Physics with KLOE and KLOE-2 Experiments at DAΦNE

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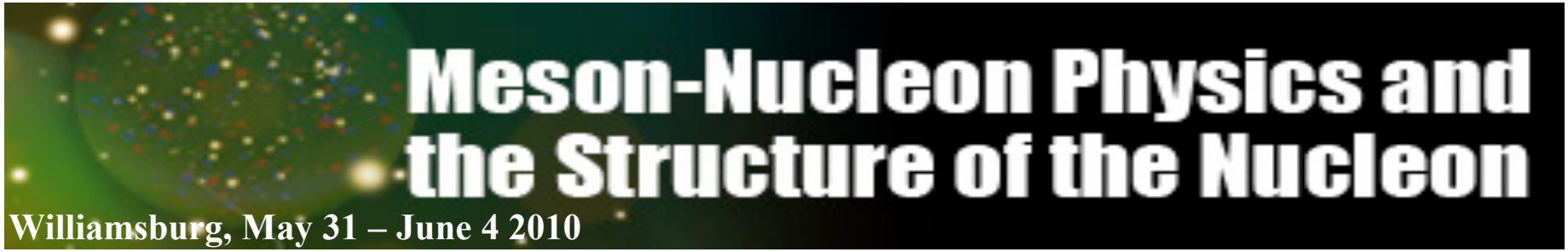
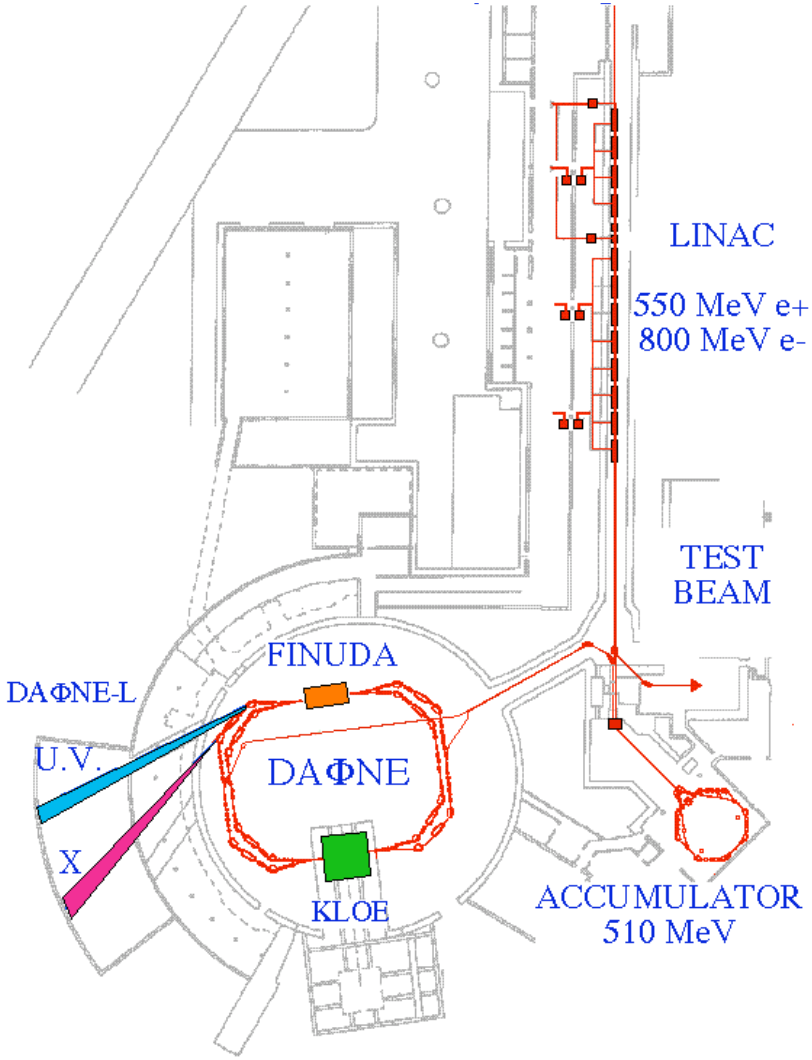
(LNF–INFN)
on behalf of the KLOE and KLOE-2 Collaborations

- **KLOE and DAΦNE upgrades**
- **KLOE results**
- **Perspectives for KLOE-2**



DAΦNE: the Frascati ϕ-factory



- e^+e^- collider @ $\sqrt{s} = M_\phi = 1019.4$ MeV
- 2 interaction regions
- Separate e^+ e^- rings
- 105+105 bunches, 2.7 ns bunch spacing
- $I^-_{peak} \sim 2.4$ A $I^+_{peak} \sim 1.5$ A
- Injection during data taking
- Crossing angle: 2×12.5 mrad

❖ Running period: 1999-2007

❖ Best performances:

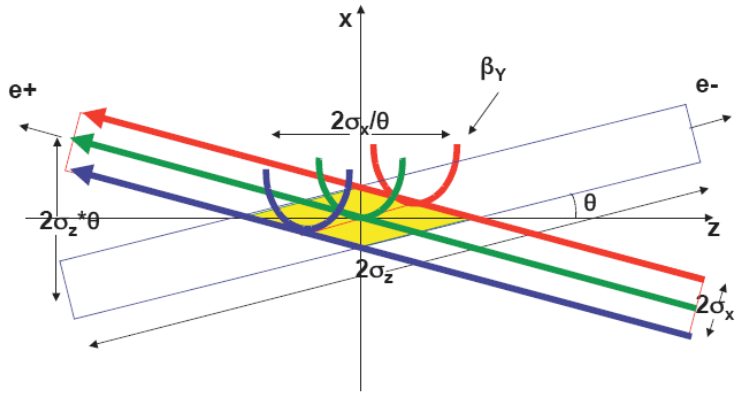
➢ $L_{peak} = 1.4\times10^{32}$ cm^{-2}s^{-1}

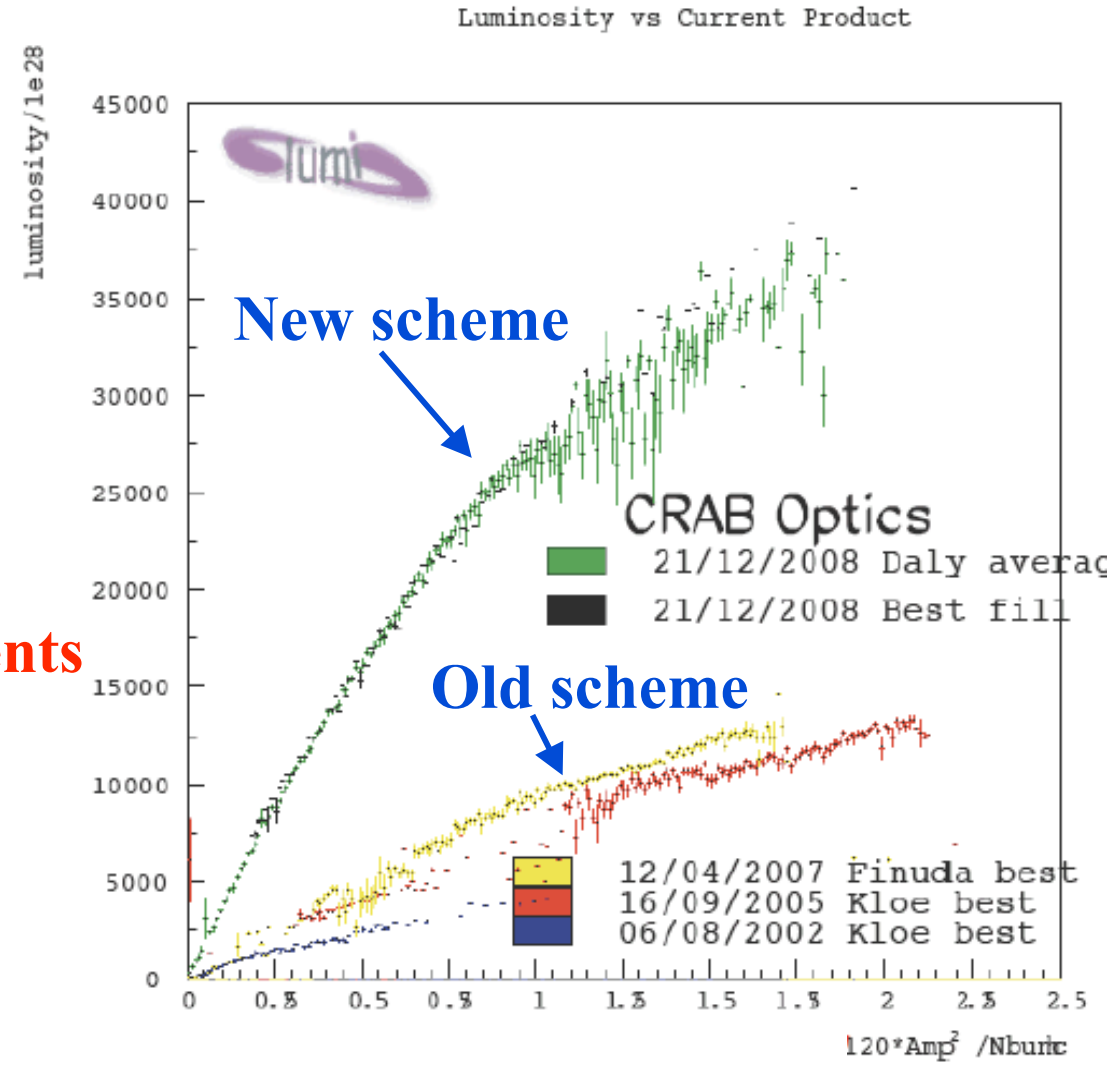
➢ $\int L dt = 8.5$ pb^{-1}/day

DAΦNE upgrade

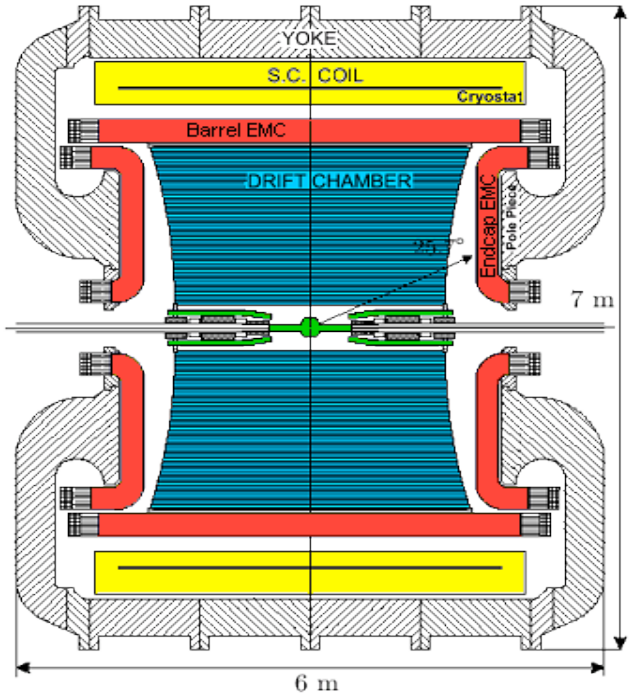
New interaction scheme implemented: large beam crossing angle + sextupoles for crabbed waist optics

- $L_{new} \sim 3 \times L_{old}$
- $\int L dt = 1\ pb^{-1}/hour$
- **Still space for improvements**





The KLOE Experiment @ DAΦNE

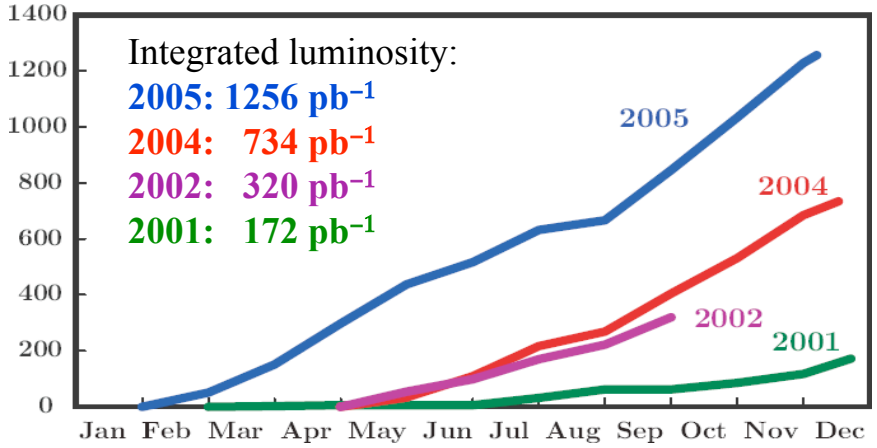


Drift chamber

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

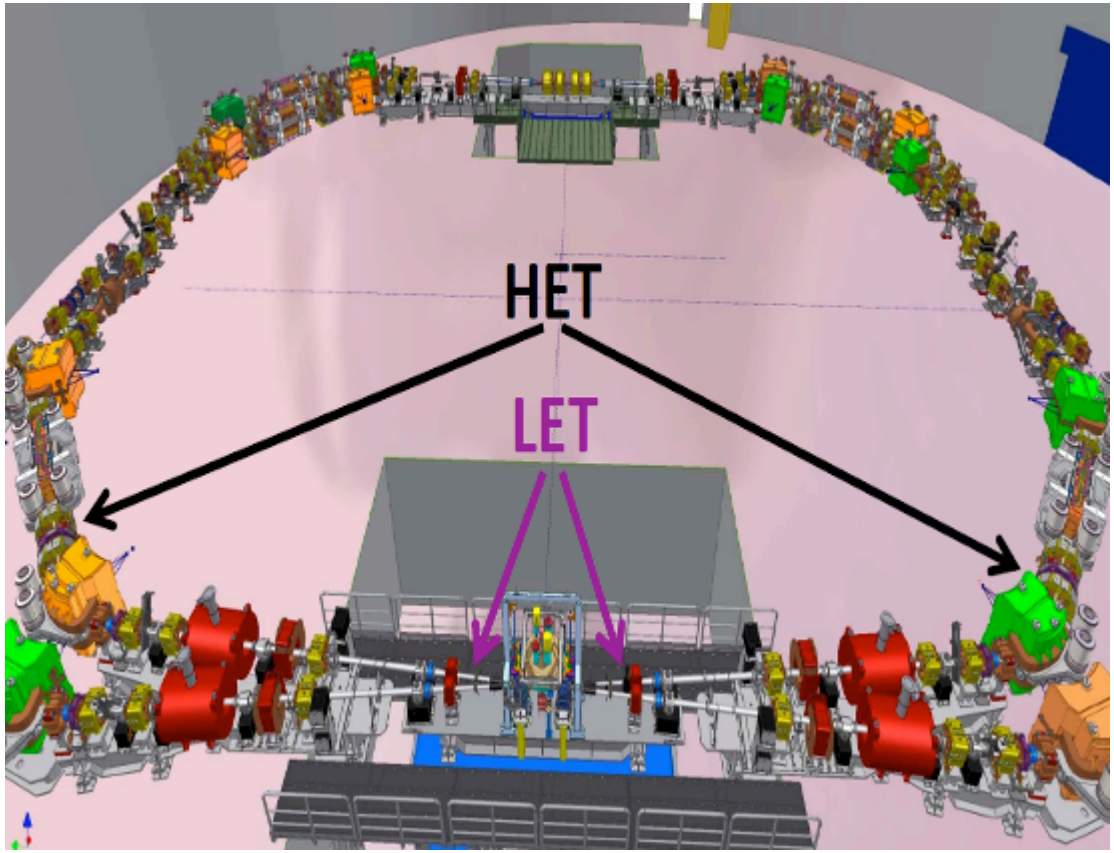


Data taking ended on March 2006

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

From KLOE to KLOE-2: γγ taggers

Minimal detector upgrade for first KLOE-2 run (≈5 fb^{-1} in 1 year): taggers to detect momentum of leptons in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$



INSTALLATION IN PROGRESS

LET: E=160-230 MeV

- **Inside KLOE detector**
- **LYSO+SiPM**
- **σ_E<10% for E>150 MeV**

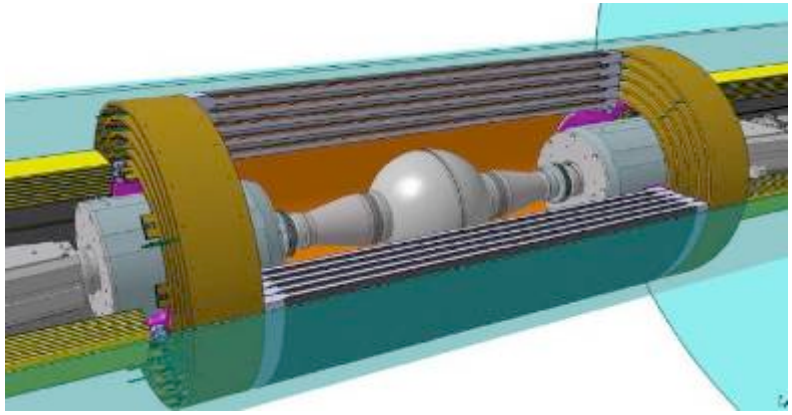
HET: E > 400 MeV

- **11 m from IP**
- **Scintillators + PMTs**
- **σ_E ~ 2.5 MeV**
- **σ_T ~ 200 ps**

From KLOE to KLOE-2: IP detectors

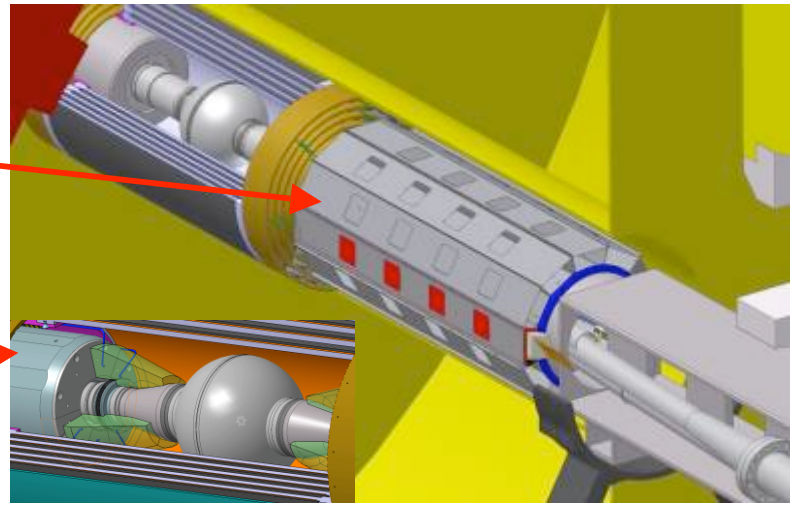
Major detector upgrades (late 2011) for second KLOE-2 run:

INNER TRACKER



- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

QCALT



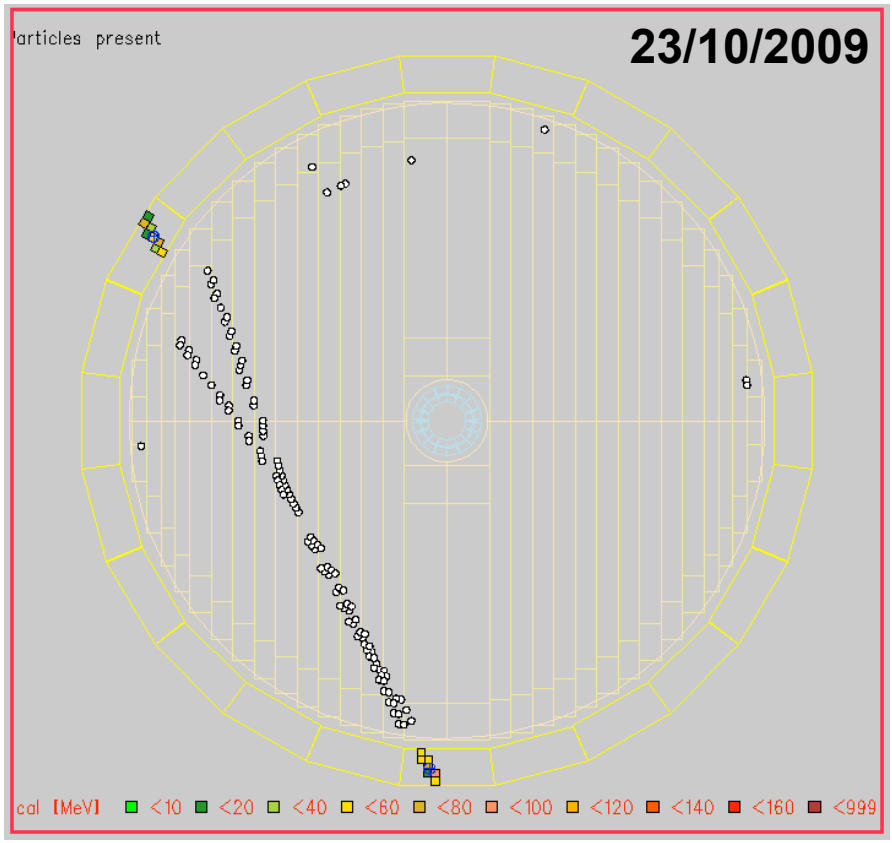
- W + scintillator tiles + SiPM/WLS
- QUADS coverage for K_L decays

