JAGIELLONIAN UNIVERSITY
IN KRAKOW

CPT and T symmetry tests with entangled kaons

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

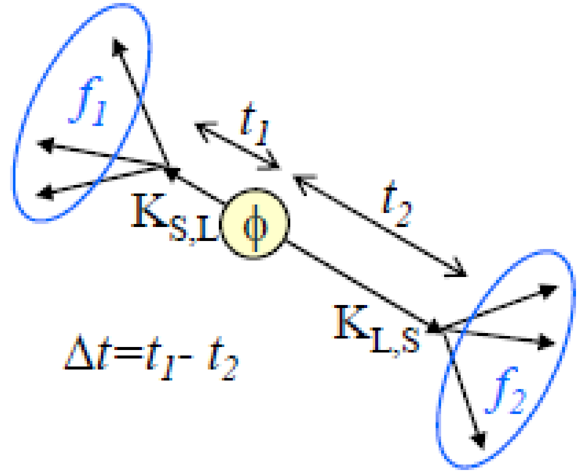
From the Vacuum to the Universe
Kitzbühel, 26.06.-01.07.2016

National Science Centre
Poland

Outline

- Quantum entanglement
- Decoherence
- CPT and Lorentz symmetry
- Other tests of discrete symmetries
- DAFNE collider and KLOE-2 detector

Quantum interferometry



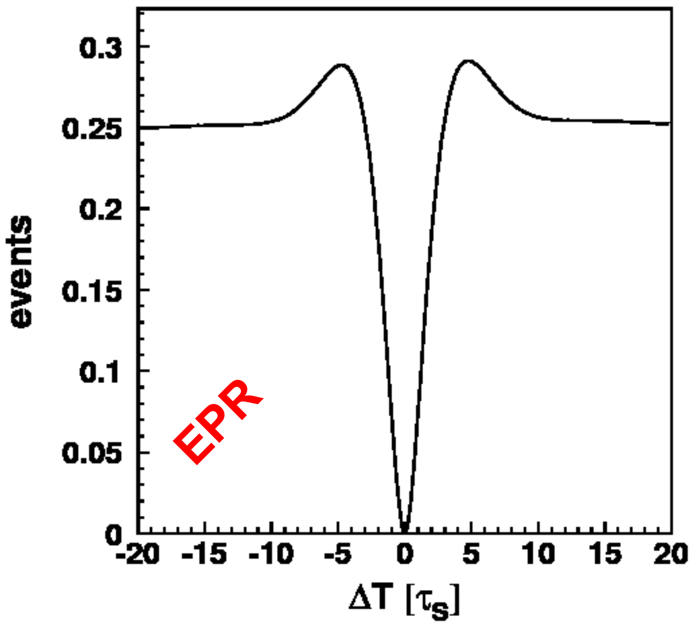
Quantum entanglement - the two decays are correlated even if kaons are distant in space
$I(f1,f1; \Delta t=0)=0$ Complete destructive quantum Interference prevents the two kaons from decaying into the same final state at the same time

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

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

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

interference term

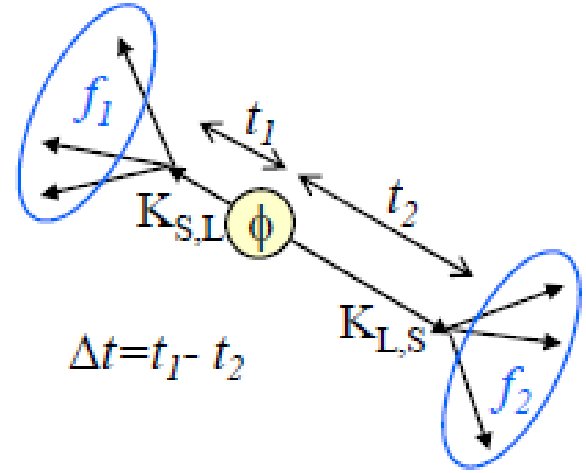


$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

$$C_{12} = \frac{|N|^2}{2} \left|\langle f_1|T|K_S\rangle\langle f_2|T|K_S\rangle\right|^2$$

$$f_i = \pi^+\pi^-,\ \pi^0\pi^0,\ \pi l \nu,\ \pi^+\pi^-\pi^0,\ 3\pi^0,\ \pi^+\pi^-\gamma \text{ ..etc}$$

Quantum interferometry



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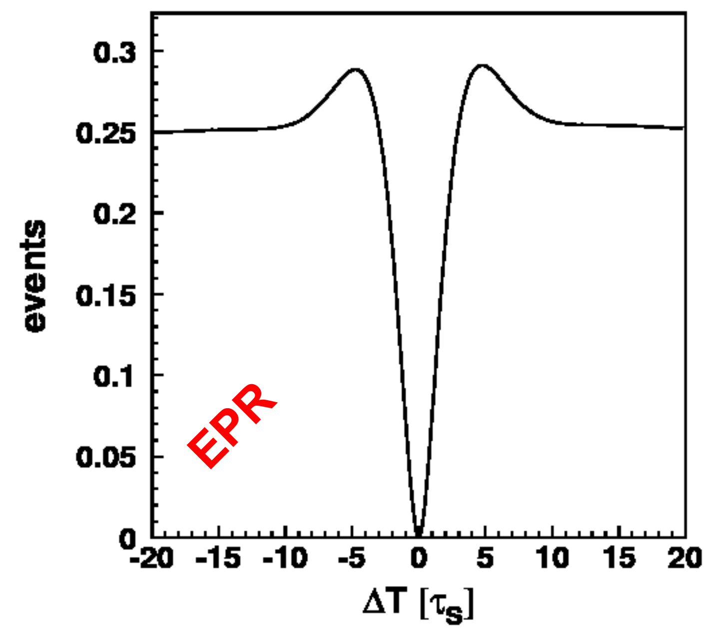


$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^0\pi^0 \Longrightarrow \frac{\varepsilon'}{\varepsilon}$ (CPV)

$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\pm \nu\, \pi^0\pi^0\pi^0, \pi\pi \Longrightarrow$ T violation

