$\phi \to \eta' \gamma$ in $\pi^+\pi^-\gamma\gamma\gamma$ and 7γ final states at KLOE

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:

$$(8.2^{+2.1}_{-1.9}) \times 10^{-5} \quad \text{CMD–2 1999}$$

$$(6.7^{+3.4}_{-2.9}) \times 10^{-5} \quad \text{SND 1998}$$

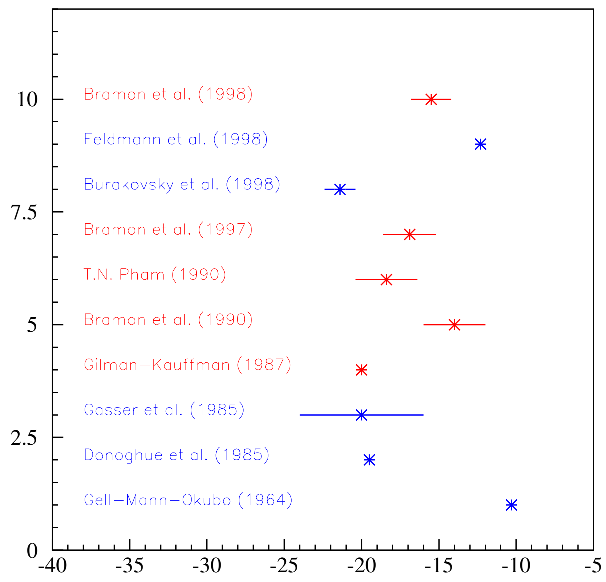
One of the goals of KLOE in its first phase is to measure BR($\phi \to \eta'\gamma$) with smaller uncertainty.

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 value of the 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



A crucial test can be performed at KLOE measuring

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

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

$\sim 10\%$ uncertainty on R_ϕ will result in $\Delta\vartheta_P \approx 1^\circ$

Analyzed decays

Charged/Neutral

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

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

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

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

Fully neutral

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

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

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

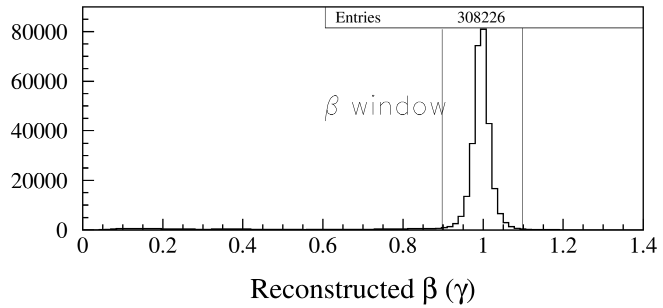
$BR \approx 1 \times 10^{-5}$

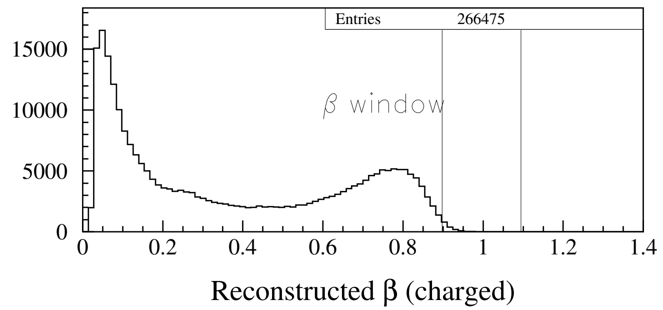
Control of systematic effects

Due to similarity in event topologies between $\phi \to \eta' \gamma$ events and the corresponding $\phi \to \eta\gamma$ ones, one can check selection efficiencies for the former estimating the (better known) BR of the latter. Moreover, most of the systematic effects are expected to cancel out in the ratio R_ϕ.

