# KLOE results in flavor physics and prospects for KLOE-2

Eryk Czerwiński
on behalf of KLOE and KLOE-2 collaborations

Capri, 11.06.2012

# Overview

- ► Flavor physics at KLOE
- ► DAΦNE collider and KLOE detector
- ► KLOE results and ongoing analyses
- ► KLOE-2 project at upgraded DAΦNE
- ► Summary

KLOE has performed:

✔ SM test in the flavor sector through precise measurements of $V_{us}$ and $R_K = \Gamma(K \to e\nu) / \Gamma(K \to \mu\nu)$

✔ measurements of all relevant parameters for charged and neutral kaons: BR's, lifetimes, form factors.

✔ CPT and quantum mechanics tests with the analysis of the QM interference of neutral kaons, $K_S$ semileptonic decays, unitary (Bell-Steinberger relation)

Details can be found e.g.:

JHEP 0804 (2008) 059

Riv. Nuovo Cim. Vol. 31, N 10, 531 (2008) *arXiv:0811.1929 [hep-ex]*

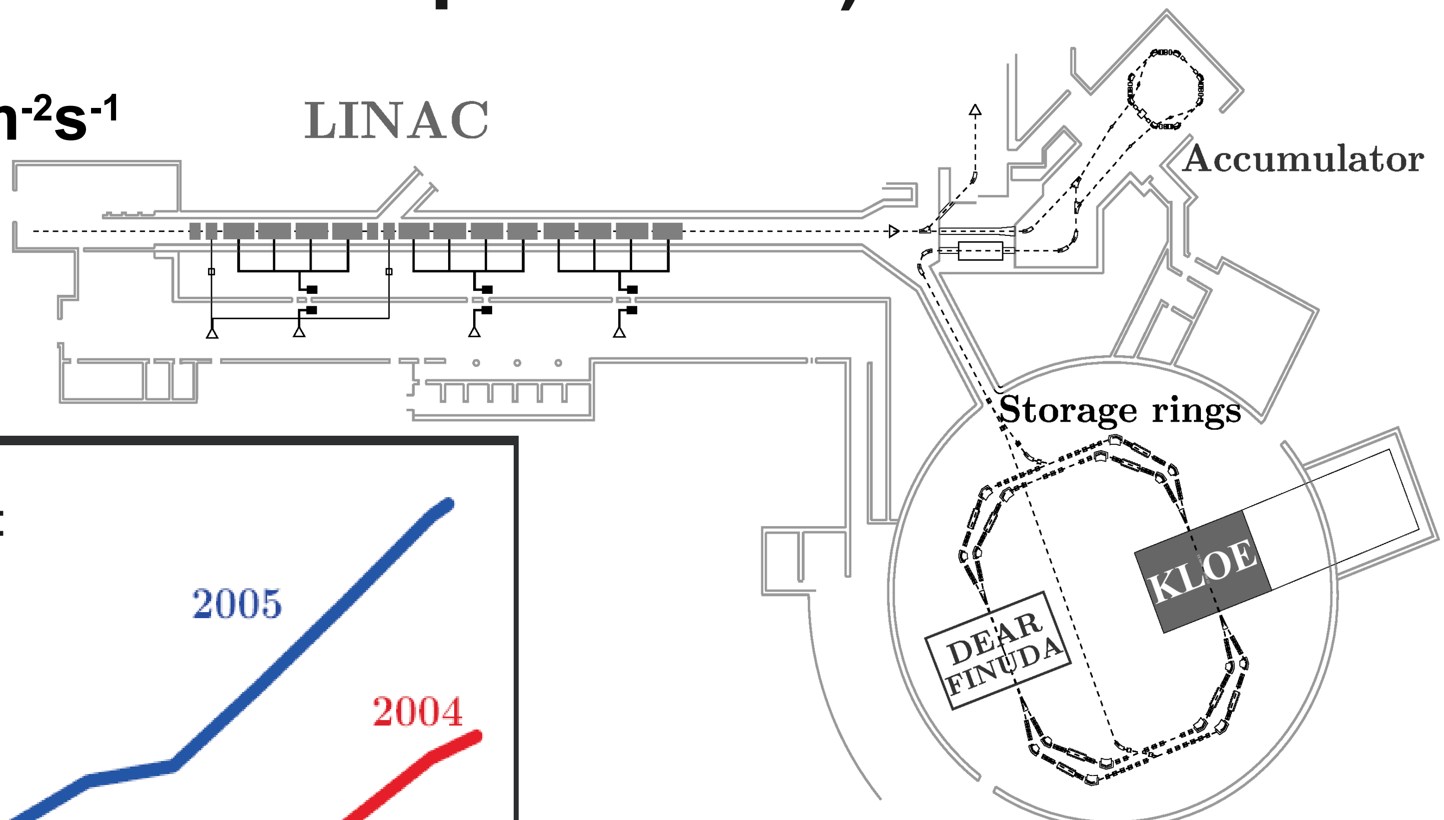
Eur.Phys.J. C64 (2009) 627

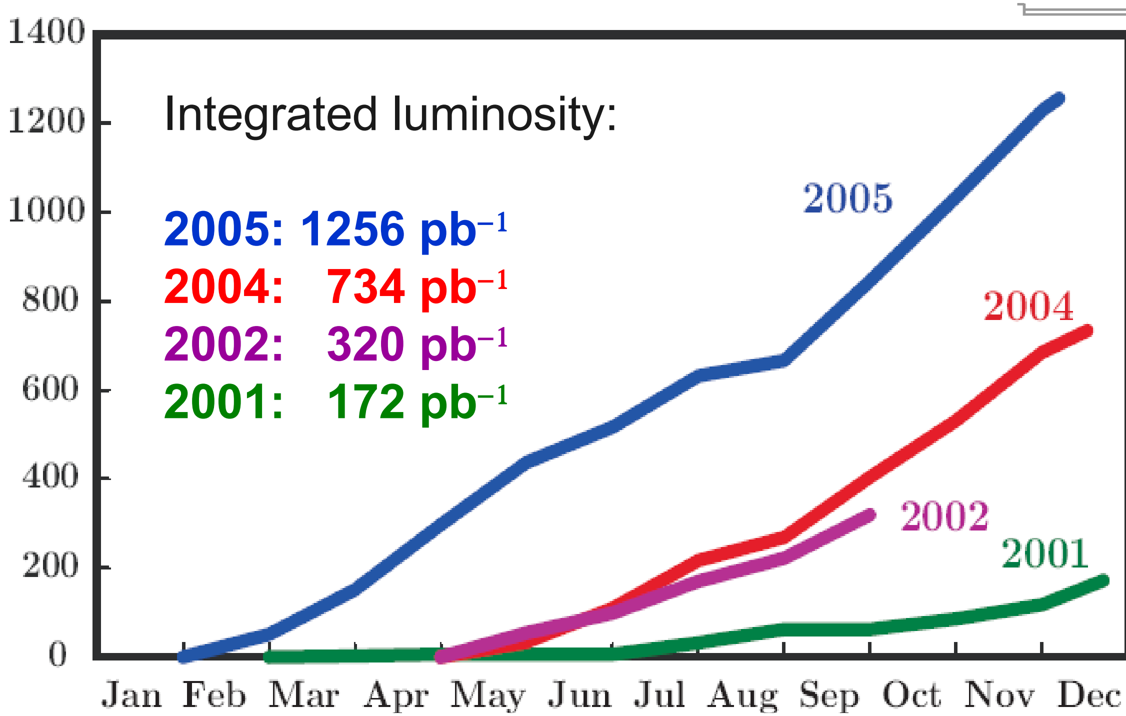
# DAΦNE (Double Annular Factory for Nice Experiments)

**1999-2007:**

$L_{peak} = 1.4 \times 10^{32}\ cm^{-2}s^{-1}$

$\int L dt = 8.5\ pb^{-1}/day$




$e^+e^-$ collider with two storage rings and two interaction points

At φ factory:

- neutral kaon pairs produced in a pure quantum state ($J^{PC}=1^{--}$)

$$|i\rangle \propto \frac{1}{\sqrt{2}}\left(|K_L, p\rangle|K_S, -p\rangle - |K_L, -p\rangle|K_S, p\rangle\right)$$

- detection of one kaon guarantees the presence of a second one with known momentum and direction (tagging)

