JAGIELLONIAN UNIVERSITY
IN KRAKOW

CPT and Lorentz symmetry tests with entangled neutral kaons at KLOE/KLOE-2

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on behalf of KLOE and KLOE-2 collaborations

FLASY 2014, University of Sussex

NATIONAL SCIENCE CENTRE
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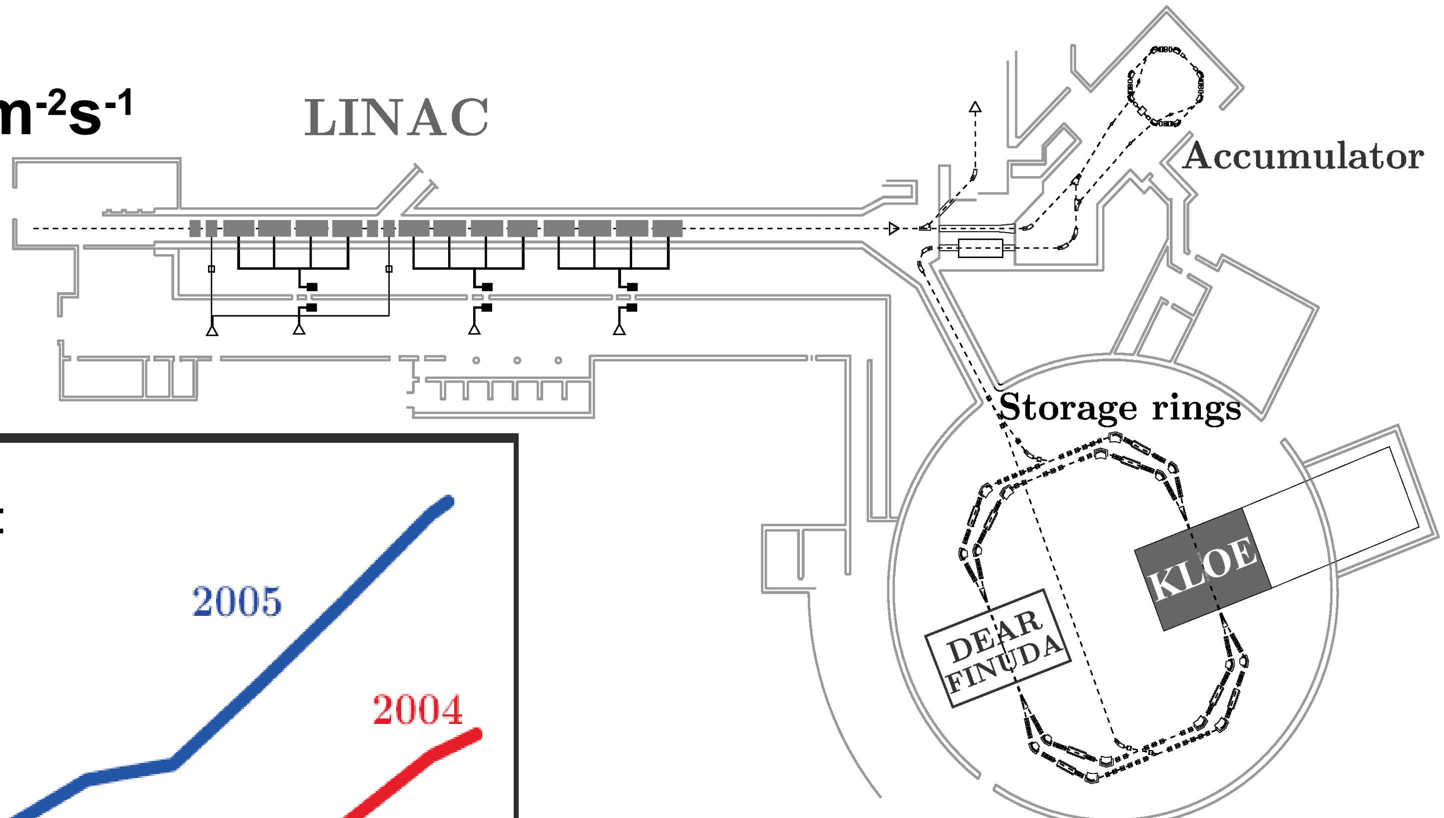
FNP
Foundation for Polish Science

