Observation of the $\Phi \to \pi^o \pi^o \gamma$ decay @ KLOE

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for the KLOE collaboration

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The $\phi \to \pi^o\pi^o\gamma$ decay

This decay allows to investigate the nature of the intermediate state: $\phi \to S\gamma \to \pi^o\pi^o\gamma$ ($S =$ scalar meson)

- $S = f_o$
  - The BR of the decay is sensitive to the f_o structure:

Model	$q\bar{q}$	$s\bar{s}$	$qq\overline{qq}$	$K\overline{K}$	gg
BR($\phi \to f_o\gamma$)	$\sim 10^{-6}$	$\sim 10^{-5}$	$\sim 10^{-4}$	$\sim 4 \times 10^{-5}$	$< 10^{-6}$

  - The shape of $\pi\pi$ invariant mass spectra depends on the model

    $\Longrightarrow$ Fit to $M_{\pi\pi}$

- $S = f_o - \sigma$ mixing
  - Fit to $M_{\pi\pi}$

Results from SND and CMD-2 experiments (VEPP-2M, Novosibirsk):

$$\text{BR}(\phi \to \pi^o\pi^o\gamma) \sim 1 \times 10^{-4}$$

Several models can fit the $M_{\pi\pi}$ spectra

Analysis scheme

Different "all-photons" final states studied in 1.84 pb^{-1}:

- $\phi \to \eta\gamma \to \gamma\gamma\gamma$ $\quad 150 < E_\gamma < 500$ MeV

  $\Longrightarrow$ **BR's normalization sample**

- $\phi \to \pi^o\gamma$ $\quad 10 < E_\gamma < 500$ MeV

  $\Longrightarrow$ **Check of the analysis techniques and detector performances in the same energy range of $\pi^o\pi^o\gamma$**

- $e^+e^- \to \omega\pi^o \to \pi^o\pi^o\gamma$ $\quad 10 < E_\gamma < 500$ MeV

  $\Longrightarrow$ **Main $\pi^o\pi^o\gamma$ background**

- $\phi \to \pi^o\pi^o\gamma$ $\quad 10 < E_\gamma < 500$ MeV

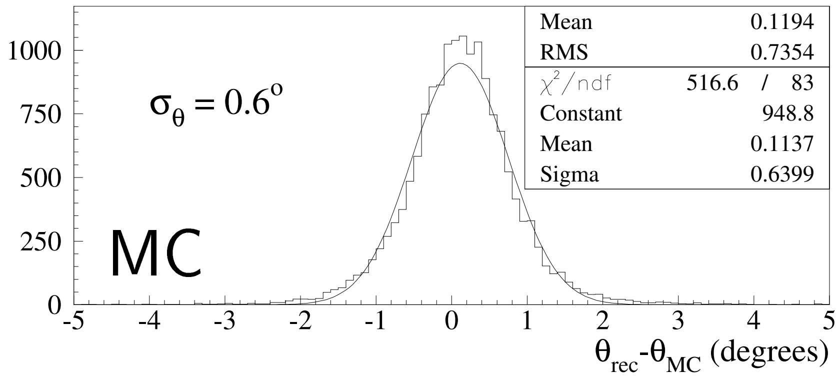
Fully neutral events selection

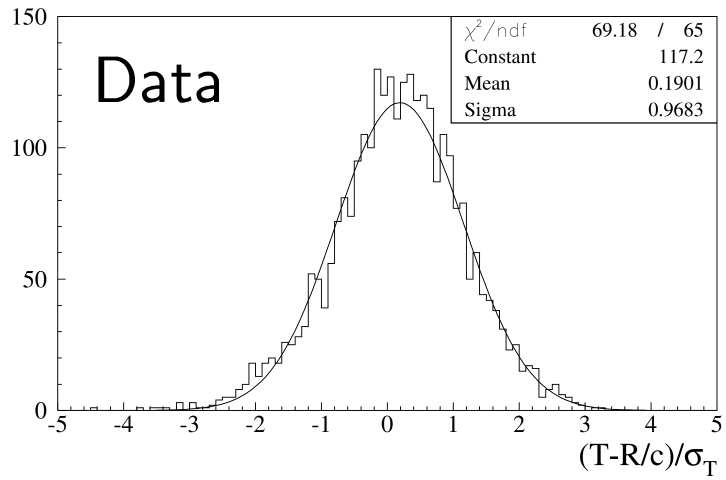
Decay signature: "n" γ's on EMC

EMC resolutions:
$\sigma_E/E = 6\%/\sqrt{E\ (\mathrm{GeV})}$
$\sigma_T = 110\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})}$

Sample selection:

- No prompt hits on QCAL
- $\theta_{rec} = Z_{cl}/R_{cl} > 21°$
- "n" EMC clusters in Time Window ($|T\text{-}R/c| < 5\,\sigma_T$)

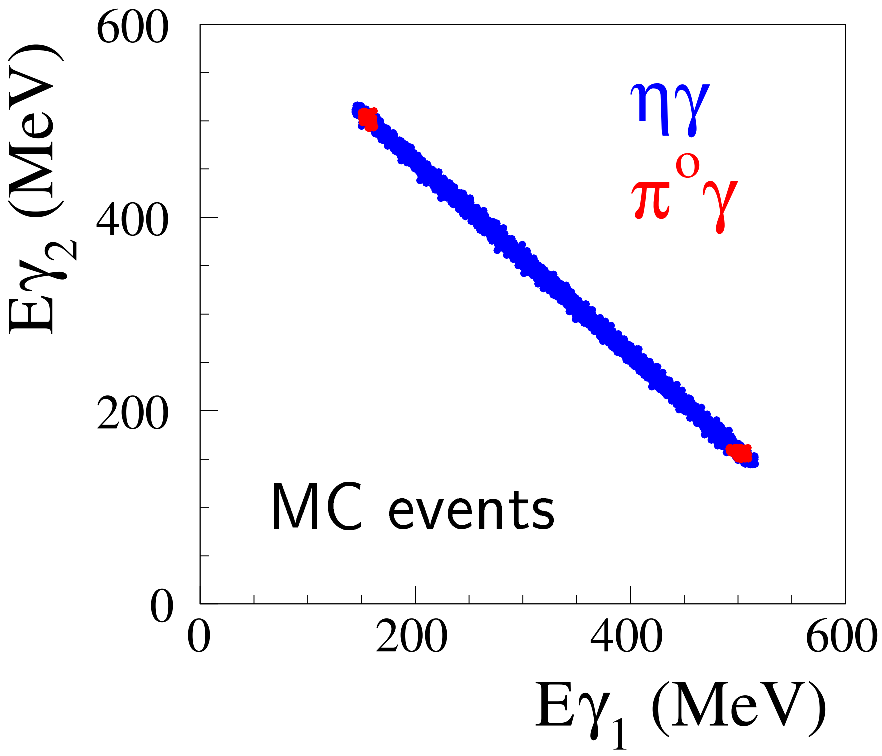


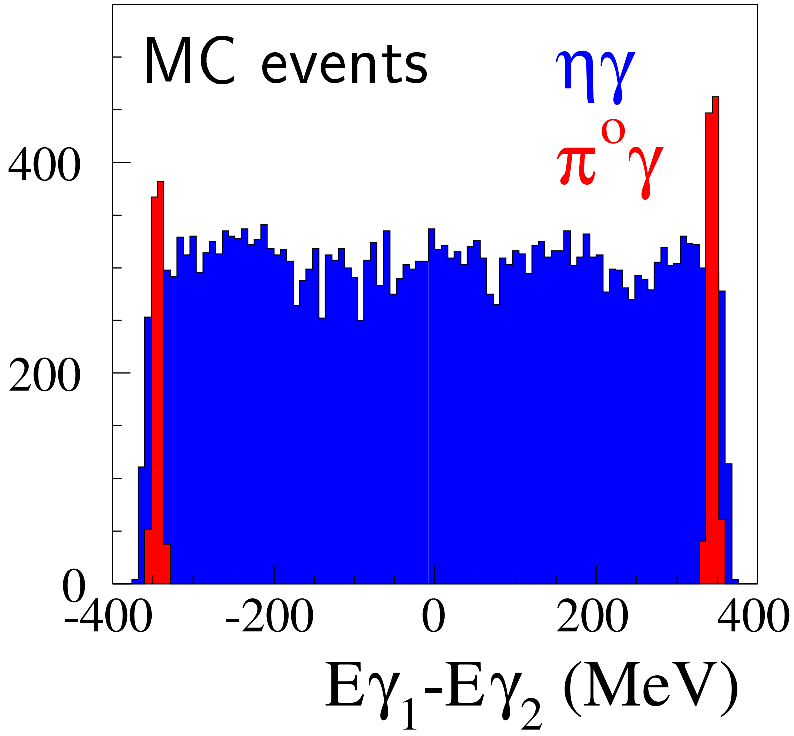


A kinematic fit is then applied [constraints: $(E, \vec{p})$ conservation + invariant masses of intermediate particles]

