Recent results on hadron physics at KLOE

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On behalf and for the KLOE and KLOE-2 Collaborations

Moriond QCD and High Energy Interactions
March 11th 2013

Indeed recent results of KLOE/KLOE-2:

- **Search for the dark matter boson**

  Phys. Lett. B 720 (2013) 111

- **Tests of Standard Model**

  …contribution to the study of g-2 anomaly

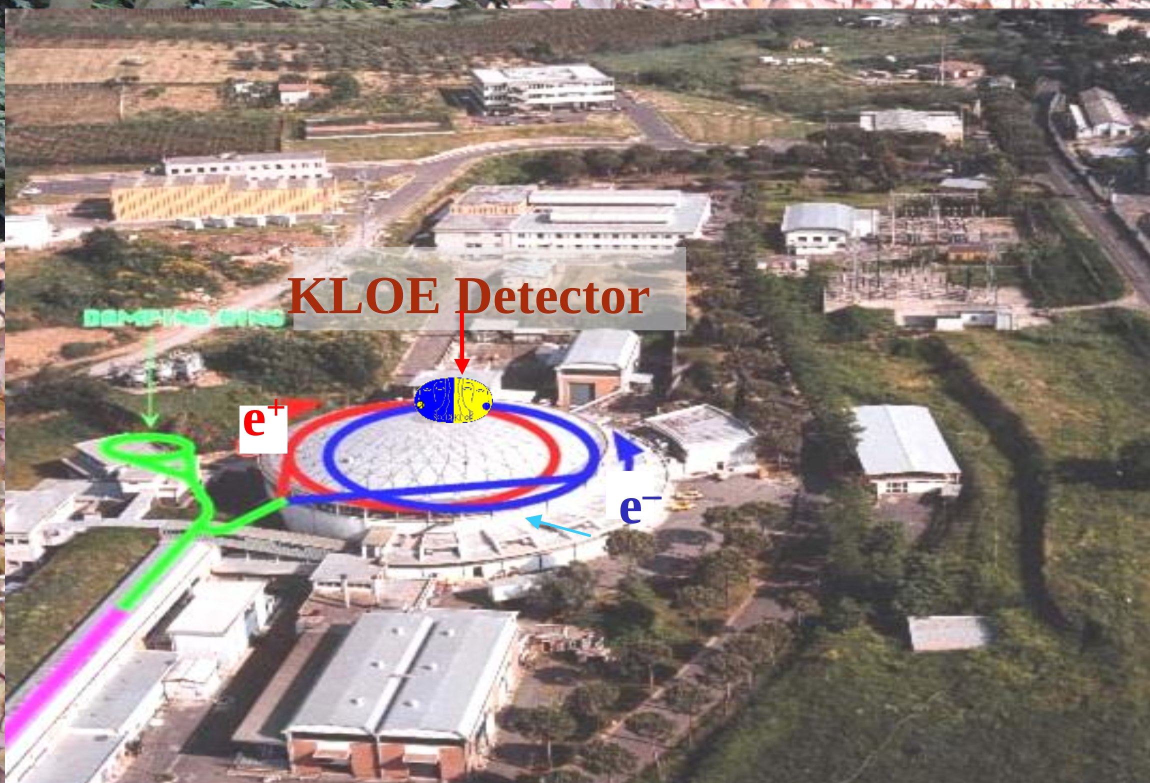
  Phys. Lett. B 720 (2013) 336

  JHEP 01 (2013) 119

- **Test of QCD anomalies and CHPT …**

  Phys. Lett. B 718 (2013) 910

DAΦNE e^+e^- collider Frascati (Rome)



- $e^+e^- \to \phi \quad \sqrt{s} \sim m_\phi = 1019.4$ MeV

BR's for selected ϕ decays	
K^+K^-	49.1%
K_SK_L	34.1%
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%
$\eta\gamma$	1.3 %
$\eta'\gamma$	0.006%

KLOE

K LOng Experiment

Drift chamber

Gas: **90% He + 10% C_4H_{10}**

$\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)

$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm

EM calorimeter

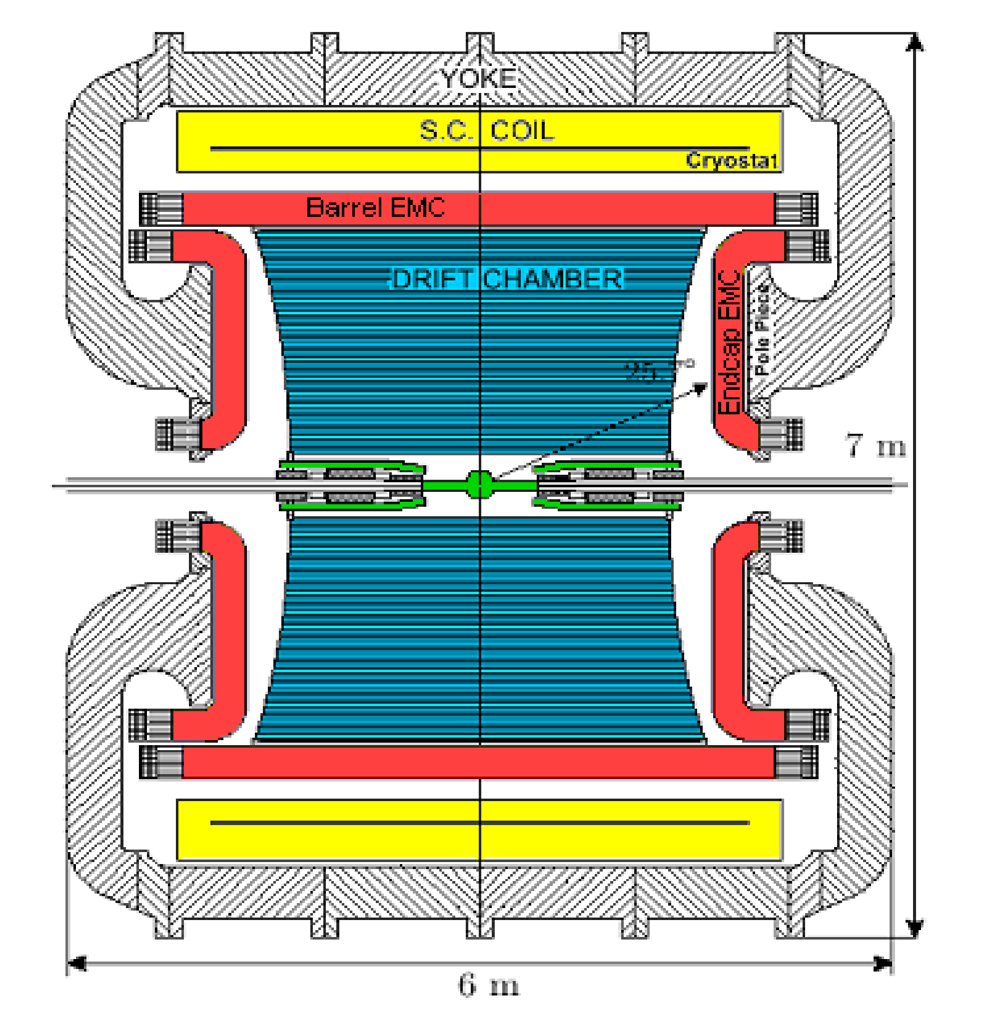
lead/scintillating fibers

98% solid angle coverage

$\sigma E / E = 5.7\% / \sqrt{E(GeV)}$

$\sigma t = 55\ ps / \sqrt{E(GeV)} \oplus 100\ ps$

PID capabilities



Magnetic field 0.52 Tesla

KLOE

completed data taking with 2.5 fb^{-1}

$$\sim 8 \cdot 10^9\ \phi\ ,\ \sim 10^8\ \eta\ ,\ \sim 5 \cdot 10^5\ \eta'$$

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Chandra 0.5 Msec image
0.5 Mpc

Princess Elisabeth of Bohemia writes on 10.vi.1643:

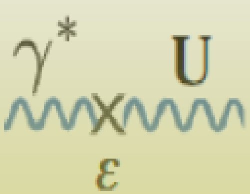
„…I don't see how the idea that you used to have about weight can guide us to the idea we need in order to judge **how the (nonextended and immaterial) soul can move the body"**

Descartes writes on 28.vi.1643:

„…I ought to have made clear that although one may wish to think of the soul as material (…), that wouldn't stop one from realizing that the soul is separable from the body. I think that those cover everything that you asked me to do in your letter."

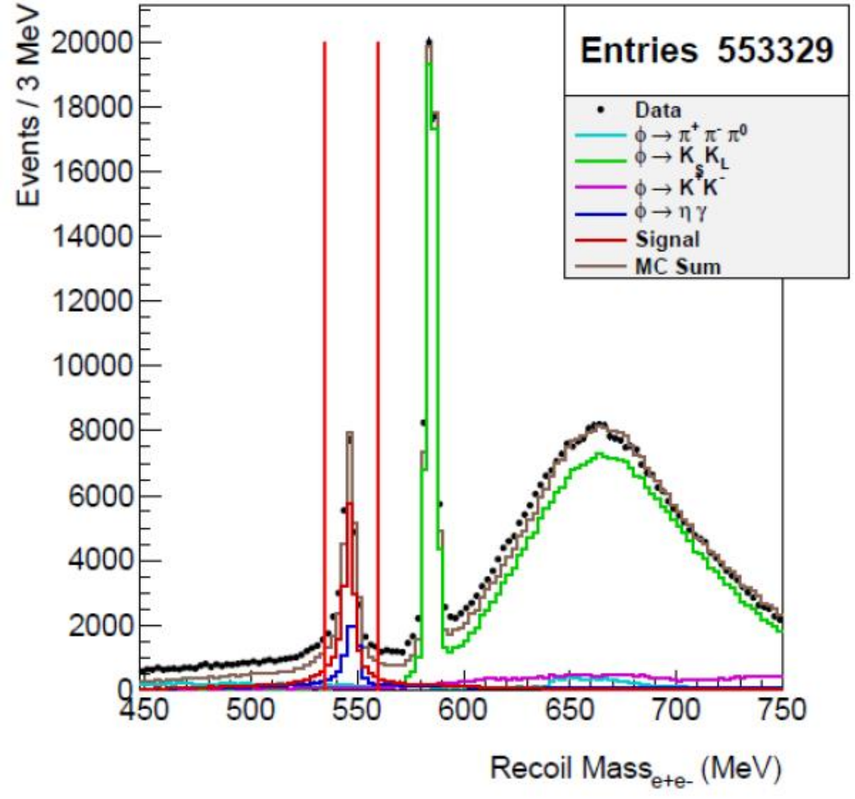
Particle physics four centuries later:
How the „non-SM dark matter" can move the „SM matter" ?:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F^{dark}_{\mu\nu}F^{\mu\nu}_{dark} - \frac{\epsilon}{2}F^{dark}_{\mu\nu}F^{\mu\nu} + |D^{\mu}\phi|^2 - V(\phi)$$



