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ON PARTICLE PHYSICS
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Latest Results from the L3 Experiment at LEP

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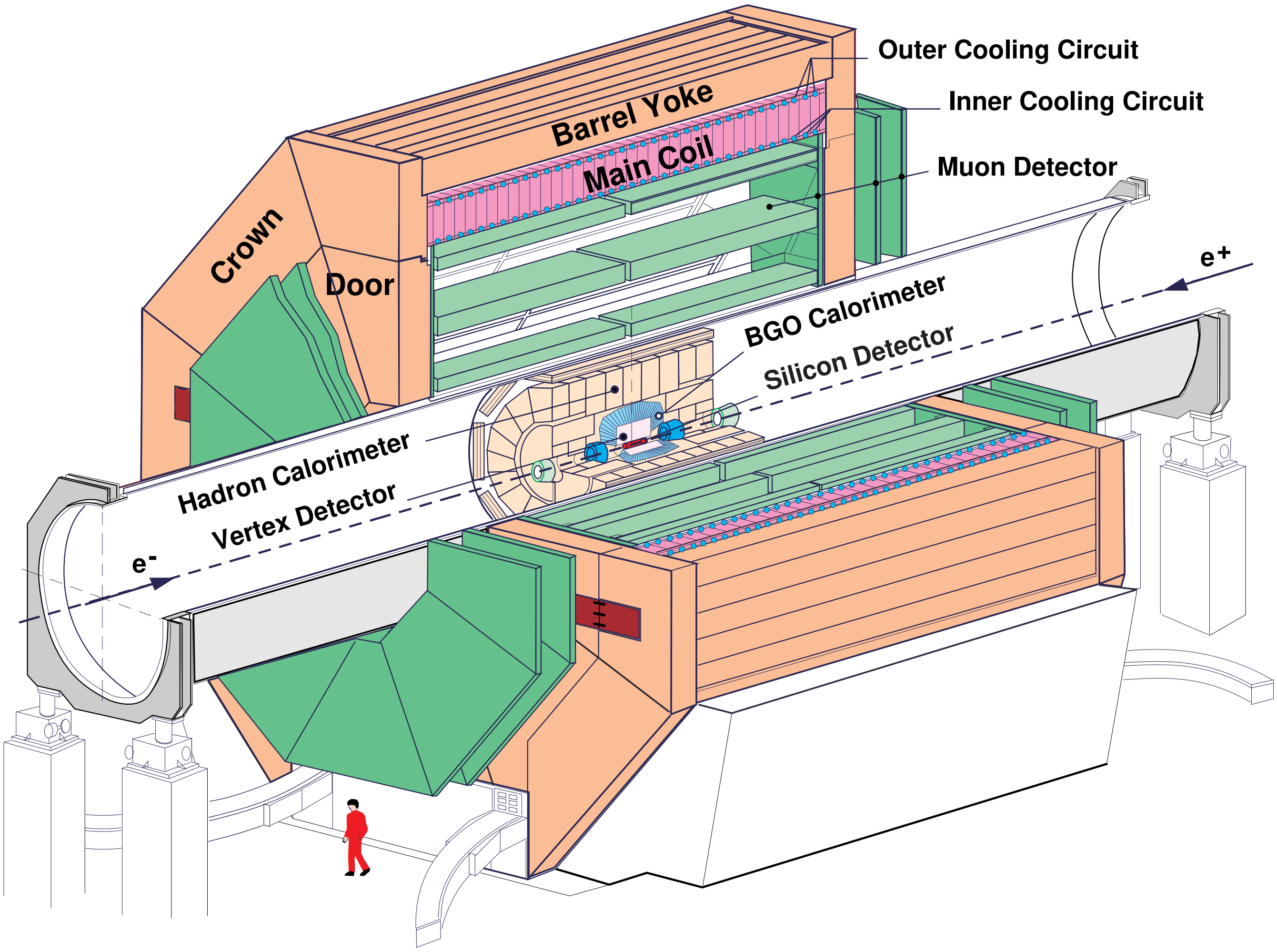
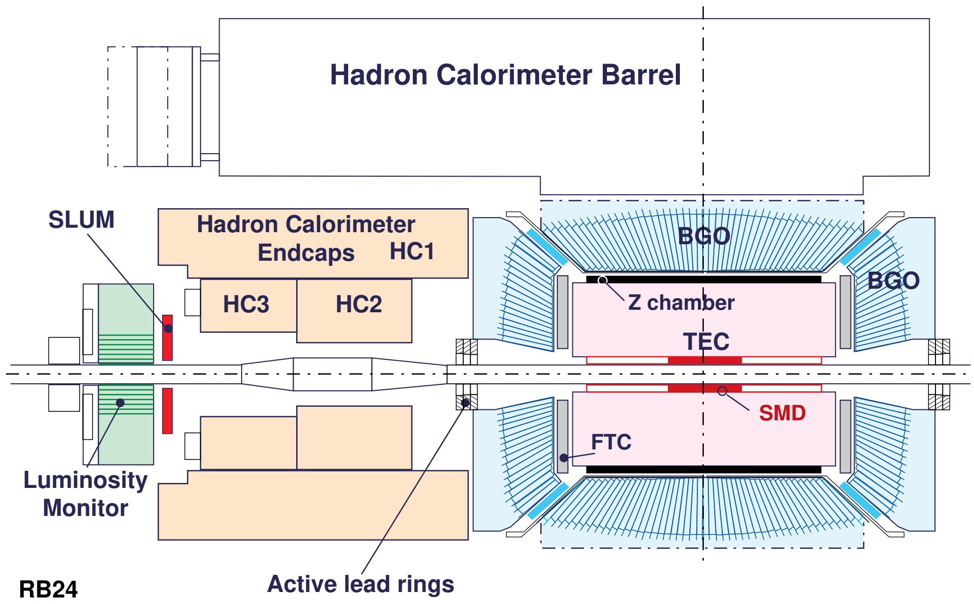
Outline:

- **Fermion Pair Production** $e^+e^- \to f\bar{f}$
- **Two Photon Physics**
- **Neutrino Counting with the Single Photon Method**

L3 Detector

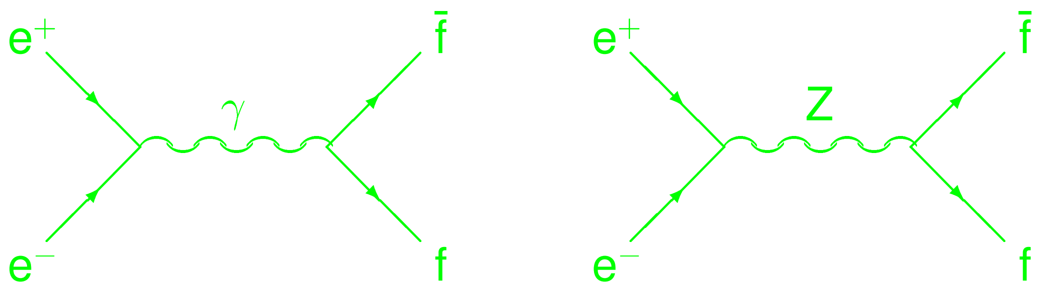


Outer Cooling Circuit
Inner Cooling Circuit
Barrel Yoke
Main Coil
Muon Detector
Crown
Door
e+
BGO Calorimeter
Silicon Detector
Hadron Calorimeter
Vertex Detector
e-



Hadron Calorimeter Barrel
SLUM
Hadron Calorimeter
Endcaps HC1
HC3
HC2
BGO
BGO
Z chamber
TEC
SMD
FTC
Luminosity
Monitor
RB24
Active lead rings

Fermion Pair Production

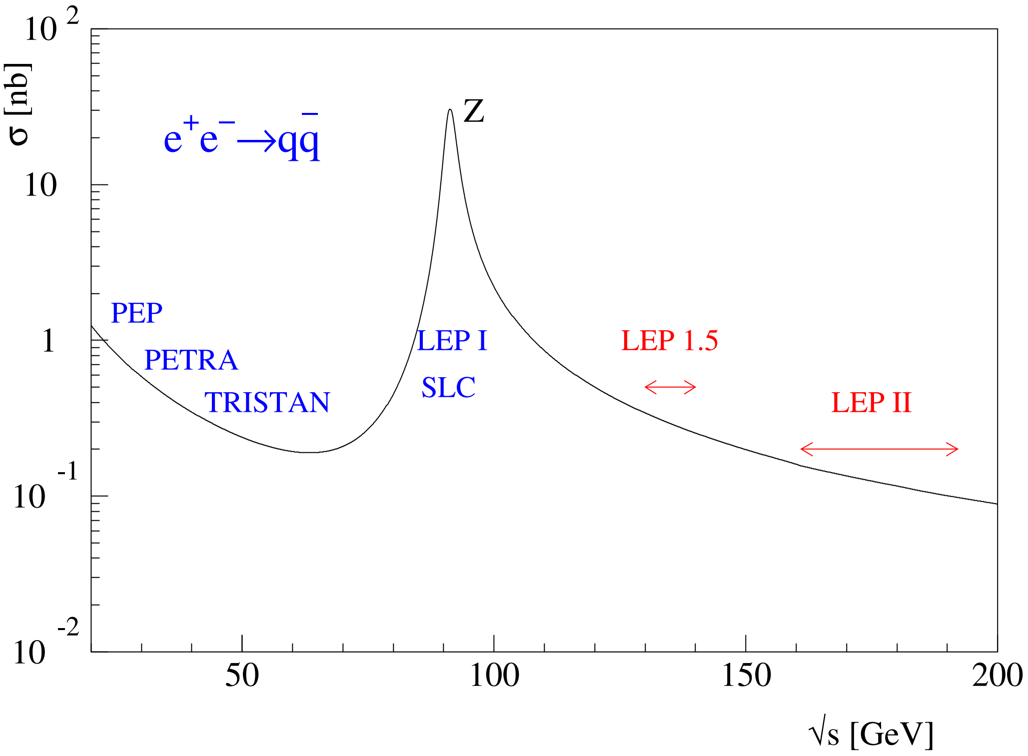


- We measure cross sections and FB asymmetries above the Z pole for the following channels:
  - $e^+e^- \to$ hadrons
  - $e^+e^- \to e^+e^-$
  - $e^+e^- \to \mu^+\mu^-$
  - $e^+e^- \to \tau^+\tau^-$
- They can be used to probe the γZ interference term above the Z pole
- The running of the strong coupling constant α_S can be evaluated at higher energies

