Recent KLOE results on hadron physics

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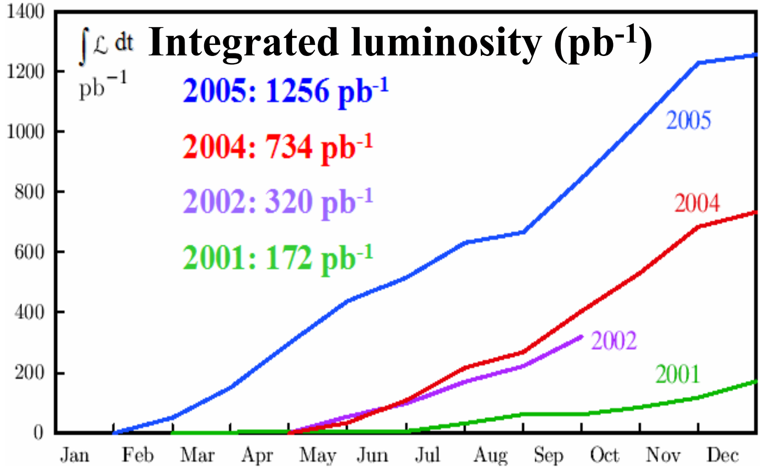
Outline

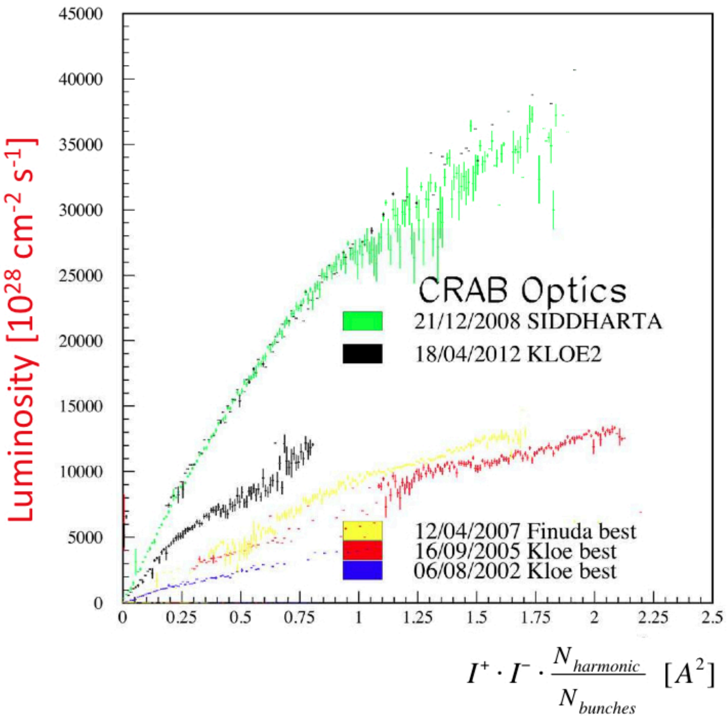
- **DAΦNE and KLOE**
- **$\eta \to \pi^+\pi^-\pi^0$**
- **Transition Form Factors from Dalitz decays**
  - $\phi \to \eta e^+e^-$
  - $\phi \to \pi^0 e^+e^-$
- **$\gamma\gamma$ physics**
  - $\gamma^*\gamma^* \to \eta$
  - $\gamma^*\gamma^* \to \pi^0\pi^0$
- **KLOE-2: detector upgrade**
- **Conclusions**

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} @ $\sqrt{s}=M_\phi$ ($\Rightarrow 8\times10^9$ ϕ 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 ⇒ long shutdown
- End 2011: commissioning resumed
- Nov-Dec. 2012: 100 pb^{-1} collected with carbon target for the study of deeply bound kaonic states (AMADEUS)
- Dec.2012-July 2013: shutdown for installation of new detectors

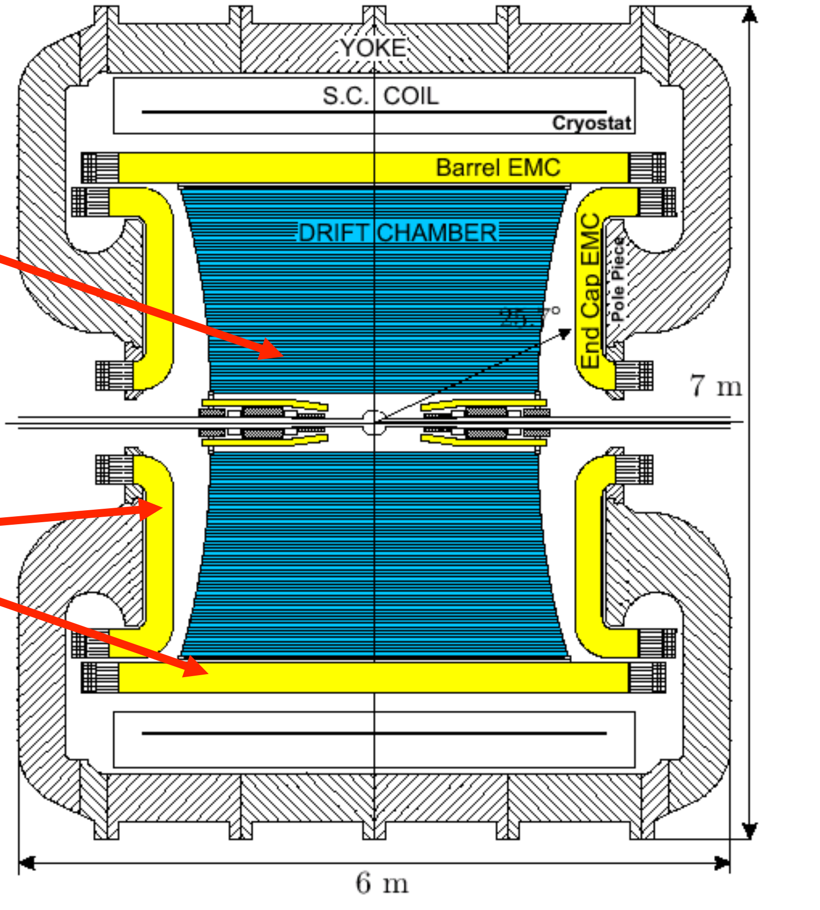


- **DAΦNE operations restarted in July 2013**
- **KLOE-2 goal: collect ~ 5 fb^{-1} in the next 2 -3 years**

[Eur.Phys.J.C68(2010),619]

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

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

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

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

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

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

Determining Q gives constraints on the light quark masses
[Leutwyler,Mod.Ph.Lett.A28(2013)1360014]

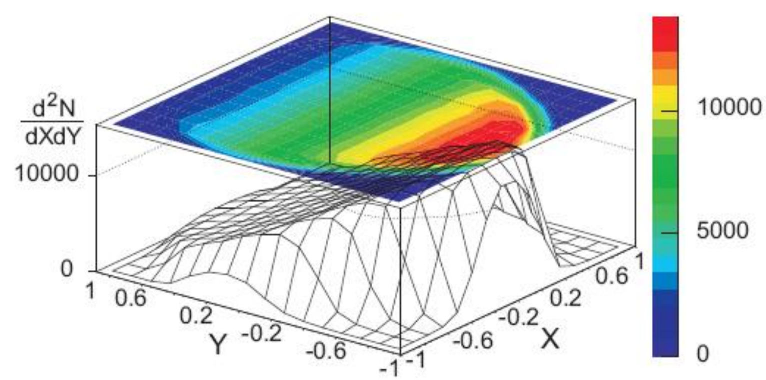
- **Previous KLOE analysis:** $\phi \to \eta\gamma$ with $\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$ final state
  L = 450 pb^{-1} $\Rightarrow$ 1.34 × 10^6 events in the Dalitz plot

$$X = \sqrt{3}\frac{E_+ - E_-}{\Delta}$$
$$Y = 3\frac{E_0 - m_0}{\Delta} - 1$$
$$(\Delta = m_\eta - 2m_{\pi^\pm} - m_0)$$

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

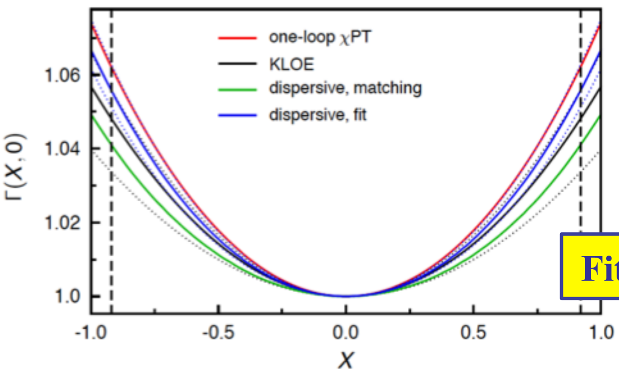
a	$-1.090 \pm 0.005\,^{+0.008}_{-0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006\,^{+0.007}_{-0.016}$
e	$-0.006 \pm 0.007\,^{+0.005}_{-0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
$P(\chi^2)$	73%

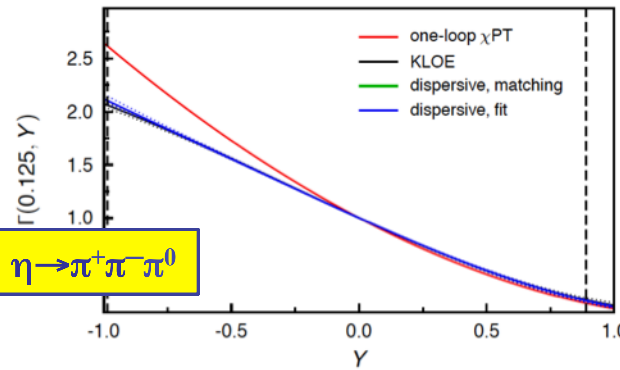
[JHEP0805(2008)006]



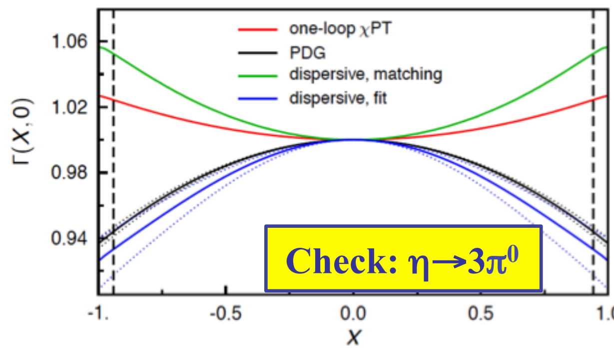
$\eta \rightarrow \pi^+\pi^-\pi^0$

- Dispersive analyses of $\eta \rightarrow 3\pi$: subtraction constants fixed from a fit to KLOE measurements of $\eta \rightarrow \pi^+\pi^-\pi^0$





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



Check: $\eta \rightarrow 3\pi^0$

$$\Rightarrow Q = 21.3 \pm 0.6$$

[Colangelo et al. PoS(EPS-HEP2011)304]

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

$$m_u = (2.02 \pm 0.14) MeV$$

$$m_d = (4.91 \pm 0.11) MeV$$

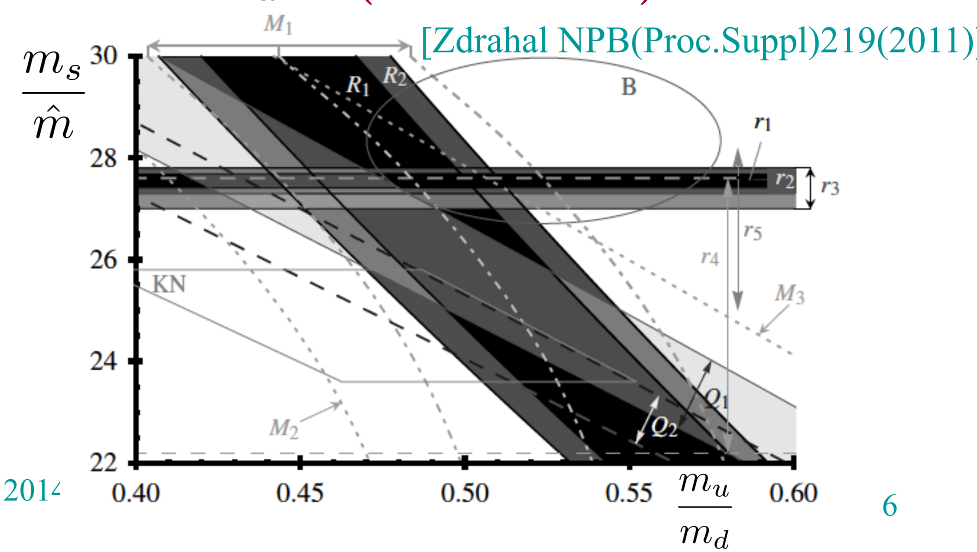
$$\Rightarrow R = \frac{m_S - \hat{m}}{m_d - m_u} = 37.7 \pm 3.3$$

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

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

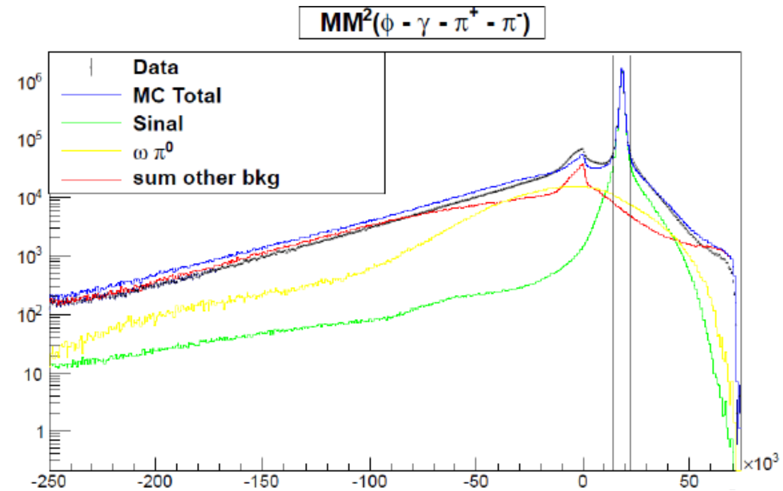
$$m_d = (4.63 \pm 0.14) MeV$$

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

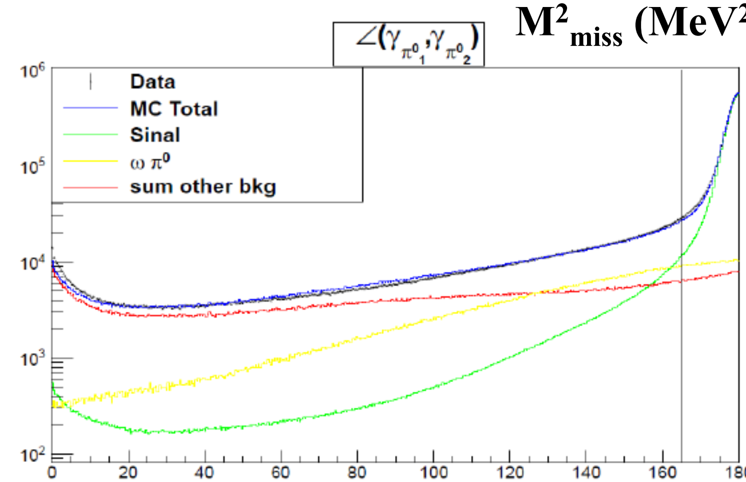


$\phi \to \eta\gamma;\ \eta \to \pi^+\pi^-\pi^0$

- **New analysis of the full KLOE data set to reduce systematics:**
  - **$L = 1.7\ fb^{-1} \Rightarrow$ about 4 times larger than previous analysis**
  - **Improved MC simulation**
  - **Selection: at least 2 charged tracks and 3 prompt photons**
  - **Bhabha rejection by kinematics + TOF**
  - **$|MM(\phi\gamma\pi^+\pi^-)-M_{\pi 0}| < 15$ MeV**
  - **$\gamma\gamma$ opening angle (π^0 rest frame) > 165°**
  - **Signal efficiency = 37.6 %**
  - **Background contamination = 0.96 %**



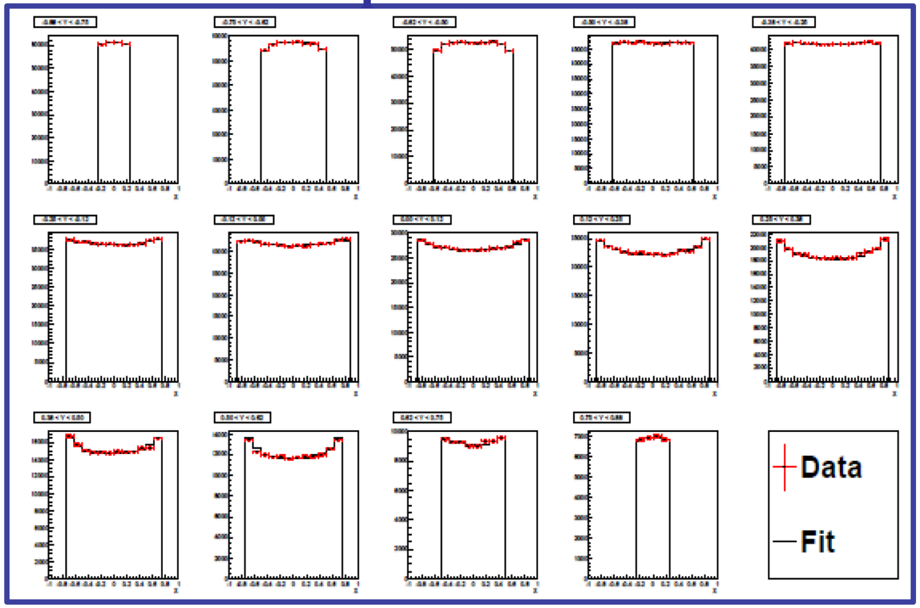
M^2_{miss} (MeV²)



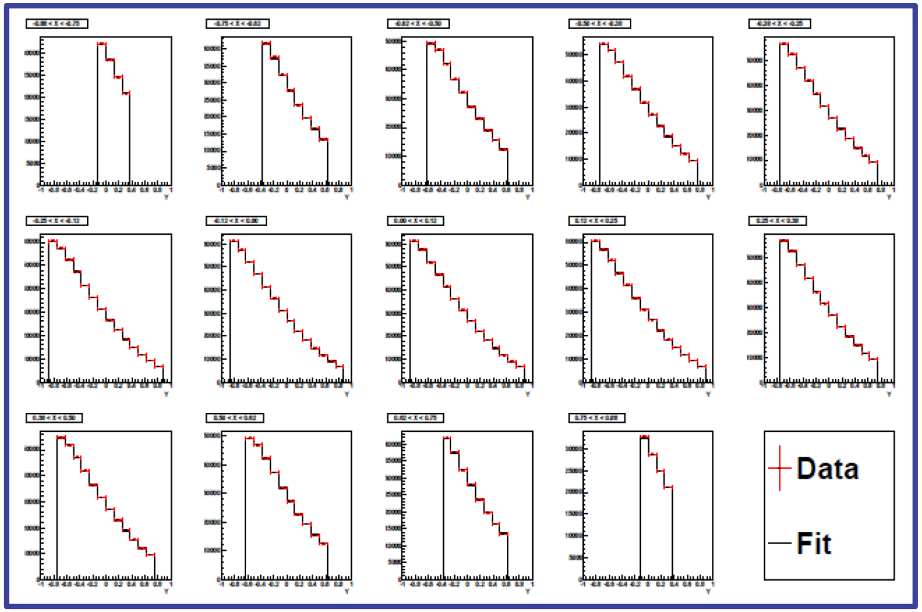
α(°)

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

Dalitz plot slices in Y



Dalitz plot slices in X

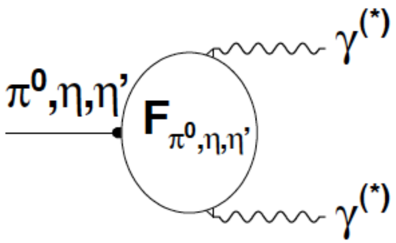


$P(\chi^2) = 27\%$

	Old analysis	New analysis
a	$-1.090 \pm 0.005 \, ^{+0.008}_{-0.019}$	-1.103 ± 0.003
b	$0.124 \pm 0.006 \pm 0.010$	0.1419 ± 0.0029
d	$0.057 \pm 0.006 \, ^{+0.007}_{-0.016}$	0.0725 ± 0.0027
f	$0.14 \pm 0.01 \pm 0.02$	0.154 ± 0.006