CCAL

- LYSO + APD
- Increase acceptance for γ's from IP (21°→10°)

From KLOE to KLOE-2: commissioning

- Roll-in completed on Jan 29th
- EMC/DCH working
- New DAQ, Slow Control,
  Data Storage systems tested
- KLOE cryostat already cool
- Beam pipe insertion in progress



- LET installation, closing of KLOE endcaps, B fields on will follow
- DAΦNE commissioning will start in 2-3 weeks

From KLOE to KLOE-2: commissioning


KLOE-2 interaction region


LET: view from DC plate


HET: Roman pot mounted on DAΦNE

KLOE-2 Physics Program

Goal: **~20 fb^{-1} in the next 3-4 years** to extend the KLOE physics program **at DAΦNE upgraded in luminosity** (approved) **and energy up to 2.4 GeV** (under discussion):

[G.Amelino-Camelia et al., arXiv:1003.3868, to be published on EPJC]

❖ **$\gamma\gamma$ physics**	➢ **Existence (and properties) of $\sigma/f_0(600)$** ➢ **Study of $\Gamma(S/PS \to \gamma\gamma)$** ➢ **PS transition form factor**
❖ **Light meson spectroscopy**	➢ **Properties of scalar/vector mesons** ➢ **Rare η decays** ➢ **η' physics**
❖ **Kaon physics**	➢ **Test of CPT (and QM) in correlated kaon decays** ➢ **Test of CPT in K_S semileptonic decays** ➢ **Test of SM (CKM unitarity, lepton universality)** ➢ **Test of ChPT (K_S decays)**
❖ **Dark matter searches**	➢ **Light bosons @ O(1 GeV)**
❖ **Hadronic cross section**	➢ **$\alpha_{em}(M_Z)$ and (g-2)**

Results on $f_0(980)/a_0(980)$ scalar mesons

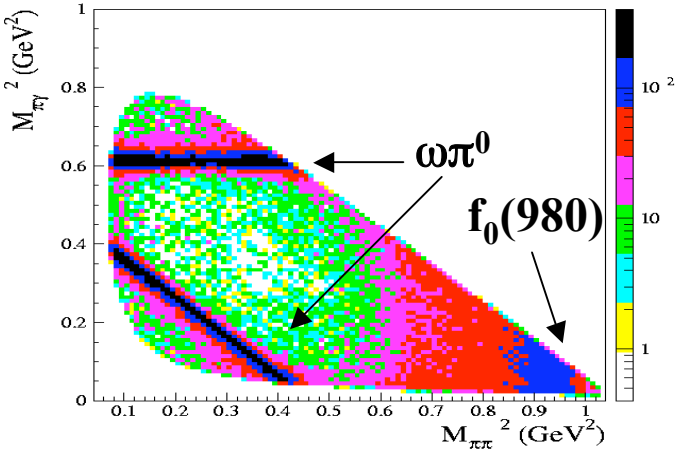
PLB 536 (2002) 209
PLB 537 (2002) 21
PLB 634 (2006) 148
EPJC 49 (2007) 473
NPB (PS) 186 (2009)
PLB 681 (2009) 5

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

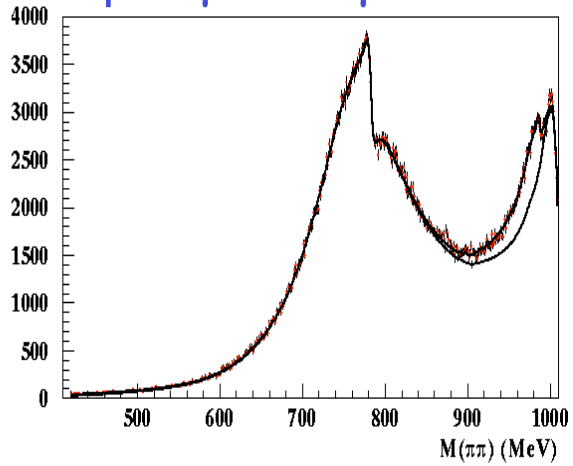
L_{int} = 450 pb^{-1}: mass/Dalitz distributions fitted with Kaon Loop

Irreducible background fitted in the amplitude taking into account interference

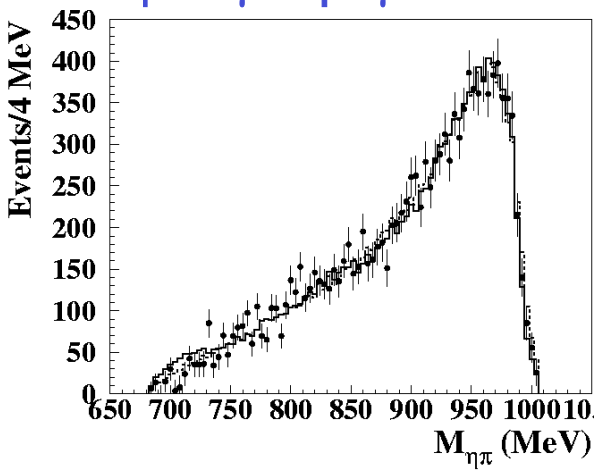
$\phi \to S\gamma \to \pi^0\pi^0\gamma$



$\phi \to S\gamma \to \pi^+\pi^-\gamma$



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



PRELIMINARY

Parameter	$\pi^+\pi^-\gamma$	$\pi^0\pi^0\gamma$	$\eta\pi^0\gamma$
M_S (MeV)	983.7	984.7± 1.9 $_{mod}$	982.5 ± 1.6 ± 1.1
g_{SKK} (GeV)	4.74	3.97 ± 0.43$_{mod}$	2.15 ± 0.06 ± 0.06
g_{SPP} (GeV)	–2.22	–1.82± 0.19 $_{mod}$	2.82 ± 0.03 ± 0.04
g^2_{SKK} / g^2_{SPP}	~4.6	~4.8	~0.6

- $g^2_{f0KK} > g^2_{f0\pi\pi}$
- σ needed in $\pi^0\pi^0\gamma$
- Sizable *s* quark content in $a_0(980)$

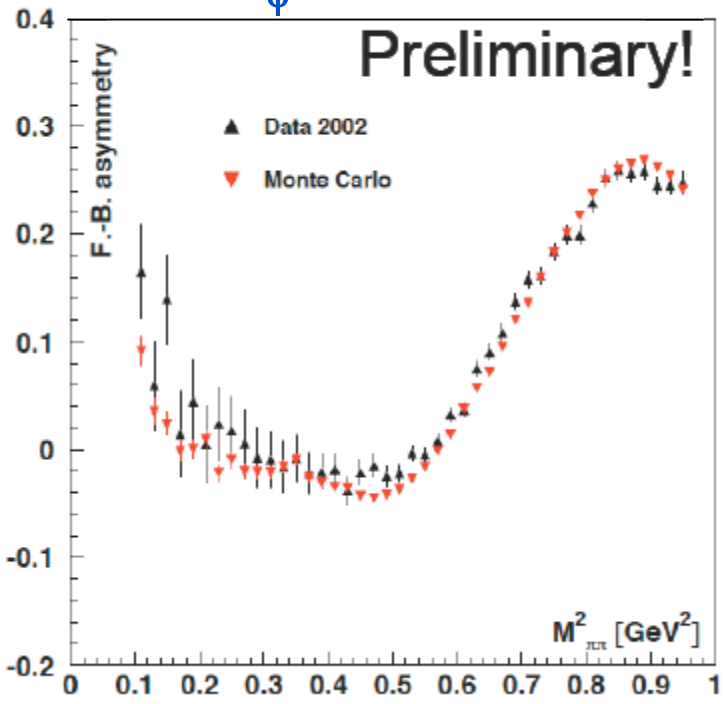
Asymmetry for $e^+e^- \rightarrow \pi^+\pi^-\gamma$ events

PRELIMINARY

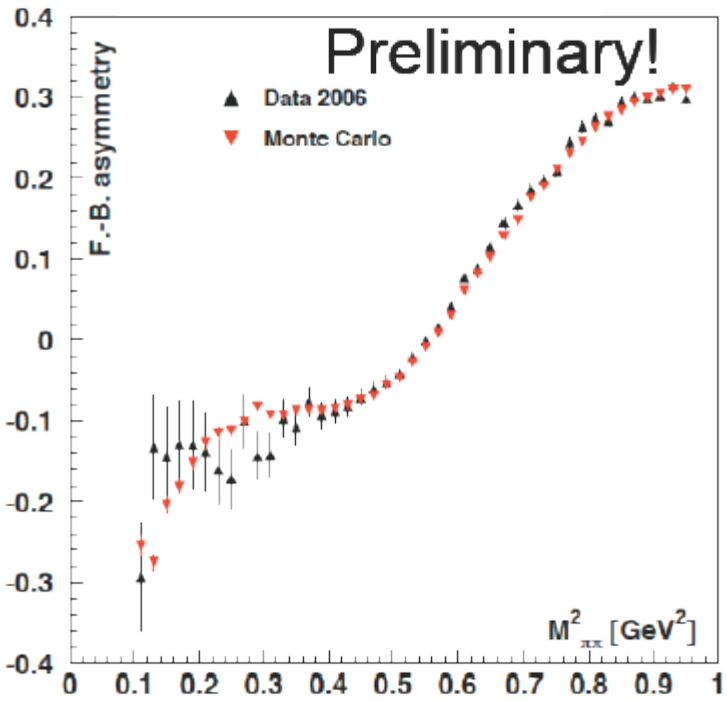
Different C parity of $\pi^+\pi^-$ for ISR and FSR+$\phi \rightarrow S\gamma$ gives rise to a non-vanishing

$$A_{FB}(M_{\pi\pi}) = \frac{N(\vartheta > 90^\circ) - N(\vartheta < 90^\circ)}{N(\vartheta > 90^\circ) + N(\vartheta < 90^\circ)}(M_{\pi\pi})$$

$\sqrt{s} = M_\phi \sim 1.0195$ GeV



$\sqrt{s} \sim 1.000$ GeV



PHOKHARA-MC with scalar+VMD contribution extracted from KLOE $\pi^0\pi^0\gamma$ analysis
[EPJC49(2007)473]

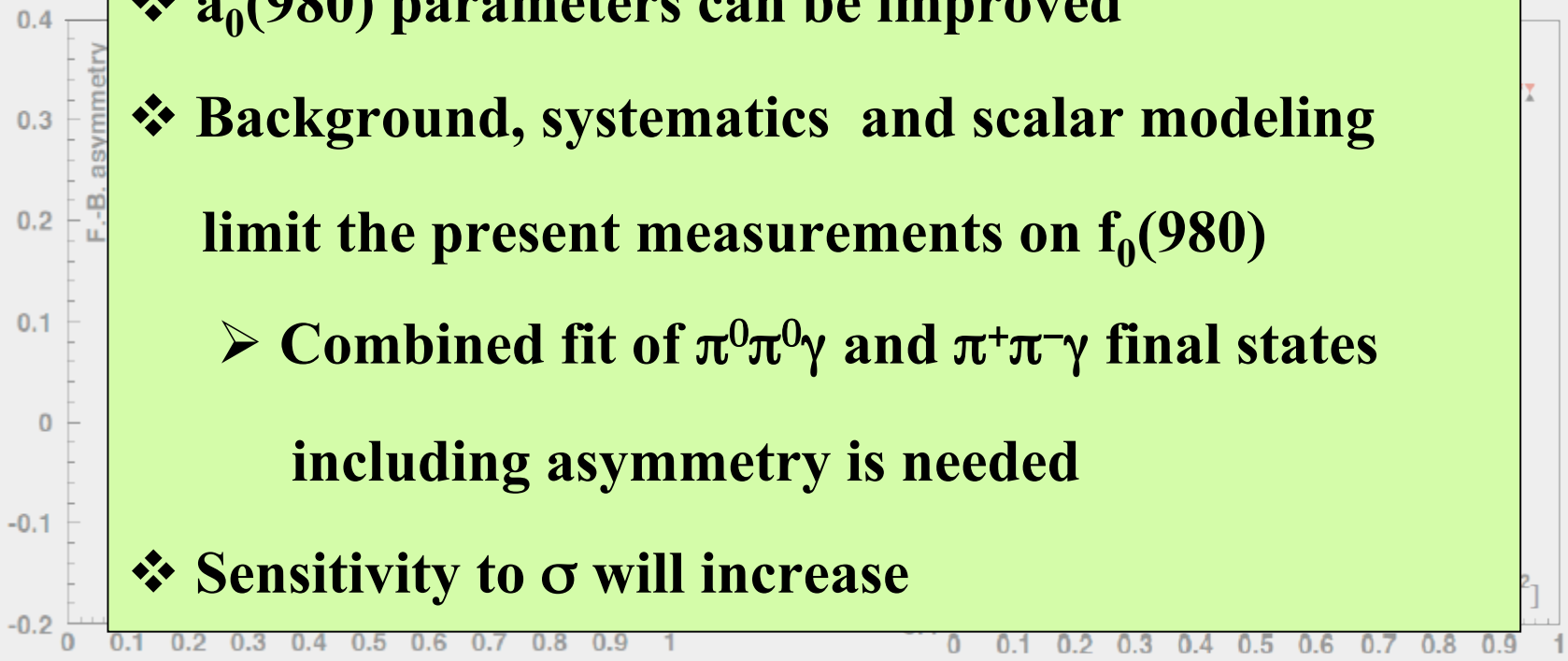
Asymmetry for $e^+e^- \to \pi^+\pi^-\gamma$ events

PRELIMINARY

Different C parity of $\pi^+\pi^-$ for ISR and FSR+$\phi \to S\gamma$ gives rise to a non-vanishing

$\phi \to S\gamma \to PP'\gamma$ @ KLOE-2:

- **$a_0(980)$ parameters can be improved**
- **Background, systematics and scalar modeling limit the present measurements on $f_0(980)$**
  - **Combined fit of $\pi^0\pi^0\gamma$ and $\pi^+\pi^-\gamma$ final states including asymmetry is needed**
- **Sensitivity to σ will increase**



PHOKHARA-MC with scalar+VMD contribution extracted from KLOE $\pi^0\pi^0\gamma$ analysis [EPJC49(2007)473]

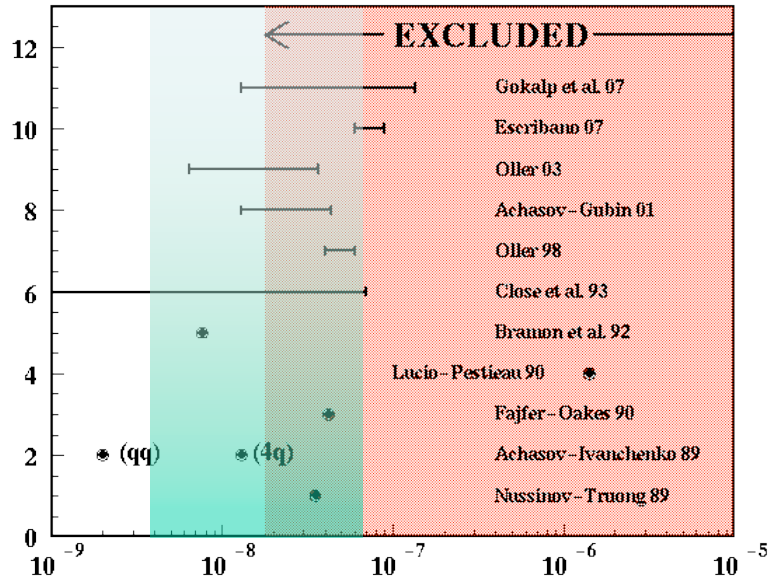
Search for $\phi \to K^0\overline{K}^0\gamma$ events

PLB 679 (2009) 10

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

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

Consistent with KLOE couplings from $\phi \to \pi\pi\gamma$, $\phi \to \eta\pi\gamma$ in the Kaon Loop model, neglecting interference



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

PLB 679 (2009) 10

- Expected to proceed mainly through $\phi \to [f_0(980)+a_0(980)]\gamma \to K^0K^0\gamma$
- Never
- Selec
- Sign
- Selec
- 2.18
  - ➢ 5
  - ➢ 2

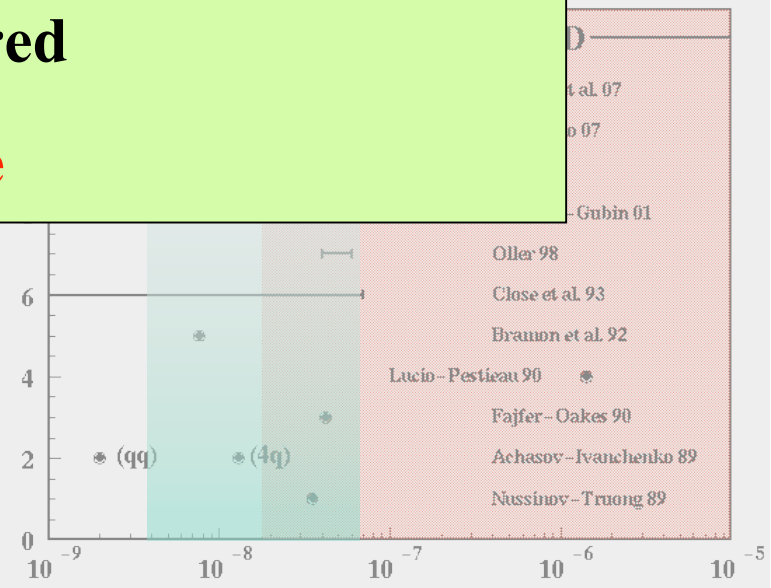
KLOE-2 with O(10 fb^{-1}):

- **Same analysis: BR($\phi \to K_SK_S\gamma$)<1×10^{-8}**
  - ➢ **Other theoretical predictions can be ruled out**
- **Inner tracker: BR($\phi \to K_SK_S\gamma$)<0.5×10^{-8}**
  - ➢ **KLOE allowed region covered**

➔ **First observation possible**

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

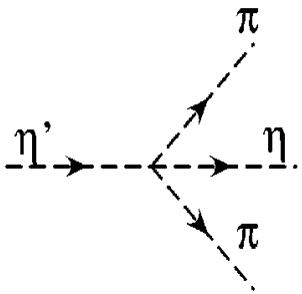
Consistent with KLOE couplings from $\phi\to\pi\pi\gamma$, $\phi\to\eta\pi\gamma$ in the Kaon Loop model, neglecting interference

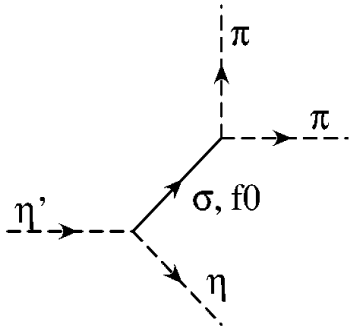


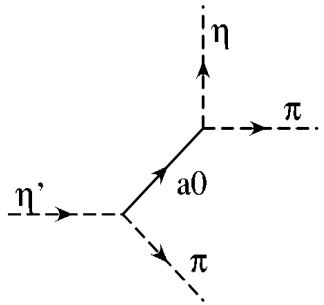
Searching for σ in η′ decays

- Test of ChPT predictions
- η′ nature: possible gluonium content can influence dynamics
- Sensitive to parameters of the intermediate scalar mesons