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

Selection criteria: charged/neutral





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

3 clusters with:

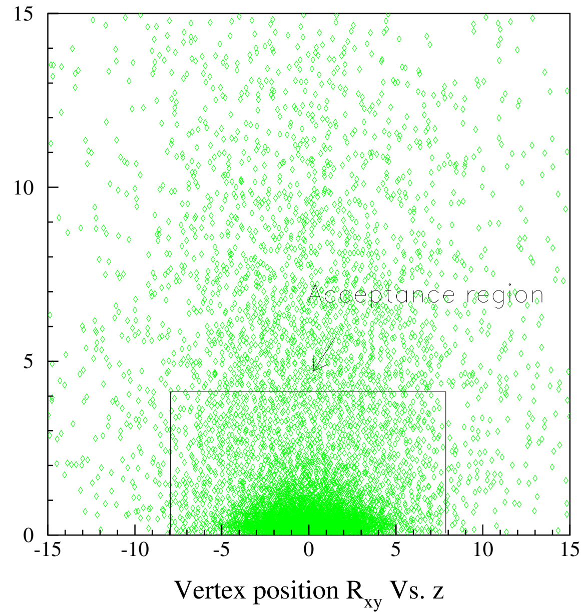
- $0.9 < \beta < 1.1$
- $\theta_\gamma > 21^\circ$

$\varepsilon_{\eta\gamma} = 77.8\%$; $\varepsilon_{\eta'\gamma} = 76.9\%$

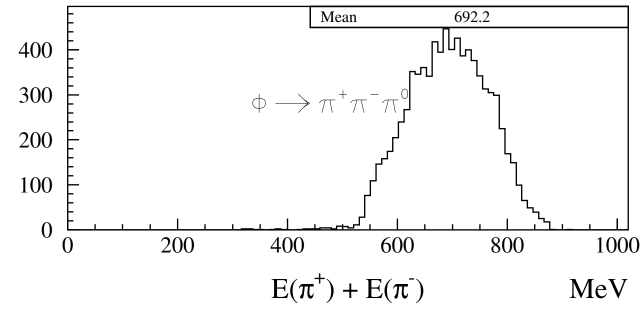
1 charged vertex within:

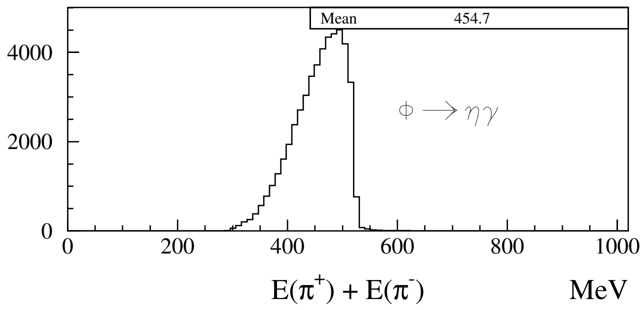
- $R_{xy} < 4\mathrm{cm}$
- $|z| < 8\mathrm{cm}$

$\varepsilon_{\eta\gamma} = 62.0\%$; $\varepsilon_{\eta'\gamma} = 57.7\%$



Selection criteria: charged/neutral





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

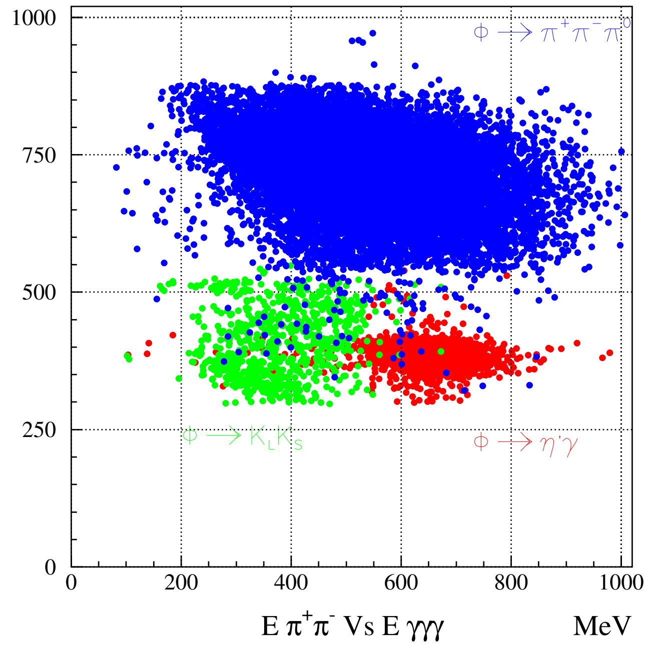
- $E_\gamma^{max} > 300$ MeV
- $E(\pi^+) + E(\pi^-) < 550$ MeV

