Recent KLOE results on Kaon Physics

12th International Conference on Heavy Quarks and Leptons

27 August 2014

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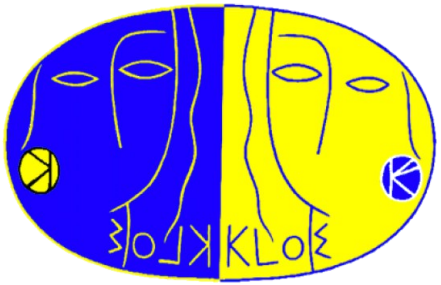

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Outline of the presentation

1. The KLOE Detector and the DAΦNE Φ-factory

2. CPT and Lorentz invariance tests at KLOE

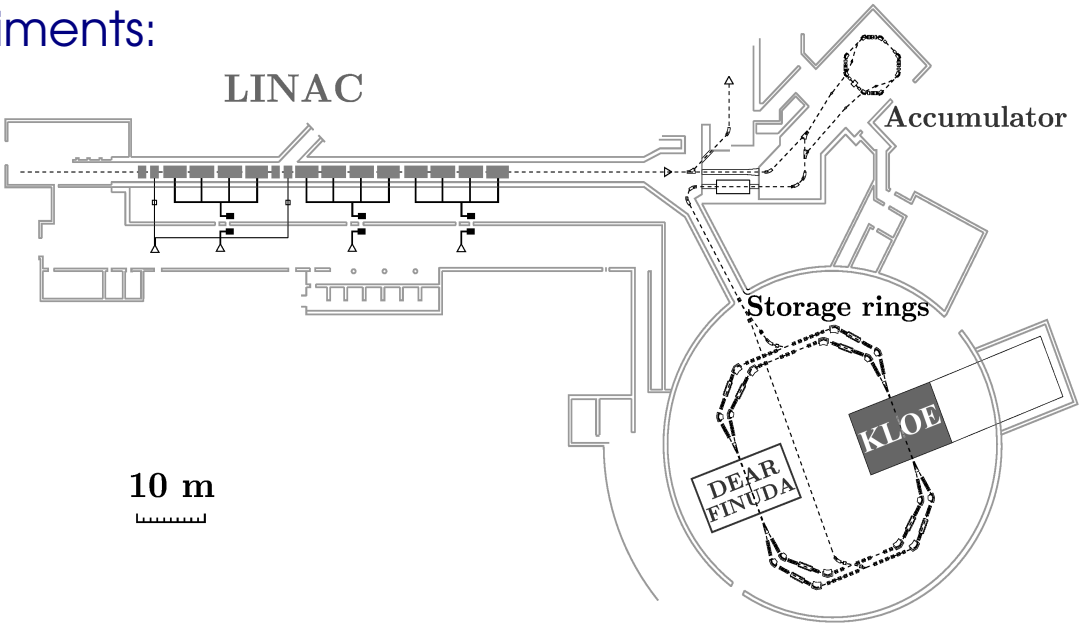
   a. Prospects with upgraded KLOE-2

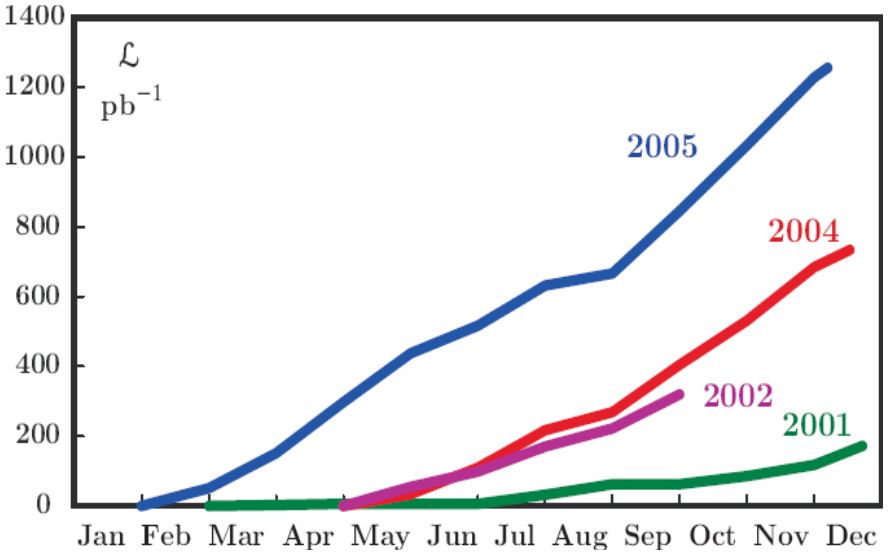
3. Measurement of the absolute BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$) at KLOE

The DAΦNE Φ-factory

Double Annular Factory for Nice Experiments:

- e^+e^- collider, $\sqrt{s} = M_\phi \approx 1020$ MeV
- Φ meson produced with $\sigma_\phi \approx 3$ μb
- separate storage rings for e^+ and e^- to reduce beam-beam interaction
- beam crossing angle 15 mrad => $p_\phi \approx 15$MeV/c





DAΦNE operations (KLOE run):

- peak luminosity of $1.4 \cdot 10^{32}$ $cm^{-2}s^{-1}$
- best daily perfomance: 8.5 pb^{-1}/day

Data taken by KLOE:

