Study of the light meson spectrum in e^+e^- and $\gamma\gamma$ collisions with KLOE at DAΦNE

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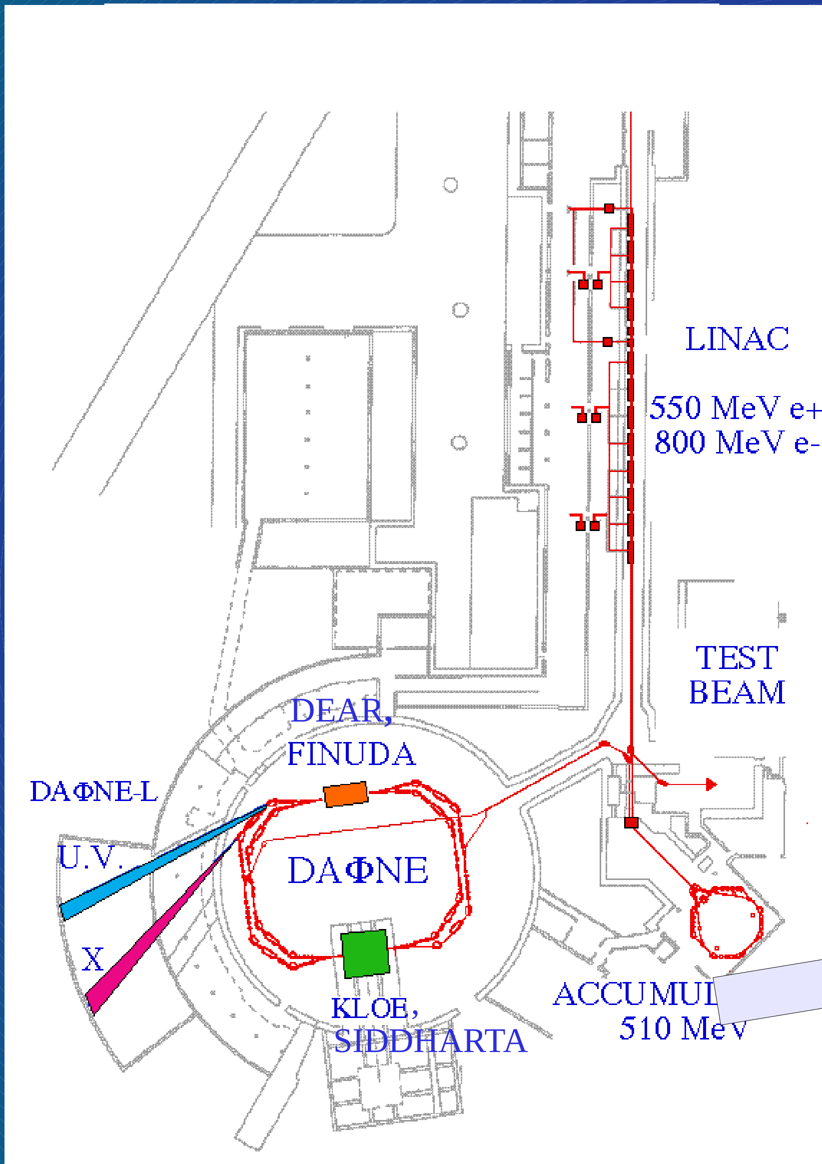
I. N. F. N. sez. Roma Tre

on the behalf of
the KLOE collaboration

**Int-Jlab Workshop
on
Hadron Spectroscopy**

**Institute of Nuclear Theory
University of Washington
Seattle-USA**

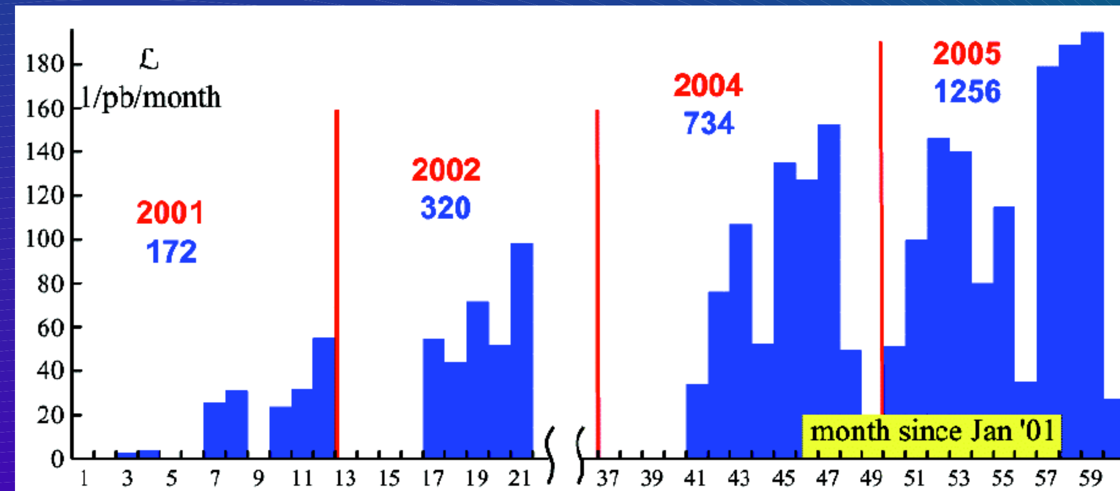
The DAΦNE high luminosity e^+e^- collider

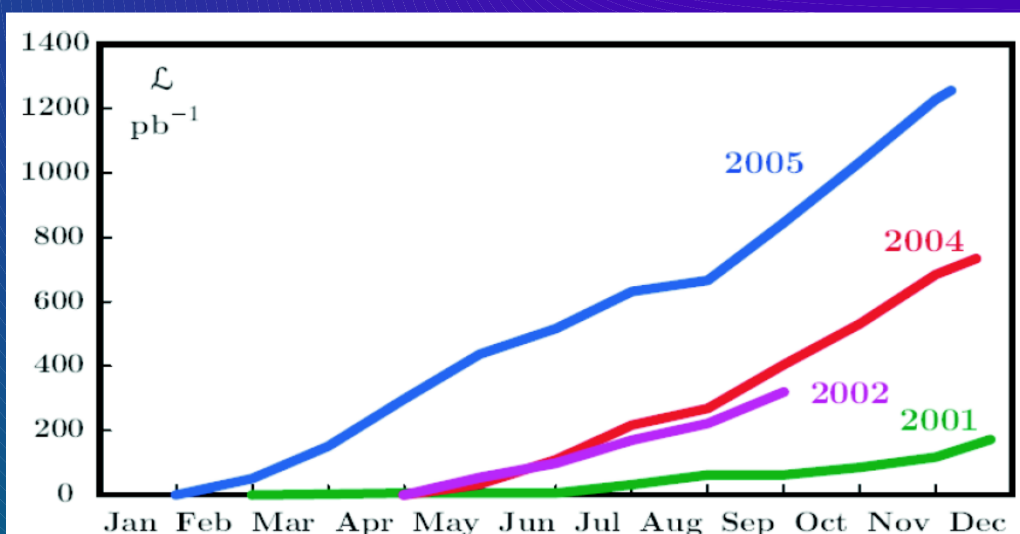


- $\sqrt{s}=m(\phi)=1019.4$ MeV, $\sigma(e^+e^- \to \phi) \sim 3\ \mu b$
- Independent e^+e^- rings to reduce beam-beam interactions
- crossing angle: 25 mrad, $p_x(\phi)$ ~12.6 MeV
- 105 + 105 bunches, crossing every 2.7 ns
- injection during acquisition
- Maximum currents $I(e^+) = 2.4$ A $I(e^-) = 1.5$ A

Collected data

- Last run- March 2006
- Max luminosity 1.3×10^{32}
- Tot. Integrated 2.5 fb^{-1}
- 200 pb^{-1} @ $\sqrt{s}$ = 1000 MeV





Events on tape
8 billions of ϕ decays

K^+K^-	4×10^9	$\pi^0\gamma$	10×10^6
$K^0\overline{K^0}$	3×10^9	$f_0\gamma$	2.6×10^6
$\pi^+\pi^-\pi^0$	1.2×10^9	$a_0\gamma$	6.3×10^5
$\eta\gamma$	100×10^6	$\eta'\gamma$	5.4×10^5

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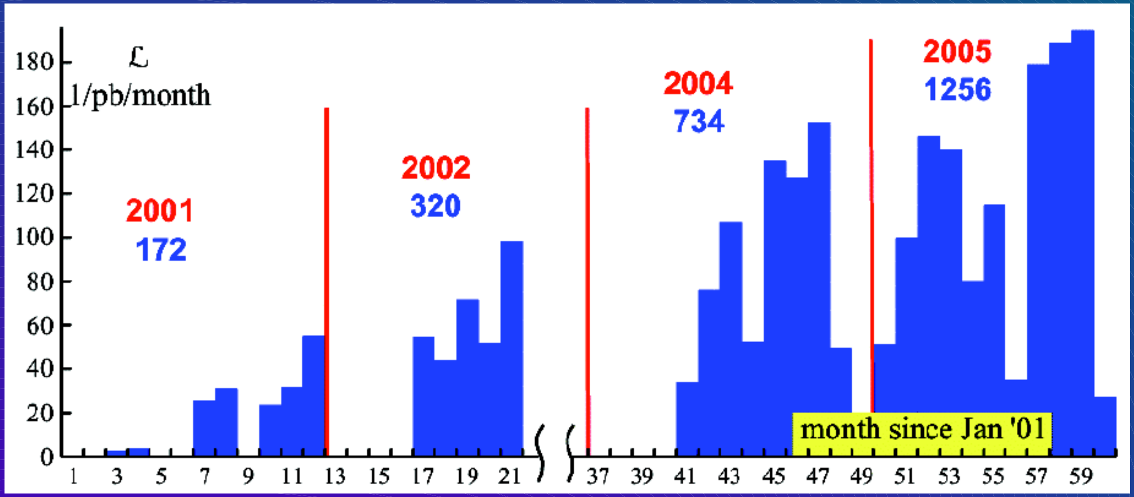

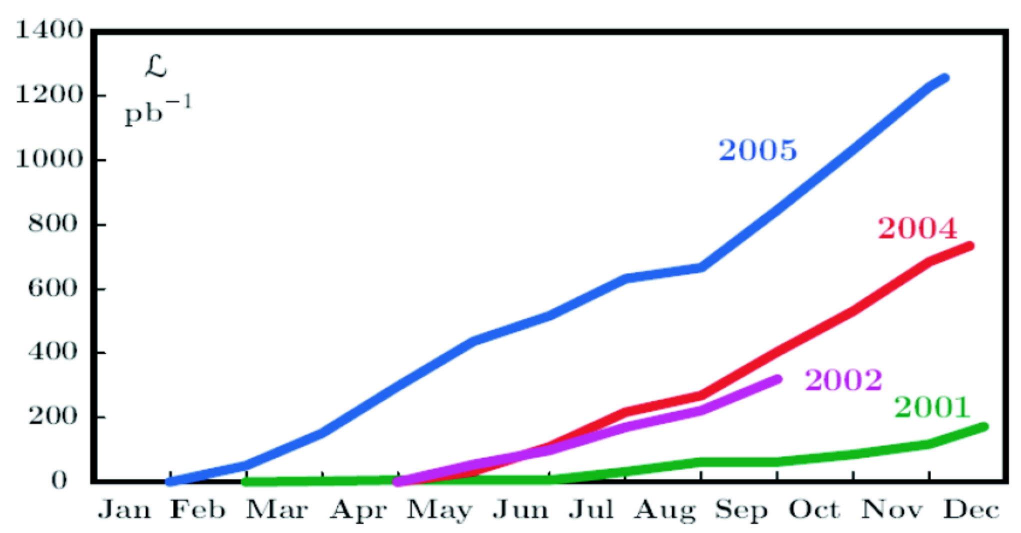

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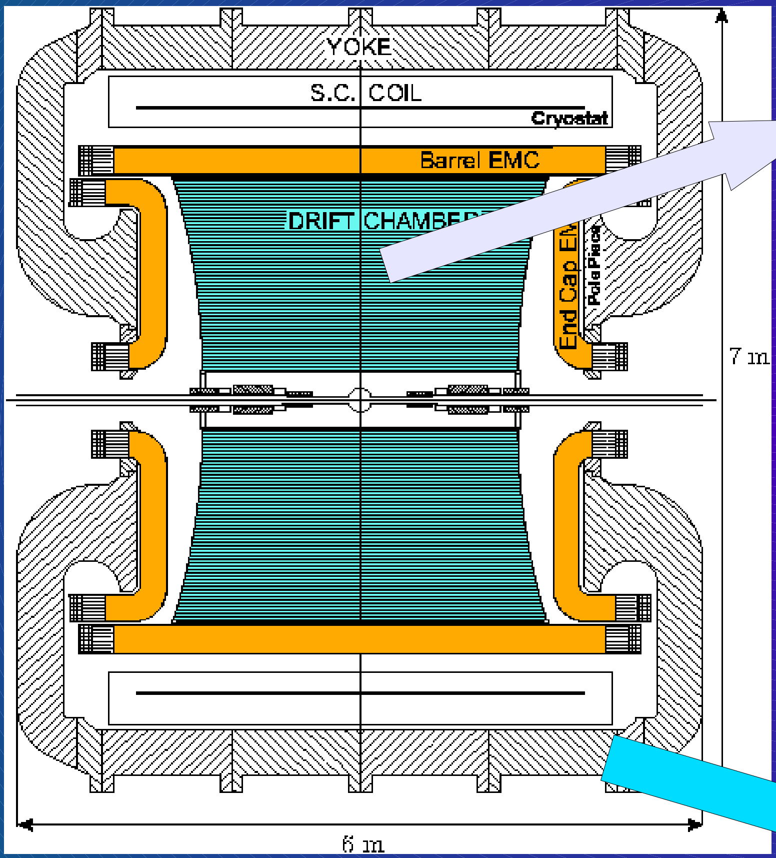
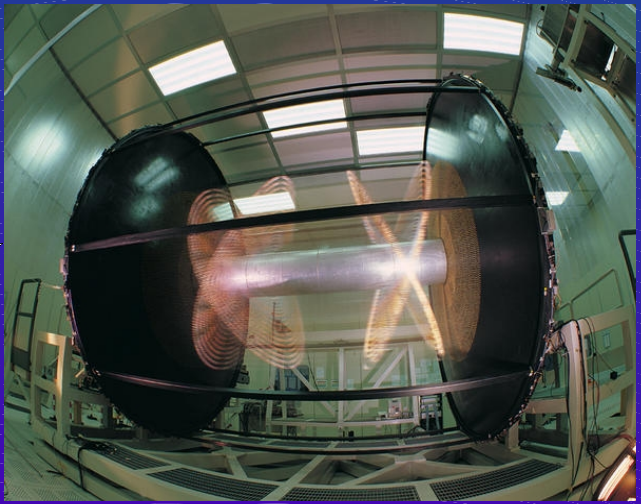
$\eta\gamma$	100×10^6	$\eta' g$	5.4×10^5

Meson Factory

Cylindrical Drift Chamber

Detector scheme





- Stereo wires structure to reconstruct longitudinal position
- 52140 wires – 12582 drift cell
- 90% He 10% iC_4H_{10}

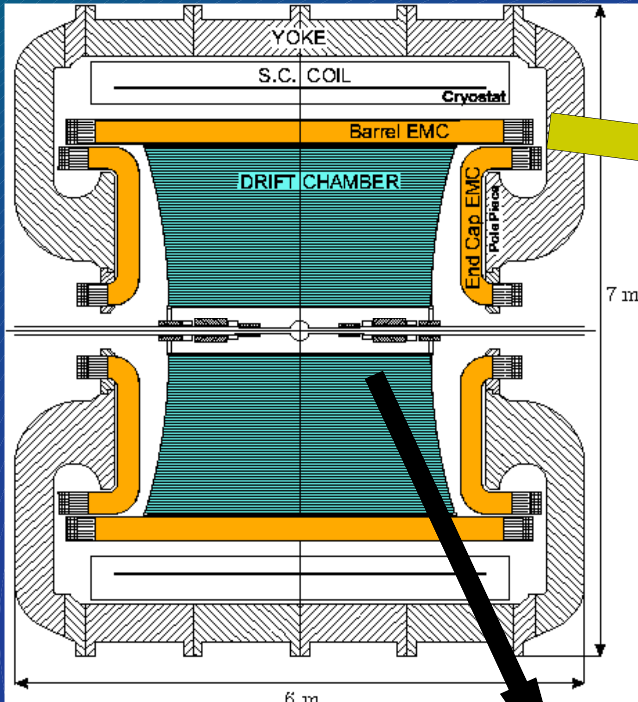
$\sigma_{vtx} = 1$ mm $\sigma_{pt}/p_t = 0.5\%$

$\sigma_{r,\phi} = 200 \mu m$ $\sigma_z = 2$ mm

Magnetic yoke.

- 0.5 T magnetic field
- Cryogenic coil working at 4.2 °K
- Coil current 2300 A

The KLOE calorimeters



Main calorimeter

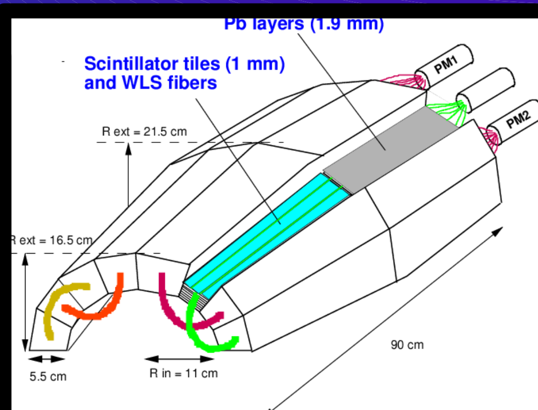
- 1 barrel + 2 end-caps
- 98% solid angle coverage
- Fine sampling Pb / Scintillating Fibers
- Hermetical coverage
- High efficiency for low energy photons
- two side PM read out, longitudinal position from arrival time

$$\sigma_t = 54\text{ps}/\sqrt{E(\text{GeV})} \oplus 140\text{ ps}$$

$$\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$$

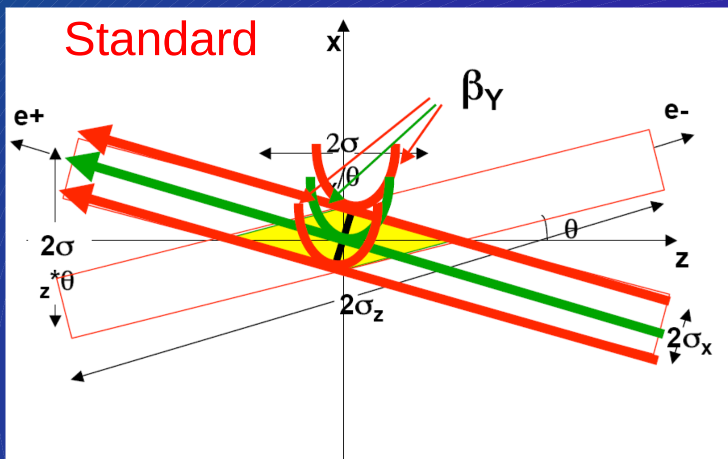
Small angle veto calorimeter

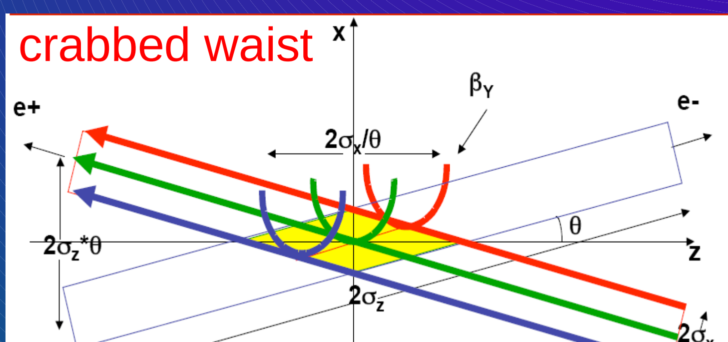
Efficiency
20 – 90 %
E 26-125 MeV
$\sigma_t = 240\text{ ps}/\sqrt{E}$ (GeV)
covered angle 23°



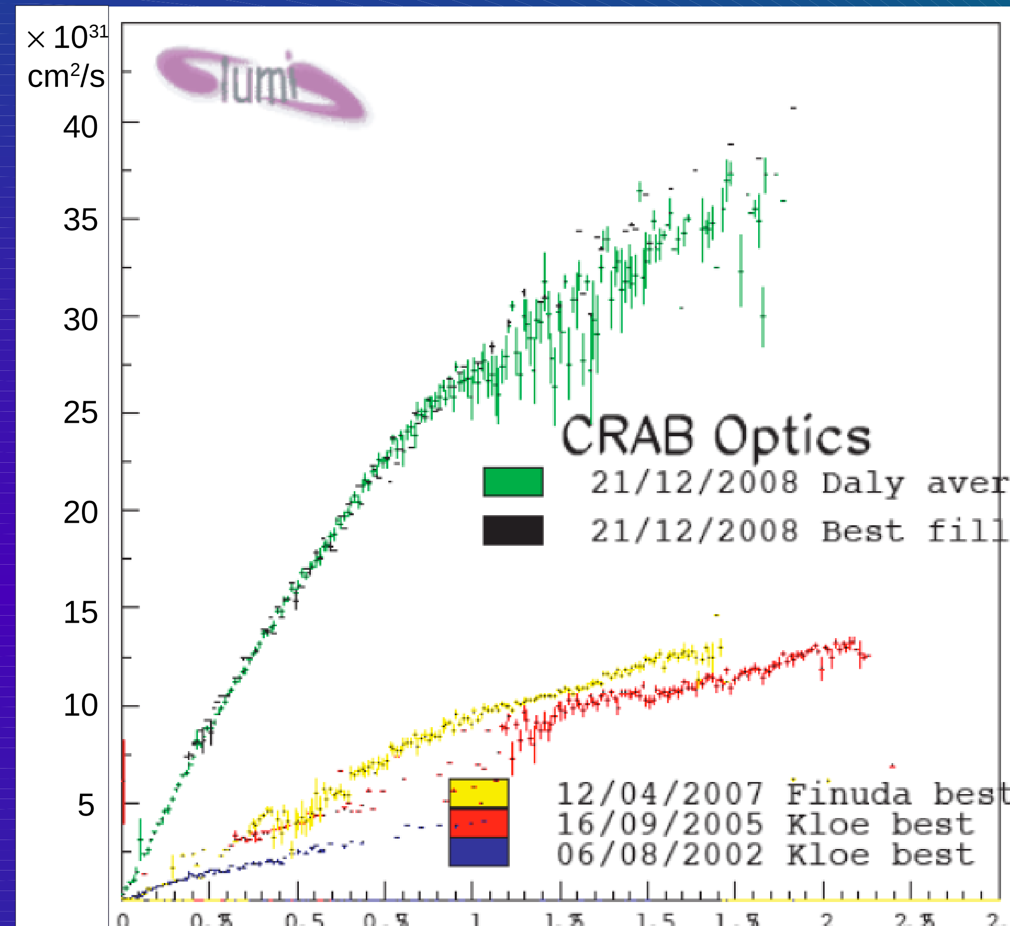
Machine optic upgrade

- High Piwinski angle
- Crabbed waist induced by properly designed sextupole





The β function is minimium along the beam intersection line.



