

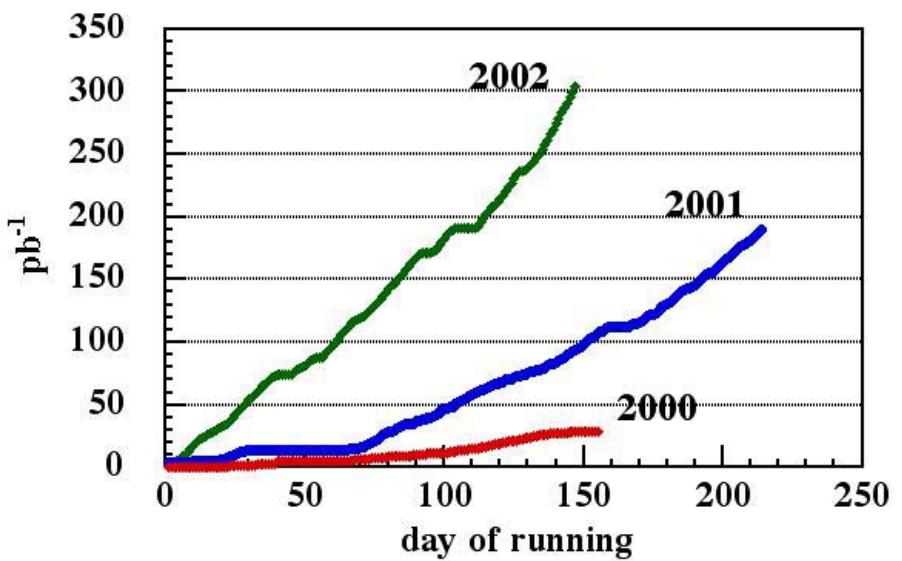
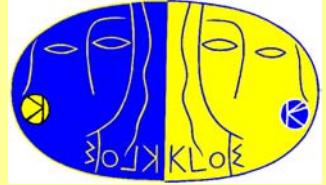


# Experimental Measurement of the $\Phi$ meson radiative decays into scalars and pseudoscalars mesons with the KLOE detector

The KLOE Coll. presented by  
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*Photon 2003 – Frascati L.N.F. 7-11 April 2003*

# KLOE data collected



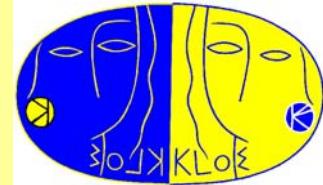
1999 run :  $2.5 \text{ pb}^{-1}$   
*machine and detector  
studies*

2000 run :  $25 \text{ pb}^{-1}$   
 $7.5 \times 10^7 \phi$   
*published results*

2001 run:  $190 \text{ pb}^{-1}$   
 $5.7 \times 10^8 \phi$   
*analysis in progress*

2002 run:  $300 \text{ pb}^{-1}$   
 $9.0 \times 10^8 \phi$   
*analysis in progress*

# KLOE



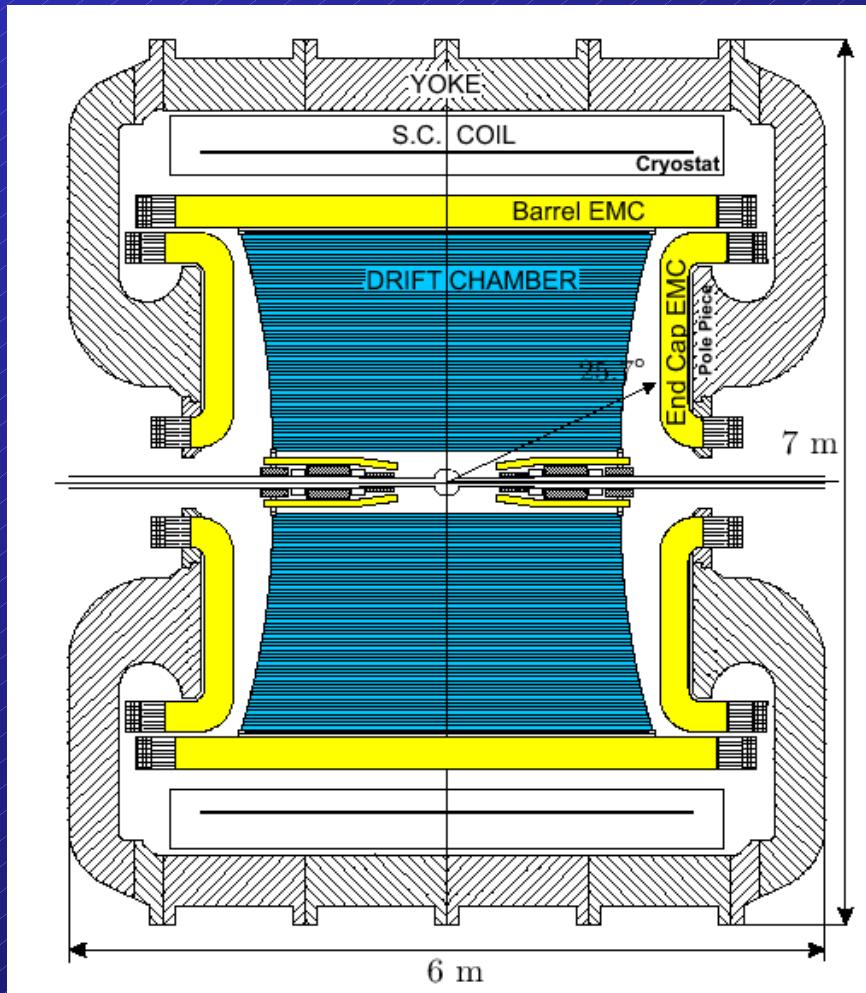
## Drift chamber:

- $\delta p/p < 0.4\%$
- $\sigma_{xy} \approx 150 \mu\text{m}$ ;  $\sigma_z \approx 2 \text{ mm}$

## E.m. calorimeter:

- $\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$
- $\sigma_t = 54 \text{ ps}/\sqrt{E(\text{GeV})} + 50 \text{ ps}$
- 98% of  $4\pi$

## Magnetic field: 0.5 T



# $\Phi$ radiative decays

- Analysis of 2000 data:  $\int L dt = 16 \text{ pb}^{-1}$

$\Phi \rightarrow \eta' \gamma / \eta \gamma$       Phys. Lett. B541 (2002), 45

$\Phi \rightarrow \pi^0 \pi^0 \gamma$       Phys. Lett. B537 (2002), 21

$\Phi \rightarrow \eta \pi^0 \gamma$       Phys. Lett. B537 (2002), 209

# $\Phi$ radiative decays

Pseudoscalar mesons ( $J^{PC} = 0^{-+}$ )

- $\eta$  (547)      ( $I=0$ )
- $\eta'$  (958)      ( $I=0$ )

Scalar mesons ( $J^{PC} = 0^{++}$ )

- $f_0(980)$       ( $I=0$ )
- $a_0(980)$       ( $I=1$ )



$$\phi \rightarrow \eta' \gamma / \phi \rightarrow \eta \gamma$$

- The mass eigenstates  $\eta$ ,  $\eta'$  are related to  $SU(3)$  octet-singlet  $\eta_8$ ,  $\eta_1$  through the mixing angle  $\vartheta_P$
- Recent 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  
 $\Rightarrow$  mixing is described by only one parameter ( $\varphi_P$ )

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

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



$\phi \rightarrow \eta' \gamma / \phi \rightarrow \eta \gamma$

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

$$R = \frac{Br(\phi \rightarrow \eta' \gamma)}{Br(\phi \rightarrow \eta \gamma)} = \cot^2 \varphi_P \left( 1 - \frac{m_s}{\bar{m}} \frac{\tan \varphi_V}{\sin 2\varphi_P} \right)^2 \left( \frac{p_{\eta'}}{p_\eta} \right)^3 ; \left( \frac{m_s}{\bar{m}} = 1.45 \right)$$

