Tests of discrete symmetries and quantum coherence with neutral kaons at the KLOE-2 experiment

2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics
Workshop on Discrete Symmetries and Entanglement
June 11th 2017

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on behalf of the KLOE and KLOE-2 Collaborations

National Science Centre
Poland

Outline of the talk

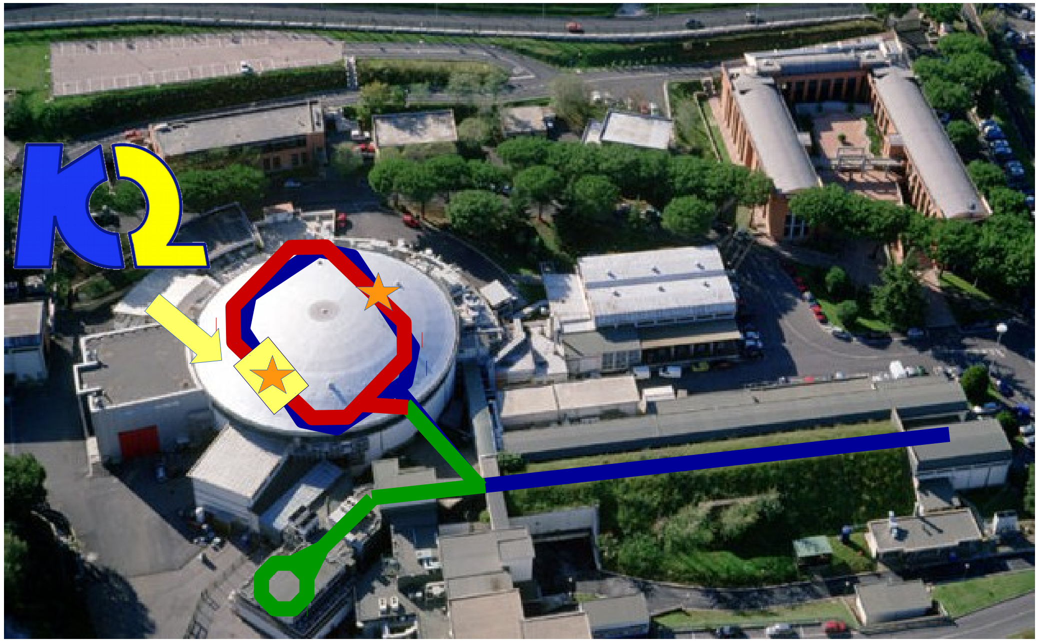
- The KLOE-2 Detector and the DAΦNE Φ-factory
- Search for CPT and Lorentz symmetry violation with the $\Phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ process
  KLOE results and perspectives for KLOE-2
- Search for quantum decoherence with $\Phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$
  Status of KLOE analysis and perspectives for KLOE-2
- Test of time-reversal and CPT symmetry in neutral kaon transitions with $\Phi \rightarrow K_S K_L \rightarrow \pi e \nu\ 3\pi^0\ (2\pi)$ decays
  Status of the analysis with KLOE and KLOE-2 data

The DAΦNE Φ-factory

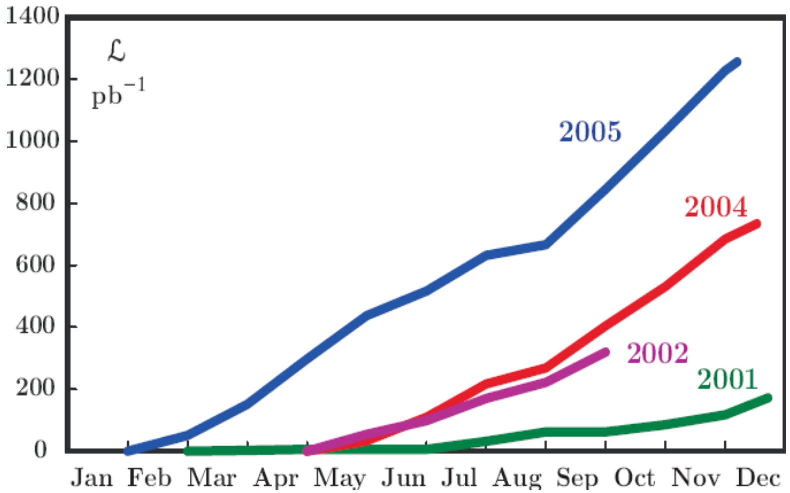
Double Annular Φ-factory for Nice Experiments:

- Located in Laboratori Nazionali di Frascati, Italy
- e^+e^- collider
- separate storage rings for e^+ and e^- to reduce beam-beam interaction
- fixed energy $\sqrt{s} = M_\phi \approx 1020$ MeV

Decay channel	Branching fraction (% units)
$\phi \to K^+K^-$	49.1
$\phi \to K^0\bar{K}^0$	34.0
$\phi \to \rho\pi, \pi^+\pi^-\pi^0$	15.4
$\phi \to \eta\gamma$	1.3



- neutral kaon pairs produced in Φ decays in an entangled state



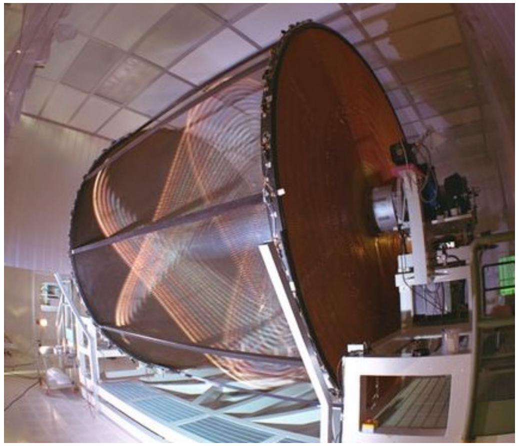
Data collected by KLOE at DAΦNE:

- 2001-2 ~0.5 fb^{-1}
- 2004-5: ~1.9 fb^{-1}

} About 10^{10} of Φ meson decays

The KLOE Detector

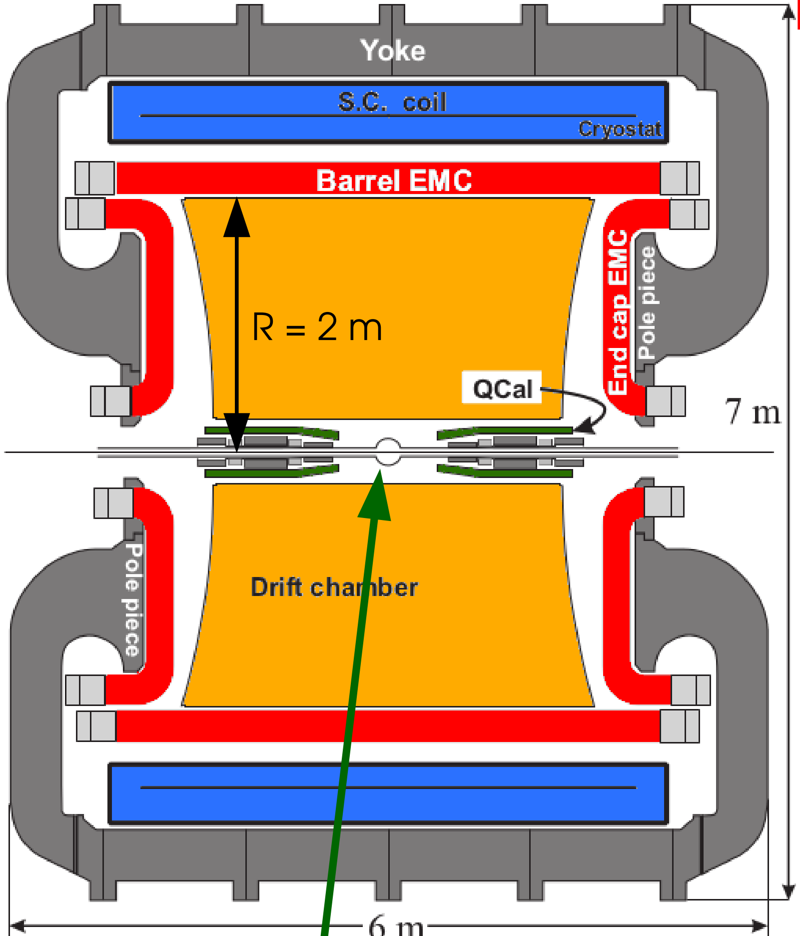
Drift Chamber (DC)



- gas: 90% He + 10% C_4H_{10}
- R_{inner} = 25 cm,
  R_{outer} = 2 m
- $\sigma_{xy} \approx 150$ μm, $\sigma_z \approx 2$ mm
- $\sigma(p_T)/p_T = 0.4\%$

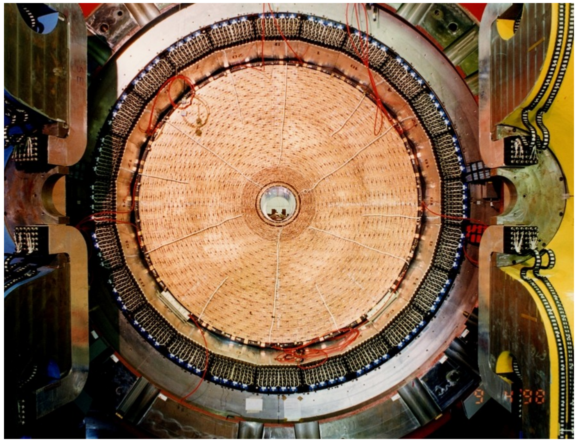
Superconducting coil

- B = 0.52 T



Spherical beam pipe around interaction point to minimize kaon regeneration
Al-Be, R = 10 cm

Electromangnetic Calorimeter (EMC)



- lead and scintillating fibers
- covering 98% of 4π
- barrel with C-shaped endcaps

$$\sigma_t = \frac{54\ ps}{\sqrt{E[GeV]}} \oplus 140ps$$

$$\sigma_E = \frac{5.7\%E}{\sqrt{E[GeV]}}$$

$$\sigma_x = \sigma_y = 1\ cm$$

$$\sigma_z = \frac{1.2\ cm}{\sqrt{E[GeV]}}$$

KLOE-2: taking data with the upgraded detector

Detector upgrades:

- QCALT – sampling calorimeter to instrument the final focusing region
  NIMA 617 (2010),105
- CCALT – LYSO calorimeter to increase acceptance for γ-s from IP
  NPB 197 (2009), 215
- New C-GEM Inner Tracker