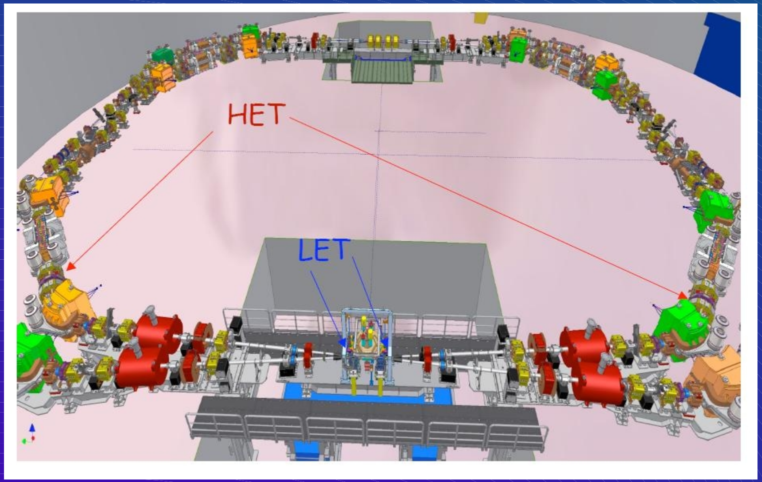
Expected performances at KLOE-2

- $L_{peak} = 5.5\times10^{32}\ cm^2/s$
- delivered luminosity $0.5 fb^{-1}$/month
- Increase the KLOE data sample of a factor 10 in few years.

Minimal detector upgrade

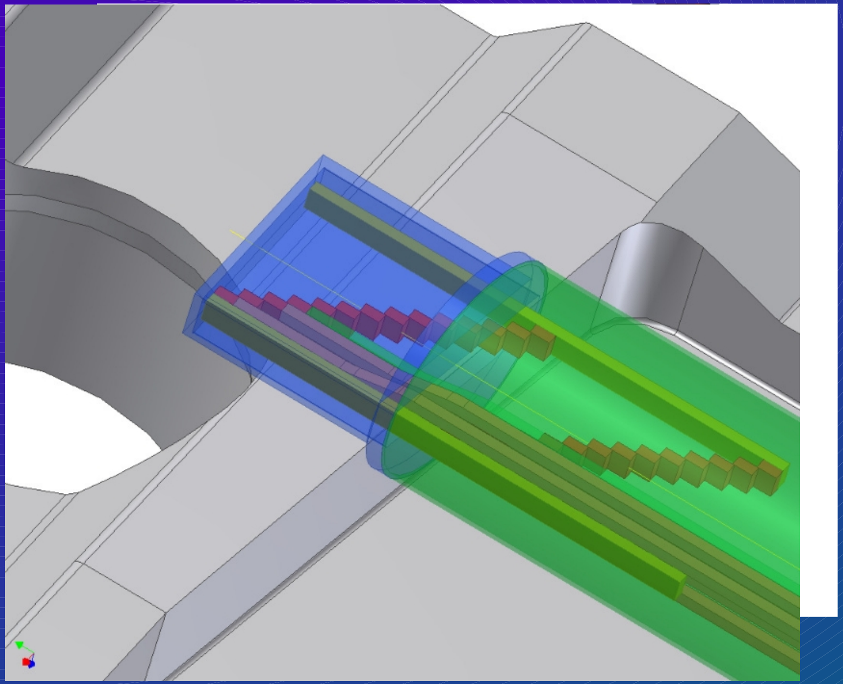
Tagger for $\gamma\gamma$ physics: to detect off-momentum $e^{\pm}$ from $e^+e^- \rightarrow \gamma^*\gamma^*\, e^+e^- \rightarrow e^+e^-\, X$

- LET: Low Energy Tagger (130-230 MeV) calorimeters, LYSO crystal + SiPM
- HET: High Energy Tagger (E > 400 MeV) position sensitive detector (strong energy-position correlation ⇒ use the DAΦNE magnets as bending magnets for an $e^{\pm}$ spectrometer)



No QCAL on quadrupoles (Pb shielding)

Luminosity goal: 5 fb^{-1} @ $\sqrt{s} \approx M_\phi$



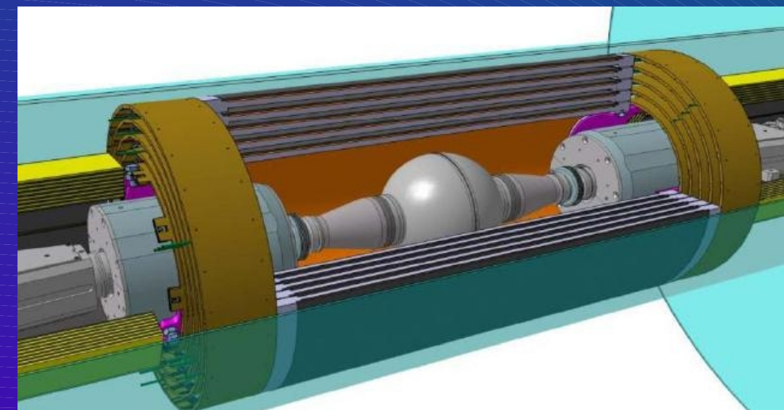
DAFNE switch off ⇒ 9th November

Detector "roll-in" ⇒ end 2009

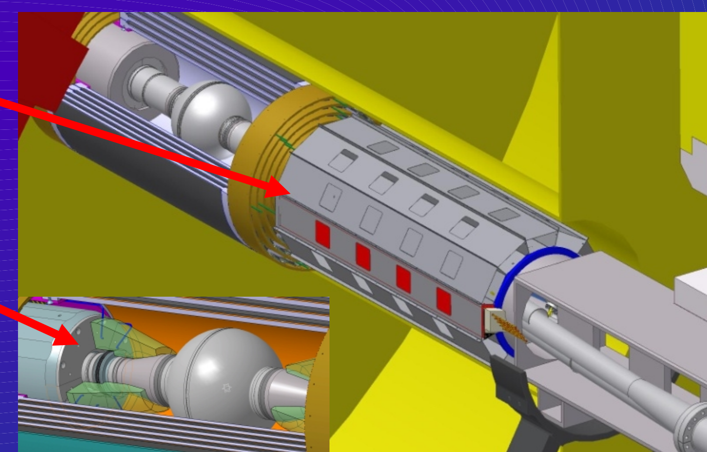
First collisions ⇒ March 2010

KLOE UPGRADE (step 1)

Major detector upgrade



- Inner tracker (between the beam pipe and the DC): 5 layers of cylindrical triple GEM: improve vertex reconstruction near the IP increase acceptance for low momentum tracks



- QCALT: W + scintillating tiles readout by Silicon PM via Wave Length Shifter fibers
- CCAL: LYSO crystals + APD; close to IP to increase acceptance for photons coming from the IP (min. angle: 21°→ 9°)

Schedule and targets

- Integrated luminosity >20 fb^{-1}
- Time scale > 2011

Status and perspectives in e^+e^- meson production and decay.

- ϕ decays to scalars, the a_0 parameters, the scalar structure and the instanton model;
- The σ meson in the η' decay;
- Search for $\phi \to (f_0 + a_0)\gamma \to K^0 K^0 \gamma \to K_S K_S \gamma$;
- The determination of the η' gluonium content;
- Measurement of the $Br(\eta \to \pi^+ \pi^- e^+ e^- (\gamma))$ and looking for unconventional CP violation in the decay;
- ChPT and the $\eta \to \pi^0 \gamma\gamma$ decay

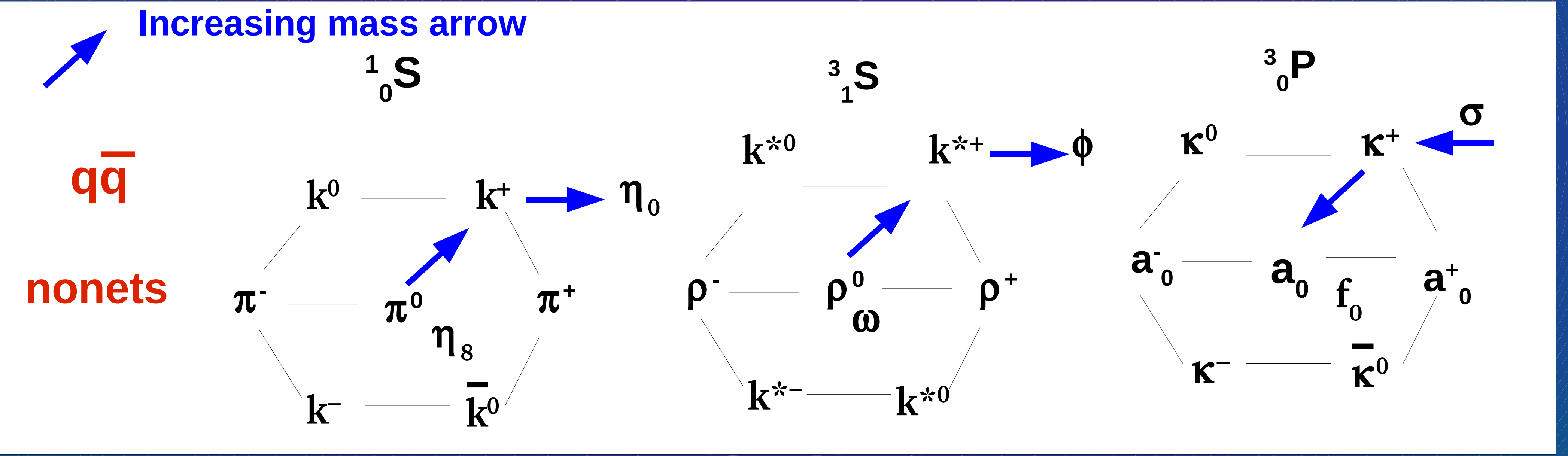
Status and prospects in $\gamma\gamma$ meson production.

- Production of the η meson;
- The σ meson in $\gamma\gamma \to \pi^0\pi^0$
- π^0, η, η' form factors and the Light by Light contribution to $(g\text{-}2)_\mu$
- the case of $\pi^0 \to e^+e^-$

Still open questions on the nature of the light scalars:

a_0 f_0 σ k

The natural answer (2 quarks states in ^3_0P configuration) cannot explain the inverted hierarchy.



Why scalars show an inverted mass spectrum respect to the pseudoscalar and vector partners?

Natural explanation in the 4q hypothesys Jaffe f_0 a_0 ssdd ssuu σ uudd

Scalars nature can be studied with the ϕ decays

$e^+e^- \to \phi \to (f_0+\sigma)\gamma \to \pi^0\pi^0\gamma,\ \pi^+\pi^-\gamma$

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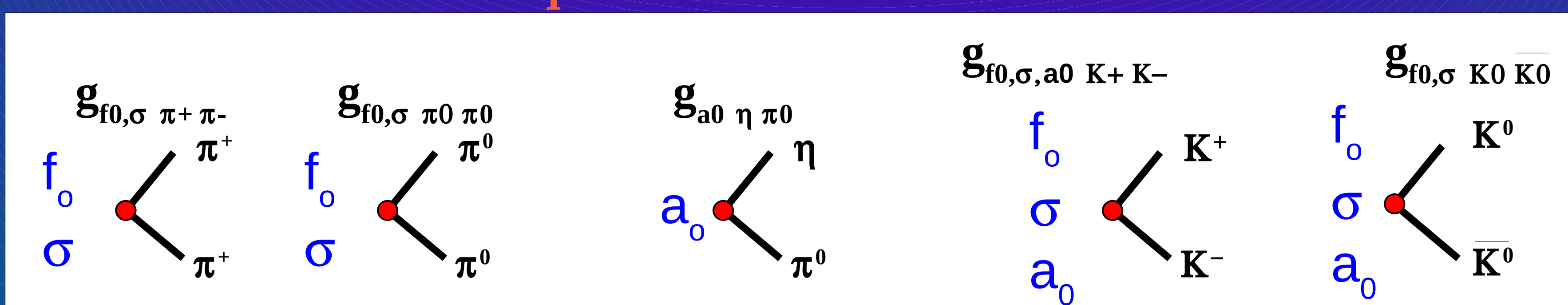
$e^+e^- \to \phi \to a_0\gamma \to \eta\pi^0\gamma$

Sensitive to the scalar structure

$e^+e^- \to \phi \to (a_0 + f_0)\,\gamma \to K^0\overline{K^0}\gamma \to K_sK_s\gamma$

Sensitive to the a_0-f_0 interference.

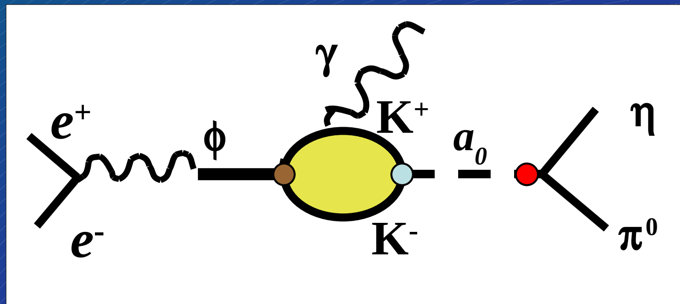
The couplings to the pseudoscalar mesons ($\pi\pi$, K^+K^-, $\eta\pi$) are sensitive to the quark structure.



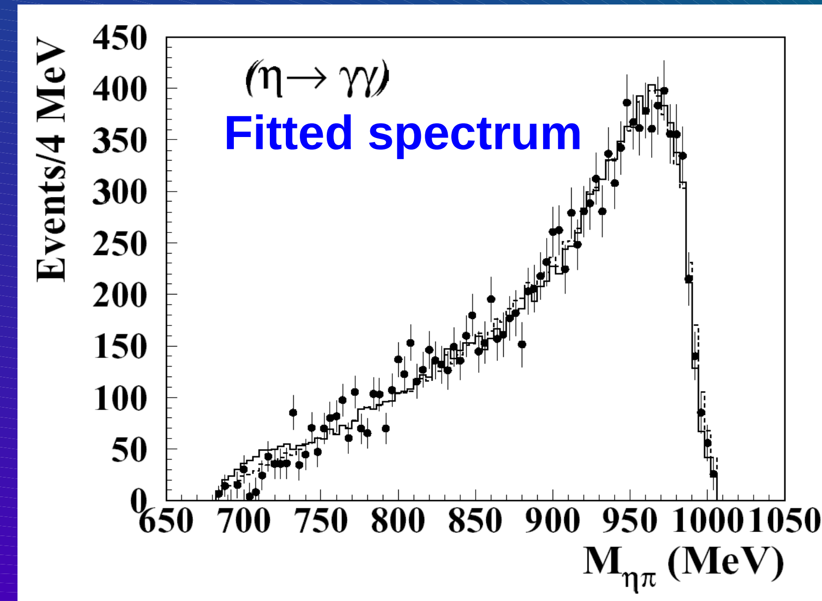
Isospin symmetry: $g_{f0,\sigma\ \pi+\pi-} = 2\,g_{f0,\sigma\ \pi0\ \pi0}$

$M_{\eta\pi 0}$ fit to $\eta\pi^0\gamma$ events at KLOE

Koan loop



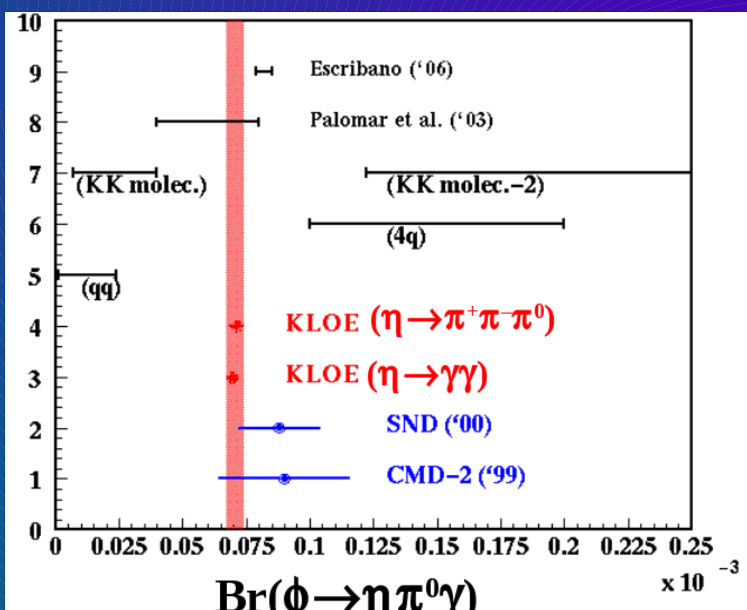
- $g_{\phi K^+K^-}$
- $g_{SK^+K^-}$
- $g_{S\eta\pi^0}$



extraction of $Br(\phi \to \eta\pi^0\gamma)$
from event counting (model independent).