- $Br(\phi \rightarrow \eta' \gamma)$  can probe the gluonic content of  $\eta'$

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



# $\phi \rightarrow \eta' \gamma / \phi \rightarrow \eta \gamma$

- Decays with  $\pi^+ \pi^- 3\gamma$  final state:

$$\begin{aligned} \phi \rightarrow \eta \gamma &; \eta \rightarrow \pi^+ \pi^- \pi^0 \\ \phi \rightarrow \eta' \gamma &; \eta' \rightarrow \pi^+ \pi^- \eta \\ \phi \rightarrow \eta \gamma &; \eta \rightarrow \gamma \gamma \end{aligned}$$

$$Br \approx 3 \times 10^{-3}$$

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

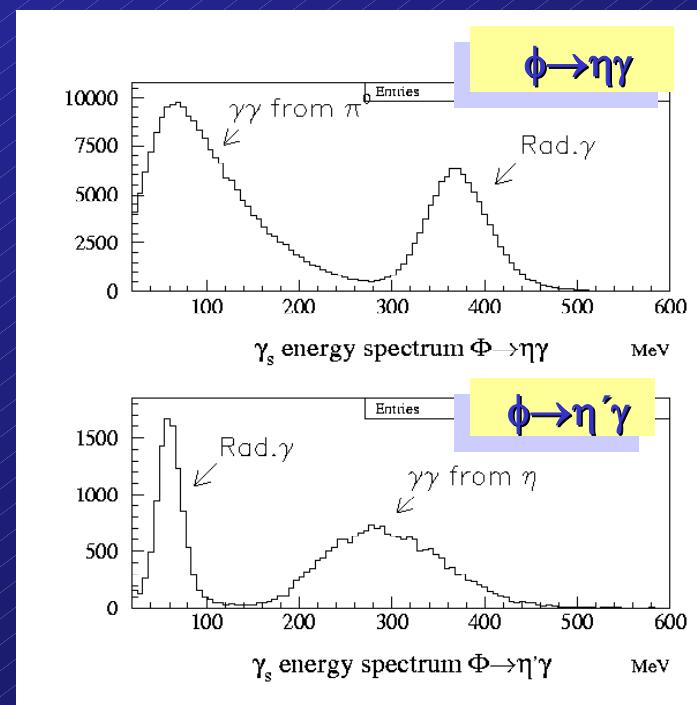
Background from  $\phi \rightarrow \pi^+ \pi^- \pi^0$  and  $\phi \rightarrow K_L K_S$  (with  $K_L$  decaying near the IP)

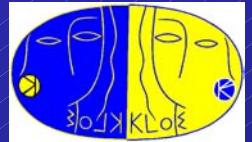
## Analysis cut:

- 1 vertex in IR with 2 tracks
- 3 prompt  $\gamma$  ( $E > 10$  MeV,  $|\cos \theta| < 0.93$ )
- Constrained kinematic fit
- topological cuts on the energy of particles

$$\varepsilon_{\text{tot}}(\eta \gamma) = 37 \%$$

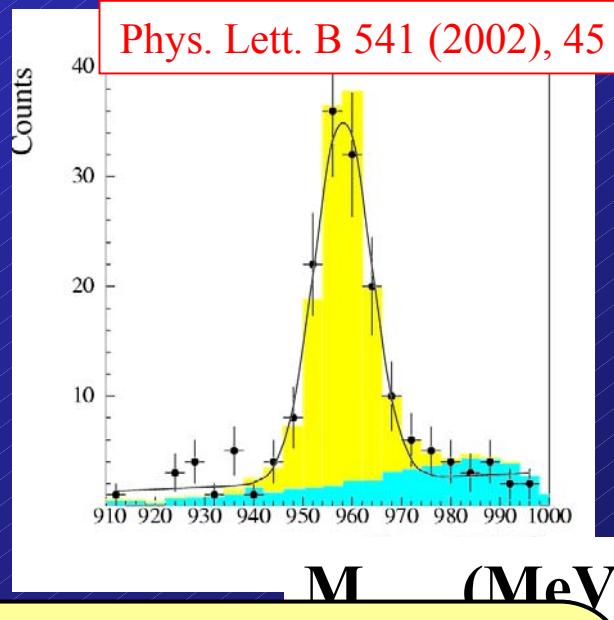
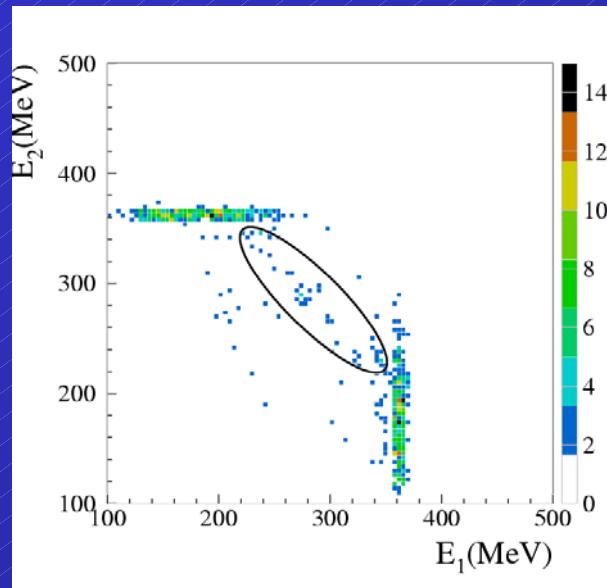
$$\varepsilon_{\text{tot}}(\eta' \gamma) = 23 \%$$





# $\phi \rightarrow \eta' \gamma / \phi \rightarrow \eta \gamma$

- Main background is  $\phi \rightarrow \eta \gamma$
- Selection: elliptic cut in the plane of the two most energetic photons



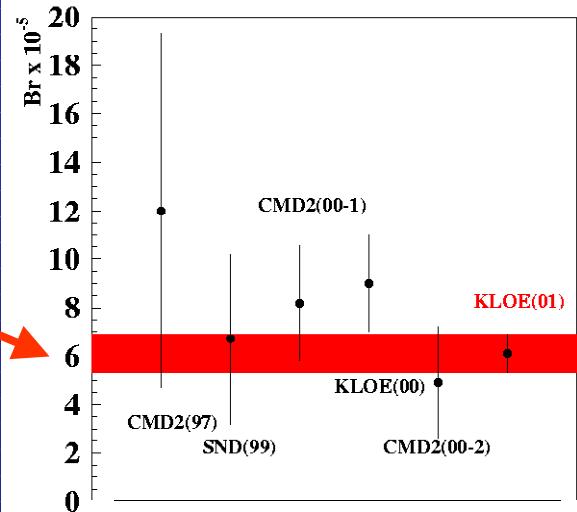
$$\begin{aligned}
 R &= \frac{N_{\eta'\gamma}}{N_{\eta\gamma}} \frac{\epsilon_{\eta\gamma}}{\epsilon_{\eta'\gamma}} \frac{\text{Br}(\eta \rightarrow \pi^+ \pi^- \pi^0) \text{Br}(\pi^0 \rightarrow \gamma\gamma)}{\text{Br}(\eta' \rightarrow \pi^+ \pi^- \eta) \text{Br}(\eta \rightarrow \gamma\gamma)} F_p = \\
 &= (4.70 \pm 0.47 \pm 0.31) \times 10^{-3}
 \end{aligned}$$

