Testing discrete symmetries with neutral kaons at KLOE-2

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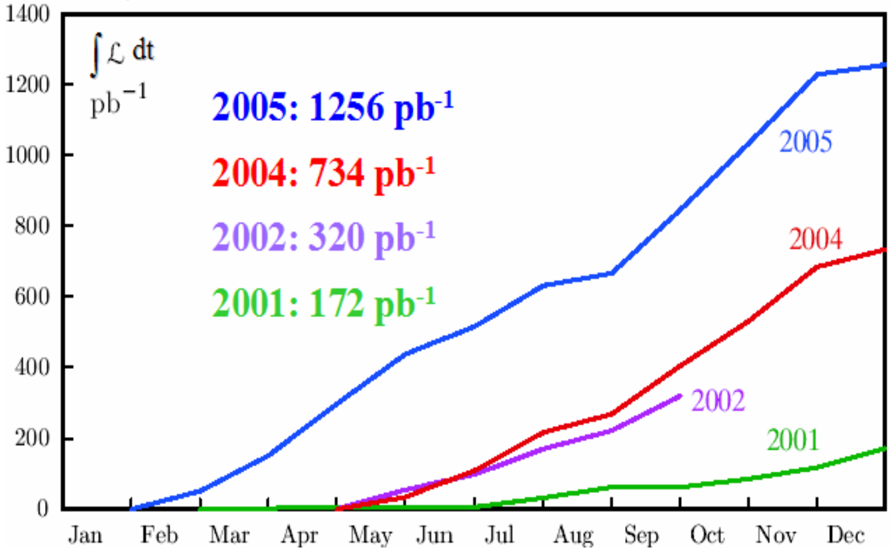
on behalf of the KLOE-2 collaboration

The KLOE detector at the Frascati ϕ-factory DAΦNE

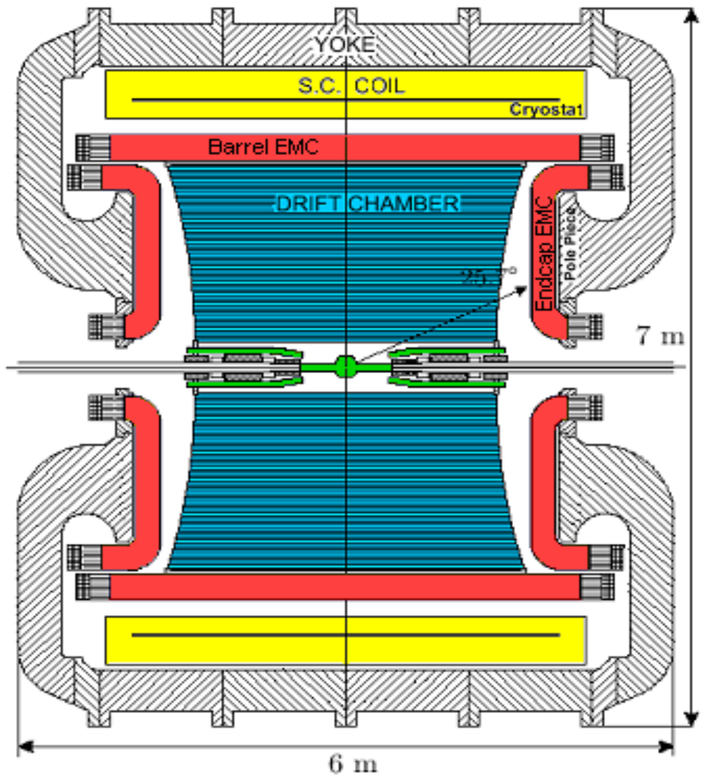
DAFNE collider

Integrated luminosity (KLOE)



Total KLOE $\int \mathcal{L}\, dt \sim$ 2.5 fb^{-1}
(2001 - 05) $\rightarrow$ $\sim 2.5\times10^9$ $K_S K_L$ pairs

