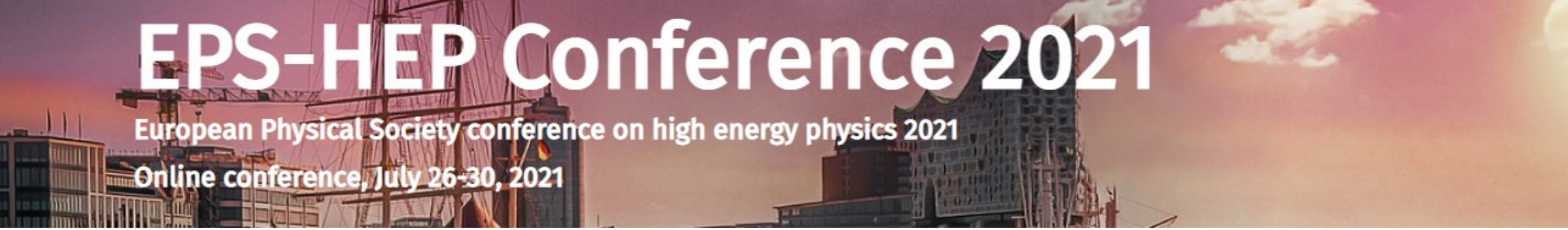


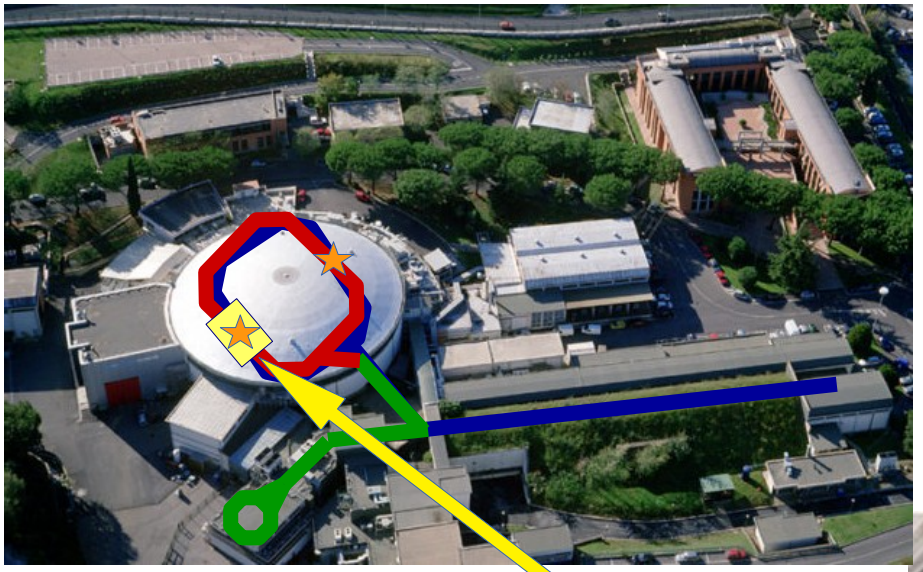
Flavour Physics and CP Violation at KLOE-2

28.07.2021

Aleksander Gajos
Jagiellonian University, Kraków, Poland

on behalf of the KLOE-2 Collaboration

KLOE and KLOE-2 at the DAΦNE Φ-factory



- Location: Laboratori Nazionali di Frascati, Italy
- DAΦNE: e^+e^- collider and a „*Phi factory*"
  - $\sqrt{s} = M_\phi \approx 1020$ MeV
    (off-peak operation possible as well)
  - neutral kaon pairs produced in Φ decays in an entangled state
  - the only existing setup of this kind

KLOE/KLOE-2 timeline:

- KLOE @ DAΦNE
  - 2001-2002
  - 2005-2006:

$L_{peak} = 1.5 \times 10^{32}\,cm^{-2}s^{-1}$
$\int Ldt = 8.5\ pb^{-1}$ per day

KLOE → KLOE-2 & DAΦNE upgrades

KLOE-2 datataking campaign:

