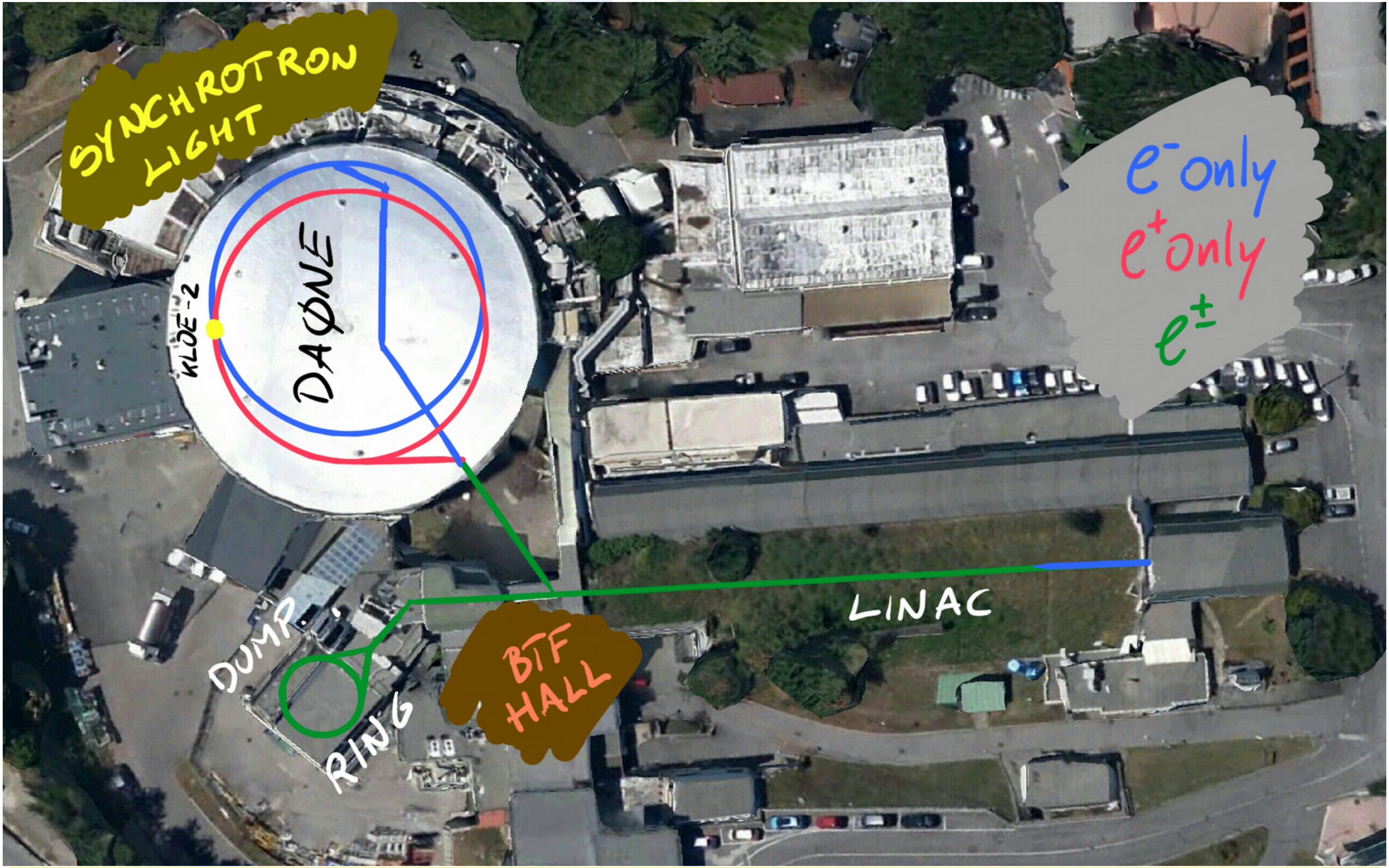
Test of discrete symmetries in transitions with entangled neutral kaons at KLOE-2

A. De Santis*
Laboratori Nazionali di Frascati - INFN
on behalf of
KLOE-2 Collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

DAΦNE: The Frascati φ-factory



KLOE-2: main detectors

Drift Chamber

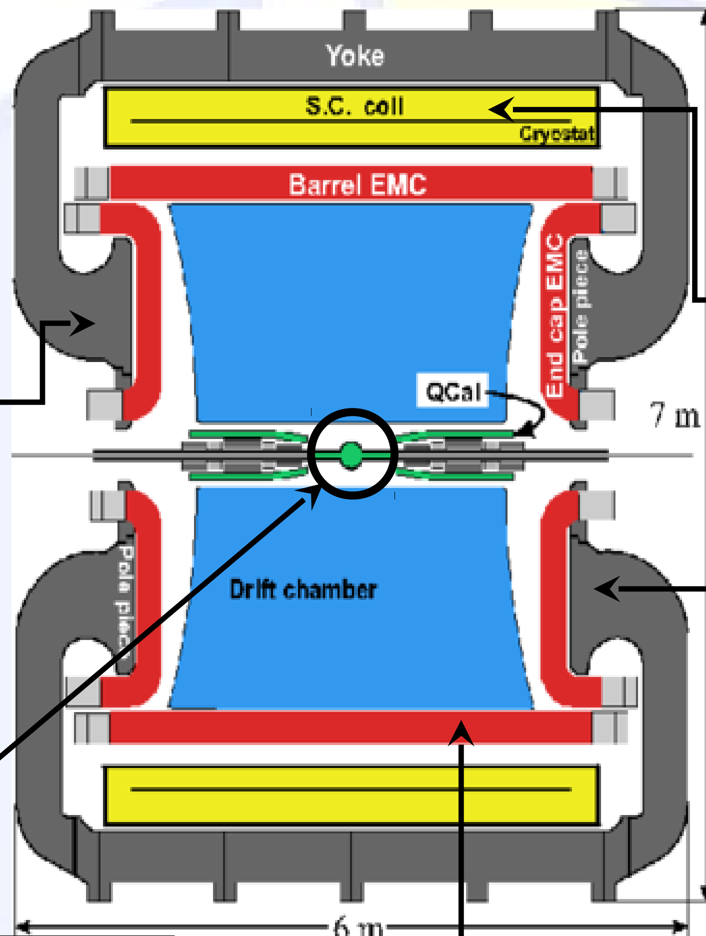
$\sigma_p/p \cong 0.4\ \%$

(tracks with $\theta > 45°$)

$\sigma^{hit} \cong 150\ \mu m$ (xy), 2 mm (z)

$\sigma^{vertex} \sim 1$ mm

General purpose detector



SC Magnet

B = 0.52 T

End Cap

Interaction point (IP)

Sphere Al-Be (Ø 20 cm)

Barrel

Calorimeter e.m.

Both side read-out (PM)

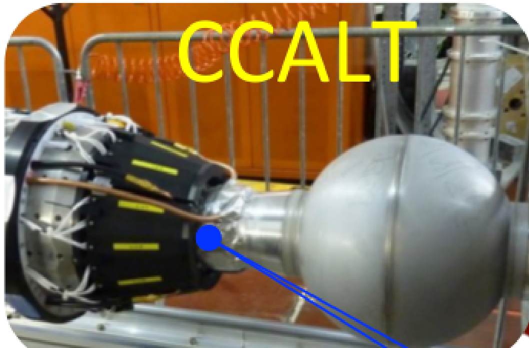
$\sim 4\pi$ solid angle coverage

$\sigma_E/E \cong 5.7\% / \sqrt{E(\mathrm{GeV})}$

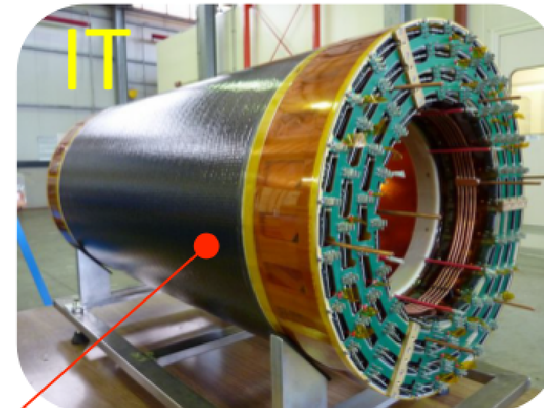
$\sigma_t \cong 54\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$

