



# Recent results on T, CP and CPT Tests with KLOE-2

Francesca Curciarello  
University of Calabria (CS), Italy



and INFN Laboratori Nazionali di Frascati (RM), Italy

on behalf of the KLOE-2 Collaboration

SSP2022

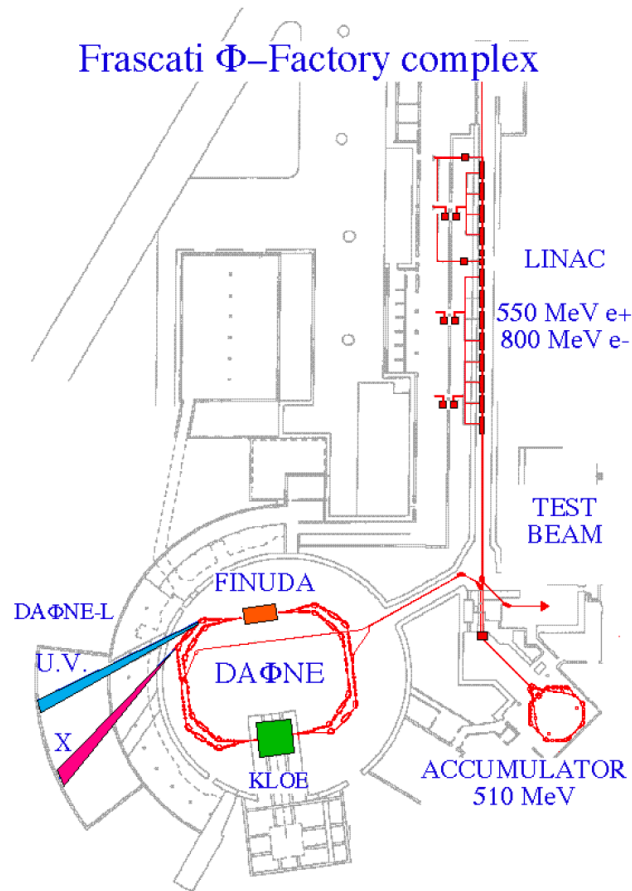
Vienna, August 29<sup>th</sup> - September 2<sup>nd</sup> 2022



- Da $\phi$ ne: the  $\phi$  factory
- KLOE and KLOE-2
- Entangled neutral Kaons at Da $\phi$ ne
- Search for decoherence and CPTV in  
 $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$
- T/CPT Tests with  $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$
- Measurement of the  $K_S \rightarrow \pi \nu e$  branching ratio
- Conclusions



# DaΦne: the $\phi$ factory



## DAΦNE UPGRADES

New interaction region: large beam crossing angle + sextupoles for crabbed waist optics  $\rightarrow$  59% increase in terms of peak luminosity

$e^+e^-$  collider @  $\sqrt{s} = M_\Phi = 1.0194$  GeV

2 interaction regions

2 separate rings

105 +105 bunches,  $T_{RF} = 2.7$  ns

Injection during data taking

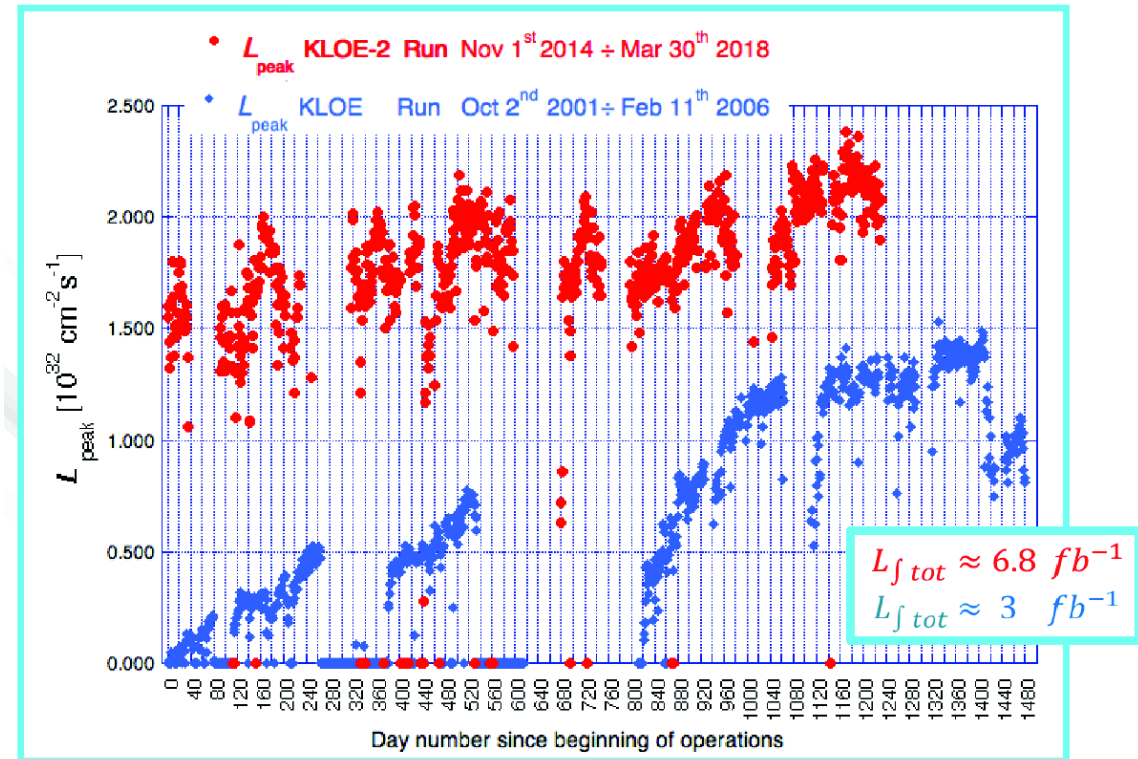
Crossing angle:  $2 \times 12.5$  mrad

Best Performance (1999–2006):

$$L_{\text{peak}} = 1.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

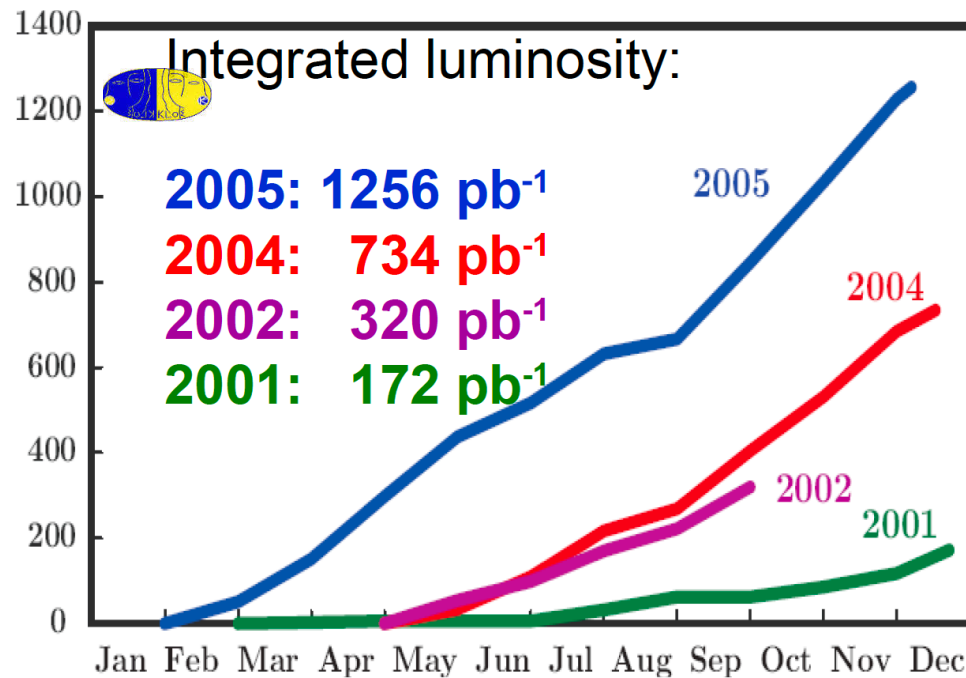
Best Performance (2014–2018):

$$L_{\text{peak}} = 2.4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

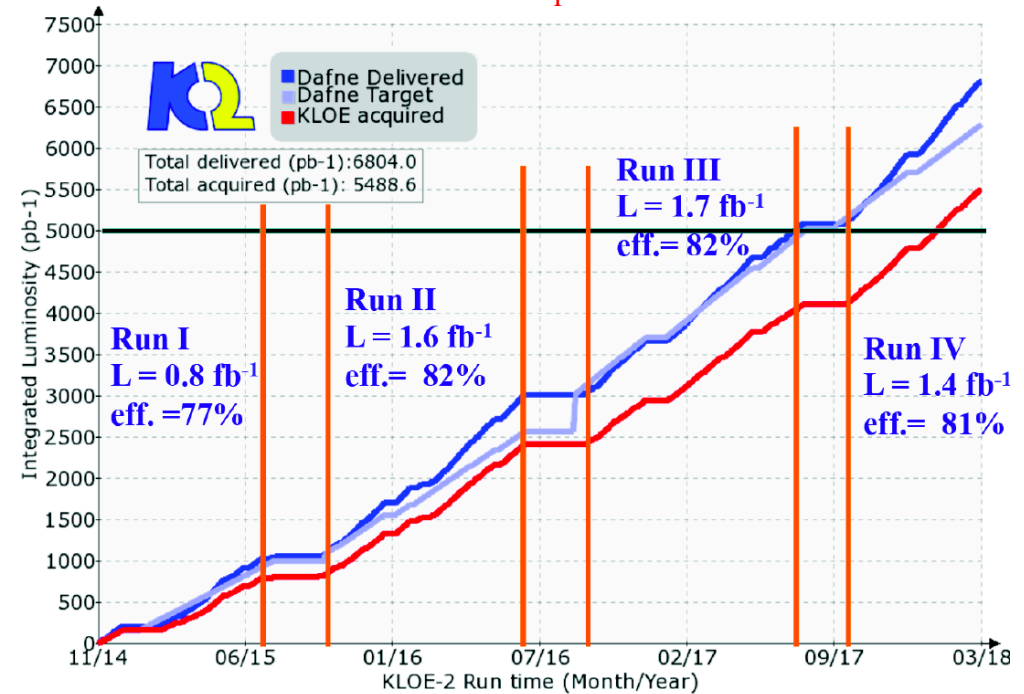




Total KLOE  $\int L_{\text{acquired}} dt \sim 2.5 \text{ fb}^{-1}$



Total KLOE-2  $\int L_{\text{acquired}} dt \sim 5.5 \text{ fb}^{-1}$



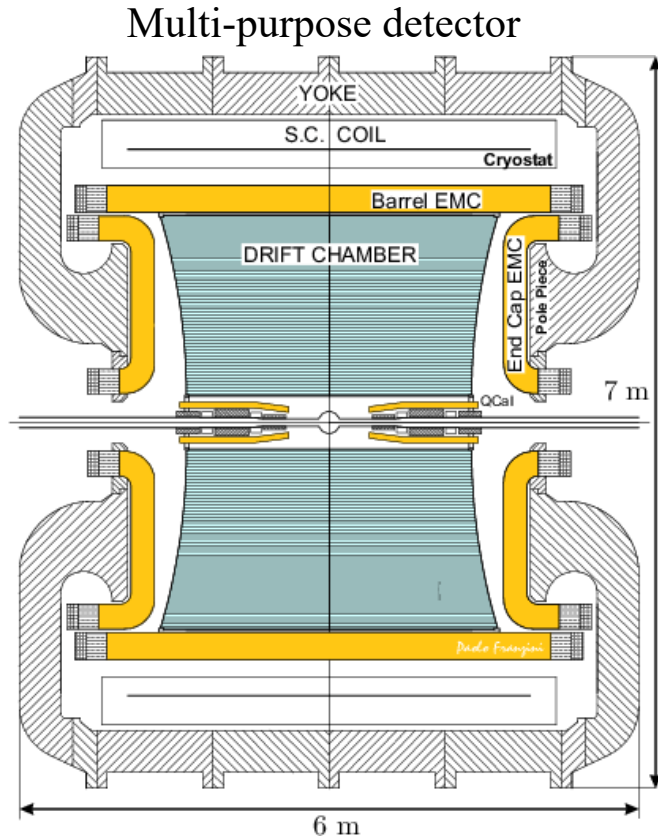
KLOE + KLOE-2 data sample:  $8 \text{ fb}^{-1}$

largest sample ever collected at the  $\phi(1020)$  peak

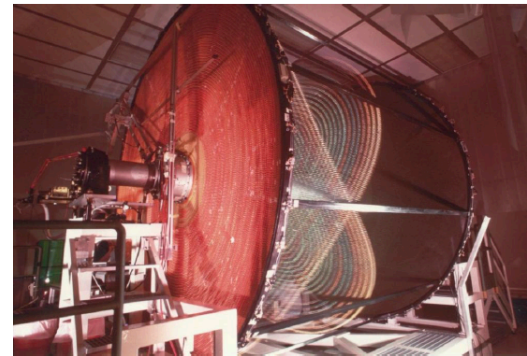
about  $2.4 \times 10^{10}$   $\phi$  mesons and  $8 \times 10^9$   $K^0 \bar{K}^0$  entangled pairs



