

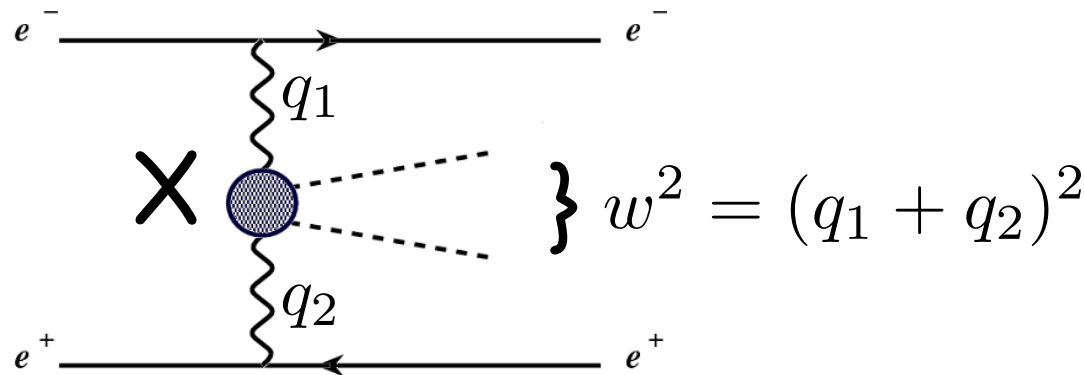
# Meson production in $\gamma\gamma$ interactions at DAΦNE

Ivan Prado Longhi on behalf of the KLOE/KLOE-2  
collaboration

IFAE Perugia, 04/28/2011



$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$$



$$X: J^{PC} = 0^{\pm+}$$

$X: \pi^0, \eta, \eta'$  pseudoscalars

$\sigma(600), f_0(980), a_0(980)$  scalars

$$\sigma(e^+e^- \rightarrow e^+e^-X) = \int dz \frac{dL_{\gamma\gamma}}{dz} \sigma_{\gamma\gamma \rightarrow X}(z)$$

$$z = \frac{w^2}{4E^2}$$

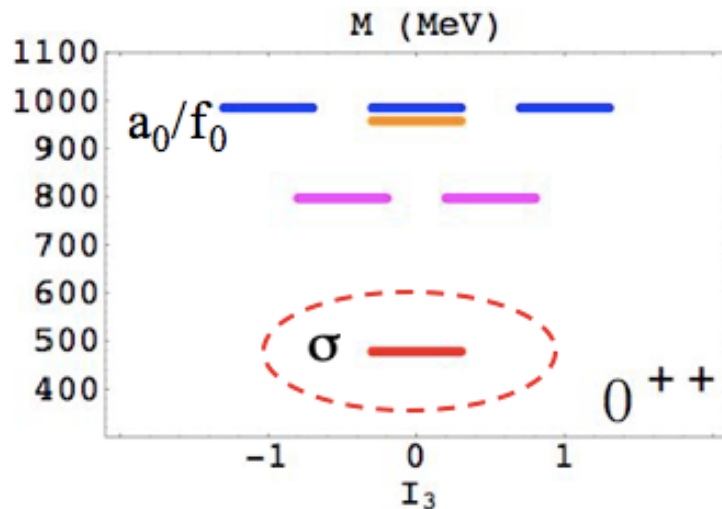
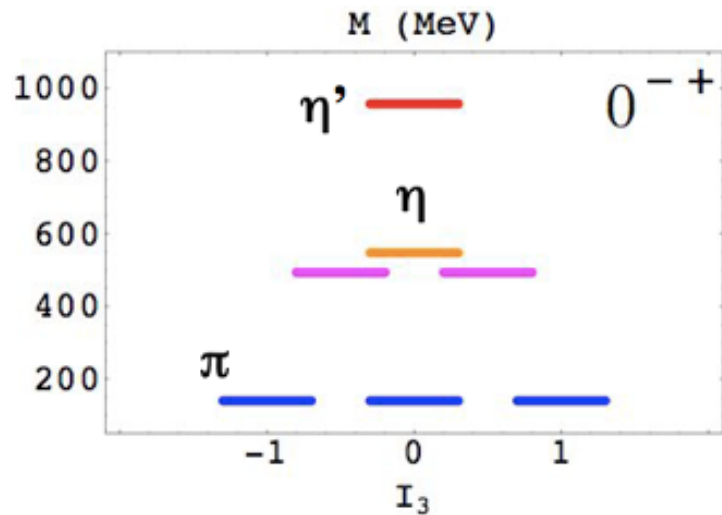
$\gamma\gamma$  cross section

$\gamma\gamma$  flux function (luminosity function)

Electron  $e$   
and positron  
emit virtual photons  
at small angles  
(DEPA Approx)

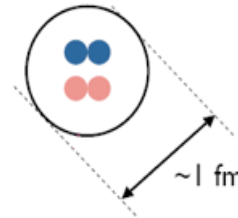
Final state  $e^+e^-$  not tagged

# Scalar and pseudoscalar mesons

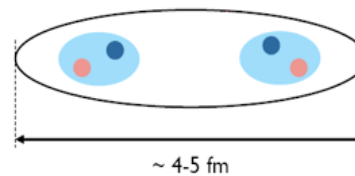


Scalars are a puzzling sector!

Inverted mass spectra exclude a quark-antiquark interpretation for the scalar nonet



✓ Diquark-antidiquark?  
(Jaffe, Achasov, Maiani et al.)



✓  $K\bar{K}$  molecules?  
(Weinstein-Isgur, Close et al., Kalashnikova et al.)

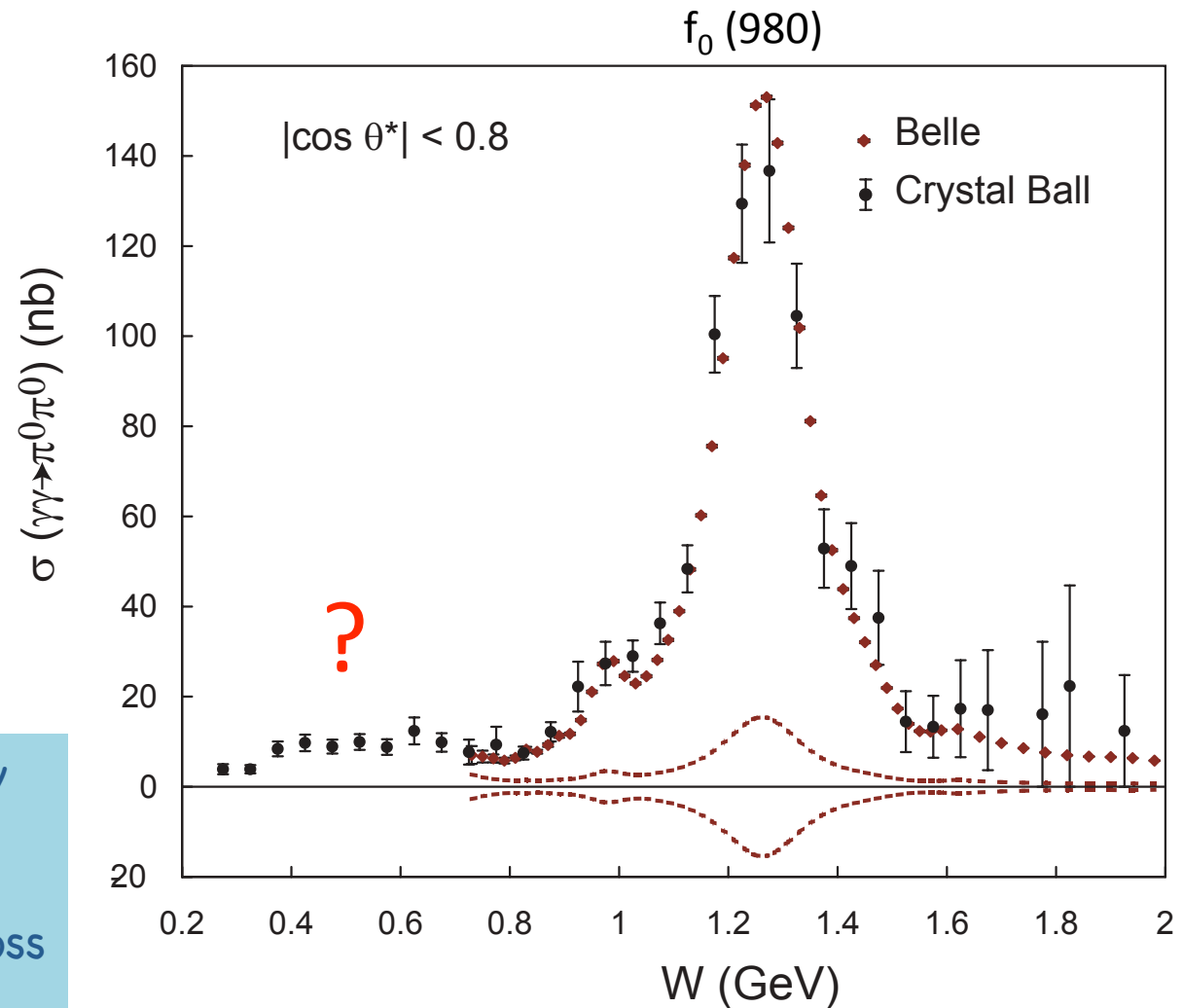
✓ Does the iso-singlet  $\sigma(600)$  exist?  
Evidences from E791, BES and CLEO  
(Dalitz plot analyses of  $D$  and  $J/\psi$  decays)

