CPT Symmetry test at KLOE-2

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on behalf of KLOE-2 Collaboration

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Overview

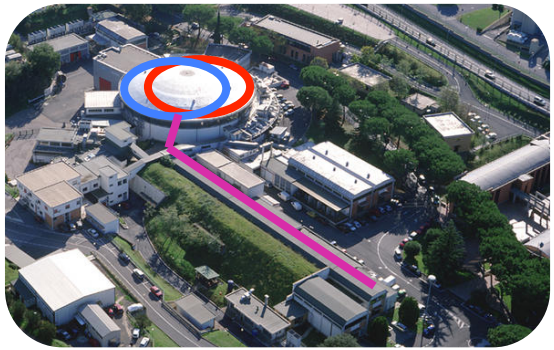
- KLOE and KLOE-2 at DAϕNE
- Ks Semileptonic Charge Asymmetry
- Direct CPT test in Kaon transitions
- Conclusions

DAϕNE & KLOE

◉DAϕNE Frascati ϕ-factory: an e^+e^- collider @ $\sqrt{s}$ =1019.4 MeV = M_ϕ

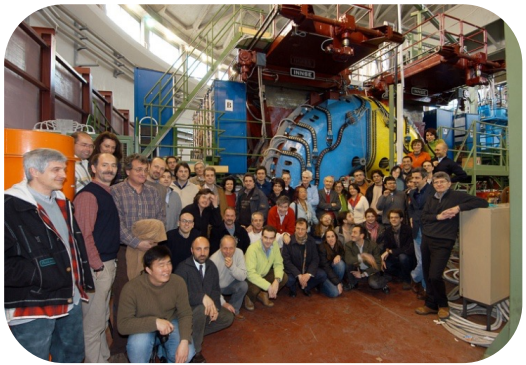
Best performance in 2005:

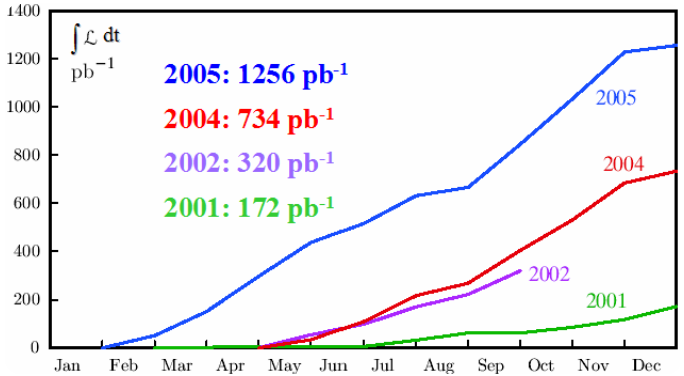
- L_{peak} = 1.4 × 10^{32} $cm^{-2}s^{-1}$
- $\int Ldt$ = 8.5 pb^{-1}/day



◉ KLOE integrated 2.5 fb^{-1} @ $\sqrt{s}=M_\phi$ (2001-05)
+ 250 pb^{-1} off-peak @ $\sqrt{s}$=1 GeV (2006)

Precision Kaon and Hadron Physics with KLOE [Rivista del Nuovo Cimento Vol.31, N.10 (2008)]



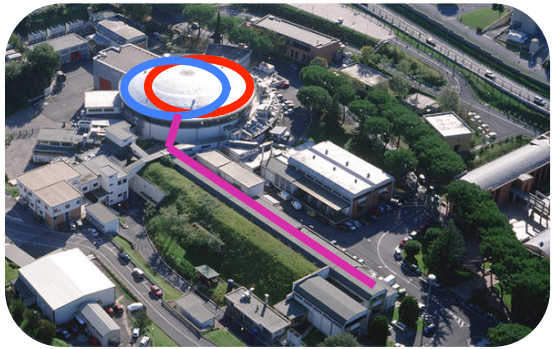


DAϕNE & KLOE-2

- DAϕNE Frascati ϕ-factory: an e^+e^- collider @ $\sqrt{s}$ =1019.4 MeV = M_ϕ and with crab-waist sextuples configuration

  Best performance in 2018:

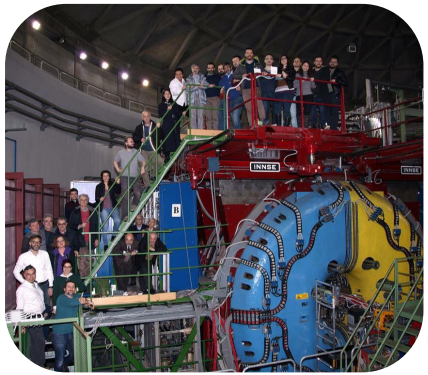
  - $L_{peak} = 2.28 \times 10^{32}\ cm^{-2}s^{-1}$
  - $\int Ldt = 14.3\ pb^{-1}$/day delivered

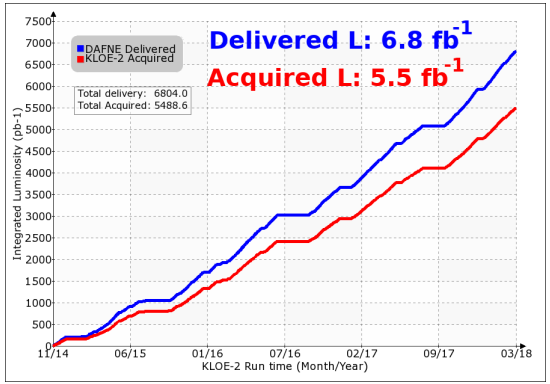


- KLOE-2 integrated 5.5 fb^{-1} @ $\sqrt{s}=M_\phi$ (2014-18)

Physics with the KLOE-2 experiment at the upgraded DAΦNE [EPJC 68 (2010)]

- Ks, η rare decays & hadron physics
- Interferometry & Symmetries
- Dark photon search