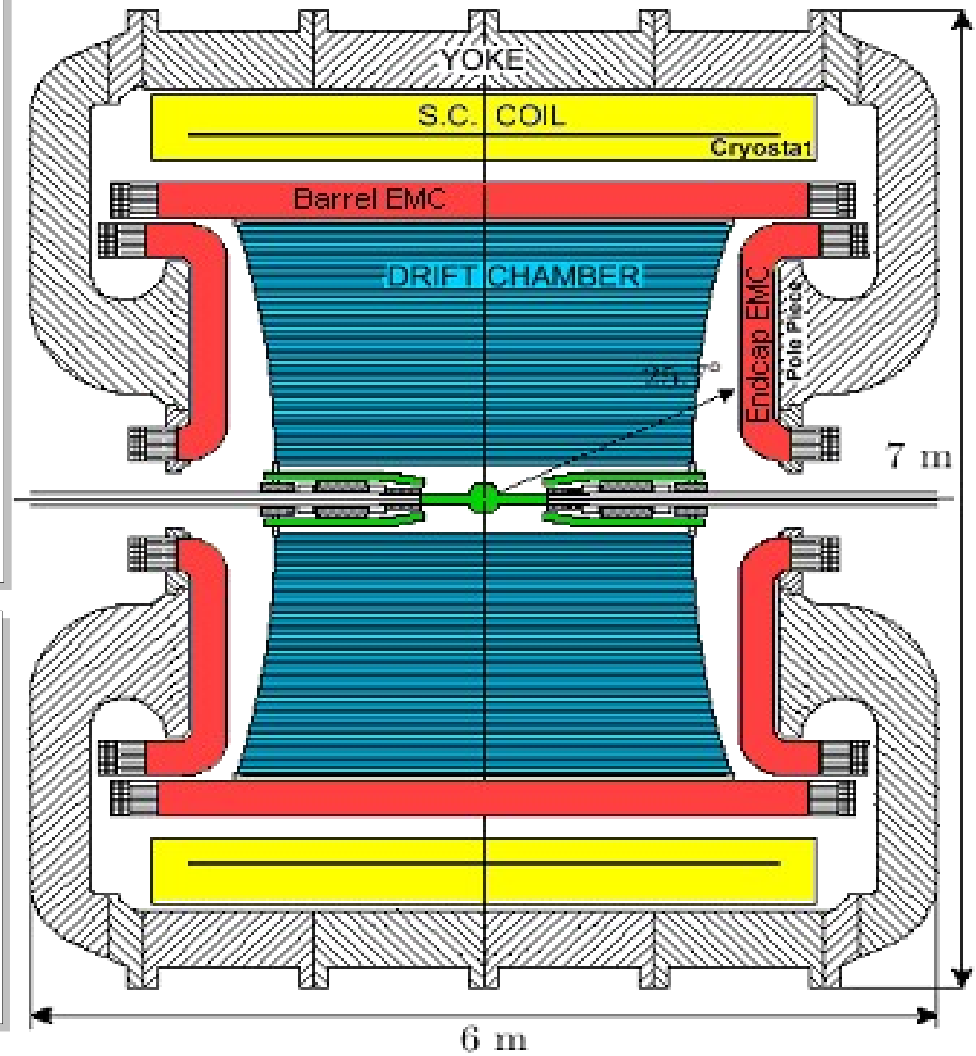
# KLOE (K LOng Experiment)

**Drift chamber**

- gas mixture: 90% He + 10% $C_4H_{10}$
- $\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} \approx 150$ μm ; $\sigma_z \approx 2$ mm

**Electromagnetic calorimeter**

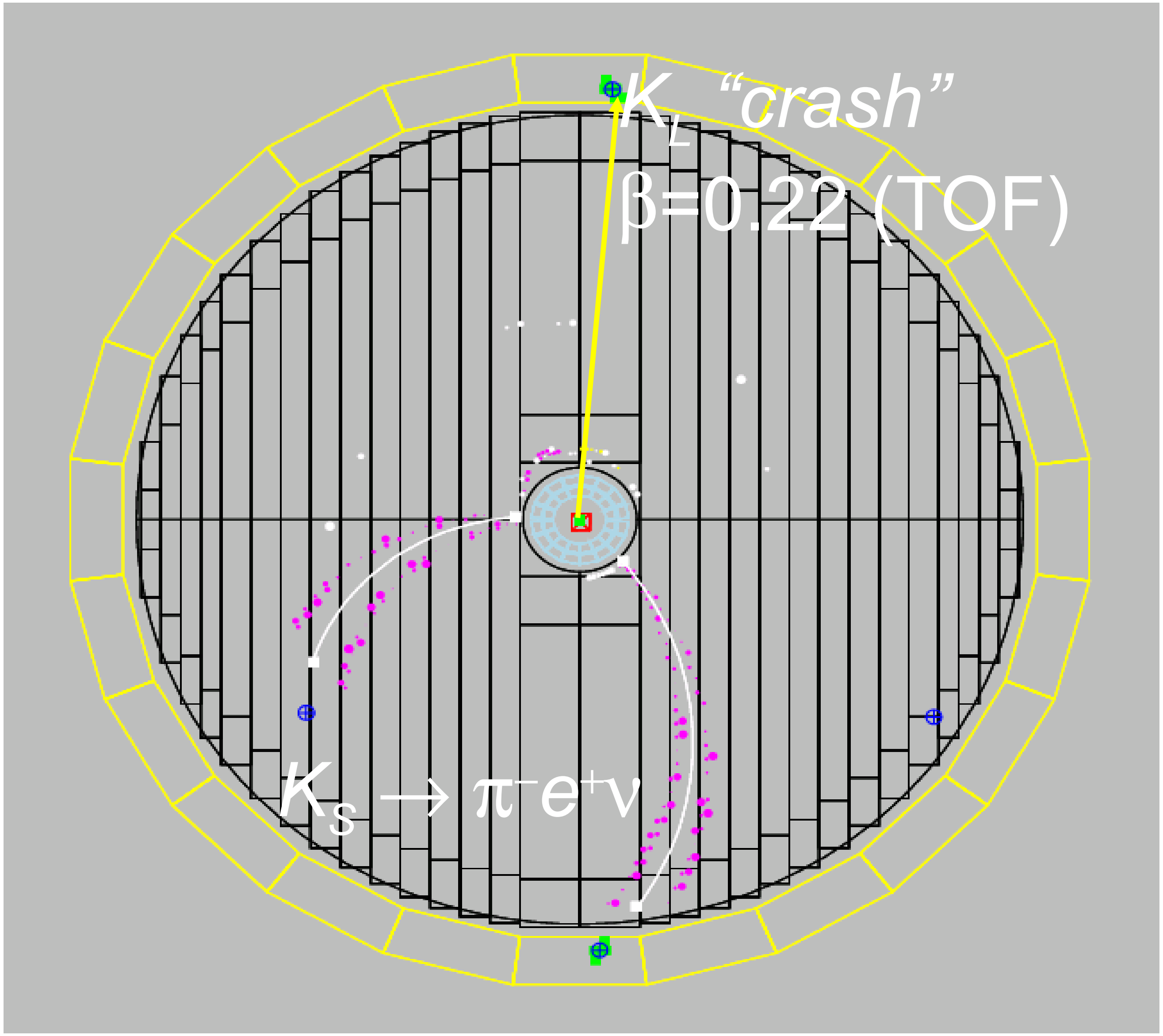
- lead/scintillating fibers
- 98% solid angle coverage
- $\sigma_E / E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_t = 57$ ps / $\sqrt{E(GeV)} \oplus 100$ ps
- PID capabilities




**Data taking ended on March 2006**

- 2.5 $fb^{-1}$ on tape @ $\sqrt{s} = M_{\phi}$ ($8\times10^9$ $\varphi$ => $6.6\times10^9$ kaon pairs)
- ~10 $pb^{-1}$ @ 1010, 1018, 1023, 1030 MeV
- 250 $pb^{-1}$ @ 1000 MeV

