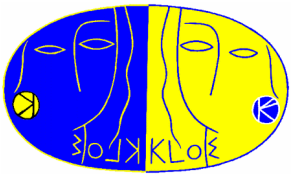


Precision tests of Quantum Mechanics and CPT symmetry with entangled neutral kaons at KLOE

Eryk Czerwiński
on behalf of KLOE-2 Collaboration

ICHEP 2022, 6-13.07.2022, Bologna, Italy

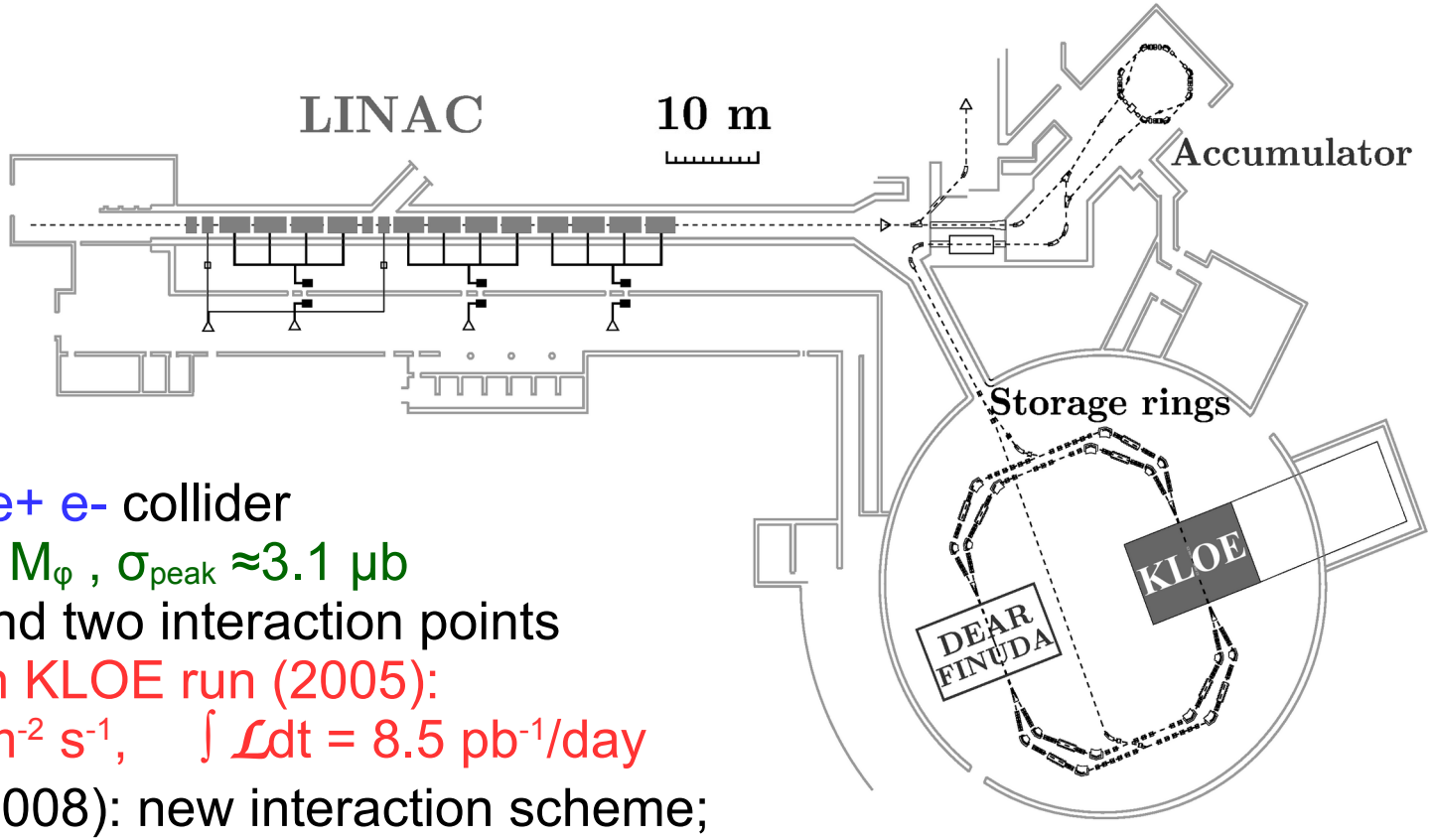
Kaon physics at φ factory

- BR($\varphi \rightarrow K^+K^-$) = 49.2%
- BR($\varphi \rightarrow K^0\bar{K}^0$) = 33.8%
- neutral kaon pairs produced in a pure quantum state ($J^{PC}=1^{--}$)

$$|i\rangle \propto \frac{1}{\sqrt{2}}\left(|K_L, p\rangle|K_S, -p\rangle - |K_L, -p\rangle|K_S, p\rangle\right)$$

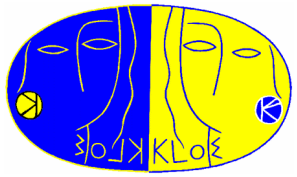
- detection of one kaon guarantees the presence of a second one with known momentum and direction (tagging)

DAΦNE e^+e^- collider

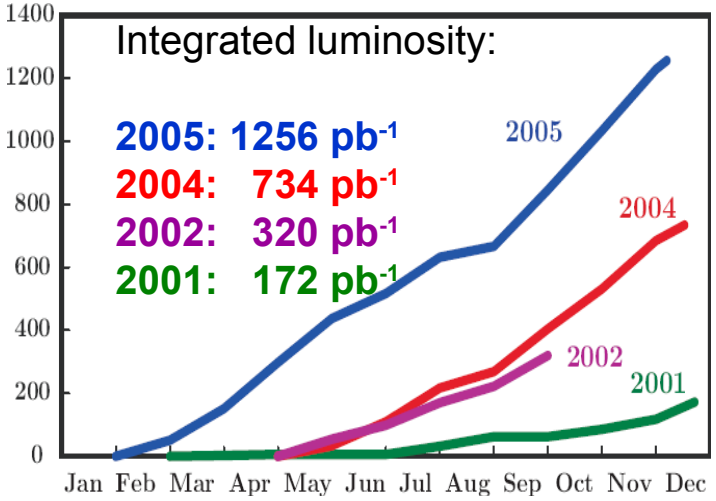


- Frascati φ-factory: e+ e- collider
  @ $\sqrt{s} \approx 1020$ MeV $\approx M_\varphi$, $\sigma_{peak} \approx 3.1$ μb
- two storage rings and two interaction points
- best performance in KLOE run (2005):
  $\mathcal{L}_{peak} = 1.5 \times 10^{32}$ cm^{-2} s^{-1}, $\int \mathcal{L} dt = 8.5$ pb^{-1}/day
- DAΦNE upgrade (2008): new interaction scheme;
- large beam crossing angle + crabbed waist sextupoles
- DAΦNE operations restarted in July 2013
- KLOE-2 run started on November 2014
- best performance in KLOE-2 run:
  $\mathcal{L}_{peak} = 2.4 \times 10^{32}$ cm^{-2} s^{-1}, $\int \mathcal{L} dt = 11$ pb^{-1}/day