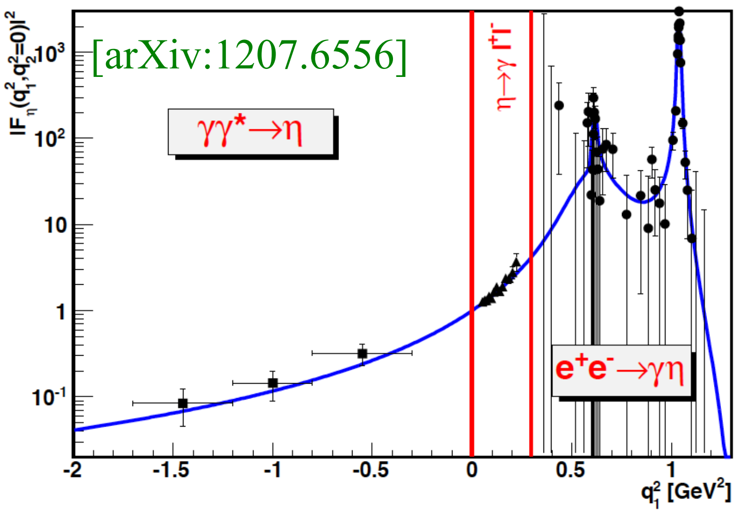
- Agreement with previous result
- *c* and *e* consistent with zero (C-violating parameters)
- Evaluation of systematics in progress

Transition Form Factors



Information on the structure of mesons comes from their coupling to photons, described by the TFFs

$$\mathcal{F}_{P\gamma\gamma}(q_1^2, q_2^2)$$



$$\left.\begin{array}{l}\gamma^\star \rightarrow P\gamma \\ P \rightarrow \gamma\gamma^\star \rightarrow \gamma\ell^+\ell^-\end{array}\right\} \text{time-like } q^2$$

$$\gamma^\star\gamma^\star \rightarrow P \quad \Rightarrow \text{space-like } q^2$$

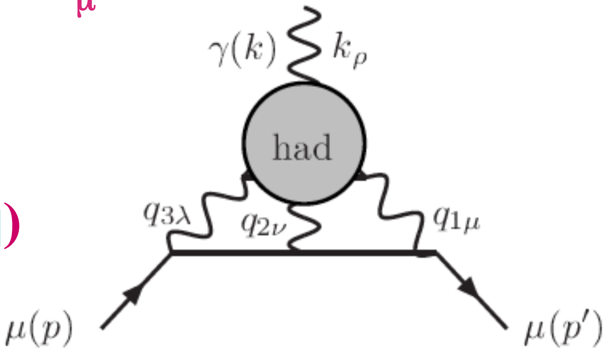
Transition Form Factors

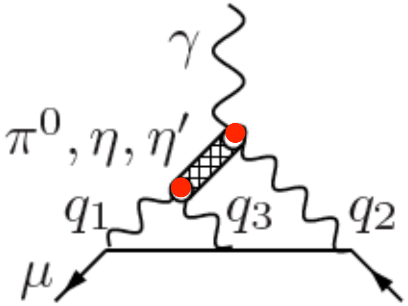
- $a_\mu^{exp} - a_\mu^{SM} = (31.25 \pm 8.54) \times 10^{-10} \Rightarrow 3.7\ \sigma$ discrepancy $[a_\mu = (g_\mu - 2)/2]$

  $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$ → main contribution to the uncertainty on a_μ^{SM}

- An important part of a_μ^{had} is the Light-by-Light scattering

  ($a_\mu^{LbL} = (11.6 \pm 3.9) \times 10^{-10}$ [Jegerlehner-Nyffeler P.Rep.477(2009)])





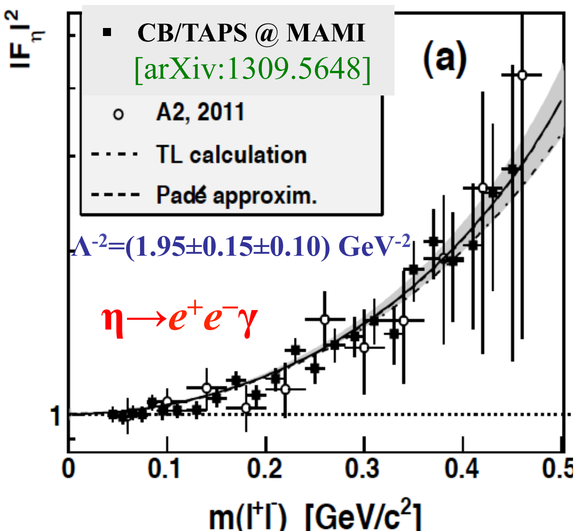
The leading contribution comes from the exchange of single pseudoscalar mesons

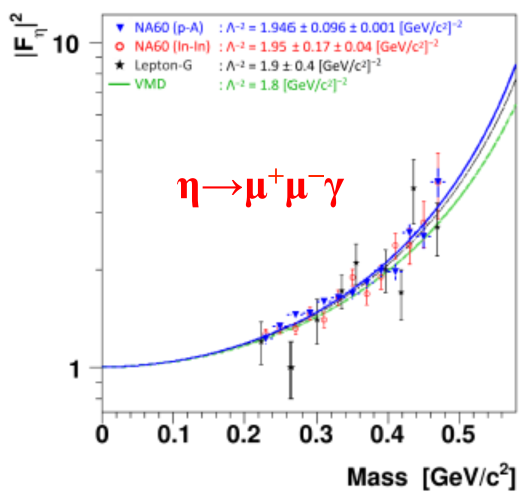
- TFFs for off-shell mesons ⇒ model dependent

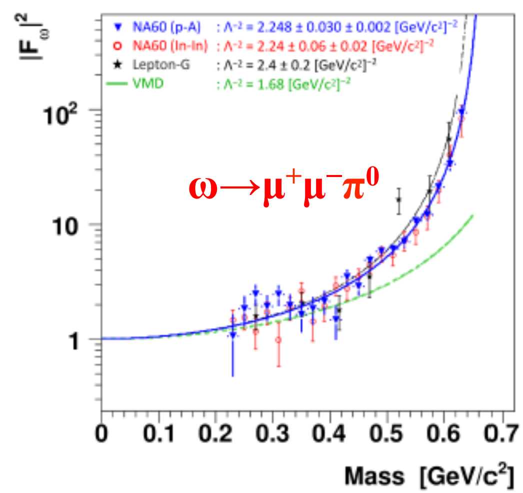
  ⇒ measurements of TFFs of on-shell mesons can help to constrain models to get a precise evaluation of the LbL contribution

Transition FFs from Dalitz decays

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

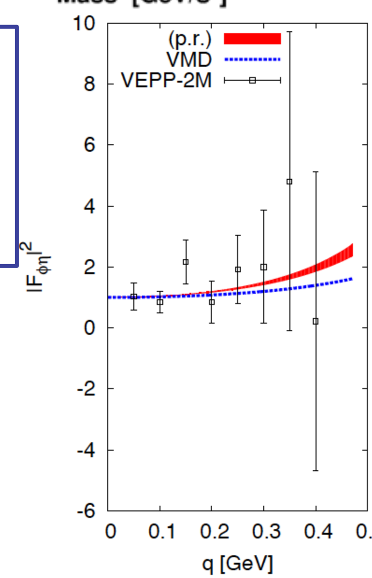






$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

Other models based on effective field theories proposed: Terschluesen-Leupold PPNP67(2012)401
Schneider et al. PRD86(2012)054013,
Ivashyn Prob.Atomic Sci.Technol.2012N1(2012)179



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

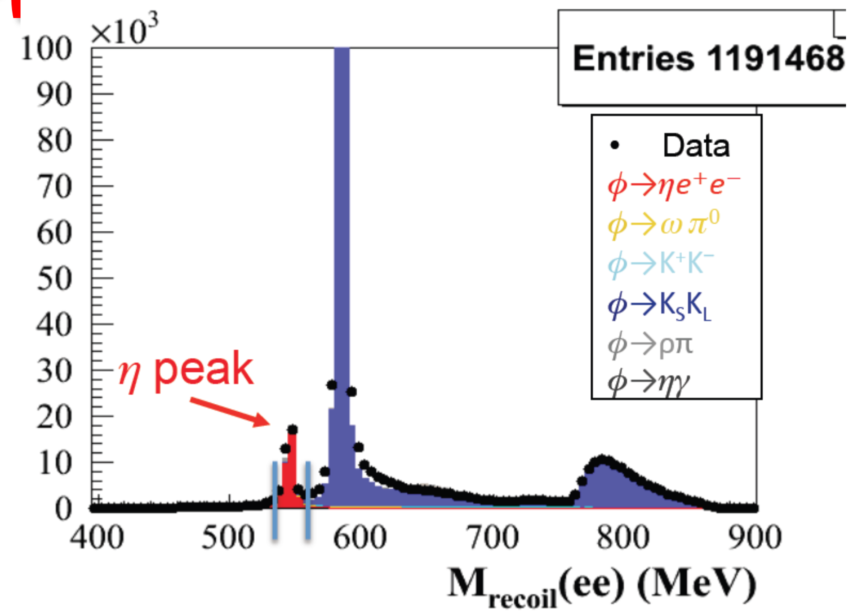
- $\phi \to \pi^0 e^+ e^-$: no data available on FF; VMD ⇒ $\Lambda^{-2} \approx 1.6$ GeV^{-2}

$\phi \to \eta e^+e^-\ ;\ \eta \to \pi^0\pi^0\pi^0$

- **Analyzed sample: 1.7 fb^{-1}**
- **2 tracks + 6 prompt photons**

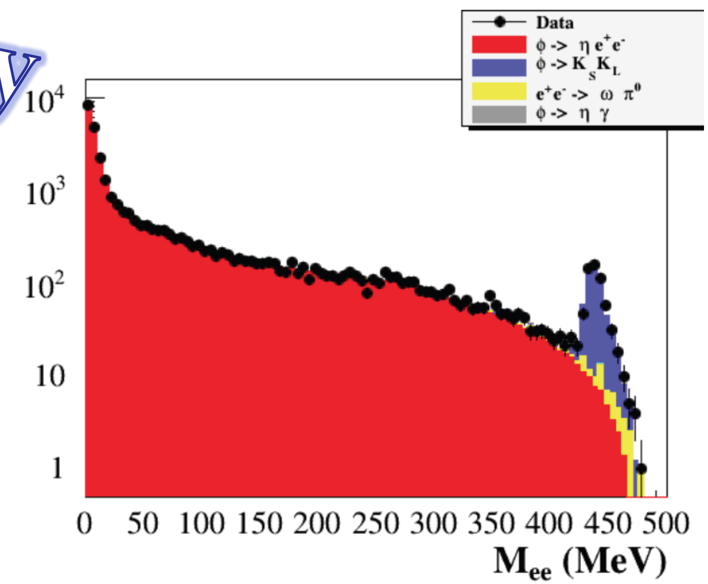
  $536.5 < M_{recoil}(ee) < 554.5$ MeV

  ~ 30000 $\phi \to \eta e^+e^-$ ($\eta \to \pi^0\pi^0\pi^0$)
- **Efficiency ≈ 15%**



Preliminary

$$BR(\phi \to \eta e^+e^-) =$$
$$= \left(1.131 \pm 0.032^{+0.011}_{-0.060}\right) \times 10^{-4}$$



SND: $(1.19 \pm 0.22)\times10^{-4}$
CMD2: $(1.14\pm0.12)\times10^{-4}$

Transition FF

- **FF extracted from a fit of the e^+e^- invariant mass to:**

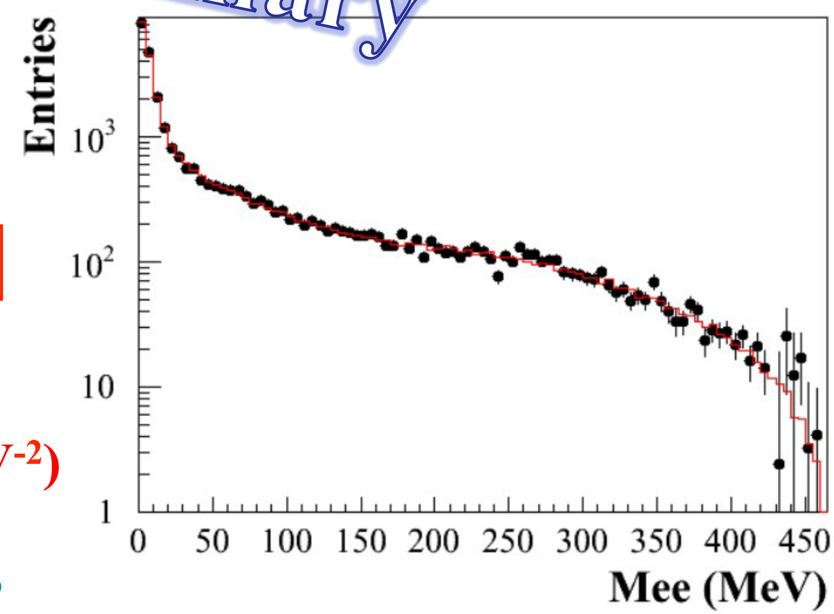
$$\frac{d}{dq^2}\frac{\Gamma(\phi\to\eta e^+e^-)}{\Gamma(\phi\to\eta\gamma)}=\frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

[Landsberg, Phys.Rept.128(1985)301]

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

$$\Rightarrow \left.\frac{dF}{dq^2}\right|_{q^2=0}=\Lambda^{-2}$$

Preliminary



$$\Lambda^{-2}=(1.17\pm0.11\pm0.09)\mathrm{GeV}^{-2}$$

(SND: (3.8 ± 1.8) GeV^{-2})

In agreement with VMD ($\Lambda^{-2} \approx M_\phi^{-2} \approx 1$ GeV^{-2})

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

- BR($\phi \to \pi^0 e^+ e^-$) = $(1.12\pm0.28)\times10^{-5}$

  ⇒ 25% uncertainty

  (SND ⇒ 52 ; CMD-2 ⇒ 46 events)

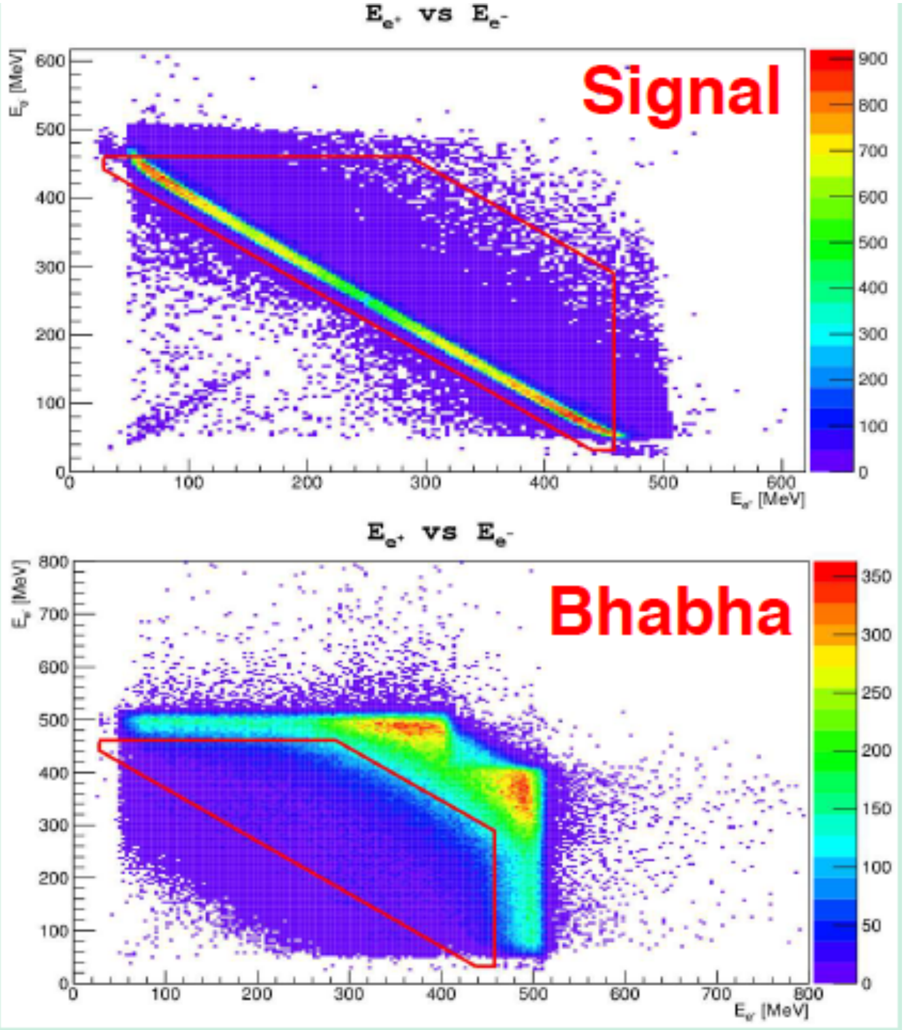
- Events with 2 tracks + 2 prompt photons
- Background:

  radiative Bhabha scattering

  (several order of magnitudes larger)

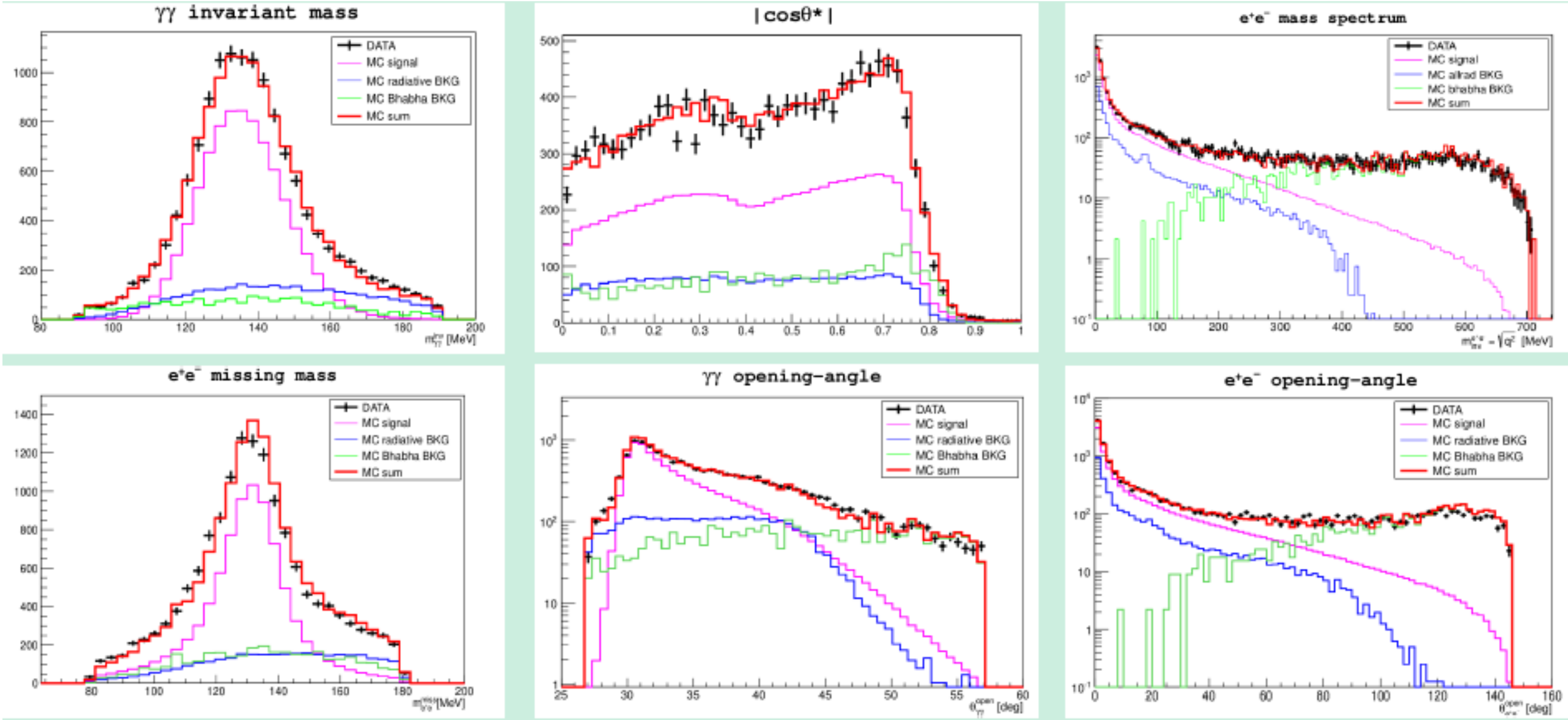
  $\phi \to \pi^0\gamma$ with photon conversion

