

KLOE Results on ϕ Radiative Decays

The KLOE Collaboration
presented by
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- ✓ DAFNE and KLOE
- ✓ The pseudoscalar decays: $\phi \rightarrow \eta\gamma / \eta'$
- ✓ The scalar decays: $\phi \rightarrow \pi\pi\gamma / \eta\pi\gamma$
- ✓ Conclusions

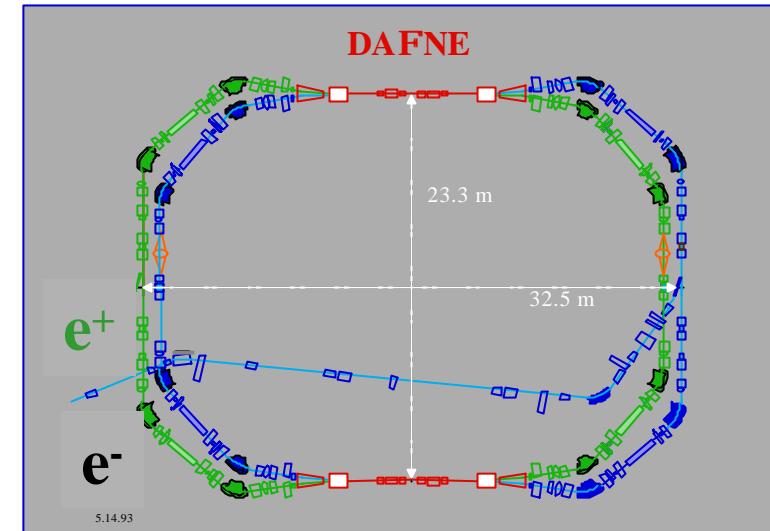
VI International Conference on Particles and Nuclei
Osaka, 30 September – 4 October, 2002

DAFNE: the Frascati ϕ -factory

e^+e^- collider @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$

$\sigma_{\text{peak}} \approx 3 \mu\text{b}$

	DESIGN	TODAY
Number of bunches :	120	51
Bunch spacing :	2.7 ns	5.4 ns
Bunch current :	40 mA	20 mA
Peak luminosity:	$5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	$7.5 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$



1999 run : 2.5 pb^{-1}

machine and detector studies

2000 run : 25 pb^{-1} ($7.5 \times 10^7 \phi$)

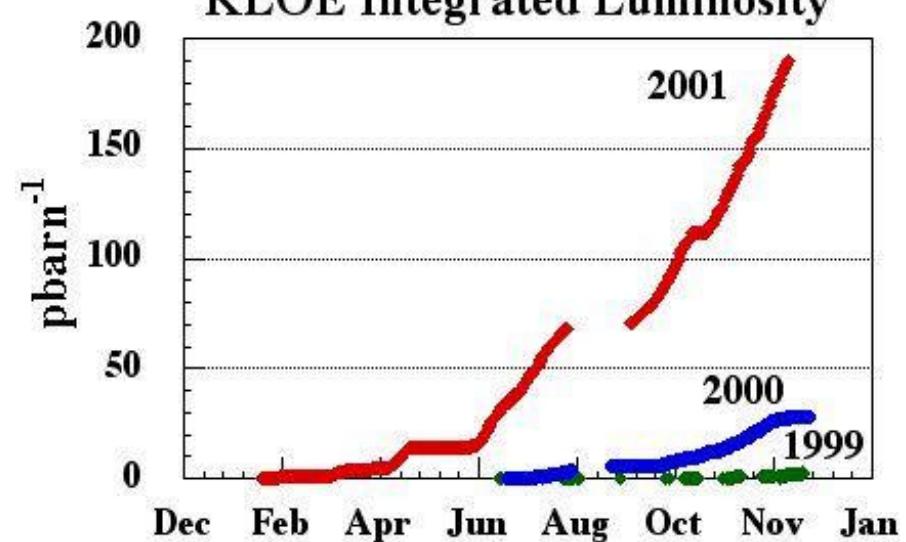
published results

2001 run: 190 pb^{-1} ($5.7 \times 10^8 \phi$)

analysis in progress

2002 run in progress: $\sim 300 \text{ pb}^{-1}$

integrated from May up to now



The KLOE experiment

ϕ decays:	K^+K^-	49.1%
	$K_L K_S$	34.3%
	$\rho\pi$	15.4%
	$\eta\gamma$	1.3%

The KLOE design was driven by the measurement of direct CP violation through the double ratio:

$$R = \Gamma(K_L \rightarrow \pi^+\pi^-) \Gamma(K_S \rightarrow \pi^0\pi^0) / \Gamma(K_S \rightarrow \pi^+\pi^-) \Gamma(K_L \rightarrow \pi^0\pi^0)$$

