Flavor Physics and Discrete Symmetries at KLOE-2

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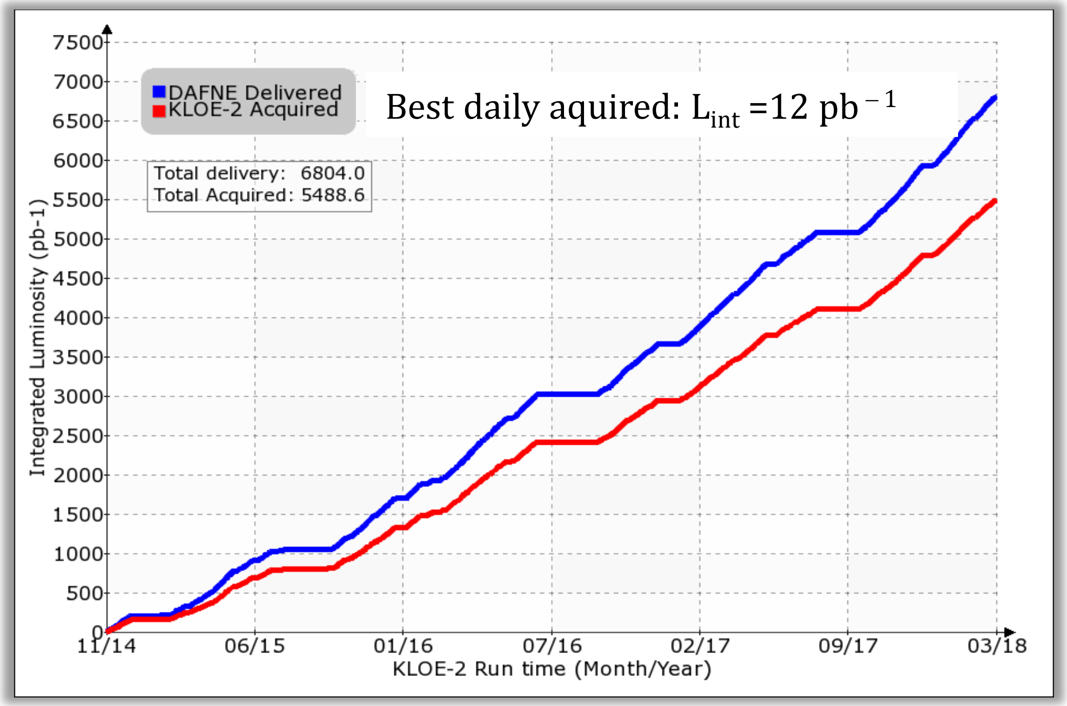
The DAFNE Φ-factory

- e^+e^- collider @ $\sqrt{s} \approx M_\varphi = 1019.4$
- $\sigma_{peak} \sim 3\ \mu b$
- Large eams crossing angle
- Novel Crab-Waist interaction scheme
- Separate e^+e^- rings to reduce beam-beam interaction
- 105 bunches in each ring with a time interval of 2.7 ns
- Peak luminosity $2.4\times10^{32}\ cm^{-2}s^{-1}$
- The total luminosity integrated by KLOE:
  $L_{int} = 5.5\ fb^{-1}$ (KLOE-2) + $2.5\ fb^{-1}$ (KLOE)



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

$\sigma_p/p = 0.4\ \%$

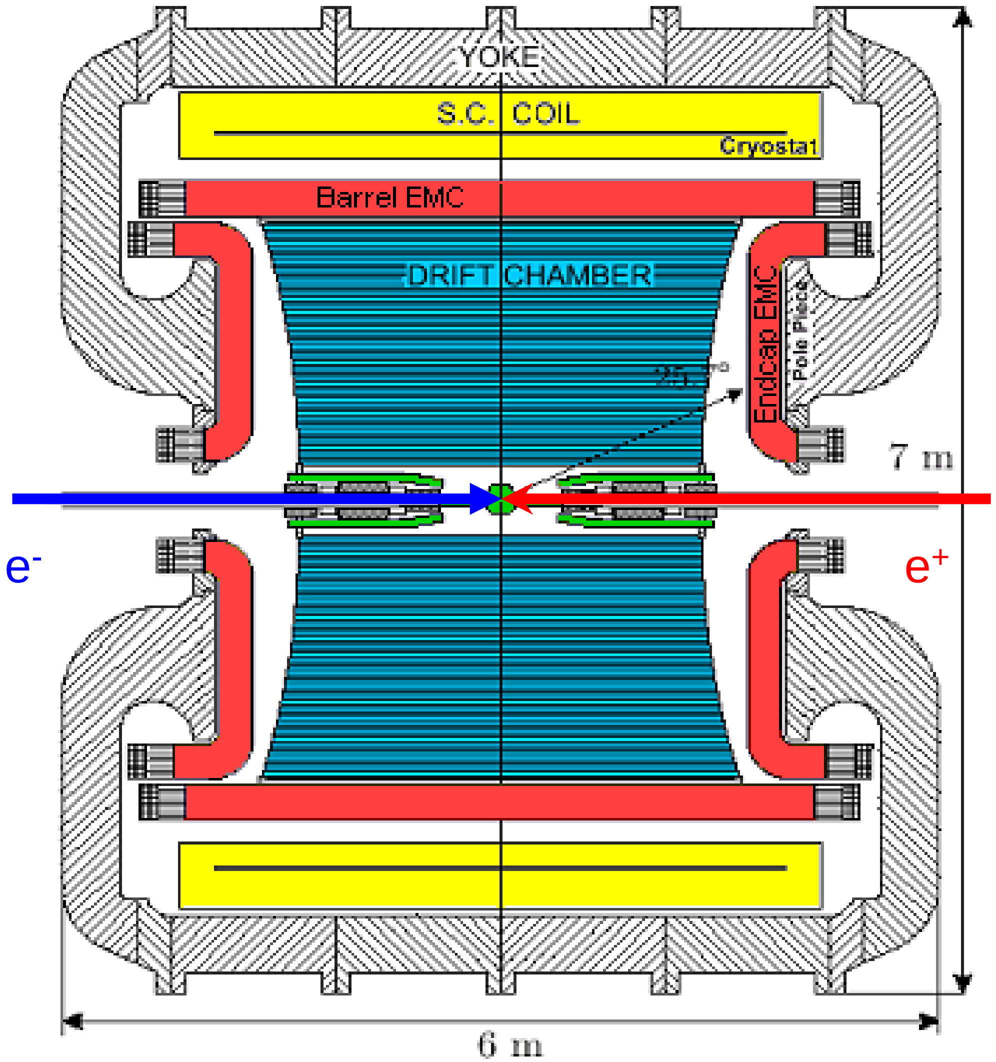
$\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2\ mm$

