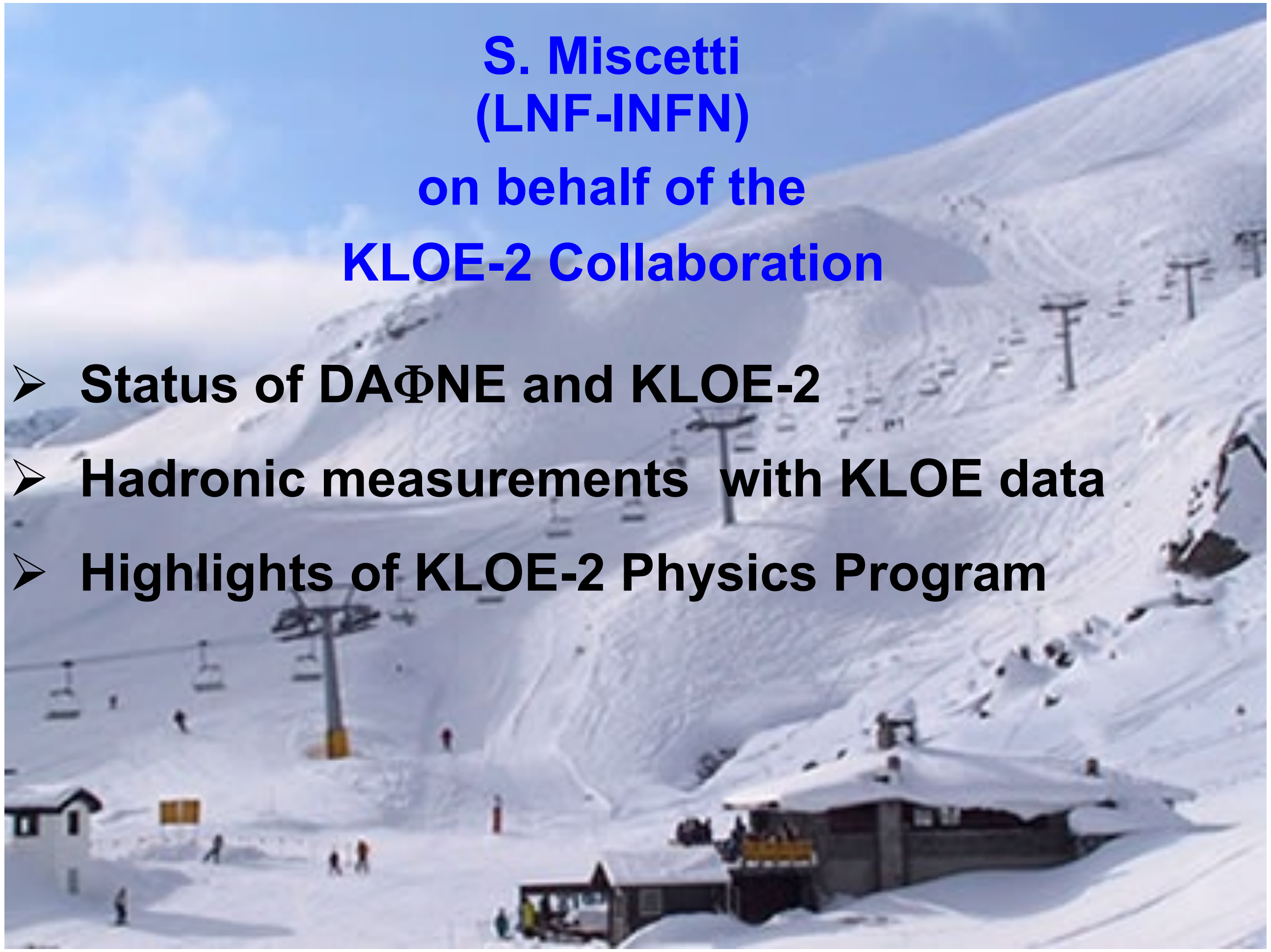
QCD and Hadronic physics with KLOE and KLOE-2



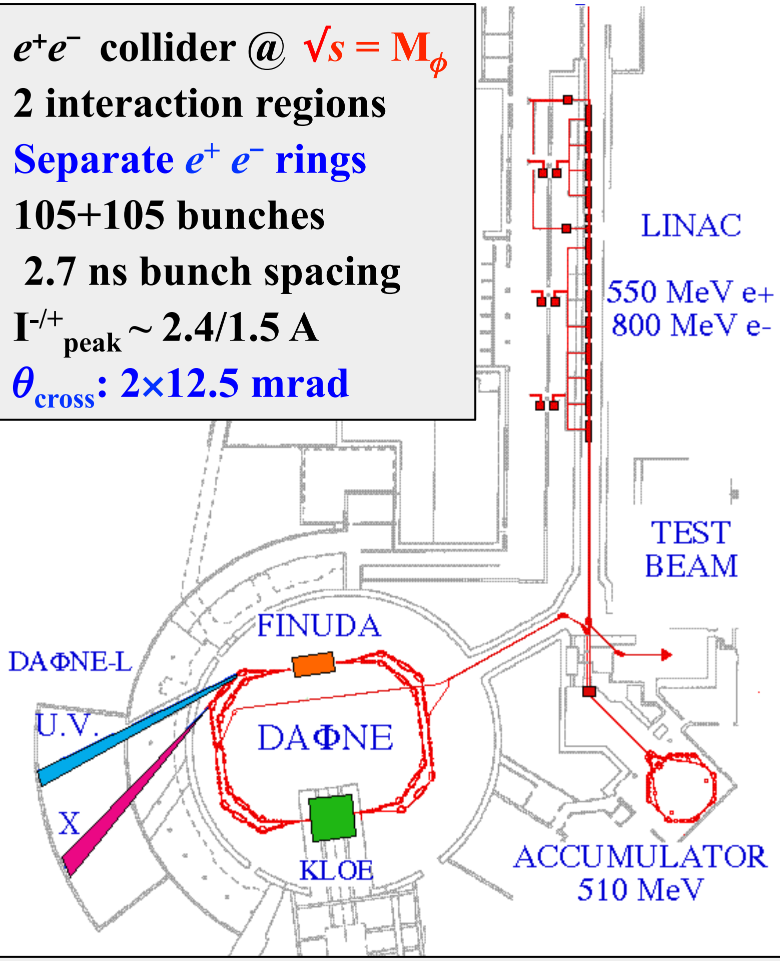
S. Miscetti
(LNF-INFN)
on behalf of the
KLOE-2 Collaboration

- Status of DAΦNE and KLOE-2
- Hadronic measurements with KLOE data
- Highlights of KLOE-2 Physics Program

XXVII Recontre De Physique de La Valle'e d'Aoste
La Thuile. 26 February 2013

DAΦNE: the Frascati ϕ-factory

- e^+e^- collider @ $\sqrt{s} = M_\phi$
- 2 interaction regions
- Separate $e^+ e^-$ rings
- 105+105 bunches
- 2.7 ns bunch spacing
- $I^{-/+}_{peak} \sim 2.4/1.5$ A
- θ_{cross}: 2×12.5 mrad

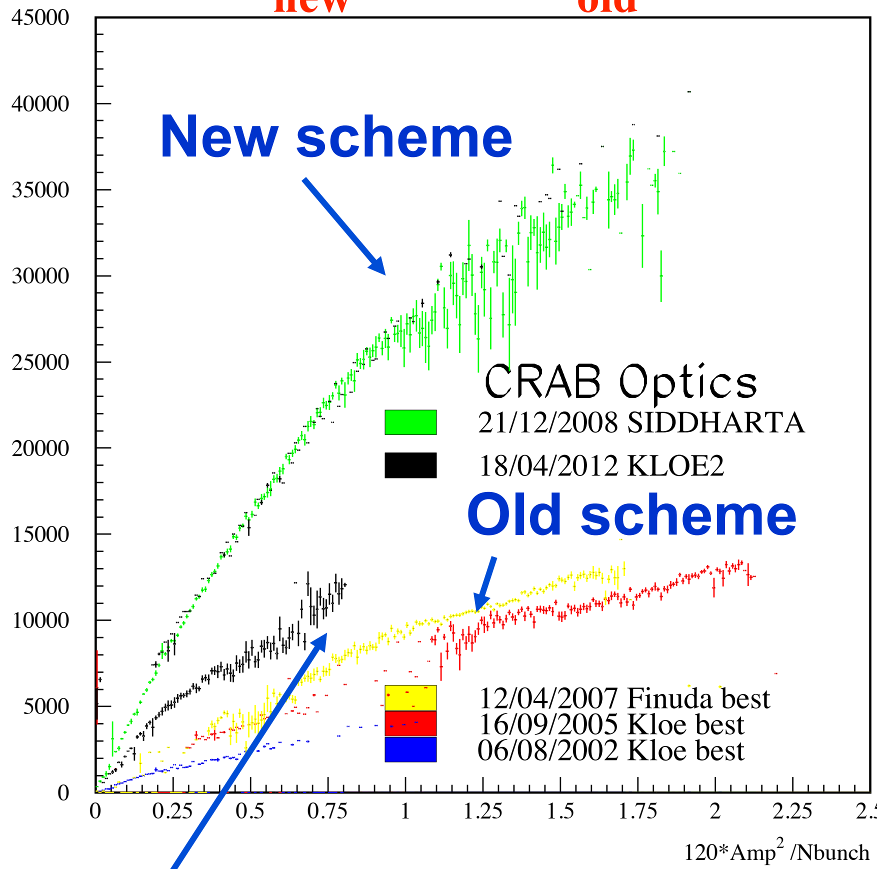


Best performances (1999-2007):

- $L_{peak} = 1.4\times10^{32}$ cm^{-2} s^{-1}
- $\int L dt = 8.5$ pb^{-1}/day

2008, new interaction scheme:

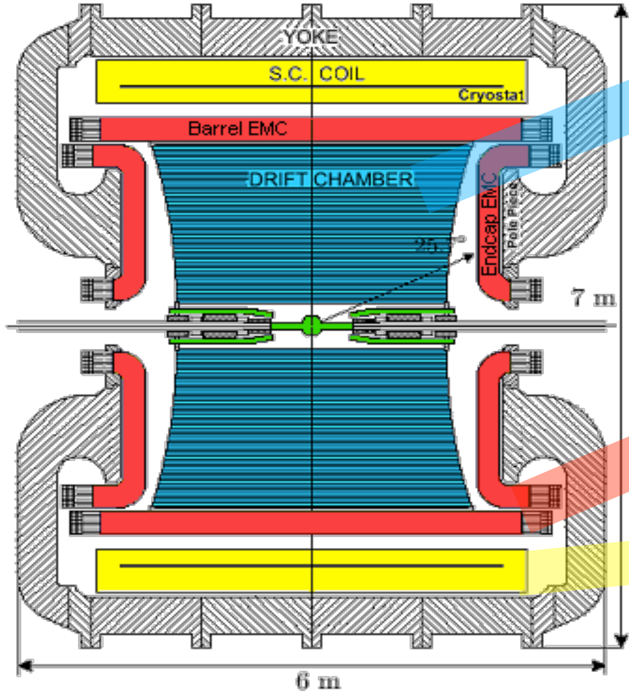
$L_{new} \sim 3 \times L_{old}$



Machine commissioning for KLOE-2 completed

The KLOE experiment

KLOE experiment took data in 2001-2006, before the DAΦNE upgrade



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

Drift chamber

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

Electromagnetic calorimeter

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

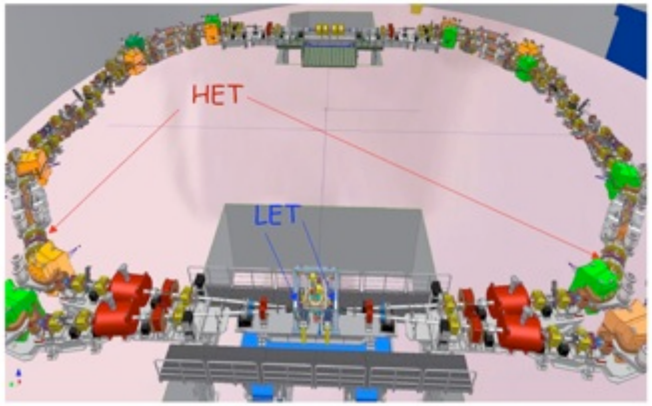
Magnetic field: 0.52 T

Physics at a ϕ-factory:

- **Kaon physics**
- **Light meson spectroscopy**
- **Hadron production in $\gamma\gamma$ collisions**
- **Search for dark force mediator**
- **Hadronic cross-section via ISR and $\pi^+\pi^-$contribution to $(g-2)_\mu$**

From KLOE to KLOE-2: $\gamma\gamma$ taggers

2+2 $\gamma\gamma$ taggers installed for the KLOE-2 run
Determine lepton momenta in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$

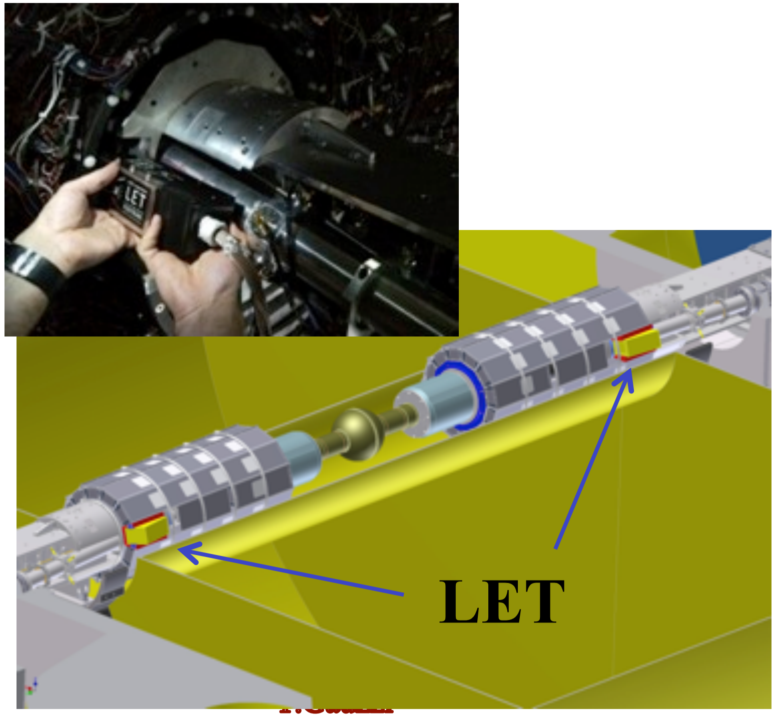


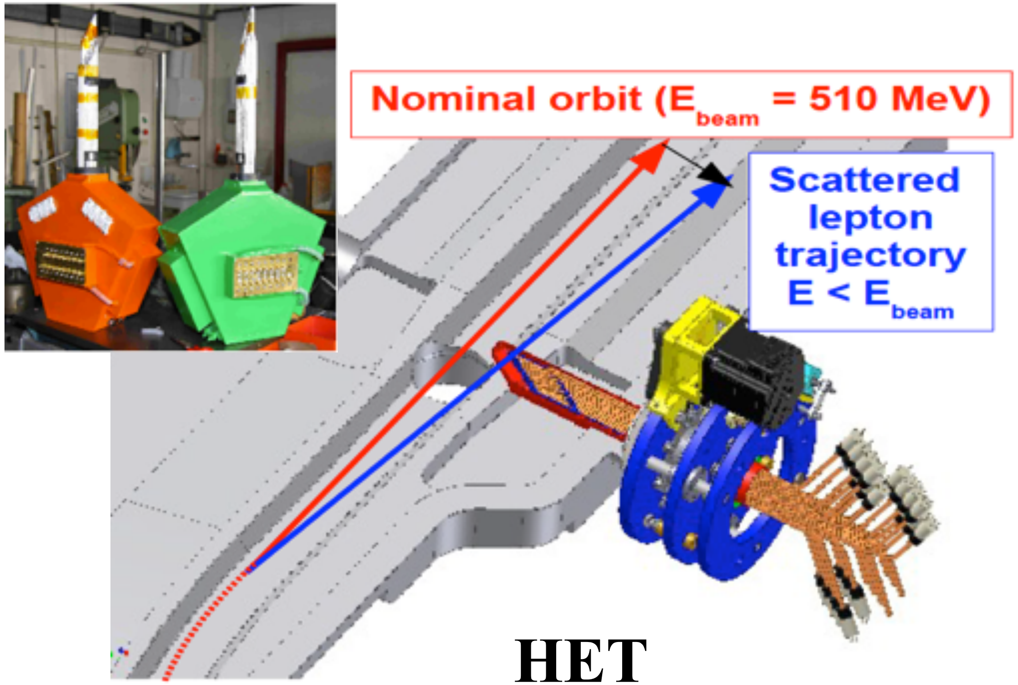
LET : E=160 – 230 MeV

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

HET : E > 400 MeV

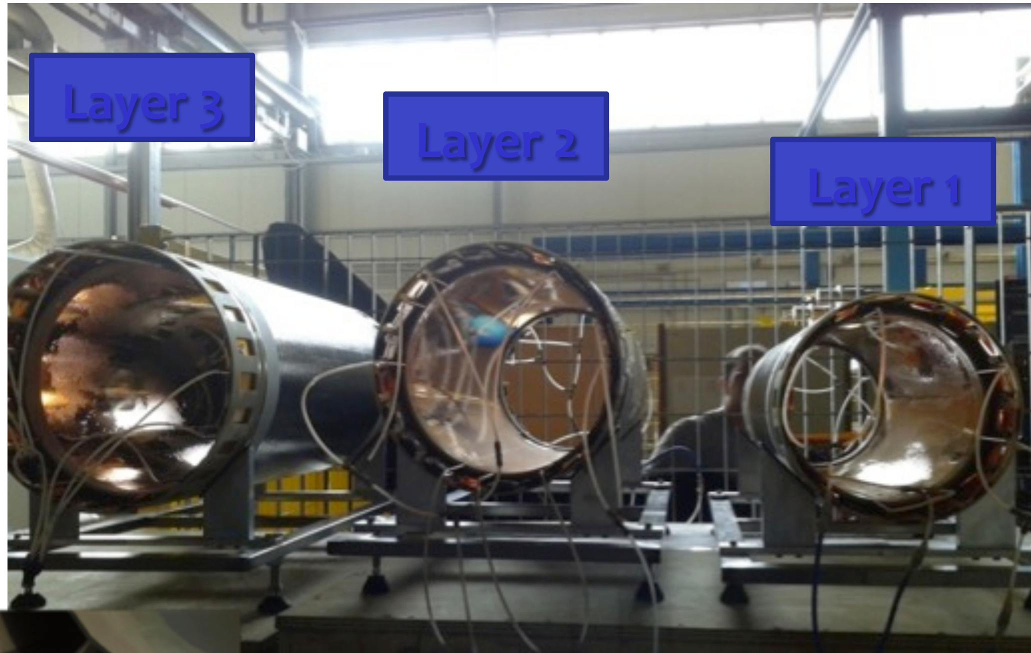
- 11 m from IP
- Scintillator hodoscopes
- $\sigma_E \sim 2.5$ MeV, $\sigma_T \sim 200$ ps





