Discrete symmetries studies at KLOE-2

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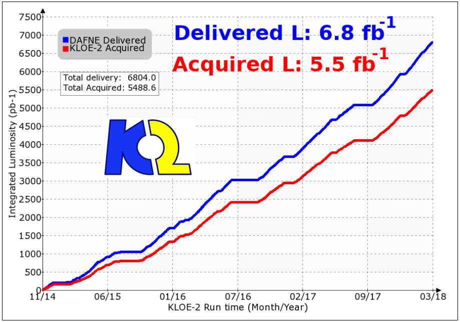
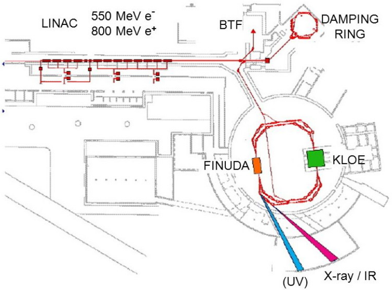
IN KRAKOW

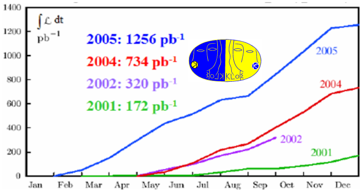
Outline

- KLOE/KLOE-2 @ DAΦNE
- K_S semileptonic charge asymmetry
- Direct test of T and CPT in neutral kaon transitions
- Search for a CP violating decay $K_S \to \pi^0\pi^0\pi^0$
- Summary

KLOE/KLOE-2 @ DAΦNE







- DAΦNE e^+e^- collider located in Frascati,
- two alternate interaction regions (one for KLOE),
- $\sqrt{s} \approx m_\Phi$, $BR(\Phi \to K_L K_S) = 34\%$,
- KLOE has collected $\sim 2.5\text{fb}^{-1}$ of data,
- KLOE-2 goal: L(acquired)>5 fb^{-1}
- KLOE-2 data-taking campaign completed on 30th March & collected 5.5 fb^{-1}

KLOE + KLOE-2 data sample: $8\text{fb}^{-1} \Rightarrow 2.4 \times 10^{10}$ ϕ mesons produced, the largest sample ever collected at the $\phi(1020)$ peak

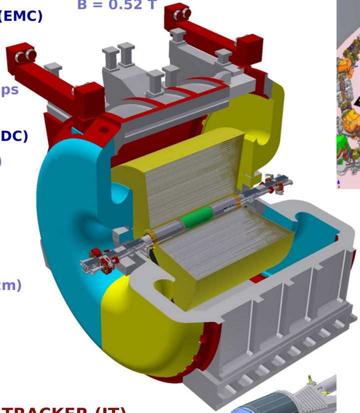
The KLOE/KLOE-2 detector

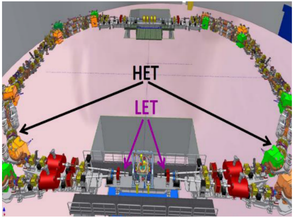
SUPERCONDUCTING MAGNET
B = 0.52 T

Electromagnetic calorimeter (EMC)
- ~4π solid angle coverage
- barrel-endcap
- $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$
- $\sigma_t = 54\ ps/\sqrt{E(GeV)} \oplus 100ps$

DRIFT CHAMBER (DC)
- (4 m ⌀ × 3.3 m)
- $\sigma_p/p = 0.4\ \%$
- $\sigma_{x/y} = 150\ \mu m$
- $\sigma_{vtx} = 2\ mm$
- $\sigma_z = 3\ mm$

INTERACTION POINT
berylium beam pipe (⌀ 10 cm)

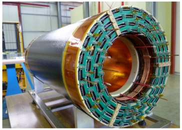




LET & HET = e+e- tagger stations for γγ interatctions

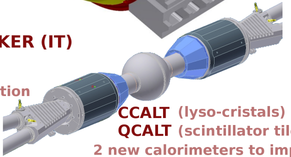
Low Energy Taggers (LET)
- LYSO with SiPM read-out
- E = 160-230 MeV