KLOE detector



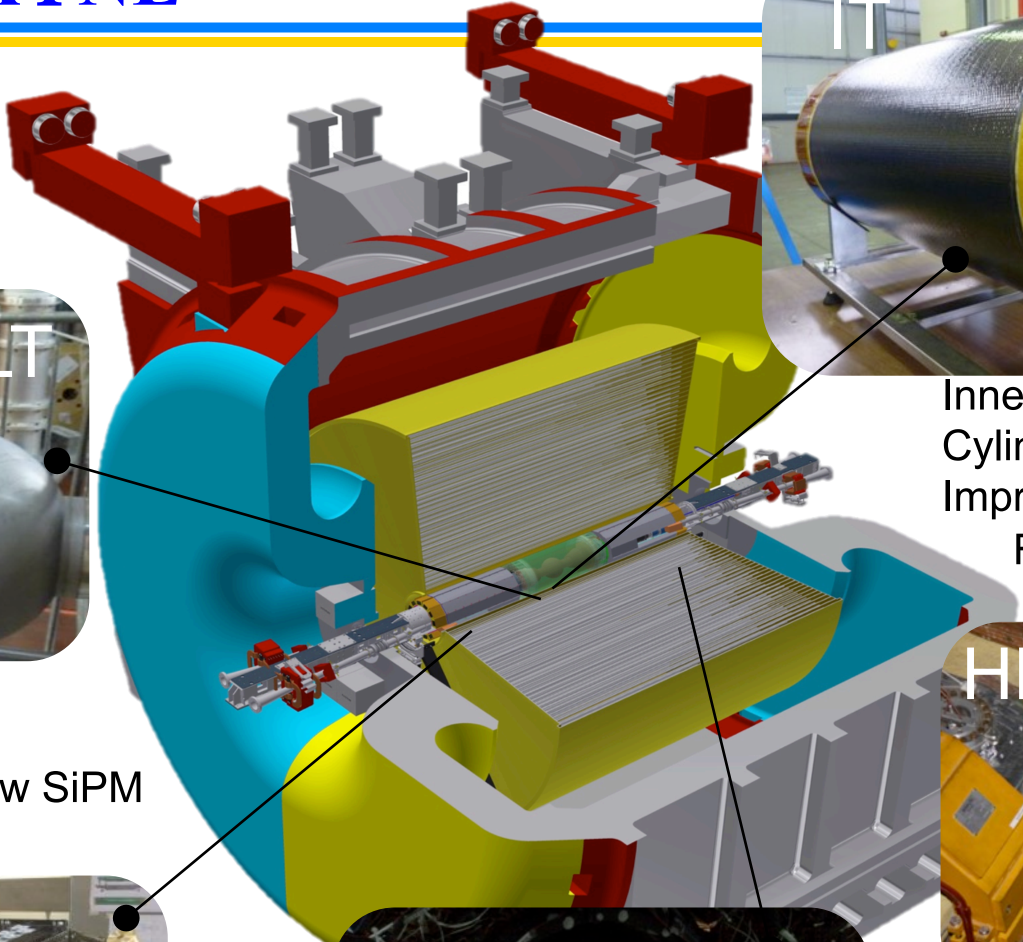
Lead/scintillating fiber calorimeter

drift chamber

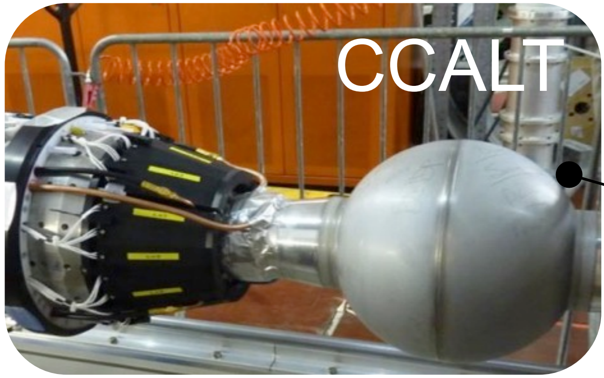
4 m diameter × 3.3 m length

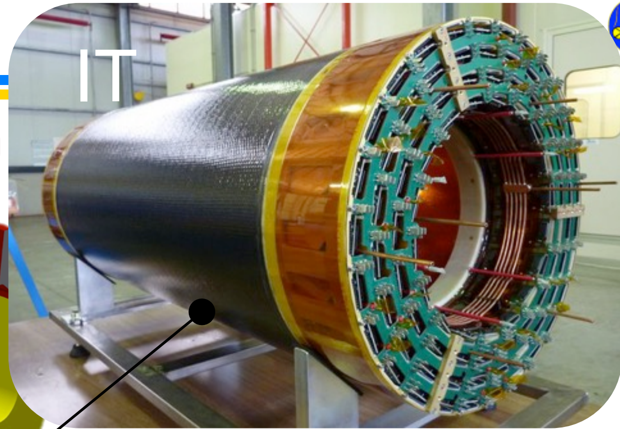
helium based gas mixture

KLOE-2 at DAΦNE



LYSO Crystal w SiPM
Low polar angle

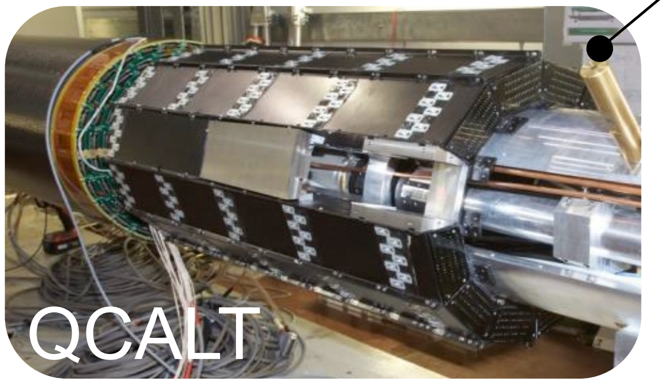




Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.

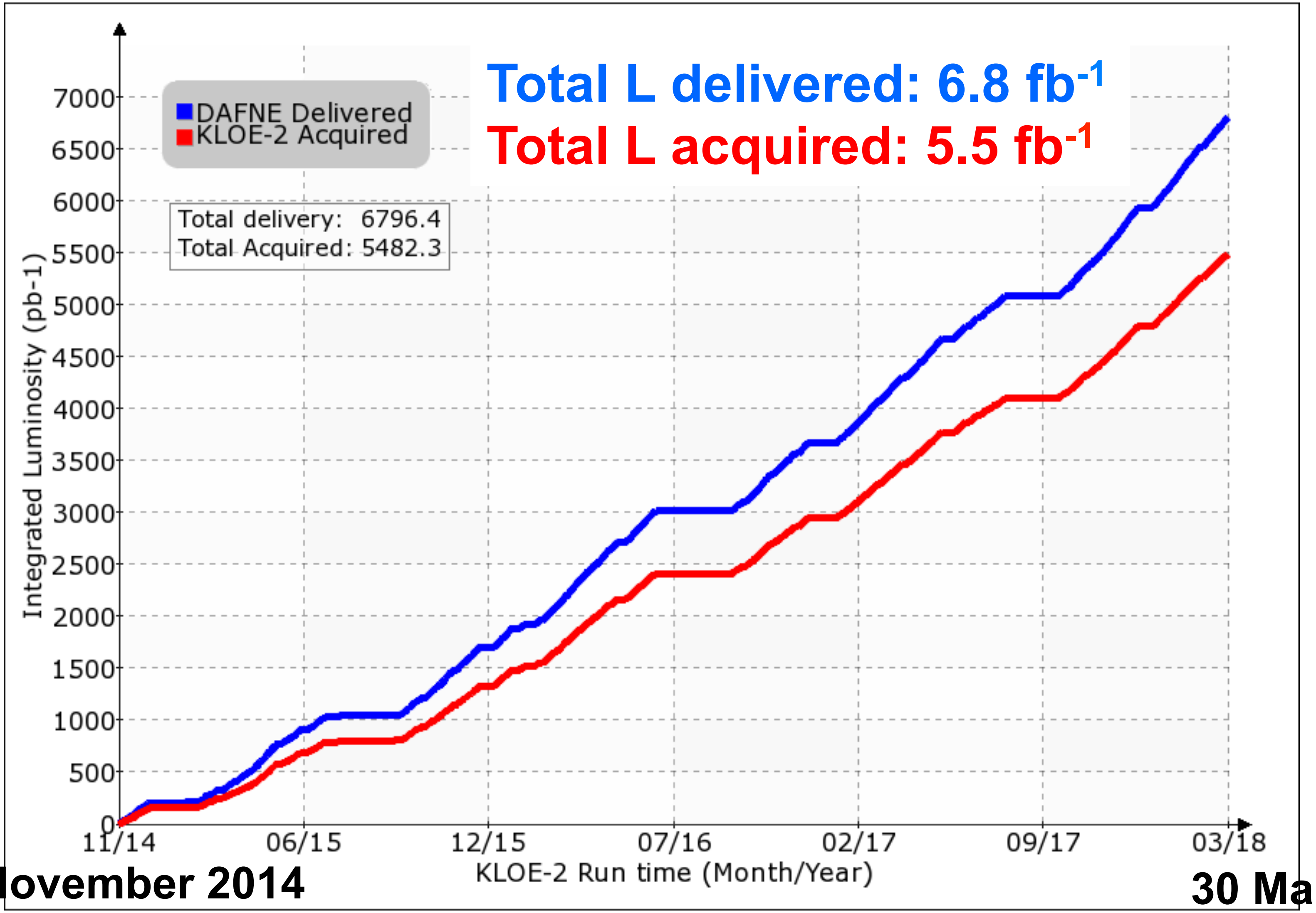
Scintillator hodoscope +PMTs

Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation



calorimeters LYSO+SiPMs
at ~ 1 m from IP

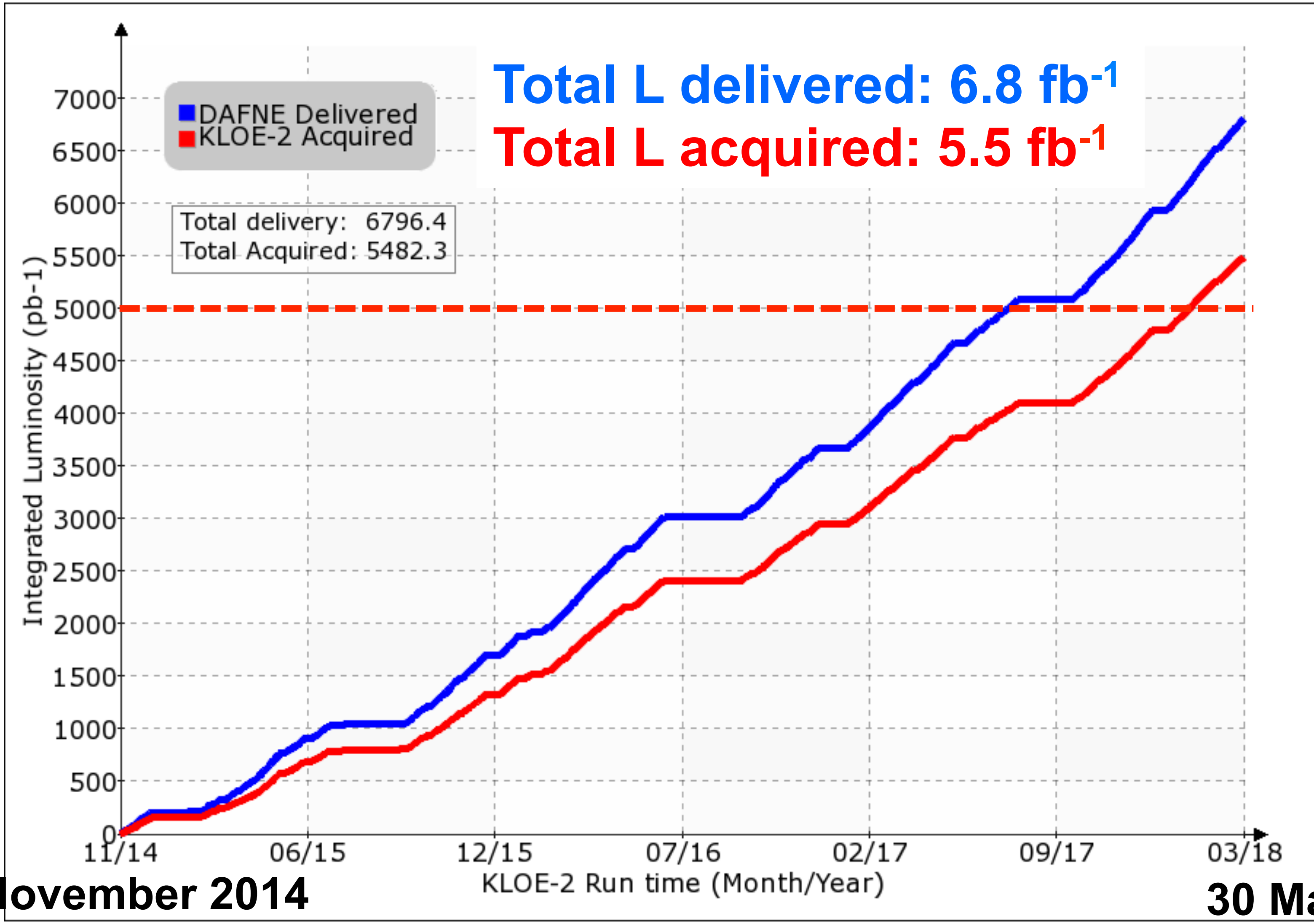
KLOE-2 run



17 November 2014 **30 March 2018**

KLOE-2 goal accomplished: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

KLOE-2 run



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KLOE-2 goal accomplished: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

