WW and ZZ production and coupling at LEP with L3

- Introduction
- L3 Detector
- Signal Definition
- Event Selection
- Results and Discussion
- Summary

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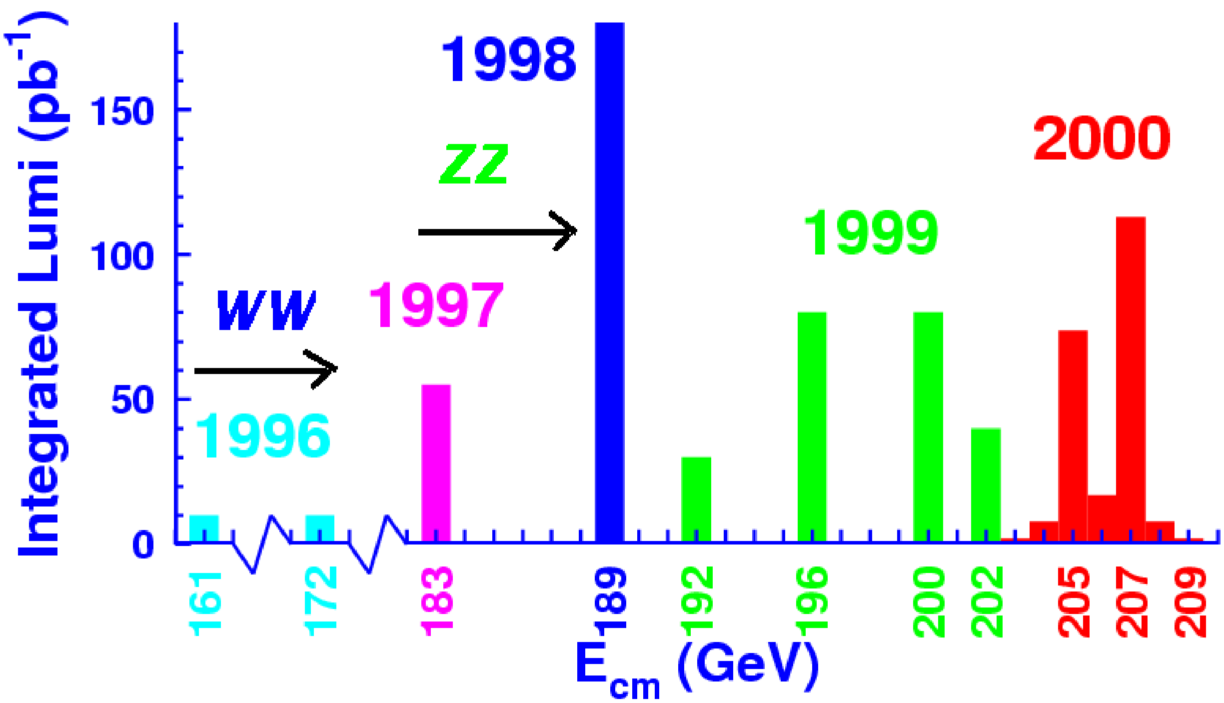
Motivation

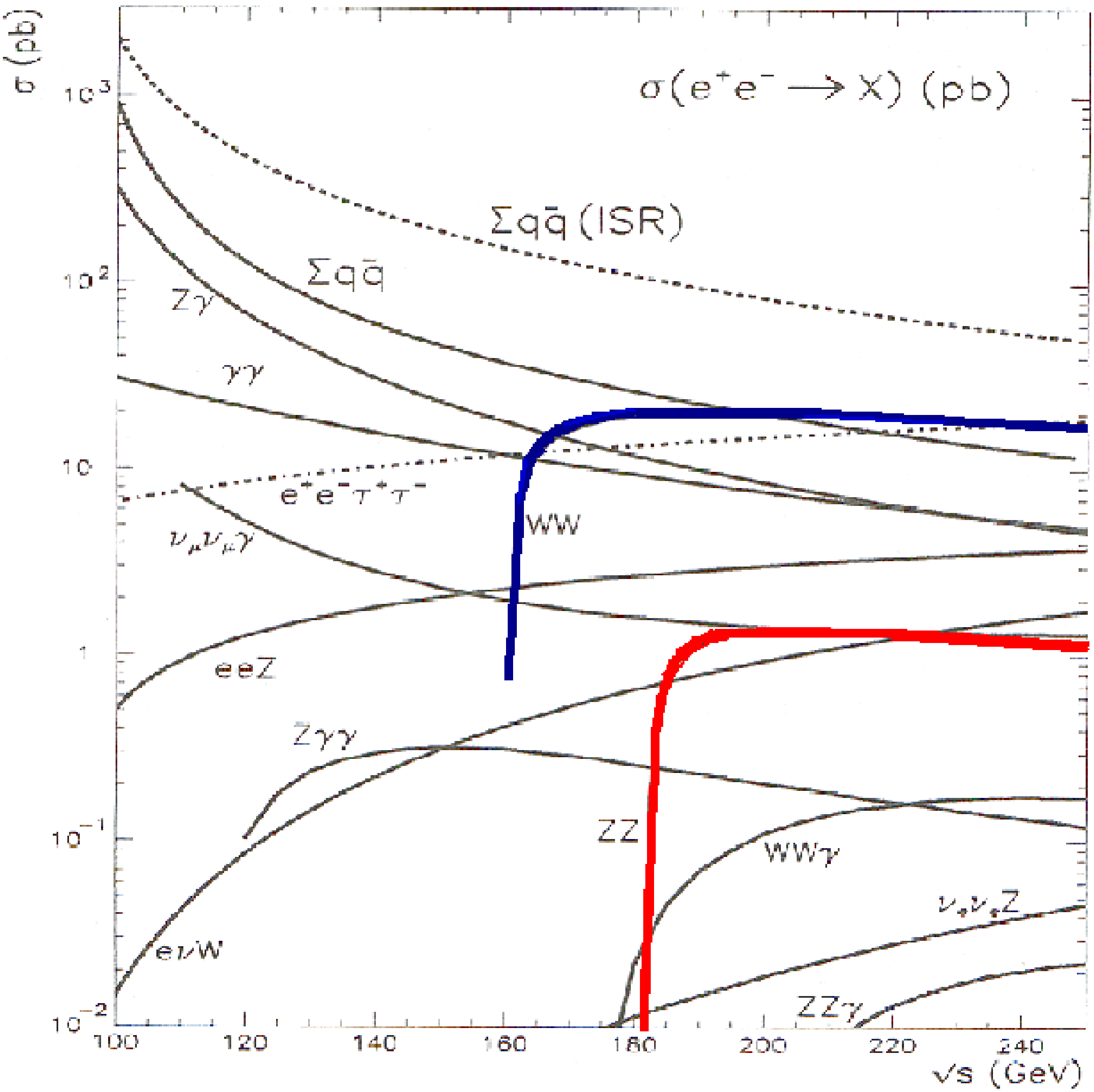
- Interactions between gauge bosons; $W^{\pm}$, Z and γ are a direct consequence of the non-abelian nature of Standard Model
- Vector boson pair productions (W^+W^-, ZZ) offer unique possibilities to study various possible gauge-boson couplings
- Any deviation from S.M. expectation in the form of:
  - ➠ Enhancement on the cross section
  - ➠ Change in angular distribution