- 2005: 1256 pb^{-1}
- 2004: 734 pb^{-1}
- 2002: 320 pb^{-1}
- 2001: 172 pb^{-1}

} ~ 2.5 fb^{-1}
~ 10^{10} Φ mesons produced

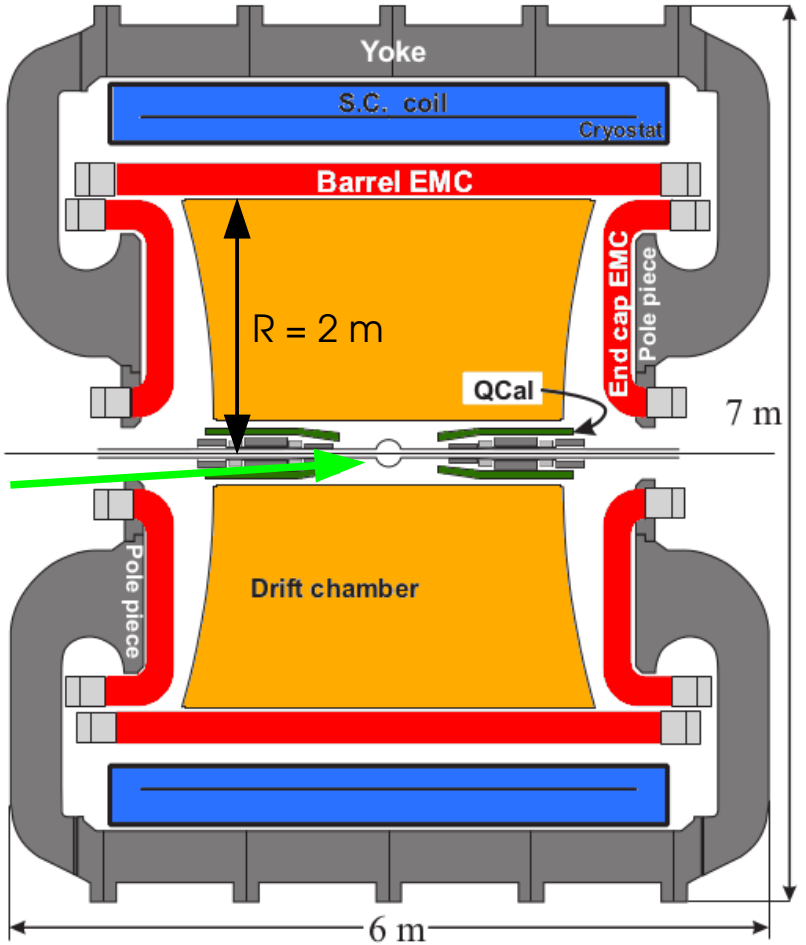
The KLOE Detector

K LOng Experiment

Large Drift Chamber

- 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
- $\sigma(p_T)/p_T = 0.4\%$

Spherical beam pipe around interaction point Al-Be, R = 10 cm



Electromangnetic Calorimeter

- lead and scintillating fibers
- hermetic coverage (98% 4π)
- barrel with
  C-shaped endcaps

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

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

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

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

Loose trigger conditions allow for a broad physics program

Superconducting coil

- B = 0.52 T

Kaon production at DAΦNE and KLOE

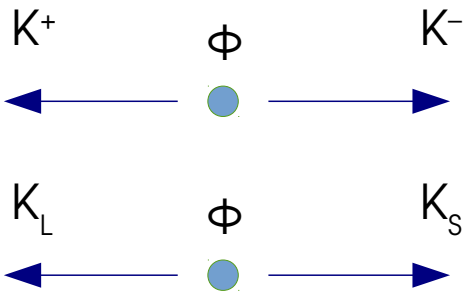
- Φ mesons produced almost at rest ($p_\Phi \approx 15$MeV/c)
- neutral and charged kaons produced in pairs in Φ decays

Decay channel	branching ratio [%]
$\phi \to K^+K^-$	48.9±0.5
$\phi \to K_S K_L$	34.2±0.4
$\phi \to \rho\pi^0, \phi \to \pi^+\pi^-\pi^0$	15.32±0.32
$\phi \to \eta\gamma$	1.309±0.024

Two unique features of the Φ-factory:

Quantum entanglement

- Neutral kaon pairs are produced in an entangled state



Tagging

- detection of a K^+ (K_L) guarantees the presence of a K^- (K_S) and *vice-versa*
- momenta opposite in the Φ frame
- pure kaon beams are easily obtained

Interferometric studies

CPT and Lorentz symmetry test

A wide range of studies possible at KLOE

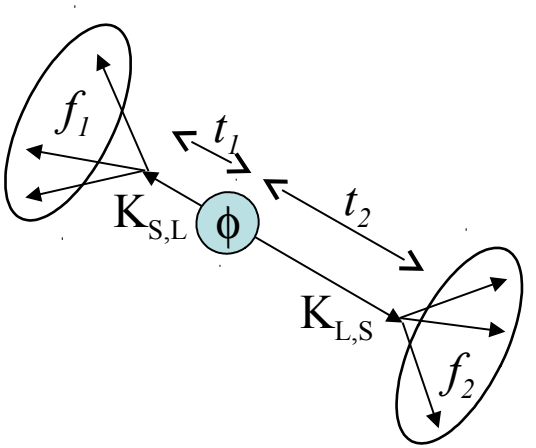
Branching ratio measurements for kaons

BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$)

Neutral kaon interferometry

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

$$|i\rangle = \frac{\mathcal{N}}{\sqrt{2}}\left(|\mathrm{K}_S(+\vec{p})\rangle\,|\mathrm{K}_L(-\vec{p})\rangle - |\mathrm{K}_L(+\vec{p})\rangle\,|\mathrm{K}_S(-\vec{p})\rangle\right)$$



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

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

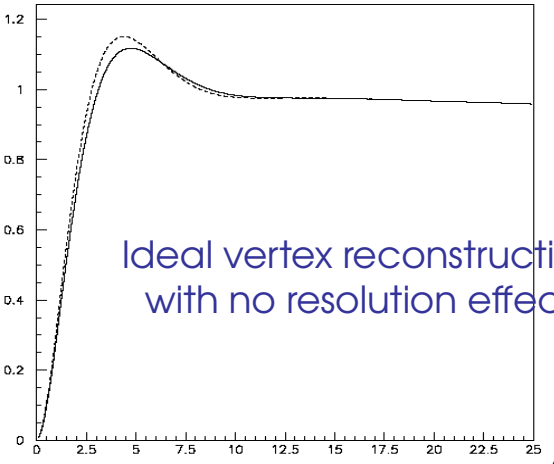
Interference term

$$\Delta m = m_L - m_S$$

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

Destructive quantum interference:

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



CPT and Lorentz symmetry test

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

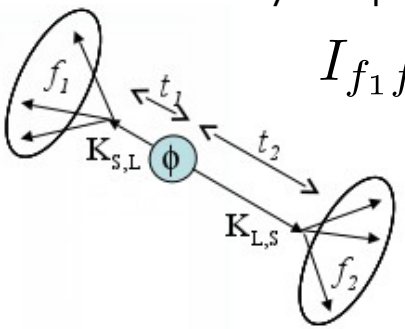
=> direction-dependent modulation of the δ CPT violation parameter:

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

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

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

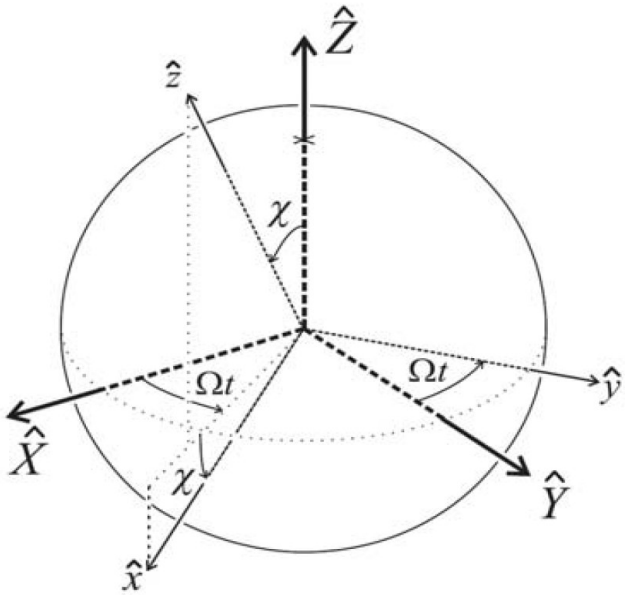
- identical final states of both kaon decays ($\pi^+\pi^-$)
- kaons can only be ordered in time by direction of momentum w.r.t. a chosen direction
- decay amplitude:



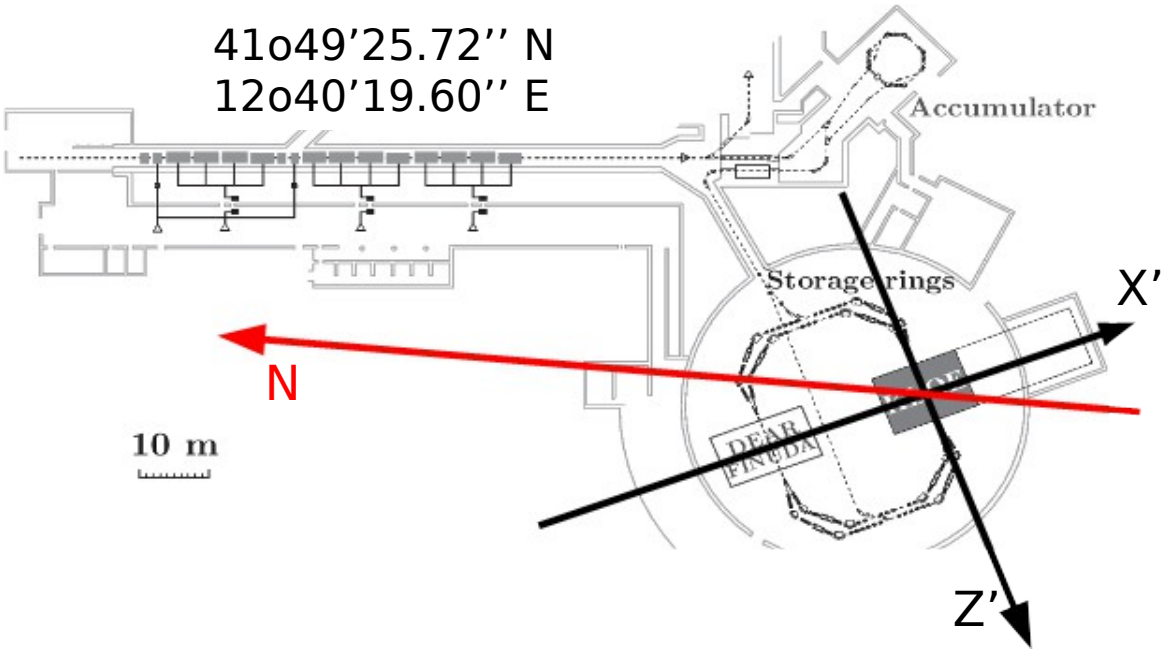
$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}} - 2\Re e\left(\eta_1\eta_2^* e^{-i\Delta m}\right)\right]$$

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

KLOE and terrestrial reference frames



KLOE reference frame:



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

Fixed terrestial reference frame:

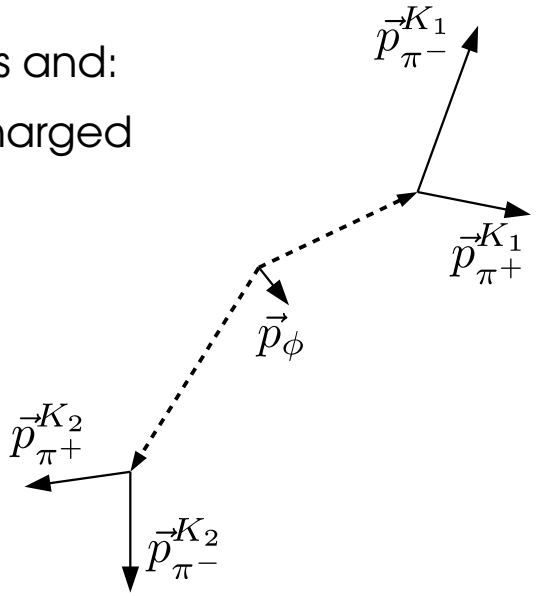
- Z axis along the Earth's rotation axis
- accounting for the sidereal time dependence due to the Earth rotation

