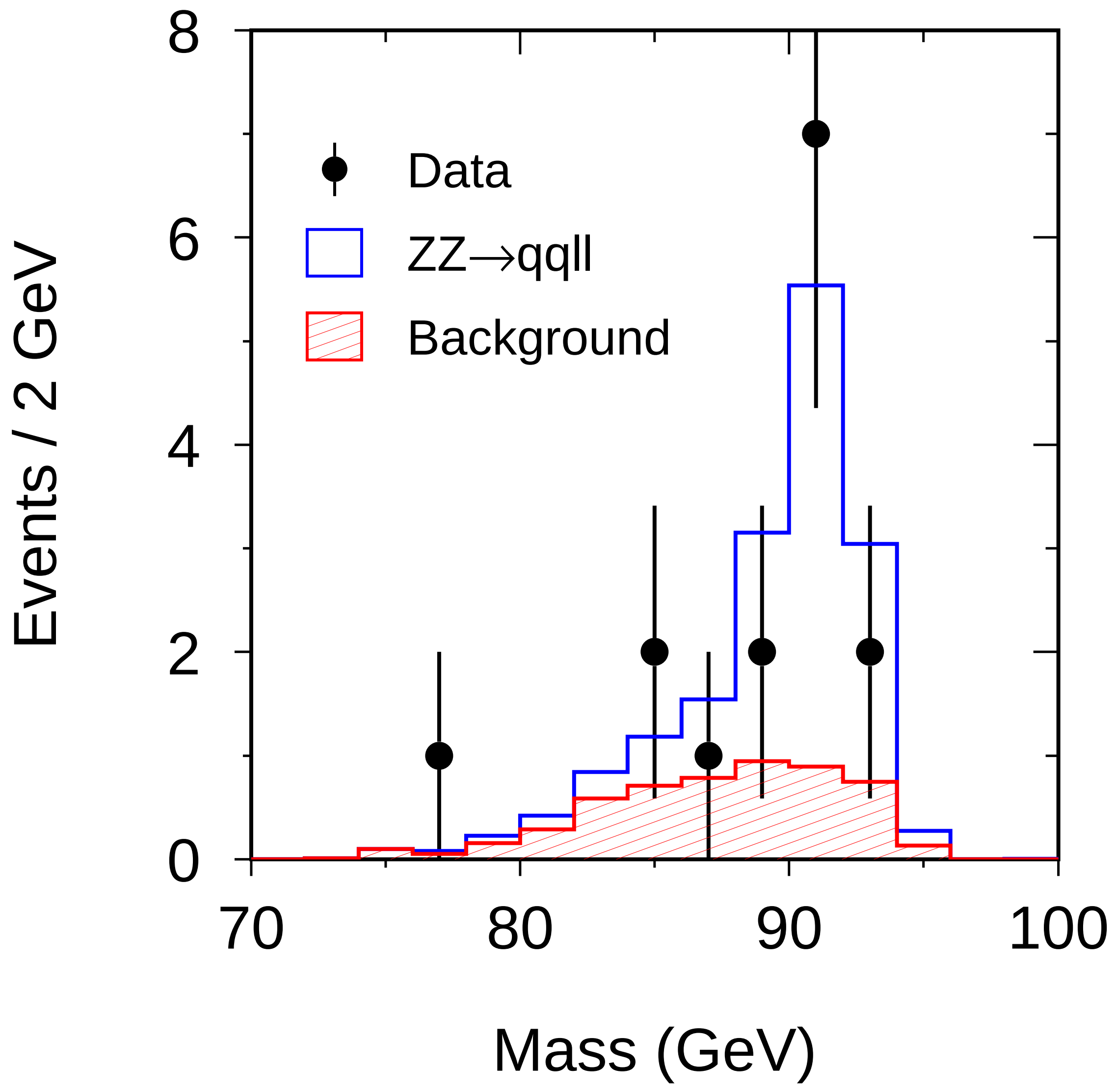
$\sqrt{s} = 183$ GeV:

Channel	ϵ (%)	N_{obs}	N_{signal}	N_{bkg}
$q\bar{q}q'\bar{q}'$ NN	34	47	2.3	46
$q\bar{q}\ell^+\ell^-$ cut	36-79	2	1.2	1.5
$q\bar{q}\nu\bar{\nu}$ NN	47	12	1.6	13.0
$\ell^+\ell^-\nu\bar{\nu}$ cut	33-37	2	0.2	1.2
$\ell^+\ell^-\ell'^+\ell'^-$ cut	15-78	0	0.1	0.1
Total	-	63	5.4	61.8

$\sqrt{s} = 189$ GeV:

Channel	ϵ (%)	N_{obs}	N_{signal}	N_{bkg}	$\sigma_{Measured}/\sigma_{SM}$
$q\bar{q}q'\bar{q}'$ NN	47	163	24.2	153	$1.00^{+0.44}_{-0.40}$
$q\bar{q}\ell^+\ell^-$ cut	32-78	15	10.9	5.4	$0.94^{+0.38}_{-0.32}$
$q\bar{q}\nu\bar{\nu}$ NN	50	40	15.7	18.9	$1.29^{+0.39}_{-0.35}$
$\ell^+\ell^-\nu\bar{\nu}$ cut	21-29	3	0.7	1.4	$2.00^{+2.20}_{-1.50}$
$\ell^+\ell^-\ell'^+\ell'^-$ cut	28-66	2	0.7	0.6	$1.50^{+2.30}_{-1.40}$
Total	-	223	52.2	179.3	