$\varepsilon_{\eta\gamma} = 99.9\%$; $\varepsilon_{3\pi} = 1.5 \cdot 10^{-3}$

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

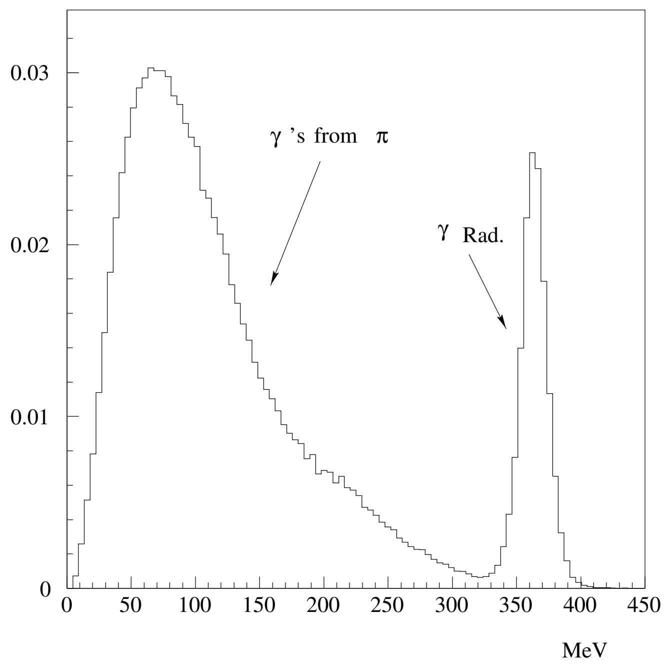
- $E(\pi^+) + E(\pi^-) < 412$ MeV
- $E_{\gamma\gamma\gamma} > 520$ MeV

$\varepsilon_{\eta'\gamma} = 98.8\%$; $\varepsilon_{Bkg} \simeq 10^{-4}$



Selection criteria: fully neutral

- 7 clusters with $0.9 < \beta < 1.1$
- $\theta_\gamma > 21^\circ$
- $|E_{tot} - 1020\,\mathrm{MeV}| < 2\sigma_E = 130\,\mathrm{MeV}$
- $E_\gamma^{max} > 300\,\mathrm{MeV}$ $(\phi \to \eta\gamma)$
- $\varepsilon_{\eta\gamma} = 42.8\%$
- $\varepsilon_{\eta'\gamma} = 46.7\%$

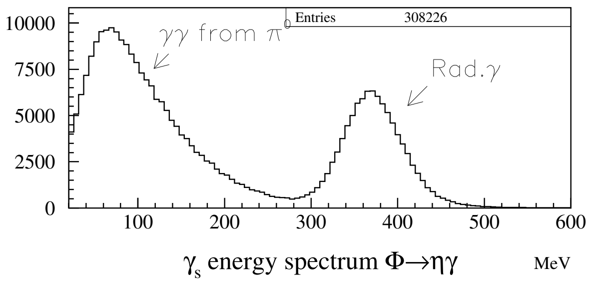


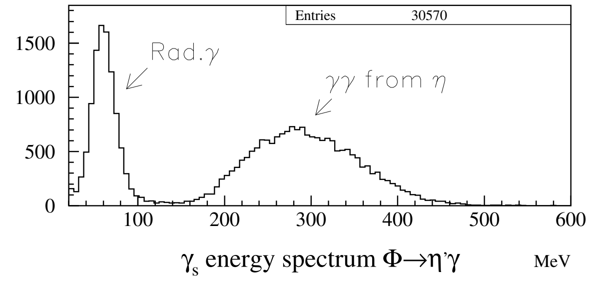
Cluster energy spectrum $\phi \to \eta\gamma$

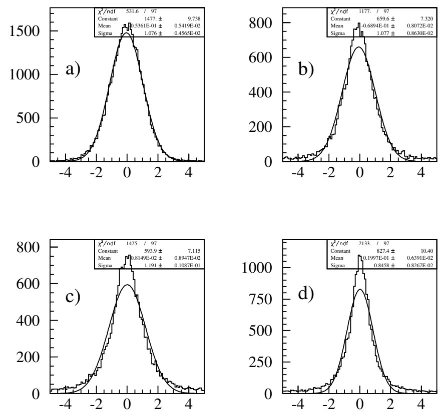
Kinematic fit: charged/neutral

No combinatorial problem: photons easily identified.
Kinematic fit in both $\phi \to \eta\gamma$ and $\phi \to \eta'\gamma$ hypothesis with all possible 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 $\phi_{\eta\gamma}$