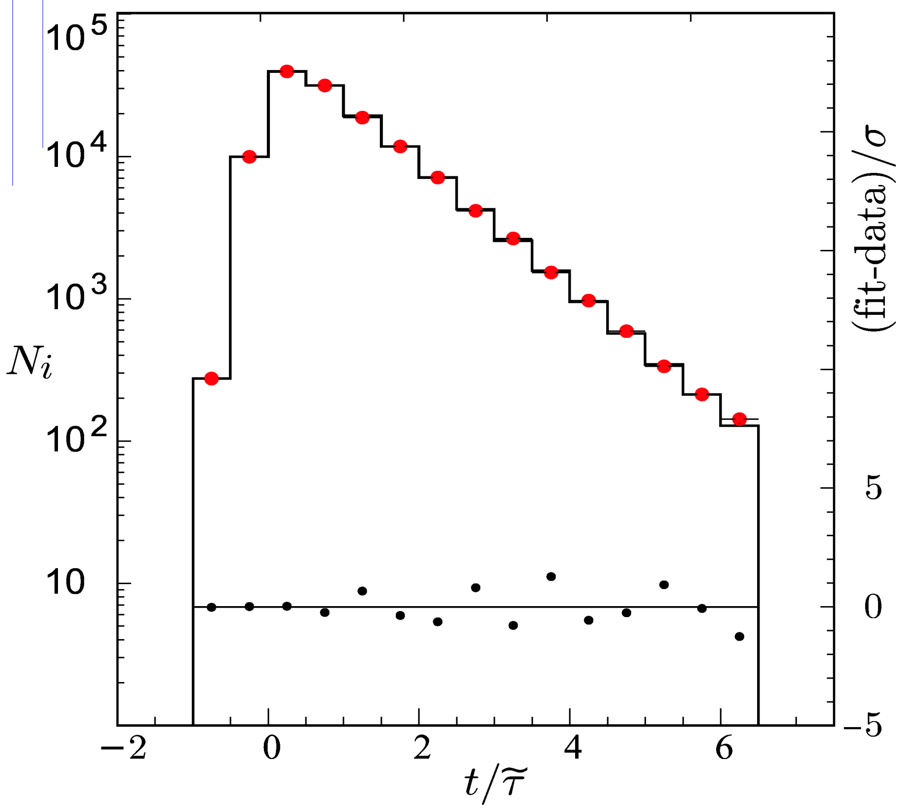
# Neutral kaons beams

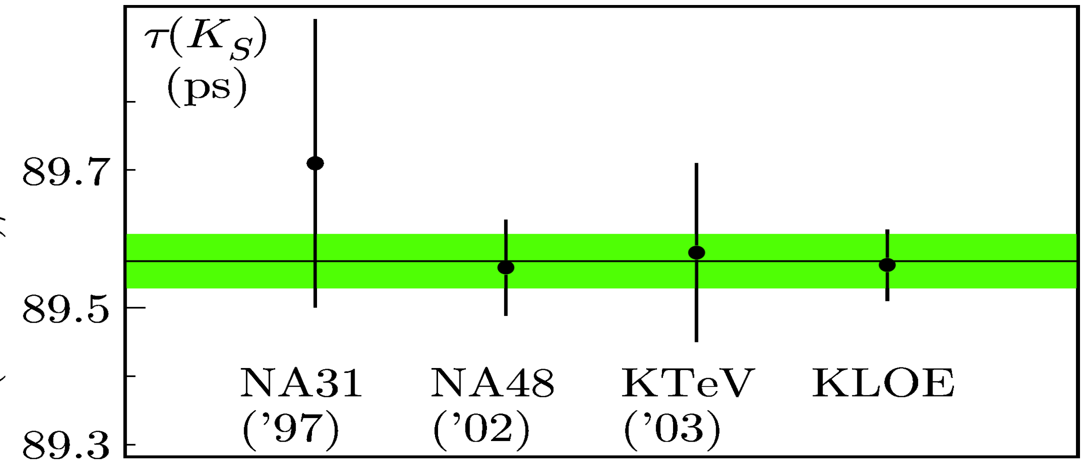



UNIQUE

$K_S$ tagged by
$K_L$ interaction in EmC

# Lifetime of $K_S$




| Systematic source | Absolute value [ps] |
|---|---|
| cuts & FV | 0.024 |
| fit range | 0.012 |
| $p'_K$ calibration | 0.033 |
| kaon mass | 0.004 |
| efficiency | 0.005 |
| total | 0.043 |

Eur. Phys. J. C (2011) 71: 1604
e-Print: arXiv:1011.2668 [hep-ex]

$\tau(K_S) = 89.562 \pm 0.029_{stat} \pm 0.043_{syst}$ ps

Last input for $V_{US}$

# Preliminary result from $K_S \to \pi^0\pi^0\pi^0$

For the $|K_S> \to 3\pi$ decay modes we can define:

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

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

$Im(\eta_{+-0})=-0.002\pm0.009$; $Im(\eta_{000}) = (-0.1\pm1.6)\text{x}10^{-2}$

$$|\eta_{000}| = \sqrt{\frac{\tau_L BR(K_S \to 3\pi^0)}{\tau_S BR(K_L \to 3\pi^0)}} < 0.018 @ 0.90\, C.L.$$

*F. Ambrosino et al.,Phys Lett. B 619, 61 (2005)*

Previous measurements of $\eta_{000}$:

| | |
|---|---|
| SND (direct measurement) | $BR(K_S \to 3\pi^0) < 1.4\text{x}10^{-5}$ |
| NA48 (interference measurement) | $BR(K_S \to 3\pi^0) < 7.4\text{x}10^{-7}$ |
| KLOE | $BR(K_S \to 3\pi^0) < 1.2\text{x}10^{-7}$ |
| SM prediction | $BR(K_S \to 3\pi^0) = 1.9\text{x}10^{-9}$ |

# Preliminary result from $K_S \to \pi^0\pi^0\pi^0$

- At the end of the analysis we count $N_{obs}$=0 event selected as signal and $N_{exp}$=0 events in MC
- SM prediction: 1 event after tagging ⇒ 0.2 after selection
- The selection efficiency for $K_S \to 2\pi^0$ decay: $\varepsilon_{2\pi} \sim 0.66$
- Normalization sample: $N_{2\pi} = 1.36 \times 10^8$
- The selection efficiency for $K_S \to 3\pi^0$ signal: $\varepsilon_{3\pi} = 0.19 \pm 0.012$
- Upper limit on signal events: $N_{3\pi} < 13$ (90% C.L.)

$$BR\left(K_S \to 3\pi^0\right) = \frac{N_{3\pi}/\varepsilon_{3\pi}}{N_{2\pi}/\varepsilon_{2\pi}} \times BR\left(K_S \to 2\pi^0\right) < 2.9 \times 10^{-8}$$

PRELIMINARY

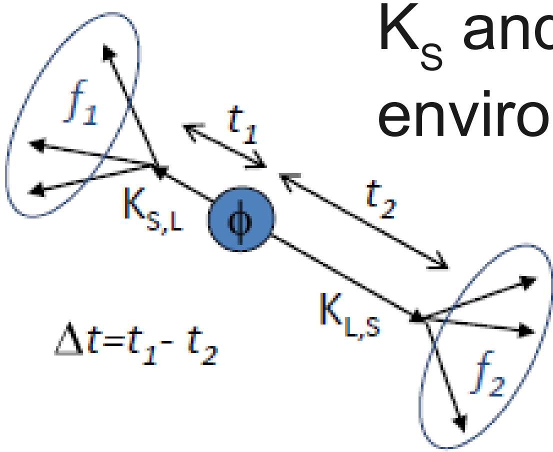
PRELIMINARY

and corresponding $|\eta_{000}| < 0.009$

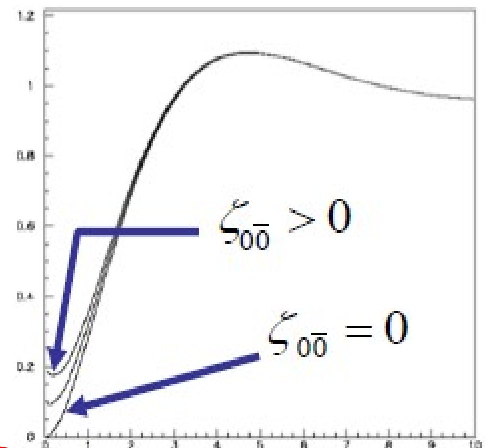
both at 90% C.L.

