First direct tests of T and CPT symmetries in transitions of neutral kaons from KLOE-2

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on behalf of the KLOE-2 collaboration

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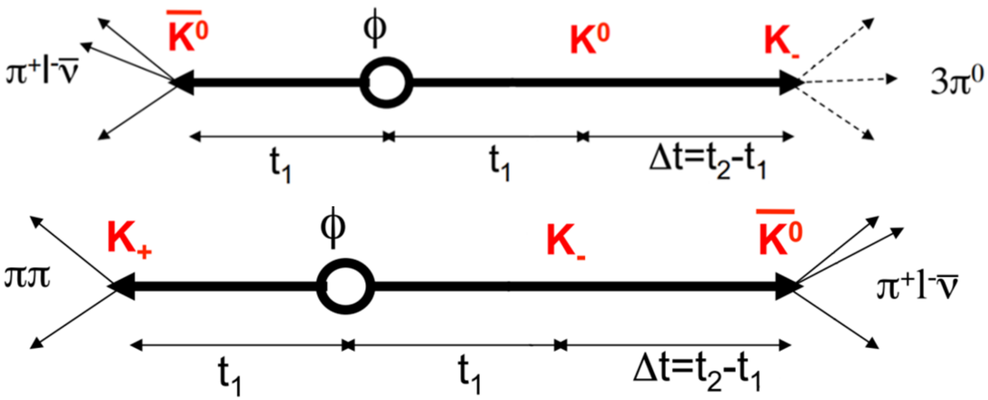
Introduction

- CPT conservation: Lorentz invariance, Locality, Unitarity
- Particles and antiparticles: equality of masses and widths, opposite charges and magnetic moments.
- Any experimental evidence of the CPT violation would point to Physics beyond the Standard Model
- CPT tests in the kaon system:
  - CPLEAR ($K^0 - \overline{K}^0$ semileptonic decay rate asymmetry),
  - KTEV ($\eta_{\pm -} - \eta_{00}$ in the $K_S K_L \rightarrow 2\pi$ interference experiment; $A_L$semileptonic asymmetry)
  - KLOE: (A_s semileptonic asymmetry, decoherence, and Lorentz violation tests with $2(\pi^+\pi^-)$ interferometry)
- T symmetry tests (CPLEAR): $R = \frac{P(\overline{K}_0 \rightarrow K^0) - P(K^0 \rightarrow \overline{K}_0)}{P(\overline{K}_0 \rightarrow K^0) + P(K^0 \rightarrow \overline{K}_0)}$
- **Tests in neutral mesons transitions (motion-reversal before the decay).**
- The decay tags the initial state and filters the final one (e. g. exploiting maximum entanglement for neutral meson-antimeson pairs)

Direct test of T and CPT in neutral kaon transitions

- Comparison between transitions of CP and flavor states

- Kaon decays used as a filter for selected flavour and CP states



$$K^0 \longrightarrow K_- \overset{CPT}{\Longleftrightarrow} K_- \longrightarrow \bar{K}^0$$

$$\bar{K}^0 \longrightarrow K_- \overset{T}{\Leftrightarrow} K_- \longrightarrow K^0$$

- **A clean and model-independent test** of T and CPT via asymmetry ratios as a function of difference Δt between the two kaon decays
  [J. Bernabeu, A. Di Domenico et al. Nucl. Phys. B868, 102 (2013), JHEP 10, 139 (2015)]

$$R_{2,T}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]} \sim \frac{I(\pi^+ l^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- l^+ \nu; \Delta t)}$$

$$R_{2,CPT}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \bar{K}^0(\Delta t)]} \sim \frac{I(\pi^+ l^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ l^- \bar{\nu}; \Delta t)}$$

$$R_{4,T}(\Delta t) = \frac{P[\bar{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \bar{K}^0(\Delta t)]} \sim \frac{I(\pi^- l^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ l^- \bar{\nu}; \Delta t)}$$

$$R_{4,CPT}(\Delta t) = \frac{P[\bar{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]} \sim \frac{I(\pi^- l^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- l^+ \nu; \Delta t)}$$

- Asymptotic shapes of $R_{2,T}(\Delta t)$ and $R_{4,T}(\Delta t)$ are sensitive to T violation ($\Delta t >> \tau_S$) while:

$$\frac{R_{2,CPT}(\Delta t \gg \tau_S)}{R_{4,CPT}(\Delta t \gg \tau_S)} = 1 - 8Re(\delta_K) - 8Re(x_-)$$

