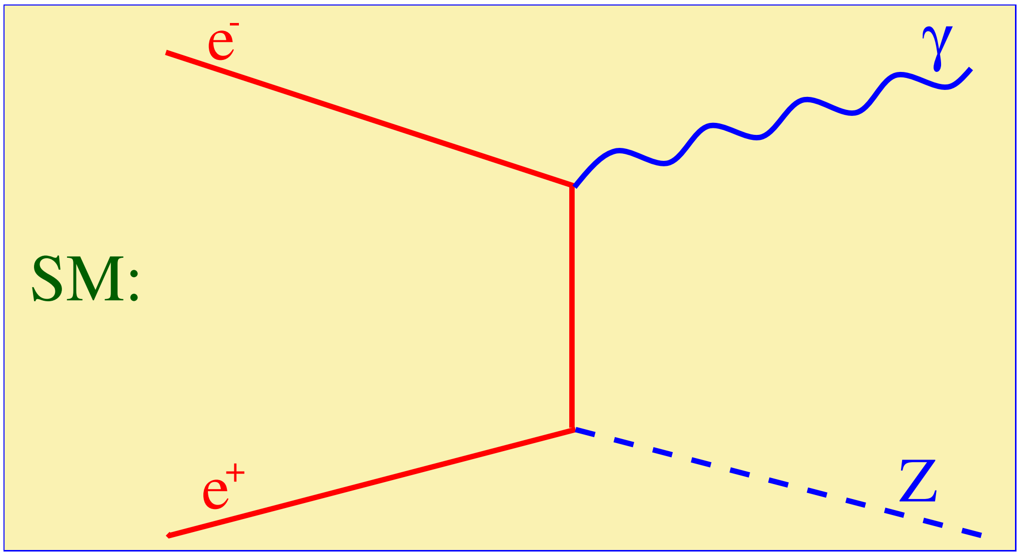
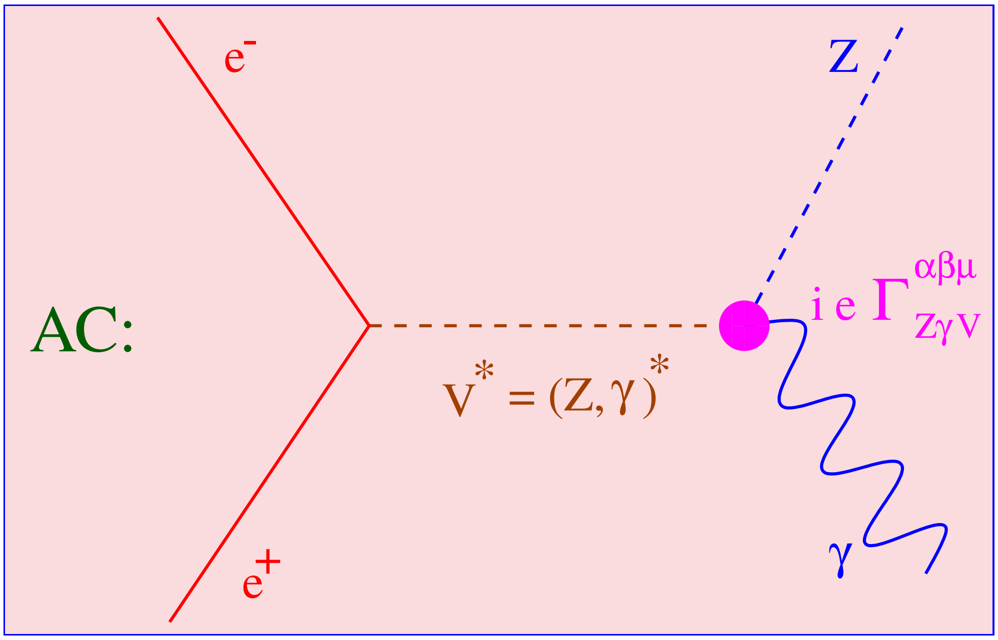
OUTLINE

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

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





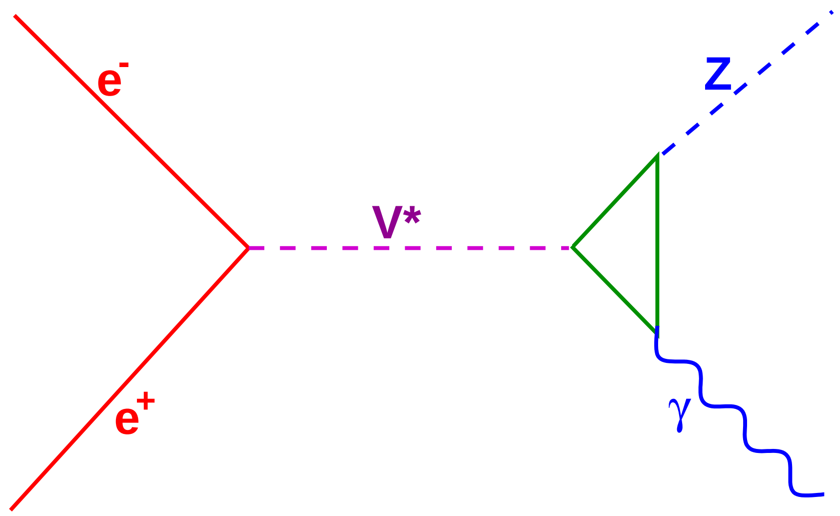
Anomalous couplings are Zero at tree level.