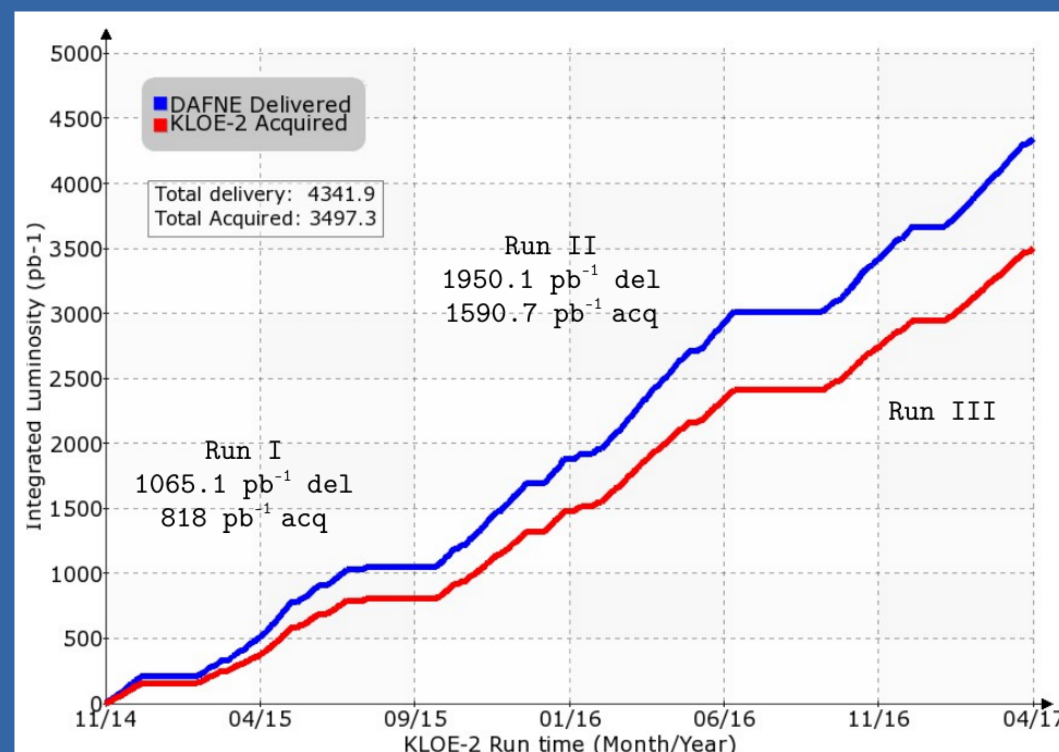
Presented in detail by Erika De Lucia on Friday

NIMA 628 (2011),194

- increased acceptance for low-p_T tracks
- Improved vertexing resolution near the IP

KLOE-2 is presently taking data

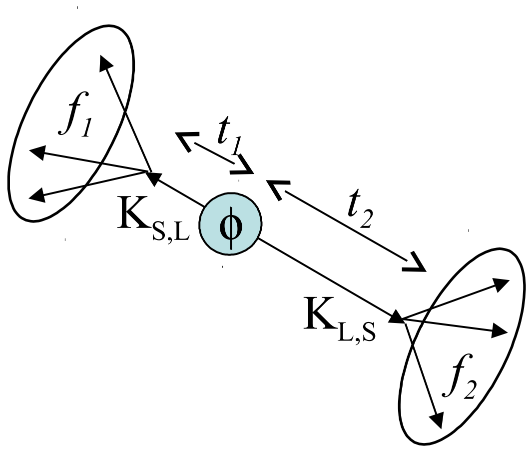
- **Goal: collect at least 5 fb^{-1}**



Neutral kaon interferometry

Neutral kaon pairs at KLOE are produced in an entangled quantum state:

$$|i\rangle = \frac{\mathcal{N}}{\sqrt{2}} \left(|K_S(+\vec{p})\rangle\, |K_L(-\vec{p})\rangle - |K_L(+\vec{p})\rangle\, |K_S(-\vec{p})\rangle \right)$$



Decay amplitude for $K_S K_L$ decaying into f_1 and f_2 final states in times t_1 and t_2

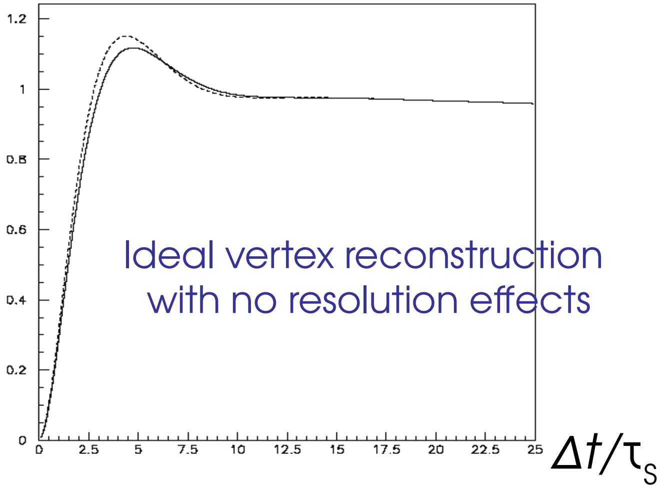
$$I(f_1,t_1;f_2,t_2) = C_{12}\left[|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}\right.$$
$$\left. -2|\eta_1||\eta_2| e^{-\frac{\Gamma_S+\Gamma_L}{2}(t_1+t_2)} cos(\Delta m(t_1 - t_2) + \varphi_2 - \varphi_1)\right]$$

$$\Delta m = m_L - m_S$$
$$\eta_j = \frac{\langle f_j | K_L \rangle}{\langle f_j | K_S \rangle}$$

Interference term

Destructive quantum interference:

- Two kaon may not decay into the same final state at the same time



CPT and Lorentz symmetry test – principle

Motivation:

- Standard Model Extension (Kostelecky)
- Anti-CPT theorem (Greenberg):

} => CPT violation should appear together with Lorentz Invariance breaking

V. A. Kostelecký Phys. Rev. D 64, 076001
O. W. Greenberg Phys. Rev. Lett. 89, 231602

=> direction-dependent modulation of the
δ CPT violation parameter:

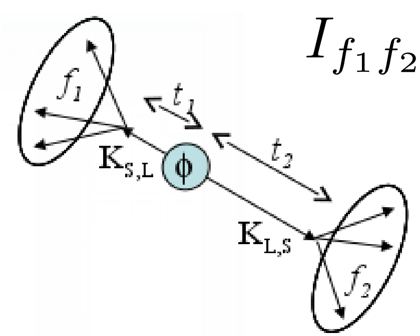
$$\delta \simeq i \, sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta \vec{a}) / \Delta m$$

where Δa_μ are coefficients of the SME Lagrangian part $\langle K | \delta H_{SME} | K \rangle \sim \beta^\mu_K \Delta a_\mu(K)$

δ can be extracted using interferometric studies with $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

- identical final states of both kaon decays ($\pi^+\pi^-$)
- kaons can only be ordered in time by direction of momentum w.r.t. a chosen direction
- decay amplitude:

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

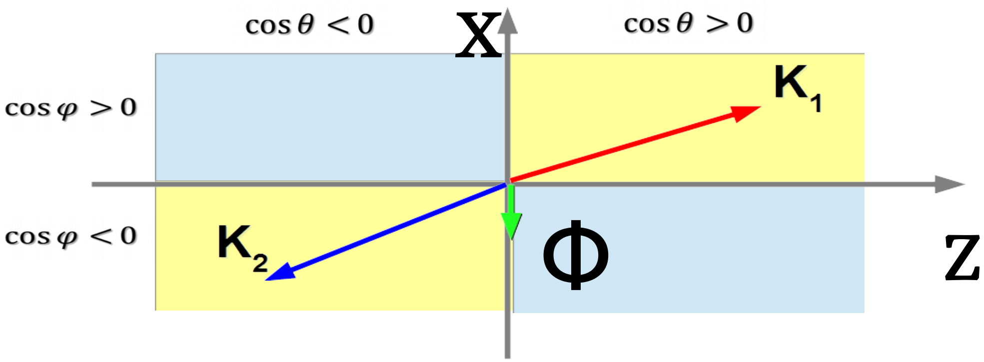


$$\eta_1 = \varepsilon_K - \delta(\vec{p}_{K_1}) \qquad \eta_2 = \varepsilon_K - \delta(\vec{p}_{K_2})$$

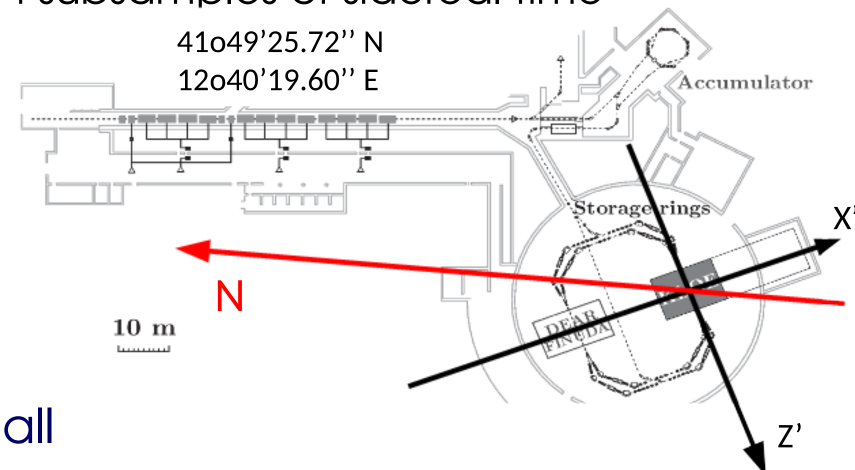
CPT and Lorentz symmetry test – KLOE analysis

$\Phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$ events are divided into:

- 2 angular subsamples

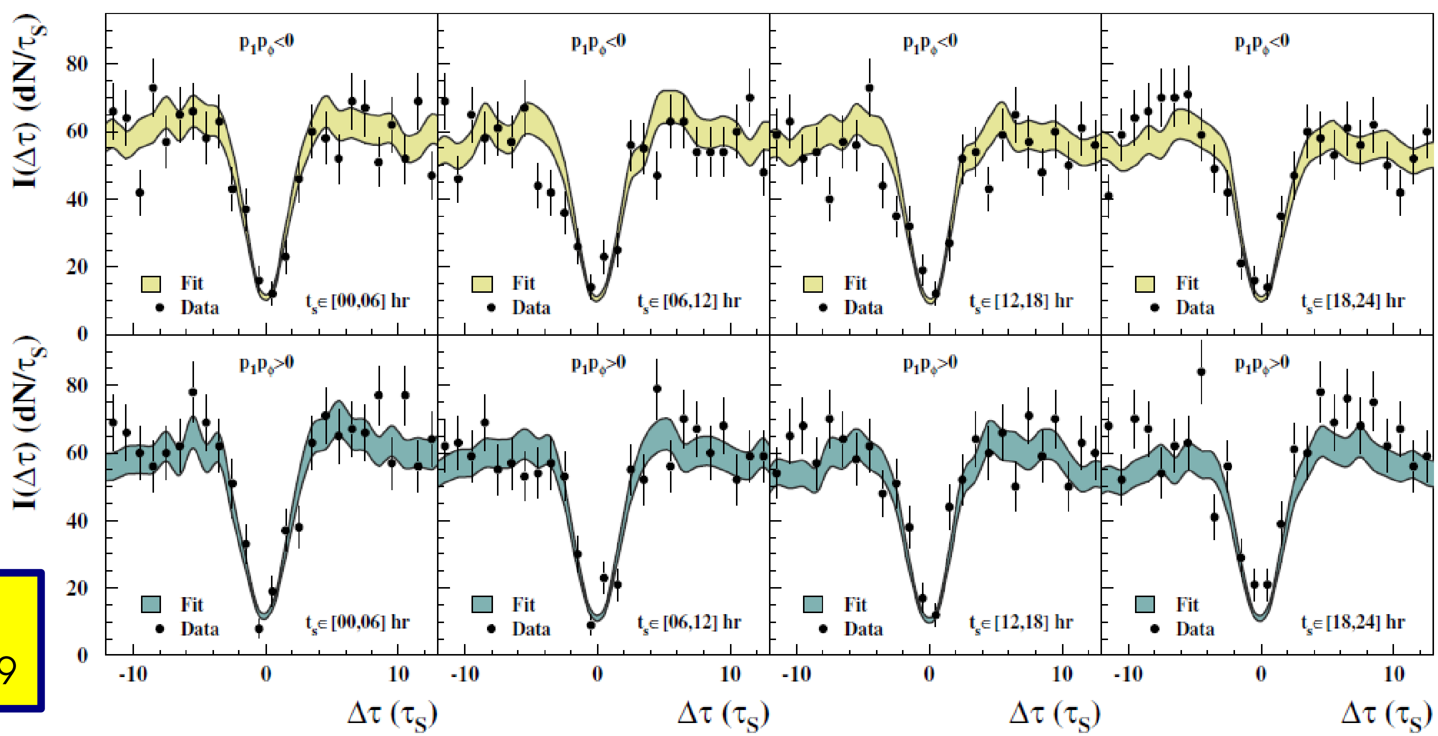


- 4 subsamples of sidereal time



Simultaneous fit is performed to Δτ distributions of all 8 subsamples

- 192 data points
- 5 free parameters
- χ^2/ndf = 211/187 (P=10%)



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

CPT and Lorentz symmetry test – results and prospects

KLOE results

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

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Phys. Lett. B 730 (2014) 89

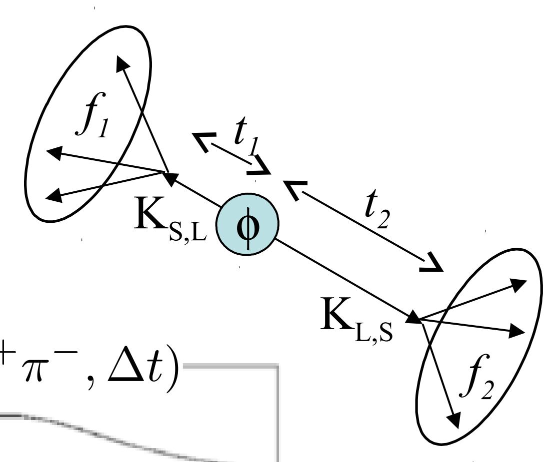
- several orders of magnitude more precise than for other meson systems
  e.g. $O(10^{-14}$ GeV) for $B^0_{(S)}$ @ LHCb
  (PRL 116 (2016) no.24, 241601)
- presently the most precise measurement in the quark sector of the SME
- dominated by statistical uncertainties
  → prospects for improvement with KLOE-2
  (goal integrated luminosity 5 fb^{-1})

Prospects with KLOE-2 (5 fb^{-1})

Parameter	Uncertainty
Δa_0	$\pm 2.2_{stat} \times 10^{-18}$ GeV
Δa_X, Δa_Y	$\pm 0.4_{stat} \times 10^{-18}$ GeV
Δa_Z	$\pm 0.5_{stat} \times 10^{-18}$ GeV

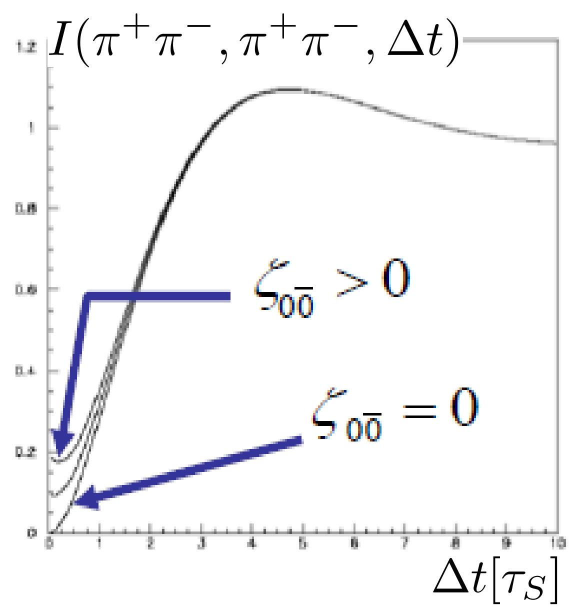
Search for quantum decoherence

$$I(f_1,t_1;f_2,t_2) = C_{12}\Big[|\eta_1|^2 e^{-\Gamma_L t_1-\Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1-\Gamma_L t_2} - 2|\eta_1||\eta_2| e^{\frac{\Gamma_S+\Gamma_L}{2}(t_1+t_2)}\cos(\Delta m(t_1-t_2)+\varphi_2-\varphi_1)\Big]$$



Furry hypothesis of "spontaneous factorization":
[W. Furry, P.R. 49 (1936) 393]

immediately after the Φ decay there may be a decoherence effect => the kaons would factorize into a non-entangled state

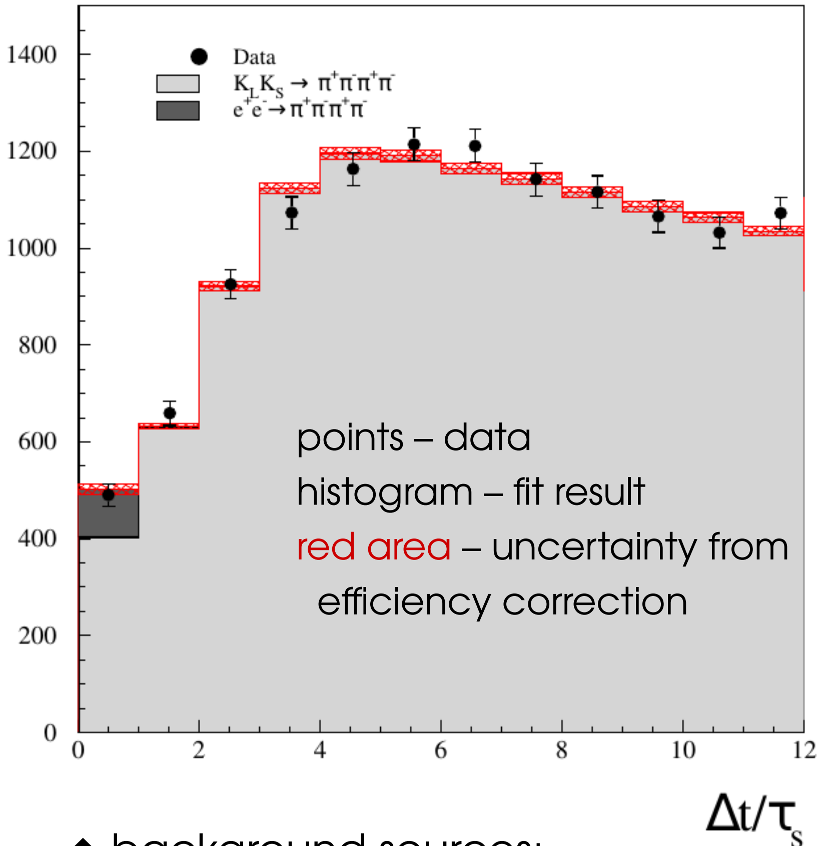


This hypothetic deviation from QM may be parametrized by ζ, measureable e.g. with $\Phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$

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

Analogously, ζ_{SL} may be defined for the K_S, K_L state basis

Quantum coherence tests – KLOE results



points – data
histogram – fit result
red area – uncertainty from efficiency correction

Last KLOE result:

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{stat} \pm 3.8_{syst}) \times 10^{-7}$$

$$\zeta_{SL} = (0.3 \pm 1.8_{stat} \pm 0.6_{syst}) \times 10^{-2}$$

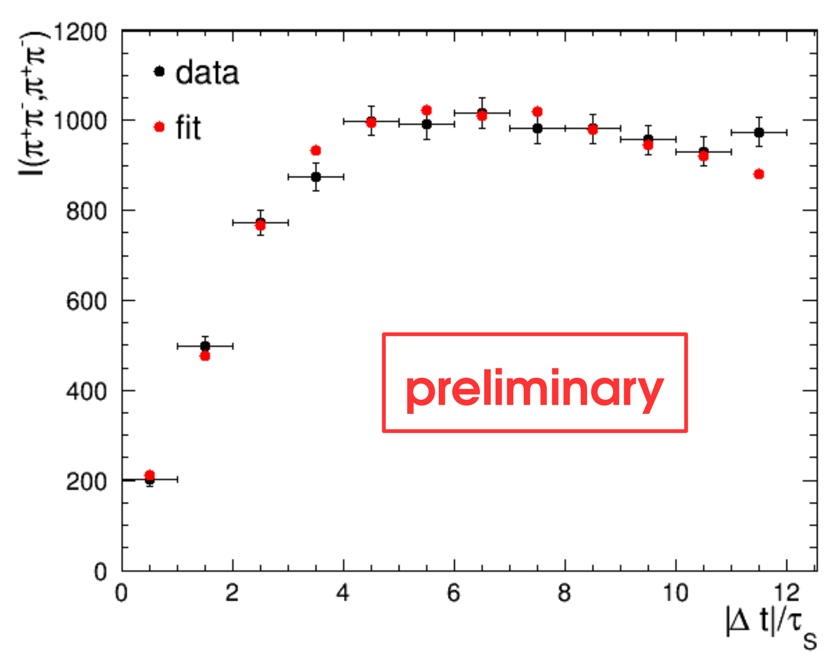
[J.Phys.Conf.Ser. 171:012008 (2009)]

High accuracy due to CP suppression in the decay channel!

