Measurement of the reaction
$e^+e^- \to \nu\bar{\nu}\gamma$
at LEP

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The L3 Collaboration

- Introduction
- Event Selection
- Determination of N_ν
- New Physics Searches
  - neutralinos
  - Limits on ν_τ magnetic moment
  - ZZγ coupling
- Conclusion and Prospects

Lake Louise Winter Institute
19-25 February 1995

Methods to determine N_ν

Fermions:

1	2	3	...
ν_e	ν_μ	ν_τ	...
e	μ	τ	...
u	c	t	...
d	s	b	...

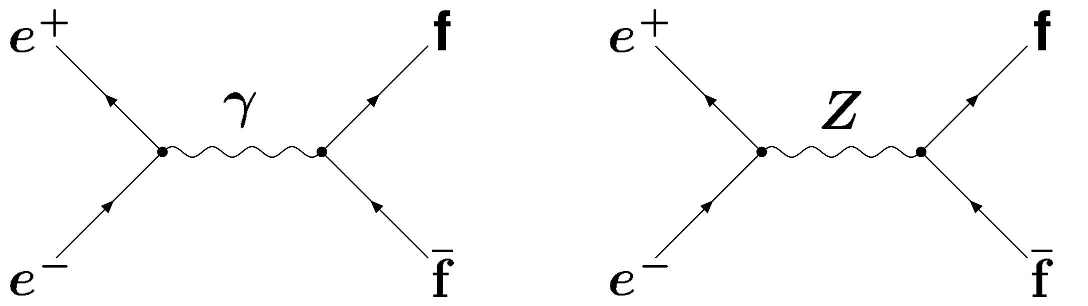
Before LEP and SLC:

$p\bar{p}$ **colliders:**	$N_\nu <$ **4.8 at 90% C.L.**
Supernova SN1987A:	$N_\nu <$ **4.8 at 95% C.L.**
$\mathrm{e^+e^-} \longrightarrow \nu\bar{\nu}\gamma$ **"Single Photon":**	$N_\nu <$ **3.9 at 90% C.L.**
Relative abundance of ^{4}He:	$N_\nu <$ **3.6 at 95% C.L.**

At LEP and SLC:

- **Z Lineshape ("Indirect" measurement)**
- **Single Photon ("Direct" measurement)**

Lowest order Feynam diagrams for $\mathrm{f\bar{f}} \neq \mathrm{e^+e^-}$



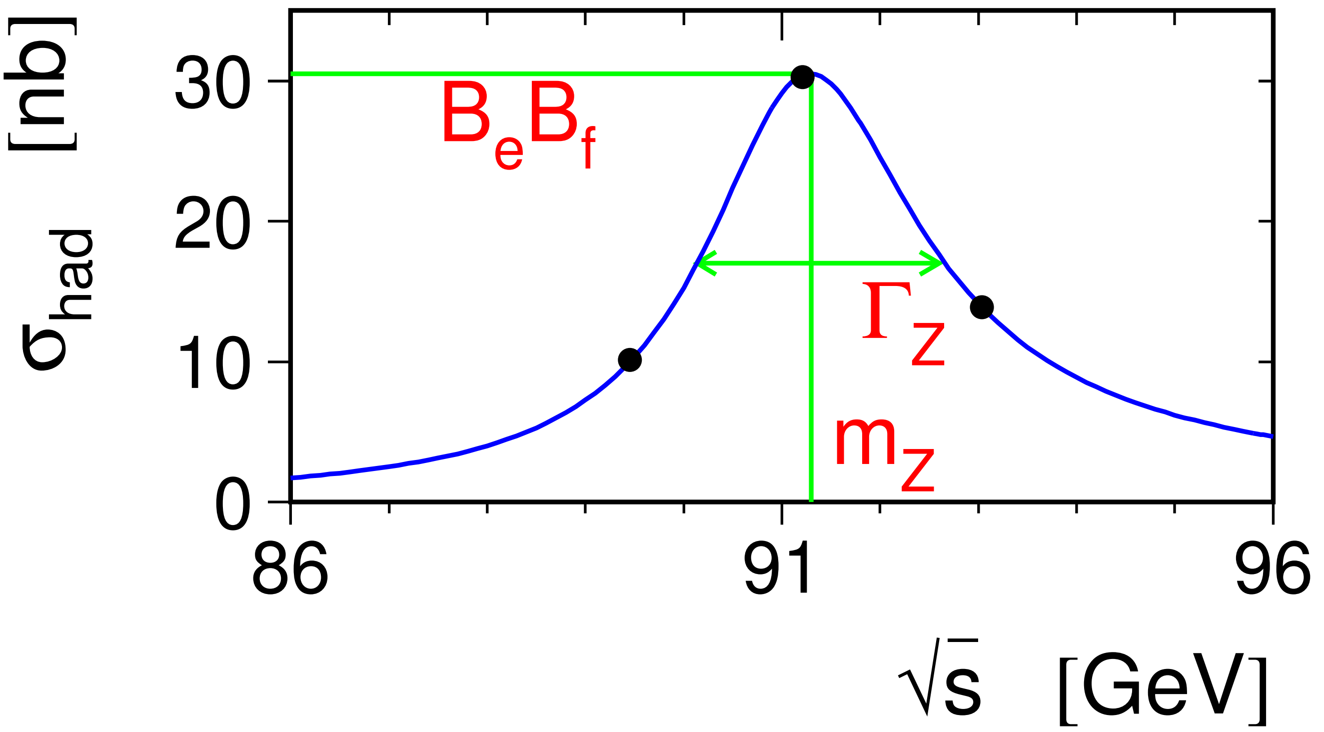
$$\sigma^0(s) = \sigma^0_\gamma + \sigma^0_\mathrm{Z} + \sigma^0_{\gamma\mathrm{Z}}$$

$$\sigma^0_\gamma = \frac{4\pi\alpha^2}{3s} Q_\mathrm{e}^2 Q_\mathrm{f}^2 N_\mathrm{f}^C$$

$$\sigma^0_\mathrm{Z} = \frac{12\pi}{m_\mathrm{Z}^2} \frac{\Gamma_{ee}}{\Gamma_\mathrm{Z}} \frac{\Gamma_\mathrm{ff}}{\Gamma_\mathrm{Z}} \frac{s\Gamma_\mathrm{Z}^2}{(s-m_\mathrm{Z}^2)^2 + s^2\Gamma_\mathrm{Z}^2/m_\mathrm{Z}^2}$$

$\sigma^0_{\gamma\mathrm{Z}} =$ **Interference term, small for** $s \simeq m_\mathrm{Z}^2$

Excitation Curve of the Z Boson



Properties of the Z boson:

Peak position: m_Z
Peak width: Γ_Z
Peak height: $\frac{12\pi}{m_Z^2}\Gamma_{ee}\Gamma_{\mathrm{ff}}/\Gamma_Z^2 = \frac{12\pi}{m_Z^2}B_e B_f$

$$\Gamma_{\mathrm{inv}} = \Gamma_Z - \Gamma_{\mathrm{had}} - 3\Gamma_{\mathrm{lep}}$$

$$N_\nu = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_l}\left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{\mathrm{SM}}$$

L3 measurement, 1990-1993 (Glasgow, 1994):