The $\phi \to \eta\gamma \to \gamma\gamma\gamma$ decay: background rejection

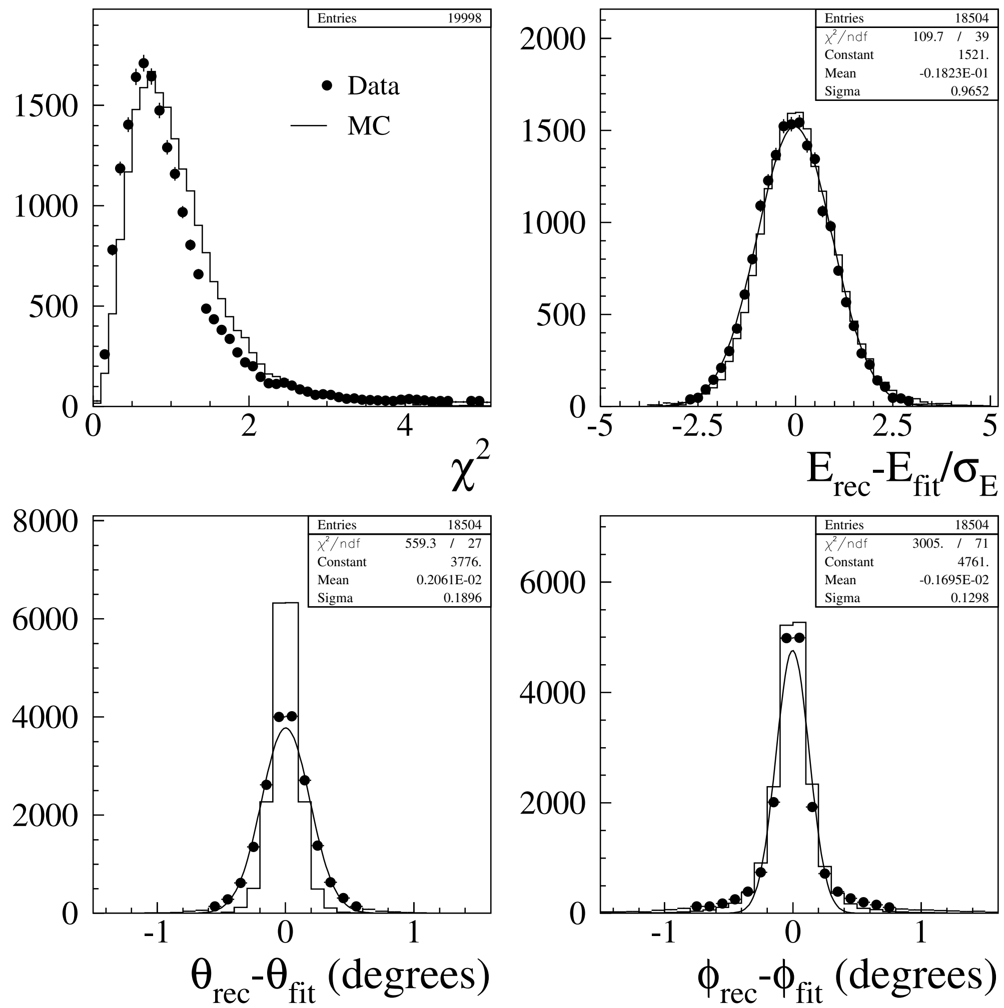
Main background: $\phi \to \pi^o\gamma$ (S/B $= 0.49\%/0.13\% = 4$)





Background rejection requires: $|E_{\gamma_1} - E_{\gamma_2}| < 330$ MeV

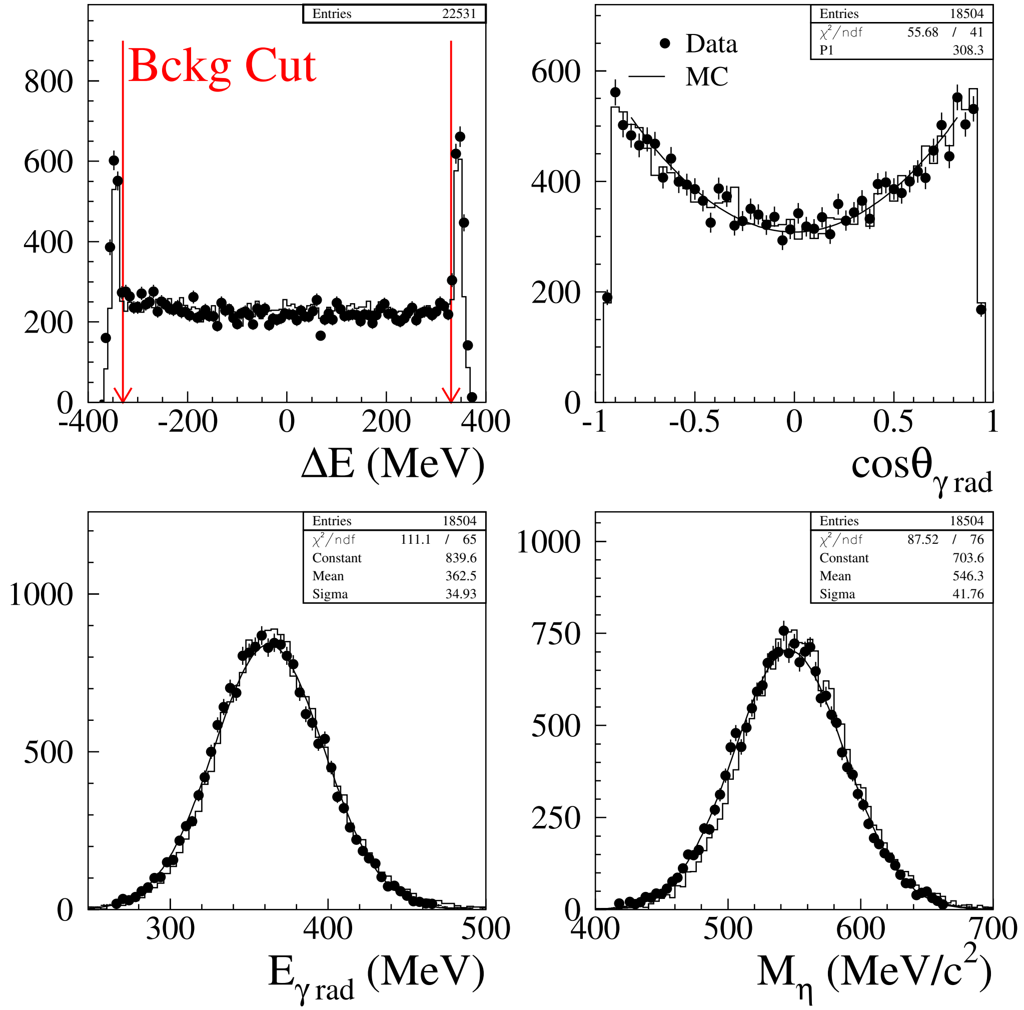
The $\phi \to \eta\gamma \to \gamma\gamma\gamma$ decay: fit results



Number of events surviving analysis cuts:

$N(N_{\rm clu} \geq 3)$	226736
$N(\theta_{\gamma' s} > 21°)$	183345
$N(3\theta_{\gamma' s}$ in TW$)$	45889
$N(\chi^2 < 3.75)$	22531
$N(\lvert\Delta E_{12}\rvert < 330)$	18504

