Rare Processes at LEP2 and Limits on the Anomalous Couplings of Gauge Bosons

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  - single W
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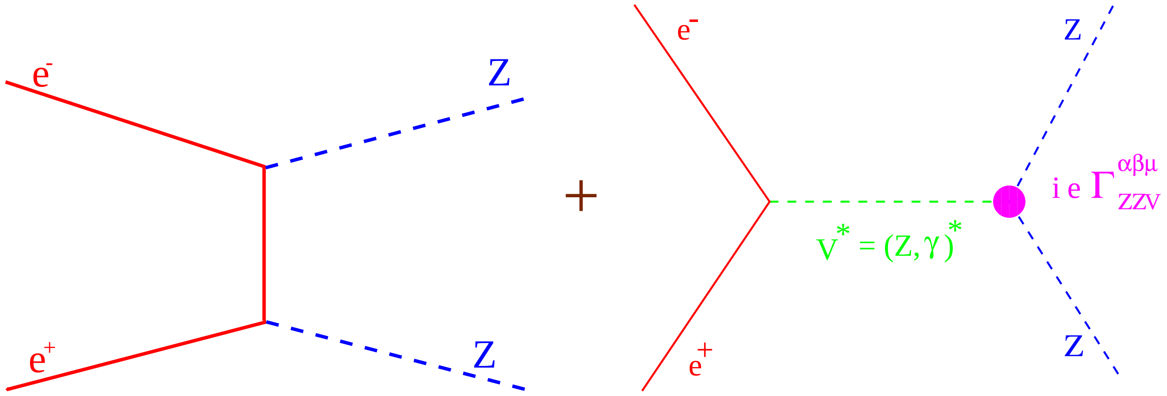
Resonant ZZ production

Kinematic threshold reached at $\sqrt{s} = 183 GeV$ (LEP2).
$e^+e^- \rightarrow ZZ$ process used to look for deviations from the standard model in triple gauge boson couplings.

Resonant ZZ final states (NC02) with non-SM couplings



Motivations:

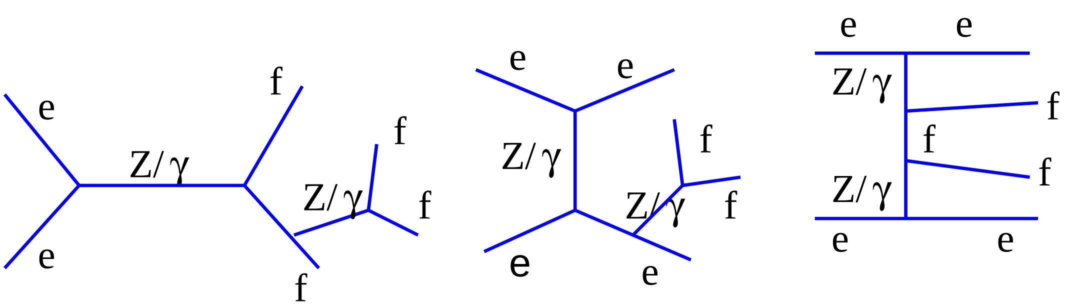
- Similar to $WW\gamma$, WWZ couplings.
- No special reason to observe WWV anomalous couplings ($V = Z,\gamma$) and not ZZV, although the low rate production and large background.

Physical origin of the anomalous couplings:

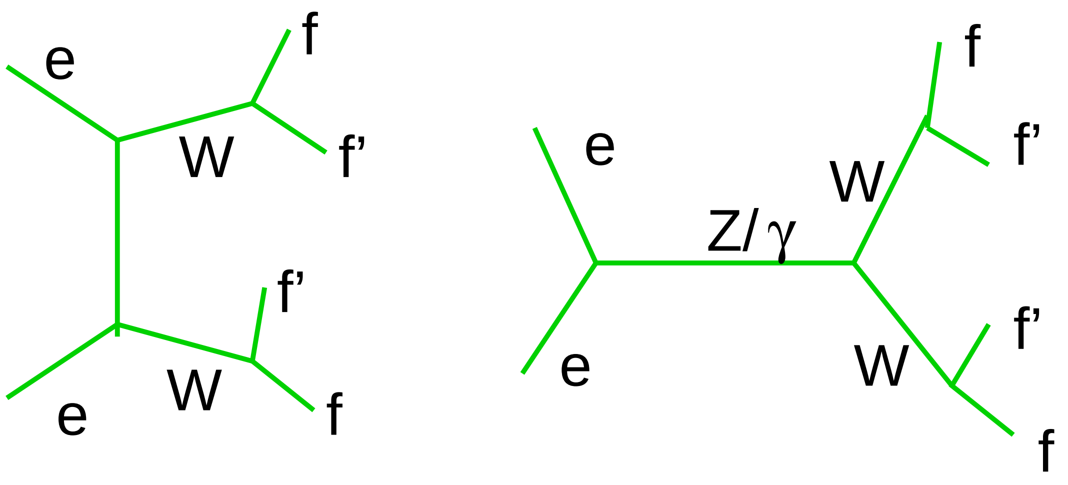
- New particles in the loop (SUSY, ...)
- Compositeness of Z.

Non Resonant and other Four Fermions Diagrams
(EXCALIBUR or PYTHIA generators)

- + non resonant diagrams for the same final states …



- + diagrams involving WW production …



Anomalous Couplings of ZZZ

The most general expression for vertex factor $\Gamma^{\alpha\beta\mu}_{ZZV}$ assumming Bose symmetry due to on-shell production and Lorentz invariance:

$$\Gamma^{\alpha\beta\mu}_{\mathrm{ZZV}} = \frac{s-m_V^2}{m_\mathrm{Z}^2}\left\{ i\, f_4^V \left((k+\bar{k})^\alpha\, g^{\mu\beta} + (k+\bar{k})^\beta\, g^{\mu\alpha}\right) \;+\; i\, f_5^V\, \varepsilon^{\alpha\beta\mu\rho}\,(q_{\mathrm{Z}\rho} - q_{\mathrm{Z}'\rho}) \right\}$$

$V = \mathrm{Z},\gamma$

Only four couplings (14 for WWV). f_4^V and f_5^V are ZERO at TREE level in the Standard Model.
Notation is that of K. Hagiwara Nucl. Phys. B282, (1987) 253.

- Non zero f_4^V leads to a C-violating, CP-violating process. Non zero f_5^V are P-violating, CP-conserving.
- The value of $\Gamma^{\alpha\beta\mu}_{\mathrm{ZZV}}$ increases with the center-of-mass energy.

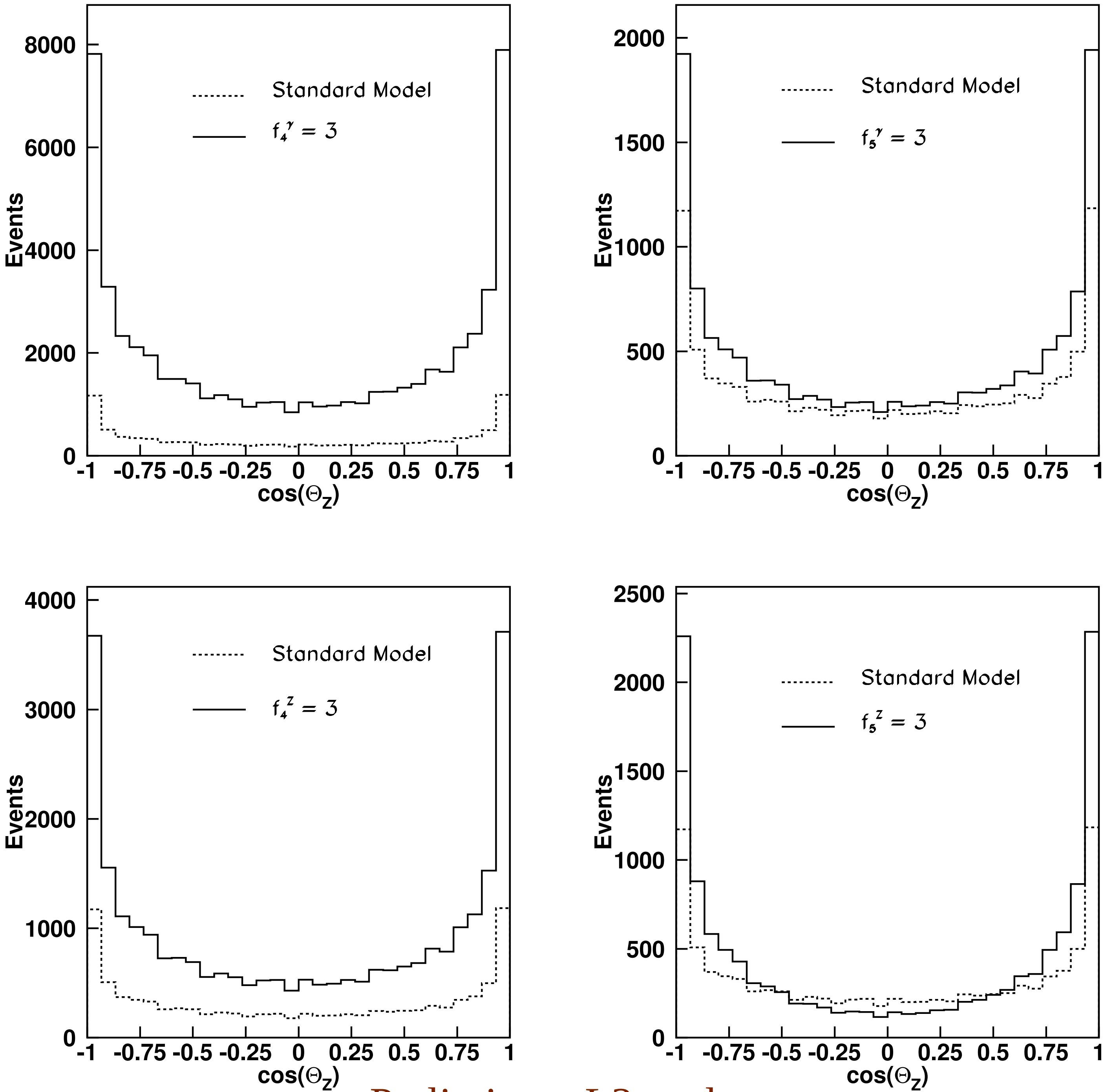
Experimental signatures

Anomalous couplings manifest themselves in 3 ways:

- Change in total cross section $\sigma(e^+e^- \rightarrow ZZ)$.
- Change in angular distribution $cos(\Theta_Z)$ of the Z.
- Change in average polarization of the Z.
  Difficult to measure at LEP.
  No futher dicussion here.

Experimental signatures.

Change in the total cross section and in the angular distribution, shown for $f_4^V = f_5^V = 3$.



Preliminary L3 study.

ZZ Cross-Section Measurement.

The LEP experiments measure the NC02 cross-section:

- ALEPH and OPAL calculate:

$$\sigma_{\mathrm{NC02}} = \frac{N_{data} - N_{bg}^{non\ 4f} - N_{4f}^{non\ ZZ\ res.}}{\mathcal{L}\varepsilon_{\mathrm{NC02}}}$$

$$N_{4f}^{non\ ZZ\ res.} = \mathcal{L}\left(\varepsilon_{4f}\sigma_{4f}^{MC} - \varepsilon_{\mathrm{NC02}}\sigma_{\mathrm{NC02}}^{MC}\right)$$

- L3 and DELPHI calculate
  correction factors for "resonant ZZ" : $\sigma_{\text{“}ZZ''}$

$$\sigma_{\mathrm{NC02}} = \frac{\sigma_{\mathrm{NC02}}^{MC}}{\sigma_{4f}^{MC\ \text{“}ZZ''}} \cdot \sigma_{\text{“}ZZ''}$$

"resonant ZZ" signal is defined through some kinematic requirements :

DELPHI: All 4-f within a mass window: $|M_Z - M_{ff,f'f'}| < 10$ GeV.
Channels in common with CC not analyzed

L3: 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 common with WW.

ZZ Selection

Events topologies

Channel	Statistics	Experimental Signature	Background
$q\bar{q}q'\bar{q}'$	Large	4 hadronic jets	Large
$q\bar{q}\nu\bar{\nu}$	Large	2 jets + missing energy	Medium
$q\bar{q}l^+l^-$	Medium	2 jets + 2 leptons	Low
$l^+l^-\nu\bar{\nu}$	Low	2 leptons + missing energy	Medium
$l^+l^-l'^+l'^-$	Low	4 leptons	Medium
$\nu\bar{\nu}\nu'\bar{\nu}'$		invisible!	

- Cut based and Neural Network methods are used.
- The better an event is b_tagged, the less important its ZZ mass constraint.
- Efficiencies are about 70% or 30% with τ-leptons

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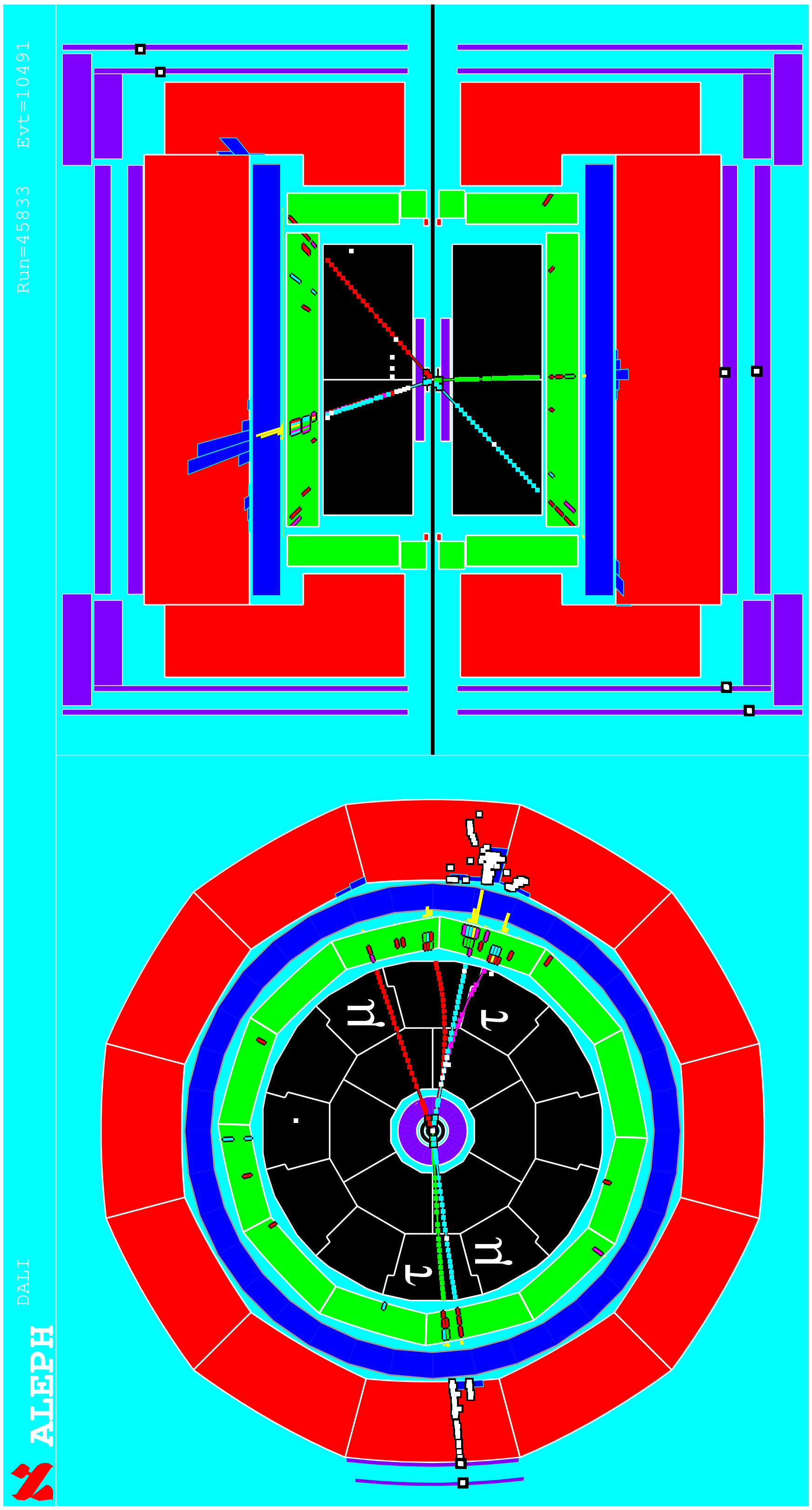
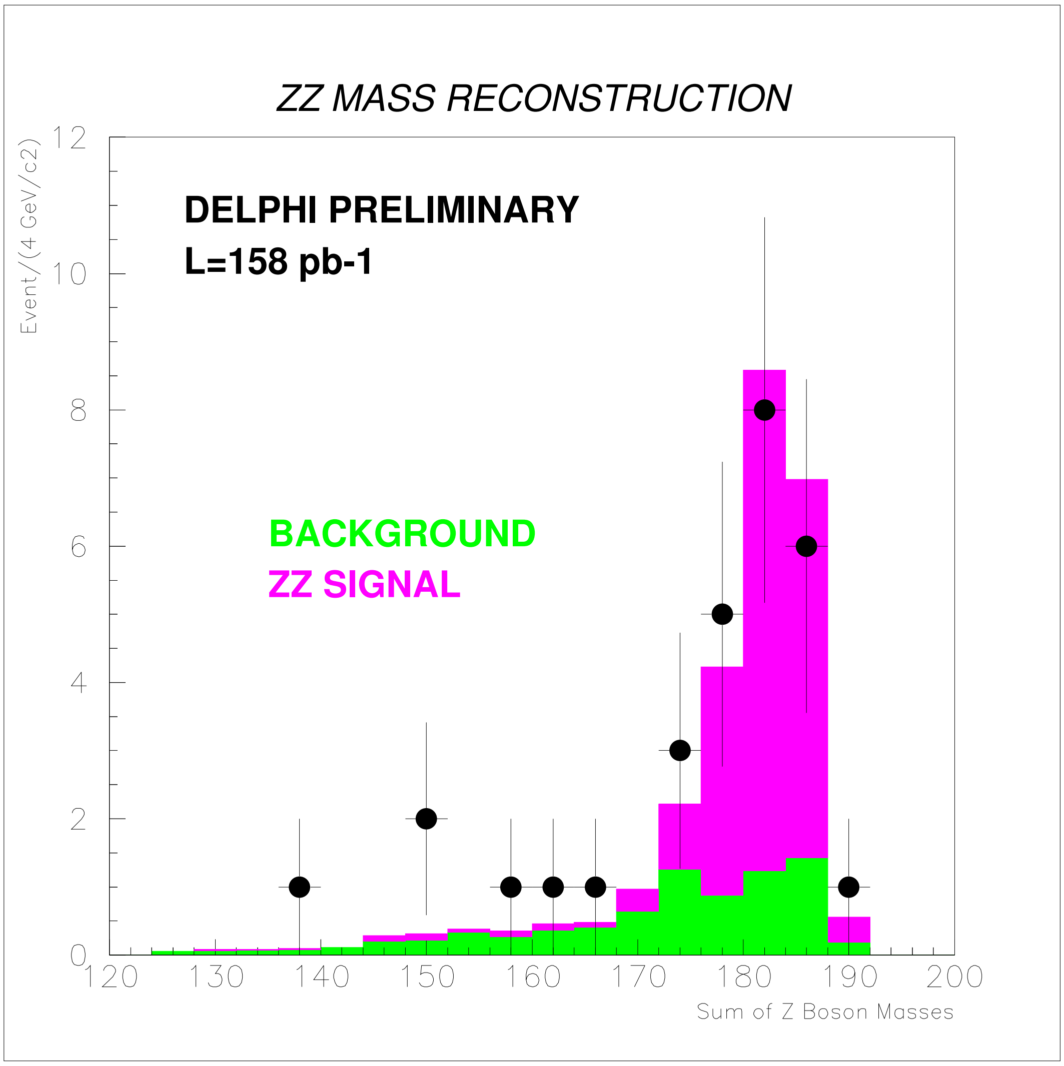