PHYSICAL INTERPRETATION OF THE ANOMALOUS COUPLINGS:

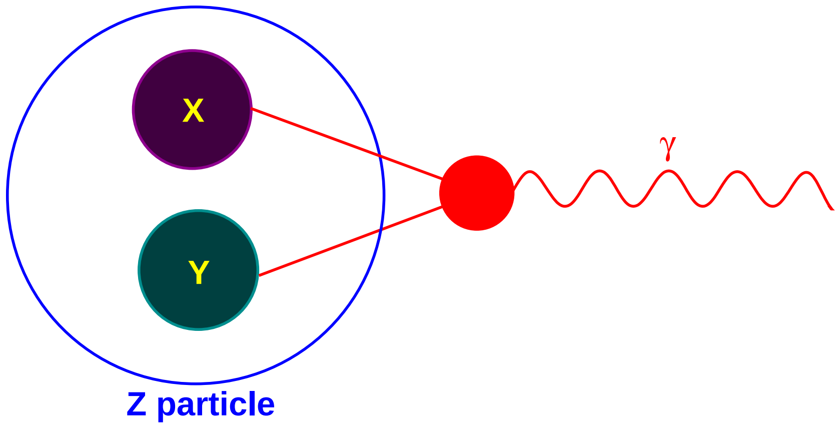
SM Value	$h_1^V, h_2^V = 0$	
at 1-loop	$h_3^V, h_4^V \neq 0$	SMALL:($h_3^Z \simeq 2.4 \times 10^{-4}$)

could be modified by

Extra-particles in the loop.



OR



Compositeness.

8 ANOMALOUS COUPLINGS

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

$$V = Z, \gamma$$

$$\boxed{\begin{array}{lcl} h_{1,2}^V & \longrightarrow & \text{CP Violating} \\ h_{3,4}^V & \longrightarrow & \text{CP Conserving} \end{array}}$$

Deviations suppresed at threshold: $\Delta = (\frac{p_Z}{E_Z})^n$

- 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

☞ Hadronic activity ($q\bar{q}\gamma$ events)

☞ Missing energy ($\nu\bar{\nu}\gamma$ events)

⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆

EXPERIMENTAL EFFECTS OF ANOMALOUS COUPLINGS

☞ Enhancement of Zγ events mostly at large angles.

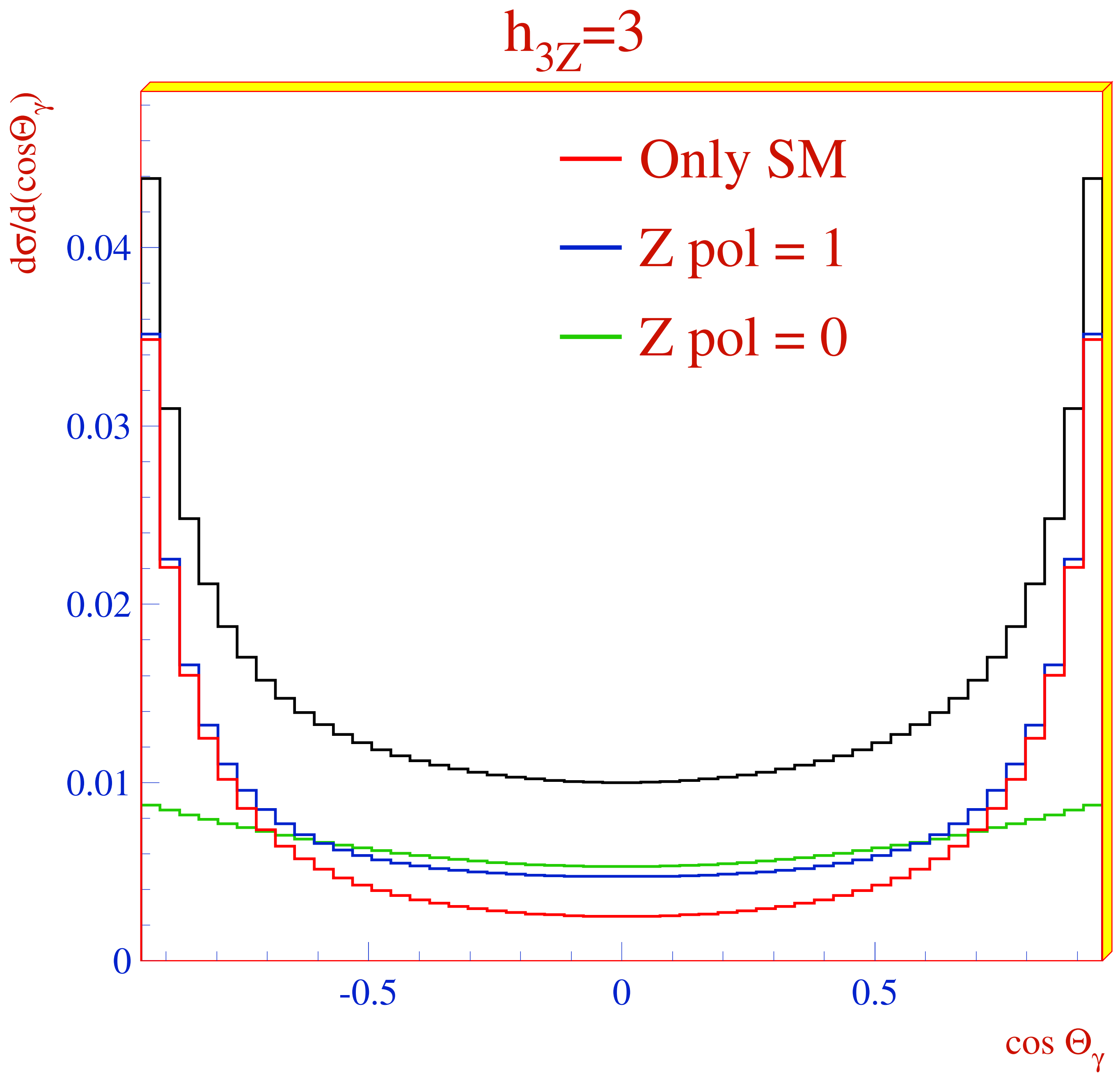
☞ Enhancement of longitudinal Z's ($\lambda_3 = 0$).