  See talk by P. Burrows

Fermion Pair Production

Total hadronic cross section as a function of the cms energy



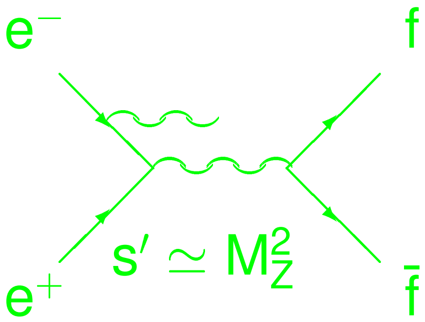
Event Sample

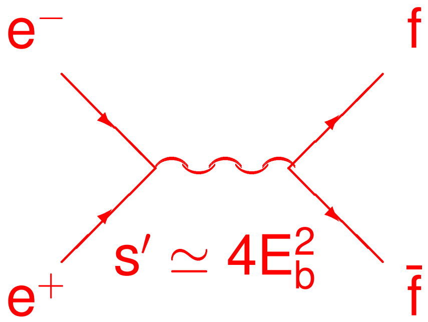
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$N_{hadrons}$	$N_{\mu^+\mu^-}$	$N_{\tau^+\tau^-}$	$N_{e^+e^-}$
130÷140	5.0	1577	75	53	246
161	10.0	1563	95	49	353
170÷172	10.0	1290	63	45	300

$161 \div 172\ GeV$ results are preliminary

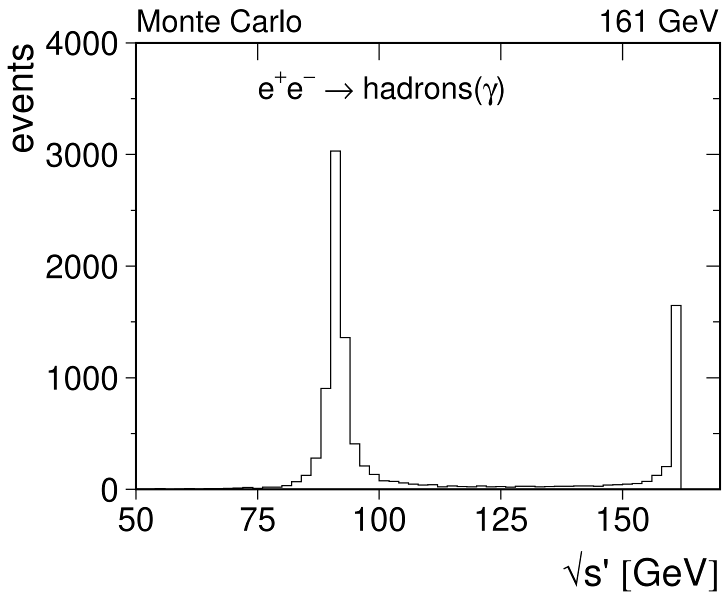
Fermion Pair Production

Effective Center of Mass Energy





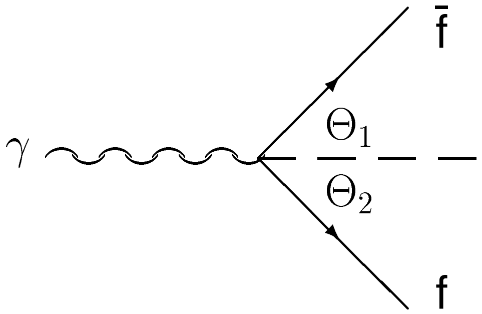
radiative return   genuine high energy



Radiative return to the Z ($\sqrt{s'/s} < 0.85$):

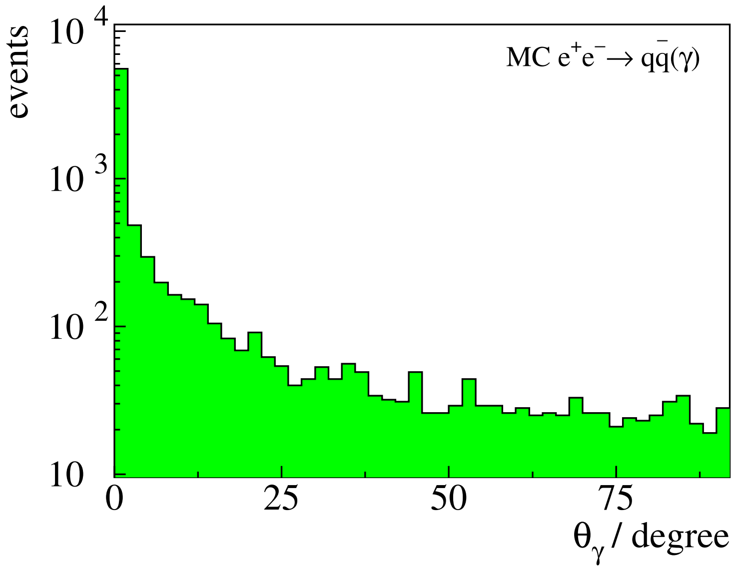
Determination of $\sqrt{s'}$

We assume three particle final state:



$$s' = s\left(1 - \frac{2\,E_\gamma}{\sqrt{s}}\right)$$

Polar angle of the initial state photon

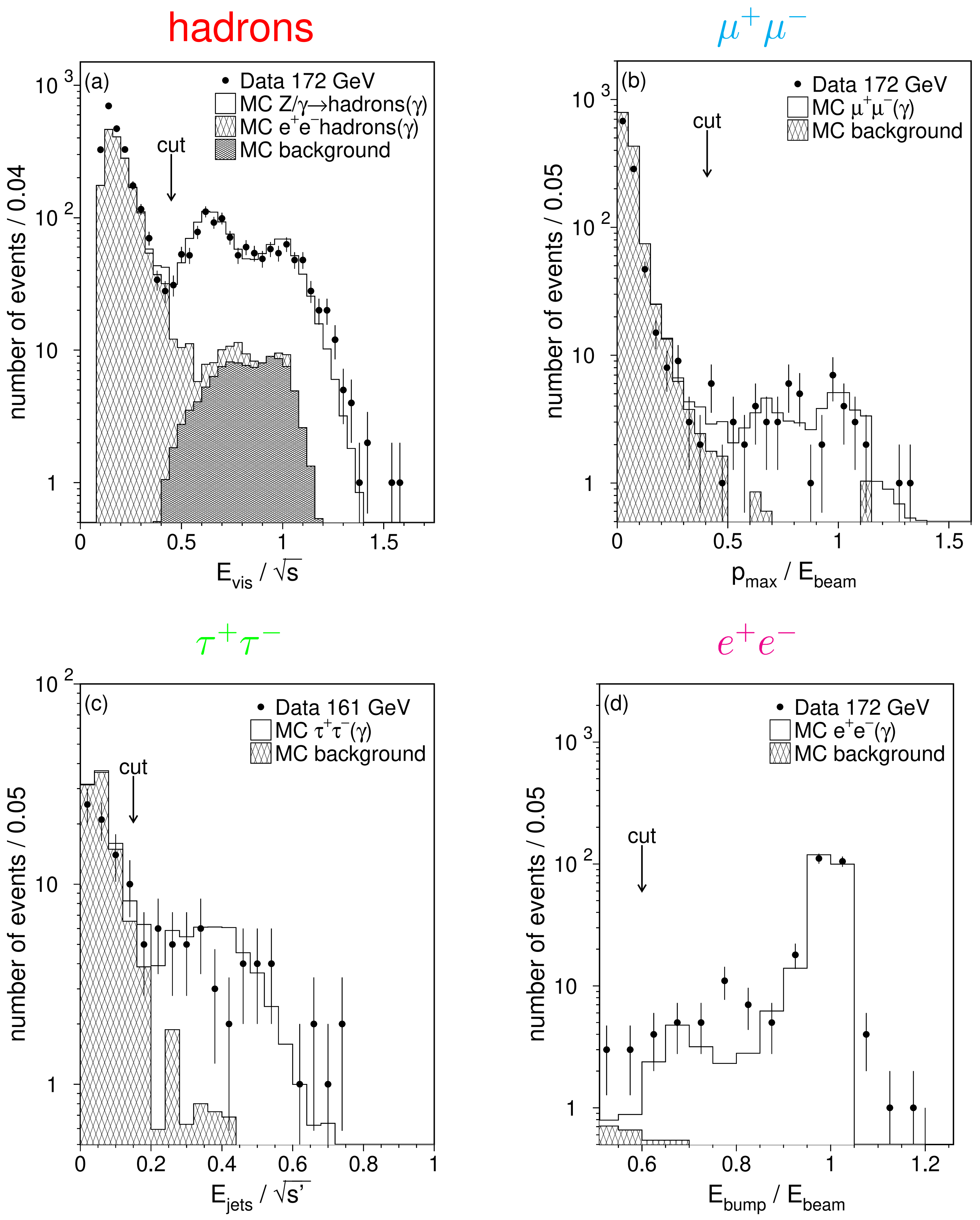


- E_γ from detected photon
- else from fermion angles ($\not{P}$ along the beam pipe) :

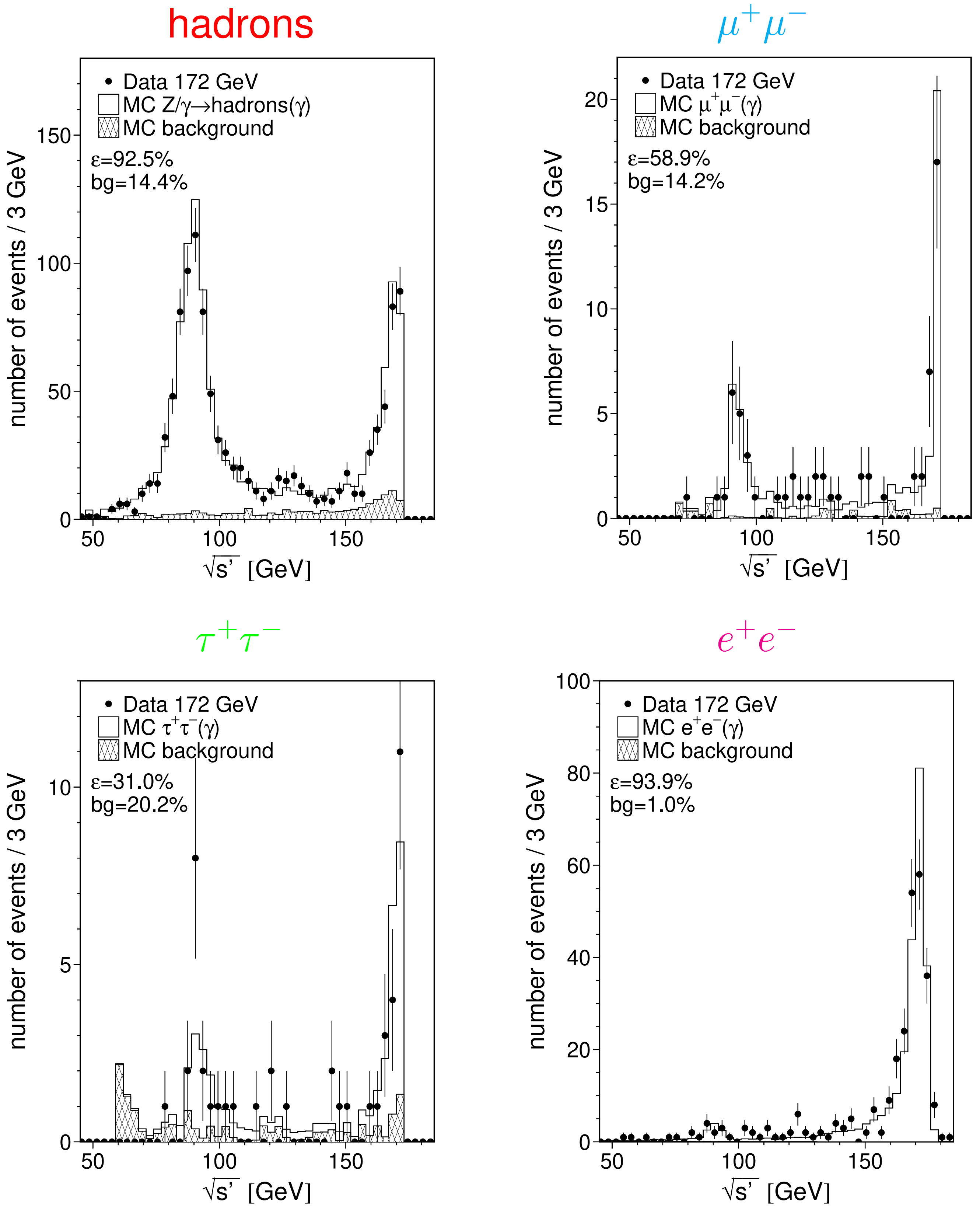
$$E_\gamma = \sqrt{s}\,\frac{|\sin(\Theta_1+\Theta_2)|}{\sin\Theta_1+\sin\Theta_2+|\sin(\Theta_1+\Theta_2)|}$$