•  $F_p = 0.95$  (interference with  $e^+ e^- \rightarrow p \rightarrow \eta(\eta')\gamma$ )



$$\phi \rightarrow \eta' \gamma / \phi \rightarrow \eta \gamma$$

- Using PDG value for  $\text{Br}(\phi \rightarrow \eta \gamma)$ :  
 $\Rightarrow \text{Br}(\phi \rightarrow \eta' \gamma) = (6.10 \pm 0.61 \pm 0.43) \times 10^{-5}$
- Pseudoscalar mixing angle:  
 $\varphi_P = (41.8 \pm 1.7)^\circ$  (flavor)  
 $\Rightarrow \vartheta_P = (-12.9 \pm 1.7)^\circ$  (octet-singlet)



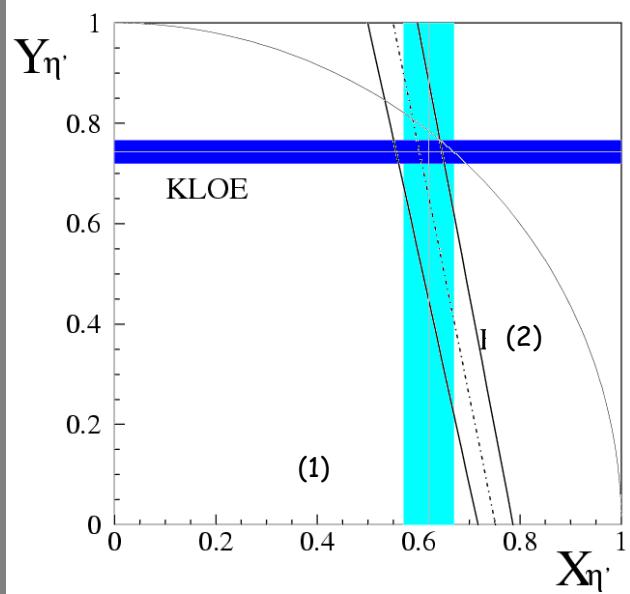
Gluonic content of  $\eta'$ :

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

Consistency check: if  $Z_{\eta'} = 0 \Rightarrow |Y_{\eta'}| = \cos \varphi_P$   
other constraints on  $X_{\eta'}$  and  $Y_{\eta'}$  from:

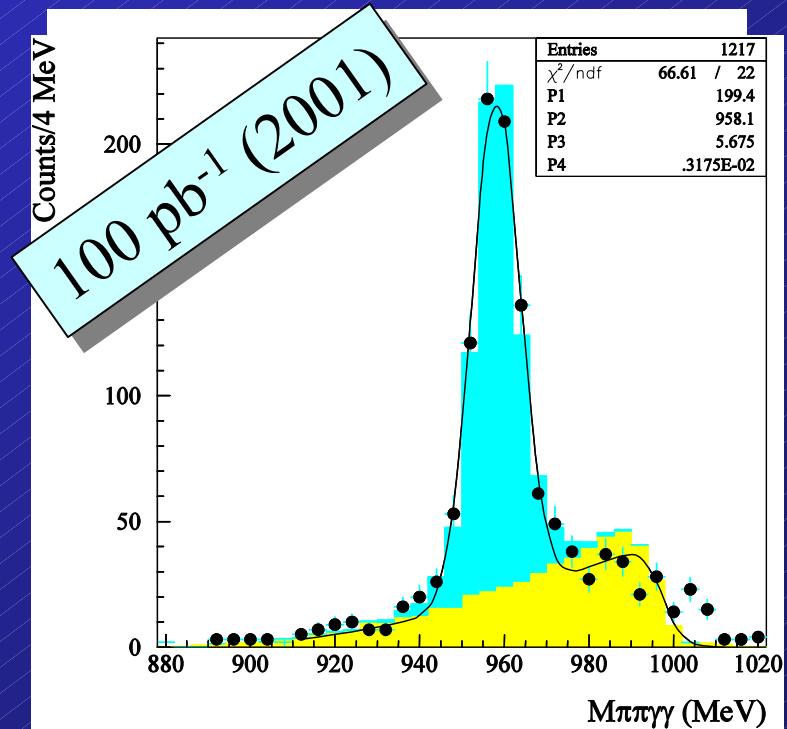
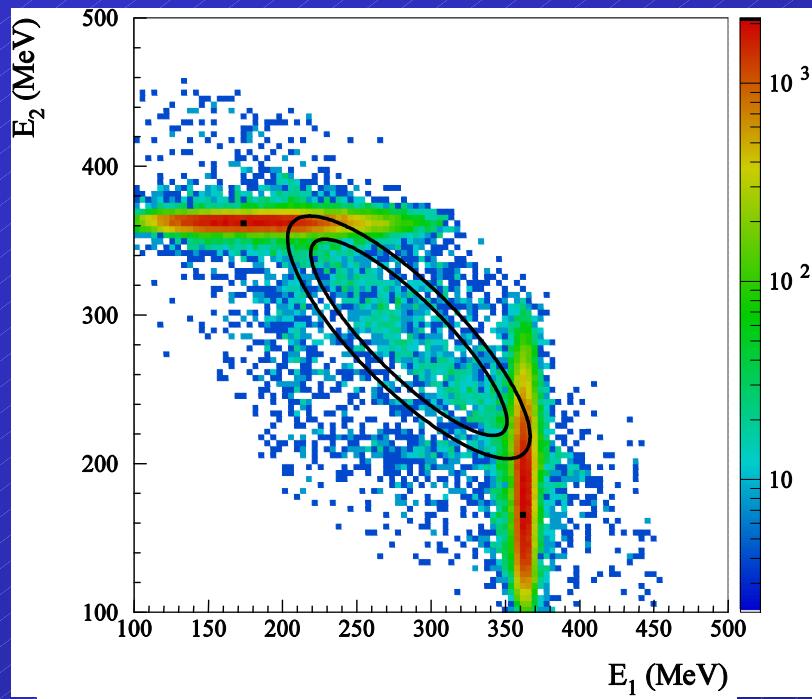
- (1)  $\Gamma(\eta' \rightarrow \rho \gamma) / \Gamma(\omega \rightarrow \pi^0 \gamma)$
- (2)  $\Gamma(\eta' \rightarrow \gamma \gamma) / \Gamma(\pi^0 \rightarrow \gamma \gamma)$