  can be attributed to the presence of anomalous Trilinear Gauge Couplings (TGC) or Quartic Coupling (QGC)



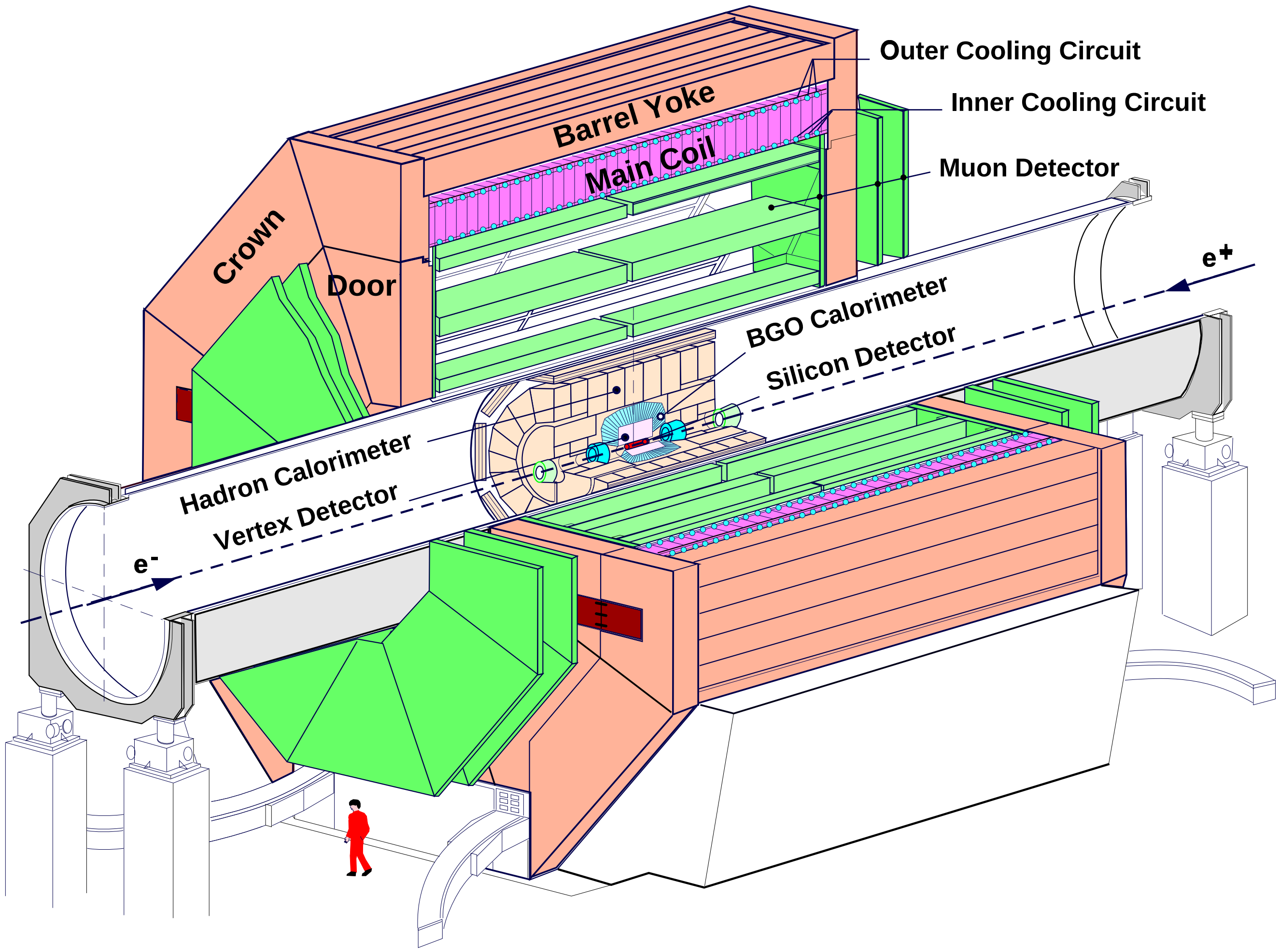
- LEP is an ideal place to precisely measure the cross section for vector boson pair production, and the couplings

Physics process in e^+e^- collision



☞ W^+W^- and ZZ events, in particular have to be selected out of a sea of competing processes

L3 Detector



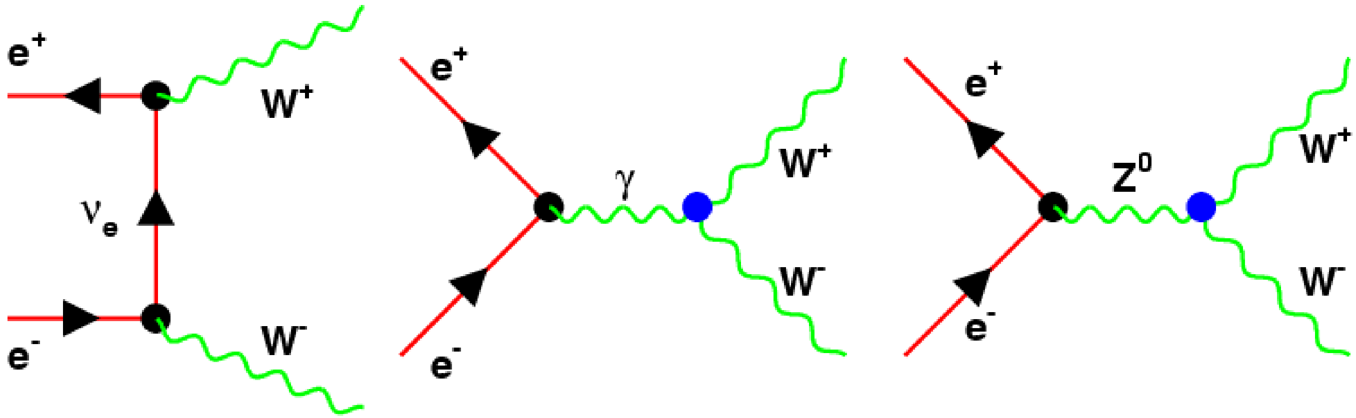
- L3 detector is one of the four LEP experiments
- High resolution for Photons/Electrons and Muons
- Good hermiticity for jet and $\not{\vec{P}}$ reconstruction