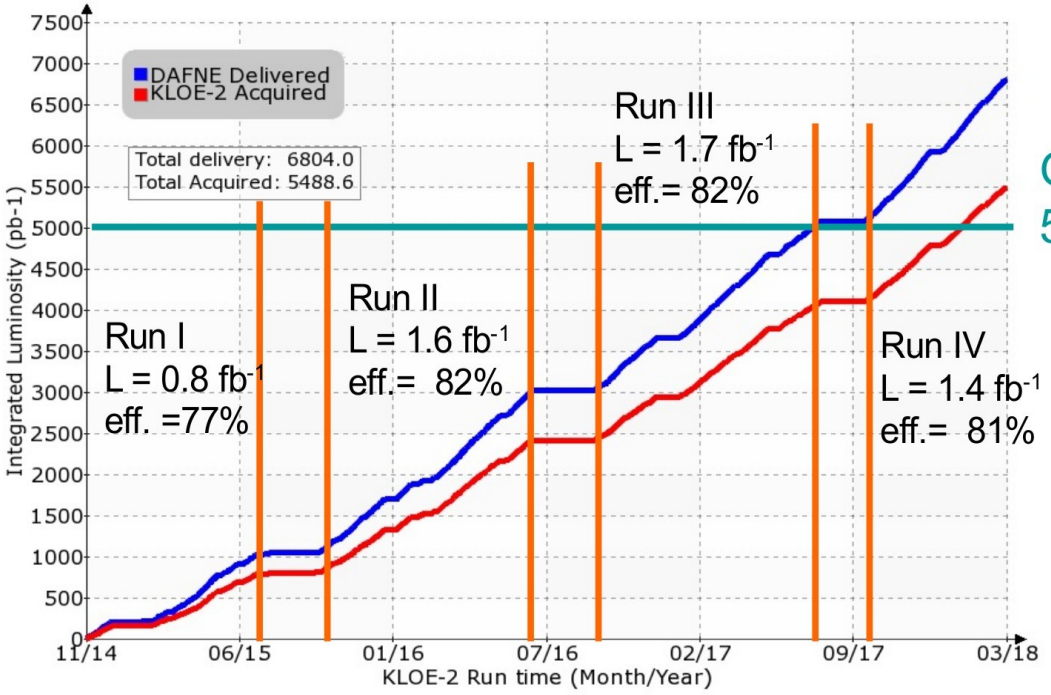
KLOE & KLOE-2



- 1999: first events collected by KLOE
- 2000 – 2006: KLOE data-taking
  ⇒ 2.5 fb $^{-1}$ @√s=M φ
  + 250 pb $^{-1}$ off-peak @ √s=1000 MeV
- 2008: DAΦNE upgrade: new interaction scheme
- Dec 2012-Jul 2013: installation of the new detectors



- July 2013: DAΦNE operations restarted
- November 2014: start of KLOE-2 run
- 2014 – 2018: KLOE-2 data-taking
- March 30, 2018: End of KLOE-2 data-taking ⇒ 5.5 fb $^{-1}$ collected @√s=M φ



Goal: 5 fb^{-1}

KLOE + KLOE-2 data sample: ~ 8 fb^{-1} ⇒ 2.4 × 10^{10} φ's produced
⇒ the largest sample ever collected at the φ(1020) peak

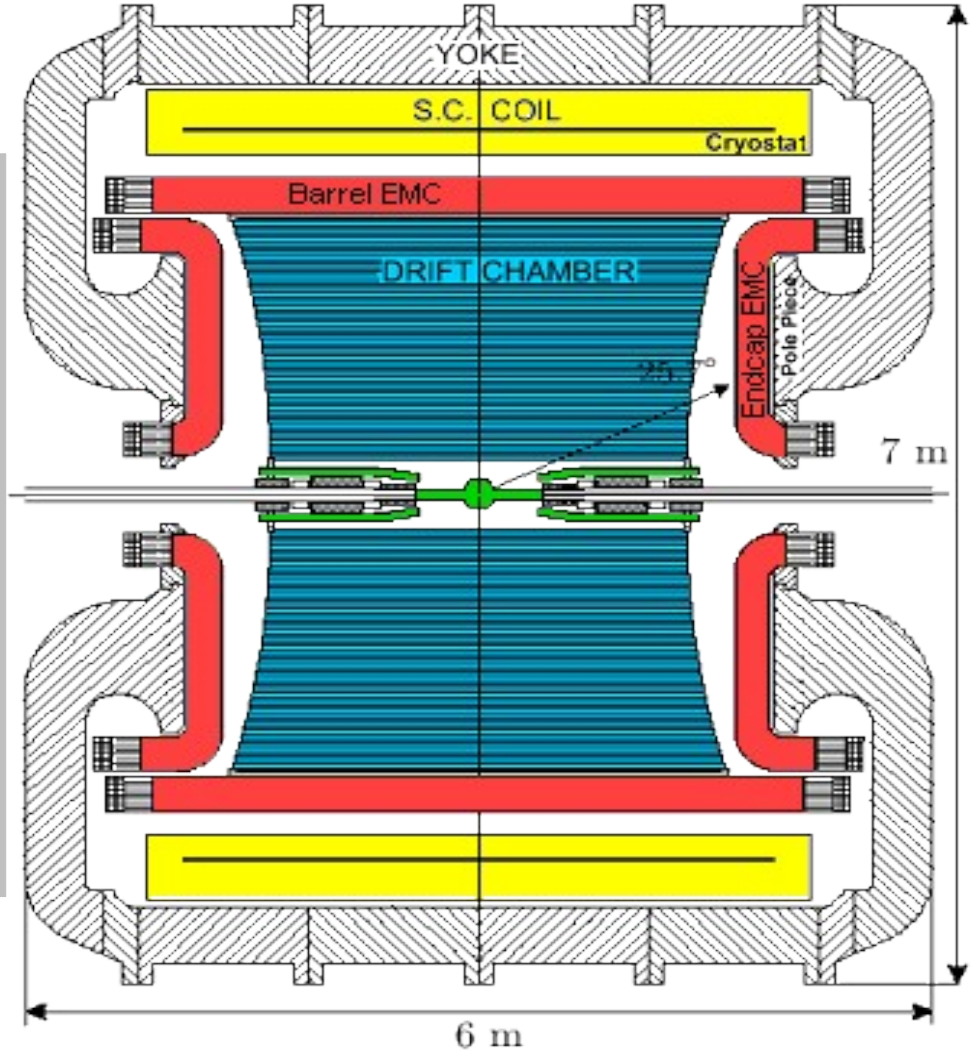
KLOE *K LOng Experiment*

Drift chamber

- gas mixture: 90% He + 10% C_4H_{10}
- $\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \approx 150$ μm ; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 3$ mm