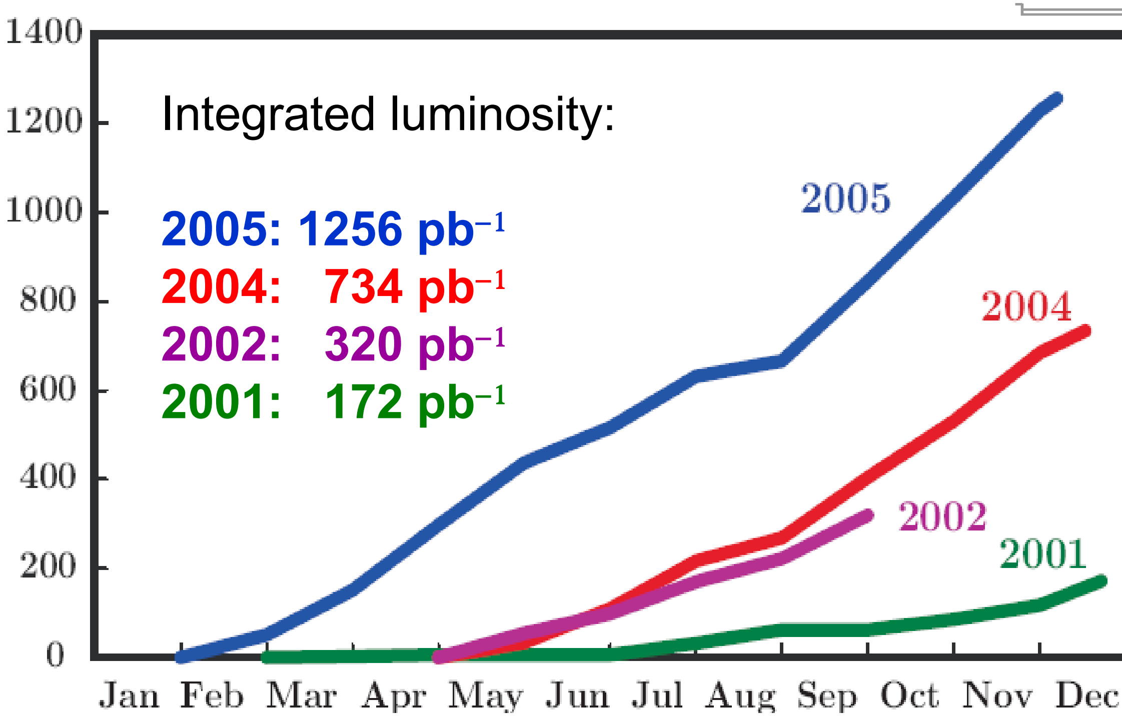
DAΦNE *Double Annular Factory for Nice Experiments*