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

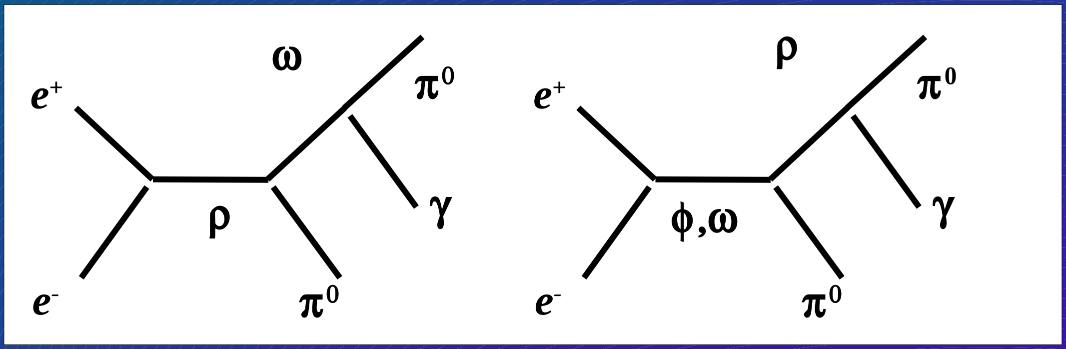
$\eta\to\pi^+\pi^-\pi^0$ – $Br(\phi\to\eta\pi^0\gamma) = (7.12 \pm 0.13_{stat} \pm 0.22_{syst}) \times 10^{-5}$

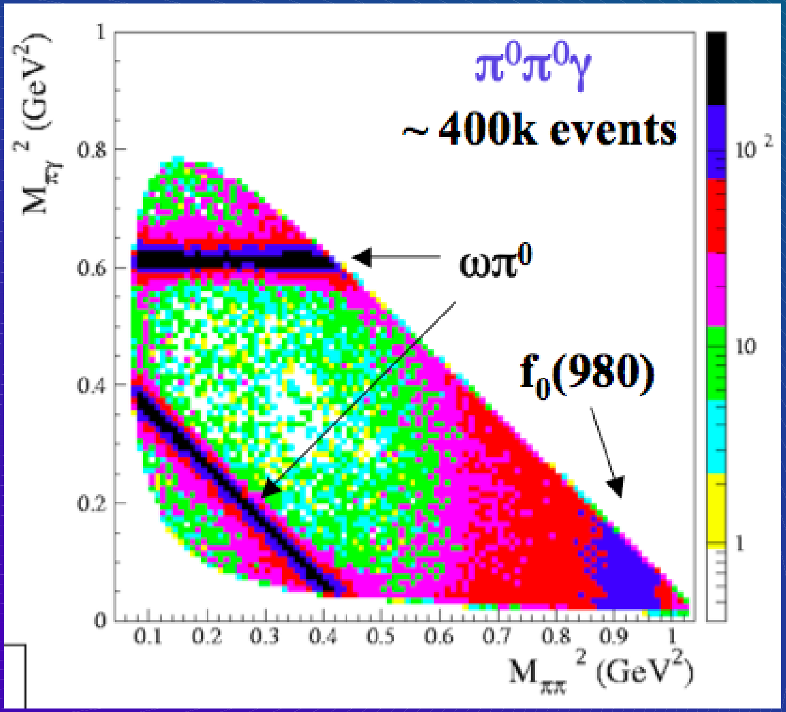


M_{a0} 982.5 ± 1.6 ± 1.1 MeV $g_{a0\eta\pi}$ 2.82 ± 0.03 ± 0.04 GeV
$Br(\phi\to\rho\pi\to\eta\gamma\pi)$ $(0.92 \pm 0.40 \pm 0.15)\times 10^{-6}$
$\delta(\phi\to\rho\pi\to\eta\gamma\pi)$ $(222 \pm 13 \pm 3)^\circ$ g_{a0K+K-} 2.15 ± 0.06 ± 0.06 GeV

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

Irreducible background fitted in the amplitude





Fitted parameters: M_{f0}, g_{f0K+K-}, $g_{f0\pi+\pi-}$ $(=\sqrt{2}\ g_{f\pi0\pi0})$

Background parameters:

$\phi_{\omega\pi0}, \phi_{\rho\pi0}, C_{\omega\pi0}, C_{\rho\pi0}, \alpha_{\rho\pi}, M_\omega, \delta_{b\rho}$

Interference phase with the scalar amplitude

- $\delta_B = \delta_B^{\pi\pi} + \delta_B^{KK}$ (elastic scattering)
- and σ(600) parameters fixed

[Achasov-Kiselev, PRD73 (2006) 054029 with PRD 74 (2006) 059902 (E)
+ private comunication for $C_{f0\sigma}$]

Fit result

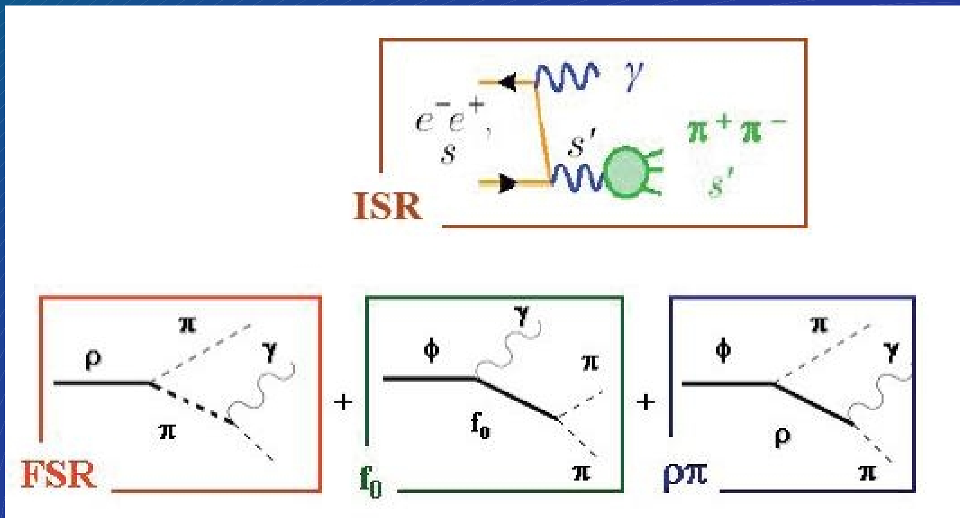
M_{f0}	=	984.7 ± 1.9 MeV
g_{f0K+K-}	=	3.97 ± 0.43 GeV
g_{f0p+p-}	=	-1.82 ± 0.19 GeV

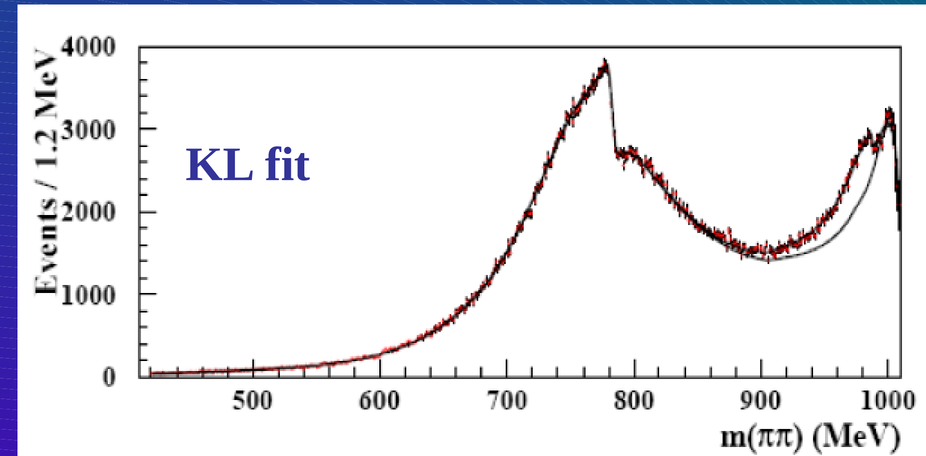
The σ needed in the fit. $P(\chi^2) \sim 10^{-4}$ without σ

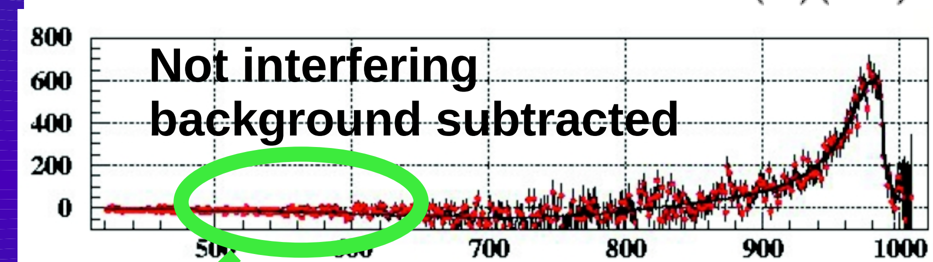
Systematic dominated by fixed parameters.
10 sets of parameters available
8 with $P(\chi^2) > 1\%$
Values are the mean and the RMS of the fit results.

$M_{\pi+\pi-}$ fit to $\pi^+\pi^-\gamma$ events

Irreducible background fitted in the amplitude







- ISR: [Kühn-Santamaria ZPC48 (1990) 455]
  Free parameters: $M_{\rho 0}$, $\Gamma_{\rho 0}$, α, β
- FSR fixed [Achasov,Gubin,Solodov PRD55(1997)2672)]
- ρπ:($\phi\rightarrow\rho^{\pm}\pi^{\mp}$; $\rho^{\pm}\rightarrow\pi^{\pm}\gamma$) VDM, a scale factor ($a_{\rho\pi}$) free
- scalar-FSR interference [Achasov-Gubin PRD57 (1998) 1987]
  - fit with σ contribution

no sensitivity to σ shown by the fit

Fit result
$P(\chi^2) = 2.5\%$

M_{f0}	=	983.7 MeV
g_{f0K+K-}	=	4.74 GeV
g_{f0p+p-}	=	-2.22 GeV

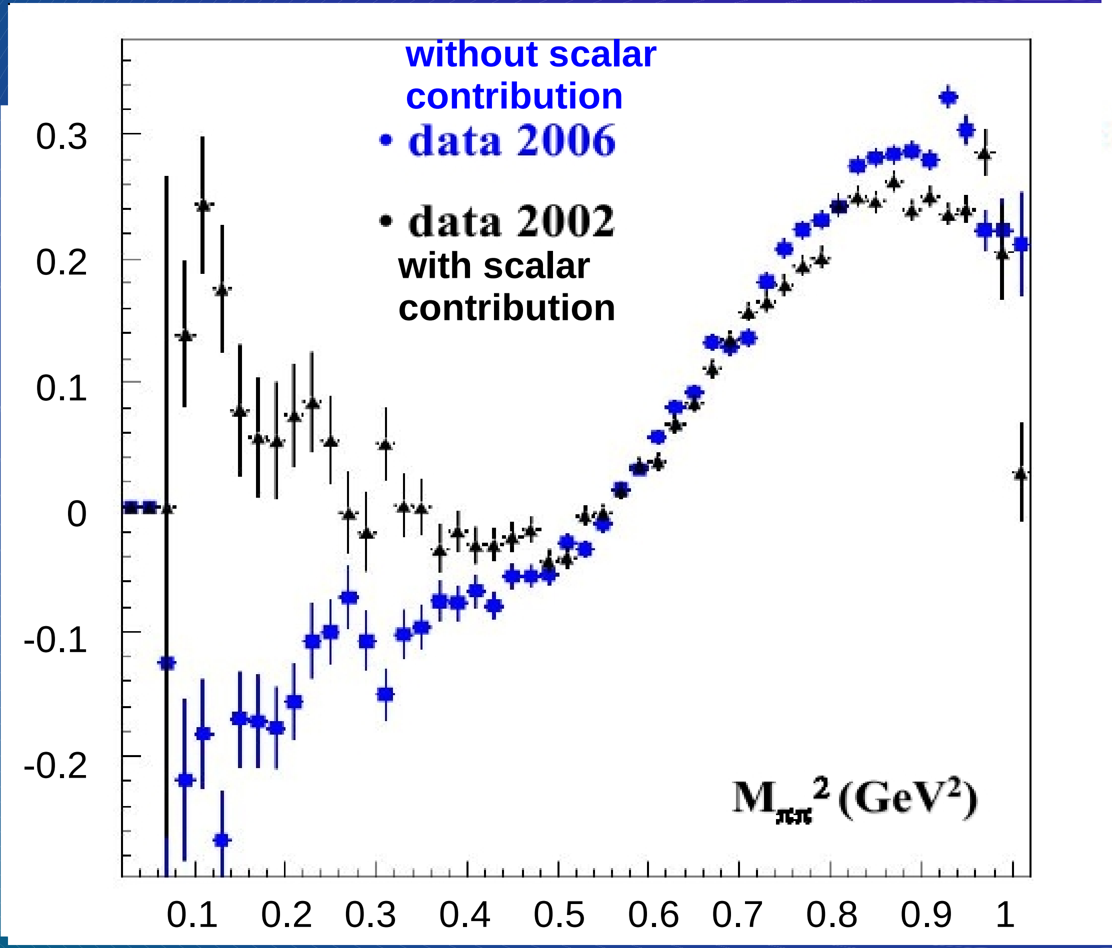
$M_{\pi+\pi-}$ fit to $\pi^+\pi^-\gamma$ events at KLOE

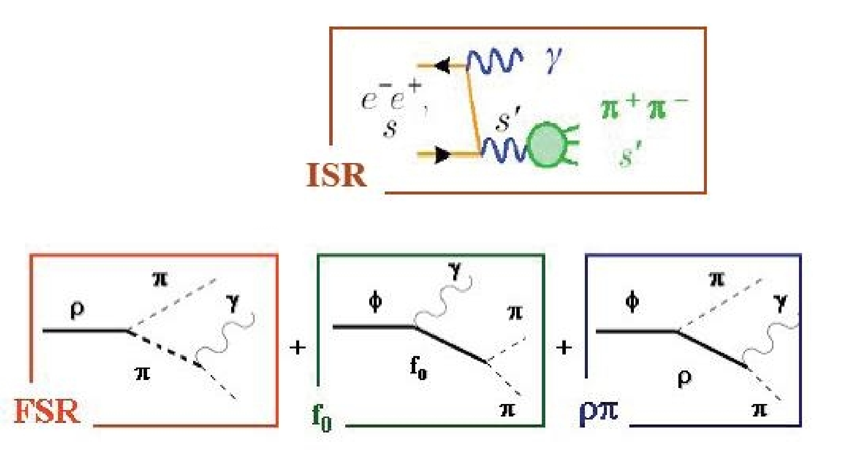
$\pi^+\pi^-$ system:

Amp(ISR) **C-odd** Amp(f0+σ) **C-even**

Amp(FSR) **C-even**

Charge Asymmetry





- with 8 fb^{-1} at KLOE-2 the statistical sensitivity to the σ presence increases of a factor 4;
- KLOE-2 can be sensitive to σ also in the charged final state.
- big effort for background handling;
- fitting the asymmetry is crucial to gain sensitivity to scalars.

Scalar couplings to pseudoscalars 2q versus 4q

Couplings compatible with a 2 quarks hypothesis with $f_0 = s\bar{s}$

4q cannot fit the small value of ga0KK.

	KLOE	SU(3)		
		4q	$q\bar{q}$	
$(g_{a0K+K-}/g_{a0\eta\pi})^2$	0.6 – 0.7	1.2 – 1.7	0.4 q (u,d)	
$(g_{f0K+K-}/g_{f0\pi+\pi-})^2$	4.6 – 4.8	>>1	>>1 ($f_0=s\bar{s}$)	1/4 ($f_0=q\bar{q}$)
$(g_{f0K+K-}/g_{a0\,K+K-})^2$	4 - 5	1	2 ($f_0=s\bar{s}$)	1 ($f_0=q\bar{q}$)

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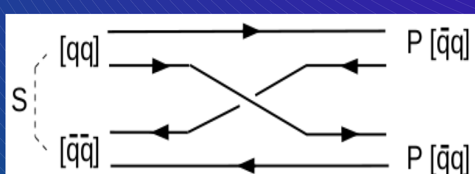
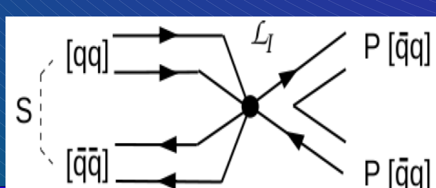
New model from T'Hooft, Isidori, Maiani, Polosa and Riquer (Phys. Lett. B662 (2008) 424

Interference between two amplitudes allows small a0KK coupling

	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





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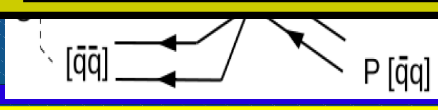
g_{a0K+K-} (GeV)	2.01 — 2.15		2.1 — 2.5	2.4 — 2.9
$g_{a0\eta\pi}$ (GeV)	2.46 — 2.82		3.3 — 3.9	6.6 — 7.9
$g_{\sigma\pi+\pi-}$ (GeV)	m_σ 441 MeV		1.6 - 2.0	1.8 - 2.2
$g_{\sigma\pi+\pi-}$ (GeV)	m_σ 541 MeV		2.6 - 3.2	2.9 - 3.6

Interference between two ampli-

		m_σ MeV	Γ_σ MeV	$g_{\sigma\pi+\pi-}$ GeV^{-1}
Caprini	PRL 96, 132001 (2006)	441	544	3.5
CLEO	Phys. Rev. D76 012001	466	446	3.5
BES2	Phys. Lett. B645 19 $J/\psi \to \omega\pi^+\pi^-$	541	504	3.2



σ in meson decays.

σ observed in

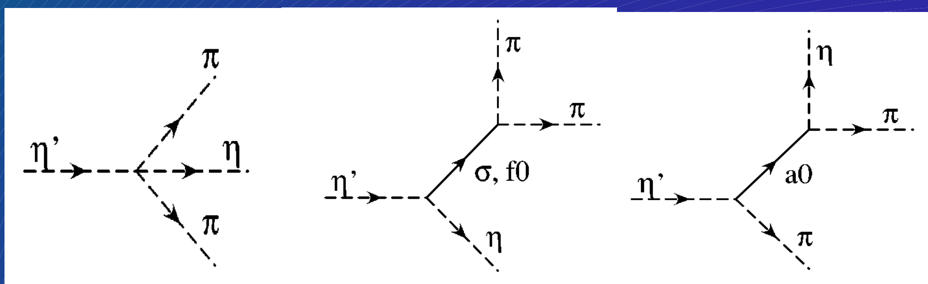
$J/\psi \rightarrow \pi^+\pi^-\omega$	$L(\pi^+\pi^-) = 0,1,2$
$\pi^+\pi^- \rightarrow \pi^+\pi^-$	$L(\pi^+\pi^-) = 0\ ,1,2\ ,..$
$D^+ \rightarrow \pi^+\pi^-\pi^+$	$L(\pi^+\pi^-) = 0,1\ ,2\ ,..\ ..$

Partial wave analysis in order to disentangle, model dependence, results dependent on heavier vector and scalar resonances.

σ meson in η'→ ππ η decay @KLOE2

$\eta' \rightarrow \pi^+ \pi^- \eta$ $\quad m_{\pi+\pi-} = [0.28 - 0.411]$ GeV

0^- $\quad 0^+$ $\quad 0^-$

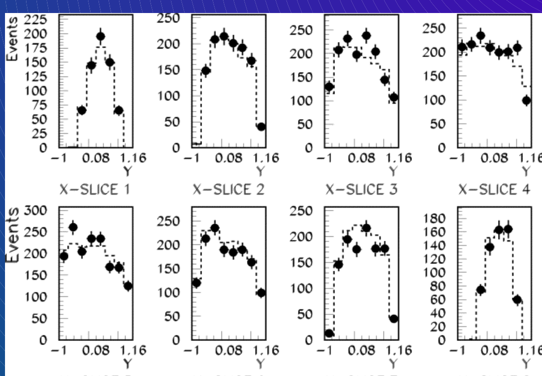


- Low energy assures no angular excitation.
- G-parity conservation forbids vector meson exchange.
- The f_0 contribution is expected to be small. The a_0 contribution is large, but σ is visible in a_0-σ interference.

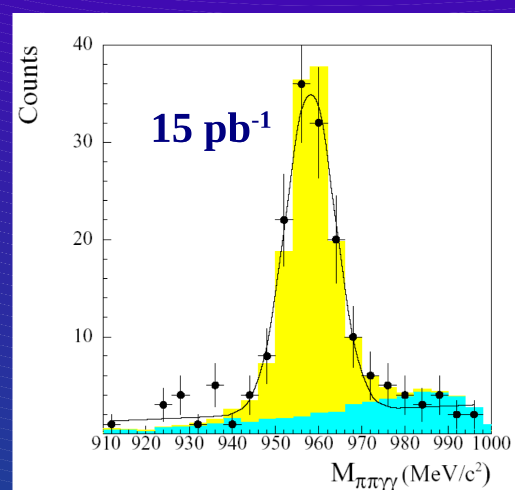
Donskov, hep/ph 0902.3329
Fariborz, Schechter, Phys. Rev. D60, 034002

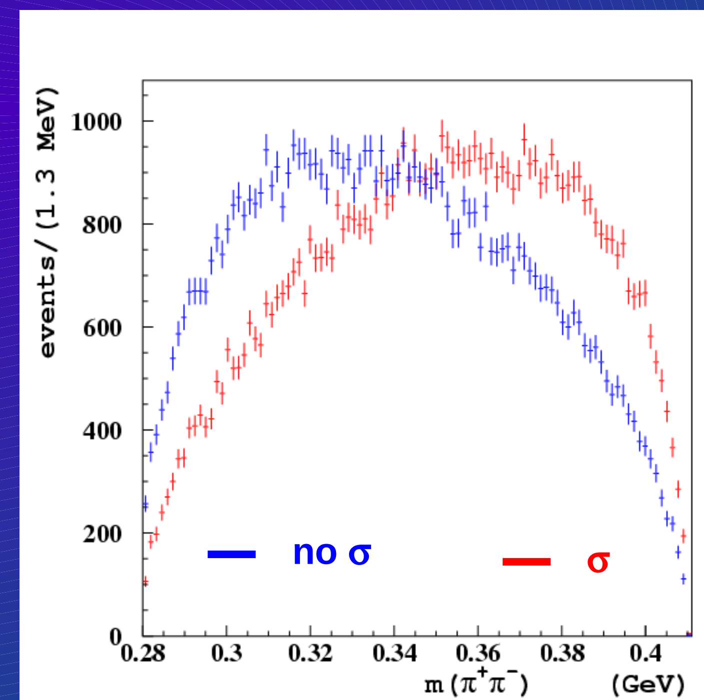
VES ~6500 events $\eta' \rightarrow \pi^+ \pi^- \eta$
Phys. Lett. B 651 (2007) 22

Events expected	730.000
$\eta \rightarrow \gamma\gamma$	287.000
efficiency (22.8)%	65.500

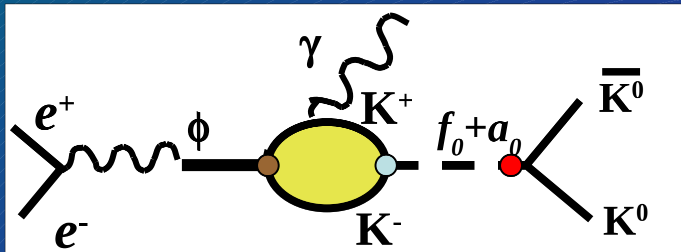


$$X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-}); \qquad Y = \frac{m_\eta + 2m_\pi}{m_\pi}\frac{T_\eta}{Q} - 1;$$





