HADRONIC PHYSICS WITH KLOE

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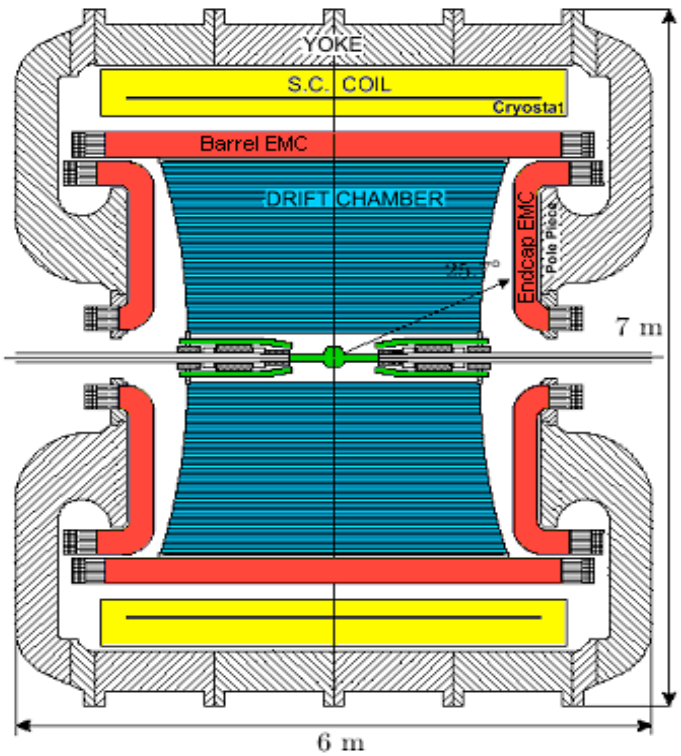
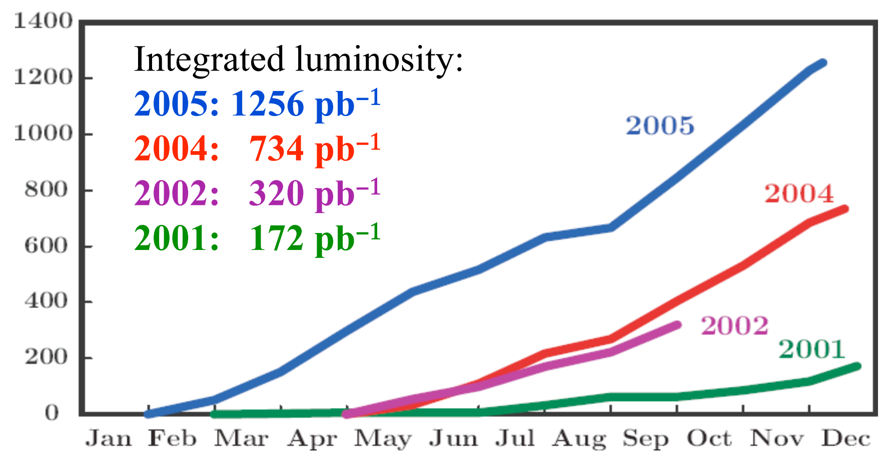
The KLOE experiment at DAΦNE



Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ (θ>45°)**
- **$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm**



Electromagnetic calorimeter

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

Data taking ended on March 2006

- **2.5 fb^{-1} on tape @ $\sqrt{s} = M_\phi$ ($8\times10^9\ \phi$)**
- **~10 pb^{-1} @ 1010, 1018, 1023 and 1030 MeV**
- **250 pb^{-1} @ 1000 MeV**

Light scalars in ϕ radiative decays

The structure of scalars below 1 GeV is still an open question:
[**$q\bar{q}$**, **$q\bar{q}q\bar{q}$** (Jaffe '77…), **KKbar molecule** (Weinstein-Isgur '90)…]

BR and mass spectra of the radiative decays **$\phi \rightarrow PP'\gamma$ sensitive to the structure of the intermediate scalar mesons**

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

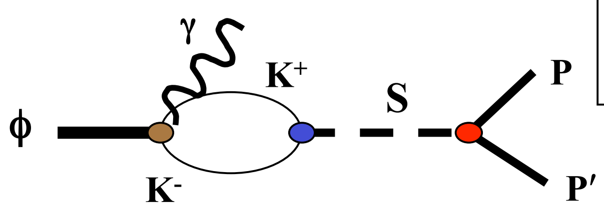
$\pi^+\pi^- \Rightarrow$ $f_0(980)/\sigma(600)$ [PLB634(2006)148]

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

$K_S K_S \Rightarrow$ $f_0(980)/a_0(980)$ [New paper in preparation]

Phenomenological models used to describe $\phi \rightarrow S\gamma \rightarrow PP'\gamma$:

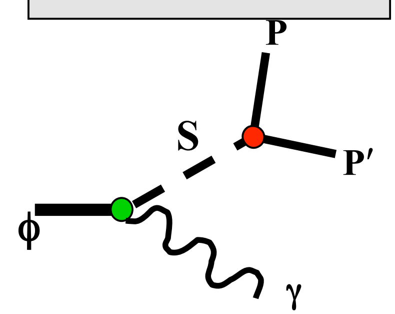
Kaon Loop



Fit params:
M_S, $g_{SPP'}$, g_{SKK}

[N.N.Achasov, V.N.Ivanchenko, NPB315 (1989) 465]
[N.N.Achasov, V.V.Gubin, PRD 56 (1997) 4084]
[N.N.Achasov, A.V.Kiselev, PRD 68 (2003) 014006]

No Structure



Fit params:
M_S, g_{fSg}, $g_{SPP'}$, g_{SKK},
continuum (polynomial)

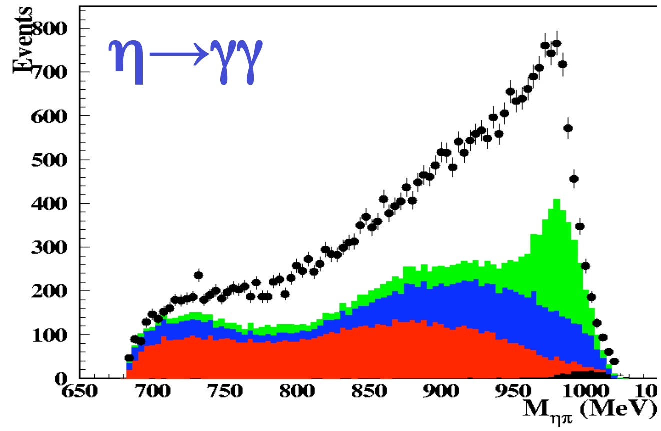
[G.Isidori, L.Maiani, M.Nicolaci, S.Pacetti, JHEP 05 (2006) 049]

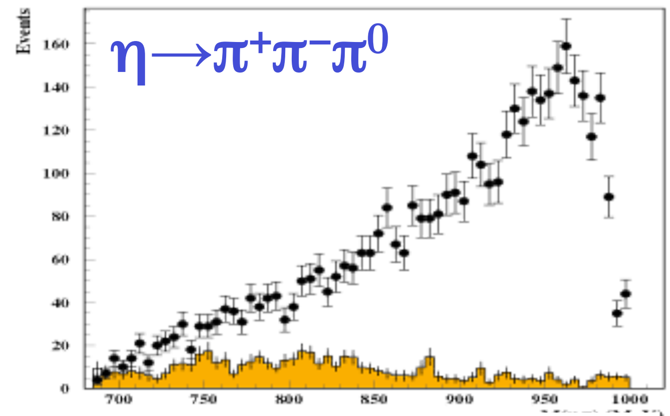
$e^+e^- \to \eta\pi^0\gamma$: search for $a_0(980)$

- ~450 pb^{-1} of e^+e^- collisions @ $\sqrt{s}=M_\phi$
- Dominated by $\phi \to a_0(980)\gamma$
- Decay channels: (1) $\eta\to\gamma\gamma$, (2) $\eta\to\pi^+\pi^-\pi^0$
- From event counting:

$$BR(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10_{stat} \pm 0.20_{syst})\times 10^{-5} \quad (1)$$

$$BR(\phi \to \eta\pi^0\gamma) = (7.12 \pm 0.13_{stat} \pm 0.22_{syst})\times 10^{-5} \quad (2)$$





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

Combined fit to $M_{\eta\pi}$ spectra:

Parameter	Kaon Loop	No Structure
M_{a0} (MeV)	982.5 ± 1.6 ± 1.1	982.5 (fixed)
g_{a0KK} (GeV)	2.15 ± 0.06 ± 0.06	2.01 ± 0.07 ± 0.28
$g_{a0\eta\pi}$ (GeV)	2.82 ± 0.03 ± 0.04	2.46 ± 0.08 ± 0.11
$g_{\phi a0\gamma}$ (GeV^{-1})	1.58 ± 0.10 ± 0.16	1.83 ± 0.03 ± 0.08
$BR(\phi\to\rho\pi\to\eta\pi\gamma)\times10^{-6}$	0.92 ± 0.40 ± 0.15	0.05 ± 4 ± 0.07
$BR(\eta\to\gamma\gamma)/BR(\eta\to\pi\pi\pi)$	1.70 ± 0.04 ± 0.03	1.70 ± 0.03 ± 0.01
$P(\chi^2)$	10.4%	30.9%

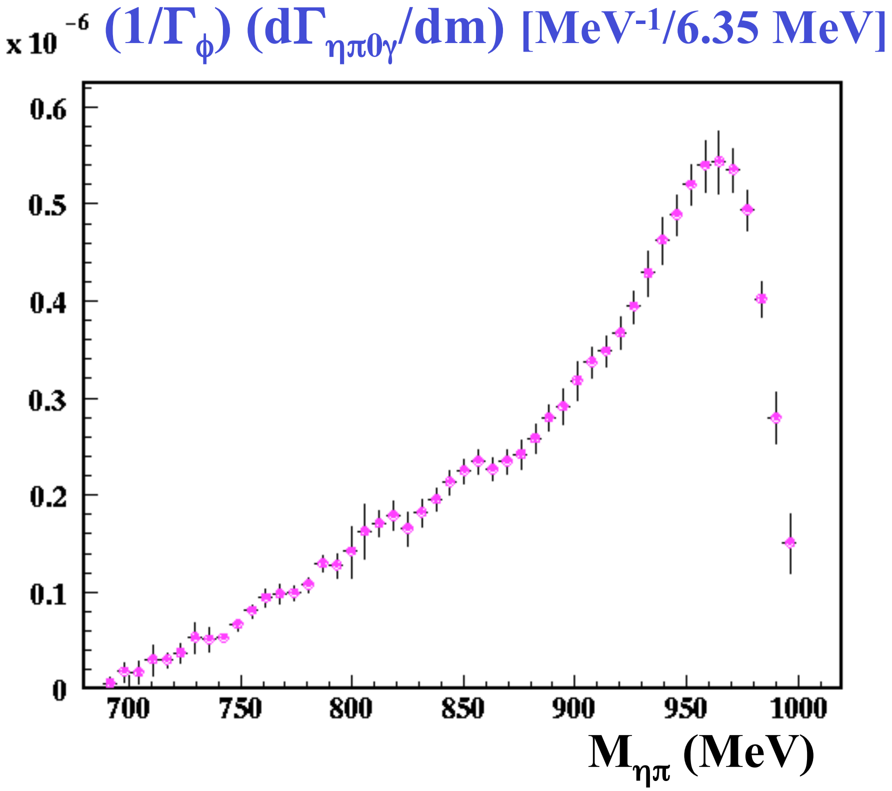
- $R = (g_{aK+K-} / g_{a\eta\pi})^2 \sim 0.6\text{-}0.7$
- R_η [PDG08] =1.73±0.04

$e^+e^- \to \eta\pi^0\gamma$: 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**



$S \to \pi\pi$ update

PRELIMINARY

~450 pb^{-1} of e^+e^- collisions @ $\sqrt{s}=M_\phi$

- ✓ Different parametrization used in the published $\pi^0\pi^0\gamma/\pi^+\pi^-\gamma$ analyses
- ✓ Marginal agreement between two channels
- ✓ New (not-combined) fit performed on both spectra with the same scalar description: latest Kaon Loop model with **f_0(980) + σ(600) + interference** [PRD73(2006)054029+erratum]
- ✓ Preliminary results are encouraging:

Channel	M_{f0} (MeV)	g_{f0KK} (GeV)	$g_{f0\pi\pi}$ (GeV)	$g^2_{f0KK} / g^2_{f0\pi\pi}$
$\pi^0\pi^0\gamma$	984.7± 1.9 $_{mod}$	3.97 ± 0.43$_{mod}$	–1.82± 0.19 $_{mod}$	~4.8
$\pi^+\pi^-\gamma$	983.7	4.74	–2.22	~4.6

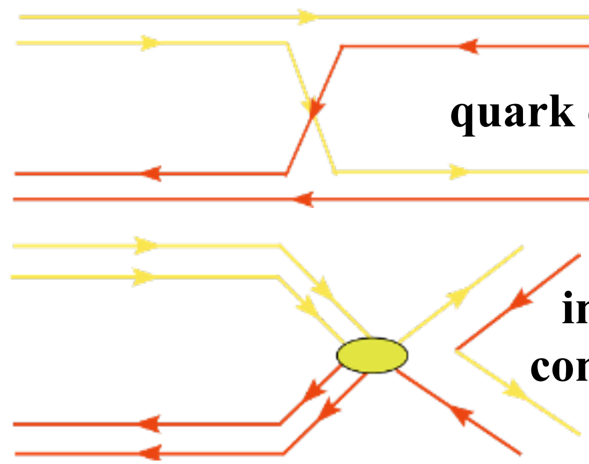
- ➢ **Better agreement between the two channels**
- ➢ **Reduced model uncertainties**
- ➢ **Combined fit in progress**

Couplings: $f_0(980)$ *vs* $a_0(980)$

New theory for scalar mesons: S(4q)→PP decays

['t Hooft,Isidori,Maiani,Polosa,Riquer, PLB662 (2008) 424]

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



1. **Inputs from KLOE measurements (g_{f0KK} , $g_{f0\pi\pi}$ + masses + φ_P)**
2. **Extraction of c_I, c_f**
3. **Evaluation of g_{a0KK} and $g_{a0\eta\pi}$**
4. **Comparison with measured g_{a0KK} , $g_{a0\eta\pi}$**

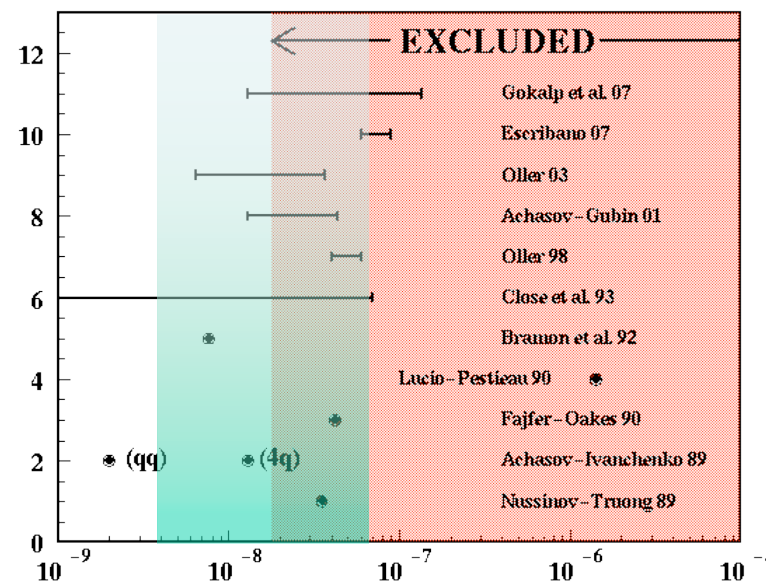
	KLOE (KL)		[qq] [qbarqbar]	qqbar
g_{f0KK} (GeV)	3.97 – 4.74	}	c_I = (-2.8 – -3.4) GeV^{-1}	c_I = (-3.9 – -4.8) GeV^{-1}
$g_{f0\pi\pi}$ (GeV)	-1.82 – -2.23		c_f = (20.5 – 24.5) GeV^{-1}	c_f = (16.5 – 19.7) GeV^{-1}
	KLOE (KL+NS)		⇓	⇓
g_{a0KK} (GeV)	2.01 – 2.15		2.1 – 2.5	2.4 – 2.9
$g_{a0\eta\pi}$ (GeV)	2.46 – 2.82		3.3 – 3.9	6.6 – 7.9