- L = 1.7 fb^{-1}
- 8777 events selected
- Signal efficiency ≈ 15%



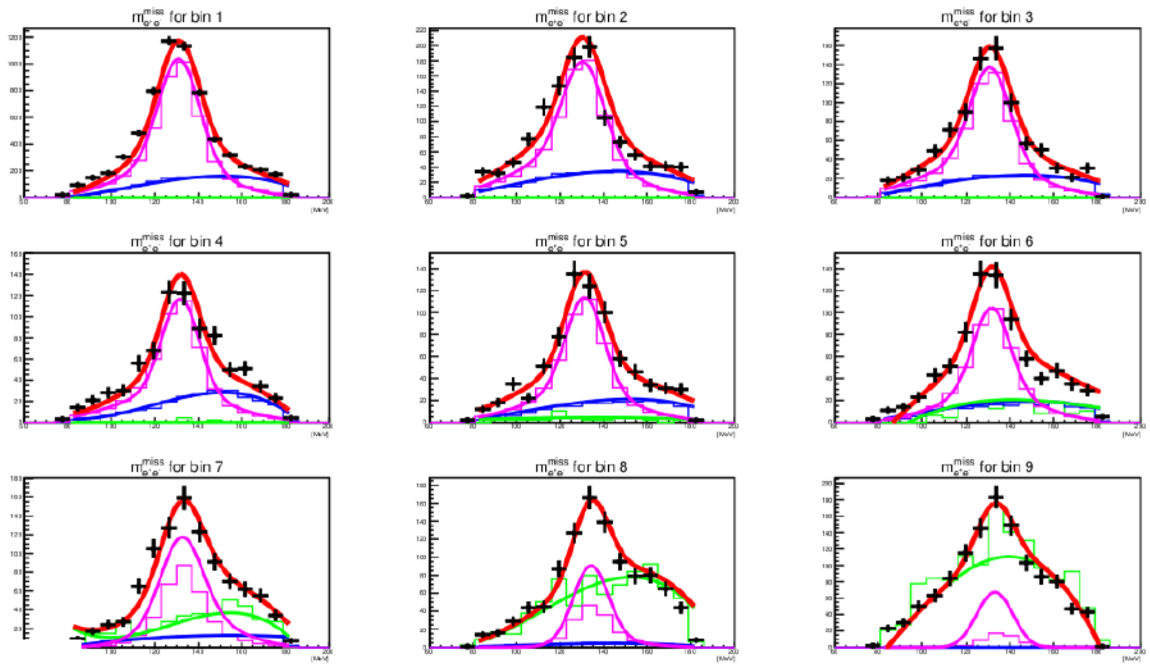
$\phi \to \pi^0 e^+ e^-$

- **Good data-MC comparison**

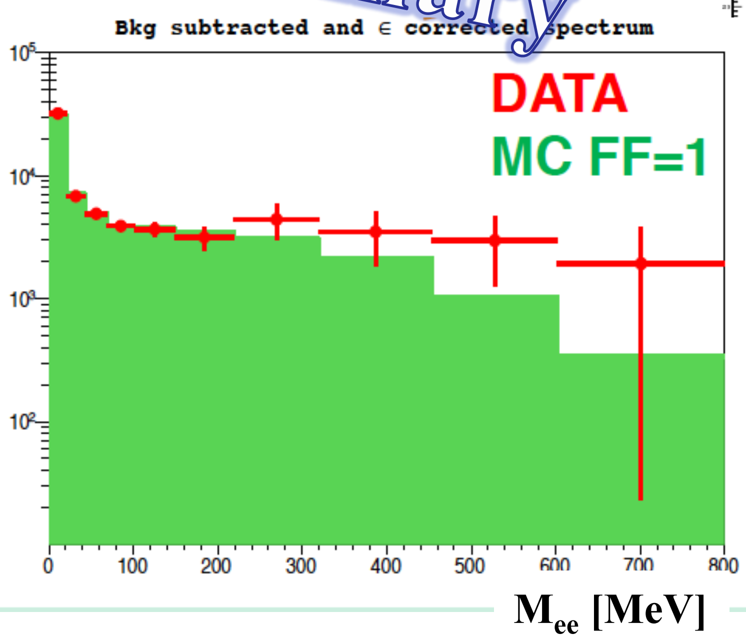


$\phi \to \pi^0 e^+ e^-$

- Background subtraction from fit to the recoil mass against e^+e^-
- Fit systematics currently limited by the MC statistics of Bhabha events



Preliminary



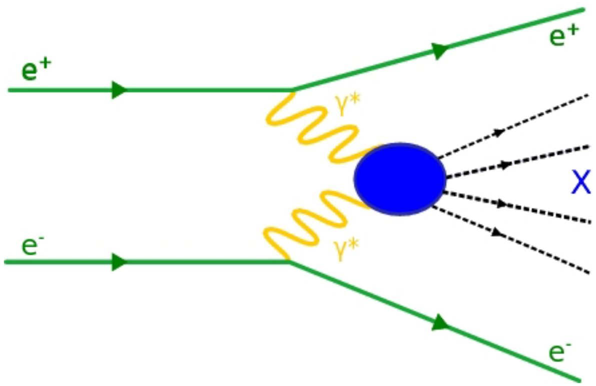
⇒ **FF extraction in progress**

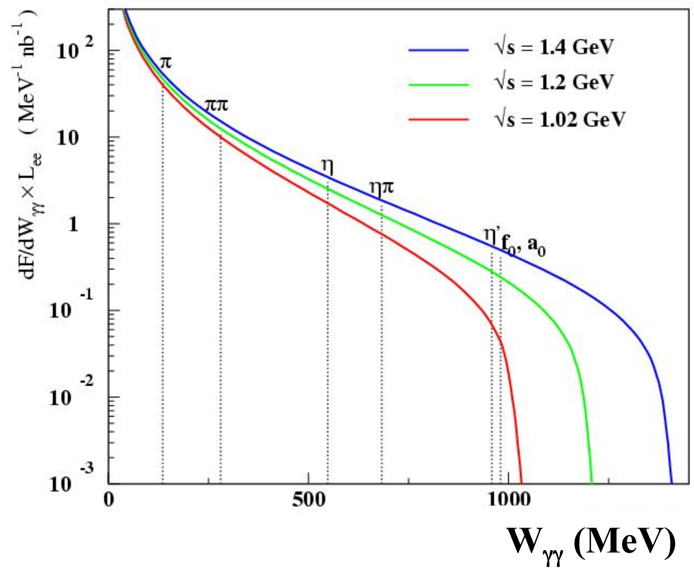
γγ physics

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

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

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





- **X = π^0, η ⇒** $\sigma_{\gamma\gamma\to X}(q_1,q_2) = \dfrac{8\pi^2}{M_X}\Gamma_{X\to\gamma\gamma}\delta[(q_1+q_2)^2 - M_X^2]\left|\mathcal{F}(q_1^2,q_2^2)\right|^2$
  - **Two-photon width Γ(X→γγ)**
  - **Transition form factors $\mathcal{F}_{X\gamma^*\gamma^*}(q_1^2,q_2^2)$ at space-like q^2**

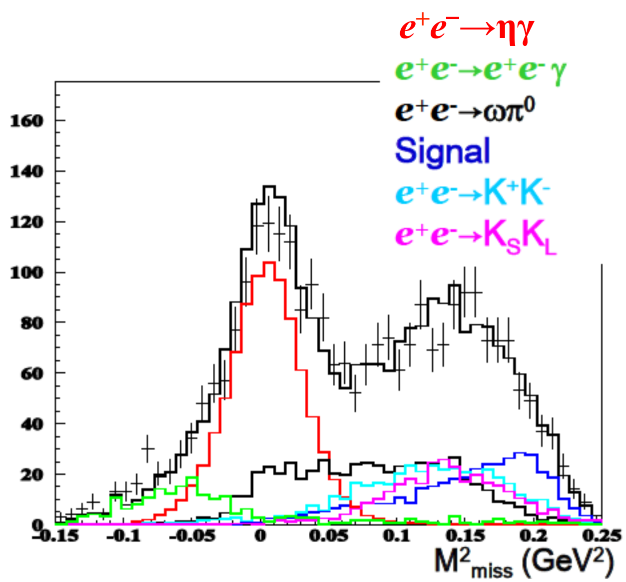
- **X = $\pi^0\pi^0$ ⇒ study of f_0(500)**

- **KLOE data: no $e^\pm$ tagging ⇒ analysis of off-peak data (√s = 1 GeV)**

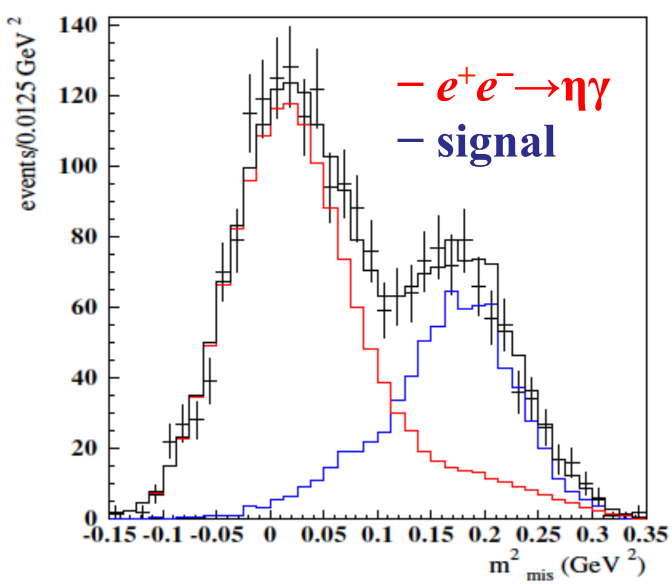
$\gamma^*\gamma^* \rightarrow \eta$

- Data sample: 240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV), no taggers
- Main bckg: $e^+e^- \rightarrow \eta\gamma$ with γ lost

- $\eta \rightarrow \pi^+\pi^-\pi^0$: events with two tracks and two prompt photons



- $\eta \rightarrow \pi^0\pi^0\pi^0$: events with no tracks and 6 prompt photons



combining the two channels:

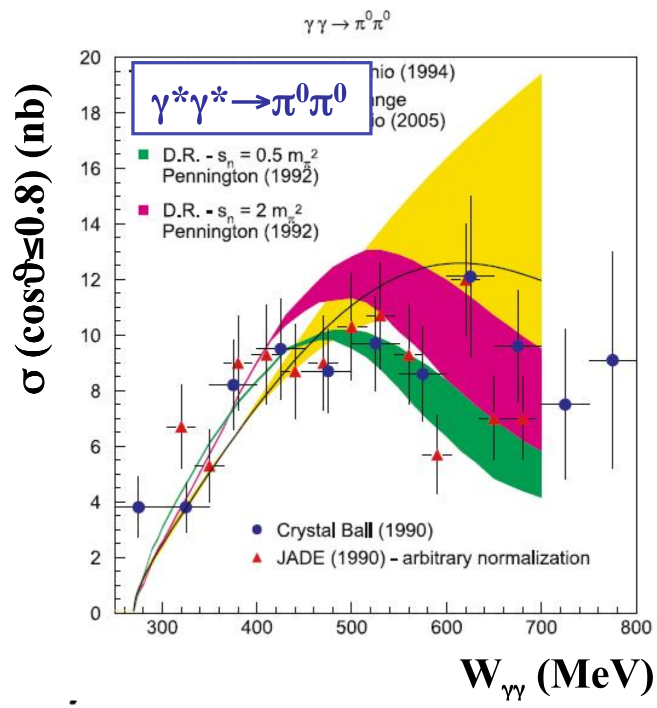
$$\sigma(e^+e^- \rightarrow e^+e^-\eta) = (32.7 \pm 1.3 \pm 0.7)\ \text{pb}$$

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

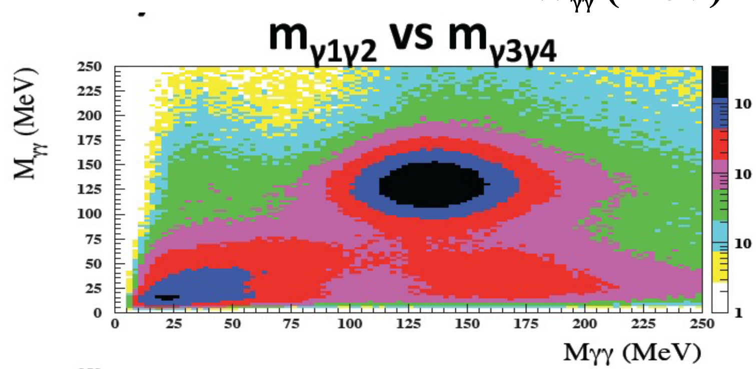
[JHEP01(2013)119]

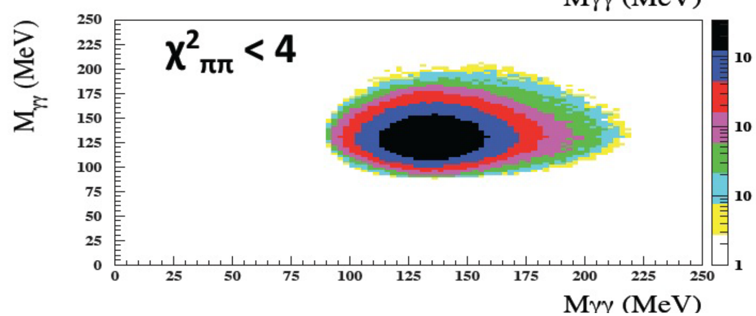
$\gamma^*\gamma^* \to \pi^0\pi^0$

- $e^+e^- \to e^+e^- \pi^0\pi^0$
- $f_0(500)\to\pi^0\pi^0$?
- Previous measurements by Crystal Ball and JADE



- 240 pb^{-1} off-peak data ($\sqrt{s}$ = 1 GeV)
- Selection:
  - 4 prompt photons
  - no late clusters in the EMC
  - no tracks in the Drift Chamber
  - best photon pairing to match 2 π^0's
    $\Rightarrow$ cut on pairing χ^2

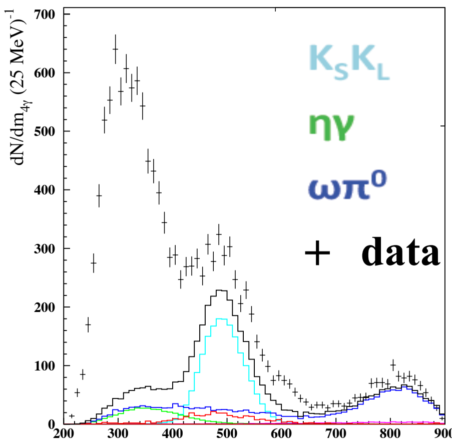




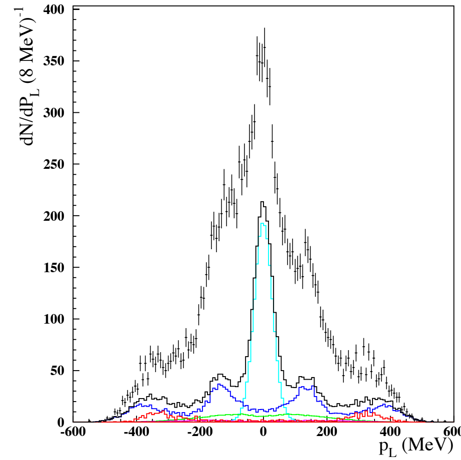
$\gamma^*\gamma^* \rightarrow \pi^0\pi^0$

- **Still some background contamination at low $m_{4\gamma}$**

⇒ asymmetric p_L distribution

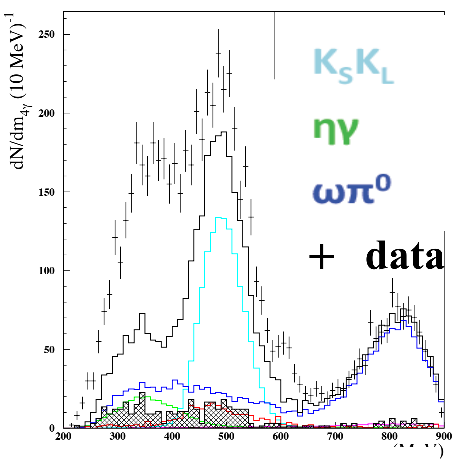


$m_{4\gamma}$ [MeV]

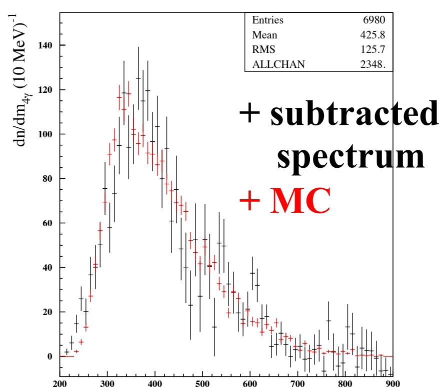


Background reduced with a multivariate analysis:

- **MC distributions for signal + known bckgd.**
- **data for residual background**



$m_{4\gamma}$ [MeV]



$m_{4\gamma}$[MeV]

- **Residual background still under study**
- **Work is in progress to extract the cross-section**

$\gamma\gamma$ physics at KLOE-2

- **KLOE-2 run at the ϕ peak**
- **Large background from ϕ decays**

$\gamma\gamma$ process

channel	Total Production ($L = 10\ fb^{-1}$)
$e^+e^- \to e^+e^-\pi^0$	4×10^6
$e^+e^- \to e^+e^-\eta$	10^6
$e^+e^- \to e^+e^-\pi^+\pi^-$	2×10^6
$e^+e^- \to e^+e^-\pi^0\pi^0$	2×10^4

ϕ decays

decay mode	esc.particle	events	bckg to:
$K_S(\pi^0\pi^0)\ K_L$	K_L	$\sim 10^9$	$\pi^0\pi^0$
$K_S(\pi^+\pi^-)\ K_L$	K_L	$\sim 2 \times 10^9$	$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$	π^0	$\sim 10^9$	
$\eta(\gamma\gamma)\ \gamma$	γ	$\sim 10^8$	η
$\pi^0(\gamma\gamma)\ \gamma$	γ	$\sim 5 \times 10^8$	π^0

- **Additional background from continuum processes**

⇒ Electron taggers are needed to reduce background

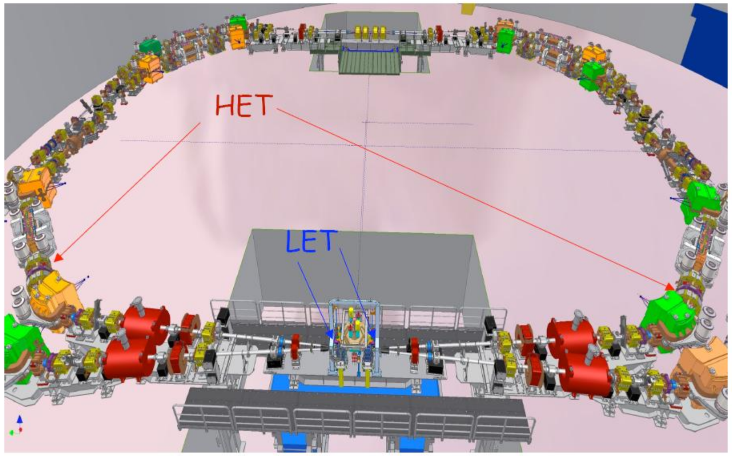
Detector upgrade

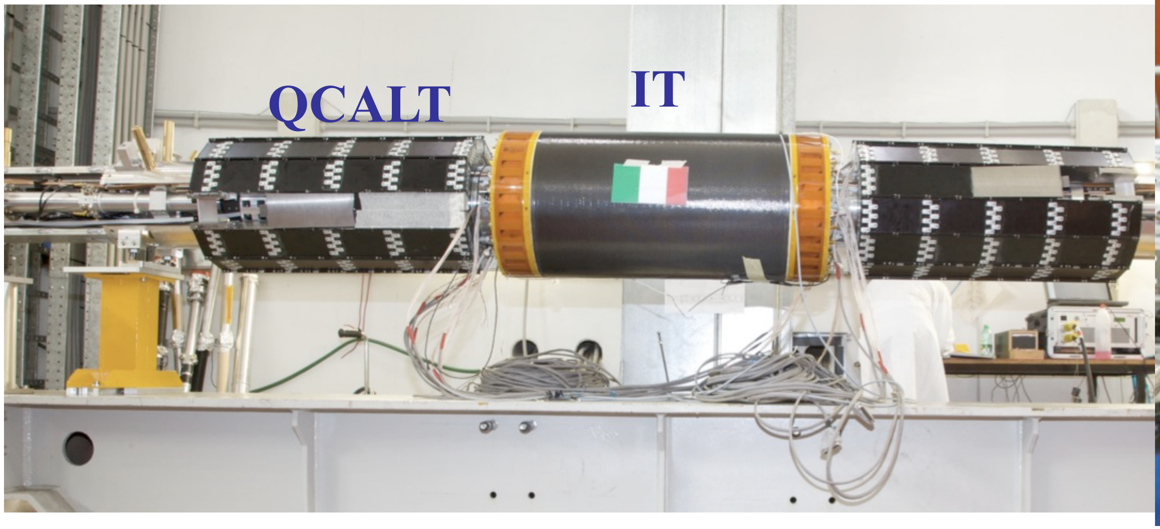
– LET + HET: taggers for scattered $e^{\pm}$ in $\gamma\gamma$ processes

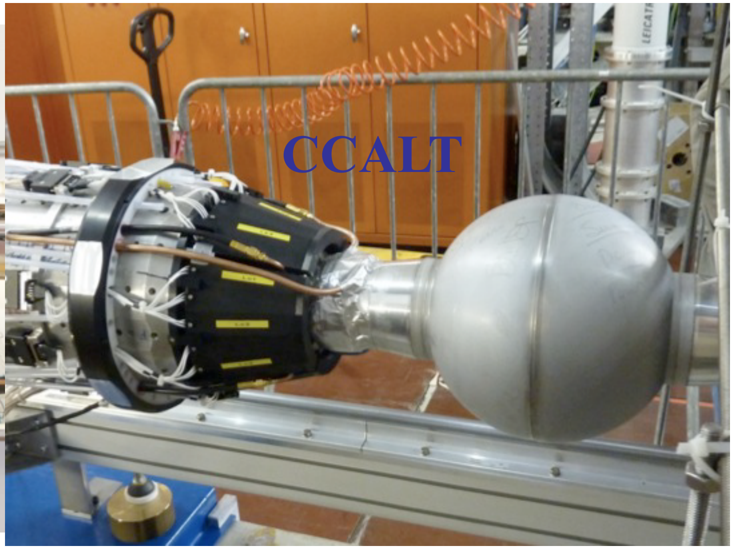
– Inner Tracker : to improve acceptance for low momemtum tracks and to achieve a better vertex recontruction