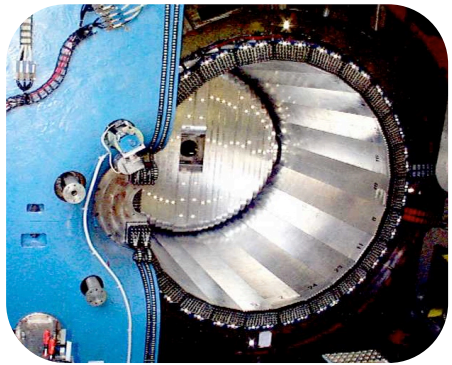


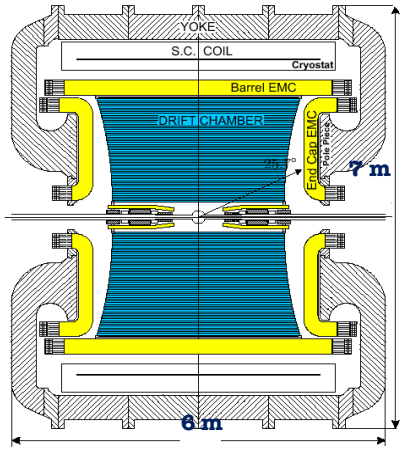
KLOE+KLOE-2 largest sample ever collected at ϕ-meson peak

KLOE detector at DAϕNE

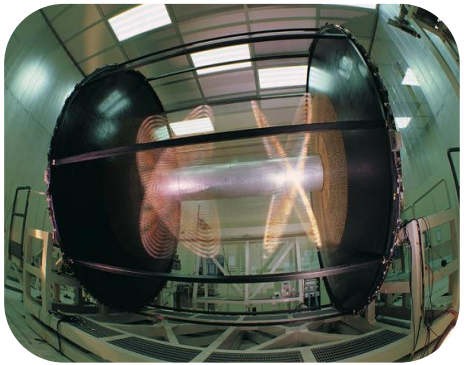
- Calorimeter System
  - EMC – Lead / Scintillating Fibers w PMT

$\sigma_E / E = 5.7\% / \sqrt{E(GeV)}$
$\sigma_t = 54\ ps / \sqrt{E(GeV)} \oplus 140\ ps$
$\sigma_{vtx}(\gamma\gamma) \sim 1.5\ cm$ (vertex reso)





- Tracking System
  - DC – He-Iso 90-10
    3.7m x 4m Drift Chamber



- Superconductive solenoid
  - 0.52 T field
- DAFNE ϕ-factory
  - $e^+ e^-$ at 1020 MeV

$\sigma_p/p = 0.4\ \%$ (θtrack > 45°)
$\sigma_{hit} = 150\ \mu m$ (xy), 2 mm (z)
$\sigma_{vertex} \sim 3\ mm$

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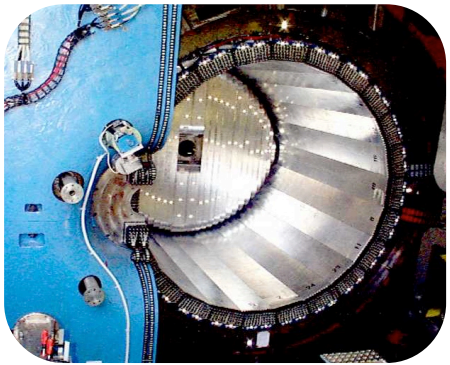

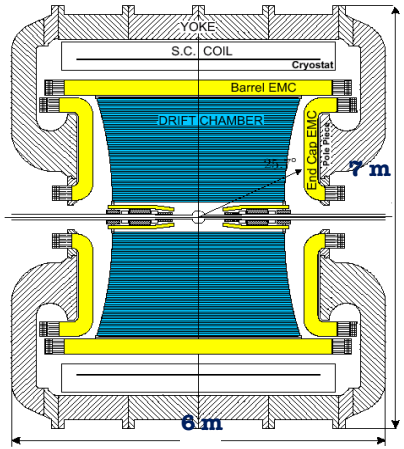

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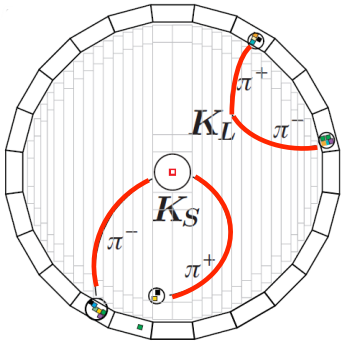

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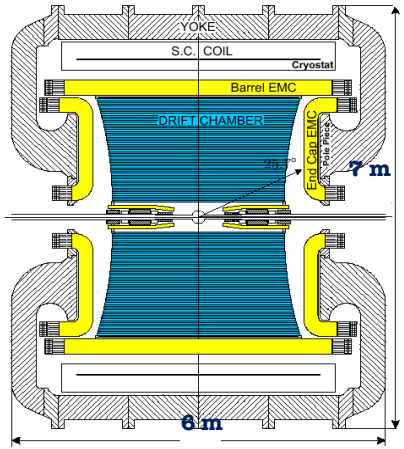

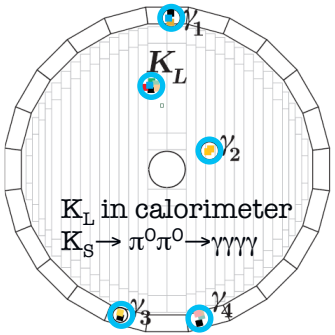

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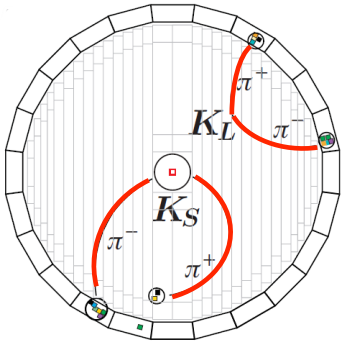

