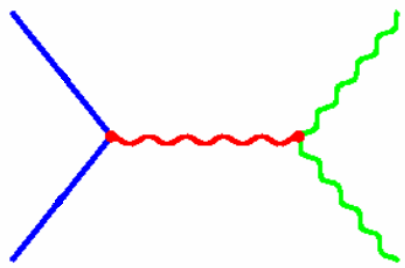
Measurement of Triple-Gauge Boson Couplings of the W boson at L3

Mark Dierckxsens



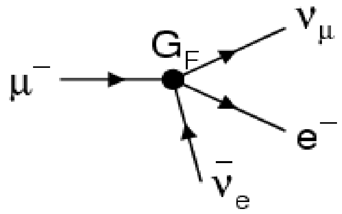
Particle Physics Seminar
Brookhaven National Laboratory
October 9, 2003

Outline

- Introduction to TGC's
- LEP and L3
- W-pair production
- TGC's from W-pairs
- Single-W production
- TGC's from single W's
- Combination of L3 results
- LEP and the Future
- Conclusions

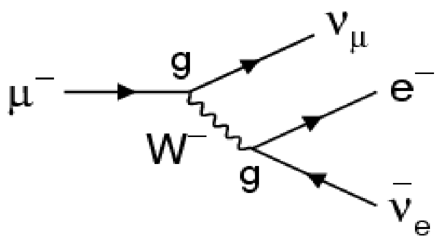
Introduction

Fermi (1934):
theory for β decay



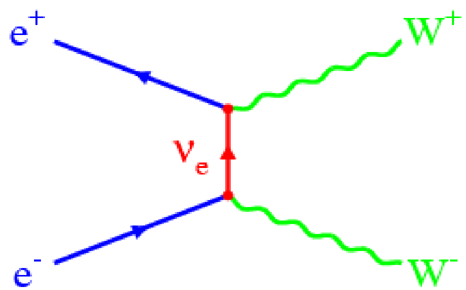
$\sigma \sim s$
☹ unitarity violation
$\sqrt{s} \simeq 300$ GeV

Schwinger, Lee and Yang (1957): W boson



$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8\,M_W^2}$$

$e^+e^- \rightarrow W^+W^-$:



☹ unitarity violation
$\sqrt{s} \simeq 1$ TeV

Introduction

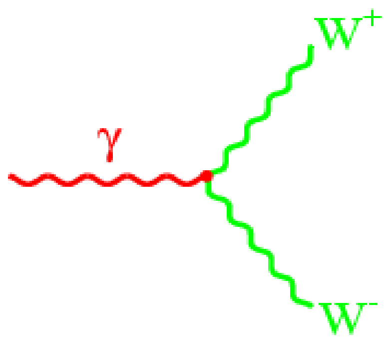
Glashow (1961): Z boson

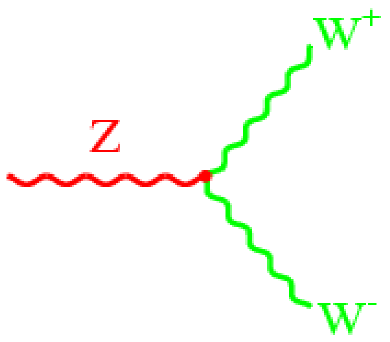
Weinberg and Salam (1967):

- local gauge symmetries $SU(2)_L$ and $U(1)_Y$
- Higgs mechanism (spont. symm. breaking)

☞ Standard Model of electroweak interactions

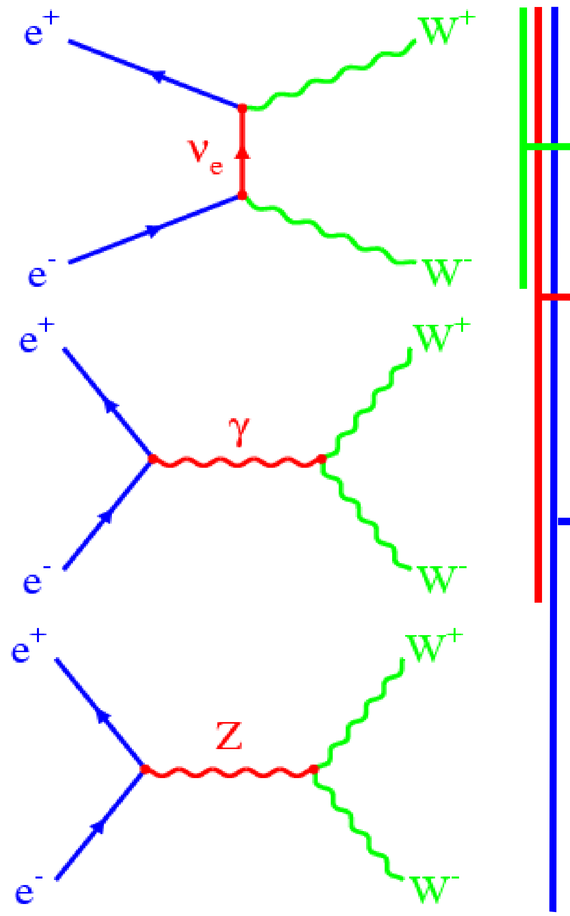
SU(2) non-Abelian ⇒ gauge boson self-couplings:

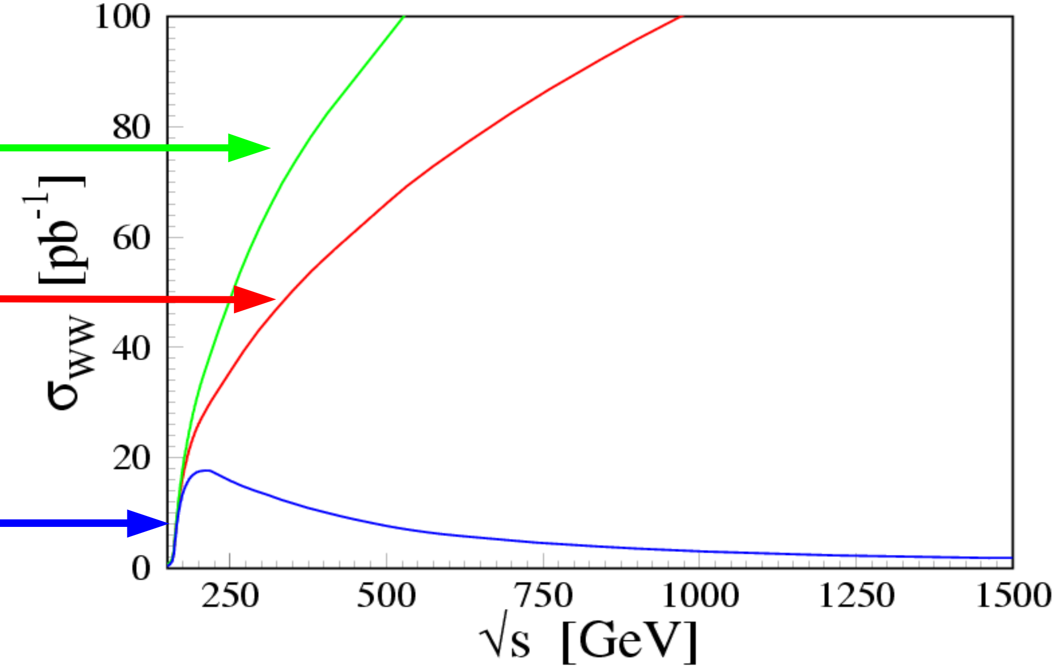




Introduction

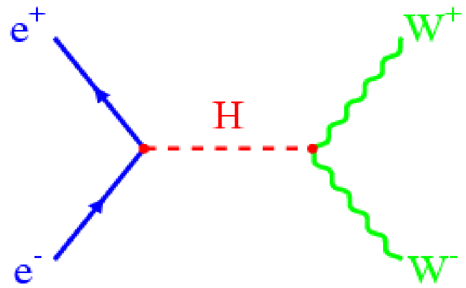
Proper high energy behaviour for $e^+e^- \rightarrow W^+W^-$





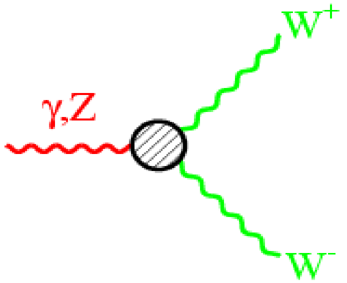
= CC03

At very high energies:



TGC parametrisation

Most general, Lorentz invariant parametrisation (V=Z,γ):



$$\frac{i\mathcal{L}_{eff}^{WWV}}{g_{WWV}} = \begin{array}{llll}
 & & & \text{SM} \\
 & & & Z,\gamma \\
g_1^V & V^{\mu}(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) & C, P & 1 \\
+\ \kappa_V & W^+_{\mu}W^-_{\nu}V^{\mu\nu} & C, P & 1 \\
+\ \lambda_V & (1/m_W^2)V^{\mu\nu}W^{+\rho}_{\nu}W^-_{\rho\mu} & C, P & 0 \\
+\ i g_4^V & W^+_{\mu}W^-_{\nu}(\partial^{\mu}V^{\nu} + \partial^{\nu}V^{\mu}) & \not{C}, P & 0 \\
+\ i g_5^V & \epsilon_{\mu\nu\rho\sigma}((\partial^{\rho}W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^{\rho}W^{+\nu}))V^{\sigma} & \not{C}, \not{P} & 0 \\
-\ \tilde{\kappa}_V & (1/2)W^-_{\mu}W^+_{\nu}\epsilon^{\mu\nu\rho\sigma}V_{\rho\sigma} & C, \not{P} & 0 \\
-\ \tilde{\lambda}_V & (1/2\,m_W^2)W^-_{\mu\nu}W^{+\mu}_{\nu}\epsilon^{\nu\rho\alpha\beta}V_{\alpha\beta} & C, \not{P} & 0
\end{array}$$

$$g_{WW\gamma} = g_{WWZ}\tan\theta_W = e$$

TGC parametrisation

Form factor behaviour: $$\psi(Q^2) = \frac{\psi(0)}{(1 + Q^2 / \Lambda_F^2)^n}$$

γWW Lagrangian $\leftrightarrow$ γW multi-pole expansion:

electric charge: $$q_W = e\, g_1^\gamma$$

magnetic dipole moment: $$\mu_W = \frac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

electric quadrupole moment: $$Q_W = \frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$

electric dipole moment: $$d_W = \frac{e}{2M_W}(\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma)$$

magnetic quadrupole moment: $$\mathcal{M}_W = \frac{e}{M_W^2}(\tilde{\kappa}_\gamma - \tilde{\lambda}_\gamma)$$

TGC parametrisation

14 couplings in general parametrisation

Reduce # couplings:

- Restrict to CP conserving couplings

- $U(1)_{e.m.}$ invariance: $g_1^{\gamma} = 1 \qquad g_5^{\gamma} = 0$

- $SU(2)_L x U(1)_Y$ invariance (lin. realis. of NP):

$$\kappa_Z = g_1^Z - \tan^2\theta_w(\kappa_\gamma - 1) \qquad \lambda_Z = \lambda_\gamma \qquad g_5^Z = 0$$

☞ 3 couplings remain: $\boxed{g_1^Z \quad \kappa_\gamma \quad \lambda_\gamma}$

Signatures of New Physics

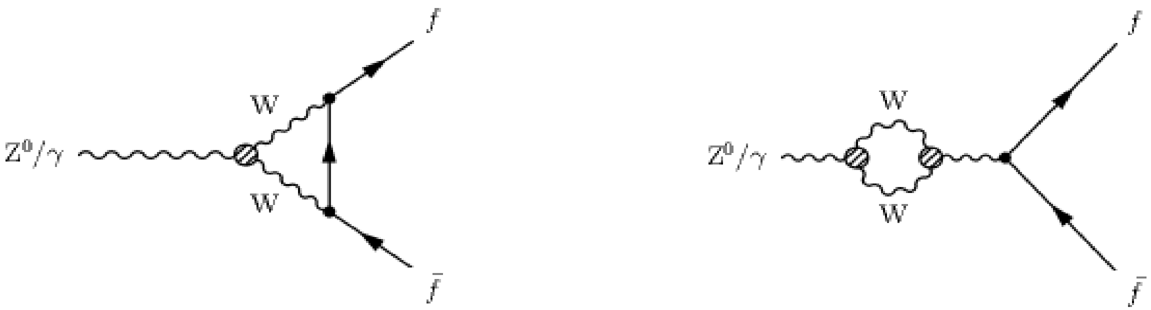
Signatures devided into two categories:

- new particles produce same final state as WW
- loop corrections modify SM boson propagators and vertices:
  - Standard Model → $O(10^{-3})$
  - Models of NP of same order, but often for specific parameter values:

    supersymmetry, two Higgs doublets models
    technicolor hadrons, additional neutral gauge bosons, composite W boson, ...

Indirect Limits

Loop corrections to low-energy processes:



- Z-peak data @ LEP1: $\left|g_1^Z - 1\right| \simeq \left|\kappa_\gamma - 1\right| < 0.02$
- Cesium weak charge: $\left|\lambda_\gamma\right| < 0.02$
- Other limits from: $(g\text{-}2)_\mu$, $b \to s\gamma$, $B \to K^{(*)}\mu^+\mu^-$,...

