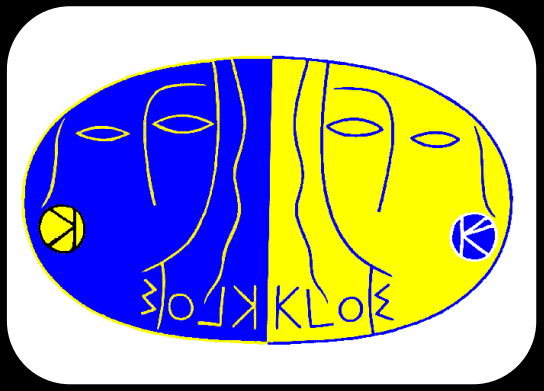


E. De Lucia

LNF-INFN

for KLOE/KLOE-2 Collaborations

Study of CP and CPT symmetry violations in Kaon decays with KLOE

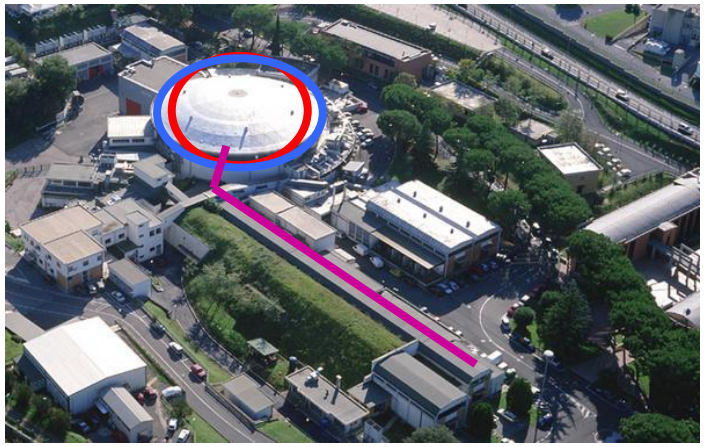
EPSHEP 2013 Stockholm, Sweden, 18-24 July 2013

KLOE at DAFNE ϕ-factory

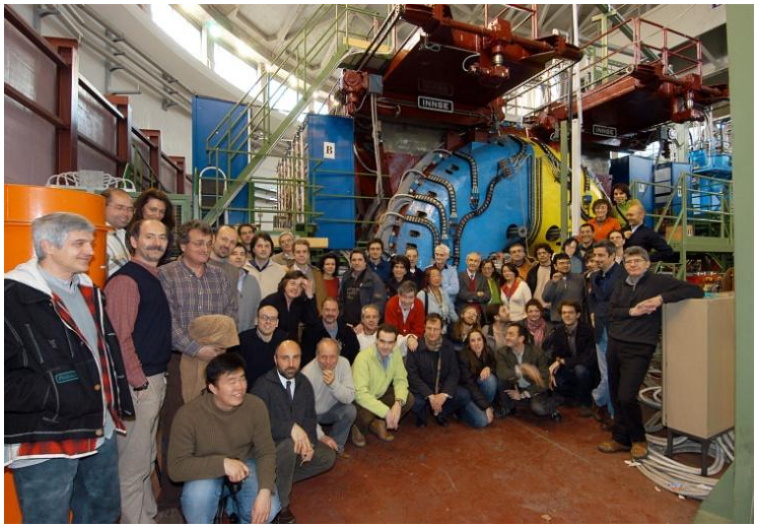
Frascati ϕ-factory ***DAϕNE***: an **e^+e^- collider @ √s =1019.4 MeV = M_ϕ**

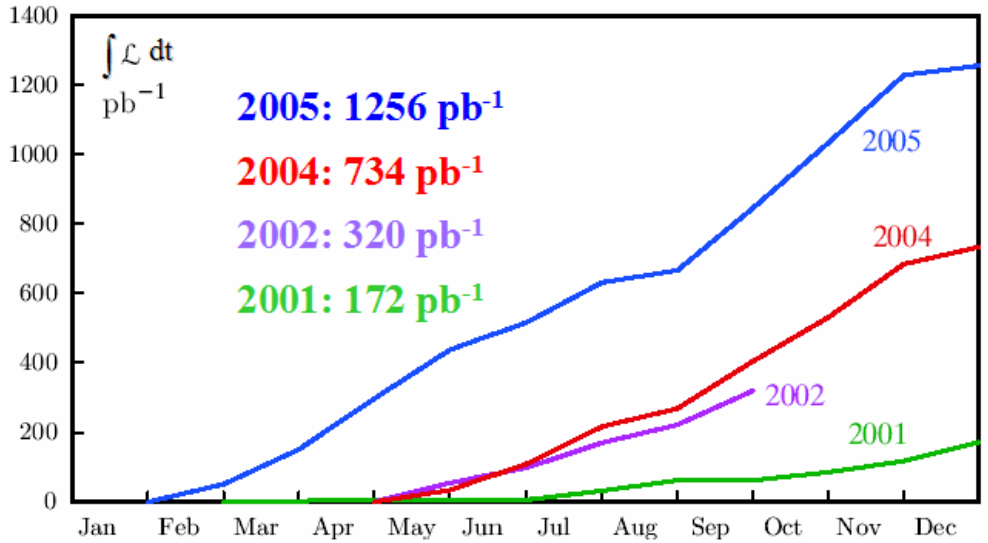
Best performance in 2005:

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



KLOE has acquired 2.5 fb^{-1} @ √s=M_ϕ (2001-05)
+ 250 pb^{-1} *off-peak* @ √s=1 GeV



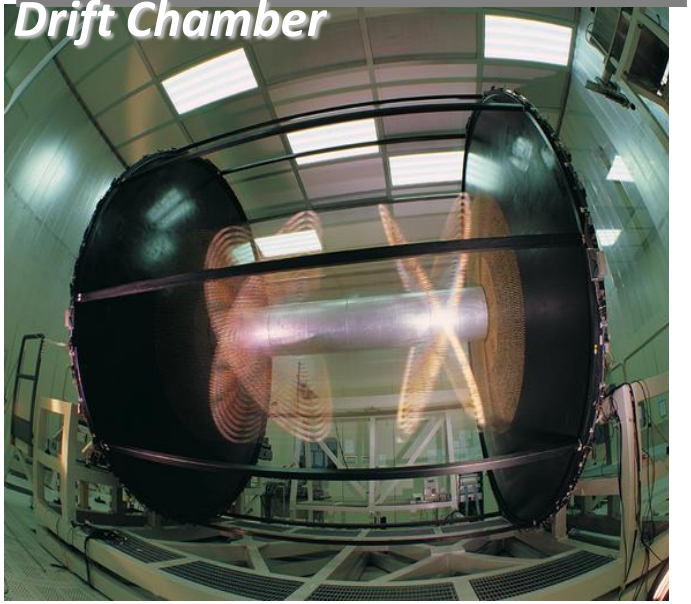


Precision Kaon and Hadron Physics with KLOE **Rivista del Nuovo Cimento Vol.31, N.10 (2008)**