Search for the dark photon at KLOE

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

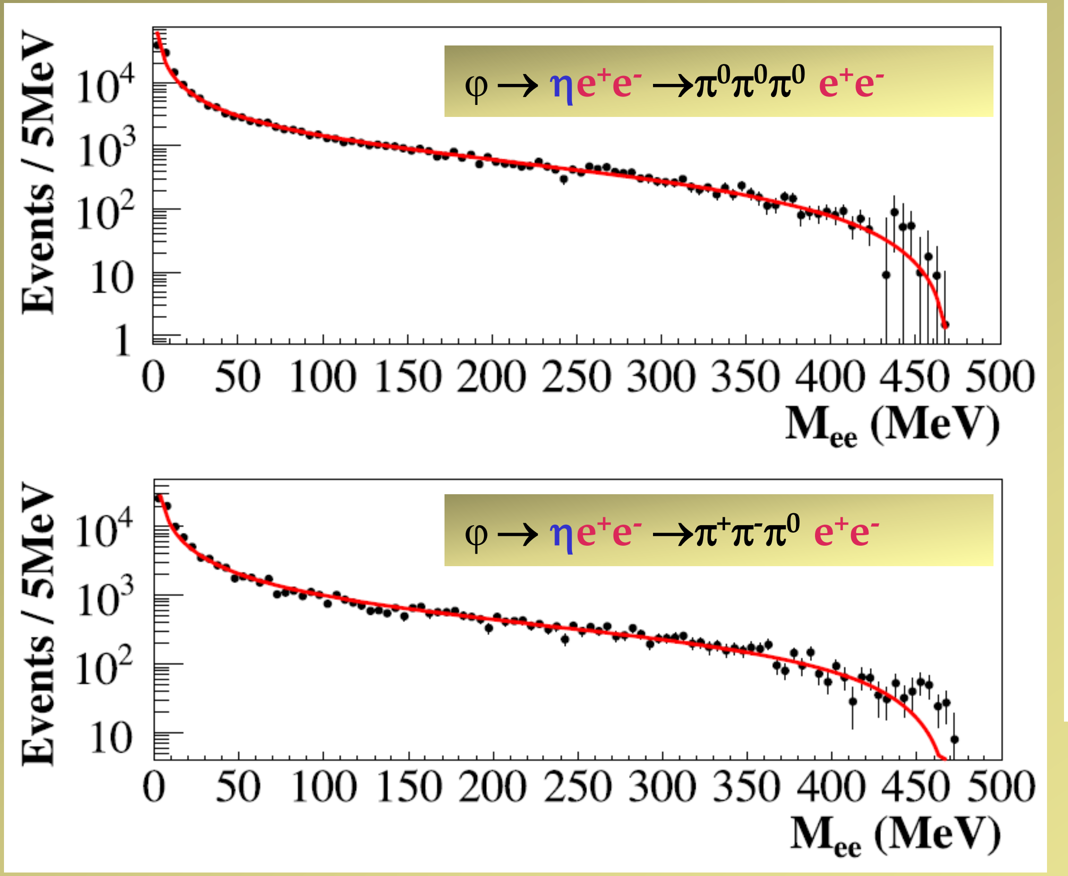


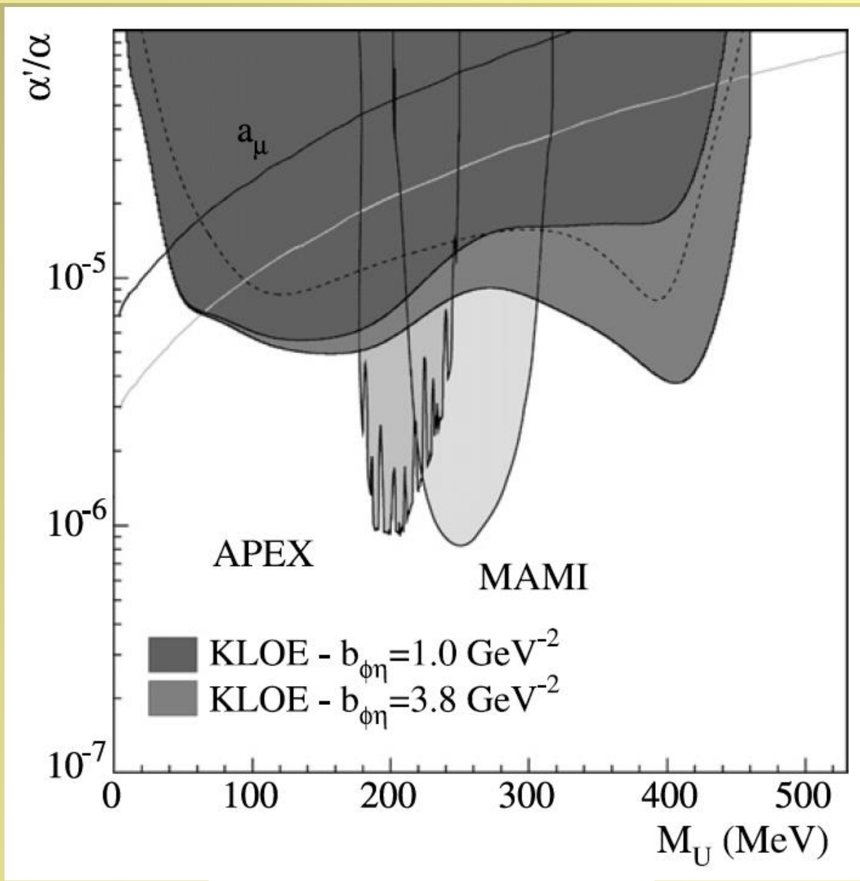
$\varphi \to \eta e^+e^- \to \pi^+\pi^-\pi^0 e^+e^- \to \pi^+\pi^-\gamma\gamma e^+e^-$

After further reduction of external conversion
we get a clear signal of $\varphi \to \eta e^+e^-$ with only ~2% background

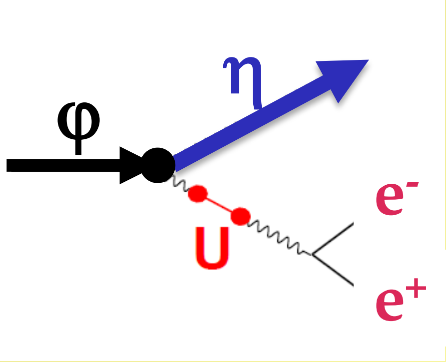
Search for the dark photon at KLOE

$\varphi \rightarrow \eta\gamma^* \rightarrow \eta e^+e^-$





$\varphi \rightarrow \eta\gamma^* \rightarrow \eta\ U \rightarrow \eta\gamma^* \rightarrow \eta e^+e^-$



KLOE/KLOE-2: Phys. Lett. B 720 (2013) 111

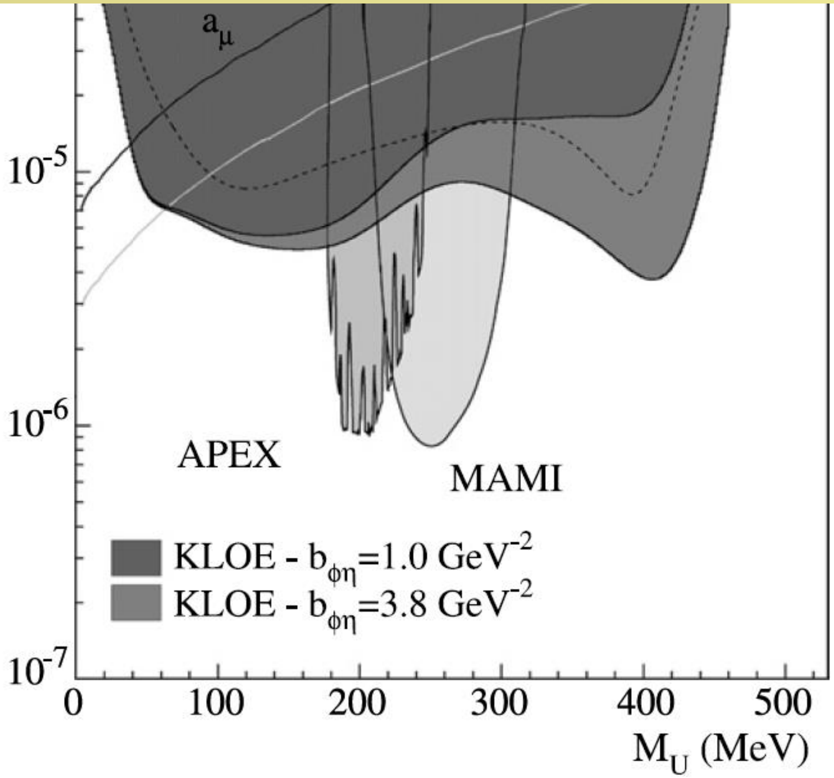
Search for the dark photon at KLOE

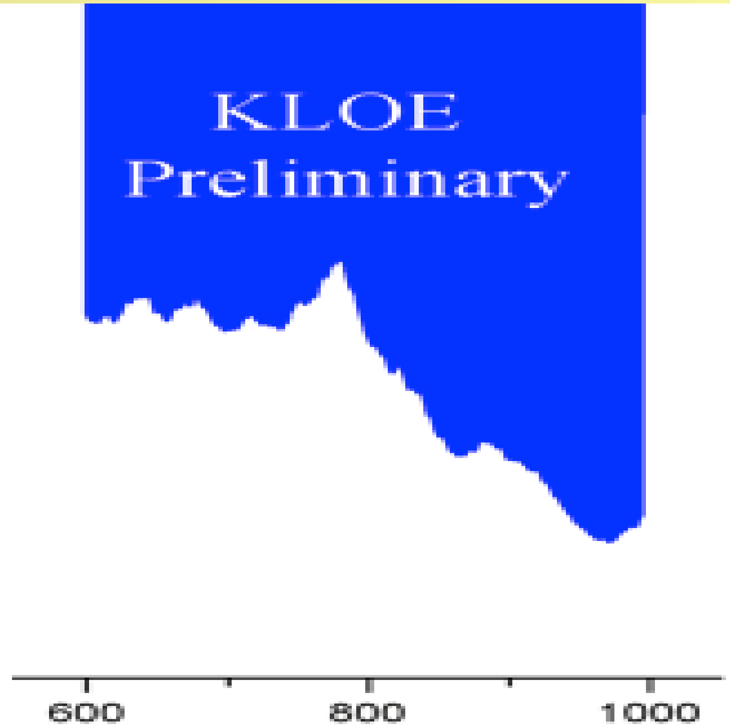
$\phi \to \eta\, \gamma^* \to \eta\, e^+e^-$

