KLOE first results on η, η'

Fabio Ambrosino

Università e Sezione INFN Napoli

for the KLOE collaboration

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The $\phi \to \eta'\gamma$ decay

The value of BR($\phi \to \eta'\gamma$) has undergone many theoretical predictions in last 20 years, ranging from $\sim 2 \times 10^{-4}$ down to $\sim 10^{-6}$ in case of large gluonic content of the η'.

The current best determinations of this BR, performed at VEPP-2M, give:

$(8.2^{+2.1}_{-1.9}$ stat. ± 1.1 syst.$) \times 10^{-5}$ CMD-2, PLB 473 337 (2000)

$(6.7^{+3.4}_{-2.9}$ stat. ± 1.0 syst.$) \times 10^{-5}$ SND, JETPL. 69 97 (1999)

KLOE has the possibility to measure this BR with smaller uncertainty.

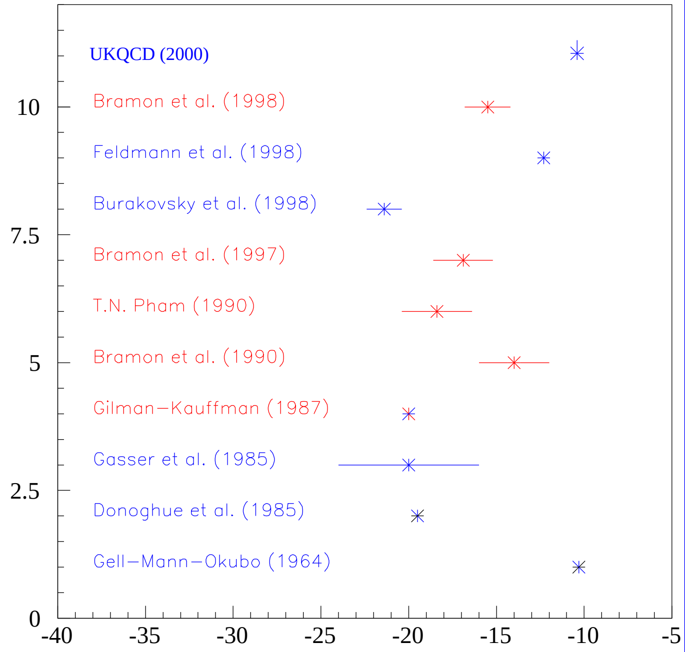
The η-η' mixing

The mass eigenstates $\eta(547)$ and $\eta'(958)$ can be related to the SU(3) octet-singlet states η_8 and η_1 through the mixing angle ϑ_P:

$$\eta(547) = \eta_8 \cos\vartheta_P - \eta_1 \sin\vartheta_P$$
$$\eta'(958) = \eta_8 \sin\vartheta_P + \eta_1 \cos\vartheta_P$$

The difference between ϑ_P and ϑ_V is an intriguing feature of QCD, and the value of the pseudoscalar mixing angle, has been discussed many times in the last 30 years:

- $\vartheta_P \sim -10^\circ$ (GMO quadratic formula)
- $\vartheta_P \sim -20^\circ$ (Chiral calculations)
- $-13^\circ < \vartheta_P < -20^\circ$
  (Phenomenological analyses)
- Two angles scenarios recently proposed



The η-η' mixing

A crucial test, originally proposed by Rosner, is to study the ratio of the $\phi \to \eta'\gamma$ and $\phi \to \eta\gamma$ decays:

$$R_\phi = \frac{BR(\phi\to\eta'\gamma)}{BR(\phi\to\eta\gamma)} = \cot^2\varphi_P \left(1 - \frac{m_s}{\bar{m}} \frac{\tan\varphi_V}{\sin 2\varphi_P}\right)^2 \left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

with $\varphi_P = \vartheta_P + \arctan\sqrt{2}$

(see *A. Bramon et al., Eur Phys. J C7 (1999)*)

Analyzed channels

Charged/Neutral

$$\Phi \xrightarrow{1.26\%} \eta\,\gamma, \quad \eta \xrightarrow{23.1\%} \pi^+\pi^-\pi^0, \quad \pi^0 \xrightarrow{98.8\%} \gamma\gamma$$

$$BR = 2.9 \times 10^{-3}$$

$$\Phi \xrightarrow{1\cdot 10^{-4}} \eta'\,\gamma, \quad \eta' \xrightarrow{43.8\%} \pi^+\pi^-\eta, \quad \eta \xrightarrow{39.2\%} \gamma\gamma$$

$$BR \approx 2 \times 10^{-5}$$

Fully neutral

$$\Phi \xrightarrow{1.26\%} \eta\,\gamma, \quad \eta \xrightarrow{32.2\%} \pi^0\pi^0\pi^0, \quad \pi^0 \xrightarrow{98.8\%} \gamma\gamma$$

$$BR = 3.9 \times 10^{-3}$$

$$\Phi \xrightarrow{1\cdot 10^{-4}} \eta'\,\gamma, \quad \eta' \xrightarrow{20.7\%} \pi^0\pi^0\eta, \quad \eta \xrightarrow{39.2\%} \gamma\gamma$$