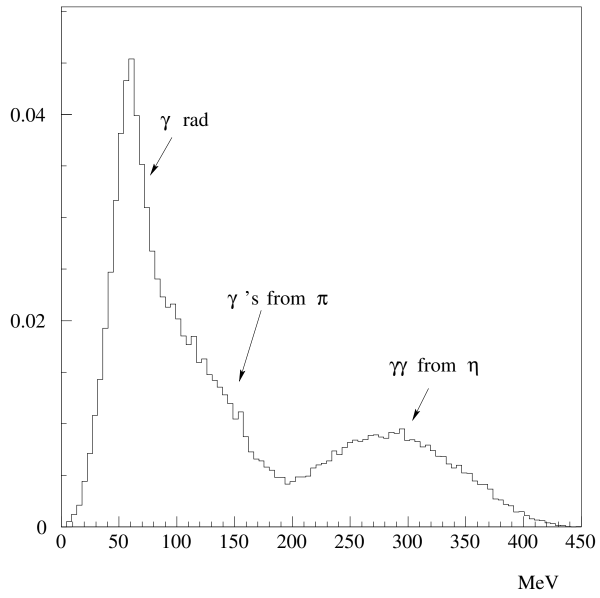


All the measured quantities are input to the fit (26 parameters):

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

Kinematic fit: fully neutral

- To perform the kinematic fit on $\eta'\gamma$ events a photon pairing procedure is applied.
- Assignment is correct in 90% of the cases
- No attempt is made to solve the combinatorial for $\eta\gamma$ events.
- 37 input parameters:
  - E, x, y, z, t $\forall\gamma$
  - Beam energies



Constraints:

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

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

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

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

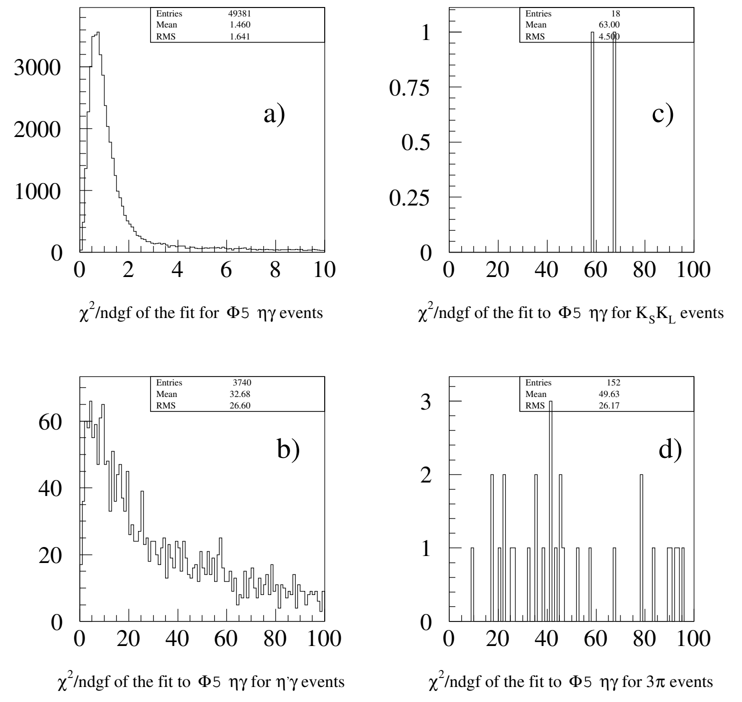
Kinematic fit: background rejection for $\eta\gamma$

$\phi \to \eta\gamma \to 7\gamma$ is background free at KLOE.

