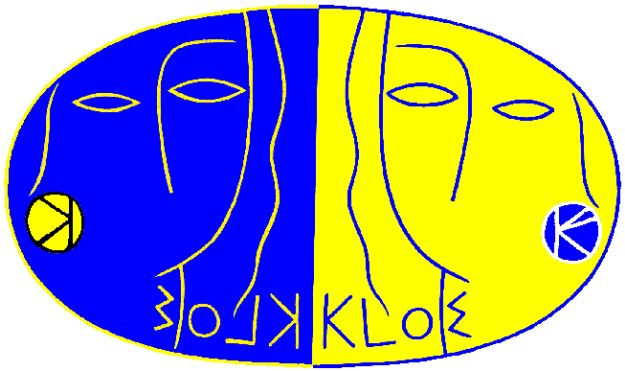
KLOE results on scalar and pseudoscalar mesons



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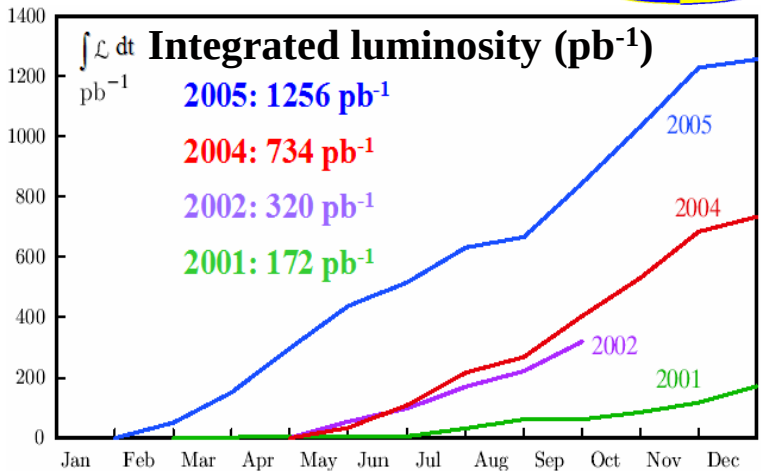
for the KLOE Collaboration

PHIPSI09
13-16 October 2009 – Beijing

DAΦNE

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

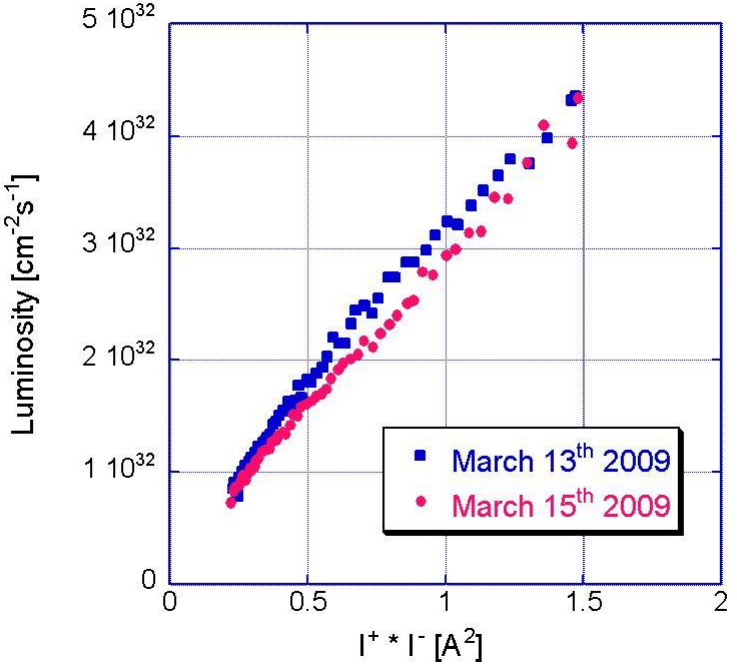
- Best performances in 2005:
  - $L_{peak} = 1.4 \times 10^{32}\ cm^{-1}s^{-1}$
  - $\int Ldt = 8.5\ pb^{-1}/day$
- KLOE: 2.5 fb^{-1} @ $\sqrt{s}=M_\phi$ ($\Rightarrow 8\times10^9$ ϕ produced)
  + 250 pb^{-1} off-peak @ $\sqrt{s}=1000$ MeV



- DAΦNE upgrade:
  New interaction scheme implemented, large beam crossing angle + crab waist

⇒ Luminosity increase: factor ~ 3
  $\int Ldt \approx 1\ pb^{-1}/hour$

- KLOE2 data-taking starting in 2010

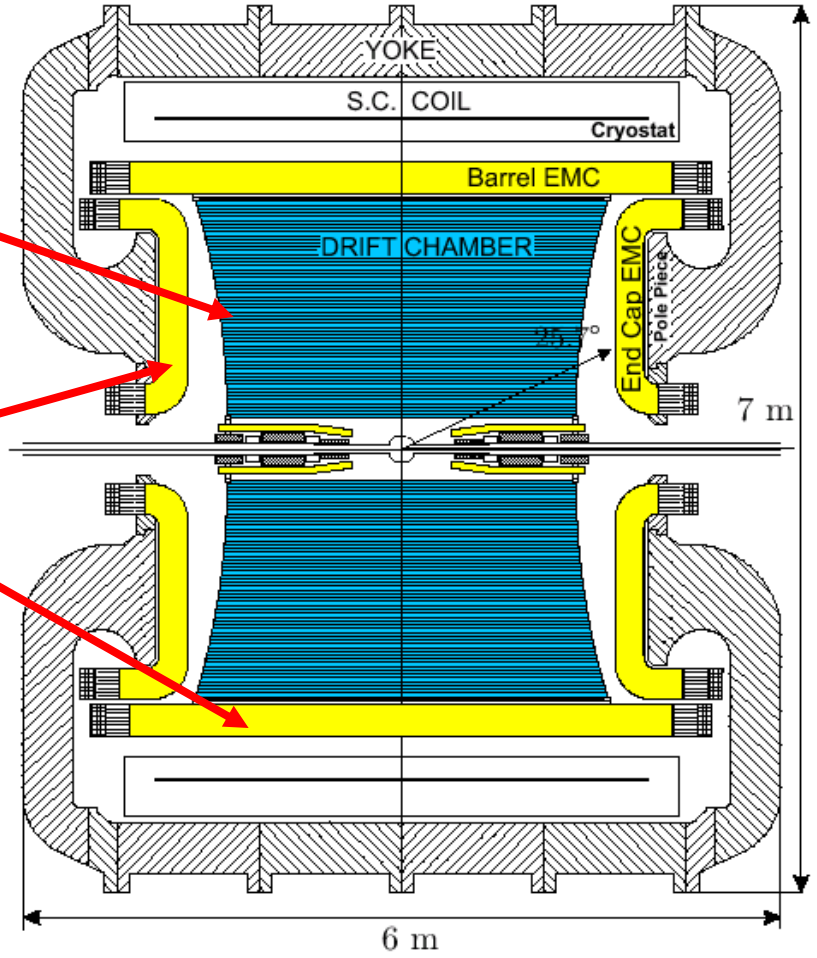


KLOE

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

E.m. 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



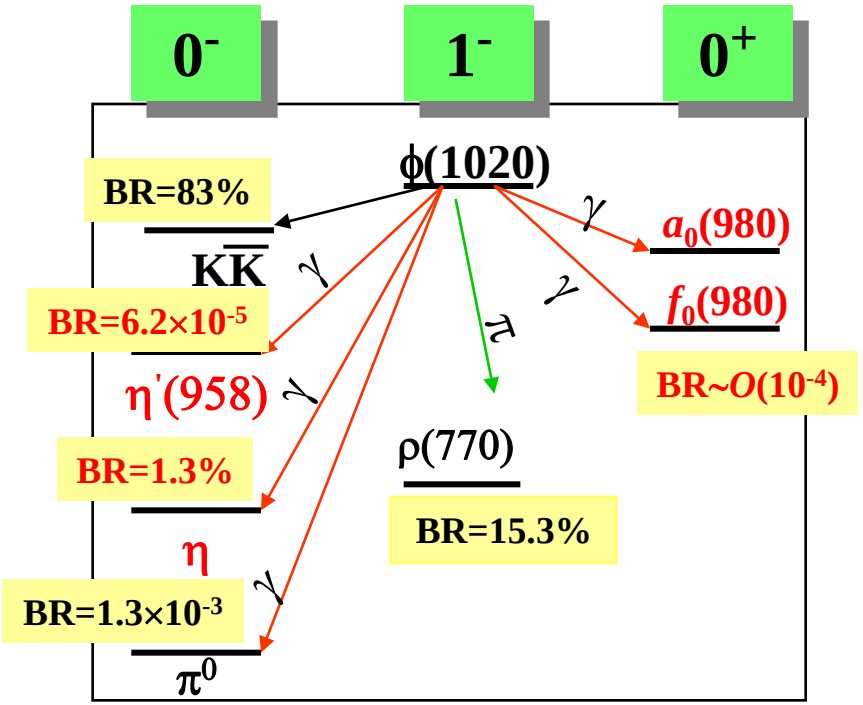
- KLOE2: two step upgrade
  - 1) taggers for $\gamma\gamma$ physics
  - 2) inner tracker +
    - new small angle calorimeters

(see G.Venanzoni's talk)

Physics at a ϕ-factory

- 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 $(g-2)_\mu$
- $\gamma\gamma$ physics

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

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

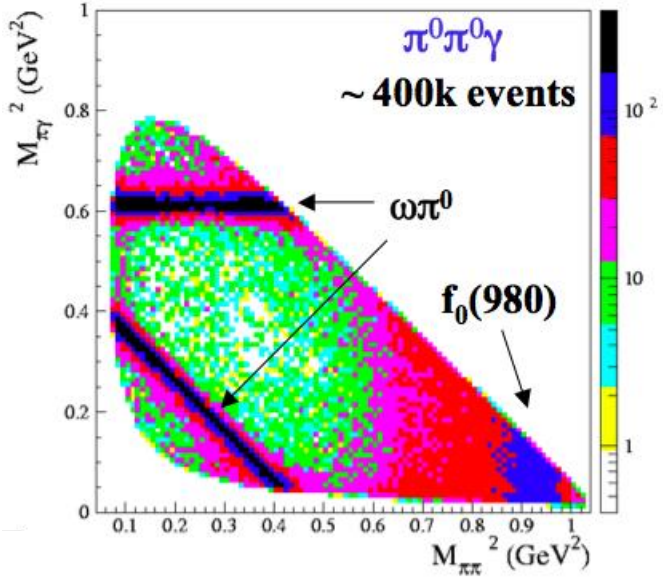
  $\eta\pi^0$ $\Rightarrow$ $a_0(980)$

  K_SK_S $\Rightarrow$ $(f_0/a_0) \to K^0\bar{K}^0$

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

$e^+e^- \to \pi\pi\gamma$: $f_0(980)$

- $f_0(980) \to \pi^0\pi^0$: Dalitz plot study; two contributions, $\phi \to S\gamma$ [S= $f_0(980)$, $\sigma(600)$] and $e^+e^- \to \omega\pi^0$ ($\omega \to \pi^0\gamma$)



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

[EPJC49(2007)473]

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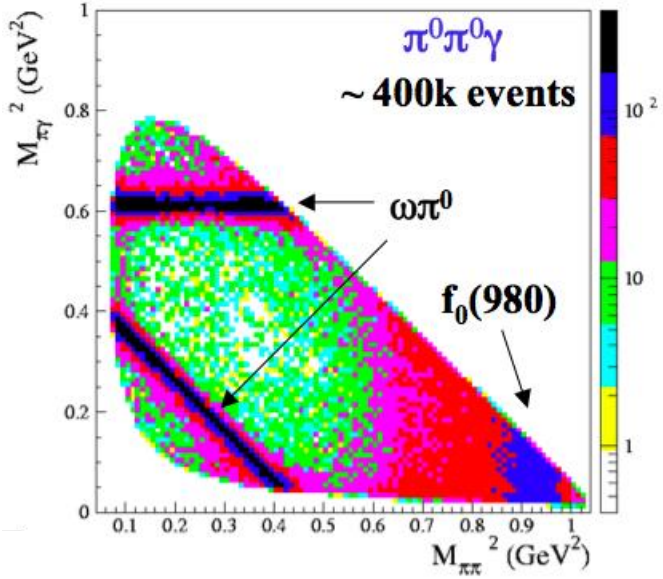

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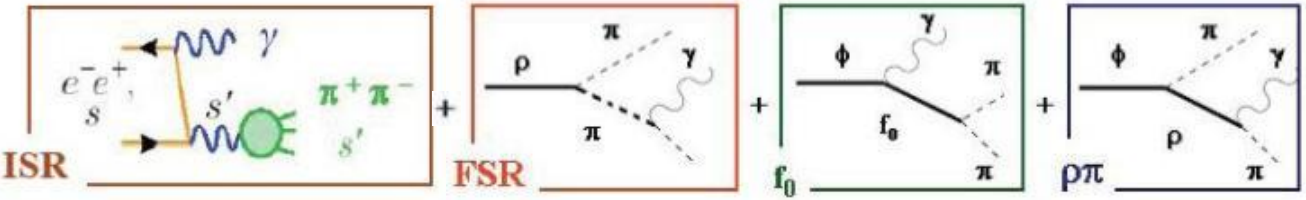
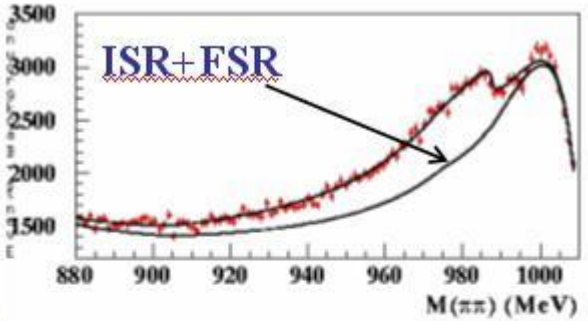
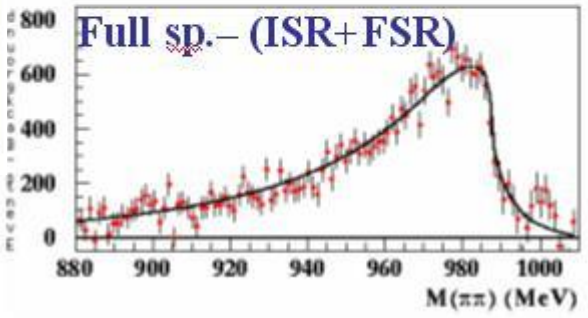
[EPJC49(2007)473]

- $f_0(980) \to \pi^+\pi^-$:

[PLB634(2006)148]







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

$f_0(980)$ parameters

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

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

$f_0(980)$ param.	$f_0\to\pi^0\pi^0$	$f_0\to\pi^+\pi^-$
M_{f0} (MeV)	984.7	983.7
$g_{f0\pi+\pi-}$ (GeV	-1.82	-2.22
g_{f0K+K-} (GeV)	3.97	4.74
$R=(g_{f0K+K-}/g_{f0\pi+\pi-})^2$	~ 4.8	~ 4.6

- Agreement between the two channels
- Next: combined fit

	$f_0\to\pi^0\pi^0$	$f_0\to\pi^+\pi^-$
$g_{\phi f0\gamma}$ (GeV^{-1})	$2.61 \pm 0.02^{+0.31}_{-0.08}$	1.2 – 2.0

- $g_{\phi f0\gamma}$ from fit to No Structure model (point-like coupling $\phi f_0\gamma$)

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

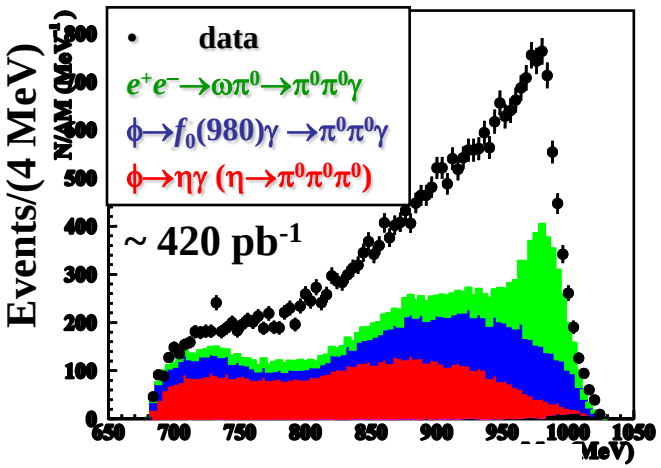
$\phi \to \eta\pi^0\gamma$: $a_0(980)$

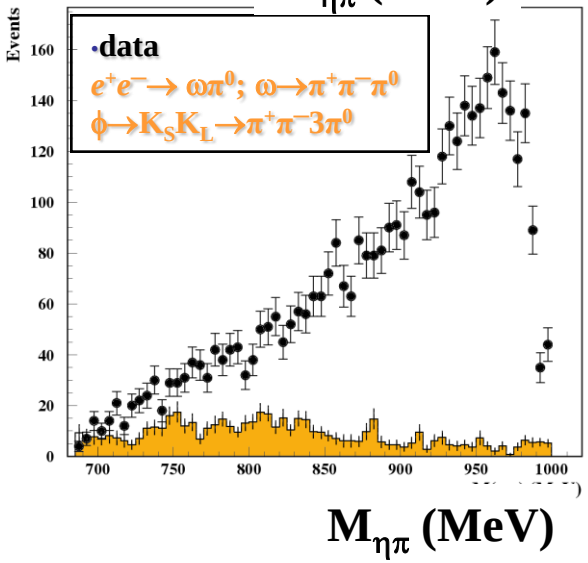
1) $\eta \to \gamma\gamma$ (Br=38.31%) $\Rightarrow$ 5 photon final state
Total background = 55%

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

2) $\eta \to \pi^+\pi^-\pi^0$ (Br=22.73%)$\Rightarrow$ 5γ + 2 tracks
Total background = 15%

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





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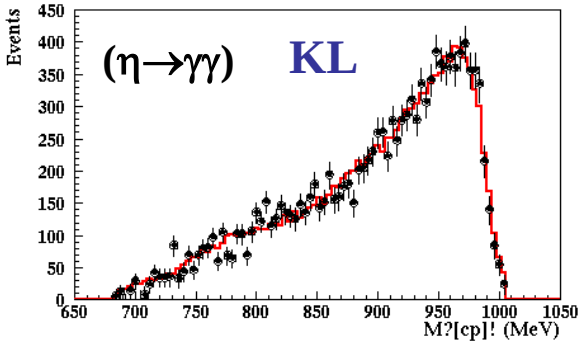
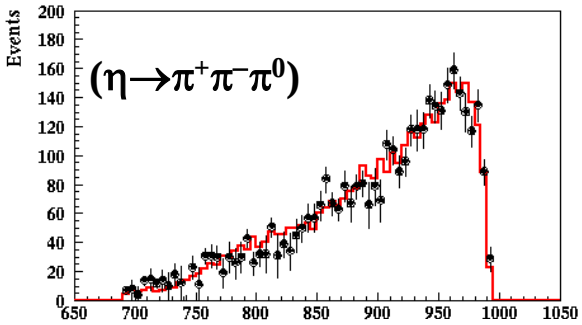
- Combined fit of the two M($\eta\pi^0$) distributions

$\Rightarrow$ Free parameter: $R_\eta = Br(\eta \to \gamma\gamma)/Br(\eta \to \pi^+\pi^-\pi^0)$





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

[PLB681(2009),5]

	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_η	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_{a0} PDG: 985.1 MeV- Belle:$982.3^{+3.2}_{-4.8}$ MeV
$\Gamma_{tot}(a_0)$=80 – 105 MeV
(PDG: 50-100 MeV, Belle: $76.5^{+17.5}_{-10.1}$ MeV
- VDM very small
- PDG $\Rightarrow R_\eta = 1.73 \pm 0.04$

a_0 and f_0 couplings

		SU(3)		
		4q	qqbar	
$(g_{a0K^+K^-} / g_{a0\eta\pi})^2$	0.6 – 0.7	1.2 – 1.7	0.4	
	Crystal Barrel: 0.525 ± 0.043			
	SND (2000) : 1.8 ± 2.5			
$(g_{f0K^+K^-}/g_{f0\pi^+\pi^-})^2$	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			
$(g_{f0K^+K^-}/g_{a0K^+K^-})^2$	4 – 5	1	2	1

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

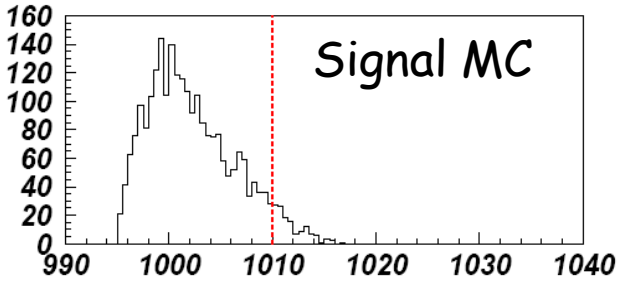
Meson	$g_{\phi M\gamma}$ (GeV^{-1})
π^0	0.13
η	0.71
η'	0.75
$a_0(980)$	1.6 – 1.8
$f_0(980)$	1.2 – 2.8

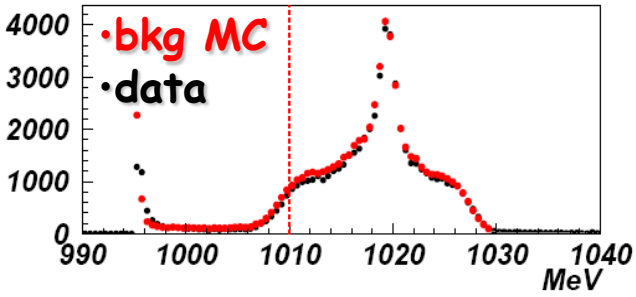
$\phi \to (f_0/a_0)\gamma \to K^0\bar{K}^0\gamma$

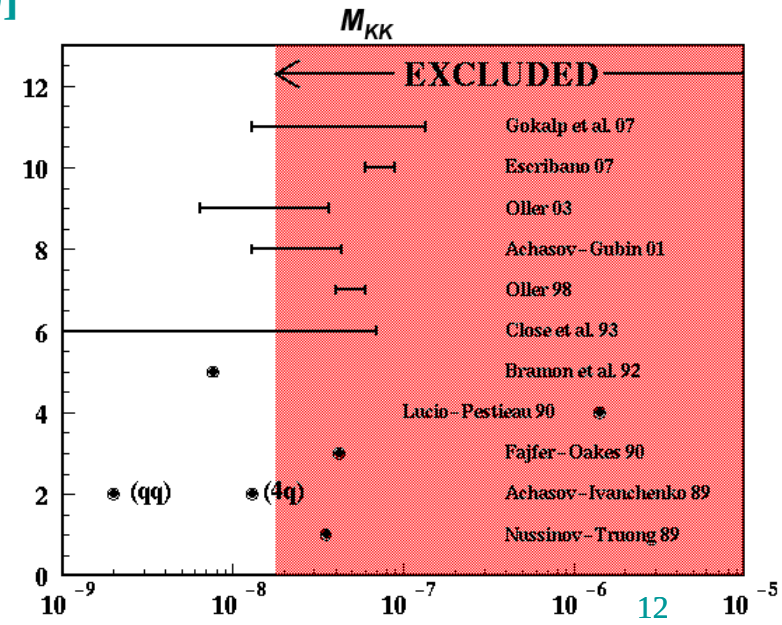
- $K^0\bar{K}^0$ with scalar quantum numbers ($J^{PC}=0^{++}$)
- Small phase space($2M_K \leq M_{KK} \leq M_\phi$)
  $\Rightarrow$ small Br expected ($10^{-9} - 10^{-7}$)
- "Golden channel" $\phi \to K_S K_S \gamma \to \pi^+\pi^-\pi^+\pi^-\gamma$
- Analyzed sample: 2.18 fb^{-1}
- 5 events in data and 3.2 background events (MC) ($\pi^+\pi^-\pi^+\pi^-(\gamma)$ from $\phi \to K_S K_L$ and from continuum)

$$Br(\phi \to K^0\bar{K}^0\gamma) < 1.9 \times 10^{-8} \ @\ 90\%\ C.L.$$

[PLB679(2009),10]







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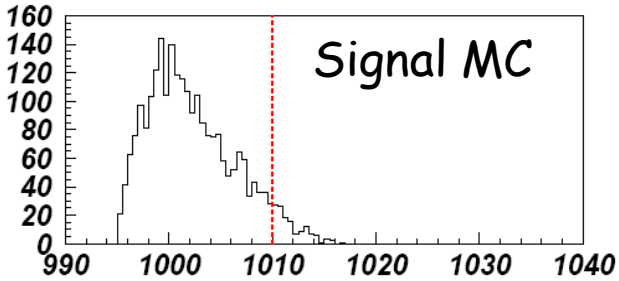
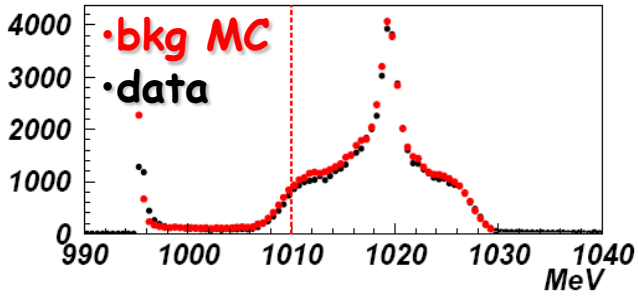




$$Br(\phi \to K^0\bar{K}^0\gamma) < 1.9 \times 10^{-8} \ @\ 90\%\ C.L.$$

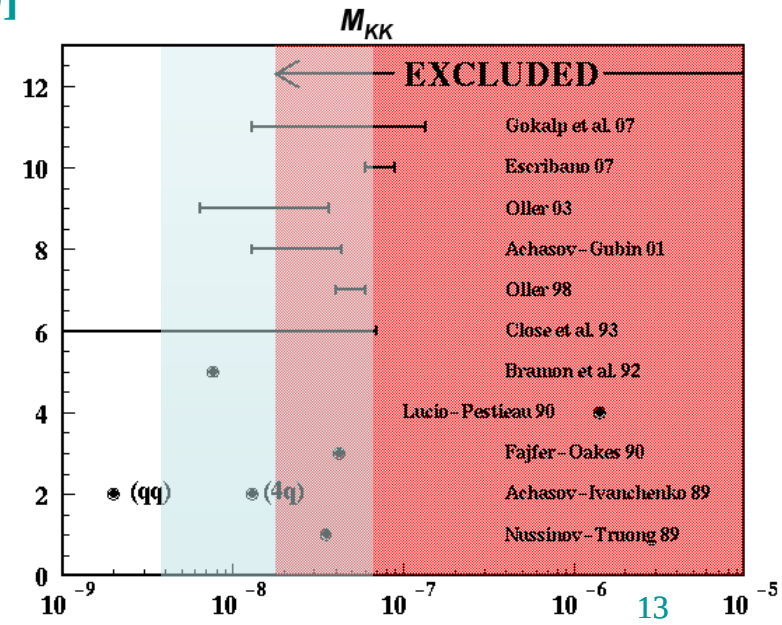
[PLB679(2009),10]

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

$\Rightarrow$ $Br(\phi \to K^0\bar{K}^0\gamma) = 4 \times 10^{-9} - 6.8 \times 10^{-8}$

- KLOE-2 sensitivity (with Inner Tracker) $\Rightarrow$ 0.5×10^{-8}

$\Rightarrow$ First observation possible



Pseudoscalar mesons

- ϕ-factory $\Rightarrow$ large samples of η and η'
- L = 2.5 fb^{-1} $\Rightarrow$ 8×10^9 ϕ $\Rightarrow$ ~ 10^8 η

  $\Rightarrow$ ~ 5×10^5 η'

- η/η' mixing and η' gluonium content
- Dynamics of $\eta \to \pi\pi\pi$ decay
- Rare η decays ($\eta \to \pi^+\pi^- e^+e^-$, $\eta \to \pi^+\pi^-\gamma$, $\eta \to e^+e^-e^+e^-$)

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.

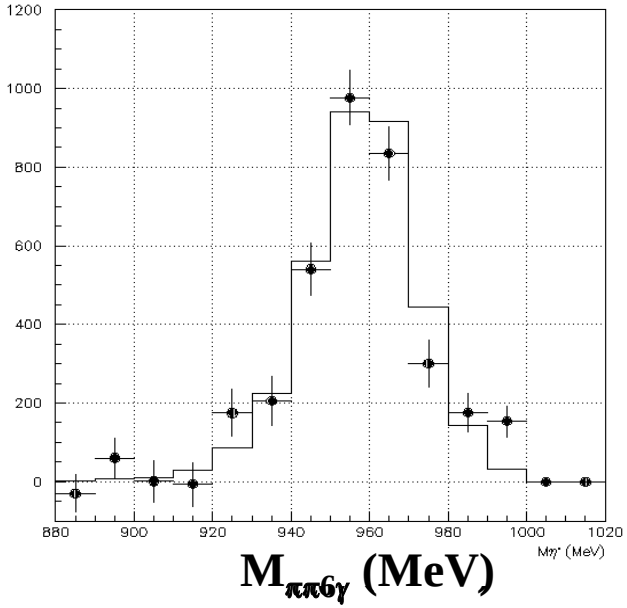
$N_{\eta\gamma} = 16.7 \times 10^6$ ev.

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

[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



[PLB648(2007)267]

- 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

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

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

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

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

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

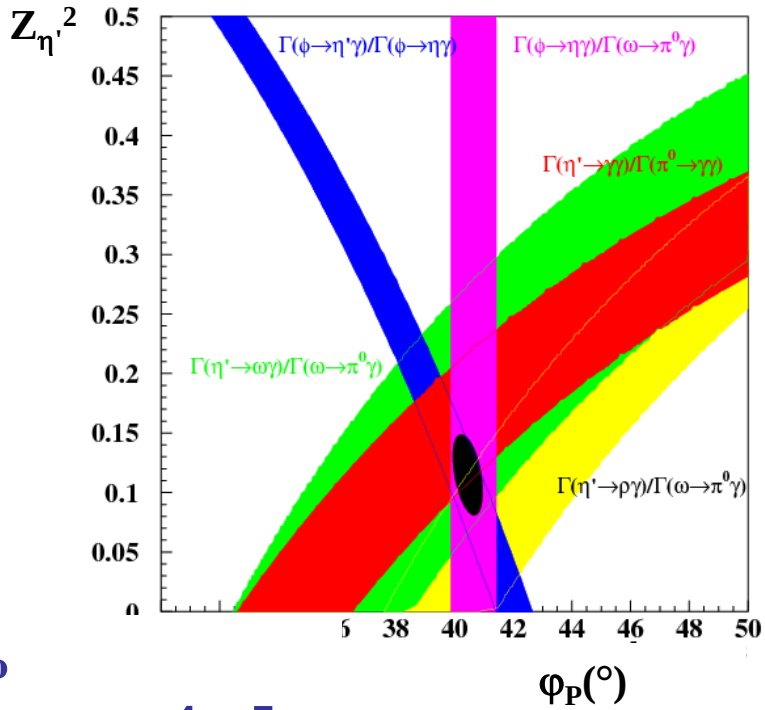
New fit: $R = \cot^2\varphi_P \cos^2\varphi_G \left(1 - \frac{m_s}{\bar{m}} \cdot \frac{C_{NS}}{C_S} \cdot \frac{\tan\varphi_V}{\sin 2\varphi_P}\right)^2 \cdot \left(\frac{p_{\eta'}}{p_\eta}\right)^3$

$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)}, \frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\omega \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)},$$

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

PDG08+ KLOE ω→π⁰γ

	New fit	PLB648
$Z_{\eta'}^2$	0.12 ± 0.04	0.14 ± 0.04
φ_P (deg.)	40.4 ± 0.6	39.7 ± 0.7
C_{NS}	0.94 ±0.03	0.91 ±0.05
C_S	0.83 ±0.05	0.89 ±0.07
φ_V (deg.)	3.32 ± 0.10	3.2
m_s/m	1.24 ± 0.07	1.24 ± 0.07
χ^2/ndf	4.6/3	1.42 / 2
P(χ^2)	20%	49%



KLOE-2: by measuring the main η' Br's @ 1%

⇒ statistical significance of $Z_{\eta'}^2$ will increase to 4 – 5 σ

[JHEP07(2009)105]

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

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

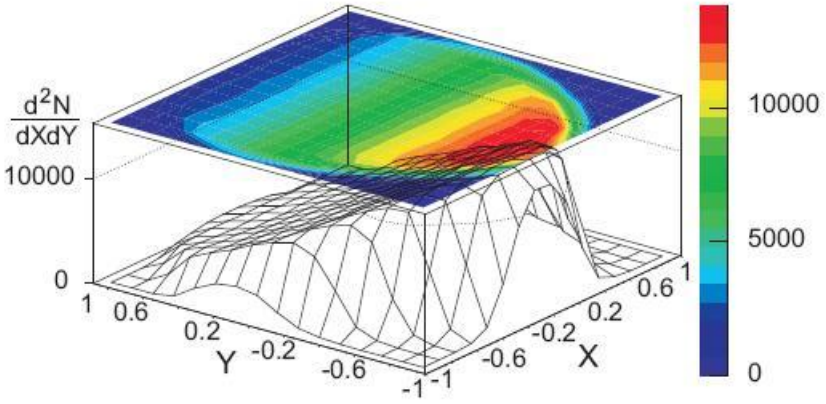
$\phi \to \eta\gamma$; $\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$ ($E_{\gamma rec}$ = 363 MeV)
450 pb^{-1} $\Rightarrow$ 1.34 $\times$ 10^6 events in the Dalitz plot

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

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

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

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]

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

- **Symmetric Dalitz plot:** $|A|^2 \propto 1 + 2\,\alpha\, Z$ $\Rightarrow$ **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)

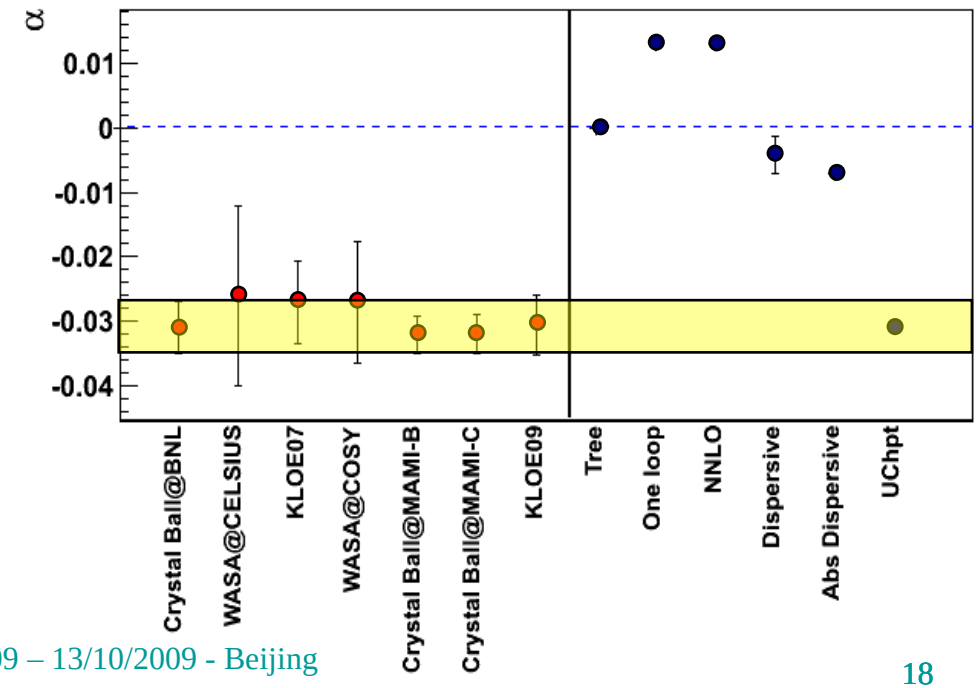
- **Binned likelihood fit, normalizing the data to MC density (pure phase-space in MC $\Rightarrow |A|^2$ =constant)**
- **450 pb^{-1} $\Rightarrow$ 6.5 ×10^5 events**

$\alpha = -0.027 \pm 0.004 \pm 0.006$

[**KLOE'07,** arXiv:0707.4137v1]

- **New analysis:**

$$\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$$



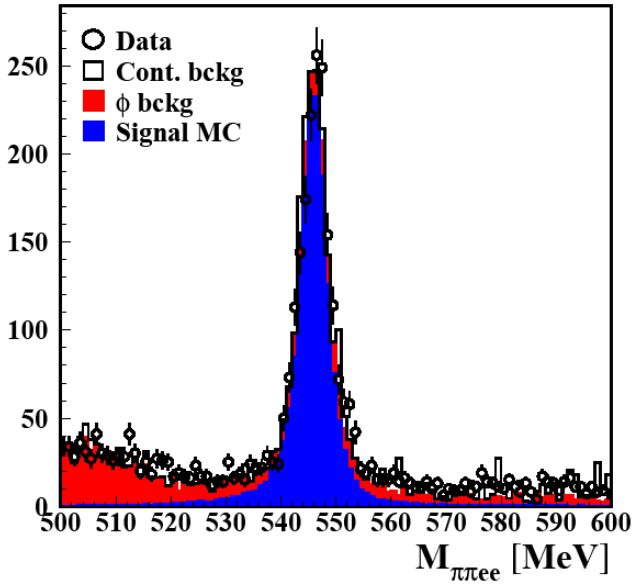
Alternative parametrization of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot with final state ππ rescattering

$\Rightarrow \quad \alpha = -0.038 \pm 0.003^{+0.012}_{-0.008}$

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

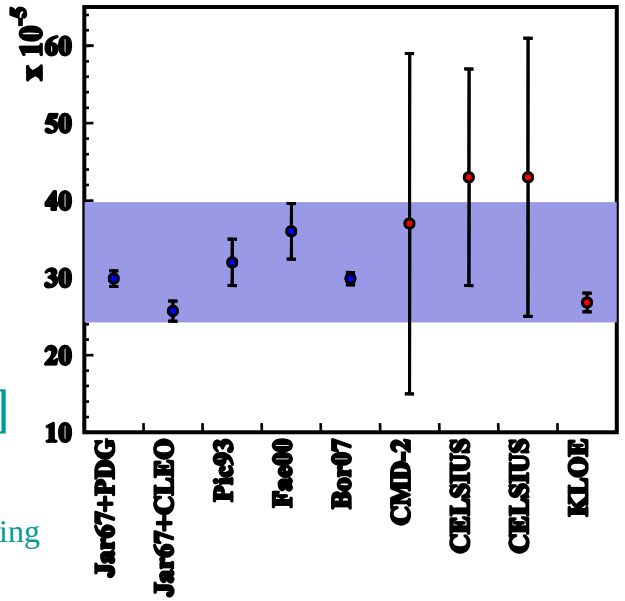
- Rare decay: χPT and VDM predictions $\Rightarrow$ Br ~ 3×10^{-4}
- 2 measurements: CMD-2 4 events
  WASA@CELSIUS 16 events

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



$$Br(\eta \to \pi^+\pi^-e^+e^-(\gamma)) = (26.8 \pm 0.9 \pm 0.7) \times 10^{-5}$$

[PLB675(2009)283]

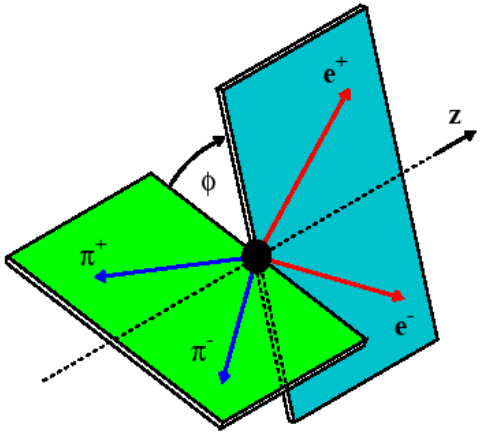


$\eta \to \pi^+\pi^-e^+e^-$

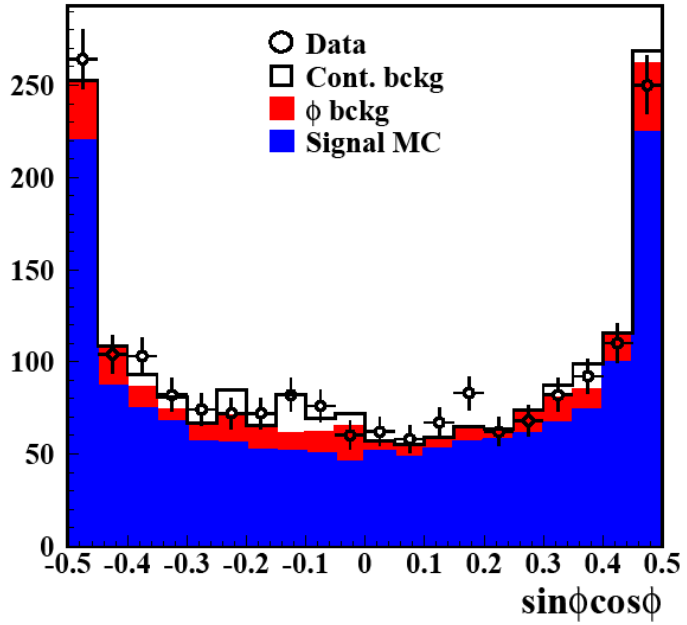
- **Non conventional CP violation mechanism (non CKM) proposed**
  [D.N.Gao MPLA17(2002)]

Interference between electric and magnetic decay amplitudes

$\Rightarrow$ plane asymmetry



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



[PLB675(2009)283]

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

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

- Study of the box anomaly
- Existing data: low statistics and not acceptance corrected CLEO results $\Rightarrow 3\,\sigma$ from previous experiments

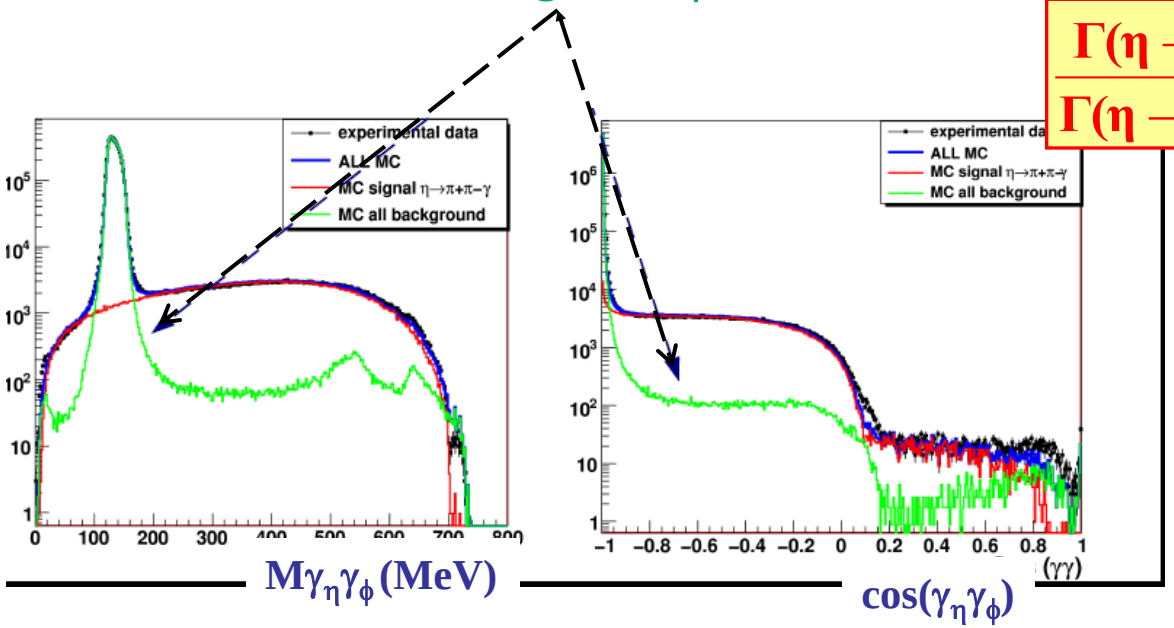
$\Gamma(\eta \to \pi^+\pi^-\gamma) / \Gamma(\eta \to \pi^+\pi^-\pi^0)$

value	events	author	year
0.203 ± 0.008	PDG average		
0.175 ± 0.007 ± 0.006	859	Lopez	2007
0.209 ± 0.004	18 k	Thaler	1973
0.201 ± 0.006	7250	Gormley	1970

- KLOE data sample: 6×10^5 events in 1.2 fb^{-1}

Simultaneous fit

residual bckg from $\phi \to \pi^+\pi^-\pi^0$

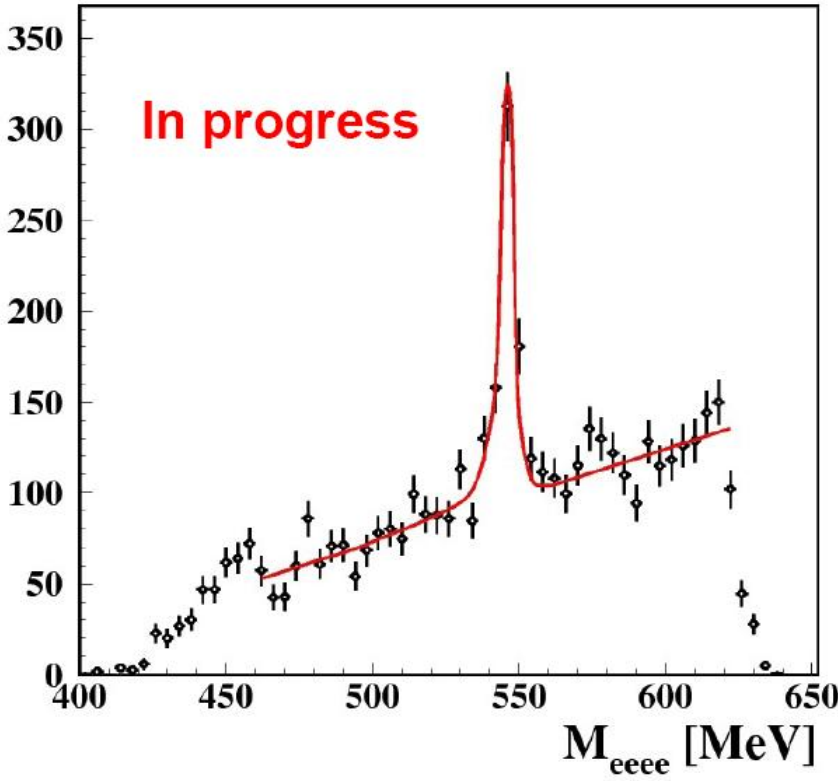


Preliminary result:

$$\frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\pi^0)} = 0.2014 \pm 0.0004(\text{stat})$$

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

- **Never observed before**
  Br < 6.9×10^{-5} @90%C.L. (CMD-2)
- **Theoretical predictions: ~ 2.5 – 2.6 $\times10^{-5}$**
- **MC simulation according to**
  Bijnens and Persson [arXiv:0106130]
- **KLOE: 413 ± 31 events ⇒ first evidence**



Conclusions

- **Important results have been achieved by KLOE in light meson spectroscopy**
- **Scalars:**
  - **Precision measurements of Br($\phi \to f_0(980)\gamma$) and Br($\phi \to a_0(980)\gamma$)**
  - **Scalar resonance parameters extracted from fits**
  - **Upper limit for $\phi \to (f_0/a_0)\gamma \to K^0\overline{K}^0\gamma$**

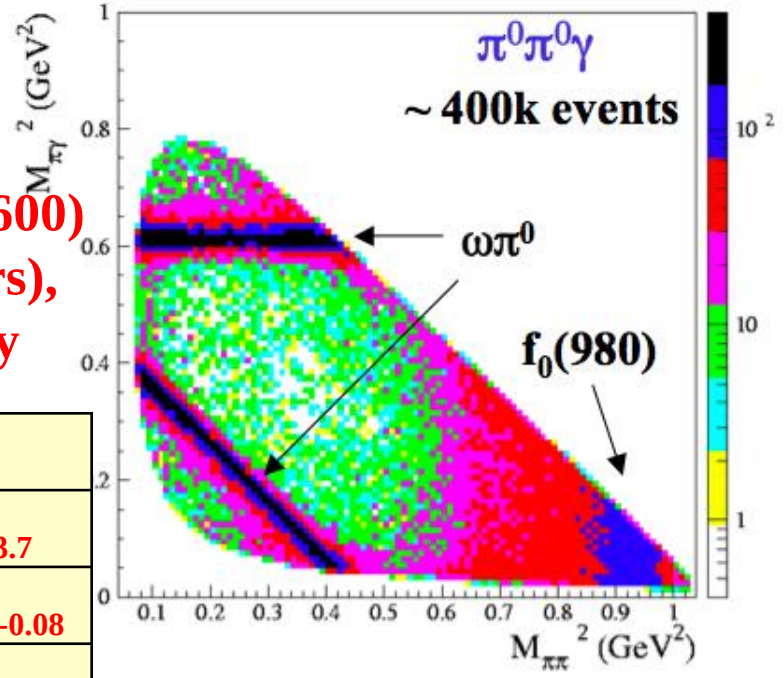
- **Pseudoscalars:**
  - **3 σ evidence of gluonium in η' (according to Rosner parametrization)**
  - **Dalitz plot of $\eta \to 3\pi$**
  - **Rare decays: $\eta \to \pi^+\pi^- e^+e^-$, $\eta \to \pi^+\pi^-\gamma$, $\eta \to e^+e^-e^+e^-$**
  - **Other analyses in progress: $\eta \to \pi^0\gamma\gamma$, $\eta \to \mu^+\mu^-$**

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

Spare slides

$e^+e^- \to \pi^0\pi^0\gamma$: $f_0(980)$

- 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



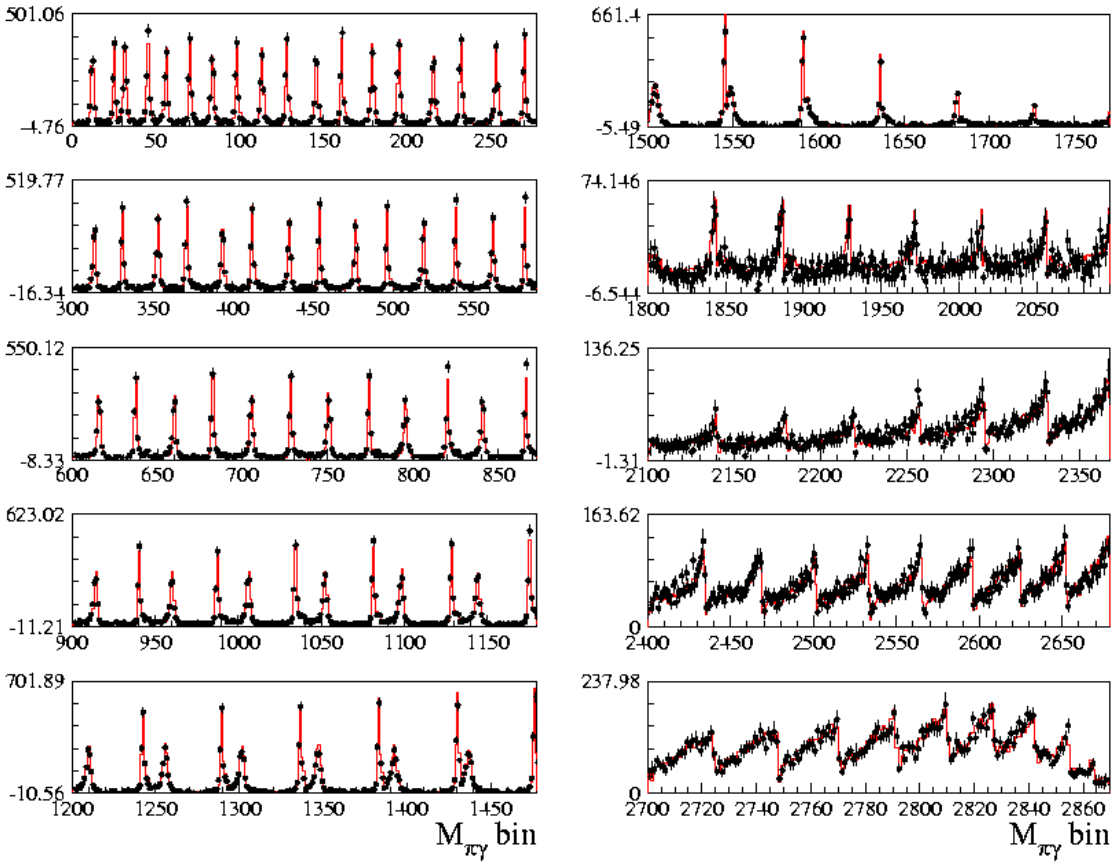
$f_0(980)$ param.	KL model	NS model
M_{f0} (MeV)	$976.8 \pm 0.3\ ^{+10.1}_{-0.6}$	$984.7 \pm 0.4^{+2.4}_{-3.7}$
$g_{\phi f\gamma}$ (GeV^{-1})	$2.78^{+0.02}_{-0.05}{}^{+1.32}_{-0.05}$	$2.61 \pm 0.02^{+0.31}_{-0.08}$
$g_{f\pi+\pi-}$ (GeV)	$-1.43 \pm 0.01^{+0.03}_{-0.60}$	$1.31 \pm 0.01^{+0.09}_{-0.03}$
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 $\sigma(600)$ $\Rightarrow$ $P(\chi^2) \to 10^{-4}$

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

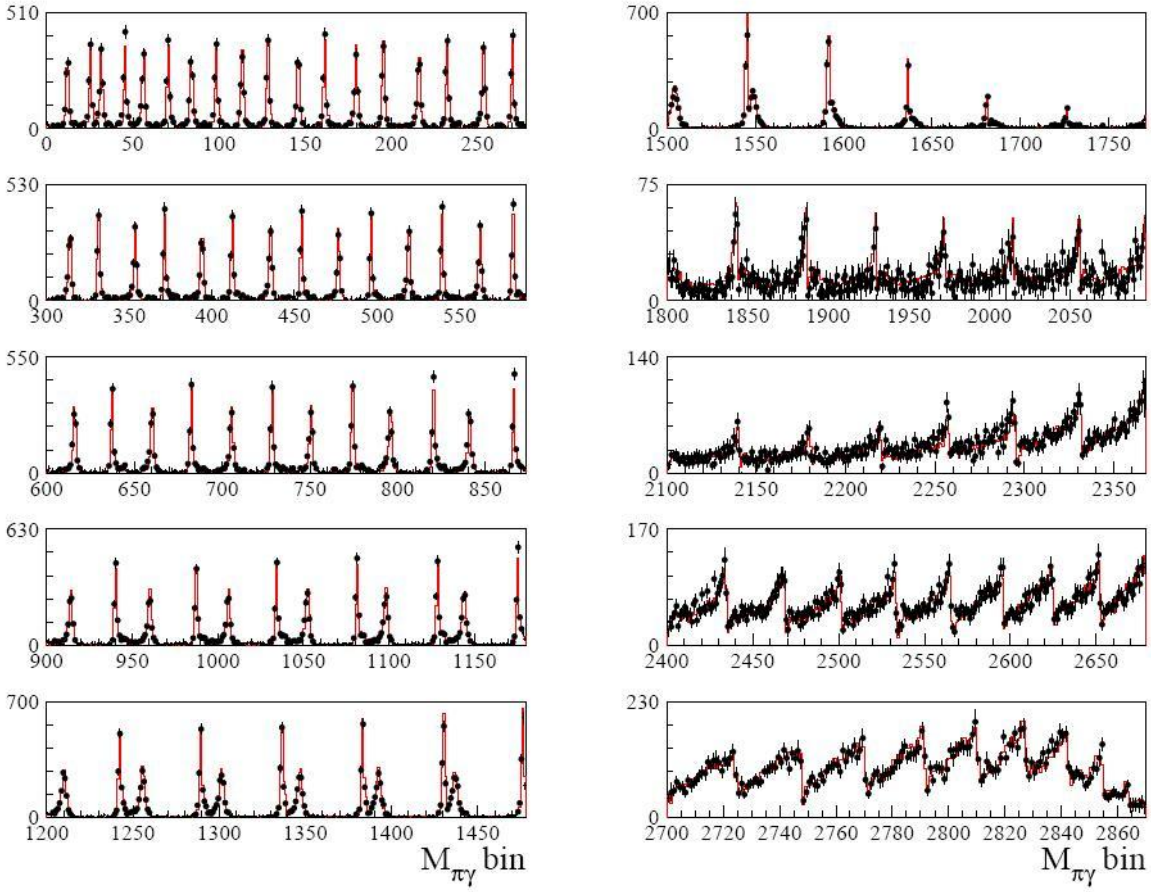
Fit result - KL



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

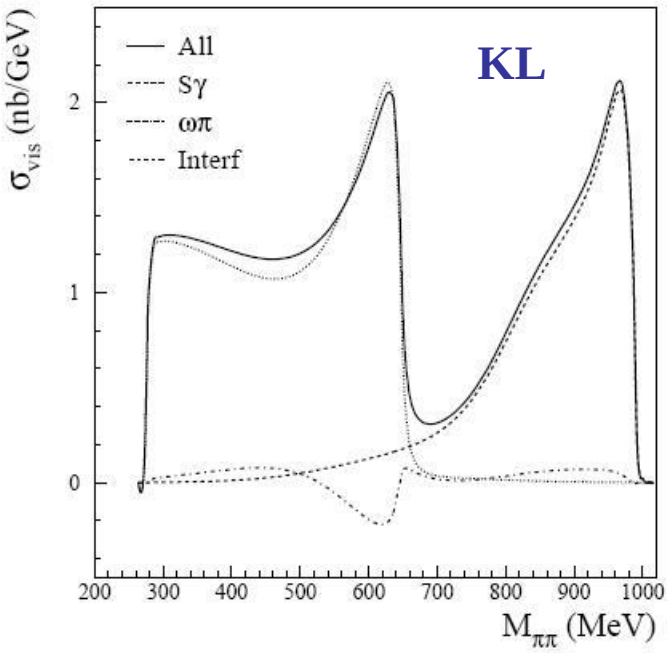


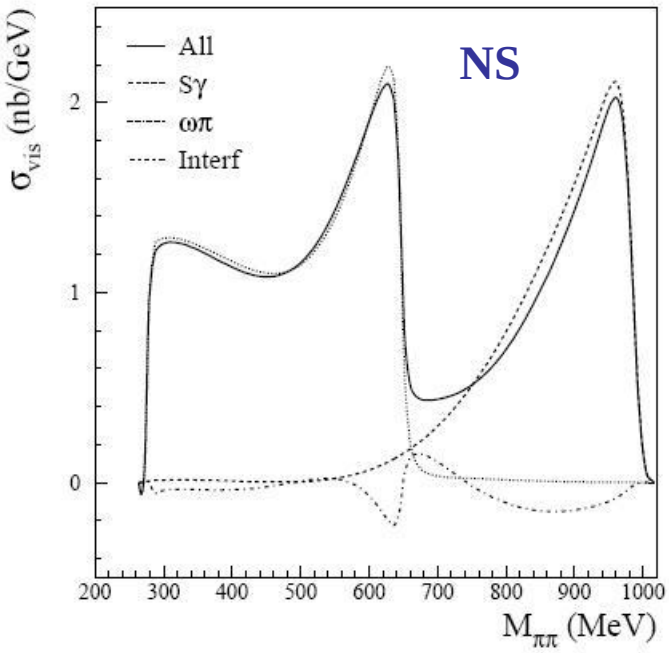
Fit result shown in $M_{\pi\pi}$ slices

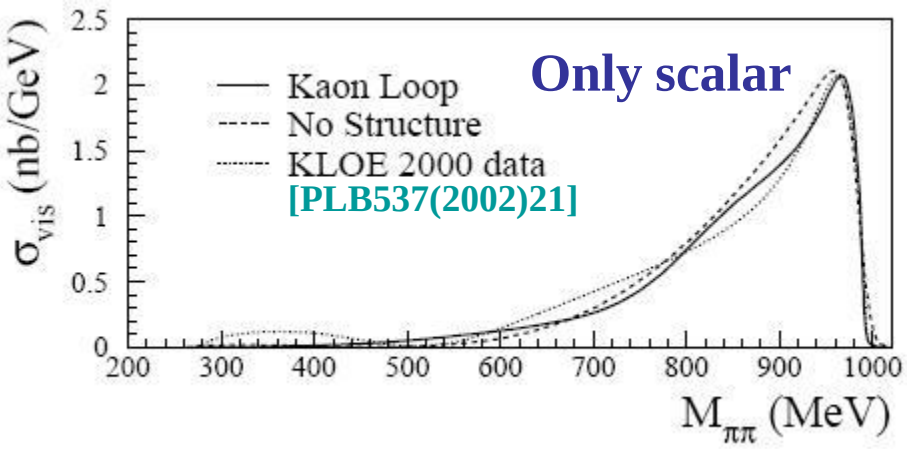
$P(\chi^2) = 4.2\ \%$

Fit results

Scalar + $\omega\pi^0$

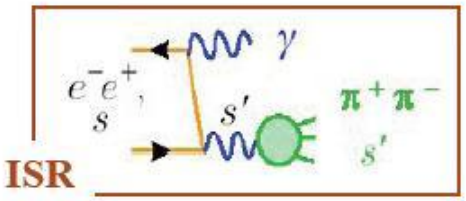


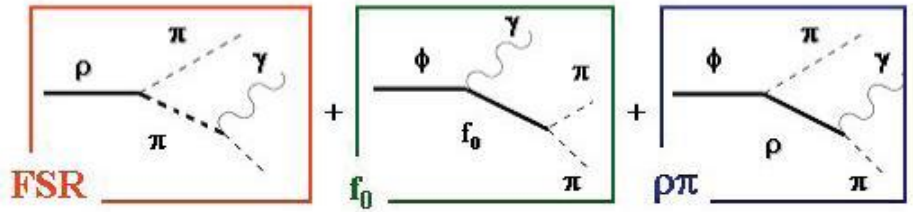


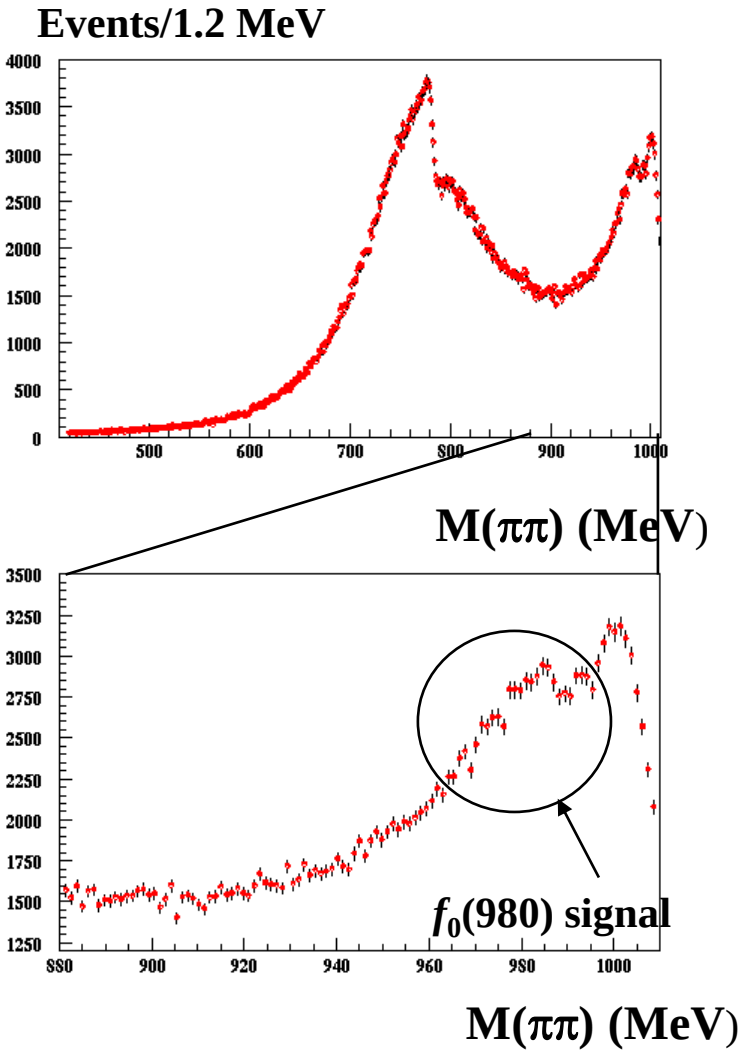


$e^+e^- \to \pi^+\pi^-\gamma$

- **Main contributions**

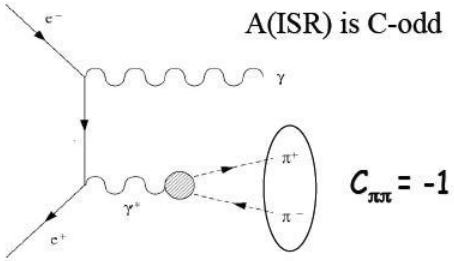


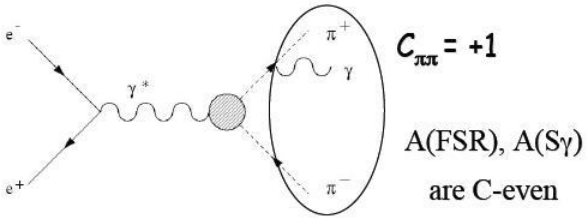




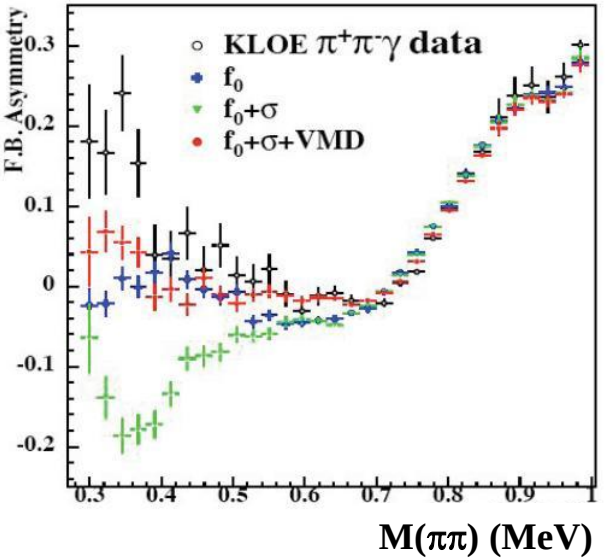
- **Event selection:** 2 charged tracks and missing momentum at large angle ($\vartheta > 45°$) + photon matching missing energy and momentum
- Data sample: 350 pb^{-1} at ϕ peak
  $\Rightarrow 6.7\times10^5$ events selected

F-B asymmetry





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

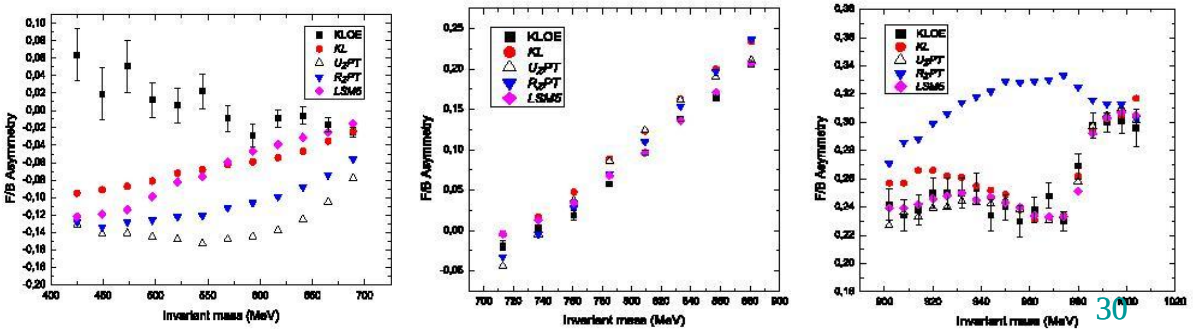


- $f_0(980)$ evidence at M(ππ) ≈ 980 MeV
- Simulation with f_0 and σ parameters from $\pi^0\pi^0\gamma$ analysis

[Pancheri, Shekhovtsova Venanzoni, arXiv0706.3027]

- Recent analysis by A.Gallegos et al. [arXiv:0908]: comparison of KLOE data with 4 different models: KL, RχPT, UχPT and LσM

P.Gauzzi



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

Unfolded $M_{\eta\pi}$ distribution

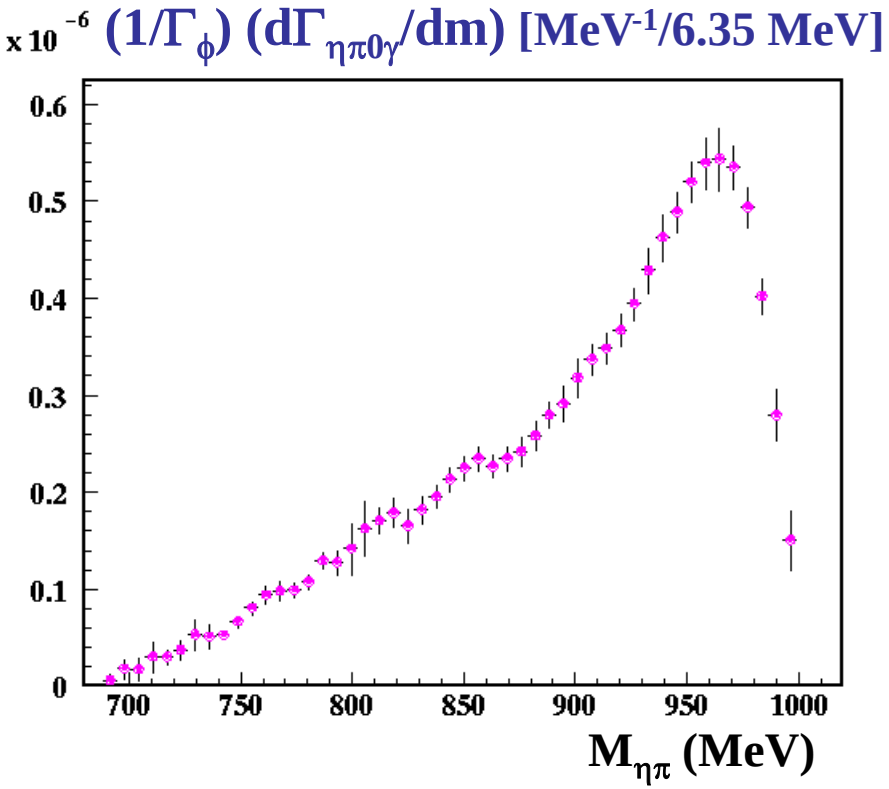
- To allow better comparison with other experimental results and theoretical models ⇒ unfolding procedure to correct data for detector and resolution effects

- Bayesian unfolding

(avoids smearing matrix inversion)

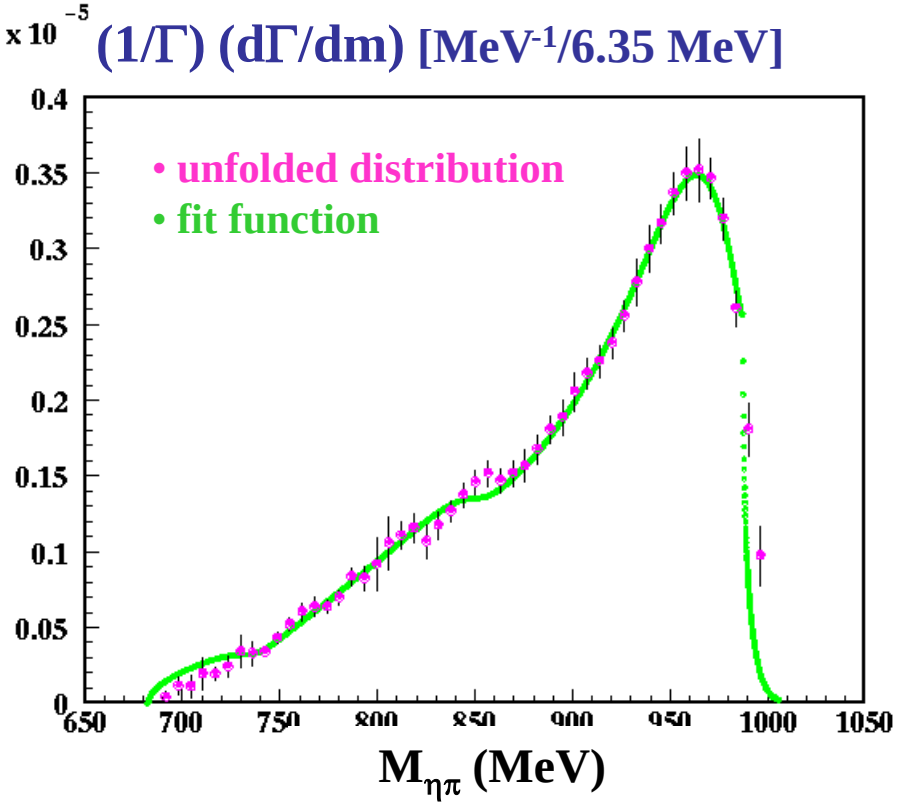
[G.D'Agostini, NIM A362 (1995), 487]

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



Check of the unfolding result

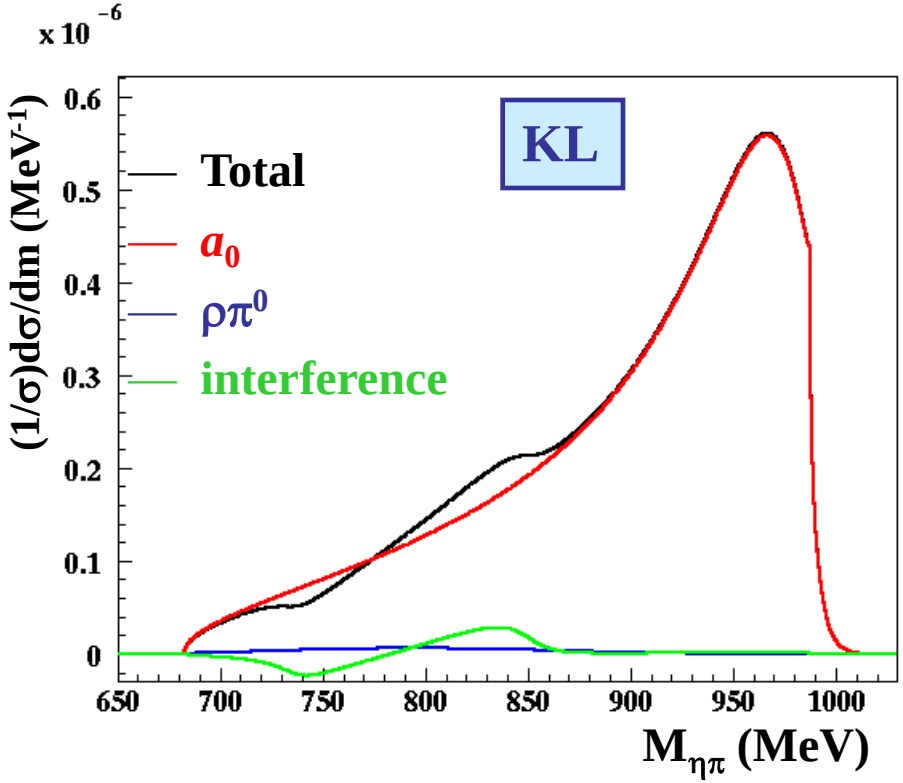
- **Fit the unfolded invariant mass distribution to the Achasov function (without smearing matrix)**

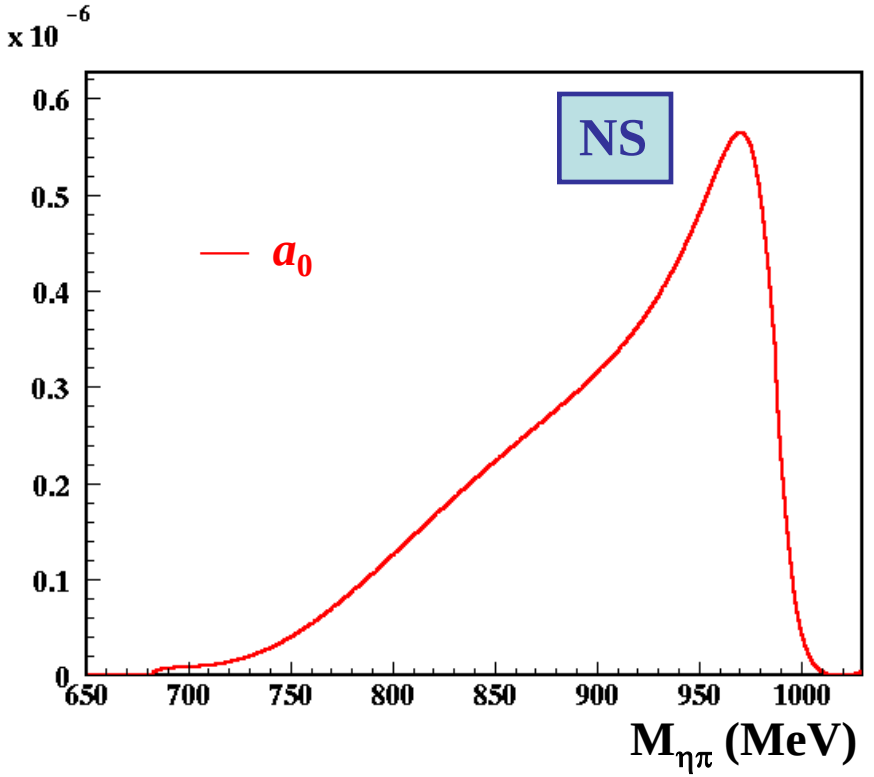


	This fit	Kaon Loop fit
M_{a0} (MeV)	980.7 ± 0.8	982.5 ± 1.3 ± 1.0
$g_{aK^+K^-}$ (GeV)	2.10 ± 0.02	2.15 ± 0.05 ± 0.06
$g_{a\eta\pi}$ (GeV)	2.84 ± 0.02	2.82 ± 0.04 ± 0.04
$g_{\phi a\gamma}$ (GeV^{-1})	1.5 ± 0.1	1.6 ± 0.1 ± 0.1
δ (°)	212 ± 8	222 ± 12 ± 3
Br(VDM) $\times 10^6$	0.88 ± 0.25	0.92 ± 0.40 ± 0.15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

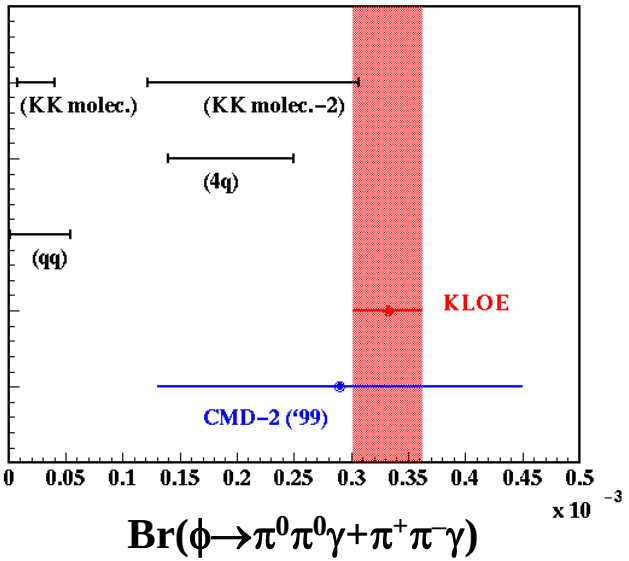
(Free parameters in red)

$a_0(980)$ shape

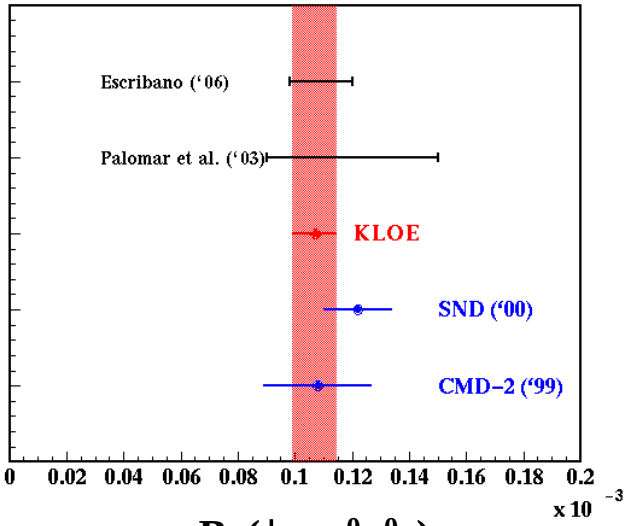

x 10 $^{-6}$
(1/σ)dσ/dm (MeV^{-1})
KL
Total
a_0
ρπ^0
interference
M$_{ηπ}$ (MeV)


x 10 $^{-6}$
NS
a_0
M$_{ηπ}$ (MeV)

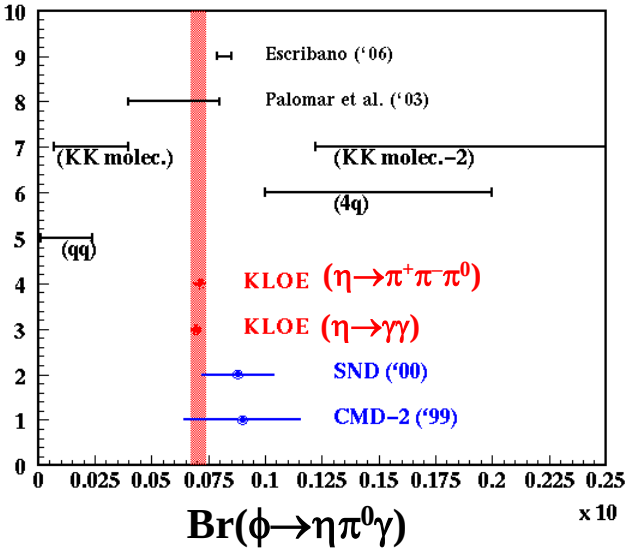
Branching ratios



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



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



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

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

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

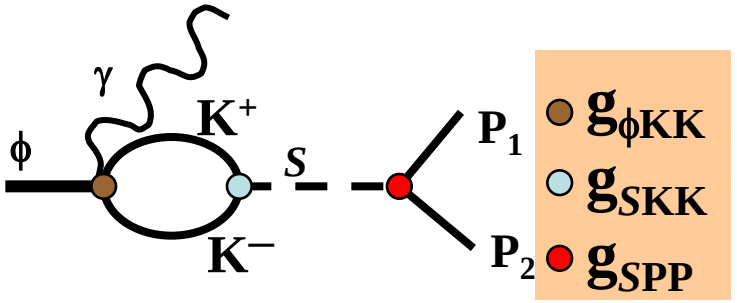
- **Only KLOE data: input g_{f0KK} , $g_{f0\pi\pi}$ + masses + φ_P ⇒output g_{a0KK} and $g_{a0\eta\pi}$**

	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 = 20.6 — 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

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



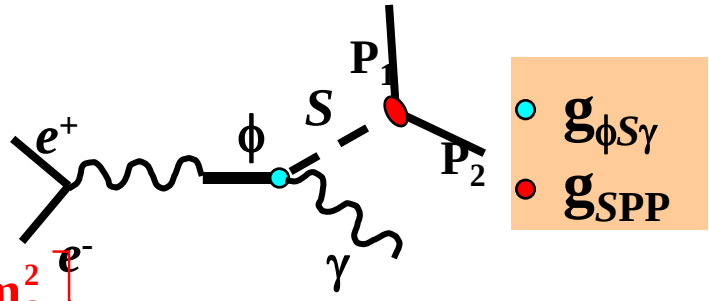
$$\frac{d\Gamma}{dm} = \frac{2\left|g(m^2)\right|^2 p_\gamma (M_\phi^2 - m^2)}{3(4\pi)^3 M_\phi^3} \left| \frac{g_{SK^+K^-} g_{SPP'}}{D_S(m^2)} \right|^2$$

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)

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)**

Scalar propagator (KL)

[Achasov-Kiselev PRD70(2004)]

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

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

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

$m_- \leq m < m_+$

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

$m < m_-$

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

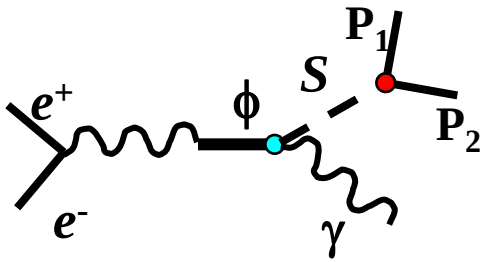
- **Scalar propagator with finite width corrections:**

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

  " $=\eta\pi^0$, K^+K^-, $K^0\bar{K}^0$, $\eta'\pi^0$ 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)**

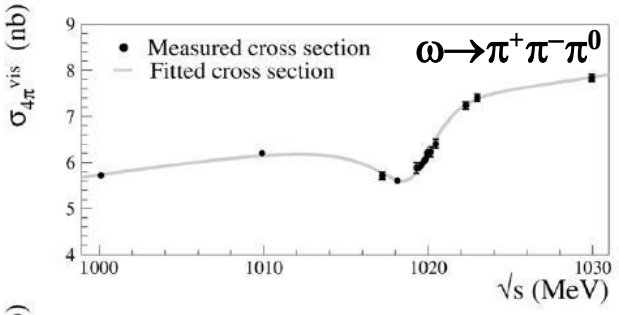
$e^+e^- \to \omega\pi^0$

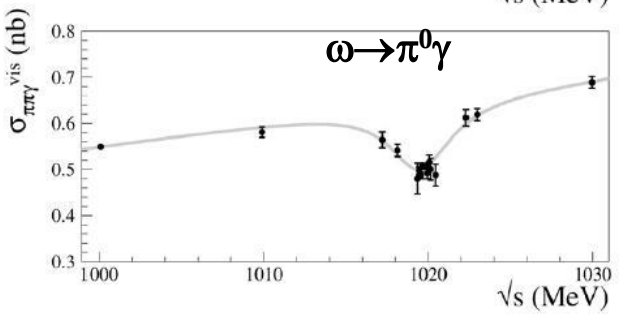
- 600 pb^{-1} with $1000 < \sqrt{s} < 1030$ MeV
- Interference with $\phi \to \omega\pi^0$ (OZI and G-parity viol.)

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

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

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]

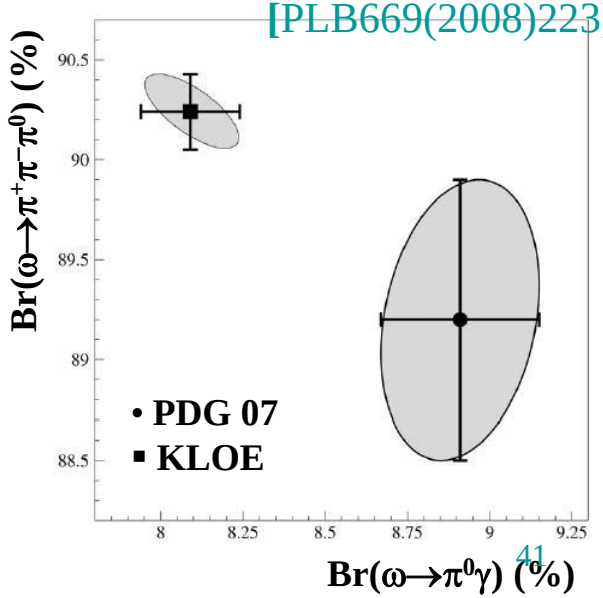
- From $\sigma_0(\pi^0\gamma)/\sigma_0(\pi^+\pi^-\pi^0)$ (with rare Br's from PDG)

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

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

$(8.92 \pm 0.24)\ \%$

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

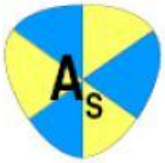


$\eta \to \pi^+\pi^-\pi^0$

- **Asymmetries ⇔ 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 ⇒

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

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

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

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

[JHEP0805(2008)006]

$\eta \to \pi^0\pi^0\pi^0$:fit procedure

The fit is done using a binned likelihood approach

We obtain an estimate of α by minimizing

$$-\sum_i n_i \log\left(\nu_i(\alpha)\right)$$

Where:

n_i = recostructed events

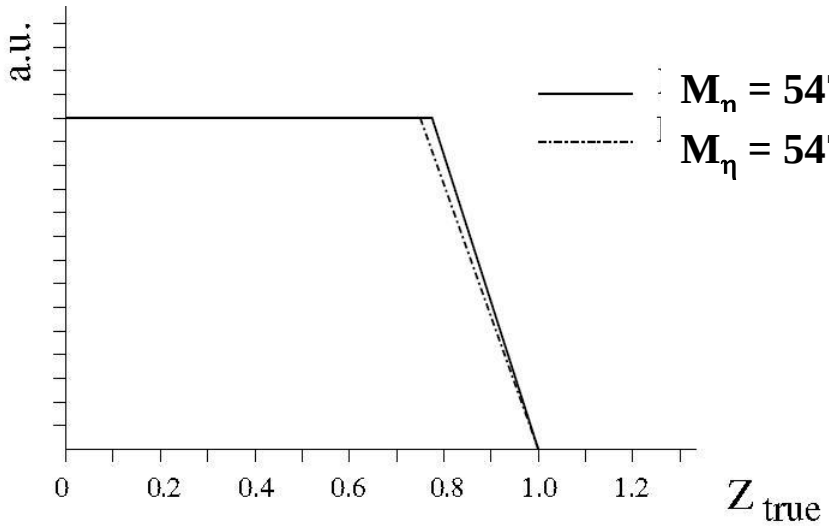
ν_i = for each MC event (according pure phase space):

- ✓ **Evaluate its z_{true} and its z_{rec} (if any!)**
- ✓ **Enter an histogram with the value of z_{rec}**
- ✓ **Weight the entry with $1 + 2\ \alpha\ z_{true}$**
- ✓ **Weight the event with the fraction of combinatorial background, for the signal (bkg) if it has correct (wrong) pairing**

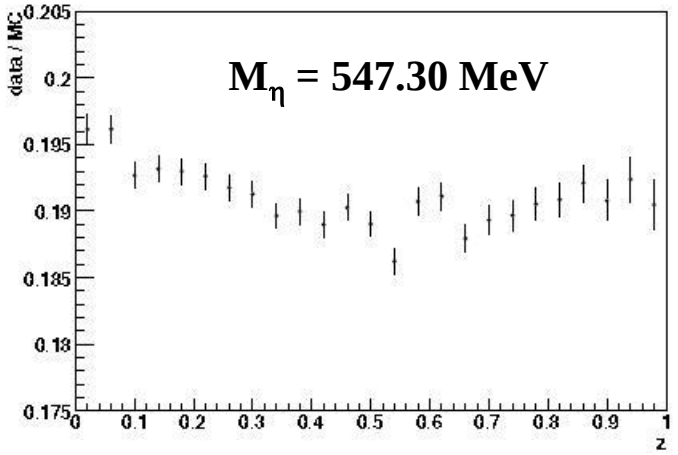
$\eta \to \pi^0\pi^0\pi^0$

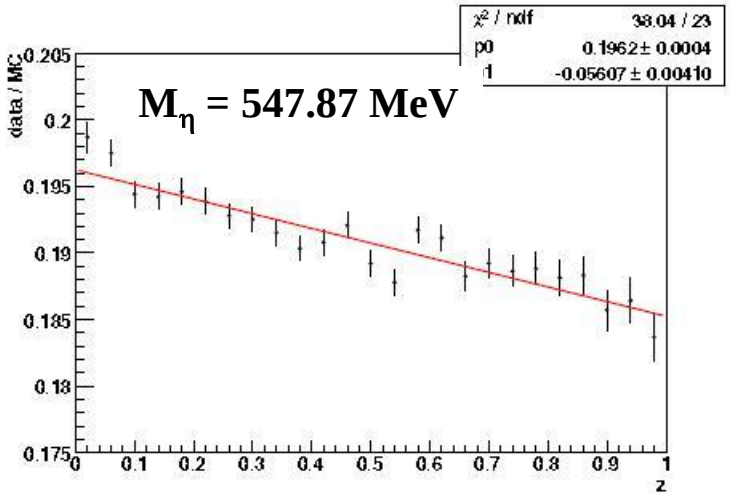
- α dependence on η mass

  $|A|^2 \propto 1 + 2\,\alpha\, Z$



Pure phase space





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

- 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)

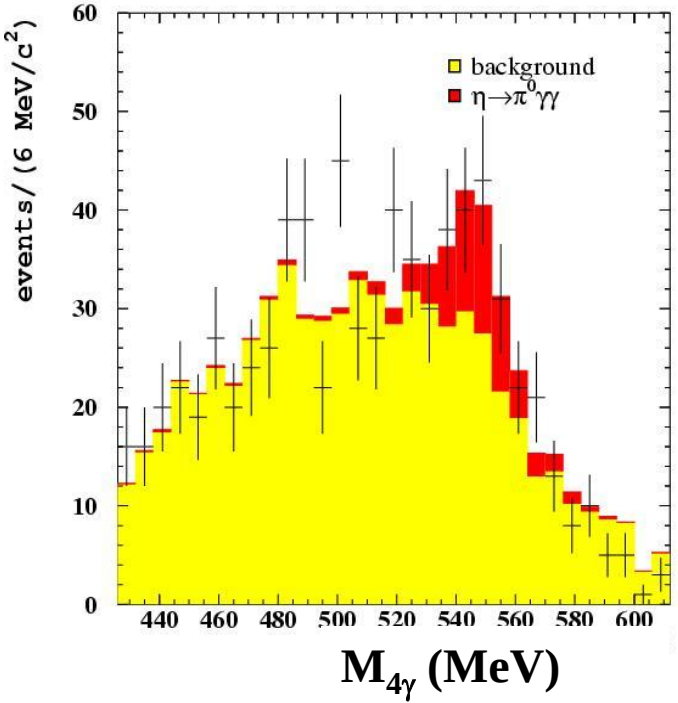
  $(22.4 \pm 4.6 \pm 1.7) \times 10^{-5}$ Crystal Ball@MAMI(2007)

  $(22.1 \pm 2.4 \pm 3.8) \times 10^{-5}$ Crystal Ball@AGS(reanalysis)
- 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 $\approx$ 450 pb^{-1}

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



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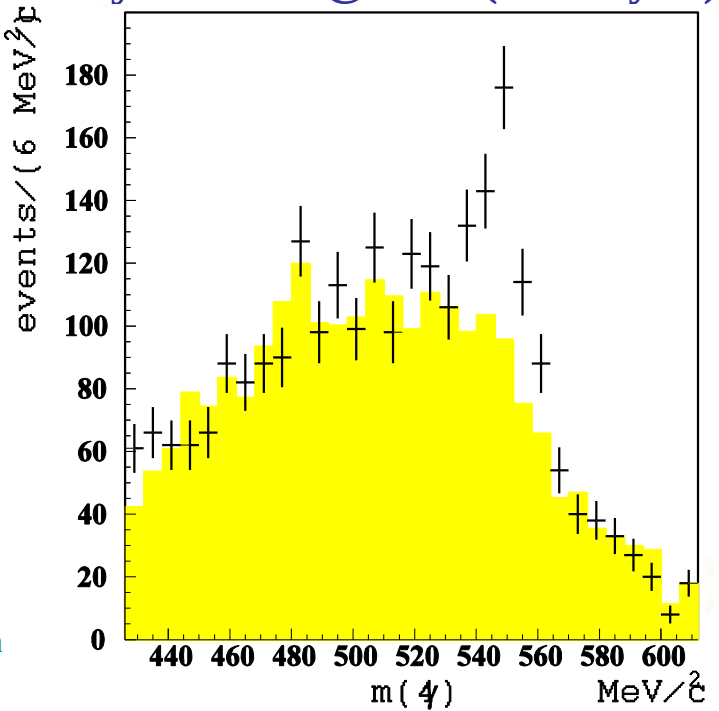
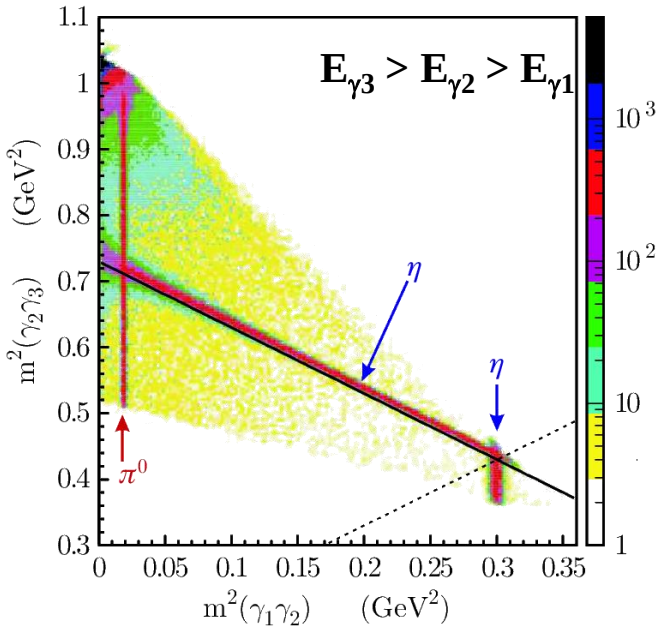
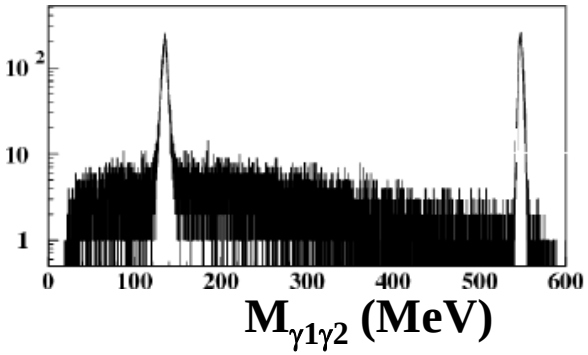
- 1.5 fb^{-1} $\Rightarrow$



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





$M_\eta = 547.874 \pm 0.007 \pm 0.029$ MeV

$M_{\pi 0} = 134.906 \pm 0.012 \pm 0.049$ MeV

PDG ⇒ 134.9766 ± 0.0006 MeV (1.4 σ)

PHIPSI [JHEP12(2007)073]

η mass measurement

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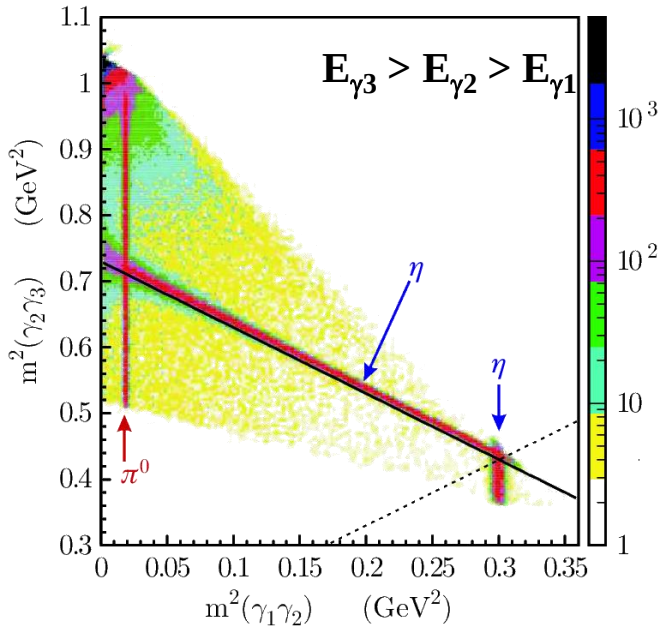

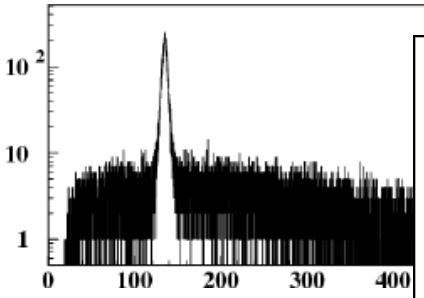

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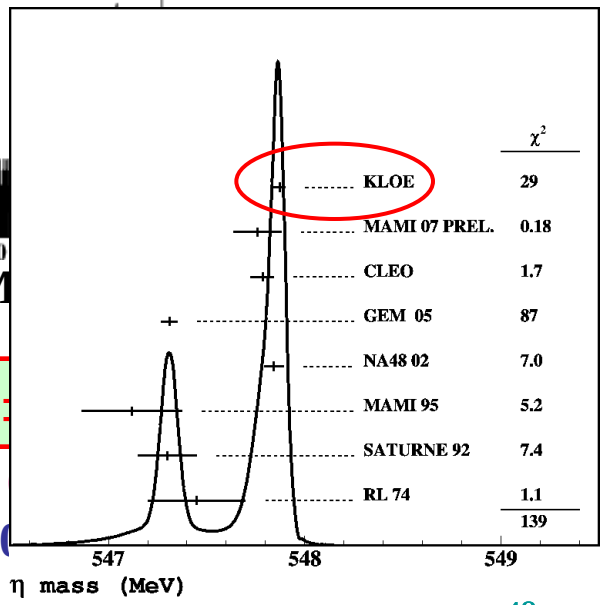
PDG ⇒ 134.9766 ± 0.00(



PHIPSI [JHEP12(2007)073]