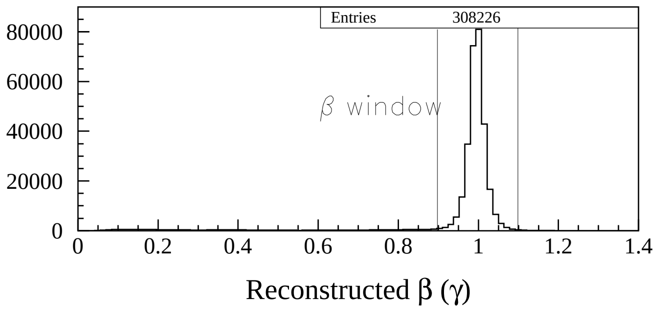
$$BR \approx 1 \times 10^{-5}$$

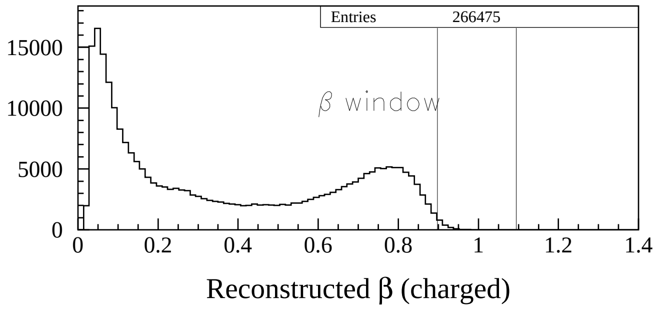
Control of systematic effects

The $\phi \to \eta\gamma$ channels are the main source of background for detecting $\phi \to \eta'\gamma$ decays, and, due to strong similarities between the two categories of events they also constitute a useful control sample to check systematic effects on analysis cuts and discrepancies with Monte Carlo simulation of the detector. Moreover, most of the systematic effects are expected to cancel out in the ratio R_ϕ when evaluated with the same final state.

Consistency checks among the relative BR's of the fully neutral and the charged/neutral channels are possible to further evaluate (and correct for) systematic effects.

Selection criteria: charged/neutral





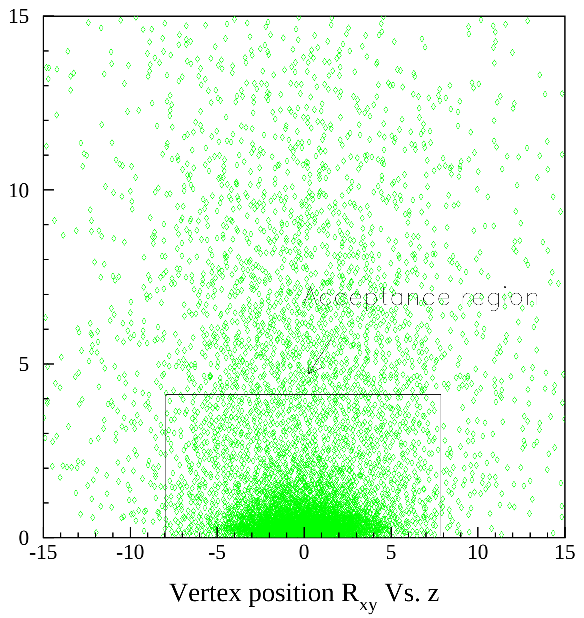
$$\beta = R_{clu}/c\,t_{clu}$$

3 clusters with:

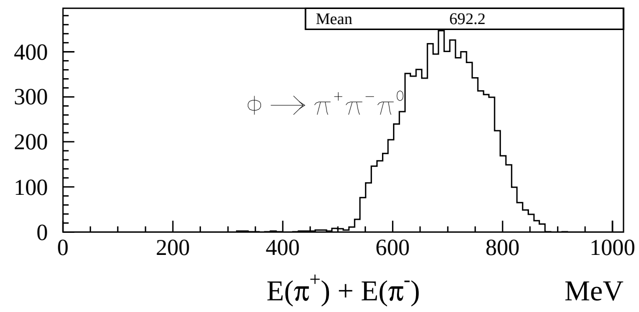
- $0.9 < \beta < 1.1$
- $\theta_\gamma > 21^\circ$

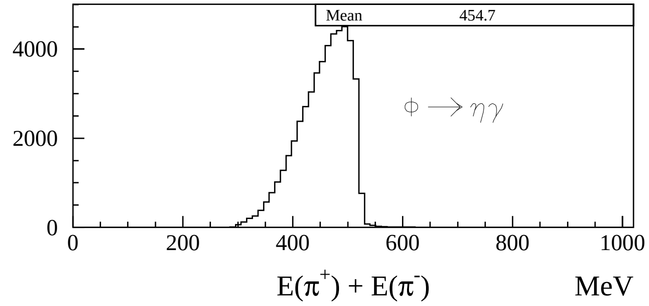
1 charged vertex within:

- $R_{xy} < 4\mathrm{cm}$
- $|z| < 8\mathrm{cm}$



Selection criteria: charged/neutral





Additional criteria for $\phi \to \eta\gamma$:

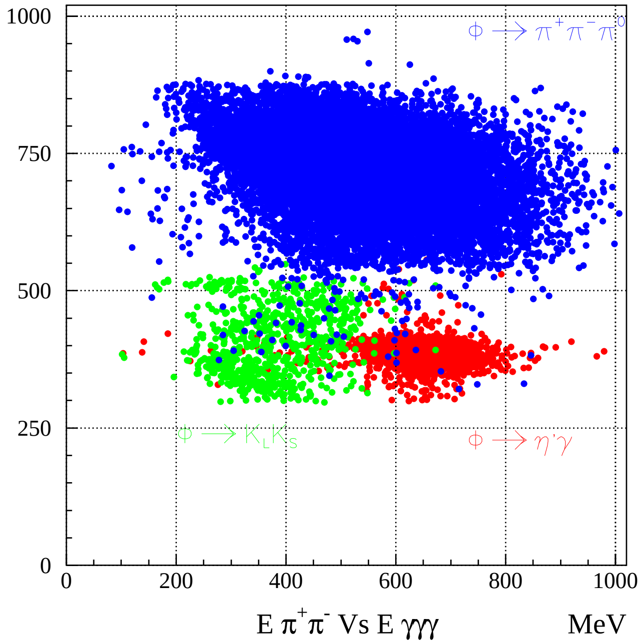
- $E_\gamma^{max} > 300$ MeV
- $E(\pi^+) + E(\pi^-) < 550$ MeV

$$\varepsilon_{3\pi} = 1.5 \cdot 10^{-3}$$

Additional criteria for $\phi \to \eta'\gamma$:

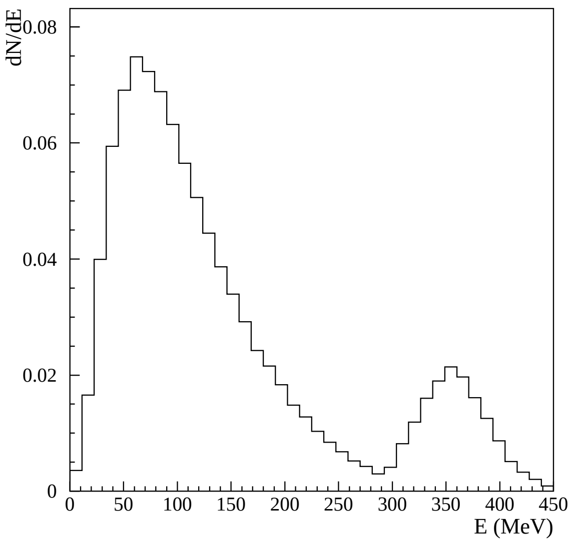
- $E(\pi^+) + E(\pi^-) < 412$ MeV
- $E_{\gamma\gamma\gamma} > 520$ MeV

$$\varepsilon_{Bkg} \simeq 10^{-4}$$



Selection criteria: fully neutral

- 7 clusters with $0.9 < \beta < 1.1$
- $\theta_\gamma > 21°$
- $|E_{tot} - 1020\,\mathrm{MeV}| < 2\sigma_E = 130\,\mathrm{MeV}$
- $E_\gamma^{max} > 300\,\mathrm{MeV}$ $(\phi \to \eta\gamma\ )$
- $\varepsilon_{\eta\gamma} = 41.3\%$
- $\varepsilon_{\eta'\gamma} = 41.1\%$

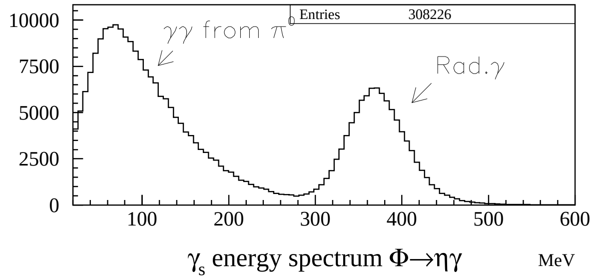


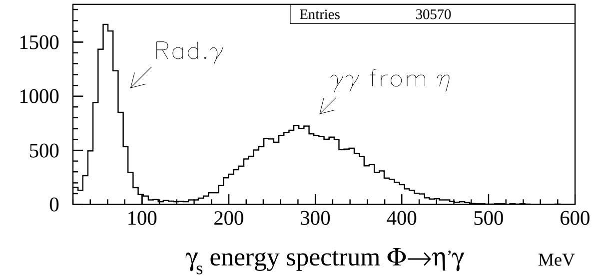
Cluster energy spectrum $\phi \to \eta\gamma$

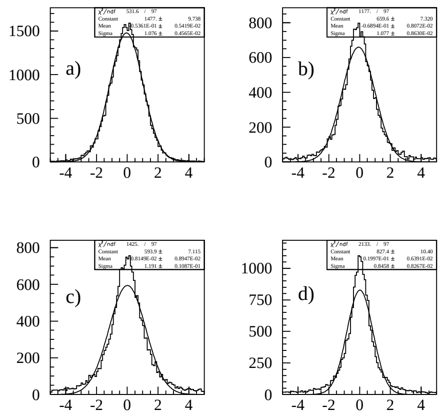
Kinematic fit: charged/neutral

No combinatorial problem: photons easily identified. Kinematic fit in both $\phi \to \eta\gamma$ and $\phi \to \eta'\gamma$ hypothesis with mass constraints:

- 4-momentum conservation
- $c \cdot t_{clu} - r_{clu} = 0 \quad \forall\gamma$
- $M_{\gamma\gamma} = M_\eta$ and $M_{\eta\pi^+\pi^-} = M_{\eta'}$ for $\phi_{\eta'\gamma}$
- $M_{\gamma\gamma} = M_{\pi^0}$ and $M_{\pi^+\pi^-\pi^0} = M_\eta$ for $\phi_{\eta\gamma}$





