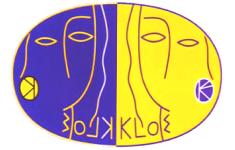


# **$\eta'$ decays at KLOE**

S. Giovannella  
(INFN Frascati)  
for the KLOE Collaboration

- ❖  **$\eta/\eta'$  mixing with  $\pi^+\pi^-3\gamma$ 's final state**
- ❖  **$\eta/\eta'$  mixing with  $\pi^+\pi^-7\gamma$ 's final state**
- ❖ **Next plans with already collected KLOE data**



# $\eta/\eta'$ mixing

- ❖ The mass eigenstates  $\eta$ ,  $\eta'$  are related to the SU(3) octet-singlet  $\eta_8$ ,  $\eta_1$  through the mixing angle  $\vartheta_P$
- ❖ Studies based on  $\chi$ PT and phenomenological analyses suggested a two mixing angle scenario
- ❖ In the quark flavour basis the two mixing angles are almost equal  
⇒ mixing is described by only one parameter ( $\varphi_P$ )

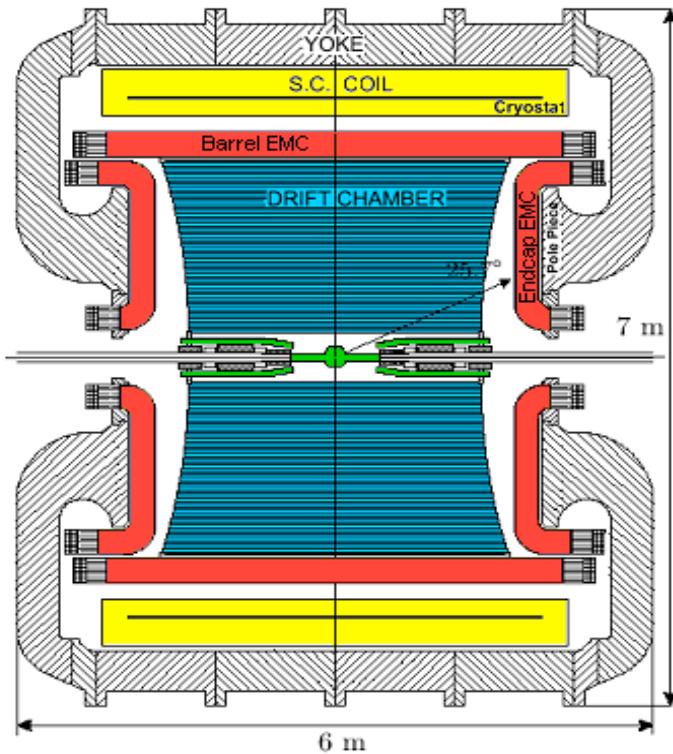
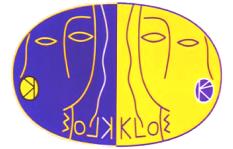
$$\boxed{\begin{aligned}\eta &= \cos\varphi_P \frac{1}{\sqrt{2}} |\bar{u}u + \bar{d}d\rangle - \sin\varphi_P |\bar{s}s\rangle \\ \eta' &= \sin\varphi_P \frac{1}{\sqrt{2}} |\bar{u}u + \bar{d}d\rangle + \cos\varphi_P |\bar{s}s\rangle\end{aligned}}$$

➤  $\varphi_P$  can be extracted from the ratio ( Bramon et al., Eur. Phys. J. C7 (1999) ) :

$$R = \frac{BR(\phi \rightarrow \eta' \tilde{a})}{BR(\phi \rightarrow \eta \tilde{a})} = \cot^2 \varphi_P \left( 1 - \frac{\bar{m}_s}{\bar{m}} \frac{\tan \varphi_V}{\sin 2\varphi_P} \right)^2 \left( \frac{p_{\eta'}}{p_\eta} \right)^3 ; \quad \left( \frac{\bar{m}_s}{\bar{m}} = 1.45 \right)$$

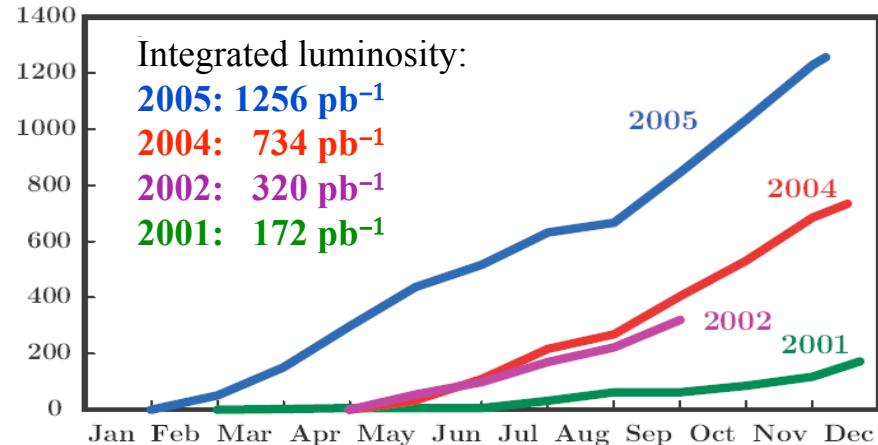
➤  $\varphi_P$  can probe the gluonium content of  $\eta'$  [Rosner PRD27(1983) 1101]  
[Kou PRD63(2001)54027]

# The KLOE experiment at DAΦNE



## Drift chamber

- ❖ Gas mixture:  $90\% \text{ He} + 10\% \text{ C}_4\text{H}_{10}$
- ❖  $\delta p_t / p_t < 0.4\% (\theta > 45^\circ)$
- ❖  $\sigma_{xy} \approx 150 \mu\text{m}; \sigma_z \approx 2 \text{ mm}$



## Electromagnetic calorimeter

- ❖ lead/scintillating fibers
- ❖ 98% solid angle coverage
- ❖  $\sigma_E / E = 5.7\% / \sqrt{E(\text{GeV})}$
- ❖  $\sigma_t = 57 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 100 \text{ ps}$
- ❖ PID capabilities

## Data taking ended on March 2006

- $2.5 \text{ fb}^{-1}$  on tape @  $\sqrt{s} = M_\phi$  ( $8 \times 10^9 \phi$ )
- $\sim 10 \text{ pb}^{-1}$  @ 1010, 1018, 1023 and 1030 MeV
- $250 \text{ pb}^{-1}$  @ 1000 MeV

# KLOE analyses on $\eta/\eta'$ mixing



$\eta/\eta'$  produced through  $\phi \rightarrow P\gamma$



Identified by the  
monochromatic recoil photon

- $E_{\text{recoil}}(\eta) = 363 \text{ MeV}$   
**very clean  $\eta$  sample**
- $E_{\text{recoil}}(\eta') = 60 \text{ MeV}$   
 **$\gamma_{\text{recoil}}$  misid. for some channels...**

$$N_\eta (2.5 \text{ fb}^{-1}) \approx 10.7 \times 10^7$$
$$N_{\eta'} (2.5 \text{ fb}^{-1}) \approx 514,000$$

---

Two analyses published:

PLB541(2002)45  $\left\{ \begin{array}{l} \phi \rightarrow \eta \gamma \rightarrow \pi^+ \pi^- \pi^0 \gamma \rightarrow \pi^+ \pi^- \gamma \gamma \gamma \\ \phi \rightarrow \eta' \gamma \rightarrow \eta \pi^+ \pi^- \gamma \rightarrow \gamma \gamma \pi^+ \pi^- \gamma \end{array} \right.$   $L_{\text{int}} = 16 \text{ pb}^{-1}$