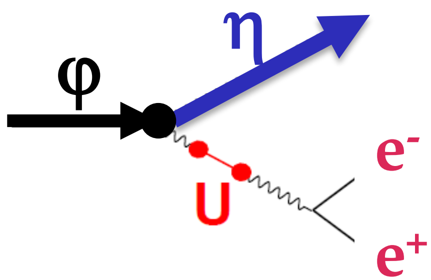
$\phi \to \eta\, \gamma^* \to \eta U \to \eta\, \gamma^* \to \eta\, e^+e^-$

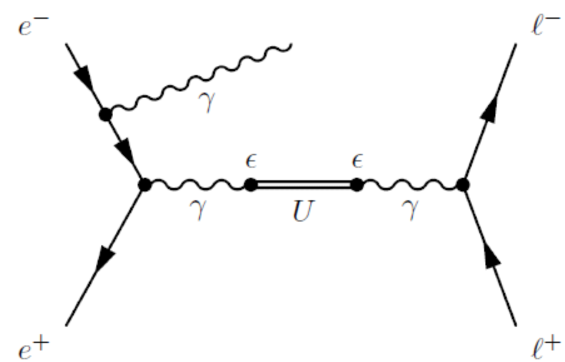
$e^+e^- \to \gamma^*\, \gamma \to \mu^+\mu^-\gamma$ (ISR)

$e^+e^- \to \gamma^*\, \gamma \to U\gamma \to \gamma^*\gamma \to \mu^+\mu^-\gamma$









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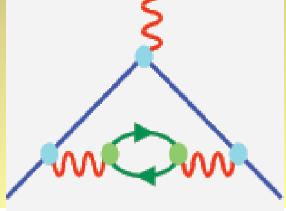
Tests of the Standard Model (g-2):
two-pion contribution to the muon anomaly a_μ



The anomalous muon magnetic moment

$a_\mu = (g_\mu - 2)/2 = (116592080 \pm 63)\ 10^{-11}$ from E821 at BNL

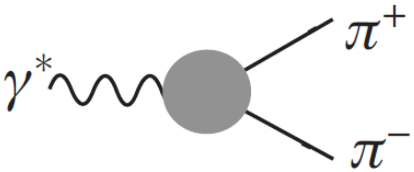
theory : $a_\mu = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$

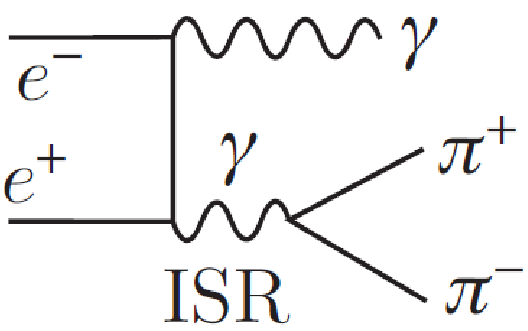
a_μ^{had} from measurements of the hadronic cross section via dispersion relation:

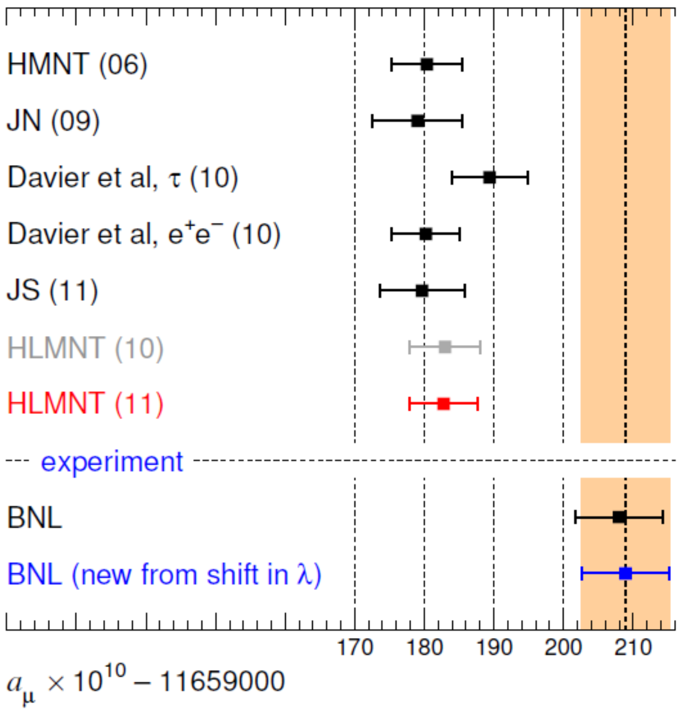
$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to had}(s) K(s) ds$$

Hadronic contritubion (a_μ^{had}~6900 10^{-11}) dominates uncertainty of a_μ calculations

70% of a_μ^{had} originates from two-pion contribution



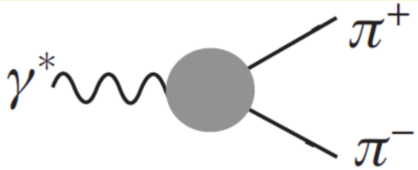




Tests of the Standard Model (g-2):

two-pion contribution to the muon anomaly a_μ

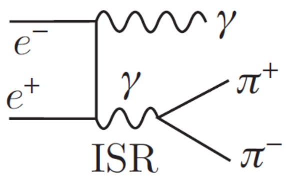
The experimental aim is to determine $\sigma_{\pi\pi}$ (s_π):

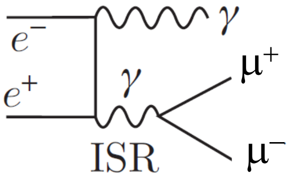


$$s \left. \frac{\mathrm{d}\sigma(\pi^+\pi^-\gamma)}{\mathrm{d}s_\pi} \right|_{\mathrm{ISR}} = \sigma_{\pi\pi}(s_\pi)\; H(s_\pi, s)$$

In order to decrease uncertainties we measure the ratio:

$$\boldsymbol{\sigma(e^+e^- \to \pi^+\pi^-\gamma)/\sigma(e^+e^- \to \mu^+\mu^-\gamma)}$$

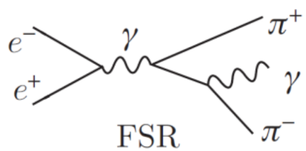




Therefore:

- Radiator function H cancels out
- Luminosity cancels out
- Vaccum polarization corretions and most radiative corrections cancel out
- Acceptance corrections cancel out to large extent

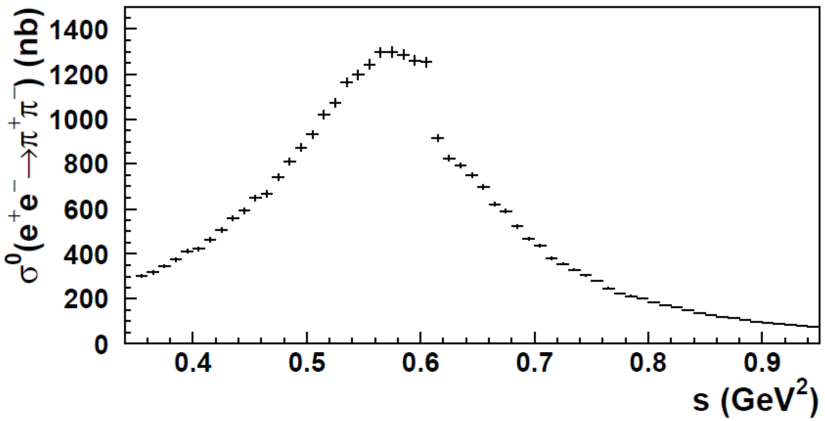
Influence of FSR



is minimized by taking into account only small anglular range for γ

Tests of the Standard Model (g-2):

two-pion contribution to the muon anomaly a_μ



$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3} \int_{s_{min}}^{s_{max}} ds\, \sigma^0_{\pi\pi(\gamma)}(s)\, K(s)$$

KLOE & KLOE-2: **Phys. Lett. B 720 (2013) 336**

$$a_\mu^{\pi\pi} = (385.1 \pm 1.1_{stat} \pm 2.6_{exp} \pm 0.8_{th}) \cdot 10^{-10}$$

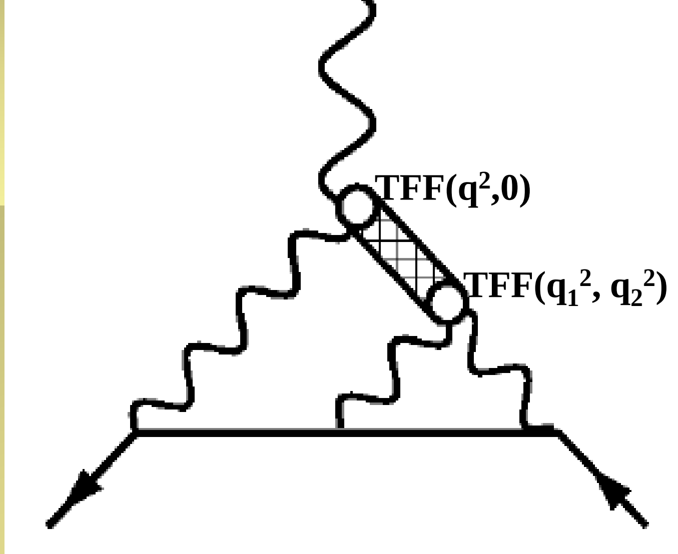
Theoretical contribution to experimental systematics reduced by 70%

Descrepancy of more than 3σ

between predictions based on SM and experimental value of $a_\mu \equiv (g-2)/2$ confirmed

Tests of the Standard Model (g-2):

light-by-light contribution to the muon anomaly a_μ



meson → γ*γ* (time like region of TFF)

$\phi \to \eta\ \gamma^* \to \eta\ e^+e^-$ (KLOE: PLB706(2012)251)