From KLOE to KLOE-2: IP detectors

Major detector upgrades ready Feb 2013.
Installation will start April 2013

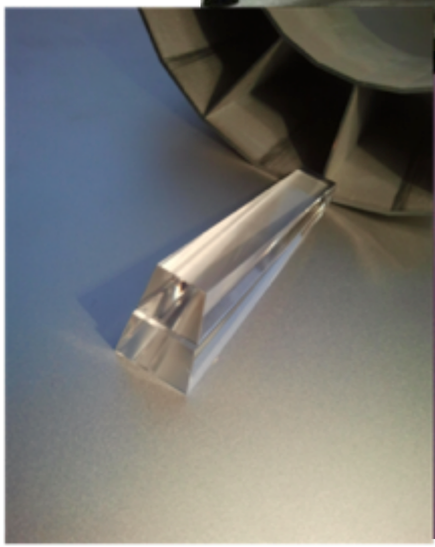


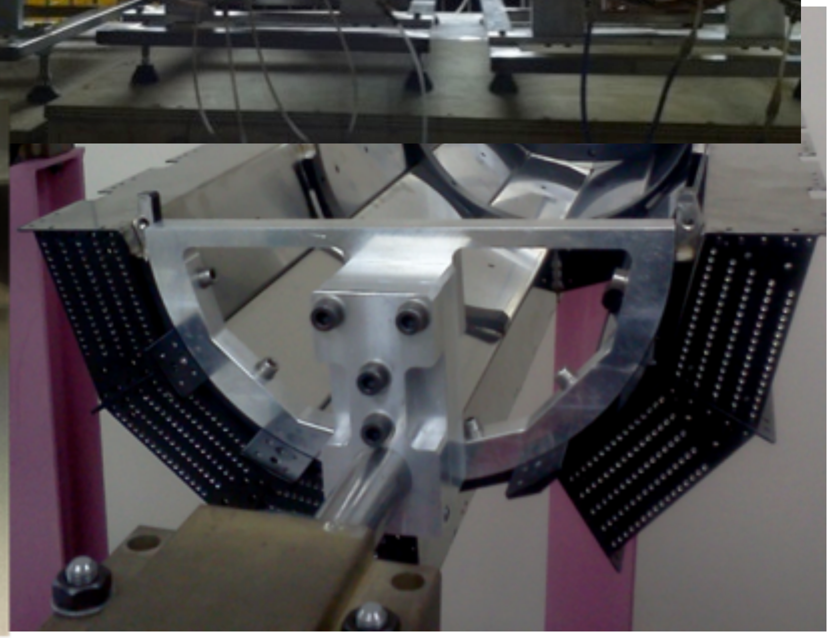
INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks
- 4 Layer completed 10 days ago

QCALT

- W/Cu + tiles +WLS/SiPM
- QUADS coverage for photons from K_L decays
- Calorimeter ready, FEE dressing in progress





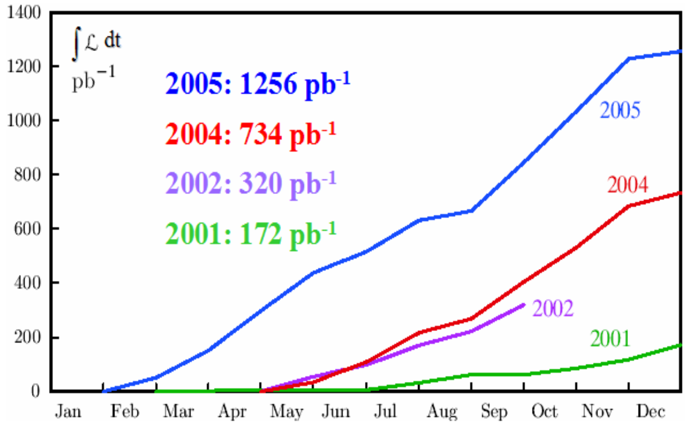
CCAL

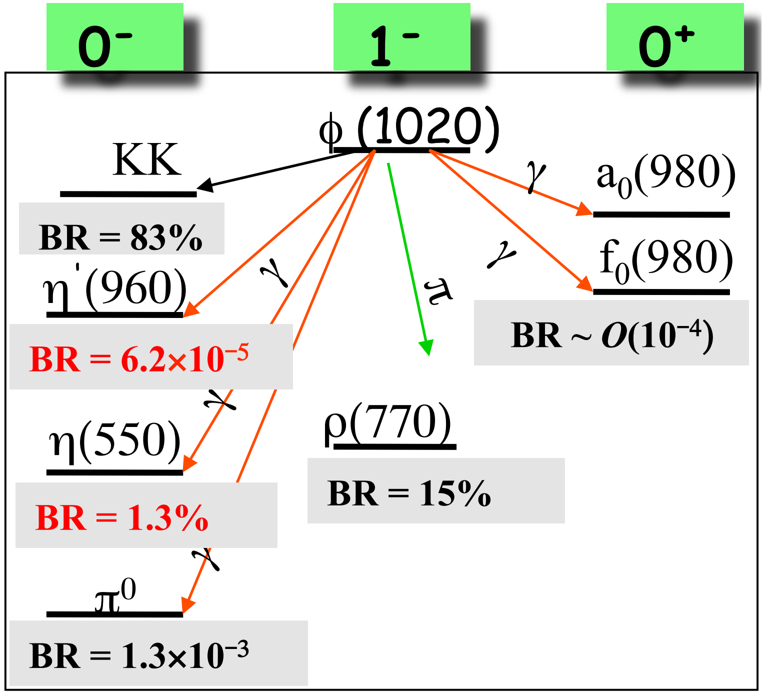
- LYSO + SiPM
- Better acceptance for low angle γ ($21^o \rightarrow 10^o$)

Still harvesting KLOE data…

KLOE dataset (2001-2005):

- ❑ 2.5 fb^{-1} @ $\sqrt{s} = M_\phi$ (~ 8×10^9 ϕ produced)
- ❑ 250 pb^{-1} @ 1000 MeV (off-peak data)





- ❖ ~ 60 publications based on KLOE data set
- ❖ The 'old' KLOE data still produce new amazing results
- ❖ Recent analyses on light mesons will be discussed

- ✧ $\eta \to 3\pi$ ⇒ light quark masses
- ✧ $\eta\ (\eta') \to \pi^+\pi^-\gamma$ ⇒ Box anomaly
- ✧ $\eta' \to \eta\pi\pi$ ⇒ CHPT
- ✧ $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$ ⇒ Transition Form Factors ⇒ Dark photons (U-Bosons)
- ✧ $e^+e^- \to e^+e^-\eta\ (\pi^0)$ ⇒ $\gamma\gamma \to \eta\ (\pi^0)$; Two-photon partial width Transition Form Factors

η→πππ decays and Quark Mass ratio

η→πππ decay ⇒ Isospin violation

$$\mathcal{L}_I = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

$$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$$

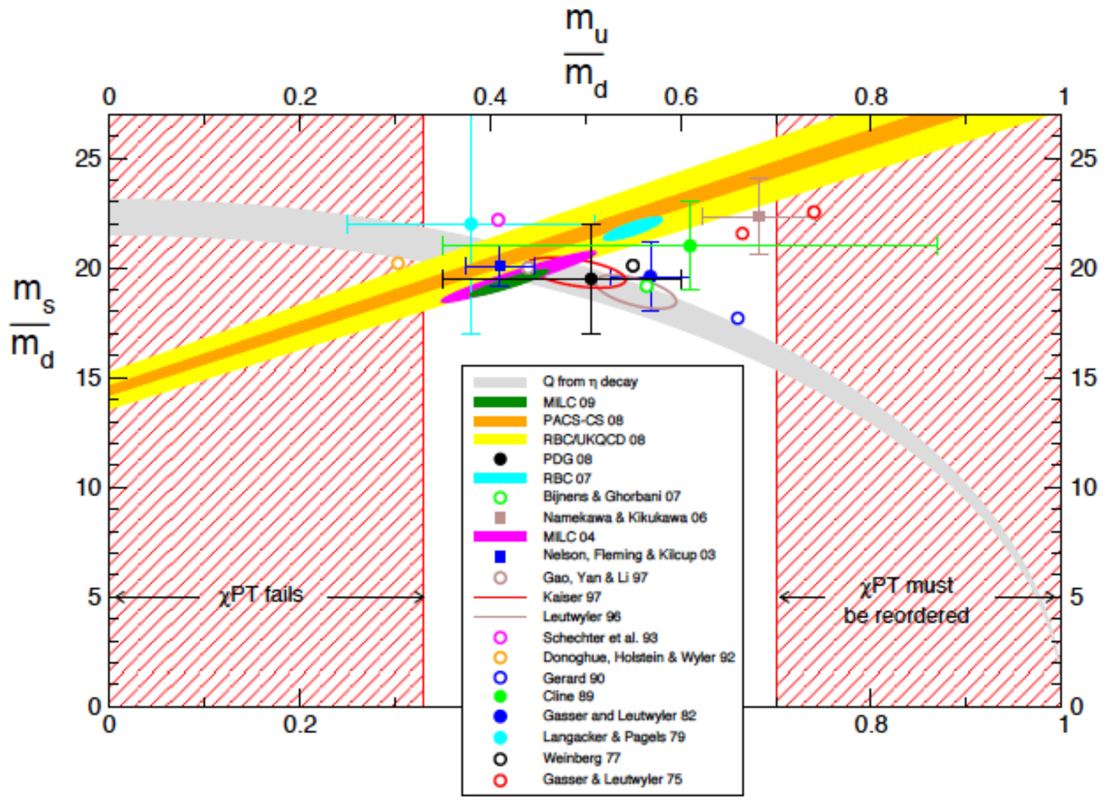
$$\Gamma_{LO}(\eta \to \pi^+\pi^-\pi^0) = 66 \text{ eV}$$
$$\Gamma_{NLO}(\eta \to \pi^+\pi^-\pi^0) = 167 \text{ eV}$$
$$\Gamma_{exp}(\eta \to \pi^+\pi^-\pi^0) = 296 \text{ eV}$$

where

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \qquad \left(\hat{m} = \frac{1}{2}(m_u + m_d)\right)$$

Determining Q constraints the quark mass ratios

[Leutwyler, PoS CD09(2009)005]



$\eta \to \pi^+\pi^-\pi^0$ data from 2004 KLOE data

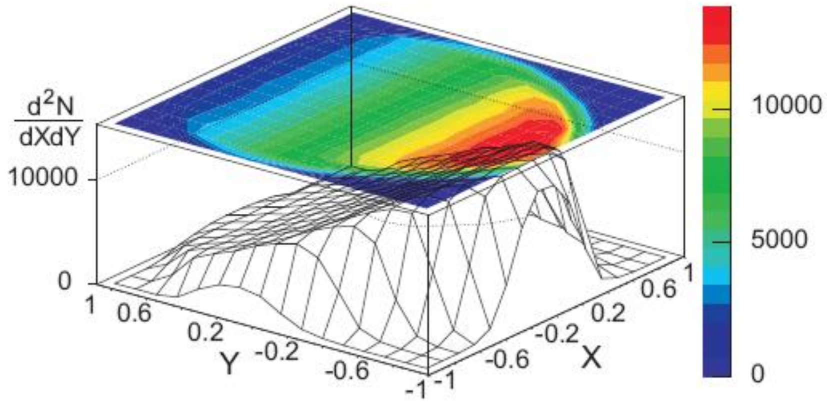
$\phi \to \eta\gamma$ ($E_{\gamma rec}$ = 363 MeV)
with $\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$ final state
450 pb^{-1} $\Rightarrow$ 1.34 × 10^6 events in the Dalitz plot

$$X = \sqrt{3}\frac{E_+ - E_-}{\Delta}$$

$$Y = 3\frac{E_0 - m_0}{\Delta} - 1$$

$$(\Delta = m_\eta - 2m_{\pi^\pm} - m_0)$$

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



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

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

[JHEP0805(2008)006]

$\eta\to\pi^0\pi^0\pi^0$ data from 2004 KLOE data

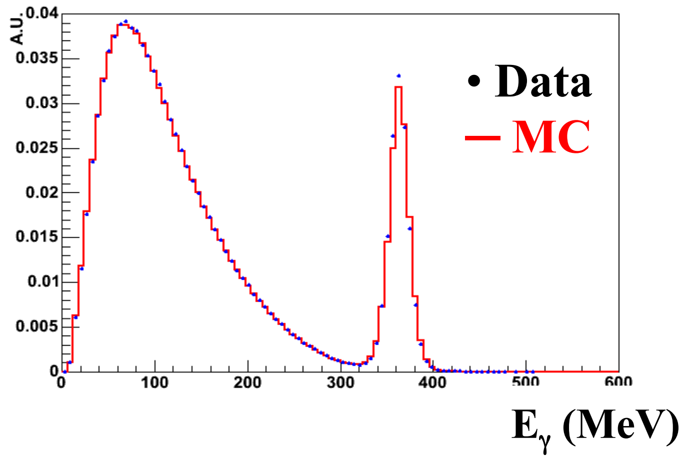
- **Symmetric Dalitz plot:**

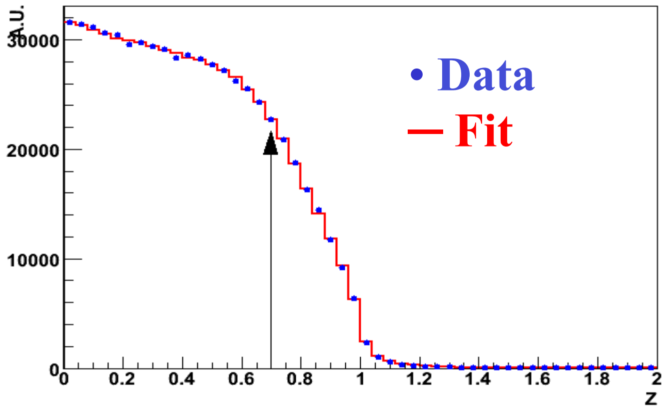
$|A|^2 \propto 1 + 2\,\alpha\, Z \quad \Rightarrow$ only one

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

(ρ = distance from the Dalitz plot center)

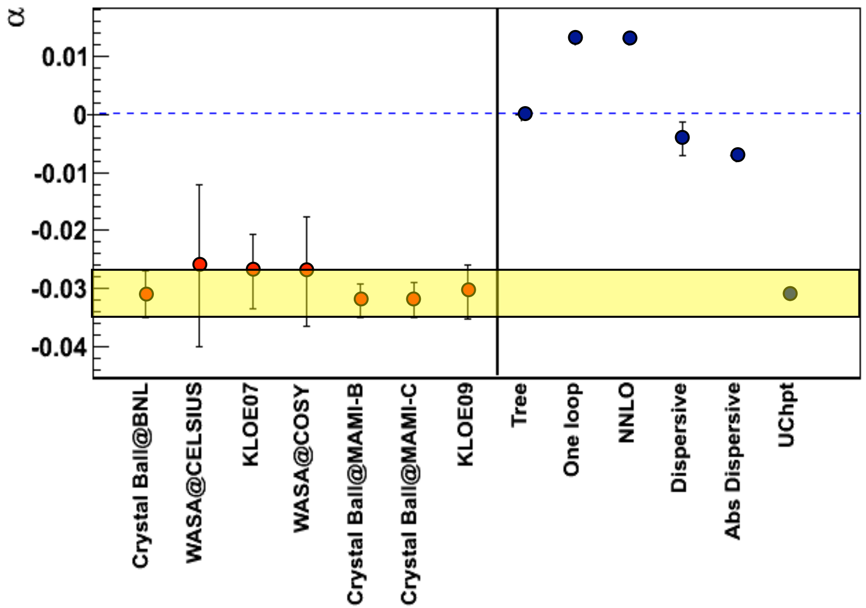
- 450 pb^{-1} ; 7 prompt photons $\Rightarrow 6.5 \times 10^5$ events





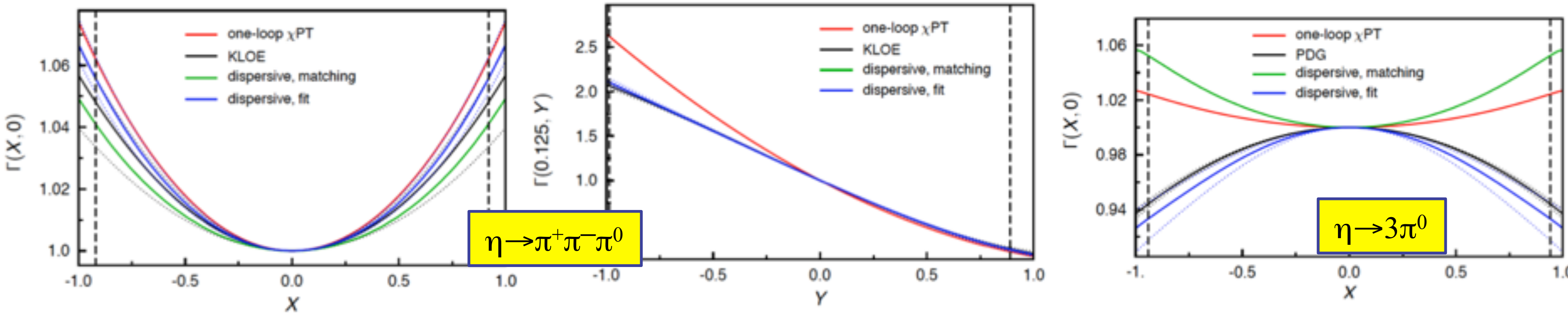
$$\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$$