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

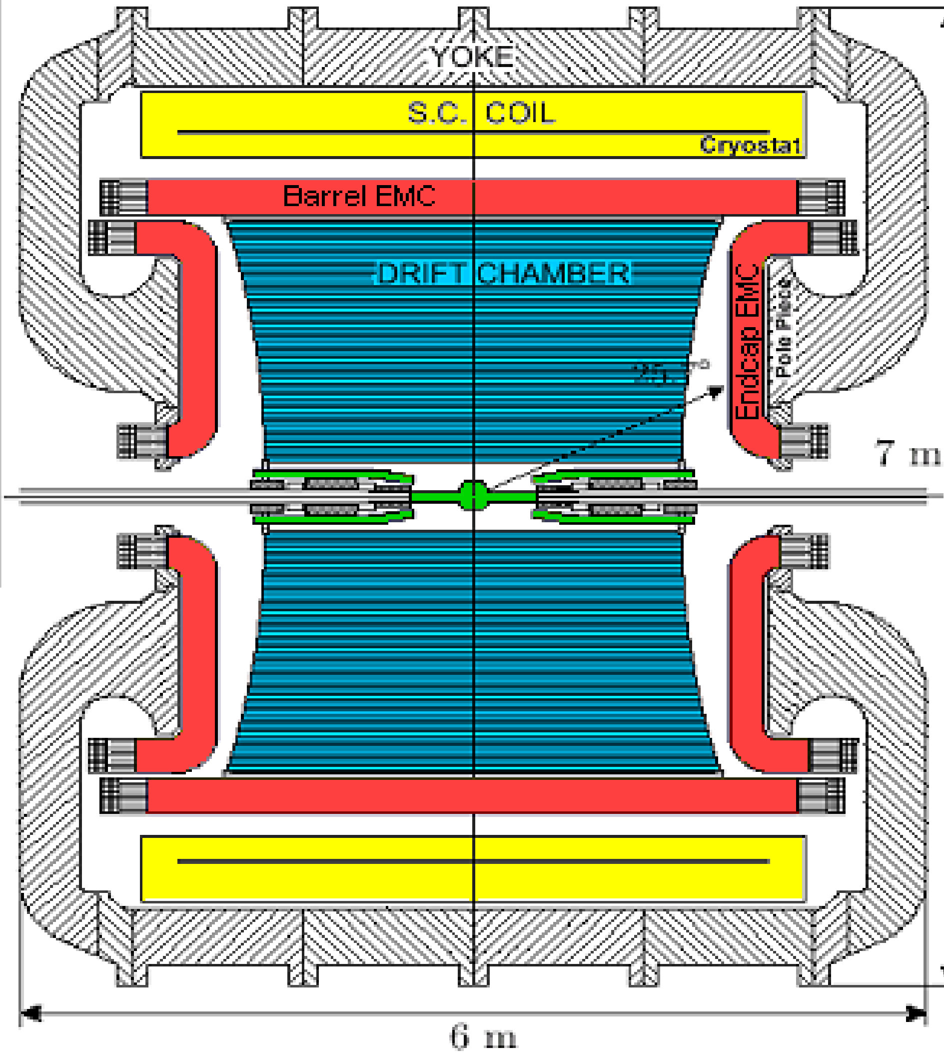
KLOE *K LOng Experiment*

Drift chamber

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

Electromagnetic calorimeter

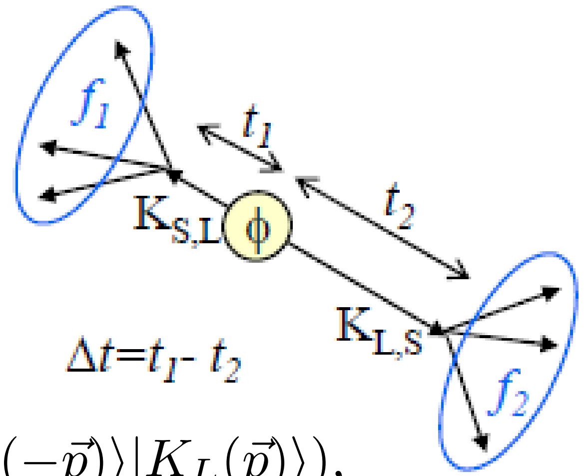
- lead/scintillating fibers
- 98% solid angle coverage
- $\sigma_E / E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_t = 57$ ps $/ \sqrt{E(GeV)} \oplus 100$ ps
- PID capabilities



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

Quantum interferometry



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

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

$$\left\{-2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2} \cos(\Delta m(t_2 - t_1) + \phi_1 - \phi_2)\right\}$$

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

interference term

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

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:

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

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

PRD64,076001
PRL89,231602

δ_K is the CPT violation parameter in the Kaon system.
According to the SME (Kostelecky) and anti-CPT theorem,
CPT violation should appear together with Lorentz Invariance breaking (Greenberg),
and thus implying a direction dependent modulation.

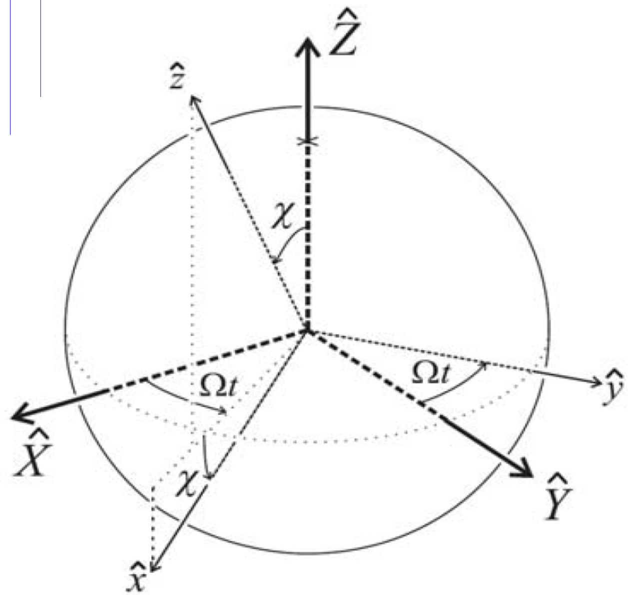
$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta\vec{a})/\Delta m$$

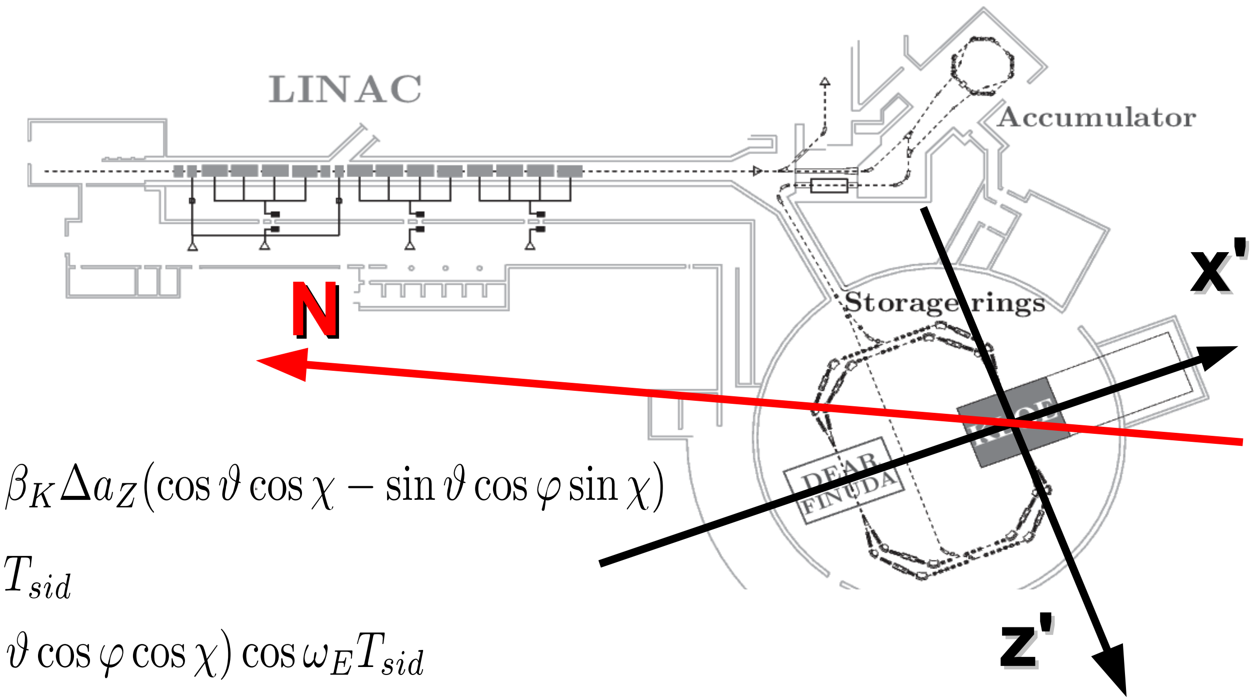
Ordering Kaon according to their momenta it is possible to have
the two η–coefficients containing two different δ_K CPT violating parameter.