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

$$e^+e^- \rightarrow Z\gamma$$

$$\sqrt{s} = 172 \text{ GeV}$$

$$\frac{d\sigma}{d\cos\theta_\gamma} DISTRIBUTION$$



$$e^+e^- \rightarrow Z\gamma$$

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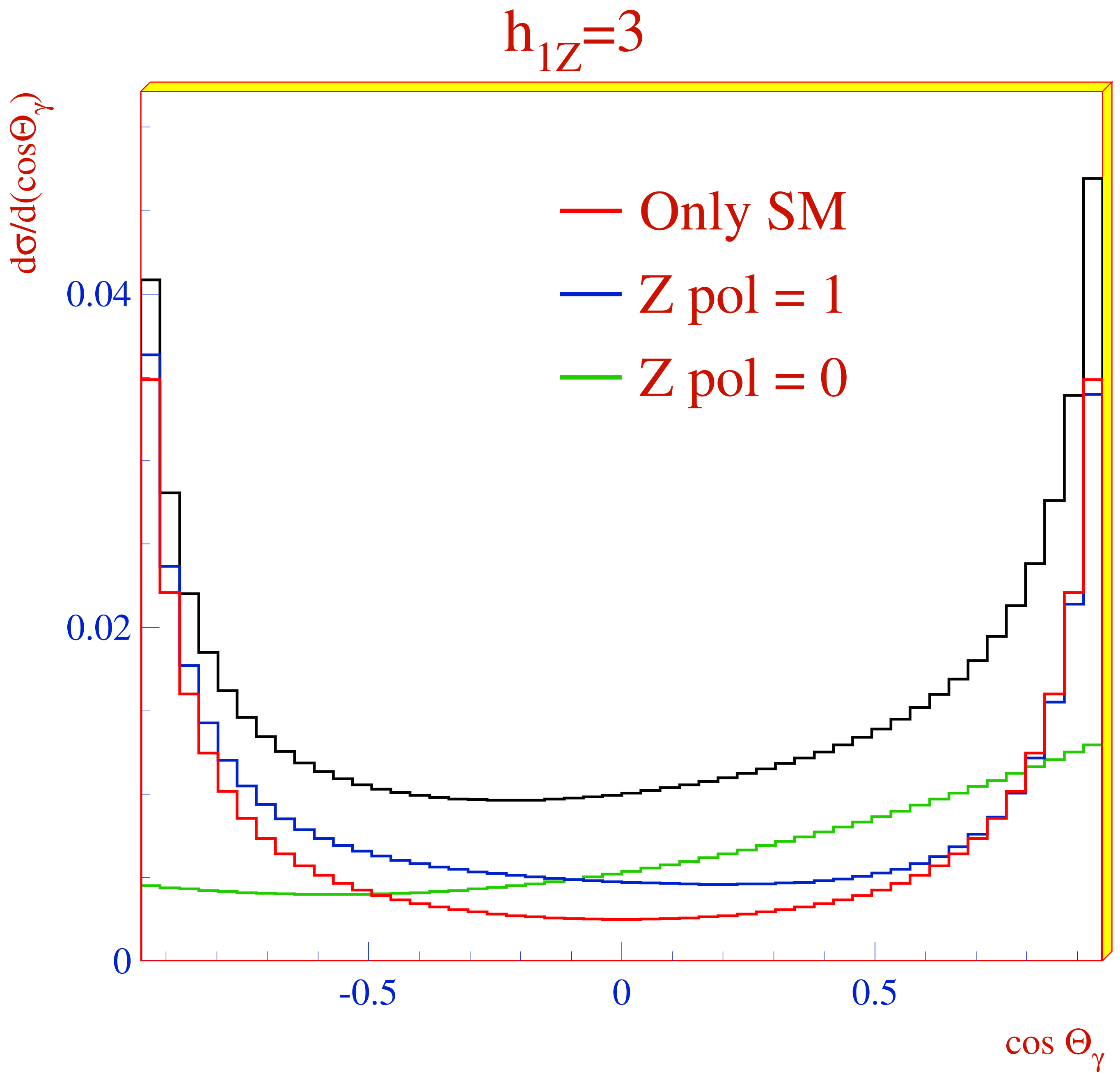


Previous Limits

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

Experiment	h_{30}^{Z}	h_{40}^{Z}
L3 (LEP1)	$\lesssim 0.7$	$\lesssim 2$
CDF	< 3	< 0.7
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

ANALYSIS PROCEDURE

Compute the amplitude $\mathcal{M}$ for the process $\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}}\gamma$ assuming Standard Model $\oplus$ Anomalous Couplings and taking into account

- Spin Correlations
- Effective Z couplings
- Non-resonant contributions
- t-channel W exchange in $\nu_e\bar{\nu}_e\gamma$
- Checked with CDF and D0 $\mathrm{f\bar{f}}\gamma$ program.

  Perfect agreement is observed

using the variables

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

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

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

$$\frac{|(\mathcal{M}_{SM}+\mathcal{M}_{AC})(E_\gamma,\theta_\gamma,\phi_\gamma,\theta_f^{CM},\phi_f^{CM};h_i^V)|^2}{|\mathcal{M}_{SM}(E_\gamma,\theta_\gamma,\phi_\gamma,\theta_f^{CM},\phi_f^{CM};h_i^V)|^2}$$

- For $\mathrm{e^+e^-} \rightarrow \nu\bar{\nu}\gamma$ the neutrino angular variables are integrated out.

- We consider that additional photon radiation effects are small or cancel in the ratio of amplitudes.

- For $\mathrm{e^+e^-} \rightarrow \mathrm{q\bar{q}}\gamma$ the angles θ_q^{CM} and ϕ_q^{CM} are substituted by the thrust axis angles and the amplitude is symmetrized under the interchange $\mathrm{q} \leftrightarrow \mathrm{\bar{q}}$.

