Light hadron physics at KLOE and KLOE-2

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Excited QCD 2013
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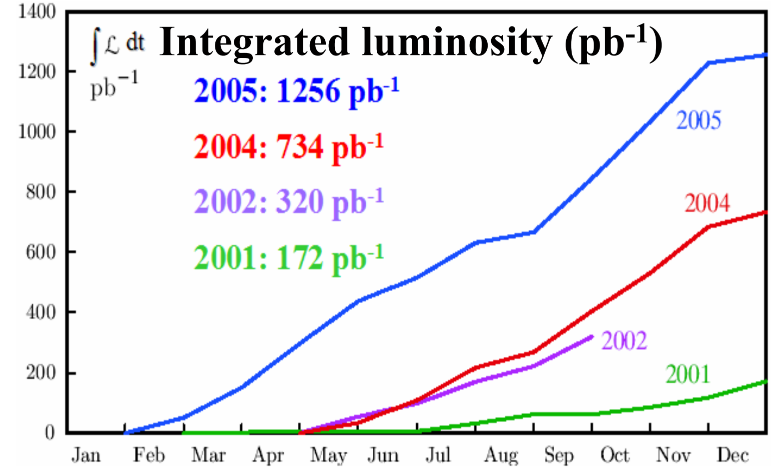
DAΦNE

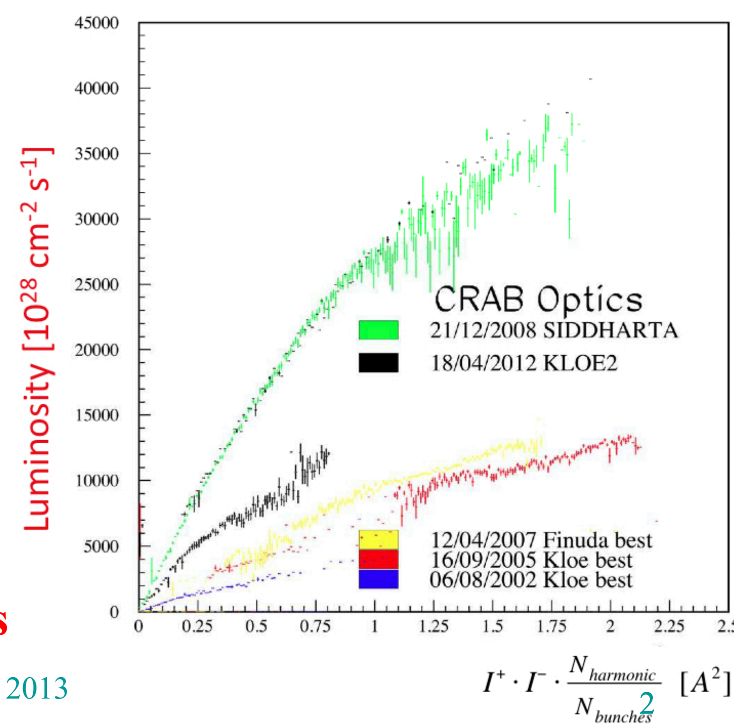
- **Frascati ϕ-factory: e^+e^- collider**
  @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$; $\sigma_{peak} \approx 3.1\ \mu b$

- **Best performance in 2005:**
  $L_{peak} = 1.4 \times 10^{32}\ cm^{-1}s^{-1}$ $\int Ldt = 8.5\ pb^{-1}/day$

- **KLOE: 2.5 fb^{-1} @ $\sqrt{s}=M_\phi$ ($\Rightarrow 8\times10^9\ \phi$ produced)**
  + 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV



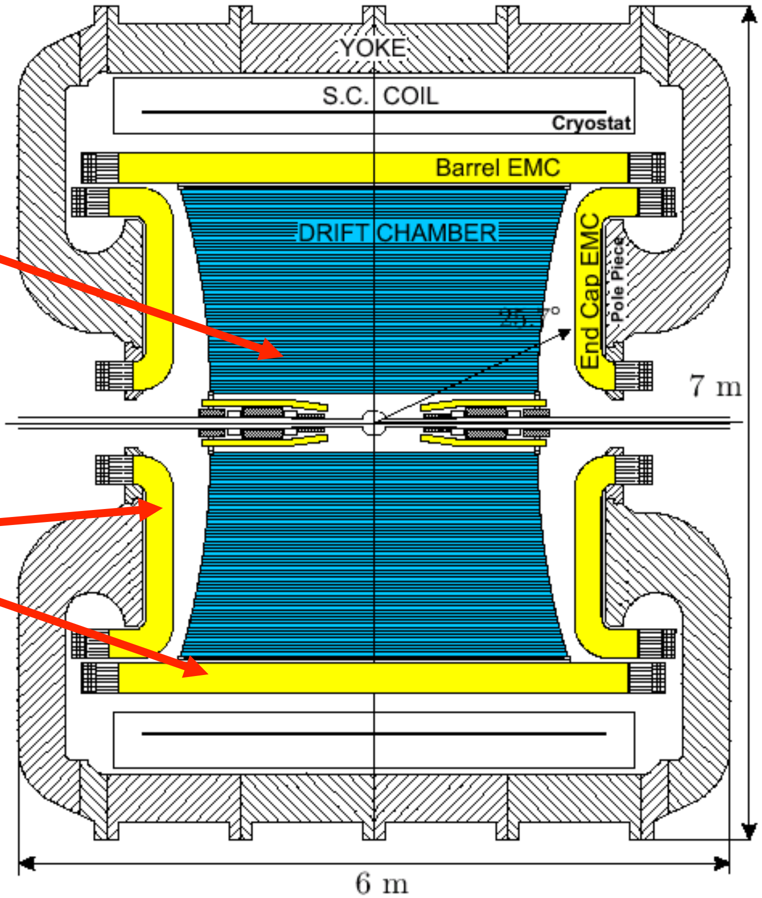
- **DAΦNE upgrade (2008): new interaction scheme;**
  large beam crossing angle + crabbed waist sextupoles
- **2010: DAΦNE commissioning for KLOE-2 start**
  several hardware failures $\Rightarrow$ long shutdown
- **End 2011: commissioning resumed**
  At present ~ same performance as in 2005
- **Nov-Dec. 2012: 100 pb^{-1} collected with**
  carbon target for AMADEUS (deeply bound kaonic nuclei)
- **Dec.2012-June 2013: shutdown for installation**
  of the new detectors



- **DAΦNE operations will restart in June 2013**
- **KLOE-2 goal: collect $O(10\ fb^{-1})$ in the next 2 -3 years**

KLOE

Drift chamber:
- gas: 90% He-10% iC_4H_{10}
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 1$ mm



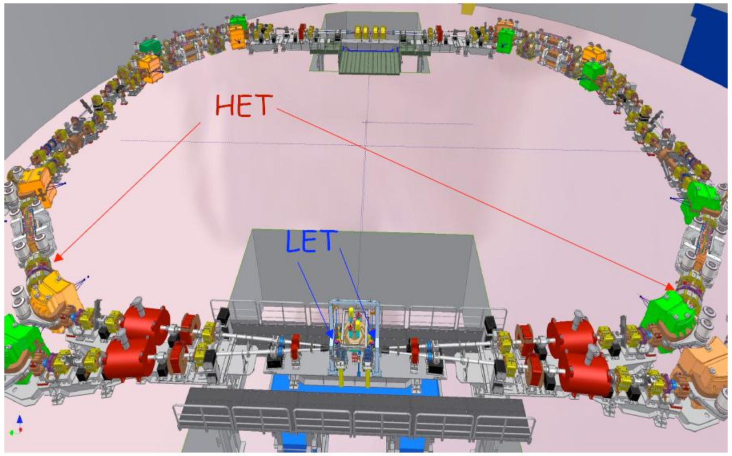
Calorimeter (Pb-Sci.Fi.):
- $\sigma_E/E = 5.7\% / \sqrt{(E(GeV))}$
- $\sigma_t = 55\ ps/\sqrt{(E(GeV))} \oplus 100\ ps$
- 98% of 4π

Magnetic field: 0.52 T

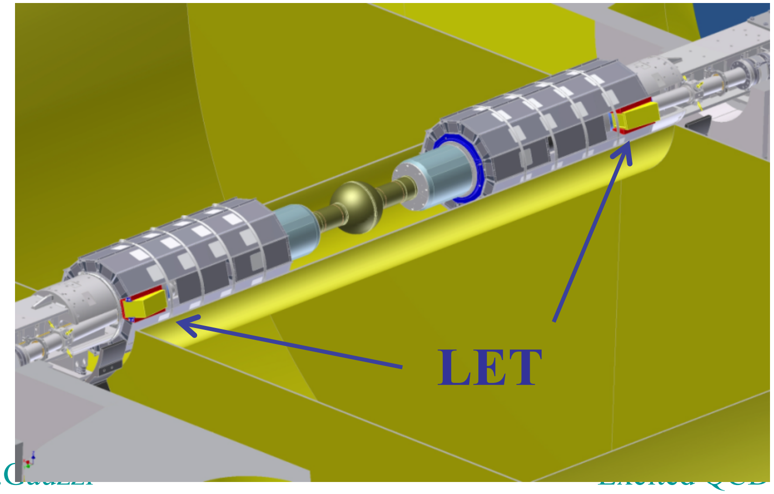
KLOE-2

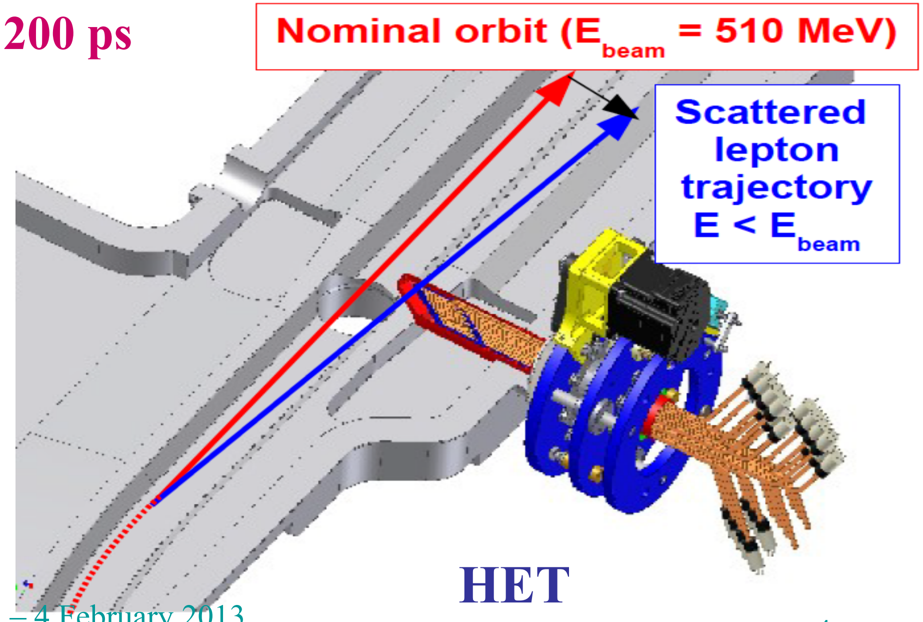
- *e*± taggers for γγ physics (already installed):

  – **Low Energy Tagger** (E_e=130-230 MeV)
  2 calorimeters, LYSO + SiPM; near the IP
  $\sigma_E/E < 10\%$ for E > 150 MeV



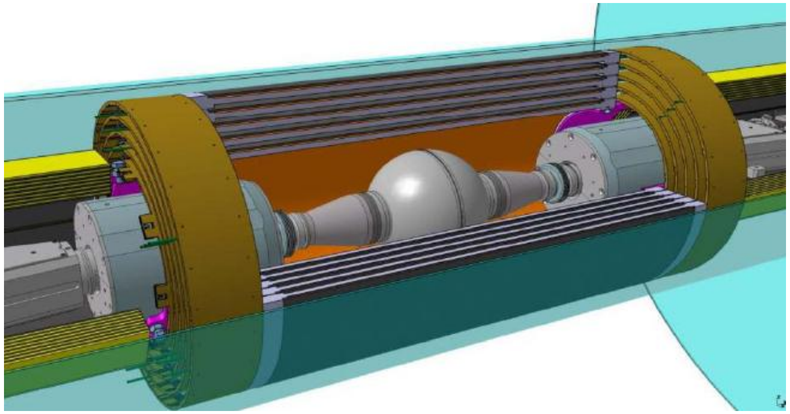
  – **High Energy Tagger** (E_e > 400 MeV)
  Scintillator hodoscope + PMTs;
  after the first dipole, ~ 11 m from IP
  pitch: 5 mm ⇒ σ_E = 2.5 MeV; $\sigma_t \approx$ 200 ps



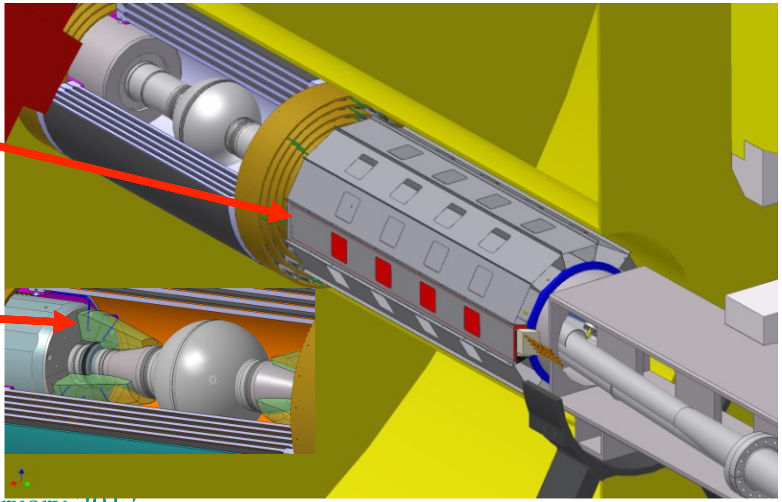


KLOE-2

- **Major upgrade (by June 2013)**
  - **Inner tracker : 4 layers of cylindrical triple GEM**
    - **improve acceptance for low momemtum tracks**
    - **better vertex recontruction**



  - **QCALT: W + scint. tiles + SiPM**
    - **quadrupole coverage for K_L decays**
  - **CCALT : LYSO + APD**
    - **increase acceptance for γ's from the IP from 21° to 10°**

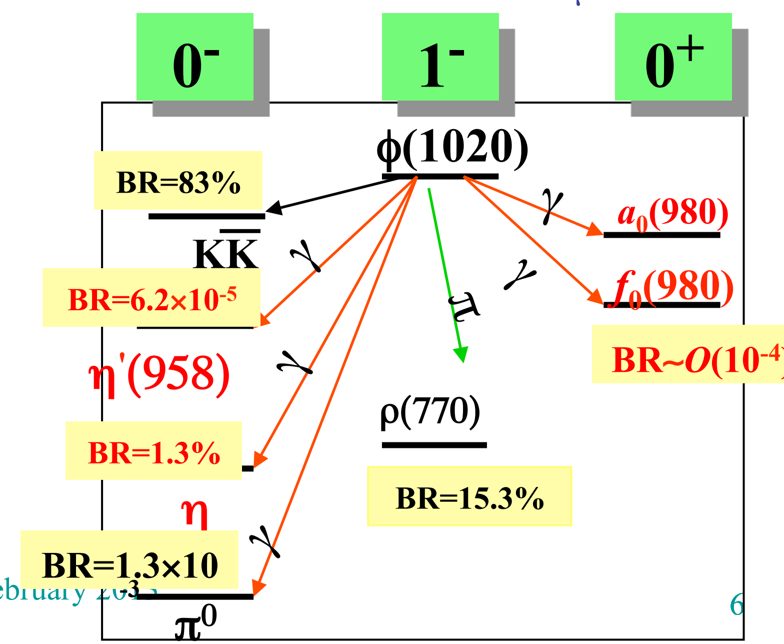


Physics at a ϕ-factory

- **Kaon physics: $|V_{us}|$ and CKM unitarity, CP and CPT violation, rare decays, ChPT tests, quantum mechanics tests**
- **Scalar and pseudoscalar mesons in ϕ radiative decays and in $\gamma\gamma$ collisions**
  - $\eta \to 3\pi$ $\Rightarrow$ Constraints on light quark masses
  - $\eta\ (\eta') \to \pi^+\pi^-\gamma$ $\Rightarrow$ Study of the box anomaly
  - $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$ $\Rightarrow$ Transition Form Factors
    $\Rightarrow$ Search for light dark photons (U-Bosons)
  - $e^+e^- \to e^+e^-\eta\ (\pi^0)$ $\Rightarrow$ $\gamma\gamma \to \eta\ (\pi^0)$; Two-photon partial width
    $\Rightarrow$ Transition Form Factors

- **Hadronic cross-section via ISR $[e^+e^- \to \gamma\ (\pi^+\pi^-)]$: hadronic corrections to $(g-2)_\mu$**

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



The $\eta \to 3\pi$ decay

- $\eta \to \pi\pi\pi$ decay $\Rightarrow$ Isospin violation

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

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

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

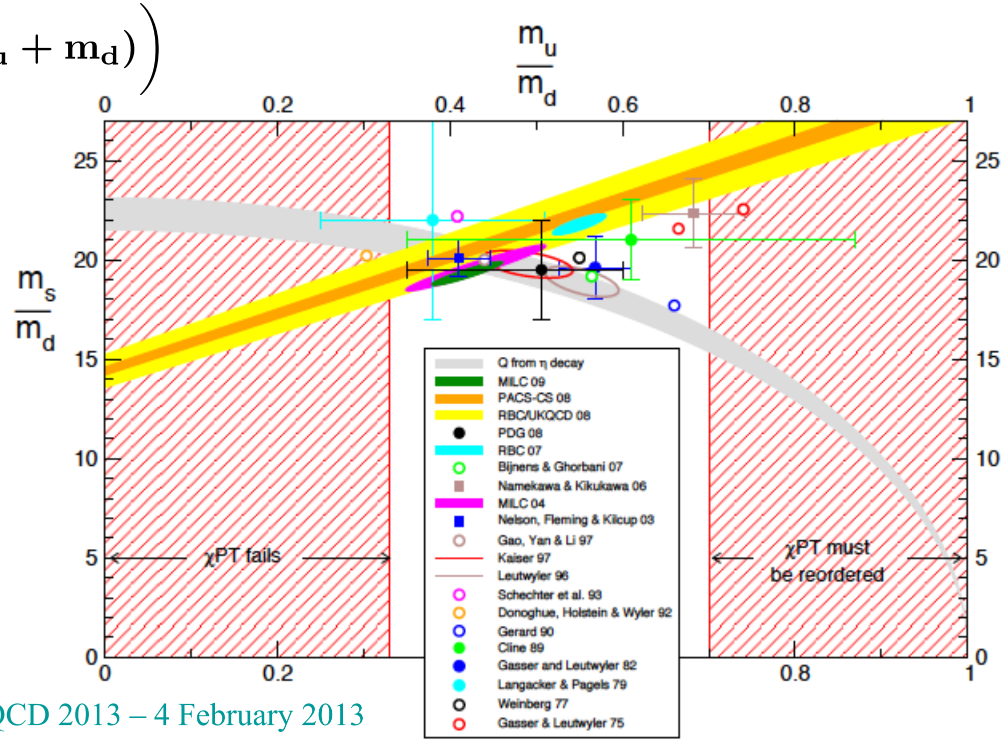
$$\Gamma_{NLO}(\eta \to \pi^+\pi^-\pi^0) = 167 \text{ eV}$$

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

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

- Determining Q gives constraints on the quark mass ratios

[Leutwyler, PoS CD09(2009)005]