- background sources:
  - coherent and incoherent kaon regeneration on the beam pipe
  - non-resonant $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$
- background conatamination accounted for in the fit

New analysis of KLOE data (1.7 fb^{-1})

- same statistics
- refined selection of $\pi^+\pi^-$ decays
- Improved sensitivity on $\zeta_{0\bar{0}}$



Quantum coherence tests – KLOE-2 prospects

Prospects with KLOE-2

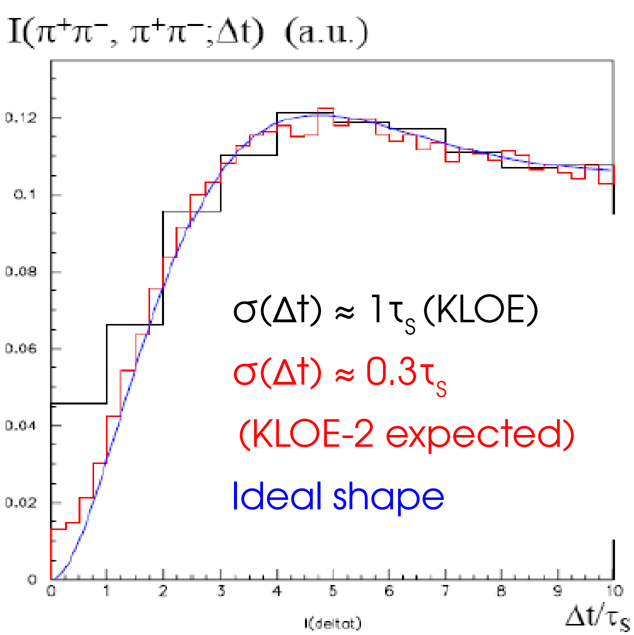
- Larger statistics (~5fb^{-1})
- new Inner Tracker
  → improved Δt resolution

Last KLOE result:

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{stat} \pm 3.8_{syst}) \times 10^{-7}$$

$$\zeta_{SL} = (0.3 \pm 1.8_{stat} \pm 0.6_{syst}) \times 10^{-2}$$

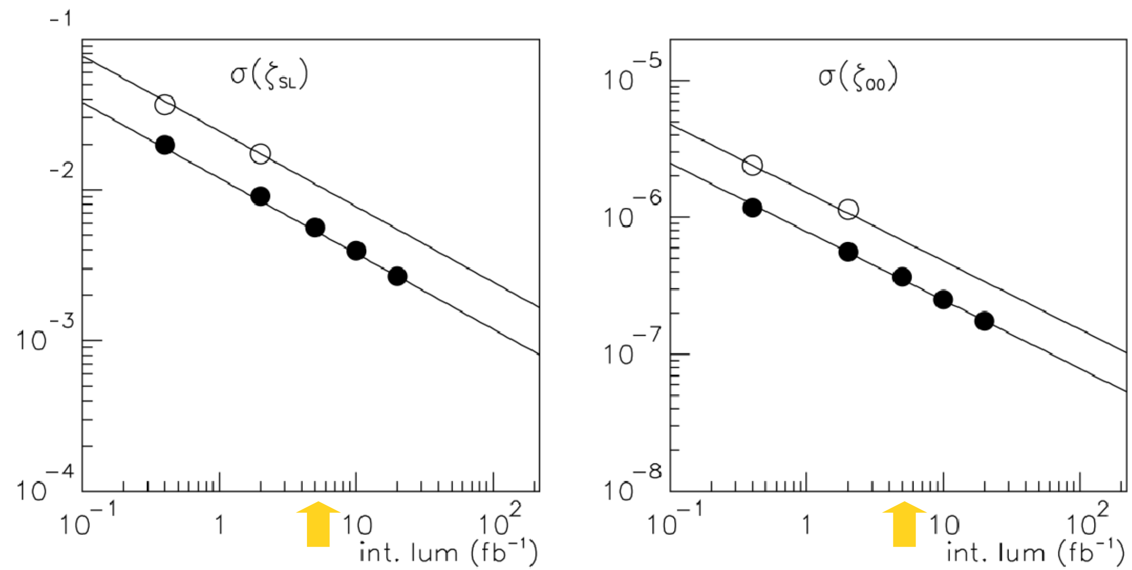
[J.Phys.Conf.Ser. 171:012008 (2009)]



Time resolution improvement expected with the KLOE-2 Inner Tracker will enhance reproduction of the interference pattern

Expected sensitivity on the ζ_{SL} and $\zeta_{0\bar{0}}$ decoherence parameters

○ without Inner Tracker ● with Inner Tracker



Symmetry tests in transitions of neutral kaons

T violation sensitive asymmetries:

$$R_2(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]}$$

$$R_4(\Delta t) = \frac{P[\overline{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \overline{K}^0(\Delta t)]}$$

[J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, Nucl. Phys. B 868 (2013) 102)]

$$P[|i\rangle \to |f\rangle] \stackrel{?}{=} P[|f\rangle \to |i\rangle]$$

$$|i\rangle \longrightarrow |f\rangle$$

Principle presented on Saturday by Antonio Di Domenico

CPT violation sensitive asymmetries:

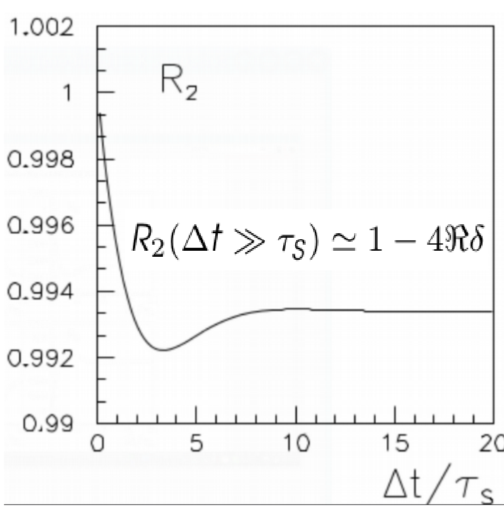
$$R_{2,CPT}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \overline{K}^0(\Delta t)]}$$

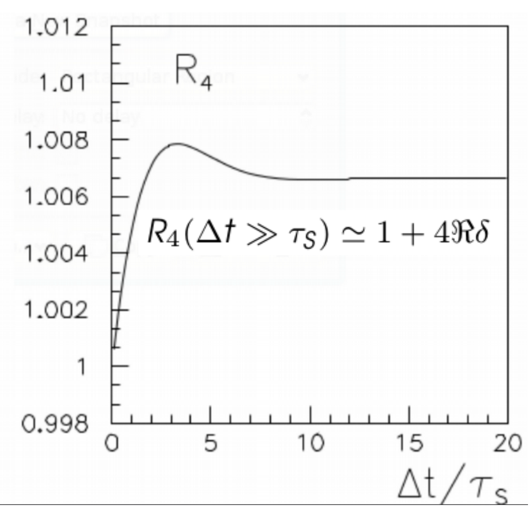
$$R_{4,CPT}(\Delta t) = \frac{P[\overline{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]}$$

$$\frac{R^{exp}_{2,CPT}(\Delta t \gg \tau_S)}{R^{exp}_{4,CPT}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

[J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, JHEP 10 (2015) 139)]

Measurement of the asymptotic value of these asymmetries (for $\Delta t \gg \tau_S$) provides information on T / CPT symmetry violation





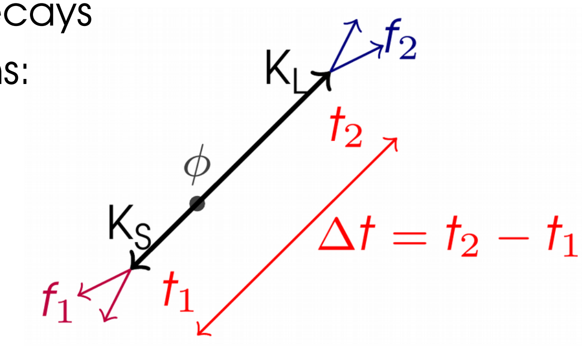
T and CPT tests are feasible at KLOE-2 with sensitivity $O(10^{-3})$.

Analysis methods are already being prepared with KLOE data.

