JAGIELLONIAN UNIVERSITY
IN KRAKOW

Recent results and perspectives with KLOE-2

Eryk Czerwiński (Jagiellonian University)
on behalf of KLOE-2 collaboration

FPCapri2016

NATIONAL SCIENCE CENTRE
POLAND

Outline

- DAΦNE collider and KLOE detector
- U boson search in $e^+e^- \rightarrow U\gamma$, $U \rightarrow \pi^+\pi^-$

  PLB 757 (2016) 356
- BR and Transition Form Factor of $\varphi \rightarrow \pi^0 e^+e^-$

  PLB 757 (2016) 362
- Dalitz plot analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$

  JHEP 1605 (2016) 019
- Quantum interferometry of K mesons
- CPT symmetry and Lorentz invariance test

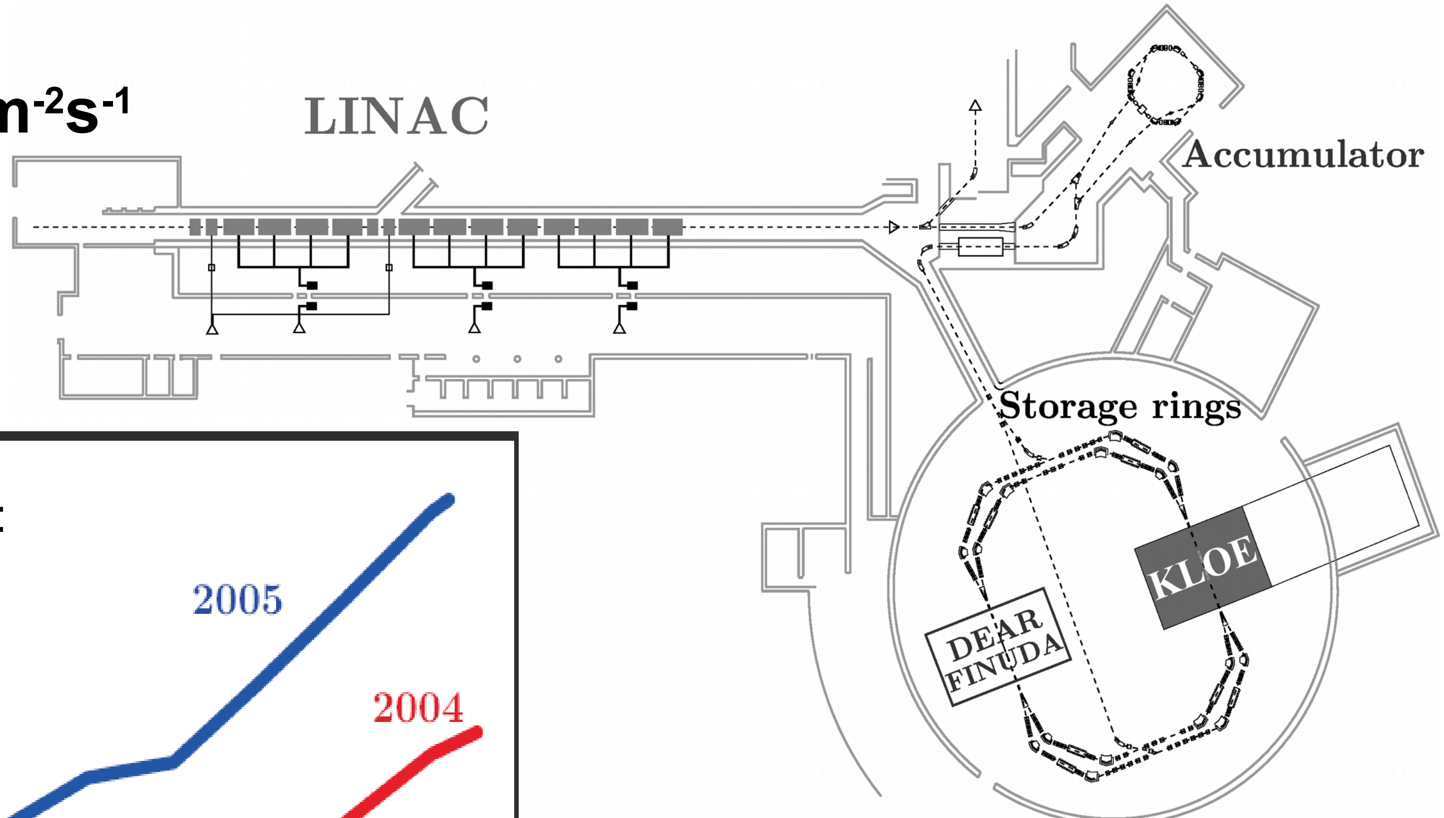
  PLB 730 (2014) 89
- Ongoing discrete symmetry tests
- KLOE-2 project
- Summary

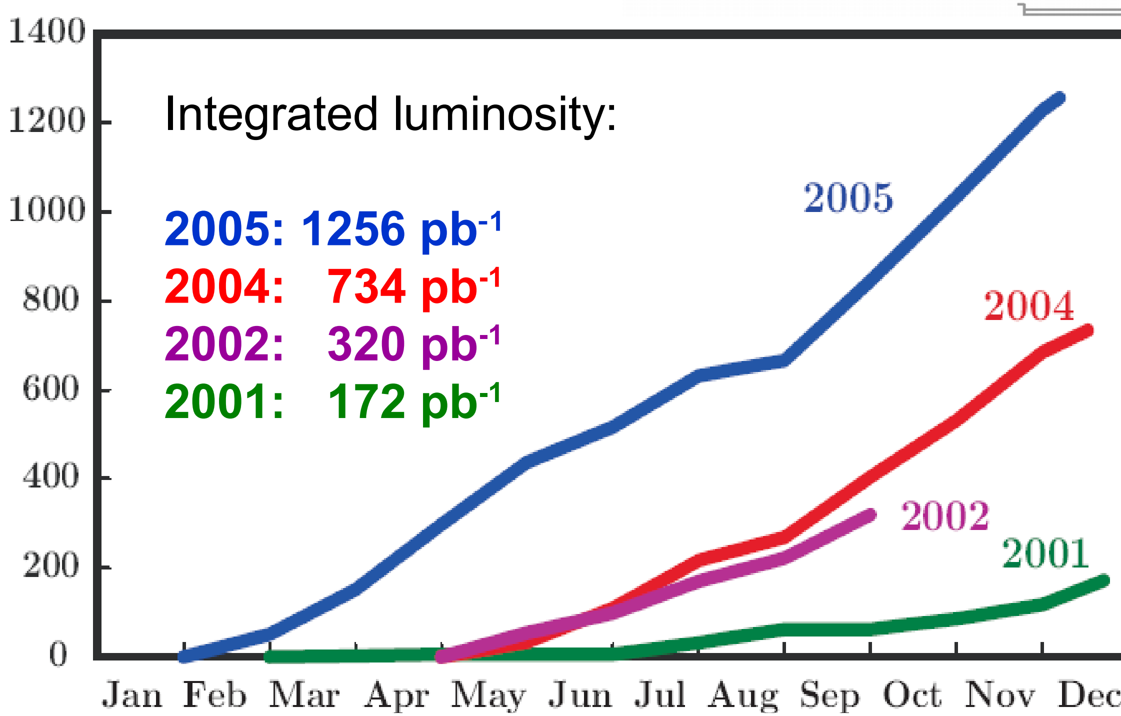
DAΦNE e^+e^- collider

1999-2007:

$\mathcal{L}_{peak} = 1.4 \times 10^{32}\ cm^{-2}s^{-1}$

$\int \mathcal{L} dt = 8.5\ pb^{-1}/day$





e^+e^- collider with two storage rings and two interaction points

KLOE *K LOng Experiment*

Drift chamber

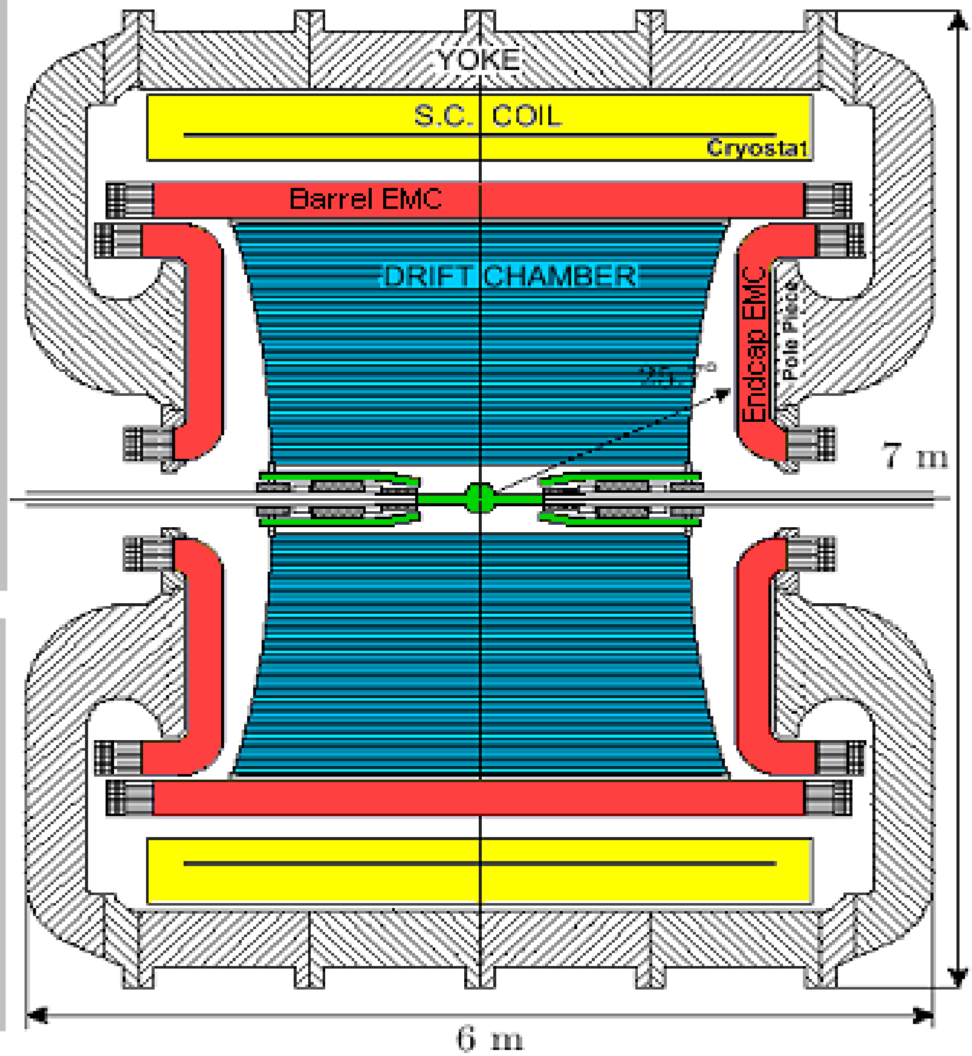
- gas mixture: 90% He + 10% C_4H_{10}
- $\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm

Electromagnetic calorimeter

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

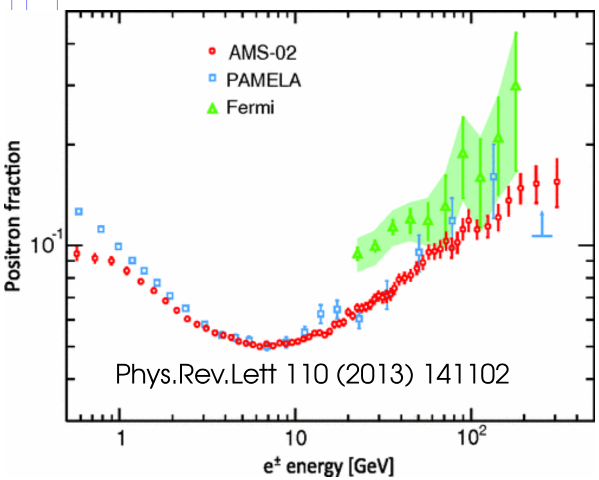
Data taking ended on March 2006

- 2.5 fb^{-1} on tape @ $\sqrt{s} = M_\phi$ ($8\times10^9\ \varphi$ => 6.6×10^9 kaon pairs)
- ~10 pb^{-1} @ 1010, 1018, 1023, 1030 MeV
- 250 pb^{-1} @ 1000 MeV



Dark photon @KLOE

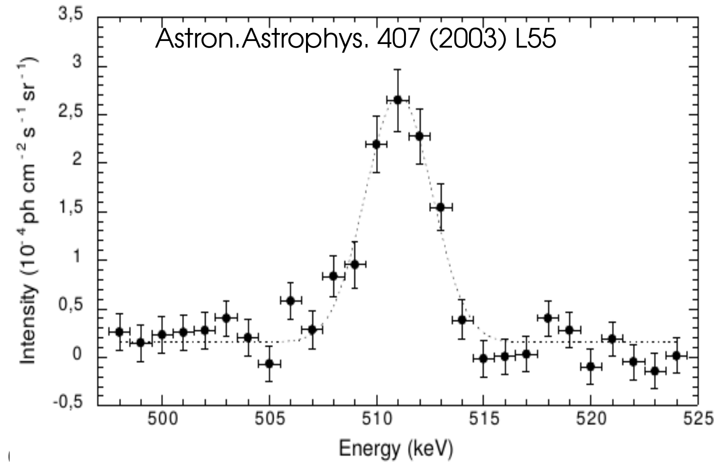
Dark force – search motivation



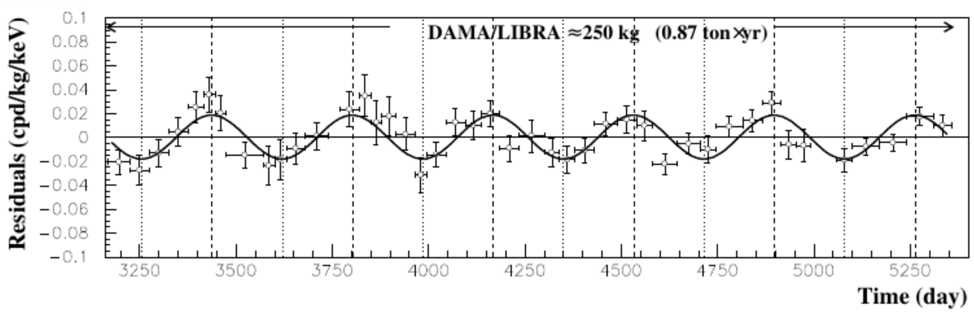
positron excess in the cosmic ray flux
no similar effect for antiprotons

511 keV gamma ray signal from the galactic center seen by the INTEGRAL satellite

the annual modulation measured by DAMA/LIBRA...



2-4 keV Eur. Phys. J. C (2010)



… and muon magnetic moment anomaly

explained with:

- Weakly Interacting Massive Particles charged under new type of interaction
- new gauge interaction mediated by a new boson: the U boson (also known as dark photon)

Dark photon @KLOE

gauge boson of the dark forces

light vector boson

could be produced in WIMP annihilations

couples to an ordinary photon through small kinetic mixing

$\varepsilon^2 = \alpha' / \alpha_{EM}$ – kinetic mixing parameter

$\varepsilon^2 \sim 10^{-8} - 10^{-3}$

=> effects observable in O(GeV)

energy scale colliders!

Analogously to the SM:

Spontaneous breaking of the $U(1)_D$ symmetry introduces **dark Higgs (h')**

@KLOE

Dalitz decays of Φ:

$e^+e^- \to \Phi \to \eta U$, $U \to e^+e^-$

$\eta \to \pi^+\pi^-\pi^0$ PLB 706 (2012) 251

$\eta \to \pi^0\pi^0\pi^0$ PLB 720 (2013) 111

Continuum processes $e^+e^- \to U\gamma$

$U \to \mu^+\mu^-$ PLB 736 (2014) 459

$U \to e^+e^-$ PLB 750 (2015) 633

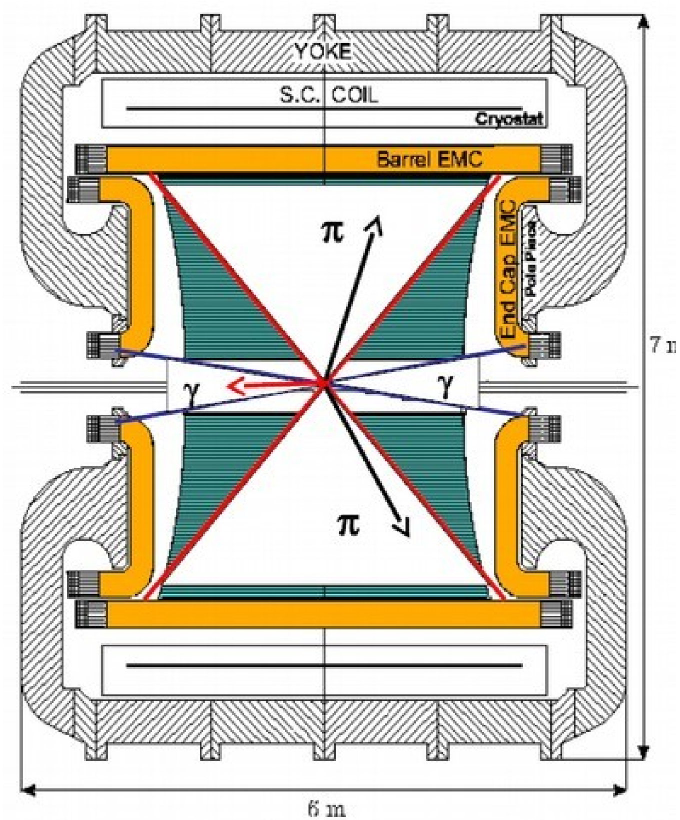
$U \to \pi^+\pi^-$ PLB 757 (2016) 356

Higgsstrahlung process:

