Z Boson Pair Production and Couplings with the L3 Detector at LEP

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L3 collaboration

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Outline

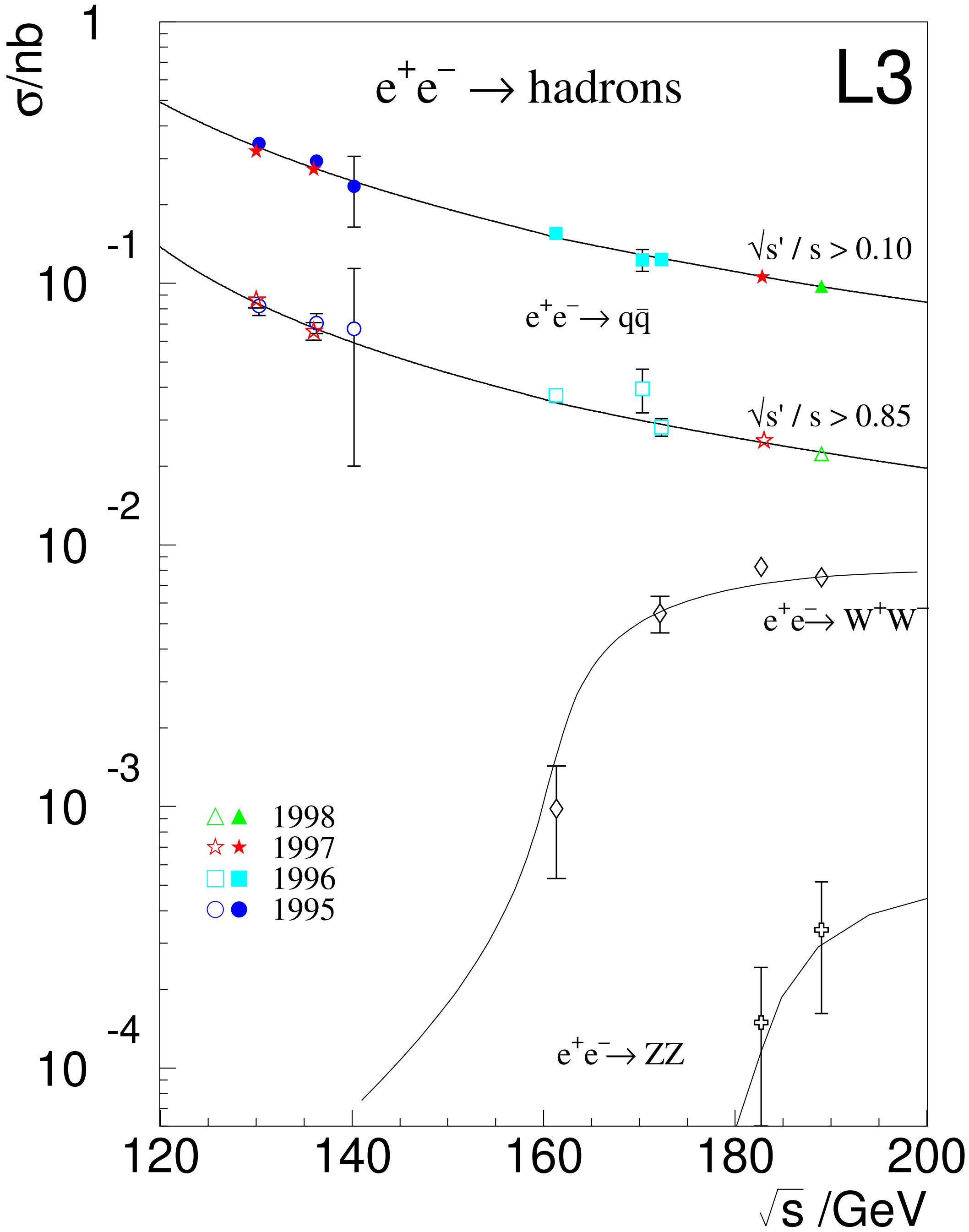
- ZZ signal at LEP2
- **Selection**
- **Cross section: Analysis and Results**
- **Anomalous couplings : Analysis and Results**

First Data in 1997 at $\sqrt{s}$=183 GeV
$\int \mathcal{L}$=**55.3 pb^{-1}**

Concentrate on 1998 with $\sqrt{s}$=189 GeV
$\int \mathcal{L}$=**176.4 pb^{-1}**

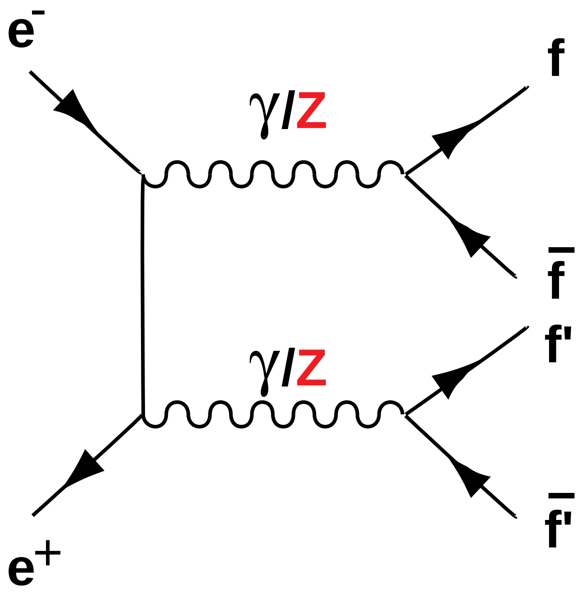
All results at $\sqrt{s}$=189 GeV are preliminary!!

- Some processes contributing at LEP2



Cross Sections at LEP2

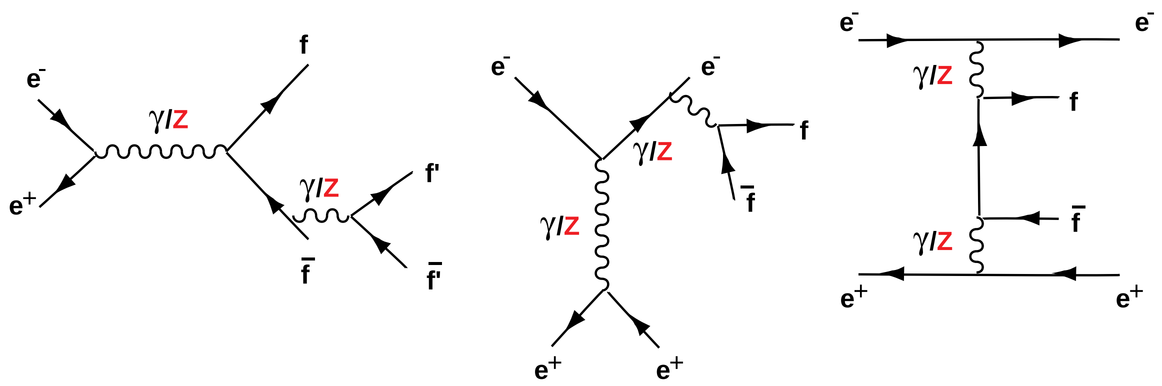
ZZ production mainly from conversion diagram