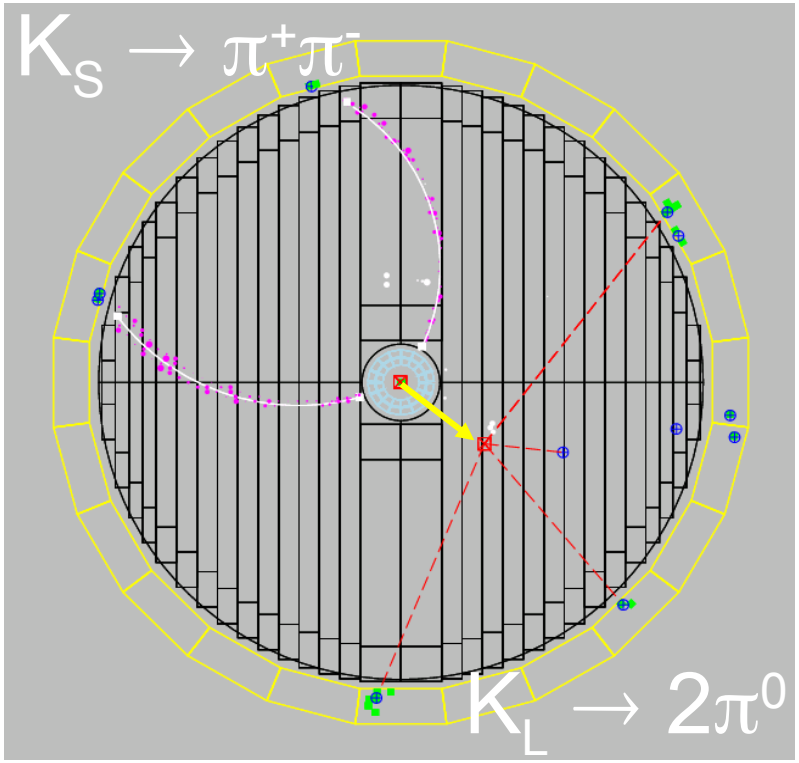
Electromagnetic calorimeter

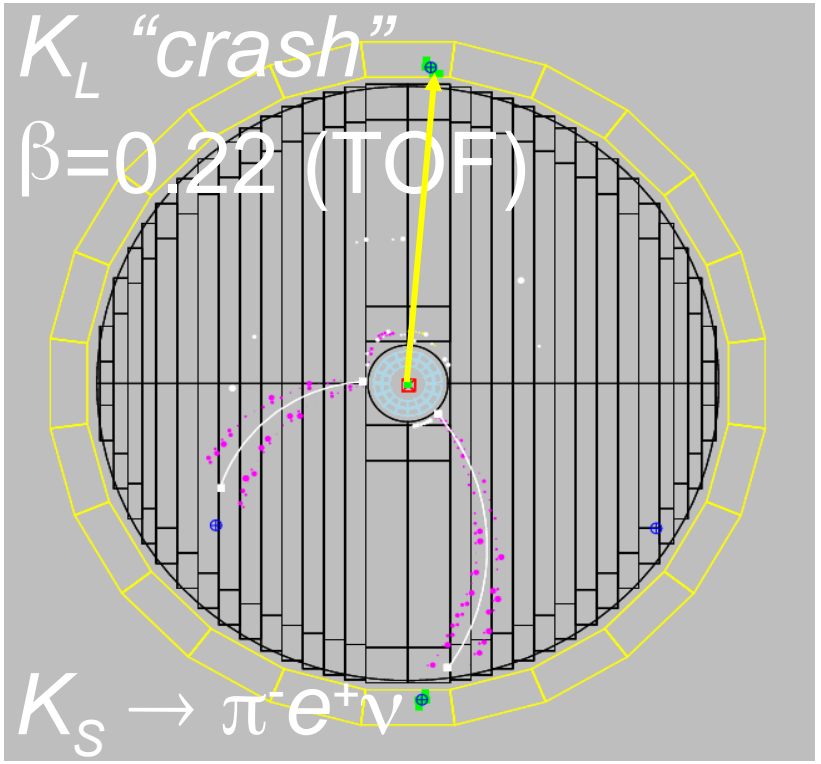
- lead/scintillating fibers
- 98% solid angle coverage
- $\sigma_E / E = 5.7\% / \sqrt{(E(GeV))}$
- $\sigma_t = 57$ ps $/ \sqrt{(E(GeV))} \oplus 100$ ps
- PID capabilities



Neutral kaon beams

UNIQUE





K_L tagged by
$K_S \to \pi^+\pi^-$ vertex at IP

K_S tagged by
K_L interaction in EmC

KLOE-2 upgrades

Inner Tracker

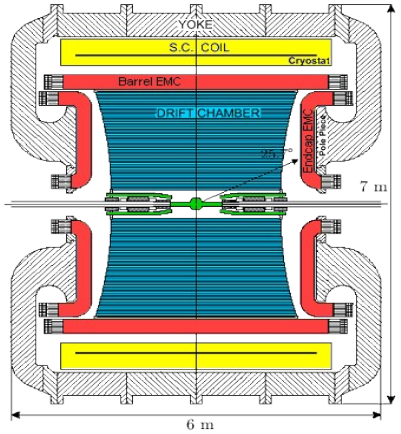
- 4 layers of cylindrical triple GEM
- better vertex reconstruction near IP
- larger acceptance for low p_t tracks