$\sigma_{vtx} \sim 3\ mm$

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

Superconducting coil

B = 0.52 T



Lead/scintillating-fiber calorimeter

- Hermetical coverage
- High efficiency for low energy photons

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

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

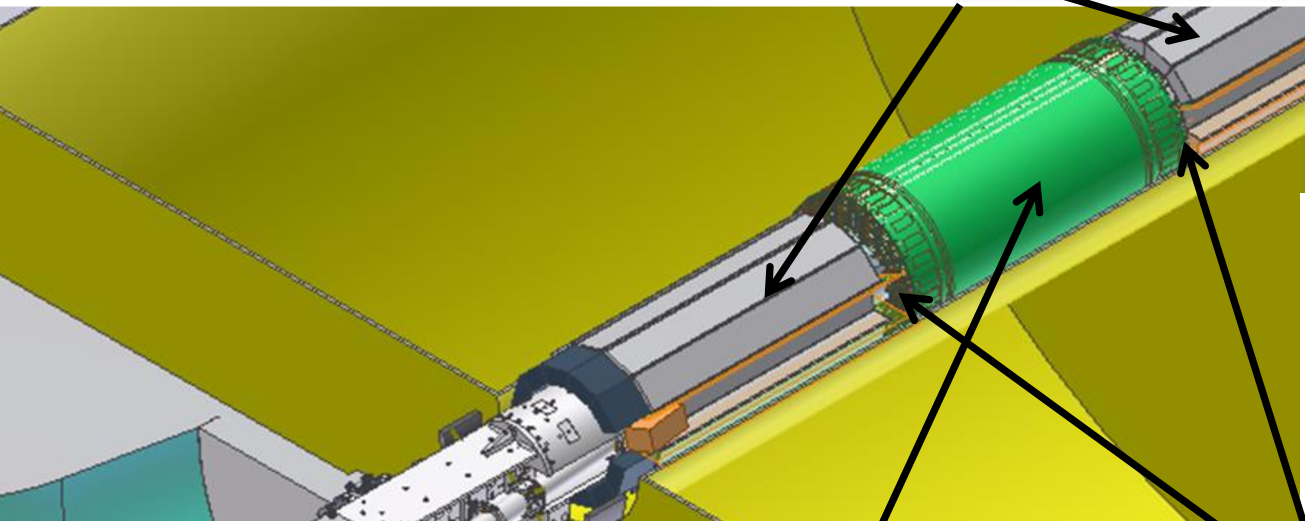
The KLOE-2 detector

QCALT

Tungsten slabs + scintillator tiles red out by SiPM's

Low-beta quadrupole coverage for KL decays

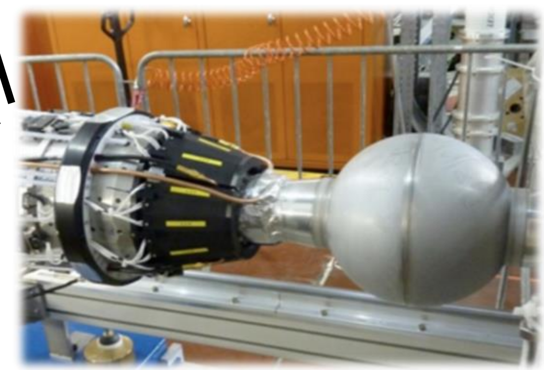
QCALT: NIMA 617, 105 (2010); Acta Phys. Pol. B 46 , 87 (2015)



CCALT

LYSO crystals+ SiPM read-out

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



CCALT: NIM A 718 , 81 (2013)

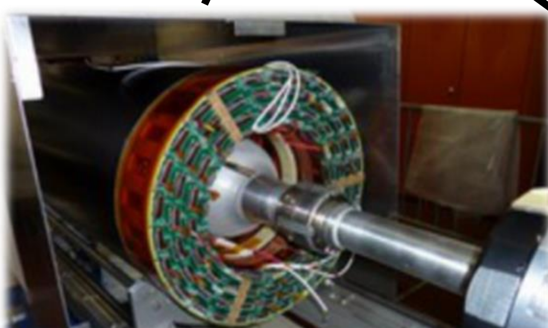
INNER TRACKER

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

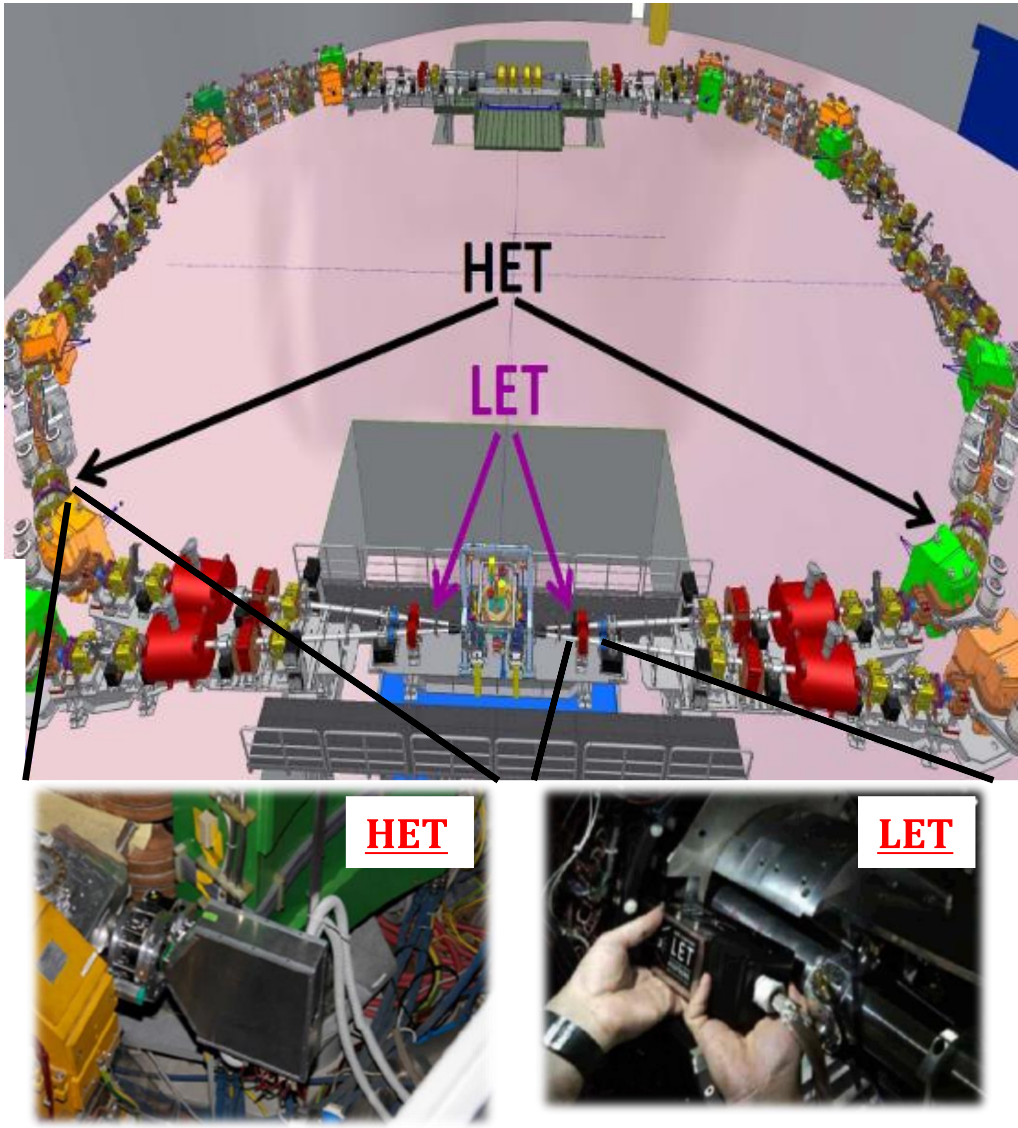
❑ **Taggers for leptons momenta measurement in the $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$ reaction**

