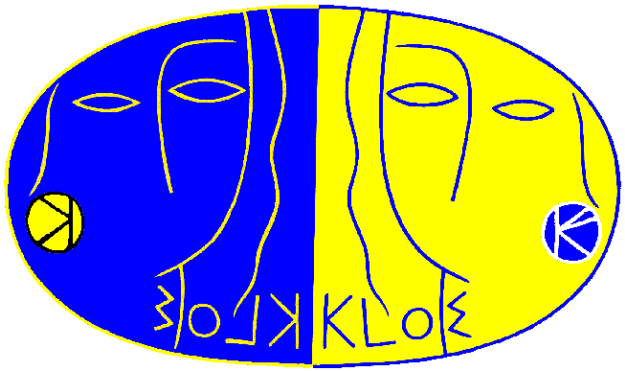
KLOE results on light meson spectroscopy



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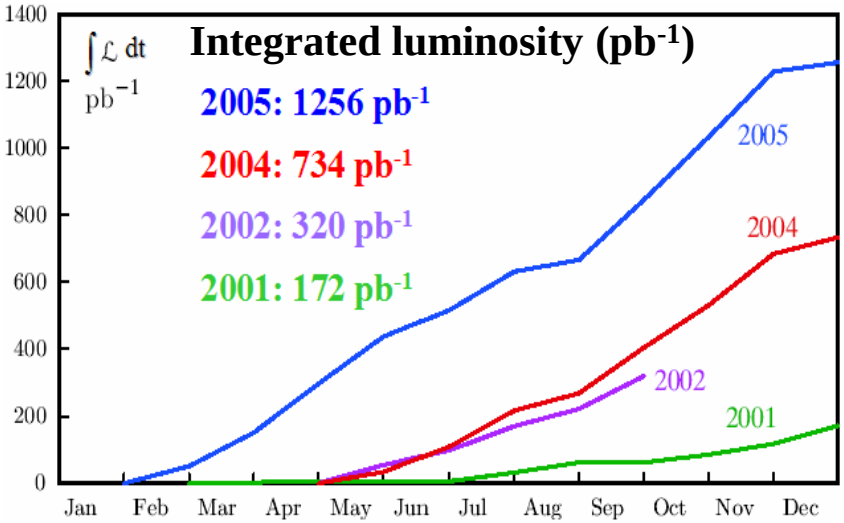
for the KLOE Collaboration

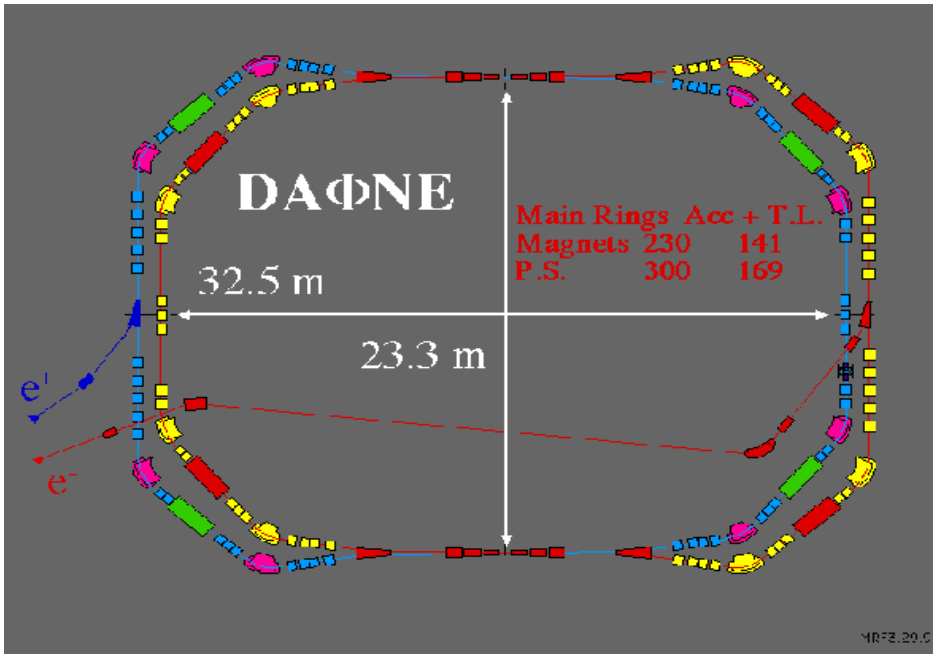
Excited QCD 09
8 -14 February 2009 – Zakopane

DAΦNE

- Frascati ϕ-factory: e^+e^- collider
  @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$; $\sigma_{peak} \approx 3.1$ μb

- Best performances in 2005:
  - $L_{peak} = 1.4 \times 10^{32}\ cm^{-1}s^{-1}$
  - $\int Ldt = 8.5\ pb^{-1}/day$





March 2006, end of KLOE data taking: 2.5 fb^{-1} on tape @ $\sqrt{s}=M_\phi$ $\Rightarrow$ 8×10^9 ϕ produced + 250 pb^{-1} off-peak (@ $\sqrt{s}$=1000 MeV + 4 energy scan points)

KLOE

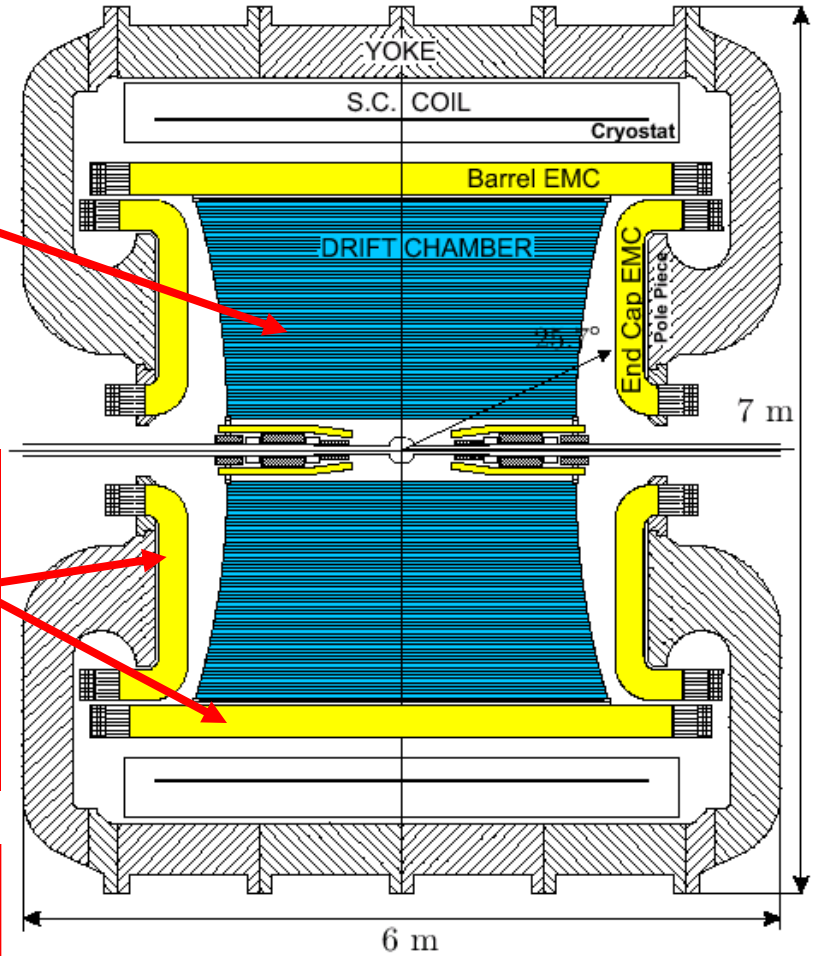
Drift chamber:

- gas: 90% He-10% iC_4H_{10}
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 1$ mm

Calorimeter (Pb-Sci.Fi.):

- $\sigma_E/E = 5.7\% / \sqrt{(E(GeV))}$
- $\sigma_t = 55\ ps/\sqrt{(E(GeV))} \oplus 100\ ps$
- 98% of 4π

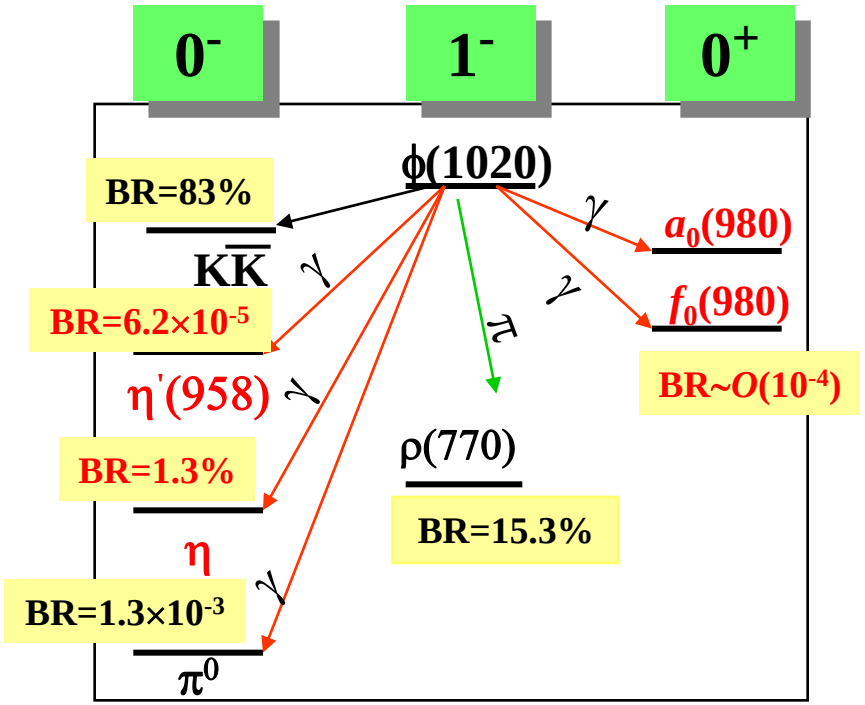
Magnetic field: 0.52 T



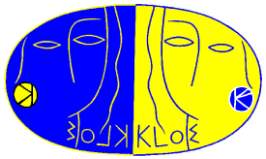
KLOE physics program

- Kaon physics: $|V_{us}|$ and CKM unitarity, CP and CPT violation, rare decays, χPT tests, quantum mechanics tests
- Light meson spectroscopy: scalar, pseudoscalar and vector mesons
- Hadronic cross-section via ISR [$e^+e^- \to \gamma\,(\pi^+\pi^-)$]: hadronic corrections to $(g-2)_\mu$

Decay channel	Events (2.5 fb^{-1})
K^+K^-	3.7×10^9
$K_L K_S$	2.5×10^9
$\rho\pi + \pi^+\pi^-\pi^0$	1.1×10^9
$\eta\gamma$	9.7×10^7
$\pi^0\gamma$	9.4×10^6
$\eta'\gamma$	4.6×10^5
$\pi\pi\gamma$	2.2×10^6
$\eta\pi^0\gamma$	5.2×10^5



Light Scalar Mesons



- **Motivation: the structure of the scalars below 1 GeV is still an open question**

  [$q\bar{q}$, $q\bar{q}q\bar{q}$, $K\bar{K}$ molecule , ...]

- **Radiative decays $\phi \to PP'\gamma$ dominated by scalar mesons ($\phi \to S\gamma$, $S \to PP'$)**

- **KLOE: P P' = $\pi^0\pi^0$ $\Rightarrow$ $f_0(980)/\sigma(600)$** [EPJC49(2007)473, PLB537(2002)21]

  $\pi^+\pi^-$ $\Rightarrow$ $f_0(980)/\sigma(600)$ [PLB634(2006)148]

  $\eta\pi^0$ $\Rightarrow$ $a_0(980)$ [new paper in preparation, PLB536(2002)209]

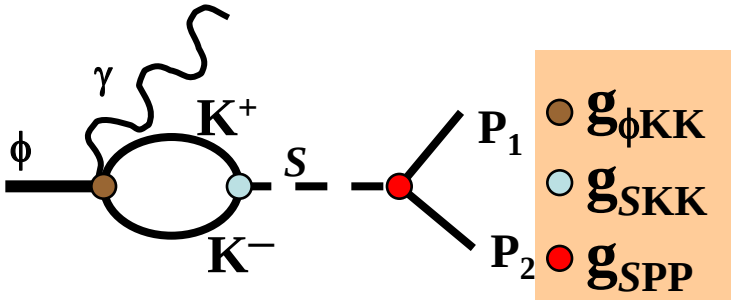
  K_SK_S $\Rightarrow$ $(f_0/a_0) \to K^0\bar{K}^0$ [paper in preparation]

$\Rightarrow$ measure Br's and the resonance parameters (masses and couplings)

$\phi \to S\gamma \to PP'\gamma$ models

1. Kaon loop

[Achasov - Ivanchenko Nucl.Phys.B315(1989)465,
Achasov - Gubin Phys.Rev.D63(2001)094007,
Achasov - Kiselev Phys.Rev.D73(2006)054029]



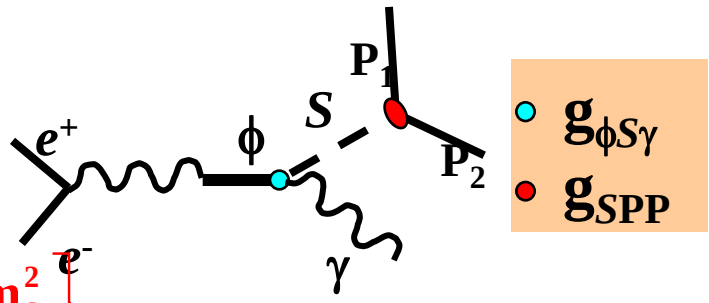
$$\frac{d\Gamma}{dm} = \frac{2\left|g(m^2)\right|^2 p_\gamma (M_\phi^2 - m^2)}{3(4\pi)^3 M_\phi^3} \left| \frac{g_{SK^+K^-} g_{SPP'}}{D_S(m^2)} \right|^2$$

Propagator withfinite width corrections

$$\left(\begin{array}{l} \pi\pi, K^+K^-, K^0\bar{K}^0, \eta\eta, \eta\eta', \eta'\eta' \text{ for } f_0(980) \\ \eta\pi^0, K^+K^-, K^0\bar{K}^0, \eta'\pi^0 \text{ for } a_0(980) \end{array} \right)$$

2. "No Structure"

[G.Isidori, L.Maiani et al., JHEP0605(2006)049]

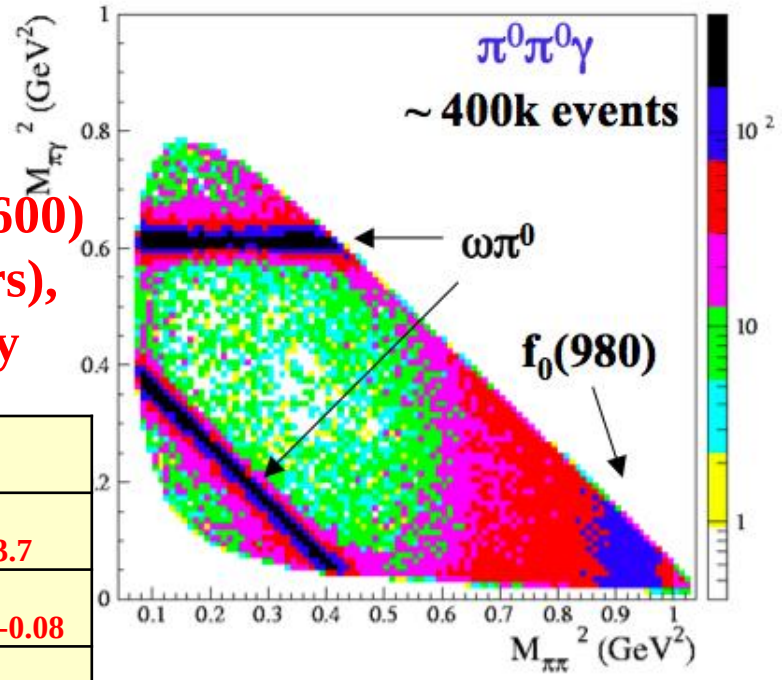


$$\frac{d\Gamma}{dm} = \frac{2p_\gamma (M_\phi^2 - m^2)}{3(4\pi(^2 M_\phi^3} \left[\frac{g_{SPP}\, g_{\phi S\gamma}}{D_S(m^2)} + \frac{a_0}{M_\phi^2} + a_1 \frac{m^2 - m_S^2}{M_\phi^4} \right]$$

E_γ^3 behaviour damped by a polynomial term (a_0 and a_1 complex)

$e^+e^- \to \pi^0\pi^0\gamma$

- Data sample: 450 pb^{-1} $\Rightarrow$ ~ 4×10^5 events
- Two contributions: $\phi \to S\gamma$ and $e^+e^- \to \omega\pi^0$
- Dalitz plot fit: Kaon Loop with $f_0(980)$ and $\sigma(600)$ (σ with fixed parameters), "No structure" with $f_0(980)$ only



$f_0(980)$ param.	KL model	NS model
M_{f0} (MeV)	$976.8 \pm 0.3\ ^{+10.1}_{-0.6}$	$984.7 \pm 0.4^{+2.4}_{-3.7}$
$g_{\phi f\gamma}$ (GeV^{-1})	$2.78^{+0.02}_{-0.05}\ ^{+1.32}_{-0.05}$	$2.61 \pm 0.02^{+0.31}_{-0.08}$
$g_{f\pi+\pi-}$ (GeV)	$-1.43 \pm 0.01^{+0.03}_{-0.60}$	$1.31 \pm 0.01^{+0.09}_{-0.03}$
g_{fK+K-} (GeV)	$3.76 \pm 0.04\ ^{+1.17}_{-0.49}$	$0.40 \pm 0.04^{+0.62}_{-0.29}$
$(g_{fK+K-}/g_{f\pi+\pi})^2$	~ 6.9	~ 0.09
$P(\chi^2)$	14.5 %	4.2 %