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

$\pi, \eta, \eta' \to \gamma\ \gamma^* \to \gamma\ e^+e^-$

$\eta \to \gamma^* \gamma^* \to e^+e^-e^+e^-$ (KLOE: PLB702(2011)324)

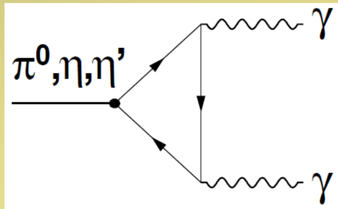
γ*γ* → meson (space-like region of TFF)

$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\eta$ (t-channel)

KLOE & KLOE-2: **JHEP 01 (2013) 119**

The most precise measurement to date of:

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



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η meson

C	P	CP
+1	-1	-1

All strong and electromagentic decays are forbidden in a first order

In SM weak decays are expected to occur at 10^{-13}

DECAYS OF ETA MESON ENABLES PRECISE TESTS OF DISCRETE SYMMETRIES, QCD ANOMALIES, CHPT…

$C(\eta) = +1\,,\ P(\eta) = -1;\ C(\pi^0) = +1\,,\ P(\pi^0) = -1$

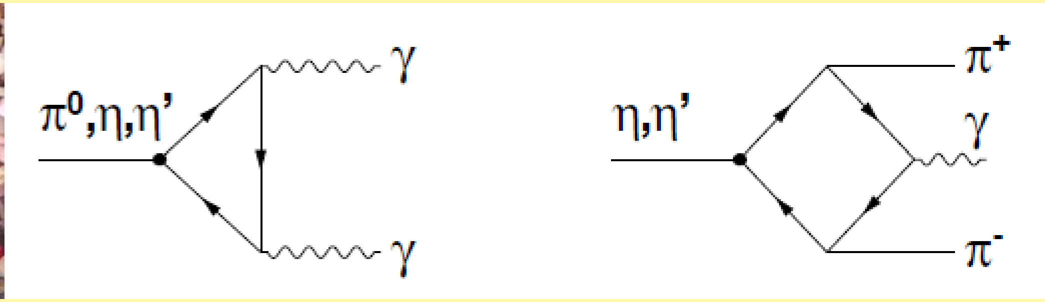
$\eta \to \pi\pi$ violates P and CP

$\eta \to \pi\pi\pi$ violates G and (I or C)

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

Second order EM $\eta \to \gamma\gamma$

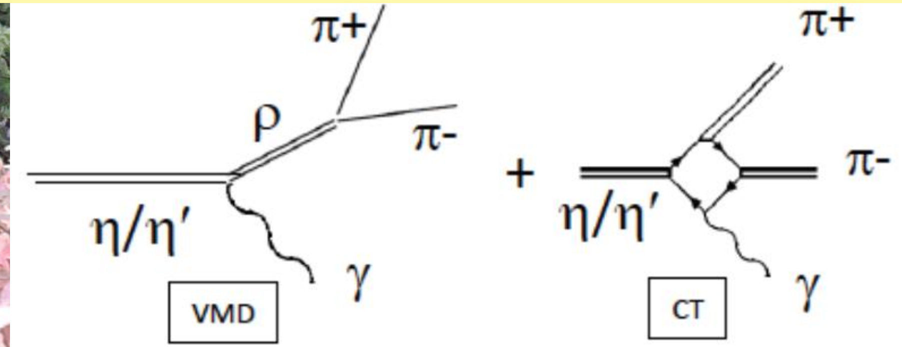
is forbidden in a massless quarks limits



$\eta \to \gamma\gamma\gamma$ violates C etc…

Tests of CHPT via box anomaly …

$\eta \to \pi^0\pi^0\gamma$ violates C **but** $\eta \to \pi^+\pi^-\gamma$ **does not if** $L(\pi^+\pi^-) = 1$



Predictions: M. Benayoun et al., EPJ C31 (2003) 525

$\Gamma(\eta \to \pi^+\pi^-\gamma) = (56.3 \pm \sim 1.7)$ eV with CT

$\Gamma(\eta \to \pi^+\pi^-\gamma) = (100.9 \pm 2.8)$ eV without CT

$$e^+e^- \to \phi \to \eta\,\gamma; \quad \eta \to \pi^+\pi^-\gamma$$

In order to decrease uncertainties we measure the ratio:

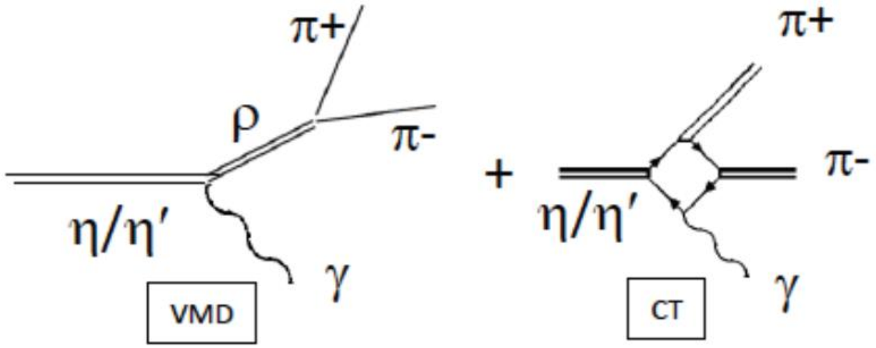
$\Gamma(\eta \to \pi^+\pi^-\gamma) / \Gamma(\eta \to \pi^+\pi^-\pi^0)$

Therefore:

- Luminosity cancels out
- Cross section of $e^+e^- \to \phi$ **cancels out**
- BR($\phi \to \eta\gamma$) cancels out
- $\eta \to \pi^+\pi^-\gamma$ **and** $\eta \to \pi^+\pi^-\pi^0$ **posses similar topologies**

which decreases to large extent systematic uncertainties.

Tests of CHPT via box anomaly …



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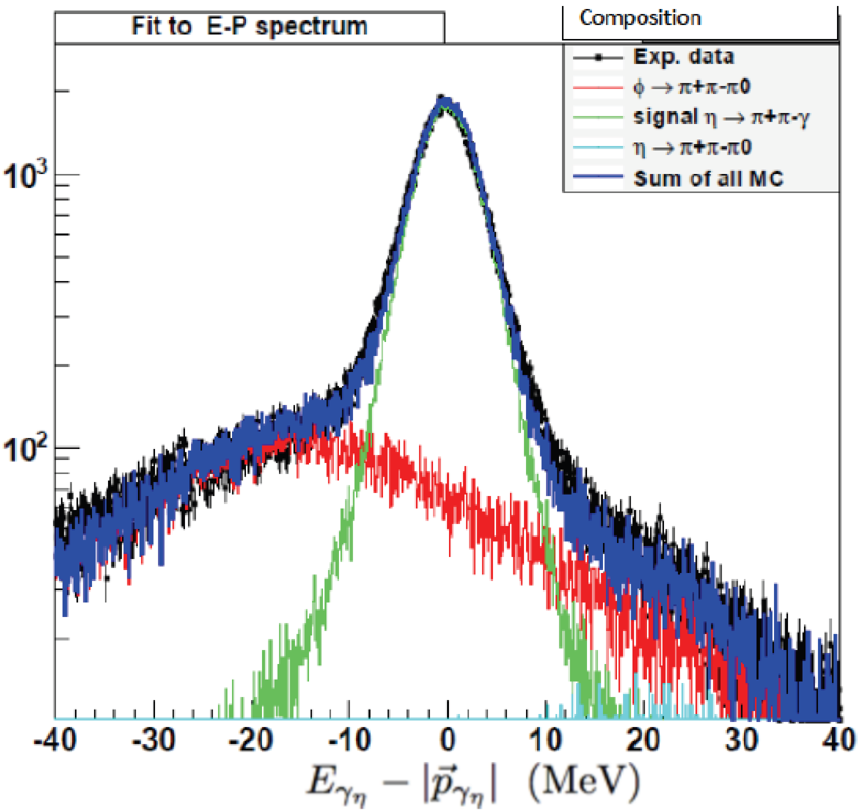


KLOE: Phys. Lett. B718 (2013) 910

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

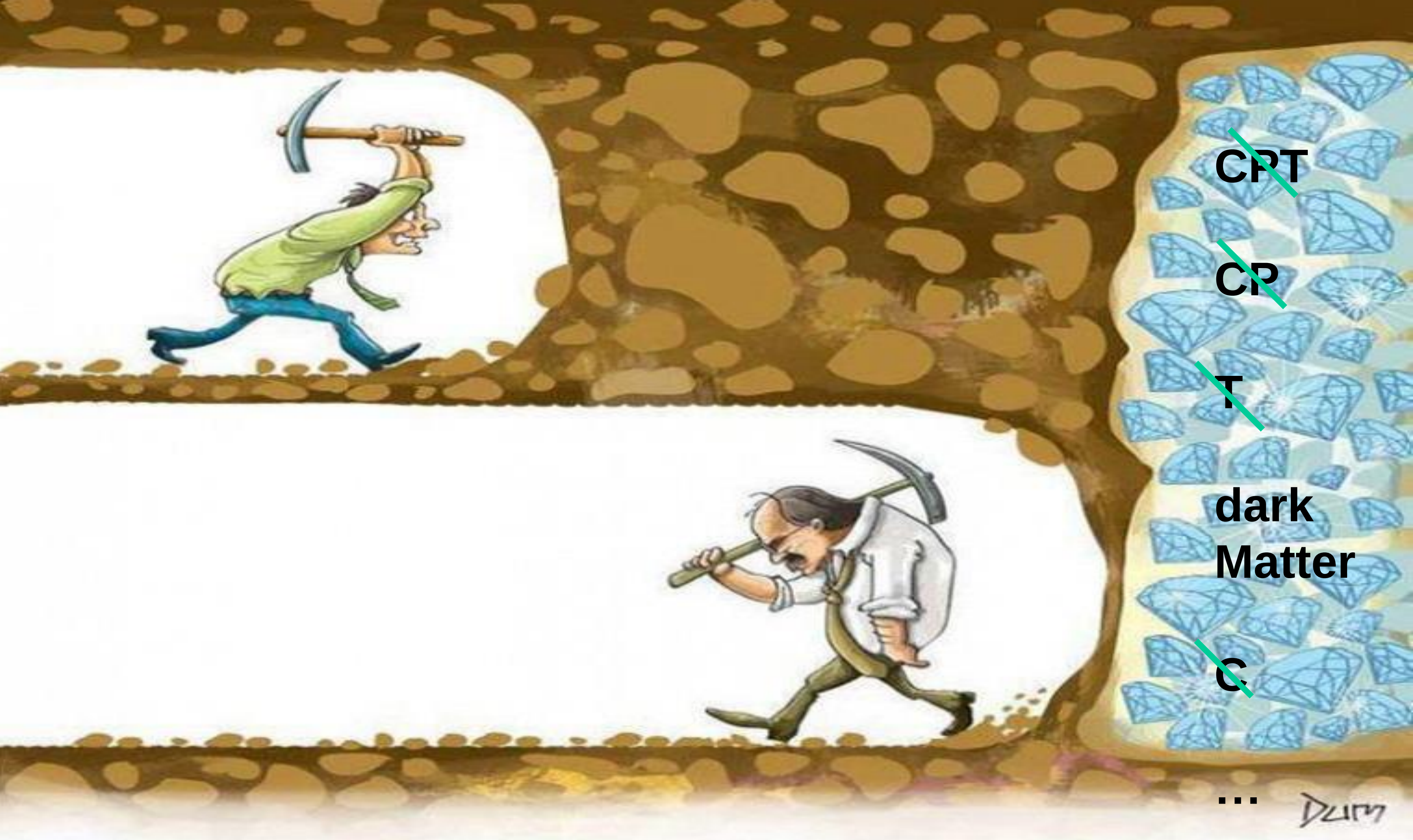
Precision improved by factor of three.