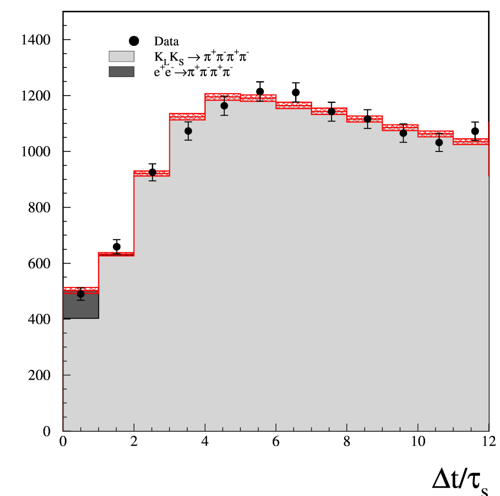
# Quantum interferometry

$$|i\rangle \propto \frac{1}{\sqrt{2}}\left(|K_L,p\rangle|K_S,-p\rangle - |K_L,-p\rangle|K_S,p\rangle\right)$$




$K_S$ and $K_L$ are entangled states: φ-factory is a unique environment to study quantum interference




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

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

$\xi = 0 \rightarrow$ QM
$\xi > 0 \rightarrow$ decoherence

PLB 642 (2006) 315
J.Phys.Conf.Ser. 171:012008 (2009)
$\xi_{0\bar{0}} = (1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}) \times 10^{-7}$

# Quantum interferometry

Kostelecky et al. developed a theoretical possibility for CPT violation based on spontaneous breaking of CPT and Lorentz symmetry, which might happen at Planck scale. It appears to be compatible with the basic tenets of quantum field theory, and retains the property of gauge invariance and renormalizability (Standard Model Extension SME)
*Kostelecky PRD61 (1999) 016002, PRD 64 (2001) 076001*

CPT violation in SME manifests to lowest order in $\delta$ (the direct CPT violation parameters vanish at first order) and exhibits a kaon momentum dependence:

$$\varepsilon_{S,L} = \varepsilon \pm \delta \qquad \delta = i \sin\varphi_{SW} e^{i\varphi_{SW}} \gamma_K \frac{\left(\Delta a_0 - \vec{\beta}_K \Delta \vec{a}\right)}{\Delta m}$$

where $\Delta a_\mu$ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation.

# Quantum interferometry

$\delta$ depends on sidereal time t since laboratory frame rotates with Earth (fixed beam). For a $\varphi$-factory there is an additional dependence on the polar and azimuthal angles $\theta$, $\varphi$ of the kaon momentum in the laboratory frame:

$$\delta(\vec{p}_K, t) = \frac{i \sin\varphi_{SW} e^{i\varphi_{SW}}}{\Delta m} \gamma_K \{ \Delta a_0 + \beta_K \Delta a_Z (\cos\theta\cos\chi - \sin\theta\cos\varphi\sin\chi) - \beta_K \Delta a_X \sin\theta\sin\varphi\sin\Omega t$$
$$+ \beta_K \Delta a_X (\cos\theta\sin\chi + \sin\theta\cos\varphi\sin\chi)\cos\Omega t + \beta_K \Delta a_Y (\cos\theta\sin\chi + \sin\theta\cos\varphi\sin\chi)\sin\Omega t$$
$$- \beta_K \Delta a_Y \sin\theta\sin\varphi\cos\Omega t \}$$

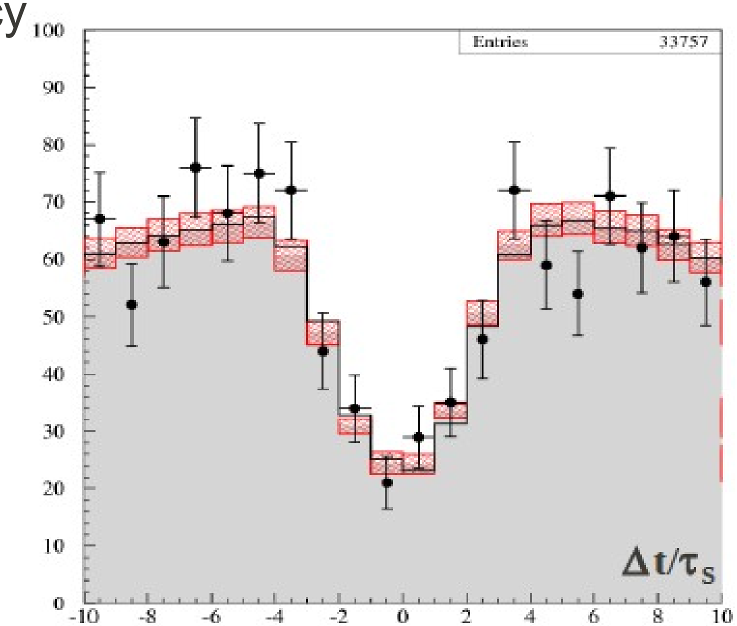
$\chi$ : angle between the z lab. axis and the Earth's rotation axis
$\Omega$: Earth's sidereal frequency

$\Delta a_{X,Y,Z}$ from $K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$
(analysis vs polar angle $\theta$ and sidereal time t)
with $\mathscr{L}$=1 fb$^{-1}$ (preliminary)

$\Delta a_X$ = (-6.3±6.0)x10$^{-18}$ GeV

$\Delta a_Y$ = ( 2.8±5.9)x10$^{-18}$ GeV

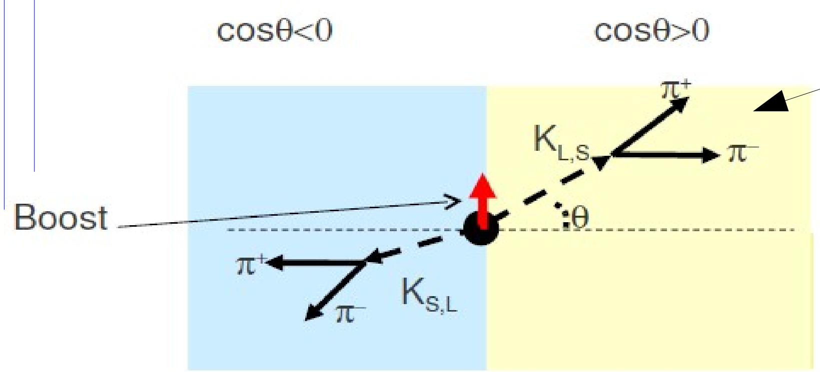
$\Delta a_Z$ = ( 2.4±9.7)x10$^{-18}$ GeV

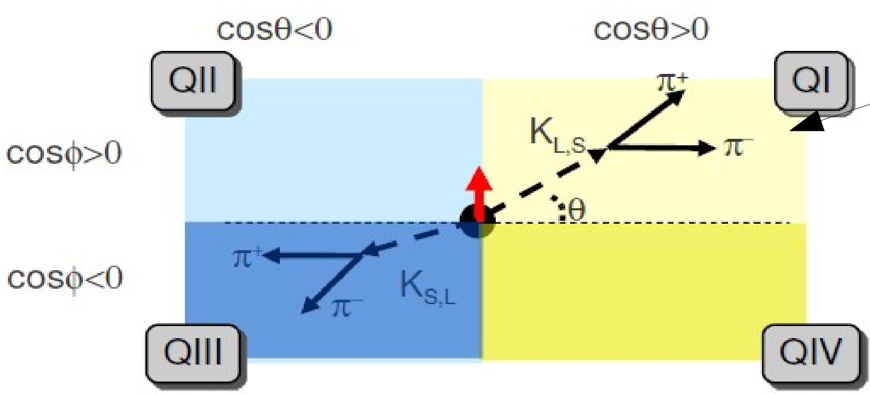



KTeV: $\Delta a_X$, $\Delta a_Y$ <9.2x10$^{-22}$ GeV @ 90% CL

BABAR: $\Delta a^B_{X,Y}$, ($\Delta a^B_0$-0.30 $\Delta a^B_Z$ )~O(10$^{-13}$ GeV) [PRL 100 (2008) 131802]