KLOE-2 run

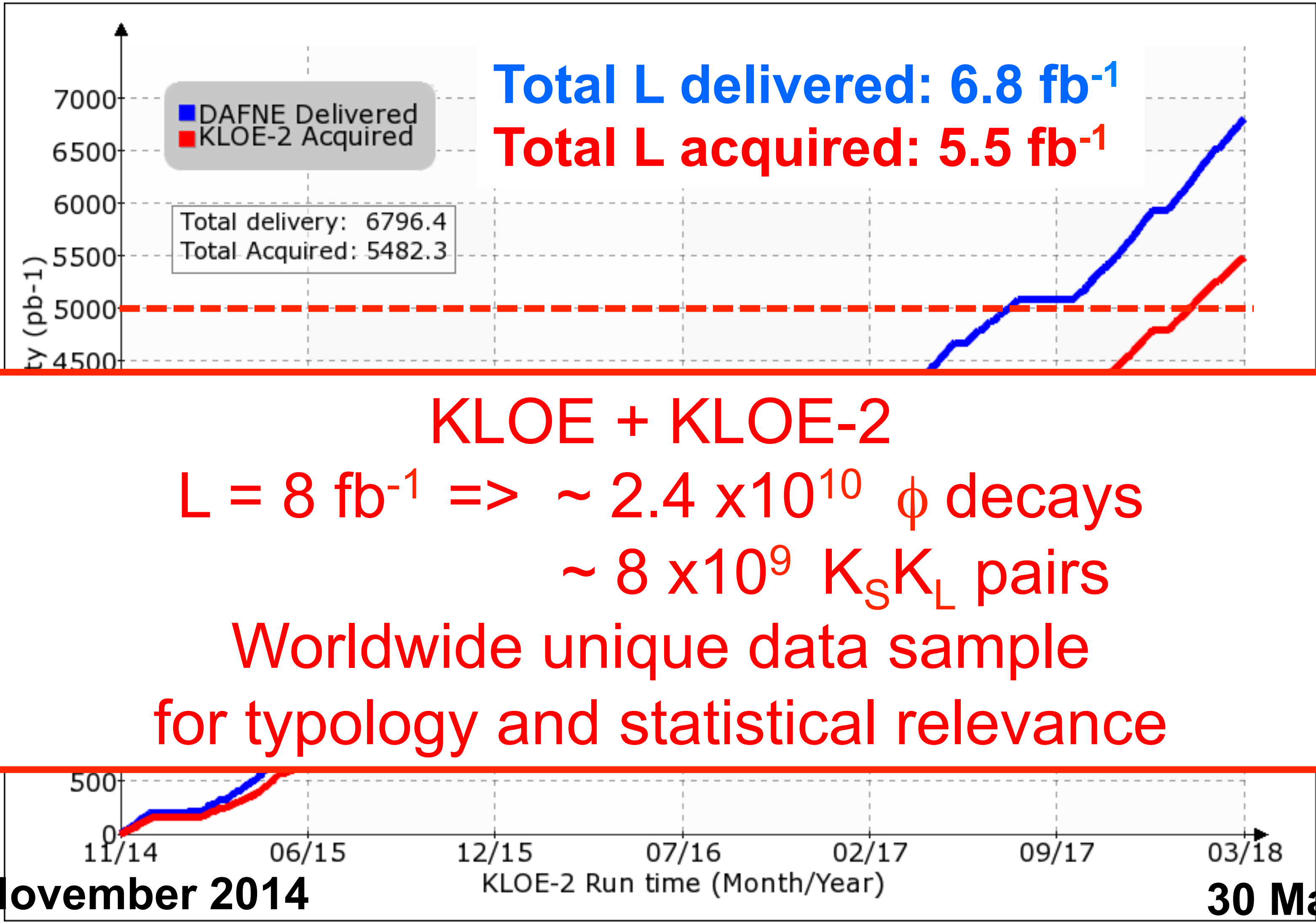
KLOE-2 data-taking closing ceremony

30 March 2018 *INFN - Laboratori Nazionali di Frascati*

see Gauzzi's talk in Detector session

KLOE-2 goal accomplis… d > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

KLOE-2 run



KLOE + KLOE-2

L = 8 fb^{-1} => ~ 2.4 x10^{10} ϕ decays

~ 8 x10^{9} $K_S K_L$ pairs

Worldwide unique data sample

for typology and statistical relevance

17 November 2014 **30 March 2018**

KLOE-2 goal accomplished: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

List of KLOE CP/CPT tests with neutral kaons

Mode	Test	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 10) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(x_-)$	$(-0.8 \pm 2.5) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(y)$	$(0.4 \pm 2.5) \times 10^{-3}$
All $K_{S,L}$ BRs, η's etc... (unitarity)	CP CPT	$Re(\varepsilon)$ $Im(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(-6.2 \pm 8.8) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(-0.7 \pm 1.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV

KLOE-2 Physics

KAON Physics:

- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \to 3\pi^0$
  direct measurement of $Im(\varepsilon'/\varepsilon)$ (lattice calc. improved)
- CKM Vus:
  K_S semileptonic decays and A_S (also CP and CPT test)
  $K\mu3$ form factors, Kl3 radiative corrections
- χpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Dark forces:

- Improve limits on:
  $U\gamma$ associate production
  $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$
- Higgstrahlung
  $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy
- Leptophobic B boson search
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Hadronic cross section

- Measurement of a_μ^{HLO} in the space-like region using Bhabha process
- ISR studies with 3π, 4π final states
- F_π with increased statistics

EPJC (2010) 68, 619, EPJ WoC 166 (2018)

Light meson Physics:

- η decays, ω decays, TFF $\phi \to \eta e^+e^-$
- C,P,CP violation:
  improve limits on $\eta \to \gamma\gamma\gamma, \pi^+\pi^-, \pi^0\pi^0, \pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$
- χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $\phi \to K_S K_S \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF
- light-by-light scattering
- axion-like particles

1. K_S semileptonic charge asymmetry
2. Direct test of T and CPT in neutral kaon transitions
3. Search for the CP violating $K_S \to \pi^0\pi^0\pi^0$ decay

K_S semileptonic charge asymmetry

K_S and K_L semileptonic charge asymmetry

T CPT viol. in mixing

$$A_{S,L} = \frac{\Gamma\left(K_{S,L} \to \pi^- e^+ \nu\right) - \Gamma\left(K_{S,L} \to \pi^+ e^- \bar{\nu}\right)}{\Gamma\left(K_{S,L} \to \pi^- e^+ \nu\right) + \Gamma\left(K_{S,L} \to \pi^+ e^- \bar{\nu}\right)} = 2\Re\varepsilon \pm 2\Re\delta - 2\Re y \pm 2\Re x_-$$

CPTV in $\Delta S=\Delta Q$ $\Delta S\neq\Delta Q$ decays

$A_{S,L}\neq 0$ signals CP violation

$A_S\neq A_L$ signals CPT violation

$\mathbf{A_L=(3.322 \pm 0.058 \pm 0.047) \times 10^{-3}}$

KTEV PRL88,181601(2002)

$\mathbf{A_S = (1.5 \pm 9.6 \pm 2.9) \times 10^{-3}}$

KLOE PLB 636(2006) 173

Data sample: L=410 pb^{-1}

$A_S - A_L = 4\left(\Re\delta + \Re x_-\right)$ → $\Re x_- = (-0.8 \pm 2.5) \times 10^{-3}$ **CPT & $\Delta S=\Delta Q$ viol.**