High Energy Taggers (HET)
- Scintillator + PMT
- 11 m from IP
- E > 400 MeV



INNER TRACKER (IT)

4 layers of triple Cylindrical-GEM
To improve the track and vertex reconstruction
First time CGEM in high energy experiment



CCALT (lyso-cristals)
QCALT (scintillator tiles and fibers with SiPM read-out)
2 new calorimeters to improve acceptance at low polar angles and for γs from KL->3pi0 decays inside the DC volume

Charge asymmetry measurement for K_S

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

$$= 2\left[Re\left(\epsilon_K\right) \pm Re\left(\delta_K\right) - Re\left(y\right) \pm Re\left(x_-\right)\right]$$

- $\mathcal{T}$ violation in $K^0\bar{K}^0$ mixing (ϵ_K)
- $\mathcal{CPT}$ violation in $K^0\bar{K}^0$ mixing (δ_K)
- $\mathcal{CPT}$ violation in $\Delta S = \Delta Q$ (y)
- $\mathcal{CPT}$ violation in $\Delta S \neq \Delta Q$ (x_-)

- $A_{S,L} \neq 0$ signals CP violation
- $A_S \neq A_L$ signals CPT violation

$$(A_S - A_L)/4 = Re(\delta_K) + Re(x_-) = (-0.5 \pm 2.5) \times 10^{-3}$$

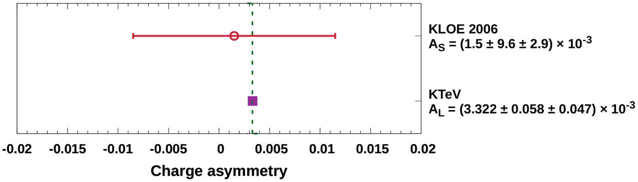
$$(A_S + A_L)/4 = Re(\epsilon_K) - Re(y) = (1.2 \pm 2.5) \times 10^{-3}$$

input from other experiments [PLB 444 (1998) 52]

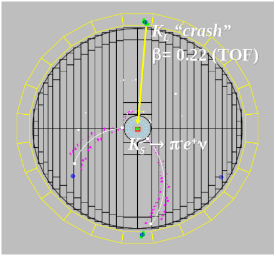
$$Re(x_-) = (-0.8 \pm 2.5) \times 10^{-3}$$

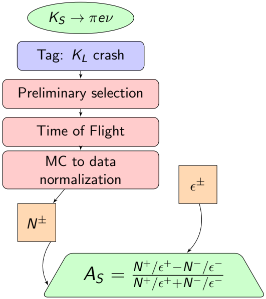
$$Re(y) = (0.4 \pm 2.5) \times 10^{-3}$$