PLB648(2007)267  $\left\{ \begin{array}{l} \phi \rightarrow \eta' \gamma, \eta' \rightarrow \pi^+ \pi^- \eta, \eta \rightarrow 3\pi^0 \\ \quad \eta' \rightarrow \pi^0 \pi^0 \eta, \eta \rightarrow \pi^+ \pi^- \pi^0 \\ \phi \rightarrow \eta \gamma, \eta \rightarrow 3\pi^0 \end{array} \right.$   $L_{\text{int}} = 427 \text{ pb}^{-1}$

# $\eta/\eta' \rightarrow \pi^+\pi^- 3\gamma$ 's analysis



Used decay chains:

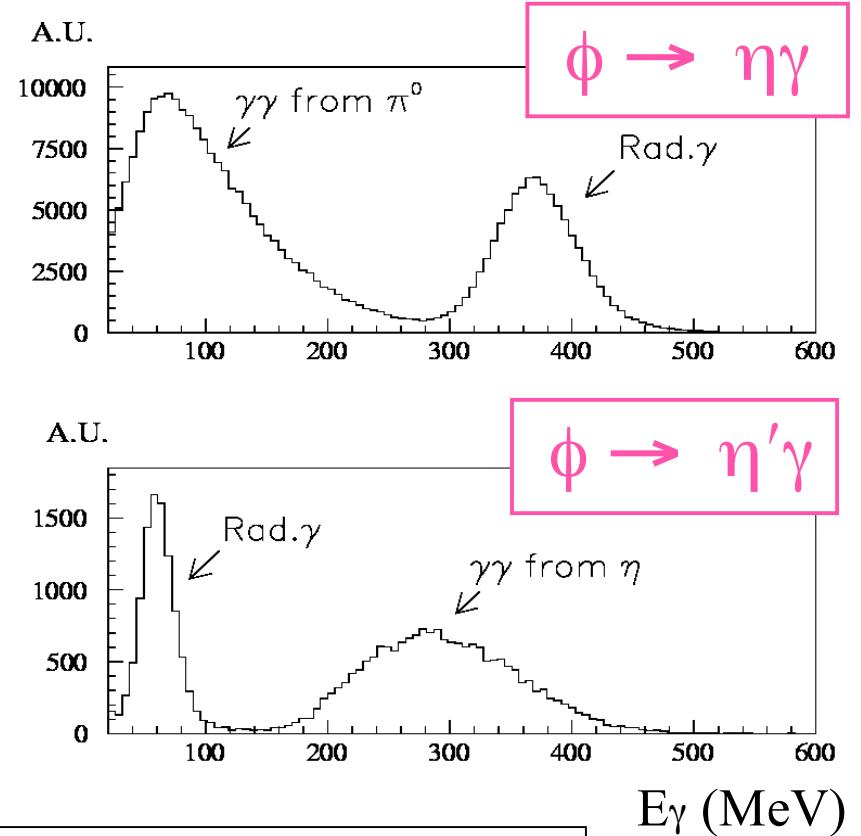
- ❖  $\phi \rightarrow \eta \gamma \rightarrow \pi^+ \pi^- \pi^0 \gamma \rightarrow \pi^+ \pi^- \gamma \gamma \gamma$
- ❖  $\phi \rightarrow \eta' \gamma \rightarrow \eta \pi^+ \pi^- \gamma \rightarrow \gamma \gamma \pi^+ \pi^- \gamma$

➤ Same topology:  
**two tracks + three photons**

➤ **Recoil photon well separated** in energy from other  $\gamma$ 's in the event

Preselection cuts:

- 1) A two tracks vertex close to IP
- 2) Three neutral clusters on time ( $|T-R/c| < 5 \sigma_t$ )
- 3) Kinematic fit imposing global 4-momentum at IP  $\Rightarrow P(\chi^2) > 1\%$
- 4) Topological cuts on the energy of the particles to remove background from  $\phi \rightarrow \pi^+ \pi^- \pi^0$  and  $\phi \rightarrow K_S K_L$

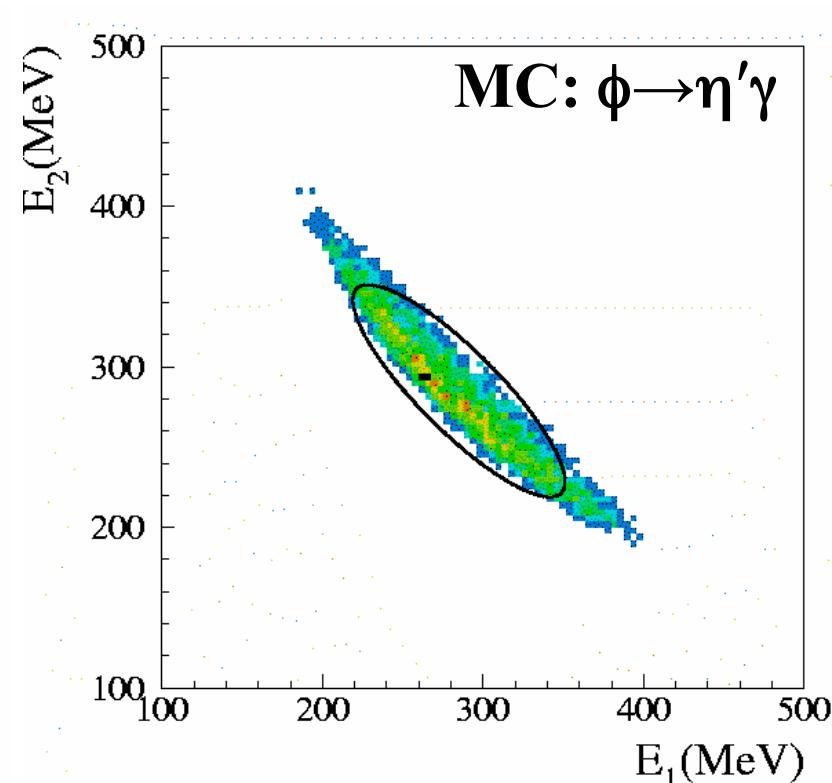
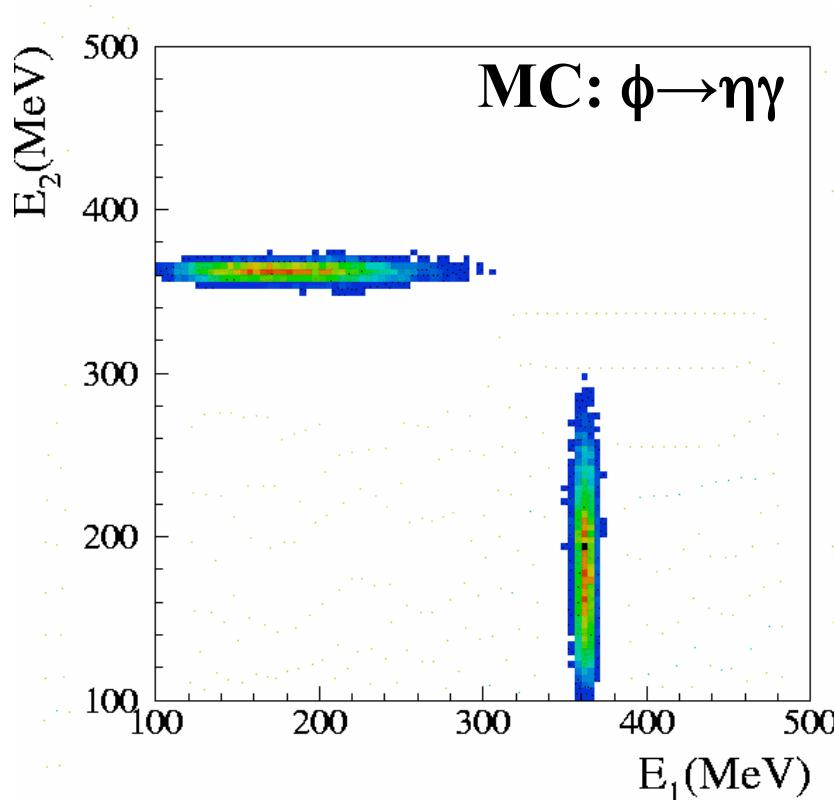