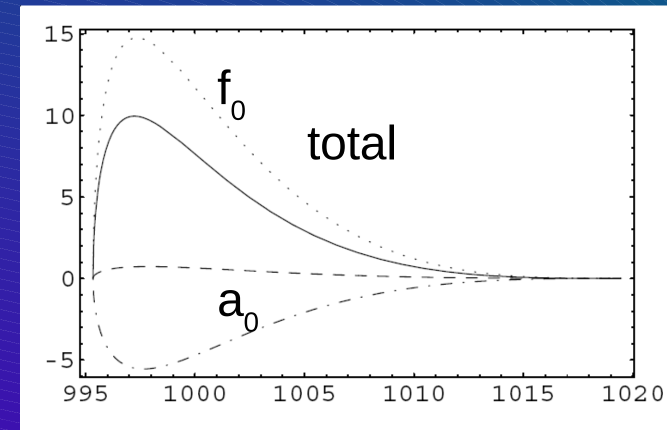
$\phi \to (f_0 + a_0)\gamma \to \bar{K}^0K^0\gamma \to K_SK_S\gamma \to \pi^+\pi^-\pi^+\pi^-\gamma$ PLB 679 (2009) 10



- $g\phi K^+K^-$
- gSK^+K^-
- gSK^0K^0

$(10^{-9}\ \text{MeV}^{-1})$ R. Escribano, Eur. Phys.J. A31 (2007) 454

$$\frac{dBr(\phi \to K^0\bar{K}^0\gamma)}{dm_{K^0\bar{K}^0}}$$



$m_{K^0\bar{K}^0}$ MeV

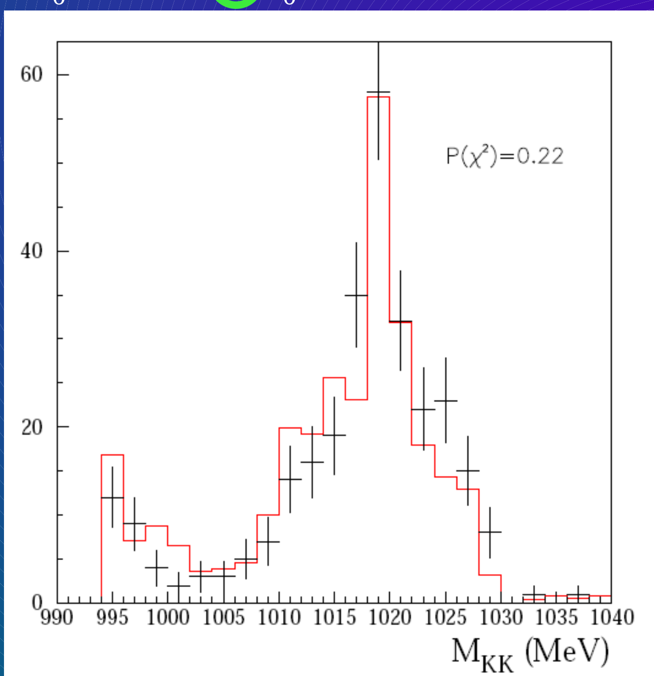
Isospin symmetry relates the couplings

$g f_0\pi^+\pi^- = 2\, g f_0\pi^0\pi^0$

$g f_0K^0K^0 = g f_0K^+K^-$

$g a_0K^0K^0 = -g a_0K^+K^-$

strong destructive interference between a_0 and f_0 is expected in the KK channel



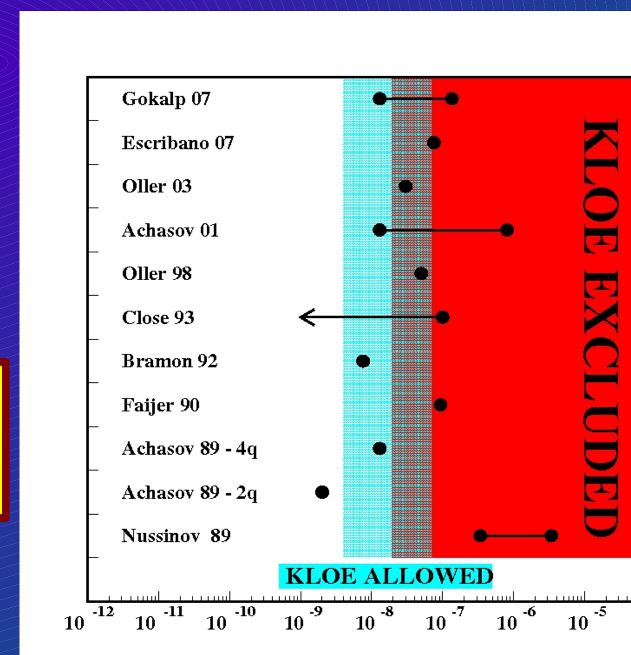
Dataset: 2.2 fb^{-1}

5 events in data (ε = 24%)

3.2 ± 0.7 exp. background

First experimental result

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



$\phi \to K^0 \bar{K}^0 \gamma$ KLOE 2 expectation

KLOE			KLOE2 8fb^{-1}	Inner Tracker
observed events	=	5	20	20
background events	=	3.2 ± 0.7	13	4
Br[$\phi \to (f_0 + a_0)\ \gamma$]		$< 1.9 \times 10^{-8}$	$< 1 \times 10^{-8}$	$< 0.5 \times 10^{-8}$

Main background from CP violating decay:

$$\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$$

(1) main background from $K_S K_L$, reducible with better vertex reconstruction

[1] N.N. Achasov, V.N. Ivanchenko, Nucl. Phys. B315 (1989) 465.

[2] S. Fajfer, R.J. Oakes, Phys. Rev. D42 (1990) 2392

[3] J. Lucio, J. Pestieau, Phys. Rev. D42 (1990) 3253.

[4] A. Bramon, A. Grau, G. Pancheri, Phys. Lett. B289 (1992) 97.

[5] J.A. Oller, Phys.Lett. B426 (1998) 7.

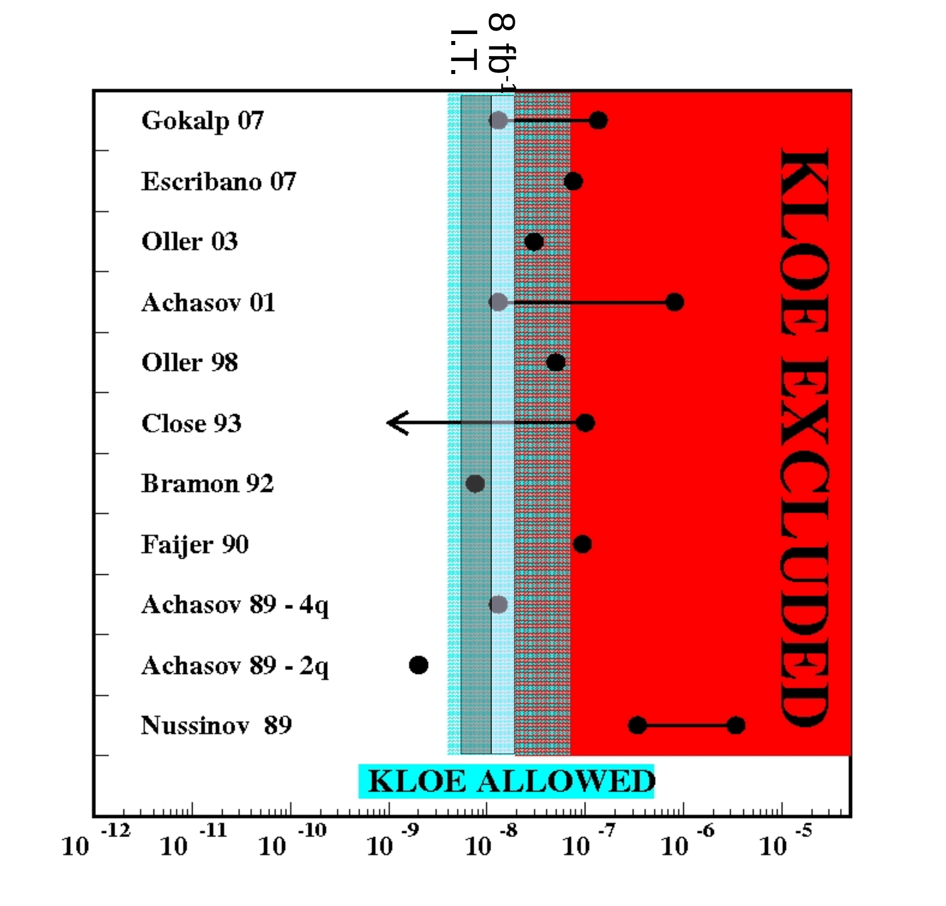
[6] N.N. Achasov, V.V. Gubin, Phys. Rev. D64 (2001) 094016.

[7] S. Nussinov, T.N. Truong, Phys. Rev. Lett. 63 (1989) 1349, Erratum 2003.

[8] J.A. Oller, Nucl. Phys. A714 (2003) 161.

[9] R. Escribano, Eur. Phys. J. A31 (2007) 454.

[10] A. Gokalp, C.S. Korkmaz, O. Yilmaz, Phys. Rev. D75 (2007) 013001.



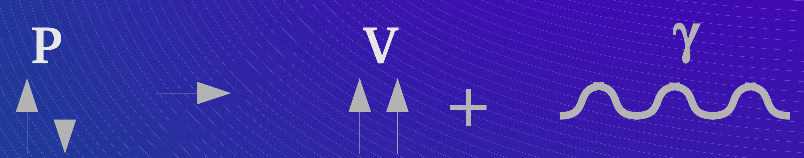
η, η': mixing and gluonium

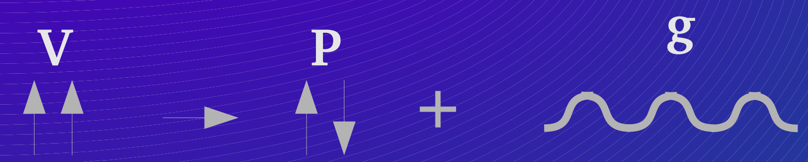
The η, η' mesons wave function can be decomposed in the quark mixing base as in the folowing (J. L. Rosner, Phys. Rev. D 27 (1983) 1101.).

$$|\eta'\rangle = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|G\rangle \qquad |\eta\rangle = \cos\psi_P|q\bar{q}\rangle - \sin\psi_P|s\bar{s}\rangle \qquad |q\bar{q}\rangle = \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}}$$

$$X_{\eta'} = \sin\psi_P \cos\psi_G$$
$$Y_{\eta'} = \cos\psi_P \cos\psi_G$$
$$Z_{\eta'} = \sin\psi_G$$

The $\phi \to \eta, \eta' \gamma$ transition is modeled according a spin flip transition





$$\Gamma(P \to V\gamma) = \frac{g^2}{4\pi}|p_\gamma|^3 \qquad \Gamma(V \to P\gamma) = \frac{1}{3}\frac{g^2}{4\pi}|p_\gamma|^3$$

Only quarks participate to the electromagnetic transition, gluonium is spectator.
It appears in the η' decay amplitudes only through the normalisation to 1 ($Y_{\eta'} \sim \cos\psi_G$)

On the meaning of gluonium

$Z_{\eta'}$ can be interpreted as a mixing with a glue ball.
The mass of this glue ball has been determined
[Hai-Yang Cheng, Phys. Rev. D79 (2009) 014024]

$\theta_i = 54.7°$ $\phi \rightarrow \psi_P$ $\phi_G \rightarrow \psi_G$

$$\frac{c\theta(s\phi - c\theta s\theta_i\Delta_G)m_{\eta'}^2 - s\theta(c\phi + s\theta s\theta_i\Delta_G)^2 m_\eta^2 - s\theta_i c\phi_G m_G^2}{c\theta(c\phi - c\theta c\theta_i\Delta_G)m_{\eta'}^2 + s\theta(s\phi - s\theta c\theta_i\Delta_G)^2 m_\eta^2 - c\theta_i c\phi_G m_G^2} = \frac{\sqrt{2}f_s}{f_q},$$

$m_G = (1.41 \pm 0.1)$ GeV

The glue-ball is identified as $\eta(1405)$
copiously produced in $J/\psi \rightarrow \eta(1405)\gamma$

Prediction $Br(\eta(1405) \rightarrow \gamma\gamma) = 6 \pm 1 \times 10^{-5}$
Decay never observed

KLOE past fit

KLOE has fitted:

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

$$\frac{\Gamma(\eta'\to\omega\gamma)}{\Gamma(\omega\to\pi^0\gamma)}=\frac{1}{3}\left(\frac{m_{\eta'}^2-m_\omega^2 m_\omega}{m_\omega^2-m_\pi^2 m_{\eta'}}\right)^3\left[z_q X_{\eta'}+2\frac{m_s}{\bar{m}} z_s\cdot\tan\psi_V\cdot Y_{\eta'}\right]^2$$

taken from a global fit without gluonium

A. Bramon, R. Escribano, M.D. Scadron Phys. Lett. B503 (2001) 271

Using KLOE measured branching ratio:

$$R_\phi=\frac{Br(\phi\to\eta'\gamma)}{Br(\phi\to\eta\gamma)}=\cot^2\psi_P\cdot\cos^2\psi_G\left(1-\frac{m_s}{\bar{m}}\frac{z_q}{z_S}\frac{\tan\psi_V}{\sin 2\psi_P}\right)^2\cdot\left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

$R_\phi = (4.77 \pm 0.09 \pm 0.19)\times 10^{-3}$

$\phi\to\eta'\gamma$: $\eta'\to\pi^+\pi^-\eta$, $\eta\to 3\pi^0$; $\eta'\to\pi^0\pi^0\eta$, $\eta\to\pi^+\pi^-\pi^0$

$\phi\to\eta\gamma$, $\eta\to 3\pi^0$

and the ratio:

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

E. Kou, Phys. Rev. D 63 (2001) 54027

KLOE new fit

New global fit with more free parameters: Z_q, Z_s, ψ_V, m_s/m

Other input are needed

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

From PDG06

Parameter	KLOE old fit	KLOE New fit	K. New fit (no Pγγ)	R.Escribano, J. Nadal JHEP 05 (2007) 6
$Z^2_{\eta'}$	0.14 ± 0.04	0.105 ± 0.037	**0.03 ± 0.06**	**0.04 ± 0.09**
ψ_P	(39.7 ± 0.7)°	(40.7 ± 0.7)°	**(41.6 ± 0.8)°**	**(41.4 ± 1.3)°**
Z_q	0.91 ± 0.05	0.866 ± 0.025	**0.85 ± 0.03**	**0.86 ± 0.03**
Z_s	0.89 ± 0.07	0.79 ± 0.05	**0.78 ± 0.05**	**0.79 ± 0.05**
ψ_V	3.2°	(3.15 ± 0.10)°	**(3.16 ± 0.10)°**	**(3.2 ± 0.1)°**
m_s/m	1.24 ± 0.07	1.24 ± 0.07	**1.24 ± 0.07**	**1.24 ± 0.07**
$P(\chi^2)$	49%	17%	**41%**	**38%**

Gluonium content @ ~3σ level confirmed ($Z_{\eta'} = 0$: $\psi_P = (41.6\pm0.5)°$, $P(\chi2)=1\%$)

$\eta'\to\gamma\gamma$ is the only measurement sensitive to the gluonium

Discrepancy with Escribano-Nadal due to the insertion of $P\to\gamma\gamma$ decay

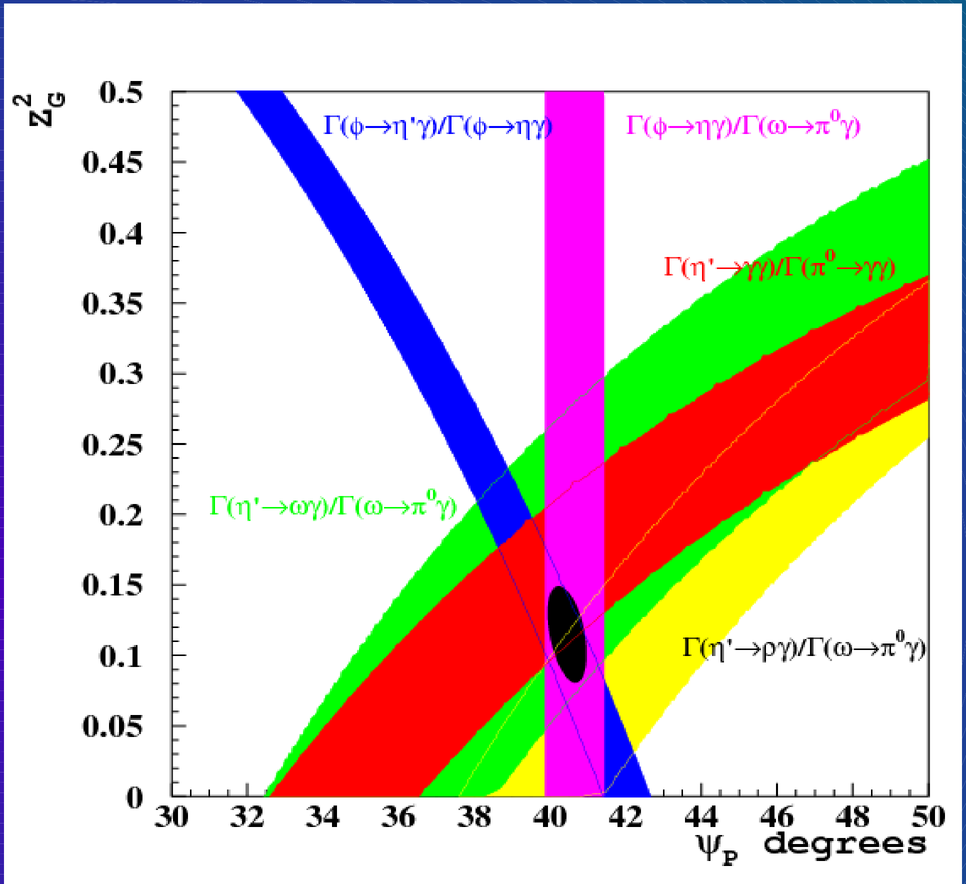
Using PDG-08 data

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

exact isospin symmetry limit

$$f_q/f_\pi=1 \qquad f_s/f_\pi=\sqrt{2f_K^2/f_\pi^2-1}$$

f_K/f_π	from lattice (UKQCD) **E.Follana *et a l.*** **Phys. Rev. Lett. 100 (2008) 062002**



$\chi^2/\text{ndof} = 4.6/3$

$P(\chi^2) = 20\%$

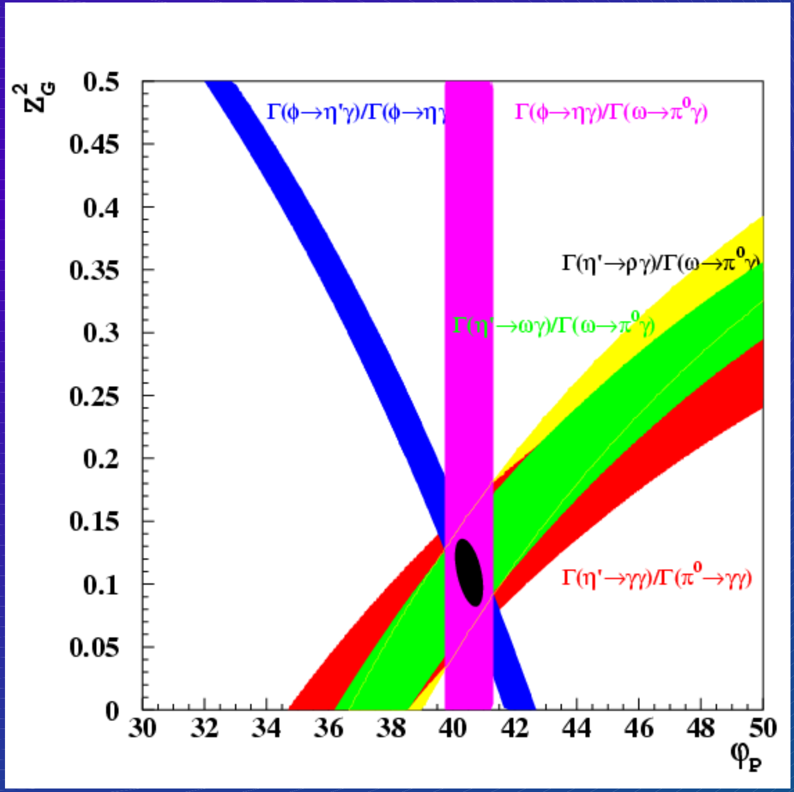
$(Z_G)^2$	0.115 ± 0.036
ψ_P	$(40.4 \pm 0.6)°$
Z_q	0.94 ± 0.03
Z_s	0.83 ± 0.05
ψ_V	$(3.32 \pm 0.09)°$
m_s/m	1.24 ± 0.07

KLOE 2 expectation

1 fb^{-1}

η'(958) DECAY MODES	Fraction (Γ_i/Γ)	events	main bkg
$\pi^+\pi^-\eta$	(44.6 ± 1.4) %	730k	—
$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)	(29.4 ± 0.9) %	480k	$\phi\to\pi^+\pi^-\pi^0$
$\pi^0\pi^0\eta$	(20.7 ± 1.2) %	340k	$\eta\gamma$ or KsKl
$\omega\gamma$	(3.02 ± 0.31) %	50k	$e^+e^-\to\omega\pi^0$
$\gamma\gamma$	(2.10 ± 0.12) %	34k	$e^+e^-\to\gamma\gamma(\gamma)$

All Br can be measured at ~1%
but systematics take the main role.



