Flavor physics at DAFNE with KLOE/KLOE-2

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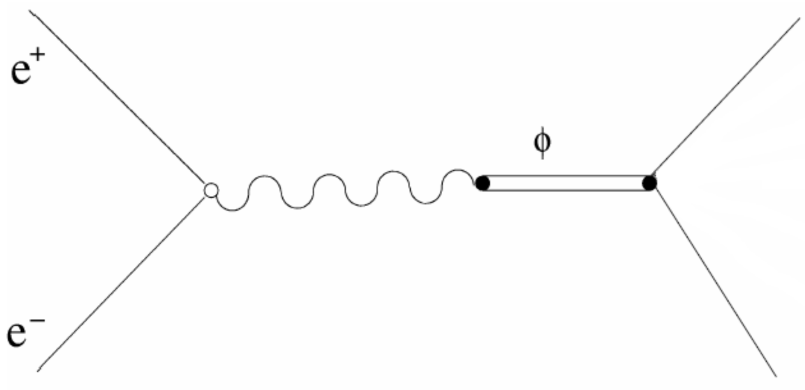
on behalf of the KLOE-2 collaboration

Outline:
- -DAFNE & KLOE/KLOE-2
- -V_{us}, lep. univ. CKM unitarity
- -CP violation in K_S decay
- -light quark masses
- -Neutral kaon interferometry
- -T symmetry test
- -conclusions

XL International Meeting on Fundamental Physics – Flavor Mini-WS
May 25th - 27th, 2012 - Benasque (Spain)