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)

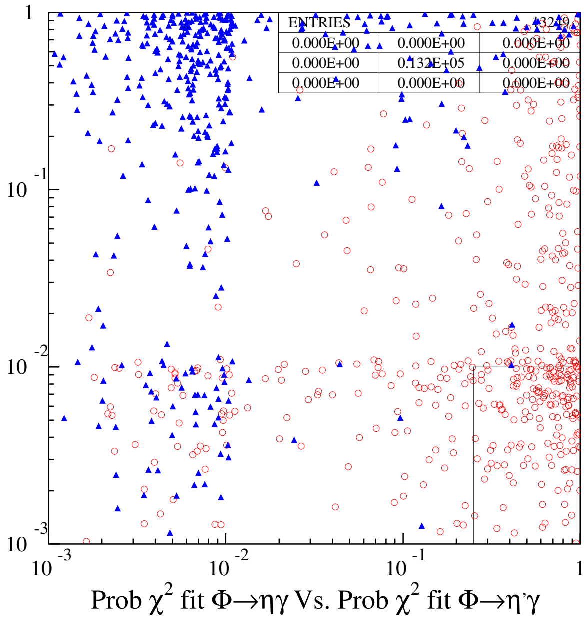


Kinematic fit: background rejection for $\eta'\gamma$

- 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:

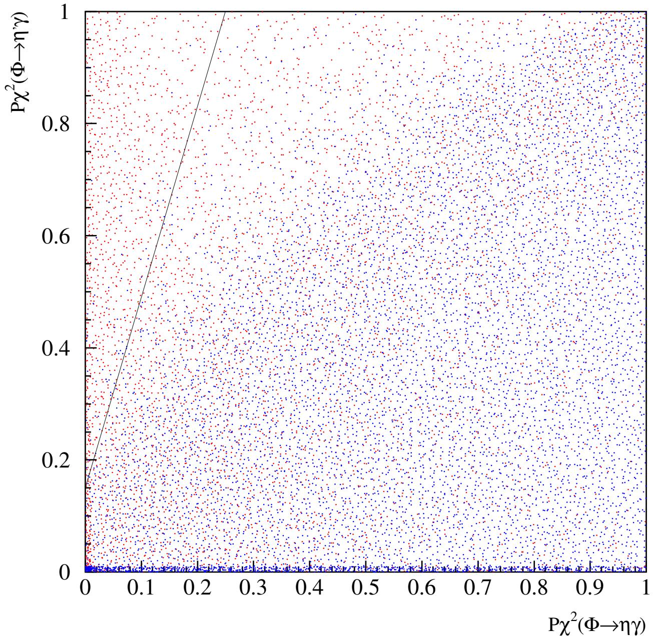
$$\mathcal{P}(\chi^2_{\eta'\gamma}) > 25\% \ \ \text{AND} \ \ \mathcal{P}(\chi^2_{\eta\gamma}) < 1\%$$

  gets rid of the charged/neutral $\eta\gamma$ background for $\eta'\gamma$ charged/neutral events.
  - $\varepsilon_{\eta'\gamma} = 55.0\%$
  - $\varepsilon_B < 4.4 \times 10^{-5}$ (90% CL)
  - Signal/Background > 35 (90% CL)
- For fully neutral events a more complex procedure has been used to reject $\phi \to \eta\gamma \to 7\gamma$'s background.

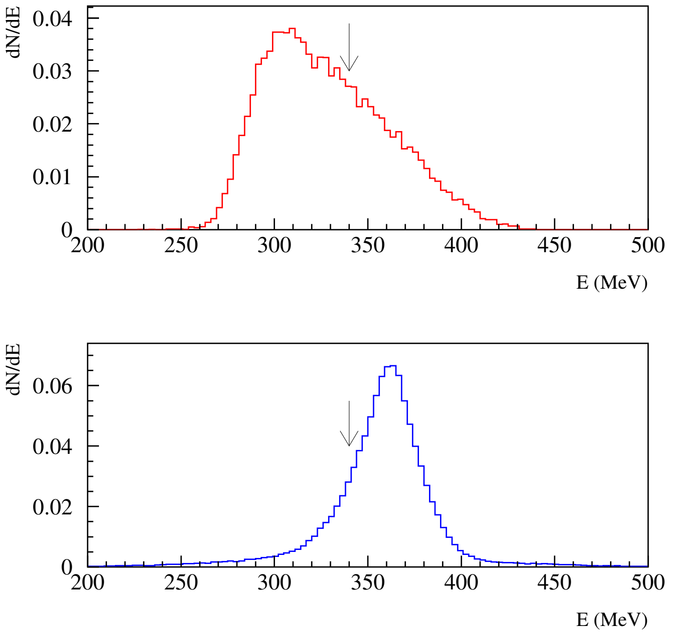


Kinematic fit: background rejection for $\eta'\gamma$

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



Most energetic γ cut



- $\varepsilon_{\eta'\gamma} = 27.0\%$
- $\varepsilon_B < 1.5 \cdot 10^{-5}$ (90% CL)
- Signal/Background > 20 (90% CL)