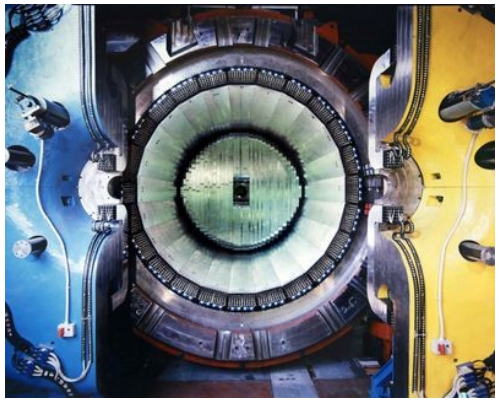
- **Nov 2014 – Mar 2018**

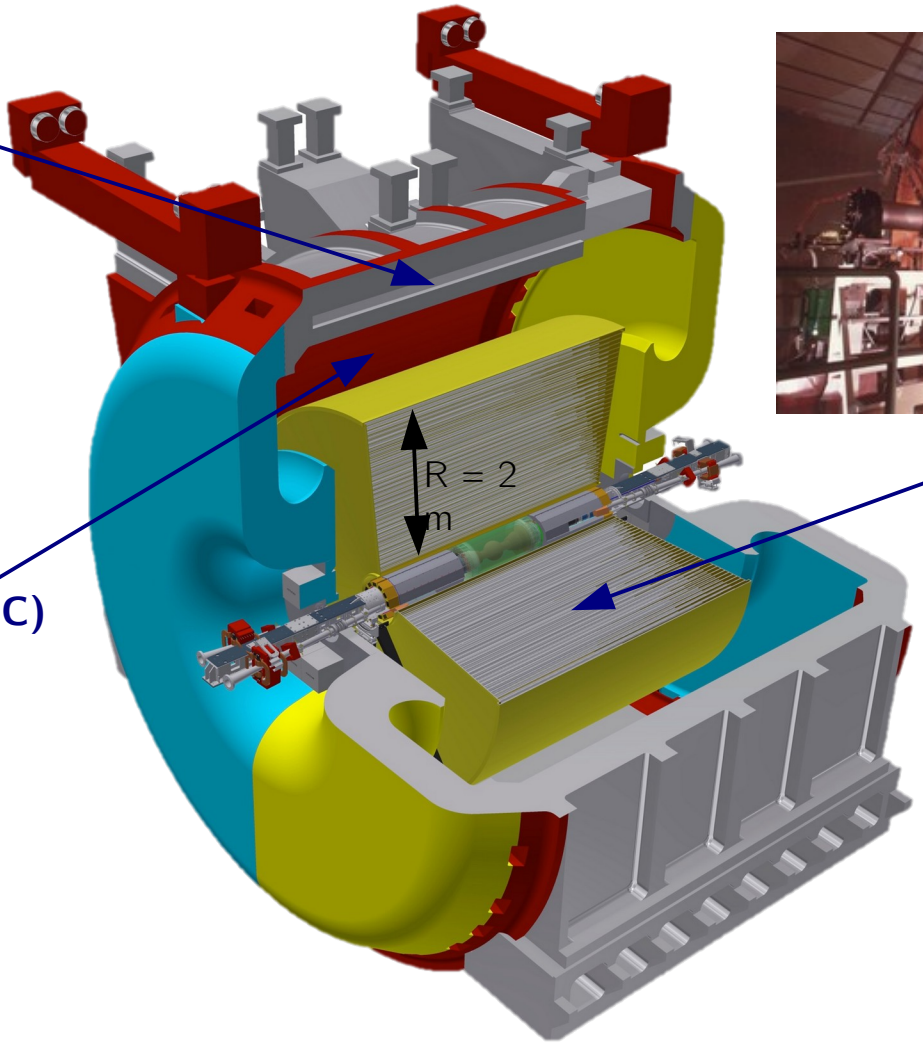
$L_{peak} = 2.4 \times 10^{32}\,cm^{-2}s^{-1}$
$\int Ldt = 14\ pb^{-1}$ per day

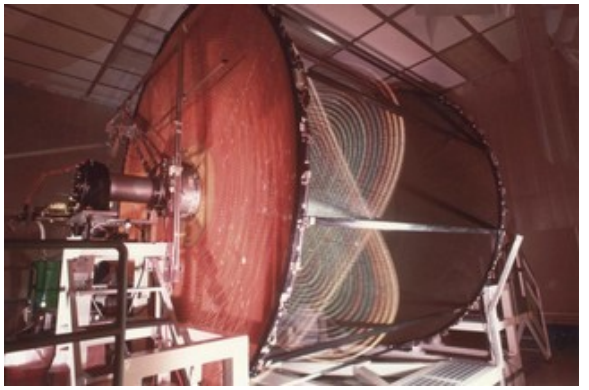
The **K LO**ng **E**xperiment – detector

Superconducting magnet

- B = 0.52 T







Drift Chamber (DC)

- gas: 90% He +10% C_4H_{10}
- R_{IN} = 25cm, R_{OUT} = 2m
- $\sigma_{xy} \approx 150$ μm, $\sigma_z \approx 2$ mm
- $\sigma(p_T)/p_T = 0.4\%$

Electromagnetic calorimeter (EMC)

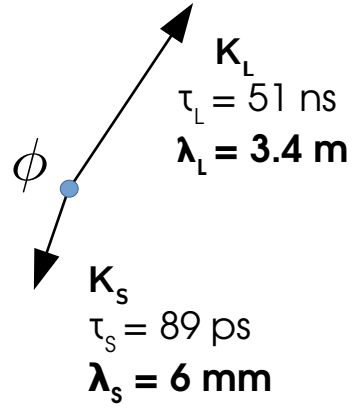
- barrel with C-shaped endcaps
- lead and scintillating fibers
- hermetic coverage (98% 4π)

$$\sigma_t = \frac{54\,ps}{\sqrt{E[GeV]}} \oplus 140ps$$

$$\sigma_E = \frac{5.7\%E}{\sqrt{E[GeV]}}$$

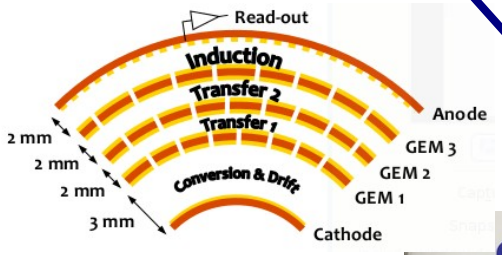
$$\sigma_x = \sigma_y = 1\,cm$$

$$\sigma_z = \frac{1.2\,cm}{\sqrt{E[GeV]}}$$



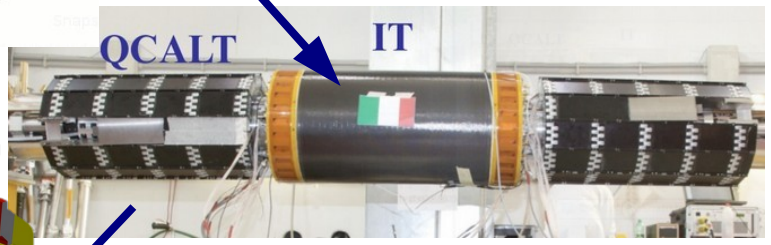
KLOE-2 upgrade and datataking

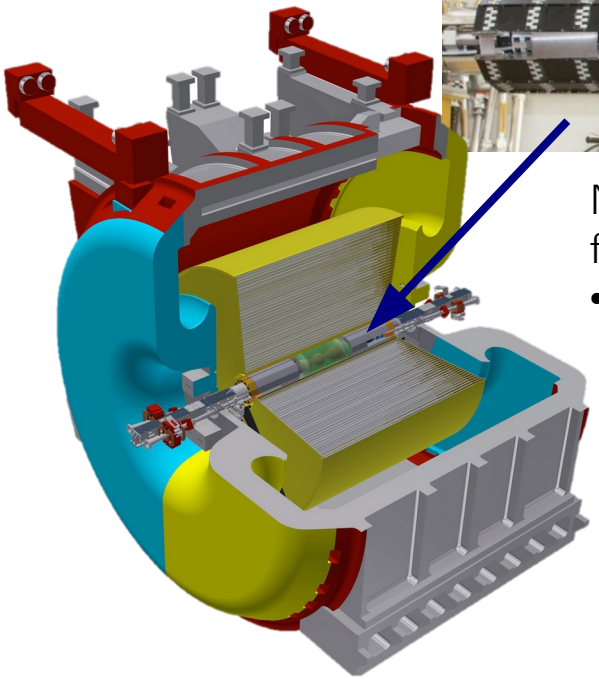
Inner Tracker



- First cylindrical GEM detector in a HEP experiment
- 4 layers of trilple-GEM
- Increasing vertexing resolution and efficiency
- Very low material budget (2% X_0)