– QCALT: W + scint. tiles + SiPM quadrupole coverage for K_L decays

– CCALT : LYSO + APD to increase acceptance for γ's from the IP (21° to 10°)





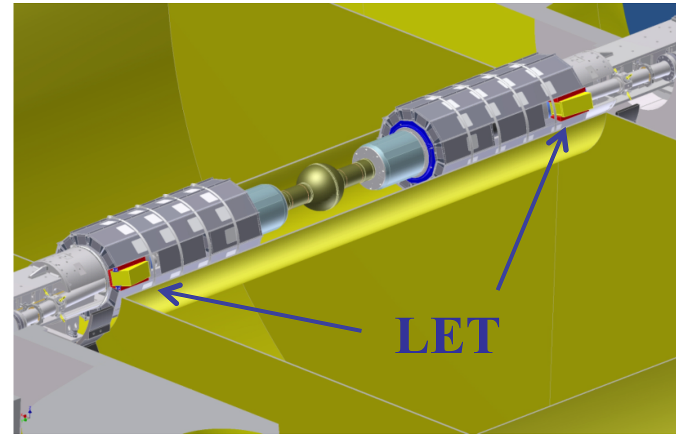


Low Energy Tagger

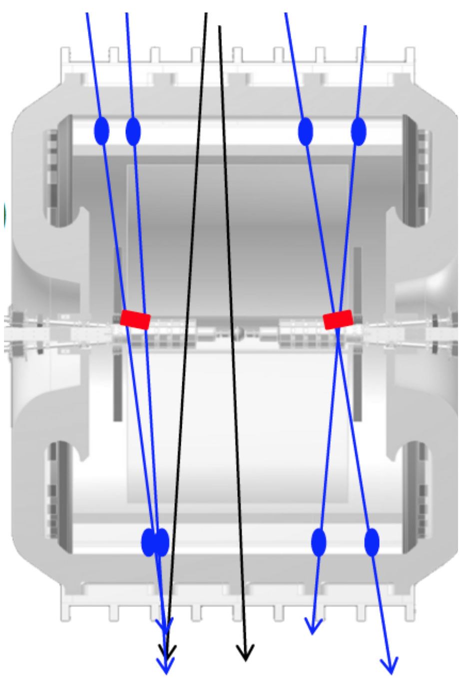
- To detect $e^{\pm}$ of E ≈ 150 – 350 MeV escaping from the beam-pipe

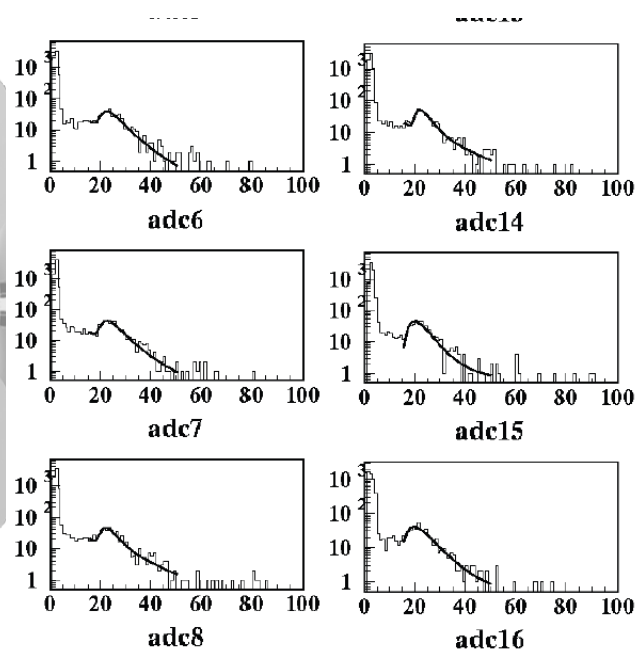
- Weak correlation between E and scattering angle

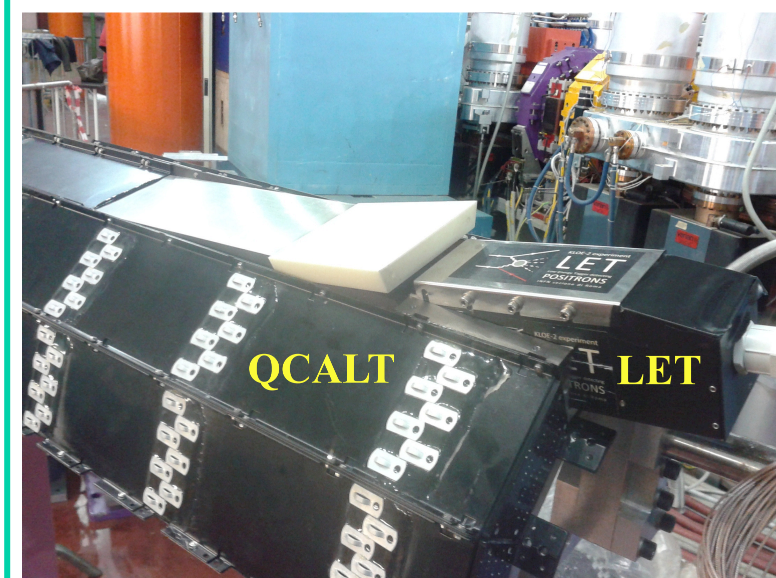
⇒ calorimeters: 20 × 2 LYSO crystals read-out by SiPM, placed at ~ 1.5 m from the IP
$\sigma_E/E < 10\%$ for E > 150 MeV



Calibration with cosmic rays (mips)

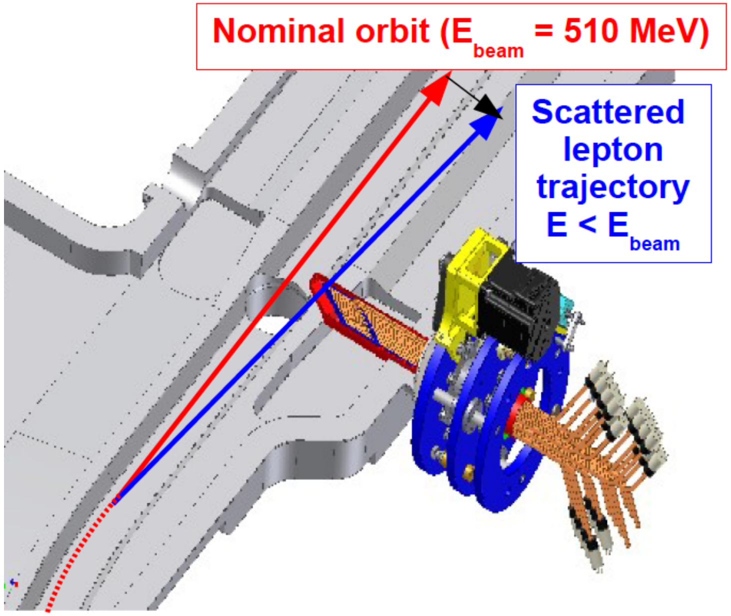


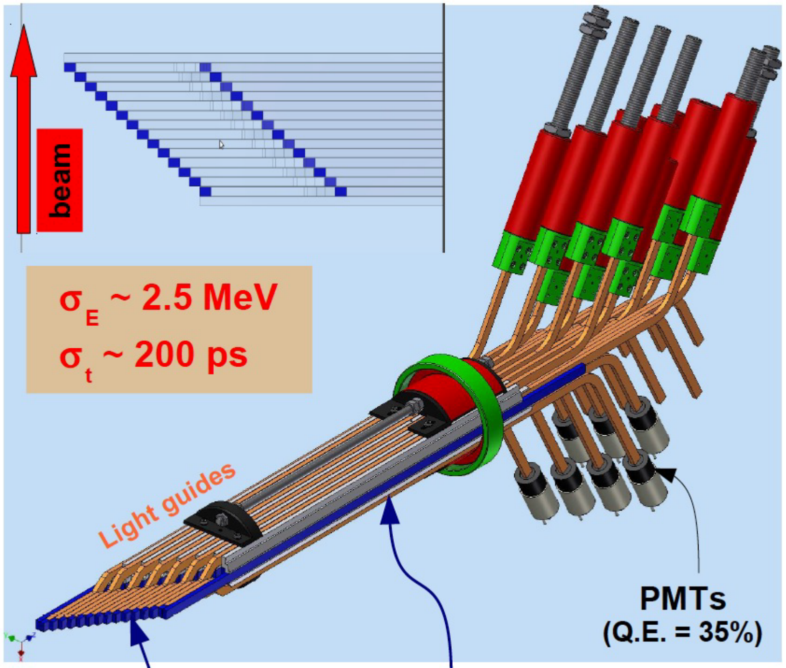




High Energy Tagger

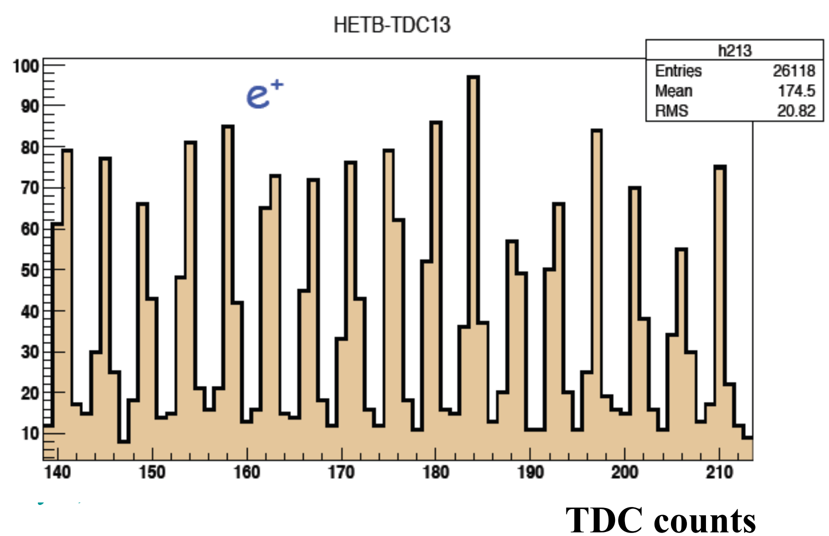
- First bending dipole of DAΦNE acts as a spectrometer for the scattered electrons (420 < E < 495 MeV)
- Strong correlation between E and $e^{\pm}$ trajectory
- Scintillator hodoscope + PMTs; pitch: 5 mm placed at ~ 11 m from IP





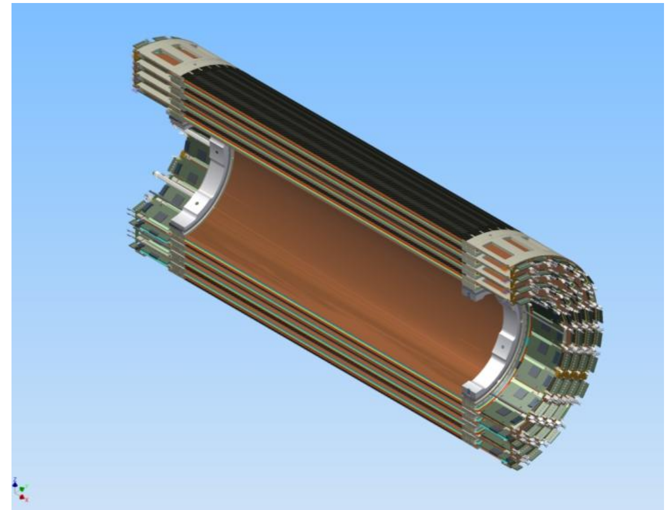
Plastic scintillators 5x3x6 mm^3 (28 ch. for each arm)

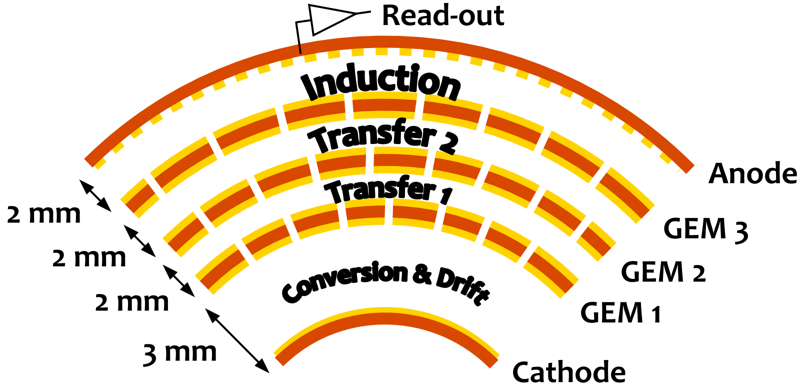
Plastic scintillator 5x3x130 mm^3 (1 ch. for each arm)

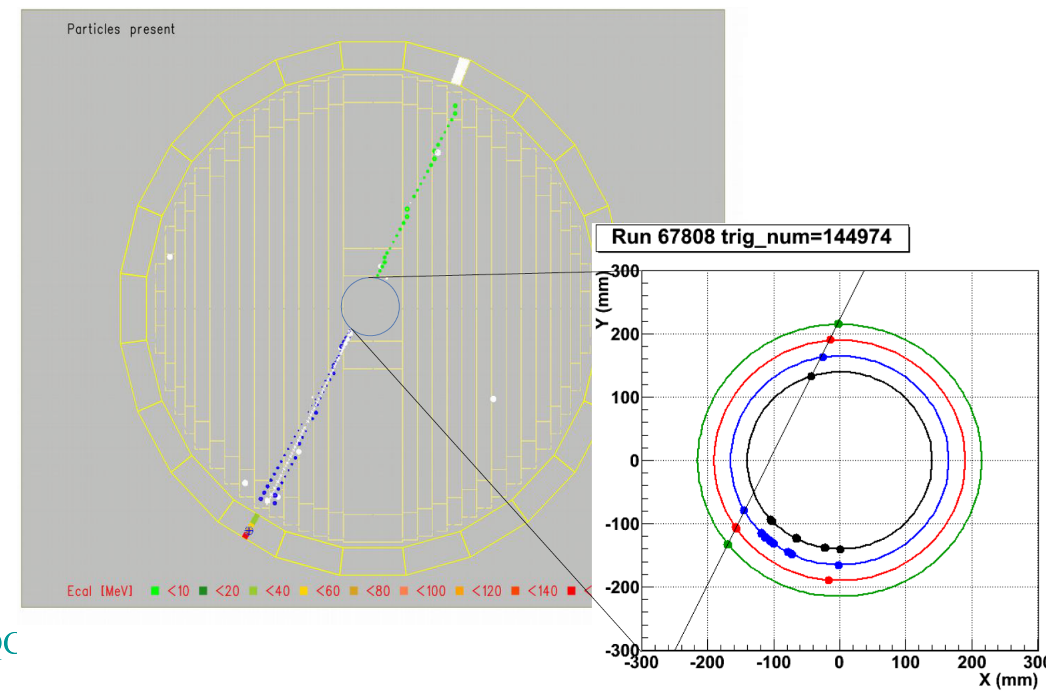


Inner Tracker

- 4 layers of cylindrical triple GEMs
- $\sigma_{r\phi} \sim 250\ \mu m$ and $\sigma_z \sim 400\ \mu m$
- XV strips-pads readout (20°÷30° stereo angle)
- 2% of radiation length in the active region





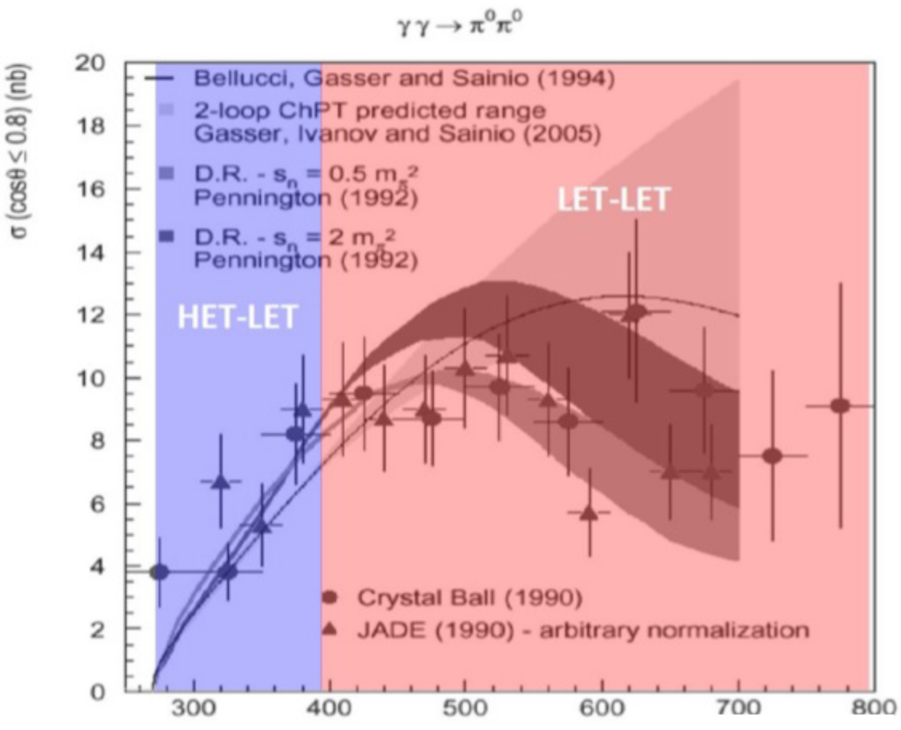


$\gamma^*\gamma^* \to \pi^0\pi^0$ @KLOE-2

- **Detection of the scattered electrons will close the kinematics and will help to reduce background**

- **Coincidences of two tagging stations cover the interesting range in $W_{\gamma\gamma}$**

With O(10 fb^{-1}) $\Rightarrow$ 2% statistical accuracy expected, using the same energy bin as Crystal Ball

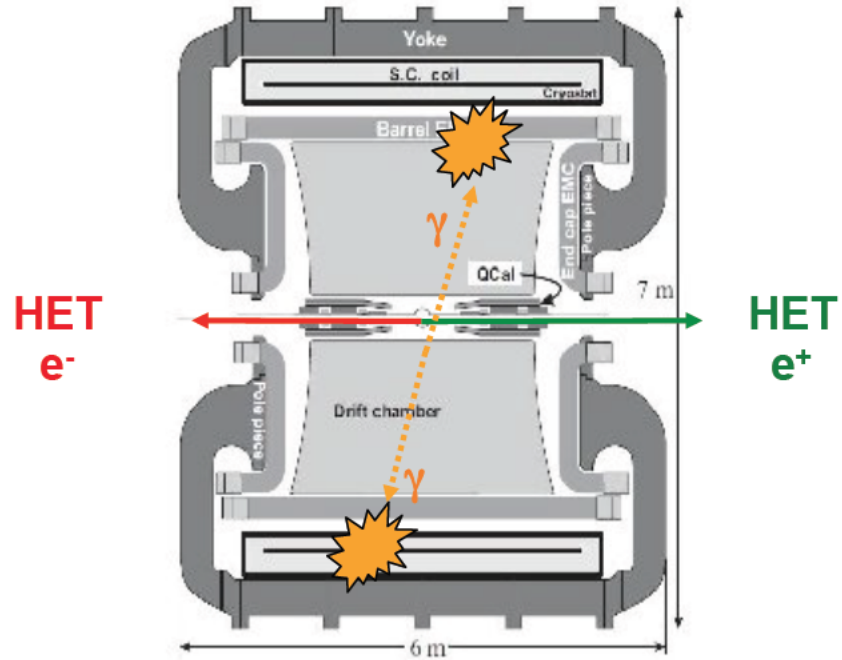


$\gamma^*\gamma^* \to \pi^0$ @KLOE-2

- $\Gamma(\pi^0 \to \gamma\gamma) = (8.09 \pm 0.11)$ eV (theory) ⇒ 1.4% uncert.

- PrimEx Coll. @JLAB ⇒ $\Gamma(\pi^0 \to \gamma\gamma) = (7.82 \pm 0.14 \pm 0.17)$ eV ⇒ 2.8% uncert.