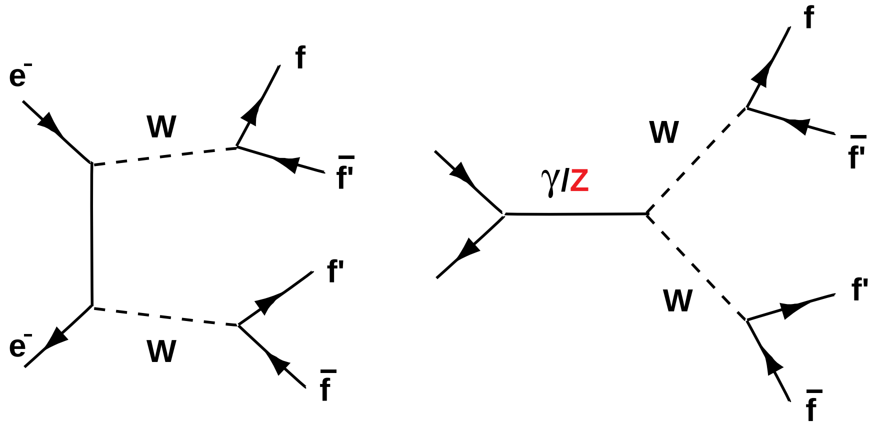
Cross section attributed to this process called σ_{ZZ}^{NC02}.

Other sources of 4-fermions final states :

- ZZ non resonant production:



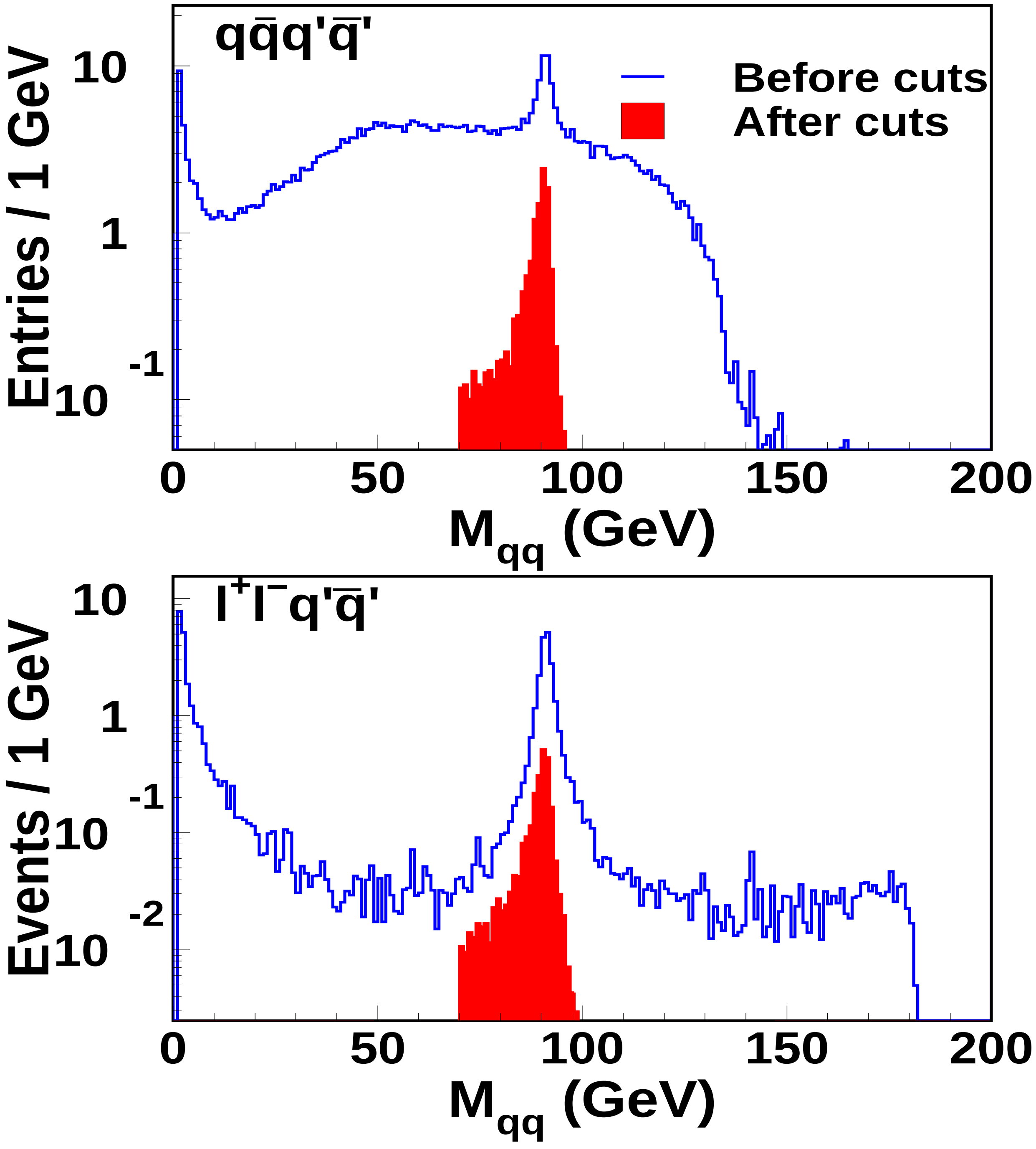
- **WW production:**



- **Monte Carlo used to simulate four-fermions final states: EXCALIBUR.**

"Isolation" of ZZ signal in EXCALIBUR:

- **Estimate the contribution of On-Shell** ZZ **production after phase space cuts at the generator level.**
- M_{ff} **and** $M_{f'\bar{f}'}$ **between 70 and 105** GeV**.**
- **For** $\mathrm{e^+e^-}$, $|cos\theta_e| < 0.95$ **(suppress multiperipheral contribution)**
- **Suppress W exchange by excluding** $75 < M_{f\bar{f}'} < 85\mathrm{GeV}$



$q\bar{q}q'\bar{q}'$
Before cuts
After cuts
Entries / 1 GeV
10
1
10^{-1}
0
50
100
150
200
M_{qq} (GeV)
$l^+l^-q'\bar{q}'$
Events / 1 GeV
10
1
10^{-1}
10^{-2}
0
50
100
150
200
M_{qq} (GeV)

Cross Sections at LEP2

Branching fractions within our signal cuts and from 'Naive' calculation:

$\mathbf{ZZ} \rightarrow$	σ **(pb)**	**Fraction**	NC02
$q_1\bar{q}_1q_2\bar{q}_2$	**0.290**	**46.8 %**	**48.9 %**
$q\bar{q}\nu\bar{\nu}$	**0.170**	**27.4 %**	**28.0 %**
$q\bar{q}l^+l^-$	**0.097**	**15.6 %**	**14.1 %**
$l^+l^-\nu\bar{\nu}$	**0.027**	**4.4 %**	**4.0 %**
$l_1^+l_1^-l_2^+l_2^-$	**0.011**	**1.8 %**	**1.0 %**
$\nu_1\bar{\nu}_1\nu_2\bar{\nu}_2$	**0.025**	**4.0 %**	**4.0 %**
ZZ	**0.620**	**100.0 %**	**100.0 %**

Selection

ZZ signal is searched for in:

- $e^+e^- \rightarrow ZZ \rightarrow q\bar{q}q'\bar{q}'$
- $e^+e^- \rightarrow ZZ \rightarrow q\bar{q}\nu\bar{\nu}$
- $e^+e^- \rightarrow ZZ \rightarrow \ell^+\ell^- q\bar{q}$
- $e^+e^- \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ **or** $\ell^+\ell^-\nu\bar{\nu}$

Common features to the selections:

Use energy momentum conservation and equal masses of the 2 Z candidates (M_{5C}).