$$X_{\eta'}^2 + Y_{\eta'}^2 = 0.94^{+0.06}_{-0.09}$$

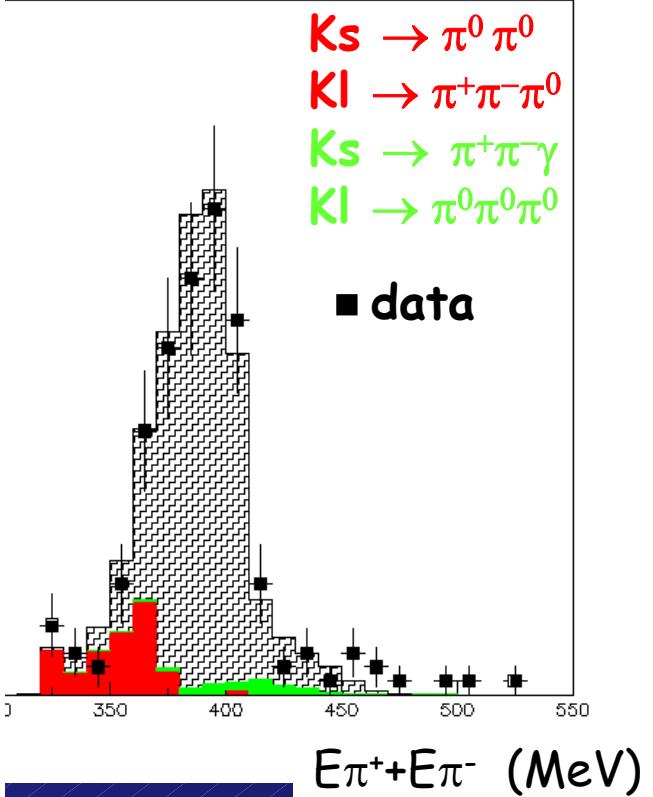
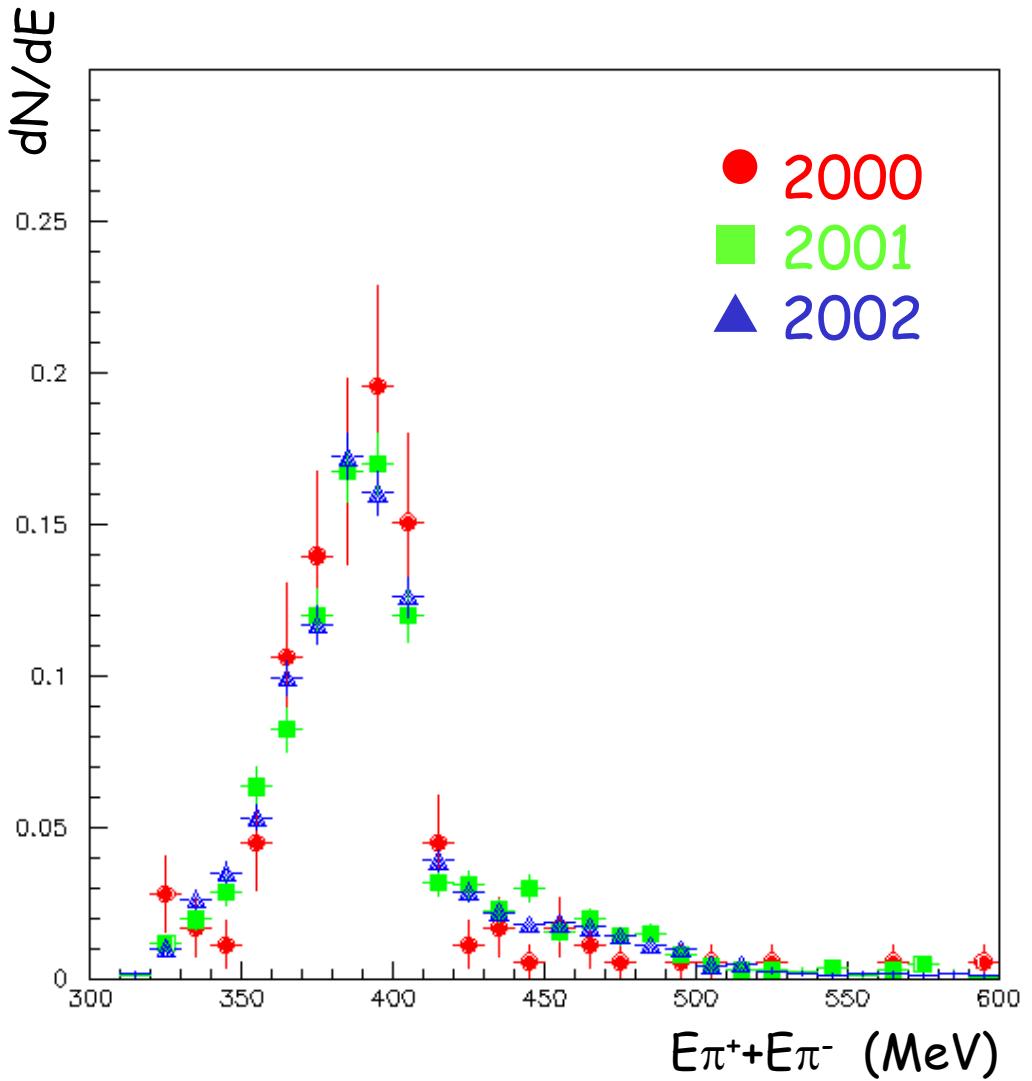




$\phi \rightarrow \eta' \gamma / \phi \rightarrow \eta \gamma$



# $\phi \rightarrow \eta' \gamma \rightarrow \pi^+ \pi^- \gamma \gamma$



preliminary, 2000 data:  $\text{Br}(\phi \rightarrow \eta' \gamma) = (7.05 \pm 0.50 \pm 0.53/-0.46) \times 10^{-5}$

$$\phi \rightarrow f_0(980) \gamma / a_0(980) \gamma$$

- The scalar mesons  $f_0(980)$ ,  $a_0(980)$  are not easily interpreted as  $qq$  states
- Jaffe(1977) suggested  $qqqq$  states
- Weinstein, Isgur (1990) suggested KK molecule
- Both BR and scalar mass spectra are sensitive to nature

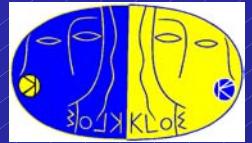
	$q\bar{q}$	$q\bar{q}q\bar{q}$	$KK$
$Br(\phi \rightarrow f_0 \gamma)$	$5 \times 10^{-5}$	$3 \times 10^{-4}$	$10^{-5}$
$Br(\phi \rightarrow a_0 \gamma)$	$2 \times 10^{-5}$	$2 \times 10^{-4}$	$10^{-5}$



# Scalar mesons ( $J^{PC} = 0^{++}$ )

- $f_0(980)$  ( $I=0$ )       $f_0 \rightarrow \pi^0\pi^0, \pi^+\pi^-$
- $a_0(980)$  ( $I=1$ )       $a_0 \rightarrow \eta\pi$

- Studied decays (data sample: 16 pb<sup>-1</sup> from the 2000 data,  $\sim 5 \times 10^7 \phi$ )  
 $\phi \rightarrow f_0\gamma$  ;  $f_0 \rightarrow \pi^0\pi^0 \Rightarrow 5\gamma$  final state  
 $\phi \rightarrow a_0\gamma$  ;  $a_0 \rightarrow \eta\pi^0$        $\eta \rightarrow \gamma\gamma$  (39%)  $\Rightarrow 5\gamma$  } Previous meas.  
 $\phi \rightarrow a_0\gamma$  ;  $a_0 \rightarrow \eta\pi^0$        $\eta \rightarrow \pi^+\pi^-\pi^0$  (23%)  $\Rightarrow 2$  ch. tracks + 5  $\gamma$  at VEPP2M
- first observation      ←



# 5 $\gamma$ final states

- |                     |  |  |
|---------------------|--|--|
|                     |  | cross sect.(nb)                          |
| • Signal:           | $\phi \rightarrow \pi^0 \pi^0 \gamma$ ( $\phi \rightarrow f_0 \gamma$ ; $\phi \rightarrow \sigma(500) \gamma$ ; $\phi \rightarrow \rho^0 \pi^0$ )<br>$\hookrightarrow \pi^0 \pi^0$ $\hookrightarrow \pi^0 \gamma$  | $\sim 0.35$                              |
|                     | $\phi \rightarrow \eta \pi^0 \gamma$ ( $\phi \rightarrow a_0 \gamma$ ; $\phi \rightarrow \rho^0 \pi^0$ )<br>$\hookrightarrow \eta \gamma$  | $\sim 0.1$                               |
| • Background:       | $e^+ e^- \rightarrow \omega \pi^0 \rightarrow \pi^0 \pi^0 \gamma$<br>$\phi \rightarrow \eta \gamma \rightarrow 3\gamma$ (with accidental $\gamma$ 's)<br>$\phi \rightarrow \eta \gamma \rightarrow \pi^0 \pi^0 \pi^0 \gamma$ (with 2 $\gamma$ lost)  | $\sim 0.5$<br>$(\sim 17)$<br>$(\sim 14)$ |
| • Sample selection: | <ul style="list-style-type: none"><li>– exactly 5 prompt photons</li><li>– <math>E_\gamma &gt; 7</math> MeV</li><li>– <math> \cos\theta  &lt; 0.93</math>    to avoid the quadrupole region</li><li>– <math>\sum_i E_i &gt; 700</math> MeV    to reject <math>\phi \rightarrow K_L K_S \rightarrow</math> neutrals</li></ul> |  |

