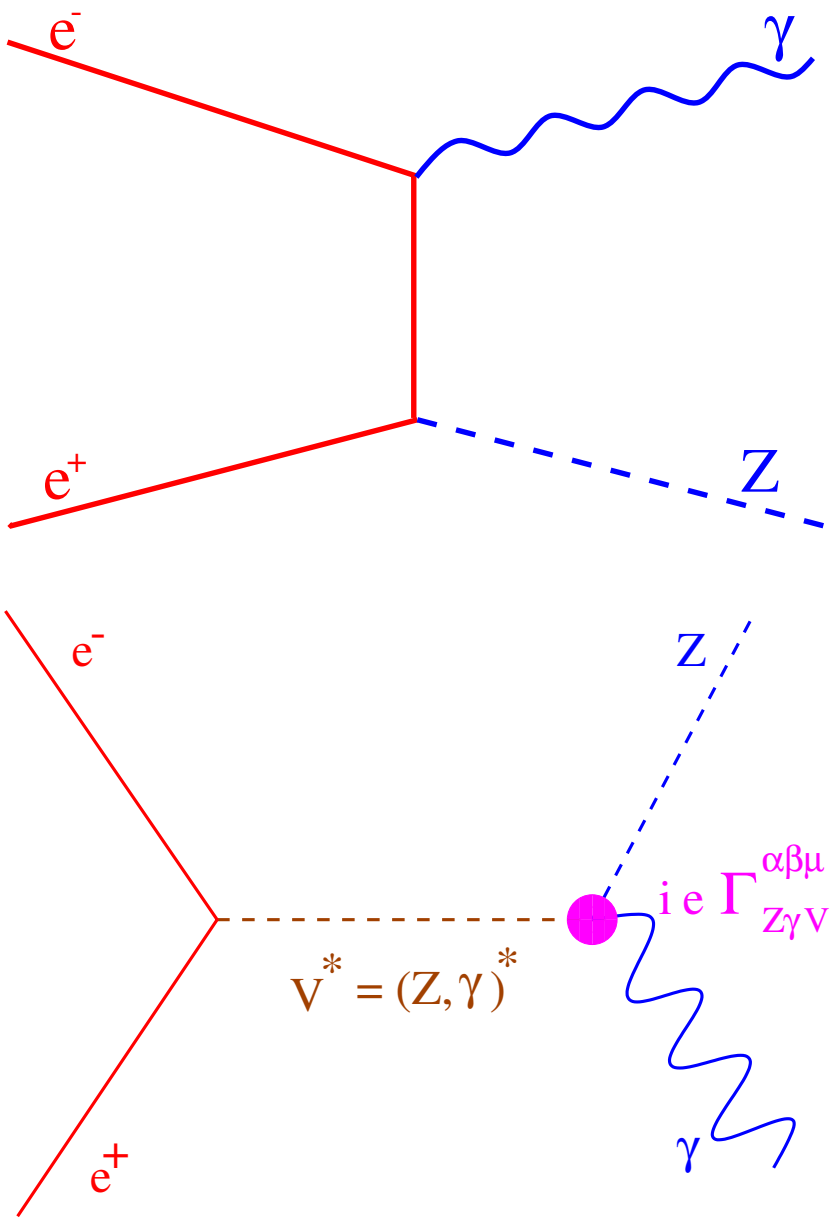
OUTLINE

- Motivation
- Anomalous Couplings Z-γ
- Analysis Procedure
- Results and Conclusions

Look for deviations from the Standard Model in Triple Gauge Boson Couplings.



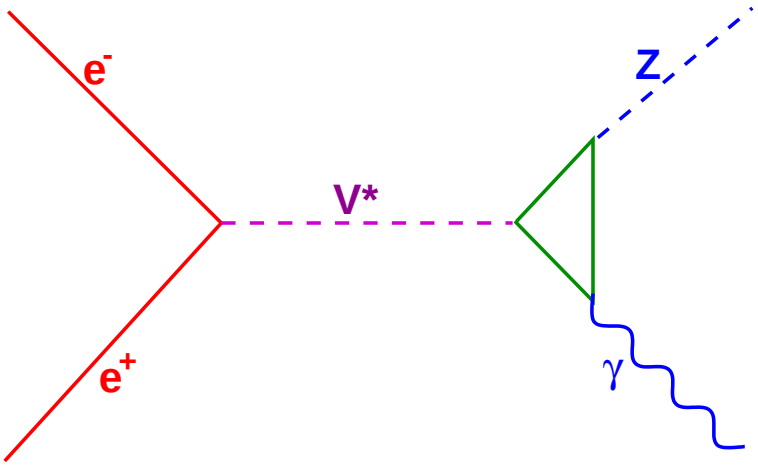
Anomalous couplings are Zero at tree level.

PHYSICAL INTERPRETATION OF THE ANOMALOUS COUPLINGS:

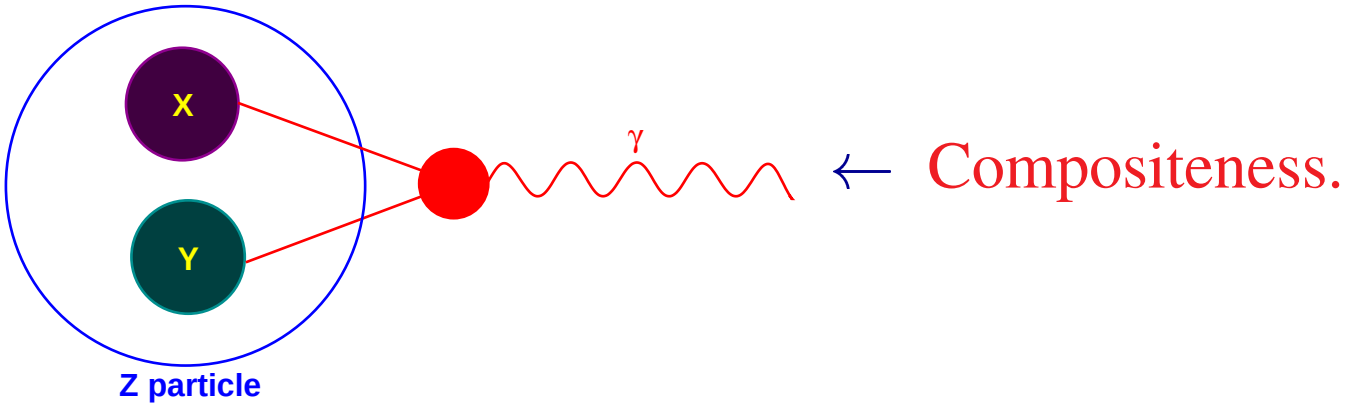
SM Value at 1-loop level: $\begin{cases} h_1^V, h_2^V = 0 \\ h_3^V, h_4^V \neq 0 \end{cases}$ SMALL:$(h_3^Z \simeq 2.4 \times 10^{-4})$

Could be modified by :

Extra-particles in the loop $\longrightarrow$



OR



$\leftarrow$ Compositeness.