PLB 636 (2006) 173

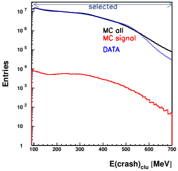


Charge asymmetry measurement for K_S

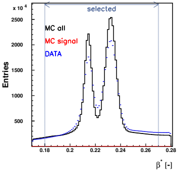




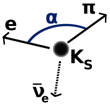
Tag: K_L crash



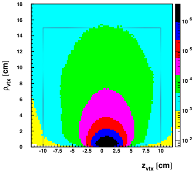
$E_{clu}(crash) > 100$ MeV



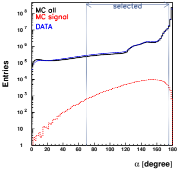
$0.17 < \beta^* < 0.28$



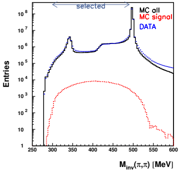
Preliminary selection



$\rho_{vtx} < 15$ cm
$|z_{vtx}| < 10$ cm

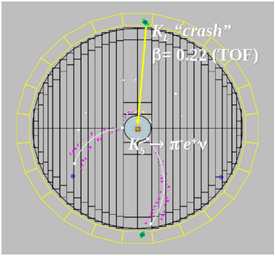


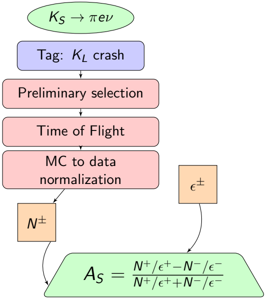
$70^\circ < \alpha < 175^\circ$



$300 < M_{inv}(\pi, \pi) < 490$ MeV

Charge asymmetry measurement for K_S

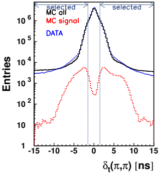


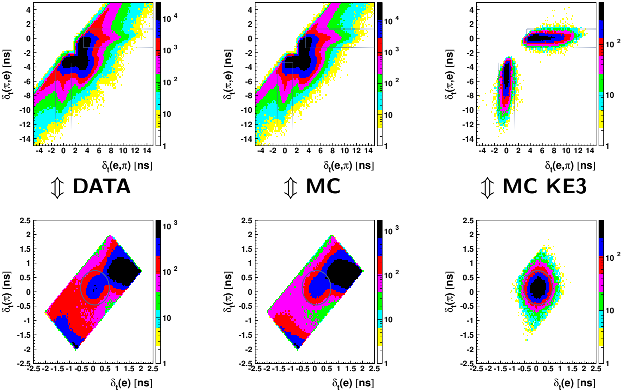


Time of flight selection

$$\delta_t(X) = t_{cl} - \frac{L}{c\beta(m_X)}$$

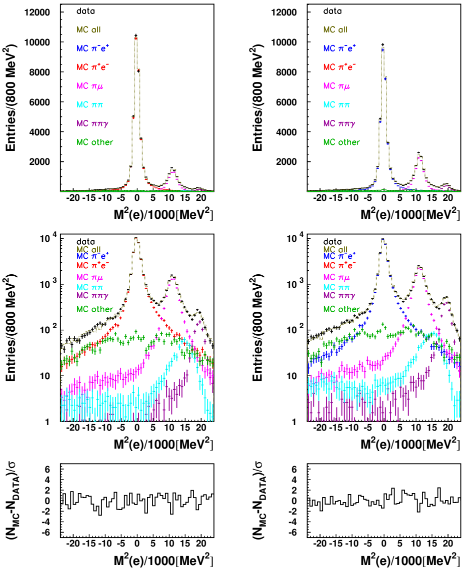
$$\delta_t(a, b) = \delta_t(a) - \delta_t(b)$$





Charge asymmetry measurement for K_S

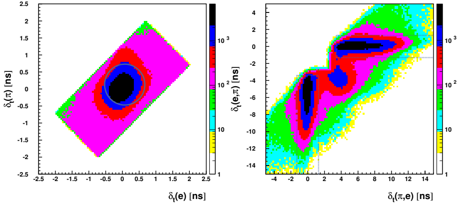
$\Downarrow \phi \rightarrow K_L K_S \rightarrow K_L(crash)\pi e \nu$



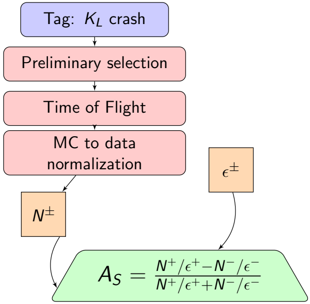
$M^2(e) = (E_{K_S} - E(\pi) - p_{miss}(\pi, e))^2 - p^2(e)$

- Fit of $M^2(e)$ distribution varying MC normalizations of signal and bkg contributions
- Control sample: $K_L \rightarrow \pi e \nu$ close to IP tagged by $K_S \rightarrow \pi^0\pi^0$
- track to EMC cluster and TOF efficiency correction from data c.s
- Due to some discrepancies between data and MC on momentum resolution the measured particle momentum components have been smeared. Parameters were tuned on c.s

$\Downarrow \phi \rightarrow K_S K_L \rightarrow \pi^0\pi^0 \pi e \nu$



Charge asymmetry measurement for K_S



Efficiency (%)	$K_S \to \pi^- e^+ \nu$	$K_S \to \pi^+ e^- \bar{\nu}$
trigger and event classification (ϵ_{TEC})	99.80 ± 0.02	99.80 ± 0.02
K_S tagging (ϵ_{TAG})	36.54 ± 0.05	36.67 ± 0.05
kinematical cuts (ϵ_{KC})	75.60 ± 0.08	75.62 ± 0.07
Track to Cluster Association (ϵ_{TCA})	42.22 ± 0.08	41.85 ± 0.08
Time of Flight (ϵ_{TOF})	64.03 ± 0.19	67.96 ± 0.18
Fit range (ϵ_{FR})	99.16 ± 0.03	99.17 ± 0.02

Contribution		Systematic uncertainty (10^{-3})
Trigger and event classification	σ_{TEC}	0.28
Tagging and preselection	$E_{clu}(crash)$	0.55
"	β^*	0.67
"	z_{vtx}	0.01
"	ρ_{vtx}	0.05
"	α	0.46
"	$M_{inv}(\pi,\pi)$	0.20
Time of flight selection	$\delta_t(\pi,\pi)$	0.71
"	$\delta_t(e,\pi)$ vs $\delta_t(\pi,e)$	0.87
"	$\delta_t(e)$ vs $\delta_t(\pi)$	1.82
Momenta smearing	σ_{MS}	0.58
Fit procedure	σ_{HBW}	0.61
"	Fit range	0.49
Total		2.6

- The new KLOE A_S analysis has been finalized with 1.63 fb^{-1} data sample

$$A_S = (-4.8 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}$$

Charge asymmetry measurement for K_S

- Combined with the previous KLOE analysis:

$$A_S = (-3.7 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}$$

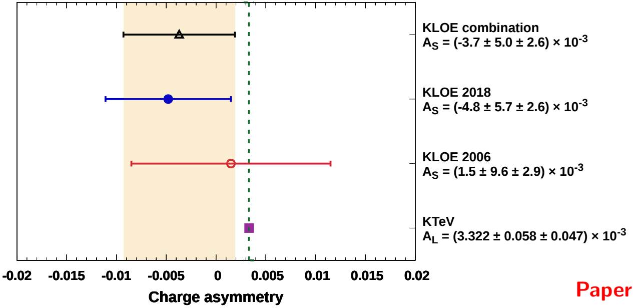
$$(A_S - A_L)/4 = Re(\delta_K) + Re(x_-) = (-1.7 \pm 1.4) \times 10^{-3}$$

$$(A_S + A_L)/4 = Re(\epsilon_K) - Re(y) = (-0.1 \pm 1.4) \times 10^{-3}$$

input from other experiments [PDG (2017)]

$$Re(x_-) = (-2.0 \pm 1.4) \times 10^{-3}$$

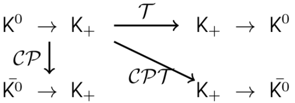
$$Re(y) = (1.7 \pm 1.4) \times 10^{-3}$$

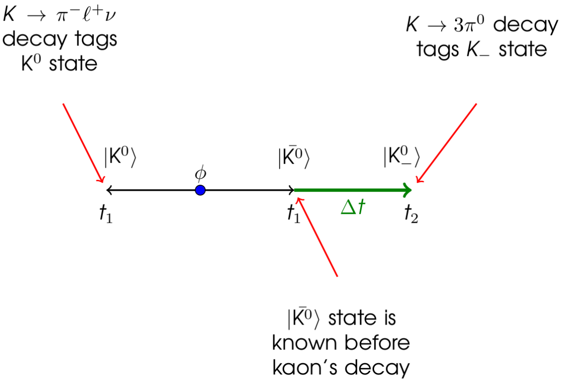


Paper in preparation

Direct test of T and CPT in neutral kaon transitions

$$|\phi\rangle = \frac{1}{\sqrt{2}}\left(K^0\bar{K}^0 - \bar{K}^0K^0\right) = \frac{1}{\sqrt{2}}\left(K_+K_- - K_-K_+\right)$$