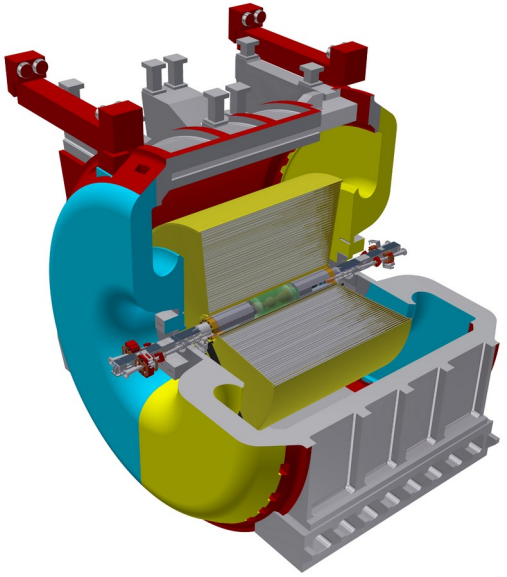
QCALT

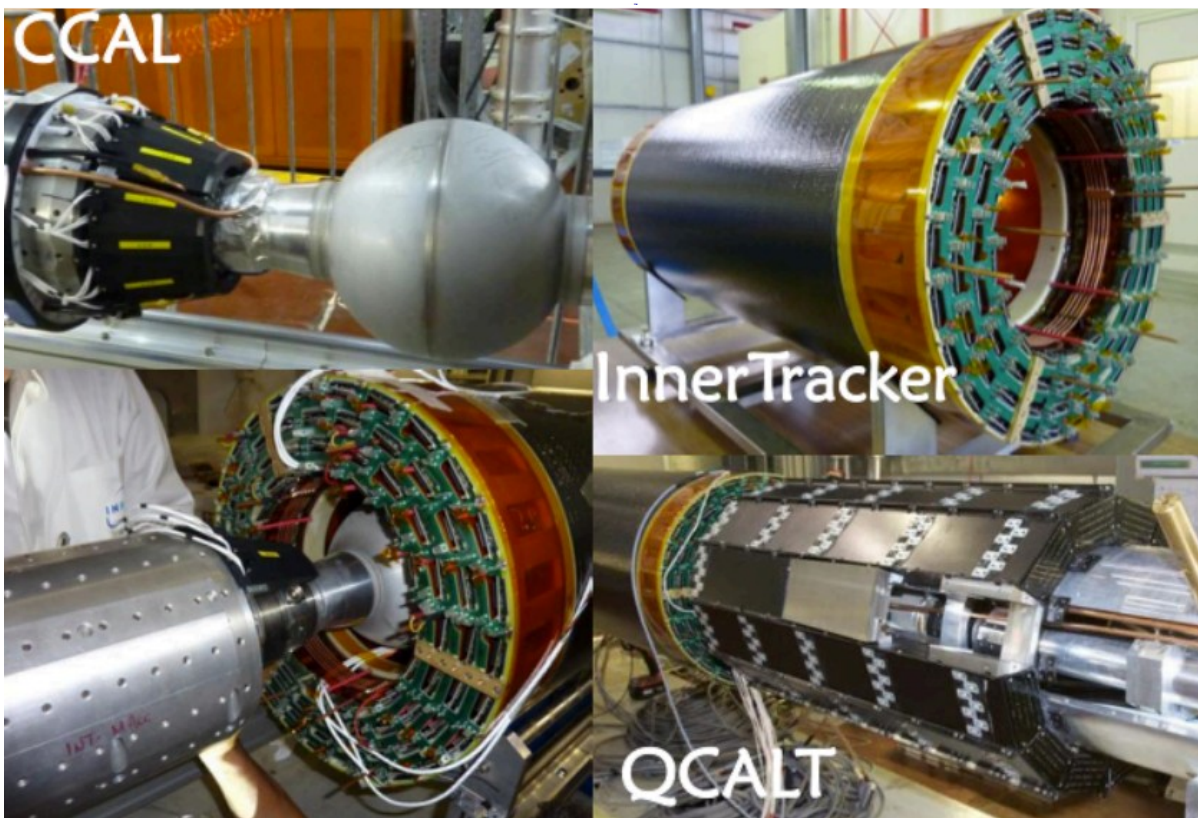
- W + scintillator tiles + SiPM/WLS
- QUADS instrumentation for K_L decays

CCALT

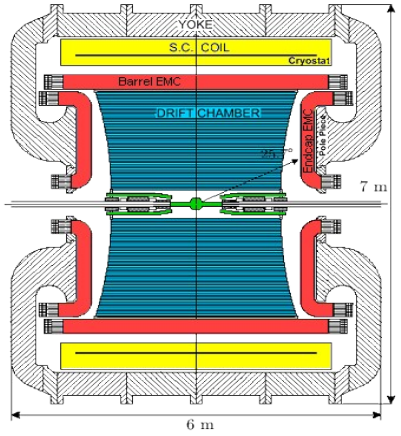
- LYSO + APD
- increase acceptance for γ's from IP (21°→8°)