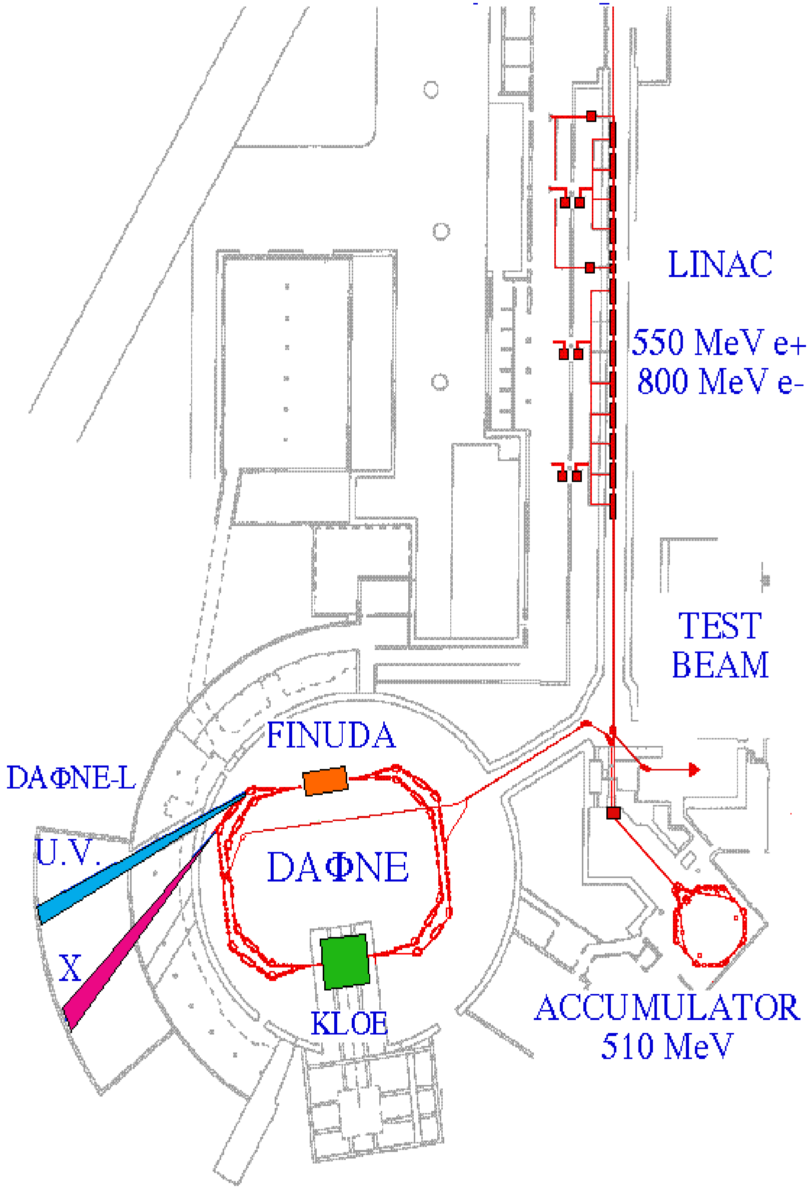
The DAΦNE Φ-factory

- e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- LAB momentum $p_\varphi \sim 15$ MeV/c
- $\sigma_{peak} \sim 3\ \mu b$
- Separate e^+e^- rings to reduce beam-beam interaction
- Beams crossing angle: 15 mrad
- Peak luminosity $1.5\times10^{32}\ cm^{-2}s^{-1}$

KLOE run:

- Daily performance: 7-8 pb^{-1}
- Best month $\int L\,dt \sim 200\ pb^{-1}$
- Total KLOE:
  $\int L\,dt \sim 2500\ pb^{-1}$ at φ mass peak
  + 250 pb^{-1} off peak (@ 1 GeV)

BR's for main φ decays	
K^+K^-	48.9%
K_SK_L	**34.2%**
$\rho\pi + \pi^+\pi^-\pi^0$	15.3%
ηγ	1.3%



The KLOE-2 detector

Large cylindrical drift chamber

- Uniform tracking and vertexing in all volume
- Helium based gas mixture (90% He – 10% $IsoC_4H_{10}$)
- Stereo wire geometry

$\sigma_p/p = 0.4\ \%$

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

$\sigma_{vtx} \sim 3$ mm

$\sigma(M_{\pi\pi}) \sim 1$ MeV

Lead/scintillating-fiber calorimeter

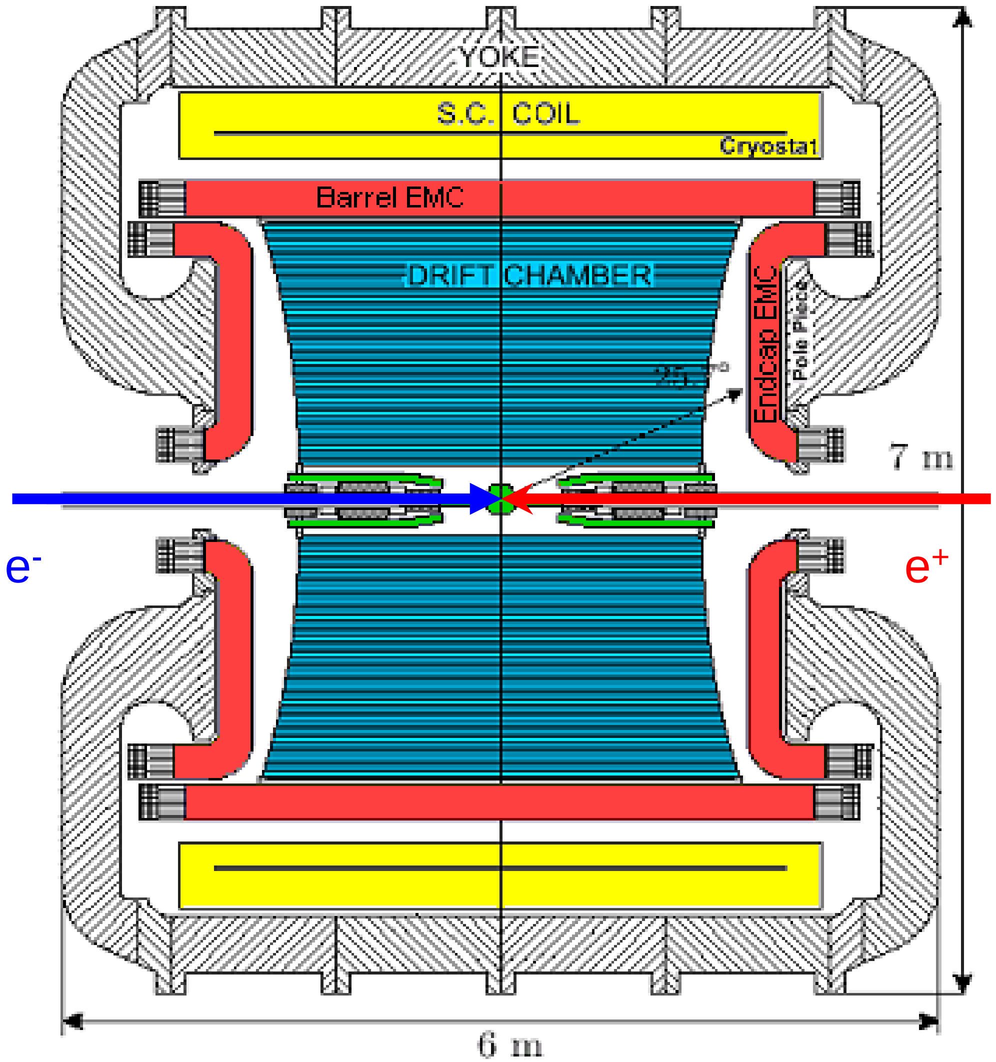
- Hermetical coverage
- High efficiency for low-energy photons