# Searching for $\sigma$ in $\gamma\gamma$ experiments

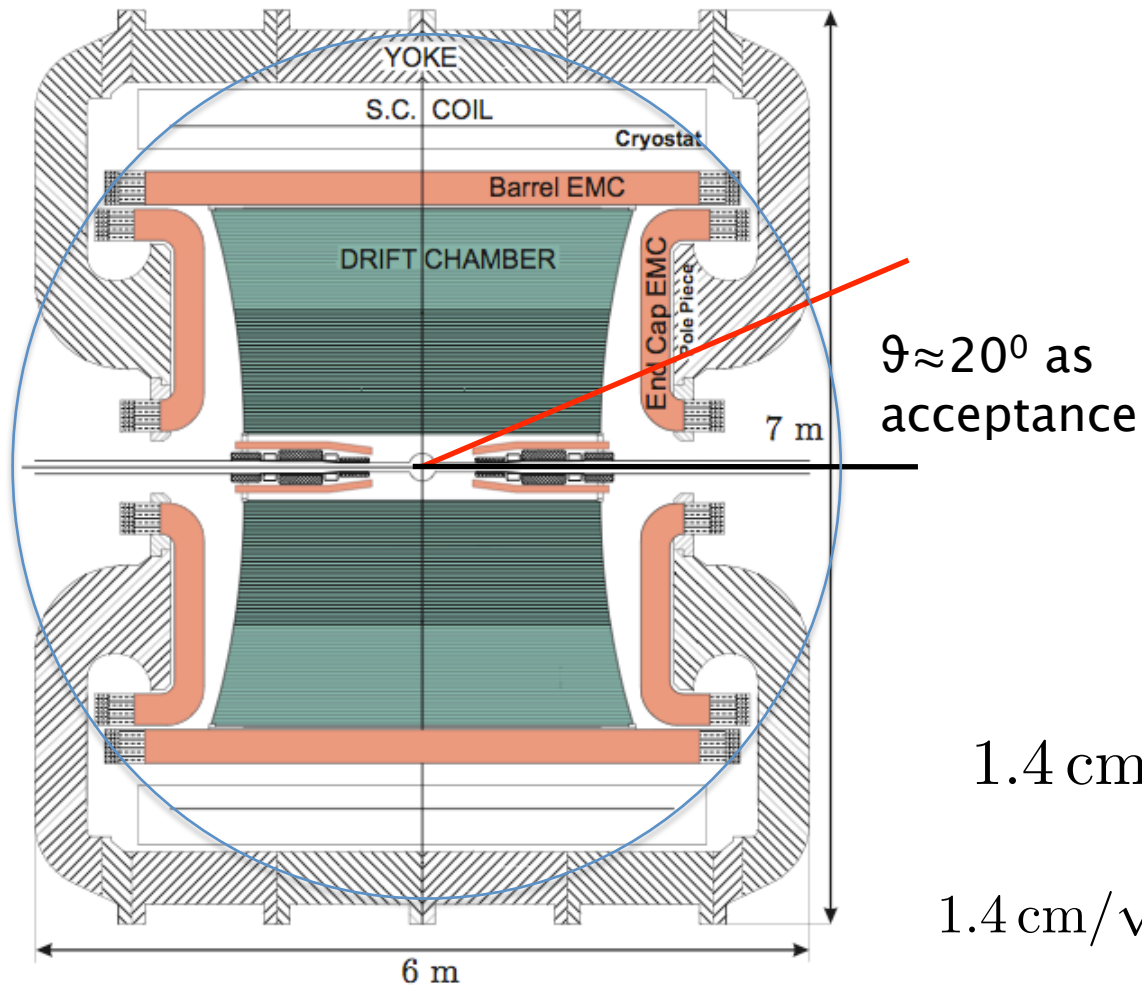
$\gamma\gamma \rightarrow \pi^0\pi^0$   
experiments in no  
final state  $e^\pm$   
tagging mode

- Jade (1990) @ PETRA
- Crystal Ball (1990) @ DORIS II
- Belle (2008) @ KEKB

Crystal Ball is the only experiment which explored the region  $w < 0.6$  GeV giving a cross section (in 1990!)



# The KLOE experiment



## *e.m. cluster resolution*

### Time resolution

$$\sigma_T \simeq \frac{57 \text{ ps}}{\sqrt{E(\text{GeV})}} \oplus 100 \text{ ps}$$

### Energy resolution

$$\frac{\sigma_E}{E} \simeq \frac{0.06}{\sqrt{E(\text{GeV})}}$$

### Space resolution

$$1.4 \text{ cm} \quad \sigma_{xy}(\text{barrel}), \sigma_x(\text{endcap})$$

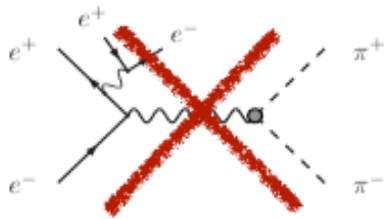
$$1.4 \text{ cm}/\sqrt{E \text{ GeV}} \quad \sigma_z(\text{barrel}), \sigma_y(\text{endcap})$$

# $\gamma\gamma$ physics at DAΦNE (KLOE experiment)

✓  $e^+e^- \rightarrow e^+e^-\sigma, \sigma \rightarrow \pi^0\pi^0$

Neutral pions channel chosen because:

- **NO** radiative return to  $\rho$  mass



- Continuum  $\gamma^*\gamma^* \rightarrow \pi^0\pi^0$  reduced respect to  $\gamma^*\gamma^* \rightarrow \pi^+\pi^-$
- **NO** annihilation  $e^+e^- \rightarrow \pi^0\pi^0$

✓  $e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow \pi^0\pi^0\pi^0$

Similar analysis, to check MC,  $\gamma\gamma$  luminosity function

Data taking conditions

$$\sqrt{s} = 1 \text{ GeV}$$

(reduction of background from  $\phi$  decays)

Integrated Luminosity

$$\mathcal{L} \simeq 240 \text{ pb}^{-1}$$

Preselctions for both analyses:

- Trigger
- Background rejection filter
- $\gamma\gamma$  filter

# $e^+e^- \rightarrow e^+e^- \sigma \rightarrow e^+e^- \pi^0\pi^0 \rightarrow e^+e^- 4\gamma$ : Analysis

We ask for 4 neutral prompt clusters with:

- $E \geq 15$  MeV
- $23^\circ < \theta < 157^\circ$ , angle of each  $\gamma$  pair  $> 30^\circ$

## Analysis cuts

$\gamma\gamma$  pairing:  $\chi^2_{\pi\pi} < 4$

$$\chi^2_{\pi\pi} = \frac{(m_{\pi^0} - m_{ij})^2}{\sigma_{ij}^2} + \frac{(m_{\pi^0} - m_{kl})^2}{\sigma_{kl}^2}$$

4  $\gamma$  only

$\chi^2_{\dagger} < 12$  (promptness)

$$\chi^2_{\dagger} = \sum_{\gamma} \frac{(r_{\gamma}/c - t_{\gamma})^2}{\sigma_{t,\gamma}^2}$$

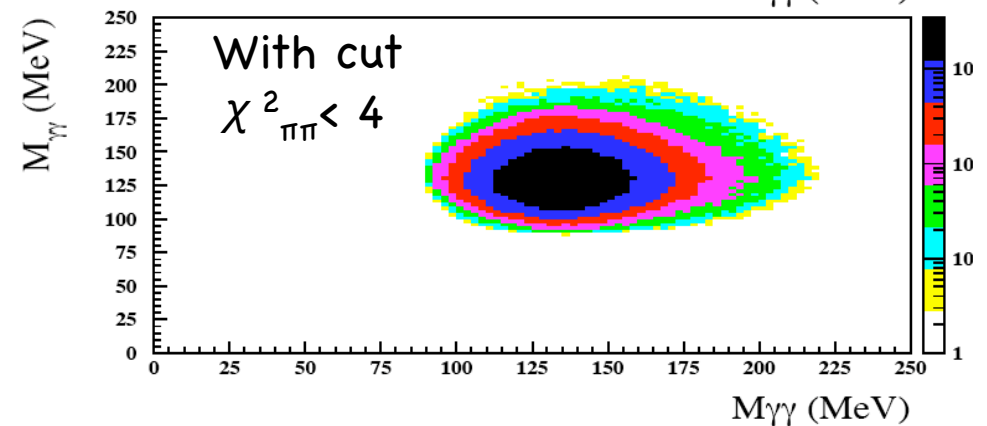
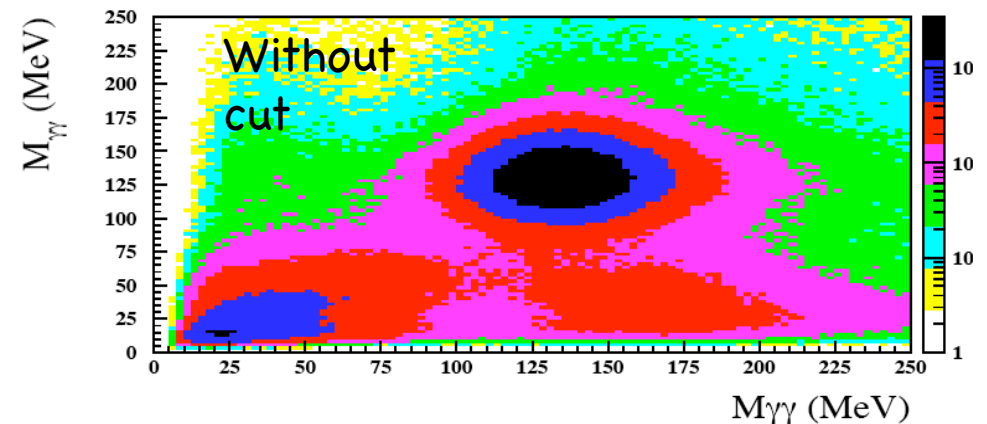
NO tracks

$R = (\sum_{\gamma} E_{\gamma}) / E_{\text{tot}} > 0.75$

$\sum_{\gamma} p_{\text{T}} < 120$  MeV

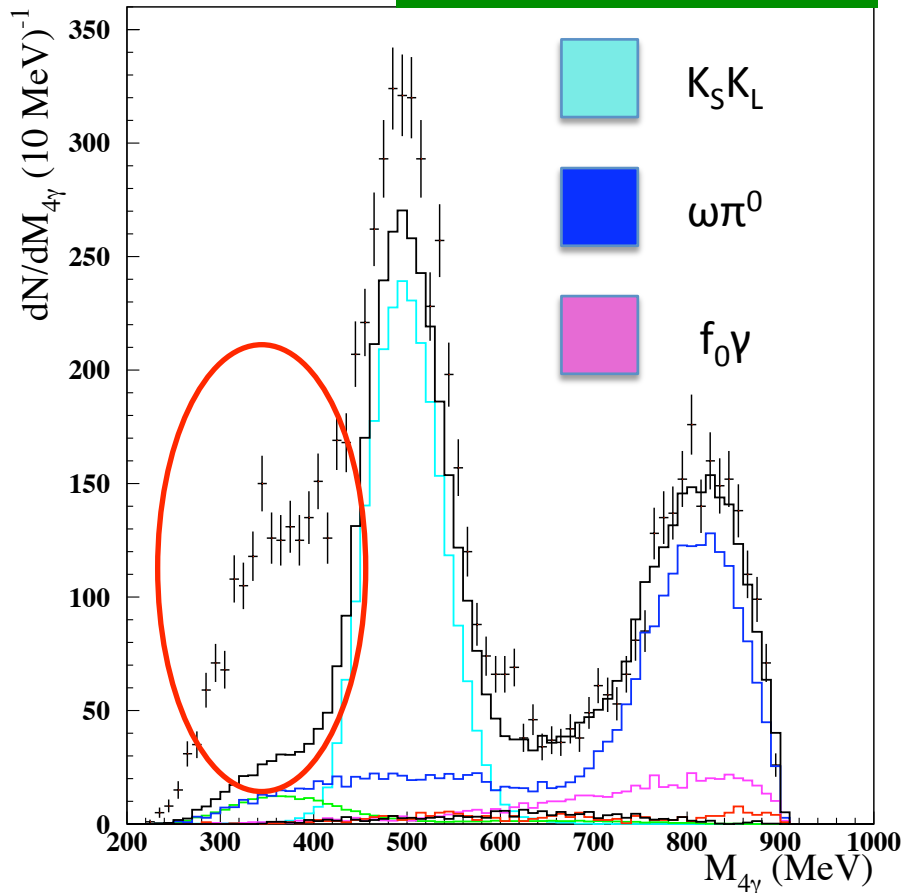
Cuts on  $\gamma$  energies

2  $\pi^0$  selection:  
 $m_{\gamma\gamma}$  vs  $m_{\gamma\gamma}$  (data)



