KLOE: data analysis report

P.Gauzzi
(Universita' La Sapienza e INFN – Roma)
for the KLOE / KLOE-2 Collaborations

42nd meeting of LNF Scientific Committee
6 - Jun - 2011

Kaon physics

K decays

Interferometry

Progress since last SC meeting	
K_S lifetime	EPJC71(2011)1604
$K^+ \rightarrow \pi^+\pi^+\pi^-$	in progress / advanced stage
$K_S \rightarrow \pi^0\pi^0\pi^0$	update with the whole statistics / advanced stage
$K_S \rightarrow \pi e \nu$	update in progress
$K_SK_L \rightarrow \pi^+\pi^-\pi^+\pi^-$	in progress
K_S regeneration	in progress
$K_SK_L \rightarrow \pi^+\pi^-\pi^0\pi^0$	in progress
$K_SK_L \rightarrow \pi^+\pi^-\pi\ell\nu$	in progress

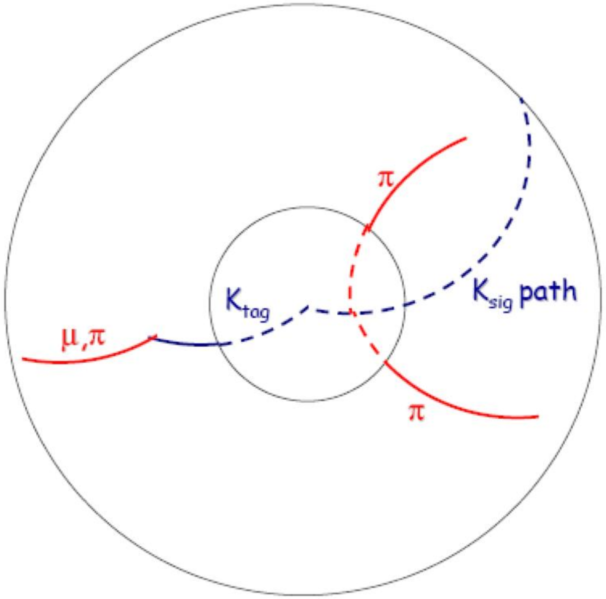
BR($K^+ \rightarrow \pi^+\pi^+\pi^-(\gamma)$)

- 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 $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ to extract the $\pi\pi$ phase shift done by NA48
- Previous measurement :

  Chiang ('72) (2330 evts) BR = (5.56 ± 0.20)%

  $\Delta BR / BR = 3.6 \times 10^{-2}$

  [PDG fit : BR = (5.59 ± 0.04) %]



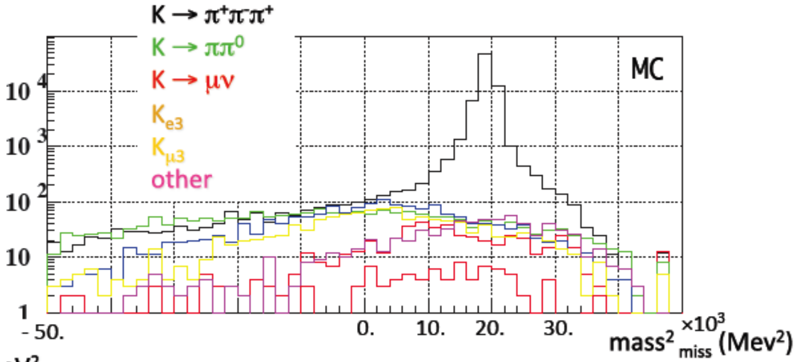
- Signal selection:
  - tag with $K \rightarrow \mu\nu, \pi\pi^0$
  - 2 tracks with vertex along the K path before the DC wall
  - K path from the extrapolation of the tag K to I.P.
  - signal peak in the missing mass distribution (3rd pion)

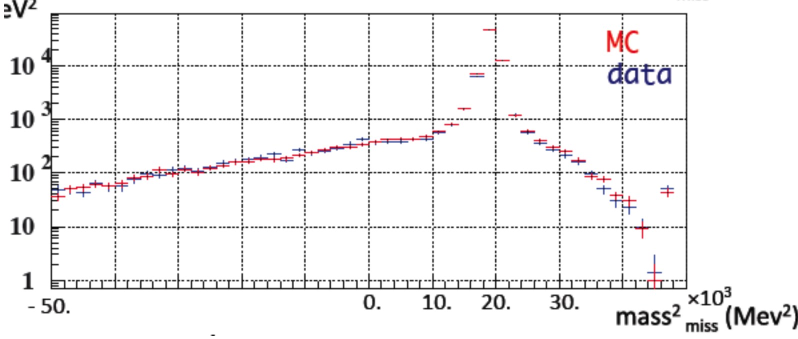
BR($K^+\rightarrow\pi^+\pi^+\pi^-(\gamma)$)

- **Analyzed sample: 174 pb^{-1}**
- **Efficiency evaluated by MC and corrected from data-MC comparison**

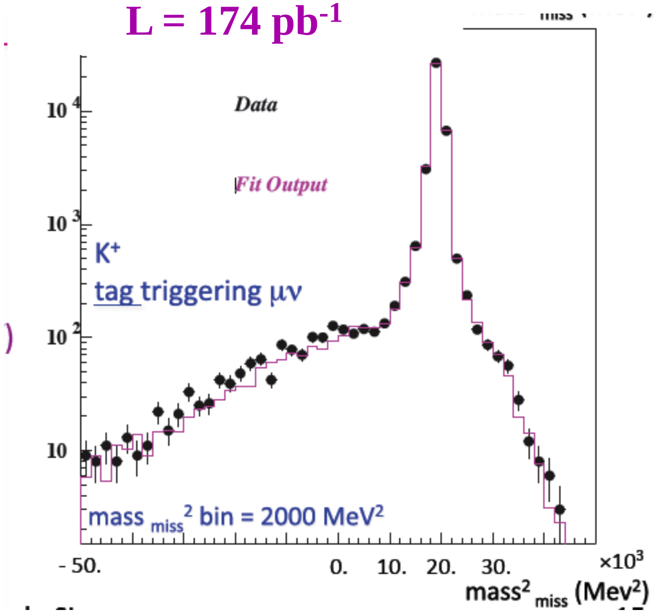
$$\varepsilon_{sel} = \varepsilon^{kine}_{sel}\,(K+ \to 3p) \times (\varepsilon^{MC}_{sel}/\varepsilon^{data}_{sel}) =$$

$$= 0.068502 \pm 0.000296$$





L = 174 pb^{-1}



- **Signal extraction from fit to m^2_{miss} spectrum with signal and bckg shapes from MC**
  ⇒ ΔBR / BR < 1 % (stat.)

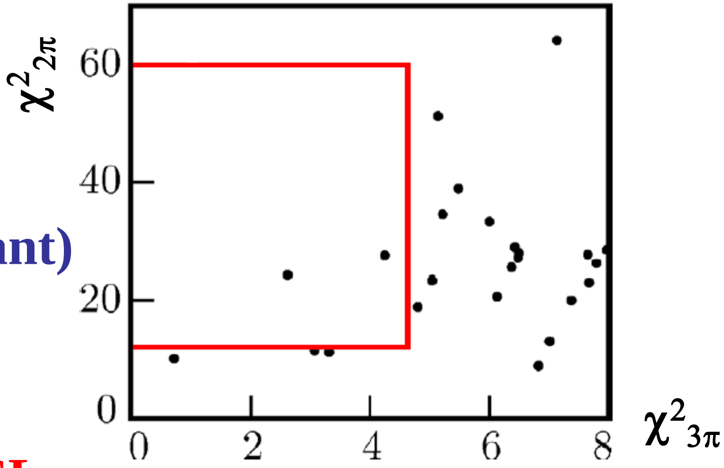
- **Systematics under evaluation**

$K_S \rightarrow 3\pi^0$ - direct search

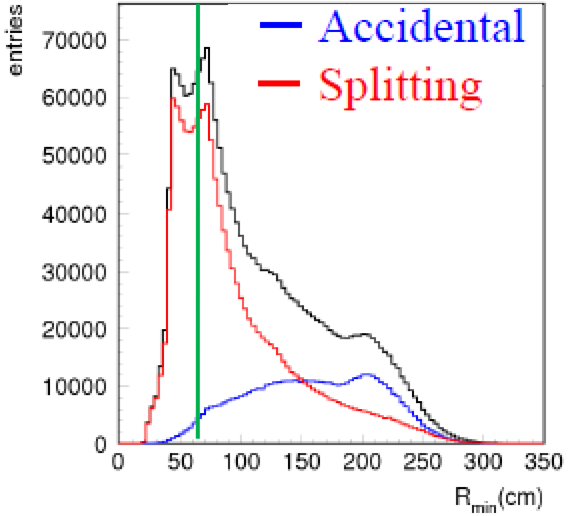
- CP violating decay; SM expect. $\Gamma(K_S \rightarrow 3\pi^0) = \Gamma(K_L \rightarrow 3\pi^0)\,|\eta_{000}|^2 \Rightarrow$ BR~ 2×10^{-9}
- Tag by K_L interactions (K_L crash) in the EmC

  $\Rightarrow$ look for events with 6 prompt γ
- Background:
  - $K_S \rightarrow 2\pi^0$ + 2 split/accidental clusters (dominant)
  - fake K_L crashes
- Old KLOE analysis [PLB619(2005)61]:

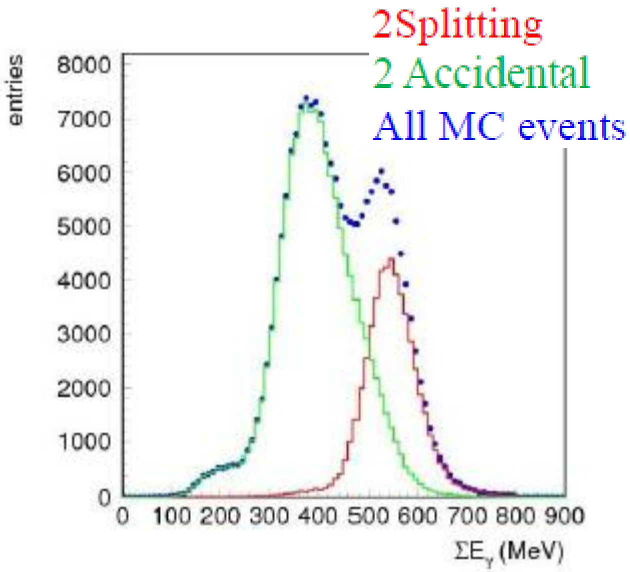
  450 pb^{-1} $\Rightarrow$ $BR(K_S \rightarrow 3\pi^0) < 1.2 \times 10^{-7}$ @ 90% CL



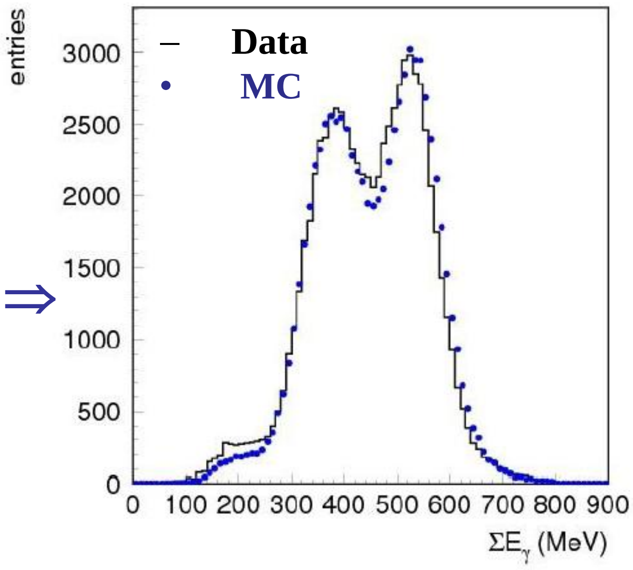
- Update with the whole statistics (2.0 fb^{-1}) :
  - fake K_L crashes rejected by hardening the $\beta^*(K_L)$ cut
  - splitting reduced by requiring a minimum distance between clusters R_{min} > 65 cm



$K_S \rightarrow 3\pi^0$ - direct search



after MC correction for splitting/accidental probabilities from data ⇒



- **Good agreement data-MC**
- **After the analysis cut optimization ⇒ 0.3 bckg events expected from MC in the signal box**
- **Evaluation of systematics in progress**
- **New MC generation needed (× 5 stat.)**

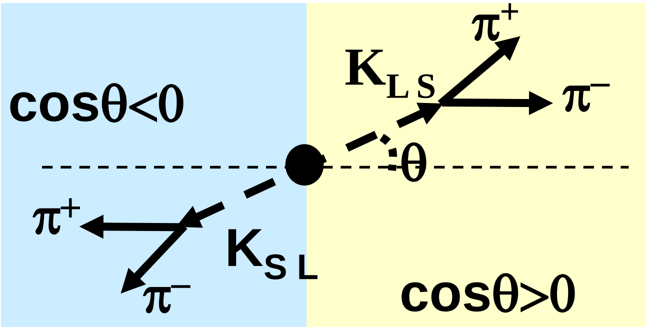
$K_S\, K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$

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

⇒ possibility of violation of CPT and Lorentz symmetry

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

$$\delta(\vec{p}_K, t) = i \sin\varphi_{SW} e^{i\varphi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a})/\Delta m$$



(analysis vs polar angle θ and sidereal time t)

- **With L =1 fb^{-1} (preliminary):**

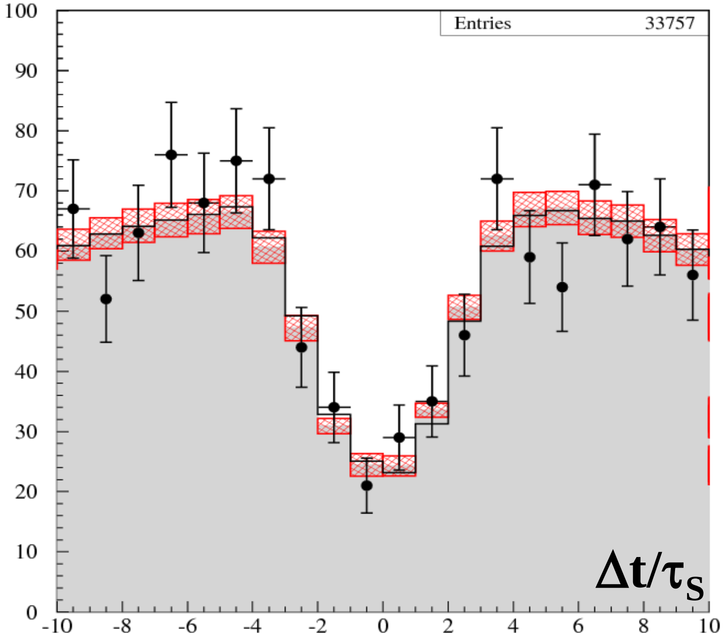
$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18}\ GeV$$

$$\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18}\ GeV$$

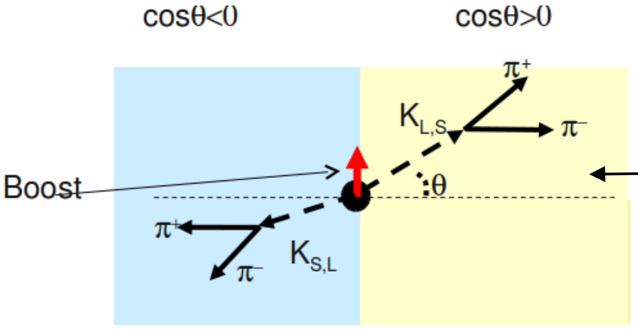
$$\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18}\ GeV$$

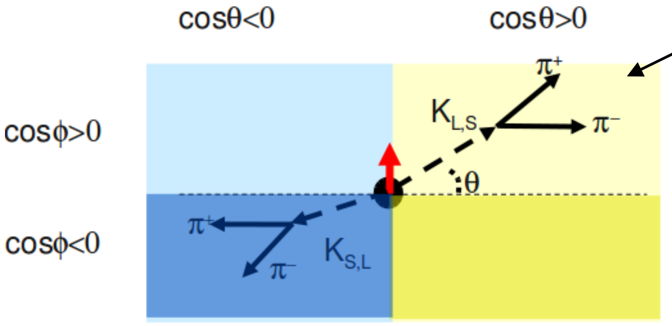
KTeV :Δa_X , Δa_Y < 9.2 × 10^{-22}GeV @ 90% CL

BABAR $\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\ \Delta a^B_Z)$ ~O(10^{-13} GeV)
[PRL 100 (2008) 131802]



Perspectives: new method & refined techniques

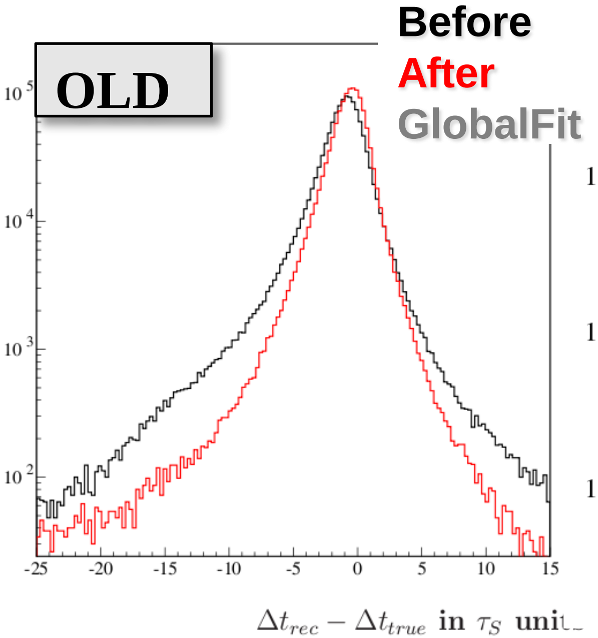


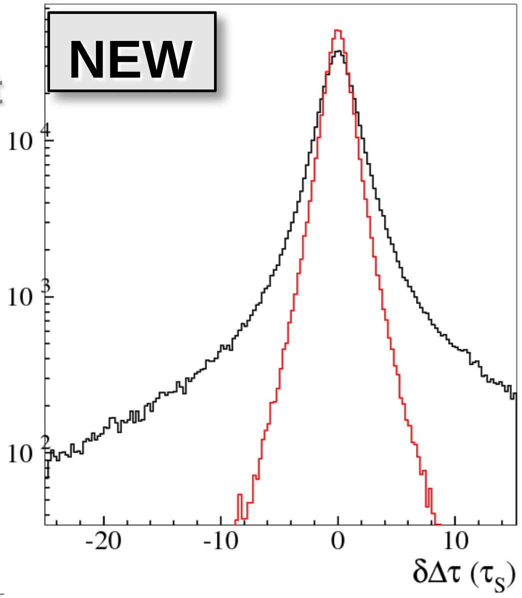


Possible effects due to Δa_0 ($\sim\gamma_K$) are washed out in the old approach: forward ($\cos\theta>0$) - backward ($\cos\theta<0$) analysis.