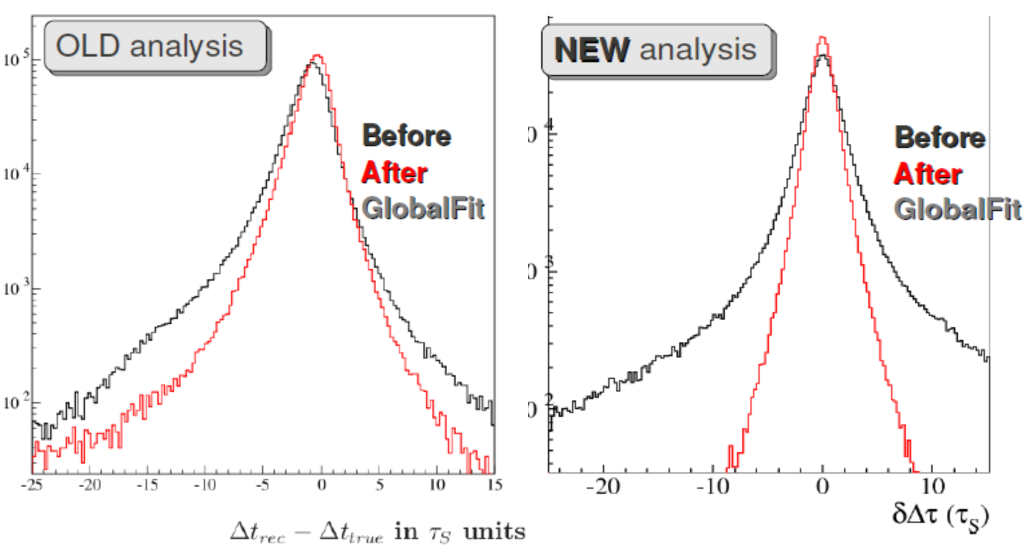
# Quantum interferometry




Possible effects due to $\Delta a0(\sim\gamma_K)$ are washed out in the old approach: forward (cosθ>0) – backward (cosθ<0) analysis.

New method exploiting the quadrant (cosθ>0 cosφ>0)-(cosθ<0 cosφ<0) analysis is under way.




Refining the techniques used to select and to analyse data it is possible to improve the resolution, acquiring more sensitivity on CPTV parameters.

# The light quark masses

The decay width of $\eta \to \pi^+\pi^-\pi^0$ disagree between experiment and $\chi$PT:

$\Gamma_{exp}$=296 ± 16 eV $\Gamma_{LO}$~ 70 eV $\Gamma_{NLO}$=160 ± 50 eV

Dalitz Plot needed to extract Q from:

$$\Gamma = \left(\frac{Q_D}{Q}\right)^4 \bar{\Gamma}$$

$\Gamma$ - experimental decay width

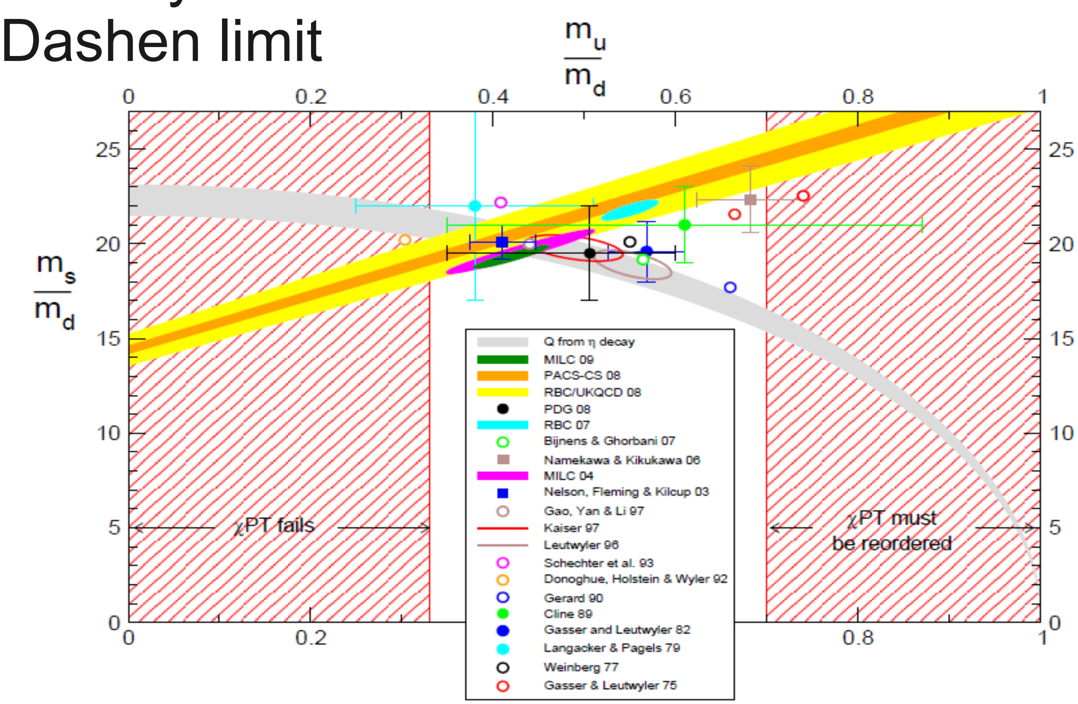
$\bar{\Gamma}$ - theoretical decay width with the Dashen limit

$Q_D$ - Q in the Dashen limit

Q is defined as:

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \qquad \hat{m} = \frac{1}{2}(m_d - m_u)$$

Provides an important constraint for the light quark mass ratio.




*H. Leutwyler, Light quark masses, Proceedings of Science, arXiv:0911.1416 (2009)*

# The light quark masses

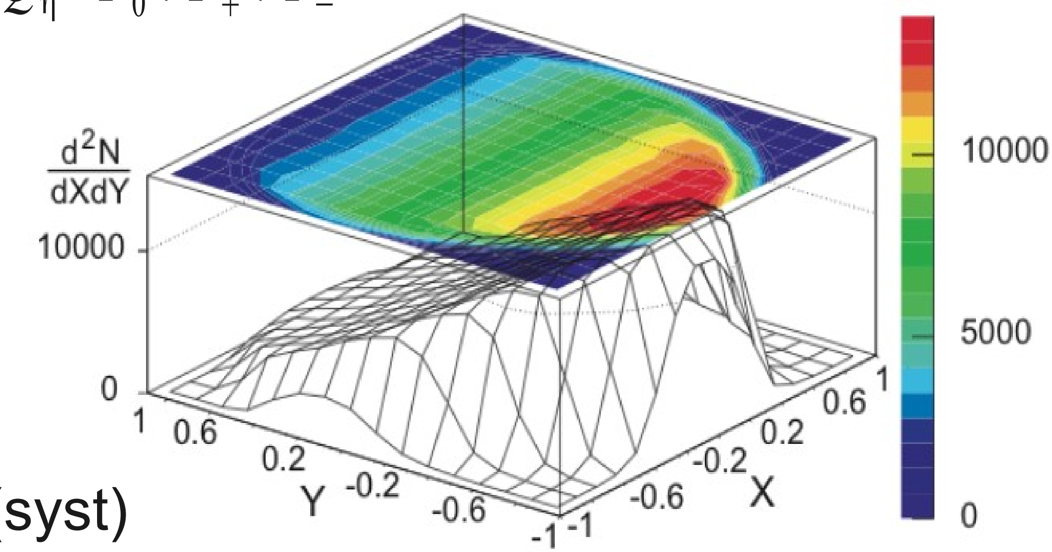
The KLOE collaboration presented a Dalitz Plot analysis of the $\eta\rightarrow\pi^+\pi^-\pi^0$ decay in 2008 using the ~450 fb$^{-1}$ collected in 2001-2002.
The Dalitz density is fitted by:

$|A(X,Y)|^2 \approx 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + \dots$

with

$$X=\sqrt{3}\frac{T_+ - T_-}{Q_\eta} \qquad Y=3\frac{T_0}{Q_\eta} \qquad Q_\eta = T_0 + T_+ + T_-$$

Odd powers of $X$ in $A(X,Y)$ imply charge conjugation violation.




The results are:

a= -1.090 ± 0.005(stat) $^{+0.008}_{-0.019}$ (syst)

b= 0.124 ± 0.006(stat) ± 0.010 (syst)

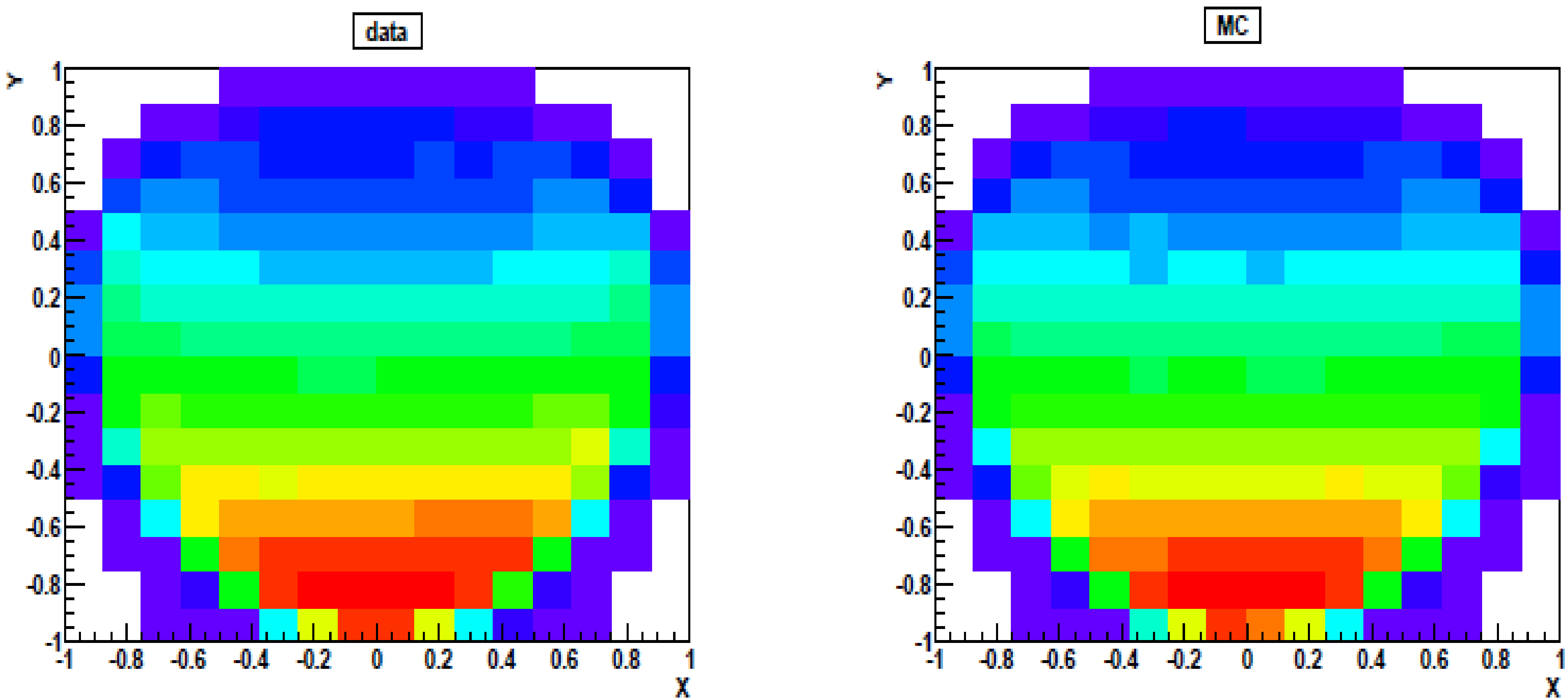
d= 0.057 ± 0.006(stat) $^{+0.007}_{-0.016}$ (syst)

f = 0.14 ± 0.01(stat) ± 0.02 (syst)

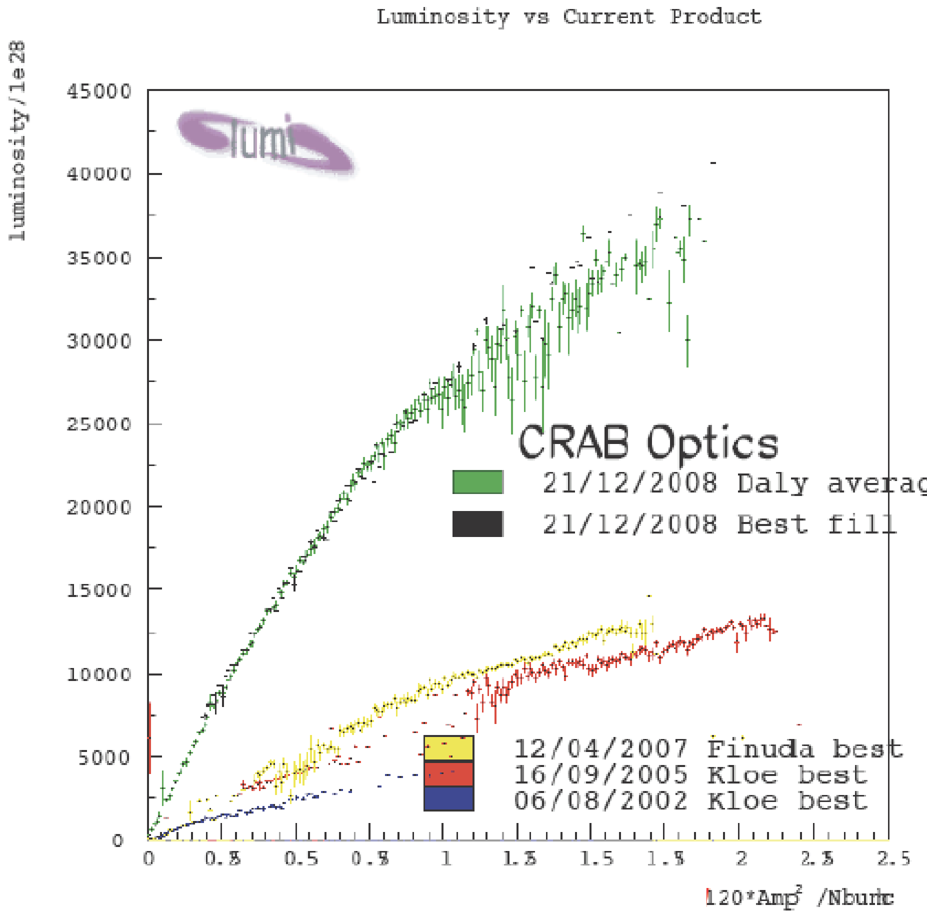
# The light quark masses

A new analysis of $\eta\rightarrow\pi^{+}\pi^{-}\pi^{0}$ Dalitz Plot is in progress with

- different and larger data set ( $2.0\text{fb}^{-1}$ from 2004-2005 run)
- different analysis scheme and improved MC description



# DAΦNE upgrade




$L_{new}$ ~ 3 × $L_{old}$ **achieved with the same circulating currents as in the past**

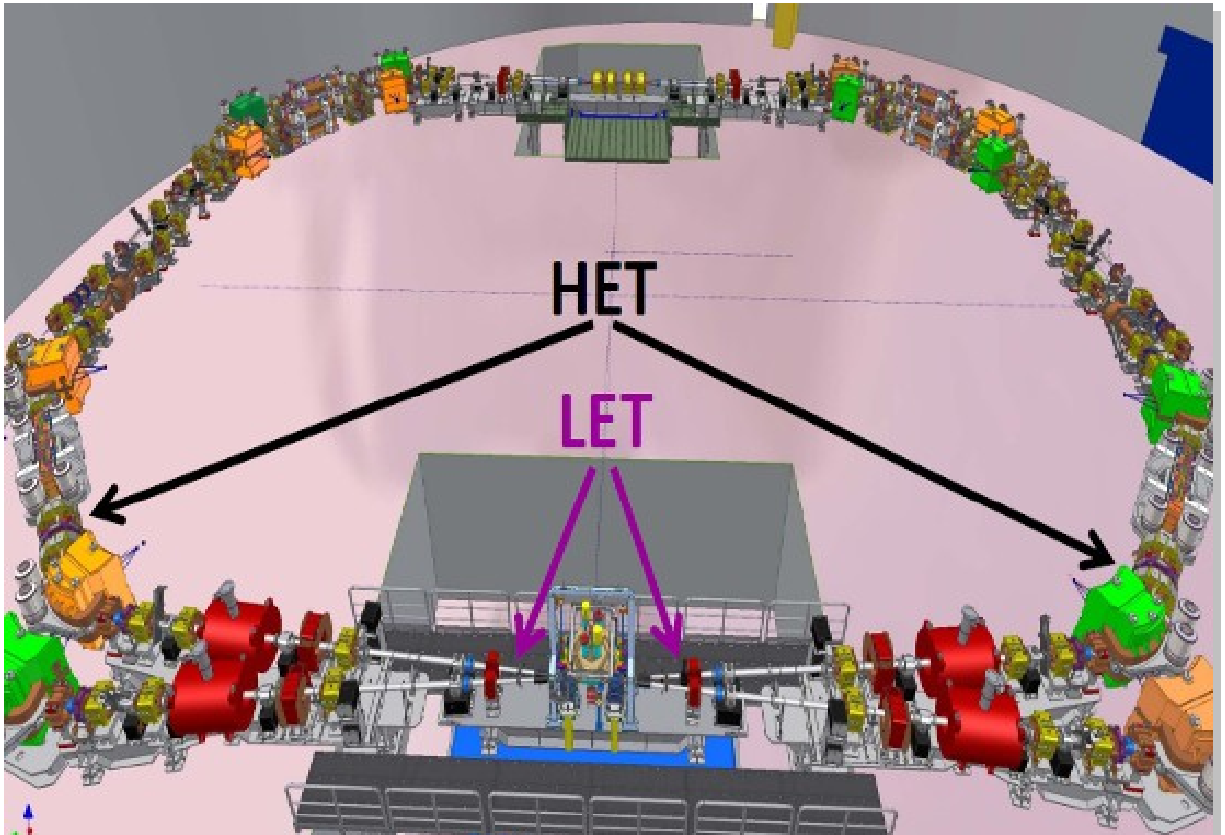
$\int L dt$ **= 1 pb$^{-1}$/hour**

**A new collision scheme worked out with:**

- **larger crossing angle**
- **reduced beam size at the crossing point**
- **sextupole pairs for crab-waist configuration of beam interaction**

KLOE-2 is starting data campaign at upgraded DAΦNE

# KLOE-2




**High Energy Taggers (HET)**
- E>400 MeV
- 11m from IP
- scintillators + PMTs
- $\sigma_E$~2.5 MeV
- $\sigma_T$~200 ps

**Low Energy Taggers (LET)**
- E=160-230 MeV
- inside KLOE detector
- LYSO+SiPM
- $\sigma_E$<10% for E>150 MeV

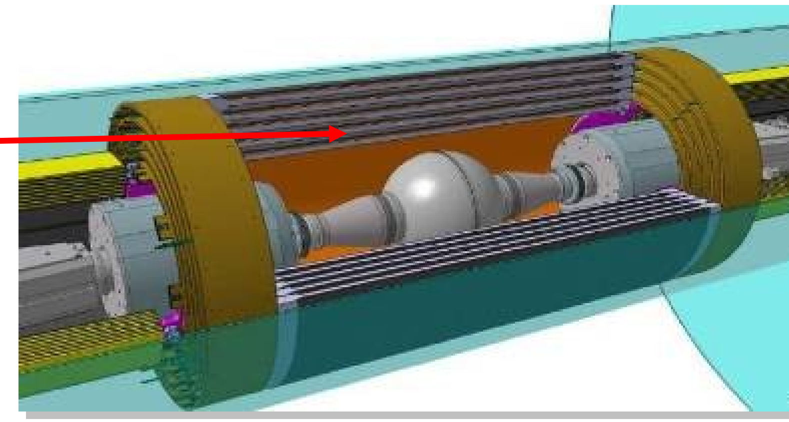
**Detector upgrade for first KLOE-2 run (≈5 $fb^{-1}$ in 1 year):**
**2+2 detector stations for leptons in $e^+e^- \rightarrow e^+e^- \gamma^*\gamma^* \rightarrow e^+e^- X$**

# KLOE-2

Major detector upgrades (late 2012) for second KLOE-2 run:

**Inner Tracker**

- 4 layers of cylindrical triple GEM
- better vertex reconstruction near IP
- larger acceptance for low $p_t$ tracks

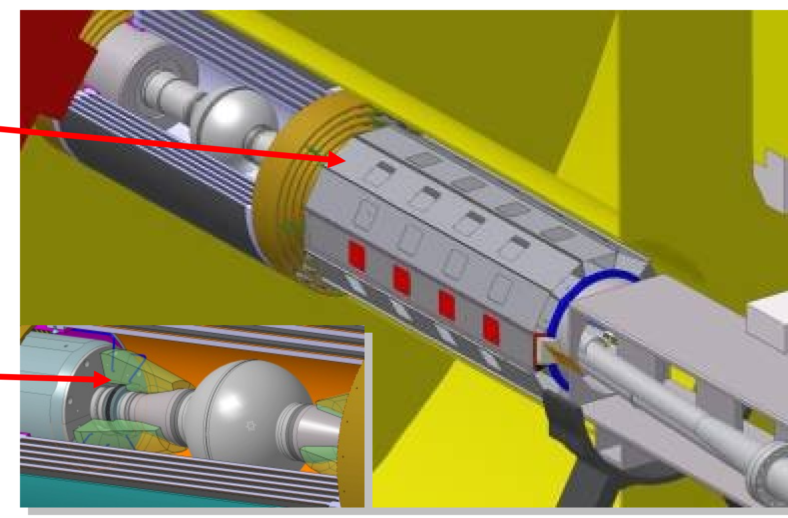


**QCALT**

- W + scintillator tiles + SiPM/WLS
- QUADS instrumentation for $K_L$ decays

**CCAL**

- LYSO + APD
- increase acceptance for γ's from IP (21°→8°)



# $f_+(0)|V_{us}|$

Present total error:

- value from KLOE 0.28% *JHEP 0804 (2008) 059*
- world average 0.23%

Expected at KLOE-2 with $5fb^{-1}$ 0.15%

World average FromFlavianet EPJC69(2010)399 | KLOE-2 prospects with $5fb^{-1}$

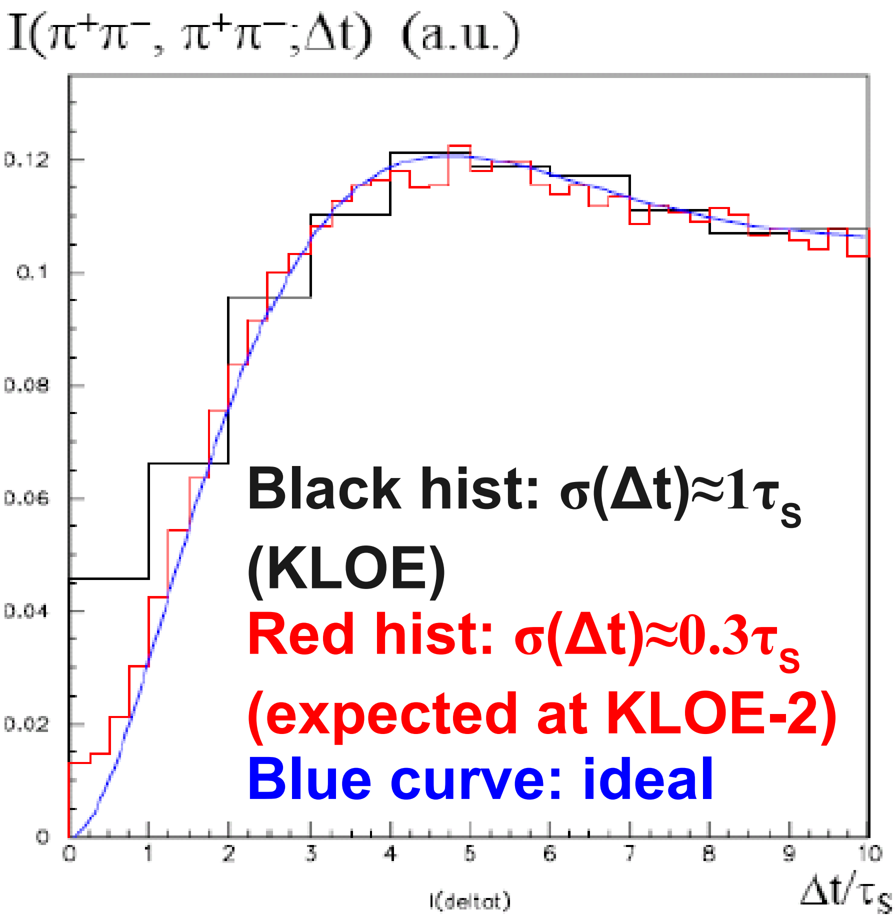
| $f_+(0)V_{us}$ | %err | BR | $\tau$ | $\delta$ | $I_{Kl}$ | %err | BR | $\tau$ | $\delta$ | $I_{Kl}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $K_Le3$ 0.2163(6) | **0.26** | 0.09 | 0.20 | 0.11 | 0.06 | 0.20 | 0.09 | 0.13 | 0.11 | 0.06 |
| $K_L\mu3$ 0.2166(6) | **0.29** | 0.15 | 0.18 | 0.11 | 0.08 | 0.24 | 0.15 | 0.13 | 0.11 | 0.08 |
| $K_Se3$ 0.2155(13) | **0.61** | 0.60 | 0.03 | 0.11 | 0.06 | 0.35 | 0.30 | 0.03 | 0.11 | 0.06 |
| $K^\pm e3$ 0.2160(11) | **0.52** | 0.31 | 0.09 | 0.40 | 0.06 | 0.38 | 0.25 | 0.05 | 0.40 | 0.06 |
| $K^\pm\mu3$ 0.2158(14) | **0.63** | 0.47 | 0.08 | 0.39 | 0.08 | 0.41 | 0.27 | 0.05 | 0.39 | 0.08 |
| Aver 0.2163(5) | **0.23** | | | | | 0.15 | | | | |