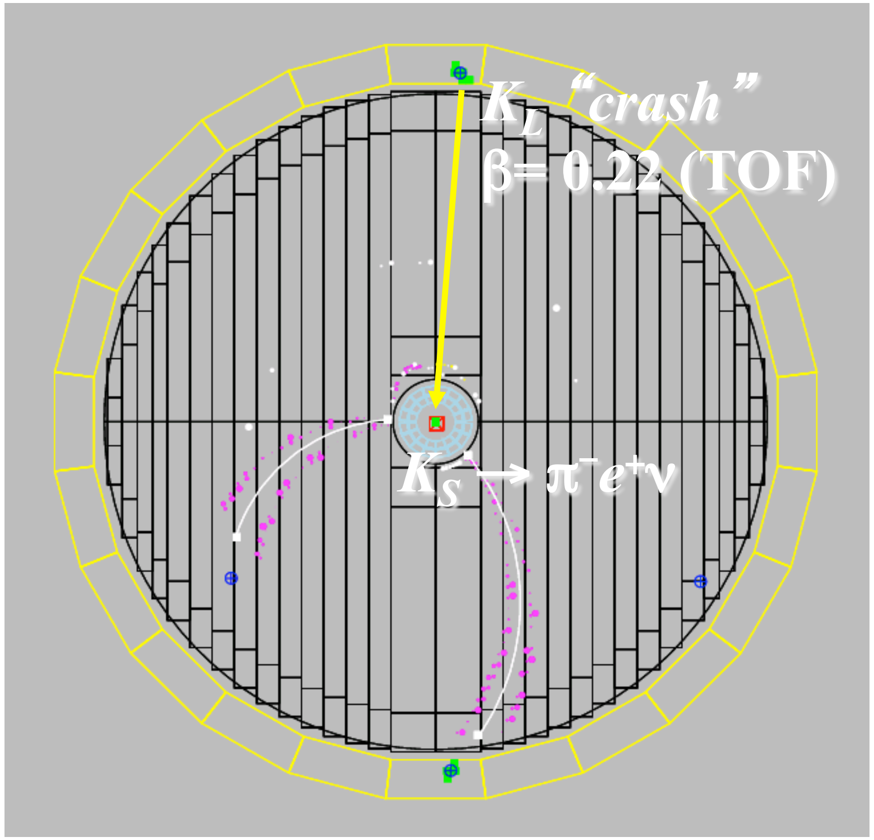
$A_S + A_L = 4\left(\Re\varepsilon - \Re y\right)$ → $\Re y = (0.4 \pm 2.5) \times 10^{-3}$ **CPT viol.**

input from other experiments

KLOE PLB 636(2006) 173

K_S semileptonic charge asymmetry

$$|i\rangle \propto \left[|K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle \right]$$



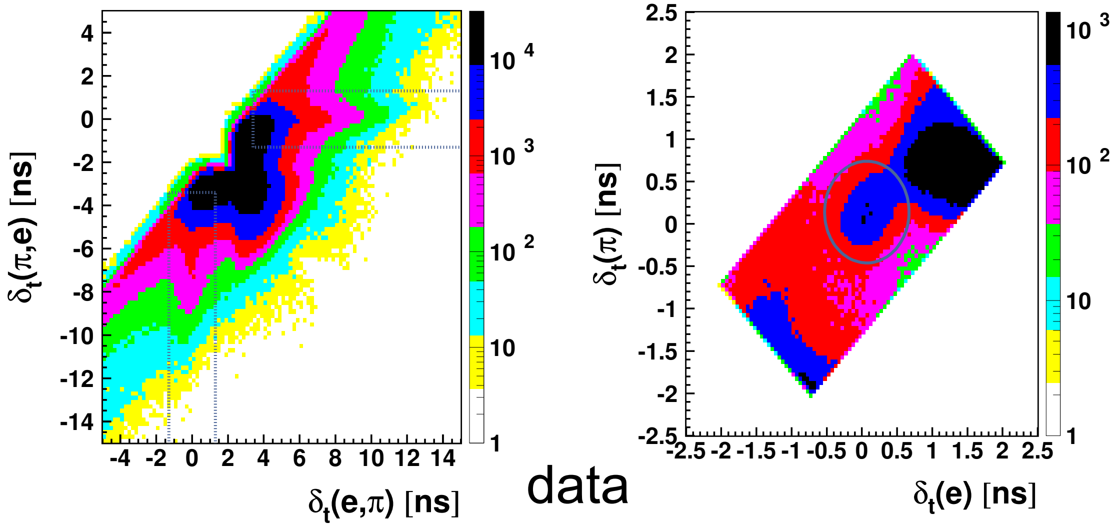
***K_S* tagged by *K_L* interaction in EmC**

Efficiency ~ 30% (largely geometrical)

- Pure K_S sample selected exploiting entanglement
- L=1.6 fb^{-1}; ~ 4 × statistics w.r.t. previous measurement
- Pre-selection: 1 vtx close to IP with $M_{inv}(\pi,\pi)<M_K$ + K_L crash
- PID with time of flight technique