NIMA 628 (2011),194,
NIM A 958 (2020), 162366

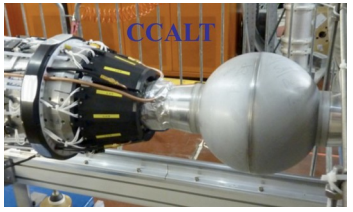




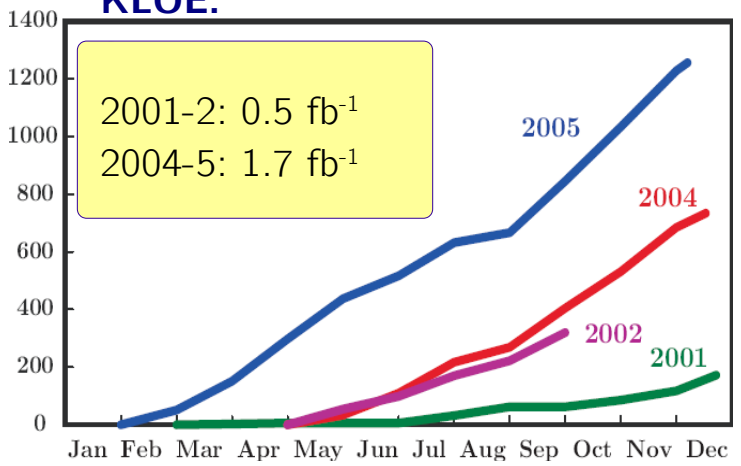
New calorimeters around the final focusing magnets

- Photon veto and energy measurement at low angles

NIMA 617 (2010),105 NPB 197 (2009), 215



KLOE:



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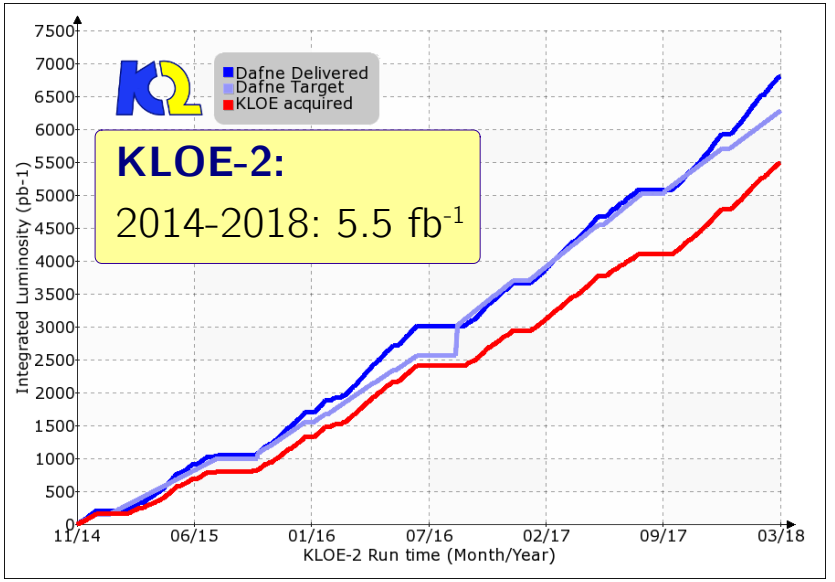


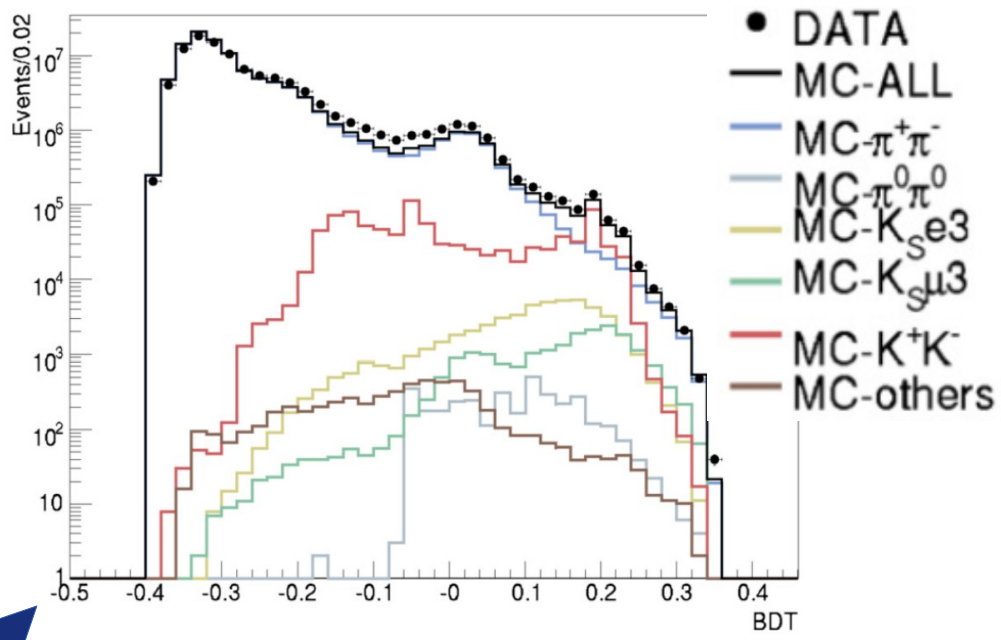
Measurement of the $K_S \to \pi\mu\nu$ branching ratio