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

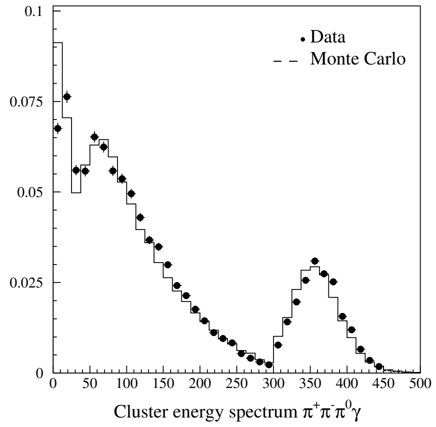
Backgrounds to $\phi \to \eta'\gamma$ charged/neutral

Signal	N/N_ϕ	ε_{Sel}	S/B
$\phi \to \eta'\gamma\ \pi^+\pi^-\gamma\gamma\gamma$	$\sim 2.3 \cdot 10^{-5}$	22.9%	-
$\phi \to \eta\gamma\ \pi^+\pi^-\gamma\gamma\gamma$	$2.9 \cdot 10^{-3}$	$< 4.4 \cdot 10^{-5}$	> 35
$e^+e^- \to \omega\pi^0$	$\sim 2.3 \cdot 10^{-3}$	$< 1.4 \cdot 10^{-4}$	> 20

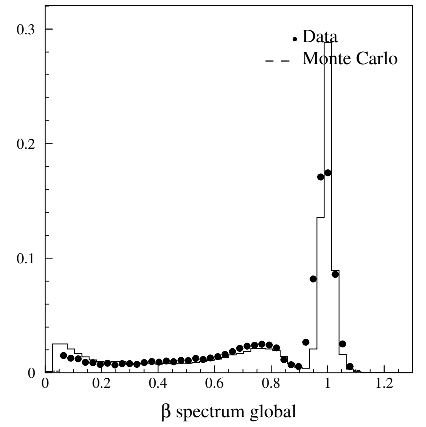
Backgrounds to $\phi \to \eta'\gamma$ fully neutral

Signal	N/N_ϕ	ε_{Sel}	S/B
$\phi \to \eta'\gamma \to 7\gamma$	$\sim 1 \cdot 10^{-5}$	12.6%	-
$\phi \to \eta\gamma \to 7\gamma$	$3.9 \cdot 10^{-3}$	$< 1.5 \cdot 10^{-5}$	> 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

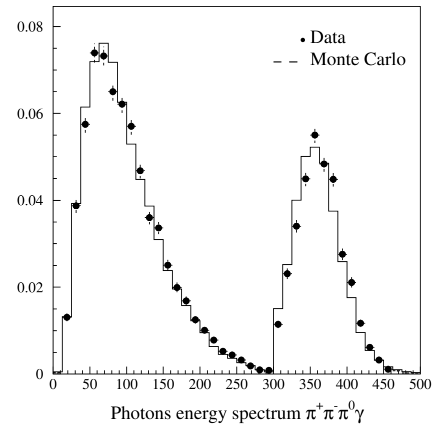
$\phi \rightarrow \eta\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$ *events*