# Data and background $m_{4\gamma}$ spectra

8090 events after selections



4 $\gamma$  invariant mass distribution

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

Background distributions normalization obtained performing a fit with expected numbers of events as starting values

	$\epsilon$	$\sigma$ (nb)	$n = \mathcal{L}\sigma\epsilon$	$n_{fit}$
$K_S K_L$	$7.5 \times 10^{-3}$	1.28	2328	2386
$\eta \rightarrow 3\pi^0$	$2.8 \times 10^{-3}$	0.284	193	213
$\omega\pi^0$	$1.4 \times 10^{-2}$	0.55	1867	2363
$f_0\gamma$	$2.9 \times 10^{-2}$	0.17	1204	510
$a_0\gamma$	$5.8 \times 10^{-3}$	0.11	155	145
$\gamma\gamma$	$2 \times 10^{-6}$	360	175	160
			5922	5777
Data			8090	

Expected values

Fit values



# $e^+e^- \rightarrow e^+e^- \eta, \eta \rightarrow 3\pi^0$

## Analysis cuts

- 6 and only 6 neutral prompt clusters, with  $E \geq 15$  MeV and  $20^\circ < \vartheta < 160^\circ$
- no tracks
- $\gamma\gamma$  pairing:  $\chi^2_{\gamma\gamma} < 10$
- $E_{\gamma 1} < 260$  MeV
- Kinematic fit and cut on  $\chi^2_{\eta}$

$$m^2_{6\gamma} = m^2_{\eta}$$

$$t_{\gamma} - |\underline{r}_{\gamma}| / c = 0 \text{ for } 6\gamma$$

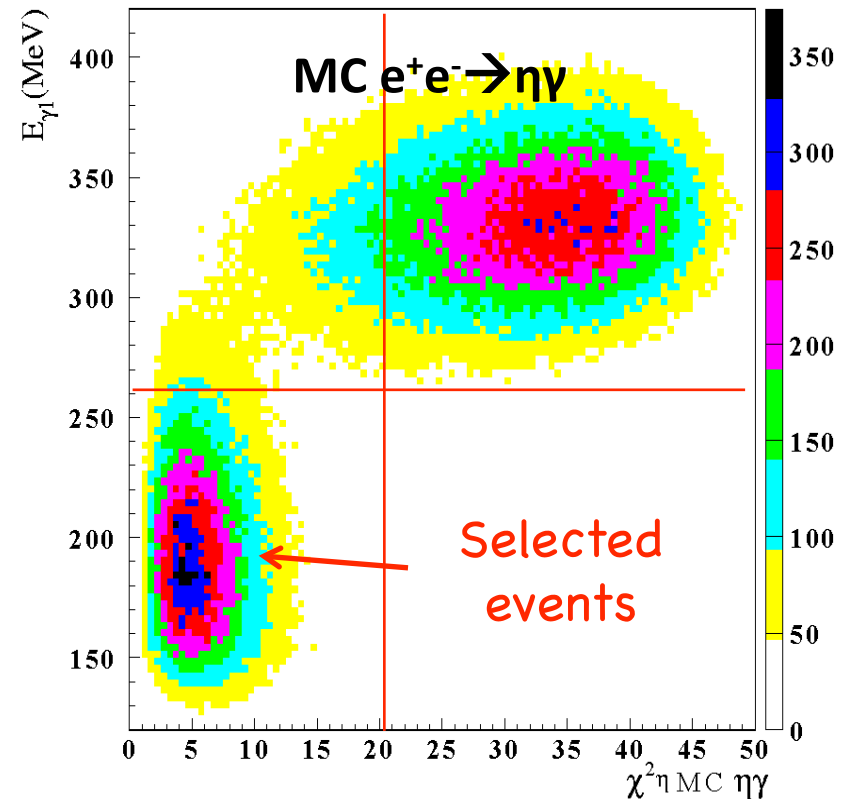
5 variables  $\times$  6 $\gamma$

7 constraints

Main bkg processes:

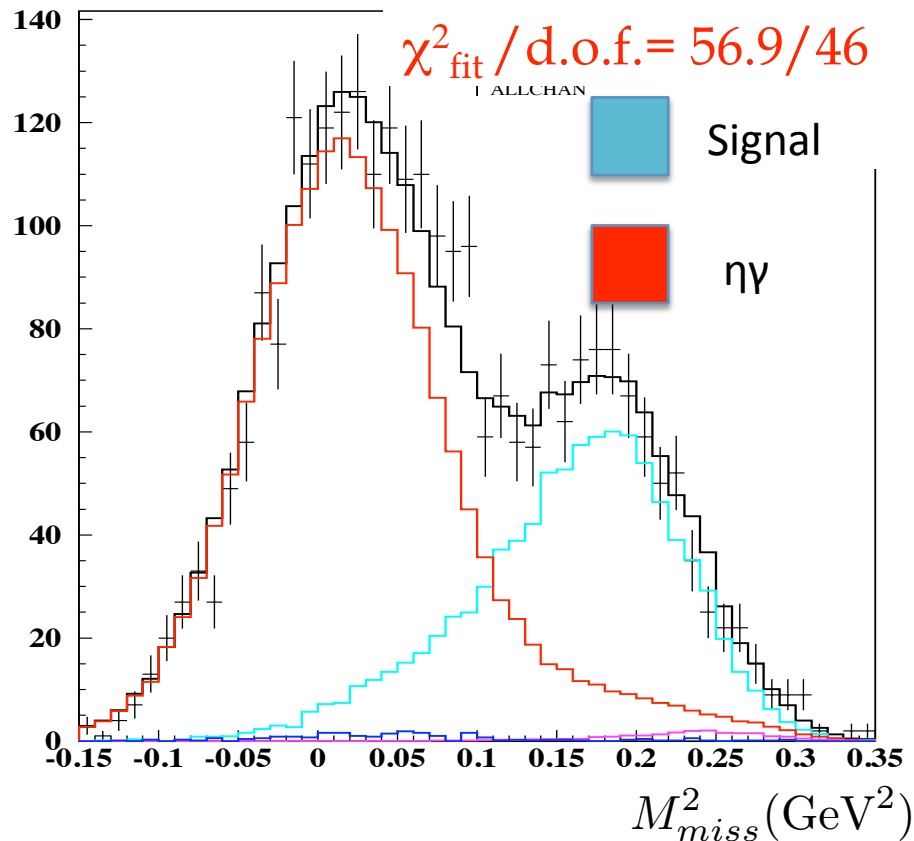
$$e^+e^- \rightarrow \eta\gamma, e^+e^- \rightarrow \omega\pi^0, e^+e^- \rightarrow K_S K_L$$

$E_{\gamma 1}$  vs  $\chi^2_{\eta}$



# $e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow \pi^0\pi^0\pi^0$ : fit to $M_{miss}^2$

2725 events after selections



$e^+e^- \rightarrow \omega\pi^0$  fixed,  
other backgrounds left free

contribution mainly  
from  $\gamma\gamma \rightarrow \eta$  and  $e^+e^- \rightarrow \eta\gamma$

From the fit:

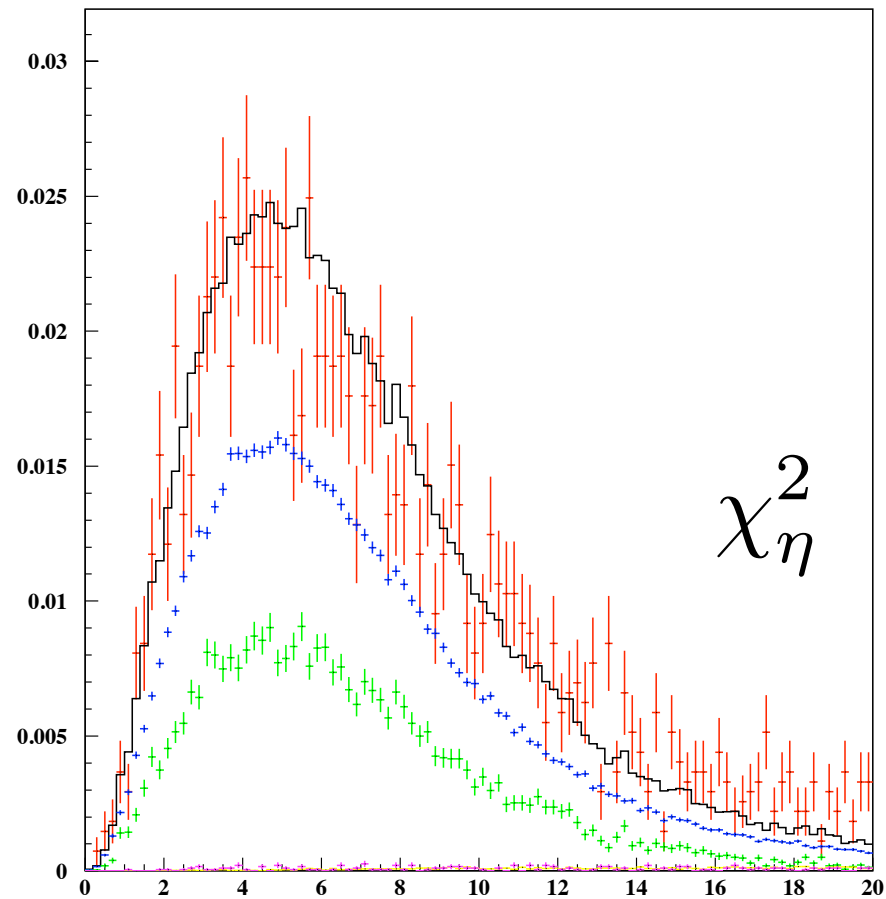
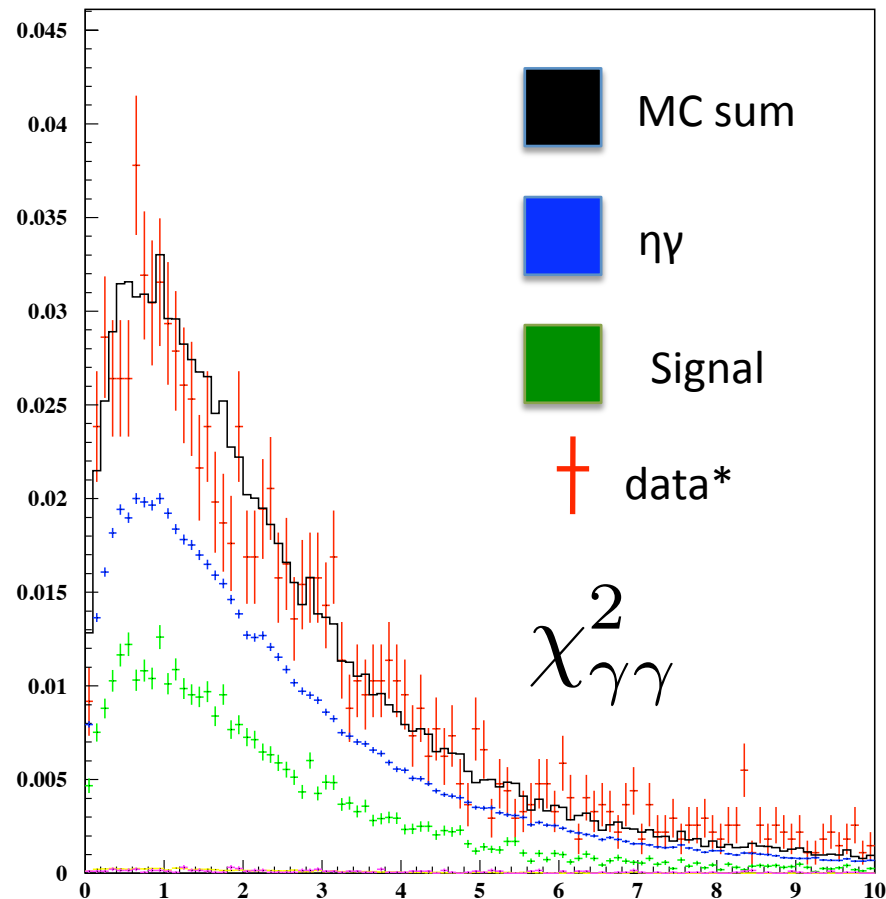
$$N(\gamma\gamma \rightarrow \eta \rightarrow \pi^0\pi^0\pi^0) = 921 \pm 35$$