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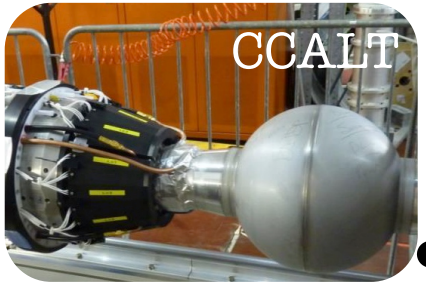
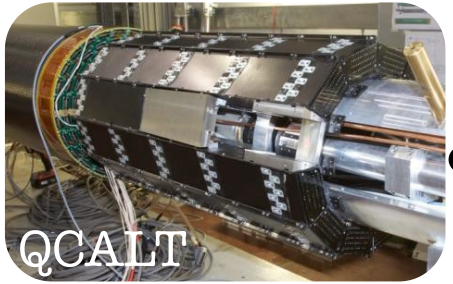
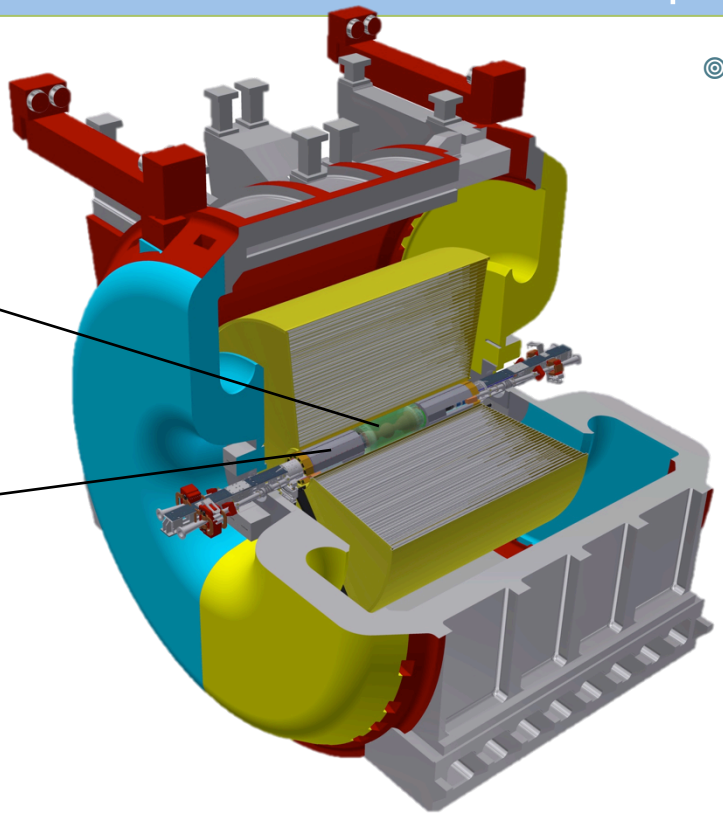
KLOE-2 detector at DAϕNE

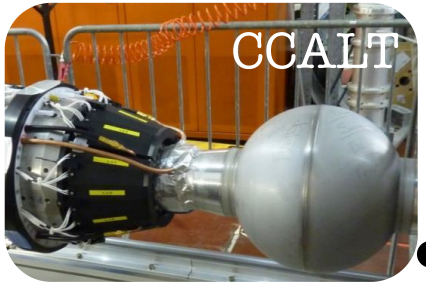


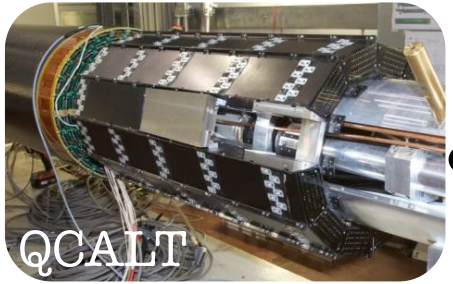


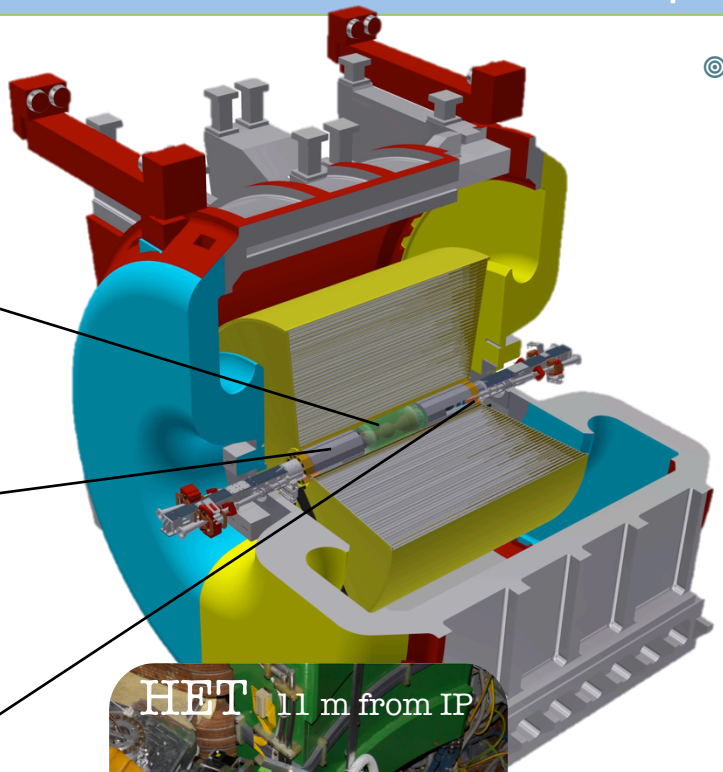


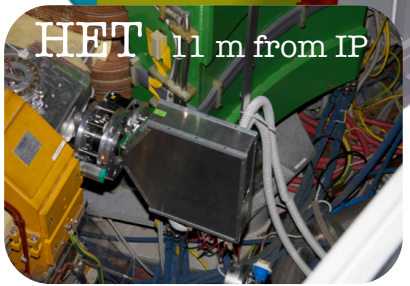
- Calorimeter System Upgraded
  - EMC – Lead / Scintillating Fibers w PMT Barrel and Endcaps
  - CCALT – LYSO Crystal w SiPM
    Increase acceptance for photons from IP (Low-β $20^{o} \rightarrow 11^{o}$)
    [Nucl. Phys B 197 (2009) 215]
  - QCALT – Tungsten / Scintillating Tiles w SiPM
    Quadrupole coverage for K_L decays [NIMA 617 (2010) 105]

KLOE-2 detector at DAϕNE









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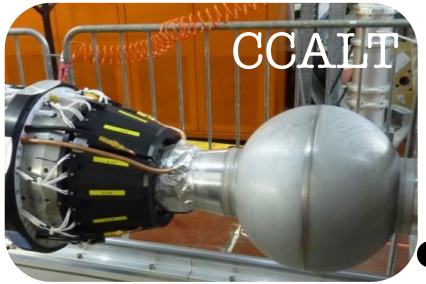
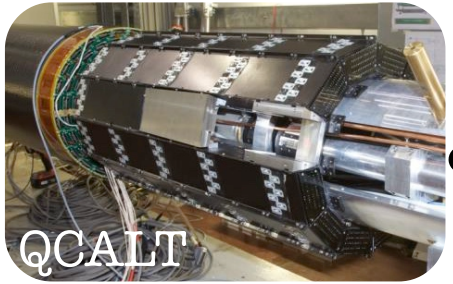
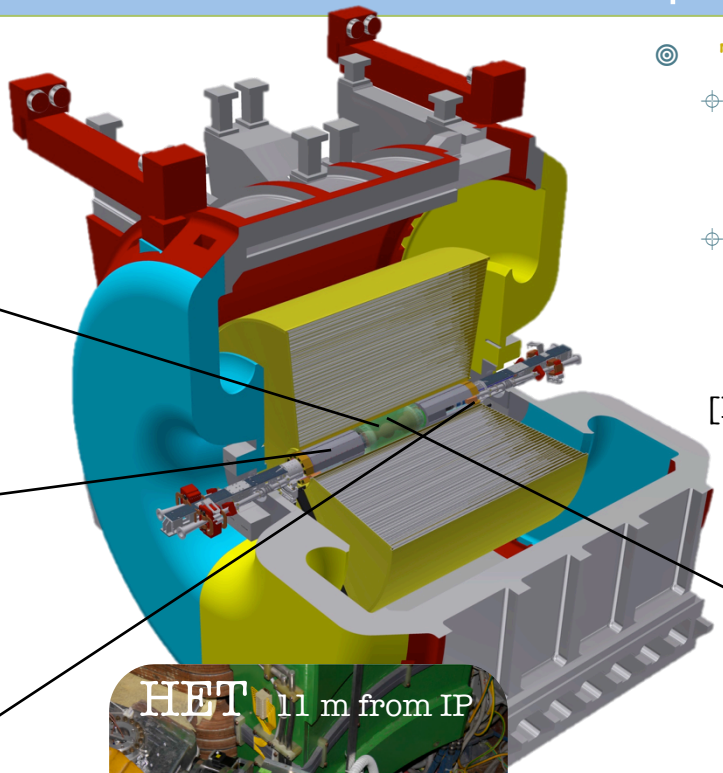
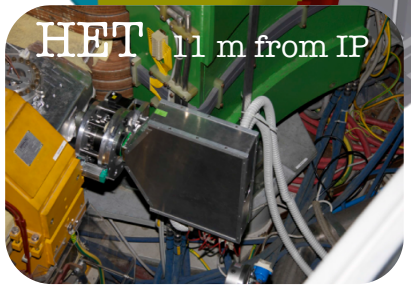
    Quadrupole coverage for K_L decays [NIMA 617 (2010) 105]
  - Lepton taggers for γγ-physics
    - LET / LYSO+SiPMs [NIMA 617 (2010) 81]
    - HET / Scint+PMTs E > 400 MeV [NIMA 617 (2010) 266]

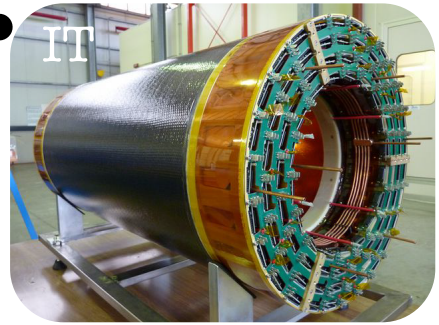
KLOE-2 detector at DAϕNE











- Tracking System Upgraded
  - DC – He-Iso 90-10
    3.7m x 4m Drift Chamber
  - Inner Tracker –First cylindrical GEM detector in a HEP experiment
    4 Cylindrical GEM detectors
    Improve vertex reconstruction at IP

[NIMA 628 (2011) 194]

Ks Semileptonic Charge Asymmetry

Charge asymmetry in semileptonic kaon decays

Among cleanest and most precise CPT symmetry test

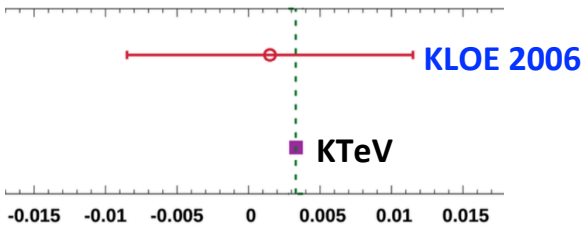
$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$
$$= 2\,[\Re(\epsilon_K) \pm \Re(\delta) - \Re(y) \pm \Re(x_-)]$$

$A_{S,L} \neq 0 \Rightarrow$ CP violation
$A_S \neq A_L \Rightarrow$ CPT violation
Assuming CPT invariance:
$A_S = A_L = 2Re(\varepsilon_K) \approx 3 \times 10^{-3}$

- CP violation in $K^0\overline{K^0}$ mixing
- CPT violation in $K^0\overline{K^0}$ mixing
- CPT violation in $\Delta S = \Delta Q$ processes
- CPT violation in $\Delta S \neq \Delta Q$ processes

KLOE Coll. [PLB 636 (2006) 173]
with 410 pb^{-1}
$A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \times 10^{-3}$

KTeV Coll. [PRL 88 181601 (2002)]
$A_L = (3.332 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$



$A_S - A_L = 4\,[\,\Re(\delta) + \Re(x_-)\,]$
$A_S + A_L = 4\,[\,\Re(\epsilon_K) - \Re(y)\,]$

$\Re(x_-) = (-0.8 \pm 2.5) \times 10^{-3}$
$\Re(y) = (0.4 \pm 2.5) \times 10^{-3}$ [PLB 636 (2006) 173]

inputs from other experiments [PLB 444 (1998) 52]

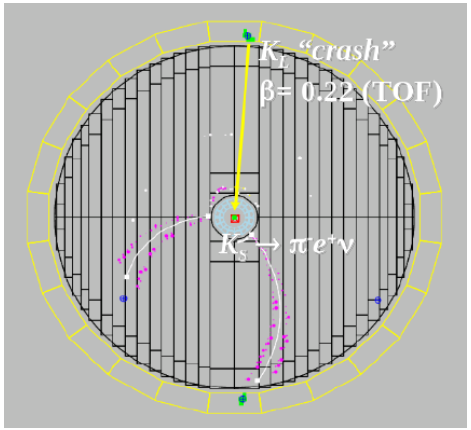
K_S charge asymmetry with 1.6 fb^{-1}

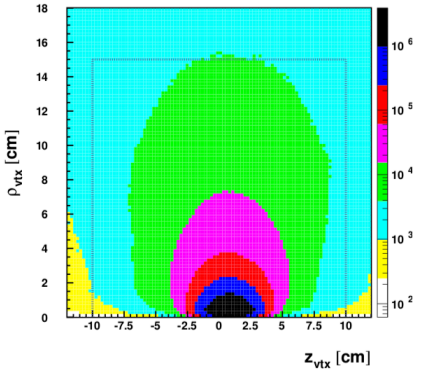
① KS tagged by KL interacting in the calorimeter (K_L-crash)

② 2-track vtx close to IP with $M_{\pi\pi} < M_K$ and 2-track α angle selection in kaon rest frame

Main backgrounds:

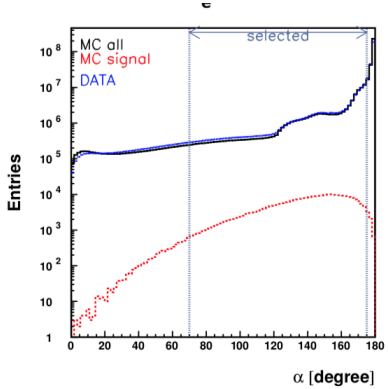
$K_S \rightarrow \pi^+\pi^-(\gamma)$ and $K_S \rightarrow \pi^+\pi^- \rightarrow \pi\mu\nu$ (π decay)



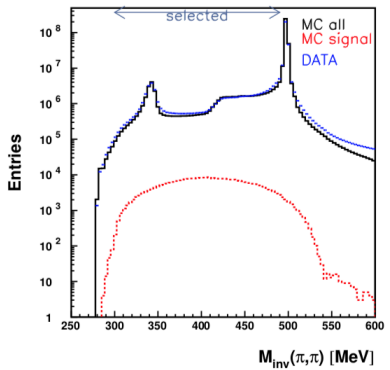


$\rho_{vtx} < 15$ cm

$|z_{vtx}| < 10$ cm



$70° < \alpha < 175°$



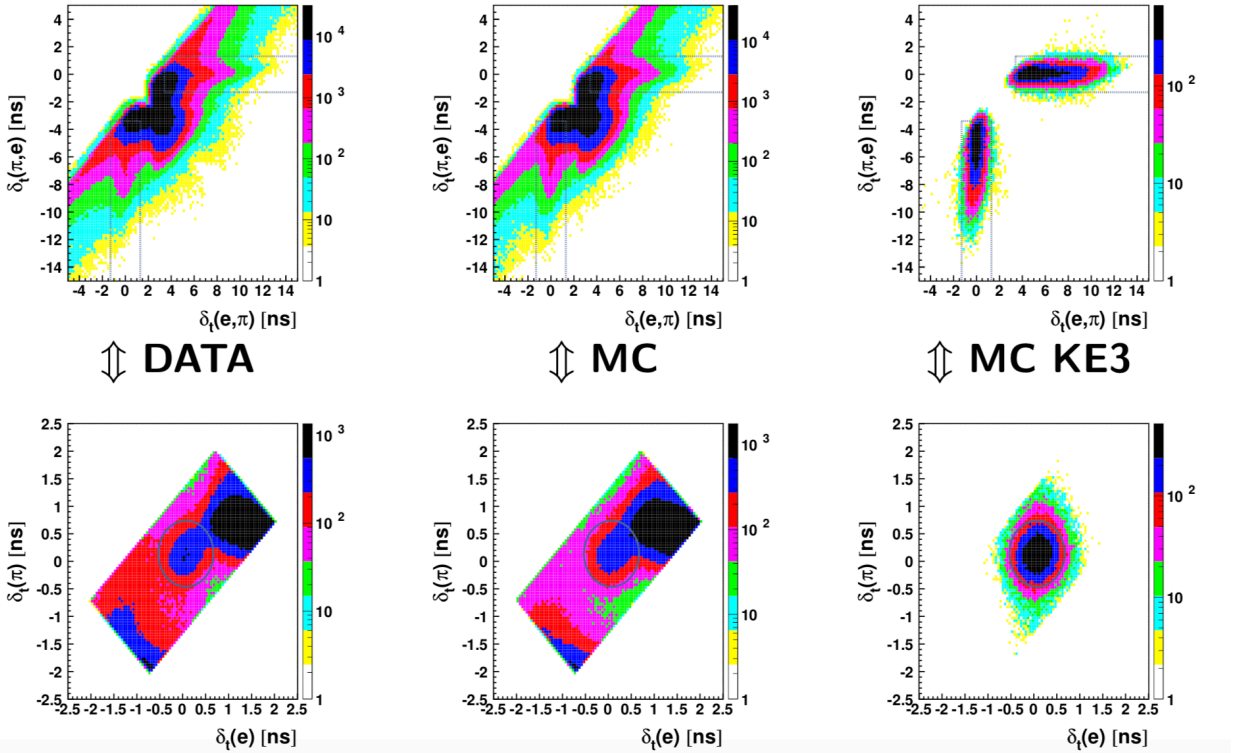
$300 < M_{inv}(\pi, \pi) < 490$ MeV

K_S charge asymmetry with 1.6 fb^{-1}

③ PID with Time of Flight (ToF)

$$\delta_t(X) = t_{cl} - \frac{L}{c\beta(m_X)}$$

$$\delta_t(a,b) = \delta_t(a) - \delta_t(b)$$



K_S charge asymmetry with 1.6 fb^{-1}

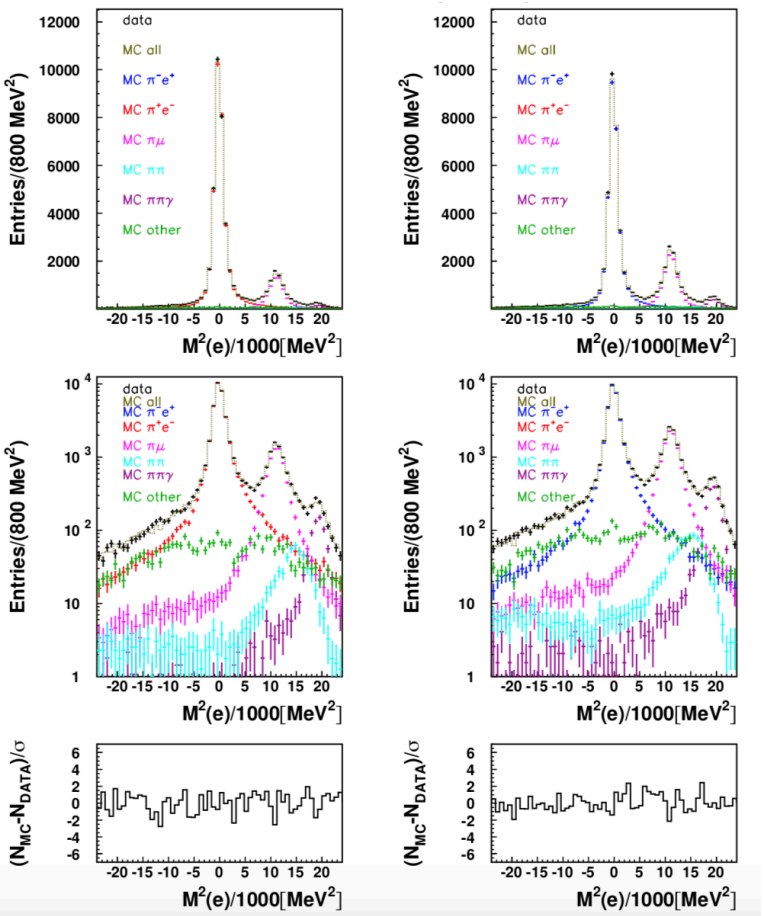
④ Signal count from fit to $M^2(e)$ distribution

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

~7x10⁴ Kse3 events

χ^2/ndf = 118/109

$\varepsilon+ = (7.39 \pm 0.03)\%$ $\varepsilon- = (7.81 \pm 0.03)\%$



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~7x10^4 Kse3 events
χ^2/ndf = 118/109
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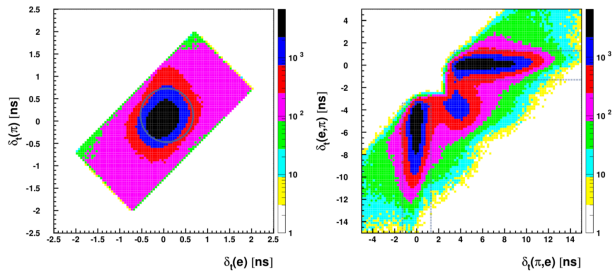
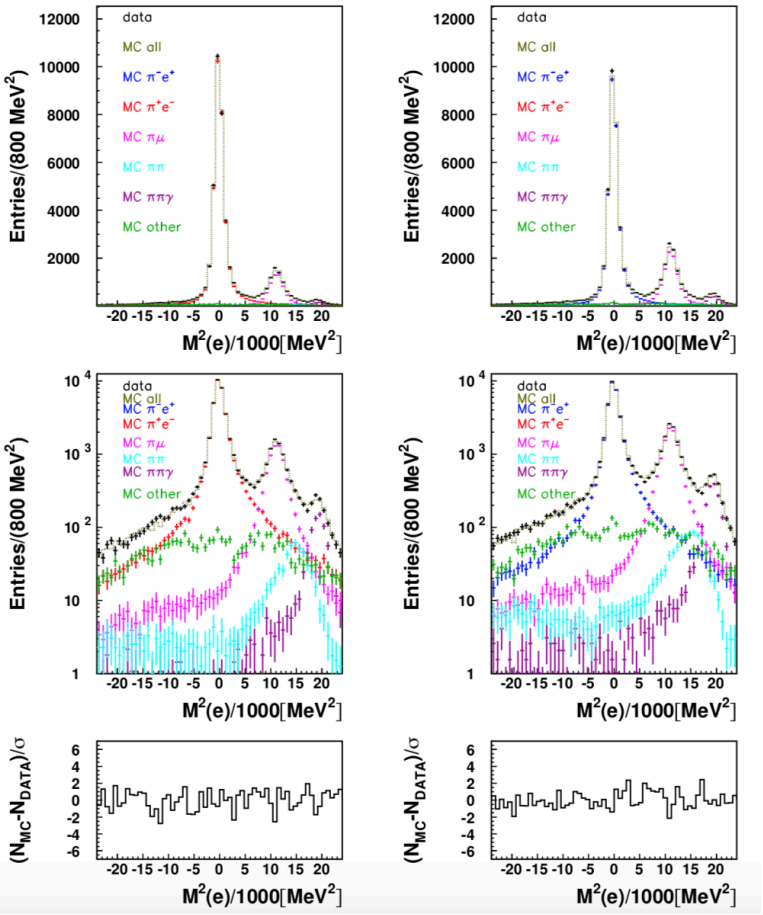
Control Sample
$K_L \to \pi e \nu$ close to IP tagged by $K_S \to \pi^0\pi^0$

- Track to EMC and TOF efficiency correction from CS
- Momentum resolution description in MC tuned with CS

$$\Downarrow \phi \to K_S K_L \to \pi^0\pi^0\pi e\nu$$





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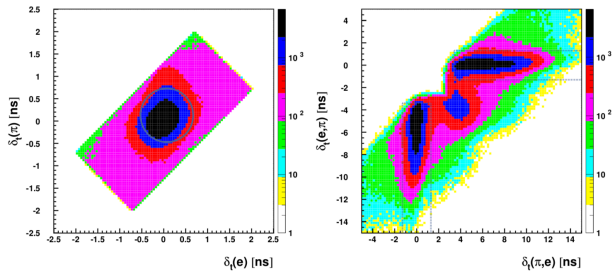
$$\Downarrow \phi \to K_S K_L \to \pi^0\pi^0\pi e\nu$$



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

Systematic uncertainties on A_S

Contribution		Systematic uncertainty (10^{-3})
Trigger and event classification	σ_{TEC}	0.28
Tagging and preselection	$E_{clu}(crash)$	0.55
"	β^*	0.67
"	z_{vtx}	0.01
"	ρ_{vtx}	0.05
"	α	0.46
"	$M_{inv}(\pi,\pi)$	0.20
Time of flight selection	$\delta_t(\pi,\pi)$	0.71
"	$\delta_t(e,\pi)$ vs $\delta_t(\pi,e)$	0.87
"	$\delta_t(e)$ vs $\delta_t(\pi)$	1.82
Momenta smearing	σ_{MS}	0.58
Fit procedure	σ_{HBW}	0.61
"	Fit range	0.49
Total		2.6

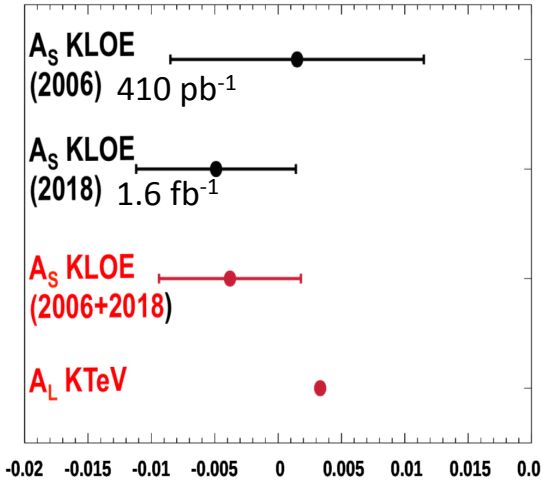
New K_S charge asymmetry result

Present result with 1.6 fb^{-1} [JHEP 09 (2018) 2]:
$A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}$

Previous KLOE result [PLB 636 (2006) 173]:
$A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \times 10^{-3}$

KLOE combined result [JHEP 09 (2018) 2]:
$A_S = (-3.8 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}$

Almost x2 precision improvement
and with KLOE-2 data: $\delta A_S(stat) \rightarrow \approx 3 \times 10^{-3}$



This result allows the most precise values of $\Re(x_-)$ and $\Re(y)$ to be evaluated:

$A_S - A_L = 4\,[\,\Re(\delta) + \Re(x_-)\,]$
$A_S + A_L = 4\,[\,\Re(\epsilon_K) - \Re(y)\,]$

inputs from other experiments [PLB 444 (1998) 52]

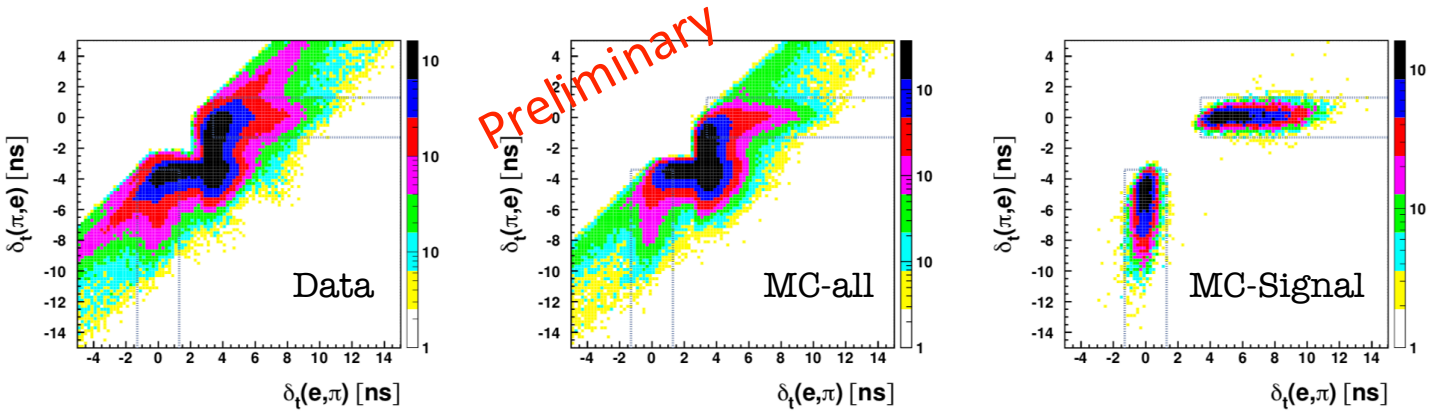
$\Re(x_-) = (-2.0 \pm 1.4) \times 10^{-3}$ CPT violation & $\Delta S \neq \Delta Q$
$\Re(y) = (1.7 \pm 1.4) \times 10^{-3}$ CPT violation

[JHEP 09 (2018) 2]

K_S charge asymmetry analysis with KLOE-2 Data

- Analyzed 0.8 fb^{-1} Data and MC sample
- KS tagged by KL interacting in the calorimeter (EMC)
- TOF analysis on KS decay products for PID
- Tagging & signal selection efficiency evaluation
- $K_S \rightarrow \pi^+\pi^-$ KLe3 control sample

KSe3 KL - interacting in EMC



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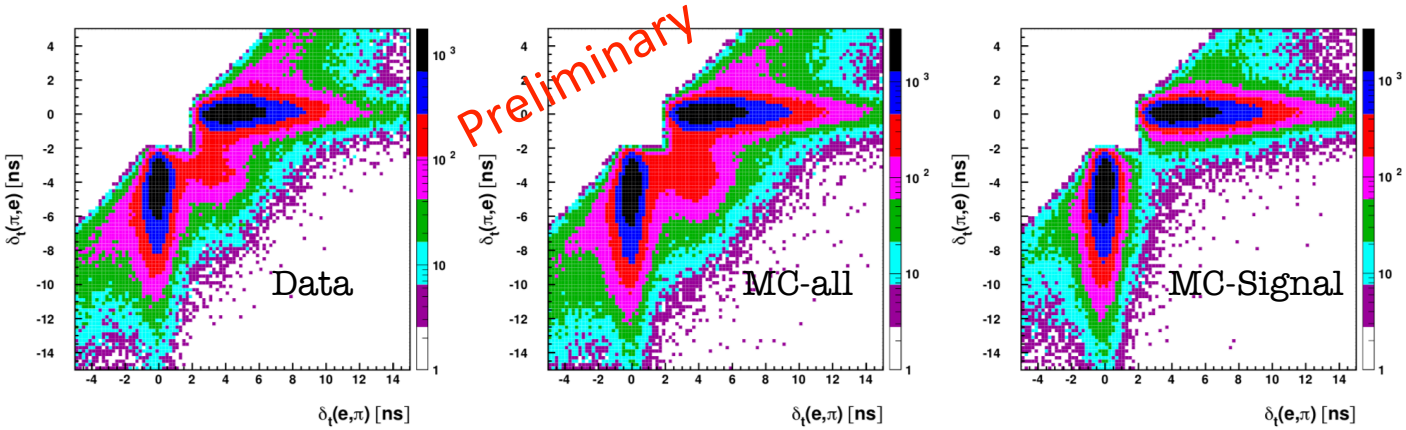


- Presently adjusting analysis scheme to face larger machine background wrt KLOE data taking campaign
- Revising streaming algorithm with independent data sample