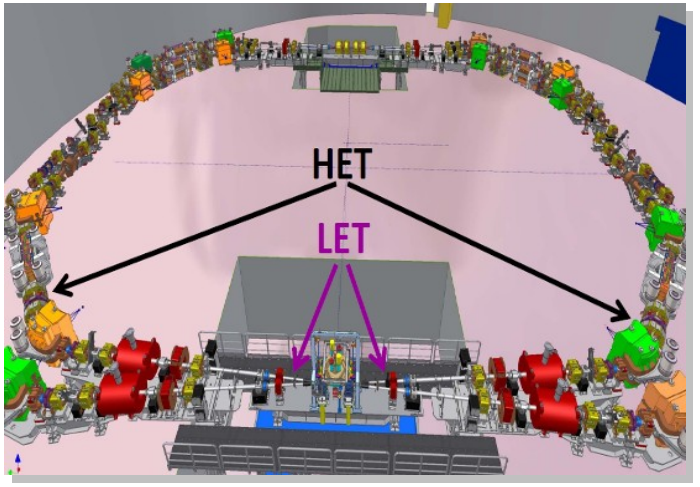






KLOE-2 upgrades





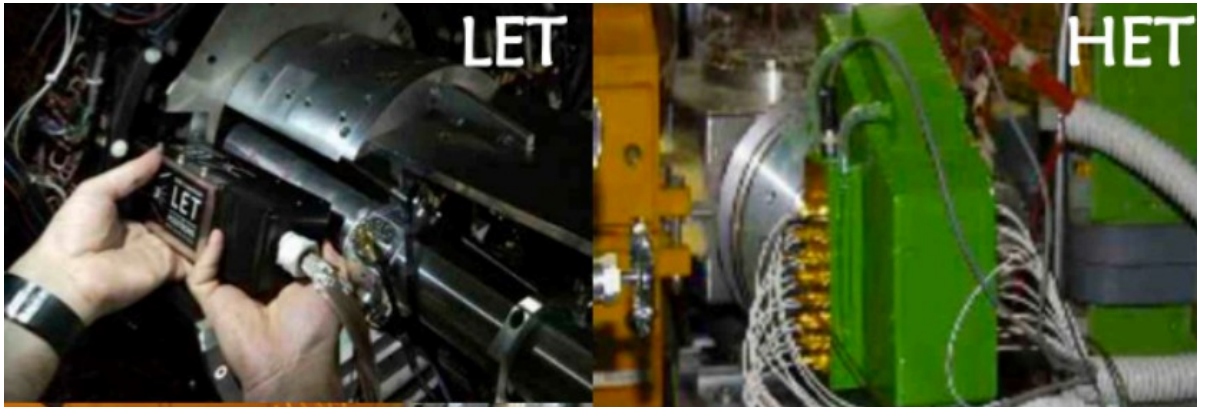
2+2 detector stations for leptons in $e^+e^- \to e^+e^- \gamma^*\gamma^* \to e^+e^- X$

High Energy Taggers (HET)

- E>400 MeV
- 11m from IP
- scintillators + PMTs

Low Energy Taggers (LET)

- E=160-230 MeV
- inside KLOE detector
- LYSO+SiPM



Test of Quantum Coherence and CPT symmetry with $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

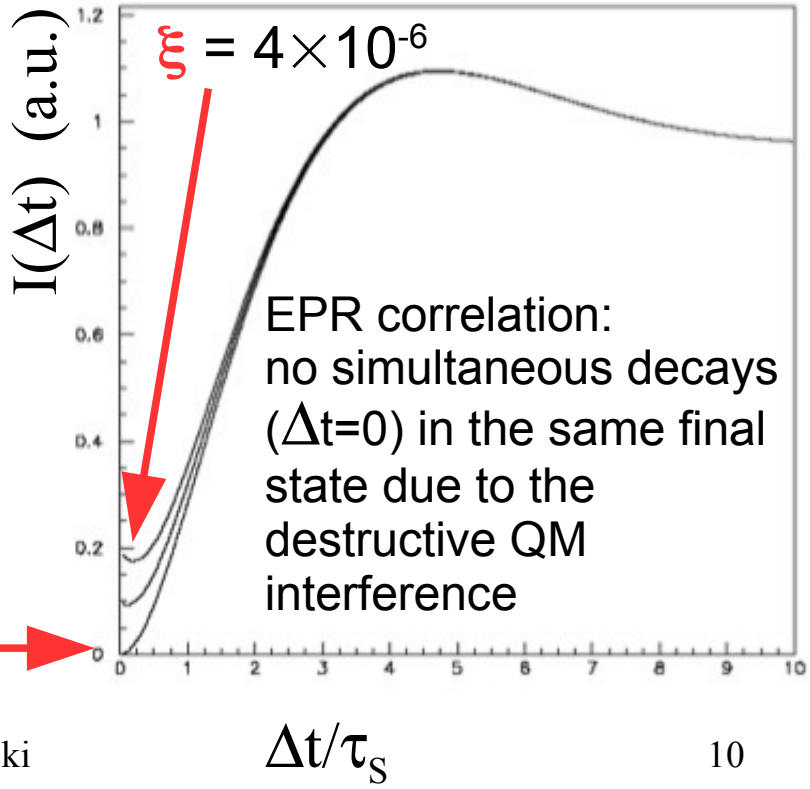
Test of quantum coherence and CPT test

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\left[\left|\langle \pi^+\pi^-,\pi^+\pi^- | K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle \pi^+\pi^-,\pi^+\pi^- | \overline{K}^0 K^0(\Delta t)\rangle\right|^2 - \left(1-\zeta_{00}\right) 2\Re\left(\langle \pi^+\pi^-,\pi^+\pi^- | K^0\overline{K}^0(\Delta t)\rangle\langle \pi^+\pi^-,\pi^+\pi^- | \overline{K}^0 K^0(\Delta t)\rangle^*\right)\right]$$

ζ depends on the decoherence mech. basis $K_0\overline{K}_0$ or K_SK_L
[Bertlmann et al. PR D60 (1999) 114032]

From CPLEAR data $\zeta_{00} = 0.4 \pm 0.7$
[Bertlmann et al. PR D60 (1999) 114032]
In the B-meson system $\zeta_{00}^B = 0.029 \pm 0.057$
[BELLE coll. PRL 99 (2007) 131802]

Decoherence parameter
$\zeta = 1$ → total decoherence (also known as Furry's hypothesis or spontaneous fact.)
[W.Furry, PR 49 (1936) 393]
QM predicts $\zeta = 0$



Test of quantum coherence and CPT test

-	$\delta\zeta_{SL}\cdot 10^2$	$\delta\zeta_{00}\cdot 10^7$	$\delta\gamma\cdot 10^{21}GeV$	$\delta Re\omega\cdot 10^4$	$\delta \mathrm{Im}\omega\cdot 10^4$	$\delta\lvert\omega\rvert\cdot 10^4$
Cut stability	± 0.56	± 2.9	± 0.33	± 0.53	± 0.65	± 0.78
4π Background	± 0.37	± 1.9	± 0.22	± 0.32	± 0.19	± 0.32
Regeneration	± 0.17	± 0.9	± 0.10	± 0.06	± 0.63	± 0.58
Resolution	± 0.18	± 0.9	± 0.10	± 0.15	± 0.09	± 0.15
Phys. Const.	± 0.04	± 0.2	± 0.02	± 0.03	± 0.09	± 0.07
Total	± 0.71	± 3.7	± 0.42	± 0.64	± 0.93	± 1.04

KLOE data: $\mathcal{L}$ = 1.7 fb $^{-1}$

improvements wrt past analysis:

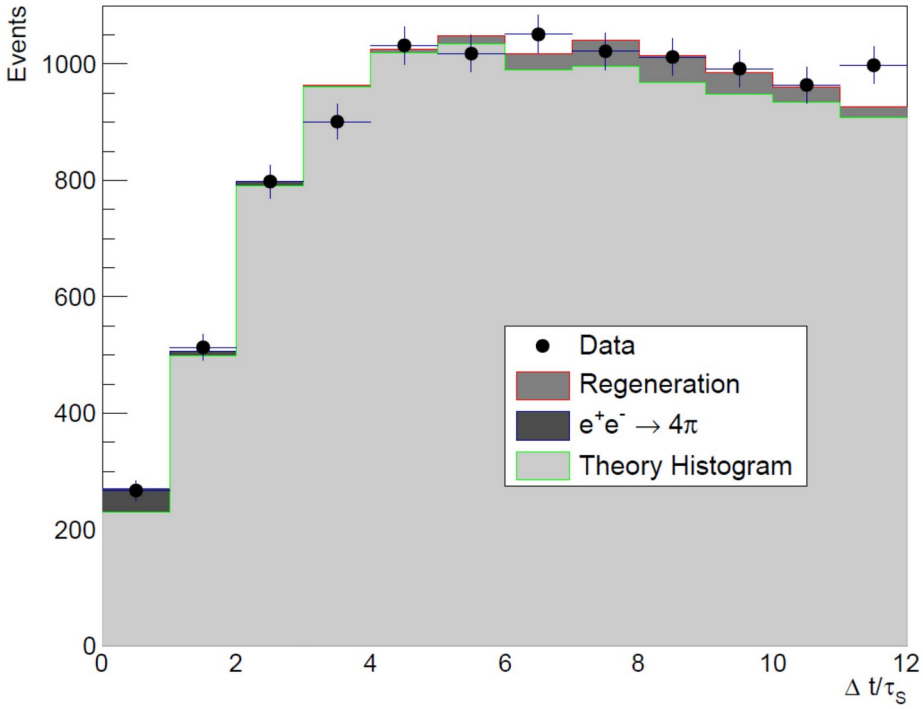
• $\cos(\theta_{\pi^+\pi^-}) > -0.975$ cut to improve Δt resolution

• improved $e^+ e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ background evaluation from 2D fit of the invariant mass.

Fit including Δt resolution and efficiency effects + regeneration.

Statistical uncertainty reduced by half.

KLOE-2 JHEP 04 (2022) 059



Test of quantum coherence and CPT test

Quantum gravity effects might induce decoherence and CPT violation
⇒ modified Liouville – von Neumann equation for the density matrix → α, β, γ CPTV parameters, in the complete positivity hypothesis $\alpha = \gamma$ and $\beta = 0$ → γ as a single independent parameter at most $\gamma = O(m^2_K / M_{Planck}) \sim 2 \times 10^{-20}$ GeV
[J.R.Ellis, J.L.Lopez, N.E.Mavromatos, D.V.Nanopoulos, PRD 53 (1996) 3846]
⇒ modification of the initial correlation of the kaon pair (at most $\omega = O(m^2_K / M_{Planck} / \Delta\Gamma) \sim 1 \times 10^{-3}$)
[J. Bernabeu, N.E.Mavromatos, J. Papavassiliou, PRL 92 (2004) 131601]

$$|i\rangle \propto \left(K^0\overline{K}^0 - K^0\overline{K}^0\right) + \omega\left(K^0\overline{K}^0 + K^0\overline{K}^0\right)$$

$$\zeta_{0\overline{0}} = (-0.5 \pm 8.0_{stat} \pm 3.7_{syst}) \times 10^{-7}$$
$$\zeta_{SL} = (0.1 \pm 1.6_{stat} \pm 0.7_{syst}) \times 10^{-2}$$
$$\gamma = (1.3 \pm 9.4_{stat} \pm 4.2_{syst}) \times 10^{-22}\ \text{GeV}$$
$$\Re\omega = \left(-2.3^{+1.9}_{-1.5 stat} \pm 0.6_{syst}\right) \times 10^{-4}$$
$$\Im\omega = \left(-4.1^{+2.8}_{-2.6 stat} \pm 0.9_{syst}\right) \times 10^{-4}$$
$$|\omega| = (4.7 \pm 2.9_{stat} \pm 1.0_{syst}) \times 10^{-4}$$
$$\phi_\omega = -2.1 \pm 0.2_{stat} \pm 0.1_{syst}\ \text{rad}$$

KLOE-2 JHEP 04 (2022) 059
improvement wrt
KLOE PLB 642 (2006) 315

Direct test of T and CPT in neutral kaon transitions with

$$K_S K_L \to \pi^{\pm} e^{\mp} \nu, 3\pi^0$$

and

$$K_S K_L \to \pi^+ \pi^-, \pi^{\pm} e^{\mp} \nu$$

T and CPT test in transitions

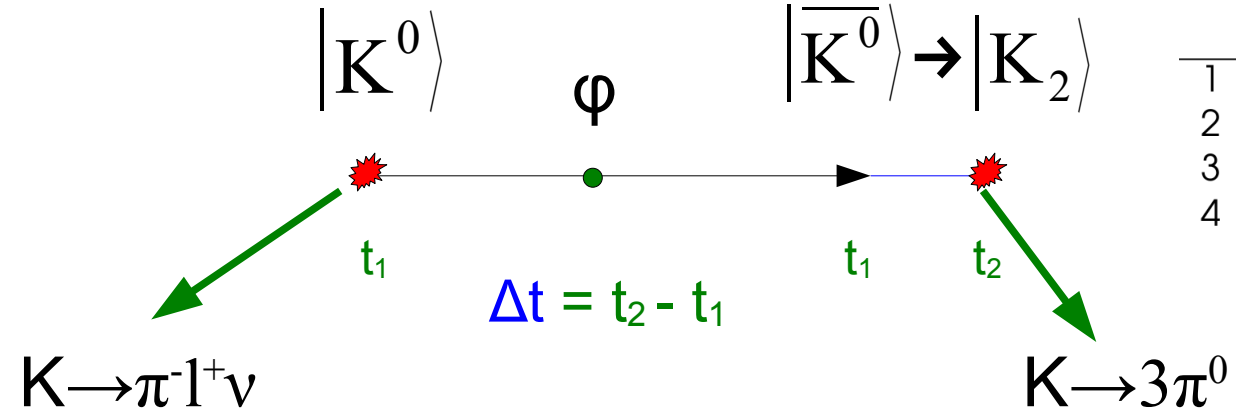
$$S|K^0\rangle = +1|K^0\rangle \qquad S = +1$$
$$S|\overline{K^0}\rangle = -1|\overline{K^0}\rangle \qquad S = -1$$
$$|K_1\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle + |\overline{K^0}\rangle] \qquad CP = +1$$
$$|K_2\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle - |\overline{K^0}\rangle] \qquad CP = -1$$