T and CPT tests in transitions: realization at KLOE-2

Kaon decays used for filtering certain states:

- semileptonic decays
  $\overline{\mathrm{K}}^0 \to \pi^+ e^- \overline{\nu}_e$
  $\mathrm{K}^0 \to \pi^- e^+ \nu_e$
- hadronic decays into 2/3 pions:
  $\mathrm{K}_- \to 3\pi^0$
  $\mathrm{K}_+ \to \pi^+\pi^-$

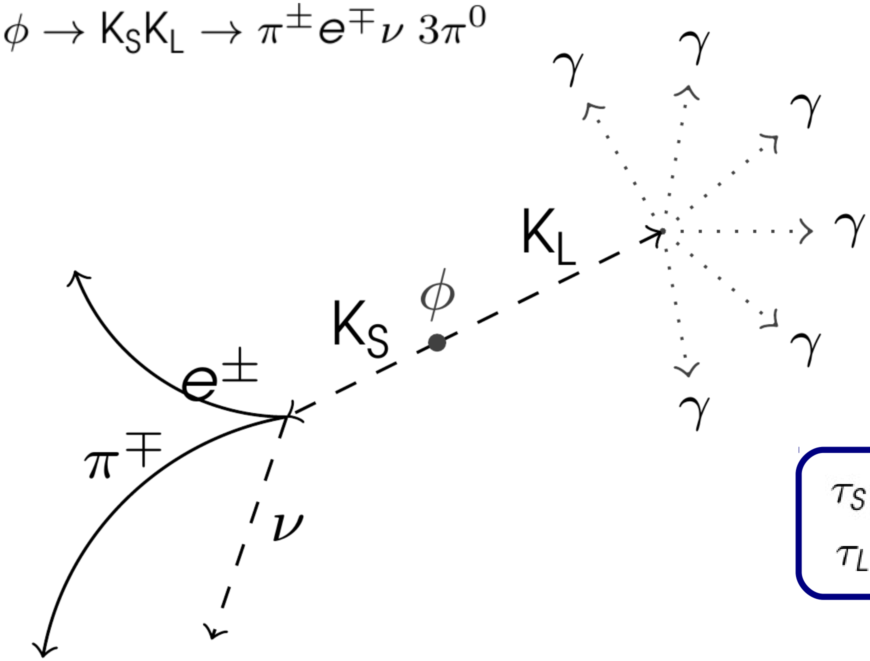


$$R_2(\Delta t) \sim \frac{I(\pi^+\ell^-\bar{\nu}, 3\pi^0; \Delta t)}{I(\pi\pi, \pi^-\ell^+\nu; \Delta t)}$$

$$R_4(\Delta t) \sim \frac{I(\pi^-\ell^+\nu, 3\pi^0; \Delta t)}{I(\pi\pi, \pi^+\ell^-\bar{\nu}; \Delta t)}$$

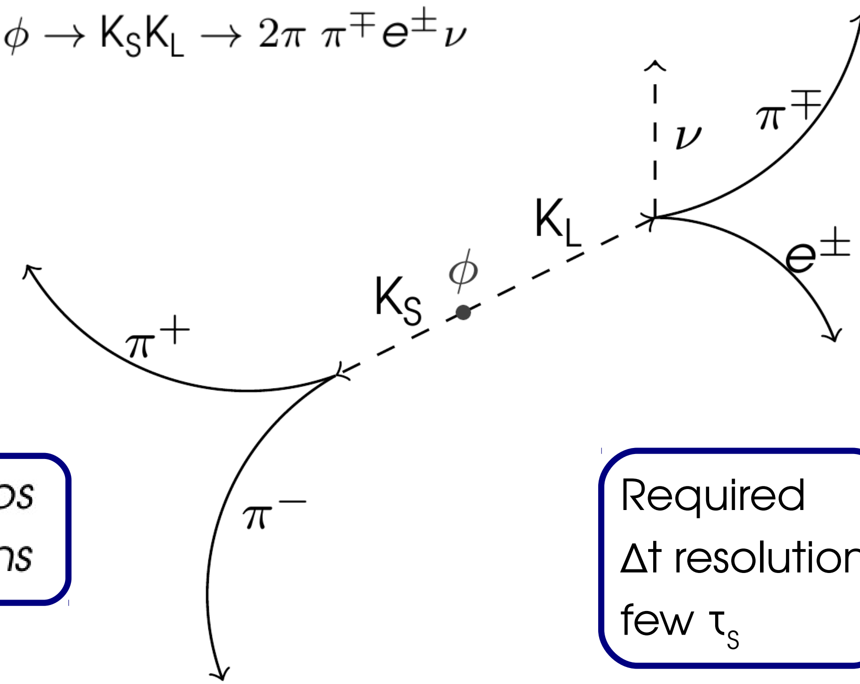
Determination of the asymmetries (R) requires identification and reconstruction of the following classes of events :

$\phi \to K_S K_L \to \pi^\pm e^\mp \nu \; 3\pi^0$



$\tau_S = 89\ ps$
$\tau_L = 51\ ns$

$\phi \to K_S K_L \to 2\pi \; \pi^\mp e^\pm \nu$



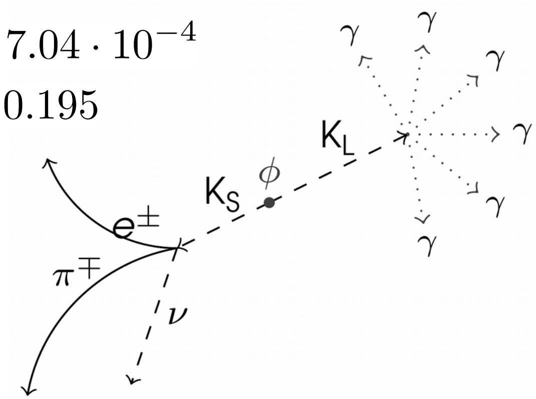
Required Δt resolution: few τ_S

T and CPT tests in transitions: analysis strategy

$\phi \rightarrow K_S K_L \rightarrow \pi^{\pm} e^{\mp} \nu \; 3\pi^0$

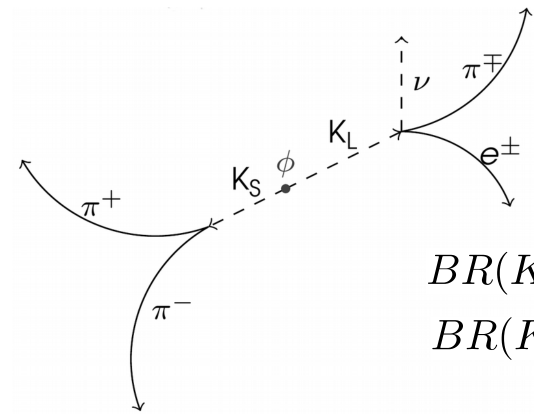
$BR(K_S \rightarrow \pi e \nu) = 7.04 \cdot 10^{-4}$

$BR(K_L \rightarrow 3\pi^0) = 0.195$



- one vertex with 2 tracks required
- cuts on 2-track invariant mass and momentum applied to reject $K_S \rightarrow \pi^+\pi^-$
- 6+ clusters not associated to DC tracks and with E > 20 MeV present in the EMC
- dedicated trilateration-based reconstruction of $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$
- Time-Of-Flight (TOF) analysis for the $e^{\pm}$ and $\pi^{\mp}$ tracks to refine the $K_S \rightarrow \pi e \nu$ selection

$\phi \rightarrow K_S K_L \rightarrow 2\pi \; \pi^{\mp} e^{\pm} \nu$



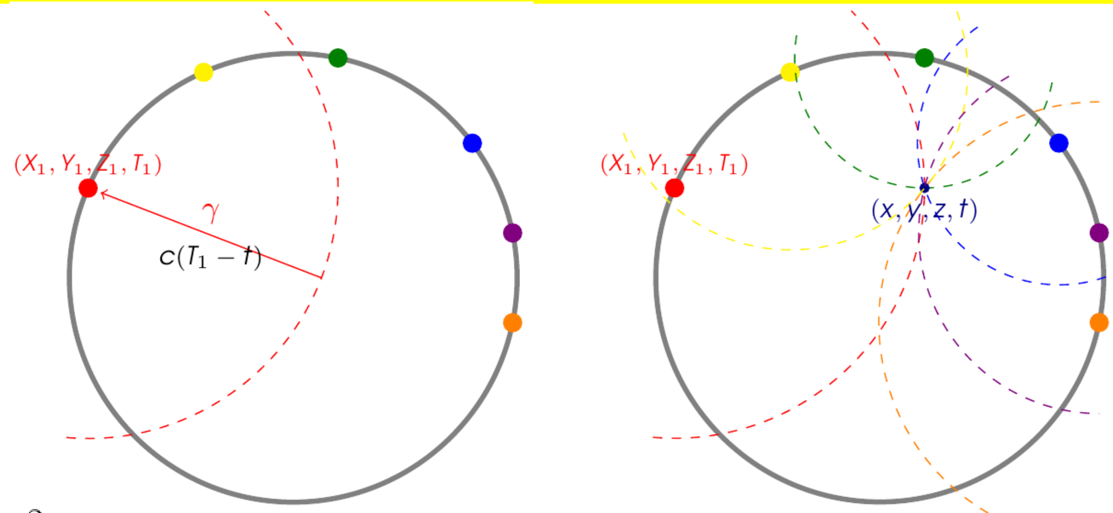
$BR(K_S \rightarrow \pi^+\pi^-) = 0.692$

$BR(K_L \rightarrow \pi e \nu) = 0.406$

- two vertices with 2 associated tracks required
- cuts on 2-track invariant mass and momentum to select $K_S \rightarrow \pi^+\pi^-$
- second vertex close to the epected K_L flight direction
- Time-Of-Flight (TOF) analysis for the $e^{\pm}$ and $\pi^{\mp}$ tracks to select $K_S \rightarrow \pi e \nu$

$K_L \to 3\pi^0$ decay reconstruction technique

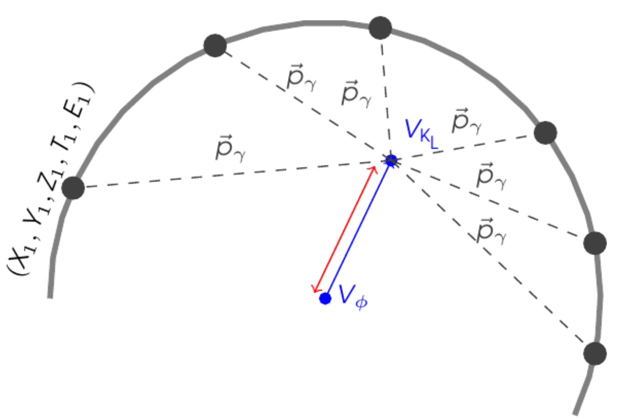
- using only information in photon interaction points in the EMC
- based on trilateration
- similar to GPS positioning
- Provides an analytical solution
- yields both decay position and decay time at once