KLOE at DAΦNE φ-factory

- 4 m diameter 3.3 m length
- 90% helium, 10% isobutane
- 12582/52140 sense/tot wires
- All-stereo geometry

Drift Chamber



$\sigma_{r\phi} = 150\ \mu m$ $\sigma_z = 2\ mm$

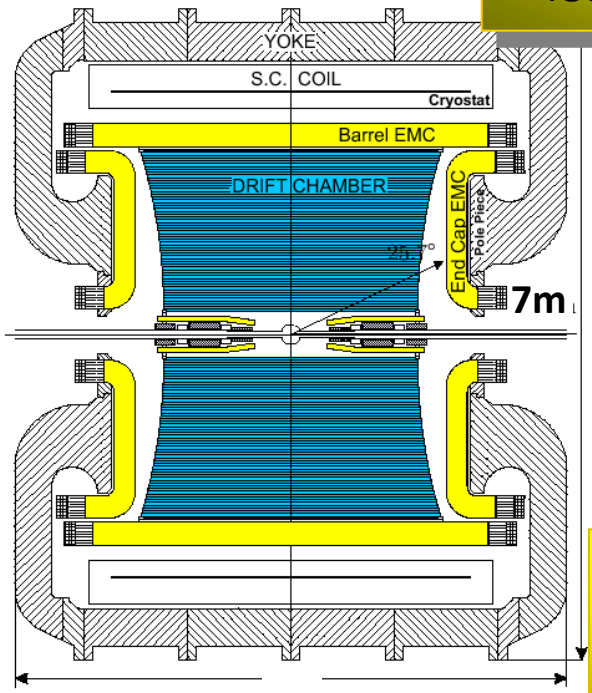
$\sigma_v = 3\ mm$ $\sigma_p/p = 0.4\ \%$

$\Phi \rightarrow K_S K_L$

$\lambda_{KS} = 0.6$ cm

$\lambda_{KL} = 340$ cm

$\lambda_{K\pm} = 95$ cm



B = 0.52 T

- Lead/scintillating fiber
- 98% coverage of solid angle
- 88 modules (barrel + end-caps)
- 4880 PMTs (two side read-out)

$\sigma_E/E = 5.4\%/\sqrt{E(GeV)}$

$\sigma_t = 54\ ps/\sqrt{E(GeV)}$

$\oplus$ **50 ps**(calib)

CPT & Lorentz Symmetry

Test with $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

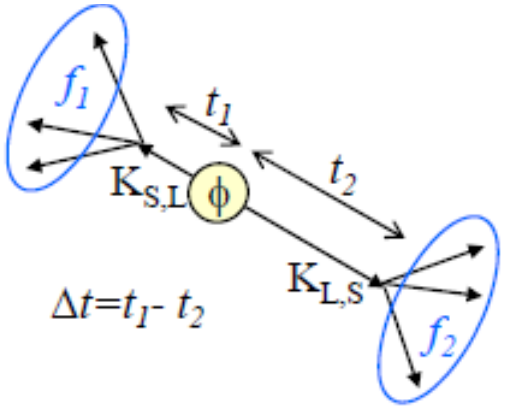
Kaon production at ϕ-factory

- ϕ-meson decays in entangled pair of neutral kaons with $J^{PC}=1^{--}$

$$|i\rangle = \frac{|K_0\rangle|\overline{K}_0\rangle - |\overline{K}_0\rangle|K_0\rangle}{\sqrt{2}} = \mathcal{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle)$$

$$|K_S\rangle = (1+\epsilon_S)|K_0\rangle + (1-\epsilon_S)|\overline{K}_0\rangle$$
$$|K_L\rangle = (1+\epsilon_L)|K_0\rangle - (1-\epsilon_L)|\overline{K}_0\rangle$$

$$\epsilon_{S/L} = \epsilon_K \pm \delta_K$$



- The decay amplitude into final states f_1, f_2 at time t_1, t_2 is:

$$I(f_1,f_2;\Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)\Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\}$$

Interference term

Quantum entanglement the two decays are correlated even if kaons are distant in space

$I(f_1,f_1; \Delta t=0)=0$ Complete destructive quantum interference prevents the two kaons from decaying into the same final state at the same time

CPT & Lorentz invariance violation

According to **Standard Model Extension** [Kostelecky PRD61(1991), 016002-PRD64(2001),076001]
CPT violation should appear together with **Lorentz Invariance breaking** thus implying a direction dependent modulation

In Sidereal Frame

$$\delta_K \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a})/\Delta m$$

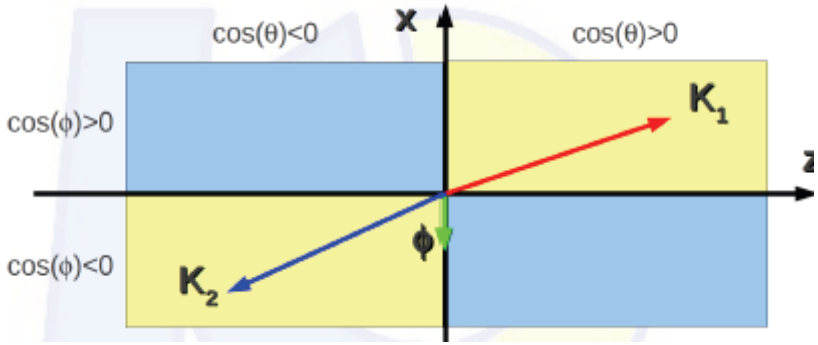
Δa_μ SME parameters related to CPT and Lorentz violation

- δ_K modulated by kaon momentum modulus and direction
- Accounting for Earth rotation (T_{sid}) and Kaon momentum in lab frame (P_K):

$$\begin{aligned}\delta_K(\vec{P}_K, T_{sid}) = \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m}\gamma_K \Big[& \Delta a_0 + \beta_K \Delta a_Z (\cos\vartheta\cos\chi - \sin\vartheta\cos\varphi\sin\chi) \\ & -\beta_K \Delta a_X \sin\vartheta\sin\varphi\sin\omega_E T_{sid} \\ & +\beta_K \Delta a_X (\cos\vartheta\sin\chi + \sin\vartheta\cos\varphi\cos\chi)\cos\omega_E T_{sid} \\ & +\beta_K \Delta a_Y (\cos\vartheta\sin\chi + \sin\vartheta\cos\varphi\cos\chi)\sin\omega_E T_{sid} \\ & +\beta_K \Delta a_Y \sin\vartheta\sin\varphi\cos\omega_E T_{sid}\Big]\end{aligned}$$