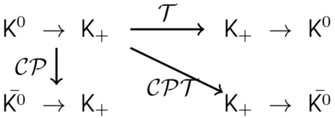


- K^0, $\bar{K}^0$ - strangeness eigenstates
- K_+, K_- - CP eigenstates of neutral kaons

K^0	$\to \pi^- l^+ \nu$	S	=+1
$\bar{K}^0$	$\to \pi^+ l^- \bar{\nu}$	S	=-1
K_+	$\to \pi^+\pi^-$	CP	=+1
K_-	$\to 3\pi^0$	CP	=-1

- Unique direct T and CPT symmetry test with kaons (model independent)
  J. Bernabeu, A. Di Domenico and P. Villanueva-Perez: Nucl.Phys. B 868 (2013) 102, JHEP 10 (2015) 139
- KLOE-2 can do significant tests with L$\sim$ 5fb^{-1}

Direct test of T and CPT in neutral kaon transitions



	Reference		T-conjugate		CPT-conjugate	
1.	$K^0 \to K_+$	$(l^-, \pi\pi)$	$K_+ \to K_0$	$(3\pi, l^+)$	$K_+ \to \bar{K}^0$	$(3\pi, l^-)$
2.	$K^0 \to K_-$	$(l^-, 3\pi)$	$K_- \to K_0$	$(\pi\pi, l^+)$	$K_- \to \bar{K}^0$	$(\pi\pi, l^-)$
3.	$\bar{K}^0 \to K_+$	$(l^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi, l^-)$	$K_+ \to K^0$	$(3\pi, l^+)$
4.	$\bar{K}^0 \to K_-$	$(l^+, 3\pi)$	$K_- \to \bar{K}^0$	$(\pi\pi, l^-)$	$K_- \to K^0$	$(\pi\pi, l^+)$

Example observable of the test

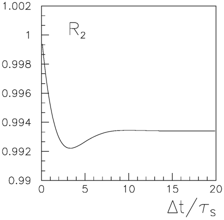
$$R_2(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K_0(\Delta t)]} \sim \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^+; \Delta t)}$$

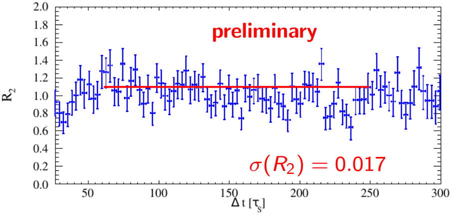
Direct test of T in neutral kaon transitions

First test of T in transitions with neutral kaons (L=1.7 fb^{-1})

$$R_2(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K_0(\Delta t)]} \sim \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^+; \Delta t)}$$

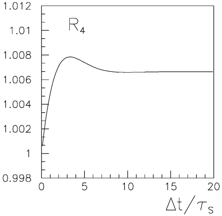
$R_2(\Delta t >> \tau_s) \approx 1 - 4Re(\epsilon_K)$

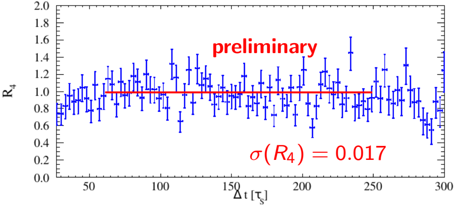




$$R_4(\Delta t) = \frac{P[\bar{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \bar{K}_0(\Delta t)]} \sim \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^-; \Delta t)}$$