- KLOE-2: $\sqrt{s} = M_\phi$
  2γ in the EMC + e^+ and e^- in the HETs
  ($|q^2| < 10^{-3}$ GeV^2 ⇒ quasi-real photons)



- σ_{tot} ($e^+e^- \to e^+e^-\pi^0$) ≈ 0.28 nb
- 1.2% acceptance

⇒ 2000 evts/fb^{-1} expected

with L = 5 fb^{-1} ⇒ $\delta\Gamma(\pi^0 \to \gamma\gamma) \approx 1\%$ achievable

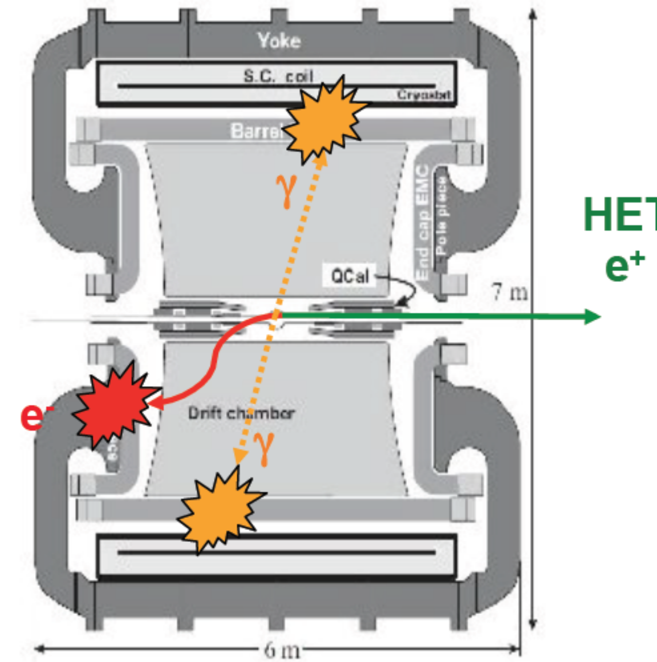
[EPJC72(2012)1917]

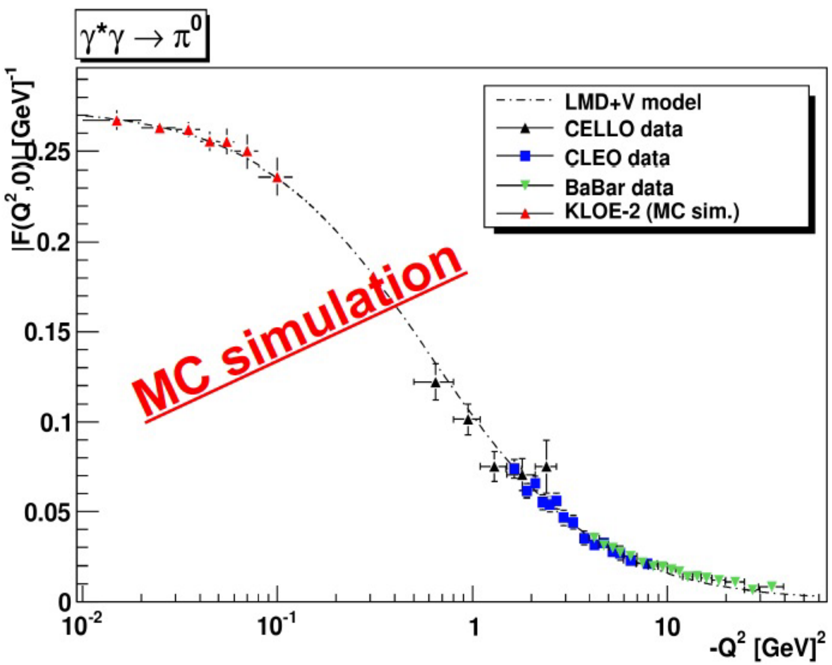
$\gamma^*\gamma^* \to \pi^0$ @KLOE-2

- $\pi^0\gamma^*\gamma$ Transition FF $\quad \mathcal{F}_{\pi^0\gamma\gamma^*}(q^2, 0)$

lepton in the HET ⇒ $|q^2| \approx 0$ quasi-real photon

lepton in the DCH/EMC ⇒ $|q^2| < 0.1\ \mathrm{GeV}^2$





- unexplored q^2 region
- check TFF parametrizations
- reduce the model dependence of the LbL scattering contribution to $(g-2)_\mu$
- with $L = 5\ \mathrm{fb}^{-1}$ ⇒ 6% error on each point

Conclusions

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

- KLOE-2: Installation of the new detectors completed
  DAΦNE operations restarted in July 2013
  Goal: collect ~ 5 fb^{-1} in the next 2 – 3 years

Rich program of measurements:

- study of η and η′ decays
- pseudoscalar meson transition form factors
- η / η′ mixing
- γγ processes at $\sqrt{s} = M_\phi$ (with $e^\pm$ taggers)
- search for dark forces
- scalar mesons: $f_0(500)$ in $\gamma\gamma \to \pi^0\pi^0$; $f_0(980)/a_0(980) \to K^0\bar{K}^0$

  [Eur.Phys.J.C68(2010),619]

Spare slides

$\phi \rightarrow \eta\gamma;\ \eta \rightarrow \pi^+\pi^-\pi^0$

- **Selection: at least 2 charged tracks and 3 prompt photons (loose cut)**

- **Most energetic photon ⇒ recoil photon from ϕ decay (363 MeV)**

- **Use constraints from kinematics (no kinematic fit) :**

$$E_{\gamma rec} = \frac{m_\phi^2 - m_\eta^2}{2(E_\phi - p_\phi \cos\theta)}$$

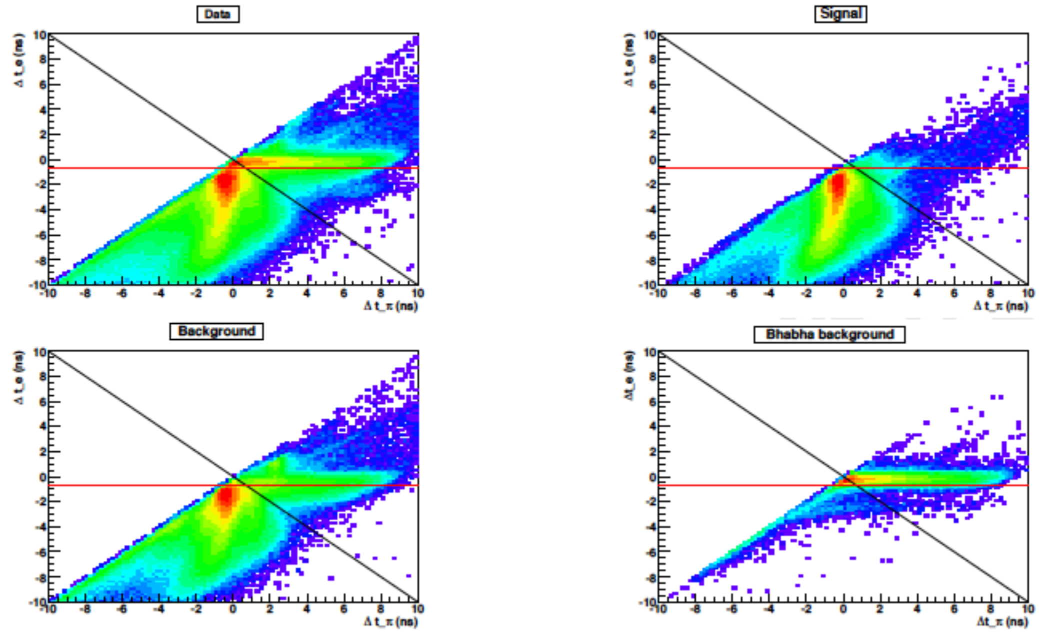
$$p_\eta = p_\phi - p_{\gamma rec}$$

$$p_{\pi^0} = p_\eta - p_{\pi^+} - p_{\pi^-}$$

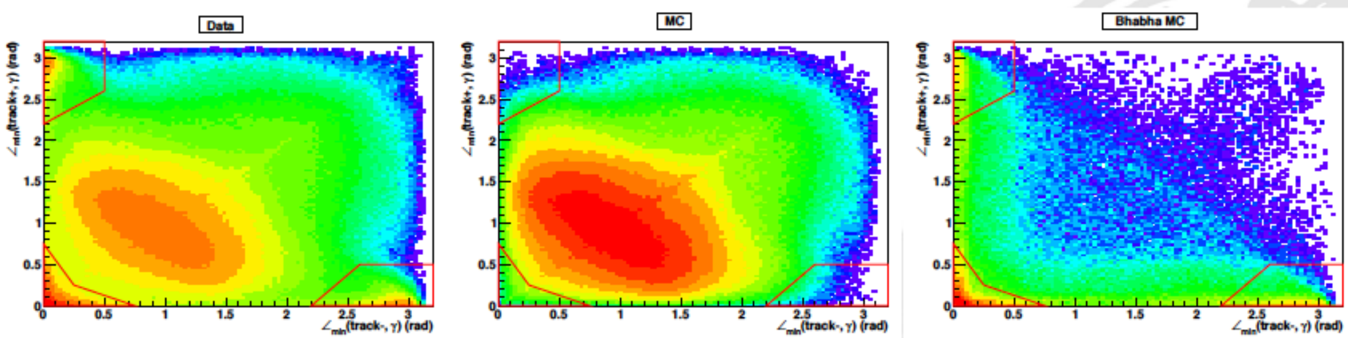
$\phi \rightarrow \eta\gamma;\ \eta \rightarrow \pi^+\pi^-\pi^0$

- **Bhabha rejection:**

***e*/π separation with TOF ⇒**

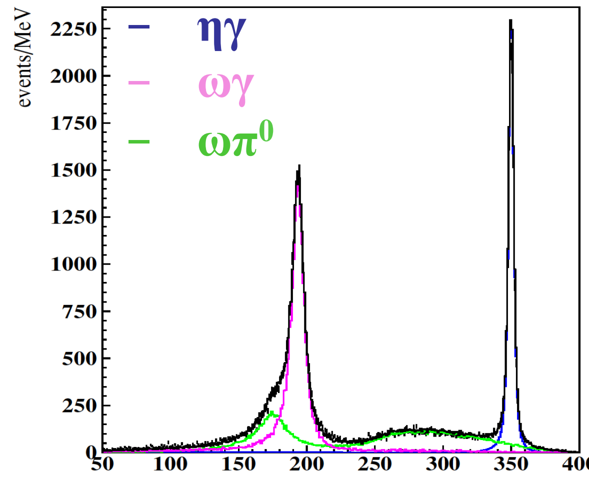


Angle between the γ's from π^0 and π^+/π^-



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

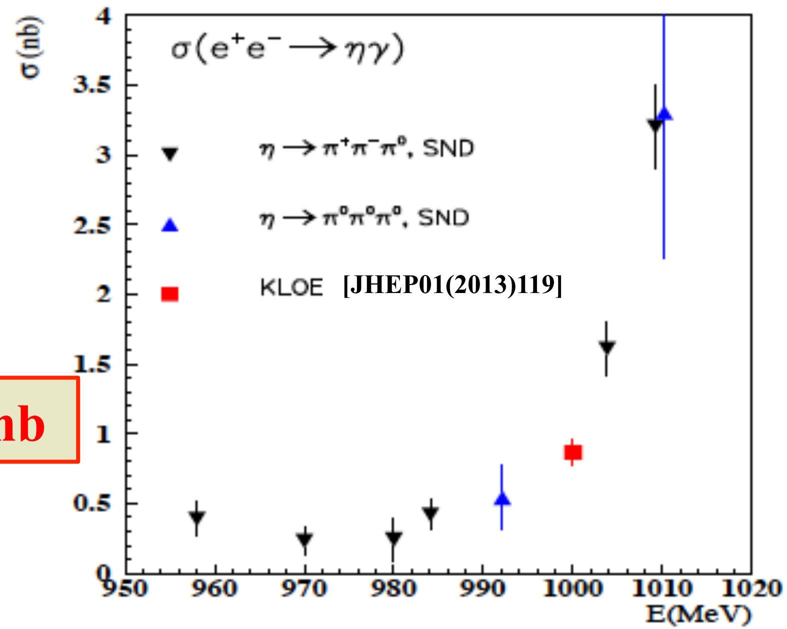
- Main background for $e^+e^- \to e^+e^-\eta$
- $e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$: 3 photons + 2 tracks
  - pion ID
  - kinematic cuts to suppress background from kaons
  - kinematic fit



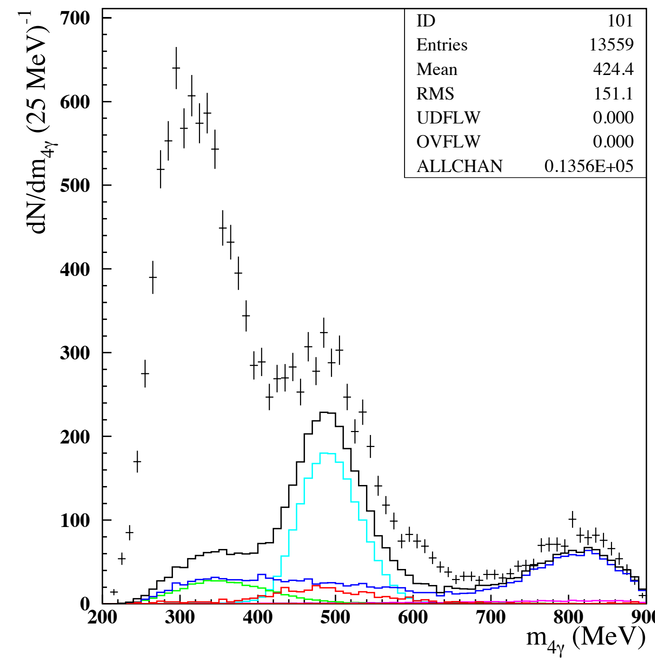
$\sigma(e^+e^- \to \eta\gamma$, 1 GeV$) = (0.856 \pm 0.008 \pm 0.016)$ nb

- Cross-check: from the fit for $\gamma\gamma \to \eta \to \pi^0\pi^0\pi^0$:

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

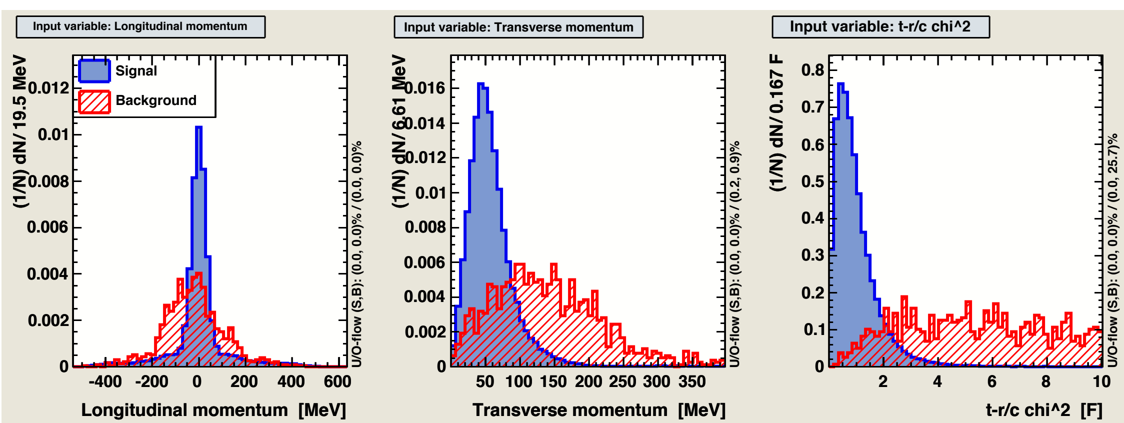


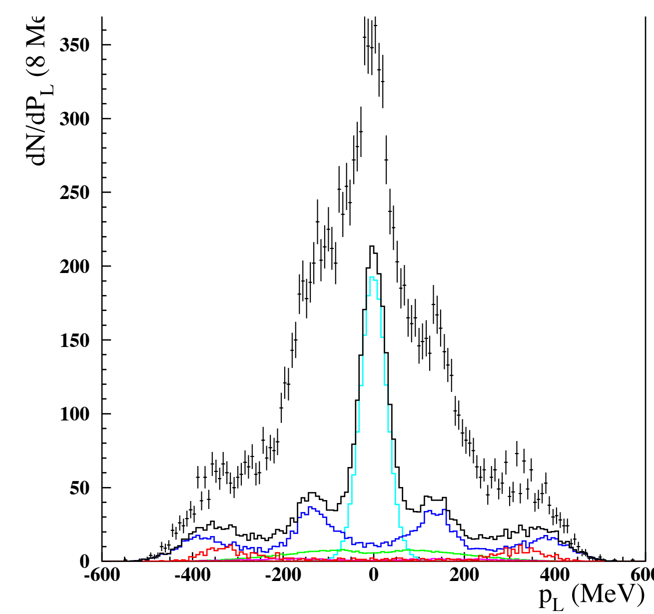
$\gamma^*\gamma^* \rightarrow \pi^0\pi^0$



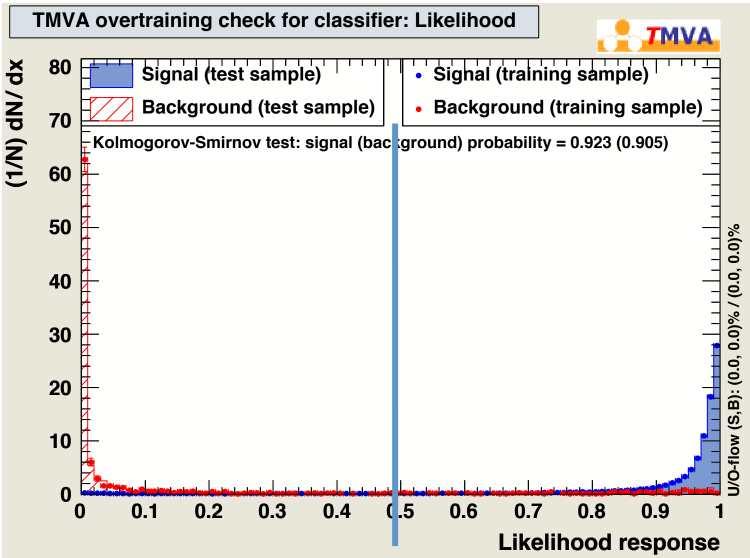
- Still some background contamination at low $m_{4\gamma}$
  $\Rightarrow$ asymmetric p_L distribution

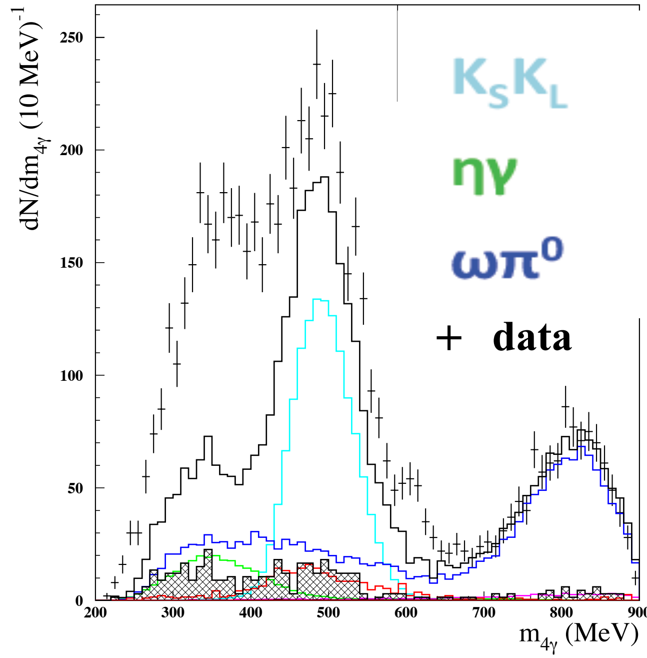
- Background reduced with a multivariate analysis by using:
  - MC distributions for signal + known bckgd.
  - data for residual background

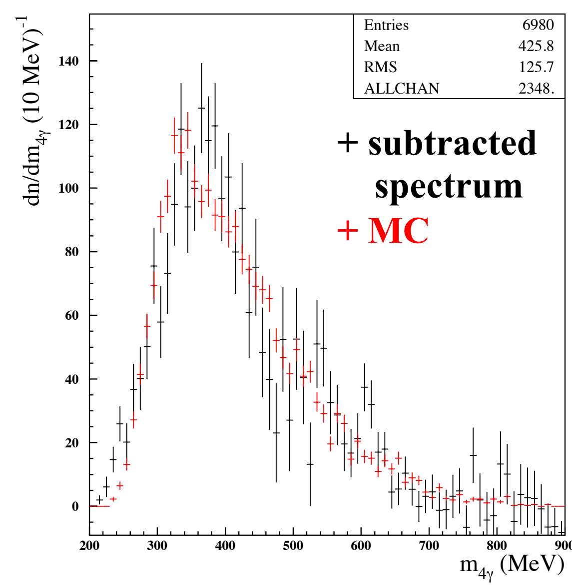




$\gamma^*\gamma^* \rightarrow \pi^0\pi^0$







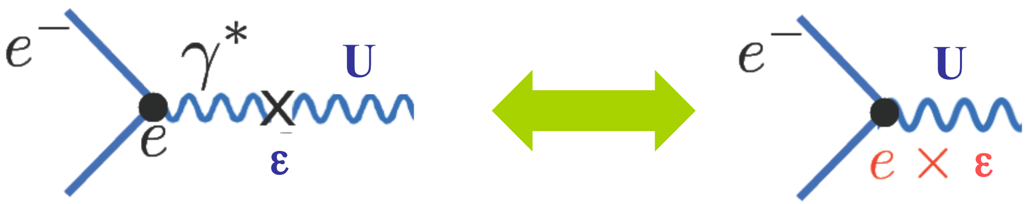
- **Residual background still under study**
- **Work is in progress to extract the cross-section**