Focus of my talk

✝ 2000 data: $217 pb^{-1}$ @ $\sqrt{s} = 201 - 209$ GeV
✝ 1999 data: $233 pb^{-1}$ @ $\sqrt{s} = 192 - 202$ GeV

WW Production

☞ As Standard Model predicts



☞ Extended to the more general Lorentz invariant form

$$
\begin{aligned}
\frac{i\mathcal{L}_{eff}^{WWV}}{g_{WWV}} &= g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} \\
&+ \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- + i g_4^V W_\mu^+ W_\nu^- (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
&+ i g_5^V \epsilon_{\mu\nu\rho\sigma} ((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu})) V^\sigma \\
&- \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}
\end{aligned}
$$

☞ Too many parameters to be measured simultaneously

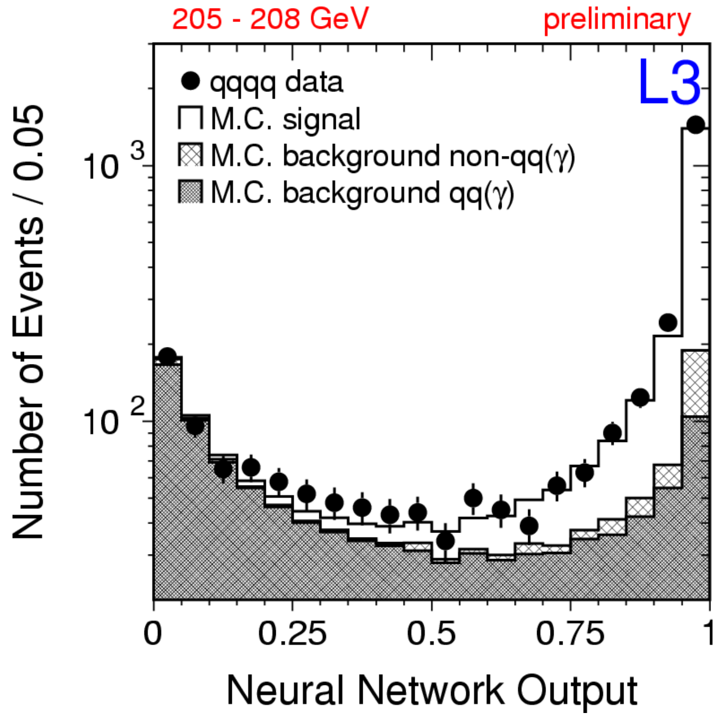
- ☆ Require C, P and CP conservation
- ✪ Require $U(1)_{em}$ gauge invariance ($g_1^\gamma \Rightarrow q_W = \pm 1$)
- ★ Still five parameters left with: $g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$
- ✯ Further reduction requires $\underbrace{SU(2)_L \bigotimes U(1)_Y}$ symmetry

❶ $\kappa_Z = \kappa_\gamma \ tan^2\theta_W$	$\kappa_Z = \kappa_\gamma = 1$ **(SM)**
❷ $\lambda_Z = \lambda_\gamma$	$\lambda_Z = \lambda_\gamma = 0$ **(,,)**
❸ g_1^Z	$g_1^Z = 1$ **(,,)**

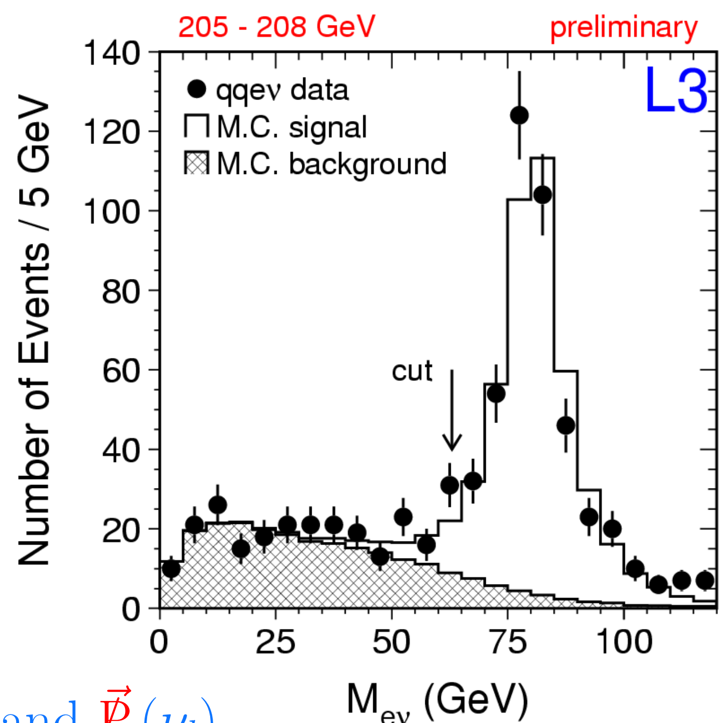
Event Selection

WW Events

- 46% $q\bar{q}'q'\bar{q} \Rightarrow$ Four jets
  - ➠ Fully balanced event
  - ➠ Large multiplicity
  - ➠ Bkg from $q\bar{q}(\gamma)$, ZZ
  - ➠ NN-based selection