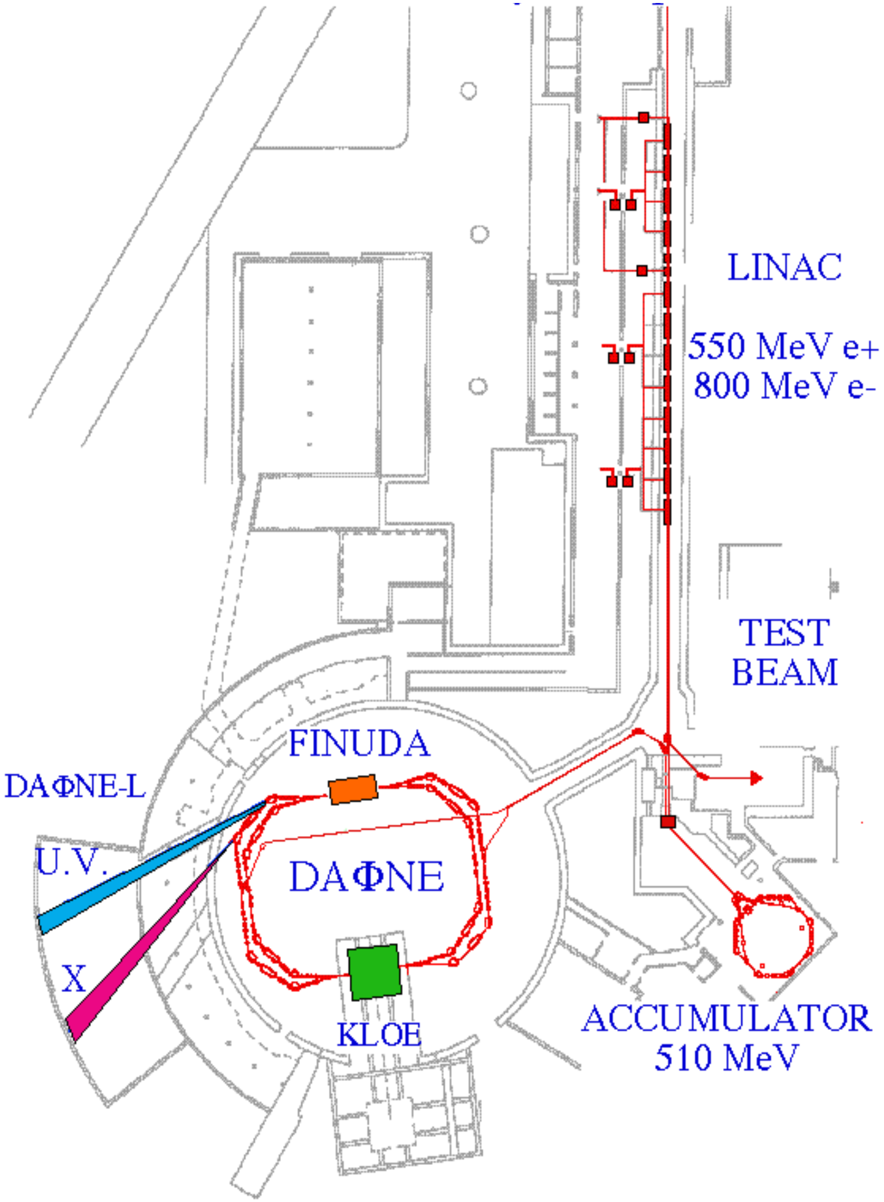
DAΦNE: the Frascati ϕ-factory



BR's for selected **Φ** *decays*	
K^+K^-	49.1%
$\boldsymbol{K_S K_L}$	**34.1%**
$\rho\pi + \pi^+\pi^-\pi^0$	15.5%
$\eta\gamma$	1.31%

- e^+e^- collider @ $\sqrt{s} = M_\phi = 1019.4$ MeV
- LAB momentum $p_\phi \sim 13$ MeV/c
- $\sigma_{peak} \sim 3\ \mu b$
- Separate e^+e^- rings to reduce beam-beam interaction
- Beams crossing angle: 12.5 mrad
- Peak luminosity $1.5\times10^{32}\ cm^{-2}s^{-1}$

DAΦNE Luminosity history



KLOE run:

Daily performance: ∫L dt 7-8 pb^{-1}

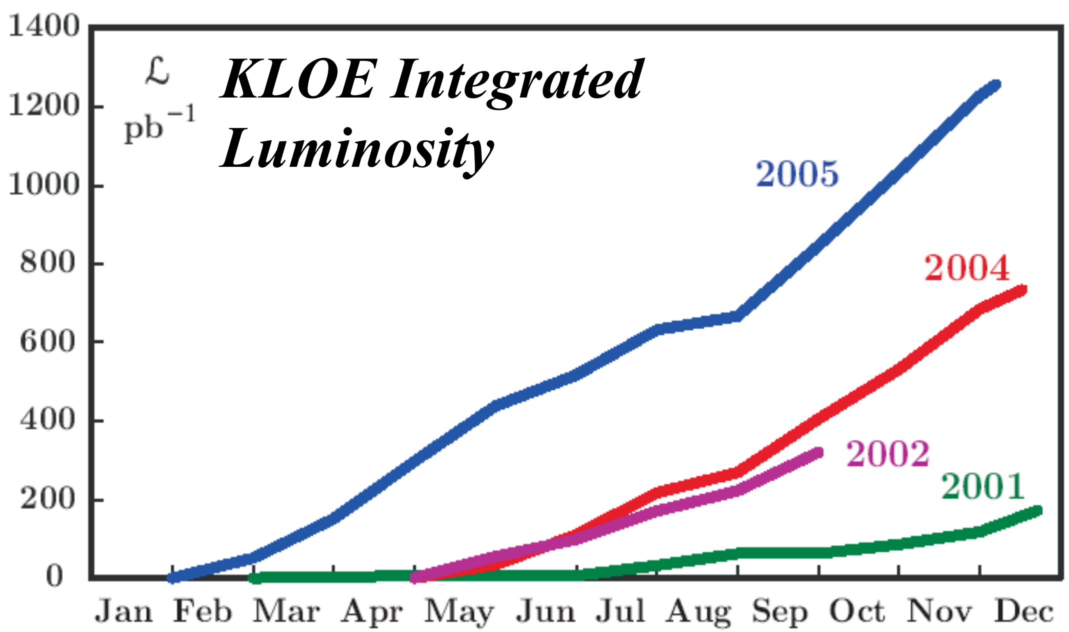
Peak L ~ $1.5\ 10^{32}$ $cm^{-2}s^{-1}$

Total KLOE ∫L dt ~ 2.4 fb^{-1} at ϕ mass peak + 250 pb^{-1} off peak (@ 1 GeV)