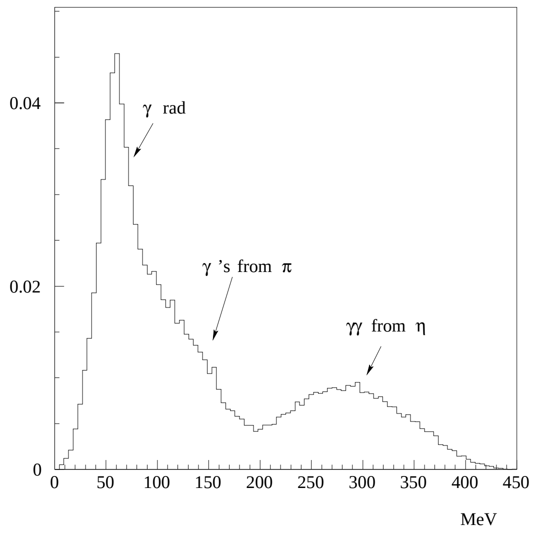


Quantities input to the fit:

- E,t,(x,y,z) for each photon
- x,y,z of charged vertex
- Beam energies
- Track parameters

Kinematic fit: fully neutral

- For $\eta'\gamma$ events a photon pairing procedure is applied, after a first step kinematic fit with no mass constraints.
- Monte Carlo study shows the assignment is correct in 90% of the cases.
- No attempt is made to pair γ's to identify π^0's in $\eta\gamma$ events.



Constraints:

$\phi \to \eta'\gamma$ (15)

- 4-momentum conservation
- $c \cdot t_{clu} - r_{clu} = 0 \quad \forall\gamma$
- $M_{\gamma 1 \gamma 2} = M_\eta$
- $M_{\gamma 3 \gamma 4} = M_{\gamma 5 \gamma 6} = M_{\pi^0}$
- $M_{\pi^0 \pi^0 \eta} = M_{\eta'}$

$\phi \to \eta\gamma$ (12)

- 4-momentum conservation
- $c \cdot t_{clu} - r_{clu} = 0 \quad \forall\gamma$
- $M_{\pi^0 \pi^0 \pi^0} = M_\eta$

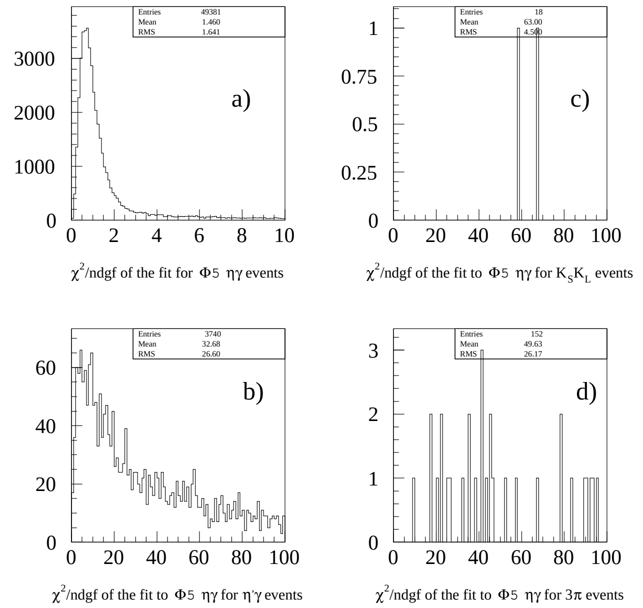
Backgrounds for $\phi \to \eta\gamma$

$\phi \to \eta\gamma \to 7\gamma$ is almost background free at KLOE. Monte Carlo simulations and fit to the η mass peak show that background is at the 0.1% level.

Possible backgrounds to $\phi \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$:

- $\phi \to K_S K_L \to$ 1 charged and 1 neutral vertex
- $\phi \to \pi^+\pi^-\pi^0$ events

when reconstruction mistakes and/or detector losses are present.
The selection scales down these events by a factor 10^{-4}, and a further cut on $\mathcal{P}(\chi^2_{\eta\gamma}) > 1\%$ completely rules them out. (Signal/Background > 900) The final selection efficiency for this channel is 31.9%



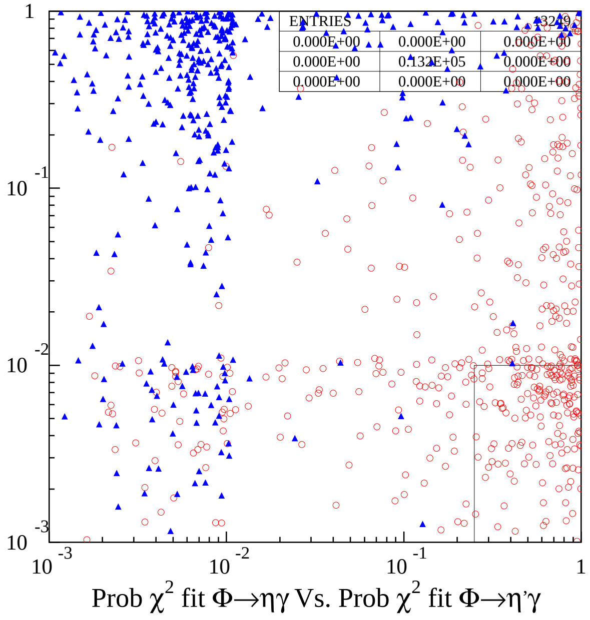
Backgrounds for $\eta'\gamma \to \pi^+\pi^-\gamma\gamma\gamma$