- 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:

$$\mathcal{L}(h_i^V) = \frac{e^{-N_t(h_i^V)} N_t^{N_o}(h_i^V)}{N_o!} \times$$

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

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 $\rightarrow$ ($\Delta < 1\%$) Not in $\nu\bar{\nu}\gamma$
- Uncertainties in $\theta_{q\bar{q}}^{CM}$, $\phi_{q\bar{q}}^{CM}$ $\rightarrow$ Thrust axis used ($\Delta \lesssim 1\%$)
- Misidentification of the photon ($\Delta \lesssim 1\%$)
- Contamination of $q\bar{q}e\nu$ ($\Delta \lesssim 1\%$)

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

- Uncertainties in E_γ, θ_γ, ϕ_γ $\rightarrow$ ($\Delta < 1\%$)

$q\bar{q}\gamma$ ANALYSIS

CUTS:

- Number of tracks > 6 (Hadrons in the event)
- Number of clusters ≥ 11 (Hadrons in the event)
- $E_{\parallel} < 0.2 E_{vis}$; $E_{\perp} < 0.15 E_{vis}$ (No Weν)
- Shower with EM profile, $|\cos\theta_{\gamma}| < \cos 14°$ (in BGO)
- $80 < m^{*}_{\mathrm{Z}} = \sqrt{s - 2E_{\gamma}\sqrt{s}} < 110$ GeV (Z resonance)

CROSS SECTIONS:

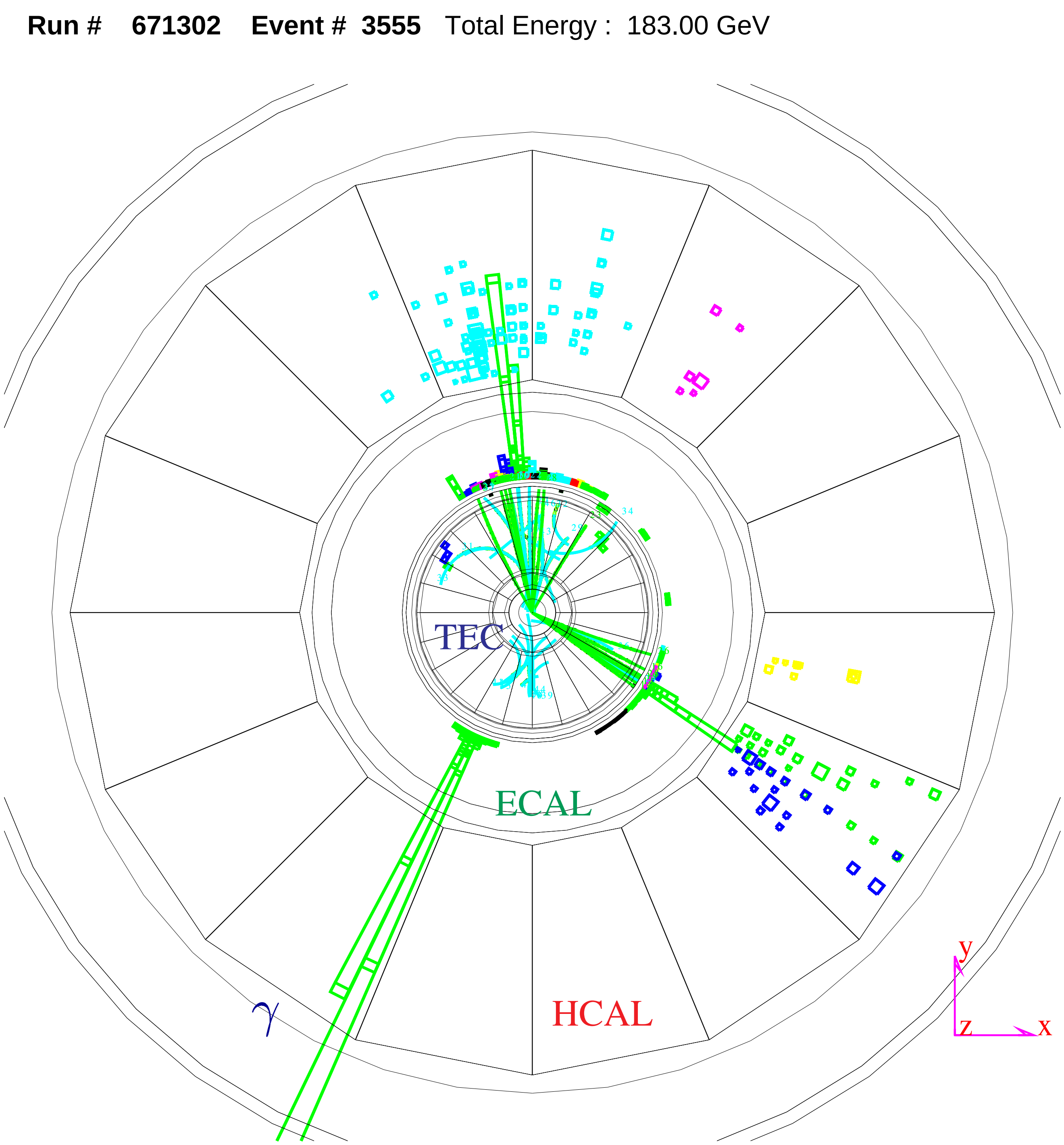
$\sqrt{s}$ (GeV)	$\sharp$ Events	Accept. (%)	σ_{gen} (pb)	$\sigma_{measured}$ (pb)
161	117	20.1 ± 0.3	54	58 ± 06
170	7	19.0 ± 0.3	46	37 ± 13
172	59	19.2 ± 0.3	45	36 ± 06
183	411	18.1 ± 0.1	39	40 ± 02

BACKGROUND:

$\mathrm{e^+e^-} \rightarrow \mathrm{WW} \rightarrow \mathrm{q\bar{q}}l\nu\ ,\ l = \mu, \tau \implies$ Negligible (0.019 %)