# $\eta/\eta' \rightarrow \pi^+\pi^- 3\gamma$ 's : sample selection



After pre-selection,  $N(\eta'\gamma)/N(\eta\gamma) \sim 5 \times 10^{-3}$

Events separated using energies of the two most energetic photons



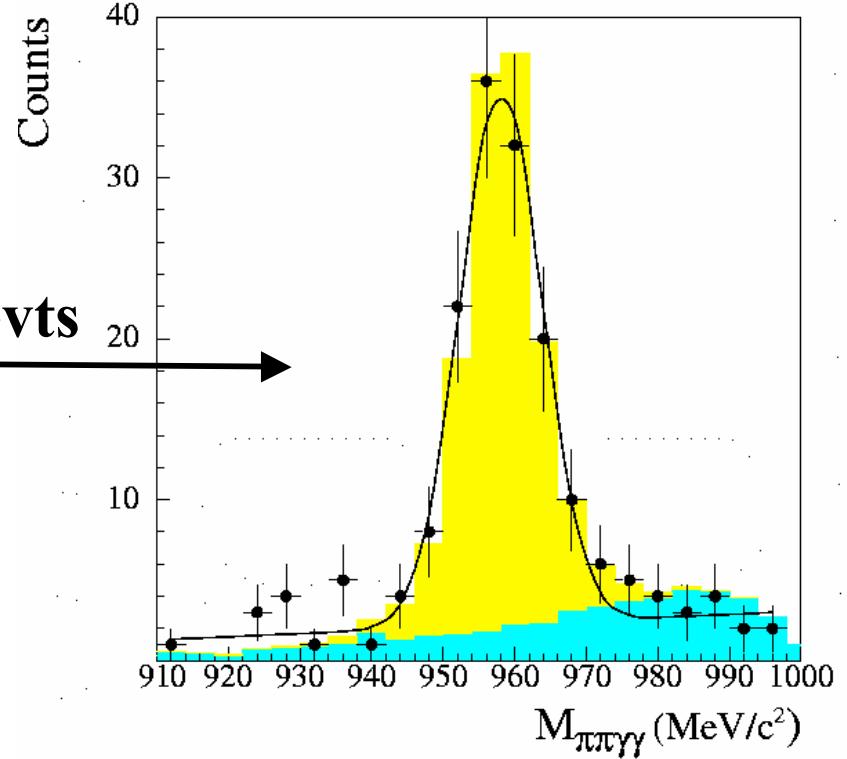
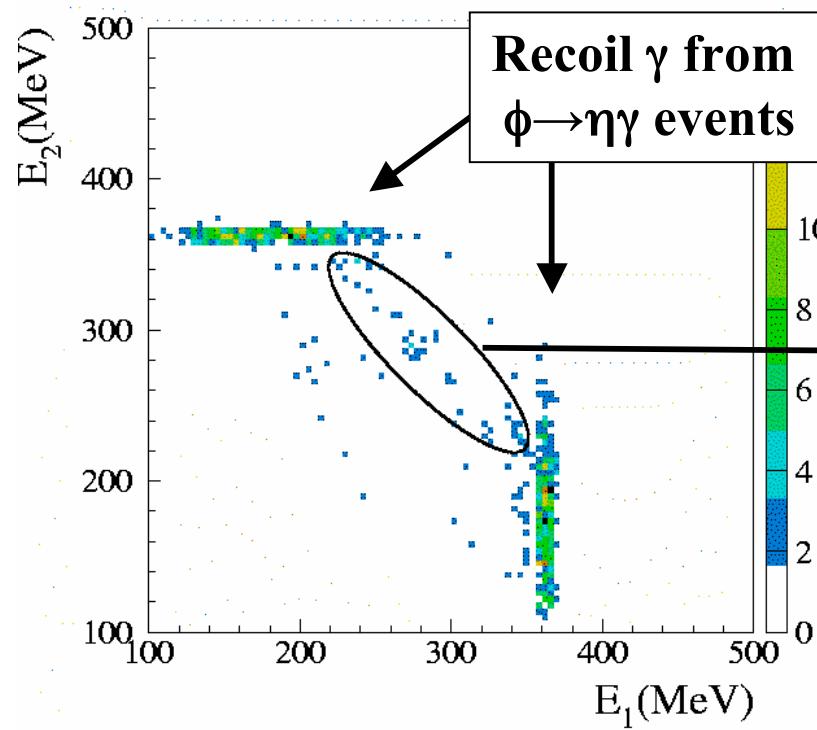
$$\varepsilon_{\text{tot}}(\eta\gamma) = 36.5\%$$

$$\varepsilon_{\text{tot}}(\eta'\gamma) = 22.8\%$$

# $\eta/\eta' \rightarrow \pi^+\pi^-3\gamma$ 's : event counting

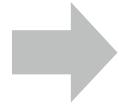


$L_{int} = 16 \text{ pb}^{-1}$



$$N(\phi \rightarrow \eta \gamma) = 50210 \pm 220$$

$$N(\phi \rightarrow \eta' \gamma) = 120 \pm 12_{\text{stat}} \pm 5_{\text{bckg}}$$



from a fit to the mass spectra  
with MC signal + ellipse  
sidebands for background



# Results on $\eta/\eta' \rightarrow \pi^+ \pi^- 3\gamma$ 's

$$R_\phi = \frac{BR(\phi \rightarrow \eta'\gamma)}{BR(\phi \rightarrow \eta\gamma)} = (4.70 \pm 0.47_{stat} \pm 0.31_{syst}) \times 10^{-3}$$

Using BR ( $\phi \rightarrow \eta\gamma$ ) from PDG:

$$BR(\phi \rightarrow \eta'\gamma) = (6.10 \pm 0.61_{stat} \pm 0.43_{syst}) \times 10^{-5}$$