- The selection scales down $K_L K_S$ and $\pi^+\pi^-\pi^0$ events by a factor 10^{-4}, and a further cut on $\mathcal{P}(\chi^2_{\eta'\gamma}) > 1\%$ again rules them out.
- The main background for $\phi \to \eta'\gamma$ events are the corresponding $\phi \to \eta\gamma$ decays.
- A cross cut on:

$$\mathcal{P}(\chi^2_{\eta'\gamma}) > 25\% \ \text{AND} \ \mathcal{P}(\chi^2_{\eta\gamma}) < 1\%$$

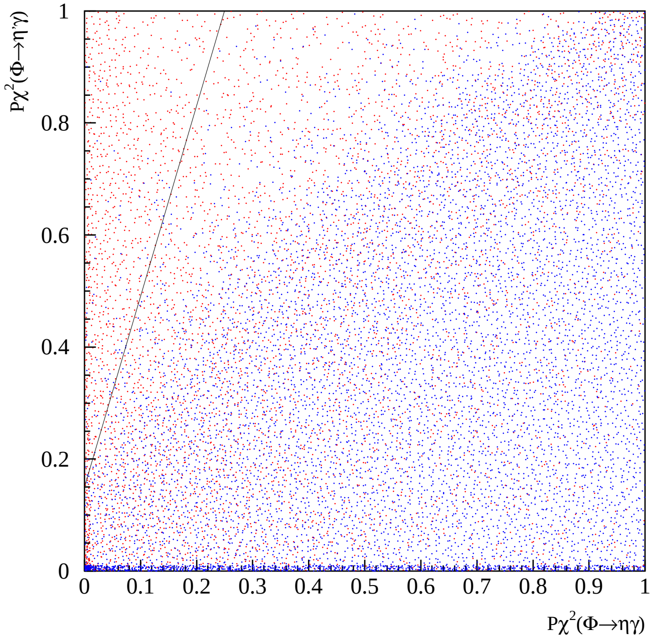
gets rid of the charged/neutral $\eta\gamma$ background for $\eta'\gamma$ charged/neutral events.

- $\varepsilon_{\eta'\gamma} = 18.6\%$
- $\varepsilon_B < 4.4 \times 10^{-5}$ (90% CL)
- Signal/Background > 35 (90% CL)

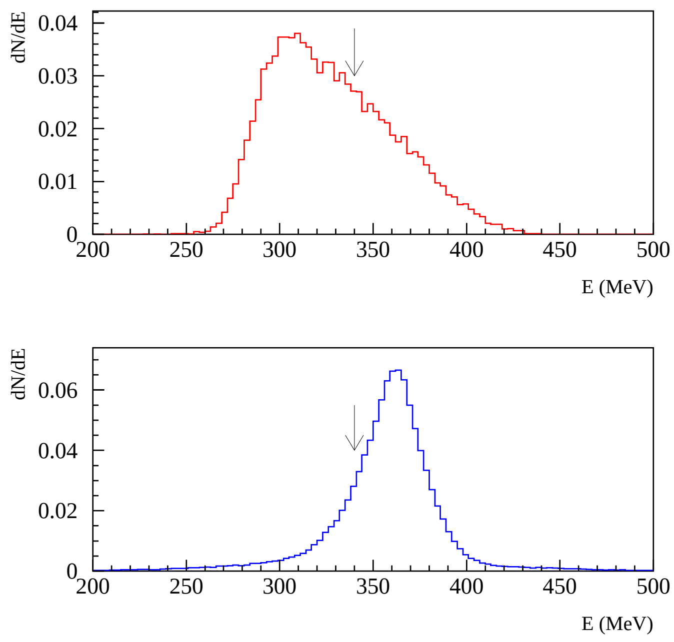


Backgrounds for $\eta'\gamma \to 7\gamma$

$\mathcal{P}(\chi^2)$ cut



Most energetic γ cut



- $\varepsilon_{\eta'\gamma} = 12.7\%$
- $\varepsilon_B < 1.5 \cdot 10^{-5}$ (90% CL)
- Signal/Background > 20 (90% CL)

Background rejection for $\eta' \gamma$: summary

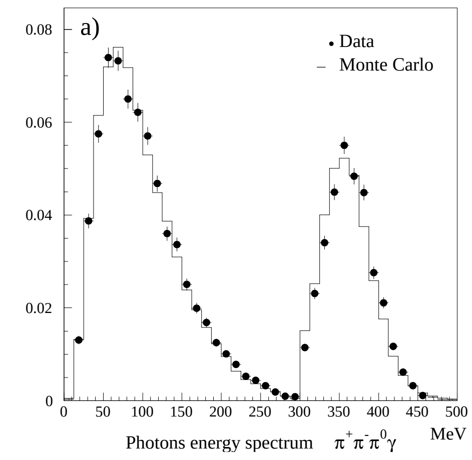
Backgrounds to $\phi \to \eta'\gamma$ charged/neutral