MC: $e^+e^- \rightarrow e^+e^-\ \sigma(500) \rightarrow e^+e^-\pi^0\pi^0$
complete matrix elem.,full phase spac
[EPJC47(2006)65]

P.Gauzzi

Search for dark forces

- **Recent astrophysical observations (AMS02, 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]

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

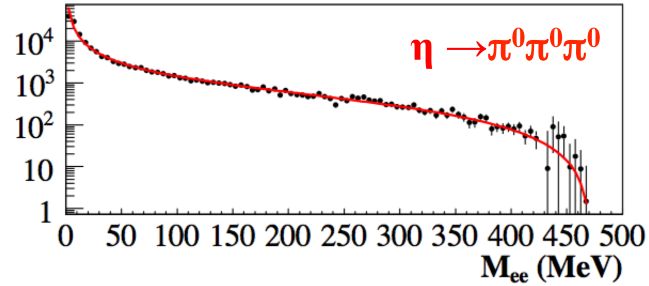
- **If the mixing parameter $\varepsilon \sim 10^{-3} - 10^{-4}$ ⇒ could be observable at KLOE**
- **Signature: $\phi \rightarrow \eta U$, $U \rightarrow \ell^+\ell^-$**

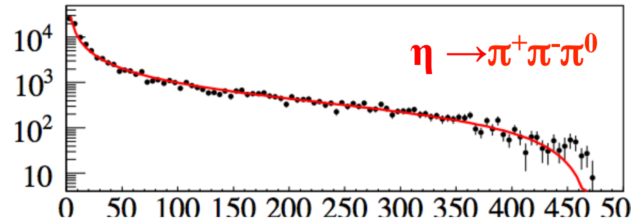
  $\Rightarrow \phi \rightarrow \eta e^+e^-$ (main background: Dalitz decay)
- **Two η decay channels analyzed: $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\eta \rightarrow \pi^0\pi^0\pi^0$**
- **Other DF searches @ KLOE: $e^+e^- \rightarrow U\gamma \rightarrow \mu^+\mu^-\gamma$;**

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

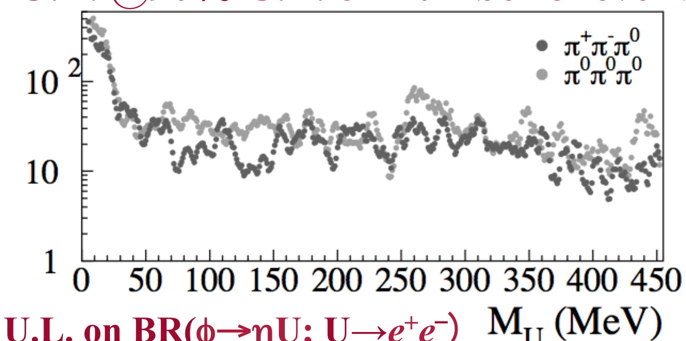
Exclusion plot on α′/α

- 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

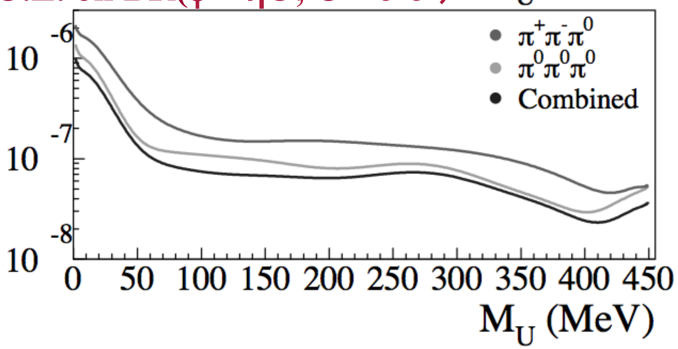




U.L. @90% C.L. on number of events

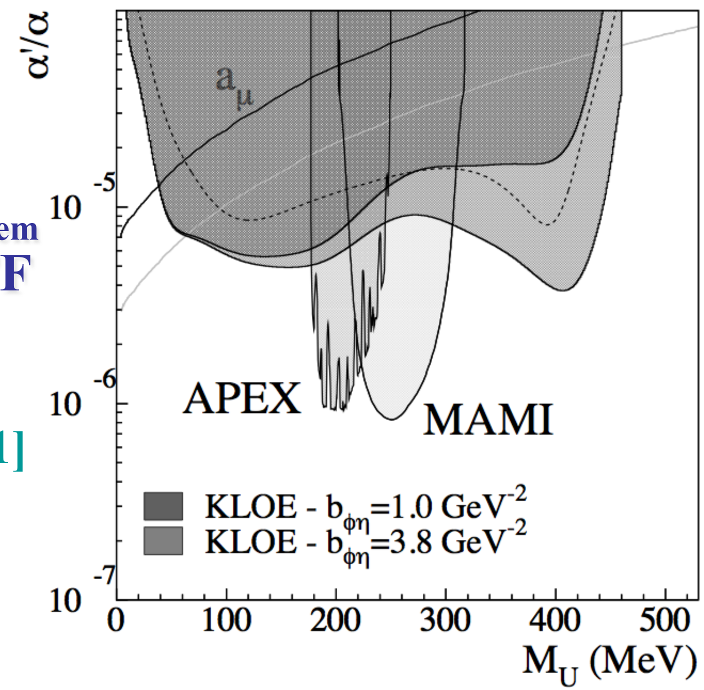


U.L. on BR($\phi \to \eta U$; $U \to e^+e^-$)



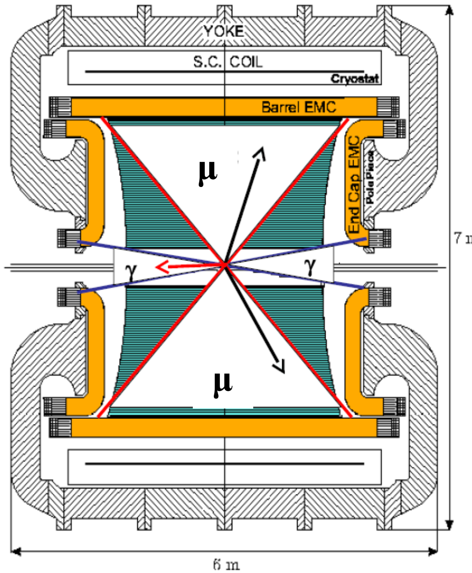
The limit on α'/α_{em} depends on the FF slope $b_{\phi\eta}$ ⇒

[PLB72092013)111]

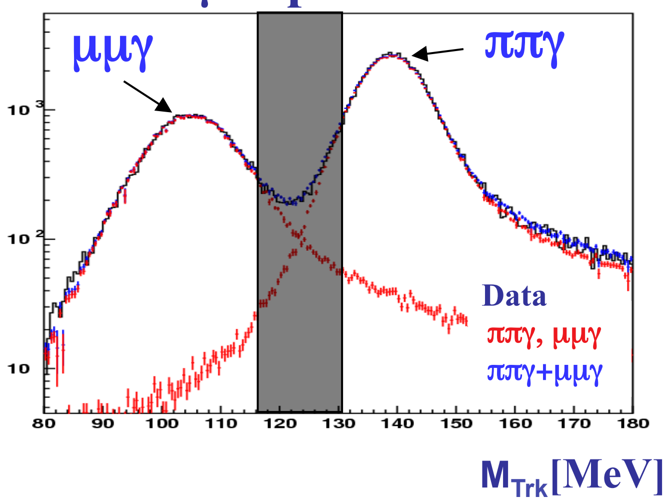


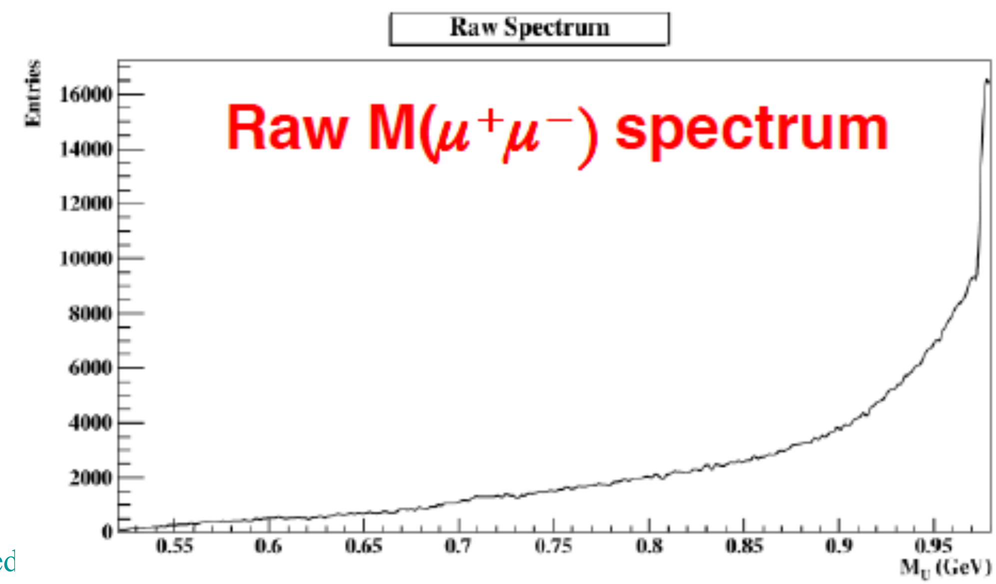
DF search in $e^+e^-\rightarrow\mu^+\mu^-\gamma$

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



π/μ separation



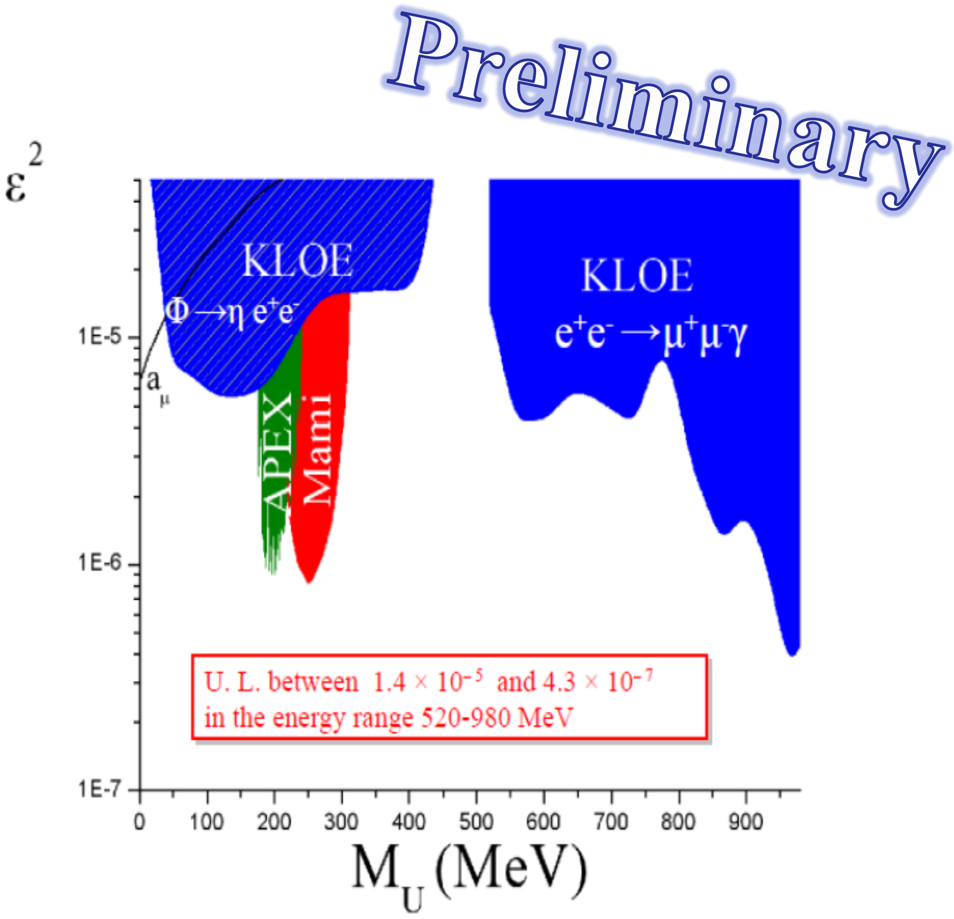


DF search in $e^+e^- \to \mu^+\mu^-\gamma$

- 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

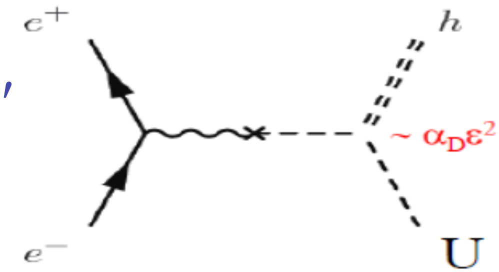
- A further factor of 2 is expected from KLOE-2 data-taking



DF searches: h′-strahlung

- Assume the existence of a higgs boson (h′) of the hidden sector
- If $M_U + M_{h'} < M_\phi$ could be observed at KLOE

$\Rightarrow e^+e^- \rightarrow Uh'$



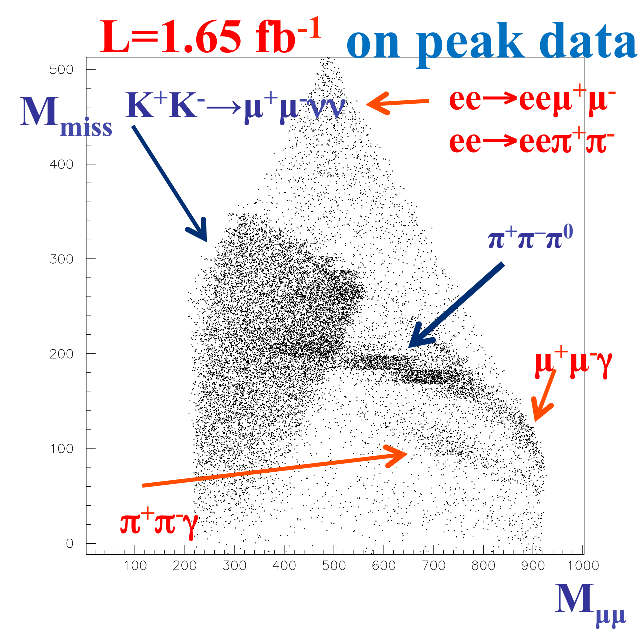
$$\sigma \simeq 20\ \text{fb}\,\frac{\alpha_D}{\alpha}\,\frac{\varepsilon^2}{10^{-4}}\,\frac{10^2\ \text{GeV}^2}{s}$$

[Batell et al.,PRD79(2009)115008]

if $M_{h'} > M_U \Rightarrow h' \rightarrow UU \rightarrow 4l$
if $M_{h'} < M_U \Rightarrow h'$ invisible (escapes the detector)
$U \rightarrow ll$

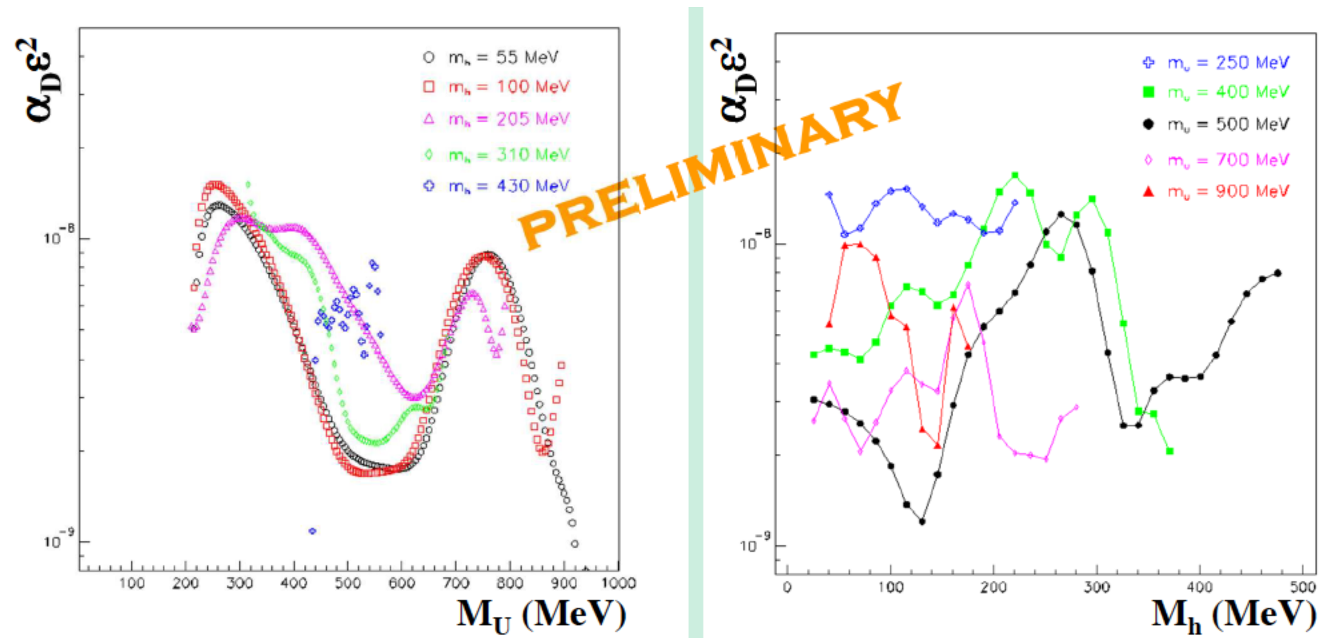
$\Rightarrow$ selected final state: $\mu^+\mu^-$ + missing energy

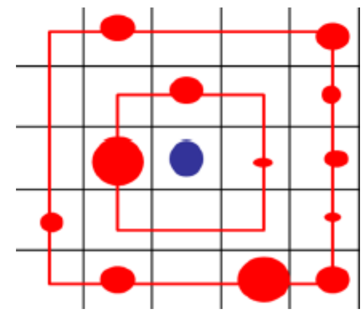
events with 2 muons coming from the IP



DF searches: h′-strahlung

- Upper limit on $\alpha_D\varepsilon^2$ extracted from the scatter plot M_{miss} vs $M_{\mu\mu}$ by considering for each bin the 5×5 bin region surrounding to evaluate the background





If $\alpha_D = \alpha \Rightarrow$ upper limit on $\varepsilon \sim 10^{-3}$

KLOE-2 physics program

Eur. Phys. J. C68(2010)619

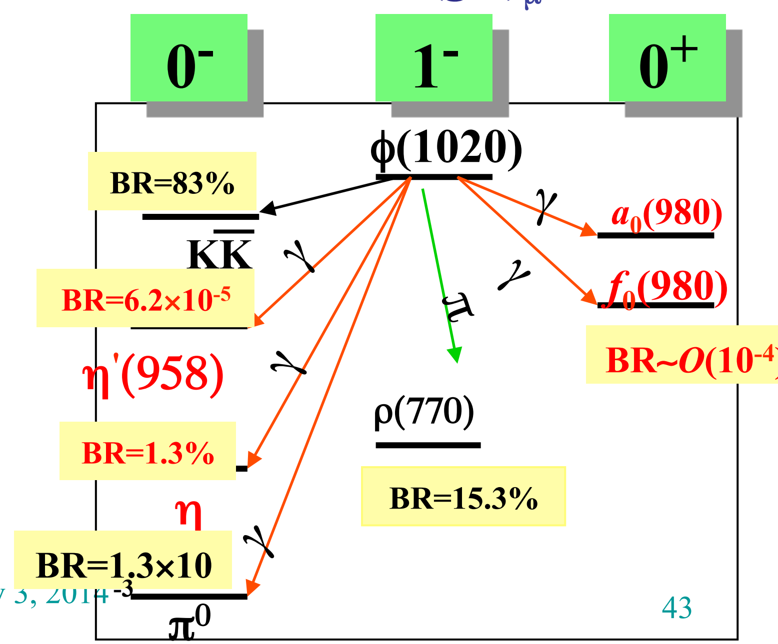
- $\gamma\gamma$ physics
  - Properties of $\sigma(500)$
  - Study of $\Gamma(S/P\rightarrow\gamma\gamma)$
  - P transition form factor
- Light meson spectroscopy
  - Properties of scalar/vector mesons
  - Rare η decays
  - η' decays
- Kaon physics
  - Test of CPT (and QM) in correlated kaon decays
  - 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 $(g_\mu\text{-}2)$

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
  - $\eta \to 3\pi$ ⇒ Constraints on light quark masses
  - $\eta\ (\eta') \to \pi^+\pi^-\gamma$ ⇒ Study of the box anomaly
  - $\phi \to \eta e^+e^-$, $\phi \to \pi^0 e^+e^-$ ⇒ Transition Form Factors
    ⇒ Search for light 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

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

Decay channel	Events (2.5 fb^{-1})
K^+K^-	3.7×10^9
K_LK_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