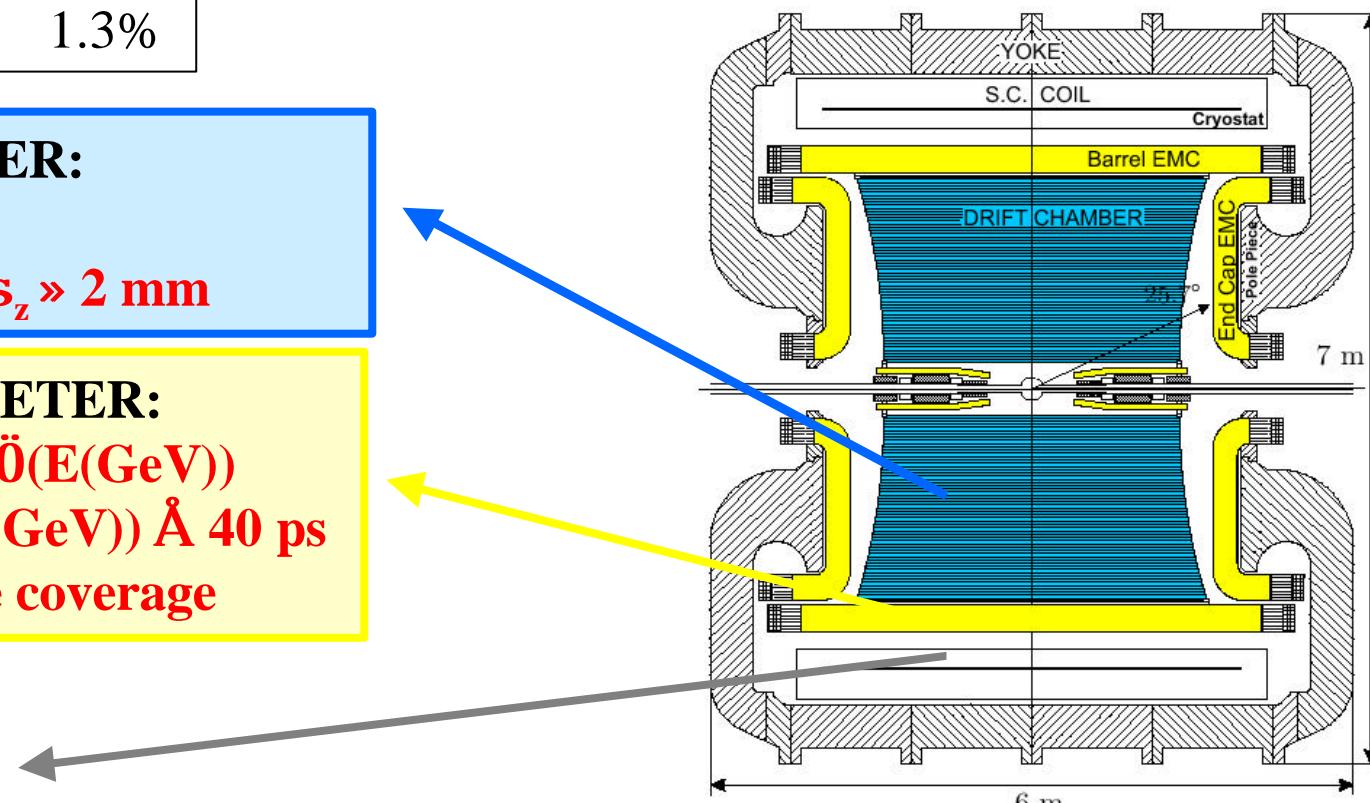
DRIFT CHAMBER:

- $d p_t / p_t < 0.4\%$
- $S_{xy} \gg 150 \text{ mm}; S_z \gg 2 \text{ mm}$

E.M. CALORIMETER:

- $S_E / E = 5.4\% / \tilde{\sigma}(E(\text{GeV}))$
- $S_t = 55 \text{ ps} / \tilde{\sigma}(E(\text{GeV})) \Delta 40 \text{ ps}$
- 98% solid angle coverage

Magnetic field:
 $B = 0.52 \text{ T}$



ϕ radiative decays

Channel	BR (PDG2002)	
$\eta\gamma$	1.30×10^{-2}	
$\pi^0\gamma$	1.24×10^{-3}	$\phi \rightarrow P(0^{-+})\gamma$
$\eta'\gamma$	$\sim 10^{-4}$	
$\pi\pi\gamma$	$\sim 10^{-4}$	
$\eta\pi^0\gamma$	$\sim 10^{-4}$	$\phi \rightarrow S(0^{++})\gamma ; S \rightarrow \pi\pi / \eta\pi$

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

$\phi \xrightarrow{\text{R}} \pi^0\pi^0\gamma$

Phys.Lett. **B 537** (2002), 21

$\phi \xrightarrow{\text{R}} \eta\pi^0\gamma$

Phys.Lett. **B 536** (2002), 209

$\phi \xrightarrow{\text{R}} \eta\phi / \eta\gamma$

Phys.Lett. **B 541** (2002), 45

$\phi \circledR \eta\gamma / \eta\psi$

- ❖ The mass eigenstates η , η' are related to the SU(3) octet-singlet η_8 , η_1 through the mixing angle ϑ_p
- ❖ Recent studies based on χ 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 (j_p)

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

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

$$R = \frac{\text{BR}(f \rightarrow \zeta' \bar{a})}{\text{BR}(f \rightarrow \zeta \bar{a})} = \cot^2 j_p \left(1 - \frac{m_s}{\bar{m}} \frac{\tan j_v}{\sin 2 j_p} \right)^2 \left(\frac{p_{\zeta'}}{p_\zeta} \right)^3 ; \left(\frac{m_s}{\bar{m}} = 1.45 \right)$$

➤ j_p can probe the gluon content of $\eta\zeta$

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

Used decay chains:

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

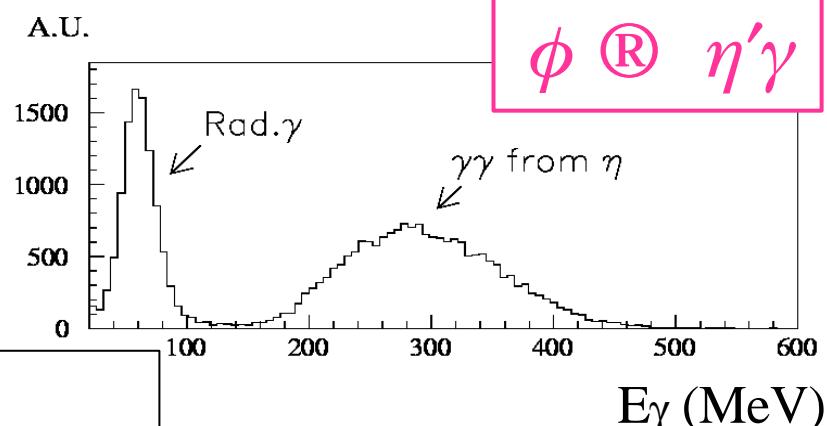
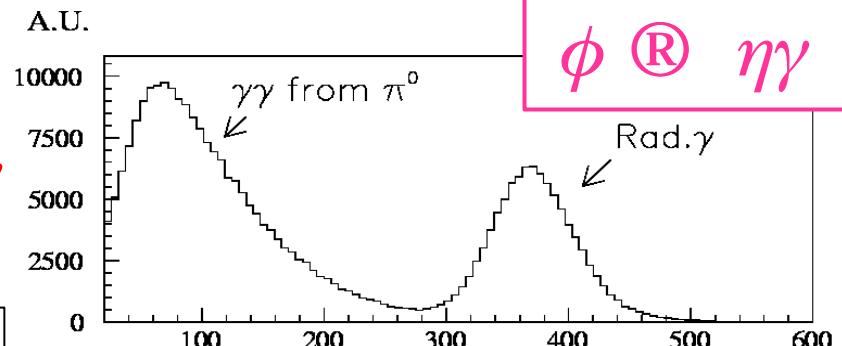
Same topology: **two tracks + three photons**