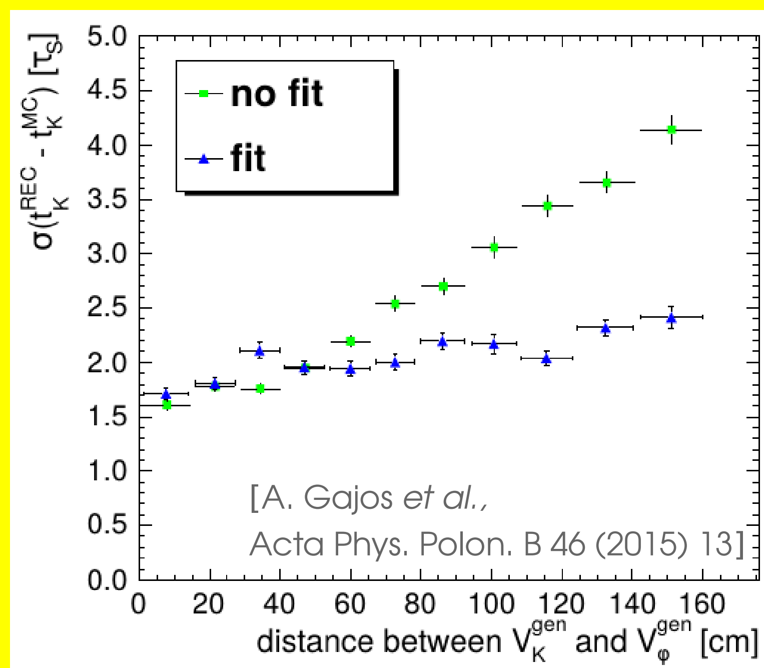
$$(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2$$
$$i = 1, \dots, 6$$

Resolution further improved with a kinematic fit with constraints:

$$M_{6\gamma} - m_{K^0} = 0$$
$$v_{K_L} \cdot t - |V_\phi - V_{K_L}| = 0$$

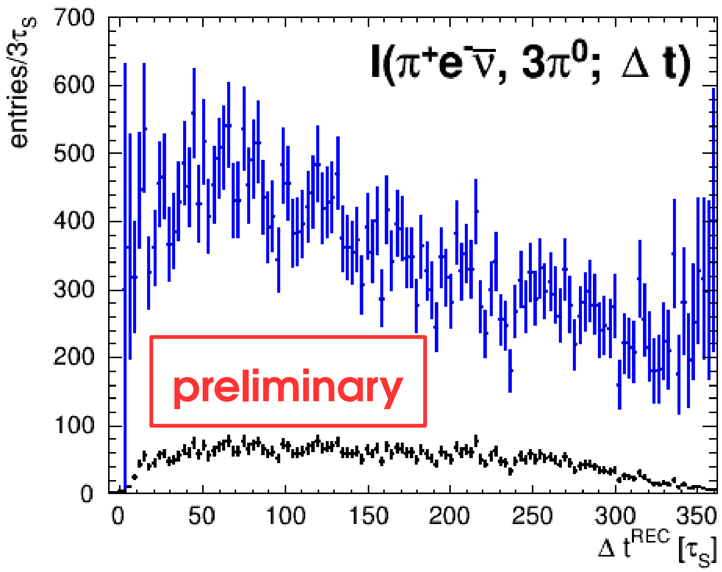


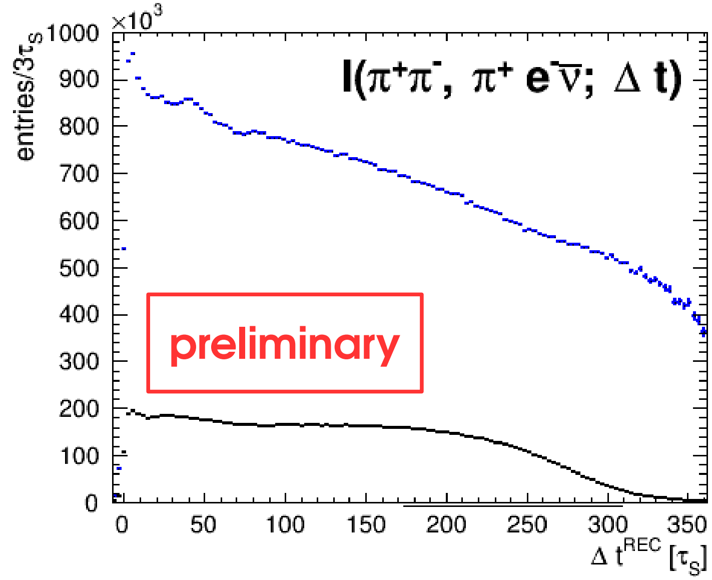
Resulting K_L decay time resolution



Preliminary results with KLOE data

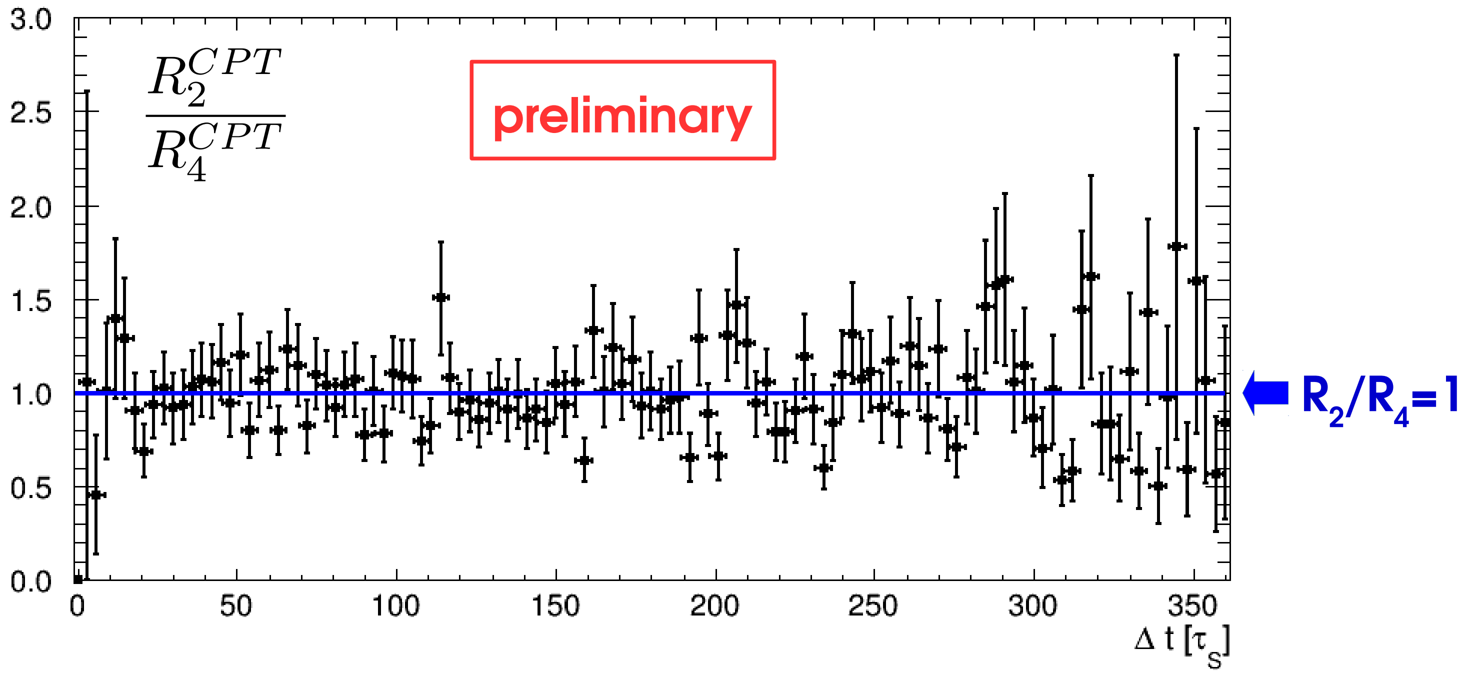
- $I(f_1,f_2;\Delta t)$ for the processes of interest obtained with 1.7 fb^{-1} of KLOE data





Black: raw spectra

Blue: efficiency-corrected



- analysis development still in progress!
- To be applied to KLOE-2 data
- Remaining background
  - $K_S \to \pi^+\pi^-$ with poor p_{trk} reconstruction

Summary

- The KLOE experiment has provided results on:
  - CPT and Lorentz invariance
  - quantum decoherence
- More analyses of KLOE data are in progress including:
  - refinements of previous KLOE result on quantum decoherence search
  - novel direct tests of T and CPT in neutral kaon transitions

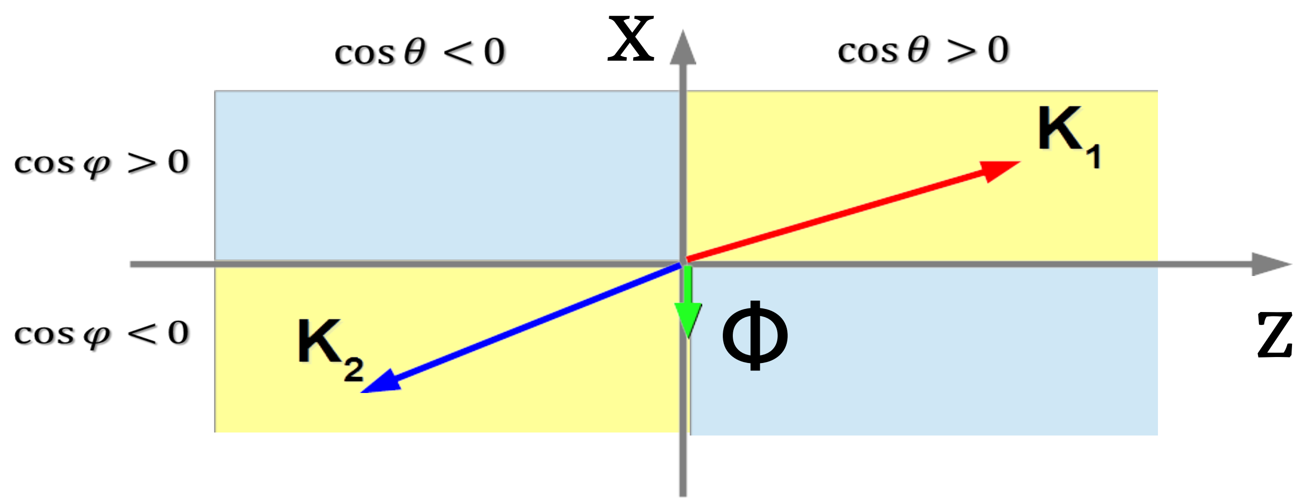
- The KLOE-2 experiment is over half-way in its data taking campaign
- Tests of discrete symmetries and QM constitute a major goal in the KLOE-2 physics programme
  - data sample of at least 5 fb^{-1} as well as the upgraded detector will improve sensitivity for all the above measurements