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: $L_{int} \approx 8\ fb^{-1}$ (2.4×10^{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]

CP violation in rare K_S decays

- $K_S \to \pi^0\pi^0\pi^0$: unambiguous sign of CP violation
- $K_S \to \pi^+\pi^-\pi^0$: CPV for for L=0,2, but contains also conserving amplitude

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0 | H | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | H | K_L \rangle} = \varepsilon + \varepsilon'_{000} \qquad \eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0 | H | K_S \rangle}{\langle \pi^+\pi^-\pi^0 | H | K_L \rangle} = \varepsilon + \varepsilon'_{+-0}$$

- In the lowest order of the χPT: $\varepsilon'_{000} = \varepsilon'_{+-0} = -2\varepsilon'$

$$Im(\eta_{+-0}) = -0.002 \pm 0.009; \qquad Im(\eta_{000}) = (-0.1 \pm 1.6) \cdot 10^{-2}$$

- KLOE set the best upper limit on $|\eta_{000}|$:

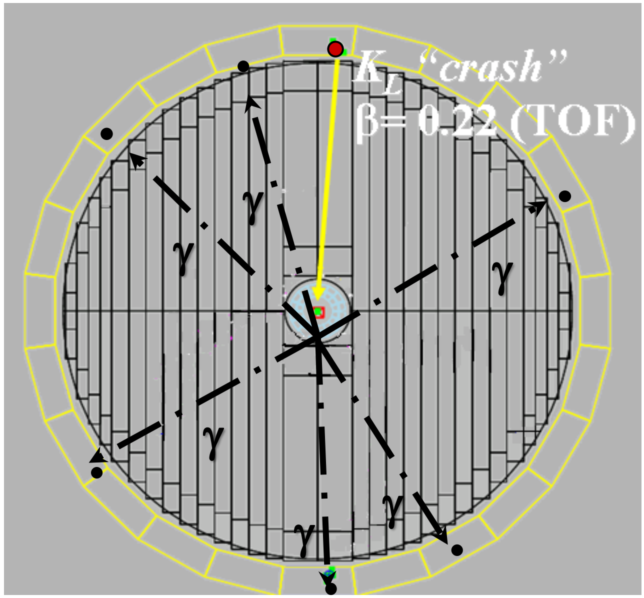
$$BR(K_S \to 3\pi^0) < 2.6 \cdot 10^{-8} \Rightarrow |\eta_{000}| = \sqrt{\frac{\tau_L \, BR(K_S \to 3\pi^0)}{\tau_S \, BR(K_L \to 3\pi^0)}} \leq 0.0088 \ @ \ 90\% \ C.L.$$

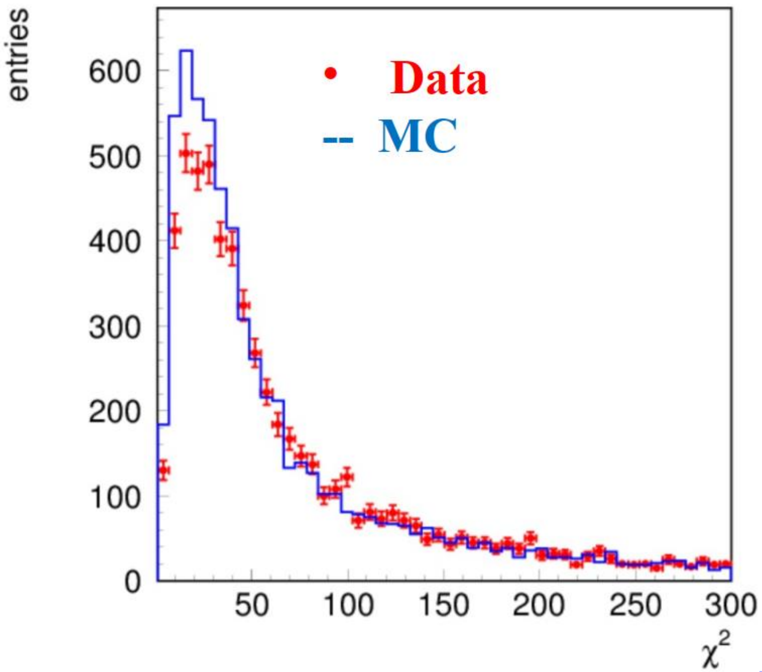
D. Babusci et al., Phys. Lett. B 723 (2013) 54

- Uncertainties of both η_{000} and η_{+-0} contribute to phase of ε
- Current experimental accuracy on BR($K_S \to \pi^+\pi^-\pi^0$) is 30% (CPLEAR, NA48 and E621)
- First direct search for $K_S \to \pi^+\pi^-\pi^0$ is ongoing with the old KLOE data set (with expected accuracy ~O(30 %))

CP violation in rare K_S decays

- Blind analysis on the KLOE-2 data sample ($\sim 4 fb^{-1}$)
- Pre-selection with the following requirements:
  - K_L-crash: E>150 MeV, $0.2 < \beta < 0.225$
  - prompt photons: $E_{cl} > 20$ MeV; $|\cos\theta_{cl}| \leq 0.915$ and $|\Delta T_{cl}| \leq \mathrm{Min}(3.0 \cdot \sigma_T(E_{cl}), 2\ \mathrm{ns})$
- $K_S \to 2\pi^0$ (4 prompt photons) used for normalization
- Main background source: $K_S \to 2\pi^0$ with two additional clusters (shower splitting/accidentals)
- With Full KLOE-2 statistics + optimized analysis we can reach Br ~ 10^{-8}