Result is consistent with CLEO PRL99(2007)122001

Finally:

$\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)$ = (54.7 ± 3.1) eV

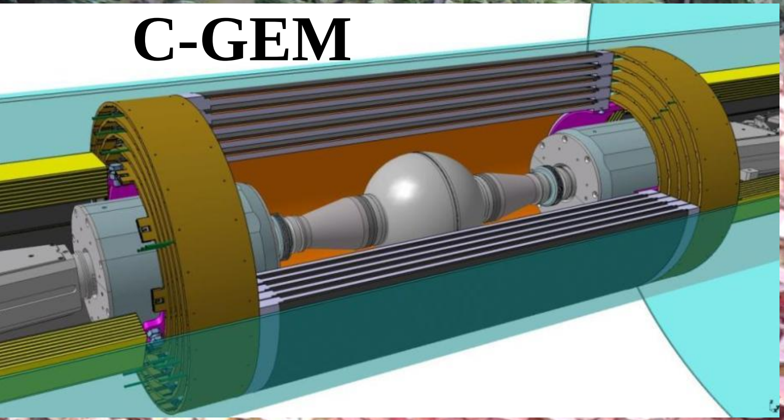
indicates dominant CT contribution

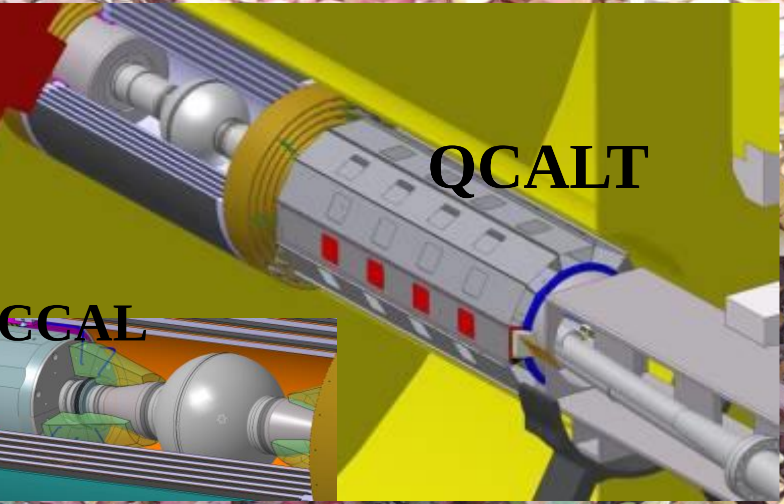


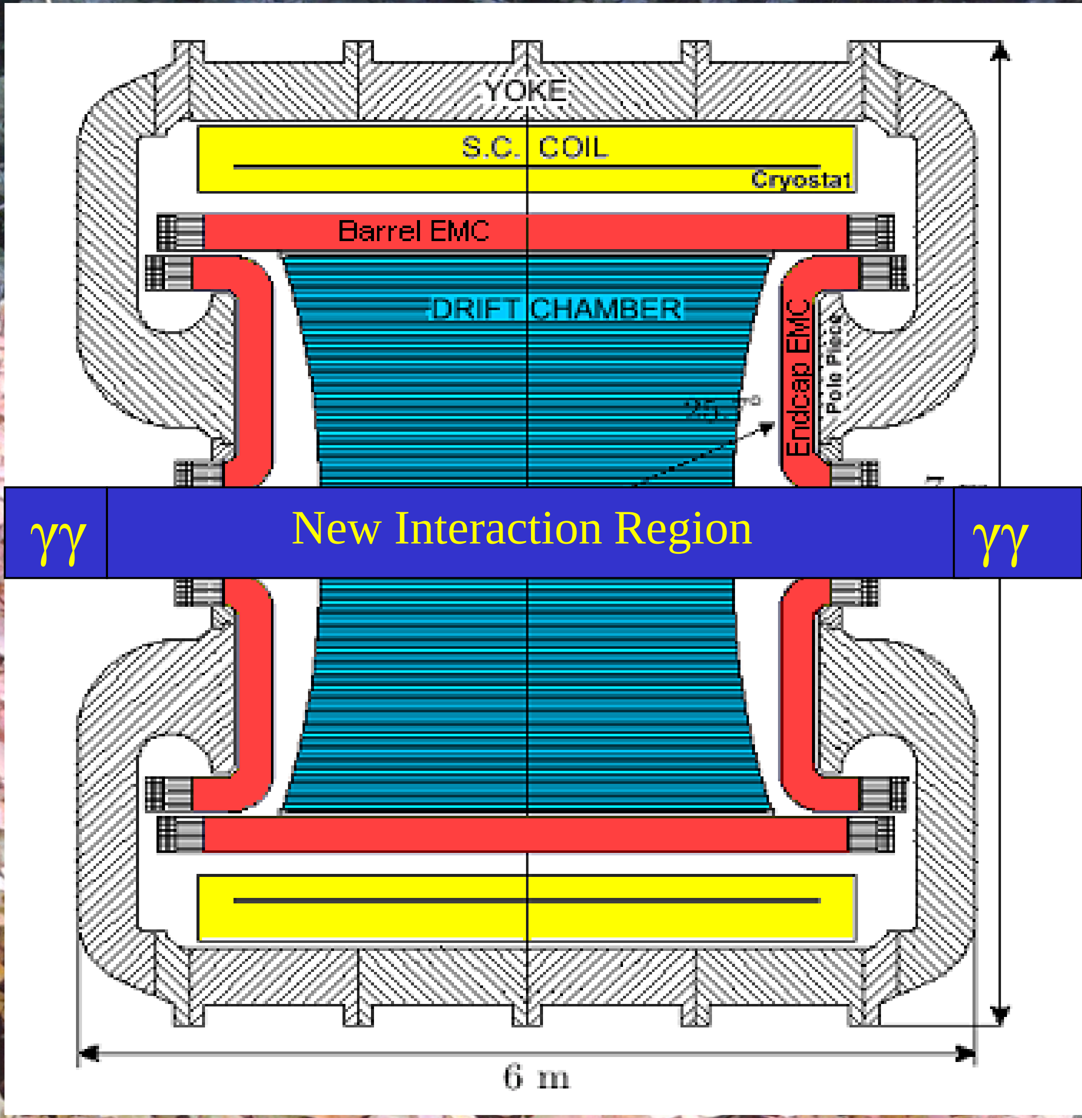
… thus we continue…

KLOE –> KLOE-2

KLOE-2



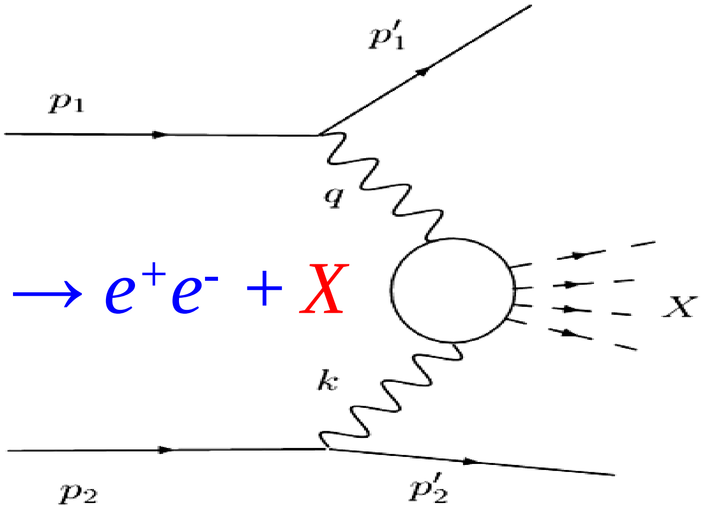




Magnetic field 0.52 Tesla

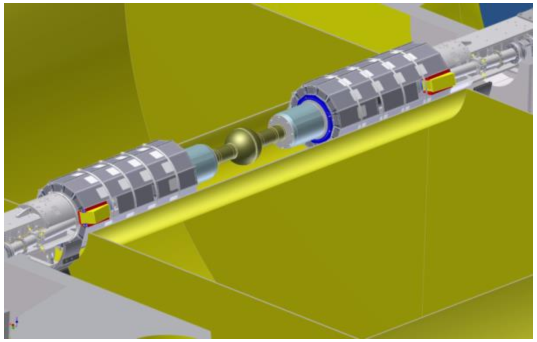
KLOE-2

$\gamma\gamma$ - interaction: $e^+e^- \rightarrow e^+e^- \gamma^*\gamma^* \rightarrow e^+e^- + X$