KLOE-2: interaction region detectors

KLOE-2



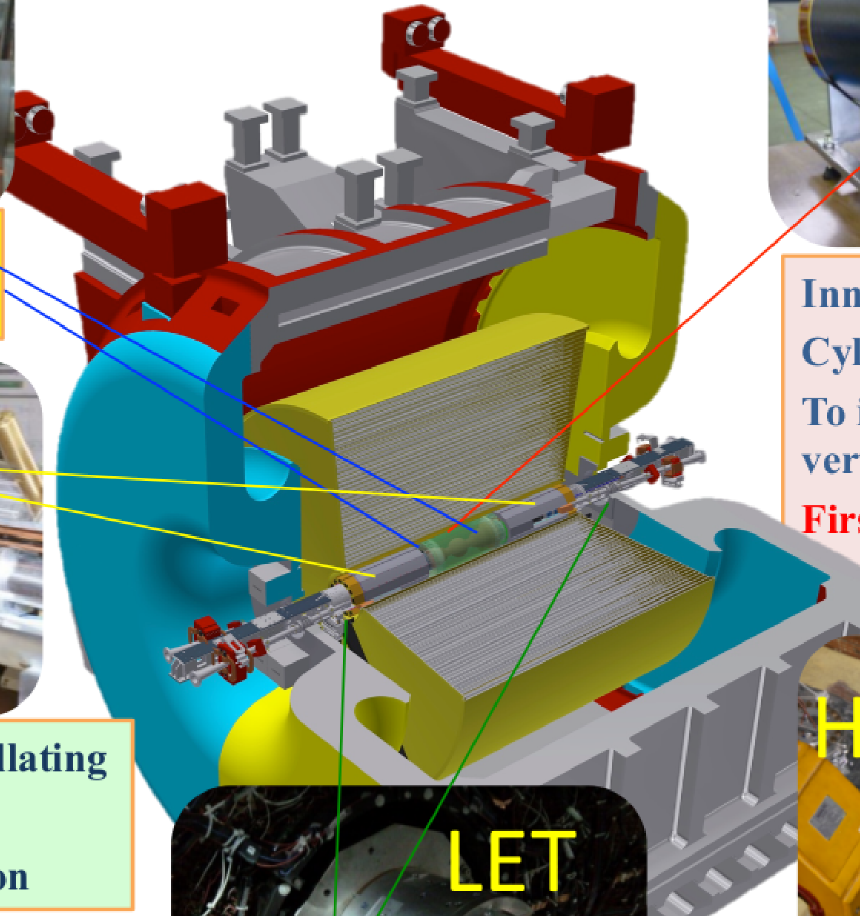
CCALT – LYSO Crystal w SiPM - Low polar angle

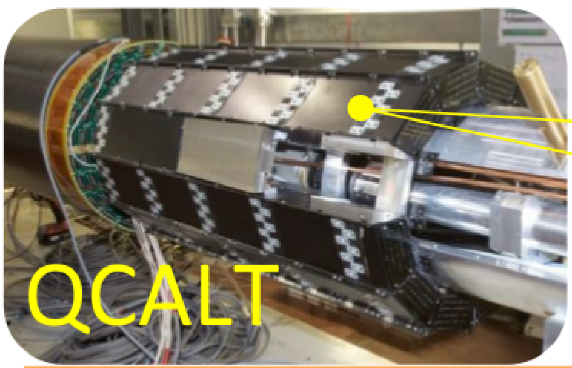


Inner Tracker – 4 layers of Cylindrical GEM detectors

To improve the track and vertex reconstruction

First time CGEM in high energy experiment





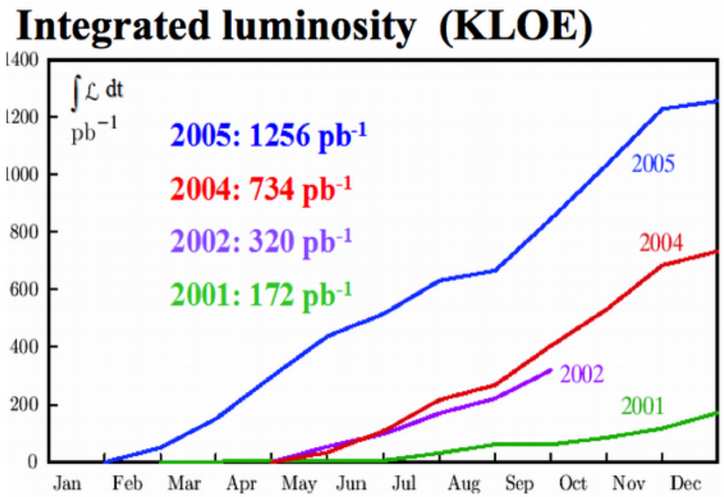
QCALT – Tungsten / Scintillating Tiles w SiPM - K_L decays Quadrupole Instrumentation

LET: 2 calorimeters LYSO + SiPMs @ ~ 1 m from IP

e^+e^- taggers for gg physics (HET)

HET: Scintillator hodoscope +PMTs pitch:5 mm; placed at 11 m from IP

KLOE-2 dataset

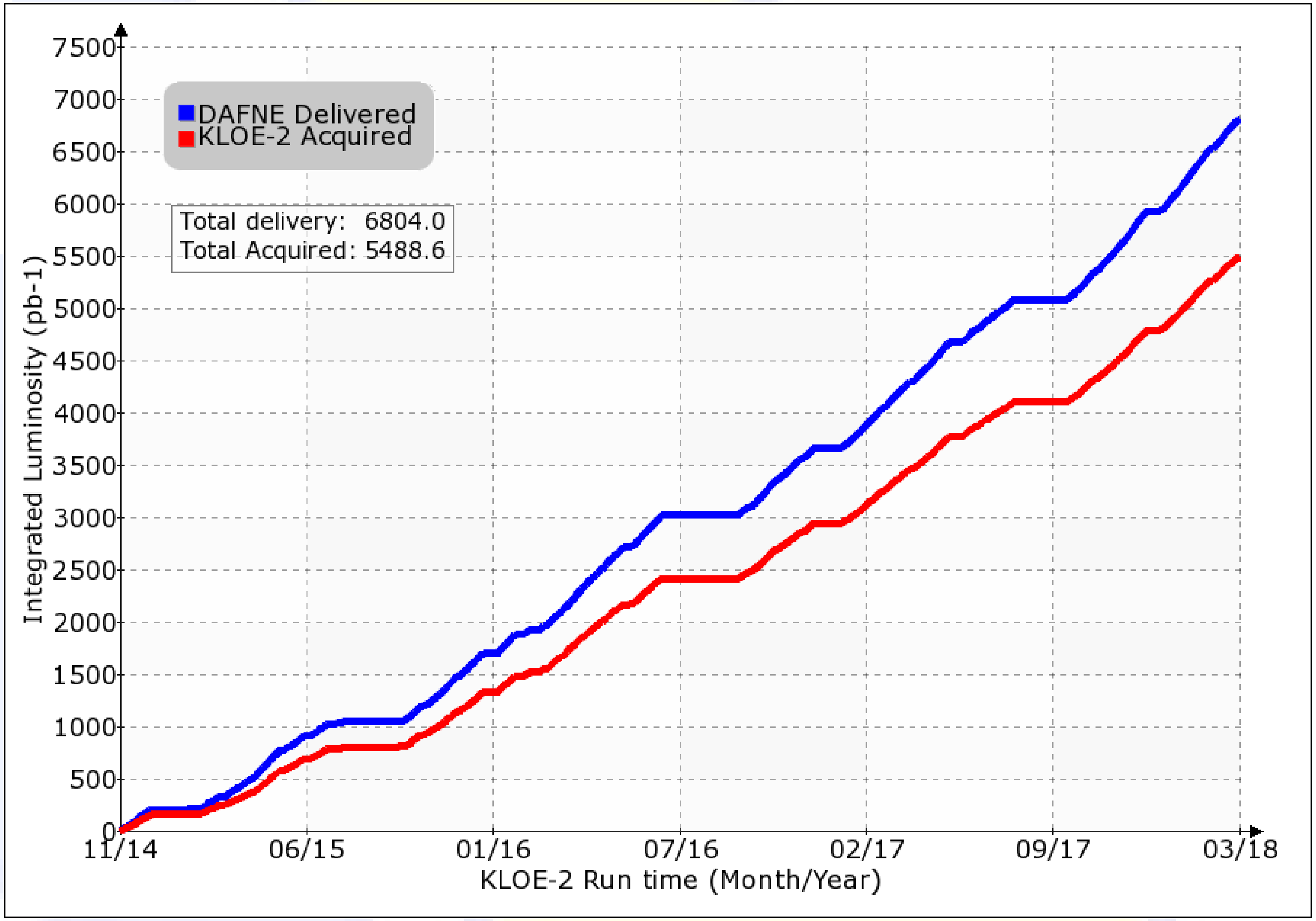


KLOE dataset:
2.5 fb^{-1}
L_{peak} = 1.52x10^{32} cm^{-2}s^{-1}

KLOE-2 dataset:

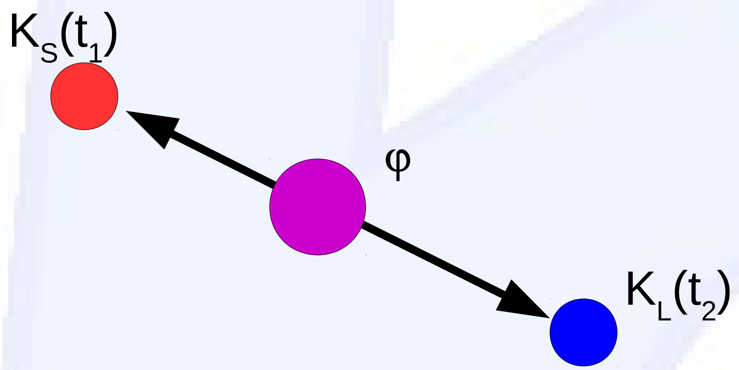
5.5 fb^{-1}(2014/18)

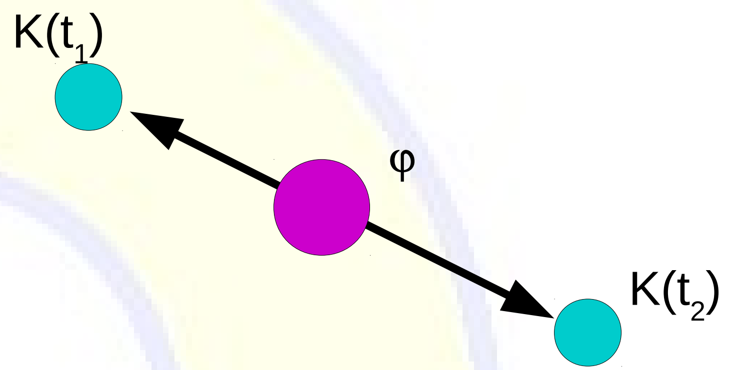
L_{peak} = 2.38x10^{32} cm^{-2} s^{-1}
(Crab-Waist)



KLOE+KLOE-2 data sample:
8 fb^{-1} → 2.4 x 10^{10} φ(1020) mesons decay recorded

Neutral kaons at KLOE-2





KAON MASS EIGENSTATES TAGGING ($t_1 \ll t_2$)

SINGLE KAON PROPERTY:

- Branching fractions
- Form factors
- Lifetimes

INTERFERENCE ($t_1 \sim t_2$)

KAON SYSTEM TIME EVOLUTION:
Tests of:

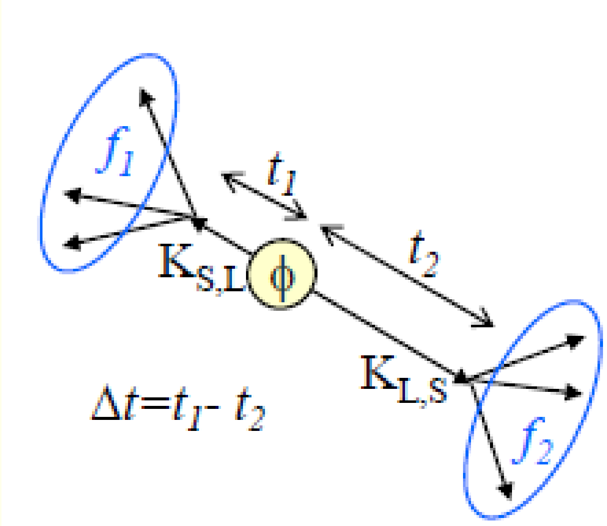
- T/CPT in transitions
- CPT & Lorentz Invariance
- QM coherence

Correlation in two kaon state

The ϕ meson decay in entangled pair of neutral kaons with $J^{PC} = 1^{--}$ quantum numbers:

$$|i\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle|\overline{K}_0\rangle - |\overline{K}_0\rangle|K_0\rangle) = \mathcal{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle),$$

The antisymmetry of the state is preserved in its time evolution; the decay amplitude for the state into final states f_1, f_2 at time t_1, t_2 is:

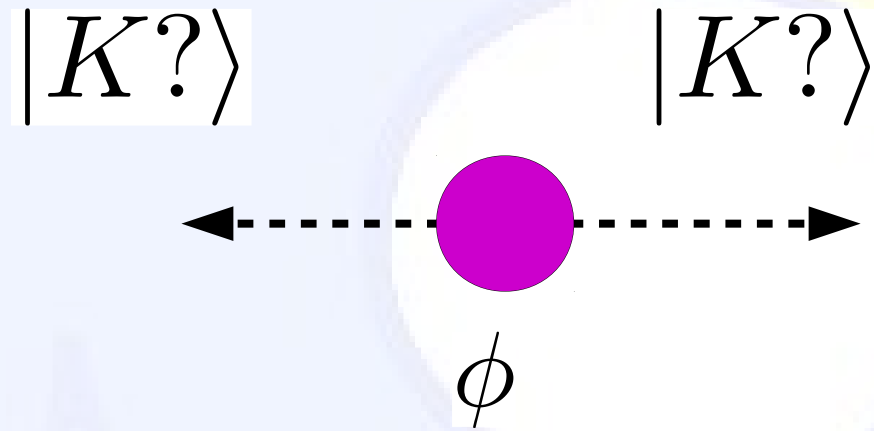


$$|\langle f_1(t_1), f_2(t_2)|i\rangle|^2 = \frac{N}{\sqrt{2}}\Big\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}$$
$$-2|\eta_1||\eta_2|e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos\Big[\Delta m(t_2 - t_1) + \phi_1 - \phi_2\Big]\Big\}$$

Interference term

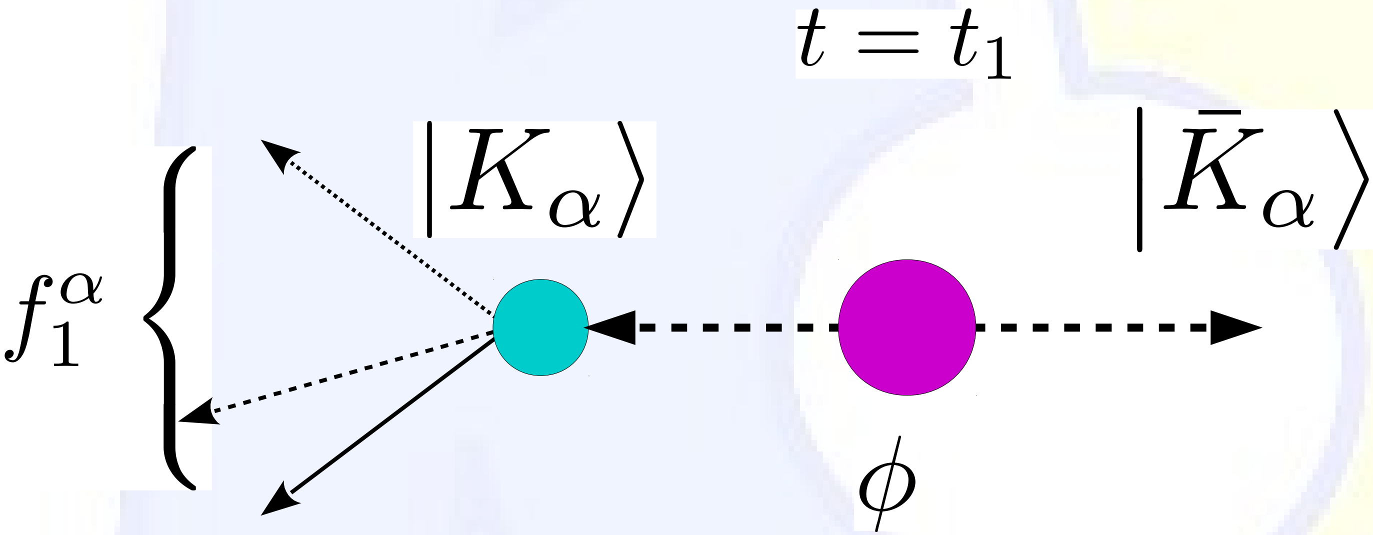
Time dependent Kaon tagging

Entanglement allows to “prepare” the initial state desired by “tagging” the other kaon decay.