Different kinematics in the final state

Background from $\phi \rightarrow \pi^+\pi^-\pi^0$ and $\phi \rightarrow K_S K_L$

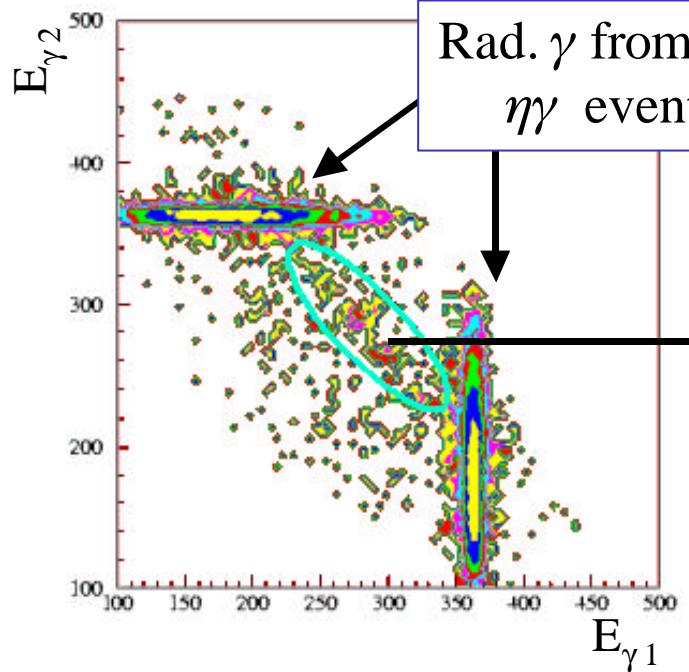
Analysis cuts:

- 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 loose χ^2 cut
- 4) Topological cuts on the energy of the particles



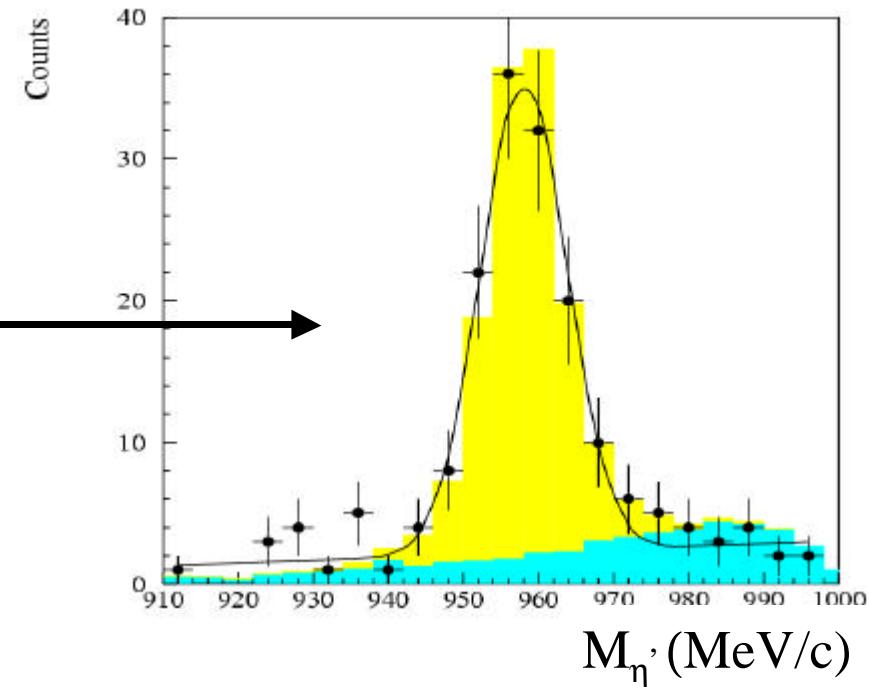
$$\begin{aligned}\epsilon_{\text{tot}}(\eta\gamma) &= 36.5\% \\ \epsilon_{\text{tot}}(\eta'\gamma) &= 22.8\%\end{aligned}$$

Results on $\phi \rightarrow \eta\gamma / \eta\psi$



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

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



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

- Using the PDG value for $\text{BR}(\phi \rightarrow \eta\gamma)$: $\text{BR}(\phi \rightarrow \eta\psi) = (6.10 \pm 0.61_{\text{stat}} \pm 0.43_{\text{syst}}) \cdot 10^{-5}$
- Pseudoscalar mixing angle: $\mathbf{J}_p = (41.8^{+1.9}_{-1.6})^\circ$ (flavor) $\mathbf{J}_P = (-12.9^{+1.9}_{-1.6})^\circ$ (octet-singlet)