New method exploiting the quadrant ($\cos\theta>0$ $\cos\phi>0$) -($\cos\theta<0$ $\cos\phi<0$) analysis is under way.

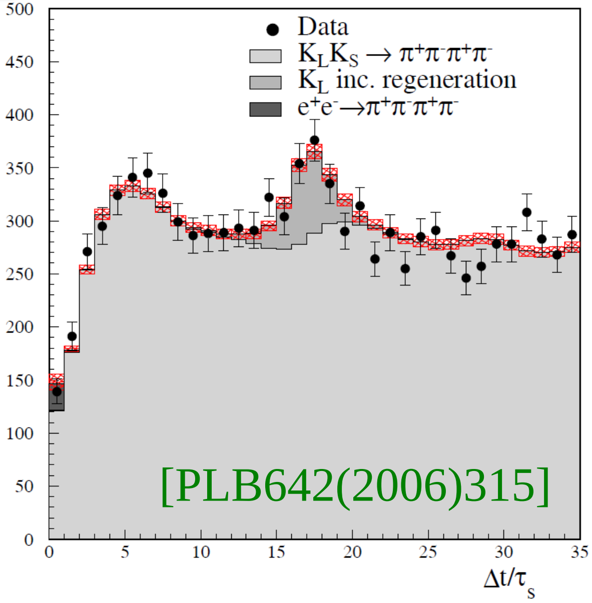
Refining the techniques used to select and to analyse data it is possible to improve the resolution, acquiring more sensitivity on CPTV parameters



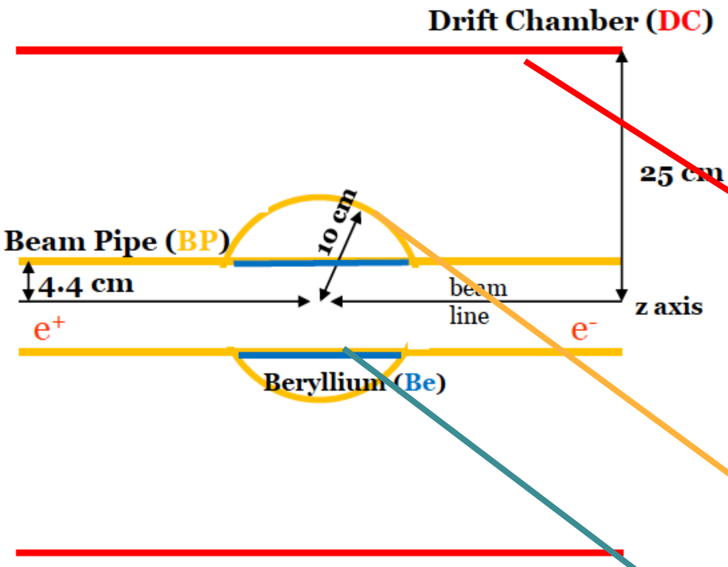


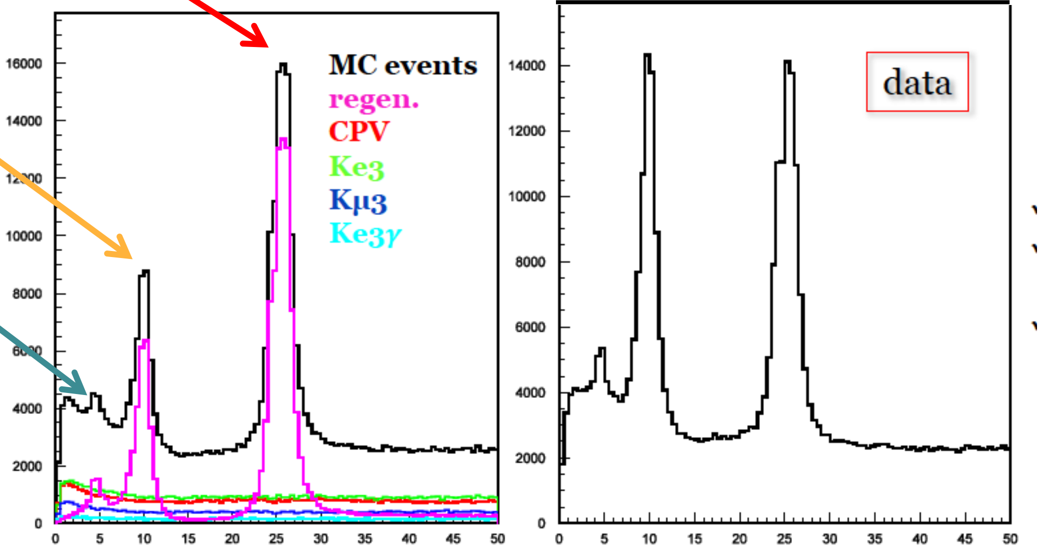
K_S regeneration

- The K_S regeneration in the beam pipe is a source of systematic error for the measurement of $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$



[PLB642(2006)315]





Data sample: 1.7 $fb^{-1} \Rightarrow$ $\pi^+\pi^-\pi^+\pi^-$ events

Hadronic physics

	Progress since last SC meeting	
η decays	$\eta \to \pi^0\pi^0\pi^0$	PLB694(2010)16
	$\eta \to e^+e^-e^+e^-$	final result submitted to PLB
	$\eta \to \pi^+\pi^-\gamma$	in progress
$\gamma\gamma$ physics	$\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0$	in progress
	$\gamma\gamma \to \eta \to \pi^0\pi^0\pi^0$	in progress
	$\gamma\gamma \to \pi^0\pi^0$	in progress
σ_{had}	σ_{had}: Large angle analysis	PLB700(2011)102
	σ_{had}: $\pi\pi\gamma/\mu\mu\gamma$	preliminary result almost ready
Search for Dark Forces	$\phi \to \eta e^+e^-, \eta \to \pi^+\pi^-\pi^0$	preliminary result almost ready
	$\phi \to \eta e^+e^-, \eta \to \gamma\gamma$	in progress
	$e^+e^- \to \mu^+\mu^-$ + missing energy	in progress

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

- **Theoretical predictions: BR ~ 2.4 – 2.6 $\times 10^{-5}$**

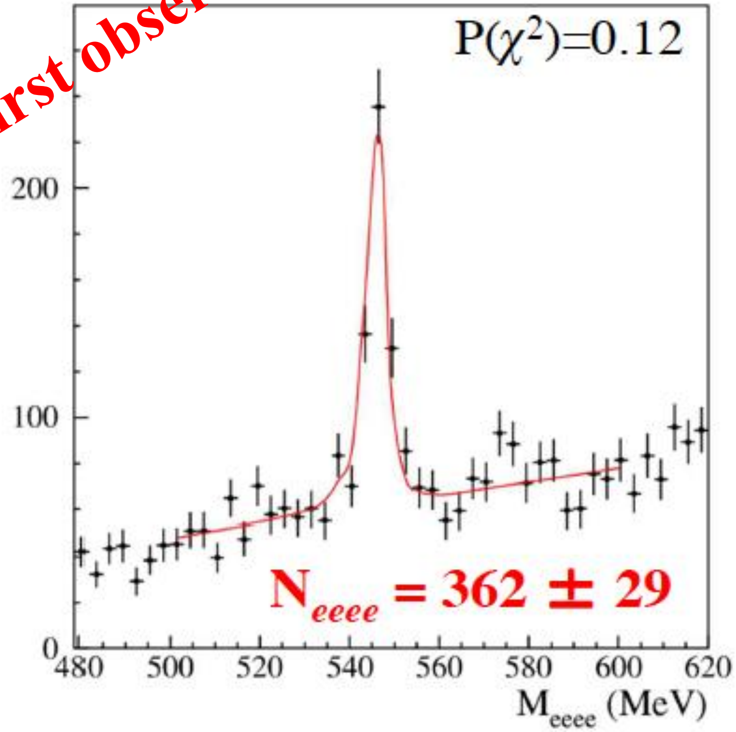
- **BR < 6.9×10^{-5} @90%C.L. (CMD-2, 2001)**
  BR < 9.7×10^{-5} @90%C.L. (WASA, 2008)
  (2 evts, with 1.3 bckg)

- **L = 1.7 fb^{-1} (same data set analyzed for**
  $\eta\to\pi^+\pi^-e^+e^-$ [PLB675(2009)283]**)**

- **MC simulation according to**
  Bijnens and Persson [hep-ph/0106130]

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

First observation



N_{eeee} = 362 ± 29

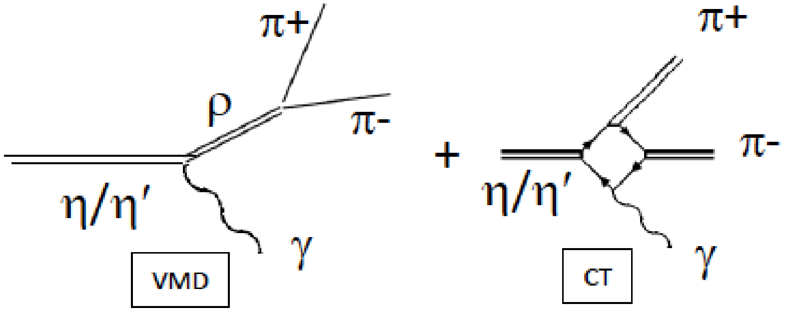
$$BR(\eta \to e^+e^-e^+e^-(\gamma)) = (2.4 \pm 0.2_{stat} \pm 0.1_{syst}) \times 10^{-5}$$

submitted to PLB [arXiv:1105.6067]

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

- $\eta \to \pi^+\pi^-\gamma$: study of the box anomaly vs resonant contribution
- $M_{\pi\pi}$ distribution needed
- Existing measurements not sufficient for unambiguous interpretation

[Benayoun et al., EPJC31, 525 (2003)]



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

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

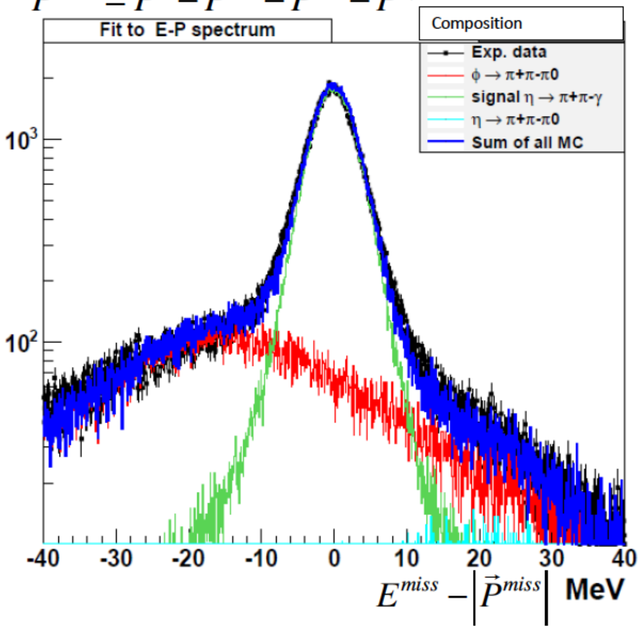
value	events	author	year
0.203 ± 0.008	PDG average		
0.175 ± 0.007 ± 0.006	859	Lopez	2007
0.209 ± 0.004	18 k	Thaler	1973
0.201 ± 0.006	7250	Gormley	1970

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

- $\phi\rightarrow\eta\gamma$, $\eta\rightarrow\pi^+\pi^-\gamma$: L = 558 pb^{-1}
- Normalization to $\eta\rightarrow\pi^+\pi^-\pi^0$
- Main background: $\phi\rightarrow\pi^+\pi^-\pi^0$
- Signal ε = 21 % (from MC)
- Signal extraction from fit to E_{miss}-p_{miss}

  ~ 205 × 10^3 signal events
- Systematics under evaluation

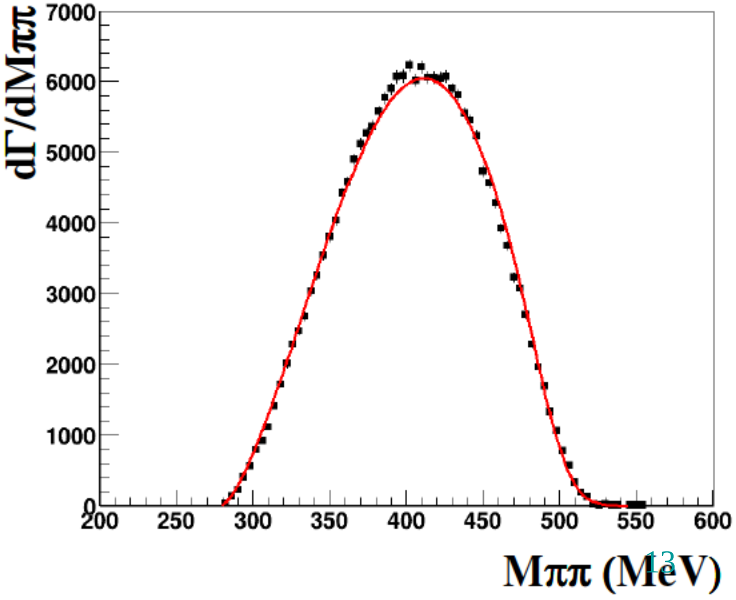
$$P^{miss} = P^{\phi} - P^{\pi^+} - P^{\pi^-} - P^{\gamma_\phi}$$



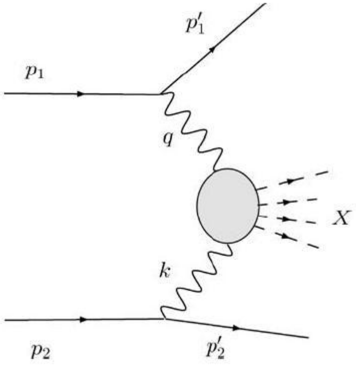
- First attempt to fit the $M_{\pi\pi}$ distribution after bckg subtraction (smearing not taken into account)
- Next: fit with the theoretical function from Benayoun et al., EPJC31, 525 (2003)

- KLOE-2: $\eta'\rightarrow\pi^+\pi^-\gamma$ ⇒10^5 events expected

  ⇒ more sensitive to box anomaly



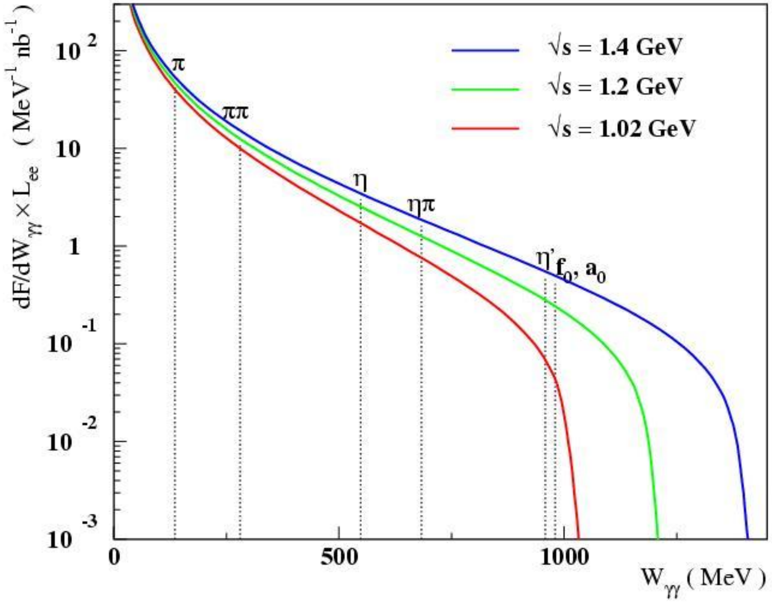
γγ physics



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

$$[C(X) = +1]$$

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



- X = $\pi^0\pi^0$ ⇒ search for σ(600)