[Faribortz-Schechter,PRD60(1999)034002]





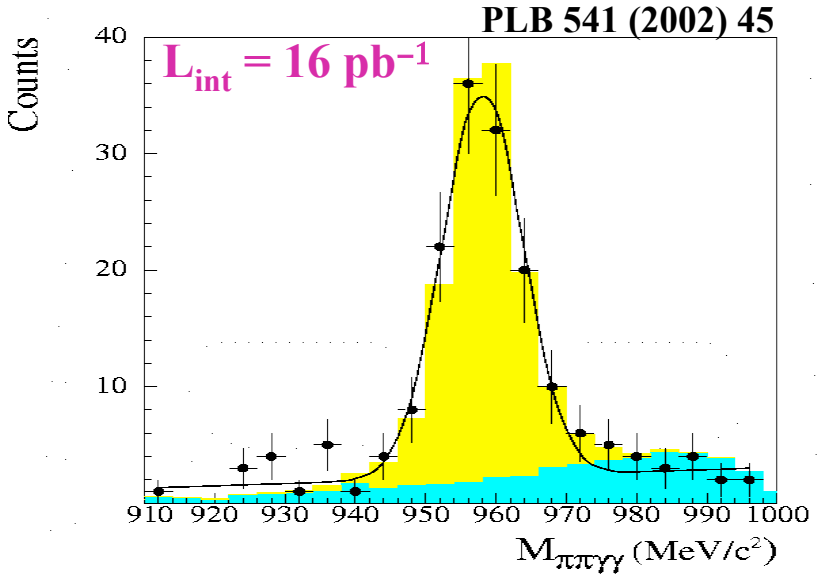


Already studied @ KLOE using η→γγ decay channel with first 16 pb^{-1}

✓ **Small (2%) residual background**

✓ **Analysis efficiency 23%, expected to be flat in the Dalitz plot**

PLB 541 (2002) 45

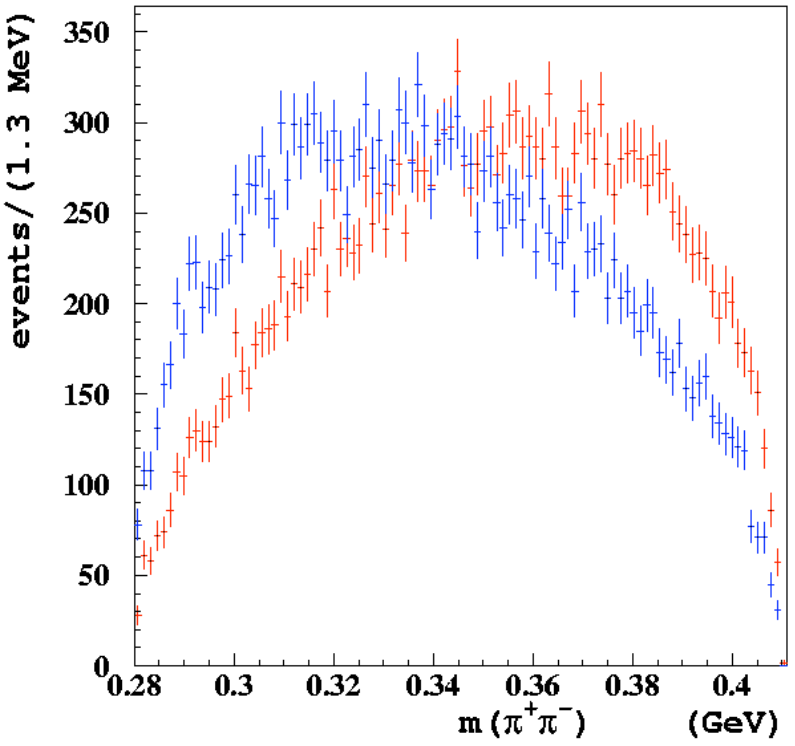


Searching for σ in η′ decays

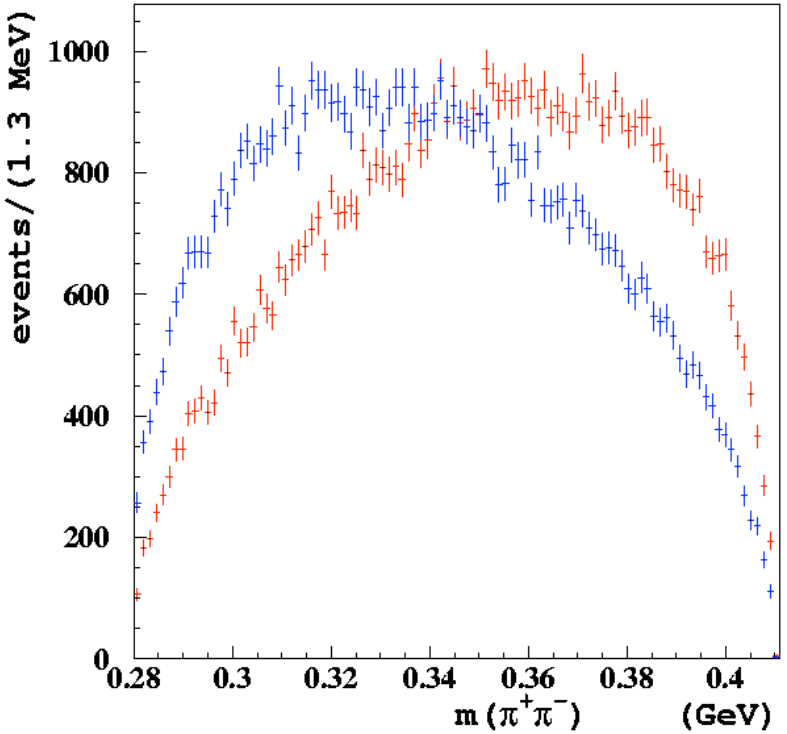
Expected $M_{\pi\pi}$ shape using Faribortz-Schechter model, including analysis efficiency (flat in $M_{\pi\pi}$). Reconstruction effects not included

Blue: without σ(600) **Red: σ(600) included**

KLOE

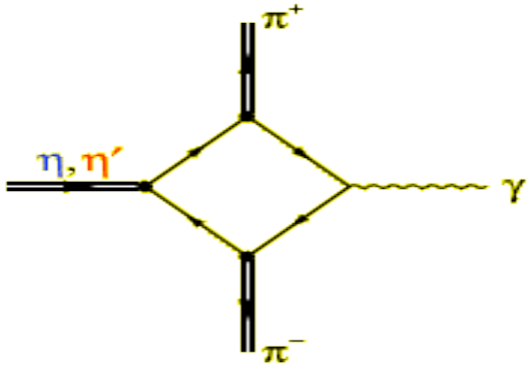


KLOE-2



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

- ✓ Significant contribution from the box anomaly expected. Study of the two pion system allows for test of ChPT and its unitarized extensions (e.g. VMD or chiral unitarity approach) → **$M_{\pi\pi}$ shape needed**



- ✓ Existing data, low in statistics and not acceptance corrected, not sufficient for unambiguous theoretical interpretation

- ✓ Latest result from CLEO on $\Gamma(\eta\to\pi\pi\gamma)/\Gamma(\eta\to\pi\pi\pi)$ differs >3σ's from old measurements

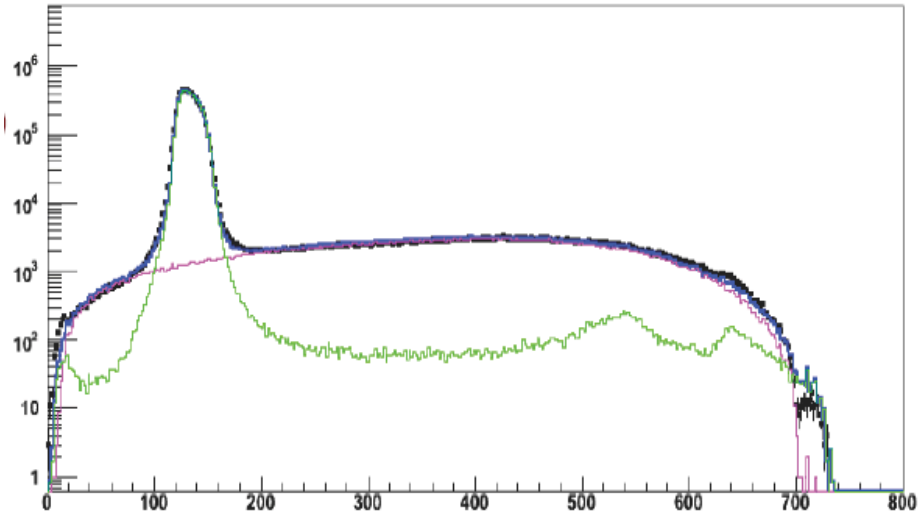
$\Gamma(\eta\to\pi^+\pi^-\gamma) / \Gamma(\eta\to\pi^+\pi^-\pi^0)$

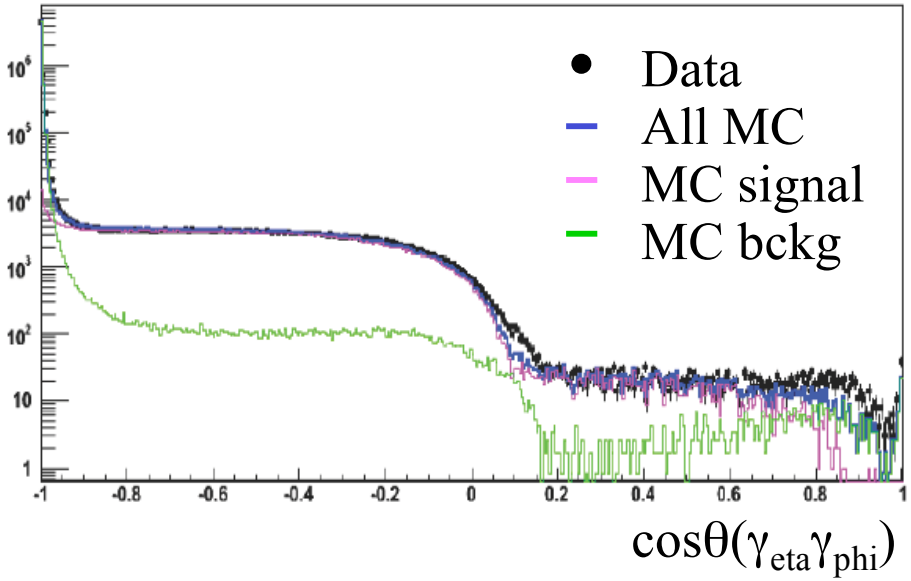
value	events	author	year
0.203 ± 0.008	PDG average		
0.175 ± 0.007 ± 0.006	859	Lopez	2007
0.209 ± 0.004	18 k	Thaler	1973
0.201 ± 0.006	7250	Gormley	1970

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

- DATA SAMPLE: **1.2 fb^{-1}**
- Kinematical cuts to remove all bckg but $\phi\to\pi^+\pi^-\pi^0$:

  ε = 29%, BKG/SIG=10:1
- Different topology in $\gamma\gamma$ distributions for signal and background
- Simultaneous fit to both spectra to extract signal





$\eta\to\pi^+\pi^-\pi^0$ selected with high efficiency (40%) and BKG/SIG=0.5%

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

PRELIMINARY

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

- **Preliminary result agrees with PDG average, confirming old results from 70s**
- We are evaluating systematics, aiming to reach ~ 1%
- Plan to use full KLOE data set to investigate the $\pi^+\pi^-$ invariant mass distribution: cuts on $M\gamma\gamma$ and $\cos\theta(\gamma\gamma)$ in the π^0 rest frame allow to reduce the background contribution to 2% with a signal efficiency of ~25%

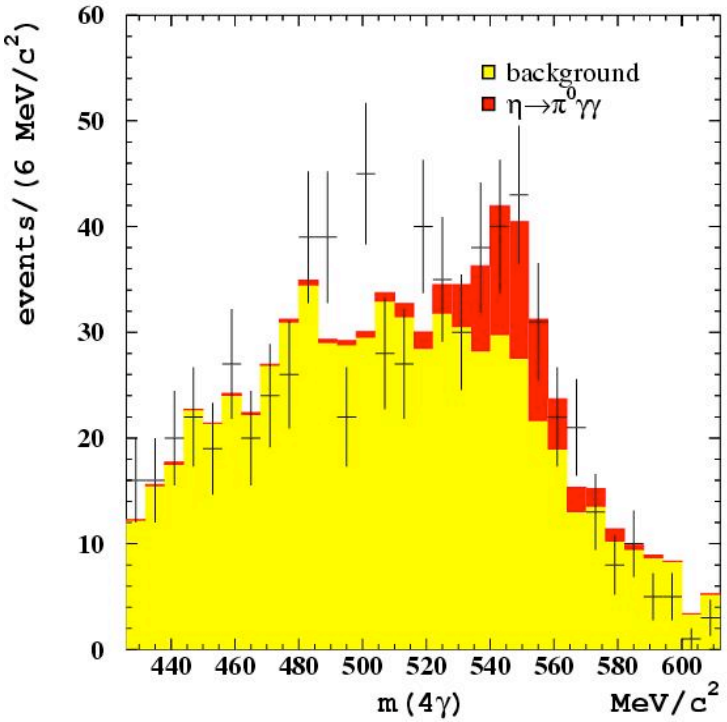
Box anomaly can be studied also for $\eta' \to \pi^+\pi^-\gamma$ with the first KLOE-2 run: ≈ 120,000 events expected

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

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

KLOE Preliminary, 2006: 3σ signal (only 1/5 of full statistics)

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



$N_{DATA} = 735$

$N_{bkg} = 667 \pm 36$

$N_{sig} = 68 \pm 23$

$N(\eta \to 3\pi^0) = 2{,}288{,}882$

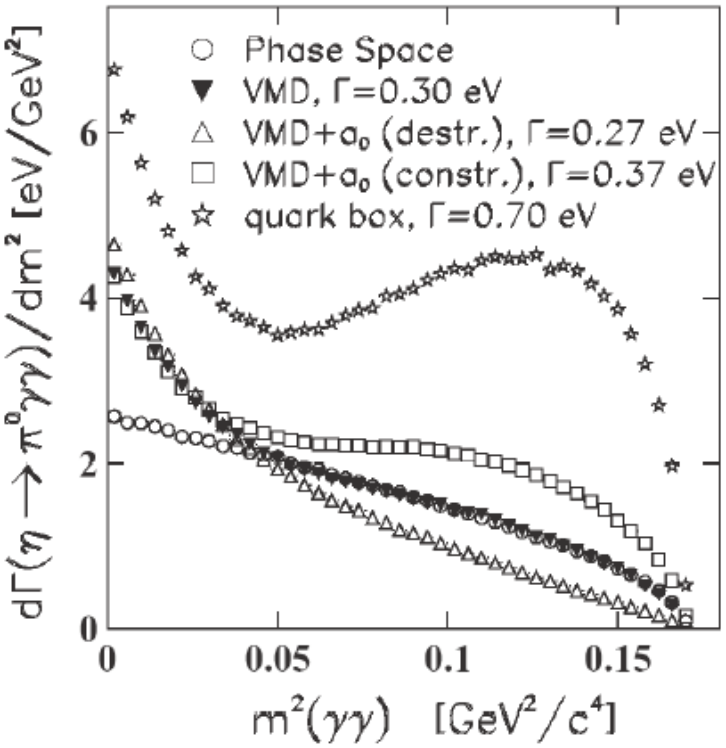
CB@AGS: **BR = (22.1 ± 2.4 ± 4.7) × 10^{-5}**
PRC 78 (2008) 015206 ~ 500 signal events

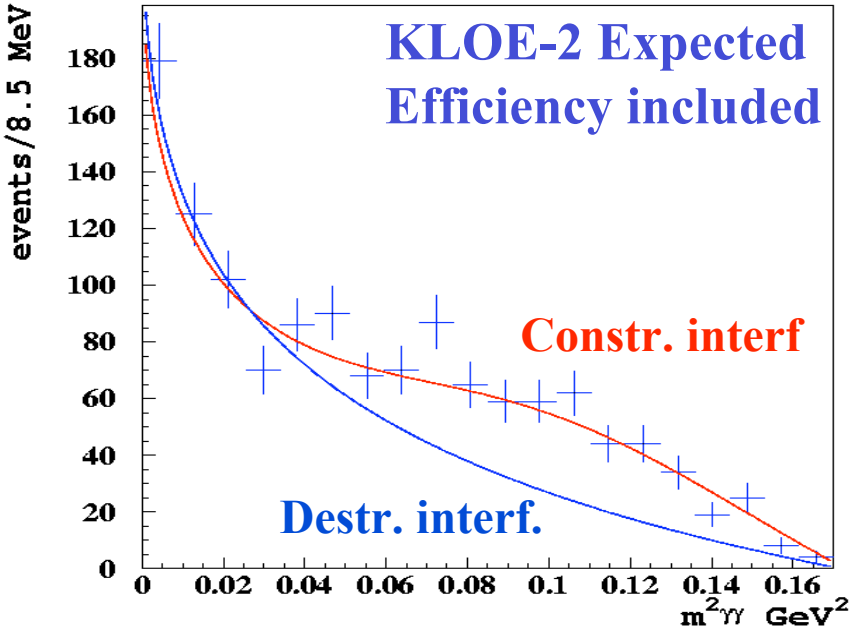
CB@MAMI-B: BR = (22.5 ± 4.6 ± 1.7) × 10^{-5}
Preliminary, arXiv:0910.1331 ~ 150 signal events

The $\eta \to \pi^0\gamma\gamma$ decay @ KLOE-2

BR with 3% accuracy with 10 fb^{-1}

$M_{\gamma\gamma}$ distribution will have enough statistics to distinguish among different theoretical models





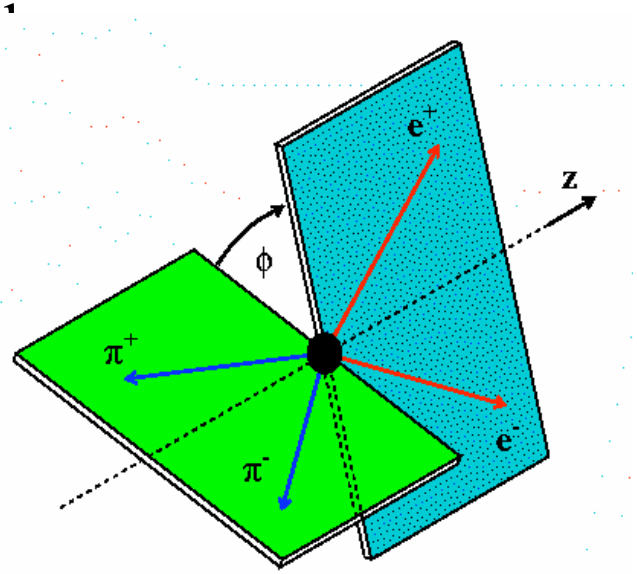
Theory: VMD+a_0(980) model
[J.N.Ng, D.J.Peters, PRD46 (1992) 5034]