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

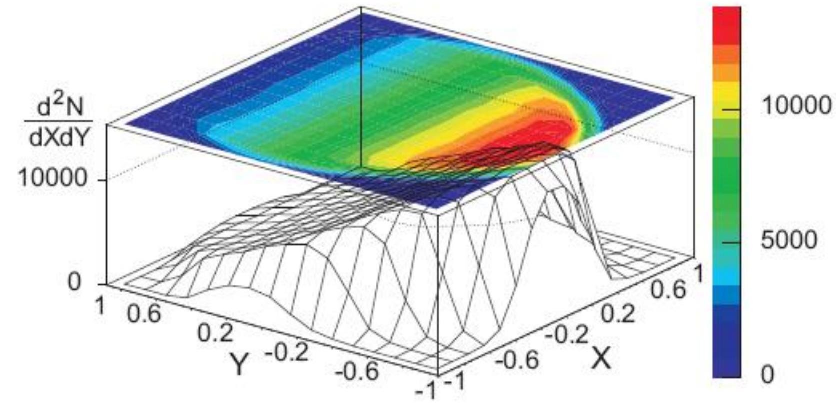
$$X = \sqrt{3}\frac{E_+ - E_-}{\Delta}$$

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

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

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

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



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]

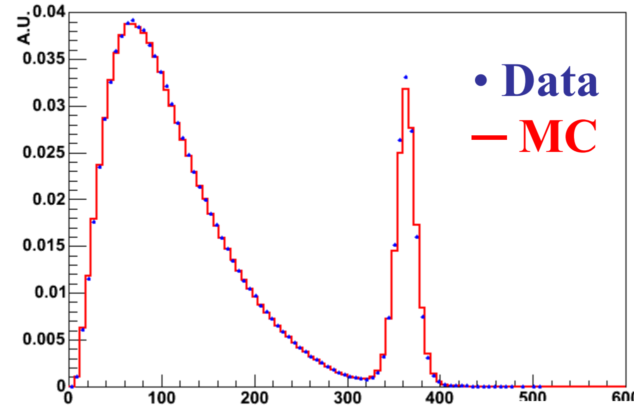
$\eta \to \pi^0\pi^0\pi^0$

- **Symmetric Dalitz plot:**

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

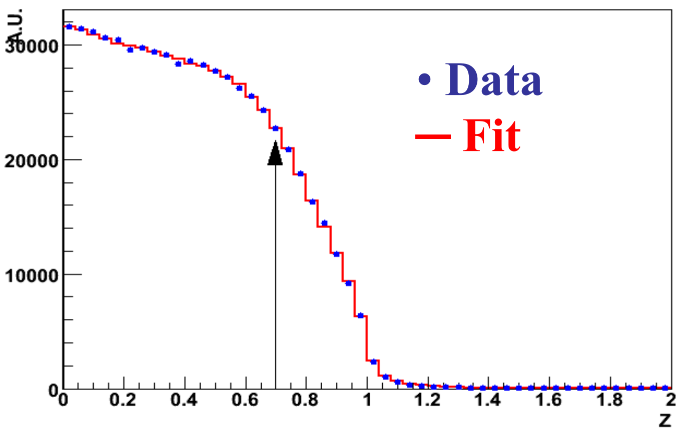
$$Z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - M_\eta}{M_\eta - 3M_\pi}\right)^2 = \frac{\rho^2}{\rho^2_{max}}$$

(ρ = distance from the Dalitz plot center)

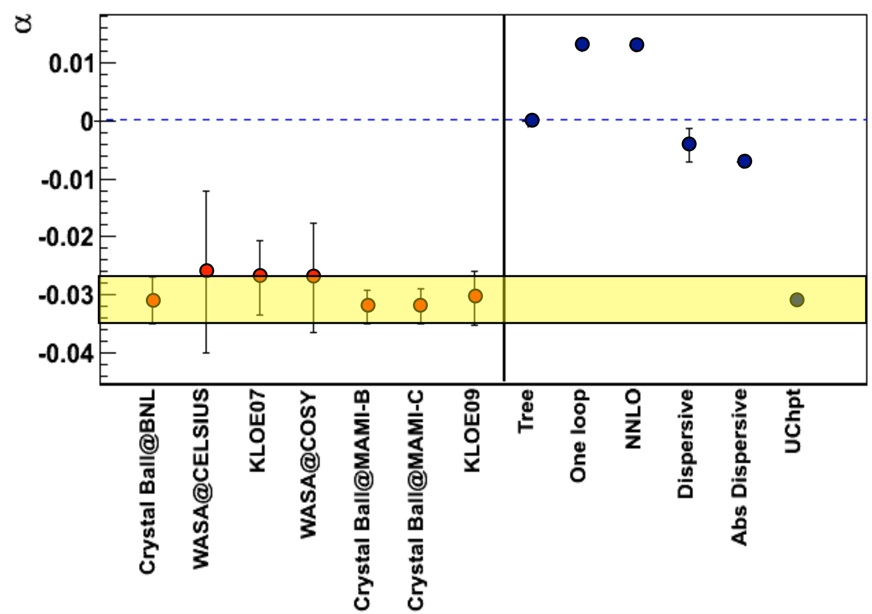


E_γ (MeV)

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



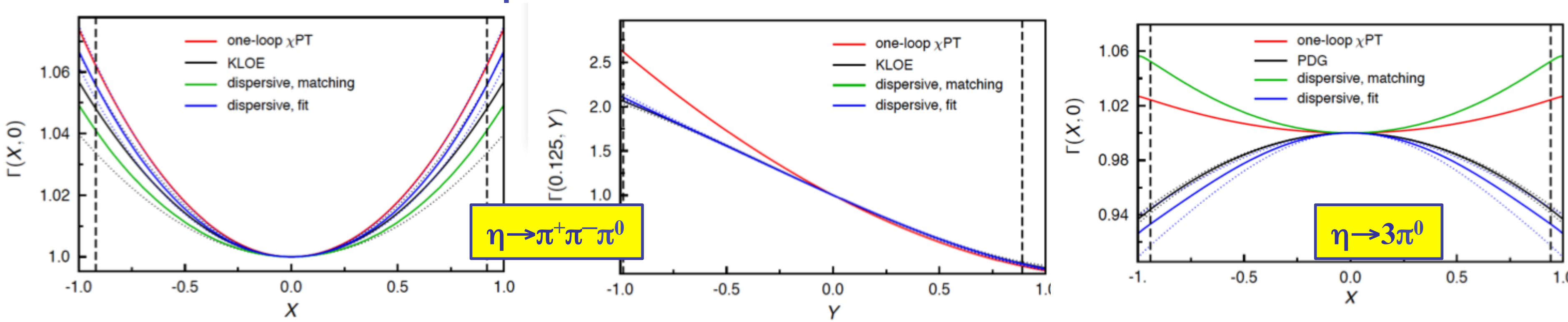
$$\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$$



[PLB 694 (2010) 16]

$\eta \to 3\pi$

- Recent dispersive analyses of $\eta \to 3\pi$: 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]

$$m_u = (2.02 \pm 0.14) MeV$$
$$m_d = (4.91 \pm 0.11) MeV$$

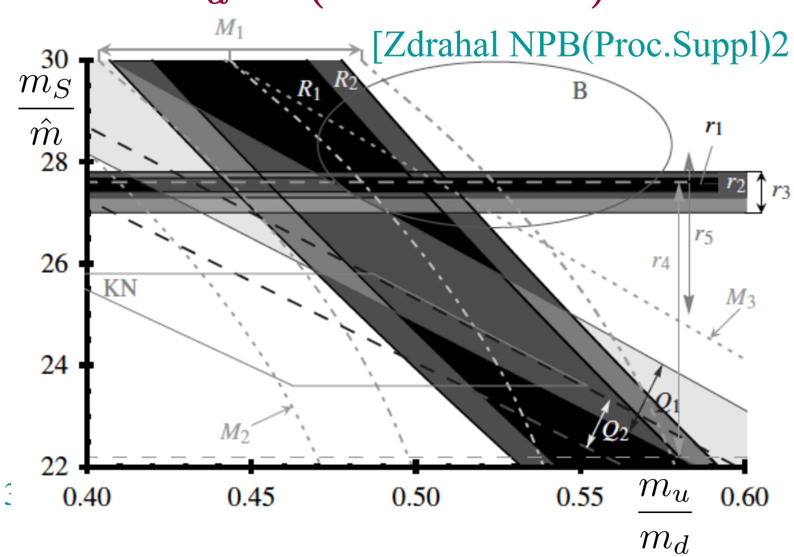
and by using $\hat{m}$ and m_S from lattice QCD $\Rightarrow$

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

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

$$m_u = (2.23 \pm 0.14) MeV$$
$$m_d = (4.63 \pm 0.14) MeV$$

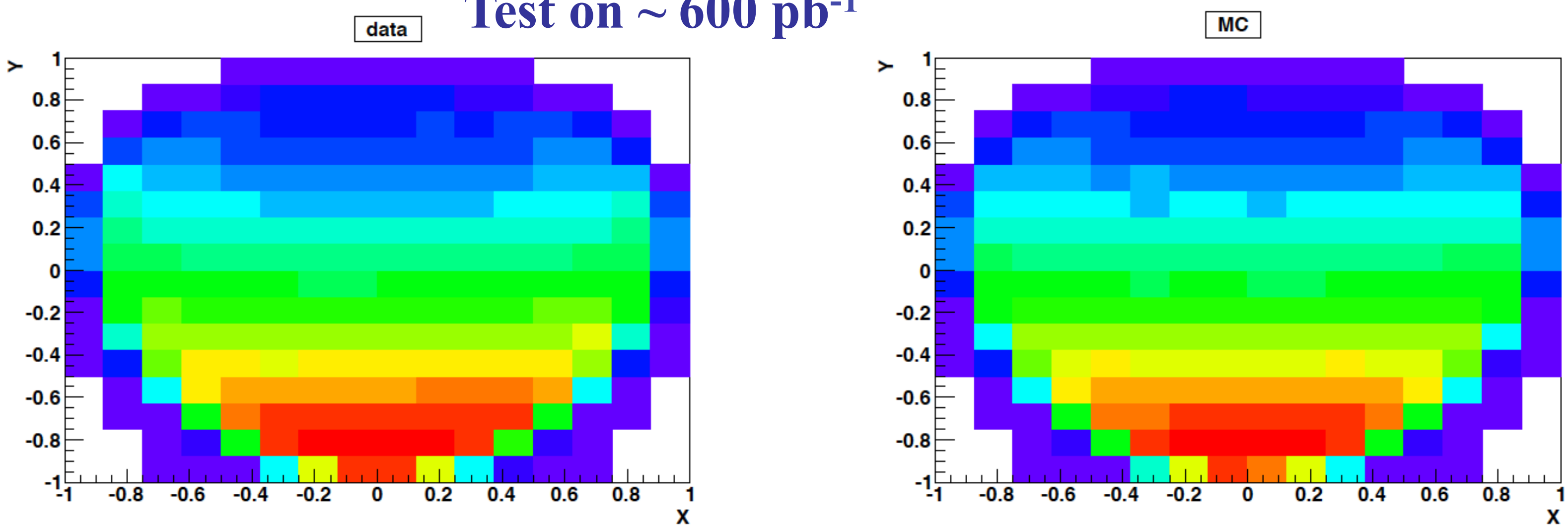
[Zdrahal NPB(Proc.Suppl)219(2011)]



$\eta \rightarrow 3\pi$

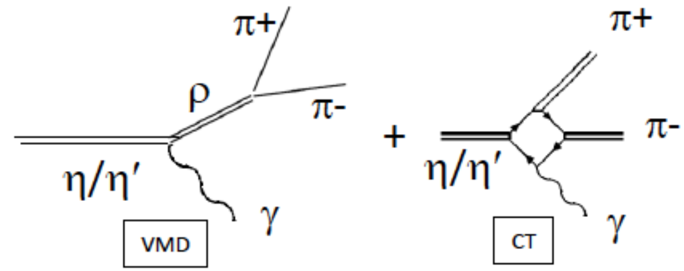
- New analysis of KLOE data in progress to reduce systematics from event selection procedure:
  - Whole dataset, ~ 2.5 fb^{-1}
  - New analysis scheme
  - Improved MC simulation

Test on ~ 600 pb^{-1}



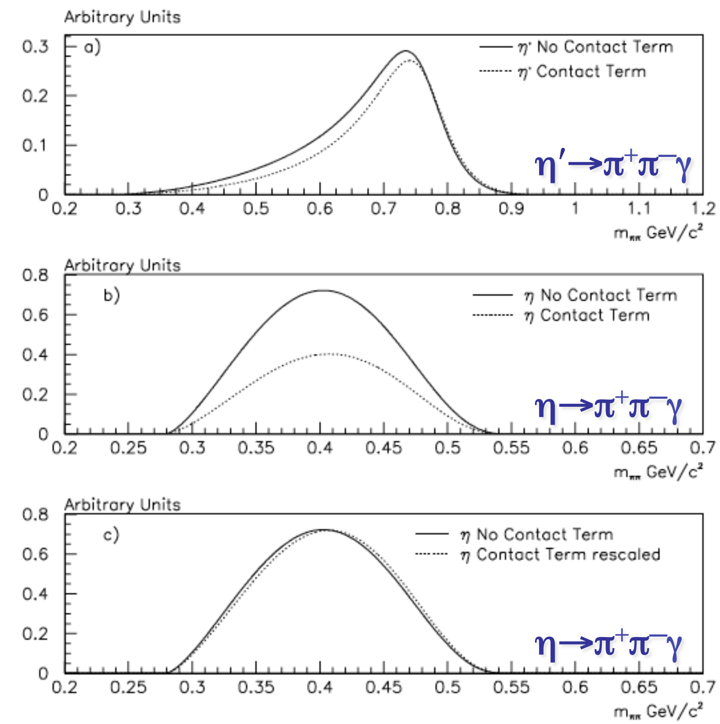
- With 5 fb^{-1} @ KLOE-2 we also expect ~ 8000 $\eta' \rightarrow \pi^+\pi^-\pi^0$ events

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



- **Study of the box anomaly:**
  Contact Term vs Resonant one
  [Benayoun et al. EPJC31(2003)525; Holstein, Phys. Scripta, T99(2002)55; Borasoy, Nissler, NPA740(2004)362, Picciotto PRD45(1992)1569]

- **CLEO result (2007) is**
  2 – 3 σ lower than previous measurements



[from Benayoun et al., EPJC31(2003)]

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

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

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

- $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-\gamma$: L = 558 pb^{-1}
- **Main background: $\phi \to \pi^+\pi^-\pi^0$**
- **Signal extracted from fit to E-p**

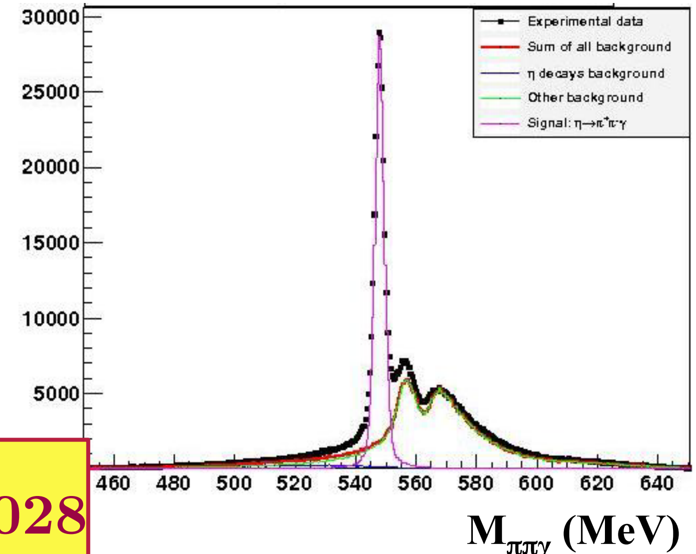
$(P^\mu = P^\mu_\phi - P^\mu_{\pi^+} - P^\mu_{\pi^-} - P^\mu_{\gamma_\phi})$

~ 2 × 10^5 events

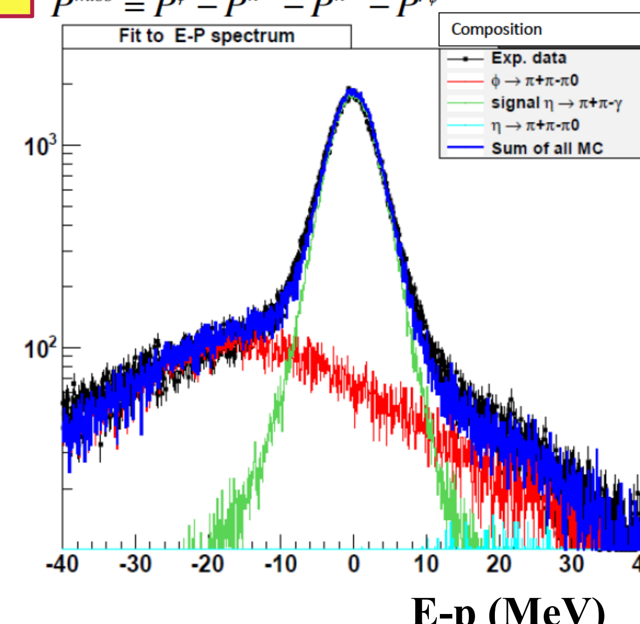
- **Normalization sample: $\eta \to \pi^+\pi^-\pi^0$**

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

[PLB718(2013)910]



$P^{miss} = P^\phi - P^{\pi^+} - P^{\pi^-} - P^{\gamma_\phi}$



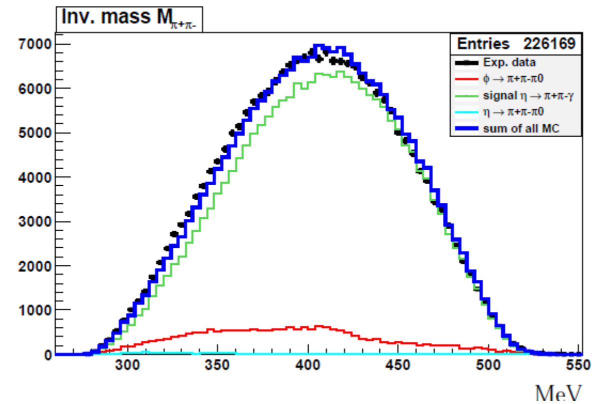
- **Consistent with CLEO measurement, with better precision**
- **Using $\Gamma(\eta \to \pi^+\pi^-\pi^0)$ from PDG**

$$\Rightarrow \Gamma(\eta \to \pi^+\pi^-\gamma) = (54.7 \pm 3.1)\ \mathrm{eV}$$

in agreement with the expectation with Contact Term

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

- Fit of the $M_{\pi\pi}$ spectrum to the parametrization of Stollenwerk et al. [PLB707(2012)184]