- X = π^0, η
  - – $\Gamma(X\to\gamma\gamma)$
  - – Transition form factors $\mathcal{F}_{X\gamma^*\gamma^*}(q_1^2,q_2^2)$ (input for the calculation of the Light-by-Light contribution to $(g-2)_\mu$)

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

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

- **KLOE: 240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV)**
- **Sample: 2 γ + 2 tracks with opposite charge**
- **Main bckg: $e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$**

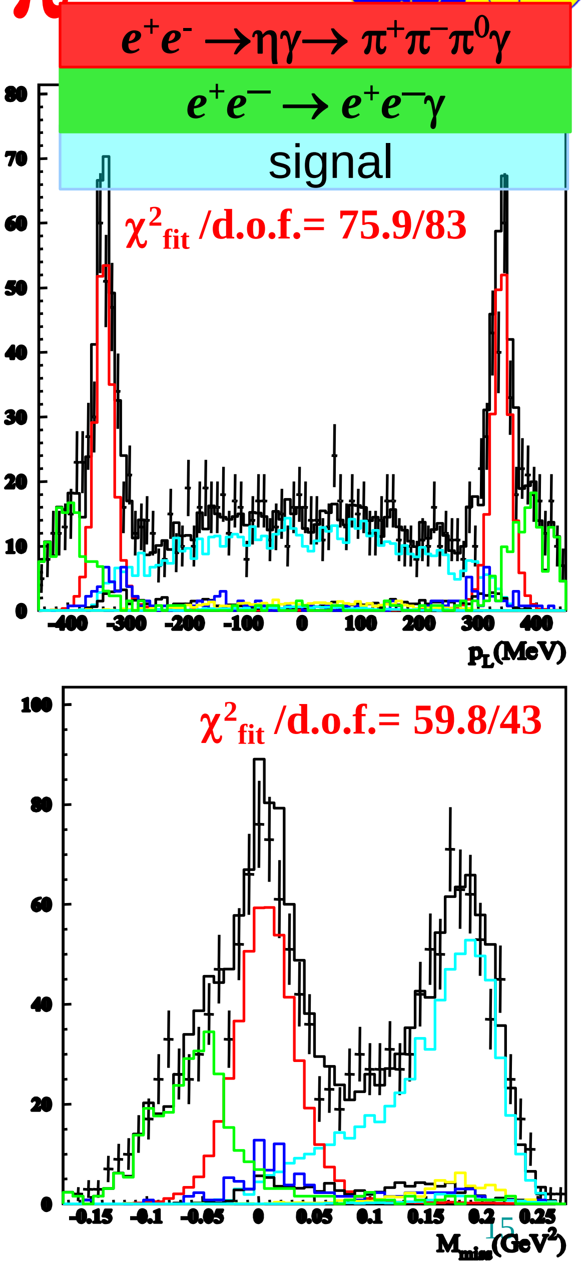
  (with the recoil photon lost in the beam pipe)

		ϵ
Signal	η	0.196
	$\eta\gamma$	9.1×10^{-3}
	$\omega\pi^0$	6.5×10^{-5}
	$\pi^+\pi^-\pi^0$	1.5×10^{-5}
	K^+K^-	1.9×10^{-5}
	K_SK_L	2.6×10^{-5}
	$e^+e^-\gamma$	$\mathcal{O}(10^{-7})$

$\Rightarrow$ **1576 events after the selection**

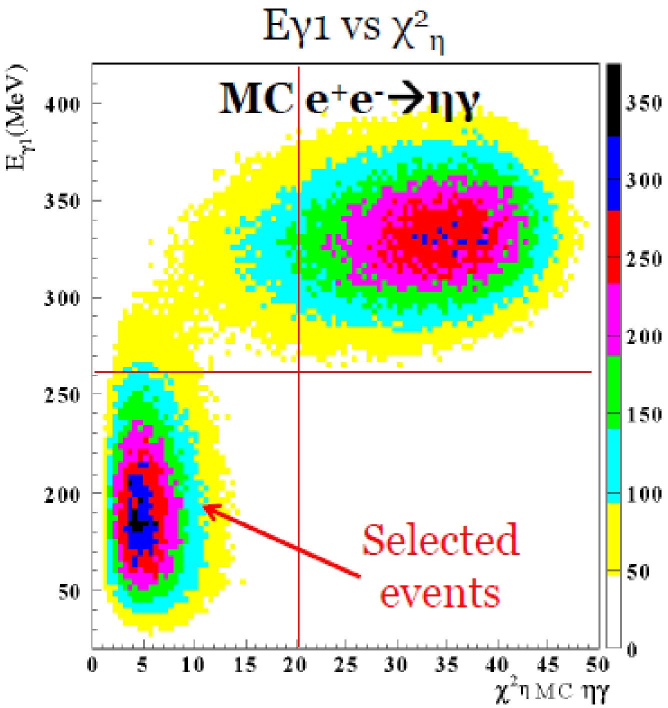
- **Fit to η longitudinal momentum (p_L) and missing mass (M_{miss})**

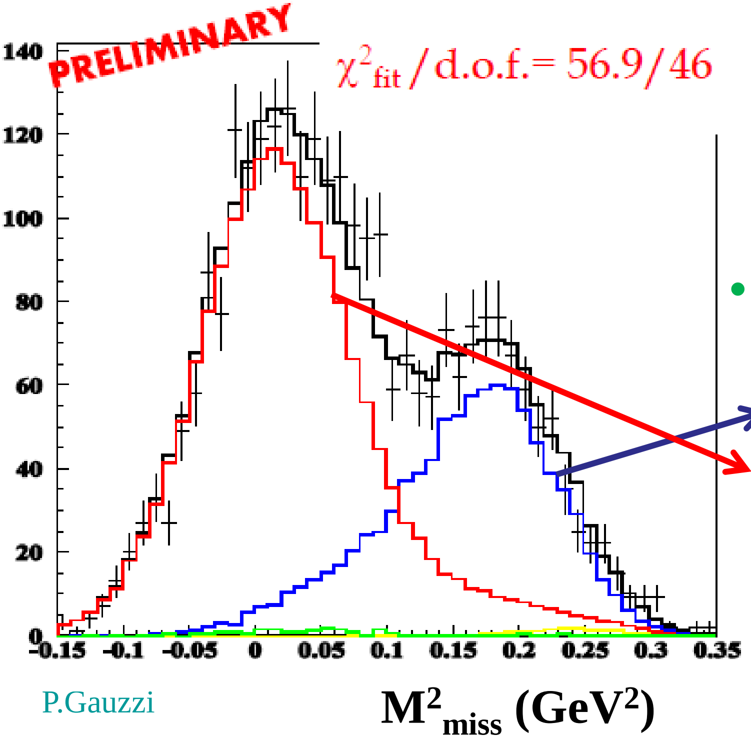
  $\Rightarrow$ **650 signal events from fit**



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

- Events with 6 prompt photons and no tracks
- Background: $e^+e^- \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ (with the recoil photon lost in the beam pipe)
- Cut on the most energetic photon (< 260 MeV) and on the χ^2 of the kinematic fit





- Fit of the missing mass distribution:

⇒ **921 signal events**

⇒ 1760 $e^+e^- \to \eta\gamma$ events

$\sigma(e^+e^- \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$, 1 GeV$)=$
$= (0.285 \pm 0.005_{stat})$ nb

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

  $\Rightarrow \sigma(e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$, 1 GeV) = $(0.198 \pm 0.002_{stat})$ nb

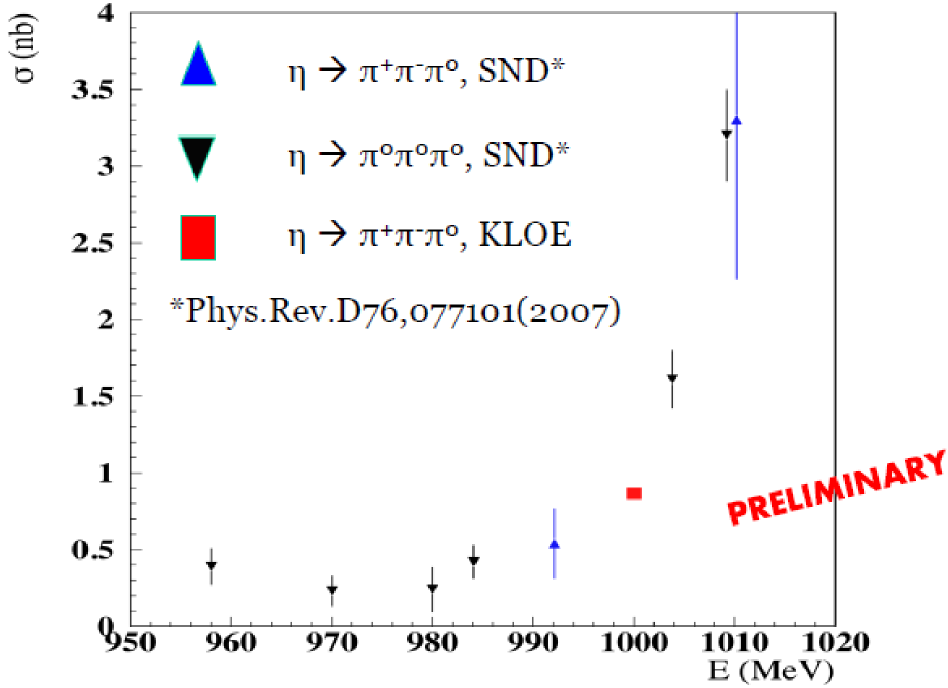
$\sigma(e^+e^- \to \eta\gamma$, 1 GeV)= $(0.866 \pm 0.009_{stat})$ nb

- In agreement with the result from

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

$\sigma(e^+e^- \to \eta\gamma$, 1 GeV)= $(0.875 \pm 0.009_{stat})$ nb

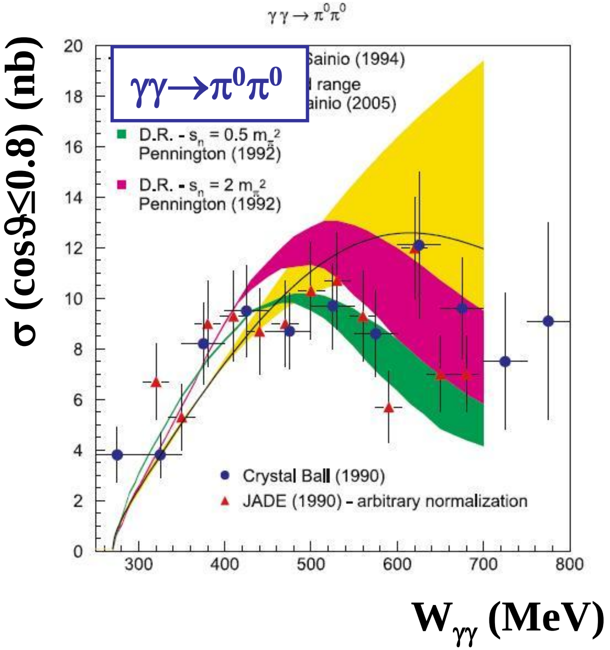
- Systematics under evaluation



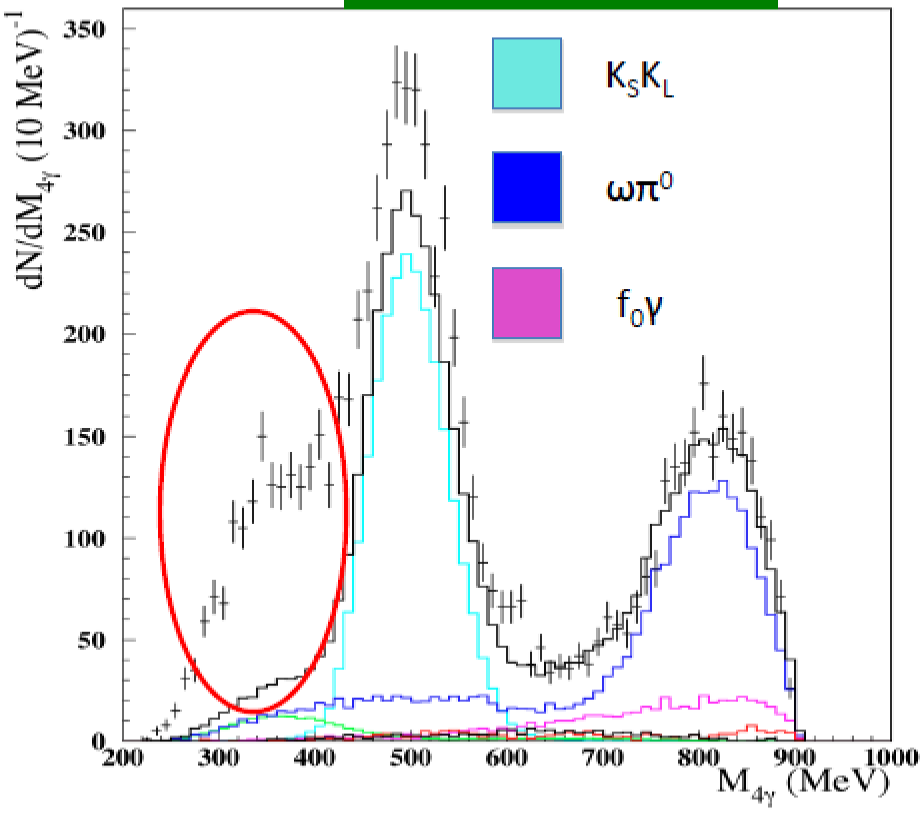
*Phys.Rev.D76,077101(2007)

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

- $e^+e^- \rightarrow e^+e^- \pi^0\pi^0$
- **4 prompt photons**
- **240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV)**
- **Excess of events with respect to background in the low mass region**
- **$\gamma\gamma \rightarrow \pi^0\pi^0$ 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

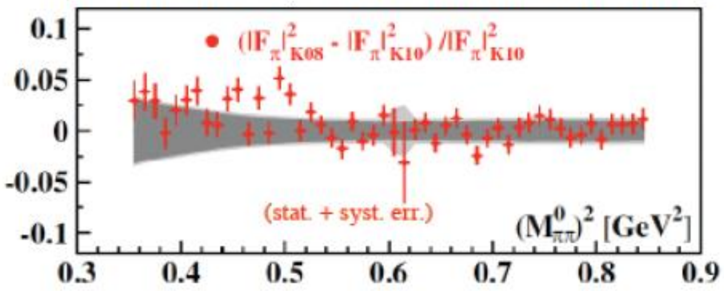
⇒ 2% statistical accuracy using the same energy bin as Crystal Ball (~20% error)

$\sigma(e^+e^-\rightarrow\pi^+\pi^-)$ with ISR

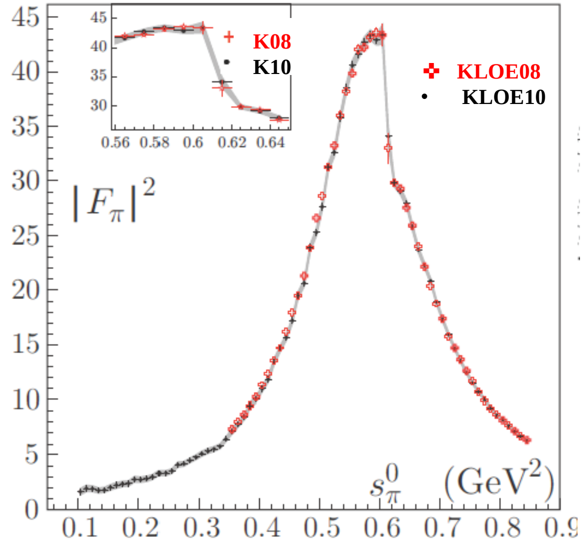
- **Large Angle analysis published: PLB700(2011)102**

$$a_\mu^{\pi\pi}(0.1\text{— }0.85\ \mathrm{GeV}^2)=(478.5 \pm 2.0_{stat} \pm 4.8_{sys} \pm 2.9_{theo})\times 10^{-10}$$

