Latest results on Kaon Physics at KLOE-2

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on behalf of the KLOE-2 collaboration

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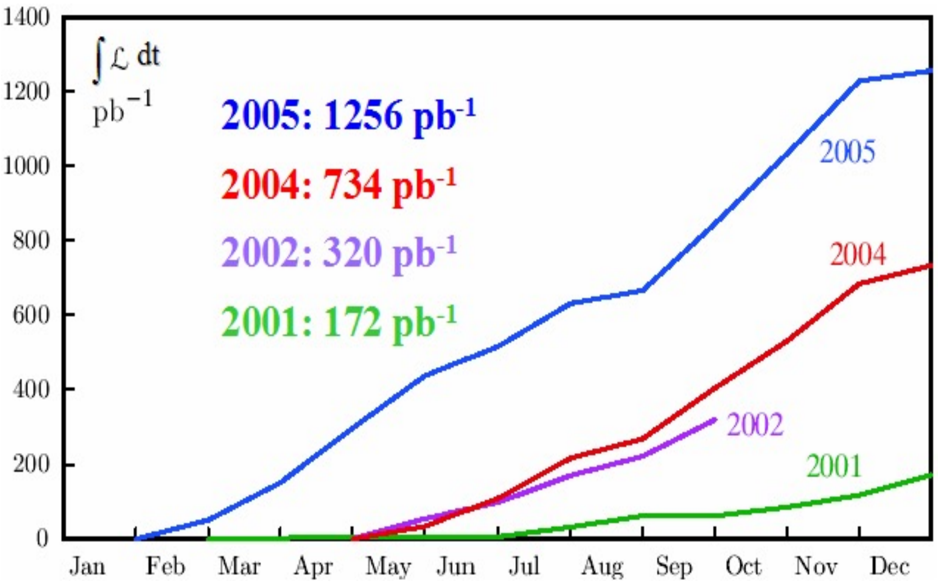
The KLOE detector at the Frascati ϕ-factory DAΦNE

DAFNE collider

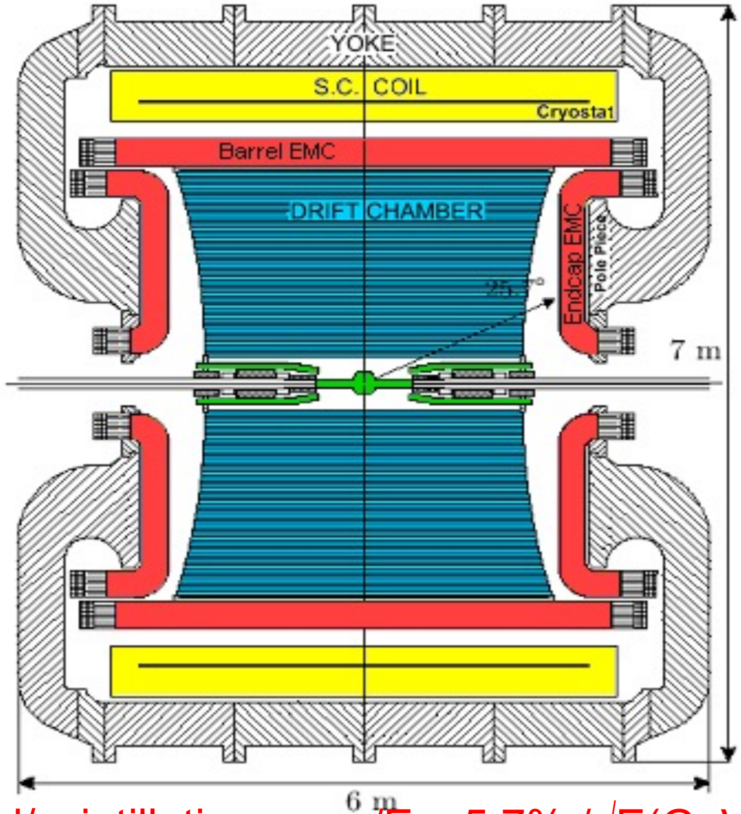
Integrated luminosity (KLOE)



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

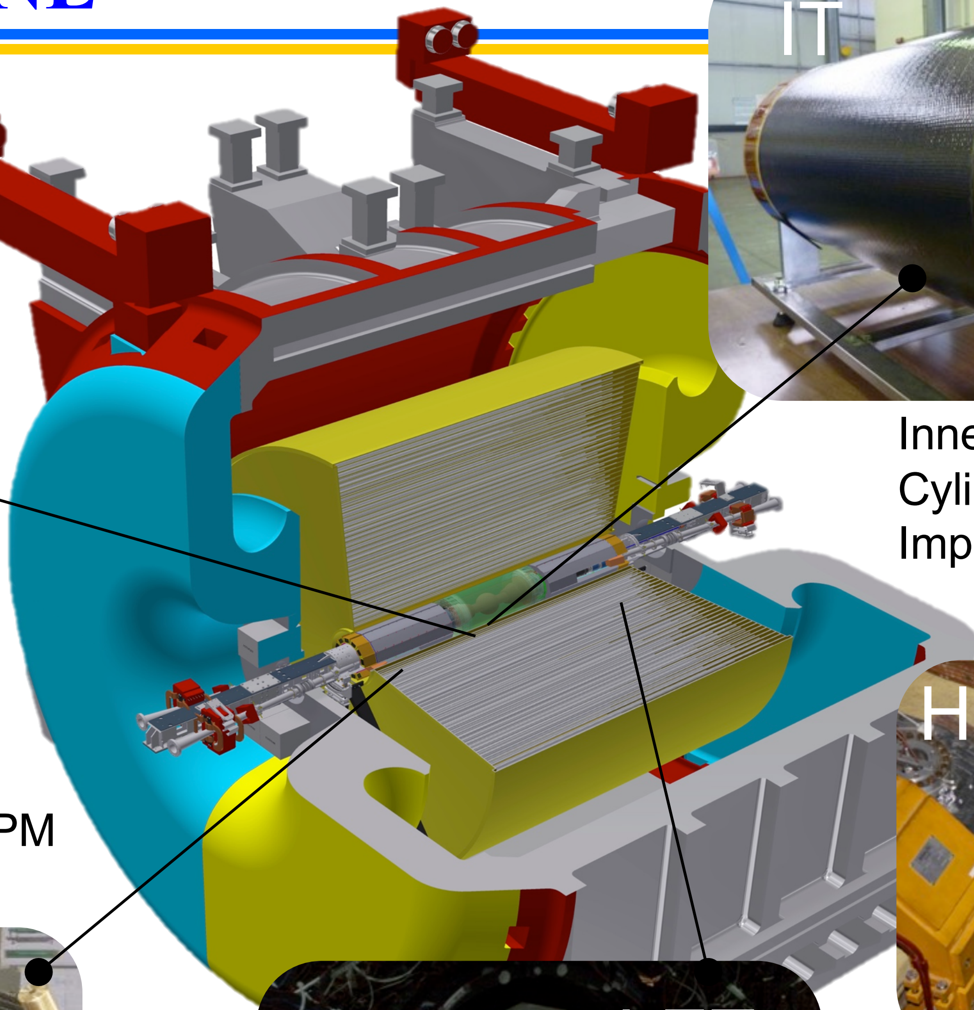
Superconducting coil B = 0.52 T



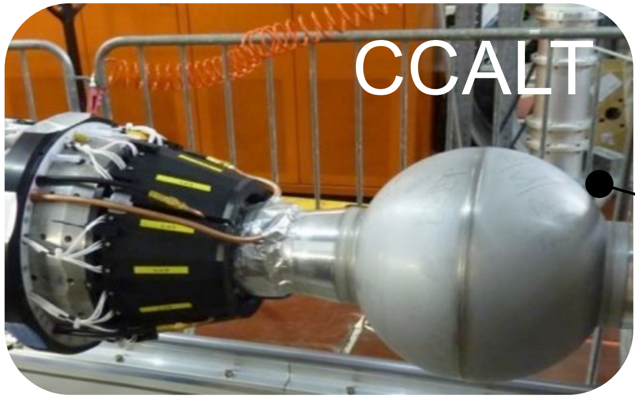
Lead/scintillating fiber calorimeter $\sigma_E/E \cong 5.7\% /\sqrt{E(\text{GeV})}$
$\sigma_t \cong 54$ ps $/\sqrt{E(\text{GeV})} \oplus 50$ ps

drift chamber; 4 m diameter $\times$ 3.3 m length
90% He - 10% isobutane gas mixture
$\sigma(p_\perp)/p_\perp \simeq 0.4$ % $\sigma_{xy} \simeq 150\ \mu$m $\sigma_z \simeq 2$ mm

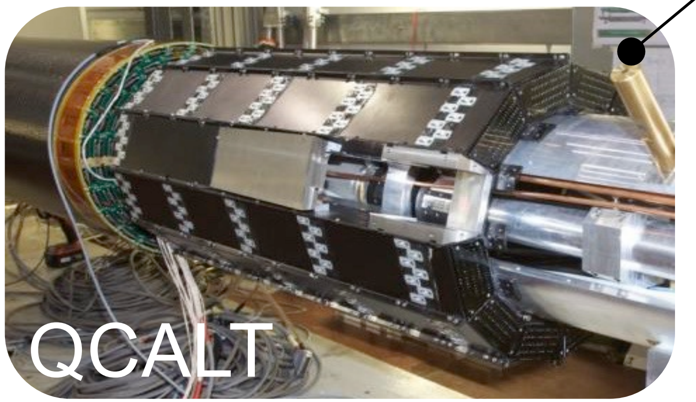
KLOE-2 at DAΦNE

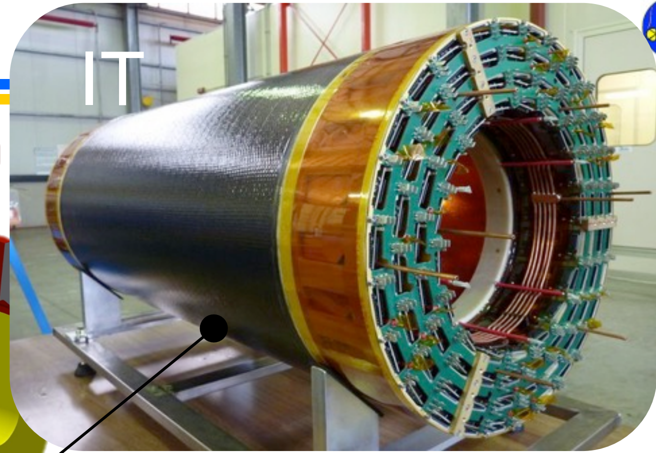


LYSO Crystal w SiPM
Low polar angle

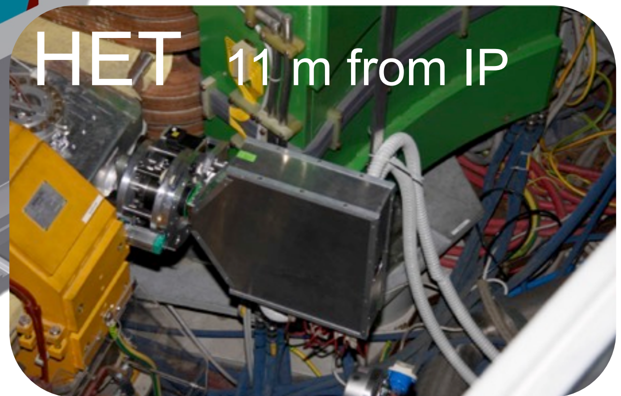


Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation





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



Scintillator hodoscope +PMTs

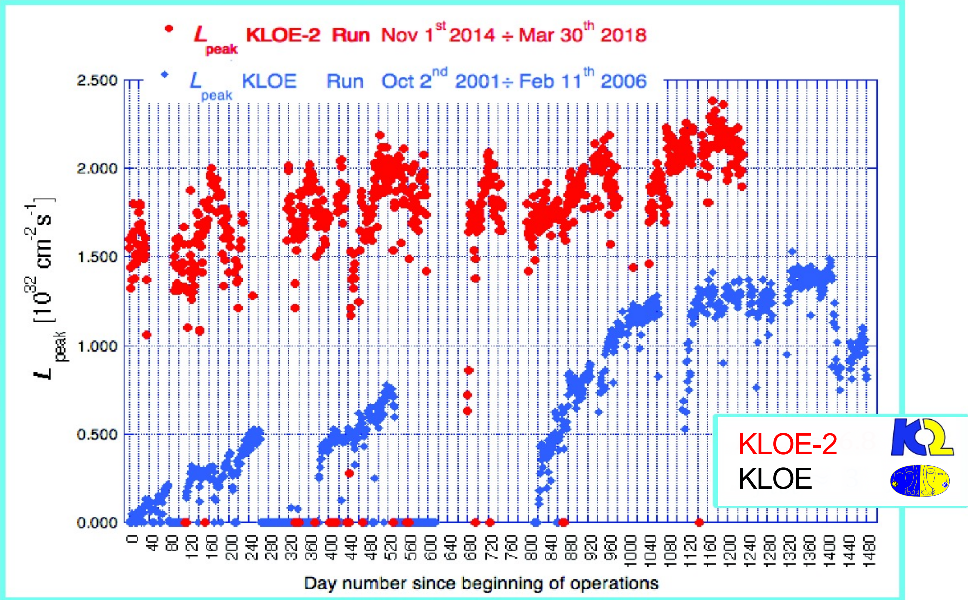
calorimeters LYSO+SiPMs
at ~ 1 m from IP