$\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

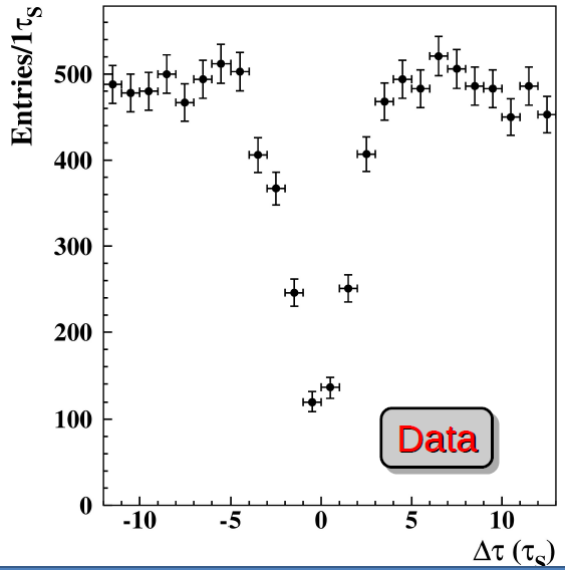
- **L = 1.7 fb^{-1}** data sample
- Same final state for both kaons ($\pi^+\pi^-$)
  Kaons ordered according to P_z.



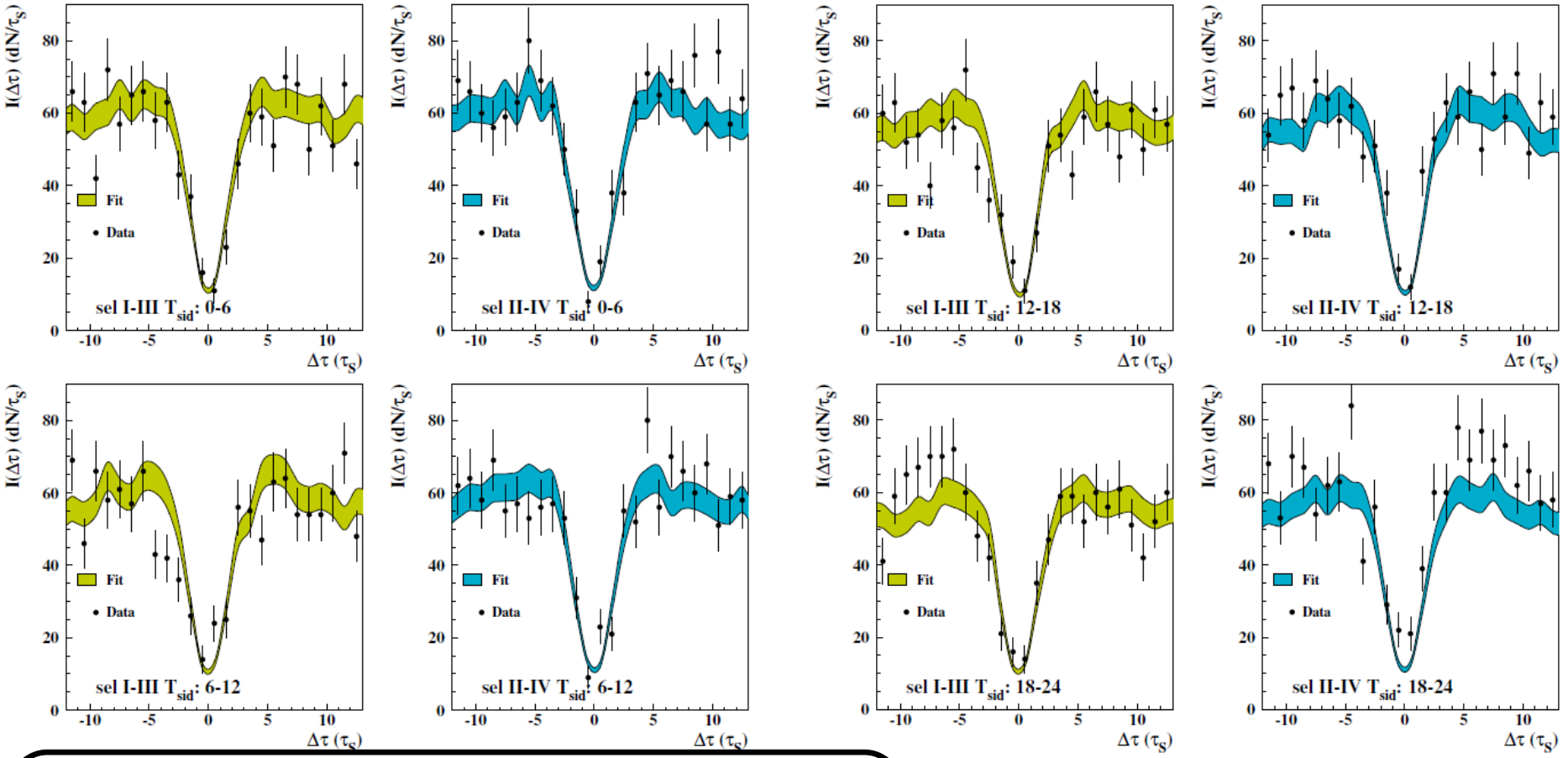
$$I(\Delta t, T_{sid}, \vartheta_{K_1}, \varphi_{K_1}) \propto e^{-\Gamma|\Delta\tau|}\Big[|\varepsilon_K - \delta_K(\vec{P}_1)|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\varepsilon_K - \delta_K(\vec{P}_\phi - \vec{P}_1)|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e\Big((\varepsilon_K - \delta_K(\vec{P}_1)(\varepsilon_K - \delta_K(\vec{P}_\phi - \vec{P}_1))^* e^{-i\Delta m\Delta\tau}\Big)\Big]$$

- Data divided in **4 Sidereal time bins x 2 angular bins**
- **Simultaneous fit of the Δt distributions to extract Δa_μ parameters**

$$\int_{\Delta\tau_i} d\Delta\tau \int_{\Delta T_{sid\,j}} dT_{sid} \int_{\Delta\Omega_h} d\Omega_{K_1}\, \rho(\Omega_{K_1}, T_{sid})\, I(\Delta\tau, T_{sid}, \Omega_{K_1})$$