Search for $\phi \rightarrow K^0\overline{K}^0\gamma$

- Expected to proceed mainly through $\phi \rightarrow [f_0(980)+a_0(980)]\gamma \rightarrow K^0K^0\gamma$
- **Never been observed**
- Selected channel: $K_SK_S\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$ Clean topology, 24% BR reduction
- Signal MC according to phase-space and radiative decay dynamics
- Selection cuts optimized on MC (bckg: **$K_SK_L(\gamma)$** , **$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-(\gamma)$**)
- 2.18 fb^{-1} data @ M_ϕ :
  - **5 EVENTS IN DATA**
  - **2.5 + 0.7 BCKG EVENTS (MC)**

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

Consistency check using KLOE couplings from $\phi \rightarrow \pi\pi\gamma$, $\phi \rightarrow \eta\pi\gamma$ in the Kaon Loop model



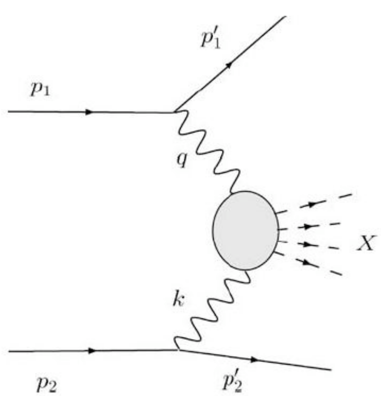
Search for $\gamma\gamma \to \sigma(600) \to \pi^0\pi^0$

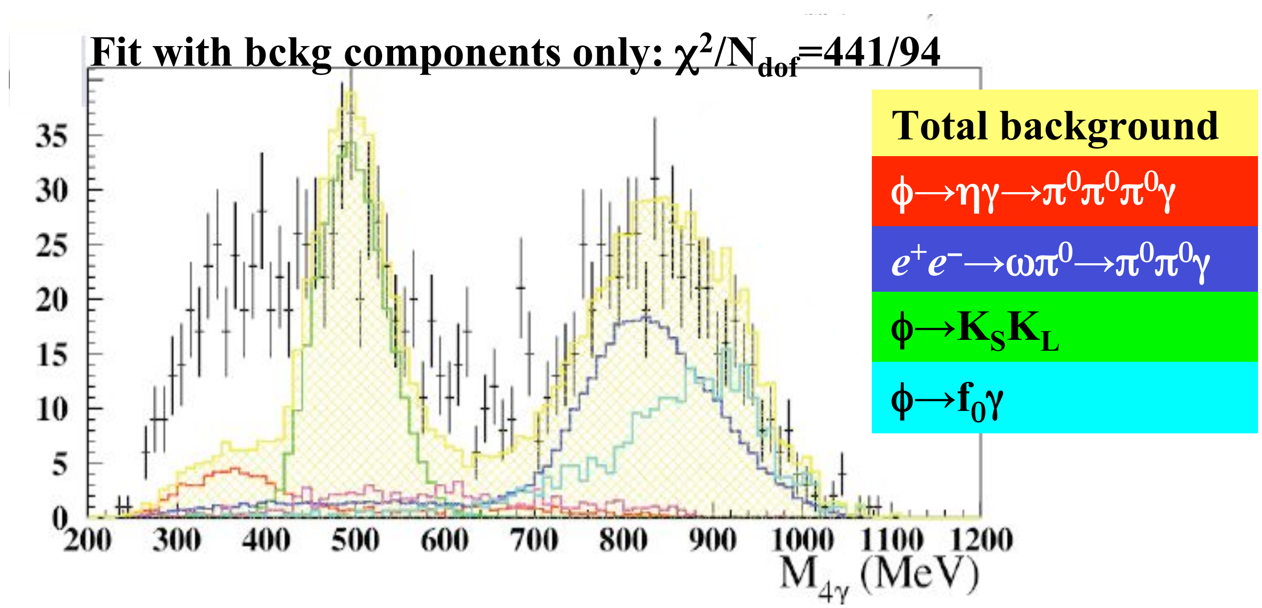
PRELIMINARY

- Long debate about the experimental evidence of the $\sigma(600)$ meson
- Evidence for a $\pi^+\pi^-$ bound state from E791, CLEO, BES
- Values of mass and width with large uncertainties
- **Indirect evidence in the $e^+e^-\to\pi^0\pi^0\gamma$ Dalitz plot analysis @ KLOE**

KLOE preliminary: 11 pb^{-1} @ $\sqrt{s}$ = 1 GeV (1/20 of the off-peak data sample)

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





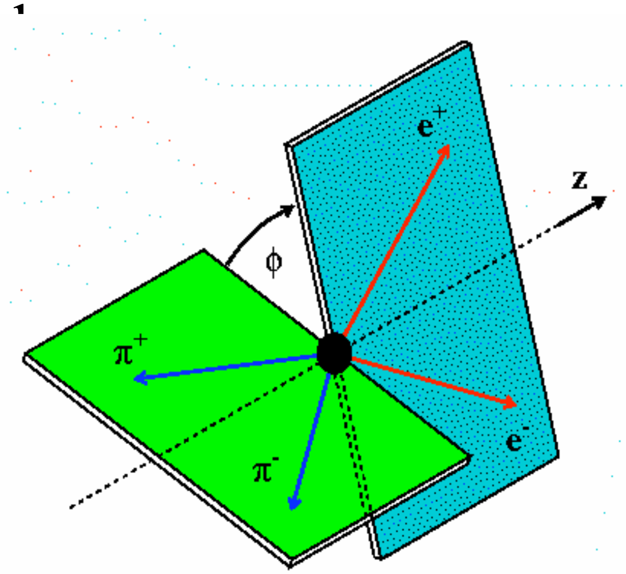
Excess of events w.r.t. the known background in the $\gamma\gamma\to\sigma(600)\to\pi\pi$ region

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

- ✓ Poorly measured (4 events CMD-2, 16 events CELSIUS-WASA)
- ✓ BR predicted by ChPT and VMD models ($2.6 \div 3.6 \times 10^{-4}$)
- ✓ η structure, using virtual photon
- ✓ Angular asymmetry between e^+e^- and $\pi^+\pi^-$

  test of non-CKM CP violation

  [D.Gao, Mod.Phys.Lett.A17 (2002) 1583]



Within SM constrained by BR($\eta \to \pi^+\pi^-$):

using experimental upper bound: **$A_\phi < 10^{-4}$**

using theoretical predictions: **$A_\phi \sim 10^{-15}$**

The unconventional CPV term increases A_ϕ up to 10^{-2}

$\eta \to \pi^+\pi^- e^+e^-$: event counting

arXiv:0812.4830

Data sample: 1.73 fb^{-1}

PID con ToF EMC info

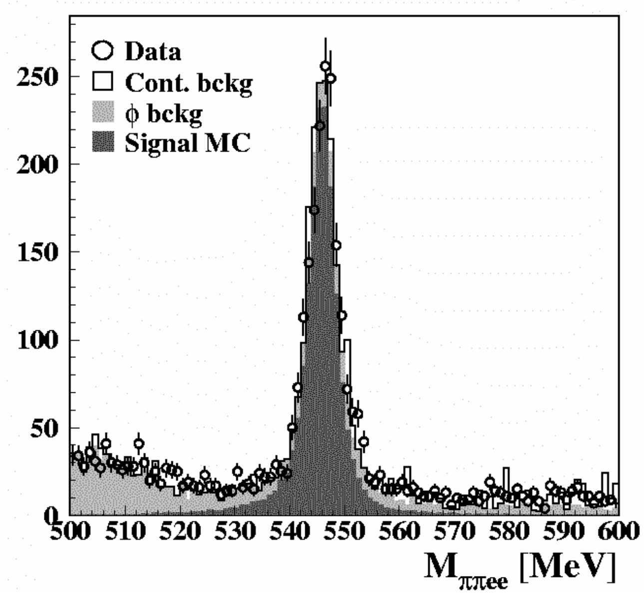
Fit on $M_{\pi\pi ee}$ side bands for background

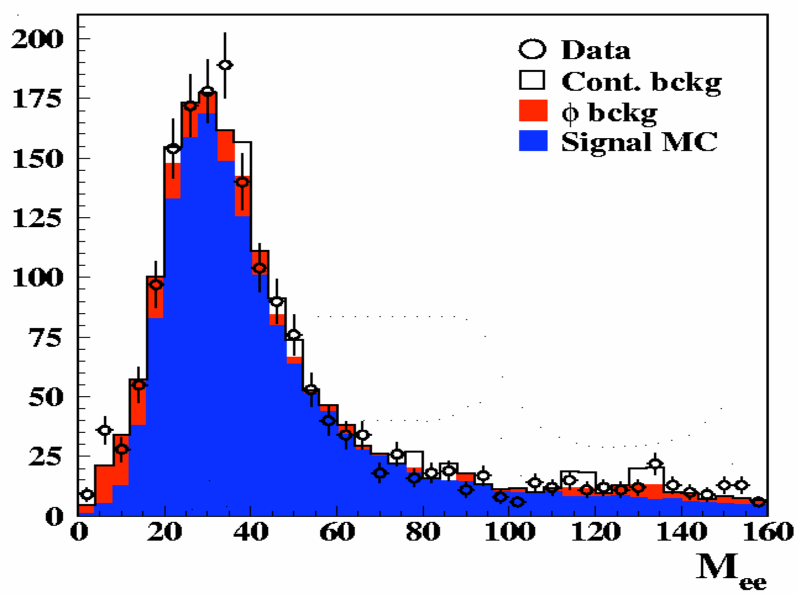
Photon conversion on Beam Pipe rejected

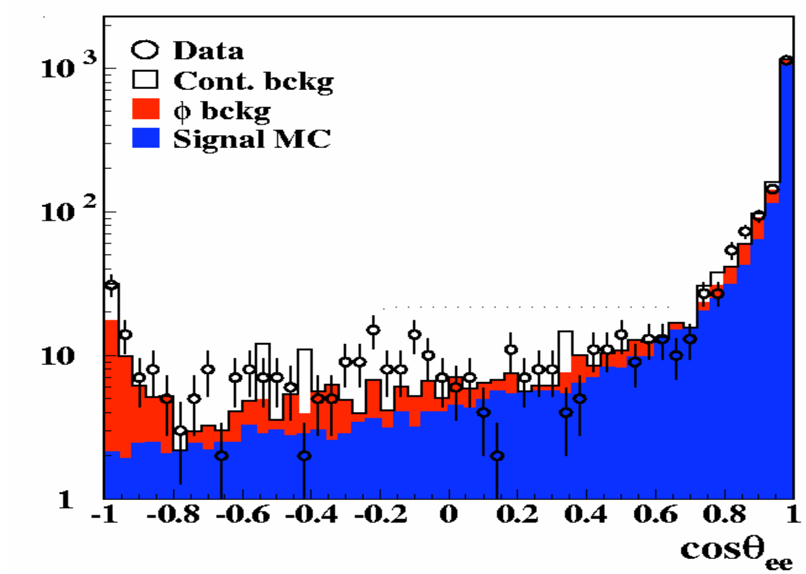
Counting on $M_{\pi\pi ee}$ in the signal region:

$N_{\pi\pi ee}$ = 1555 ± 52 (368 bckg evts)

Analysis efficiency: 8%



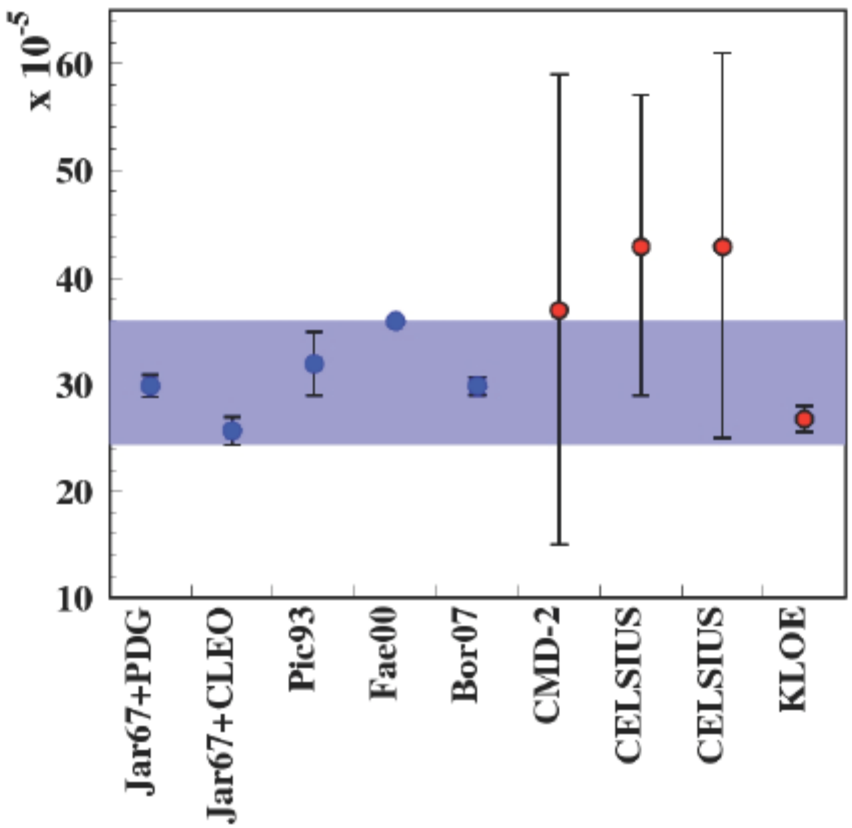


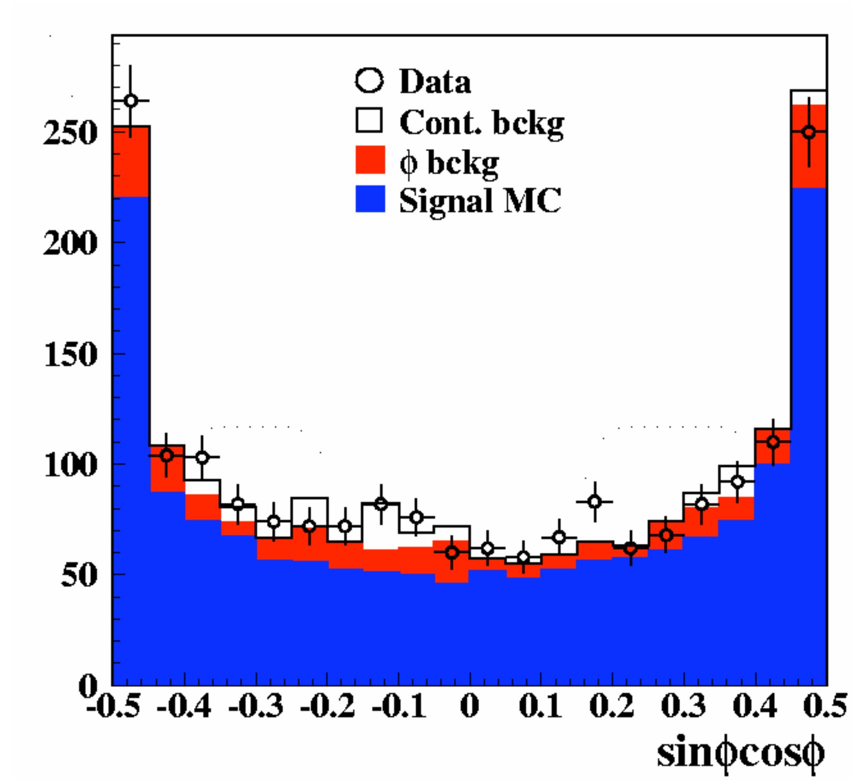


$\eta \to \pi^+\pi^- e^+e^-$: results

arXiv:0812.4830

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





$$A_\phi = \frac{N_{\sin\phi\cos\phi} - N_{\sin\phi\cos\phi}}{N_{\sin\phi\cos\phi} + N_{\sin\phi\cos\phi}}$$

$A_\phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{syst}) \times 10^{-2}$

1st measurement!