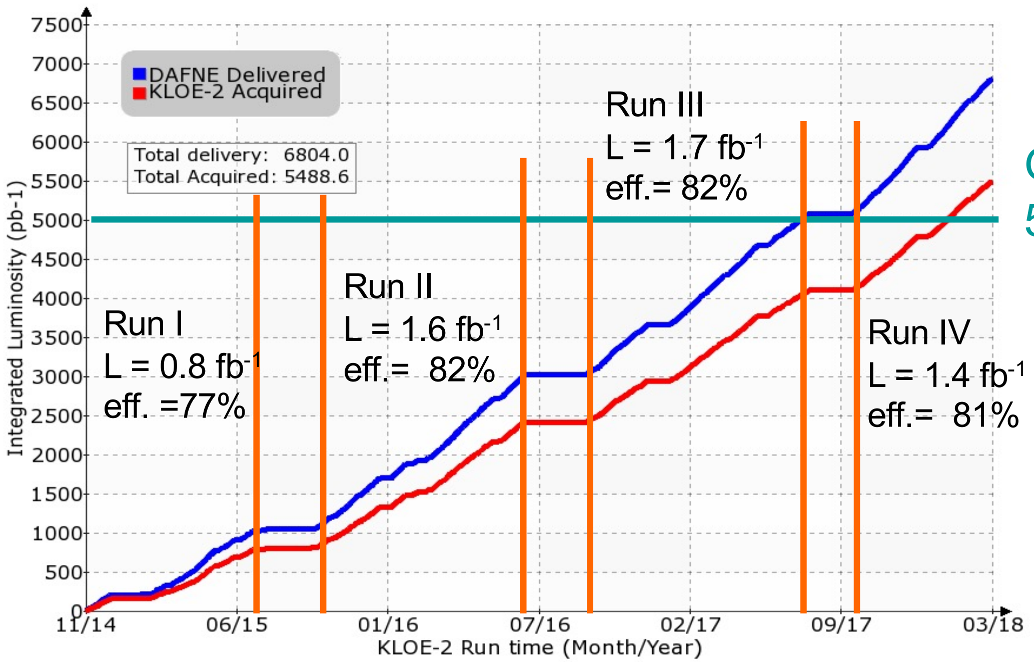
The KLOE-2 data-taking

- **DAΦNE upgrade (2008) with a new interaction scheme with large Piwinski angle~(σz/σx)(θ/2) + crab waist sextupoles**
- **Dec.2012-July 2013: installation of KLOE-2 new detectors**
- **July 2013: DAΦNE operations started for KLOE-2**
- **November 17, 2014: start of KLOE-2 run**
- **March 30, 2018: End of KLOE-2 data-taking**

⇒ 5.5 fb^{-1} collected @$\sqrt{s}=M_\phi$

- **Best performance in KLOE-2 run:**
  $L_{peak} = 2.4 \times 10^{32}\ cm^{-2}s^{-1}$ $\int Ldt = 14\ pb^{-1}/day$





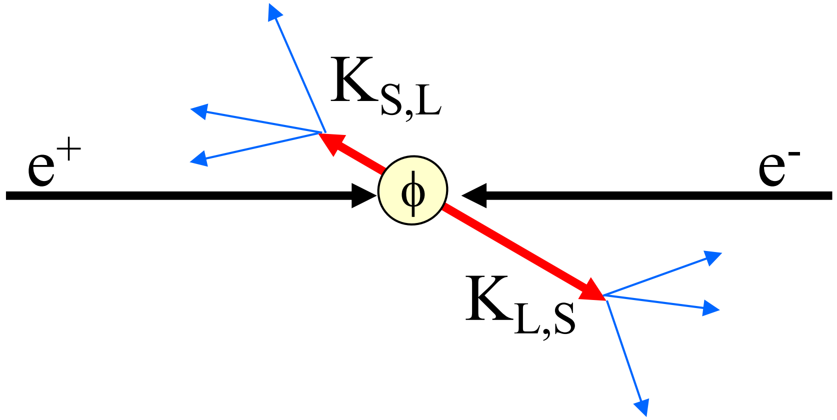
Goal: 5 fb^{-1}

KLOE + KLOE-2 data sample:
- ~ 8 fb^{-1} ⇒ 2.4 × 10^{10} φ's produced
- ~ 8 x10^9 K_SK_L pairs
- ~ 3 x10^8 η's
- ⇒ the largest sample ever collected at the φ(1020) peak in e^+e^- collisions

Neutral kaons at a ϕ-factory

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \to \phi \qquad \sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- BR($\phi \to K^0\bar{K}^0$) $\sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:



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

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

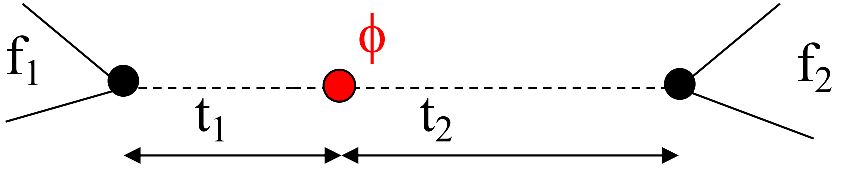
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

$p_K = 110$ MeV/c

$\lambda_S = 6$ mm $\qquad \lambda_L = 3.5$ m

EPR correlations in entangled neutral kaons

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$



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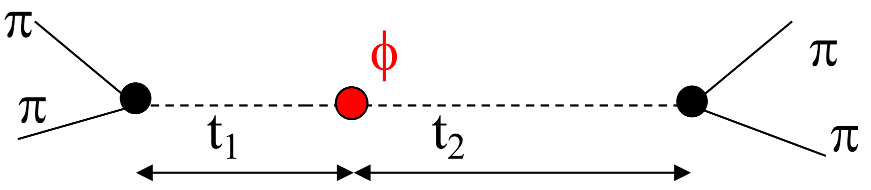

Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$
(this specific channel is suppressed by CP viol.
$|\eta_{+-}|^2 = |A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-)|^2 \sim |\varepsilon|^2 \sim 10^{-6}$)

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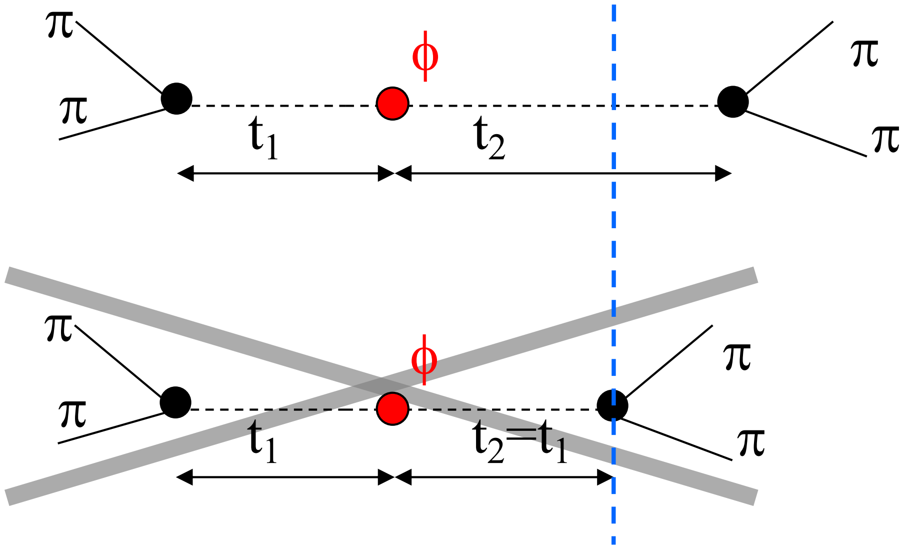

EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the fully destructive quantum interference

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EPR correlations in entangled neutral kaons

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0\right\rangle\left|\overline{K}^0\right\rangle - \left|\overline{K}^0\right\rangle\left|K^0\right\rangle\right]$$

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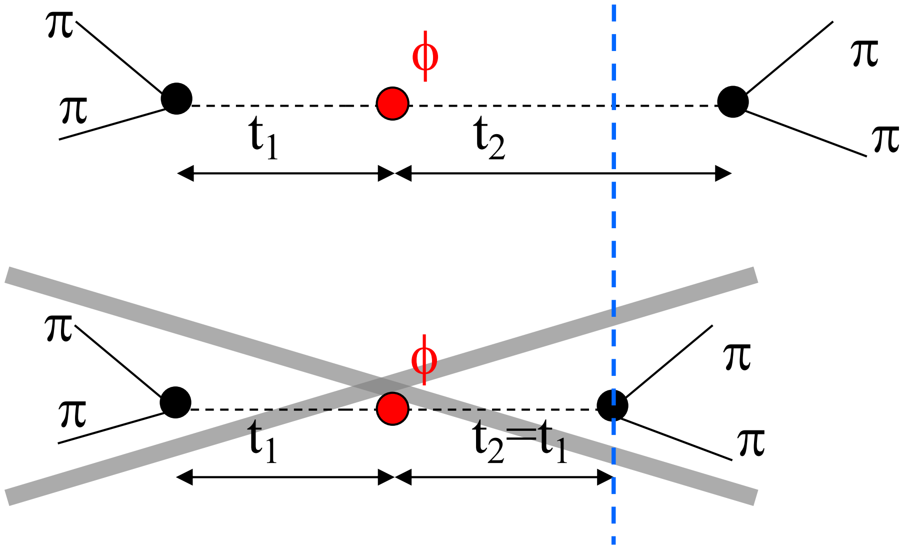