Non perturbative part: pion FF

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

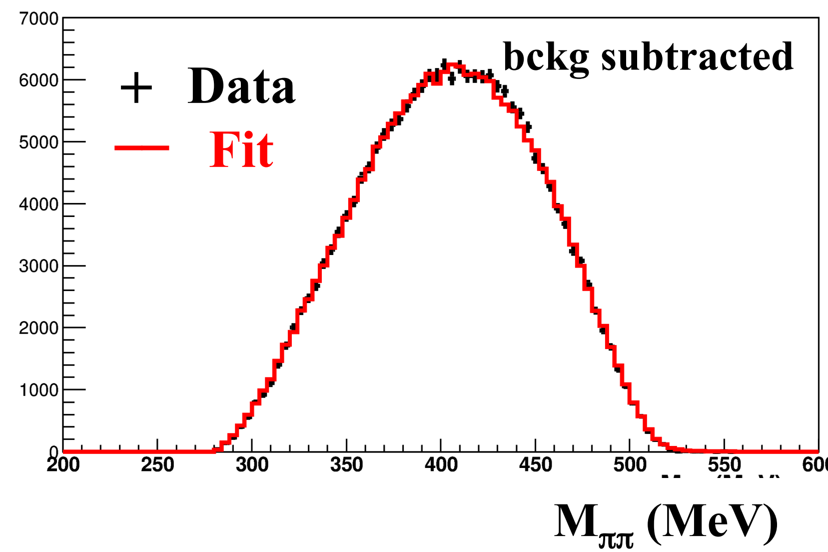
$$(s_{\pi\pi} = M^2_{\pi\pi})$$

Process-specific part:

$$P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \mathcal{O}(s^2_{\pi\pi})$$

$$\boxed{\alpha = (1.32 \pm 0.08 \pm 0.10)\ \mathrm{GeV}^{-2}}$$

[PLB718(2013)910]

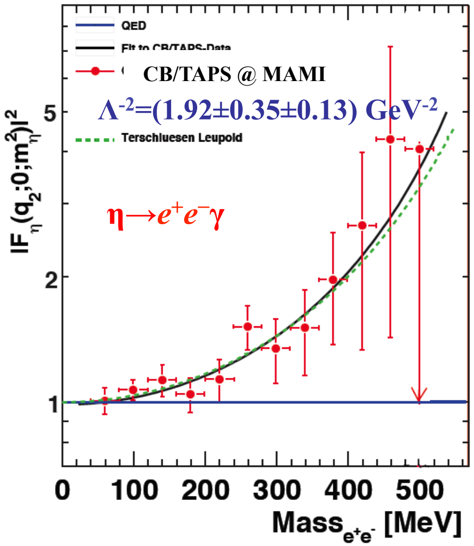


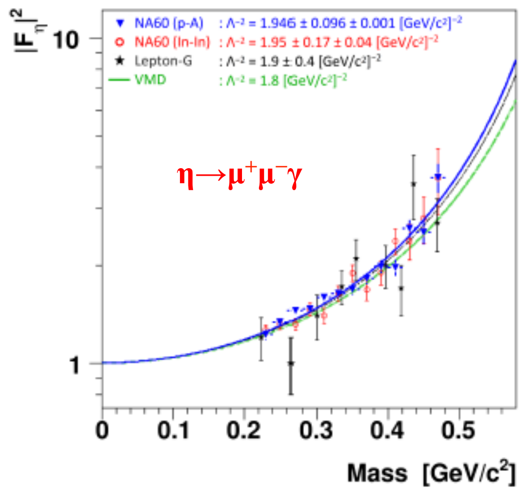
WASA@COSY: [PLB 707(2012)243]

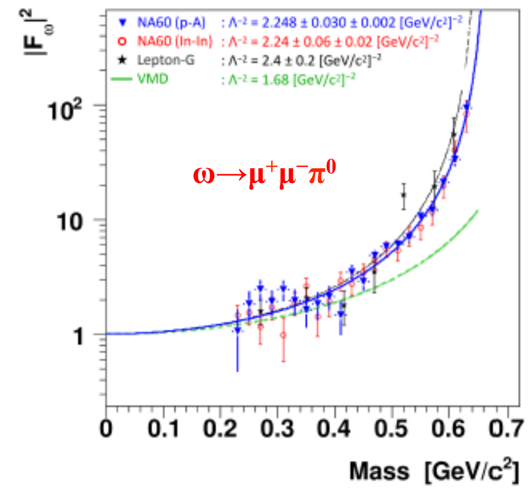
$$\alpha = (1.89 \pm 0.25 \pm 0.59)\ \mathrm{GeV}^{-2}$$

Transition FFs from Dalitz decays

- **Naive VMD approach well describes $\eta \to \gamma \ell^+ \ell^-$, but fails for $\omega \to \pi^0 \ell^+ \ell^-$**

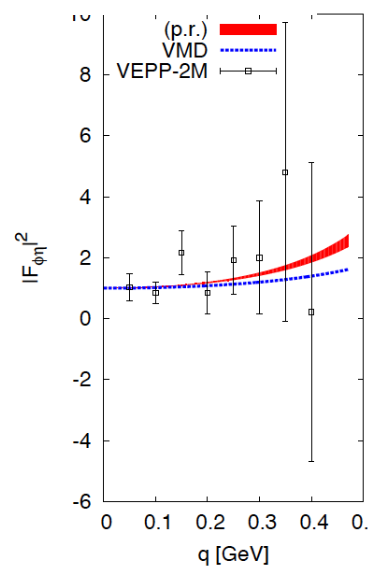






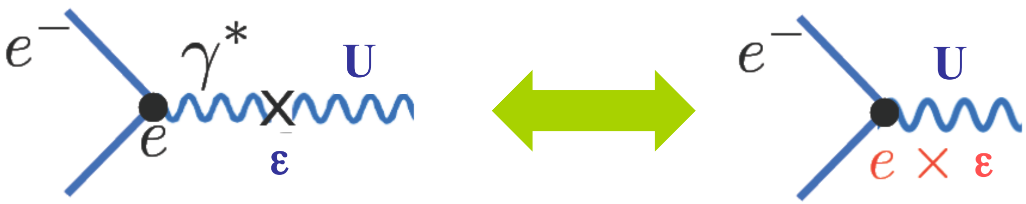
$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2} \qquad (q^2 = M^2_{\ell^+\ell^-})$$

- $\phi \to \eta e^+ e^-$: Λ^{-2} = (3.8 ± 1.8) GeV^{-2} (~ 50% error) **SND @ VEPP-2M**
  VMD $\Rightarrow$ $\Lambda^{-2} \approx M_\phi^{-2} \approx 1$ GeV^{-2}



Search for dark forces

- **Recent astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA) could be interpreted by assuming the existence of a light dark sector that interacts with SM particles through a mixing of a new gauge boson (U-boson) with *O*(1 GeV) mass, with the photon**



[Arkani-Hamed et al. PRLD79(2009), 015014
Essig et al., PRD80(2009)015003]

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

- **If the mixing parameter $\varepsilon \sim 10^{-3} - 10^{-4}$ $\Rightarrow$ could be observable at KLOE**
- **Signature: $\phi \rightarrow \eta U$, $U \rightarrow \ell^+\ell^-$** $\Rightarrow$ **$\phi \rightarrow \eta e^+e^-$**
- **Two η decay channels analyzed: $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\eta \rightarrow \pi^0\pi^0\pi^0$**

Other DF searches @ KLOE: $e^+e^- \rightarrow U\gamma \rightarrow \mu^+\mu^-\gamma$;
$e^+e^- \rightarrow h'U \rightarrow \mu^+\mu^-$ + missing energy

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

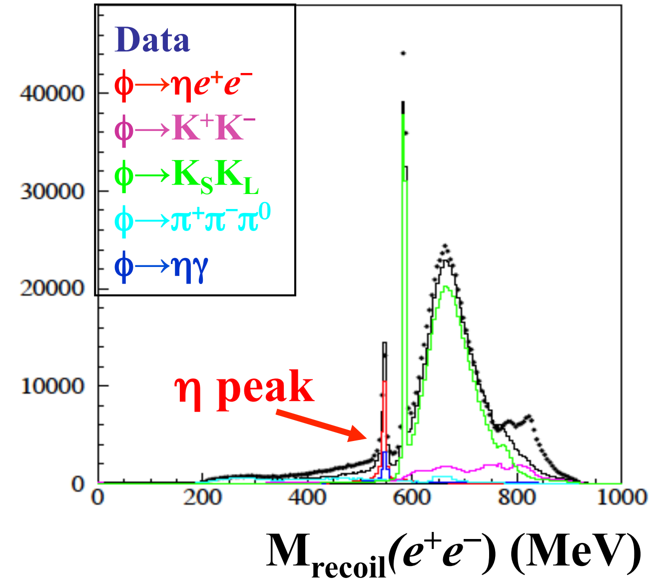
- Analyzed sample: 1.7 fb^{-1}

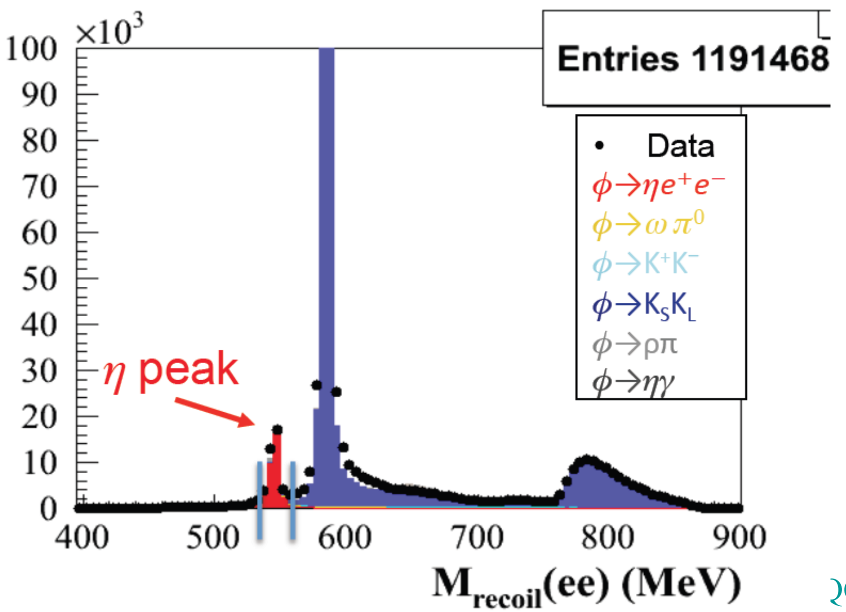
$\eta \to \pi^+\pi^-\pi^0$:

- 4 tracks + 2 prompt photons
- Best $\pi^+\pi^-\gamma\gamma$ match to the η mass

$535 < M_{recoil}(ee) < 560$ MeV

~13000 $\phi \to \eta e^+e^-$ ($\eta \to \pi^+\pi^-\pi^0$) candidates





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

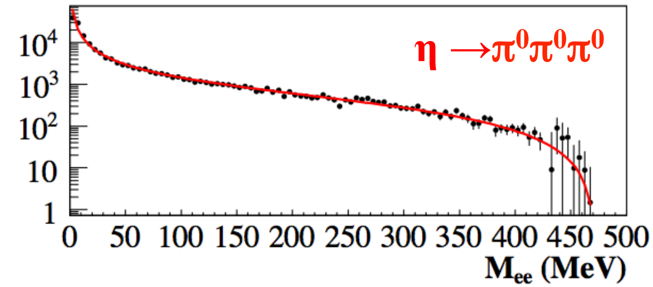
- 2 tracks + 6 prompt photons

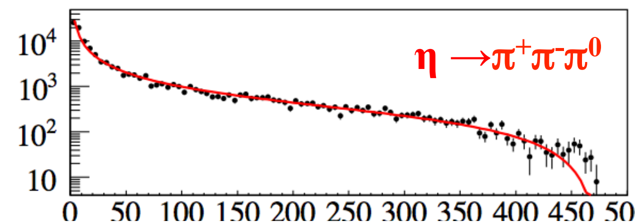
$536.5 < M_{recoil}(ee) < 554.5$ MeV

~ 30000 $\phi \to \eta e^+e^-$ ($\eta \to \pi^0\pi^0\pi^0$)

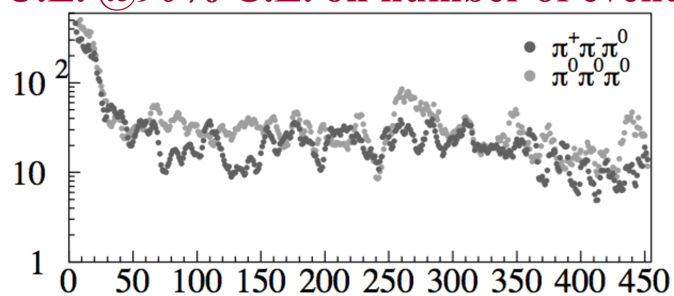
Exclusion plot on α'/α

- Upper limit for $\phi \to \eta U$ evaluated in 1 MeV step in M_{ee}
  (MC simulation from Reece, Wang, JHEP 07(2009)051)
- Bckg from fit to M_{ee} distribution excluding the 5 bins around the selected one
- Upper limit evaluated with the CL_S method

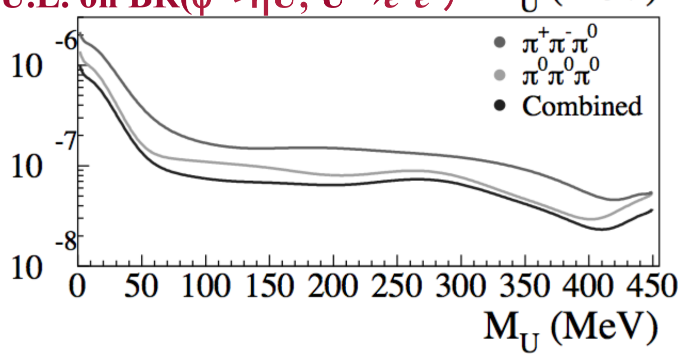




U.L. @90% C.L. on number of events

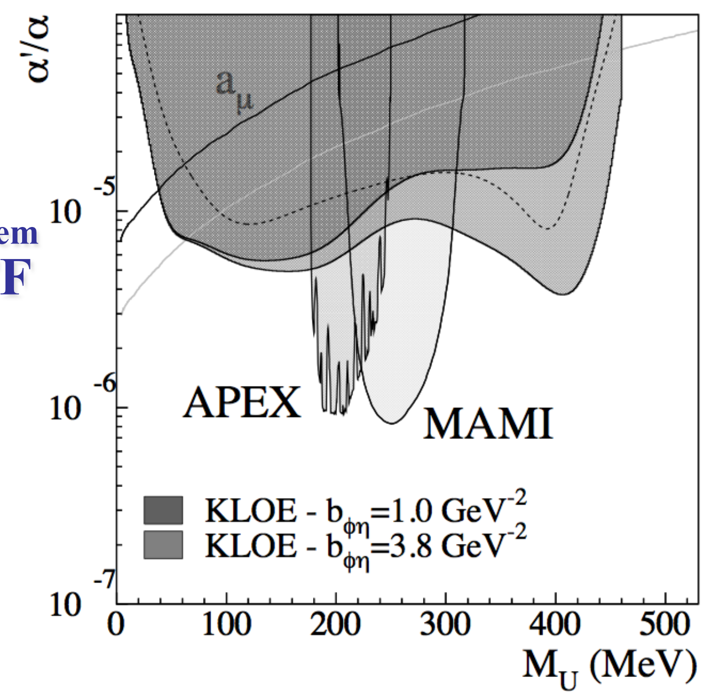


U.L. on BR($\phi \to \eta U$; $U \to e^+e^-$)

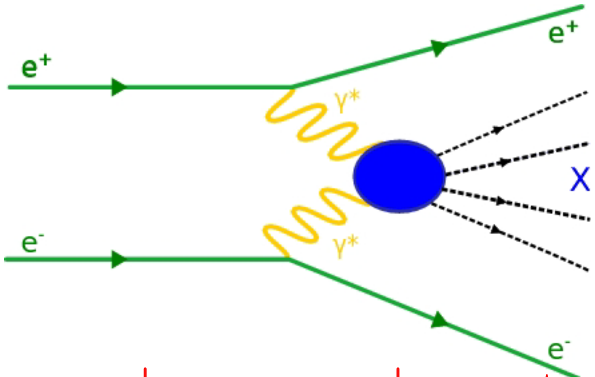


The limit on α'/α_{em} depends on the FF slope $b_{\phi\eta}$ $\Rightarrow$

[arXiv:1210.3927 accepted by PLB]



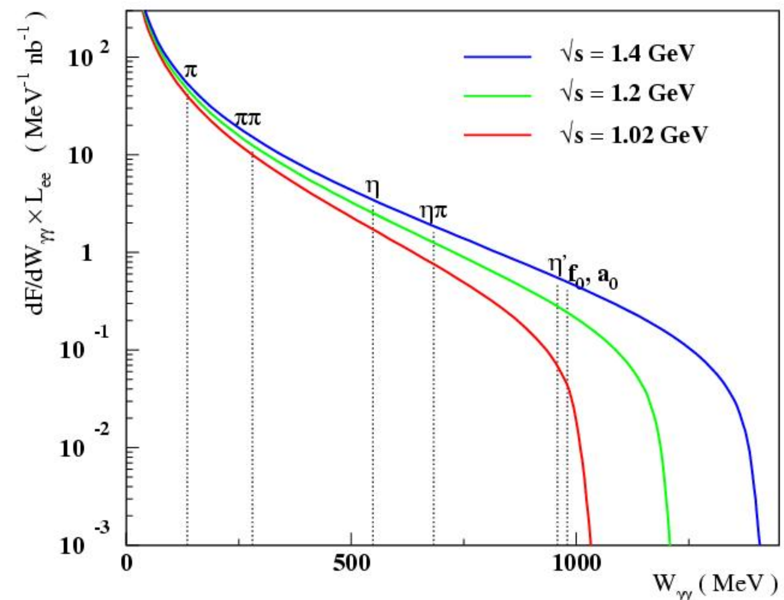
γγ physics



$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^- X$$

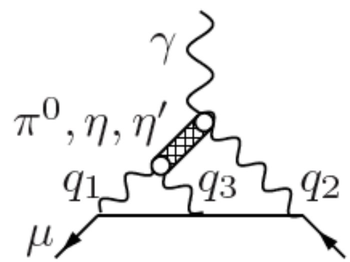
$$[\mathrm{C(X)} = +1]$$

$$\frac{dN}{dW_{\gamma\gamma}} = L_{int}\frac{dF}{dW_{\gamma\gamma}}\sigma(\gamma\gamma \to X)$$



- $X = \pi^0, \eta$
  - Two-photon width $\Gamma(X \to \gamma\gamma)$
  - Transition form factors $F_{X\gamma^*\gamma^*}(q_1^2, q_2^2)$

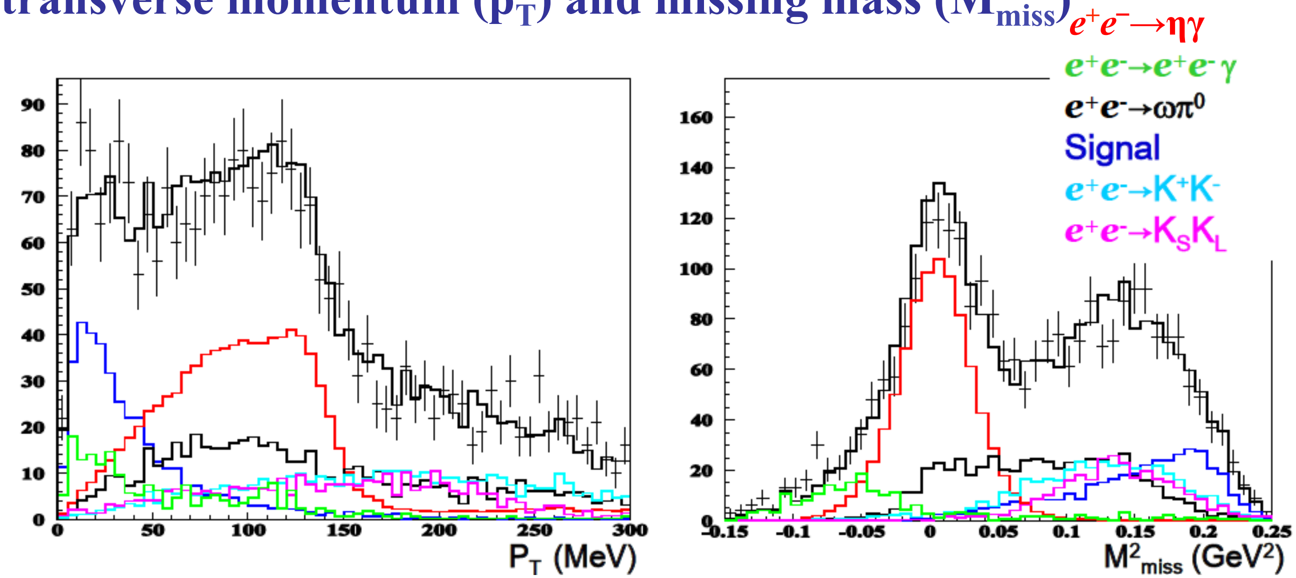
  (input for calculation of the Light-by-Light contribution to g-2 of the muon)
- $X = \pi^0\pi^0 \Rightarrow$ study of $\sigma(600)$



