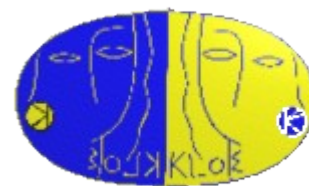


Hadronic physics at KLOE

Roberto Versaci
on behalf of the KLOE collaboration



Outline



Detector

Light scalar mesons:

$$\phi \rightarrow a_0 \gamma \rightarrow \eta \pi^0 \gamma$$

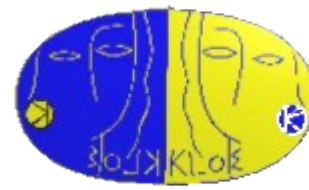
$$\phi \rightarrow (f_0 + a_0) \gamma \rightarrow K^0 \bar{K}^0 \gamma$$

$$\gamma \gamma \rightarrow \pi^0 \pi^0$$

η - η' mixing and η' gluonium content

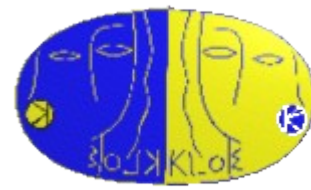
$$\eta \rightarrow \pi^+ \pi^- e^+ e^-$$

KLOE-2 perspectives

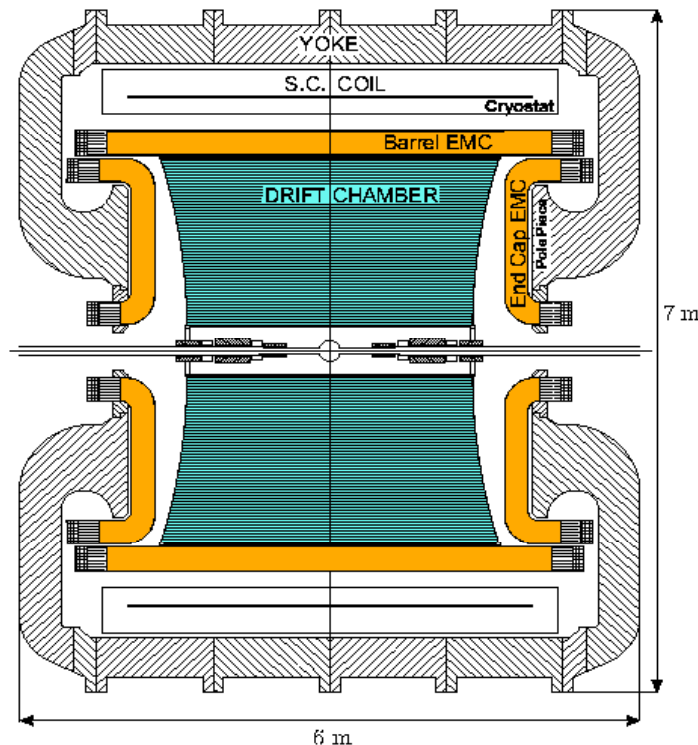
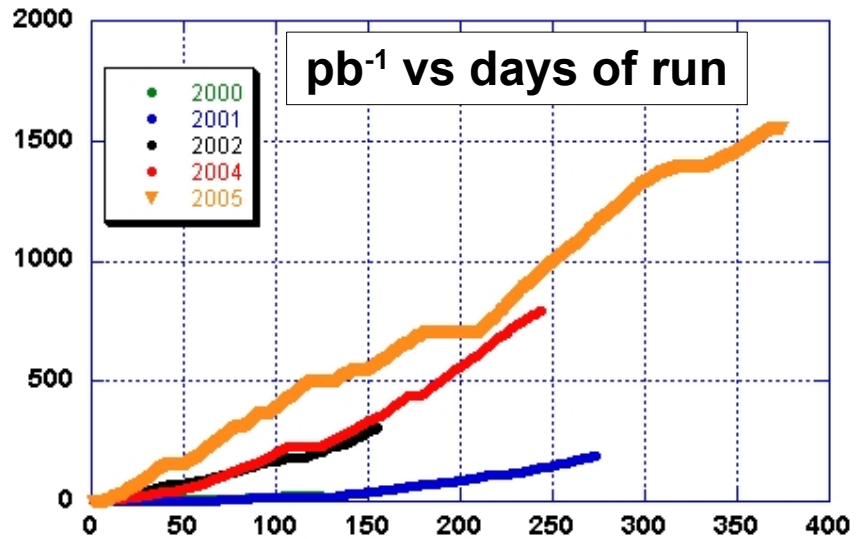


The experimental apparatus

KLOE @ DAΦNE



e^+e^- collider @ $\sqrt{s} = m_\phi$
 $\sim 2.5 \text{ fb}^{-1}$ collected
 $\sim 8 \times 10^9 \phi$
 240 pb^{-1} @ 1 GeV



Drift Chamber

90% He 10% C₄H₁₀

$$\sigma_{r\phi} = 150 \mu\text{m}$$

$$\sigma_z = 2 \text{ mm}$$

$$\sigma_p/p \sim 4 \times 10^{-3}$$

Electromagnetic Calorimeter

Lead-scintillating fibers

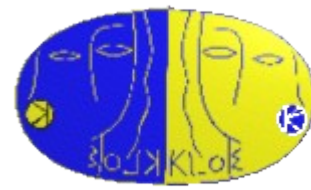
$$\sigma_t = 57 \text{ ps} / \sqrt{(E[\text{GeV}])} \oplus 100 \text{ ps}$$

$$\sigma_E = 0.057 / \sqrt{(E[\text{GeV}])}$$



Light scalars mesons

Light scalars in ϕ radiative decays



Scalar structure below 1 GeV is an open point: $q\bar{q}, q\bar{q}q\bar{q}$, KK molecule...

BR and mass spectra of $\phi \rightarrow PP'\gamma$ sensitive to intermediate scalar meson structure

At KLOE PP' :

$$\pi^0\pi^0 \Rightarrow f_0(980)/\sigma(600)$$

EPJC49(2007)473, PLB537(2002)21

$$\pi^+\pi^- \Rightarrow f_0(980)/\sigma(600)$$

PLB634(2006)148

arXiv:0904.2539

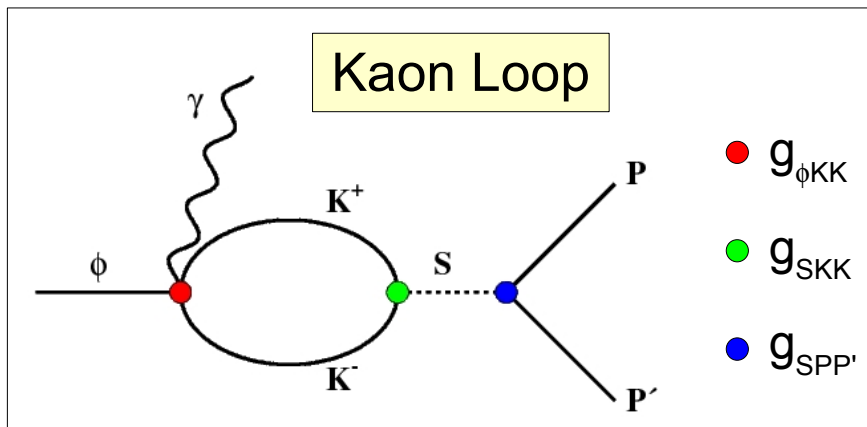
$$\eta\pi^0 \Rightarrow a_0(980)$$

PLB536(2002)209, New paper submitted to PLB

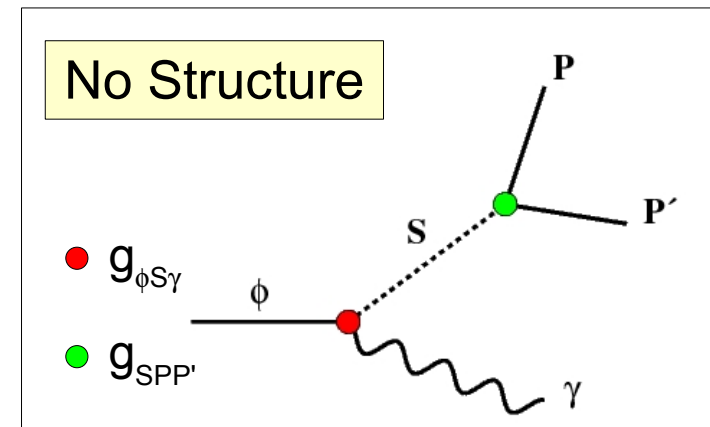
$$K_S K_S \Rightarrow f_0(980)/a_0(980)$$