Use Neural Network to enhance the discrimination between WW,$q\bar{q}(\gamma)$, and ZZ. NN output variable depends on the decay channel.

- **To reject WW, input variables include event shape, event mass, jet masses, total missing momentum ,** *etc.*.
- **To reject $q\bar{q}(\gamma)$, input variables are event thrust, fraction of transverse energy, Y_{34} value, energies of the jets,** *etc.*.

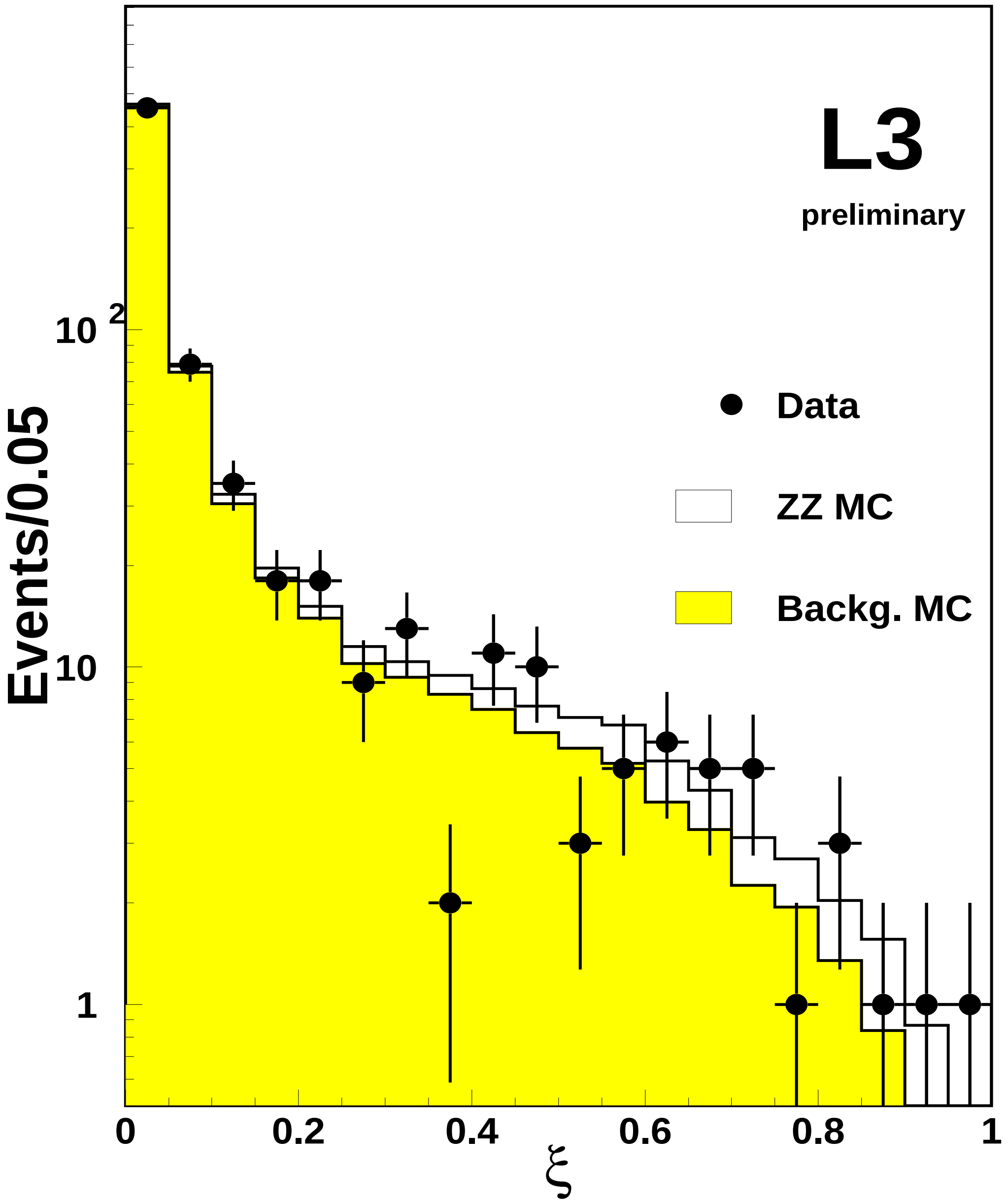
Fit the distributions of the discriminant variable to extract the signal.

$q\bar{q}q'\bar{q}'$ final states

- **4 jet events with high multiplicity.**
- **Constrain 2 di-jets to the Z mass (3 possible combinations).**
- **Choose best dijet combination with $M_{5C} >$ 85 GeV**
- **Neural Network to discriminate against WW and $q\bar{q}(\gamma)$ backgrounds.**
- **Discrimination variable ξ: NN combined with Mass from 5-C kinematic fit.**

Selection efficiency:66%

Number of events in the Data	:	**714**
Total MC Signal+Background expected	:	**663**
Signal expected	:	**33.8**