- **KLOE: no $e^\pm$ tagging $\Rightarrow \sqrt{s} = 1$ GeV**
- **KLOE-2: $\sqrt{s} = M_\phi \Rightarrow$ Tagger is essential to reduce the background from the ϕ and to close the kinematics**

$\gamma\gamma \to \eta; \quad \eta \to \pi^+\pi^-\pi^0$

- **Data sample: 240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV), no taggers**
- **Select events with two tracks and two prompt photons**
- **Main bckg: $e^+e^- \to \eta\gamma$ with γ lost**
- **Fit to $\pi^+\pi^-\gamma\gamma$ transverse momentum (p_T) and missing mass (M_{miss})**



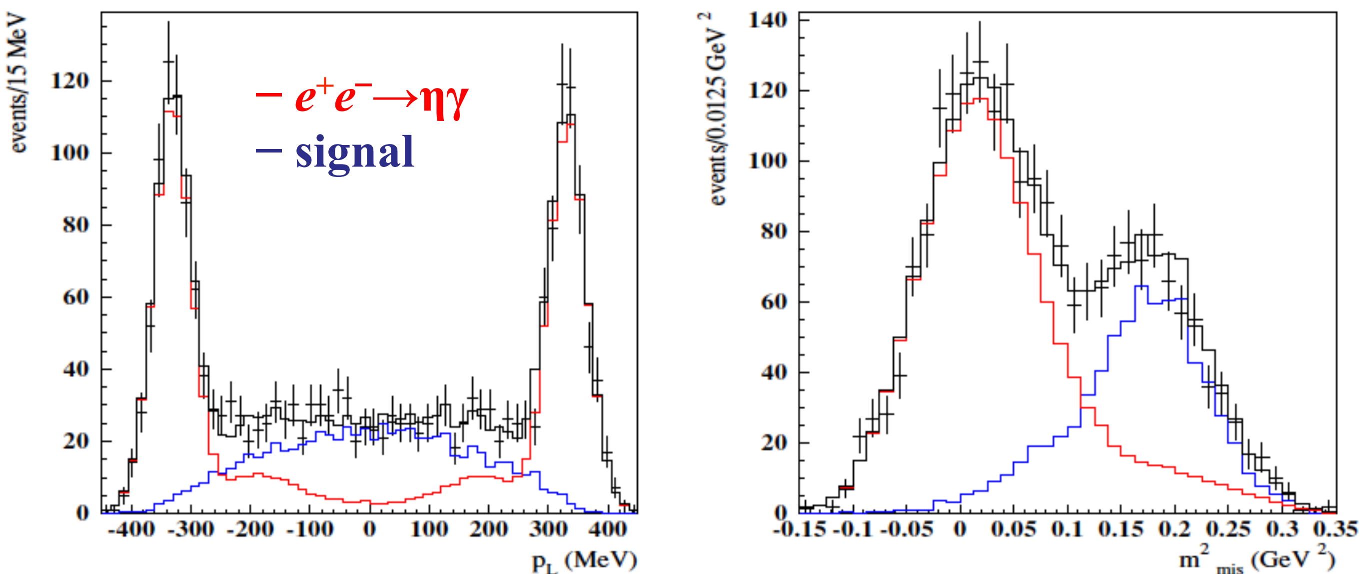
- **2720 events in the final sample ⇒ 394 signal events from fit**

$$\sigma(e^+e^- \to e^+e^-\eta) = (34.5 \pm 2.5 \pm 1.3)\ \text{pb}$$

[JHEP01(2013)119]

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

- Select events with no tracks and 6 prompt photons
- Background: $e^+e^- \to \eta\gamma$ with γ lost
- Fit to 6γ longitudinal momentum (p_L) and missing mass (M_{miss})



- 2166 events in the final sample: ~1/3 signal

$$\sigma(e^+e^- \to e^+e^-\eta) = (32.0 \pm 1.5 \pm 0.9)\ \mathrm{pb}$$

- Combining the two measurements:

$$\sigma(e^+e^- \to e^+e^-\eta) = (32.7 \pm 1.3 \pm 0.7)\ \mathrm{pb}$$

[JHEP01(2013)119]

Determination of Γ(η→γγ)

- **Extraction of the γγ width from:**

Differential γγ luminosity

$$\sigma(e^+e^- \to e^+e^-\eta) = \int \sigma_{\gamma\gamma\to\eta}(q_1, q_2)\Phi(q_1, q_2)\frac{d\vec{q}_1}{E_1}\frac{d\vec{q}_2}{E_2}$$

$$\sigma_{\gamma\gamma\to\eta} = \frac{8\pi^2}{m_\eta}\Gamma(\eta\to\gamma\gamma)\delta(w^2 - m_\eta^2)|F(q_1^2, q_2^2)|^2$$

and assuming:

$$F(q_1^2, q_2^2) = \frac{1}{1-bq_1^2}\frac{1}{1-bq_2^2} \quad \text{with } b = 1.94\ \text{GeV}^{-2}$$

$$\boxed{\Rightarrow \Gamma(\eta\to\gamma\gamma) = (520 \pm 20 \pm 13)\ \text{eV}}$$

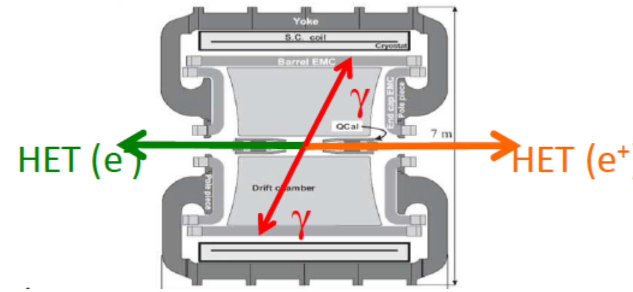
most precise measurement to date

[JHEP01(2013)119]

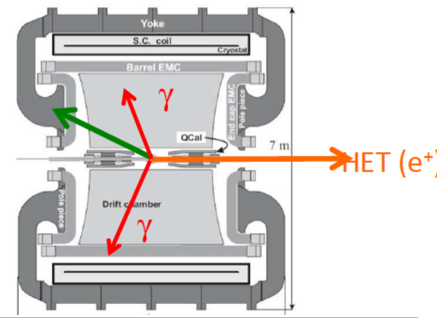
PDG average: $\Gamma(\eta\to\gamma\gamma) = (510 \pm 26)\ \text{eV}$

$\gamma\gamma \to \pi^0$ @KLOE-2

- $\Gamma(\pi^0 \to \gamma\gamma) = (8.09 \pm 0.11)$ eV (theory); 1.4% uncert.
  PriMex Coll. $\Rightarrow \Gamma(\pi^0 \to \gamma\gamma) = (7.82 \pm 0.14 \pm 0.17)$ eV ;
  2.8% uncert.
- KLOE-2: $\sqrt{s} = M_\phi$
  2γ in the EMC + e^+ and e^- in the HET
  (quasi-real photons; $|q^2| < 10^{-3}$ GeV^2)

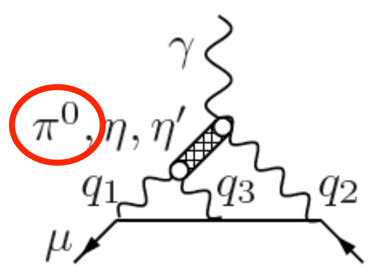


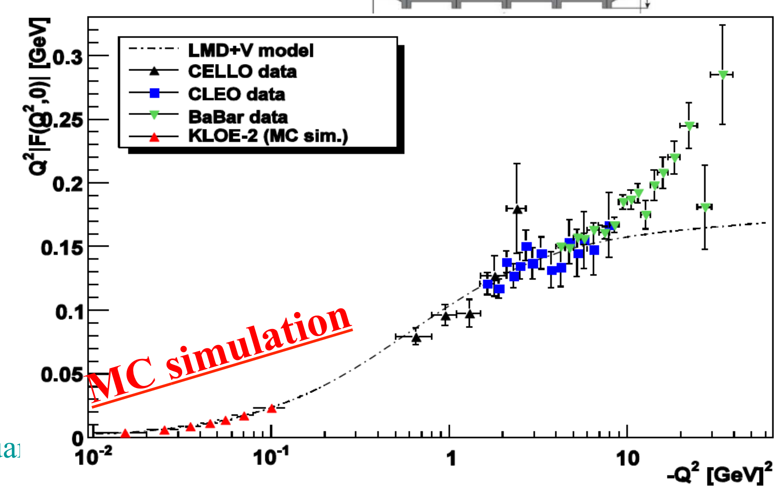
- $\sigma_{eff} \approx 3.4$ pb $\Rightarrow$ ~2000 evts/fb: with 5 fb^{-1} $\Rightarrow \delta\Gamma(\pi^0 \to \gamma\gamma) \approx 1\%$



- $\pi^0\gamma^*\gamma$ Transition FF, with a quasi-real photon ($q^2 \approx 0$, lepton in the HET) and a virtual one ($|q^2| < 0.1$ GeV^2, lepton in the DCH):

– unexplored q^2 region
– check TFF parametrizations
– reduce the model dependence of the LbL scattering contribution to $(g-2)_\mu$





[EPJC72(2012)1917]

Conclusions

- KLOE is continuing to exploit the high statistics samples of light mesons collected at DAΦNE to perform precision measurements in hadron spectroscopy

- KLOE-2: Installation of the new detectors in progress
  DAΦNE operations will restart in next June
  Goal: collect O(10 fb^{-1})in the next 2 – 3 years

Rich program of measurements in light hadron physics

- study of η and η' decays
- η / η' mixing
- search for dark forces
- $\gamma\gamma$ 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 $\gamma\gamma \to \pi^0\pi^0$; $f_0/a_0(980) \to K^0\bar{K}^0$
  [Eur.Phys.J.C68(2010),619]

9^{th} International Workshop on e+e− collisions from ϕ to ψ

Spare slides

KLOE-2 physics program

Eur. Phys. J. C68(2010)619

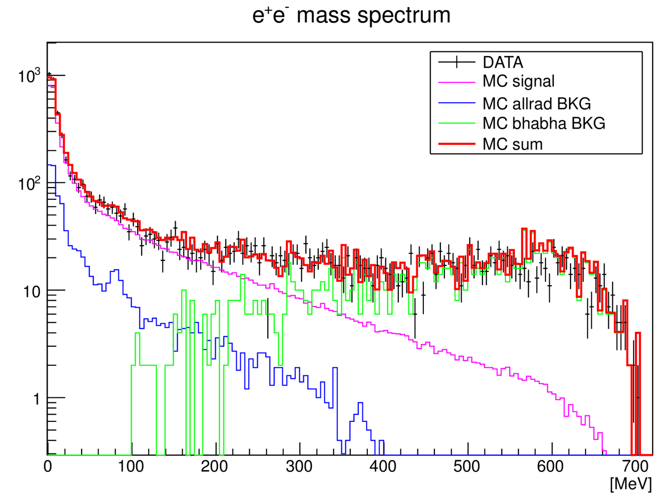
- $\gamma\gamma$ physics
  - Properties of $\sigma(600)$
  - Study of $\Gamma(S/P \rightarrow \gamma\gamma)$
  - P transition form factor
- Light meson spectroscopy
  - Properties of scalar/vector mesons
  - Rare η decays
  - η' decays
- Kaon physics
  - Test of CPT (and QM) in correlated kaon decays
  - 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 $(g_\mu\text{-}2)$

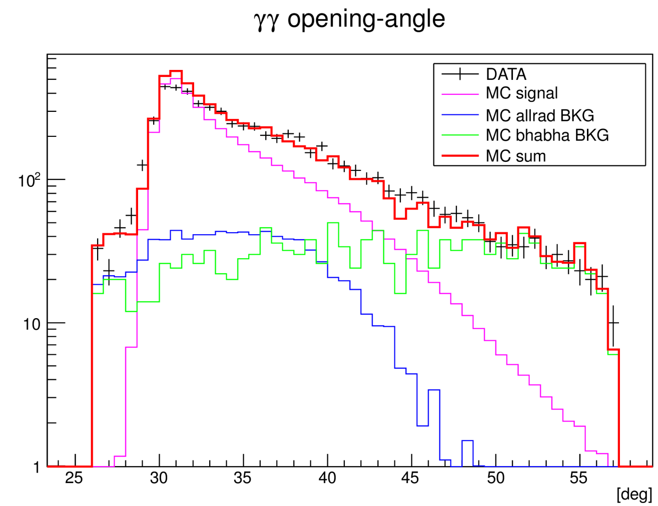
$\phi \rightarrow \pi^0 e^+ e^-$

- **BR($\phi \rightarrow \pi^0 e^+ e^-$) = $(1.12 \pm 0.28) \times 10^{-5}$**
- **$\Rightarrow$ 25% uncertainty**
- **SND $\Rightarrow$ 52 ; CMD-2 $\Rightarrow$ 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 …**

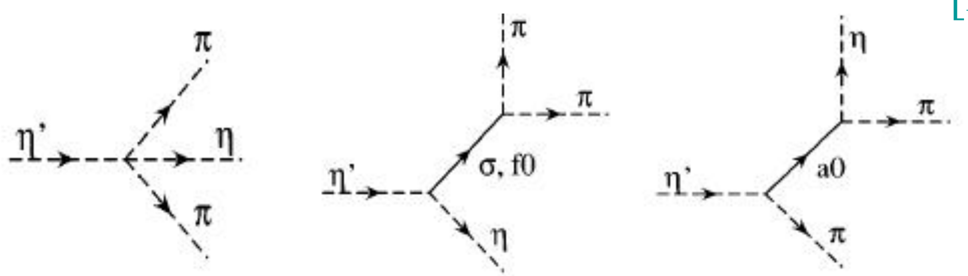


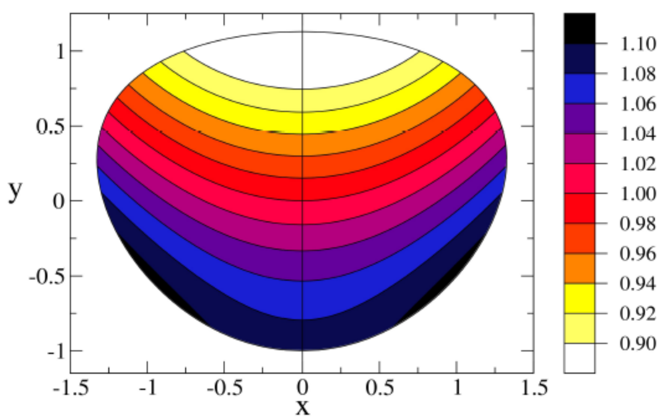


$\eta' \to \eta\pi^+\pi^-$

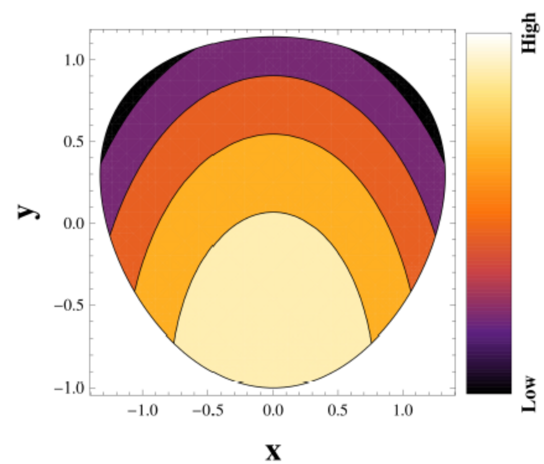
- **Test of ChPT and its extensions**
- **Study of $\eta - \pi$ final state interactions**
- **Sensitive to scalar resonances: $a_0(980)$ dominant, but $\sigma(600)$ also present**

[Fariborz-Schechter PRD60(1999)034002
Donskov et al.,arXiv:0902.3320]





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



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

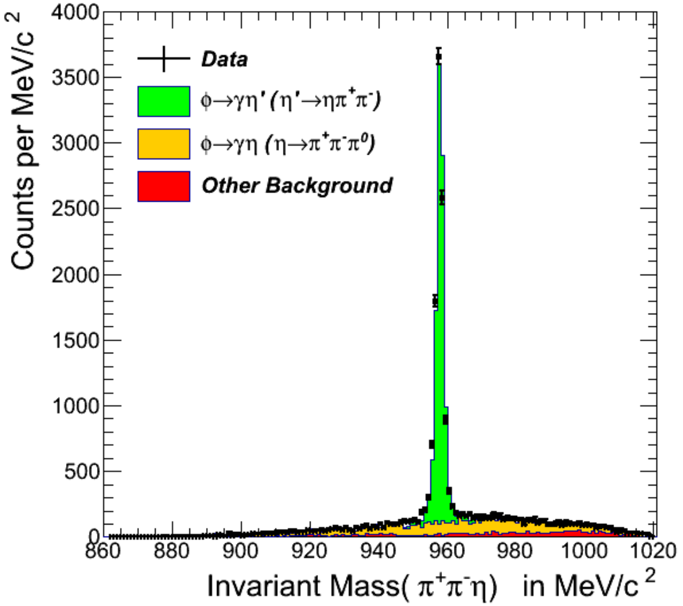
$$X = \frac{\sqrt{3}(T_{\pi^+} - T_{\pi^-})}{T_{\pi^+} + T_{\pi^-} + T_{\eta}}$$

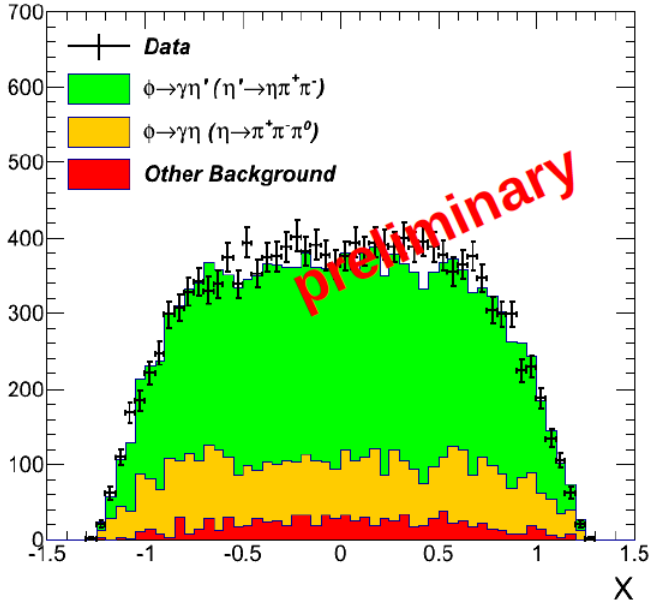
$$Y = \frac{m_\eta + 2m_{\pi^\pm}}{m_{\pi^\pm}} \frac{T_\eta}{T_{\pi^+} + T_{\pi^-} + T_\eta} - 1$$