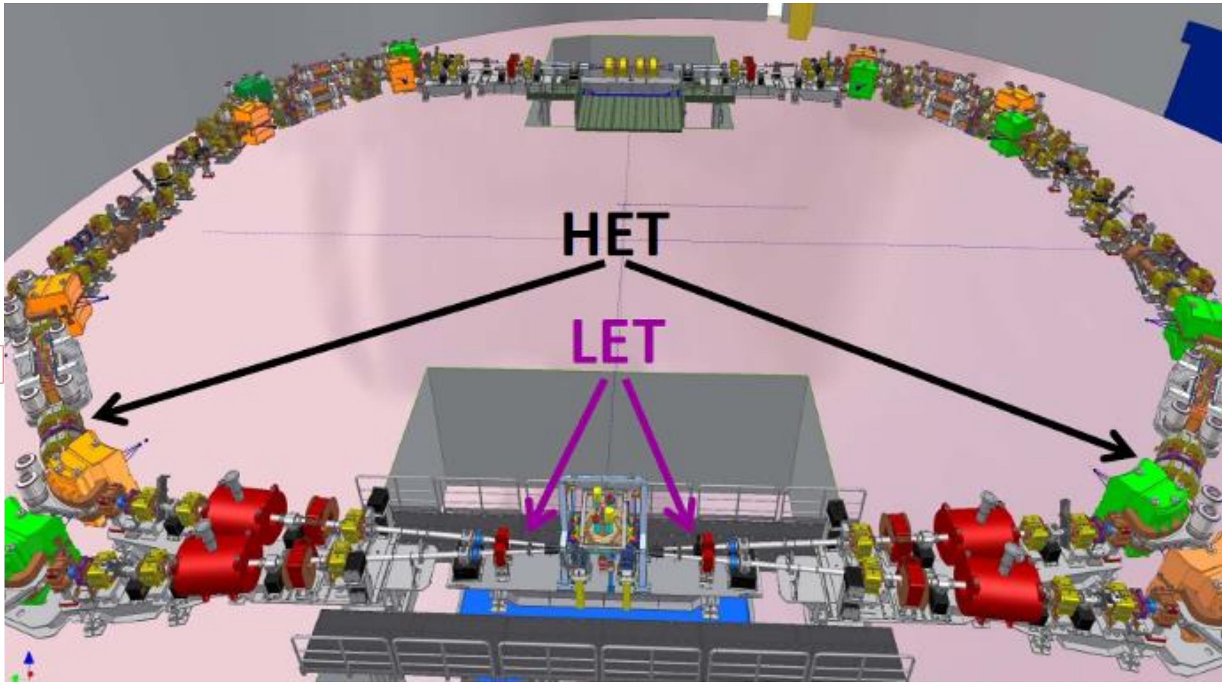


LET: E=160-230 MeV

LYSO+SiPM **σ_E<10% for E>150 MeV**



KLOE-2



HET: E > 400 MeV

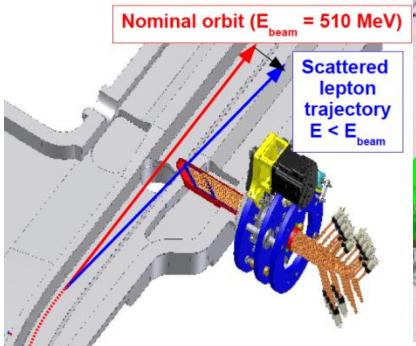
11 m from IP

Scintillators

+ PMTs

σ_E ~ 2.5 MeV

σ_T ~ 200 ps



KLOE –> KLOE-2

2.5 fb^{-1} –> ~10 fb^{-1} (expected)

$\sim 8 \cdot 10^{9}\ \phi$ –> $\sim 3 \cdot 10^{10}\ \phi$

…

Detector upgrade is in progress …

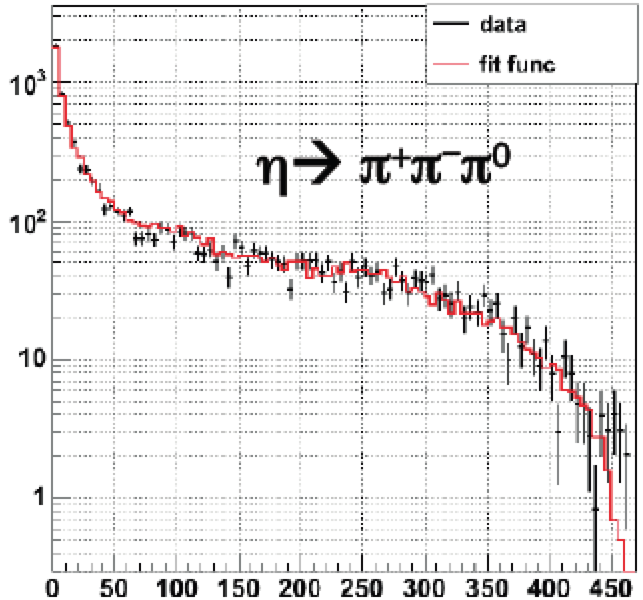
DAΦNE operation will restart in June 2013

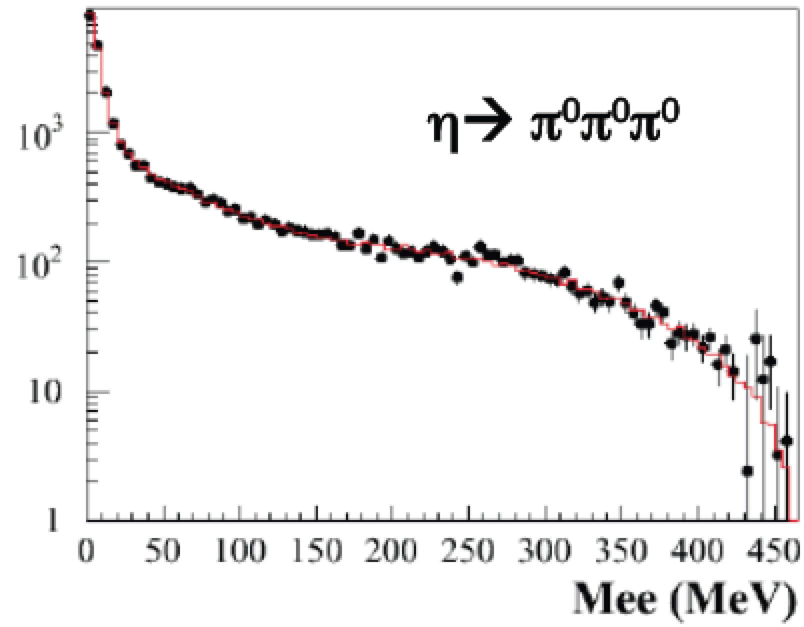

THANK YOU
FOR YOUR ATTENTION

ADDITIONAL SLIDES

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

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





✓ **High precision on slope reachable (few % w.r.t. 50% of SND measurement)**

✓ **Very different systematics on the two channels. Combined fit planned**

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

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

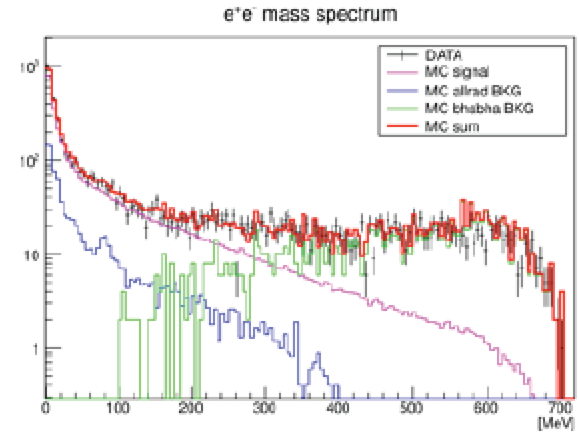
  ⇒ 25% uncertainty
- SND ⇒ 52 ; CMD-2 ⇒ 46 events

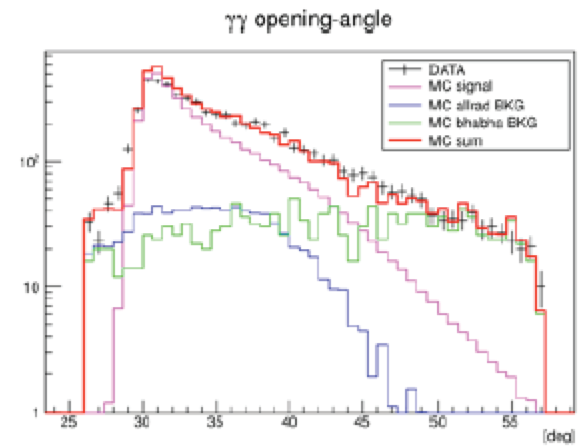
- Events with 2 tracks + 2 prompt photons
- Background:

  radiative Bhabha scattering

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

- Signal efficiency ≈ 16%
- Data –MC comparison (840 pb^{-1})
- Work in progress …





Selected examples of investigations planned by the KLOE-2

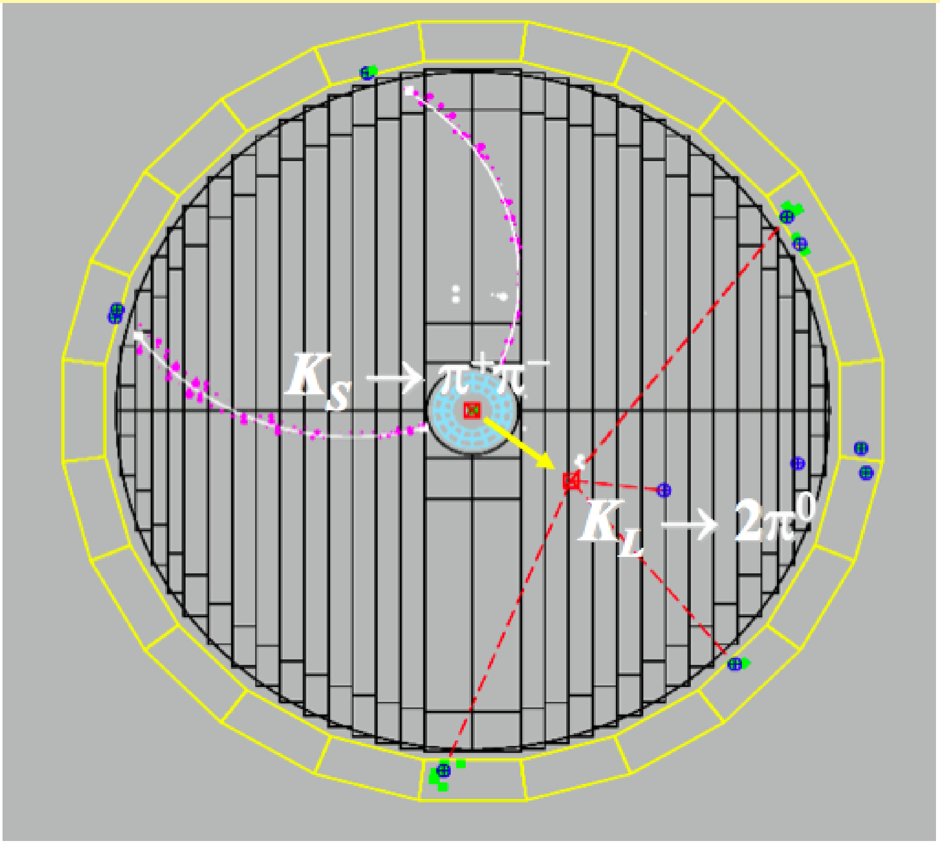
KLOE-2 Physics Programme
arXiv:1003.3868
Eur. Phys. J. C68 (2010) 619