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

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

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

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

PLB 675 (2009) 283

Data sample: 1.73 fb^{-1}

PID with ToF EMC info

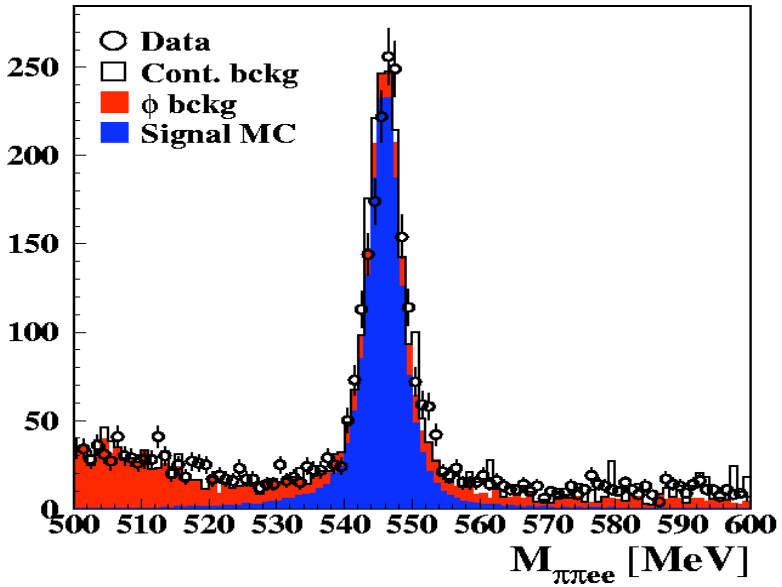
Fit on $M_{\pi\pi ee}$ side bands for background

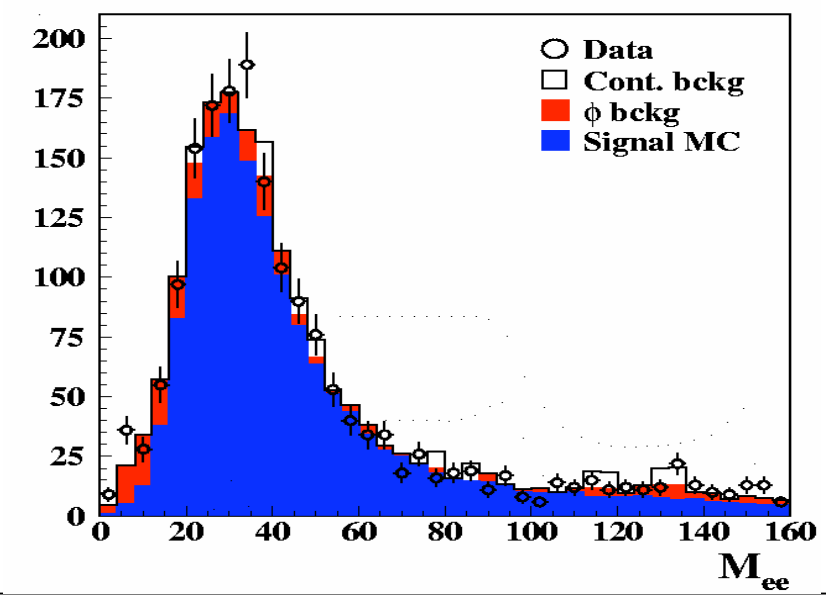
Photon conversion on Beam Pipe rejected

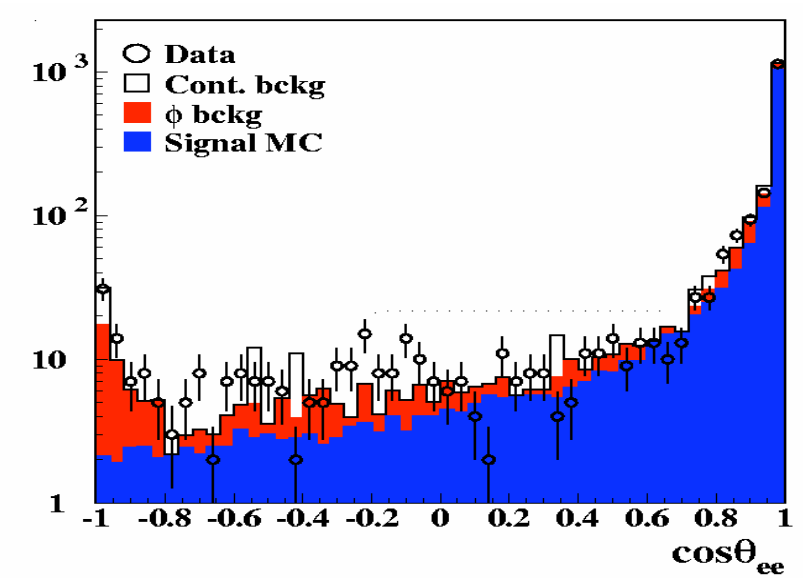
Counting on $M_{\pi\pi ee}$ in the signal region:

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

Analysis efficiency: 8%



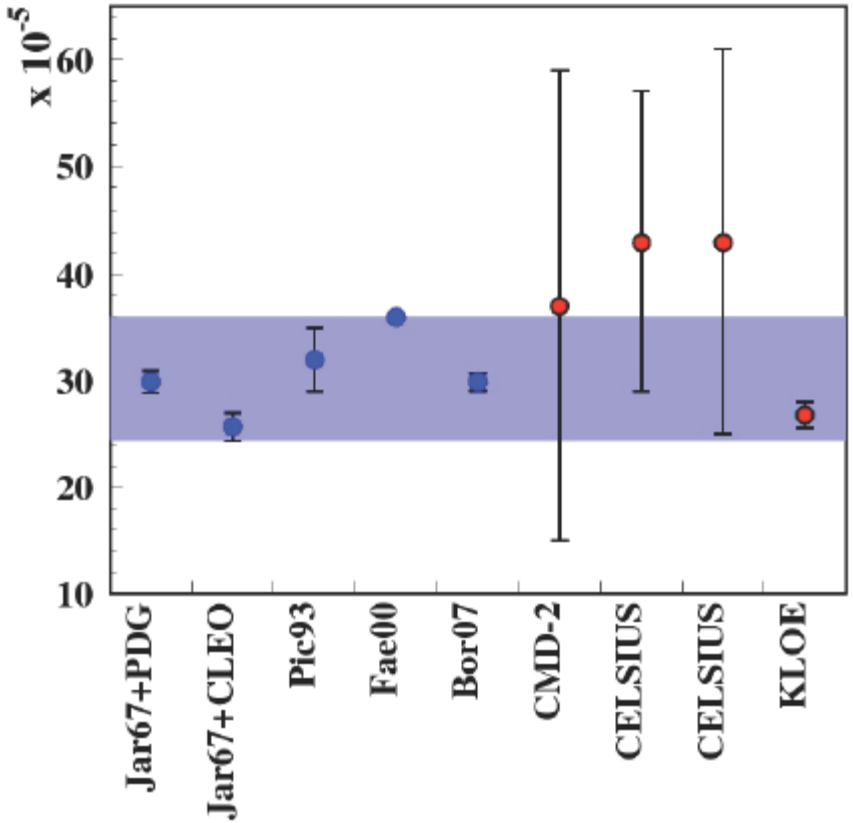


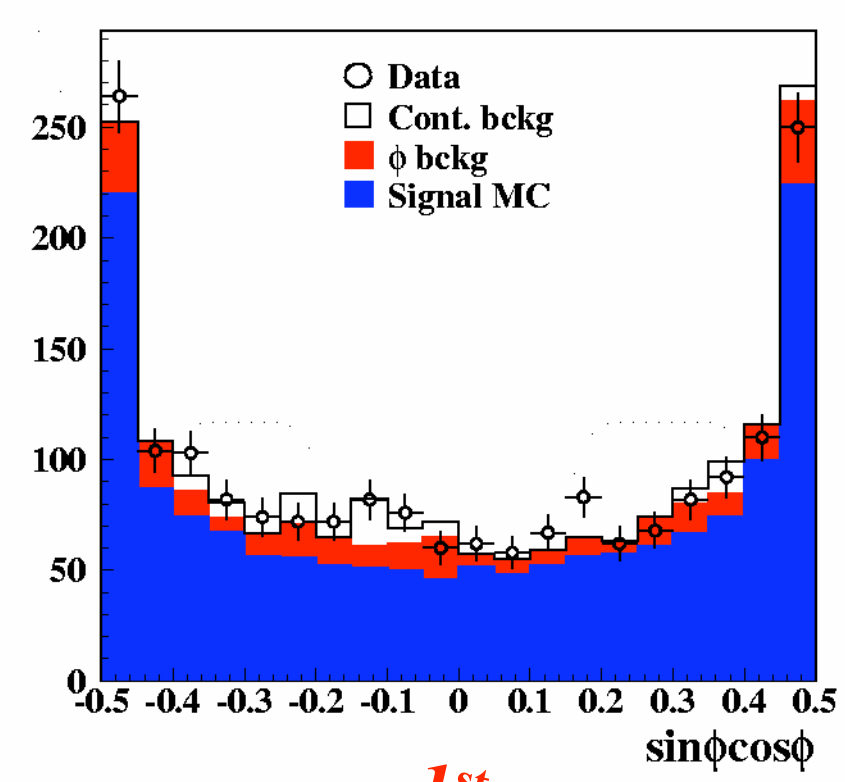


$\eta \to \pi^+\pi^- e^+ e^-$: results

PLB 675 (2009) 283

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





1st measurement!

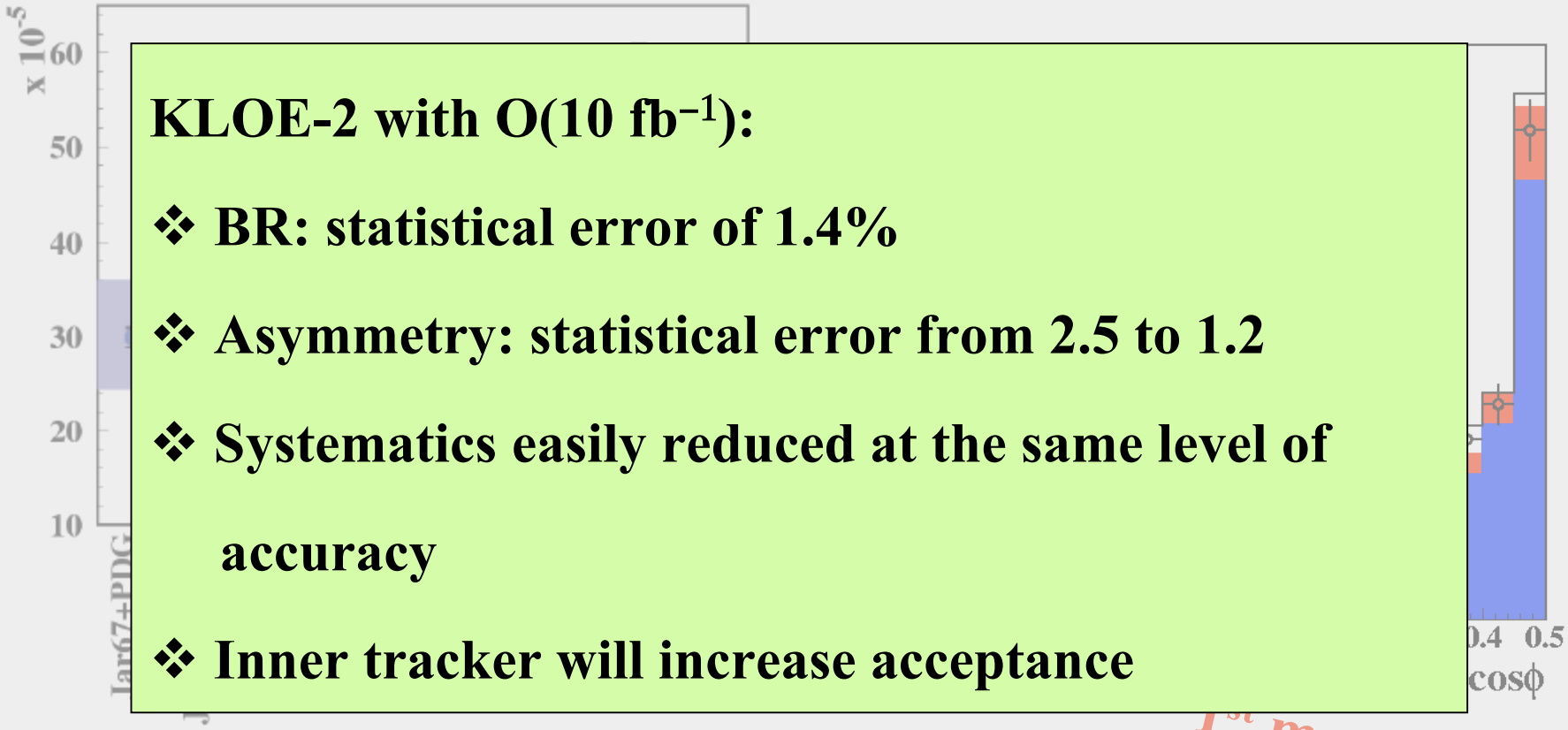
$$A_\phi = \frac{N_{\sin\phi\cos\phi} - N_{\sin\phi\cos\phi}}{N_{\sin\phi\cos\phi} + N_{\sin\phi\cos\phi}}$$

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

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

PLB 675 (2009) 283

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



KLOE-2 with O(10 fb^{-1}):

- **BR: statistical error of 1.4%**
- **Asymmetry: statistical error from 2.5 to 1.2**
- **Systematics easily reduced at the same level of accuracy**
- **Inner tracker will increase acceptance**

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

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

1st measurement!

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

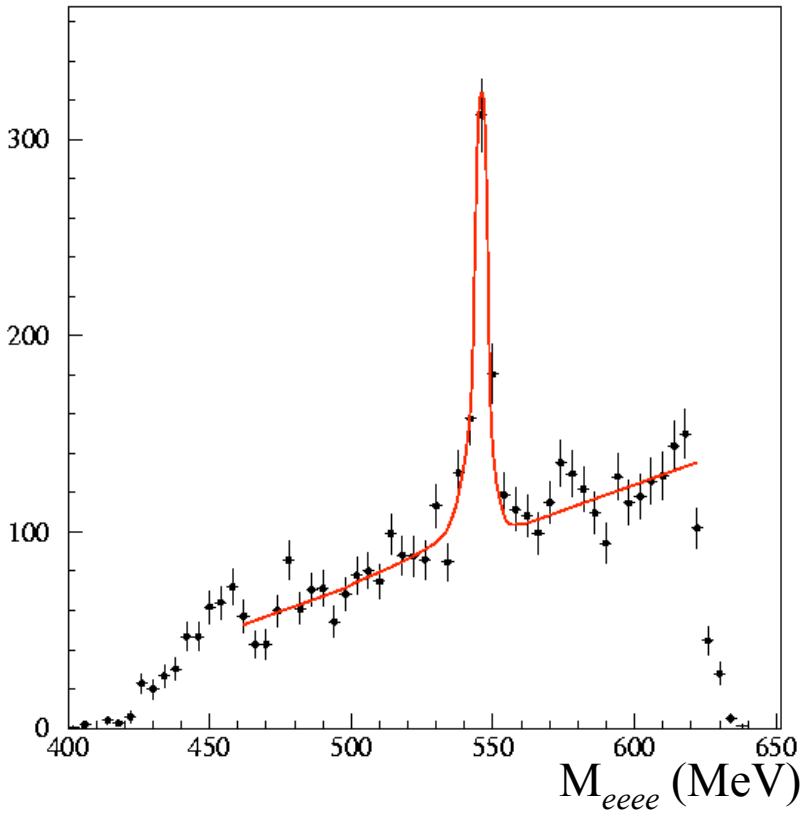
FIRST OBSERVATION!

- Data sample: **1.7 fb^{-1}**
- MC simulation according to J.Bijnens and F. Persson, arXiv:0106130

(courtesy of J.Bijnens)

- FSR included
- e^+e^- pairs from photon conversion on Beam Pipe and Drift Chamber wall rejected
- Remaining background from ϕ decays subtracted
- Fit to M_{eeee} distribution with MC signal + continuum background shapes yields:

$$N_{eeee} = 413 \pm 31$$



η/η′ mixing: gluonium content in η′ PLB 648 (2007) 267

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

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)]

$\varphi_P = (39.7 \pm 0.7)°$

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

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

η/η′ mixing: gluonium content in η′ JHEP07 (2009) 105

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

Other SU(3) relations need to be included :

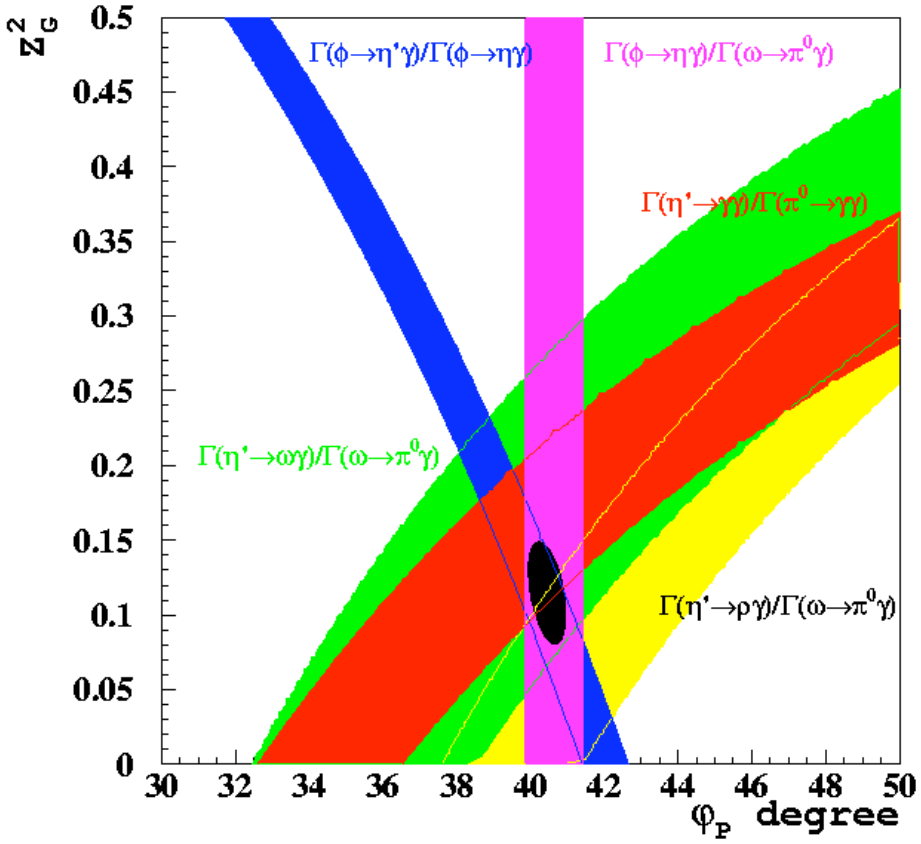
$$\frac{\Gamma(\omega\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(\rho\to\pi^0\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(\phi\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(\phi\to\pi^0\gamma)}{\Gamma(\omega\to\pi^0\gamma)},\quad \frac{\Gamma(K^{*+}\to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

Parameter	Old fit	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 ± 0.7)°	(40.7 ± 0.7)°	(41.6 ± 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 ± 0.10)°	(3.16 ± 0.10)°
m_s/m	1.24 ± 0.07	1.24 ± 0.07	1.24 ± 0.07
$P(\chi^2)$	49%	17%	40.7%