L3 RESULTS



Z boson Mass in qqll events
from 5C kinematic fit

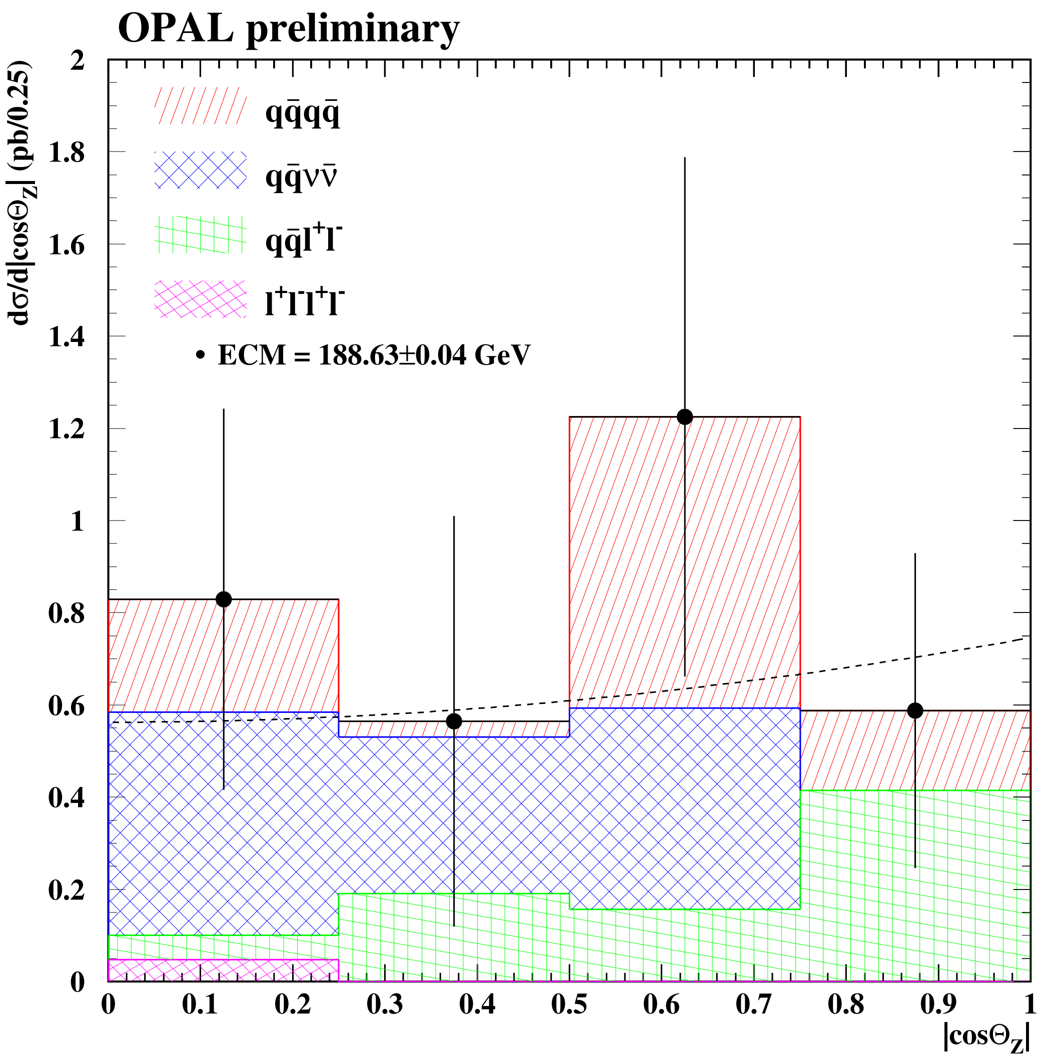
OPAL RESULTS

$\sqrt{s} = 183$ GeV:

Channel	ϵ (%)	N_{obs}	N_{signal}	N_{bkg}
$q\bar{q}q'\bar{q}'$	64 ± 8	1	0.09 ± 0.01	0.12 ± 0.08
$q\bar{q}\ell^+\ell^-$	26-70	0	0.76 ± 0.02	0.32 ± 0.04
$q\bar{q}\nu\bar{\nu}$	30 ± 2	2	0.88 ± 0.07	1.75 ± 0.24
$\ell^+\ell^-\ell'^+\ell'^-$	57 ± 4	1	0.65 ± 0.04	0.38 ± 0.18
Total	-	4	2.38	2.57

$\sqrt{s} = 189$ GeV:

Channel	ϵ (%)	N_{obs}	N_{signal}	N_{bkg}
$q\bar{q}q'\bar{q}'$	38 ± 2	45	12.20 ± 0.70	37.65 ± 3.93
$q\bar{q}\ell^+\ell^-$	27-75	9	6.71 ± 0.15	1.00 ± 0.38
$q\bar{q}\nu\bar{\nu}$	35 ± 3	20	8.36 ± 0.61	7.51 ± 0.94
$\ell^+\ell^-\ell'^+\ell'^-$	57 ± 4	1	0.65 ± 0.04	0.38 ± 0.18
Total	-	75	27.92	46.54