PRELIMINARY

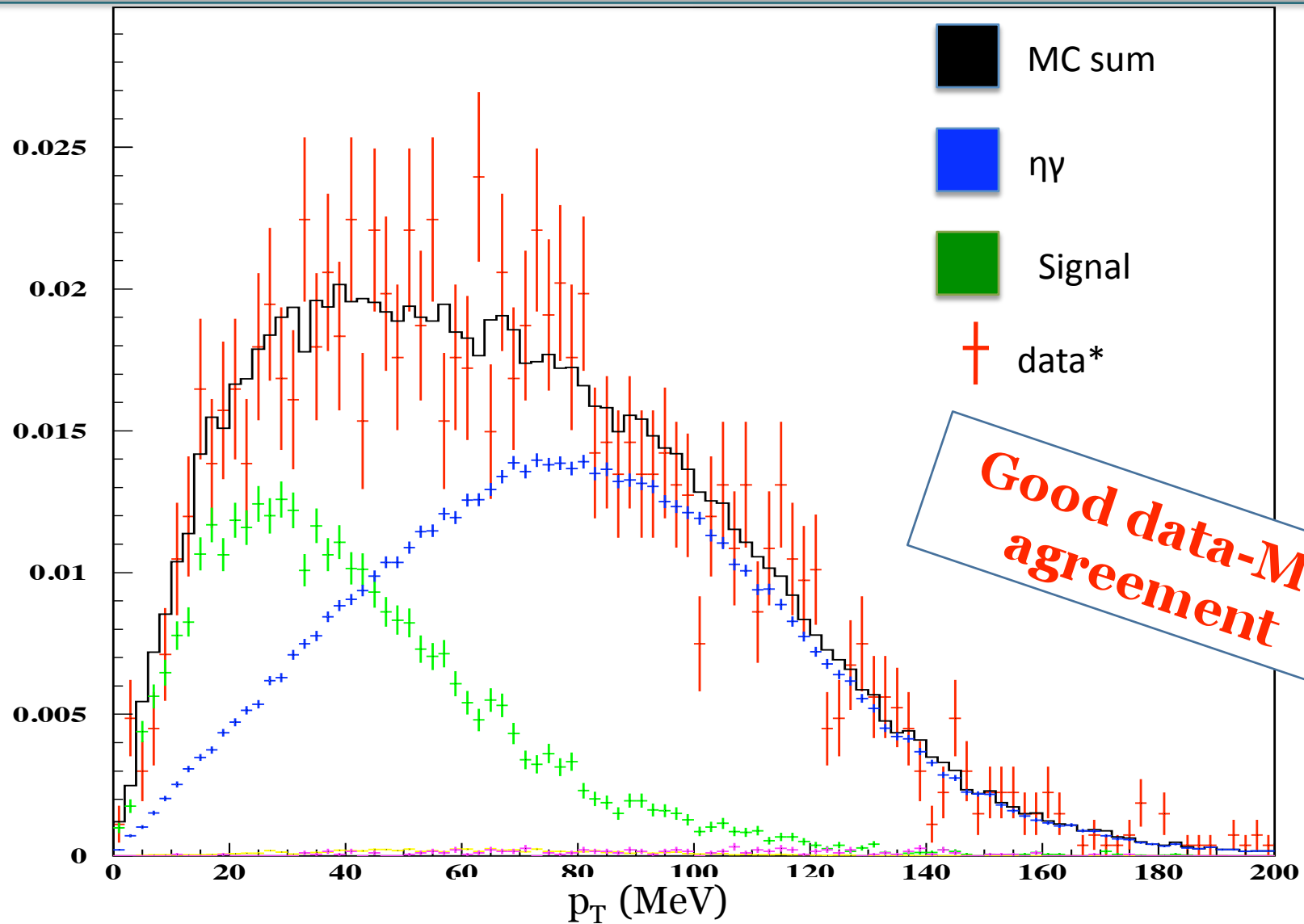
$e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow 3\pi^0$

# Data MC comparison on $\chi^2_\eta$ and $\chi^2_{\gamma\gamma}$

MC contributions normalized to the cross sections obtained from the fit



# Data MC comparison on $P_T$



$e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow 3\pi^0$

# Analysis calibration

From  $e^+e^- \rightarrow e^+e^-\eta$ ,  $\eta \rightarrow 3\pi^0$  fit one obtains the cross section for  $\eta\gamma$  production @ 1 GeV as well

$$\sigma(e^+e^- \rightarrow \eta\gamma \rightarrow \pi^0\pi^0\pi^0\gamma) = (0.285 \pm 0.005) \text{ nb}$$

(statistical error only)

Dividing for  $\text{BR}(\eta \rightarrow \pi^0\pi^0\pi^0) = 32.57\%$  one gets

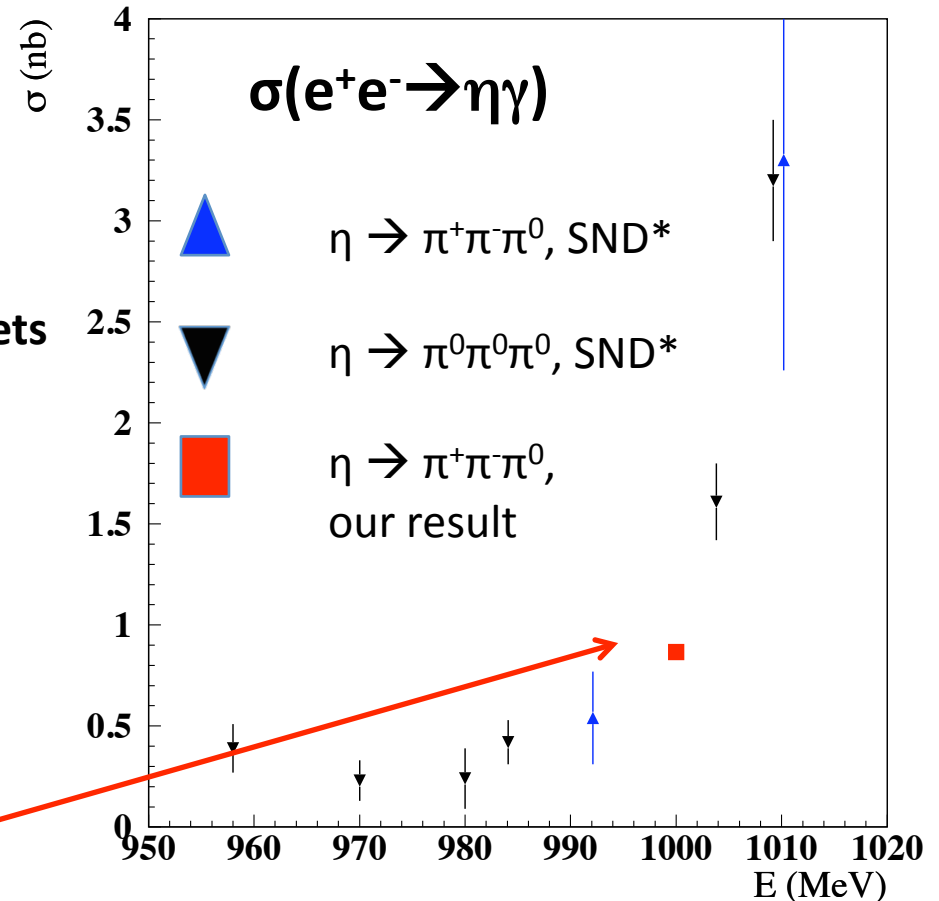
$$\sigma(e^+e^- \rightarrow \eta\gamma, 1 \text{ GeV}) = 0.875 \pm 0.009 \text{ nb}$$

(statistical error only)

in agreement with our previous result obtained in the charged channel analysis

$$\sigma(e^+e^- \rightarrow \eta\gamma, 1 \text{ GeV}) = 0.866 \pm 0.009 \text{ nb}$$

(statistical error only)