# $\phi \rightarrow \pi^0 \pi^0 \gamma$

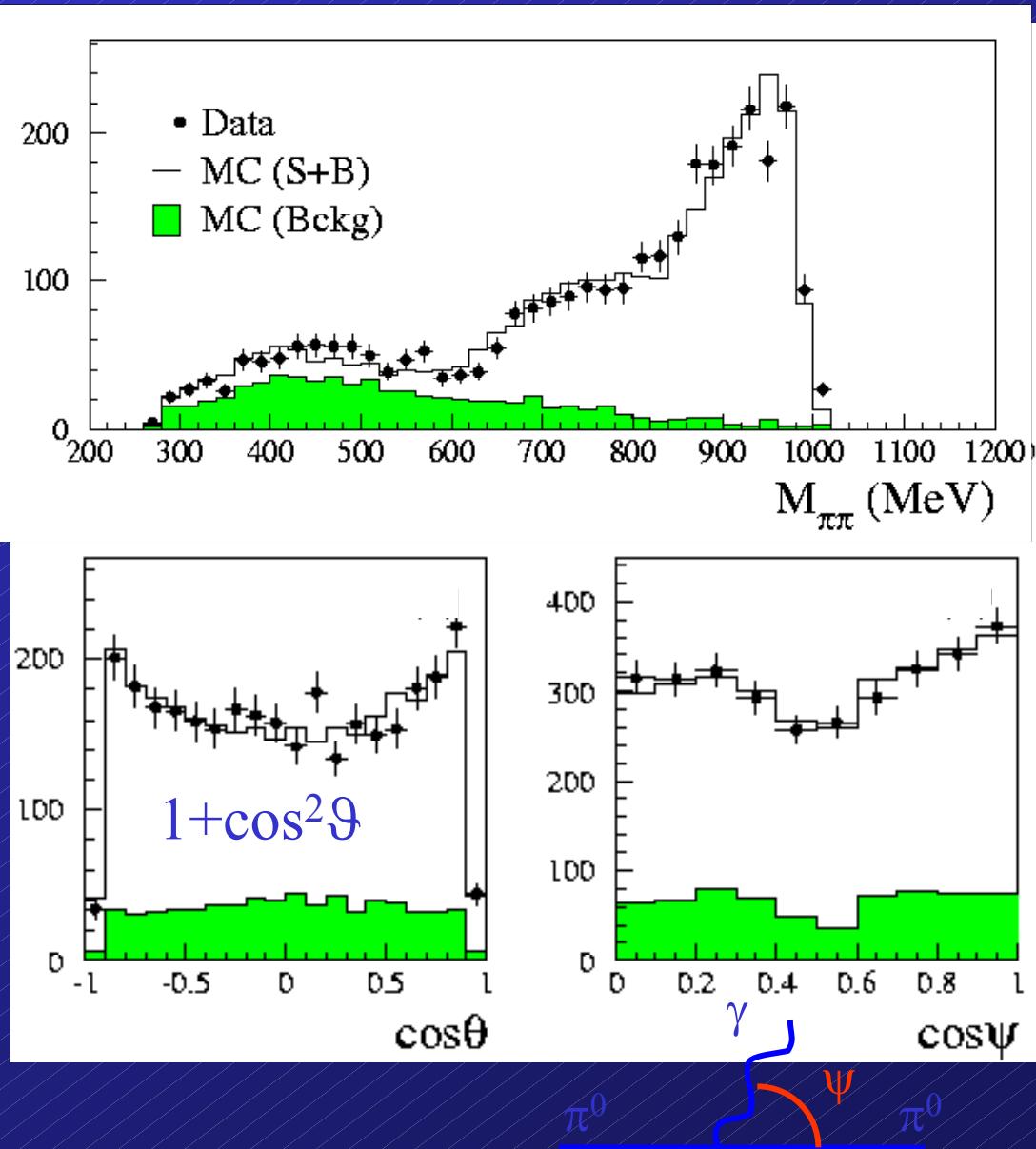


- Constrained kinematic fit to improve resolutions
- Photon pairing
- $|M_{\gamma\gamma} - M_\pi| < 5\sigma(M_\pi)$
- Reject events with:  $|M_{\pi\gamma} - M_\omega| < 3\sigma(M_\omega)$

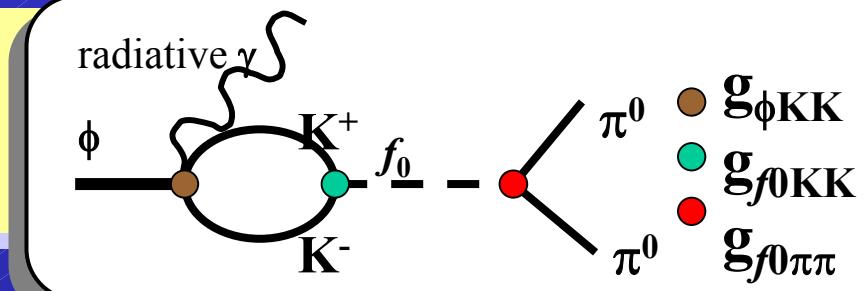
$\Rightarrow 3102$  events  
 $\langle \varepsilon \rangle = 40\%$

Estimated backgr. ( $\sim 20\%$ )

$e^+ e^- \rightarrow \omega \pi^0 \rightarrow \pi^0 \pi^0 \gamma$	$339 \pm 24$
$\phi \rightarrow \eta \pi^0 \gamma$	$166 \pm 16$
$\phi \rightarrow \eta \gamma \rightarrow \pi^0 \pi^0 \pi^0 \gamma$	$159 \pm 12$



# Fit to $M_{\pi\pi}$ spectrum



- Model :

1)  $\phi \rightarrow f_0 \gamma$  dominated by kaon loop

(Achasov-Ivanchenko, Nucl.Phys.B315(1989))

2)  $f_0$  propagator with finite width corrections

3)  $\sigma(500) \Rightarrow$  B-W with  $M_\sigma = 478$  MeV and  $\Gamma_\sigma = 324$  MeV

(Fermilab E791-Phys.Rev.Lett.86(2001)770)

4) point-like coupling of  $\sigma(500)$  to  $\phi$

(Gokalp,Yilmaz,Phys.Rev.D64(2001))

5)  $\rho\pi$  + interference term parameterizations  
from Achasov-Gubin, (Phys.Rev.D63(2001))

- Two fits:

Fit A :  $|(\phi \rightarrow f_0 \gamma) + (\phi \rightarrow \rho^0 \pi^0)|^2$

Fit B :  $|(\phi \rightarrow f_0 \gamma) + (\phi \rightarrow \sigma \gamma) + (\phi \rightarrow \rho^0 \pi^0)|^2$