Paper submitted to PLB arXiv:0903.4115

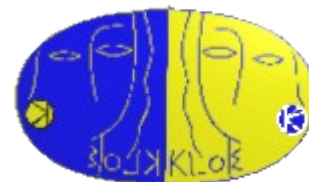
Phenomenological models used to describe $\phi \rightarrow S\gamma \rightarrow PP'\gamma$:



N. Achasov *et al.* NPB315(1989) 465
 N. Achasov *et al.* PRD56(1997) 4084
 N. Achasov *et al.* PRD68(2003) 014006

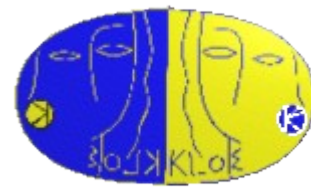


G. Isidori *et al.* JHEP 05(2006) 049



$$\phi \rightarrow a_0(980)\gamma \rightarrow \eta\pi^0\gamma$$

Measurement of the BR



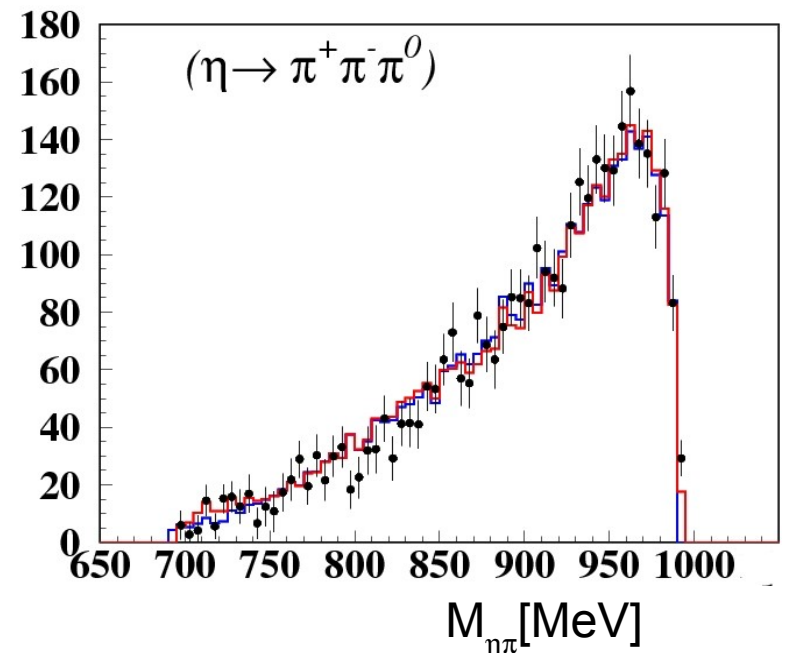
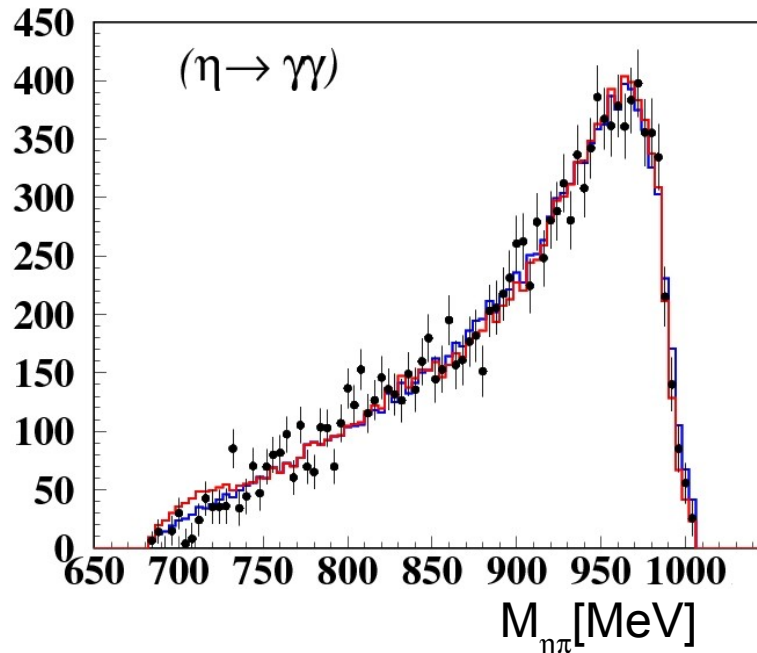
Dataset $\sim 400 \text{ pb}^{-1}$

Kinematic fit: four momentum conservation,
photon speed of light and π^0 and η mass

Event counting after background subtraction

$$\begin{aligned} \eta \rightarrow \gamma\gamma & \quad \text{BR}(\phi \rightarrow \eta \pi^0 \gamma) = (7.01 \pm 0.10_{\text{stat.}} \pm 0.20_{\text{syst.}}) \times 10^{-5} \\ \eta \rightarrow \pi^+ \pi^- \pi^0 & \quad \text{BR}(\phi \rightarrow \eta \pi^0 \gamma) = (7.12 \pm 0.13_{\text{stat.}} \pm 0.22_{\text{syst.}}) \times 10^{-5} \end{aligned}$$

Fit with both
Kaon-Loop
and
No-Structure
models



Fit to $\eta\pi^0$ mass distribution

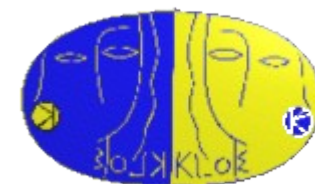


	Kaon-Loop	No-Structure
$P(\chi^2)$	0.104	0.309
M_{a_0} [MeV]	$982.5 \pm 1.6 \pm 1.1$	982.5 (fixed)
$g_{a_0K+K^-}$ [GeV]	$2.15 \pm 0.06 \pm 0.06$	$2.01 \pm 0.07 \pm 0.28$
$g_{a_0\eta\pi^0}$ [GeV]	$2.82 \pm 0.03 \pm 0.04$	$2.46 \pm 0.08 \pm 0.11$
$g_{\phi a_0\gamma}$ [GeV ⁻¹]	$1.58 \pm 0.10 \pm 0.16$	$1.83 \pm 0.03 \pm 0.08$
$BR(\phi \rightarrow \rho\pi \rightarrow \eta\pi\gamma)$	$(0.92 \pm 0.40 \pm 0.15) \cdot 10^{-6}$	$(0.05 \pm 4 \pm 0.07) \cdot 10^{-6}$
$BR(\eta \rightarrow \gamma\gamma)/BR(\eta \rightarrow 3\pi)$	$1.70 \pm 0.04 \pm 0.03$	$1.70 \pm 0.03 \pm 0.01$
$R_{a_0} = (g_{a_0K+K^-}/g_{a_0\eta\pi^0})^2$	$0.58 \pm 0.03 \pm 0.03$	$0.67 \pm 0.06 \pm 0.13$