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

$\sigma_t = 54/\sqrt{E(GeV)} \oplus 100$ ps

Superconducting coil

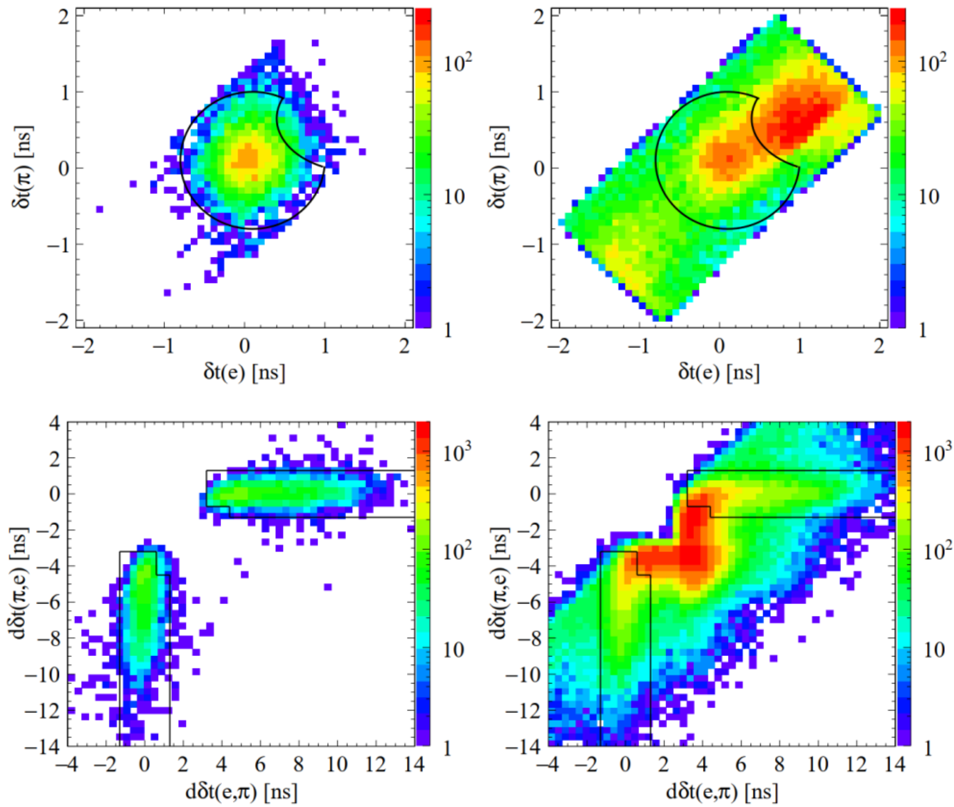
B = 0.52 T



Direct test of T and CPT in neutral kaon transitions

- Assuming $\Delta S = \Delta Q$ rule semileptonic decays give the flavor of the kaon: $K^0 \to \pi^- e^+ \nu$ and $\bar{K}^0 \to \pi^+ e^- \nu$
- Two categories of events to be identified: $\phi \longrightarrow K_S K_L \longrightarrow \pi^{\pm} e^{\mp} \nu, 3\pi^0$; $\phi \longrightarrow K_S K_L \longrightarrow \pi^+ \pi^-, \pi^{\mp} e^{\pm} \nu$
- **Early semileptonic decay**
  - Two tracks from the IP with invariant mass $m_{\pi\pi} > 490$ MeV/c^2 (under the $\pi^+\pi^-$ hypothesis)
  - Time-Of-Flight analysis for leptons and pions to refine the $K_S \to \pi e \nu$ selection

$$\delta t(m_X) = T - \frac{L}{c\beta(m_X)}$$



- The main background sources:
  - $K_S \to \pi^+ \pi^+ (\gamma)$
  - $K_S \to \pi^+ \pi^+ \to \pi \mu \upsilon$ (π decay before entering the DC)
  - Pion/muon DC track misidentified as e^+/e^-

- Signal purity refinement with Multilayer Perceptron two particle binary classifiers (TMVA)
  - EMC showers structure vs associated track momentum
  - training with data control samples (K_L decays)

- **$K_L \to 3\pi^0 \to 6\gamma$ selection**:
  - At least 6 EMC clusters with E>20 MeV not associated with tracks
  - Total 6 clusters energy: 350 MeV/c^2 < E_{tot} < 700 MeV/c^2
  - Dedicated trilateration-based reconstruction of $K_L \to 3\pi^0 \to 6\gamma$
    [A. Gajos et al., Acta Phys. Polon. B 46 (2015) 13]

- Main background source: $K_S \to 2\pi^0$ + accidental/splitting (suppressed by vertex reconstruction of 4 γ subsets)

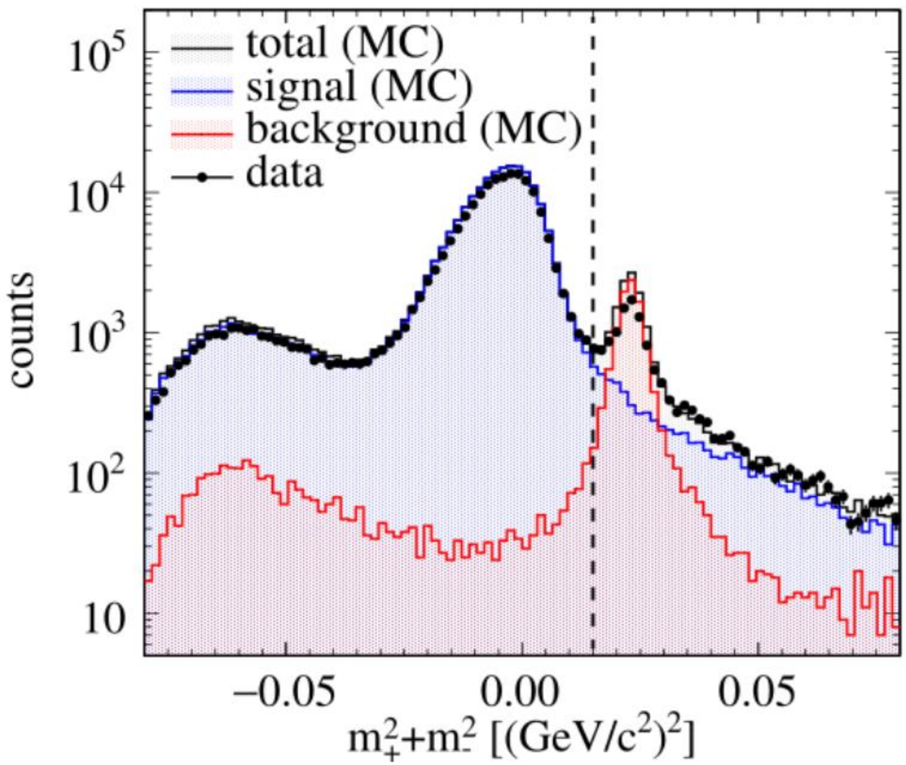
- **Selection of the $K_S K_L \to (\pi^+\pi^-)\,(\pi^\pm e^\mp \nu)$ events**