Earth rotation effect: δ(θ,ϕ) and KLOE & SME reference frames

$$\hat{N}\hat{x'} = cos(\gamma) \Rightarrow \gamma = 220(2)^\circ \equiv 3.84(3)$$

$$\hat{N}\hat{z'} = cos(\delta) \Rightarrow \delta = 130(2)^\circ \equiv 2.26(3)$$





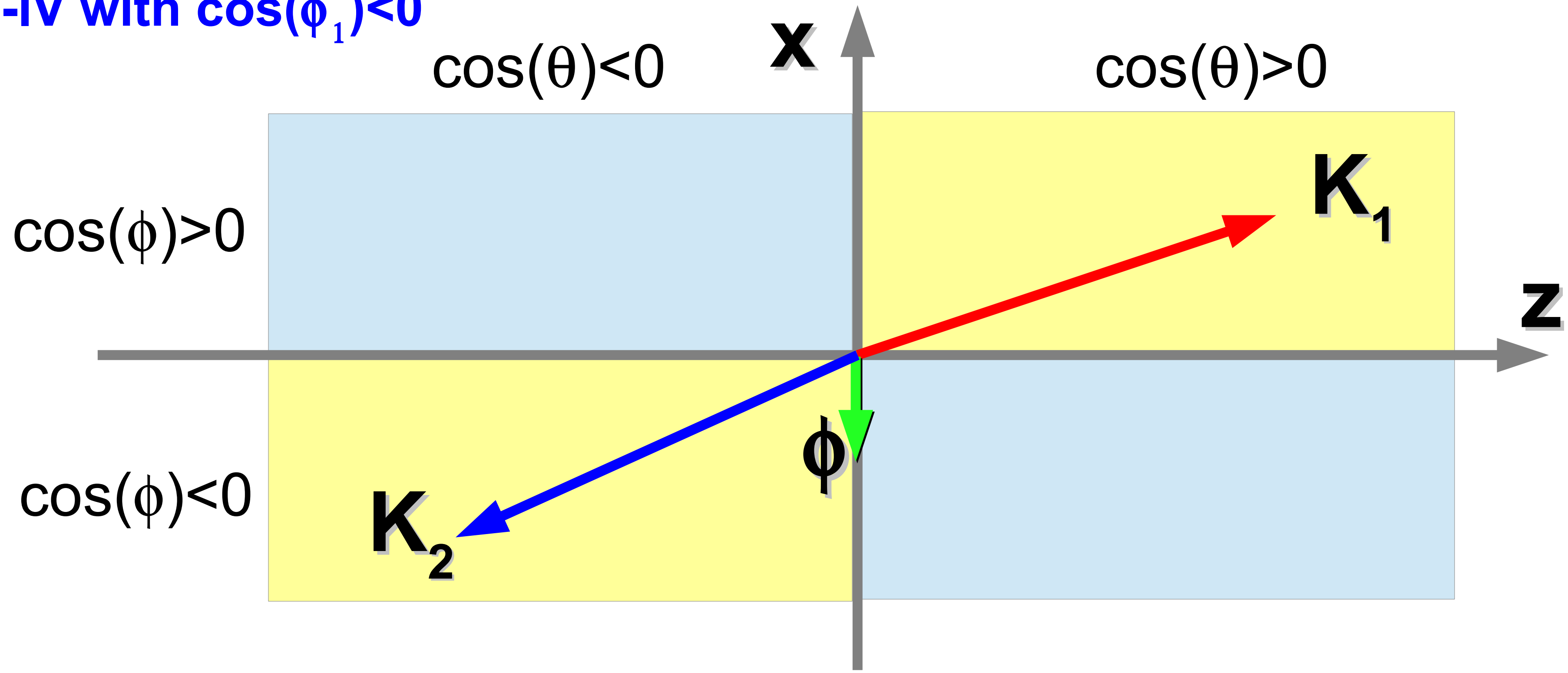
$$\begin{aligned}\delta_K(\vec{P}_K, T_{sid}) \quad = \quad & \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \Big[\Delta a_0 + \beta_K \Delta a_Z (\cos\vartheta \cos\chi - \sin\vartheta \cos\varphi \sin\chi) \\ & -\beta_K \Delta a_X \sin\vartheta \sin\varphi \sin\omega_E T_{sid} \\ & +\beta_K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

Analysis strategy $e^+e^- \rightarrow \varphi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$

Kaons are ordered according to their z momenta component: **$\cos(\theta_1)>0$**

Dataset is divided in two samples:

- **Sel I-III with $\cos(\phi_1)>0$**
- **Sel II-IV with $\cos(\phi_1)<0$**



Data divided in 4 Sidereal time bins x 2 angular bins (192 data points)