KLOE08-KLOE10 fractional difference



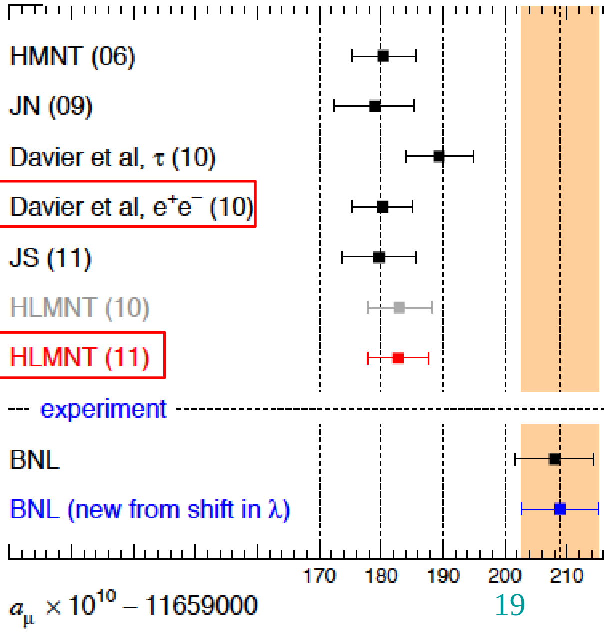
(Grey band = L.A. error)



- **Combined Small Angle (KLOE08) and Large Angle (KLOE10) :**

$$a_\mu^{\pi\pi}(0.1\text{— }0.95\ \mathrm{GeV}^2)=(488.6 \pm 5.0) \times 10^{-10}$$

include KLOE08 and KLOE10 results



3.3 σ discrepancy a_μ^{SM} - a_μ^{exp} confirmed

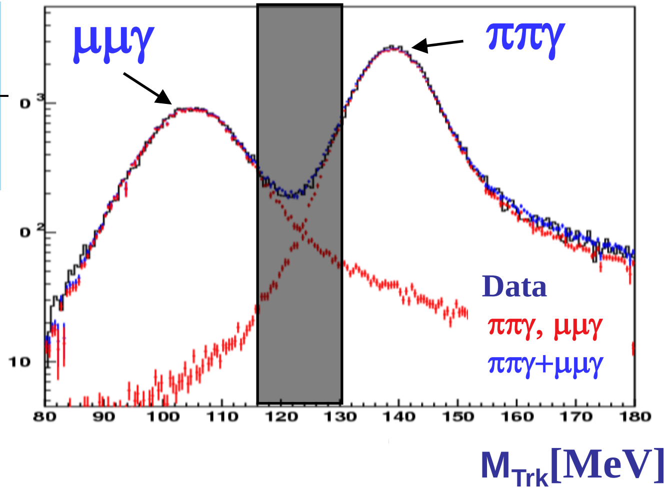
[Hagiwara et al., arXiv:1105.3149]

Pion FF 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 $\sqrt{s} = M_\phi$

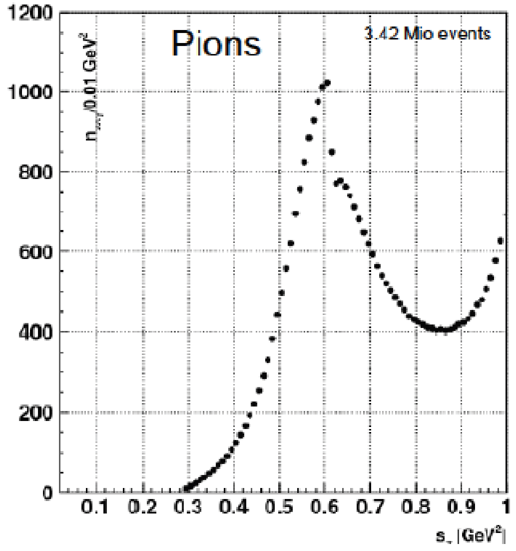
$$\underbrace{|F_\pi(s')|^2 \cdot \left(1+\underset{\substack{\uparrow \\ \text{Corr. due to FSR}}}{\eta}(s')\right)}_{\hookrightarrow\ a_\mu \text{ disp. integral}} = \frac{4\left(1+2m_\mu^2/s'\right)\beta_\mu}{\beta_\pi^3} \cdot \frac{\left(d\sigma_{\pi\pi\gamma}/ds'\right)^{ISR+FSR}}{\left(d\sigma_{\mu\mu\gamma}/ds'\right)^{ISR}}$$

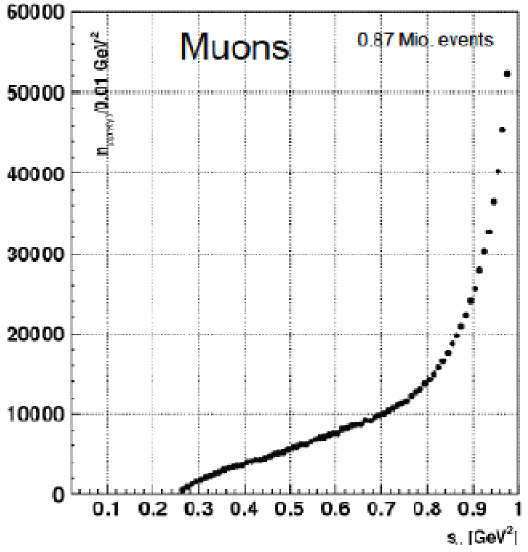
„Observed“ cross sections



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

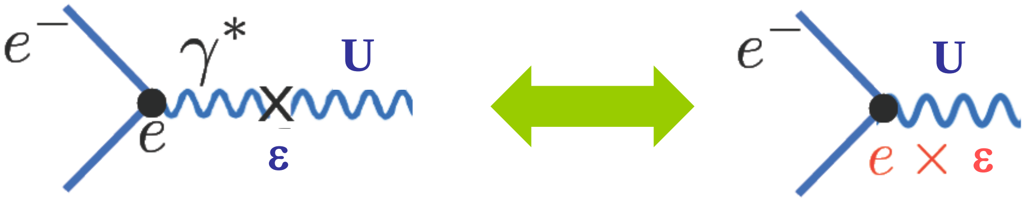
- Preliminary result will be released soon
  ⇒ we plan to show it
  at HEP EPS 2011 in Grenoble





Search for dark forces

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

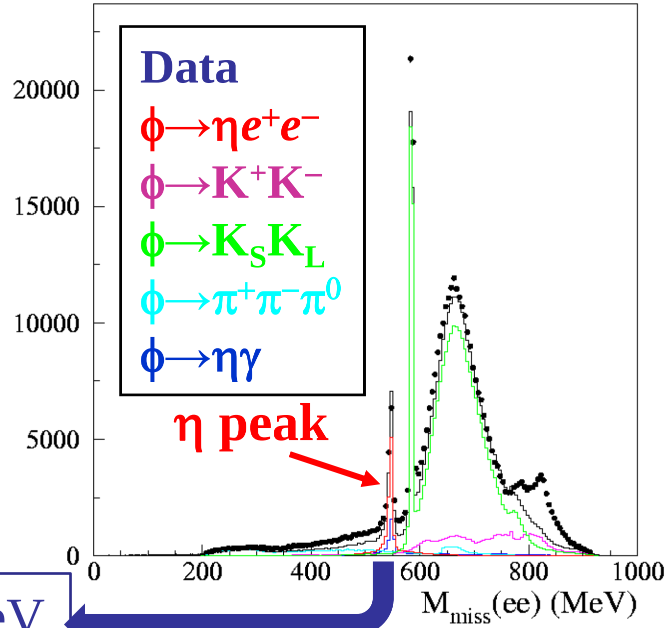


[Arkani-Hamed et al. PRLD79(2009), 015014
Essig et al., PRD80(2009)015003]

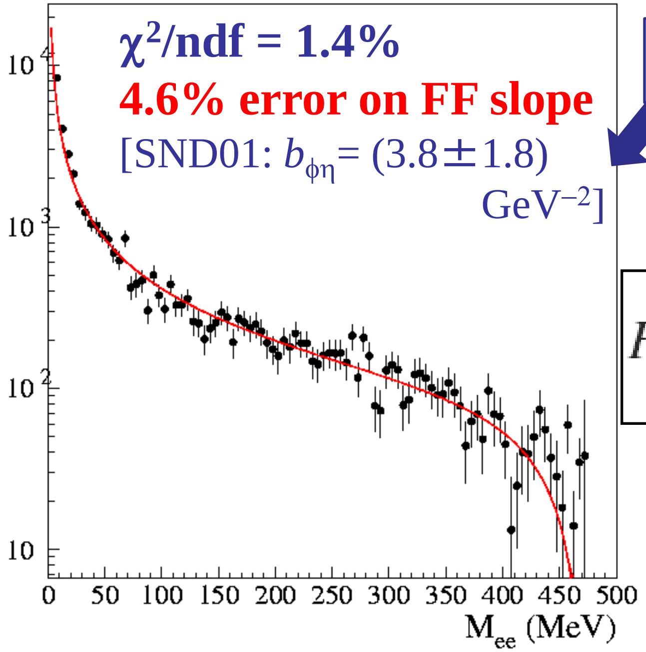
- If the mixing parameter $\varepsilon \sim 10^{-3} - 10^{-4}$ ⇒ could be observable at KLOE
- Possible signatures:
  - $e^+e^- \to U\gamma \to \ell^+\ell^-\gamma \Rightarrow e^+e^- \to \mu^+\mu^-\gamma$ under evaluation
  - rare meson decays, $\phi \to \eta U$, $U \to \ell^+\ell^-$; $\phi \to \eta e^+e^-$ $\eta \to \pi^+\pi^-\pi^0$ / $\eta \to \gamma\gamma$
  - if there is a dark higgs particle (h') , with $m_{h'} < M_U$
    ⇒ higgs'-strahlung $e^+e^- \to U^* \to Uh'$, with $U \to \ell^+\ell^-$ (two leptons + missing energy, h' undetected)

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

- **Analysis performed on 739 pb^{-1}**
- **4 tracks in a cylinder around IP + 2 prompt γ**
- **Main bckg: Dalitz decays $\phi \rightarrow \eta e^+e^-$**
- **Best $\pi^+\pi^-\gamma\gamma$ match to the η mass**
- **~7000 $\phi \rightarrow \eta e^+e^-$ with $\eta \rightarrow \pi^+\pi^-\pi^0$ candidates**
- **Very small contamination from $\phi \rightarrow \eta\gamma$ events**



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



χ^2/ndf = 1.4%

4.6% error on FF slope

[SND01: $b_{\phi\eta}$= (3.8±1.8) GeV^{-2}]

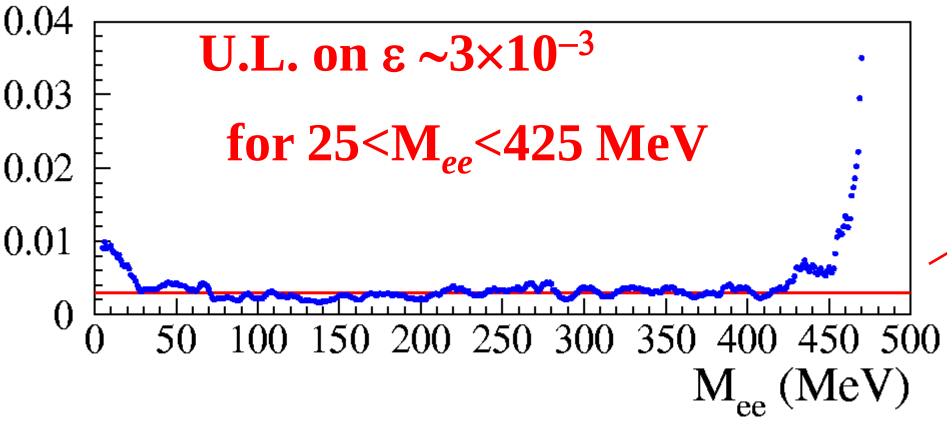
- **Extract form factor slope from fit to M_{ee}**

$$\boxed{F(q^2) = \frac{1}{1 - q^2/\Lambda^2}} \left\{ \begin{array}{l} b = dF/dq^2|_{q^2=0} \\ b_{\phi\eta} = \Lambda_{\phi\eta}^{-2} \approx 1/m_\phi^2 \approx 1 \text{ GeV}^{-2} \end{array} \right.$$

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

Exclusion plot for ε

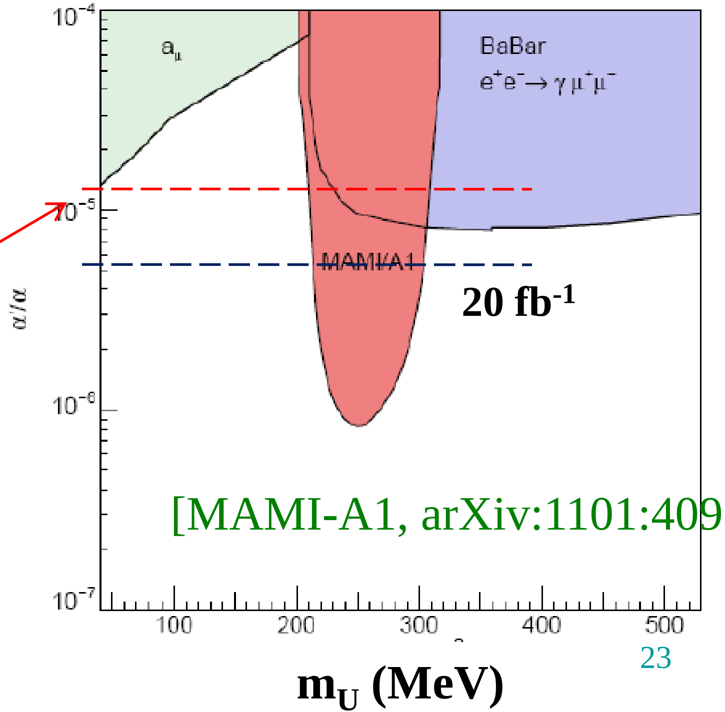
- $\phi \to \eta U$ **MC sample** [Reece-Wang, JHEP0907:051 (2009)] **divided in sub-samples of 1 MeV in M_{ee}(true)**
- **Expected background ($\phi \to \eta e^+e^-$) shape from our fit to M_{ee} distribution repeated each time excluding the 5 bins around the selected one**
- **For each M_{ee}(true) bin, signal hypothesis excluded @ 95% C.L. using the CL_S method**



U.L. on ε ~3×10^{-3}

for $25<M_{ee}<425$ MeV

$\alpha'/\alpha = \varepsilon^2$



20 fb^{-1}

[MAMI-A1, arXiv:1101:4091]

- **Can be combined with $\phi \to \eta U$ with $\eta \to \gamma\gamma$**

Conclusions

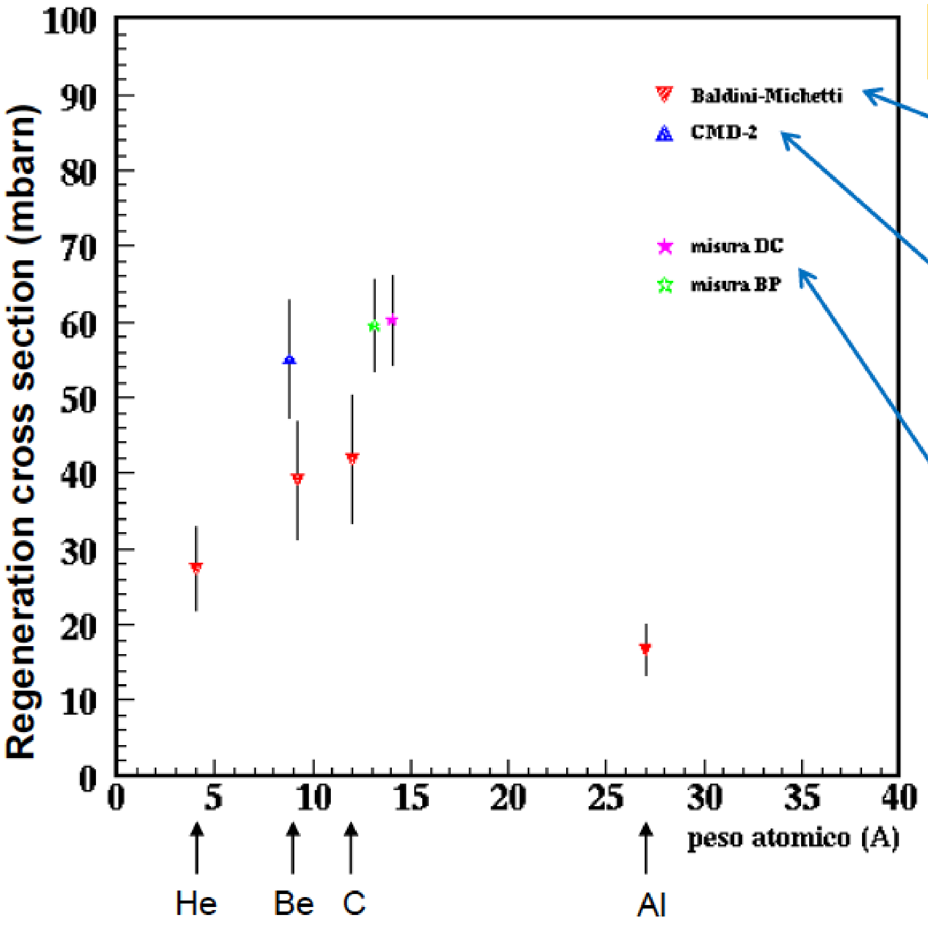
- **Achievements in 2010 – first half of 2011:**
  - **3 published papers**
  - **1 paper submitted to PLB**
  - **4 analyses in well advanced stage (preliminary results almost ready)**
  - **many analyses in progress**