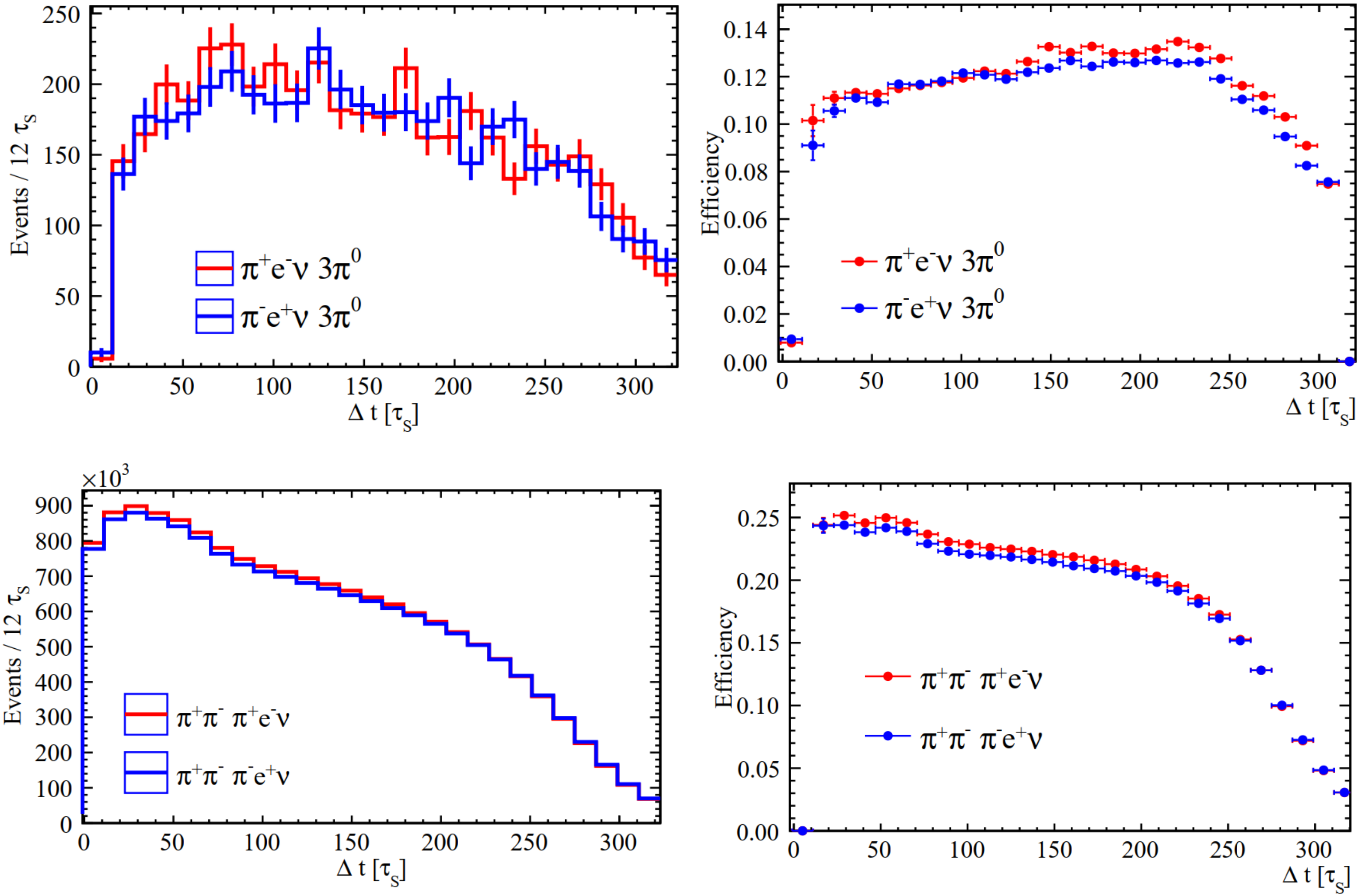
- Early $\pi^+\pi^-$ decay reconstruction: two tracks from the IP with $|m_{\pi\pi} - m_{K^0}| < 10$ MeV/c^2

- Semileptonic decay selection: two(not previously selected) tracks

- Main background channels: $\pi^+\pi^-\pi^0$ and $\pi^\pm\mu^\mp\nu$ semileptonic decays

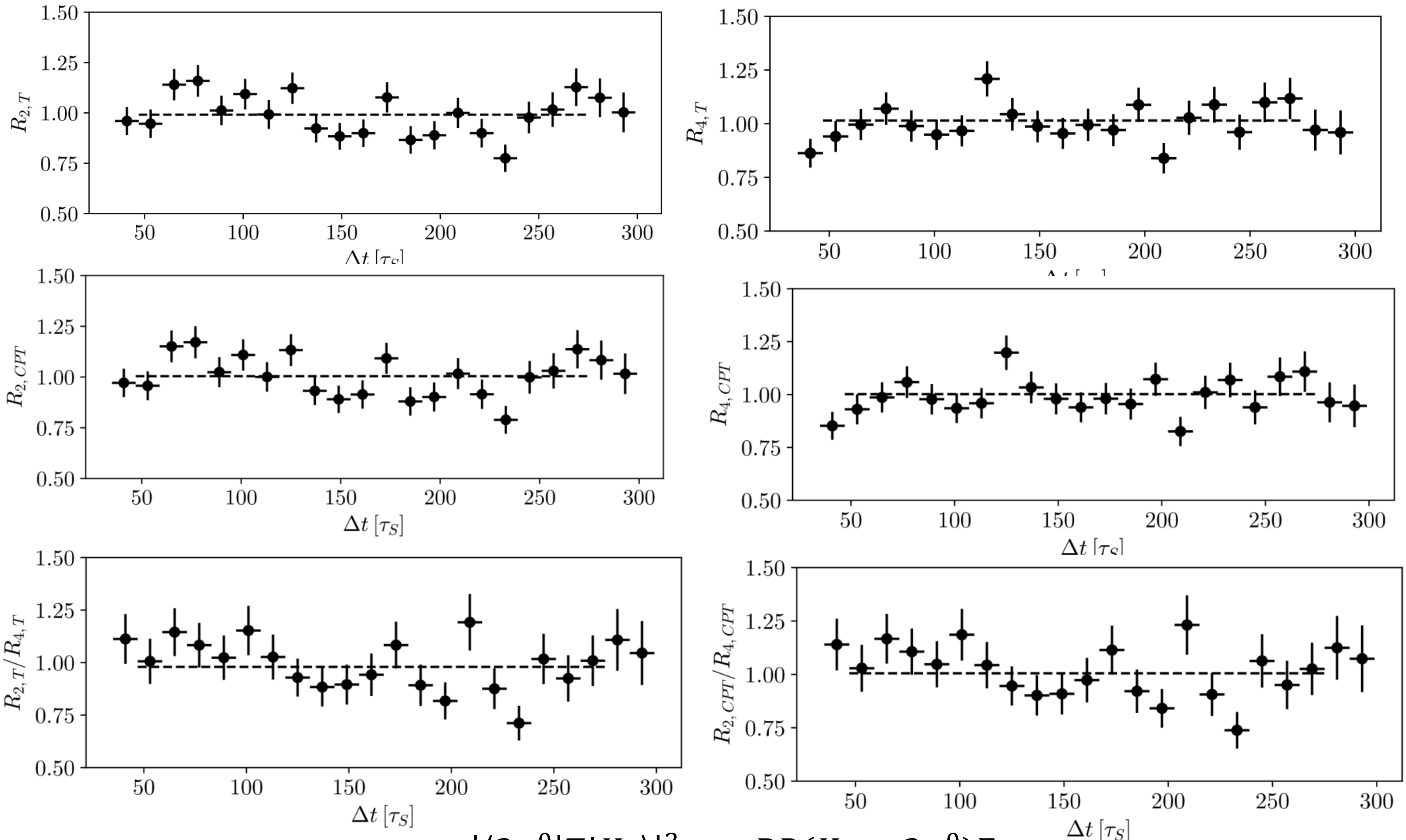
$$m_\pm^2 = (E_K - E(\pi)_\mp - |\vec{p}_{miss}|)^2 - |\vec{p}_\pm|^2$$