$$\boxed{N_\nu = 2.98 \pm 0.03}$$

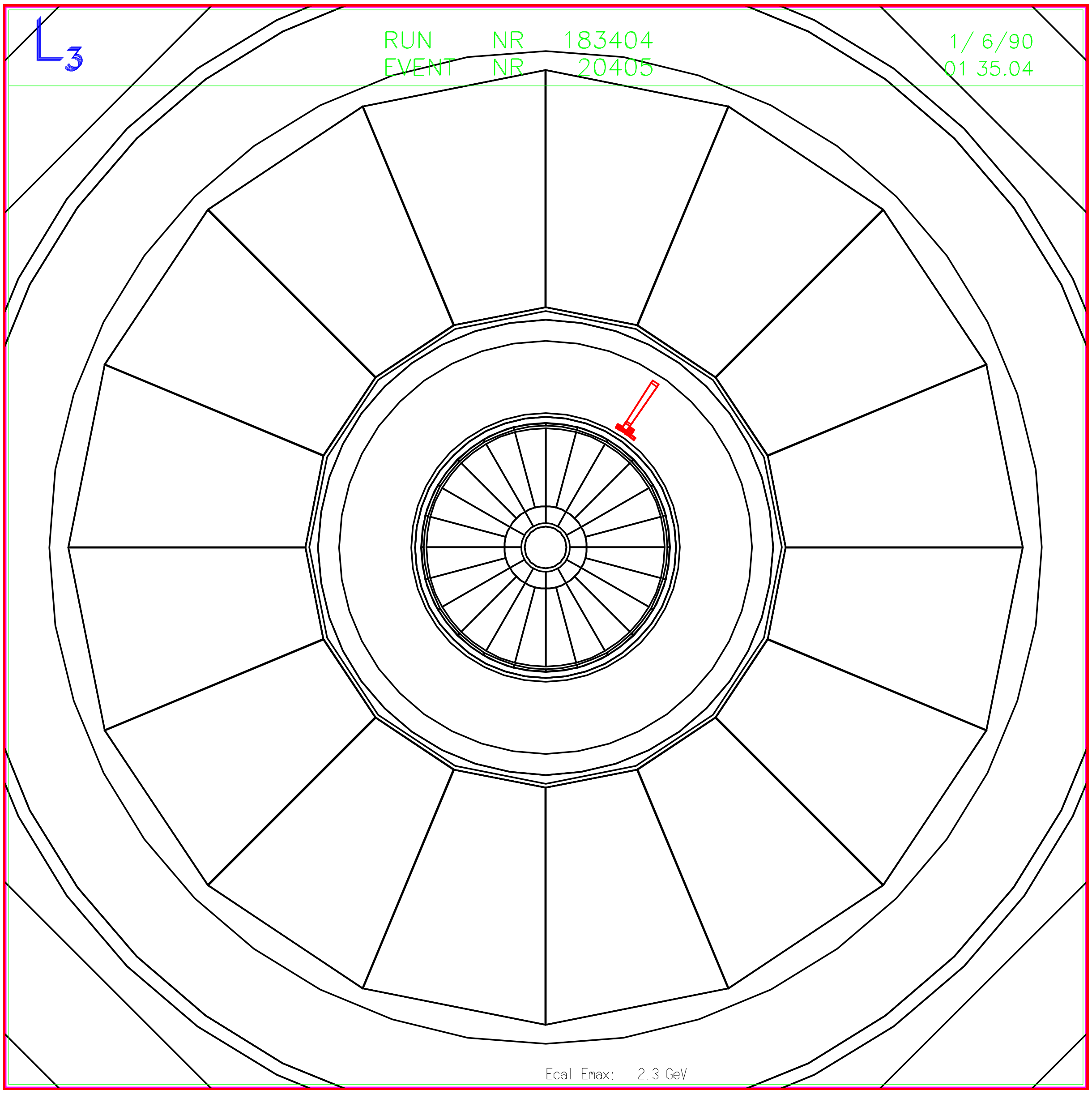
The "Direct" method

Lineshape: **Z decays not accounted for in hadronic or leptonic selection are counted as "invisible"**

Measurement of

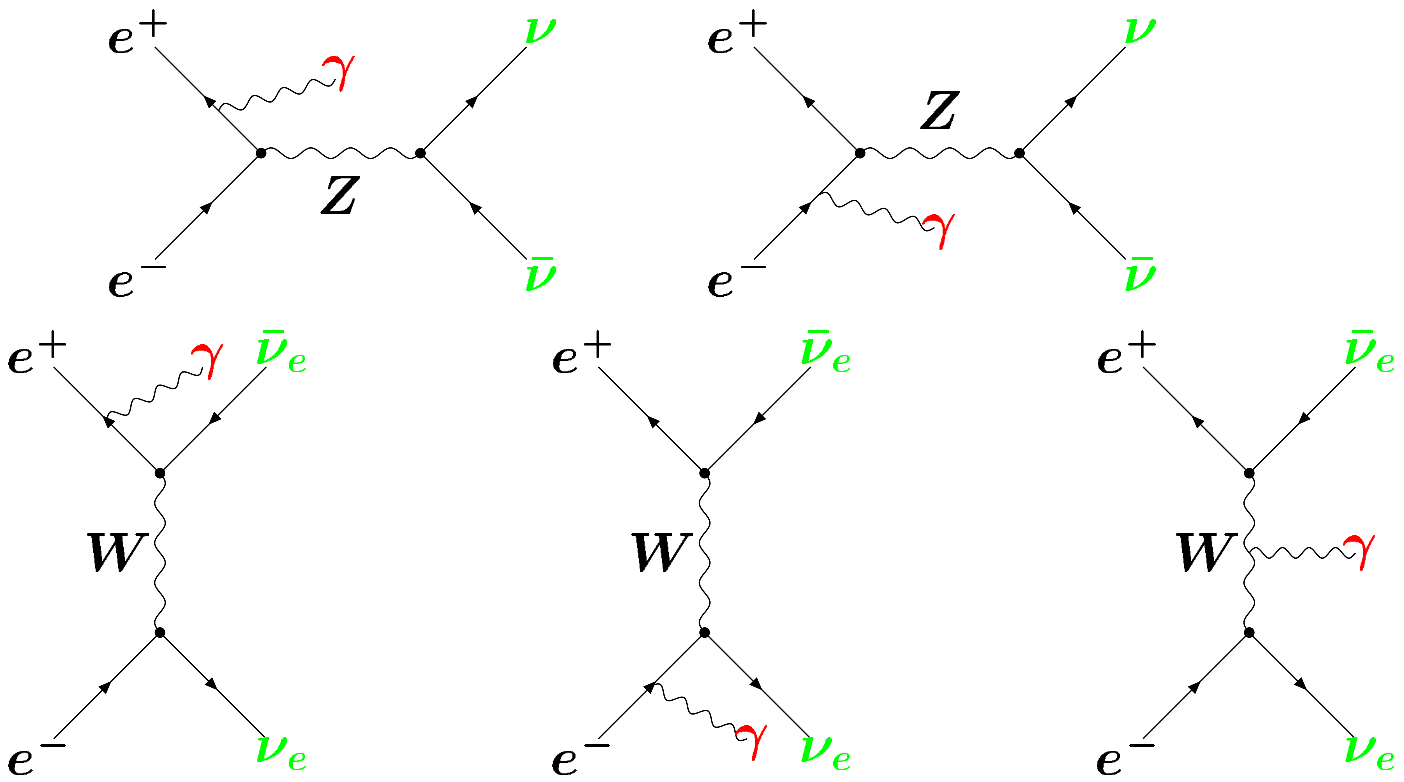
$$e^+e^- \longrightarrow \gamma + \textit{Missing Energy}$$

is a direct measurement of the invisible Z width



NIKHEF Cross Section for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$

$$\sigma_{\nu\bar{\nu}\gamma} = \int_0^1 dz R(z,s)\sigma^0_{\nu\bar{\nu}}((1-z)s)\ ; \quad z = 2E_\gamma/\sqrt{s}$$

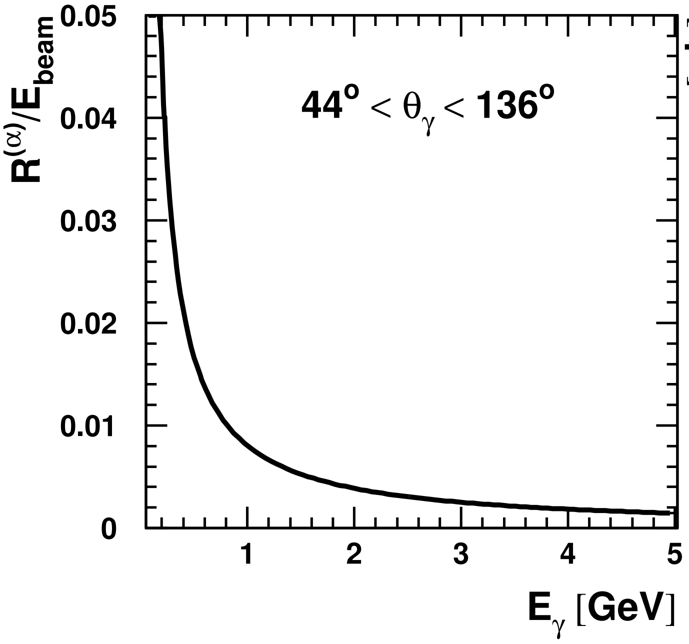


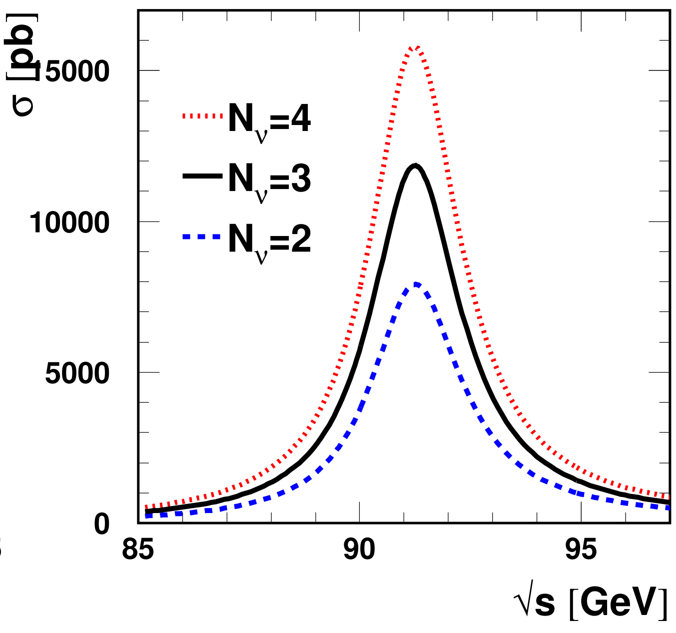
$$R^{(\alpha)}(z,\cos\theta;s) = \frac{\alpha}{\pi}\frac{1+(1-z)^2}{z}\frac{1}{1-\cos^2\theta}$$

$$\sigma^0_{\nu\bar{\nu}}(s) = \frac{G_F^2 s}{12\pi}\left(2 + \frac{2(g_v+g_a)\,(1-s/M_Z^2) + N_\nu(g_v^2+g_a^2)}{[1-s/M_Z^2]^2 + \Gamma_Z^2/M_Z^2}\right)$$