CAVEAT: In practice is more difficult and MC corrections are needed

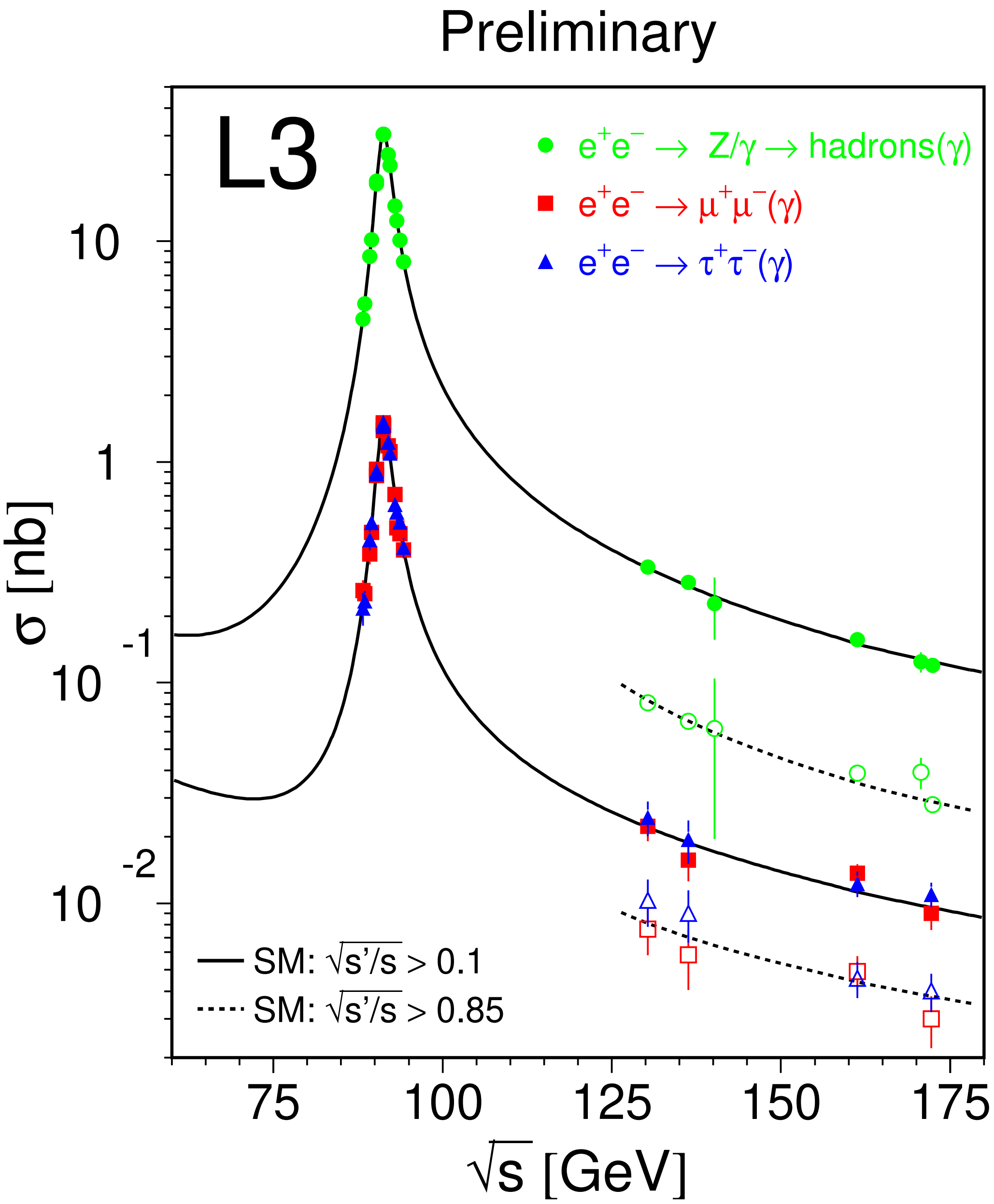
Some selection variables



Effective Center of Mass Energy



Cross-section measurement



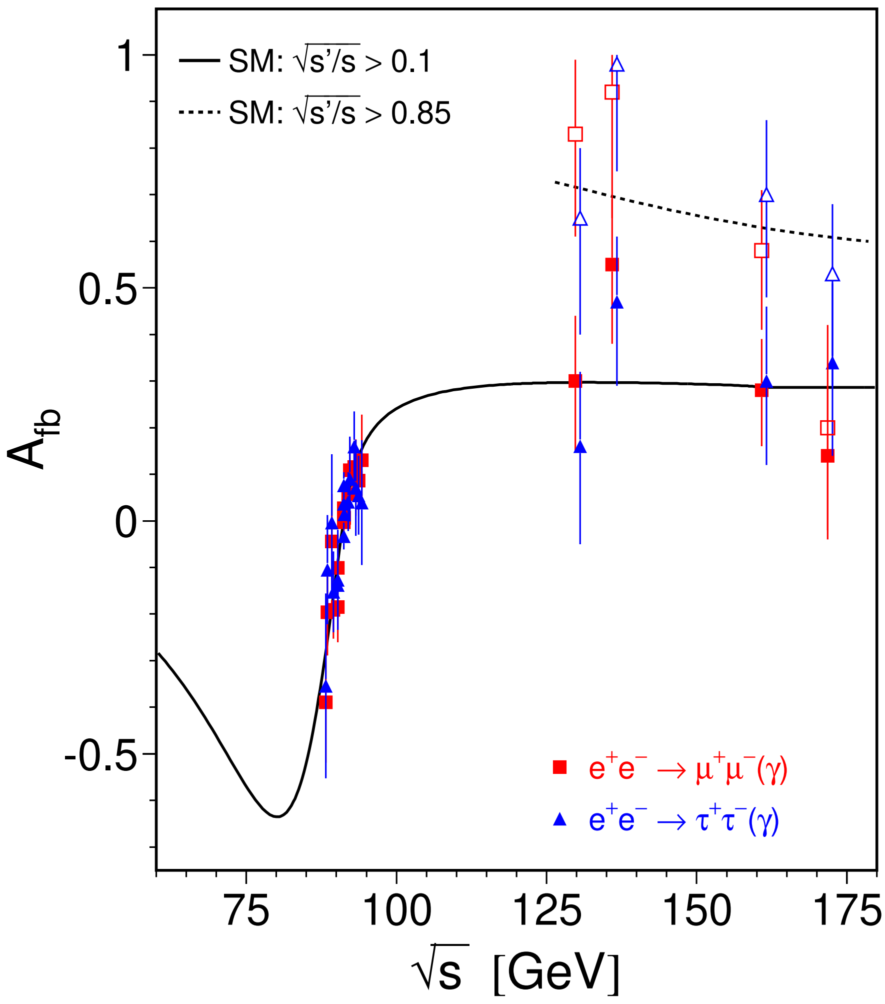
$161 \div 172\ GeV$ results are preliminary

Leptonic forward-backward asymmetries

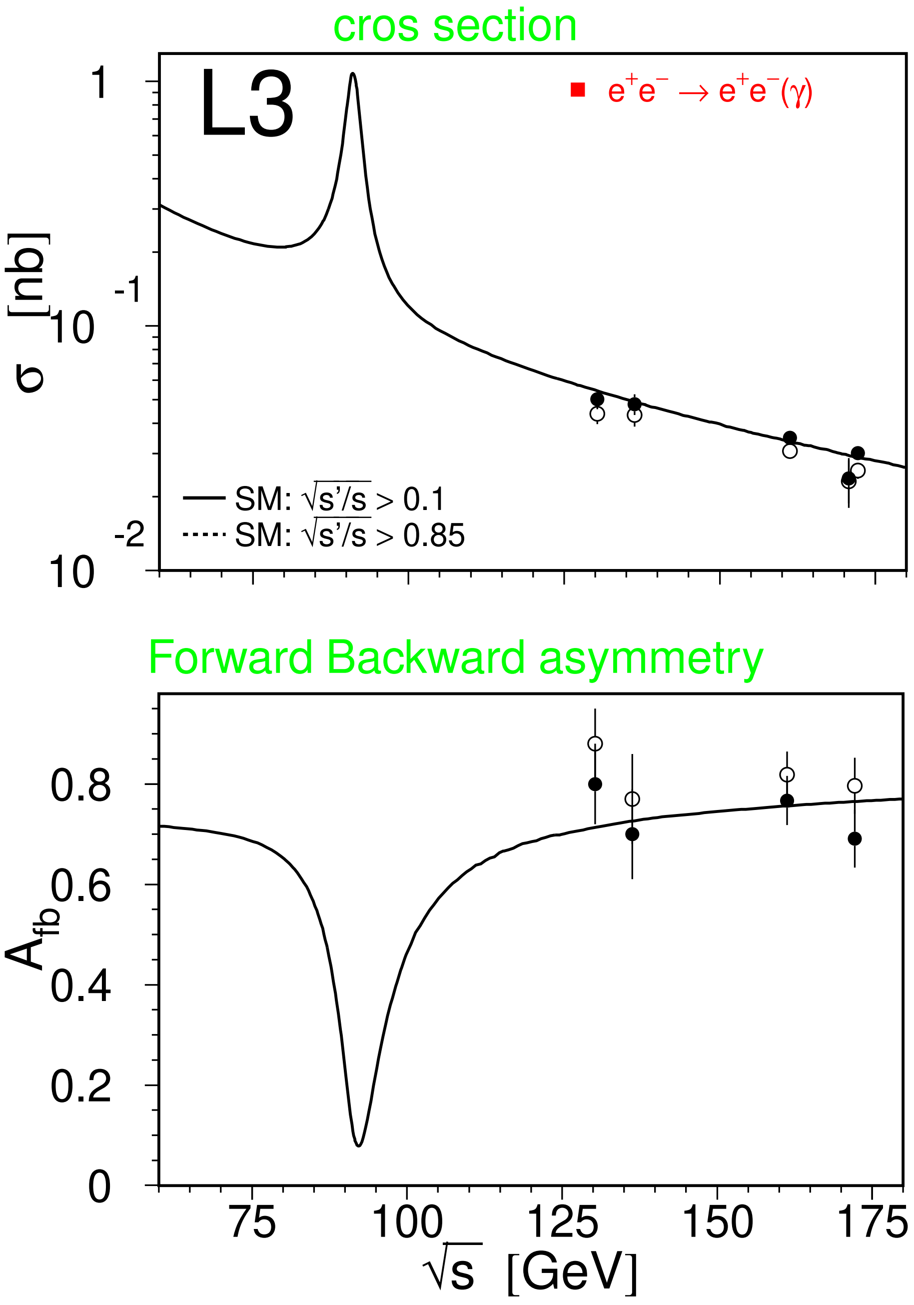
$$\mathcal{A}_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

$$\frac{d\sigma}{d\,cos\theta} \propto \frac{3}{8} \cdot (1 + \cos^2\theta) + \mathcal{A}_{FB} \cdot cos\theta$$