ZZ Mass Reconstruction

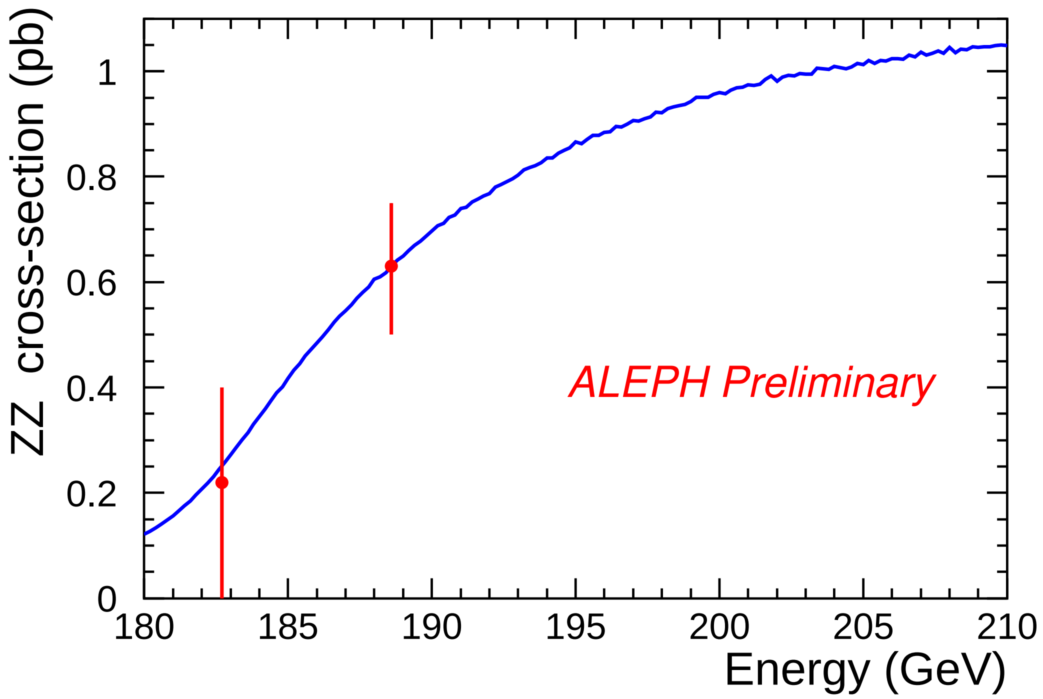


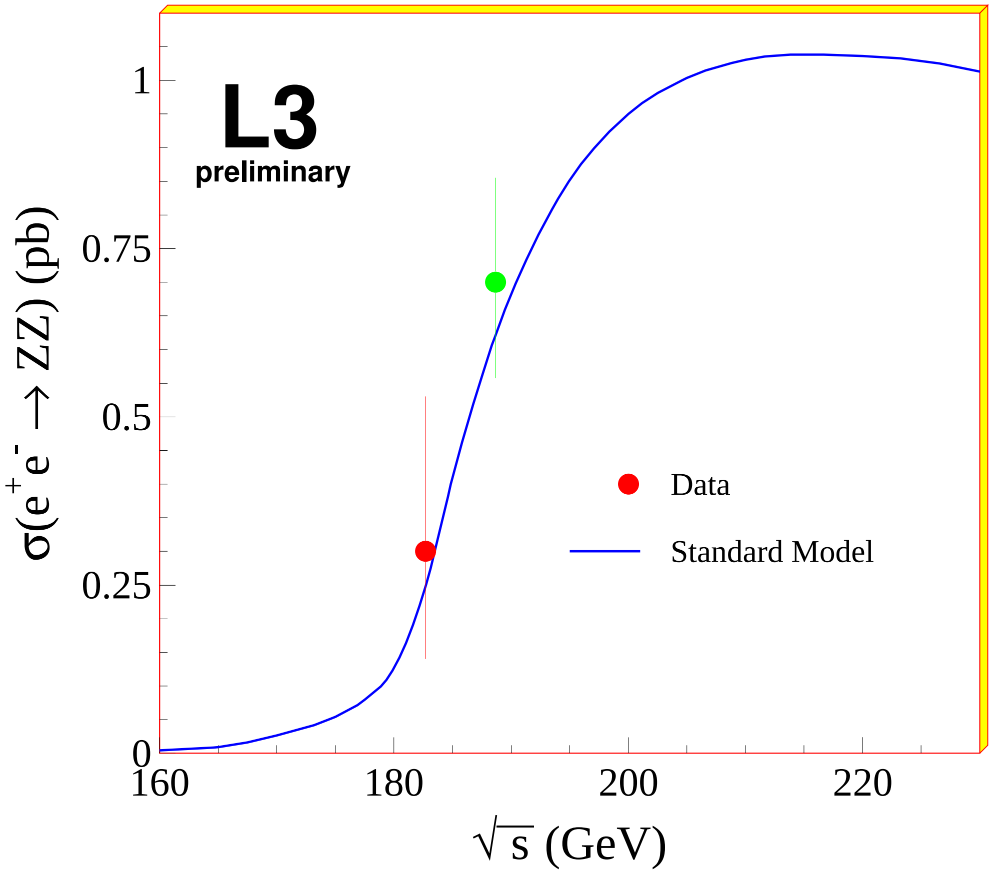
ZZ Cross-section Measurement Results

Cross-sections at 189 GeV are measured for NC02 processes or Resonant “ZZ” defined through kinematic cuts.
Data are corrected for 4f background by multiplicative or subtractive method.

Experiment	$\sigma(\sqrt{s} = 189\text{ GeV})\ [pb]$	
	NC02	“ZZ within cuts”
ALEPH	$0.63 \pm 0.12 \pm 0.05$	
DELPHI	0.58 ± 0.17	
L3	$0.71^{+0.16}_{-0.15}$	$0.68^{+0.15}_{-0.14}$
OPAL	$0.57^{+0.14}_{-0.12}$	
My Private Average	$0.62 \pm 0.07_{stat}$	
SM prediction	$\simeq 0.61\text{-}0.63$	

ZZ Cross-section





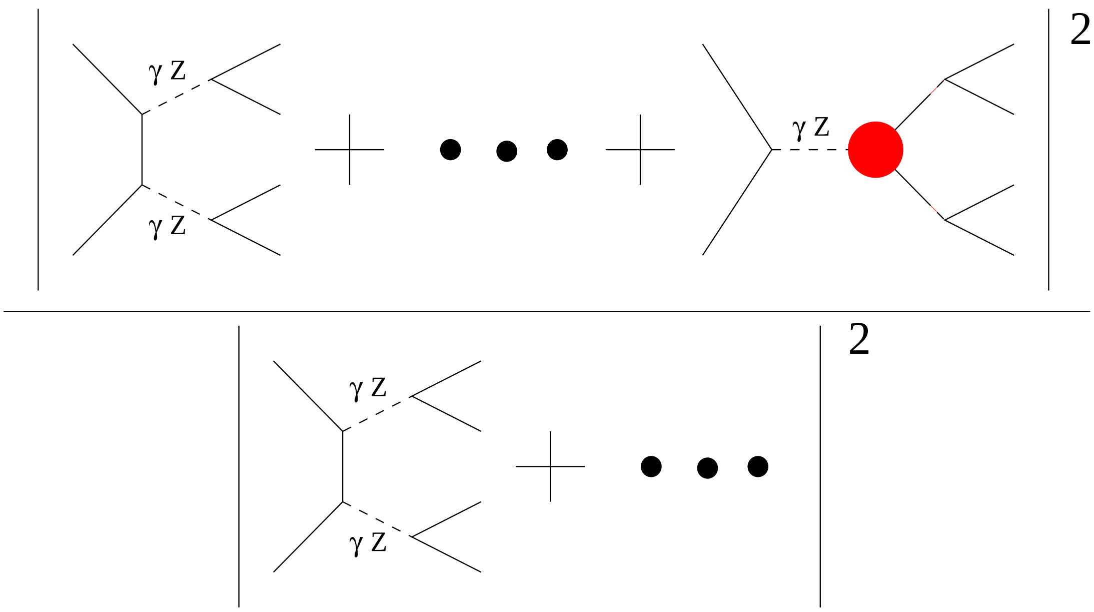
THE L3 REWEIGHTING PROCEDURE

The amplitude for the ZZ anomalous coupling diagram has been calculated analytically, and the result has been implemented in the routine used by Excalibur including all Feynman Diagrams.