Signal	N/N_ϕ	ε_{Sel}	S/B
$\phi \to \eta'\gamma\ \pi^+\pi^-\gamma\gamma\gamma$	$\sim 2.3 \cdot 10^{-5}$	18.6%	-
$\phi \to \eta\gamma\ \pi^+\pi^-\gamma\gamma\gamma$	$2.9 \cdot 10^{-3}$	$< 4.4 \cdot 10^{-5}$	> 35
$e^+e^- \to \omega\pi^0$	$\sim 2.3 \cdot 10^{-3}$	$< 1.4 \cdot 10^{-4}$	> 20

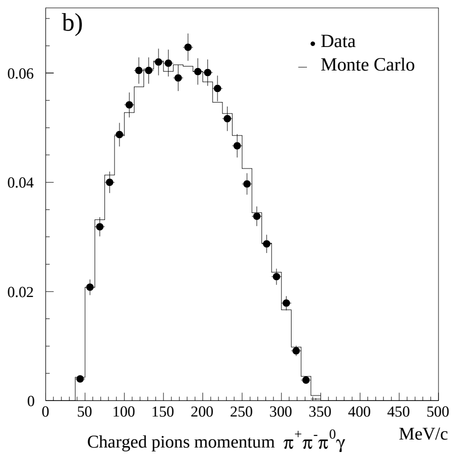
Backgrounds to $\phi \to \eta'\gamma$ fully neutral

Signal	N/N_ϕ	ε_{Sel}	S/B
$\phi \to \eta'\gamma \to 7\gamma$	$\sim 1 \cdot 10^{-5}$	12.7%	-
$\phi \to \eta\gamma \to 7\gamma$	$3.9 \cdot 10^{-3}$	$< 1.5 \cdot 10^{-5}$	> 20
$\phi \to K_S K_L \to 10\gamma$	2%	$< 5 \cdot 10^{-6}$	> 13
$\phi \to K_S K_L \to 8\gamma$	$\sim 10^{-4}$	$< 5 \cdot 10^{-5}$	> 250
$\phi \to a_0\gamma \to 5\gamma$	$\sim 3 \cdot 10^{-4}$	$< 1.2 \cdot 10^{-4}$	> 35
$\phi \to f_0\gamma \to 5\gamma$	$\sim 8 \cdot 10^{-5}$	$< 2.4 \cdot 10^{-4}$	> 65

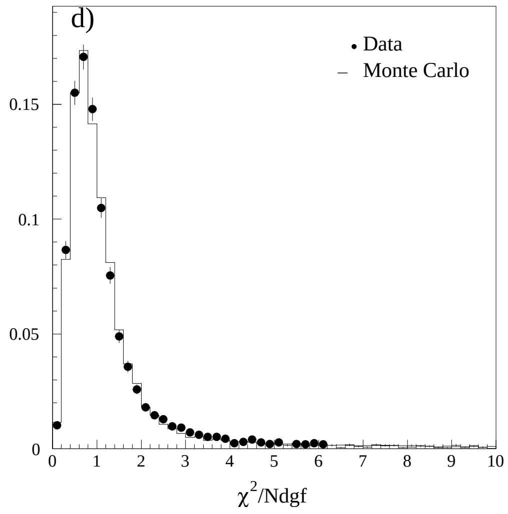
$\phi \to \eta\gamma \to \pi^+ \pi^- \pi^0 \gamma$ *events*