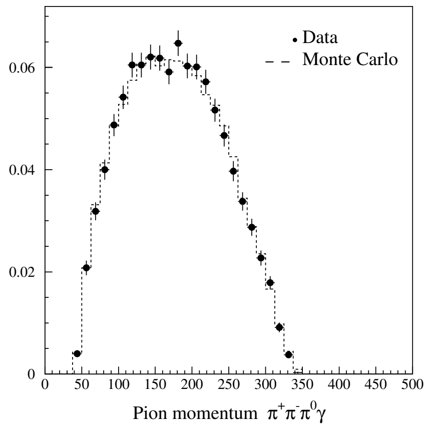
Cluster energy spectrum



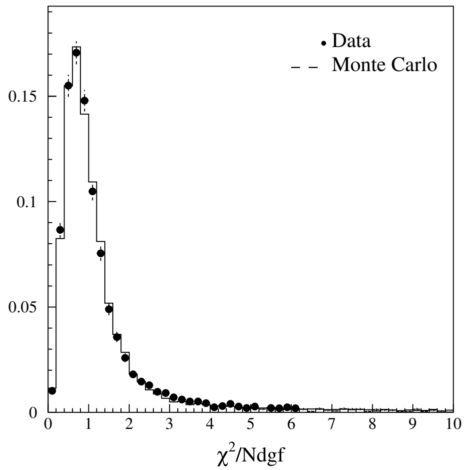
Cluster β spectrum



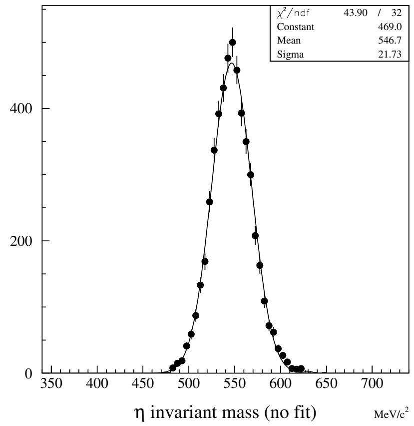
Photons energy spectrum



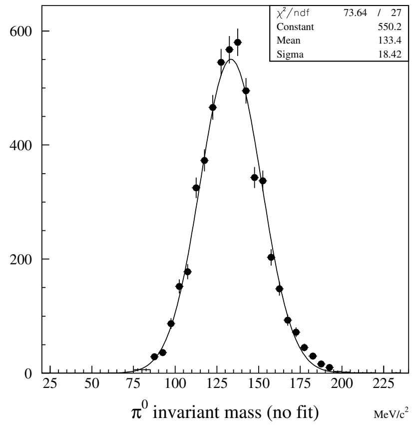
Charged π momentum spectrum



Kinematic fit χ^2

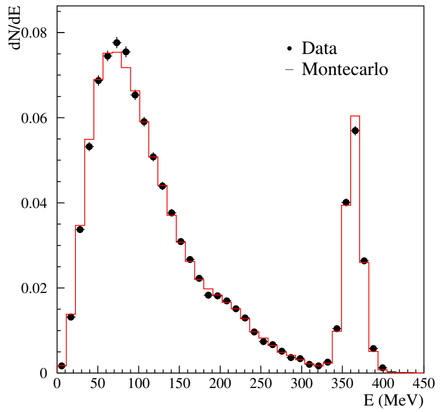


η invariant mass

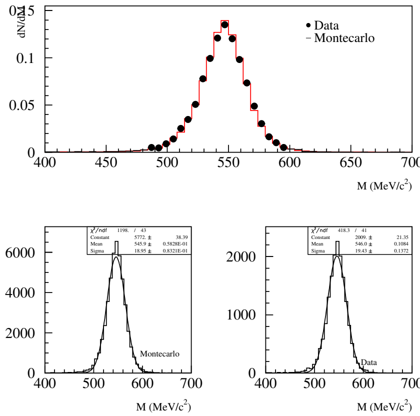


π^0 invariant mass

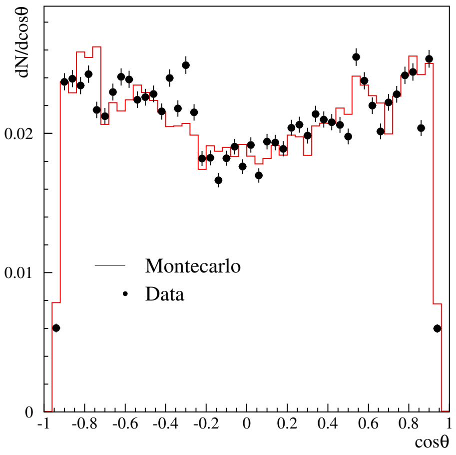
$\phi \to \eta\gamma \to \pi^0\,\pi^0\,\pi^0\,\gamma$ *events*



Cluster energy spectrum



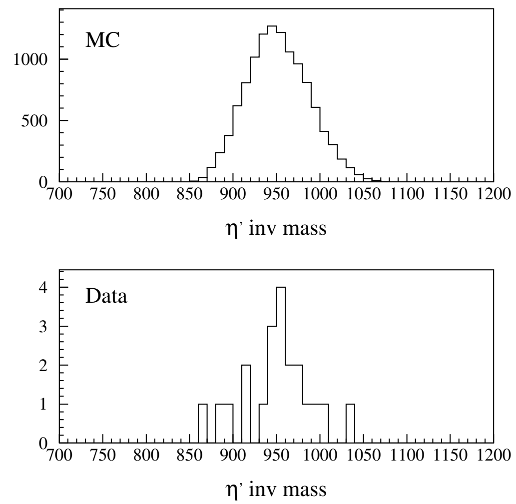
η invariant mass



$\cos\theta$ distribution for rad. γ

$\phi \to \eta' \gamma$ events (updated)

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



η' 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 2.42 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 : preliminary results from KLOE (updated)

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. Furhter systematic effects to be considered are the ones on the evaluation of efficiencies which we evaluate comparing the BR($\phi \to \eta\gamma$) obtained from our analysis with the PDG value. One then gets:

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

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

$$R_\phi = \left(7.3^{+4.0}_{-2.7}(\text{stat.}) \pm 1.1(\text{syst.})\right) \cdot 10^{-3}$$

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

Complete systematic effects evaluation is in progress

F. Ambrosino
Università e Sezione INFN Napoli

The $\phi \to \eta'\gamma$ branching ratio (updated)

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

$$BR(\phi \to \eta'\gamma) = (8.9 \pm 2.0(\text{stat.}) \pm 0.5(\text{syst.})) \cdot 10^{-5}$$

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 and to the current PDG value:

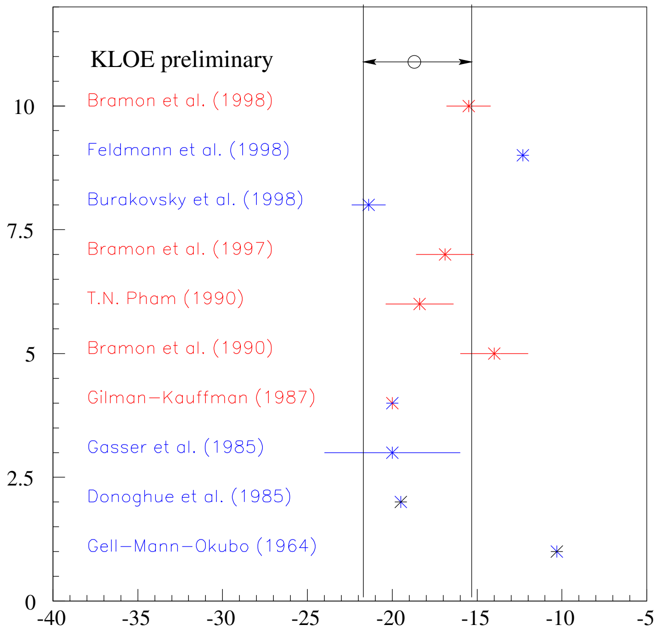
$$BR(\phi \to \eta'\gamma) = \begin{cases} (12^{+7}_{-5}) \cdot 10^{-5} & \text{PDG} \\ (8.2^{+2.1}_{-1.9}) \cdot 10^{-5} & \text{CMD-2} \\ (6.7^{+3.4}_{-2.9}) \cdot 10^{-5} & \text{SND} \end{cases}$$

Complete systematic effects evaluation is in progress

The mixing angle (updated)

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

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



Complete systematic effects evaluation is in progress

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.
- Preliminary analysis of 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.
- Preliminary results show evidence for $R_\phi \simeq 6 - 7 \cdot 10^{-3}$ or BR($\phi \to \eta'\gamma$) $\simeq 8 - 9 \cdot 10^{-5}$.
- The higher statistics available in next future will reduce uncertainties and (hopefully) solve the $\eta - \eta'$ mixing angle puzzle.