Simultaneous fit of the Δt distributions to extract Δa_μ parameters

Observable definition

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

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

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

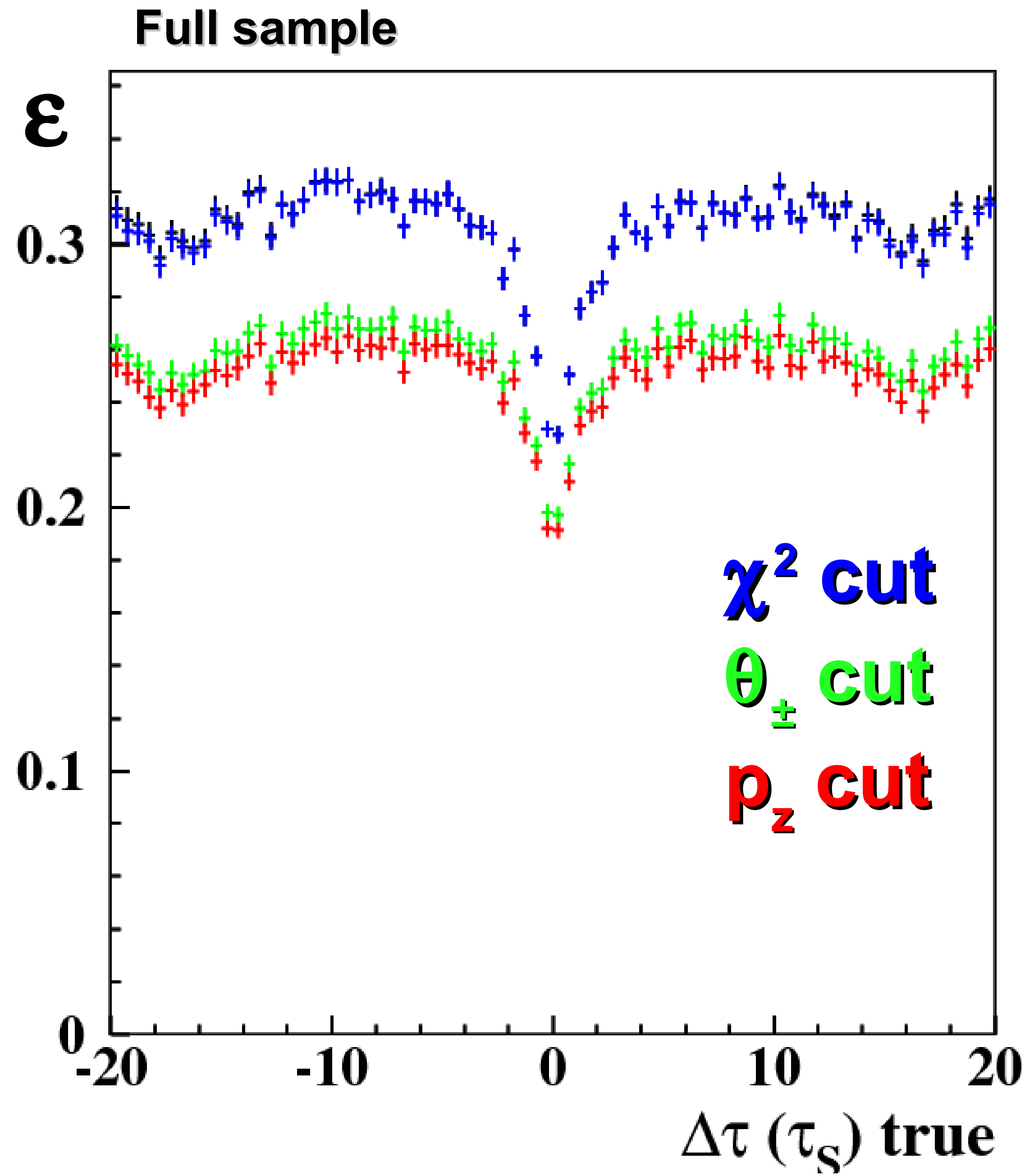
$$P_K = -\frac{\sqrt{((4\beta^2 - 4\beta^4)\cos^2\alpha + 4\beta^2 - 4)\,M_K^2 + (\beta^4 - 2\beta^2 + 1)M_\phi^2}}{\sqrt{1-\beta^2}(2\beta^2\cos^2\alpha - 2)} + \frac{(\beta - \beta^3)M_\phi\cos\alpha}{\sqrt{1-\beta^2}(2\beta^2\cos^2\alpha - 2)}$$