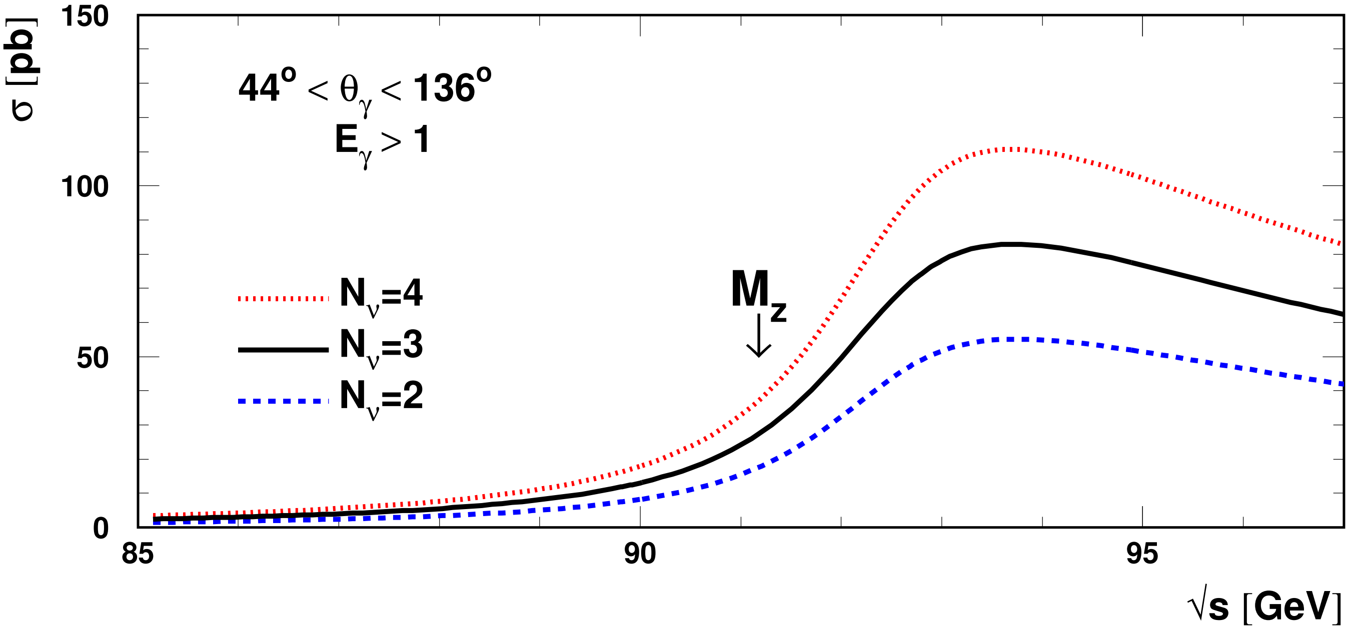
Note: W contribution $\approx 3\%$, depending on $\sqrt{s}$

Cross Section for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$





$$\sigma_{\nu\bar{\nu}\gamma} = \int_0^1 dz R(z, s) \sigma^0_{\nu\bar{\nu}}((1-z)s)$$



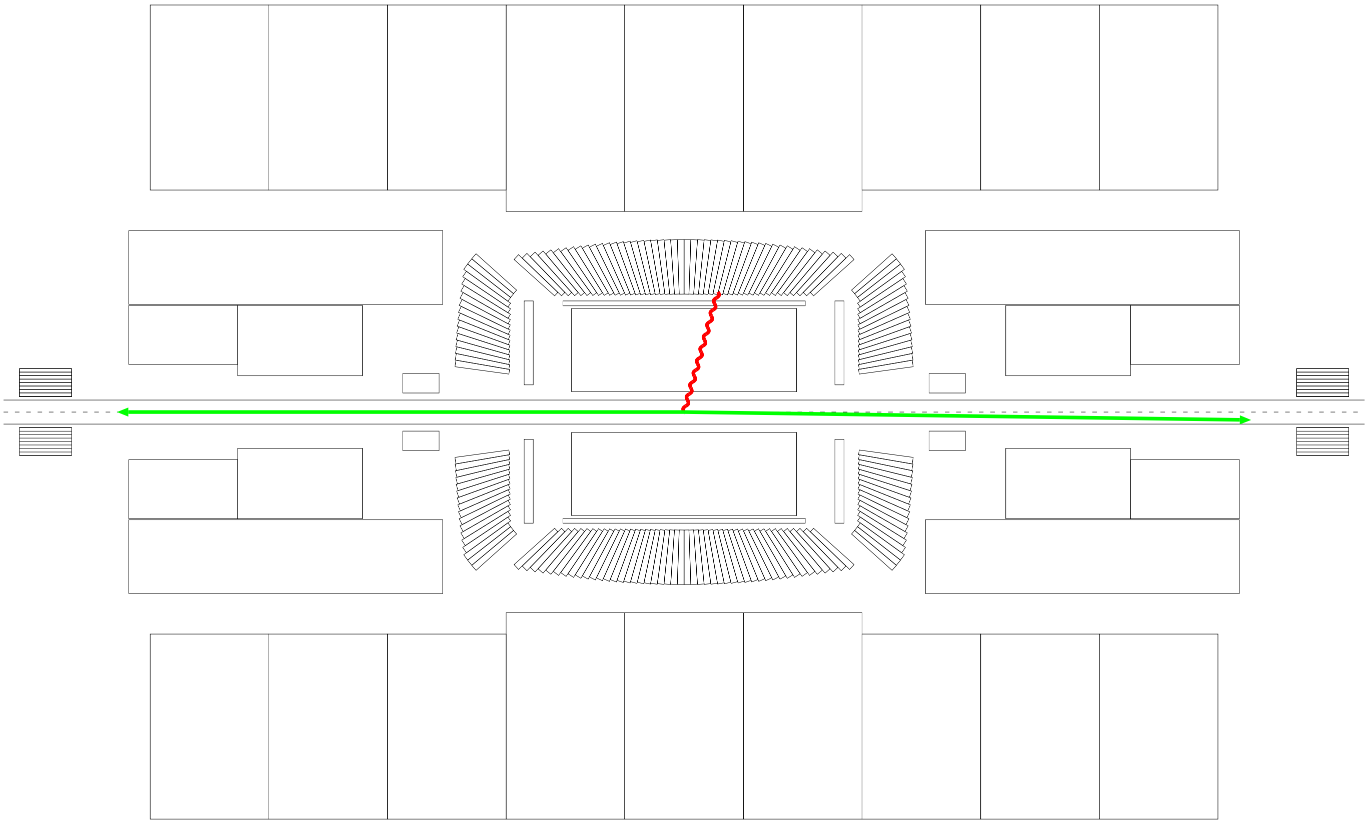
Best done above the Z-resonance.

Backgrounds

- $\mathrm{e}^+\mathrm{e}^- \longrightarrow \mathrm{e}^+\mathrm{e}^-\gamma$
- $\mathrm{e}^+\mathrm{e}^- \longrightarrow \gamma\gamma\gamma$
- $\mathrm{e}^+\mathrm{e}^- \longrightarrow \mu^+\mu^-\gamma$
- $\mathrm{e}^+\mathrm{e}^- \longrightarrow \tau^+\tau^-\gamma$
- $\mathrm{e}^+\mathrm{e}^- \longrightarrow \mathrm{e}^+\mathrm{e}^-R, R \longrightarrow \gamma X$
- $\mathrm{e}^+\mathrm{e}^- \longrightarrow \mathrm{e}^+\mathrm{e}^-ll\gamma \quad (l = e, \mu)$
- **Cosmic Rays**
- **Detector Occupancy**

Background suppression

Need Good hermiticity to suppress background
Main background: $e^+e^- \rightarrow e^+e^-\gamma$