η/η′ mixing: gluonium content in η′

$$R_\phi = \frac{BR(\phi \to \eta'\gamma)}{BR(\phi \to \eta\gamma)} = (4.77 \pm 0.09_{stat} \pm 0.19_{syst}) \times 10^{-3}$$

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Gluonium content in η′ evaluated using Rosner model: **[Rosner PRD27(1983) 1101]** **[Kou PRD63(2001)54027]**

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

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

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

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

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

SU(3) relations between decay modes:

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

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

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

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

Gluonium content extracted using Z_N, Z_{NS} evaluated assuming $Z^2_{\eta'}=0$:

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

φ_P = (39.7 ± 0.7)°

$Z^2_{\eta'}$ = 0.14 ± 0.04

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

η/η' mixing: gluonium content in η'

Preliminary

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

Other SU(3) relations need to be included :

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

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

- **Gluonium content @ ~3σ level confirmed**
- **Forcing $Z_{\eta'}$=0 : $\phi_P = (41.6\pm0.5)°$ with $P(\chi^2)$=1%**
- **Discrepancy with Escribano-Nadal** ($Z_{\eta'} = 0.04 \pm 0.09$, $\phi_P = (41.4\pm1.3)°$) [JHEP05(2007)006] **due to the insertion of Pγγ transitions**

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

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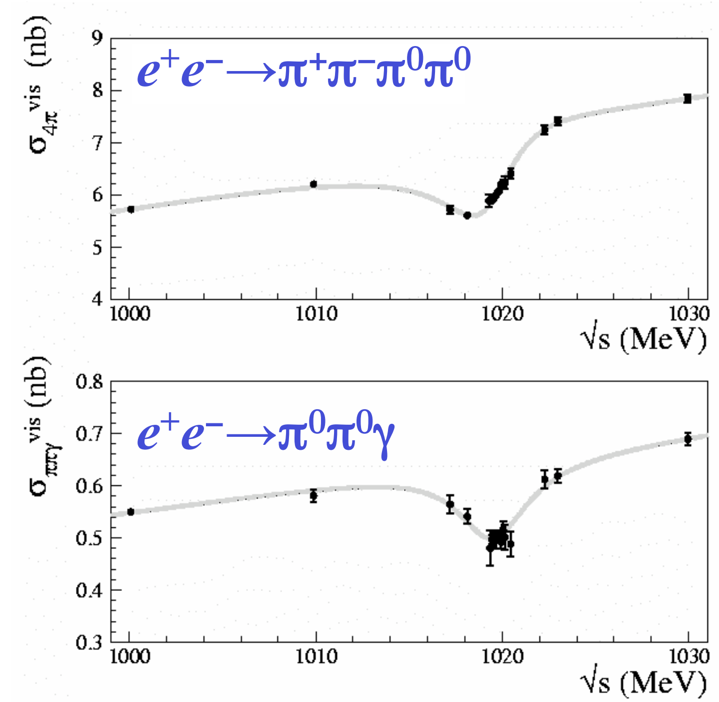
Interference pattern between non-resonant $e^+e^-\to\omega\pi^0$ and ϕ decays:

$$\sigma(\sqrt{s}) = \sigma_0(\sqrt{s})\left|1 - Z\frac{M_\phi\Gamma_\phi}{D_\phi}\right|$$

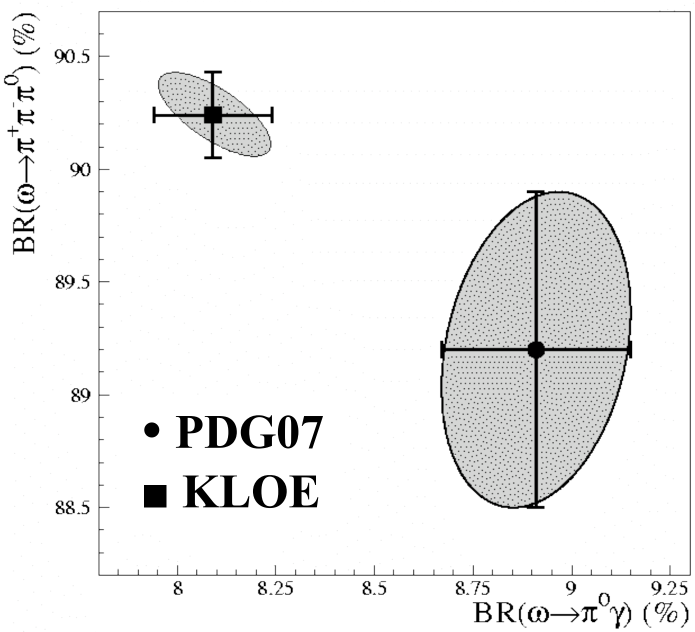
Model indep. $\sigma_0(\sqrt{s})$:

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



From $\Gamma(\omega\to\pi^0\gamma)/\Gamma(\omega\to\pi^+\pi^-\pi^0)$ + unitarity (rare BRs (~2%)):

$BR(\omega\to\pi^+\pi^-\pi^0) = (90.24 \pm 0.19)\%$
$BR(\omega\to\pi^0\gamma) = (8.09 \pm 0.14)\%$



From fit parameters + $BR(\omega\to\pi^+\pi^-\pi^0)$:

$$BR(\phi\to\omega\pi^0) = \frac{\sigma_0^{\omega\pi}\left|Z_{4\pi}\right|^2}{\sigma_\phi} = (5.63 \pm 0.70)\times 10^{-5}$$

OZI + G-parity violating

$$\text{SND(2000)}: BR(\phi\to\omega\pi^0) = (5.2^{+1.3}_{-1.1})\times 10^{-5}$$

$\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma))$ measurement

The comparison between experiment and theory for the muon anomaly a_μ is a precise test of SM

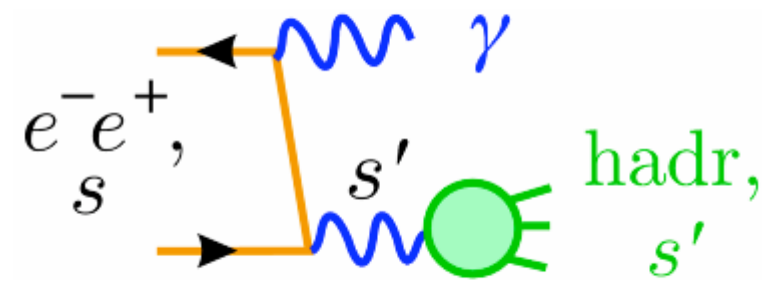
Theoretically, the error on a_μ is dominated by the hadronic contribution, that have to be evaluated from data

$e^+e^- \rightarrow \pi^+\pi^-$ in the range < 1 GeV contributes 70% to a_μ!

KLOE has shown, for the first time, that it is possible to measure $\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)$ at fixed $\sqrt{s}$ with high accuracy using ISR to extract $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ for $\sqrt{s'}$ from $2M_\pi$ to $\sqrt{s}$ [PLB606(2005)12]

Neglecting FSR effects:

$$s \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi}(s) \times H(s)$$



Requires precise calculations of the radiator function H(*s*)

⇒ PHOKHARA MC NLO generator

[H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, EPJC27(2003)]

$\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma))$ measurement

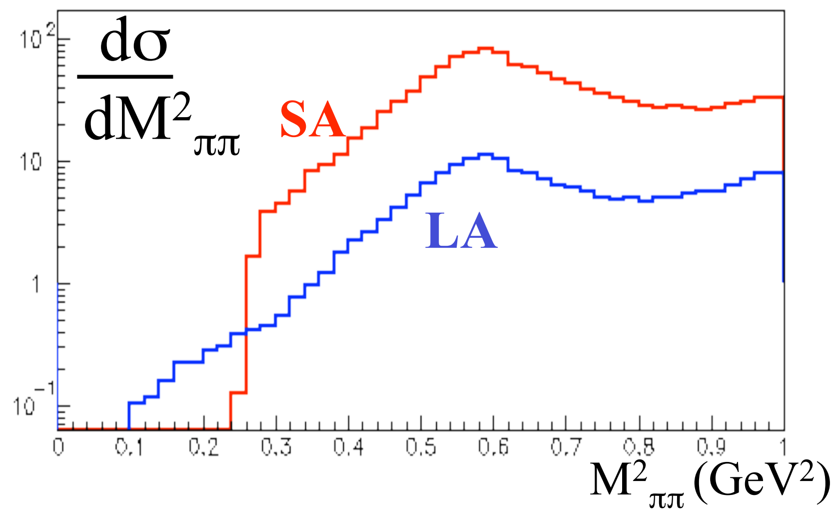
$$\frac{d\sigma^{obs}_{\pi\pi\gamma(\gamma)}}{dM^2_{\pi\pi}} = \frac{\Delta N_{\rm Obs} - \Delta N_{\rm Bkg}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon_{\rm Sel}} \cdot \frac{1}{\int L dt}$$

- Background rejection with PID using EMC info ($ee\gamma/\mu\mu\gamma$) and kin. cuts ($\phi \rightarrow \pi\pi\pi$)
- **Efficiencies mostly evaluated on data with two independent methods**
- Luminosity from Bhabha scattering events with 55°<θ<125° [EPJC47(2006)589] [Generator used for σ_{eff}: BABYAGA (NPB758(2006)22)]

Two samples used:

1) **Small angle: $\theta_{\pi\pi} < 15^o$ or $\theta_{\pi\pi} > 165^o$**
   - Higher cross section (21 nb vs 3 nb)
   - Less background
   - Kinematically limited

2) **Large angle: $50^o < \theta_\gamma < 130^o$**
   - Higher background (FSR + $\phi \rightarrow \pi^+\pi^-\pi^0 / f_0\gamma$)
   - All $M_{\pi\pi}$ spectrum



$\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ measurement

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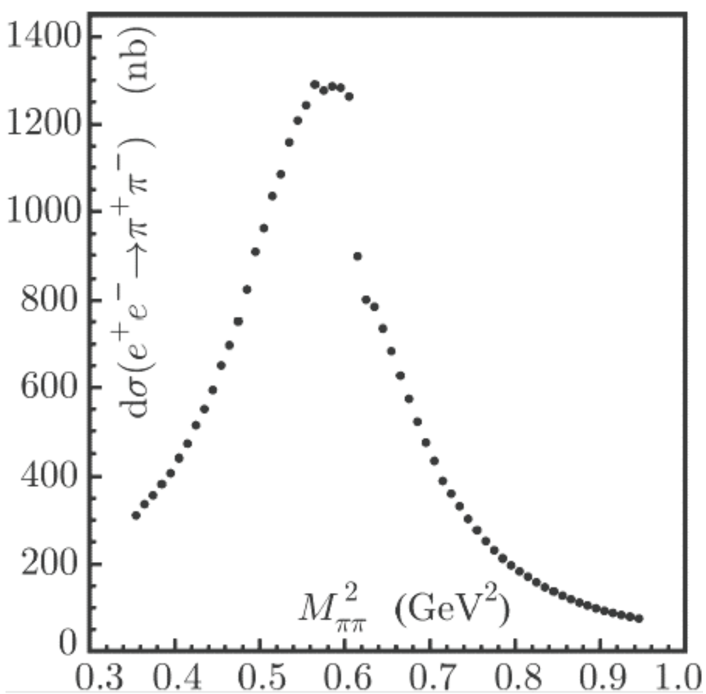
SMALL ANGLE ANALYSIS

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int_{0.35\mathrm{GeV}^2}^{0.95\mathrm{GeV}^2} ds\, \sigma(e^+e^- \to \pi^+\pi^-)\, K(s)$$

$\sigma_{\pi\pi}$ *vs* $M^0_{\pi\pi}$, undressed from vacuum polarization and inclusive for FSR



$a_\mu^{\pi\pi}(0.35\text{–}0.95\ \mathrm{GeV}^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{syst} \pm 2.3_{the}) \times 10^{-10}$

Systematic errors on $a_\mu^{\pi\pi}$:

Experimental fractional error = 0.6 %

Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
π/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.1%
Acceptance (θ_π)	negligible
Unfolding	negligible
Software Trigger	0.1%
$\sqrt{s}$ dep. Of H	0.2%
Luminosity $(0.1_{th} \oplus 0.3_{exp})$%	0.3%

Theoretical fractional error = 0.6 %

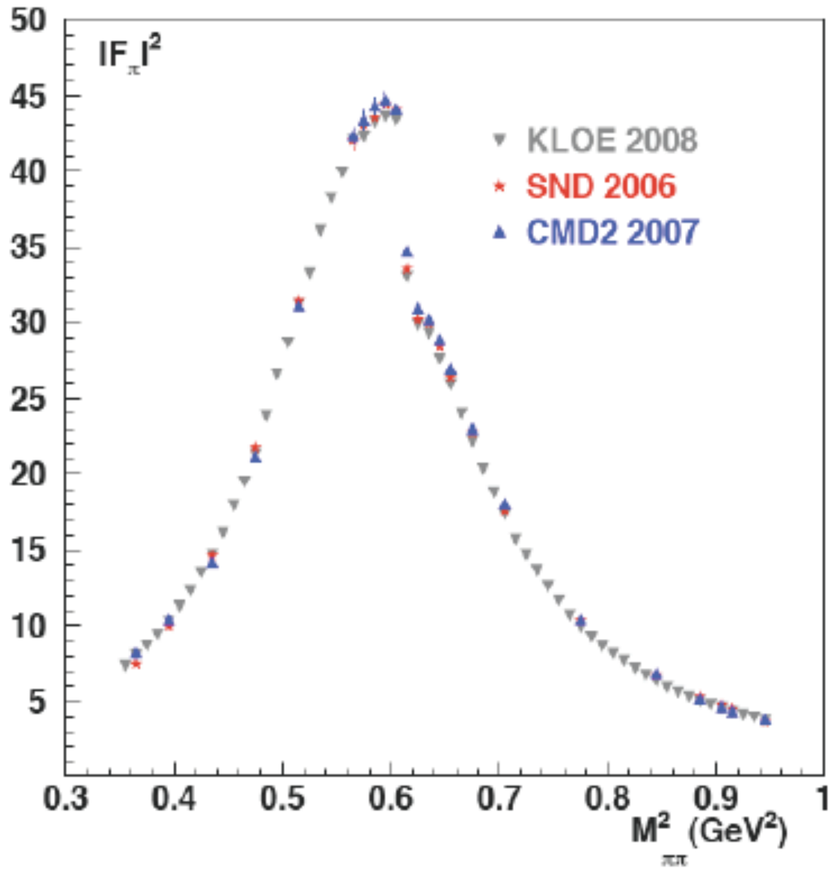
FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	0.1%

Results are also expected in near future from:

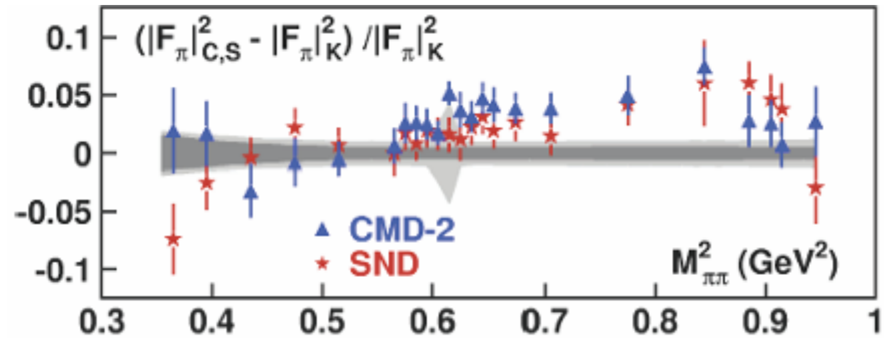
- **ππγ/μμγ ratio**
- **photon detected at large angle**
- **off-resonance data (1GeV)**