## Vertical cross-section view of the KLOE detector



Superconducting coil  $B = 0.52 \text{ T}$



Barrel + 2 end-caps:

Pb/scintillating fiber,  
4880 PM

$$\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$$

$$\sigma_T = 54\text{ps}/\sqrt{E(\text{GeV})} \oplus 140\text{ps}$$

$$\sigma_{xy} \sim 150\mu\text{m}$$

$$\sigma_z = 2\text{mm}$$

$$\sigma_{p_\perp}/p_\perp \sim 0.4\% \text{ (LA tracks)}$$

$$\text{vertex resolution} \sim 3\text{mm}$$

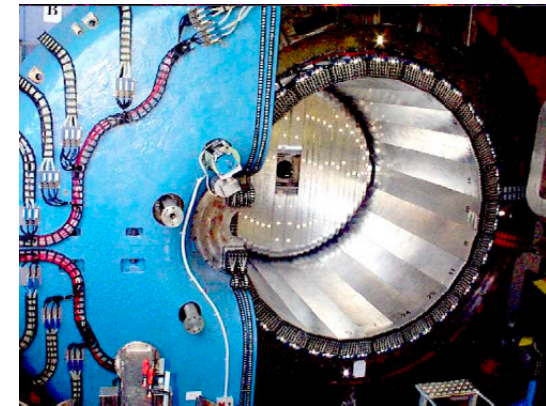
12,000 sense wires

Stereo geometry

4m diameter, 3m long

gas mixture: 90% He 10%

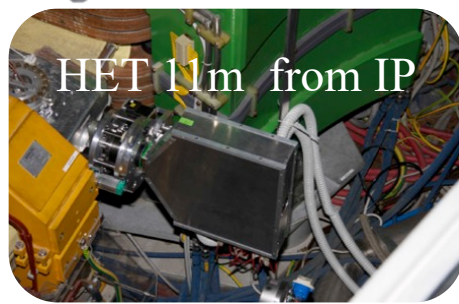
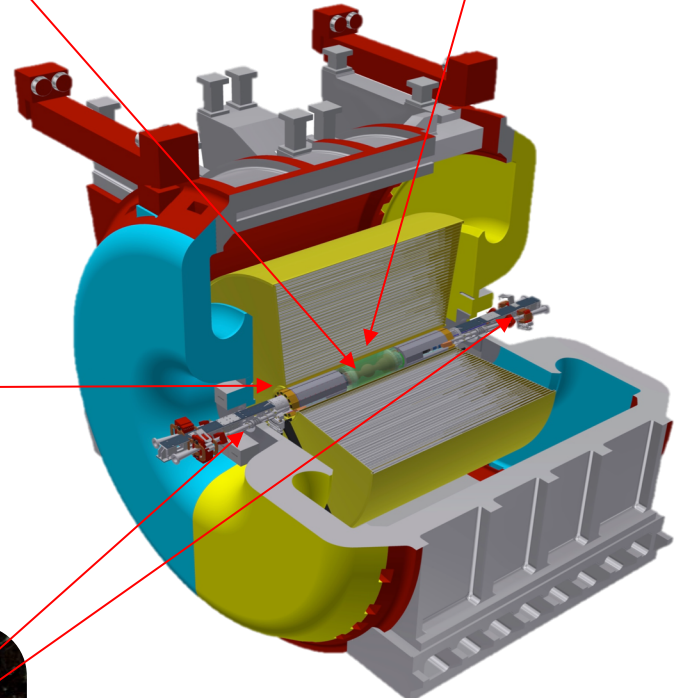
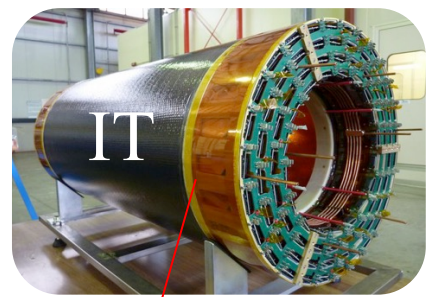
$i\text{C}_4\text{H}_{10}$



End-caps C-shaped to  
minimize dead zones:  
98% coverage of full  
solid angle



# The KLOE/KLOE-2 Apparatus



## INNER TRACKER:

four layers of cylindrical triple GEM  
better vertex reconstruction near IP  
higher acceptance to low  $p_t$  tracks

## CCALT:

LYSO crystal + SiPM  
increase of angular acceptance to  $\gamma$ 's from IP  
from  $21^\circ$  to  $10^\circ$

## QCAET:

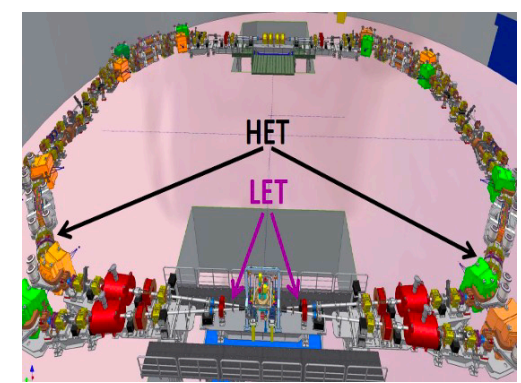
W + Scintillator tiles + WLS/SiPM  
QUADS coverage for  $K_L$  decays

## LET and HET :

Low and High energy tagger stations for  $e^+e^-$   
coming from two-photon interaction

LET: LYSO + SiPM

HET: EJ228 plastic scintillator hodoscope +  
Xilinx Virtex-5 FPGA



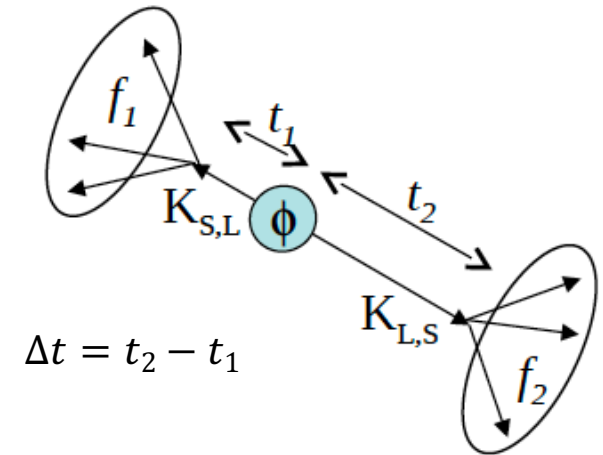


# Entangled neutral Kaons at DaΦne



$\phi$  mesons are produced at DaΦne nearly at rest with  $\sigma_\phi \sim 3 \mu\text{b}$  and decay in  $K_S K_L$  the 34% of the times

About  $10^6 K_S K_L$  per  $\text{pb}^{-1}$  are produced as collinear couples in a pure coherent, entangled and antisymmetric quantum state  $J^{PC}=1^-$  with  $p_K=110 \text{ MeV}/c$ ,  $\lambda_S = 6 \text{ mm}$  and  $\lambda_L = 3.5 \text{ m}$



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

$$= \frac{N}{\sqrt{2}} \left[ |K_S(\vec{p})\rangle |K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle |K_S(-\vec{p})\rangle \right]$$

$$N = \sqrt{\left(1 + |\varepsilon_S|^2\right) \left(1 + |\varepsilon_L|^2\right)} / (1 - \varepsilon_S \varepsilon_L) \cong 1$$

**KAON TAGGING** ( $t_1 \ll t_2$ )

Study single kaon property:

- Branching fractions
- Form factors
- Lifetimes

**INTERFERENCE** ( $t_1 \sim t_2$ )

Study of Kaon system time evolution  $\rightarrow$  tests of:

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

Ideal system to study fundamental discrete symmetries and quantum mechanics

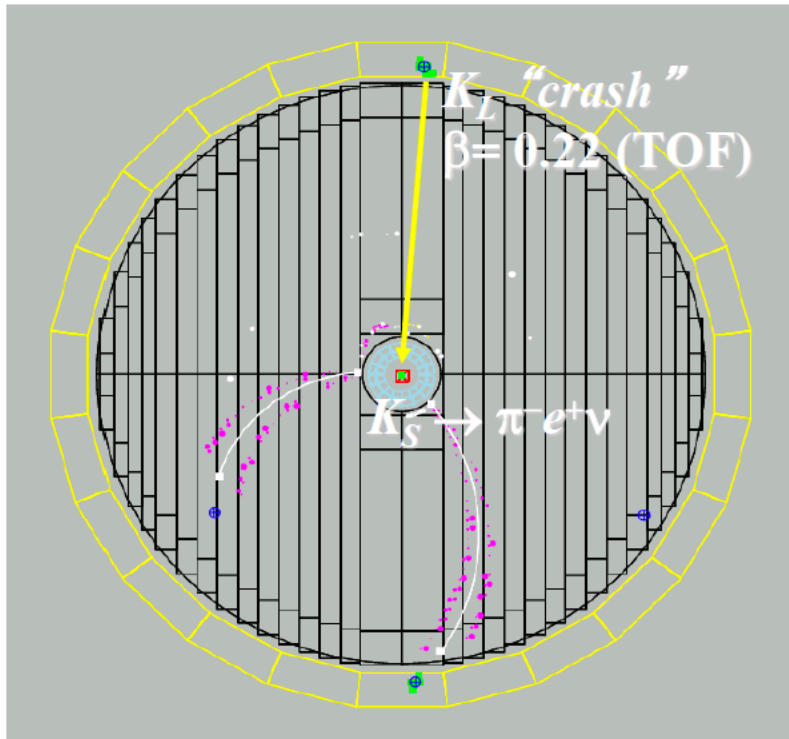


# Entangled neutral Kaons at DaΦne

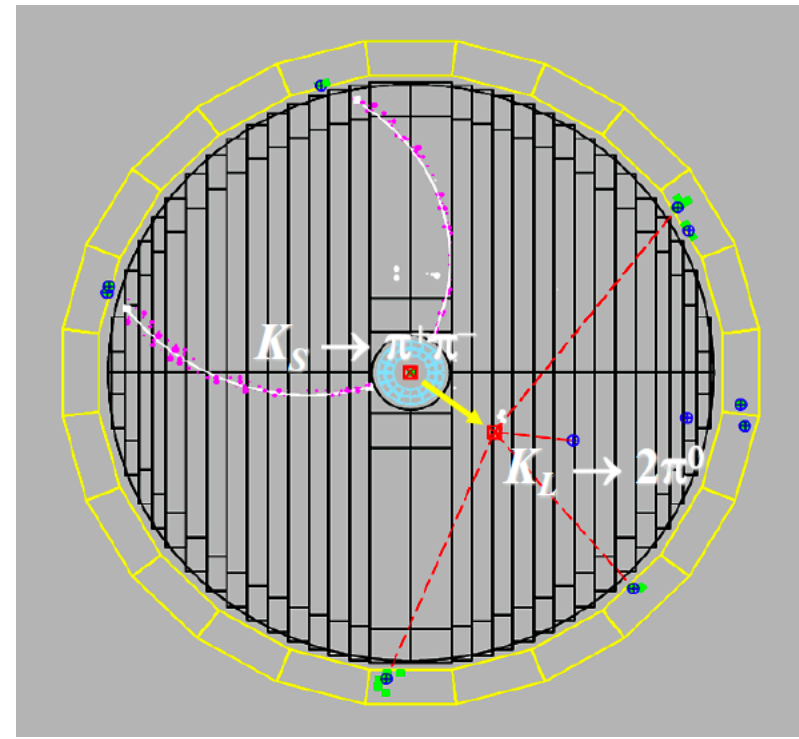


The observation of a  $K_S$  in an event signals (tags) the presence of a  $K_L$ , with known p and direction, and vice-versa →

highly pure, almost monochromatic, back-to-back, mutual-tagging  $K_S$  and  $K_L$  beams