**Pseudoscalar mixing angle** in the quark flavor basis:

$$\varphi_P = (41.8^{+1.9}_{-1.6})^\circ$$

**Pseudoscalar mixing angle** in the octet-singlet basis:

$$\vartheta_P = (-12.9^{+1.9}_{-1.6})^\circ$$

# $\eta/\eta' \rightarrow \pi^+\pi^- 3\gamma$ 's : gluonium content in $\eta'$

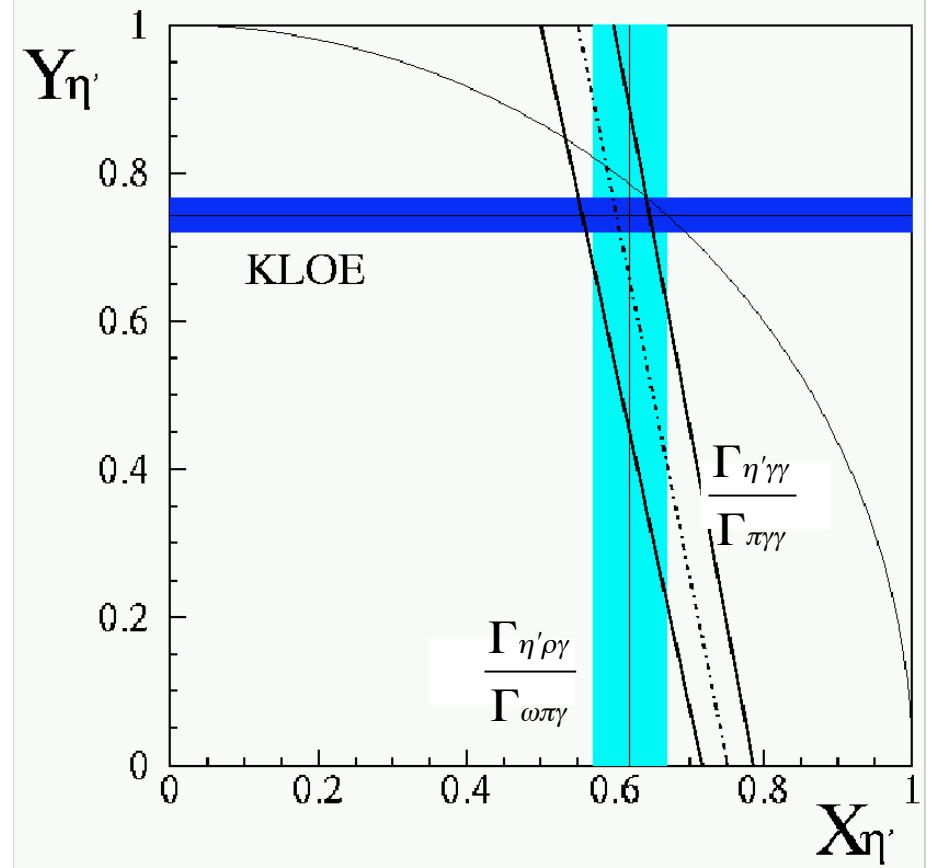


Combined analysis to evaluate the possible gluon content of  $\eta'$

$$\eta' = X_{\eta'} |\bar{u}u + \bar{d}d\rangle/\sqrt{2} + Y_{\eta'} |\bar{s}s\rangle + Z_{\eta'} |G\rangle$$

Assuming  $Z_{\eta'} = 0$  :

1. Constraints on  $X_{\eta'}$ ,  $Y_{\eta'}$  from other channels
2.  $Y_{\eta'} = \cos\varphi_P$  from KLOE
3. Check consistency in the  $X_{\eta'} - Y_{\eta'}$  plane with  $X_{\eta'}^2 + Y_{\eta'}^2 = 1$

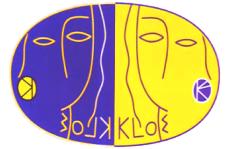


Minimizing the related  $\chi^2$  function:

$$Z_{\eta'}^2 = 0.06^{+0.09}_{-0.06}$$



**Gluonium content in  $\eta'$  lower than 15%**



# $\eta/\eta' \rightarrow \pi^+\pi^- 7\gamma$ 's analysis

$\text{BR}(\phi \rightarrow \eta'\gamma)/\text{BR}(\phi \rightarrow \eta\gamma)$  measured using the following decay chains:

- ❖  $\phi \rightarrow \eta'\gamma, \eta' \rightarrow \pi^+\pi^-\eta, \eta \rightarrow 3\pi^0$   
 $\eta' \rightarrow \pi^0\pi^0\eta, \eta \rightarrow \pi^+\pi^-\pi^0$
  - ❖  $\phi \rightarrow \eta\gamma, \eta \rightarrow 3\pi^0$
- $\left. \right\}$  2 tracks + 7 photons

Signal selection for  $\phi \rightarrow \eta'\gamma$ :

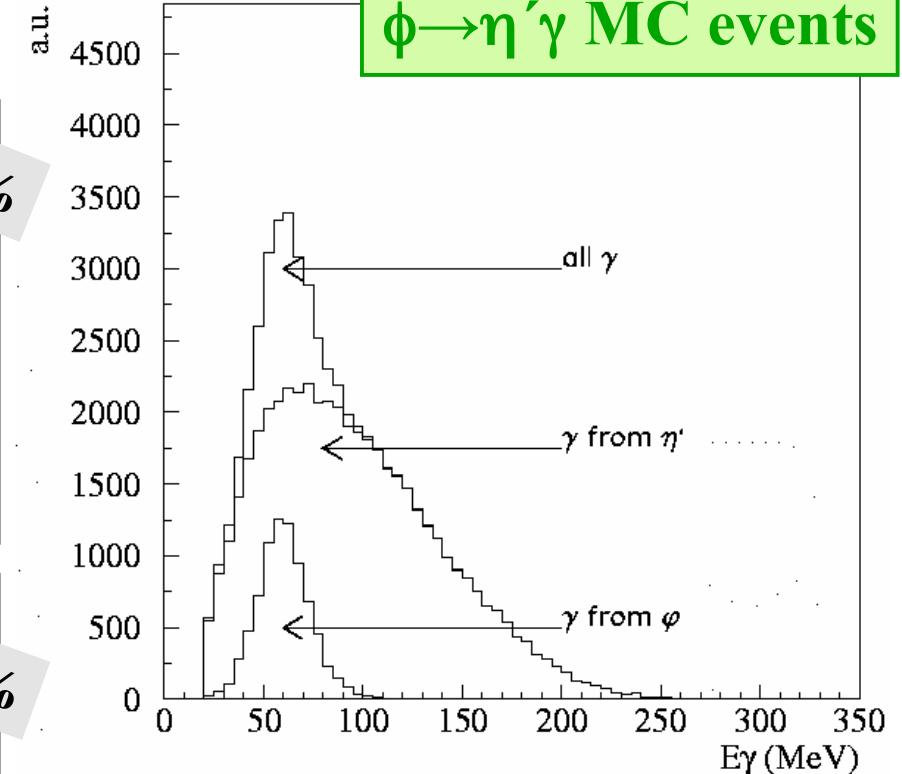
1. Two tracks vertex near I.P.
2. Seven neutral clusters on time
3. Event not tagged as  $K_S K_L$
4. Kinematic fit imposing global 4-momentum conservation @ I.P.

Signal selection for  $\phi \rightarrow \eta\gamma$ :