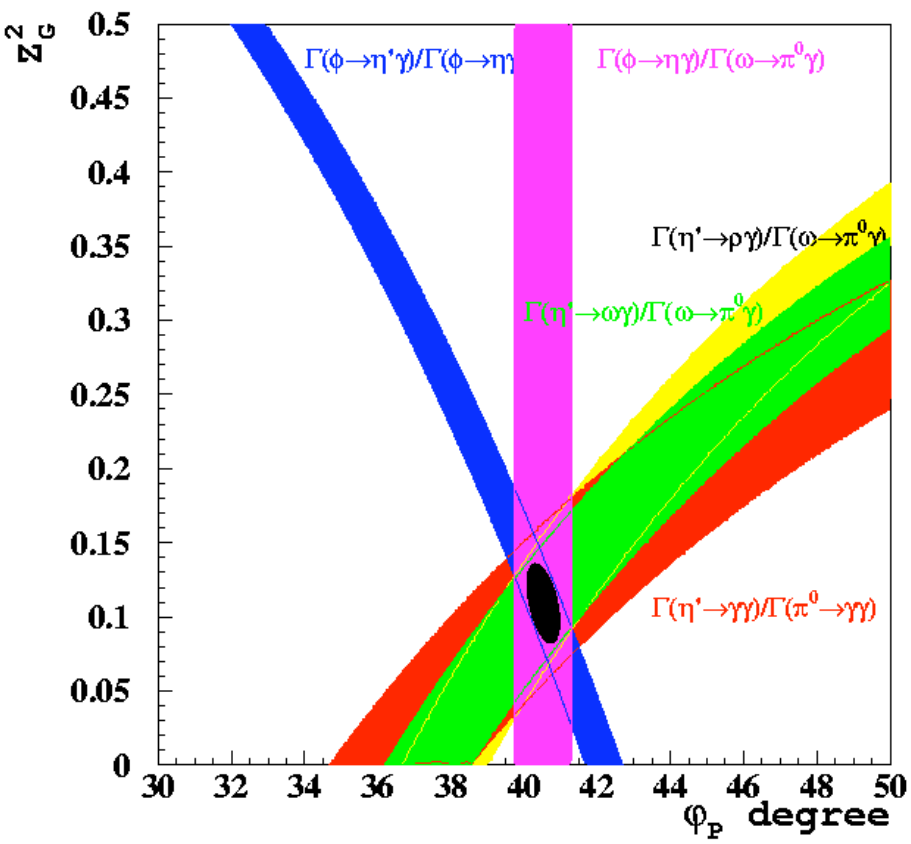
- **Gluonium content @ ~3σ level confirmed**
- **Forcing $Z_{\eta'}$=0 : ϕ_P = (41.6±0.5)° with P(χ^2)=1%**
- **Discrepancy with Escribano-Nadal** ($Z_{\eta'}$= 0.04 ± 0.09 , ϕ_P = (41.4±1.3)°) [JHEP05(2007)006] **due to the inclusion of Pγγ transitions**

η/η′ mixing: from KLOE to KLOE-2

KLOE: global fit result



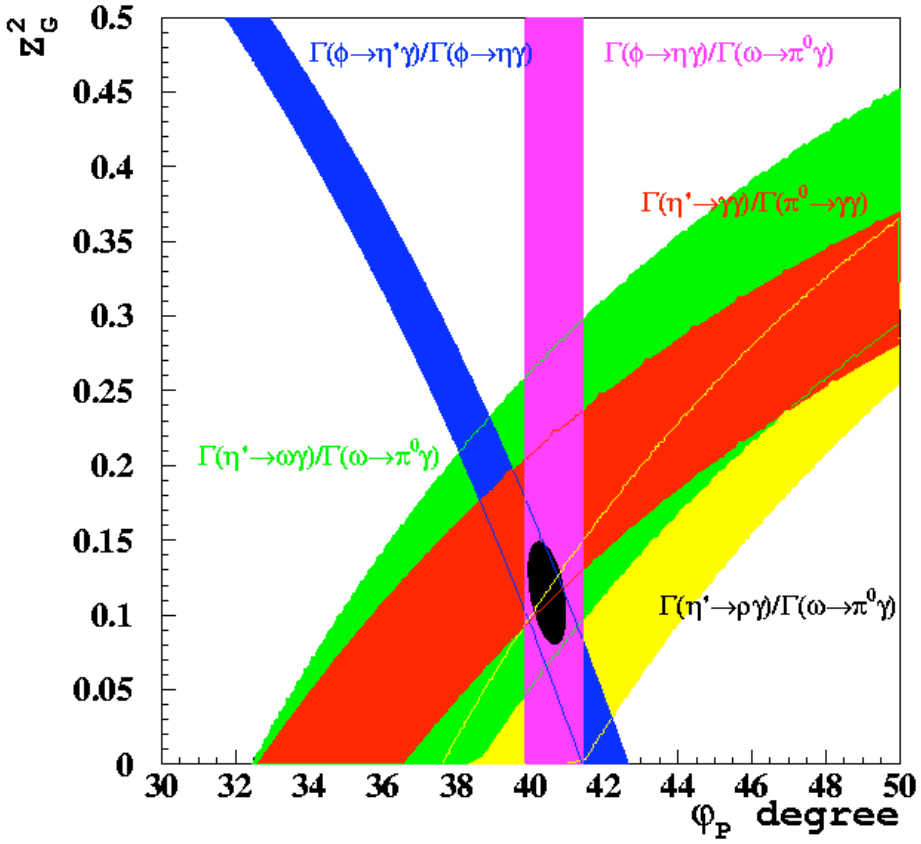
KLOE-2 expectation measuring η′ BRs with 1% accuracy



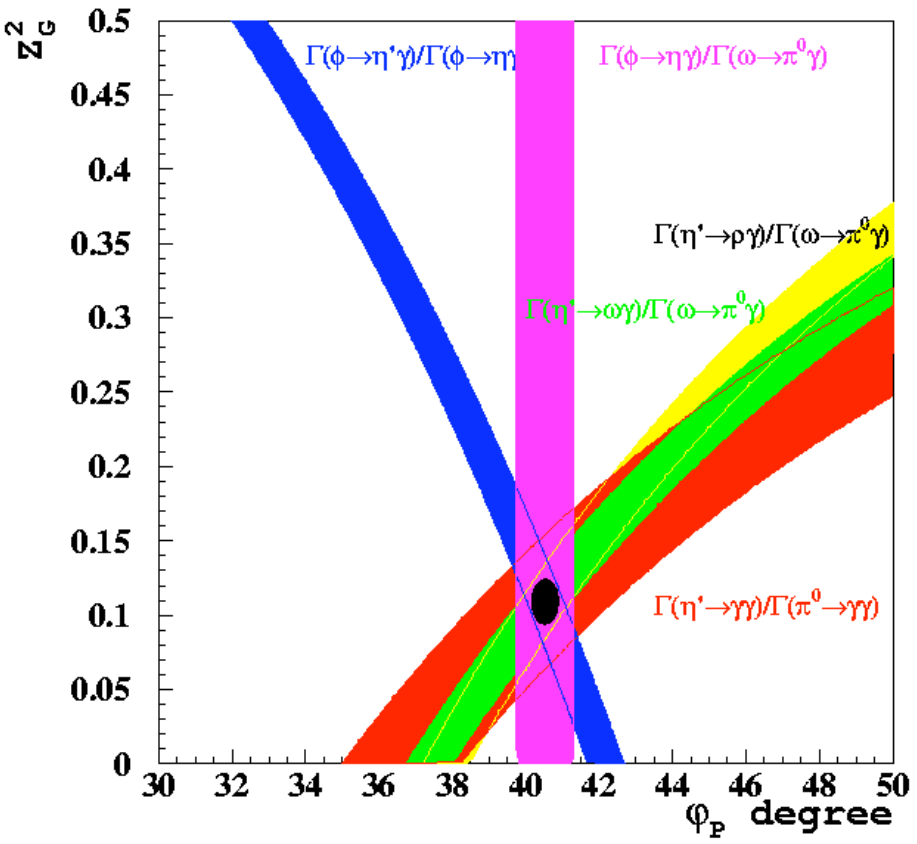
Sensitivity to the gluonium also without the η′→γγ decay

η/η′ mixing: from KLOE to KLOE-2

KLOE: global fit result

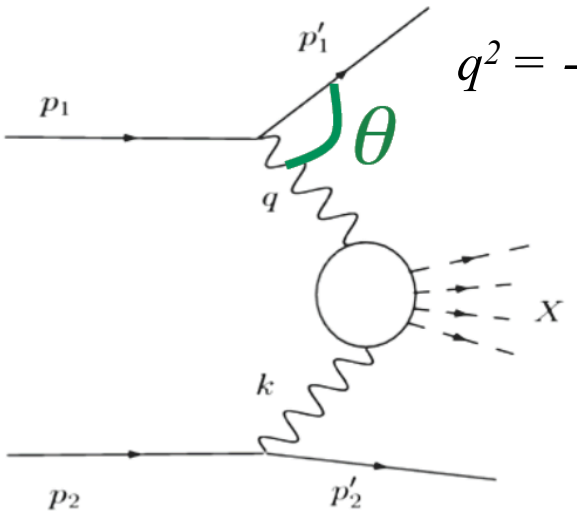


KLOE-2 expectation measuring also η′ width with 1.4% accuracy



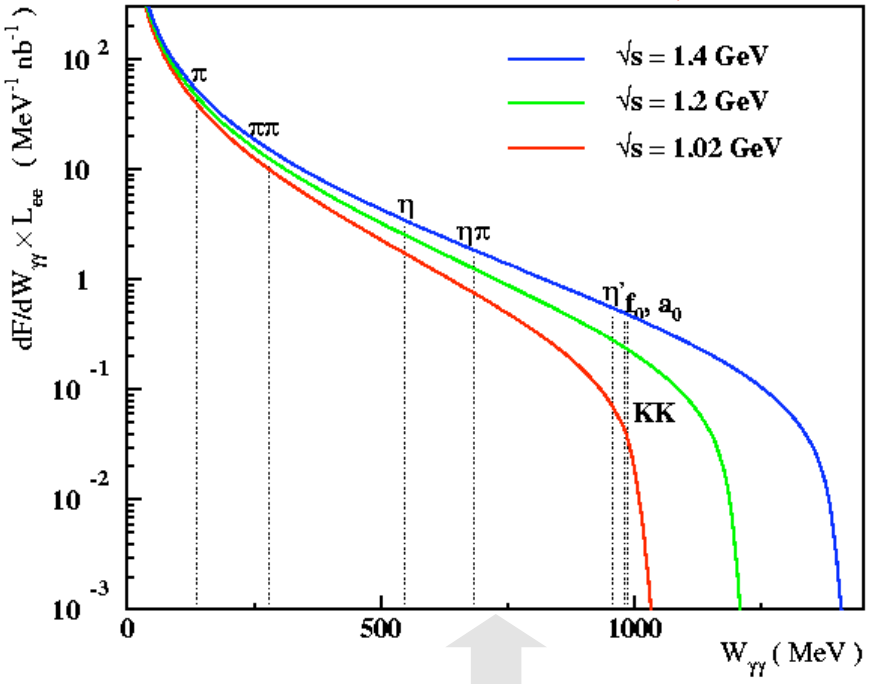
Run at $\sqrt{s} \geq 1.2$ GeV required

γγ physics: the $e^+e^- \rightarrow e^+e^-X$ process



$$q^2 = -2EE'(1-\cos\theta)$$

Weizsäcker-Williams approx, $|q_\gamma^2| \ll W^2$



Tagger is essential to reduce bckg from ϕ and to close kinematics

$$N_{e^+e^- \rightarrow e^+e^- X} = L_{ee} \int \frac{dF_{\gamma\gamma}}{dW_{\gamma\gamma}} \sigma_{\gamma\gamma \rightarrow X}(W_{\gamma\gamma})\, dW_{\gamma\gamma}$$

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

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

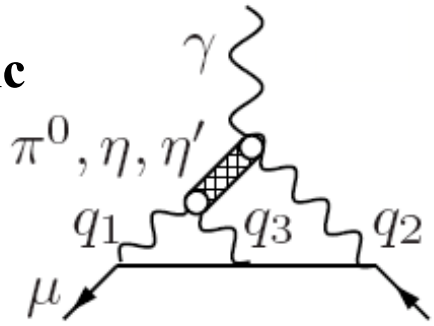
$L_{int} = 1$ fb^{-1}

$\sqrt{s}$ (GeV)	π^0	η	η'
1.02	4.1×10^5	1.2×10^5	1.9×10^4
2.4	7.3×10^5	3.7×10^5	3.6×10^5

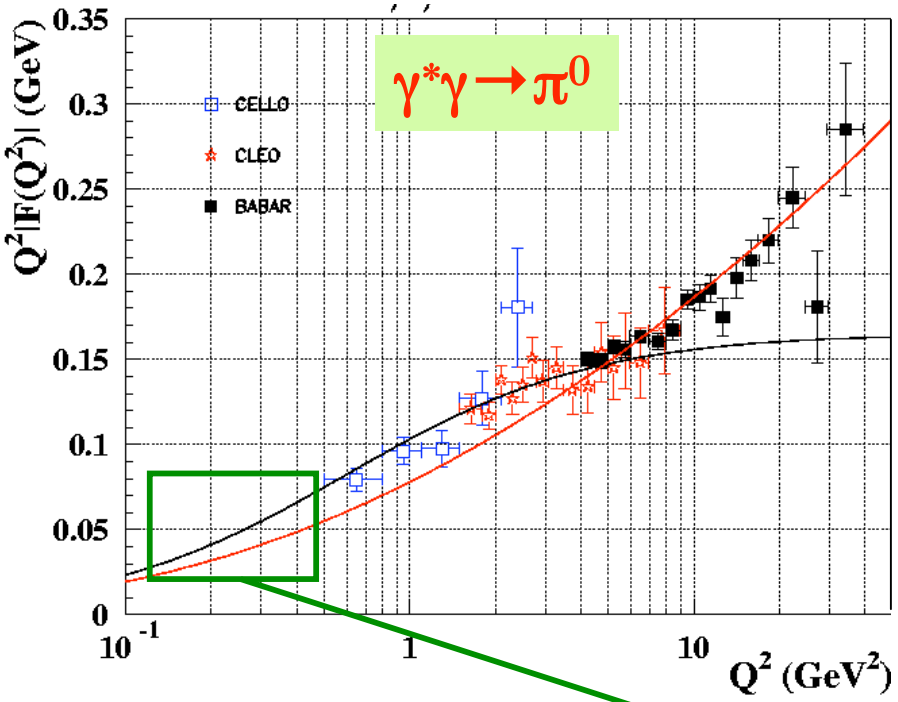
γγ physics: meson transition form factors

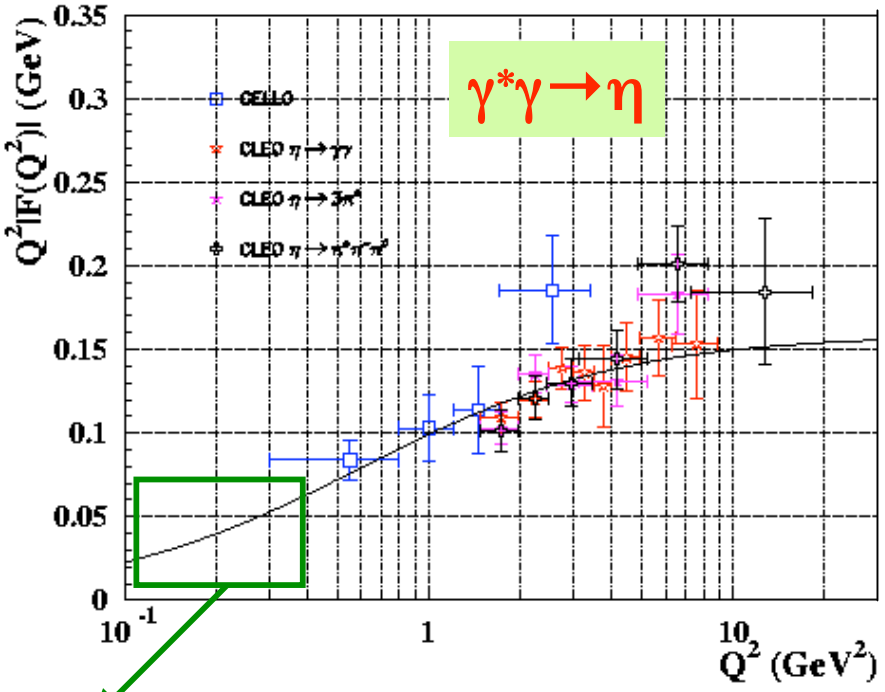
Slope of transition form factors near $q^2=0$ crucial for hadronic light-by-light contributions to g-2

$$\sigma_{\gamma\gamma\to R}(q_1,q_2) \propto \Gamma_{R\to\gamma\gamma}\frac{8\pi^2}{M_R}\delta((q_1+q_2)^2-M_R^2)\left|F(q_1^2,q_2^2)\right|^2$$



γ*γ→P ⇒ F(P²,q²,0)



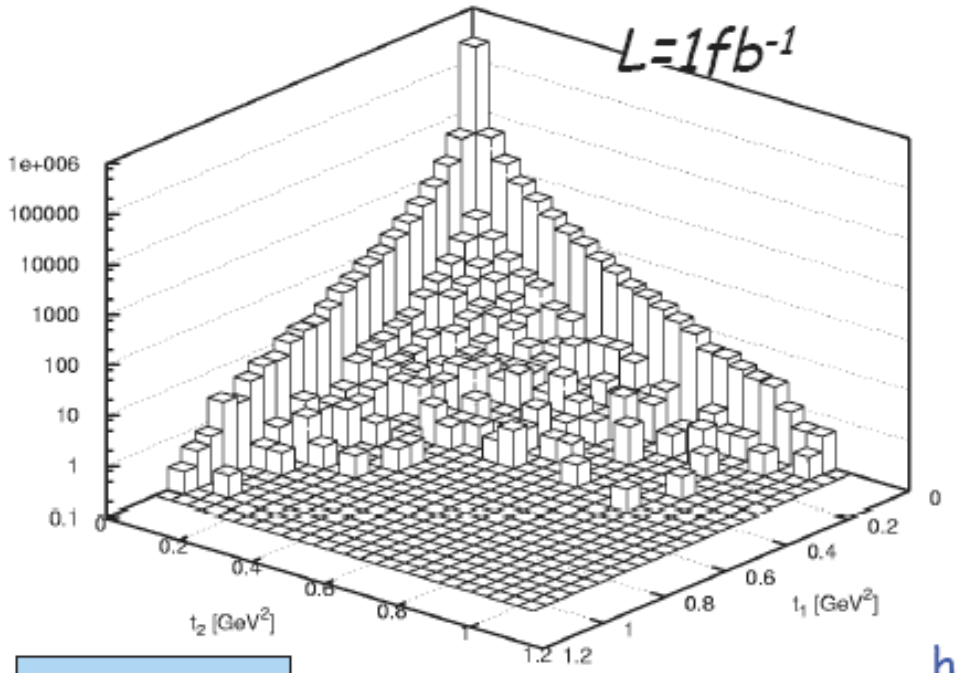


KLOE-2

Meson transition form factors: $\gamma^*\gamma^* \rightarrow \pi^0$

studies with **EKHARA Monte Carlo** generator

($e^+e^- \rightarrow e^+e^-\pi^0$ added in a new version)



No tagging

Preliminary

- Henryk Czyz (Katowice)
- Sergiy Ivashyn (Katowice, Kharkov)

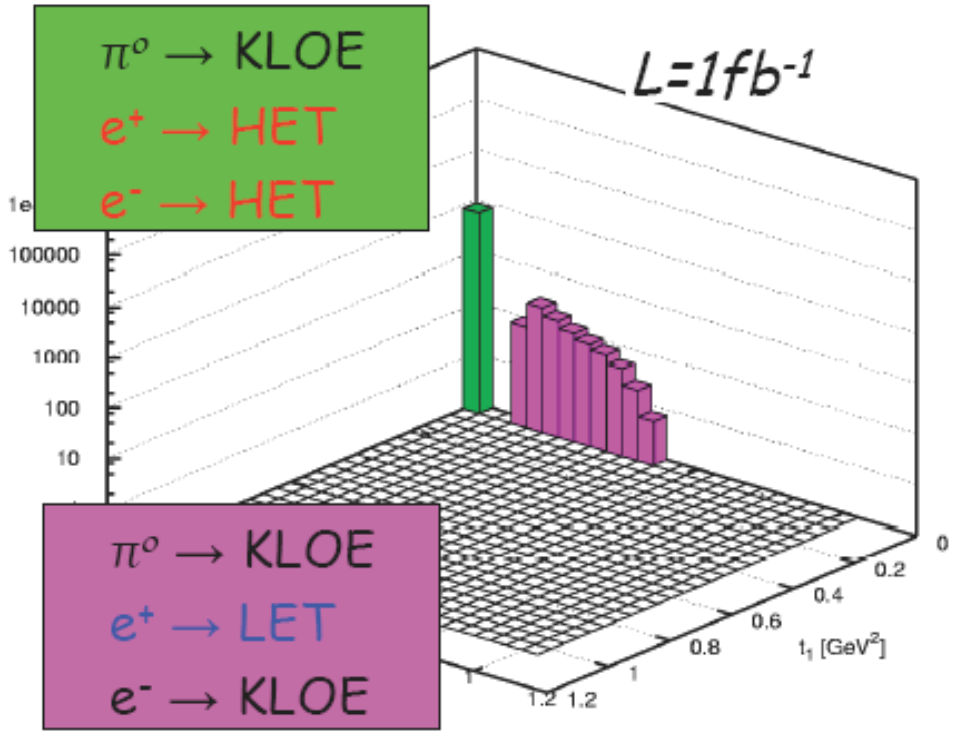
http://prac.us.edu.pl/~ekhara

Number of expected events @ KLOE/KLOE-2

Meson transition form factors: $\gamma^*\gamma \rightarrow \pi^0$

studies with **EKHARA Monte Carlo** generator

($e^+e^- \rightarrow e^+e^-\pi^0$ added in a new version)



Preliminary

- Henryk Czyz (Katowice)
- Sergiy Ivashyn (Katowice, Kharkov)

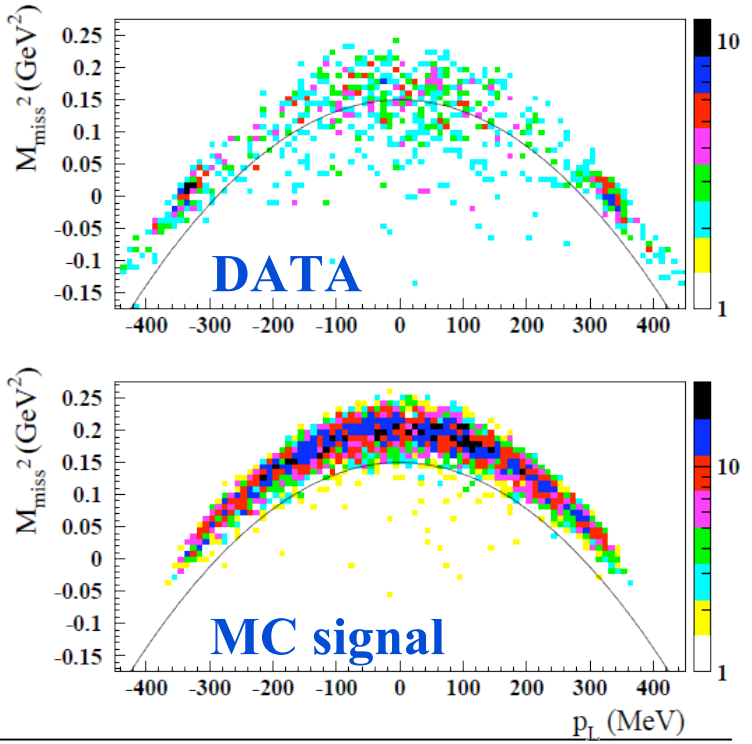
http://prac.us.edu.pl/~ekhara

KLOE-2 data will fix the slope at $q^2=0$

γγ physics: $\Gamma_\eta(\gamma\gamma)$ measurement

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT	√s (GeV)
0.510±0.026 OUR FIT						
0.510±0.026 OUR AVERAGE						
0.51 ±0.12 ±0.05	36	BARU	90	MD1	$e^+e^- \to e^+e^-\eta$	**7.2-10.4**
0.490±0.010±0.048	2287	ROE	90	ASP	$e^+e^- \to e^+e^-\eta$	**29**
0.514±0.017±0.035	1295	WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-\eta$	**9.4-10.6**
0.53 ±0.04 ±0.04		BARTEL	85E	JADE	$e^+e^- \to e^+e^-\eta$	**34.6**

- **$\gamma\gamma \to \eta$ studied at KLOE**
- **Data sample: 240 pb^{-1} @ $\sqrt{s}$ = 1 GeV (reduced bckg contamination from ϕ)**
- **Selected channel: $\eta \to \pi^+\pi^-\pi^0$**
- **Main background: $\phi \to \eta\gamma$ with undetected photon**

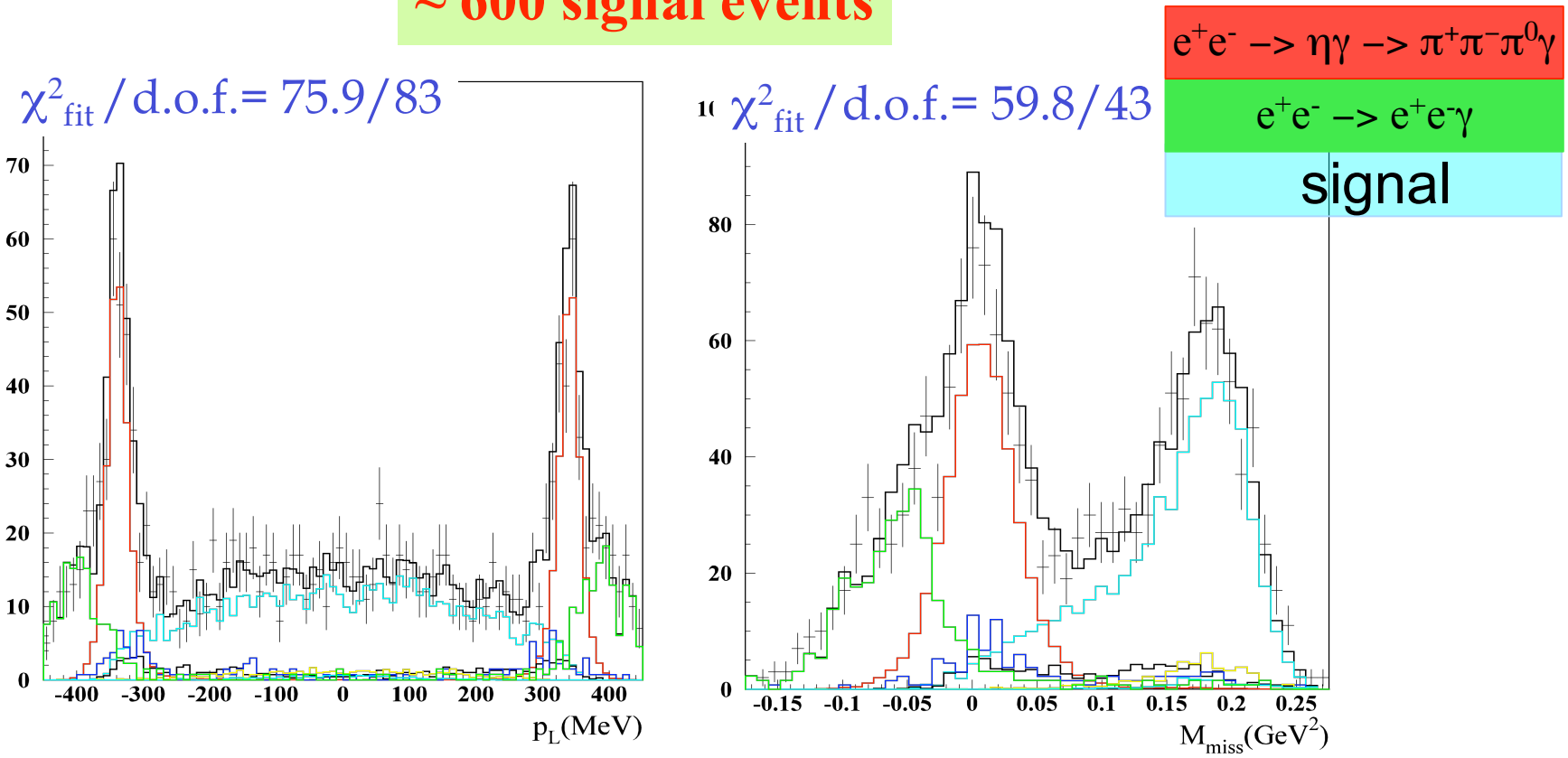


$\gamma\gamma \rightarrow \eta$: fit results

PRELIMINARY

Fit to p_L and M_{miss}^2 with signal and background shapes

~ 600 signal events



- Extraction of $\sigma(e^+e^- \rightarrow e^+e^-\eta)$ and $\Gamma_{\gamma\gamma}$ in progress
- Statistical accuracy on $\Gamma_{\gamma\gamma}$ comparable with existing measurements

Search for $\gamma\gamma \rightarrow \sigma \rightarrow \pi\pi$

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

Only process to measure directly the $\sigma\gamma\gamma$ coupling → infer structure

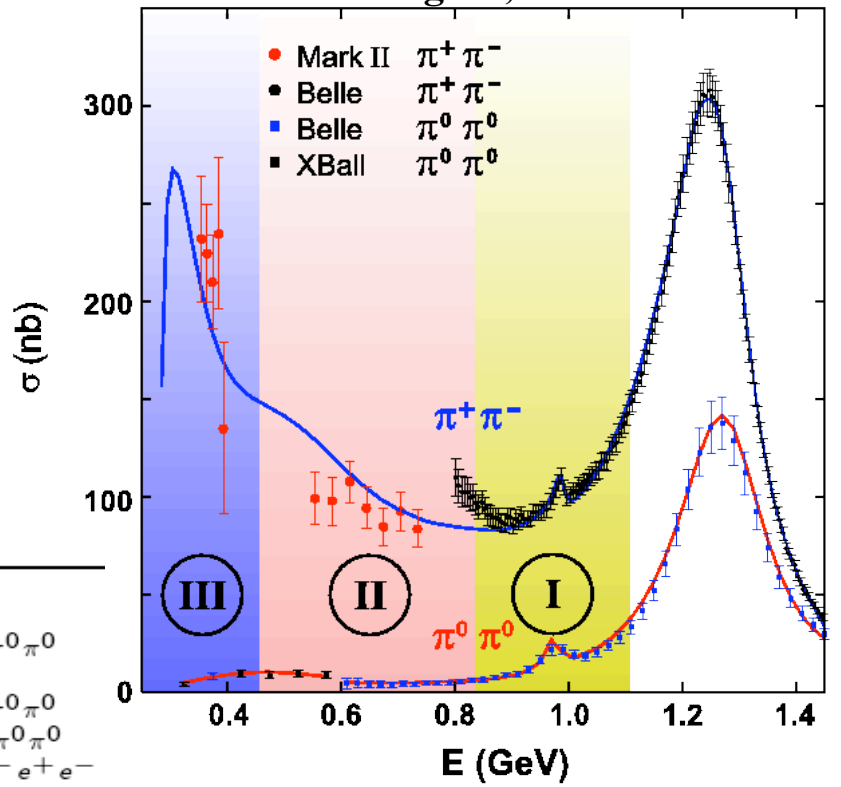
$\pi^0\pi^0$ preferred w.r.t. $\pi^+\pi^-$ due to smaller background contamination

$f_0(600)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$

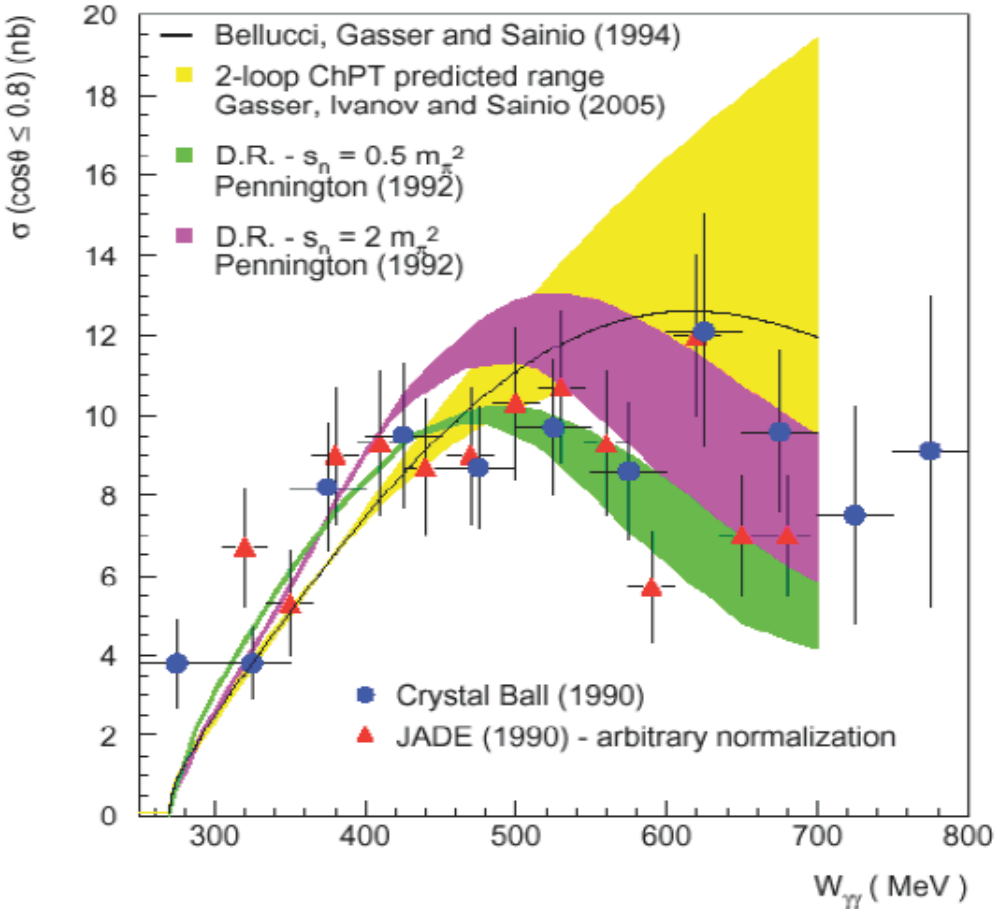
VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2±0.4	[48] BERNABEU	08	RVUE	
3.9±0.6	[49] MENNESSIER	08	RVUE	$\gamma\gamma \rightarrow \pi^+\pi^-, \pi^0\pi^0$
4.1±0.3	[50] PENNINGTON	06	RVUE	$\gamma\gamma \rightarrow \pi^0\pi^0$
3.8±1.5	[51,52] BOGLIONE	99	RVUE	$\gamma\gamma \rightarrow \pi^+\pi^-, \pi^0\pi^0$
5.4±2.3	[51] MORGAN	90	RVUE	$\gamma\gamma \rightarrow \pi^+\pi^-, \pi^0\pi^0$
10 ±6	COURAU	86	DM1	$e^+e^- \rightarrow \pi^+\pi^- e^+e^-$

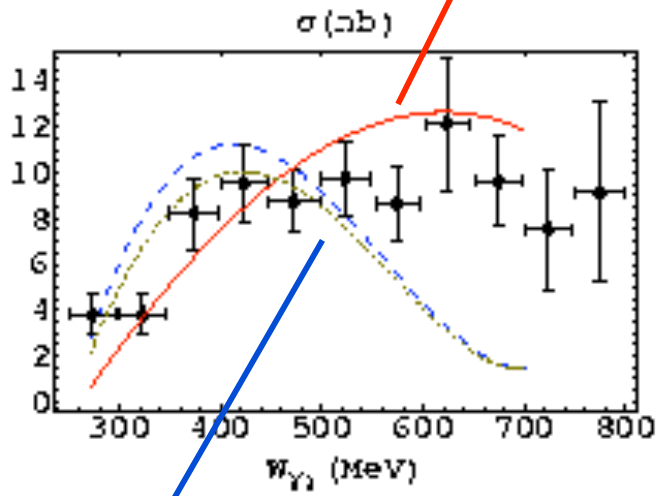
Pennington, arXiv:0906.1072



$\gamma\gamma \rightarrow \pi^0\pi^0$ at low energies

Cleanest channel to assess existence and nature of the σ meson





ChPT

Resonant contribution

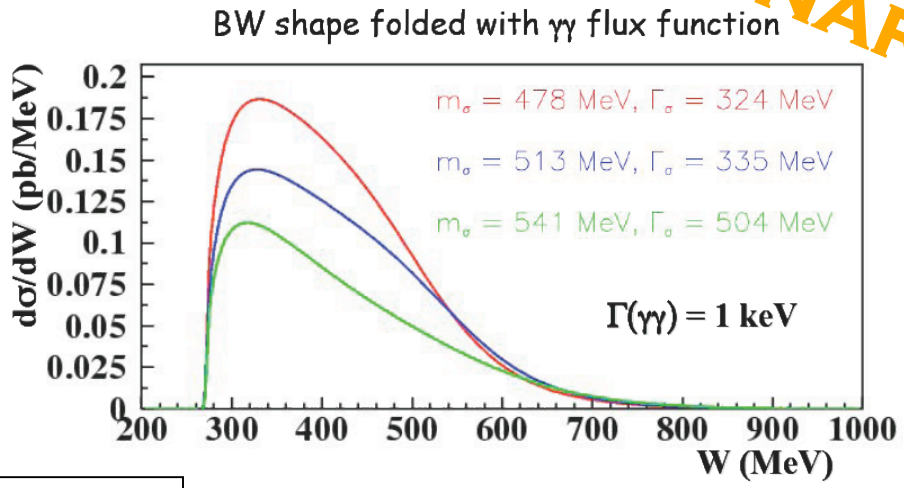
$\gamma\gamma \rightarrow \sigma \rightarrow \pi^0\pi^0$

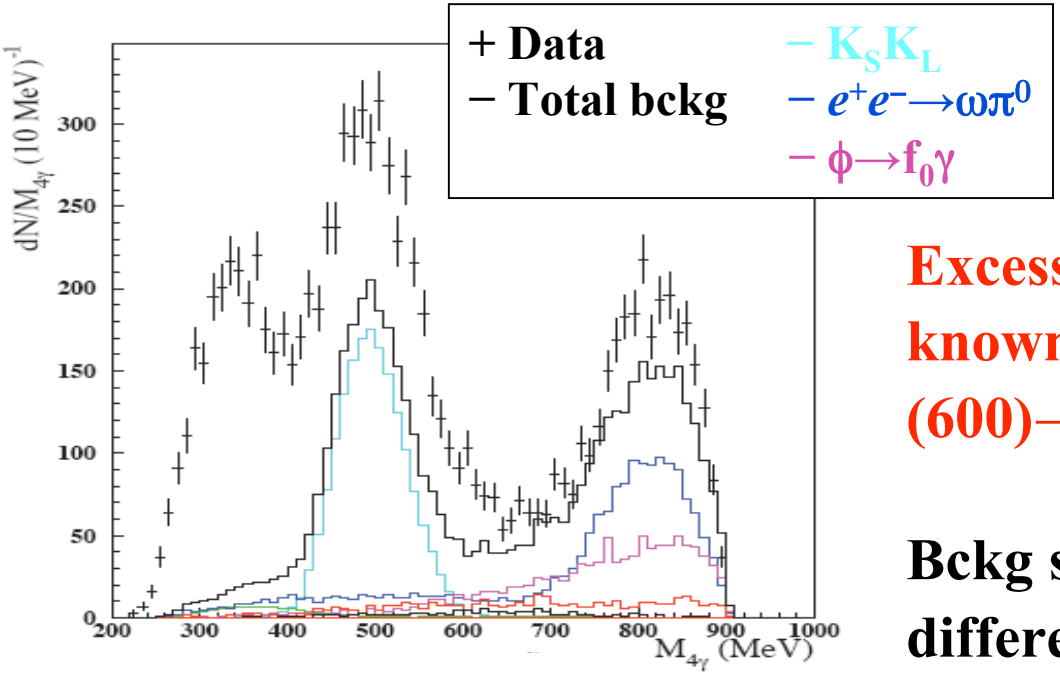
[Nguyen, Piccinini, Polosa, EPJC 47 (2006) 65]

$\gamma\gamma \rightarrow \pi^0\pi^0$: $M_{4\gamma}$

PRELIMINARY

- 240 pb^{-1} @ $\sqrt{s}$ = 1 GeV
- 10188 events after selection
- Bckg normalized using measured x-sections