$\cos\theta_Z$ for the selected events

LEP σ^{ZZ} at $\sqrt{s} = 183$ GeV

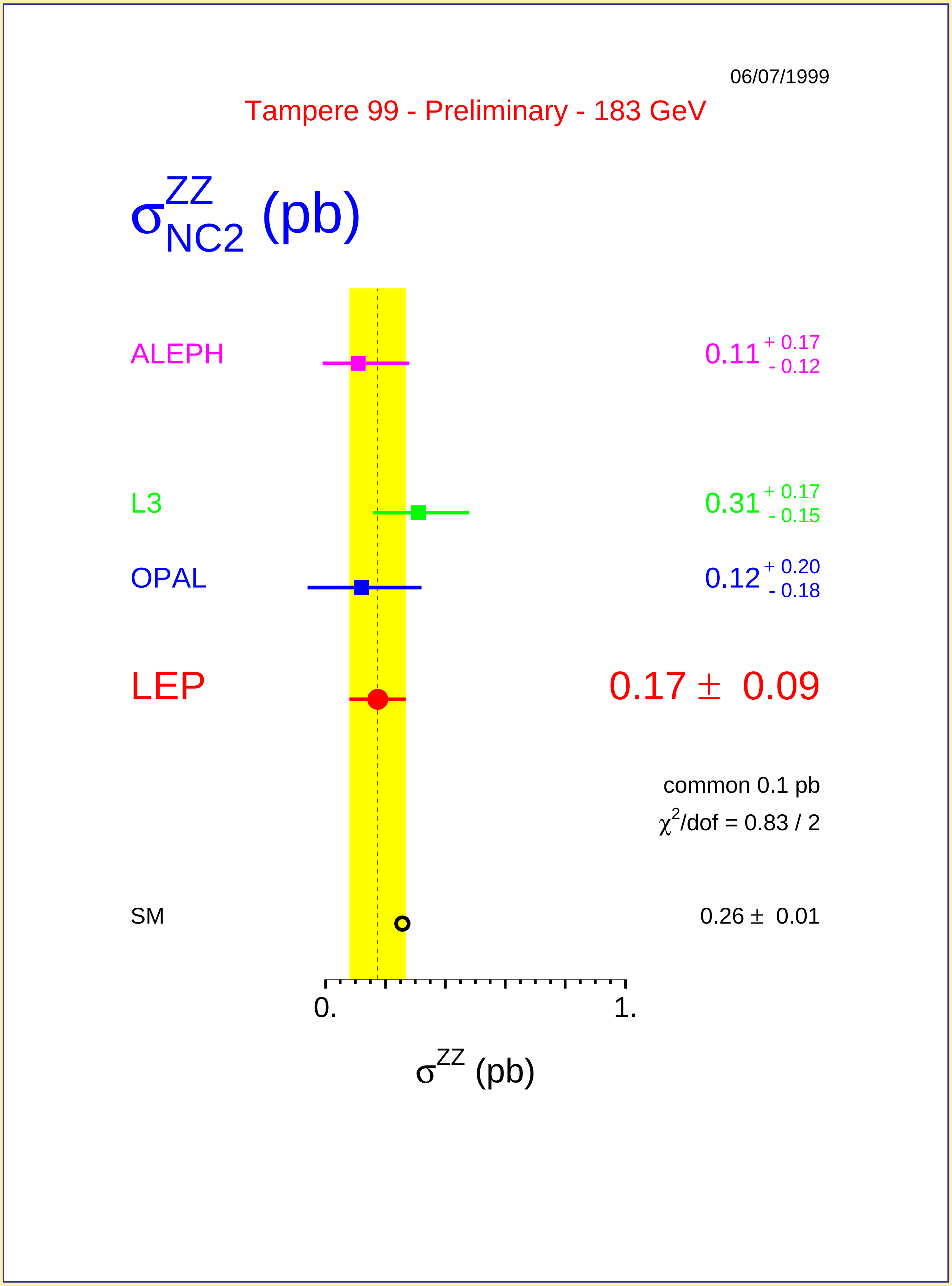
Experiment	σ NC02 ZZ (pb)	σ 4f within cuts (pb)
ALEPH	$0.110^{+0.160}_{-0.110} \pm 0.041$	-
DELPHI	-	-
L3	$0.310^{+0.160}_{-0.150} \pm 0.051$	$0.300^{+0.220}_{-0.160} \pm 0.051$
OPAL	$0.120^{+0.200}_{-0.180} \pm 0.025$	-

Combining all these results:

$$\sigma^{ZZ}_{NC02} = 0.174 \pm 0.090 \pm 0.026 \text{ pb}$$

STANDARD MODEL CROSS SECTION $= 0.26 \pm 0.01$ pb

LEP σ^{ZZ} at $\sqrt{s} = 183$ GeV



LEP σ^{ZZ} at $\sqrt{s} = 189$ GeV

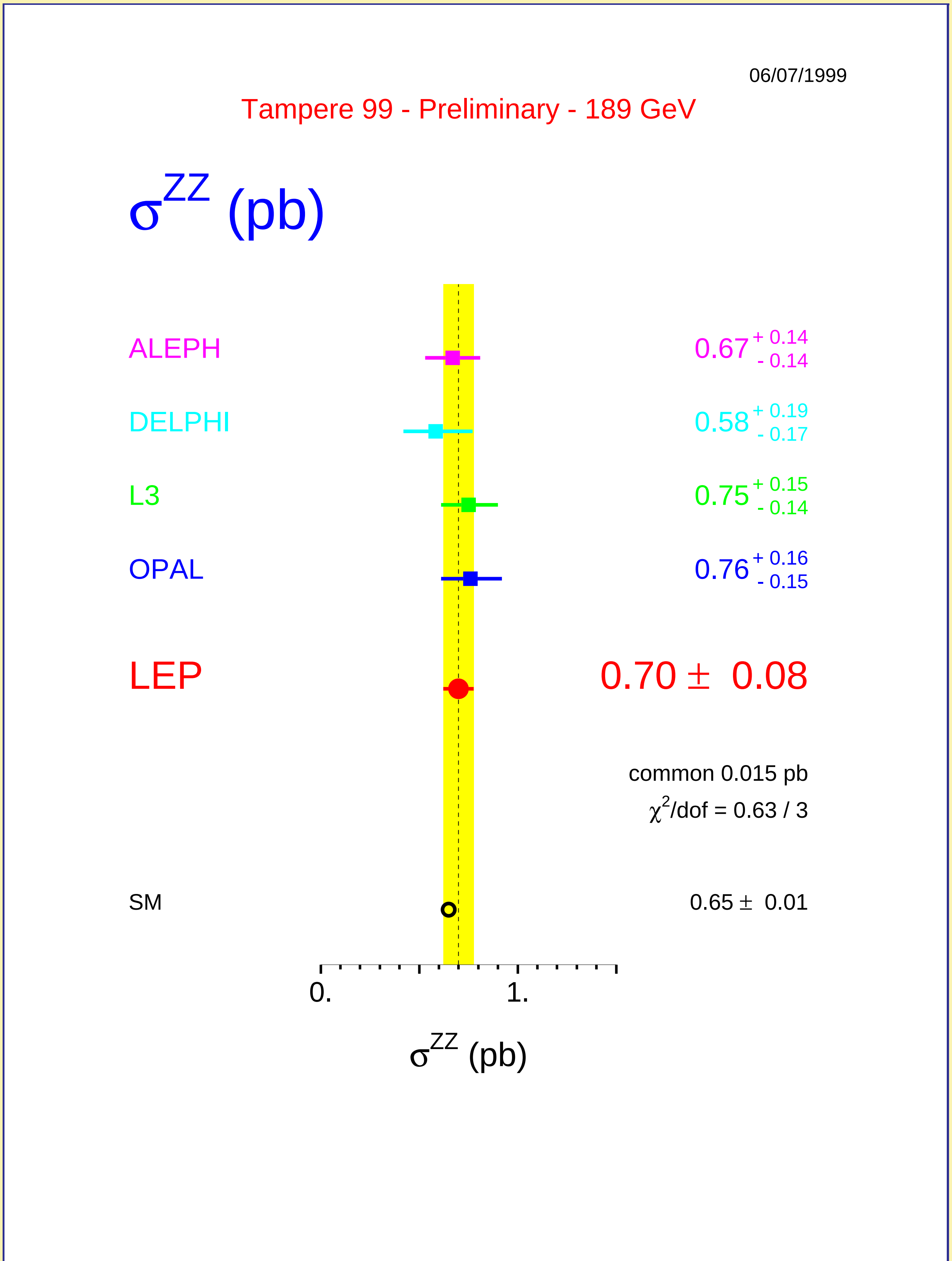
Experiment	σ NC02 ZZ (pb)	σ 4f within cuts (pb)
ALEPH	$0.670 \pm 0.130 \pm 0.041$	-
DELPHI	$0.584^{+0.177}_{-0.153} \pm 0.061$	-
L3	$0.750^{+0.150}_{-0.140} \pm 0.028$	$0.730^{+0.150}_{-0.140} \pm 0.028$
OPAL	$0.760^{+0.140}_{-0.130} \pm 0.065$	-

Combining all these results:

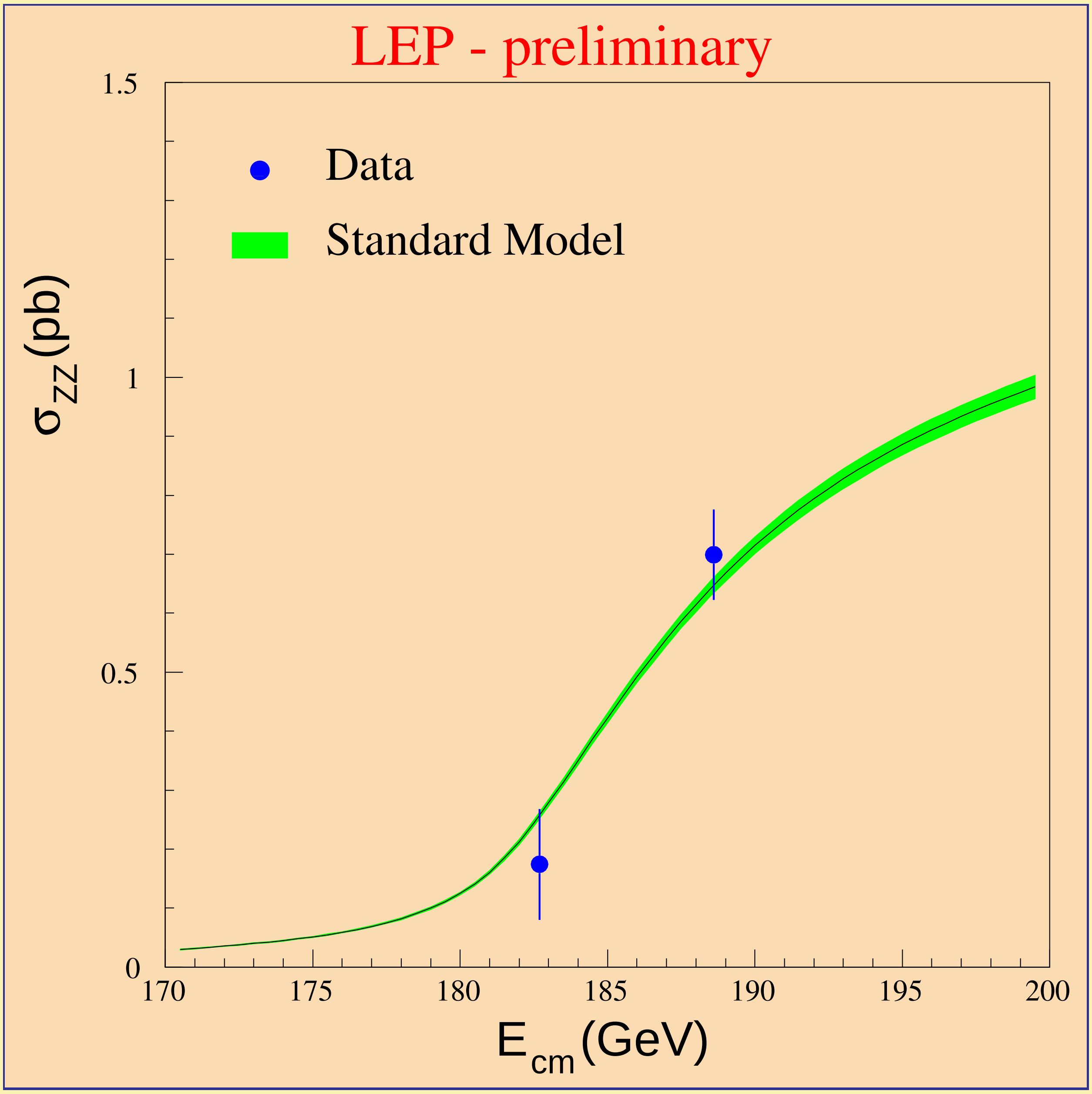
$$\sigma^{ZZ}_{NC02} = 0.699 \pm 0.072 \pm 0.027 \text{ pb}$$

STANDARD MODEL CROSS SECTION $= 0.65 \pm 0.01$ pb

LEP σ^{ZZ} at $\sqrt{s} = 189$ GeV



LEP ZZ CROSS-SECTION



ANOMALOUS COUPLINGS

Motivation $\Rightarrow$ Look for deviations
of the SM in gauge bosons couplings
Similar to WWγ, WWZ AC

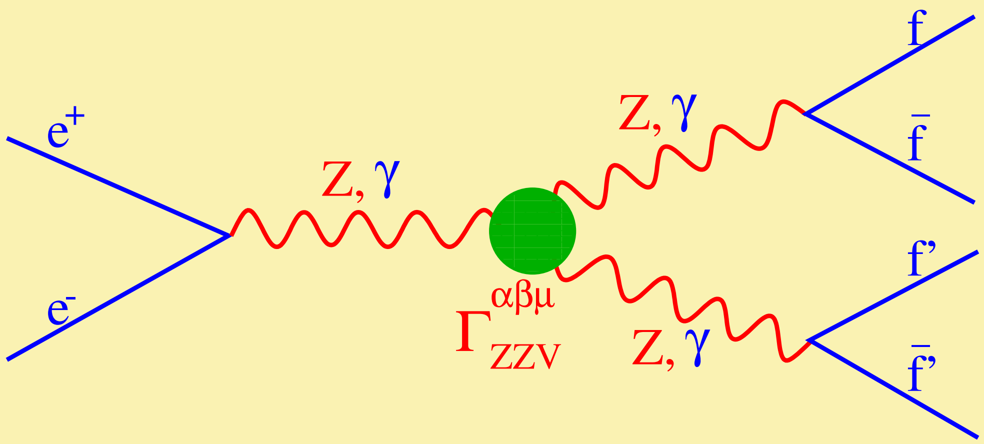
Physics under AC
Compositeness
New particles in loops