$$\cos\alpha = -\sin\vartheta_K \cos\phi_K$$

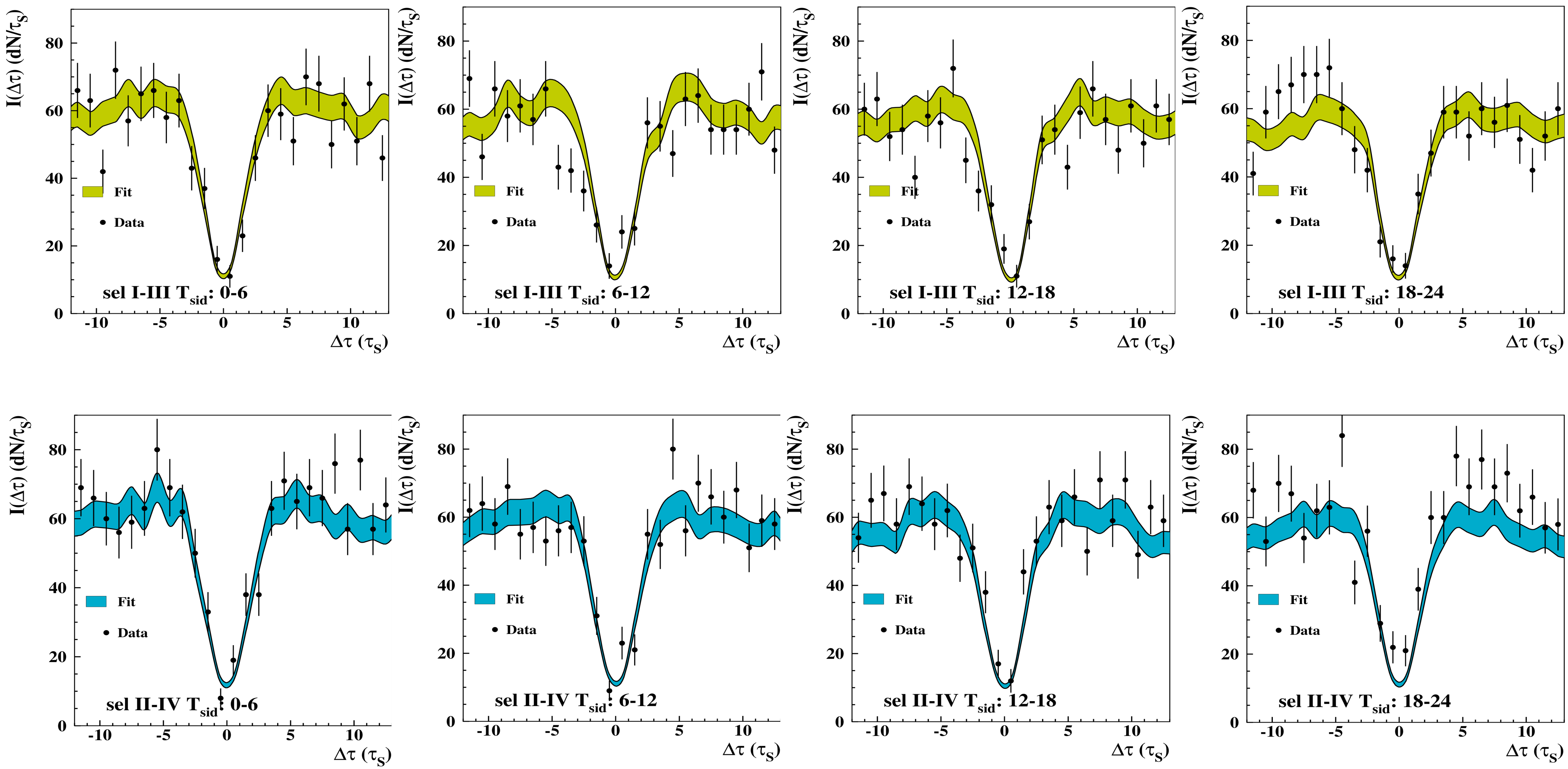
MC efficiency

The efficiency is almost constant except for the region $\Delta\tau/\tau_S \sim 0$, due to loss in the tracking and vertexing efficiency due to extrapolation.

Absolute efficiencies are shown in the plot.



Results



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

Final results on CPT & Lorentz invariance tests

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

$$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys})\ 10^{-18}\ \text{GeV}$$
$$\Delta a_X = (\ 0.9 \pm 1.5_{stat} \pm 0.6_{sys})\ 10^{-18}\ \text{GeV}$$
$$\Delta a_Y = (-2.0 \pm 1.5_{stat} \pm 0.5_{sys})\ 10^{-18}\ \text{GeV}$$
$$\Delta a_Z = (\ 3.1 \pm 1.7_{stat} \pm 0.6_{sys})\ 10^{-18}\ \text{GeV}$$

Error includes:
- ⊕ data statistics (~10%)
- ⊕ Data/MC errors (~2%)
- ⊕ MC statistical error on efficiency(~5%)

Resulting χ^2_{Fit} :
211/187 (P=10%)

Par	Cut stability	Fit Range	Bkg. subtr	KLOE ref. frame	**Total**
Δa_0	1.1	2.4	1.3	1.0	**3.1**
Δa_X	0.3	0.3	0.4	0.2	**0.6**
Δa_Y	0.2	0.3	0.2	0.2	**0.5**
Δa_Z	0.2	0.2	0.4	0.4	**0.6**