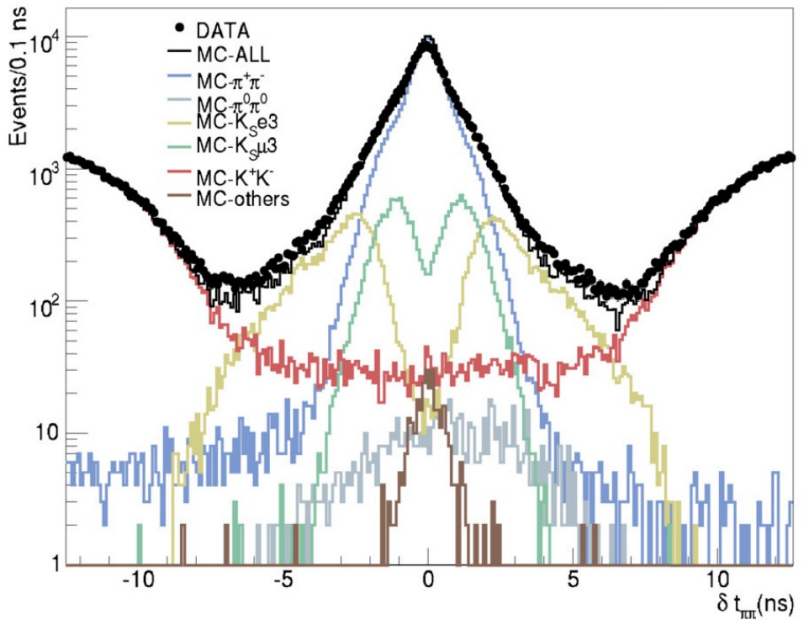
Motivation:

- $BR(K_S \to \pi\mu\nu)$ was never measured before
- Independent determination of $|V_{US}|$
- Test of the lepton-flavour universality

Analysis:

- Performed with the complete KLOE dataset ($1.7 fb^{-1}$)
- Presence of K_S tagged by interaction of K_L in the calorimter
- event selection based on:
  - BDT using kinematic variables
  - time-of-flight analysis
- Signal efficiencies obtained using $K_L \to \pi\mu\nu$ events

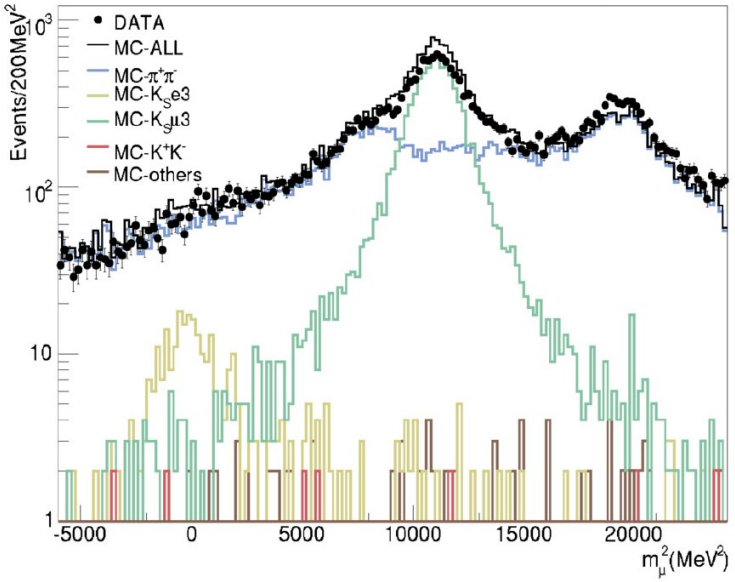


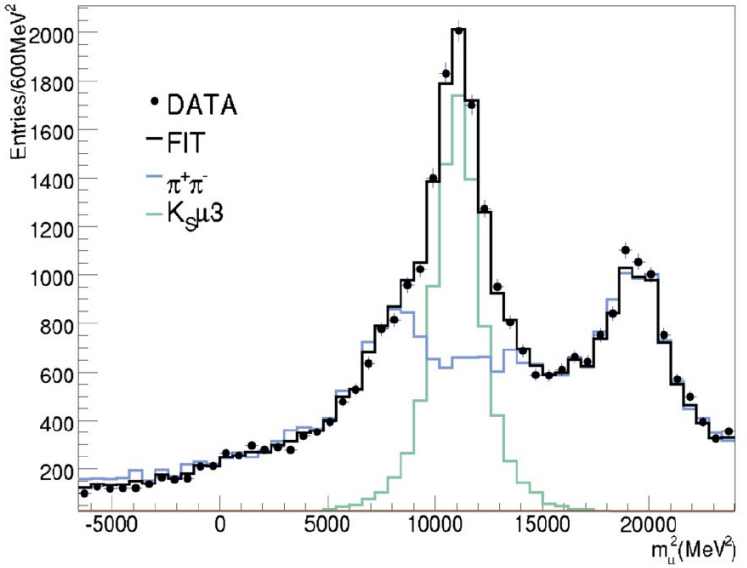


Measurement of the $K_S \to \pi\mu\nu$ branching ratio

- $K_S \to \pi\mu\nu$ events counted using a fit to the spectrum of reconstructed muon mass squared
- $K_S \to \pi^+\pi^-$ used as a normalization sample
- 7223 ± 180 signal events found

$$m_\mu^2 = (E_{K_S,tag} - E_\pi - p_{miss})^2 - \vec{p}_\mu^{\,2}$$





First ever measurement:

$BR(K_S \to \pi\mu\nu) = (4.56 \pm 0.11_{stat} \pm 0.17_{syst}) \times 10^{-4}$

in agreement with the expected value assuming lepton-flavour universality:

$BR(K_S \to \pi\mu\nu) = (4.69 \pm 0.06) \times 10^{-4}$

$\Gamma(\pi^\pm \mu^\mp \nu_\mu)/\Gamma_{total}$ **Γ_9/Γ**

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
4.56±0.20 OUR FIT					
4.56±0.11±0.17	7223	[1] BABUSCI	20	KLOE	direct measurement

[1] Value obtained by normalizing to the KLOE measurement $B(K_S^0 \to \pi^+\pi^-) = (69.196 \pm 0.051)\%$. Also comparison with the PDG 18 based derived value leads to a lepton flavor universality test $|V_{us}\, f_+(0)|^2_{K_S^0 \to \pi\mu\nu} / |V_{us}\, f_+(0)|^2_{K_S^0 \to \pi e\nu} = 0.975 \pm 0.044$.