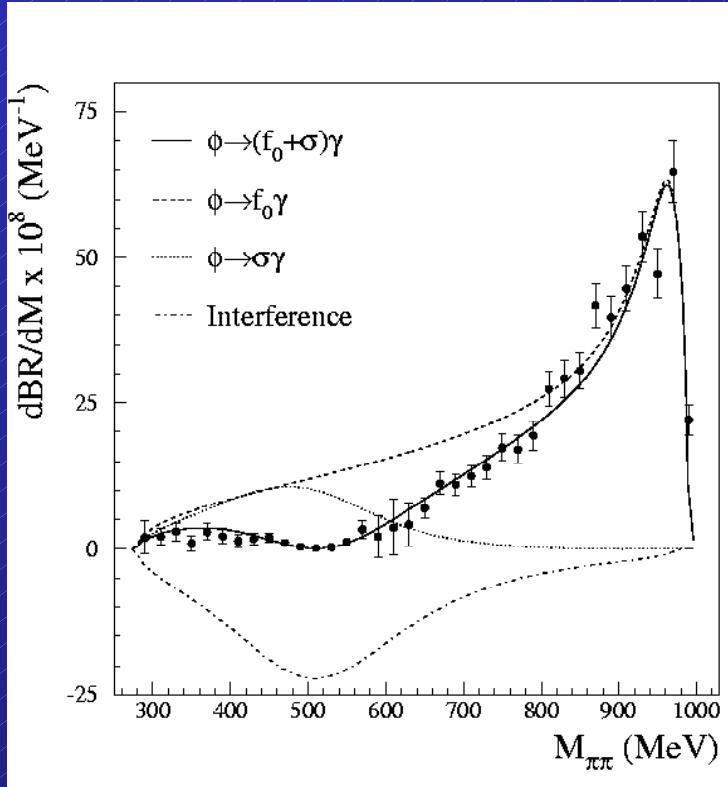
Free parameters:  $M_{f0}$ ,  $g_{f0KK}^2$ ,  $g_{f0\pi\pi}^2/g_{f0KK}^2$ ,  $g_{\phi\sigma\gamma}$  and  $(g_{\phi\rho\pi}g_{\rho\pi\gamma})^2$



# Fit results

	A	B
$\chi^2/\text{ndf}$	<b>109.5/33</b>	<b>43.2/32</b>
$M_{f_0}$ (MeV)	$962 \pm 4$	$973 \pm 1$
$g^2_{f_0\text{KK}}/(4\pi)$ (GeV $^2$ )	$1.29 \pm 0.14$	$2.79 \pm 0.12$
$g^2_{f_0\text{KK}}/g^2_{f_0\pi\pi}$	$3.22 \pm 0.29$	$4.00 \pm 0.14$
$g_{\phi\sigma\gamma}$	—	$0.060 \pm 0.008$

(  $\rho\pi$  contribution negligible )



$$\text{Br}(\phi \rightarrow \pi^0 \pi^0 \gamma) = (1.09 \pm 0.03 \pm 0.05) \times 10^{-4} \text{ (Fit B)}$$

(SND:  $(1.22 \pm 0.18 \pm 0.18 \pm 0.18) \times 10^{-4}$ )

$\Rightarrow$  Large  $\text{Br}(\phi \rightarrow f_0 \gamma) = (4.47 \pm 0.21) \times 10^{-4}$  for  $M_{\pi\pi} < 700 \text{ MeV}$

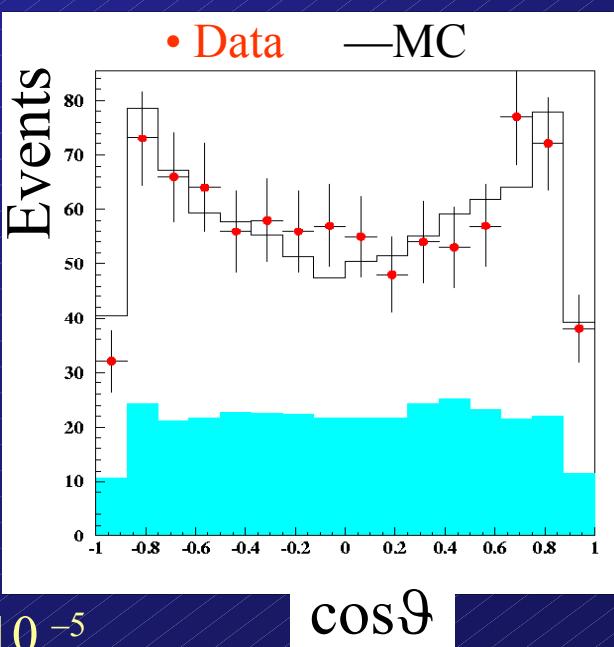
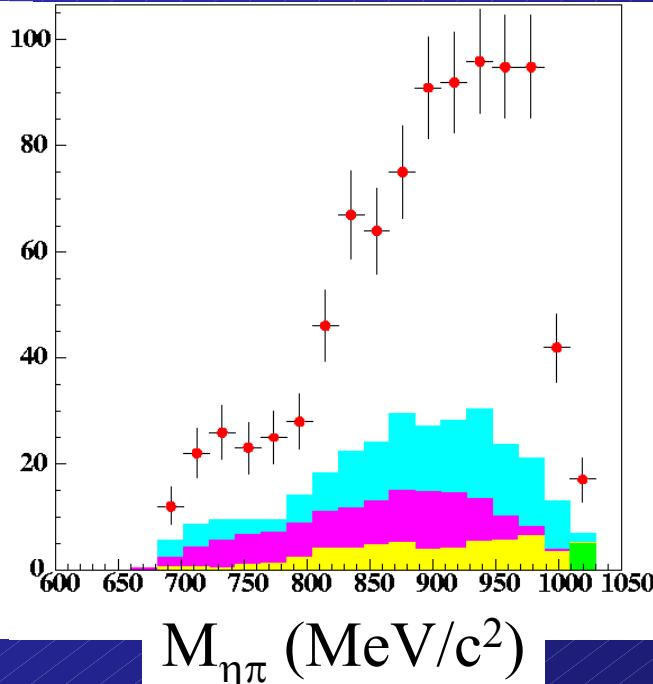
# $\phi \rightarrow \eta \pi^0 \gamma$ (with $\eta \rightarrow \gamma\gamma$ )

- Constrained kinematic fit to improve resolutions
  - Photon pairing: (1)  $\pi^0 \pi^0 \gamma$ ; (2)  $\eta \pi^0 \gamma$   
⇒ reject  $\pi^0 \pi^0 \gamma$  events
  - $M_{\pi\pi} < 760$  MeV (reject  $f_0 \gamma$  events)
  - $|M_{\gamma\gamma} - M_\eta| < 3\sigma(M_\eta)$   
⇒ 916 events
- $\langle \varepsilon \rangle = 32\%$

• Estimated backgr.: (~30%)	
$e^+ e^- \rightarrow \omega \pi^0 \rightarrow \pi^0 \pi^0 \gamma$	$54 \pm 6$
$\phi \rightarrow \pi^0 \pi^0 \gamma$	$152 \pm 16$
$\phi \rightarrow \eta \gamma \rightarrow \pi^0 \pi^0 \pi^0 \gamma$	$98 \pm 10$
$\phi \rightarrow \eta \gamma \rightarrow \gamma \gamma \gamma$	$5 \pm 2$

$$\text{Br}(\phi \rightarrow \eta \pi^0 \gamma) = (8.51 \pm 0.51 \pm 0.57) \times 10^{-5}$$

SND :  $(8.8 \pm 1.4 \pm 0.9) \times 10^{-5}$ ; CMD-2:  $(9.0 \pm 2.4 \pm 1.0) \times 10^{-5}$



$$\phi \rightarrow \eta \pi^0 \gamma \rightarrow \pi^+ \pi^- + 5\gamma \quad (\eta \rightarrow \pi^+ \pi^- \pi^0)$$