Sensitivity to the gluonium also without the $\eta'\to\gamma\gamma$

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

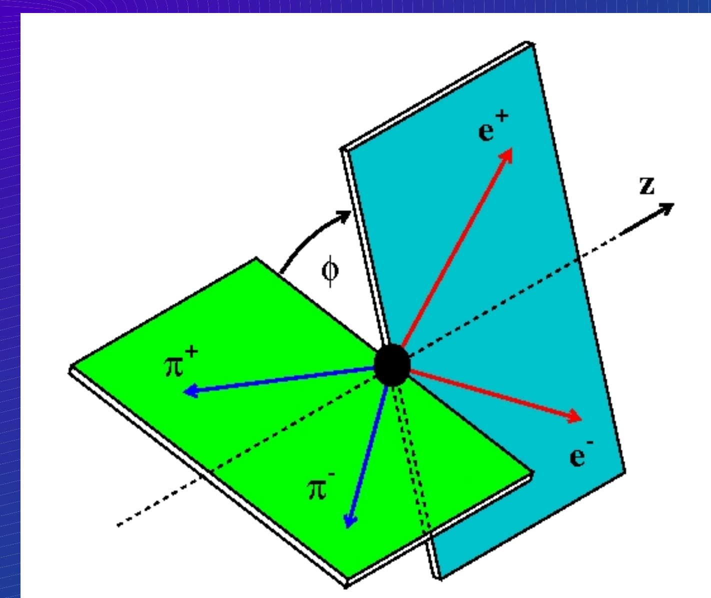
- Poorly measured (4 events CMD-2, 16 events CELSIUS-WASA)
- Br predicted by Chiral Perturbation Theory and VMD models $(26 \div 36) \cdot 10^{-5}$
- η structure using virtual photon

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

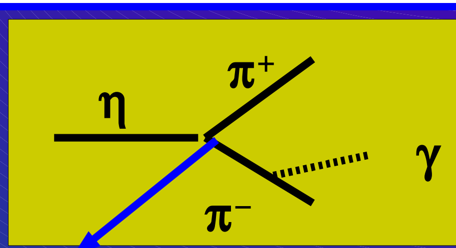
CP violation source not constrained by CKM measurements and neutron electric dipole moment

$$\mathcal{O} = \frac{1}{m_\eta^3} G \bar{s} i \sigma_{\mu\nu} \gamma_5 (p-q)^\nu s \bar{\psi} \gamma^\mu \psi$$

} asymmetry in the particle decay angle



Within the SM:



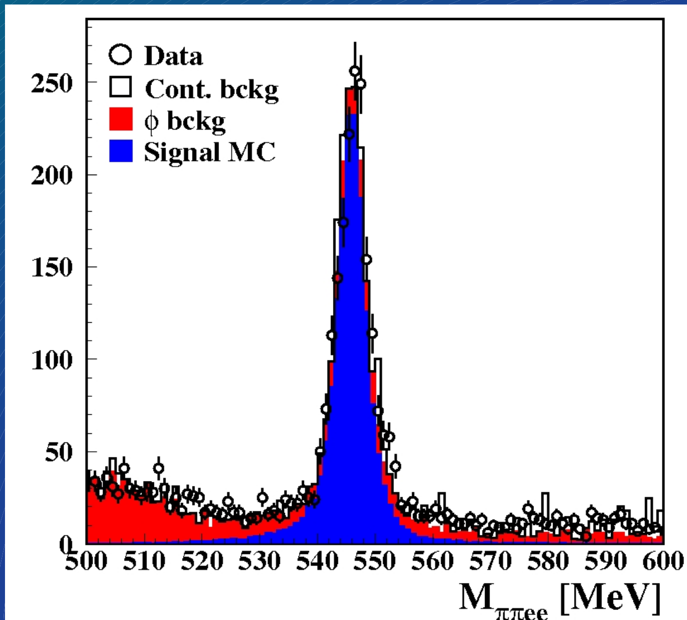
$A_\phi < 10^{-4}$

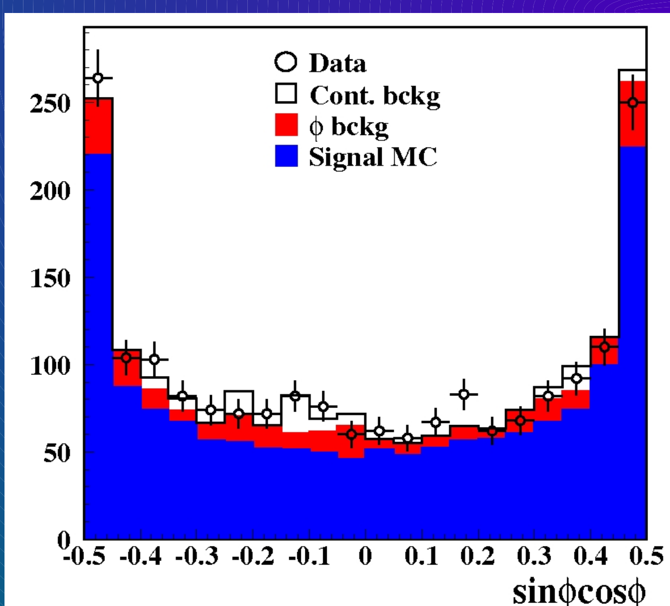
S. M.

$A_\phi \sim 10^{-15}$

$Br(\eta \to \pi^+\pi^-) < 1.3 \times 10^{-5}$
KLOE, Phys. Lett. B606 (2005) 276

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

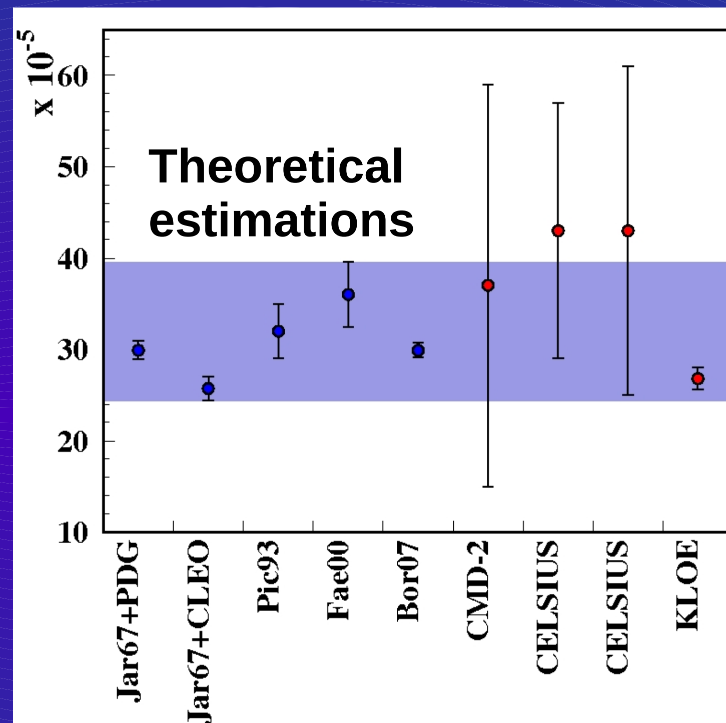




$BR(\eta \to \pi^+ \pi^- e^+ e^- (\gamma))$

$(26.8 \pm 0.9_{Stat.} \pm 0.7_{Syst.}) \times 10^{-5}$

KLOE-2



$A_\phi = (-0.6 \pm 2.5_{Stat.} \pm 1.8_{Syst.}) \cdot 10^{-2}$

$|G| < 1.8$

Asymmetry statistical error decreases from 2.5 to 1.2 just for luminosity.

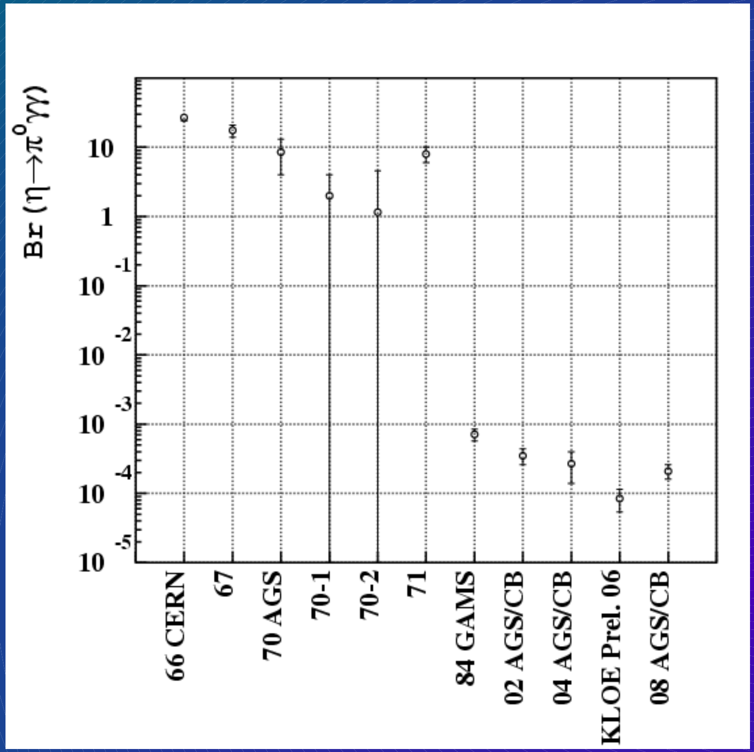
$|G| < 1$

The inner tracker imroves the reconstruction of 4 tracks.

First measurement of the CP asymmetry and attempt to constraint $|G|$.

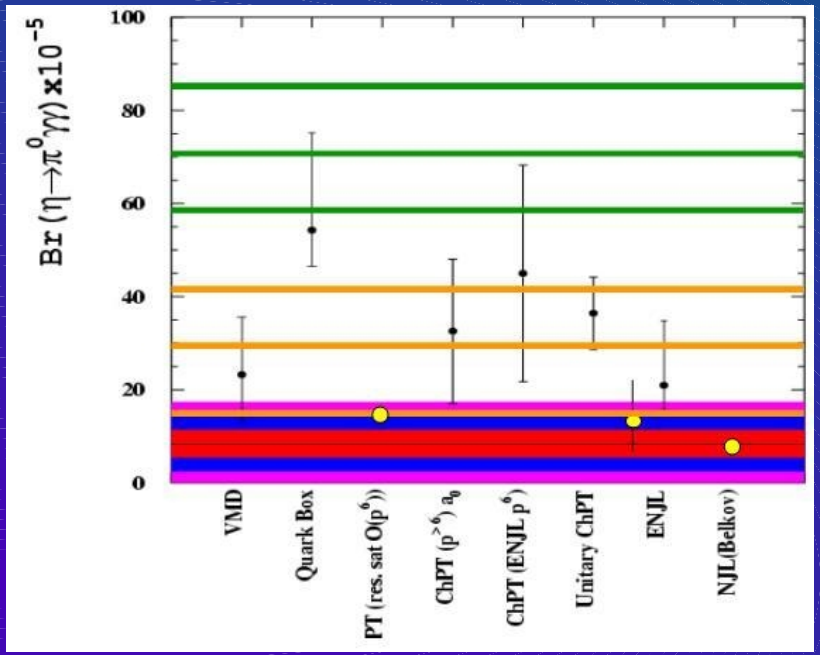
The $\eta \to \pi^0 \gamma\gamma$ decay

Past measurements (very long history)



} 2.2σ discrepancy

Theoretical predictions



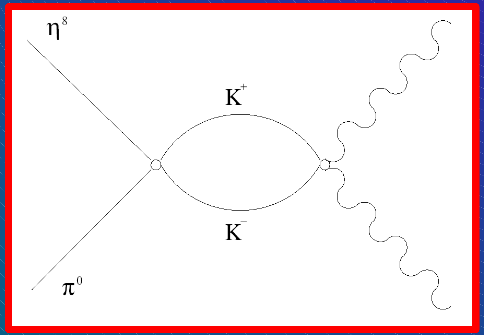
p^4 $\Gamma \sim 7.18 \times 10^{-3}$ eV

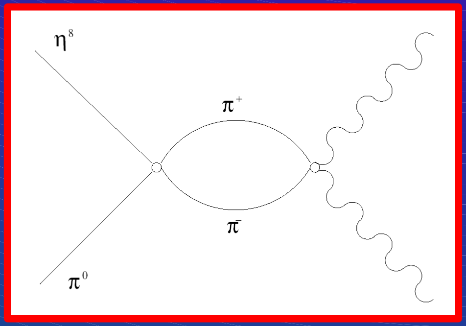
VMD and scalar exchange start at p^6

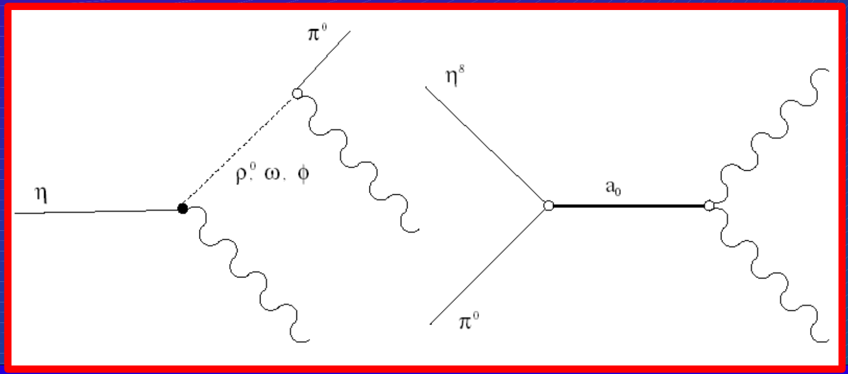
p^6 VMD $\Gamma \sim 0.18$ eV

Full VMD $\Gamma \sim 0.31$ eV

Full VMD + a0 $\Gamma \sim 0.42 \pm 0.20$ eV



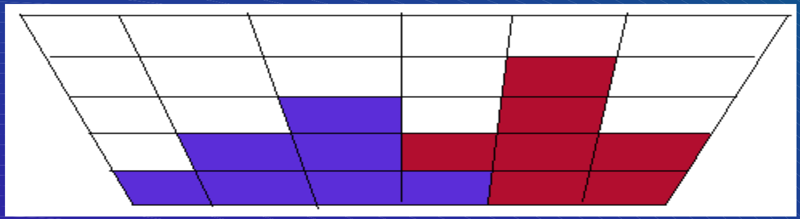


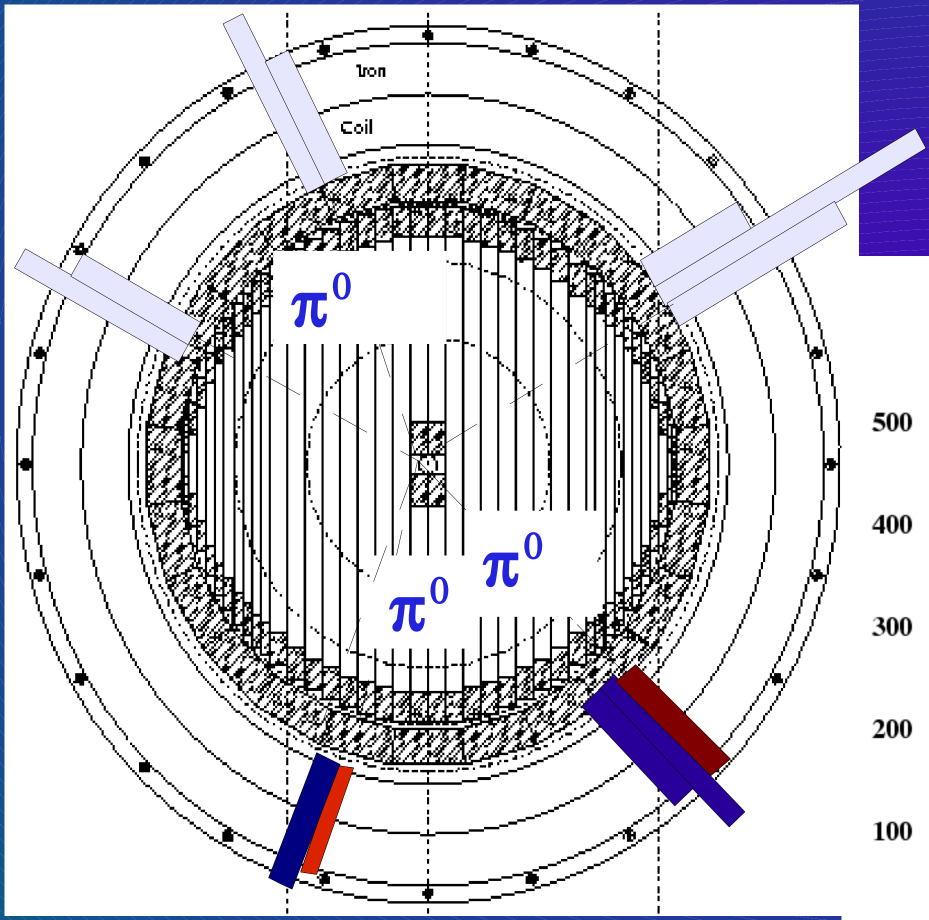


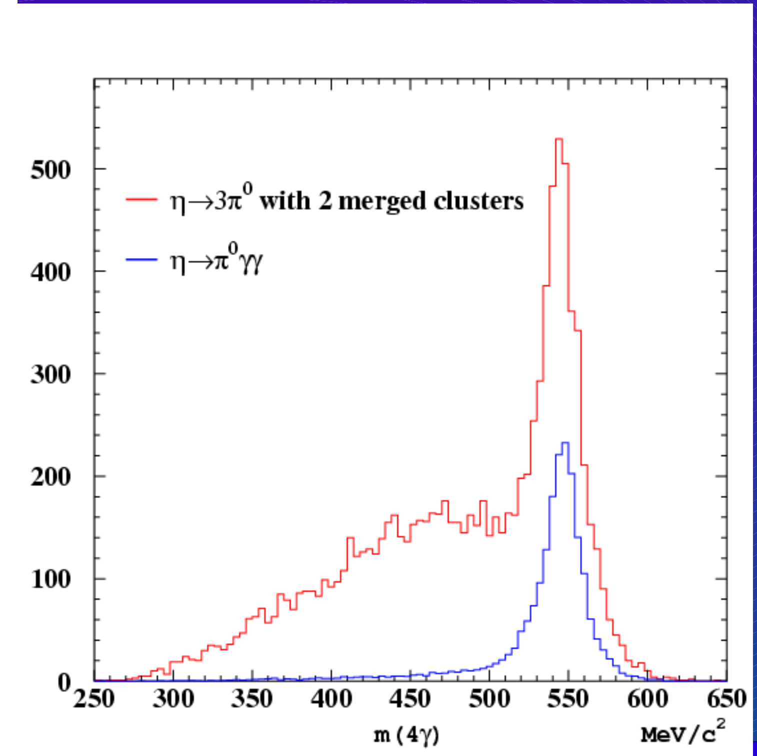
The merging of photons

$\phi \rightarrow \eta\gamma_{\phi}$

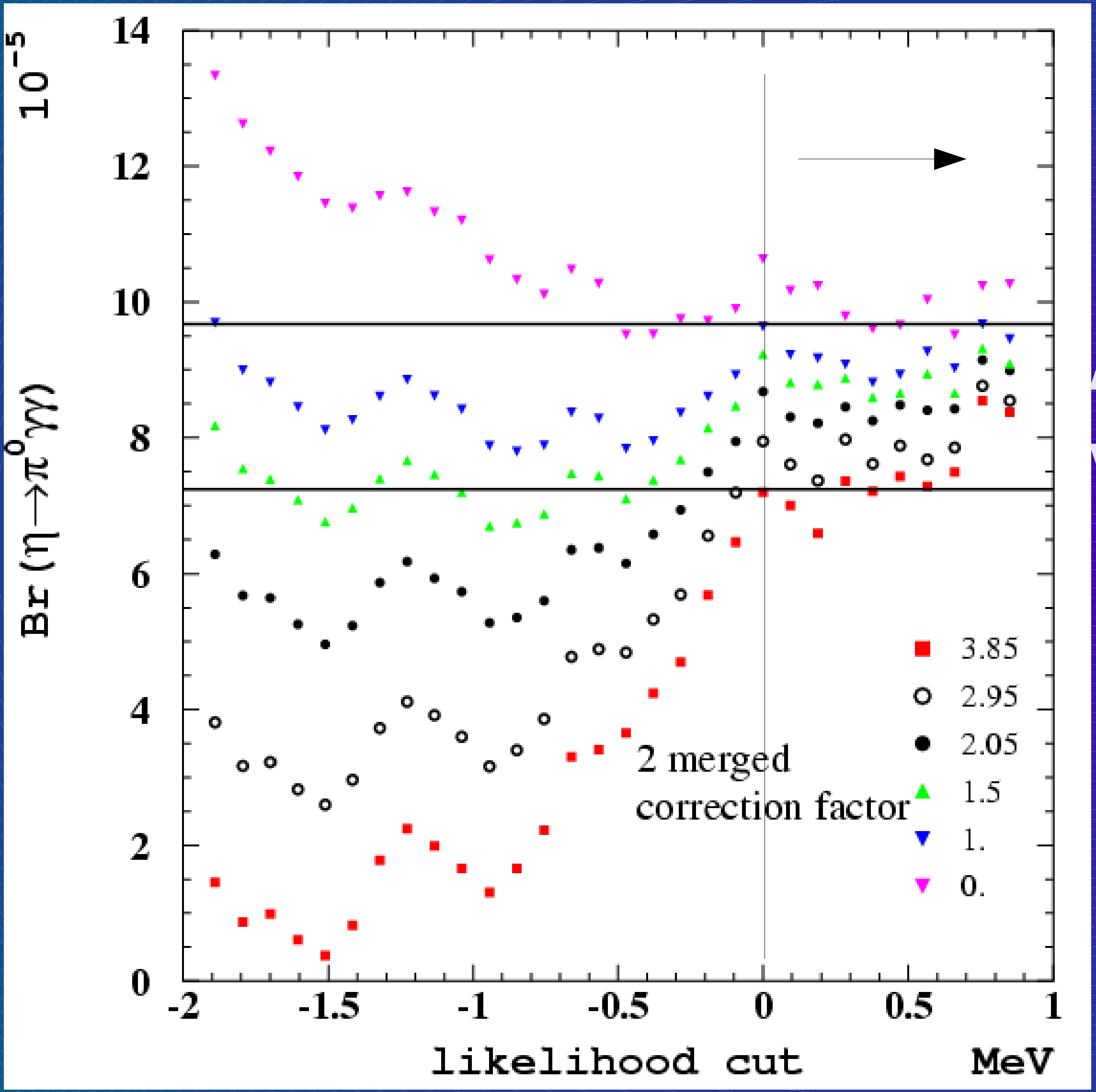
$\hookrightarrow \pi^0\pi^0\pi^0 \quad 7\gamma$