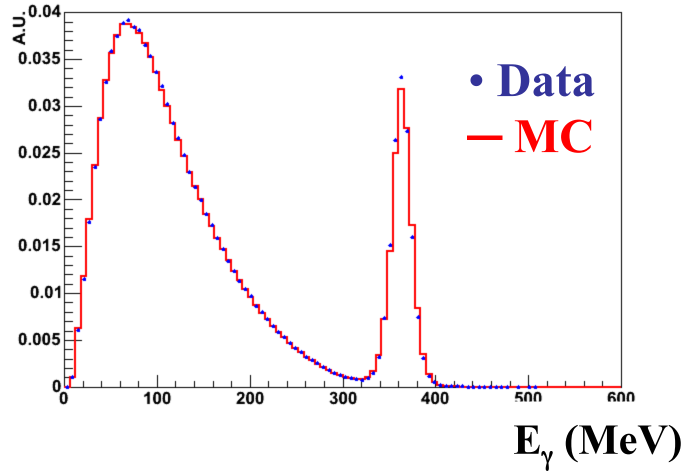
$\eta \rightarrow \pi^0\pi^0\pi^0$

- **Symmetric Dalitz plot:**

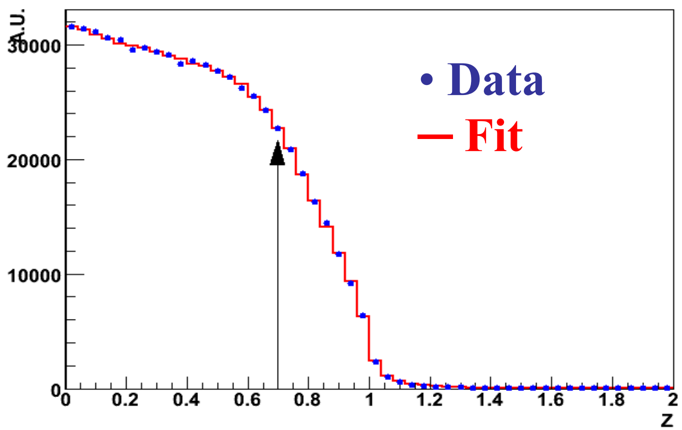
$$|A|^2 \propto 1 + 2\,\alpha\, Z \quad \Rightarrow \text{only one parameter}$$

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

(ρ = distance from the Dalitz plot center)

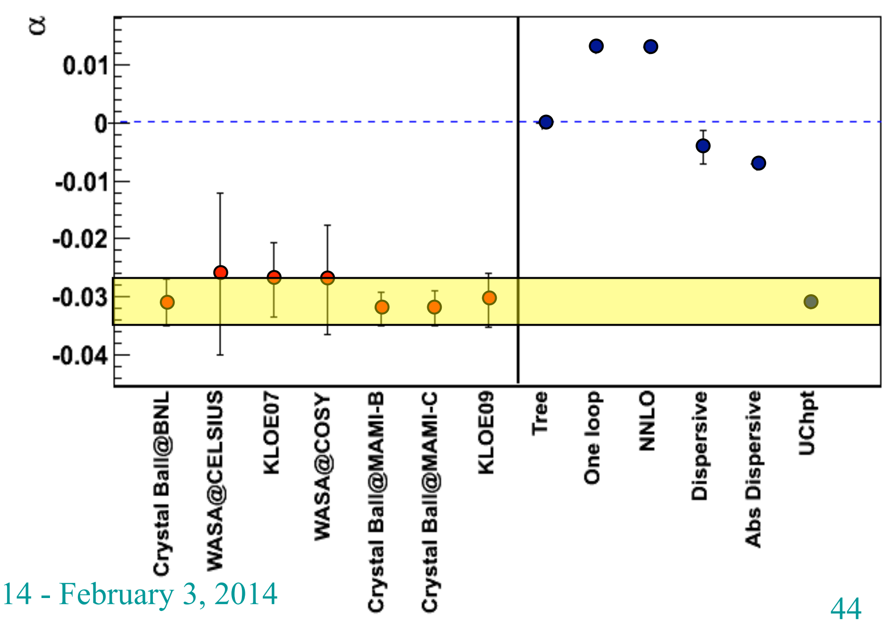


- 450 pb^{-1} ; 7 prompt photons $\Rightarrow 6.5 \times 10^5$ events



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

[PLB 694 (2010) 16]



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

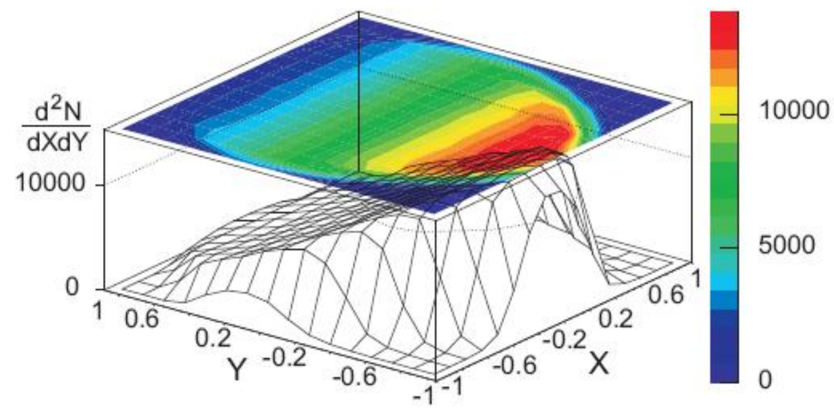
$$X = \sqrt{3}\,\frac{E_+ - E_-}{\Delta}$$

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

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

$\phi \to \eta\gamma$ ($E_{\gamma rec}$ = 363 MeV)
with $\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$ final state
450 pb^{-1} $\Rightarrow$ 1.34 × 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(□^{2})	73%

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

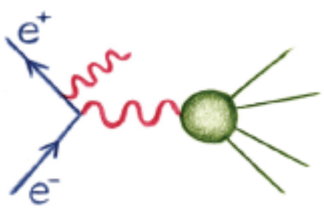
[JHEP0805(2008)006]

$\sigma(e^+e^-\to$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}

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

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



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

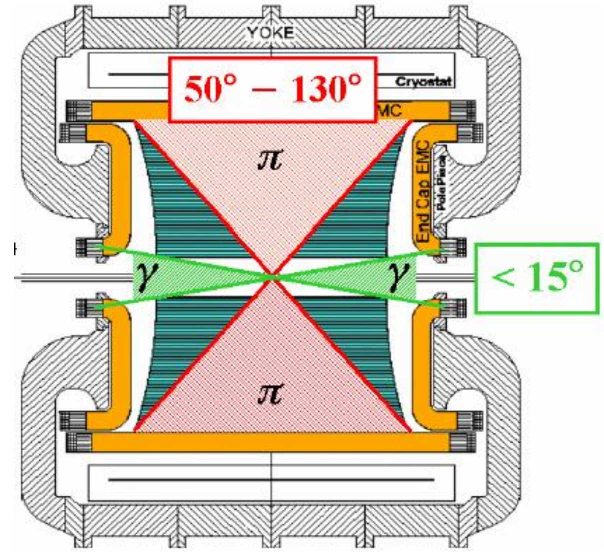
- Different analyses: (1) photon emitted at Small Angle (S.A. analysis) [PLB606(2005)12, PLB670(2009)285]
  (2) photon emitted at Large Angle (L.A. analysis) [PLB700(2011)102]
  (3) photon at S.A., $\sigma(e^+e^-\to\pi^+\pi^-\gamma)/\sigma(e^+e^-\to\mu^+\mu^-\gamma)$ [PLB720(2013)336]

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

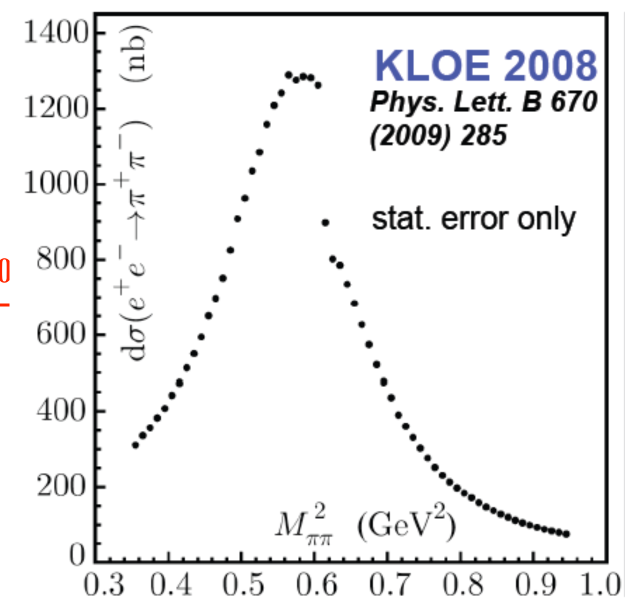
$$\vec{p}_\gamma = -(\vec{p}_+ + \vec{p}_-)$$

- 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) = $(387.2 \pm 0.5_{stat} \pm 2.4_{syst} \pm 2.3_{th}) \times 10^{-10}$



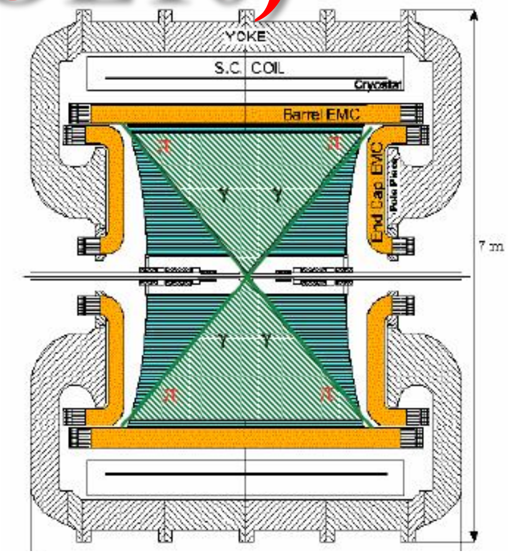
L.A. analysis (KLOE10)

- 2 pions at large angle (ϑ>50°)
- Photon detected at large angle (ϑ>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}

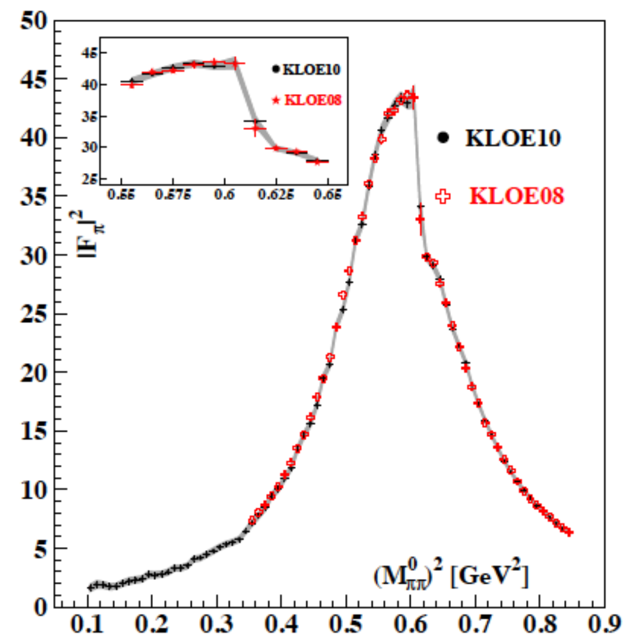


$a_\mu^{\pi\pi}$(0.1–0.85 GeV^2) = (478.5±2.0$_{stat}$±5.0$_{syst}$±4.5$_{th}$)×10^{-10}

[PLB700(2011)102]

- Good agreement with KLOE08
- Combined KLOE08 + KLOE10:

$a_\mu^{\pi\pi}$(0.1–0.95 GeV^2) = (488.6±6.0)×10^{-10}



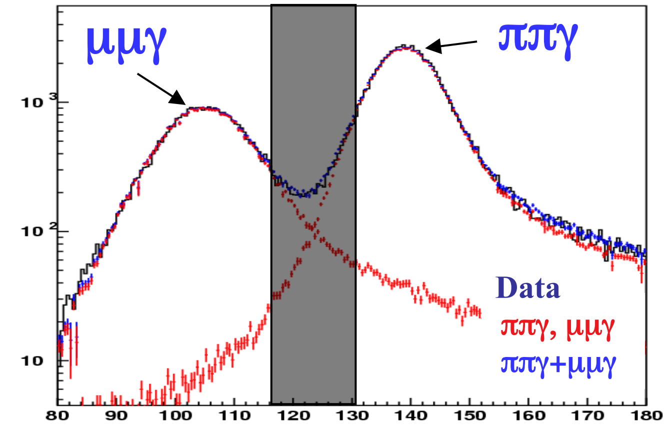
σ_{had} from $\pi\pi\gamma$ / $\mu\mu\gamma$

- $|F_\pi|^2$ from the ratio $\sigma(e^+e^-\to\pi^+\pi^-\gamma)/\sigma(e^+e^-\to\mu^+\mu^-\gamma)$ at $\sqrt{s} = M_\phi$
  Small Angle analysis (photon not detected; $\vartheta_\gamma < 15°$)

[PLB720(2013)336]

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

kinematical factor ($\sigma_{\mu\mu}^{Born} / \sigma_{\pi\pi}^{Born}$) — meas. quantities

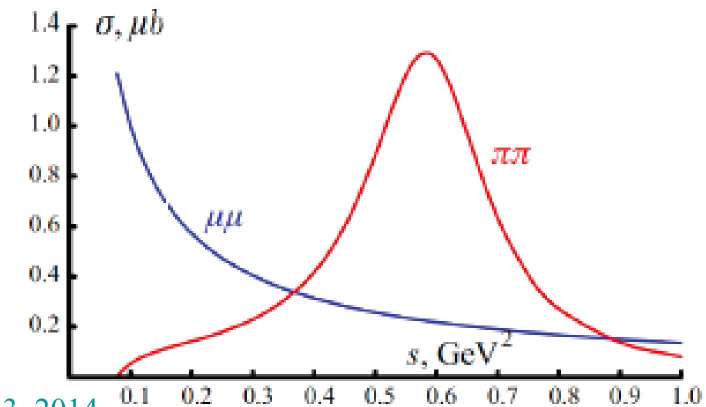


- Many factors cancel in the ratio:
  - radiator function
  - luminosity from Bhabhas
  - vacuum polarization

Separation btw $\pi\pi\gamma$ and $\mu\mu\gamma$ using M_{TRK}
- muons: $M_{Trk} < 115$ MeV
- pions : $M_{Trk} > 130$ MeV

Very important control of π/μ separation in the ρ region ($\sigma_{\pi\pi} >> \sigma_{\mu\mu}$)

$\sigma(e^+e^-\to\pi^+\pi^-)$ and $\sigma(e^+e^-\to\mu^+\mu^-)$

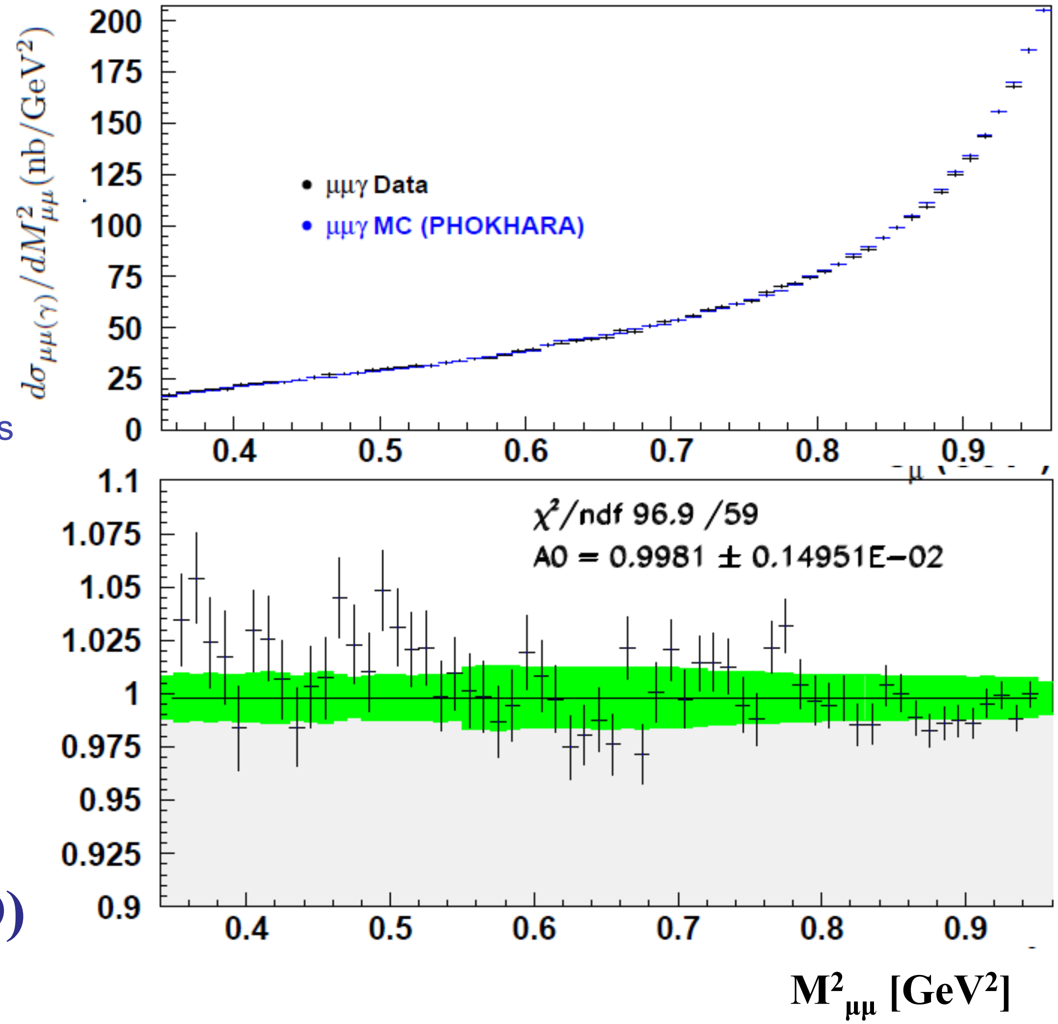


μμγ - data/MC comparison

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

$$\frac{d\sigma^{DATA}_{\mu\mu\gamma(\gamma)}}{d\sigma^{MC}_{\mu\mu\gamma(\gamma)}} = 0.998 \pm 0.001_{stat} \pm 0.011_{sys}$$

- The systematic error has been averaged on $M^2_{\mu\mu}$
- Good agreement with PHOKHARA MC (QED @ NLO)

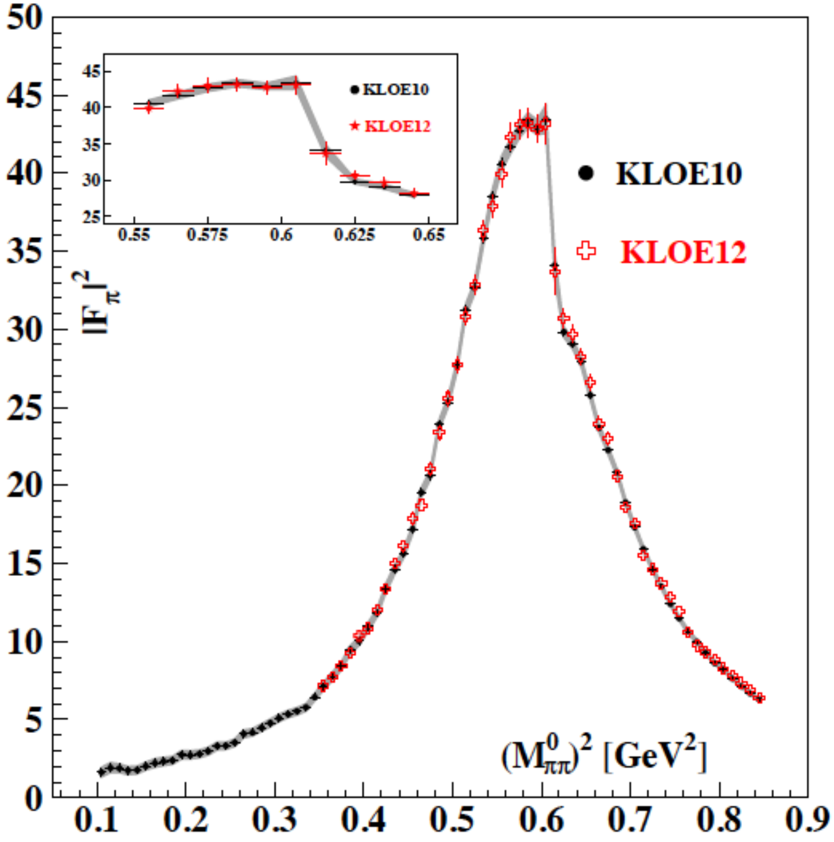


KLOE12 vs KLOE10

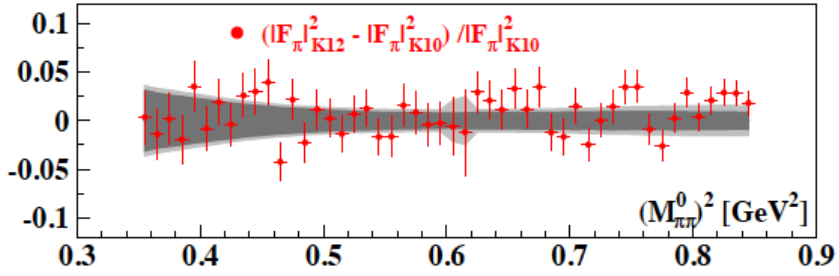
KLOE12: $\pi\pi\gamma / \mu\mu\gamma$ [PLB720(2013)336]