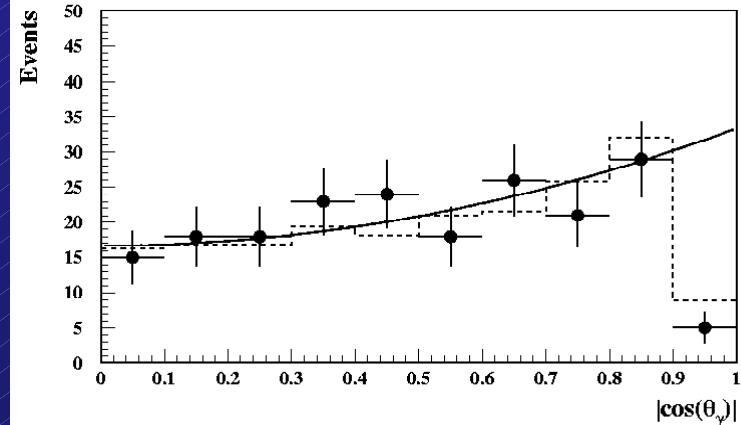
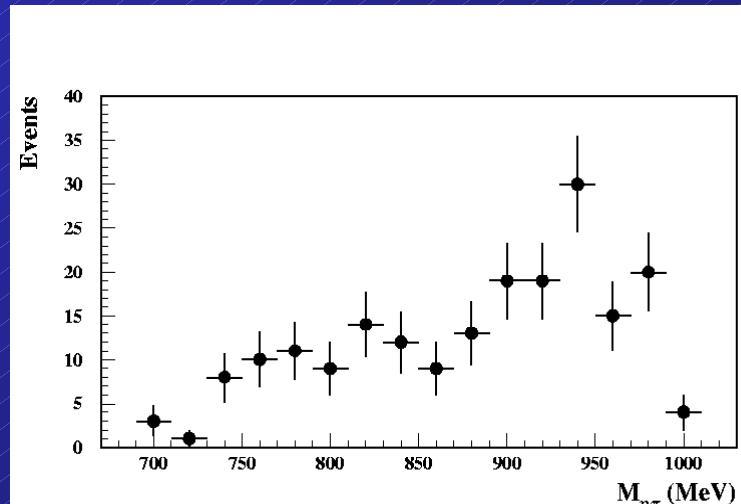
- No background with the same final state
- Backgr.: 2 Tracks + 3/4 photons ( $e^+e^- \rightarrow \omega \pi^0 ; \omega \rightarrow \pi^+ \pi^- \pi^0$ )  
( $\phi \rightarrow \eta \gamma ; \eta \rightarrow \pi^+ \pi^- \pi^0$ )

**2 Tracks + 6 photons**  
( $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0$ )

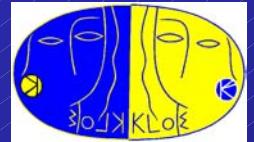
- 1 vertex in IR with 2 tracks
- 5 prompt  $\gamma$  ( $E > 10$  MeV,  $|\cos\theta| < 0.93$ )
- Constrained kinematic fit
- $M_{\pi^+ \pi^-} < 425$  MeV (reject  $K_S \rightarrow \pi^+ \pi^-$ )

$\Rightarrow 197$  events       $\langle \varepsilon \rangle = 19\%$   
estimated backgr.  $4 \pm 4$  events

$$Br(\phi \rightarrow \eta \pi^0 \gamma) = (7.96 \pm 0.60 \pm 0.47) \times 10^{-5}$$



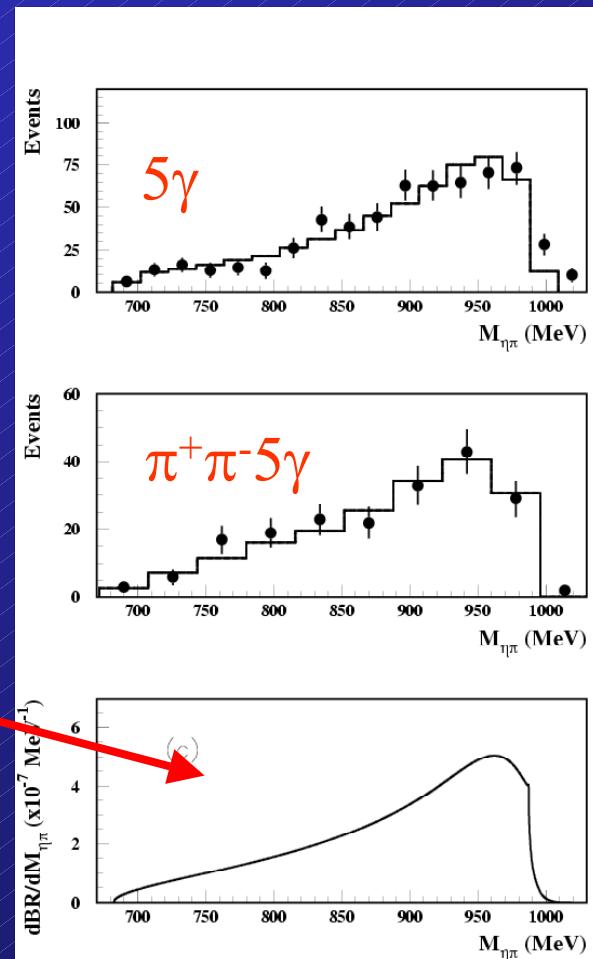
# Fit to $M_{\eta\pi}$ spectrum



- Same model as for the  $f_0$  (kaon loop)
- Combined fit, relative normalization fixed to  $\text{Br}(\eta \rightarrow \gamma\gamma)/\text{Br}(\eta \rightarrow \pi^+\pi^-\pi^0)$
- Free parameters:  
 $g_{a0\text{KK}}^2$ ,  $g_{a0\pi\pi}/g_{a0\text{KK}}$  and  $\text{Br}(\phi \rightarrow \rho^0\pi^0 \rightarrow \eta\pi^0\gamma)$   
 $M_{a0}=984.8$  MeV (PDG) fixed

$\chi^2/\text{ndf}$	27.2/25
$g_{a0\text{KK}}^2/(4\pi)$ (GeV $^2$ )	$0.40 \pm 0.04$
$g_{a0\eta\pi}/g_{a0\text{KK}}$	$1.35 \pm 0.09$
$\text{Br}(\phi \rightarrow \rho^0\pi^0 \rightarrow \eta\pi^0\gamma)$	$(0.5 \pm 0.5) \times 10^{-5}$

$$\text{Br}(\phi \rightarrow a_0\gamma \rightarrow \eta\pi^0\gamma) = (7.4 \pm 0.7) \times 10^{-5}$$