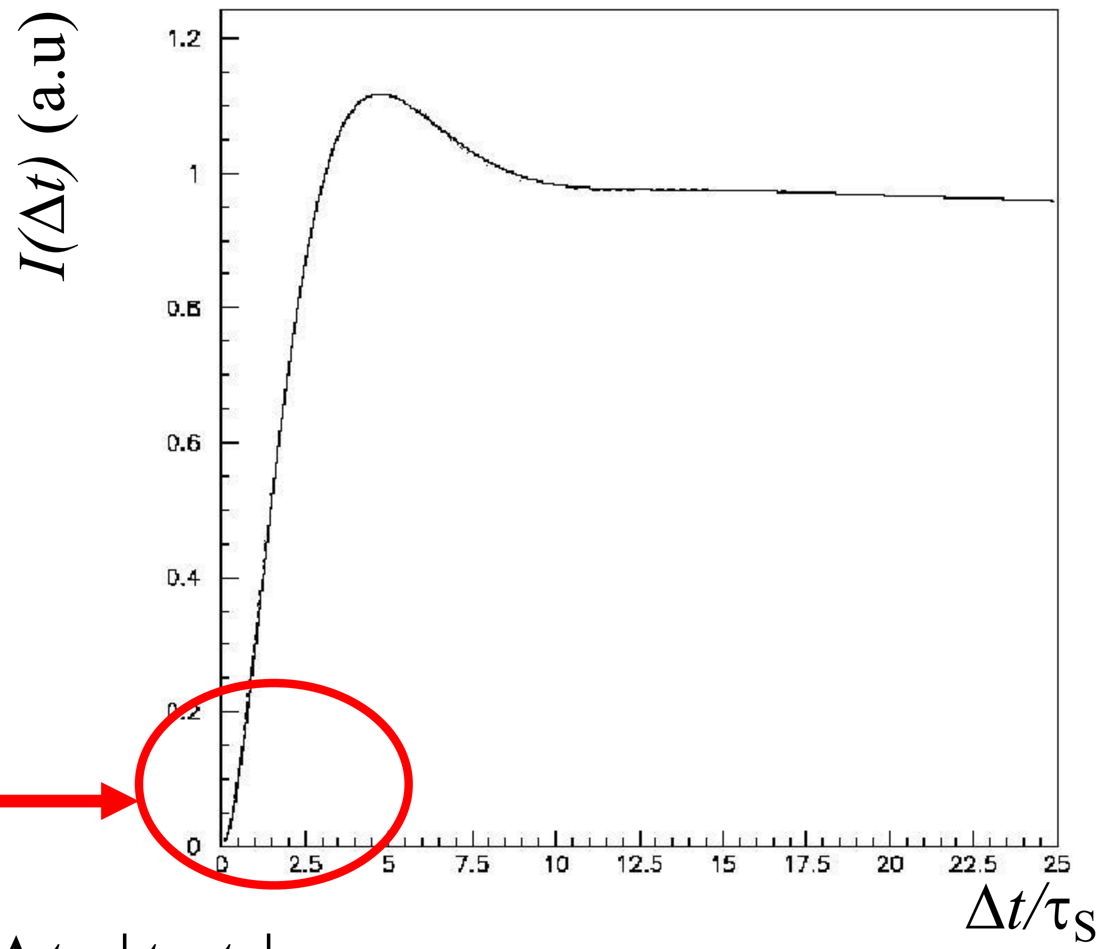

EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the fully destructive quantum interference

$\Delta t = |t_1 - t_2|$

Search for decoherence and CPT violation effects in the entangled neutral kaon system

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0\right\rangle\left|\overline{K}^0\right\rangle - \left|\overline{K}^0\right\rangle\left|K^0\right\rangle\right]$$

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

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^+\pi^-$: test of quantum coherence

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$

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$$-\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\Big]$$

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$$\left. -\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\left\langle\pi^+\pi^-,\pi^+\pi^-\right|K^0\overline{K}^0(\Delta t)\right\rangle\left\langle\pi^+\pi^-,\pi^+\pi^-\right|\overline{K}^0K^0(\Delta t)\right\rangle^*\right)\right]$$

Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \to \quad$ QM

$\zeta_{0\bar{0}} = 1 \quad \to \quad$ total decoherence

(also known as Furry's hypothesis or spontaneous factorization)
W.Furry, PR 49 (1936) 393

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

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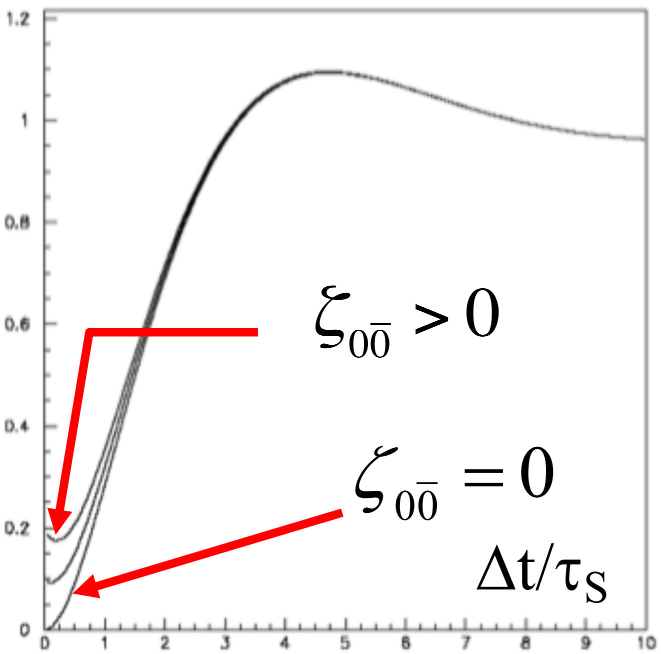
$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\left[\left|\left\langle \pi^+\pi^-,\pi^+\pi^- \middle| K^0\overline{K}^0(\Delta t)\right\rangle\right|^2 + \left|\left\langle \pi^+\pi^-,\pi^+\pi^- \middle| \overline{K}^0 K^0(\Delta t)\right\rangle\right|^2 \right.$$
$$\left. -(1-\zeta_{0\bar{0}})\cdot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

I(Δt) (a.u.)



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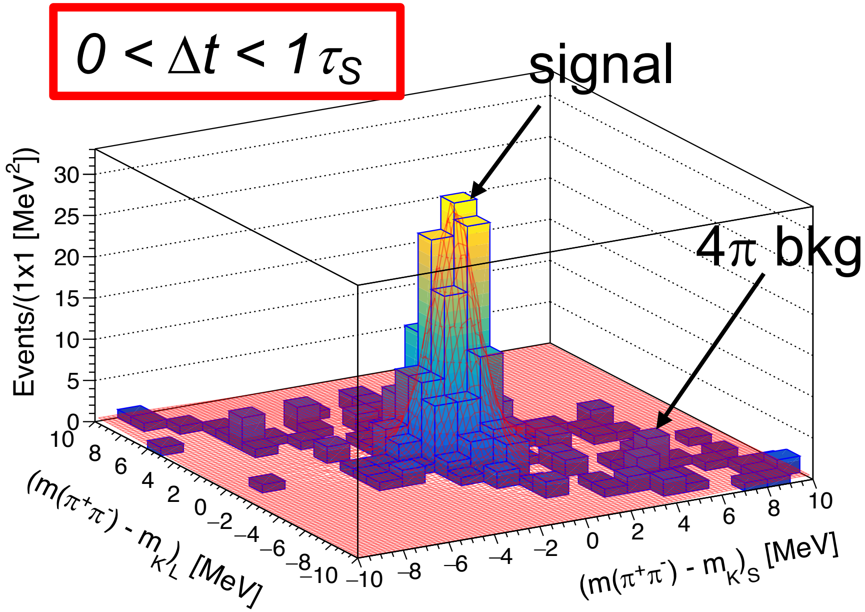
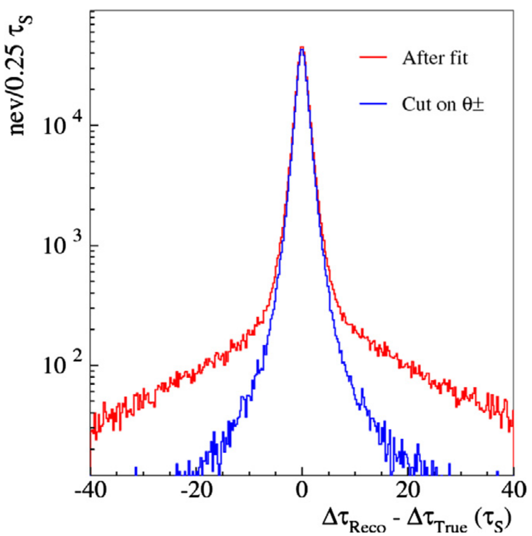
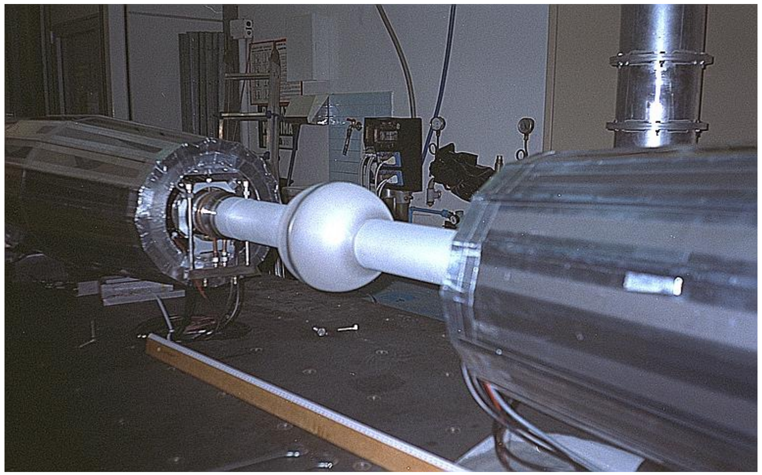
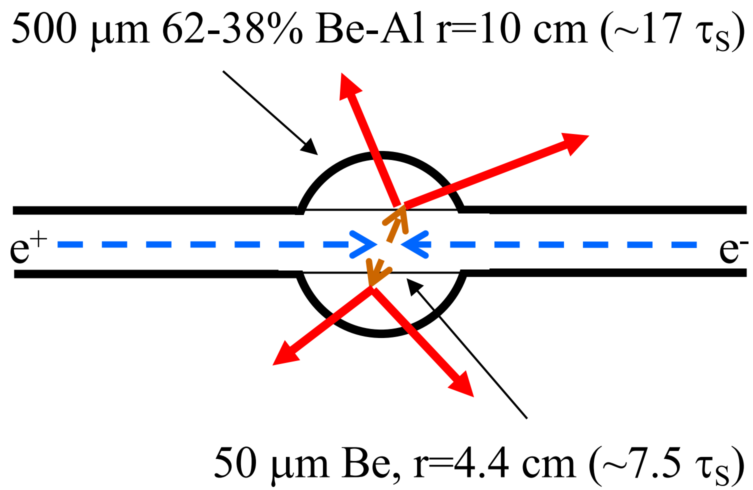
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: 1.7 fb^{-1}
- Fit of Δt distribution taking into account resolution, efficiency and background effects.
- Improvements wrt previous analysis:
    - more precise $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ background determination from a 2D fit of $K_{S,L}$ invariant mass distribution
    - fiducial volume chosen to avoid regeneration background from the spherical beam pipe
    - cut on $\pi^+\pi^-$ opening angle to reduce tails in Δt resolution









$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

KLOE-2 JHEP 04 (2022) 059

$$\boxed{\zeta_{0\bar{0}} = \left(-0.5 \pm 8.0_{stat} \pm 3.7_{syst}\right)\times 10^{-7}}$$

CP violating process:

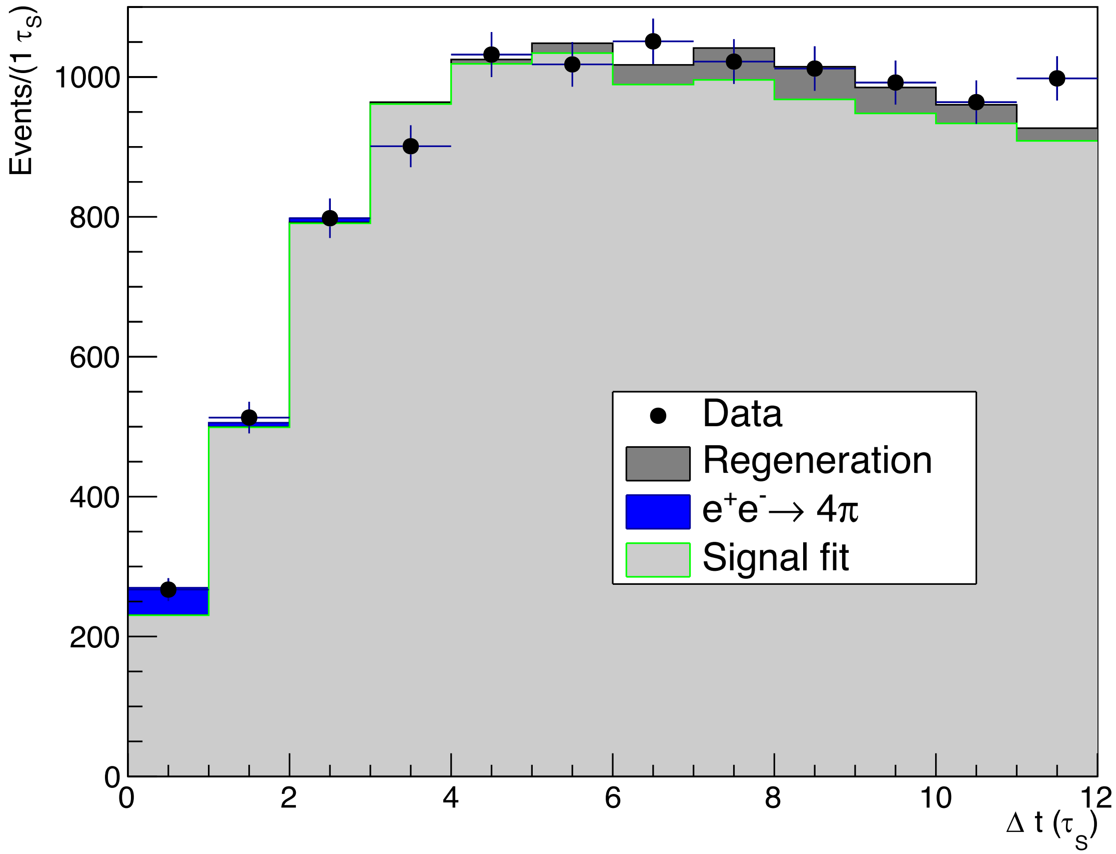
terms $\zeta_{00}/|\eta_{+-}|^2$ with $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$

=> high sensitivity to ζ_{00} ;

CP violation in kaon mixing acts as amplification mechanism

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$



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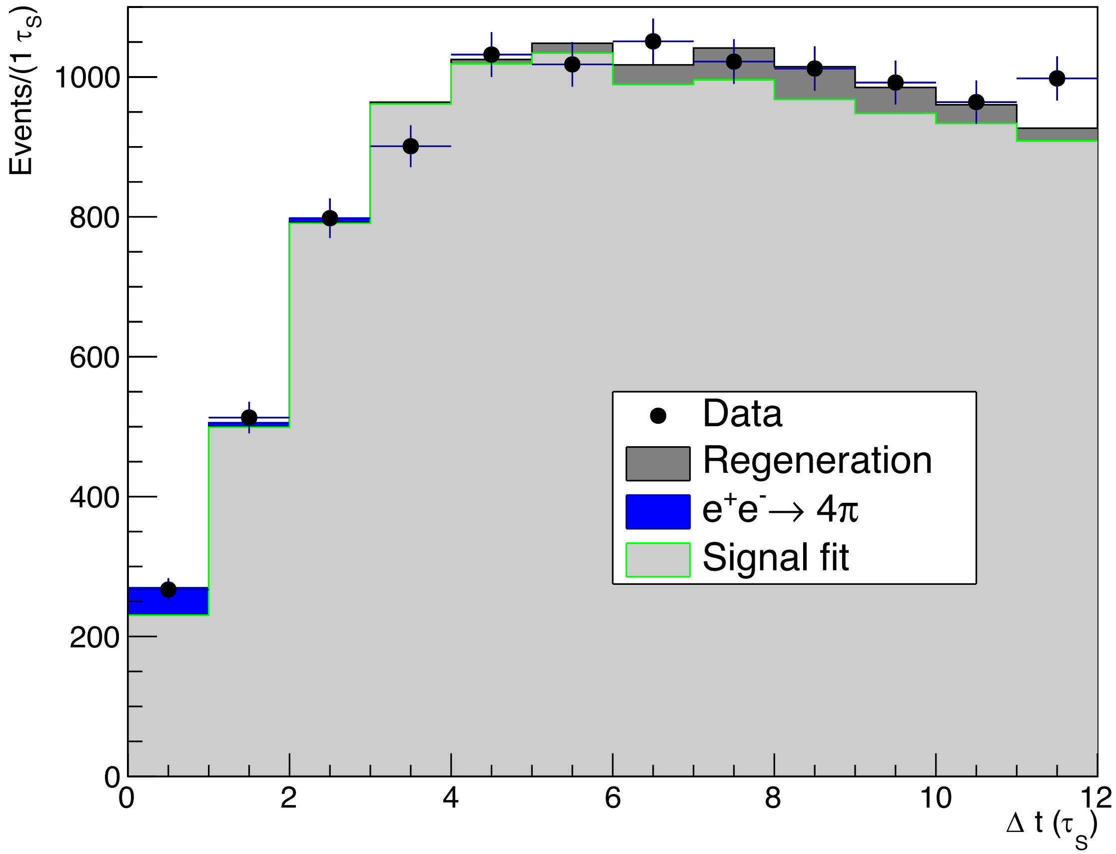


Possible decoherence due quantum gravity effects (apparent loss of unitarity) implying also CPT violation => modified Liouville – von Neumann equation for the density matrix of the kaon system depends on a CPTV parameter γ [J. Ellis et al. PRD53 (1996) 3846]

In this scenario γ can be at most:

$$O(m_K^2/M_{PLANCK}) = 2\times10^{-20}\ GeV$$

KLOE-2 result

$$\gamma = \left(1.3 \pm 9.4_{stat} \pm 4.2_{syst}\right) \times 10^{-22}\ \mathrm{GeV}$$

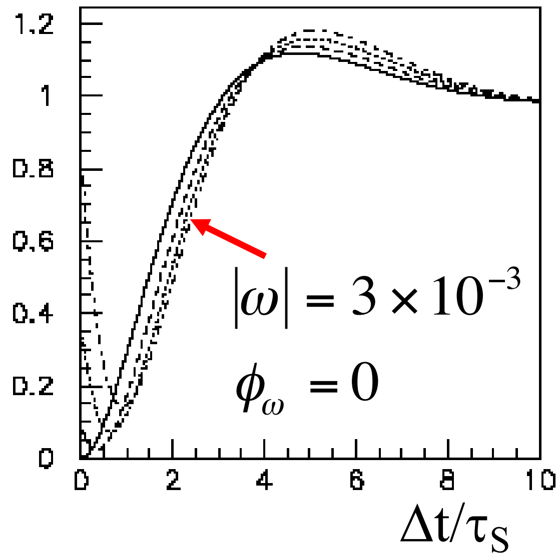
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\ \pi^+\pi^-$: CPT violation in entangled K states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

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

I($\pi^+\pi^-$, $\pi^+\pi^-$;Δt) (a.u.)



at most one expects:

$$\boxed{|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}}$$

In some microscopic models of space-time foam arising from non-critical string theory [Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014] : $|\omega| \sim 10^{-4} \div 10^{-5}$

The maximum sensitivity to ω is expected for $f_1=f_2=\pi^+\pi^-$ (terms: $|\omega|/|\eta_{+-}|$)
All CPTV effects induced by QG ($\alpha,\beta,\gamma,\omega$) could be simultaneously disentangled.

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^+\pi^-$: CPT violation in entangled K states

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$$\propto \left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right) + \omega\left(|K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle\right)$$

at most one expects:

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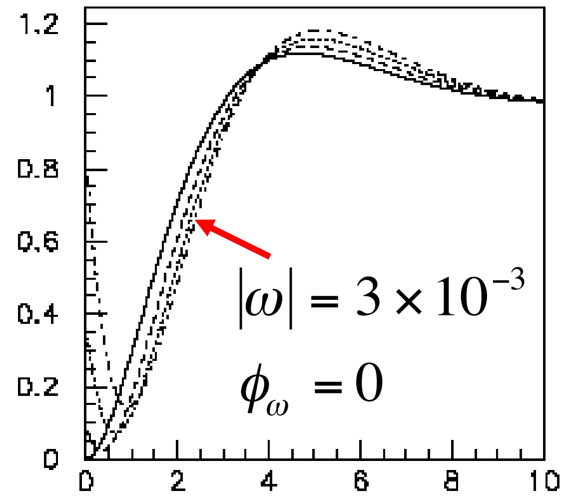
$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



$\Delta t/\tau_S$

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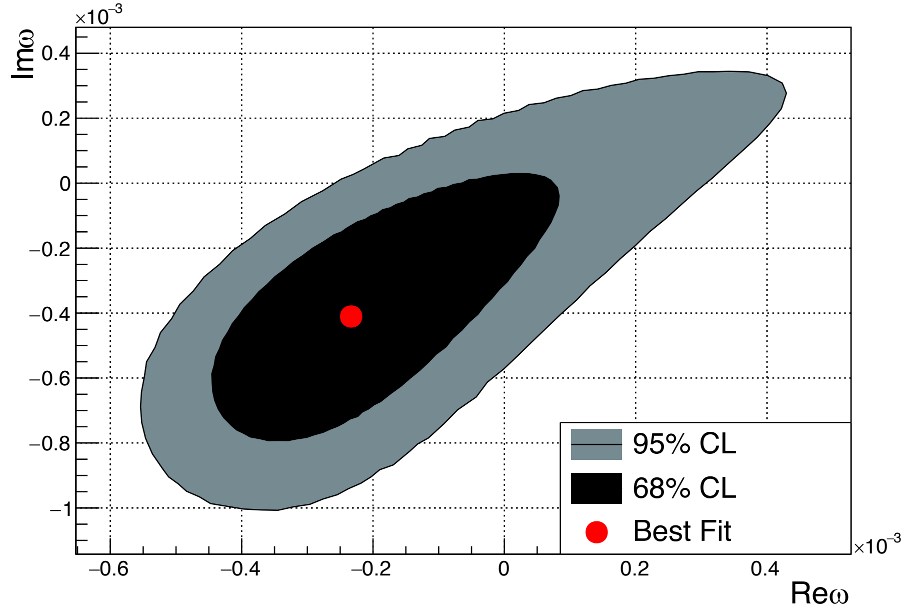
All CPTV effects induced by QG $(\alpha,\beta,\gamma,\omega)$ could be simultaneously disentangled.

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled K states

The fit with $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$ yields (1.7 fb-1):

$$\Re\omega = \left(-2.3^{+1.9}_{-1.5\,stat} \pm 0.6_{syst}\right)\times 10^{-4}$$
$$\Im\omega = \left(-4.1^{+2.8}_{-2.6\,stat} \pm 0.9_{syst}\right)\times 10^{-4}$$
$$|\omega| = \left(4.7 \pm 2.9_{stat} \pm 1.0_{syst}\right)\times 10^{-4}$$
$$\phi_\omega = -2.1 \pm 0.2_{stat} \pm 0.1_{syst}\ \text{rad}$$



from $|\omega|^2 = \dfrac{\mathrm{BR}(\phi \to K_S K_S, K_L K_L)}{\mathrm{BR}(\phi \to K_S K_L)}$

$\mathrm{BR}(\phi \to K_S K_S, K_L K_L) < 2.4\times 10^{-7}$
at 90% C.L.