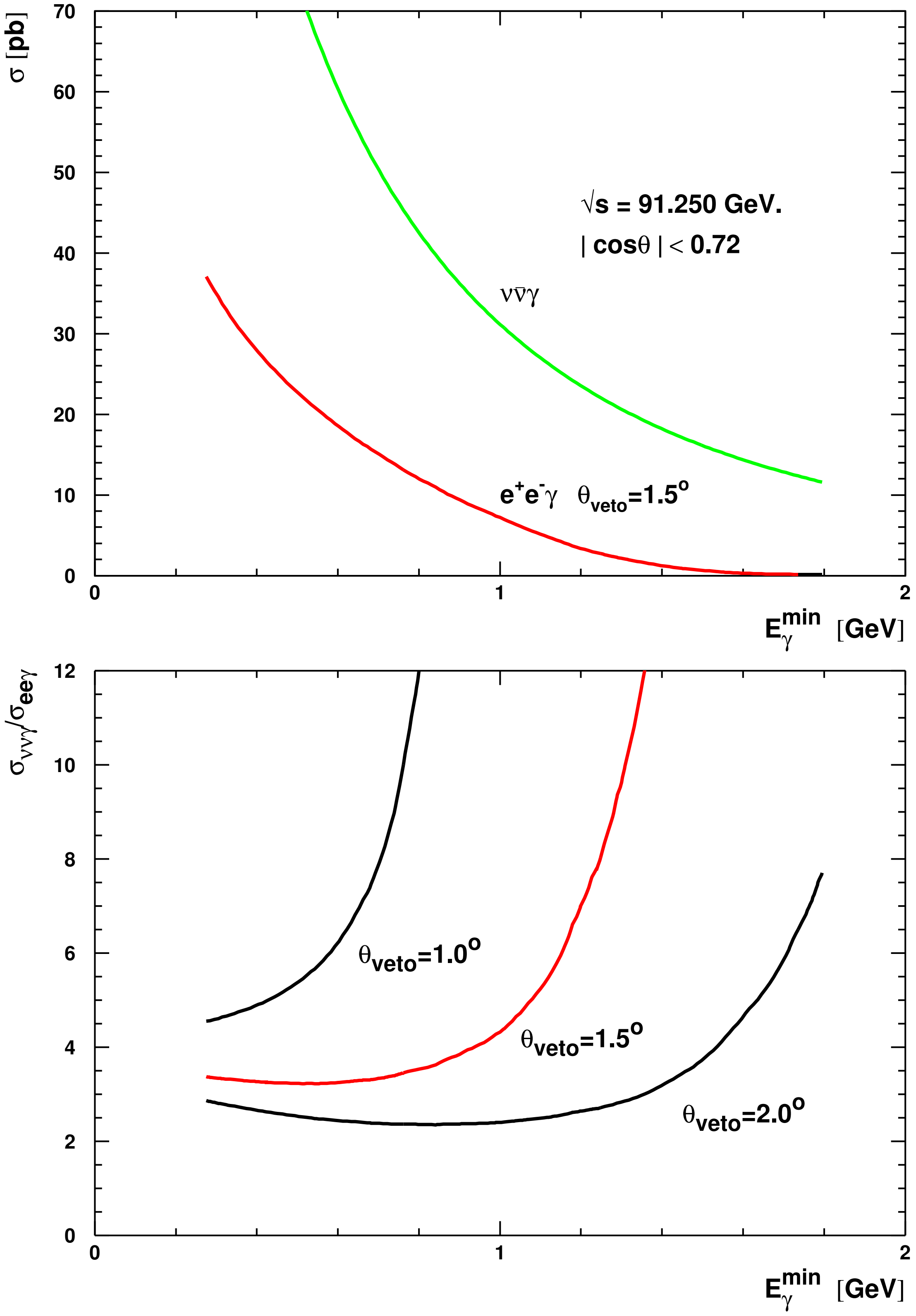


Smallest angle at which particles can be detected:

$$\theta_{\text{veto}} = 1.5^o$$

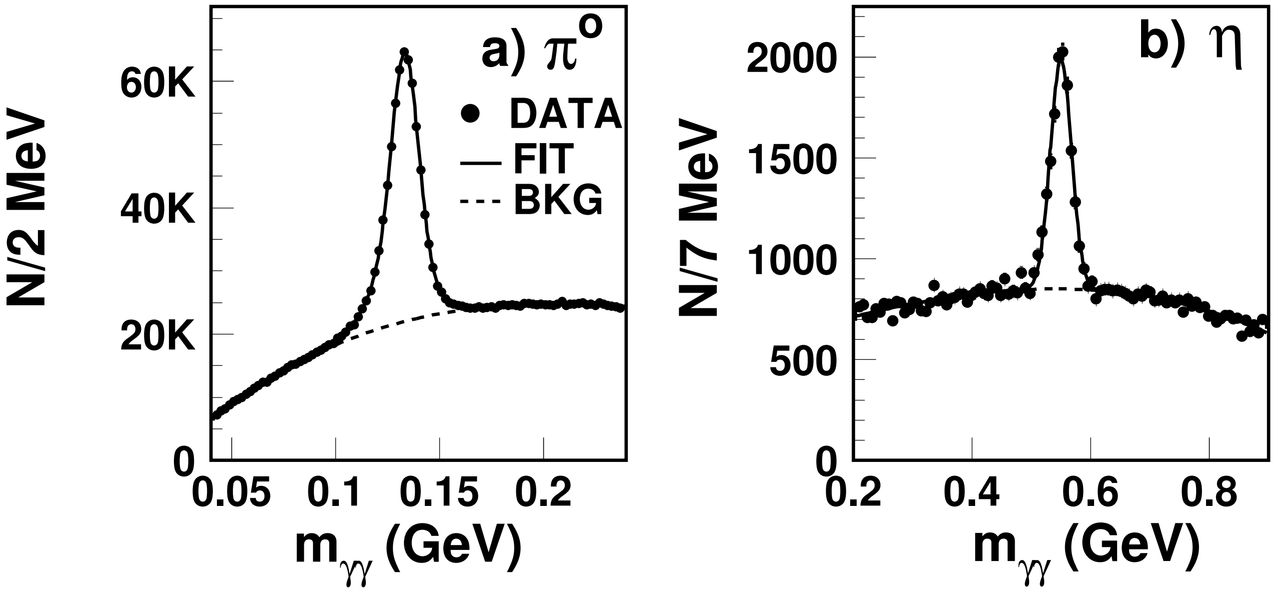
Note: small gap at $\approx 4^o$

Requirements: Hermeticity

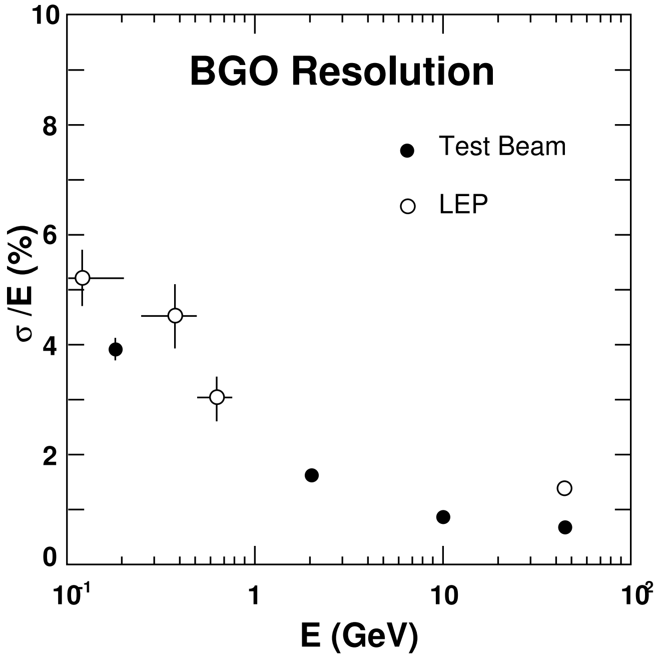


Energy Scale/Resolution

Absolute Energy Scale: 0.8%



Energy resolution

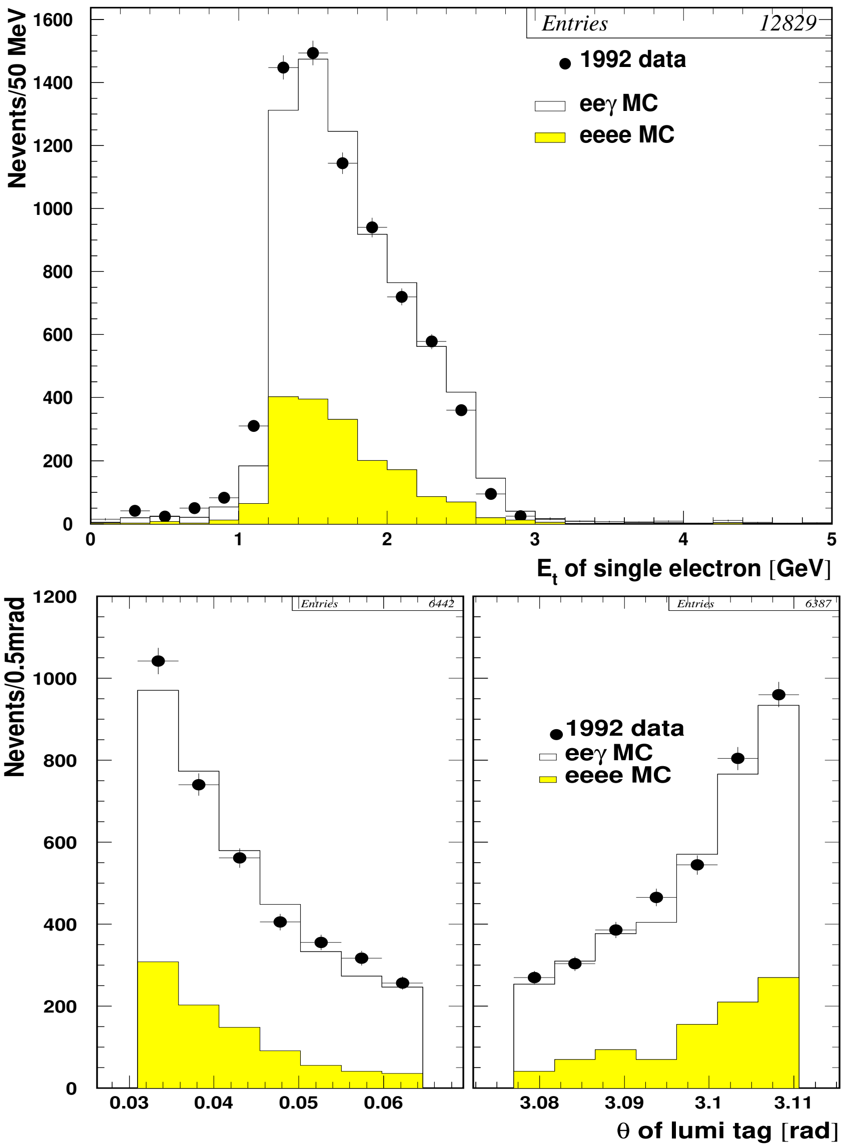


$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{1.54}{\sqrt{E}} + 0.38\right)^2 + 1.18^2 + \frac{0.25}{E^2}} \; (E \text{ in GeV})$$