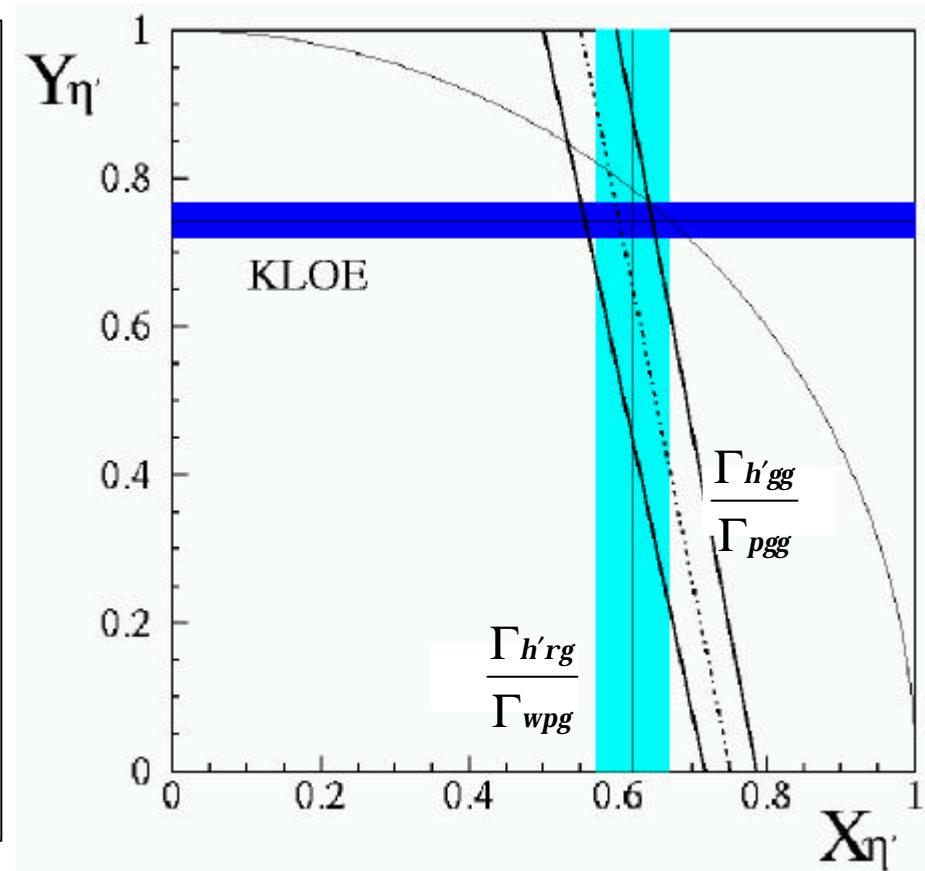
Gluon content of $\eta\zeta$

Combined analysis to evaluate the possible gluon content of η'

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

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

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



Minimizing the related χ^2 function:

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

Gluon content of $\eta\zeta$ lower than 15%

$\phi \rightarrow \eta\psi \rightarrow \pi^+\pi^-7g$

KLOE Preliminary

Two contributions:

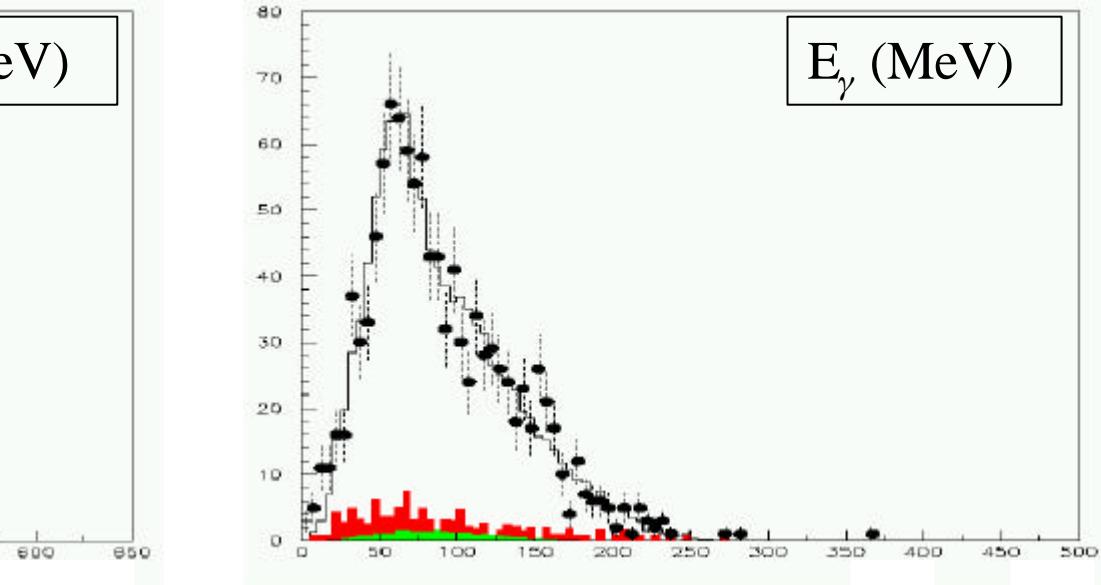
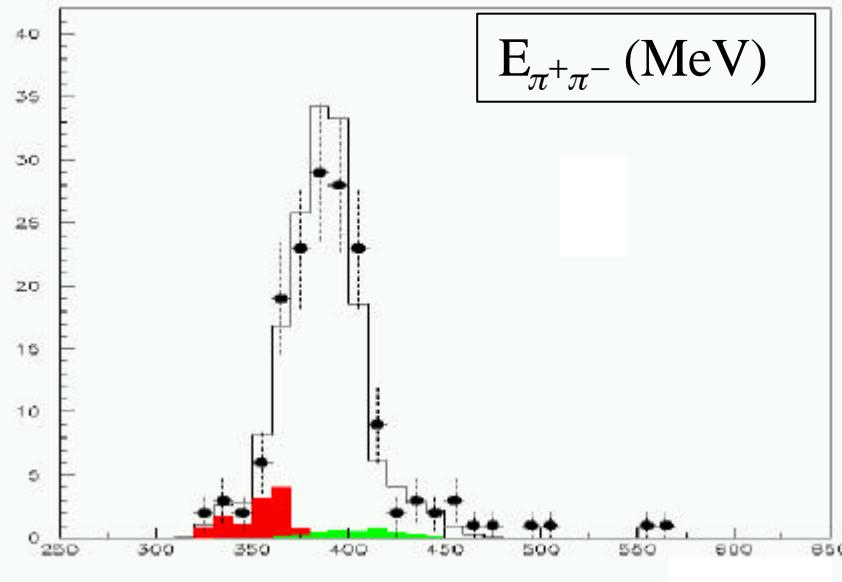
- $\eta' \rightarrow \eta\pi^+\pi^-$
 $\downarrow \pi^0\pi^0\pi^0$
- $\eta' \rightarrow \eta\pi^0\pi^0$
 $\downarrow \pi^+\pi^-\pi^0$
- Bckg from $\phi \rightarrow K_SK_L$

First observation of these decays

$$N_{\pi^+\pi^-\gamma} = 155 \pm 12$$

$$BR(\phi \rightarrow \eta\psi) = (7.05 \pm 0.61^{+0.94}_{-0.97}) \cdot 10^{-5}$$

In agreement with the $\phi \rightarrow \eta'\gamma \rightarrow \pi^+\pi^-3\gamma$ analysis