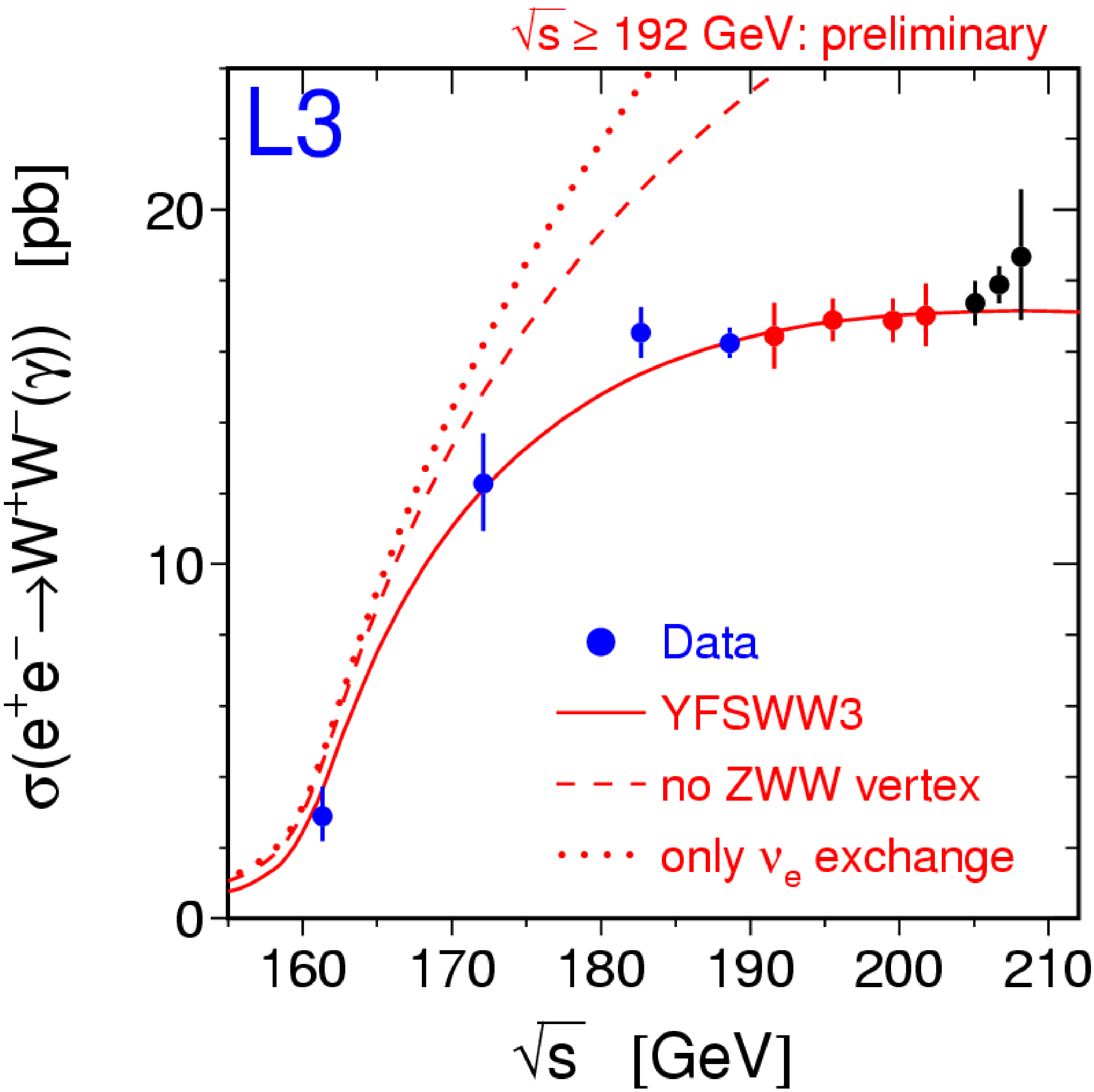
- 44% $q\bar{q}'l\nu \Rightarrow$ Two jets, one lepton and $\vec{\not P}\,(\nu_l)$
  - ➠ Well isolated lepton
  - ➠ Large multiplicity
  - ➠ Cut-based selection



- 10% $l\bar{\nu}\bar{l}'\nu' \Rightarrow$ Two leptons and $\vec{\not P}\,(\nu_l)$
  - ➠ Ask for 2 energetic and acoplanar leptons
  - ➠ Reject hadronic events using multiplicity

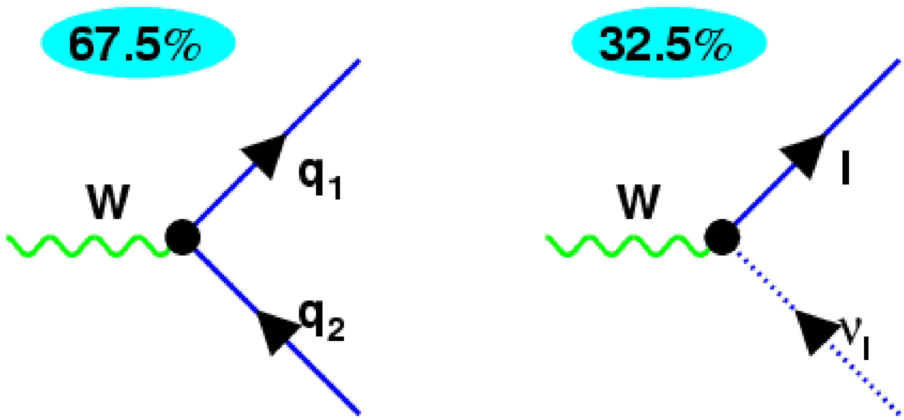
WW Production Cross section

- σ_{WW} is determined by fitting the total likelihood which is the product of $\mathcal{P}(N_i, \mu_i)$ for each i-th process



✔ σ_{WW} already puts stringent constraints on TGC excluding models without ZWW and γWW vertex