Planned analyses	
K_L lifetime	**preliminary (2009)**
FF from $K_{\ell 3}$	**update**
$K^{\pm}$ lifetime	**update**
$K^{\pm}_{\ell 3}$	**update**
$\eta \to \pi^+\pi^-\pi^0$	**update with the whole statistics starting /PHD student from Uppsala**
$\eta' \to \eta\pi\pi$	**update with the whole statistics starting / Post doc from Uppsala**
$\eta \to \pi^0\gamma\gamma$	**preliminary (2008) -- no data available now**

Spares

K_S regeneration

- **Experimental and theoretical cross-section**



K_L momentum at KLOE: 110MeV/c

theoretical evaluations by R. Baldini and A. Michetti ('96):

$$\sigma_{\mathrm{reg}}^{\mathrm{Be}} = 40.7 \pm 1.1 \text{ mbarn}$$

Novosibirsk CMD-2 result ('99) - - only existing measurement at this momentum value:

$$\sigma_{\mathrm{reg}}^{\mathrm{Be}} = 55.1 \pm 7.7 \text{ mbarn}$$

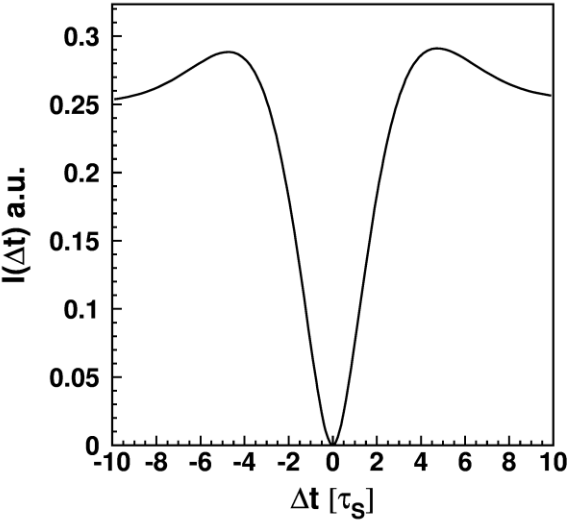
S. Bocchetta analysis ('06):

$$\sigma_{\mathrm{reg}}^{\mathrm{DC}} = 60.2 \pm 0.8^{stat} \pm 6.0^{syst} \text{ mb}$$

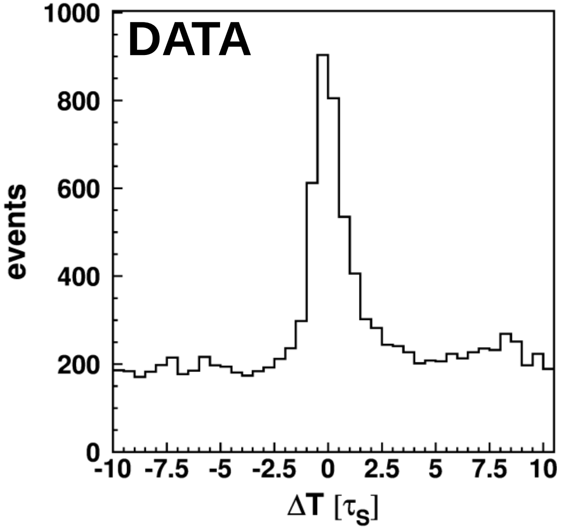
$$\sigma_{\mathrm{reg}}^{\mathrm{BP}} = 59.6 \pm 0.6^{stat} \pm 6.0^{syst} \text{ mb}$$

$$\sigma_{\mathrm{reg}}^{\mathrm{Be}} = \ldots ? \leftarrow$$ still missing for KLOE

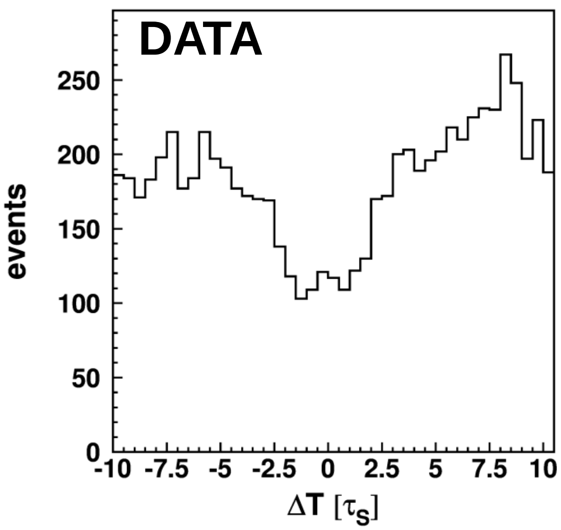
$K_S\ K_L \rightarrow \pi^+\pi^-\pi^0\pi^0$



- The distribution of the decay time difference between the kaons is sensitive to both Re(ε′/ε) and Im(ε′/ε)
- L = 1.45 fb^{-1}; 1 charged vertex + 4 neutral clusters
- **Bckg: $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^+\pi^-\pi^0\pi^0$**
- First look to the data
- **Work in progress to refine analysis technique and improve the vertex resolution**



Before $\omega\pi^0$ rejection

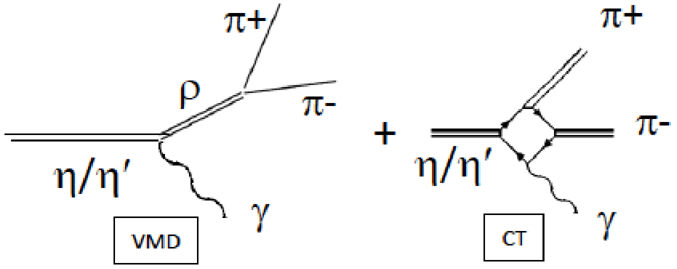


After $\omega\pi^0$ rejection

Box anomaly

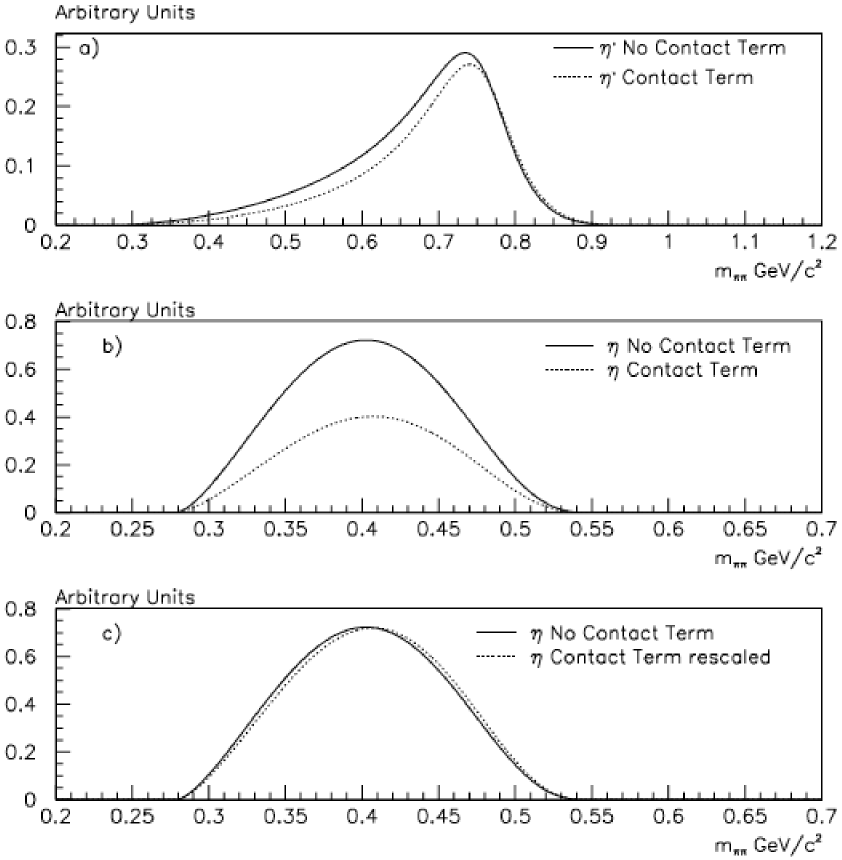
- **HLS model:**

[Benayoun et al., EPJC31, 525 (2003)]



  - **$\eta'\to\pi^+\pi^-\gamma$: shape is distorted by the contact term**

  - **$\eta\to\pi^+\pi^-\gamma$: $M_{\pi\pi}$ shape slightly sensitive to contact term; effect on absolute value**



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

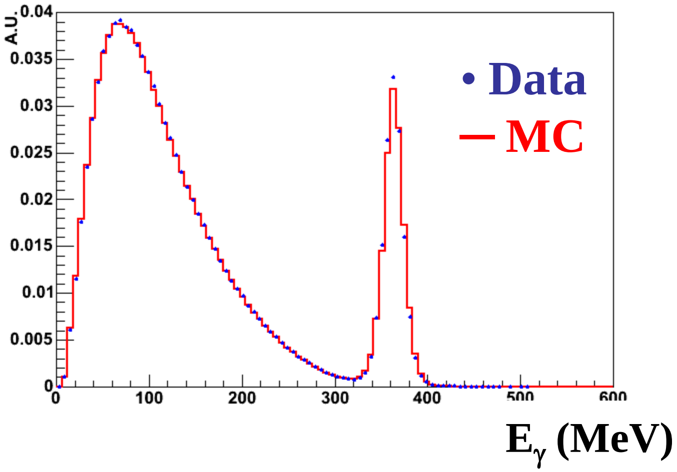
- $\eta\rightarrow\pi\pi\pi$ decay $\Rightarrow$ Isospin violation $L_I = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$

- 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)



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

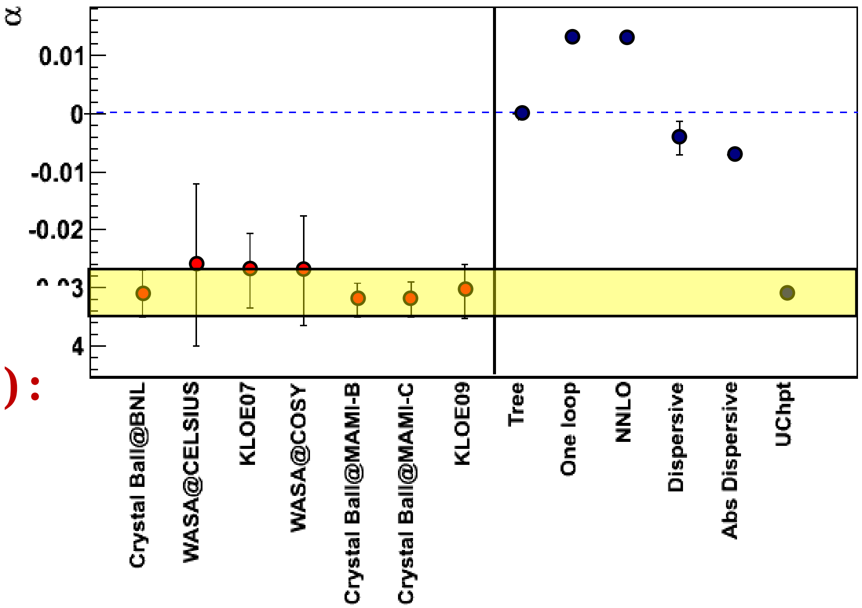
$$\boxed{\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}}$$

$\Rightarrow$ PLB694(2010)16

Strong interactions mix the two amplitudes $A(\eta\rightarrow\pi^+\pi^-\pi^0)$ and $A(\eta\rightarrow\pi^0\pi^0\pi^0)$: from the Dalitz plot of $\eta\rightarrow\pi^+\pi^-\pi^0$

$\Rightarrow$ $\alpha = -0.038 \pm 0.003^{+0.012}_{-0.008}$

[JHEP0805(2008)006]



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

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

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

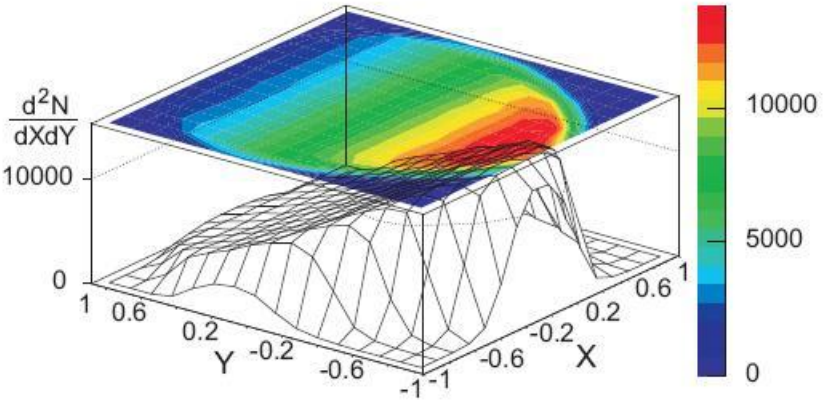
$\phi\to\eta\gamma$; $\eta\to\pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$ ($E_{\gamma rec}$ = 363 MeV)
450 $pb^{-1} \Rightarrow 1.34 \times 10^6$ events in the Dalitz plot

$$X = \sqrt{3}\,\frac{E_+ - E_-}{Q}\ ;\ Y = 3\,\frac{E_0 - m_0}{Q}$$

$$(Q = m_\eta - 2m_{\pi^\pm} - m_{\pi^0})$$

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

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



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

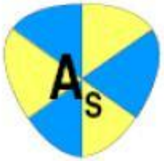
[JHEP0805(2008)006]

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

- Asymmetries ⇔ C violation

Left-right asymmetry(*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 $\Delta I = 1$ $A_S = (8 \pm 10^{+8}_{-13}) \times 10^{-4}$

PDG'06 ⇒

$$A_{LR} = (9 \pm 17) \times 10^{-4}$$

$$A_Q = (-17 \pm 17) \times 10^{-4}$$

$$A_S = (18 \pm 16) \times 10^{-4}$$

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

[JHEP0805(2008)006]

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

- **χPT: $O(p^2) \propto Q = 0$;**

  $O(p^4)$ @ tree level = 0; $O(p^4)$ @ 1 loop suppressed by G-parity

  $\Rightarrow O(p^6)$ test
- **Recent measurements ⇒ Br($\eta\to\pi^0\gamma\gamma$): $(7.2\pm1.4)\times10^{-4}$ GAMS (1984)**

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

  $(22.5 \pm 4.6 \pm 1.7)\times10^{-5}$ Crystal Ball@MAMI-B [arXiv:0910.1331]

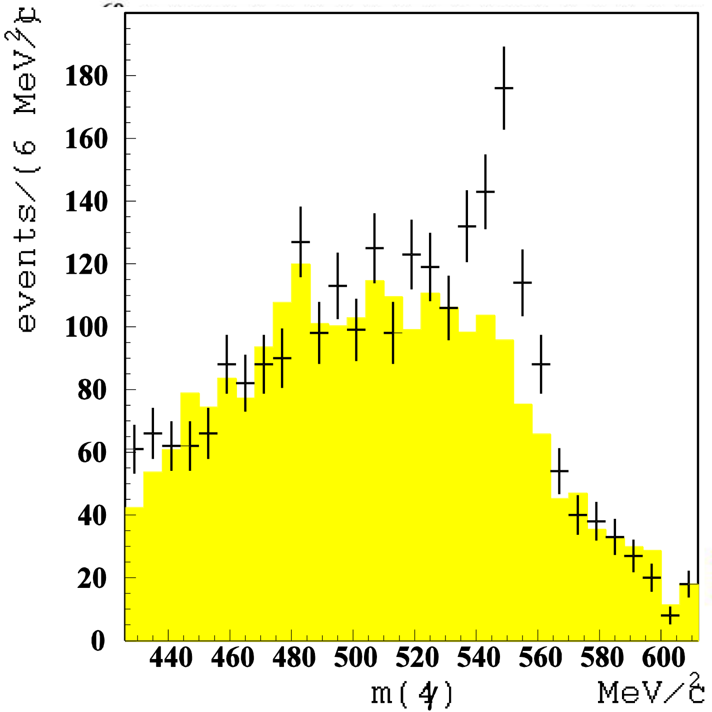
  $(22.1 \pm 2.4 \pm 4.7)\times10^{-5}$ Crystal Ball@AGS [PRC78(2008)015206]
- **KLOE ⇒ $\phi\to\eta\gamma$; $\eta\to\pi^0\gamma\gamma$**
- **Backg.: (1) 5γ processes: $\phi\to a_0\gamma$, $f_0\gamma$;**