$K^0 \to \pi^- l^+ \nu_l \qquad S = +1$

$\overline{K}^0 \to \pi^+ l^- \overline{\nu}_l \qquad S = -1$

$K_1 \to \pi\pi \qquad CP = +1$

$K_2 \to 3\pi^0 \qquad CP = -1$



	Transition		$\mathcal{T}$-conjugate	
1	$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
2	$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$
3	$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
4	$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$

$$|\overline{K^0}\rangle \to |K_2\rangle \xrightarrow{T} |K_2\rangle \to |\overline{K^0}\rangle$$

Direct, model independent tests. Only feasible with entangled neutral mesons [Nucl. Phys. B 868 (2013) 102, JHEP 1510 (2015) 139].
First observation in system of B mesons by the BABAR Collaboration: [Phys. Rev. Lett. 109 (2012) 211801]

T and CPT test in transitions

$$R_2^T(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^+ e^- \overline{\nu}, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)} \times \frac{1}{D},$$

$$R_4^T(\Delta t) = \frac{P[\overline{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \overline{\mathrm{K}}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^+ e^- \overline{\nu}; \Delta t)} \times \frac{1}{D},$$

$$R_2^{CPT}(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \overline{\mathrm{K}}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^+ e^- \overline{\nu}, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^+ e^- \overline{\nu}; \Delta t)} \times \frac{1}{D},$$

$$R_4^{CPT}(\Delta t) = \frac{P[\overline{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)} \times \frac{1}{D}.$$

$$D = \frac{\mathrm{BR}(\mathrm{K_L} \to 3\pi^0)\tau_S}{\mathrm{BR}(\mathrm{K_S} \to \pi^+\pi^-)\tau_L}$$

Single ratios at limits:

$$R_2^T(\Delta t \gg \tau_S) \simeq 1 - 4\,\mathrm{Re}\,\epsilon, \qquad R_2^{CPT}(\Delta t \gg \tau_S) \simeq 1 - 4\,\mathrm{Re}\,\delta,$$

$$R_4^T(\Delta t \gg \tau_S) \simeq 1 + 4\,\mathrm{Re}\,\epsilon, \qquad R_4^{CPT}(\Delta t \gg \tau_S) \simeq 1 + 4\,\mathrm{Re}\,\delta,$$

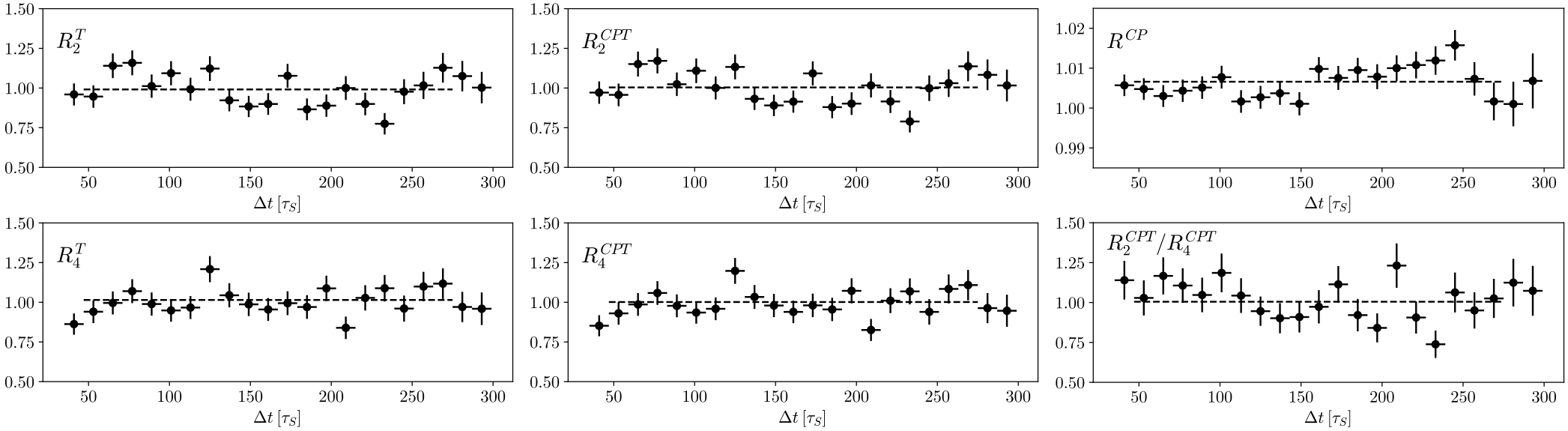
CPT double ratio at limits:

$$R_2^{CPT}(\Delta t \gg \tau_S)/R_4^{CPT}(\Delta t \gg \tau_S) = 1 - 8\,\mathrm{Re}\,\delta - 8\,\mathrm{Re}\,x_-,$$