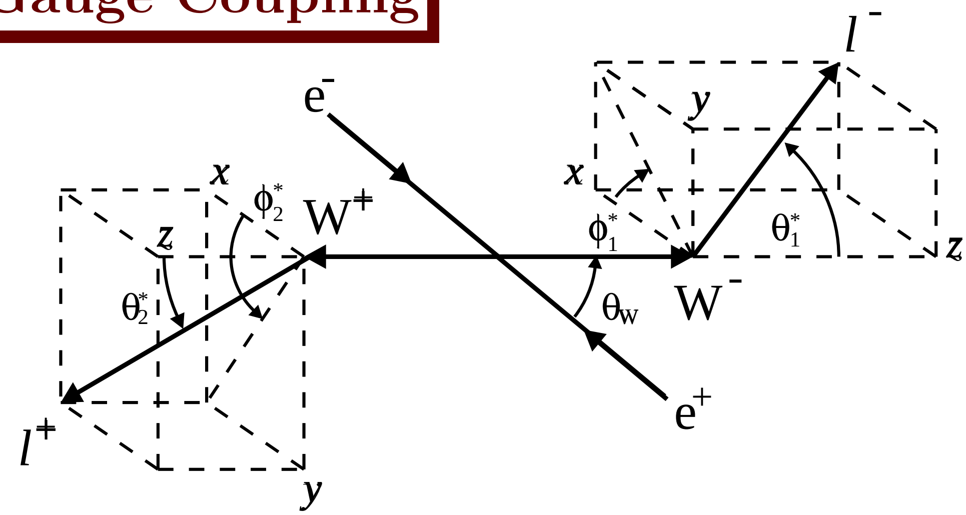
W-Decay Branching Fractions



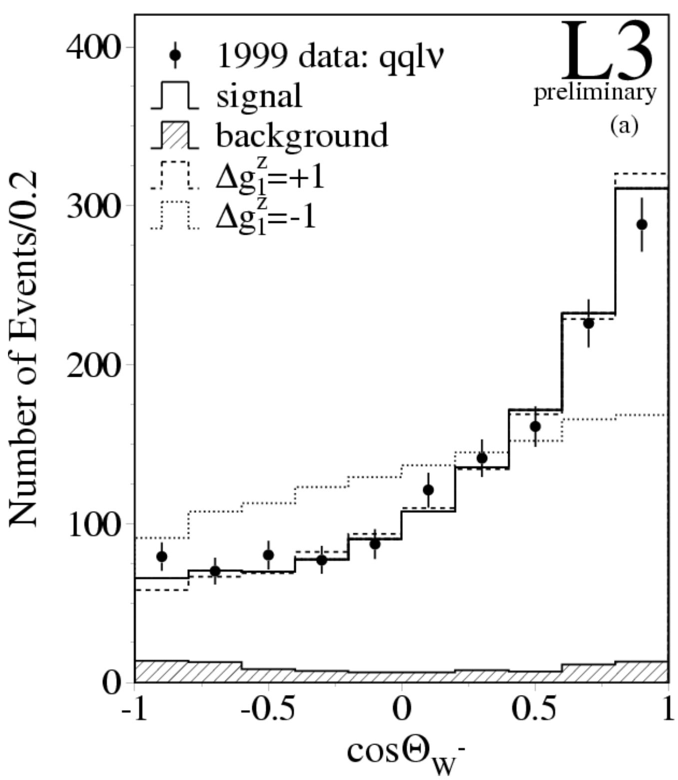
- σ_i for signal process i is $r_i \sigma_{WW}$, with r_i given in terms of hadronic and leptonic B.F. of W
  - $r_{qqqq} = [B(W \to qq)]^2$
  - $r_{qql\nu} = 2B(W \to qq)B(W \to l\nu)$
  - $r_{l\nu l\nu} = [B(W \to l\nu)]^2$
  - $r_{l\nu l'\nu'} = 2B(W \to l\nu)B(W \to l'\nu')$
- Sum of the hadronic and leptonic B.F. is constrained to unity

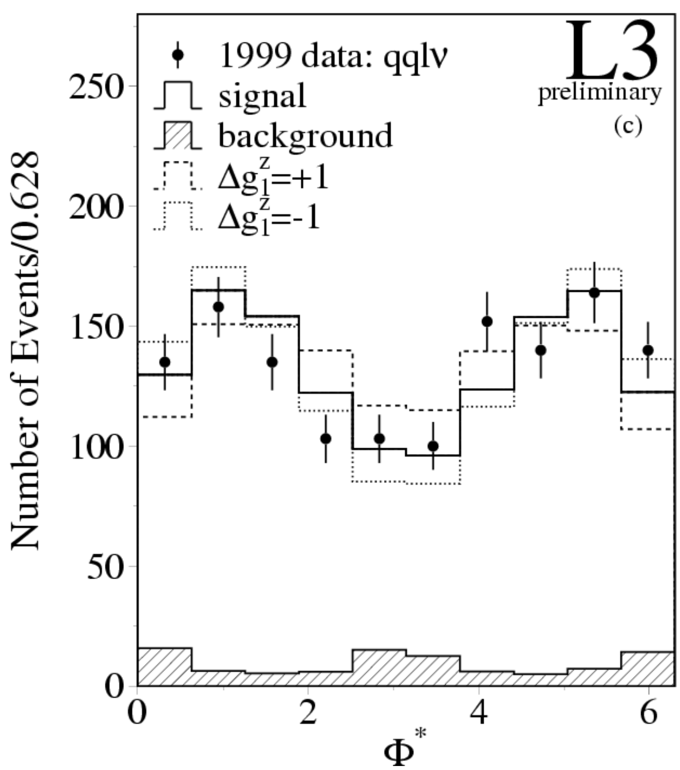
Branching Fraction[%]	Lepton Non-Universality	Lepton Universality
$W \to e\nu$	$10.40 \pm 0.26 \pm 0.14$	-
$W \to \mu\nu$	$9.72 \pm 0.27 \pm 0.15$	-
$W \to \tau\nu$	$11.78 \pm 0.38 \pm 0.21$	-
$W \to l\nu$	-	$10.55 \pm 0.13 \pm 0.11$
$W \to qq$	$68.10 \pm 0.41 \pm 0.33$	$68.34 \pm 0.40 \pm 0.33$