[PLB 694 (2010) 16]



Q mass ratio constraints from KLOE data

- **Recent dispersive analyses of $\eta\to3\pi$: subtraction constants fixed from a fit to KLOE measurements of $\eta\to\pi^+\pi^-\pi^0$**



$\Rightarrow Q = 21.3 \pm 0.6$ [Colangelo et al. PoS(EPS-HEP2011)304]

and by using $\hat{m}$ and m_s from lattice QCD $\Rightarrow$

$m_u = (2.02 \pm 0.14) MeV$

$m_d = (4.91 \pm 0.11) MeV$

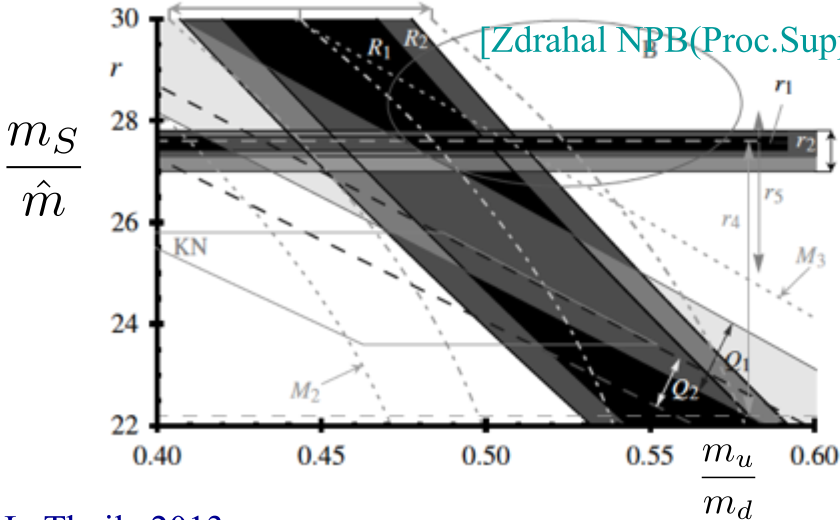
$$\Rightarrow R = \frac{m_S - \hat{m}}{m_d - m_u} = 37.7 \pm 3.3$$

[Kampf et al., PRD84(2011)114015]

$m_u = (2.23 \pm 0.14) MeV$

$m_d = (4.63 \pm 0.14) MeV$

[Zdrahal NPB(Proc.Suppl)219(2011)

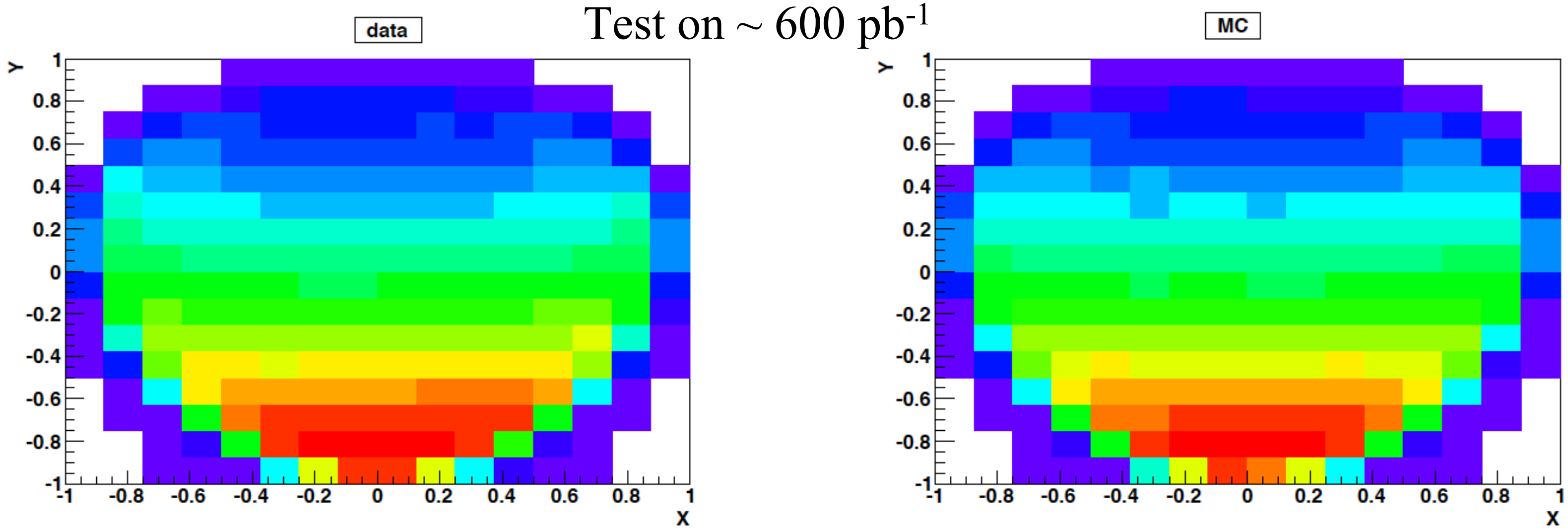


$\eta \to \pi^+\pi^-\pi^0$ data from full KLOE dataset

New analysis of KLOE data in progress to reduce systematics from event selection procedure:

- **Whole dataset, ~ 2.5 fb^{-1}**
- **New analysis scheme**
- **Improved MC simulation**

Test on ~ 600 pb^{-1}

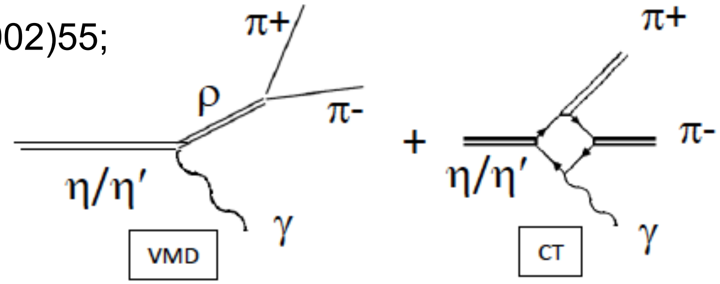


- **With 5 fb^{-1} @ KLOE-2 we also expect ~ 8000 $\eta' \to \pi^+\pi^-\pi^0$ events**

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

Study of the box anomaly: test of ChPT and its unitarized extensions

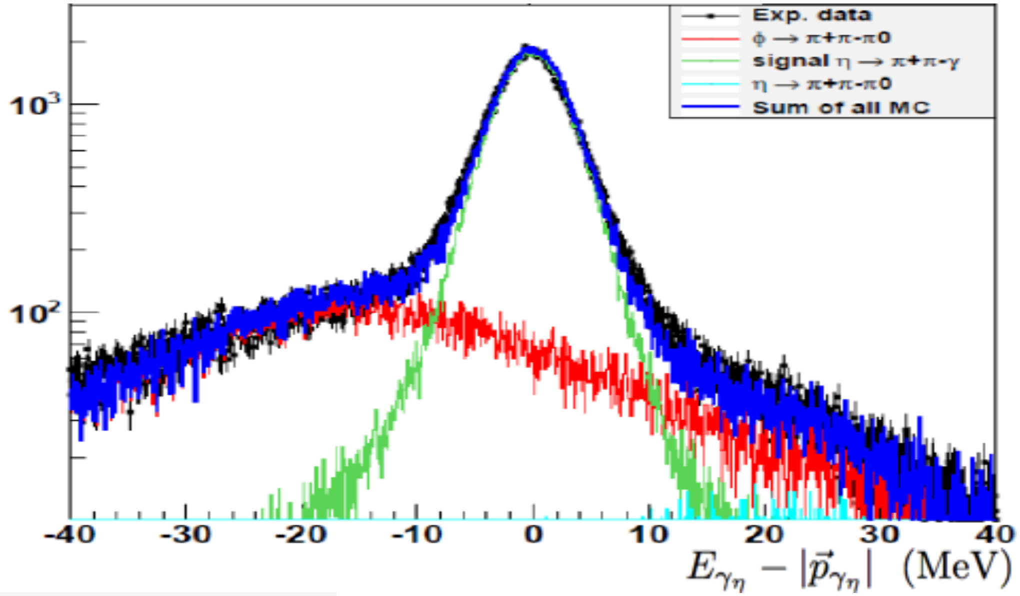
[Benayoun et al. EPJC31(2003)525; Holstein, Phys. Scripta, T99(2002)55; Borasoy, Nissler, NPA740(2004)362, Picciotto PRD45(1992)1569]



Sizeable effect of the Contact Term expected both in $\Gamma(\eta\to\pi^+\pi^-\gamma)$ and in $M_{\pi\pi}$ distribution

- Data sample: **558 pb^{-1}**
- **N($\eta\to\pi^+\pi^-\gamma$) = 204,950**
- **N($\eta\to\pi^+\pi^-\pi^0$) = 1.19×10^6**
- **B/S = 10%** **B/S = 0.65%**
- Main background: $\phi\to\pi^+\pi^-\pi^0$

PLB 78(2013)910

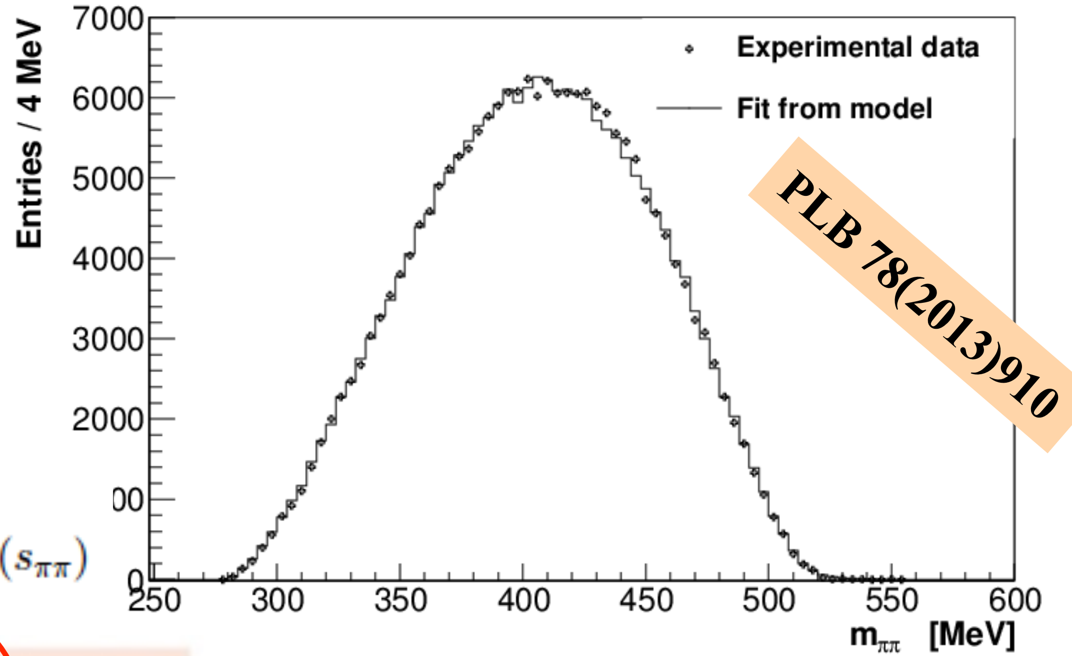


$$\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005_{stat} \pm 0.0028_{syst}$$

Consistent with CLEO measurement, with a factor of 3 improved precision

$\eta \to \pi^+\pi^-\gamma$: fit to the $M_{\pi\pi}$ spectrum

Fit to the $M_{\pi\pi}$ spectrum according to the model independent parametrization of *Stollenwerk et al.* *PLB 707 (2012), 184*



$$\frac{d\Gamma(\eta \to \pi^+\pi^-\gamma)}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2\,\Gamma_0(s_{\pi\pi})$$

$$\mathcal{A}(\delta,\alpha) = \underbrace{A(\delta)}_{\text{fitted to BR}}\left(\underbrace{1+\alpha\, s_{\pi\pi} + \mathcal{O}(s^2_{\pi\pi})}_{\text{extracted from the spectrum}}\right)\underbrace{F_V(s_{\pi\pi})}_{\text{universal}}$$

Reaction-specific term.
Simple ChPT predicts $\alpha \sim 1\ \mathrm{GeV}^{-2}$

$$\alpha = (\,1.32 \pm 0.08_{stat}\ {}^{+0.10}_{-0.09\ syst} \pm 0.02_{th}\,)\ \mathrm{GeV}^{-2}$$

Previous measurement: $\alpha_{WASA} = (\,1.89 \pm 0.25 \pm 0.59 \pm 0.002\,)\ \mathrm{GeV}^{-2}$

PLB 707 (2012) 243

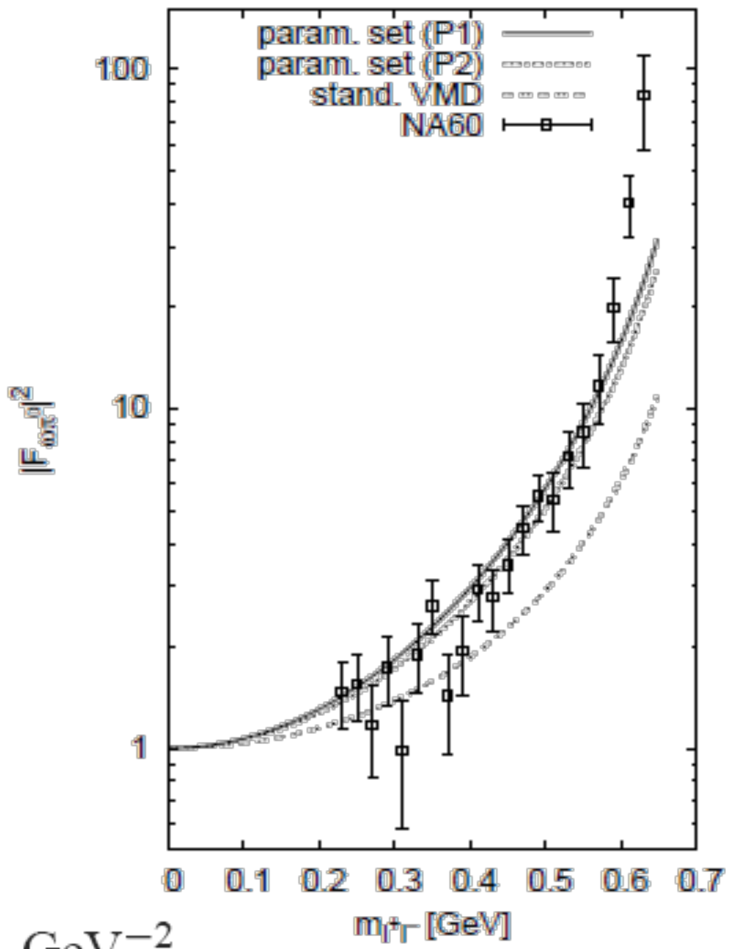
Transition FF from Φ Dalitz Decay

➢ Interest in studying low energy vector and pseudo-scalar Dalitz decay increased.