$$\delta_t(X) = (t_{cl} - T_0) - \frac{L}{c\beta(X)} \quad ; \quad X = e,\pi$$

$$\delta_t(X,Y) = \delta_t(X)_1 - \delta_t(Y)_2$$

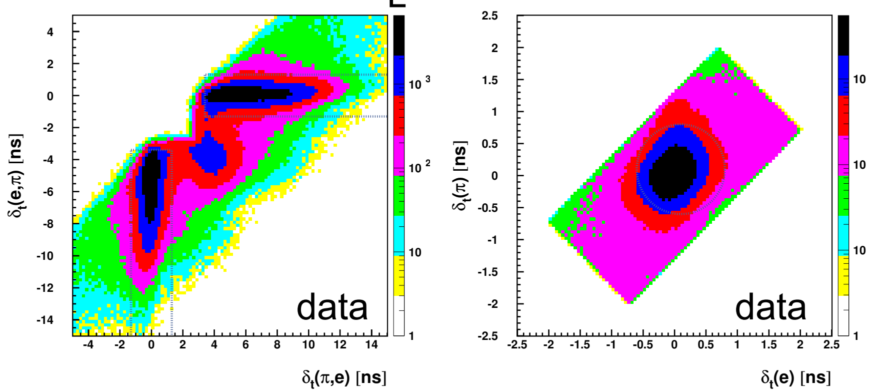


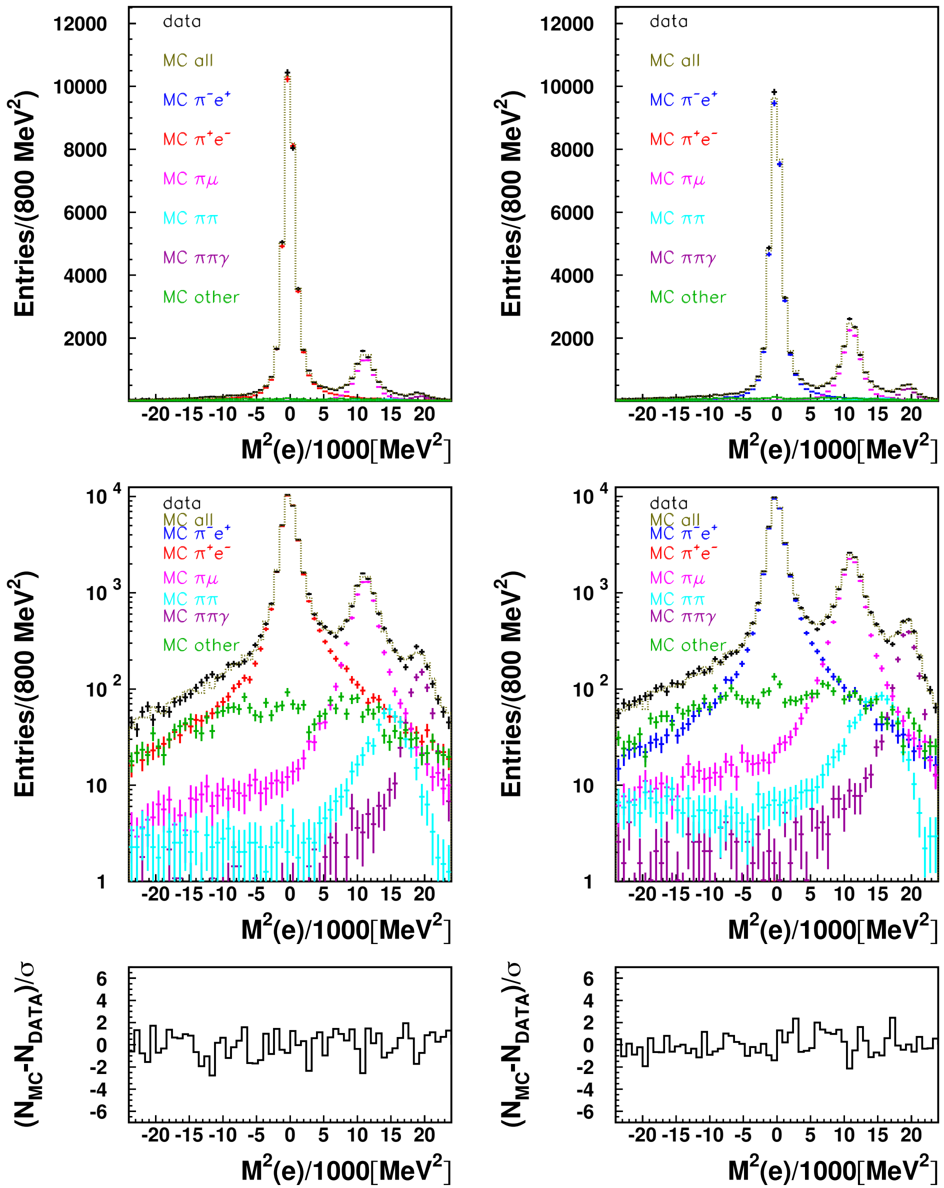
K_S semileptonic charge asymmetry

- Fit of $M^2(e)$ distribution varying MC normalizations of signal and bkg contributions.
- Total $\chi^2/ndf = 118/109$
- Total efficiencies: $\varepsilon^+=(7.39\pm0.03)\%$ and $\varepsilon^-=(7.81\pm0.03)\%$

- Control sample: $K_L \to \pi e \nu$ close to IP tagged by $K_S \to \pi^0\pi^0$
- track to EMC cluster and TOF efficiency correction from control sample

$K_L \to \pi e \nu$





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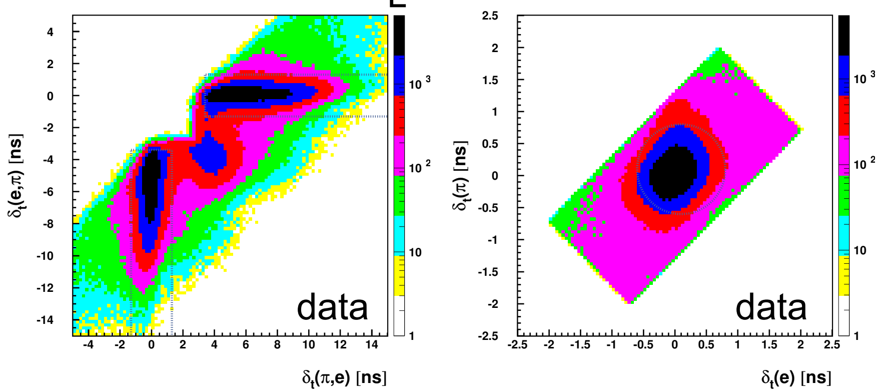
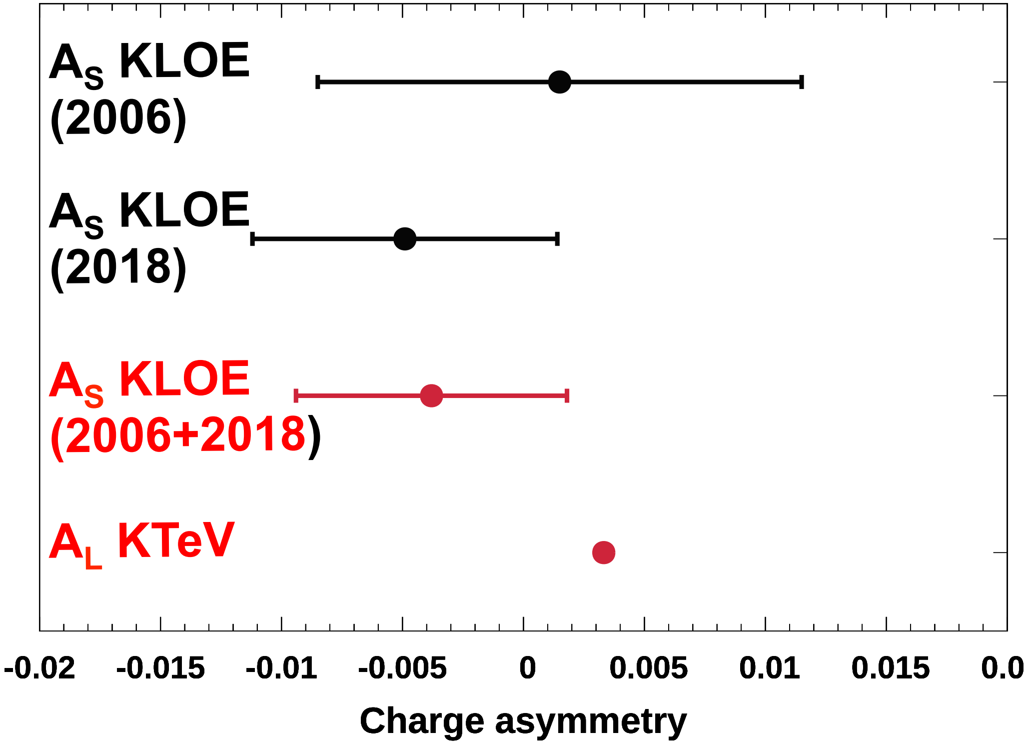


$$A_S = \frac{N(\pi^- e^+)/\varepsilon^+ - N(\pi^+ e^-)/\varepsilon^-}{N(\pi^- e^+)/\varepsilon^+ + N(\pi^+ e^-)/\varepsilon^-}$$

Systematic uncertainties on A_S

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

K_S semileptonic charge asymmetry



Data sample: L=1.7 fb^{-1}

KLOE (2018)

$$A_S = (-4.8 \pm 5.6 \pm 2.6) \times 10^{-3}$$

Combination KLOE(2006)+KLOE (2018)

$$A_S = (-3.8 \pm 5.0 \pm 2.6) \times 10^{-3}$$

arXiv:1806.08654 [hep-ex]

Submitted to JHEP

It will improve the CPT test (Imδ) using Bell-Steinberger relationship

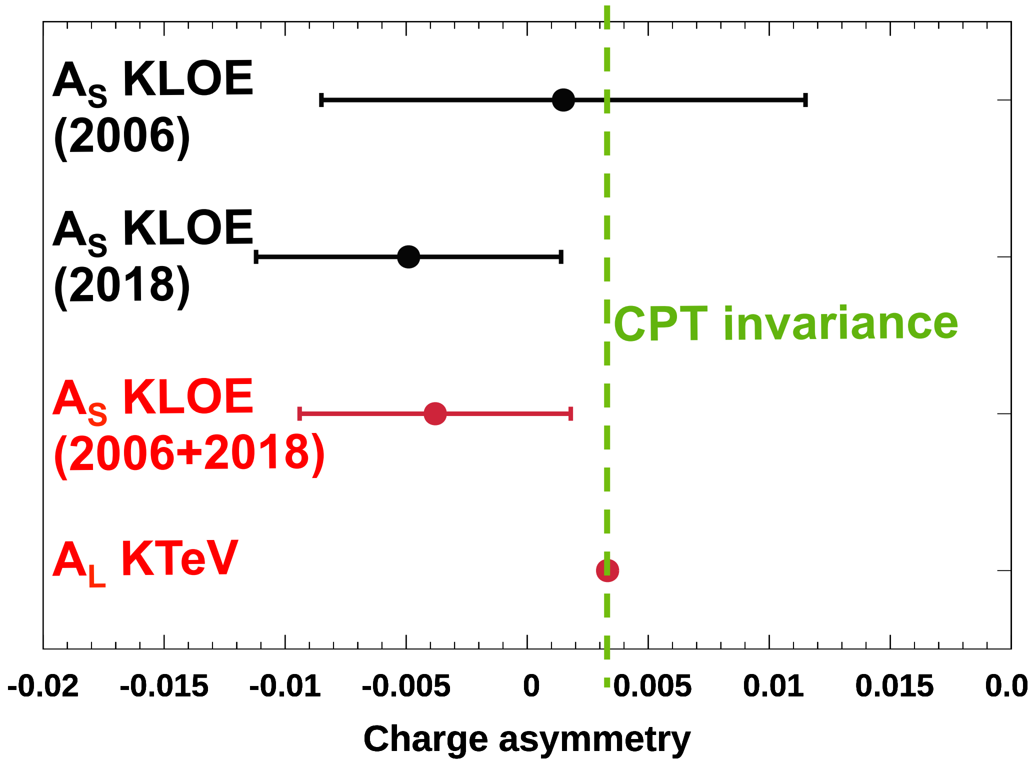
with KLOE-2 data: δA_S(stat) → ~ 3×10^{-3}