(Corrections are needed to the formula for events with hard ISR)



$$\underline{e^+e^- \rightarrow e^+e^-\gamma}$$



solid points are total sample events

open points are high energy sample events

The two electron are required to be inside the volume $44° < \vartheta < 136°$

The solid line is the SM prediction for the total sample

Determination of the γZ Interference

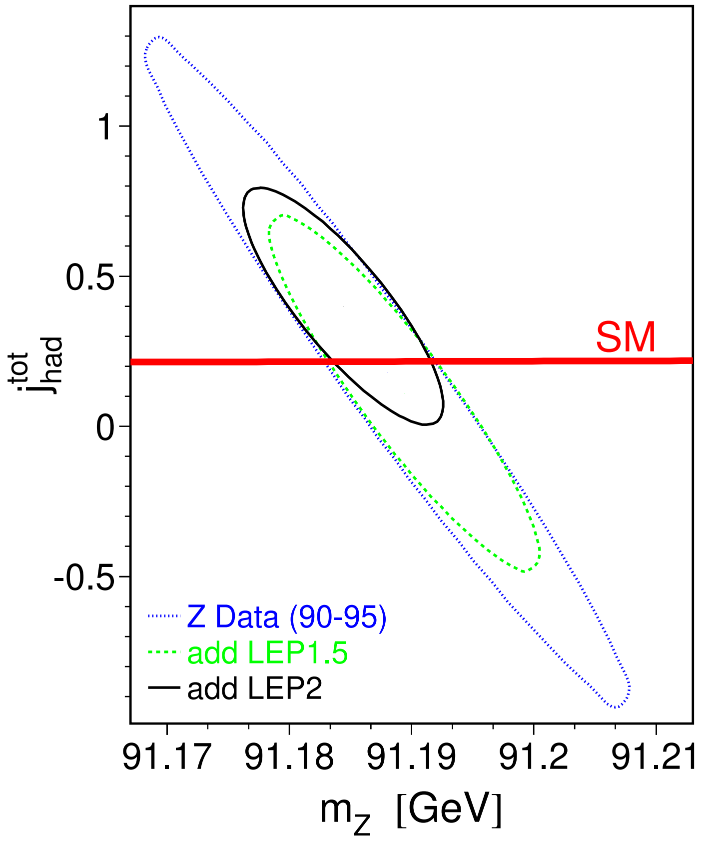
$$\sigma_{total} = \sigma_Z + \sigma_\gamma + \sigma_{int}$$

$$\sigma_{int} = \frac{4}{3}\pi\alpha^2 \, j_f \, \frac{(s-m_Z{}^2)}{(s-m_Z{}^2)^2+m_Z{}^2\cdot\Gamma_Z{}^2}$$

Usually j_f is set to the SM values to get $m_Z, \Gamma_Z, \cdots$

j_{had} can be measured with a complete model independent fit

Preliminary



Data	j_{had}^{tot}	M_Z (MeV)
LEP 1	0.18 ± 0.73	$91188. \pm 13.$
LEP 1 + 140 + 160+172	0.40 ± 0.26	91184.7 ± 5.4
SM:	0.21	91188.1 ± 2.9

Two Photon Physics

- The process $e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^- hadrons$ is the main contribution to hadron production above the Z resonance

- This process must be controlled with the best possible accuracy, being the most important background for other physics channels and it is also a very dangerous source of fake new physics signature

  See talk by M.Schmitt

- Nevertheless two photon physics is very important by itself, being an ideal place to study the complex nature of the photon.

- I will present:

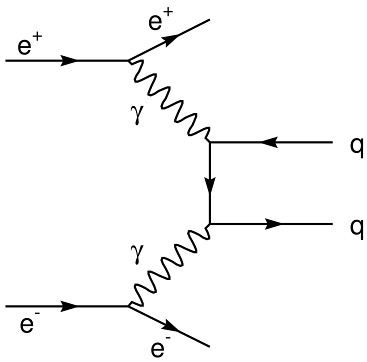
  – A measurement of the $\gamma\gamma \to hadrons$ cross section

  – Some exclusive states production in $\gamma\gamma$ collisions

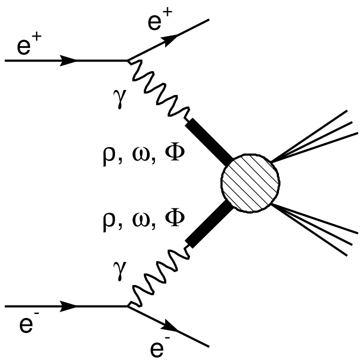
Two Photon Physics

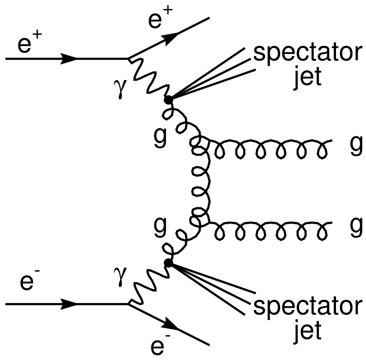
$\gamma\gamma \rightarrow hadrons$

Direct (QED)

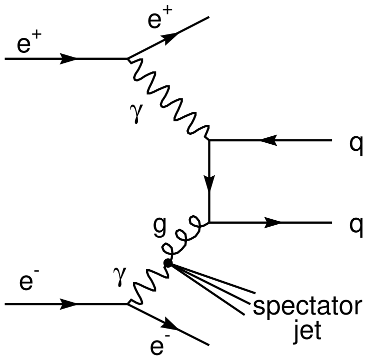


VMD Model





Double Resolved



Single Resolved

VMD Diagram is dominant at low Q^2 transfer

Monte Carlo programs have been very recently improved based also on the knowledge of γp and pp scattering data

PYTHYA: (G.A.Schuler and T.Sj$\ddot{o}$strand)
PHOJET: (R.Engel and J.Ranft)

Determination of $\sigma(\gamma\gamma \to hadrons)$

- We determine the center of mass energy in the $\gamma\gamma$ rest frame ($W_{\gamma\gamma}$) from the visible effective mass spectrum (W_{vis}) by using an unfolding procedure

- $\Rightarrow$ We get the number of events $N_{\gamma\gamma}$ for every $W_{\gamma\gamma}$ bin. We measure:

$$\frac{d\,\sigma\,(e^+e^- \to e^+e^- hadrons)}{d\,W_{\gamma\gamma}} = \frac{N_{\gamma\gamma}}{\mathcal{L}_{ee} \cdot \mathcal{A}}$$

  $\mathcal{L}_{ee}$ is the integrated luminosity. $\mathcal{A}$ is the overall acceptance in the given $W_{\gamma\gamma}$ bin. It includes trigger and selection efficiencies.

- $$\frac{d\,\sigma\,(e^+e^- \to e^+e^- hadrons)}{d\,W_{\gamma\gamma}} = \mathcal{L}_{\gamma\gamma} \times \sigma(\gamma\gamma \to hadrons)$$

  $\mathcal{L}_{\gamma\gamma}$ is the luminosity function. (G.A.Schuler CERN-TH/96-297)

- $$\sigma(\gamma^*\gamma^* \to hadrons) = \sigma(W_{\gamma\gamma}, Q_1^2, Q_2^2)$$

- If ($Q^2 \ll W_{\gamma\gamma}$) $\Rightarrow \sigma(W_{\gamma\gamma}, Q_1^2, Q_2^2) = F^2(Q_1^2) \cdot F^2(Q_2^2) \cdot \sigma(W_{\gamma\gamma}, 0., 0.)$

  $F(Q^2)$ is the form factor of the virtual photon.

- We perform a numerical integration of $\mathcal{L}_{\gamma\gamma} \times F(Q^2)$ for each $W_{\gamma\gamma}$ bin to extract the cross section for real photons interaction

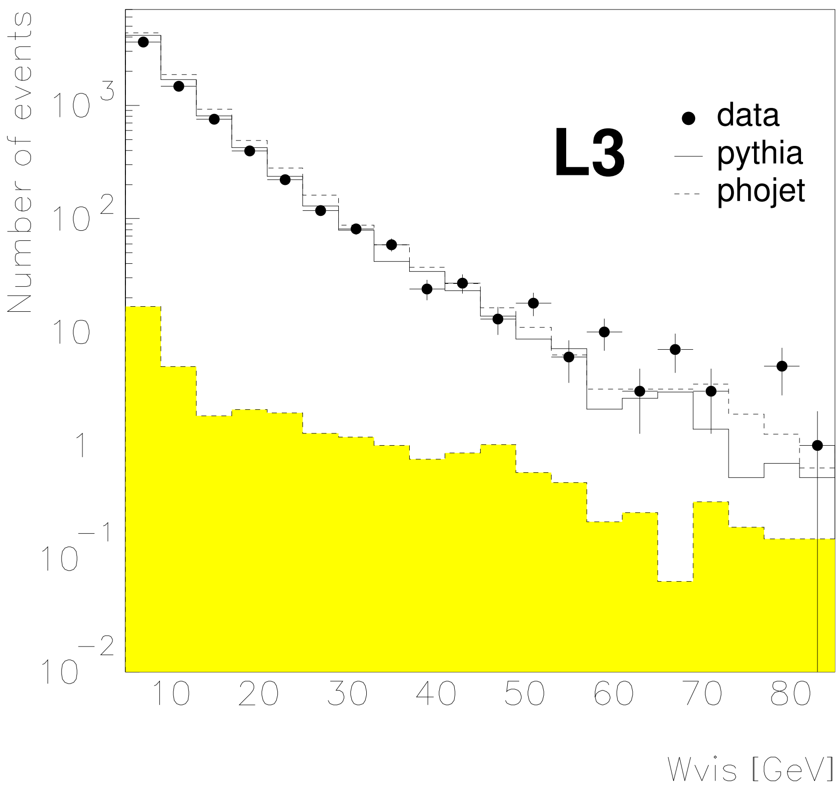
$$\underline{\sigma(W_{\gamma\gamma}, 0., 0.)}$$