Only 4 Couplings due
to on-shellness and Bose symmetry
f_4^V, f_5^V, $V = \gamma, Z$
f_4^V: C ODD, CP ODD
f_5^V: C,P ODD, CP EVEN

These couplings are
Zero at tree level
in the Standard Model
(very small value through loops)

Anomalous contribution
increases with $\sqrt{s}$

ANOMALOUS COUPLINGS

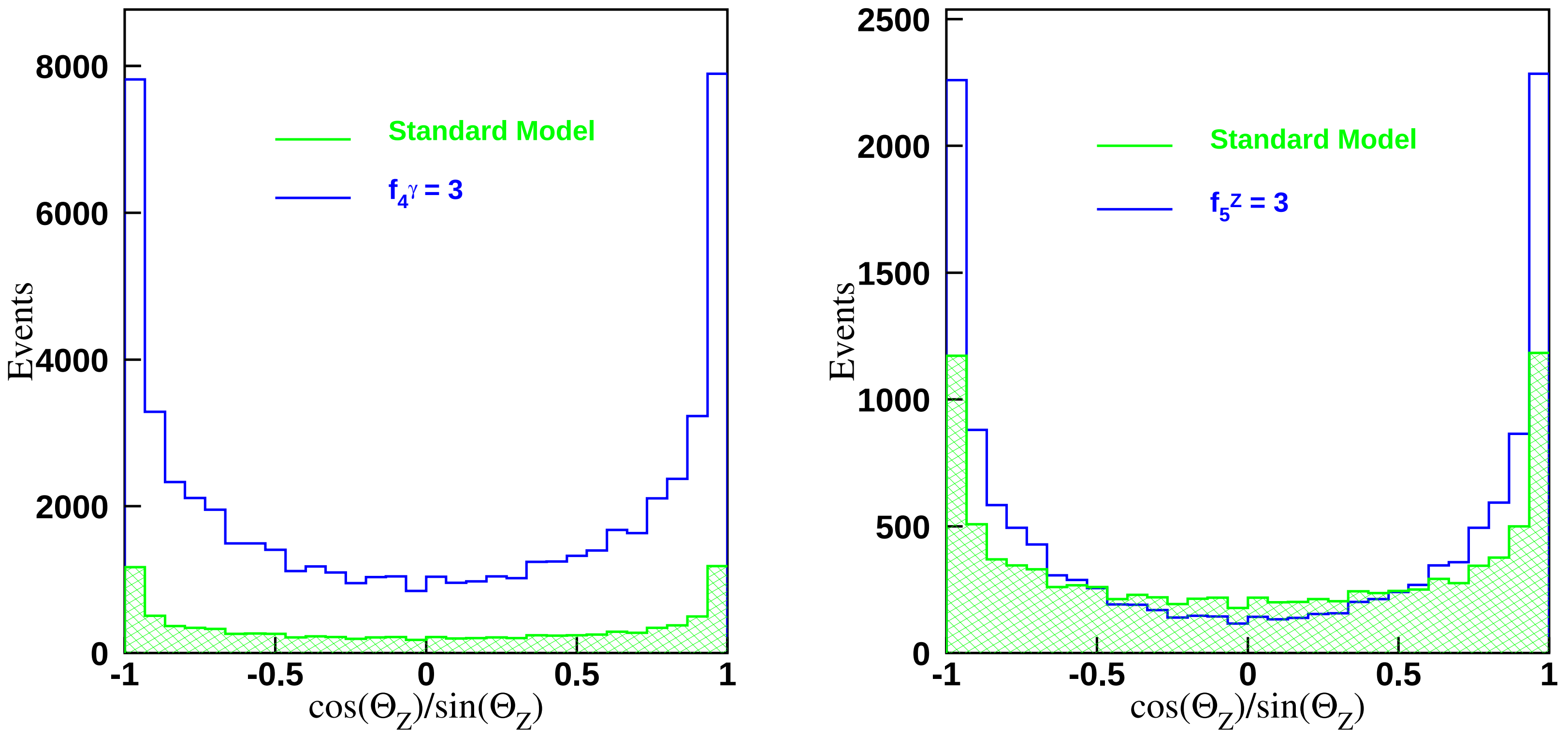


Most general vertex function $\Gamma^{\alpha\beta\mu}_{ZZV}$
On-Shell + Lorentz Invariant

Has 3 experimental effects:

1. Change in the total cross section
2. Change in the angular distribution
3. Change in the average polarization

ANOMALOUS COUPLINGS



Then a fit of the cross section SM+AC (dependent on the couplings) to the data is done. No evidence of AC is found, and limits at 95% C. L. are set.

ANOMALOUS COUPLINGS

RESULTS

L3	DELPHI
$-1.1 \leq f_4^\gamma \leq 1.1$	$-1.6 \leq f_4^\gamma \leq 1.6$
$-3.0 \leq f_5^\gamma \leq 2.9$	$-3.8 \leq f_5^\gamma \leq 3.8$
$-1.9 \leq f_4^Z \leq 1.9$	$-2.6 \leq f_4^Z \leq 2.6$
$-4.9 \leq f_5^Z \leq 4.7$	$-7.0 \leq f_5^Z \leq 5.7$

OPAL

$$-1.2 \leq Re(f_4^\gamma) \leq 1.2$$
$$-3.2 \leq Re(f_5^\gamma) \leq 3.0$$
$$-2.0 \leq Re(f_4^Z) \leq 2.0$$
$$-5.1 \leq Re(f_5^Z) \leq 3.6$$

$$-1.2 \leq Im(f_4^\gamma) \leq 1.2$$