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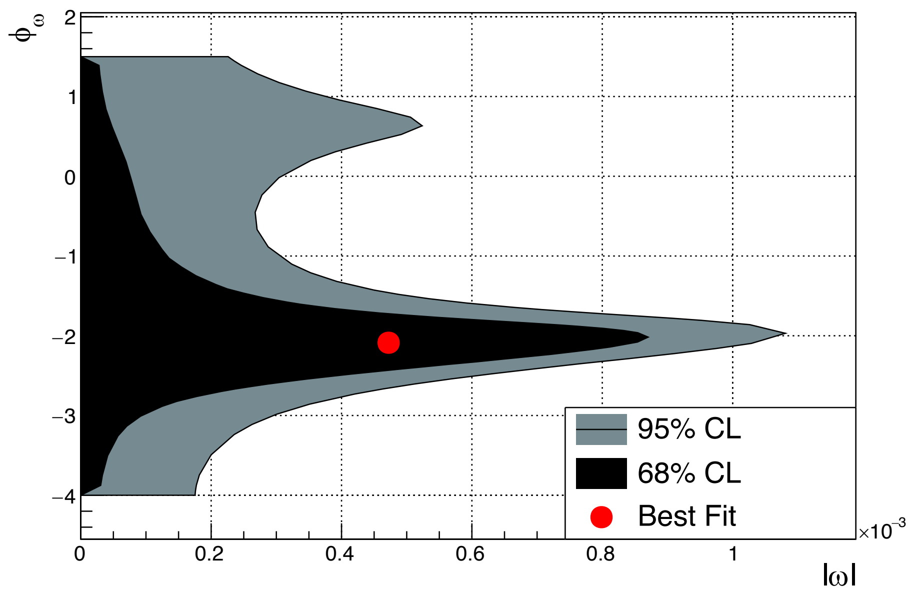

In the B system:
$-0.0084 \le \Re\omega \le 0.0100$ at 95% C.L.
Alvarez, Bernabeu, Nebot JHEP 11 (2006) 087
(see also Bernabeu et al, EPJC (2017) 77:865)

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: summary of results

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

$$\lambda \cong \frac{\zeta_{SL}}{\Gamma_S} = (0.1 \pm 1.2_{stat} \pm 0.5_{syst})\times 10^{-16}\ \mathrm{GeV}$$

$\mathrm{BR}(\phi \rightarrow K_S K_S, K_L K_L) < 2.4\times 10^{-7}$
at 90% C.L.

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[improvement x2 wrt
KLOE PLB 642(2006) 315]

Systematic uncertainties

	$\delta\zeta_{SL}$ $\cdot 10^2$	$\delta\zeta_{0\bar{0}}$ $\cdot 10^7$	$\delta\gamma$ $\cdot 10^{21}$ 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
4π 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
Δt 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

Entanglement of neutral kaons as a tool for testing discrete symmetries

Direct CPT test in transitions

- Is it possible to test the CPT symmetry directly in transition processes between kaon states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states?

- CPT violating effects may not appear at first order in diagonal mass terms (survival probabilities) while they can manifest at first order in transitions (non-diagonal terms).

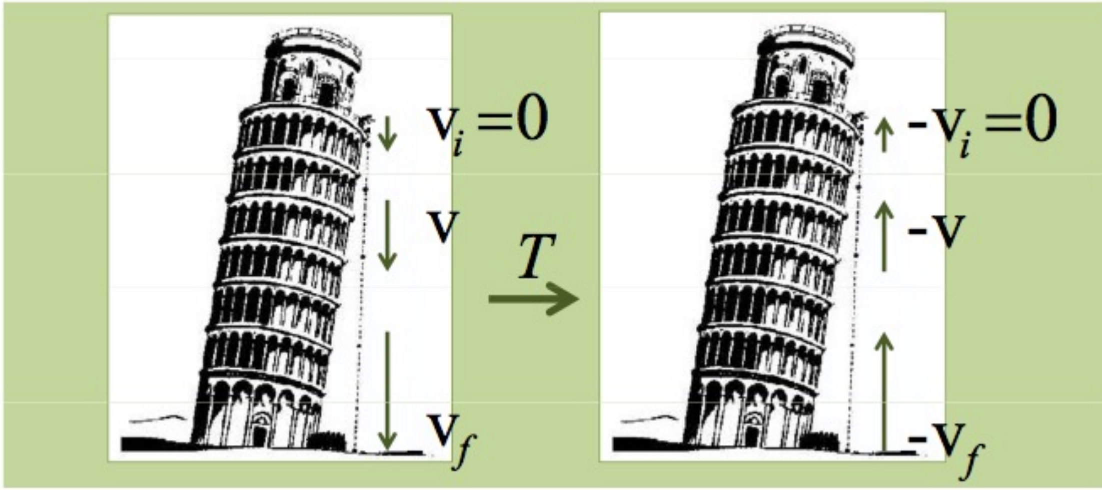
- Clean formulation required. Possible spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have to be well under control.

- In standard WWA the test is related to $\mathrm{Re}\delta$, a genuine CPT violating effect independent of $\Delta\Gamma$, i.e. not requiring the decay as an essential ingredient.

Probing CPT: J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139
Time-reversal violation: J. Bernabeu, A.D.D., P. Villanueva, NPB 868 (2013) 102

Time Reversal

•The transformation of a system corresponding to the inversion of events in time, or reversed dynamics, with the formal substitution $\Delta t \rightarrow -\Delta t$, is usually called '**time reversal**', but a more appropriate name would actually be **motion reversal**.



•Exchange of in ↔ out states and reversal of all momenta and spins tests time reversal, i.e. the symmetry of the responsible dynamics for the observed process under time reversal (transformation implemented in QM by an antiunitary operator)

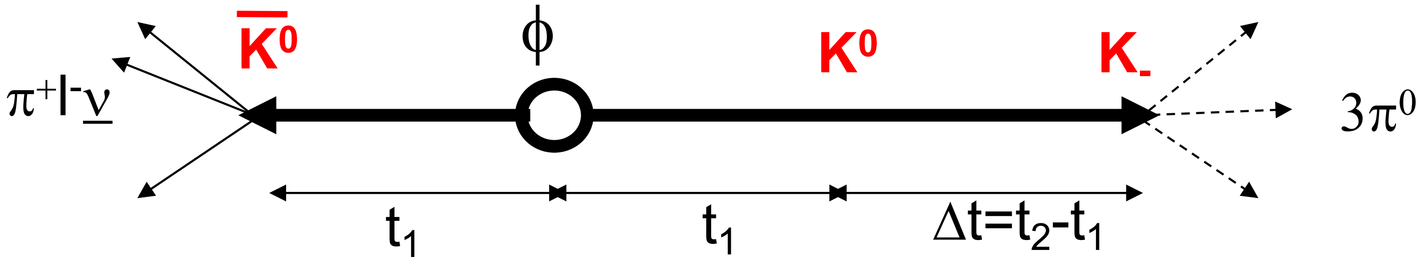
•Similarly for CPT tests: the exchange of in ↔ out states etc.. is required.

Entanglement in neutral kaon pairs

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

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

- decay as filtering measurement
- entanglement -> preparation of state



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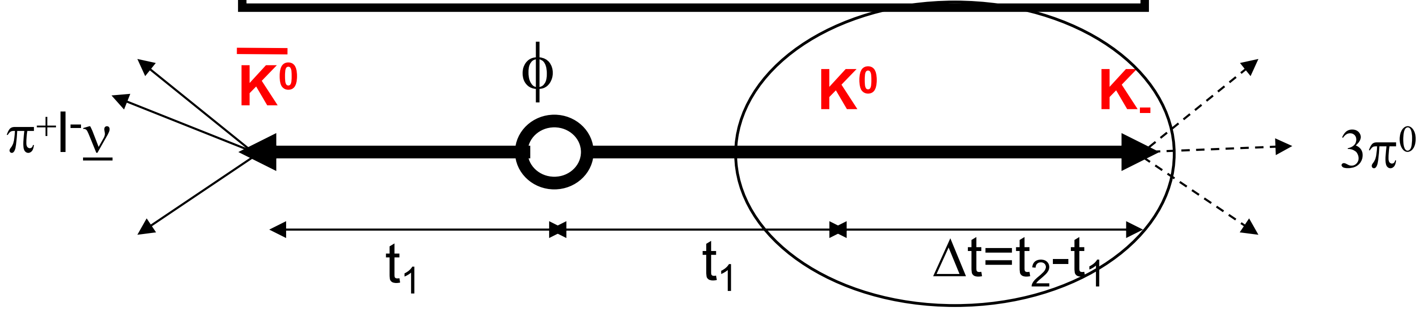

$K^0 \rightarrow K_-$ reference process

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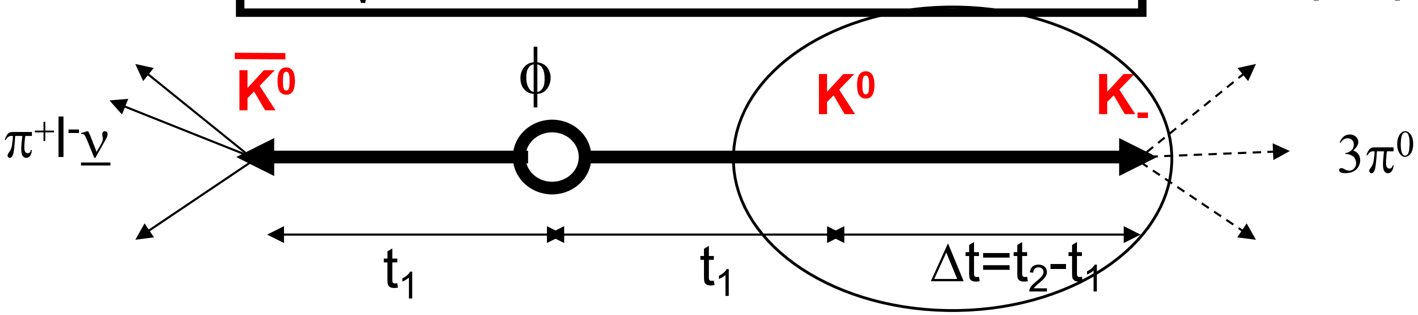

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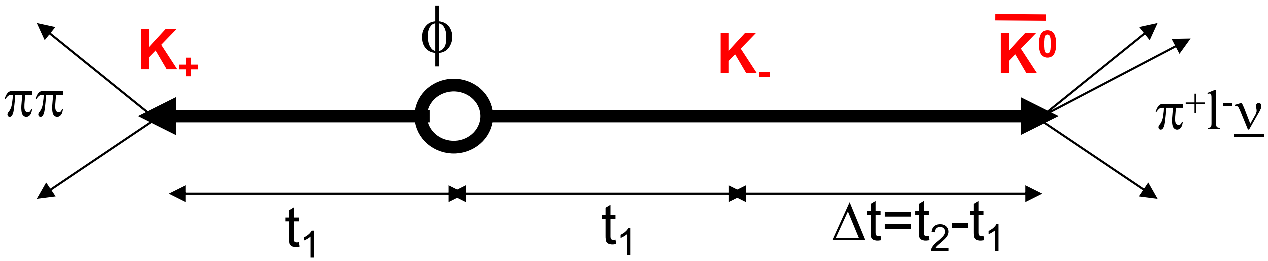