✻ 8 ANOMALOUS COUPLINGS

$$\Gamma^{\alpha\beta\mu}_{\mathrm{Z}\gamma\mathrm{V}} = \frac{s - m_V^2}{m_{\mathrm{Z}}^2} \times \left| \begin{array}{l} h_1^V \ (p_\gamma^\mu g^{\alpha\beta} - p_\gamma^\alpha g^{\beta\mu}) \\ h_2^V \ \frac{p_V^\alpha}{m_{\mathrm{Z}}}[(p_\gamma p_V) g^{\beta\mu} - p_\gamma^\mu p_V^\beta] \\ h_3^V \ \epsilon_\rho^{\alpha\beta\mu} p_\gamma^\rho \\ h_4^V \ \epsilon_{\rho V}^{\mu\beta} p_V^\rho p_\gamma^V \end{array} \right.$$

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

$h_{1,2}^V \longrightarrow$ CP Violating

$h_{3,4}^V \longrightarrow$ CP Conserving

✻ Deviations suppressed at threshold : $\Delta = (\frac{p_{\mathrm{Z}}}{E_{\mathrm{Z}}})^n$

- ZZ at threshold (poor limits).
- WW "almost" at threshold (medium limits).
- Zγ far from threshold (good limits).

* EXPERIMENTAL SIGNATURE OF Zγ EVENTS

  Production of an almost monoenergetic photon of very high energy

* EXPERIMENTAL EFFECTS OF ANOMALOUS COUPLINGS

  Enhancement of Zγ events mostly at large angles.

  Enhancement of longitudinal Z's ($\lambda_3 = 0$).

  $\cos\theta_\gamma$ asymmetry for CP violating couplings.

✻ Choice of the parameters

Due to unitary constraints, anomalous couplings must satisfy $$\lim_{s\to\infty} h_i^V = 0$$

The conventional choice is to assume the dependence:

$$h_i^V = \frac{h_{i0}^V}{(1+s/\Lambda^2)^3}\ ;\ i=1,3$$

$$h_i^V = \frac{h_{i0}^V}{(1+s/\Lambda^2)^4}\ ;\ i=2,4$$

In e^+e^- colliders the scale of new physics ,Λ, must be $\Lambda > \sqrt{s}$ which is fixed. Therefore, no assumptions on the energy dependence of the form factors are needed, and we can consider : $h_i^V = h_{i0}^V$.

Another parametrization using the new physics scales is the following :

$$\frac{\sqrt{\alpha}h_i^V}{m_Z^2} \equiv \frac{1}{\Lambda_{iV}^2}; i=1,3$$

$$\frac{\sqrt{\alpha}h_i^V}{m_Z^4} \equiv \frac{1}{\Lambda_{iV}^4}; i=2,4$$

PRESENT LIMITS

ZZγ CP conserving couplings at 95% C.L. ($\Lambda = 500$ GeV):

Experiment	h_{30}^{Z}	h_{40}^{Z}
L3 (LEP1)	< 0.7	< 2
CDF	< 1.6	< 0.4
D0	< 0.78	< 0.19

Z$\gamma\gamma$ CP conserving couplings at 95% C.L. ($\Lambda = 500$ GeV):

Experiment	h_{30}^{γ}	h_{40}^{γ}
CDF	< 3.1	< 0.8
D0	< 0.8	< 0.2

(For DO, better limits with $\Lambda = 750$ GeV)

Limits at LEP2(L3) are comparable in sensitivity to the best presents limits and these are the first limits which make use of hadronic decays of the Z.

ANALYSIS PROCEDURE

- Compute the amplitude $\mathcal{M}$ for the process $e^+e^- \rightarrow f\bar{f}\gamma$ assuming Standard Model $\oplus$ Anomalous Couplings, using the variables

$$E_\gamma, \theta_\gamma, \phi_\gamma, (\theta^{CM}_{f\bar{f}}, \phi^{CM}_{f\bar{f}})$$

and taking into account

  - Spin Correlations
  - Effective Z couplings
  - Non-resonant contributions
  - t-channel W exchange in $\nu_e\bar{\nu}_e\gamma$

Perfect agreement with CDF and DO $f\bar{f}\gamma$ program

- Distributions in the presence of anomalous couplings can be obtained from the Standard Model distributions simply by reweighting according to:

$$w(E_\gamma, \theta_\gamma, \phi_\gamma, \theta_f^{CM}, \phi_f^{CM}; h_i^V) =$$

$$\frac{|(\mathcal{M}_{SM}+\mathcal{M}_{AC}(h_i^V))|^2}{|\mathcal{M}_{SM}|^2}$$

- For $e^+e^- \to \nu\bar{\nu}\gamma$ the neutrino angular variables are integrated out.
- We consider that additional photon radiation effects are small or cancel in the ratio of amplitudes.
- For $e^+e^- \to q\bar{q}\gamma$ the $q\bar{q}$ angles are substituted by the jet thrust axis angles and the square of the amplitudes is symmetrized under the interchange $q \leftrightarrow \bar{q}$.

- Consider the channels $q\bar{q}\gamma$ (70% of Z decays) and $\nu\bar{\nu}\gamma$ (20% of Z decays)
- To quantify the deviations, we determine the value of a given anomalous coupling which maximizes the likelihood function:

$$\mathcal{L}(h_i^V) = \frac{e^{-N_t(h_i^V)} N_t^{No}(h_i^V)}{N_o!} \times$$

$$\prod_{j=1}^{N_o} \frac{w_j(E_{\gamma j},\theta_{\gamma j},\phi_{\gamma j},\theta_{fj}^{\mathrm{CM}},\phi_{fj}^{\mathrm{CM}};h_i^V)}{N_t(h_i^V)}$$

N_o = Number of observed events
$N_t(h_i^V)$ = Number of expected events
$w_j/N_t(h_i^V)$ $\propto$ Probability density for event j

- Uncertainties:

$q\bar{q}\gamma$:

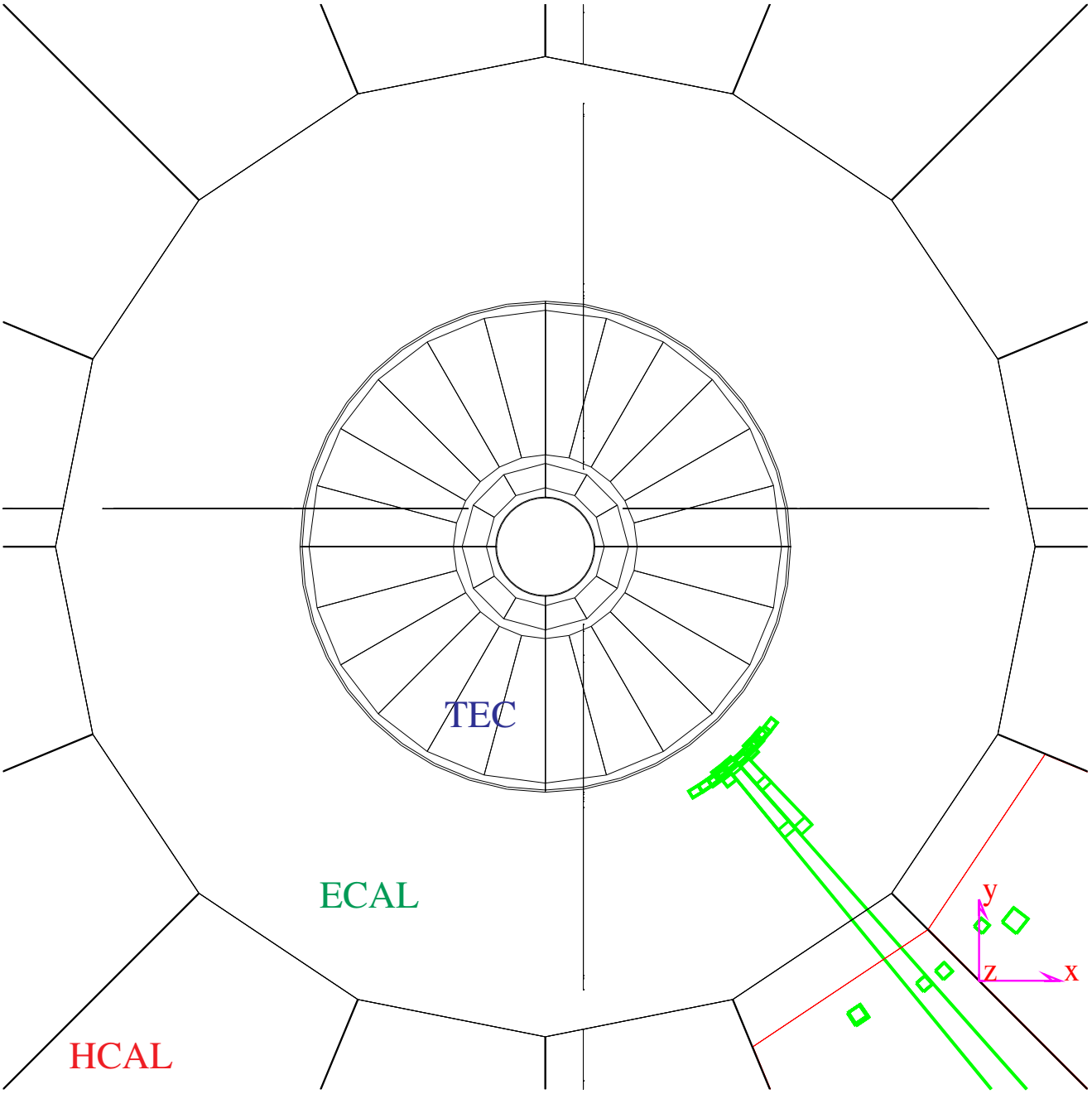
- Final State Radiation
- Uncertainties in θ_q^{CM}, ϕ_q^{CM} $\rightarrow$ Thrust axis used
- Misidentification of the photon
- Contamination of $q\bar{q}e\nu$