Time dependent Kaon tagging

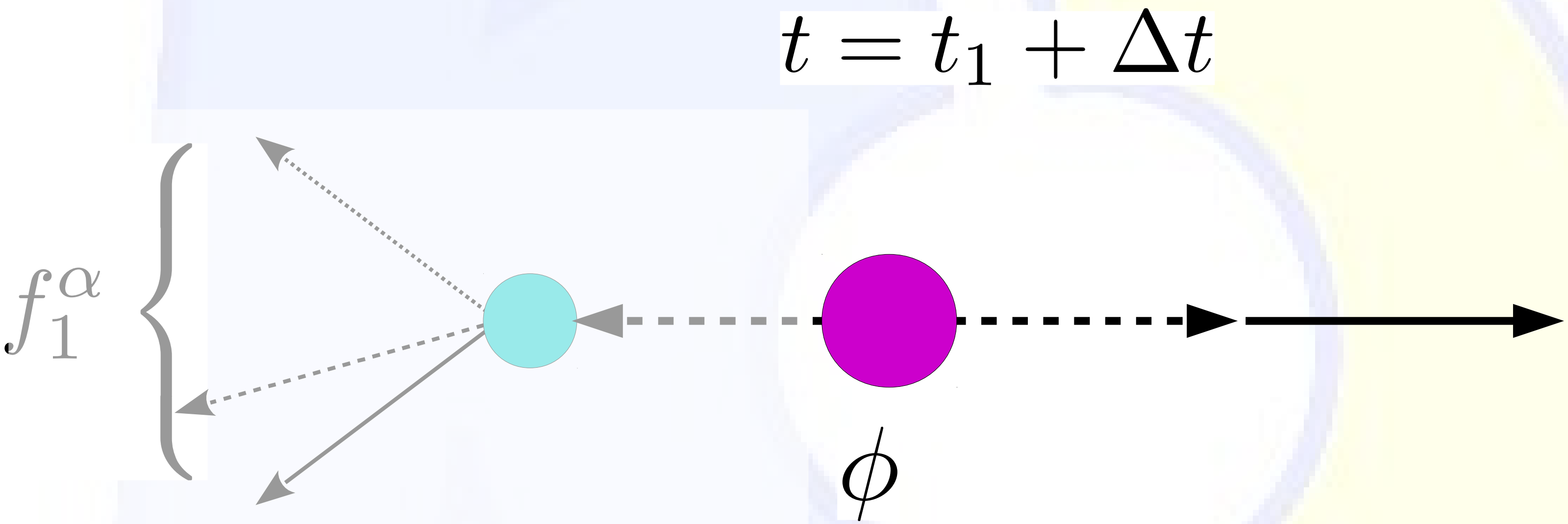
Entanglement allows to "prepare" the initial state desired by "tagging" the other kaon decay.



The "first kaon" (K_α) decays (f_1^α) is observed at t_1. This decay reveal the state of the kaon system at the time t_1.

Time dependent Kaon tagging

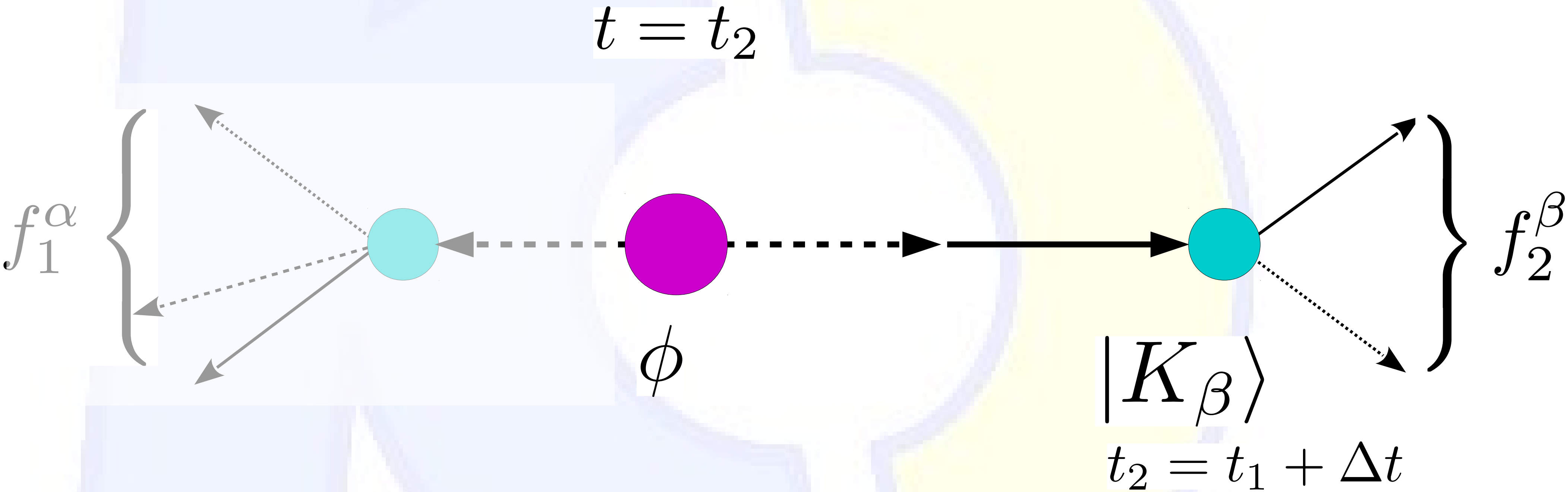
Entanglement allows to "prepare" the initial state desired by "tagging" the other kaon decay.



The "second kaon" evolve from the tagged initial state

Time dependent Kaon tagging

Entanglement allows to "prepare" the initial state desired by "tagging" the other kaon decay.



The f_2^{β} decay is observed at t_2. In this way we have to possibility to observe the $|\bar{K}_\alpha\rangle \rightarrow |K_\beta\rangle$ transition probability as a function of the time difference Δt.

Transition amplitudes transformations

Transformations under discrete symmetry connect different transitions between CP and Flavor eigenstates.

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

$K^0/\bar{K}^0$ Flavor eigenstate

K_+/K_- CP eigenstate

<u>Direct and model independent tests</u> of time-reversal (T) and CPT symmetry → comparison of **transition rates between flavor and CP eigenstates**

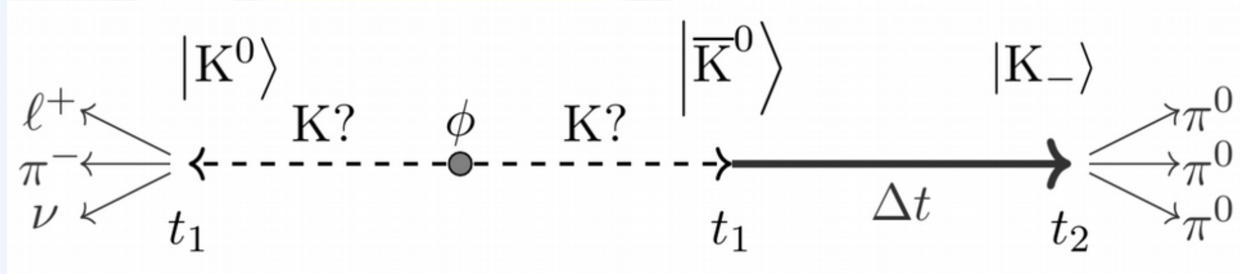
Bernabeu et al Nucl.Phys. B 868 (2013) 102
Bernabeu et al. JHEP 10 (2015) 139

Direct T and CPT tests in transitions of neutral kaons

Eigenstate

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

A decay in the semileptonic channel select the opposite flavor state.