Two Photon Physics

Event Sample: $\sqrt{s} = 130 \div 140\ GeV$ $\mathcal{L}$=$4.98\ pb^{-1}$

Event Selection

- Four good tracks with $P_\perp > 100\ MeV/c$
  (To eliminate leptonic channels)
- $0.5 < E_{ECAL} < 30\ GeV$; $E_{HCAL} < 20\ GeV$
  (To eliminate fermion pair hadrons)
- Anti Tag: $E_{LUMI} < 30\ GeV$ ($\Rightarrow < Q^2 > \simeq\ 0.025\ GeV^2$)
- Visible effective mass (W_{vis}) $> 5\ GeV$



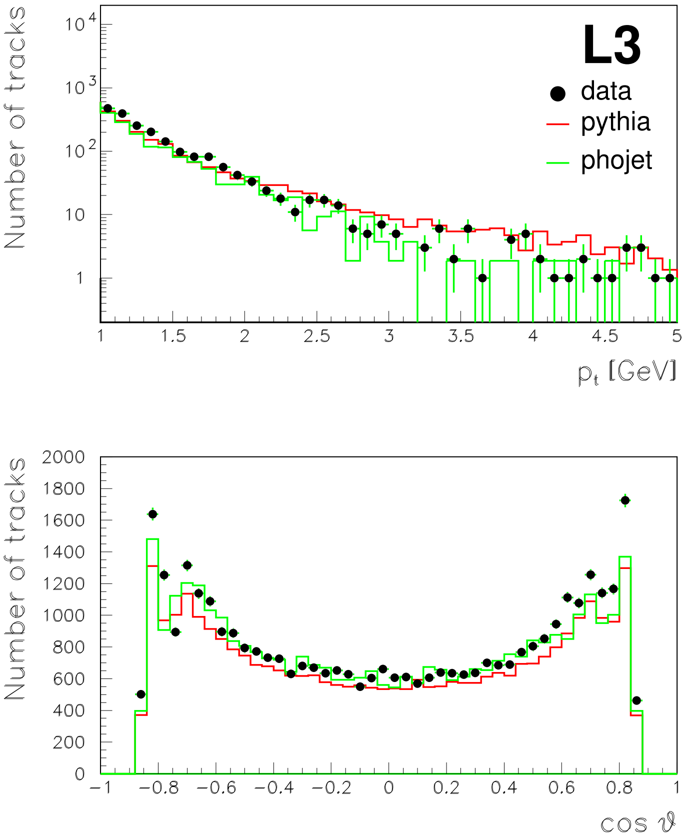
$\Rightarrow$ 6822 Events Selected

This measurement is optimally carried out at energies above the Z peak because has less “background” from the $Z \rightarrow hadrons$ decays

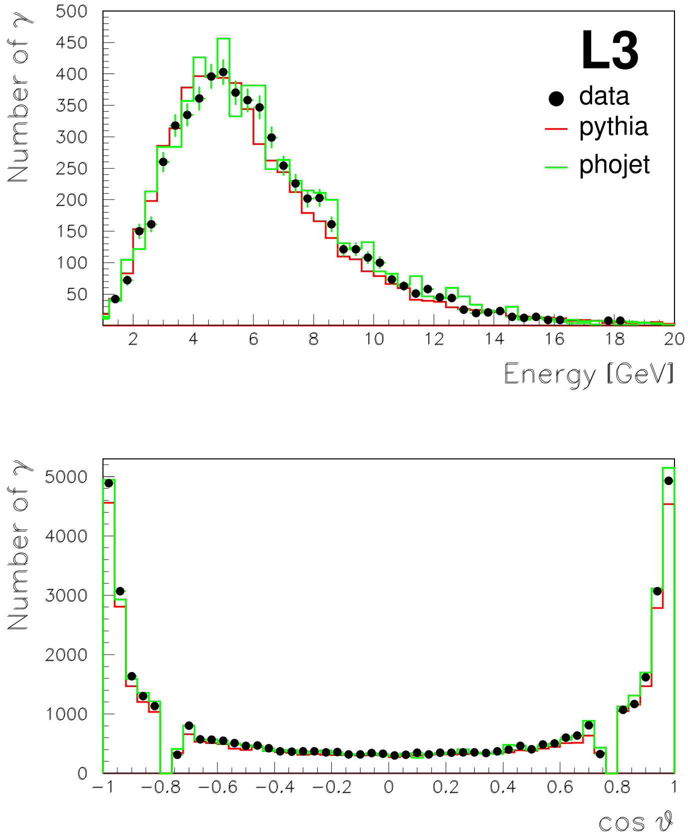
Two Photon Physics

W_{vis} of the event is calculated from the four momentum vectors of the tracks and the clusters reconstructed in the calorimeters.

Tec Tracks $(P_\perp)$



ECAL total Energy



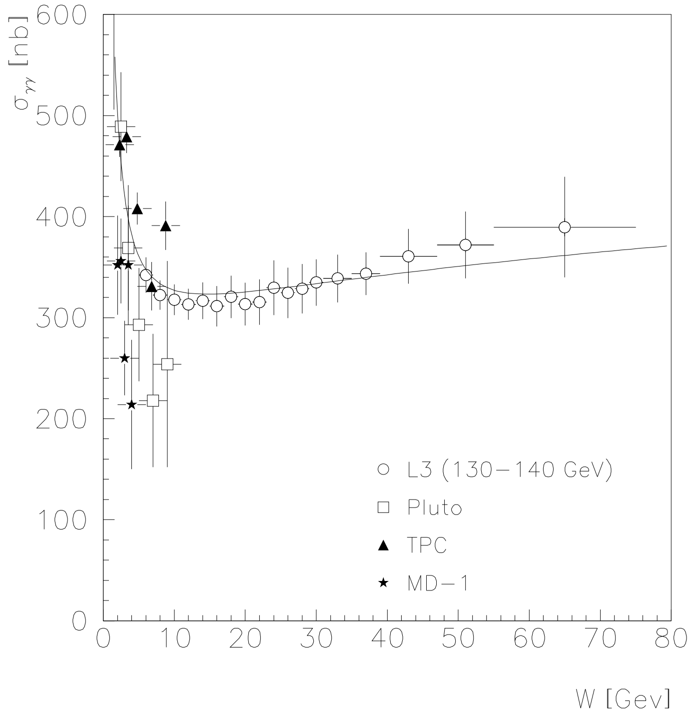
$$TEC : \Delta P_\perp / P_\perp \ = \ 1.8\% \cdot P_\perp(GeV)$$

$$ECAL : \Delta E/E \ = \ 1.5\%/\sqrt{E}(GeV) \ + \ 0.4\%$$

Monte Carlo events are normalized to the integrated luminosity of the data. The differences between the two generators and between the simulated events and the data are at most 30% *for some bins.*

Results (Preliminary)

L3 data plus previous results



- We have a strong correlation due to the unfolding procedure
- The cross section energy dependence can be interpreted by Regge models
- A universal parametrization for $hadron - hadron$ total cross section is:

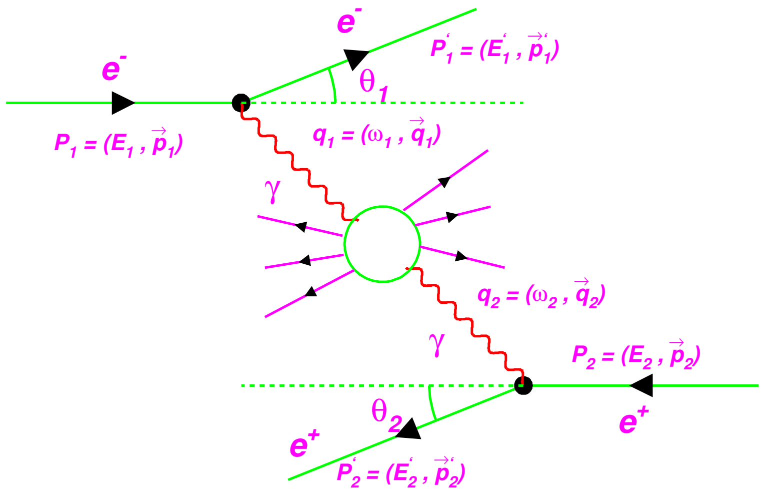
$$\sigma_{\gamma\gamma} = A \cdot W^{0.079} + B \cdot W^{-0.4678}$$

From the fit we get: $A = 181 \pm 4 \; nb$ $B = 575 \pm 25 \; nb$

- What is really important is that the cross section has been measured in the range $5 < W_{\gamma\gamma} < 75 \; GeV$ for the first time.

Current analysis of the 161 and 172 GeV and future LEP data will still improve the cross section measurement and will establish if the cross section is really rising with the energy or not.

$e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^- \; R$



Resonance: neutral meson, C = +1 ; J = 0 , 2, ...

(For high Q^2 it is also possible to have J=1)

$$\sigma(e^+e^- \rightarrow e^+e^- R) = \int \sigma(\gamma\gamma \rightarrow R) \cdot d\mathcal{L}_{\gamma\gamma}(W_{\gamma\gamma}, Q_1^2, Q_2^2)$$

$$\sigma(\gamma\gamma \rightarrow R) \;=\; 8\pi \frac{(2J_R+1)}{M_R}\,\Gamma^R_{\gamma\gamma}\,\frac{M_R\Gamma_R}{(W^2_{\gamma\gamma}-M_R^2)^2+M_R^2\Gamma_R}$$

$$\sigma(e^+e^- \rightarrow e^+e^- R) = \mathcal{K} \cdot \Gamma^R_{\gamma\gamma}$$

$$\sigma(e^+e^- \rightarrow e^+e^- R) = \frac{N(R) - N_{bkg}}{\mathcal{L}_{ee} \cdot \epsilon \cdot Br}$$

Final state particle energies are in the range $0.1 \div 1.$ GeV
$\Rightarrow$ L3 is very suitable for this analysis

By tagging the scattered electron is possible to evaluate the photon Q^2

Two Photon Physics

Motivation of the analysis $\gamma\gamma \rightarrow R$

- Since photons are not directly involved in strong interactions they are well suited to explore the structure of hadrons and the properties of their constituents. For instance the π^0 width is one of the most direct argument of the color degree of freedom of quarks.
- QCD predicts the existence of glueballs. An important signature for these states should be their small $\gamma\gamma$ coupling.
- QCD does not yet allow to prove or disprove the existence of four-quark states. Large $\gamma\gamma$ couplings are expected for some of these states.
- $\Gamma_{\gamma\gamma}$ of heavy quark system allow testing of QCD potential models.
- Light quark spectroscopy: information on the single-octet mixing for pseudoscalar and tensor mesons can be obtained.