KLOE10: Large Angle analysis (photon detected at $\vartheta_\gamma > 50°$) – off peak data

[PLB700(2011)102]



Fractional difference:



band: KLOE10 error

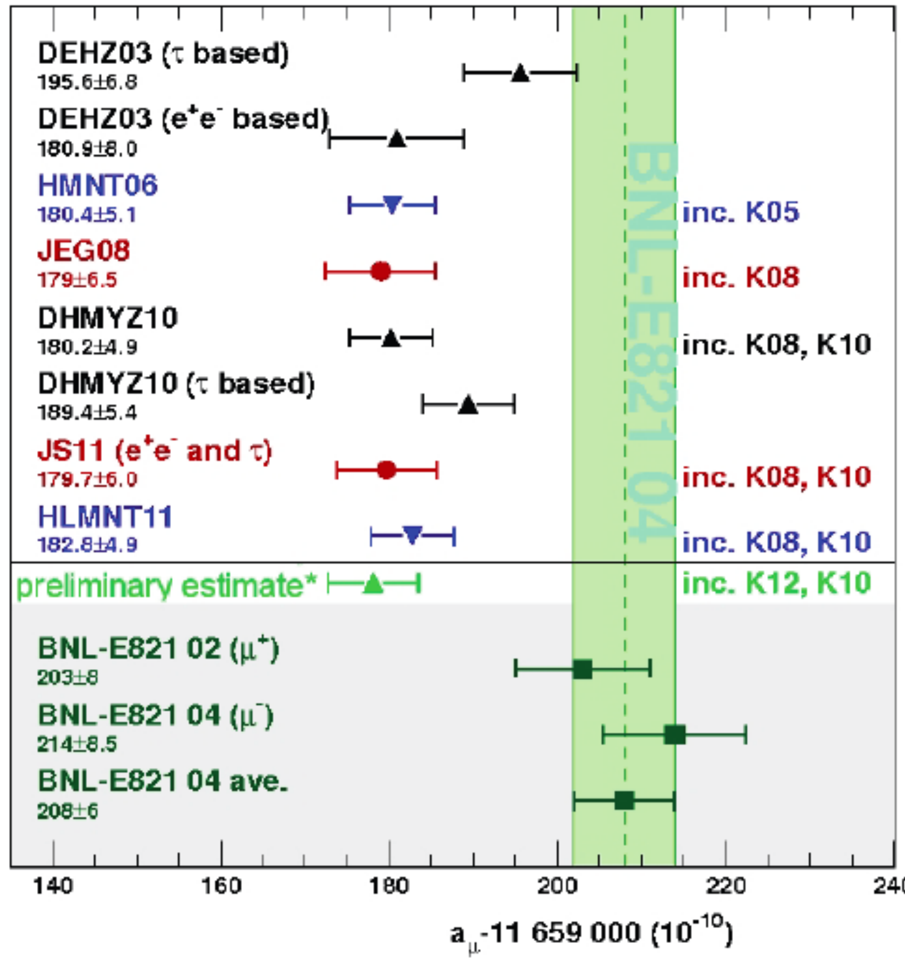
Excellent agreement between the two independent measurements

Summary on a_μ

$a_\mu^{exp} - a_\mu^{theo,SM}$:
3.3 σ discrepancy confirmed

$$\Delta a_\mu^{\pi\pi} = \int_{s_{min}}^{s_{max}} \sigma^0_{\pi\pi(\gamma)}(s) \cdot K(s)\, ds$$

Data	$\Delta^{\pi\pi} a_\mu \cdot 10^{10}$ $0.35 < s < 0.85$ GeV²
$\sigma_{\pi\pi(\gamma)} / \sigma_{\mu\mu(\gamma)}$, SA- γ_{ISR}	$377.4 \pm 1.1_{stat} \pm 2.7_{sys+th}$
Abs. $\sigma_{\pi\pi(\gamma)}$, SA- γ_{ISR}	$379.6 \pm 0.4_{stat} \pm 3.3_{sys+th}$
Abs. $\sigma_{\pi\pi(\gamma)}$, LA- γ_{ISR}	$376.6 \pm 0.9_{stat} \pm 3.3_{sys+th}$



* Our extrapolation based on DHMYZ10

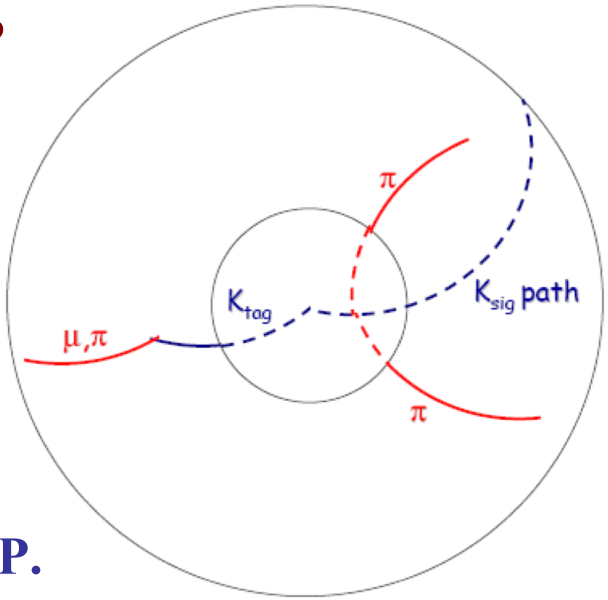
$BR(K^+ \to \pi^+\pi^+\pi^-(\gamma))$

- Measurement of the absolute BR, to complete the program of precise measurement of the dominant $K^{\pm}$ decay channels
- The amplitude enters the cusp analysis of $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ to extract the $\pi\pi$ phase shift done by NA48
- Previous measurements :

  Chiang ('72) (2330 evts) BR = (5.56 ± 0.20)% ⇒ $\Delta BR / BR = 3.6 \times 10^{-2}$

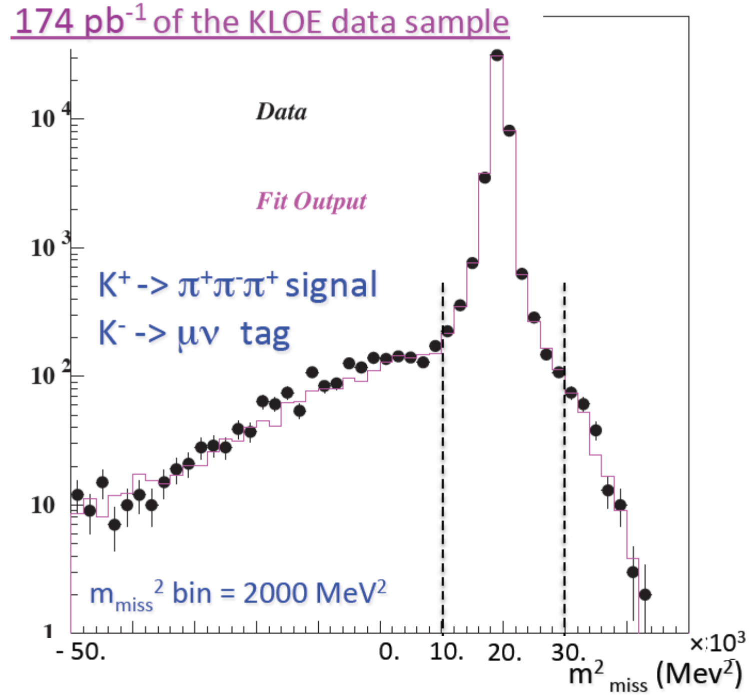
  KLOE (2008) (fit to $1-\Sigma_i BR_i$) BR = (5.68 ± 0.22)%

  Flavianet fit (2010) : BR = (5.73 ± 0.16) %



- Signal selection:
  - tag with $K \to \mu\nu, \pi\pi^0$
  - 2 tracks with vertex along the K path before the DC wall
  - K path from the extrapolation of the tag K to I.P.
  - signal peak in the missing mass distribution (3rd pion)

$BR(K^+ \to \pi^+\pi^+\pi^-(\gamma))$



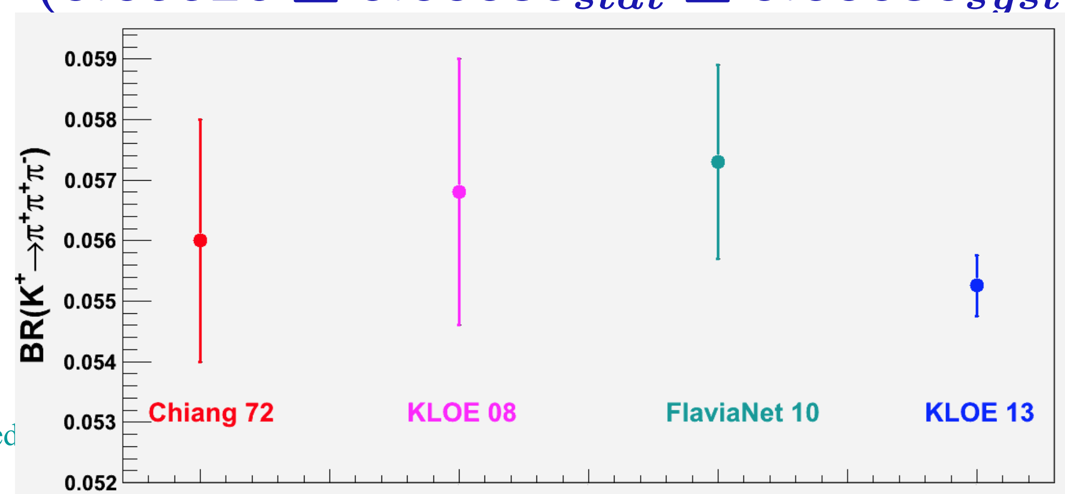
- Analyzed sample: 174 pb^{-1}
- Efficiency evaluated by MC and corrected from data-MC comparison
- Signal extraction from fit to m^2_{miss} spectrum with signal and bckg shapes from MC

$$N(K^+ \to 3\pi) = 45054.1 \pm 212.2 \text{ evts}$$

$$N(K^- \to \mu\nu) = 12065087$$

$$BR(K^+ \to \pi^+\pi^+\pi^-(\gamma)) = (0.05526 \pm 0.00035_{stat} \pm 0.00036_{syst})$$

$$\Delta BR/BR = 9.2 \times 10^{-3}$$



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

- **Standard Model Extension** [Kostelecky et al., PRD61(1999)016002,PRD64(2001)076001]

⇒ **possibility of violation of CPT and Lorentz invariance**

$$\varepsilon_{L,S} = \varepsilon_K \pm \delta$$

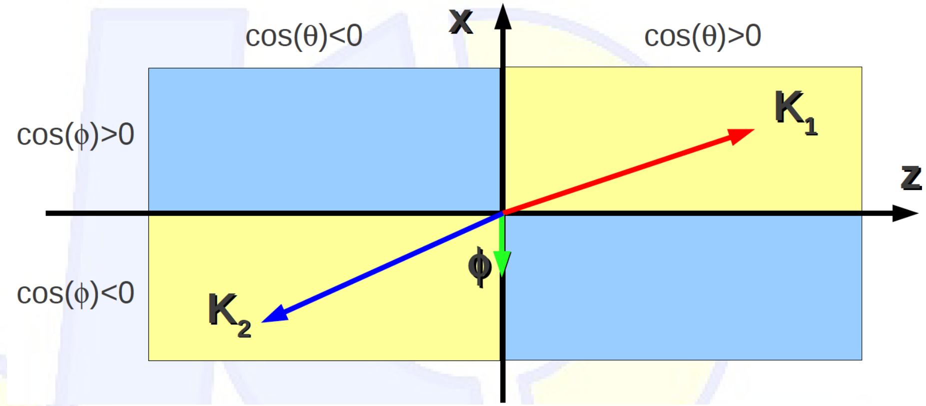
$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a})/\Delta m$$

- **δ depends on the orientation of the K momentum with respect to the fixed vector Δ*a* :**
  - **angular distributions**
  - **earth rotation effects (T$_{sid}$ = sidereal time)**

$$\begin{aligned} \delta_K(\vec{P}_K, T_{sid}) = & \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \Big[\Delta a_0 + \beta_K \Delta a_Z (\cos\vartheta \cos\chi - \sin\vartheta \cos\varphi \sin\chi) \\ & - \beta_K \Delta a_X \sin\vartheta \sin\varphi \sin\omega_E T_{sid} \\ & + \beta_K \Delta a_X (\cos\vartheta \sin\chi + \sin\vartheta \cos\varphi \cos\chi) \cos\omega_E T_{sid} \\ & + \beta_K \Delta a_Y (\cos\vartheta \sin\chi + \sin\vartheta \cos\varphi \cos\chi) \sin\omega_E T_{sid} \\ & + \beta_K \Delta a_Y \sin\vartheta \sin\varphi \cos\omega_E T_{sid} \Big] \end{aligned}$$

Analysis strategy

- $L = 1.7\ fb^{-1}$ analyzed
- Kaons ordered according the z momentum component



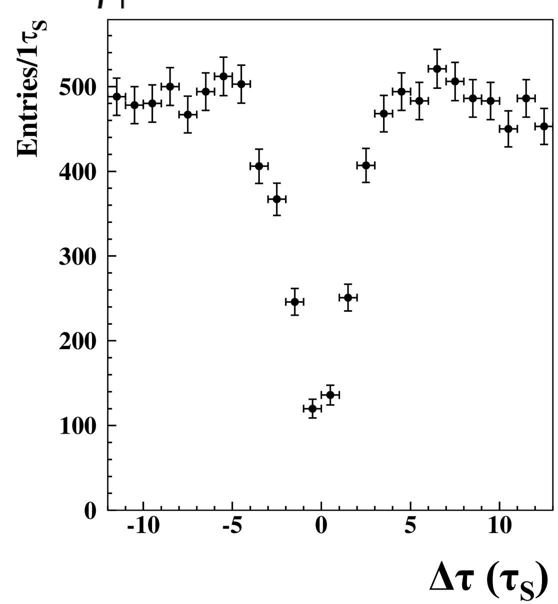
$$I(\Delta t, T_{sid}, \vartheta_{K_1}, \varphi_{K_1}) \propto$$

$$e^{-\Gamma|\Delta\tau|}\Big[|\varepsilon_K - \delta_K(\vec{P}_1)|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\varepsilon_K - \delta_K(\vec{P}_\phi - \vec{P}_1)|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} -$$

$$-2\Re e\Big((\varepsilon_K - \delta_K(\vec{P}_1))(\varepsilon_K - \delta_K(\vec{P}_\phi - \vec{P}_1)^*)e^{-i\Delta m\Delta\tau}\Big)\Big]$$

- Data divided into 8 samples: 4 sidereal time bins × 2 angular bins

$$\int_{\Delta\tau_i} d\Delta\tau \int_{\Delta T_j} dT \int_{\Delta\Omega_h} d\Omega_{K_1}\, \rho(\Omega_{K_1}, T)\, I(\Delta\tau, T, \Omega_{K_1})$$



- Simultaneous fit of the Δτ distributions to extract the Δa_μ parameters

Fit result

$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys})\ 10^{-18}$ GeV

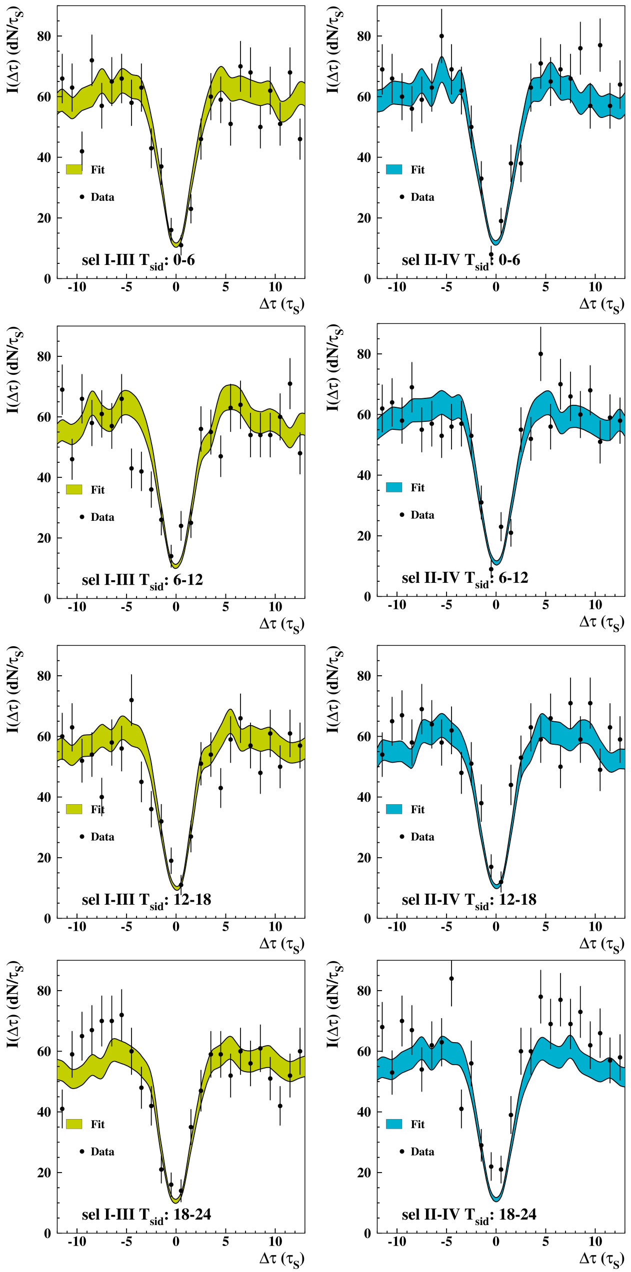
$\Delta a_X = (0.9 \pm 1.5_{stat} \pm 0.6_{sys})\ 10^{-18}$ GeV

$\Delta a_Y = (-2.0 \pm 1.5_{stat} \pm 0.5_{sys})\ 10^{-18}$ GeV

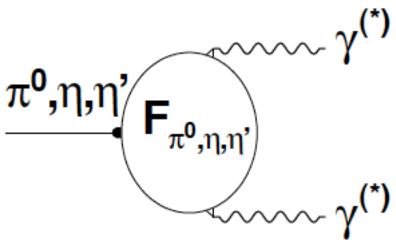
$\Delta a_Z = (3.1 \pm 1.7_{stat} \pm 0.6_{sys})\ 10^{-18}$ GeV

$$\chi^2/ndf = 211.7/184 \quad \Rightarrow \quad P(\chi^2) = 8\%$$

[PLB730(2014)89]

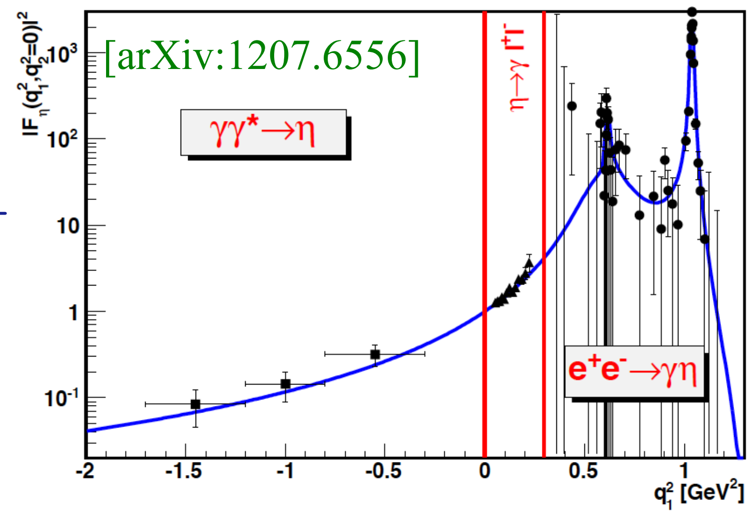


Transition Form Factors

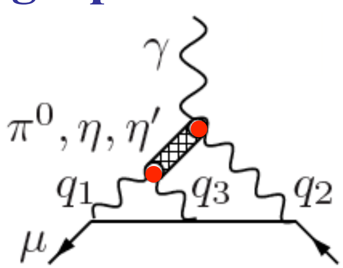


Information on the structure of mesons come from their coupling to photons, described by the TFFs

$$\mathcal{F}_{P\gamma\gamma}(q_1^2, q_2^2) \left\{ \begin{array}{l} \gamma^\star \to P\gamma \\ P \to \gamma\gamma^\star \to \gamma\ell^+\ell^- \\ \gamma^\star\gamma^\star \to P \end{array} \right.$$



- **Light-by-Light scattering contribution to g-2 of the muon is dominated by single pseudoscalar exchange**



- **TFFs for off-shell mesons ⇒ model dependent ⇒ measurements can help to constrain models**