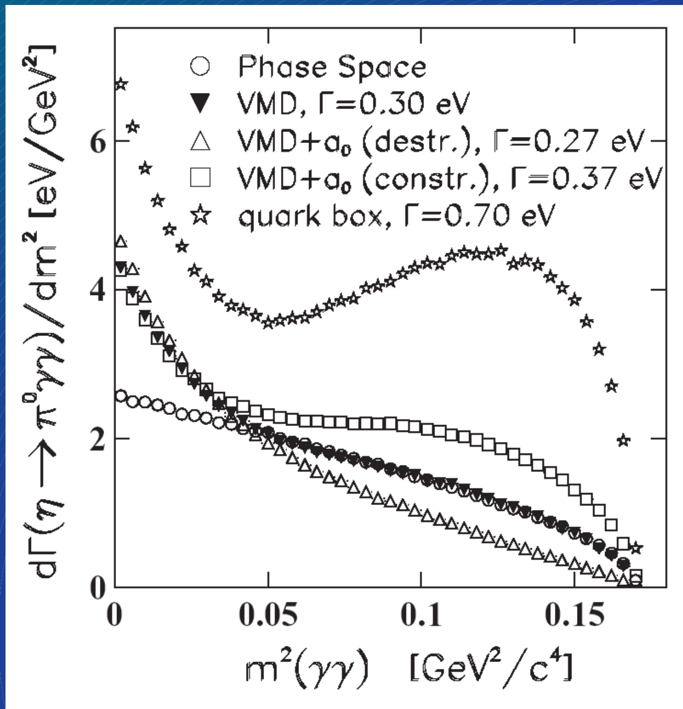
If 2 merged clusters background is underestimated, it is counted as a signal

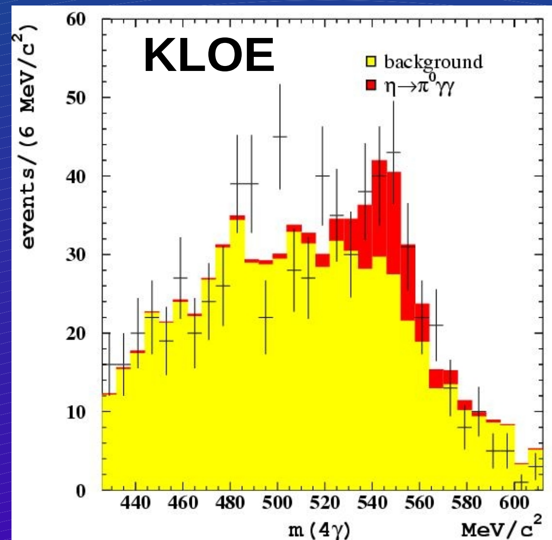


Selected region

1.1 systematic error (background composition and likelihood cut)

The Br and the $m_{\gamma\gamma}$ spectrum





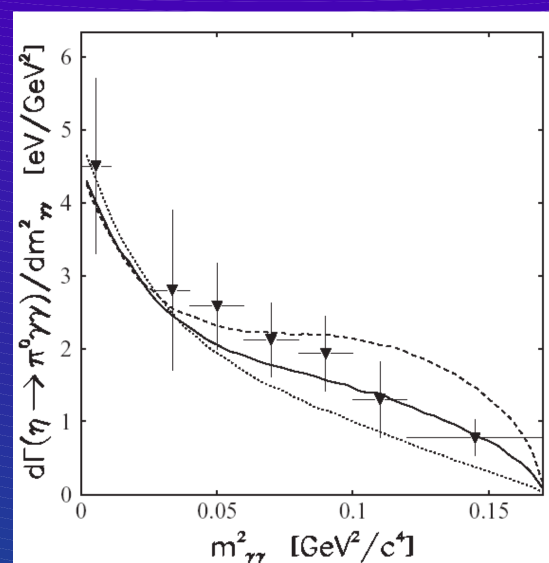
AGS/CB 08
Phys. Rev. C 78, 015206 (2008)

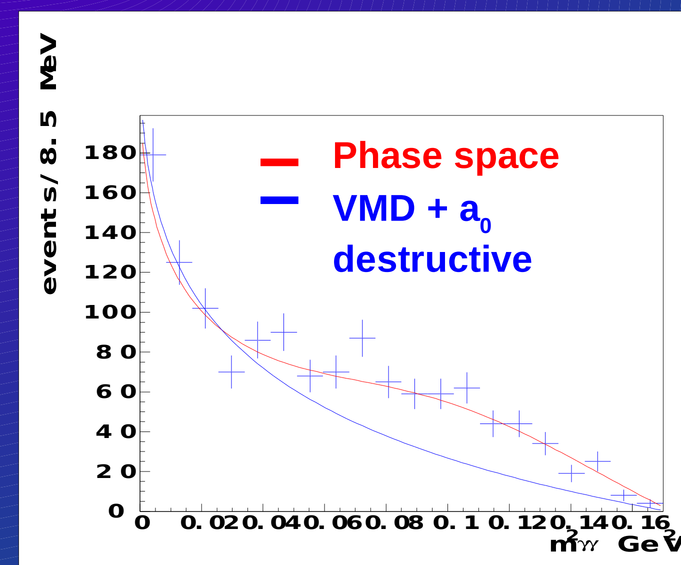
N events 1300
at KLOE 2 (efficiency included)

dBr/Br (stat.) 3%
(20% present uncertainty)

KLOE2
sensitivity to the spectrum

The $m_{\gamma\gamma}$ spectrum can be also analysed with good accuracy.

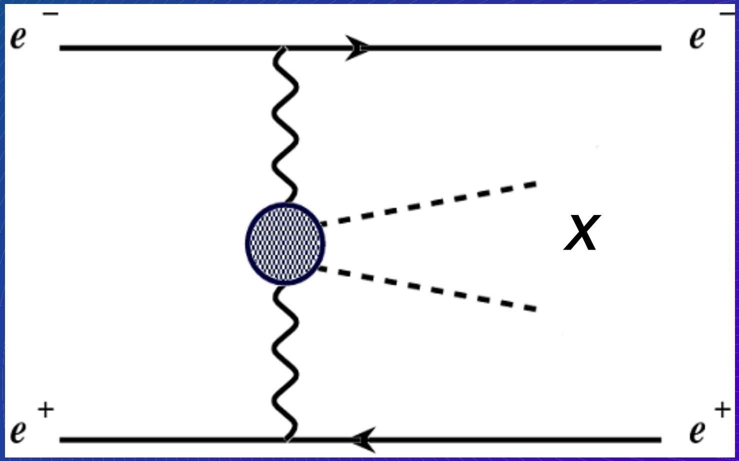


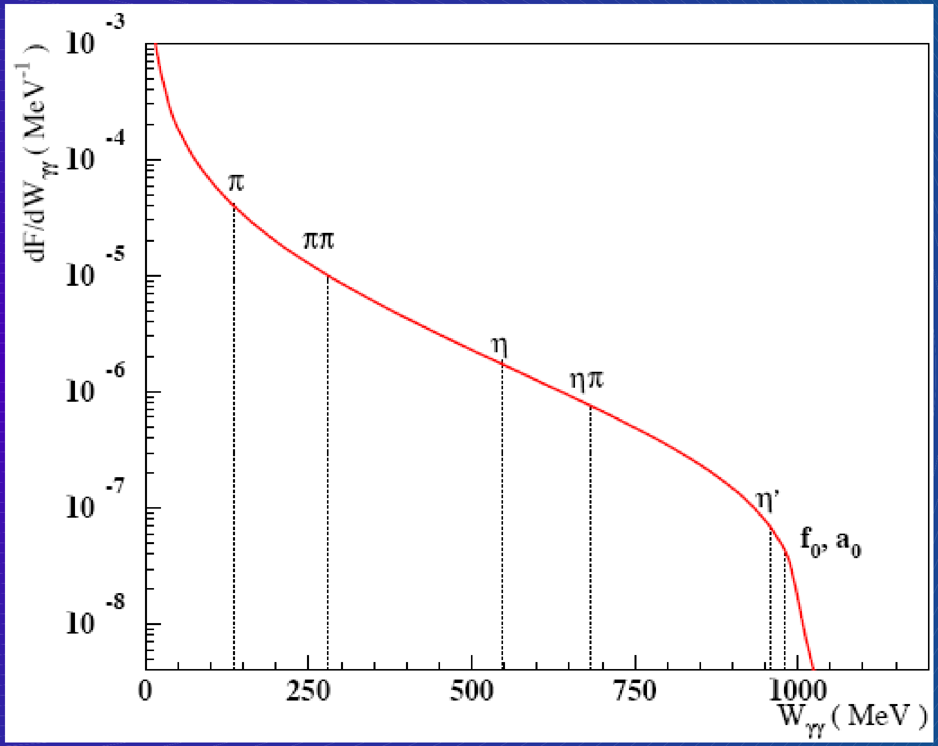


$\gamma\gamma$ Physics at KLOE and KLOE 2

γγ Luminosity

Weizsäcker-Williams approximation
$|q_\gamma^2| << W^2$





$$\sigma_{e^+e^-\to e^+e^-X} = \frac{16\alpha^2\Gamma_{X\gamma\gamma}}{m_X^3}\left(\ln\frac{E_b}{m_e}\right)^2\left((y^2+2)^2\,\ln\frac{1}{y} - (1-y^2)\,(3+y^2)\right)$$

$$y = m_X/(2E_b)$$

$e^+e^- \to e^+e^-\eta(\to\pi^+\pi^-\pi^0)$

Data Sample: **250 pb^{-1} @ $\sqrt{s}$ = 1 GeV**

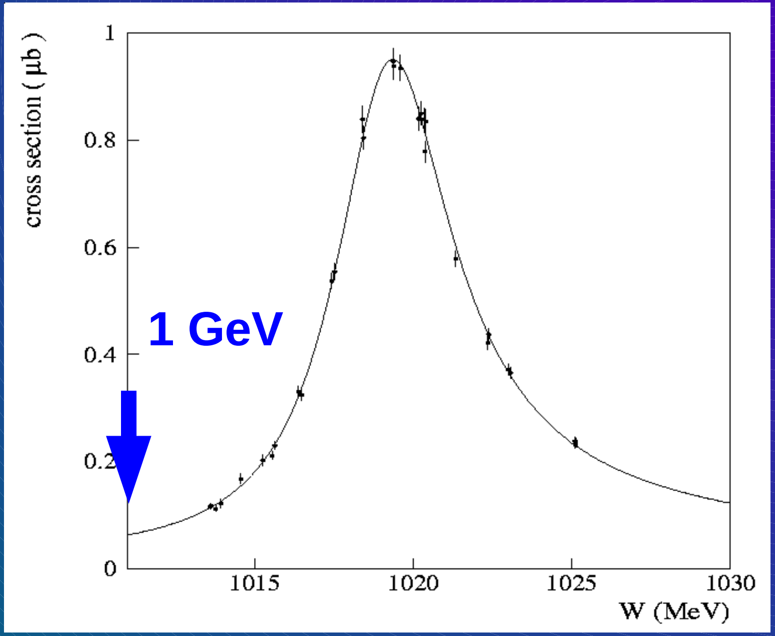
Main Background: $\phi\to\eta\gamma$ (γ undetected at small angle)

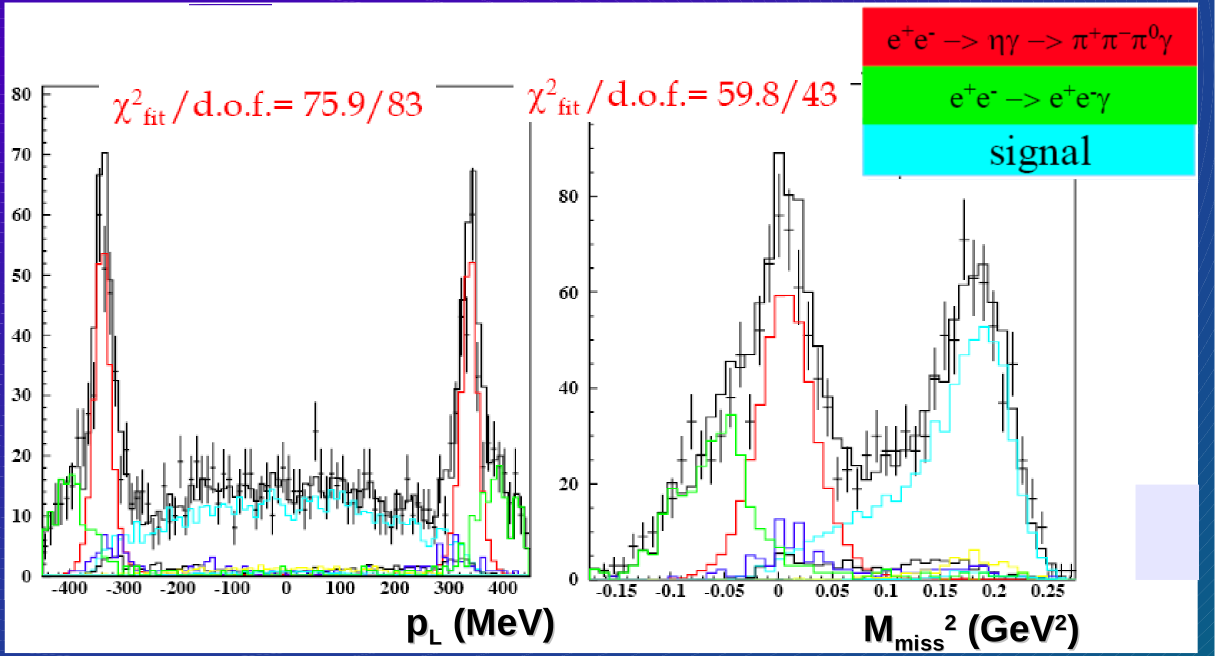
Bkg signature: $P_L = |\vec{p}_\gamma|\cos\theta \sim |\vec{p}_\gamma| = |\vec{p}_{miss}| = \frac{m_\phi^2 - m_\eta^2}{2m_\phi} \sim 360\, MeV$

$N_{sig} = 646$ $N_{sig} = 625$

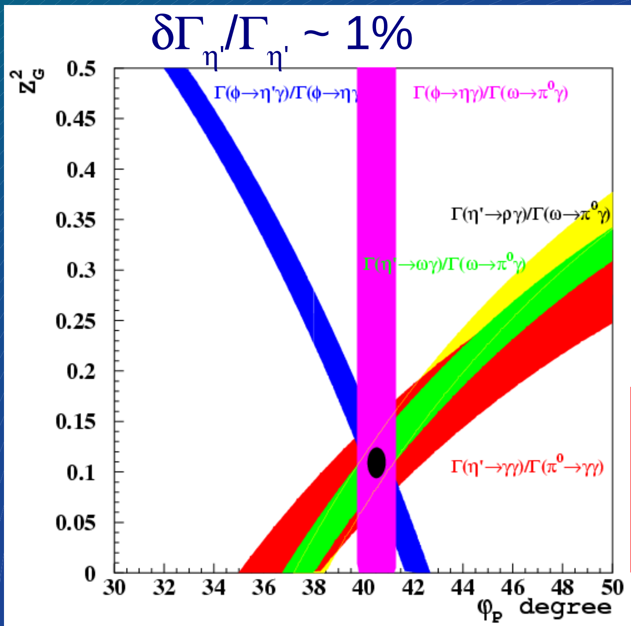
Bkg dumping

$\delta\Gamma/\Gamma \sim 5\%$ same order of present accuracy.

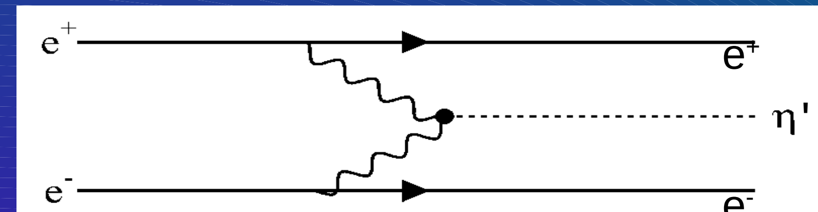




Measurement of the η' width @KLOE2



$$\Gamma_{\eta'} = \frac{\Gamma_{\eta'\to\gamma\gamma}}{Br(\eta'\to\gamma\gamma)}$$



$$\sigma_{e^+e^-\to e^+e^-\eta'}(s) = \frac{8\alpha^2\Gamma_{\eta'\to\gamma\gamma}}{m_{\eta'}^3} \times \left[f\left(\frac{m_{\eta'}^2}{s}\right)\left(ln\frac{m_V^2 s}{m_e^2 m_{\eta'}^2} - 1\right)^2 - \frac{1}{3}\left(ln\frac{s}{m_{\eta'}^2}\right)^3 \right]$$

background

	$e^+e^- \to \eta' e^+e^-$		$e^+e^- \to \phi(\gamma) \to \eta'\gamma(\gamma)$		
$\sqrt{s}GeV$	σ (pb)	events at 1 fb^{-1}	σ (pb)	events at 1 fb^{-1}	S/$\sqrt{B}$
0.987 ($2m_{K^+}$)	2.3	2300	0.23	230	152
0.995 ($2m_{K^0}$)	2.9	2900	0.67	670	112
1.020 (m_ϕ)	5.1	5100	190	190000	12
1.2	20	20000	1.2	1200	578
1.4	39	39000	5.8	5800	512

Very long run at low energy would be required.