In L3 at LEP1 the resonance studied are:

Resonance	final state	J^{PC}
η'(958)	$\pi^+\pi^-\gamma$	0^{-+}
a_2(1320)	$\pi^+\pi^-\pi^0$	2^{++}
f_2'(1525)	$\pi^+\pi^-\pi^+\pi^-$	2^{++}
η_c(2980)	12 channels	0^{-+}
χ_{c2}(3555)	e$^+$e$^-\gamma, \mu^+\mu^-\gamma$	2^{++}

Mass Spectrum

$\gamma\gamma \rightarrow \ \eta' \rightarrow \pi^+\pi^-\gamma$

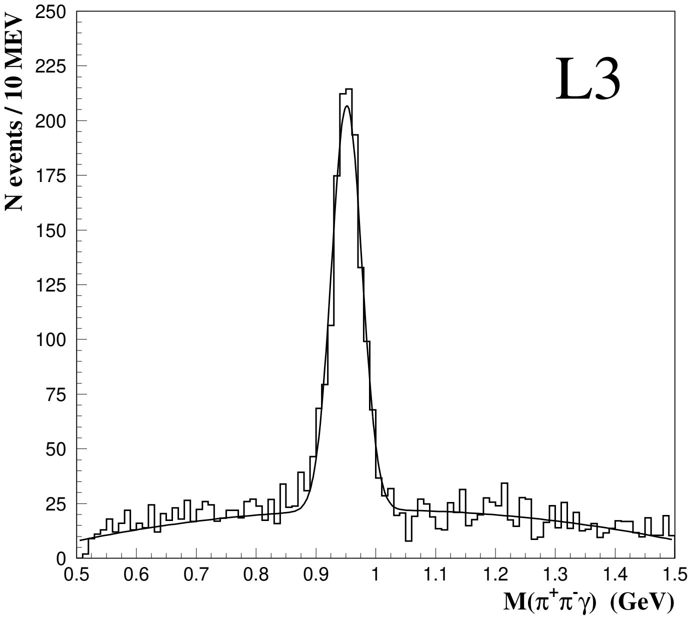
mass spectrum after the subtraction of

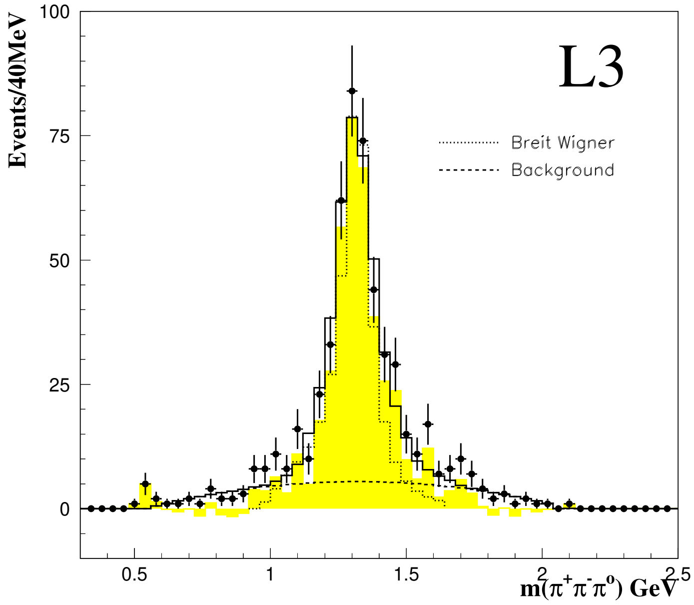
$a_2 \rightarrow \pi^+\pi^-\pi^0$

$\gamma\gamma \rightarrow \ a_2 \rightarrow \pi^+\pi^-\pi^0$

mass spectrum for events with

$M(\pi\pi^0) < (m_\rho + 250 MeV)$





$$\mathcal{L} = 97.7\ pb^{-1}$$
$$\epsilon \ = \ 2.5\%$$
$$N(\eta') \ = \ 1213 \pm 40$$
$$\Gamma_{\gamma\gamma}(\eta') = $$
$$4.38 \pm 0.14 \pm 0.51\ KeV$$

$$\mathcal{L} = 117.7\ pb^{-1}$$
$$\epsilon \ = \ 0.5\%$$
$$N(a_2) \ = \ 371 \pm 20$$
$$\Gamma_{\gamma\gamma}(a_2) = $$
$$1.03 \pm 0.06 \pm 0.10\ KeV$$

(η_c: Phys. Lett. B 318 (1993) 575)

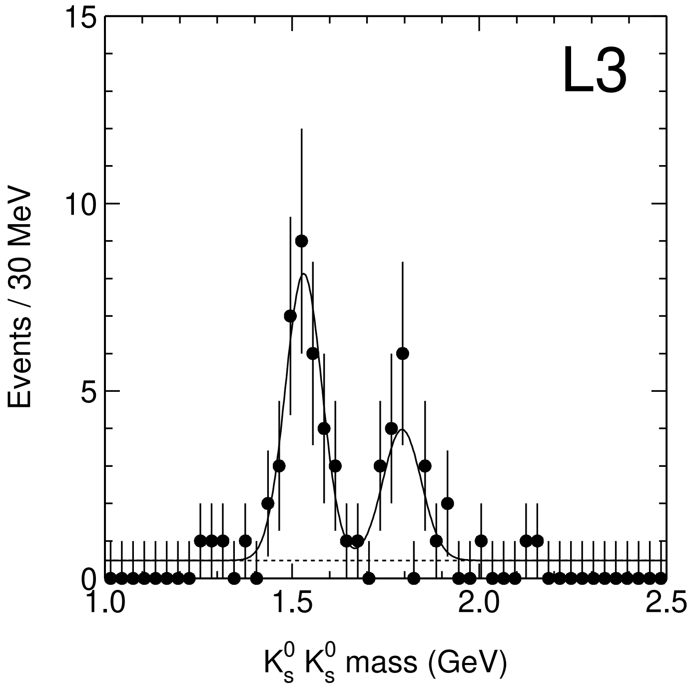
Two Photon Physics

Mass Spectrum

$\gamma\gamma \rightarrow \ f_2' \rightarrow K_S^0 K_S^0$

mass spectrum for events with

$| M_{(}\pi^+\pi^-) - M(K_S^0) \mid < 25 \ MeV$



$\mathcal{L} = 114.0 \ pb^{-1}$

$\epsilon \ = \ 1.9\%$

$N(f_2') \ = \ 31 \pm 6$

$\Gamma_{\gamma\gamma}(f_2') \times Br(f_2' \rightarrow K\bar{K}) =$

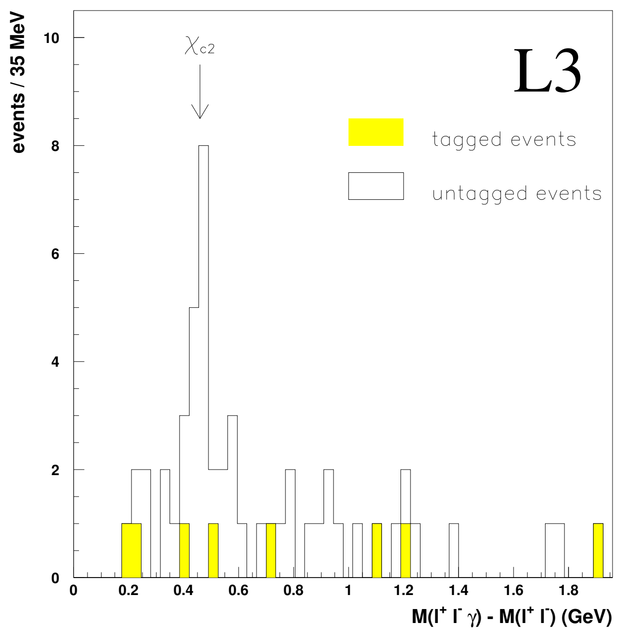
$0.093 \pm 0.018 \pm 0.022 \ KeV$

$\gamma\gamma \rightarrow \ \chi_{c2} \rightarrow l^+l^-\gamma$

$M(l^+l^-\gamma) - M(l^+l^-)$ spectrum

we expect a peak at

$(M(\chi_{c2}) - M(J/\psi))$ = 0.459 GeV



$\mathcal{L} = 142.0 \ pb^{-1}$

$\epsilon \ = \ 7.6\%$

$N(\chi_{c2}) \ = \ 11 \pm 4$

$\Gamma_{\gamma\gamma}(\chi_{c2}) =$

$1.5 \pm 0.6 \pm 0.3 \ KeV$

We look forward for the 500 pb^{-1} foreseen at LEP 2

Neutrino Counting

Before the LEP startup a fourth fermion family was not excluded:

N_ν	$<$ 4.8	95% C.L.	Supernova SN1987a
N_ν	$<$ 3.6	95% C.L.	Abundance of ^{4}He
N_ν	$<$ 4.8	90% C.L.	$p\bar{p}$ collider
N_ν	$<$ 3.9	90% C.L.	e^+e^- collider

At LEP 1 ($\sqrt{s} \simeq M_Z$) N_ν is extracted by measuring the Z $\rightarrow \nu\bar{\nu}$ partial width. Two methods are used:

1. Indirect measurement of $\Gamma(\mathrm{Z} \rightarrow \nu\bar{\nu})$.

   We get Γ_{inv} by subtracting the partial widths into visible channel from the Z total width:

   $$\Gamma_{\nu\nu} = \Gamma_{\mathrm{inv}} = \Gamma_{\mathrm{Z}} - \Gamma_{\mathrm{had}} - 3 \cdot \Gamma_\ell$$

   - We assume that the visible channels have all been properly taken into account
   - Precision is limited by the luminosity systematic error and by the selection efficiencies

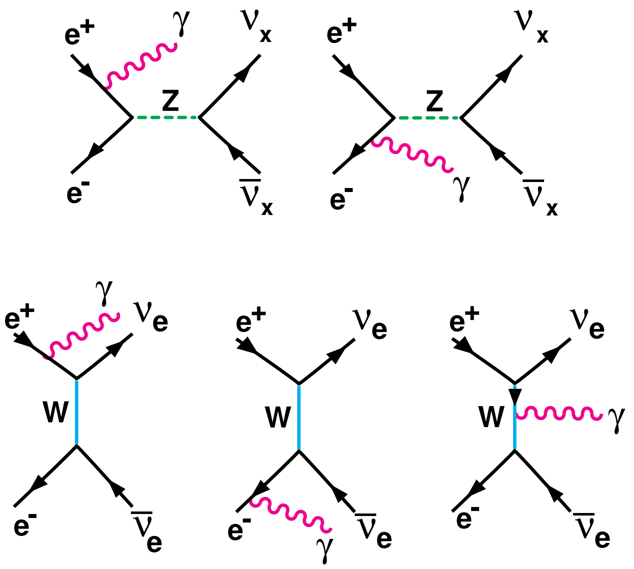
2. Direct measurement of the the decays Z $\rightarrow \nu\bar{\nu}$.
   Z decays into invisible particles are identified by means of the "single photon" from the reaction $e^+e^- \rightarrow \gamma\mathrm{Z} \rightarrow \nu\bar{\nu}\gamma$.