Therefore, for any 4-fermion MC event, knowing the 4 four-momenta, the corresponding amplitude squared is calculated as a function of the anomalous couplings.

Then to obtain distributions with anomalous couplings, the SM distributions are reweighted, event by event, according to the ratio of matrix elements:

Weight =

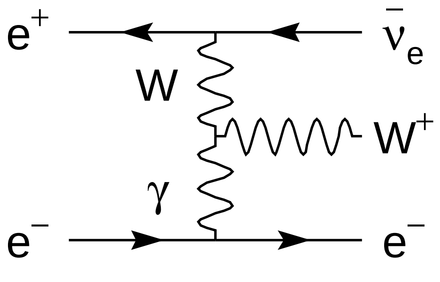


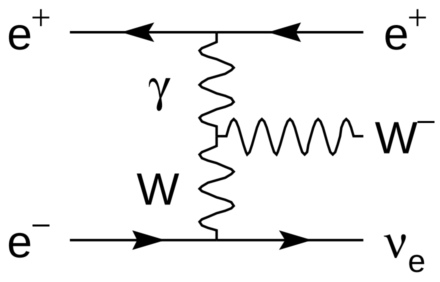
ZZ Anomalous Couplings Results

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

(L3 95% CL Preliminary)

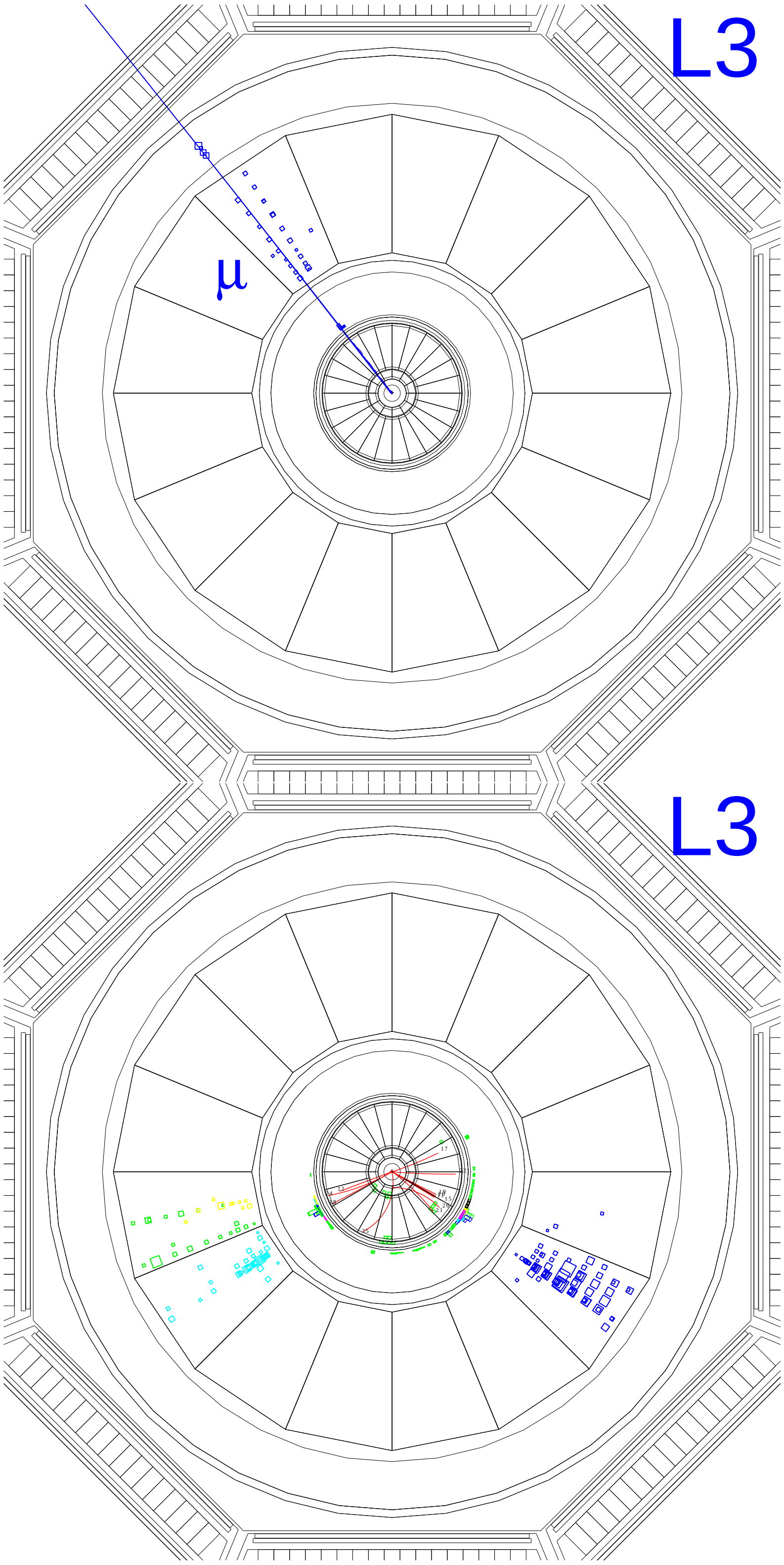
Single W Production





- This process is sensitive to γWW couplings : κ_γ, λ_γ.
- Electron escapes along the beam pipe.
- Signal Definition (example from L3 where cuts are defined at generator level):
  $|\cos\theta_{e^+}| > 0.997$
  $min(E_f, E_{\bar{f}'}) > 15$ GeV
  $|\cos\theta_{e^-}| < 0.75$, for events $e^+\nu_e e^-\overline{\nu}_e$ only
- jj + $\not{E}$ and l + $\not{E}$ events : very clean signals.

Single W Events

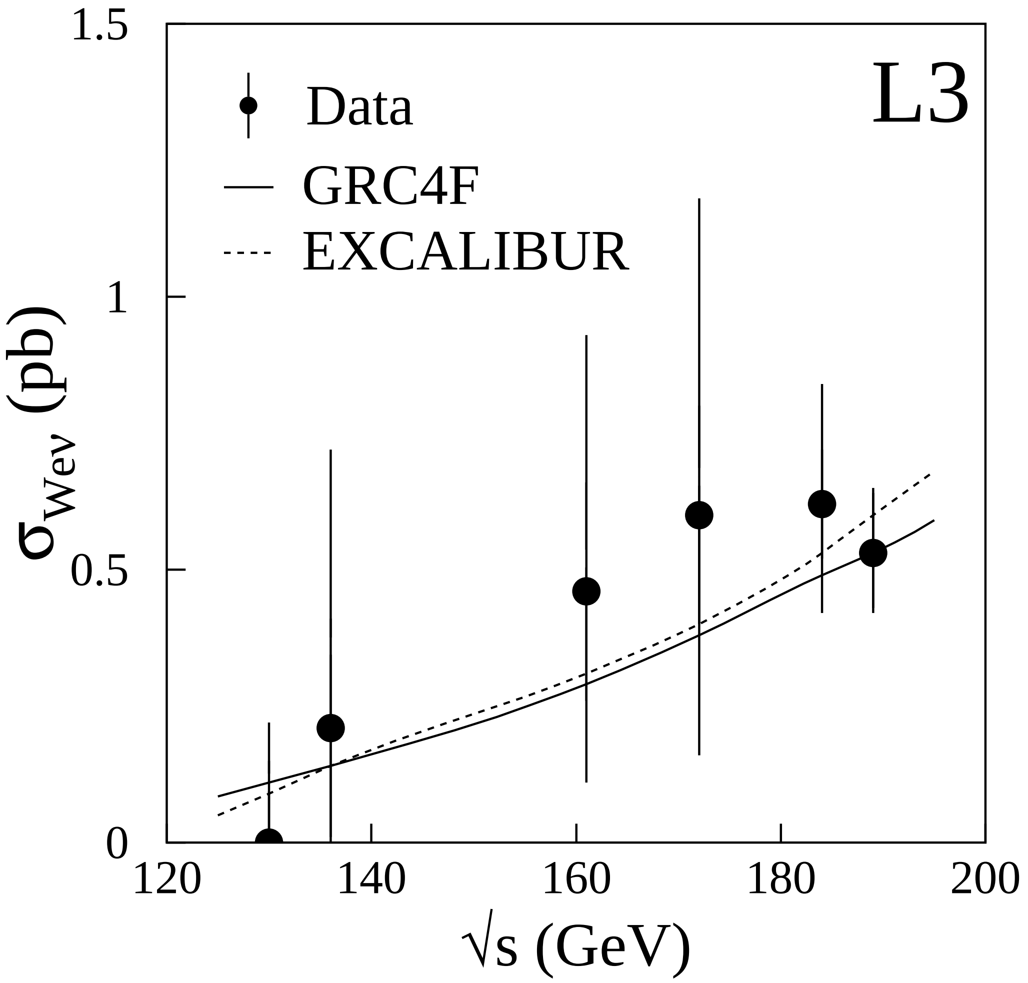


Single W Preliminary Results

Results for $\sigma_{We\nu}(\sqrt{s} = 189\ GeV)$ from L3:

$\sigma(e^+e^- \rightarrow We\nu) = (0.53^{+0.12}_{-0.11} \pm 0.03)$ pb

$\sigma_{GRC4F} = 0.53$ pb, $\sigma_{EXC} = 0.60$ pb



Results for $\sigma_{We\nu}(\sqrt{s} = 183\ GeV)$ from ALEPH:

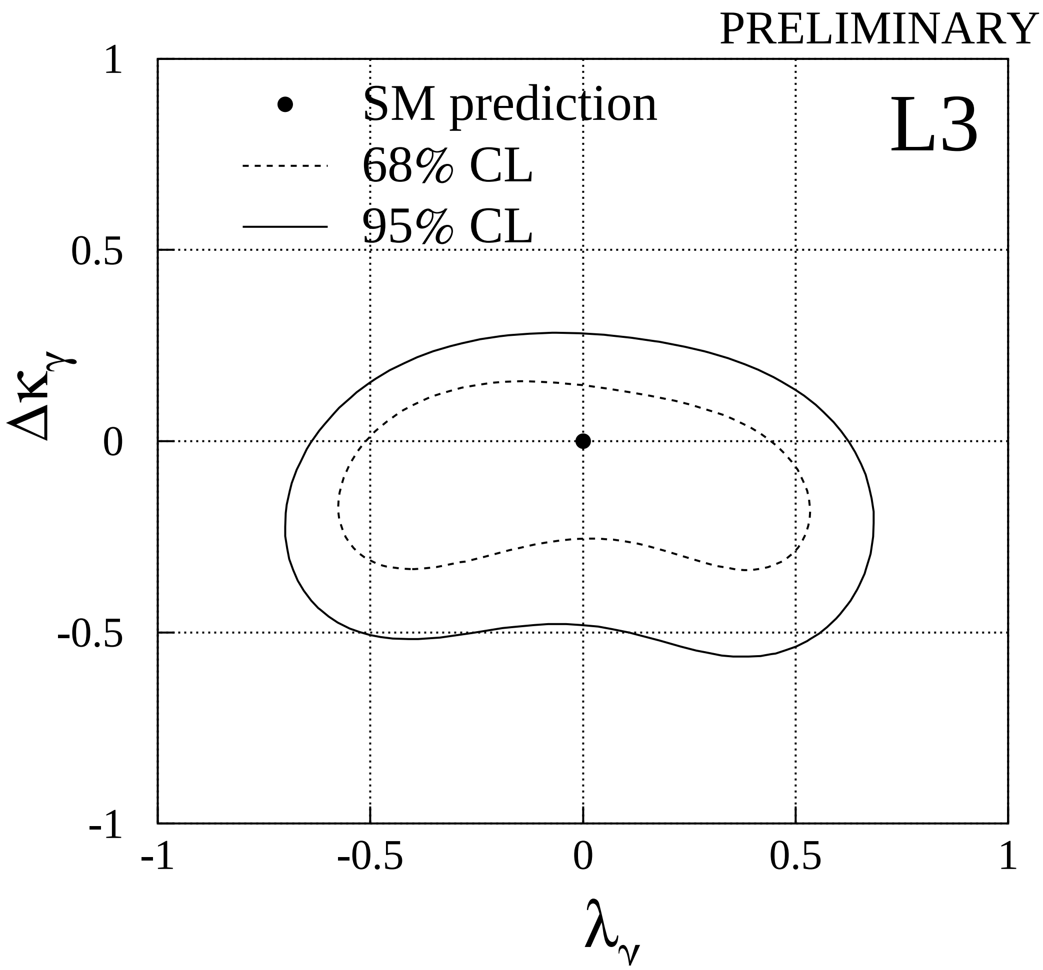
$\sigma(e^+e^- \rightarrow We\nu) = (0.40 \pm 0.17 \pm 0.04)$ pb

Single W: κ_γ, λ_γ 95% CL.

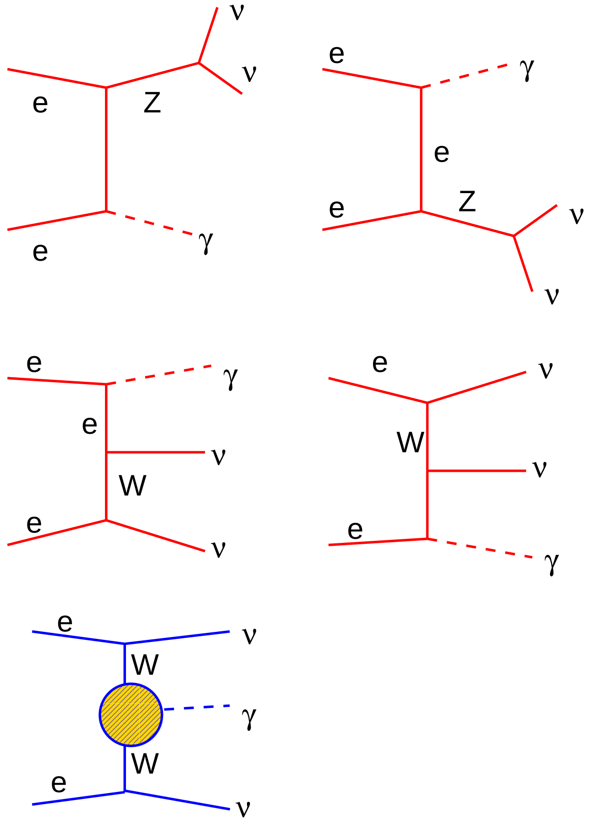
ALEPH	$-1.6 < \Delta\kappa_\gamma < 1.5$	$-1.6 < \lambda_\gamma < 1.6$	183 GeV
DELPHI	$-0.4 < \Delta\kappa_\gamma < 0.9$	$-1.13 < \lambda_\gamma < 1.14$	183 GeV
L3	$-0.42 < \Delta\kappa_\gamma < 0.22$	$-0.64 < \lambda_\gamma < 0.61$	189 GeV
OPAL	$-2.6 < \Delta\kappa_\gamma < 2.6$	$-3.1 < \lambda_\gamma < 3.1$	161-172 GeV

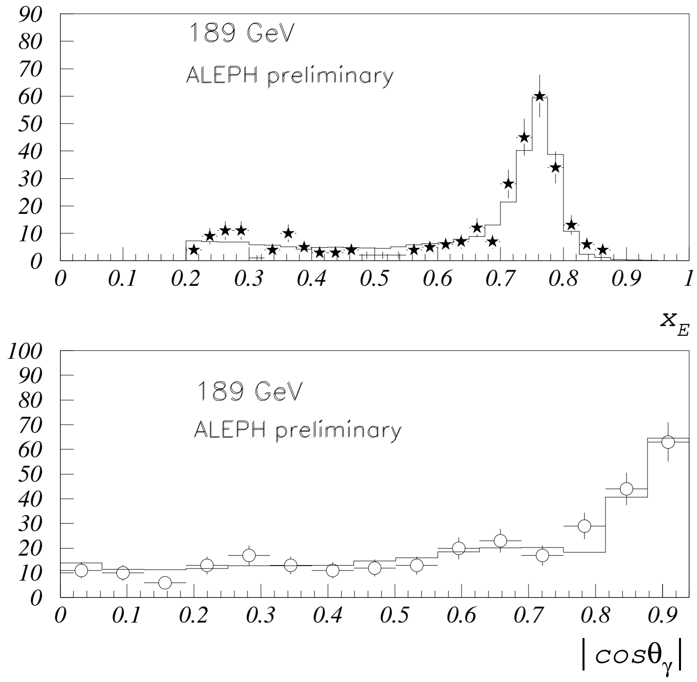
Precision of κ_γ, the WWγ dipole coupling, measurement is comparable
to that from W pairs.