34 @8fb^{-1}

Possible at higher energies

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

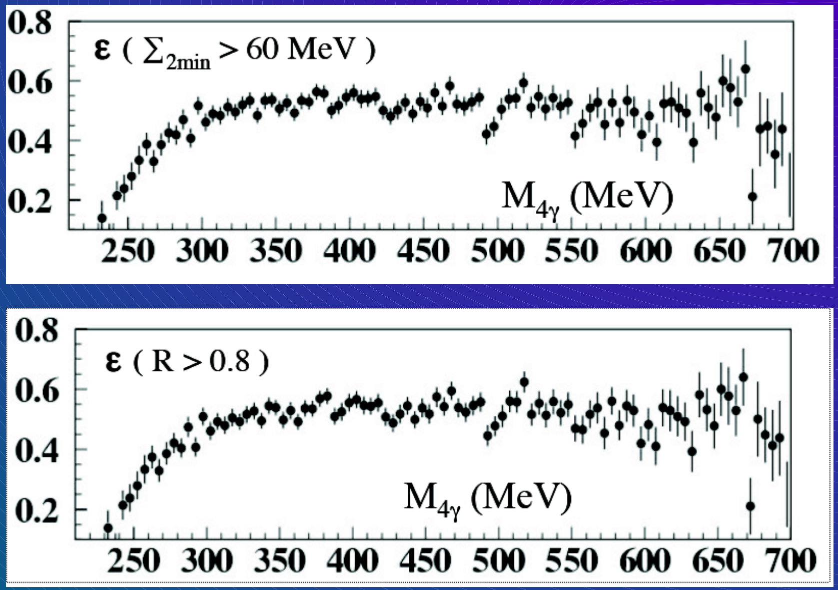
Event characteristics

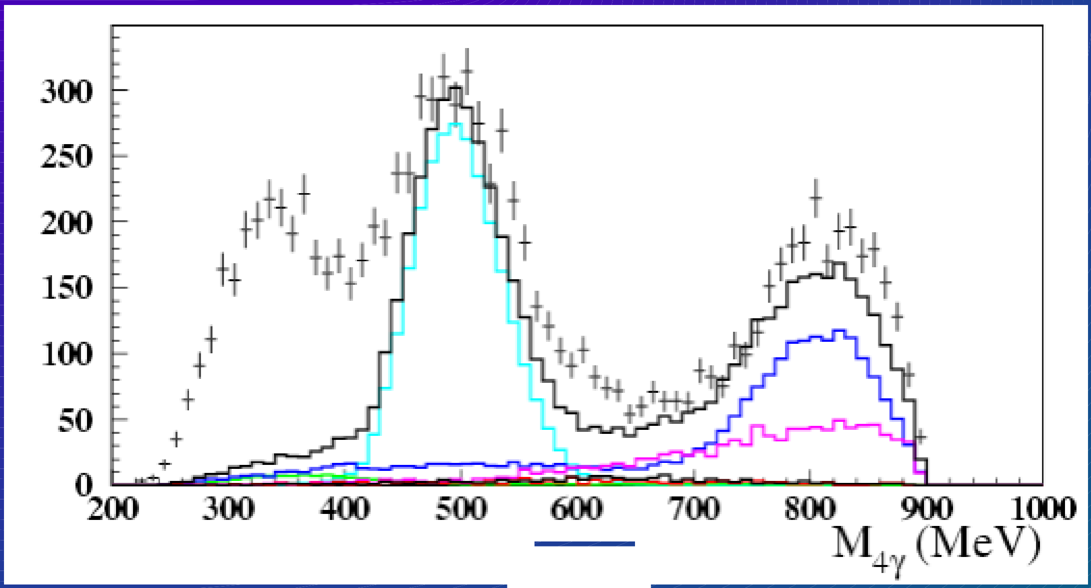
- outgoing electrons are undetected;
- Missing energy (kinematic is not closed);
- Background from events with undetected energy:

  K_sK_L (K_L passing calorimeter without energy deposition)

Analysis strategy

- 4 (E > 15 MeV) clusters in the calorimeter
- DC tracks veto
- ΣE_{min}(2 clusters) > 60 MeV
- (4 cluster energy) > 0.8×(all visible energy)





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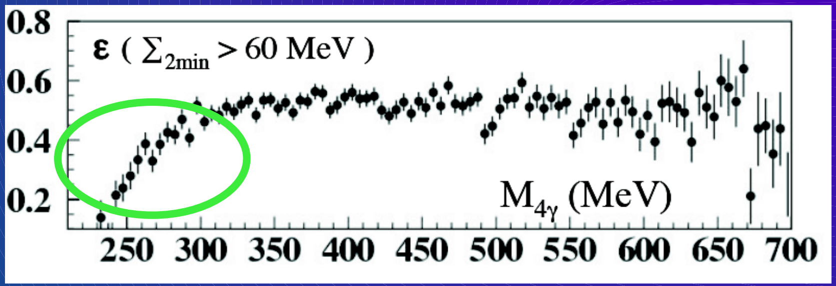
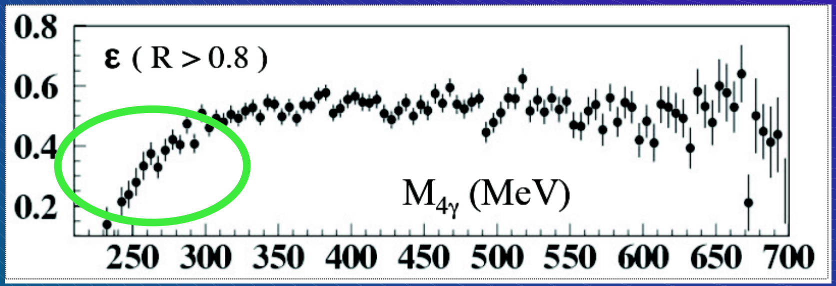
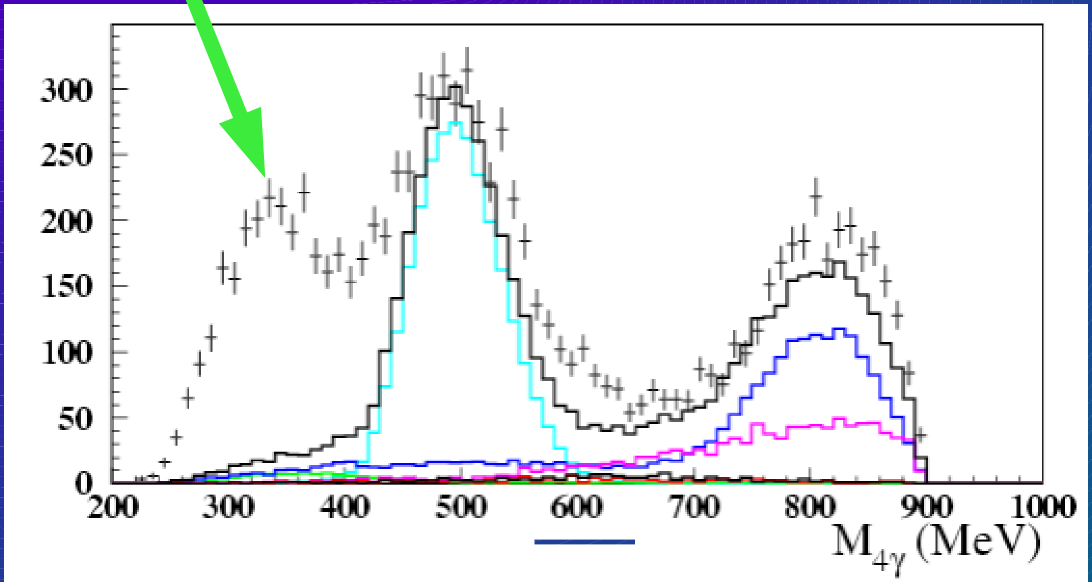
Event excess (~4000)
Shape strongly efficiency dependent







Event characteristics

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Analysis strategy

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- DC tracks veto
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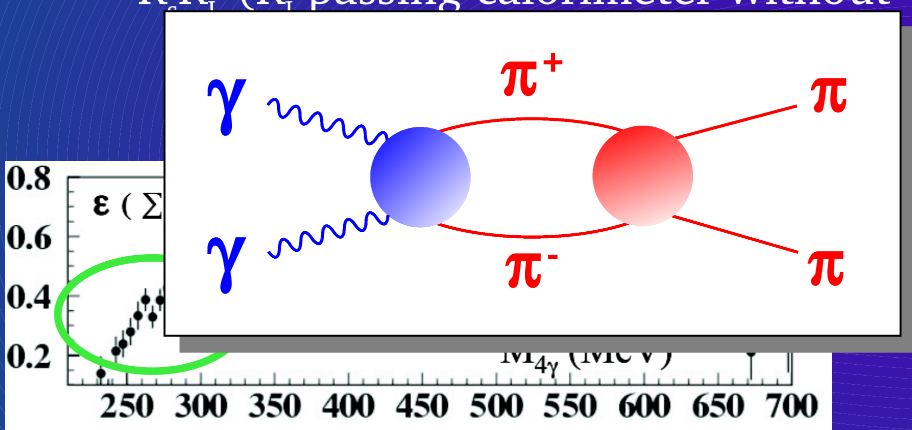
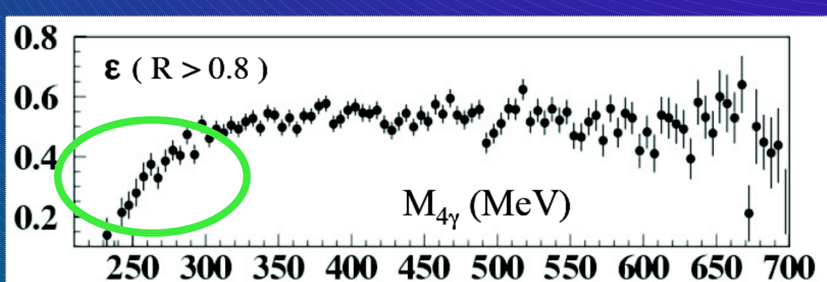
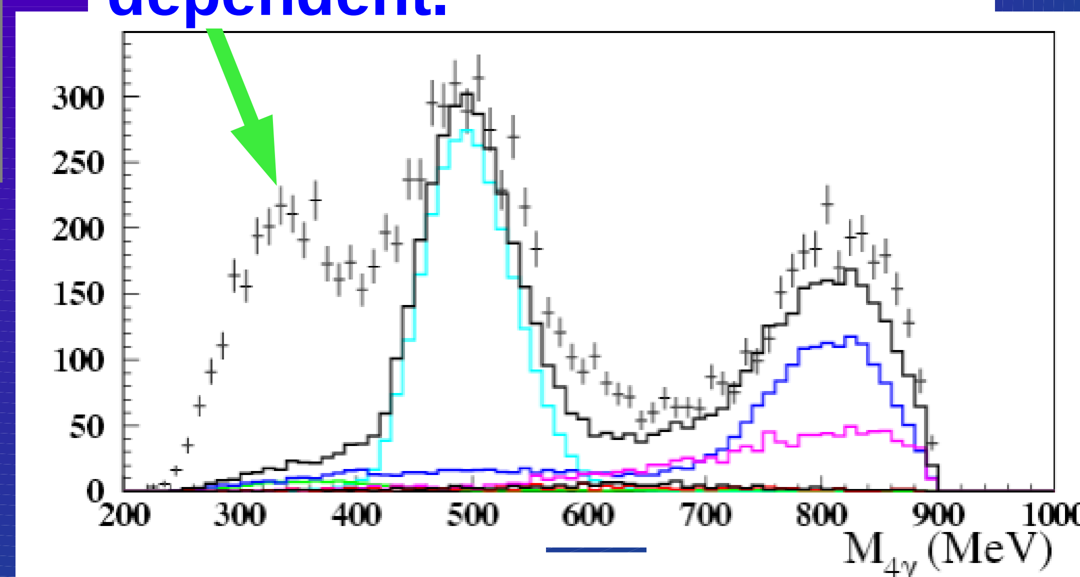
- (4 cluster energy) > 0.8×(all visible energy)

ent

σ extraction needs partial wave analysis and is model dependent.

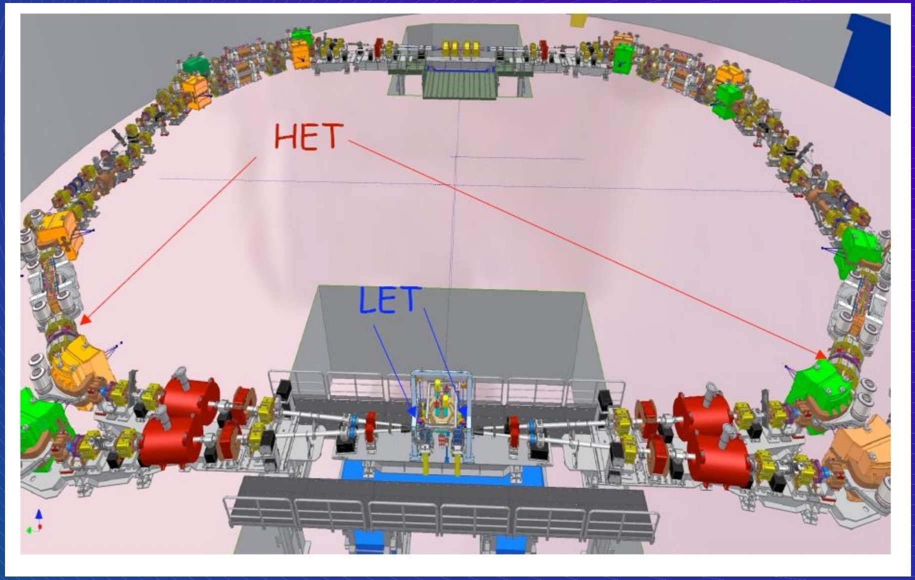


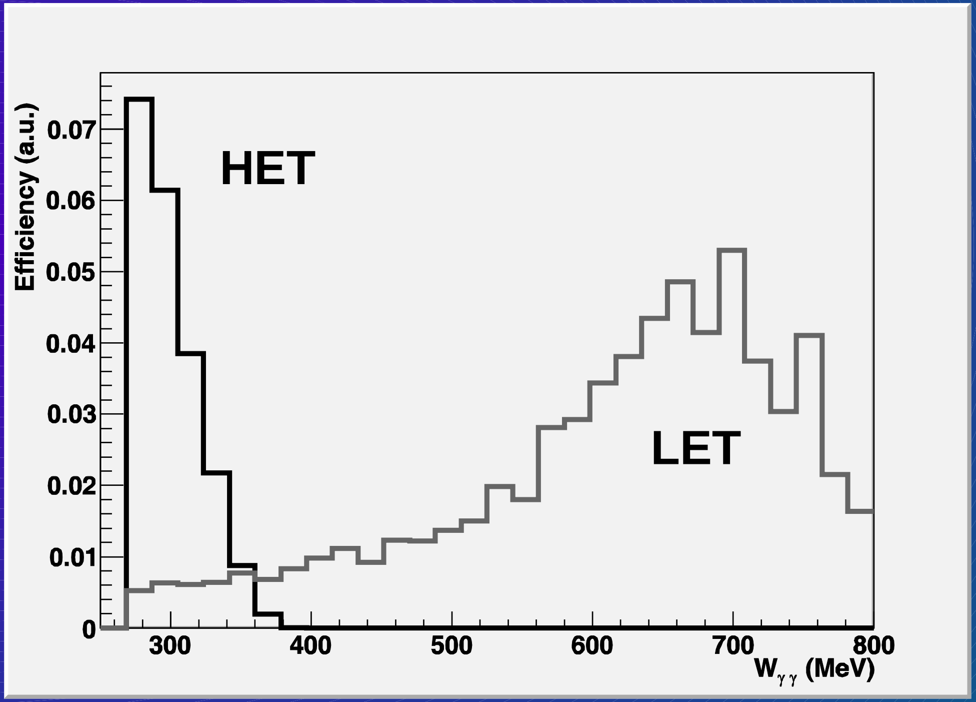




Run at the ϕ peak

- Background much more difficult to handle ⇒ γγ Tagger
- Kinematic can be closed measuring e^+e^- momenta





$(g-2)_\mu$ contribution

F. Jegerlehner, A. Nyffeler arXiv: 0902.3360

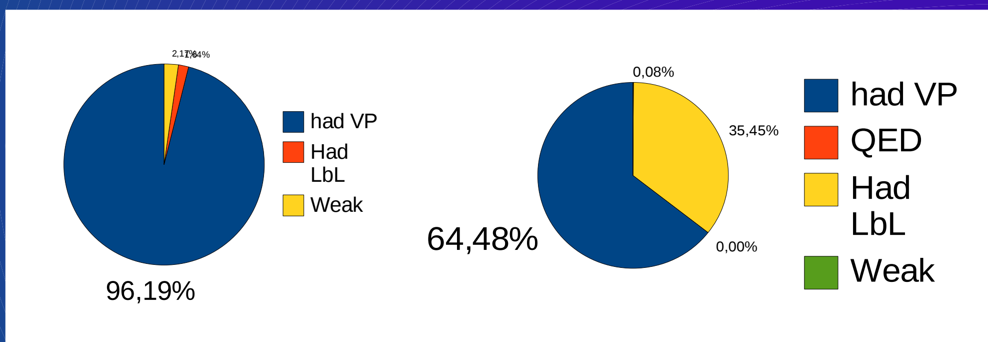
$a_\mu^{exp} = 1.16592080(63) \times 10^{-3}$

$a_\mu^{the} = 1.16591790(65) \times 10^{-3}$

$\Delta a_\mu = 3.2\ \sigma$

a_μ fractional contribution (QED (99.99%) excluded)

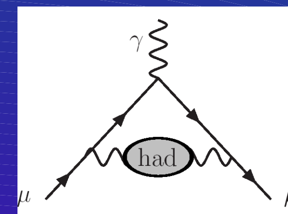
Δa_μ fractional contribution



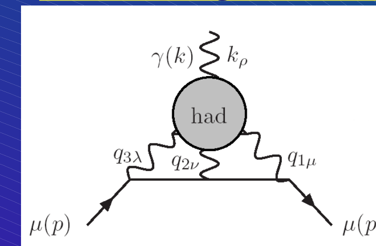
$$a_\mu^{\mathrm{LbL};\pi^0} = -e^6 \int \frac{d^4q_1}{(2\pi)^4}\frac{d^4q_2}{(2\pi)^4} \frac{1}{q_1^2 q_2^2 (q_1+q_2)^2[(p+q_1)^2-m_\mu^2][(p-q_2)^2-m_\mu^2]} \times \left[\frac{\mathcal{F}_{\pi^{0*}\gamma^*\gamma^*}(q_2^2,q_1^2,q_3^2)\ \mathcal{F}_{\pi^{0*}\gamma^*\gamma}(q_2^2,q_2^2,0)}{q_2^2-m_\pi^2} T_1(q_1,q_2;p) + \frac{\mathcal{F}_{\pi^{0*}\gamma^*\gamma^*}(q_3^2,q_1^2,q_2^2)\ \mathcal{F}_{\pi^{0*}\gamma^*\gamma}(q_3^2,q_3^2,0)}{q_3^2-m_\pi^2} T_2(q_1,q_2;p) \right],$$

Main uncertainty sources

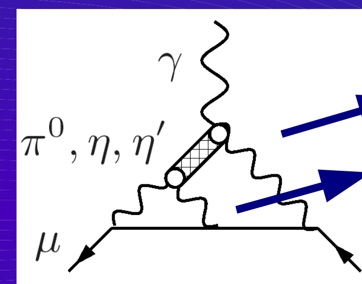
Hadronic Vacuum polarization



Hadronic Light by Light

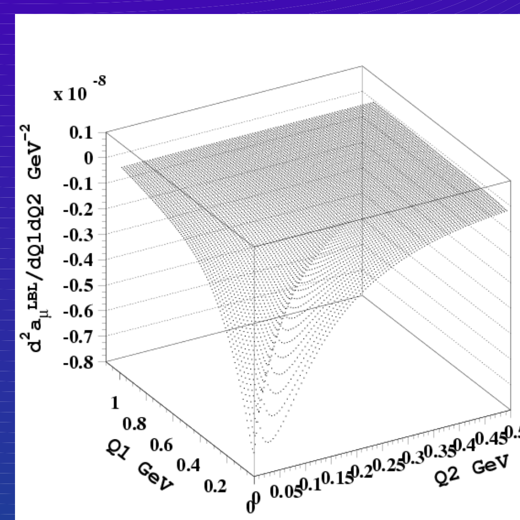


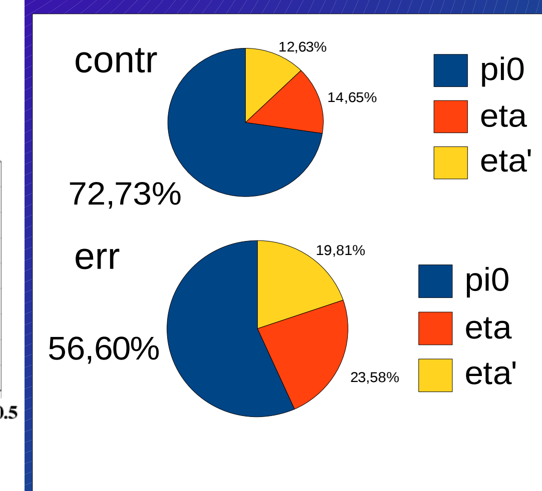
Pseudoscalar exchange



$F_{PS}(q^2, q_3^2, 0)$

$F_{PS}(q^2, q_1^2, q_2^2)$





Small q^2 values are leading.

Possible parametrisations

Several form factors have been proposed to full fill accurate theoretical predictions for the high energy behavior):

Bijnens Persson, hep-ph/0106130

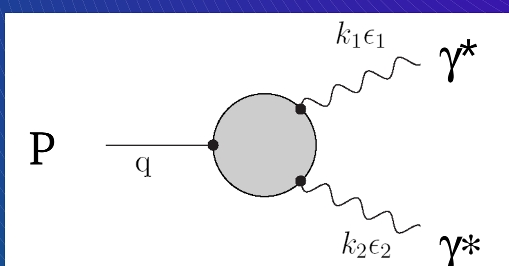
$F(0,0) = 1$

Theoretical constraints:

$q^2 \rightarrow \infty \qquad F(q^2,0) \sim 1/q^2$

$\qquad\qquad\quad F(q^2,q^2) \sim 1/q^2$

Perturbative QCD limits.