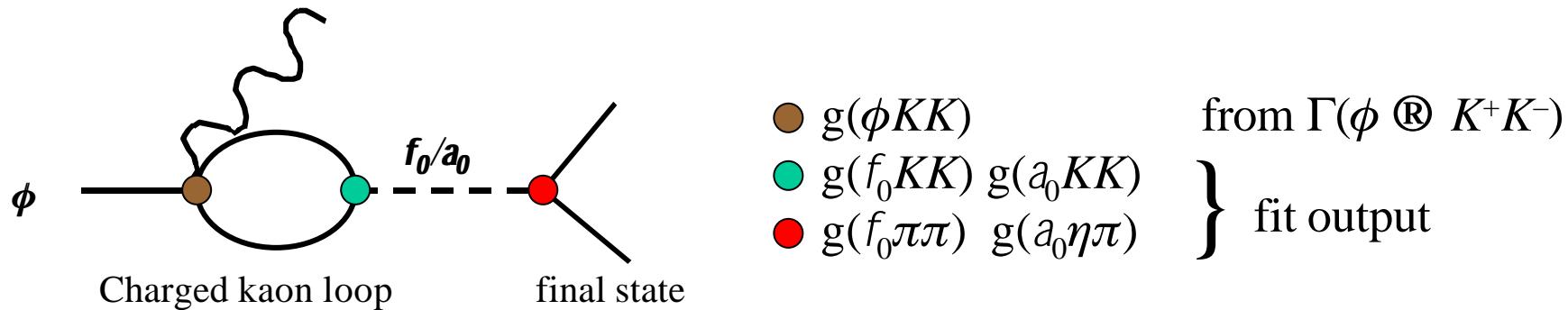


$\phi \circledR f_0(980)\gamma / a_0(980)\gamma$

- ❖ $f_0(980)$ and $a_0(980)$ scalar mesons **not easily interpreted as $q\bar{q}$ states**
- ❖ Other interpretations suggested:
 - ⇒ **$q\bar{q}q\bar{q}$ states** [Jaffe 1977]
 - ⇒ **$K\bar{K}$ molecule** [Weinstein, Isgur 1990]

Both $BR(\phi \rightarrow S\gamma)$ and scalar mass spectra are sensitive to their nature
[Achasov, Ivanchenko 1989]

Fit to the spectra using a phenomenological approach:



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

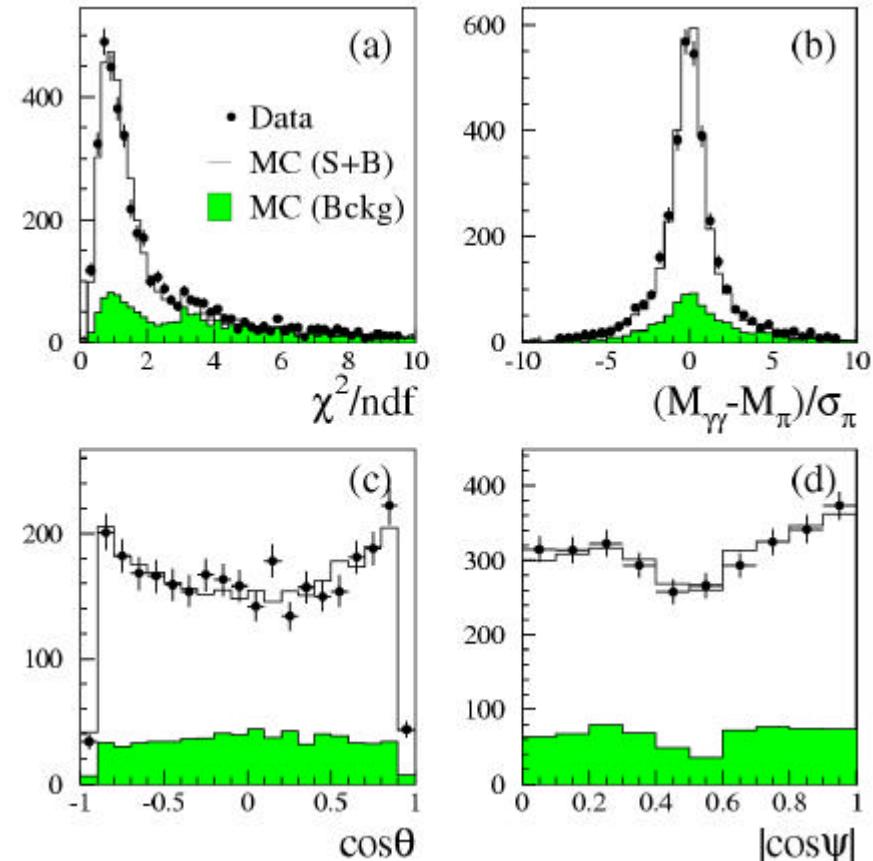
Background processes:

- $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$ (S/B=0.80)
- $\phi \rightarrow \eta\pi^0\gamma \rightarrow \gamma\gamma\pi^0\gamma$ (S/B=3.52)
- $\phi \rightarrow \eta\gamma \rightarrow \pi^0\pi^0\pi^0\gamma$ (S/B=0.03)

Analysis steps:

- 1) Five neutral clusters on time
- 2) $E_{\text{tot}} > 800 \text{ MeV}$, $|\vec{p}_{\text{tot}}| < 200 \text{ MeV}$
- 3) Kinematic fit and photon pairing
- 4) Cut on π^0 masses ($|M_{\gamma\gamma} - M_\pi| < 5\sigma(M_\pi)$)
- 5) $e^+e^- \rightarrow \omega\pi^0$ background rejection

$$N_{\pi\pi\gamma} = 2438 \pm 61$$



$$\text{BR}(\phi \rightarrow \pi^0\pi^0\gamma) = (1.09 \pm 0.03_{\text{stat}} \pm 0.05_{\text{syst}}) \times 10^{-4}$$

[CMD-2: $(0.92 \pm 0.08 \pm 0.06) \times 10^{-4}$ SND: $(1.14 \pm 0.10 \pm 0.12) \times 10^{-4}$]

$\phi \rightarrow f_0(980)\gamma \rightarrow \pi^0\pi^0\gamma$

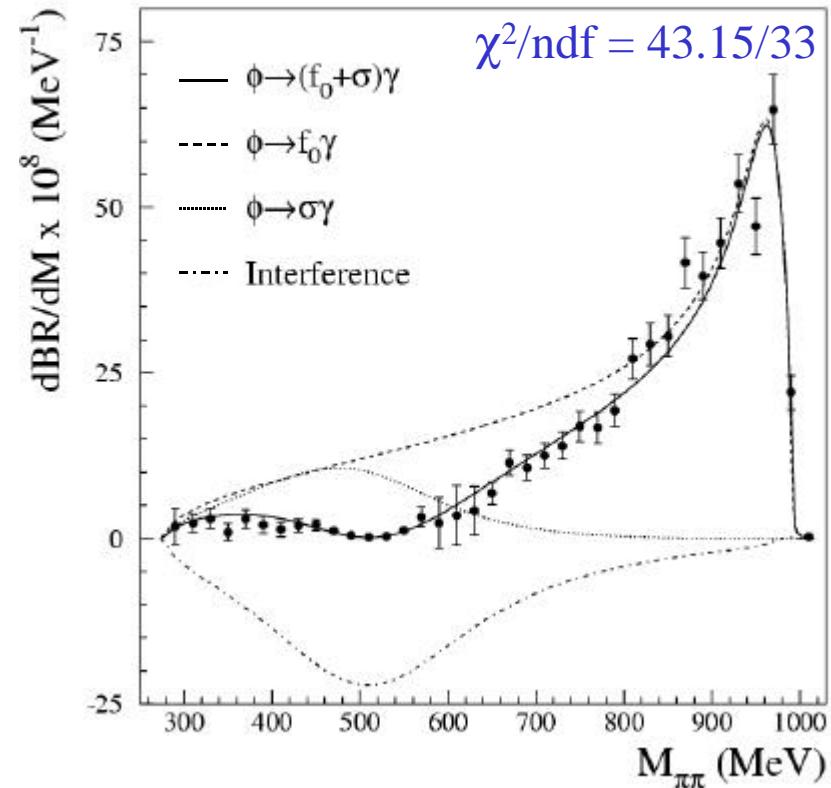
Fit to the $M_{\pi\pi}$ spectrum with:

- 1) $\phi \rightarrow f_0\gamma \rightarrow \pi^0\pi^0\gamma$
- 2) $\phi \rightarrow \sigma\gamma \rightarrow \pi^0\pi^0\gamma$
 $M_\sigma = 478 \text{ MeV}, \Gamma_\sigma = 324 \text{ MeV}$
[FNAL E791 – PRL 86 (2001)]
- 3) $\phi \rightarrow \rho^0\pi^0 \rightarrow \pi^0\pi^0\gamma$

- Strong 1), 2) negative interf.
- Negligible contribution from 3)

Fit results:

$M(f_0) = 973 \pm 1 \text{ MeV}$
$g^2(f_0 KK)/4\pi = 2.79 \pm 0.12 \text{ GeV}^2$
$g(f_0\pi\pi)/g(f_0 KK) = 0.50 \pm 0.01$
$g(\phi\sigma\gamma) = 0.060 \pm 0.008$
$\text{BR}(\phi \rightarrow f_0\gamma \rightarrow \pi^0\pi^0\gamma) = (1.49 \pm 0.07) \cdot 10^{-4}$



Fit parameters compatible
with q-q-q-q model

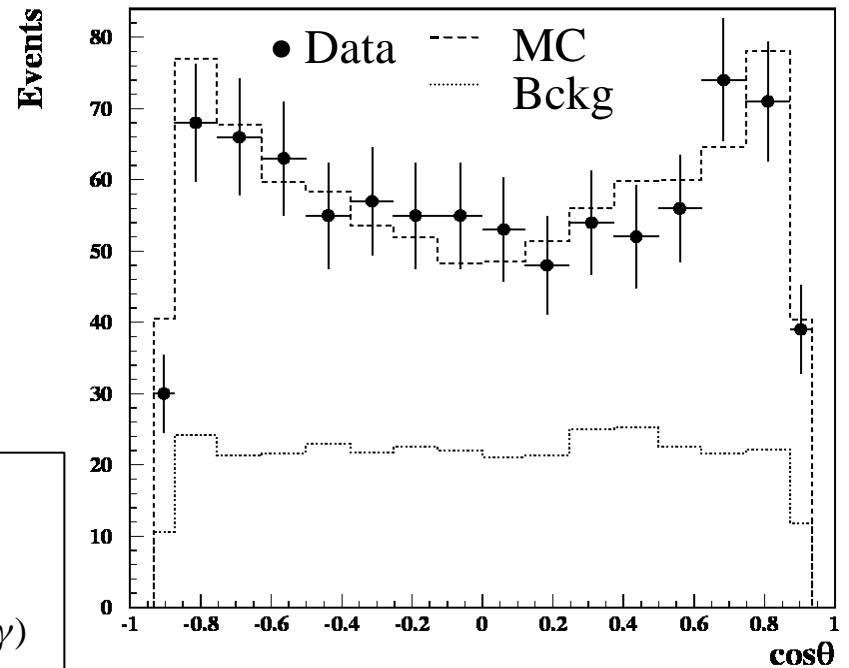
$\phi \rightarrow \eta\pi^0\gamma$

Background processes:

- $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$ (S/B=0.23)
- $\phi \rightarrow \pi^0\pi^0\gamma$ (S/B=0.29)
- $\phi \rightarrow \eta\gamma \rightarrow \gamma\gamma\gamma$ (S/B=7.0×10⁻⁴)
- $\phi \rightarrow \eta\gamma \rightarrow \pi^0\pi^0\pi^0\gamma$ (S/B= 8.6×10⁻⁴)

Analysis steps:

- 1) Five neutral clusters on time
- 2) $E_{\text{tot}} > 800$ MeV
- 3) Kinematic fit and photon pairing ($\eta\pi^0\gamma$ & $\pi^0\pi^0\gamma$)
- 4) Cut on η mass ($|M_{\gamma\gamma} - M_\eta| < 3\sigma(M_\eta)$)
- 5) $M_{\pi\pi} < 760$ MeV ($\phi \rightarrow f_0\gamma$ rejection)
- 6) $E_\gamma < 340$ MeV ($\phi \rightarrow \eta\gamma$ rejection)



$$N_{\eta\pi\gamma} = 607 \pm 36$$

$$\text{BR}(\phi \rightarrow \eta\pi^0\gamma) = (8.5 \pm 0.5_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-5}$$

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

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

First observation

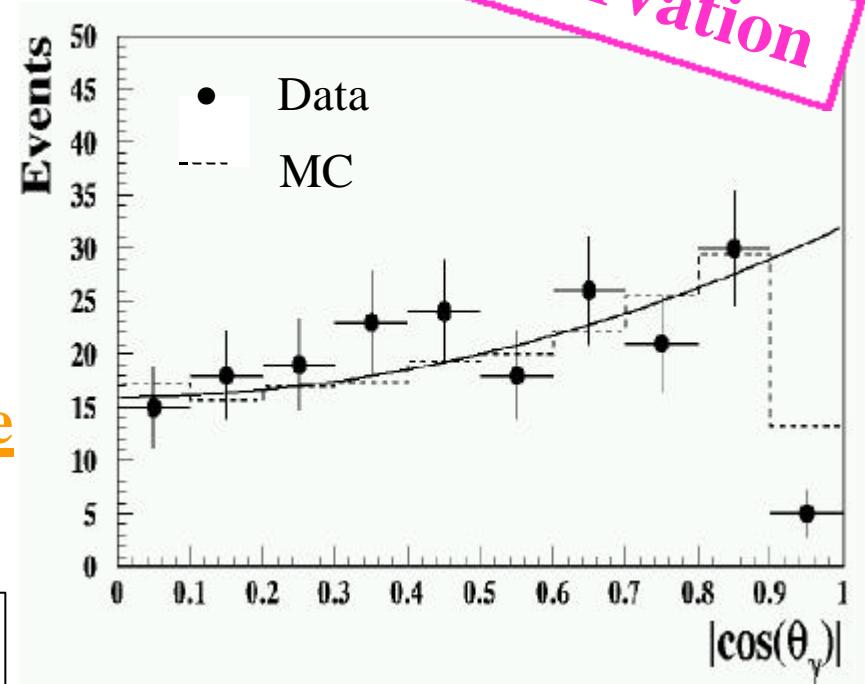
Background processes:

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

► No bckg with the same final state

Analysis steps:

- 1) Vertex in the IR with two tracks
- 2) Five neutral clusters on time
- 3) $900 < E_{\text{tot}} < 1160 \text{ MeV}$, $|\vec{p}_{\text{tot}}| < 100 \text{ MeV}$
- 4) $|\vec{p}_+| + |\vec{p}_-| < 420 \text{ MeV}$
- 5) Kinematic fit and photon pairing



$$N_{\eta\pi\gamma} = 197 \pm 14$$

$$\text{BR}(\phi \rightarrow \eta\pi^0\gamma) = (8.0 \pm 0.6_{\text{stat}} \pm 0.5_{\text{syst}}) \cdot 10^{-5}$$

[In agreement with the $\phi \rightarrow \eta\pi^0\gamma \rightarrow \gamma\gamma\pi^0\gamma$ measurement]

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

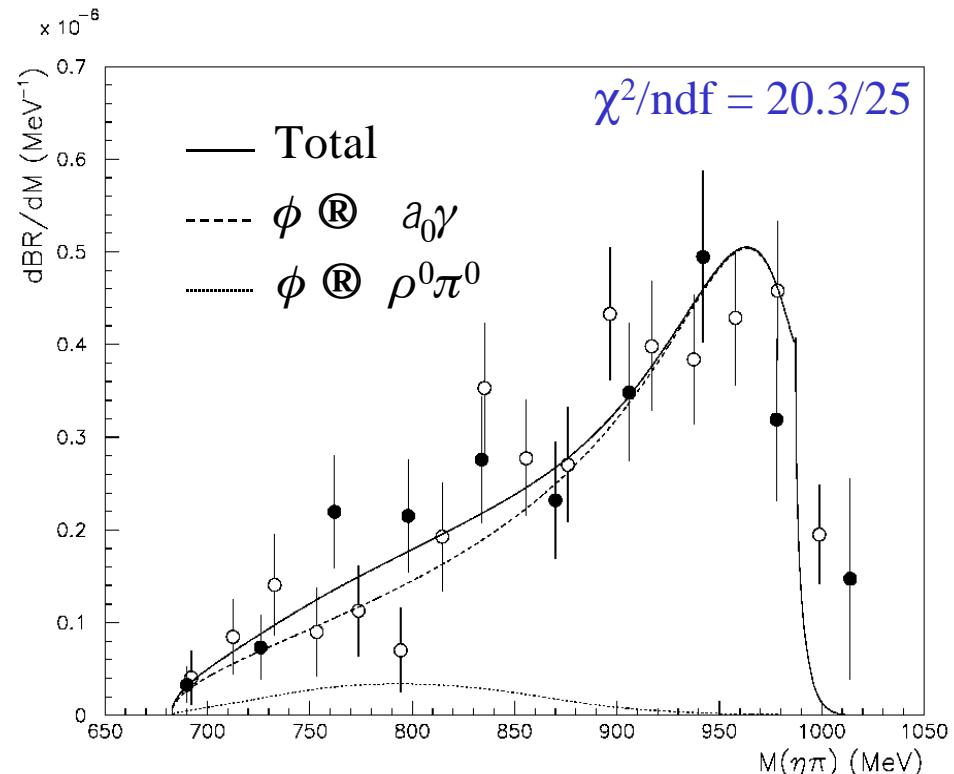
- ◆ Combined fit to the $M_{\eta\pi}$ spectrum
- ◆ Relative normalization fixed to $\text{BR}(\eta \rightarrow \gamma\gamma) / \text{BR}(\eta \rightarrow \pi^+\pi^-\pi^0)$

- 1) $\phi \rightarrow a_0\gamma \rightarrow \eta\pi^0\gamma$
- 2) $\phi \rightarrow \rho^0\pi^0 \rightarrow \eta\pi^0\gamma$

- $\phi \rightarrow a_0\gamma$ dominating
- $\phi \rightarrow \rho^0\pi^0$ negligible

Fit results:

$M(a_0) = 984.8 \text{ MeV}$	(FIXED)
$g^2(a_0 KK)/4\pi = 0.40 \pm 0.04 \text{ GeV}^2$	
$g(a_0\eta\pi)/g(a_0 KK) = 1.35 \pm 0.09$	
$\text{BR}(\phi \rightarrow a_0\gamma \rightarrow \eta\pi^0\gamma) = (7.4 \pm 0.7) \cdot 10^{-5}$	