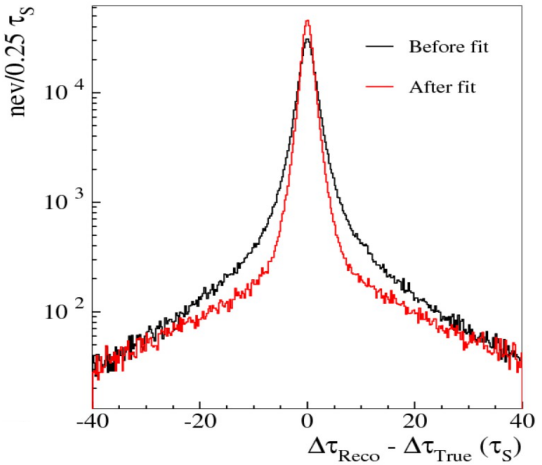
ϑ, φ – polar and azimuthal angles of K momentum in LAB frame

Analysis strategy

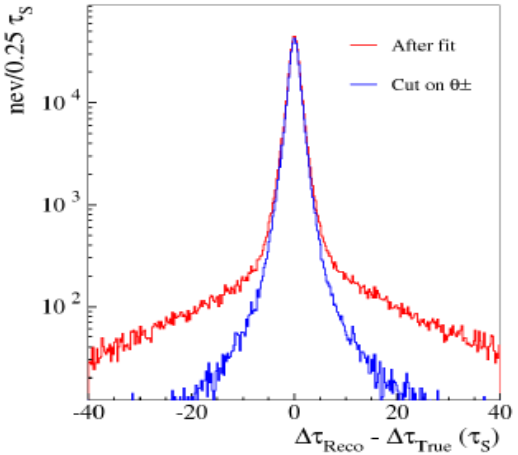
Event selection requirements:

- 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



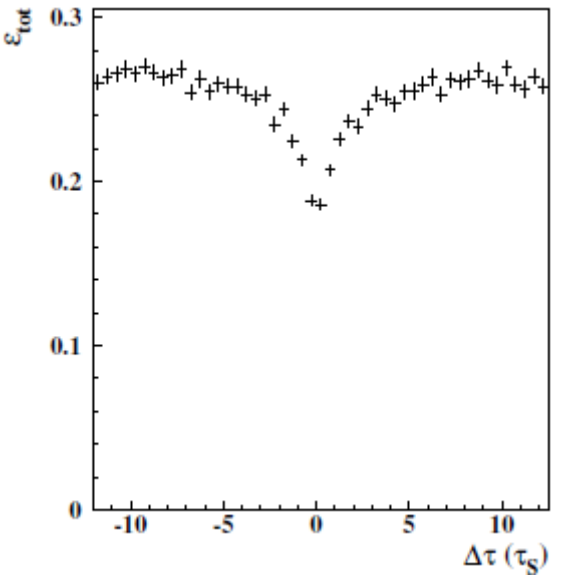
A cut on the pion tracks opening angle: $\cos\theta_{\pm} < -0.975$ improves time resolution

Residual background contamination:

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

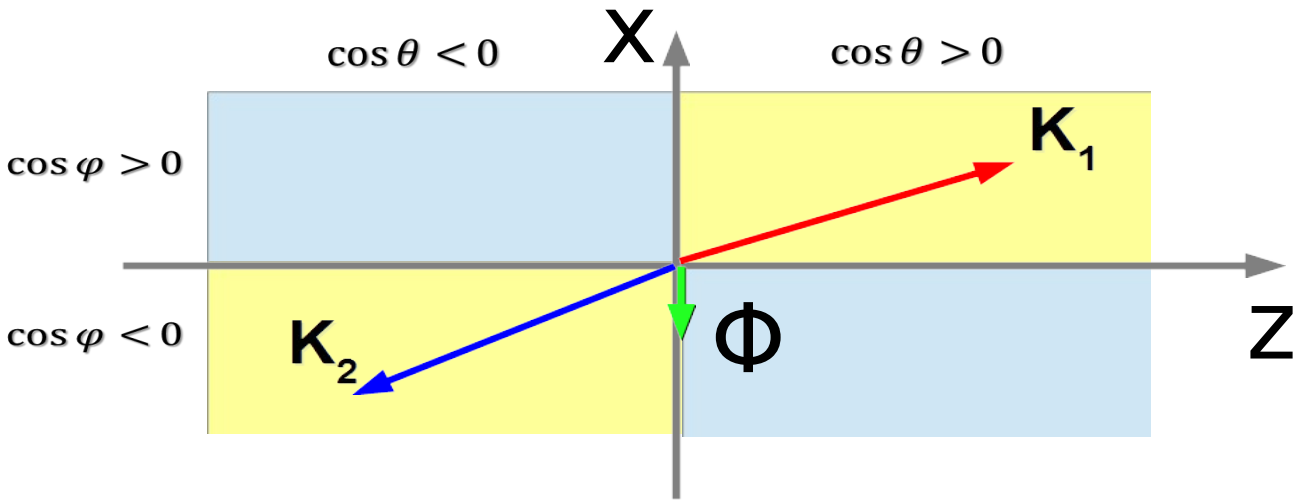
Resulting efficiency:

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



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: $p_K p_\Phi < 0$

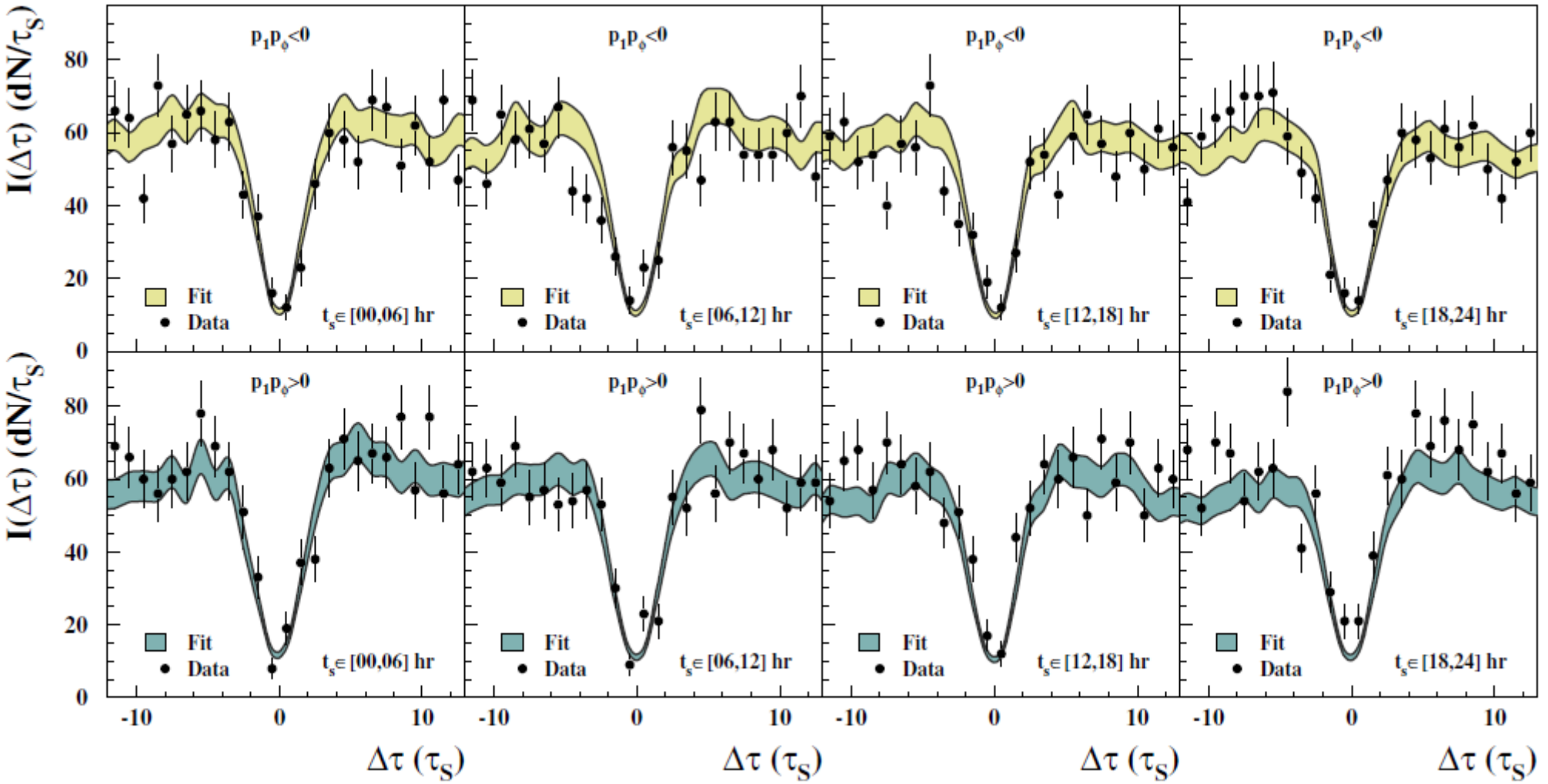


- next, dataset is divided into 4 sidereal time bins

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.

Time-dependent decay amplitudes fit



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

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Phys. Lett. B 730 (2014) 89

Final Results of CPT and Lorentz invariance tests

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

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- reached the expected sensitivity in the SME kaon sector
- several orders of magnitude more precise than for other meson systems ($O(10^{-13}\text{GeV})$ for B, D)
- presently the most precise measurements in the quark sector of the SME
- dominated by statistical uncertainties → prospects for improvement with KLOE-2

Systematic uncertainties:

Par.	Cut stability	Fit Range	Bkg. Subtr.	KLOE ref. frame	**Total**
Δa_0	1.1	24	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**

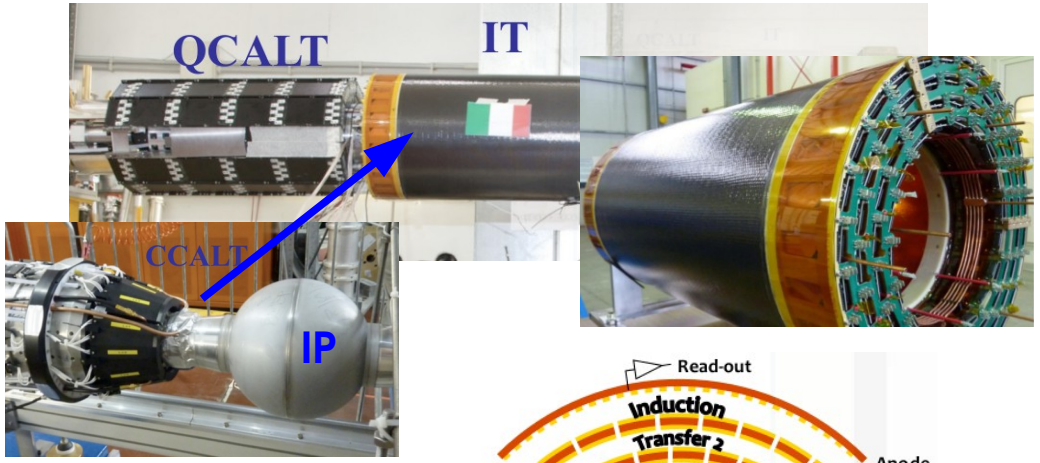
KLOE upgrade to KLOE-2

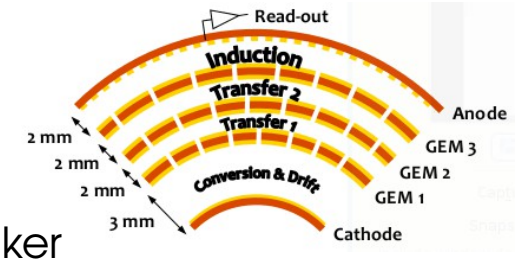
Detector upgrades:

NIMA 617 (2010),105

- QCALT – sampling calorimeter to instrument the final focusing region
- CCALT – LYSO calorimeter to increase acceptance for γ-s from IP

NPB 197 (2009), 215

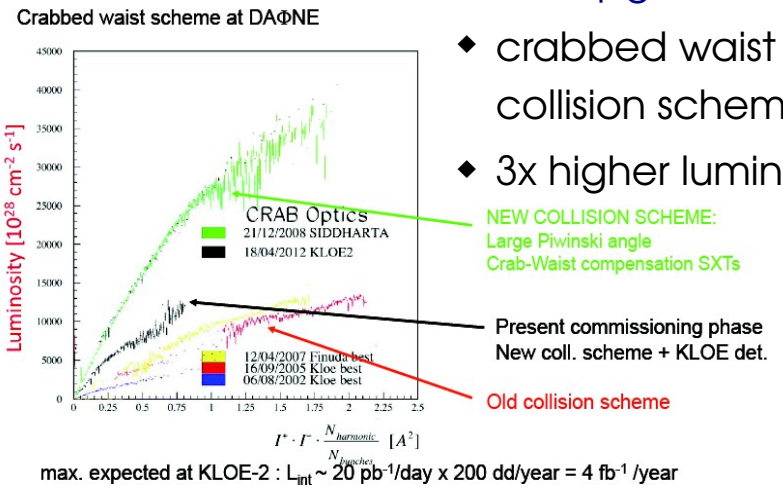




- new Inner Tracker
  - first cylindrical GEM detector ever built
  - 4 layers of triple GEM
  - increased acceptance for low-p_T tracks
  - Improved vertexing resolution near the IP

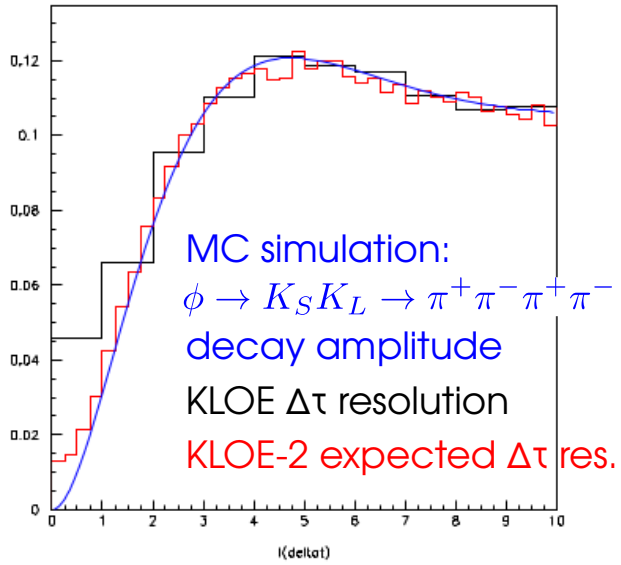
NIMA 628 (2011),194

DAΦNE upgrade:



- crabbed waist collision scheme
- 3x higher luminosity

KLOE-2 is starting operation with the goal to collect 5 fb^{-1} in 2-3 years



Absolute BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$) measurement

Motivation:

- completes the program of precise and fully inclusive measurements of $K^\pm$ dominant branching ratios at KLOE

$K^+ \to \mu\nu$	0.6366(18)	0.3%	PLB 632 (2006)
$K^+ \to \pi^+\pi^0$	0.2065(9)	0.5%	PLB 666 (2008)
$K^\pm \to \pi^0 e^\pm \nu$	0.0497(5)	1.0%	JHEP 02 (2008)
$K^\pm \to \pi^0 \mu^\pm \nu$	0.0324(4)	1.2%	JHEP 02 (2008)
$K^\pm \to \pi^\pm\pi^0\pi^0$	0.0176(3)	1.7%	PLB 597 (2004)
$\tau^\pm$	12.347(30) ns	0.24%	JHEP 01 (2008)

- needed to perform a global fit to $K^\pm$ branching ratios

- this BR enters in the CUSP analysis to extract the $\pi\pi$ phase shift done by NA48 (PLB 633(2006))