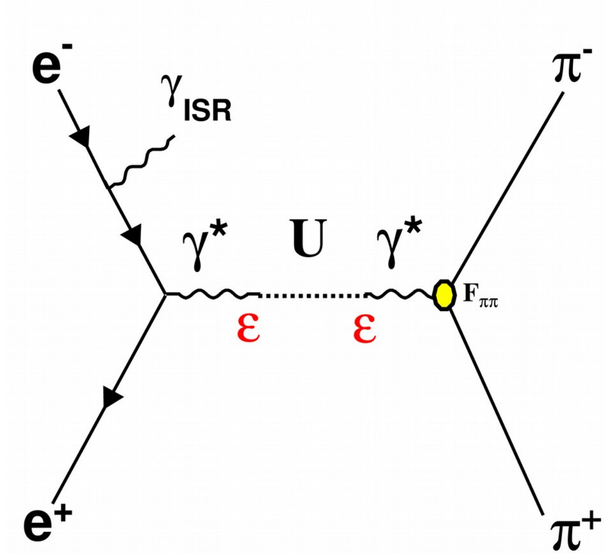
$e^+e^- \to Uh'$ PLB 747 (2015) 365

$e^+e^- \to U\gamma \to \pi^+\pi^-\gamma$ **Phys. Lett. B757 (2016) 356**

1.93 fb^{-1} of KLOE data



In the ρ-ω region dominant branching fraction into hadrons limits sensitivity of leptonic channels



2 tracks ($50^o<\theta_\mu<130^o$)

undetected ISR γ ($\theta_\gamma<15^o$ or $\theta_\gamma>165^o$)

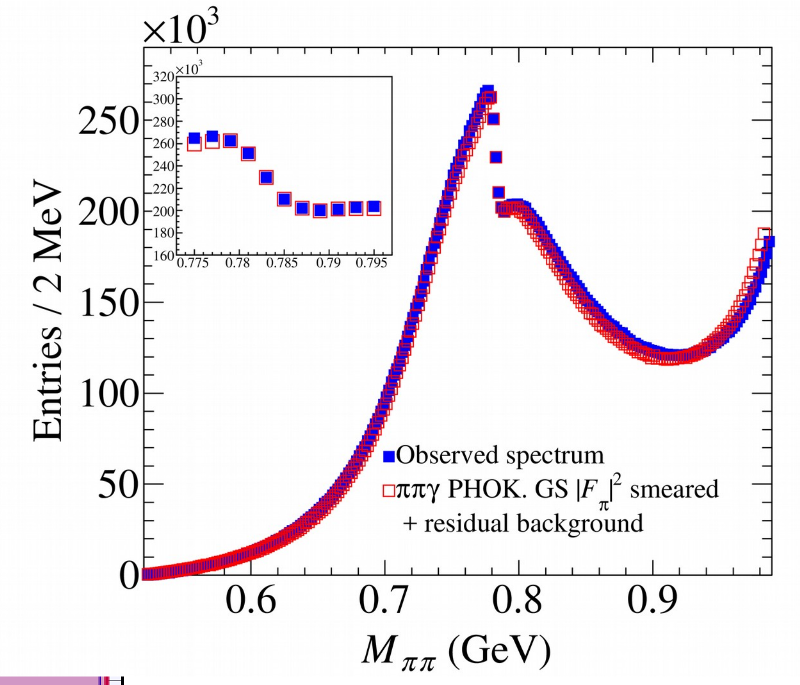
strong suppression of FSR and $\Phi\to\pi^+\pi^-\pi^0$

selection based on kimenatical variables

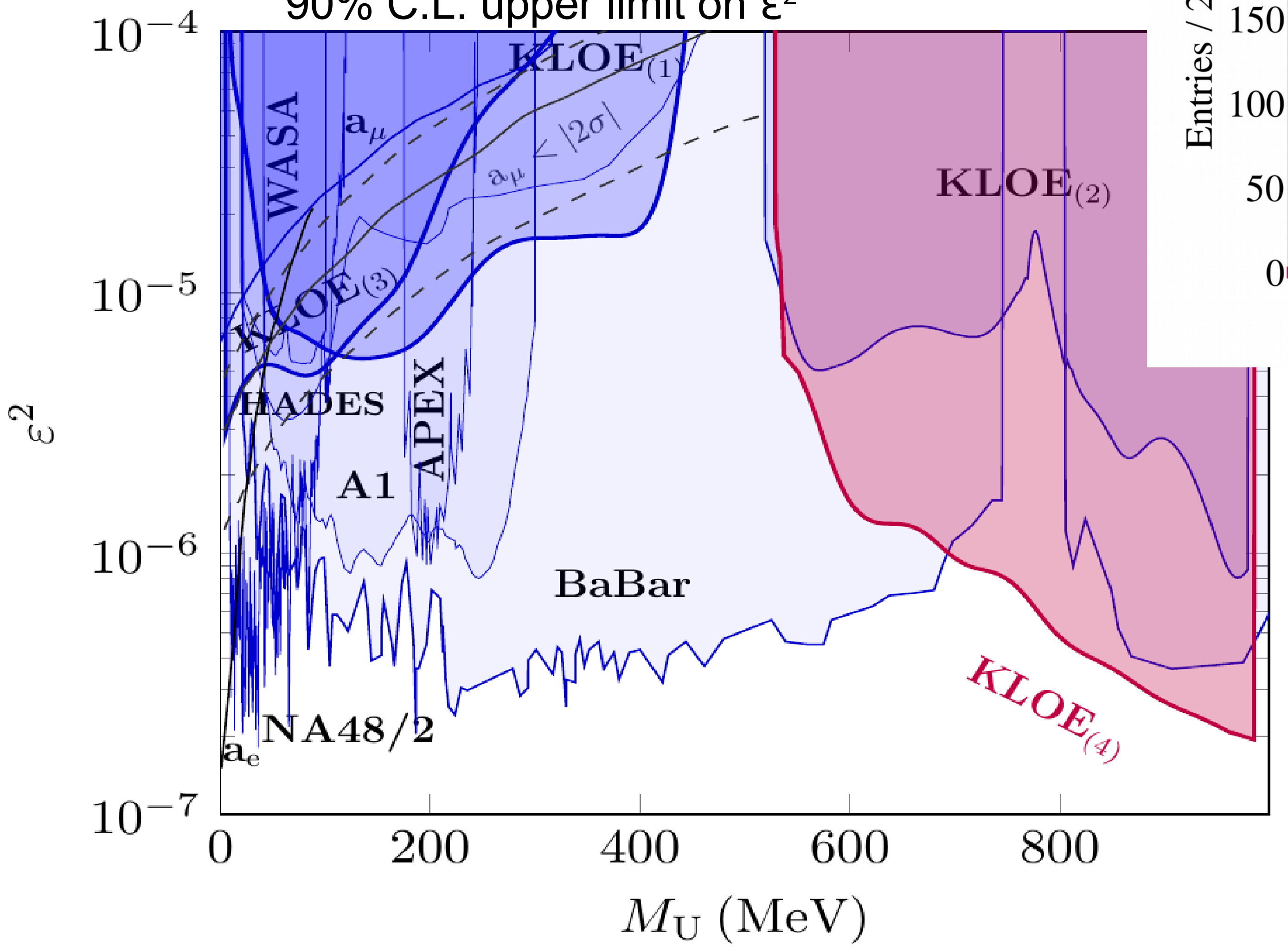
$e^+e^- \to U\gamma \to \pi^+\pi^-\gamma$

Phys. Lett. B757 (2016) 356

dedicated simulation with PHOKHARA + Gounaris-Sakhurai pion form factor parametrisation [PRL 21 (1968) 24] to describe the ρ-ω region



90% C.L. upper limit on ε^2



KLOE(1) – Dalitz Φ→ηe+e-
KLOE(2) – e+e-→μ+μ-γ
KLOE(3) – e+e-→e+e-γ
KLOE(4) – e+e-→π+π-γ

Branching Ratio
and
Transition Form Factor
of
$\varphi \rightarrow \pi^0 e^+ e^-$ decay

BR and TFF of $\varphi \to \pi^0 e^+ e^-$ PLB 757(2016)362

1.69 fb^{-1} from the 2004-2005 KLOE data

Meson Transition Form Factors (TFF): as test on the theoretical description of meson structure, Light-by-Light contribution to a_μ, used for determination of upper limit on dark forces searches