95% CL from two parameter fit ($\Delta\kappa_\gamma = \kappa_\gamma - 1$) :



Trilinear Gauge Couplings from single photon ($WW\gamma$)





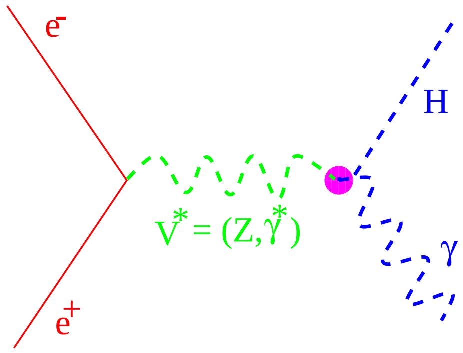
A global fit is performed to the total number of events and the angular and energetic γ spectra ($X_E = E_\gamma / E_{CM}$).
The analysis of data from 189 GeV gives:

(PRELIMINARY RESULTS FROM ALEPH)

$$\Delta\kappa_\gamma = 0.3 \pm 0.8(stat) \pm 0.2(syst)$$

$$\lambda_\gamma = 0.3 \pm 1.0(stat) \pm 0.2(syst)$$

Anomalous couplings through the $\mathbf{e^+e^-} \rightarrow \mathbf{H}\boldsymbol{\gamma}$ process (Preliminary results from L3).



- In the Higgs sector, it is easier to generate anomalous than for gauge bosons.

- Important:
  Access to large Higgs masses.
  Sensitivity to anomalous couplings is not better at higher energies.

- $\mathrm{H}\gamma\gamma$ and $\mathrm{HZ}\gamma$ not present in the SM at tree level.

$$g_{\mathrm{H}\gamma\gamma} = -\frac{g\, m_{\mathrm{W}} \sin^2\theta_{\mathrm{W}}}{2} \left(\frac{f_{\mathrm{WW}}}{\Lambda^2} + \frac{f_{\mathrm{BB}}}{\Lambda^2} \right)$$

$$g^{(1)}_{\mathrm{HZ}\gamma} = \frac{g\, m_{\mathrm{W}} \sin\theta_{\mathrm{W}}}{2\cos\theta_{\mathrm{W}}} \left(\frac{f_{\mathrm{W}}}{\Lambda^2} - \frac{f_{\mathrm{B}}}{\Lambda^2} \right)$$

$$g^{(2)}_{\mathrm{HZ}\gamma} = \frac{g\, m_{\mathrm{W}} \sin\theta_{\mathrm{W}}}{\cos\theta_{\mathrm{W}}} \left(\sin^2\theta_{\mathrm{W}} \frac{f_{\mathrm{BB}}}{\Lambda^2} - \cos^2\theta_{\mathrm{W}} \frac{f_{\mathrm{WW}}}{\Lambda^2} \right)$$

Λ is scale of new physics.

Anomalous couplings through the $\mathbf{e^+e^-} \rightarrow \mathbf{H}\gamma$ process.

- $f_B, f_W \iff \Delta\kappa_\gamma, \Delta\kappa_Z, \Delta g_1^Z$

$$\Delta\kappa_\gamma = \frac{m_W^2}{2}\left(\frac{f_W}{\Lambda^2} + \frac{f_B}{\Lambda^2}\right)$$

$$\Delta\kappa_Z = \frac{m_Z^2}{2}\left(\cos^2\theta_W \frac{f_W}{\Lambda^2} - \sin^2\theta_W \frac{f_B}{\Lambda^2}\right)$$

$$\Delta g_1^Z = \frac{m_Z^2}{2}\frac{f_W}{\Lambda^2}$$

- Three scenarios used by L3:

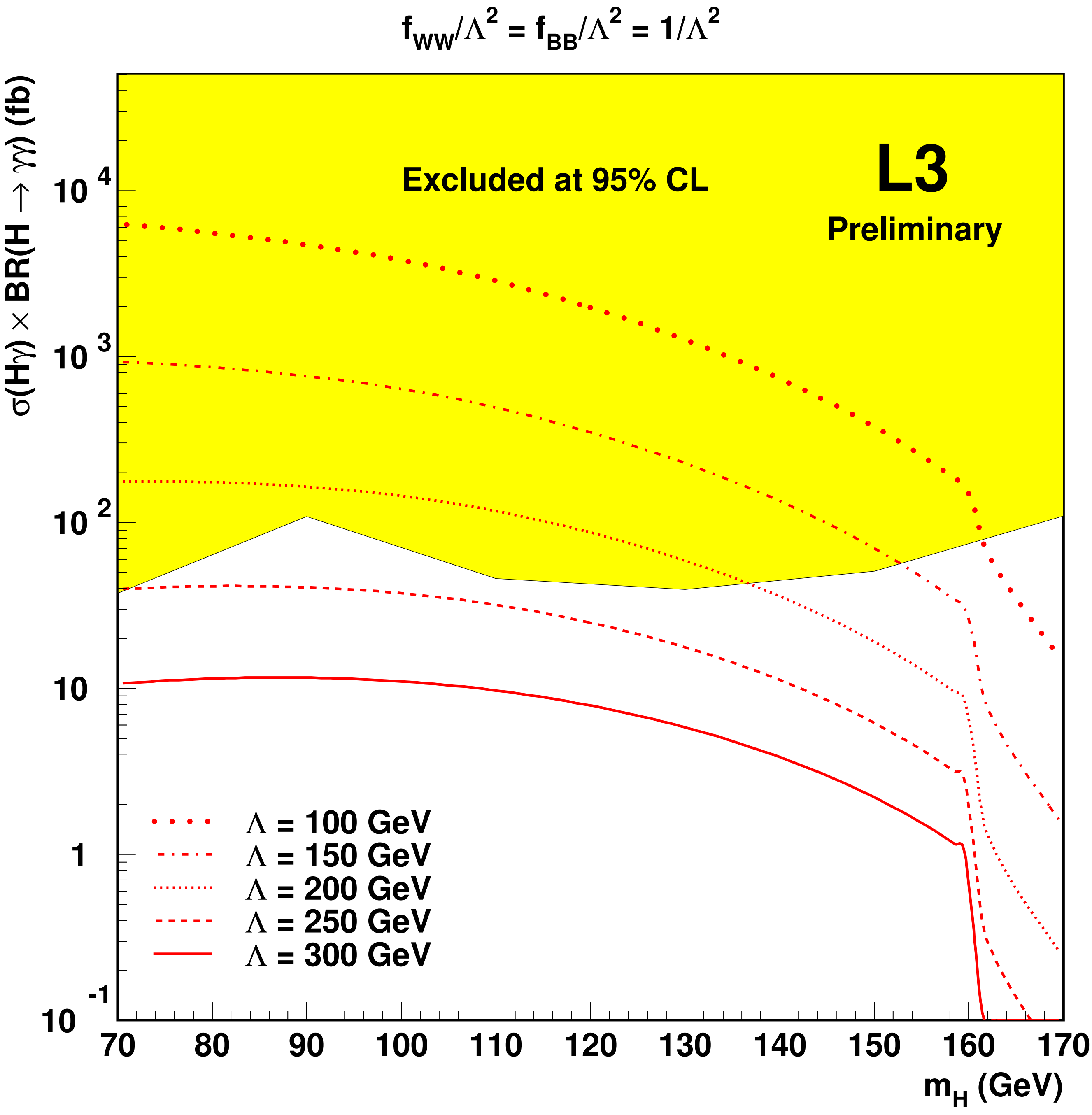
1. All WWV anomalous couplings are extremely small, $f_W = f_B = 0$ and all anomalous effect are due to f_{WW} and f_{BB}.
2. Only WWV anomalous couplings are assumed to exist: $f_{WW} = f_{BB} = 0$. The process $e^+e^- \rightarrow H\gamma \rightarrow \gamma\gamma$ is highly suppressed, and the $H \rightarrow b\bar{b}$ decay is dominant for Higgs masses below 100 GeV. Limits may be directly interpreted in terms of $\Delta\kappa_Z, \Delta\kappa_\gamma$.
3. All four anomalous couplings have similar sizes : $f_W = f_B = f_{WW} = f_{BB}$.
   Limits are interpreted in terms of $\Delta\kappa_\gamma$.

Signal and Backgrounds

- Explored Higgs mass range : $70GeV < m_H < 170GeV$ at $\sqrt{s} = 189$ GeV.
- The Higgs particle is assumed to behave as a narrow resonance in the decays
  $H \to \gamma\gamma$ and $H \to \mathrm{b\bar{b}}$
- Backgrounds :
  QED process for $\mathrm{e^+e^-} \to \mathrm{H}\gamma \to \gamma\gamma\gamma$.
  $\mathrm{e^+e^-} \to \mathrm{Z}\gamma$ for the process $\mathrm{e^+e^-} \to \mathrm{H}\gamma \to \mathrm{b\bar{b}}\gamma$.