$\mathrm{e^+e^-} \rightarrow \mathrm{WW} \rightarrow \mathrm{q\bar{q}}e\nu \implies$ 1.5 %

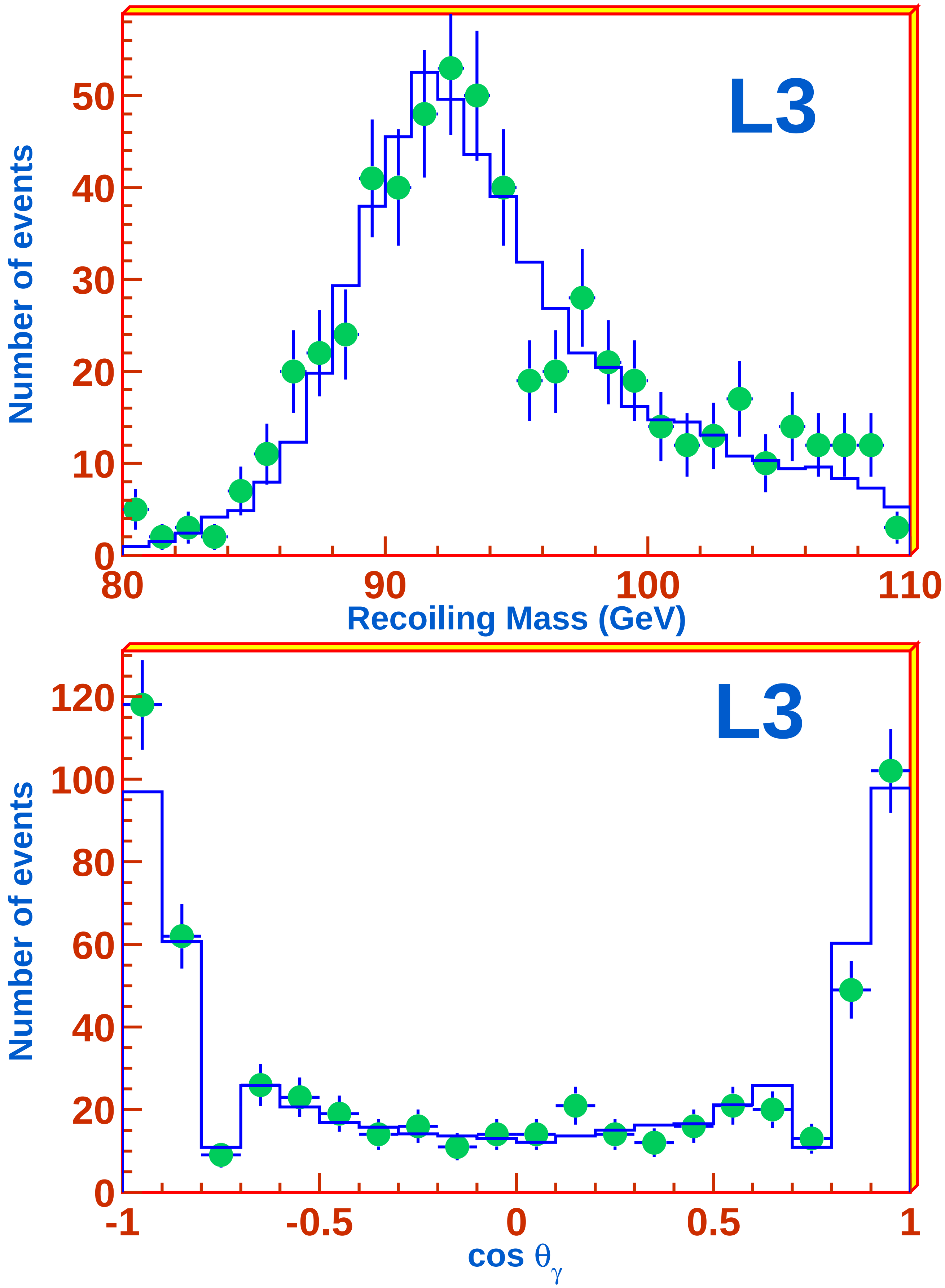
$$\int \mathcal{L}dt = \begin{cases} 9.95 & \mathrm{pb}^{-1} \quad at \quad \sqrt{s} = 161 \mathrm{~GeV} \\ 0.97 & \mathrm{pb}^{-1} \quad at \quad \sqrt{s} = 170 \mathrm{~GeV} \\ 8.48 & \mathrm{pb}^{-1} \quad at \quad \sqrt{s} = 172 \mathrm{~GeV} \\ 55.46 & \mathrm{pb}^{-1} \quad at \quad \sqrt{s} =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