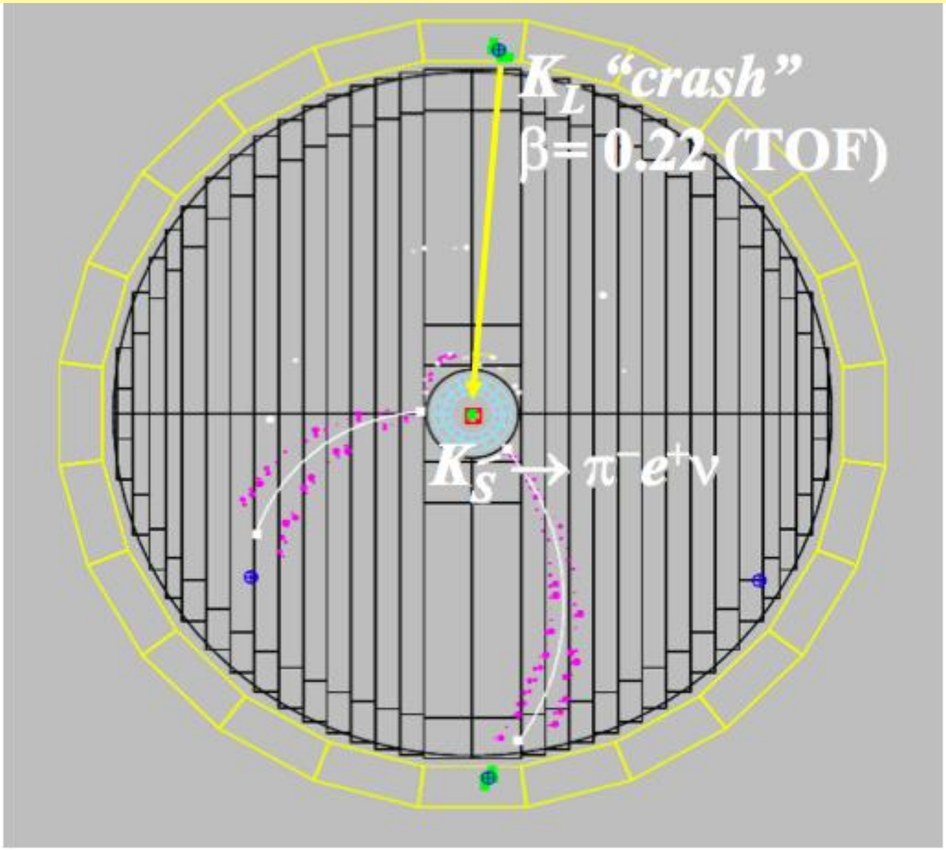
- Tests of descrete symmetries (CP, CPT, …)
- Tests of quantum mechanics
  -time-evolution of the entangled pairs of neutral kaons
  -passive kaonic quantum eraser (unique at KLOE)
- Universality of the weak interaction of leptons and quarks
- Lepton universality
  Search for possible deviations from SM expectation of $\Gamma(K^{\pm} \to e\nu)/\Gamma(K \to \mu\nu)$ to 0.4% precision
- Investigations of the structure of the scalar mesons
- Gamma gamma interaction
- Study of the muon anomalous magnetic moment α_{μ}
  and the evolution of the fine structure constant α_{em}
  determination of the excitation function for the $e^+e^- \rightarrow$ hadrons
- Dark Matter : search for narrow di-lepton resonances

Ks tagging a unique feature at KLOE

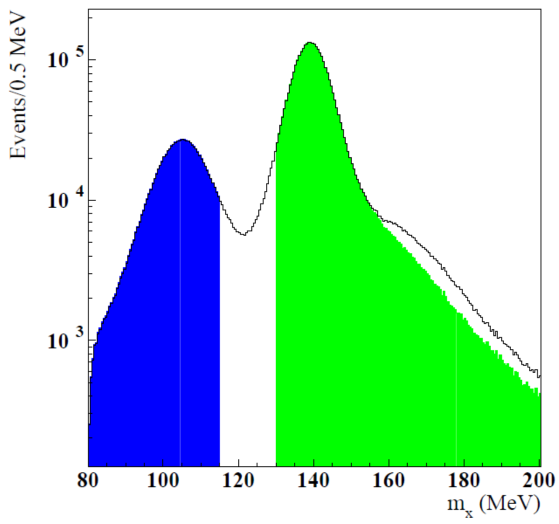
$$e^+e^- \rightarrow \varphi \rightarrow |K_{S,}p\rangle|K_{L,}\text{-}p\rangle - |K_{S,}\text{-}p\rangle|K_{L,}p\rangle$$

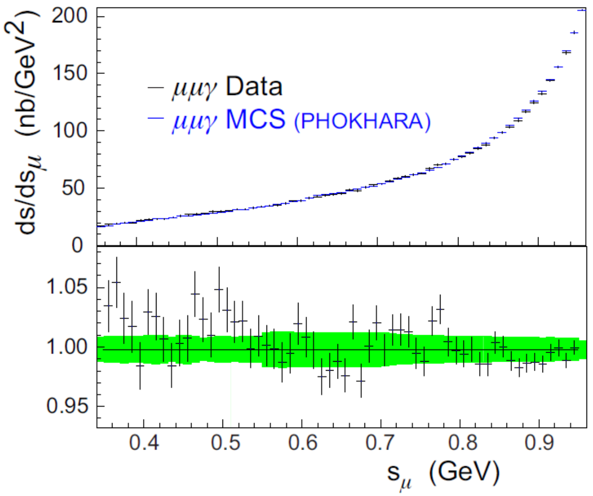
φ: $J^{CP} = 1^{--}$

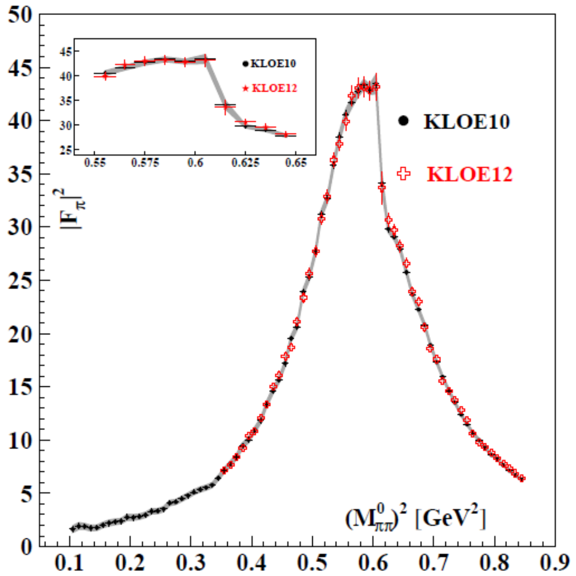




KLOE & KLOE-2: **Phys. Lett. B 720 (2013) 336**

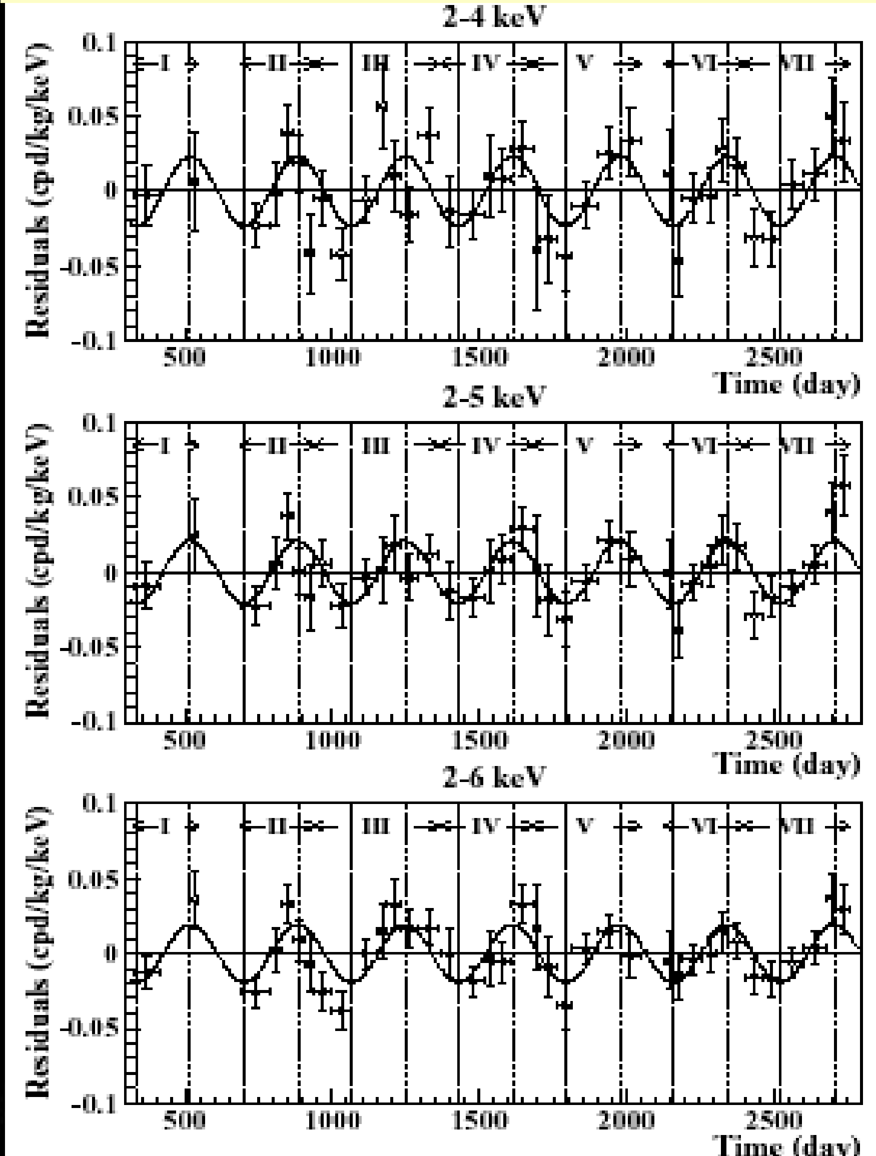






$$|F_\pi(s')|^2 = \frac{3}{\pi}\frac{s'}{\alpha^2\beta_\pi^3}\ \sigma^0_{\pi\pi(\gamma)}(s')(1+\delta_{VP})(1-\eta_\pi(s'))$$