Triple Gauge Coupling

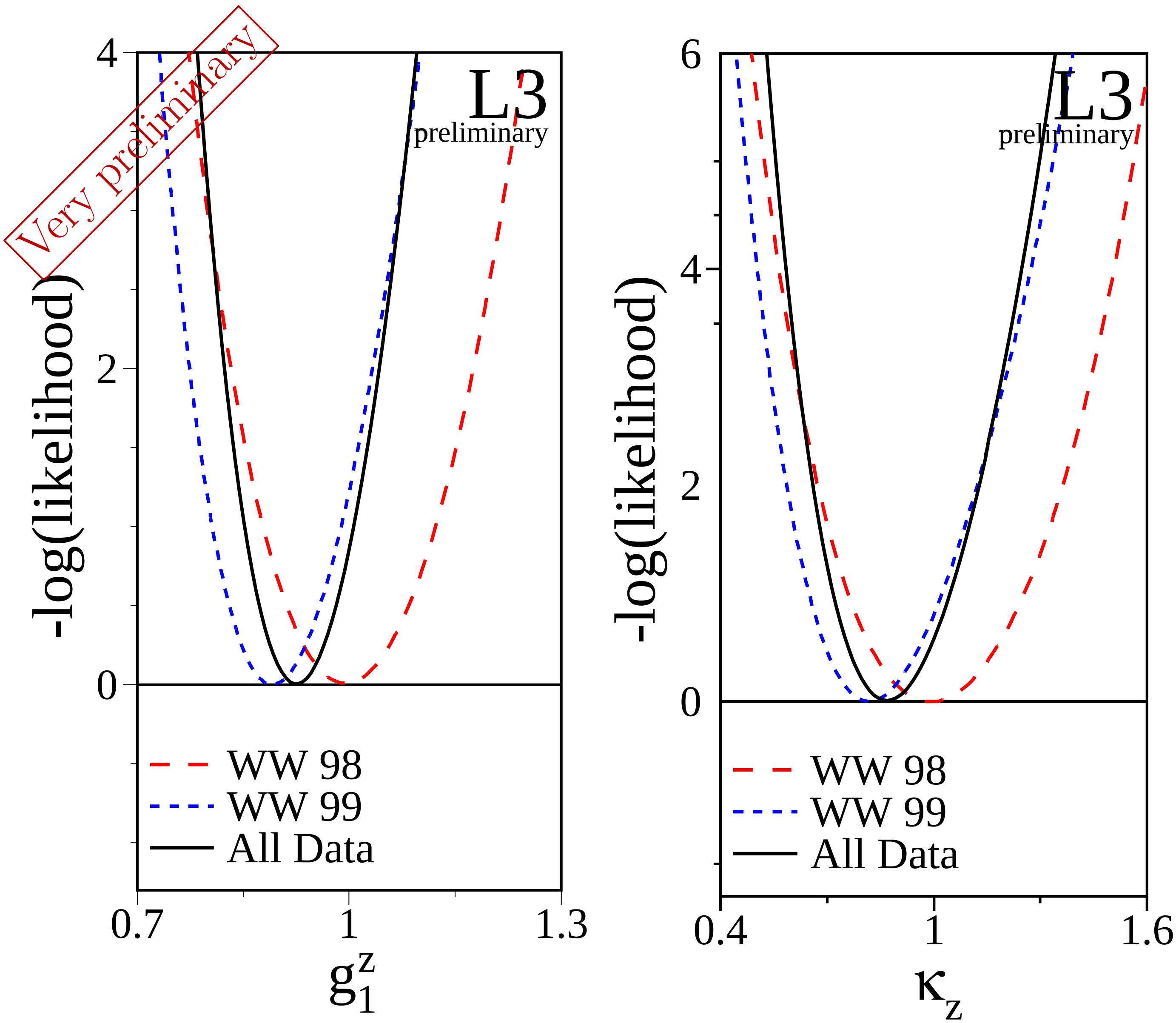


- Use W-decay as the polarimeter
  - ➠ $cos\theta_W$, the decay polar angle of the W^-
  - ➠ $cos\theta_1^*, \phi_1^*$ of the fermion in the W^- rest-frame
  - ➠ $cos\theta_2^*, \phi_2^*$ of the anti-fermion in the W^+ rest-frame





- $cos(\theta_W)$: Highest sensitivity to TGC
- Sensitivity increasing with $\sqrt{s}$



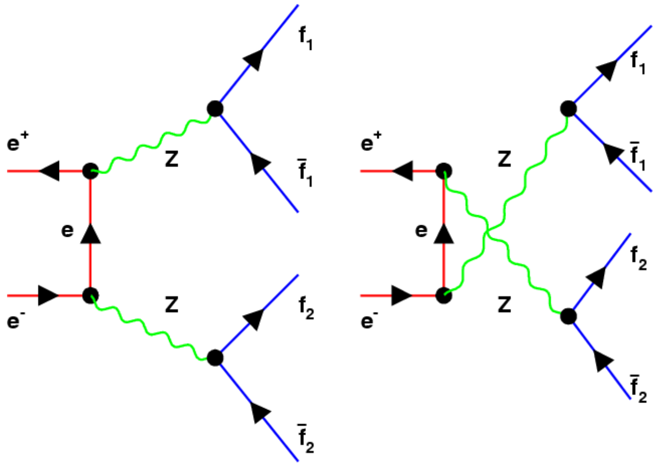
Limits on TGC

$0.82 < g_1^Z < 1.04$	$-0.34 < \lambda_Z < 0.16$
$0.66 < \kappa_Z < 1.12$	$-0.19 < \lambda_\gamma < 0.05$
$0.73 < \kappa_\gamma < 1.20$	$-0.52 < g_5^Z < 0.42$

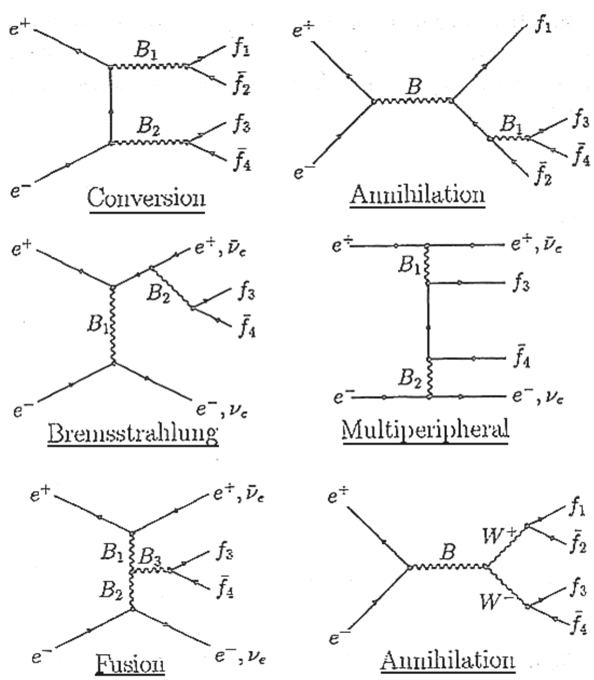
Signal Definition

- Z-pair production is mainly via t and u channel electron exchange (Neutral Current 02 diagram)