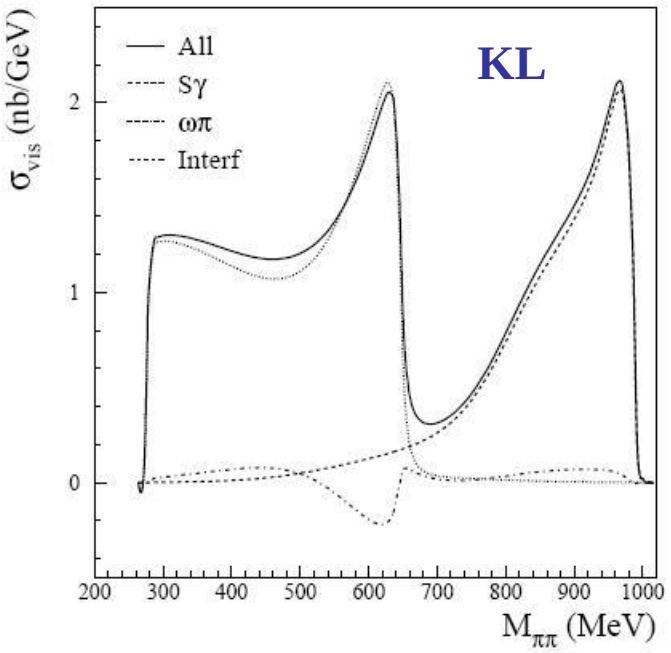
$\sigma(600)$ fixed parameters :
[Achasov,Kiselev,PRD73(2006)054029]
M_σ=462 MeV; Γ_σ=286 MeV
$g_{\sigma K+K-}$=0.5 GeV
$g_{\sigma\pi+\pi-}$= 2.4 GeV

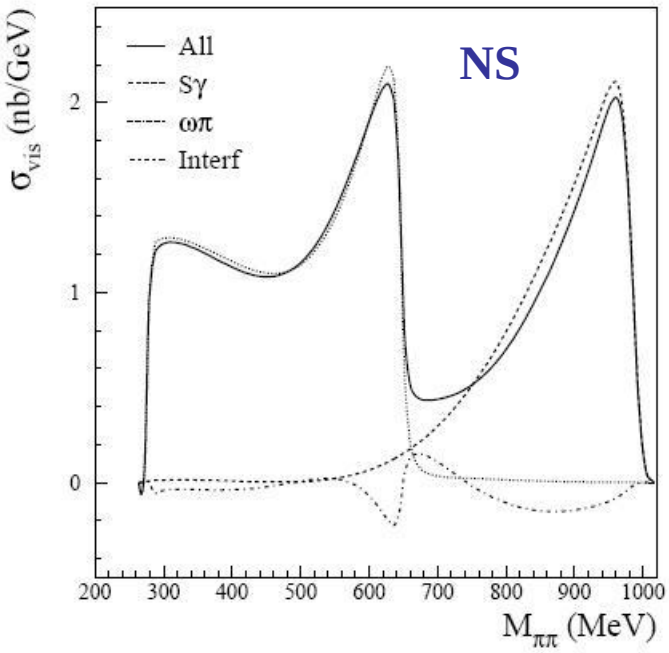
- KL fit without $\sigma(600)$ $\Rightarrow$ $P(\chi^2) \to 10^{-4}$

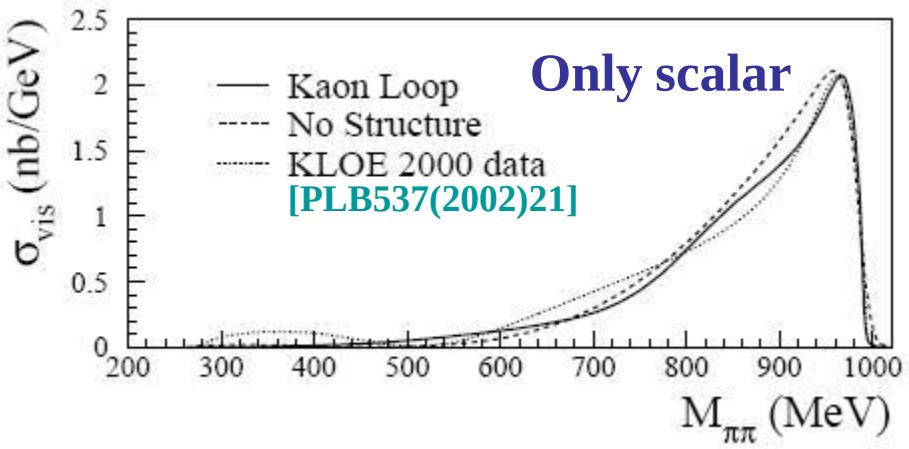
$$Br(\phi \to S\gamma \to \pi^0\pi^0\gamma) = (1.07\ ^{+0.01}_{-0.03(fit)}\ ^{+0.04}_{-0.02(syst)}\ ^{+0.05}_{-0.06(mod)}) \times 10^{-4}$$

Fit results

Scalar + $\omega\pi^0$

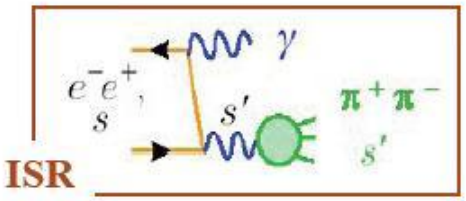


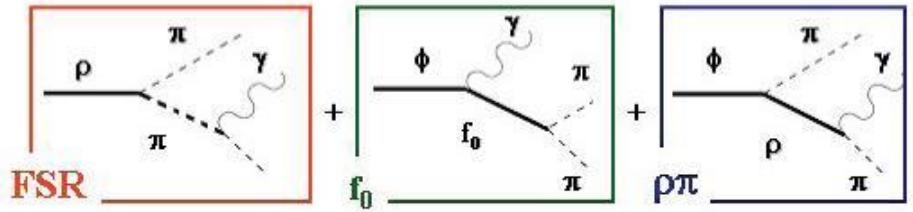


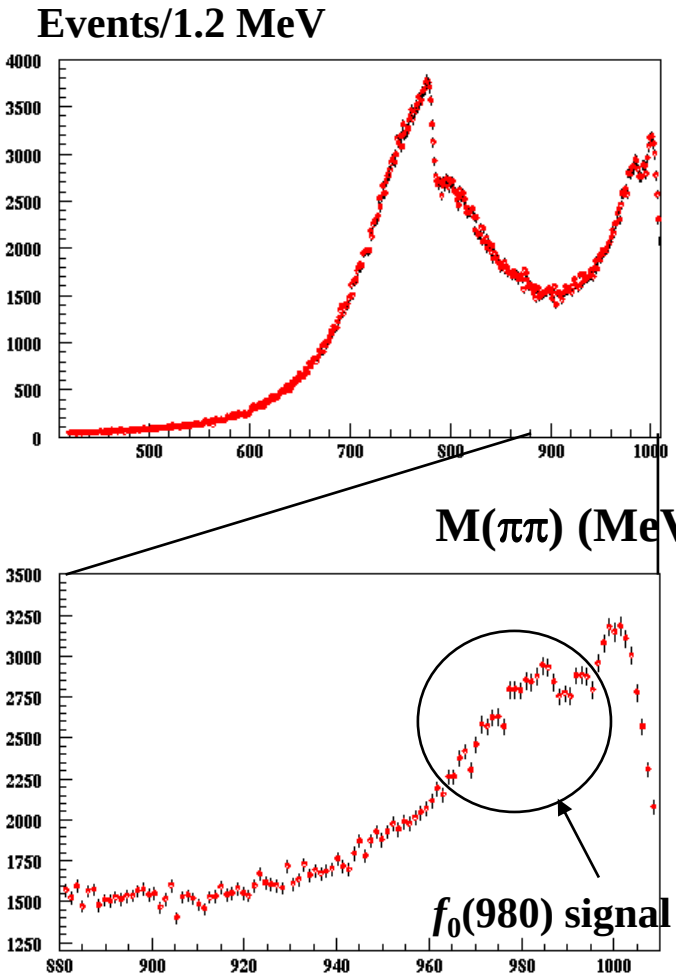


$e^+e^- \to \pi^+\pi^-\gamma$

- **Main contributions**





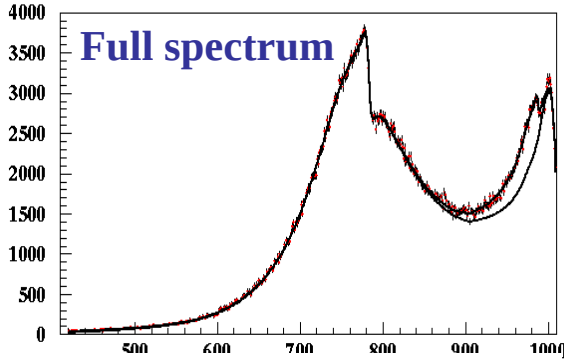


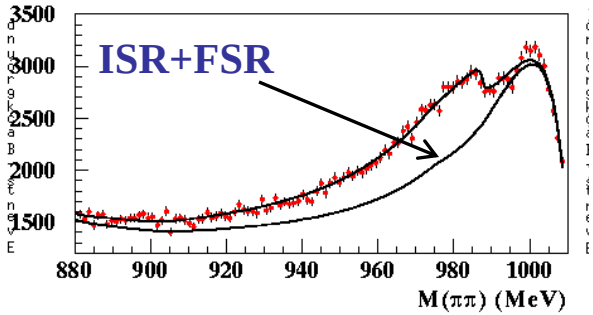
- **Event selection: 2 charged tracks and missing momentum at large angle ($\vartheta > 45°$) + photon matching missing energy and momentum**

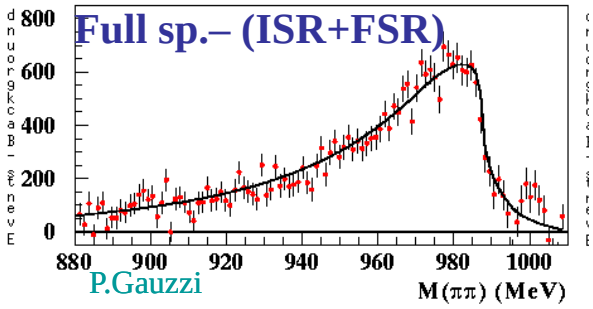
- **Data sample: 350 pb^{-1} at ϕ peak**
  $\Rightarrow$ 6.7×10^5 events selected

M(ππ) fit

$$\frac{d\sigma}{dm} = (\text{ISR}) + (\text{FSR}) + (\rho\pi) + (\text{scalar}) + (\text{scalar} - \text{FSR interf.})$$







P.Gauzzi

	$f_0 \to \pi^+\pi^-$		$f_0 \to \pi^0\pi^0$	
$f_0(980)$ param.	KL model	NS model	KL model	NS model
M_{f0} (MeV)	980 – 987	973 – 981	976.8	984.7
$g_{\phi f\gamma}$ (GeV^{-1})		1.2 – 2.0	2.78	2.61
$g_{f\pi+\pi-}$ (GeV)	3.0 – 4.2	0.9 – 1.1	-1.43	1.31
g_{fK+K-} (GeV)	5.0 – 6.3	1.6 – 2.3	3.76	0.40
$P(\chi^2)$	4.2%	4.4%		

- Destructive f_0-FSR interference preferred
- ρπ term compatible with zero
- No sensitivity to σ(600)
- $R = (g_{fK+K-} / g_{f\pi+\pi-})^2 = 2.2 – 2.8$ (KL); 2.6 – 4.4 (NS)

$$Br(\phi \to f_0\gamma \to \pi^+\pi^-\gamma) = (2.1 - 2.4)\times 10^{-4}$$

$$[\sim 2\,Br(\phi \to \pi^0\pi^0\gamma)]$$

$f_0(980) \to \pi\pi$ update

- **Latest version of the Kaon Loop model** [Achasov, private communication]
- **Fit the $\pi^0\pi^0\gamma$ Dalitz plot and the $M(\pi^+\pi^-)$ distribution with the same scalar amplitude (with $\sigma(600)$)**

$f_0(980)$ param.	$f_0 \to \pi^0\pi^0$	$f_0 \to \pi^+\pi^-$
M_{f0} (MeV)	984.7 ± 1.9 (model)	983.7
$g_{f0\pi+\pi-}$ (GeV	-1.82 ± 0.19 (model)	-2.22
g_{fK+K-} (GeV)	3.97 ± 0.43 (model)	4.74
$R=(g_{fK+K-}/g_{f\pi+\pi-})^2$	~ 4.8	~ 4.6

KLOE preliminary

- **Better agreement between the two channels**
- **Reduced model uncertainties**
- **Other uncertainties under evaluation**
- **Next: combined fit**

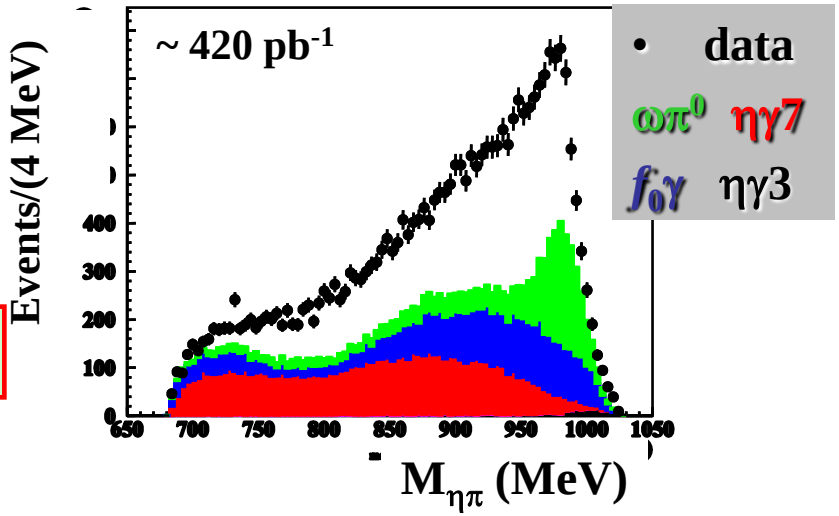
$\phi \to \eta\pi^0\gamma$ $(\eta \to \gamma\gamma, \pi^+\pi^-\pi^0)$

1) $\eta \to \gamma\gamma$ (Br=38.31%) $\Rightarrow$ 5 photon final state

Total background = 55% (MC)

($\phi \to f_0(980)\gamma \to \pi^0\pi^0\gamma$; $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$;

$\phi \to \eta\gamma$ with $\eta \to \pi^0\pi^0\pi^0$)



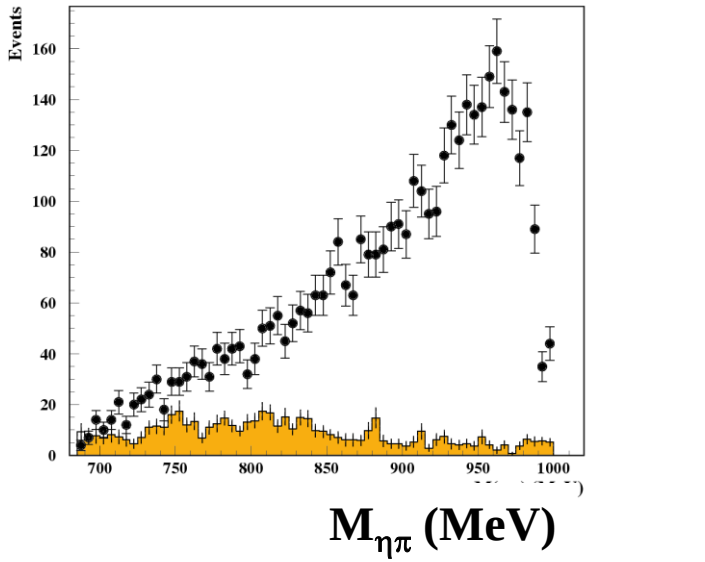
$$Br(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10_{stat} \pm 0.20_{syst}) \times 10^{-5}$$

2) $\eta \to \pi^+\pi^-\pi^0$ (Br=22.73%)$\Rightarrow$ 5γ + 2 tracks

Total background = 15% ($\pi^+\pi^-$+ 4 or 6 γ

from $e^+e^- \to \omega\pi^0$; $\omega \to \pi^+\pi^-\pi^0$

and $\phi \to K_S K_L \to \pi^+\pi^- 3\pi^0$)



$$Br(\phi \to \eta\pi^0\gamma) = (7.12 \pm 0.13_{stat} \pm 0.22_{syst}) \times 10^{-5}$$

Combining the two results:

$$Br(\phi \to \eta\pi^0\gamma) = (7.06 \pm 0.22) \times 10^{-5}$$

[arXiv:0707.4609]

$M(\eta\pi^0)$ fit

- **Combined fit of the two $M(\eta\pi^0)$ distributions**

  $\Rightarrow$ **Free parameter: $R_\eta = Br(\eta\to\gamma\gamma)/Br(\eta\to\pi^+\pi^-\pi^0)$**
- **Kaon Loop. $a_0(980)$ free parameters: M_{a0}, g_{aK+K-}, $g_{a\eta\pi}$**

  $\phi\to\rho\pi^0$, $\rho\to\eta\gamma$ **(VDM)** [Achasov-Gubin PRD63(2001)094007]