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

- Decay chain: $\phi \to \eta'\gamma$, $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$
- L = 1.7 fb^{-1} analyzed
- Main background: $\eta \to \pi^+\pi^-\pi^0$
- ε = 23%; B/S ratio = 0.2
- 10160 events selected

To be compared with 44000 evts from BES-III [PRD83(2011)012003]





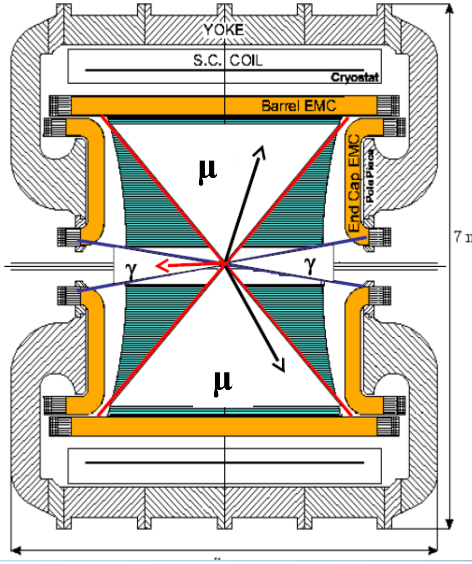
- Dalitz plot projection (940 < $M_{\eta\pi\pi}$ < 980 MeV)
- KLOE-2: with O(10 fb^{-1})

~ 2.5×10^5 $\eta' \to \eta\pi^+\pi^-$ ($\eta \to \gamma\gamma$) evts expected

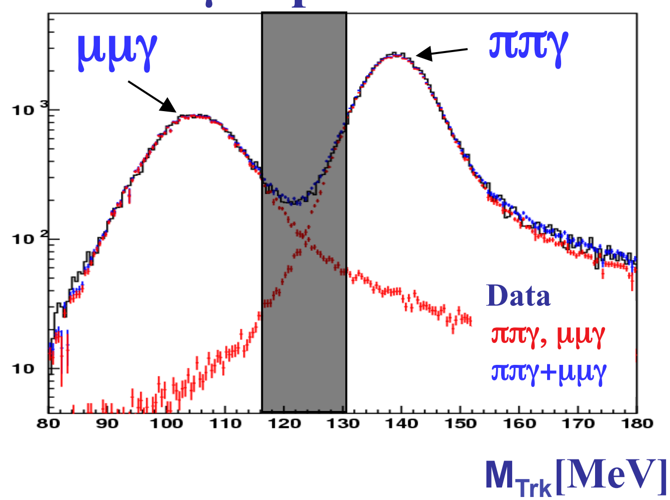
ε = 23% $\Rightarrow$ ~ 60000 events

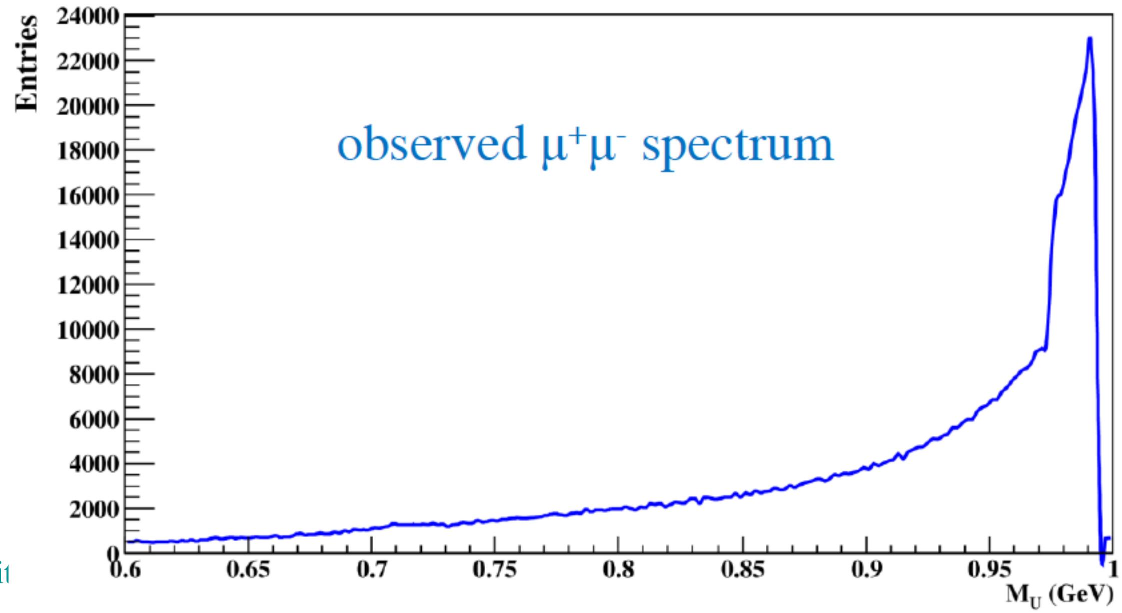
DF search in $e^+e^- \to \mu^+\mu^-\gamma$

- $e^+e^- \to U\gamma \to \mu^+\mu^-\gamma$: look for a narrow peak above the continuum
- L = 240 pb^{-1}
- Photon at small angle (ϑ<15° - not detected)
  low FSR contribution + reduction of $\phi \to \pi^+\pi^-\pi^0$ bckg
- Two tracks with opposite sign at large angle (ϑ>50°)



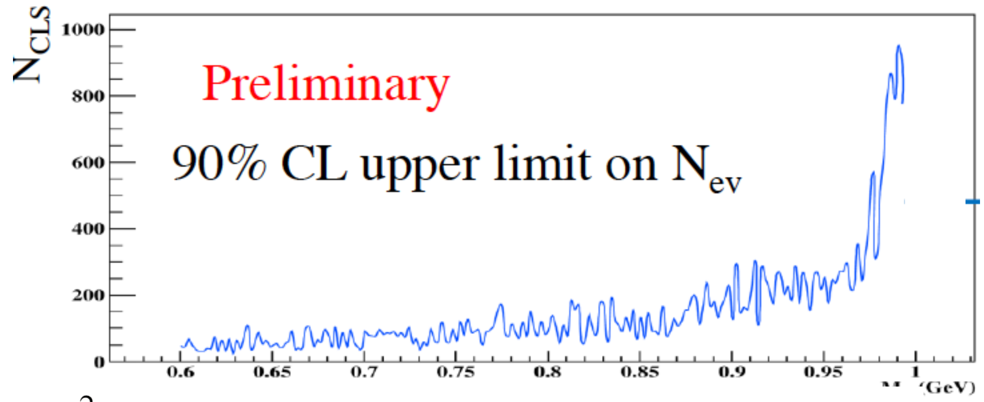
π/μ separation





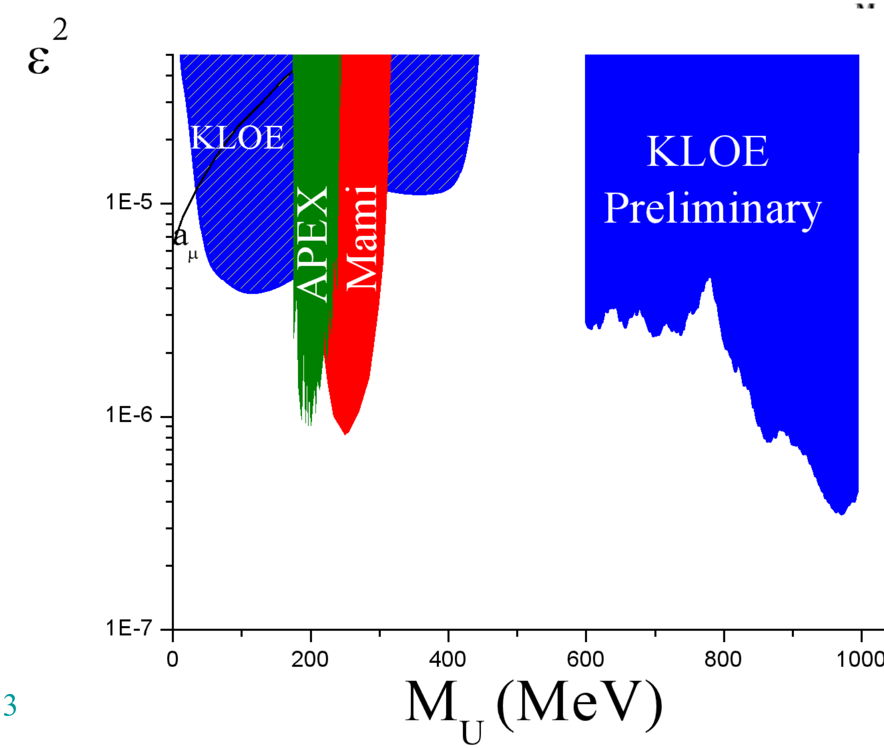
DF search in $e^+e^- \to \mu^+\mu^-\gamma$

- Upper limit with the CL_S method



- With the full KLOE statistics, 2.5 fb^{-1}, the sensitivity will improve by a factor of ~ 3

- A further factor of 2 is expected from KLOE-2 data-taking

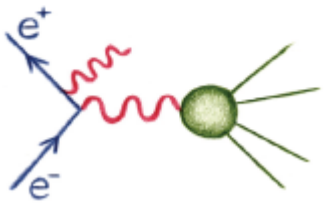


$\sigma(e^+e^- \to$ hadr.) below 1 GeV

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

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

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



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

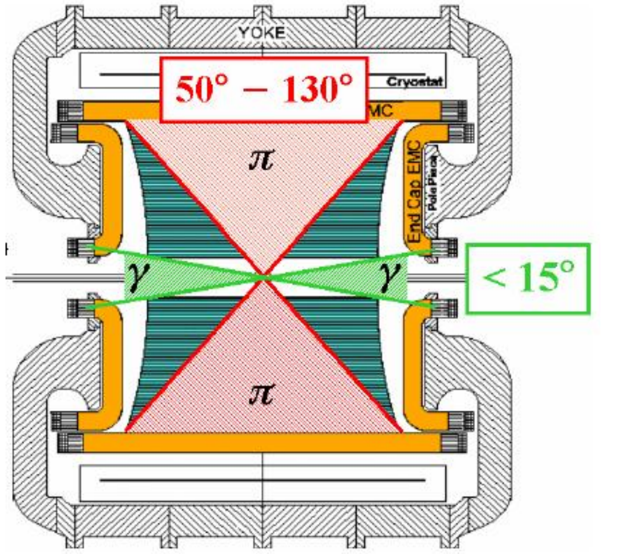
- Different analyses: (1) photon emitted at Small Angle (S.A. analysis)
  [PLB606(2005)12, PLB670(2009)285]
  (2) photon emitted at Large Angle (L.A. analysis)
  [PLB700(2011)102]
  (3) photon at S.A., $\sigma(e^+e^- \to \pi^+\pi^-\gamma)/\sigma(e^+e^- \to \mu^+\mu^-\gamma)$
  [arXiv-submit:0616958,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

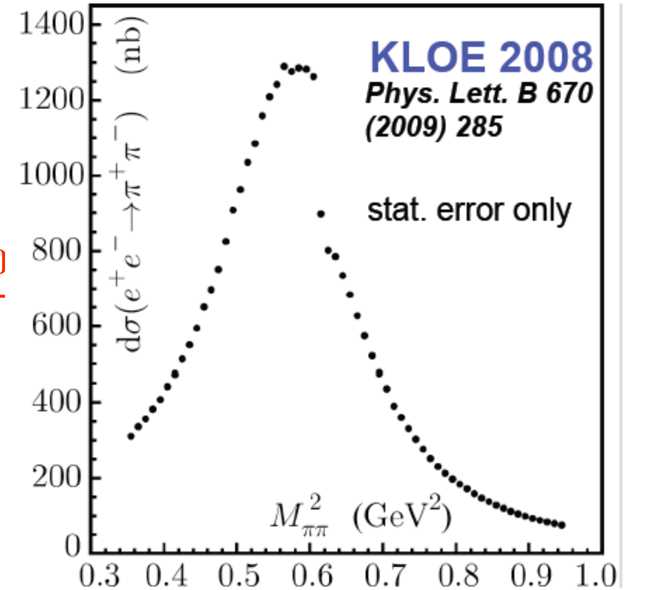
$$\vec{p}_\gamma = -(\vec{p}_+ + \vec{p}_-)$$

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



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

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



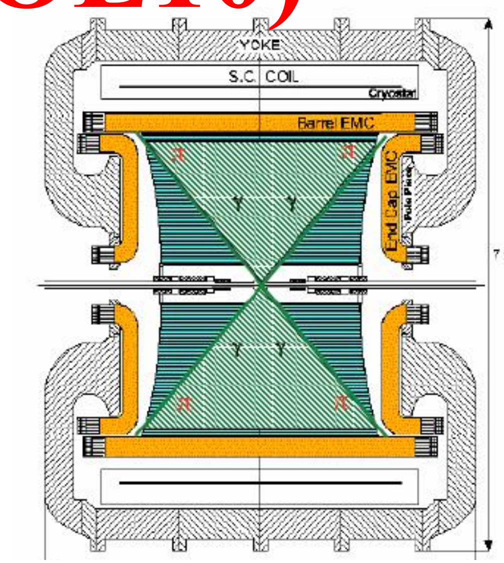
L.A. analysis (KLOE10)

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

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

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

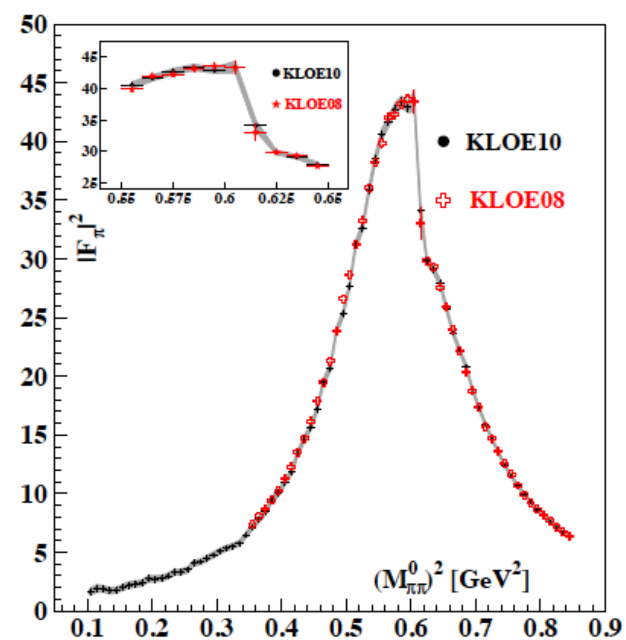


$$a_\mu^{\pi\pi}(0.1\text{–}0.85\ \mathrm{GeV}^2) = (478.5 \pm 2.0_{stat} \pm 5.0_{syst} \pm 4.5_{th}) \times 10^{-10}$$

[PLB700(2011)102]

- Good agreement with KLOE08
- Combined KLOE08 + KLOE10:

$$a_\mu^{\pi\pi}(0.1\text{–}0.95\ \mathrm{GeV}^2) = (488.6 \pm 6.0) \times 10^{-10}$$

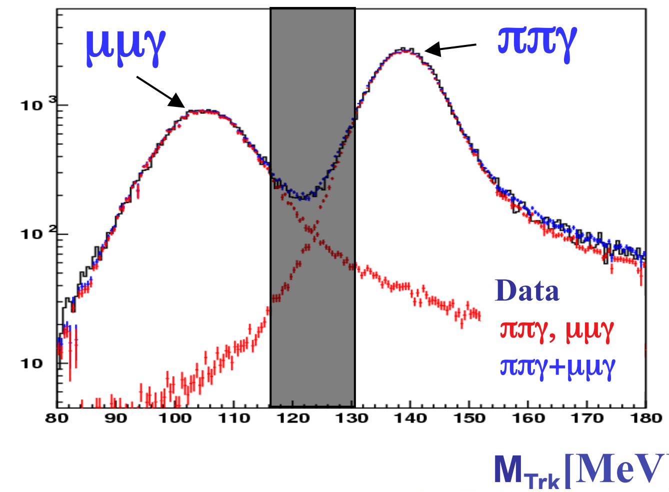


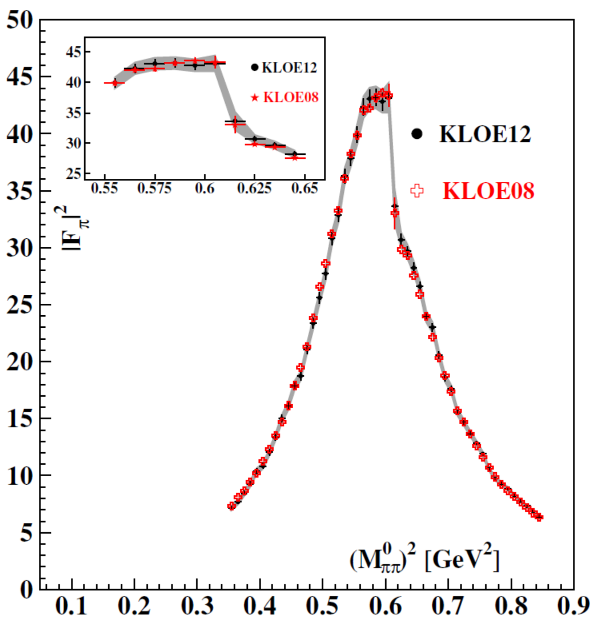
$\pi^+\pi^-\gamma$ / $\mu^+\mu^-\gamma$ (KLOE12)

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

S.A. analysis
Same sample as KLOE08

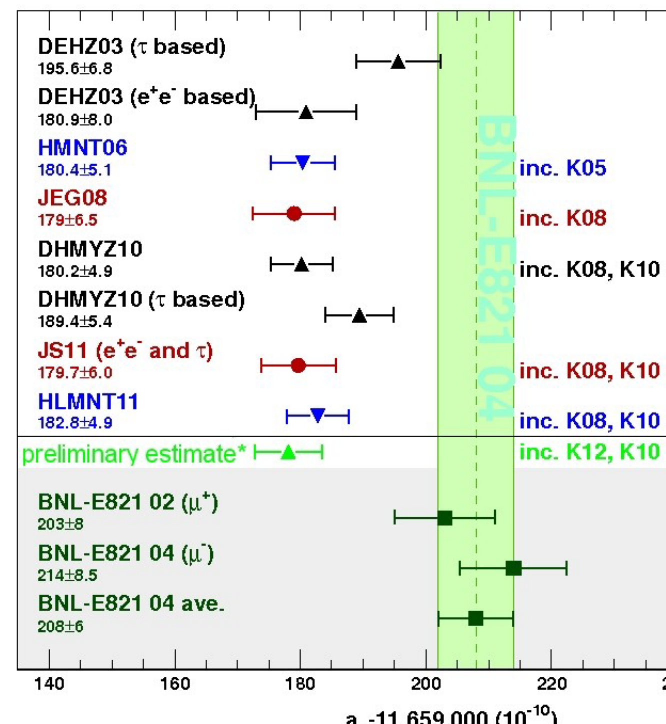
- **Many factors cancel in the ratio:**
  - — radiator function
  - — luminosity from Bhabhas
  - — vacuum polarization





3 σ discrepancy confirmed

[arXiv-submit:0616958]