Events / 12 τ_S
$\Delta t\ [\tau_S]$
$\pi^+e^-\nu\ 3\pi^0$
$\pi^-e^+\nu\ 3\pi^0$
Efficiency
$\times10^3$
$\pi^+\pi^-\ \pi^+e^-\nu$
$\pi^+\pi^-\ \pi^-e^+\nu$

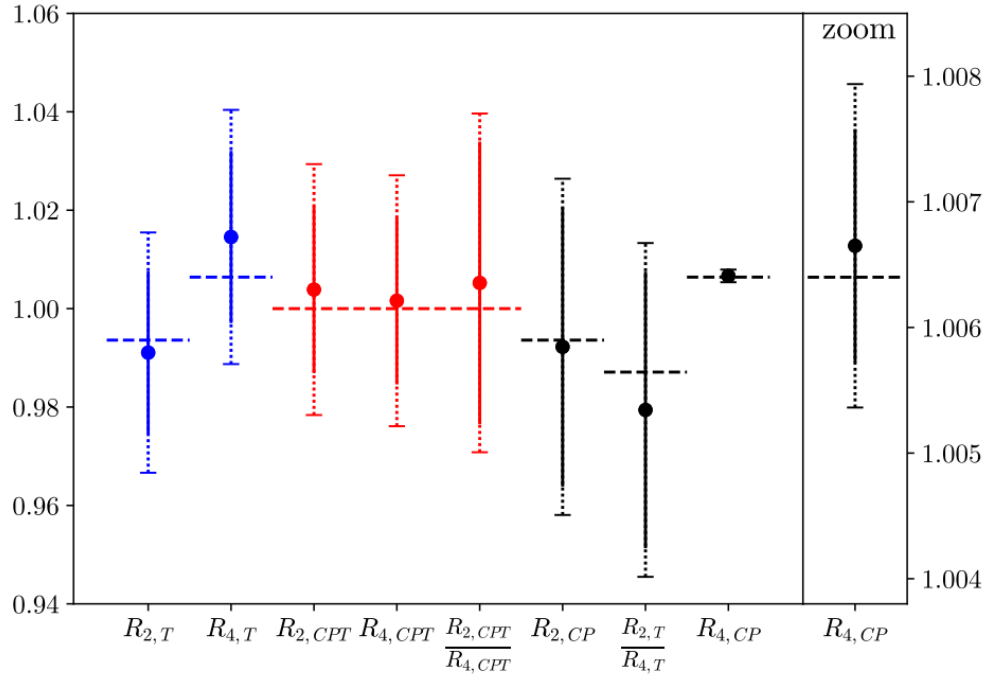
Direct test of T and CPT in neutral kaon transitions



$$R\,(\Delta t_i) = \frac{N_i \varepsilon'_i}{N_i \varepsilon_i D}$$

$$\mathrm{D} = \frac{|\langle 3\pi^0 | T | K_- \rangle|^2}{|\langle \pi^+\pi^- | T | K_+ \rangle|^2} = \frac{BR(K_L \to 3\pi^0)\Gamma_L}{BR(K_S \to \pi^+\pi^-)\Gamma_S}$$

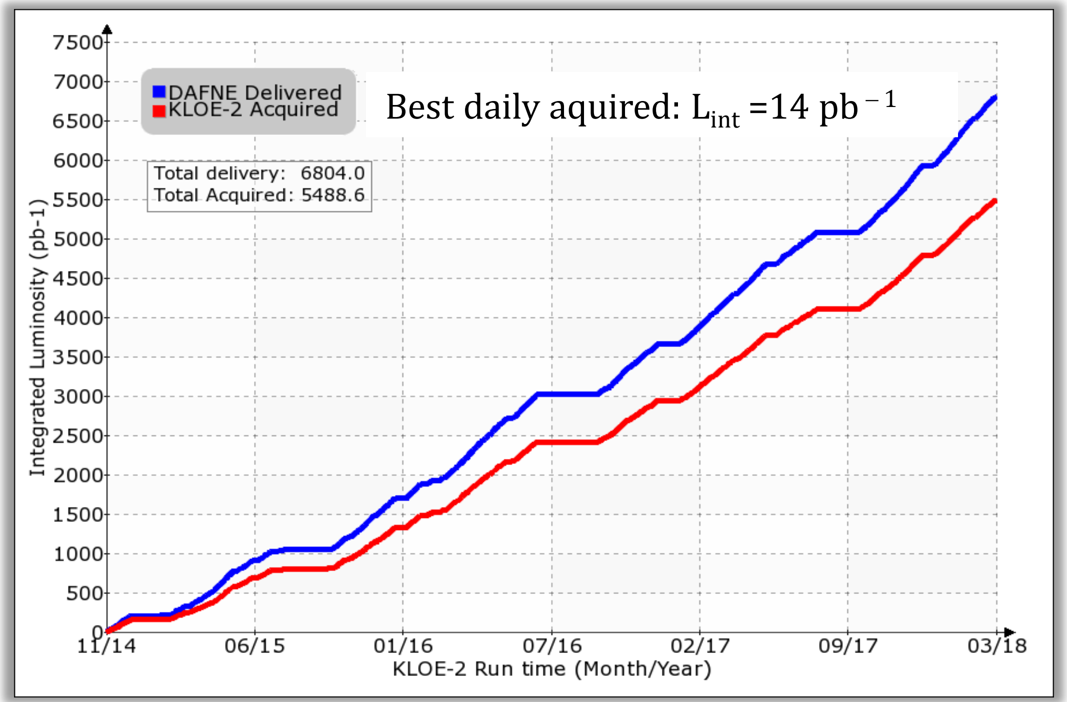
$$
\begin{aligned}
R_{2,T} &= 0.991 \quad \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_{D},\\
R_{4,T} &= 1.015 \quad \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_{D},\\
R_{2,CPT} &= 1.004 \quad \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_{D},\\
R_{4,CPT} &= 1.002 \quad \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_{D},\\
R_{2,CP} &= 0.992 \quad \pm 0.028_{stat} \pm 0.019_{syst},\\
R_{4,CP} &= 1.00665 \quad \pm 0.00093_{stat} \pm 0.00089_{syst},\\
DR_{T,CP} &= 0.979 \quad \pm 0.028_{stat} \pm 0.019_{syst},\\
DR_{CPT} &= 1.005 \quad \pm 0.029_{stat} \pm 0.019_{syst}.
\end{aligned}
$$