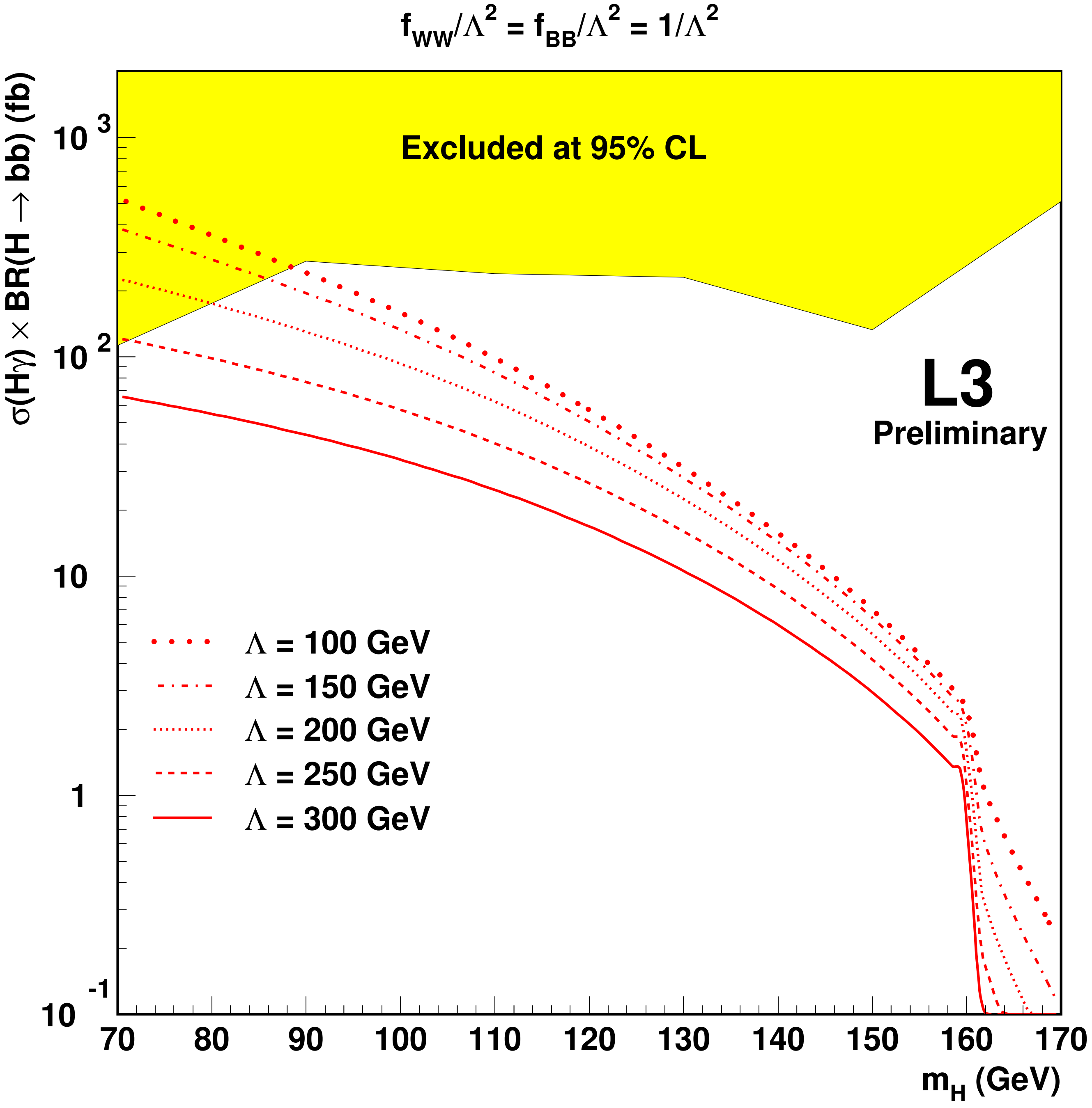
$e^+e^- \to H\gamma \to \gamma\gamma$ Expected Cross-Section.

The most sensitive.
Scenario I (No WWV anomalous couplings)



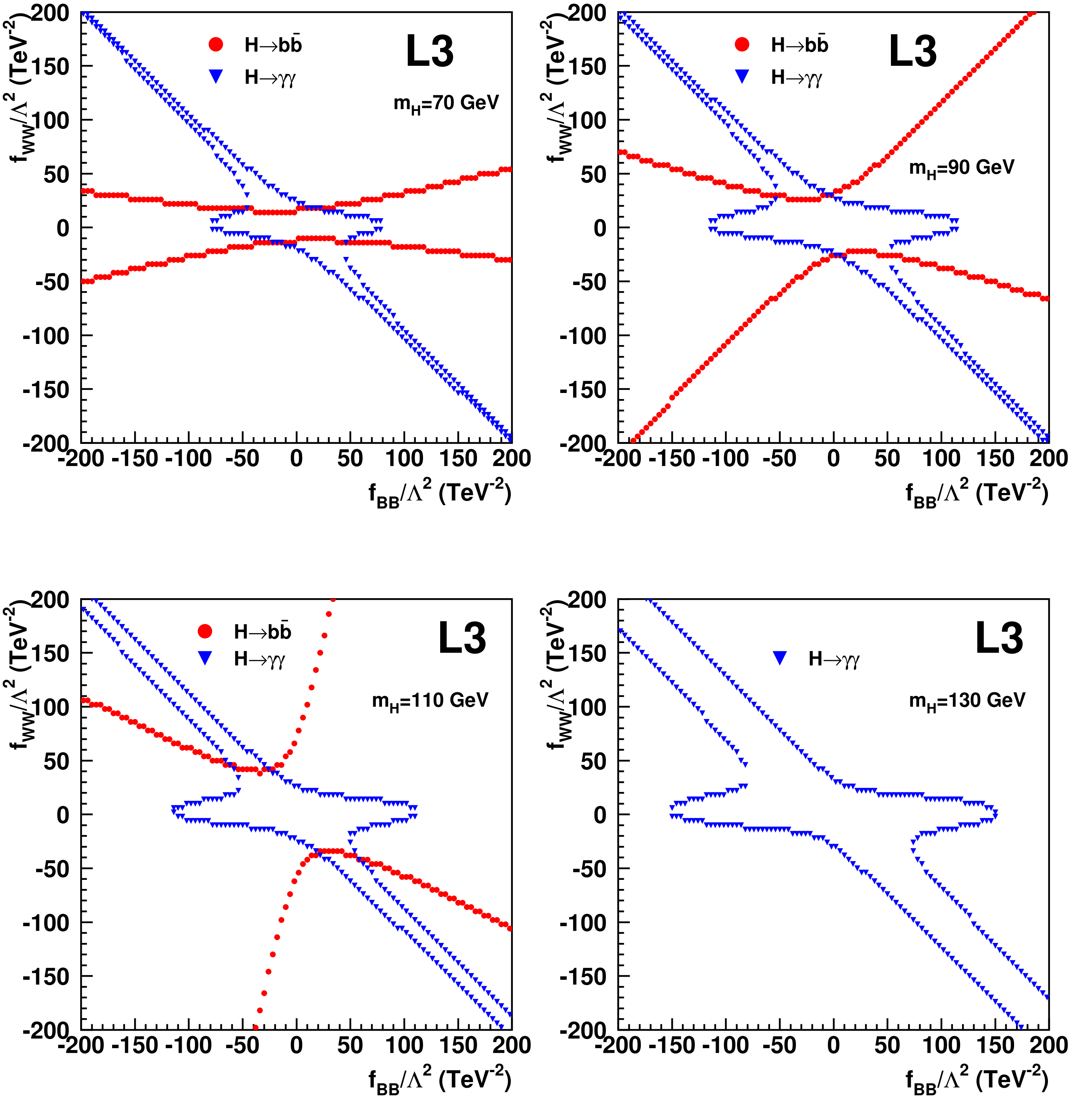
$e^+e^- \to H\gamma \to b\bar{b}\gamma$ Expected Cross-Section.

Scenario I (No WWV anomalous couplings)



Limits on $\frac{f_{WW}}{\Lambda^2}$, $\frac{f_{BB}}{\Lambda^2}$ at 95% CL.