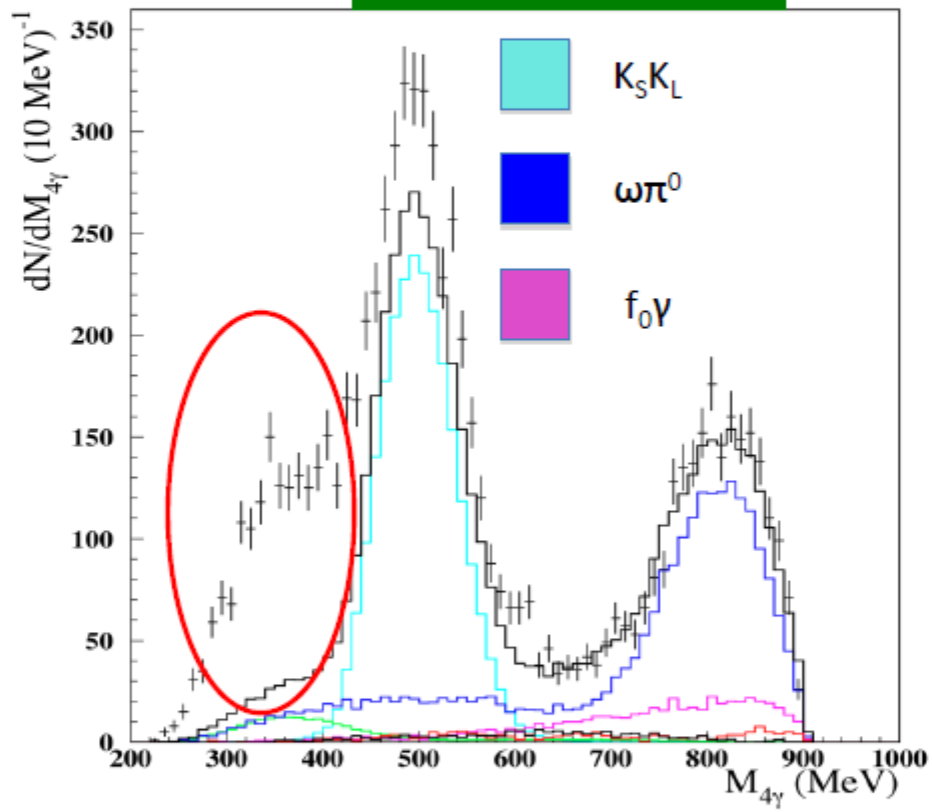


<u>$a_\mu^{\pi\pi}$ (0.35–0.95 GeV^2) = $(385.1 \pm 1.1_{stat} \pm 4.4_{syst} \pm 1.2_{th}) \times 10^{-10}$</u>

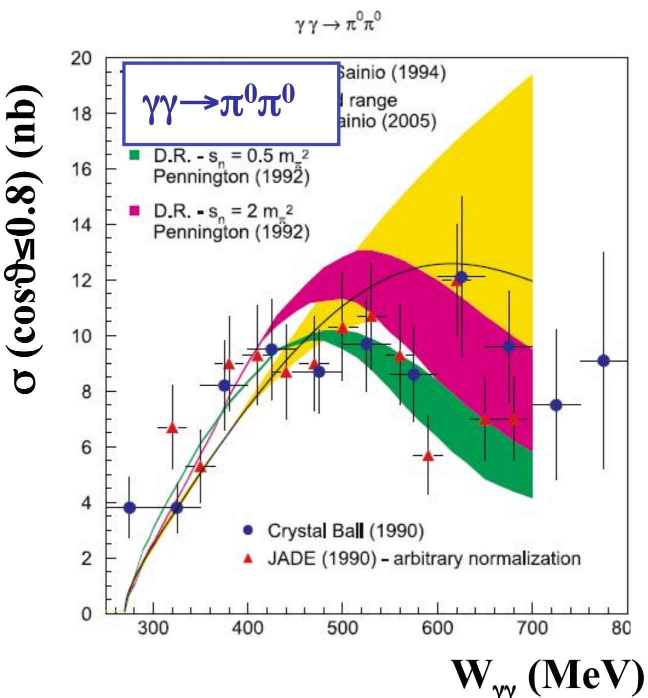
$\gamma\gamma \to \pi^0\pi^0$

- $e^+e^- \to e^+e^- \pi^0\pi^0$
- 240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV)
- Selected sample: 4 prompt photons
- Excess of events (~2000) with respect to background in the low mass region
- $\gamma\gamma \to \pi^0\pi^0$ cross-section evaluation in progress

8090 events after selections



4γ invariant mass distribution

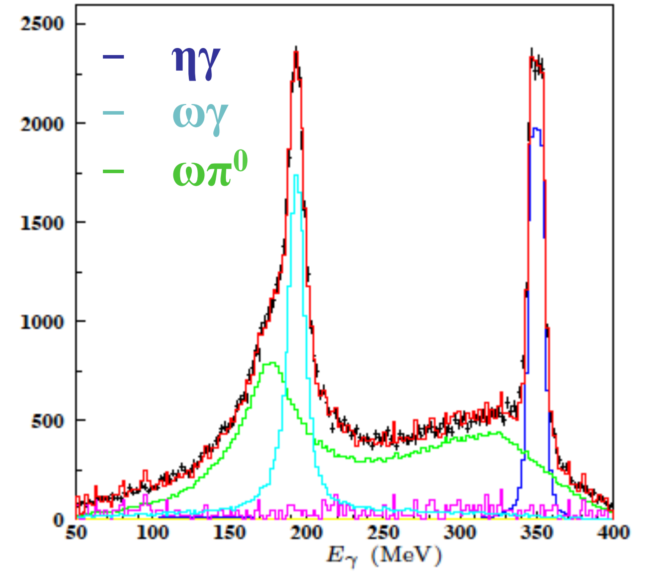


KLOE-2: O(10 fb^{-1})at $\sqrt{s} = M_\phi$ with $e^\pm$ tagging

⇒ 2% statistical accuracy using the same energy bin as Crystal Ball (~20% error)

$\sigma(e^+e^- \to \eta\gamma)$ @1 GeV

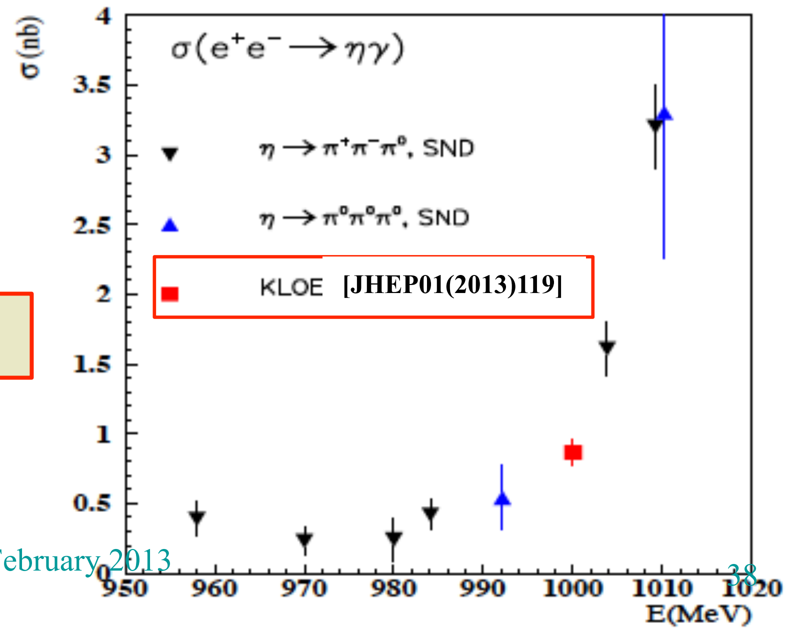
- $e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$: 3 photons + 2 tracks
  - pion ID
  - kinematic cuts to suppress background from kaons
  - kinematic fit



$\sigma(e^+e^- \to \eta\gamma, \text{1 GeV}) = (0.856 \pm 0.008 \pm 0.016)$ nb

- From the fit for $\gamma\gamma \to \eta \to \pi^0\pi^0\pi^0$:

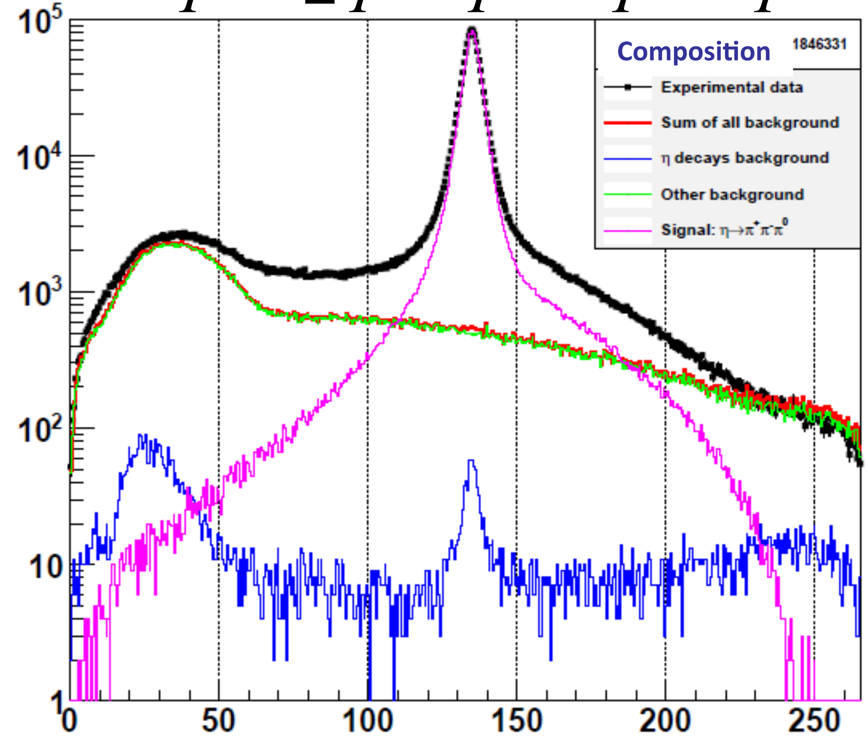
$\sigma(e^+e^- \to \eta\gamma, \text{1 GeV}) = (0.853 \pm 0.025 \pm 0.008)$ nb



Normalization Sample: $\eta \to \pi^+\pi^-\pi^0$

- $\eta \to \pi^+\pi^-\pi^0$
- $\mathcal{L} = 558\ \mathrm{pb}^{-1}$
- $N(\eta \to \pi^+\pi^-\pi^0) = 1.19 \times 10^6$
- $\varepsilon = (22.77 \pm 0.02)\%$
- $B/S = 0.65\%$
- $\sigma(e^+e^- \to \phi \to \eta\gamma) = 41.8 \pm 0.2$ nb

$$P^{miss} = P^{\phi} - P^{\pi^+} - P^{\pi^-} - P^{\gamma_\phi}$$



M (MeV)

BR($\eta \to \pi^+\pi^-\pi^0$) = (22.41 ±0.03 ±0.35)%

PDG: BR($\eta \to \pi^+\pi^-\pi^0$) = (22.74 ±0.28)%

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

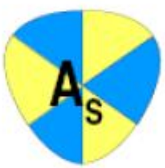
- **Asymmetries $\Leftrightarrow$ test of C conservation:**

Left-right asymmetry (related to *c*, *e* parameters)

$$A_{LR} = (9 \pm 10^{+9}_{-14}) \times 10^{-4}$$

Quadrant asymmetry: $\cancel{C}$ in $\Delta I = 2$

$$A_{Q} = (-5 \pm 10^{+3}_{-5}) \times 10^{-4}$$



Sextant asymmetry: $\cancel{C}$ in $\Delta I = 1$

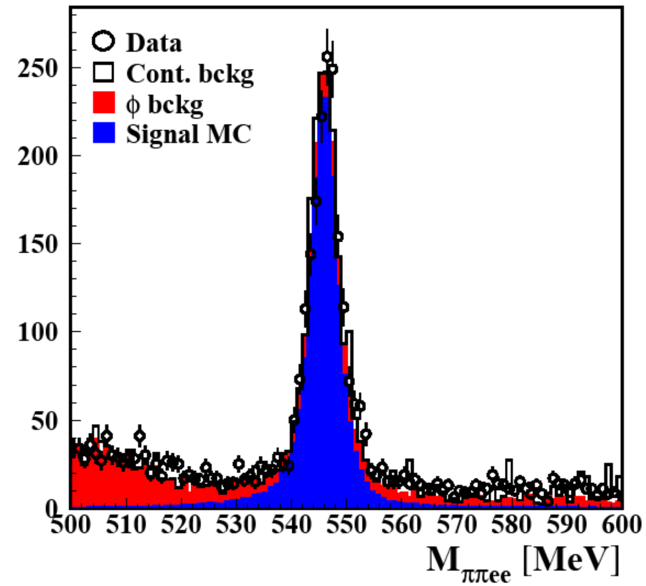
$$A_{S} = (8 \pm 10^{+8}_{-13}) \times 10^{-4}$$

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

[JHEP0805(2008)006]

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

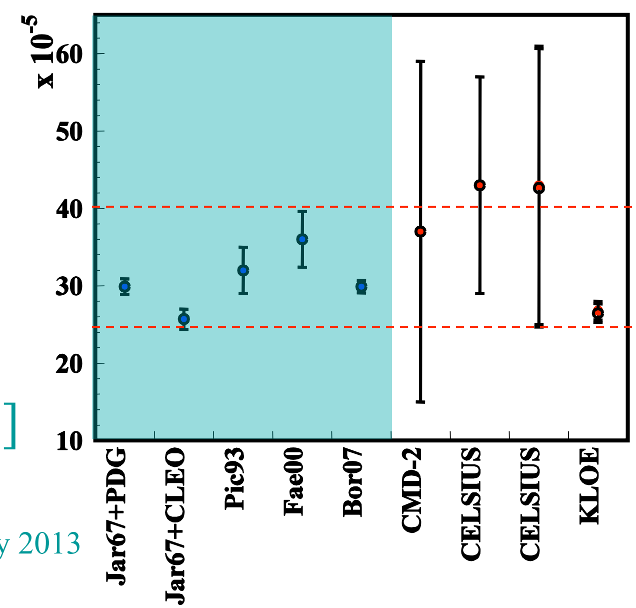
- Rare decay: ChPT and VDM predictions $\Rightarrow$ Br ~ 3×10^{-4}
- 2 measurements: CMD-2 4 events
  WASA@CELSIUS 16 events



- Data sample: 1.7 fb^{-1}
- $M(\pi^+\pi^- e^+e^-)$ distribution:
  fit with signal + background (MC)
  $\Rightarrow$ 1555 ± 52 signal events
  368 background "

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

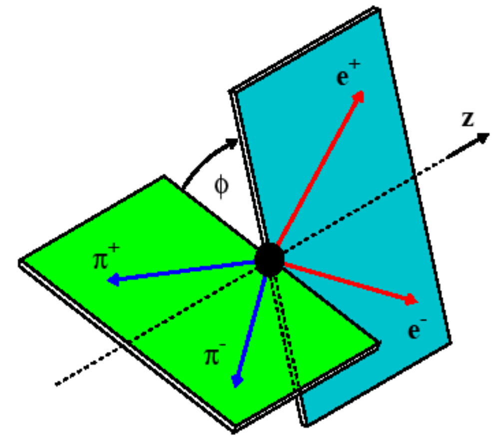
[PLB675(2009)283]



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

- Plane asymmetry ⇒ test of CP violation
- Constraints from $Br(\eta \to \pi^+\pi^-)$: expt. $A_{CP} < 10^{-4}$
  th. (SM) $A_{CP} < 10^{-15}$

$$A_{CP} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

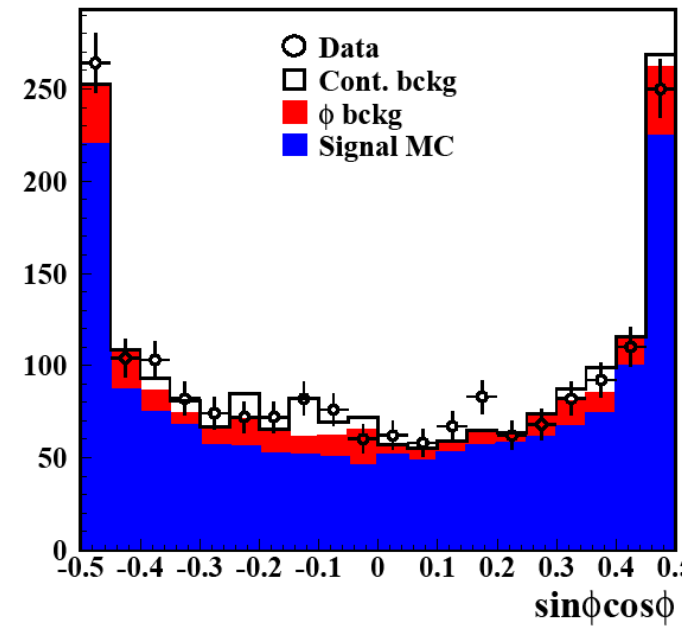


- Non conventional CP violation mechanism (non CKM) proposed ⇒ A_{CP} up to 2×10^{-2}

[D.N.Gao MPLA17(2002)]

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

[PLB675(2009)283]



- KLOE-2 with $O(10\ fb^{-1})$:
  - Inner Tracker will increase acceptance
  - statistical uncert. on Br ⇒ 1.4%
  - factor of 2 in sensitivity to A_{CP}

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

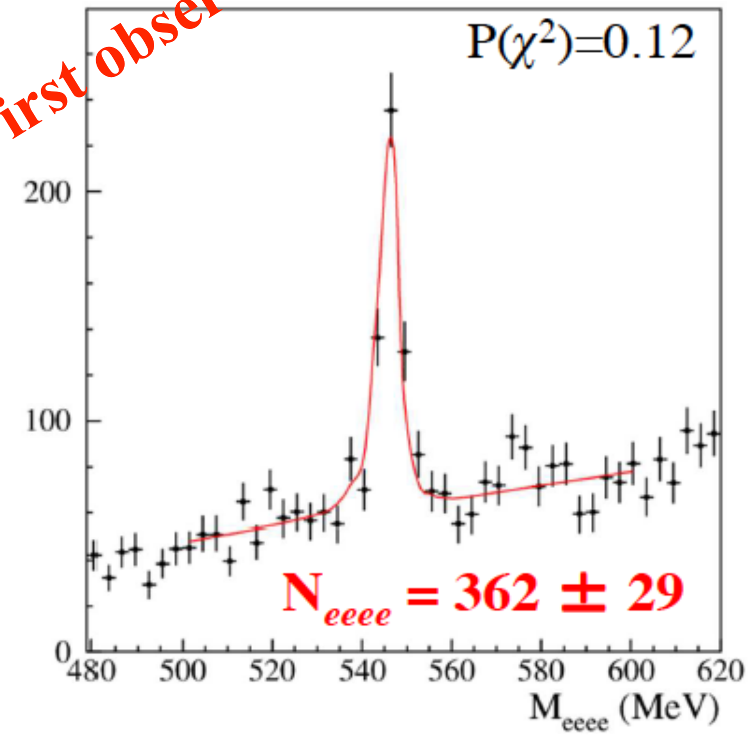
- **Theoretical predictions: BR ~ 2.4 – 2.6 ×10^{-5}**

- **BR < 6.9×10^{-5} @90%C.L. (CMD-2, 2001)**
  BR < 9.7×10^{-5} @90%C.L. (WASA, 2008)
  (2 evts, with 1.3 bckg)