Measurement of the charge asymmetry in $K_S \to \pi e \nu$

Charge asymmetry in semileptonic decays of neutral kaons:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

S = decays of K_S L = decays of K_L

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

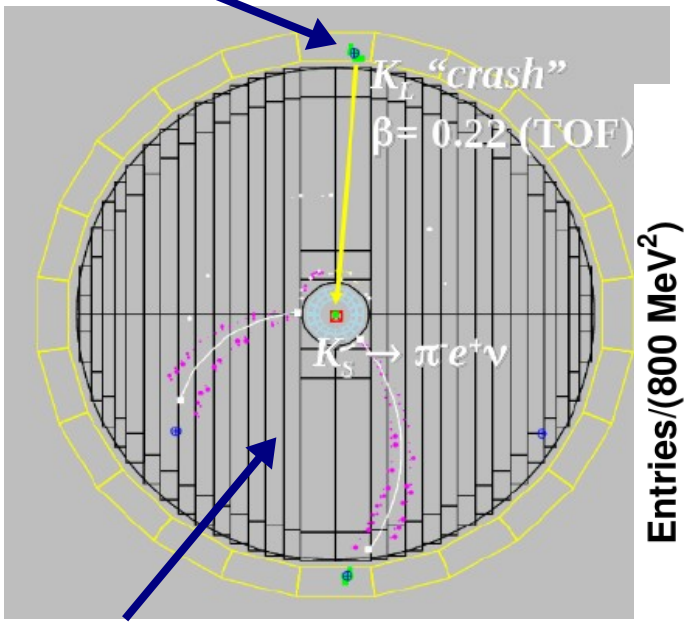
$A_S \neq A_L \Rightarrow$ CPT violation

Assuming CPT invariance:

$A_S = A_L = 2Re(\varepsilon_K) \approx 3 \times 10^{-3}$

Analysis:

K_S tagged by K_L interaction in the calorimeter



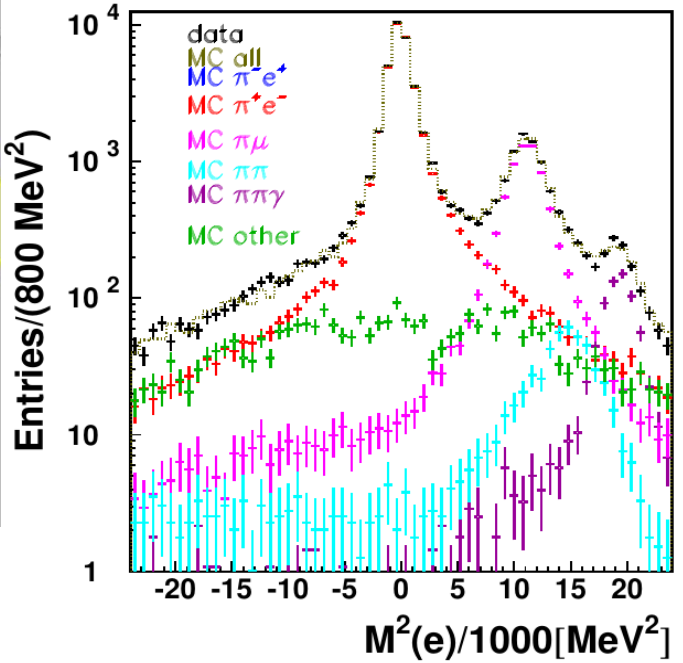
Time of flight analysis for the K_S decay products

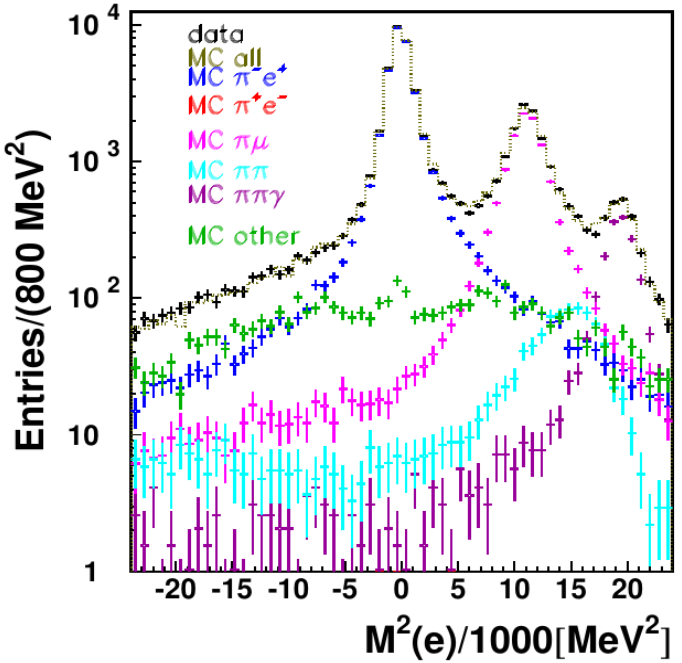
Signal: $\Phi \to K_S K_L \to \pi e \nu$ K_L(EMC)

Main backgrounds:

$K_S \to \pi^+\pi^-(\gamma)$ $K_S \to \pi^+\pi^- \to \pi\mu\nu$ (pion decay)

Signal event counting on $M^2(e) = [E_{K_S} - E(\pi) - E_\nu]^2 - p^2(e)$





New result on charge asymmetry in $K_S \to \pi e \nu$

New most precise A_S measurement:

$A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}$

Previous KLOE measurement:

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

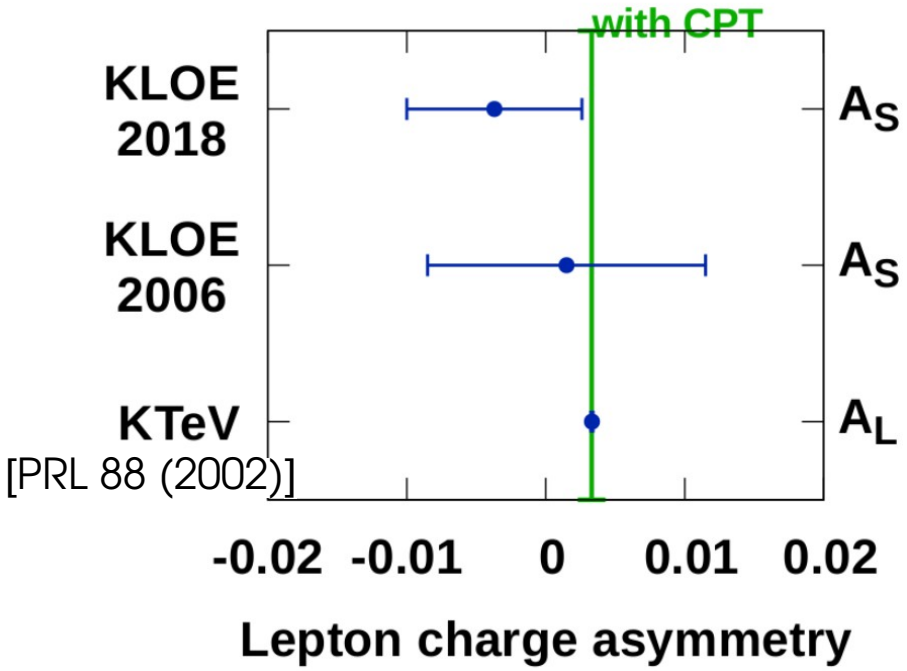
(~4x smaller sample)

[PLB 636 (2006) 173]

Combined result on A_S:

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

JHEP 1809 (2018) 021



[PRL 88 (2002)]

$$A_S - A_L = 4[\,\mathrm{Re}(\delta_K) + \mathrm{Re}(x_-)\,]$$
$$A_S + A_L = 4[\,\mathrm{Re}(\epsilon_K) - \mathrm{Re}(y)\,]$$

known from other measurements

The most precise determination of Re(x_) and Re(y):

$\mathrm{Re}(x_-) = (-2.0 \pm 1.4) \times 10^{-3}$

$\mathrm{Re}(y) = (1.7 \pm 1.4) \times 10^{-3}$

Perpsectives:

Using over 5 fb^{-1} of KLOE-2 data, the statistical uncertainty on A_S can be reduced to 3×10^{-3}

Search for CP violation with rare K_S decays

$$\eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0|H|K_S\rangle}{\langle \pi^+\pi^-\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{+-0}$$

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0|H|K_S\rangle}{\langle \pi^0\pi^0\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{000}$$

In the lowest order of χPT: $\varepsilon'_{000} = \varepsilon'_{+-0} = -2\varepsilon'$

$Im(\eta_{+-0}) = -0.002 \pm 0.009$

$Im(\eta_{000}) = (-0.1 \pm 1.6) \times 10^{-2}$

$K_S \to 3\pi^0$ – a geniune CP-violating decay

- SM prediction: $BR(K_S \to 3\pi^0) = 1.9 \times 10^{-9}$
- Best upper limit comes from **KLOE**:
  - $BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$
  - $|\eta_{000}| < 0.0088$ @ 90% C.L.

Phys Lett. B 723 (2013) 54

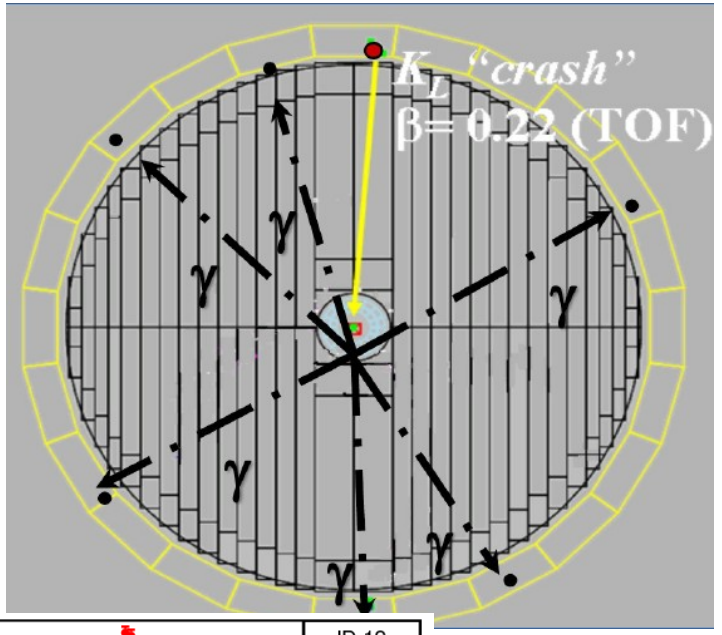
$K_S \to \pi^+\pi^-\pi^0$

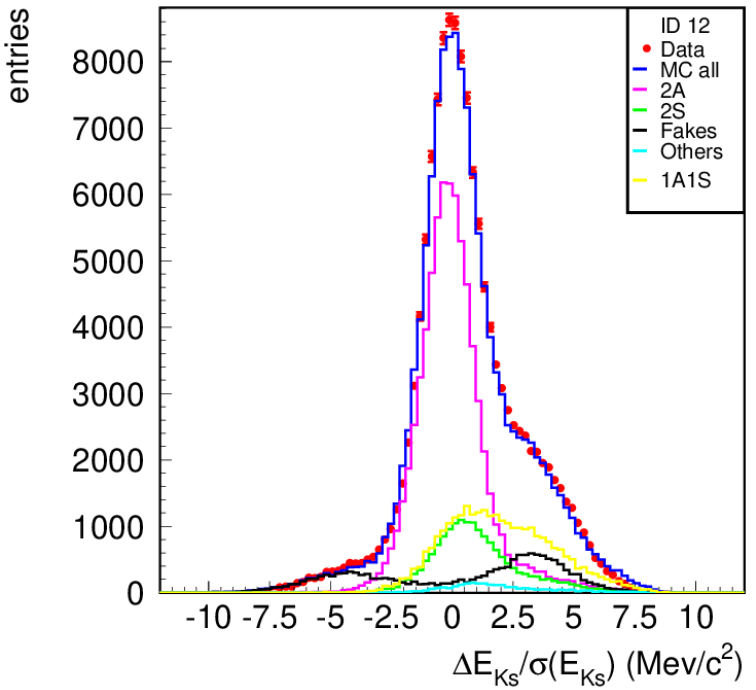
- CP-violating only for L=0, 2
- current accuracy ~30%
- search for $K_S \to \pi^+\pi^-\pi^0$ with the KLOE dataset is in progress

Search for $K_S \to 3\pi^0$ with KLOE-2

$K_S \to 3\pi^0$ at KLOE-2

- KLOE-2 data analysis ongoing
  - about 5 fb^{-1}
- Tagging of K_S with K_L interaction in the calorimeter
- $K_S \to 2\pi^0$ (4 prompt photons) used as normalization sample
- Main background: $K_S \to 2\pi^0$ with 2 split/accidental calorimeter clusters
- Also testing an MVA approach
- **Expected sensitivity with full KLOE-2 statistics & optimized analysis $\lesssim 10^{-8}$**



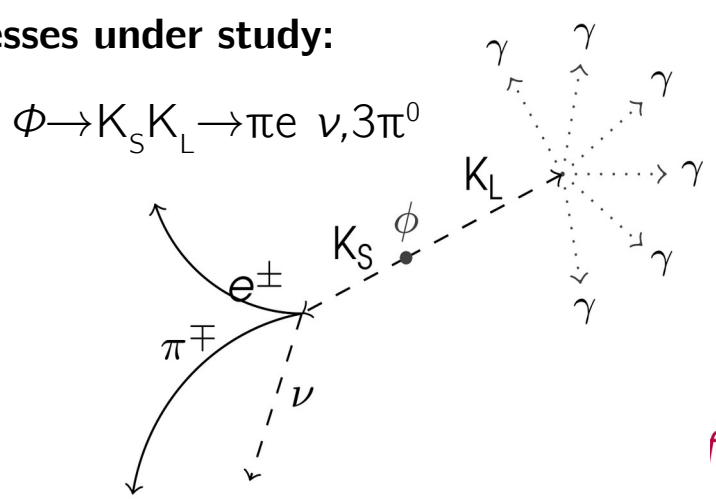


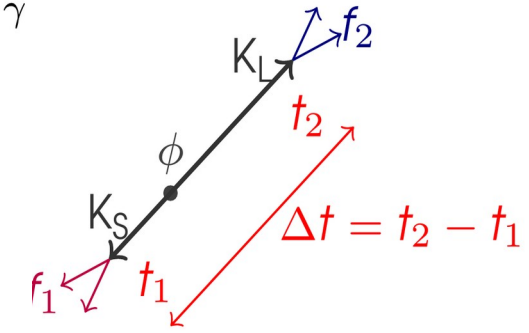
Direct T and CPT tests in transitions of neutral kaons

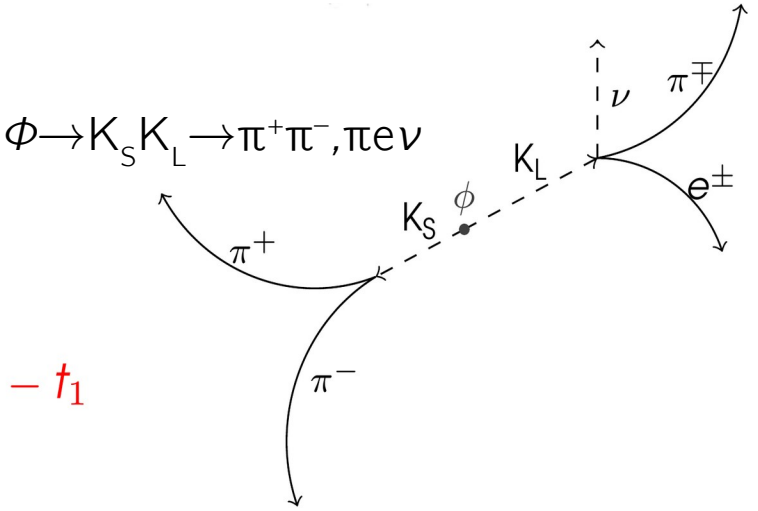
- direct, model independent tests
- only feasible with entangled neutral mesons
- the only measurement to date: T violation @ BaBar (B mesons) >5σ [PRL 109 (2012) 211801]

Nucl. Phys. B 868 (2013) 102
JHEP 1510 (2015) 139

Processes under study:







Observables of the tests (we focus on the asymptotic region):

T-violation sensitive

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

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

CPT-violation sensitive

$$R_2^{CPT}(\Delta t) \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

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

Double ratios:

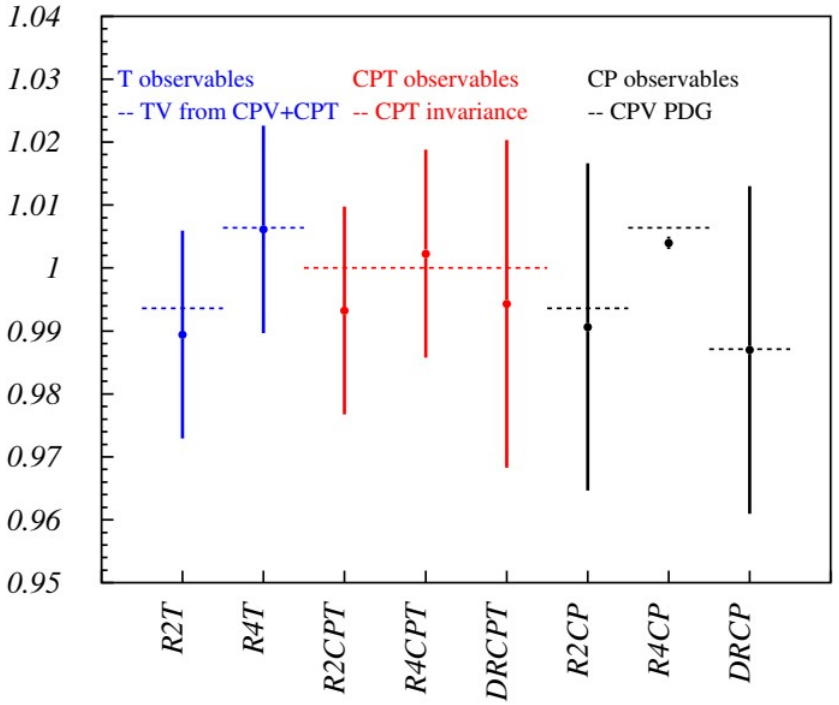
$$\frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$$