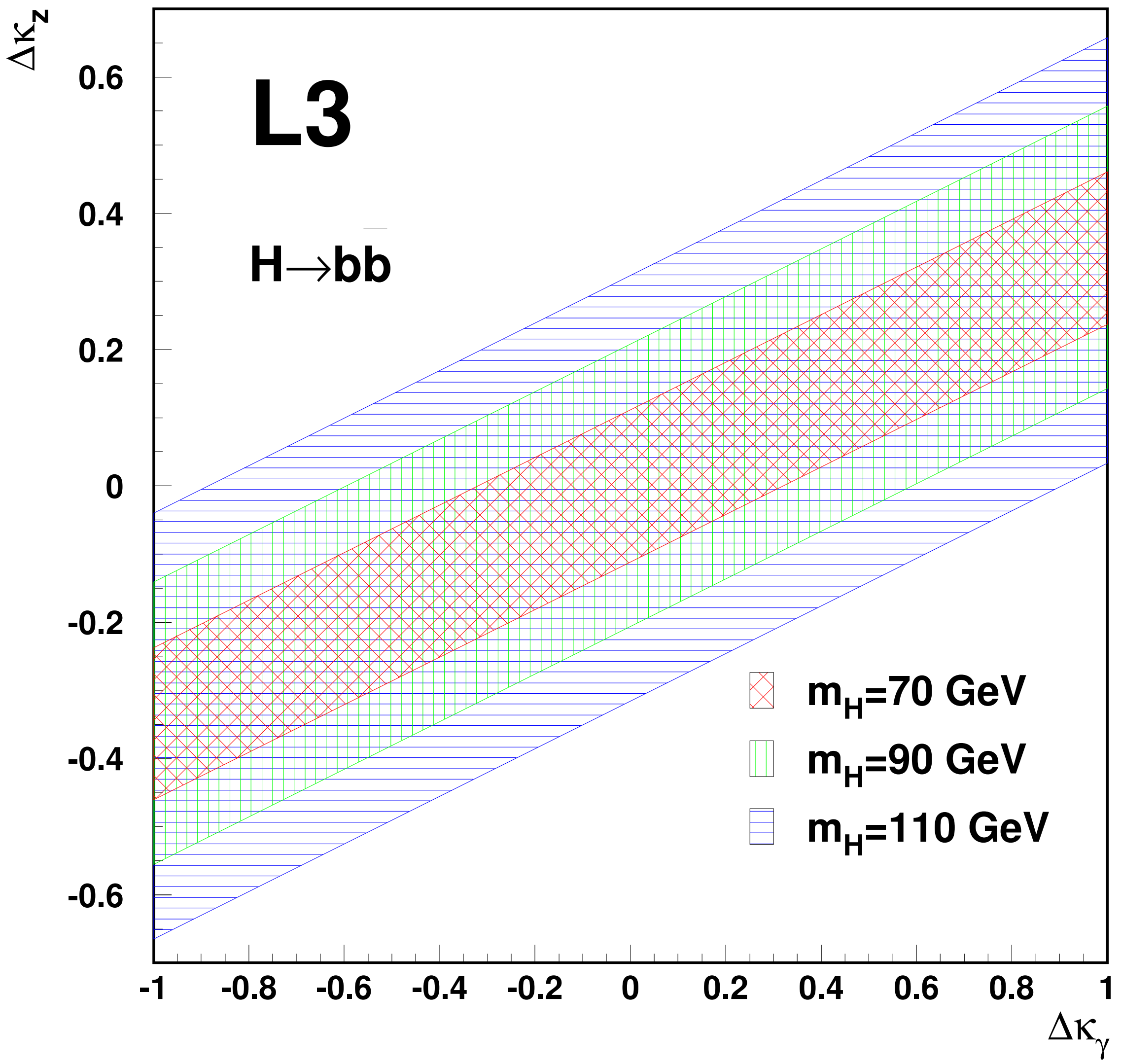
Scenario I (No WWV anomalous couplings).
Allowed region is containing $f_{WW} = f_{BB} = 0$.



Limits on Anomalous WWV couplings at 95% CL.

Allowed regions.
Scenario II (only WWV anomalous couplings):
$f_{WW} = f_{BB} = g_{H\gamma\gamma} = 0$

$$\frac{f_W}{\Lambda^2} = f(\Delta\kappa_\gamma, \Delta\kappa_Z)$$
$$\frac{f_B}{\Lambda^2} = g(\Delta\kappa_\gamma, \Delta\kappa_Z)$$

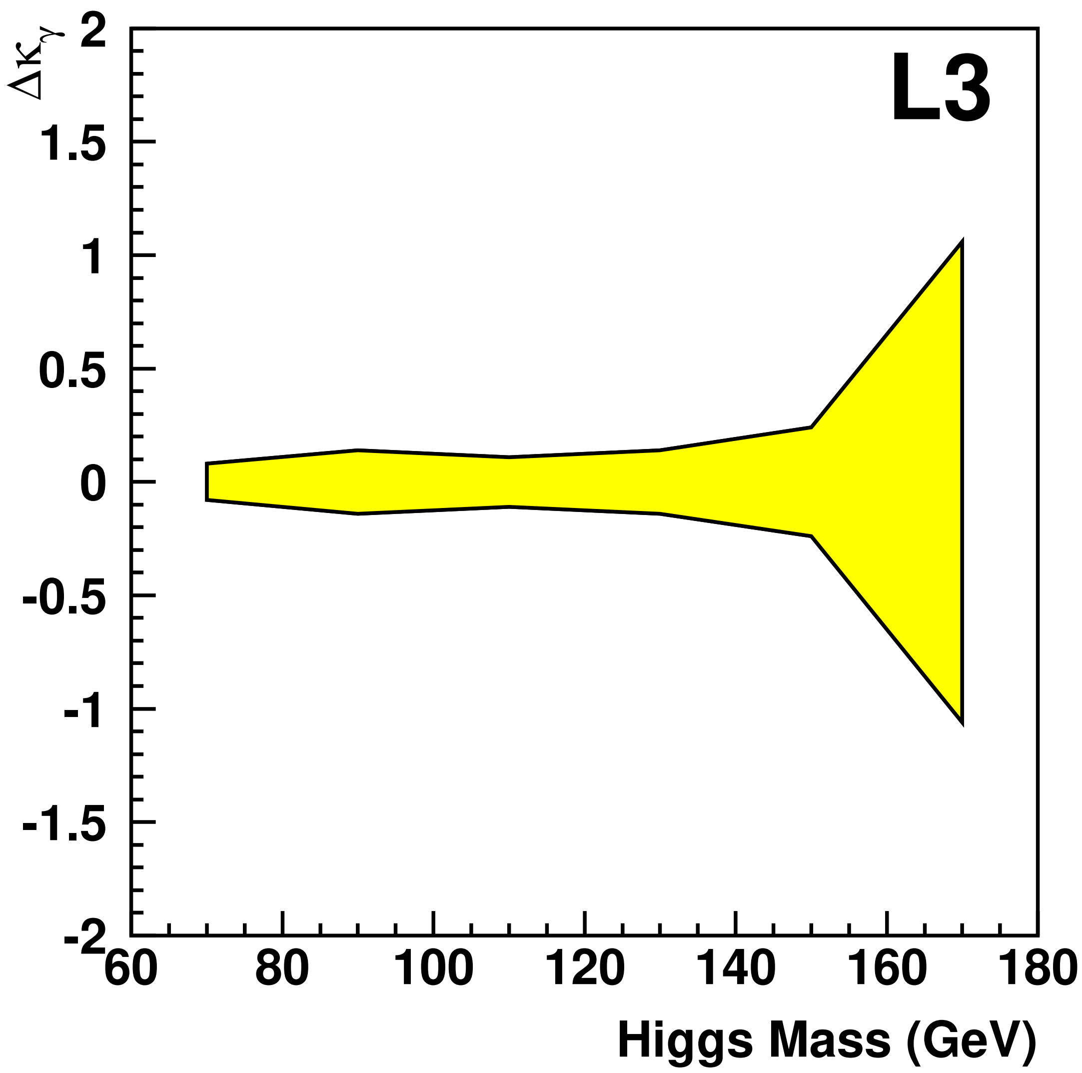


Higgs mass vs $\Delta\kappa_\gamma$

Scenario III

Common sizes for all anomalous couplings

$$\frac{f_{\mathrm{WW}}}{\Lambda^2} = \frac{f_{\mathrm{BB}}}{\Lambda^2} = \frac{f_{\mathrm{W}}}{\Lambda^2} = \frac{f_{\mathrm{B}}}{\Lambda^2} = \frac{F}{\Lambda^2} = f(\Delta\kappa_\gamma)$$



Conclusions (95% CL Preliminary Results)

- No deviation from the Standard Model is observed.

- ZZ Final state
  - My Private Average (ADLO) :
    $\sigma(\sqrt{s} = 189 GeV) = 0.62 \pm 0.07_{stat}$ pb
  - Limits on Anomalous Couplings at 189 GeV (L3) :
    $-1.7 \leq f_4^Z \leq 1.8 \quad -4.7 \leq f_5^Z \leq 4.7$
    $-1.0 \leq f_4^\gamma \leq 1.1 \quad -2.8 \leq f_5^\gamma \leq 2.9$

- Single W Final state
  - Cross sections at 189 GeV:
    $\sigma_{expected} = 0.53$ pb (GRC4F), 0.60 pb (EXC);
    $\sigma_{observed} = (0.53^{+0.12}_{-0.11} \pm 0.03)$ pb (L3).
  - Limits on κ_γ, λ_γ at 189 GeV (L3)
    $-0.42 < \Delta\kappa_\gamma < 0.22$
    $-0.64 < \lambda_\gamma < 0.61$

- Trilinear gauge Couplings from single photon
  - From Aleph at 189 GeV:
    $\Delta\kappa_\gamma = 0.3 \pm 0.8(stat) \pm 0.2(syst)$
    $\lambda_\gamma = 0.3 \pm 1.0(stat) \pm 0.2(syst)$

Conclusions (cont'd)

- Limit on Anomalous Hγ Production from L3 at $\sqrt{s}$ =189 GeV
  - No evidence for anomalous couplings Higgs production is found.
  - No event from $e^+e^- \rightarrow H\gamma \rightarrow \gamma\gamma$ process for Higgs masses up to 170 GeV.
  - $|\Delta\kappa_\gamma|$ in range 0.1 to 0.2 for higgs masses up to 150 GeV, if only anomalous WWV couplings are present.