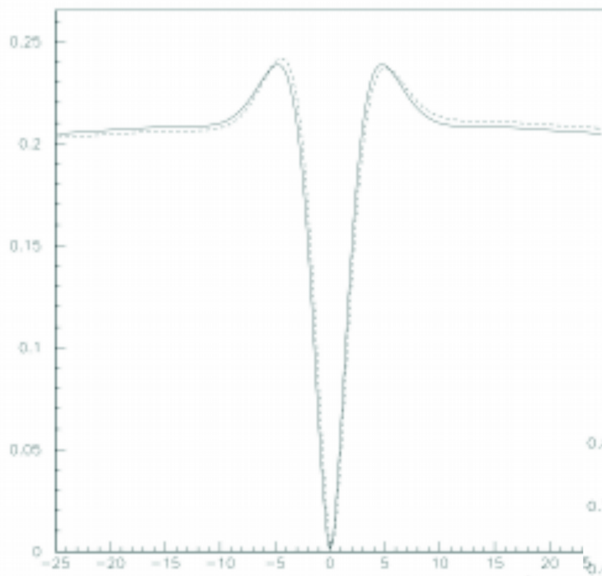
$\phi \longrightarrow K_S K_L \longrightarrow \pi^- l^+ \nu\, \pi^+ l^- \bar{\nu} \Longrightarrow$ CPT and $\Delta S = \Delta Q$

$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\mp \nu \pi\pi \Longrightarrow$ CPT and $\Delta S = \Delta Q$ rule

$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^+\pi^-$ CPT, Quantum Mechanics

Quantum interferometry

$I(\Delta t)$ (a.u)



$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^0\pi^0$

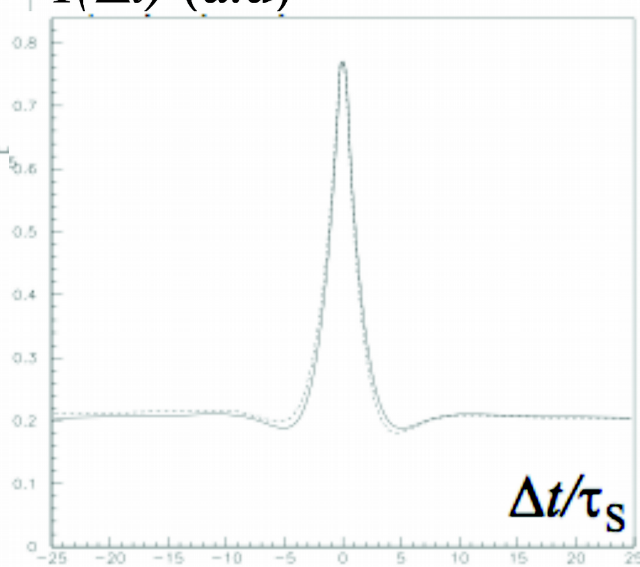
$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$\Re\delta + \Re x_-$$

$$\Im\delta + \Im x_+$$

$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \;\; \pi^-\ell^+\nu$

$I(\Delta t)$ (a.u)



$\Delta t/\tau_S$

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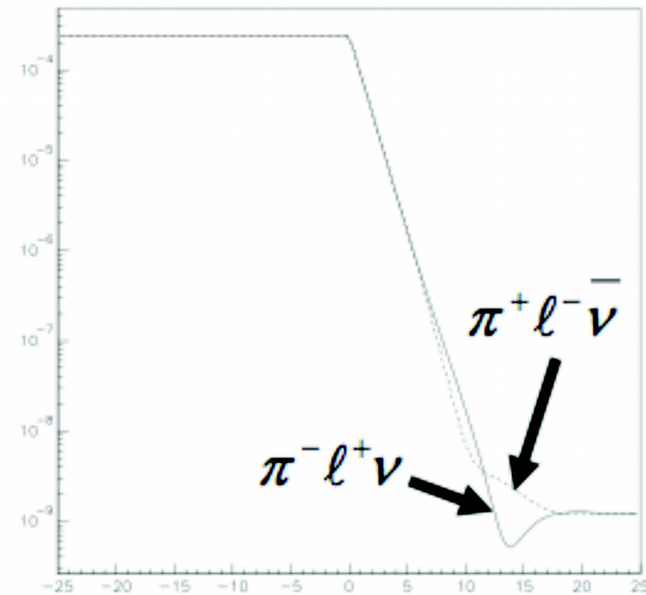

$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi\pi \;\; \pi\ell\nu$

$$A_L = 2\Re\varepsilon - \Re\delta - \Re y - \Re x_-$$

$$\phi_{\pi\pi}$$

Decoherence

Quantum entanglement - the two decays are correlated even if kaons are distant in space

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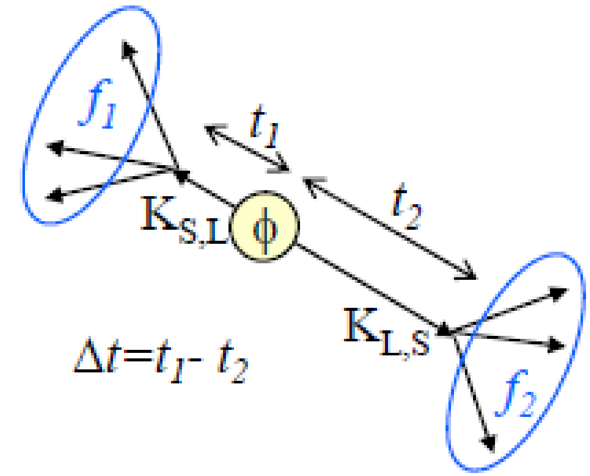


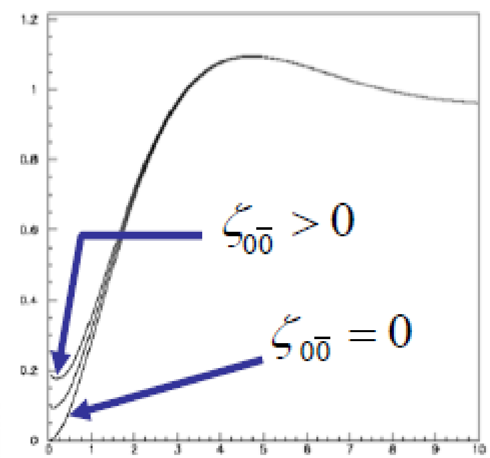
$$|i\rangle = \frac{1}{\sqrt{2}}\left(|K_0\rangle|\overline{K}_0\rangle - |\overline{K}_0\rangle|K_0\rangle\right) = \mathcal{N}\left(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle\right),$$

$$I(f_{1},t_1;f_{2},t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}\right.$$

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

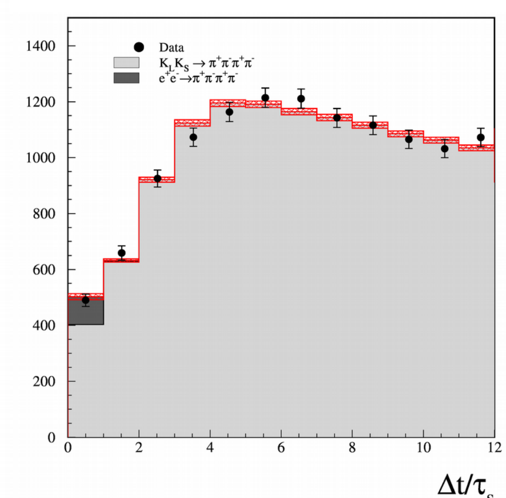
interference term

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



$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\Big[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle\right|^2$$

$$-(1-\zeta_{0\bar{0}})\cdot 2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\Big]$$



J.Phys.Conf.Ser. 171:012008 (2009)

$\xi_{0\bar{0}} = (1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}) \times 10^{-7}$

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 parameters.

Final results on CPT & Lorentz invariance tests

The best sensitivity ever reached in the quark sector

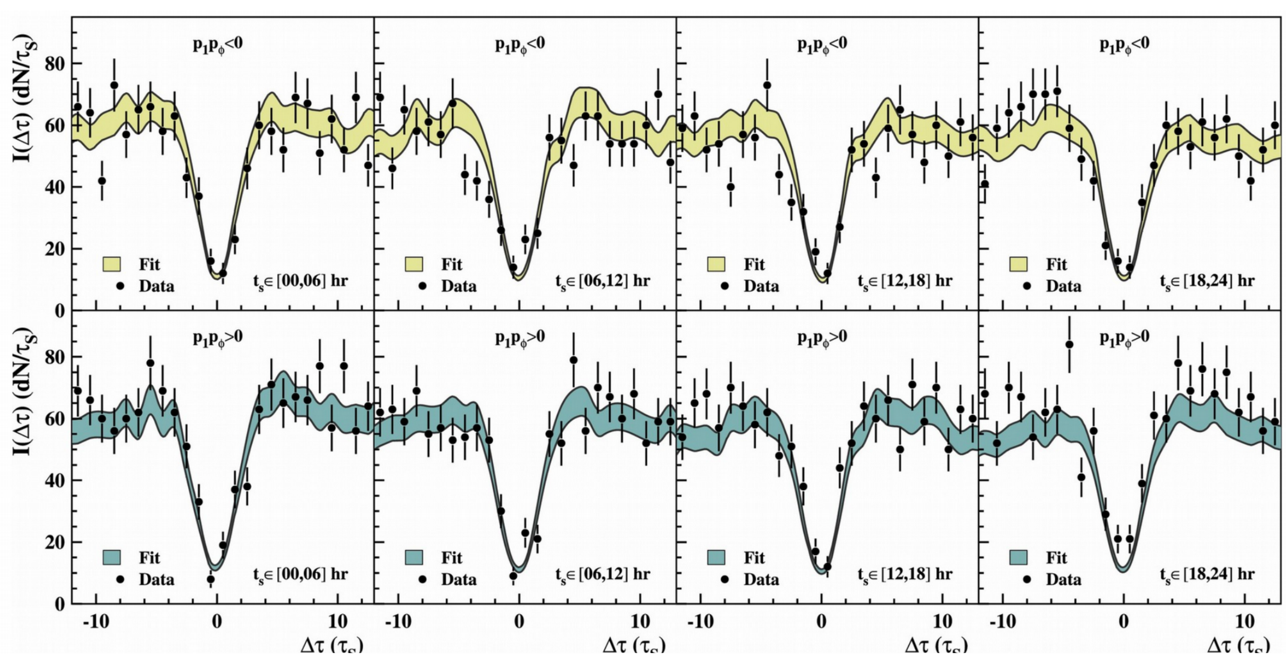
$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys})\ 10^{-18}$ GeV

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



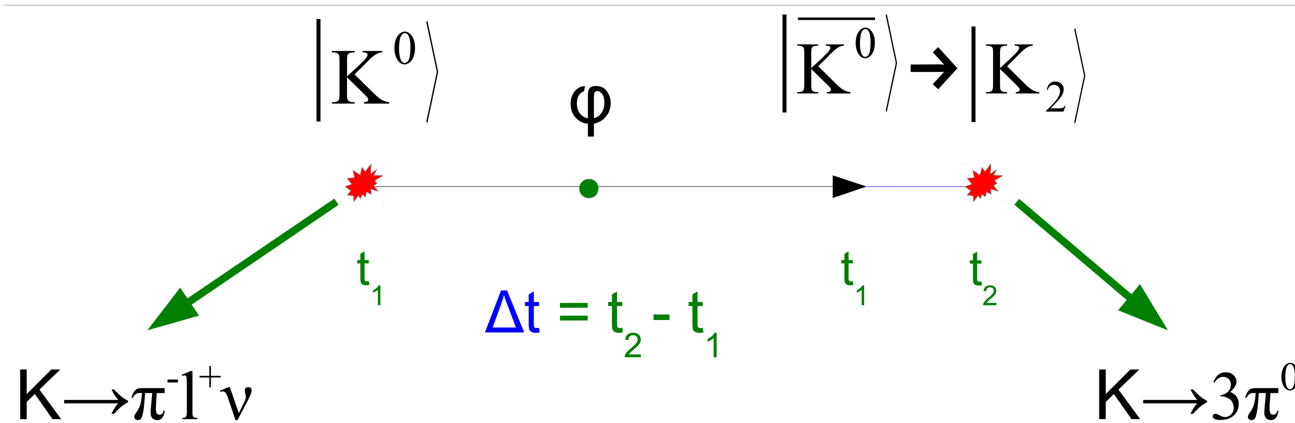
Ongoing symmetries test in transition

A ↔ B

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

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

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



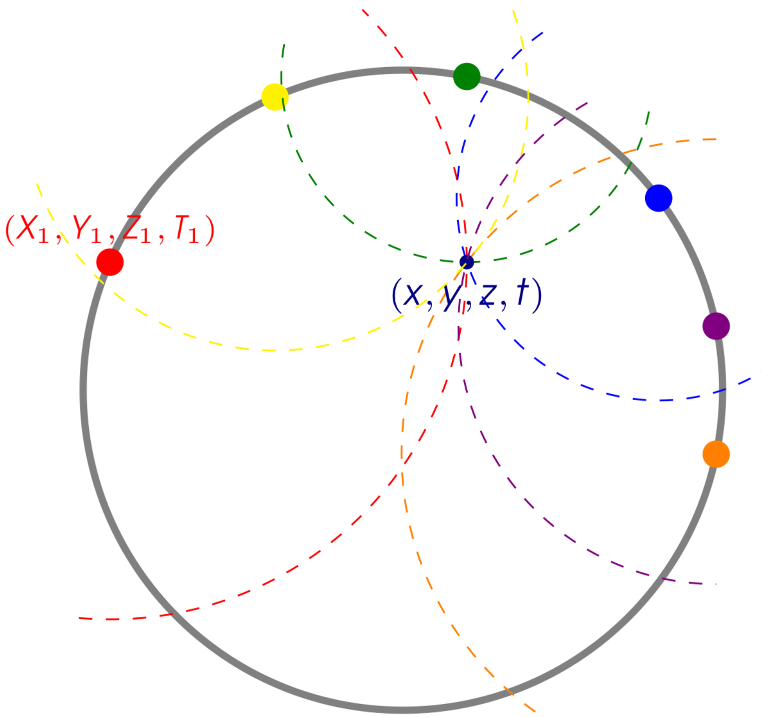
J. Bernabeu,
A. Di Domenico
and P. Villanueva-Perez:
Nucl. Phys. B 868 (2013) 102,
JHEP 10 (2015) 139

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

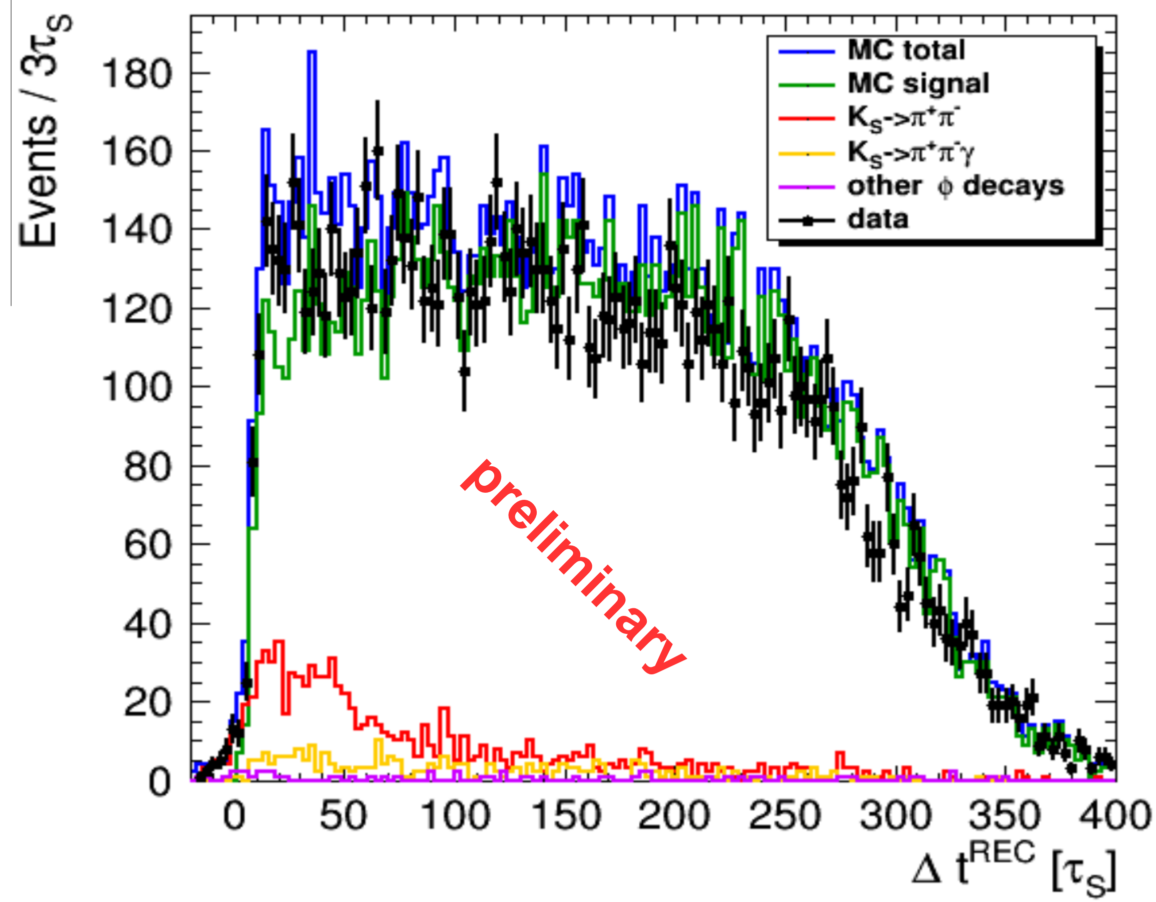
Ongoing symmetries test in transition

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 fit.



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



Charge assymetry test for K_S

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

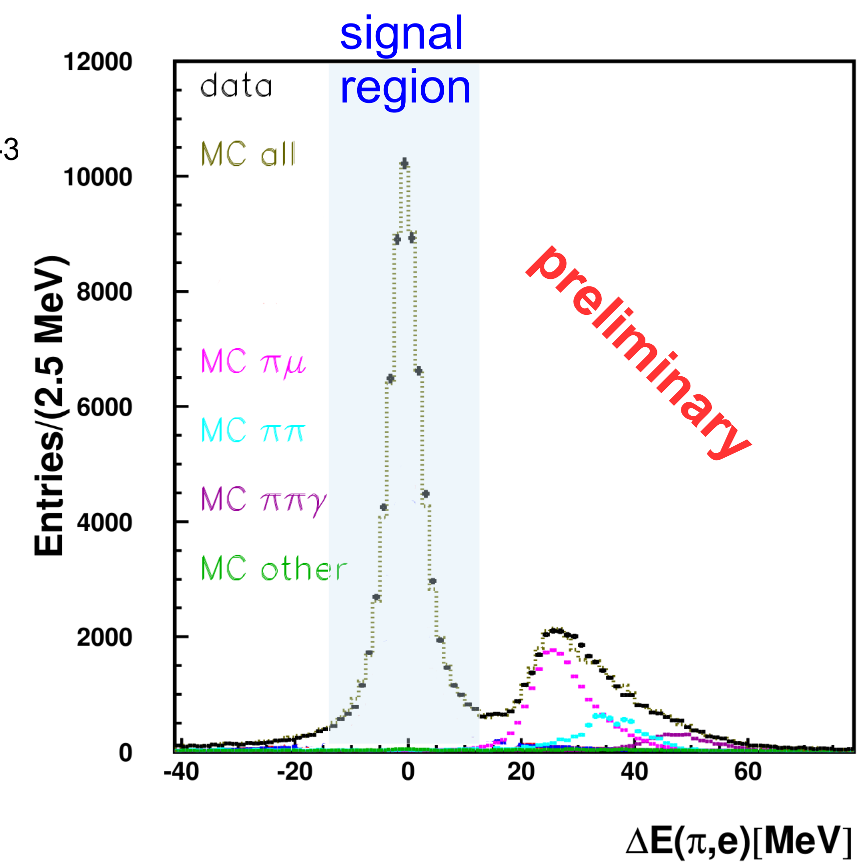
Finalization of new KLOE analysis with ~2 times improved statistical accuracy ($1.7 fb^{-1}$ data sample).

Assuming CPT invariance: $A_S = A_L = 2Re(\varepsilon_K) \approx 3\times10^{-3}$

$A_L = (3.332 \pm 0.058_{stat} \pm 0.047_{syst})$ 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 assymetry values for K_L and K_S tests fundamental assumptions of Standard Model.



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

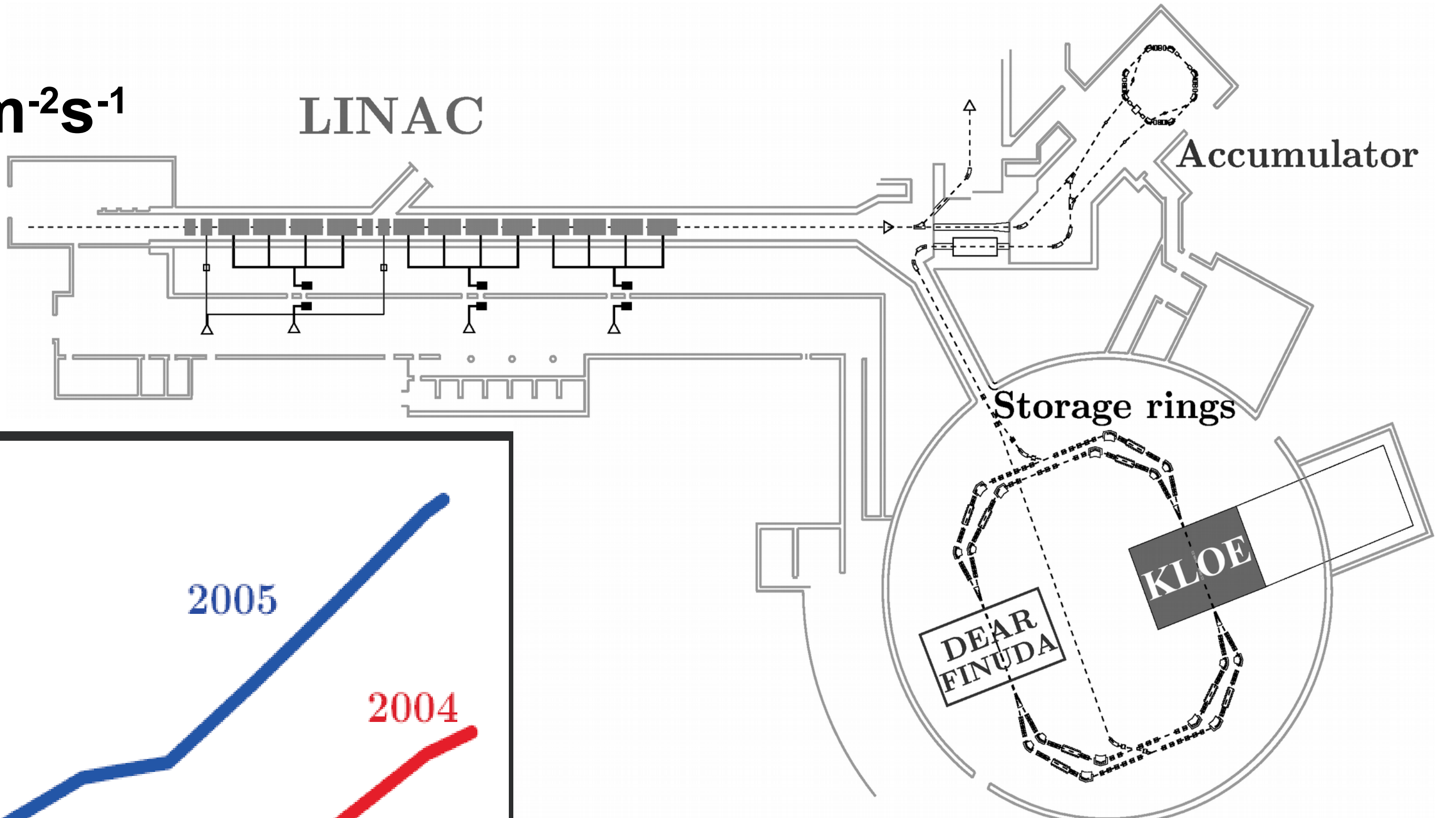
KLOE-2 project

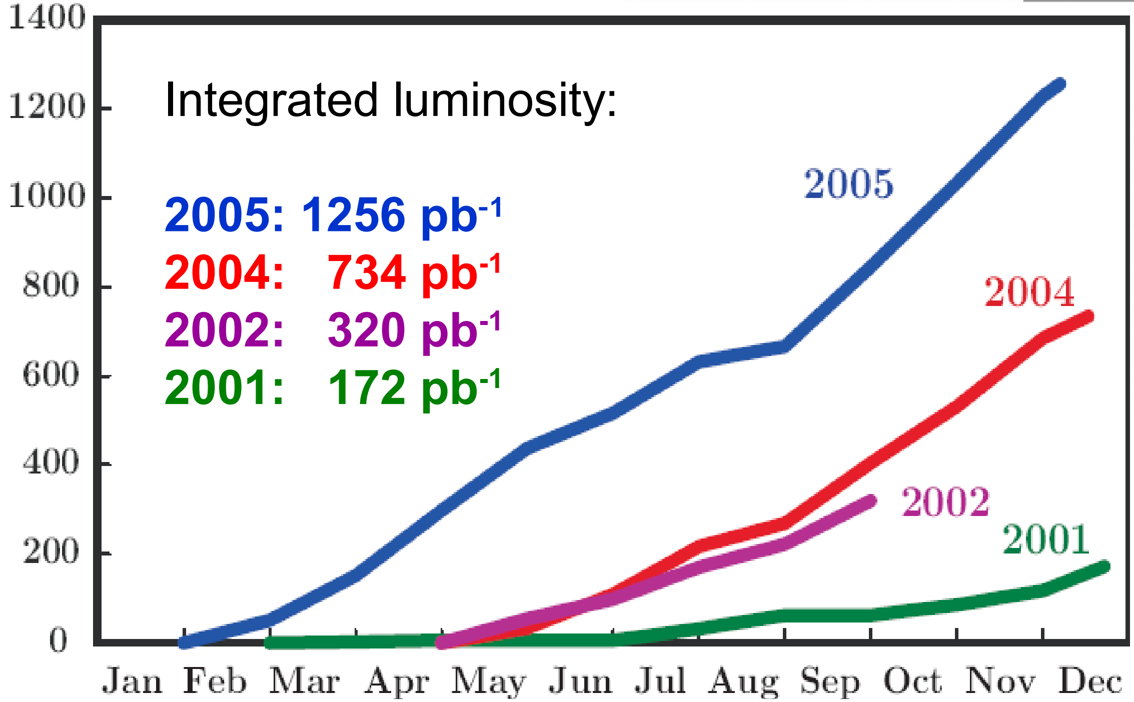
DAΦNE e^+e^- collider

1999-2007:

$\mathcal{L}_{peak}$ **= 1.4 x 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

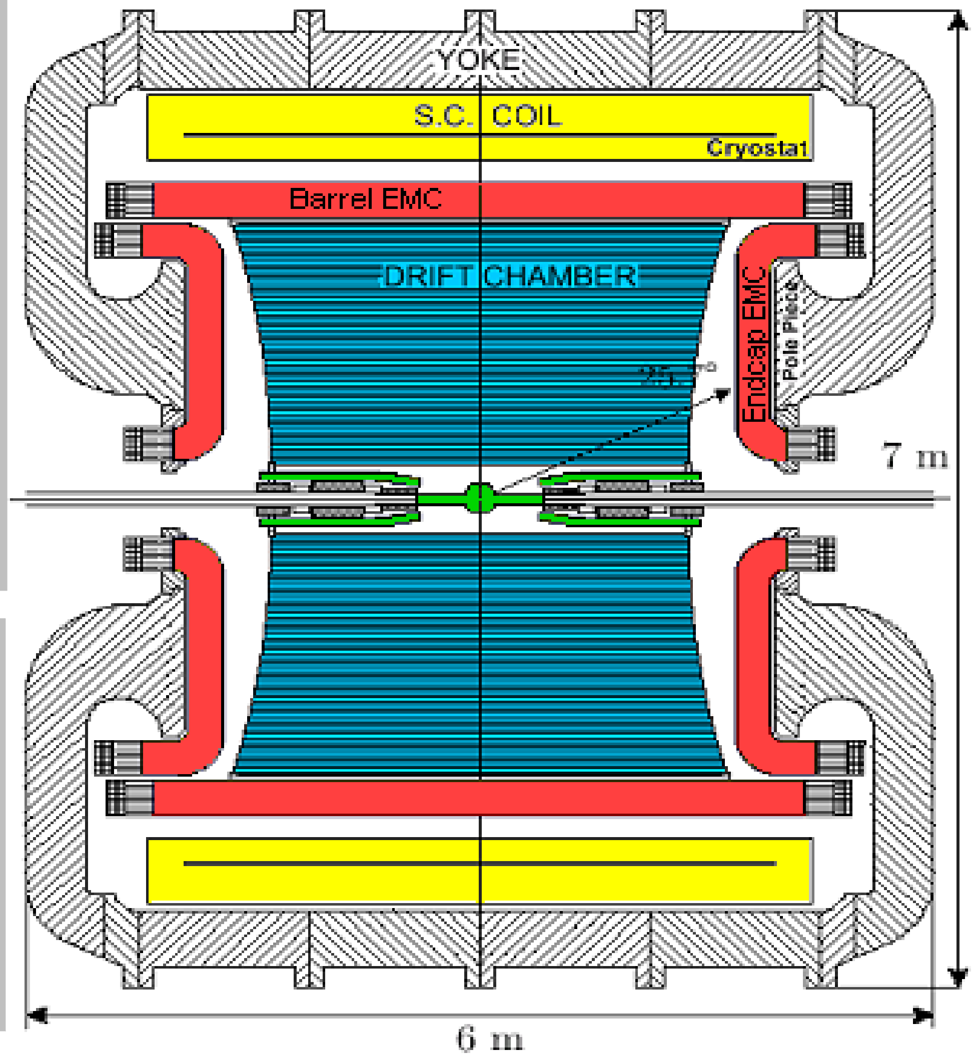
KLOE *K LOng Experiment*

Drift chamber

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

Electromagnetic calorimeter

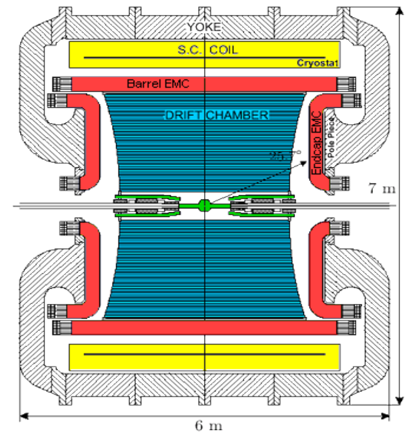
- lead/scintillating fibers
- 98% solid angle coverage
- $\sigma_E / E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_t = 57$ ps / $\sqrt{E(GeV)} \oplus 100$ ps
- PID capabilities

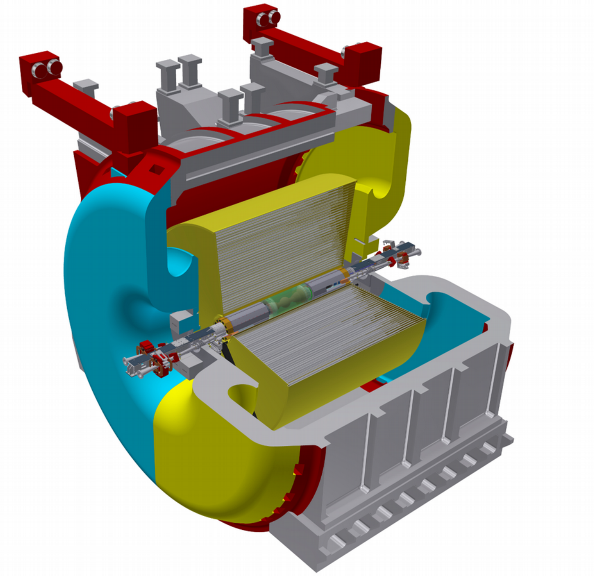


Data taking ended on March 2006

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

KLOE-2 upgrades





Inner Tracker

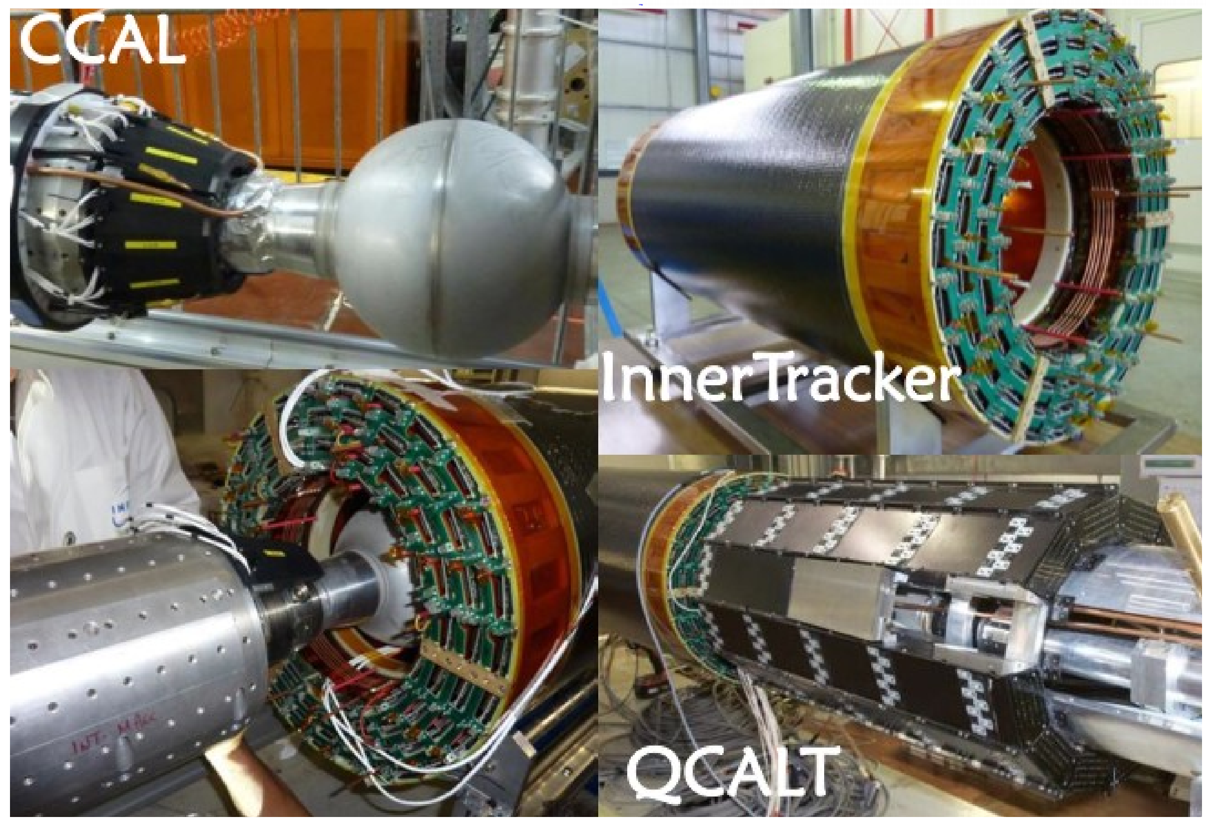
- 4 layers of cylindrical triple GEM
- better vertex reconstruction near IP
- larger acceptance for low p_t tracks

QCALT

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

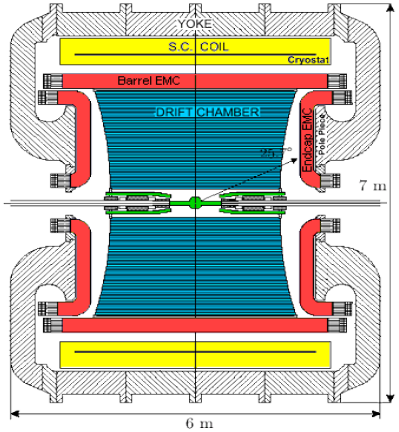
CCALT

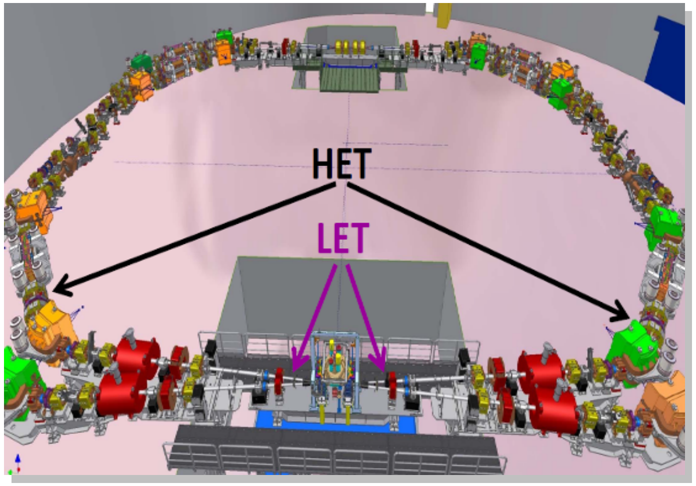
- LYSO + APD
- increase acceptance for γ's from IP (21°→8°)



KLOE-2 upgrades

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



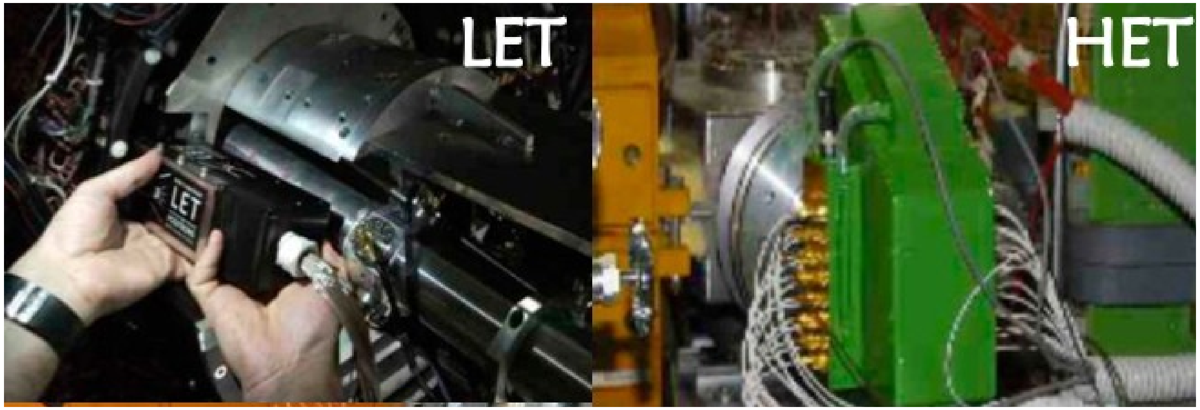


High Energy Taggers (HET)

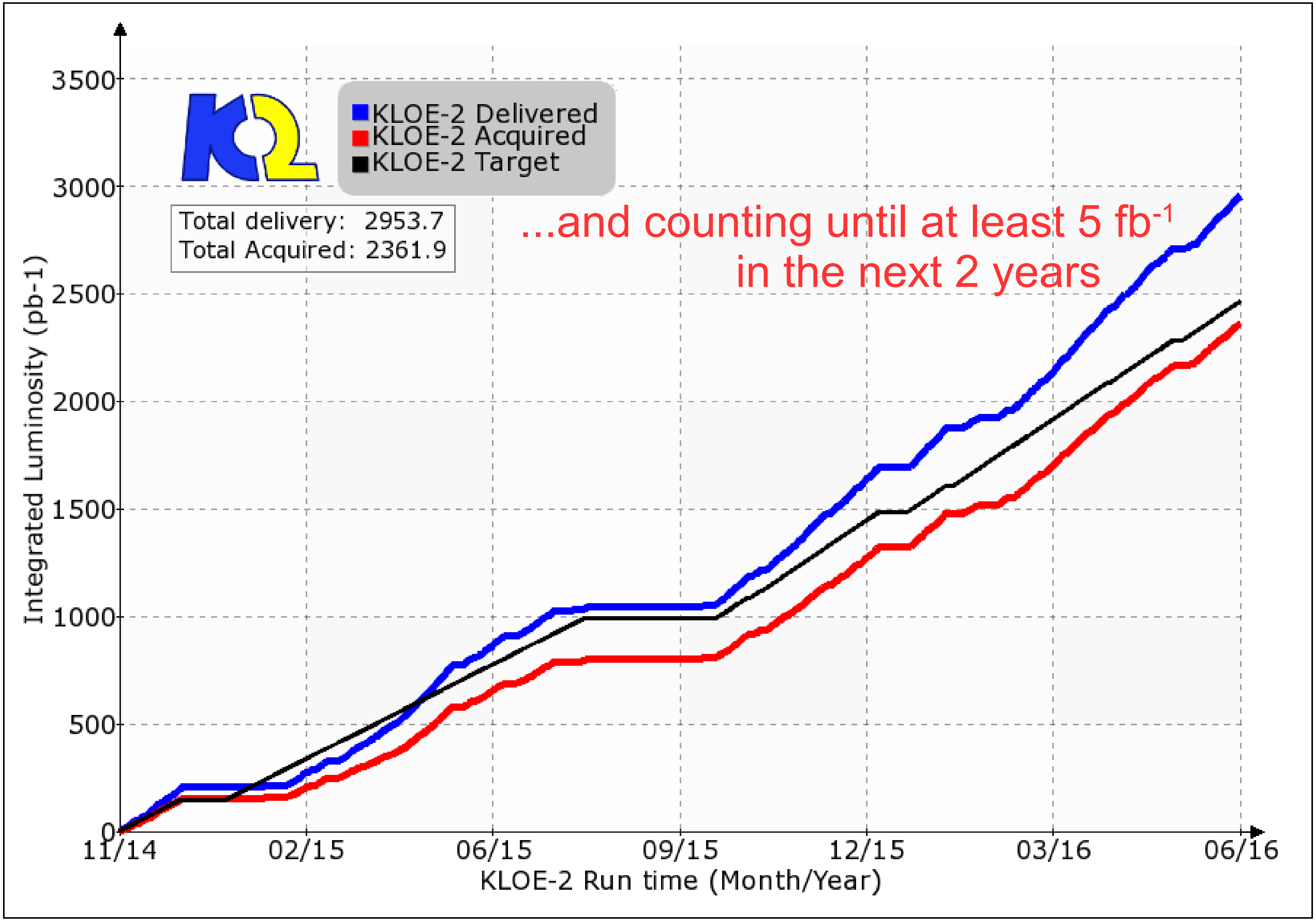
- E>400 MeV
- 11m from IP
- scintillators + PMTs

Low Energy Taggers (LET)

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



Luminosity KLOE-2 @ DAΦNE



Summary
KLOE-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

Thank you

Danke

Grazie

Merci

Dziękuję

ありがとう