Single-Electron Control Sample

Use $e^+e^- \longrightarrow e^+e^-\gamma$ with

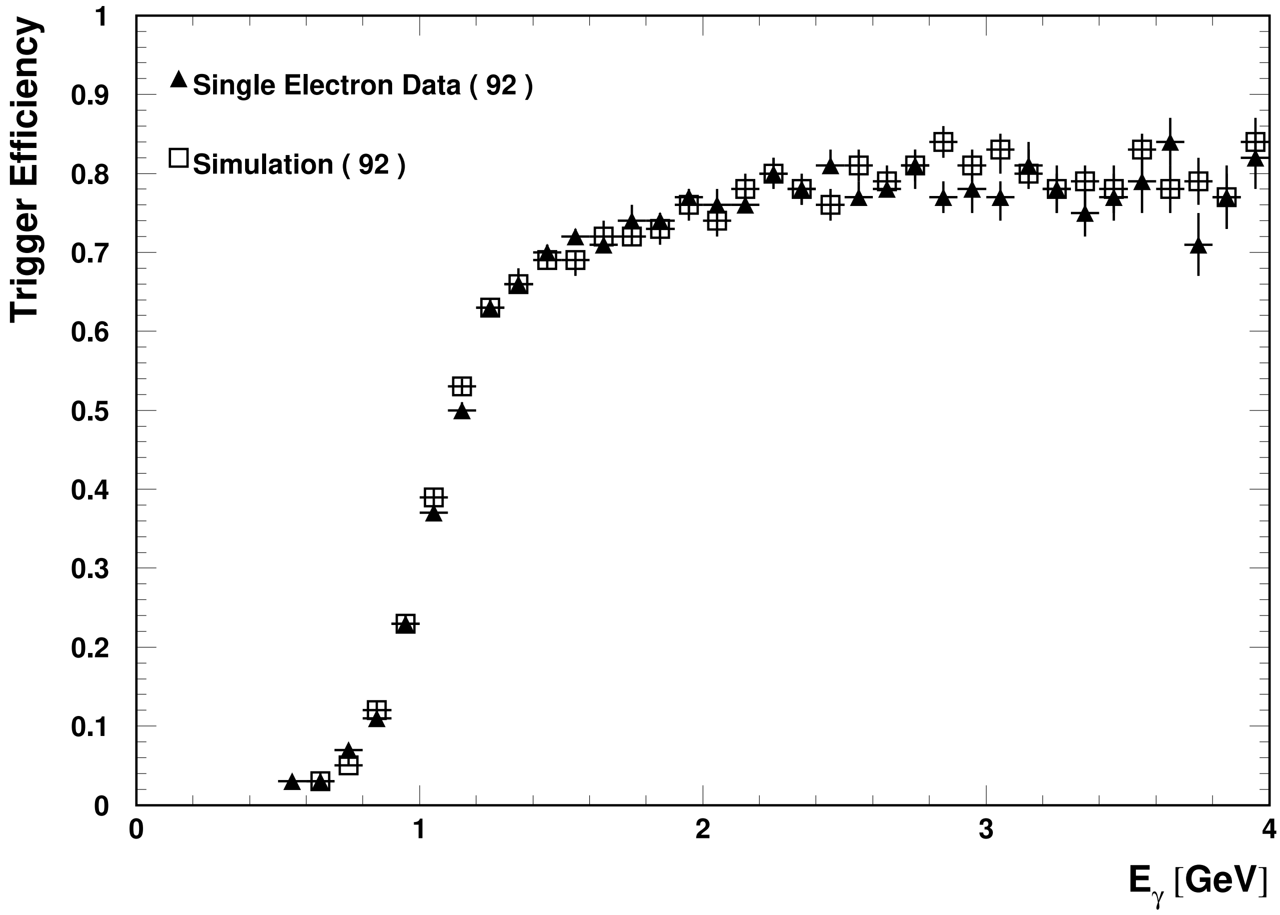
- electron at large angle
- tag in luminosity monitor



$$\frac{\sigma - \sigma_{\mathrm{MC}}}{\sigma_{\mathrm{MC}}} = 2.8\% \pm 2.5$$

Requirements: Trigger

Need good trigger for low energy photons



Simulation takes into account:

- measured gain and resolution of each channel
- channel status
- detector noise

Event Selection

Acceptance:

- Single Photon Trigger
- $44^o < \theta_\gamma < 136^o$
- $E_\gamma > 1$ GeV

Neutral, Isolated topology:

- $N_{\text{charged tracks}} = 0$
- $N_{\text{ECAL}}^{E>0.1, N_{\text{xtal}}>3} = 1$

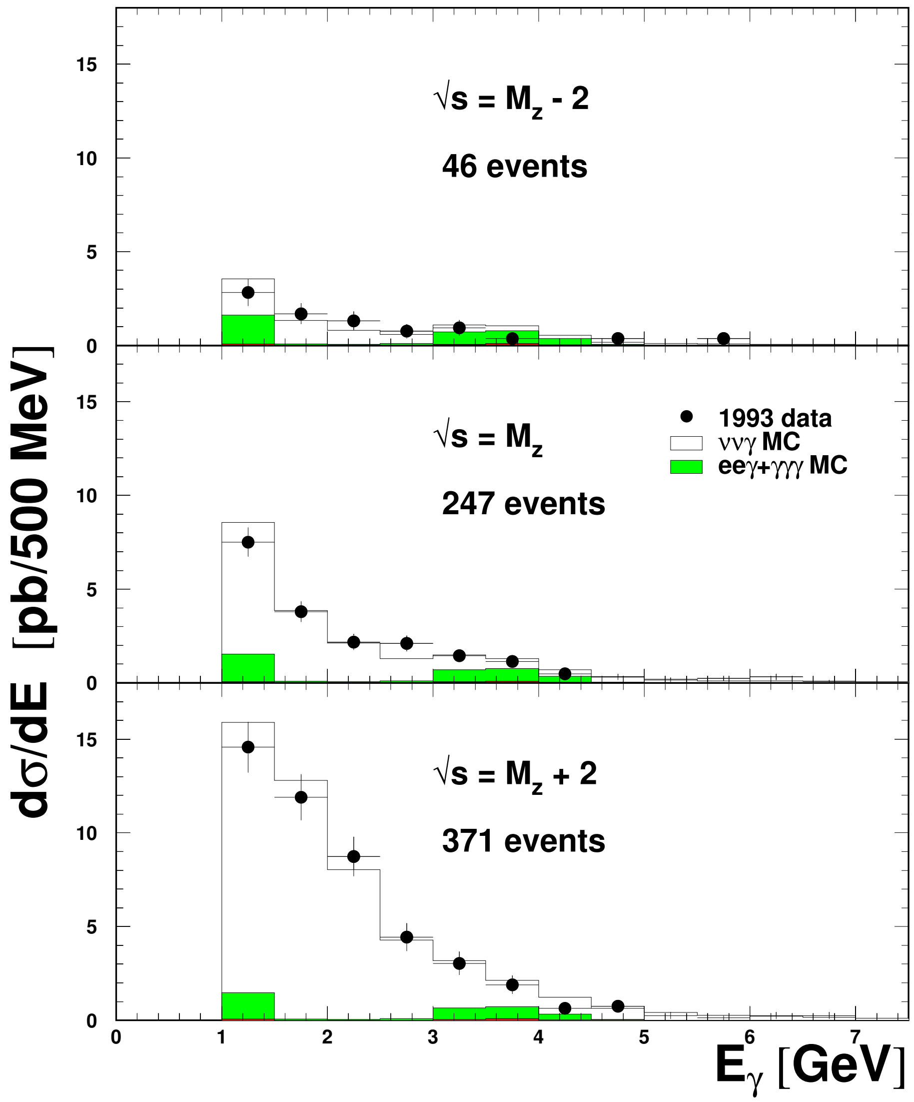
Good EM shower:

- $\chi^2_{\text{EM}} < 5$
- $\text{Skewness} > 0.25$
- $E^{\Sigma_{3\times3}}/E^{\Sigma_{5\times5}} > 0.95$

Background rejection:

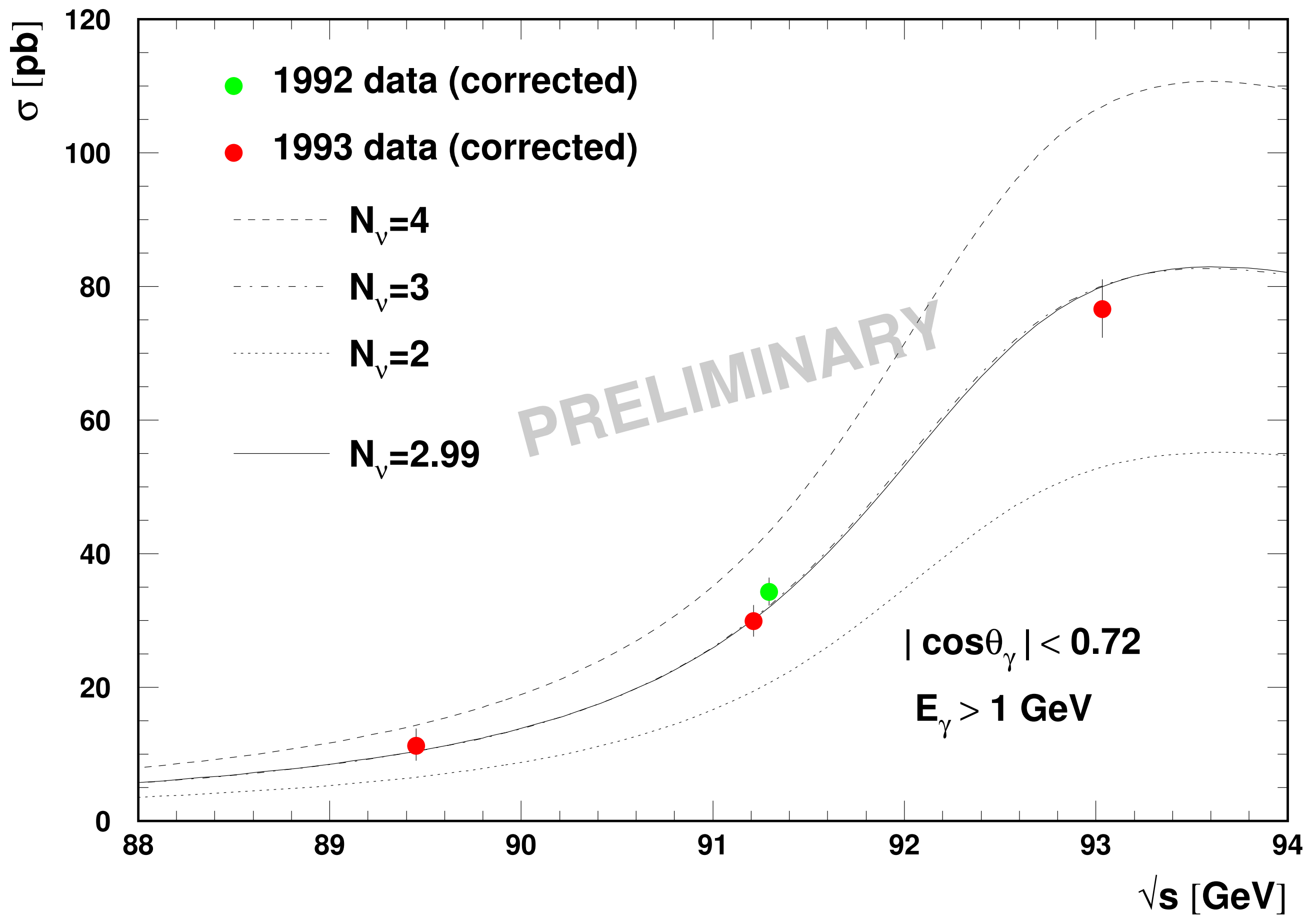
- $E_{\text{lumi}} < 5$ GeV
- $E_{\text{hcal}} < 5$ GeV
- $E_{\text{alr,vis}} < 0.1$ GeV
- no minimum ionizing track in HCAL
- no track in MUCH

Selected Sample



	$\sqrt{s}$(GeV)	$\int\mathcal{L}dt(\mathrm{pb}^{-1})$	N_{obs}	$N^{\nu\bar{\nu}\gamma}_{\mathrm{exp}}$	$N^{\mathrm{bckgrnd}}_{\mathrm{exp}}$
1991	88.6-93.7	9.57	202	196.6	29.9
1992	91.294	19.13	399	315.0	66.9
1993	89.452	5.32	46	30.7	20.5
	91.211	12.38	247	208.3	45.7
	93.034	7.90	371	364.7	28.0

Determination of N_ν



From a binned likelihood fit to $\mathrm{d}\sigma/\mathrm{dE}_\gamma$ with:

$$\frac{\mathrm{d}\sigma}{\mathrm{dE}_\gamma} = R(\mathrm{E}_\gamma, s)\sigma_0(s')$$

$$\sigma_0(s) = \frac{12\pi}{M_Z^2}\frac{s\Gamma_e N_\nu \Gamma_\nu}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} + W\,contrib.$$

Taking $M_Z, \Gamma_Z, \sin^2\bar{\theta}_{\rm eff}$ from the L3 measurement:

$$\boxed{N_\nu = 2.99 \pm 0.10 \pm 0.08}$$

PRELIMINARY

New Physics Searches

Use of $d\sigma/dE_{\gamma}$ for searches

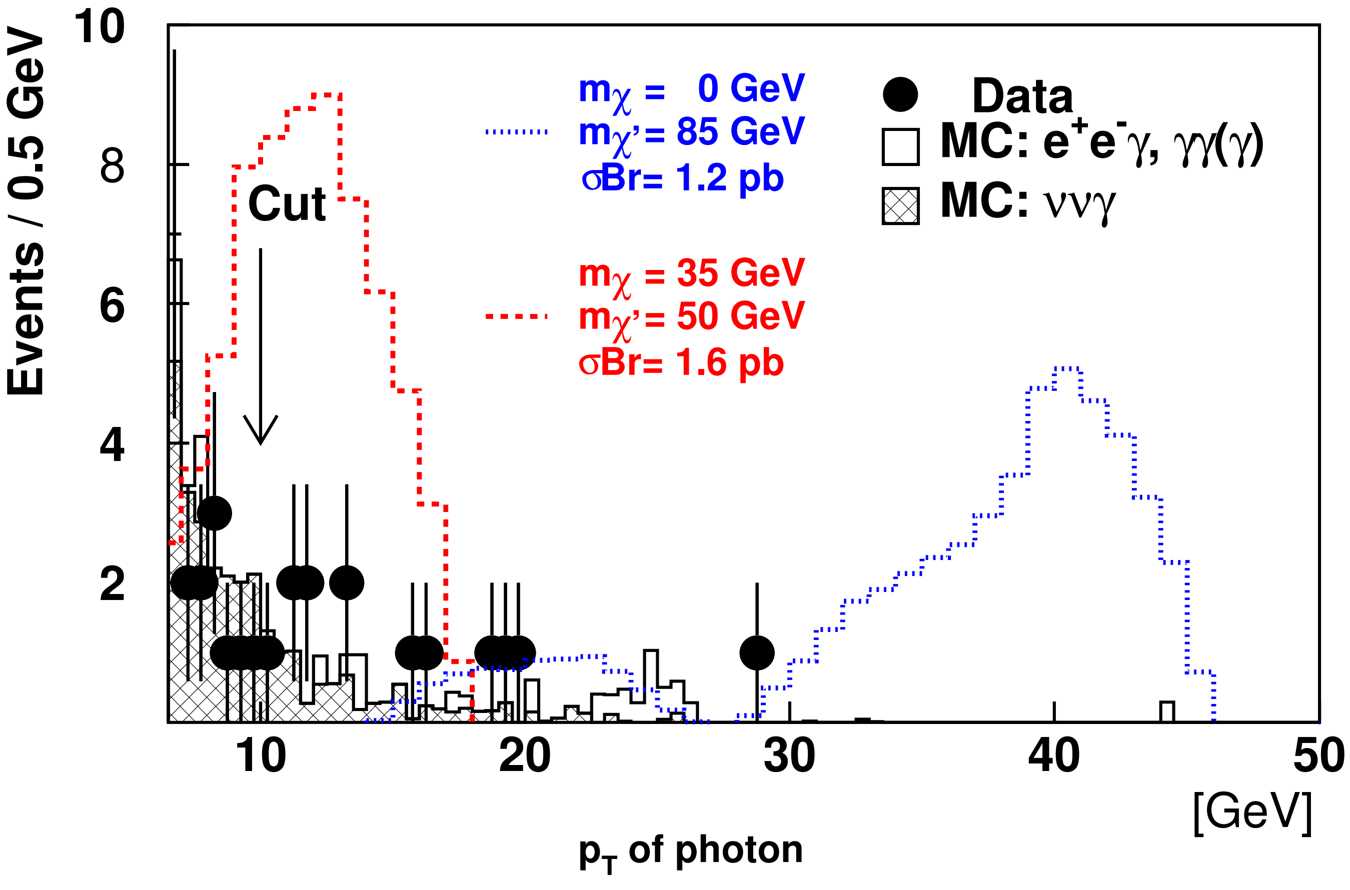
- Neutralinos
- Magnetic moment of neutrinos
- ZZγ coupling

Based on 2.4×10^{6} Z-decays

Neutralino searches

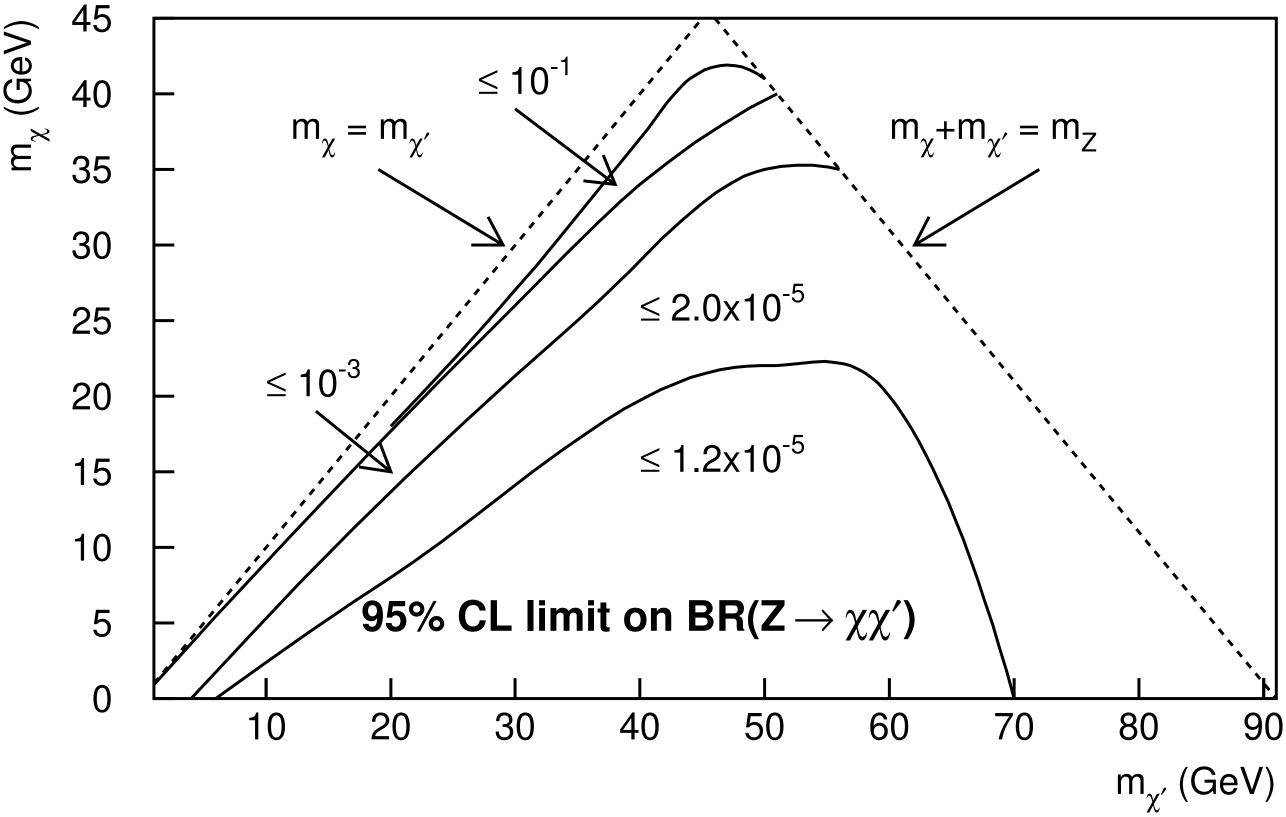
- **supersymmetric partners of γ, Z, H^0:**
  $\chi, \chi', \chi'', \chi'''$

$$e^+e^- \longrightarrow Z \longrightarrow \chi\ \chi'$$
$$\longrightarrow \chi\gamma$$



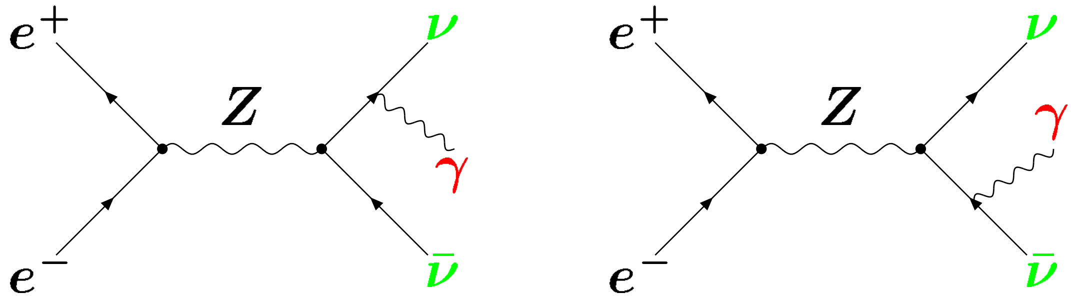
Neutralino searches

including $\chi' \rightarrow \chi\gamma, \chi e^+e^-, \chi\mu^+\mu^-, \chi q\bar{q}$



Lower Limits on Neutralino Masses (GeV), 95 % CL)				
particle	$\tan\beta > 1$	$\tan\beta > 2$	$\tan\beta > 3$	$m_{\tilde{g}} > 100 GeV$ all $\tan\beta$
χ	0	20	23	18
χ'	0	46	52	20

Magnetic Moment of ν



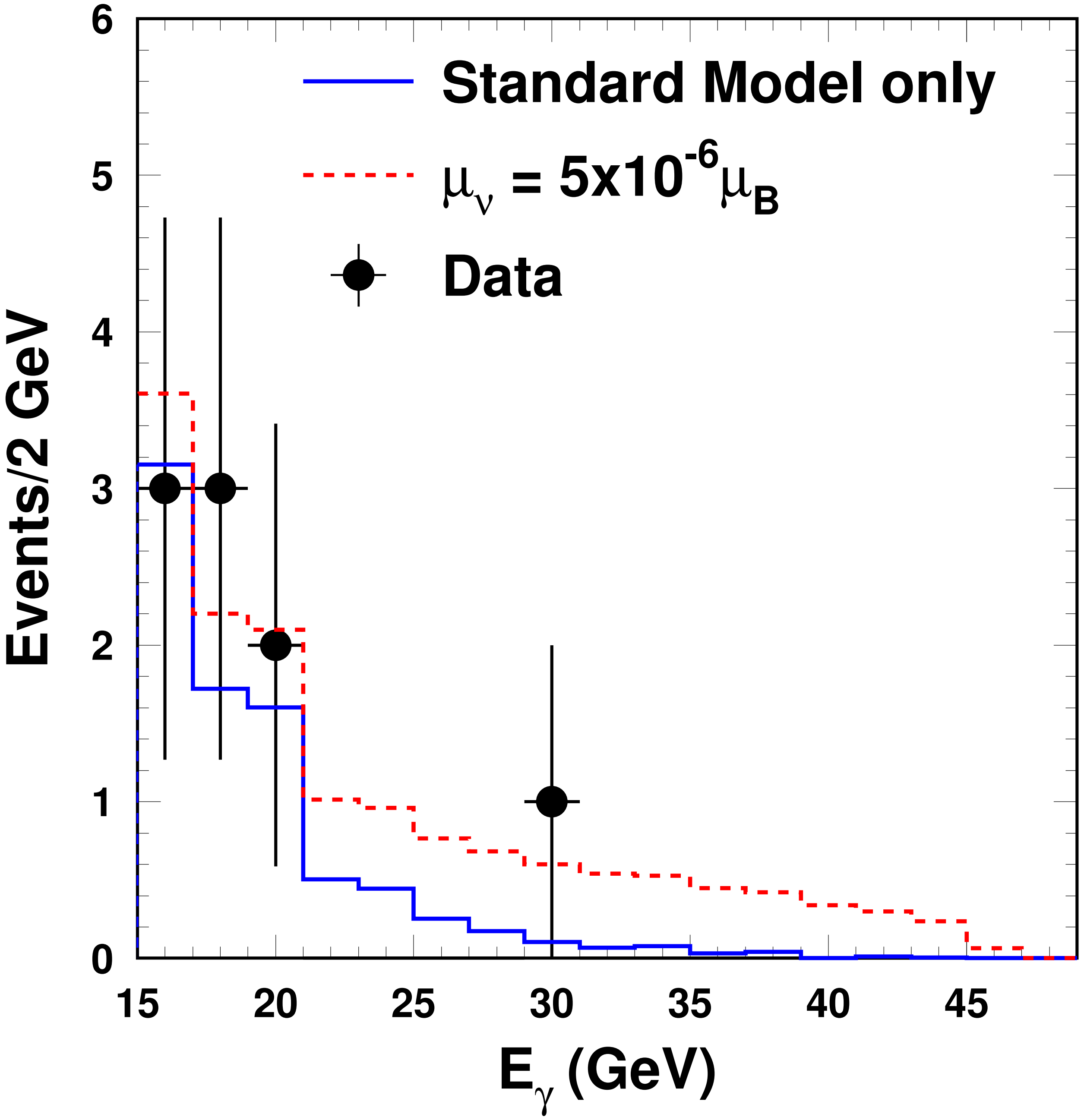
$$\sigma \propto \mu_\nu^2$$

Existing limits from $\nu\ e$ scattering (Krakauer et al.):

- $\mu_{\nu_e} < 10.8\ 10^{-10}\mu_B$ **(90%CL)**
- $\mu_{\nu_\mu} < 7.4\ 10^{-10}\mu_B$ **(90%CL)**

$\longrightarrow$ **Limit on magnetic moment of ν_τ**

Magnetic Moment of ν_τ



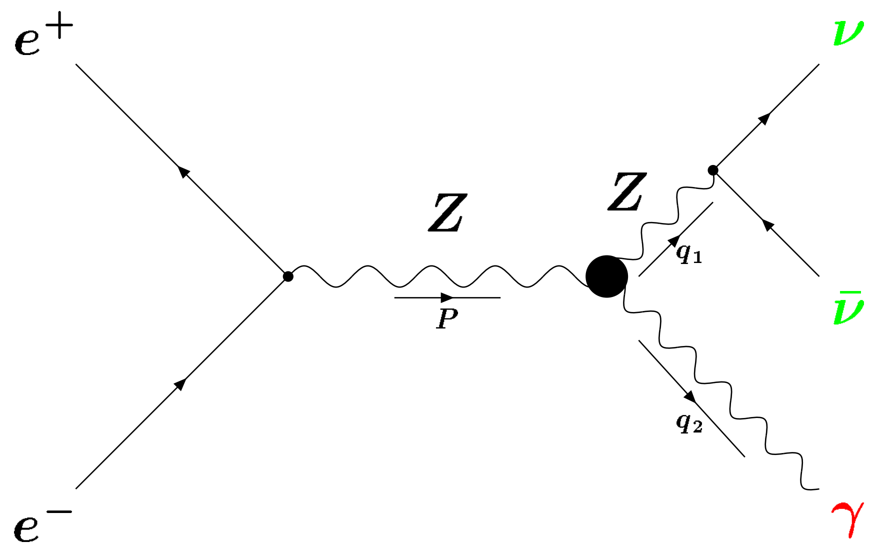
Requiring $E_\gamma > \frac{1}{2}E_{\rm beam}$ (SM: 1.2 events):

$$\boxed{\mu_{\nu_\tau} < 4.1 \times 10^{-6}\mu_B \quad \text{at } 90\%\text{CL}}$$