CPT & Lorentz Symmetry Test: Result



$$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys}) \times 10^{-18}\ \text{GeV}$$
$$\Delta a_X = (\ 0.9 \pm 1.5_{stat} \pm 0.6_{sys}) \times 10^{-18}\ \text{GeV}$$
$$\Delta a_Y = (-2.0 \pm 1.5_{stat} \pm 0.5_{sys}) \times 10^{-18}\ \text{GeV}$$
$$\Delta a_Z = (\ 3.1 \pm 1.7_{stat} \pm 0.5_{sys}) \times 10^{-18}\ \text{GeV}$$

Paper in preparation

χ^2 = 211/184 (P=8%)

Fit error include Data/MC correction (~2%) and single bin efficiency (~5%)

CP violating $K_S \to \pi^0\pi^0\pi^0$ decay

$K_S \to \pi^0\pi^0\pi^0$ a pure CP violating decay

$$|K_S\rangle = \frac{1}{\sqrt{(1+|\varepsilon_S|)}}\left[|K_1\rangle + \varepsilon_S|K_2\rangle\right] \qquad \varepsilon_S = \varepsilon + \delta$$

$$|K_L\rangle = \frac{1}{\sqrt{(1+|\varepsilon_L|)}}\left[|K_2\rangle + \varepsilon_L|K_1\rangle\right] \qquad \varepsilon_L = \varepsilon - \delta$$

$3\pi^0$ is a pure CP=-1 state

observation of $K_S \to \pi^0\pi^0\pi^0$ unambiguous sign of ~~CP~~ in mixing and/or in decay

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0 | T | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | T | K_L \rangle} = \varepsilon + \varepsilon'_{000}$$

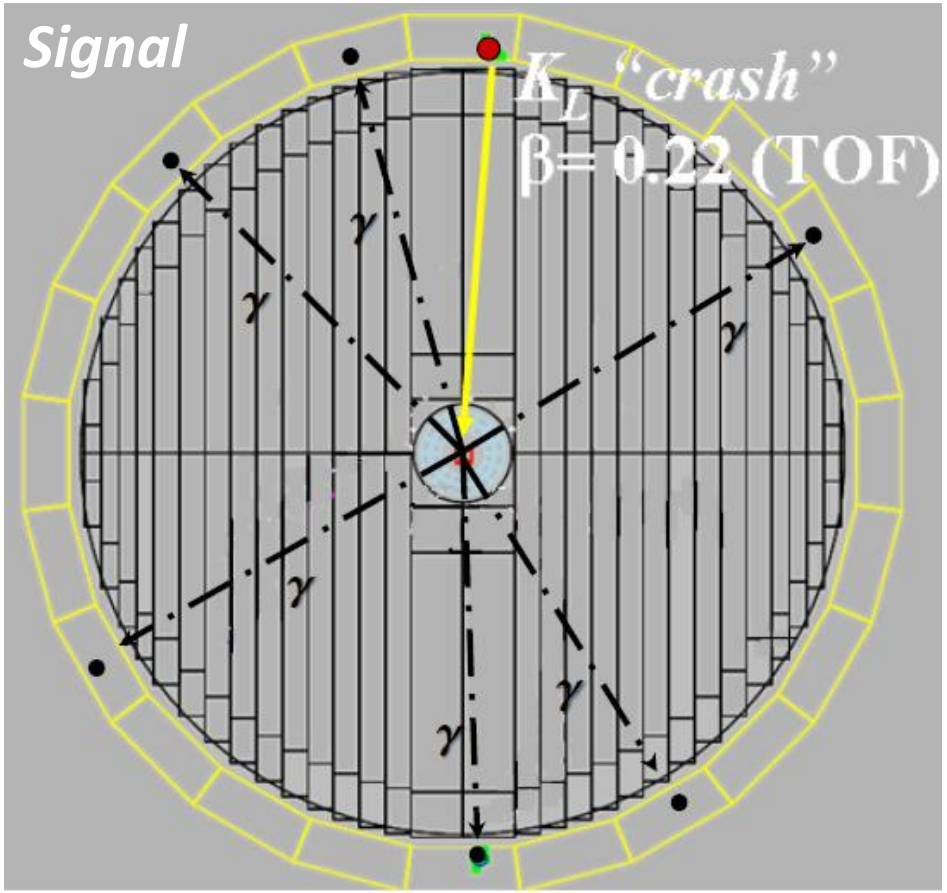
To lowest order in χPT: $\varepsilon'_{000} = -2\varepsilon'$
[Li, Wolfenstein PRD21 (1980),178]
If CPT is conserved $\eta_{000} \cong \varepsilon$

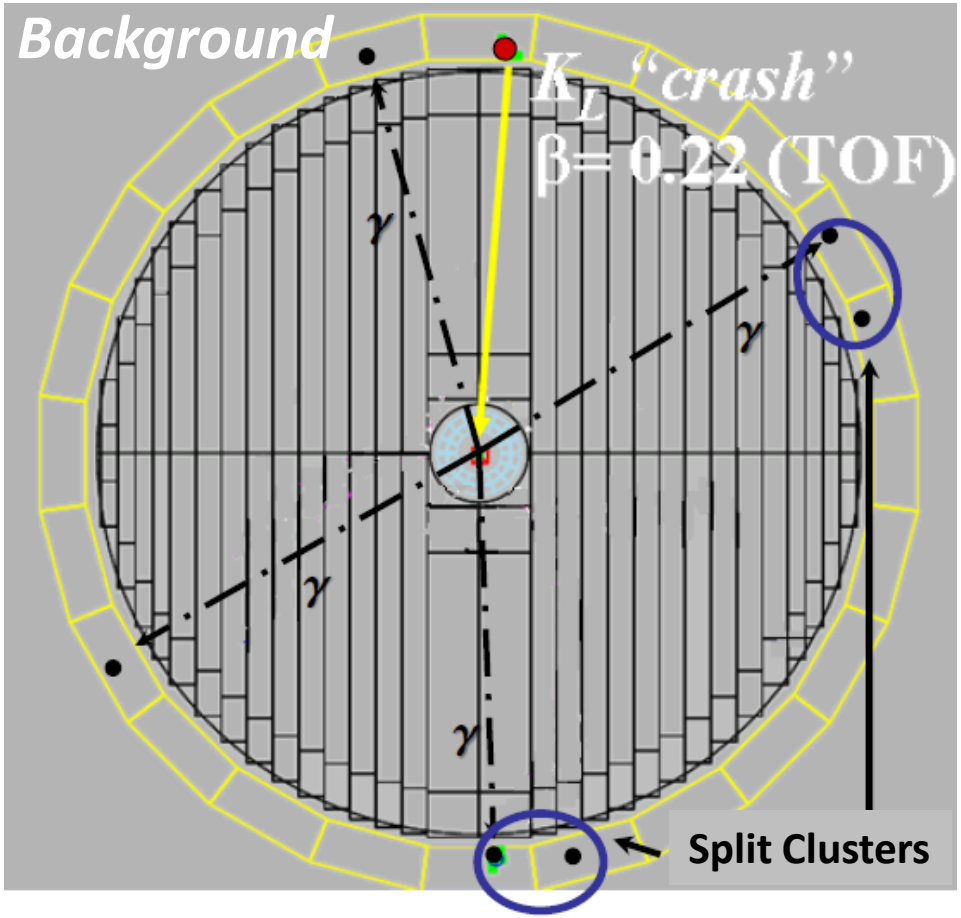
$$|\eta_{000}| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}}$$