1. Seven neutral clusters on time
2.  $320 < E_{\gamma \text{ recoil}} < 400 \text{ MeV}$

$$\varepsilon(\eta'\gamma) = 22.7\%$$

$$\varepsilon(\eta\gamma) = 32.9\%$$



Radiative  $\gamma$  and  $\gamma$ 's from  $\pi^0$  overlapped

# $\eta/\eta' \rightarrow \pi^+\pi^- 7\gamma$ 's : event counting

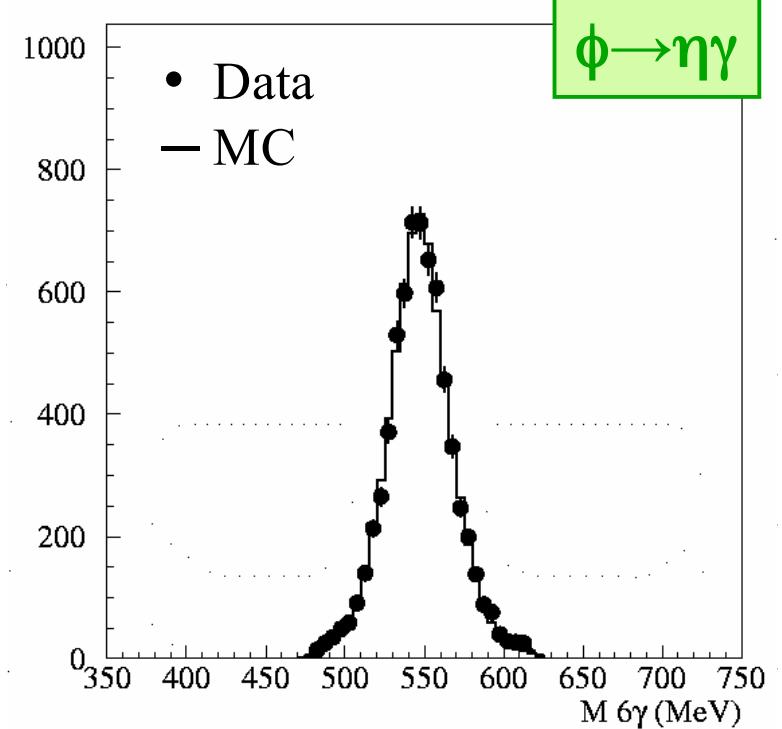
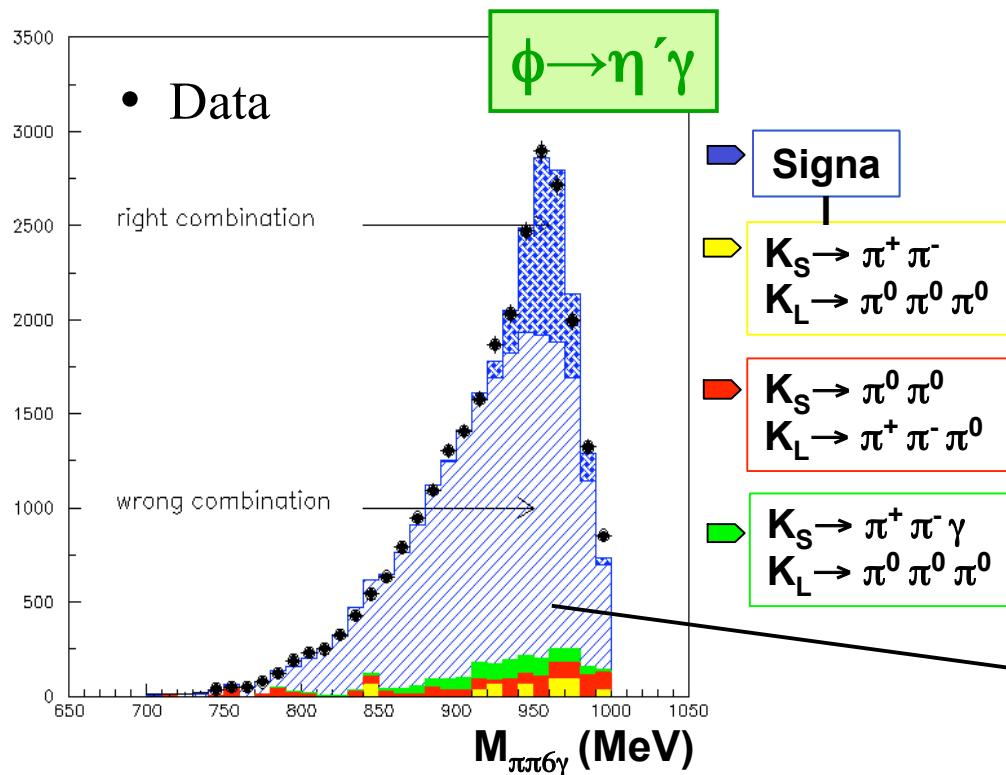


427 pb<sup>-1</sup> @  $\sqrt{s} = M_\phi$  from 2001/2002 data

$N(\eta\gamma) = 1665000 \pm 1300$  (Background free)

$N(\pi^+\pi^- 7\gamma)$ 's =  $3750 \pm 60$  ( $N_{\text{bckg}} = 345$ )

$N(\eta'\gamma) = 3405 \pm 61_{\text{stat}} \pm 28_{\text{syst}}$



Wrong combination:  
radiative  $\gamma$  used to construct  
the  $\eta'$  invariant mass



# $\eta/\eta' \rightarrow \pi^+ \pi^- 7\gamma$ 's : results

$$R_\phi = \frac{BR(\phi \rightarrow \eta'\gamma)}{BR(\phi \rightarrow \eta'\gamma)} = \frac{N^{\eta'\gamma}}{N^{\eta\gamma}} \cdot \frac{\epsilon^{\eta\gamma} \cdot BR(\eta \rightarrow 3\pi^0)}{[BR_{crg}\epsilon_{crg} + BR_{ntr}\epsilon_{ntr}]} \cdot K_\rho$$

Interf.  
 $A(\phi \rightarrow \eta/\eta \times \gamma)$ ,  
 $A(\rho \rightarrow \eta/\eta \times \gamma)$

$$\begin{aligned} BR_{crg} &= BR(\eta' \rightarrow \pi^+ \pi^- \eta) BR(\eta \rightarrow \pi^0 \pi^0 \pi^0) \\ BR_{ntr} &= BR(\eta' \rightarrow \pi^0 \pi^0 \eta) BR(\eta \rightarrow \pi^+ \pi^- \pi^0) \end{aligned}$$

All BRs taken  
from PDG

$$R_\phi = (4.74 \pm 0.09_{stat} \pm 0.20_{syst}) \times 10^{-3}$$

$$BR(\phi \rightarrow \eta'\gamma) = (6.17 \pm 0.12_{stat} \pm 0.28_{syst}) \times 10^{-5}$$

Systematics dominated by the knowledge of  $\eta, \eta \times$  BRs

In agreement with previous KLOE results:

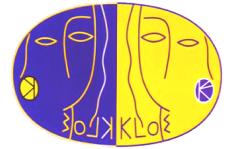
[Phys. Lett. B541 (2002) 45-51]

$$R = (4.70 \pm 0.47_{stat} \pm 0.31_{sys}) \cdot 10^{-3}$$

$$BR(\phi \rightarrow \eta'\gamma) = (6.10 \pm 0.61 \pm 0.43) \cdot 10^{-5}$$

Source	Syst. Err.
Filfo-Evcl	1%
TRK	1%
VTX	1%
Bckg.sub.	0.1%
$\epsilon_\eta / \epsilon_{\eta'}$	0.4%
$\chi^2$	1.5%
BR"	3%
Total	4%

# $\eta/\eta' \rightarrow \pi^+ \pi^- 7\gamma$ 's : gluonium content in $\eta'$



Formal parametrization for  $\eta'$  gluonium content measurement:

$$|\eta'\rangle = X_{\eta'} \frac{1}{\sqrt{2}} |u\bar{u} + d\bar{d}\rangle + Y_{\eta'} |s\bar{s}\rangle + Z_{\eta'} |glue\rangle$$

$$|\eta\rangle = \cos\varphi_P \frac{1}{\sqrt{2}} |u\bar{u} + d\bar{d}\rangle - \sin\varphi_P |s\bar{s}\rangle$$

Using SU(3) relations between decay modes and measured BRs:

$$\frac{\Gamma(\eta' \rightarrow \rho\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)} = C_{M2} Z_{NS} \left( \sin(\varphi_G) \cos(\varphi_P) \right)^2$$

$$R_\phi = \cot^2(\varphi_P) \cos^2(\varphi_G) \left( 1 - C_V \frac{Z_{NS}}{Z_N} \frac{1}{\sin(2\varphi_P)} \right)^2 \left( \frac{p_{\eta'}}{p_\eta} \right)^3$$

$$\frac{\Gamma(\eta' \rightarrow \gamma\gamma)}{\Gamma(\pi^0 \rightarrow \gamma\gamma)} = C_{M1} \left( 5 \cos(\varphi_G) \sin(\varphi_P) + \sqrt{2} \frac{f_q}{f_s} \cos(\varphi_G) \cos(\varphi_P) \right)^2$$