$VP\gamma^*$ transitions not fully described by VMD
it works for $\eta \to \gamma \ell^+\ell^-$ fails for $\omega \to \pi^0 \ell^+\ell^-$

$$\frac{d}{dq^2}\frac{\Gamma(\phi\to\eta e^+e^-)}{\Gamma(\phi\to\eta\gamma)} = \frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times$$

$$\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$



FF slope:

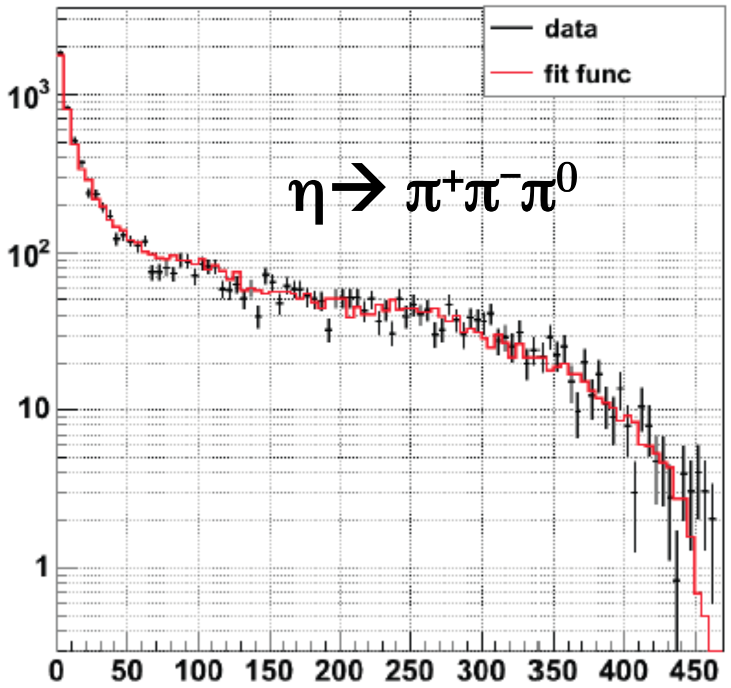
$$F(q^2) = \frac{1}{1-q^2/\Lambda^2}$$

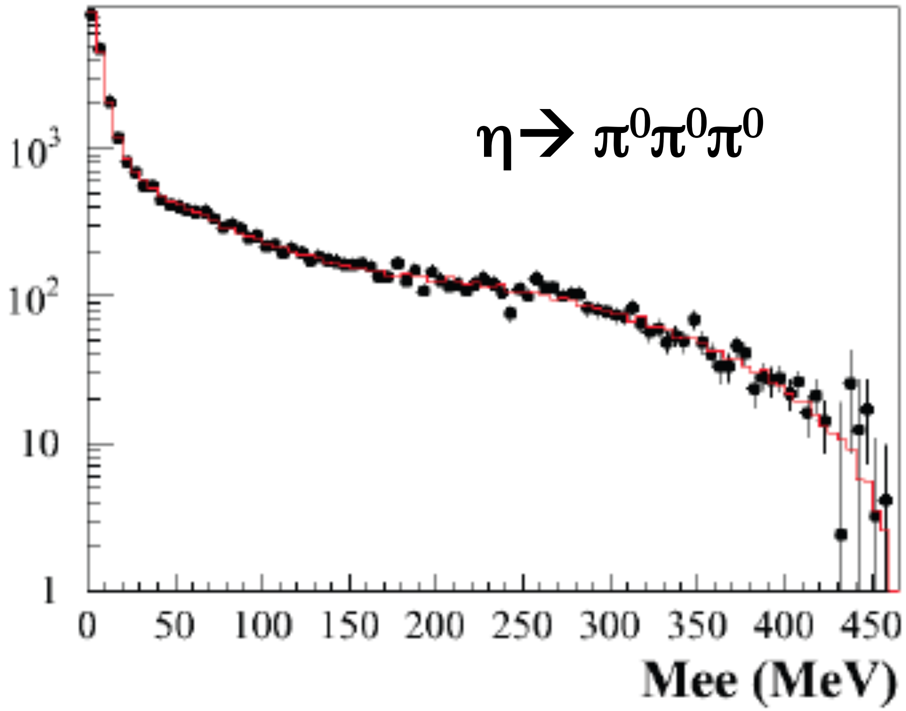
$$\begin{cases} b = dF/dq^2|_{q^2=0} \\ b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} \approx 1/m_\phi^2 \approx 1\ \mathrm{GeV}^{-2} \end{cases}$$

- **$\phi\to\eta e^+e^-$: Λ^{-2} = (3.8 ± 1.8) GeV^{-2} (~ 50% error) SND @ VEPP-2M**

$\Phi \rightarrow \eta$ e+e- Dalitz Decay

- Slopes measurement for the $\Phi \rightarrow \eta\, e^+e^-$ decay in progress with ~ 1.7 fb^{-1} and for two main η decay channels ($\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$)
- Progresses also for the measurement of $\Phi \rightarrow \pi^0 e^+e^-$
- Plans to study also PS → Vγ^* exist (e.g. $\pi^0,\eta \rightarrow \gamma$ e+e−)





- ✓ **High precision on slope reachable (few % w.r.t. 50% of SND measurement)**
- ✓ **Very different systematics on the two channels. Combined fit planned**

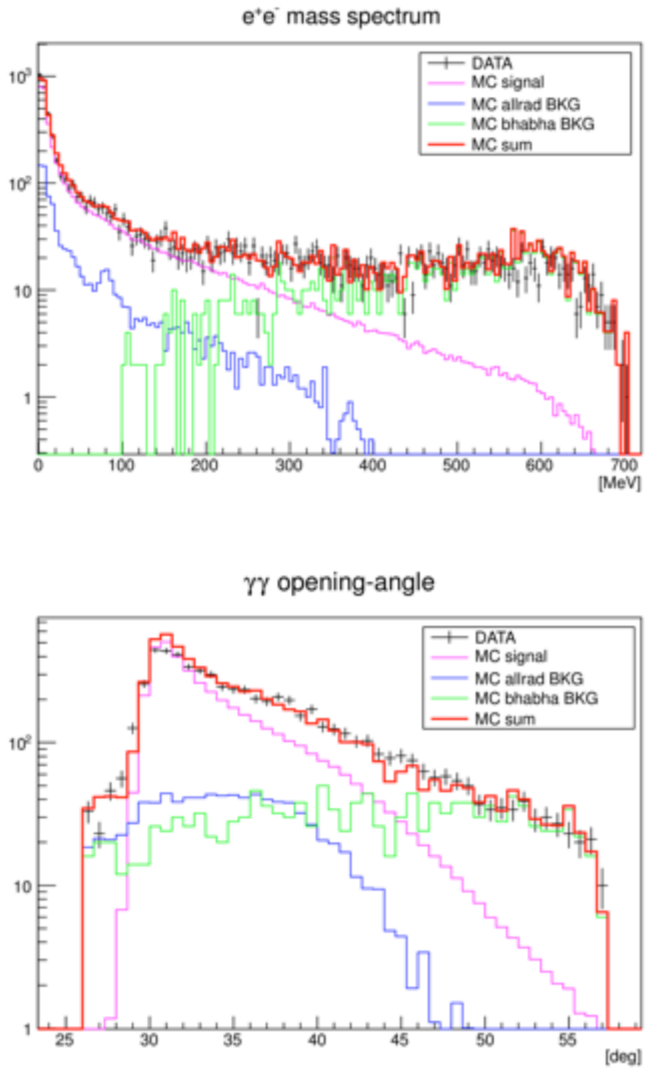
$\Phi \rightarrow \pi^0 e^+e^-$ Dalitz Decay

- **BR($\phi \rightarrow \pi^0 e^+ e^-$) = (1.12±0.28)×$10^{-5}$**

  ⇒ 25% uncertainty
- **SND ⇒ 52 ; CMD-2 ⇒ 46 events**
- **Events with 2 tracks + 2 prompt photons**
- **Background:**

  radiative Bhabha scattering

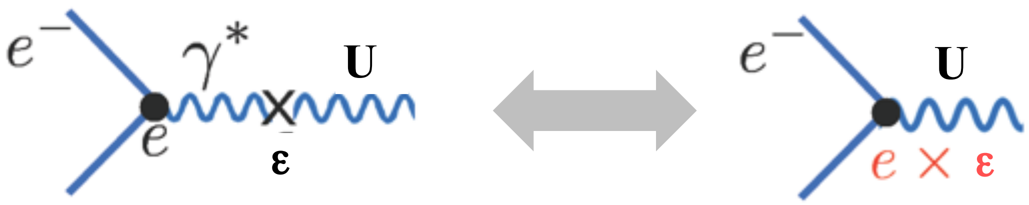
  $\phi \rightarrow \pi^0\gamma$ with photon conversion
- **Signal efficiency ≈ 16%**
- **Data –MC comparison (840 pb^{-1})**
- **Work in progress …**



Low energy dark forces

Several unexpected astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA, CoGent…) could be explained with the existence of a hidden gauge sector weakly coupled with SM through a mixing mechanism of a new **gauge boson (U, A', V…)** with the photon:

[Arkani-Hamed et al. PRD79 015014 (2009)]
[Essig et al., PRD80 015003 (2009)]



$$\varepsilon^2 = \frac{\alpha'}{\alpha_{em}}$$

If the mixing parameter $\varepsilon \sim 10^{-3} - 10^{-4}$ ⇒ observable at KLOE

- **Signature: all Φ Dalits Decays … see next slide**
- **Other DF searches @ KLOE:**

$e^+e^- \rightarrow U\gamma \rightarrow \mu^+\mu^-\gamma$;

$e^+e^- \rightarrow h'U \rightarrow \mu^+\mu^-$ + missing energy

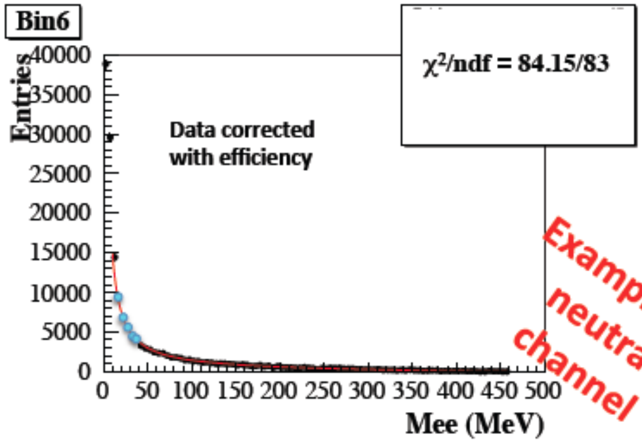
Search for dark forces @ KLOE: $\phi \to \eta U$

Meson having radiative decay to one photon can decay to a U boson with $BR(X \to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times BR(X \to Y\gamma)$

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

Irreducible background:
ϕ **Dalitz decay** $\phi \to \eta\gamma^* \to \eta l^+l^-$

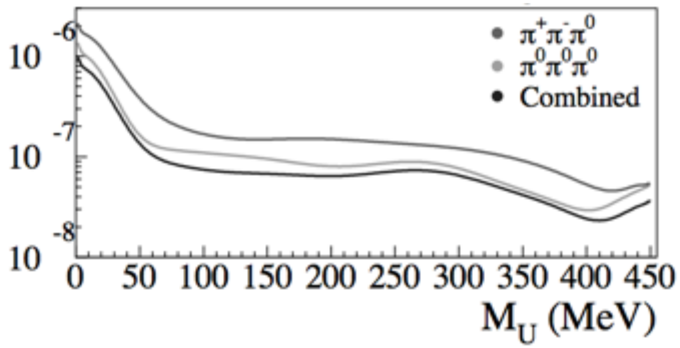
Fit to the M_{ee} distribution to extract bckg shape



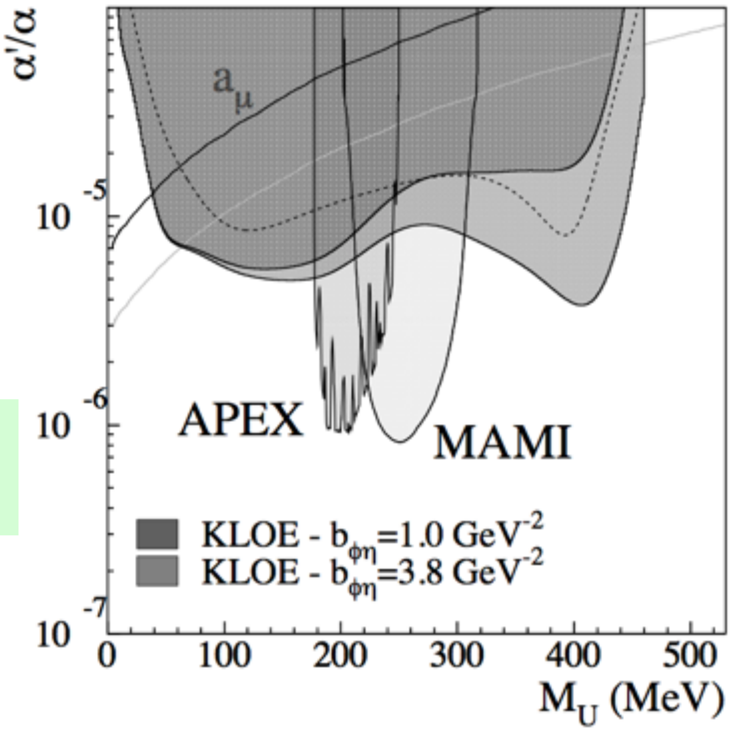
Example neutral channel

PLB online DOI: 10.1016 /j.physletb. 2013.01.067

U.L. on BR($\phi \to \eta U$; $U \to e^+e^-$)



Limit depends on FF slope



$\alpha'/\alpha \leq 1.5\times10^{-5}$ @ 90% C.L. for $30<M_U<420$ MeV
$\alpha'/\alpha \leq 5.0\times10^{-6}$ @ 90% C.L. for $60<M_U<190$ MeV

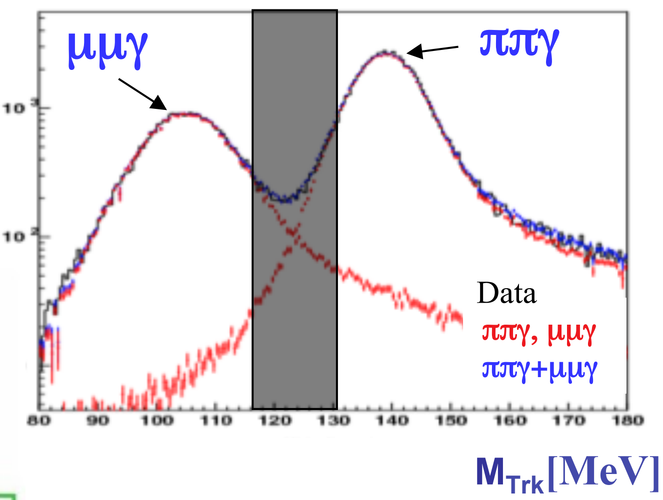
Detour on Hadronic Cross Section

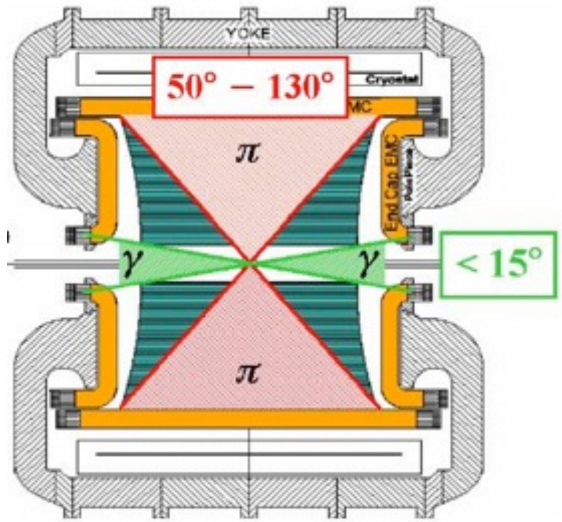
$$|F_\pi(s')|^2 \approx \frac{4\left(1+2m_\mu^2/s'\right)\beta_\mu}{\beta_\pi^3}\;\frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}$$

S.A. analysis same sample as KLOE08

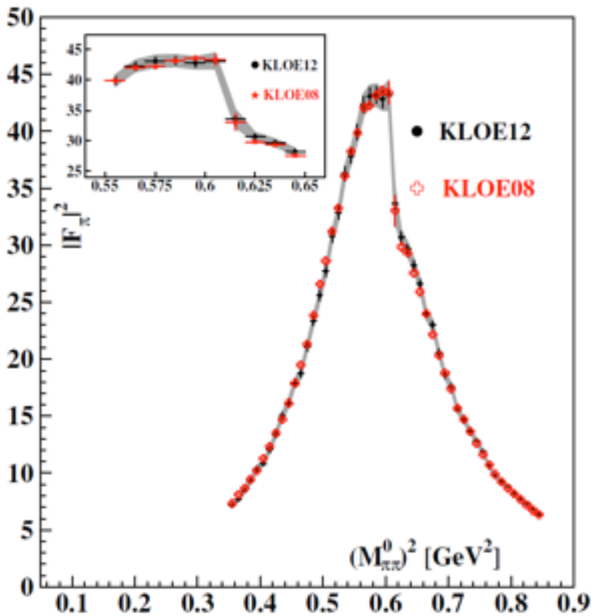
- Measurement done with $\pi\pi\gamma/\mu\mu\gamma$
- Many factors cancel in this ratio:

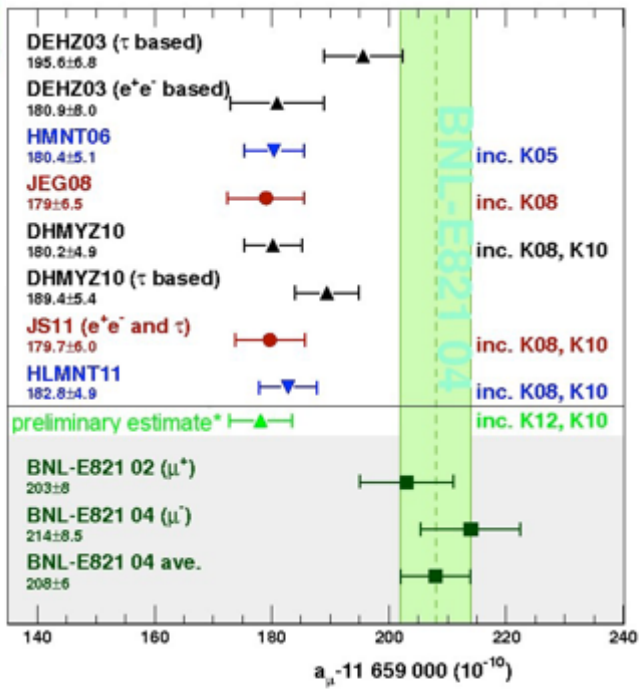
— radiator function
— luminosity from Bhabhas
— vacuum polarization





3 σ discrepancy confirmed



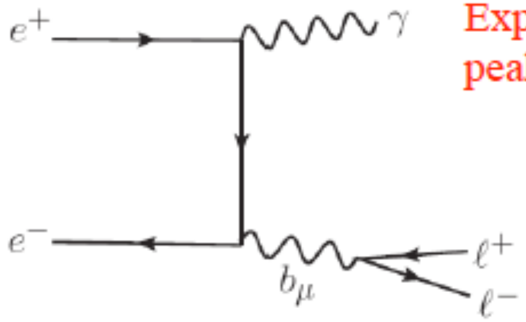


[Accepted by PLB arXiv-submit:0616958]

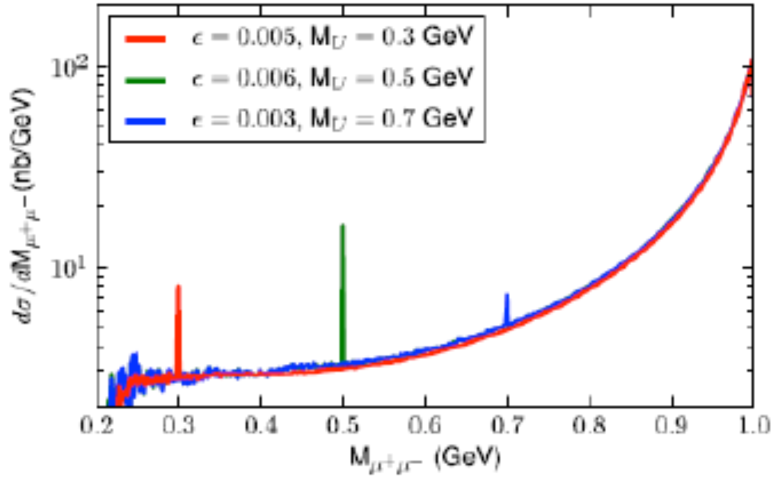
$a_\mu^{\pi\pi}$ (0.35–0.95 GeV^2) = $(385.1 \pm 1.1_{stat} \pm 4.4_{syst} \pm 1.2_{th}) \times 10^{-10}$