$$A_S - A_L = 4(\Re\delta + \Re x_-) \rightarrow \Re x_- = (-2.0 \pm 1.4) \times 10^{-3}$$ CPT & $\Delta S = \Delta Q$ viol.

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \rightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$ CPT viol.

input from other experiments

K_S semileptonic charge asymmetry



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CPT & $\Delta S = \Delta Q$ viol.

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$

CPT viol.

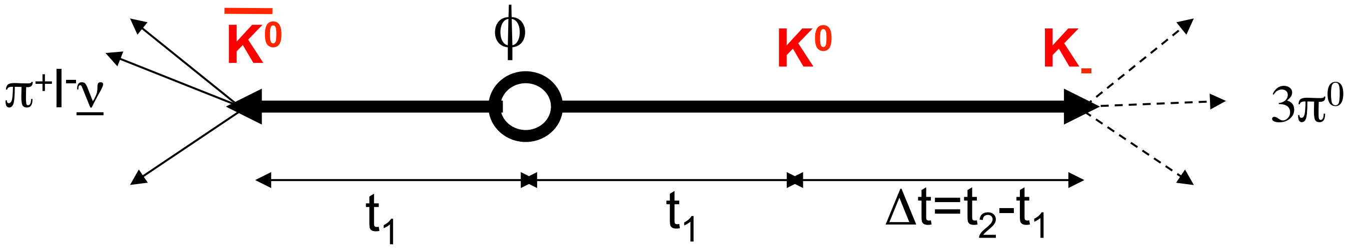
input from other experiments

Direct test of T and CPT in neutral kaon transitions

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

•decay as filtering measurement
•entanglement → preparation of state



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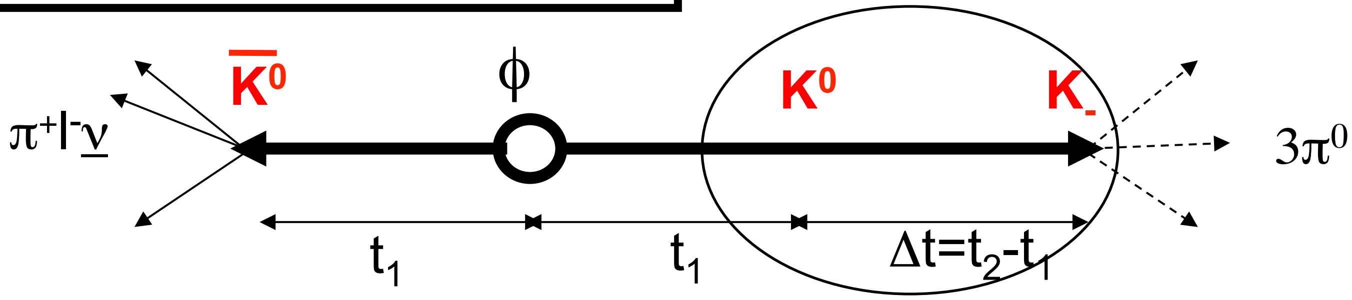

$K^0 \rightarrow K_-$ reference process

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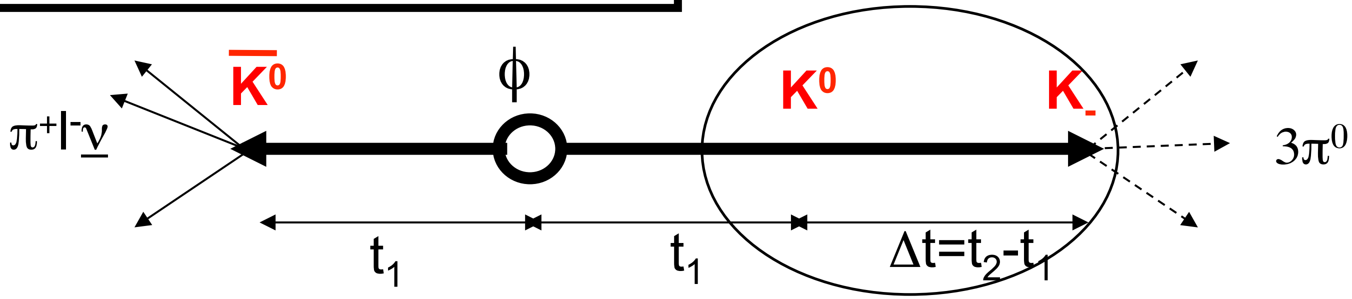
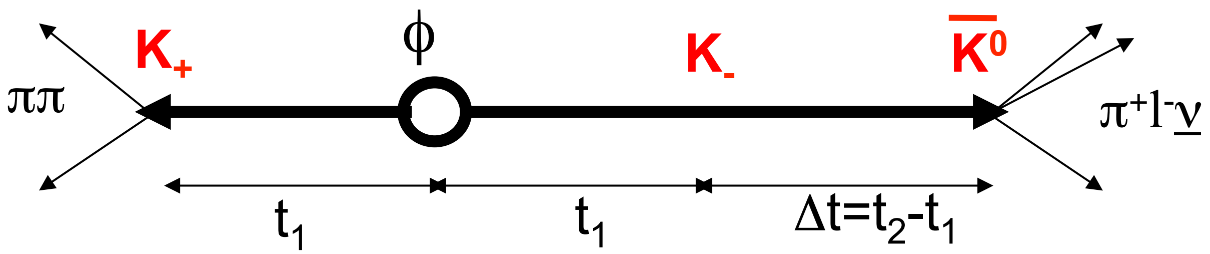
- decay as filtering measurement
- entanglement → preparation of state



$K^0 \to K_-$ reference process



Direct test of T and CPT in neutral kaon transitions

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$$
\begin{aligned}
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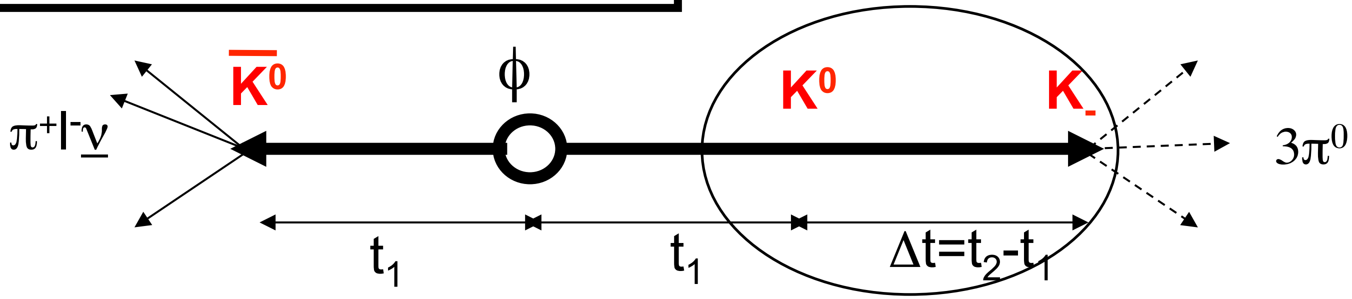
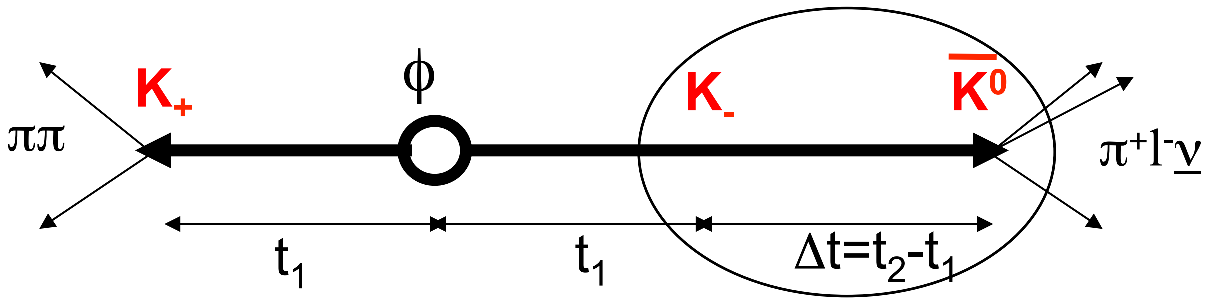
&= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]
\end{aligned}
$$

•decay as filtering measurement
•entanglement → preparation of state



$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \bar{K}^0$ CPT-conjugated process



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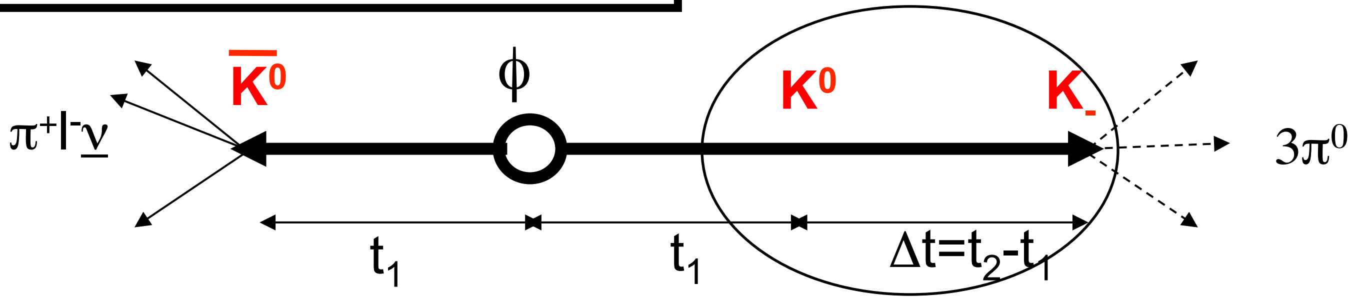
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

- decay as filtering measurement
- entanglement → preparation of state



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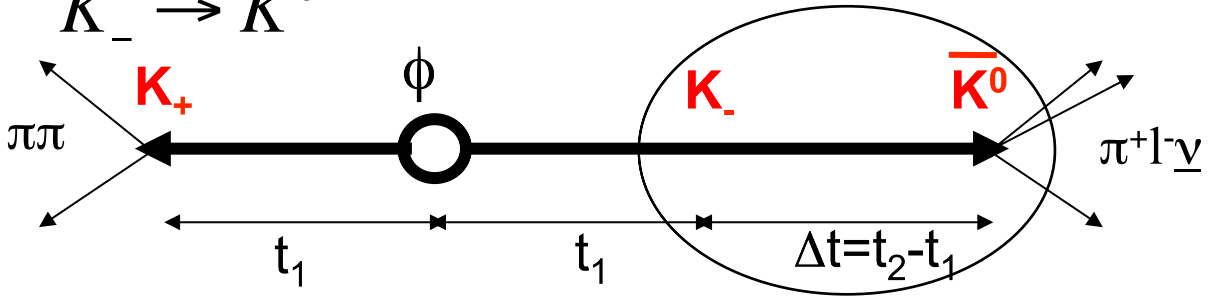
$K_- \rightarrow \bar{K}^0$ CPT-conjugated process

Note: CP and T conjugated process

$\bar{K}^0 \rightarrow K_-$ $\quad K_- \rightarrow K^0$



Direct test of T and CPT in neutral kaon transitions

Reference	T-conjug.	CP-conjug.	CPT-conjug.
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$

Unique direct CPT and T test in kaon transitions, theoretically very clean and model independent. Negligible spurious effects from $\Delta S \neq \Delta Q$ or direct CP violation.

One can define the following ratios of probabilities:

$$
\begin{aligned}
R_{1,\mathrm{T}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] \\
R_{2,\mathrm{T}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_{3,\mathrm{T}}(\Delta t) &= P\left[K_+(0) \to K^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right] \\
R_{4,\mathrm{T}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]
\end{aligned}
$$

T

$$
\begin{aligned}
R_{1,\mathrm{CPT}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right] \\
R_{2,\mathrm{CPT}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \\
R_{3,\mathrm{CPT}}(\Delta t) &= P\left[K_+(0) \to K^0(\Delta t)\right] / P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] \\
R_{4,\mathrm{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]
\end{aligned}
$$

CPT

Any deviation from $R_{i,/T/CPT}$=1 constitutes a violation of T/CPT symmetry

J. Bernabeu, A.D.D., P. Villanueva JHEP 10 (2015) 139, NPB 868 (2013) 102, A.D.D., APPB 48 (2017) 1919

Direct test of T and CPT in neutral kaon transitions

- First test of T and CPT in transitions with neutral kaons (L=1.7 fb^{-1})
- $\phi \to K_S K_L \to \pi e^{\pm} \nu \; 3\pi^0$ and $\pi^+\pi^- \; \pi e^{\pm}\nu$
- Selection efficiencies estimated from data with 4 independent control samples

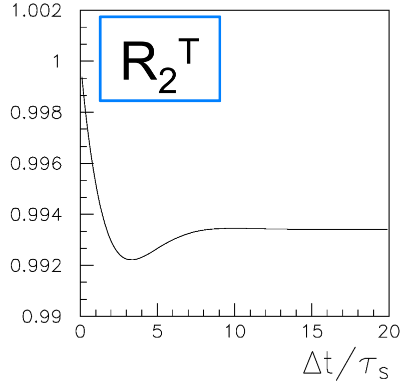
$K_S K_L \to \pi e^{\pm} \nu \; 3\pi^0$ → $K_S \to \pi e \nu$ Klcrash ; $K_S K_L \to \pi^+\pi^- \; 3\pi^0$

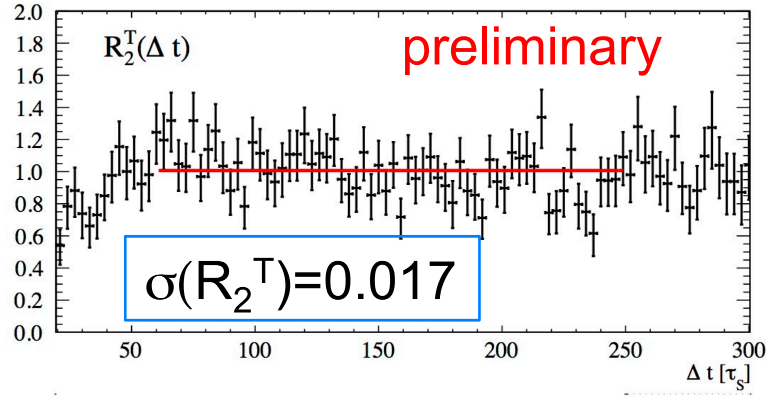
$K_S K_L \to \pi^+\pi^- \; \pi e^{\pm} \nu$ → $K_S \to \pi^+\pi^-$-Klcrash ; $K_S K_L \to \pi^0\pi^0 \; \pi e \nu$

T test

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

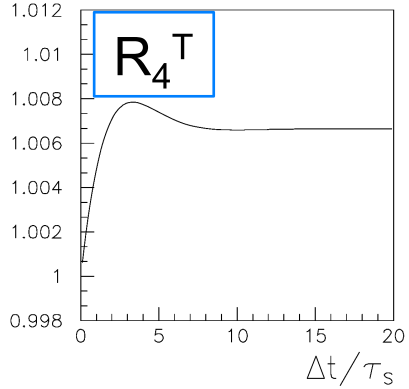
$$R_{2,T}(\Delta t >> \tau_S) = 1 - 4\Re\varepsilon$$