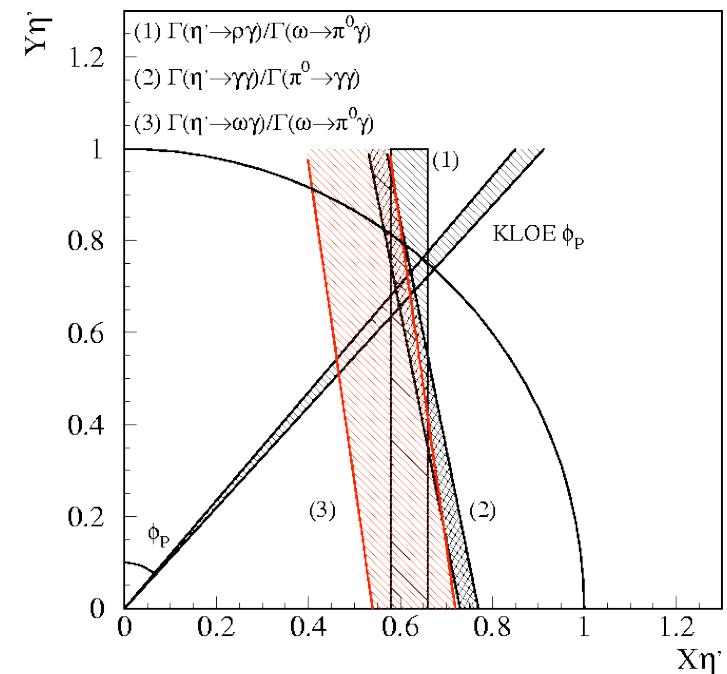
$$\frac{\Gamma(\eta' \rightarrow \omega\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)} = C_{M3} \left( Z_{NS} \sin(\varphi_G) \cos(\varphi_P) + 2 C_V Z_S \sin(\varphi_G) \sin(\varphi_P) \right)^2$$

$Z_N, Z_{NS}$  evaluated assuming  $Z_{\eta'}^2 = 0$

[Bramon et al., EPJC 7 (1999); PLB 503 (2001)]

$$X_{\eta'} = \cos\phi_G \sin\varphi_P \quad Y_{\eta'} = \cos\phi_G \cos\varphi_P$$

$$Z_{\eta'} = \sin\phi_G$$

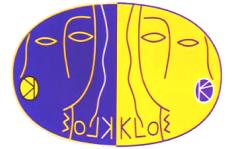


**NO GLUONIUM hypothesis:**

$$\varphi_P = (41.5 \pm 0.6 - 0.7)^\circ$$

$$P(\chi^2) = 0.01$$

# $\eta/\eta' \rightarrow \pi^+ \pi^- 7\gamma$ 's : gluonium content in $\eta'$

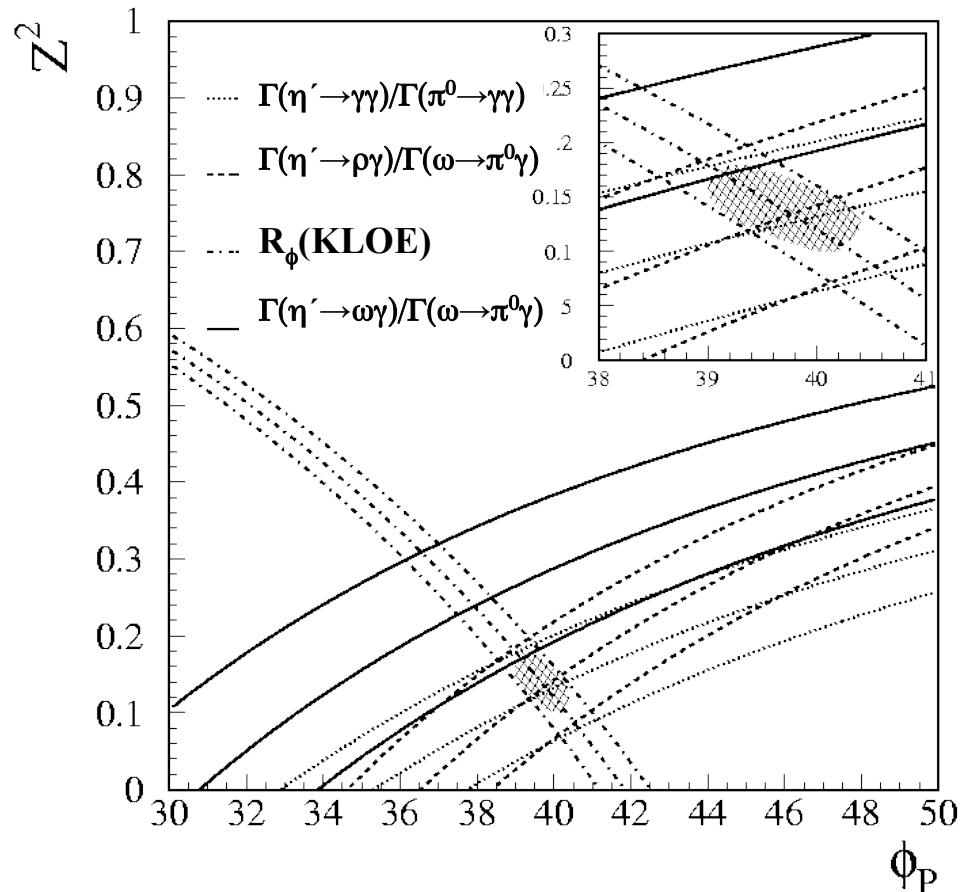


Allowing for gluonium content in  $\eta'$  :

$$\begin{aligned}\chi^2/N_{\text{dof}} &= 1.42/2 \\ \cos^2\phi_G &= 0.86 \pm 0.04 \\ \cos^2\phi_P &= 0.592 \pm 0.012\end{aligned}$$



$$\begin{aligned}\phi_P &= (39.7 \pm 0.7)^\circ \\ Z^2_{\eta'} &= 0.14 \pm 0.04 \\ P(\chi^2) &= 49\%\end{aligned}$$



Gluonium content @  $\sim 3\sigma$  level

# $\eta/\eta'$ mixing: gluonium content in $\eta'$



Preliminary

Global fit with more free parameters (also  $Z_N$ ,  $Z_{NS}$ ,  $\phi_V$ ,  $m_s/m$ )

Other SU(3) relations included :

$$\frac{\Gamma(\omega \rightarrow \eta\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)}, \quad \frac{\Gamma(\rho \rightarrow \pi^0\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)}, \quad \frac{\Gamma(\phi \rightarrow \eta\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)}, \quad \frac{\Gamma(\phi \rightarrow \pi^0\gamma)}{\Gamma(\omega \rightarrow \pi^0\gamma)}, \quad \frac{\Gamma(K^{*+} \rightarrow K^+\gamma)}{\Gamma(K^{*0} \rightarrow K^0\gamma)}$$

Parameter	KLOE published	New fit	New fit (no P $\gamma\gamma$ )
$Z_{\eta'}$	$0.14 \pm 0.04$	$0.105 \pm 0.037$	$0.03 \pm 0.06$
$\phi_P$	$(39.7 \pm 0.7)^\circ$	$(40.7 \pm 0.7)^\circ$	$(41.6 \pm 0.8)^\circ$
$Z_{NS}$	$0.91 \pm 0.05$	$0.866 \pm 0.025$	$0.85 \pm 0.03$
$Z_S$	$0.89 \pm 0.07$	$0.79 \pm 0.05$	$0.78 \pm 0.05$
$\phi_V$	$3.2^\circ$	$(3.15 \pm 0.10)^\circ$	$(3.16 \pm 0.10)^\circ$
$m_s/m$	$1.24 \pm 0.07$	$1.24 \pm 0.07$	$1.24 \pm 0.07$
$P(\chi^2)$	49%	17%	40.7%