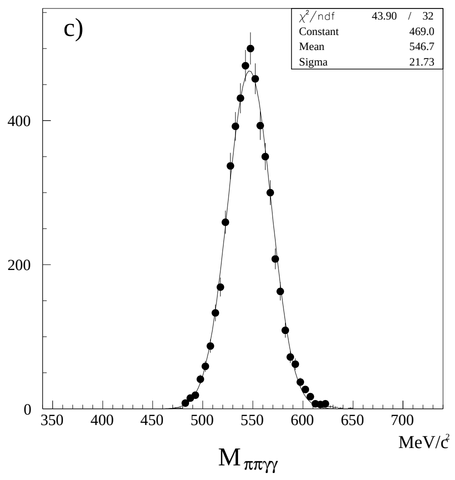
Photons energy spectrum



Charged π momentum spectrum



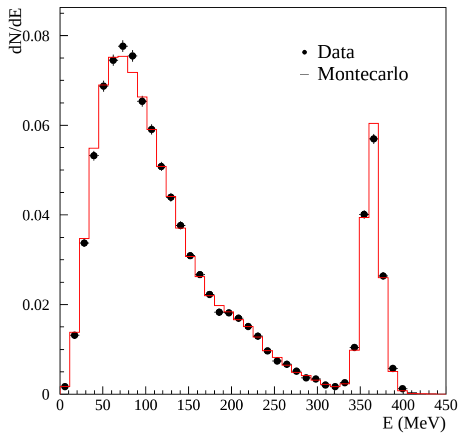
Kinematic fit χ^2

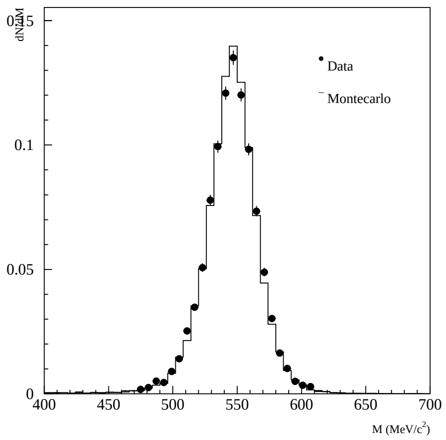


$\pi^+ \pi^- \gamma\gamma$ invariant mass

Discrepancies between data and Monte Carlo always at level 1-2%

$\phi \to \eta\gamma \to \pi^0\,\pi^0\,\pi^0\,\gamma$ *events*



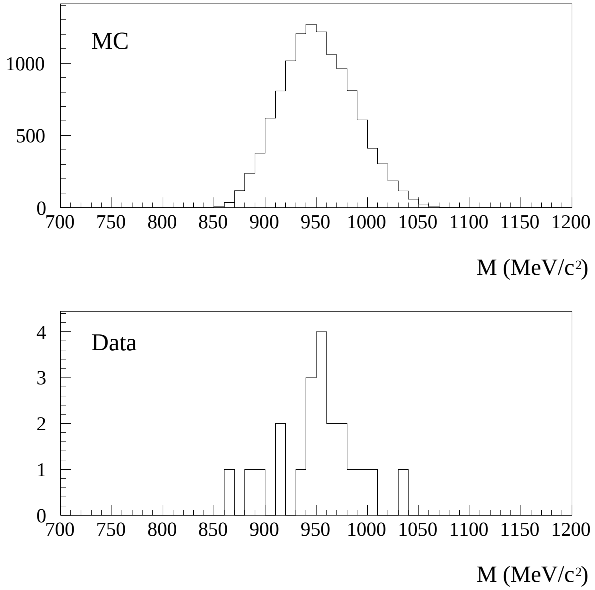


Cluster energy spectrum $\qquad$ $\pi^0\,\pi^0\,\pi^0$ invariant mass

Discrepancies between data and Monte Carlo always at level 1-2%

$\phi \to \eta' \gamma$ events

Applying all the selection cuts on the analyzed statistics we are left with 21 ± 4.6 events in the charged/neutral channel and $6^{+3.3}_{-2.2}$ events in the fully neutral one. This is the first observation of the decay chain $\phi \to \eta' \gamma \to \eta \pi^0 \pi^0 \gamma \to 7\gamma$.



$\pi^+ \pi^- \gamma \gamma$ invariant mass for $\phi \to \eta' \gamma \to \pi^+ \pi^- \eta \gamma$ events (reconst. output, no fit)
The expected background from $\eta\gamma$ is < 0.9 events at 90% CL

Results obtained with 2.4 pb^{-1} statistics

Determination of R_ϕ: method

The measured ratio of observed events is given by

$$R_{obs} \equiv \frac{N^{\eta'}_{obs}}{N^{\eta}_{obs}} = \frac{N_\phi}{N_\phi} \cdot \frac{BR(\phi_{\eta'\gamma})}{BR(\phi_{\eta\gamma})} \cdot \frac{\varepsilon_{\eta'\gamma}}{\varepsilon_{\eta\gamma}} \cdot \frac{BR(\eta'_{\pi^+\pi^-\eta}) \cdot BR(\eta_{\gamma\gamma})}{BR(\eta_{\pi^+\pi^-\pi^0}) \cdot BR(\pi^0{}_{\gamma\gamma})}$$

for the charged/neutral final states and

$$R_{obs} \equiv \frac{N^{\eta'}_{obs}}{N^{\eta}_{obs}} = \frac{N_\phi}{N_\phi} \cdot \frac{BR(\phi_{\eta'\gamma})}{BR(\phi_{\eta\gamma})} \cdot \frac{\varepsilon_{\eta'\gamma}}{\varepsilon_{\eta\gamma}} \cdot \frac{BR(\eta'_{\pi^0\pi^0\eta}) \cdot BR(\eta_{\gamma\gamma}) \cdot [BR(\pi^0{}_{\gamma\gamma})]^2}{BR(\eta_{\pi^0\pi^0\pi^0}) \cdot [BR(\pi^0{}_{\gamma\gamma})]^3}$$

for fully neutral final states.
Solving for $R_\phi \equiv BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma)$ one gets:

$$R_\phi = R_{obs} \cdot \frac{\varepsilon_{\eta\gamma}}{\varepsilon_{\eta'\gamma}} \cdot R_{BR}$$

Determination of R_ϕ : first results from KLOE

The uncertainty on R_ϕ depends on the uncertainty on the intermediate BR's, $\Delta R_{BR}/R_{BR}$. Using current PDG values for the intermediate BR's, together with their errors one gets $R_{BR} = 1.33 \pm 0.05$ for charged/neutral events and $R_{BR} = 3.92 \pm 0.25$ for fully neutral events. Further systematic effects to be considered are the ones on the evaluation of efficiencies (especially for low energy photons) and the ones due to Monte Carlo-Data discrepancies on the distributions of variables on which the cuts are set. For fully neutral events, moreover, a 5% systematic effect due to wrong photon assignment has been evaluated.

$$R_\phi = (7.1 \pm 1.6(\text{stat.}) \pm 0.3(\text{syst.})) \cdot 10^{-3}$$

from the $\pi^+\pi^-\gamma\gamma\gamma$ final state (21 ± 4.6) and:

$$R_\phi = \left(6.9^{+3.8}_{-2.5}(\text{stat.}) \pm 0.9(\text{syst.})\right) \cdot 10^{-3}$$

from the 7γ final state ($6^{+3.3}_{-2.2}$ events).