Standard Model prediction:
$BR(K_S \to 3\pi^0) = 1.9 \cdot 10^{-9}$

$K_S \to \pi^0\pi^0\pi^0$ Analysis Strategy (I)

- K_S tagged by K_L interaction in EmC (K_L "crash")



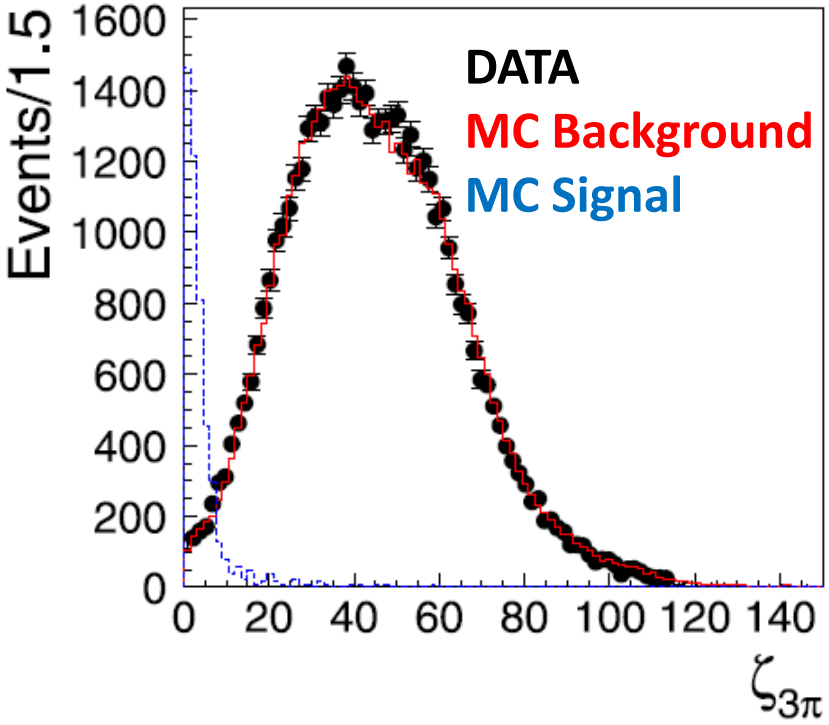


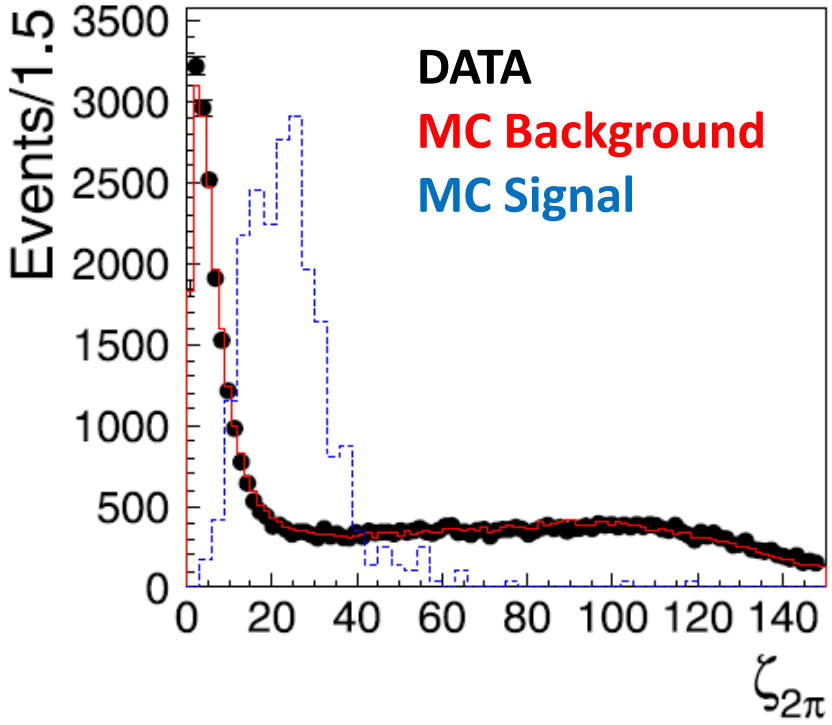
$K_S \to 3\pi^0 \to 6\gamma$

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

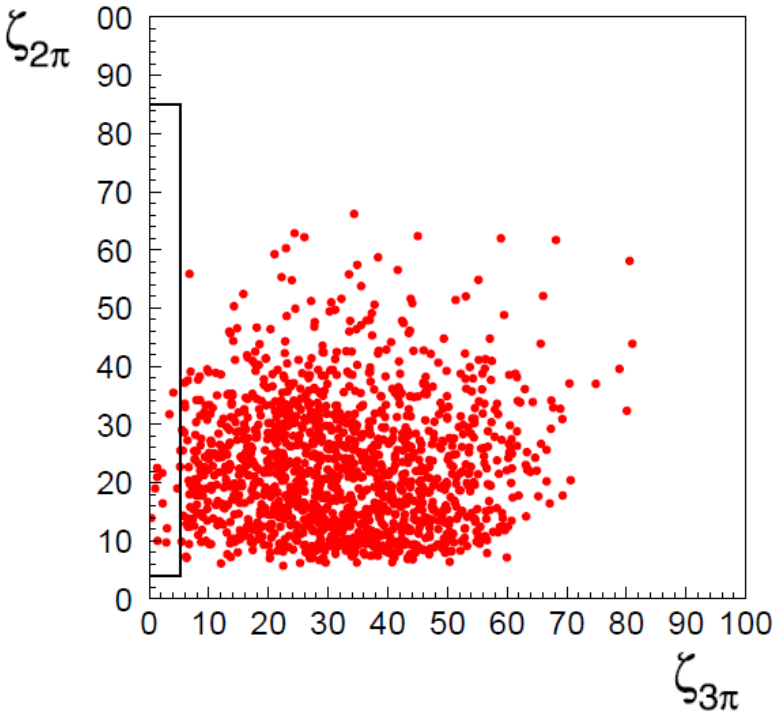
$K_S \to \pi^0\pi^0\pi^0$ Analysis Strategy (II)