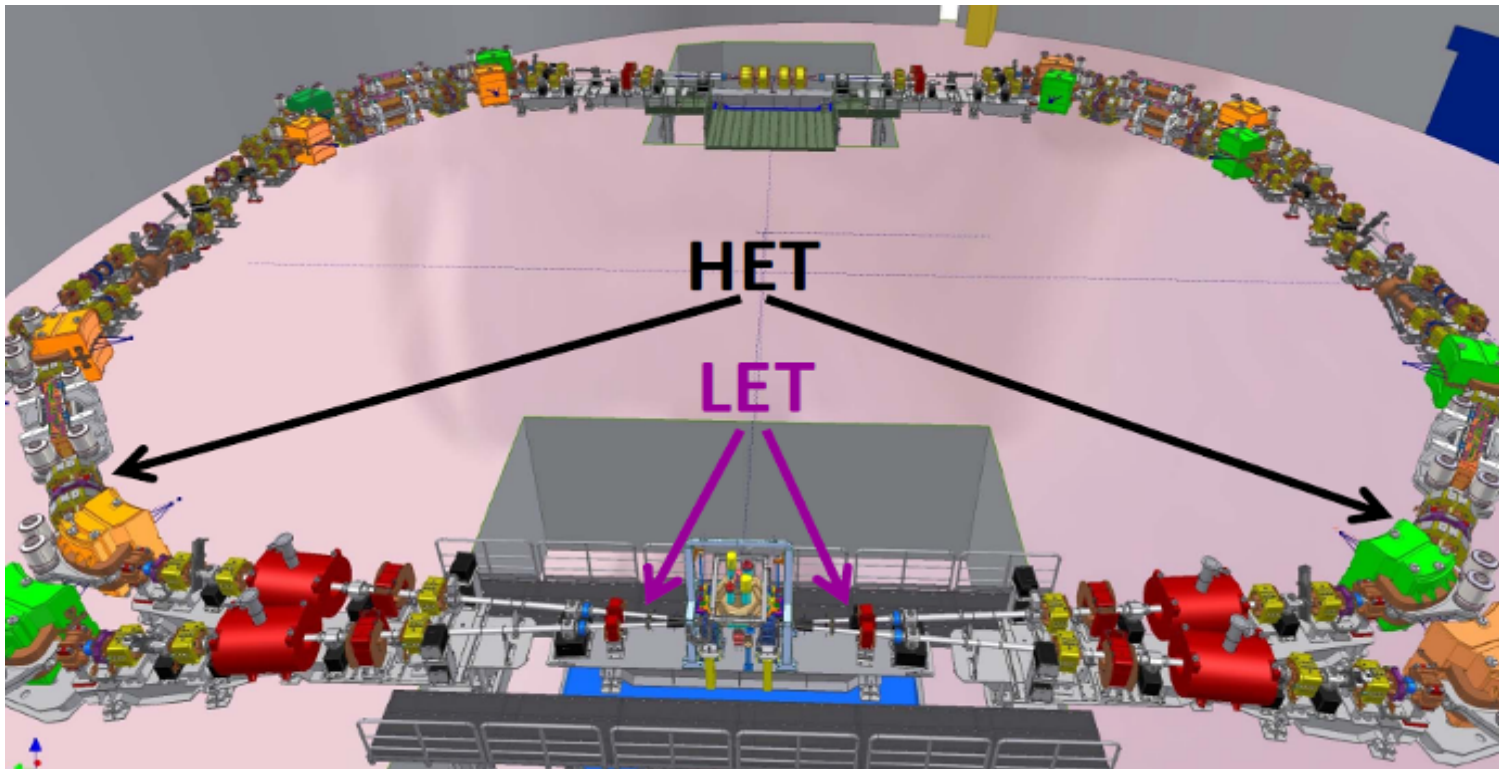
\*Phys.Rev.D76,077101(2007)

# KLOE-2: the taggers for $\gamma\gamma$ physics

Detector upgrade for the first KLOE-2 run :  
2+2 detector stations for leptons in  $e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^- X$



- LET (Low Energy Taggers) are LYSO calorimeters placed inside KLOE
- HET (High Energy Taggers) are scintillator hodoscopes placed 11 m from the IP



# Conclusions

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- ✓  $e^+e^- \rightarrow e^+e^-\pi^0\pi^0$  analysis shows a clear excess of events in the low invariant mass region, where a contribution from  $\sigma(600)$  is expected
- ✓ work is in progress to obtain a  $\gamma\gamma \rightarrow \pi^0\pi^0$  cross section as a function of the invariant mass (first after Crystal Ball in 1990)
- ✓  $\gamma\gamma \rightarrow \eta \rightarrow 3\pi^0$  analysis is solid (good data-MC agreement) and provides the first evidence of the  $\gamma\gamma \rightarrow \eta \rightarrow 3\pi^0$  signal @  $\sqrt{s}=1\text{ GeV}$
- ✓ These analyses show that KLOE is suitable for  $\gamma\gamma$  physics, which is of great interest (meson structures, hadronic light-by-light contribution to  $g-2$ )
- ✓ New analysis possibilities with final state  $e^\pm$  taggers installed in KLOE-2

A horizontal scroll graphic with a light brown, textured background. The scroll is partially unrolled, with the top and bottom edges curled up. The word "SPARES" is written in the center of the scroll in a black, serif font.

SPARES



# Work in progress: $\gamma\gamma \rightarrow \pi^0\pi^0$ cross section

---

$$\sigma_{\gamma\gamma}(w) = \frac{dn/dw}{\epsilon(w)dL/dw}$$

✓ Signal efficiency from MC  $e^+e^- \rightarrow e^+e^- \sigma \rightarrow e^+e^- \pi^0\pi^0$

F. Nguyen, F. Piccinini, A. Polosa  
Eur. Phys. J. C47(2006)65

based on the complete matrix element calculation and on the full phase space generation -  $\sigma$  resonance modelled as a BW with mass and width given by BES II

✓  $\gamma\gamma$  luminosity function  $dL/dw$ :

- Brodsky, Kinoshita, Terazawa, Phys. Rev. ,D4(1971)1532
- Budnev et al., Phys. Rept.4(1975)181
- Bonneau, Gourdin, Martin, Nucl. Phys. B54(1973)573

The one used in  
Crystal Ball analysis

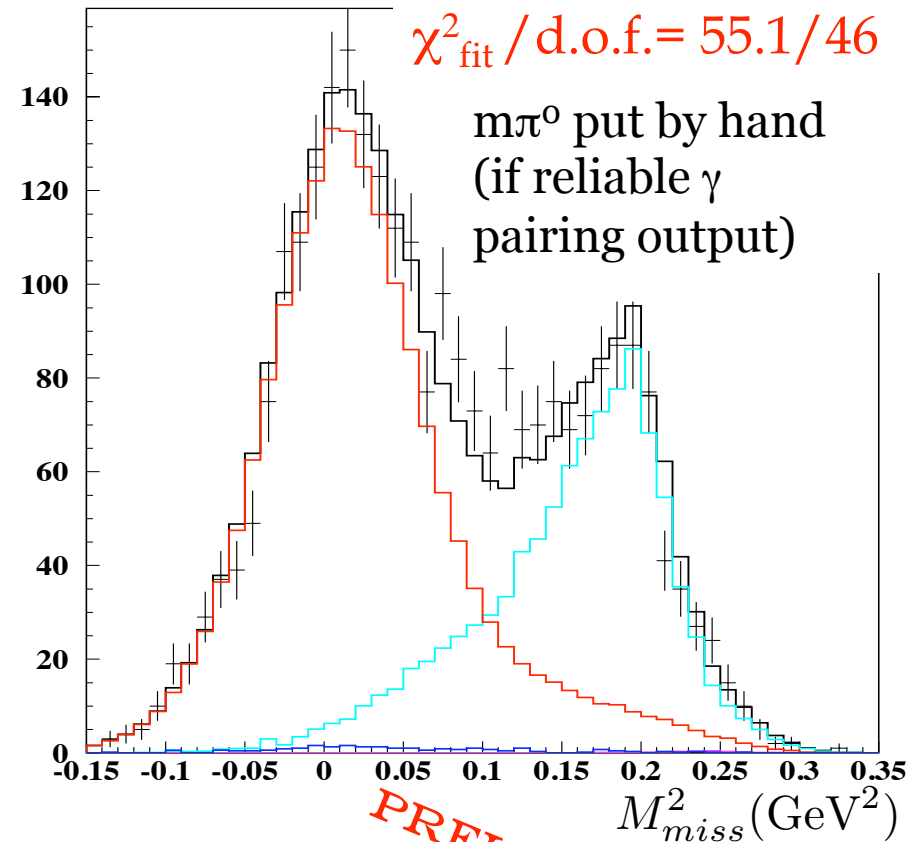
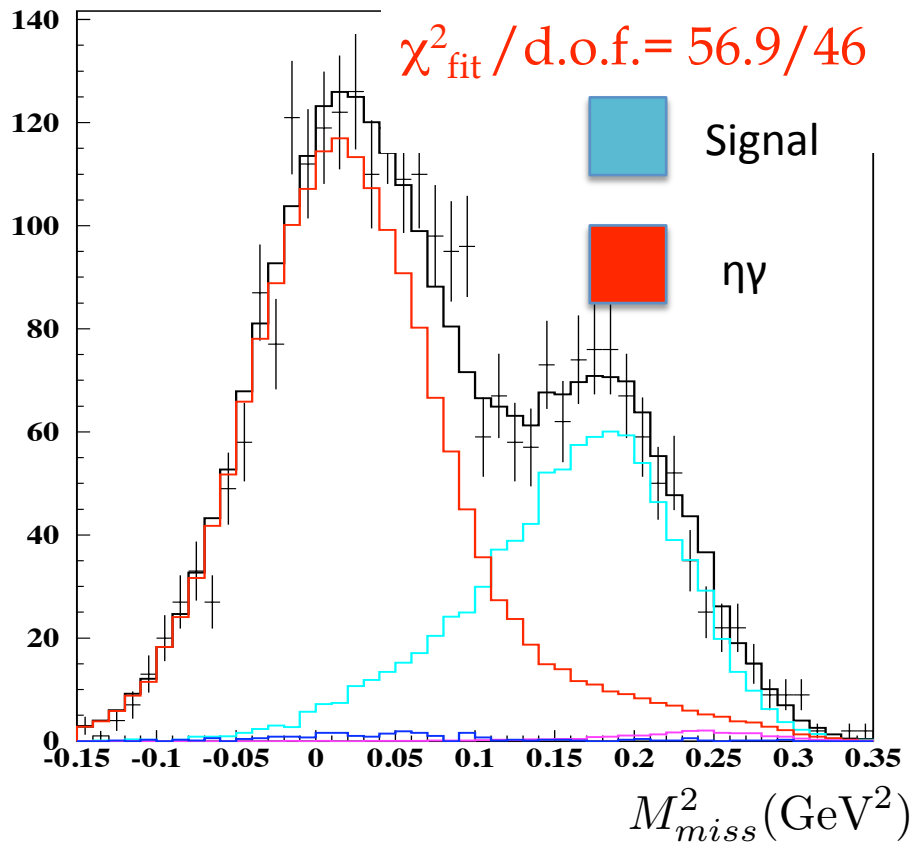
$$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$$

# $e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow \pi^0\pi^0\pi^0$ : fit to $M_{miss}^2$

$e^+e^- \rightarrow \omega\pi^0$  fixed, other backgrounds left free

2725 events after selections

contribution mainly from  $\gamma\gamma \rightarrow \eta$  and  $e^+e^- \rightarrow \eta\gamma$



From the fit:

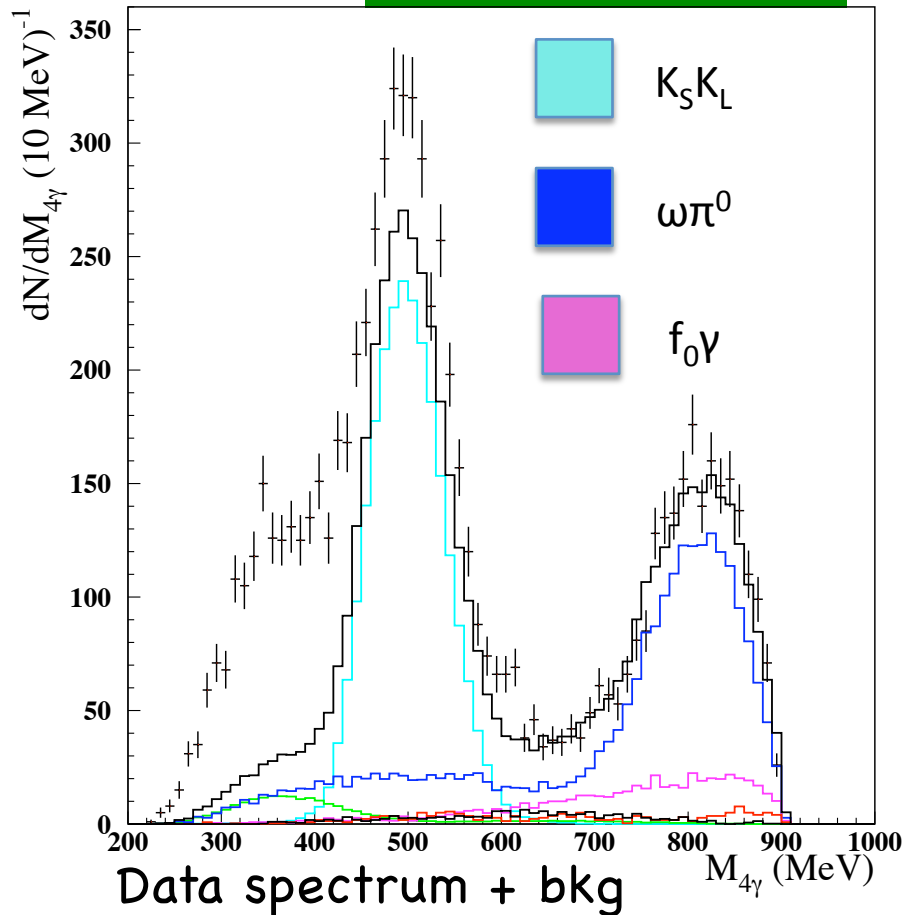
$$N(\gamma\gamma \rightarrow \eta \rightarrow \pi^0\pi^0\pi^0) = 921 \pm 35$$

$e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow 3\pi^0$

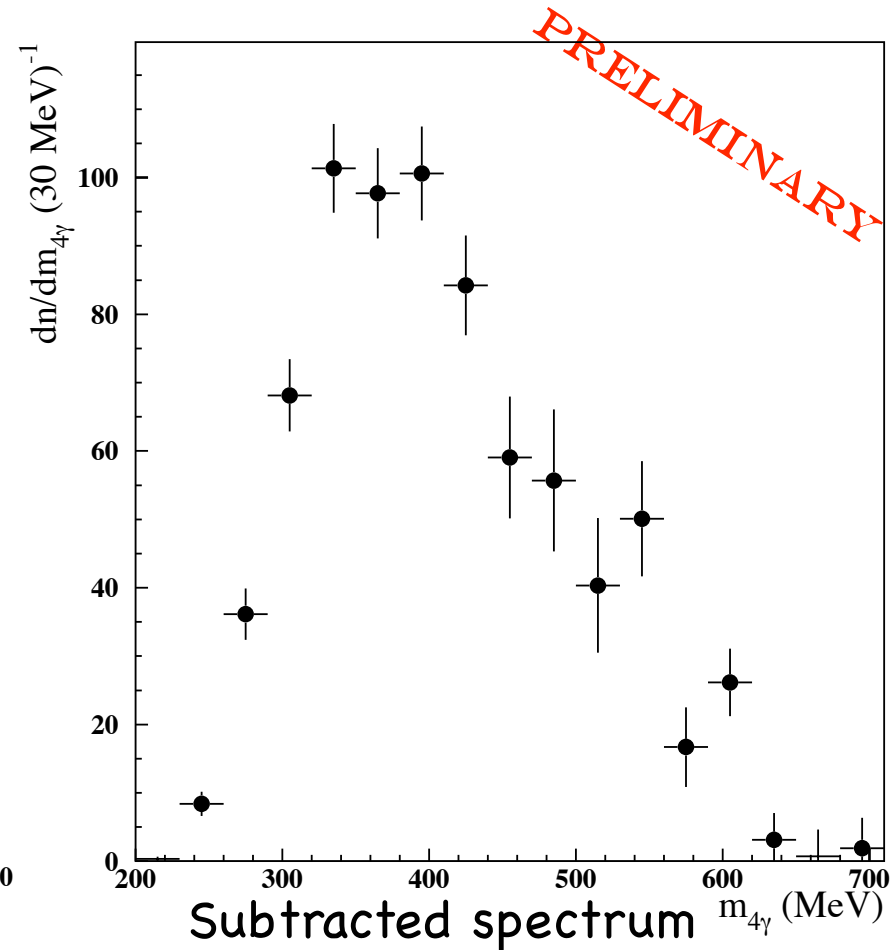
# Background subtraction

Bonus track

8090 events after selections



Bkg distributions normalized to expected numbers of events



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

# $e^+e^- \rightarrow e^+e^- \sigma \rightarrow e^+e^- \pi^0\pi^0 \rightarrow e^+e^- 4\gamma$ : Analysis

Bonus track

At least 4 clusters:

- neutral
- prompt
- $E \geq 15$  MeV
- $23^\circ < \vartheta < 157^\circ$

Analysis cuts

$$\chi^2_{\pi\pi} < 4$$

4  $\gamma$  only

NO tracks

$$R = (\sum_{\gamma} E_{\gamma}) / E_{\text{tot}} > 0.75$$

$$\sum_{\gamma} p_{T} < 80 \text{ MeV}$$

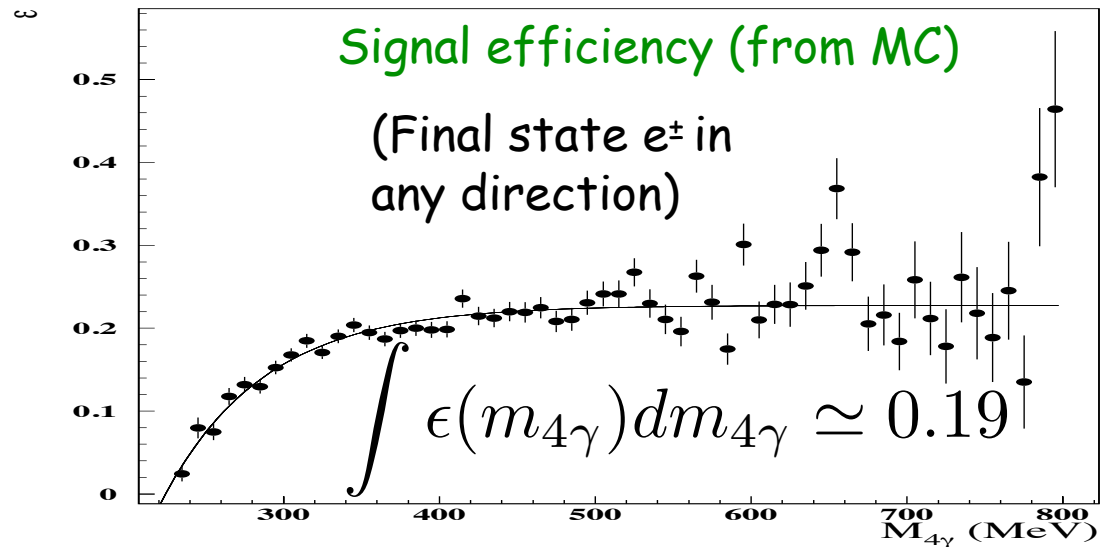
Cuts on  $\gamma$  energies

$$\chi^2_{\dagger} < 12$$

$$\chi^2_t = \sum_{\gamma} \frac{(r_{\gamma}/c - t_{\gamma})^2}{\sigma_{t,\gamma}^2}$$

BKG efficiencies (from MC)

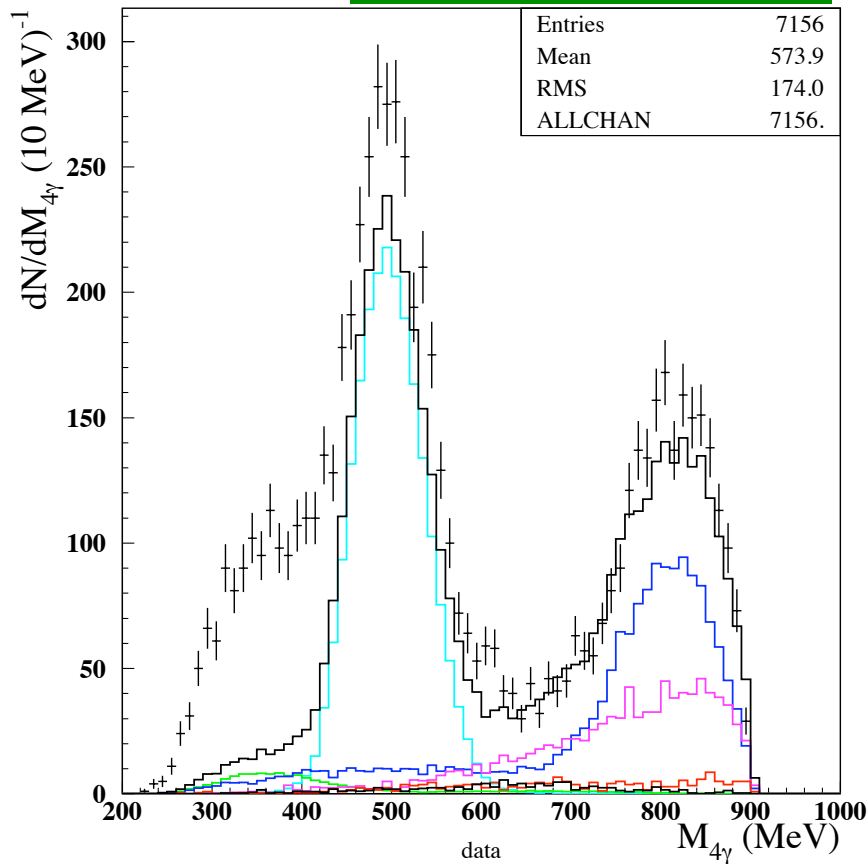
	$\epsilon$	$\sigma$ (nb)	$n = \mathcal{L}\sigma\epsilon$
$K_S K_L$	$7 \times 10^{-3}$	1.28	2173
$\eta \rightarrow 3\pi^0$	$2 \times 10^{-3}$	0.284	138
$\omega\pi^0$	$1.2 \times 10^{-2}$	0.55	1600
$f_0\gamma$	$2.3 \times 10^{-2}$	0.17	948
$a_0\gamma$	$4 \times 10^{-3}$	0.11	175
$\gamma\gamma$	$2 \times 10^{-6}$	360	107
			5141