Fit output

Sizable strange quark content in the $a_0(980)$ meson

Fit to $\eta\pi^0$ mass distribution

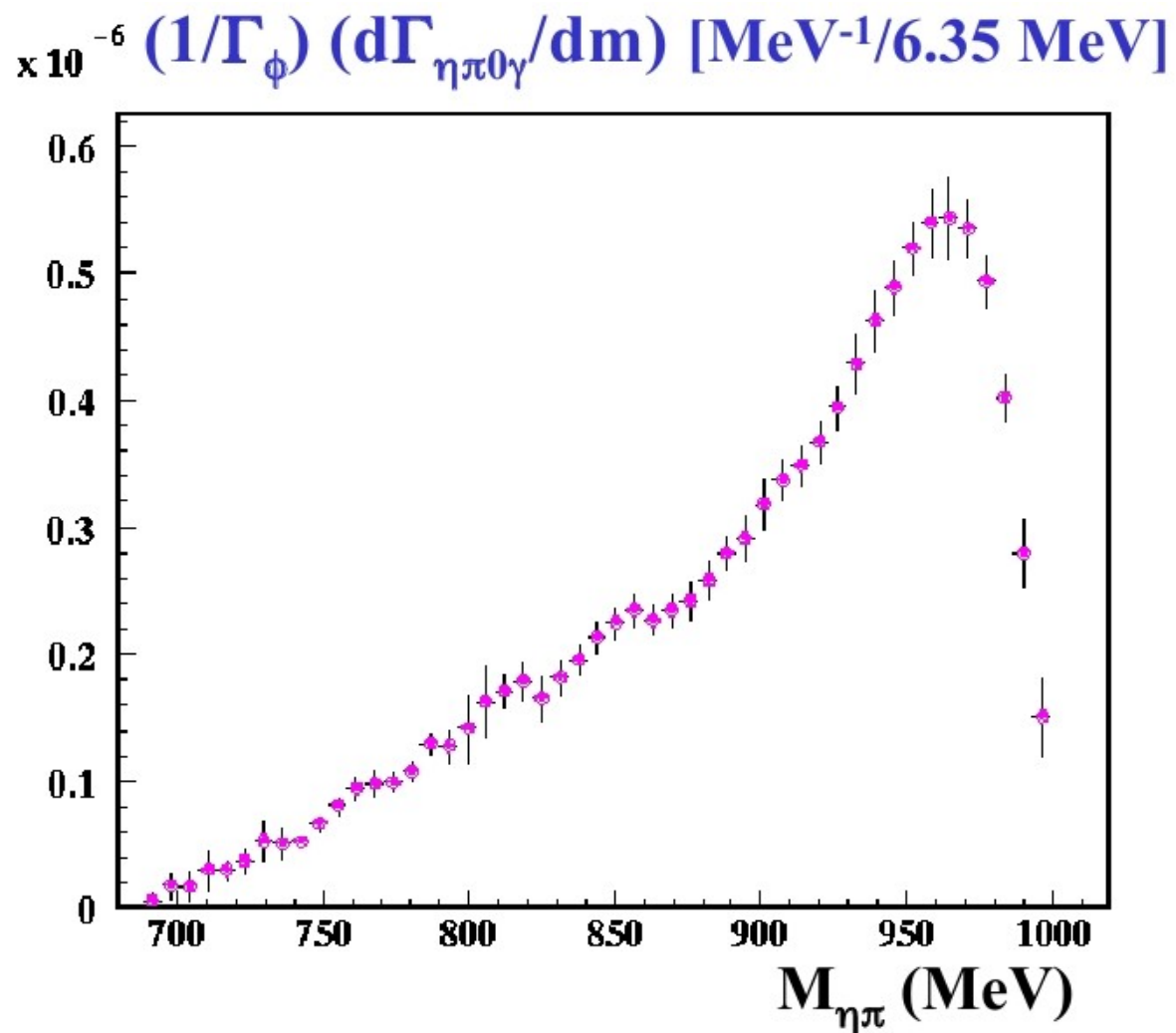


Distribution unfolded
to account for
detector resolution

Bayesian unfolding
(does not require inversion
of the smearing matrix)

G.D'Agostini,
NIM A362(1995), 487

Average of the
two $M_{\eta\pi}$ distributions





$\phi \rightarrow K^0 \bar{K}^0 \gamma$ decay

Upper limit on the BR



Proceeds $\phi \rightarrow [f_0(980)+a_0(980)]\gamma \rightarrow K^0\bar{K}^0\gamma$ decay

Selected channel: $K_S K_S \gamma \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$ \longrightarrow Clean topology
24% of the events

Dataset: 2.2 fb^{-1}

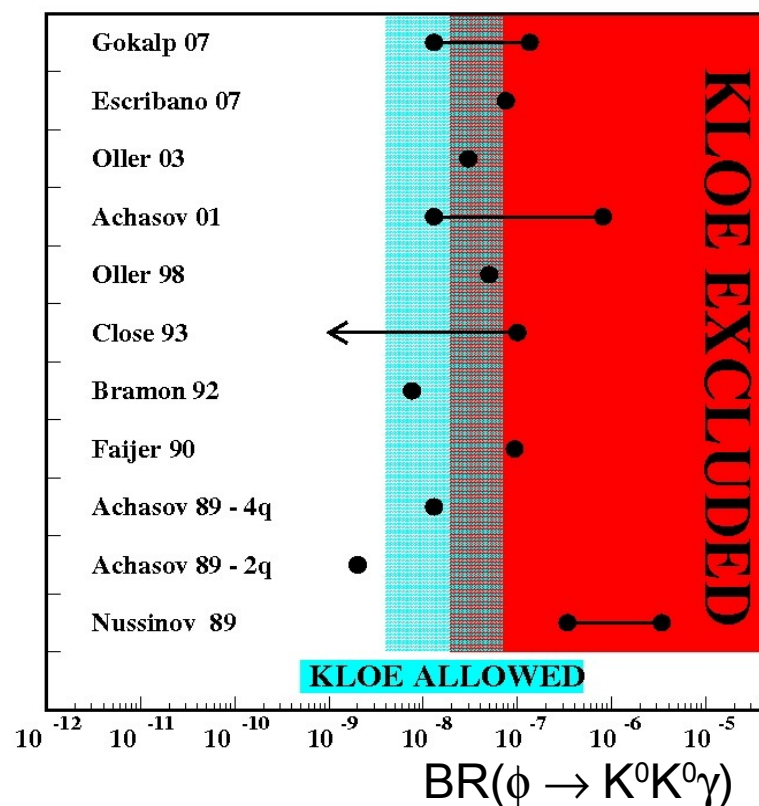
5 events in data vs **3.2 ± 0.7 background events expected**

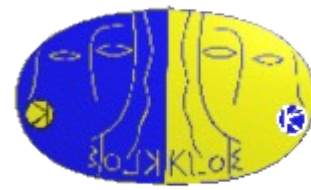
First experimental result

$$\text{BR}(\phi \rightarrow K^0\bar{K}^0\gamma) < 1.9 \times 10^{-8}$$

at 90% Confidence Level

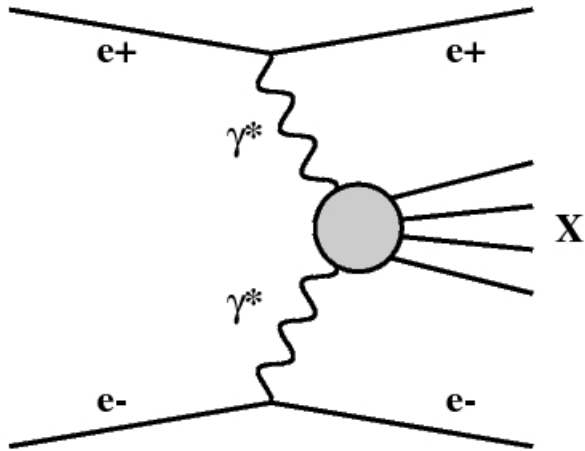
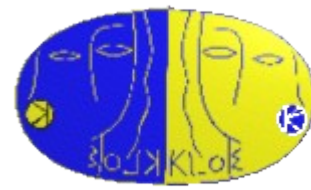
Consistent with other
KLOE results on scalars





$\gamma\gamma$ physics

Search for $\gamma\gamma \rightarrow \sigma(600) \rightarrow \pi^0\pi^0$



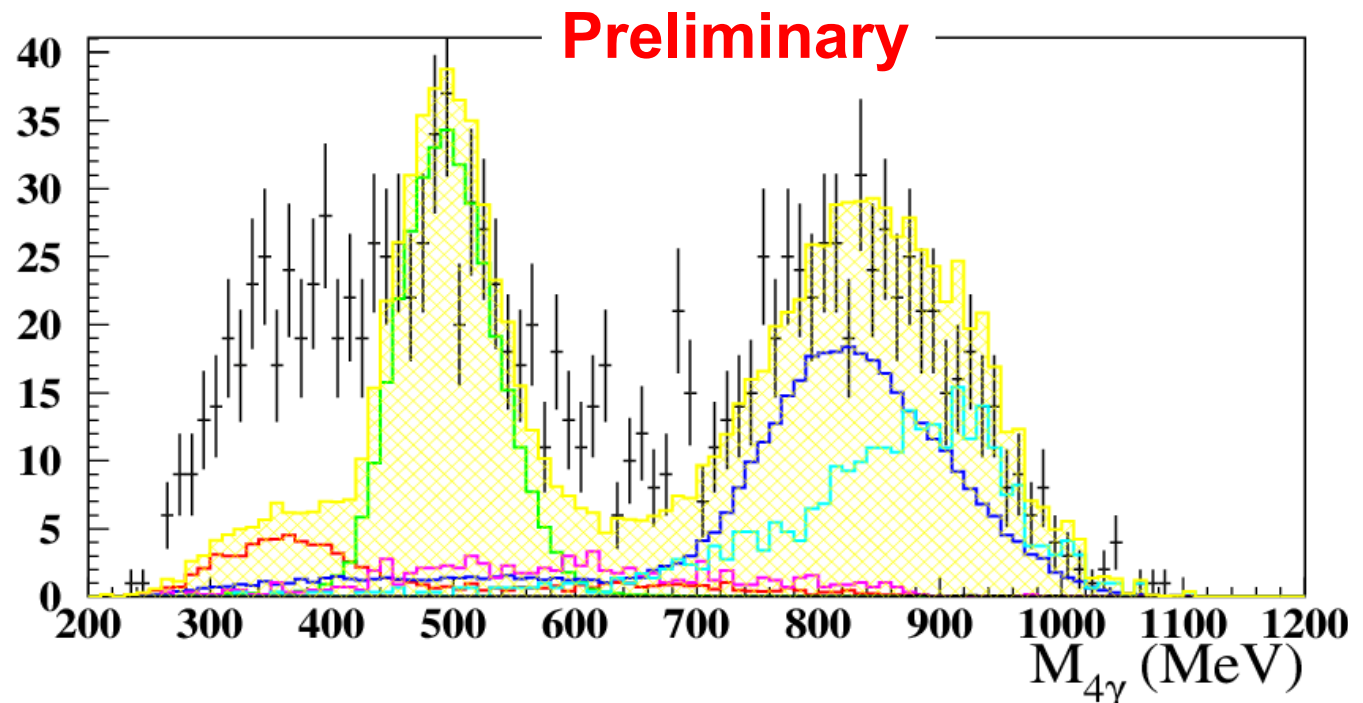
11 pb⁻¹ @ $\sqrt{s} = 1$ GeV (~240 pb⁻¹ available)