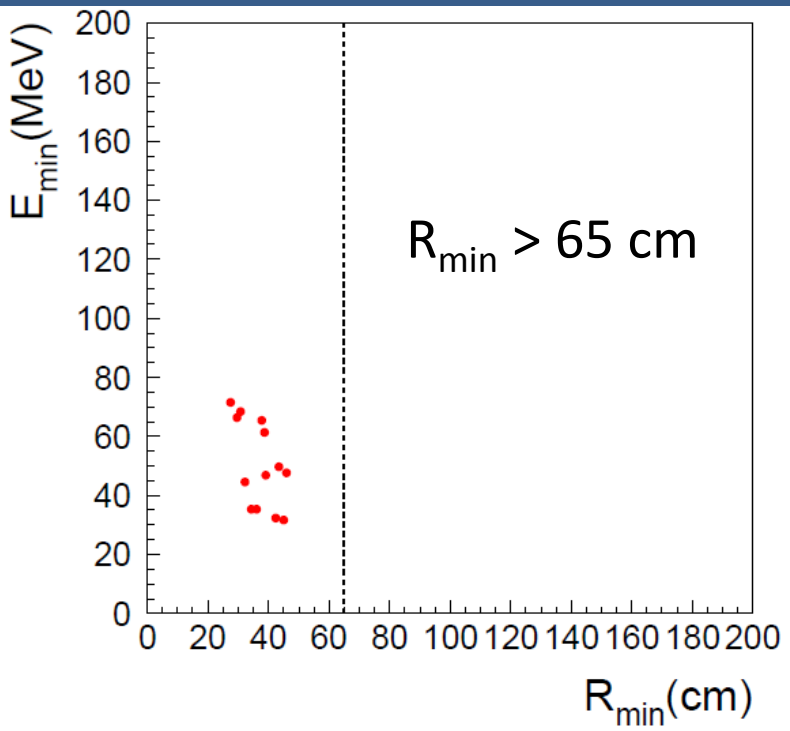
- Previous KLOE analysis and best upper limit **[PLB 619(2005),61]** updated:
  - improved K_S tagging algorithm hardening β^* (K_L) cut for K_L-crash ID
  - improved clustering procedure to reject split clusters
  - **1.7 fb^{-1}** KLOE entire data set (~8x10^7 tagged K_SK_L pairs)
- Select **6 γ sample**
- Reject Background with χ^2-like variable $\zeta_{3\pi}$ ($K_S \to 3\pi^0$ hyp.) & $\zeta_{2\pi}$ ($K_S \to 2\pi^0$ hyp.)





CP violating $K_S \to \pi^0\pi^0\pi^0$ decay: Result





$N_{DATA} = 0$
$N_{MC} = 0$
$N_{SM} = 0.12$

- $N_{3\pi0} \leq 2.33/\varepsilon_{3\pi0}$ at 90% C.L.
- $\varepsilon_{3\pi0} = 0.23(1)$
- Normalized to
  $N_{2\pi0}/\varepsilon_{2\pi0} = (1.142 \pm 0.005) \times 10^8$

PLB 723 (2013) 54

$BR(K_S \to \pi^0\pi^0\pi^0) < 2.6 \times 10^{-8}$ @ 90% C.L.

$|\eta_{000}| < 0.0088$ @ 90% C.L.

U.L. improved with respect to PLB 619
x5 on $BR(K_S \to \pi^0\pi^0\pi^0)$ and x2 on $|\eta_{000}|$

First observation at KLOE-2 feasible

Near Future: KLOE-2

The KLOE-2 Project: Physics & Collider

❖ **The KLOE-2 project aims at improving the successful and fruitful results achieved by the KLOE Collaboration in Kaon and Hadron Physics and extending the physics program to**:

- $\gamma\gamma$-physics from $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- + X$
- search for particles from "hidden sectors" that might explain dark matter

Physics program
(see **EPJC 68 (2010) 619-681**)

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

Detector upgrade:

- $\gamma\gamma$ tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

Improve precision on QM, CPT observables by approximately an order of magnitude

❖ **The project will exploit the new interaction scheme implemented on the Frascati DAFNE phi-factory collider** with the SIDDHARTA experiment in 2008/09 with:

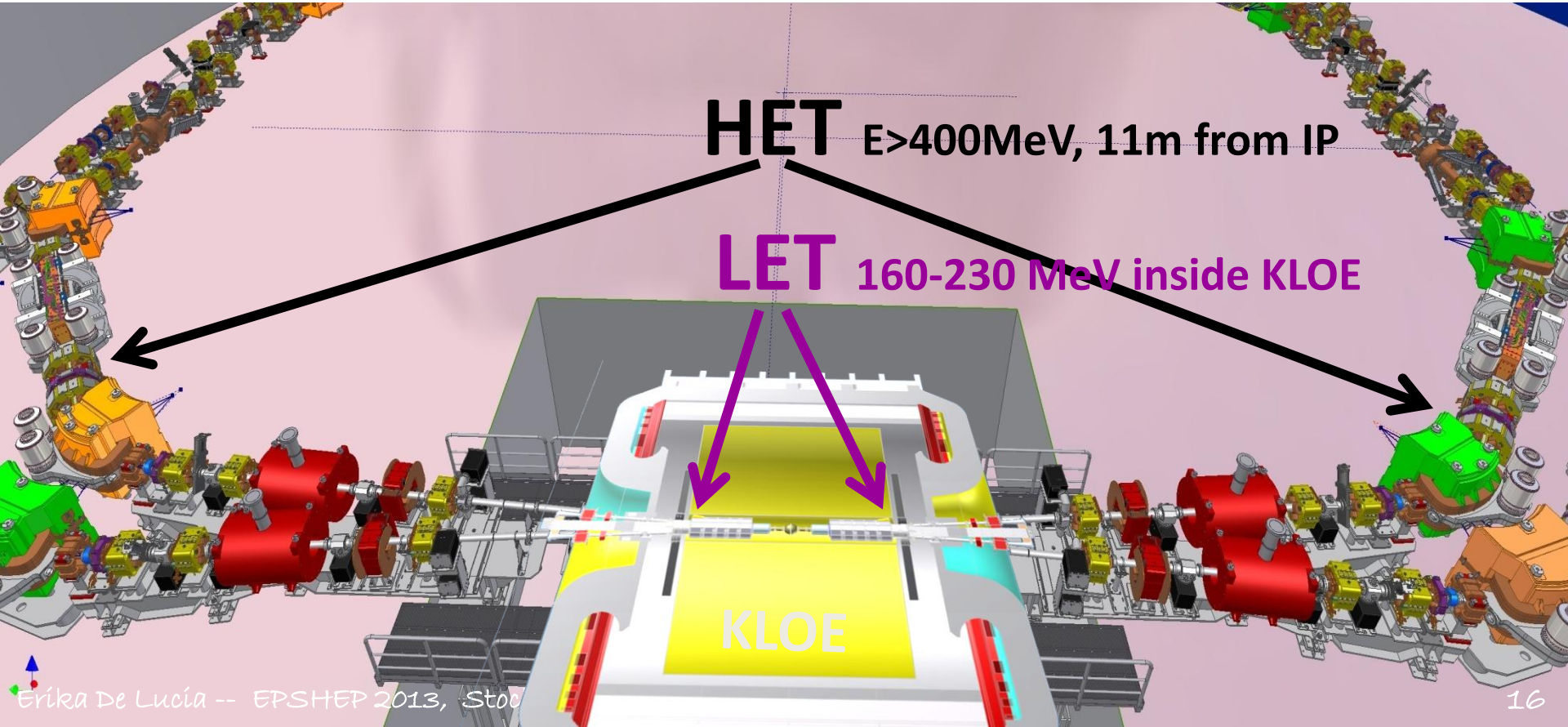
- Larger beam crossing angle and crab-waist sextupoles
- Luminosity increase up to a factor of ~3

The KLOE-2 Project: detector upgrades

1st phase/step-0 :

LET & HET ***[NIMA 617 (2010),81 & 266]***

- ✓ LYSO+SiPMs & Scint+PMTs
- ✓ Lepton taggers for $\gamma\gamma$-physics



The KLOE-2 Project: detector upgrades

1st phase/step-0 :

LET & HET ***[NIMA 617 (2010),81 & 266]***

- ✓ LYSO+SiPMs & Scint+PMTs
- ✓ Lepton taggers for $\gamma\gamma$-physics

2nd phase /step-1 now :

CCAL ***[Nucl. Phys. B 197 (2009),215]***

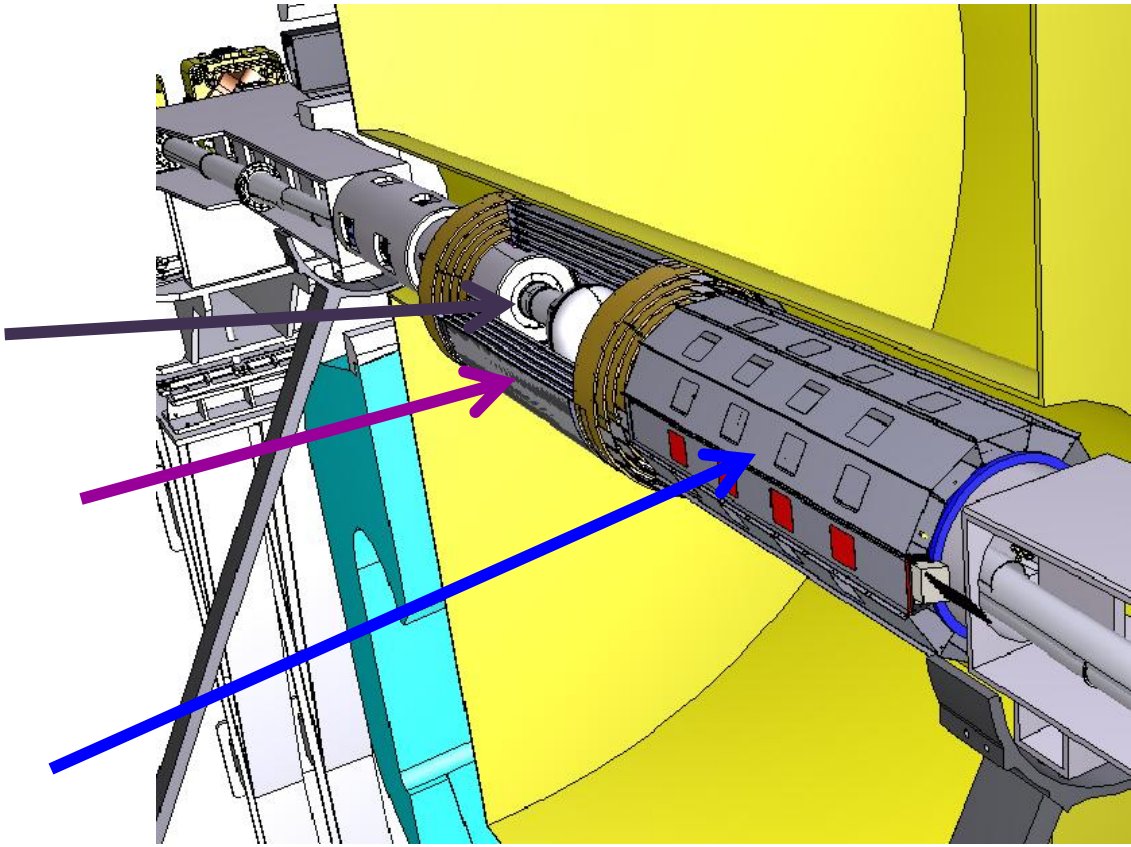
- ✓ LYSO + APD
- ✓ Increase acceptance for γ's from IP (21 →10)

INNER TRACKER ***[NIMA 628 (2011),194]***

- ✓ 4 layers of cylindrical triple GEM
- ✓ Better vertex reconstruction near IP
- ✓ Larger acceptance for low pt tracks

QCALT ***[NIMA 617 (2010),105]***

- ✓ W + scintillator tiles + SiPM/WLS
- ✓ quadrupoles coverage for K_L decays



The KLOE-2 Project: detector upgrades

1st phase/step-0 :