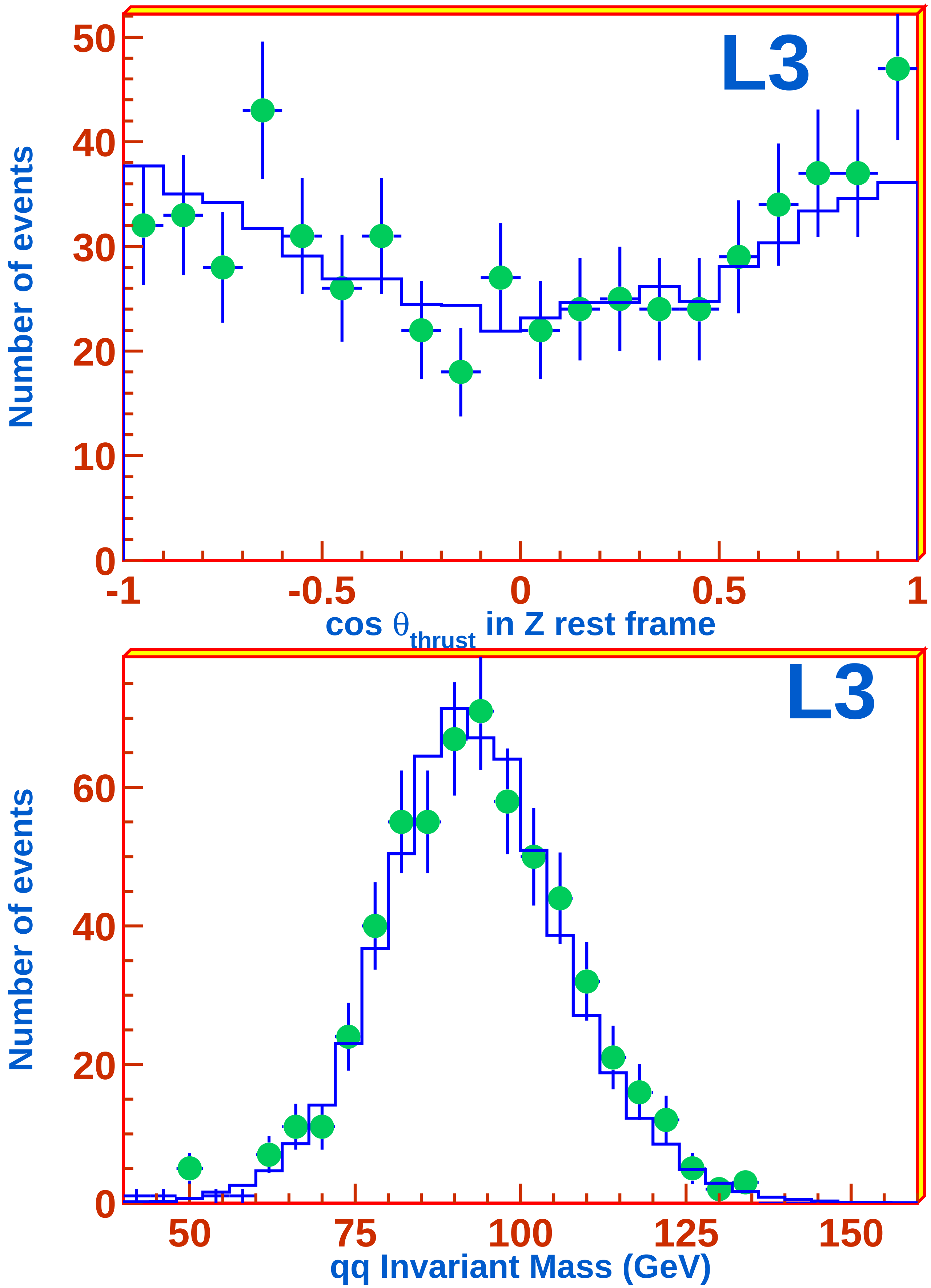


Transverse Imbalance :	.0080	**Longitudinal Imbalance :**	-.0287

Thrust :	.8696	**Major :**	.3386	**Minor :**	.0379

Event DAQ Time :	*970802 132946*


L3
Number of events
50
40
30
20
10
0
80
90
100
110
Recoiling Mass (GeV)
L3
Number of events
120
100
80
60
40
20
0
-1
-0.5
0
0.5
1
cos θ_γ


L3
Number of events
0
10
20
30
40
50
-1
-0.5
0
0.5
1
cos θ_{thrust} in Z rest frame
L3
Number of events
0
20
40
60
50
75
100
125
150
qq Invariant Mass (GeV)

PRELIMINARY RESULTS

$q\bar{q}\gamma$ channel

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

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

CUTS:

- Number of tracks $= 0$
- Number of clusters ≤ 10
- Scintillator counters signals in time
- $\sqrt{E_{\parallel}^2 + E_{\perp}^2} > 0.95 E_{vis}$
- $E_{\perp} > 0.2 E_{vis}$
- Shower with EM profile; $|\cos\theta_\gamma| < \cos 16°$
- $80 < m^*_{\mathrm{Z}} = \sqrt{s - 2E_\gamma\sqrt{s}} < 110$ GeV

CROSS SECTIONS:

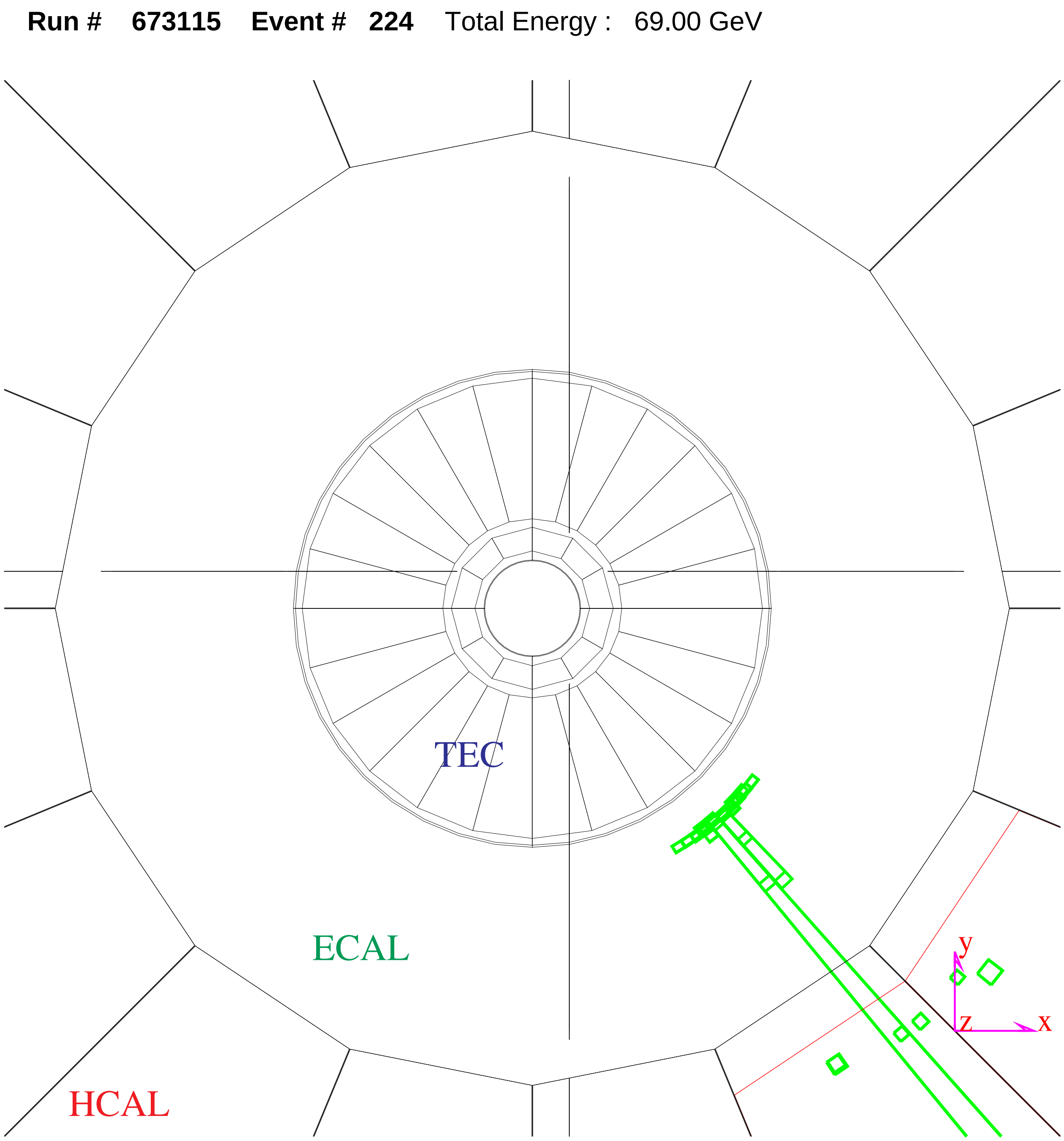
$\sqrt{s}$ (GeV)	♯ Events	Accept. (%)	σ_{gen} (pb)	$\sigma_{measured}$ (pb)
161	29	3.27 ± 0.08	72	89 ± 19
170	1	3.02 ± 0.08	66	34 ± 25
172	21	3.01 ± 0.08	67	82 ± 20
183	102	2.93 ± 0.04	60	63 ± 06

BACKGROUND:

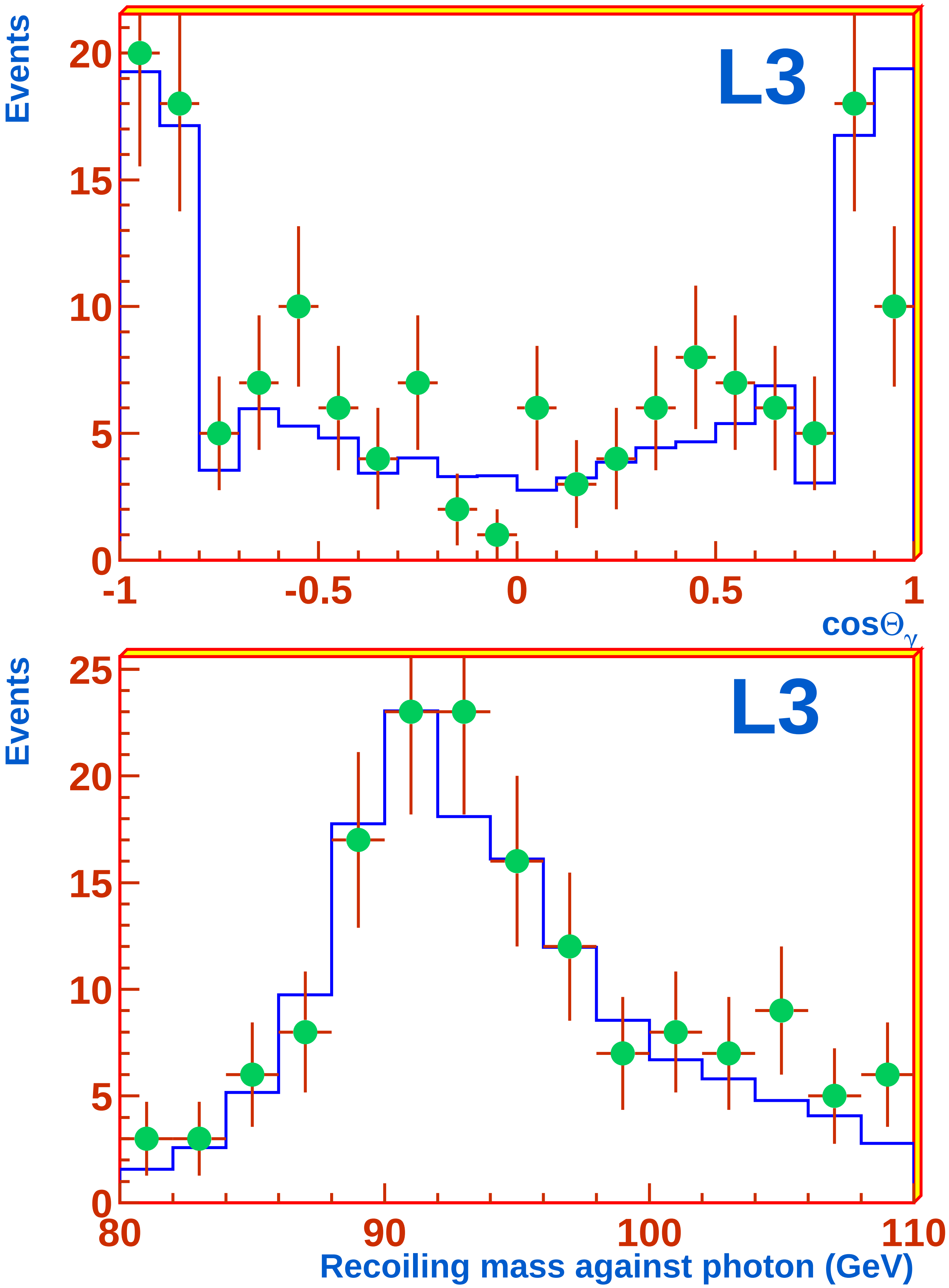
$\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}\gamma(\gamma)$ $\Longrightarrow$ Negligible