K_S semileptonic charge asymmetry

CP violation

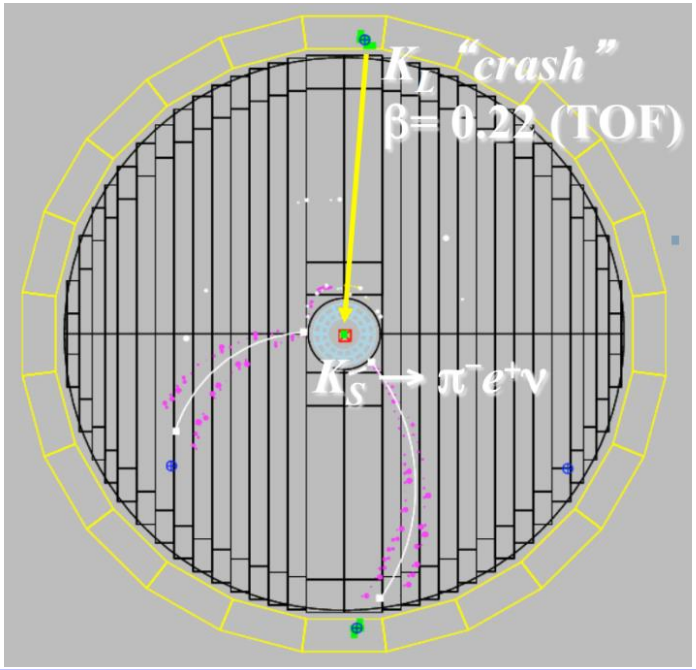
CPTV in mixing

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \upsilon) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\upsilon})}{\Gamma(K_{S,L} \to \pi^- e^+ \upsilon) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\upsilon})} = 2[Re(\varepsilon_K) \pm Re(\delta_K) - Re(y) \pm Re(x_-)]$$

CPT & ΔS= ΔQ violation

ΔS≠ΔQ amplitudes

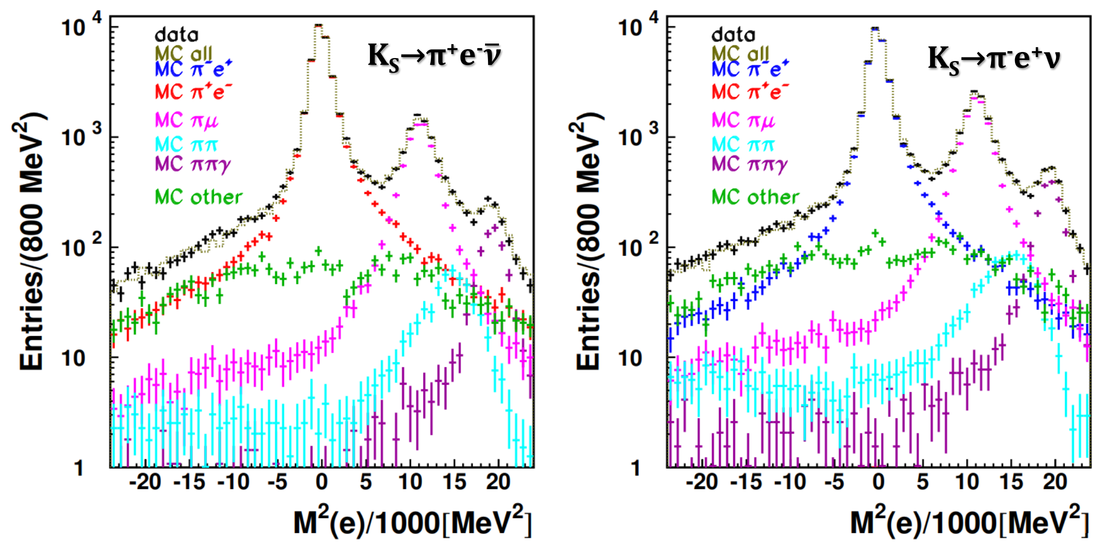
- $A_S \neq A_L \Longrightarrow$ CPT violation
- Analysis of the whole KLOE statistics (1.7 fb^{-1})
- Tagging with K_L interaction in the calorimeter (ε~30%)
- PID based on time-of-flight measurement
- Control sample: $K_L \to \pi e \nu$ close to IP tagged by $K_S \to \pi^0 \pi^0$ (track-to-cluster association and TOF efficiency corrections)



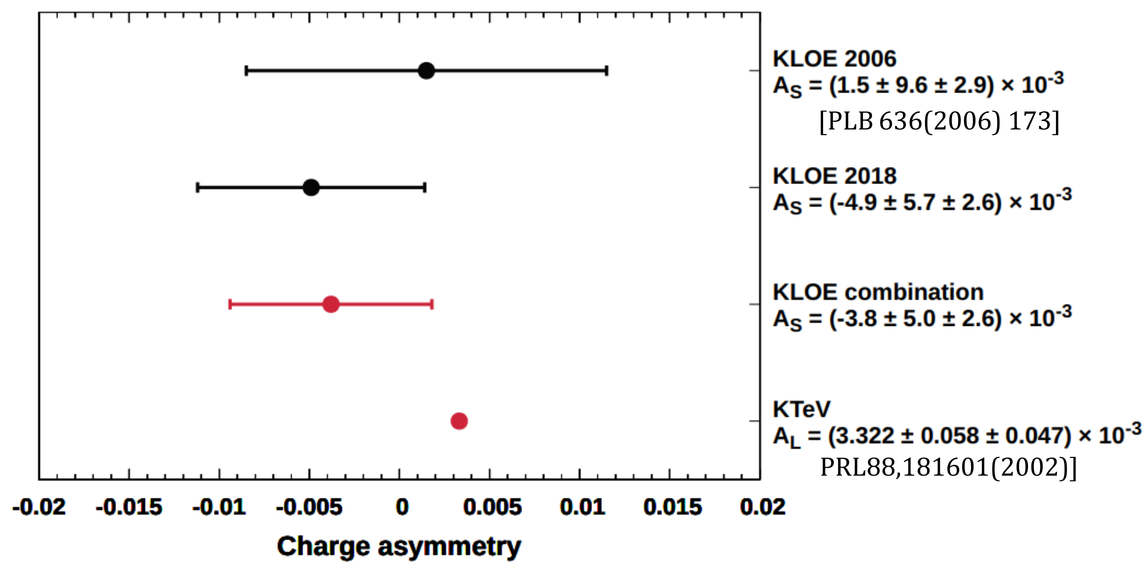
K_S semileptonic charge asymmetry

$$M(e)^2 = \left[E_{K_S} - E_\pi - E_\nu\right]^2 - p^2(e)$$

Fit of $M^2(e)$ distribution varying MC normalizations of signal and background contributions



- ❖ Result combined with the previous KLOE analysis:
  $A_S = (-3.8 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}$
- ❖ Using the present knowledge on A_L, ε_K and δ_K:
  $Re(x_-) = (-2.0 \pm 1.4) \times 10^{-3}$
  $Re(y) = (1.7 \pm 1.4) \times 10^{-3}$
- ❖ **With KLOE-2 data we expect further improvement of sensitivity ($\sim 3 \cdot 10^{-3}$)**



[JHEP 1809 (2018) 021]

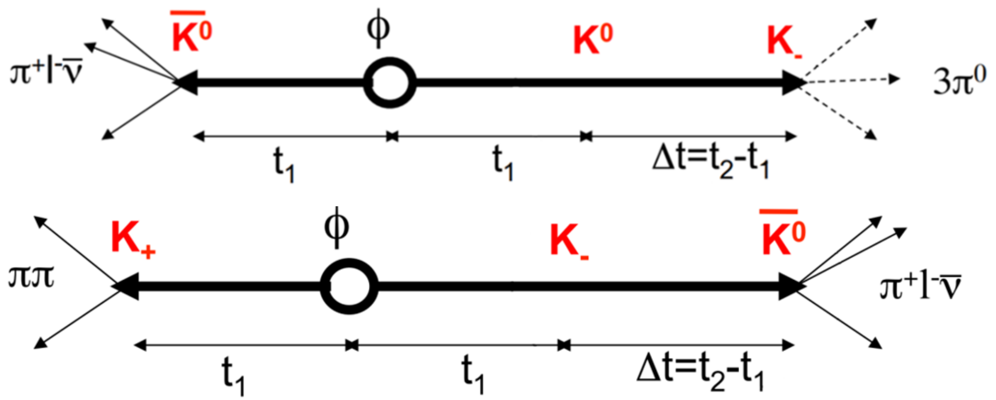
Direct test of T and CPT in neutral kaon transitions

$$|i> = \frac{1}{\sqrt{2}}\left[|K^0>|\overline{K^0}> - |\overline{K^0}> + |K^0>\right] = \frac{1}{\sqrt{2}}\left[|K_+>|K_-> - |K_->|K_+>\right]$$

- Comparison between transitions of CP and flavour states
- Kaon decays used as a filter for selected flavour and CP states

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

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



- Clean and model independent test of T and CPT via asymmetry ratios in 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)]

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

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

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

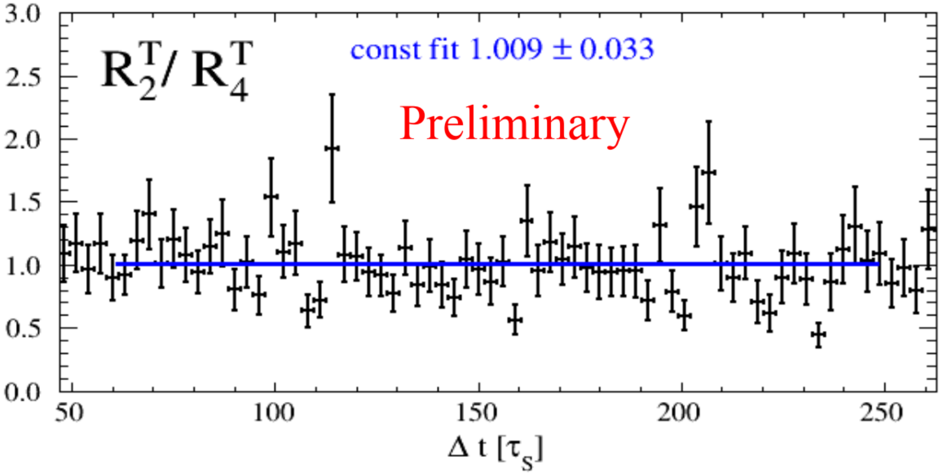
$$R_{4,CPT}(\Delta t) = \frac{P[\overline{K}^0(0)\to K_-(\Delta t)]}{P[K_-(0)\to K^0(\Delta t)]} \sim \frac{I(\pi^- l^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- l^+ \nu; \Delta t)}$$

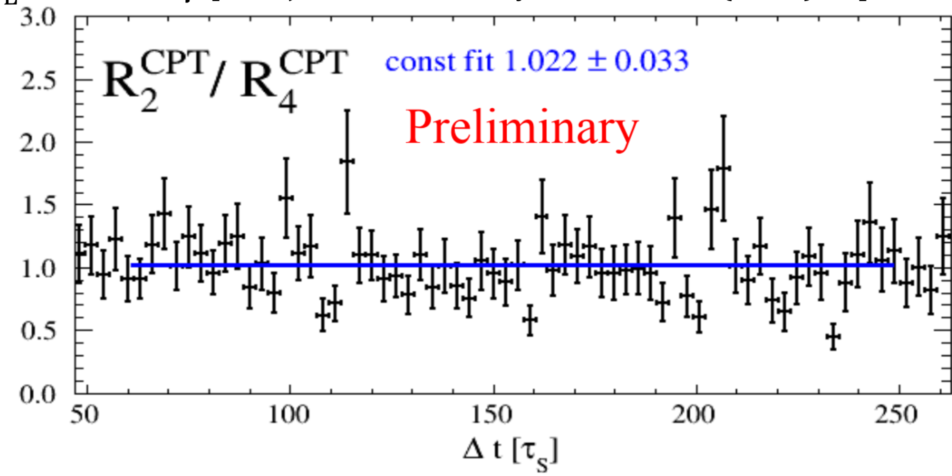
Direct test of T and CPT in neutral kaon transitions

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

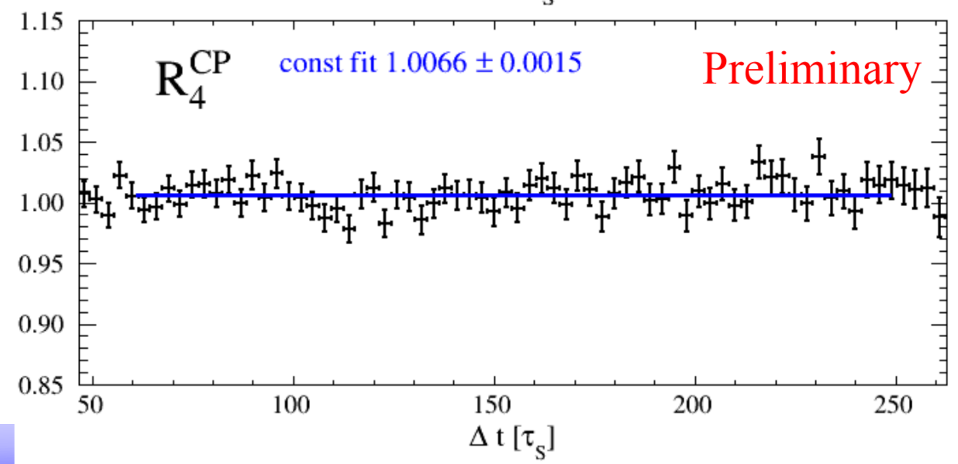
$$\frac{R_{2,CPT}(\Delta t \gg \tau_S)}{R_{4,CPT}(\Delta t \gg \tau_S)} = 1 - 8Re(\delta_K) - 8Re(x_-)$$

- Two categories of events to be identified: $\phi \longrightarrow K_S K_L \longrightarrow \pi^{\pm} e^{\mp} \nu, 3\pi^0$ and $\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-, \pi^{\mp} e^{\pm} \nu$
- Time-Of-Flight analysis for leptons and pions to refine the $K_S \rightarrow \pi e \nu$ selection
- Dedicated trilateration-based reconstruction of $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ [A. Gajos et al., Acta Phys. Polon. B 46 (2015) 13]



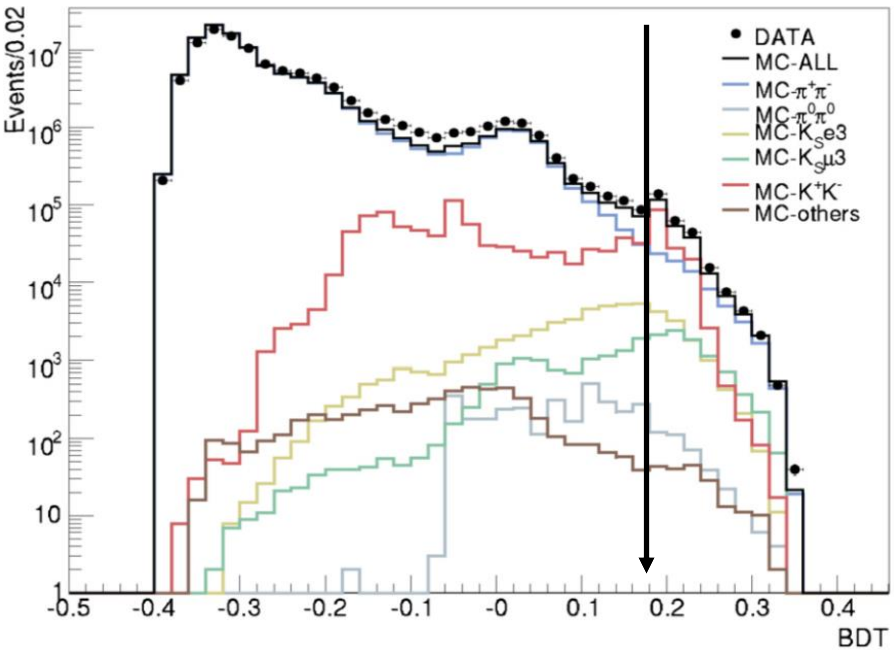


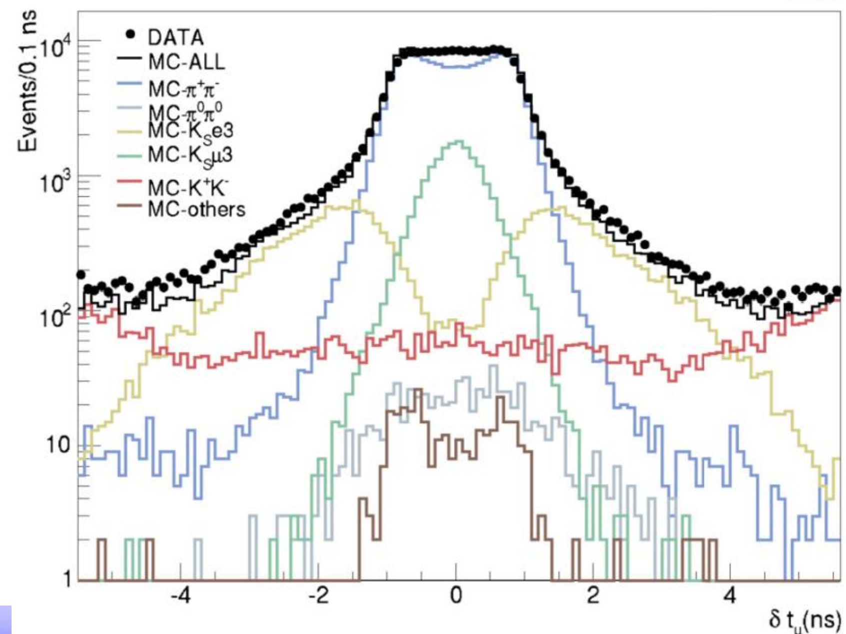
$$R_{4,CP}(\Delta t) \sim \frac{I(\pi^+\pi^-, \pi^- l^+ \nu; \Delta t)}{I(\pi^+\pi^-, \pi^+ l^- \bar{\nu}; \Delta t)} = 1 + 4Re(\varepsilon) \approx 1.0064$$



Lepton universality test with the $K_s \to \pi\mu\nu$ decay

- First measurement of the the $K_s \to \pi\mu\nu$ branching ratio
- Test of the lepton universality & $|V_{us}|$ measurement.
- Analysis of 1.6 fb^{-1} of the KLOE statistics
- Tagging with K_L interaction in the calorimete (ε~30%)
- Preselection with two tracks from the IP with opposite curvature
- The $K_S \to \pi\mu\nu$ decays selected by a boosted decision tree built with kinematic variables + time-of-flight measurement.
- Normalization sample: $Ks \to \pi^+\pi^-$
- Main sources of background: $Ks \to \pi^+\pi^-$ & $\varphi \to K^+K^-$



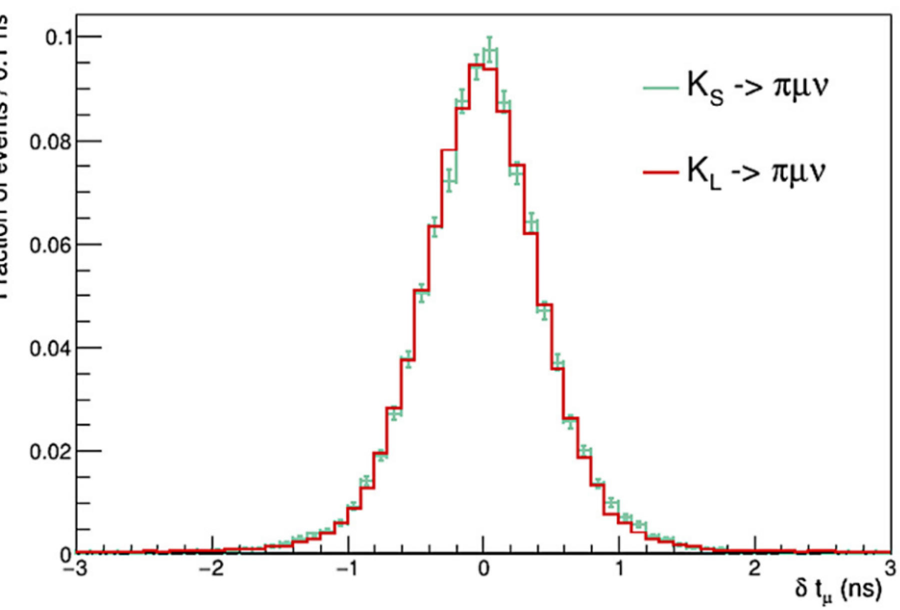


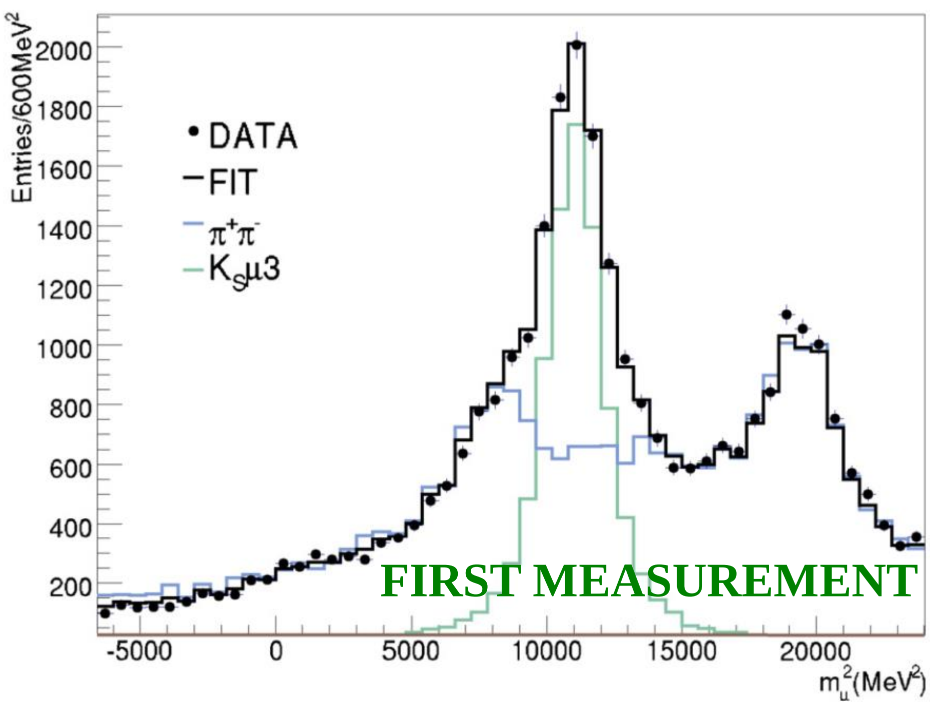
Lepton universality test with the $K_s \to \pi\mu\nu$ decay

- Signal efficiencies evaluated using data control sample of $K_L \to \pi\mu\nu$ decays
- Number of signal events estimated with a fit to the muon mass squared
- Assuming universality of the kaon–lepton coupling: $BR(K_s \to \pi\mu\nu) = (4.69 \pm 0.06) \times 10^{-4}$

$$\boldsymbol{BR(K_s \to \pi\mu\nu) = \left(4.56\ \pm 0.11_{stat} \pm 0.17_{syst}\right) \times 10^{-4}}$$

[PLB 804 (2020) 135378]



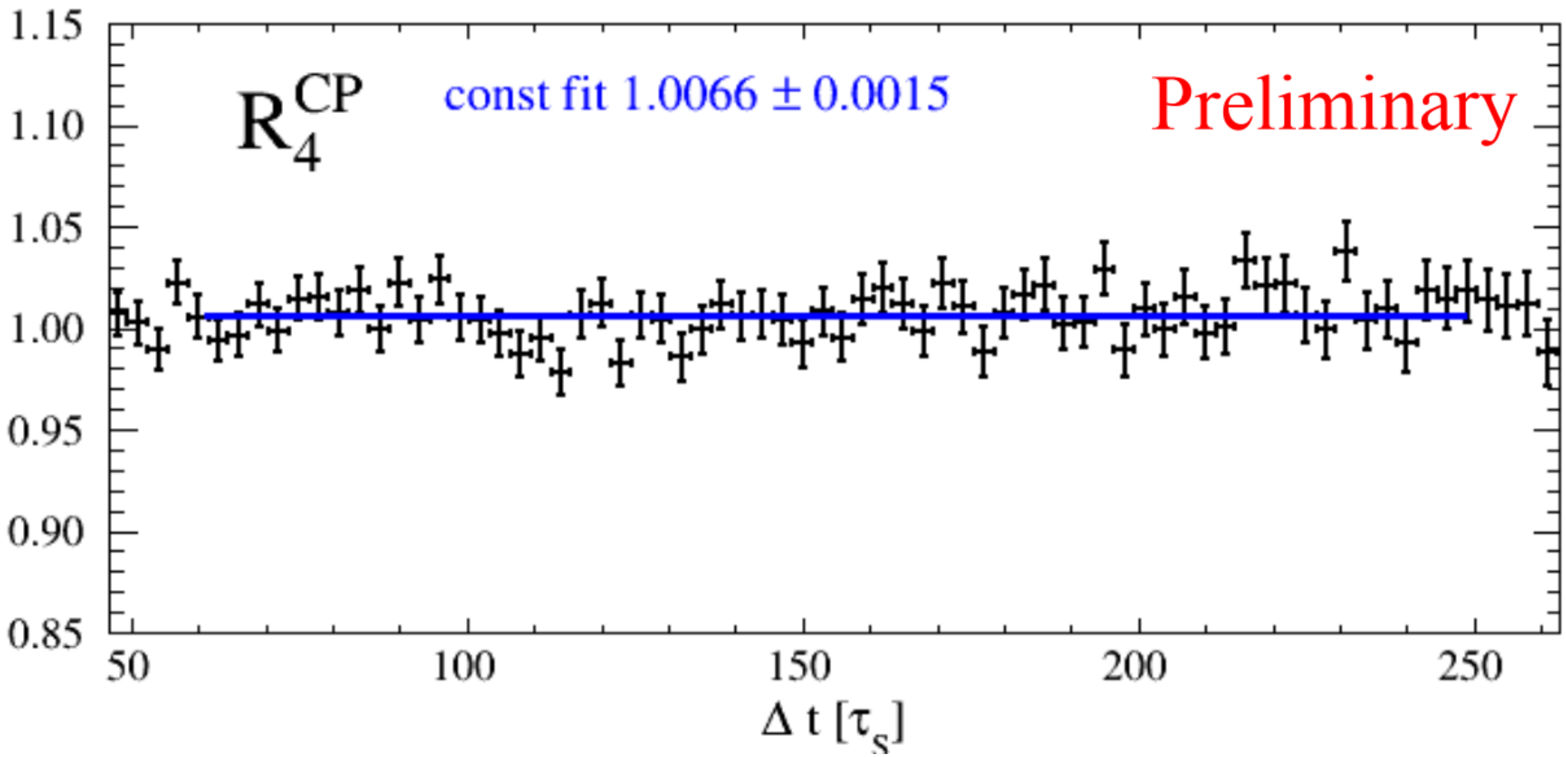


Summary and outlook

- KLOE-2 collected, together with the previous KLOE run, an unique data sample at the φ meson mass energy
- Studies of discrete symmetries with neutral kaons is one of the main goals of the KLOE-2 physics program
- Analysis of the KLOE dataset to refine K_S semileptonic charge asymmetry measurement, determine for the first time branching ration of the $Ks \to \pi\mu\nu$ decay and to perform novel direct T and CPT tests in neutral kaon transitions is being completed.
- KLOE-2 increased statistics together with new detectors broadens the KLOE physics program and extends the sensitivity reach.

Thank You for attention

SPARES



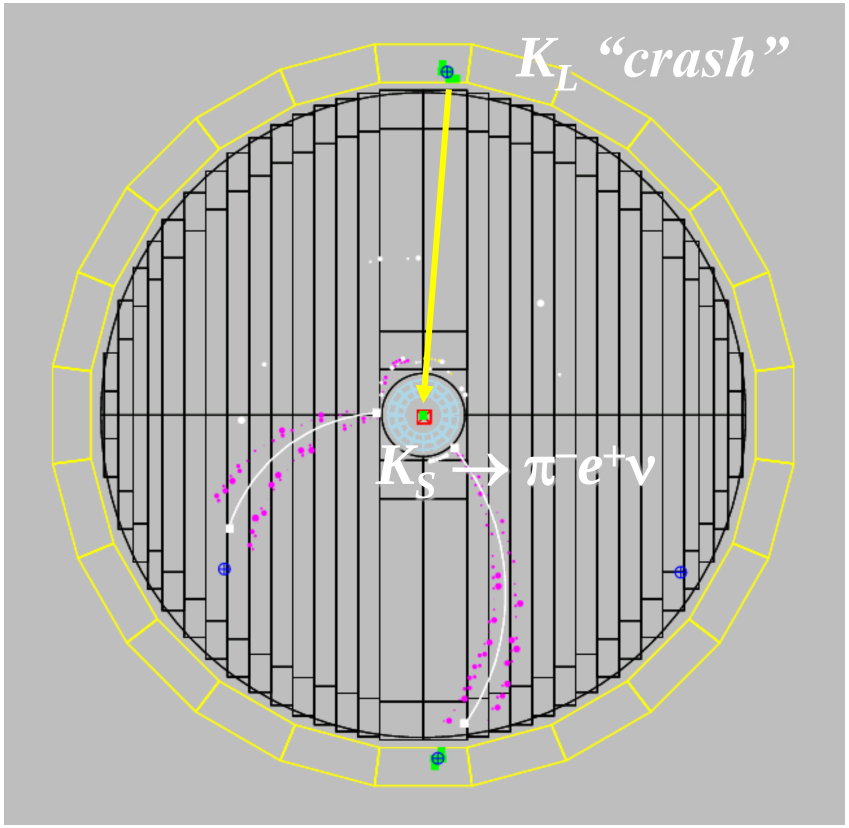
$$R_4^{CP}(\Delta t) = \frac{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

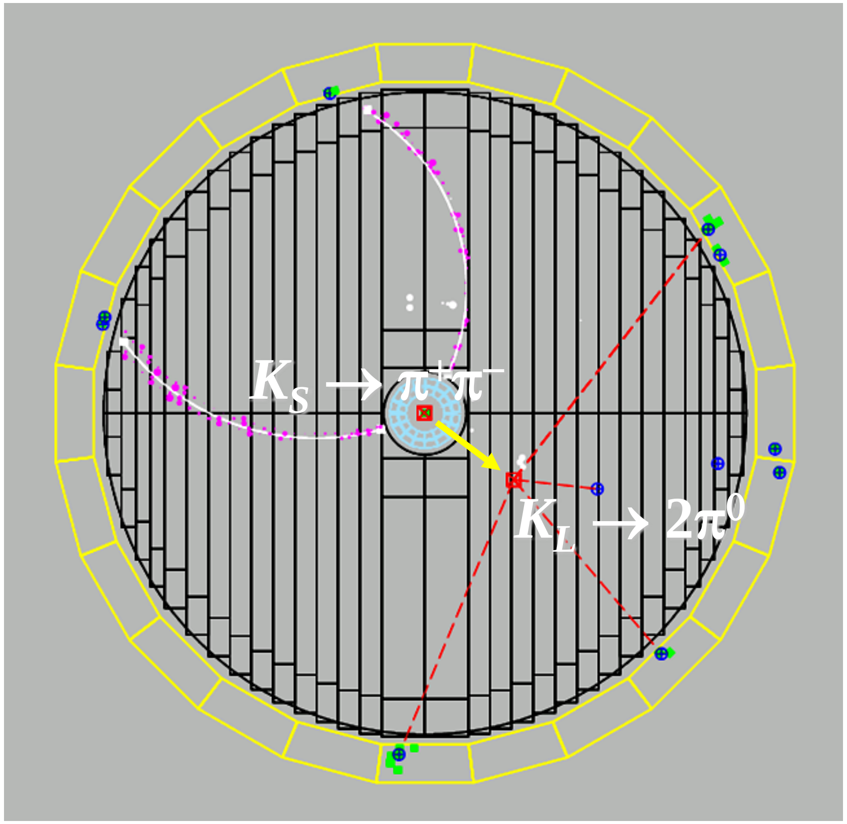
Expected:

$$R_4^{CP}(\Delta t \gg \tau_S) = 1 + 4\Re\epsilon \approx 1.0064$$

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°

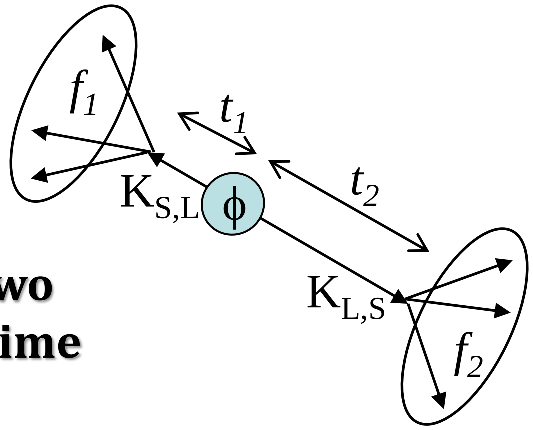
K_L momentum resolution: ~ 2 MeV

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:

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

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

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

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

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

PLB 642(2006) 315
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