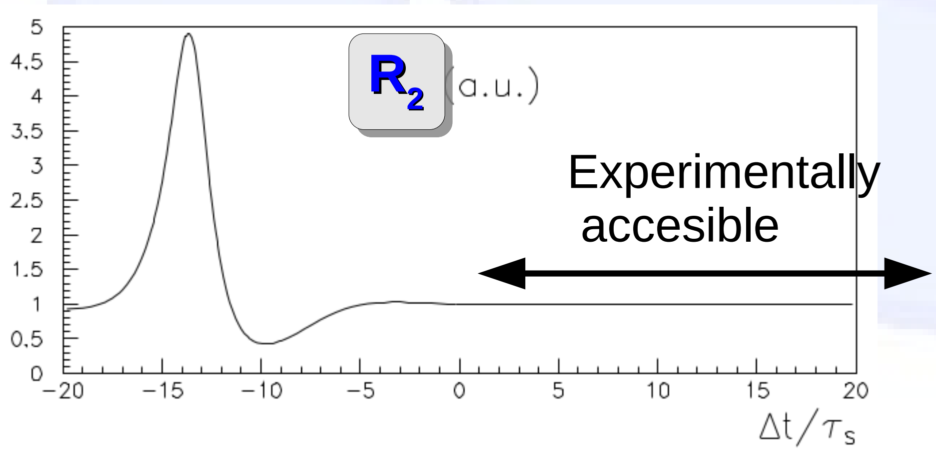
Amplitude ratio

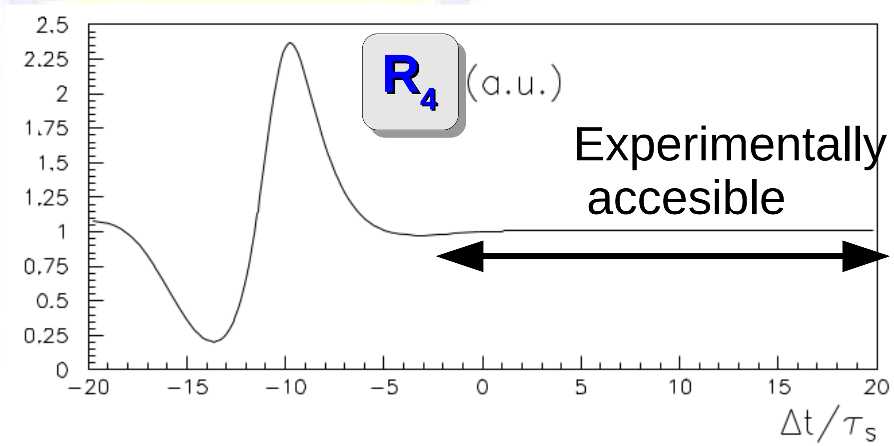
Observable

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

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

T symmetry



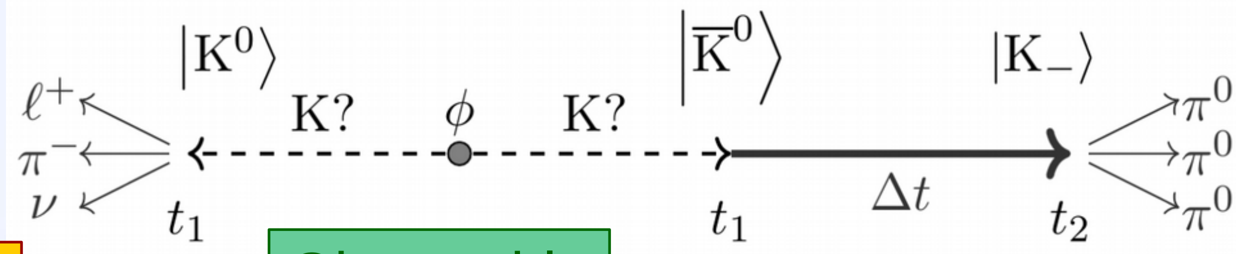


Direct T and CPT tests in transitions of neutral kaons

Eigenstate

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

Entanglement allows to "prepare" the initial state desired by "tagging" the other kaon decay.



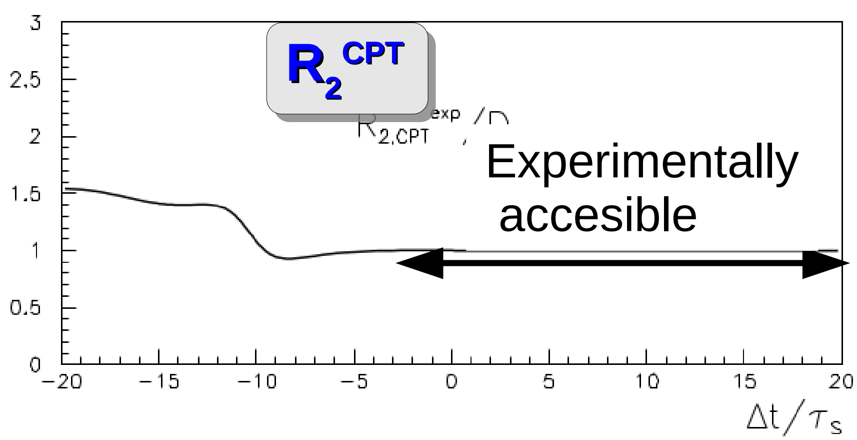
Amplitude ratio

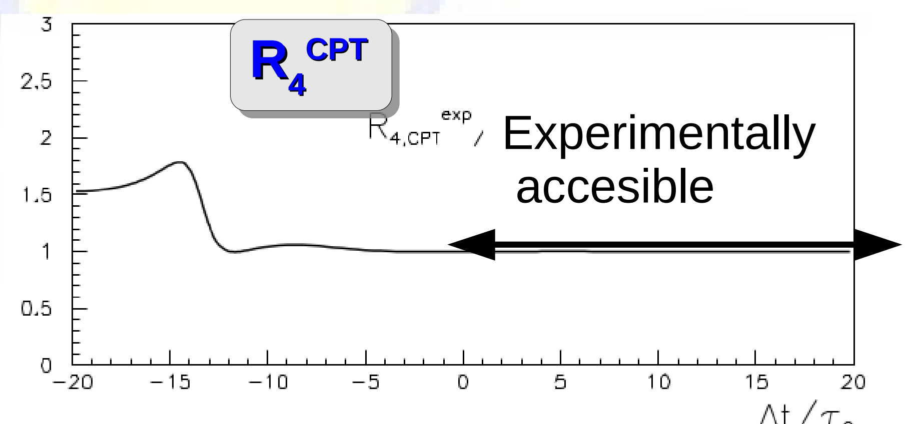
Observable

$$R_2^{CPT}(\Delta t) = \frac{P(K^0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow \bar{K}^0(\Delta t))} \sim \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^- \Delta t)}$$

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

CPT symmetry





Observables

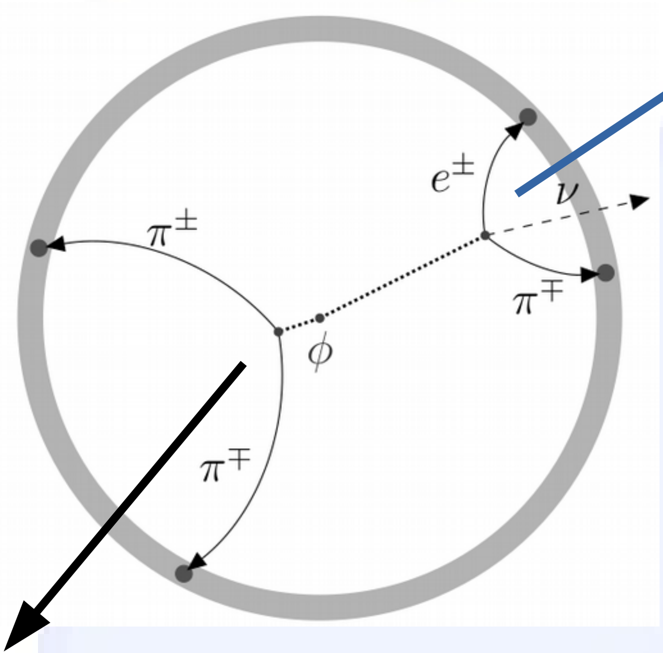
All ratios are build with the same pair of decays:

Denominator contains a charged vertex decay without kinematic closure (neutrino escapes) and a decay vertex without tracks. This particular pair of decays has never been used before in KLOE-2 analysis.

$$\frac{I(l^{\pm},3\pi^{0};\Delta t)}{I(\pi\pi,l^{\pm}\Delta t)}$$

The numerator is the simplest case because has larger statistics in the Δt region of interest and has a very well studied decay, $K \rightarrow \pi\pi$, tipically used for tagging.