$K_S$  tagged by the  $K_L$  interaction in the KLOE EMC → unique signature  
 $\varepsilon \sim 30\%$  (mainly geometrical)



$K_L$  tagged by the  $K_S \rightarrow \pi\pi$  vertex at the IP,  $\varepsilon \sim 70\%$  (mainly geometrical)

$$K_S/K_L \sigma_\theta \sim 1^\circ, \quad K_S/K_L \sigma_p \sim 2\text{MeV}$$



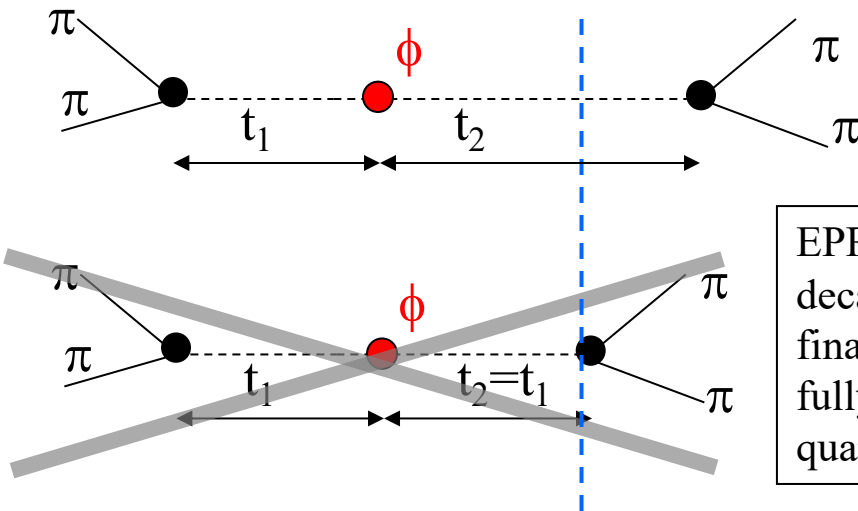
# Search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$



$$f_1 = f_2 = \pi^+ \pi^-$$

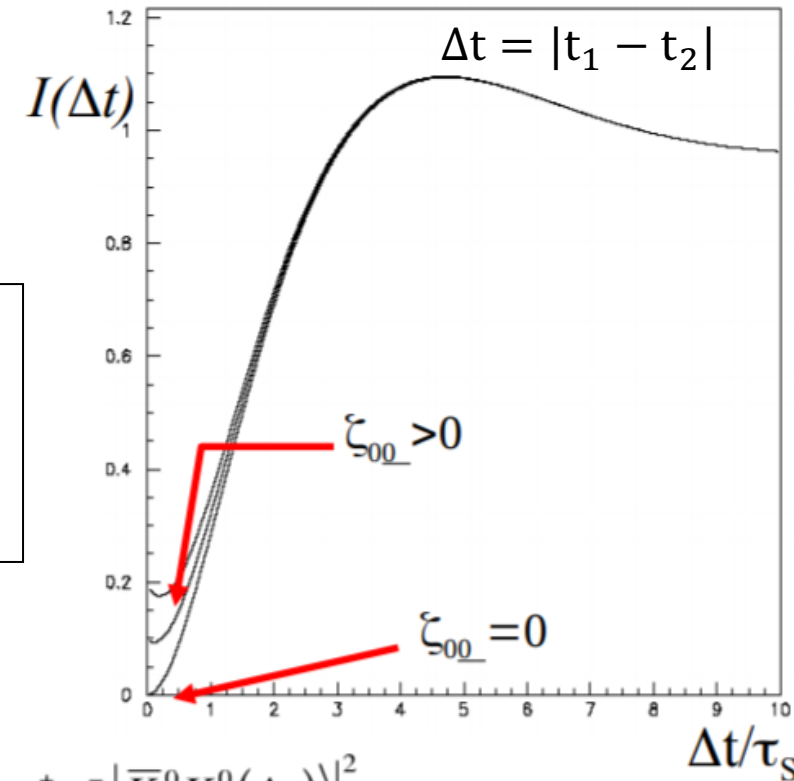
$$|\hat{i}\rangle = \frac{1}{\sqrt{2}} [ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle ]$$

**CP violating process:** CP violation in kaon mixing acts as amplification mechanism  $\rightarrow$  high sensitivity to  $\zeta_{00}$  due to terms  $\zeta_{00}/|\eta_{+-}|^2$  with  $|\eta_{+-}|^2 \sim |\epsilon|^2 \sim 10^{-6}$



EPR: no simultaneous decays ( $\Delta t=0$ ) in the same final state due to the fully destructive quantum interference

Most precise test of quantum coherence in an entangled system.



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

**$\zeta_{00}$  decoherence parameter** in the  $K^0 \bar{K}^0$  basis (  $\zeta_{00} = 0 \rightarrow$  no decoherence,  $\zeta_{00} = 1 \rightarrow$  fully decoherence)

[ or  $\zeta_{SL}$  in the  $K_S K_L$  basis].



# Search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$



Decoherence effects might arise in a quantum gravity picture implying CPT violation

[Ellis et. al, NP B241 (1984) 381; Ellis, Mavromatos et al. PRD53 (1996)3846 ]:

- Relevant parameter in the modified time evolution of neutral kaons:  
 $\gamma$  parameter (at most  $\gamma = O(m_K^2 / M_{planck}) \approx 2 \times 10^{-20}$  GeV).
- Initial entangled state modified adding a tiny symmetric part  $\rightarrow \omega$  effect  
(at most  $\omega = O(m_K^2 / M_{planck} / \Delta\Gamma) \sim 1 \times 10^{-3}$ )

$$|i\rangle \propto \frac{1}{\sqrt{2}} [ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle ] + \omega [ |K^0\rangle |\bar{K}^0\rangle + |\bar{K}^0\rangle |K^0\rangle ] \longrightarrow \text{[in the } K^0 \bar{K}^0 \text{ basis]}$$

$$\text{[in the } K_S K_L \text{ basis]} \longleftarrow |i\rangle \propto [ |K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle ] + \omega [ |K_S\rangle |K_S\rangle - |K_L\rangle |K_L\rangle ]$$

Previous KLOE measurement  $L = 380 \text{ pb}^{-1}$

KLOE PLB 642 (2006) 315



$$\zeta_{SL} = (1.8 \pm 4.0 \pm 0.7) \cdot 10^{-2}$$

$$\zeta_{00} = (1.0 \pm 2.1 \pm 0.4) \cdot 10^{-6}$$

$$\gamma = (1.3_{-1.4}^{+2.8} \pm 0.4) \cdot 10^{-21} \text{ GeV}$$

$$\Re(\omega) = (1.1_{-5.3}^{+8.7} \pm 0.9) \cdot 10^{-4}$$

$$\Im(\omega) = (3.4_{-5.0}^{+4.8} \pm 0.6) \cdot 10^{-4}$$



# Search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$



**Statistics:** KLOE data corresponding to  $L = 1.7 \text{ fb}^{-1}$

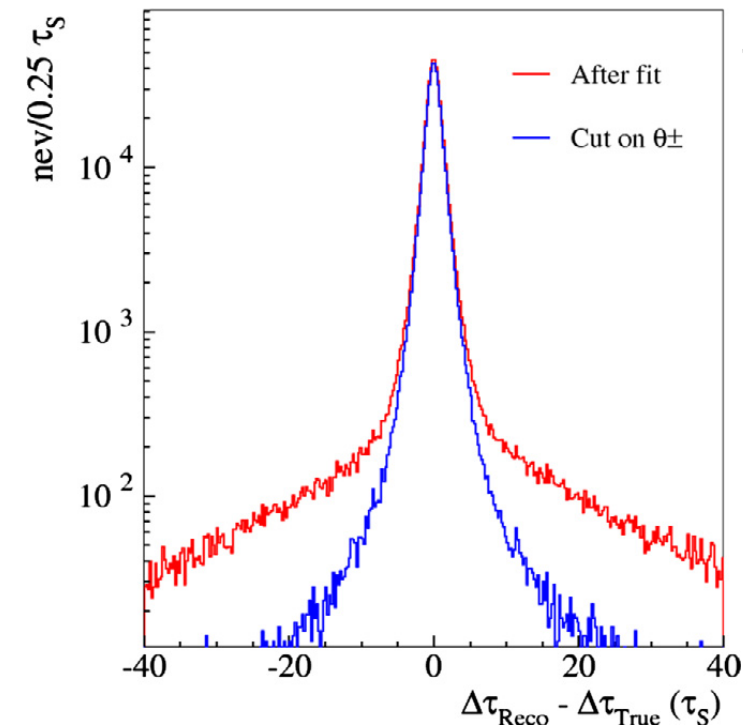
## Event selection:

- 2 vertices with 2 opposite curvature tracks each
- At least one vertex in a cylindrical fiducial volume with  $\rho < 10 \text{ cm}$  and  $|z| < 20 \text{ cm}$
- For each of the 2 vertices ( $i=1,2$ ):
- $|m_i(\pi^+ \pi^-) - m_K| < 5 \text{ MeV}$
- $|\vec{p}_{i+}^* + \vec{p}_{i-}^*| - p_K^* < 10 \text{ MeV}$  with  $\vec{p}_{i\pm}^*$  pion momenta of the vertex  $i$  and  $p_K^* = \sqrt{\frac{s}{4} - m_K^2}$  kaon momenta in the  $\phi$  rest frame
- $-50 < E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2 < 10 \text{ MeV}^2$ ,  $\sqrt{E_{\text{miss}}^2 + |\vec{p}_{\text{miss}}|^2} < 10 \text{ MeV}$   
with  $\vec{p}_{\text{miss}} = \vec{p}_\phi - \vec{p}_1 - \vec{p}_2$  and  $E_{\text{miss}} = E_\phi - E_1 - E_2$

Kin Fit to improve resolution on Kaon decay vertices

## Main improvements wrt past analysis:

- $\cos(\theta_{\pi^+ \pi^-}) > -0.975$  cut to improve  $\Delta t$  resolution
- improved  $e^+ e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  background evaluation