Systematic uncertainties

Effect	R_2^T	R_4^T	R_2^{CPT}	R_4^{CPT}	R_2^T/R_4^T	R_2^{CPT}/R_4^{CPT}	R_2^{CP}	R_4^{CP}
Residual background model	0.002738	0.004615	0.002789	0.004429	0.004432	0.004414	0.004369	–
Smoothing of efficiencies from MC	0.002460	0.005310	0.002430	0.005260	0.006700	0.006830	0.006760	0.000165
Δt bin width	0.008000	0.005000	0.007500	0.005500	0.009000	0.009000	0.008900	0.000030
Fit range position	0.007250	0.007280	0.007270	0.007260	0.005140	0.005270	0.005200	0.000205
Fit range width	0.001110	0.005080	0.000858	0.005050	0.006070	0.005480	0.005780	0.000359
Effects of cuts in the $\pi e\nu\ 3\pi^0$ selection								
K_S vertex ρ	0.000411	0.002300	0.000417	0.002260	0.002240	0.002290	0.002270	–
K_S vertex z	0.000397	0.000242	0.000405	0.000239	0.000736	0.000760	0.000748	–
$M(\pi,\pi)$	0.002480	0.001340	0.002520	0.001310	0.001560	0.001630	0.001600	–
1^{st} TOF cut	0.001600	0.002220	0.001620	0.002190	0.003830	0.003950	0.003890	–
2^{nd} TOF cut parameter A	0.000671	0.000581	0.000684	0.000569	0.000878	0.000899	0.000889	–
2^{nd} TOF cut parameter B	0.000369	0.000433	0.000375	0.000426	0.000076	0.000077	0.000076	–
2^{nd} TOF cut parameter C	0.000152	0.000399	0.000154	0.000393	0.000278	0.000283	0.000281	–
2^{nd} TOF cut parameter D	0.001420	0.000850	0.001450	0.000836	0.002050	0.002110	0.002080	–
3^{rd} TOF cut circle R	0.005140	0.004470	0.005230	0.004390	0.003560	0.003640	0.003600	–
3^{rd} TOF cut ellipse A	0.002280	0.001020	0.002320	0.001000	0.002760	0.002850	0.002800	–
3^{rd} TOF cut ellipse B	0.000412	0.000993	0.000420	0.000973	0.000956	0.000975	0.000965	–
$e/\pi/\mu$ classification	0.004000	0.004330	0.004070	0.004250	0.009100	0.009340	0.009220	–
Classifier training with data/MC	0.002620	0.000800	0.002630	0.000810	0.002050	0.002170	0.002110	–
Effects of cuts in the $\pi^+\pi^-\ \pi e\nu$ selection								
K_S vertex ρ	0.000002	0.000002	0.000002	0.000002	0.000000	0.000000	–	0.000000
K_S vertex z	0.000007	0.000003	0.000003	0.000007	0.000004	0.000004	–	0.000005
$M(\pi,\pi)$	0.002220	0.002280	0.002240	0.002260	0.000024	0.000024	–	0.000027
$\lvert\vec{p}_{tot}\rvert$	0.000152	0.000181	0.000178	0.000154	0.000021	0.000021	–	0.000022
$m_+^2 + m_-^2$	0.001480	0.001320	0.001310	0.001490	0.000202	0.000208	–	0.000210
1^{st} TOF cut parameter A	0.000021	0.000385	0.000389	0.000020	0.000392	0.000405	–	0.000426
1^{st} TOF cut parameter B	0.001450	0.001080	0.001070	0.001470	0.000407	0.000417	–	0.000417
2^{nd} TOF cut parameter R_1	0.000171	0.000256	0.000262	0.000175	0.000126	0.000130	–	0.000140
2^{nd} TOF cut parameter R_2	0.001570	0.001200	0.001190	0.001590	0.000399	0.000410	–	0.000414
Total systematic uncertainty	**0.014**	**0.015**	**0.014**	**0.015**	**0.019**	**0.019**	**0.019**	**0.00089**
Uncertainty on the D factor	0.012	0.012	0.012	0.012				
Including the D factor	0.018	0.019	0.019	0.019				

T and CPT test in transitions

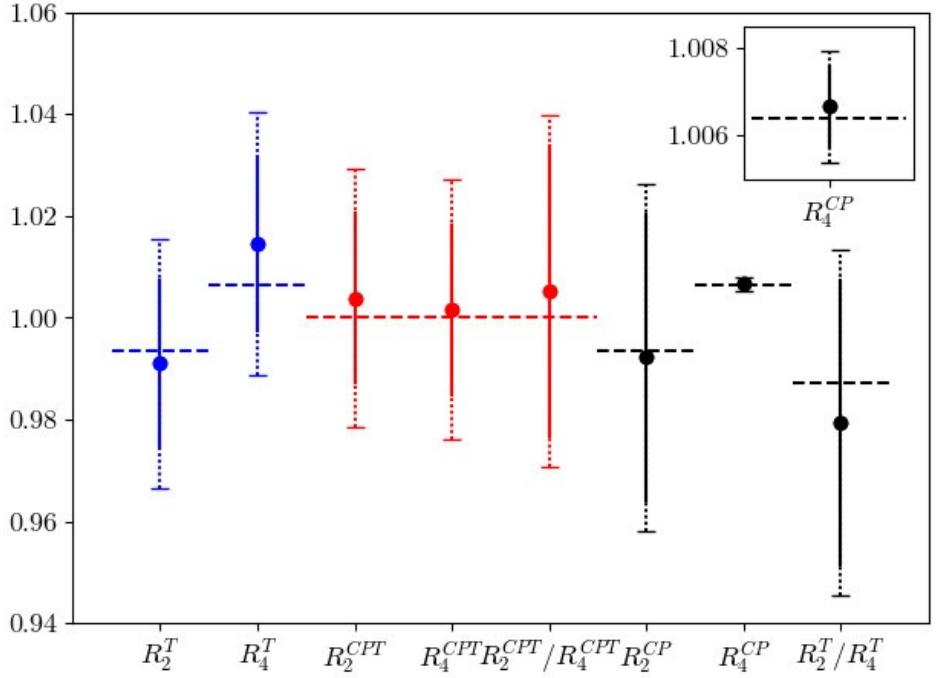


- Analysed data $\mathcal{L}$=1.7 fb^{-1}
- Four processes studied: $\phi \rightarrow K_S K_L \rightarrow \pi e^{\pm}\nu\ 3\pi^0$ and $\pi^+\pi^-\ \pi e^{\pm}\nu$ in the asympotic regime.
- Time of flight technique to identify semileptonic decays.
- Residual background subtraction for $\pi e^{\pm}\nu\ 3\pi^0$ channel.
- Selection efficiencies estimated from data with 4 independent control samples.

T and CPT test in transitions

$$
\begin{aligned}
R_2^T &= 0.991 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D, \\
R_4^T &= 1.015 \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_D, \\
R_2^{CPT} &= 1.004 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D, \\
R_4^{CPT} &= 1.002 \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_D, \\
R_2^{CP} &= 0.992 \pm 0.028_{stat} \pm 0.019_{syst}, \\
R_4^{CP} &= 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst}, \\
R_2^T/R_4^T &= 0.979 \pm 0.028_{stat} \pm 0.019_{syst} \\
R_2^{CPT}/R_4^{CPT} &= 1.005 \pm 0.029_{stat} \pm 0.019_{syst}
\end{aligned}
$$

Error bars:
solid – stat
dotted – total



First T and CPT test in kaon transitions

KLOE-2 result (2022)
(paper in preparation)

Conclusions

• The entangled neutral kaon system at a φ-factory is an excellent laboratory for the study of discrete symmetries.

• KLOE-2 data-taking succesfully closed on March 30 (2018)
~ 20 years after the first events collected in KLOE.

• Luminosity goal reached ⇒ acquired 5.5 fb^{-1}.

• KLOE + KLOE-2 sample ⇒ ~8 fb^{-1} largest sample in the world at the φ peak

• Latest studies on entangled neutral kaons:
Improved search for decoherence and CPT violation effects,
First direct test of T and CPT symmetries in neutral kaon transitions.

• The analysis of KLOE-2 data ongoing.