LET & HET ***[NIMA 617 (2010),81 & 266]***

- ✓ LYSO+SiPMs & Scint+PMTs
- ✓ Lepton taggers for $\gamma\gamma$-physics

2nd phase /step-1 now :

CCAL ***[Nucl. Phys. B 197 (2009),215]***

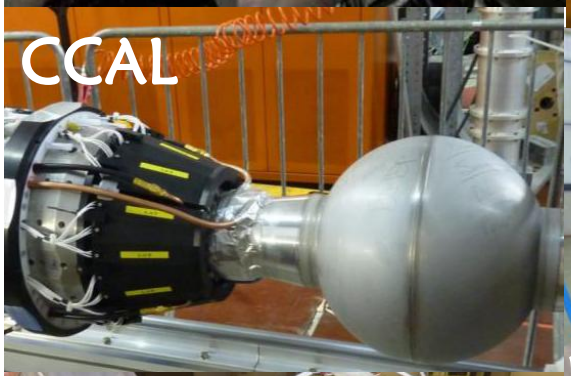
- ✓ LYSO + APD
- ✓ Increase acceptance for γ's from IP (21 →10)

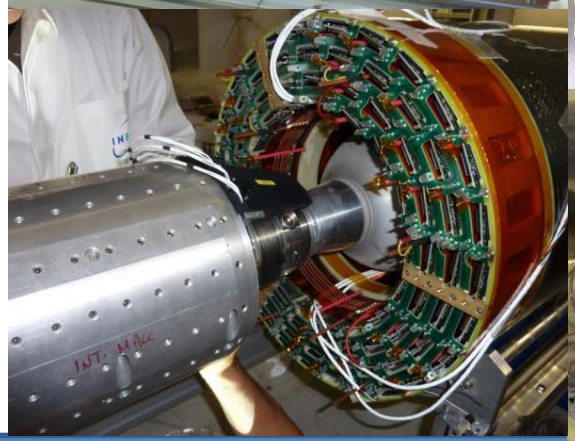
INNER TRACKER ***[NIMA 628 (2011),194]***

- ✓ 4 layers of cylindrical triple GEM
- ✓ Better vertex reconstruction near IP
- ✓ Larger acceptance for low pt tracks

QCALT ***[NIMA 617 (2010),105]***

- ✓ W + scintillator tiles + SiPM/WLS
- ✓ quadrupoles coverage for K_L decays





Conclusions

- Kaon Interferometry is a powerful tool to test fundamental symmetries. Expected sensitivity of 10^{-18} GeV on Standard Model Extension parameters from Kaon sector reached.
  Final result ready to be published

- New Best Upper Limit on BR($K_S \to \pi^0\pi^0\pi^0$) and $|\eta_{000}|$
  At KLOE-2 benefits from new low-θ calorimeters and possible first observation of the decay

- KLOE-2 Physics Run in preparation
  New Detectors Integrated on DAFNE beam-pipe
  KLOE-2 Commissioning will start soon, together with DAFNE

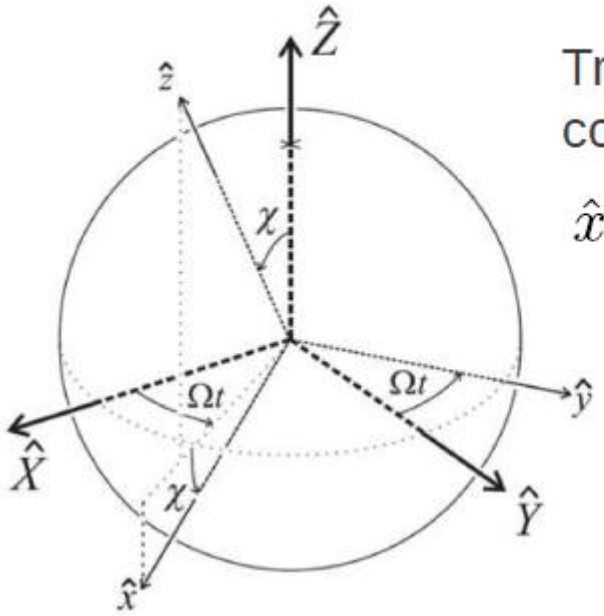
Thank you

More KLOE talks tomorrow:

- *Hadron Physics Studies at KLOE (C. Bloise)- E1 Session*
- *New determination of e+e- hadronic cross-section below 1 GeV with KLOE (G. Venanzoni)- F2 Session*

SPARES

CPT & Lorentz Invariance: Earth Rotation



Transformation of δ parameter in a terrestrial coordinate system where:

$$\hat{x} \in \Pi : \alpha\hat{z} + \beta\hat{Z}; \alpha, \beta \in \mathcal{R}$$

$$\begin{aligned}\delta_K(\vec{P}_K, T_{sid}) \;=\; & \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m}\gamma_K \Big[\Delta a_0 + \beta_K \Delta a_Z(\cos\vartheta\cos\chi - \sin\vartheta\cos\varphi\sin\chi) \\ & -\beta_K \Delta a_X \sin\vartheta\sin\varphi\sin\omega_E T_{sid} \\ & +\beta_K \Delta a_X(\cos\vartheta\sin\chi + \sin\vartheta\cos\varphi\cos\chi)\cos\omega_E T_{sid} \\ & +\beta_K \Delta a_Y(\cos\vartheta\sin\chi + \sin\vartheta\cos\varphi\cos\chi)\sin\omega_E T_{sid} \\ & +\beta_K \Delta a_Y \sin\vartheta\sin\varphi\cos\omega_E T_{sid}\Big]\end{aligned}$$

$K_S \to \pi^0\pi^0\pi^0$ Analysis Strategy

preselection

- ✓ K_S tagged by K_L crash
- ✓ 6 γ clusters, no tracks from IP
- ✓ kinematic fit to refine cluster parameters

to reject background compare 3π vs 2π hypotheses

$\chi^2_{3\pi}$ – pairing of 6γ clusters with best π^0 mass estimates

$\chi^2_{2\pi}$ – best pairing of 4γ's out of 6: π^0 masses, $E(K_S)$, $P(K_S)$, c.m. angle between π^0s

signal box optimized using dedicated MC subsample

$4 < \chi^2_{2\pi} < 84.9$ and $\chi^2_{3\pi} < 5.2$

final cuts on residual $K_S \to 2\pi^0$

1) $\Delta E = M_\phi/2 - \sum E_\pi \cong M_{\pi 0}$ if signal

2) $R_{min} > 65$ cm distance between γ clusters