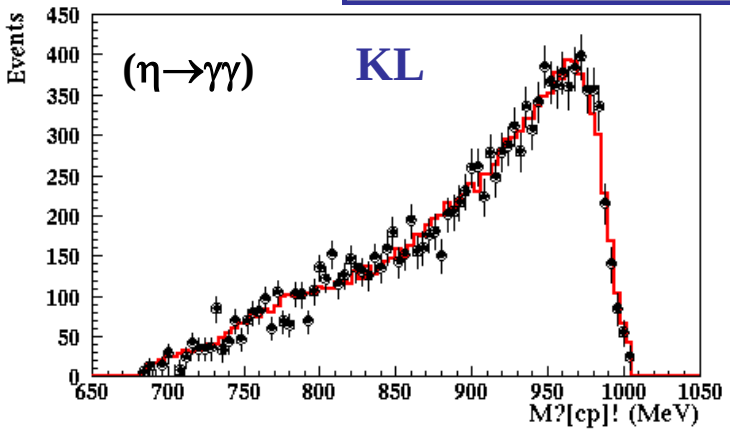
  $\Rightarrow$ **Free parameters: $Br(\phi\to\rho\pi^0\to\eta\pi^0\gamma)$ + δ (phase)**
- **No structure. Parameters: g_{aK+K-}, $g_{a\eta\pi}$, $g_{\phi a\gamma}$, Br(VDM)**

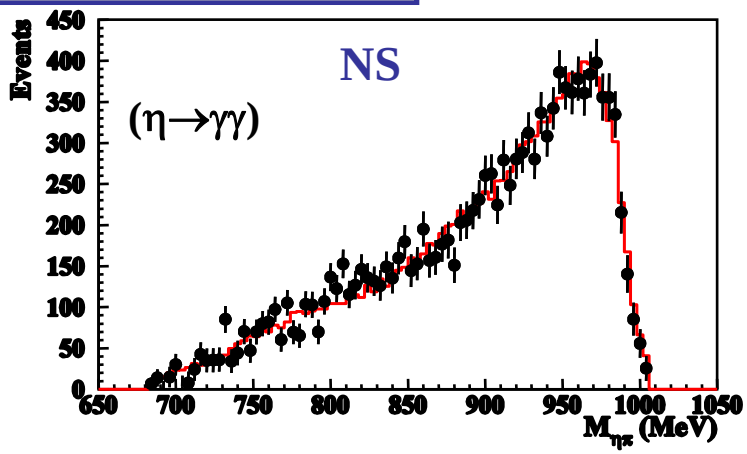
	KL	NS
M_{a0} (MeV)	982.5 ± 1.6 ± 1.1	982.5 (fixed)
g_{aK+K-} (GeV)	2.15 ±0.06 ± 0.06	2.01 ± 0.07± 0.28
$g_{a\eta\pi}$ (GeV)	2.82 ± 0.03± 0.04	2.46 ± 0.08 ± 0.11
$g_{\phi a\gamma}$ (GeV^{-1})	1.58 ± 0.10± 0.16	1.83± 0.03 ± 0.08
Br(VDM) $\times 10^6$	0.92 ± 0.40 ± 0.15	~ 0
$R_\eta = Br(\eta\to\gamma\gamma)/Br(\eta\to\pi^+\pi^-\pi^0)$	1.70±0.04± 0.03	1.70 ±0.03 ± 0.01
$R=(g_{aK+K-}/g_{a\eta\pi})^2$	0.58 ± 0.03± 0.03	0.67 ± 0.06 ± 0.13
$P(\chi^2)$	10.4%	30.9%

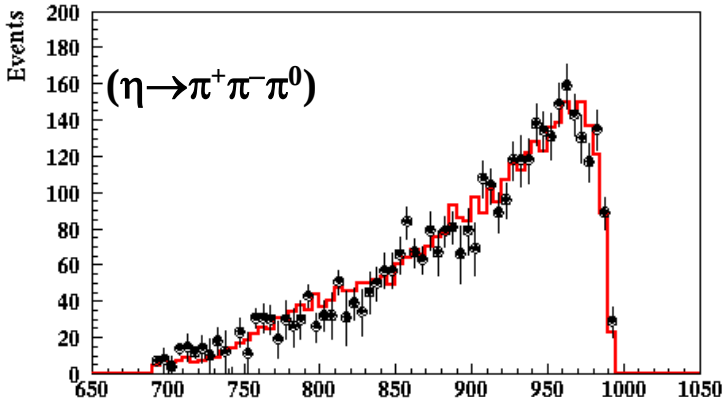
- **$M(a_0)$ fixed for NS fit**
- **PDG $\Rightarrow R_\eta = 1.73 \pm 0.04$**
- **VDM very small**

Fit results

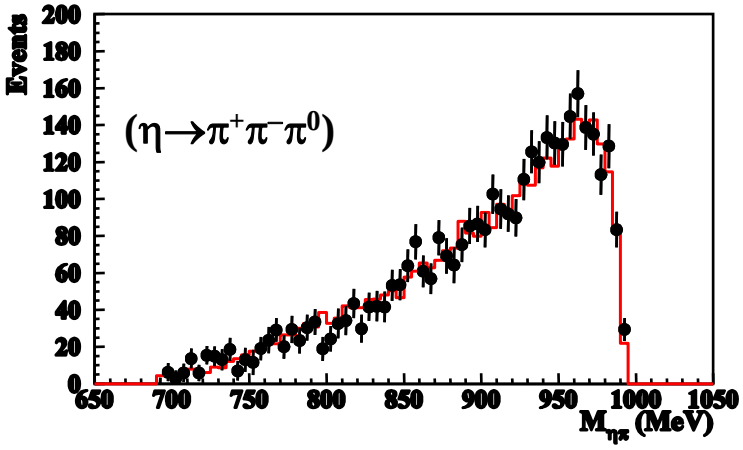
- data
- fit (with resolution and smearing)



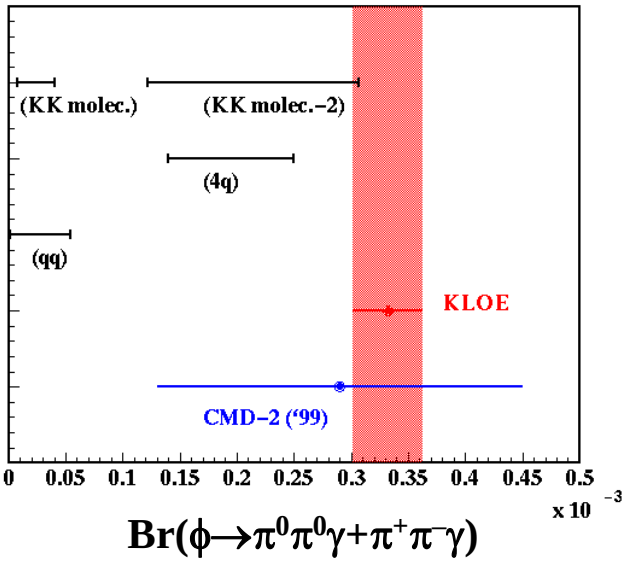




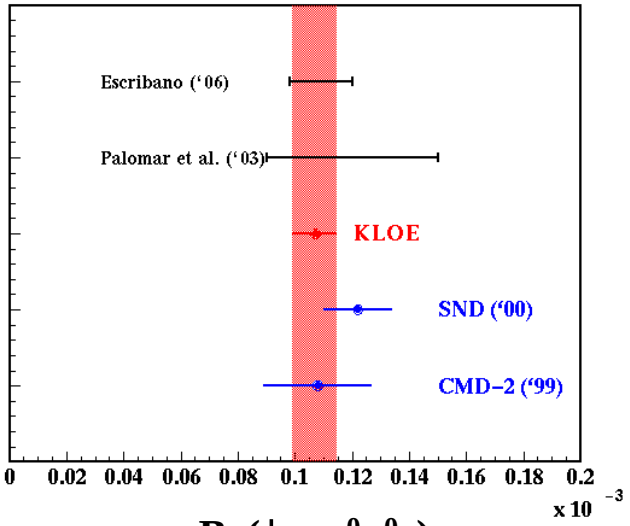
$M_{\eta\pi}$ (MeV)



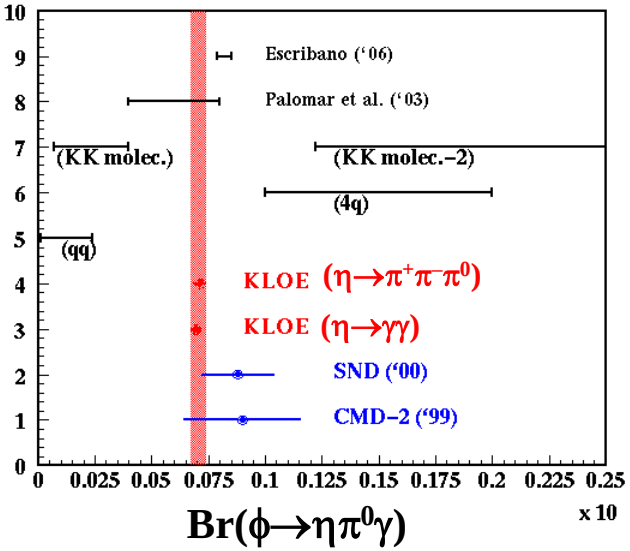
Branching ratios



$Br(\phi \to \pi^0\pi^0\gamma + \pi^+\pi^-\gamma)$



$Br(\phi \to \pi^0\pi^0\gamma)$



$Br(\phi \to \eta\pi^0\gamma)$

qq: Achasov-Ivanchenko NPB315(1989)
Close et al., NPB389(1993)
4q: Achasov-Ivanchenko NPB315(1989)
KK molec.: Close et al., NPB389(1993)
Achasov et al., PRD56(1997)
KK molec.-2: Kalashnikova et al., EPJA24(2005)
Palomar et al., NPA729(2003): UχPT
Escribano, PRD74(2006): Linear σ model

Couplings

		SU(3)		
		4q	qqbar	
$(g_{aK+K-} / g_{a\eta\pi})^2$	0.6 – 0.7	1.2 – 1.7	0.4	
	SND (2000) : 1.8 ± 2.5			
$(g_{fK+K-}/g_{f\pi+\pi-})^2$	4.6 – 4.8	>> 1	>> 1 (f_0=ssbar)	1/4 (f_0=nnbar)
	CMD-2 (1999) : 3.61 ± 0.62			
	SND (2000) : 4.6 ± 0.8			
	BES (2005) : 4.21 ± 0.33			
$(g_{fK+K-}/g_{aK+K-})^2$	4 – 5	1	2	1

- Large $g_{\phi S\gamma}$ ⇒ sizeable *s* quark content ?

Meson	$g_{\phi M\gamma}$ (GeV^{-1})
π^0	0.13
η	0.71
η'	0.75
$a_0(980)$	1.6 – 1.8
$f_0(980)$	1.2 – 2.7

Instanton model

- **"New theory of scalar mesons"** ['t Hooft,Maiani et al. PLB662(2008),424]**: instantons provide a mechanism for $f_0(980) \to \pi\pi$ independent from mixing with the σ in both hypotheses 4q and qqbar**

$$\mathcal{L}_{dec}(S) = c_f O_f(S) + c_I O_1(S)$$

Processes	$\mathcal{A}_{th}([qq][\bar{q}\bar{q}])$ with inst.	$\mathcal{A}_{th}([qq][\bar{q}\bar{q}])$ no inst.	best fit	$\mathcal{A}_{th}(q\bar{q})$ with inst.	$\mathcal{A}_{th}(q\bar{q})$ no inst.	$\mathcal{A}_{expt}$
$\sigma \to \pi^+\pi^-$	input	input	1.6	input	input	3.22 ± 0.04
$\kappa^+ \to K^0\pi^+$	7.3	7.7	3.3	6.0	5.5	5.2 ± 0.1
$f_0 \to \pi^+\pi^-$	input	[0–1.6]	1.6	input	[0–1.6]	1.4 ± 0.6
$f_0 \to K^+K^-$	6.7	6.4	3.5	6.4	6.4	3.8 ± 1.1
$a_0 \to \pi^0\eta$	6.7	7.6	2.7	12.4	11.8	2.8 ± 0.1
$a_0 \to K^+K^-$	4.9	5.2	2.2	4.1	3.7	2.16 ± 0.04

- **Only KLOE data: input g_{f0KK} , $g_{f0\pi\pi}$ + masses + φ_P ⇒output g_{a0KK} and $g_{a0\eta\pi}$**

	KLOE (KL)		$[qq][\bar{q}\bar{q}]$	$q\bar{q}$
$g_{f0K^+K^-}$ (GeV)	3.97 — 4.74	}	c_I = - 2.8 — - 3.4 GeV^{-1}	c_I = - 3.9 — - 4.8 GeV^{-1}
$g_{f0\pi^+\pi^-}$ (GeV)	-1.82 — -2.23	}	c_f = 20.5 — 24.5 GeV^{-1}	c_f = 16.5 — 19.7 GeV^{-1}
			⇓	⇓
$g_{a0K^+K^-}$ (GeV)	2.01 — 2.15		2.1 — 2.5	2.4 — 2.9
$g_{a0\eta\pi}$ (GeV)	2.46 — 2.82		3.3 — 3.9	6.6 — 7.9

$\phi \to (f_0/a_0)\gamma \to K^0\overline{K}^0\gamma$

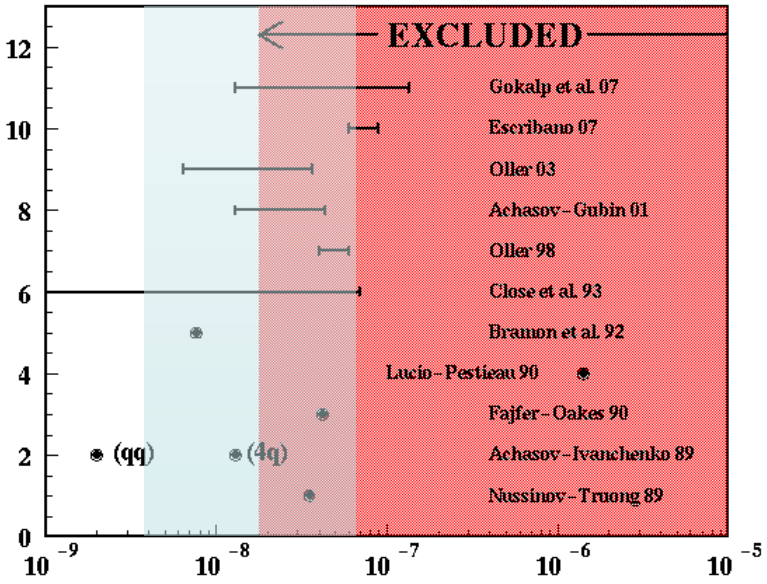
- $K^0\overline{K}^0$ with scalar quantum numbers ($J^{PC}=0^{++}$)
- Very small phase space available ($2M_K \le M(KK) \le M_\phi$) $\Rightarrow$ small Br expected
- "Golden channel" $\phi \to K_S K_S \gamma \to \pi^+\pi^-\pi^+\pi^-\gamma$

- Analyzed sample: 2.18 fb^{-1}; efficiency = 24.8%
- **Selection:** 2 vertices near the IP, with 2 tracks + γ required (E_{max} = 24 MeV) to reject $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$
- 5 events in data
- 3.2 background events (MC) ($\pi^+\pi^-\pi^+\pi^-(\gamma)$ from $\phi \to K_S K_L$ and from continuum)

$$Br(\phi \to K^0\overline{K}^0\gamma) < 1.9\times10^{-8} \ @\ 90\%\ C.L.$$

- Consistency check: using the KLOE couplings from $\phi \to \pi\pi\gamma$, $\eta\pi^0\gamma$ in the Kaon Loop model

$\Rightarrow$ $Br(\phi \to K^0\overline{K}^0\gamma) = 4\times10^{-9} - 6.8\times10^{-8}$



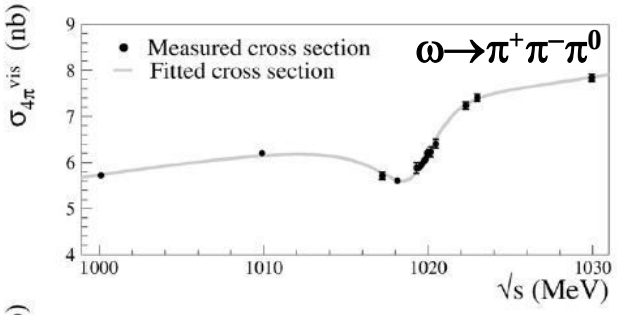
$e^+e^- \to \omega\pi^0$

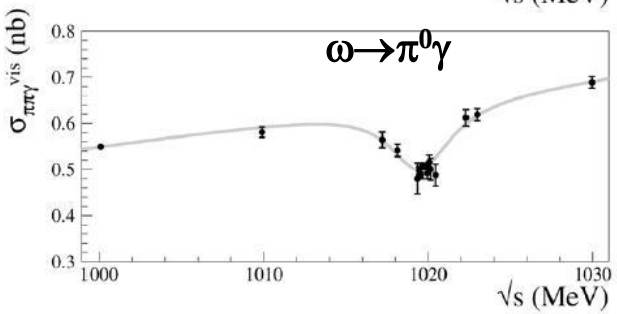
- 600 pb^{-1} with $1000 < \sqrt{s} < 1030$ MeV
- Interference with $\phi \to \omega\pi^0$ (OZI and G-parity viol.)

$$\sigma_{vis}(\sqrt{s}) = \sigma_{nr}(\sqrt{s})\left(1 - Z\frac{M_\phi \Gamma_\phi}{D_\phi(\sqrt{s})}\right)$$

$$\sigma_{nr}(\sqrt{s}) = \sigma_0 + \sigma' \cdot (\sqrt{s} - M_\phi)$$

Parameter	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$	$e^+e^- \to \pi^0\pi^0\gamma$
σ_0 [nb]	$7.89 \pm 0.06 \pm 0.07$	$0.724 \pm 0.010 \pm 0.003$
$\Re e(Z)$	$0.106 \pm 0.007 \pm 0.004$	$0.011 \pm 0.015 \pm 0.006$
$\Im m(Z)$	$-0.103 \pm 0.004 \pm 0.003$	$-0.154 \pm 0.007 \pm 0.004$
σ' [nb/MeV]	$0.064 \pm 0.003 \pm 0.001$	$0.0053 \pm 0.0005 \pm 0.0002$





[PLB669(2008)223]

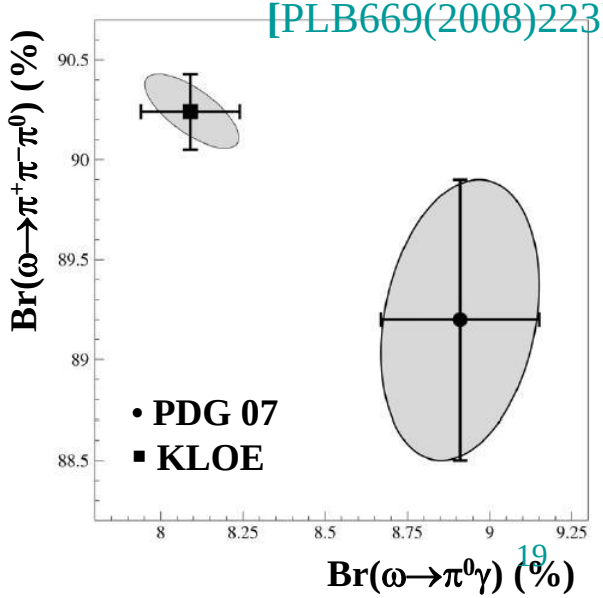
- From $\sigma_0(\pi^0\gamma)/\sigma_0(\pi^+\pi^-\pi^0)$ (with rare Br's from PDG)

$\mathrm{Br}(\omega \to \pi^+\pi^-\pi^0) = (90.24 \pm 0.19)\%$

$\mathrm{Br}(\omega \to \pi^0\gamma) = (8.09 \pm 0.14)\%$ (~3 σ from PDG)

(8.92 ± 0.24) %

$\Rightarrow \mathrm{Br}(\phi \to \omega\pi^0) = (4.4 \pm 0.6) \times 10^{-5}$



Pseudoscalar mesons

- ϕ-factory $\Rightarrow$ large samples of η and η'
- $L = 2.5\ fb^{-1} \Rightarrow 8 \times 10^9\ \phi \Rightarrow \sim 10^8\ \eta$
  $\Rightarrow \sim 5 \times 10^5\ \eta'$

- η/η' mixing and η' gluonium content [PLB648(2007)267, PLB541(2002)45]
- Rare η decays ($\eta \to \pi^+\pi^- e^+e^-$, $\eta \to \pi^0\gamma\gamma$, $\eta \to \pi^+\pi^-\gamma$)
- Dynamics of $\eta \to \pi\pi\pi$ decay [JHEP0805(2008)006]
- Precise measurement of the η mass [JHEP0712(2007)073]

Mixing η/η´

- $\phi \to \eta'\gamma$; $\eta' \to \eta\,\pi^+\pi^-$; $\eta \to \pi^0\pi^0\pi^0$
  $\eta' \to \eta\pi^0\pi^0$; $\eta \to \pi^+\pi^-\,\pi^0$
- $\phi \to \eta\gamma$; $\eta \to \pi^0\pi^0\pi^0$

} Final state: $\pi^+\pi^- + 7\,\gamma$

$L = 427\ pb^{-1}$

$N_{\eta'\gamma} = 3407 \pm 61 \pm 43$ ev.

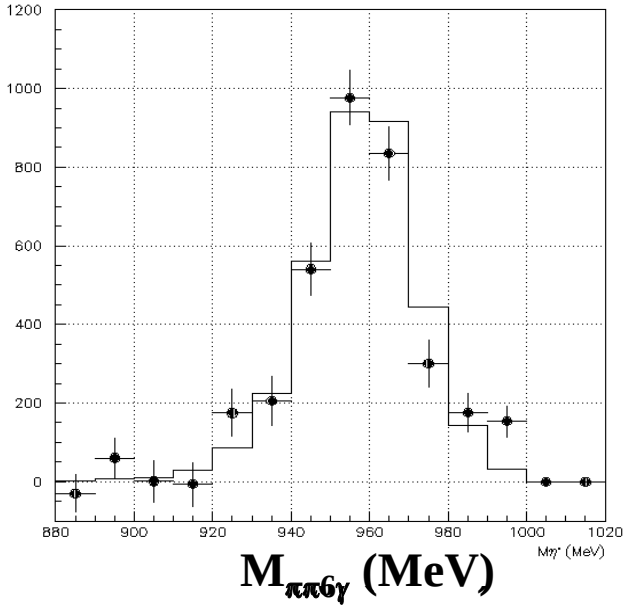
$N_{\eta\gamma} = 16.7 \times 10^6$ ev.

$$R = \frac{Br(\phi \to \eta'\gamma)}{Br(\phi \to \eta\gamma)} = (4.77 \pm 0.09 \pm 0.19) \times 10^{-3}$$

[systematics dominated by $\delta Br(\eta' \to \eta\pi\pi) = 3\%$]

$\Rightarrow$ $Br(\phi \to \eta'\gamma) = (6.20 \pm 0.11 \pm 0.15) \times 10^{-5}$

Inv.mass of $\pi^+\pi^-$+ 6γ out of 7



- Pseudoscalar mixing angle: $\left|q\bar{q}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|u\bar{u}\right\rangle + \left|d\bar{d}\right\rangle\right)$

$$\eta = \cos\varphi_P \left|q\bar{q}\right\rangle - \sin\varphi_P \left|s\bar{s}\right\rangle$$

$$\eta' = \sin\varphi_P \left|q\bar{q}\right\rangle + \cos\varphi_P \left|s\bar{s}\right\rangle$$

$$R = \cot^2\varphi_P \left(1 - \frac{m_s}{\bar{m}} \cdot \frac{C_{NS}}{C_S} \cdot \frac{\tan\varphi_V}{\sin 2\varphi_P}\right)^2 \cdot \left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

$\varphi_P = (41.4 \pm 0.3 \pm 0.9)^\circ \Rightarrow \vartheta_P = (-13.3 \pm 0.3 \pm 0.9)^\circ$

η´ gluonium content

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

$$X_{\eta'} = \cos\varphi_G \sin\varphi_P$$

$$Y_{\eta'} = \cos\varphi_G \cos\varphi_P$$

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

$$Z_{\eta'} > 0 \Leftrightarrow X_{\eta'}^2 + Y_{\eta'}^2 < 1$$

[Rosner PRD27(1983) 1101, Kou PRD63(2001)54027]

$$R = \cot^2\varphi_P \cos^2\varphi_G \left(1 - \frac{m_s}{\bar{m}} \cdot \frac{C_{NS}}{C_S} \cdot \frac{\tan\varphi_V}{\sin 2\varphi_P}\right)^2 \cdot \left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} = \frac{1}{9}\left(\frac{m_{\eta'}}{m_\pi}\right)^3 \left(5X_{\eta'} + \sqrt{2}\frac{f_q}{f_s} Y_{\eta'}\right)^2$$

$$\frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)} = \frac{C_{NS}}{\cos\varphi_V} 3\left(\frac{m_{\eta'}^2 - m_\rho^2}{m_\omega^2 - m_\pi^2}\frac{m_\omega}{m_{\eta'}}\right)^3 X_{\eta'}^2$$

$$\frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \pi^0\gamma)} = \frac{1}{3}\left(\frac{m_{\eta'}^2 - m_\omega^2}{m_\omega^2 - m_{\pi^1}^2}\frac{m_\omega}{m_{\eta'}}\right)^3 \left(C_{NS}X_{\eta'} + 2\frac{m_s}{\bar{m}} C_S \tan\varphi_V Y_{\eta'}\right)^2$$

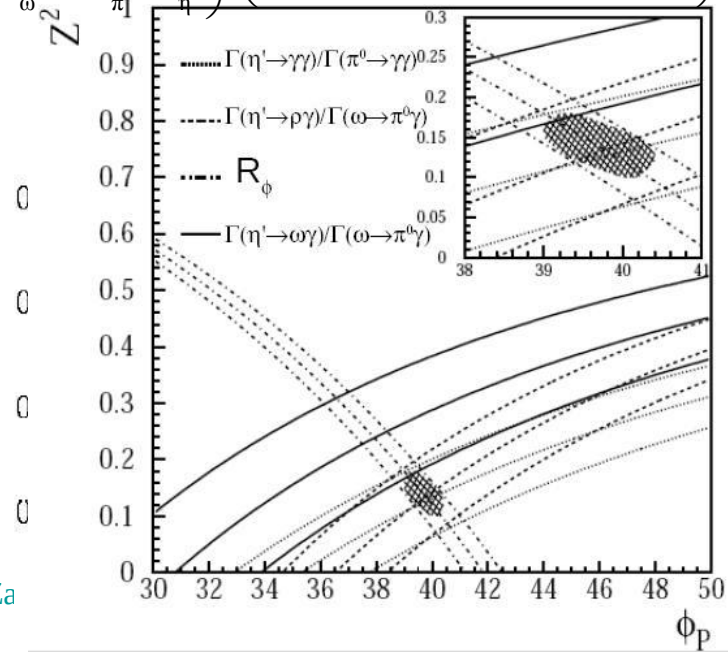
Fixed parameters:

Parameter	f_q	f_s	C_{NS}	C_S	$\frac{m_s}{\bar{m}}$
Value	1 ± 0.01	1.4 ± 0.014	0.91 ± 0.05	0.89 ± 0.07	1.24 ± 0.07

$\varphi_P = (39.7 \pm 0.7)°$

$Z_{\eta'}^2 = 0.14 \pm 0.04$

$P(\chi^2) = 49\ \%$



η' gluonium content

- **Additional constraints to determine more parameters:**

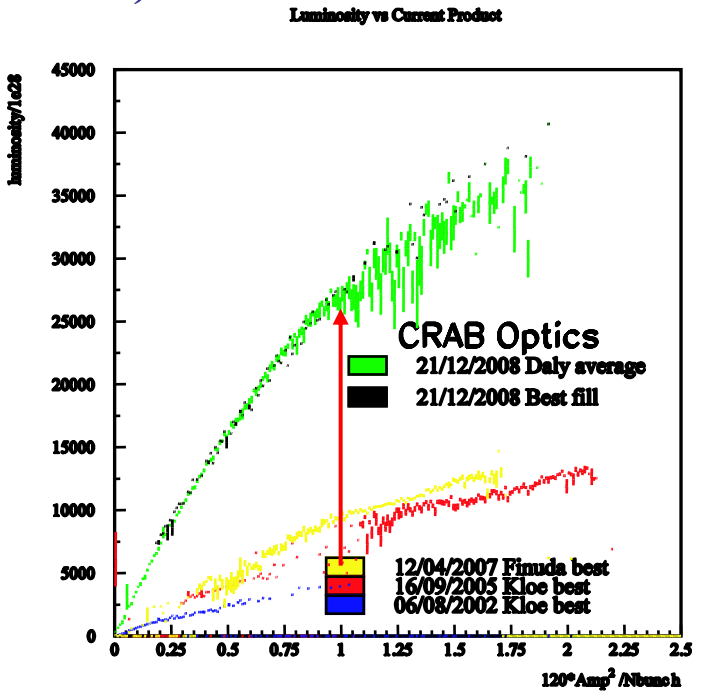
$$\frac{\Gamma(\omega\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(\rho\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(\phi\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(\phi\to\pi^0\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(K^{*+}\to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

	New fit	PLB648
$Z_{\eta'}^2$	0.11 ± 0.04	0.14 ± 0.04
φ_P (deg.)	40.7 ± 0.7	39.7 ± 0.7
C_{NS}	0.87 ±0.03	0.91 ±0.05
C_S	0.79 ±0.05	0.89 ±0.07
φ_V (deg.)	3.15 ± 0.10	3.2
m_s/m	1.24 ± 0.07	1.24 ± 0.07
χ^2/ndf	5./3	1.42 / 2
$P(\chi^2)$	17%	49%

- **Forcing $Z_{\eta'}=0 \Rightarrow \varphi_P=(41.6\pm0.5)°$ with $P(\chi^2)=1\%$**
- **Discrepancy with Escribano-Nadal $Z_{\eta'}^2=0.04\pm0.09$; $\varphi_P=(41.4\pm1.3)°$** [JHEP05(2007)006] **(fit without $\eta'\to\gamma\gamma$)**
- **Fit with the new Br($\omega\to\pi^0\gamma$) in progress**

Future prospects – KLOE2

- New scheme to increase the DAΦNE luminosity by a factor *O*(5) is being implemented (large crossing angle + "crabbed waist")



Program:

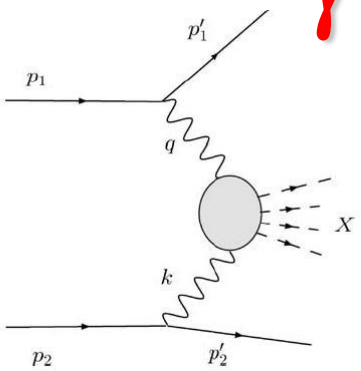
1. New KLOE data-taking will start at the end of 2009, with the present detector + tagger for $\gamma\gamma$ physics $\Rightarrow$ ~ 5 fb^{-1}
2. Detector upgrade: inner tracker, new small angle calorimeters, …
3. KLOE-2 data taking $\Rightarrow$ 50 fb^{-1} in 3 – 4 years

KLOE-2 physics items

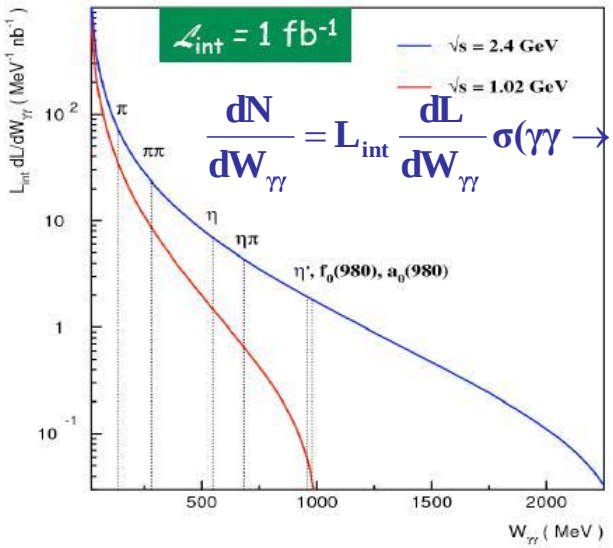
- Kaon physics: CKM unitarity, Quantum Mechanics tests with entangled kaon states, Lepton universality ($K^{\pm}\to e^{\pm}\nu$ / $K^{\pm}\to\mu^{\pm}\nu$), K_S rare decays
- Light hadrons: search for $\sigma(600)$ in $\gamma\gamma \to \sigma \to \pi^0\pi^0$, $\phi \to (f_0/a_0)\gamma \to K^0\overline{K}^0\gamma$ η, η' decays

(www.lnf.infn.it/lnfadmin/direzione/roadmap/LoIKLOE.pdf)

γγ physics @ KLOE-2

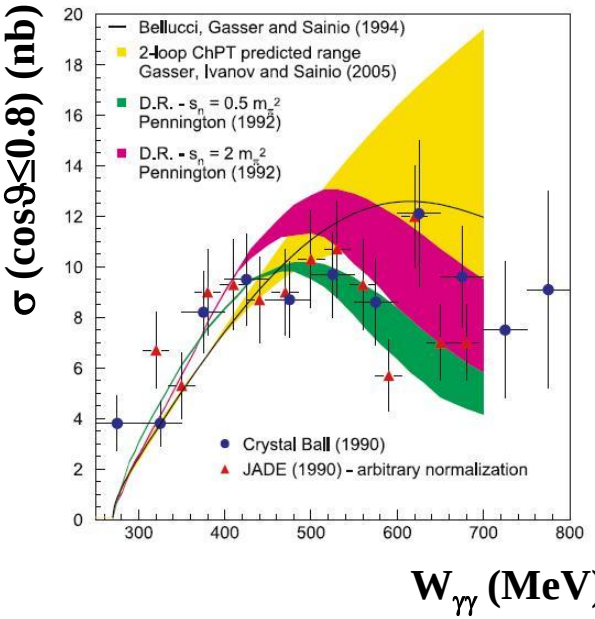


$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- X$$
$$\left[J^{PC}(X) = 0^{\pm+}, 2^{\pm+}\right]$$

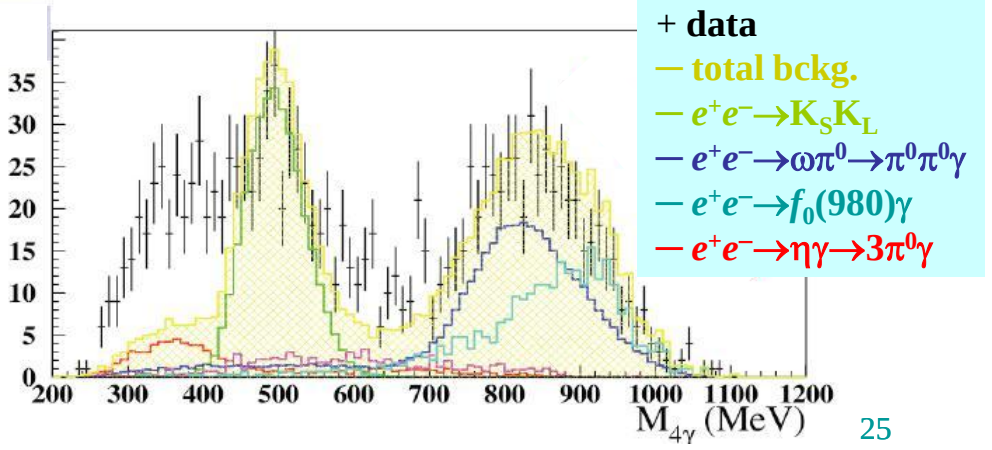


- $X = \pi^0, \eta, \eta' \Rightarrow \Gamma(P \to \gamma\gamma)$
- $X = \pi^0\pi^0 \Rightarrow \gamma^*\gamma^* \to \sigma(600) \to \pi^0\pi^0$

  with $L = 5$ fb^{-1} $\Rightarrow$ err. ≈ 2%

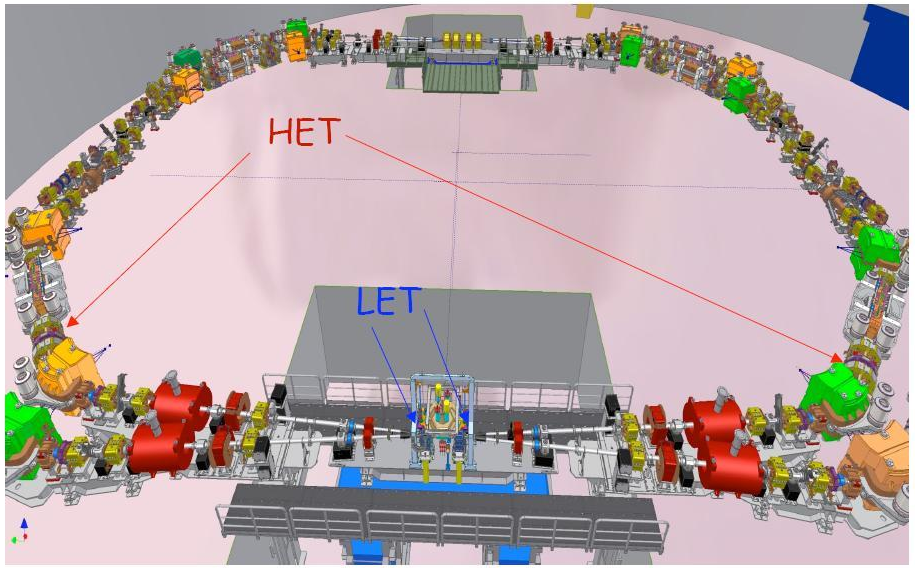


Preliminary KLOE meas., 11 pb^{-1} @ √s=1 GeV



Tagger for γγ physics

- $e^{\pm}$ tagger needed to reject background from $\phi \rightarrow K_S K_L$ (K_L lost, $K_S \rightarrow \pi\pi$ S/B ~ 10^{-3}-10^{-4}) and to improve resolution on $W_{\gamma\gamma}$
- 2 detectors:
  - LET (Low Energy Tagger)
    Crystals + SiPM
    σ_E/E= 5 – 10% , σ_t ~ 2 ns
    @ $E_e \approx$200 MeV
  - HET (High Energy Tagger)
    uses dipoles as $e^{\pm}$ spectrometer
    position detector needed (σ < 1mm)
    @ 11 m from IP
- Coincidence will cover the interesting $W_{\gamma\gamma}$ range



	E_e' (MeV)	E_γ (MeV)
LET	(165 - 235)	(275 - 345)
HET	(330 - 390)	(120, 180)

Conclusions

- **Important results have been achieved by KLOE in light meson spectroscopy**
- **Scalars:**
  - **Precision Br($\phi \to f_0(980)\gamma$) and Br($\phi \to a_0(980)\gamma$) have been measured**
  - **Large couplings to ϕ and to KK have been obtained from fits**
  - **$\sigma(600)$ needed to fit the $\pi^0\pi^0\gamma$ Dalitz plot**
  - **Combined analysis of $f_0 \to \pi^0\pi^0$ and $f_0 \to \pi^+\pi^-$ started**
  - **Upper limit set for $\phi \to (f_0/a_0)\gamma \to K^0\bar{K}^0\gamma$**

- **$\omega\pi^0$: precision measurement of the main ω Br's and Br($\phi \to \omega\pi^0$)**

- **Pseudoscalars:**
  - **Using the Rosner model we see evidence (~3 σ) of gluonium in η'**
  - **Other meas. not shown in this talk (Dalitz plot of $\eta \to 3\pi$, precise measurement of η mass, $\eta \to \pi^0\gamma\gamma$, $\eta \to \pi^+\pi^- e^+e^-$)**

- **DAΦNE upgrade – KLOE 2: possibility of new or more precise measurements in hadron spectroscopy**

Spare slides

Unfolded $M_{\eta\pi}$ distribution

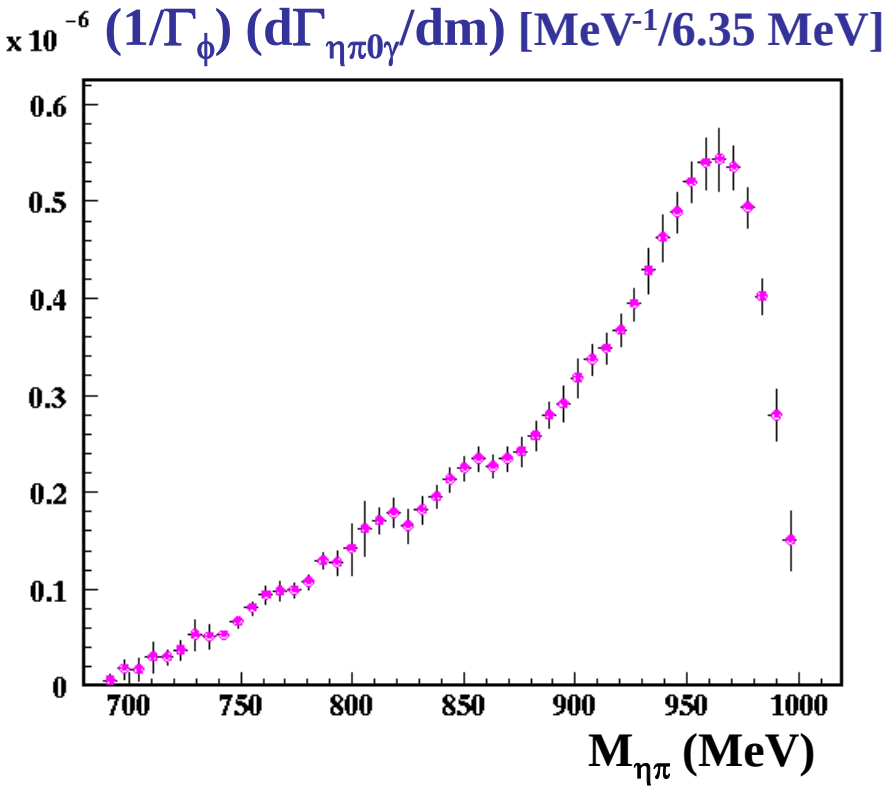
- To allow better comparison with other experimental results and theoretical models ⇒ unfolding procedure to correct data for detector and resolution effects

- Bayesian unfolding

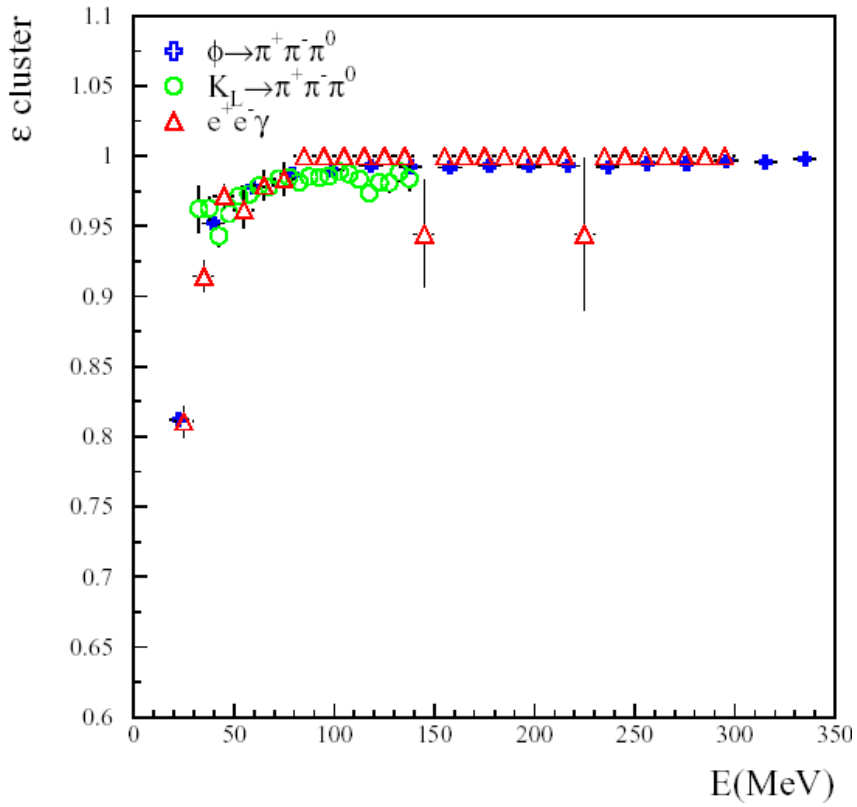
(avoids smearing matrix inversion)

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

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



Photon efficiency



Measured using the extrapolated energy and position by D.C. in
(1) $\pi^+\pi^-\pi^0$ final states (2 tracks + 2 photons)
(2) $e^+e^-\gamma$
(3) $K_L \rightarrow \pi^+\pi^-\pi^0$

➔ e = 100% (> 98%) E > 80 MeV
➔ e = 100% → 80% E = 80 → 20 MeV

Dalitz plot fit

- **Kaon Loop with σ(600):** $M_{KL} \propto g(m^2) e^{i\delta_B} \sum_{S,S'=f_0,\sigma} g_{SK\bar{K}} \; G^{-1}_{SS'} \; g_{S'\pi\pi}$

  - **Free parameters for $f_0(980)$: M_{f0}, g_{fK+K-}, $g_{f\pi+\pi-}$ ($=\sqrt{2}\; g_{f\pi0\pi0}$)**
  - **$\delta_B=\delta_B^{\pi\pi} + \delta_B^{KK}$ and σ(600) parameters fixed** [Achasov-Kiselev,PRD73(2006)054029]
  - **$\omega\pi^0 + \phi \rightarrow \rho\pi$ VDM parametrization + interference terms (7 free parameters)**

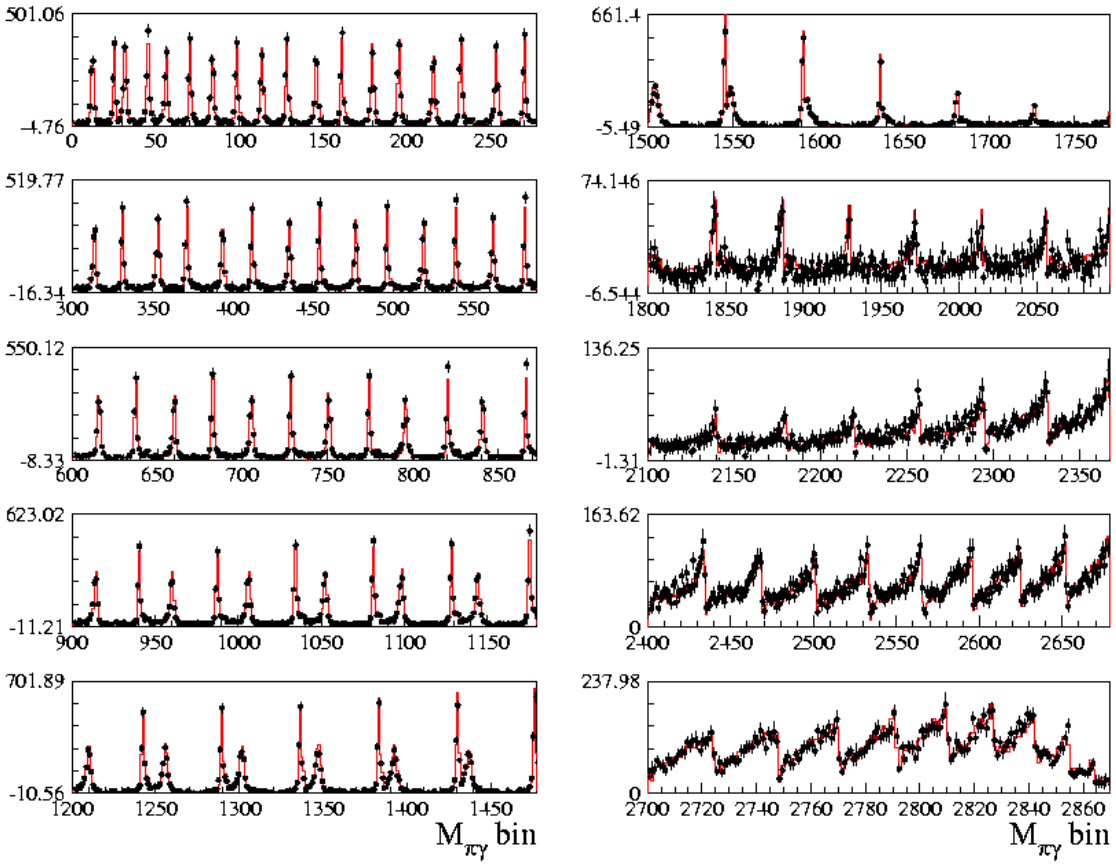
"No structure" without σ(600)

- **Free parameters: M_{f0}, g_{fK+K-}, $g_{f\pi+\pi-}$, $g_{\phi f\gamma}$, a_0, a_1, b_1**

$$M_{NS} \propto \frac{e}{4F_\phi} \frac{sM_\phi^2}{D_\phi(s)} \left[\frac{g_{f_0\pi\pi} g_{\phi f_0\gamma}}{D_{f_0}(m^2)} + \frac{a_0 e^{ib_0 \frac{v_\pi(m)}{m_\phi}}}{m_\phi^2} + a_1 e^{ib_1 \frac{v_\pi(m)}{m_\phi}} \frac{m^2 - m_{f_0}^2}{m_\phi^4} \right]$$

- **Vector amplitude : same parametrization as for KL (7 parameters)**

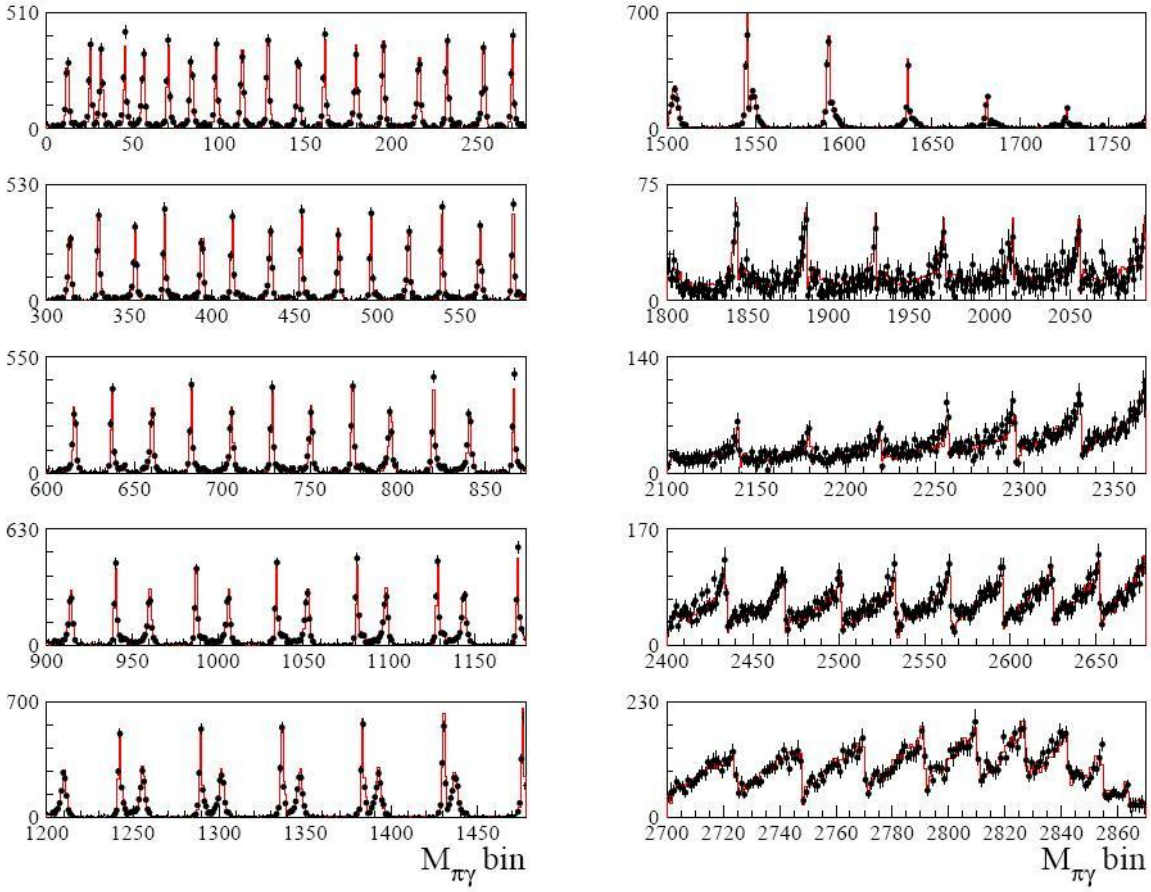
Fit result - KL



Best fit shown in $M_{\pi\pi}$ slices χ^2/ndf = 2754 / 2676 $P(\chi^2)$ = 14.5 %

Bad quality fit without σ(600) $P(\chi^2) \rightarrow 10^{-4}$

Fit result - NS



Fit result shown in $M_{\pi\pi}$ slices

$P(\chi^2) = 4.2$ %

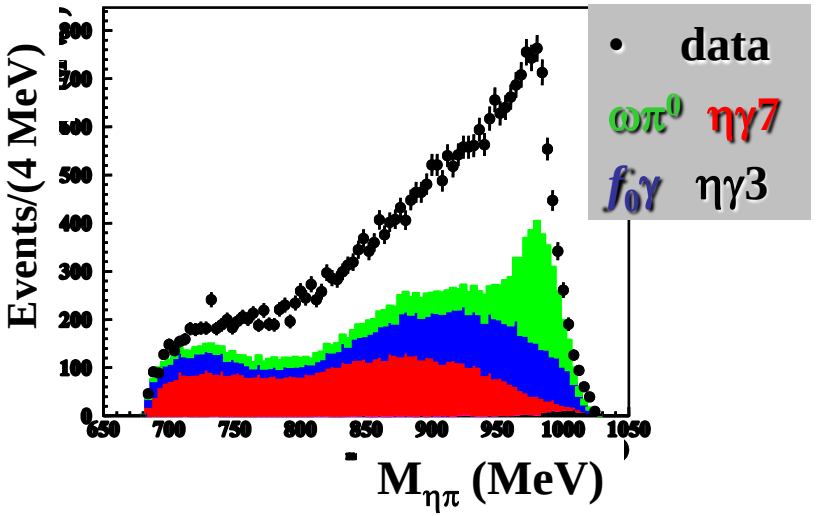
$\phi \to \eta\pi^0\gamma$; $\eta \to \gamma\gamma$

Event selection: 5 prompt photons with $\theta_\gamma > 21^o$; no tracks

Kinematic fit: energy-momentum conservation $\Rightarrow$ best γ pairing to π^0 and η

Kinematic fit with constraints on π^0 and η masses

3×10^4 events --Global $\varepsilon \approx 38\%$



Background processes:

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

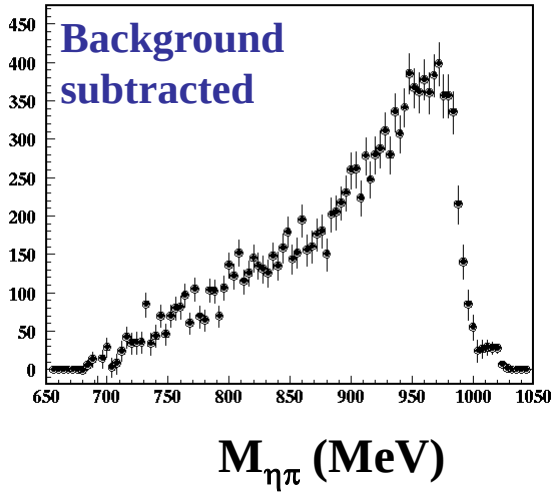
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$

$\phi \to \eta\gamma$; $\eta \to \pi^0\pi^0\pi^0$

$\phi \to \eta\gamma$; $\eta \to \gamma\gamma$

- Total background = 55% (evaluated by MC)
- Normalizing to the number of produced ϕ's

$[N_\phi = (1.24 \pm 0.03) \times 10^9]$



$$Br(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10_{stat} \pm 0.23_{syst}) \times 10^{-5}$$

[arXiv:0707.4609]

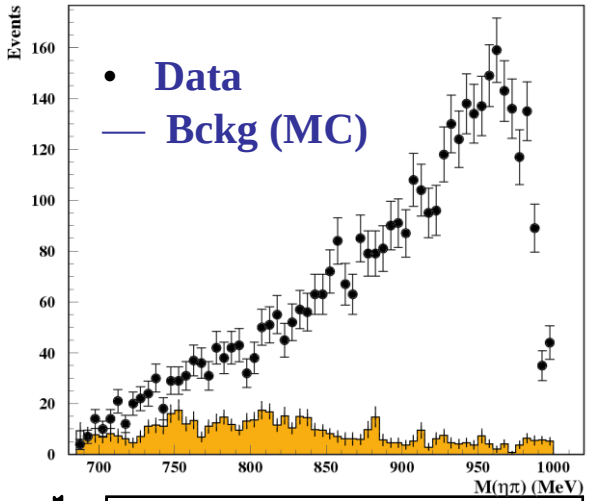
$\phi \to \eta\pi^0\gamma$; $\eta \to \pi^+\pi^-\pi^0$

Event selection: 2 charged tracks + 5 prompt photons with $\theta_\gamma > 21^o$

Kinematic fit: energy-momentum conservation $\Rightarrow$ best γ pairing to π^0's

Kinematic fit with constraints on π^0 and η masses

4.5×10^4 events --Global $\varepsilon \approx 20\%$

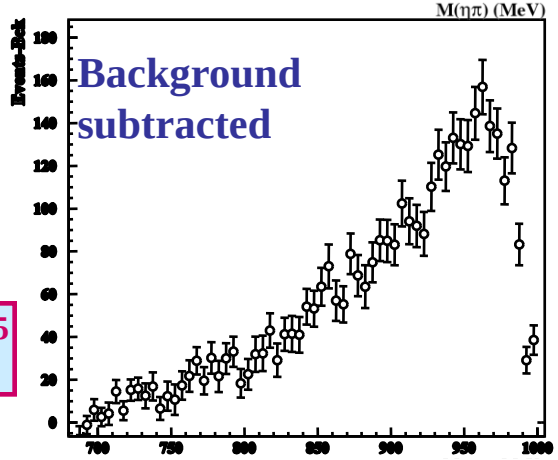


Total background = 15%

($\pi^+\pi^-$ + 4 or 6 photons from $e^+e^- \to \omega\pi^0$; $\omega \to \pi^+\pi^-\pi^0$

$\phi \to K_S K_L \to \pi^+\pi^- 3\pi^0$)

Normalizing to the number of ϕ's



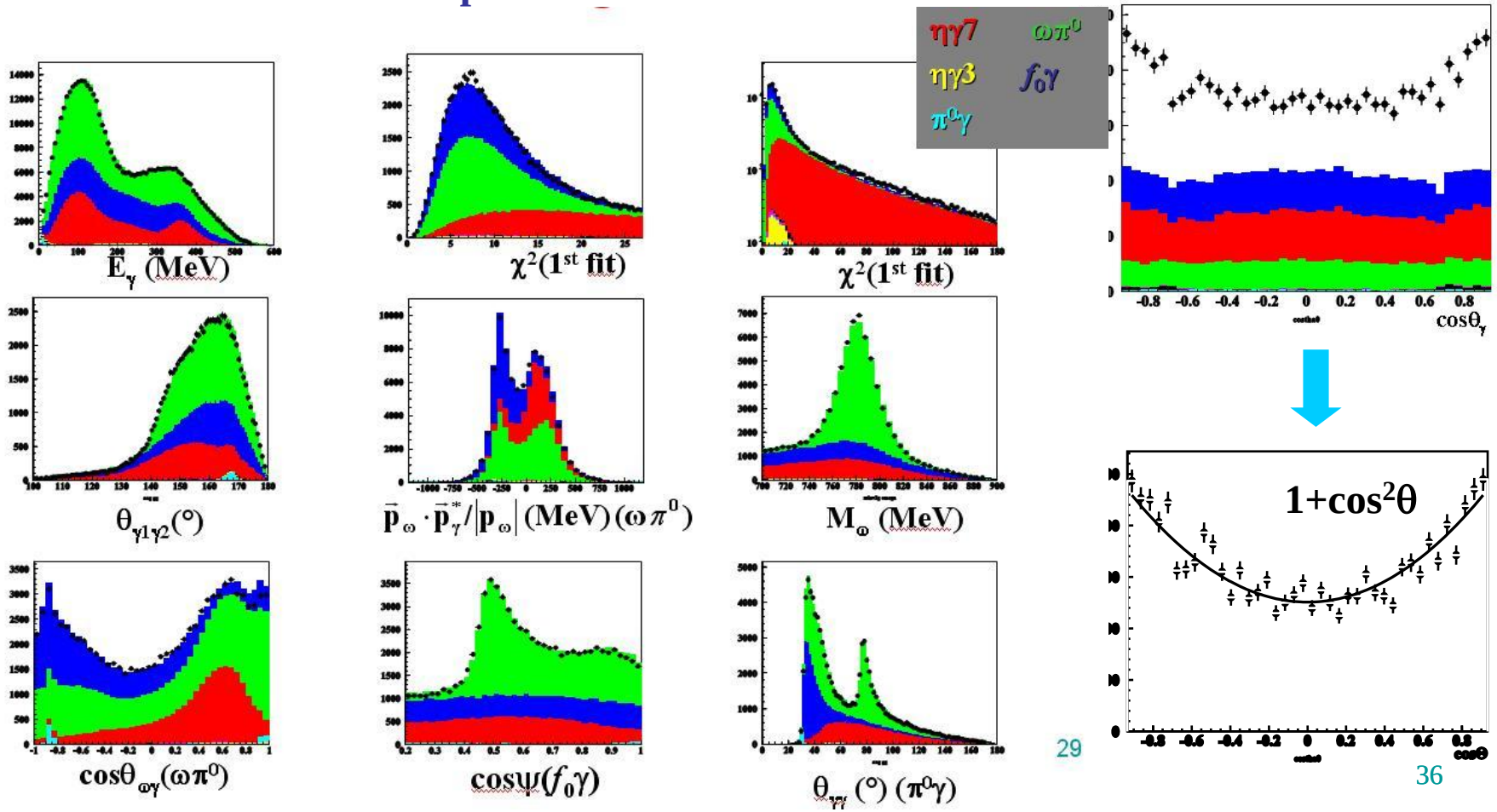
$$Br(\phi \to \eta\pi^0\gamma) = (7.12 \pm 0.13_{stat} \pm 0.24_{syst}) \times 10^{-5}$$

Combining the two results:

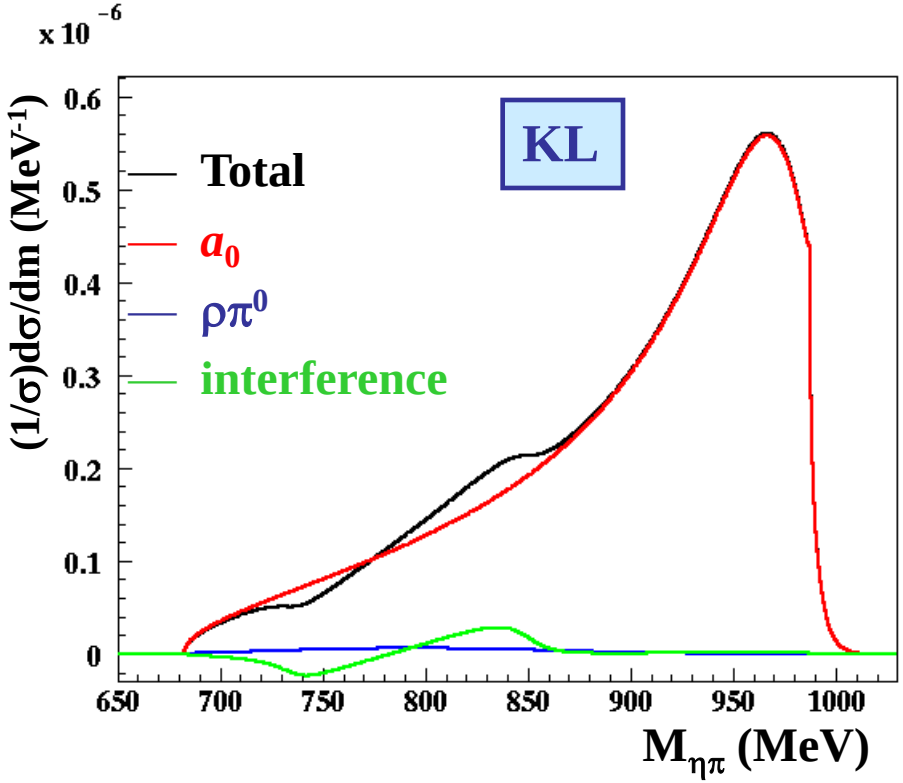
$$Br(\phi \to \eta\pi^0\gamma) = (7.06 \pm 0.08_{stat} \pm 0.11_{syst} \pm 0.18_{norm}) \times 10^{-5}$$

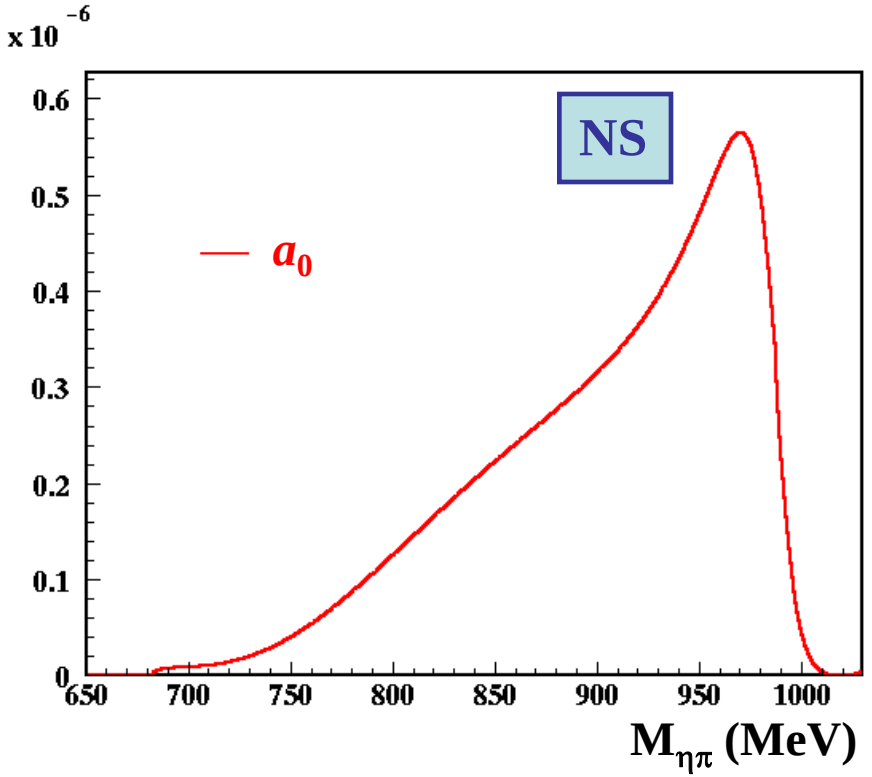
$\phi \to \eta\pi^0\gamma$; $\eta \to \gamma\gamma$

- **Irreducible background subtraction: selection of data samples background dominated; signal content ~ few %**
- **A weight for each background process has been obtained from the fit of some distributions with MC shapes.**



$a_0(980)$ shape


x 10 −6
(1/σ)dσ/dm (MeV-1)
KL
Total
a0
ρπ0
interference
Mηπ (MeV)


x 10 −6
NS
a0
Mηπ (MeV)

Scalar propagator (KL)

[Achasov-Kiselev PRD70(2004)]

$$D_R(m) = m_R^2 - m^2 + \sum_{ab} [\mathrm{Re}\Pi_R^{ab}(m_R^2) - \Pi_R^{ab}(m^2)]$$

$m_a \geq m_b,\ m \geq m_+,$

$$\Pi_R^{ab}(m^2) = \frac{g_{Rab}^2}{16\pi}\left[\frac{m_+ m_-}{\pi m^2}\ln\frac{m_b}{m_a} + \rho_{ab}\left(i + \frac{1}{\pi}\ln\frac{\sqrt{m^2 - m_-^2} - \sqrt{m^2 - m_+^2}}{\sqrt{m^2 - m_-^2} + \sqrt{m^2 - m_+^2}}\right)\right]$$

$m_- \leq m < m_+$

$$\Pi_R^{ab}(m^2) = \frac{g_{Rab}^2}{16\pi}\left[\frac{m_+ m_-}{\pi m^2}\ln\frac{m_b}{m_a} - |\rho_{ab}(m)| + \frac{2}{\pi}|\rho_{ab}(m)|\arctan\frac{\sqrt{m_+^2 - m^2}}{\sqrt{m^2 - m_-^2}}\right].$$

$m < m_-$

$$\Pi_R^{ab}(m^2) = \frac{g_{Rab}^2}{16\pi}\left[\frac{m_+ m_-}{\pi m^2}\ln\frac{m_b}{m_a} - \frac{1}{\pi}\rho_{ab}(m)\ \ln\frac{\sqrt{m_+^2 - m^2} - \sqrt{m_-^2 - m^2}}{\sqrt{m_+^2 - m^2} + \sqrt{m_-^2 - m^2}}\right].$$

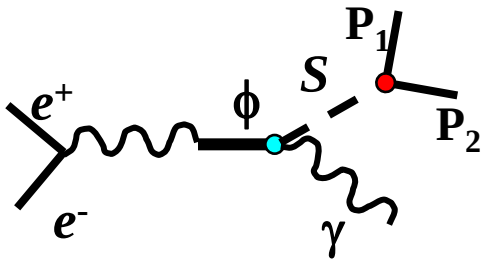
- **Scalar propagator with finite width corrections:**

  [$a,b=\pi\pi$, K^+K^-, $K^0\overline{K}^0$, $\eta\eta$, $\eta\eta'$, $\eta'\eta'$ for $f_0(980)$;

  " $=\eta\pi^0$, K^+K^-, $K^0\overline{K}^0$, $\eta'\pi^0$ for $a_0(980)$]

$\phi \to S\gamma$ models

2. "No Structure" [G.Isidori, L.Maiani et al., JHEP0605(2006)049]



- $g_{\phi S\gamma}$
- g_{SPP}

$$M_{NS} \propto \frac{e}{4F_\phi} \frac{sM_\phi^2}{D_\phi(s)} \left[\frac{g_{SPP}\, g_{\phi S\gamma}}{D_S(m^2)} + \frac{a_0}{m_\phi^2} + a_1 \frac{m^2 - m_S^2}{m_\phi^4} \right]$$

- **The scalar is a BW with energy-dependent width, taking into account for $K^+K^-, K^0\overline{K}^0$ threshold opening (Flatte' formula)**

Fit of $M(\pi^+\pi^-)$

$$\frac{d\sigma}{dm} = (\mathrm{ISR}) + (\mathrm{FSR}) + (\rho\pi) + (\mathrm{scalar}) + (\mathrm{scalar} - \mathrm{FSR\ \ interf.})$$

- **ISR: pion FF ($\rho + \omega + \rho'$)** [Kühn-Santamaria ZPC48 (1990) 455]
  - **Free parameters: $M_{\rho 0}$, $\Gamma_{\rho 0}$, α, β (sizes of ω and ρ' contributions)**
  - **ω and ρ' masses and widths fixed**

- **FSR fixed** [Achasov,Gubin,Solodov PRD55(1997)2672)]

- **$\rho\pi$:($\phi \to \rho^{\pm}\pi^{\mp}$; $\rho^{\pm} \to \pi^{\pm}\gamma$) VDM, a scale factor ($a_{\rho\pi}$) free**

- **scalar-FSR interference** [Achasov-Gubin PRD57 (1998) 1987]

- **scalar amplitude: 1. Kaon loop**

  Free parameters: M_{f0}, g_{fK+K-}, $g_{f\pi+\pi-}$

  2. No structure

  Free parameters: M_{f0}, g_{fK+K-}, $g_{f\pi+\pi-}$, $g_{\phi f\gamma}$, a_0, a_1, b_1

$\eta \to \pi^0\gamma\gamma$

- χPT: $O(p^2) \propto Q = 0$;

  $O(p^4)$ @ tree level = 0; $O(p^4)$ @ 1 loop suppressed by G-parity

  $\Rightarrow O(p^6)$ test

- Recent measurements $\Rightarrow$ Br($\eta \to \pi^0\gamma\gamma$): $(7.2 \pm 1.4) \times 10^{-4}$ GAMS (1984)

  $< 8.4 \times 10^{-4}$@90% C.L. SND (2001)

  $(3.5 \pm 0.7 \pm 0.6) \times 10^{-4}$ Crystal Ball@AGS (2005)

  $(2.24 \pm 0.46 \pm 0.17) \times 10^{-4}$ Crystal Ball@MAMI(2007)

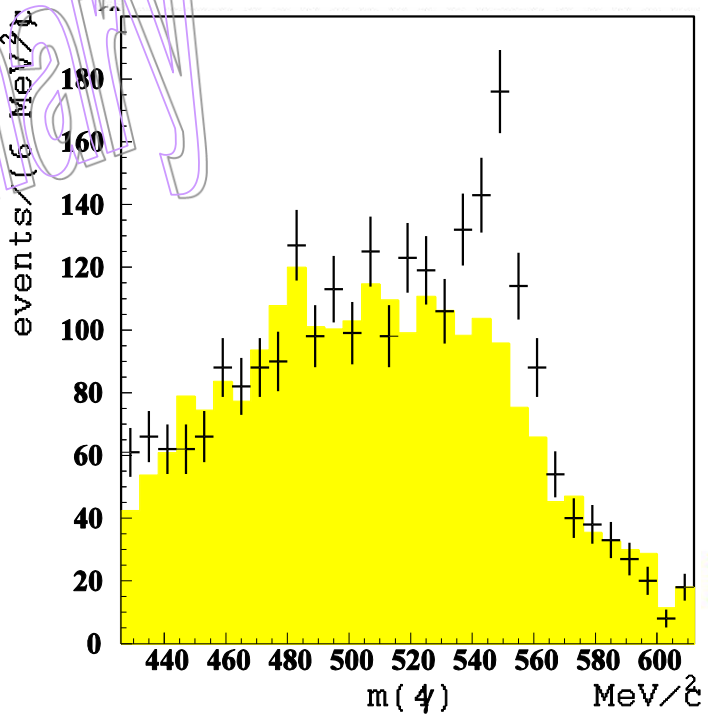
- KLOE $\Rightarrow$ $\phi \to \eta\gamma$; $\eta \to \pi^0\gamma\gamma$
- Backg.: (1) 5γ processes: $\phi \to a_0\gamma, f_0\gamma$;

  $e^+e^- \to \omega\pi^0$ ($\omega \to \pi^0\gamma$)

  (2) $\phi \to \eta\gamma$; $\eta \to \pi^0\pi^0\pi^0$
- L ≈ 450 pb^{-1}

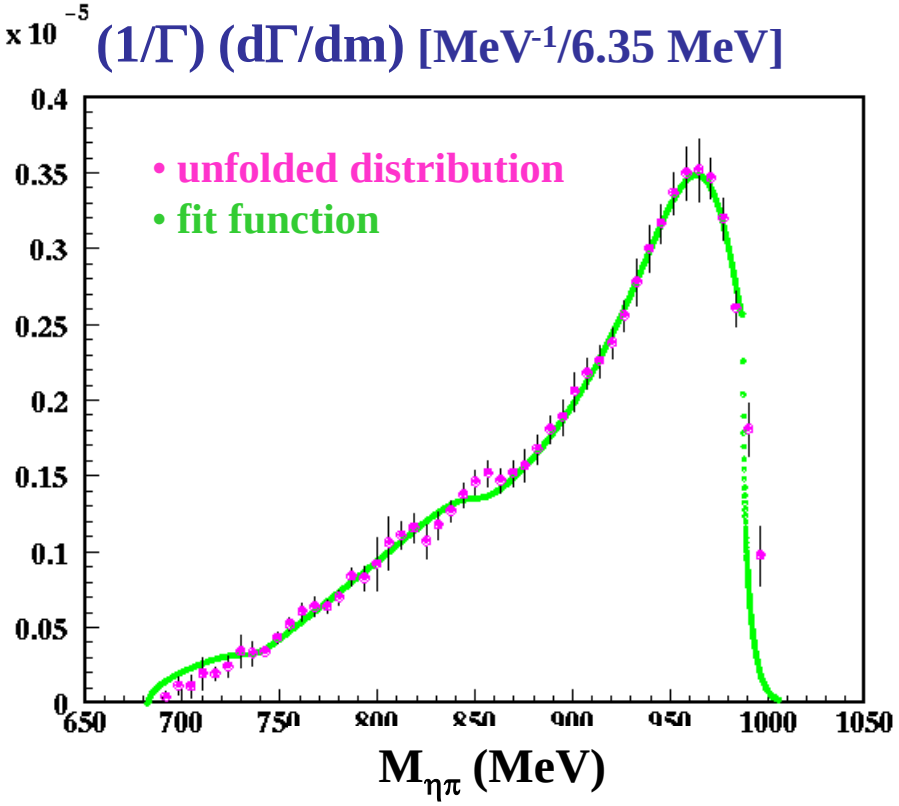
$\Rightarrow$ **Br($\eta \to \pi^0\gamma\gamma$) = (8.4 ± 2.7 ± 1.4) × 10^{-5}**

- 1.5 fb^{-1} $\Rightarrow$



Check of the unfolding result

- **Fit the unfolded invariant mass distribution to the Achasov function (without smearing matrix)**



	This fit	Kaon Loop fit
M_{a0} (MeV)	980.7 ± 0.8	982.5 ± 1.3 ± 1.0
$g_{aK^+K^-}$ (GeV)	2.10 ± 0.02	2.15 ± 0.05 ± 0.06
$g_{a\eta\pi}$ (GeV)	2.84 ± 0.02	2.82 ± 0.04 ± 0.04
$g_{\phi a\gamma}$ (GeV^{-1})	1.5 ± 0.1	1.6 ± 0.1 ± 0.1
δ (°)	212 ± 8	222 ± 12 ± 3
Br(VDM) ×10^6	0.88 ± 0.25	0.92 ± 0.40 ± 0.15
$R_{a0}=(g_{a0K^+K^-}/g_{a0\eta\pi})^2$	0.55 ± 0.01	0.58 ± 0.02 ± 0.03
χ^2 / ndf	62.7/46	157.6 / 136
P(χ^2)	5.1%	9.9%

(Free parameters in red)

$\eta \to \pi^+\pi^-\pi^0$

- $\eta \to \pi\pi\pi$ decay $\Rightarrow$ Isospin violation $\quad L_I = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$

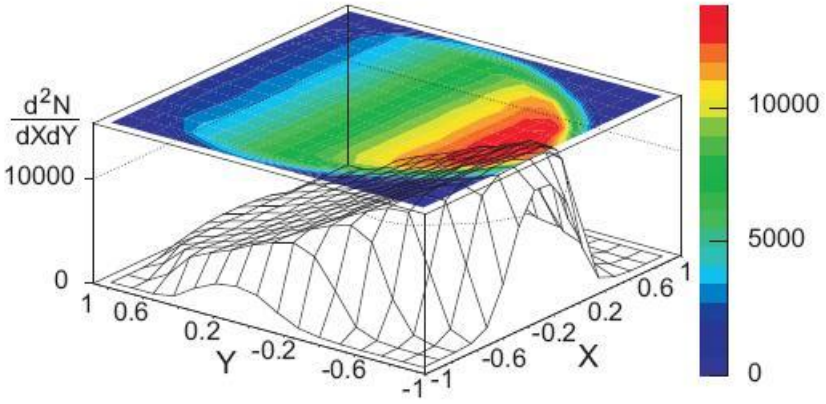
$\phi \to \eta\gamma$; $\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$ ($E_{\gamma rec}$ = 363 MeV)
450 pb^{-1} $\Rightarrow$ 1.34 $\times$ 10^6 events in the Dalitz plot

$$X = \sqrt{3}\frac{E_+ - E_-}{Q}\,;\; Y = 3\frac{E_0 - m_0}{Q}$$

$$(Q = m_\eta - 2m_{\pi^\pm} - m_{\pi^0})$$

$$|A(X,Y)|^2 = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3$$

a	$-1.090 \pm 0.005\ ^{+\,0.008}_{-\,0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006\ ^{+\,0.007}_{-\,0.016}$
e	$-0.006 \pm 0.007\ ^{+\,0.005}_{-\,0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
P(χ^2)	73%



- c, e compatible with zero (C violation)
- fit without cubic term (fY^3) $\Rightarrow$ P(χ^2) ~ 10^{-6}

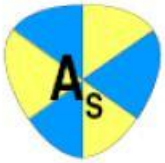
] [JHEP0805(2008)006]

$\eta \to \pi^+\pi^-\pi^0$

- **Asymmetries $\Leftrightarrow$ C violation**

Left-right asymmetry(*c*, *e* parameters) $A_{LR} = (9 \pm 10^{+9}_{-14}) \times 10^{-4}$

Quadrant asymmetry: $\not C$ in $\Delta I = 2$ $A_Q = (-5 \pm 10^{+3}_{-5}) \times 10^{-4}$



Sextant asymmetry: $\not C$ in $\Delta I = 1$ $A_S = (8 \pm 10^{+8}_{-13}) \times 10^{-4}$

PDG'06 $\Rightarrow$

$A_{LR} = (9 \pm 17) \times 10^{-4}$

$A_Q = (-17 \pm 17) \times 10^{-4}$

$A_S = (18 \pm 16) \times 10^{-4}$

- **All asymmetries compatible with zero at 10^{-3} level**

[JHEP0805(2008)006]

$\eta \to \pi^0\pi^0\pi^0$

- **Symmetric Dalitz plot:** $|A|^2 \propto 1 + 2\,\alpha\, Z$ **⇒ only one parameter**

$$Z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - M_\eta}{M_\eta - 3M_\pi}\right)^2 = \frac{\rho^2}{\rho^2_{max}}$$

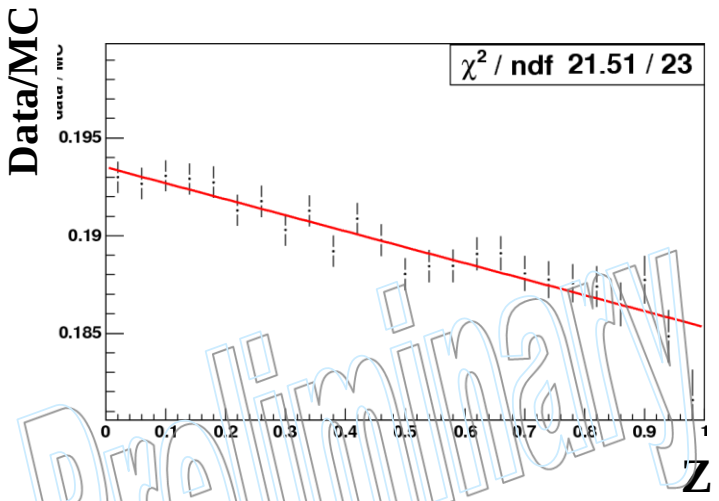
(ρ = distance from the Dalitz plot center)

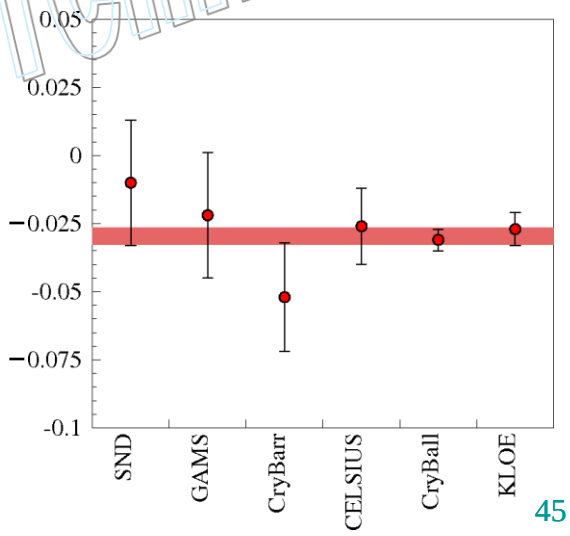
- α evaluated normalizing the data to MC density (pure phase-space ⇒ $|A|^2$ =constant)

- 450 pb^{-1} ⇒ 6.5 ×10^5 events

$$\alpha = -0.027 \pm 0.004^{+0.004}_{-0.006}$$

(using the KLOE value of the η mass)

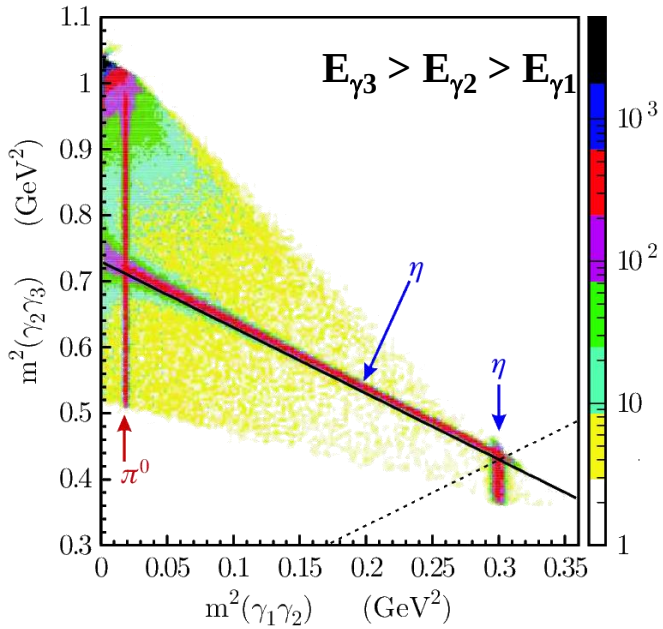


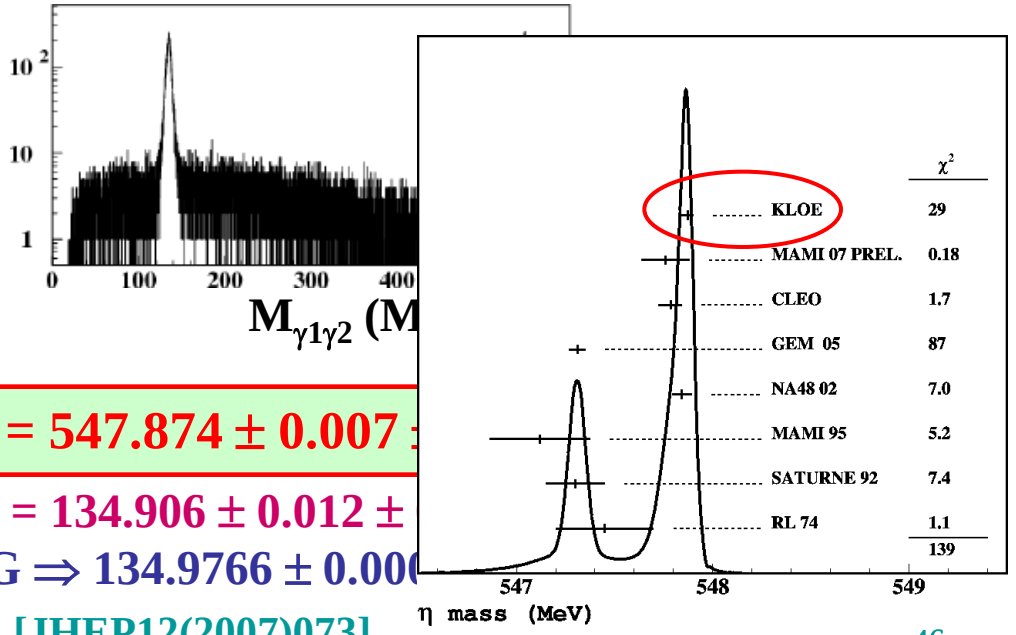


[arXiv:0707.4137v1]

η mass measurement

- 8 σ discrepancy: GEM (COSY) ⇒ $M_\eta = 547.311 \pm 0.028 \pm 0.032$ MeV
  $(p + d \rightarrow {}^3He + \eta)$
  NA48 ⇒ $M_\eta = 547.843 \pm 0.030 \pm 0.041$ MeV
  $(\pi^- + p \rightarrow \eta + n$ with $\eta \rightarrow 3\pi^0)$
- Recent CLEO-c measurement: $M_\eta = 547.785 \pm 0.017 \pm 0.057$ MeV $(\psi' \rightarrow J/\psi\, \eta)$
- KLOE: $\phi \rightarrow \eta\gamma$; $\eta \rightarrow \gamma\gamma$ check with $\phi \rightarrow \pi^0\gamma$; $\pi^0 \rightarrow \gamma\gamma$





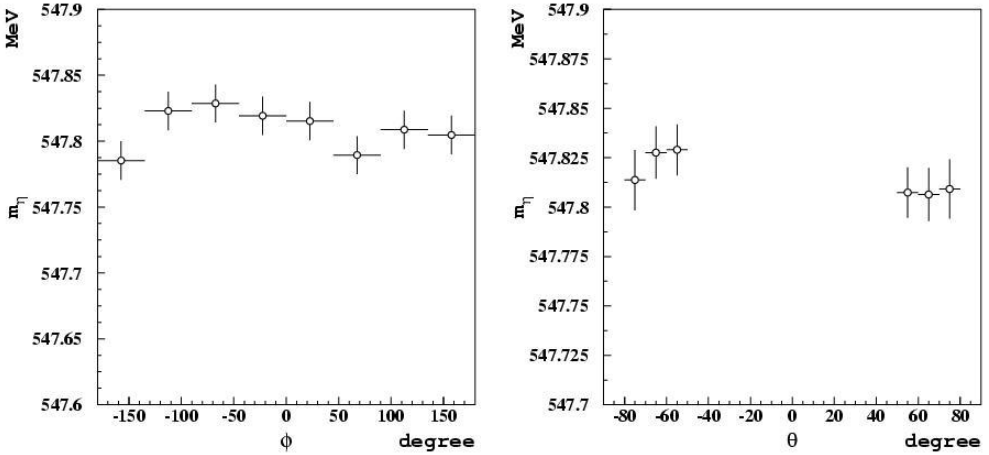
$M_\eta = 547.874 \pm 0.007$:

$M_{\pi 0} = 134.906 \pm 0.012 \pm$

PDG ⇒ 134.9766 ± 0.00

Systematics on M_η (1)

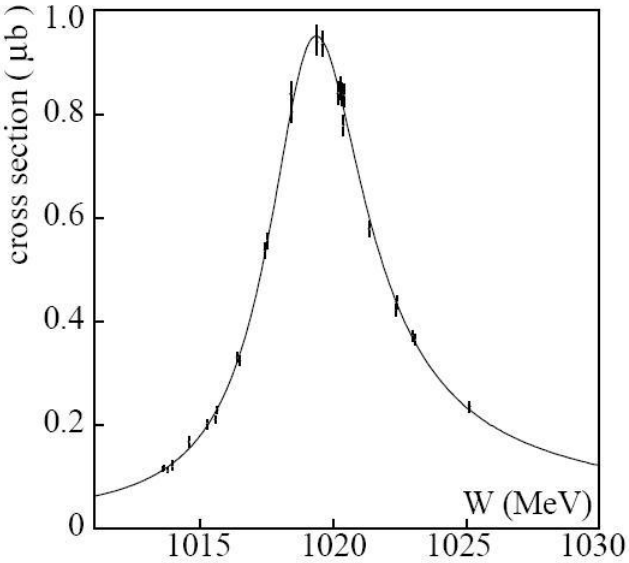
- Vertex (IP) position from Bhabha events (run by run)
  + detector misalignment (with $\pi^+\pi^-\gamma$ events)
- Calorimeter calibration (run by run) with *mip* + Bhabha scattering events; energy scale set with $e^+e^-\to\gamma\gamma$
- Linearity better than 1% for $E_\gamma > 75$ MeV
- ϑ and φ non uniformity (normal to the 3γ plane)
- Dalitz plot cut



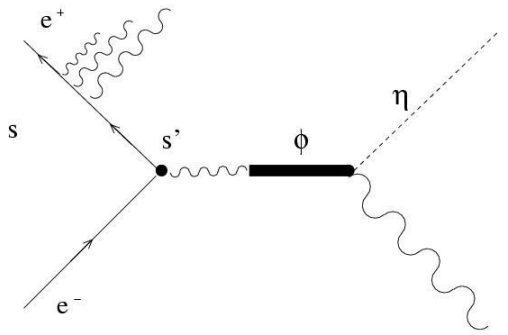
Systematics on M_η (2)

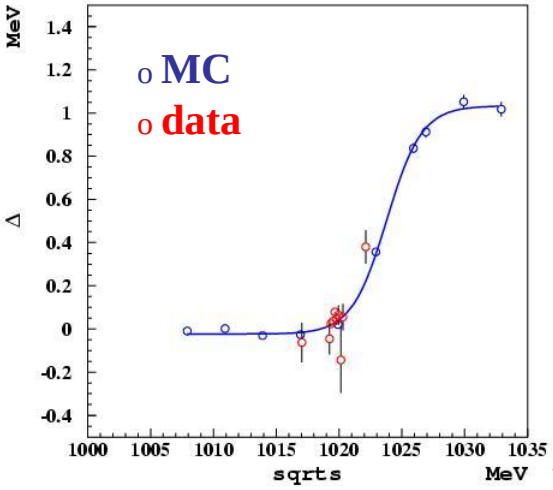
- $\sqrt{s}$ run by run with Bhabha events (stat. uncert. ~ 3 keV)
- Absolute energy scale: ϕ peak from fit of $e^+e^- \to K_S K_L$, normalized to CMD2 measurement (resonance depolarization)

  $\Rightarrow M_\phi = 1019.483 \pm 0.011 \pm 0.025$ MeV



- Initial State Radiation

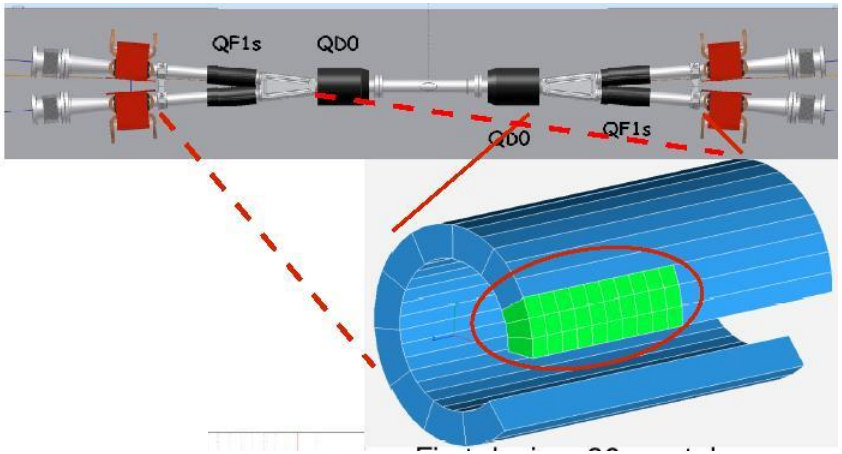




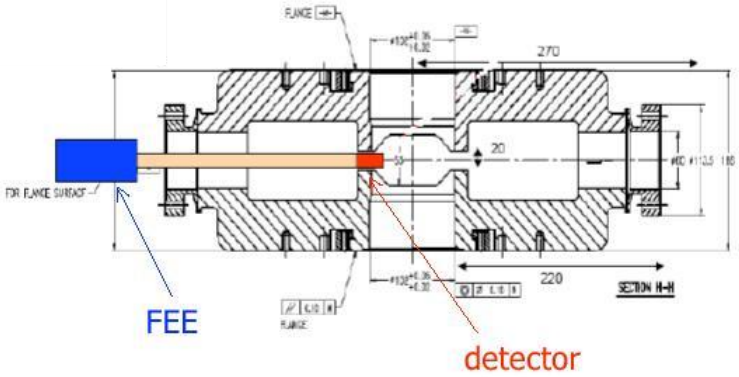
Systematic effect	m_η (keV)	m_{π^0} (keV)
Vertex position	4	6
Calorimeter energy scale	4	1
Calorimeter non-linearity	4	11
θ angular uniformity	10	44
ϕ angular uniformity	15	12
χ^2 cut	<1	4
Dalitz plot cut	12	4
ISR emission	8	9
Total	24	48

Tagger for γγ physics

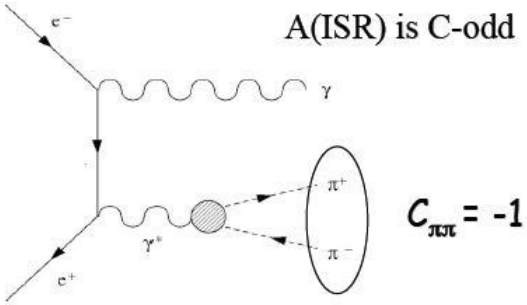
- **LET: crystals read-out by SiPM**
  requirements: $\sigma_E/E = 5 - 10\%/\sqrt{E}$
  @ E≈200 MeV
  time resolution $\sigma_t \sim 2$ ns

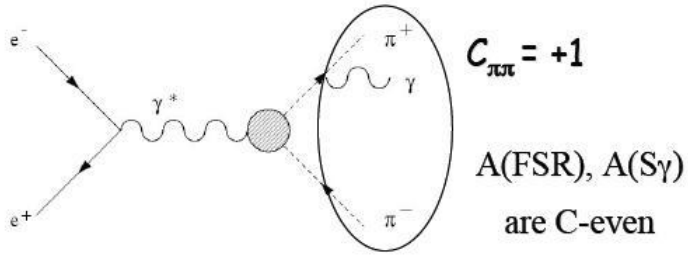


- **HET: space resolution < 1 mm**



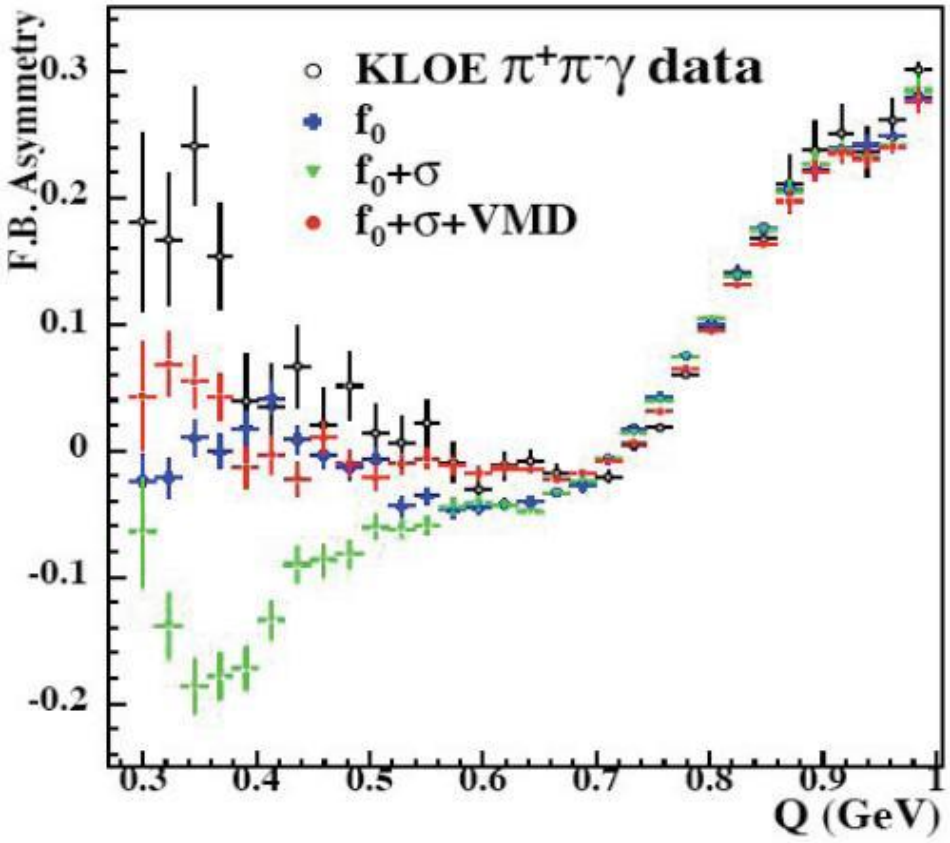
F-B asymmetry





$$A_{FB} = \frac{N(\vartheta_+ > 90°) - N(\vartheta_+ < 90°)}{N(\vartheta_+ > 90°) + N(\vartheta_+ < 90°)}$$

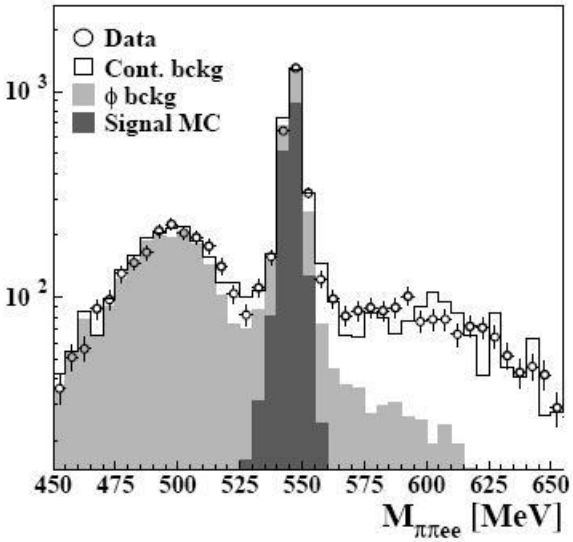
- **$f_0(980)$ evidence at M(ππ) ≈ 980 MeV**
- **Data-MC agreement recovered also at low M(ππ)**
  [Pancheri, Shekhovtsova Venanzoni, PLB642(2006),342]
- **Improved simulation with f_0 and σ parameters from $\pi^0\pi^0\gamma$ analysis**
  [Pancheri, Shekhovtsova Venanzoni, arXiv0706.3027]

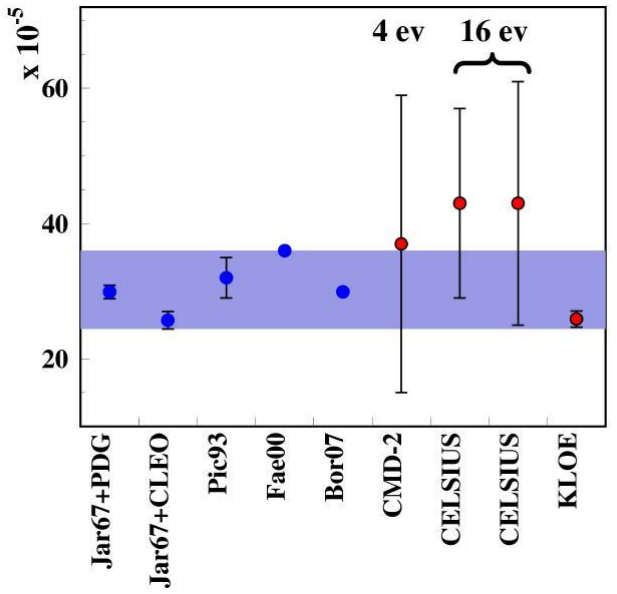


$\eta \to \pi^+\pi^-e^+e^-$

- Rare decay: χPT and
  VDM predictions $\Rightarrow$ Br ~ 3×10^{-4}
- 2 measurements: CMD-2 4 events
  WASA@CELSIUS 16 events

- Data sample: 1.73 fb^{-1}
- $M(\pi^+\pi^-e^+e^-)$ distribution:
  fit with signal + background (MC)
  $\Rightarrow$ 1555 ± 52 signal events
  368 background "



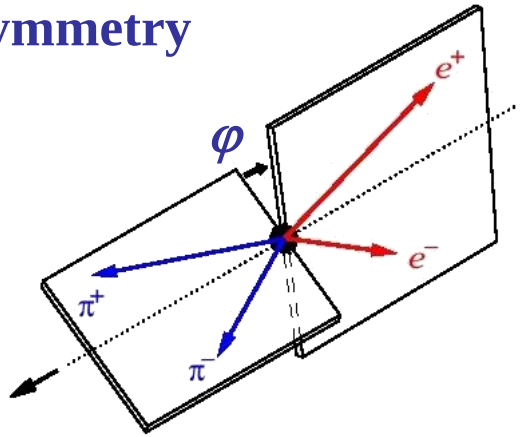


$Br(\eta \to \pi^+\pi^-e^+e^-) = (2.68 \pm 0.09 \pm 0.07) \times 10^{-4}$

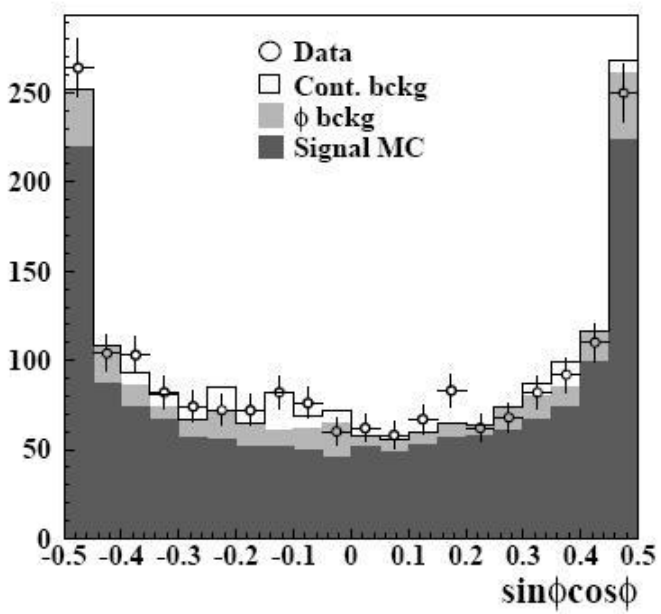
$\eta \to \pi^+\pi^-e^+e^-$

- **D.N.Gao** [MPLA17(2002)] **proposed a non conventional CP violation mechanism (non CKM)**

⇒ plane asymmetry



$$A_{CP} = \frac{N(\sin\varphi\cos\varphi > 0) - N(\sin\varphi\cos\varphi < 0)}{N(\sin\varphi\cos\varphi > 0) + N(\sin\varphi\cos\varphi < 0)} \sim O(10^{-2})$$



$$A_{CP} = (-0.6 \pm 2.5 \pm 1.8) \times 10^{-2}$$