DAMA/LIBRA

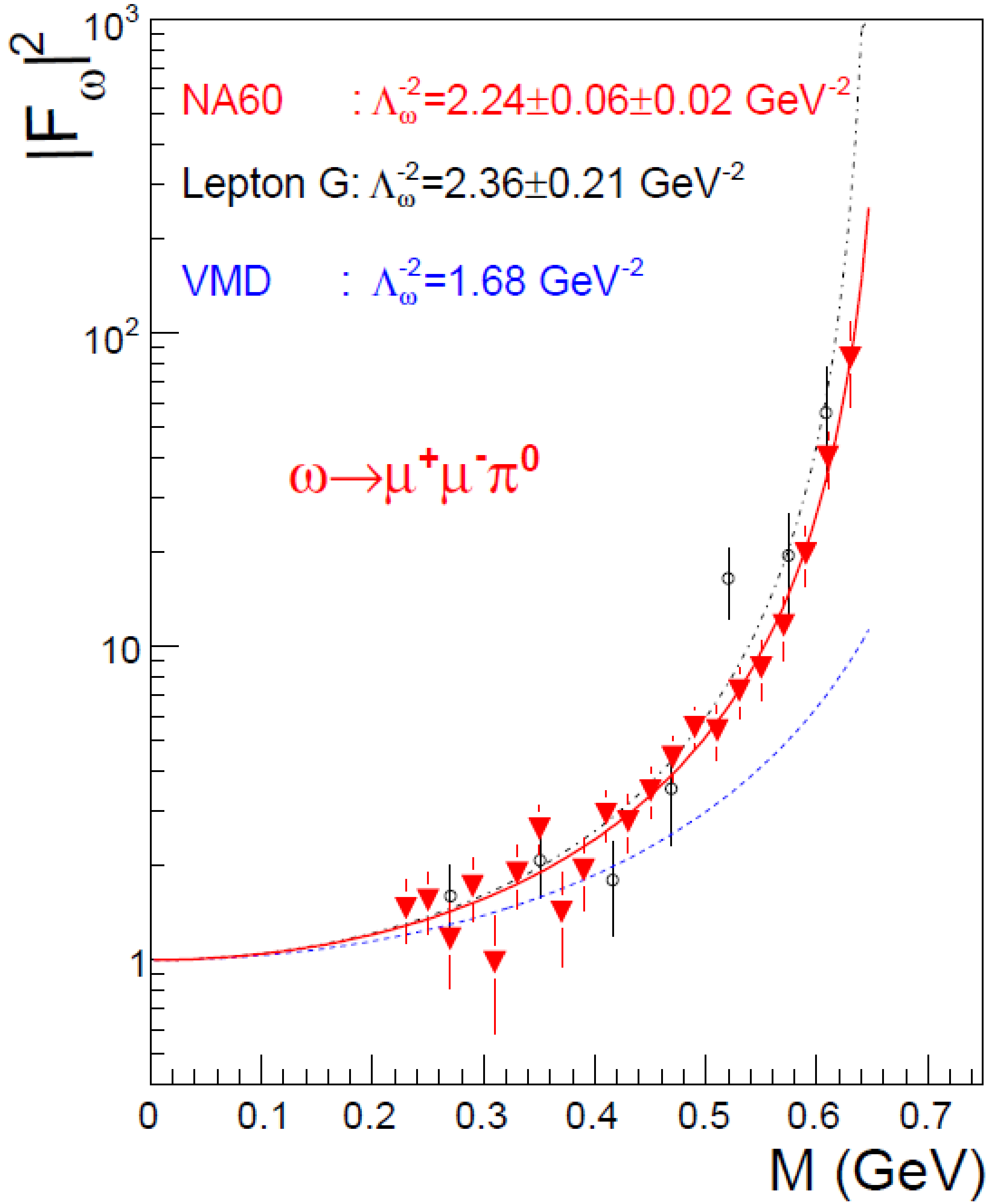


Charakterystyki sygnału

- cos(t)
- okres jednego roku
- faza – lato/zima
- niskie energie
- amplituda ≤ 7%
- sygnał w jednym detektorze

dopasowanie $A\cos[\omega(t-t_0)]$
A = (0.0200 ± 0.0032) cpd/kg/keV
t_0 = (140 ± 22) day
T = (1.00 ± 0.01) year

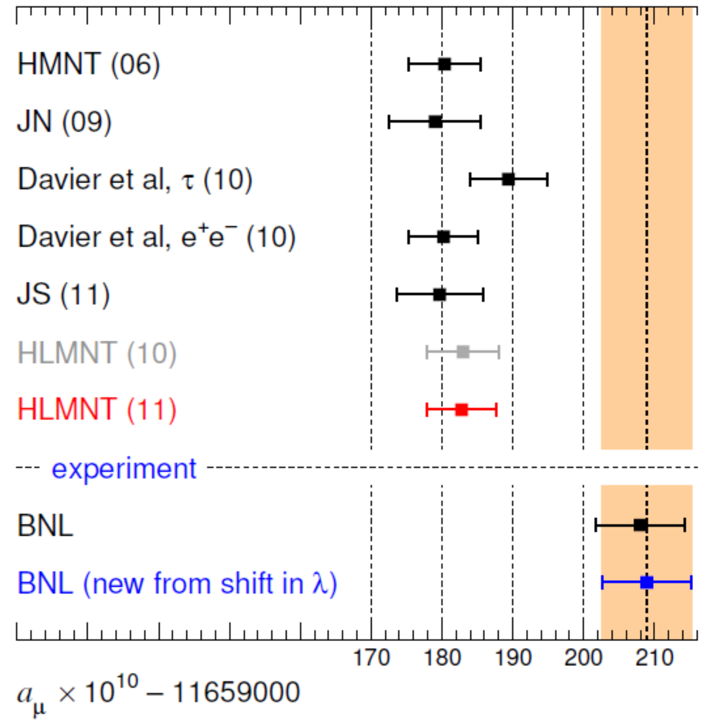
Źródło: astro-ph/0311046, 3 Listopad 2003



$|F_\omega|^2$
NA60 : Λ_ω^{-2}=2.24±0.06±0.02 GeV^{-2}
Lepton G: Λ_ω^{-2}=2.36±0.21 GeV^{-2}
VMD : Λ_ω^{-2}=1.68 GeV^{-2}
$\omega \to \mu^+ \mu^- \pi^0$
10^3
10^2
10
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
M (GeV)

Error	[6]	[7]	[4]	prospect
δa_μ^{SM}	6.5	4.9	4.9	3.5
δa_μ^{HLO}	5.3	4.2	4.3	2.6
δa_μ^{HLbL}	3.9	2.6	2.6	2.5
$\delta(a_\mu^{SM} - a_\mu^{EXP})$	8.8	8.0	8.0	4.0

Table 1: Estimated uncertainties δa_μ in units of 10^{-10} according to Refs. [6, 7, 4] and (last column) prospects in case of improved precision in the e^+e^- hadronic cross section measurement (the prospect on δa_μ^{HLbL} is an *educated guess*). Last row: Uncertainty on Δa_μ assuming the present experimental error of 6.3 from BNL-E821 [8] (first two columns) and of 1.6 (last column) as planned by the future $(g{-}2)$ experiments [9, 10].



The measurements of the muon anomaly a_μ have been a important benchmark for the development of QED and the Standard Model. In the recent years, following the impressive accuracy (0.54 ppm) reached by the E821 experiment at BNL, a worldwide effort from different theoretical and experimental groups has significantly improved the SM prediction. At present there appears to be a 3σ difference between the experimental value and the SM prediction of a_μ. This discrepancy, which would fit well with SUSY expectations, is a valuable constraint in restricting physics beyond the Standard Model, guiding the interpretation of LHC results. In order to clarify the nature of the observed discrepancy between theory and experiment, and eventually firmly establish (or constrain) new physics effects, new direct measurements of the muon $g{-}2$ with a fourfold improvement in accuracy have been proposed at Fermilab by E989 and J-PARC. First results from E989 could be available around 2017/18.

The experiment consists of repeated fills of the storage ring, each time introducing an ensemble of muons into a magnetic storage ring, and then measuring the two frequencies ω_a and ω_p. The muon lifetime at the magic momentum is 64.4 μs, and the data collection period is typically 700 μs. The $g-2$ precession period is 4.37 μs, and the cyclotron period ω_C 149 ns.
Because of parity violation in the weak decay of the muon, a correlation exists between the muon spin and the direction of the high-energy decay electrons. Thus as the spin rotates relative to the momentum, the number of high-energy decay electrons is modulated by the frequency ω_a, as shown in Fig. 6. The E821 storage ring was constructed as a super-ferric magnet, meaning that the iron determined the shape of the magnetic field. Thus the magnetic field needed to be well below saturation and was chosen to be 1.45 T. The resulting ring had a central orbit radius of 7.112 m, and 24 detector stations were placed symmetrically around the inner radius of the storage ring. The detectors were made of Pb/SciFi electromagnetic calorimeters which measured the decay electron energy and time of arrival. The detector geometry and number were optimized to detect the high energy decay electrons, which carry the largest asymmetry, and thus information on the muon spin direction at the time of decay. In this design, many of the lower-energy electrons miss the detectors, reducing background and pileup.

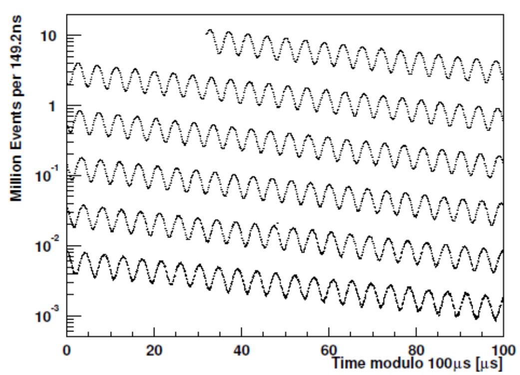


Figure 6: Distribution of electron counts versus time for the 3.6 billion muon decays. The data are wrapped around modulo 100 μs [8].