- **Data sample: 1.7 fb^{-1}**
- **MC simulation according to Bijnens and Persson** [hep-ph/0106130]
- **e^+e^- pairs from photon conversions in the beam pipe and Drift Chamber wall rejected**

- **Fit with signal + background from continuum ($e^+e^- \to e^+e^-\gamma$ with γ conversion)**

First observation



$$BR(\eta \to e^+e^-e^+e^-(\gamma)) = (2.4 \pm 0.2_{stat} \pm 0.1_{syst}) \times 10^{-5}$$

[PLB702(2011)324]

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

- 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($\eta \to \pi^0\gamma\gamma$): $(7.2\pm1.4)\times10^{-4}$ GAMS (1984)

  $< 8.4 \times10^{-4}$@90% C.L. SND (2001)

  $(22.1 \pm 2.4 \pm 4.7)\times10^{-5}$ Crystal Ball@AGS (2008)

  $(22.4 \pm 4.6 \pm 1.7)\times10^{-5}$ Crystal Ball@MAMI(2009)

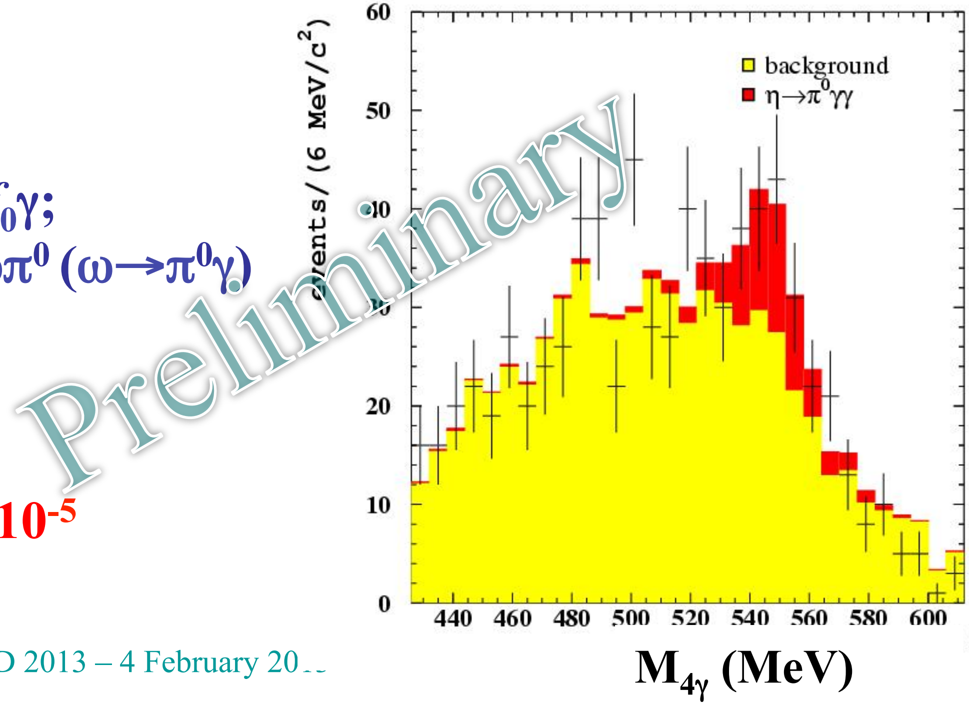
- KLOE $\Rightarrow$ $\phi \to \eta\gamma$; $\eta \to \pi^0\gamma\gamma$
- Bckg.: (1) 5γ processes: $\phi \to a_0\gamma, f_0\gamma$;

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

  (2) $\phi \to \eta\gamma$; $\eta \to \pi^0\pi^0\pi^0$

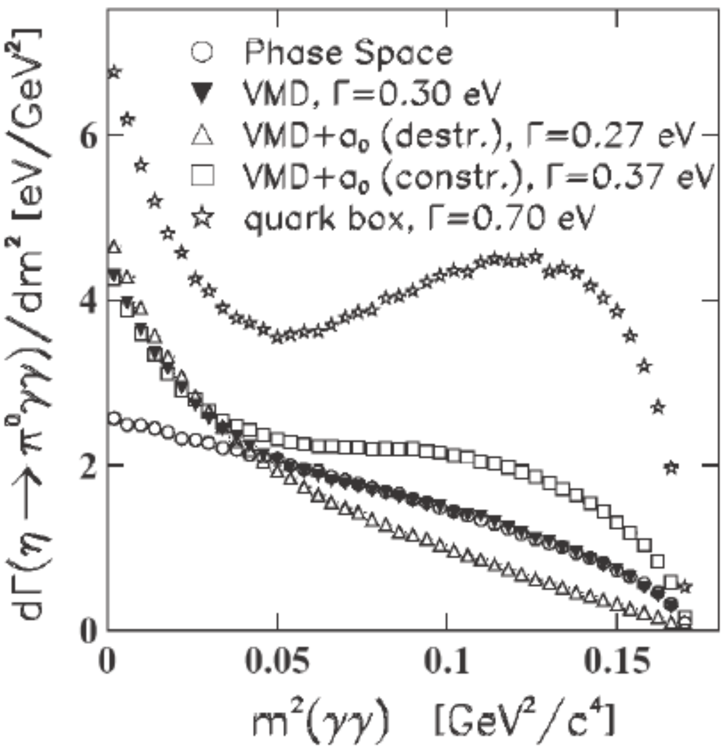
- L ≈ 450 pb^{-1}

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

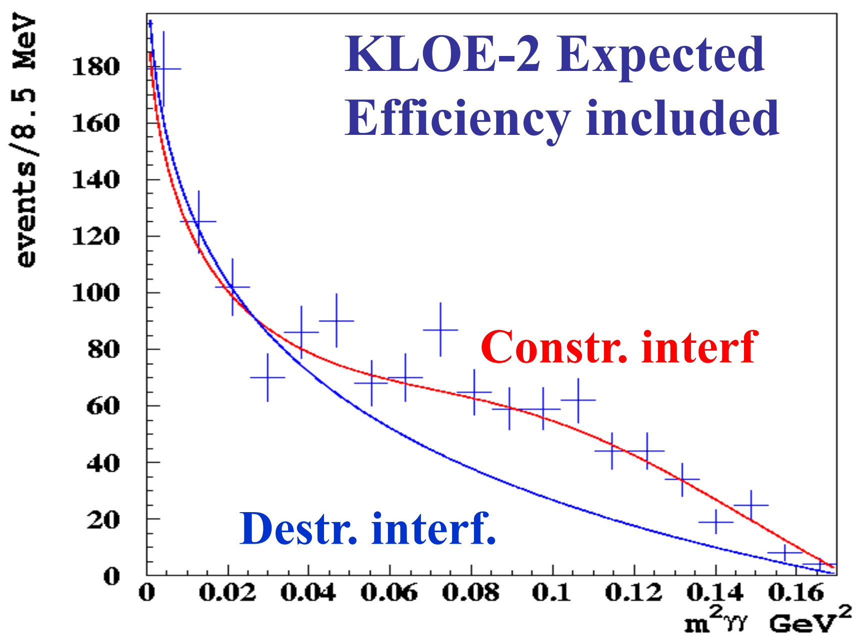


$\eta \rightarrow \pi^0\gamma\gamma$ @ KLOE-2

- KLOE-2, O(10 fb^{-1}) $\Rightarrow$ ~ 3% accuracy on Br
- $M_{\gamma\gamma}$ distribution to distinguish among different theoretical models



[Prakhov et al., PRC78(2008)015206]



[VMD + a0: Ng-Peters, PRD46(1992)5034]

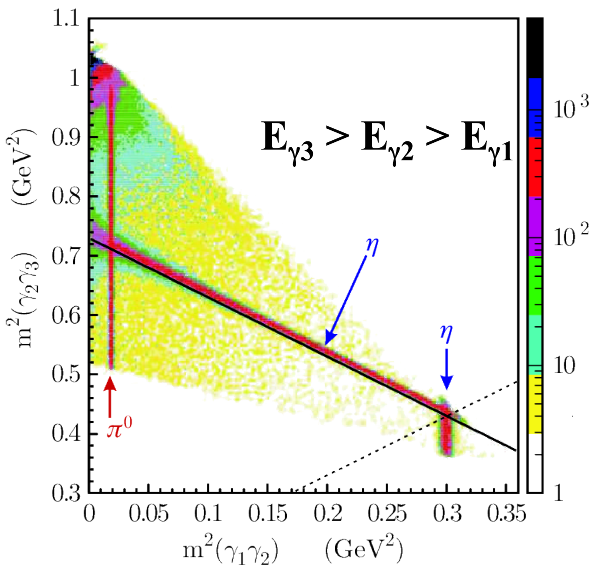
η mass

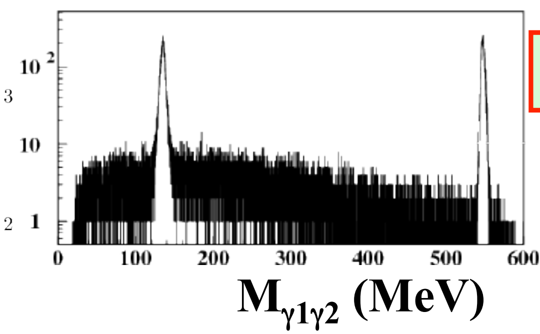
- 8 σ discrepancy: GEM (COSY) $\Rightarrow M_\eta = 547.311 \pm 0.028 \pm 0.032$ MeV $(p + d \rightarrow {}^3He + \eta)$

  NA48 $\Rightarrow M_\eta = 547.843 \pm 0.030 \pm 0.041$ MeV $(\pi^- + p \rightarrow \eta + n$ with $\eta \rightarrow 3\pi^0)$

  CLEO-c $\Rightarrow M_\eta = 547.785 \pm 0.017 \pm 0.057$ MeV $(\psi' \rightarrow J/\psi\ \eta)$

- KLOE: $\phi \rightarrow \eta\gamma$; $\eta \rightarrow \gamma\gamma$ check with $\phi \rightarrow \pi^0\gamma$; $\pi^0 \rightarrow \gamma\gamma$ [JHEP12(2007)073]

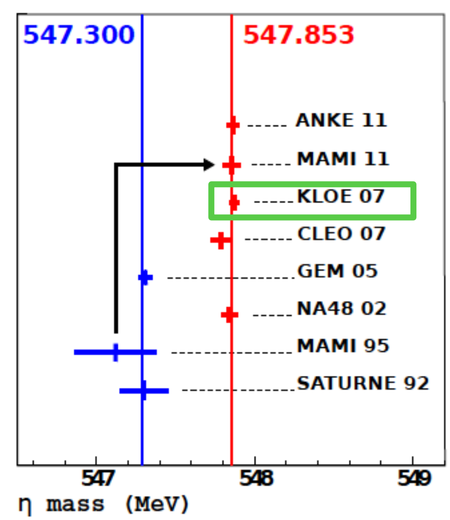




$M_\eta = 547.874 \pm 0.007 \pm 0.029$ MeV

$M_{\pi0} = 134.906 \pm 0.012 \pm 0.049$ MeV

(PDG $\Rightarrow 134.9766 \pm 0.0006$ MeV)



- Preliminary measurement by ANKE@COSY

  $(p + d \rightarrow {}^3He + \eta)$ $M_\eta = 547.869 \pm 0.007 \pm 0.040$ MeV

Mixing η/η'

- $\phi \to \eta'\gamma$; $\eta' \to \eta\,\pi^+\pi^-$; $\eta \to \pi^0\pi^0\pi^0$
  $\eta' \to \eta\pi^0\pi^0$; $\eta \to \pi^+\pi^-\pi^0$ } Final state: $\pi^+\pi^- + 7\gamma$
- $\phi \to \eta\gamma$; $\eta \to \pi^0\pi^0\pi^0$

L= 427 pb^{-1}

$N_{\eta'\gamma} = 3407 \pm 61 \pm 43$ ev.

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

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

[systematics dominated by $\delta Br(\eta' \to \eta\pi\pi)$=3%]

$\Rightarrow$ $Br(\phi \to \eta'\gamma) = (6.20 \pm 0.11 \pm 0.15) \times 10^{-5}$

- Pseudoscalar mixing angle: $\left(|q\bar{q}\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)\right)$

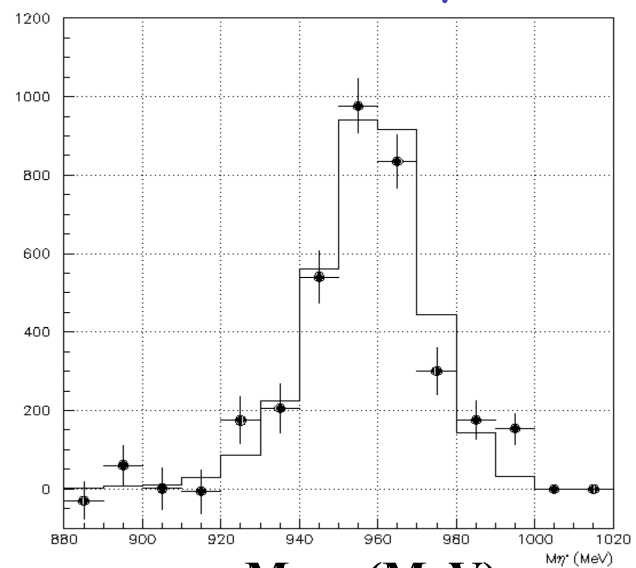
$$\eta = \cos\varphi_P |q\bar{q}\rangle - \sin\varphi_P |s\bar{s}\rangle$$

$$\eta' = \sin\varphi_P |q\bar{q}\rangle + \cos\varphi_P |s\bar{s}\rangle$$

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

$$\boxed{\varphi_P = (41.4 \pm 0.3 \pm 0.9)^\circ \Rightarrow \vartheta_P = (-13.3 \pm 0.3 \pm 0.9)^\circ}$$

Inv.mass of $\pi^+\pi^- + 6\gamma$ out of 7



$M_{\pi\pi6\gamma}$ (MeV)

[PLB648(2007)267]

η' gluonium content

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

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

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

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

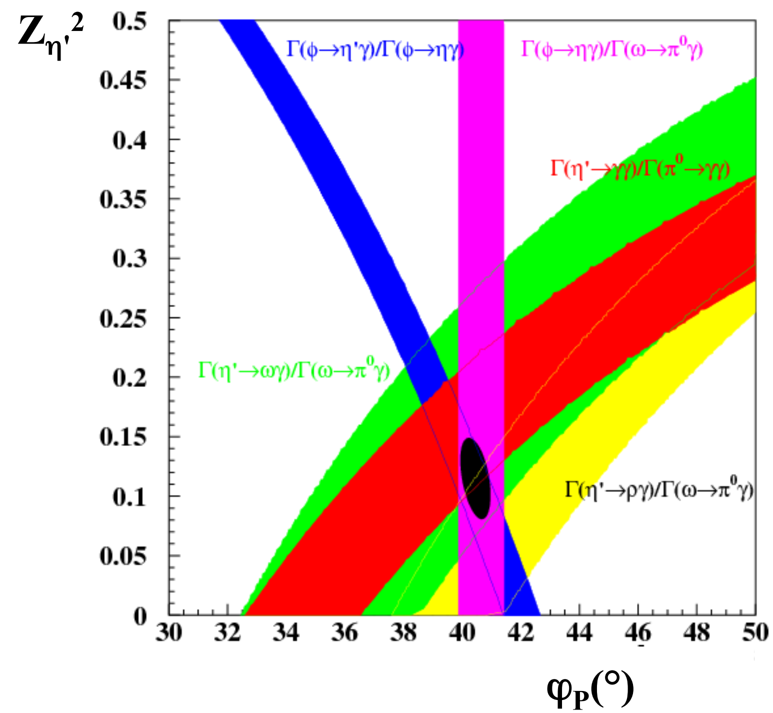
[Rosner PRD27(1983) 1101,
Kou PRD63(2001)54027]

Fit:

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

$$\left.\begin{array}{l} \frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)}, \frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\omega \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \\ \frac{\Gamma(\rho \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\phi \to \eta\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(\phi \to \pi^0\gamma)}{\Gamma(\omega \to \pi^0\gamma)}, \frac{\Gamma(K^{*+} \to K^+\gamma)}{\Gamma(K^{*0} \to K^0\gamma)} \end{array}\right\} \begin{array}{l}\textbf{PDG08+}\\ \textbf{KLOE}\\ \omega\to\pi^0\gamma\end{array}$$

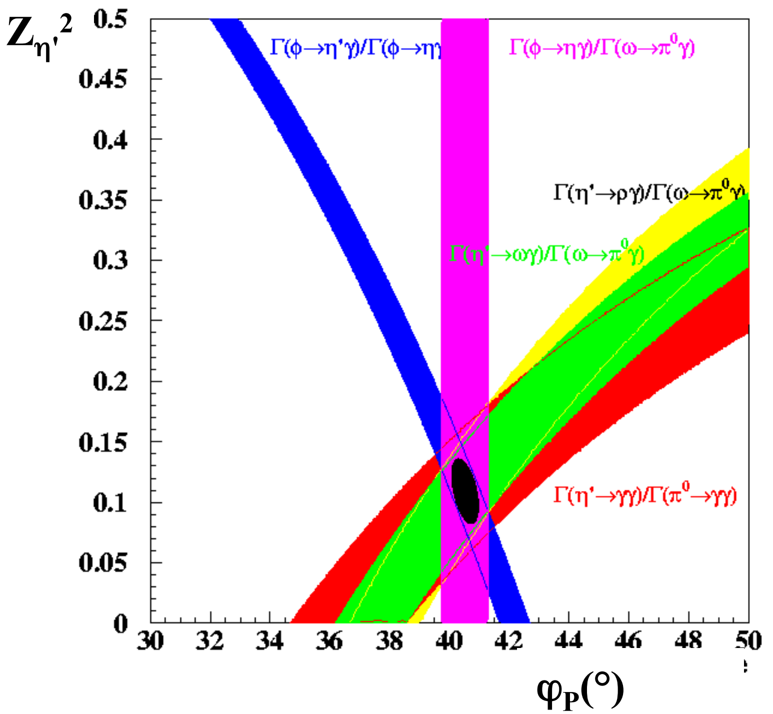
	New fit	PLB648
$Z_{\eta'}^2$	0.12 ± 0.04	0.14 ± 0.04
φ_P (deg.)	40.4 ± 0.6	39.7 ± 0.7
C_{NS}	0.94 ±0.03	0.91 ±0.05
C_S	0.83 ±0.05	0.89 ±0.07
φ_V (deg.)	3.32 ± 0.10	3.2
m_s/m	1.24 ± 0.07	1.24 ± 0.07
χ^2/ndf	4.6/3	1.42 / 2
$P(\chi^2)$	20%	49%



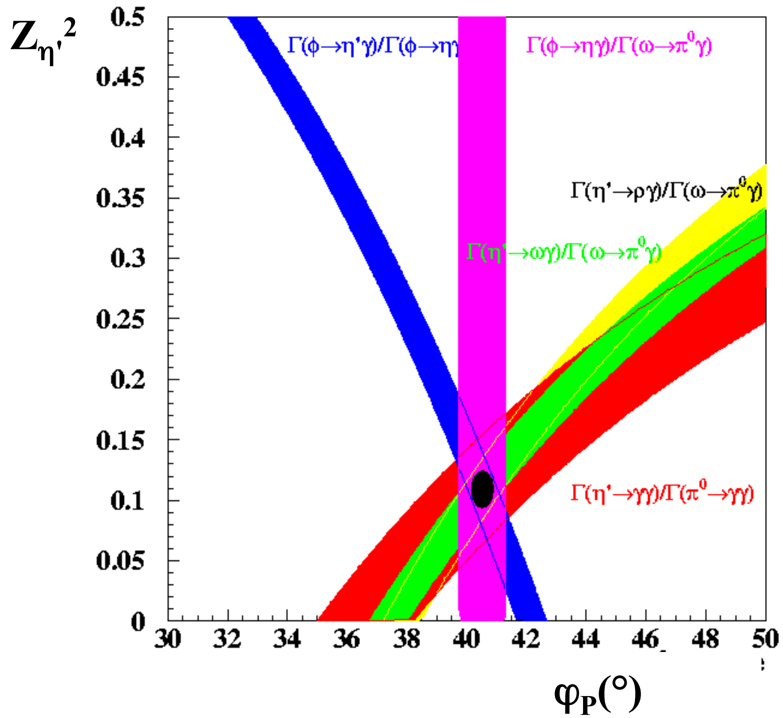
[JHEP07(2009)105]

Mixing η/η´ @ KLOE-2

By measuring the main η' Br's @ 1%



By measuring the η' width @ 1.4% (run at $\sqrt{s} \geq 1.2$ GeV needed)



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

Light Scalar Mesons

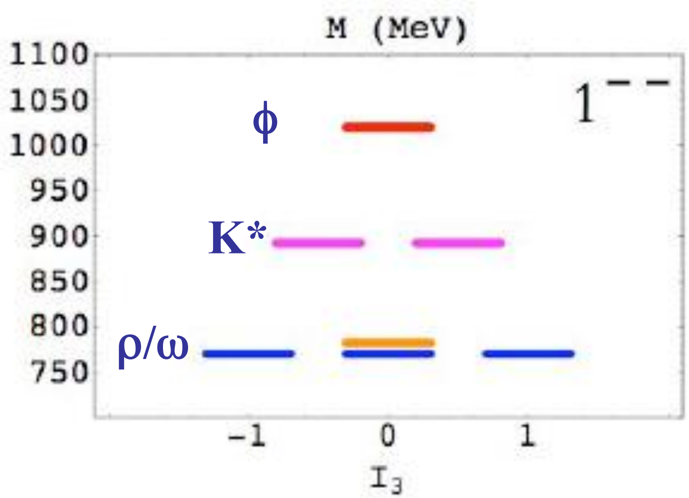
Open problems: - do $\sigma(600)$, $\kappa(800)$, $f_0(980)$, $a_0(980)$ belong to the same SU(3) nonet ($^3P_0$) ?