Thank you
for your attention!
BAR

Backup Slides

Analysis strategy

- kaons are ordered in time by their **z** momentum component
- dataset is divided into 2 samples
  - kaon with cosθ>0 having: $p_K p_\Phi > 0$
  - kaon with cosθ>0 having: $p_K p_\Phi < 0$

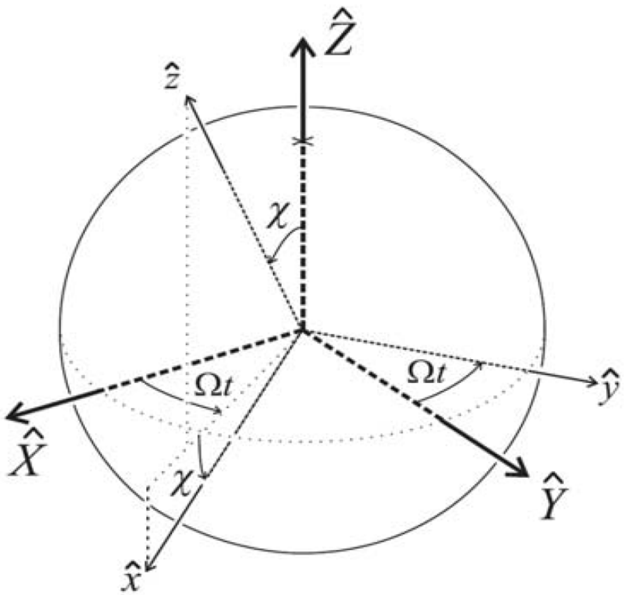


- next, dataset is divided into 4 sidereal time bins

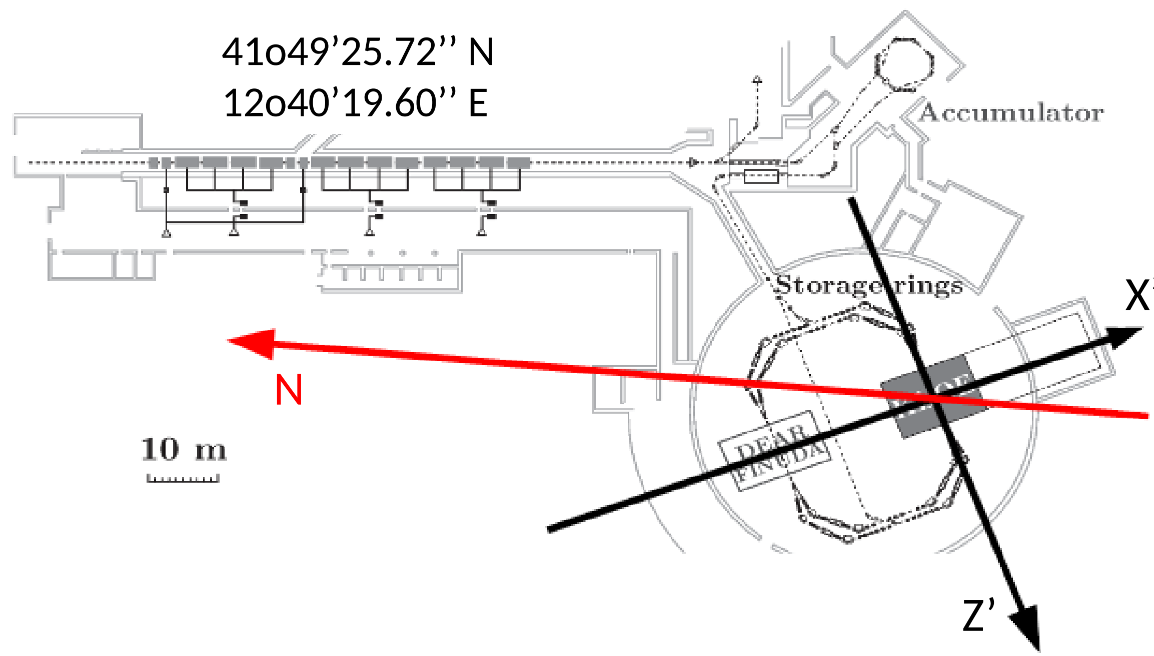
2 angular bins x 4 time bins = 8 samples

Simultaneous fit is performed to Δτ distributions of all 8 samples to extract the Δa_μ coefficients.

KLOE and terrestrial reference frames



KLOE reference frame:



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

Fixed terrestial reference frame:

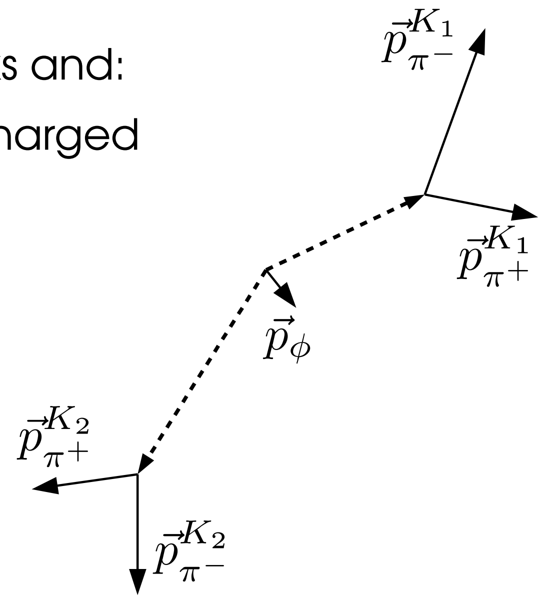
- Z axis along the Earth's rotation axis
- accounting for the sidereal time dependence due to the Earth rotation

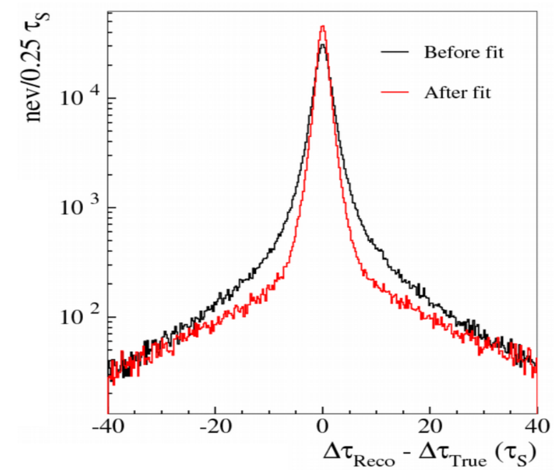
ϑ, φ – polar and azimuthal angles of K momentum in LAB frame

Analysis strategy

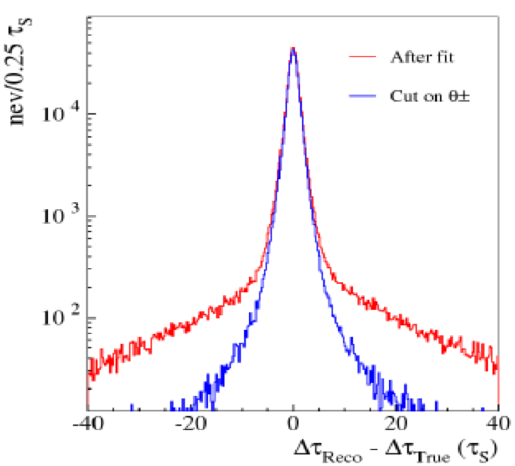
Event selection requirements:

- 2 reconstructed vertices with 2 tracks and:
  - $|M_{rec} - m_K| < 5\,\mathrm{MeV}$ (assuming charged pion mass hypothesis)
  - $\sqrt{E^2_{miss} + |\vec{p}|^2_{miss})} < 10\,\mathrm{MeV}$
  - $-50\,\mathrm{MeV}^2 < M^2_{miss} < 10\,\mathrm{MeV}^2$
  - $|p^{rec}_K{}_{1,2} - p^0_K| < 10\,\mathrm{MeV}$
- $\Delta\tau \in [-12\tau_S; 12\tau_S]$ to avoid kaon regeneration on beam pipe





A global kinematic fit applied to improve kaon decay length reconstruction



A cut on the pion tracks' opening angle: $\cos\theta_\pm < -0.975$ improves time resolution

Residual background contamination:

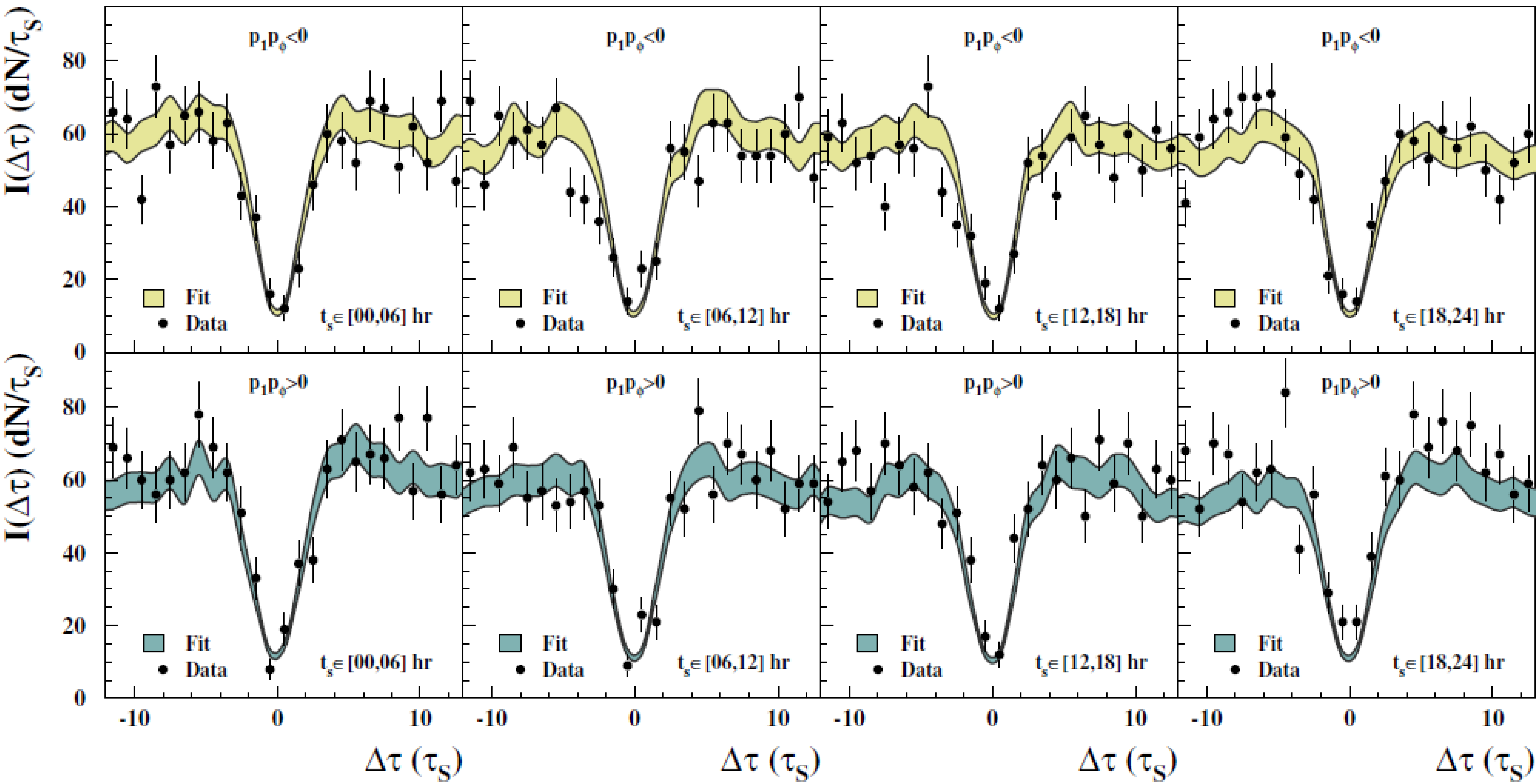
- kaon regeneration (2%)
- $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ (0.5%)