The DAFNE Φ-factory upgrade

- Novel Crab-Waist interaction scheme with large Piwinski angle
- Separate e^+e^- rings to reduce beam-beam interaction
- Peak luminosity 2.4×10^{32} $cm^{-2}s^{-1}$

- **Largest sample ever collected at the φ(1020) peak in e^+e^- collisions: L_{int} = 8 fb^{-1} (KLOE-2: 5.5 fb^{-1}, KLOE: 2.5 fb^{-1})**



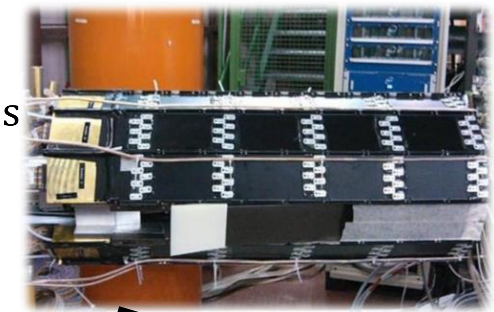
The KLOE-2 detector

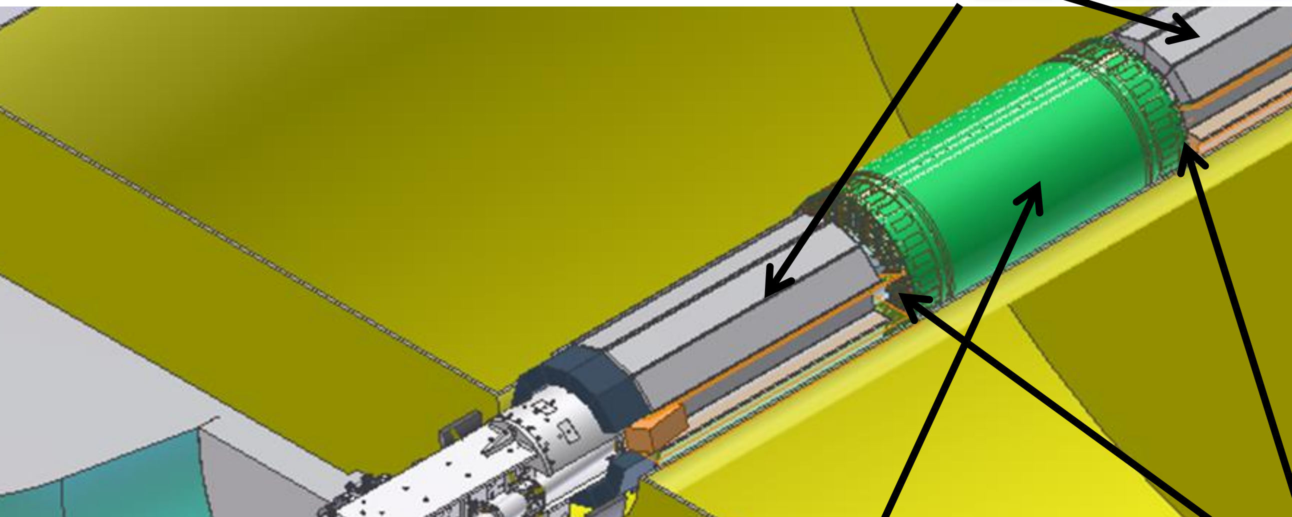
QCALT

Tungsten slabs + scintillator tiles read out by SiPM’s

Low-beta quadrupole coverage for KL decays

QCALT: NIMA 617, 105 (2010); Acta Phys. Pol. B 46 , 87 (2015)

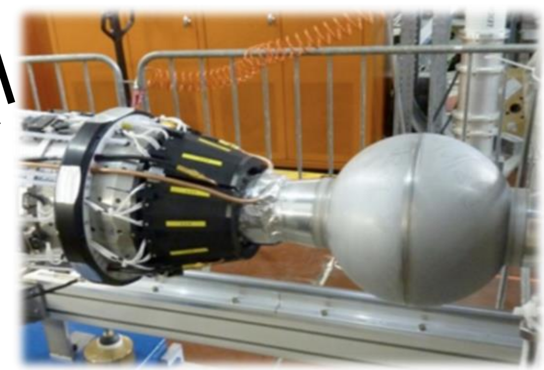




CCALT

LYSO crystals+ SiPM read-out

Increased acceptance for γ’s from IP ($24^{o}\rightarrow 11^{o}$)



CCALT: NIM A 718 , 81 (2013)