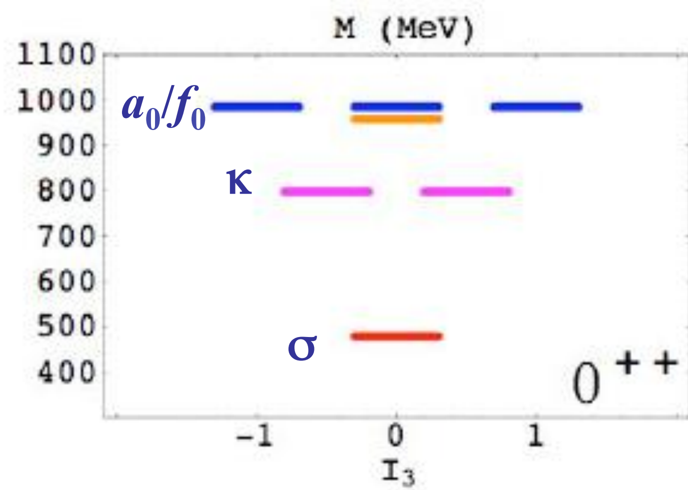
- if so, why the inverted mass spectrum ?

The $q\bar{q}$ structure of the light scalars can be questioned

Alternative explanations: $q\bar{q}q\bar{q}$ states (Jaffe '77, Maiani et al.,),

$K\bar{K}$ molecules (Weinstein-Isgur '90), ….





Scalar mesons at KLOE

- ϕ radiative decays:
  - $\phi \to \pi^0\pi^0\gamma$, $\pi^+\pi^-\gamma$ $\Rightarrow$ $f_0(980)/\sigma(600) \to \pi\pi$
  - $\phi \to \eta\pi^0\gamma$ $\Rightarrow$ $a_0(980) \to \eta\pi^0$
  - $\phi \to K_S K_S \gamma$ $\Rightarrow$ $(f_0/a_0) \to K\bar{K}$

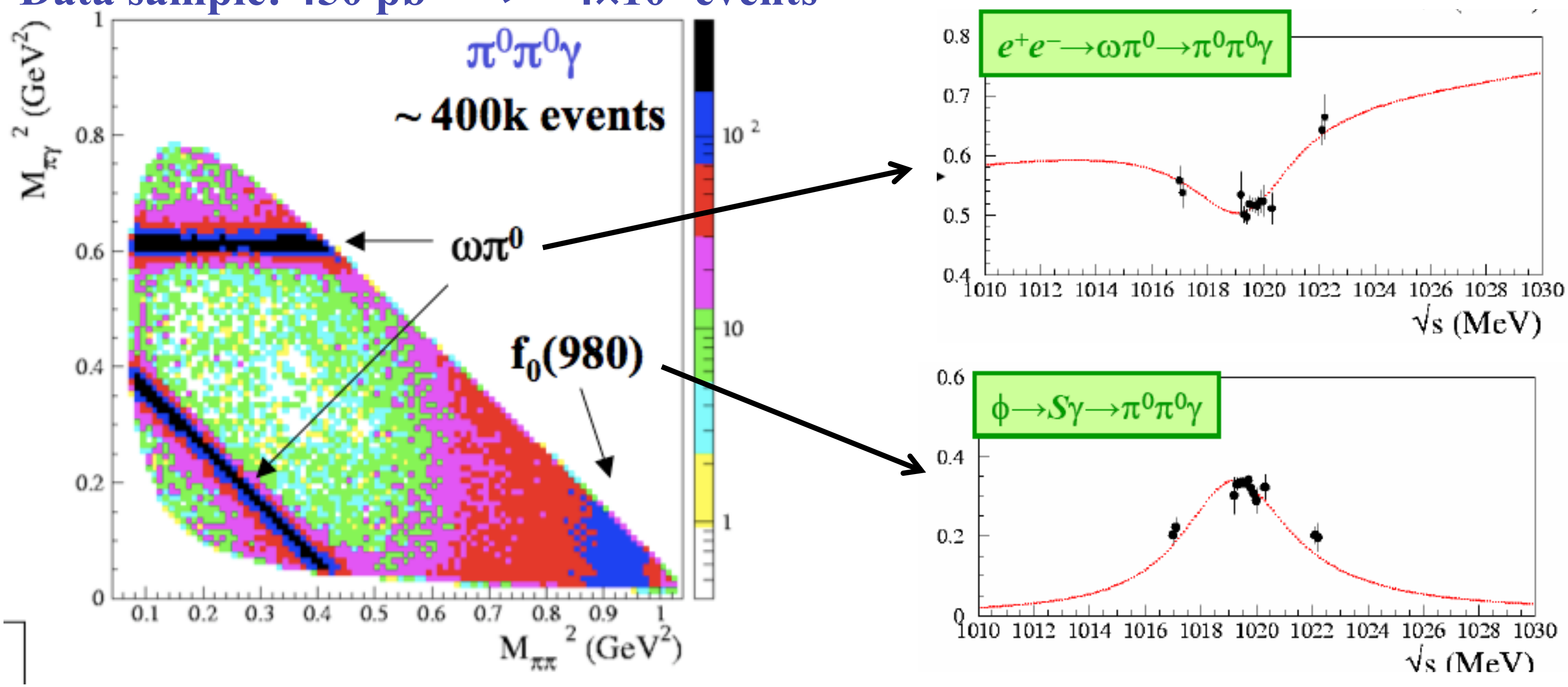
1. Measurement of the branching ratios

2. Extraction of the resonance parameters, masses and couplings (g_{SPP}, g_{SKK}, $g_{\phi S\gamma}$), from the fit of the invariant mass distributions or Dalitz plot

- $\gamma\gamma$ physics: $e^+e^- \to e^+e^-\pi^0\pi^0$ to study $\gamma\gamma \to \sigma(600) \to \pi^0\pi^0$

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

- $f_0(980) \to \pi^0\pi^0$: Dalitz plot study; two contributions, $\phi \to S\gamma$ [S= $f_0(980)$, $\sigma(600)$] and $e^+e^- \to \omega\pi^0$ ($\omega \to \pi^0\gamma$)
- Data sample: 450 pb^{-1} $\Rightarrow$ ~ 4×10^5 events

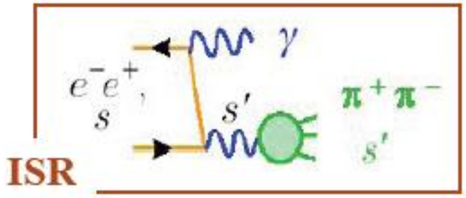


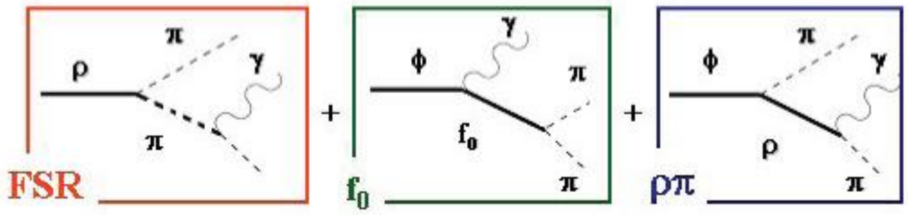
[EPJC49(2007)473]

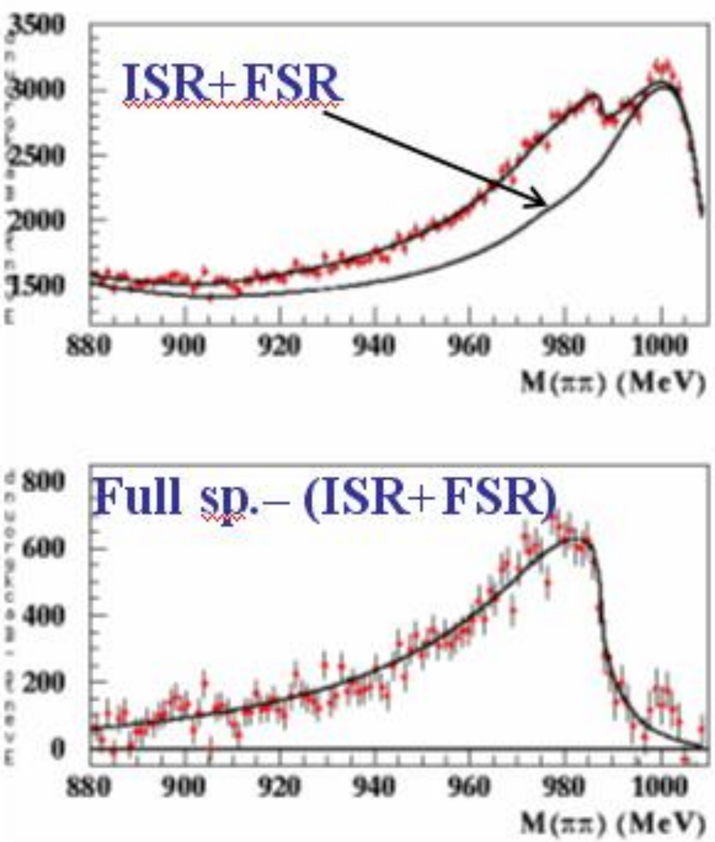
$$Br(\phi \to S\gamma \to \pi^0\pi^0\gamma) = = (1.07^{+0.01}_{-0.03}(fit)\,{}^{+0.04}_{-0.02}(syst)\,{}^{+0.05}_{-0.06}(mod)) \times 10^{-4}$$

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

Main contributions







Event selection: 2 charged tracks and missing momentum at large angle (ϑ> 45°) + photon matching missing energy and momentum

Data sample: 350 pb^{-1} at ϕ peak
$\Rightarrow 6.7\times10^5$ events selected

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

f_0(980) parameters

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

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

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

- Agreement between the two channels

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

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

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

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

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

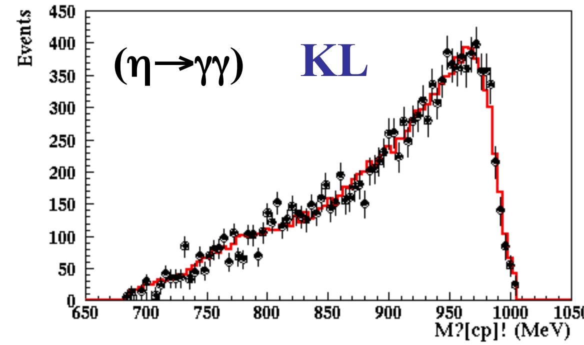
$$\boxed{Br(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10 \pm 0.20) \times 10^{-5}}$$

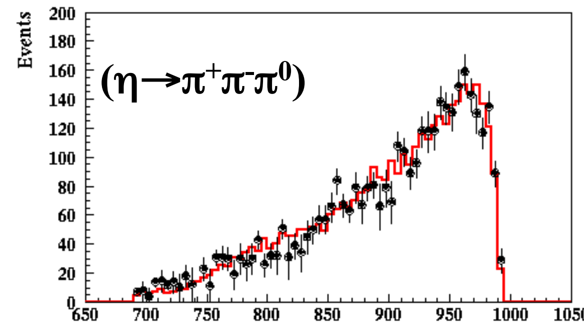
2) $\eta \to \pi^+\pi^-\pi^0$ (Br=22.73%) $\Rightarrow$ 5γ + 2 tracks
Total background = 15%

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

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

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





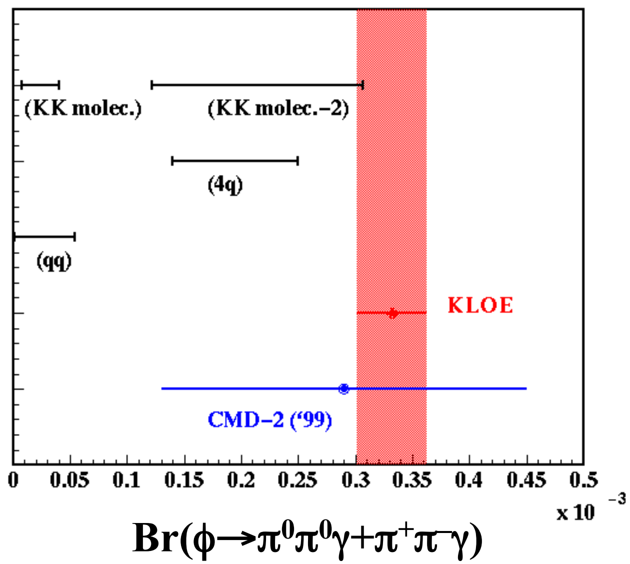
$M_{\eta\pi}$ (MeV)

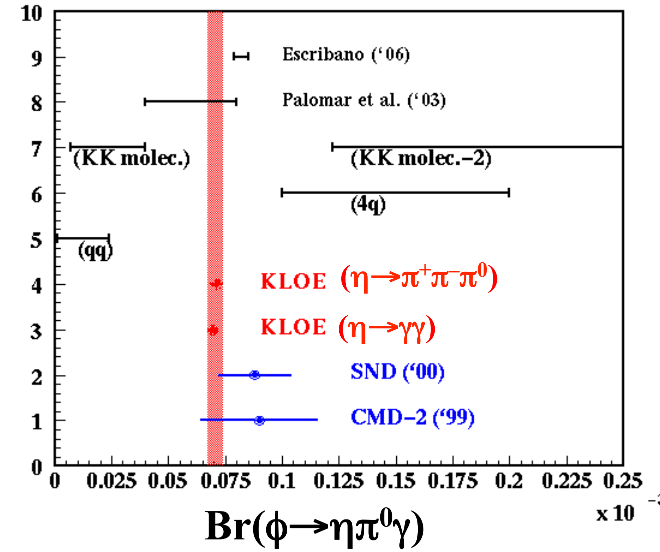
[PLB681(2009),5]

	KL	NS
M_{a0} (MeV)	982.5 ± 1.6 ± 1.1	982.5 (fixed)
g_{aK+K-} (GeV)	2.15 ±0.06 ± 0.06	2.01 ± 0.07± 0.28
$g_{a\eta\pi}$(GeV)	2.82 ± 0.03± 0.04	2.46 ± 0.08 ± 0.11
$g_{\phi a\gamma}$ (GeV^{-1})	1.58 ± 0.10± 0.16	1.83± 0.03 ± 0.08
Br(VDM)×10^6	0.92 ± 0.40 ± 0.15	~ 0
R_η	1.70±0.04± 0.03	1.70 ±0.03 ± 0.01
$R=(g_{aK+K-}/g_{a\eta\pi})^2$	0.58 ± 0.03± 0.03	0.67 ± 0.06 ± 0.13
$P(\chi^2)$	10.4%	30.9%

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

$qq\bar{q}\bar{q}$ *vs* $q\bar{q}$





		SU(3)		
		4q	qqbar	
$(g_{a0K+K-} / g_{a0\eta\pi})^2$	0.6 — 0.7	1.2 — 1.7	0.4	
	Crystal Barrel: 0.525 ± 0.043			
	SND (2000) : 1.8 ± 2.5			
$(g_{f0K+K-}/g_{f0\pi+\pi-})^2$	4.6 — 4.8	>> 1	>> 1 (f_0=ssbar)	1/4 (f_0=nnbar)
	CMD-2 (1999) : 3.61 ± 0.62			
	SND (2000) : 4.6 ± 0.8			
	BES (2005) : 4.21 ± 0.33			
$(g_{f0K+K-}/g_{a0K+K-})^2$	4 — 5	1	2	1

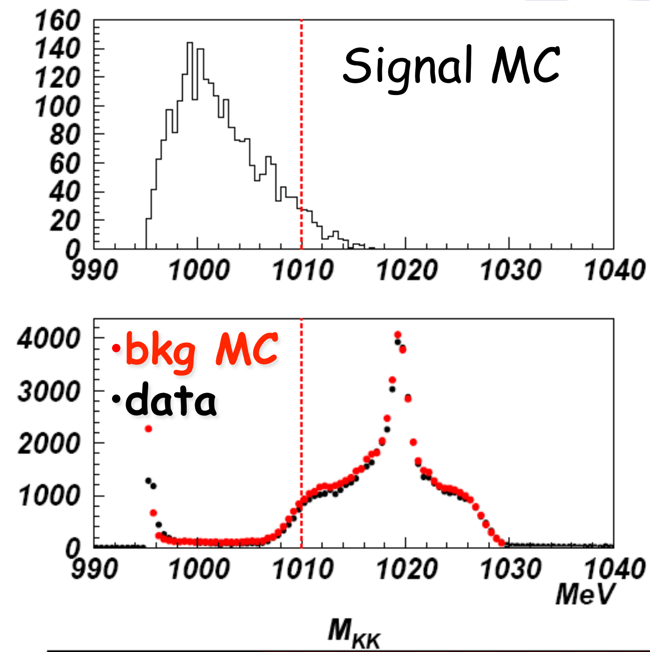
$\phi \to (f_0/a_0)\gamma \to K^0\bar{K}^0\gamma$

- $K^0\bar{K}^0$ with scalar quantum numbers ($J^{PC}=0^{++}$)
- Small phase space ($2M_K \le M_{KK} \le M_\phi$)
  $\Rightarrow$ 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)

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

[PLB679(2009),10]



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

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

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

$\Rightarrow$ **First observation possible**