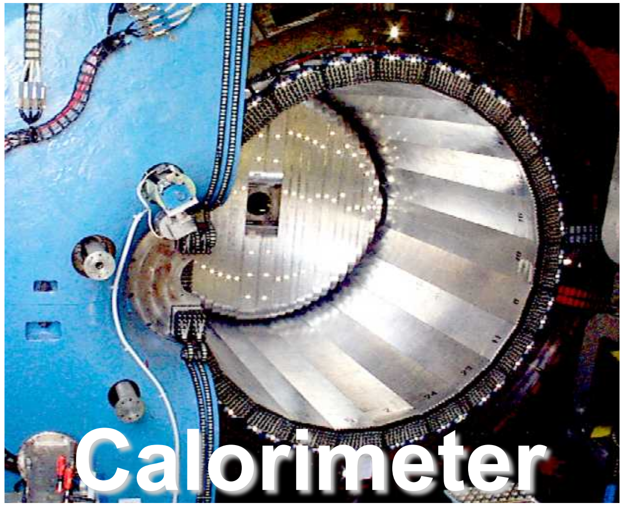
→ ~2.5×10^9 K_SK_L pairs

→ ~3.6×10^9 K^+K^- pairs

→ ~10^8 η's



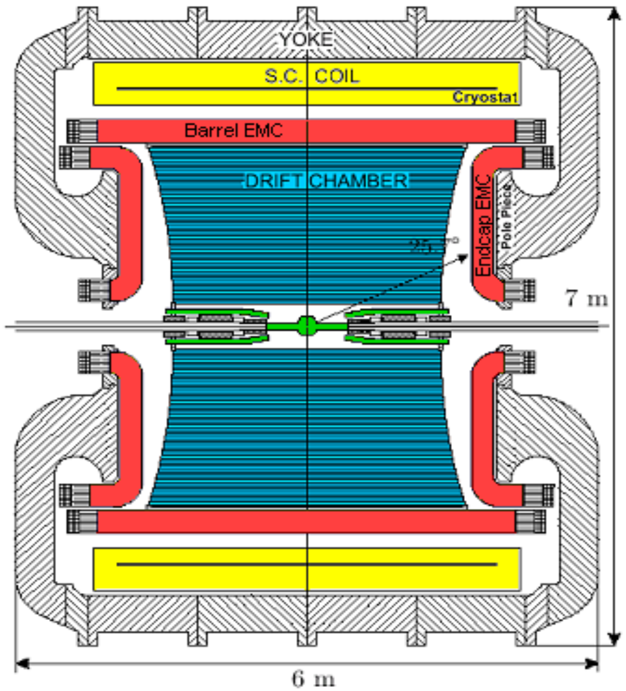
The KLOE detector at DAΦNE



Lead/scintillating fiber
4880 PMTs
98% coverage of solid angle

Superconducting coil

B = 0.52 T



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

$\sigma_E/E \cong 5.7\% /\sqrt{E(\text{GeV})}$

$\sigma_t \cong 54$ ps $/\sqrt{E(\text{GeV})} \oplus 50$ ps
(relative time between clusters)

$\sigma_{\gamma\gamma} \sim 2$ cm (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

$\sigma_p/p \cong 0.4\ \%$ (tracks with $\theta > 45°$)

$\sigma_x^{hit} \cong 150\ \mu m$ (xy), 2 mm (z)

$\sigma_x^{vertex} \sim 1$ mm

KLOE results in kaon physics

- **KLOE has measured all relevant inputs for charged and neutral kaons: BR's, lifetimes, form factors**
- **SM test in the flavor sector** through precise measurements of V_{us} and $R_K = \Gamma(K \to e\nu) / \Gamma(K \to \mu\nu)$
- **CPT and quantum mechanics tests** with the analysis of the QM interference of neutral kaons, K_s semileptonic decays, unitary (Bell-Steinberger relation)
- **Recent results and ongoing analysis**
  - ✓ K_S lifetime [Eur. Phys. J. C 71, 1604 (2011)]
  - ✓ $\mathbf{K_S \to \pi^0\pi^0\pi^0}$ (preliminary result)
  - ✓ $\mathbf{K_S K_L \to \pi^+\pi^-\pi^+\pi^-}$ (QM/CPT tests updated; further studies in progress)
  - ✓ $K^+ \to \pi^+\pi^+\pi^-$
  - ✓ K_S regeneration

$K_L \to \pi e \nu$	0.4008 ± 0.0015 [50]
$K_L \to \pi \mu \nu$	0.2699 ± 0.0014 [50]
$K_L \to 3\pi^0$	0.1996 ± 0.0020 [50]
$K_L \to \pi^+\pi^-\pi^0$	0.1261 ± 0.0011 [50]
$K_L \to \pi^+\pi^-$	$(1.963 \pm 0.21) \times 10^{-3}$ [62]
$K_L \to \gamma\gamma$	$(5.569 \pm 0.077) \times 10^{-4}$ [63]
$K_S \to \pi^+\pi^-$	0.60196 ± 0.00051 [55]
$K_S \to \pi^0\pi^0$	0.30687 ± 0.00051 [55]
$K_S \to \pi e \nu$	$(7.05 \pm 0.09) \times 10^{-4}$ [54]
$K_S \to \gamma\gamma$	$(2.26 \pm 0.13) \times 10^{-6}$ [64]
$K_S \to 3\pi^0$	$<1.2 \times 10^{-7}$ at 90% C.L. [65]
$K_S \to e^+e^-(\gamma)$	$<9 \times 10^{-9}$ at 90% C.L. [66]
$K^+ \to \mu^+\nu(\gamma)$	0.6366 ± 0.0017 [52]
$K^+ \to \pi^+\pi^0(\gamma)$	0.2067 ± 0.0012 [53]
$K^+ \to \pi^0 e^+\nu(\gamma)$	0.04972 ± 0.00053 [51]
$K^+ \to \pi^0 \mu^+\nu(\gamma)$	0.03237 ± 0.00039 [51]
$K^+ \to \pi^+\pi^0\pi^0$	0.01763 ± 0.00034 [67]

$$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-5}$$

$|V_{us}| = 0.2253 \pm 0.0007$ JHEP04(2008)059

$\tau_S = 89.562 \pm 0.029_{stat} \pm 0.043_{syst}$ [ps]

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- new scheme of the interaction region (crabbed waist scheme) at DAΦNE (proposal by P. Raimondi)
- increase L by a factor x 3 demonstrated by a successful experimental test

KLOE-2 experiment:

- extend the KLOE physics program at DAΦNE upgraded in luminosity
- Collect O(10) fb^{-1} of integrated luminosity in the next 2-3 years

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

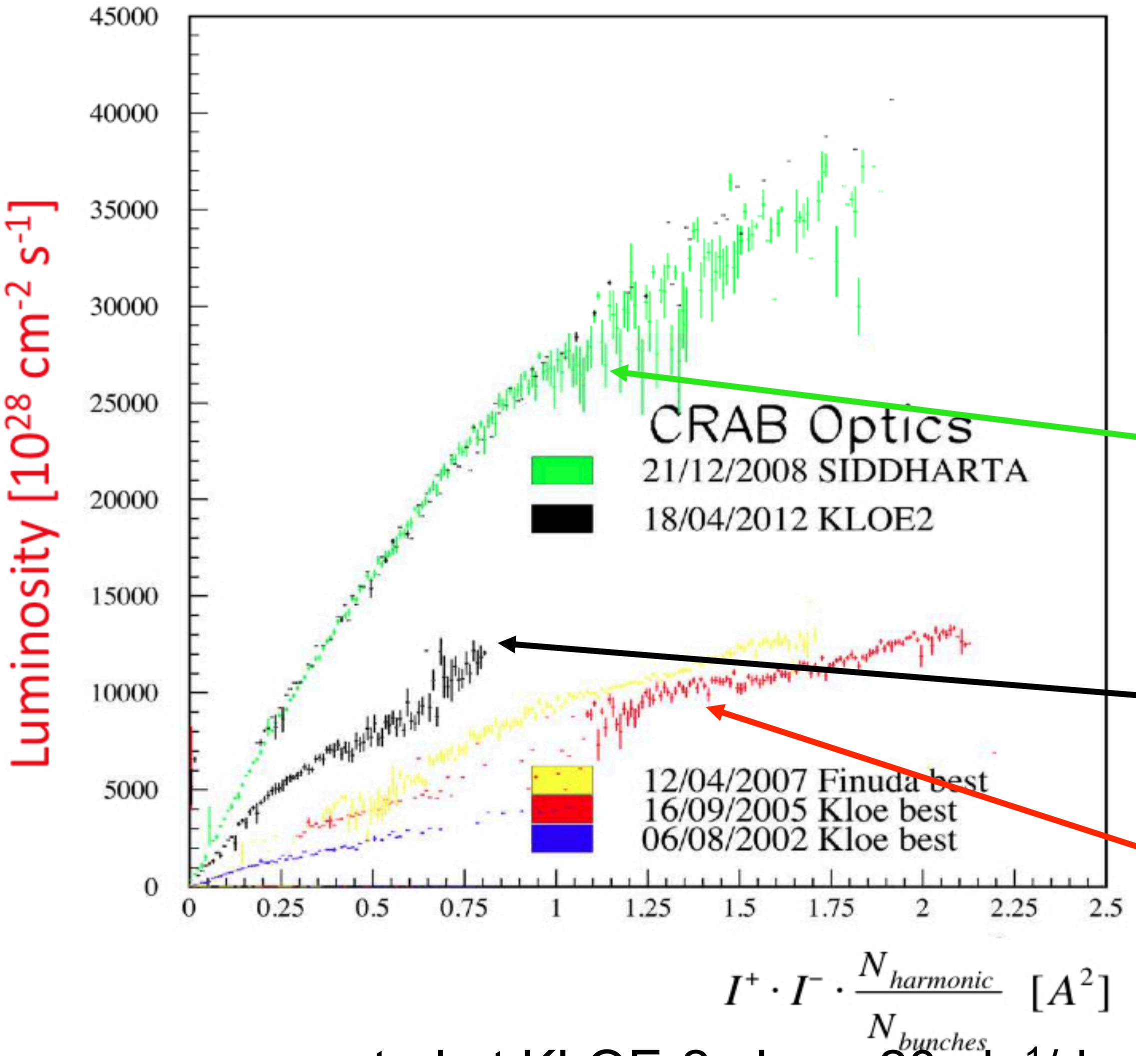
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

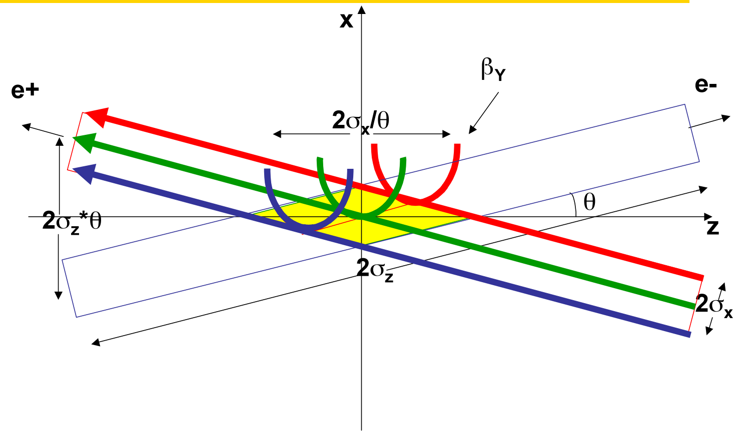
Detector upgrade:

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

DAΦNE luminosity upgrade

Crabbed waist scheme at DAΦNE





Crabbed waist is realized with a sextupole in phase with the IP in X and at $\pi/2$ in Y

NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

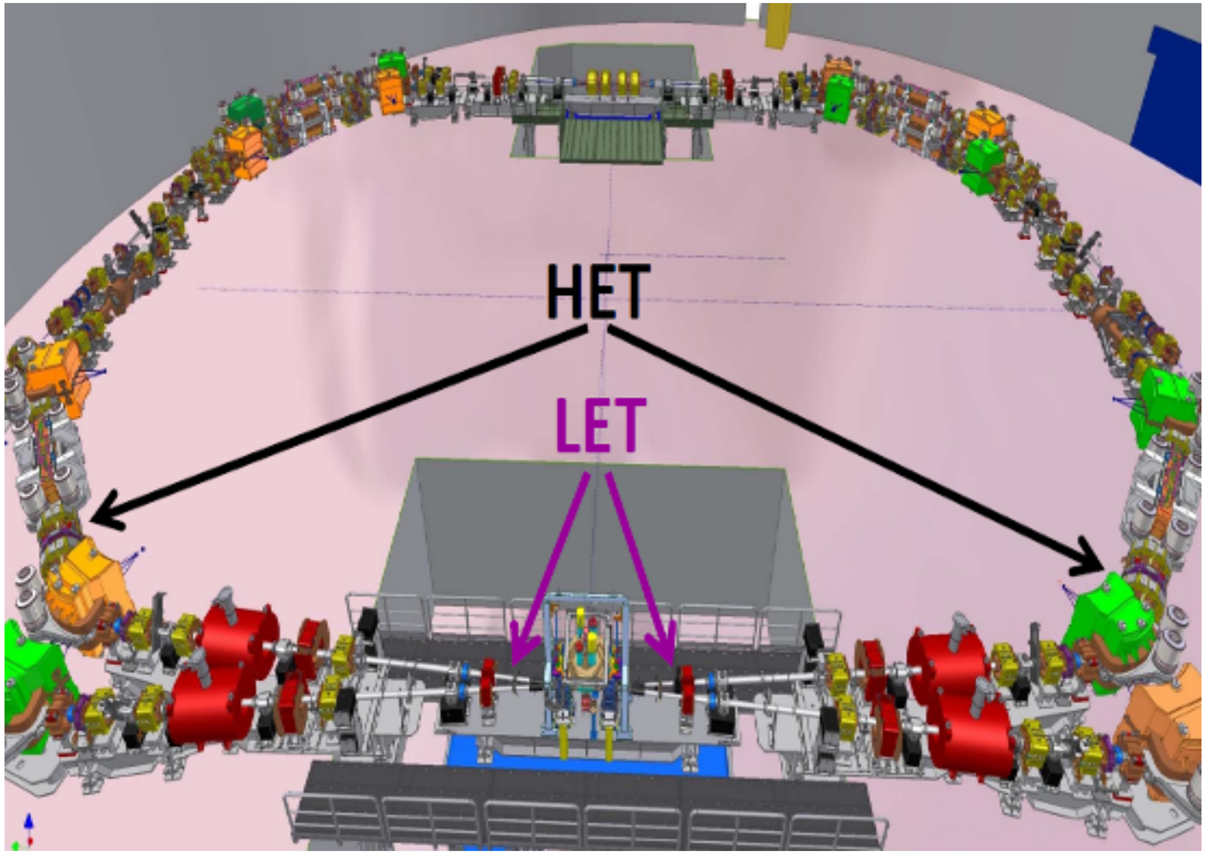
Present commissioning phase
New coll. scheme + KLOE det.

Old collision scheme

max. expected at KLOE-2 : L_{int} ~ 20 pb^{-1}/day x 200 dd/year = 4 fb^{-1} /year

From KLOE to KLOE-2: γγ taggers

Measurement of leptons momenta in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$



LET: E_e ~ 160-230 MeV

- **Inside KLOE detector**
- **LYSO+SiPM**
- **σ_E<10% for E>150 MeV**

HET: E_e > 400 MeV

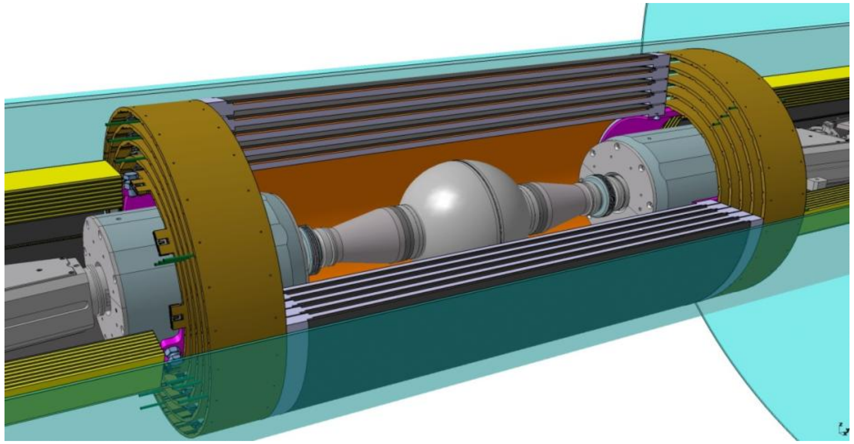
- **11 m from IP**
- **Scintillator hodoscopes**
- **σ_E ~ 2.5 MeV**
- **σ_T ~ 200 ps**

γγ taggers are installed and ready for the first KLOE-2 run (STEP0) in autumn 2011
~ 5 fb^{-1} of integrated luminosity expected

From KLOE to KLOE-2: IP detectors

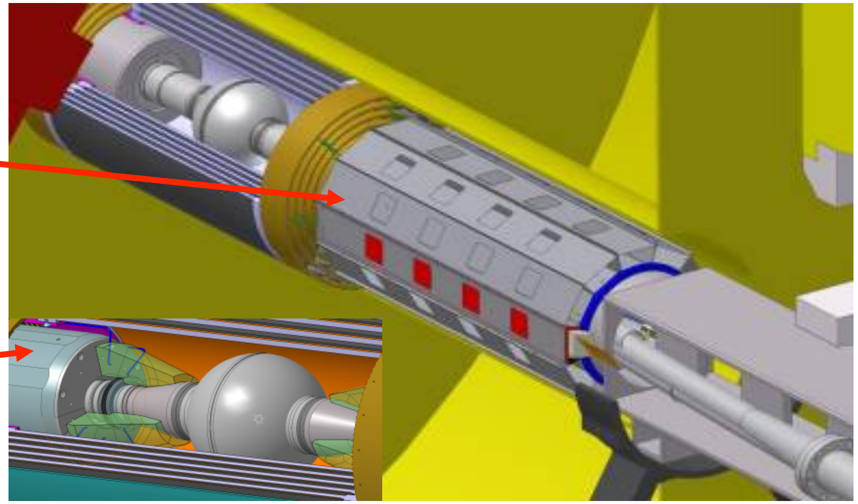
Major detector upgrades for second KLOE-2 run (STEP1):

INNER TRACKER



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

QCALT

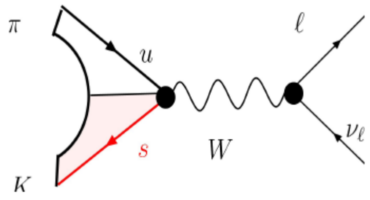


- W + scintillator tiles + SiPM/WLS
- Low-beta quadrupoles: coverage for K_L decays

CCALT

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

Vus, lepton universality, and CKM unitarity at KLOE

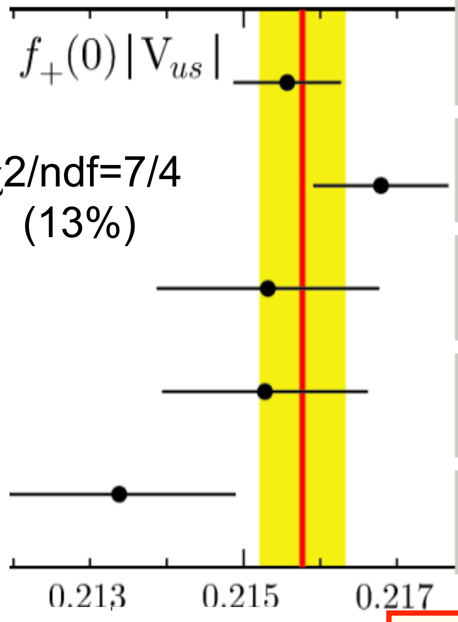


$$\Gamma(K_{\ell 3(\gamma)}) = |V_{us}|^2 |f_+(0)|^2 \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW} I_{K\ell} (1+\delta_{EM}^{K\ell} + \delta_{SU(2)}^{K\pi})^2$$

$K_{\ell 3}$: $K \to \pi \ell \nu$

All KLOE exp. inputs but K_S lifetime:

τ_S subsequently measured by KLOE: EPJC 71(2011)1604



	$f_+(0)\vert V_{us}\vert$	err %
K_Le3	0.2155(7)	0.3
$K_L\mu3$	0.2167(9)	0.4
K_Se3	0.2152(14)	0.7
$K^\pm e3$	0.2152(13)	0.6
$K^\pm\mu3$	0.2132(15)	0.7

KLOE average
$|V_{us}|f_+(0) = 0.2157(6)$ (*0.28%*)

$|V_{us}| = 0.2237(13)$ 0.6%

JHEP04(2008)059

Lepton universality

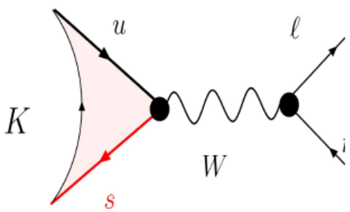
$$r_{\mu e} \equiv \frac{|f_+(0)\,V_{us}|^2_{\mu3,\ \mathrm{exp}}}{|f_+(0)\,V_{us}|^2_{e3,\ \mathrm{exp}}}$$

$r_{\mu e} = 1.000(8)$

π decays: $(r_{\mu e})_\pi = 1.0042(33)$

τ decays: $(r_{\mu e})_\tau = 1.0005(41)$

$|V_{us}/V_{ud}| = 0.2323(15)$



$K_{\ell 2}$: $K \to \ell \nu$

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(K_{\pi 2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K(1-m_\mu^2/m_K^2)^2}{m_\pi(1-m_\mu^2/m_\pi^2)^2} (1+\delta_{EM})$$