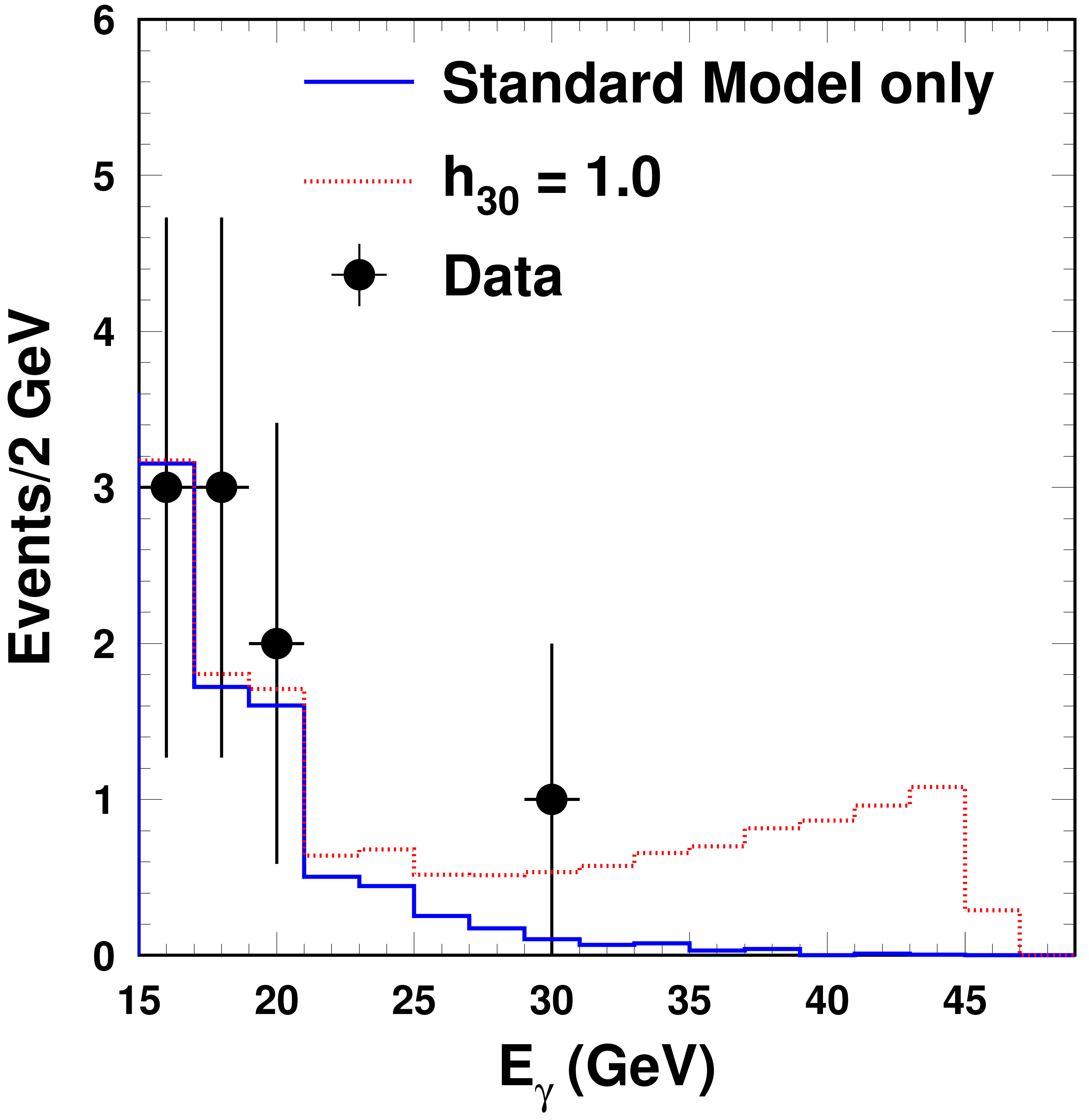
Grotch et al.(1988, combined data from ASP,CELLO,MAC, Mark J):

$$\mu_{\nu_\tau} < 4 \times 10^{-6}\mu_B \quad \text{at } 90\%\text{CL}$$

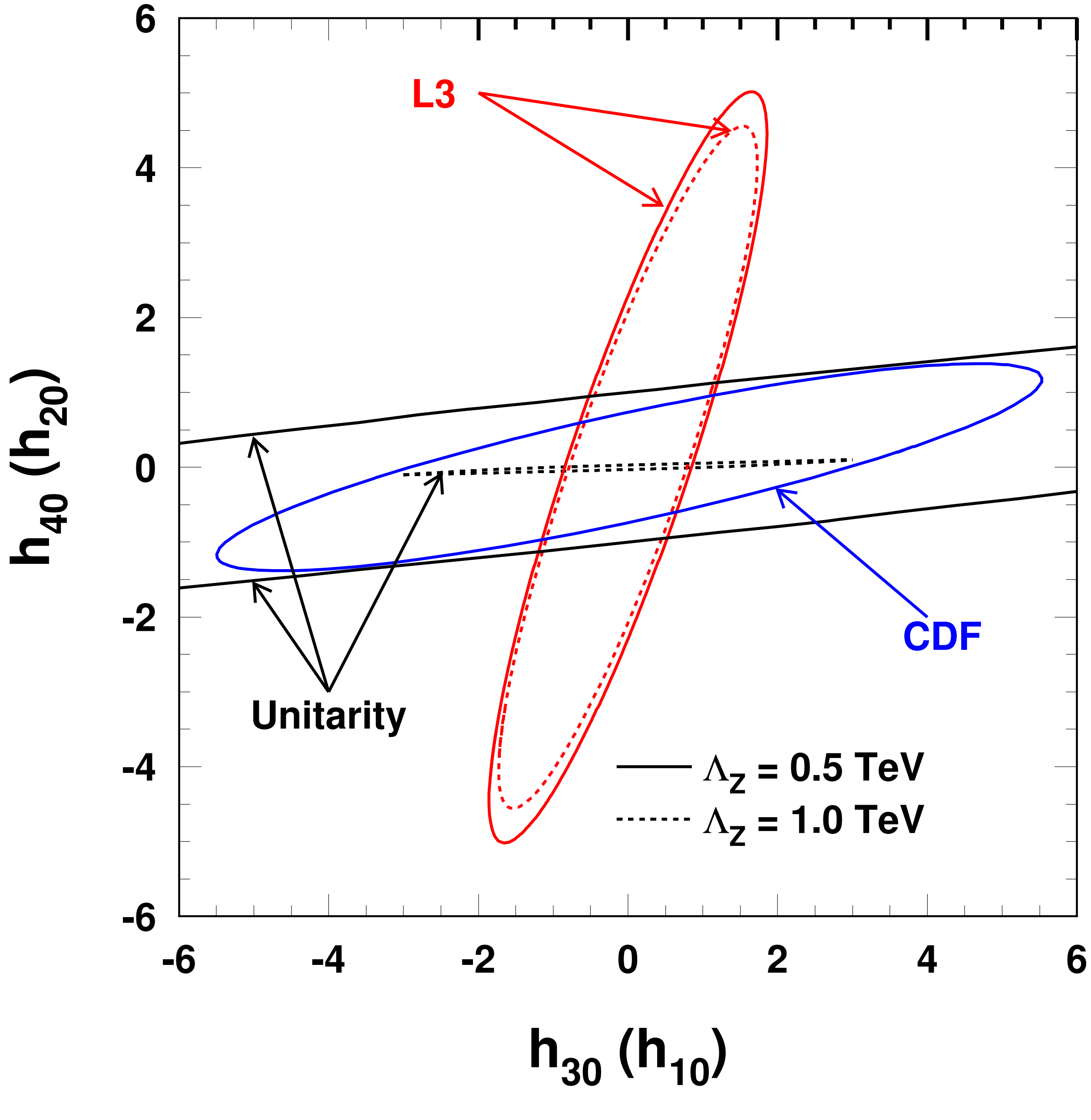
Anomalous ZZγ coupling



$$
\begin{aligned}
\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(q_1, q_2, P) \; = \; & \frac{P^2 - q_1^2}{m_Z^2} \times \\
\Bigg(\; & \frac{h_{10}}{(1 + P^2/\Lambda^2)^3} \left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \\
& \frac{h_{20}}{(1 + P^2/\Lambda^2)^4} \frac{P^\alpha \left((P \cdot q_2) g^{\mu\beta} - q_2^\mu P^\beta\right)}{m_z^2} + \\
& \frac{h_{30}}{(1 + P^2/\Lambda^2)^3} \varepsilon^{\mu\alpha\beta\rho} q_{2\rho} + \\
& \frac{h_{40}}{(1 + P^2/\Lambda^2)^4} \frac{P^\alpha \varepsilon^{\mu\beta\rho\sigma} P_\rho q_{2\sigma}}{m_z^2} \quad \Bigg)
\end{aligned}
$$


Standard Model only
h30 = 1.0
Data
Events/2 GeV
0
1
2
3
4
5
6
15
20
25
30
35
40
45
Eγ (GeV)

Anomalous ZZγ coupling



Conclusions and Prospects

- $N_\nu = 2.99 \pm 0.10 \pm 0.08$ PRELIMINARY

  Good agreement with Lineshape result: 2.98 ± 0.03

- $m_\chi > 18$ **GeV (95% CL,** $\tan\beta > 2$ **or** $m_{\tilde{g}} > 100$ **GeV)**
- $\mu_{\nu_\tau} < 4.1 \times 10^{-6}\ \mu_B \quad (90\%\mathrm{CL})$
- **limits on Anomalous** $ZZ\gamma$ **Coupling**

- **Measurements are limited by statistics:**

  1990–1993: 60 pb^{-1}

  $\longrightarrow$ **1990–1994: 100 pb^{-1}**

  $\longrightarrow$ **End of LEP-I running: 200 pb^{-1} ?**