Direct CPT test in Kaon transitions

Direct test of CPT with kaons

◎ Entangled neutral kaons at a phi-factory - KLOE/KLOE-2 uniqueness

◎ Direct and model independent tests of CPT symmetry through the comparison of transition rates between flavor and CP eigenstates

Strangeness eigenstates	CP eigenstates
$K^0 \to \pi^- e^+ \nu$	$K_+ \to \pi^+ \pi^-$
$\bar{K}^0 \to \pi^+ e^- \bar{\nu}$	$K_- \to 3\pi^0$
Lepton charge tags strangeness state	*Final state tags CP-even/odd states*

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

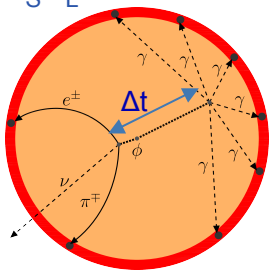
CPT test ratios:

$$R_2^{CPT}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \bar{K}^0(\Delta t)]}$$

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

[Nucl. Phys. B 868 (2013) 102], JHEP 10 (2015) 139]

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



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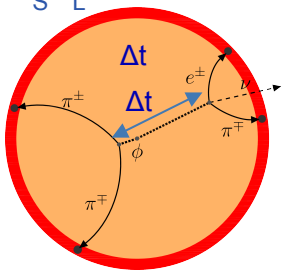

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$$K_- \to 3\pi^0$$

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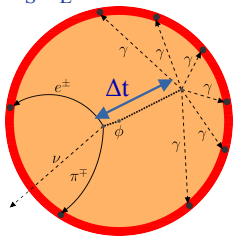
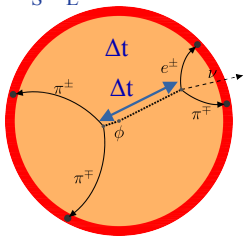


$K_S K_L \to \pi^+\pi^-\, \pi e^{\pm} \nu$



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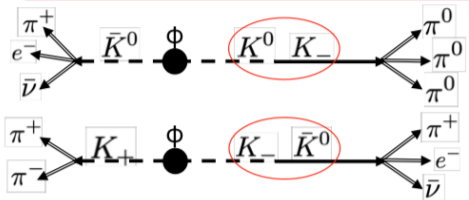
[Nucl. Phys. B 868 (2013) 102], JHEP 10 (2015) 139]

Measure two processes:

$K_S K_L \to \pi^+ e^- \bar{\nu}\; 3\pi^0$ and $K_S K_L \to \pi^+\pi^-\, \pi^+ e^- \bar{\nu}$



Entanglement: preparation of states
Kaon decays: filter measurement

Direct test of CPT with kaons

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◎ Direct and model independent tests of CPT symmetry through the comparison of transition rates between flavor and CP eigenstates

◎ $\phi \rightarrow K_S K_L \rightarrow \pi e^{\pm}\nu\, 3\pi^0$ and $\pi^+\pi^-\ \pi e^{\pm}\nu$

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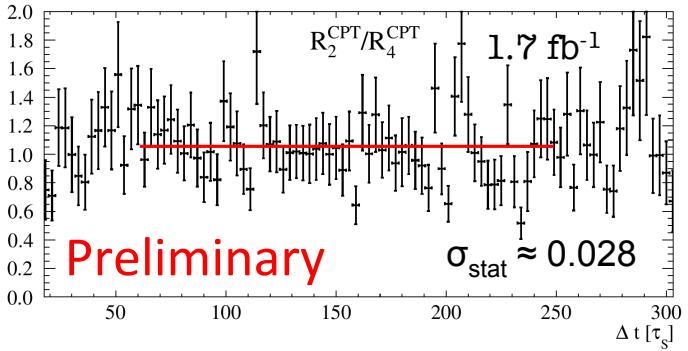

$$DR_{CPT} = \frac{R_{2,CPT}(\Delta t >> \tau_S)}{R_{4,CPT}(\Delta t >> \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

Cleanest CPT observable
DR_{CPT} different from 1 implies CPT violation
Never measured to date

◎ Systematic checks undergoing
◎ 10^{-3} sensitivity with KLOE+KLOE-2
◎ DR_{CPT} connected to $A_{S,L}$
$DR_{CPT} = 1 + 2\,(A_L - A_S)$ using A_L from KTeV and A_S from KLOE: $DR_{CPT} = 1.016 \pm 0.011$ (preliminary)

KLOE-2 Physics Programme

More physics results to come and not only from Kaons

Kaon Physics:

- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- Search for CP-violating decay $K_S \to 3\pi^0$
- K_S semileptonic decays and A_S (also CP and CPT test)
- ChpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

see A. Selce's talk

Light meson Physics:

- η decays, ω decays, TFF $\phi \to \eta e^+e^-$
- Discrete symmetries C,P,CP violation:
  improve limits on $\eta \to \pi^+\pi^-$, $\pi^0\pi^0$, $\gamma\gamma\gamma$,$\pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^-e^+e^-$ (non-CKM CP viol.)
- ChPT studies with $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $\phi \to K_SK_S\gamma$ (1st obs?)
- $\gamma\gamma$ Physics: measurement of $\pi^0 \to \gamma\gamma$ width and $F_{\pi 0\gamma^*\gamma}$ TFF with $e+e- \to e+e- \pi^0$
- Search for axion-like particles

Highest priority with KLOE/KLOE-2 ongoing analysis

Dark forces:

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

Hadronic cross section

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

Further details:
KLOE-2 Collaboration: EPJ C68 (2010) 619
Proceedings EPJ WoC 166 (2018)
KLOE-2 Workshop on e+e- collision physics at 1 GeV [https://agenda.infn.it/event/kloe2ws]

Conclusions

- The entangled neutral kaon system at a ϕ-factory is a unique laboratory to study discrete symmetries
- Discrete symmetry test with neutral kaons is one of the key issues at KLOE-2 including several high precision tests of CPT and Quantum Mechanics
- A new result on Ks Semileptonic Charge Asymmetry has been presented with a x2 precision improvement with respect to previous results
- The direct test of CPT in kaon transitions with DR_{CPT} provides the cleanest CPT observable with 10^{-3} sensitivity with KLOE+KLOE-2 data
- KLOE-2 at DAϕNE completed successfully its data taking campaign in March 2018 collecting 5.5 fb^{-1}

KLOE + KLOE-2 data represents the largest sample ever collected at ϕ-meson peak

More physics results to come and not only from kaons