.... back to DF searches in e+e→ μμγ

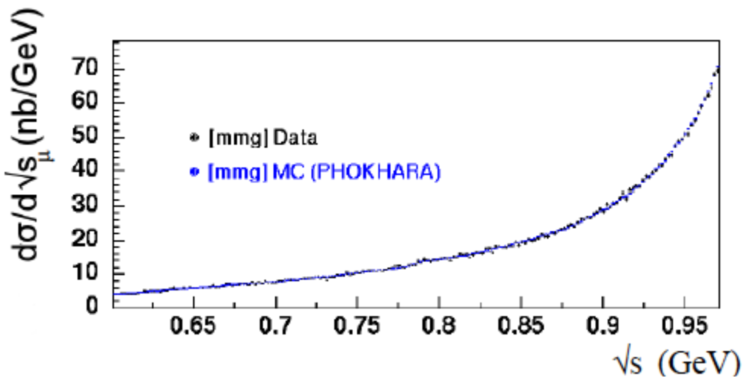
Production of a photon plus an U boson and decay in a lepton pairs: $e^+ e^- \rightarrow U\gamma \rightarrow l^+ l^- \gamma$, $l = e,\mu$

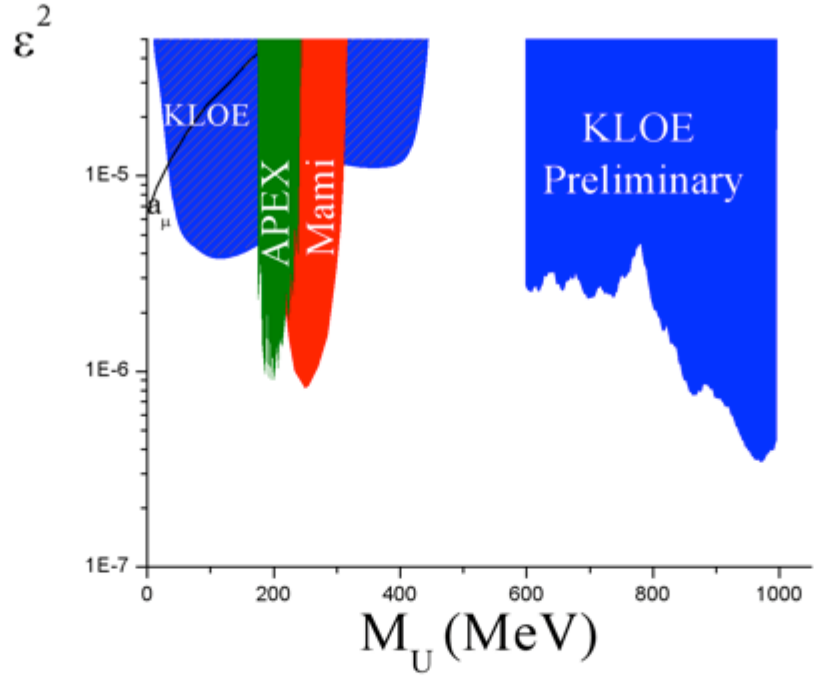


Expect a narrow Breit-Wigner peak above the continuum

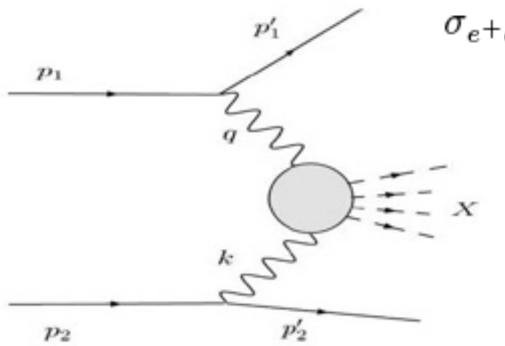


- Upper limit with the CL_s method
- Same sample of F_π (240 pb^{-1} @ M_Φ, SA)
- Full KLOE statistics, 2.5 fb^{-1} + enlarging acceptance → sensitivity x 3 (4)
- Additional factor of 2 from KLOE-2 data-taking





$\gamma\gamma$ physics @ KLOE: $\Gamma_\eta(\gamma\gamma)$ measurement



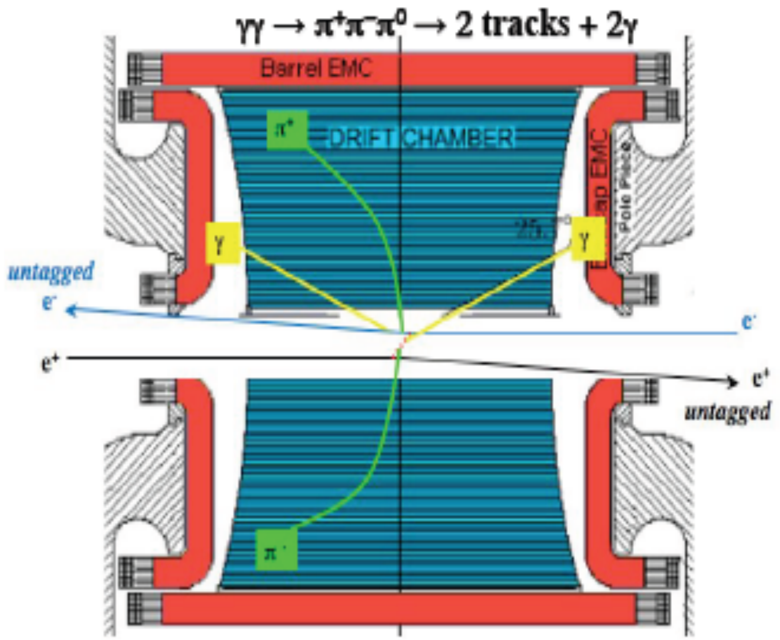
$$\sigma_{e^+e^-\to e^+e^-X} = \frac{16\alpha^2\Gamma_{X\gamma\gamma}}{m_X^3}\left(\ln\frac{E_b}{m_e}\right)^2\left((y^2+2)^2\ \ln\frac{1}{y} - (1-y^2)\ (3+y^2)\right)$$

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

KLOE: **no $e^\pm$ tagging** → **$\sqrt{s}$ = 1 GeV**

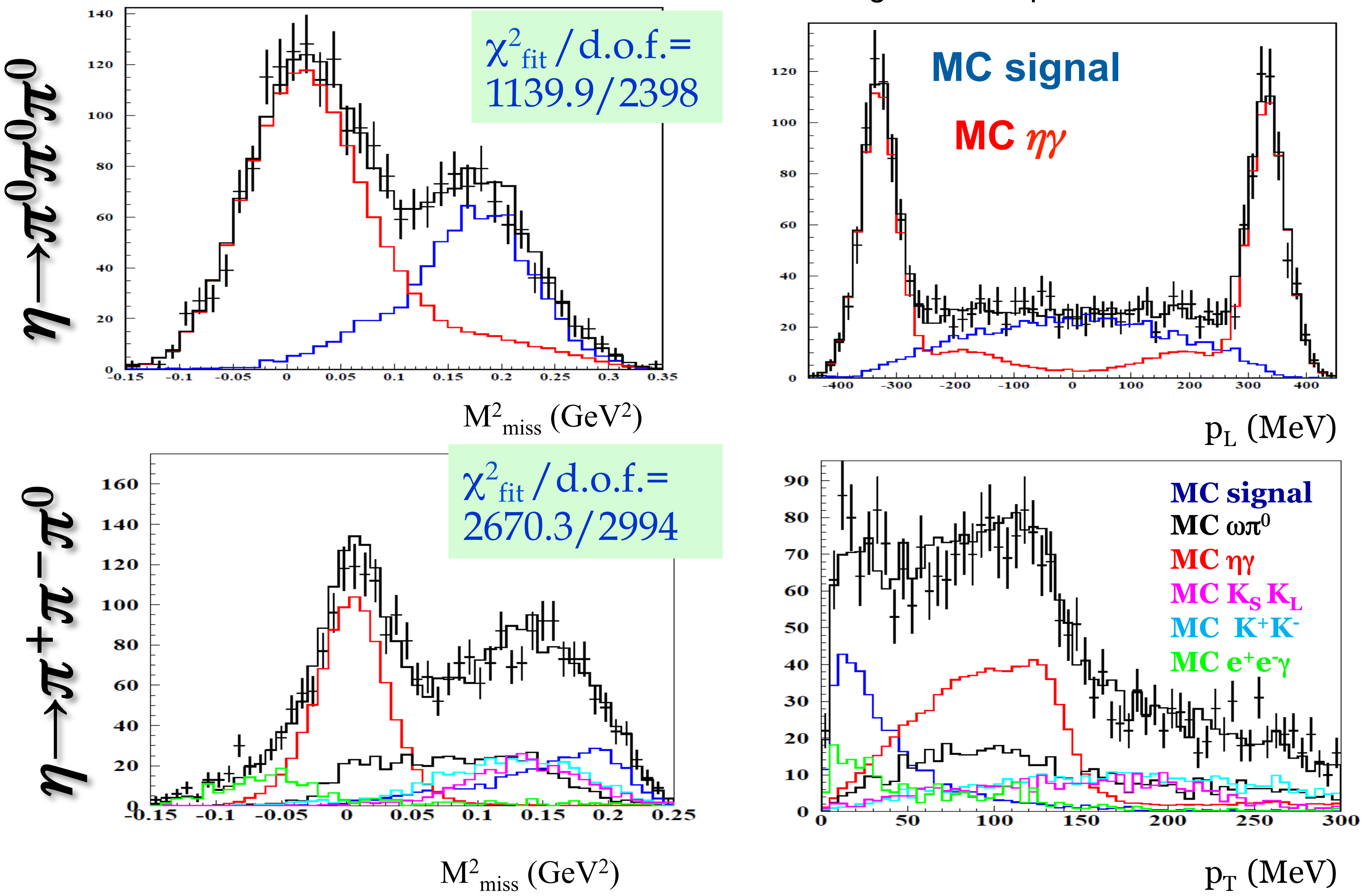
KLOE-2: tagger to reduce background from ϕ and to close kinematics → **$\sqrt{s} = M_\phi$**

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



$\gamma\gamma \to \eta \to \pi\pi\pi$

2D fit to $M_{miss}^2 - p_{L/T}$ plane with signal and background shapes



$\gamma\gamma\rightarrow\eta\rightarrow\pi\pi\pi$: results

JHEP – 1301(2013)119

Neutral channel, ~720 signal events:

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s} = 1\ \text{GeV}) = (32.0 \pm 1.5_{stat} \pm 0.9_{syst} \pm 0.2_{BR(\eta\rightarrow 3\pi)})\ \text{pb}$$

Charged channel, ~390 signal events:

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s} = 1\ \text{GeV}) = (34.5 \pm 2.5_{stat} \pm 1.0 \pm 0.7_{ff} \pm 0.4_{BR(\eta\rightarrow 3\pi)})\ \text{pb}$$

Combined (correlated errors on neutrals, Lum, FF and rel. BRs)

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s} = 1\ \text{GeV}) = (32.7 \pm 1.3_{stat} \pm 0.7_{syst})\ \text{pb}$$

- ***KLOE measurements same precision w.r.t. best previous results***
- ***Extraction of $\Gamma(\eta\rightarrow\gamma\gamma)$ from X-sec measurement, FF and $\gamma\gamma$-flux***

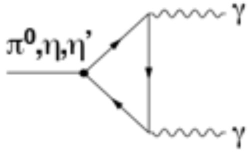
$$\Gamma(\eta \rightarrow \gamma\gamma) = (520 \pm 20_{stat} \pm 13_{syst})\ \text{eV}.$$

In agreement with PDG value of the width 510±26 ev. Most precise single determination

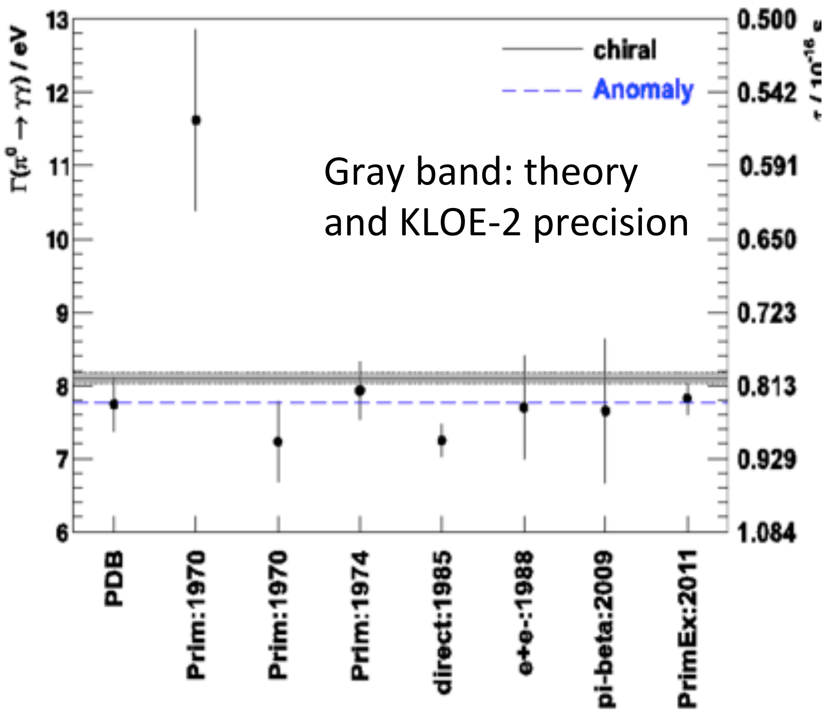
KLOE-2 prospects: $e^+e^-\rightarrow e^+e^-\pi^0$

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ width

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ **at 1%** feasible at KLOE-2 with 5-6 fb^{-1}



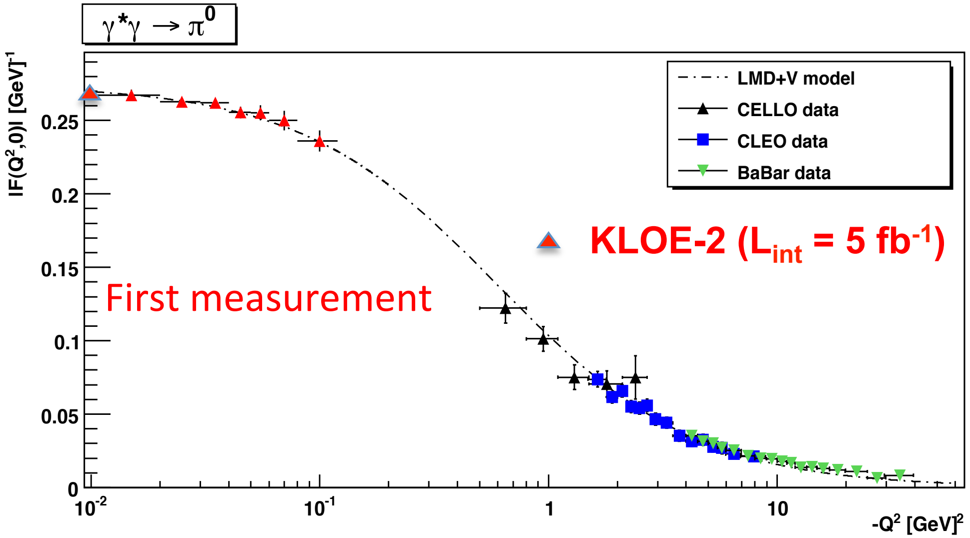
The coincidence between KLOE and HET taggers select a very clean sample of ~1900 events per fb^{-1} (σ_{eff} = 3.4 pb)



$\pi^0 \rightarrow \gamma\gamma^*$ transition form factor in the space-like region at low Q^2

$\mathcal{F}_{\pi^0\gamma\gamma^*}$ **at 5-6%** feasible at KLOE-2 with 5 fb^{-1}

The coincidences between KLOE and one of the HET stations are used



Light-by-light term to muon anomaly : both measurements, width and $\mathcal{F}_{\pi^0\gamma\gamma^*}$ contribute to a factor of ~2 reduction in the theoretical error, dominated by pseudoscalar (π^0) contribution

Conclusions

- The KLOE high statistics data sample still **produces copious results in light hadronic physics** such as η,η', Dalitz decay of ϕ, η, π , $\gamma\gamma$-physics, hadronic cross section, Kaon decays and interferometry, Dark bosons

- **DAΦNE commissioning concluded**
  - KLOE detector ~ operational, KLOE-2 upgrades being completed
  - Installation of new detectors will start in few weeks
  - Expect to collect O(10 fb^{-1}) in the next 2-3 years

- **Rich physics program available for KLOE-2** [Eur. Phys. J. C 68 (2010), 619]

For light hadron physics

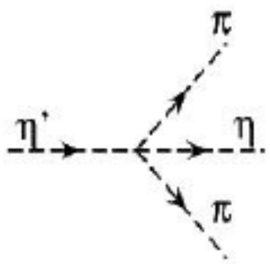
- **study of η and η' decays, CHPT in $\eta \to \pi^0\gamma\gamma$, η' decay**
- **η / η' mixing → gluonium content**
- **$\gamma\gamma$ processes at $\sqrt{s} = M_\phi$ (with $e^\pm$ taggers):
  $\Gamma(\pi^0 \to \gamma\gamma)$, $P\gamma\gamma$ transition form factors,
  scalar mesons: $\sigma(600)$ in $\gamma\gamma \to \pi^0\pi^0$;**