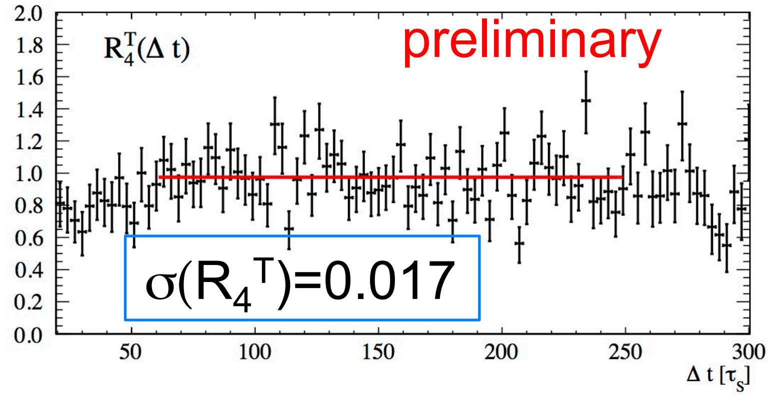




$$R_{4,T}(\Delta t) = \frac{P\left[\overline{K}^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to \overline{K}^0(\Delta t)\right]}$$

$$R_{4,T}(\Delta t >> \tau_S) = 1 + 4\Re\varepsilon$$





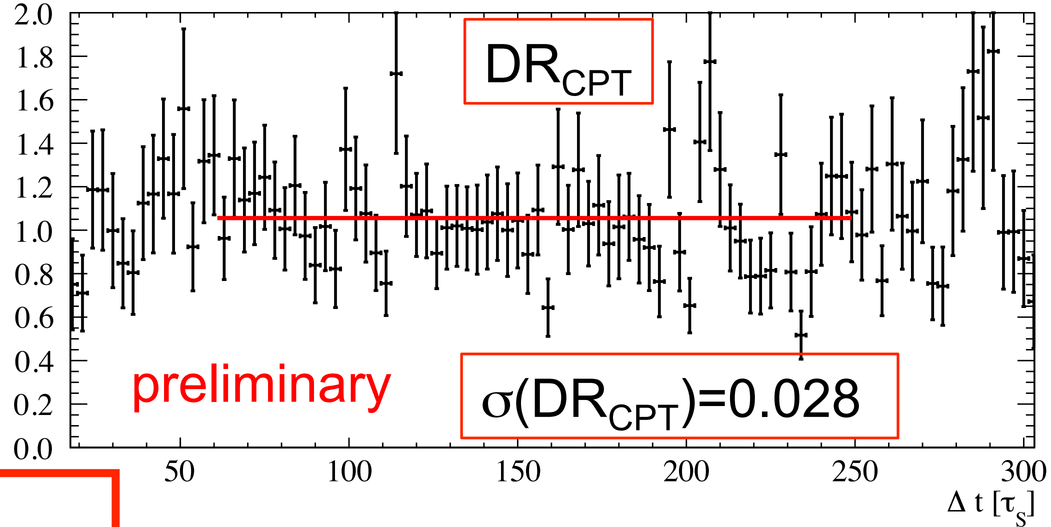
Direct test of T and CPT in neutral kaon transitions

CPT test

(L=1.7 fb^{-1})

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

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



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

DR$_{CPT}$ is the cleanest CPT observable; DR$_{CPT}$≠1 implies CPT violation.
KLOE-2 can reach a precision <1%.

There exists a connection between DR$_{CPT}$ and the A$_{S,L}$ charge asymmetries :

$$DR_{CPT} = 1 + 2(A_L - A_S)$$

Using KTeV result on A$_L$ and KLOE on A$_S$: **DR$_{CPT}$= 1.016 ± 0.011** (preliminary)

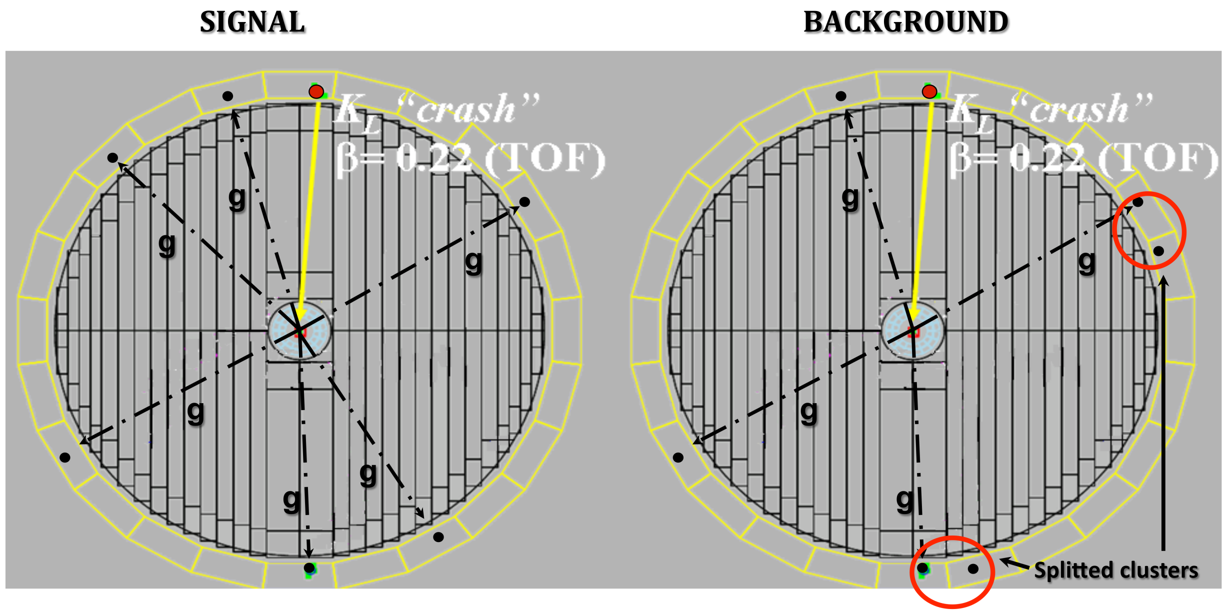
Search for the CP violating $K_S \to \pi^0\pi^0\pi^0$ decay

$3\pi^0$ 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: $BR(K_S \to 3\pi^0) = 1.9 \cdot 10^{-9}$ PLB 723 (2013) 54

Best upper limit by KLOE with 1.7 fb^{-1} **$BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% CL**

- "K_L crash" (K_L in the EMC) + 6 prompt photons
- Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
- Main bckg: $K_S \to 2\pi^0$ (4 prompt photons), also used for normalization
- KLOE-2: selection criteria hardened to face the larger machine bkg: ~ 10x better bkg rejection



$K_S \to 3\pi^0 \to 6\gamma$ $K_S \to 2\pi^0$ + accidental/splitted clusters
$K_L \to 3\pi^0$, $K_S \to \pi^+\pi^-$ („fake K_L crash")

KLOE-2 data analysis ($L \approx 300$ pb^{-1}): with old analysis scheme 1 event selected as a signal ($\varepsilon_{3\pi}$ ~ 19 %) $\Rightarrow Br(K_S \to 3\pi^0) \lesssim 2.5\times10^{-7}$ @90% CL (preliminary)
Full KLOE-2 statistics + optimized analysis can reach $\lesssim 10^{-8}$

Conclusions

- The KLOE-2 experiment at the upgraded DAΦNE successfully completed its data taking campaign collecting $L=5.5\ fb^{-1}$ by the end of March 2018.
- The KLOE+KLOE-2 data sample (~ 8 fb^{-1}) is worldwide unique for typology and statistical relevance.

- The entangled neutral kaon system at a ϕ-factory is an excellent laboratory for the study of discrete symmetries.
- The analysis of the full KLOE data set is being completed:
  - new measurement of the K_S semileptonic charge asymmetry (paper submitted)
  - first test of T and CPT in neutral kaon transitions: analysis in advanced phase; the connection of the CPT test with $A_{S,L}$ opens new interesting possibilities.

- The study of discrete symmetries with neutral kaons is one of the key issues at KLOE-2. Several KLOE results will be significantly improved.
- The analysis of KLOE-2 data already started on several benchmark processes ($K_S \to \pi l \nu$, $K_S \to \pi^+\pi^-$, $K_S \to \pi^0\pi^0$, $K_L \to \pi^+\pi^-$, $K_L \to 3\pi^0$, etc.)
- Among them a preliminary study searching for the CP violating $K_S \to 3\pi^0$ decay shows the possibility to further improve the limit on this BR.