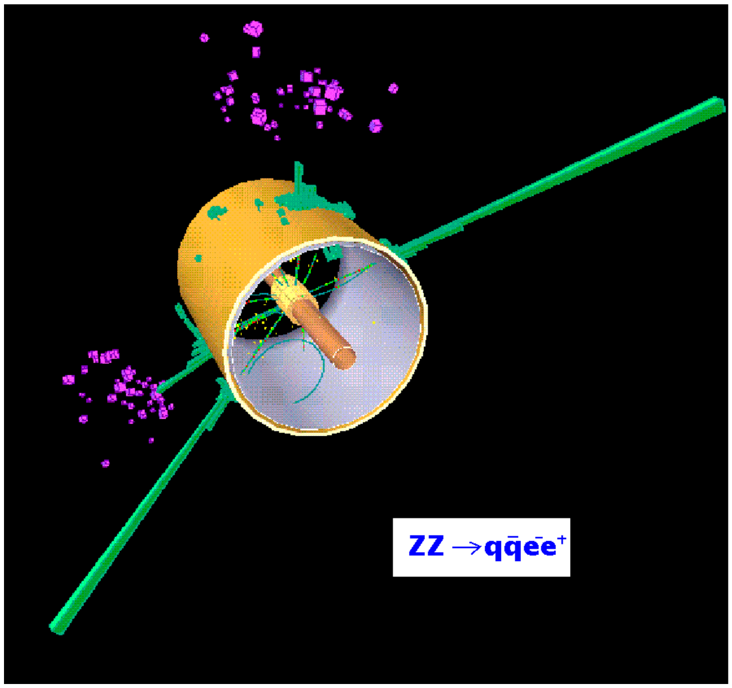
ZZ production



- Other potential sources of 4-fermion final states

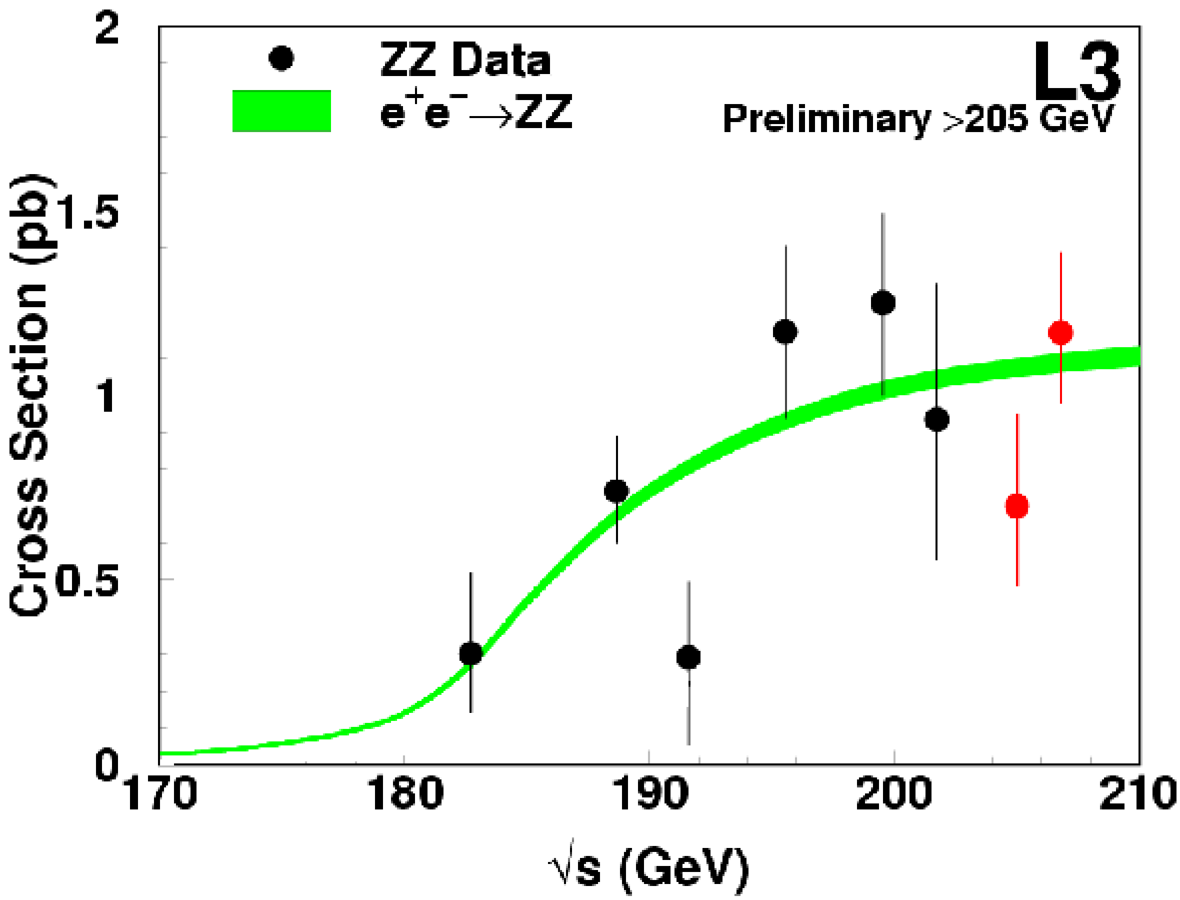


- Define phase space cuts
  - $M_{f_1\bar{f}_1,f_2\bar{f}_2} \in$ 70-105 GeV *vs.* γ^* exchange
  - $M_{f_1\bar{f}_2,f_2\bar{f}_1} \notin$ 75-85 GeV *vs.* WW production
  - $|\cos\theta_e| < 0.95$ *vs.* Multi-peripheral diagram



Channel	Statistics	Signature	Background
$q\bar{q}q\bar{q}$	Highest (49%)	Four jets	QCD ($q\bar{q}gg$) $W^+W^- \rightarrow q\bar{q'}q'\bar{q}$
$q\bar{q}\nu\bar{\nu}$	High (28%)	Two jets and $\not{\vec{P}}$	QCD ($q\bar{q}\gamma$),$We\nu$ $W^+W^- \rightarrow q\bar{q'}l\nu$
$q\bar{q}\ell^+\ell^-$	Medium (14%)	Two jets Two leptons	$W^+W^- \rightarrow q\bar{q'}l\nu$ Non-reso. ZZ
$\ell^+\ell^-\nu\bar{\nu}$	Low (4%)	Two leptons and $\not{\vec{P}}$	$W^+W^- \rightarrow l\nu l\nu$ 2-fermions
$\ell^+\ell^-\ell^+\ell^-$	Lowest(1%)	Four leptons	Non-reso. ZZ