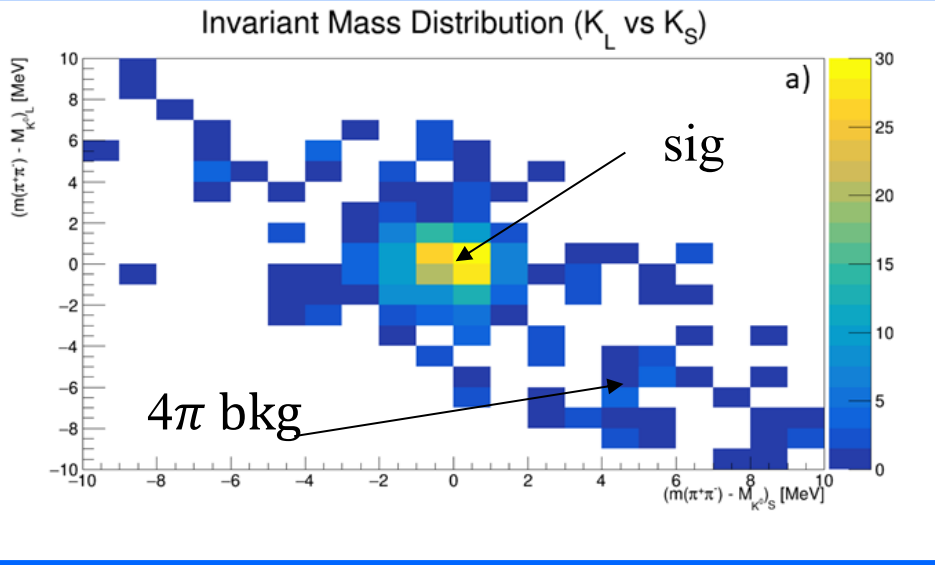


# Search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

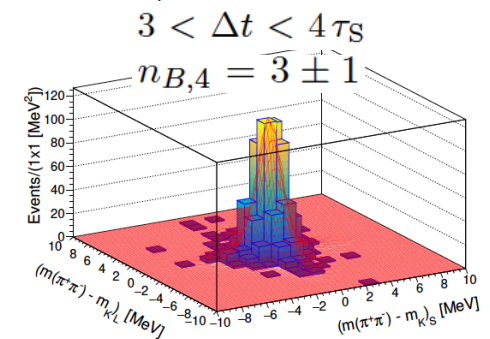
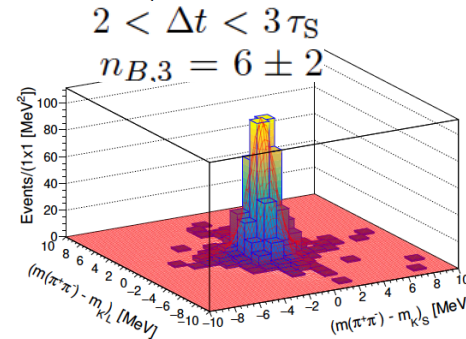
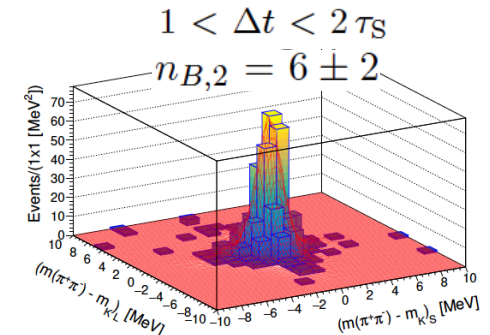
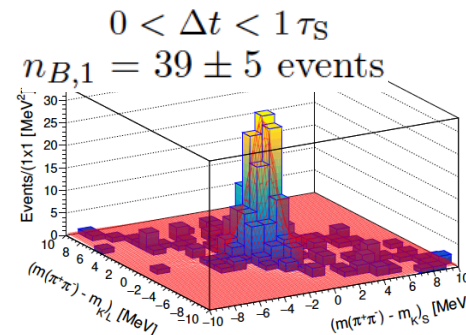


Two main background sources survive above selection:

- non-resonant production of 4  $\pi$ , 0.5% in the range  $0 < \Delta t < 12 \tau_S$ , mainly concentrated at  $\Delta t \approx 0$
- kaon regeneration on spherical beam pipe, it peaks at  $\Delta t \approx 17 \tau_S \rightarrow$  rejected by restricting the fit in the  $0 < \Delta t < 12 \tau_S$  range

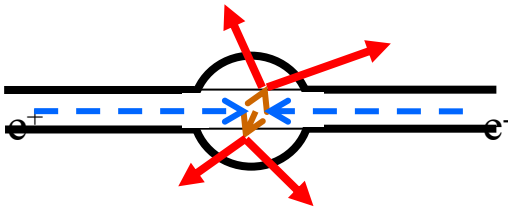


$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$  background evaluated from 2D unbinned ML fit in bins of  $\Delta t$  in the bkg region and then extrapolated to sig region



Sphere: 500  $\mu\text{m}$  62-38% Be-Al  $r=10$  cm ( $\sim 17 \tau_S$ )

Cylinder: 50  $\mu\text{m}$  Be,  $r=4.4$  cm ( $\sim 7.5 \tau_S$ )



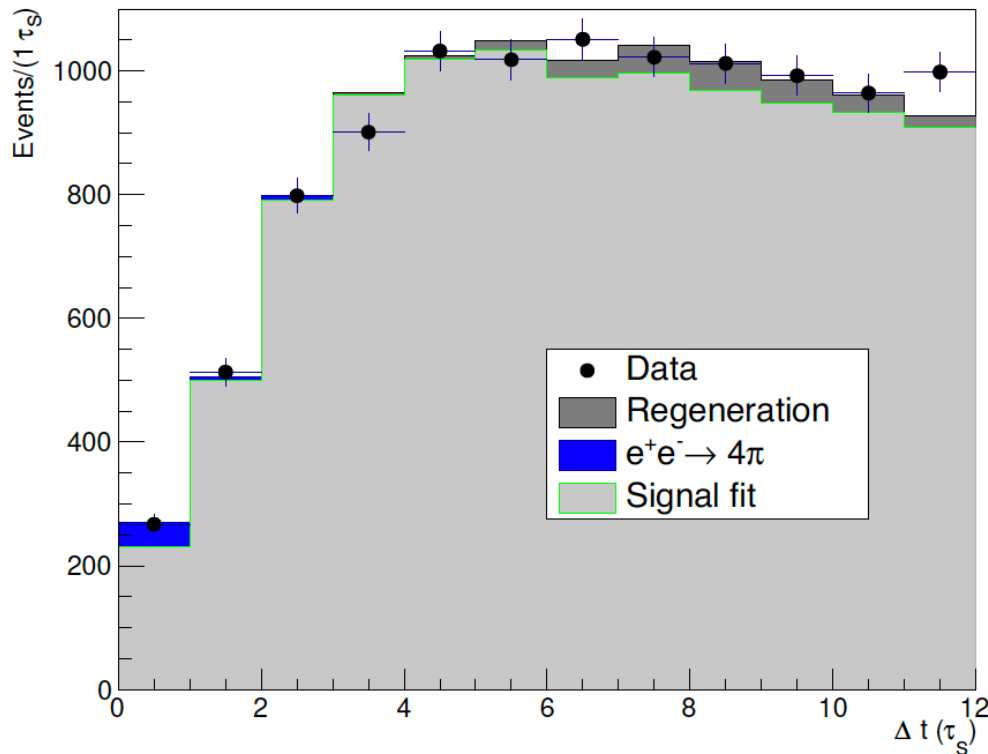
Residual regeneration bkg from thin pipe cylinder dominated by incoherent regeneration and evaluated through MC



# Search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$



KLOE-2 JHEP 04 (2022) 059



## Results on decoherence parameters

$$\zeta_{SL} = (0.1 \pm 1.6_{\text{stat}} \pm 0.7_{\text{syst}}) \cdot 10^{-2}$$

$$\zeta_{00} = (-0.05 \pm 0.80_{\text{stat}} \pm 0.37_{\text{syst}}) \cdot 10^{-6}$$

$$\gamma = (0.13 \pm 0.94_{\text{stat}} \pm 0.42_{\text{syst}}) \cdot 10^{-21} \text{ GeV}$$

## 90% CL Upper limits

$$\zeta_{SL} < 0.030$$

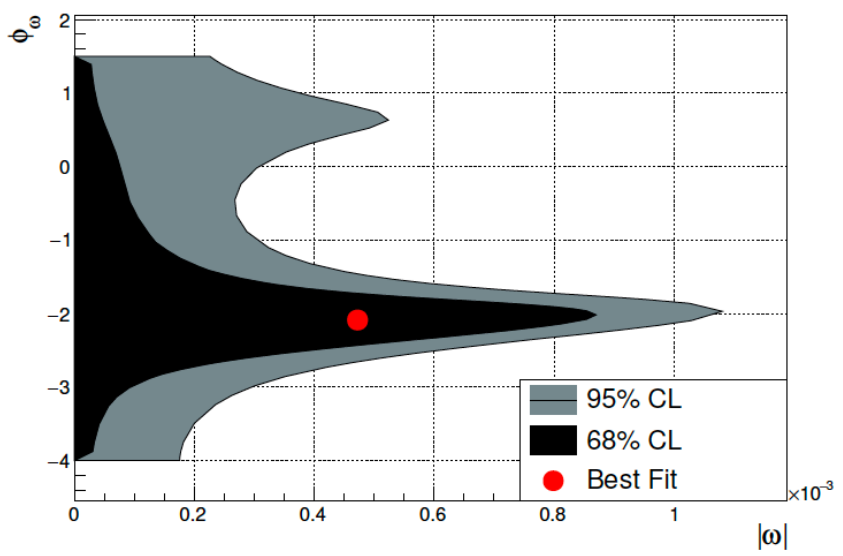
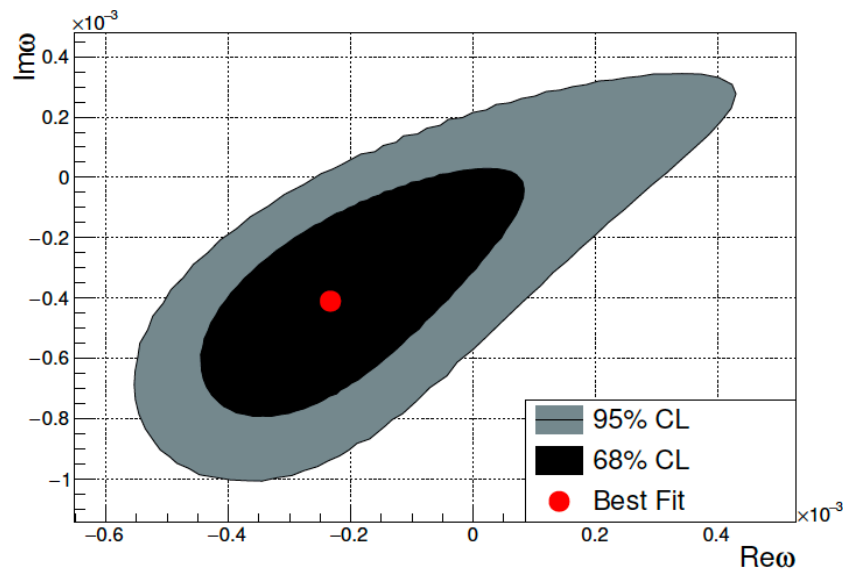
$$\zeta_{00} < 1.4 \cdot 10^{-6}$$

$$\gamma < 1.8 \cdot 10^{-21} \text{ GeV}$$

Fit including  $\Delta t$  resolution and efficiency effects + regeneration;  
**Statistical uncertainty reduced by half**  
**Central values consistent with zero**