Fit parameters not well described by $q\bar{q}q\bar{q}$ model

Conclusions and outlook

- ✓ First KLOE papers on ϕ radiative decays published using 2000 data:

Measurement of $\text{BR}(\phi \rightarrow \eta\gamma)$

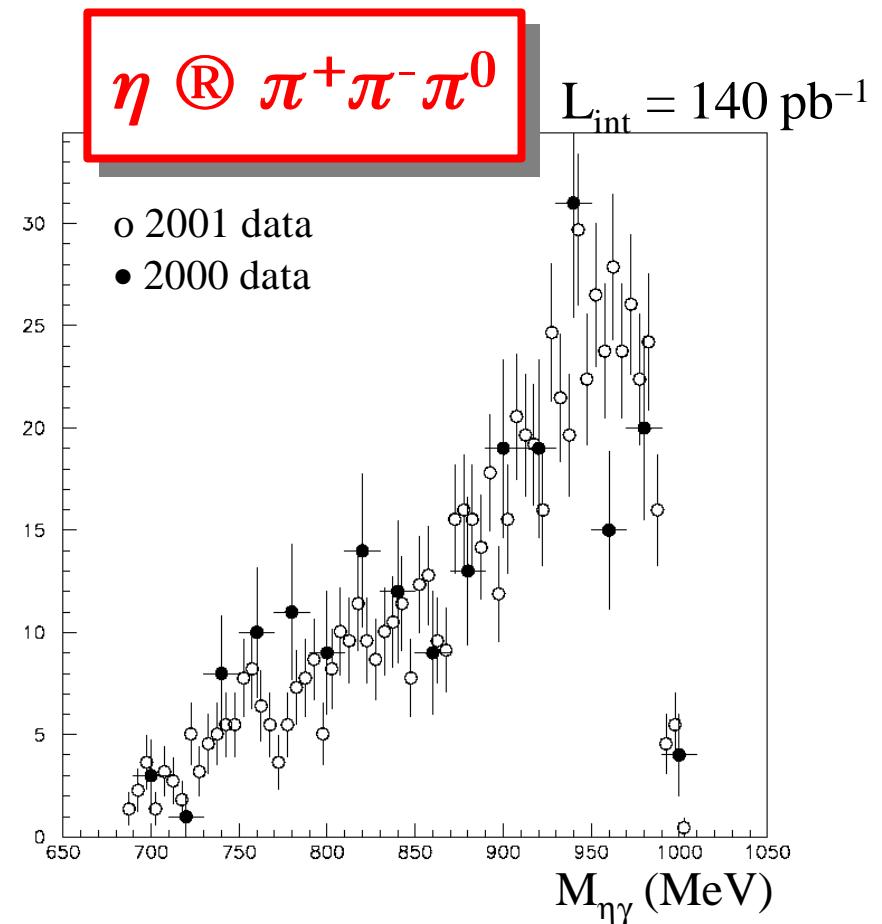
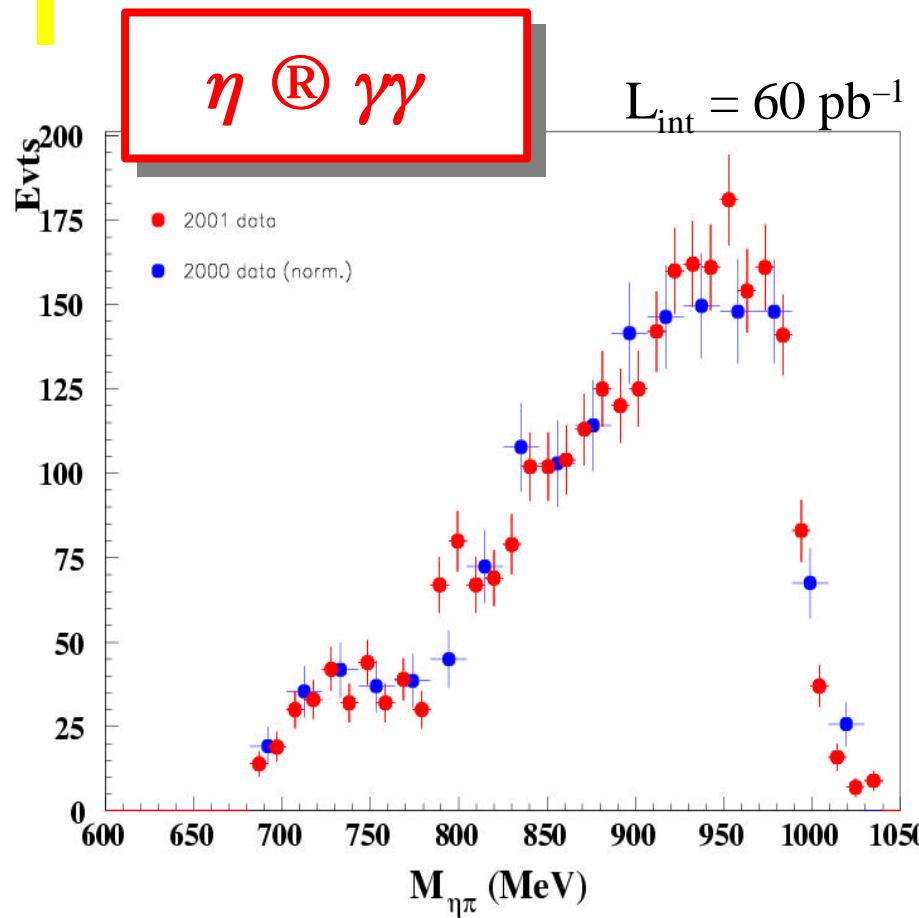
$\eta - \eta'$ mixing angle in the quark flavor basis

Measurement of $\text{BR}(\phi \rightarrow \pi^0\pi^0\gamma)$, $\text{BR}(\phi \rightarrow \eta\pi^0\gamma)$

Couplings of $f_0(a_0)$ to KK and to $\pi\pi$ ($\eta\pi$)

- ✓ Analyses in progress on the 2001 data sample with ~ 10 times more statistics and improved systematics
- ✓ Other 300 pb⁻¹ from 2002 data taking to be used

$\phi \rightarrow \eta\pi^0\gamma$ raw spectra from 2001 data



Spectra are normalized to the integrated luminosity