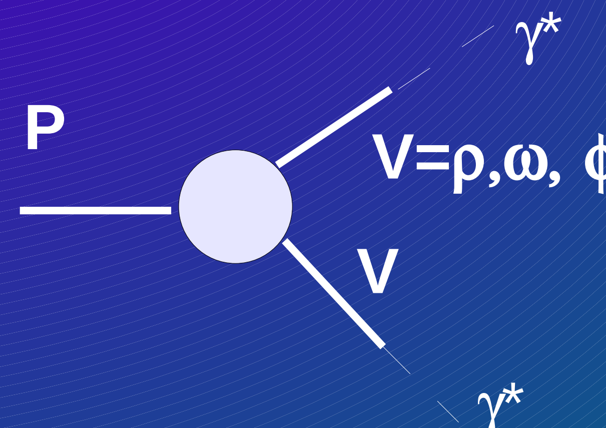
$$F(k_1^2, k_2^2) = 1$$

$$F(k_1^2, k_2^2) = \frac{m_\rho^4}{(m_\rho^2 - k_1^2)(m_\rho^2 - k_2^2)}$$

$$F(k_1^2, k_2^2) = \frac{m_\rho^2}{(m_\rho^2 - k_1^2 - k_2^2)}$$

$$F(k_1^2, k_2^2) = \frac{m_\rho^4 - \frac{4\pi^2 \; F_\pi^2}{N_c} \; (k_1^2 + k_2^2)}{(m_\rho^2 - k_1^2)(m_\rho^2 - k_2^2)}$$

Double Vector Meson Dominance



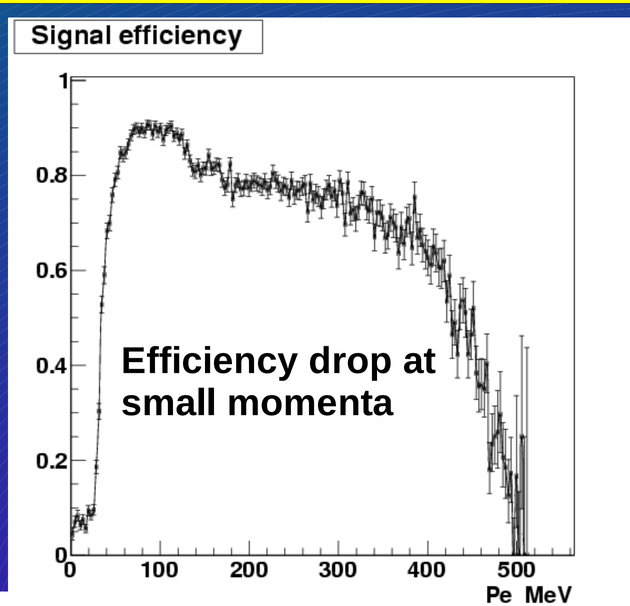
Studying form factors in the Dalitz decays

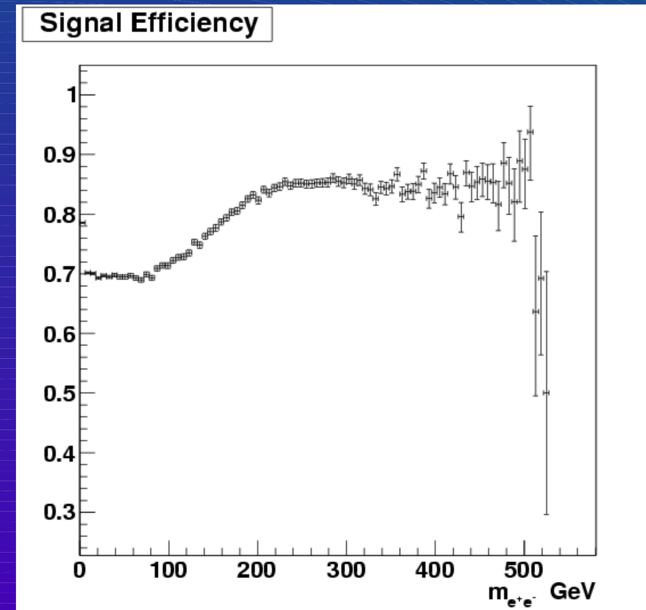
Time-like region π^0, η

	Intermediate channel		Events
$\pi^0 \to e^+e^-\gamma$	$\phi \to \pi^+\pi^-\pi^0$	$\pi^+\pi^-e^+e^-\gamma$	8×10^7
$\pi^0 \to e^+e^-e^+e^-$	$\phi \to \pi^+\pi^-\pi^0$	$\pi^+\pi^-e^+e^-e^+e^-$	1.3×10^5
$\eta \to e^+e^-\gamma$	$\phi \to \eta\gamma$	$e^+e^-\gamma$	2.4×10^5
$\eta \to e^+e^-e^+e^-$	$\phi \to \eta\gamma$	$e^+e^-e^+e^-\gamma$	2.3×10^4

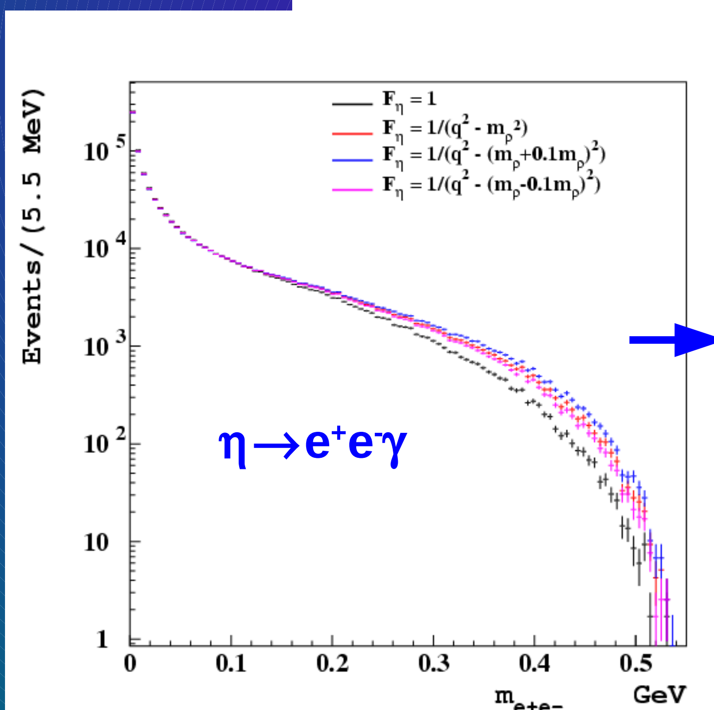
$\eta \to e^+e^-g$, $\mu^+\mu^-\gamma$ form factor $F\gamma^*\gamma^*$ at KLOE2.

Efficiency curve as a function of e^- momentum.



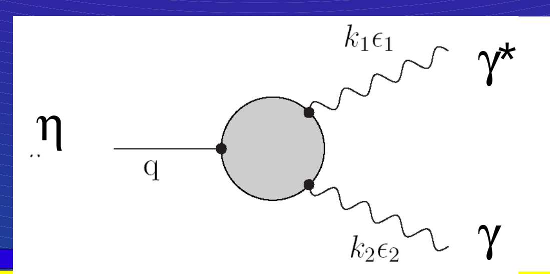


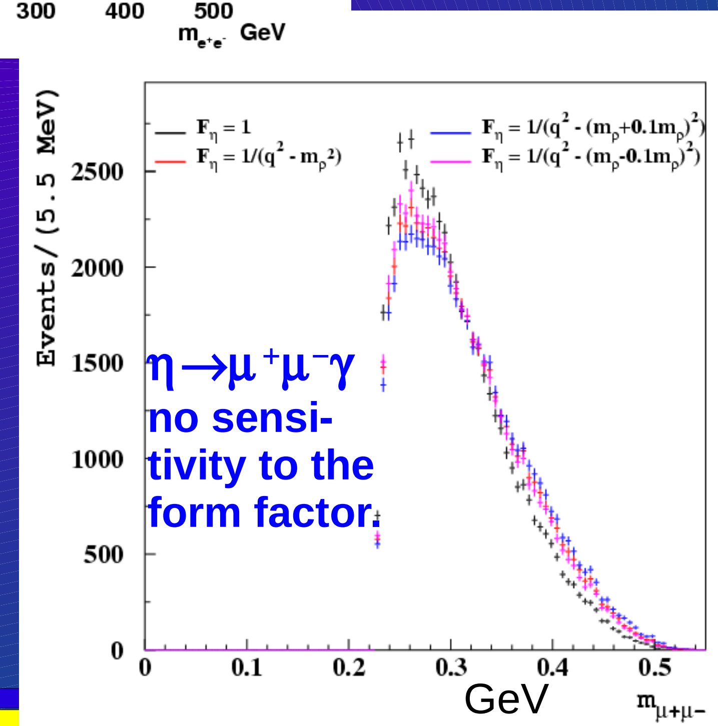
sensitivity in the whole m_{e+e-} range.



VMD form factor usually used for description.

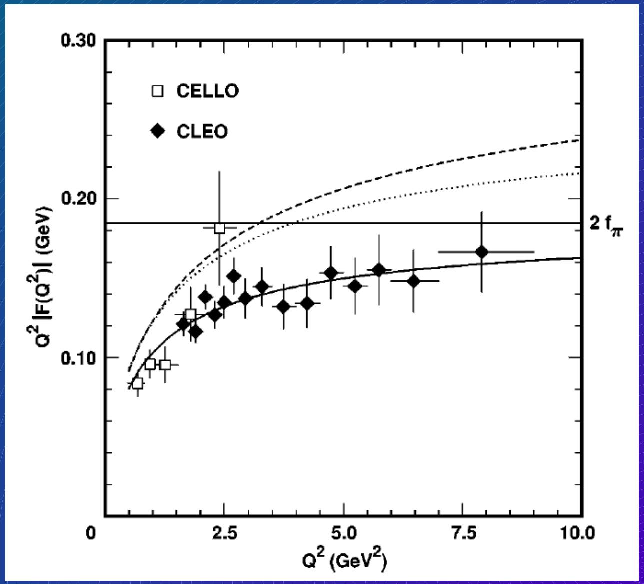
Good sensitivity to the form factor shape.
Systematic uncertainty will be the main issue.

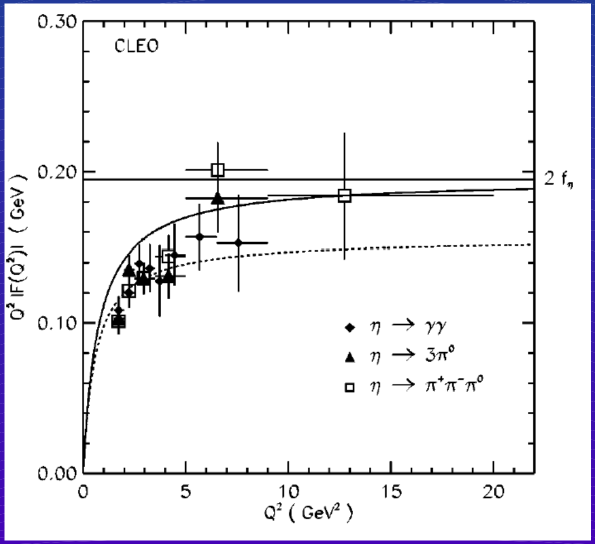


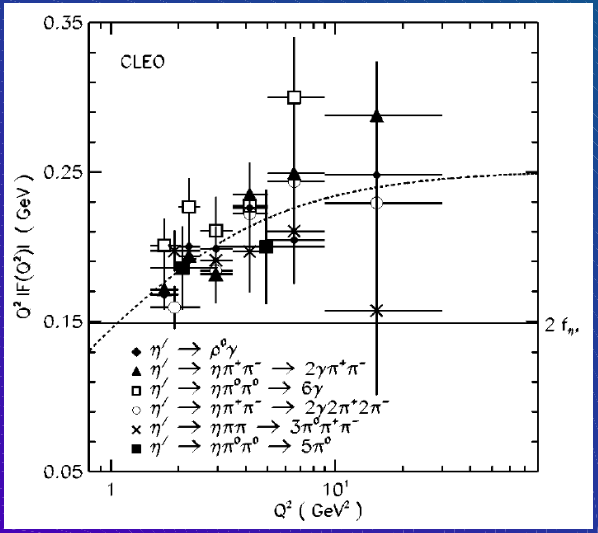


Present data

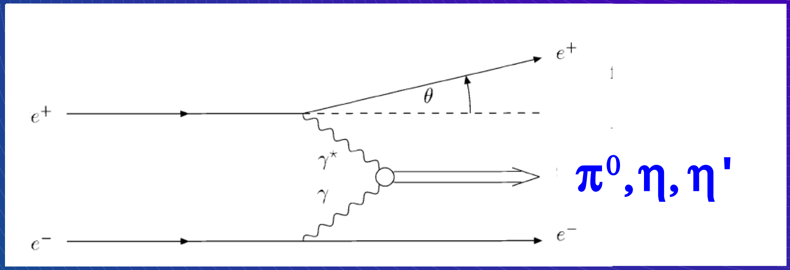
Today data available only for Fγ*γ from CELLO, CLEO, Babar

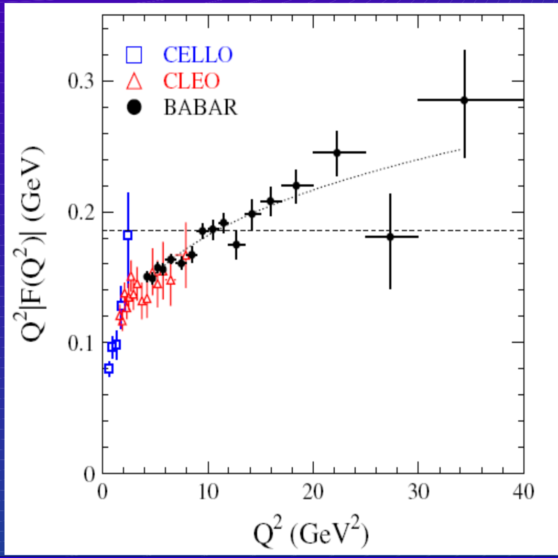






New interesting data from Babar





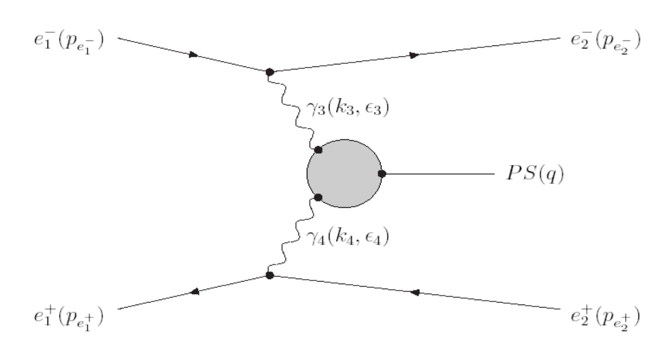
PRD80 (2009) 052002

Is the asymptotic limit more far than expected?

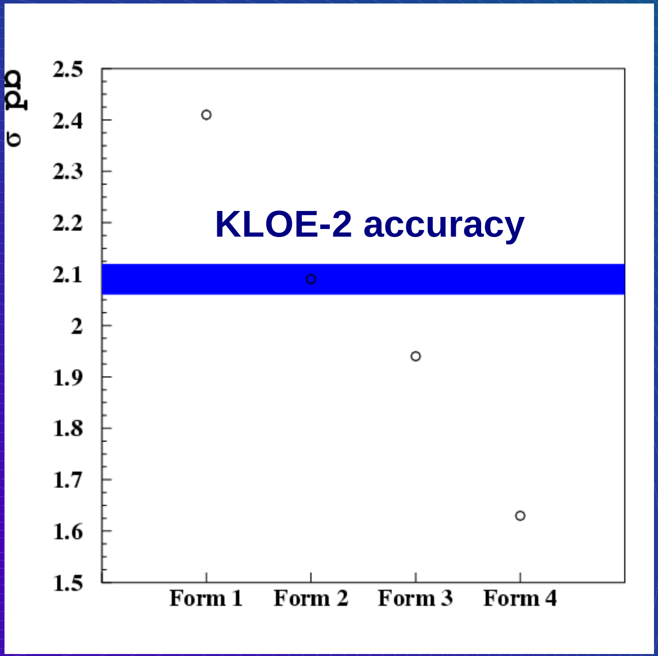
$e^+e^- \to e^+e^-P$ at KLOE 2

Outgoing leptons in the detector.

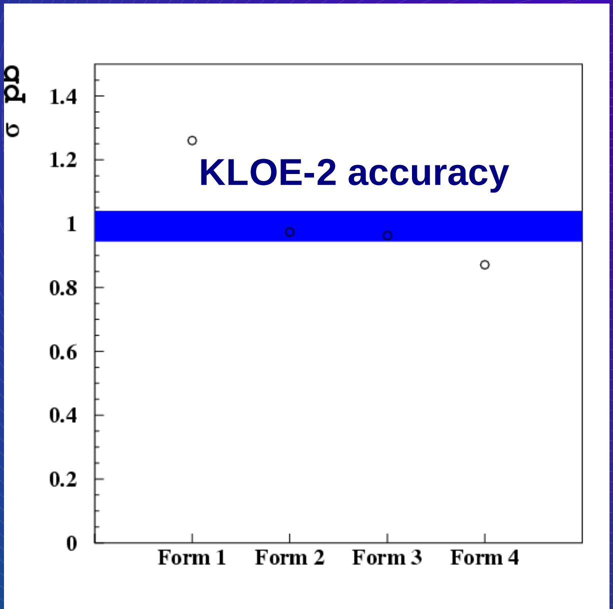
Bijnens Persson, hep-ph/0106130



π^0



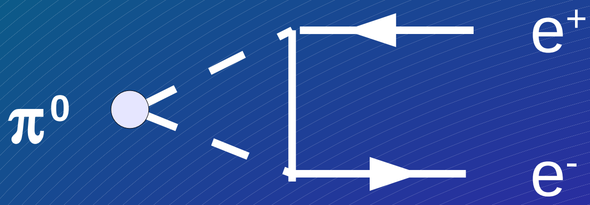
η



- π^0: The 4 form factors are clearly identificable;
- η: KLOE-2 can distinguish form factor 1,4 and 2-3.
- Using tagger we could reach sensitivity to distinguish form factor 2 from 3 (under study).

η' No way without going to higher energies..

A look at the $\pi^0 \to e^+e^-$



$$B = \frac{Br(\pi^0 \to e^+ e^-)}{Br(\pi^0 \to \gamma\gamma)} = 2\beta \left(\frac{\alpha}{\pi} \frac{m_e}{m_{\pi^0}} \right)^2 |R(\pi^0 \to e^+ e^-)|^2$$

$$\Im R(\pi^0 \to e^+ e^-) = \frac{\pi}{2\beta} \ln \frac{1-\beta}{1+\beta}$$

Model independent.
On shell photons

$\Re R(\pi^0 \to e^+ e^-) = 0 \Rightarrow B = B^{min} = B^{unit}$ **Unitarity bound** $B \geq B^{unit} = 4.75 \times 10^{-8}$

Model dependent, loops with large off-shell photons. It depends on the $F_{\pi^0\gamma^*\gamma^*}(q^2_1, q^2_2)$

Using double VMD form factor [1] obtains: $B = (6.41 \pm 0.19) \times 10^{-8}$

B_{exp} (KteV) [2] $= (7.39 \pm 0.29 \pm 0.25) \times 10^{-8}$ it is at 2 σ

From ChPT and $\eta \to \mu^+\mu^-$ [3] gets $(8.3 \pm 0.4) \times 10^{-8}$

@KLOE2 Copious number of η from $\phi \to \eta\gamma$ 2000 $\eta \to \mu^+\mu^-$ expected (allow to make the theoretical prediction more reliable).

[1] Amettler et al. PRD48 (1993) 3388
[2] Abuzaid et al. PRD75 (2007) 012004
[3] D. Gomez et al., PRL80 (4633) 1998

Conclusions

Theorist experimental interactions

what we like

- they provide Monte Carlo generators;
- they provide usable model to fit our data;
- they make clear statements about what can be used to validate their models;

what we like really a lot

- they provide Fortran code with their model to fit :-)

what we don't like

- if their model is ruled out they say it isn't a problem;
- if it is a problem they say that the data are wrong;
- the model goodness depends on the conclusions.

Conclusion & Outlook

- New KLOE data on a_0 together with the old f_0 results nicely agree with the 4 quark hypothesis in the instanton model;

- First upper limit on $\phi \to (f_0 + a_0)\gamma \to K^0 \bar{K}^0 \gamma \to K_S K_S \gamma$, sensitivity near the obsevation threshold;

- Refit of the η' gluonium content confirms the 3σ KLOE claim, the main sensitive measurement has been identified with the $\eta' \to \gamma\gamma$;

- Precise measurement of the $\eta \to \pi^+ \pi^- e^+ e^- (\gamma)$ branching ratio and first measurement of the CP violating asymmetry.

OUTLOOK: see next talk of P. Gauzzi

The C violating $\eta \to \gamma\gamma\gamma$

- Signal topology: $\phi \to \eta\gamma \to 4\gamma$
- Kinematic fit with energy momentum conservation

$$N_{\eta\to 3\gamma} \leqslant 63.1 \quad \text{at 90\% CL,}$$
$$\leqslant 80.8 \quad \text{at 95\% CL.}$$

$$BR(\eta \to \gamma\gamma\gamma) \leqslant 1.6 \times 10^{-5} \quad \text{at 90\% CL}$$
$$\leqslant 2.0 \times 10^{-5} \quad \text{at 95\% CL}$$