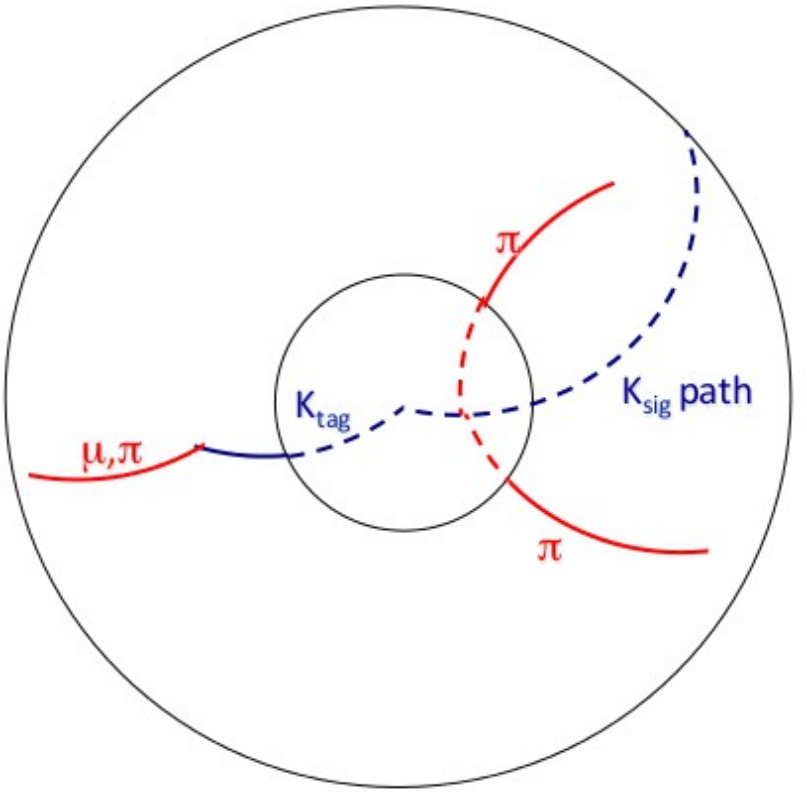
- available measurement dates back to 1972 (no information on radiation cut-offs):

  I.H. Chiang, et al. : $BR(K^+ \to \pi^+\pi^-\pi^+) = (5.56 \pm 0.20)\%$ $\quad \Delta BR/BR = 3.6 \times 10^{-2}$
  (PRD 6 (1972), 1254)

  KLOE fit 2008 : $BR(K^+ \to \pi^+\pi^-\pi^+) = (5.68 \pm 0.22)\%$ $\quad \Delta BR/BR = 3.8 \times 10^{-2}$
  Flavianet fit 2010 : $BR(K^+ \to \pi^+\pi^-\pi^+) = (5.73 \pm 0.16)\%$ $\quad \Delta BR/BR = 2.7 \times 10^{-2}$
  (EPJC 69 (2010) 399)

BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$) – analysis overview

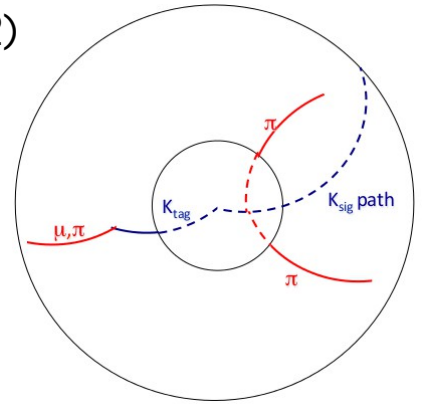
- using 174 pb^{-1} KLOE data sample
- Using K^+ rather than K^- (factor 10^3 smaller nuclear cross-section for K^+ at $p \approx 100$ MeV)
- triggering by $K^- \to \mu^-\nu$ or $K^- \to \pi^-\pi^0$ on one side
  - tag and signal hemispheres
- track of the tagging K backward extrapolated to the IP to obtain a virtual path of the signal kaon
- in the signal hemisphere we require two reconstructed tracks making a vertex along the signal K path in the fiducial volume before the DC inner wall (R^{DC}_{inner} = 25 cm)
- Number of signal events obtained from the missing mass spectrum of the 3rd pion

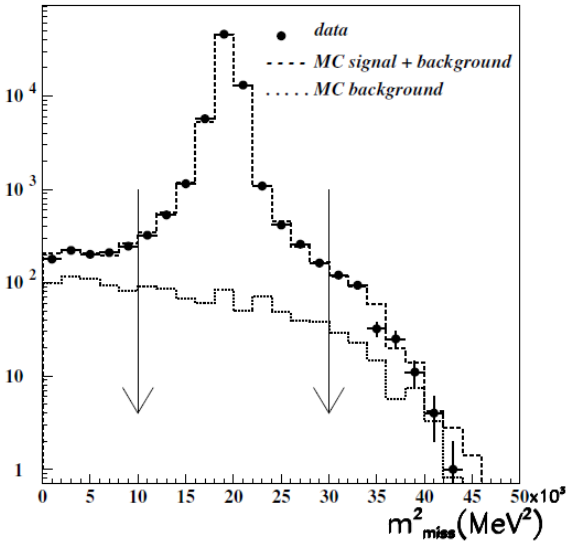


BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$) – signal selection

Requirements for the two secondary tracks:

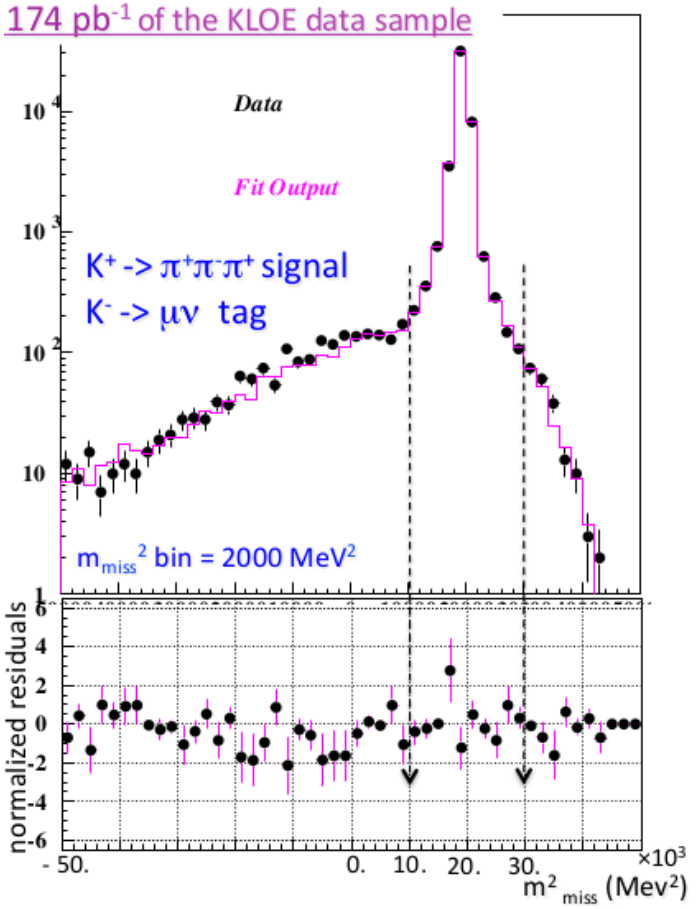
- no charge requirements
- DCA < 3 cm (track 1,2– signal K path)
- DCA_{12} < 3cm (track 1 – track 2)
- $p^*_{m\pi}$ < 190 MeV
- $|\cos\theta_{12}| < 0.9$
- $\rho_{xy} \leq 26$ cm