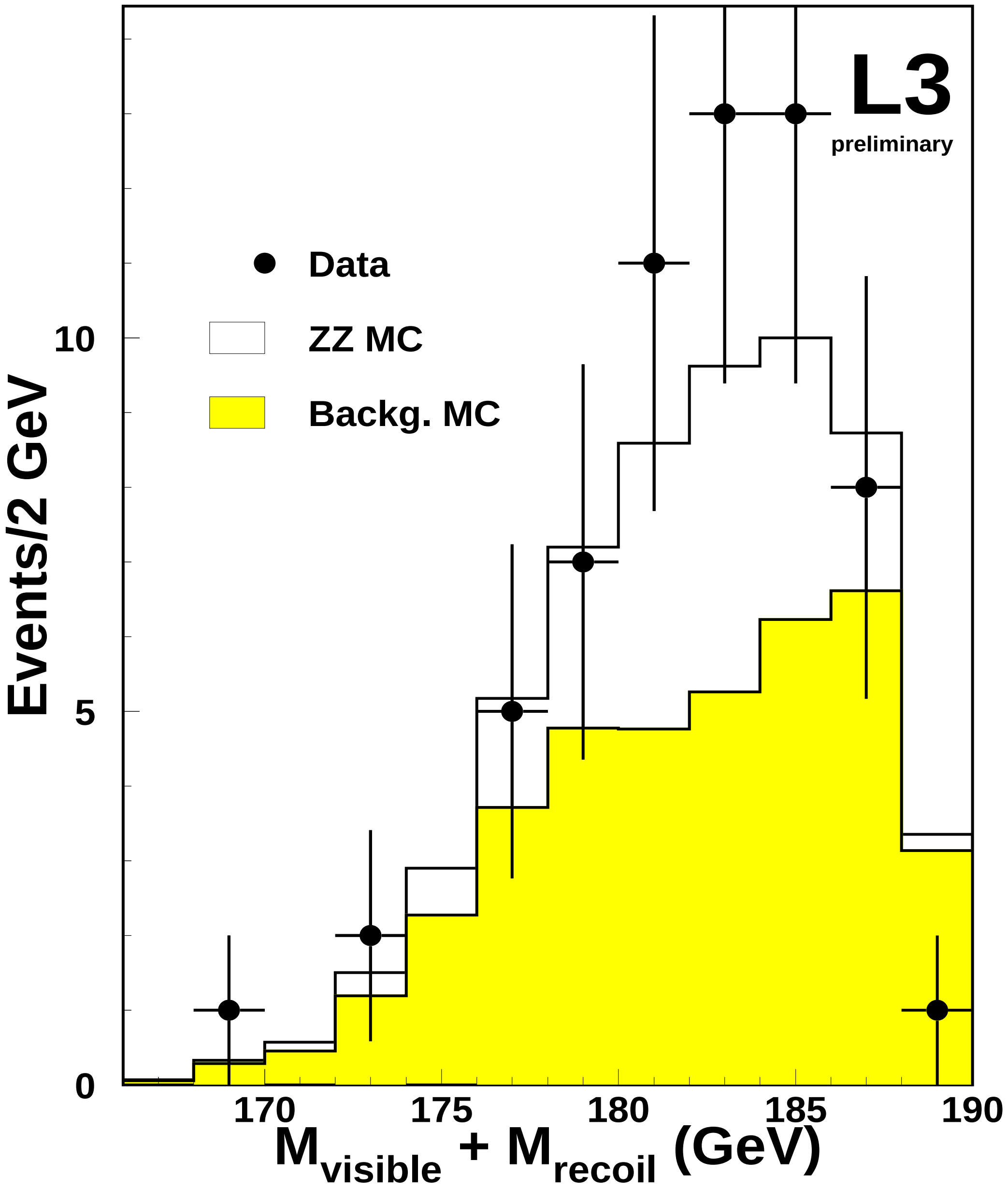

L3
preliminary
Data
ZZ MC
Backg. MC
Events/0.05
10^2
10
1
0
0.2
0.4
0.6
0.8
1
ξ

$q\bar{q}\nu\bar{\nu}$ final states

- **High multiplicity hadronic events.**
- **Events with 2 jets constrained to the** Z **mass, missing energy, and little energy in the forward regions ($<$ 10GeV). These cuts reject $\ell^+\ell^-(\gamma)$, and multiperipheral $e^+e^-f\bar{f}$ final states.**
- **Transverse missing energy $>$ 5 GeV longitudinal momentum $<$ 40% of visible energy to reject $q\bar{q}(\gamma)$**
- **Further Neural Network to discriminate against WW background.**
- **Discrimination variable: Mass of the $q\bar{q}$ system + recoil mass.**

Selection efficiency: 61%

Number of events in the Data	**:**	**61**
Total MC Signal+Background expected	**:**	**58**
Signal expected	**:**	**19**

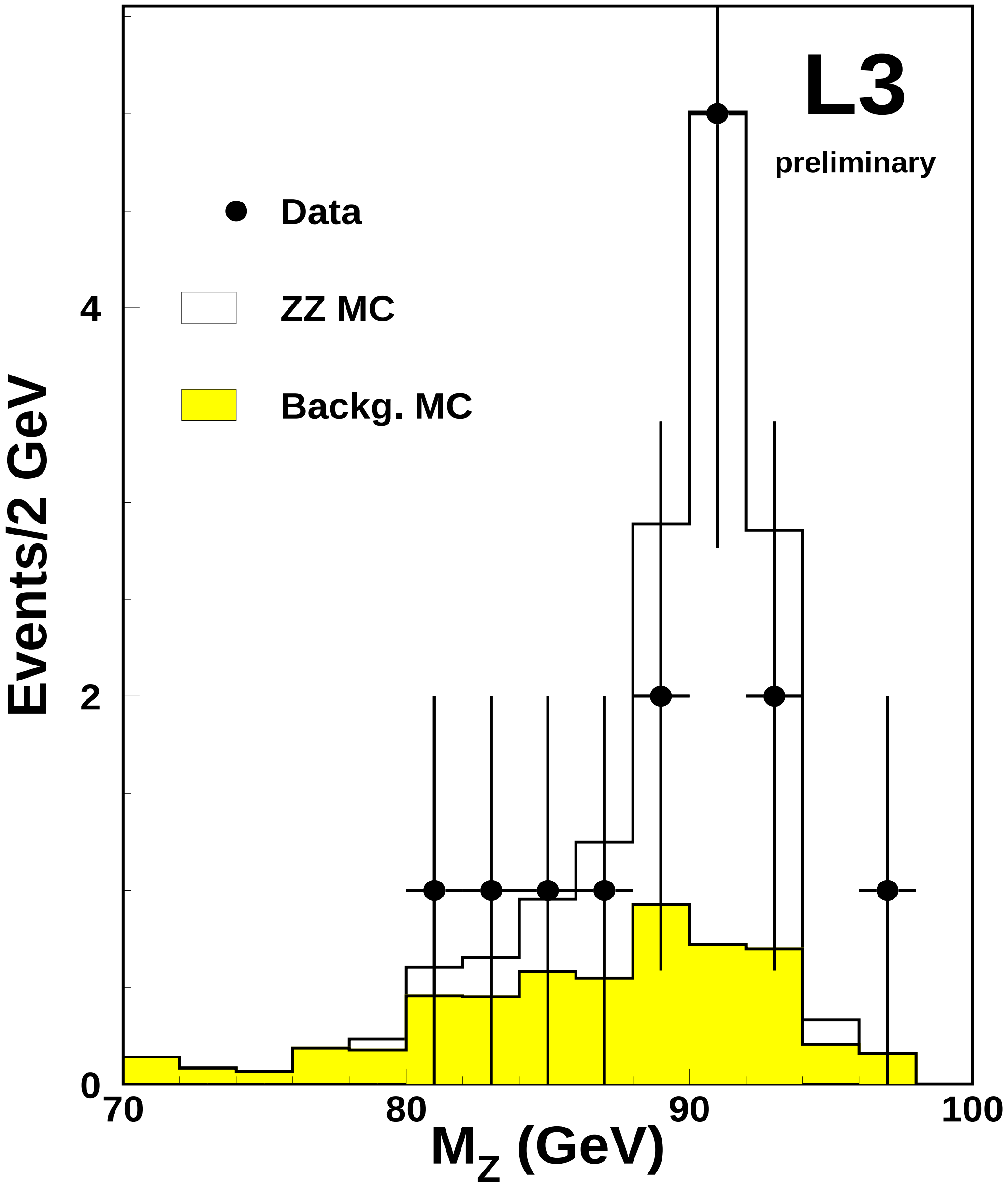

L3
preliminary
Data
ZZ MC
Backg. MC
Events/2 GeV
0
5
10
170
175
180
185
190
$M_{visible} + M_{recoil}$ (GeV)

$q\bar{q}\ell^+\ell^-$ final states

- **Events with 2 hadronic jets and a pair of isolated leptons.**
- **Individual selections for each channel, but combine them to take into account events belonging to more than 1 channel.**
- **Discrimination variable: Mass from 5-C kinematic fit.**
- **Selection Efficiency:**

	qqee **sel.**	qq$\mu\mu$ **sel.**	qq$\tau\tau$ **sel.**
qqee	**73 %**	**0 %**	**0 %**
qq$\mu\mu$	**0 %**	**55 %**	**1 %**
qq$\tau\tau$	**4 %**	**6 %**	**28 %**

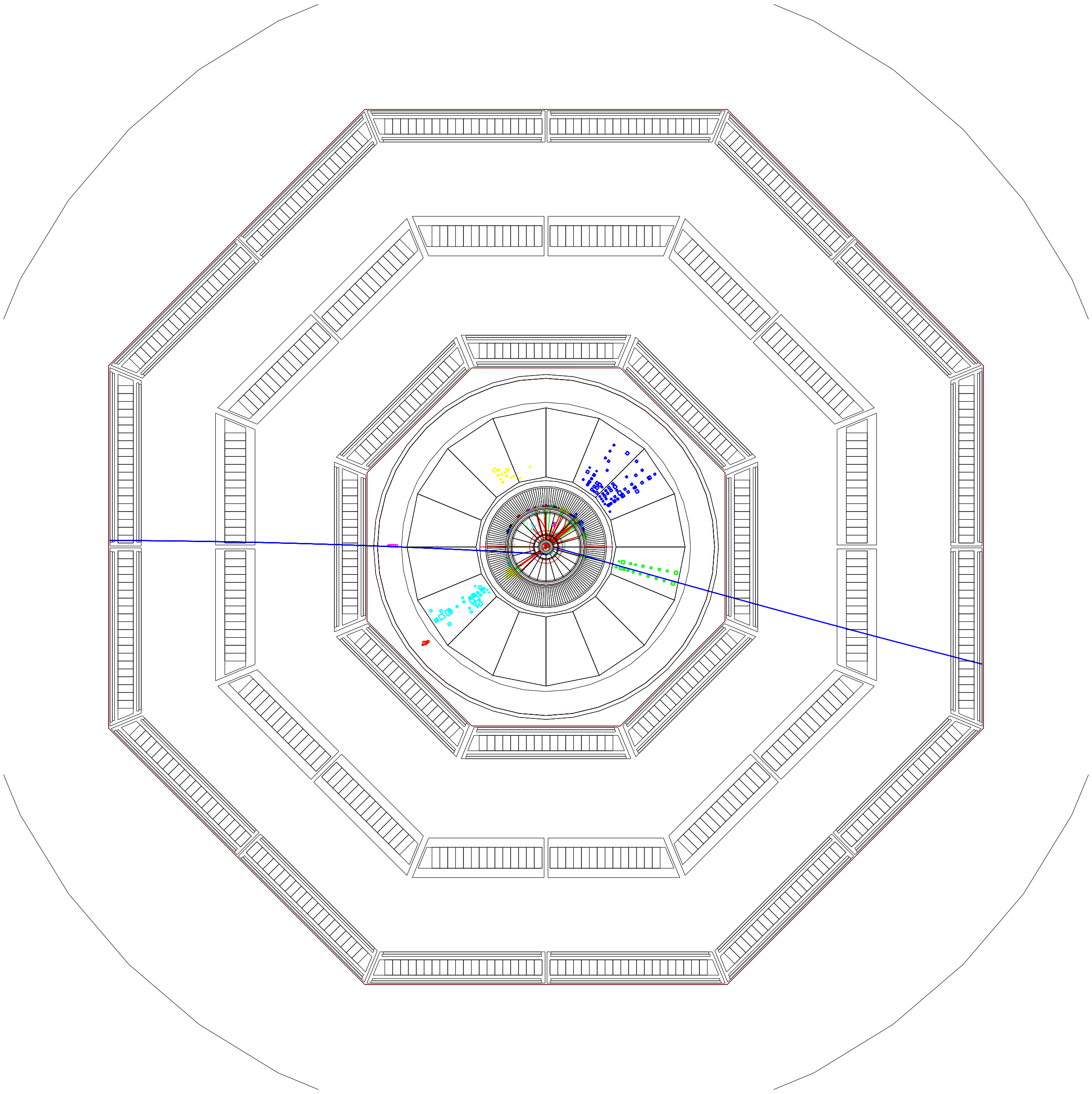
Number of events in the Data : 14
Total MC Signal+Background expected: 15
Signal expected : 10



L3
preliminary
Data
ZZ MC
Backg. MC
Events/2 GeV
0
2
4
70
80
90
100
M_Z (GeV)

$q\bar{q}\ell^+\ell^-$ final states

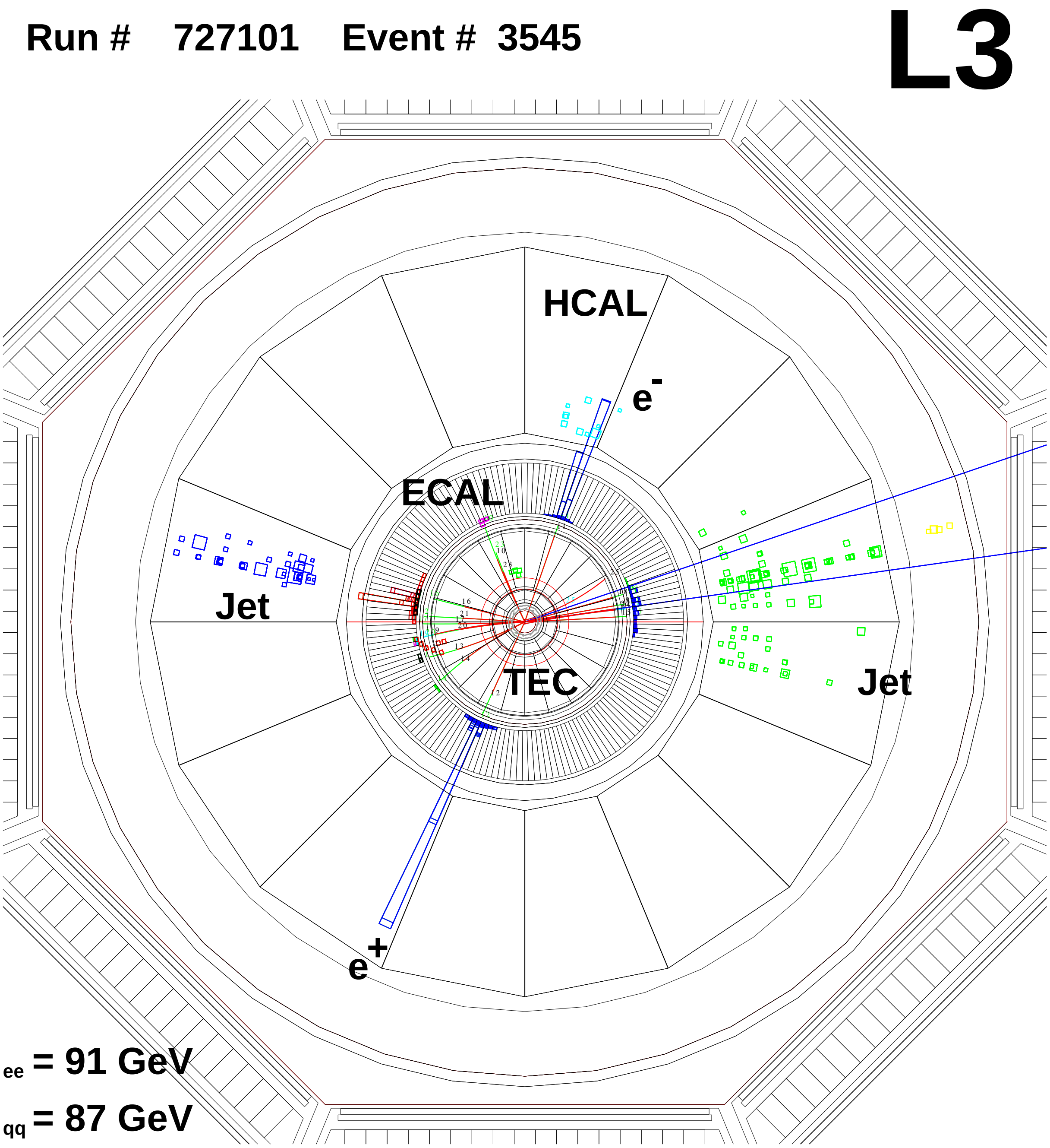
Run # **705301** **Event #** **24** Total Energy : 171.88 GeV



Transverse Imbalance :	.0830	**Longitudinal Imbalance :**	-.0744		
Thrust :	.8584	**Major :**	.4065	**Minor :**	.1667
Event DAQ Time :	*980713 51332*				

$q\bar{q}\ell^+\ell^-$ final states

Run # 727101 Event # 3545



$M_{ee} = 91$ GeV

$M_{qq} = 87$ GeV

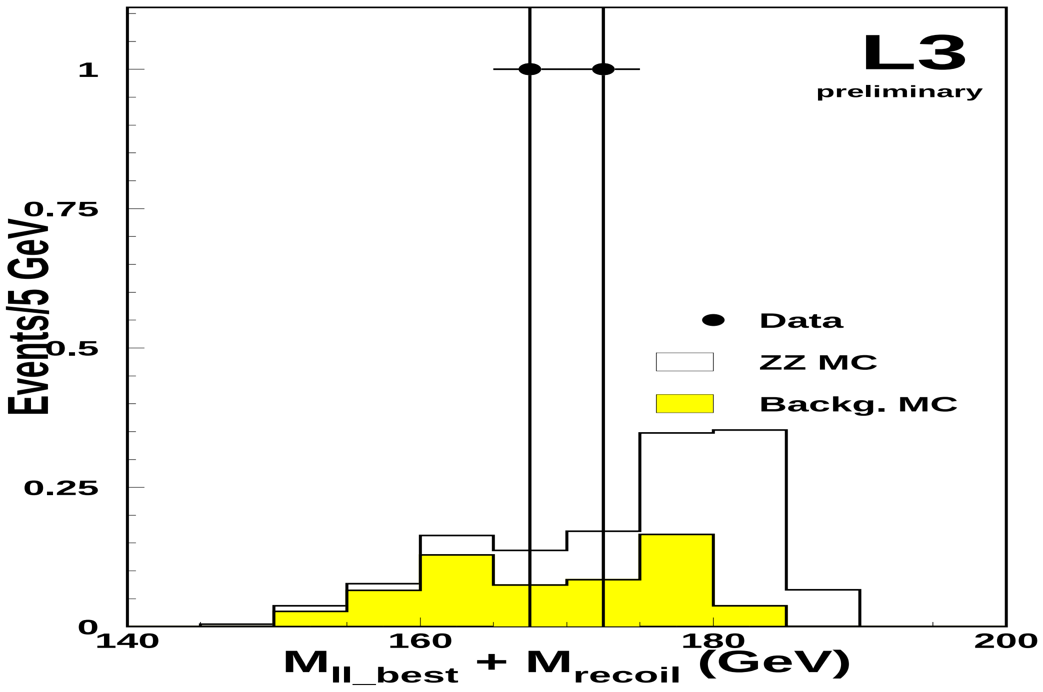
$M_{5C} = 89$ GeV

$\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states

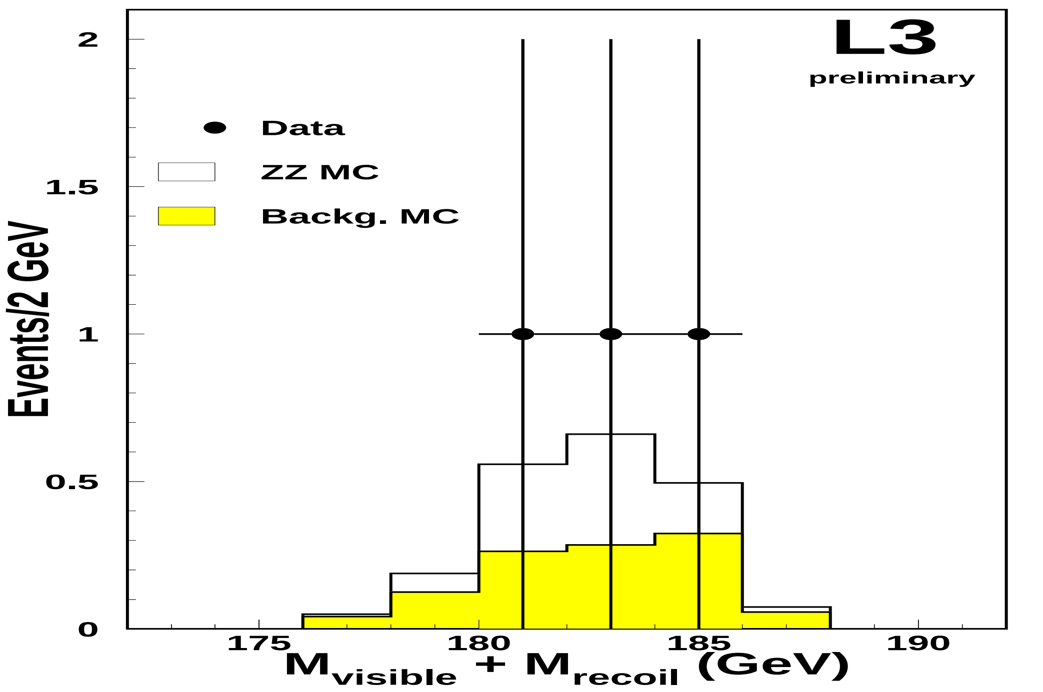
- **Low multiplicity events.**
- **Leptons must be identified and grouped in same-flavor pairs.**
- **Large missing Energy** ($80 < E_{vis} < 100$GeV) **if** $\ell^+\ell^-\nu\bar{\nu}$.
- **Lepton pair mass and recoil mass must be between 70 and 105** GeV.
- **Discrimination variable: Mass of the (best) measured** $\ell^+\ell^-$ **pair + recoil mass.**
- **Selection Efficiency:**

eeee	**56 %**	$\mu\mu\mu\mu$	**41 %**
ee$\mu\mu$	**66 %**	$\mu\mu\tau\tau$	**28 %**
ee$\tau\tau$	**29 %**	$\tau\tau\tau\tau$	**2.4 %**
ee$\nu\nu$	**29 %**	$\mu\mu\nu\nu$	**21 %**

Number of events in the Data : 5
Total MC Signal+Background expected: 3.2
Signal expected : 1.4



L3
preliminary
Events/5 GeV
0
0.25
0.5
0.75
1
140
160
180
200
Data
ZZ MC
Backg. MC
M_ll_best + M_recoil (GeV)



L3
preliminary
Events/2 GeV
0
0.5
1
1.5
2
175
180
185
190
Data
ZZ MC
Backg. MC
M_visible + M_recoil (GeV)

- **Fit $\sigma_{ZZ}^{data}/\sigma_{ZZ}^{SM}$, ratio of the Measured Cross Section to the expected SM cross section computed using EXCALIBUR.**
- **Results of the measurement for individual channels of $\sigma_{ZZ}^{data}/\sigma_{ZZ}^{SM}$:**

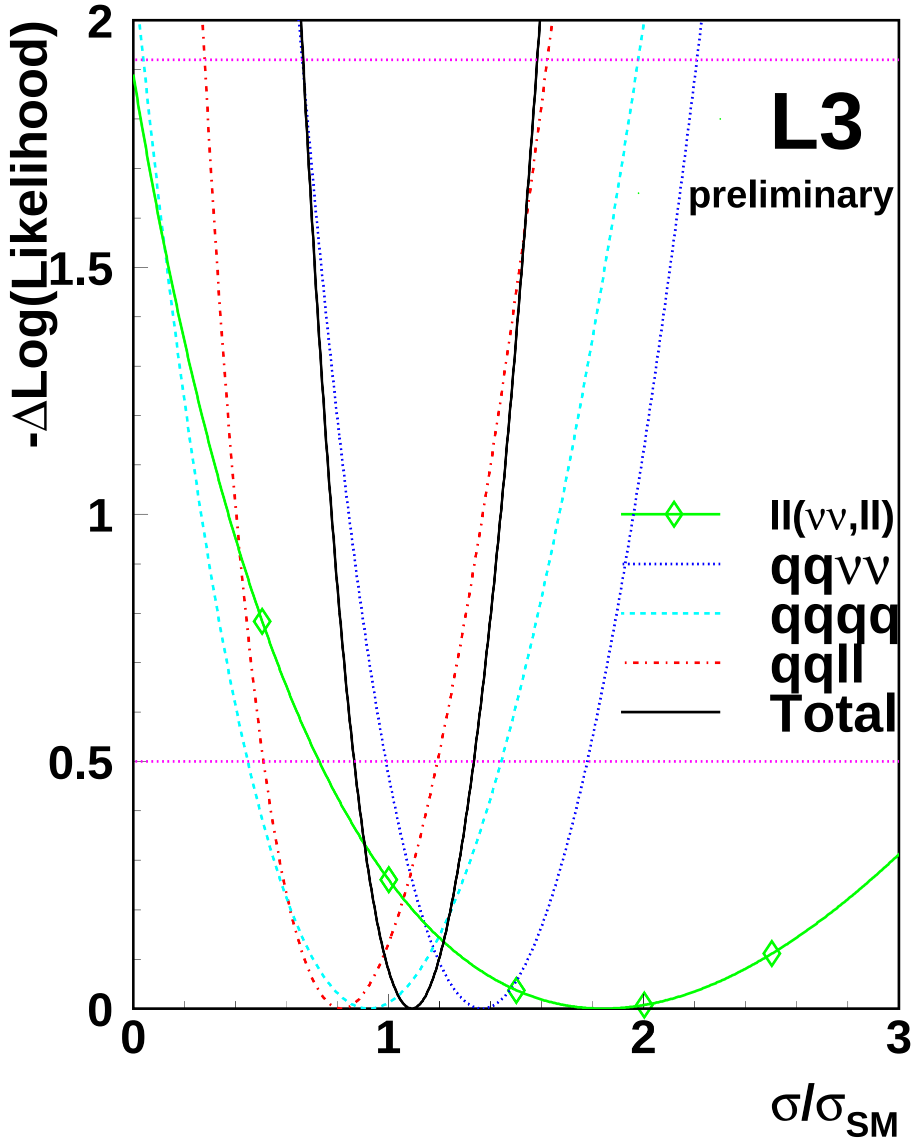
$$\mathrm{q\bar{q}q'\bar{q}'} : \mathbf{0.92}^{+0.50}_{-0.47}$$
$$\mathrm{q\bar{q}}\nu\bar{\nu} : \mathbf{0.82}^{+0.37}_{-0.31}$$
$$\mathrm{q\bar{q}}\ell^+\ell^- : \mathbf{1.37}^{+0.41}_{-0.38}$$
$$\ell^+\ell^-\ell'^+\ell'^- : \mathbf{1.5}^{+2.3}_{-1.4}$$
$$\ell^+\ell^-\nu\bar{\nu} : \mathbf{2.1}^{+2.2}_{-1.5}$$

Statistical error only!

To extract total measured cross section:

- **Assume Branching Ratios extracted from EXCALIBUR.**
- **Combine all individual channels into a log-likelihood fit.**
- **Fit $\sigma_{ZZ}^{data}/\sigma_{ZZ}^{SM}$**