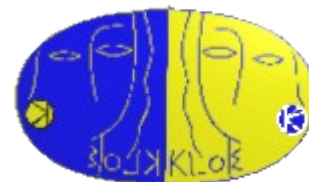
Fit to data using only background components

$\chi^2 / \text{dof} = 441 / 94$

Excess of events wrt known background

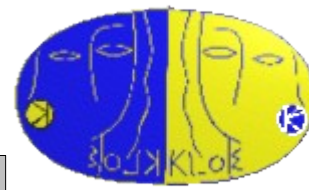
- Total bckg
- $\phi \rightarrow \eta\gamma \rightarrow \pi^0\pi^0\pi^0\gamma$
- $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$
- $\phi \rightarrow K_S K_L$
- $\phi \rightarrow f_0\gamma$
- $e^+e^- \rightarrow \gamma\gamma$





η - η' mixing and η' gluonic content

KLOE old result



$$R_\phi = \frac{\text{BR}(\phi \rightarrow \eta' \gamma)}{\text{BR}(\phi \rightarrow \eta \gamma)} = (4.77 \pm 0.09_{\text{stat.}} \pm 0.19_{\text{syst.}}) \times 10^{-3}$$

PLB 648 (2007) 267

η and η' decomposed in the quark mixing base

Rosner
PRD 27 (1983) 1101

$\phi_P = \eta - \eta'$ mixing angle

$$|\eta'\rangle = X_{\eta'} |q\bar{q}\rangle + Y_{\eta'} |s\bar{s}\rangle + Z_G |G\rangle$$

$$|\eta\rangle = \cos \phi_P |q\bar{q}\rangle - \sin \phi_P |s\bar{s}\rangle$$

$$X_{\eta'} = \sin \phi_P \cos \phi_G$$

$$Y_{\eta'} = \cos \phi_P \cos \phi_G$$

$$Z_G = \sin \phi_G \text{ gluonium content}$$

$$\phi_P = (39.7 \pm 0.7)^\circ$$

$$(Z_G)^2 = 0.14 \pm 0.04$$

$$P(\chi^2) = 0.49$$

Gluonium at 3σ

Imposing $Z_G = 0 \rightarrow P(\chi^2) = 0.01$

Parameters from
Bramon *et al.* PLB 503 (2001) 271
where $Z_G = 0$ is assumed

KLOE new fit



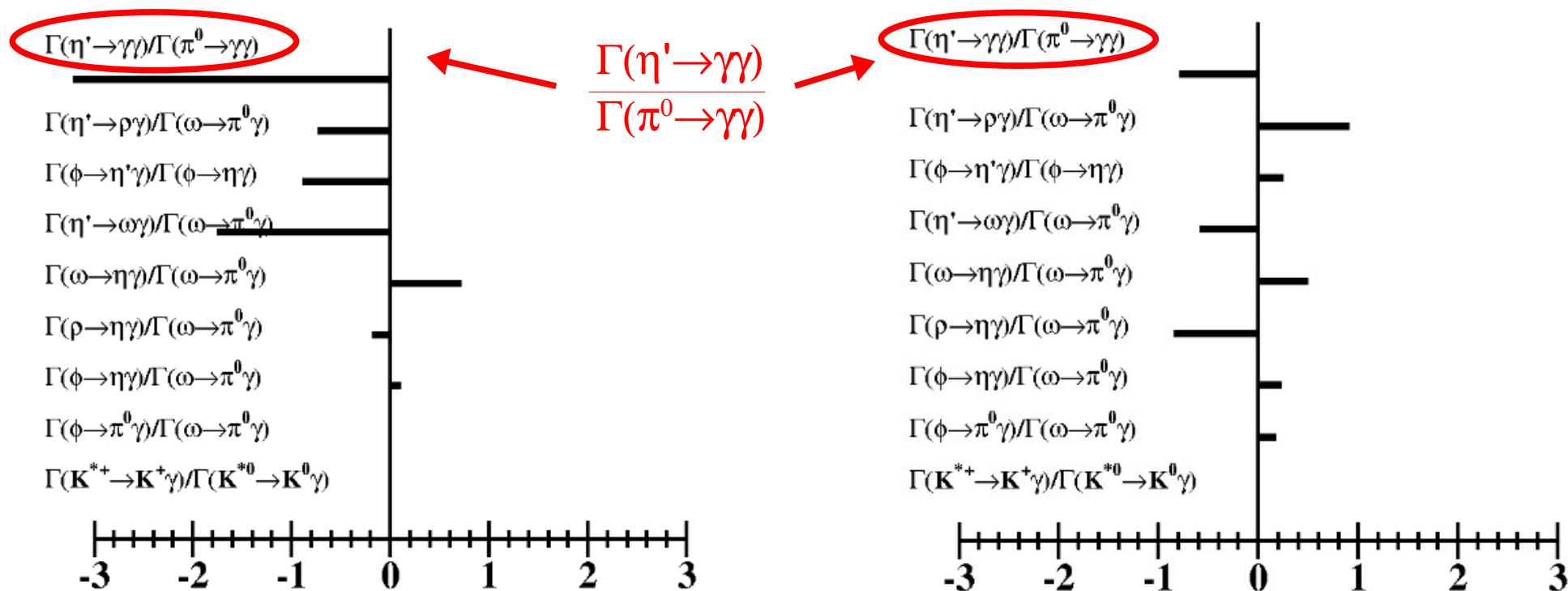
w/o glue

w/ glue

$\chi^2/\text{dof} = 14.7/4$	$(Z_G)^2$	fixed 0	0.115 ± 0.036	$\chi^2/\text{dof} = 4.6/3$
$P(\chi^2) = 0.005$	ϕ_P	$(41.4 \pm 0.5)^\circ$	$(40.4 \pm 0.6)^\circ$	$P(\chi^2) = 0.20$

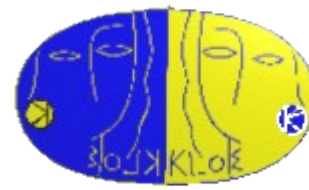
Using PDG 2008 + KLOE results on ω + 5 constraints more