$$-3.2 \leq Im(f_5^\gamma) \leq 3.0$$
$$-2.0 \leq Im(f_4^Z) \leq 1.9$$
$$-5.2 \leq Im(f_5^Z) \leq 5.4$$

Conclusions 1

- The $e^+e^- \to$ ZZ cross section has been measured at $\sqrt{s} = 183$ GeV and $\sqrt{s} = 189$ GeV at LEP

$$\sigma_{\mathrm{ZZ}}(\sqrt{s} = 183\ \ \mathrm{GeV}) = 0.174 \pm 0.090 \pm 0.026\ \text{pb}$$
$$\sigma_{\mathrm{ZZ}}(\sqrt{s} = 189\ \ \mathrm{GeV}) = 0.699 \pm 0.072 \pm 0.027\ \text{pb}$$

First error is statistical and second is systematic

- These are the first measurements at e^+e^- colliders
- Good agreement with the Standard Model is found

Conclusions 2

- *The following limits on the anomalous couplings ZZV have been set:*

L3

$$-1.1 \le f_4^\gamma \le 1.1$$
$$-3.0 \le f_5^\gamma \le 2.9$$
$$-1.9 \le f_4^Z \le 1.9$$
$$-4.9 \le f_5^Z \le 4.7$$

DELPHI

$$-1.6 \le f_4^\gamma \le 1.6$$
$$-3.8 \le f_5^\gamma \le 3.8$$
$$-2.6 \le f_4^Z \le 2.6$$
$$-7.0 \le f_5^Z \le 5.7$$

OPAL

$$-1.2 \le Re(f_4^\gamma) \le 1.2 \qquad -1.2 \le Im(f_4^\gamma) \le 1.2$$
$$-3.2 \le Re(f_5^\gamma) \le 3.0 \qquad -3.2 \le Im(f_5^\gamma) \le 3.0$$
$$-2.0 \le Re(f_4^Z) \le 2.0 \qquad -2.0 \le Im(f_4^Z) \le 1.9$$
$$-5.1 \le Re(f_5^Z) \le 3.6 \qquad -5.2 \le Im(f_5^Z) \le 5.4$$