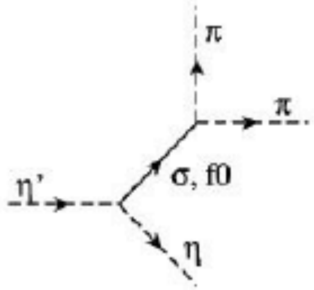
ADDITIONAL MATERIAL

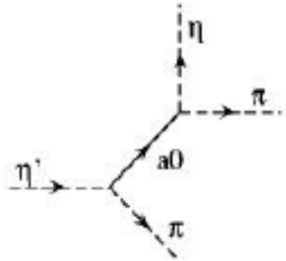
Study of η − π interactions in $\eta' \to \eta\pi^+\pi^-$

- Study η-π interaction
  - Quantum numbers favor scalar resonances

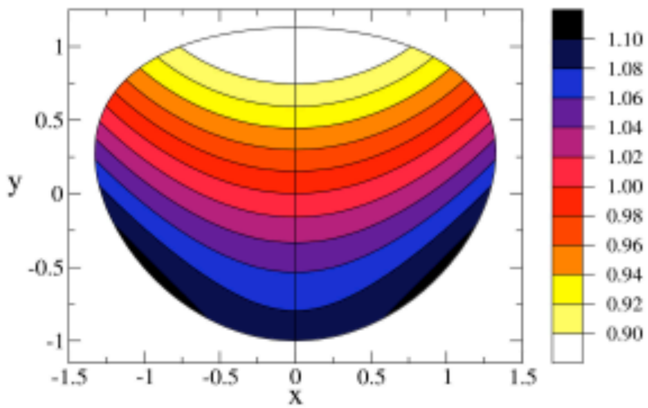
[Faribortz-Schechter,PRD60(1999)034002]



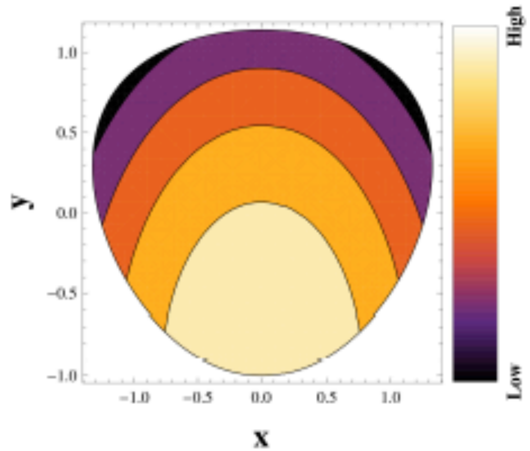




- Test predictions of ChPT and extensions



a_0(980) I=1 dominance
Borasoy et al. EPJ A26 (2007) 383



LN_c-ChPT
Escribano et al. JHEP 1105 (2011) 094

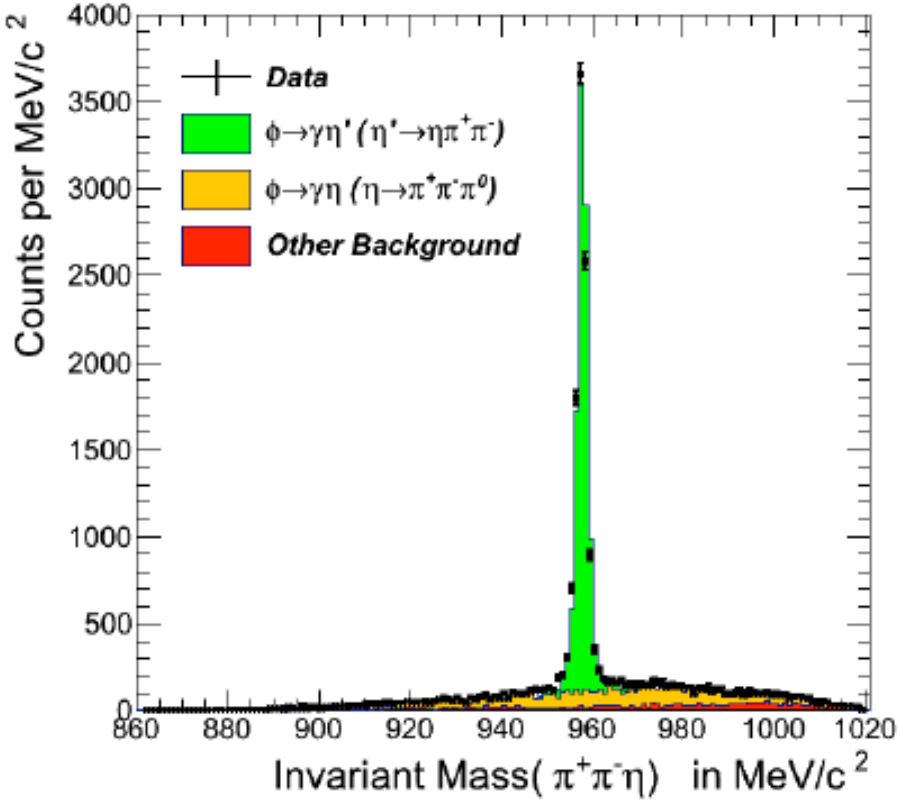
$$X = \frac{\sqrt{3}(T_{\pi^+}-T_{\pi^-})}{T_{\pi^+}+T_{\pi^-}+T_\eta}$$

$$Y = \frac{m_\eta+2m_{\pi^\pm}}{m_{\pi^\pm}}\frac{T_\eta}{T_{\pi^+}+T_{\pi^-}+T_\eta}-1$$

- Predictions differ on percent level → high precision needed

Study of η−π interactions in $\eta' \rightarrow \eta\pi^+\pi^-$

- 1.7 fb^{-1} analyzed
- Background suppression by multiple hypothesis kinematic fitting
- Main background $\eta \rightarrow \pi^+\pi^-\pi^0$
- B/S = 0.2
- ε = 23%
- 10160 ± 110 events reconstructed



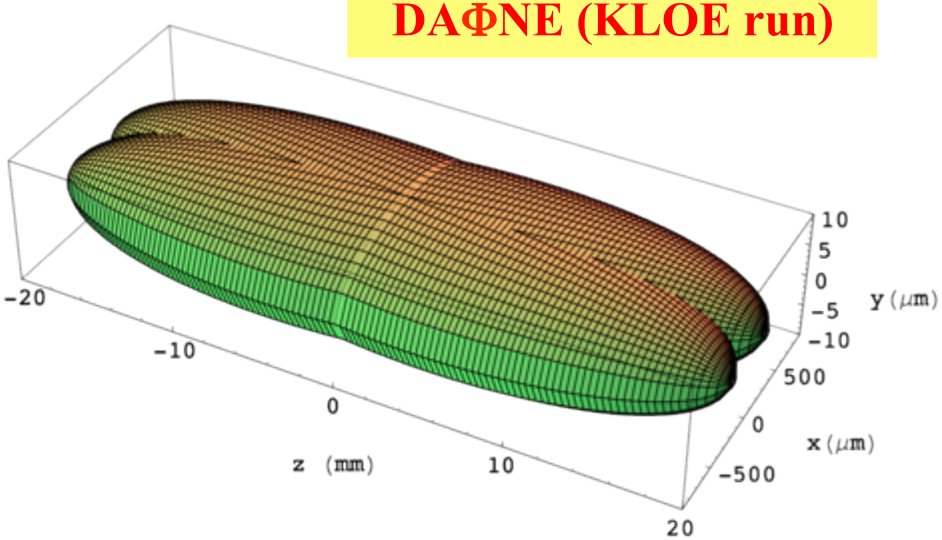
Previous Measurements:

BNL (sum)	1400 events	Phys. Rev. D10 916 (1974)
CLEO	6700 events	Phys. Rev. Lett. 84 26 (2000)
VES	7000 events	Phys. Lett. B651, 22-26 (2007)
BES III	44000 events	Phys. Rev. D83, 012003 (2011)

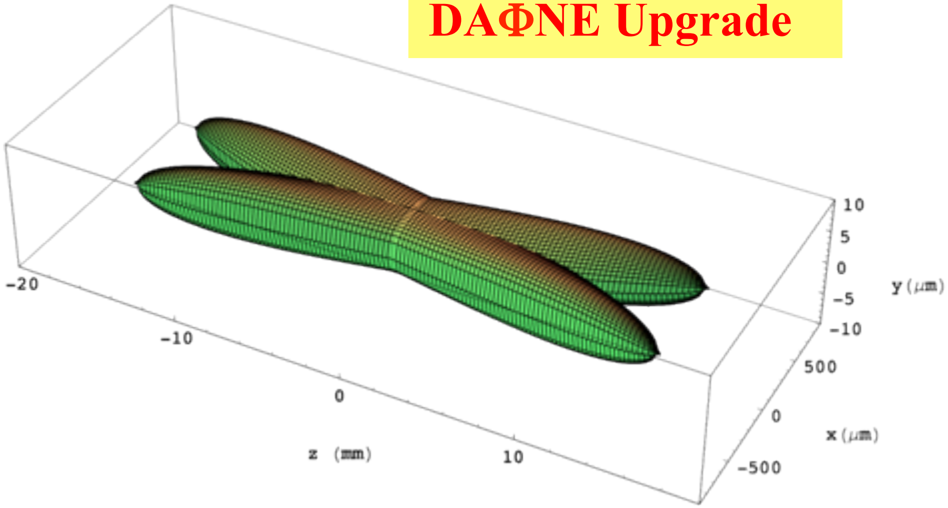
With 10 fb^{-1} @ KLOE-2 we expect ~ 50000 $\eta' \rightarrow \eta\,\pi^+\pi^-$ events

DAΦNE: beam profiles @ IP and parameters

DAΦNE (KLOE run)

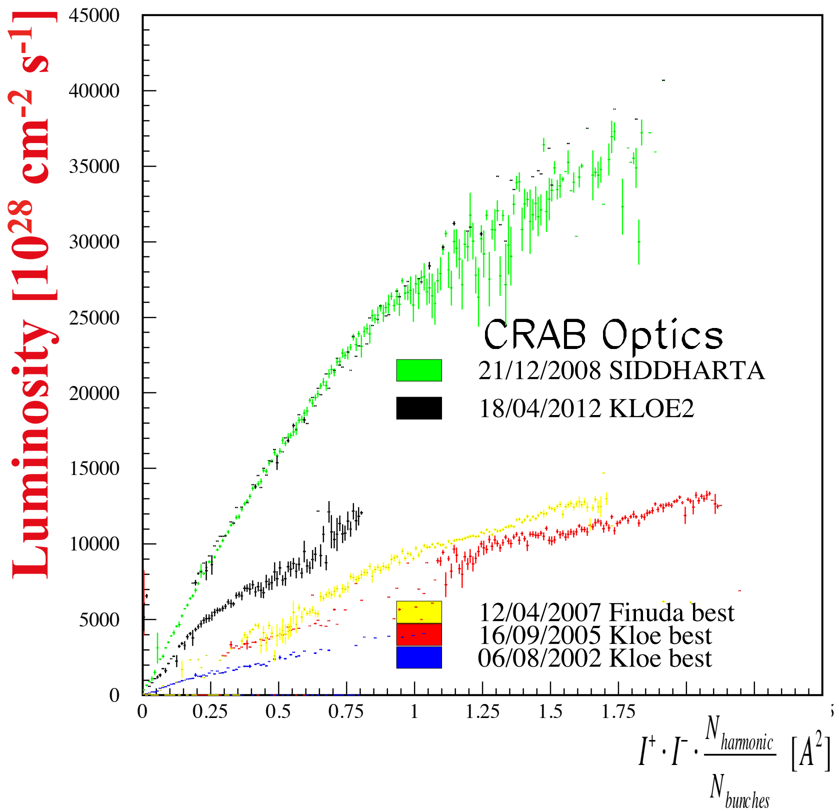


DAΦNE Upgrade



	DAΦNE (KLOE run)	DAΦNE Upgrade
I_{bunch} (mA)	13	13
N_{bunch}	110	110
β_y^* (cm)	1.7	0.65
β_x^* (cm)	170	20
σ_y^* (μm)	7	2.6
σ_x^* (μm)	700	200
σ_z (mm)	25	20
θ_{cross} (mrad) (half)	12.5	25
$\Phi_{Piwinski}$	0.45	2.5
L ($cm^{-2}s^{-1}$)	1.5×10^{32}	$>5 \times 10^{32}$

Commissioning of the KLOE-2 run



Best performances:

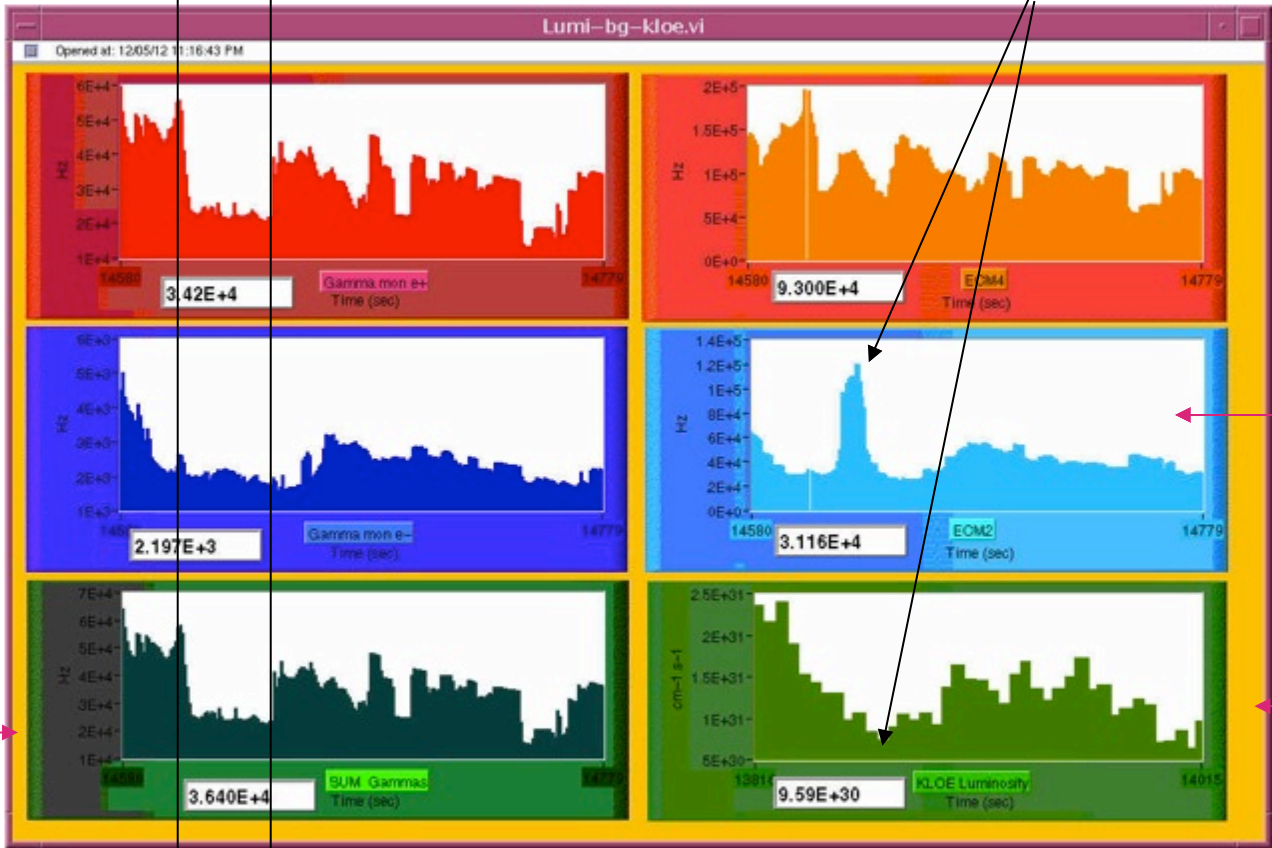
- L = 1.5×10^{32} cm^{-2}s^{-1} (0.8 mA + 0.8mA) (as best KLOE run with 1.8 A + 1.3 A)
- Background level x 2-3 w.r.t. KLOE

- First collisions for KLOE-2 @ end 2010, followed by long machine shutdowns due to severe hardware problems
- DAΦNE commissioning started on November 2011
- Performances obtained for the Siddharta 2008 run not yet reached
- Machine studies concluded → now 6 months shutdown to install upgrades → Temperature control on BeamPipe
- Crab Waist is working→ machine optimization still to be done
- New beam pipe under construction.