$\omega$  model contour plots



Results on decoherence parameters

$$\Re\omega = \left(-2.3_{-1.5}^{+1.9}\text{stat} \pm 0.6_{\text{syst}}\right) \cdot 10^{-4}$$

$$\Im\omega = \left(-4.1_{-2.6}^{+2.8}\text{stat} \pm 0.9_{\text{syst}}\right) \cdot 10^{-4}$$

$$|\omega| = (4.7 \pm 2.9_{\text{stat}} \pm 1.0_{\text{syst}}) \cdot 10^{-4}$$

$$\phi_\omega = -2.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{syst}} \text{ (rad)}$$

$$|\omega|^2 = \frac{\text{BR}(\phi \rightarrow K_S K_S, K_L K_L)}{\text{BR}(\phi \rightarrow K_S K_L)}$$

$$\text{BR}(\phi \rightarrow K_S K_S, K_L K_L) < 2.4 \cdot 10^{-7}$$

Systematic sources

	$\delta\zeta_{\text{SL}}$ $\cdot 10^2$	$\delta\zeta_{00}$ $\cdot 10^7$	$\delta\gamma$ $\cdot 10^{21} \text{ GeV}$	$\delta\Re\omega$ $\cdot 10^4$	$\delta\Im\omega$ $\cdot 10^4$	$\delta \omega $ $\cdot 10^4$	$\delta\phi_\omega$ (rad)
Cut stability	0.56	2.9	0.33	0.53	0.65	0.78	0.07
$4\pi$ background	0.37	1.9	0.22	0.32	0.19	0.32	0.04
Regeneration	0.17	0.9	0.10	0.06	0.63	0.58	0.05
$\Delta t$ resolution	0.18	0.9	0.10	0.15	0.09	0.15	0.02
Input phys. const.	0.04	0.2	0.02	0.03	0.09	0.07	0.01
Total	0.71	3.7	0.42	0.64	0.93	1.04	0.10



# T/CPT Tests with $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$



**Concept:** J. Bernabeu et al., Nucl. Phys. B 868 (2013) 102, JHEP 1510 (2015) 139 First such measurement with kaons

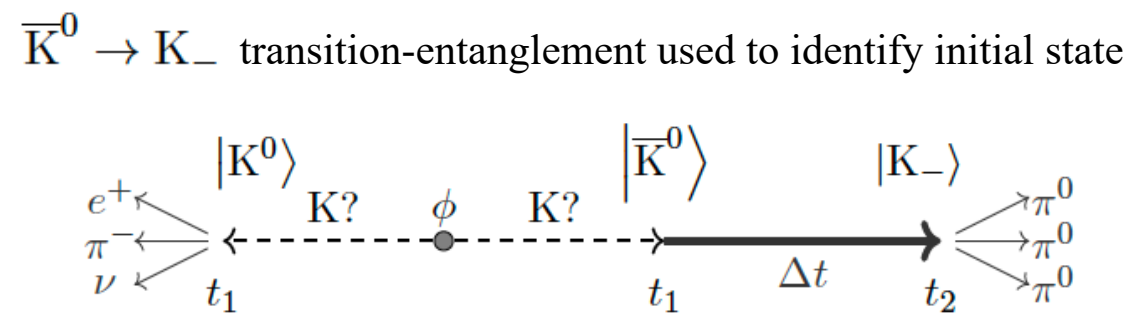
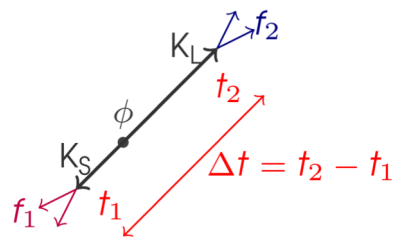
Direct, model independent test of the T and CPT symmetry => observe a given Kaon state and its T and CPT conjugates => transitions between pure-flavor and CP-definite eigenstates

Flavor states

$$\bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$$
$$K^0 \rightarrow \pi^- e^+ \nu_e$$

CP states

$$K_- \rightarrow 3\pi^0$$
$$K_+ \rightarrow \pi^+ \pi^-$$
  
$$|K_+\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle + |\bar{K}^0\rangle]$$
$$|K_-\rangle = \frac{1}{\sqrt{2}} [|K^0\rangle - |\bar{K}^0\rangle]$$



Transition probabilities

Experimental observables

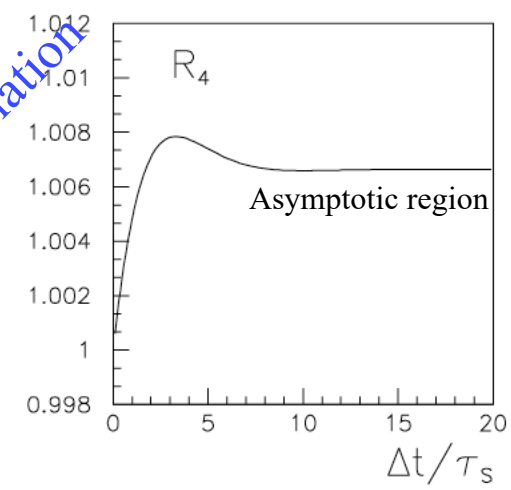
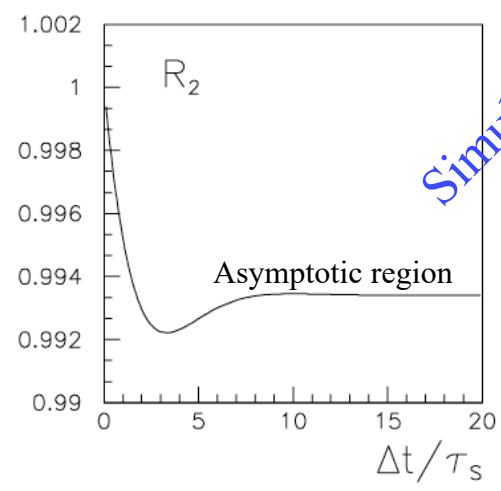
We focus on the asymptotic region  $\Delta t \gg \tau_s$ :

$$R_2^T(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]} \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+ \pi^-, \pi^- e^+ \nu; \Delta t)}$$

$$R_4^T(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]} \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+ \pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$$R_2^T(\Delta t \gg \tau_S) \simeq 1 - 4 \text{Re} \epsilon \quad R_4^T(\Delta t \gg \tau_S) \simeq 1 + 4 \text{Re} \epsilon$$

$\text{Re} \epsilon \neq 0$  implies TV





In general, four independent T, CP and CPT tests are possible:

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

Each process is experimentally identified by a time-ordered pair of kaon decays into the corresponding final states

T-violation sensitive

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

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

CPT-violation sensitive

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

$$R_4^{CPT}(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]} = \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+ \pi^-, \pi^- e^+ \nu; \Delta t)} \times \frac{1}{D}$$

$$D = \frac{\text{BR}(K_L \rightarrow 3\pi^0)\tau_S}{\text{BR}(K_S \rightarrow \pi\pi)\tau_L} = 0.5076(59) \times 10^{-3} \rightarrow \text{from past KLOE measurements}$$

Double ratios (independent from the D factor)

$$\frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(3\pi^0, e^-) I(\pi^+ \pi^-, e^-)}{I(3\pi^0, e^+) I(\pi^+ \pi^-, e^+)}$$

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



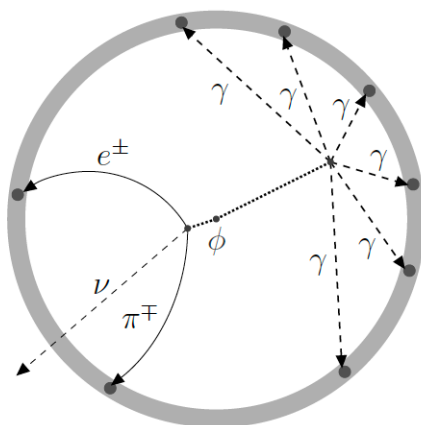
# T/CPT Tests with $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$



Sample Statistics:  $1.7 \text{ fb}^{-1}$  of KLOE data, two classes of events, four processes

Scheme of the two classes of events in a cross-sec view of KLOE

$K_S K_L \rightarrow \pi^\pm e^\mp \nu 3\pi^0$  event



**Pre-selection:**

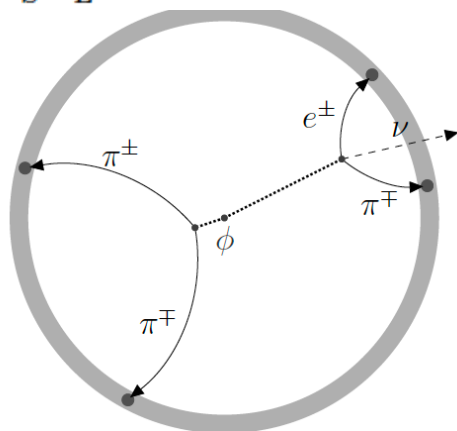
- vtx with 2 tracks close to IP (cutting close to IP to reject  $K_S \rightarrow \pi\pi \rightarrow \pi\mu$ )
- 6 neutral clusters' set
- Reconstructing  $K_L \rightarrow 3\pi^0$
- Reconstruction of kaon decay times and  $\Delta t$

**Analysis:**

- $K_S \rightarrow \pi e \nu$  selection cuts
- TCA requirement for 2 tracks
- Time of flight analysis and cuts
- Cut on  $R/(T \cdot c)$  for neutral clusters to reject  $K_S \rightarrow \pi^0 \pi^0$
- Kinematic fit
- ANN-based classification of  $e/\pi$  and  $e/\mu$  EMC clusters and tracks

$S/B \sim 20$

$K_S K_L \rightarrow \pi^+ \pi^- \pi^\pm e^\mp \nu$  event



**Pre-selection:**

- vtx with 2 tracks close to IP
- $M(\pi\pi)$  and  $|p|$  cuts for 2 tracks
- Exactly 1 other vtx with 2 tracks passing a missing mass cut
- Reconstruction of kaon decay times and  $\Delta t$

**Analysis:**

- TCA requirement for 2 tracks from  $K_L$  decay vertex
- Time of flight analysis and cuts

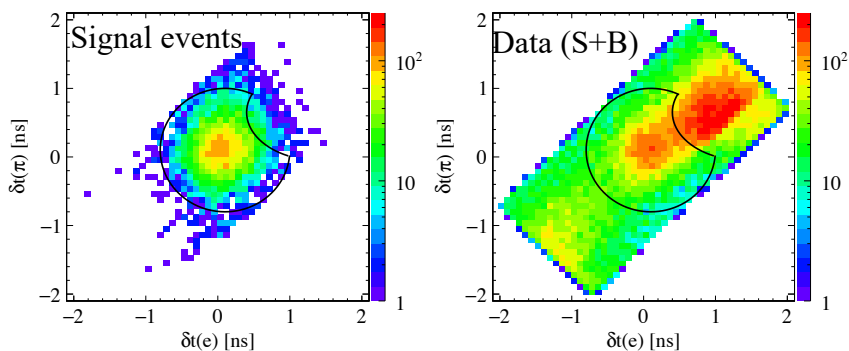
$S/B \sim 70$



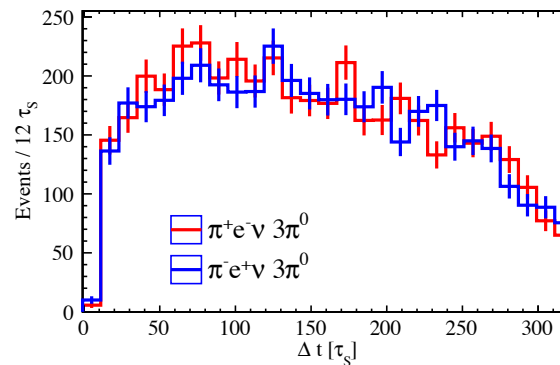
# T/CPT Tests with $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$