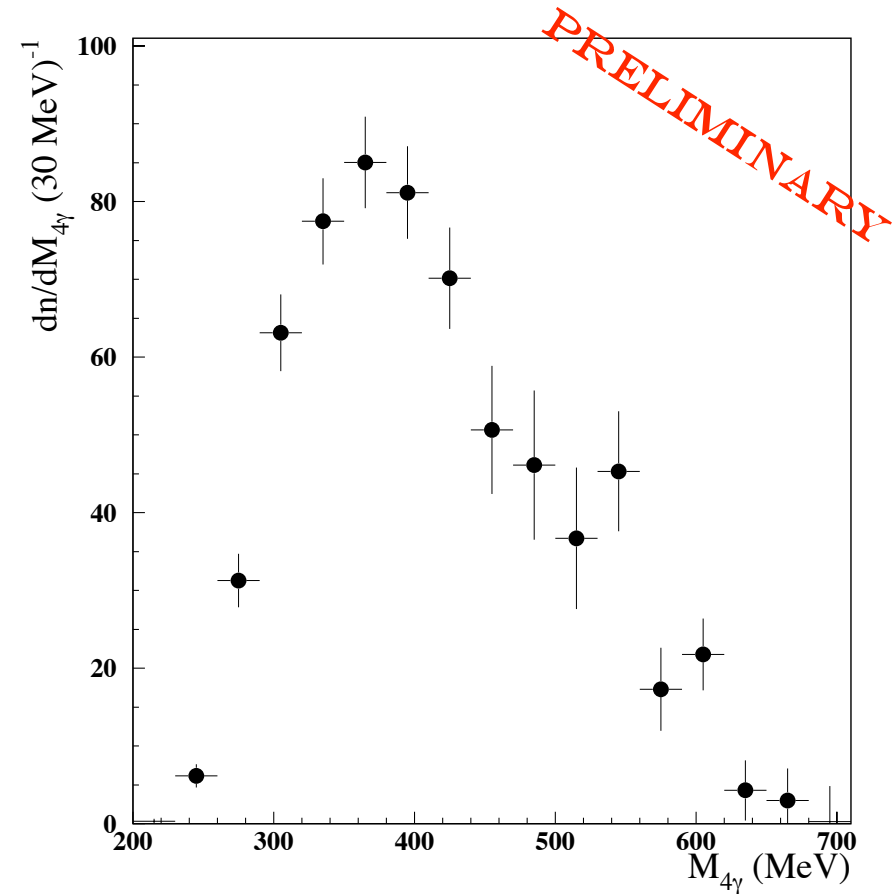
# Background subtraction

Bonus track

7156 events after selections



Data spectrum + bkg



Subtracted spectrum

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

# $e^+e^- \rightarrow e^+e^- \sigma \rightarrow e^+e^- \pi^0\pi^0 \rightarrow e^+e^- 4\gamma$ : Analysis

Bonus track

At least 4 clusters:

- neutral
- prompt
- $E \geq 15$  MeV
- $23^\circ < \vartheta < 157^\circ$

Analysis cuts

$$\chi^2_{\pi\pi} < 4$$

4  $\gamma$  only

NO tracks

$$R = (\sum_{\gamma} E_{\gamma}) / E_{\text{tot}} > 0.75$$

$$\sum_{\gamma} p_{T} < 80 \text{ MeV}$$

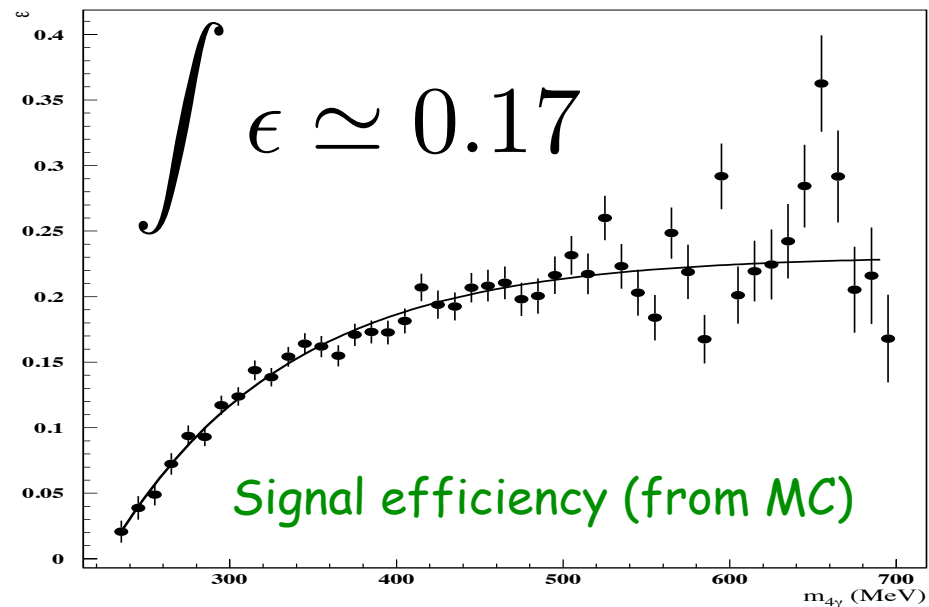
Cuts on  $\gamma$  energies

$$\chi^2_{\text{t}} < 12$$

$$\vartheta_{\text{min}} > 30^\circ$$

$$\chi^2_{\text{t}} = \sum_{\gamma} \frac{(r_{\gamma}/c - t_{\gamma})^2}{\sigma_{t,\gamma}^2}$$

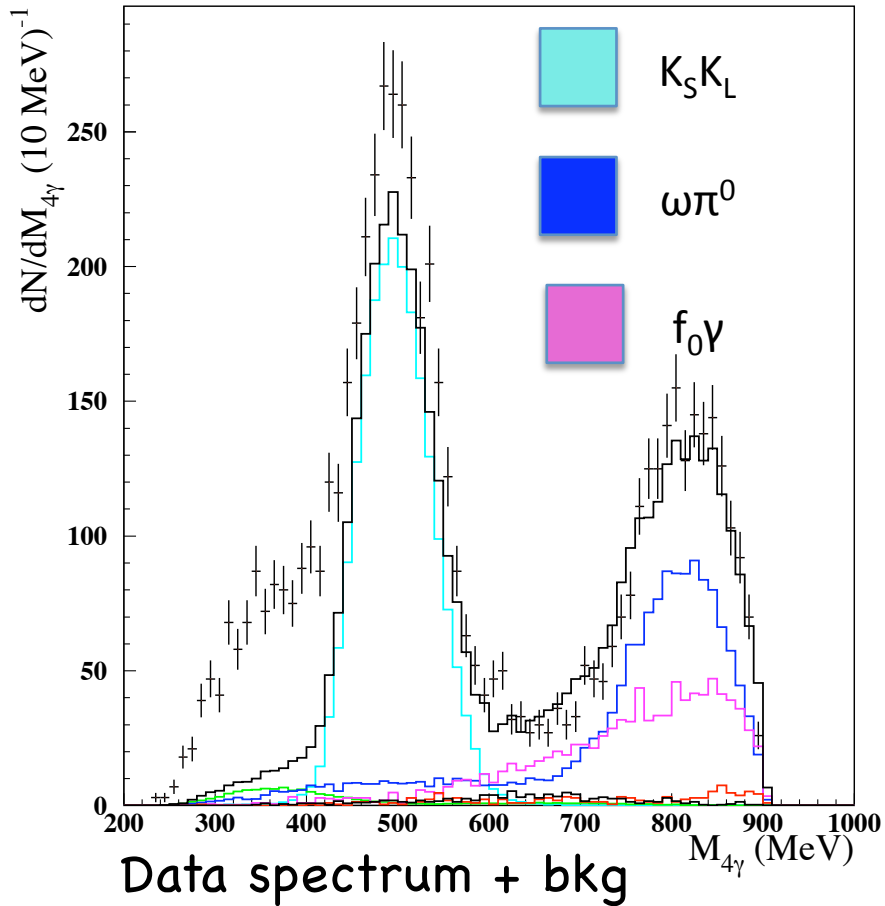
	$\epsilon$	$\sigma$ (nb)	$n = \sigma \epsilon$
$K_S K_L$	$6.7 \times 10^{-3}$	1.28	2080
$\eta \rightarrow 3\pi^0$	$1.7 \times 10^{-3}$	0.284	117
$\omega\pi^0$	$1.1 \times 10^{-2}$	0.55	1467
$f_0\gamma$	$2.3 \times 10^{-2}$	0.17	948
$a_0\gamma$	$3.7 \times 10^{-3}$	0.11	105
$\gamma\gamma$	$1.2 \times 10^{-6}$	360	99
			4816
Data			6311



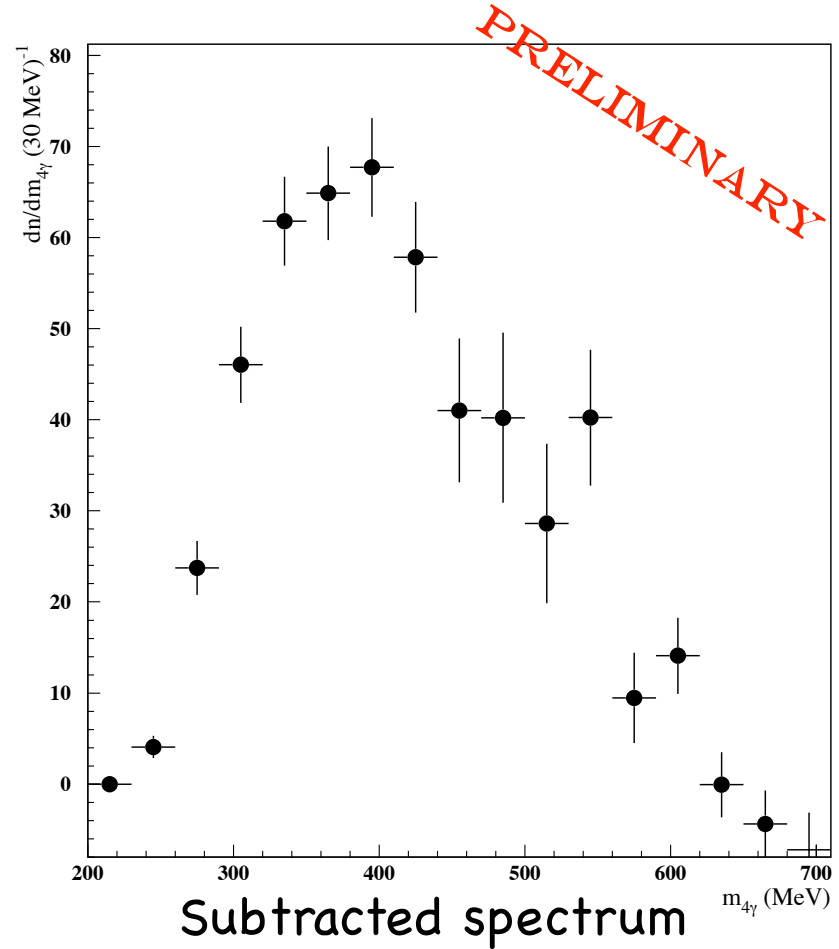
# Background subtraction

Bonus track

6311 events after selections



Bkg distributions normalized to expected numbers of events



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

# $e^+e^- \rightarrow e^+e^- \eta, \eta \rightarrow \pi^+\pi^-\pi^0$

Bonus track

## Analysis cuts

- 2 and only 2 neutral prompt clusters, with  $E \geq 15$  MeV and  $20^\circ < \vartheta < 160^\circ$
- 2 tracks of opposite charge
- $\gamma\gamma$  pairing:  $\chi^2_{\gamma\gamma} < 8$
- $e^\pm/\pi^\pm$  likelihood: to select  $\pi^\pm$  events
- Kinematic fit and cut on  $\chi^2_\eta$