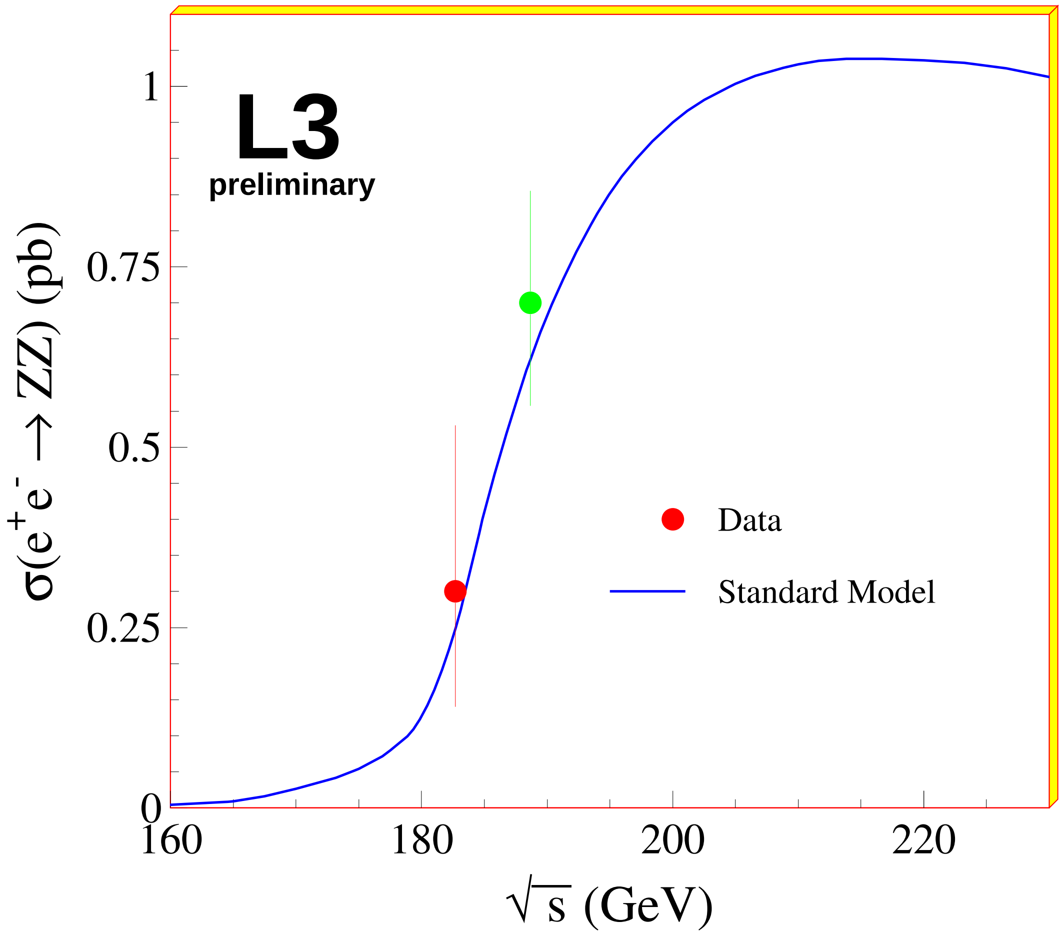
Cross Sections



$$\sigma_{ZZ}^{data}/\sigma_{ZZ}^{SM} = 1.09^{+0.24}_{-0.23}.$$

Total cross section within the cuts applied in EXCALIBUR:

Cross Sections



at $\sqrt{s}$=189 GeV,

$$\sigma_{ZZ} = 0.68^{+0.15}_{-0.14} \text{ pb} \qquad (\sigma^{SM}_{ZZ} = 0.62 \text{ pb})$$

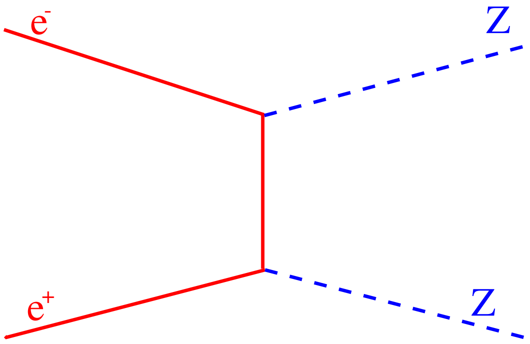
Statistical Error only

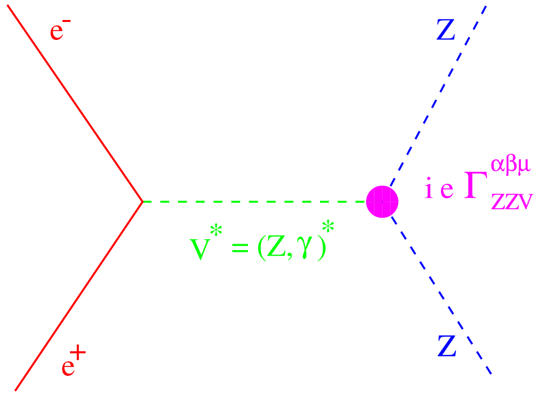
at $\sqrt{s}$=183 GeV,

$$\sigma_{ZZ} = 0.30^{+0.22+0.07}_{-0.16-0.03} \text{ pb} \qquad (\sigma^{SM}_{ZZ} = 0.25 \text{ pb})$$

Anomalous Couplings

ZZ final states with non-SM couplings





SM tree level:
Couplings of fermions to neutral Gauge Boson

$\Gamma^{\alpha\beta\mu}_{ZZV}$:
Triple Gauge Boson anomalous coupling

- No access to ZZZ coupling so far.
- 2 possible couplings $f_4^{Z,\gamma}$ and $f_5^{Z,\gamma}$ in Anomalous Vertex function $\Gamma^{\alpha\beta\mu}_{ZZV}$:
  - $f_4^{Z,\gamma} \neq 0 \Rightarrow$ $\not{C}$ $\not{C}P$ contribution
  - $f_5^{Z,\gamma} \neq 0 \Rightarrow$ $\not{P}$ CP contribution
- Interferences with the SM amplitudes:

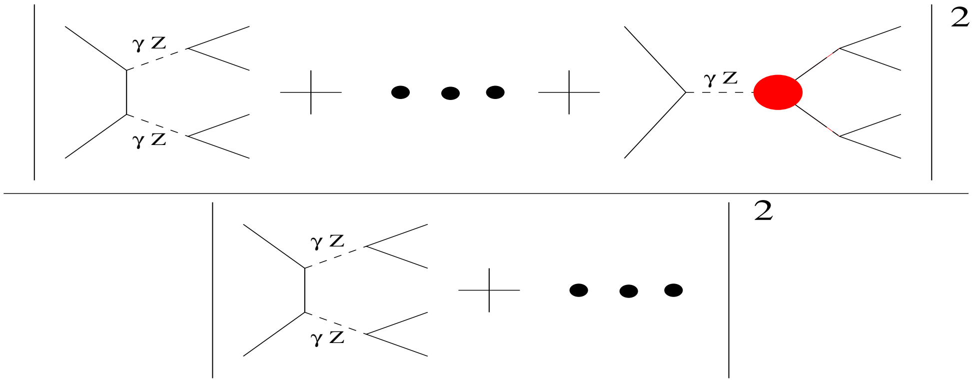
$$|M_{SM}|^2 \longrightarrow |M_{SM} + M_{AC}|^2$$

- Anomalous couplings will manifest themselves as:
  - Change of the total cross section $e^+e^- \rightarrow ZZ$
  - Modification of angular distribution

Anomalous Couplings

- Fit distributions already used for cross section measurement.
- Reweight MC to include Anomalous Couplings:

Weight =



- Compare data with MC.

Limits at 95% CL:

$$-1.7 < f_4^Z < 1.8$$
$$-4.7 < f_5^Z < 4.7$$
$$-1.0 < f_4^\gamma < 1.1$$
$$-2.8 < f_5^\gamma < 2.9$$

Factor 2 improvement with respect to limits determined at 183 GeV.

- Improvements expected because M_{AC} increases with $\sqrt{s}$.

Summary

- ZZ signal now available at LEP2 with sizeable cross section.

- Cross Sections are measured for all available decay channels:
  ZZ$\longrightarrow$ $q\bar{q}q'\bar{q}'$, $q\bar{q}\nu\bar{\nu}$, $\ell^+\ell^-q\bar{q}$,
  $\ell^+\ell^-\ell'^+\ell'^-$, $\ell^+\ell^-\nu\bar{\nu}$

- Total cross section:

  $$\sigma_{ZZ}^{measured} = 0.68^{+0.15}_{-0.14}\ \mathrm{pb}$$

  In terms of NC02 diagrams:

  $$\sigma_{ZZ}^{NC02} = 0.71^{+0.16}_{-0.15}\ \mathrm{pb}$$

  In good agreement with SM.

- No Anomalous couplings found so far. Improved constraints due to higher center-of-mass energy.

- Hope that this channel be the Background of another one in 1999!