$R_4(\Delta t >> \tau_s) \approx 1 + 4Re(\epsilon_K)$





Direct test of CPT in neutral kaon transitions

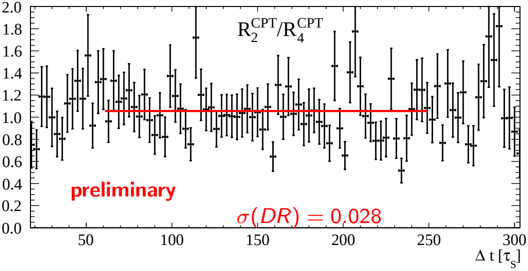
First test of CPT in transitions with neutral kaons (L=1.7 fb^{-1})

$$R_2^{CPT} = \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^-; \Delta t)}$$

$$R_4^{CPT} = \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^+; \Delta t)}$$

$$\frac{R_2^{CPT}(\Delta t >> \tau_s)}{R_4^{CPT}(\Delta t >> \tau_s)} = 1 - 8Re(\delta_K) - 8Re(x_-)$$

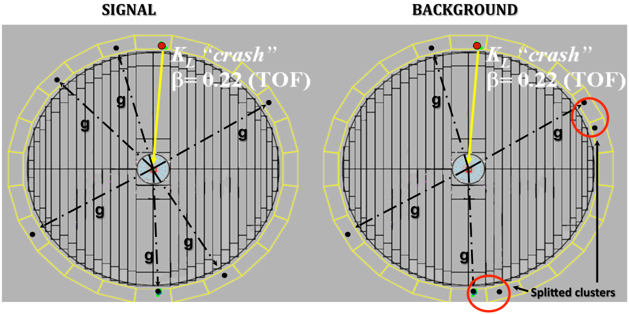
$$\approx 1 + 2(A_L - A_S)$$



$$\text{CPT invariance} \Rightarrow \frac{R_2^{CPT}(\Delta t >> \tau_s)}{R_4^{CPT}(\Delta t >> \tau_s)} = 1$$

Search for a CP violating decay $K_S \to \pi^0\pi^0\pi^0$

- $3\pi^0$ is a pure CP=-1 state; observation of $K_S \to 3\pi^0$ is an unambiguous sign of CP violation in mixing and/or in decay.
- Standard Model prediction: $BR(K_S \to 3\pi^0) = 1.9 \times 10^{-9}$
- Best upper limit by KLOE with 1.7 fb^{-1} (PLB 723 (2013) 54)
  $BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% CL



$K_S \to 3\pi^0 \to 6\gamma$

$K_S \to 2\pi^0$ + accidental/splitted clusters
$K_L \to 3\pi^0$, $K_S \to \pi^+\pi^-$ („fake K_L crash")

- the analysis is based on γ counting and kinematic fit (in the $2\pi^0$ and $3\pi^0$ hypothesis)
- searching for "KL crash" (KL in the EMC) + 6 prompt photons
- Main bckg: $K_S \to 2\pi^0$ (4 prompt photons), also used for normalization
- at KLOE-2: Selection criteria hardened to face the larger machine background ~10 times better background rejection

- KLOE-2 data analysis (L=300 pb^{-1}): With the old analysis scheme 1 event selected as a signal: $\Rightarrow Br(K_S \to 3\pi^0) < 2.5 \times 10^{-7}$ @ 90% CL (preliminary)
- Full KLOE-2 statistics+optimized analysis could reach $\leq 10^{-8}$

Summary

- The study of discrete symmetries with neutral kaons is one of the key issues at KLOE-2 including several high precision tests of CPT and Quantum Mechanics.
- The analysis of the full KLOE data set is in progress:
  - a new measurement of the K_S semileptonic charge asymmetry
  - the analysis for first test of T and CPT in neutral kaon transitions processes is ongoing.
- KLOE/KLOE-2 all together have completed the data-taking and collected about 8 fb^{-1} data at ϕ peak
- The analysis of KLOE-2 data started on several benchmark processes. Among them a preliminary study searching for the CP violating $K_S \to 3\pi^0$ decay shows the possibility to improve the sensitivity on this BR.

Thank you for your attention