   - We have less assumption on SM, but the statistics is limited
   - Great experimental difficulties to detect low energy photons

Neutrino Counting

Tree-level Feynman diagrams

$e^+e^- \longrightarrow \nu\,\bar{\nu}\,\gamma$



$$\sigma_0(s) = \frac{G_F^2 s}{12\pi} \cdot (N_\nu \cdot \frac{(g_v^2+g_a^2)}{[1-s/M_z^2]^2+\Gamma_z^2/M_z^2} + 2 + \frac{2(g_v+g_a)[1-s/M_z^2]}{[1-s/M_z^2]^2+\Gamma_z^2/M_z^2})$$

The W contribution at $\sqrt{s} \simeq m_Z$ is of the order $4 \div 5\%$ of σ_{total}.

We used a second order order Monte Carlo (C.Maña et al.) and an analytical formula using the structure function approach.

$$\sigma(s) = \int_{x_{min}}^{1} dx \int_{-y_{max}}^{y_{max}} dy H(x,y,s)\sigma_0((1-x)s)$$

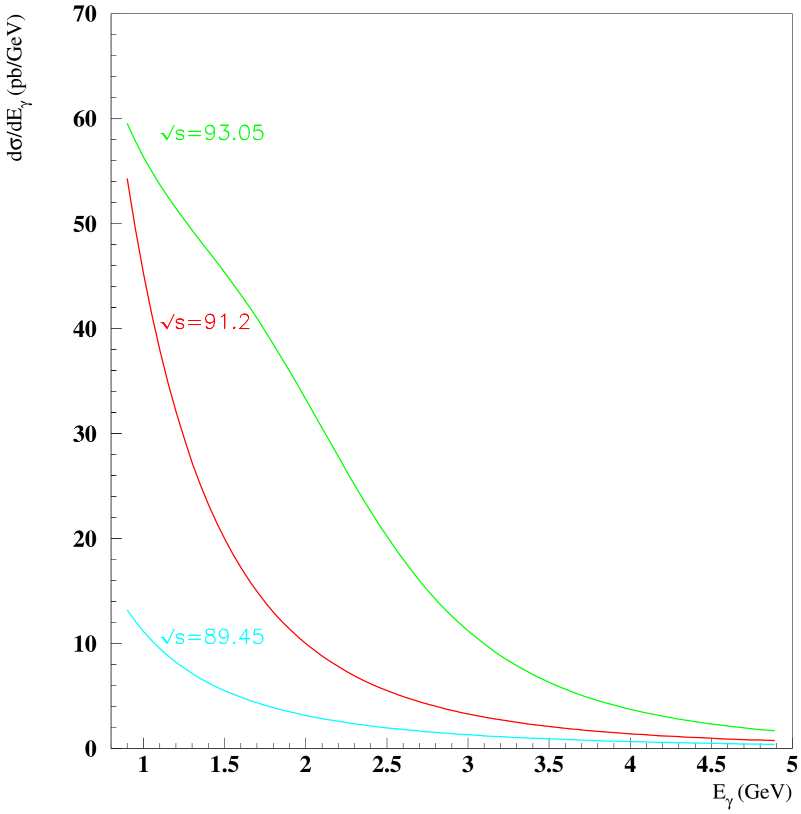
$x = 2E_\gamma/\sqrt{s}$ and $y = \cos(\theta_\gamma)$

CAVEAT: ν_X can be any neutral weakly interacting particle with $M_\nu \ < \ E_{beam}$ (for instance a Neutralino)

Neutrino Counting

Key points of the measurements

Photon energy spectrum



At $\sqrt{s} \sim m_Z$ the $\frac{d\sigma}{dE_\gamma}$ falls very rapidly as E_γ increases

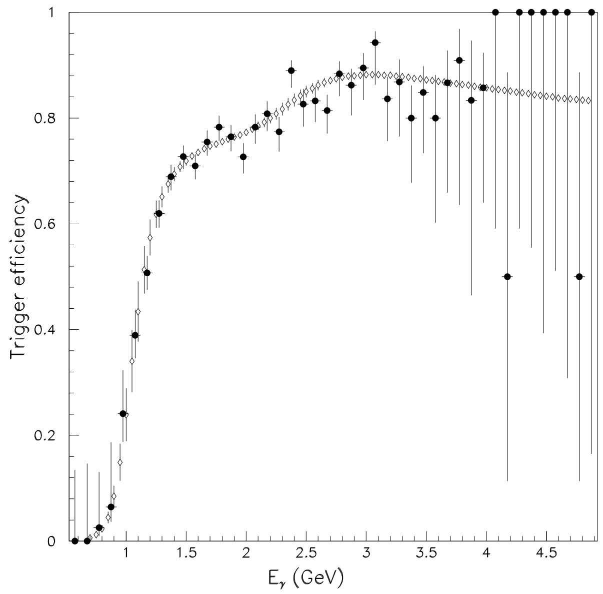
$\Downarrow$

- Trigger on low energy single photons (O(1 GeV))
- Very good knowledge of the absolute energy scale around 1 GeV
- Veto at the lowest possible ϑ angle to cope with the background coming from $e^+e^- \to e^+e^-\gamma$
- Detector hermeticity
- Control of the cosmic rays background

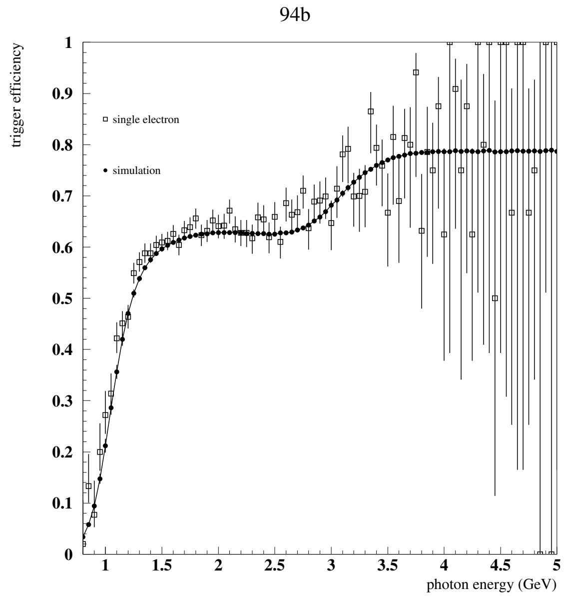
Neutrino Counting

Trigger efficiency

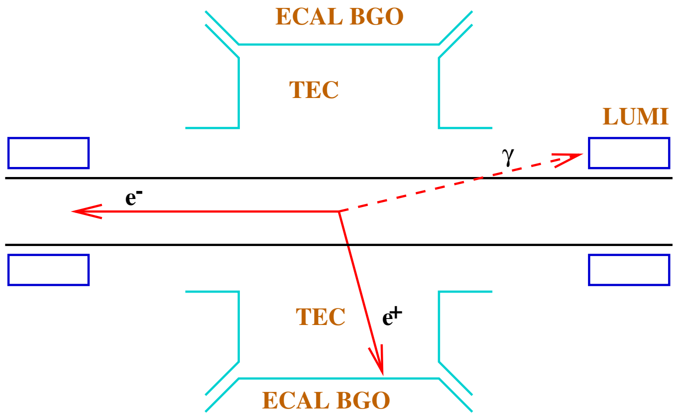
91 Data



94 Data



Single γ trigger efficiency is measured by using single electron events that are triggered by an independent trigger.



Trigger efficiency is also simulated by taking into account the status of the trigger channels, the resolution and calibration of the trigger ADC, the electronic noise and the photon shower profile

The systematic error induced by the trigger efficiency is $< 2\%$.

Neutrino Counting

Event Selection

1. Fiducial volume: $45^\circ < \theta_\gamma < 135^\circ$, $E_\gamma > 1$GeV

2. Veto against detector activity:
   - Only one energy deposit in the BGO barrel.
   - No TEC tracks
   - No activity in muon spectrometer
   - Less than 3 GeV in HCAL
   - Less than 1.5 GeV in the Luminosity monitors
   - No activity in Active Lead Ring

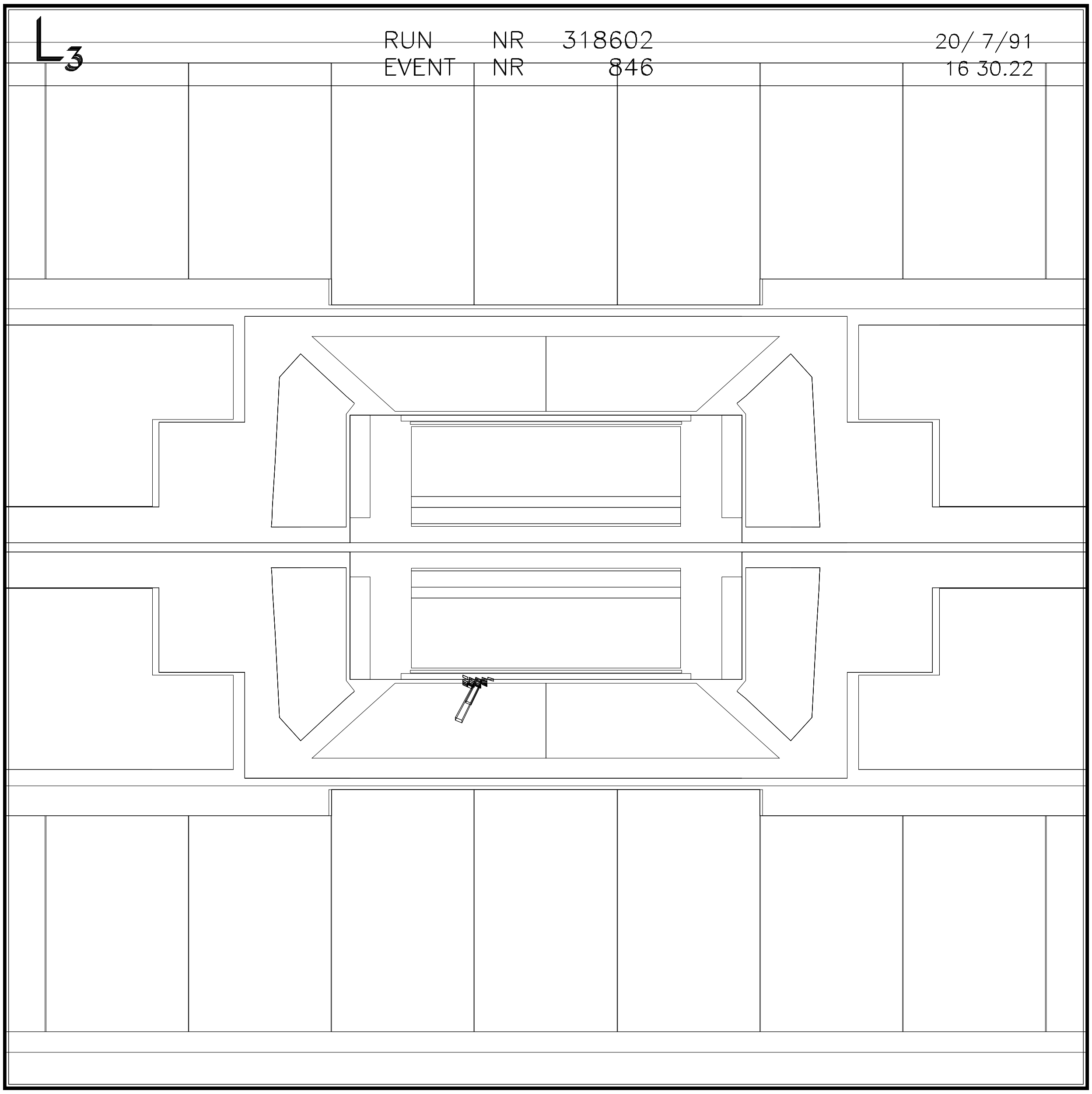
3. Electromagneticity of the BGO cluster