DAΦNE and KLOE upgrades

KLOE-2 physics program

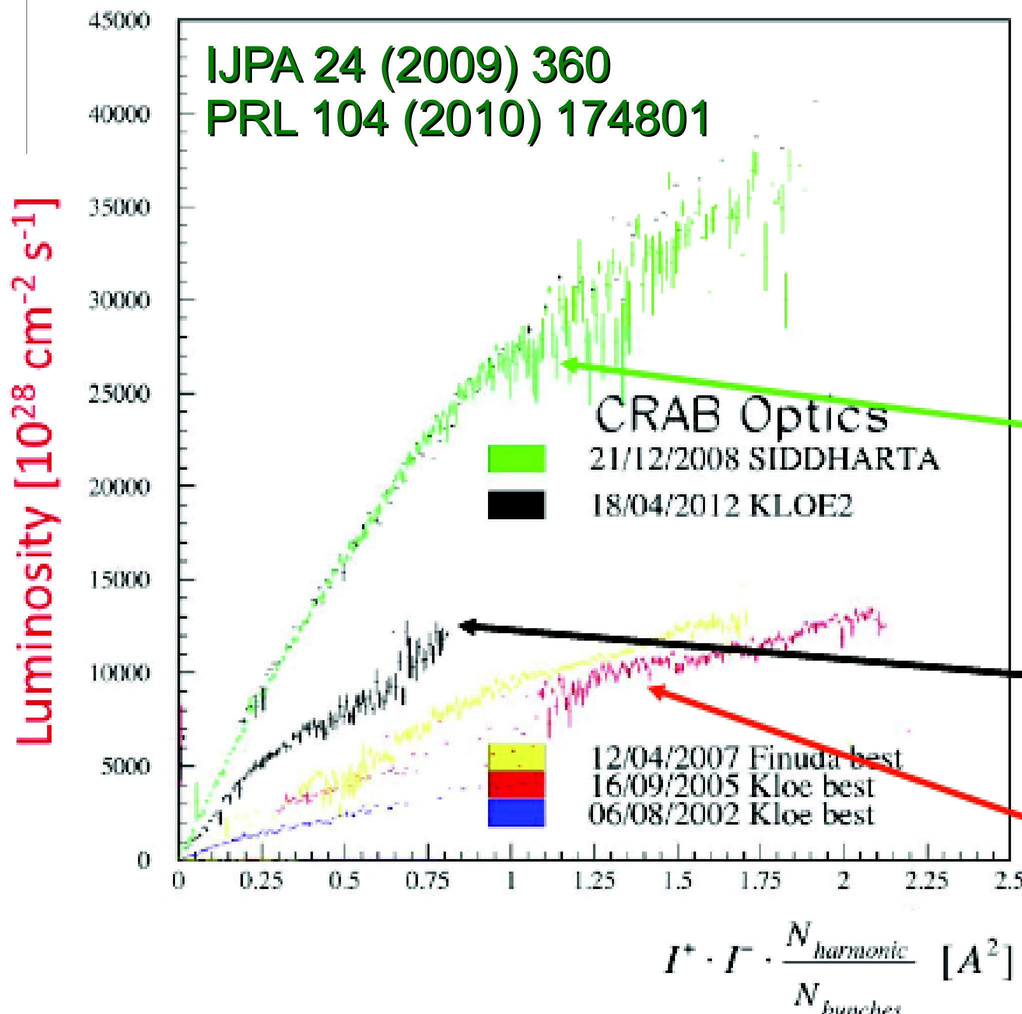
- $\gamma\gamma$ physics: existence (and properties) of $\sigma/f_0(600)$; study of $\Gamma(S/PS\rightarrow\gamma\gamma)$; PS transition form factor;
- light meson spectroscopy: properties of scalar/vector mesons; rare η decays; η' physics;
- kaon physics: test of CPT (and QM) in correlated kaon decays; test of CPT in K_S semileptonic decays; test of SM (CKM unitarity, lepton universality); test of ChPT (K_S decays);
- dark 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

DAΦNE upgrade

A new collision scheme is working with:

- **larger crossing angle**
- **reduced beam size at the crossing point**
- **sextupole pairs for crab-waist configuration of beam interaction**