# Summary of fit results



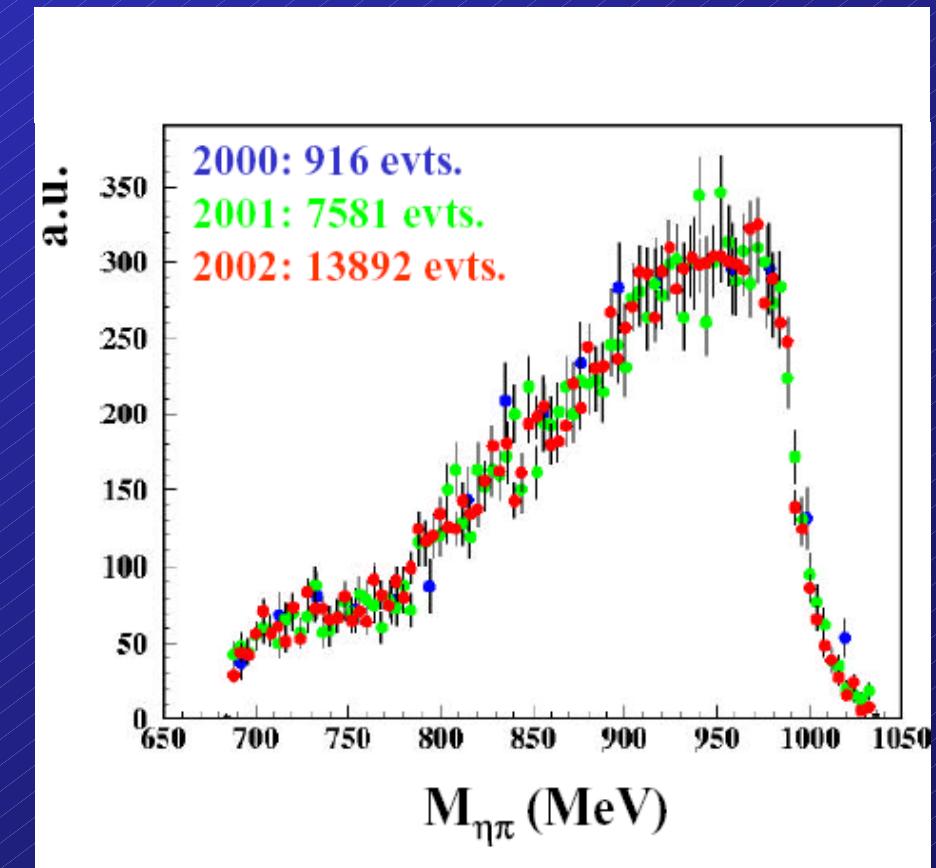
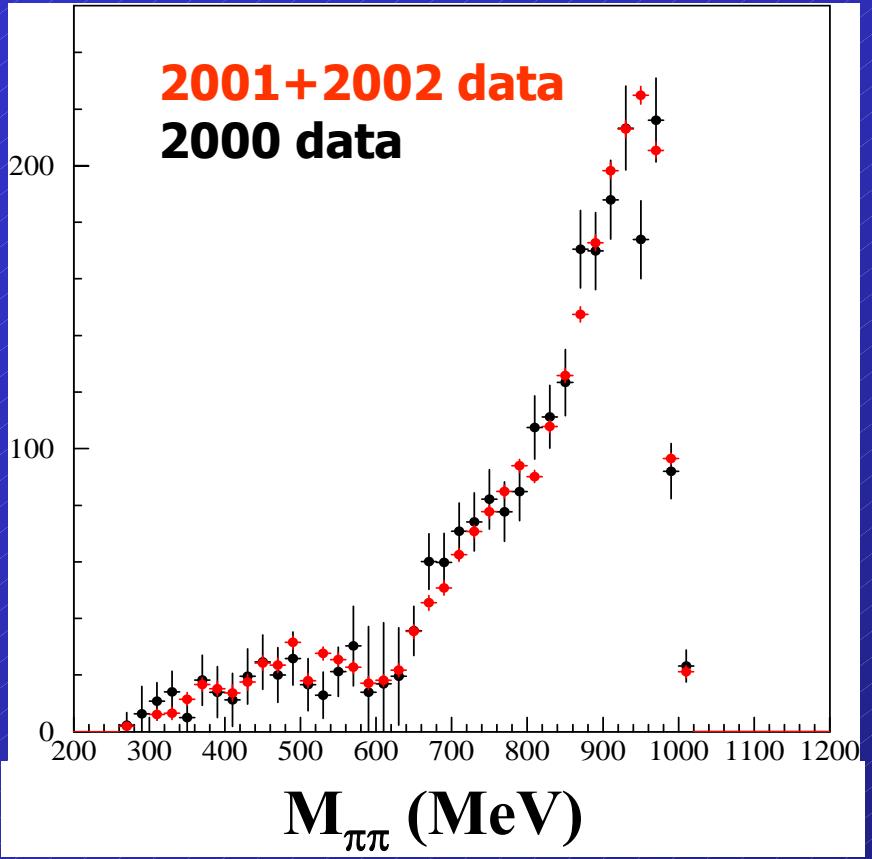
- Comparison with predictions from Achasov-Ivanchenko, Nucl.Phys.B315(1989)

$f_0$ model	KLOE	$s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$s\bar{s}$
$g_{f0KK}^2/(4\pi)$ (GeV $^2$ )	$2.79 \pm 0.12$	2.3 $(=g_{a0KK}^2/4\pi)$	0.15 $(=g_{a0KK}^2/4\pi)$	0.3 $(=2g_{a0KK}^2/4\pi)$
$g_{f0\pi\pi}/g_{f0KK}$	$0.50 \pm 0.01$	0.3—0.5	2	0.5
$\text{Br}(\phi \rightarrow \pi^0 \pi^0 \gamma) \times 10^4$	$1.09 \pm 0.07$	$\sim 1$	$\sim 0.15$	$\sim 0.2$

$a_0$ model		$s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$	$(u\bar{u} - d\bar{d})/\sqrt{2}$
$g_{a0KK}^2/(4\pi)$ (GeV $^2$ )	$0.40 \pm 0.04$	2.3 $(=g_{f0KK}^2/4\pi)$	0.15 $(=g_{f0KK}^2/4\pi)$
$g_{a0\eta\pi}/g_{a0KK}$	$1.35 \pm 0.09$	0.91	1.53
$\text{Br}(\phi \rightarrow a_0 \gamma) \times 10^4$	$0.74 \pm 0.07$	$\sim 2$	$\sim 0.2$

- $f_0$  parameters are compatible with  $q\bar{q}q\bar{q}$  model
- $a_0$  parameters seem not compatible with  $q\bar{q}q\bar{q}$  model

# $\phi \rightarrow f_0(980) \gamma / a_0(980) \gamma$



# Conclusions

- First KLOE papers on  $\phi$  radiative decays published using 2000 events:

Measurement of  $\text{Br}(\phi \rightarrow \eta' \gamma)$  and of  $\varphi_P$ ,  $\eta' - \eta$  mixing angle  
in the quark flavor basis

Measurement of  $\text{Br}(\phi \rightarrow \pi^0 \pi^0 \gamma)$  and  $\text{Br}(\phi \rightarrow \eta \pi^0 \gamma)$   
Couplings of  $f_0(a_0)$  to  $KK$  and to  $\pi\pi$  ( $\eta\pi$ )

- Analysis in progress on 2001+2002 events  
 $16\text{pb}^{-1}$  (2000)  $\Rightarrow 500\text{pb}^{-1}$  :  
more statistics, models with more free parameters



# Models



- Predictions from Achasov-Ivanchenko, Nucl.Phys.B315(1989)

$f_0$ model	$s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$s\bar{s}$
$g_{f0KK}^2/(4\pi)$ (GeV <sup>2</sup> )	2.3 $(=g_{a0KK}^2/4\pi)$	0.15 $(=g_{a0KK}^2/4\pi)$	0.3 $(=2g_{a0KK}^2/4\pi)$
$g_{f0\pi\pi}/g_{f0KK}$	0.3—0.5	2	0.5
$\text{Br}(\phi \rightarrow \pi^0 \pi^0 \gamma) \times 10^4$	$\sim 1$	$\sim 0.15$	$\sim 0.2$

$a_0$ model	$s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$	$(u\bar{u} - d\bar{d})/\sqrt{2}$
$g_{a0KK}^2/(4\pi)$ (GeV <sup>2</sup> )	2.3 $(=g_{f0KK}^2/4\pi)$	0.15 $(=g_{f0KK}^2/4\pi)$
$g_{a0\eta\pi}/g_{a0KK}$	0.91	1.53
$\text{Br}(\phi \rightarrow a_0 \gamma) \times 10^4$	$\sim 2$	$\sim 0.2$

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==== Author : KLOE Collab. (Speaker: Camilla Di Donato) Type : Experimental Measurement of the Phi meson radiative decays into scalars and pseudoscalars mesons.

The Kloe experiment has measured the radiative decays of the Phi meson into pi0, eta and eta'(958); these measurements are relevant to assess the mixing in the pseudoscalar nonet as well as to evaluate the gluon content in the eta'(958). Moreover also the radiative decays into pi0 pi0 gamma and eta pi0 gamma have been measured. These decays are dominated by the final states f0(980) and a0(980). The measurement of the branching ratios and of the pi0-pi0 or eta-pi0 invariant mass spectrum helps to understand the controversial nature of the above scalar mesons.

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