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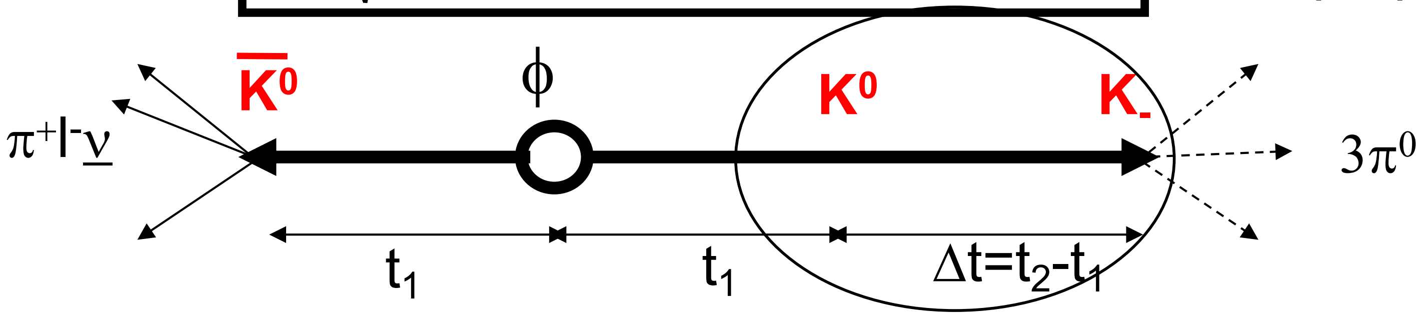
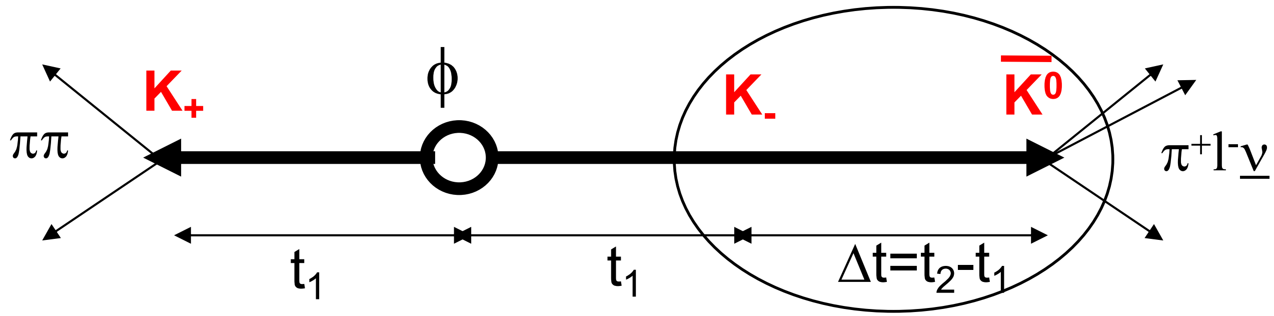


$K^0 \rightarrow K_-$ reference process

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



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- decay as filtering measurement
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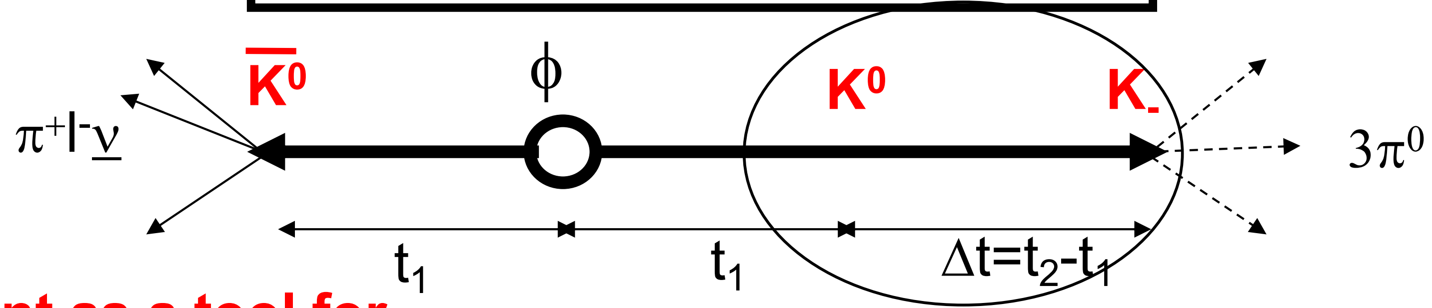
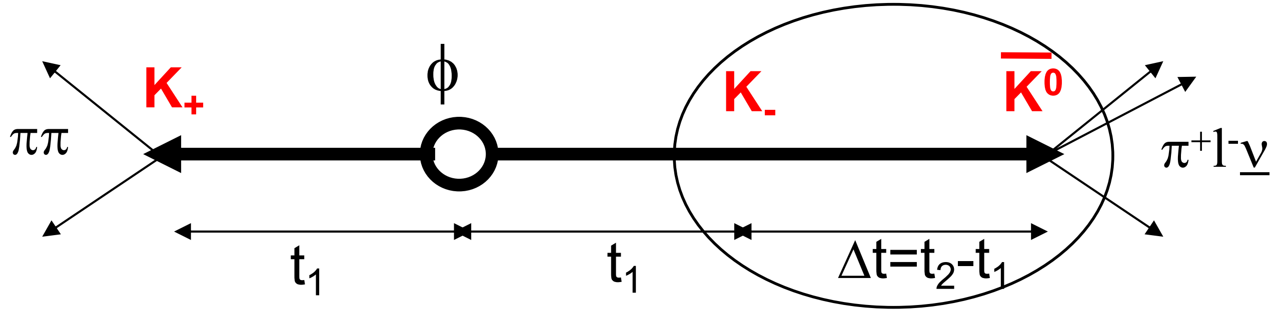


Entanglement as a tool for in <-> out state inversion

$K^0 \to K_-$ reference process

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



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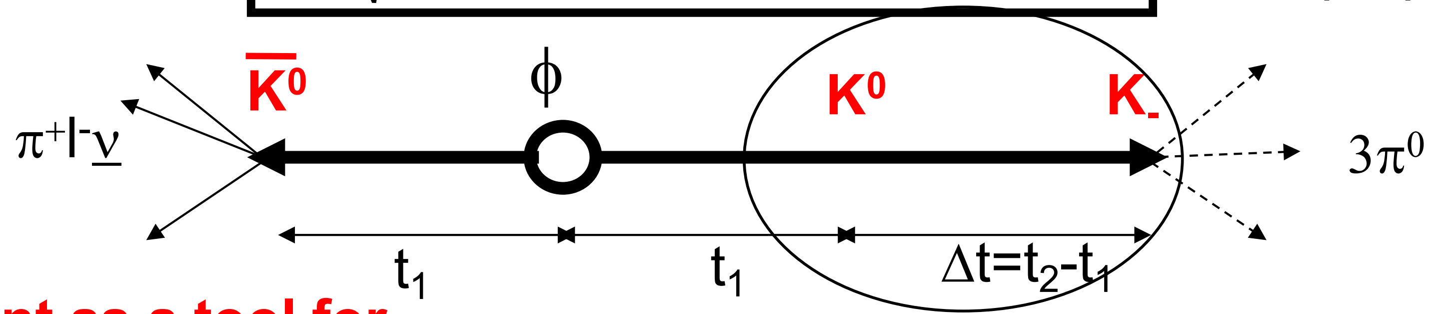


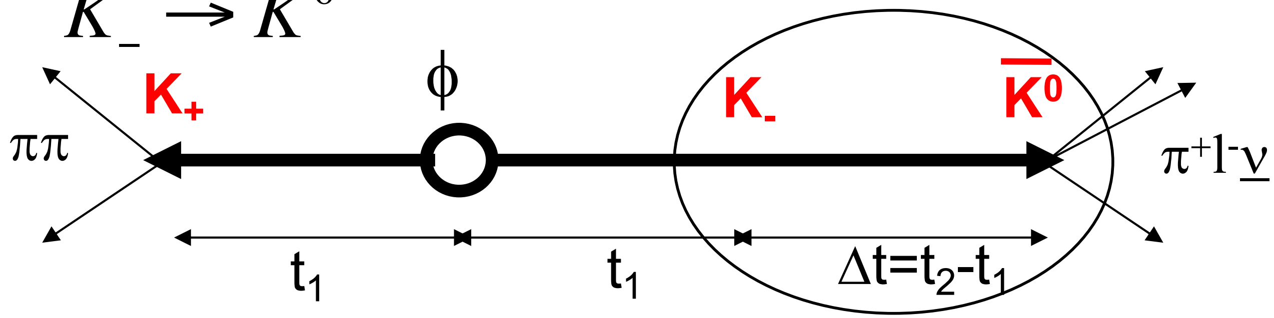
Entanglement as a tool for in <-> out state inversion

$K^0 \rightarrow K_-$ reference process

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

Note: CP and T conjugated process

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



T, CP, CPT tests in neutral kaon transitions at KLOE

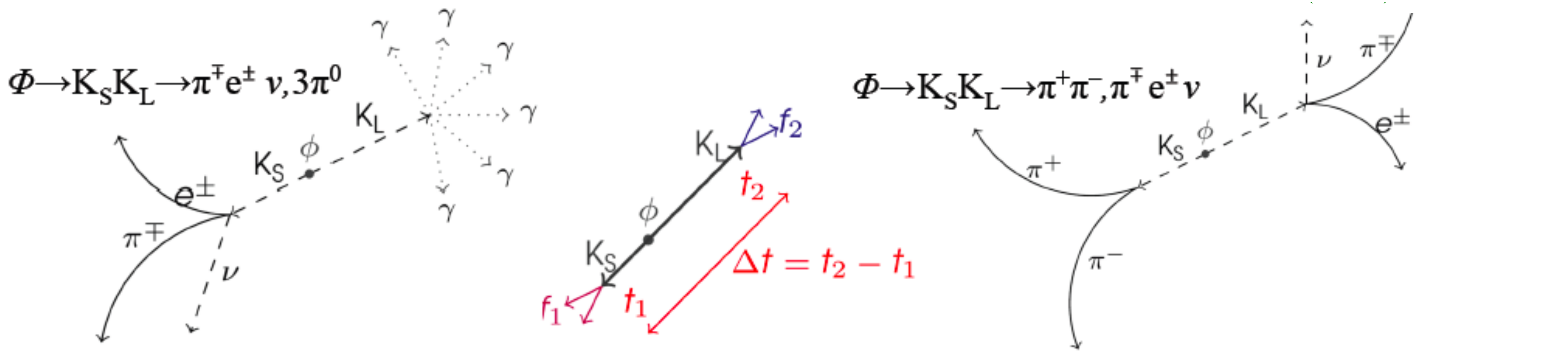
CPT **T** **CP** **observables**

$$R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)} \qquad R^{\rm exp}_{2,\mathcal{T}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\pi\pi,\ell^+;\Delta t)} \qquad R^{\rm exp}_{2,\mathcal{CP}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\ell^+,3\pi^0;\Delta t)}$$

$$R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^+,3\pi^0;\Delta t)}{I(\pi\pi,\ell^+;\Delta t)} \qquad R^{\rm exp}_{4,\mathcal{T}}(\Delta t) \equiv \frac{I(\ell^+,3\pi^0;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)} \qquad R^{\rm exp}_{4,\mathcal{CP}}(\Delta t) \equiv \frac{I(\pi\pi,\ell^+;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)}$$

$$\mathcal{DR}_{\mathcal{CPT}}(\Delta t \gg \tau_S) \equiv \frac{R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t \gg \tau_S)} \qquad \mathcal{DR}_{\mathcal{T},\mathcal{CP}}(\Delta t \gg \tau_S) \equiv \frac{R^{\rm exp}_{2,\mathcal{T}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\mathcal{T}}(\Delta t \gg \tau_S)} \equiv \frac{R^{\rm exp}_{2,\mathcal{CP}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\mathcal{CP}}(\Delta t \gg \tau_S)}$$

Corresponding to study the following processes at KLOE:



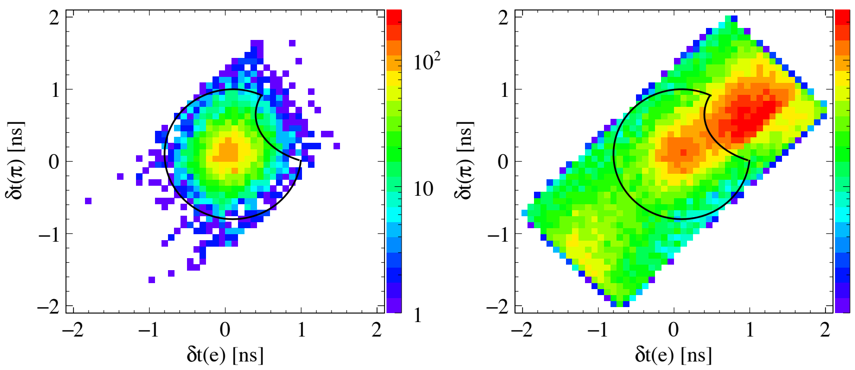
T, CP, CPT tests in neutral kaon transitions at KLOE

- Analysed data L=1.7 fb^{-1}
- Four processes studied:

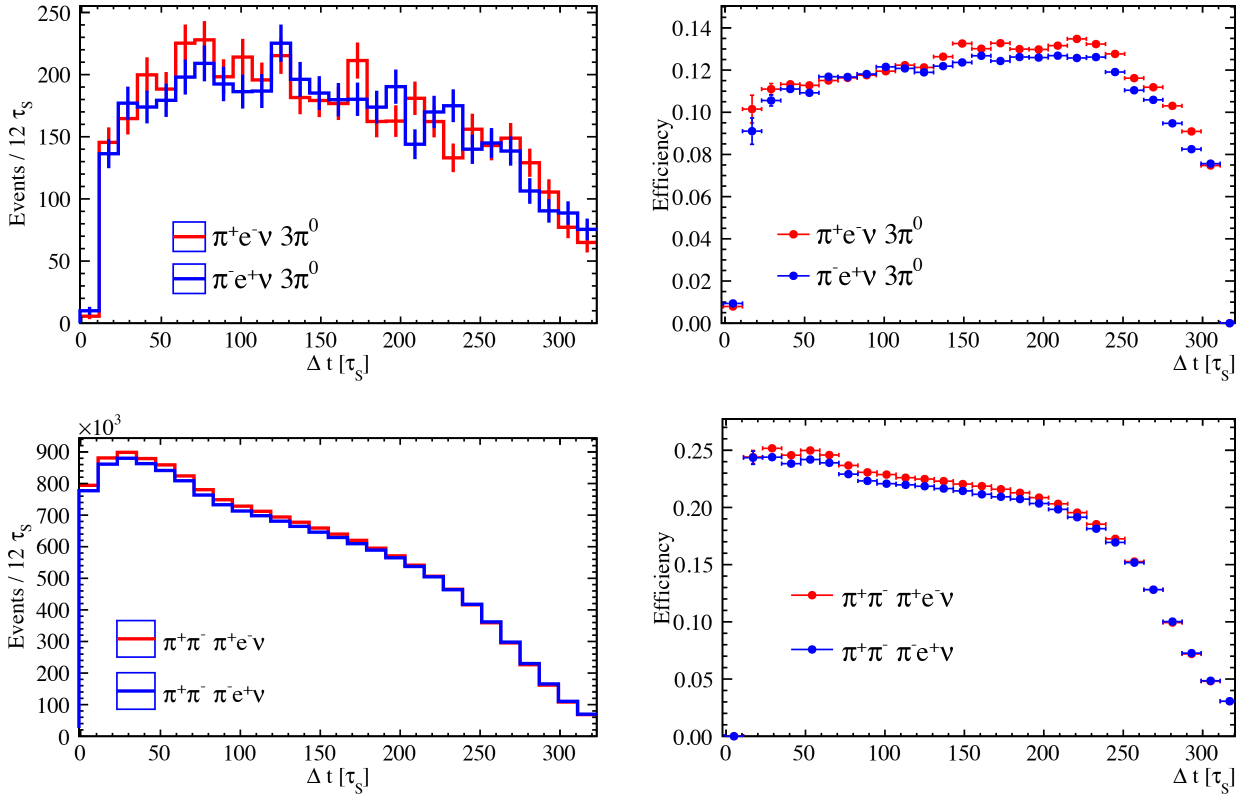
$\phi \to K_S K_L \to \pi e^{\pm}\nu\ 3\pi^0$ and $\pi^+\pi^-\ \pi e^{\pm}\nu$ in the asympotic regime: $\Delta t \gg \tau_S$

- Time of flight technique to identify semileptonic decays

MC K_S signal　　　Data



Measured double kaon decay intensities　　　efficiencies



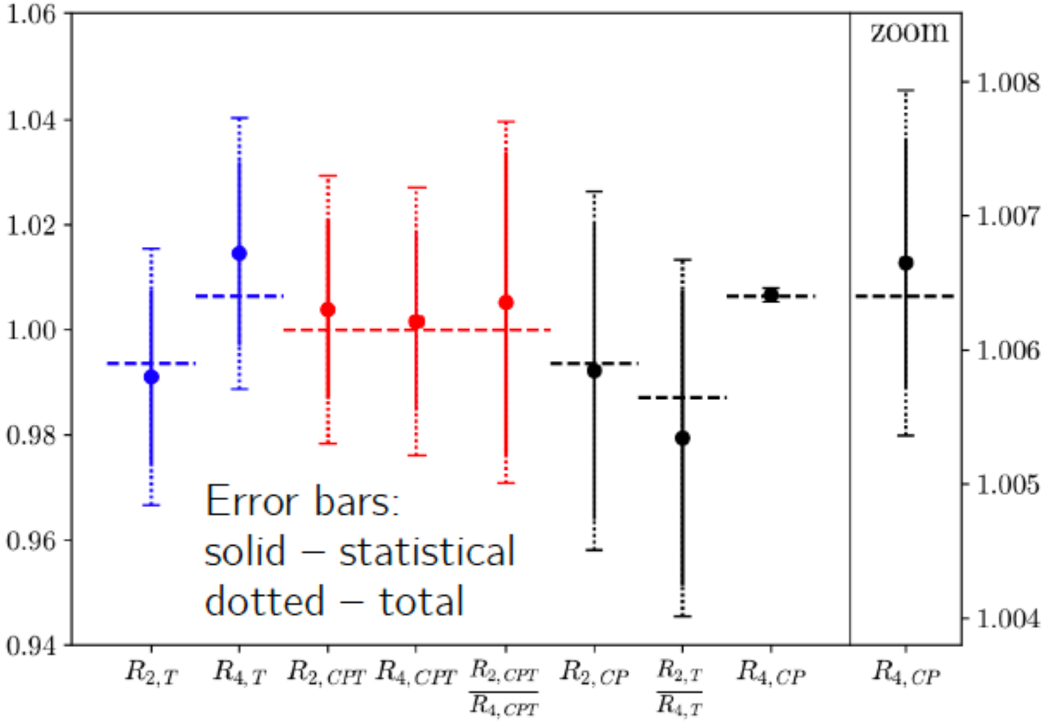
- residual background subtraction for $\pi e^{\pm}\nu\ 3\pi^0$ channel
- MC selection efficiencies corrected from data with 4 independent control samples

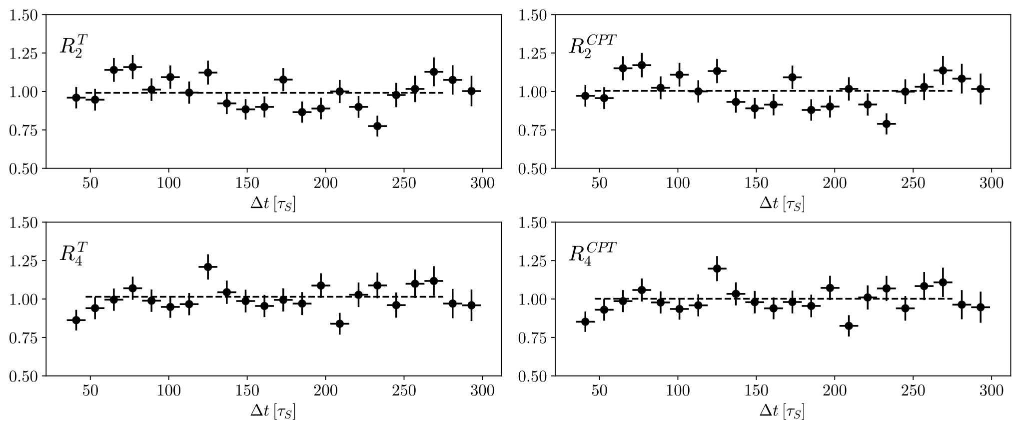
$K_S K_L \to \pi e^{\pm}\nu\ 3\pi^0$　　　$K_S K_L \to \pi^+\pi^-\ \pi e^{\pm}\nu$

$K_S \to \pi e \nu$ Klcrash　　$K_S K_L \to \pi^+\pi^-\ 3\pi^0$　　$K_S \to \pi^+\pi^-$ Klcrash　　$K_S K_L \to \pi^0\pi^0\ \pi e \nu$

T, CP, CPT tests in neutral kaon transitions at KLOE

horizontal dashed lines denote expected values:
CPT invariance and TV extrapolated from observed CPV (PDG)

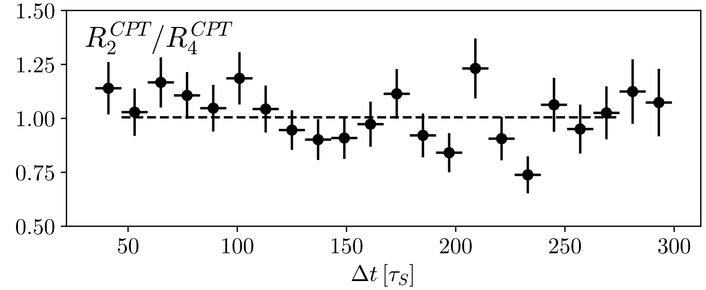




KLOE-2 result (2022)

(paper in preparation)

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



First T and CPT test in kaon transitions

Entanglement of neutral kaons as a tool for K_S studies

K_S tagging at KLOE

For times $t_1 >> \tau_S$ (or $t_2 >> \tau_S$):

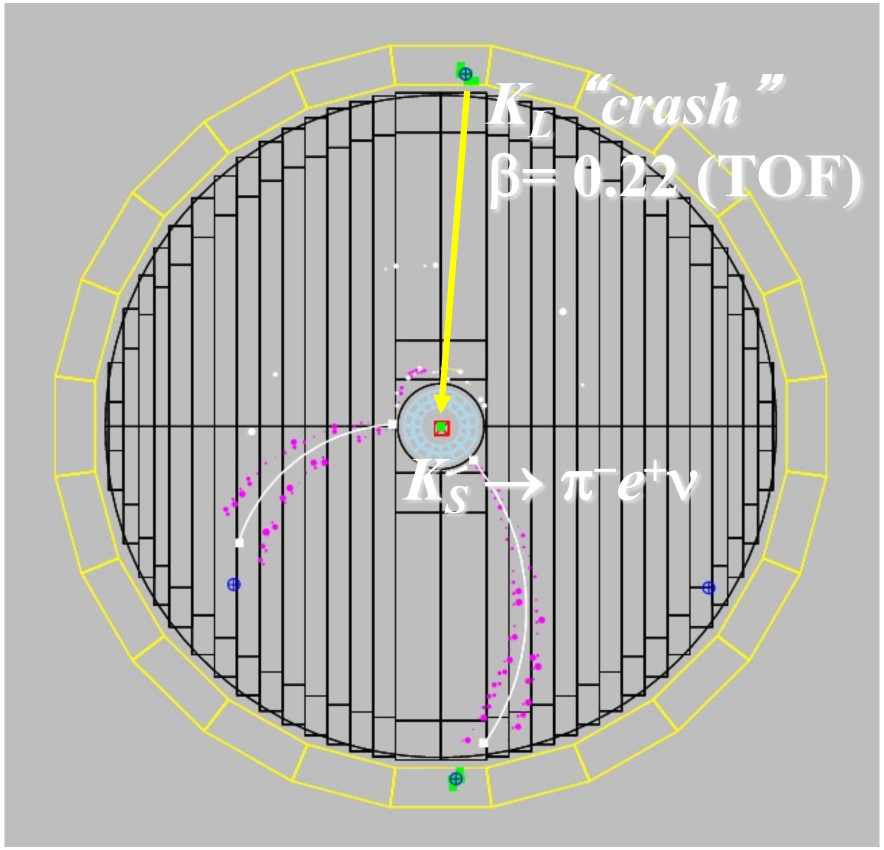
$$I(f_1,t_1;f_2,t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} \cancel{- 2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2} \cos[\Delta m(t_2 - t_1) + \phi_1 - \phi_2]}\right\}$$