5 variables  $\times 2\gamma$

4 constraints

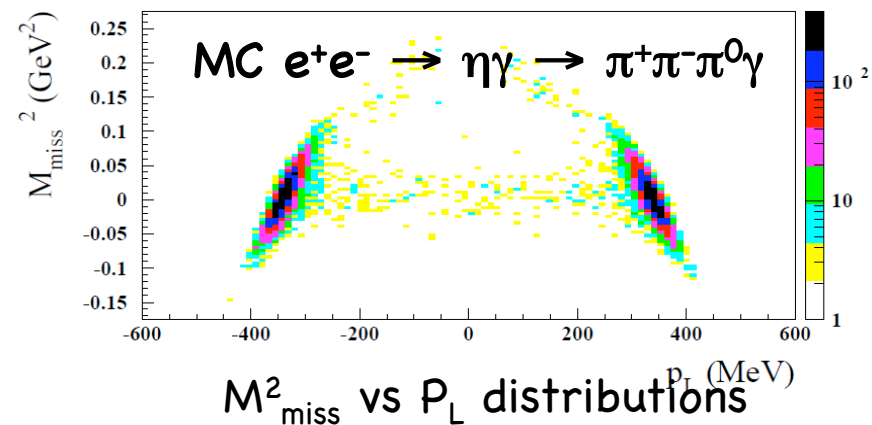
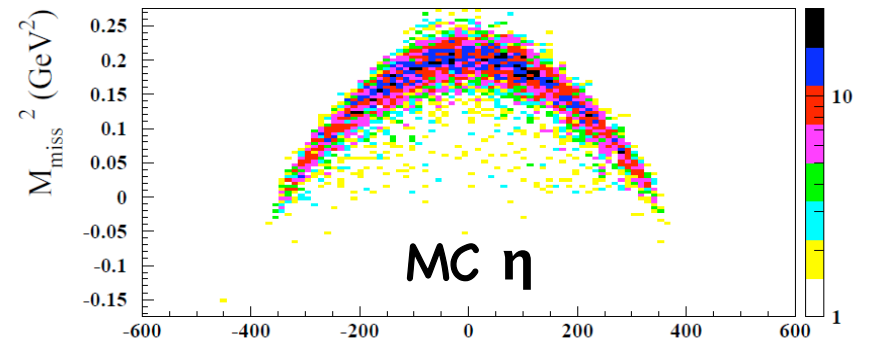
$$m^2_{\gamma\gamma} = m^2_{\pi^0}$$

$$m^2_{\pi^+\pi^-\gamma\gamma} = m^2_\eta$$

$$t_\gamma - |\underline{r}_\gamma| / c = 0 \text{ for } 2\gamma$$

Main bkg processes:

$$e^+e^- \rightarrow \eta\gamma, e^+e^- \rightarrow e^+e^-\gamma, e^+e^- \rightarrow \omega\pi^0, \\ e^+e^- \rightarrow K^+K^-, e^+e^- \rightarrow K_S K_L$$

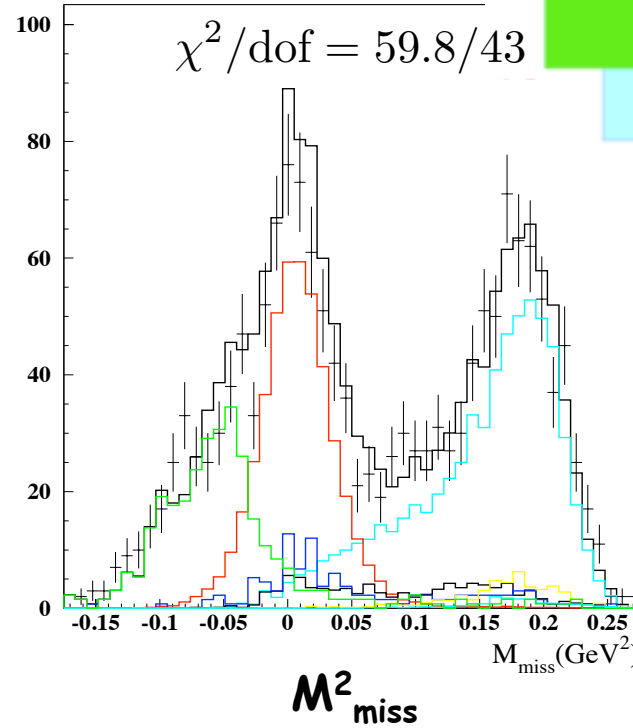
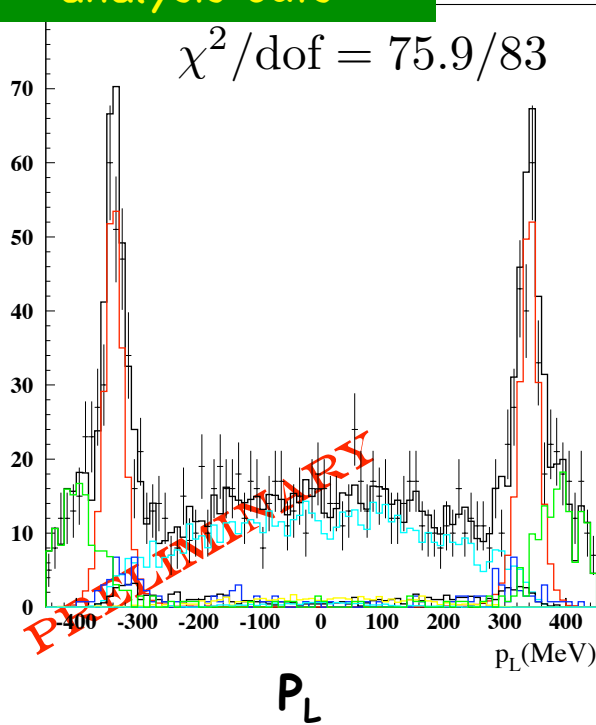




# $e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$ : fit in $p_L$ and $m_{\text{miss}}^2$

Bonus track

1576 events survive analysis cuts



$e^+e^- \rightarrow \eta\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$

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

signal

	$\epsilon$
$\eta$	0.196
$\eta\gamma$	$9.1 \times 10^{-3}$
$\omega\pi^0$	$6.5 \times 10^{-5}$
$\pi^+\pi^-\pi^0$	$1.5 \times 10^{-5}$
$K^+K^-$	$1.9 \times 10^{-5}$
$K_S K_L$	$2.6 \times 10^{-5}$
$e^+e^-\gamma$	$\mathcal{O}(10^{-7})$

Bkg reduction factors

Fit in  $p_L$  gives:

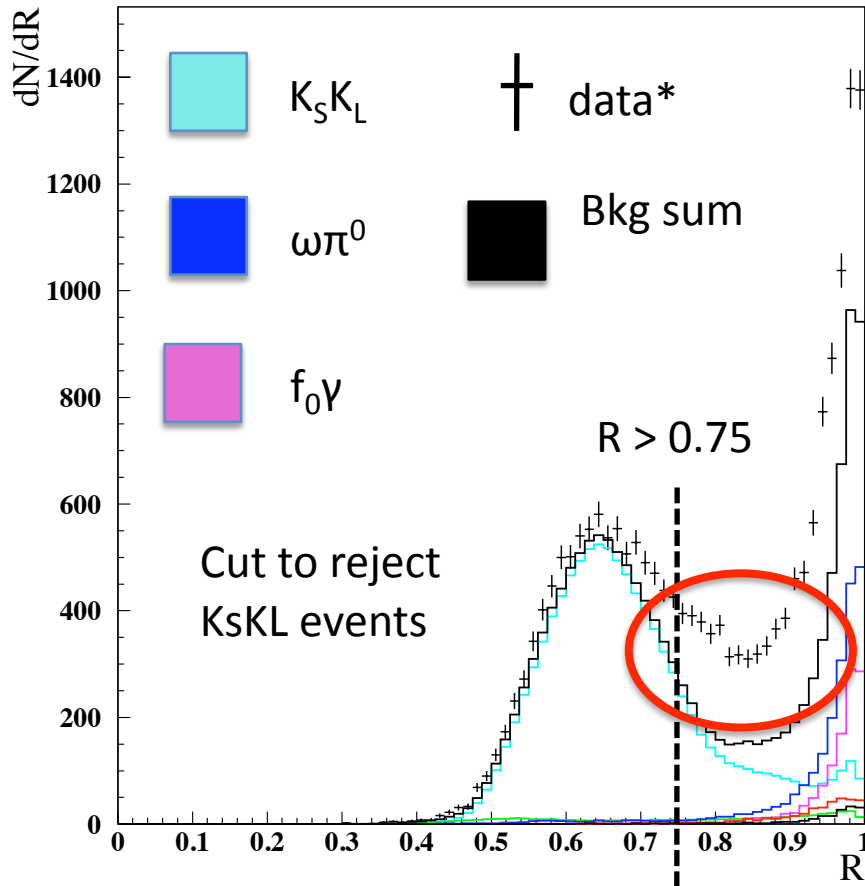
$$n_{e\nu} = 650 \pm 25$$

$e^+e^- \rightarrow e^+e^-\eta, \eta \rightarrow \pi^+\pi^-\pi^0$

# $e^+e^- \rightarrow e^+e^- \sigma \rightarrow e^+e^- \pi^0\pi^0 \rightarrow e^+e^- 4\gamma$ : Analysis

Bonus track

Variable R 
$$R = \frac{\sum_{i=1}^4 E_i}{E_{calo}}$$



Data and background MC normalized according to cross section and efficiencies as evaluated after the selections:

- $\chi^2_{\pi\pi} < 4$
- 4  $\gamma$  only
- NO tracks in the DC
- Cuts on photons energies

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