- Max integrated Lum~ 8.2 pb/day
- Max Lum/hour ~ 420 nb sustained for 10 hours → O(10 pb/day)
- **Max lum expected O (20 pb/Day) x 200 dd/year ~ 4 fb/Year**

OFF ON

Min luminosity, highest background when the sextupoles are OFF



KLOE background

DAΦNE luminosity monitor

KLOE luminosity monitor

Steps toward higher Luminosity

da 2.x fb-1/year a 3.5 fb-1

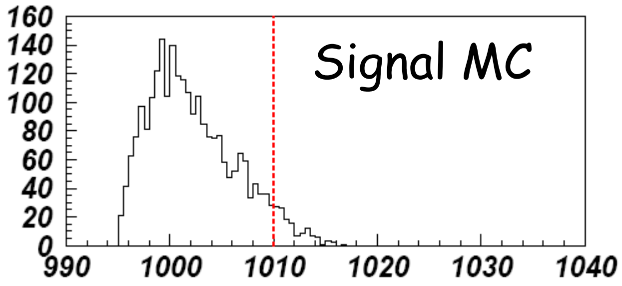
1. Optics
2. Stronger crab waist sextupoles
3. Beam dynamics optimization
4. Higher beam currents
5. More bunches (102 → 110-112)
6. New power supplies for e-cloud clearing electrodes
7. Machine studies and fine tuning
8. Better vacuum (conditioning, scrabbing)
9. Improved injection by implementing fast kickers
10. Higher uptime coming from more reliable & stable subsystem

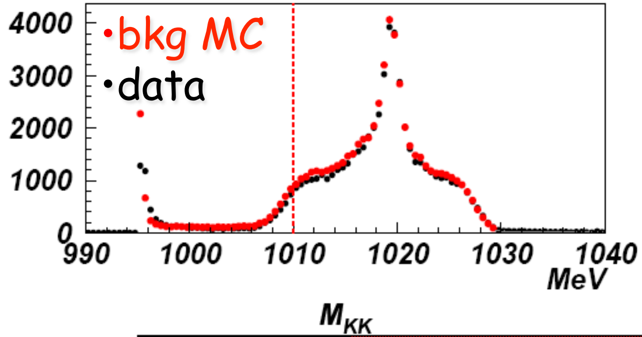
C. Milardi

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

- $K^0\bar{K}^0$ with scalar quantum numbers ($J^{PC}=0^{++}$)
- Small phase space ($2M_K \leq M_{KK} \leq M_\phi$)
  $\Rightarrow$ small Br expected ($10^{-9} - 10^{-7}$)

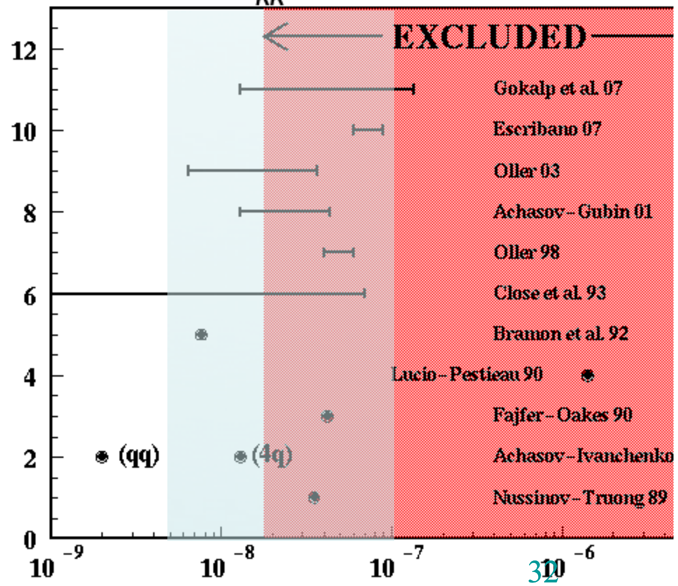
- "Golden channel" $\phi \to K_S K_S \gamma \to \pi^+\pi^-\pi^+\pi^-\gamma$
- Analyzed sample: **2.2 fb^{-1}**
- **5 events in data and 3.2 background events (MC) ($\pi^+\pi^-\pi^+\pi^-(\gamma)$ from $\phi \to K_S K_L$ and from continuum)**





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

[PLB679(2009),10]



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

$$\Rightarrow \quad Br(\phi \to K^0\bar{K}^0\gamma) = 4 \times 19^{-9} - 6.8 \times 10^{-8}$$

KLOE-2: sensitivity for Br $\Rightarrow$ 5×10^{-9}
(with Inner Tracker)

$\Rightarrow$ First observation possible

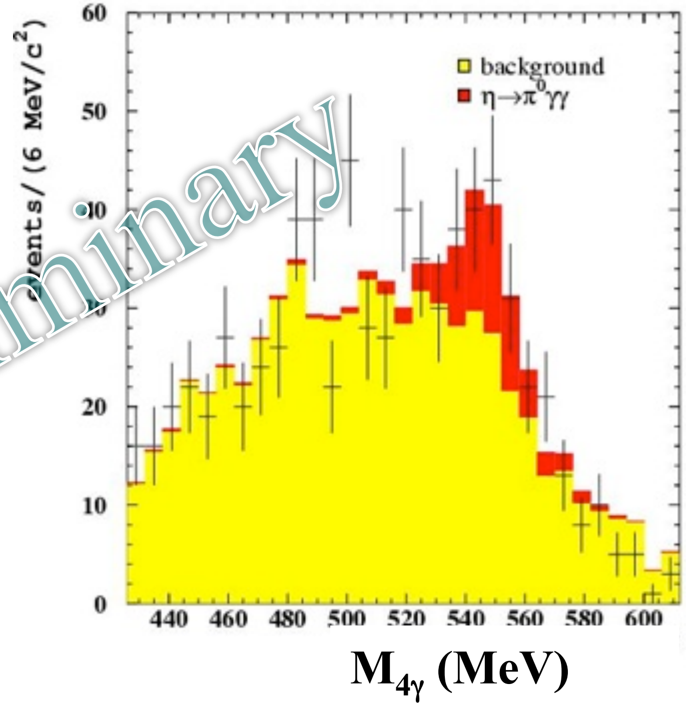
$\eta \to \pi^0 \gamma\gamma$

- ChPT: $O(p^2) \propto Q = 0$;
  $O(p^4)$ @ tree level = 0; $O(p^4)$ @ 1 loop suppressed by G-parity
  $\Rightarrow O(p^6)$ test
- Prev. measurements $\Rightarrow Br(\eta \to \pi^0 \gamma\gamma)$: $(7.2 \pm 1.4) \times 10^{-4}$ GAMS (1984)
  $< 8.4 \times 10^{-4}$ @90% C.L. SND (2001)
  $(22.1 \pm 2.4 \pm 4.7) \times 10^{-5}$ Crystal Ball@AGS (2008)
  $(22.4 \pm 4.6 \pm 1.7) \times 10^{-5}$ Crystal Ball@MAMI(2009)

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

- $L \approx 450$ pb^{-1}

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



KLOE-2 prospects: search for U boson

- Analysis of $e^+e^- \to U\gamma \to \mu\mu\gamma$ planned on:

  i) 2 fb^{-1} sample with small-angle (un-detected SA) photon

  ii) 200 pb^{-1} @ 1 GeV sample with large-angle (detected) ISR photons

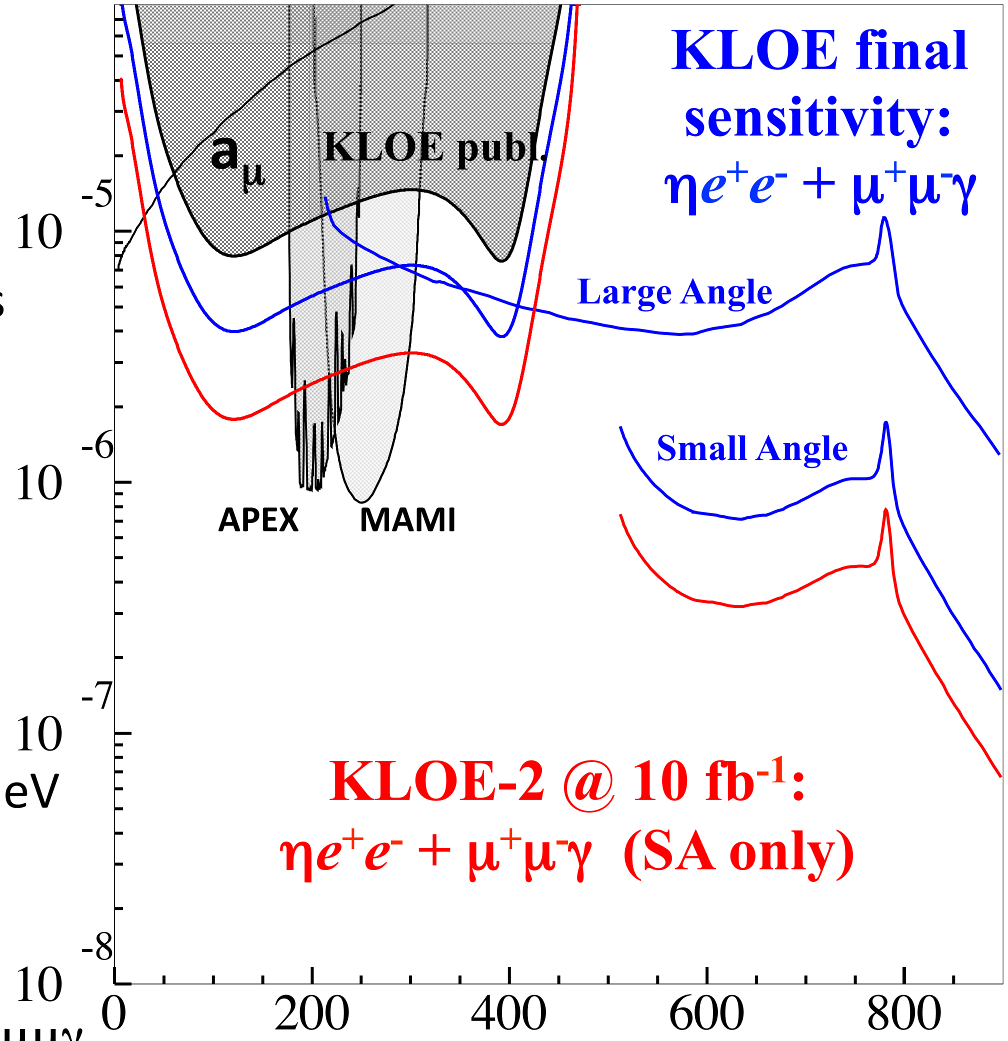
  .

  → SA will provide the best results in the range ~ 500 <M_U< 1000 MeV

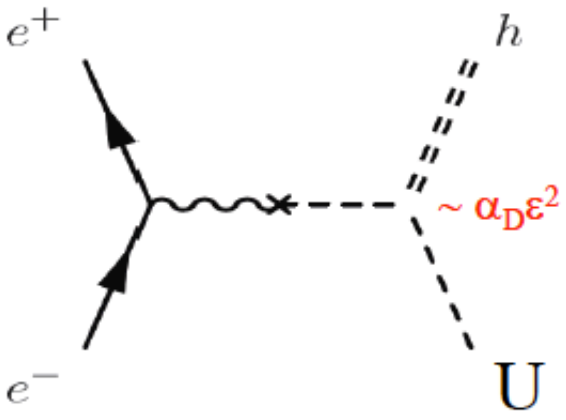
- KLOE-2 @ 10 fb^{-1} will improve of a factor of ~ 3:

  → in the mass range 100<M_U<400 MeV with the $\phi \to \eta U$ channel

  → in the mass range 500-1000 MeV with the SA sample of $e^+e^- \to U\gamma \to \mu\mu\gamma$



Dark forces : ee → hU higgsstrahlung process



Very different scenarios depending on

- $m_h < m_U \Rightarrow$ **"invisible"**
- $m_h > m_U \Rightarrow h \to uu \to 4l, \pi + 2l, \pi$

$\varepsilon = 10^{-3}$

$\alpha_D = \alpha_{em}$ ⇒ $\tau_h > 5\ \mu s \to \beta\gamma c\tau > 100$ m

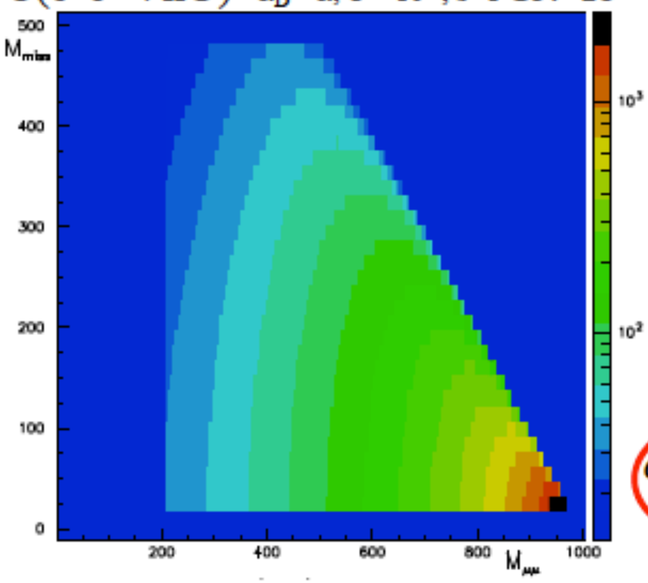
rapidly increasing with decreasing ε

$m_{U,h} \sim 100$ MeV

invisible up to $\varepsilon \approx 10^{-2} \div 10^{-1}$ depending on m_h

We study only the muon case $m_h < m_U$: $e^+e^- \to \mu^+\mu^-$ + missing energy

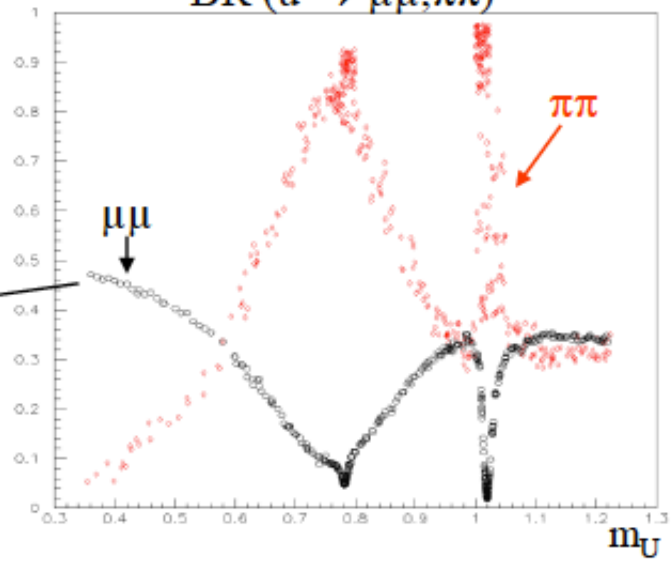
$\sigma(e^+e^- \to hU)$ $\alpha_D = \alpha$, $\varepsilon = 10^{-3}$, $s = 1$ GeV^2 fb



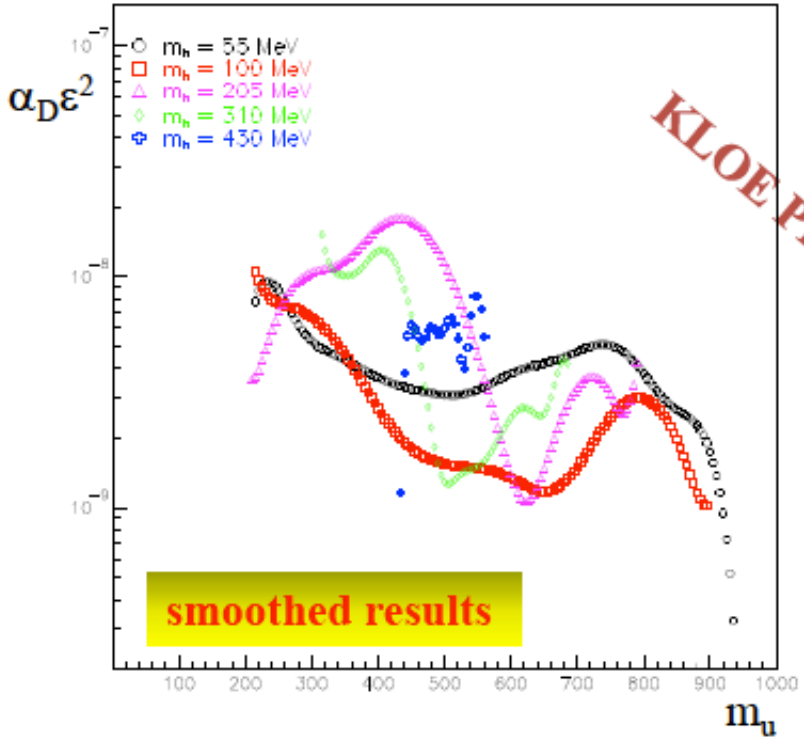
Batell, Pospelov, Ritz , Phys. Rev. D 79, 115008 (2009)

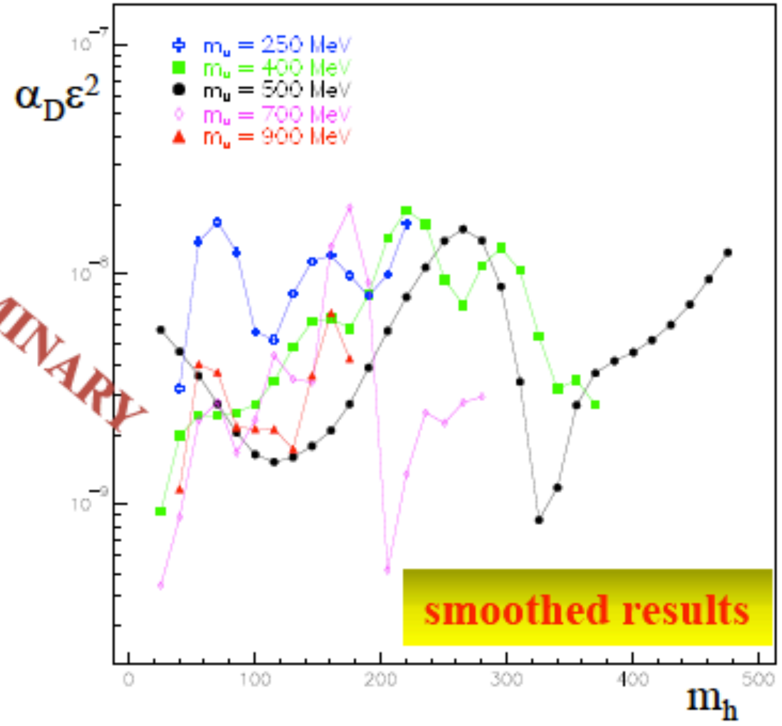
$$\sigma_{hU} \propto \frac{1}{s} \frac{1}{(1 - \frac{m_u^2}{s})^2}$$

BR (u → μμ,ππ)



Dark forces : ee → hU higgsstrahlung process





Limits ~ $10^{-8} \div 10^{-9}$ in $\alpha_D\varepsilon^2$, which translate in $10^{-3} \div$ some 10^{-4} in ε, if $\alpha_D = \alpha_{em}$

Search complementary with BaBar one (same process , different final state and phase space)

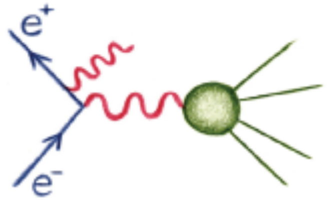
Expect a ≈ 2.5 improvement on the limits in KLOE2 because of luminosity + suppression of the K^+K^- background due to the Inner Tracker insertion → full study of the $\varepsilon \approx 10^{-4}$ region