=> the state behaves like an incoherent mixture of states:

$$|K_S(t_1)\rangle|K_L(t_2)\rangle \quad \text{or} \quad |K_L(t_1)\rangle|K_S(t_2)\rangle$$

the selection of a pure K_S beam is possible exploiting entanglement
(unique at a ϕ-factory, not possible at fixed target experiments)

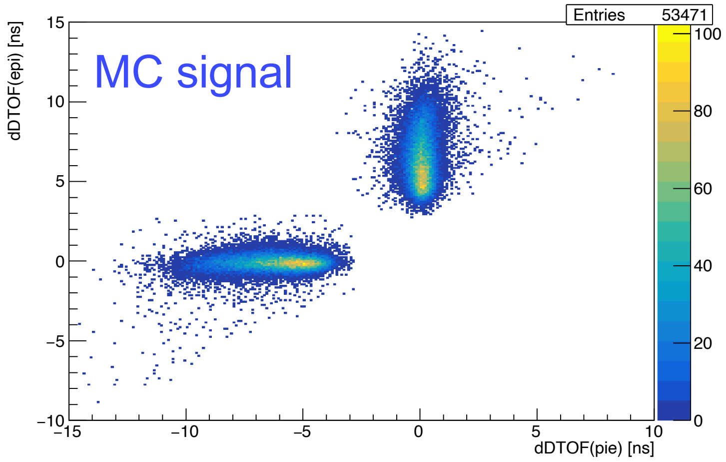
A recent study on this quantum effect:
J. Bernabeu, A.D.D. "Can future observation of the living partner post-tag the past decayed state in entangled neutral K mesons?" PRD 105 116004(2022)

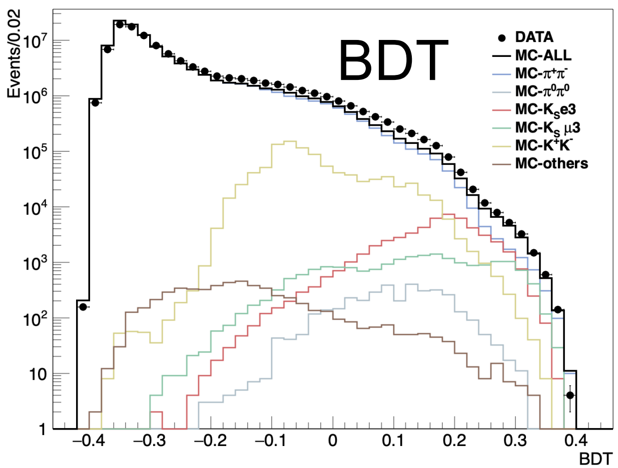


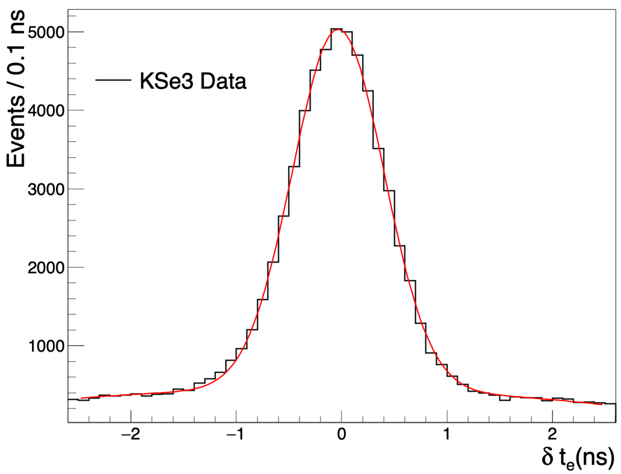
K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in ϕ)
K_S momentum resolution: ~ 2 MeV

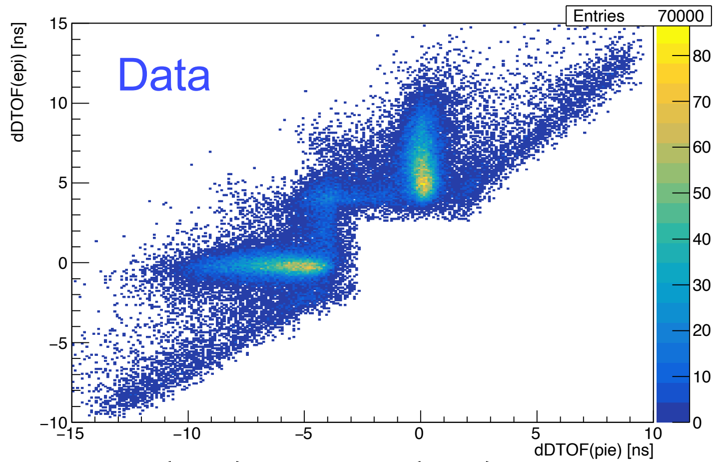
Measurement of the $K_S \to \pi e \nu$ branching ratio

- Analysed L=1.63 fb^{-1}
- 1 vtx close to IP + K_L interaction in the calorimeter (KL crash)
- $K_S \to \pi^+\pi^-$ as normalization sample
- K_S semileptonic signal selection:
  - boosted decision tree (BDT) with kinematic variables to reject main background from $K_S \to \pi^+\pi^-$ and $\phi \to K^+K^-$
  - PID with Time of Flight based on the comparison of two hypotheses: if $|\delta t_1(\pi) - \delta t_2(e)| < |\delta t_1(e) - \delta t_2(\pi)|$ track-1 is assigned to π and track-2 to e, otherwise the opposite mass assignment is chosen. Cut on $|\delta t_e| < 1$ ns corresponding to $\min[|\delta t(e\pi)|, |\delta t_1(\pi e)|]$









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

Measurement of the $K_S \to \pi e \nu$ branching ratio

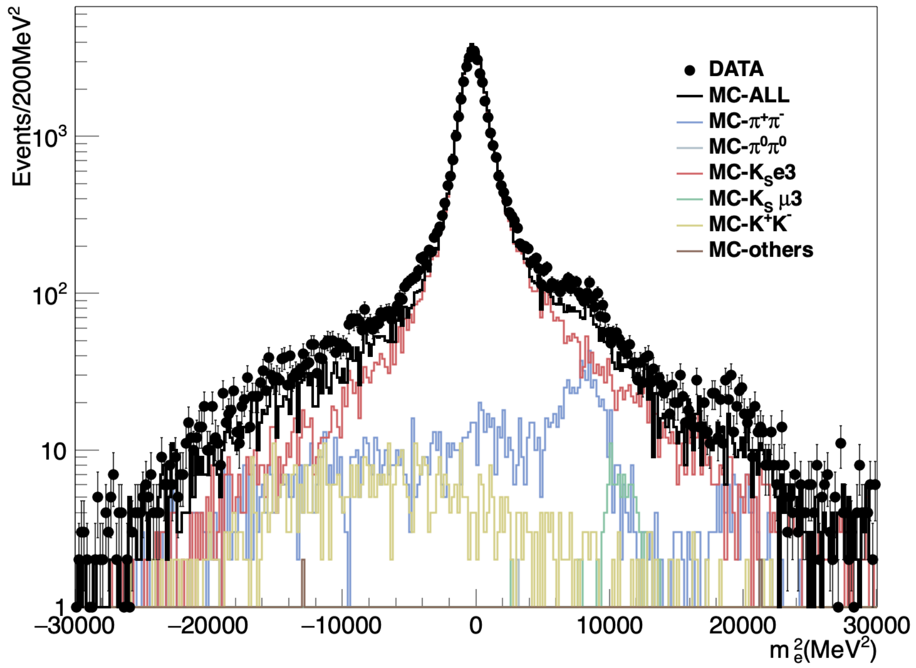
- Signal count from fit to $M^2(e)$ distribution

$$m_e^2 = (E_{K_S} - E_\pi - p_{\rm miss})^2 - p_e^2$$

- 49647 ± 316 K_{Se3} events

- Selection efficiency from $K_S \to \pi^+\pi^-$ K_{Le3} close to IP data control sample
- $\varepsilon = (19.38 \pm 0.04)\%$

- Study of systematic uncertainties from: BDT and TOF selection cuts, fit range, trigger, on-line filter, event classification, T0 determination, K_L-crash and β^* selection, K_S identification



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

Systematic uncertainties of efficiencies

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

KLOE-2 result (2022)
arXiv :2208.04872v2 [hep-ex]
(submitted to JHEP)

Measurement of the $K_S \to \pi e \nu$ branching ratio

- Combination of the previous result from KLOE based on an independent data sample (L=0.41 fb^{-1}) BR(K_{Se3})=(7.046 ± 0.078± 0.049)x10^{-4} [KLOE PLB636 (2006)] gives:

$$\boxed{\mathrm{BR}(K_S \to \pi e \nu)=\left(7.153 \pm 0.037_{stat} \pm 0.043_{syst}\right)\times 10^{-4}}$$

KLOE-2 combined result (2022)
arXiv :2208.04872v2 [hep-ex] (submitted to JHEP)

- From

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

using the values S_{EW} = 1.0232±0.0003 [Marciano, Sirlin PRL 71 (1993) 3629] and $I_K^e = 0.15470 \pm 0.00015$ and $\delta_{EM}^{Ke} = (1.16 \pm 0.03)\times 10^{-2}$ [Seng, Galviz, Marciano, Meissner, PRD 105, (2022) 013005] we derive:

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

Conclusions

- The entangled neutral kaon system at a ϕ-factory is a unique laboratory for the search for decoherence effects, the study of discrete symmetries, and K_S physics
- 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.
- KLOE+KLOE-2 data sample (~ 8 fb^{-1}) represents the largest sample ever collected at ϕ-meson peak

- Latest studies on entangled neutral kaons:
  - Improved search for decoherence and CPT violation effects in $\phi \to \mathbf{K_S K_L} \to \pi^+\pi^- \pi^+\pi^-$ in same cases with a precision reaching the interesting Planck's scale region.
  - First direct test of T and CPT symmetries in neutral kaon transitions.
  - A new measurement of the $K_S \to \pi e \nu$ branching fraction, with almost a factor of two improvement of previous result, and a new derivation of $f_+(0)\,|V_{us}|$.

- These results add up to previous studies on kaons, e.g. on $K_S \to \pi \mu \nu$, A_S and CPT and Lorentz symmetry tests.

- Several new and improved results expected from the analyses of the whole dataset, see:

KLOE-2 Physics programme
KLOE-2 Collaboration: EPJ **C68** (2010) 619
Proceedings: EPJ WoC 166 (2018)
https://agenda.infn.it/event/kloe2ws