Comparison with CMD2/SND on $|F_\pi|^2$

$$|F_\pi|^2 = \frac{3s}{\pi\alpha^2\beta_\pi^3}\sigma_{\pi\pi}(s)$$



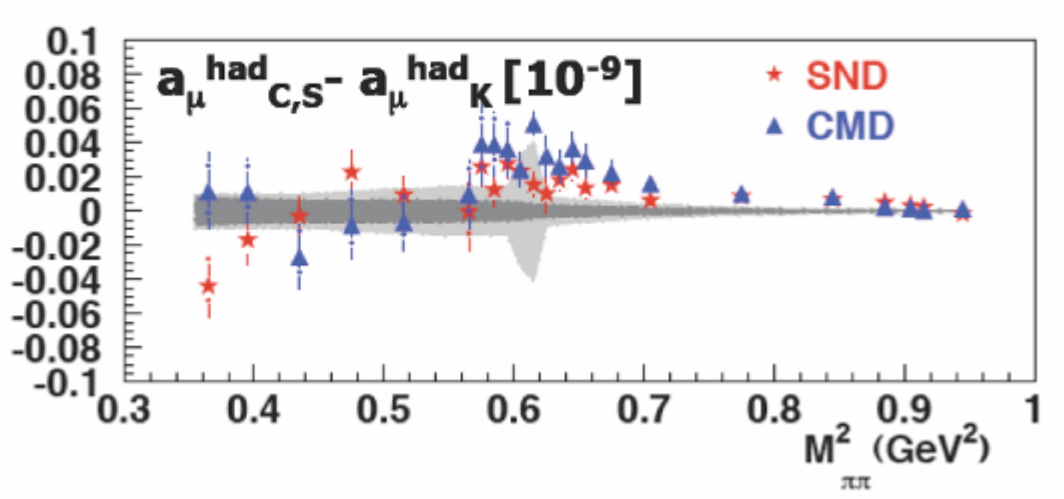
Statistical errors only

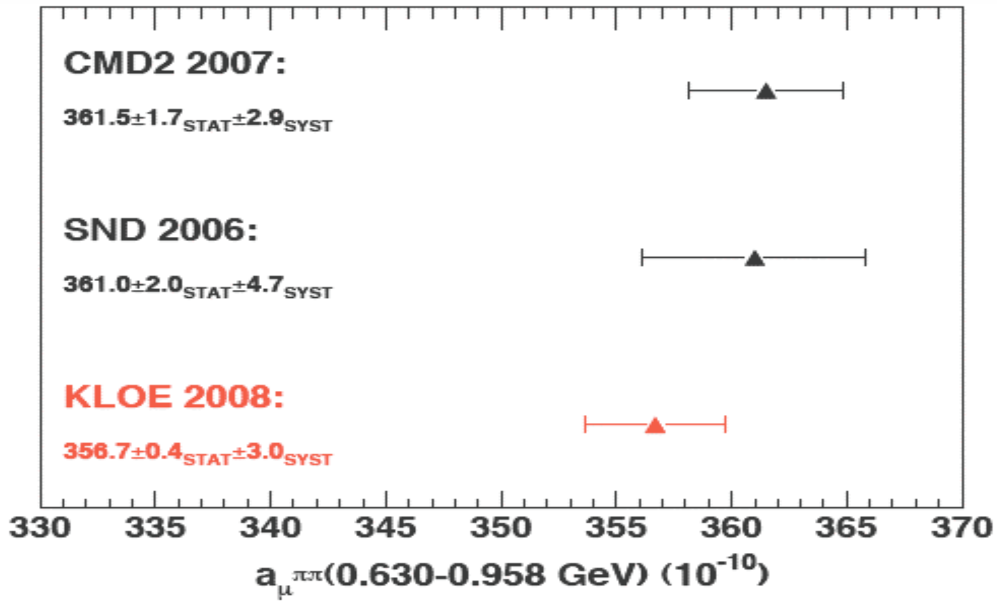


Grey band: KLOE total error
Data points: CMD2/SND experiments

CMD2 and SND data have been averaged over width of KLOE bin (0.01 GeV^2)

Comparison with CMD2/SND on $a_\mu^{\pi\pi}$





Average value: 359.2 ± 2.1 with χ^2/ndf = 1.24/2

Conclusions

- **Important results have been obtained by KLOE in hadronic physics:**

Measurement of BR($\phi \to f_0(980)\gamma$) and BR($\phi \to a_0(980)\gamma$)
Large couplings of $f_0(980)/a_0(980)$ to ϕ and to KK
$\sigma(600)$ needed in the description of the $\pi^0\pi^0\gamma$ Dalitz plot
Upper limit set for $\phi \to KK\gamma$
Excess of events in the $\sigma(600)$ mass region for $e^+e^- \to e^+e^-\pi^0\pi^0$

BR + first measurement of the CPV plane asymmetry for $\eta \to \pi^+\pi^- e^+e^-$
Gluonium content @ 3σ level in η' using the Rosner model
Accurate measurement of Dalitz plot parameters for $\eta \to \pi\pi\pi$ [JHEP05(2008)006]
Precise measurement of η mass [JHEP12(2007)073]
Forbidden η decays: $\eta \to \pi^+\pi^-$, $\eta \to \gamma\gamma\gamma$ [PLB 606 (2005) 276]

Not shown today

Precise measurement of the main ω BR's and of BR($\phi \to \omega\pi^0$)

$\pi\pi$ contribution to the muon anomaly with ($0.6\%_{exp} \oplus 0.6\%_{theo}$) uncertainty

- **DAΦNE upgrade + KLOE2: new and more precise measurements will follow**

Future prospects: KLOE2

New scheme to increase 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 γγ physics** ⇒ **~ 5 fb^{-1}**
2. **Detector upgrade**: inner tracker, new small angle calorimeters…
3. **KLOE-2 data taking** ⇒ **50 fb^{-1} in 3 – 4 years**

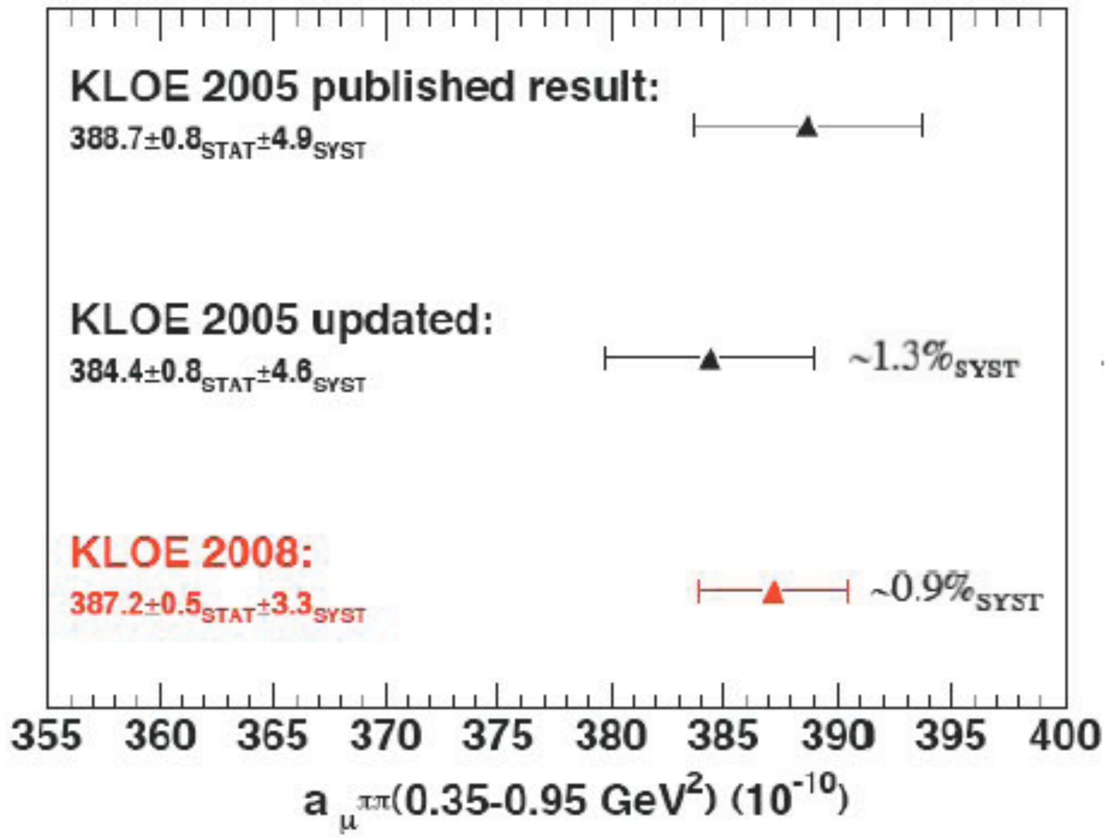
KLOE-2 physics program:

❖ **Kaon physics: CKM unitarity, Quantum Mechanics tests, lepton universality ($K^{\pm}\to e^{\pm}\nu$ / $K^{\pm}\to\mu^{\pm}\nu$), K_S rare decays**

❖ **Light hadrons: search for σ(600) in $\gamma\gamma \to \sigma \to \pi^0\pi^0$, $\phi \to (f_0/a_0)\gamma \to KK\gamma$ rare η decays, η′ physics**

$\sigma(e^+e^-\to\pi^+\pi^-\gamma(\gamma))$ measurement

PLB 670 (2009) 285



Comparison with to 2005

error table on exp. systematics

PLB606(2005)12

Trigger	0.3%
Reconstruction filter	0.6%
Background	0.3%
M_{trk} cuts	0.2%
Particle ID	0.1%
Tracking	0.3%
Vertex	0.3%
Acceptance	0.3%
Unfolding	0.2%
Luminosity $(0.5_{th} \oplus 0.3_{exp})$%	0.6%

$\Sigma_{exp,2005} = 0.9\% (\oplus 0.9\% Th)$

This work (2008):

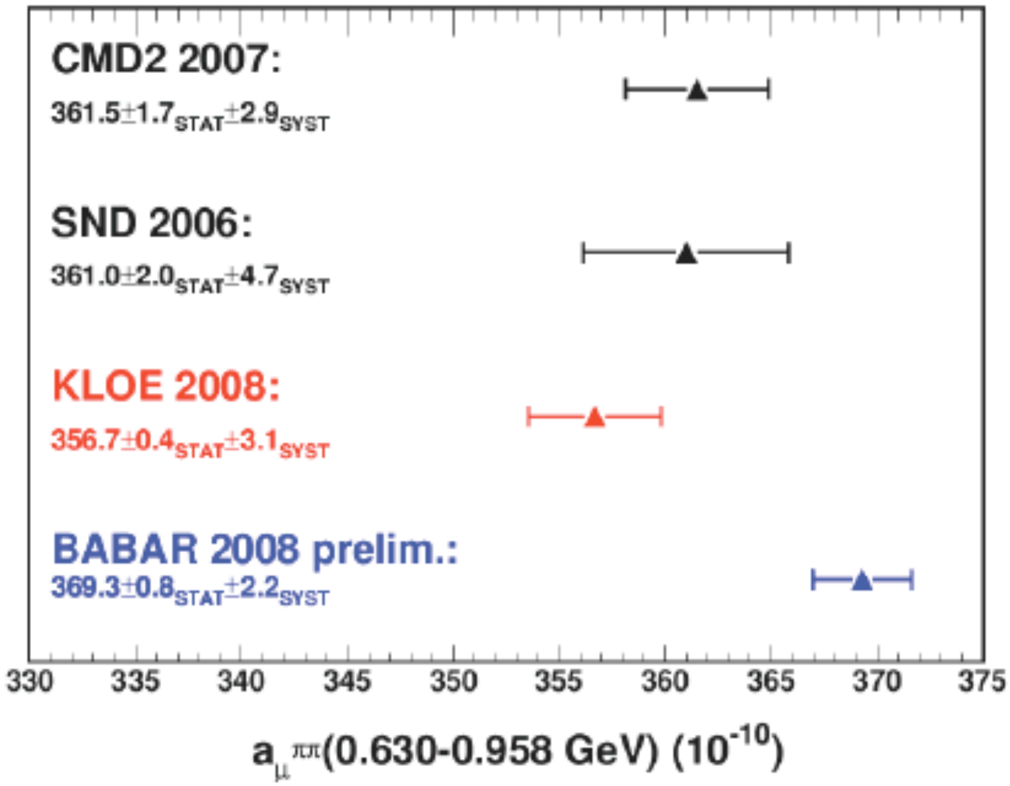
Trigger	0.1%
Reconstruction filter	-
Background	0.3%
M_{trk} cuts	0.2%
Particle ID	-
Tracking	0.3%
Vertex	-
Acceptance	0.1%
Unfolding	-
Software Trigger	0.1%
$\sqrt{s}$ dep. of H	0.2%
Luminosity $(0.1_{th} \oplus 0.3_{exp})$%	0.3%

$\Sigma_{exp,2008} = 0.6\% (\oplus 0.6\% Th)$

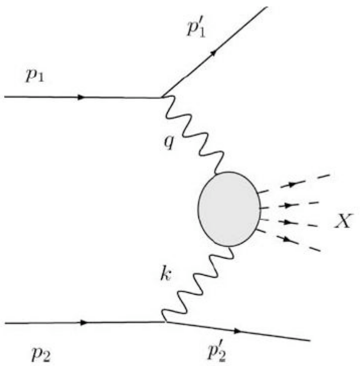
- Many sistematic effects improved !
- Almost everywhere efficiencies evaluated on data by two independent methods

- 30% CV inefficiency recovered in 2002 by additional software trigger level
- Improved offline-event filter -> syst.error <0.1%
- new generator BABAYAGA@NLO theory error from 0.5% to 0.1%
- Trigger efficiency updated due to a doublecounting

Comparisons on $a_\mu^{\pi\pi}$



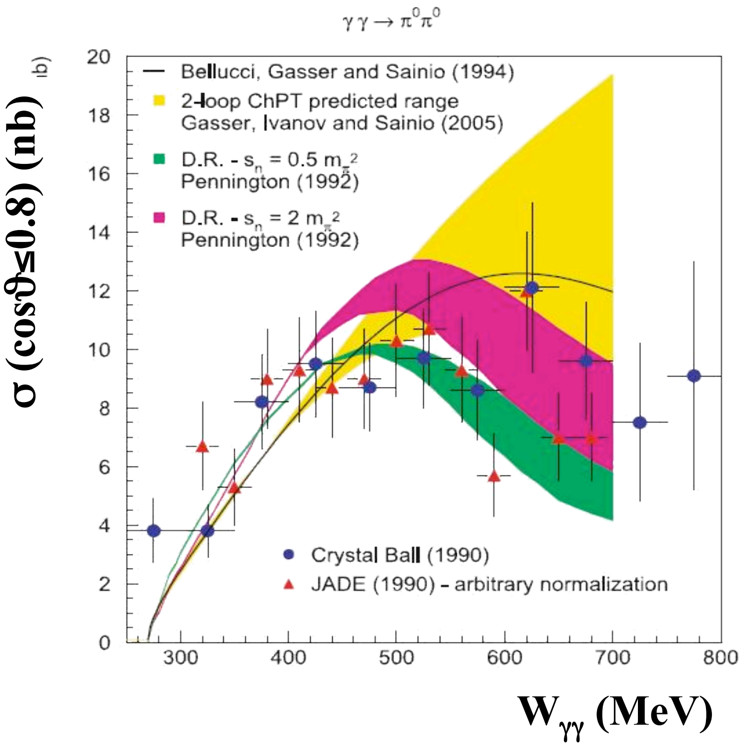
γγ physics @ KLOE/KLOE2

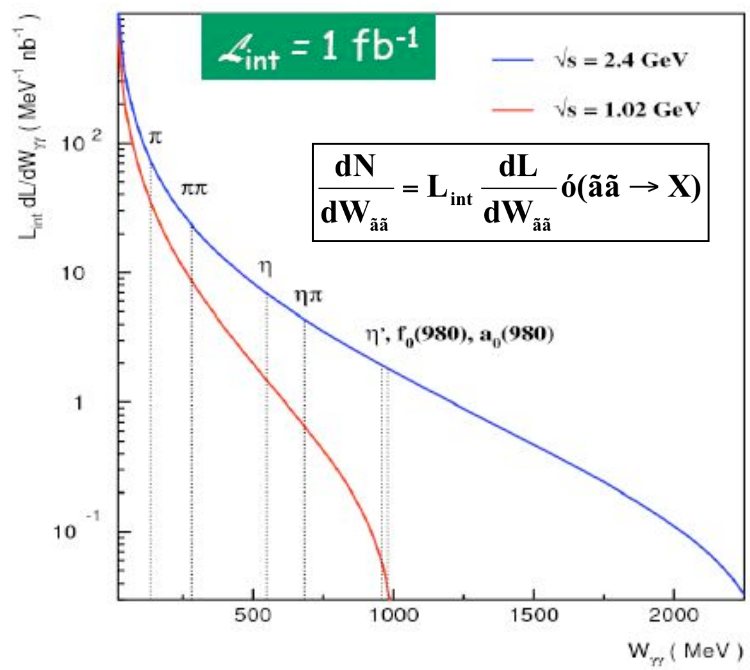


$$e^+e^- \rightarrow e^+e^-\tilde{a}^*\tilde{a}^* \rightarrow e^+e^-X$$

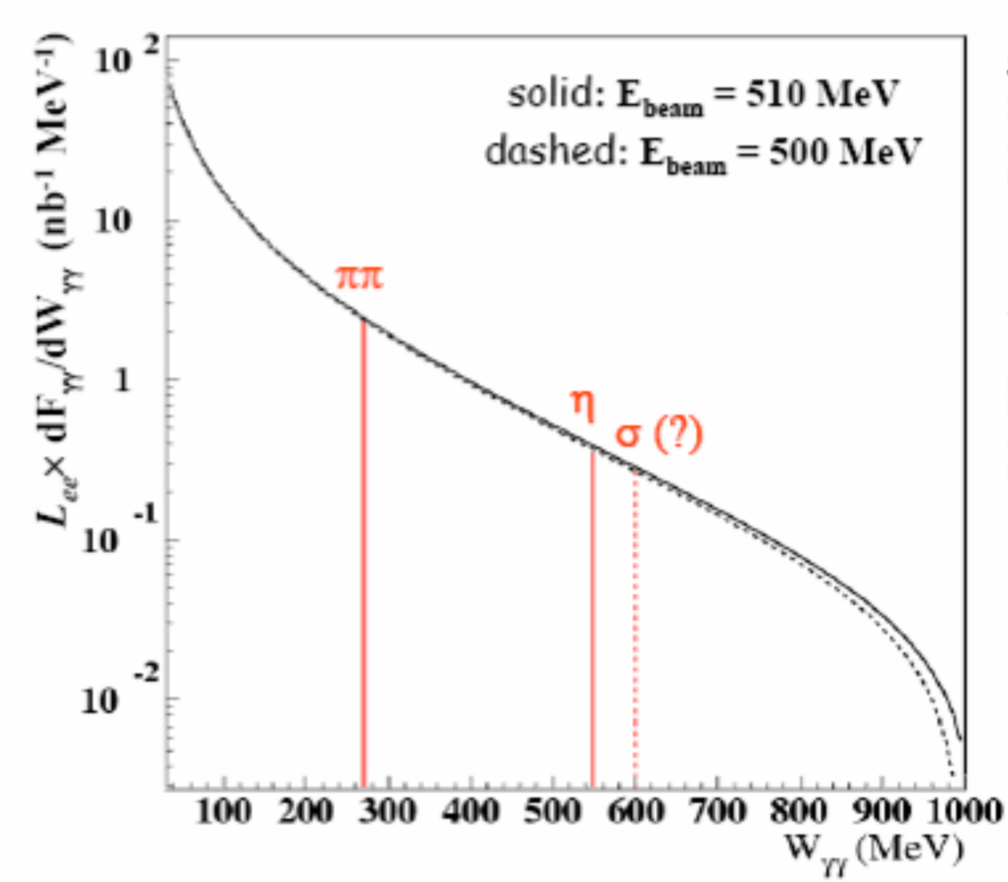
$$\left[J^{PC}(X) = 0^{\pm +}, 2^{\pm +}\right]$$

- X = π^0, η, η′ ⇒ Γ(P→γγ)
- X = $\pi^0\pi^0$ ⇒ γ*γ*→ σ(600) → $\pi^0\pi^0$
  with L=5 fb^{-1} ⇒ err. ≈ 2%

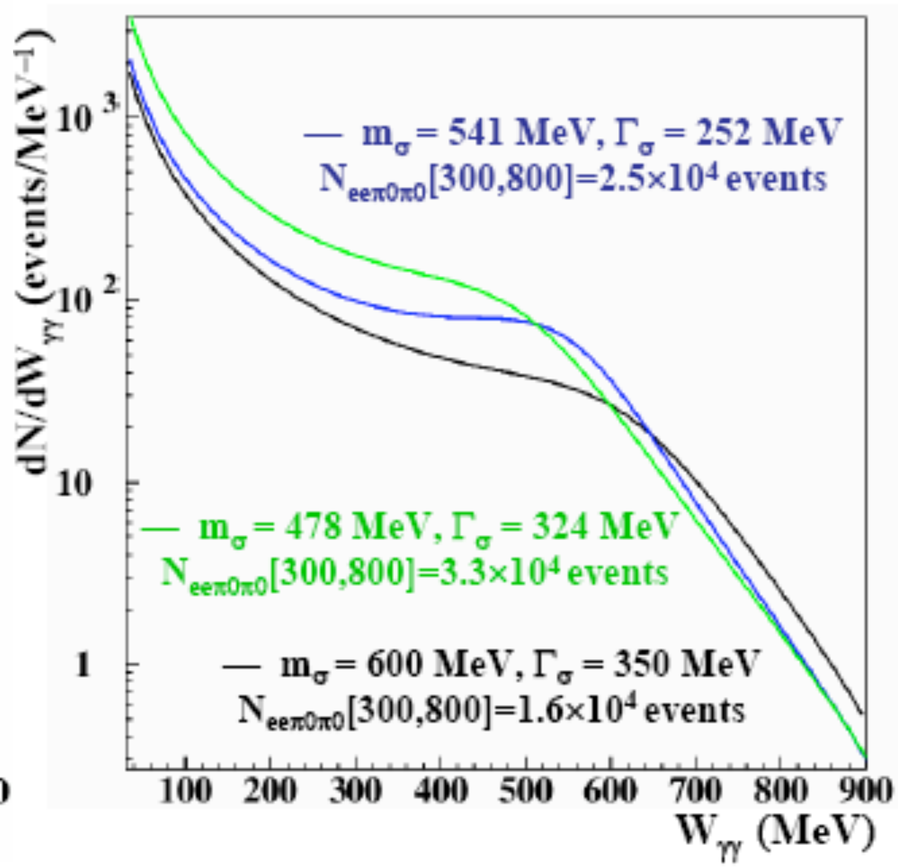




KLOE: $\gamma\gamma \to \sigma$ production



$e^+e^- \to e^+e^-\sigma \to e^+e^-\pi^0\pi^0$,
event yield with 250 pb^{-1}:



No loss in statistics from 1020 MeV to 1000 MeV

$\pi^+\pi^-$: too much background from ISR/FSR

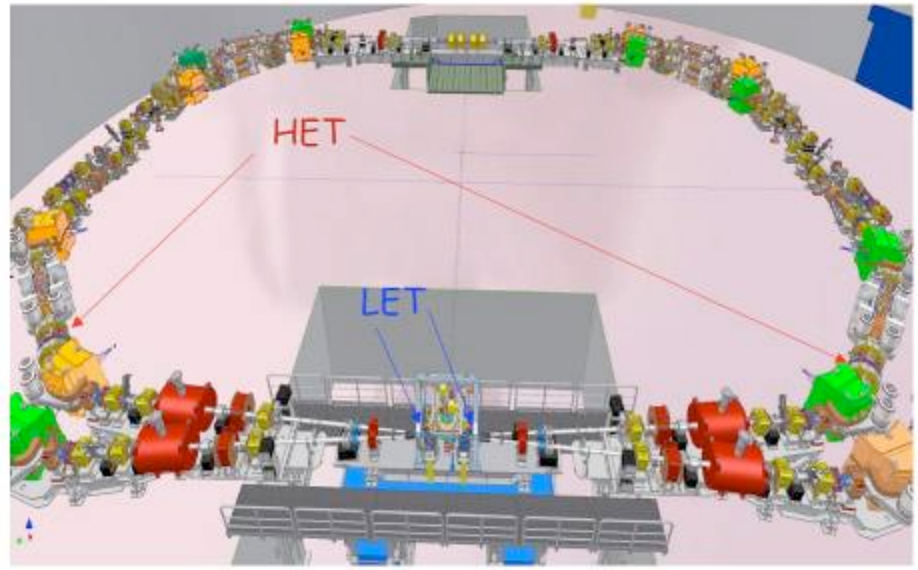
$\pi^0\pi^0$: expected (not interfering) background:

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

$e^+e^- \to \omega\gamma_{ISR} \to \pi^0\gamma\gamma_{ISR}$

Tagger for $\gamma\gamma$ physics

- $e^{\pm}$ tagger needed to reject background from $\phi \to K_S K_L$ (K_L lost, $K_S \to \pi\pi$ S/B ~ 10^{-3}-10^{-4}) and to improve resolution on $W_{\gamma\gamma}$

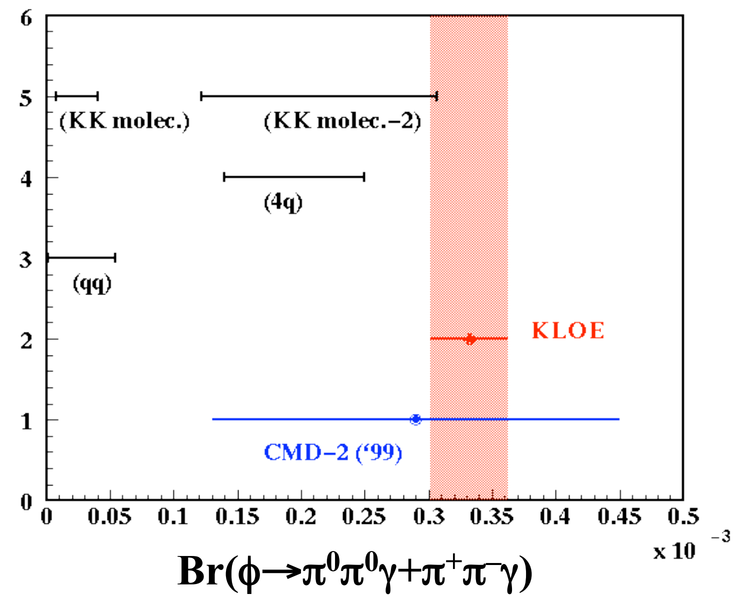


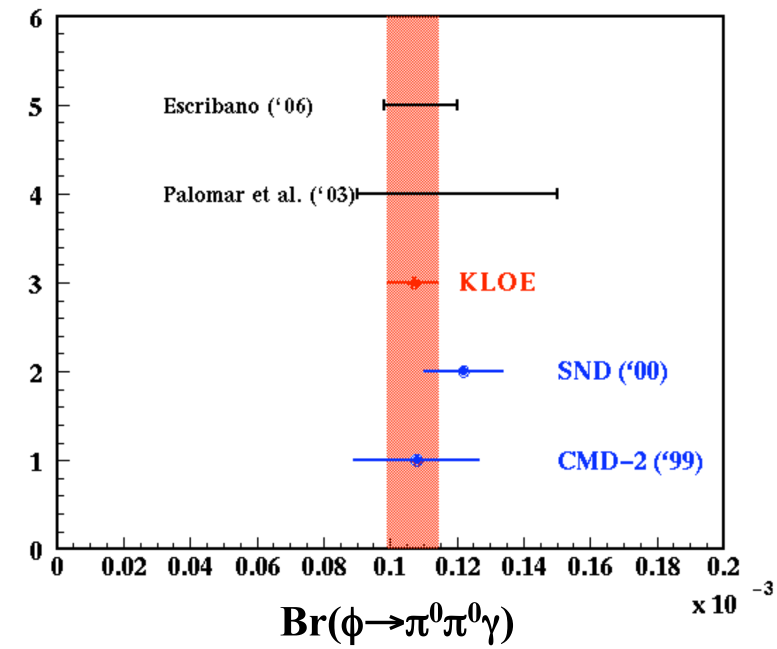
- 2 detectors:
  - LET (Low Energy Tagger)
    Crystals + SiPM
    σ_E/E= 5 – 10% , σ_t ~ 2 ns
    @ $E_e \approx 200$ MeV

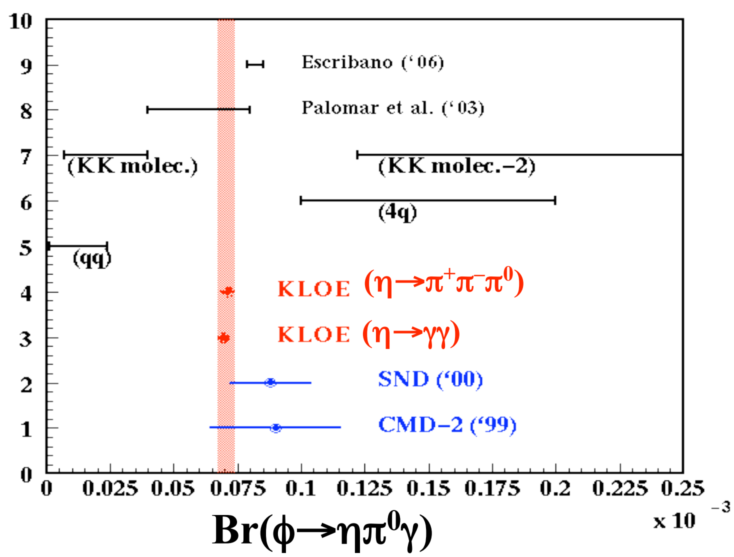
	E_e' (MeV)	E_γ (MeV)
LET	(165 - 235)	(275 - 345)
HET	(330 - 390)	(120, 180)

  - 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

BR of scalar mesons







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 of scalar mesons

		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

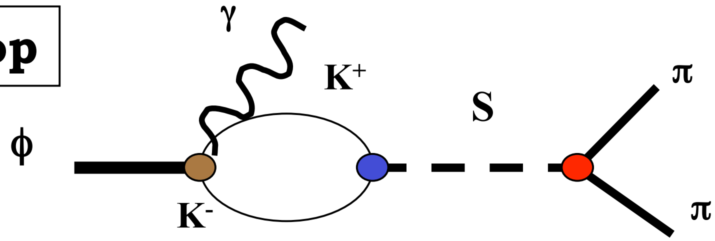
Light scalars in ϕ radiative decays

~450 pb^{-1} of e^+e^- collisions @ $\sqrt{s}=M_\phi$

Contributions from **$\phi\to S\gamma$**, with **$S=f_0(980)/\ \sigma(500)/a_0(980)$** searched for in $\pi\pi\gamma$, $\eta\pi\gamma$ final , state. Large and partly unknown continuum backgrounds, with sizable interference

Both **BR($\phi\to S\gamma$) and scalar mass spectra are sensitive to scalar structure**

Kaon Loop

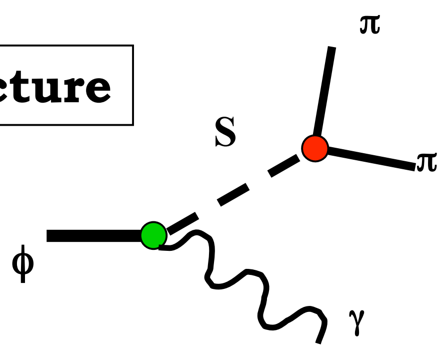


Fit params:
M_S, $g_{S\pi\pi}$, g_{SKK}

Dipole transition (E_γ^3) dumped by loop function, KK channel opening taken into account

[N.N.Achasov, V.N.Ivanchenko, NPB315 (1989) 465]
[N.N.Achasov, V.V.Gubin, PRD 56 (1997) 4084]
[N.N.Achasov, A.V.Kiselev, PRD 68 (2003) 014006]

No Structure



Fit params:
M_S, g_{fSg}, $g_{S\pi\pi}$, g_{SKK} ,
continuum (polynomial)

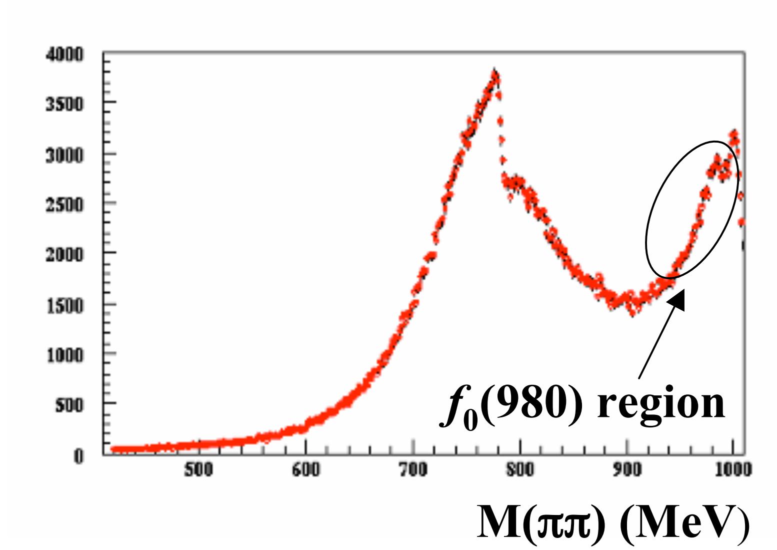
Dipole transition (E_γ^3) dumped by polynomial terms, KK channel opening taken into account

[G.Isidori, L.Maiani, M.Nicolaci, S.Pacetti, JHEP 05 (2006) 049]

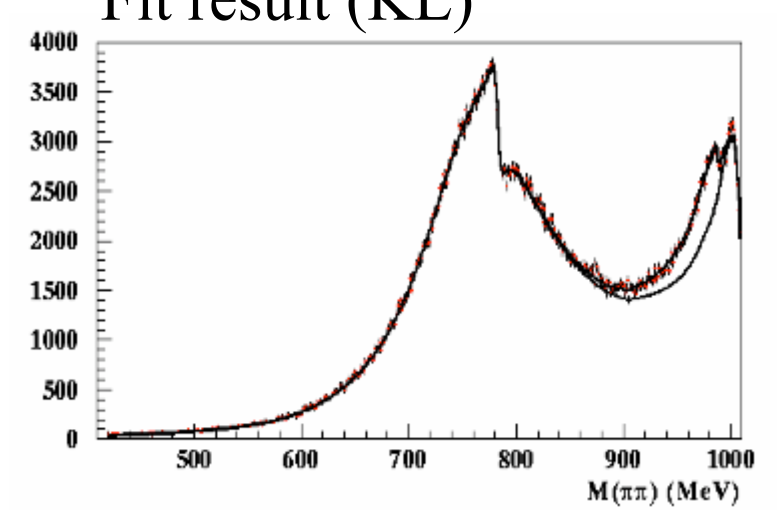
The $\pi^+\pi^-\gamma$ final state

KLOE, PLB 634 (2006) 148

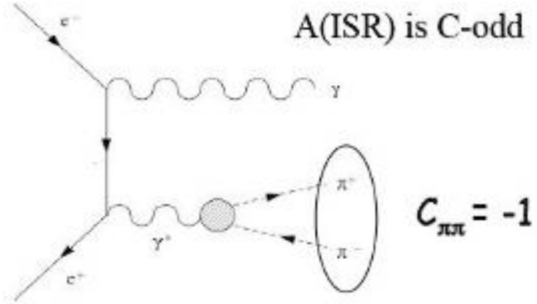
- $e^+e^- \to \pi^+\pi^-\gamma$ events with the photon at large angle ($45° < \vartheta_\gamma < 135°$)
- Main contributions: ISR+FSR
- Search for the f_0 signal as a deviation on $M(\pi^+\pi^-)$ spectrum from the expected ISR + FSR shape
- $e^+e^-\gamma$ bckg events rejected using EMC $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\pi^0$ bckg suppressed by means of kinematics
- **676,000 events selected** (2001+2002)

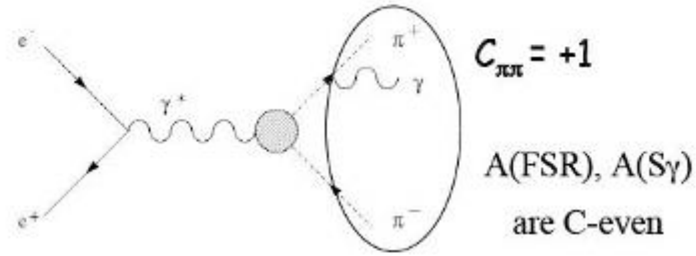


Fit result (KL)



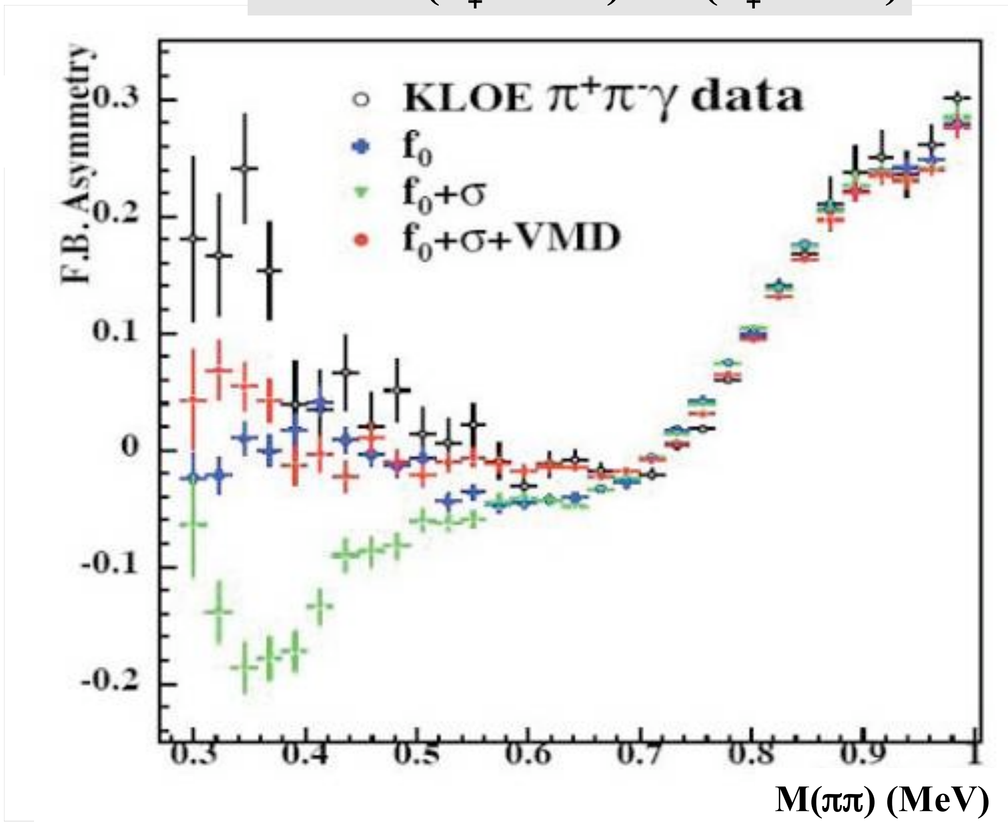
$\pi^+\pi^-\gamma$: Forward-backward asymmetry





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

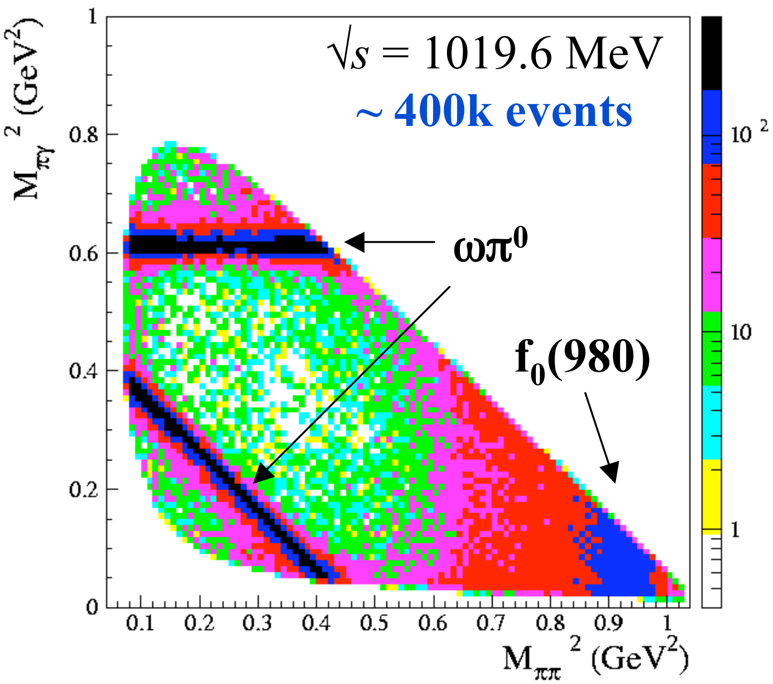
- **Clear f_0(980) signal**
- **Data-MC agreement recovered also at low M(ππ)**
  [Pancheri, Shekhovtsova, Venanzoni, PLB642(2006),342]
- **Improved simulation with f_0 and σ parameters from $\pi^0\pi^0\gamma$ analysis**
  [Pancheri, Shekhovtsova, Venanzoni, arXiv0706.3027]

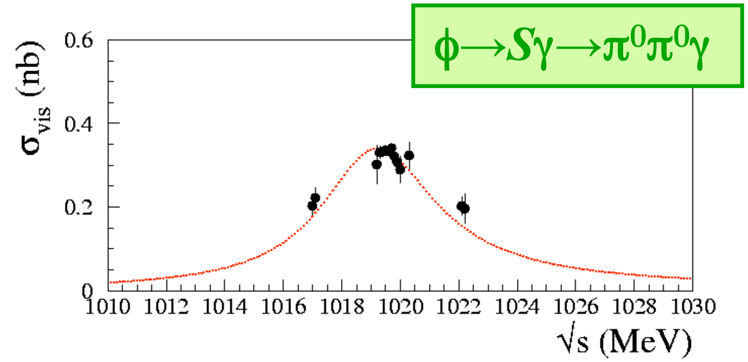


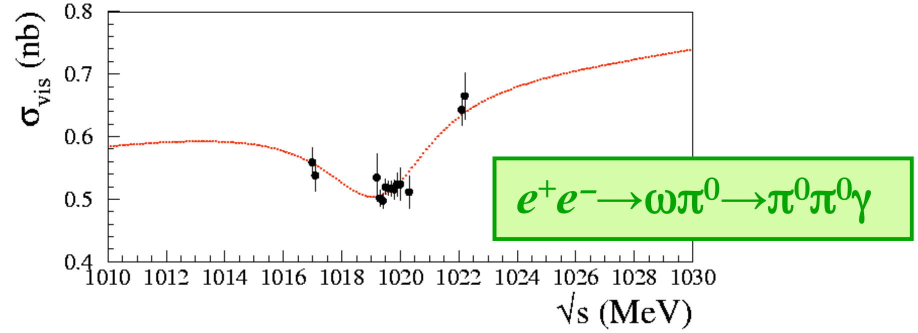
The $\pi^0\pi^0\gamma$ final state

KLOE, EPJC 49 (2007) 473

Two main contributions to $\pi^0\pi^0\gamma$ final state @ M_ϕ:







Bi-dimensional analysis of Dalitz-plot, with interference between two channels

Improved KL parametrization [PRD73(2006)054029]:
combined fit to $\pi\pi$ scattering data and to already published KLOE data on $\phi\to S\gamma$ gives ten sets of parameters able to describe both distributions

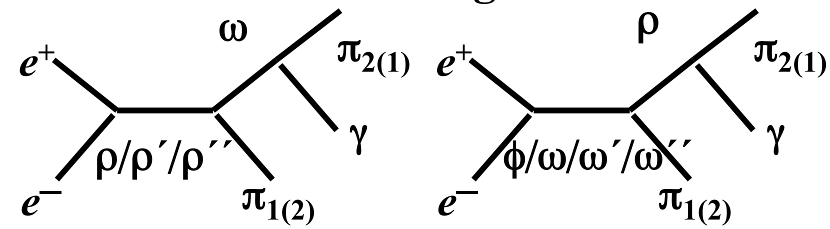
KLOE: $e^+e^- \to \pi^0\pi^0\gamma$

KLOE, Eur. Phys. J. C 49 (2007) 473

Fit to the $\pi^0\pi^0\gamma$ Dalitz plot

$$\frac{d\sigma}{dm} = \left(\frac{d\sigma}{dm}\right)_{VMD} + \left(\frac{d\sigma}{dm}\right)_{Scalar} + \left(\frac{d\sigma}{dm}\right)_{\mathrm{interf}}$$

VMD diagrams



- ❖ Fit Dalitz plot with both No-Structure and Kaon Loop models for data taken @ 1019.75 MeV
- ❖ Improved description for KL [N.N.Achasov, A.V.Kiselev, PRD73 (2006) 054029]
  - ✓ Insertion of a KK scattering phase
  - ✓ New parametrization of ππ scattering phase δ_0^0
  - ✓ **Scalar contributions: f_0(980) and σ(600)**
  - ✓ **Combined fit to ππ scattering data and** to already published KLOE data on $\phi \to S\gamma$ gives ten sets of parameters able to describe both distributions