INNER TRACKER

First cylindrical GEM detector

4 layers with 700 mm active length

Better vertex reconstruction near IP

Larger acceptance for low p_t tracks

Increased sensitivity for the kaon interferometry measurements

IT: Acta Phys. Pol. B 46, 73 (2015); NIMA 628 (2011),194

KLOE upgrades: γγ taggers

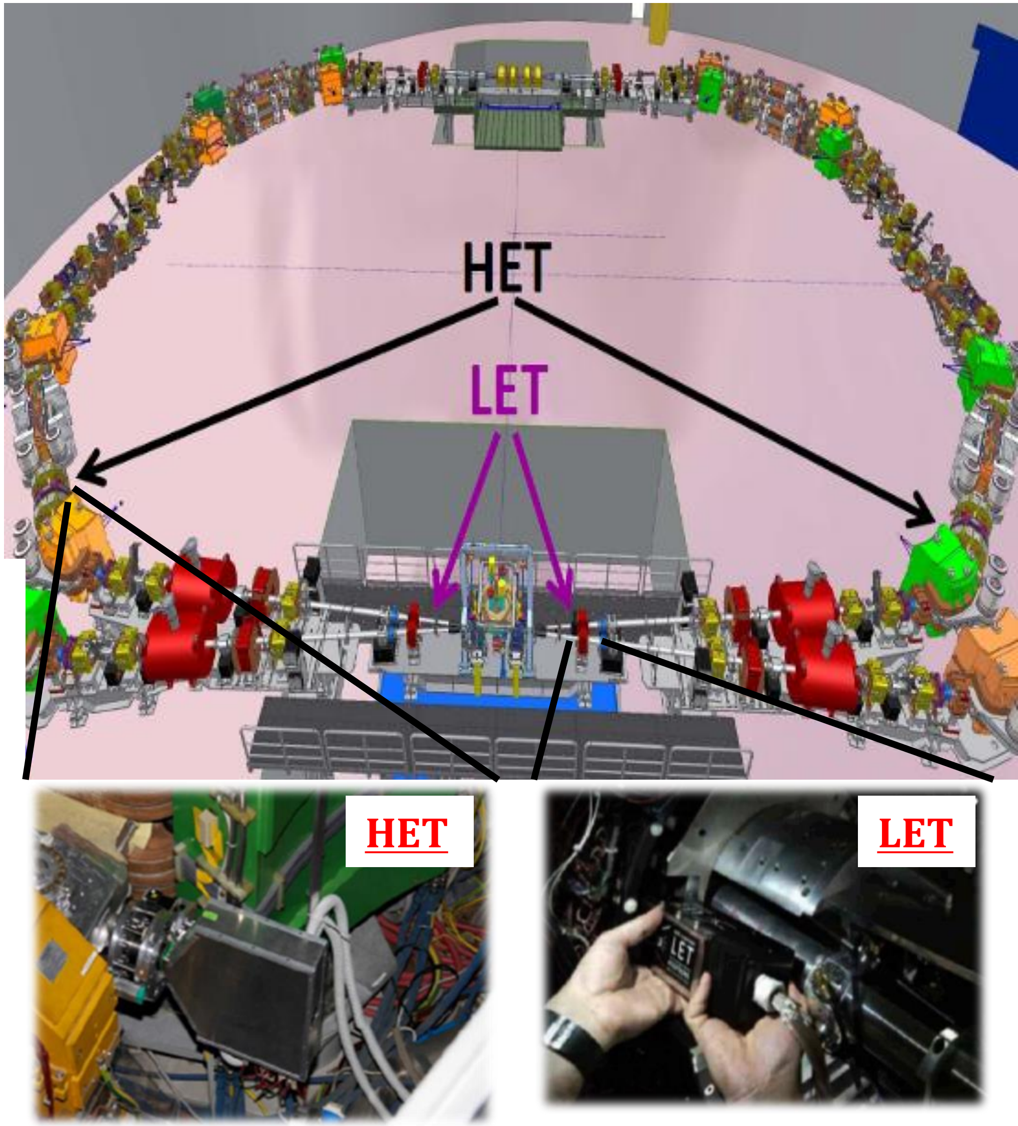
- **Taggers for leptons momenta measurement in the $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$ reaction**

LET: E_e ~ 150-400 MeV

- Inside KLOE detector
- 20 LYSO crystals in a matrix of 6 x 7.5 x 12 cm^3 readout by SiPM
- $\sigma_E/E<10\%$ for E>150 MeV

HET: E_e > 400 MeV

- Plastic scintillator hodoscopes
- Placed after first dipoles (11 m from IP)
- Capable to resolve the RF frequency on-line and cross-correlate the signal with KLOE trigger
- σ_E ~ 2.5 MeV; σ_T ~ 200 ps



Acta Phys. Pol. B 46, 81 (2015)
NIM A 617, 266 (2010)
NIM A 617, 81 (2010)

KLOE-2 Physics

KLOE & KLOE-2 gathered an unique data sample: $L_{int} \approx 8\ fb^{-1}$ (2.4 x 10^{10} φ decays)

- **γγ physics**
  - π^0 width and $\pi^0 \to \gamma\gamma^*$ transition form factor in the space-like region
- **Light meson spectroscopy**
  - Properties of scalar/vector mesons
  - Rare η decays
  - η' physics
- **Kaon physics**
  - Test of CPT (and QM) in correlated kaon decays
  - Tests of CP & CPT in K_S 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 contribution to (g-2))

[G.Amelino-Camelia et al., Eur. Phys. J. C 68 (2010), 619-681]

Summary and outlook

- The entangled neutral kaon system at a f-factory is a unique laboratory for the study of discrete symmetries.
- KLOE-2 collected, together with the previous KLOE run, an unique data sample at the φ meson mass energy.
- We have performed the first direct test of T and CPT in neutral kaon transitions with a precision of few percent on the corresponding observables
- No evidence of T and CPT symmetries violation.
- CP violation in transitions observed with a significance of 5.2σ (consistent with the known CP violation in the neutral kaons mixing)