Resulting efficiency:

- almost flat except $\Delta\tau/\tau_S \sim 0$
- due to worse tracking and vertexing efficiency at $\Delta\tau/\tau_S \sim 0$

χ^2 cut
$\vartheta_\pm$ cut
p_z cut

Time-dependent decay amplitudes fit

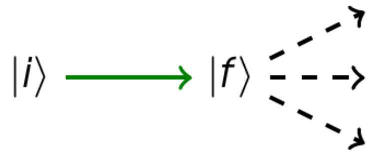


- simultaneous fit
- 192 data points
- 5 free parameters
- $\chi^2/ndf = 211/187$ (P=10%)

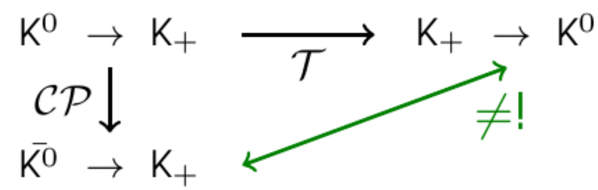
KLOE-2 Collaboration
Phys. Lett. B 730 (2014) 89

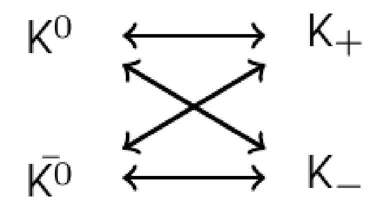
Principle of the direct T test

$P[|i\rangle \rightarrow |f\rangle] \overset{?}{=} P[|f\rangle \rightarrow |i\rangle]$



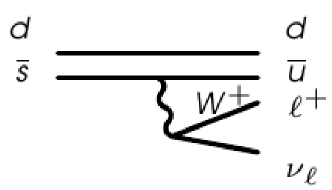
Example:



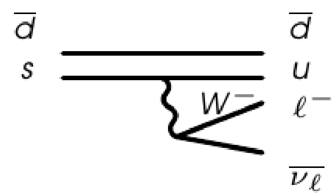


- Kaon decays are used for filtering certain flvour and CP-definite states:

$K^0 \rightarrow \pi^- \ell^+ \nu_l$



$\bar{K^0} \rightarrow \pi^+ \ell^- \bar{\nu}_l$



$K_+ \rightarrow \pi^+\pi^- / \pi^0\pi^0$

$\mathcal{CP}(\pi^+\pi^-) = +1$

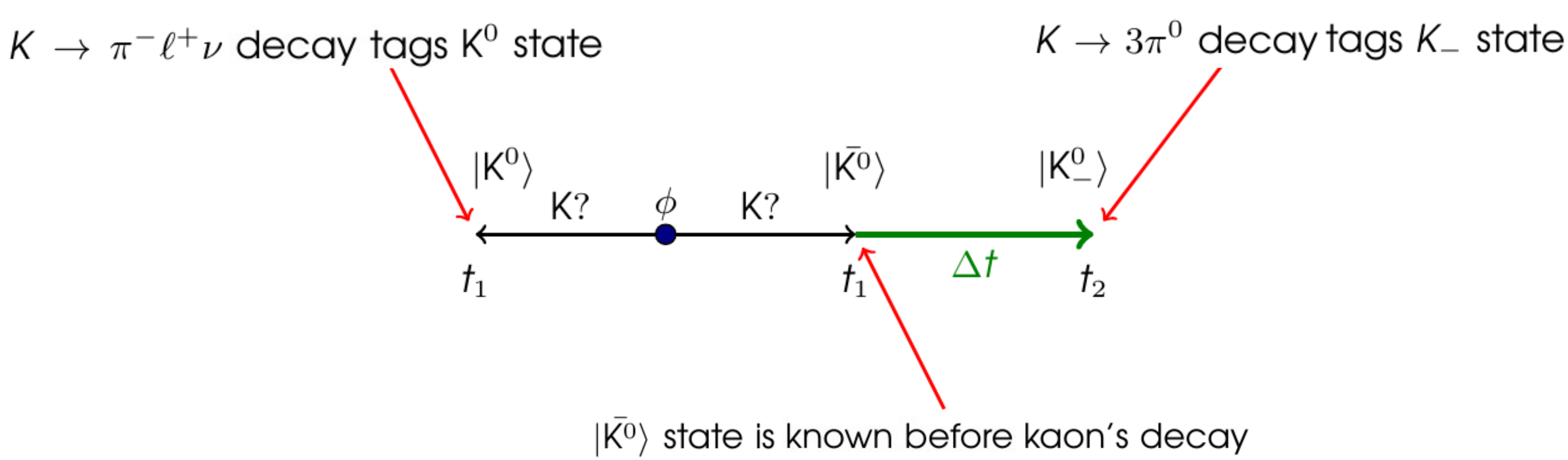
$\mathcal{CP}(\pi^0\pi^0) = +1$

$K_- \rightarrow 3\pi^0$

$\mathcal{CP}(\pi^0\pi^0\pi^0) = -1$

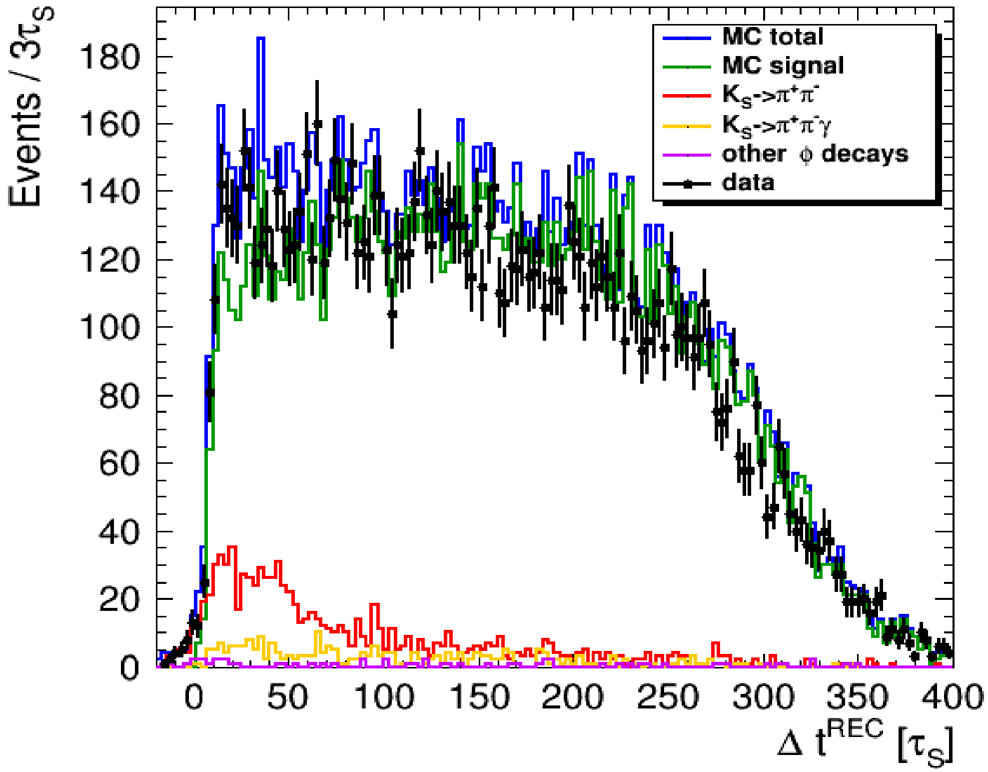
- quantum entanglement used for identifying initial state for the transition:

$$|\phi\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|K^0(+\vec{p})\rangle\,|\bar{K^0}(-\vec{p})\rangle - |\bar{K^0}(+\vec{p})\rangle\,|K^0(-\vec{p})\rangle\right)$$



$K_S K_L \rightarrow \pi e \nu \; 3\pi^0$ – status of selection

Results obtained with full 2004-2005 data sample ($1.7 fb^{-1}$) and corresponding MC.



Selected sample composition:

90% - $K_S \rightarrow \pi e \nu$ and $K_L \rightarrow 3\pi^0$ (signal)

6.6% - $K_S \rightarrow \pi^+\pi^-$ and $K_L \rightarrow 3\pi^0$

1.8% - $K_S \rightarrow \pi^+\pi^-\gamma$ and $K_L \rightarrow 3\pi^0$

1.6% - other background components

process	% in
$K_S \rightarrow \pi^+\pi^-$	3.9 %
$K_S \rightarrow \pi^+\pi^- \rightarrow \pi \mu\nu$	2.7 %
$K_S \rightarrow \pi^+\pi^-\gamma$	1.8 %

Signal selection efficiency: