Recent Results on Kaon Physics at KLOE-2

Alessandro Di Cicco
INFN Roma Tre and Laboratori Nazionali di Frascati
On behalf of the KLOE-2 Collaboration

Outline

- KLOE and KLOE-2 at DAΦNE ϕ-factory
- Measurement of the charge asymmetry in K_S semileptonic decays for CP and CPT violation tests
- Direct test of T and CPT symmetries using transitions of neutral kaons
- Measurement of the pure CP-violating $K_S \rightarrow \pi^0\pi^0\pi^0$ decay
- Summary and perspectives

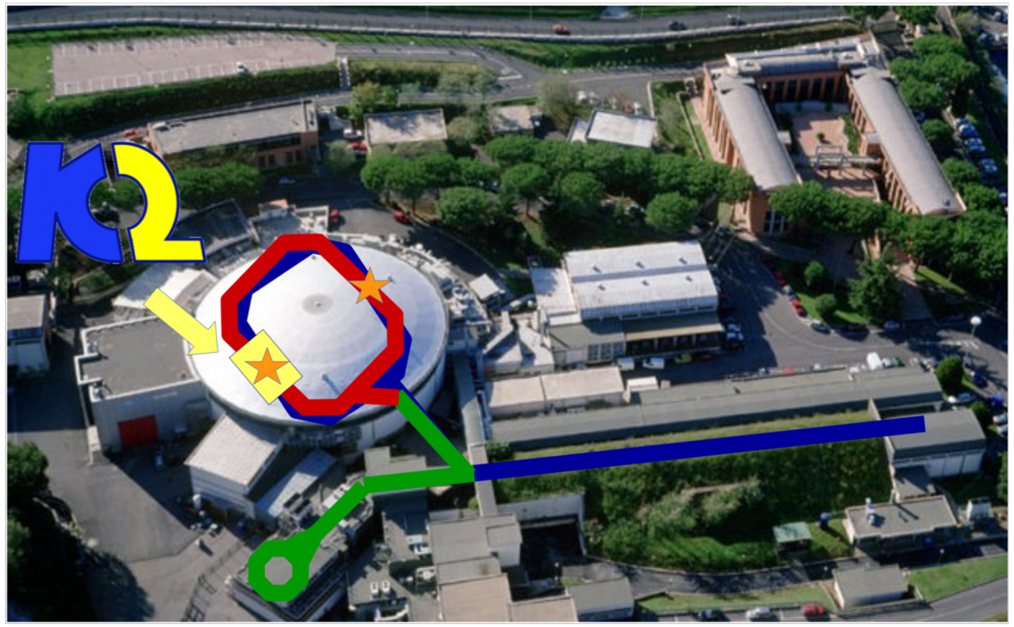
KLOE and KLOE-2 at DAΦNE ϕ-factory

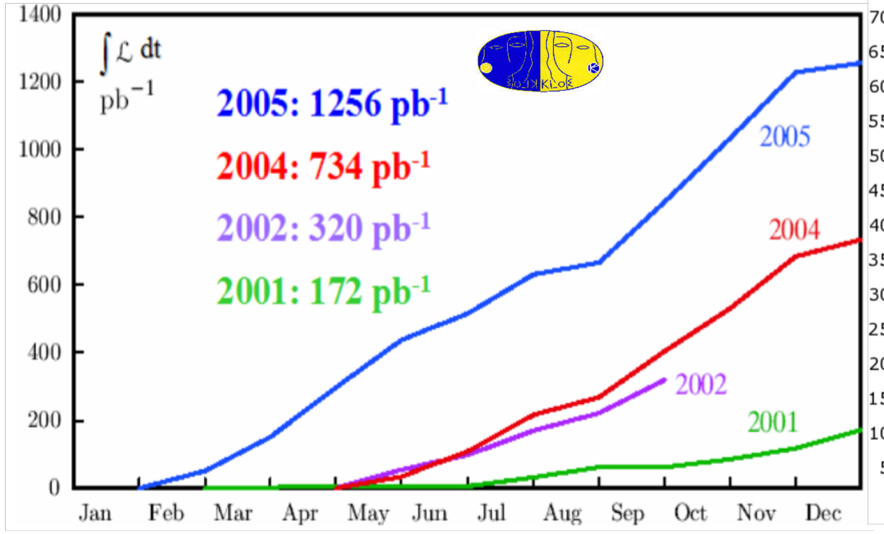
INFN – Laboratori Nazionali di Frascati

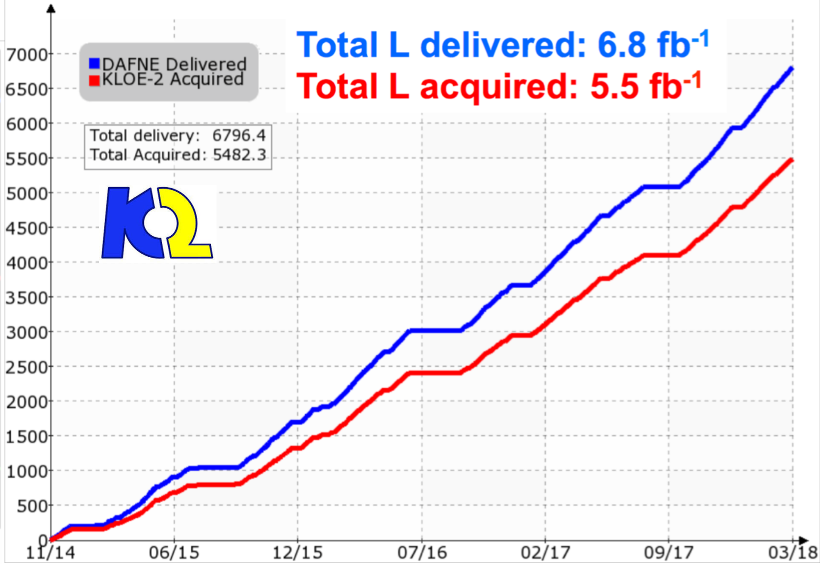
e^+e^- collisions at $\sqrt{s} = m_\phi \approx 1020$ MeV

ϕ main decays	BR
K^+K^-	49 %
$K_L K_S$	34 %
ρπ/πππ	15 %
ηγ	1 %

Kaon pairs produced in an *entangled state*







KLOE and KLOE-2 have collected together the largest sample of $e^+e^- \rightarrow \phi$ ever:
$\sim 8\ fb^{-1} \Rightarrow 2.4 \times 10^{10}\ \phi$ mesons

KLOE and KLOE-2 experiments

Superconducting magnet

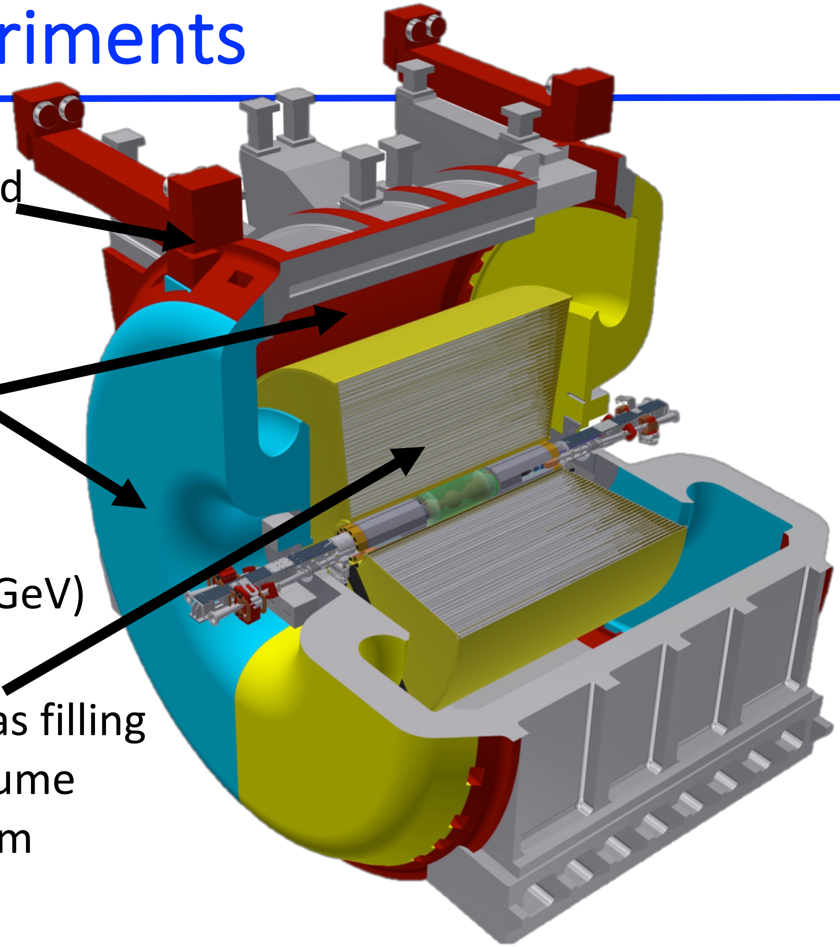
- 0.52 T axial magnetic field

Electromagnetic calorimenter

- Barrel & End-caps
- Lead & scintillating fibers
- Hermetic coverage (98% x 4π)
- $\sigma_t = 54\ \text{ps} / \sqrt{E(\text{GeV})} \oplus 140\ \text{ps}$
- $\sigma_E = 5.7\% / \sqrt{E(\text{GeV})}$
- $\sigma_x = \sigma_y = 1\ \text{cm}$, $\sigma_z = 1.2\ \text{cm} / \sqrt{E(\text{GeV})}$

Drift Chamber

- 90% He + 10% C_4H_{10} gas filling
- $\sim 50\ m^3$ detecting volume
- $\sigma_{xy} \approx 150\ \mu m$, $\sigma_z \approx 2\ mm$
- $\sigma(p_T)/p_T = 0.4\ \%$



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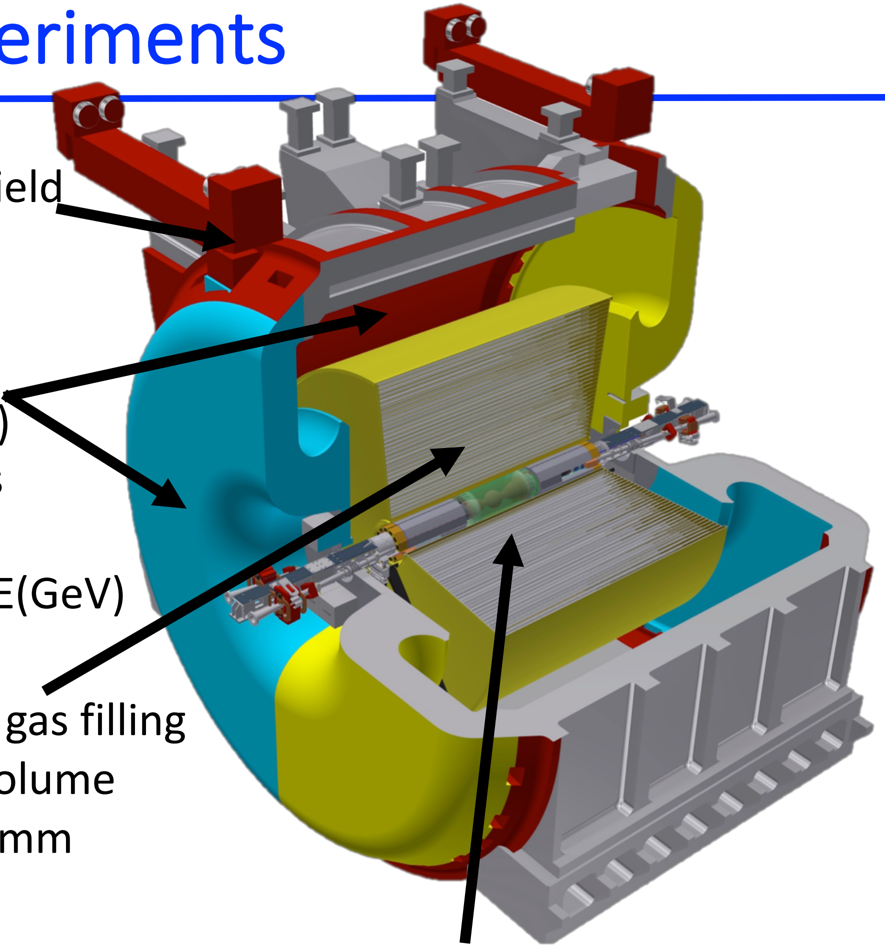
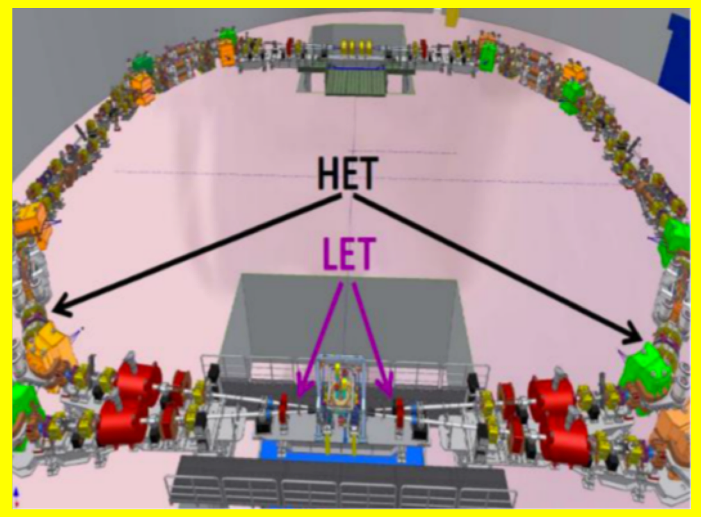
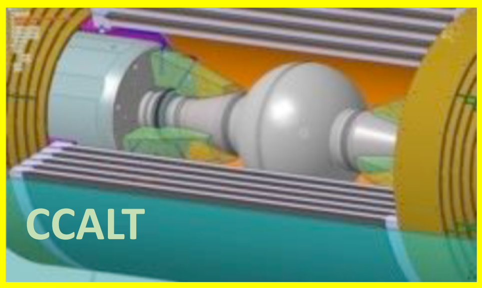
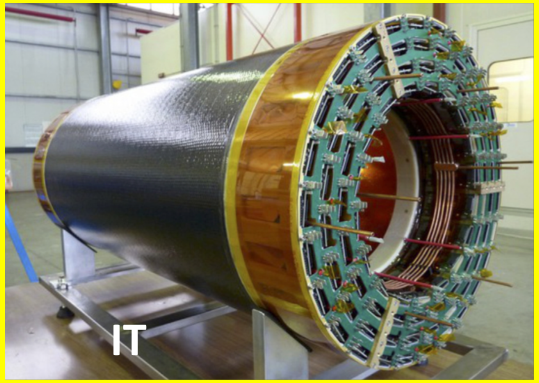
- $\sigma_x = \sigma_y$ = 1 cm, σ_z = 1.2 cm / √E(GeV)

Drift Chamber
- 90% He + 10% C_4H_{10} gas filling
- ~ 50 m^3 detecting volume
- σ_{xy} ≈ 150 μm, σ_z ≈ 2 mm
- $\sigma(p_T)/p_T$ = 0.4 %









Detector improvements
- New cylindrical-GEM Inner Tracker

NIMA 628 (2011) 194

- New calorimeters

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

CP and CPT tests with $K_{S(L)} \rightarrow \pi e \nu$

Charge asymmetry in semileptonic decays of neutral kaons:

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

$$= 2\left[\Re(\epsilon_K) \pm \Re(\delta) - \Re(y) \pm \Re(x_-)\right]$$

- $\Re(\epsilon_K)$: CP violation
- $\Re(\delta)$: CPT violation in $K^0\underline{K}^0$ mixing
- $\Re(y)$: CPT violation in $\Delta S = \Delta Q$ processes
- $\Re(x_-)$: CPT violation in $\Delta S \neq \Delta Q$ processes

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

$A_S \neq A_L \Rightarrow$ CPT violation

Assuming CPT invariance:

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

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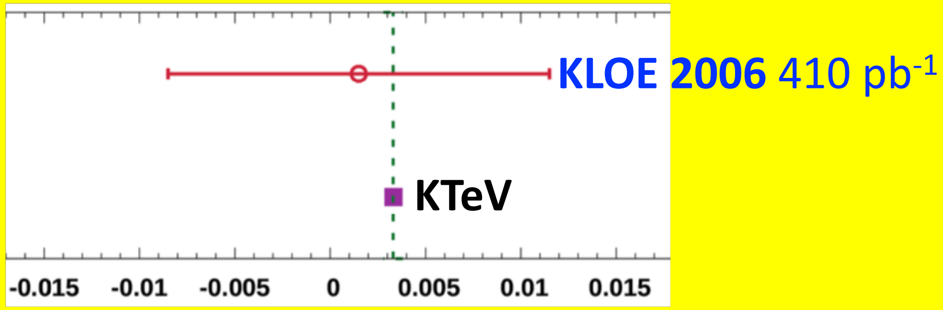
KLOE Collaboration PLB 636 (2006) 173

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



KTeV Collaboration PRL 88 181601 (2002)

$A_L = (3.332 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$

CP and CPT tests with $K_{S(L)} \to \pi e \nu$

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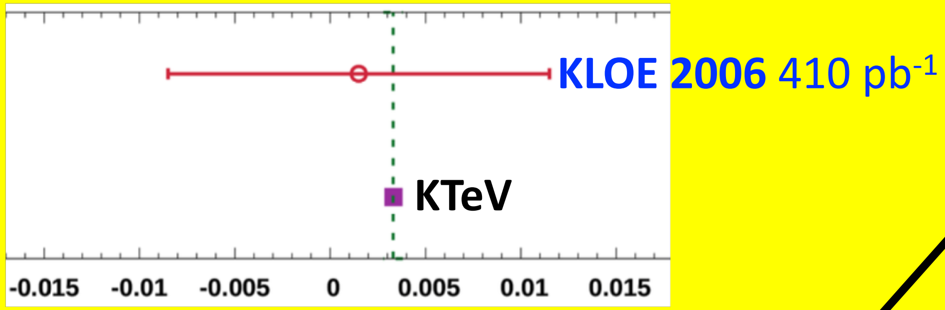

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$A_S - A_L = 4\left[\Re(\delta) + \Re(x_-)\right]$

$A_S + A_L = 4\left[\Re(\epsilon_K) - \Re(y)\right]$

inputs from other experiments

PLB 444 (1998) 52

$\Re(x_-) = (-0.8 \pm 2.5) \times 10^{-3}$

$\Re(y) = (0.4 \pm 2.5) \times 10^{-3}$

PLB 636 (2006) 173

Charge asymmetry measurement at KLOE

Signal decay

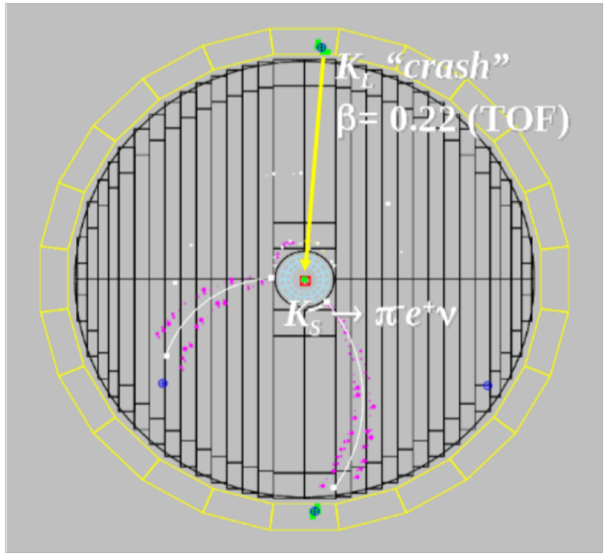
$\phi \rightarrow K_S K_L \rightarrow \pi e \nu\ K_L(\text{crash})$

Control sample

$\phi \rightarrow K_S K_L \rightarrow \pi^0 \pi^0\ \pi e \nu$

Main backgrounds

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



Event selection

K_S tagged by K_L interacting in the calorimeter

TOF analysis performed on K_S decay products for PID

Charge asymmetry measurement at KLOE

Signal decay

$\phi \rightarrow K_S K_L \rightarrow \pi e \nu$ K_L(crash)

Control sample

$\phi \rightarrow K_S K_L \rightarrow \pi^0 \pi^0$ $\pi e \nu$

Main backgrounds

- $K_S \rightarrow \pi^+\pi^-(\gamma)$
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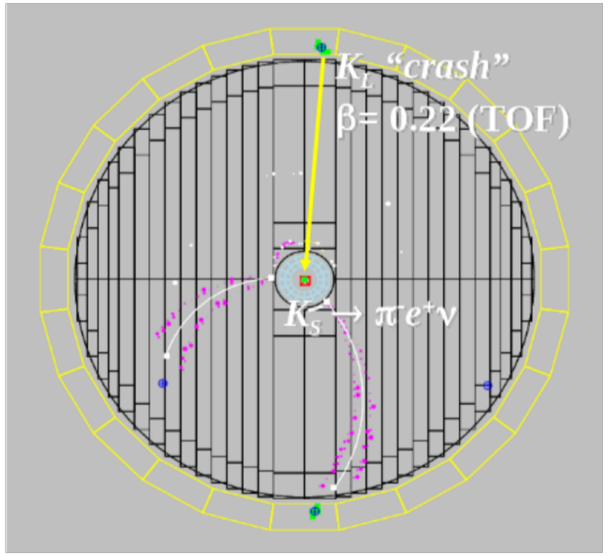
Signal event counting

Fit of $M^2(e)$ data spectrum using MC-simulated distributions for signal and backgrounds

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



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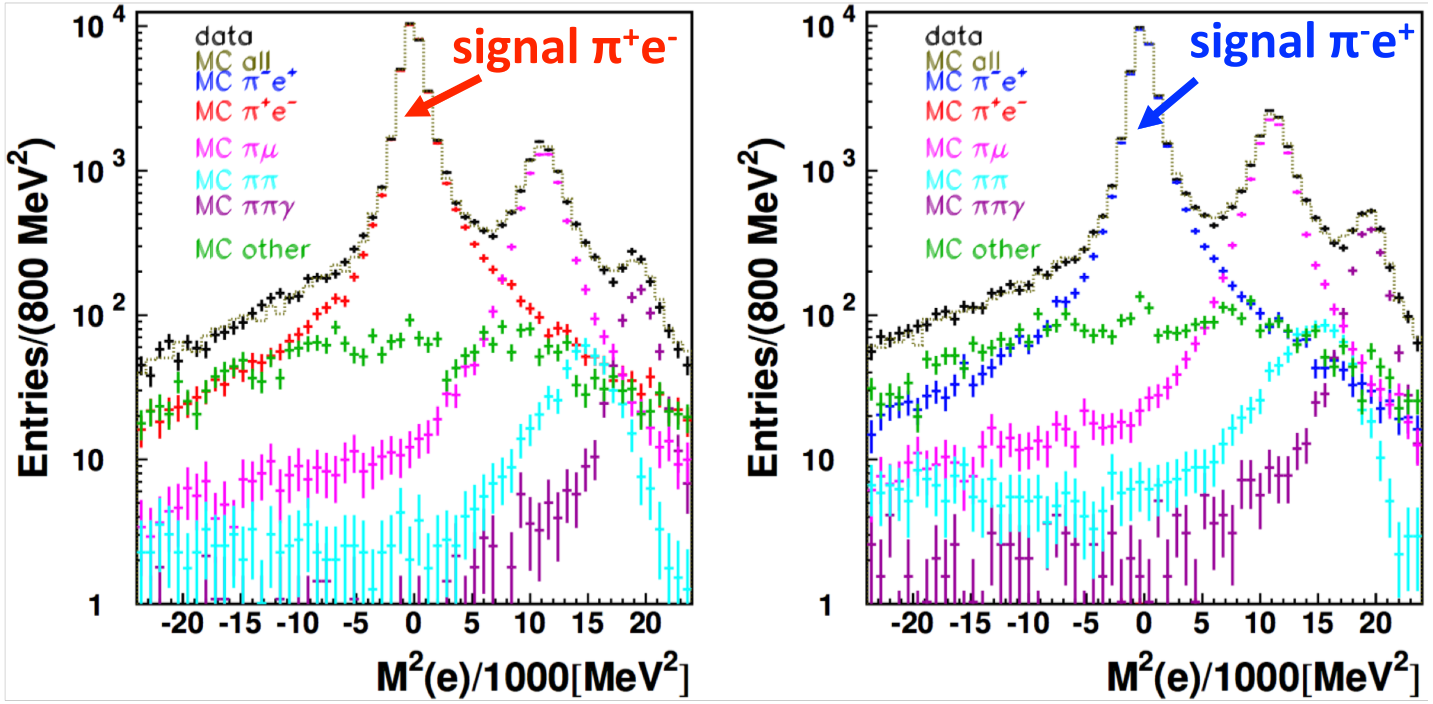


New results on charge asymmetry measurements at KLOE

New most precise measurement of A_S:

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

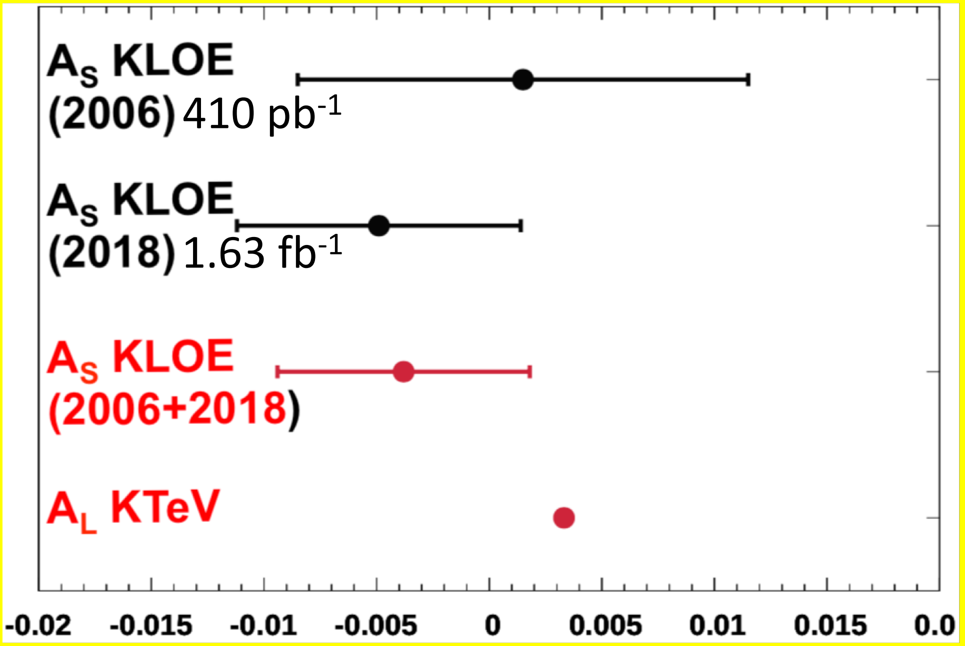
Previous KLOE measurement of A_S:

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

Combined KLOE2006 + KLOE2018 result:

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

JHEP 09 (2018) 21



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

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

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

With more than 5 fb^{-1} of KLOE-2 data the statistical uncertainty on A_S determination can be reduced to 3×10^{-3}

Direct tests of T and CPT symmetries in neutral kaon transitions

First *direct* and *model independent* test of T and CPT:

- compare rates of transitions between strangeness and CP eigenstates
- only feasible with *entangled neutral kaon pairs*

Strangeness eigenstates

$$K^0 \to \pi^- e^+ \nu$$
$$\bar{K}^0 \to \pi^+ e^- \bar{\nu}$$

Lepton charge tags strangeness state

CP eigenstates

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

Final state tags CP-even/odd states

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

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Any deviation form 1 signals T/CPT violation

J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, NPB 868 (2013) 102
J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, JHEP 10 (2015) 139

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Measure two processes:

$K_S K_L \to \pi^+ e^- \underline{\nu}$ $3\pi^0$ and **$K_S K_L \to \pi^+ \pi^-$ $\pi^+ e^- \underline{\nu}$**

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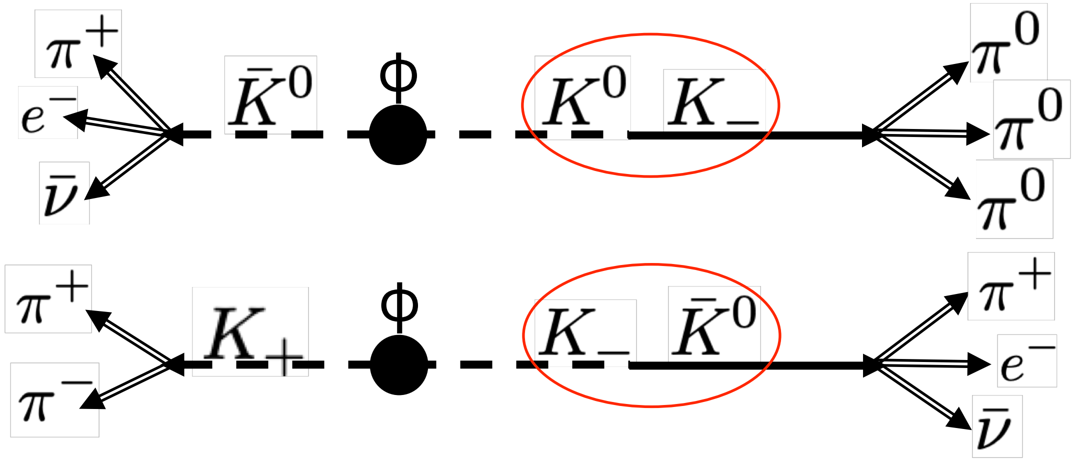

Entanglement: preparation of states
Kaon decays: filter measurement

J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, NPB 868 (2013) 102
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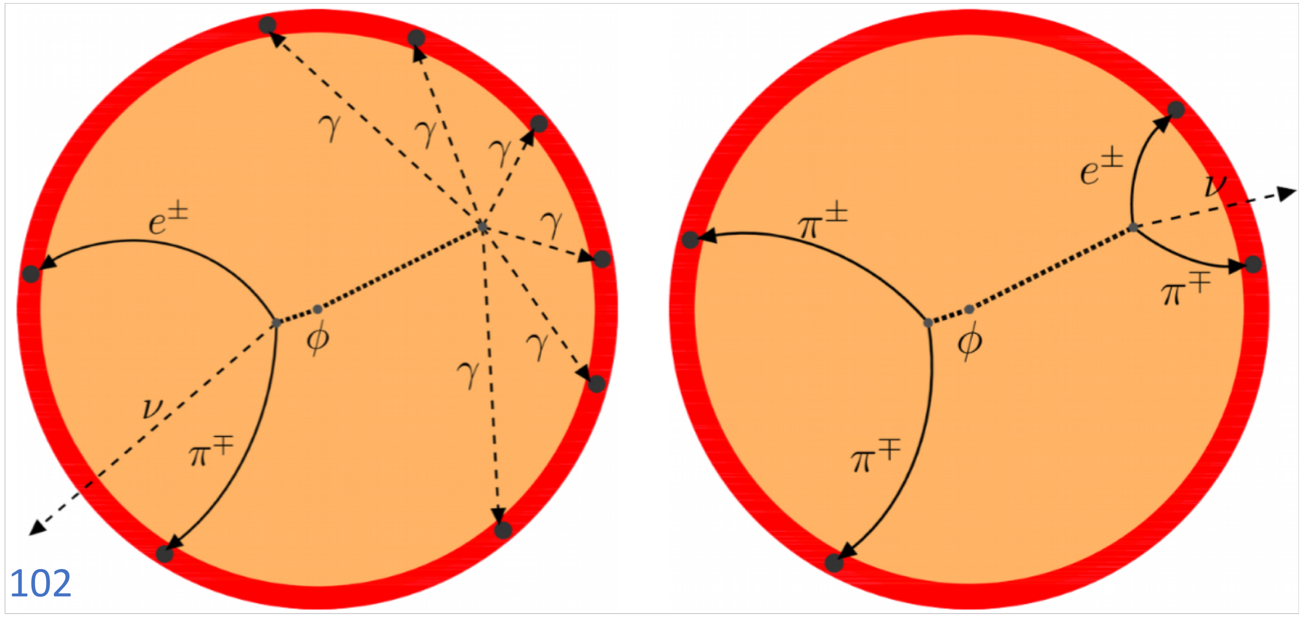

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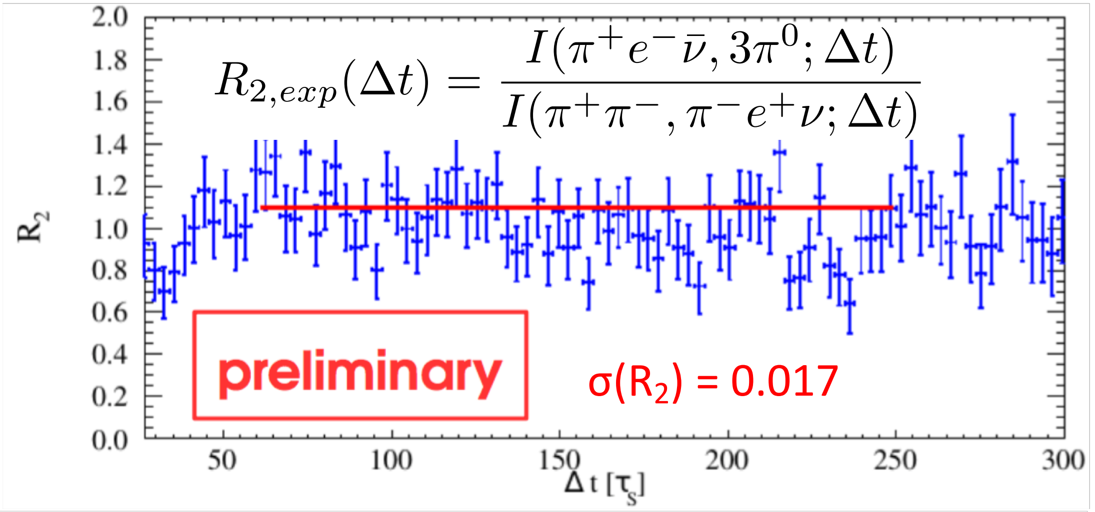
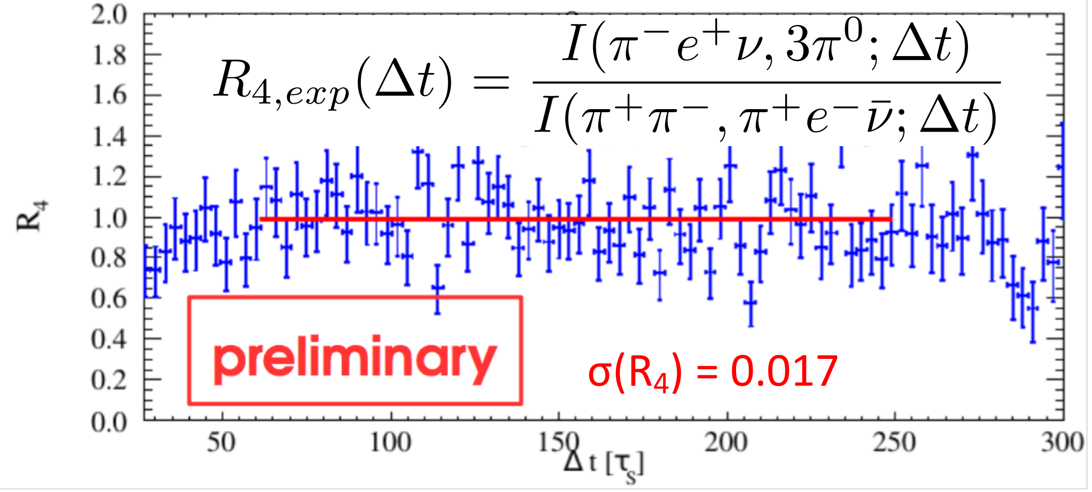
T and CPT-violation sensitive observables: preliminary results

First direct T and CPT violation tests with KLOE data

T-violating ratios





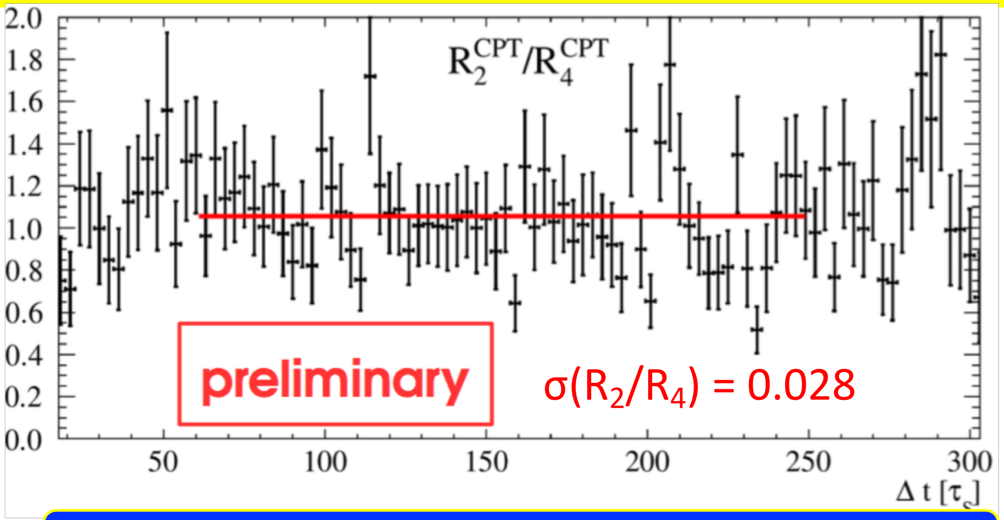
CPT-violating double-ratio

$$R^{CPT}_{2,exp}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$$R^{CPT}_{4,exp}(\Delta t) = \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

$$\frac{R^{CPT}_{2,exp}(\Delta t \gg t)}{R^{CPT}_{4,exp}(\Delta t \gg t)} = 1 - 8\Re(\delta) - 8\Re(x_-) \sim 1 + 2(A_L - A_S)$$

Pure and genuine CPT-violating observable effect



10^{-3} sensitivity using the full KLOE + KLOE-2 dataset

Branching Ratio of $K_S \rightarrow \pi^0\pi^0\pi^0$ CP-violating Decay

Observing $K_S \rightarrow \pi^0\pi^0\pi^0$ is an unambiguous sign of CP violation (CP = -1 for $3\pi^0$ state)

- Standard Model prediction: BR = 1.9×10^{-9}
- Best upper limit by KLOE with 1.7 fb^{-1}: BR < 2.5×10^{-8} @ CL = 90% PLB 273 (2013) 54

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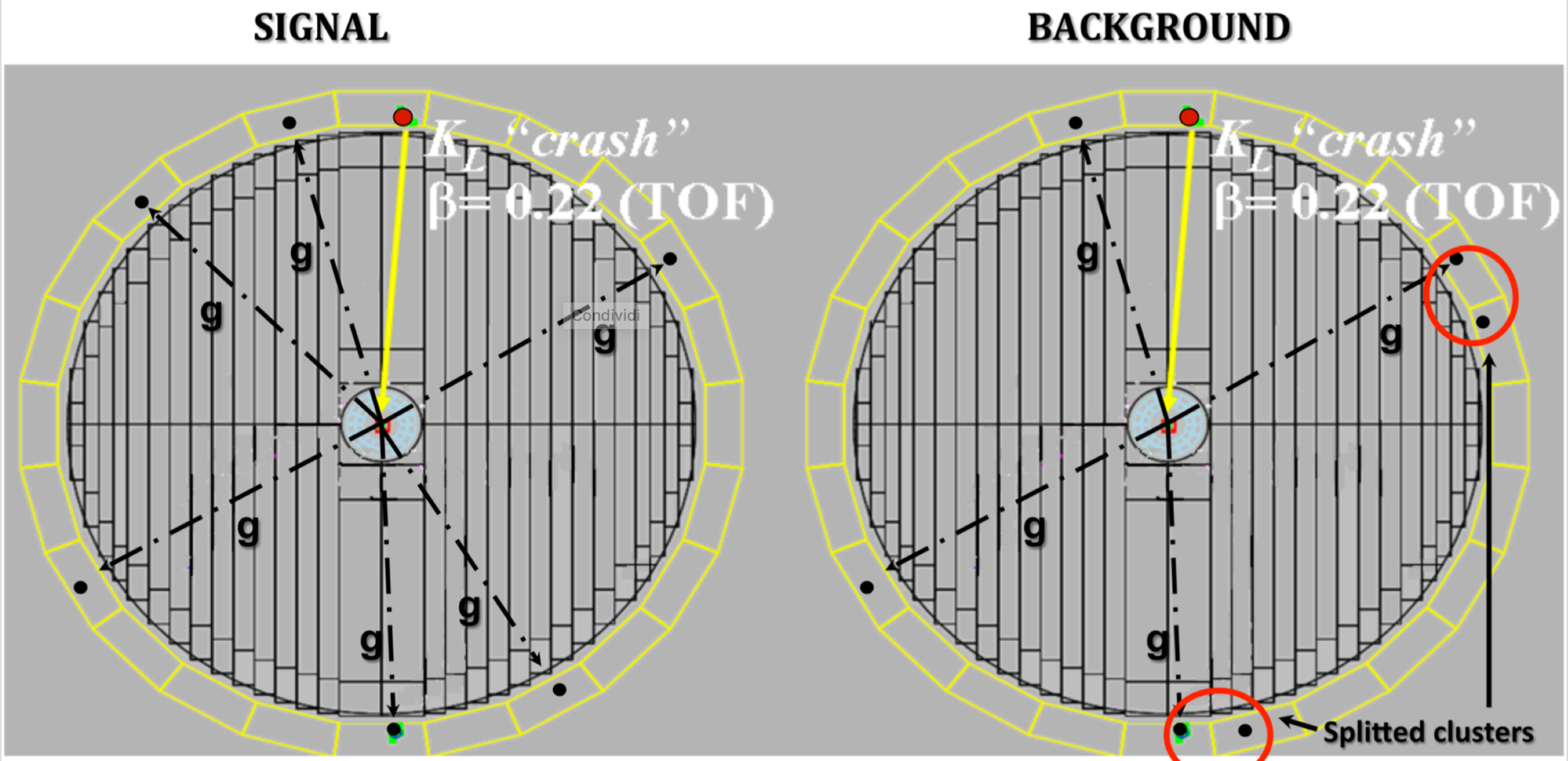

$K_S \rightarrow 3\pi^0 \rightarrow 6\gamma$

$K_S \rightarrow 2\pi^0$ + accidental/splitted clusters
$K_L \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+\pi^-$ („fake K_L-crash")

KLOE-2 data analysis ongoing.
Found 1 signal event in 300 pb^{-1} data with KLOE analysis scheme:
BR < 2.5×10^{-7} @ CL = 90% (preliminary)

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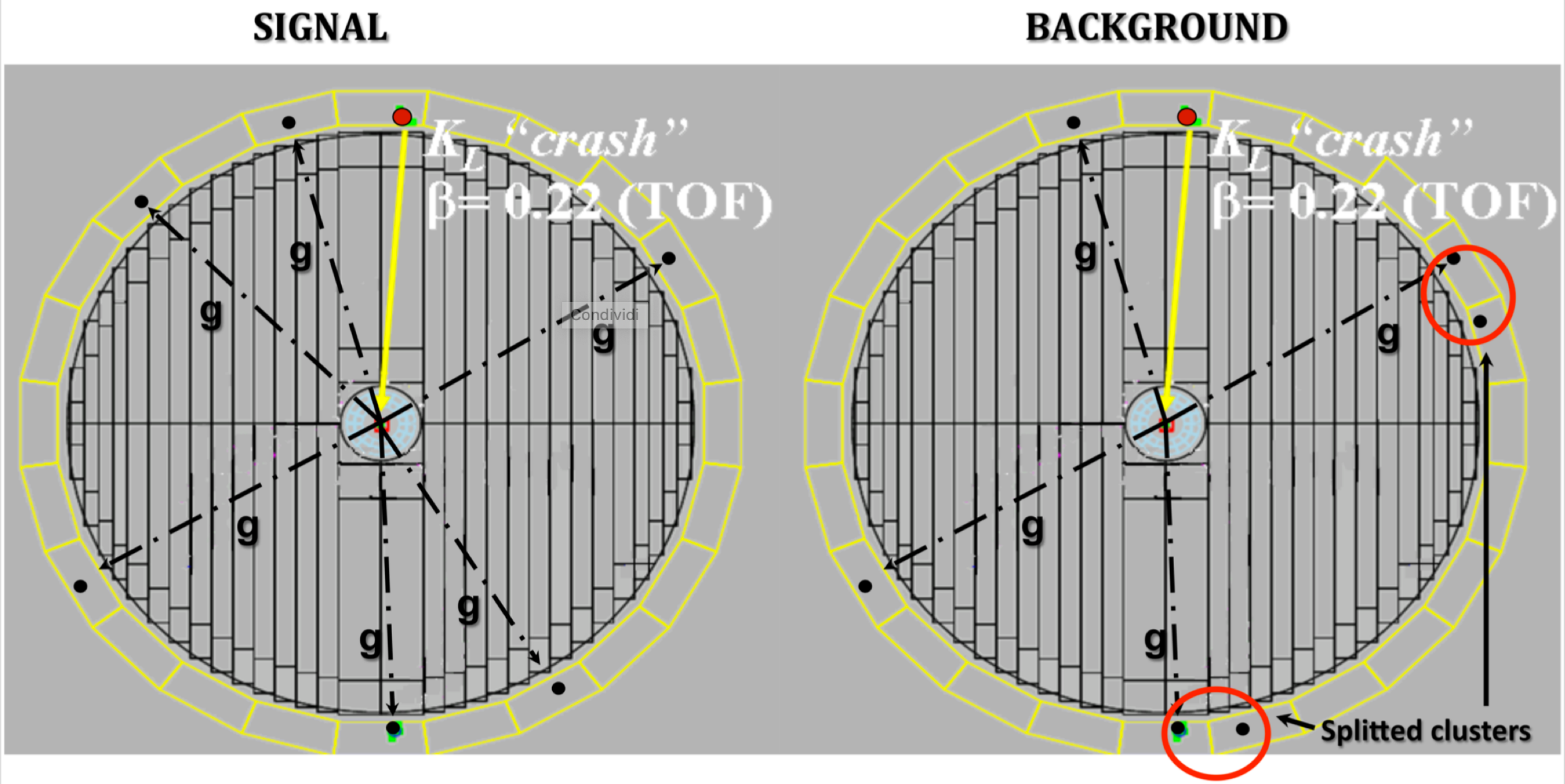

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$\lesssim 10^{-8}$ sensitivity expected using the full KLOE-2 dataset and optimized analysis to better reject x 10 machine background

Conclusions

- **KLOE-2 acquired 5.5 fb^{-1} of data**
  - collecting the largest sample of e^+e^- interacions at the ϕ-meson peak (KLOE + KLOE-2)
- Tests of discrete symmetries are among the major goals of KLOE and KLOE-2

- A new *most precise measurement of the charge asymmetry in semileptonic K_S decays* has been published in JHEP using all KLOE data
  - Expected sensitivity down to 3 x 10^{-3} using also KLOE-2 data

- A *first direct test of T and CPT symmetries* is being performed with entangled neutral kaon pairs using KLOE data
  - Expected sensitivity down to 10^{-3} using also KLOE-2 data

- Measurement of BR($K_S \rightarrow \pi^0\pi^0\pi^0$) pure CP-violating decay. Best upper limit set by KLOE.
  - Expected sensitivity $\lesssim 10^{-8}$ using full KLOE-2 dataset & optimized analysis to reject larger background