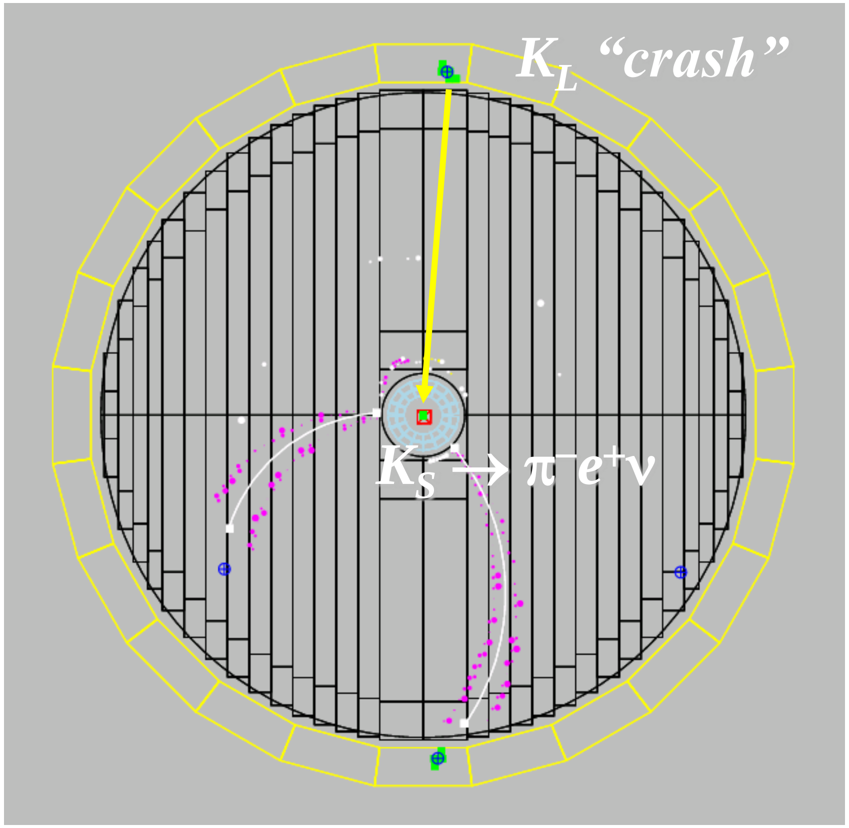
Thank You for attention

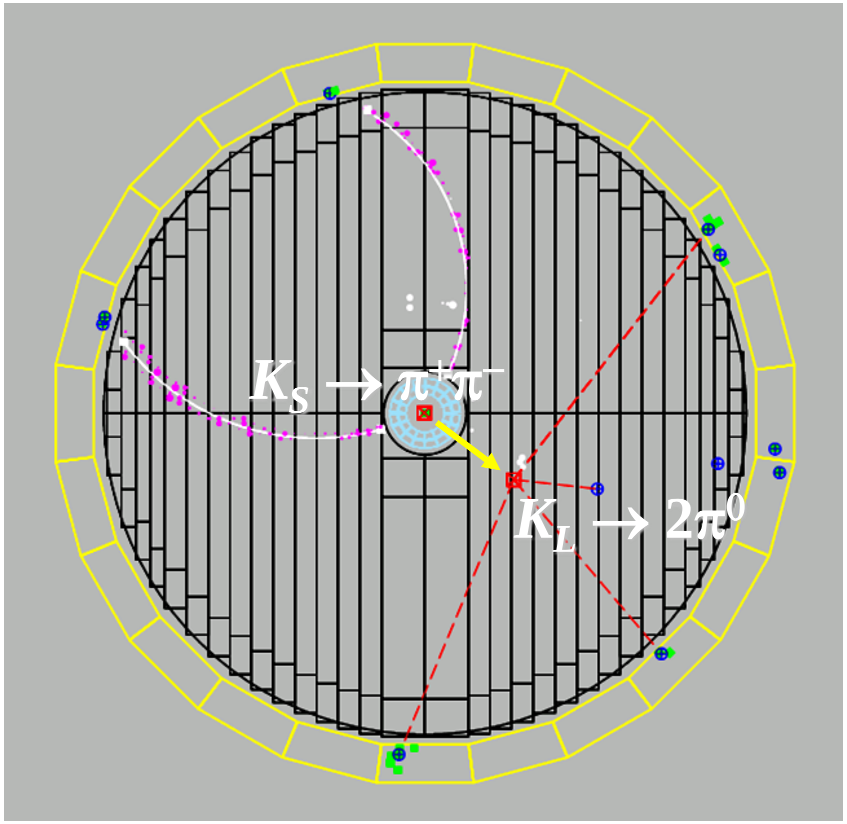
SPARES

Effect	$R_{2,T}$ $\times 10^{-3}$	$R_{4,T}$ $\times 10^{-3}$	$R_{2,CPT}$ $\times 10^{-3}$	$R_{4,CPT}$ $\times 10^{-3}$	$DR_{T,CP}$ $\times 10^{-3}$	DR_{CPT} $\times 10^{-3}$	$R_{2,CP}$ $\times 10^{-3}$	$R_{4,CP}$ $\times 10^{-3}$
Background model	2.74	4.62	2.79	4.43	4.43	4.41	4.37	–
Efficiency smoothing	2.46	5.31	2.43	5.26	6.70	6.83	6.76	0.17
Δt bin width	8.00	5.00	7.50	5.50	9.00	9.00	8.90	0.03
Fit range	7.33	8.88	7.32	8.84	7.95	7.60	7.78	0.41
Effects of cuts in the $(\pi e \nu)(3\pi^0)$ selection								
K_S vertex location cuts	0.57	2.31	0.58	2.27	2.36	2.41	2.39	–
$M(\pi,\pi)$ cut	2.48	1.34	2.52	1.31	1.56	1.63	1.60	–
TOF cuts	6.08	5.32	6.19	5.23	6.40	6.58	6.49	–
$e/\pi/\mu$ classification	4.78	4.40	4.85	4.33	9.33	9.59	9.46	–
Effects of cuts in the $(\pi^+\pi^-)(\pi e \nu)$ selection								
K_S vertex location cuts	0.007	0.004	0.004	0.007	0.004	0.004	–	0.005
$M(\pi,\pi)$ and $\|\vec{p}\|$ cuts	2.14	1.68	1.67	2.17	0.70	0.72	–	0.74
$m_+^2 + m_-^2$ cut	1.48	1.32	1.31	1.49	0.20	0.21	–	0.21
TOF cuts	2.14	1.68	1.67	2.17	0.70	0.72	–	0.74
Total systematic uncertainty	**14**	**15**	**14**	**15**	**19**	**19**	**19**	**0.89**
D factor total uncertainty	12	12	12	12	–	–	–	–

K_S and K_L tagging

A Φ-factory offers the possibility to select pure kaon beams:





K_S tagged by K_L interaction in EmC
Efficiency ~ 30%
K_S angular resolution: ~ 1° (0.3° in φ)
K_S momentum resolution: ~ 2 MeV

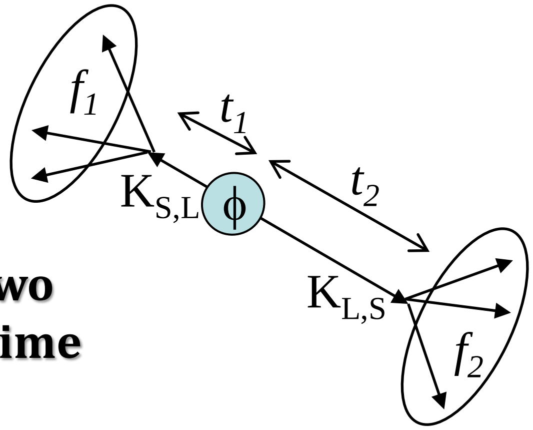
K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP
Efficiency ~ 70%
K_L angular resolution: ~ 1°
K_L momentum resolution: ~ 2 MeV

Kaon interferometry at the Φ-factory

- ϕ decays provide entangled kaons pairs:

$$|\phi> = \frac{1}{\sqrt{2}}\left(|K^0>|\overline{K^0}> - |\overline{K^0}>|K^0>\right) = N(|K_S(\vec{p})>|K_L(-\vec{p})> - |K_S(-\vec{p})>|K_L(\vec{p})>)$$

$$N = \frac{\sqrt{(1+|\varepsilon_S|^2)(1+|\varepsilon_L|^2)}}{(1-\varepsilon_S\varepsilon_L)}$$



- **Complete destructive quantum interference prevents the two kaons from decaying into the same final state at the same time**

❖ Interference patterns for different kaon decays provide studies of different symmetries:

$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^0\pi^0 \Longrightarrow \frac{\varepsilon'}{\varepsilon}$ (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 $\Delta S = \Delta Q$ rule

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

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

PLB 642(2006) 315
J.Phys.Conf.Ser.171(2009) 012008