The $\phi \to \eta'\gamma$ branching ratio

We use the obtained R_ϕ value to evaluate BR($\phi \to \eta'\gamma$) as $R_\phi \cdot BR(\phi \to \eta\gamma\ )$:

$$BR(\phi \to \eta'\gamma\ ) = (8.9 \pm 2.0(\text{stat.}) \pm 0.6(\text{syst.})) \cdot 10^{-5}$$

where we use only the $\pi^+\pi^-\gamma\gamma\gamma$ final state events.

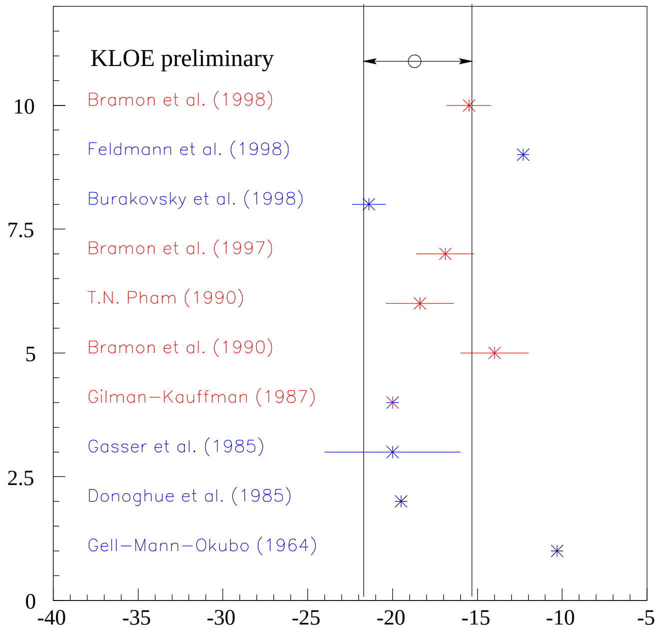
This is to be compared to the current most precise measurement given by CMD-2 and SND collaborations:

$$BR(\phi \to \eta'\gamma\ ) = \begin{cases} (8.2^{+2.1}_{-1.9} \pm 1.1) \cdot 10^{-5} & \text{CMD-2} \\ (6.7^{+3.4}_{-2.9} \pm 1.0) \cdot 10^{-5} & \text{SND} \end{cases}$$

The mixing angle

Using the relation between R_ϕ and the mixing angle one gets :

$$\vartheta_P = \left(-18.9^\circ{}^{+3.6^\circ}_{-2.8^\circ}(\text{stat.}) \pm 0.6^\circ(\text{syst.})\right)$$



As already mentioned a pure and abundant sample of $\phi \to \eta\gamma$ decays has been collected in both $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ final state.

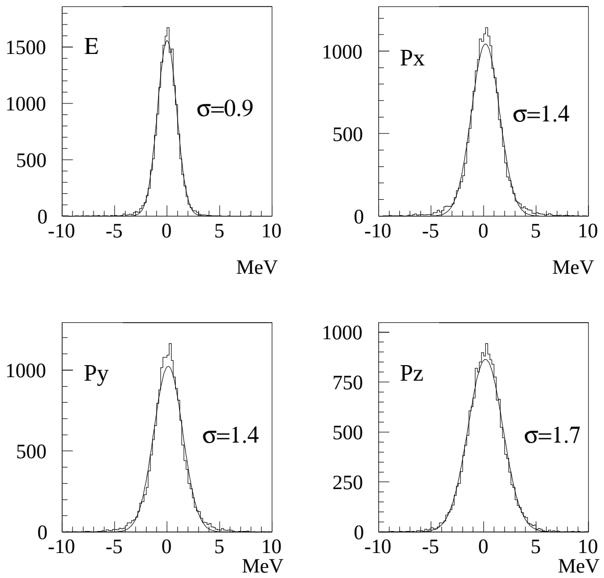
Work is in progress to:

- fit the Dalitz plot shape of $\eta \to \pi^+\pi^-\pi^0$ to extract momentum dependence of the matrix element. After kinematic fit a resolution on pion momenta in their rest frame of 1.5-2 MeV is achieved.

- measure the ratio

$$R = \frac{\eta \to \pi^0\pi^0\pi^0}{\eta \to \pi^+\pi^-\pi^0}$$

Statistics collected is already at PDG level, currently addressing systematics.



Monte Carlo momentum resolution for charged pions in rest frame

Conclusions

- Measuring BR($\phi \to \eta'\gamma$)/BR($\phi \to \eta\gamma$) is a test for both the gluon content of the η' and the value of the pseudoscalar mixing angle ϑ_P.
- Analysis of first KLOE data shows that the $\phi \to \eta\gamma$ control data set compare very favourably with simulations.
- First $\eta'\gamma$ events have been observed in both the $\pi^+\pi^-\gamma\gamma\gamma$ and the 7 γ final states.
- First results give for $R_\phi \simeq 6 - 7 \cdot 10^{-3}$ or BR$(\phi \to \eta'\gamma\ ) \simeq 8 - 9 \cdot 10^{-5}$.
- Work is in progress in measuring relevant parameters of the η decay into three pions
- The higher statistics available in next future will reduce uncertainties and give deeper insight in the $\eta - \eta'$ mixing angle puzzle.