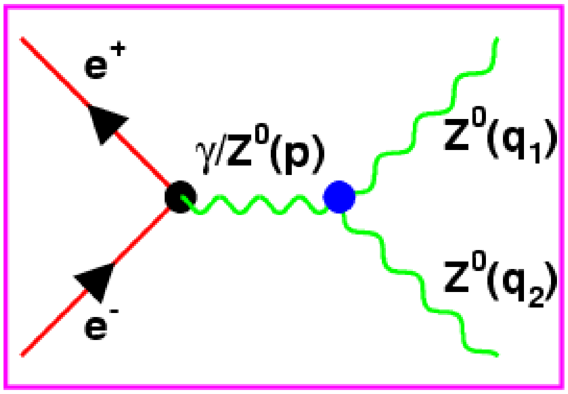
ZZ Production Cross section



$\sqrt{s}$(GeV)	σ^{SM}(pb)	$\sigma^{measured}$(pb)	$\mathcal{R} = \frac{\sigma^{NC02}}{\sigma^{cut}}$
192	0.79	$0.29 \pm 0.22 \pm 0.02$	1.0000
196	0.92	$1.17 \pm 0.24 \pm 0.09$	1.0085
200	1.00	$1.25 \pm 0.25 \pm 0.09$	1.0000
202	1.03	$0.93 \pm 0.38 \pm 0.07$	1.0215
205	1.07	$0.70\ ^{+0.25}_{-0.22}$	0.9857
207	1.08	$1.18\ ^{+0.21}_{-0.20}$	0.9915

Anomalous Couplings from Z-pair

???



$$-i\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,p) = \frac{s-m_V^2}{m_Z^2}\left(f_4^V(p^\alpha g^{\mu\beta}+p^\beta g^{\mu\alpha})+f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right)$$

f_4^V (CP-violating) and f_5^V (CP-conserving) are absent in SM

➠ To find out the impact of non-zero f_4^V and f_5^V:

- Re-weight MC sample including Anomalous Couplings
- Maximum likelihood fit to the most significant distribution
- Repeat the exercise for each f_i^V, fixing others to zero

<u>95 % C.L. limits</u>

$-0.68 \leq f_4^Z \leq 0.68$

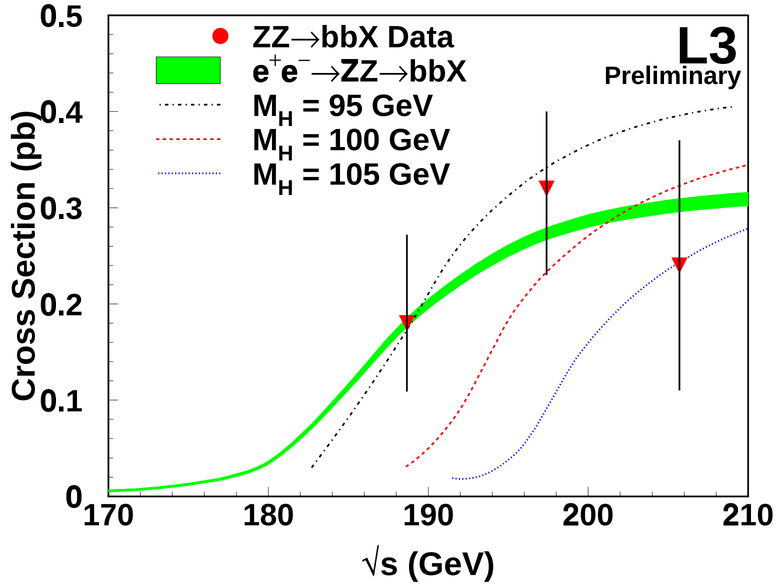
$-1.03 \leq f_5^Z \leq 1.13$

$-0.40 \leq f_4^\gamma \leq 0.40$

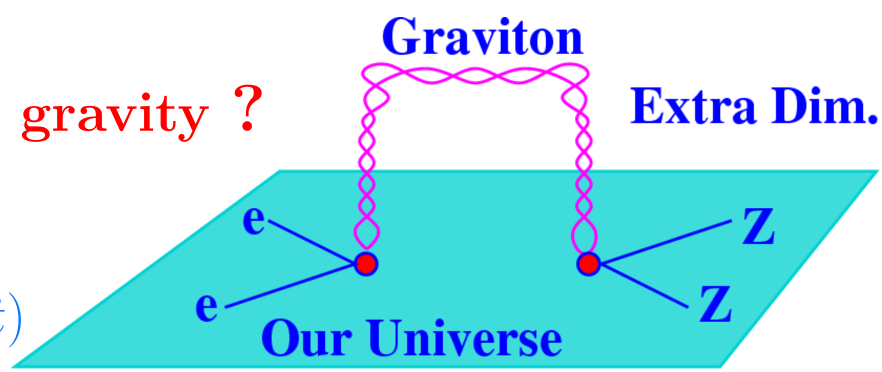
$-0.84 \leq f_5^\gamma \leq 0.87$

Benchmark to Higgs at LEP

- Verifies the capability of our detector to discover Higgs
- Because of identical final states and similar value of cross section



☞ **And how about gravity ?**



$$\frac{d\sigma}{d\Omega}(s,t) = \frac{d\sigma^{SM}}{d\Omega}(s,t) + \frac{\lambda}{M_S^4}\,\alpha_{Inter}(s,t) + \frac{\lambda^2}{M_S^8}\,\beta_{LSG}(s,t)$$

✎ Fit to the σ^{ZZ} or angular information

✎ Extract 95% C.L. lower limits on M_S:

λ = -1	λ = +1
1.2 TeV	1.2 TeV

- Over the past several years, extreme precision measurement and new energy frontier have been the trade marks of LEP
- Here we have discussed a particular case of vector boson pair productions and various possible gauge-boson couplings
- All our results, are in excellent agreement with the Standard Model predictions, without any evidence to go beyond it