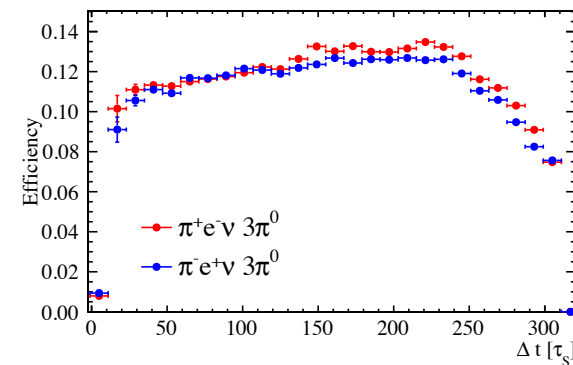
Time of flight technique to identify semi-leptonic decays



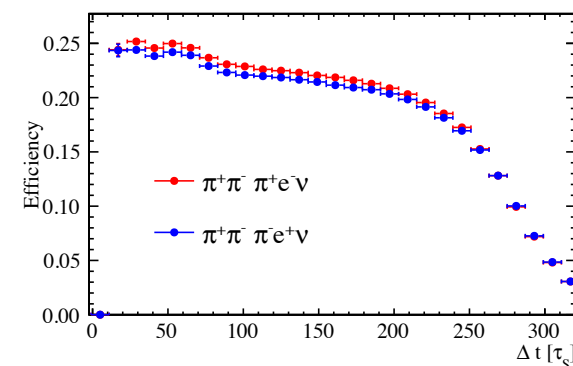
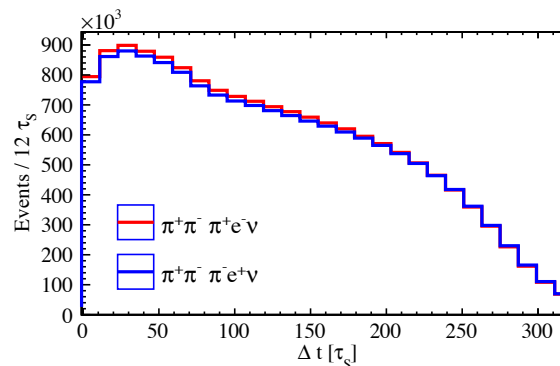
Measured double kaon decay intensities



Efficiency

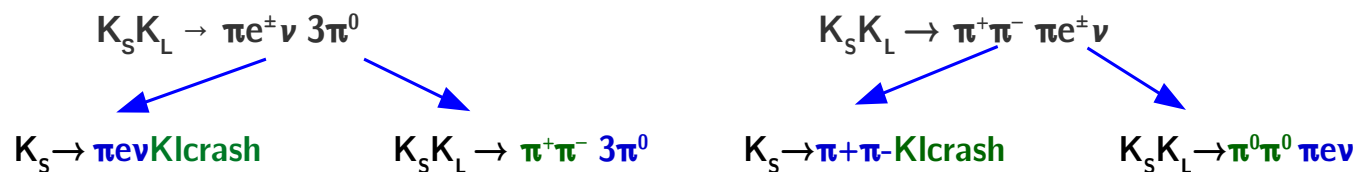


$K_L \rightarrow 3\pi^0$  identification: reconstructing  $K_L$  decay point for all 6-cluster candidate sets (trilateration method to find  $K_L$  decay point and time) and choosing the most likely candidate set



Residual background subtraction for  $\pi e^\pm \nu 3\pi^0$  channel

MC selection efficiencies corrected from data with 4 independent control samples



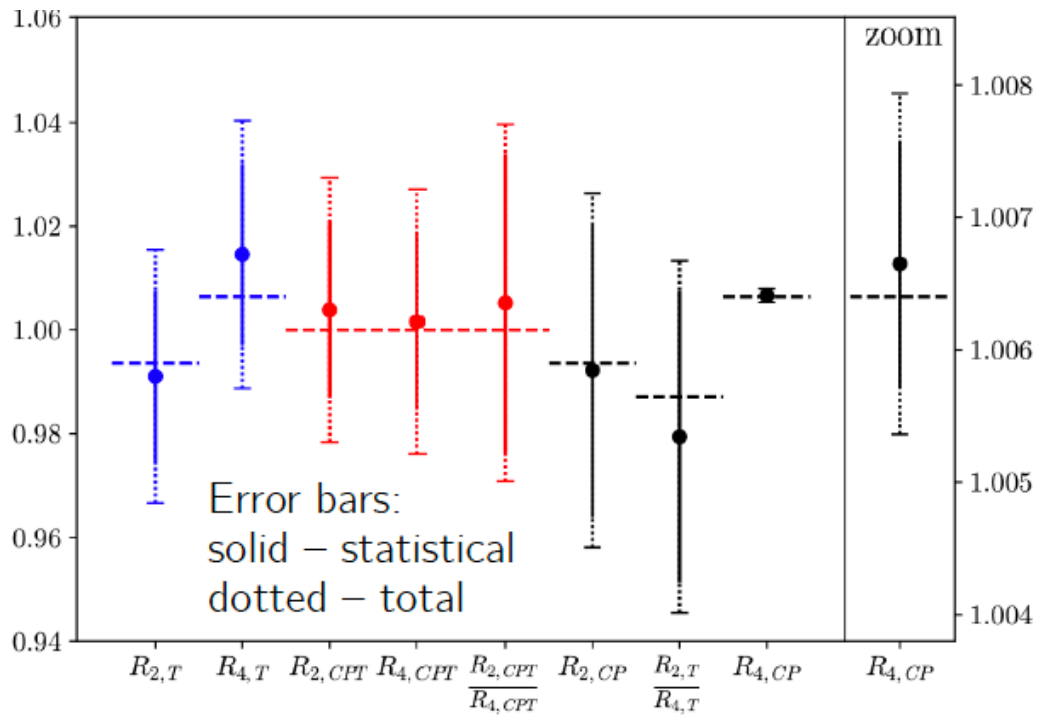


# T/CPT Tests with $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$



Horizontal dashed lines denote expected values:

CPT invariance and TV extrapolated from observed CPV (PDG)



**KLOE-2 result (2022)**

Paper in preparation

$$R_2^T = 0.991 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D,$$

$$R_4^T = 1.015 \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_D,$$

$$R_2^{CPT} = 1.004 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D,$$

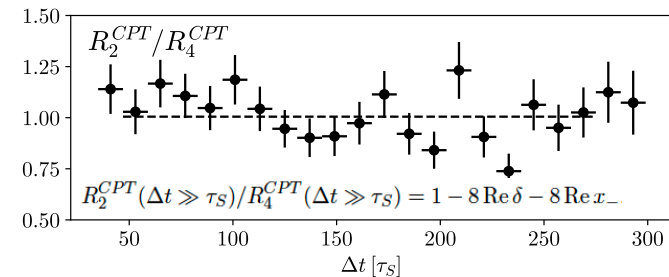
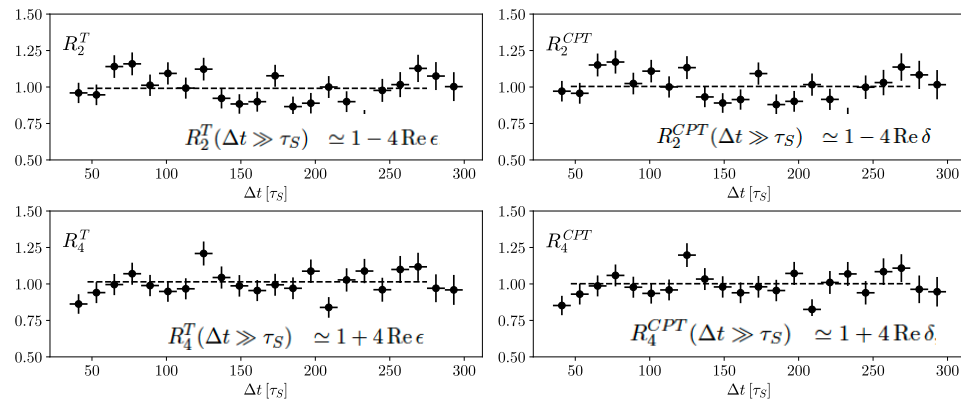
$$R_4^{CPT} = 1.002 \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_D,$$

$$R_2^{CP} = 0.992 \pm 0.028_{stat} \pm 0.019_{syst},$$

$$R_4^{CP} = 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst},$$

$$R_2^T/R_4^T = 0.979 \pm 0.028_{stat} \pm 0.019_{syst},$$

$$R_2^{CPT}/R_4^{CPT} = 1.005 \pm 0.029_{stat} \pm 0.019_{syst}.$$



**First T and CPT test in kaon transitions**



# Measurement of the $K_S \rightarrow \pi e \nu$ branching ratio



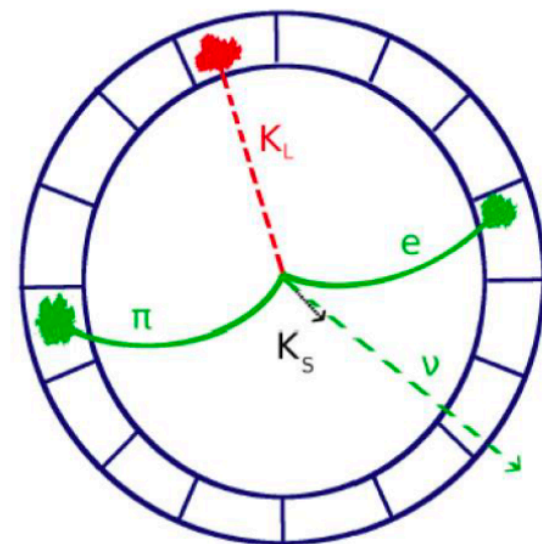
$|V_{us}|$  CKM matrix element is best measured from Kaon meson semi-leptonic decays

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell + \delta_{SU2}) C^2 |V_{us}| f_+^2(0) I_K^\ell$$

$\text{BR}(K_S \rightarrow \pi e \nu)$  less precise than  $K_L$  and  $K^+/K^-$

$\text{BR}(K_S \rightarrow \pi e \nu) = (7.046 \pm 0.078 \text{ stat} \pm 0.049 \text{ syst}) \times 10^{-4}$   
[PLB 636 (2006) 173] Measured by KLOE with  $0.4 \text{ fb}^{-1}$   
1.4% uncertainties level, 1.1 % stat  $\pm$  0.7 % syst

Goal: improve  $\text{BR}(K_S \rightarrow \pi e \nu)$  measurement to have a  $|V_{us}|$  evaluation from  $K_S \rightarrow \pi e \nu$  decay comparable with others contribution



$ V_{us} f_+(0)$			% err	Approx. contrib. to % err from:				
				BR	$\tau$	$\Delta$	Int	
0.21	0.215							
		$K_L e3$	0.2162(5)	0.23	0.09	0.20	0.02	0.05
		$K_L \mu3$	0.2167(6)	0.29	0.15	0.18	0.11	0.07
		$K_S e3$	0.2154(13)	0.60	0.60	0.02	0.02	0.05
		$K_S \mu3$	0.2126(47)	2.2	2.2	0.02	0.11	0.07
		$K^\pm e3$	0.2167(7)	0.32	0.27	0.06	0.17	0.05
		$K^\pm \mu3$	0.2167(11)	0.50	0.45	0.06	0.21	0.07

Average:  $|V_{us}| f_+(0) = 0.21635(38)$   $\chi^2/\text{ndf} = 2.14/5$  (83%)