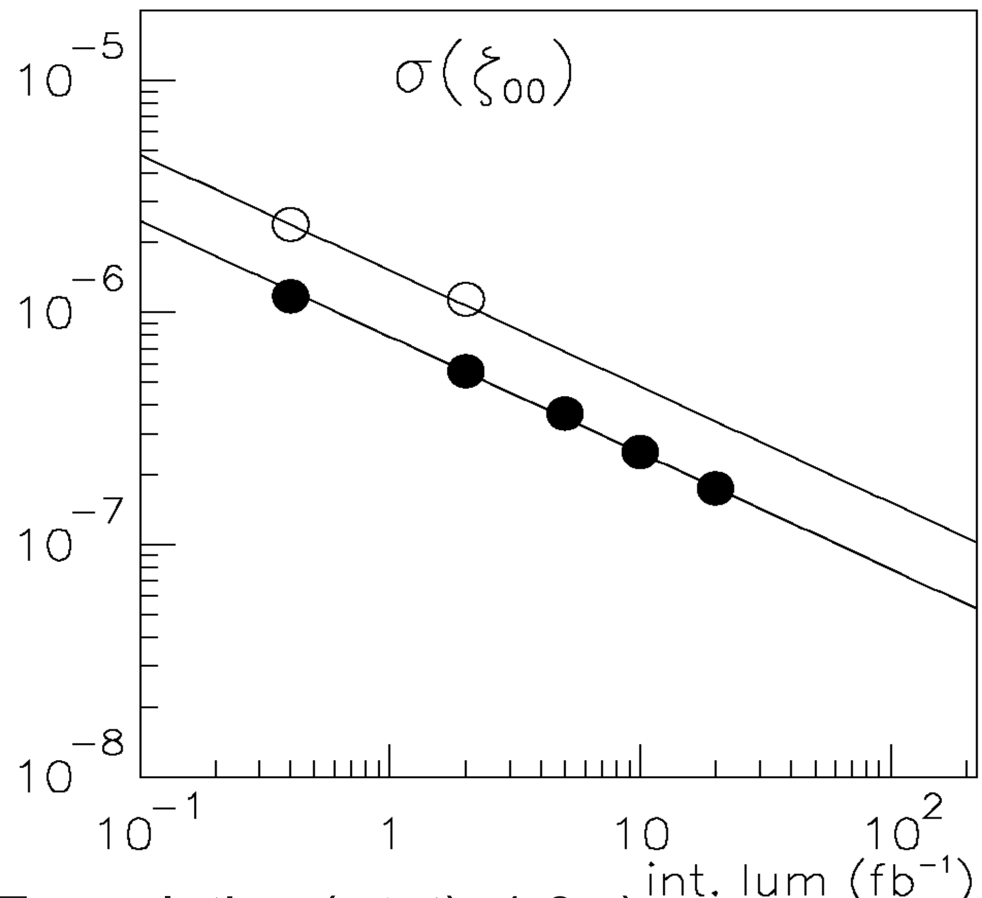
# QM and CPT test at KLOE-2

## KLOE-2 prospects with $5fb^{-1}$

| Parameter | Present best measurement | KLOE-2 ($5\ fb^{-1}$) |
|---|---|---|
| $\zeta_{0\bar{0}}$ | $(0.1 \pm 1.0) \times 10^{-6}$ | $\pm 0.26 \times 10^{-6}$ |
| $\zeta_{SL}$ | $(0.3 \pm 1.9) \times 10^{-2}$ | $\pm 0.49 \times 10^{-2}$ |
| $\alpha$ | $(-0.5 \pm 2.8) \times 10^{-17}$ GeV | $\pm 5 \times 10^{-17}$ GeV |
| $\beta$ | $(2.5 \pm 2.3) \times 10^{-19}$ GeV | $\pm 0.5 \times 10^{-19}$ GeV |
| $\gamma$ | $(1.1 \pm 2.5) \times 10^{-21}$ GeV<br>(compl. pos. hyp.)<br>$(0.7 \pm 1.2) \times 10^{-21}$ GeV | $\pm 0.75 \times 10^{-21}$ GeV<br>(compl. pos. hyp.)<br>$\pm 0.33 \times 10^{-21}$ GeV |
| $\mathrm{Re}\,\omega$ | $(-1.6^{+3.0}_{-2.1} \pm 0.4) \times 10^{-4}$ | $\pm 0.7 \times 10^{-4}$ |
| $\mathrm{Im}\,\omega$ | $(-1.7^{+3.3}_{-3.0} \pm 1.2) \times 10^{-4}$ | $\pm 0.86 \times 10^{-4}$ |
| $\Delta a_0$ | (KLOE prelim.: $(0.4 \pm 1.8) \times 10^{-17}$ GeV) | $\pm 0.52 \times 10^{-17}$ GeV |
| $\Delta a_Z$ | (KLOE prelim.: $(2.4 \pm 9.7) \times 10^{-18}$ GeV) | $\pm 2.2 \times 10^{-18}$ GeV |
| $\Delta a_X$, $\Delta a_Y$ | (KLOE prelim.: $\pm 6 \times 10^{-18}$ GeV | $\pm 1.3 \times 10^{-18}$ GeV |

# QM, CPT tests with neutral kaons




- ○ sensitivity with the present KLOE resolution ($\sigma(\Delta t) \approx 1.0\tau_S$)
- ● sensitivity with improved resolution ($\sigma(\Delta t) \approx 0.3\tau_S$ expected at KLOE-2)

# KLOE-2 physics program

**Goal: ~20 $fb^{-1}$ in the next 3-4 years to extend the KLOE physics program at DAΦNE upgraded in luminosity (approved)**

| | |
|---|---|
| ➢ γγ physics: | existence (and properties) of $\sigma/f_0(600)$; |
| | study of $\Gamma(S/PS\to\gamma\gamma)$; |
| | PS transition form factor; |
| ➢ light meson spectroscopy: | properties of scalar/vector mesons; |
| | rare η decays; |
| | η' physics; |
| ➢ kaon physics: | test of CPT (and QM) in correlated kaon decays; |
| | test of CPT in $K_S$ semileptonic decays; |
| | test of SM (CKM unitarity, lepton universality); |
| | test of ChPT ($K_S$ decays); |
| ➢ dark forces searches: | light bosons @ O(1 GeV); |
| ➢ hadronic cross section: | $\alpha_{em}(M_Z)$ and (g-2). |

**Details in EPJ C68 (2010) 619, arXiv:1003.3868**

# Summary

► KLOE-2 is going to continue the physics program of KLOE, with special emphasis on CPT and QM tests.

► KLOE measured with high precision all relevant parameters for charged and neutral kaons: BR's, lifetimes, form factors. Several test of the standard model, discrete symmetries and quantum mechanics were performed.

► KLOE-2 data taking campaign is starting.

# Acknowledgment

**MesonNet**: Meson Physics in Low-Energy QCD

(successor of PrimeNet)

A network within the project

„Study of Strongly Interacting Matter” (Hadron Physics3)

an *Integrating Activity* within the *Seventh Framework Program of EU*.

http://www2.fz-juelich.de/ikp/mesonnet/

# The End?

# No!

# A new beginning!