$K_SK_L \rightarrow \pi^+\pi^-$; $\pi e\nu$ event selection

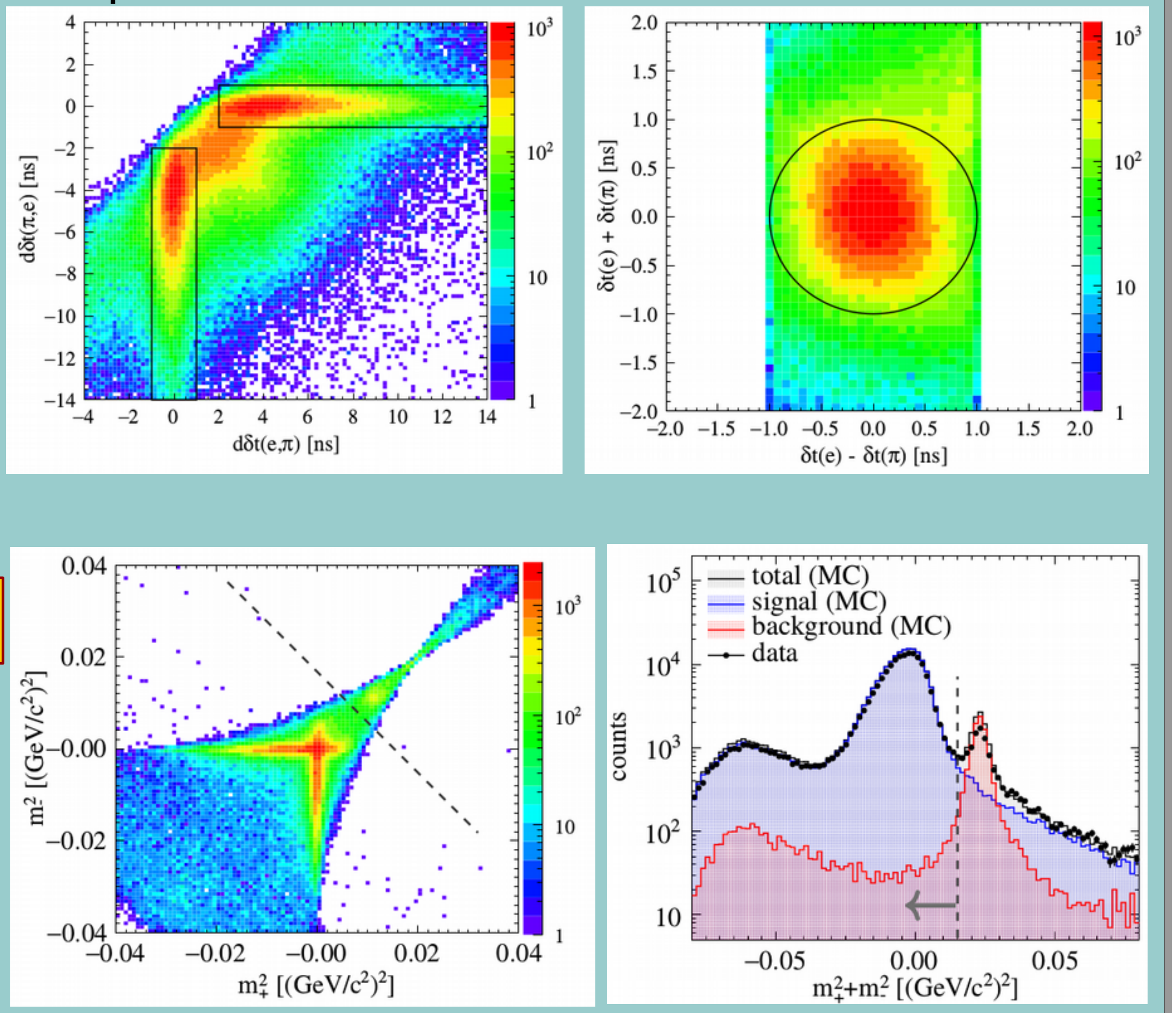


A second vertex is required with tracks associated to EMC clusters in order to perform PID using TOF

+ $\delta t(\pi e)$ hypothesis

+ lepton mass

Preliminary

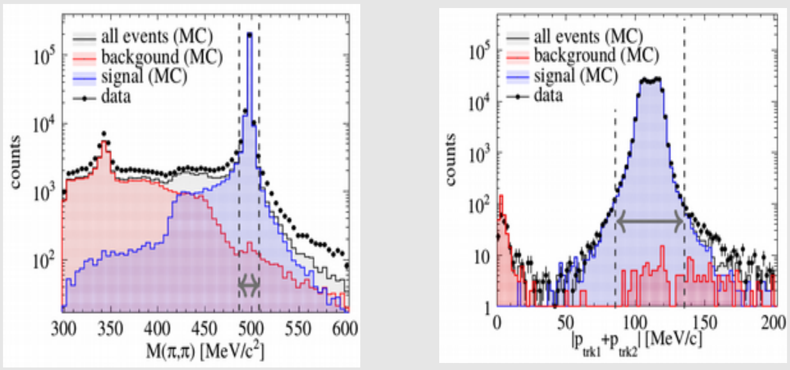


One vertex ($K \rightarrow \pi\pi$) kinematically closed:

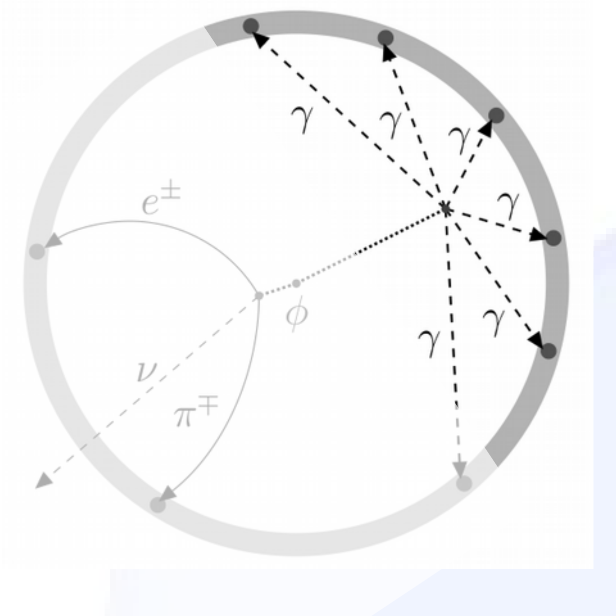
+ Invariant mass at the vertex

+ Total momentum

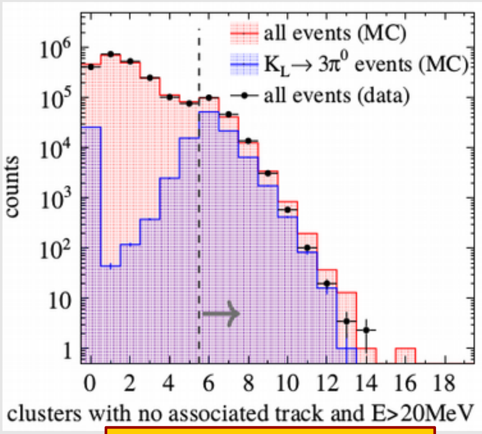
Preliminary



$K_S K_L \to 3\pi^0$; $\pi e \nu$ selection

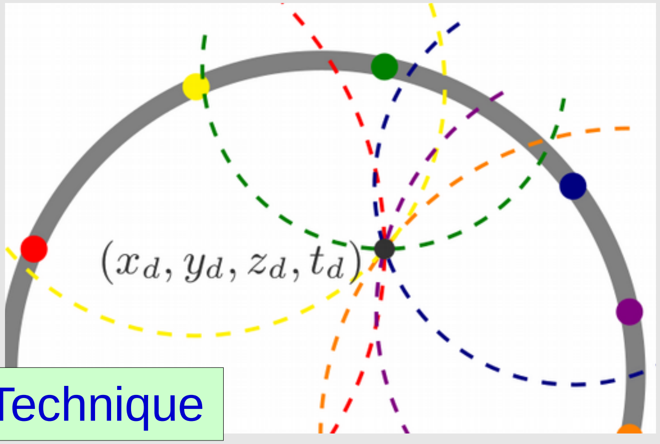


Events with 6 photon candidate are selected.



Preliminary

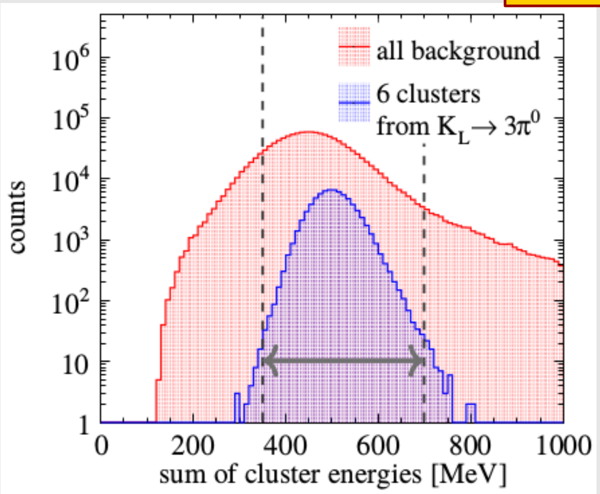
And a "neutral vertex" is constructed

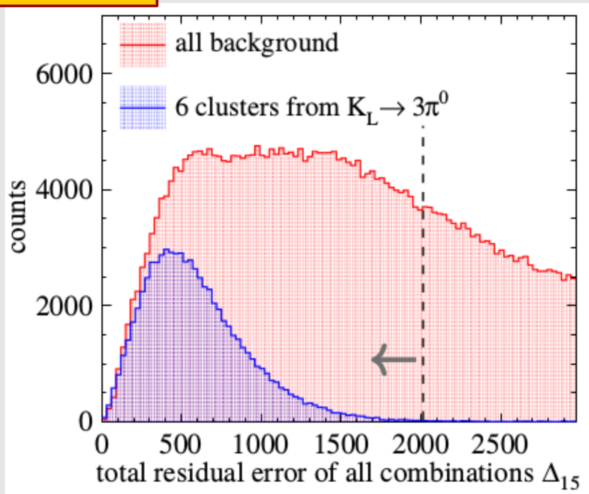


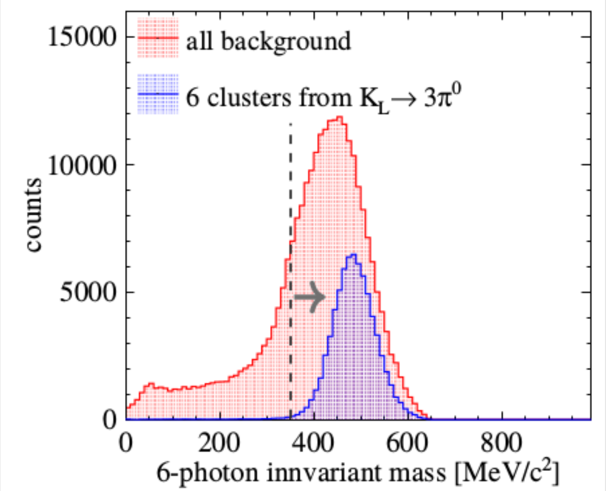
GPS Technique

Many selections are required to clean the sample and identify signal. All cuts are based on the neutral vertex reconstructed and imply the kinematic closure of the decay.

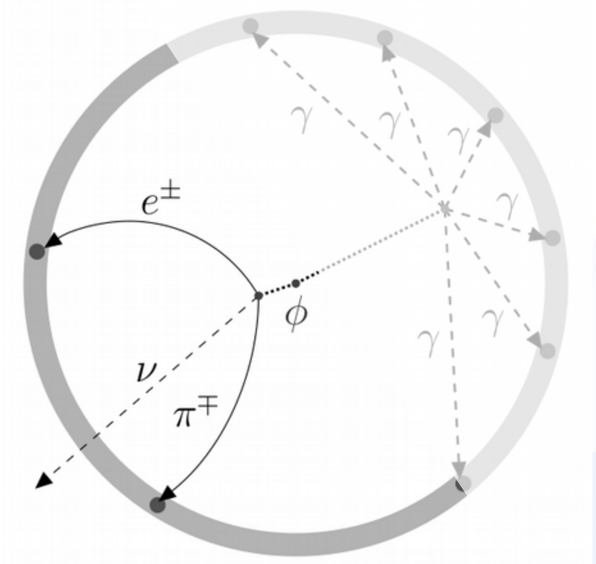
Preliminary







$K_SK_L \rightarrow 3\pi^0$; $\pi e\nu$ selection

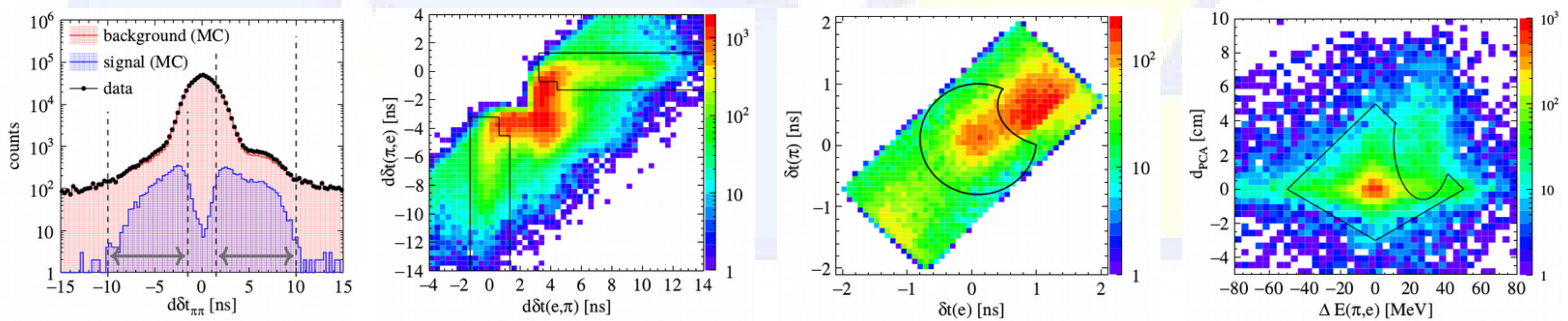


The semileptonic decay can't be selected as for the normalization sample, because the kaon momentum is reconstructed from the 6 photons with larger resolution.

Time information from EMC and tracking from DCH have to be exploited deeply to properly select the semileptonic decay.

Using different mass hypothesis for the two tracks and combining them the selection is performed.

Preliminary



From observed to observables

$$\frac{I(l^{\pm}, 3\pi^0; \Delta t)}{I(\pi\pi, l^{\pm}\Delta t)}$$

$$\downarrow$$

$$I(l^{\pm}, 3\pi^0; \Delta t) = N(l^{\pm}, 3\pi^0; \Delta t)/\epsilon(\Delta t)$$

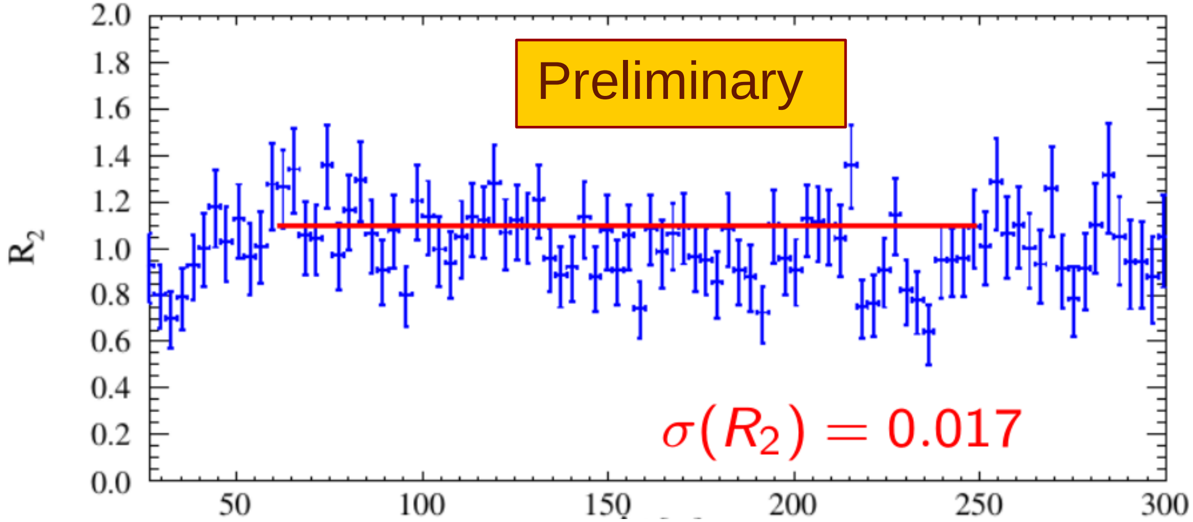
To construct observables we have to correct the number of observed event in each category by the efficiency.

Many different control samples have to be considered in order to properly cross check the Monte-Carlo simulation avoiding systematical correlation and statistical independence between efficiency correction.

Direct T symmetry test in transitions of neutral kaons

$$\sim \frac{I(l^-,3\pi^0;\Delta t)}{I(\pi\pi,l^+;\Delta t)}$$

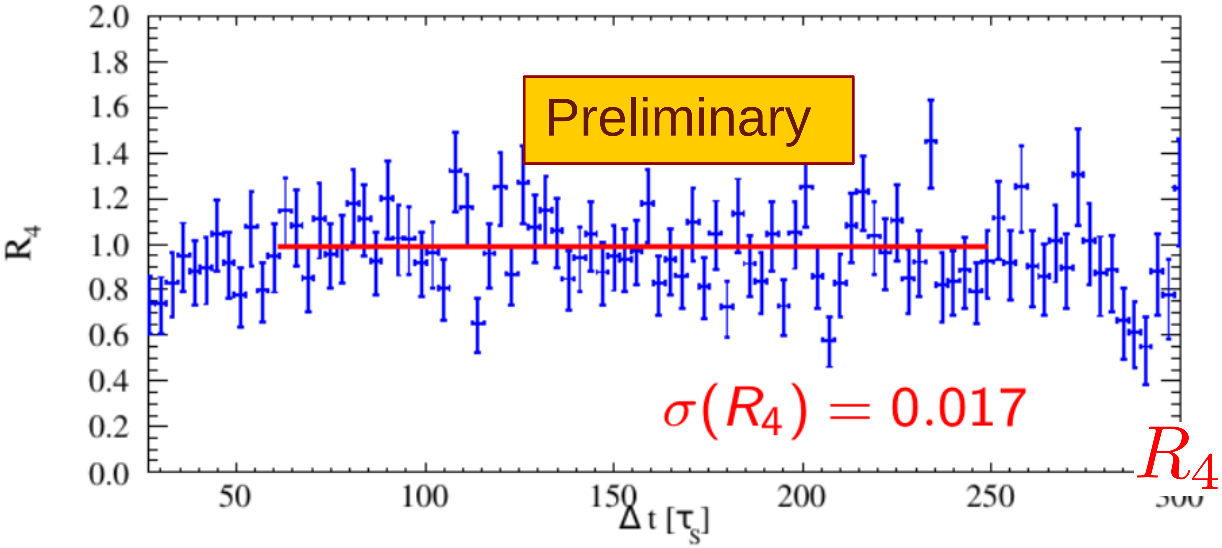
$$R_2 = \frac{K^0(0) \to K_-(\Delta t)}{K_-(0) \to K^0(\Delta t)}$$



$$R_2(\Delta t >> \tau_S) \sim 1 - 4\Re e(\varepsilon_K)$$

$$\sim \frac{I(l^+,3\pi^0;\Delta t)}{I(\pi\pi,l^-;\Delta t)}$$

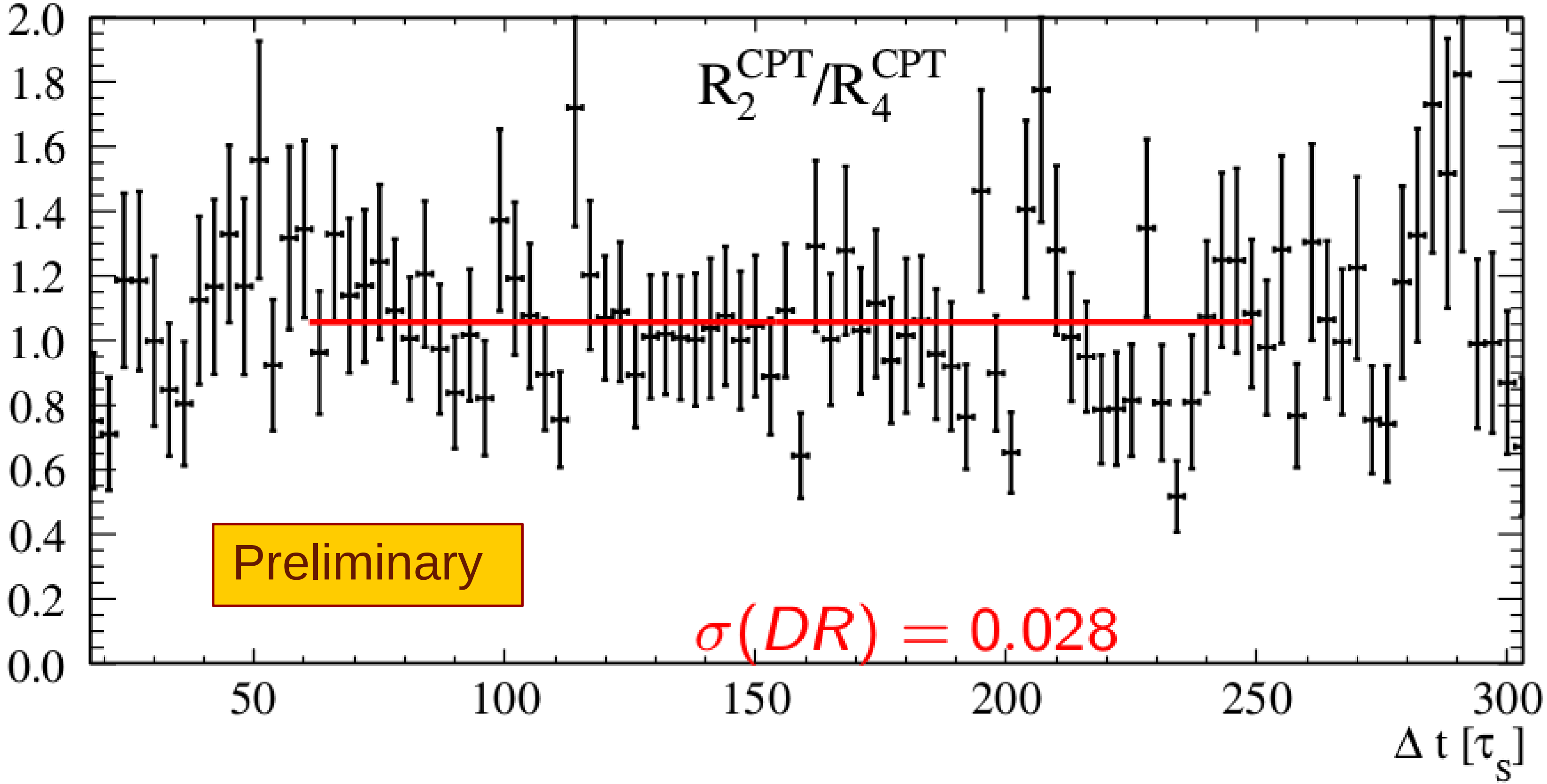
$$R_4 = \frac{\bar{K}^0(0) \to K_-(\Delta t)}{K_-(0) \to \bar{K}^0(\Delta t)}$$



$$R_4(\Delta t >> \tau_S) \sim 1 + 4\Re e(\varepsilon_K)$$

Direct CPT symmetry test in transitions of neutral kaons

$$R_2^{CPT} = \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^-; \Delta t)} \qquad R_4^{CPT} = \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^+; \Delta t)}$$



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

Conclusions & Outlook

- KLOE-2 data-taking has been completed with 5.5 fb^{-1} acquired
- A total sample of 8 fb^{-1} of data at φ peak is now available
- Preliminary results on discrete symmetry tests in transitions are encouraging
- Tests of discrete symmetries with neutral kaons are a key issues at KLOE-2 physics program and data analysis is in progress