Pulls = (Meas.-Fit)/ $\sigma_{\text{Measurement}}$



Agreement with old result: gluonium at 3σ confirmed

KLOE new fit



w/ glue

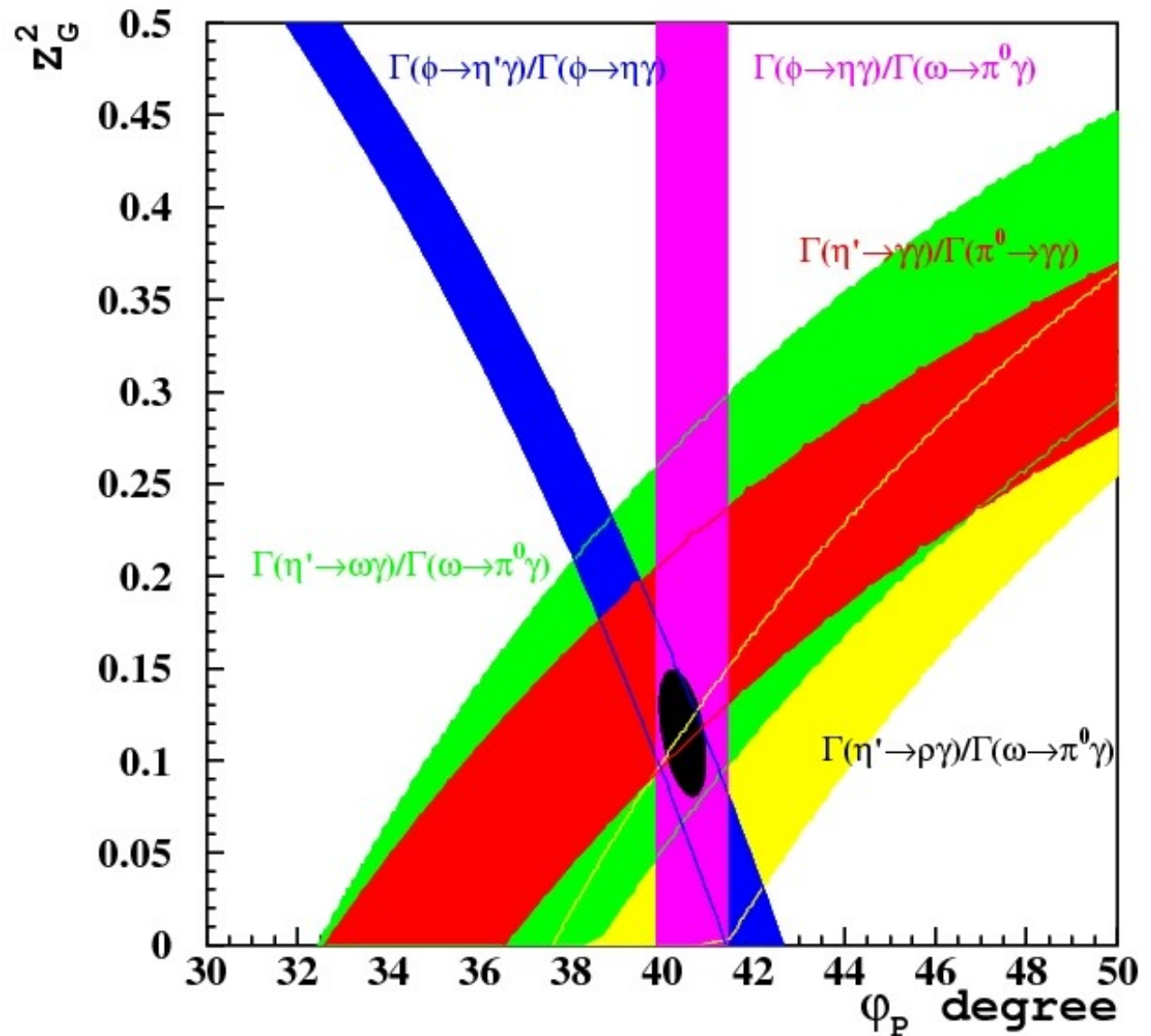
$(Z_G)^2$	0.115 ± 0.036
ϕ_P	$(40.4 \pm 0.6)^\circ$
Z_q	0.94 ± 0.03
Z_s	0.83 ± 0.05
ϕ_V	$(3.32 \pm 0.09)^\circ$
m_s/m	1.24 ± 0.07

$$\chi^2/\text{dof} = 4.6/3$$

$$P(\chi^2) = 0.20$$

Using PDG 2008

KLOE results on ω
5 constraints more

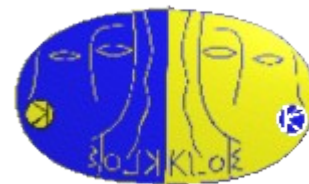


Agreement with old result: gluonium at 3σ confirmed



$\eta \rightarrow \pi \pi e e$ decay

Motivations



Poorly measured (4 events CMD-2, 16 events CELSIUS-WASA)

BR predicted by ChPT and VMD models $(26 \div 36) \cdot 10^{-5}$

η structure using virtual photon

Angular asymmetry between ee and $\pi\pi$

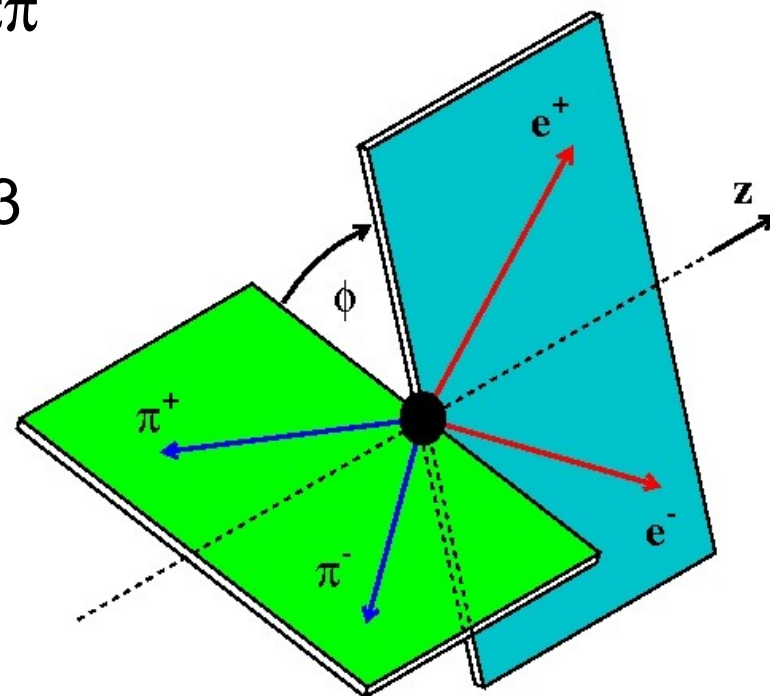
Test of non-CKM CP violation

Gao, Mod. Phys. Lett. A17(2002) 1583

Within SM constrained by $BR(\eta \rightarrow \pi\pi)$:

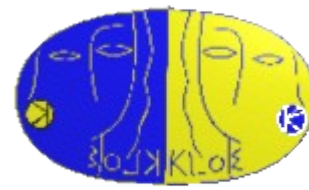
Experiment: $A_\phi < 10^{-4}$

Theory: $A_\phi \sim 10^{-15}$



The unconventional CPV term can increase A_ϕ up to 10^{-2}

Analysis scheme



Data sample: 1.7 fb^{-1}

PID using TOF from EMC info

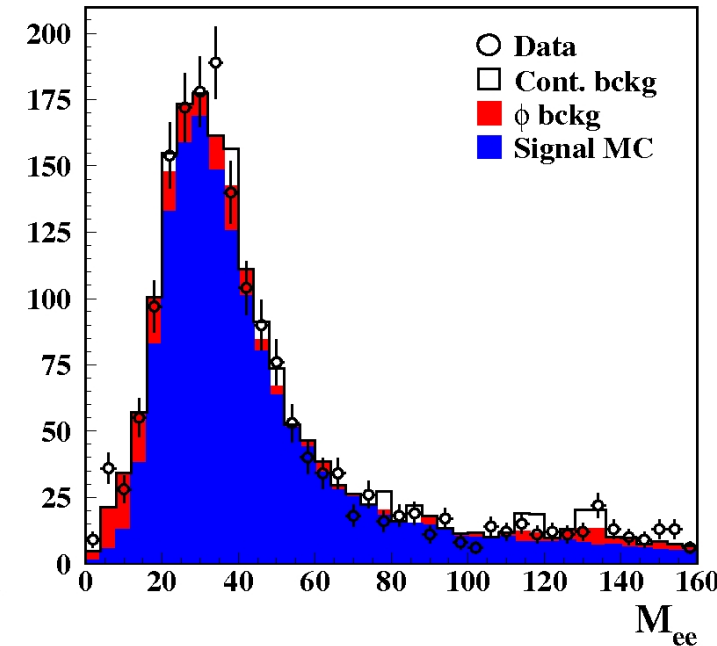
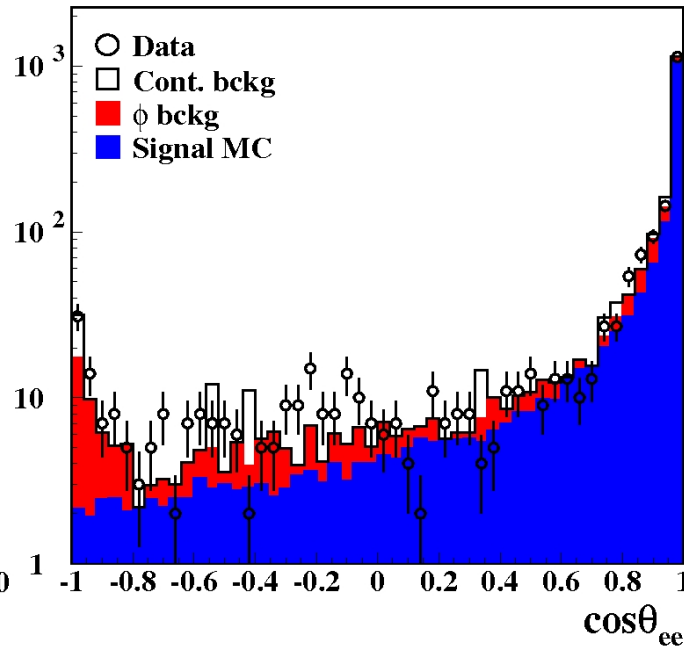
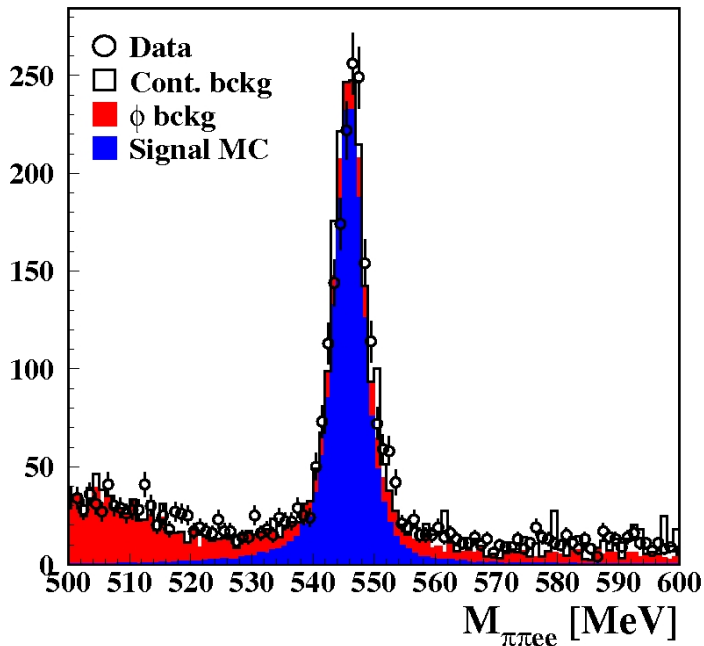
Fit to $M_{\pi\pi ee}$ sidebands for background scale factors