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

  (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 ± 2.7 ± 1.4) × 10^{-5}

- **1.5 fb^{-1} ⇒**

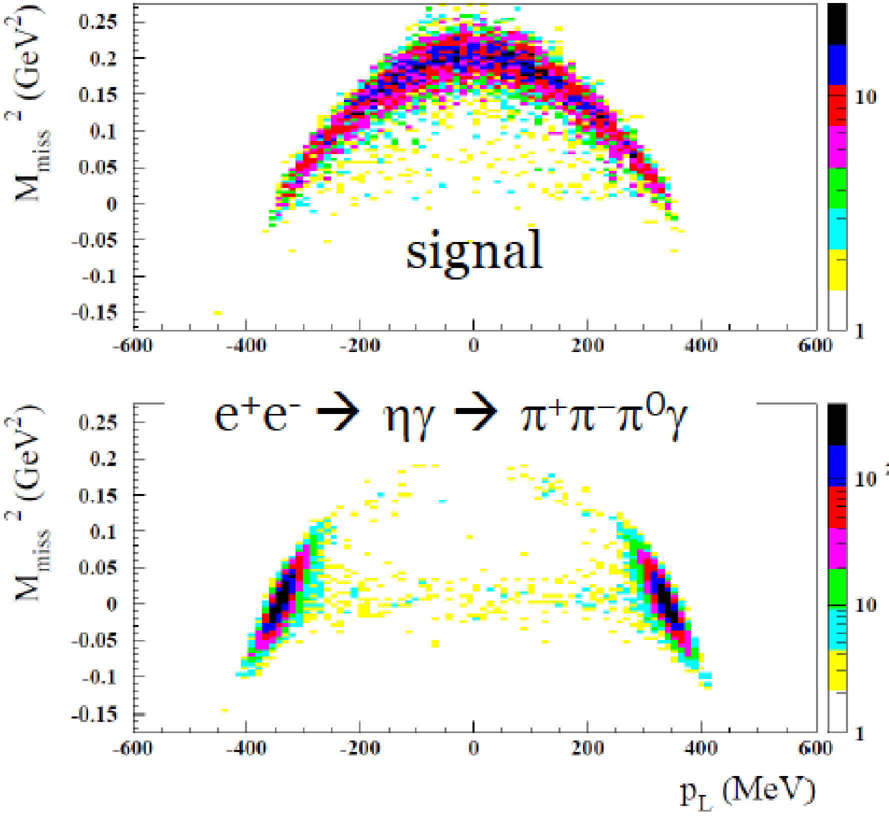


$\gamma\gamma\rightarrow\eta,\ \ \eta\rightarrow\pi^+\pi^-\pi^0$

- **Analysis based on M^2_{miss}, p_L, p_T**

$$M^2_{miss} \approx s + M^2_\eta - 2E_T\sqrt{s} - \frac{p_L^2}{E_T}\sqrt{s}$$

$$E_T = \sqrt{p_T^2 + M_\eta^2} \approx M_\eta$$



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

2 photons + 2 tracks with opposite charge

- **$\gamma\gamma$ pairing**

$$\chi^2_{pair} = \left(\frac{M_{\gamma\gamma} - M_{\pi^0}}{\sigma(M_{\gamma\gamma})}\right)^2$$

$$\frac{\sigma(M_{\gamma\gamma})}{M_{\gamma\gamma}} = \frac{1}{2}\left(\frac{\sigma_{E_i}}{E_i} \oplus \frac{\sigma_{E_j}}{E_j}\right)$$

$$M^2_{\gamma\gamma} = 2E_iE_j(1-\cos\theta_{ij})$$

- **Charged Pion ID**
- **Kinematic fit: cut on χ^2_η**

$$\chi^2_\eta = \sum\frac{(P_i - P_i^{meas})^2}{\sigma_i^2} + \sum\lambda_j^k C_j(P_1^k \ldots P_N^k)$$

$\mathbf{m^2_{\gamma\gamma} = m^2_{\pi 0}}$

$\mathbf{m^2_{\pi+\pi-\gamma\gamma} = m^2_\eta}$

$\mathbf{t_\gamma - |\underline{r}_\gamma| / c = 0}$ **for 2γ**

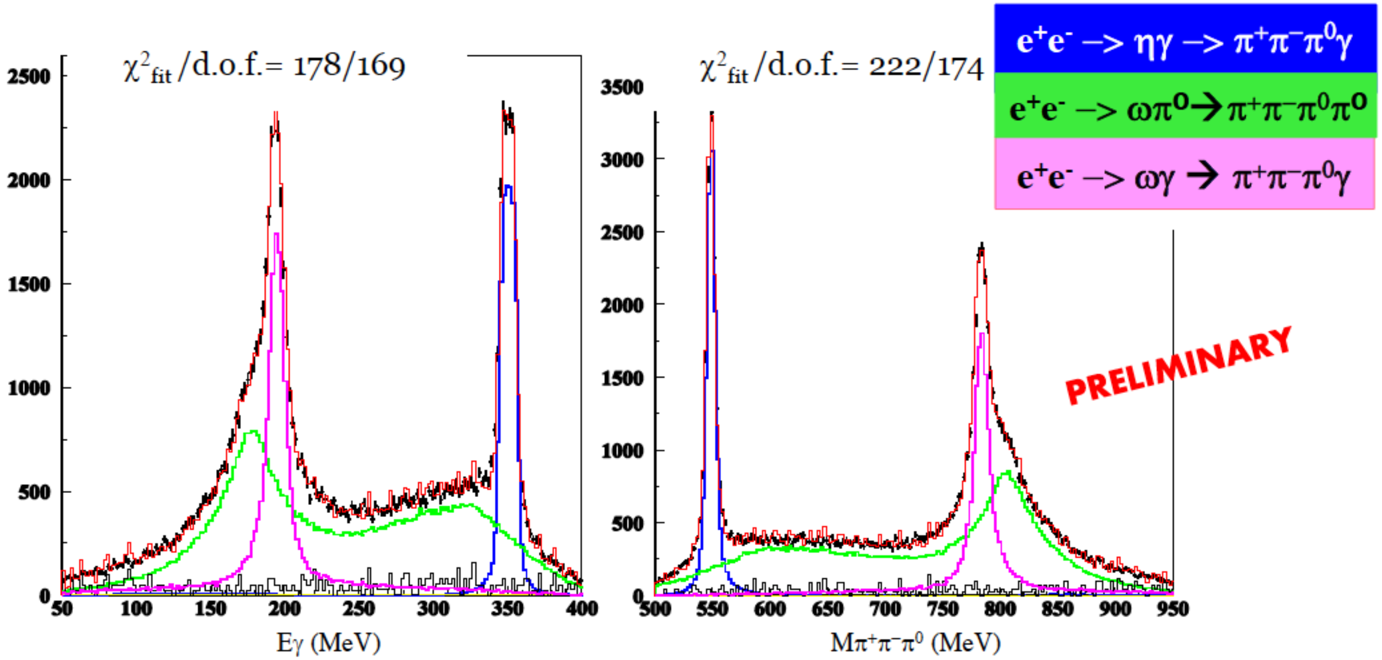
5 variables × 2γ

4 constraints

$\sigma(e^+e^- \to \eta\gamma)$ @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 kaon decays



$\sigma(e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$, 1 GeV) = $(0.198 \pm 0.002_{stat})$ nb

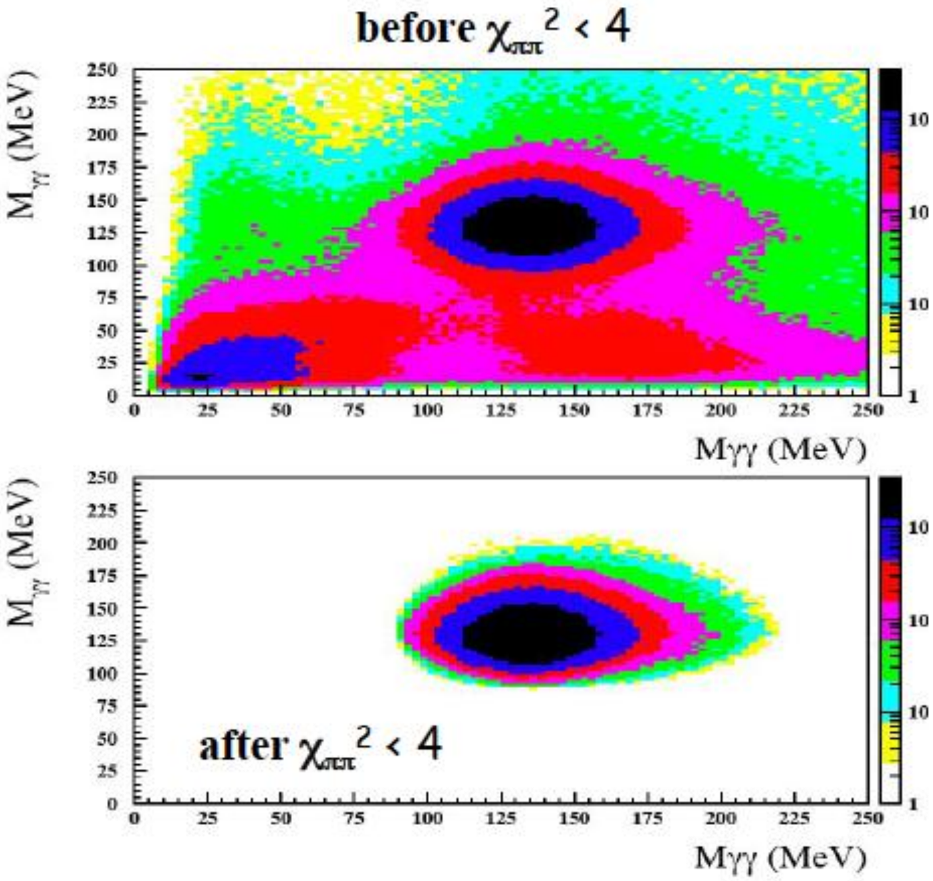
$\gamma\gamma \to \pi^0\pi^0$

- *$e^+e^- \to e^+e^- \pi^0\pi^0$*
- **4 prompt photons**
- **240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV)**
- **Best photon pairing to match two π^0's**

$$\chi^2_{pair} = \left(\frac{M_{ij} - m_{\pi 0}}{\sigma(E_i, E_j)}\right)^2 + \left(\frac{M_{lk} - m_{\pi 0}}{\sigma(E_l, E_k)}\right)^2$$

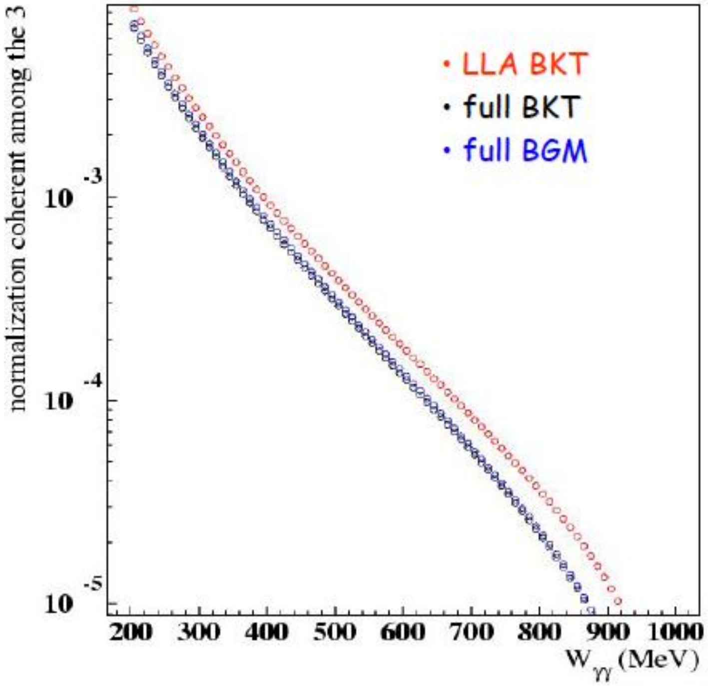
$$\frac{\sigma(E_i, E_j)}{M_{ij}} = \frac{1}{2}\left(\frac{\sigma_{E_i}}{E_i} \oplus \frac{\sigma_{E_j}}{E_j}\right)$$

$$M^2_{ij} = 2E_iE_j(1 - \cos\theta_{ij})$$

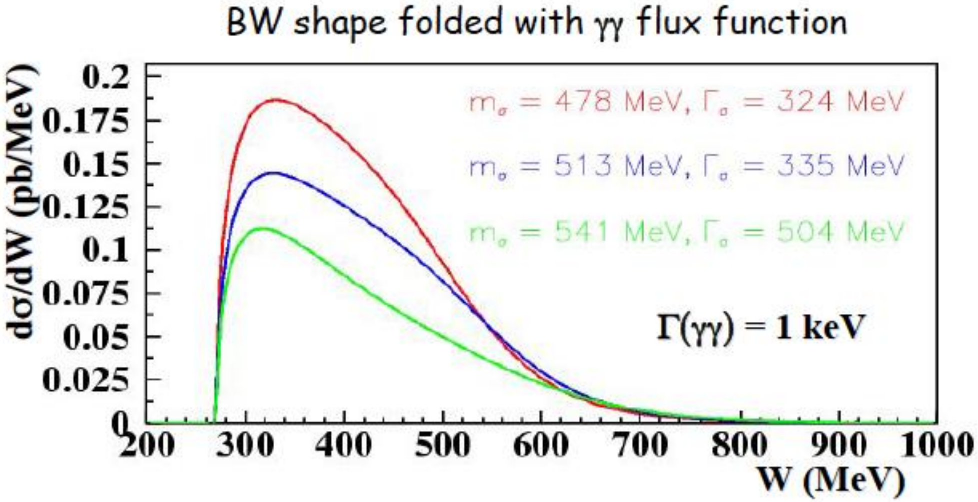


$\gamma\gamma\rightarrow\pi^0\pi^0$

Flux function



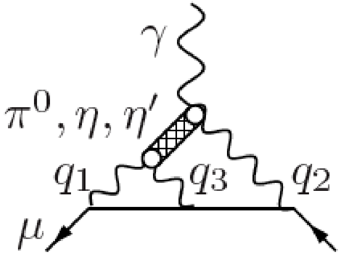
$M_{\pi\pi}$ shape

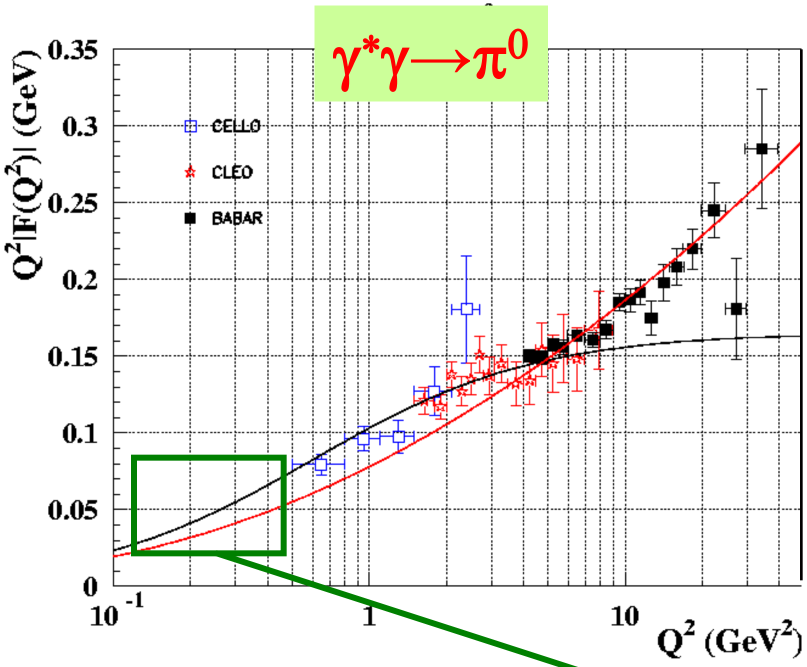


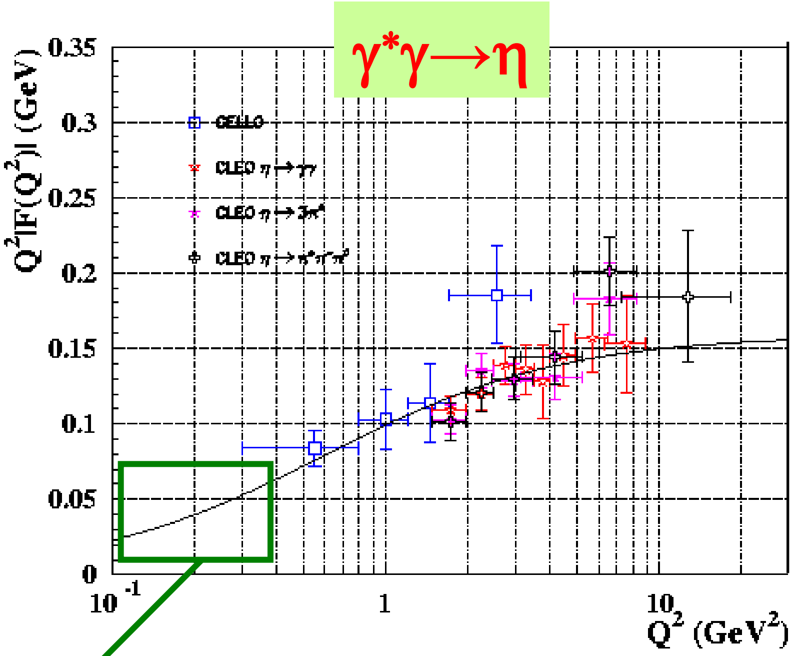
- LLA BKT = Brodsky-Kinoshita-Terazawa in the Leading Logarithm Approximation
- full BKT = Brodsky-Kinoshita-Terazawa with no approximation
- full BGM = Bonneau-Gourdin-Martin (stessa funzione usata da Crystal Ball)