What we measure:

$$\mathcal{B}(K_S \rightarrow \pi e \nu) = \frac{N_{\pi e \nu}}{\epsilon_{\pi e \nu}} \times \frac{\epsilon_{\pi \pi}}{N_{\pi \pi}} \times R_\epsilon \times \mathcal{B}(K_S \rightarrow \pi^+ \pi^-)$$

Sig events  $\rightarrow$  Selection eff

Norm events  $\rightarrow$   $R_\epsilon = (\epsilon_{\pi \pi} / \epsilon_{\pi e \nu})_{\text{com}}$



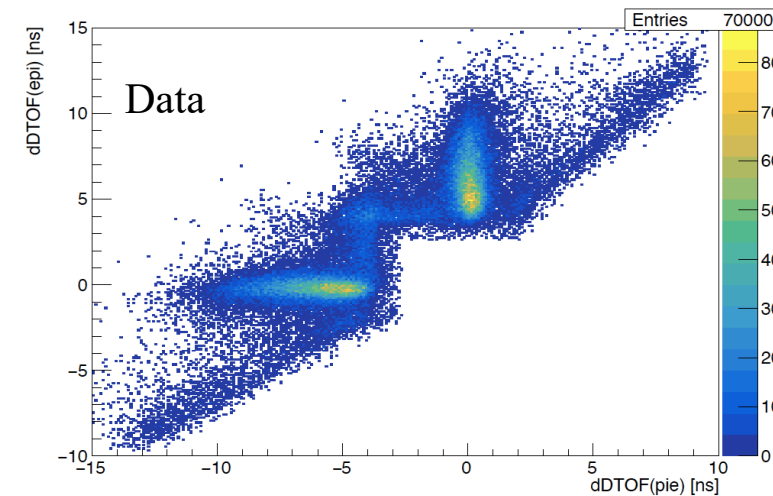
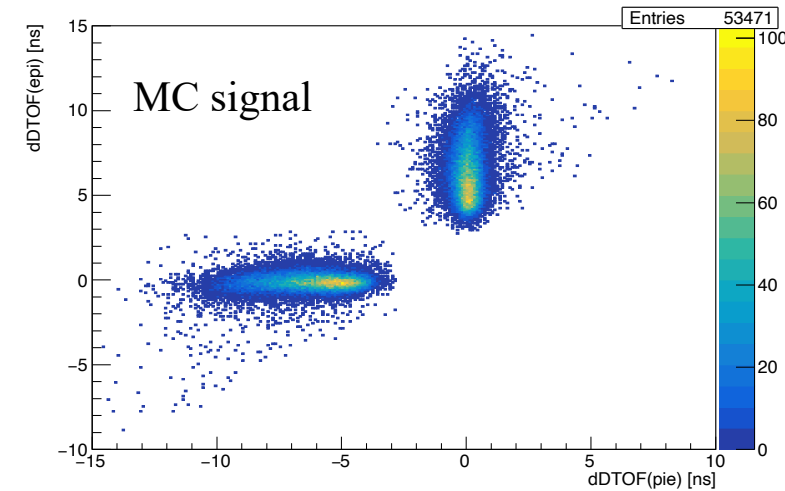
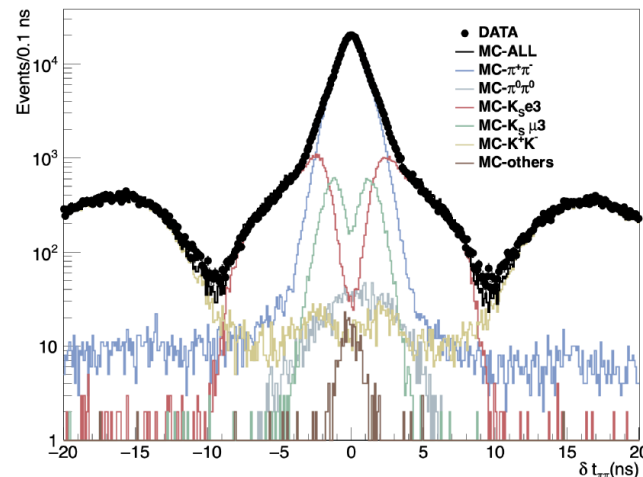
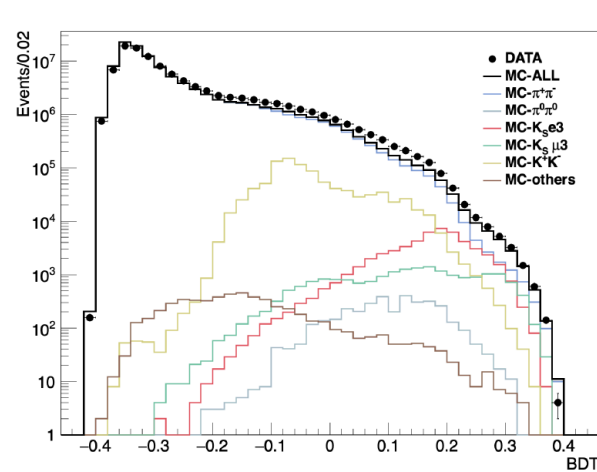
# Measurement of the $K_S \rightarrow \pi e \nu$ branching ratio



- Analyzed  $L=1.63 \text{ fb}^{-1}$
  - 1 vtx close to IP +  $K_L$  interaction in the calorimeter (KL crash)
  - $K_S \rightarrow \pi^+ \pi^-$  as normalization sample
  - $K_S$  semi-leptonic signal selection:
    - boosted decision tree (BDT) with kinematic variables to reject main background from  $K_S \rightarrow \pi^+ \pi^-$  and  $\phi \rightarrow K^+ K^-$
    - PID with Time of Flight comparing two hypothesis:
      - if  $|\delta t_{1,\pi} - \delta t_{2,e}| < |\delta t_{1,e} - \delta t_{2,\pi}| \Rightarrow$  track-1 assigned to  $\pi$  and track-2 to  $e$ , otherwise the opposite mass assignment is chosen.
- A cut on the time difference  $\delta t_e = \min[|\delta t_{\pi e}|, |\delta t_{e\pi}|]$  is applied :  $|\delta t_e| < 1 \text{ ns}$

BDT

$$2.5 \text{ ns} < |\delta t_{\pi\pi}| < 10 \text{ ns}$$



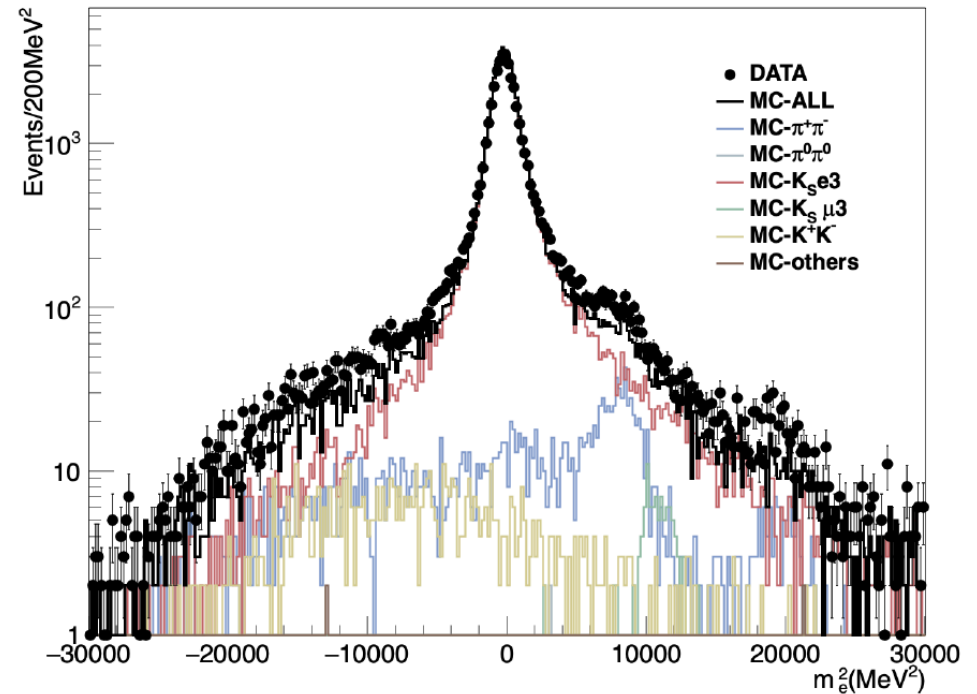
$\delta t(e\pi)$  vs  $\delta t(\pi e)$



# Measurement of the $K_S \rightarrow \pi e \nu$ branching ratio



- Signal count from fit to  $M^2(e)$  distribution
- $49647 \pm 316$   $K_{Se3}$  events
- Selection efficiency from  $K_S \rightarrow \pi^+ \pi^-$   $K_L \rightarrow \pi e \nu$  close to IP data control sample
- Study of systematic uncertainties from:  
BDT and TOF selection cuts, fit range, trigger,  
on-line filter, event classification, T0 determination,  
 $K_L$ -crash and  $\beta^*$  selection,  $K_S$  identification



Including systematic uncertainty, factors involved in the BR extraction are:

$$\epsilon_{\pi^+ \pi^-} = (96.657 \pm 0.088)\%$$

$$\epsilon_{\pi e \nu} = (19.38 \pm 0.10)\%$$

$$R_\epsilon = 1.1882 \pm 0.0059$$

KLOE new BR

$$\text{BR}(K_S \rightarrow \pi e \nu) = (7.211 \pm 0.046_{\text{stat}} \pm 0.052_{\text{syst}}) \times 10^{-4}$$



- KLOE previous result:

$\text{BR}(K_{S^3}) = (7.046 \pm 0.078 \pm 0.049) \times 10^{-4}$  [KLOE PLB636 (2006)] (independent control sample  $L=0.41 \text{ fb}^{-1}$ )

Combined BR

$$\text{BR}(K_S \rightarrow \pi e \nu) = (7.153 \pm 0.037_{\text{stat}} \pm 0.043_{\text{syst}}) \times 10^{-4}$$

- From

$$\mathcal{B}(K_S \rightarrow \pi \ell \nu) = \frac{G^2 (f_+(0) |V_{us}|)^2}{192 \pi^3} \tau_S m_K^5 I_K^\ell S_{\text{EW}} (1 + \delta_{\text{EM}}^{K\ell})$$

Using the values  $S_{\text{EW}} = 1.0232 \pm 0.0003$  [Marciano, Sirlin PRL 71 (1993) 3629]

and  $I_K^e = 0.15470 \pm 0.00015$  and  $\delta_{\text{EM}}^{Ke} = (1.16 \pm 0.03) \times 10^{-2}$

[Seng, Galviz, Marciano, Meissner, PRD 105, (2022) 013005]

we derive:

$$f_+(0) |V_{us}| = 0.2170 \pm 0.0009$$

**KLOE-2 result (2022)**

Paper submitted to JHEP



- KLOE+KLOE-2 data sample, about  $8\text{fb}^{-1}$ , represents the largest sample ever collected at the  $\phi(1020)$  peak
- Entangled neutral Kaons copiously produced at DAΦNE are ideal to investigate fundamental discrete symmetries and QM
- KLOE data have been used to test various models which predicts QM decoherence and CPTV exploiting the  $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  channel and reaching unprecedented precision on measured quantum decoherence parameters (JHEP 04 (2022) 059)
- The first direct test of T and CPT symmetries with  $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$  has also been performed using KLOE data, the paper is in preparation
- Moreover, a new combined measurement of the  $K_S \rightarrow \pi \nu e$  branching ratio, obtained from KLOE data improving precision of a factor of two, has been just submitted to JHEP



SPARE SLIDES



KLOE-2 coll. EPJC (2010) 68, 619

<http://agenda.infn.it/event/kloe2ws> procs. EPJ WoC 166 (2018)