$\nu\bar{\nu}\gamma$ and $q\bar{q}\gamma$:

- Uncertainties in E_γ, θ_γ, ϕ_γ

The largest systematic error is $< 10\%$ of the statistical error.

Run # **673115** **Event #** **224** Total Energy : 69.00 GeV



Transverse Imbalance :	.6895		**Longitudinal Imbalance :**	-.7241	
Thrust :	1.0000	**Major :**	.0000	**Minor :**	.0000
Event DAQ Time :	*970813 44506*				

$\nu\bar{\nu}\gamma$ ANALYSIS

CUTS:

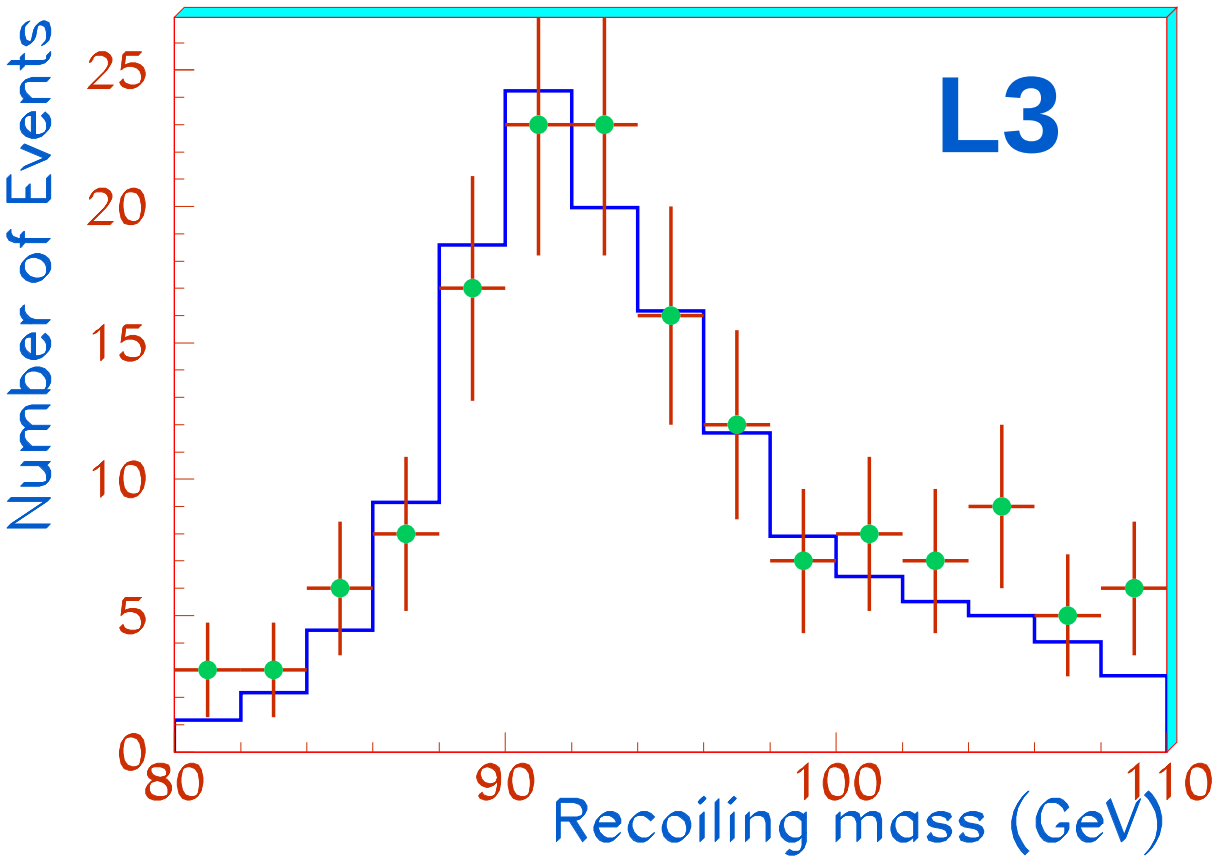
- Number of tracks $= 0$
- Number of clusters ≤ 10
- $\sqrt{E_{\parallel}^2 + E_{\perp}^2} > 0.95 E_{vis}$; $E_{\perp} > 0.2 E_{vis}$
- Electromag. shower profile; $|\cos\theta_{\gamma}| < \cos 16^{\circ}$
- $80 < m_{\mathrm{Z}}^{*} = \sqrt{s - 2E_{\gamma}\sqrt{s}} < 110$ GeV