$\sigma(e^+e^-\to$ hadr.) below 1 GeV

- ~ 3 σ discrepancy between a_μ^{SM} - a_μ^{exp} [a_μ= (g_μ-2)/2]
- $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$ → main contribution to the uncertainty on a_μ^{SM}

$$a_\mu^{\mathrm{had,LO}} = 1 \big/ (4\pi^3) \int_{4m_\pi^2}^{\infty} \sigma(e^+e^- \to \mathrm{hadr.}) K(s) ds \quad ; \quad K(s) \sim 1/s$$

- $\sigma(e^+e^-\to$ hadr.) below 1 GeV is dominated by $e^+e^-\to\pi^+\pi^-$
- ϕ - factory: fixed √s ⇒ Initial State Radiation method



$$s \cdot \frac{d\sigma(e^+e^- \to \pi^+\pi^- + \gamma)}{ds_\pi} = \sigma(e^+e^- \to \pi^+\pi^-)\, H(s, s_\pi)$$

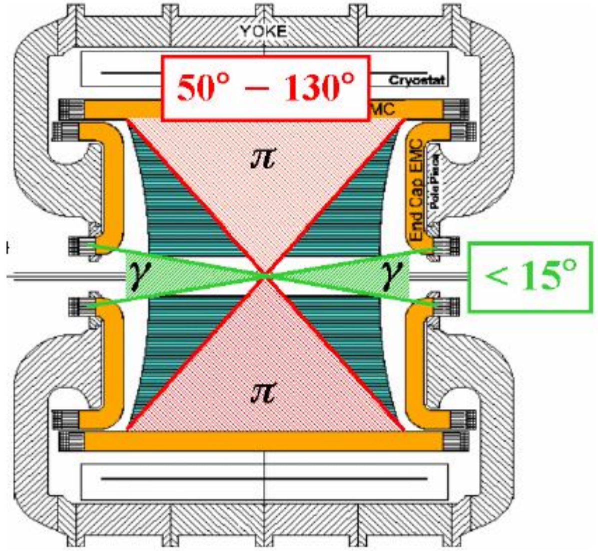
- Different analyses: (1) photon emitted at Small Angle (S.A. analysis)
  [PLB606(2005)12, PLB670(2009)285]
  (2) photon emitted at Large Angle (L.A. analysis)
  [PLB700(2011)102]
  (3) photon at S.A., $\sigma(e^+e^-\to\pi^+\pi^-\gamma)/\sigma(e^+e^-\to\mu^+\mu^-\gamma)$
  [arXiv-submit:0616958, submitted to PLB]

S.A. analysis (KLOE08)

- **2 pions at large angle (ϑ>50°)**
- **Photon at small angle (ϑ<15° - not detected) to reduce FSR**
- **Photon momentum reconstructed from kinematics**

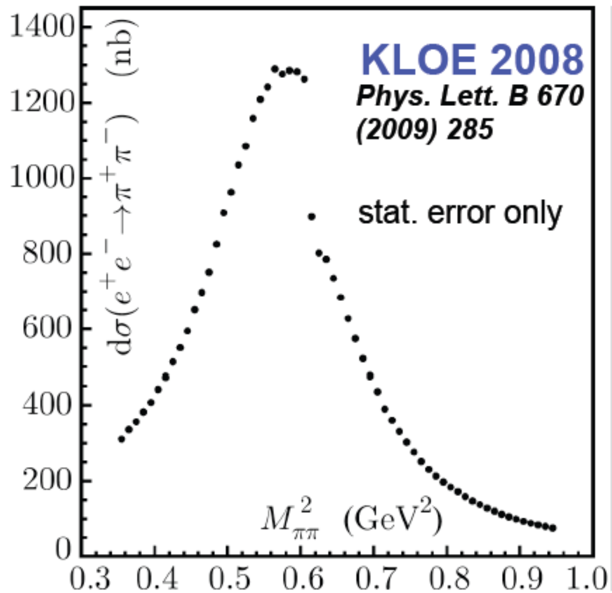
$$\vec{p}_\gamma = -(\vec{p}_+ + \vec{p}_-)$$

- **240 pb^{-1} from 2002 data-taking**



$$a_\mu^{\pi\pi} = \int_{s_1}^{s_2} \sigma_{ee\to\pi\pi}(s) K(s) ds$$

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



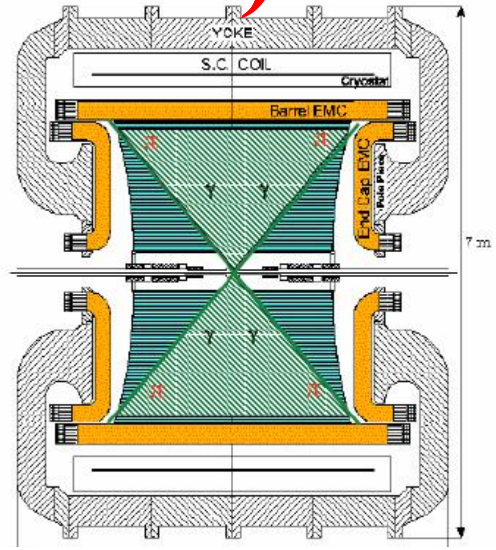
L.A. analysis (KLOE10)

- 2 pions at large angle ($\vartheta>50°$)
- Photon detected at large angle ($\vartheta>50°$)
- Threshold region accessible
- Lower statistics
- Larger contribution from FSR

Larger background from $\phi\rightarrow\pi^+\pi^-\pi^0$

Irreducible background from $\phi\rightarrow f_0\gamma\rightarrow\pi^+\pi^-\gamma$

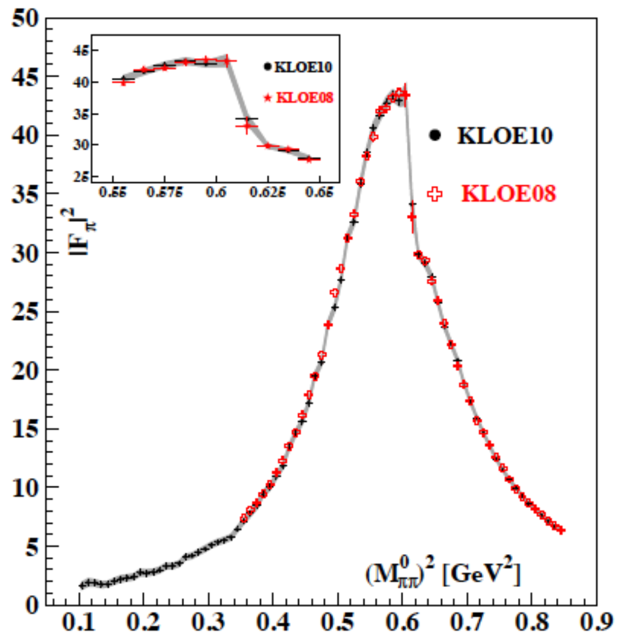
Use off-peak data ($\sqrt{s}$ = 1 GeV); L = 233 pb^{-1}



$a_\mu^{\pi\pi}$ (0.1–0.85 GeV^2) = $(478.5\pm2.0_{stat}\pm5.0_{syst}\pm4.5_{th})\times10^{-10}$

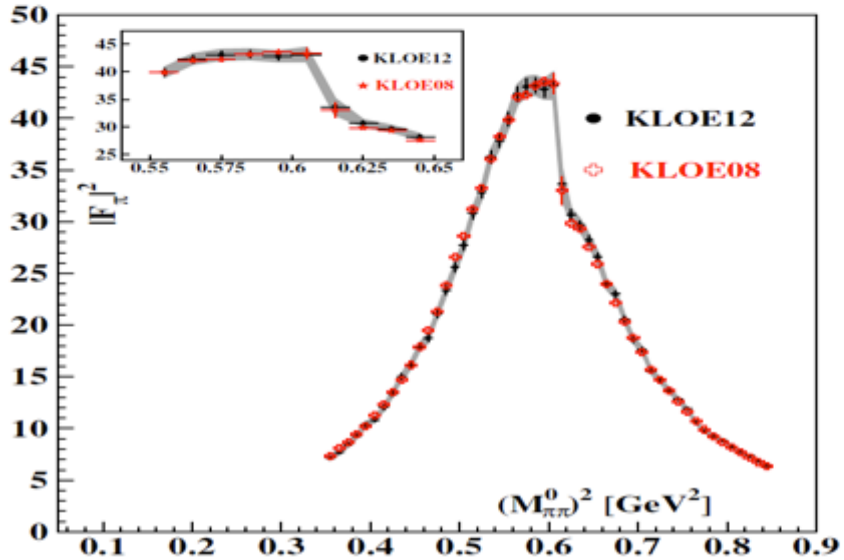
[PLB700(2011)102]

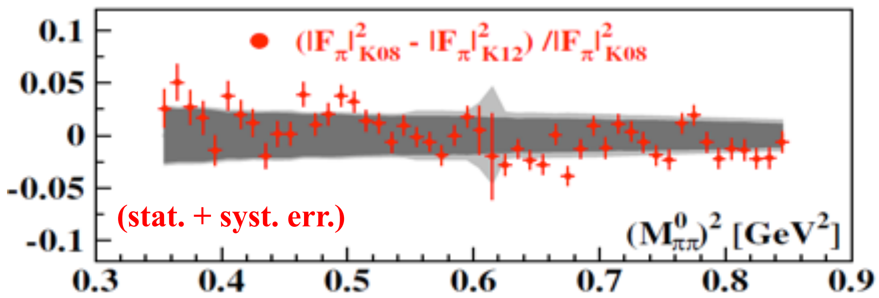
- Good agreement with KLOE08
- Combined KLOE08 + KLOE10:
  $a_\mu^{\pi\pi}$ (0.1–0.95 GeV^2) = $(488.6\pm6.0)\times10^{-10}$



$|F_\pi|^2$ from $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio

Syst. errors (%)	KLOE08 $\Delta^{\pi\pi}a_\mu$ abs	KLOE12 $\Delta^{\pi\pi}a_\mu$ ratio
Reconstruction Filter	negligible	negligible
Background subtraction	0.3	$0.8\ (0.3_{\pi\pi\gamma} \oplus 0.8_{\mu\mu\gamma})$
Trackmass	0.2	$0.4\ (0.2_{\pi\pi\gamma} \oplus 0.4_{\mu\mu\gamma})$
Particle ID	negligible	negligible
Tracking	0.3	$0.6\ (0.3_{\pi\pi\gamma} \oplus 0.5_{\mu\mu\gamma})$
Trigger	0.1	$0.1\ (0.1_{\pi\pi\gamma})$
Unfolding	negligible	negligible
Acceptance ($\theta_{\pi\pi}$)	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	$0.1\ (0.1_{\pi\pi\gamma} \oplus 0.1_{\mu\mu\gamma})$
Luminosity	$0.3\ (0.1_{th} \oplus 0.3_{exp})$	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	1.1
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.3
Rad. function H	0.5	-
Total theory systematics	0.6	0.3
Total systematic error	0.9	1.2





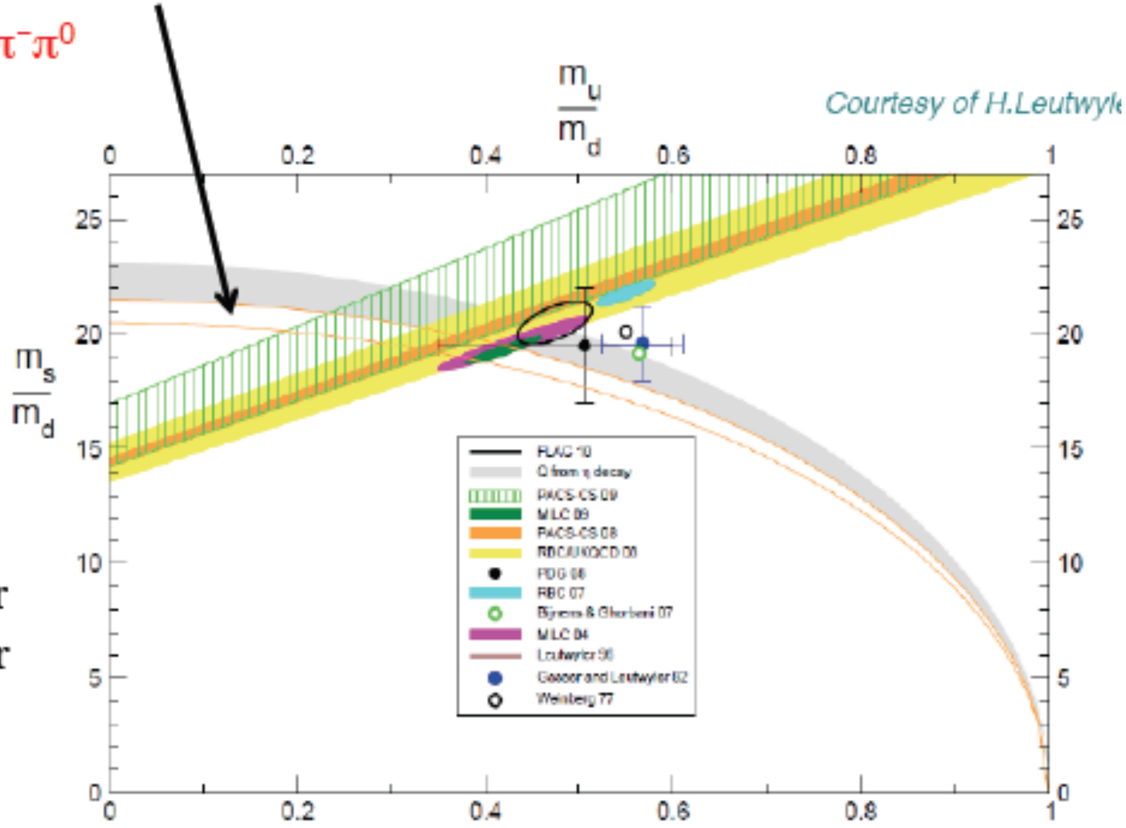
Good agreement between the two measurements, especially in the ρ region

KLOE12: $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = (385.1 \pm 1.1_{stat} \pm 4.4_{syst} \pm 1.2_{theo}) \cdot 10^{-10}$

KLOE08: $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \mathrm{GeV}^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{syst} \pm 2.3_{theo}) \cdot 10^{-10}$

The light quark masses: study of $\eta \to 3\pi$ decay

- Using dispersive relations and the fit to the $\eta \to \pi^+\pi^-\pi^0$ data a reasonable agreement with precise experimental analyses of the $\eta \to \pi^0\pi^0\pi^0$ channel, is obtained.
- The Q value obtained with this procedure provides useful information on quark masses.
- New more precise data on $\eta \to \pi^+\pi^-\pi^0$ important in order to reduce systematics on Q^2 associated to the residual mismatch with the neutral channel.
- New analysis of the whole KLOE dataset (~2fb^{-1}) with new analysis strategy to reduce systematics
- At KLOE-2 with the inner tracker and more data we expect a further significant improvement

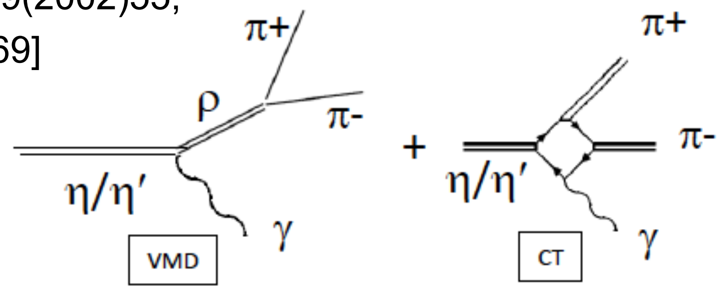


Emilie Passemar HEP2011, Grenoble, 22 July 2011

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

➢ **Study of the** **box anomaly**: test of ChPT and its unitarized extensions
[Benayoun et al. EPJC31(2003)525; Holstein, Phys. Scripta, T99(2002)55; Borasoy, Nissler, NPA740(2004)362, Picciotto PRD45(1992)1569]

Sizeable effect of the Contact Term expected both in $\Gamma(\eta\to\pi^+\pi^-\gamma)$ and in $M_{\pi\pi}$ distribution



Decay	PDG 2010	Prediction with Contact Term (HLS)	Prediction without Contact Term
$\eta\to\pi^+\pi^-\gamma$	60±4 eV	56.3±1.7 eV	100.9±2.8 eV
$\eta'\to\pi^+\pi^-\gamma$	60±5 keV	48.9±3.9 keV	57.5±4.0 keV

HLS: Benayoun, Eur. Phys. J. C31 (2003) 525

➢ CLEO result (2007)
~ 3 σ' s lower than previous measurements

$\Gamma_{CLEO}(\eta\to\pi^+\pi^-\gamma)=(52\pm4)$ eV

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

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

$\eta \to \pi^+\pi^-\gamma$: fit to the $M_{\pi\pi}$ spectrum

"Model–independent approach to η/ η′ →π⁺π⁻γ

(Stollenwerk, Hanhart, Kupsc, Meiβner and Wirzba PLB707 (2012) 184-190)

$$\frac{d\Gamma(\eta \to \pi^+\pi^-\gamma)}{ds_{\pi\pi}} = \left|AP(s_{\pi\pi})F_V(s_{\pi\pi})\right|^2 \Gamma_0(s_{\pi\pi})$$

$$F_V(s_{\pi\pi}) = 1 + (2.12 \pm 0.01)s_{\pi\pi} + (2.13 \pm 0.01)s_{\pi\pi}^2 + (13.80 \pm 0.14)s_{\pi\pi}^3$$

$$P(s_{\pi\pi}) = 1 + \alpha \cdot s_{\pi\pi}$$

$$\Gamma_0(s_{\pi\pi}) = \frac{1}{3 \cdot 2^{11} \cdot \pi^3 m_\eta^3}\left(m_\eta^2 - s_{\pi\pi}\right)^3 s_{\pi\pi}\,\sigma(s_{\pi\pi})^3$$

$$\sigma(s_{\pi\pi}) = \sqrt{1 - 4m_\pi^2 / s_{\pi\pi}}$$

Free parameters: $\begin{cases} A \\ \alpha \end{cases}$