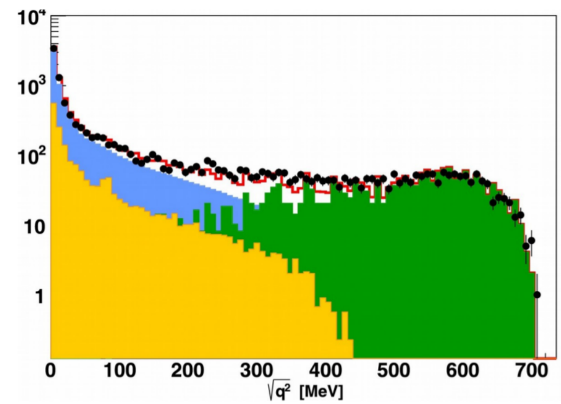
$$\mathrm{BR}\left(\phi \to \pi^0 e^+ e^-\right) = \left(1.35 \pm 0.05\ ^{+0.05}_{-0.10}\right) \times 10^{-5}$$

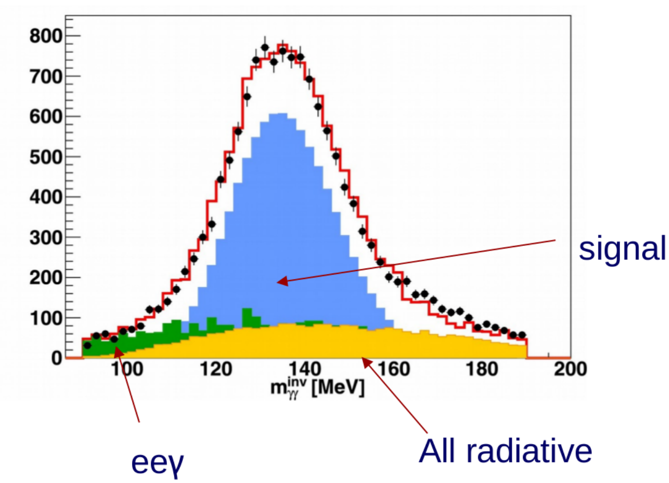
$b_{\Phi\pi 0} = 2.02 \pm 0.11\ \mathrm{GeV}^{-2}$

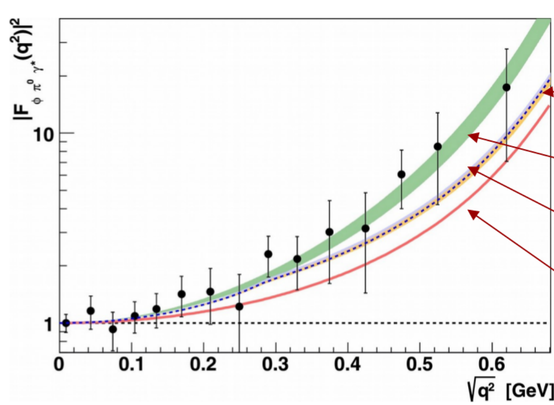
The first measurement of the transition form factor $|F_{\varphi\pi}(q)|$

~ 9500 signal events selected

Main background: radiative bhabha scattering and $\Phi \to \pi^0\ \gamma$







S. P. Schneider, B. Kubis, F. Niecknig, Phys. Rev. D 86 (2012) 054013. 219

S. Ivashyn, Prob. Atomic. Sci. Technol. 2012, N1 (2012) 179

I. Danilkin, et al., Phys. Rev. D 91 (2015) 094029

L. G. Landsberg, Phys. Rept. 128 (1985) 301

The Dalitz plot distribution of $\eta \rightarrow \pi^+\pi^-\pi^0$ decay

The η → π⁺π⁻π⁰ Dalitz plot distribution

JHEP 1605 (2016) 019

isospin violating process → mainly proceeds via strong interaction

constraint in the light quark masses

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \quad with\ \hat{m} = \frac{1}{2}(m_d + m_u)$$

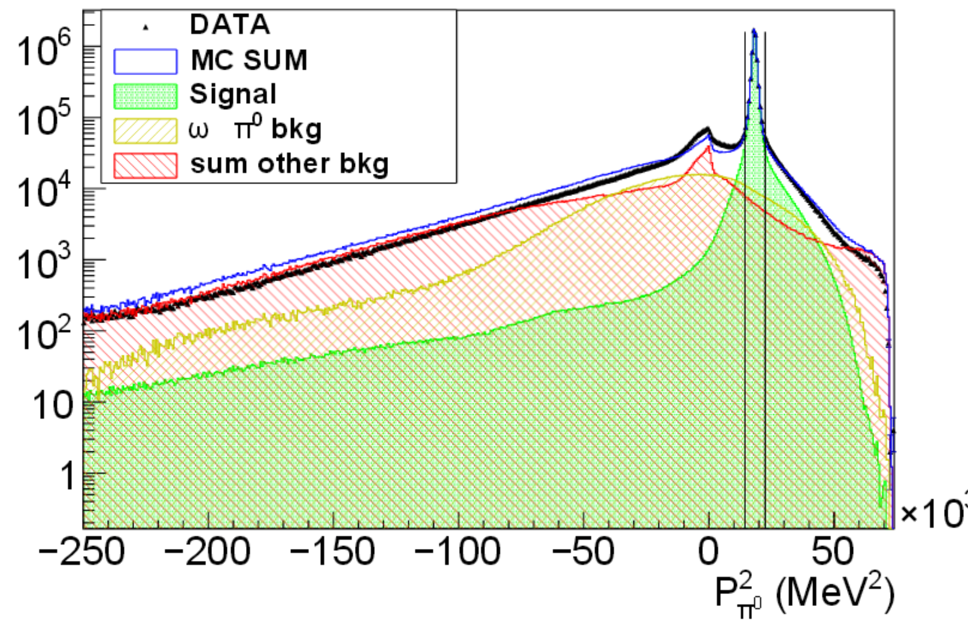
description of the low energy strong interactions (ChPT)

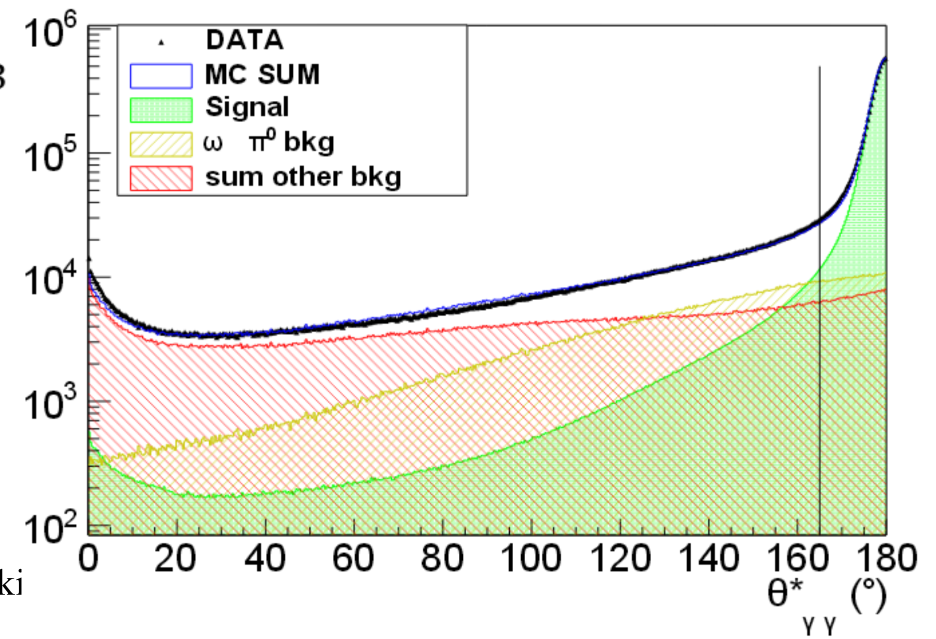
Dalitz density distribution in η-rest frame can be parametrized as a polinomial expansion around X = Y = 0

$$|A(X,Y)|^2 \approx 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \cdots$$

$$X = \sqrt{3}\frac{T_{\pi^+} T_{\pi^-}}{Q_\eta};\ Y = \frac{3T_{\pi^0}}{Q_\eta} - 1;\ Q_\eta = T_{\pi^+} T_{\pi^-} T_{\pi^0}$$

where (odd powers of X must be zero for C-invariance)





The $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution

JHEP 1605 (2016) 019

1.6 fb^{-1} from the 2004-2005 KLOE data

Dalitz plot parameters:

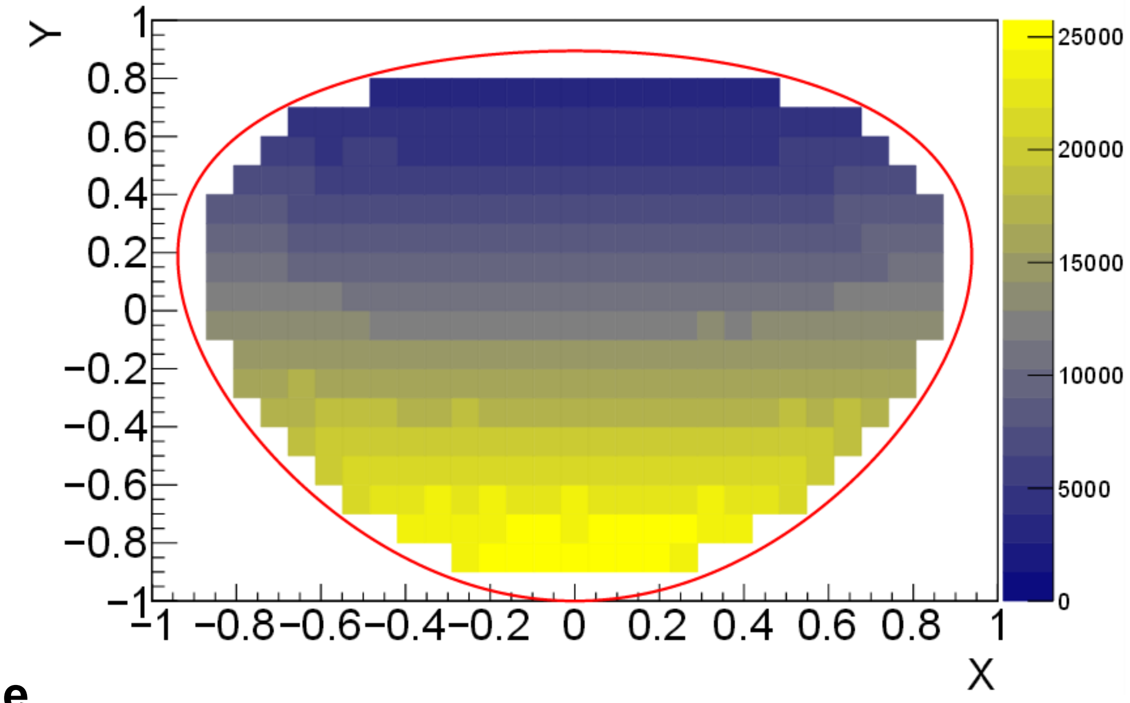
$$a = -1.095 \pm 0.003^{+0.003}_{-0.002}$$

$$b = +0.145 \pm 0.003 \pm 0.005$$

$$d = +0.081 \pm 0.003^{+0.006}_{-0.005}$$

$$f = +0.141 \pm 0.007^{+0.007}_{-0.008}$$

$$g = -0.044 \pm 0.009^{+0.012}_{-0.013}$$



~4.7 x 10^6 events

***g* parameter determined for the first time**

χ^2/ndof = 354/361

Prob = 0.60

Charge asymmetries:

$$A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}$$

$$A_Q = (+1.8 \pm 4.5^{+4.8}_{-2.3}) \cdot 10^{-4}$$

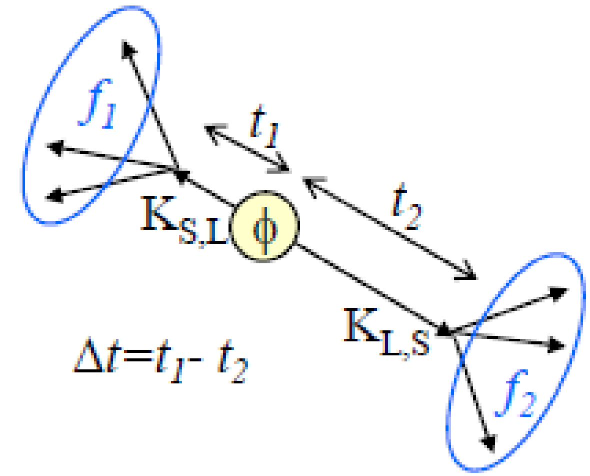
$$A_S = (-0.4 \pm 4.5^{+3.1}_{-3.5}) \cdot 10^{-4}$$

C-violating parameters consistent with zero

→ sensitive test using integrated charge asymmetries

Quantum interferometry of K mesons

Quantum interferometry



Quantum entanglement - the two decays are correlated even if kaons are distant in space
I(f1,f1; Δt=0)=0 Complete destructive quantum Interference prevents the two kaons from decaying into the same final state at the same time

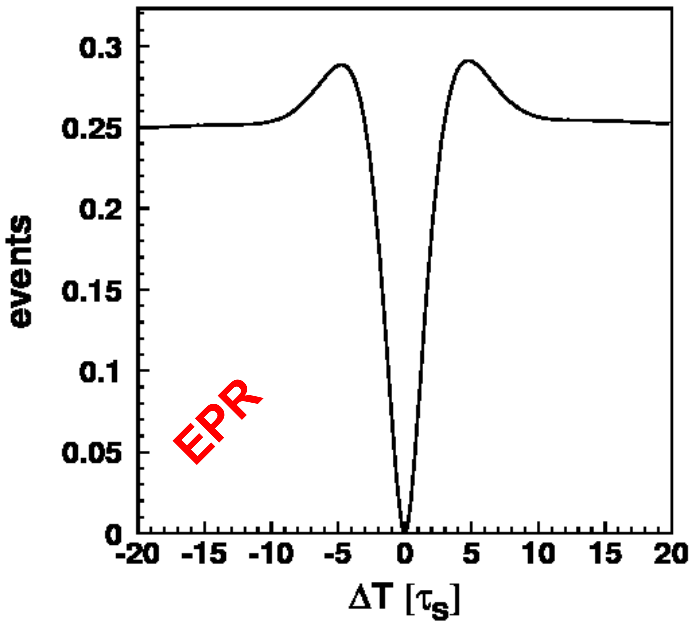
$$|i\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle|\overline{K}_0\rangle - |\overline{K}_0\rangle|K_0\rangle) = \mathcal{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle),$$

$$I(f_1,t_1;f_2,t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}\right\}$$

$$\left\{-2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos(\Delta m(t_2-t_1)+\varphi_1-\varphi_2)\right\}$$

interference term

$$\eta_j = \frac{\langle f_j|K_L\rangle}{\langle f_j|K_S\rangle}$$



$$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^0\pi^0 \Longrightarrow \frac{\varepsilon'}{\varepsilon}\ \text{(CPV)}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\pm \nu\ \pi^0\pi^0\pi^0, \pi\pi \Longrightarrow \text{T violation}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^- l^+ \nu\ \pi^+ l^- \bar{\nu} \Longrightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\mp \nu\pi\pi \Longrightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$
$$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^+\pi^-\ \text{CPT, Quantum Mechanics}$$

CPT & Lorentz invariance violation: Standard Model Extension framework

Using the same final state for both kaons ($\pi^+\pi^-$) the two decay are distinguished only by the kaon momentum direction. The decay amplitude is written as follows:

$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_1\eta_2^* e^{-i\Delta m\Delta\tau}\right)\right]$$

$$\eta_1 = \eta_\pm = \varepsilon_K - \delta(\vec{p}_{K^1}) \qquad \eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2})$$

δ_K is the CPT violation parameter in the Kaon system.

According to the SME (Kostelecky) [*PRD64,076001*] and anti-CPT theorem, CPT violation should appear together with Lorentz Invariance breaking (Greenberg) [*PRL89,231602*], and thus implying a direction dependent modulation.

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

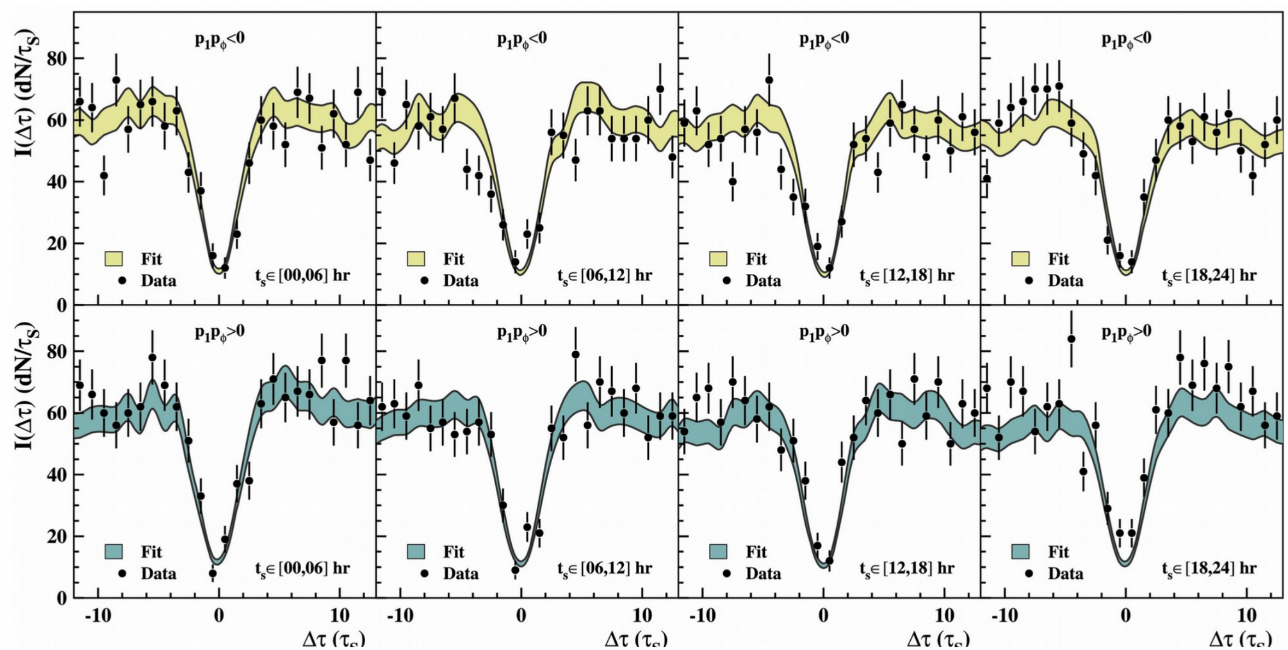
Ordering Kaon according to their momenta it is possible to have the two η–coefficients containing two different δ_K CPT violating parameter.