Selected region of the missing mass distribution:

- 10 000 MeV² < m^2_{miss} < 30 000 MeV²
- S/B ≈ 88 for $K_{\mu 2}$ tag and 84 for $K_{\pi 2}$



Fit to missing mass spectrum

to extract number of signal events

- X^2/ndf = 44.8/46 for $K_{\mu 2}$ tag
- X^2/ndf = 42.9/45 for $K_{\pi 2}$ tag

Final Result of absolute BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$)

$$\mathrm{BR}(K^+ \to \pi^+\pi^-\pi^+) = \frac{N_{K\to 3\pi}}{N_{tag}} \times \frac{1}{\epsilon_{sel} C_{TB} C_f C_{crv}}$$

Corrections:
- ϵ_{sel} – selection efficiency
- C_{TB} – tag bias
- C_f – machine bkg. Filter
- C_{crv} – cosmic ray veto

- sample tagged with $K_{\mu 2}$:

  $\mathrm{BR}(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = 0.05552 \pm 0.00034_{stat} \pm 0.00034_{syst}$

- sample tagged with $K_{\pi 2}$:

  $\mathrm{BR}(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = 0.05587 \pm 0.00053_{stat} \pm 0.00033_{syst}$

Combined result:

$$\mathrm{BR}(K^+ \to \pi^+\pi^-\pi^+(\gamma)) = 0.05552 \pm 0.00034_{stat} \pm 0.00034_{syst}$$

KLOE-2 Collaboration
Submitted to Phys. Lett. B

Fit of the six largest $K^\pm$ BRs using KLOE results with Σ BR($K^\pm \to f$) = 1
χ^2 /ndf = 0.24/1
(CL = 0.63)

Parameter	Value	Correlation coefficients					
$\mathrm{BR}(K^\pm_{\mu 2})$	0.6372(11)						
$\mathrm{BR}(K^\pm_{\pi 2})$	0.2070(9)	0.55					
$\mathrm{BR}(\pi^\pm\pi^-\pi^+)$	0.0558(4)	-0.23	-0.05				
$\mathrm{BR}(K^\pm_{e3})$	0.0498(5)	0.42	-0.15	0.06			
$\mathrm{BR}(K^\pm_{\mu 3})$	0.0324(4)	-0.39	0.14	-0.05	-0.58		
$\mathrm{BR}(\pi^\pm\pi^0\pi^0)$	0.01764(25)	-0.13	0.05	-0.02	0.04	-0.04	
$\tau_{K^\pm}$ (ns)	12.344(29)	0.20	0.19	-0.14	0.05	-0.04	0.02

Summary

- Quantum interferometry with entangled kaon pairs at the DAΦNE Φ-factory is a powerful tool for testing the fundamental symmetries and searches for physics beyond the Standard Model
- KLOE has performed a test of CPT and Lorentz invariance reaching the sensitivity of $O(10^{-18}$ GeV)
- KLOE has completed its programme of of precise and fully inclusive measurements of $K^{\pm}$ branching ratios
- A new measurement of BR($K^+ \to \pi^+\pi^-\pi^+(\gamma)$) was performed at KLOE with precision ~5 time better than than previous result
- Upgraded KLOE-2 is starting operation with a view to higher statistics and better precision

Thank you for your attention!

Backup Slides

Sun-centered reference frame

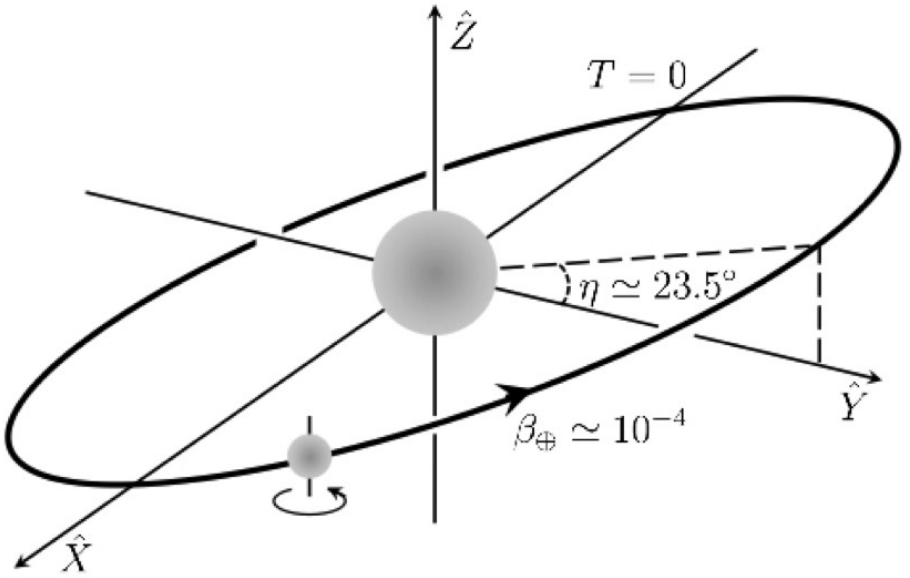


FIG. 1: Standard Sun-centered inertial reference frame [9].