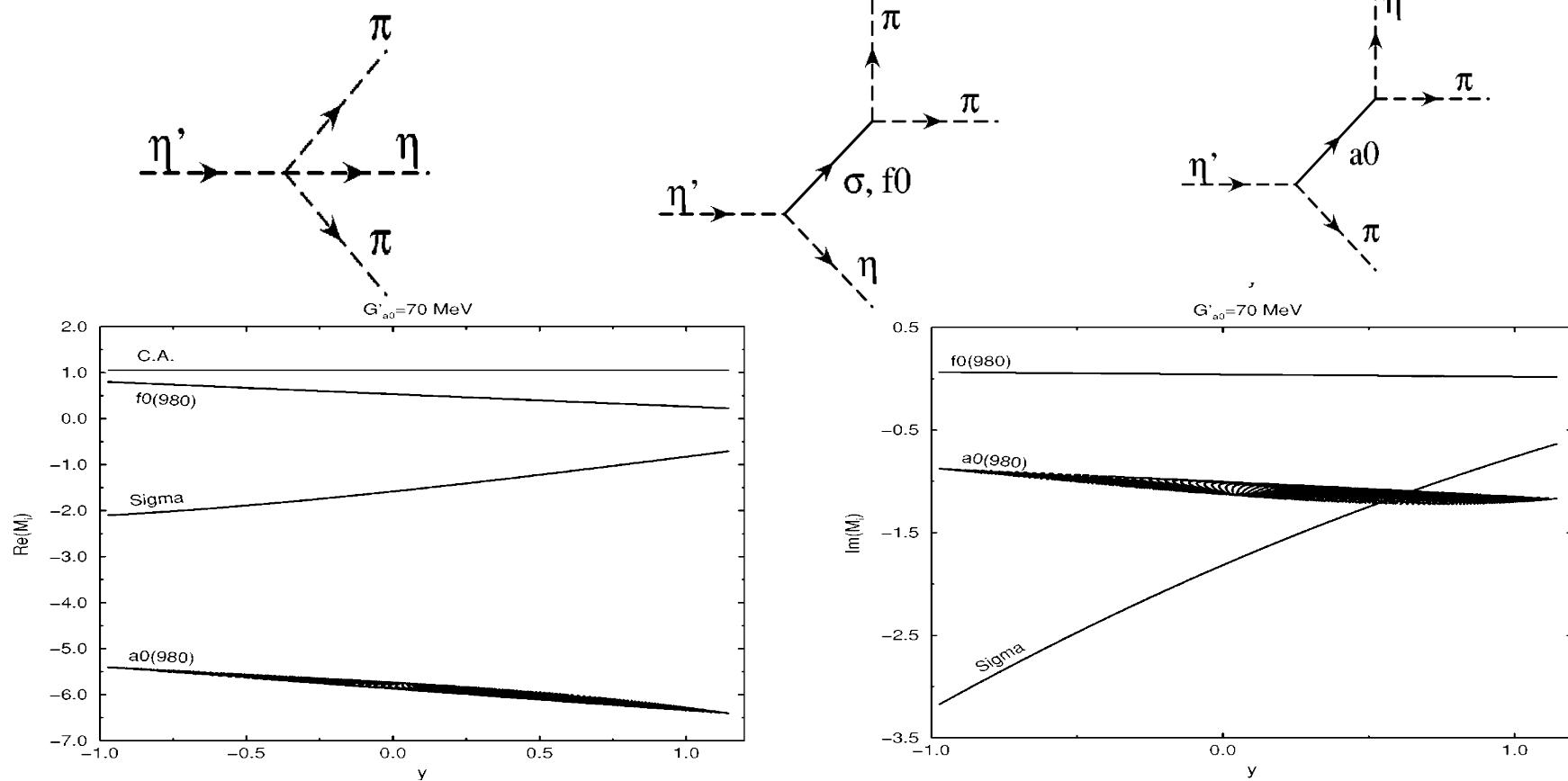
- Gluonium content @  $\sim 3\sigma$  level confirmed
- Forcing  $Z_{\eta'}=0$  :  $\phi_P = (41.6 \pm 0.5)^\circ$  with  $P(\chi^2)=1\%$
- Discrepancy with Escribano-Nadal (  $Z_{\eta'} = 0.04 \pm 0.09$  ,  $\phi_P = (41.4 \pm 1.3)^\circ$  ) [JHEP05(2007)006] due to the insertion of  $P\gamma\gamma$  transitions

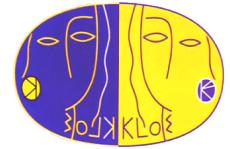
# $\eta' \rightarrow \pi\pi\eta$ : Dalitz plot analysis



- Test of ChPT predictions
- $\eta'$  nature: possible gluonium content can influence dynamics
- Sensitive to parameters of the intermediate scalar mesons  
(no tree contributions from VMD)

[Faribotz-Schechter, PRD60(1999)034002]





Reactions:

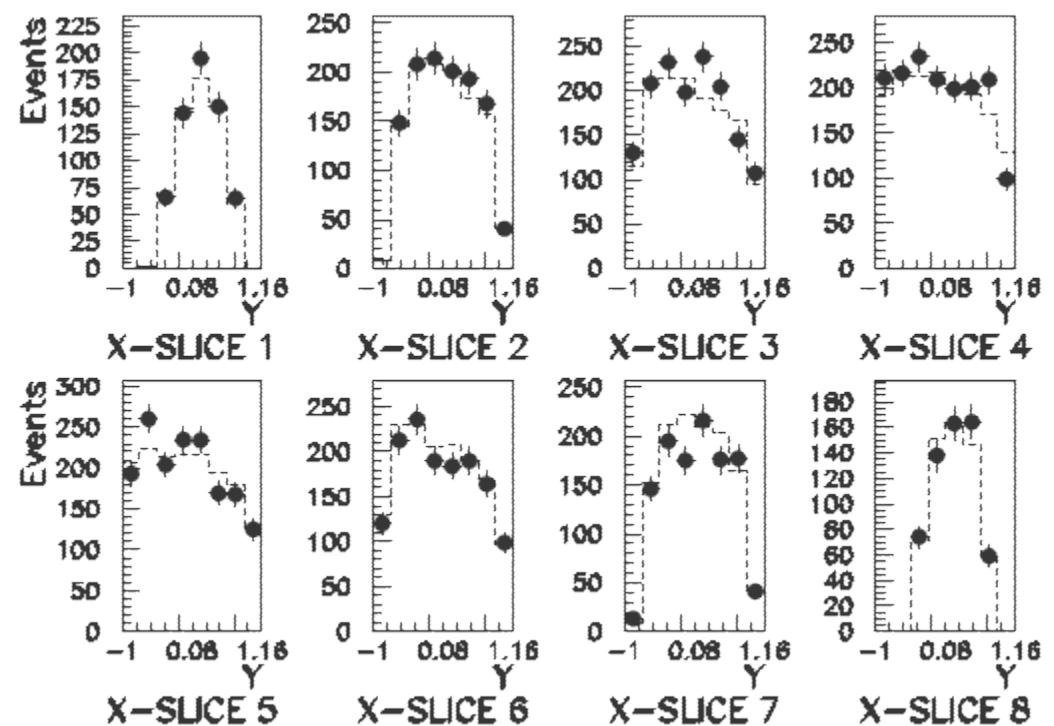
- (1)  $\pi^- p \rightarrow \eta' n$  (charge exchange)  $N_{\text{ev}} \sim 14.6 \times 10^3$  5% bckg
- (2)  $\pi^- N \rightarrow \eta' \pi^- N$  (diffractive-like prod.)  $N_{\text{ev}} \sim 7 \times 10^3$  15% bckg

Kinematic fit to  $\eta \rightarrow \gamma\gamma$  events

Fit results:  
sliced Dalitz plot



- Data
- - MC weighted with fit results



# $\eta' \rightarrow \pi^+ \pi^- \eta$ @ VES : fit results

VES, PLB 651 (2007) 22



Fit parameters extracted separately for the two channels and then combined

Dalitz plot parametrization:  $|M|^2 = 1 + aY + bY^2 + cX + dX^2$

$$X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-}) \quad Y = \frac{m_\eta + 2m_\pi}{m_\pi} \frac{T_\eta}{Q} - 1$$

T: kinetic energy in the  $\eta'$  rest frame  
 $Q = T_\eta + T_{\pi^+} + T_{\pi^-}$

Coeff.	Combined fit	Borasoy-Nissler, Eur.Phys.J.A26(2005)
$a$	$-0.127 \pm 0.016 \pm 0.008$	$-0.116 \pm 0.011$
$b$	$-0.106 \pm 0.028 \pm 0.014$	$-0.042 \pm 0.034$
$c$	$+0.015 \pm 0.011 \pm 0.014$	
$d$	$-0.082 \pm 0.017 \pm 0.008$	$+0.010 \pm 0.022$
$\chi^2/\text{Ndf}$	$129.3/114$	

**CLEO:**  
 $\Re(\alpha) = -0.21 \pm 0.025$

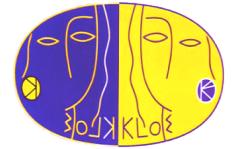
with Dalitz plot parametrization:

$$|M|^2 = |1 + \alpha Y|^2 + cX + dX^2$$

$\alpha$  complex,  $a b c d$  real :  
equivalent parametrizations  
if  $b > a^2/4$

- $b < 0$  @  $3.4 \sigma$  → linear parametrization not correct
- $c$  consistent with C-parity conservation

# $\eta' \rightarrow \pi^+ \pi^- \eta$ @ KLOE



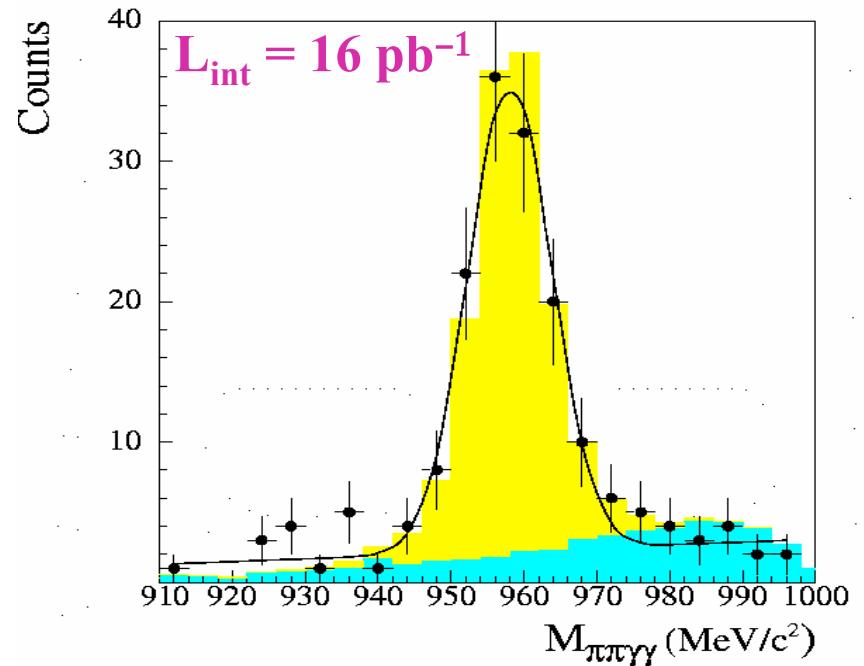
Already studied @ KLOE with  $\eta \rightarrow \gamma\gamma$  decay channel for first  $\eta/\eta'$  mixing measurement

- ✓ We know how to select it with small residual background
- ✓ Analysis efficiency 23%, expected flat in the Dalitz plot

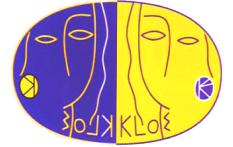
With  $2.5 \text{ fb}^{-1}$ , after analysis cuts:

$$N(2.5 \text{ fb}^{-1}) \approx 21,000$$

Comparable with VES statistics



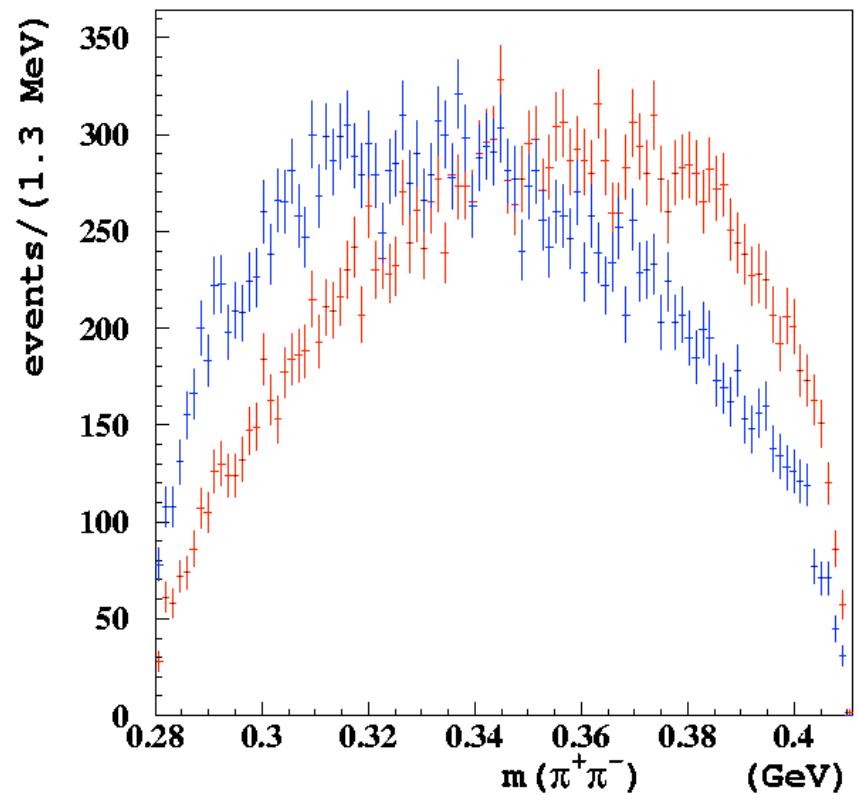
# $\eta' \rightarrow \pi^+ \pi^- \eta$ @ KLOE



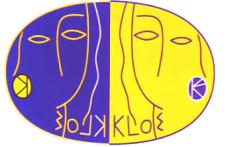
Expected  $M_{\pi\pi}$  shape using Faribotz-Schechter model with  
2.5  $\text{fb}^{-1}$  @ KLOE, including analysis efficiency (flat in  $M_{\pi\pi}$ )  
Reconstruction effects not included

**Blue: without  $\sigma(600)$**

**Red:  $\sigma(600)$  included**



# Conclusions



- ❖  **$\eta'$  analyses focused on  $\eta/\eta'$  mixing and gluonium content in  $\eta'$ :**
  - **Gluonium content in  $\eta'$  @  $\sim 3\sigma$  level**
  - **Systematics dominated by intermediate BRs**
  - **Good data quality, small background contribution for several  $\eta'$  decay channels**
- ❖ **Next in line: measurement of  $\eta' \rightarrow \pi^+ \pi^- \eta$  Dalitz plot**