The $\phi \to \eta\gamma \to \gamma\gamma\gamma$ decay: data analysis



$E_{rad} = 362.5$ MeV

$\sigma_{E_{rad}} = 34.9$ MeV

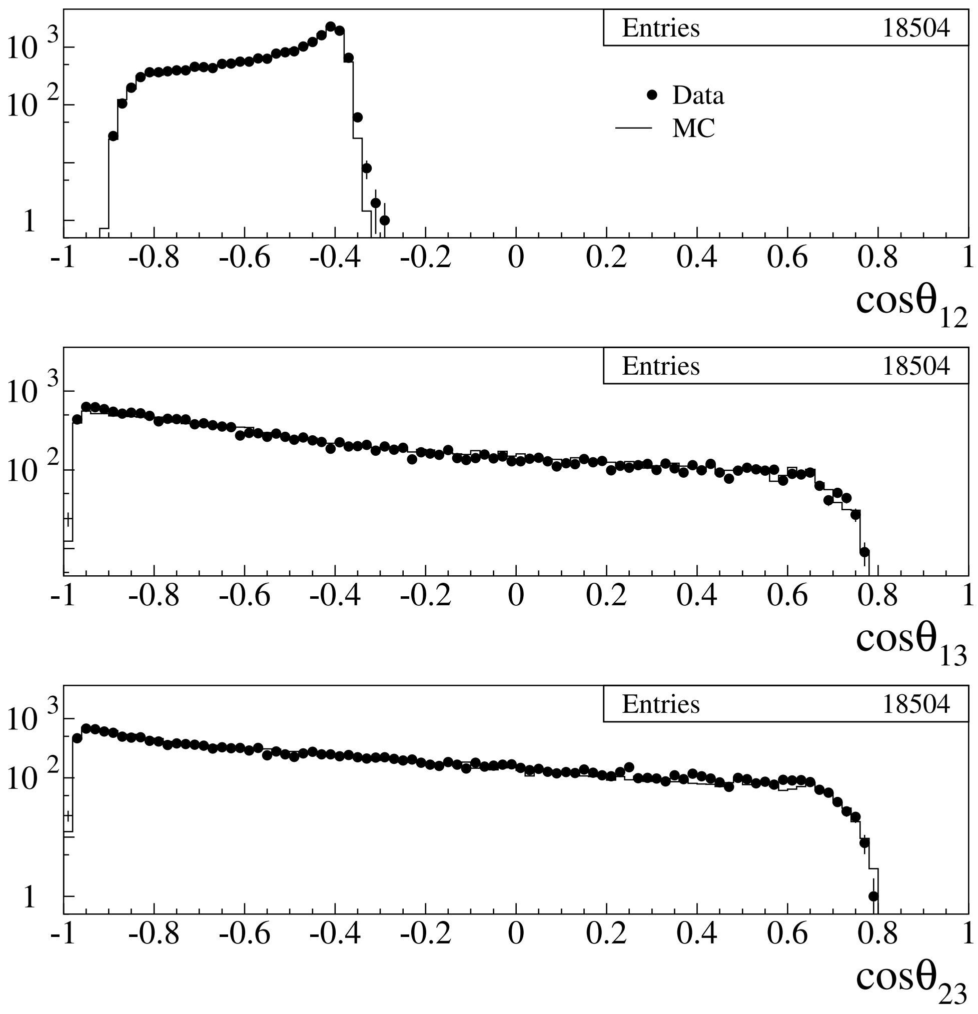
$M_\eta = 546.3\ \mathrm{MeV}/c^2$

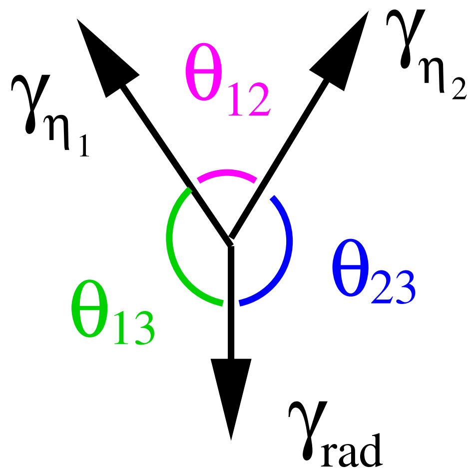
$\sigma_\eta = 41.8\ \mathrm{MeV}/c^2$

$N_{\eta\gamma} = 18504 \pm 136$

$N_{bckg} \sim 0$

The $\phi \to \eta\gamma \to \gamma\gamma\gamma$ decay: angular distributions





$\gamma_{1,2}$: photons' assigned to η

γ_3: radiative photon

ϕ cross section measurement

σ_ϕ calculated measuring

$$\sigma(e^+e^- \to \phi \to \eta\gamma \to \gamma\gamma\gamma) = \frac{N_{\eta\gamma}}{\mathcal{L} \times \varepsilon_{\rm ana}}$$

and using BR$(\phi \to \eta\gamma \to \gamma\gamma\gamma) = (0.49 \pm 0.02)\%$ (PDG)

$\varepsilon_{\rm ana}$, estimated from MC, has contribution from background rejection + event classification ($\varepsilon_{\rm cl}$), sample selection ($\varepsilon_{\rm sel}$), χ^2 cut (ε_{χ^2}) and ΔE cut ($\varepsilon_{\Delta E}$):

$\varepsilon_{\rm cl}$	$\varepsilon_{\rm sel}$	ε_{χ^2}	$\varepsilon_{\Delta E}$	$\varepsilon_{\rm ana}$
76.0%	93.7%	98.5%	91.3%	64.3%

Preliminary

$$\boxed{\sigma_\phi = (\,3.19 \pm 0.02\,({\rm stat.}) \pm 0.26\,({\rm syst.})\,)\ \mu{\rm b}}$$

CMD-2: $\sigma_\phi = (3.114 \pm 0.034 \pm 0.048)\ \mu$b

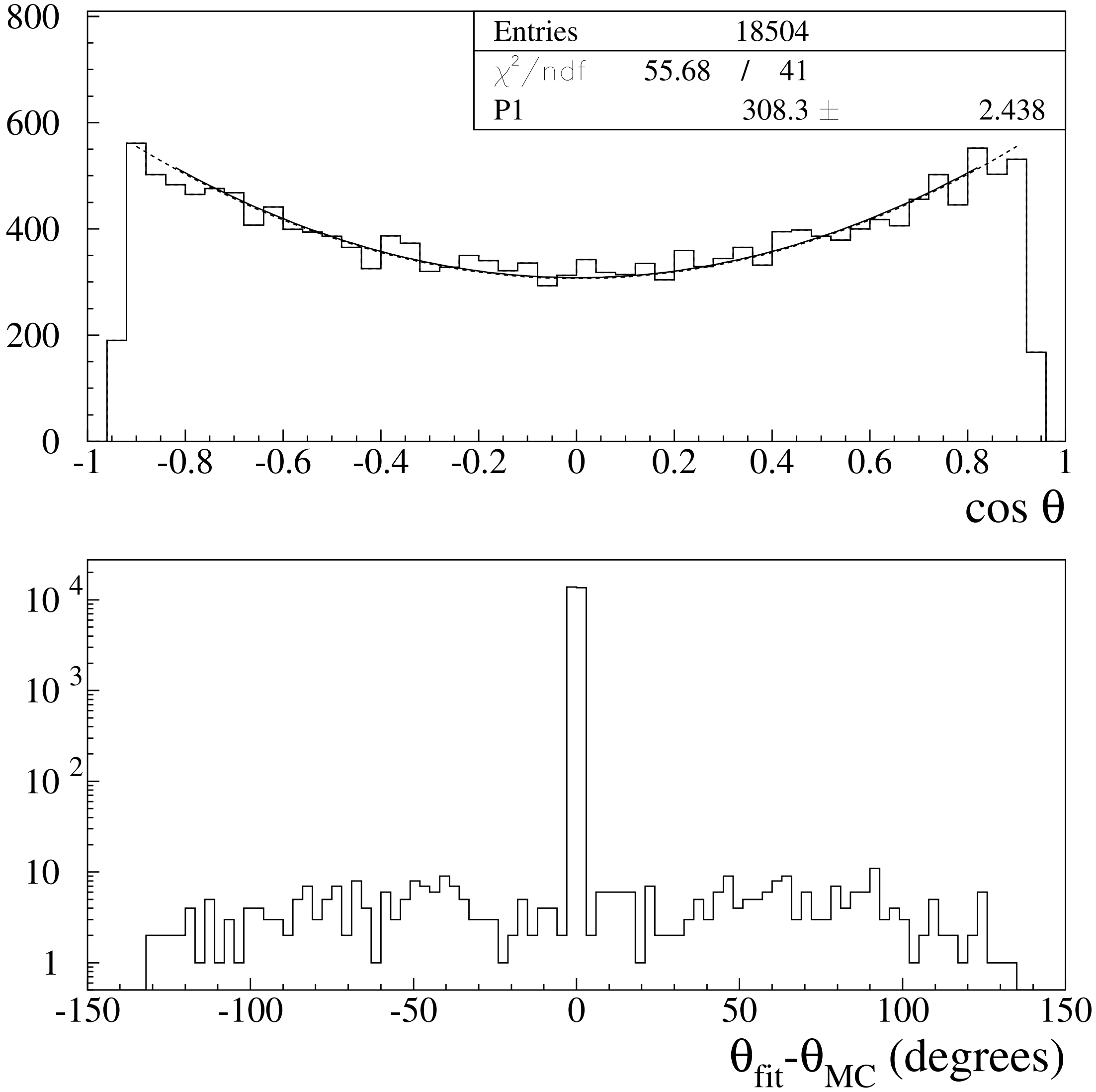
Complete estimation of systematics in progress

ϕ cross section measurement: errors evaluation

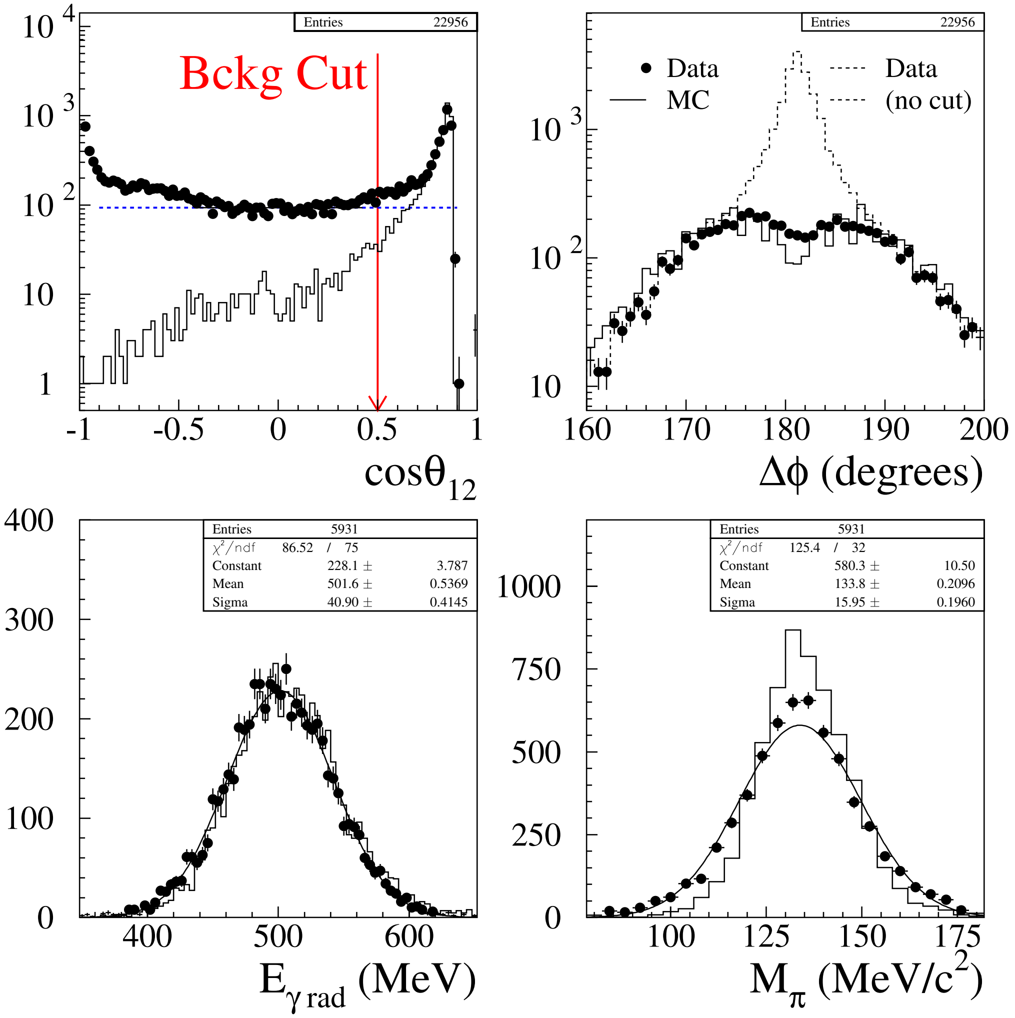
The relative errors are estimated, when possible, from data:

Variable	Value	METHOD
$N_{\eta\gamma}$	0.6%	Statistics
BR$_{\gamma\gamma\gamma}$	4%	From PDG
$\mathcal{L}$	5%	Comparing trigger vs L3 vs offline values
$\varepsilon_{\rm cl}$	5%	Conservative estimate based on a small sample
$\varepsilon_{\rm sel}$	1.0%	Fit to $\cos\theta_{\gamma\,\rm rad}$ distribution in different angular regions for acceptance. No contributions from TW cut (TW$_{\rm max}$ $2 \to 3$ ns: no changes) and clustering ($\varepsilon_{\rm MC} = 99.9\%$)
ε_{χ^2}	0.6%	50% of the wrong assignments percentage as obtained from MC
$\varepsilon_{\Delta E}$	0.3%	Comparison between the events loss counted with MC and the estimate on data fitting the $\lvert\Delta E\rvert < 300$ MeV region

ϕ cross section measurement: errors evaluation



The $\phi \to \pi^o\gamma$ decay: data analysis



$\mathrm{E_{rad}} = 501.6$ MeV

$\sigma_{\mathrm{E_{rad}}} = 40.9$ MeV

$\mathrm{M}_{\pi^o} = 133.8\,\mathrm{MeV}/c^2$

$\sigma_{\pi^o} = 16.0\,\mathrm{MeV}/c^2$

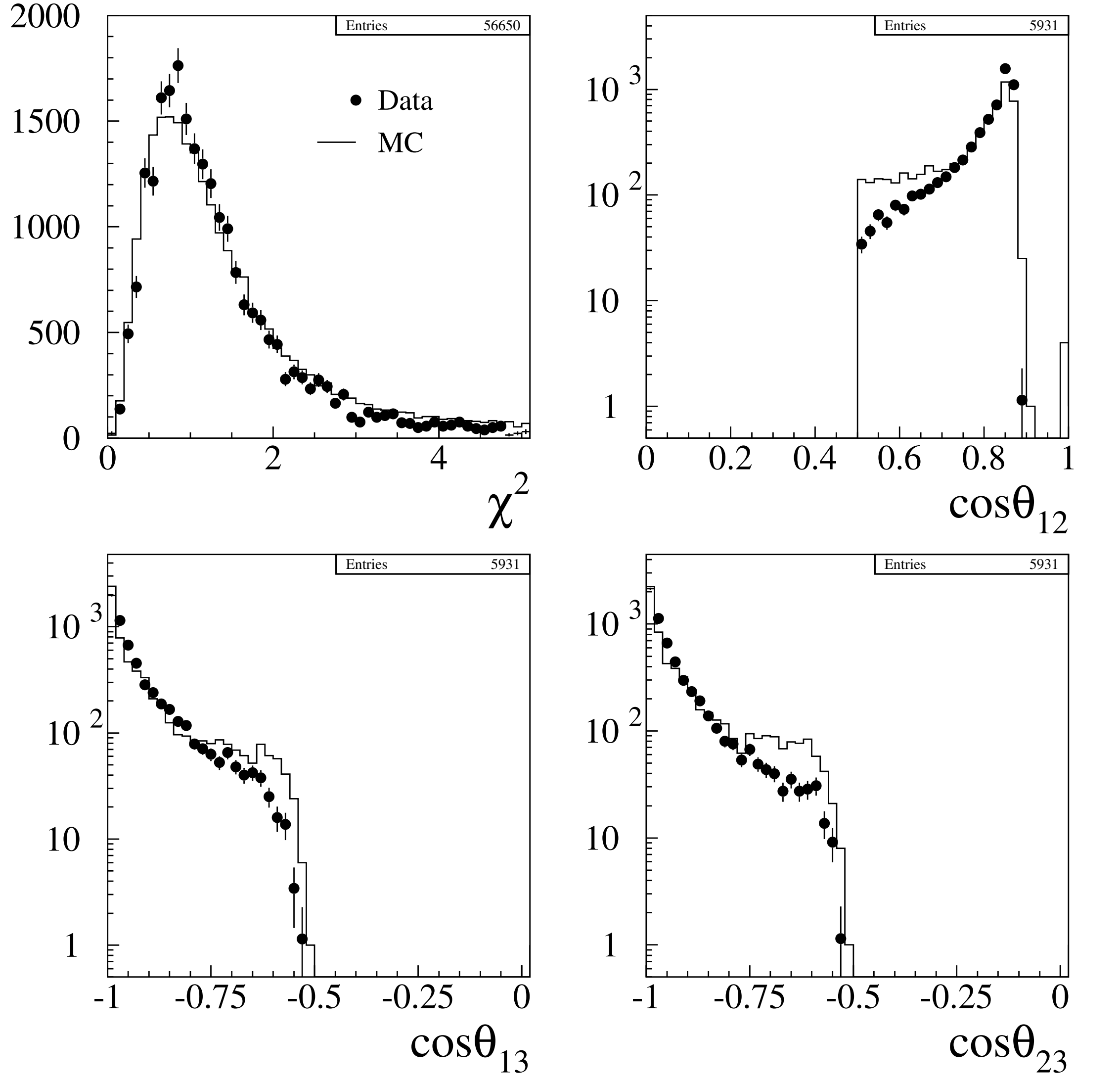
$\mathrm{N_{obs}} = 5931 \pm 77$

$\mathrm{N_{bkg}} = 2144 \pm 30$

$\mathrm{N}_{\pi^o\gamma} = 3787 \pm 83$

QED bkg. evaluation: flat fit in $-0.4 < \cos\theta_{12} < +0.4$ region

The $\phi \to \pi^o\gamma$ decay: fit results



$\eta\gamma/\pi^o\gamma$: relative BR measurement

$$R_{3\gamma} = \frac{\mathrm{BR}(\phi \to \eta\gamma \to \gamma\gamma\gamma)}{\mathrm{BR}(\phi \to \pi^o\gamma)} = \frac{N_{\eta\gamma}}{\varepsilon_{\mathrm{tot}}(\eta\gamma)} \cdot \frac{\varepsilon_{\mathrm{tot}}(\pi^o\gamma)}{N_{\pi\gamma}}$$

Also for $\pi^o\gamma$, $\varepsilon_{\mathrm{ana}}$ evaluated from MC:

$\varepsilon_{\mathrm{cl}}$	$\varepsilon_{\mathrm{sel}}$	ε_{χ^2}	$\varepsilon_{\mathrm{cut}}$	$\varepsilon_{\mathrm{ana}}$
79.4%	87.6%	80.4%	88.3%	49.3%

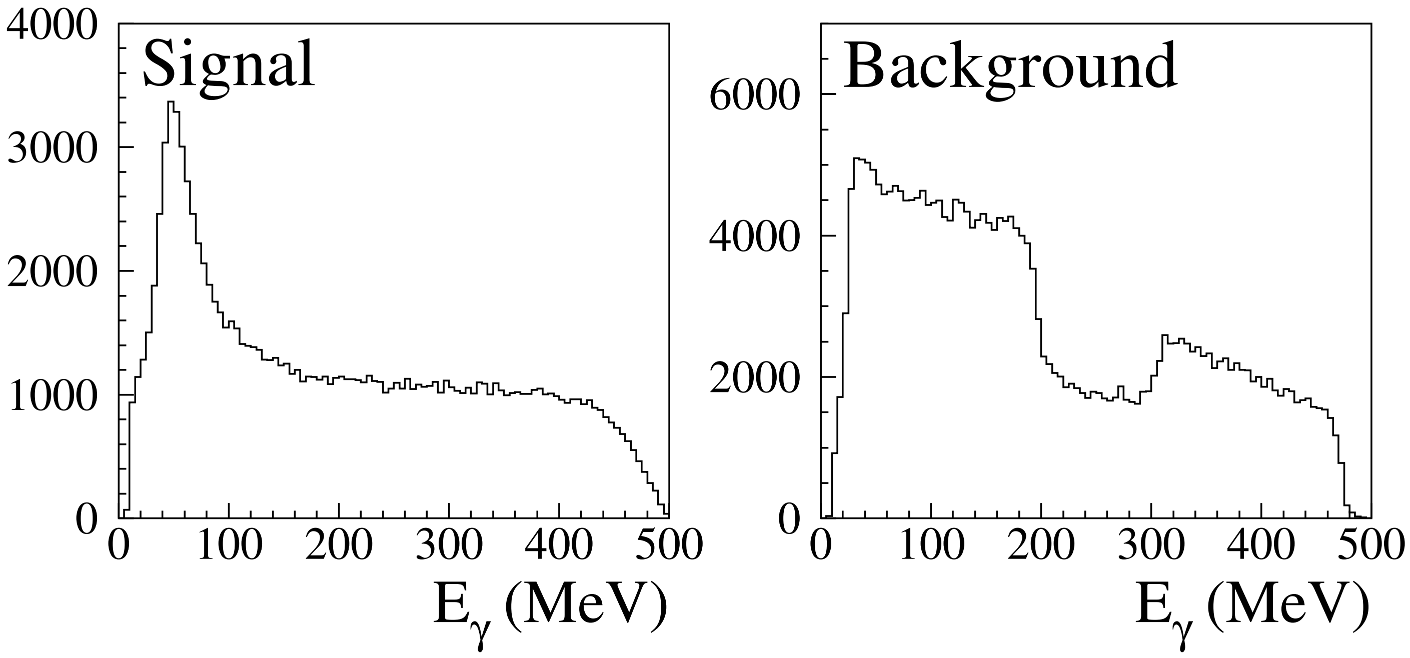
Preliminary

$$\boxed{R_{3\gamma} = 3.75 \pm 0.08\,(\mathrm{stat.}) \pm 0.24\,(\mathrm{syst.})}$$

PDG: $R_{3\gamma} = 3.77 \pm 0.40$

Complete estimation of systematics in progress

MC study: the $\phi \to f_o\gamma \to \pi^o\pi^o\gamma$ decay

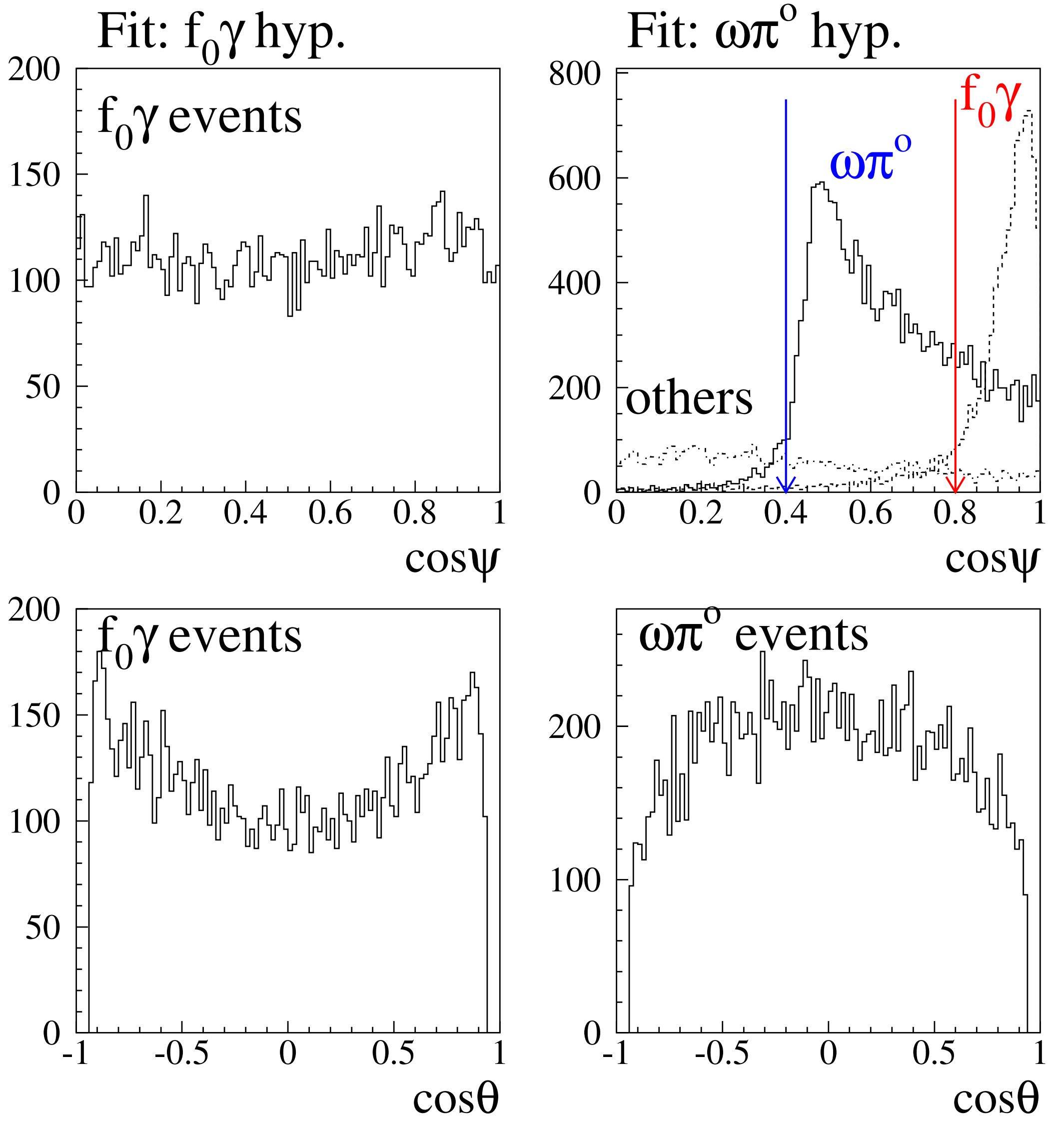


Background	S/B
$e^+e^- \to \omega\pi^o \to \pi^o\pi^o\gamma$	0.52
$\phi \to \rho\pi^o \to \pi^o\pi^o\gamma$	3.0
$\phi \to a_o\gamma \to \eta\pi^o\gamma \to 5\gamma$	3.1
$\phi \to \eta\gamma \to \pi^o\pi^o\pi^o\gamma$	0.02

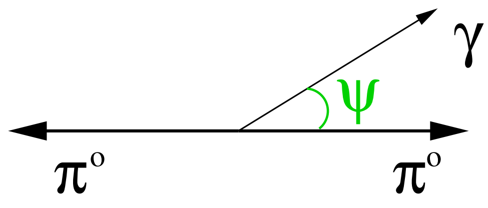
Fit procedure:

- First fit: $(E, \vec{p})$ and ToF constraints applied
- Pairing: best $\gamma's$ pairing with two π^o + $M_{\pi\pi} > 700$ MeV
- Second fit: constraints on π^o masses also required

MC study: $\phi \to f_o\gamma \to \pi^o\pi^o\gamma$ background rejection

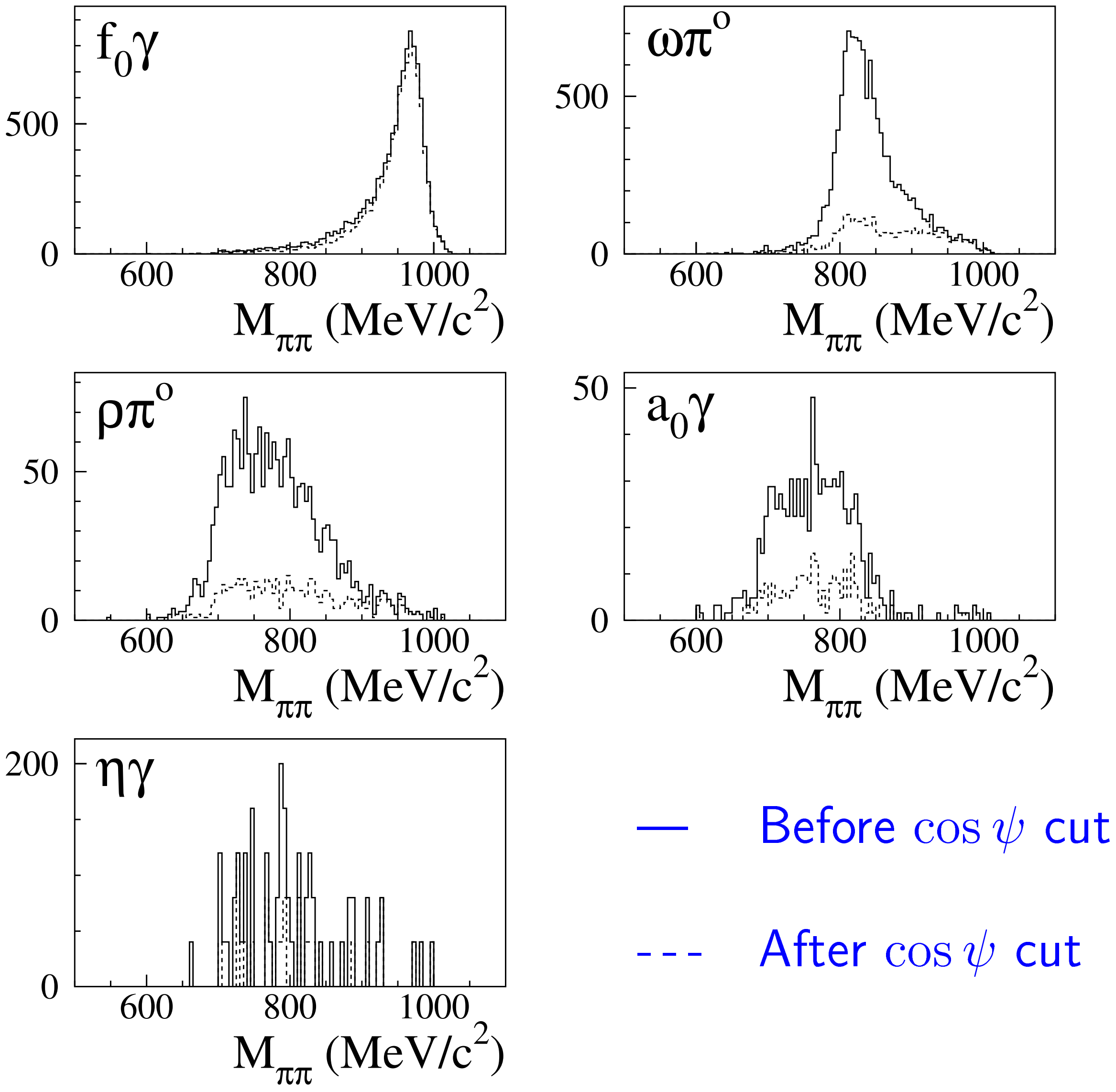


ψ angle def.:

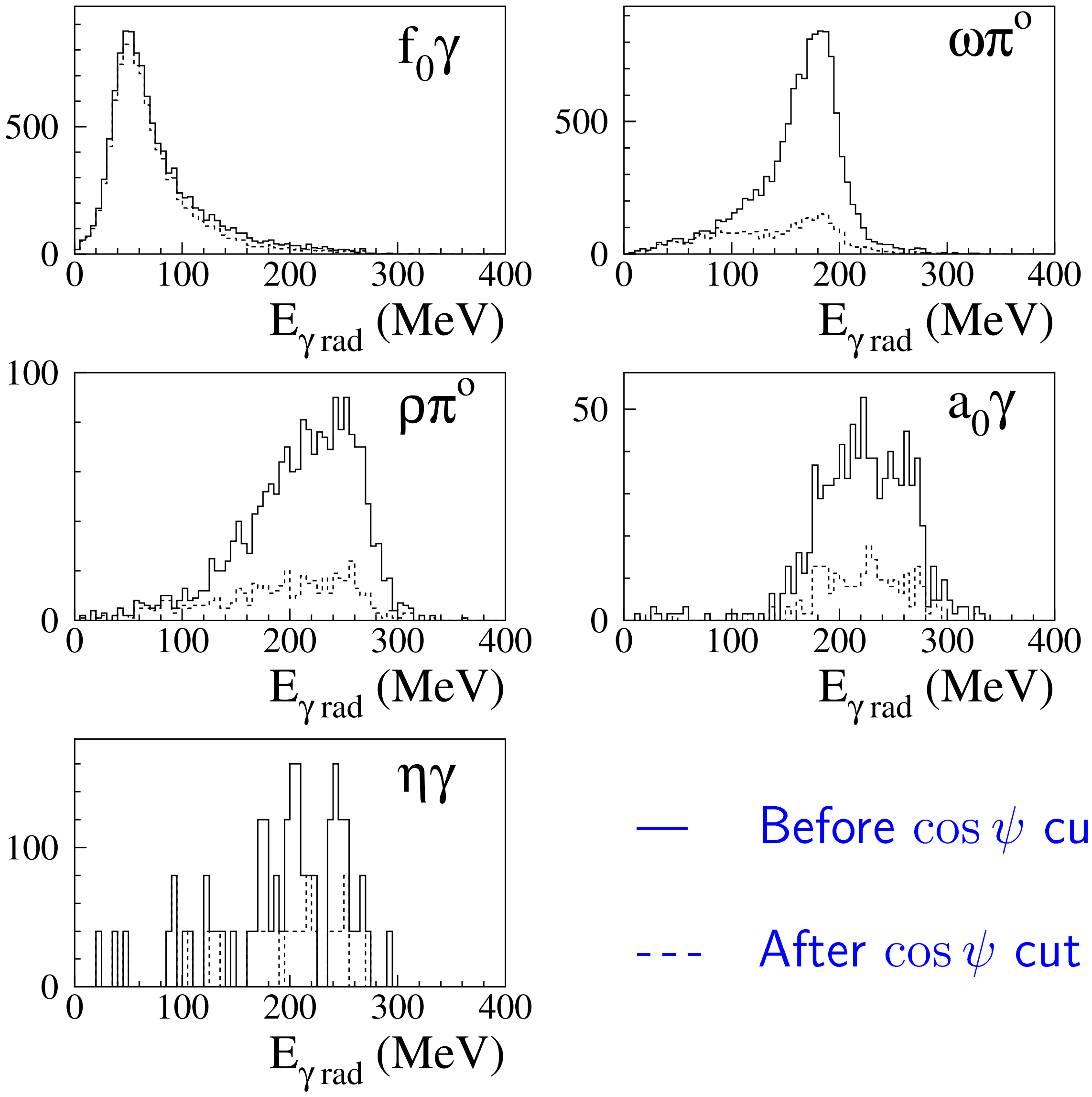


in $\pi\pi$ rest frame

MC study: invariant mass of $\pi^o\pi^o$ pairs



MC study: radiative photon energy spectrum



— Before $\cos\psi$ cut

- - - After $\cos\psi$ cut

MC study: analysis efficiencies

$f_o\gamma$

Decay channel	$\varepsilon_{\rm cl}$	$\varepsilon_{\rm sel+\chi^2}$	$\varepsilon_{\rm cut}$	$\varepsilon_{\rm tot}$	S/B
$f_o\gamma$	76.6%	60.7%	88.6%	41.2%	—
$\omega\pi^o$	79.4%	31.9%	25.8%	6.5%	3.6
$\rho\pi^o$	75.0%	23.5%	25.6%	4.5%	30.6
$a_o\gamma$	68.3%	16.6%	28.4%	3.2%	45.9
$\eta\gamma$	75.0%	0.3%	45.2%	9×10^{-4}	12.2

$\omega\pi^o$

Decay channel	$\varepsilon_{\rm cl}$	$\varepsilon_{\rm sel+\chi^2}$	$\varepsilon_{\rm cut}$	$\varepsilon_{\rm tot}$	S/B
$\omega\pi^o$	79.4%	60.8%	75.1%	36.2%	—
$f_o\gamma$	76.6%	49.8%	11.4%	4.3%	14.9
$\rho\pi^o$	75.0%	44.0%	40.5%	13.4%	15.8
$a_o\gamma$	68.3%	22.7%	18.5%	2.9%	94.7
$\eta\gamma$	75.0%	0.5%	43.2%	1.7×10^{-3}	10.3

$\pi^o\pi^o\gamma/\omega\pi^o$ data analysis

Number of events surviving analysis cuts:

$$N(N_{\rm clu} \geq 5) = 51666$$

$$N(\theta_{\gamma's} > 21^\circ) = 37678$$

$$N(5\theta_{\gamma's} \text{ in TW}) = 1815$$

$\boldsymbol{\omega\pi^o}$ **:**

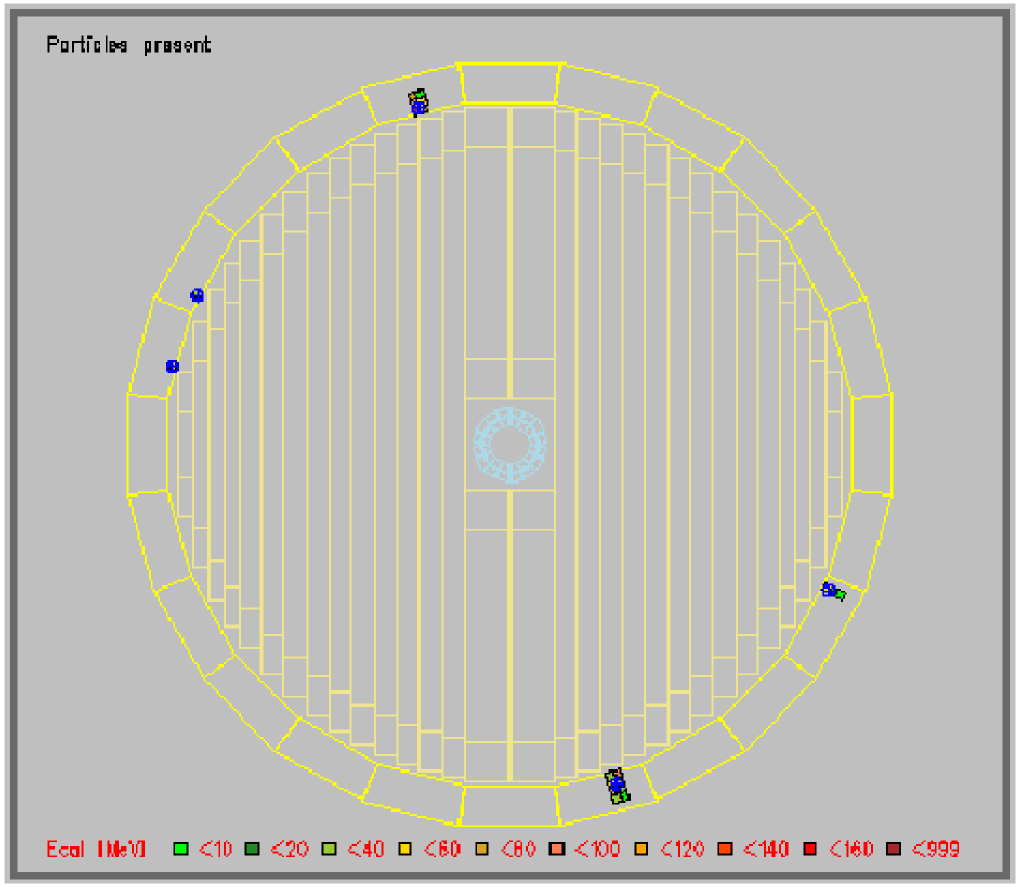
$$N(\chi^2 \text{ cut}) = 980$$

$$N(\cos\psi \text{ cut}) = 529$$

$\boldsymbol{\pi^o\pi^o\gamma}$:

$$N(\chi^2 \text{ cut}) = 679$$

$$N(\cos\psi \text{ cut}) = 307$$



Fit:

$M_{\pi\pi} = 960.0$ MeV

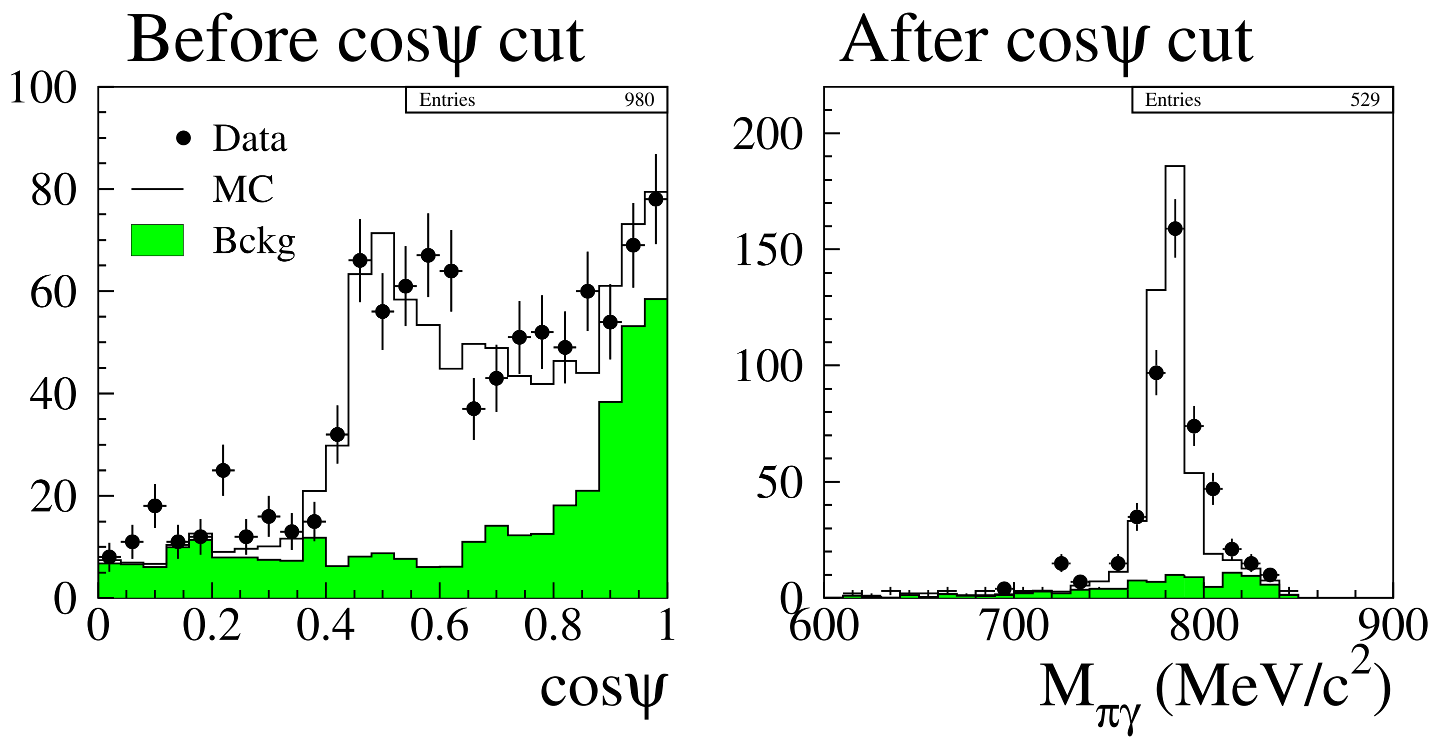
$E_{\gamma_{\rm rad}} = 53.2$ MeV

EMC:

$M_{\pi_1} = 112$ MeV

$M_{\pi_2} = 123$ MeV

$e^+e^- \to \omega\pi^o \to \pi^o\pi^o\gamma$: cross section measurement



$$N_{\mathrm{bckg}} = 93 \pm 7 \quad \Longrightarrow \quad N_{\omega\pi} = 436 \pm 25$$

Preliminary

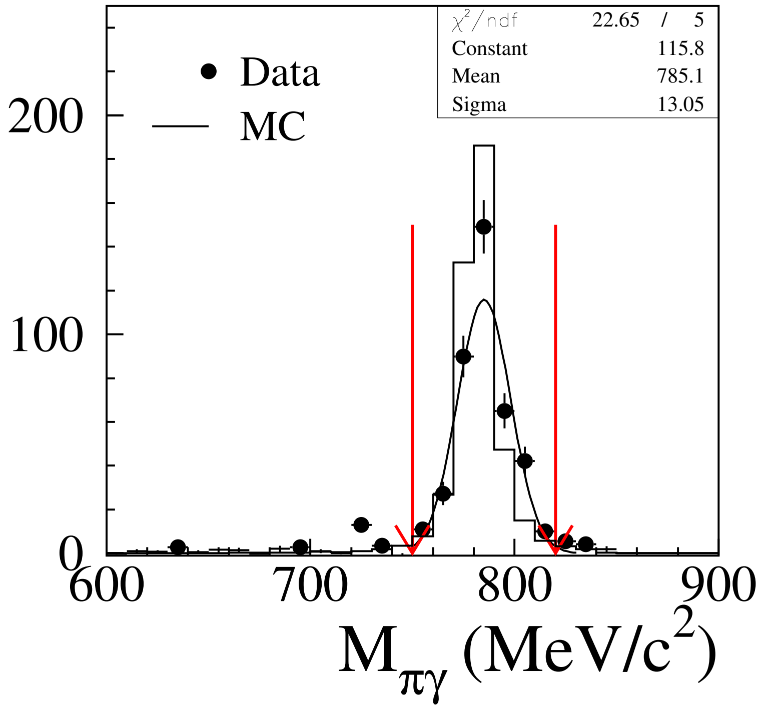
$$\boxed{\sigma = (\,0.65 \pm 0.04\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})\,)\ \text{nb}}$$

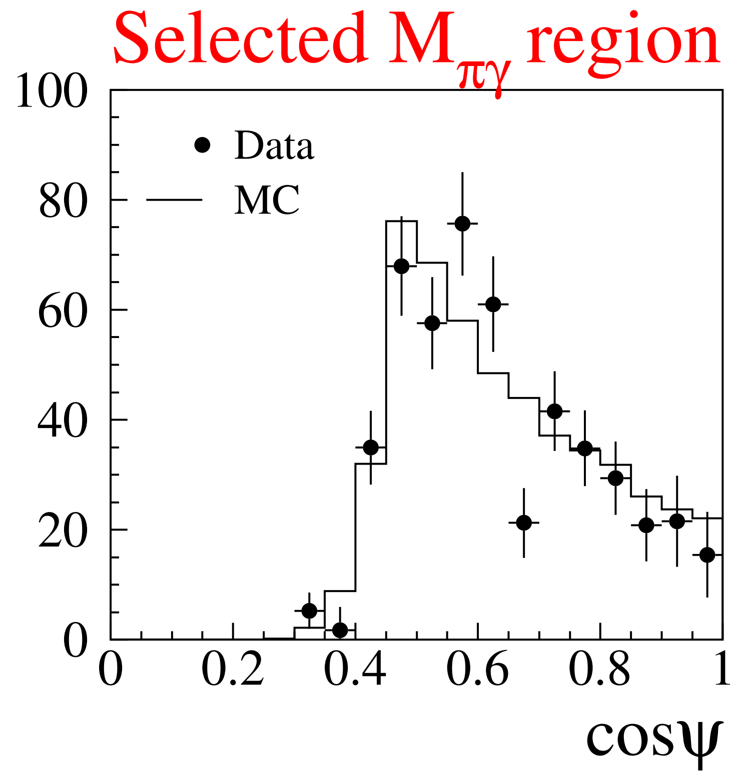
$$\sigma_{\mathsf{SND}} = (0.64 \pm 0.08)\ \text{nb}$$

Complete estimation of systematics in progress

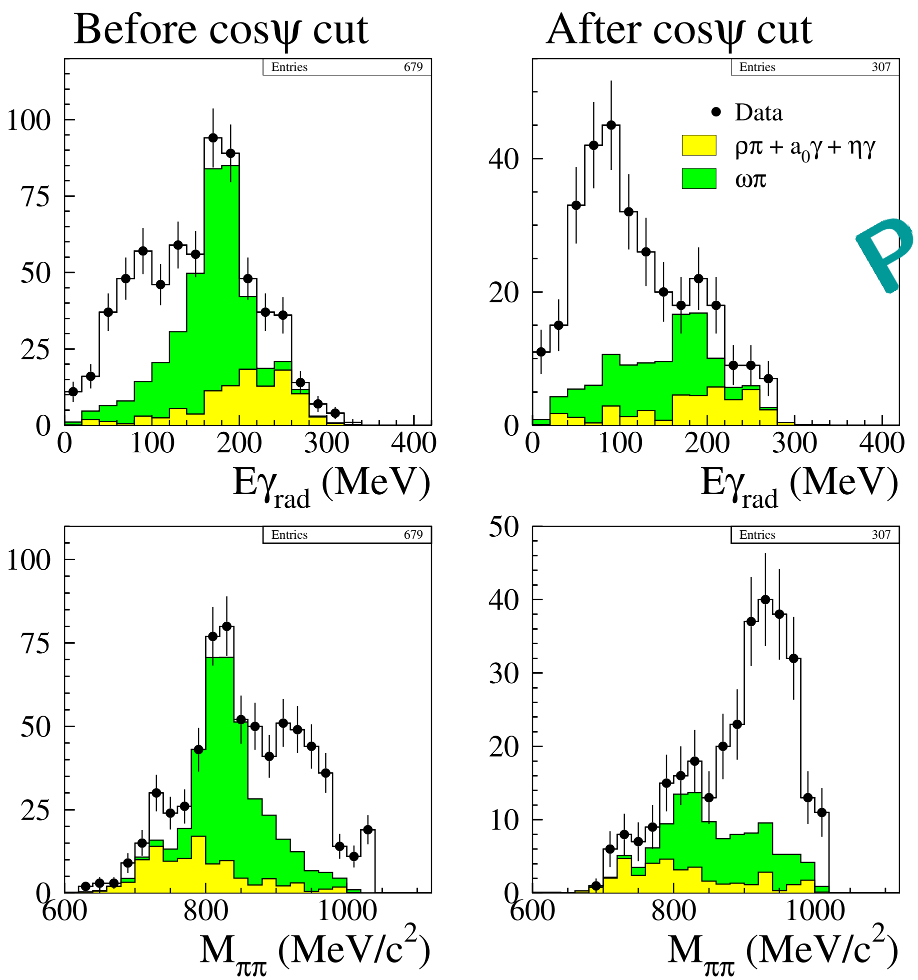
$e^+e^- \to \omega\pi^o \to \pi^o\pi^o\gamma$: background subtraction

Distributions after background subtraction:





The $\phi \to \pi^o\pi^o\gamma$ decay: data analysis



Preliminary

For $M_{\pi\pi} > 700$ MeV:

$N_{\mathrm{obs}} = 307 \pm 18$

$N_{\mathrm{bkg}} = 114 \pm 11$

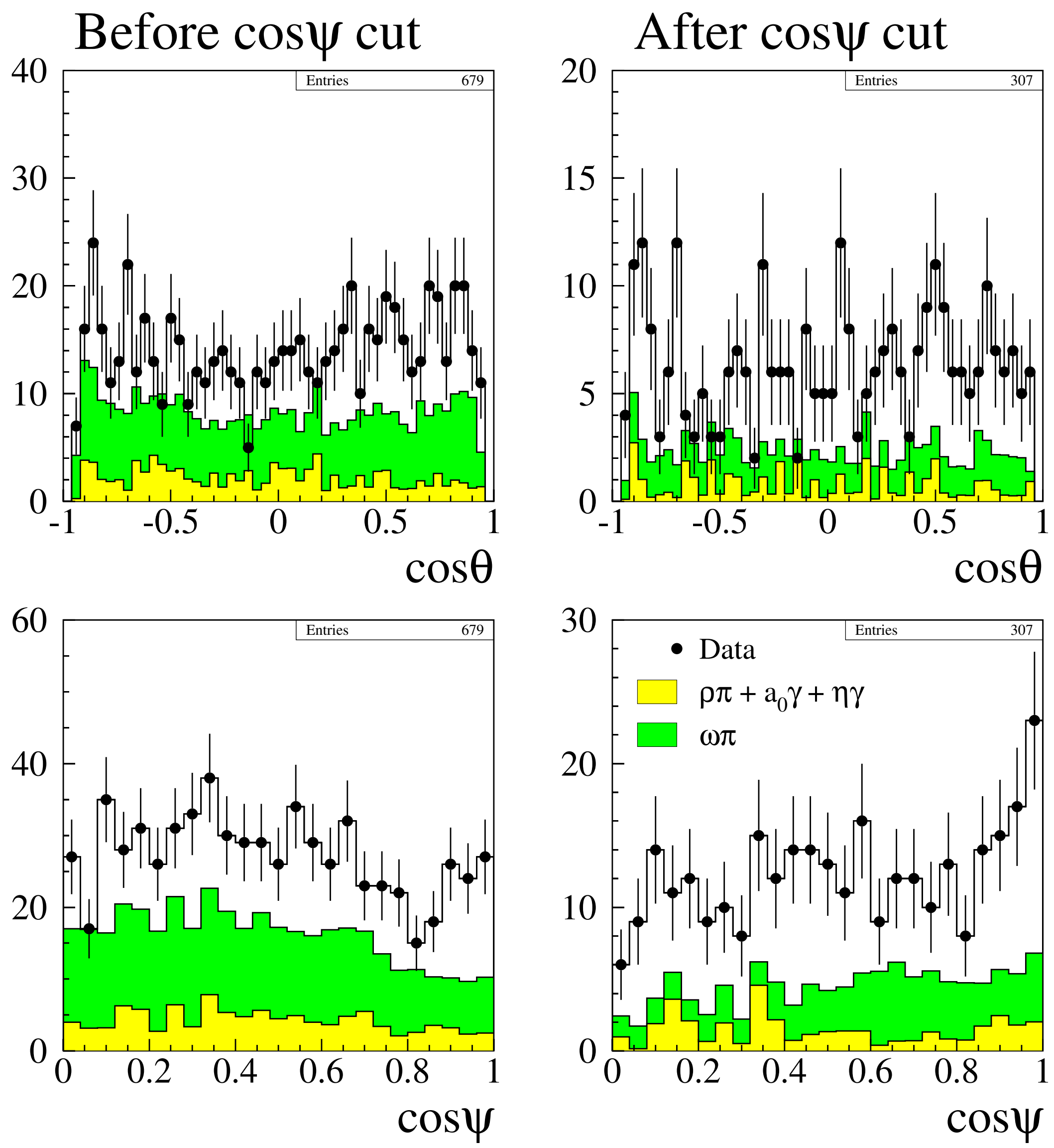
$N_{\pi\pi\gamma} = 193 \pm 21$

$$\mathrm{BR} = (\,0.80 \pm 0.10\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})\,) \times 10^{-4}$$

$$\mathrm{BR}_{\mathrm{SND}} = (1.14 \pm 0.10 \pm 0.12) \times 10^{-4}$$

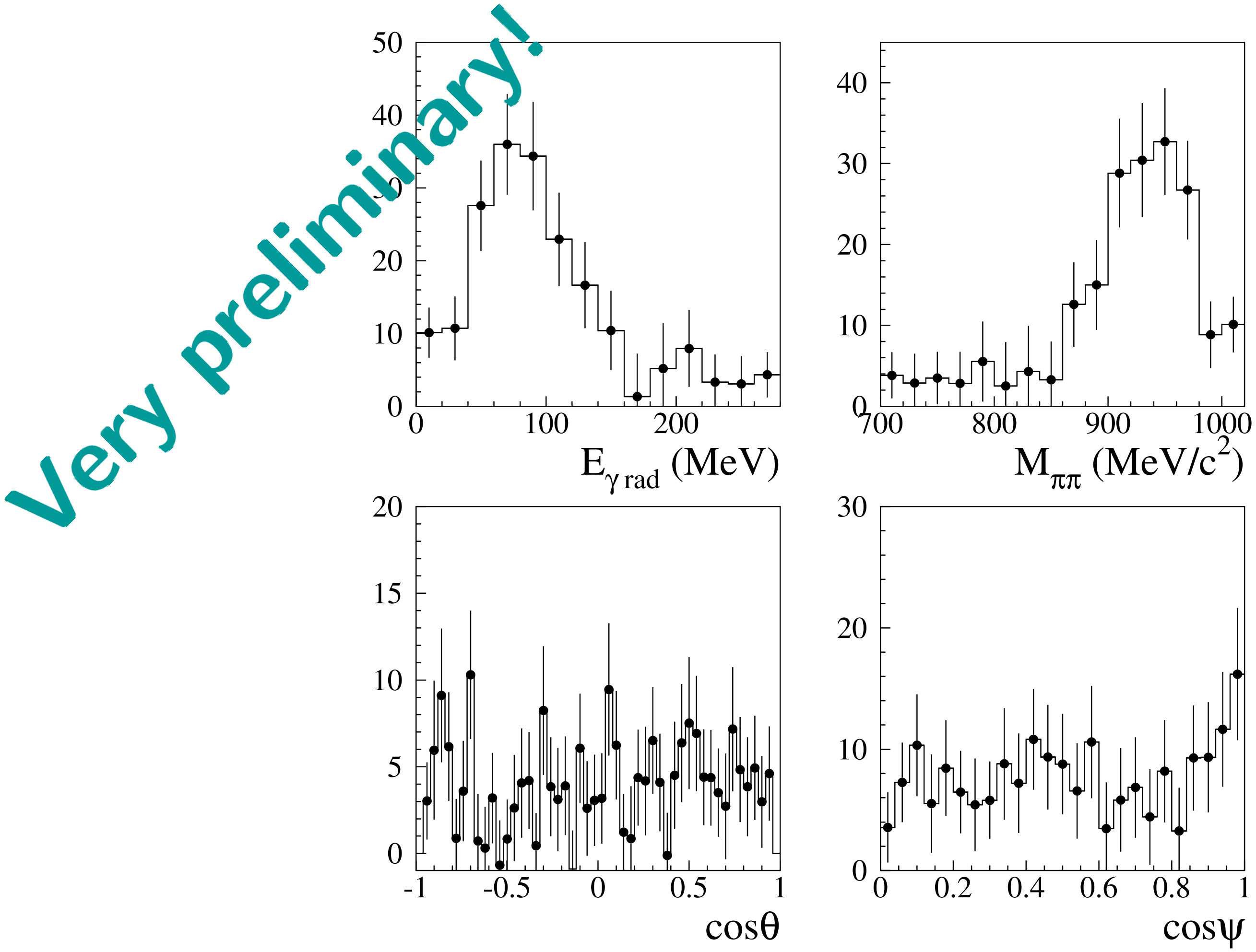
$$\mathrm{BR}_{\mathrm{CMD-2}} = (1.06 \pm 0.09 \pm 0.06) \times 10^{-4}$$

The $\phi \to \pi^o\pi^o\gamma$ decay: angular distributions



The $\phi \to \pi^o\pi^o\gamma$ decay: background subtraction

Distributions after background subtraction:



* Efficiencies as a function of $M_{\pi\pi}$ not yet evaluated

Conclusions

- Search of $\phi \to \pi^o\pi^o\gamma$ decay has been performed using 1.84 pb^{-1} collected @ KLOE
- Calibration samples ($\eta\gamma$, $\pi^o\gamma$ and $\omega\pi^o$):
  - $\to$ give results of σ_ϕ, BR($\eta\gamma$)/BR($\pi^o\gamma$) and $\sigma(\omega\pi^o)$ in excellent agreement with expected values
  - $\to$ show that the simulation nicely reproduce data
- We observe 193 ± 21 $\phi \to \pi^o\pi^o\gamma$ events with $M_{\pi\pi} > 700$ MeV, corresponding to a preliminary BR:

$$\mathrm{BR} = (\, 0.80 \pm 0.10 \, (\mathrm{stat.}) \pm 0.08 \, (\mathrm{syst.}) \,) \times 10^{-4}$$

- Work is in progress to evaluate systematics, study analysis efficiency *vs* $M_{\pi\pi}$ and fit the $M_{\pi\pi}$ spectra