## KAON Physics:

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

## Hadronic cross section

- ISR studies with  $3\pi$ ,  $4\pi$  final states
- $F_p$  with increased statistics
- Measurement of  $a_\mu^{\text{HLO}}$  in the space-like region using Bhabha process

## Dark forces:

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

## Light meson Physics:

- $\eta$  decays,  $\omega$  decays
- Transition Form Factors
- C,P,CP violation: improve limits on  
 $\eta \rightarrow \gamma\gamma\gamma$ ,  $\pi^+\pi^-$ ,  $\pi^0\pi^0$ ,  $\pi^0\pi^0\gamma$
- improve  $\eta \rightarrow \pi^+\pi^-e^+e^-$
- $\chi pT$  :  $\eta \rightarrow \pi^0\gamma\gamma$
- Light scalar mesons:  $f_0(500)$  in  $\Phi \rightarrow K_S K_S \gamma$
- $\gamma\gamma$  Physics:  $\gamma\gamma \rightarrow \pi^0$  and  $\pi^0$  TFF
- Search for axion-like particles



# Search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

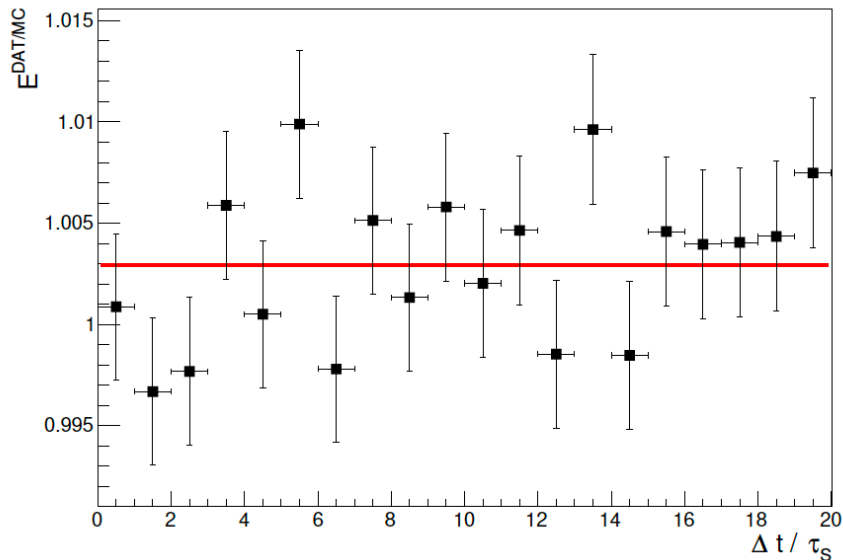


$$\epsilon_{\text{tot}} = \epsilon_{\text{trig}} \epsilon_{\text{reco}} \epsilon_{\text{cuts}} \longrightarrow$$

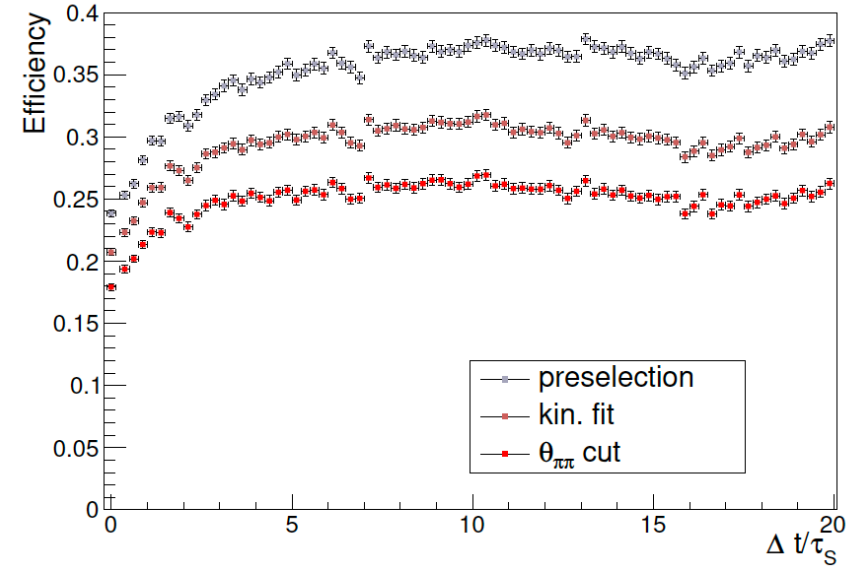
Only dependence on  $\Delta t$  is crucial not  $\epsilon_{\text{tot}}$  absolute global value

From MC

Data/MC corrected using independent control samples of high-purity  $K_S K_L \rightarrow \pi^+ \pi^- \pi \mu \nu$  with  $p$  distribution overlapping signal



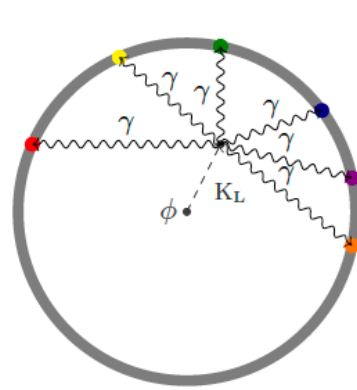
Small correction obtained as ratio of data/MC  $\Delta t$  distributions of  $K_S K_L \rightarrow \pi^+ \pi^- \pi \mu \nu$  events



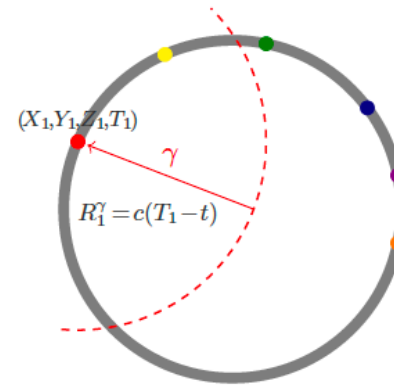
- $\epsilon_{\text{tot}} \sim 25\%$  in average, small reduction at  $\Delta t \approx 0$  due to:
- lower reconstruction probability due to longer extrapolation length of both tracks to IP
  - possible swap of tracks associated to different kaon decay vertices for vertices close in time



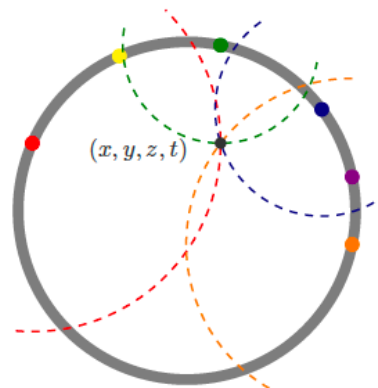
Trilateration-based method to identify  $K_L$  decay point and time



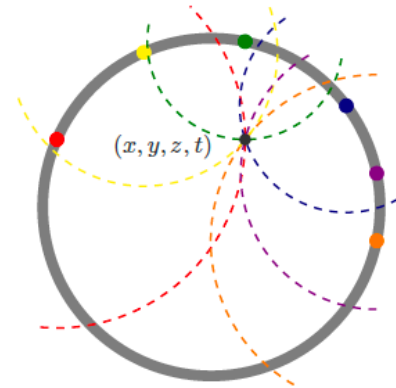
(a) Schematic presentation of a  $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$  decay in the transverse view of KLOE EMC (gray band) which records at maximum 6 photon interaction points (labeled with dots of different colors).



(b) For each of the points of  $\gamma$  interaction in the detector, a set of possible creation points of this  $\gamma$  quantum is a sphere (dashed line) centered at the known location of the EMC cluster and with a radius parametrized by an unknown time  $t$  of  $K_L$  decay.



(c) The  $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$  decay vertex is found as an analytically-calculated intersection of the possible origin spheres of at least 4 recorded photons.



(d) If 5 or 6 photons were registered, the additional reference points can be used to find the intersection numerically, minimizing effects if uncertainties on determination of EMC cluster locations and times.



CP-asymmetric ratios independent of D parameter:

$$R_2^{CP}(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]} = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}$$

$$R_4^{CP}(\Delta t) = \frac{P[K_-(0) \rightarrow K^0(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]} = \frac{I(\pi^+ \pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+ \pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

CP tests are performed along with T and CPT ones as cross-check and control of systematic effects



# T/CPT Tests with $\phi \rightarrow K_S K_L \rightarrow 3 \pi^0 \pi \nu e, \pi \pi \pi \nu e$



## Systematics

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
$\Delta t$ 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 $\rho$	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 <sup>st</sup> TOF cut	0.001600	0.002220	0.001620	0.002190	0.003830	0.003950	0.003890	–
2 <sup>nd</sup> TOF cut parameter A	0.000671	0.000581	0.000684	0.000569	0.000878	0.000899	0.000889	–
2 <sup>nd</sup> TOF cut parameter B	0.000369	0.000433	0.000375	0.000426	0.000076	0.000077	0.000076	–
2 <sup>nd</sup> TOF cut parameter C	0.000152	0.000399	0.000154	0.000393	0.000278	0.000283	0.000281	–
2 <sup>nd</sup> TOF cut parameter D	0.001420	0.000850	0.001450	0.000836	0.002050	0.002110	0.002080	–
3 <sup>rd</sup> TOF cut circle R	0.005140	0.004470	0.005230	0.004390	0.003560	0.003640	0.003600	–
3 <sup>rd</sup> TOF cut ellipse A	0.002280	0.001020	0.002320	0.001000	0.002760	0.002850	0.002800	–
3 <sup>rd</sup> 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 $\rho$	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
$ \vec{p}_{tot} $	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 <sup>st</sup> TOF cut parameter A	0.000021	0.000385	0.000389	0.000020	0.000392	0.000405	–	0.000426
1 <sup>st</sup> TOF cut parameter B	0.001450	0.001080	0.001070	0.001470	0.000407	0.000417	–	0.000417
2 <sup>nd</sup> TOF cut parameter $R_1$	0.000171	0.000256	0.000262	0.000175	0.000126	0.000130	–	0.000140
2 <sup>nd</sup> TOF cut parameter $R_2$	0.001570	0.001200	0.001190	0.001590	0.000399	0.000410	–	0.000414
<b>Total systematic uncertainty</b>	<b>0.014</b>	<b>0.015</b>	<b>0.014</b>	<b>0.015</b>	<b>0.019</b>	<b>0.019</b>	<b>0.019</b>	<b>0.00089</b>
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				



# Measurement of the $K_S \rightarrow \pi e \nu$ branching ratio



Selection	$R_\epsilon = (\epsilon_{\pi\pi}/\epsilon_{\pi e \nu})_{\text{com}}$
Trigger	$1.0297 \pm 0.0003$
On-line filter	$1.0054 \pm 0.0001$
Event classification	$1.0635 \pm 0.0004$
T0 time	$1.0063 \pm 0.0001$
$K_L$ -crash	$1.0295 \pm 0.0010$
$K_S$ vertex reconstr.	$1.0418 \pm 0.0009$
$R_\epsilon$	$1.1882 \pm 0.0012$

Selection	Efficiency
Preselection (from MC)	$0.9961 \pm 0.0002$
Kin. variables selection	$0.9720 \pm 0.0007$
BDT selection	$0.6534 \pm 0.0013$
TCA selection	$0.4639 \pm 0.0009$
TOF selection	$0.6605 \pm 0.0012$
Total	$0.1938 \pm 0.0006$

Selection	$\delta\epsilon_{\pi e \nu}^{\text{syst}} [10^{-4}]$	$\delta\epsilon_{\pi^+\pi^-}^{\text{syst}} [10^{-4}]$
BDT selection	5.3	
TCA & TOF selection	6.0	
Fit parameters	3.0	
$K_S \rightarrow \pi^+\pi^-$ efficiency		8.8
Total	8.5	8.8