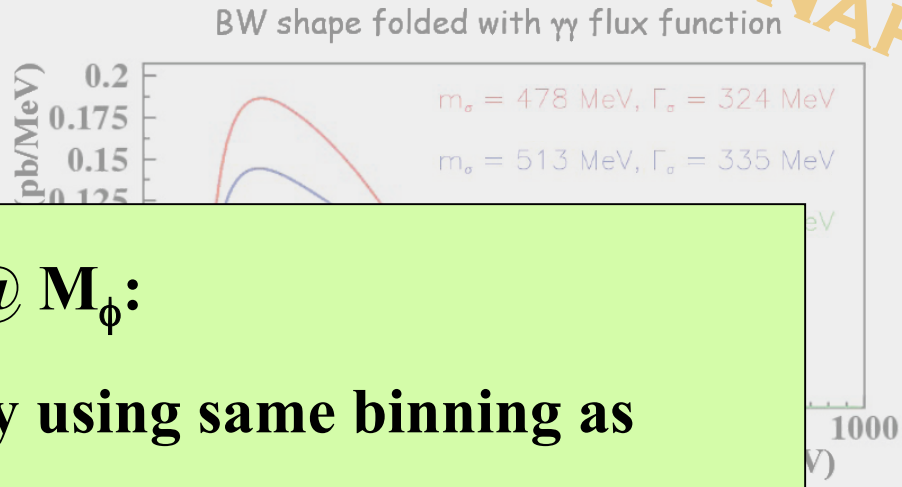
Excess of ~4000 events w.r.t. known backgrounds in the $\gamma\gamma\rightarrow\sigma(600)\rightarrow\pi^0\pi^0$ region

Bckg subtraction and study of differential x-sec in progress

$\gamma\gamma \rightarrow \pi^0\pi^0$: $M_{4\gamma}$

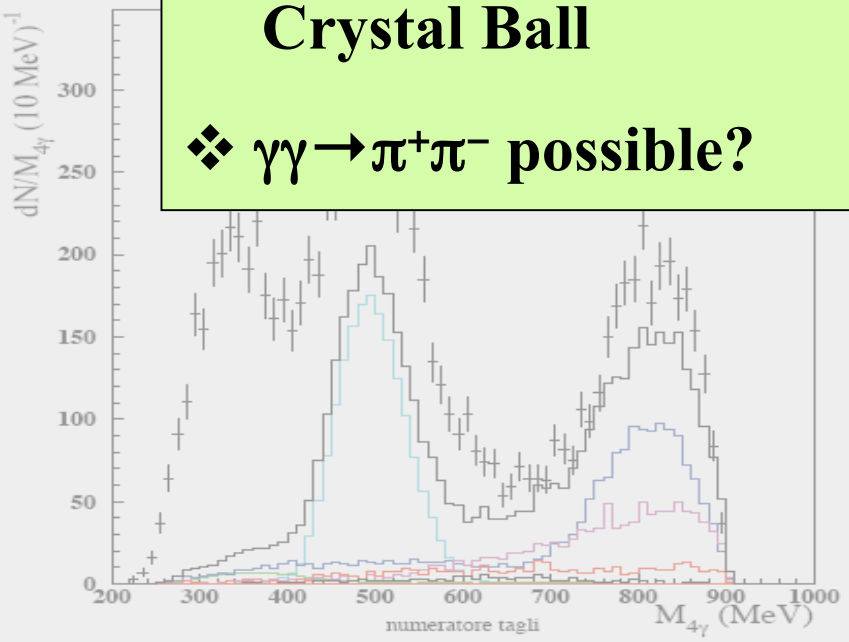
PRELIMINARY

- 240 pb^{-1} @ $\sqrt{s}$ = 1 GeV
- 10188 events after selection
- Bck
  mea



KLOE-2 with O(5 fb^{-1}) @ M_ϕ:

- **2% statistical accuracy using same binning as Crystal Ball**
- **$\gamma\gamma \rightarrow \pi^+\pi^-$ possible?**



Excess of ~4000 events w.r.t. known backgrounds in the $\gamma\gamma \rightarrow \sigma(600) \rightarrow \pi^0\pi^0$ region

Bckg subtraction and study of differential x-sec in progress

Conclusions

- **High statistics samples of light mesons produced at KLOE allowed to perform precision measurement and to look for very rare decays**

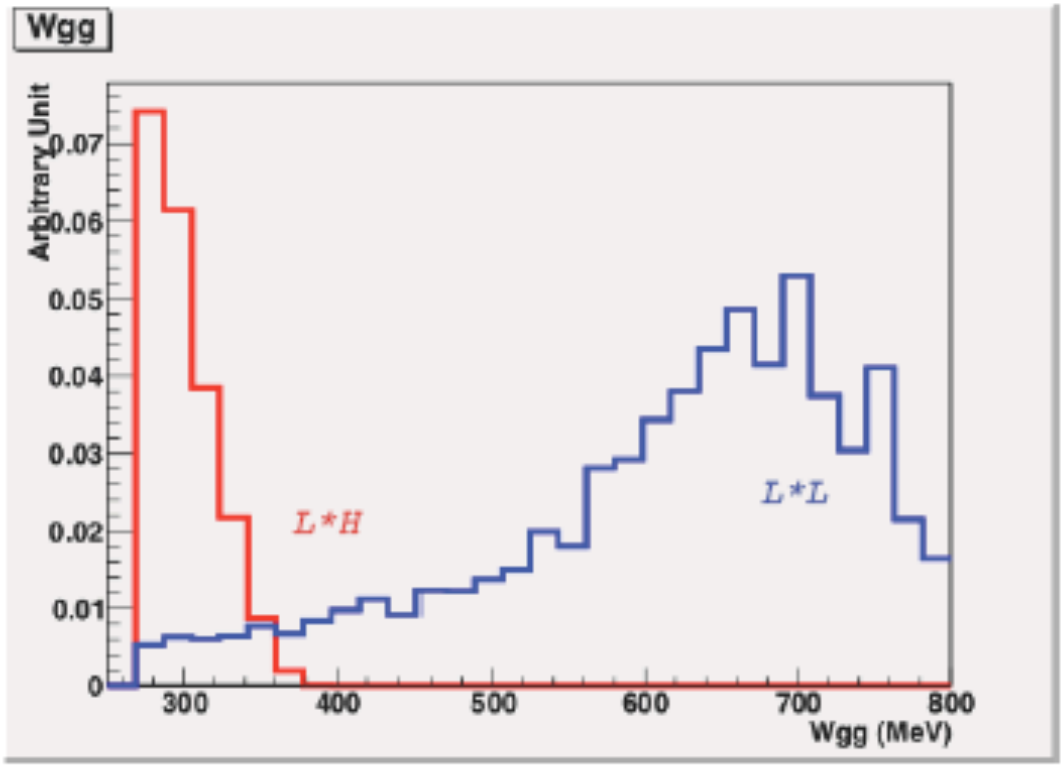
KLOE results on hadron physics

- $\Gamma(\phi\to\eta'\gamma)/\Gamma(\phi\to\eta\gamma)$, PLB 541 (2002) 45
- $\phi\to\eta\pi^0\gamma$, PLB 536 (2002) 209
- $\phi\to\pi^0\pi^0\gamma$, PLB 537 (2002) 21
- $\phi\to\pi^+\pi^-\pi^0$, PLB 561 (2003) 55
- $\eta\to\gamma\gamma\gamma$, PLB 591 (2004) 49
- $\sigma(e^+e^-\to\pi^+\pi^-)$, PLB 606 (2005) 12
- $\eta\to\pi^+\pi^-$, PLB 606 (2005) 276
- $\Gamma(\phi\to l^+l^-)$, PLB 608 (2005) 199
- $\phi\to\pi^+\pi^-\gamma$, PLB 634 (2006) 148
- η mass, JHEP 12 (2007) 073
- $e^+e^-\to\pi^0\pi^0\gamma$, EPJC 49 (2007) 473
- $\Gamma(\phi\to\eta'\gamma)/\Gamma(\phi\to\eta\gamma)$, PLB 648 (2007) 267
- $\eta\to\pi^+\pi^-\pi^0$, JHEP 05 (2008) 006
- $e^+e^-\to\omega\pi^0$, PLB 669 (2008) 223
- $\sigma(e^+e^-\to\pi^+\pi^-)$, PLB 606 (2005) 12
- η/η' mixing, JHEP 07 (2009) 105
- $\eta\to\pi^+\pi^-e^+e^-$, PLB 675 (2009) 283
- $\phi\to K^0K^0\gamma$, PLB 679 (2009) 10
- $\phi\to\eta\pi^0\gamma$, PLB 681 (2009) 5
- $\eta\to\pi^0\pi^0\pi^0$, arXiv:1004.1319, sub. to PLB

- **KLOE-2 is going to start a new data taking campaign:**
  - ❖ **detector ready to take data**
  - ❖ **installation of $\gamma\gamma$ taggers in progress**
  - ❖ **rich physics program available on arXiv:1003.3868**

Backup slides

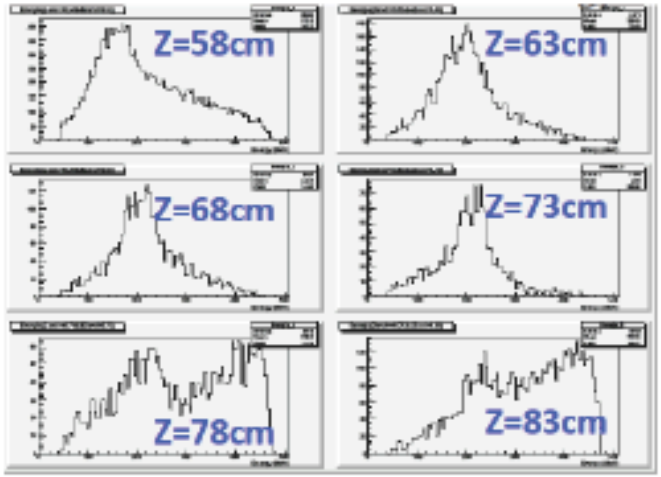
Taggers acceptance

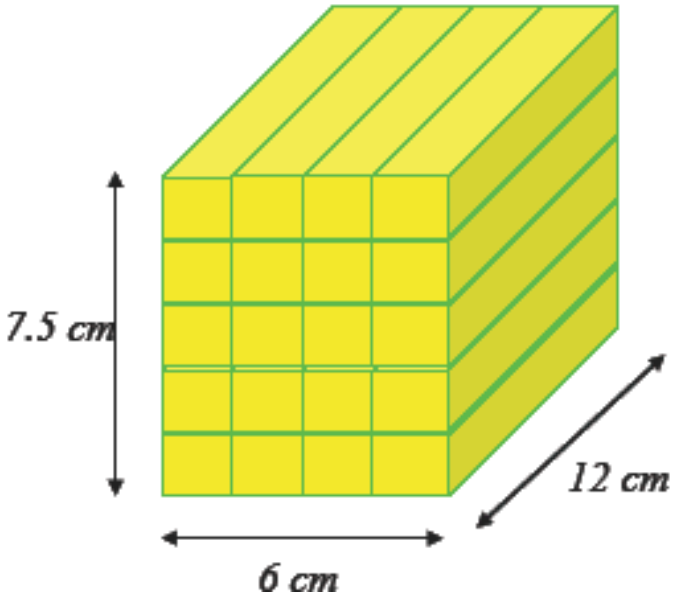


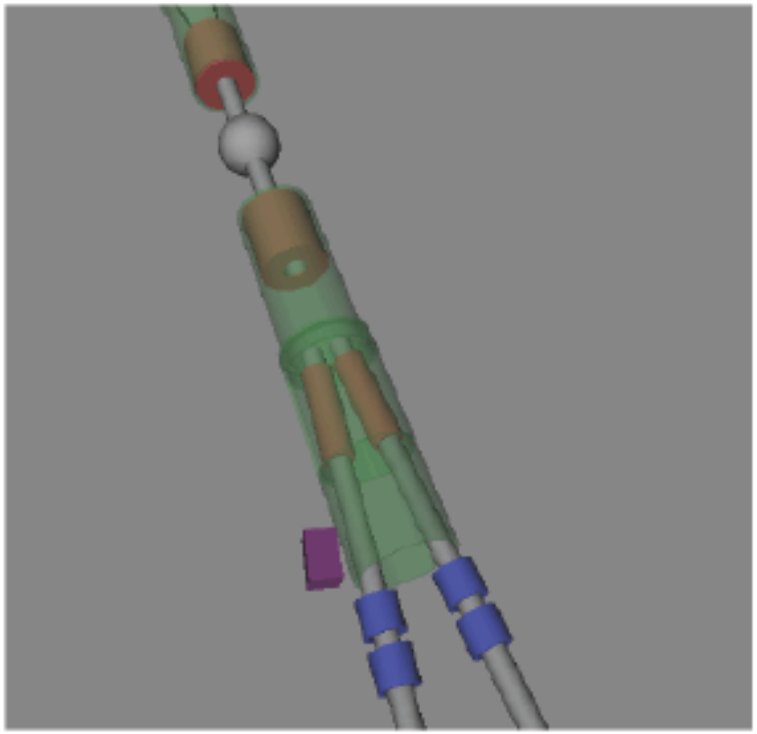
In this study we consider only the reaction $\gamma\gamma \rightarrow \pi^0\pi^0$

- Single arm acceptance: HET = 14%, LET = 17%
- Single Total acceptance (only 1 tagger fired) = 54%
- Double arm acceptance (H*H + 2*L*(H) + L*L) = 2+5+3 = 10%

LET detector



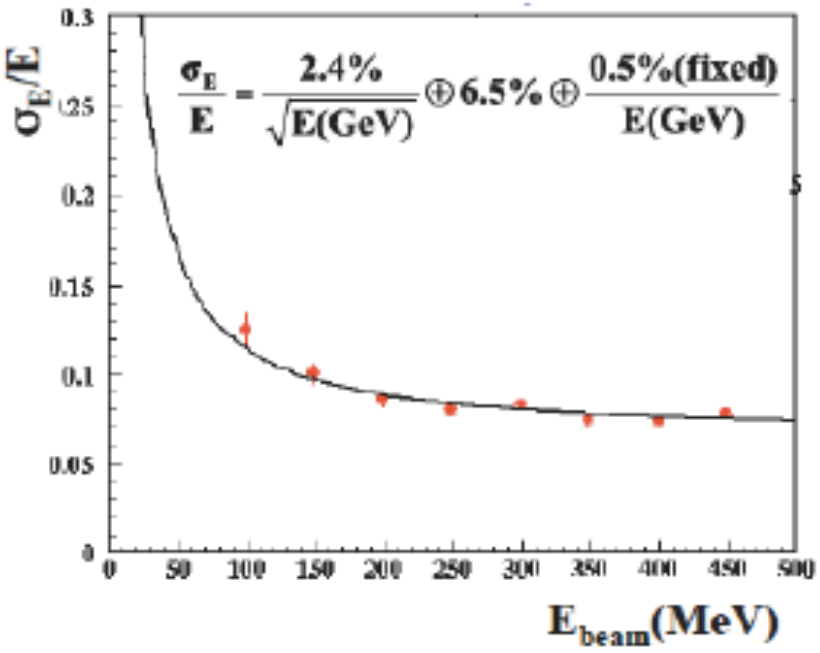


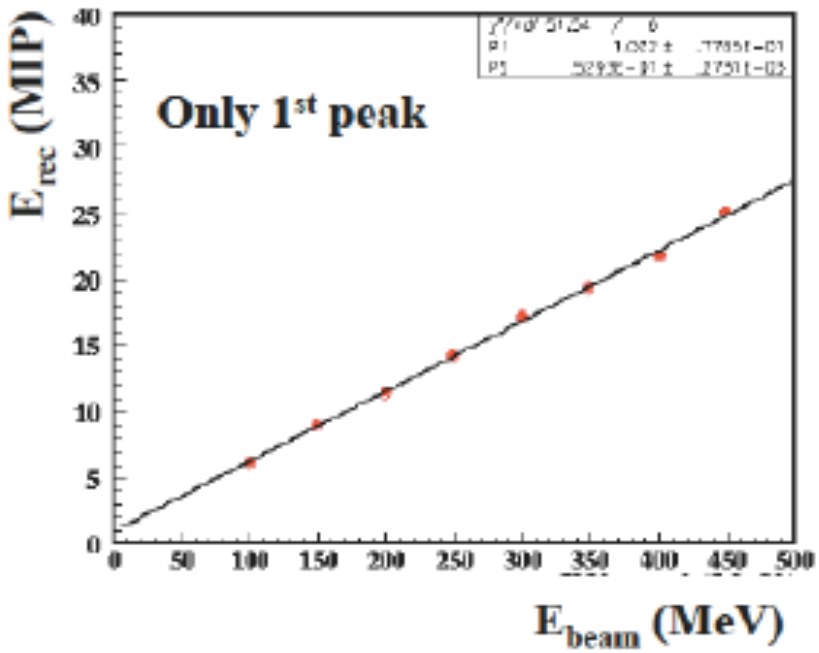


LET: Low Energy Tagger
(160-230 MeV) lepton energy

Calorimeters, LYSO + SiPM

LET performances

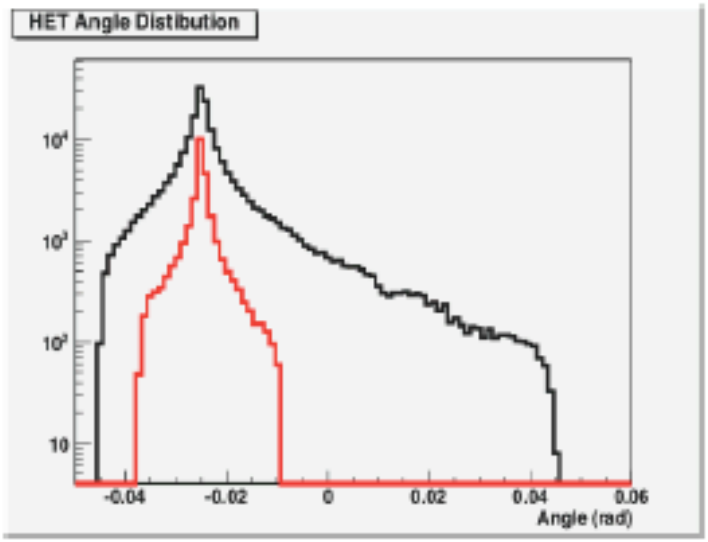


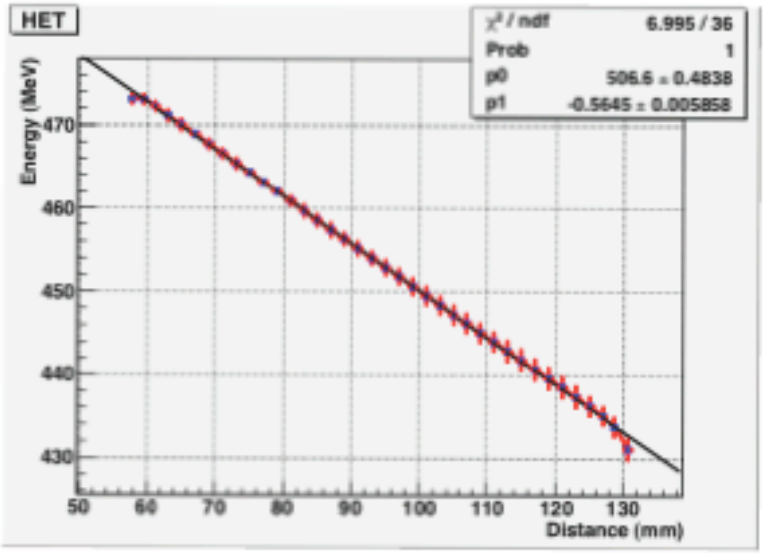


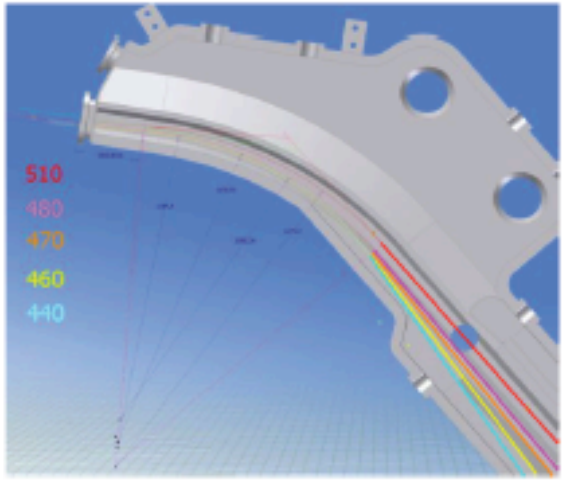
- *3rd term is fixed, since we have about 5 MeV noise*
- *Statistical term higher than expected (20 p.e./MeV → less than 1%/$E^{1/2}$(GeV))*
- *Contribution to constant term due to lateral leakage (matrix not fully readout)*
- *There is an unknown contribution from the beam*
- *Resolution is better than 10% for E > 150 MeV*

HET detector

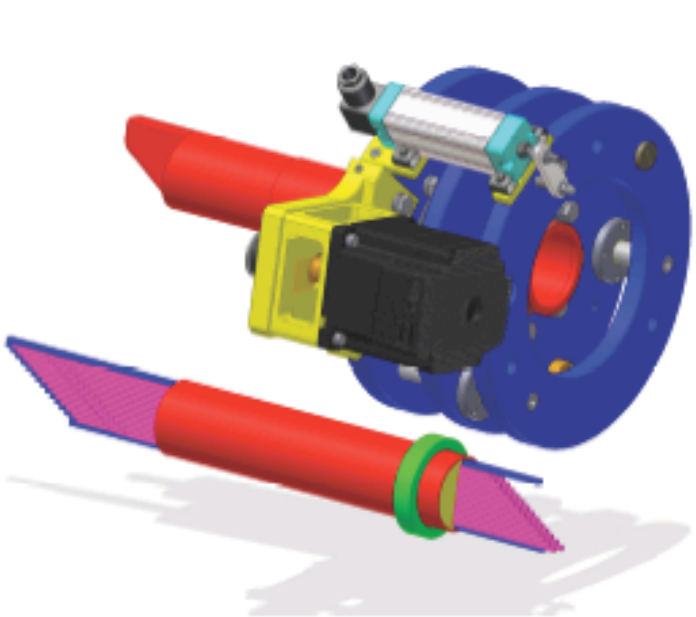
The detector will be located at 11 m from the IP behind a bending magnet. Plastics + PMTs

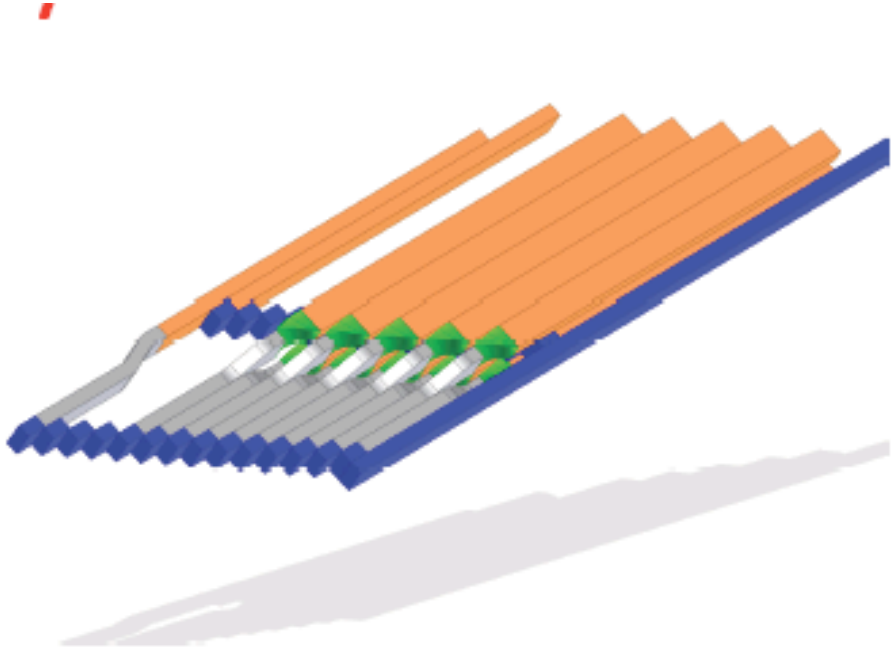






HET detector

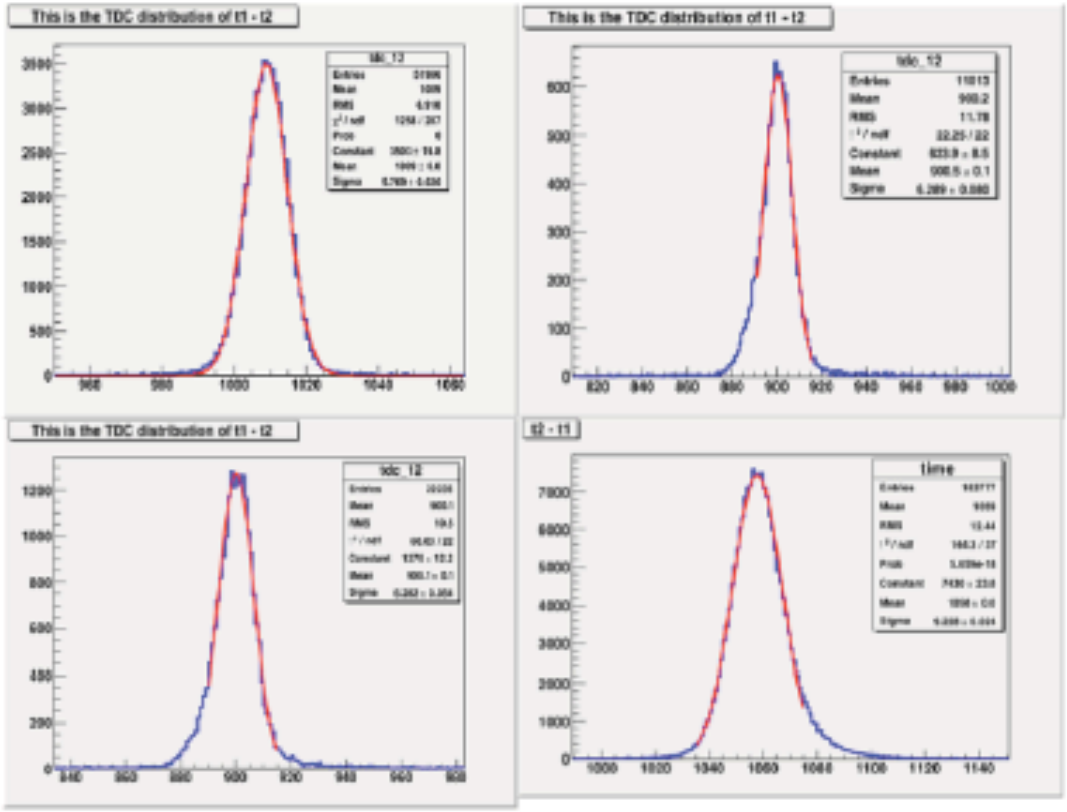




- Minimum safe distance from beam line is of 3-5 cm.
- Hodoscope made by two rows of 15 scintillators of 3x5x6 mm^3 → pitch resolution ~ 5 mm, i.e. 2.5 MeV momentum resolution.
- Fast EJ228 (ELJEN) scintillator used. Light transported to photosensor with light guides. PMT Hamamatsu R9880-U110 readout (QE≈35%).

HET performances

HET prototype successfully tested at LNF-BTF during September 2009



L.Y. in excess of 40 pe/MIP → 200 ps resolution which should allow clear separation between consecutive bunches.

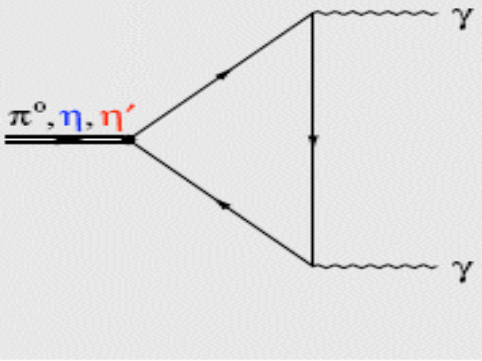
$\eta \to \pi^+\pi^-\gamma$: contributions

Anomalies in QCD

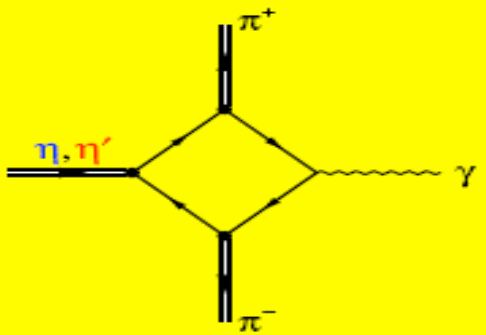
Wess-Zumino-Witten Lagrangian

J. Wess, B.Zumino, Phys. Lett. B 37 (1971) 95
E. Witten, Nucl. Phys. B 223 (1983) 422

$$L_{WZW} = L_{AVV} + L_{AAAV} + \dots$$



triangle anomaly



box anomaly

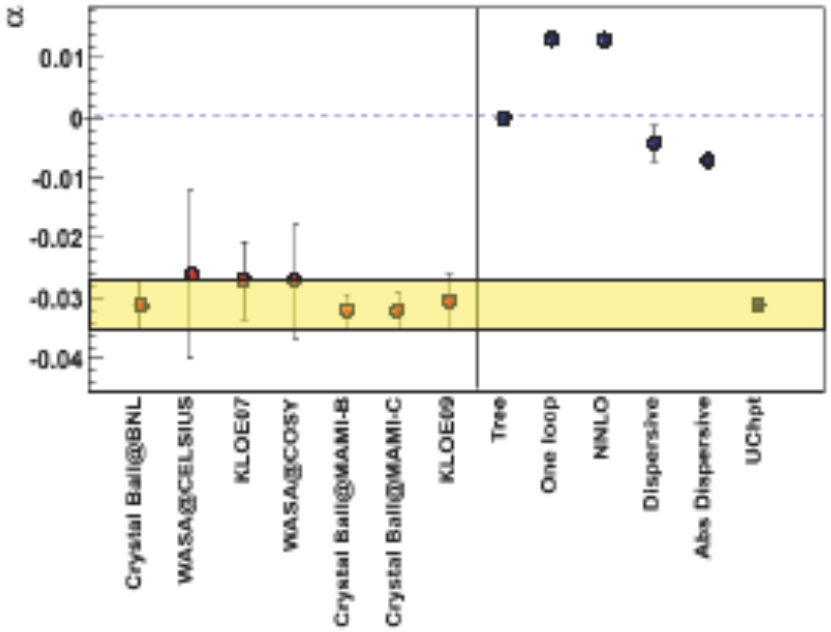
- Resonant contribution:
  1. ρ production with its subsequent decay to a pion pair (VDM)
  2. existence of a small non-VDM contribution
- Anomalous contribution:
  box anomaly (similar to the classical triangle anomaly), responsible for $\eta/\eta' \to \pi^+\pi^-\gamma$ decays predicted by PCAC and by the Wess-Zumino-Witten chiral lagrangian

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

At the lowest order $\eta \to \pi^0\pi^0\pi^0$ decay amplitude can be parametrize by

$$|A|^2 \propto 1 + 2\,\alpha\, z \qquad \text{where} \qquad z = \frac{2}{3}\sum_{i=1}^{3}\frac{(3E_i - M_\eta)^2}{(M_\eta - 3M_\pi)^2}$$

The slope α was measured to be negative and small in disagreement with CA $(\alpha = 0)$
The explanation of this effect poses a challenge for **ChPT**
LO calculations in ChPT coincide with CA
NLO calculations significantly improve the agreement for the partial decay width
but predict a small positive value $(\alpha > 0)$.

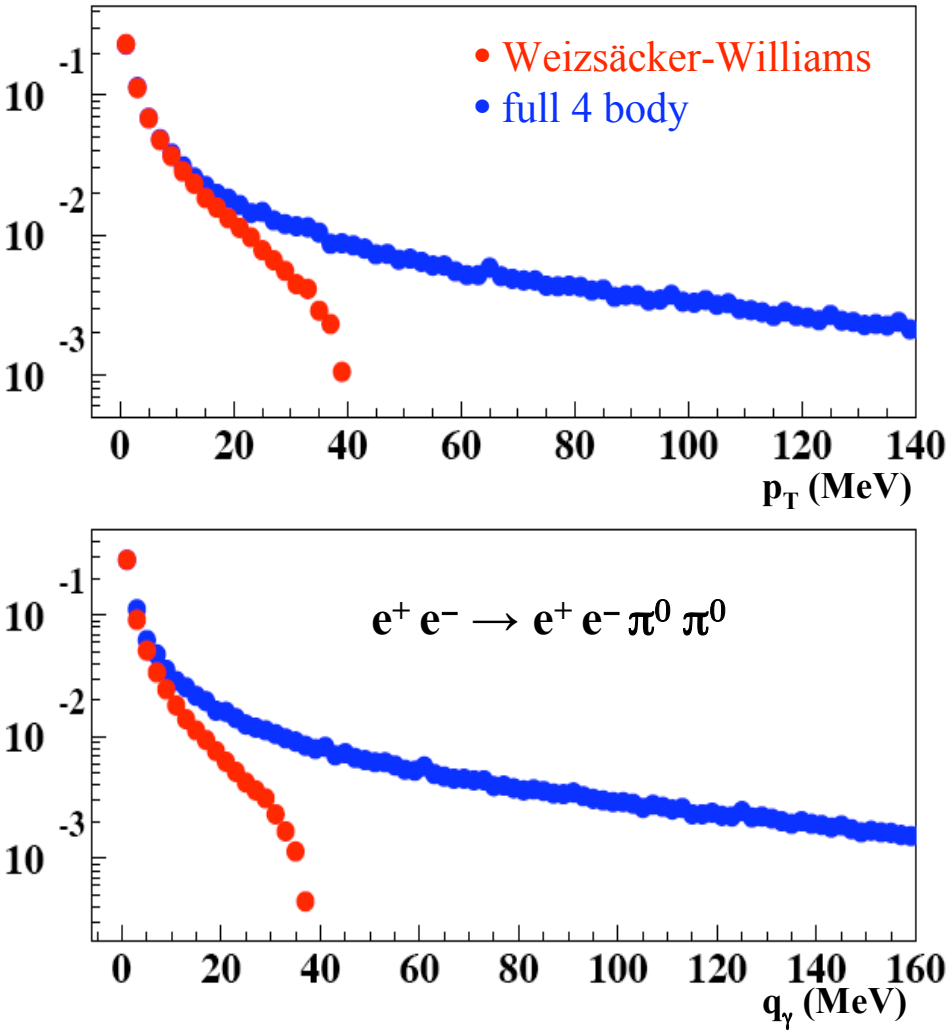


KLOE final:
615000 events
Fit Z in the range [0 ÷ 0.7]:

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

arXiv:1004.1319
Submitted to PLB

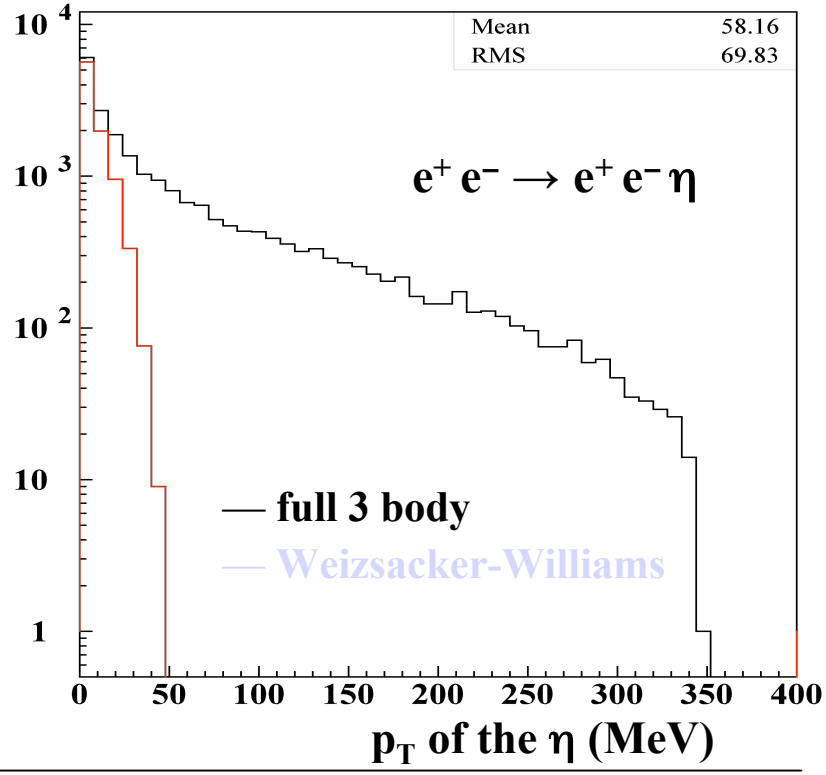
Comparison btw W.W. and phase space



F.Nguyen, F. Piccinini & A. Polosa
Eur.Phys.J.C47(2006)65

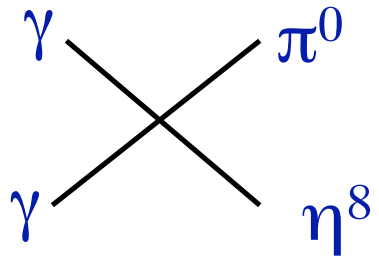
1) W.W. is reproduced with a cut $\theta < 5^o$ for final state e^+e^-

2) impact at the % level within cuts (p_T < 80 MeV)



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

p^2 { L_2 contributions at tree level:



$= 0\ (Q = 0)$

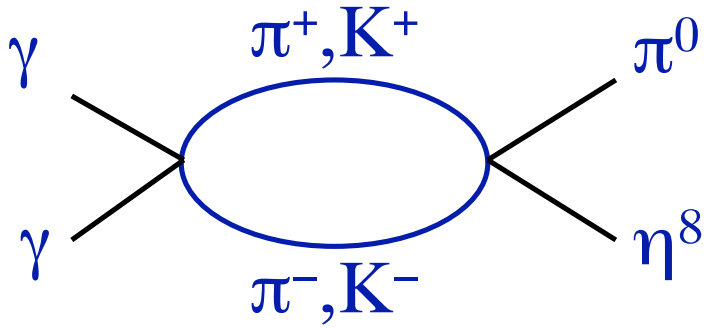
p^4 {

Coupling proportional to the charges, zero also for L_4 @ tree level.

1-loop contributions from L_2 vertices, suppressed by G parity conservation and kaon mass suppression:

$\Gamma_{\pi\text{-loops}} = 0.84 \times 10^{-3}$ eV

$\Gamma_{\text{K-loops}} = 2.45 \times 10^{-3}$ eV



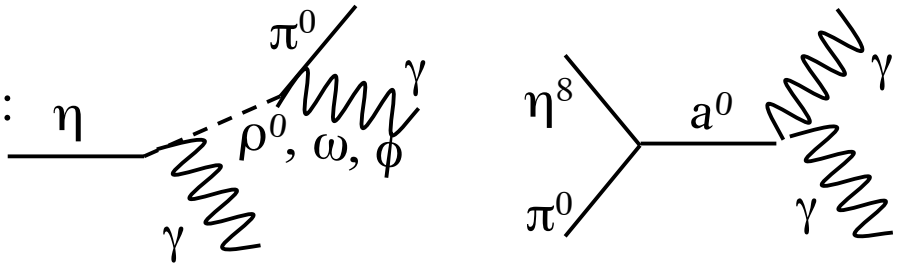
p^6 {

L_6 coefficients determined by the meson propagator. Th. expectations:

$\Gamma^6_{\text{VMD}} = (\ 0.42 \pm 0.20\ )$ eV

$\Gamma^6_{\text{ENJL}} = (\ 0.58 \pm 0.3\ \ )$ eV

$\Gamma^6_{\text{Ch unit}} = (\ 0.47 \pm 0.10\ )$ eV



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