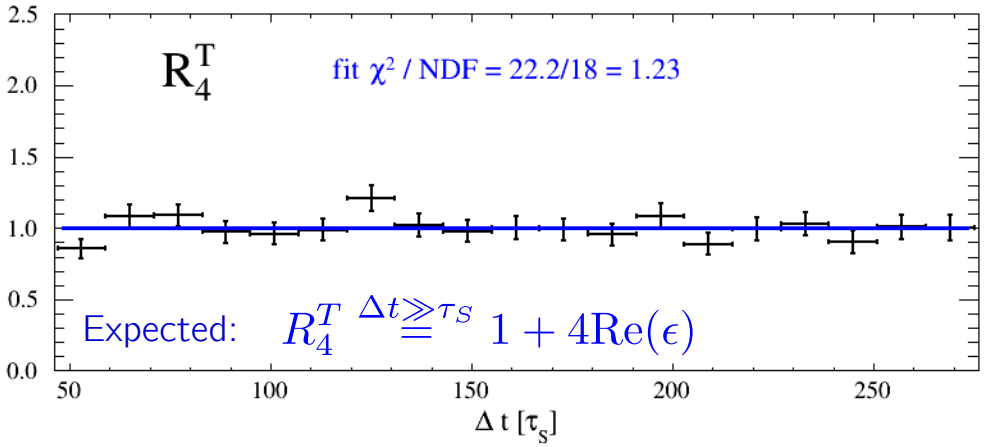
$$\frac{R_2^{CPT}}{R_4^{CPT}}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

Direct T and CPT tests in transitions of neutral kaons

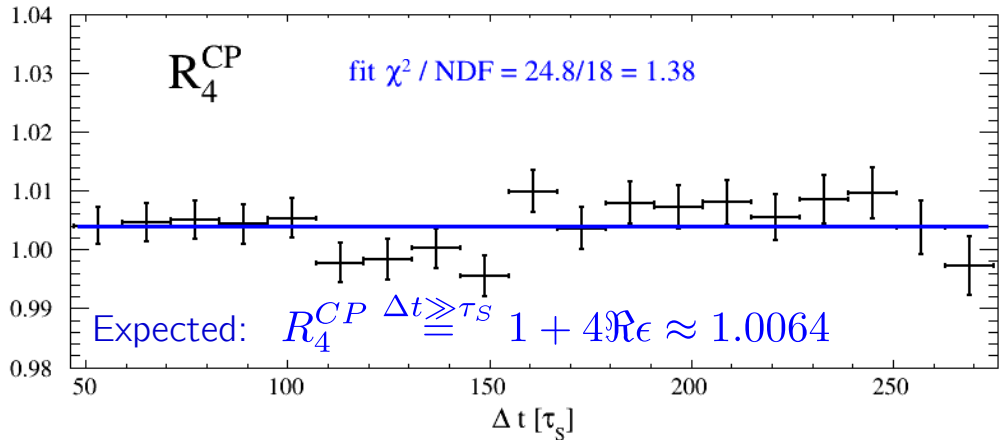
- Analysis at the final stage

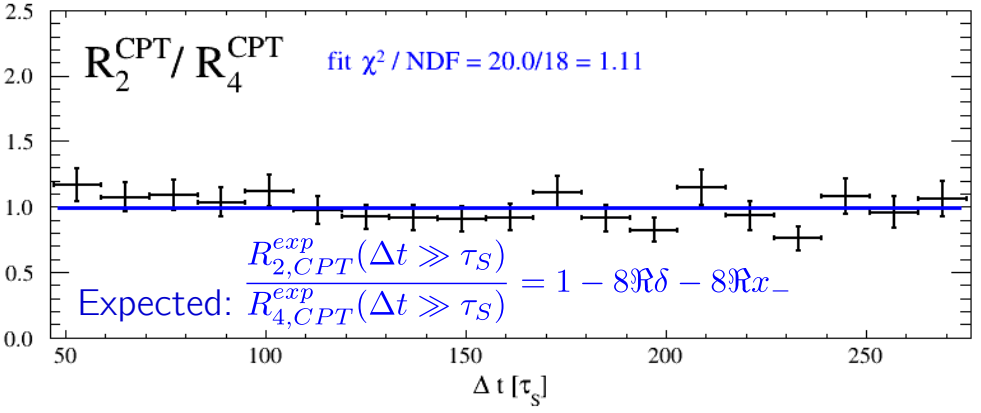
Preliminary results
(statistical uncertainty only)





Note different scale!





Summary and perspectives

- **KLOE & KLOE-2 data sample** = ~8 fb^{-1} = ~2.4 x 10^{10} of Φ meson decays recorded
  - Worldwide-unique data sample
  - Neutral kaon pairss – especially useful for CP violation studies and strangeness physics

- **Results are still obtained from KLOE data:**
  - Improved determination of charge asymmetry in K_S semileptonic decays
  - First measurement of BR($K_S \to \pi\mu\nu$)
  - Direct T and CPT tests in transitions of neutral kaons

Also see the poster
Tests of CPT symmetry and quantum coherence with entangled neutral kaons at KLOE-2
by Riccardo D'Amico

- **First KLOE-2 data analyses are in progress:**
  - Search for the CP-violating $K_S \to 3\pi^0$ decay

- **More new and improved results expected from KLOE-2**

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

Thank you

for your attention!