$\mathrm{e^+e^-} \rightarrow \mathrm{WW} \rightarrow e\nu_e l\nu_l$ $\Longrightarrow$ Negligible

We consider this channel as Background Free



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


Events
20
15
10
5
0
-1
-0.5
0
0.5
1
L3
cosΘγ
Events
25
20
15
10
5
0
80
90
100
110
L3
Recoiling mass against photon (GeV)

PRELIMINARY RESULTS

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

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

PRELIMINARY RESULTS

Combined Limits

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

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

We prefer to fit the following parameters:

$$\boxed{\begin{aligned} \frac{\sqrt{\alpha}h_i^V}{m_Z^2} &\equiv \frac{1}{\Lambda_{iV}^2}; i=1,3 \\ \frac{\sqrt{\alpha}h_i^V}{m_Z^4} &\equiv \frac{1}{\Lambda_{iV}^4}; i=2,4 \end{aligned}}$$

PRELIMINARY RESULTS

Compositeness Scales

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

Conclusions

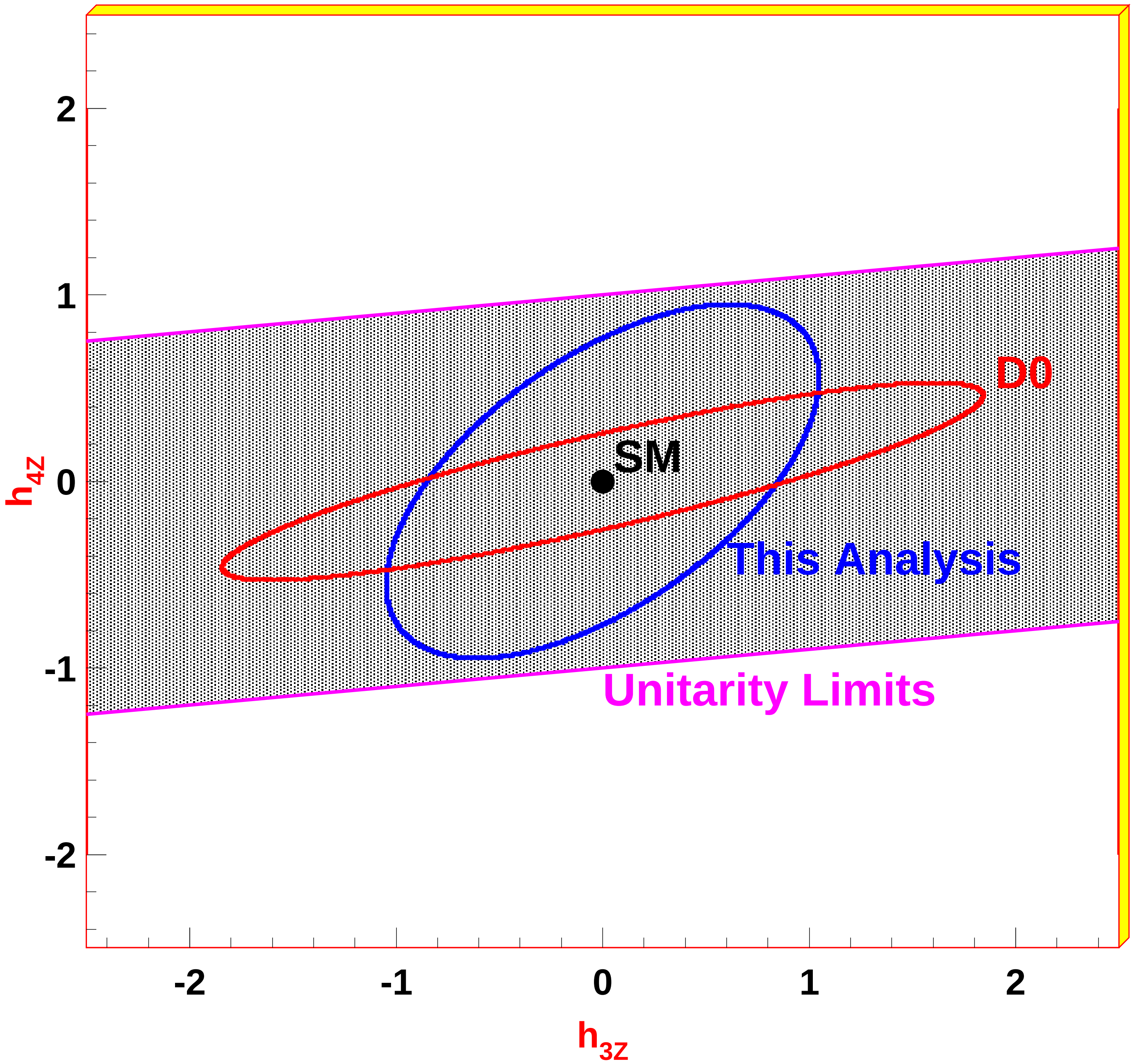
▶ The channels $e^+e^- \to q\bar{q}\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma$ have been used to set limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.

▶ The sample used is the L3 data taken at $160\mathrm{GeV} < \sqrt{s} < 183\mathrm{GeV}$, which corresponds to a total luminosity of 75 pb^{-1}.

▶ There are no indications of anomalous couplings. All the values obtained are compatible with zero.

▶ These limits are competitive with the best published limits and suppose a large improvement respect to the limits set by L3 previously.

95% C. L. Contour for h_4^Z.vs.h_3^Z



95% C. L. Contour for h_4^γ.vs.h_3^γ