   The transverse shower profile of the BGO cluster must be consistent with what expected from the one produced by photons coming from the interaction vertex

Main Backgrounds

- $e^+e^- \to (e^+e^-)\gamma)$
- $e^+e^- \to (\gamma\gamma)\gamma$
- 2γ physics: $e^+e^- \to e^+e^- R \to e^+e^- \gamma X$
- $e^+e^- \to e^+e^- \ell^+\ell^- \gamma$
- Bremsstrahlung of cosmic muons

A Single Photon Candidate

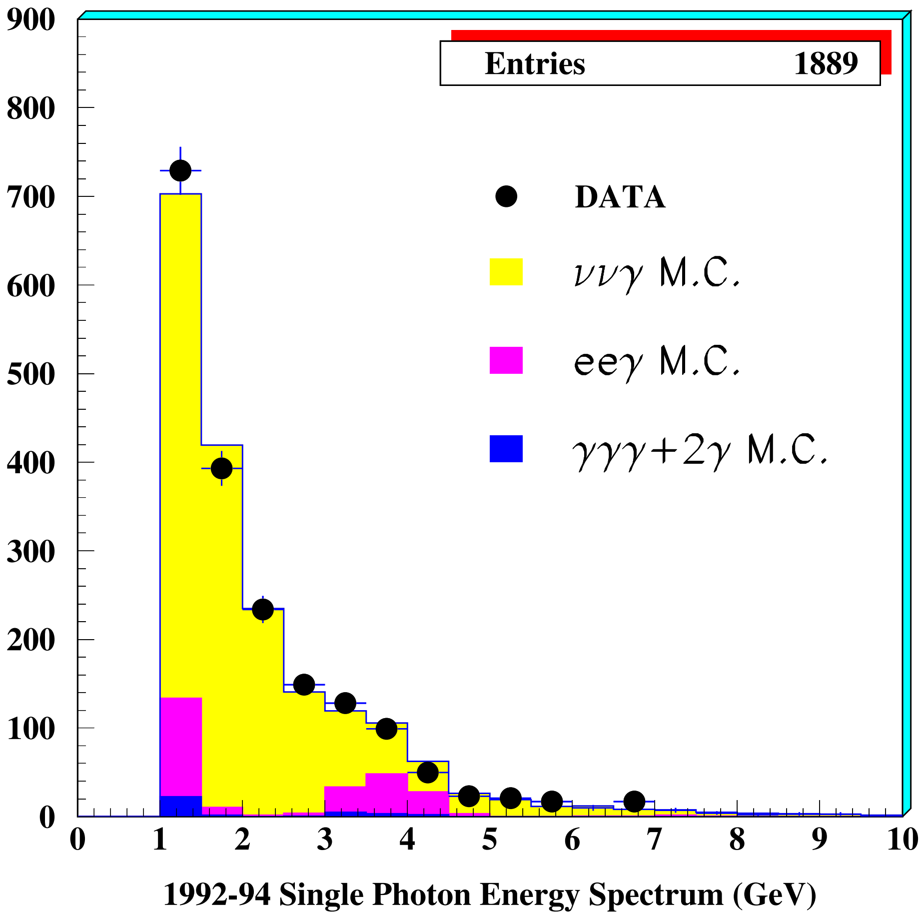


To see nothing is more difficult than to see something

Neutrino Counting

Event Sample

	$\int \mathcal{L}\,dt$ (pb^{-1})	data	predicted events	
			$\nu\bar{\nu}\gamma$	background
1991	9.57	202	169.6	30.0
1992	20.52	456	381.3	69.5
1993	29.90	731	644.4	88.9
1994	39.88	702	596.1	110.7
Total	99.87	2091	1791.4	299.1



Neutrino Counting

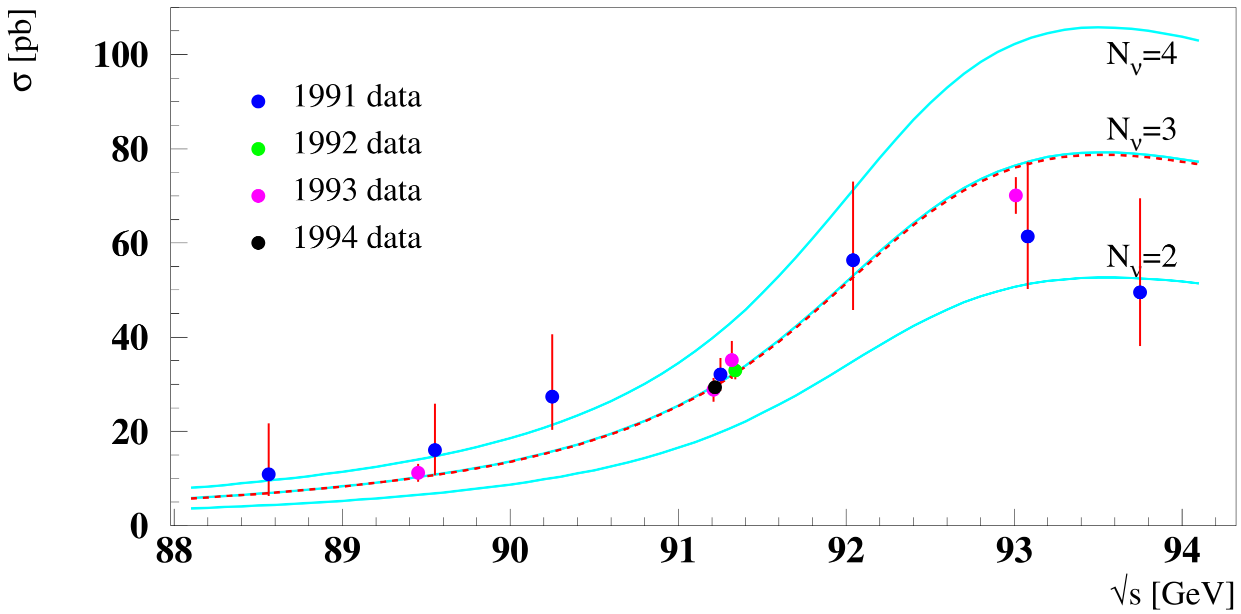
Results:(Preliminary)

From a likelihood fit to the $91 \div 94$ data we extract the invisible width:

$$\boxed{\Gamma_{\text{inv}} = 498. \pm 12.\ \text{(stat.)} \pm 12.\ \text{(sys.)}\ MeV}$$

$$\Rightarrow \quad \boxed{N_\nu = 2.98 \pm 0.07\ \text{(stat.)} \pm 0.07\ \text{(sys.)}}$$

Cross section dependence on $\sqrt{s}$



With the indirect method (Line Shape 90÷ 95 data)
L3 measures $N_\nu = 3.001 \pm 0.017$

Neutrino Counting

High energy single photon

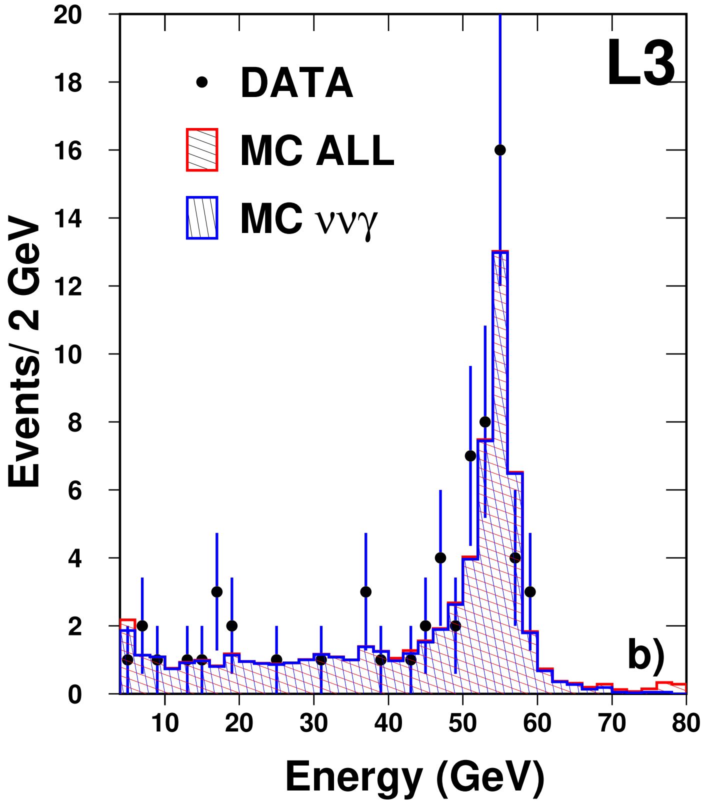
Single photon at CMS energies above the Z peak could be the signature for new physics, like for instance:

$$e^+e^- \to Z \to \chi_1^0 \ \chi_2^0$$
$$\lfloor \gamma \ \chi_1^0$$

In this case the main background comes from $\nu\bar{\nu}\gamma$ events.

We then search for an excess of single photon events

(PRELIMINARY) *Single photon energy at* $\sqrt{s} = 161 \ GeV$



Data are consistent with what we expect from $\nu\bar{\nu}\gamma$ signal.

Conclusions

- Fermion pair production cross sections and asymmetries have been measured at energies above the Z pole. The SM still holds very well.

- LEP2 is an ideal place to study two photon physics and produce very interesting physics results.

- One of the major outcome of the LEP1 physics program is the determination of the number of fermion families.
  L3 has measured this number also with the single photon method, obtaining:

$$N_\nu = 2.98 \pm 0.10$$

- L3 has measured the W mass at the 161 GeV run:

$$M_W = 80.85^{+0.49}_{-0.42} \pm 0.10\ GeV$$

- No evidence for new physics yet