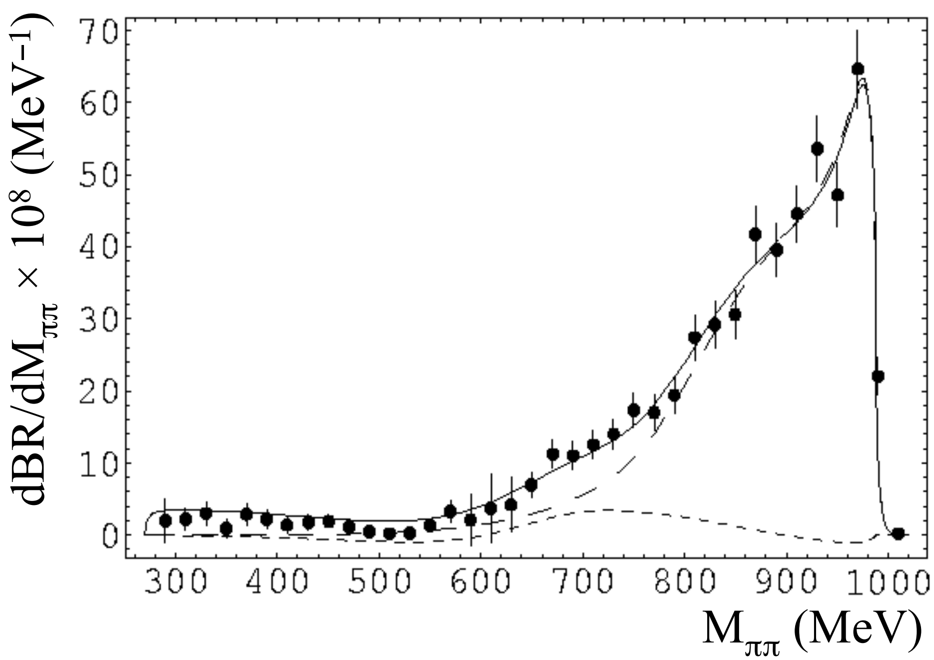
KLOE: $e^+e^- \to \pi^0\pi^0\gamma$

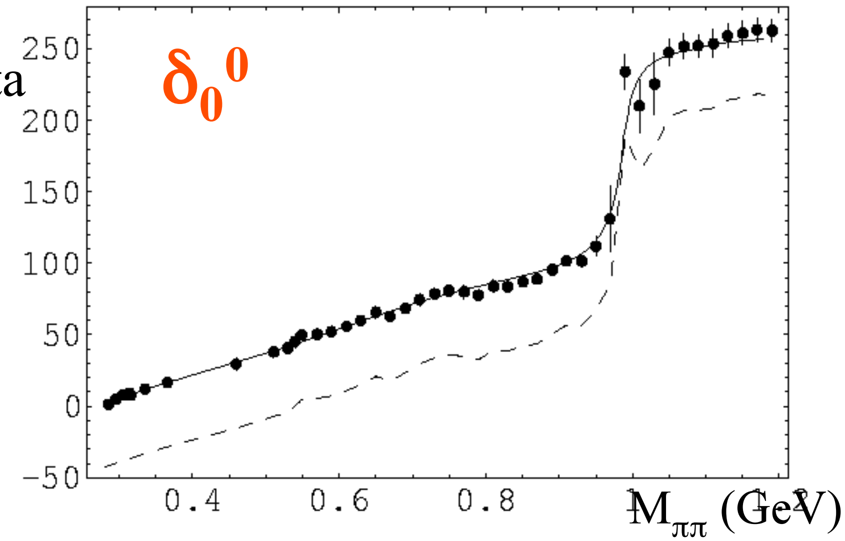
KLOE, Eur. Phys. J. C 49 (2007) 473

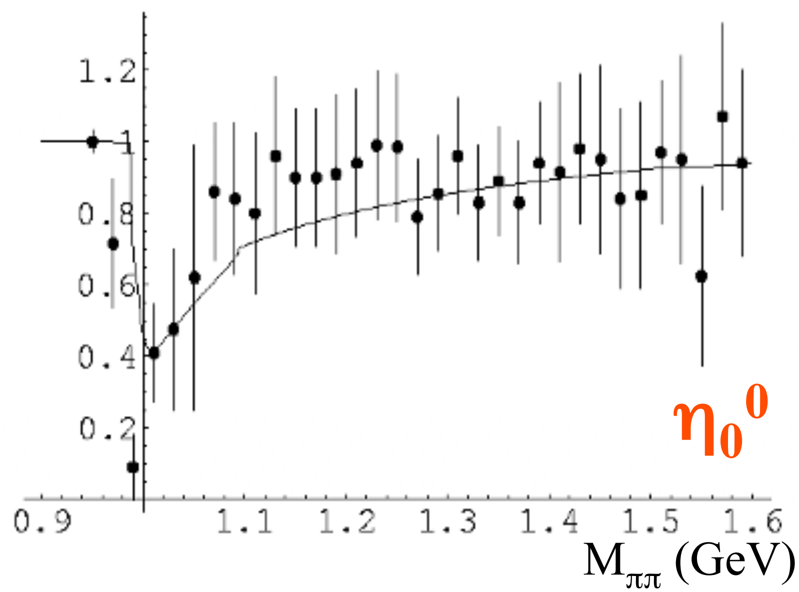
Improved Kaon Loop parametrization

Combined fit to KLOE 2000 + ππ scattering data

dBR/dM$_{\pi\pi}$ (KLOE 2000 data)







$S\to\pi\pi$: fit results

KLOE, Phys. Lett. B 634 (2006) 148
KLOE, Eur. Phys. J. C 49 (2007) 473

KL fit results:

$\pi^0\pi^0$: $\sigma(600)$ [fixed values] needed to describe data

$\pi^+\pi^-$: not sensitive to $\sigma(600)$

both channels: $f_0(980)$ strongly coupled to KK

NS fit results:

both channels: only $f_0(980)$ sufficient to describe data

$\pi^0\pi^0$ vs $\pi^+\pi^-$: larger $g_{\phi f0\gamma}$ but weaker KK coupling

Kaon Loop

Parameter	$\pi^+\pi^-\gamma$	$\pi^0\pi^0\gamma$
M_{f0} (MeV)	980—987	$976.8 \pm 0.3^{+0.9}_{-0.6} \pm 10.1$
g_{f0KK} (GeV)	5.0—6.3	$3.76 \pm 0.04^{+0.15}_{-0.08}{}^{+1.16}_{-0.48}$
$g_{f0\pi\pi}$ (GeV)	3.0—4.2	$-1.43 \pm 0.01^{+0.01}_{-0.06}{}^{+0.03}_{-0.60}$
$g^2_{f0KK} / g^2_{f0\pi\pi}$	2.2—2.8	$6.9 \pm 0.1^{+0.2}_{-0.1}{}^{+0.3}_{-3.9}$

No Structure

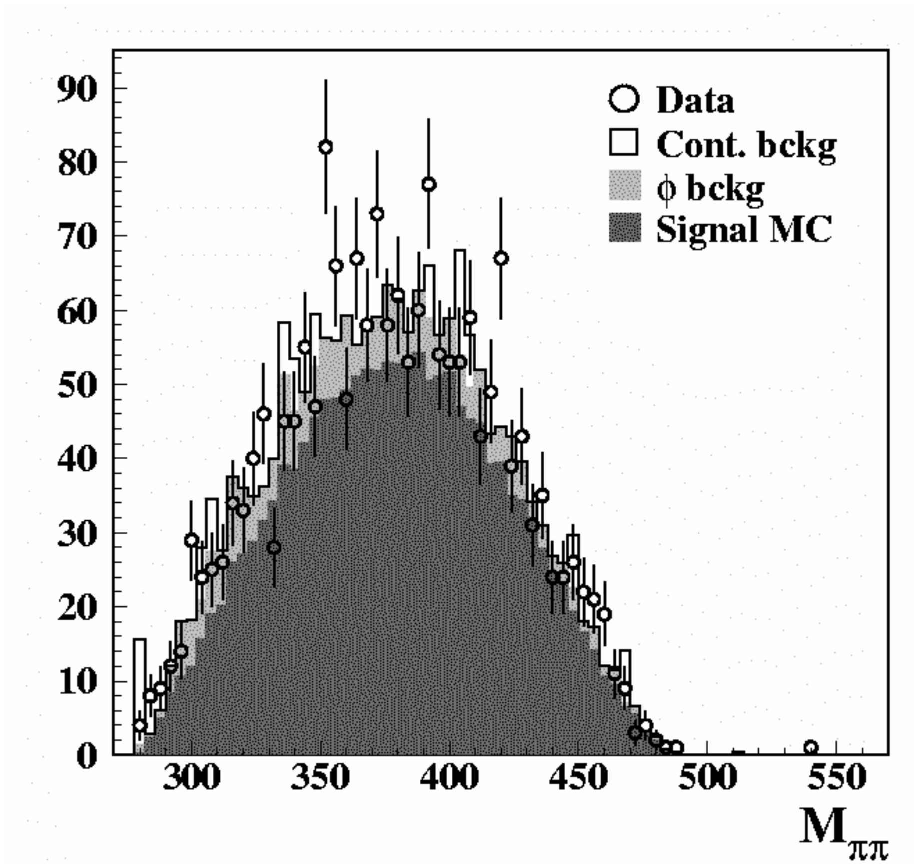
Parameter	$\pi^+\pi^-\gamma$	$\pi^0\pi^0\gamma$
M_{f0} (MeV)	973—981	$984.7 \pm 0.4^{+2.4}_{-3.7}$
g_{f0KK} (GeV)	1.6—2.3	$0.40 \pm 0.04^{+0.62}_{-0.29}$
$g_{f0\pi\pi}$ (GeV)	0.9—1.1	$1.31 \pm 0.01^{+0.09}_{-0.03}$
$g^2_{f0KK} / g^2_{f0\pi\pi}$	2.6—4.4	$0.09 \pm 0.02^{+0.44}_{-0.08}$
$g_{\phi a0\gamma}$ (GeV^{-1})	1.2—2.0	$2.61 \pm 0.02^{+0.31}_{-0.08}$

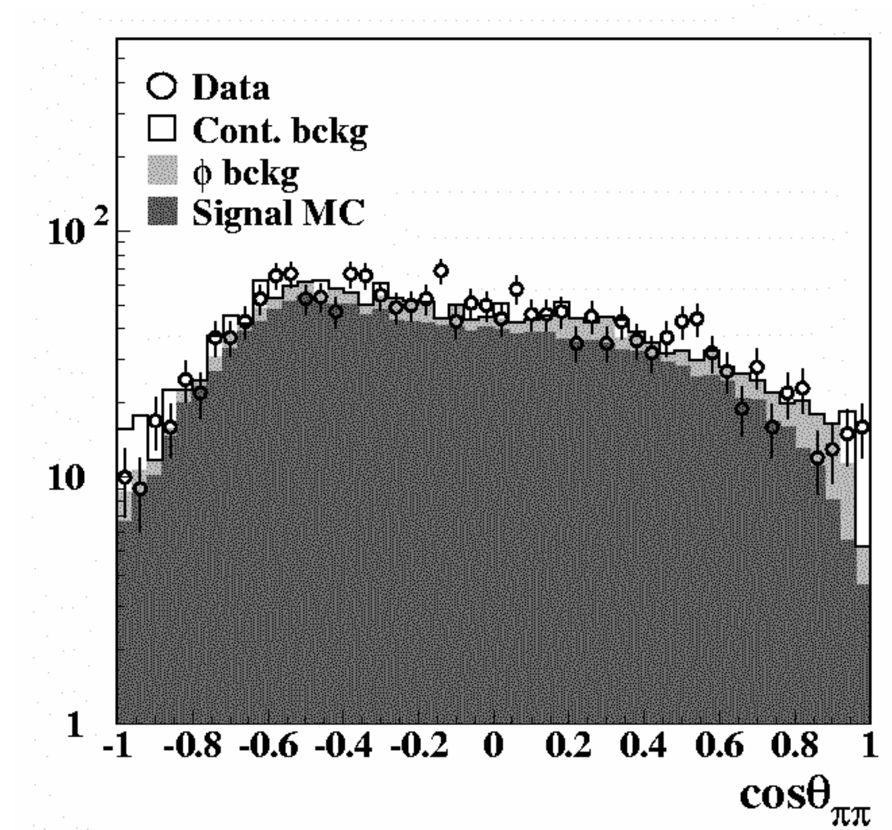
Confidence intervals given by exp. systematics, except for KL in the $\pi^0\pi^0\gamma$ channel (theory)

Marginal agreement between $\pi^0\pi^0$ and $\pi^+\pi^-$

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

$\eta \to \pi^+\pi^- e^+e^-$: data-MC comparison





η´ gluonium content

KLOE, PLB 648 (2007) 267

Formal parametrization for η´ gluonium content measurement:

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

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

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

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

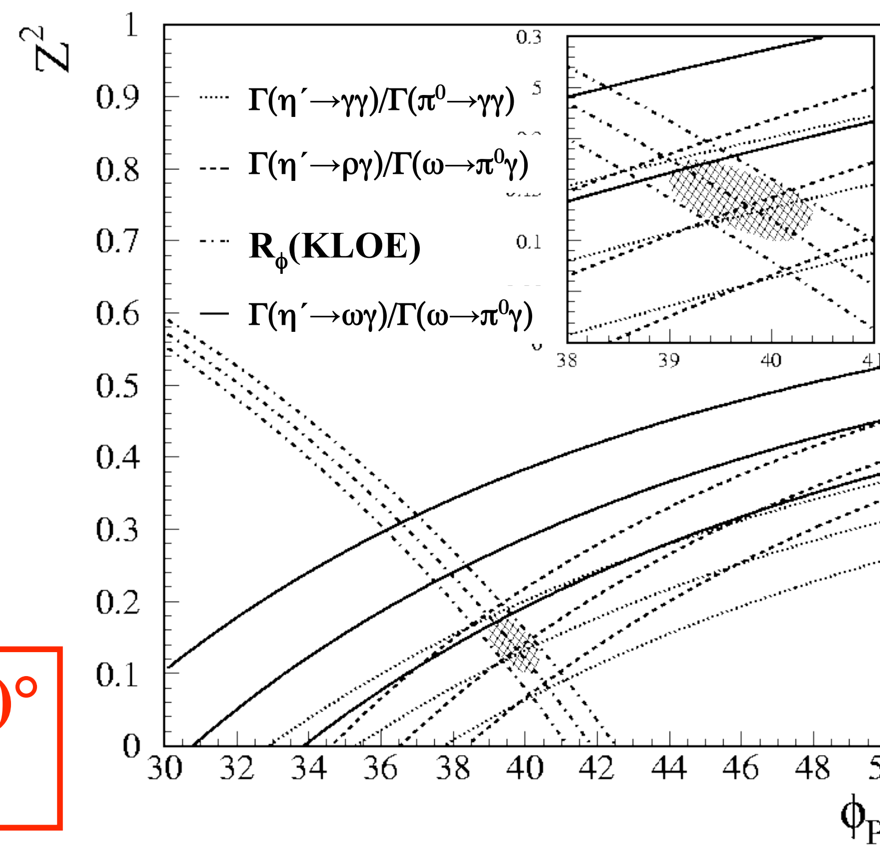
$$Z_{\eta'} = \sin\phi_G$$

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

χ^2/N_{dof}=1.42/2

$\cos^2\phi_G = 0.86 \pm 0.04$
$\cos^2\varphi_P = 0.592 \pm 0.012$

$\varphi_P = (39.7 \pm 0.7)°$ $|\phi_G| = (22 \pm 3)°$
$Z^2_{\eta'} = 0.14 \pm 0.04$



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

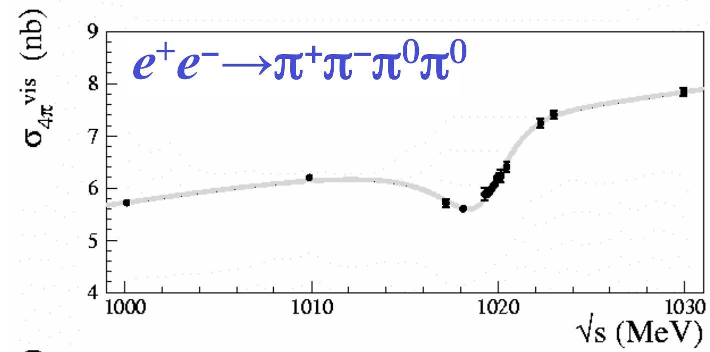
PLB 669 (2008) 223

Interference pattern between non-resonant $e^+e^-\to\omega\pi^0$ and ϕ decays:

$$\sigma(\sqrt{s}) = \sigma_0(\sqrt{s})\left|1 - Z\frac{M_\phi\Gamma_\phi}{D_\phi}\right|^2$$

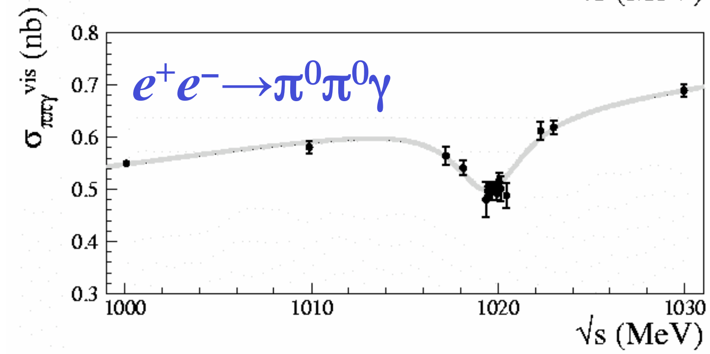
Model indep. $\sigma_0(\sqrt{s})$:

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



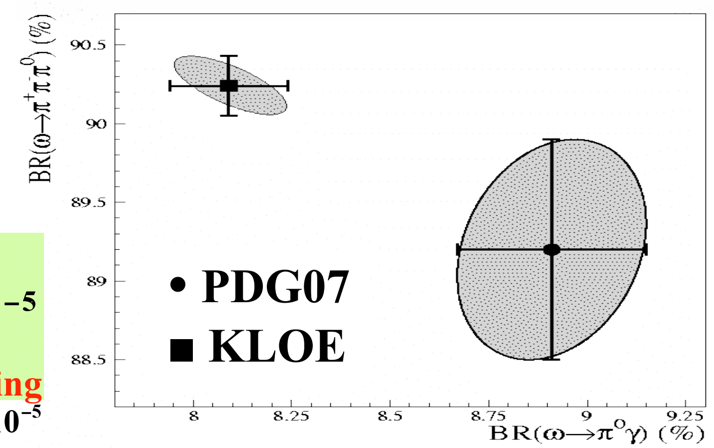
Fit results:

Parameter	$\pi^+\pi^-\pi^0\pi^0$	$\pi^0\pi^0\gamma$
σ_0^i (nb)	7.89 ± 0.06 ± 0.07	0.724 ± 0.010 ± 0.003
$\Re_i(Z)$	0.106 ± 0.007 ± 0.004	0.011 ± 0.015 ± 0.006
$\Im_i(Z)$	−0.103 ± 0.004 ± 0.003	−0.154 ± 0.007 ± 0.004
σ'_i (nb/MeV)	0.064 ± 0.003 ± 0.001	0.0053 ± 0.0005 ± 0.0002



From $\Gamma(\omega\to\pi^0\gamma)/\Gamma(\omega\to\pi^+\pi^-\pi^0)$ + unitarity using rare BRs (~2%):

$BR(\omega\to\pi^+\pi^-\pi^0) = (90.24 \pm 0.19)\%$
$BR(\omega\to\pi^0\gamma) = (8.09 \pm 0.14)\%$



$$BR(\phi\to\omega\pi^0) = \frac{\sigma_0^{\omega\pi}\left|Z_{4\pi}\right|^2}{\sigma_\phi} = (5.63 \pm 0.70)\times 10^{-5}$$

OZI + G-parity violating

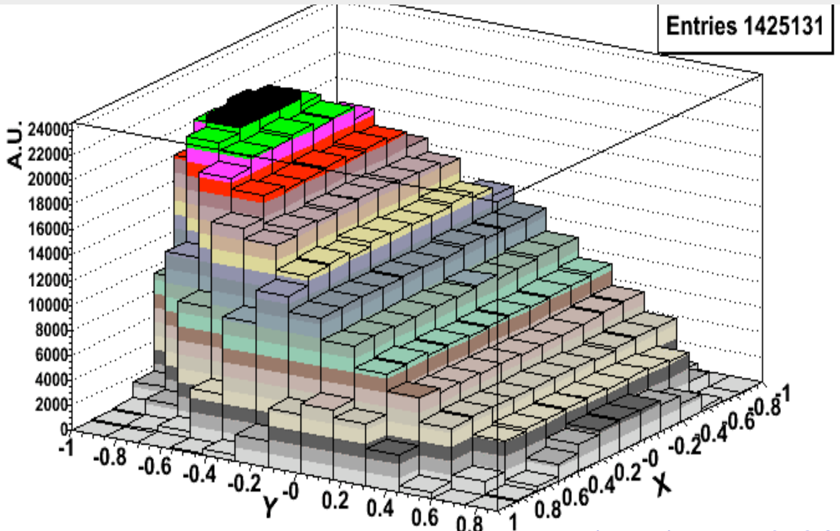
$\text{SND(2000)}: BR(\phi\to\omega\pi^0) = (5.2^{+1.3}_{-1.1})\times 10^{-5}$

KLOE: $\eta\to\pi^+\pi^-\pi^0$ dynamics

EPJC05(2008)006

19×10^6 η from $\phi\to\eta\gamma$. Tagging: recoil monochromatic photon (363 MeV)

$$|M^2| = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3$$



Bckg. contamination ~ 0.3%

$$a = -1.090 \pm 0.005\,(\text{stat})\,^{+0.008}_{-0.019}\,(\text{syst})$$
$$b = 0.124 \pm 0.006\,(\text{stat}) \pm 0.010\,(\text{syst})$$
$$d = 0.057 \pm 0.006\,(\text{stat})\,^{+0.007}_{-0.016}\,(\text{syst})$$
$$f = 0.14 \pm 0.01\,(\text{stat}) \pm 0.02\,(\text{syst})$$
$$c = 0.002 \pm 0.003\,(\text{stat}) \pm 0.001\,(\text{syst})$$
$$e = -0.006 \pm 0.007\,(\text{stat})\,^{+0.005}_{-0.003}\,(\text{syst})$$

Lowest order current algebra ($b=a^2/4$) not satisfied

C-parity conservation

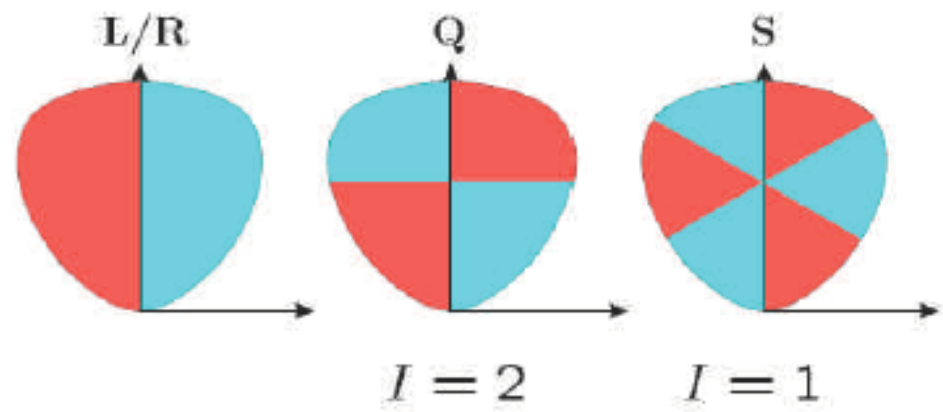
Borasoy-Nissler, Eur. Phys. J. A 26 (2005):

$a = -1.20 \pm 0.07$ $\quad b = 0.28 \pm 0.05$ $\quad c = 0.05 \pm 0.02$

$\eta \rightarrow \pi^+\pi^-\pi^0$ dynamics

EPJC05(2008)006

C-parity conservation tested also with the charge asymmetries:



Left-Right C-invariance
Quadrant C-invariance in ΔI=2 amplit.
Sextant C-invariance in ΔI=1 amplit.
(see *J.G.Layter et al.,Phys.Rev.Lett.29 (1972) 316*)

$$A_{LR} = \frac{N_1 - N_2}{N_1 + N_2} \quad A_Q = \frac{N_1 + N_3 - N_2 + N_4}{N_1 + N_3 + N_2 + N_4} \quad A_S = \frac{N_1 + N_3 + N_5 - N_2 + N_4 + N_6}{N_1 + N_3 + N_5 + N_2 + N_4 + N_6}$$

$$A_{LR} = (\;\;0.09 \pm 0.10\,(\text{stat})\,^{+0.09}_{-0.14}\,(\text{syst})\,) \times 10^{-2}$$

$$A_Q = (-0.05 \pm 0.10\,(\text{stat})\,^{+0.03}_{-0.05}\,(\text{syst})\,) \times 10^{-2}$$

$$A_S = (\;\;0.08 \pm 0.10\,(\text{stat})\,^{+0.08}_{-0.13}\,(\text{syst})\,) \times 10^{-2}$$

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

$\eta\rightarrow\pi^0\pi^0\pi^0$ dynamics

PRELIMINARY
KLOE, arXiv:0707.4137

Dalitz plot density described with a single parameter: $|A|^2 \propto 1 + 2\,\alpha\, z$

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

E_i : Energy of the *i*-th pion in the η rest frame
ρ : Distance from the center of the Dalitz plot
ρ_{max} : Maximum value of ρ

17×10^6 η from $\phi\rightarrow\eta\gamma$. Tagging: recoil monochromatic photon (363 MeV)

Three different purity samples of photon pairing into π^0:

1. **LOW** **Purity = 75.4% , ε =30.3%**
2. **MEDIUM** **Purity = 92.0% , ε =13.6%**
3. **HIGH** **Purity = 97.6% , ε = 4.3%**

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

Systematics related to different purity results

Current best measurement from Crystal Ball: $\alpha = -0.031 \pm 0.004_{stat+syst}$

Chiral unitarity approach calculation [Borasoy-Nissler,Eur.Phys.J.A26(2005)]: $\alpha = -0.031 \pm 0.003$

KLOE: $\eta\to\pi^0\pi^0\pi^0$ dynamics

PRELIMINARY

KLOE, arXiv:0707.4137

Systematics:

γ energy resolution

	Low Pur. $\sigma_\alpha^{syst}(\cdot 10^{-3})$	Med. Pur. $\sigma_\alpha^{syst}(\cdot 10^{-3})$	High Pur. $\sigma^{syst}\alpha(\cdot 10^{-3})$
RES	-9	-4	-3
Range	-4	-4	$-3+3$
Purity	$-1+3$	$+4$	-4
BKG	0.	0.	$-1+1$
M_η	-1	-2	-5
Total	$-10+3$	$-6+4$	$-8+3$

Previous preliminary KLOE result: $\boldsymbol{\alpha = -0.014 \pm 0.004_{stat} \pm 0.005_{syst}}$

New preliminary KLOE result: $\boldsymbol{\alpha = -0.027 \pm 0.004_{stat}\,{}^{+0.004}_{-0.006}{}_{syst}}$

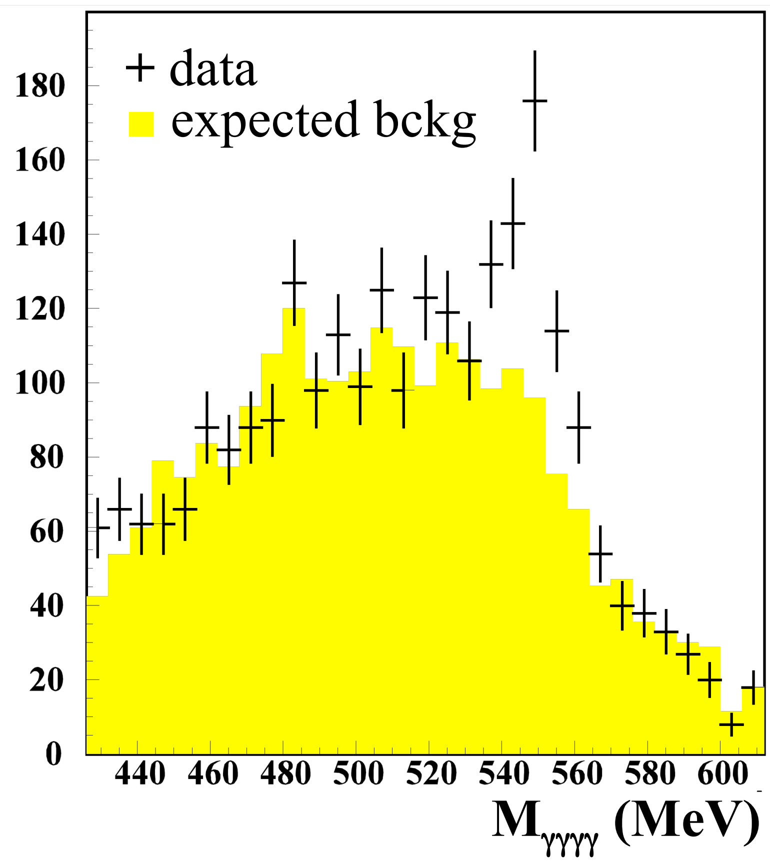
The M_η value used in generation was taken from PDG, 500 keV less than new KLOE measurement. This gave larger accessible phase space in data, and thus a higher value of α. **Now the difference is properly taken into account**

A flash on $\eta \to \pi^0 \gamma\gamma$

ChPT "golden mode": **p^2 null, p^4 suppressed, p^6 dominates**

KLOE has presented a 3σ signal (only 1/5 of full statistics)

$$\mathrm{BR}(\eta \to \pi^0 \gamma\gamma) = (8.4 \pm 2.7_{stat} \pm 1.4_{syst}) \times 10^{-5}$$



CB@MAMI-B: BR = (22.5 ± 4.6 ± 1.7) × 10^{-5}
CB@AGS: BR = (22.1 ± 2.4 ± 3.8) × 10^{-5}

Analysis repeated with 1.5 fb^{-1} (2005 data):

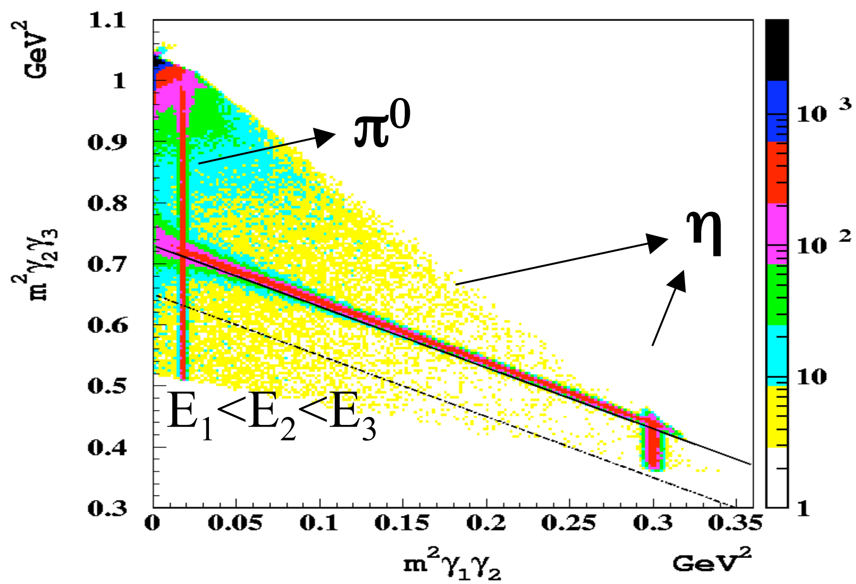
- **the signal is confirmed**
- **BR updated result with the full sample will have ~15% error**

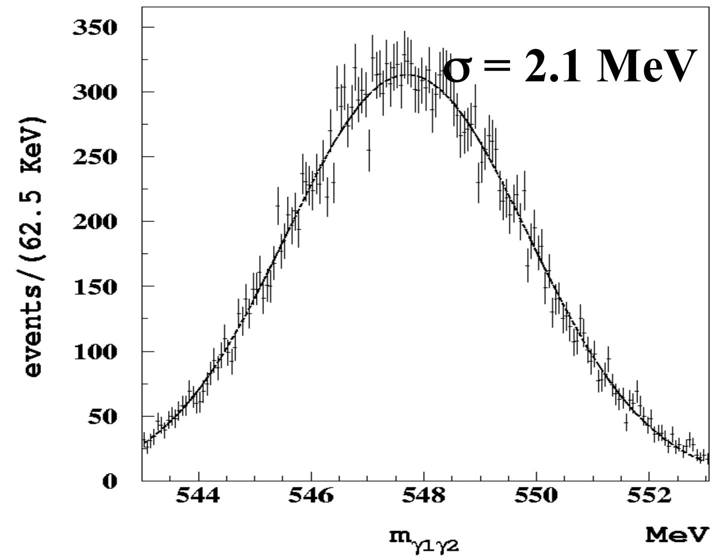
Measurement of η mass

EPJC12(2007)073

❖ **17×10^6 η** from **φ→ηγ**: Kinematic fit applied on φ →γγγ events

❖ η and π^0 selected by looking at different Dalitz plot regions





$$M_\eta = (\,547.874 \pm 0.007 \pm 0.029\,)\ \text{MeV}$$

Mass scale checked with $M_{\pi 0}$: 1.4 σ from PDG06

Systematics dominated by uniformity of the detector response