Final results on CPT & Lorentz invariance tests

The best sensitivity ever reached in the quark sector

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

KLOE-2 Collaboration: Phys. Lett. B 730 (2014) 89



Ongoing symmetries test in transition

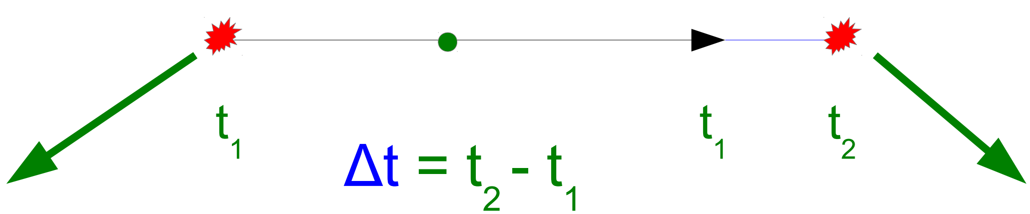
$A \leftrightarrow B$

$$S|K^0\rangle = +1|K^0\rangle$$
$$S|\overline{K^0}\rangle = -1|\overline{K^0}\rangle$$

$$\overline{K^0} \rightarrow \pi^+ l^- \overline{\nu_l} \quad S = -1$$
$$K^0 \rightarrow \pi^- l^+ \nu_l \quad S = +1$$

$$|K_1\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle + |\overline{K^0}\rangle] \quad CP = +1$$
$$|K_2\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle - |\overline{K^0}\rangle] \quad CP = -1$$
$$K_1 \rightarrow \pi\pi \quad CP = +1$$
$$K_2 \rightarrow 3\pi^0 \quad CP = -1$$

$|K^0\rangle$ φ $|\overline{K^0}\rangle \rightarrow |K_2\rangle$



$K \rightarrow \pi^- l^+ \nu$ $K \rightarrow 3\pi^0$

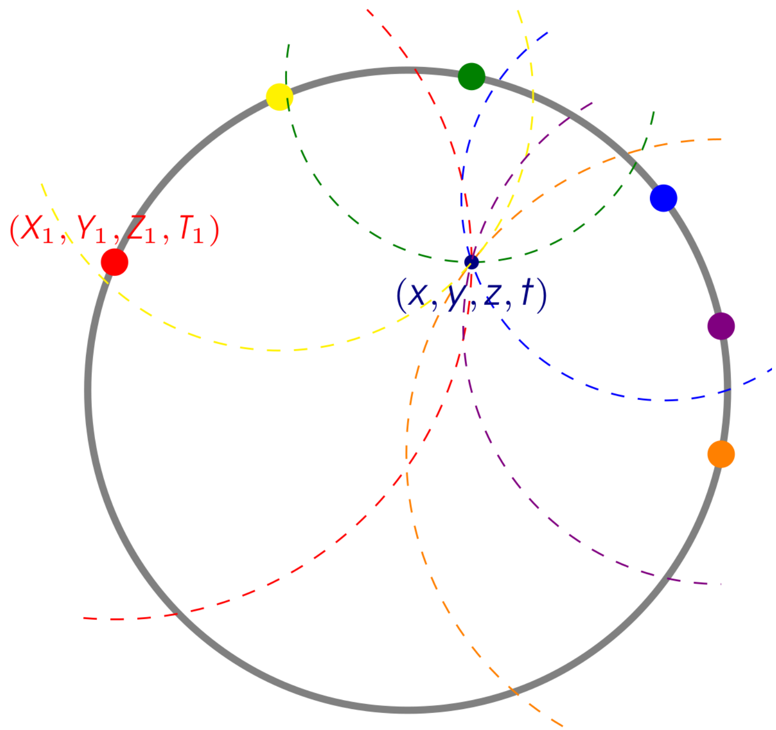
J. Bernabeu,
A. Di Domenico
and P. Villanueva-Perez:
Nucl. Phys. B 868 (2013) 102,
JHEP 10 (2015) 139

$$|\overline{K^0}\rangle \rightarrow |K_2\rangle \xrightarrow{T} |K_2\rangle \rightarrow |\overline{K^0}\rangle$$

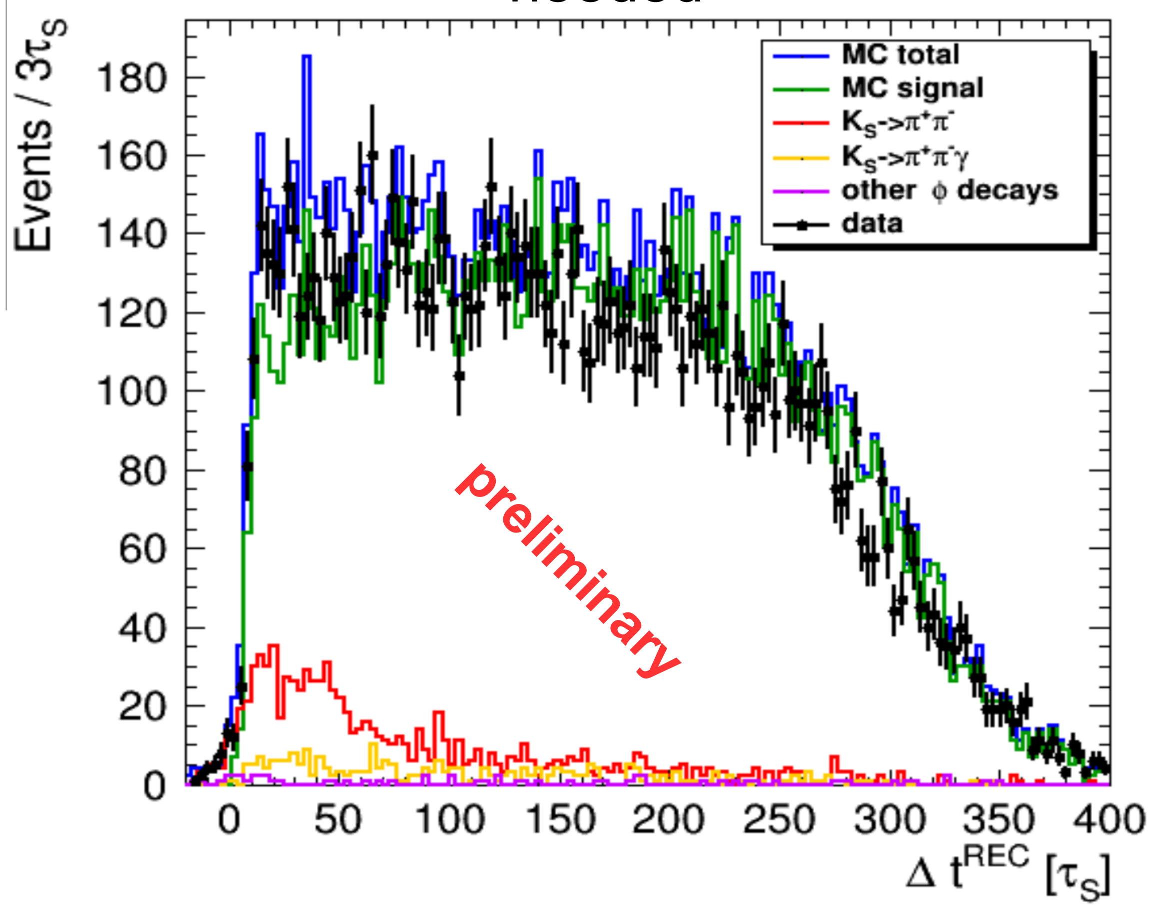
Ongoing symmetries test in transition

Reconstruction mathematically similar to GPS positioning: for each calorimeter hit - a set of possible γ origin points is a sphere $(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2$, i=1, . . . , 6.

Decay vertex lies on the intersection of the spheres, at least 4 of them necessary to find the $K_L \to 3\pi^0$ decay point and time, additional two γ hits can be used to improve accuracy of reconstruction with a kinematic.



$\varphi \to K_S K_L \to \pi^{\pm} l^{\mp} \nu 3\pi^0$ and $\varphi \to K_S K_L \to \pi^+ \pi^- \pi^{\pm} l^{\mp} \nu$ needed



Charge assymetry test for K_S

$$A_{S/L} = \frac{\Gamma(K_{S/L} \to \pi^- e^+ \nu) - \Gamma(K_{S/L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S/L} \to \pi^- e^+ \nu) + \Gamma(K_{S/L} \to \pi^+ e^- \bar{\nu})}$$

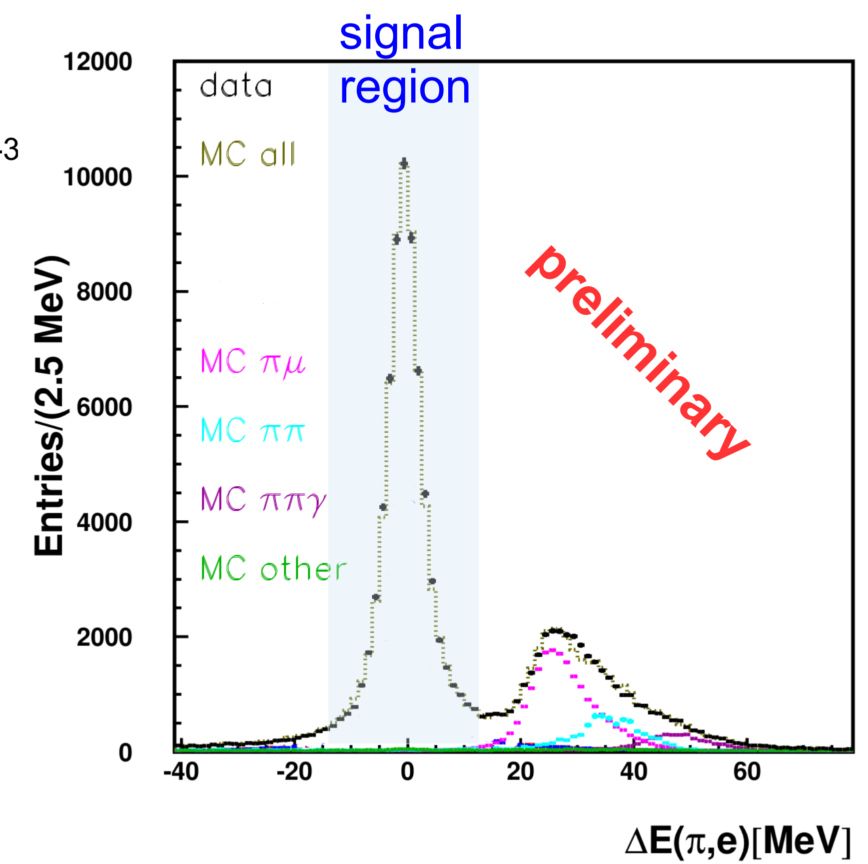
Finalization of new KLOE analysis with ~2 times improved statistical accuracy ($1.7 fb^{-1}$ data sample).

Assuming CPT invariance: $A_S = A_L = 2Re(\varepsilon_K) \approx 3 \times 10^{-3}$

$A_L = (3.332 \pm 0.058_{stat} \pm 0.047_{syst})$ x10-3
KteV collaboration, Phys. Rev. Lett. 88 (2002)

$A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst})$ x10-3
KLOE collaboration, PLB 636 (2006) 173

Determination of charge assymetries values for K_L and K_S tests fundamental assumptions of Standard Model.



$\Delta E(\pi, e) = E_{miss} - p_{miss}$

KLOE-2

KLOE-2 physics program

- **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);
- **$\gamma\gamma$ physics:**
  - existence (and properties) of $\sigma/f_0(600)$;
  - study of $\Gamma(S/PS\rightarrow\gamma\gamma)$;
  - PS transition form factor;
- **light meson spectroscopy:**
  - properties of scalar/vector mesons;
  - rare η decays;
  - η' physics;
- **dark forces searches:**
  - light bosons @ O(1 GeV);
- **hadronic cross section:**
  - $\alpha_{em}(M_Z)$ and (g-2).

Details in EPJ C68 (2010) 619, arXiv:1003.3868

KLOE-2 upgrades

Inner Tracker

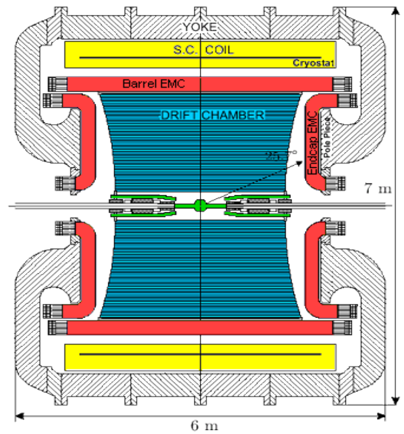
- 4 layers of cylindrical triple GEM
- better vertex reconstruction near IP
- larger acceptance for low p_t tracks

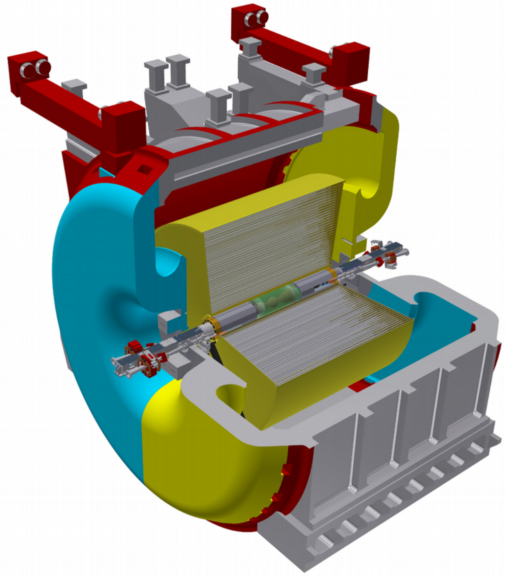
QCALT

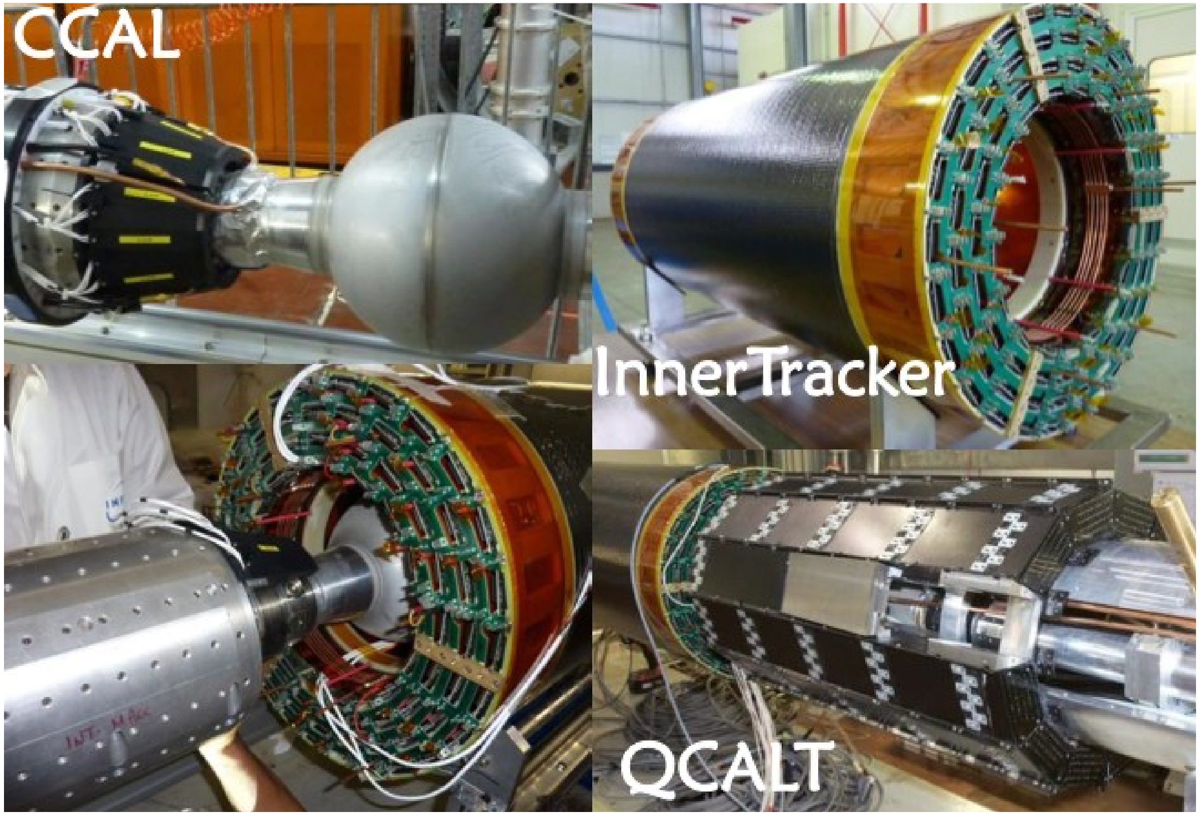
- W + scintillator tiles + SiPM/WLS
- QUADS instrumentation for K_L decays

CCALT

- LYSO + APD
- increase acceptance for γ's from IP (21°→8°)

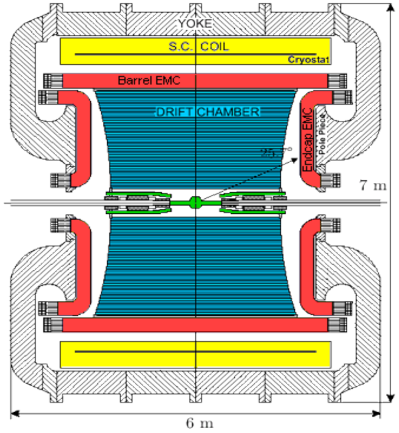


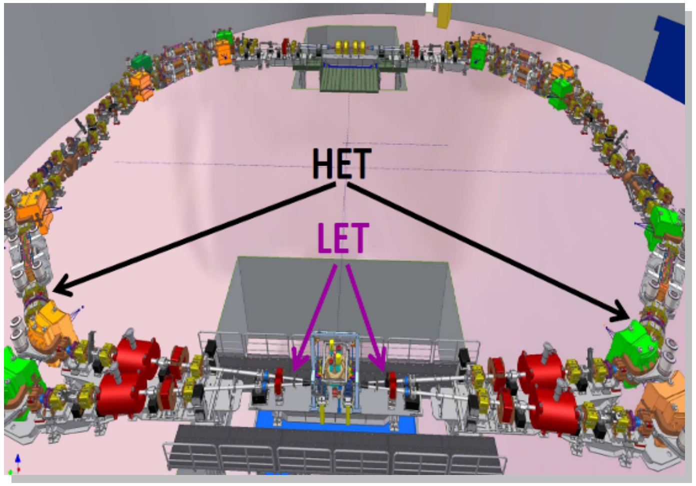




KLOE-2 upgrades

2+2 detector stations for leptons in $e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^- X$



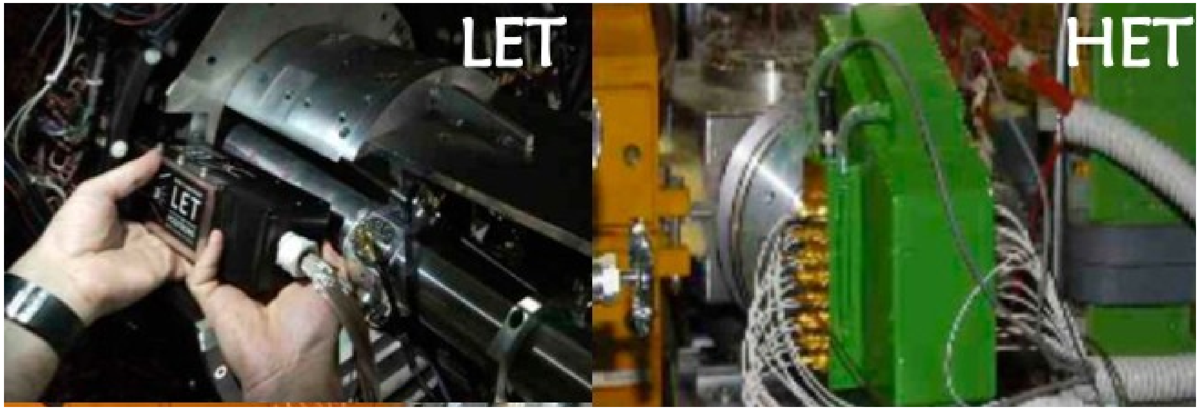


High Energy Taggers (HET)

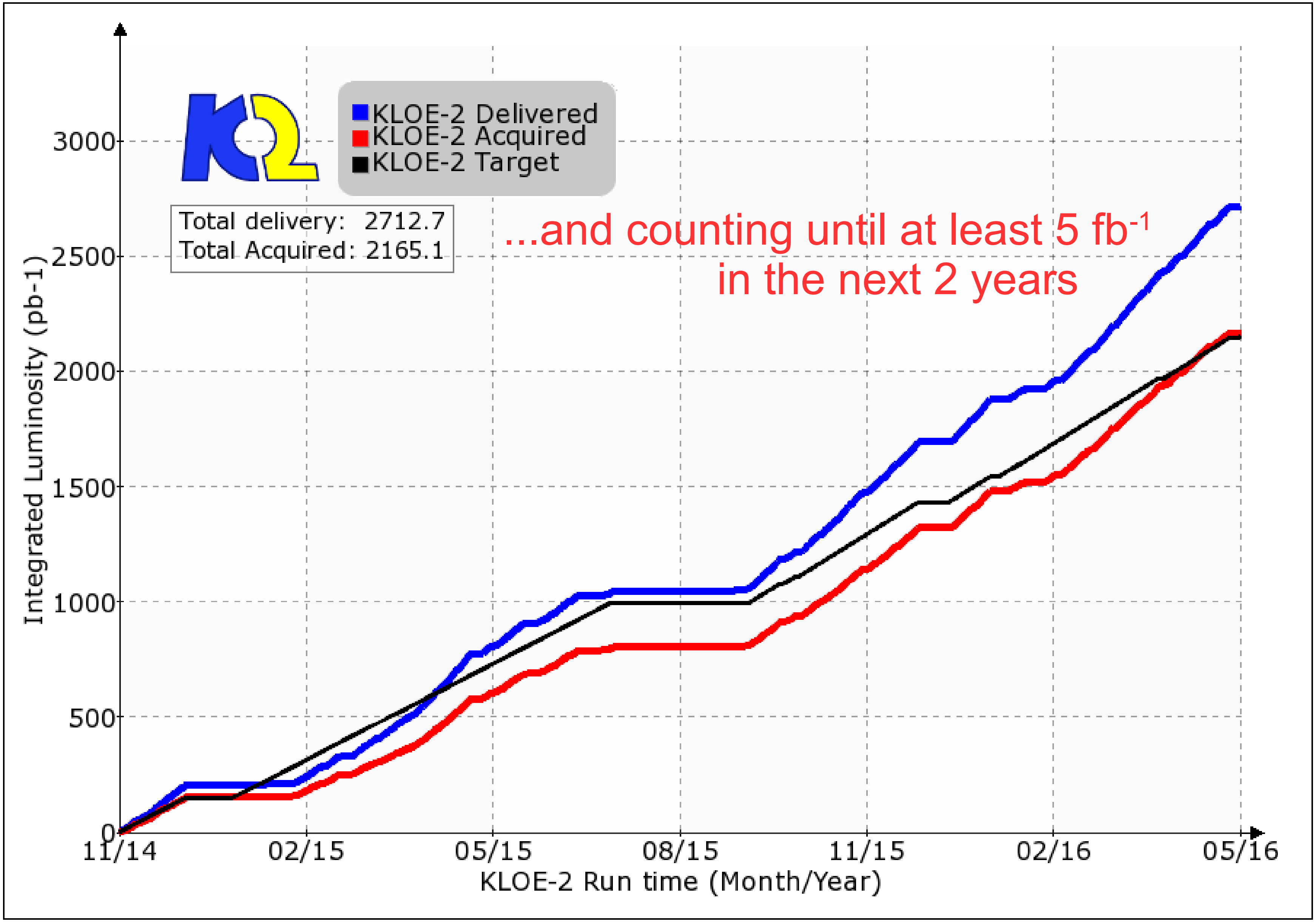
- E>400 MeV
- 11m from IP
- scintillators + PMTs

Low Energy Taggers (LET)

- E=160-230 MeV
- inside KLOE detector
- LYSO+SiPM



Luminosity KLOE-2 @ DAΦNE



Summary

- KLOE produced many interesting results in the recent years and it is still providing precise and competetive measurements:
  - dark photon, $e^+e^- \to U\gamma$, $U \to \pi^+\pi^-$, PLB 757 (2016) 356
  - BR and TTF, $\varphi \to \pi^0 e^+e^-$, PLB 757 (2016) 362
  - Dalitz plot analysis, $\eta \to \pi^+\pi^-\pi^0$, JHEP 1605 (2016) 019
  - CPT symmetry, Lorentz invariance test, PLB 730 (2014) 89
  - ongoing T and CPT symmetry tests

- The KLOE-2 quest will continue with a goal of at least 5fb^{-1} collection in the next 2 years

Thank you

Danke

Grazie

Merci

Dziękuję

ありがとう