γγ→single pseudoscalar

- **Measurement of $\Gamma(P\to\gamma\gamma)$**
- **Transition form factors $\mathcal{F}_{P\gamma^*\gamma^*}(q_1^2,q_2^2)$:**
  - **input for the calculation of the Light-by-Light contribution to g-2 of the muon**







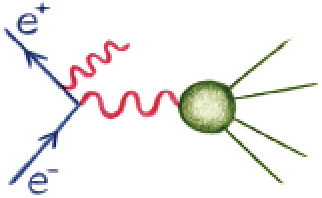
KLOE-2

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

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



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

- Two 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)

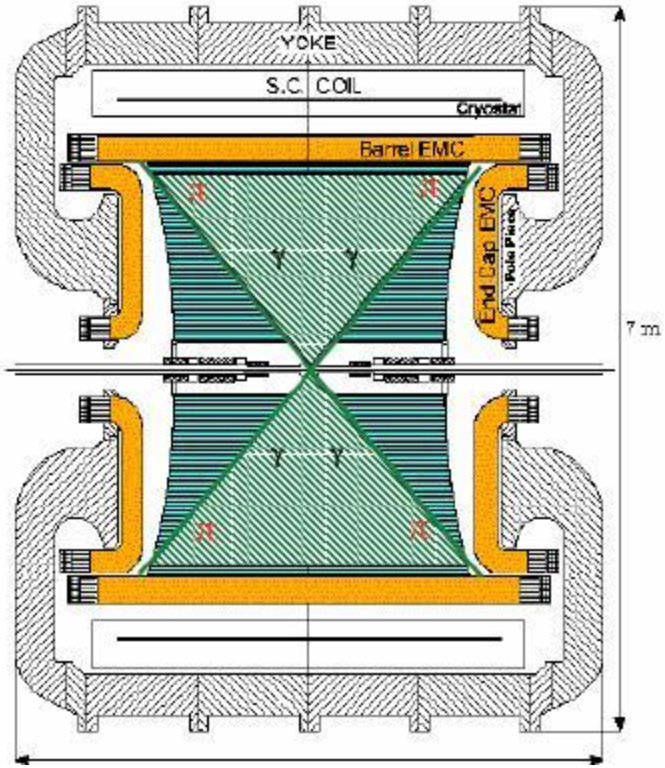
[PLB700(2011)102]

L.A. analysis

- 2 pions at large angle ($\vartheta>50°$)
- Photon detected at large angle ($\vartheta>50°$)
- Kinematics closed
- 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 data collected at $\sqrt{s}$ = 1 GeV, below the ϕ peak:

233 pb^{-1} from 2006 data-taking

Result on L.A. analysis

- **Good agreement between S.A. (KLOE08) and L.A. (KLOE09) analyses**

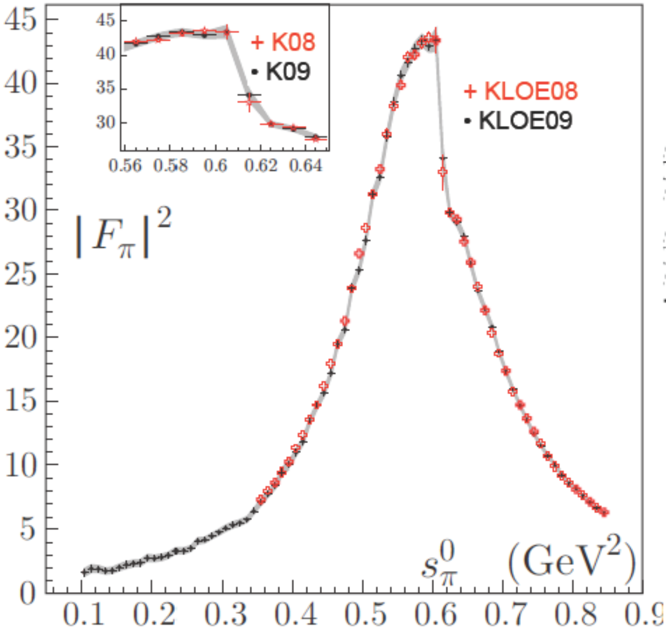
$$a_\mu^{\pi\pi}(0.1\text{─}\ 0.85\ \mathrm{GeV}^2)=(478.5 \pm 2.0_{stat} \pm 4.8_{sys} \pm 2.9_{theo}) \times 10^{-10}$$

- **Agreement with CMD-2 and SND, some difference with BaBar**
- **3.2 σ discrepancy a_μ^{SM} - a_μ^{exp} confirmed**
- **In progress: measurement of the $\sigma(e^+e^-\to\pi^+\pi^-)$ from the ratio $\pi^+\pi^-\gamma$ / $\mu^+\mu^-\gamma$ (radiator function, int. luminosity and vacuum polarization cancel)**
- **KLOE-2:**

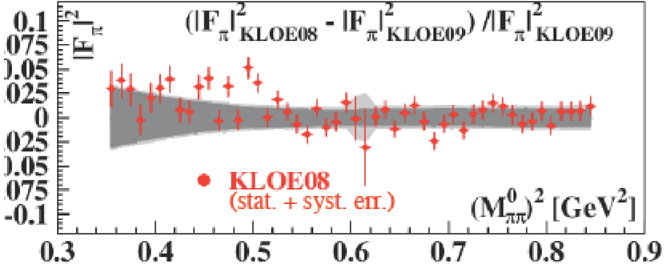
δσ ~ 0.4% for √s < 1 GeV with ISR @ 1 GeV, 2 fb^{-1}

δσ ~ 2% for 1<√s < 2 GeV with energy scan

(if DAΦNE energy → 2 ─ 2.5 GeV)



(Grey band = L.A. error)



Result on L.A. analysis

$$\sigma_{\pi\pi}(s_\pi) = \frac{\pi\alpha^2\beta_\pi^3}{3s}\left|F_\pi(s_\pi)\right|^2$$

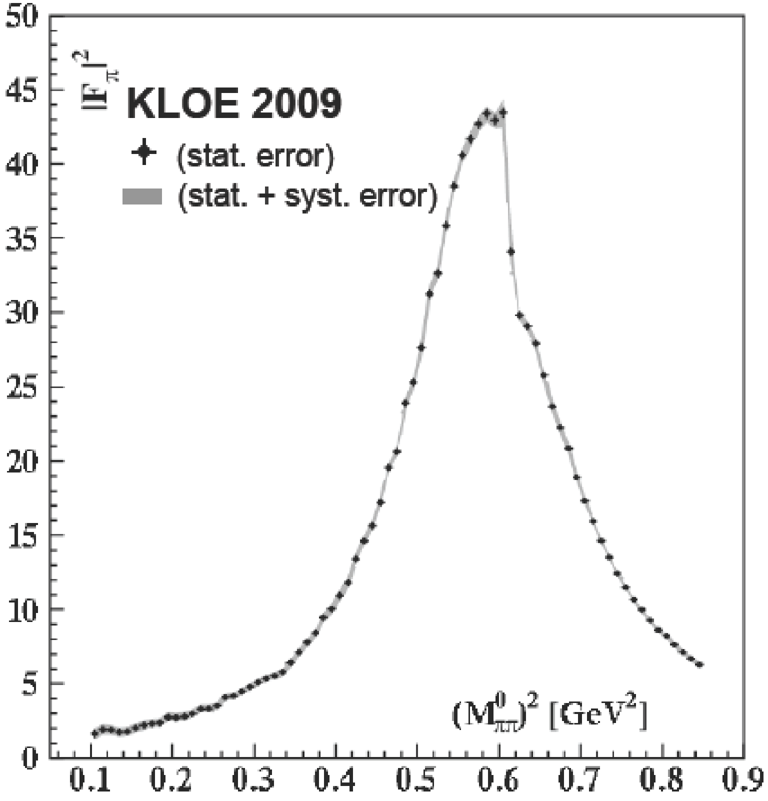


Table of systematic errors on $a_\mu^{\pi\pi}$(0.1-0.85 GeV^2):

Reconstruction Filter	< 0.1%
Background	0.5%
f_0+ρπ	0.4%
Omega	0.2%
Trackmass	0.5%
π/e-ID and TCA	< 0.1%
Tracking	0.3%
Trigger	0.2%
Acceptance	0.4%
Unfolding	negligible
Software Trigger	0.1%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

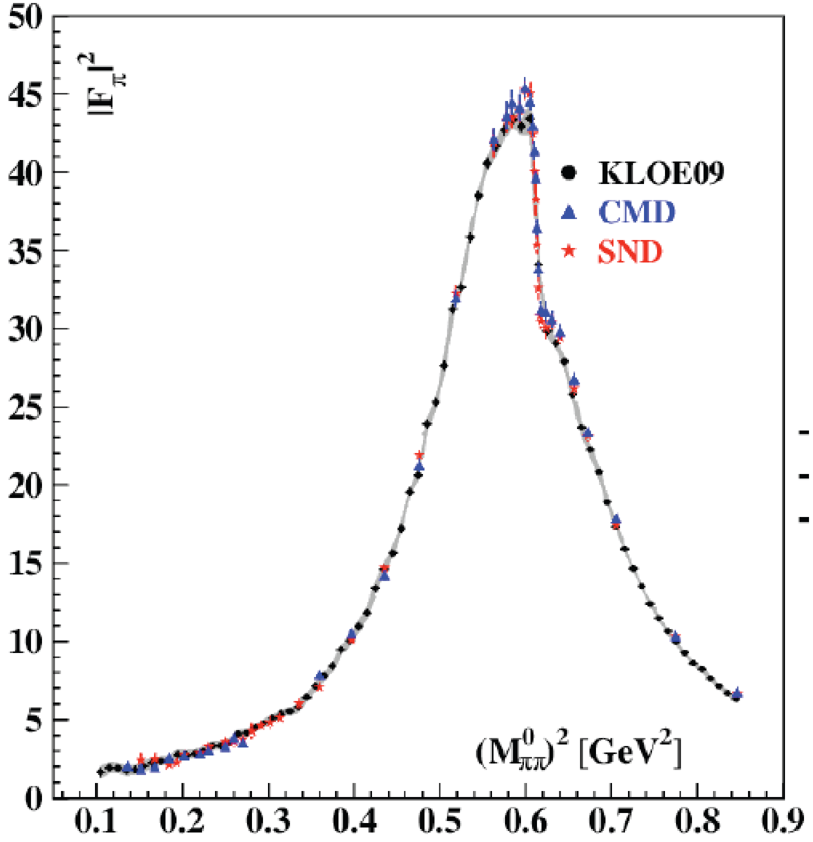
experimental fractional error on $a_\mu^{\pi\pi}$ = 1.0 %

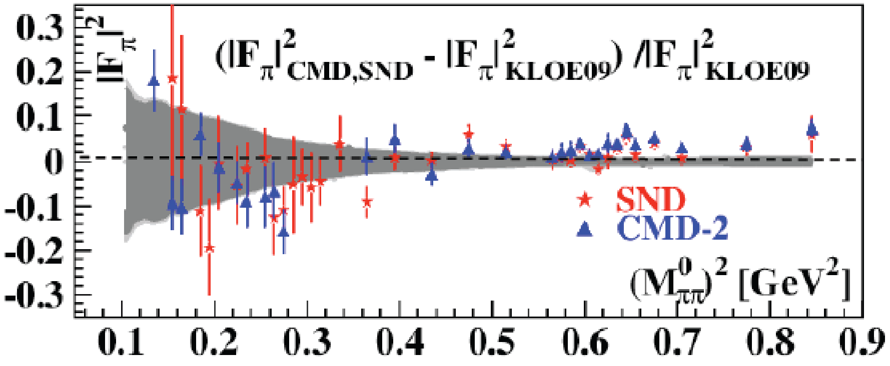
FSR resummation	0.3%
Radiator H	0.5%
Vacuum polarization	< 0.1%

theoretical fractional error on $a_\mu^{\pi\pi}$ = 0.6 %

$a_\mu^{\pi\pi}$(0.1– 0.85 GeV^2) = (478.5 ± 2.0$_{stat}$ ±4.8$_{sys}$ ±2.9$_{theo}$) × 10^{-10}

KLOE vs CMD-2 / SND

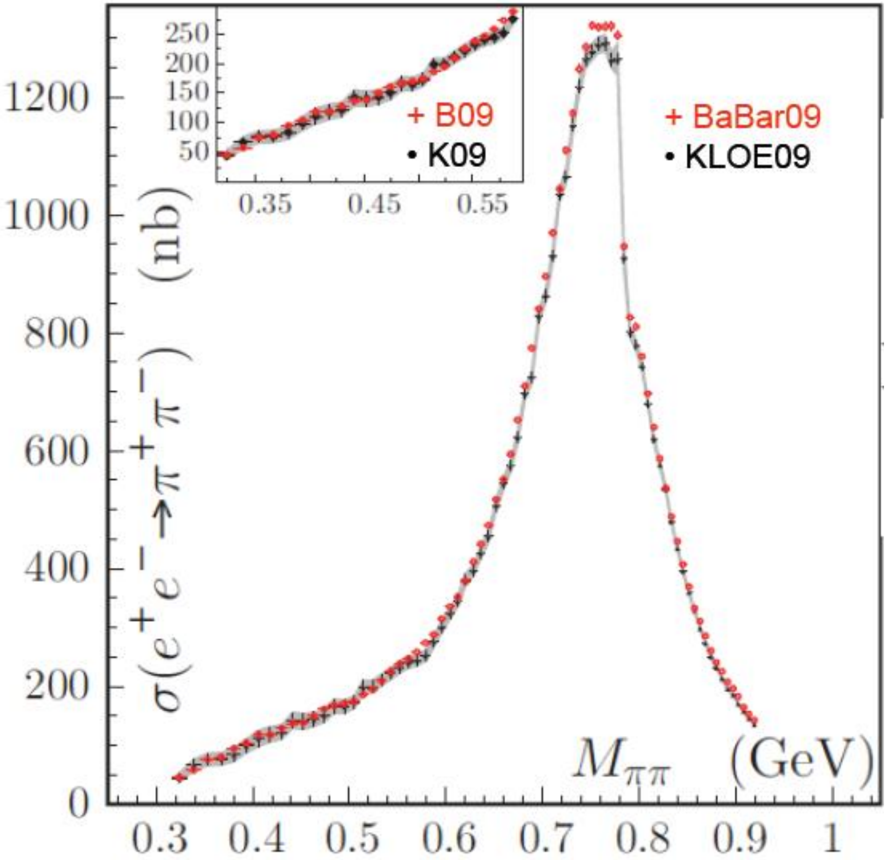


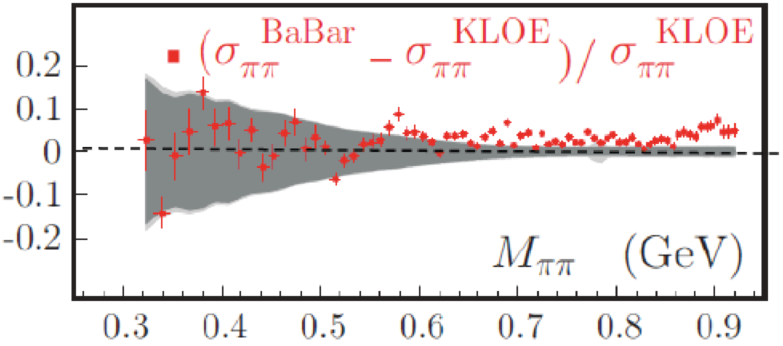


(Grey band = KLOE error)

- Good agreement below the ρ peak
- Above the ρ peak KLOE slightly lower

KLOE vs BaBar





(Grey band = KLOE error)

- **Good agreement below 0.6 GeV**
- **Above 0.6 GeV BaBar higher by 2 – 3%**

$a_\mu^{\pi\pi}$ for different expt.