Direct Limits

- PEP & PETRA: $e^+e^- \to \nu\nu\gamma$ $\sqrt{s}$ = 30-40 GeV

  $-73 < \kappa_\gamma < 36$

- Limits derived by UA2, ZEUS, CDF

- DØ: $W\gamma$, WZ, WW $\sqrt{s}$ = 1.8 TeV, Λ_F = 2 TeV

  $0.71 < g_1^Z < 1.57$

  $0.78 < \kappa_\gamma < 1.44$

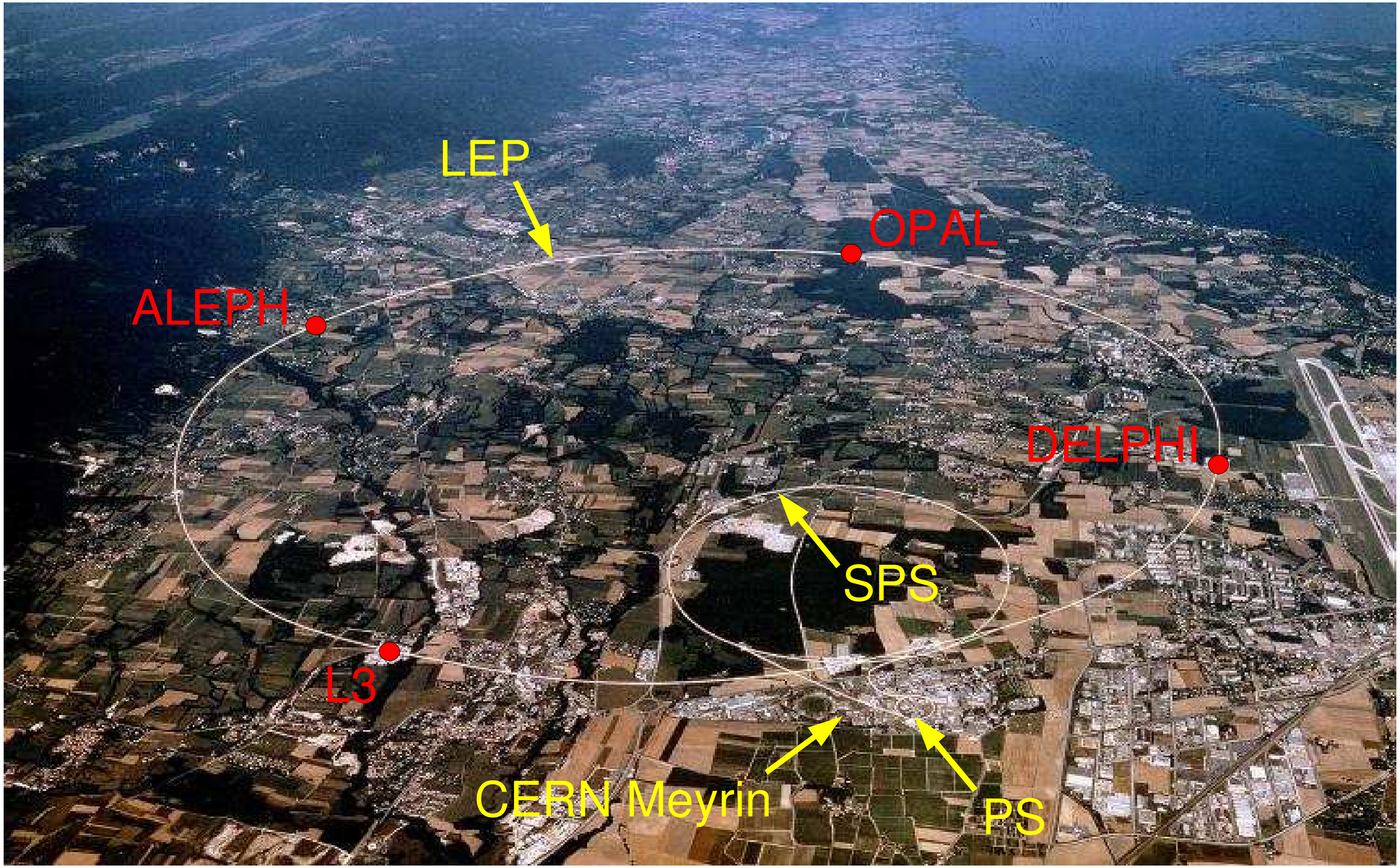
  $-0.20 < \lambda_\gamma < 0.20$

- LEP2 expected sensitivities $\sqrt{s} \geq 2M_W$ = 161 GeV

  $| g_1^Z - 1 | \simeq | \lambda_\gamma | \leq 0.03$

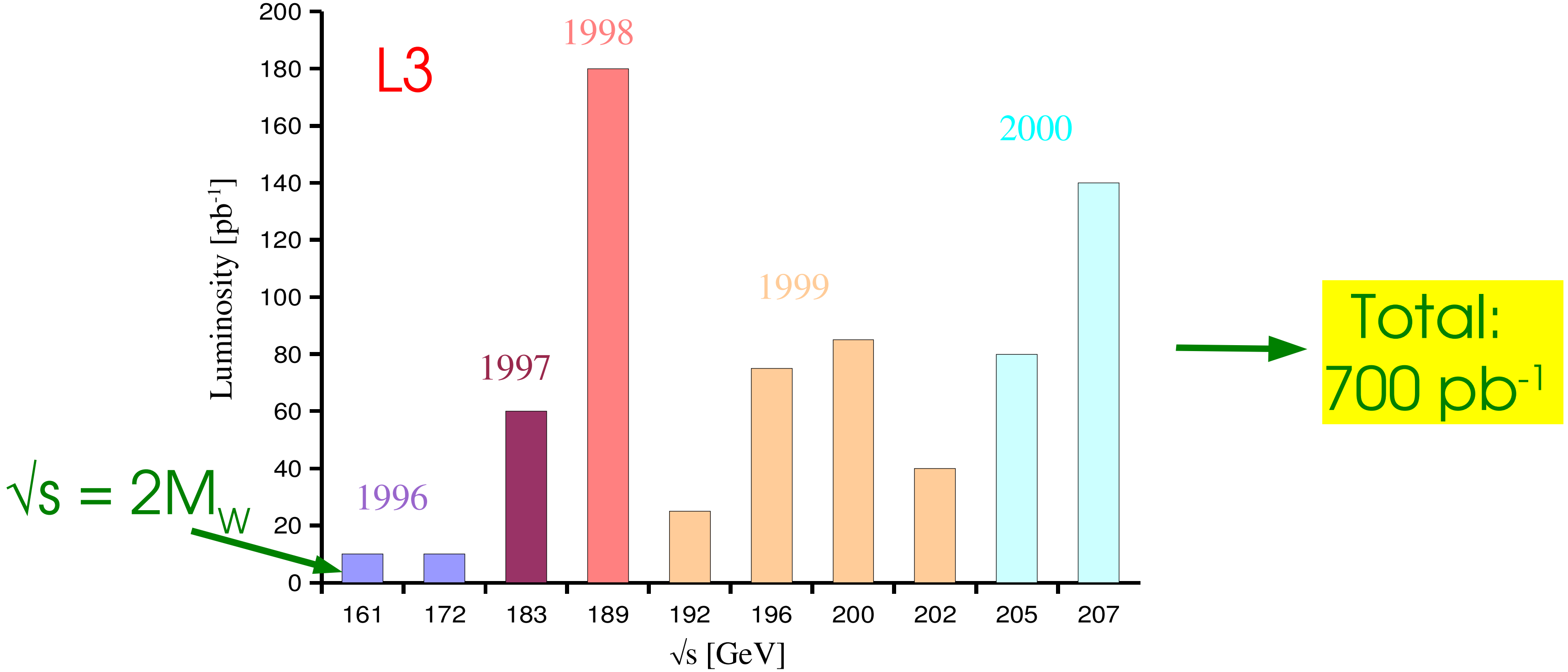
  $| \kappa_\gamma - 1 | \leq 0.10$

LEP Collider

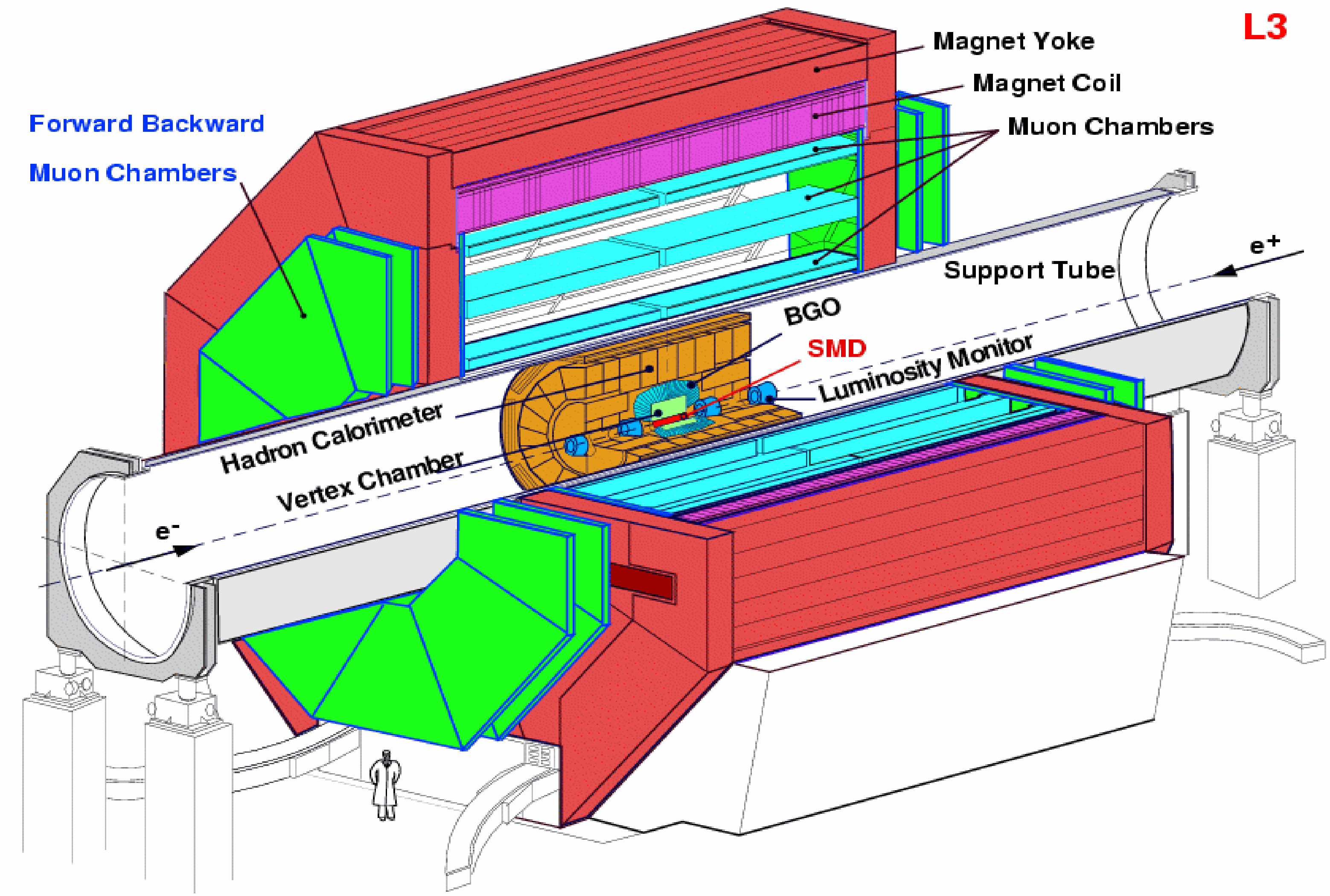


LEP Collider

LEP1:	1989-1994	$\sqrt{s} \simeq 90$ GeV
LEP1.5:	1995	$\sqrt{s} = 130\text{-}140$ GeV
LEP2:	1996-2000	$\sqrt{s} = 161\text{-}209$ GeV

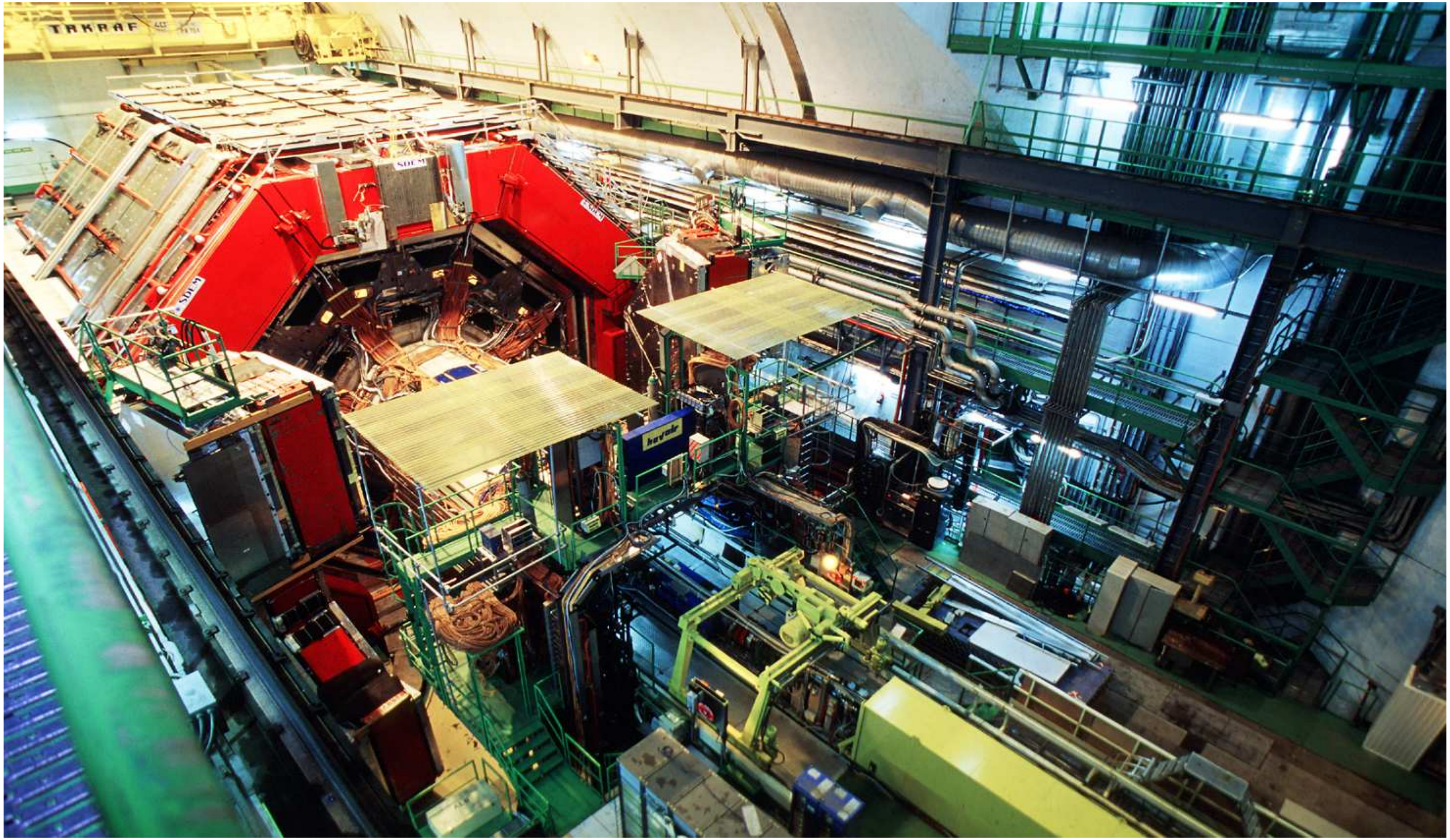


L3 Detector

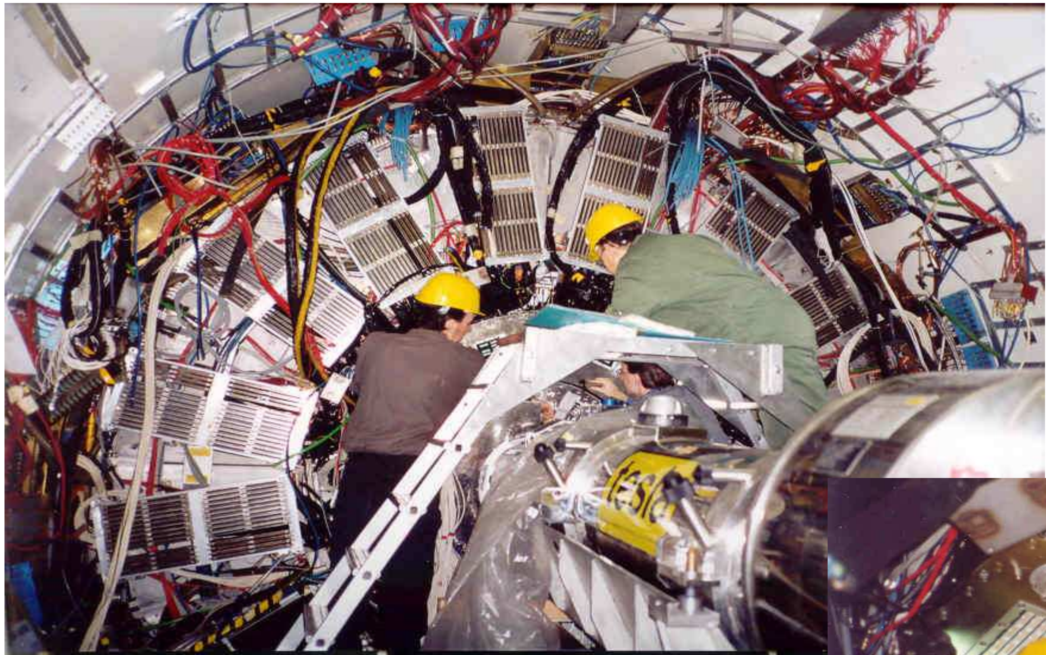


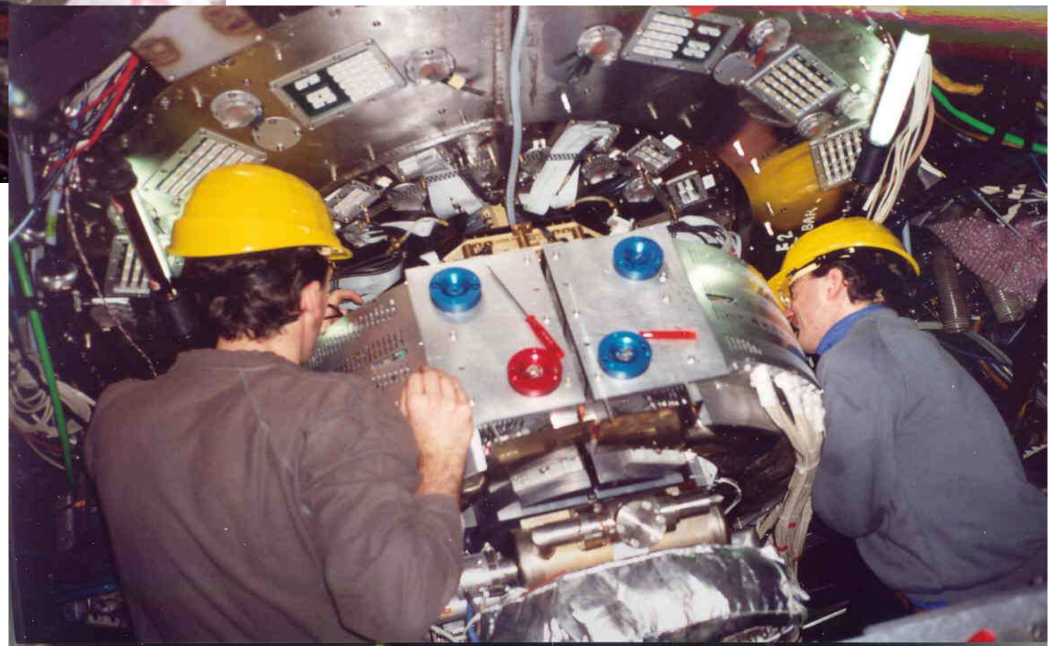
L3
Magnet Yoke
Magnet Coil
Muon Chambers
Forward Backward
Muon Chambers
Support Tube
e+
BGO
SMD
Luminosity Monitor
Hadron Calorimeter
Vertex Chamber
e-

L3 Detector



L3 Detector

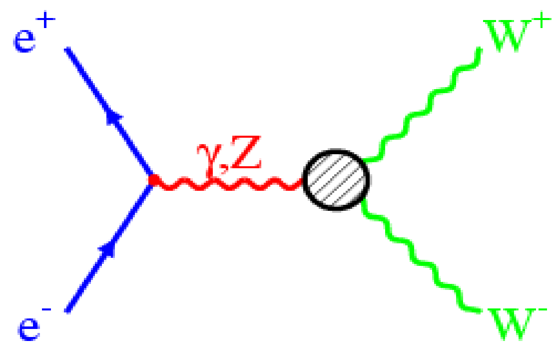


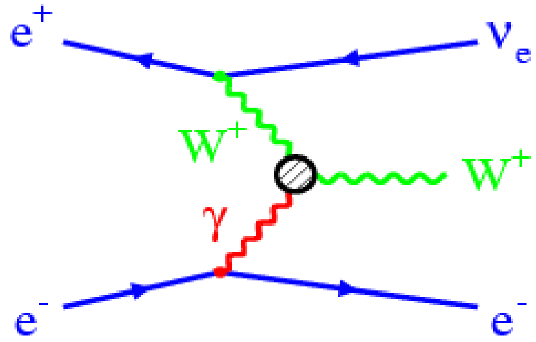


L3 ex-Detector

TGC's at LEP

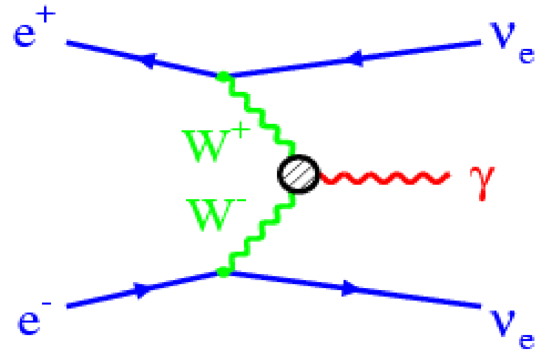
W-pair production





single-W production

single-γ production



W-pair Production

CC03 cross section:

- steep rise at threshold ⇒ 11600 WW events
- max @ 208 GeV: $\sigma = 17.2\ pb^{-1}$

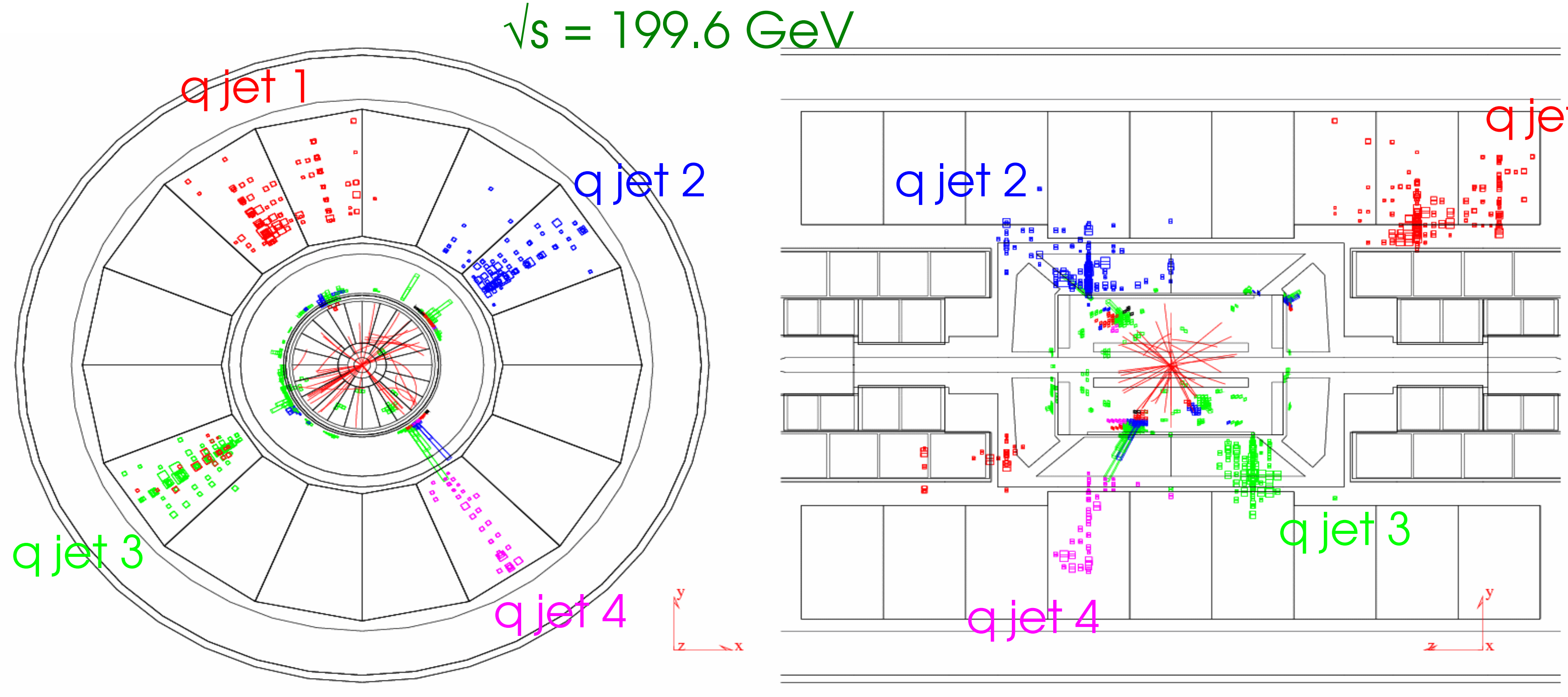
Decay channels:

		qqqq	hadronic	(46%)	
WW	$\rightarrow$	qqlν	semi-leptonic	(44%)	with l=e,μ,τ
		lνlν	leptonic	(11%)	

Backgrounds:

- 4f processes: non-resonant, single-W, single-Z, ZZ
- fermion pairs: qq(γ), ll(γ)
- 2-photon processes: $\gamma\gamma \rightarrow$ ff, hadrons

WW → qqqq



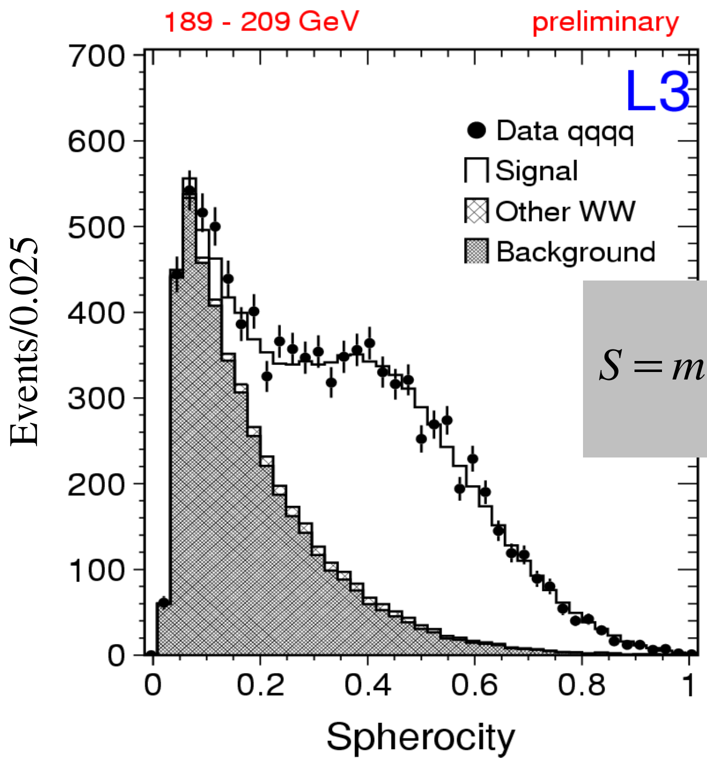
4 quarks jets: high multiplicity
no missing energy or momentum

WW → qqqq

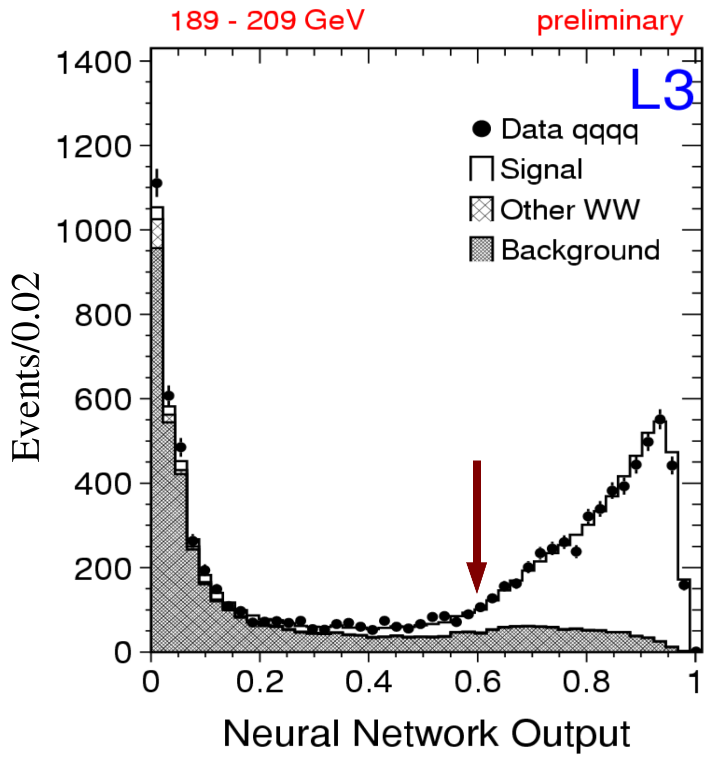
pre-selection: $\epsilon \simeq 92\%,\ \pi \simeq 50\%$

NN output > 0.6: $\epsilon \simeq$ 83-88%

$\pi \simeq$ 79-81%



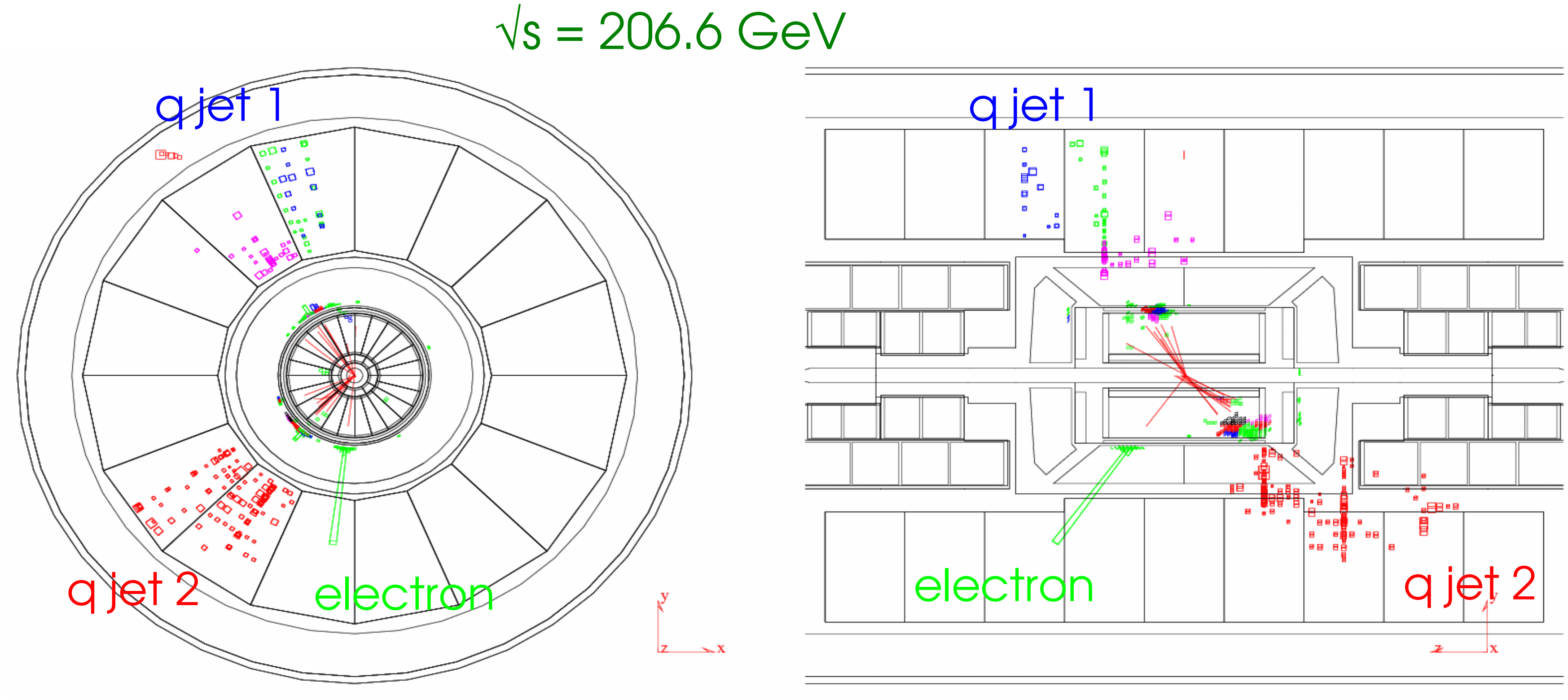
$$S = min \frac{(\sum_i |\hat{n} \times \vec{p}_i|)^2}{(\sum_i |\vec{p}_i|)^2}$$



backgrounds: qq(γ), ZZ

5234 events (189 ≤ √s ≤ 209 GeV)

WW → qqeν

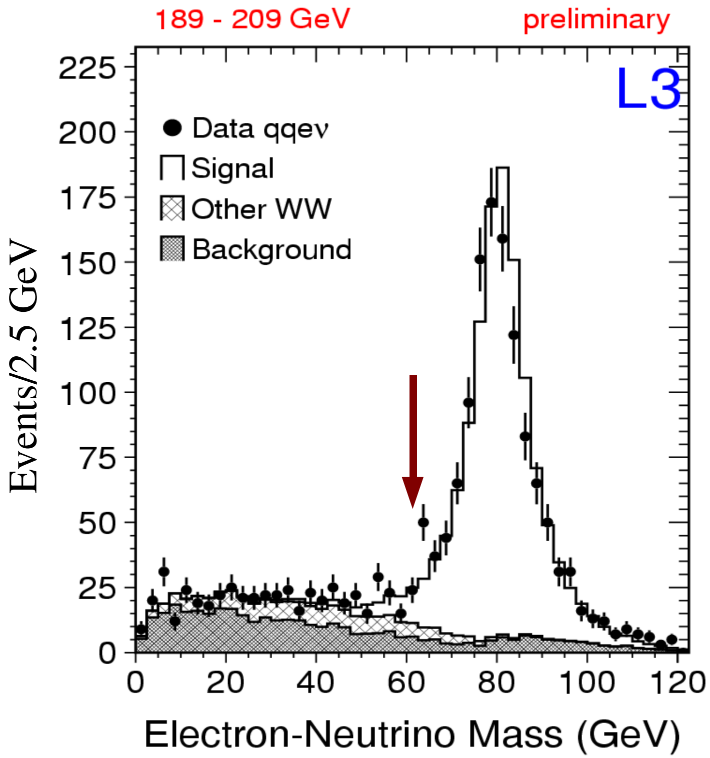


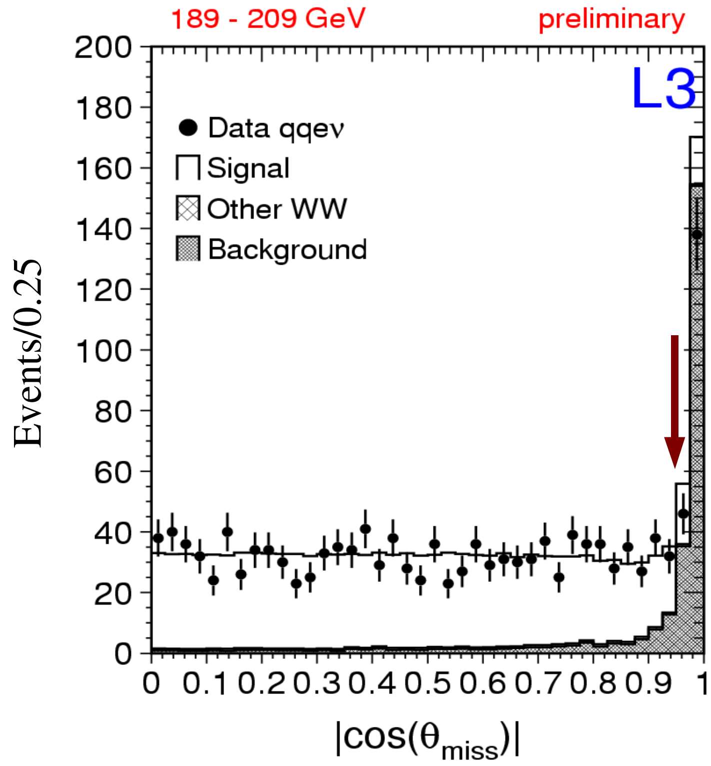
2 quark jets: high multiplicity
energetic electron
escaping neutrino: missing energy & momentum

WW → qqeν

Cut based selection:

$$\epsilon \simeq 81\text{-}88\%,\ \pi \simeq 90\%$$

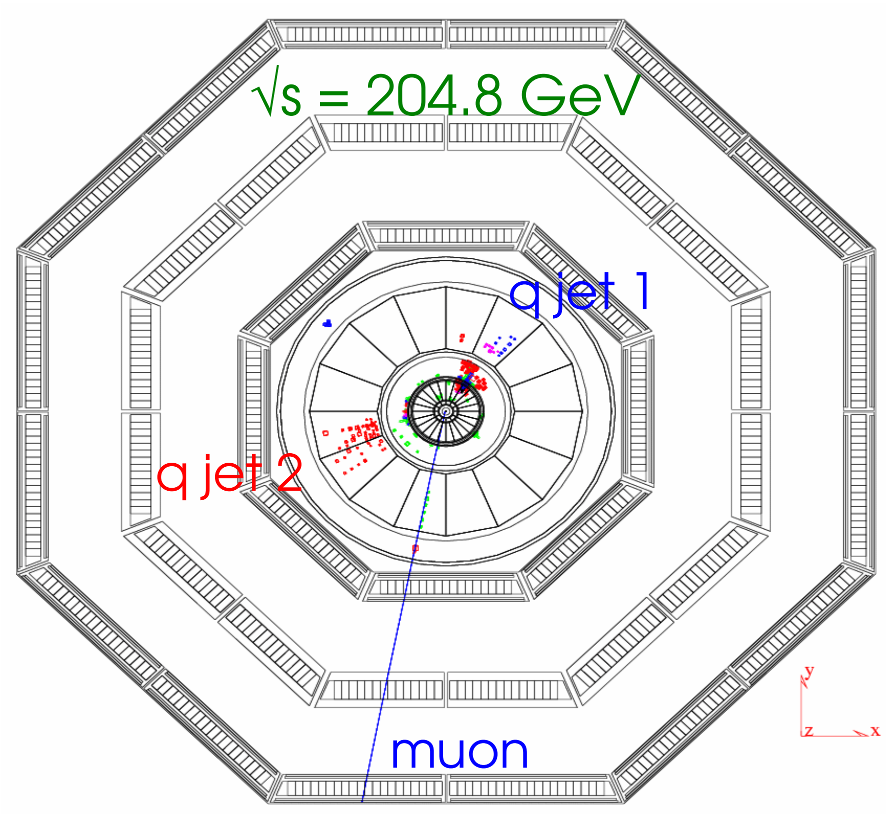


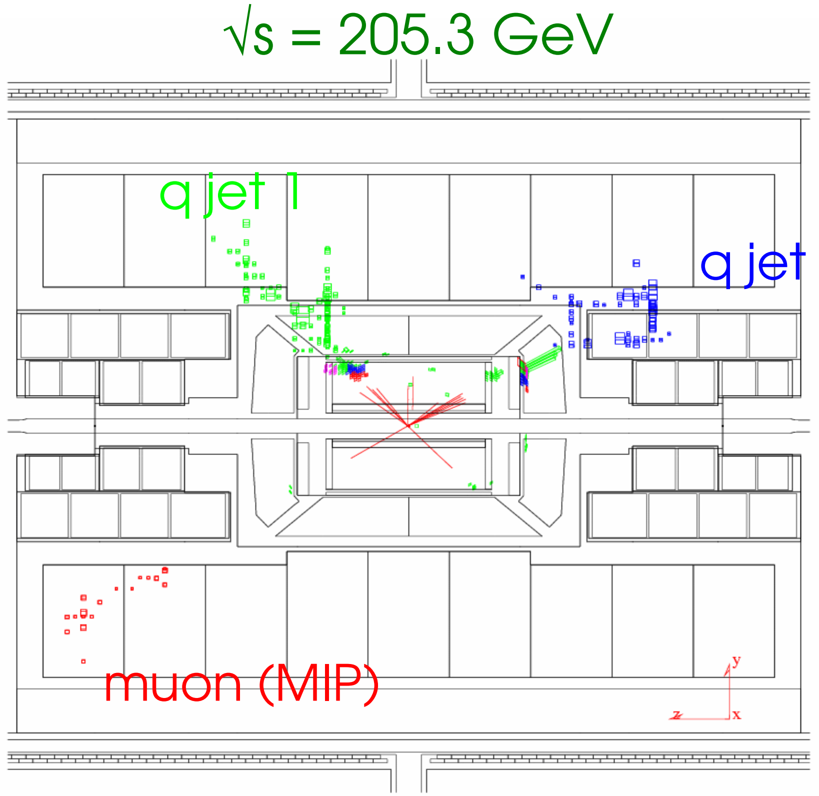


backgrounds: Weν, qq(γ), ZZ, Zee, WW

1269 events (189 ≤ √s ≤ 209 GeV)

WW → qqμν



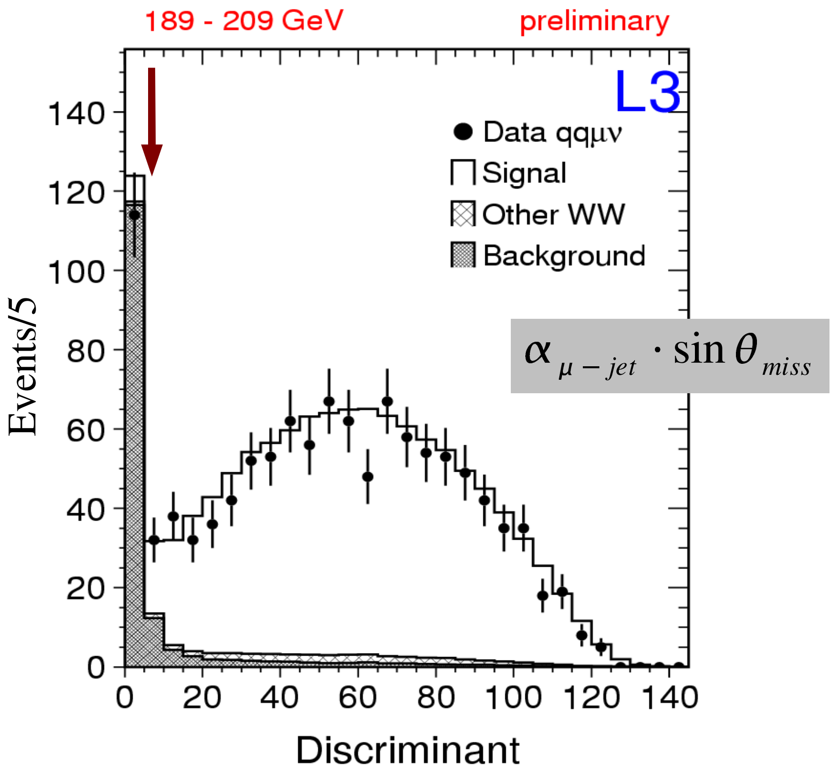


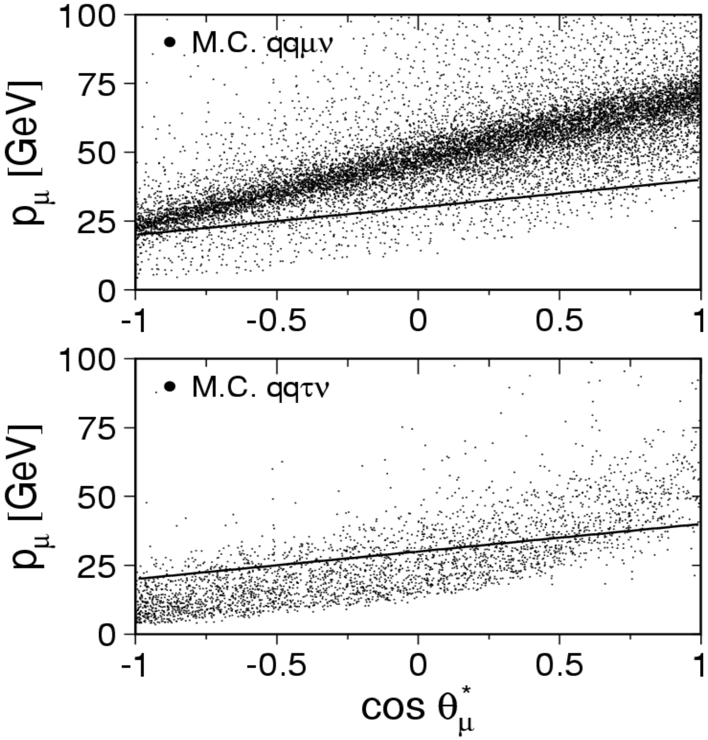
2 quark jets: high multiplicity
high momentum muon (muon chambers or MIP)
escaping neutrino: missing energy & momentum

WW → qqμν

Cut based selection:

$$\epsilon \simeq 74\text{-}77\%,\ \pi \simeq 91\%$$

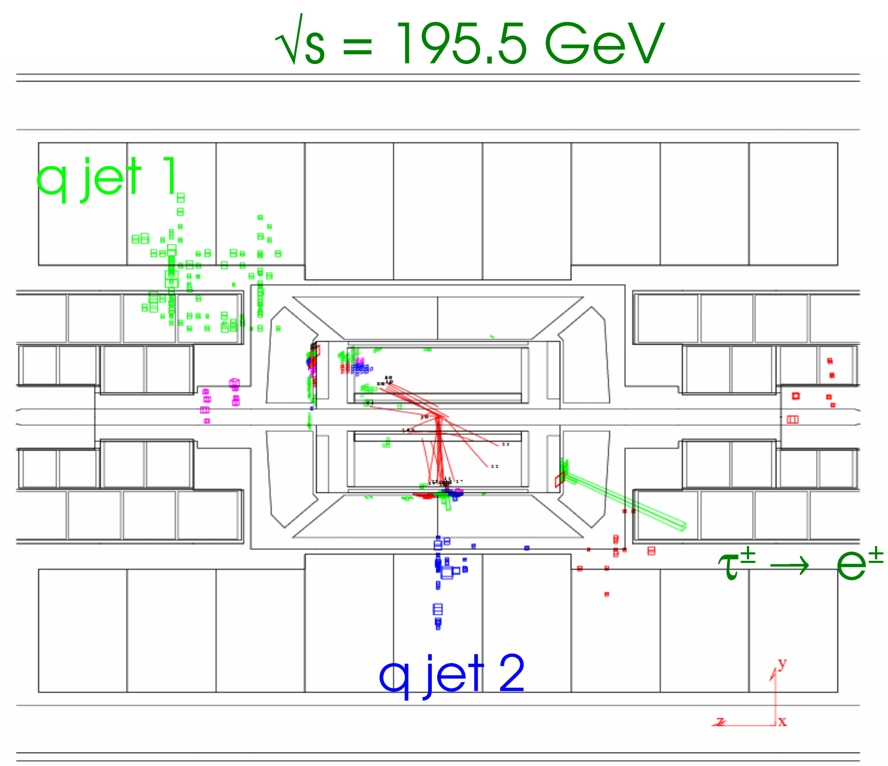


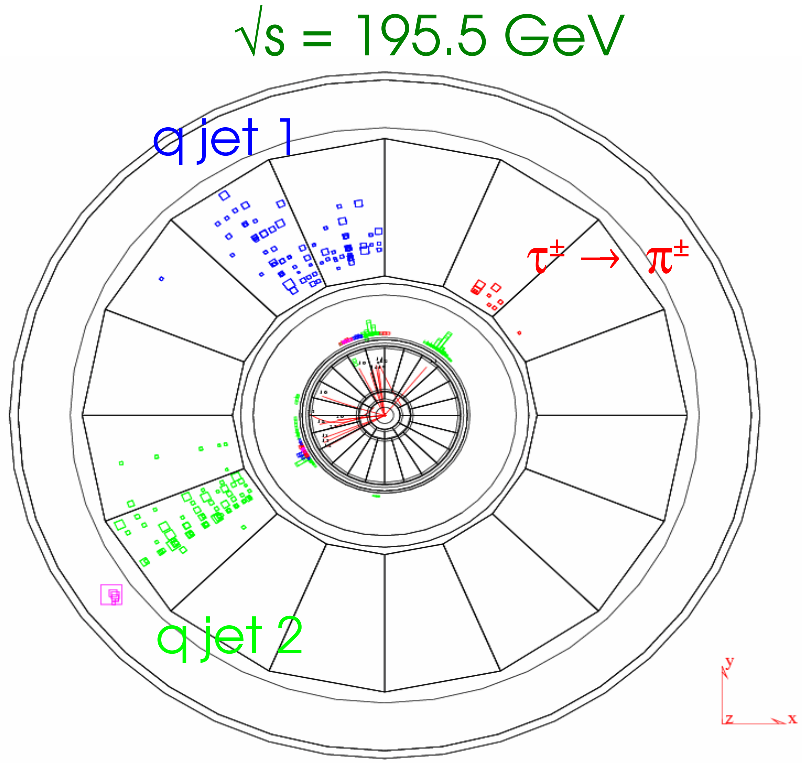


backgrounds: WW, qq(γ), ZZ

1187 events ($189 \leq \sqrt{s} \leq 209$ GeV)

WW → $qq\tau\nu$



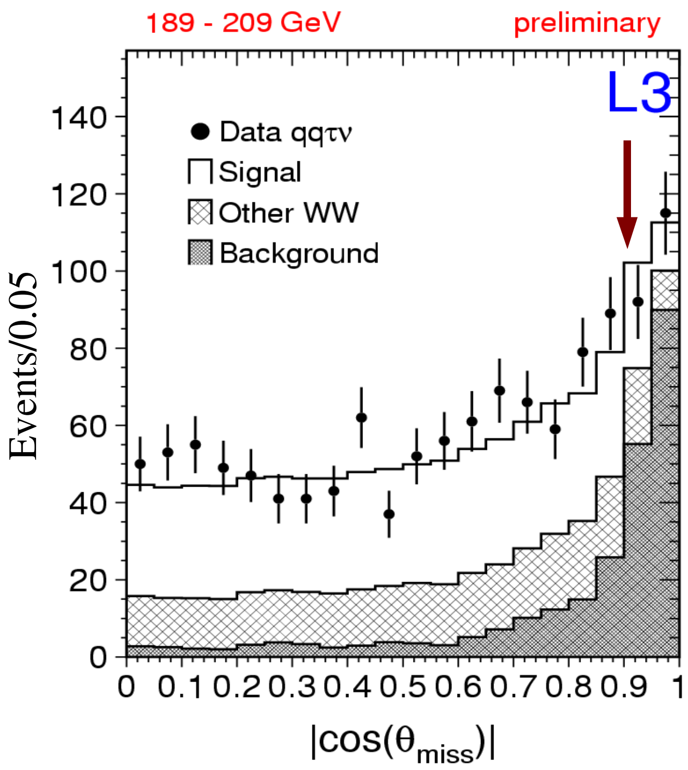


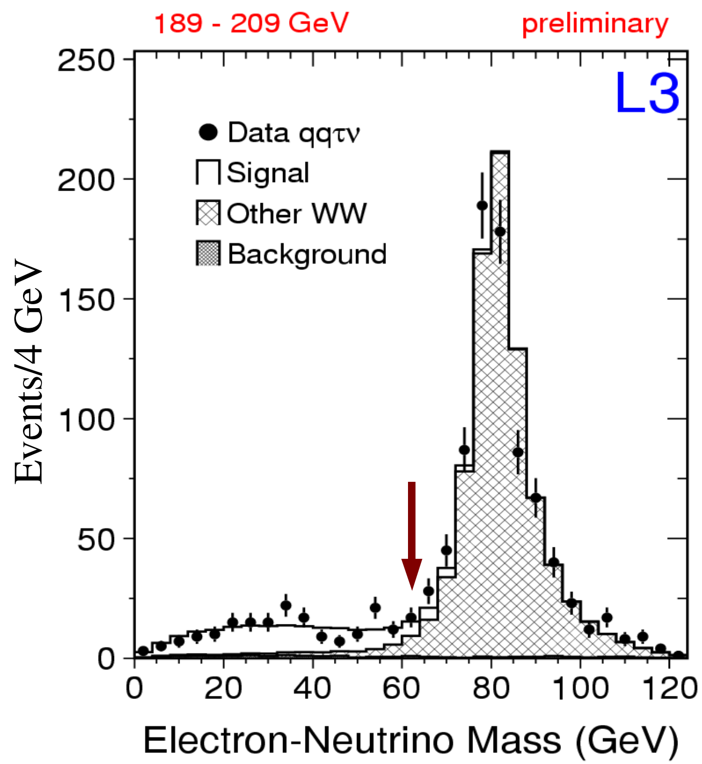
2 quark jets: high multiplicity
tau identification: electrons, muons, hadrons
escaping neutrinos: missing energy & momentum

WW → qqτν

Cut based selection:

$$\epsilon \simeq 50\text{-}55\%,\ \pi \simeq 62\text{-}66\%$$

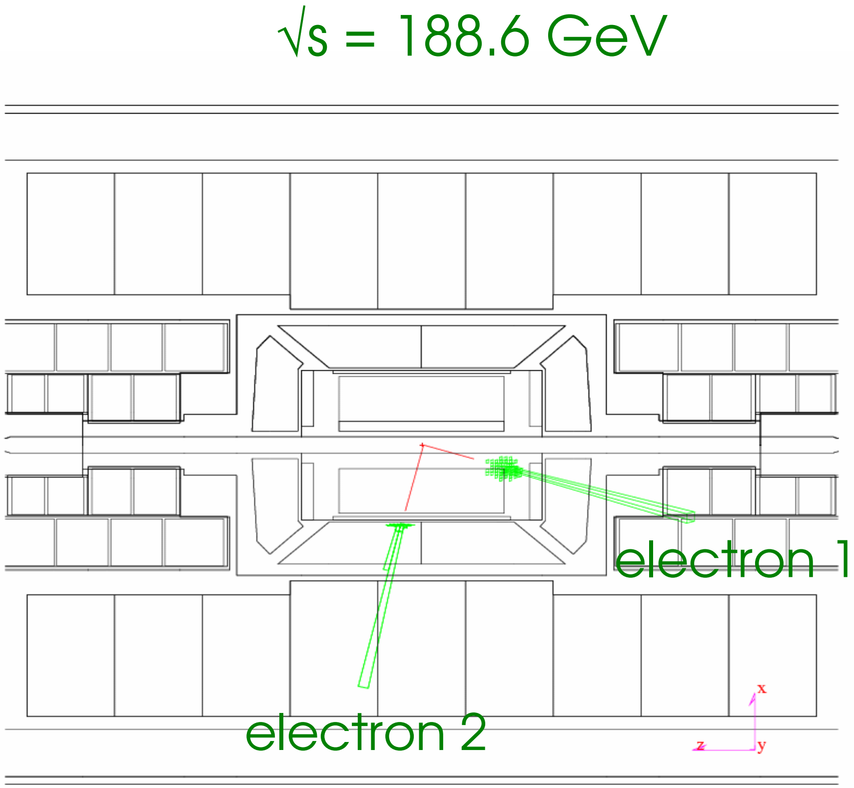


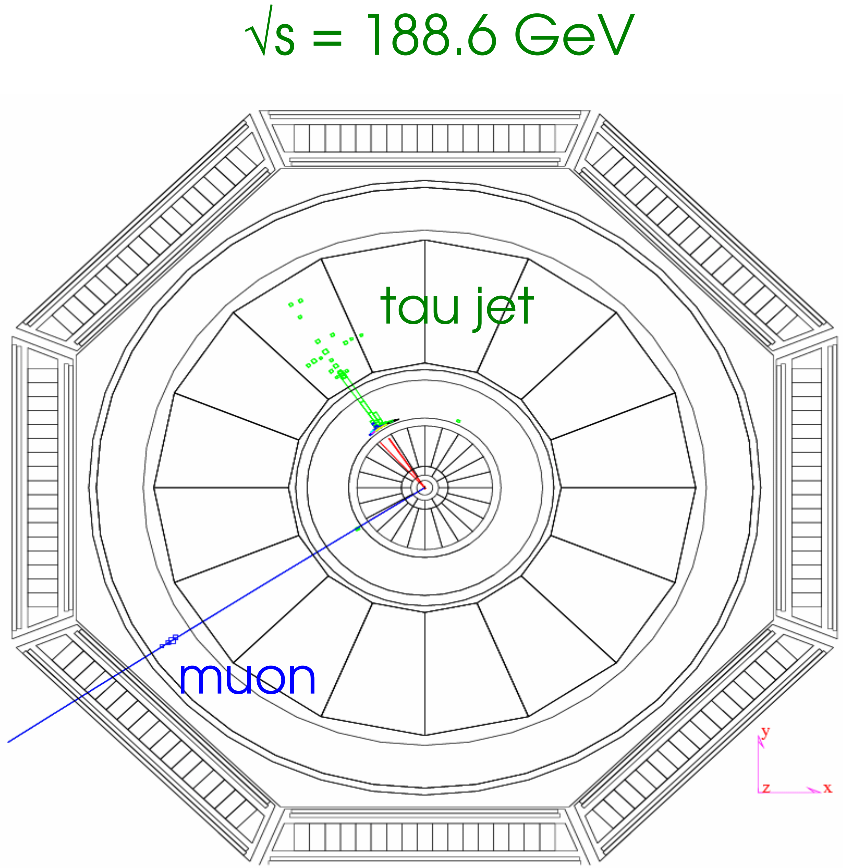


backgrounds: WW, qq(γ), ZZ, Zee

1405 events ($189 \leq \sqrt{s} \leq 209$ GeV)

WW → lνlν





no quarks: low multiplicity

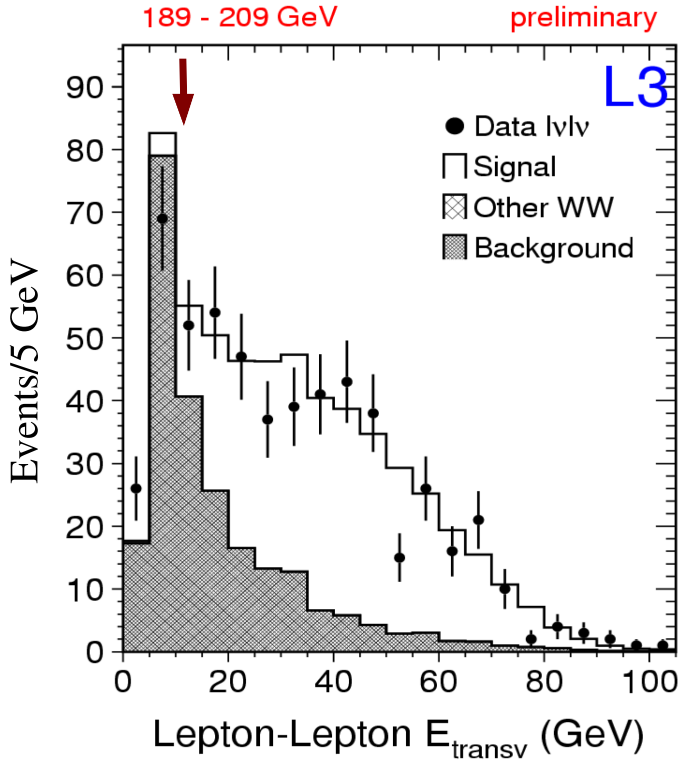
2 leptons: electrons, muons, taus

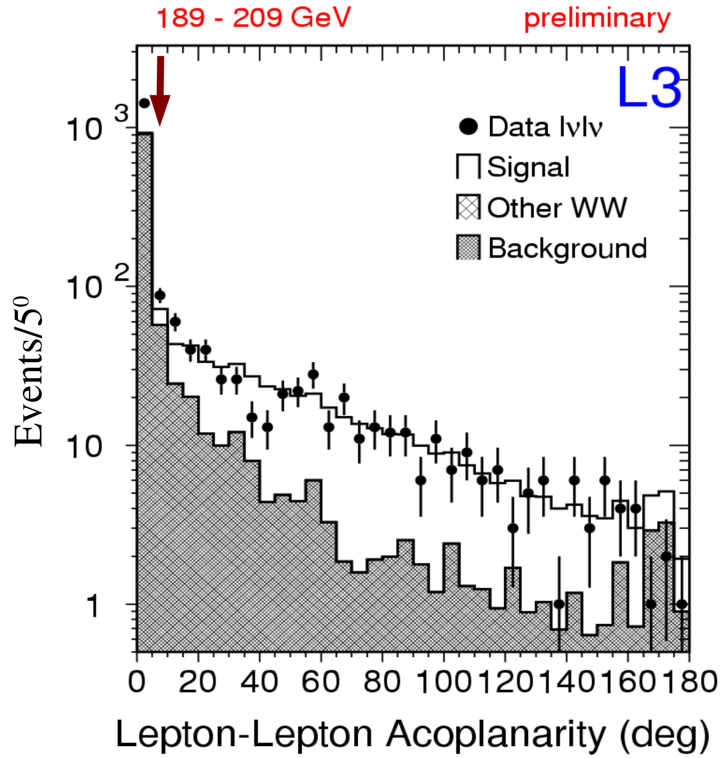
escaping neutrinos: acoplanar, acolinear leptons

WW → lνlν

Cut based selection:

$$\epsilon \simeq 53\text{-}58\%,\ \pi \simeq 76\text{-}87\%$$

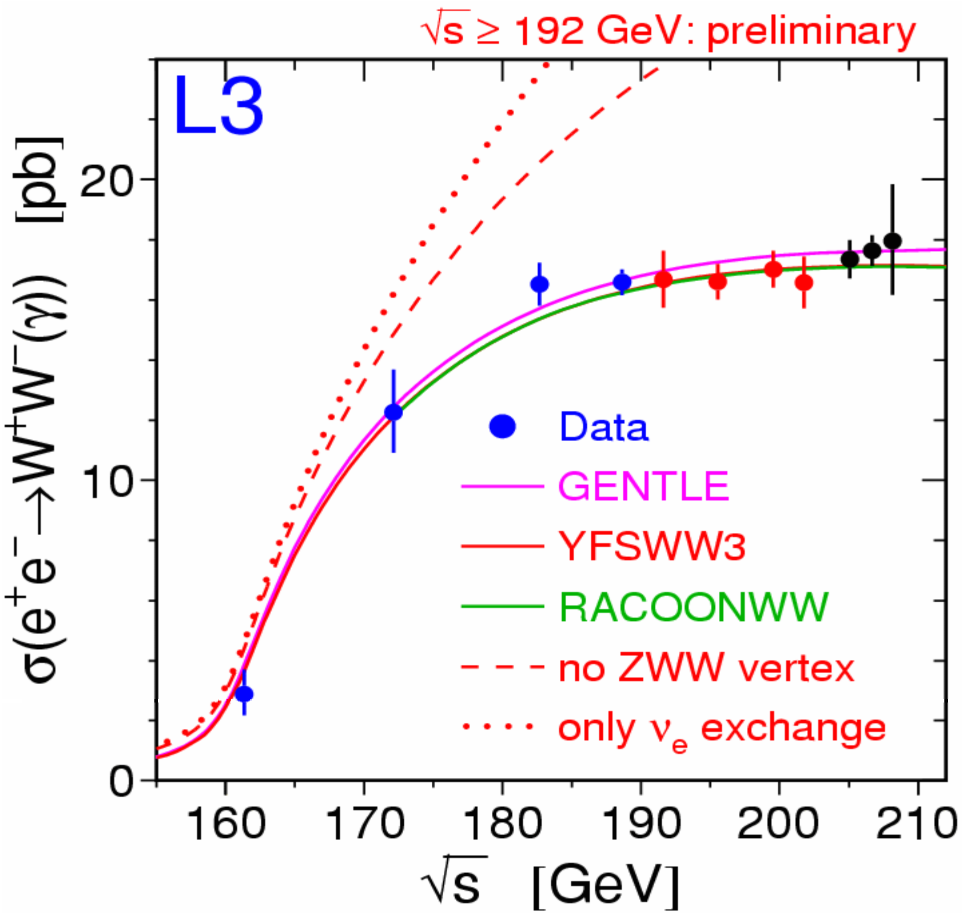


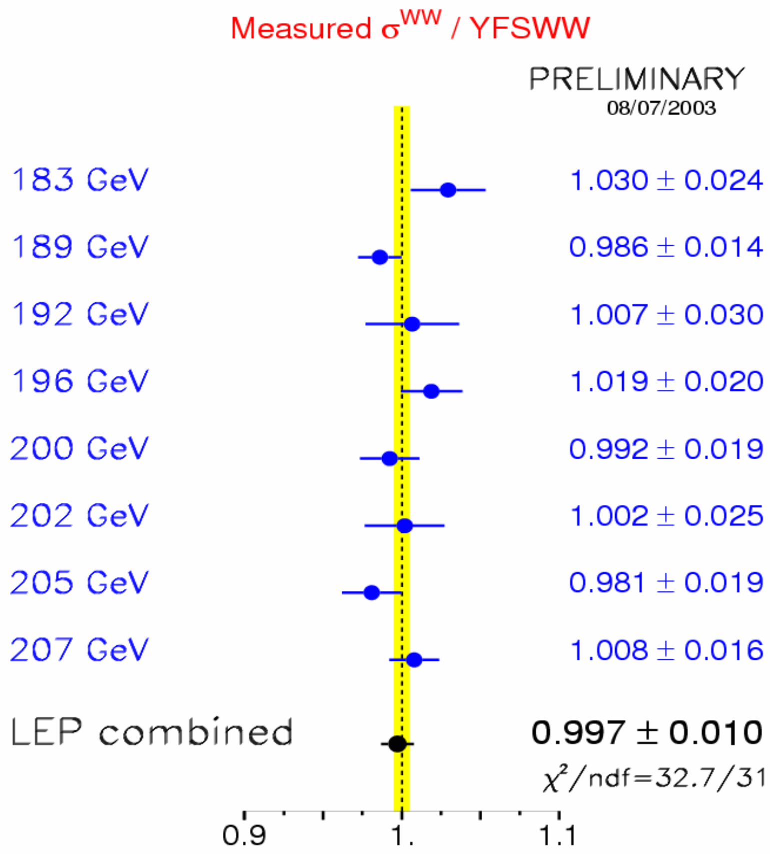


backgrounds: γγ, ll(γ)

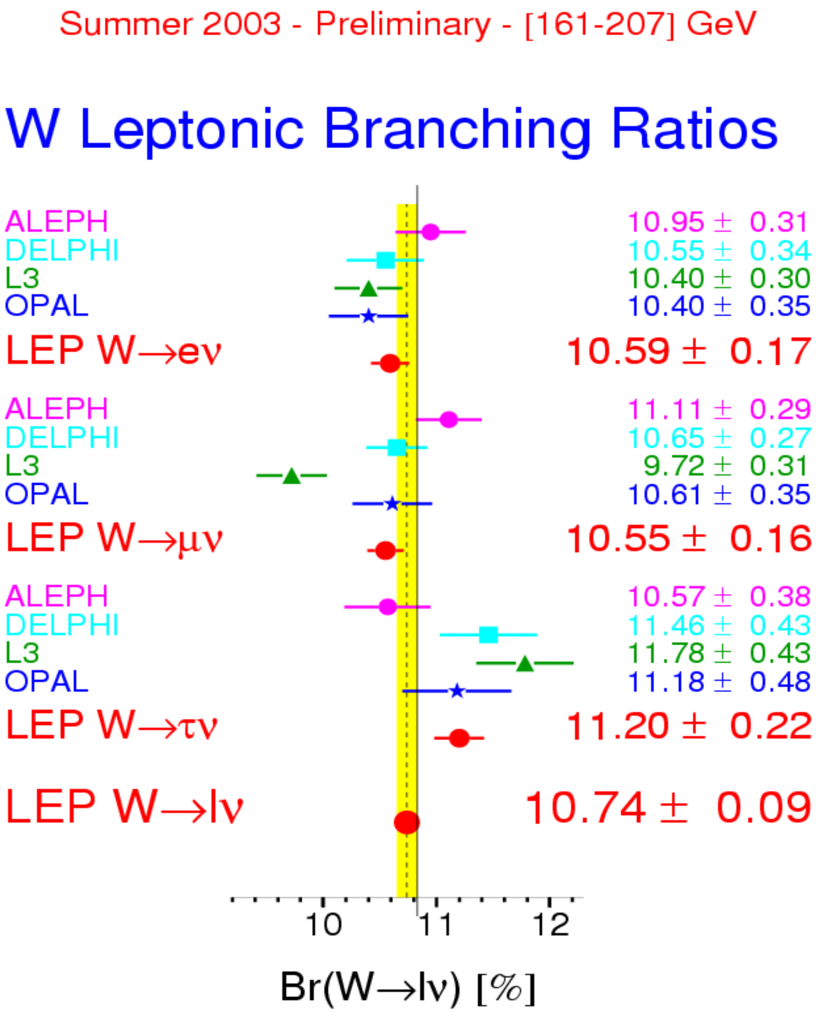
726 events ($189 \leq \sqrt{s} \leq 209$ GeV)

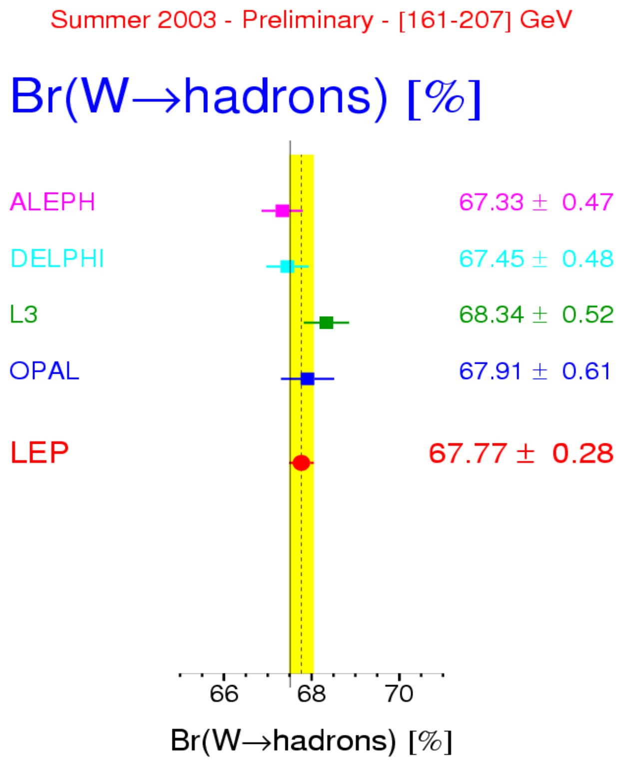
WW Cross Section





W Branching Ratios and V_{cs}

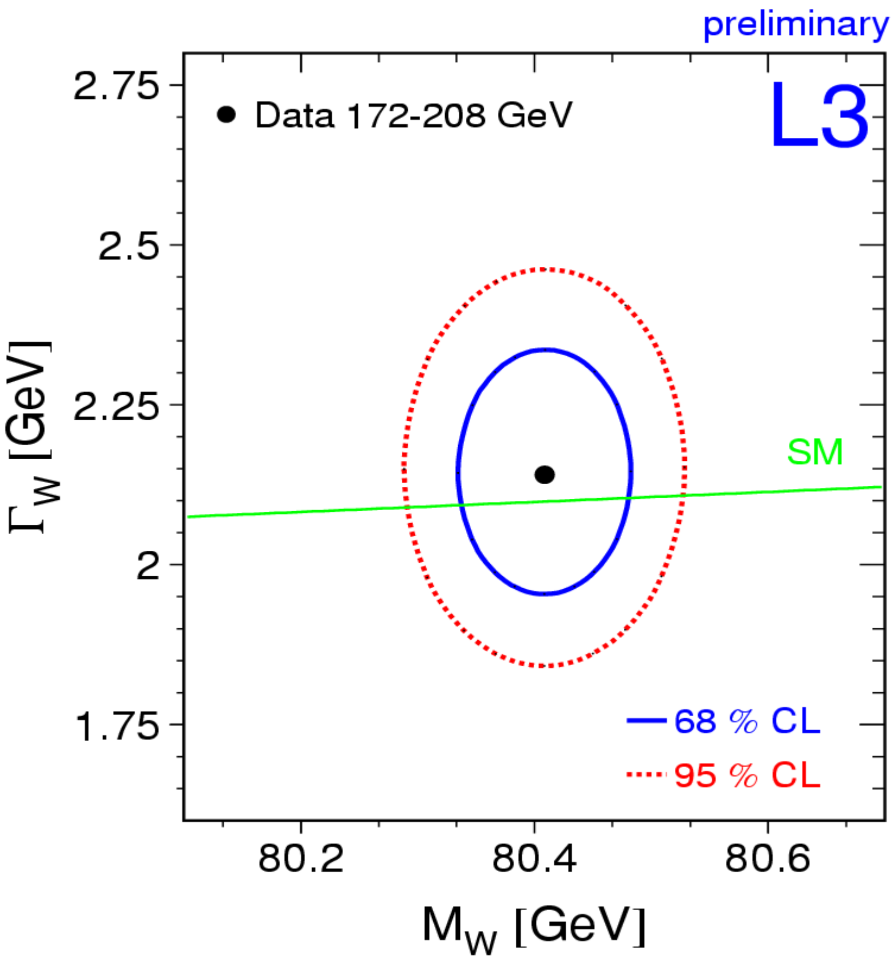


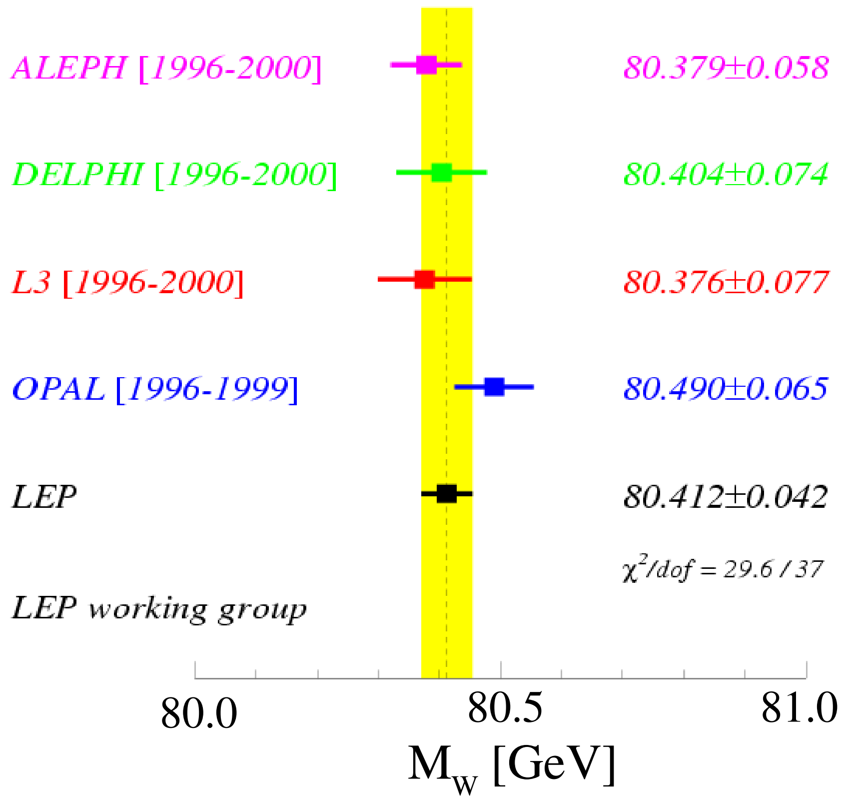


$$\frac{1}{3\,Br\,(W \to l\,\nu)} = 1 + (1 + \frac{\alpha\,(M_W)}{\pi})\sum_{i=u,c}^{j=d,s,b} |V_{ij}|^2$$

$$\Rightarrow |V_{cs}| = 0.989 \pm 0.014$$

W Mass and Width





$$\Gamma_W = 2.150 \pm 0.091 \text{ GeV}$$

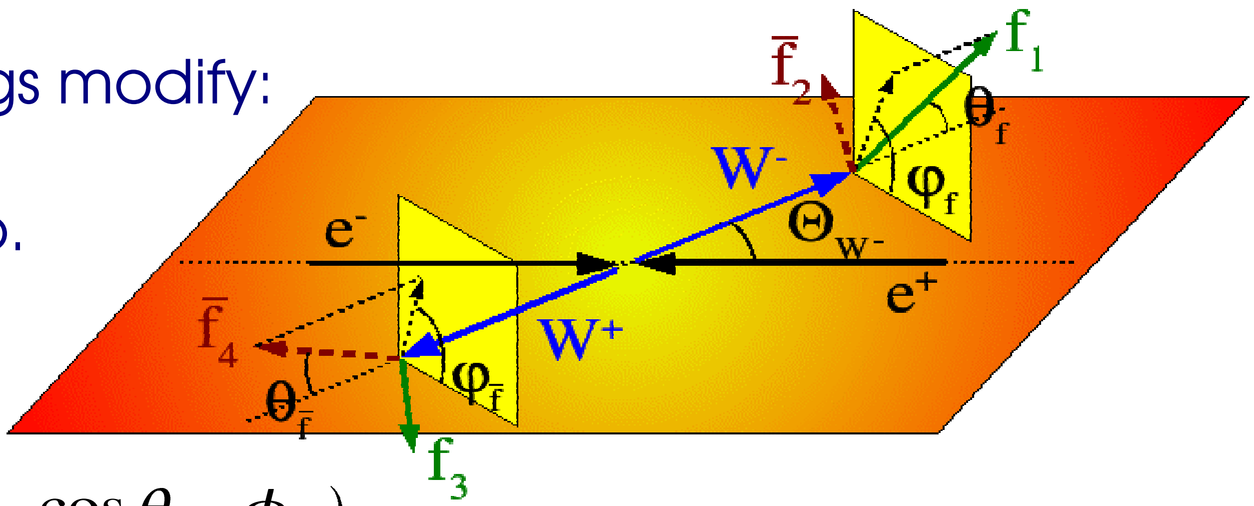
TGC's from WW

How many phase space variable?

4 particles in final state	16
4-momentum consevation	-4
masses of particles	-4
W masses (zero width)	-2
unpolarised beams (azim. indep.)	-1
# independent variables	5

Anomalous couplings modify:

- total cross section
- WW helicity comb.



$$(\cos \Theta_{W^-}, \cos \theta_f, \phi_f, \cos \theta_{\bar{f}}, \phi_{\bar{f}})$$

Constrained Fits

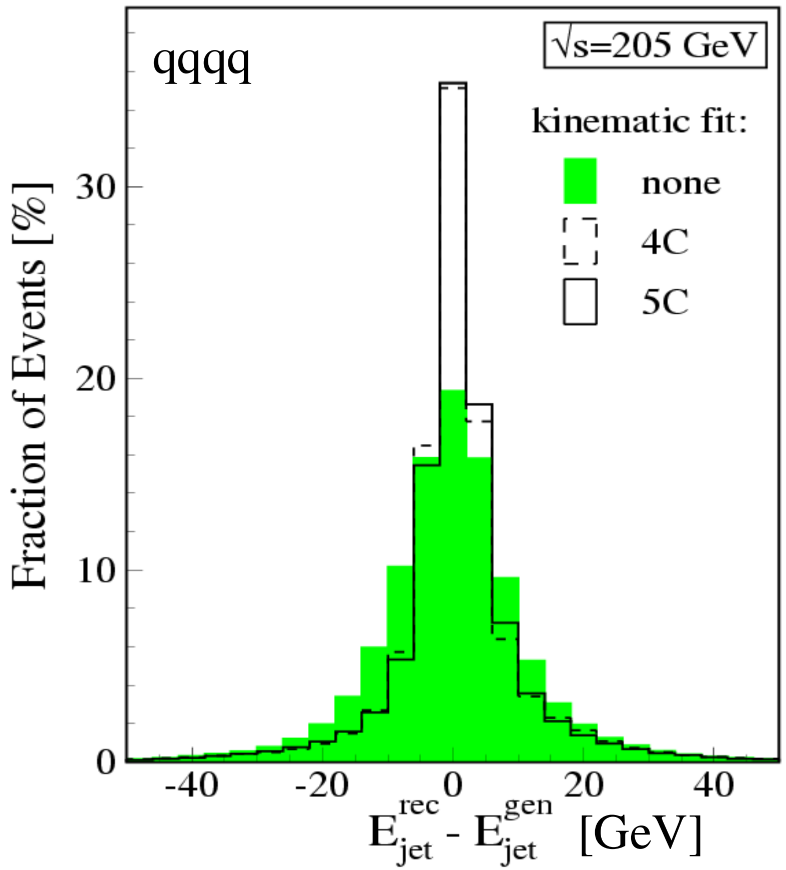
Improve resolutions by putting constraints on the event:

a) Energy and momentum conservation:

$$\sum_{i=1}^{4} E_i = \sqrt{s} \qquad \sum_{i=1}^{4} \vec{p}_i = 0$$

b) Equal W mass:

$$M_{W^-} = M_{W^+}$$



- qqqq: a) = 4C
  a)+b) = 5C
- qqeν & qqμν: a) = 1C
  a)+b) = 2C
- qqτν: scaling jet energies to √s/2
- lνlν: no constraints

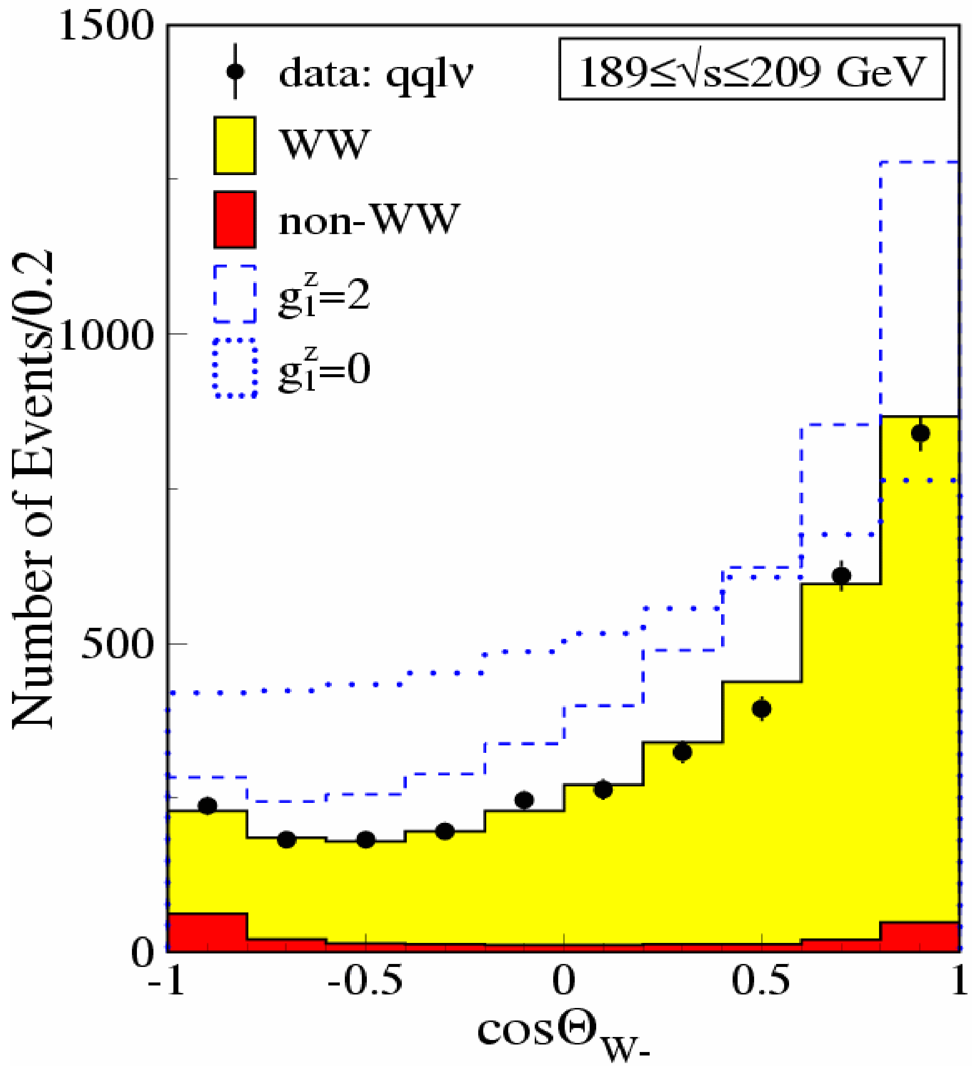
Phase Space Variables: qqlν

W⁻ production angle

- W direction from quarks
- W charge from lepton

lepton charge measurement checked with Z-peak calibration data, using

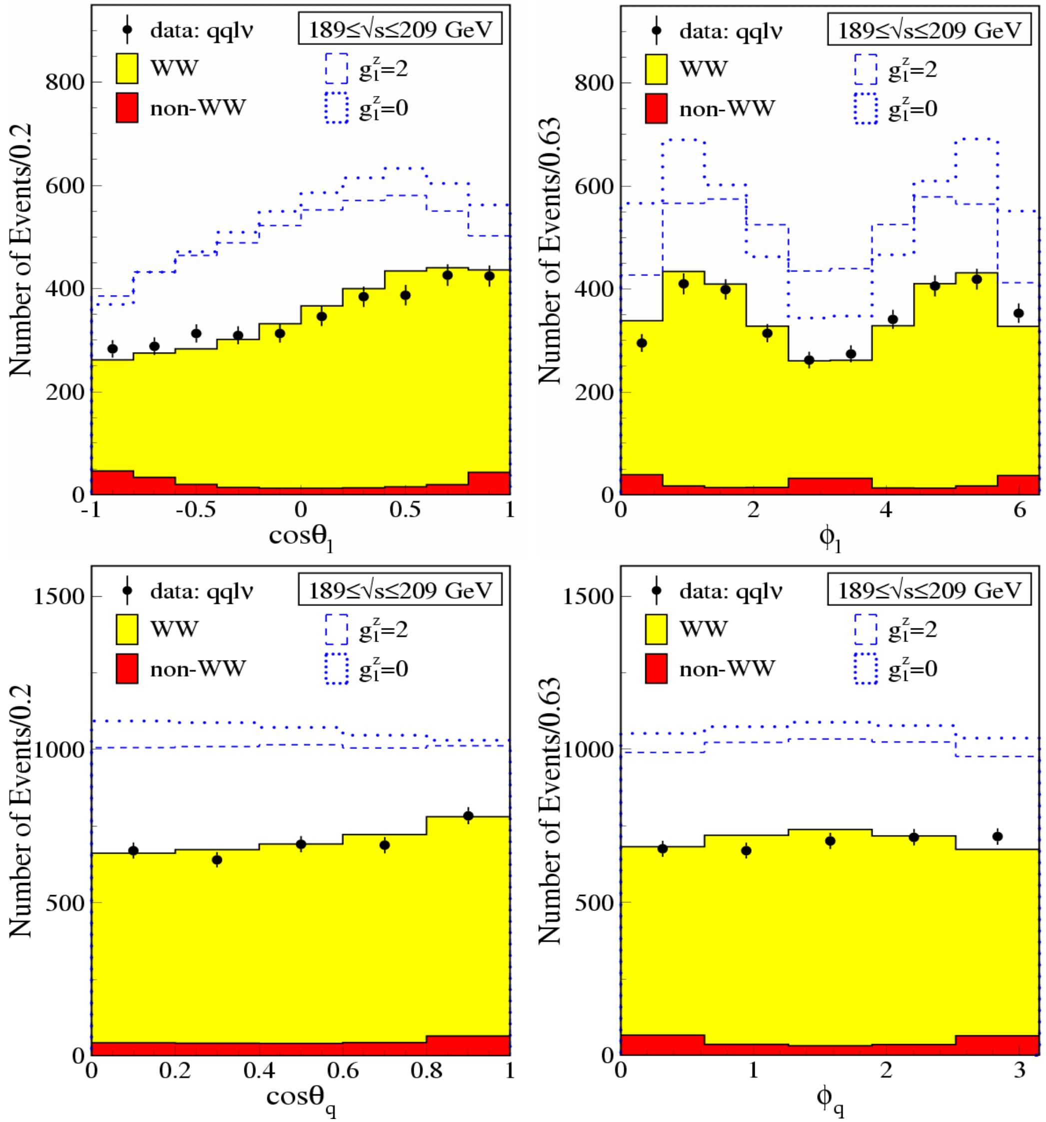
$Z \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$



Phase Space Variables: qqlν

Decay angles

- fermions boosted to parent's rest frame
- leptons: choose decay angles of negative lepton
  $(\theta_{l-}, \phi_{l-}) \Leftrightarrow (\pi - \theta_{l+}, \pi + \phi_{l+})$
- quarks: no flavour tagging → angles are folded

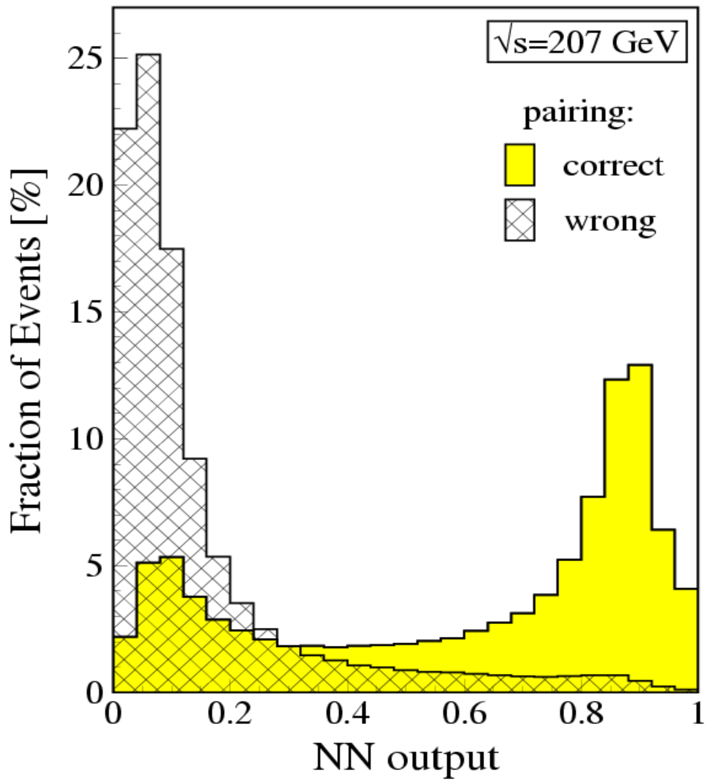


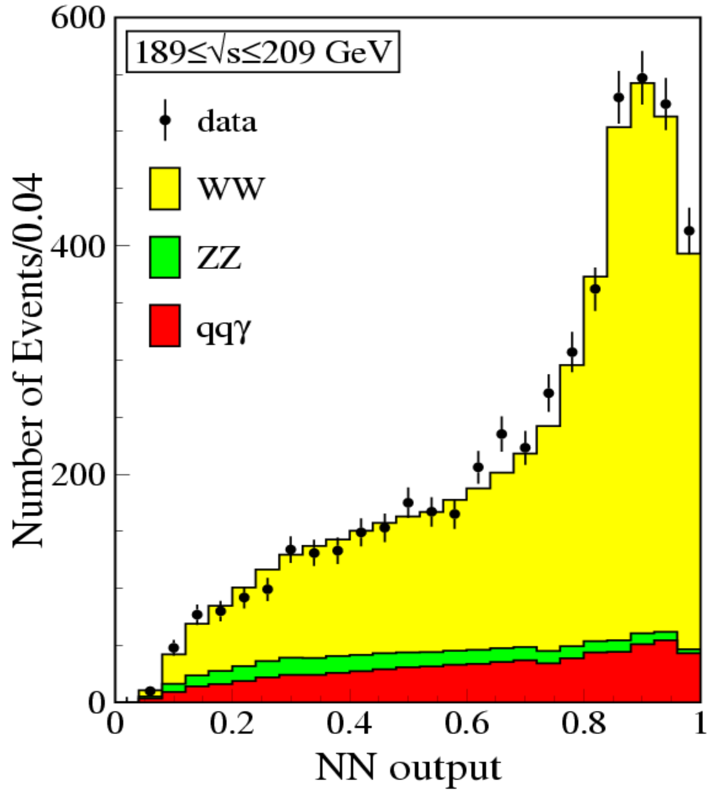
Phase Space Variables: qqqq

Jet Pairing:

4 jets → 3 pairs

Neural Network: $\epsilon \simeq 77\%$





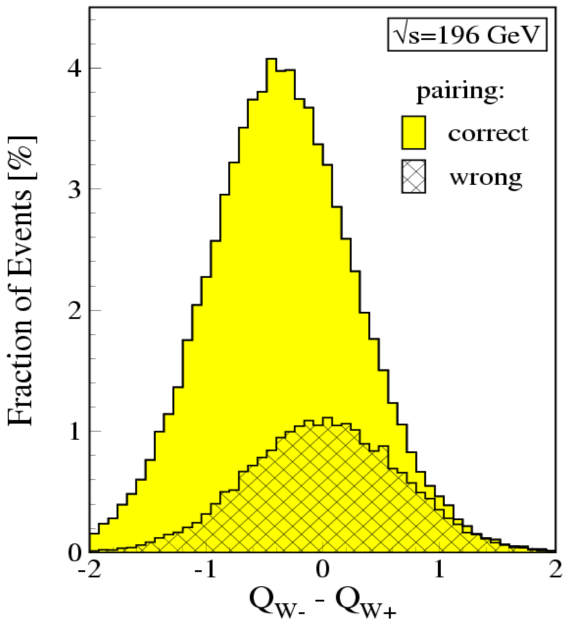
Phase Space Variables: qqqq

Jet charge: $$Q_{jet} = \frac{\sum_i q_i (p^i_{par})^{0.5}}{\sum_i (p^i_{par})^{0.5}}$$

$$p^i_{par} = \vec{p}_i \cdot \frac{\vec{p}_{jet}}{|\vec{p}_{jet}|}$$

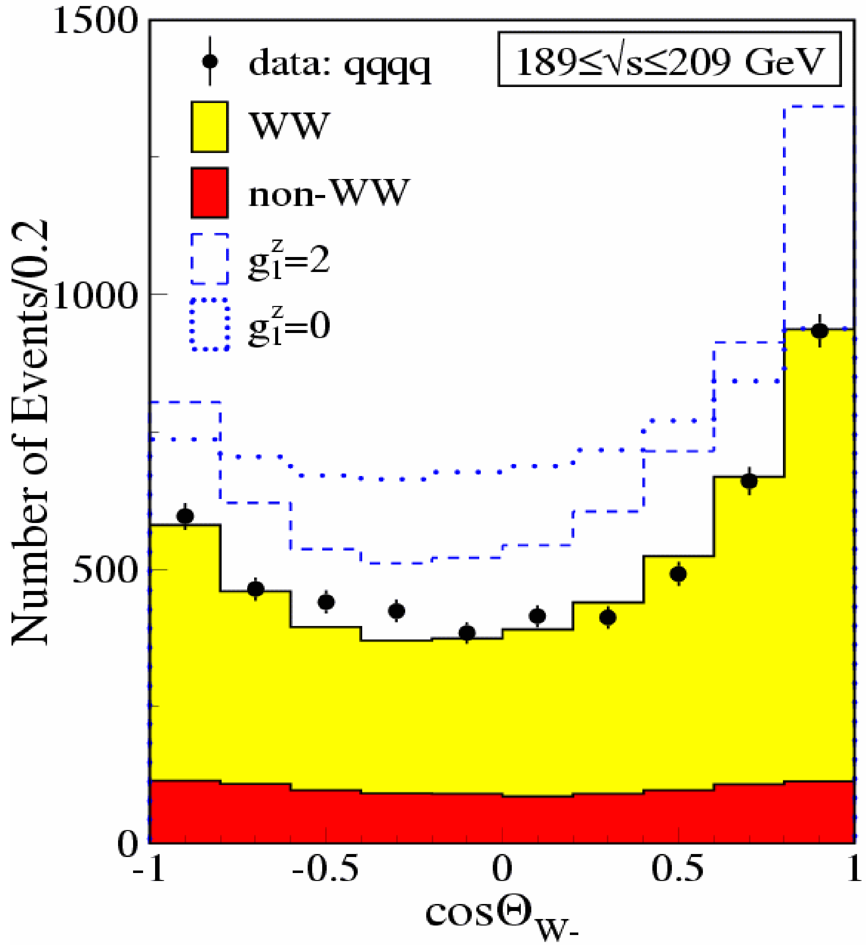
single jet: $\epsilon \simeq 62\%$

$Q_{W-} - Q_{W+}$: $\epsilon \simeq 69\%$



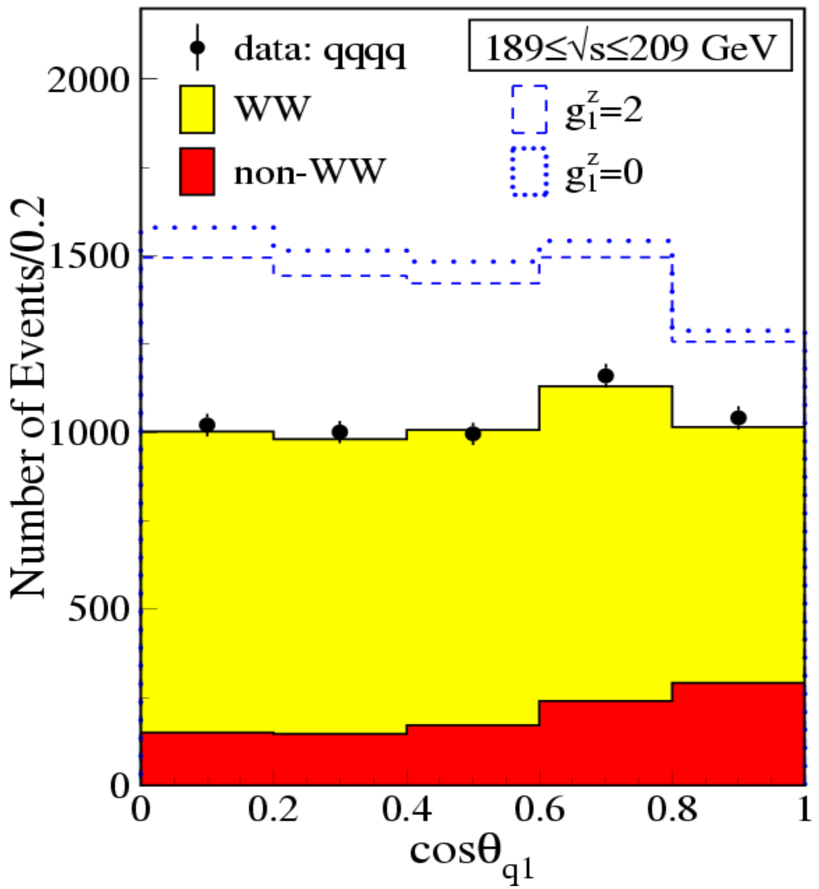
Q_W meas. checked with $qq\mu\nu$: $\Delta\epsilon/\epsilon \simeq 4\%$

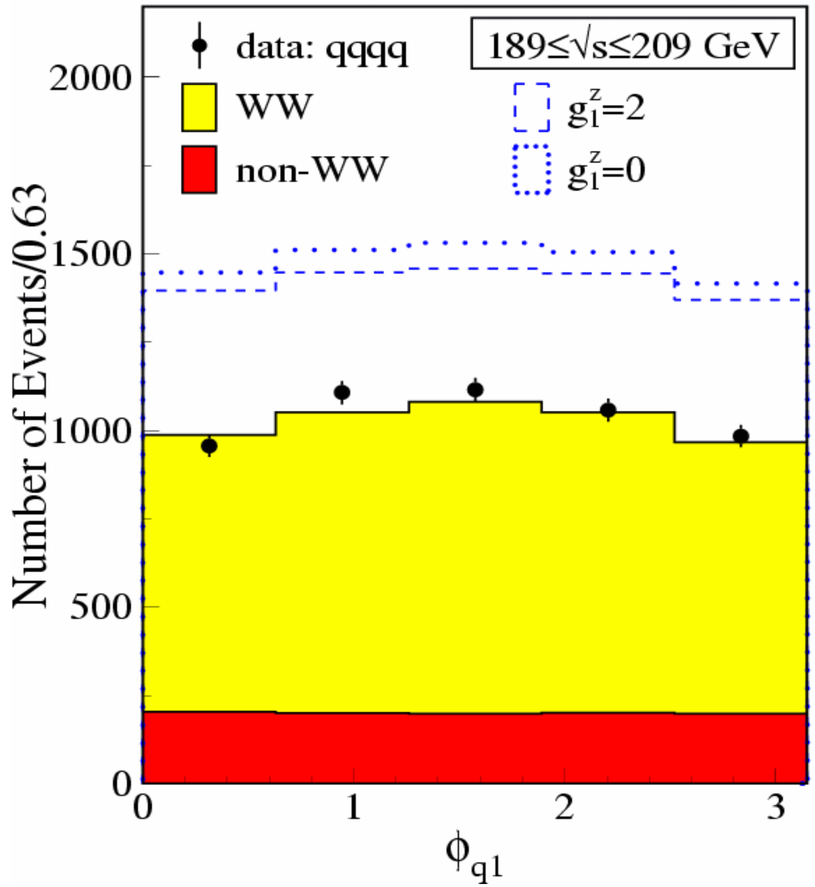
W⁻ production angle



Phase Space Variables: qqqq

Decay angles



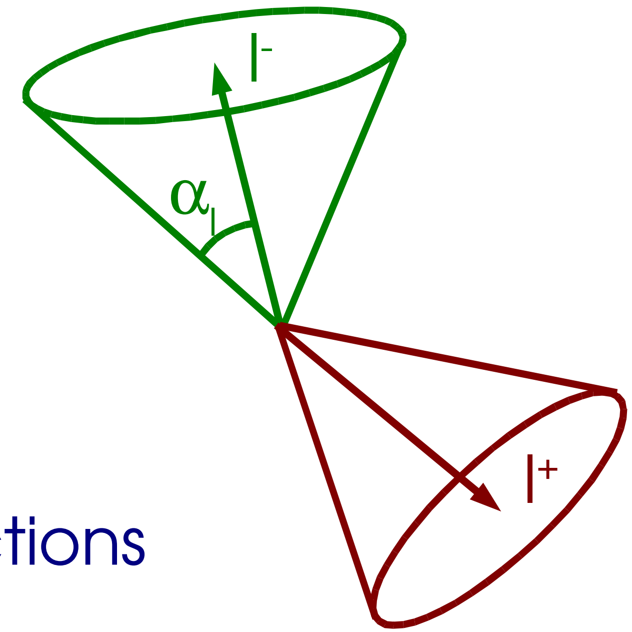


Phase Space Variables: $l\nu l\nu$

- Decay involves at least 2 neutrinos
- When no $W \to \tau\nu$, only 6 unknowns:
  decay angles can be reconstructed

Angle between lepton and parent W, α_l, is related to lepton energy E_l:

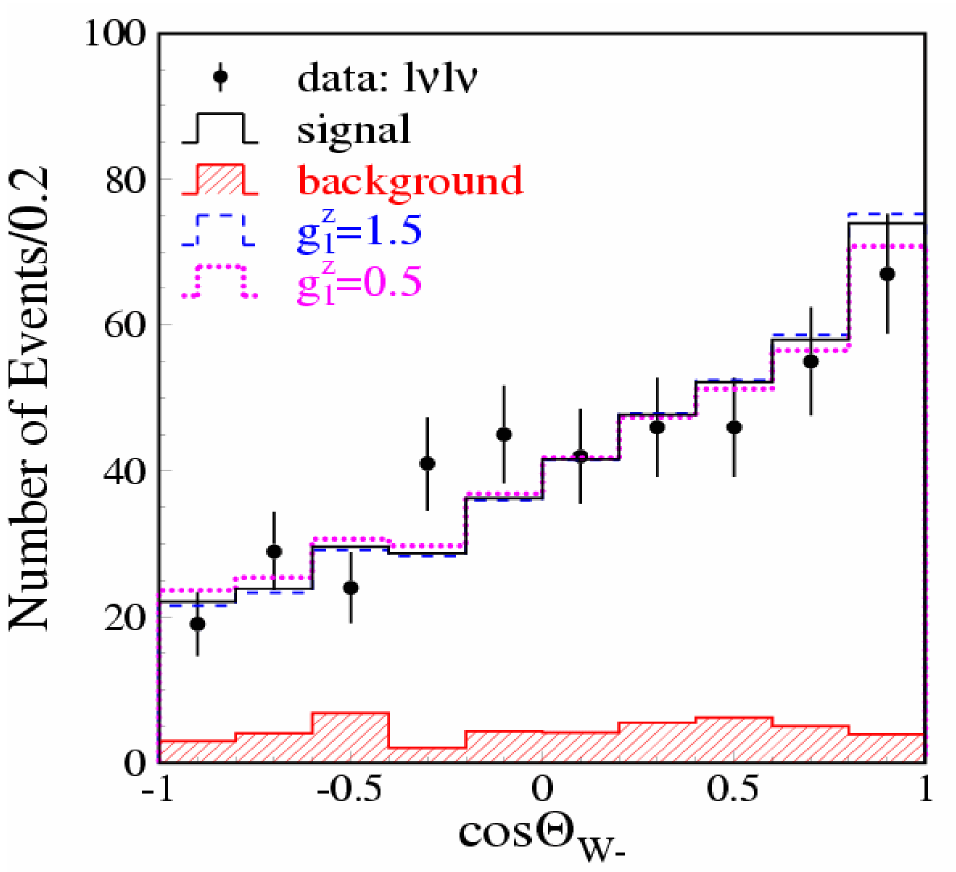
$$\cos\alpha_l = \frac{1}{\beta} - \gamma\frac{M_W}{2E_l}\left(\frac{1}{\beta} - \beta\right)$$

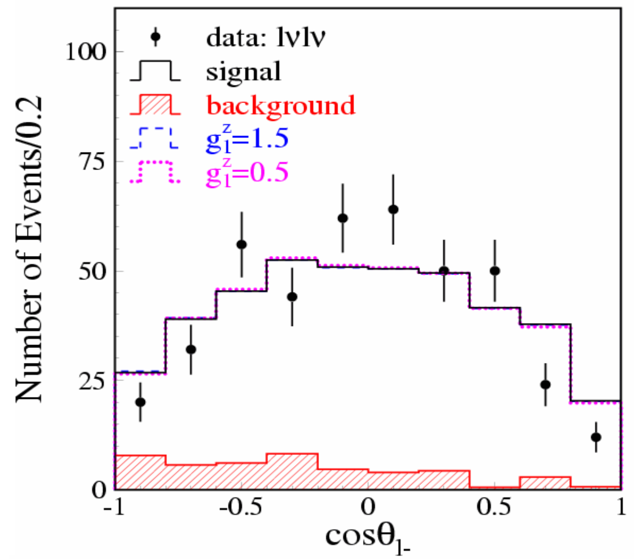


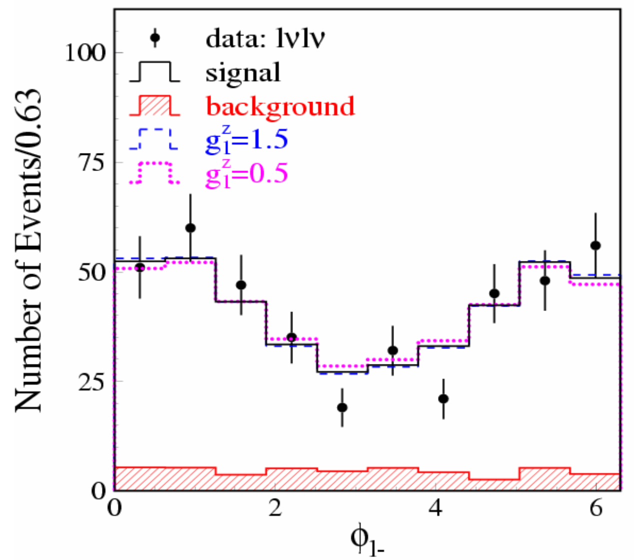
2 cones: intersection gives 2 W directions
resolution and finite width effects:
imaginary solutions, take real part

Phase Space Variables: lνlν

Each solution enters with weight ½





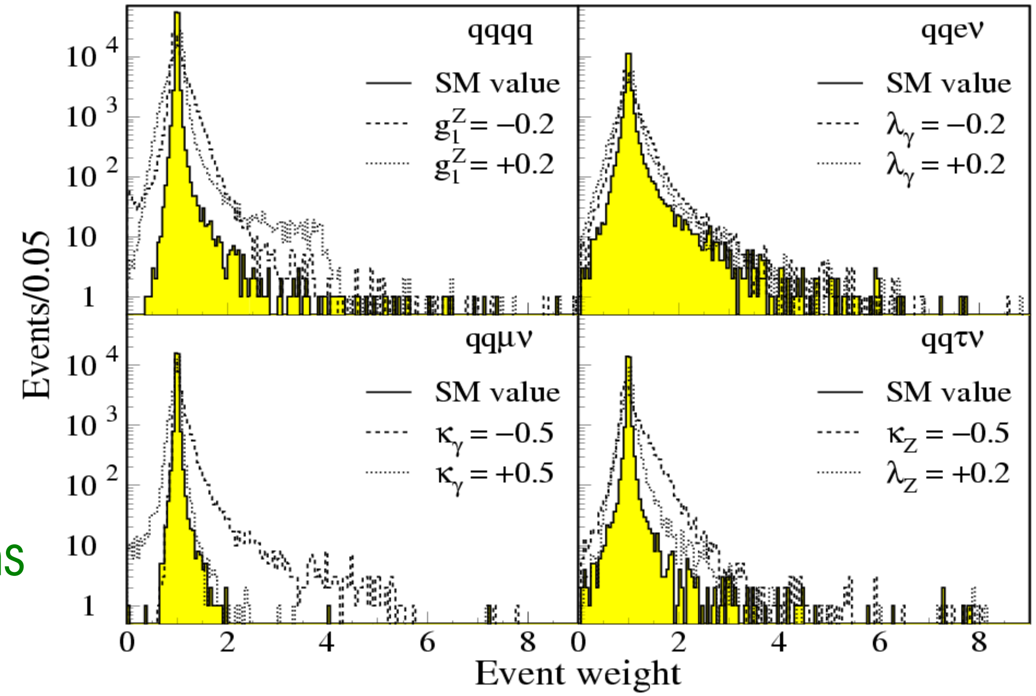


Fit Method

Reweighting events:

$$w(\psi) = \frac{\left|\mathcal{M}^{4f}(\Omega,\psi)\right|^2}{\left|\mathcal{M}^{CC03}(\Omega,\psi_{MC})^2\right|}$$

- $\mathcal{M}$ from EXCALIBUR
- signal events CC03, takes into account all 4f diagrams



Binned maximum likelihood fit to 5-dim phase space:

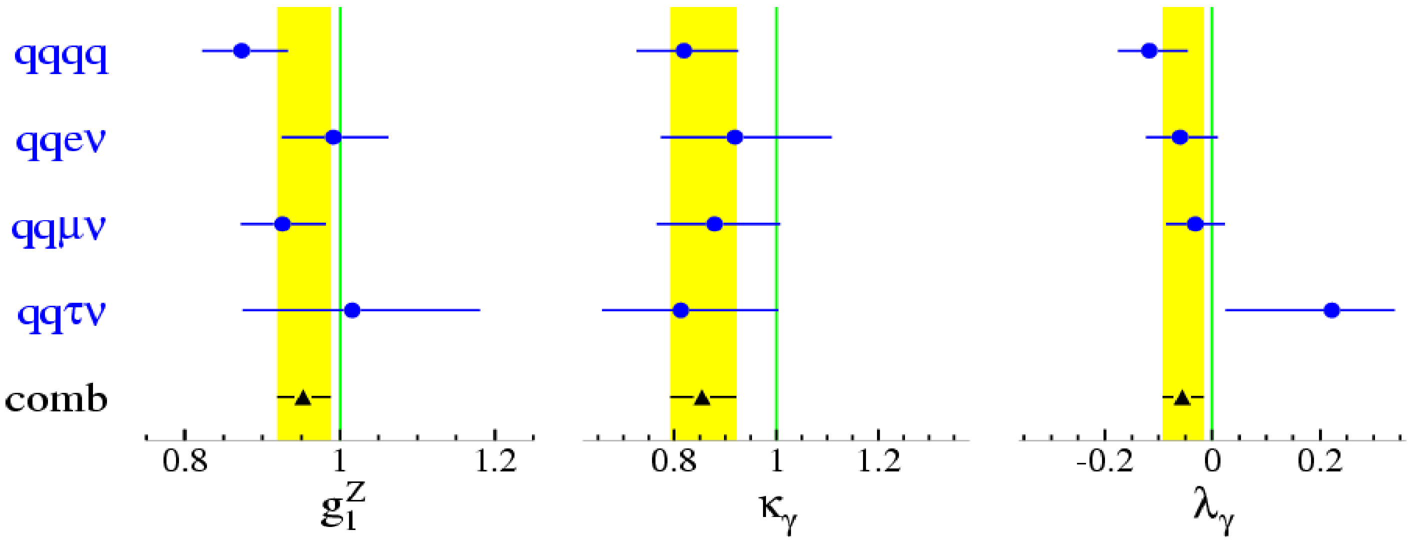
$$L = \prod_i^{bins} P(N_i, \mu_i(\psi)) \qquad \mu_i(\psi) = \mathcal{L} \sum_j^{sig+back} \left(\frac{\sigma_{gen}^j}{N_{gen}^j} \sum_{n \in bin\ i} w_n(\psi) \right)$$

Fit each decay channel and √s separately

TGC's from WW: results

1-parameter fits, only statistical errors (68 % CL)

$161 \leq \sqrt{s} \leq 209$ GeV $\qquad \kappa_Z = g_1^Z - \tan^2\theta_w(\kappa_\gamma - 1), \quad \lambda_Z = \lambda_\gamma$



$\sigma_{stat} = 0.035 \qquad \sigma_{stat} = 0.064 \qquad \sigma_{stat} = 0.038$

lνlν channel not used:

$\sigma(g_1^Z) = \pm 0.19$, $\sigma(\kappa_\gamma) = \pm 0.50$, $\sigma(\lambda_\gamma) = \pm 0.14$

TGC's from WW: results

with constraints:

$$g_1^Z = 0.927 \pm 0.035 \pm 0.021 \qquad (SM = 1)$$

$$\kappa_\gamma = 0.850 \pm 0.064 \pm 0.040 \qquad (SM = 1)$$

$$\lambda_\gamma = -0.057 \pm 0.038 \pm 0.023 \qquad (SM = 0)$$

no constraints:

$$g_5^Z = 0.00 \pm 0.15 \pm 0.06 \qquad (SM = 0)$$

$$\kappa_Z = 0.871 \pm 0.059 \pm 0.035 \qquad (SM = 1)$$

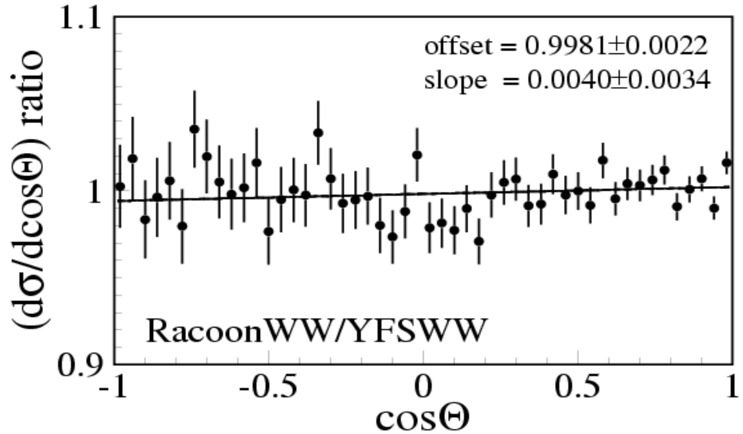
$$\lambda_Z = -0.100 \pm 0.067 \pm 0.036 \qquad (SM = 0)$$

stat. syst.

TGC's from WW: results

Sources of systematic uncertainties:

- Largest contributions:
  - charge measurement — $W \to l\nu$ with $Z \to l^+l^-$; $W \to qq$ with $qq\mu\nu$
  - MC statistics — divide up large MC samples
  - quark fragmentation — compare JETSET, HERWIG, ARIADNE
- Modest contributions:
  - modelling of signal and background — σ, $d\sigma/d\cos\Theta_W$
  - initial and final state radiation
- Small contributions:
  - jet and lepton reconstruction
  - W mass and width
  - Bose-Einstein correlations
  - Colour reconnection



Weν Selection

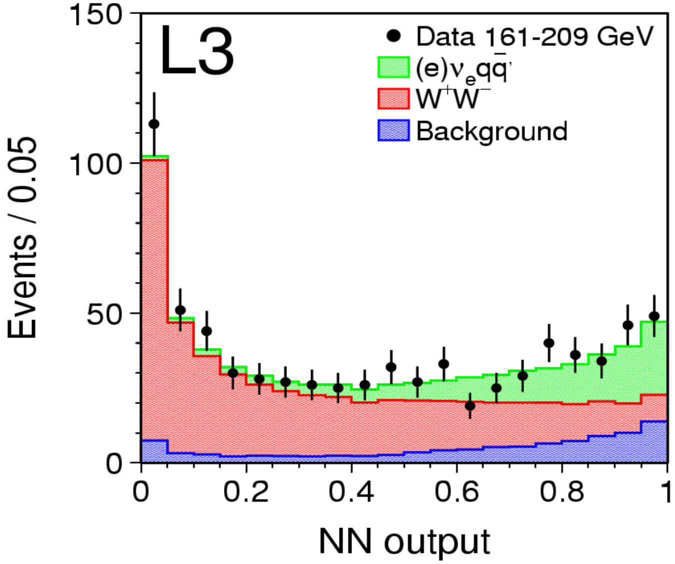
$e^+e^- \rightarrow e^\pm \nu_e W^\mp$:

- $e^\pm$ scattered at low polar angles
- signatures: W decay products, p_T imbalance

Hadronic decays: $W \rightarrow qq$

Pre-selection + NN

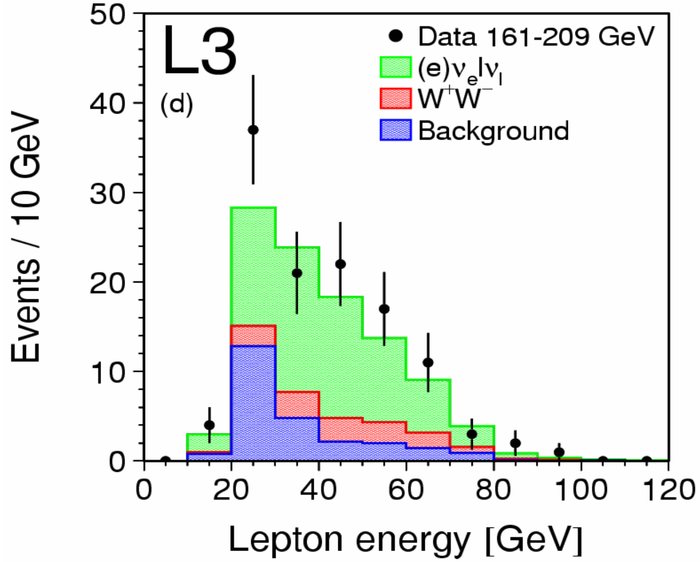
740 candidates



Leptonic decays: $W \rightarrow l\nu$

selection of single lepton

121 candidates



Weν cross section

phase space cuts:

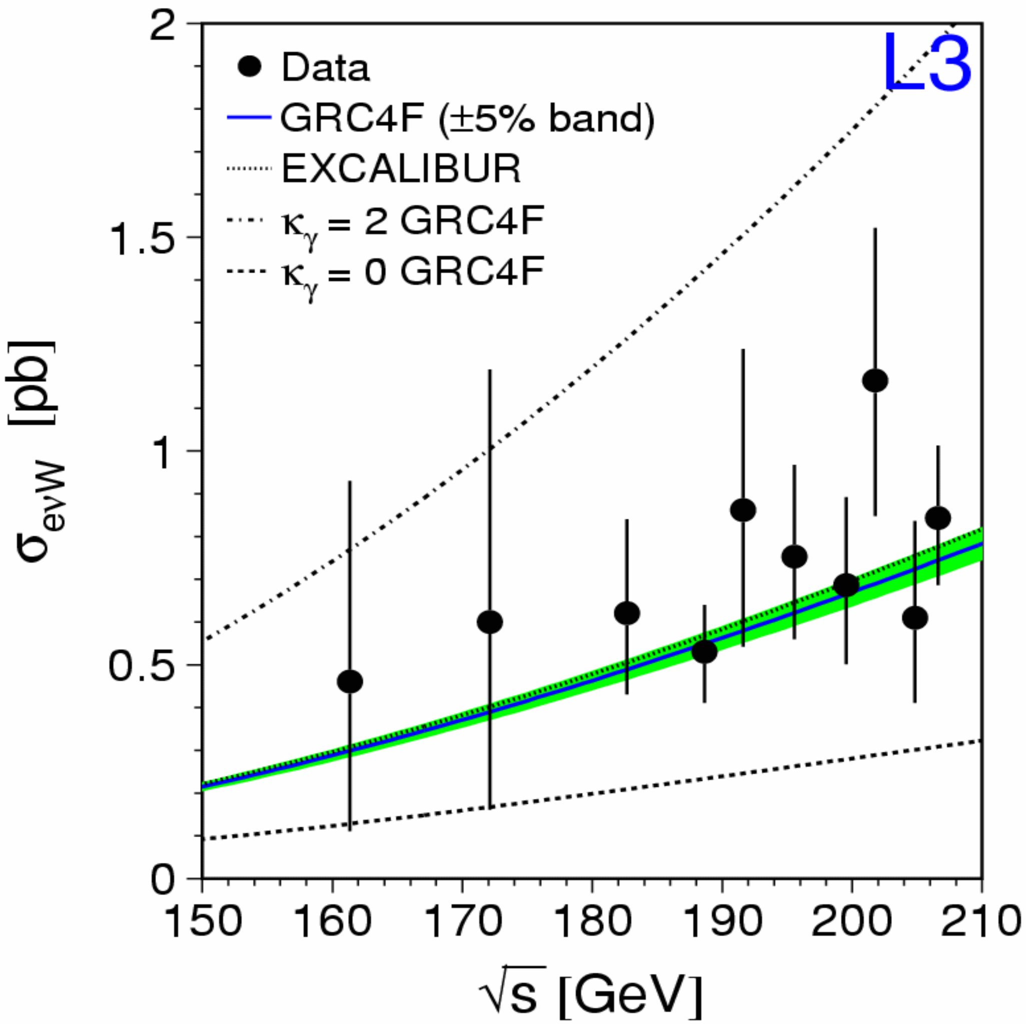
$$|\cos\theta_{e+}| > 0.997$$
$$min\,(E_f, E_{\bar{f}}) > 15\,GeV$$
$$|\cos\theta_{e-}| < 0.75 \quad (e^+ \nu_e e^- \bar{\nu}_e)$$

hadronic: $\epsilon \simeq$ 41-53%

$\pi \simeq$ 20-24%

leptonic: $\epsilon \simeq$ 48-54%

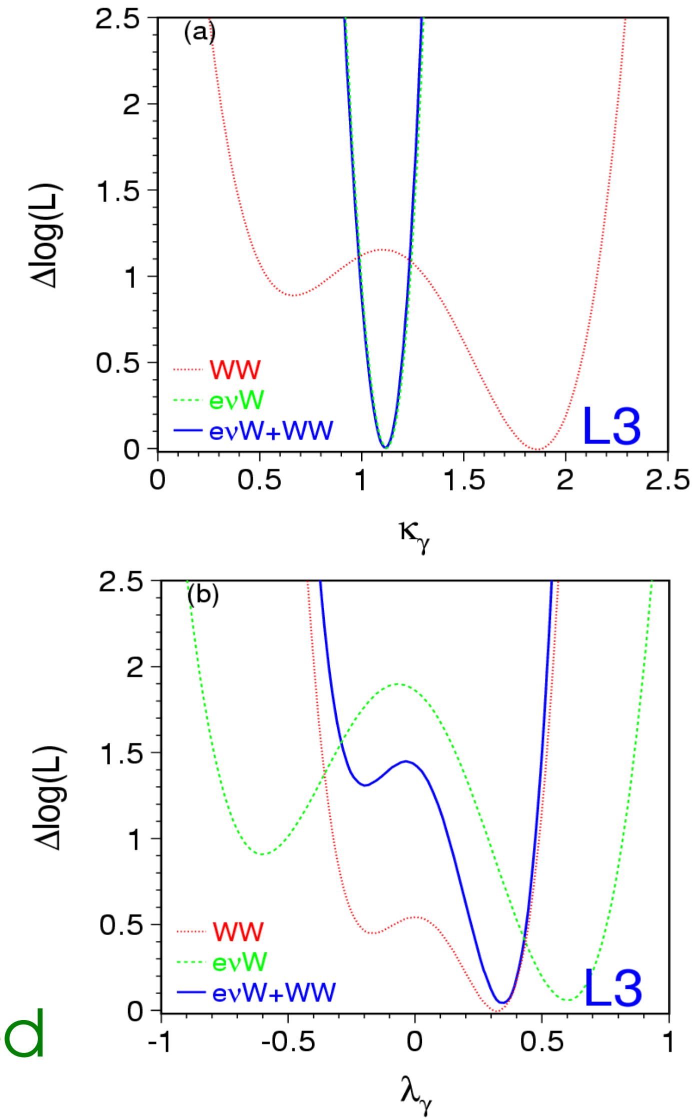
$\pi \simeq$ 56-63%



TGC's from Weν

- Same fit method as for W-pairs
- phase space:
  - hadronic: Neural Network output
  - lepton: energy spectrum
- dominant systematic error:
  uncertainty $\sigma_{tot} \pm 5\%$
- 156 out of 740 hadronic single-W events also in qqlν selections:
  - 75% WW
  - 7% single-W
  - 18% background

combination: events only accepted in WW selections

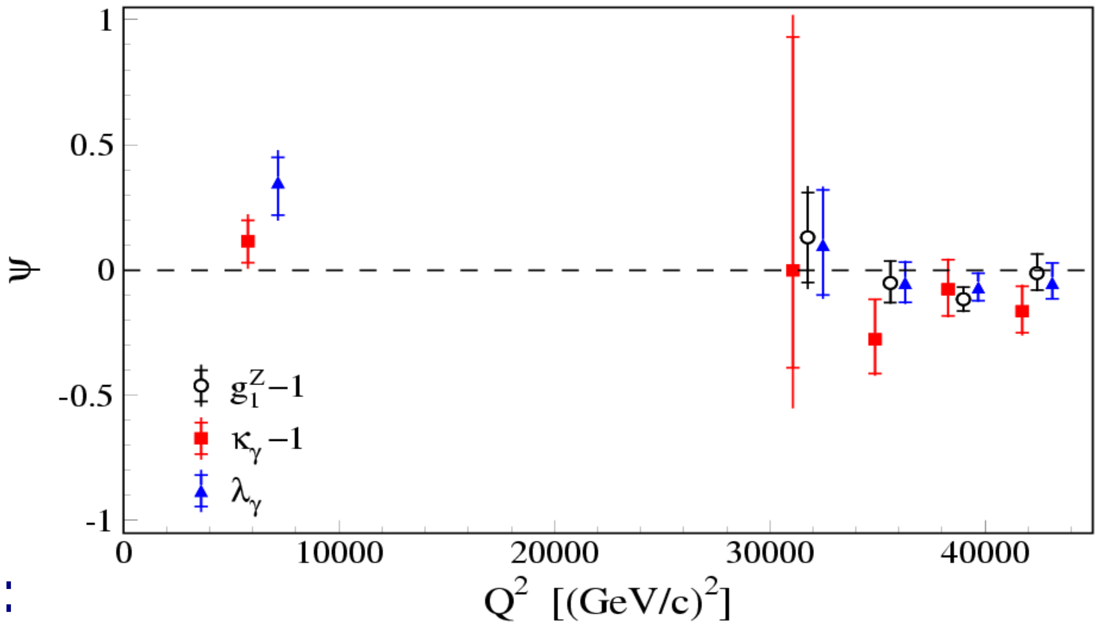


Combined L3 results

Q^2 dependence?

single-W: $Q^2 = M^2_W$

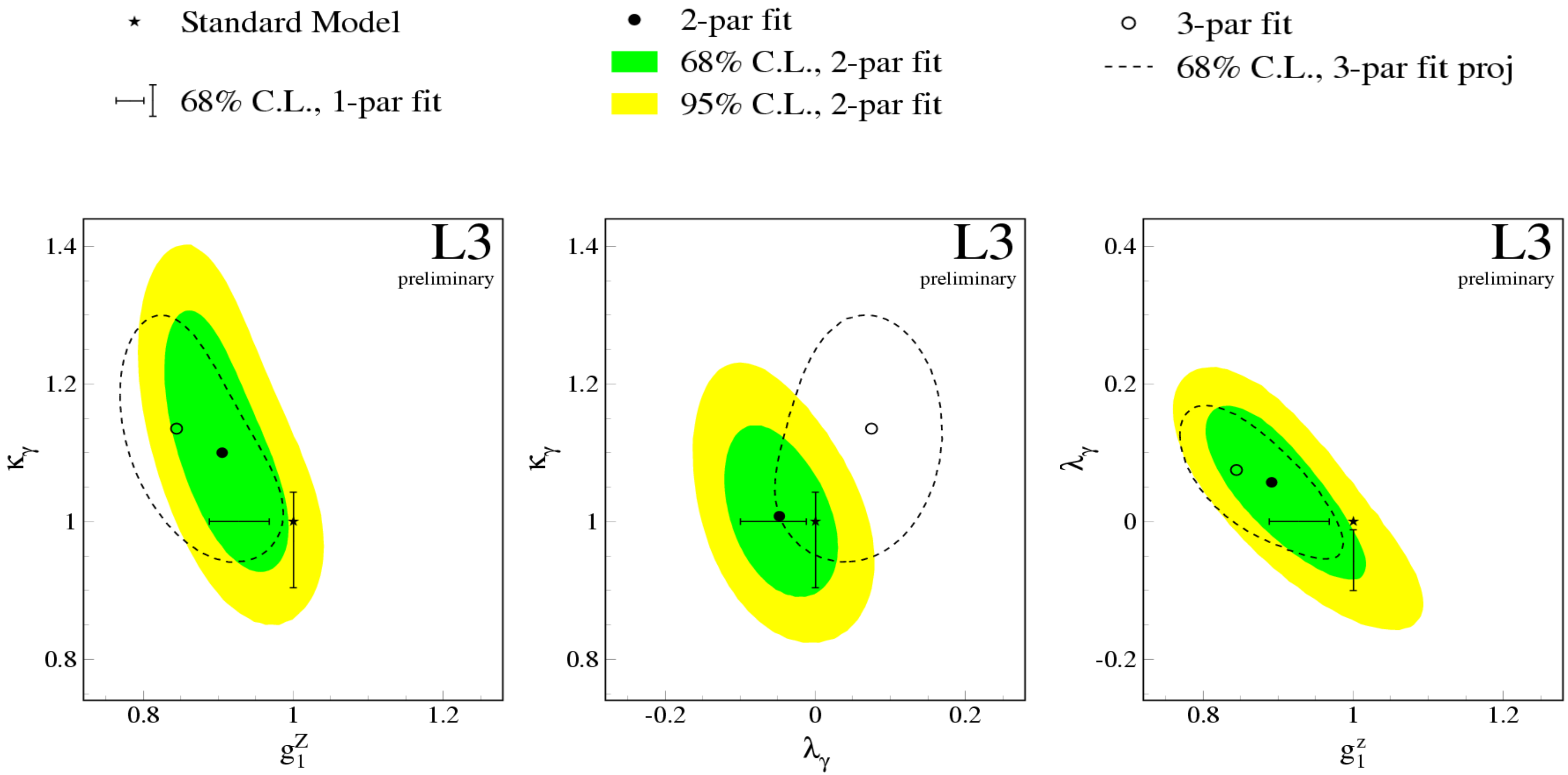
W-pairs: $Q^2 = s$



161 GeV $\leq \sqrt{s} \leq$ 209 GeV:

	g_1^Z	κ_γ	λ_γ
$We\nu$	-	1.179±0.078±0.067	0.30 ± 0.15 ± 0.08
WW	0.927±0.035±0.021	0.850±0.064±0.040	-0.057±0.038±0.023
Combined	0.927±0.035±0.021	0.972±0.064±0.021	-0.057±0.037±0.022
	(SM = 1)	(SM = 1)	(SM = 0)

Combined L3 results



The W boson

- magnetic dipole and electric quadrupole moment:

$$\mu_W = \frac{e}{2M_W}(1+\kappa_\gamma+\lambda_\gamma) \qquad \mu_W = (1.960 \pm 0.076)\frac{e}{2M_W} = (1.245 \pm 0.048)\cdot 10^{-5}\,\mu_B$$

$$\rho = 0.49$$

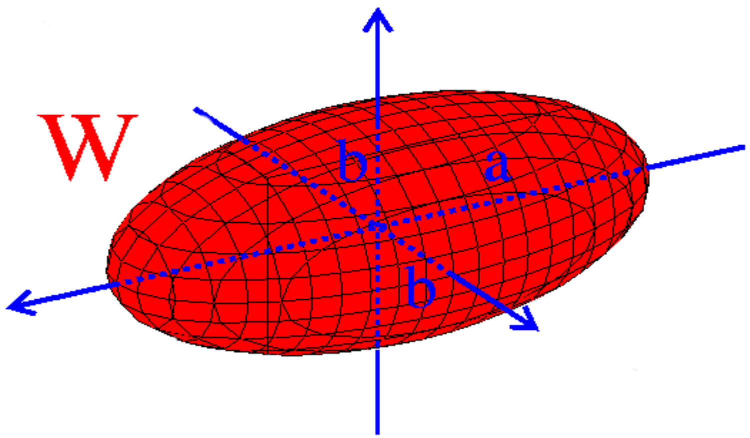
$$Q_W = \frac{e}{M_W^2}(\kappa_\gamma-\lambda_\gamma) \qquad Q_W = (1.06 \pm 0.11)\frac{e}{M_W^2} = (3.18 \pm 0.33)\cdot 10^{-36}\,e\,m^2$$

- Assume W boson is ellipsoid with homogeneously distributed charge:

$$R_W \equiv \frac{(a+b)}{2} = \frac{\delta\mu_W}{\mu_W M_W}$$

$$\Delta_W \equiv \frac{(a^2-b^2)}{2} = \frac{5}{4}\delta Q_W$$

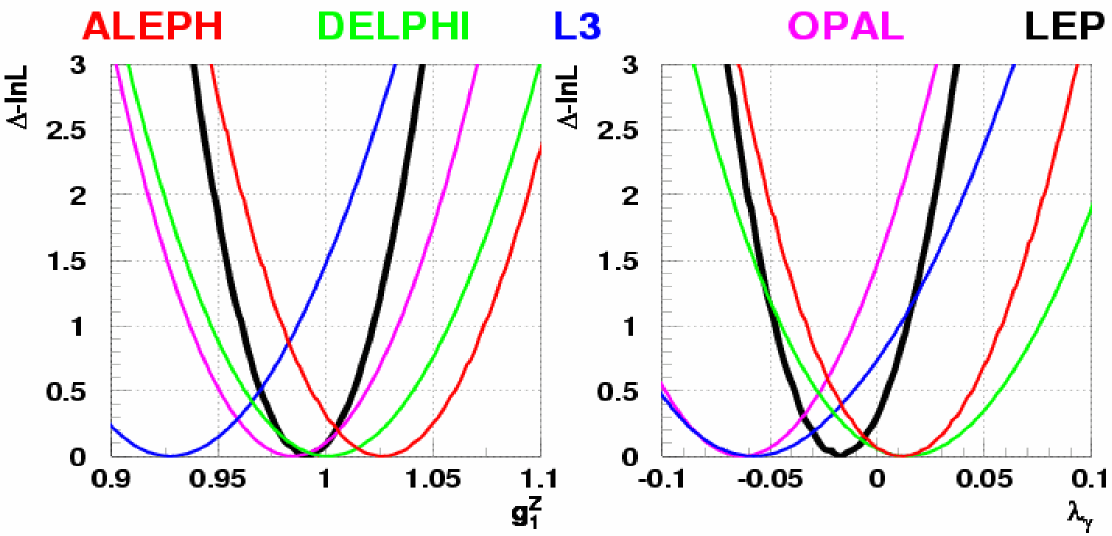
δ = difference wrt SM value

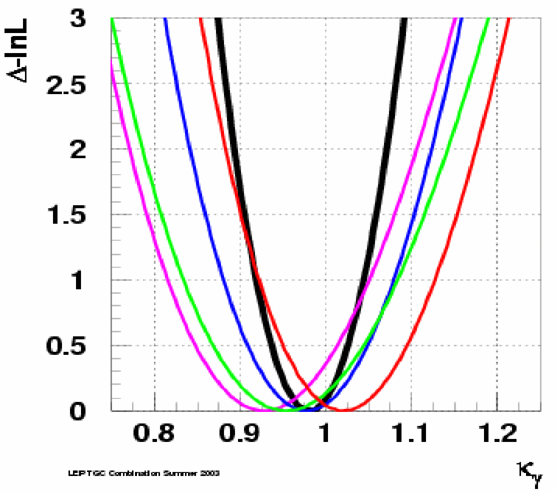


$$R_W = (-1.0 \pm 1.9)\cdot 10^{-19}\,m$$

$$\Delta_W = (0.42 \pm 0.84)\cdot 10^{-36}\,m^2$$

Combined LEP results





LEP preliminary

$$\kappa_\gamma = 0.984^{+0.042}_{-0.047}$$

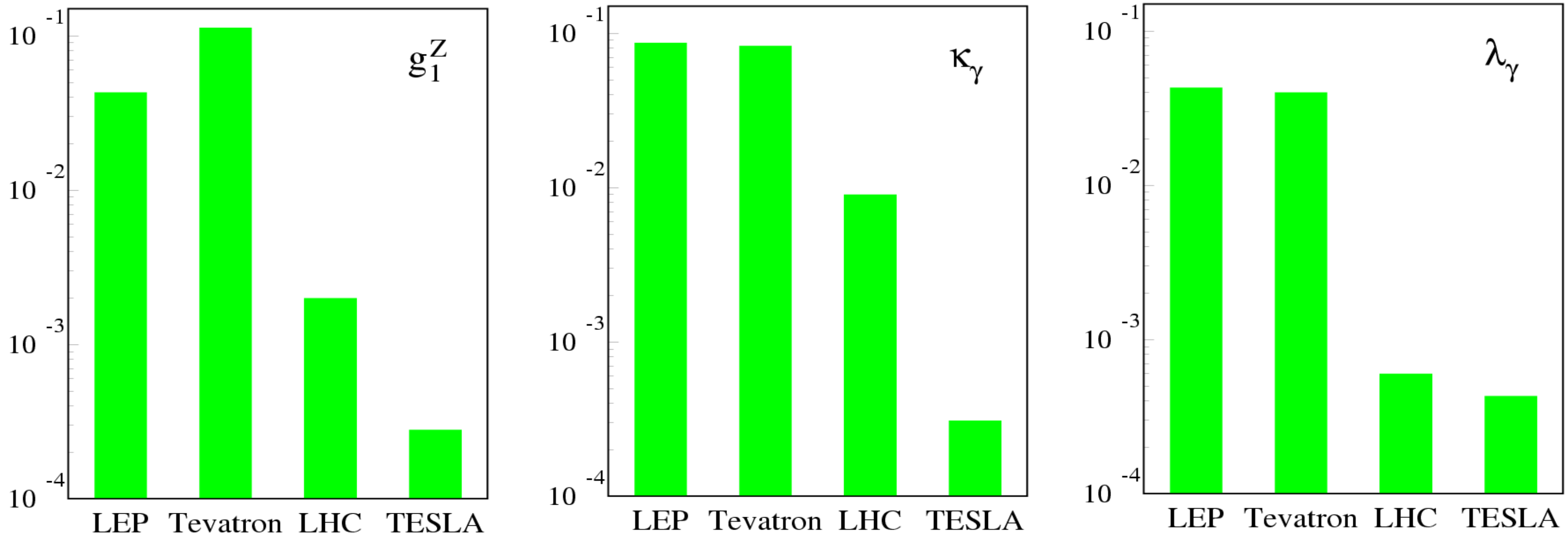
$$\lambda_\gamma = -0.016^{+0.021}_{-0.023}$$

$$g_1^Z = 0.991^{+0.022}_{-0.021}$$

LEP vs Future

95% CL upper limits under assumptions:

- Tevatron: DØ + CDF, scaling to 10 fb^{-1}, Λ_F = 2 TeV
- LHC: ATLAS+CMS, 500 fb^{-1}, Λ_F = 10 TeV
- TESLA: e$^+$e$^-$ mode, polarised beams, 500 fb^{-1} @ $\sqrt{s}$ = 500 GeV



Conclusions

- ✔ Measurements of Triple Gauge-boson Couplings: direct test of the non-Abelian nature of electroweak theory
- ✔ Results from W-pairs and single-W's were presented
- ✔ Strength and structure of the trilinear vertices are in agreement with the Standard Model predictions
- ✔ W boson is pointlike down to scales of 10^{-19} m
- ✔ Significant improvements expected from LHC and LC