Photon conversion on Beam Pipe rejected

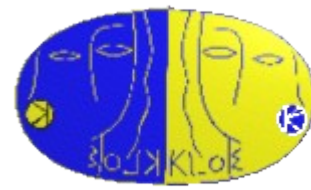
Counting on $M_{\pi\pi ee}$ in the signal region: $N_{\pi\pi ee} = 1555 \pm 52$

Analysis efficiency $\sim 8\%$

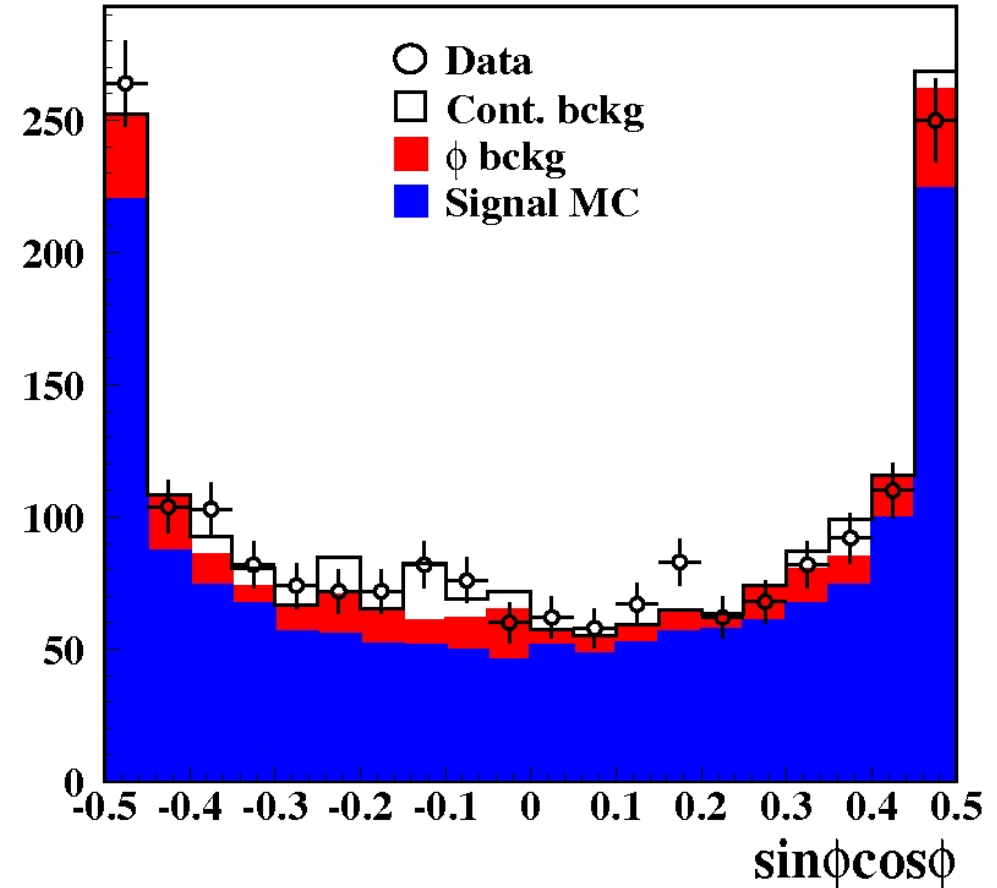
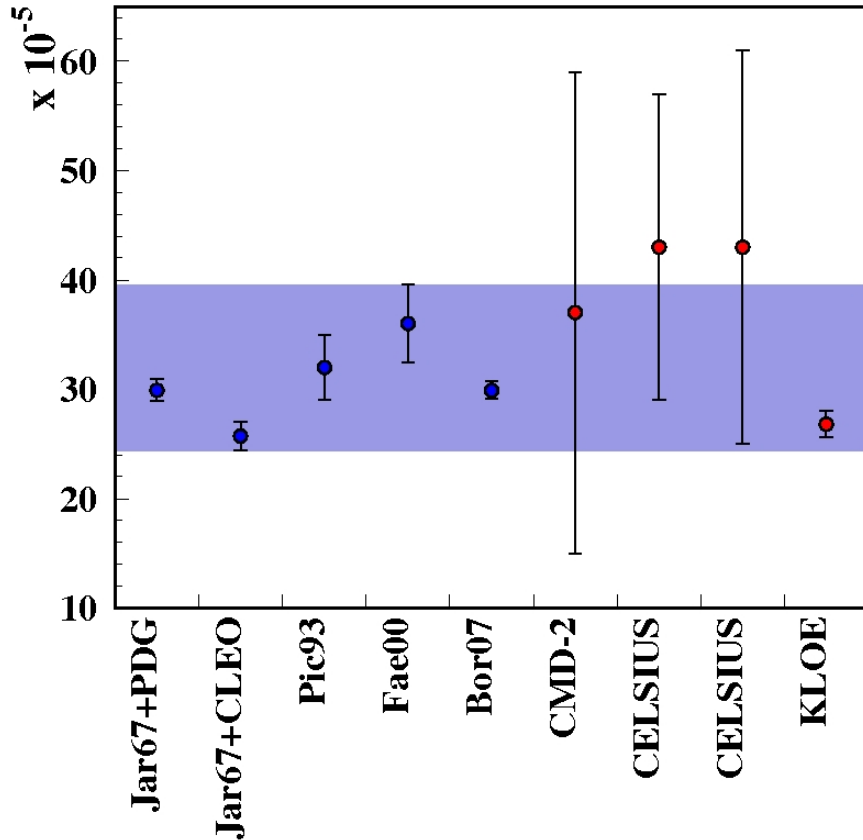
368 bckg events



Results: BR and A_ϕ

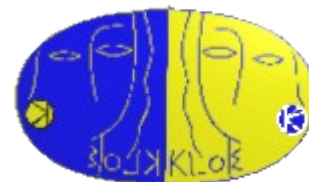


$$\text{BR}(\eta \rightarrow \pi^+ \pi^- e^+ e^- (\gamma)) = (26.8 \pm 0.9_{\text{Stat.}} \pm 0.7_{\text{Syst.}}) \cdot 10^{-5}$$



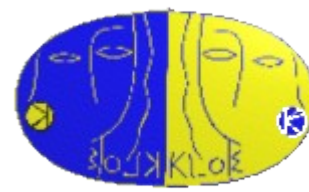
$$A_\phi = (-0.6 \pm 2.5_{\text{Stat.}} \pm 1.8_{\text{Syst.}}) \cdot 10^{-2}$$

First measurement!