$a_\mu^{\pi\pi}(0.35\text{-}0.85 GeV^2)$:

KLOE08 (small angle) $a_\mu^{\pi\pi} = (379.6 \pm 0.4_{stat} \pm 2.4_{sys} \pm 2.2_{theo}) \cdot 10^{-10}$

KLOE09 (large angle) $a_\mu^{\pi\pi} = (376.6 \pm 0.9_{stat} \pm 2.4_{sys} \pm 2.1_{theo}) \cdot 10^{-10}$

$a_\mu^{\pi\pi}(0.152\text{-}0.270 GeV^2)$:

KLOE09 (large angle) $a_\mu^{\pi\pi} = (48.1 \pm 1.2_{stat} \pm 1.2_{sys} \pm 0.4_{theo}) \cdot 10^{-10}$

CMD-2 $a_\mu^{\pi\pi} = (46.2 \pm 1.0_{stat} \pm 0.3_{sys}) \cdot 10^{-10}$

$a_\mu^{\pi\pi}(0.397\text{-}0.918 GeV^2)$:

KLOE08 (small angle) $a_\mu^{\pi\pi} = (356.7 \pm 0.4_{stat} \pm 3.1_{sys}) \cdot 10^{-10}$

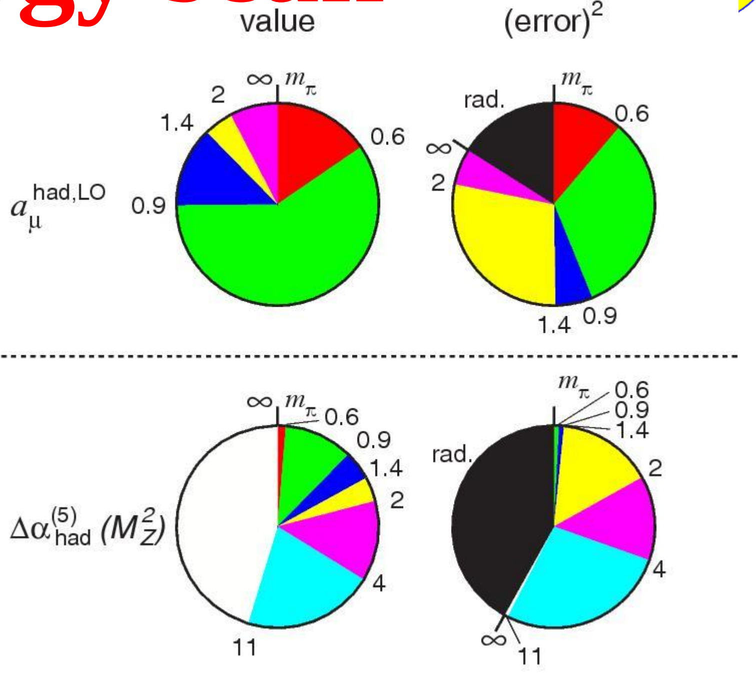
CMD-2 $a_\mu^{\pi\pi} = (361.5 \pm 1.7_{stat} \pm 2.9_{sys}) \cdot 10^{-10}$

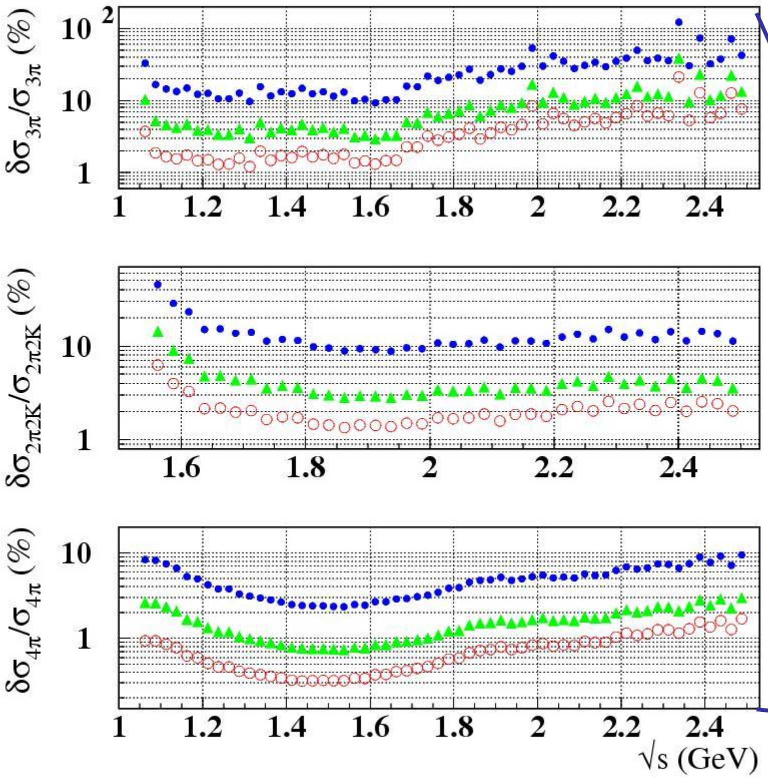
SND $a_\mu^{\pi\pi} = (361.0 \pm 2.0_{stat} \pm 4.7_{sys}) \cdot 10^{-10}$

BaBar $a_\mu^{\pi\pi} = (365.2 \pm 1.9_{stat} \pm 1.9_{sys}) \cdot 10^{-10}$

σ_{had} with energy scan

- **The region 1- 2.5 GeV contributes 55% to δa_μ and 40% to $\delta\Delta\alpha_{had}^{(5)}$**





- **Published BaBar results 89 fb^{-1} (ISR)**

▲ **BaBar × 10**

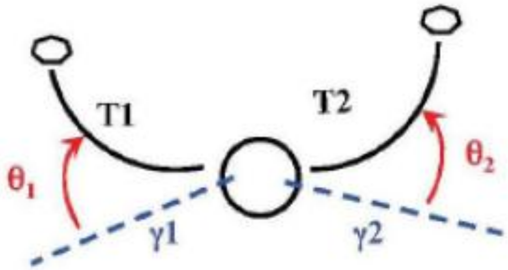
o **KLOE-2 energy scan: 20 pb^{-1}/point @ L= 10^{32} cm^{-2} s^{-1}, 25 MeV bin**

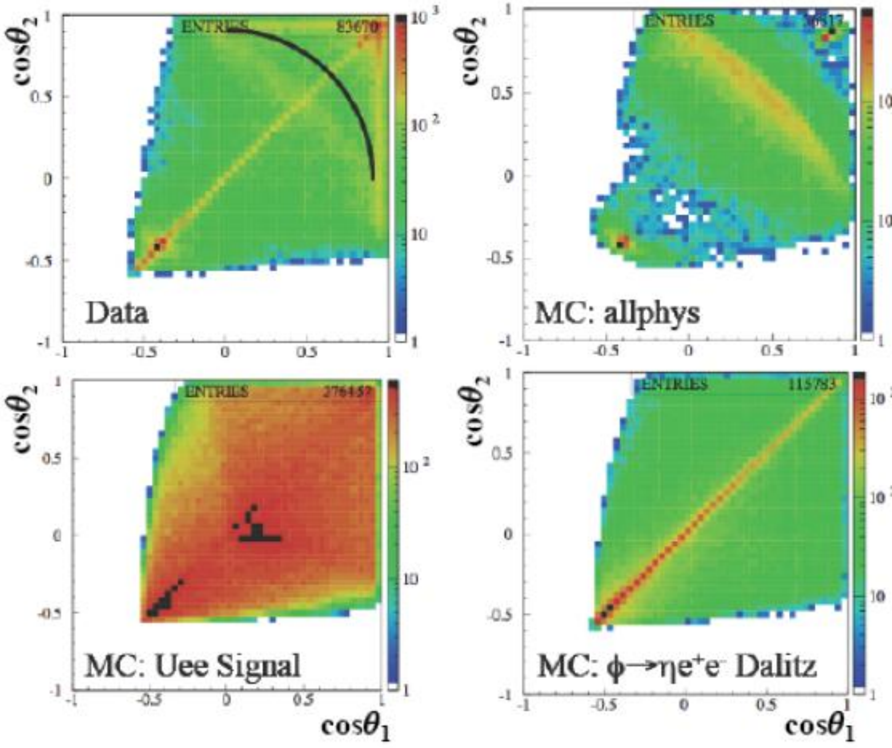
⇒ 1 year data-taking

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

- 2 “electron” tracks (ToF) in a cylinder around IP + 2 photon candidates

- Photons back-to-back in the η rest frame

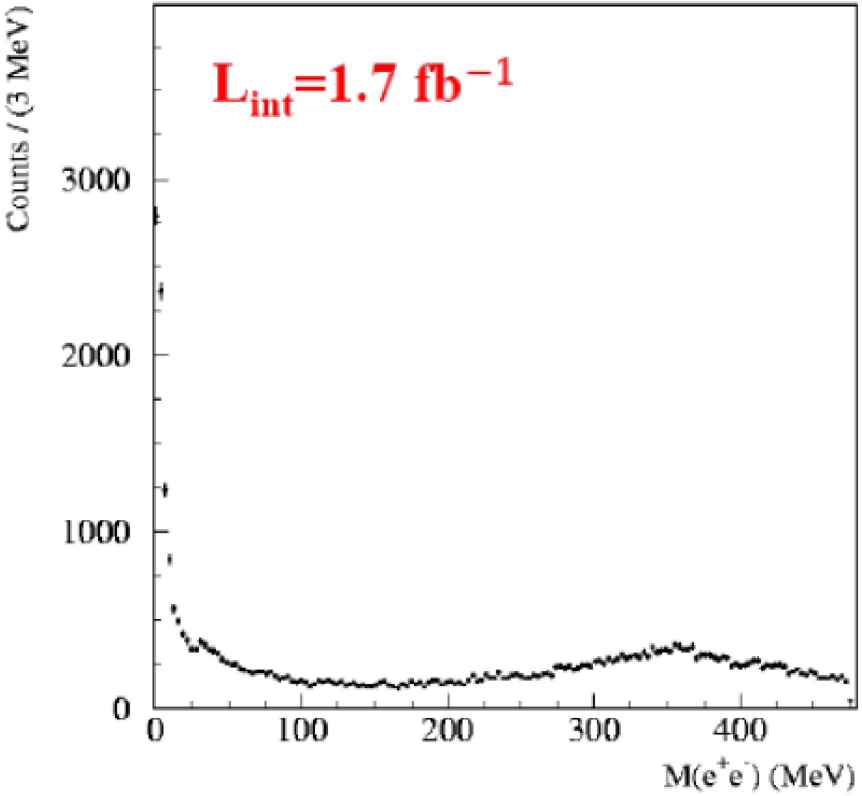




- Background from double radiative Bhabha events reduced by looking at the angles between the tracks and the photons

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

- M_{ee} spectrum after all cuts



- Evidence for $\phi \to \eta e^+e^-$, $\eta \to \gamma\gamma$, Dalitz decays in the low M_{ee} region
- Still some residual background at high M_{ee} masses

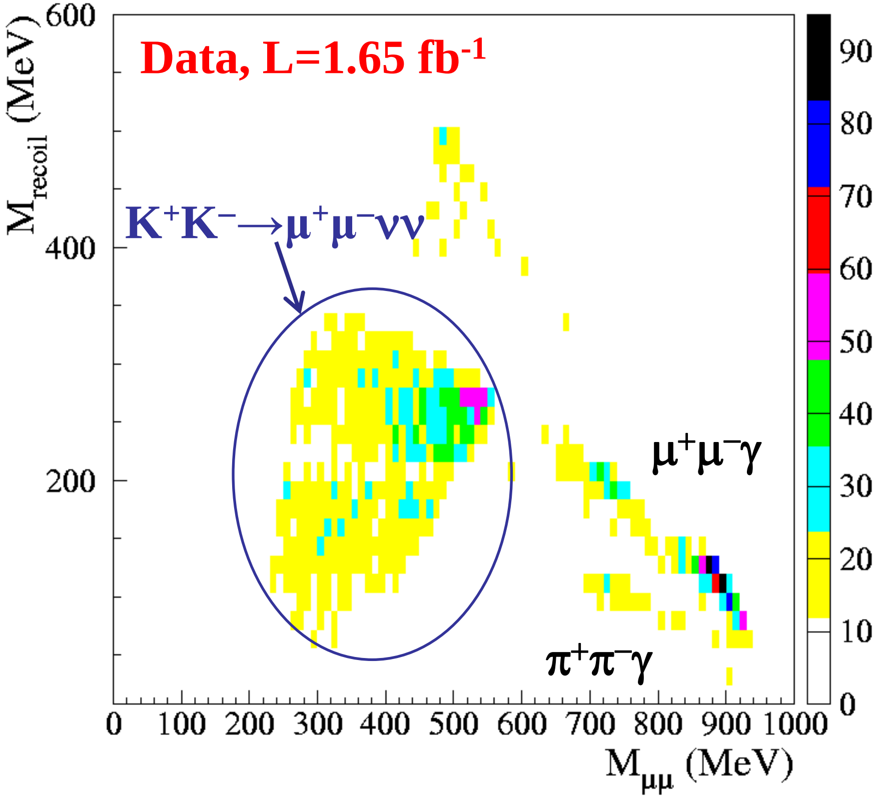
$e^+e^- \rightarrow h'U$

- Signature: $e^+e^- \rightarrow \ell^+\ell^-$ + missing energy (h′ not detected)
- e^+e^- final state not selected by Event Classification ⇒ use $\mu^+\mu^-$
- Background processes

$\phi \rightarrow K^+K^-$, $K^\pm \rightarrow \mu^\pm \nu$

$$\left.\begin{array}{l}\phi \rightarrow \pi^+\pi^-\pi^0 \\ e^+e^- \rightarrow \mu^+\mu^-\gamma,\ \pi^+\pi^-\gamma\end{array}\right\}\text{ with } \gamma \text{ lost}$$

- Most background comes from ϕ



$e^+e^- \to h'U$

- **Signature: $e^+e^- \to \ell^+\ell^-$ + missing energy (h′ not detected)**
- **e^+e^- final state not selected by Event Classification ⇒ use $\mu^+\mu^-$**
- **Background processes**

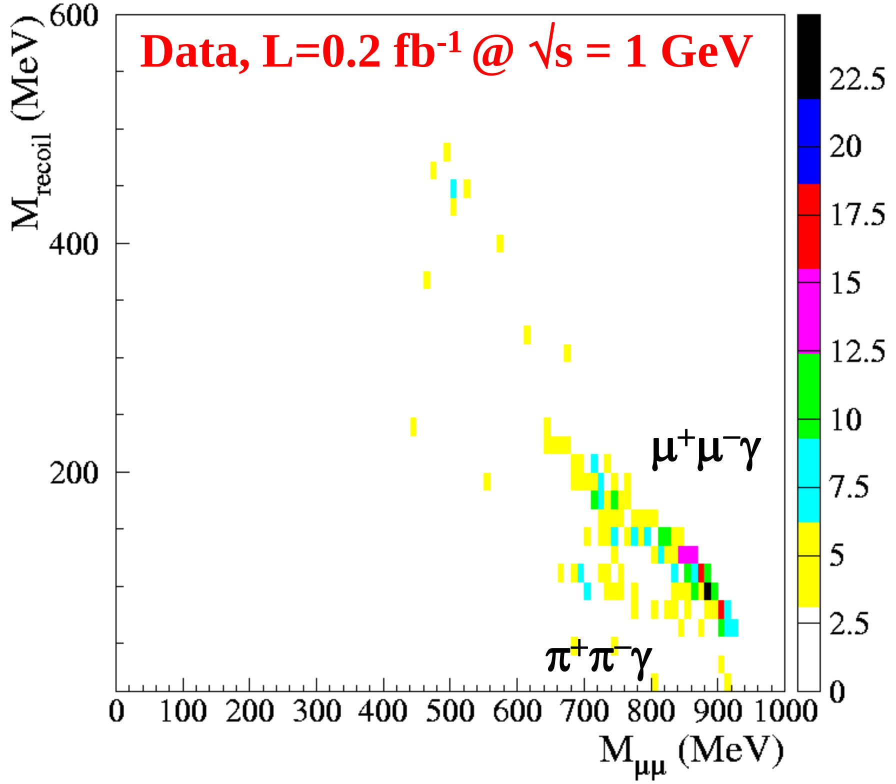
  $\phi \to K^+K^-$, $K^\pm \to \mu^\pm\nu$

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

  $e^+e^- \to \mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$

  with γ lost
- **Most background comes from ϕ**

  ⇒ strongly reduced by looking at off-peak data
- **A long off-peak run (L = *O*(fb^{-1})) would be very useful**
- **IT insertion should give major benefits to the on/off-peak analysis**
- **Plans to search for $U \to e^+e^-$ (different background and phase space) with *ad hoc streaming***



KLOE-2 physics program

Goal: ~20 fb^{-1} in the next 3 – 4 years to extend the KLOE physics program at DAΦNE upgraded in luminosity

G.Amelino-Camelia et al., EPJC68(2010)619

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