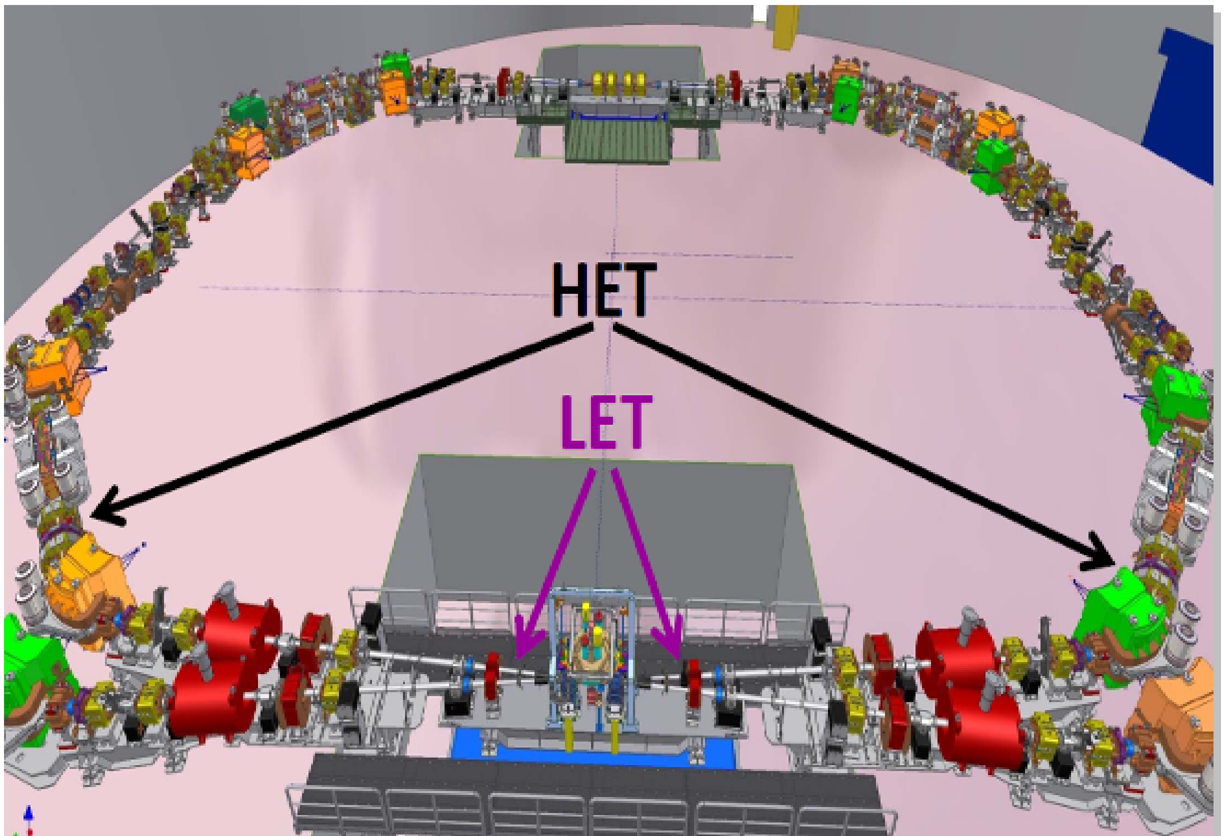
NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

Present commissioning phase
New coll. scheme + KLOE det.

Old collision scheme

max. expected at KLOE-2 : L_{int} ~ 20 pb^{-1}/day x 200 dd/year = 4 fb^{-1} /year

$\gamma\gamma$ taggers at KLOE-2



High Energy Taggers (HET)
- E>400 MeV
- 11m from IP
- scintillators + PMTs
- σ_E~2.5 MeV
- σ_T~200 ps

Low Energy Taggers (LET)
- E=160-230 MeV
- inside KLOE detector
- LYSO+SiPM
- σ_E<10% for E>150 MeV

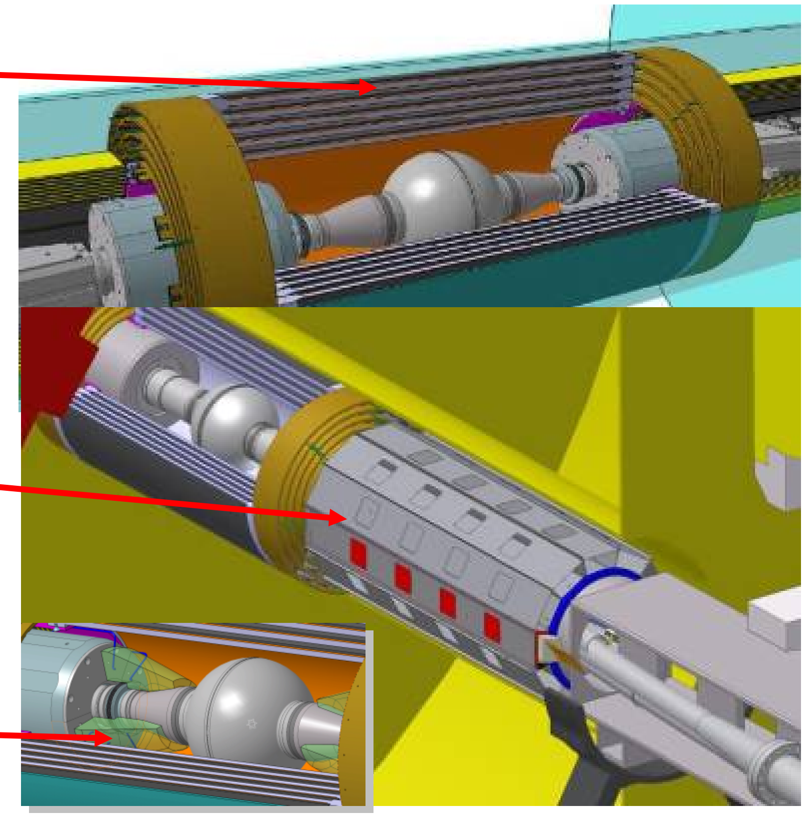
2+2 detector stations for leptons in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$

KLOE-2 Upgrades: IR instrumentation

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°)



IT: NIMA 628 (2011),194
QCALT: NIMA 617 (2010),105
CCALT: NPB 197 (2009), 215

Summary

- new result of kaon interferometry in the area of fundamental symmetries;
- KLOE-2 commissioning started;
- KLOE-2 is going to continue the physics program of KLOE, with special emphasis on CPT and QM tests.

Thank you

Danke

Grazie

Merci

Dziękuję

ありがとう