$\eta \rightarrow e e e e$ decay

Analysis scheme



Data sample: 1.7 fb^{-1}

Photon conversion on Beam Pipe
and Drift Chamber wall rejected

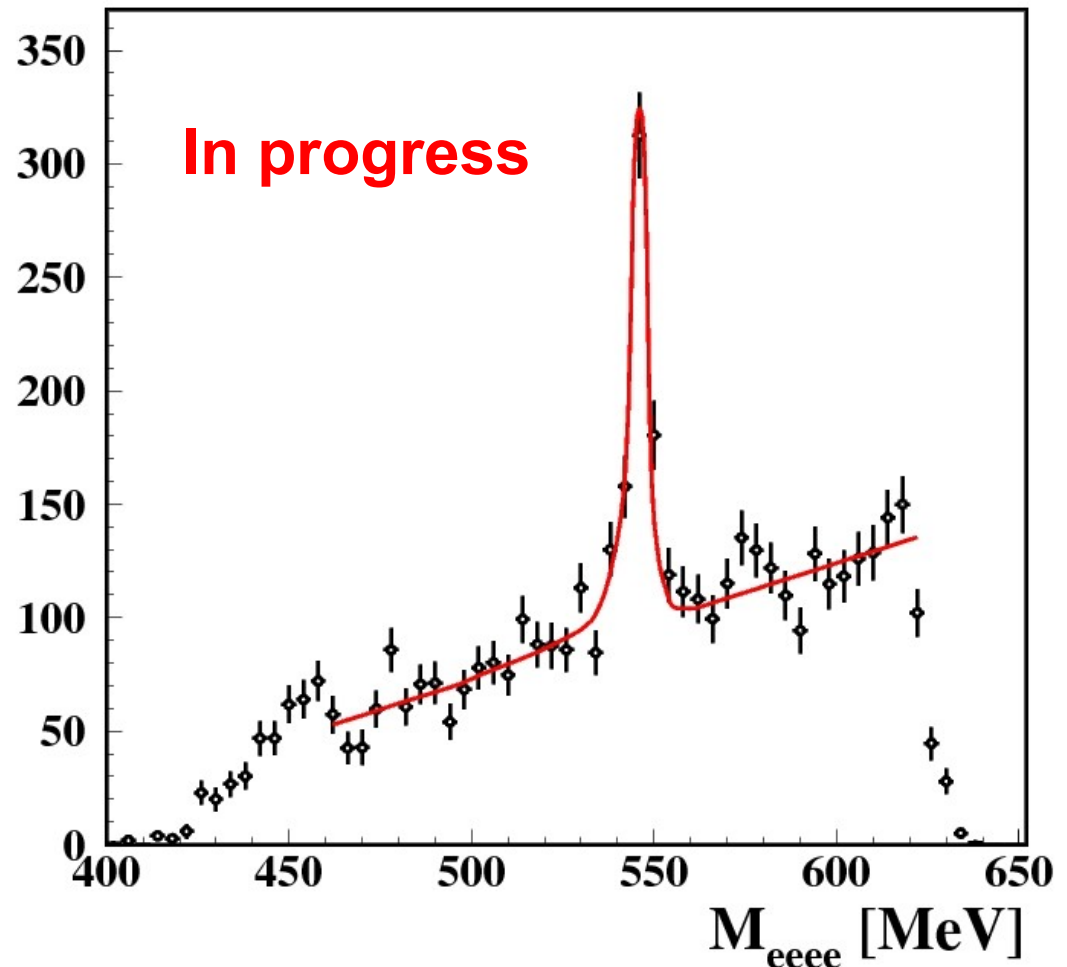
Remaining background from
 ϕ decay is subtracted

Fit M_{eeee} distribution for signal
and continuum bckg
to obtain shapes

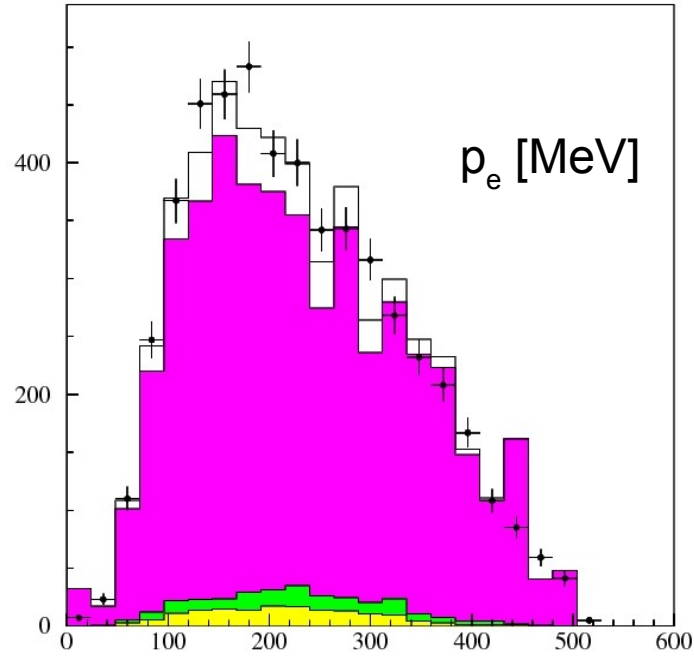
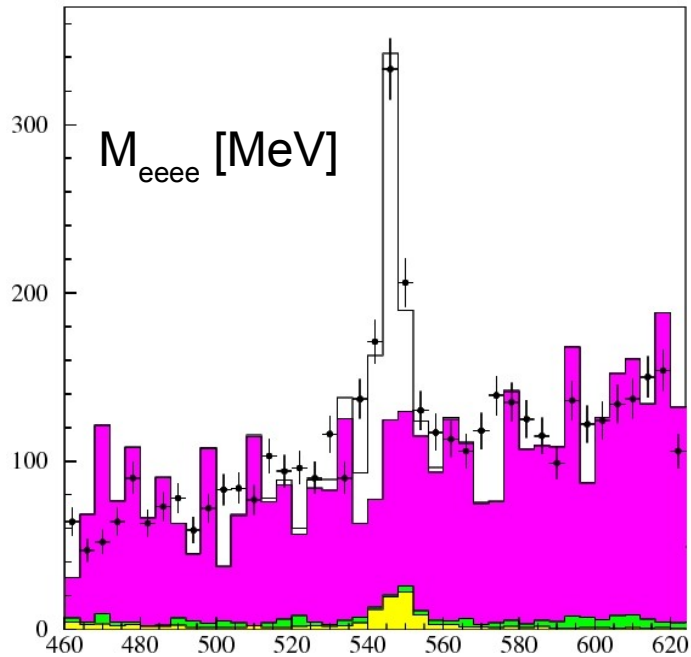
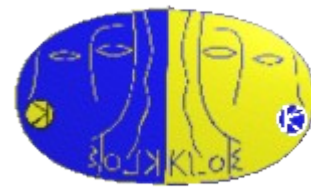
These are used to fit M_{eeee}
distribution for data