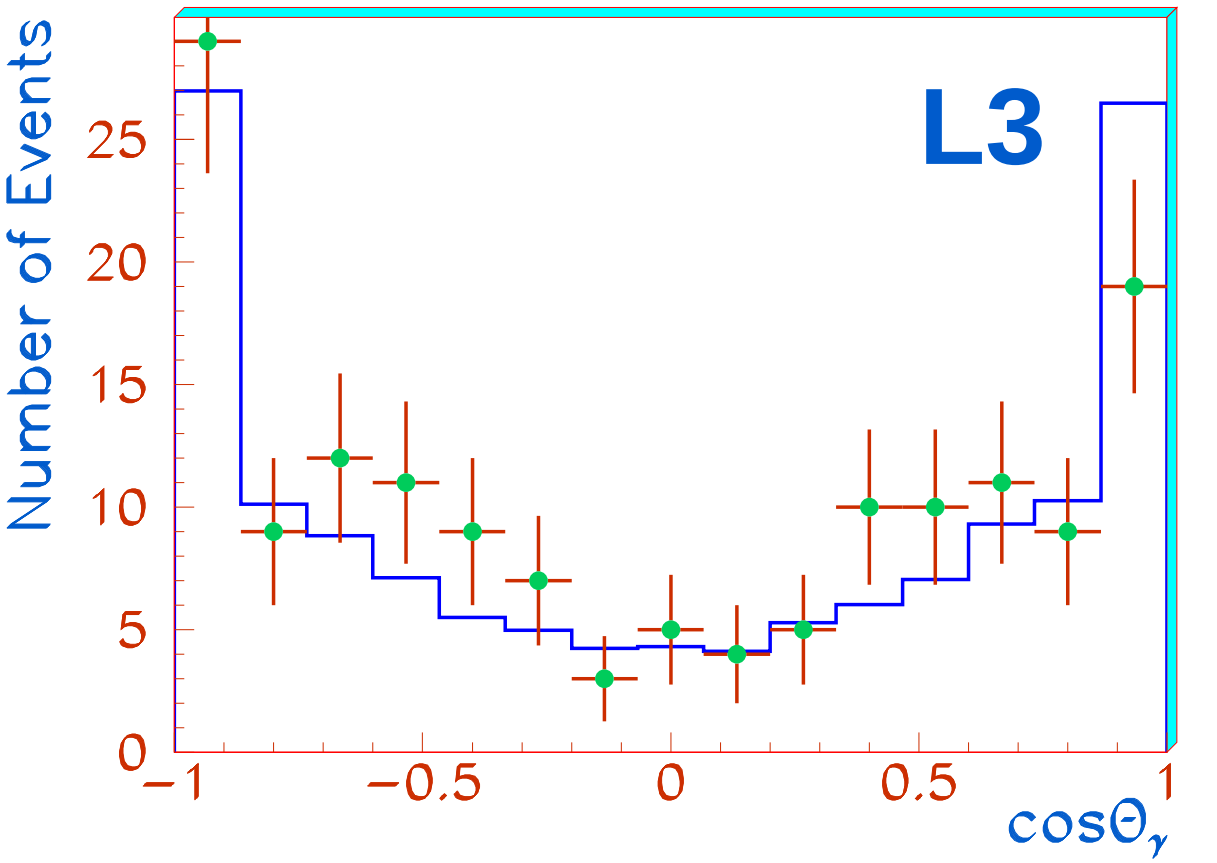
This channel is Background free.

CROSS SECTIONS:

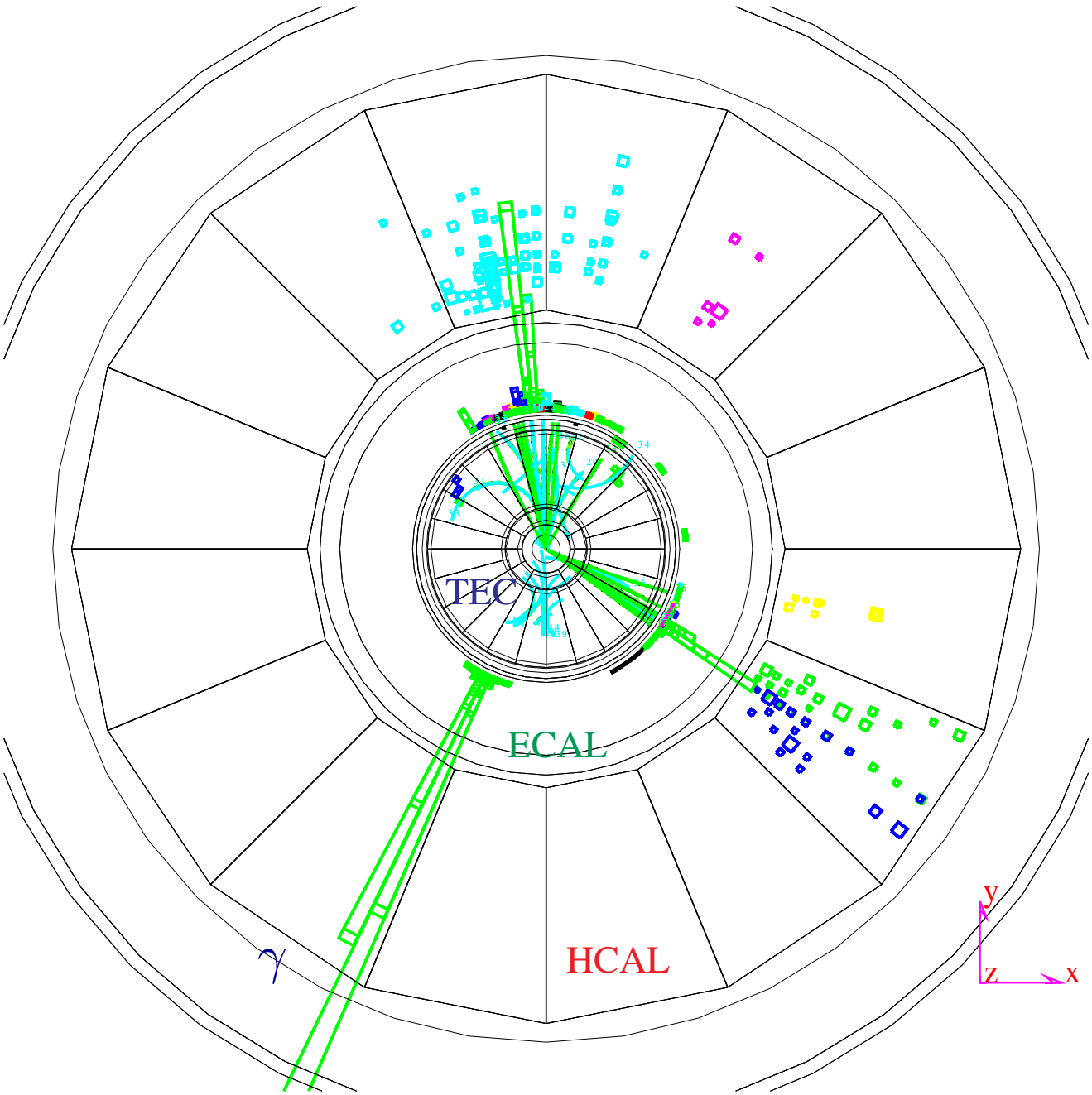
$\sqrt{s}$ (GeV)	♯ Events	Accept. (%)	σ_{SM} (pb)	$\sigma_{measured}$ (pb)
161	29	27.1 ± 0.2	7.50	11 ± 2
170	1	24.4 ± 0.2	7.06	4 ± 3
172	21	24.8 ± 0.2	6.96	10 ± 3
183	102	32.3 ± 0.1	5.45	6 ± 1

$$\int \mathcal{L}dt = \begin{cases} 9.95 \ \mathrm{pb}^{-1} \ at \ \sqrt{s} = 161 \ \mathrm{GeV} \\ 0.97 \ \mathrm{pb}^{-1} \ at \ \sqrt{s} = 170 \ \mathrm{GeV} \\ 8.48 \ \mathrm{pb}^{-1} \ at \ \sqrt{s} = 172 \ \mathrm{GeV} \\ 55.46 \ \mathrm{pb}^{-1} \ at \ \sqrt{s} = 183 \ \mathrm{GeV} \end{cases}$$


L3
Number of Events
25
20
15
10
5
0
80
90
100
110
Recoiling mass (GeV)


L3
Number of Events
25
20
15
10
5
0
−1
−0.5
0
0.5
1
cosΘγ

Run # 671302 Event # 3555 Total Energy : 183.00 GeV



Transverse Imbalance :	.0080		**Longitudinal Imbalance :**	-.0287	
Thrust :	.8696	**Major :**	.3386	**Minor :**	.0379
Event DAQ Time :	*970802 132946*				

$q\bar{q}\gamma$ ANALYSIS

CUTS:

- Number of tracks > 6 (Hadrons in the event)
- Number of clusters ≥ 11 (Hadrons in the event)
- $E_{\perp} < 0.15 E_{vis}$; $E_{\parallel} < 0.2 E_{vis}$ (No Weν)
- Electromag. shower profile, $|\cos\theta_{\gamma}| < \cos 14^{\circ}$; (in ECAL)
- $80 < m_{Z}^{*} = \sqrt{s - 2E_{\gamma}\sqrt{s}} < 110$ GeV (Z resonance)

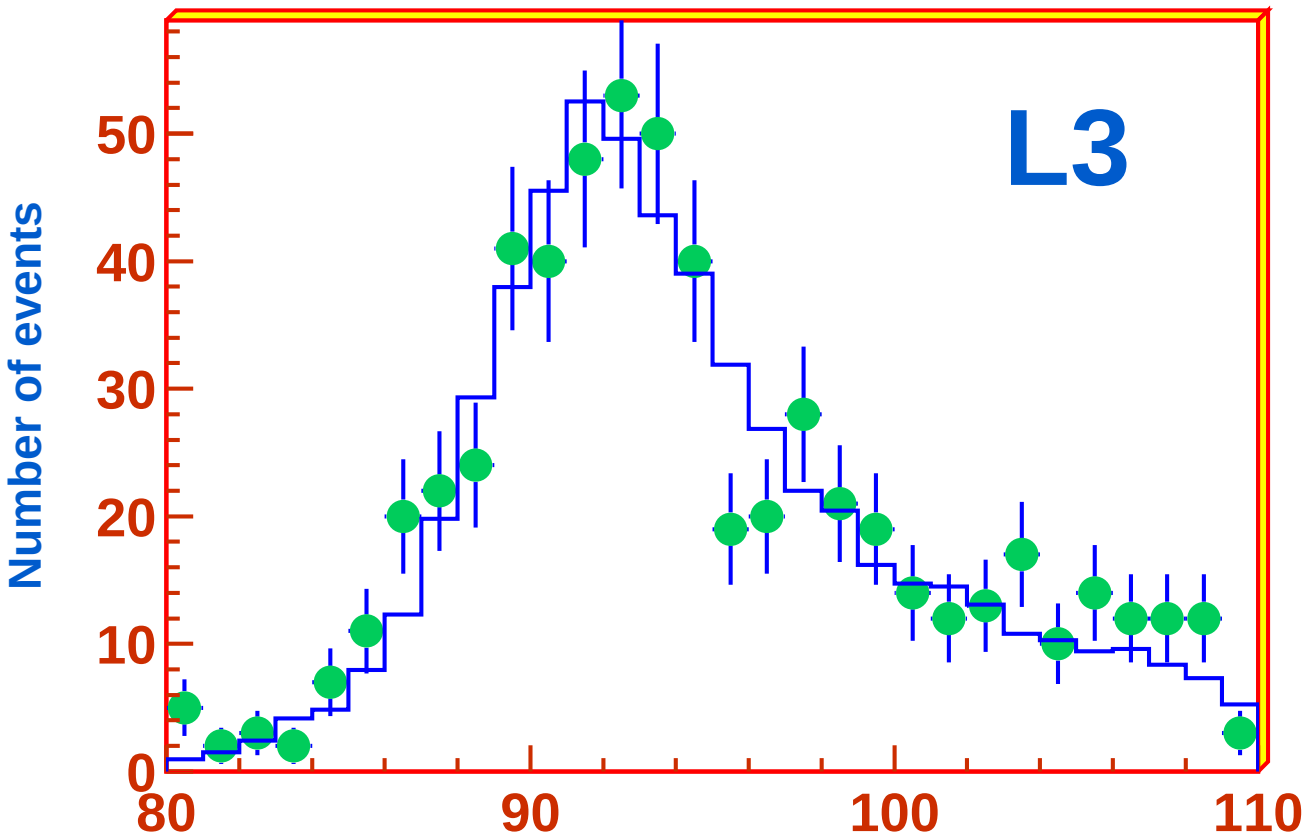
BACKGROUND:

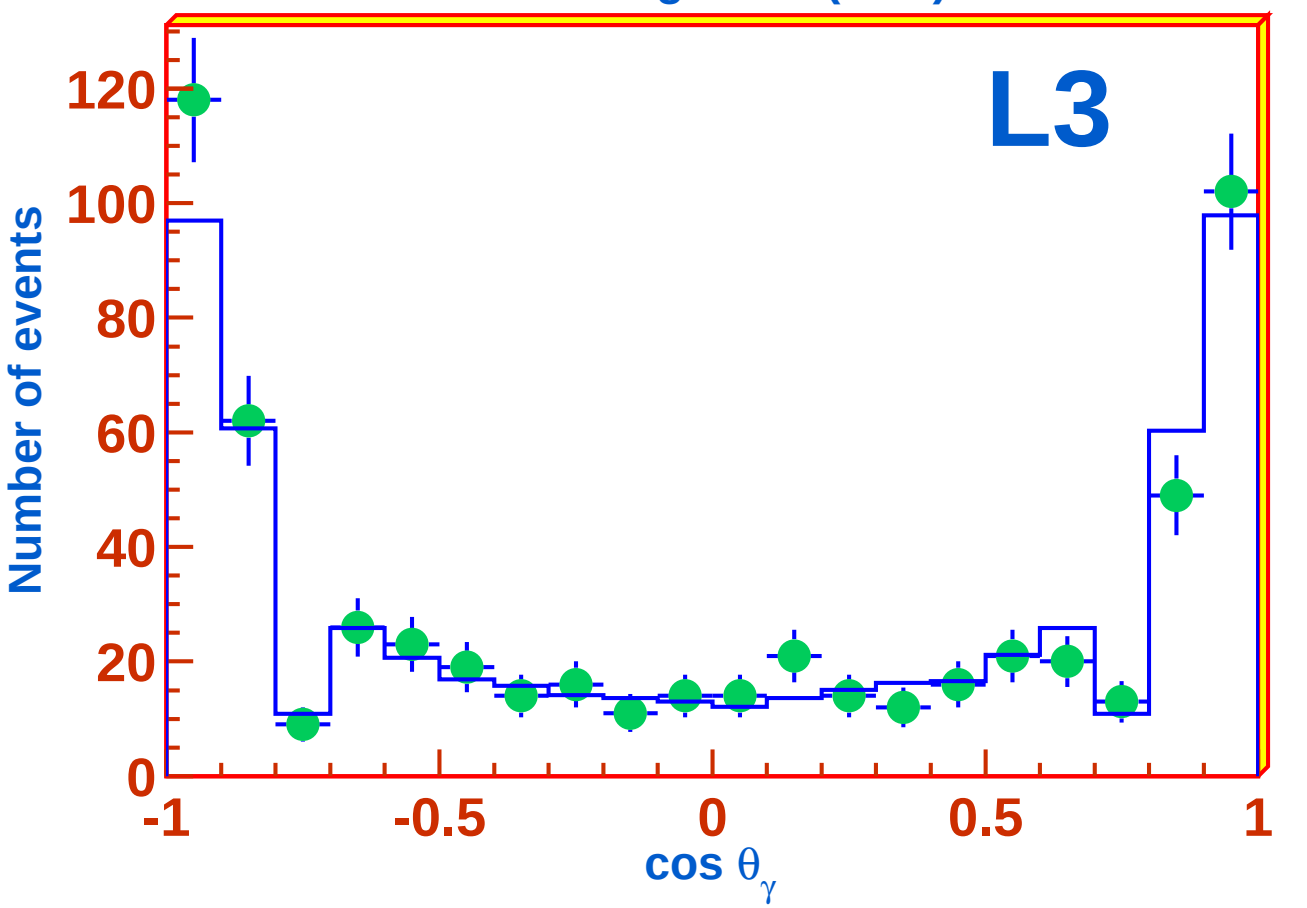
$e^{+}e^{-} \rightarrow q\bar{q}e\nu \longrightarrow 1.5\%$

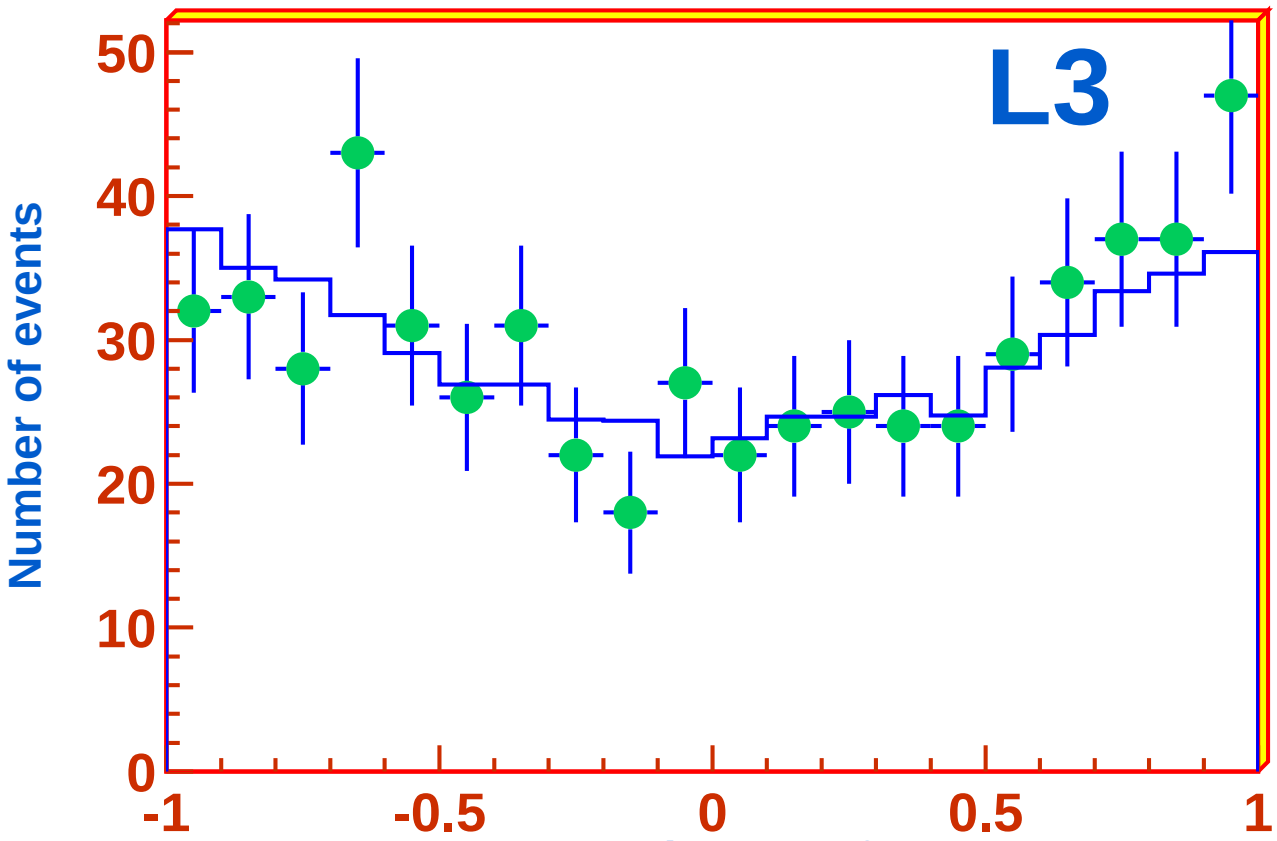
$e^{+}e^{-} \rightarrow q\bar{q}l\nu\ (l = \mu\tau) \longrightarrow$ Negligible

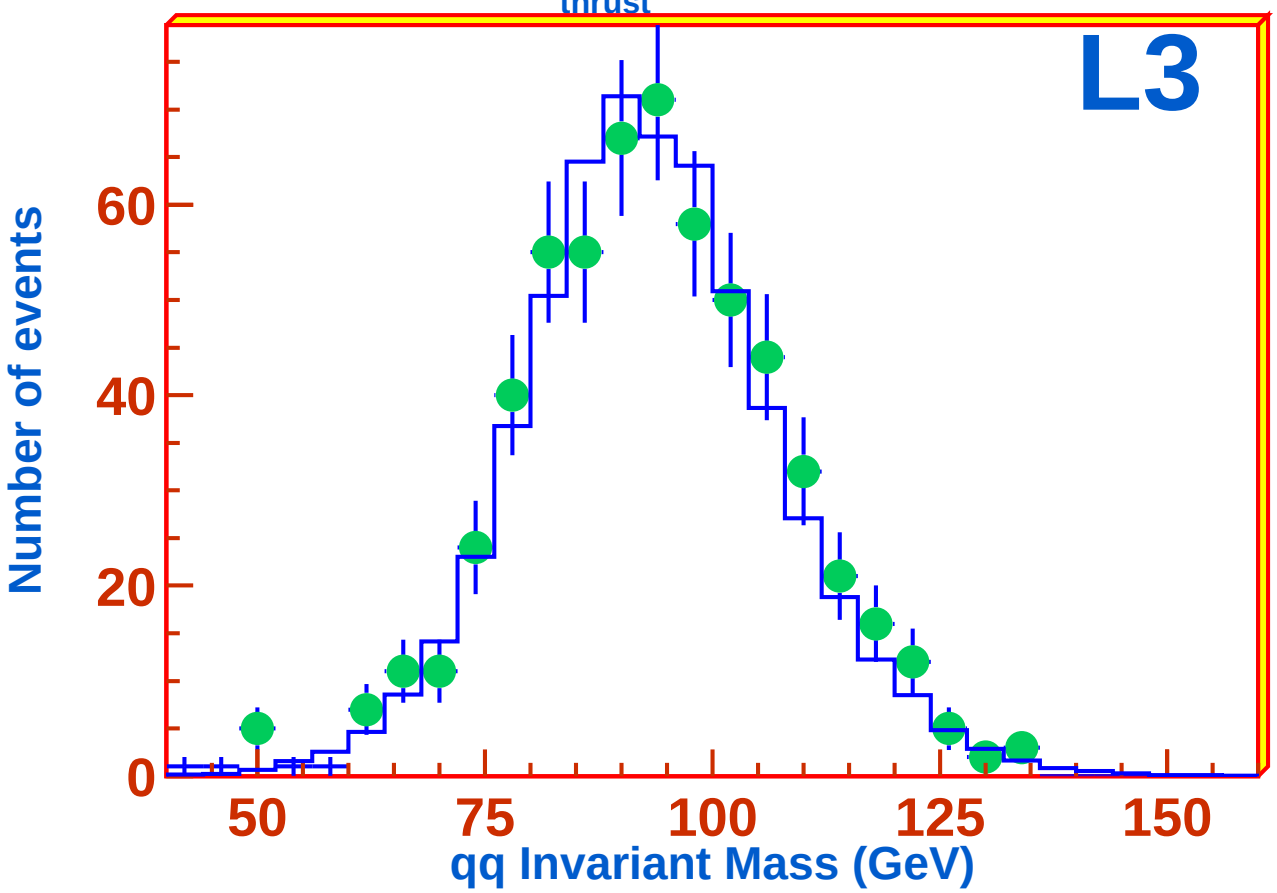
CROSS SECTIONS:

$\sqrt{s}$ (GeV)	♯ Events	Accept. (%)	σ_{SM} (pb)	$\sigma_{measured}$ (pb)
161	117	38.9 ± 0.3	28	30 ± 3
170	7	35.1 ± 0.3	25	21 ± 7
172	59	36.9 ± 0.4	23	19 ± 3
183	410	32.5 ± 0.1	22	23 ± 1


L3
Number of events
0
10
20
30
40
50
80
90
100
110
Recoiling Mass (GeV)


L3
Number of events
0
20
40
60
80
100
120
-1
-0.5
0
0.5
1
cos θγ


L3
Number of events
50
40
30
20
10
0
-1
-0.5
0
0.5
1
cos θthrust in Z rest frame


L3
Number of events
60
40
20
0
50
75
100
125
150
qq Invariant Mass (GeV)

PRELIMINARY RESULTS

New Physics Scales

Parameter	Fitted Value	95% CL Sensitivity
Λ_{1Z}	$\frac{1}{\Lambda^2_{1Z}} = (-0.21 \pm 0.18) \times 10^{-5}$	$\Lambda_{1Z} > 495$ GeV
Λ_{2Z}	$\frac{1}{\Lambda^4_{2Z}} = (+0.16 \pm 0.15) \times 10^{-9}$	$\Lambda_{2Z} > 248$ GeV
Λ_{3Z}	$\frac{1}{\Lambda^2_{3Z}} = (-0.15 \pm 0.22) \times 10^{-5}$	$\Lambda_{3Z} > 465$ GeV
Λ_{4Z}	$\frac{1}{\Lambda^4_{4Z}} = (+0.20 \pm 0.15) \times 10^{-9}$	$\Lambda_{4Z} > 249$ GeV
$\Lambda_{1\gamma}$	$\frac{1}{\Lambda^2_{1\gamma}} = (-0.00 \pm 0.13) \times 10^{-5}$	$\Lambda_{1\gamma} > 673$ GeV
$\Lambda_{2\gamma}$	$\frac{1}{\Lambda^4_{2\gamma}} = (-0.00 \pm 0.12) \times 10^{-9}$	$\Lambda_{2\gamma} > 263$ GeV
$\Lambda_{3\gamma}$	$\frac{1}{\Lambda^2_{3\gamma}} = (-0.16 \pm 0.09) \times 10^{-5}$	$\Lambda_{3\gamma} > 718$ GeV
$\Lambda_{4\gamma}$	$\frac{1}{\Lambda^4_{4\gamma}} = (+0.13 \pm 0.08) \times 10^{-9}$	$\Lambda_{4\gamma} > 290$ GeV

PRELIMINARY RESULTS $q\bar{q}\gamma$ channel	
95% CL Limits (Λ = 500 GeV)	95% CL (Limits Λ = 750 GeV)
$-0.72 < h_{10}^{Z} < 0.34$	$-0.59 < h_{10}^{Z} < 0.28$
$-0.25 < h_{20}^{Z} < 0.56$	$-0.19 < h_{20}^{Z} < 0.43$
$-0.69 < h_{30}^{Z} < 0.44$	$-0.57 < h_{30}^{Z} < 0.36$
$-0.19 < h_{40}^{Z} < 0.64$	$-0.15 < h_{40}^{Z} < 0.48$
$-0.33 < h_{10}^{\gamma} < 0.31$	$-0.27 < h_{10}^{\gamma} < 0.25$
$-0.27 < h_{20}^{\gamma} < 0.28$	$-0.21 < h_{20}^{\gamma} < 0.21$
$-0.46 < h_{30}^{\gamma} < 0.05$	$-0.37 < h_{30}^{\gamma} < 0.04$
$-0.05 < h_{40}^{\gamma} < 0.37$	$-0.04 < h_{40}^{\gamma} < 0.29$

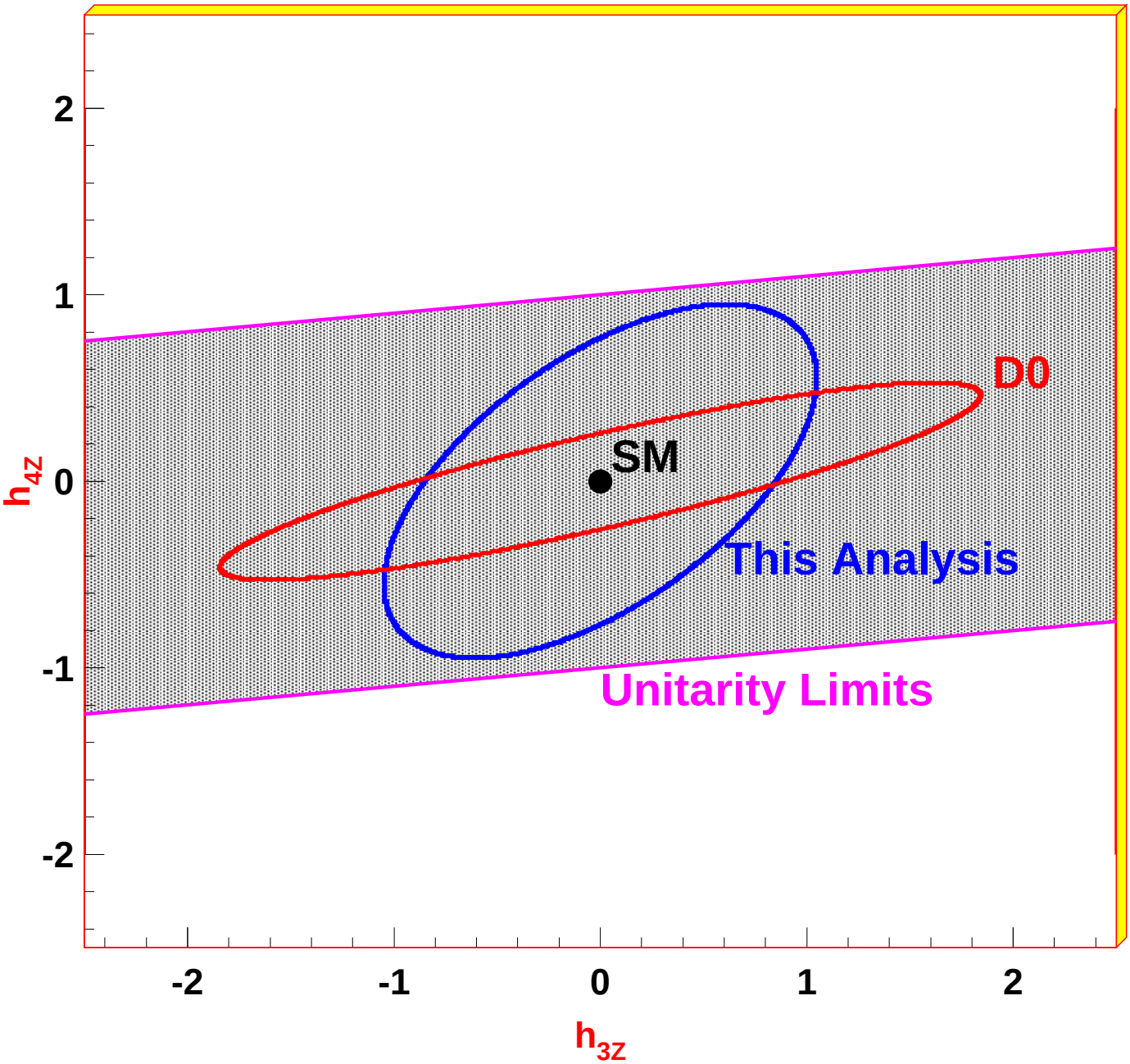
PRELIMINARY RESULTS

$\nu\bar{\nu}\gamma$ channel

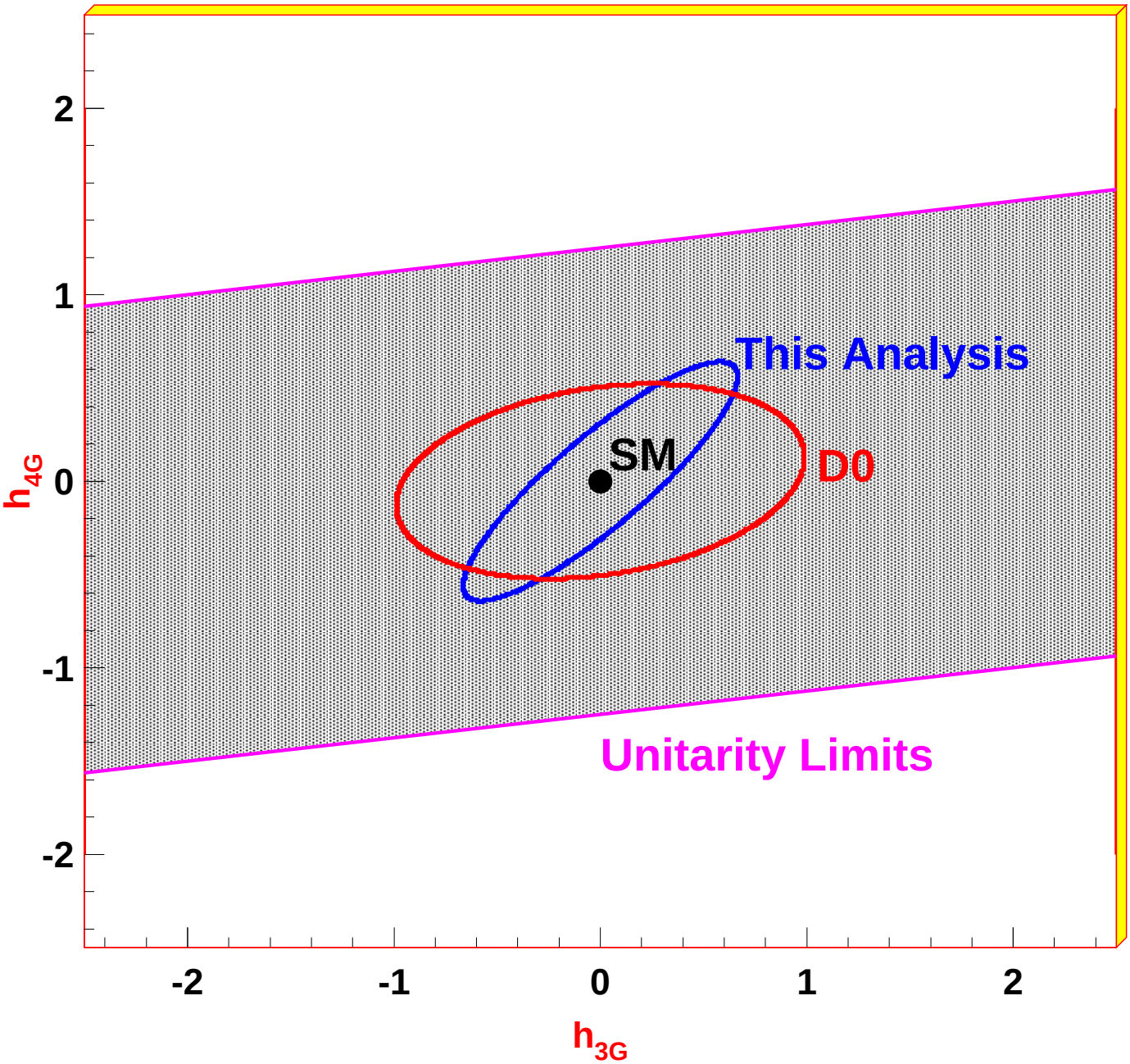
95% CL Limits (Λ = 500 GeV)	95% CL (Limits Λ = 750 GeV)
$-1.28 < h_{10}^{Z} < 1.01$	$-1.04 < h_{10}^{Z} < 0.82$
$-0.71 < h_{20}^{Z} < 1.05$	$-0.54 < h_{20}^{Z} < 0.79$
$-1.25 < h_{30}^{Z} < 1.28$	$-1.02 < h_{30}^{Z} < 1.03$
$-1.06 < h_{40}^{Z} < 1.04$	$-0.80 < h_{40}^{Z} < 0.79$
$-0.78 < h_{10}^{\gamma} < 0.76$	$-0.63 < h_{10}^{\gamma} < 0.62$
$-0.63 < h_{20}^{\gamma} < 0.65$	$-0.48 < h_{20}^{\gamma} < 0.49$
$-0.77 < h_{30}^{\gamma} < 0.78$	$-0.62 < h_{30}^{\gamma} < 0.63$
$-0.65 < h_{40}^{\gamma} < 0.64$	$-0.49 < h_{40}^{\gamma} < 0.48$

PRELIMINARY RESULTS Combined Limits	
95% CL Limits (Λ = 500 GeV)	95% CL (Limits Λ = 750 GeV)
$-0.73 < h_{10}^{Z} < 0.28$	$-0.59 < h_{10}^{Z} < 0.23$
$-0.20 < h_{20}^{Z} < 0.56$	$-0.15 < h_{20}^{Z} < 0.43$
$-0.69 < h_{30}^{Z} < 0.44$	$-0.56 < h_{30}^{Z} < 0.36$
$-0.18 < h_{40}^{Z} < 0.62$	$-0.14 < h_{40}^{Z} < 0.47$
$-0.34 < h_{10}^{\gamma} < 0.31$	$-0.27 < h_{10}^{\gamma} < 0.25$
$-0.27 < h_{20}^{\gamma} < 0.28$	$-0.20 < h_{20}^{\gamma} < 0.21$
$-0.45 < h_{30}^{\gamma} < 0.04$	$-0.37 < h_{30}^{\gamma} < 0.04$
$-0.05 < h_{40}^{\gamma} < 0.37$	$-0.04 < h_{40}^{\gamma} < 0.28$

95% C. L. Contour for h_4^Z.vs.h_3^Z ($\Lambda = 500$ GeV)



95% C. L. Contour for h_4^γ.vs.h_3^γ ($\Lambda = 500$ GeV)



CONCLUSIONS

- No evidence of Anomalous Couplings has been found
- These are the first limits obtained at LEP2 and the first limits which make use of hadronic decays of the Z boson
- We exclude new physics in the range 250-750 GeV, depending on the type of coupling.
- These limits are comparable in sensitivity to the best present limits.
- Since there is no need of energy-dependent form factor for e^+e^- colliders, our new physics scale limits can be considered as independent of the coupling behaviour at $E > \sqrt{s}$.