$$N_{\text{eeee}} = 413 \pm 31$$

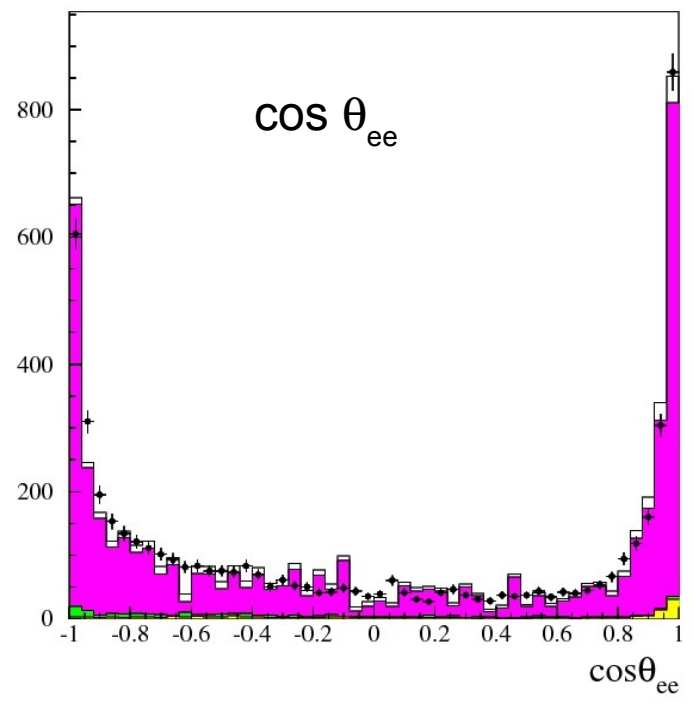
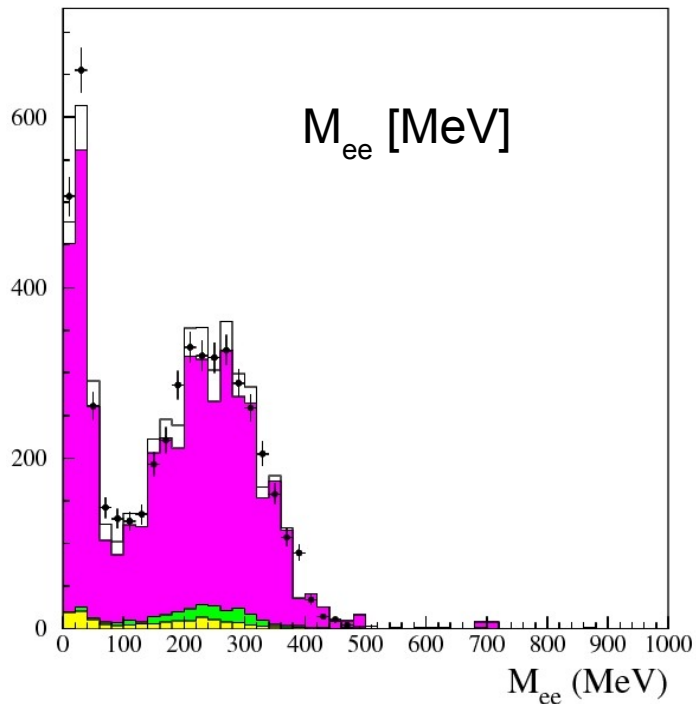
First observation!

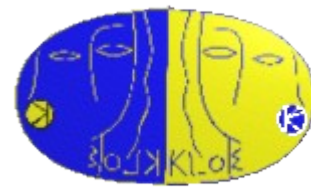


Data-MC comparison



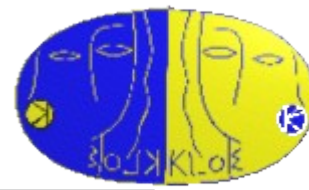
- Data
- MC signal
- Cont. bckg
- ϕ bckg





Conclusions

Summary of results



$$\text{BR}(\phi \rightarrow \eta \pi^0 \gamma) = (7.01 \pm 0.10_{\text{stat.}} \pm 0.20_{\text{syst.}}) \times 10^{-5} \quad \eta \rightarrow \gamma \gamma$$

$$\text{BR}(\phi \rightarrow \eta \pi^0 \gamma) = (7.12 \pm 0.13_{\text{stat.}} \pm 0.22_{\text{syst.}}) \times 10^{-5} \quad \eta \rightarrow \pi^+ \pi^- \pi^0$$

a_0 mass spectrum

Sizable strange quark content

$$\text{BR}(\phi \rightarrow K^0 \bar{K}^0 \gamma) < 1.9 \times 10^{-8} \quad \text{at 90\% confidence level}$$

Preliminary result on $\gamma\gamma$ physics:

excess of events wrt known background

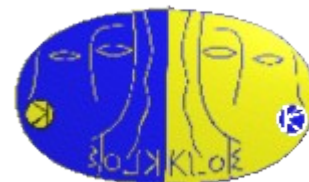
η' gluonium content confirmed at 3σ : $(Z_G)^2 = 0.115 \pm 0.036$

$$\text{BR}(\eta \rightarrow \pi^+ \pi^- e^+ e^- (\gamma)) = (26.8 \pm 0.9_{\text{Stat.}} \pm 0.7_{\text{Syst.}}) \cdot 10^{-5}$$

$$1^{\text{st}} \text{ measurement of: } A_\phi = (-0.6 \pm 2.5_{\text{Stat.}} \pm 1.8_{\text{Syst.}}) \cdot 10^{-2}$$

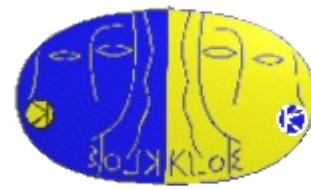
1^{st} observation of the $\eta \rightarrow e^+ e^- e^+ e^-$ decay ~ 400 events

...and more still to come!

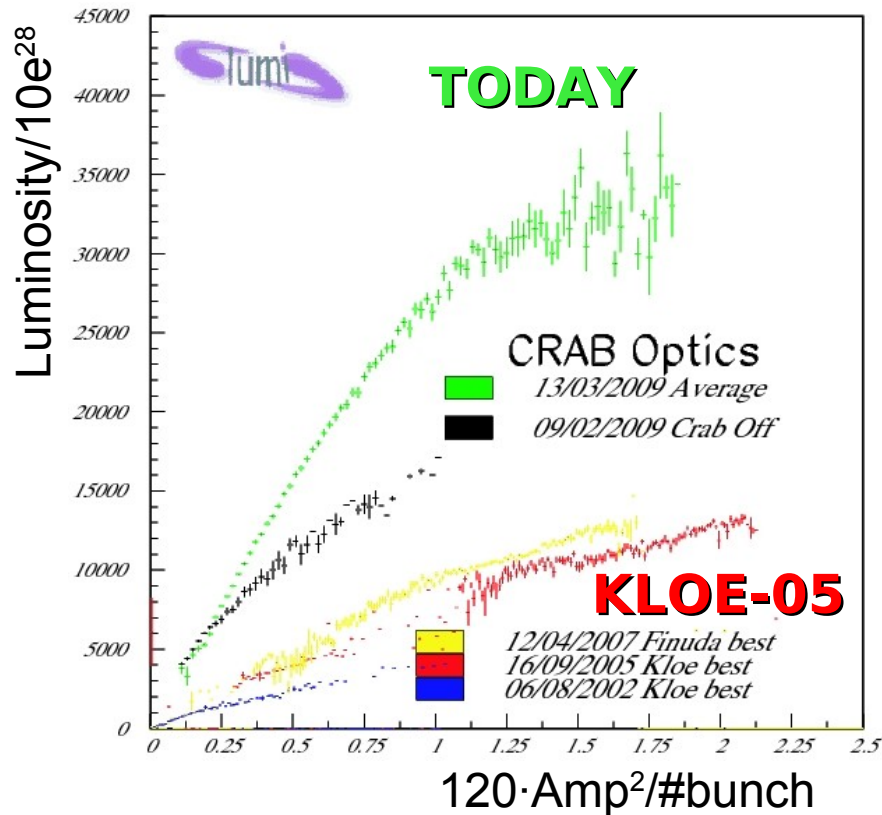


KLOE-2 perspectives on hadron physics

DAΦNE and KLOE upgrades



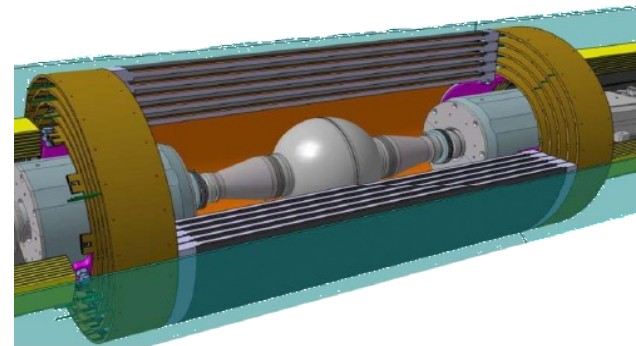
New machine magnetic scheme: **crab waist**



STEP-0 [2009]: **5fb⁻¹**
γ tagger

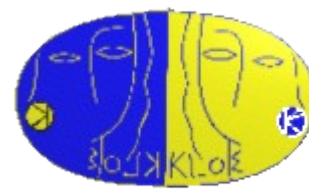
STEP-1 [2011]: **>20fb⁻¹**
Low Angle Calorimeter
Quadrupole Calorimeter
Inner Tracker

New interaction region:
larger crossing angle



KLOE-2 perspectives

(on hadron physics)



Reduce $\phi \rightarrow (f_0 + a_0)\gamma \rightarrow K^0\bar{K}^0\gamma$ UL
(first observation of the decay?)

$\gamma\gamma$ physics will profit of dedicated detectors (e^+e^- tagger)

Improve result on $\eta \rightarrow \pi^+\pi^-e^+e^-$ BR and CPV asymmetry

Refinement of rare η decay measurements

Measurement of the η' BR's at 1% is expected to solve the gluonium puzzle even without $\eta' \rightarrow \gamma\gamma$ BR

Open a window on η' physics