$1-|V_{ud}|^2-|V_{us}|^2 = 4(7)\times10^{-4}$ @0.6σ

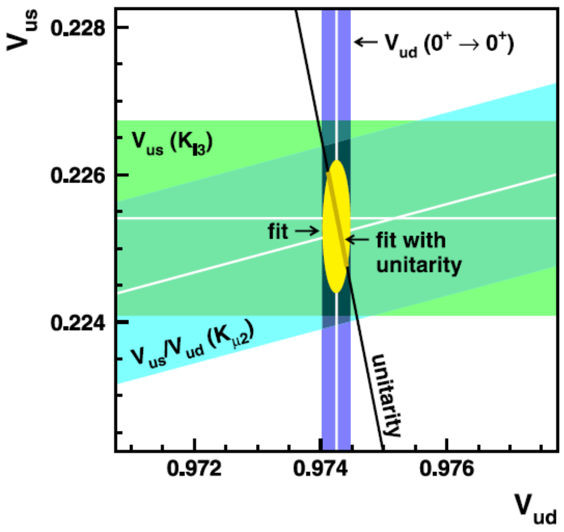
World Average: 6×10^{-4} accuracy

Prospects for $f_+(0)|V_{us}|$ at KLOE-2

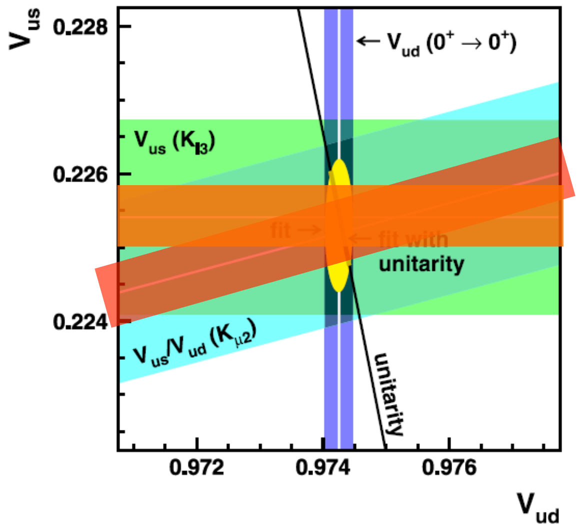
World average from Flavianet EPJC69(2010)399

improvements possible at KLOE-2 with $L \sim 5\ fb^{-1}$

$f_+(0)V_{us}$	%err	BR	τ	δ	I_{Kl}	%err	BR	τ	δ	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**				



	$f_+(0)V_{us}$
KLOE today	**0.28%**
World average	0.23%
KLOE-2 ($5fb^{-1}$) + W.A.	**0.15%**



Recent progress on LQCD calculation→ precision on $f_+(0)$, f_K/f_π of $O(0.1\%)$ feasible (now at ~0.5%)

Prospects for $f_+(0)|V_{us}|$ at KLOE-2

World average from Flavianet EPJC69(2010)399

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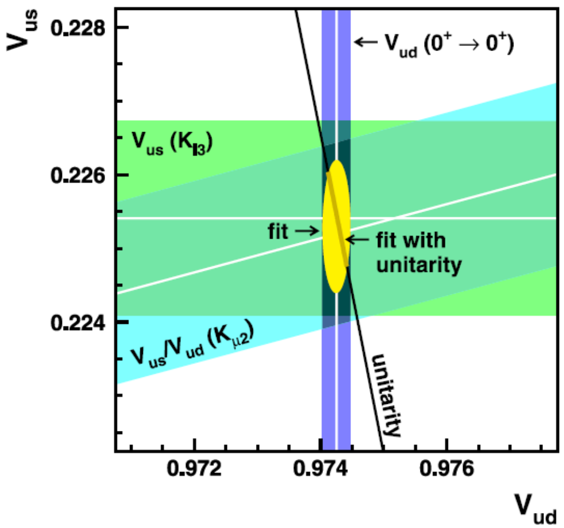

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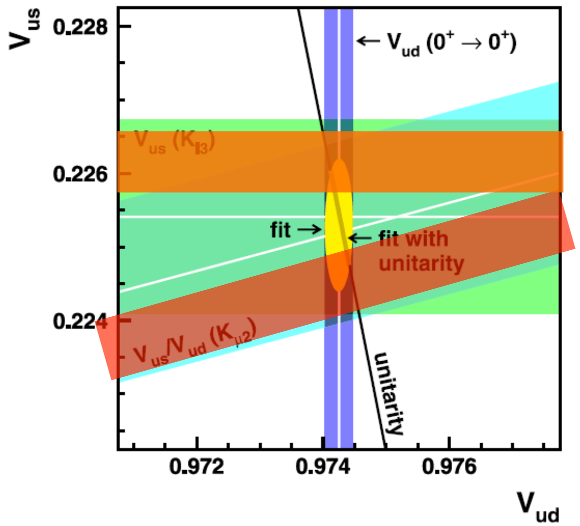


Recent progress on LQCD calculation→ precision on $f_+(0)$, f_K/f_π of $O(0.1\%)$ feasible (now at ~0.5%)

$K_S \to \pi^0\pi^0\pi^0$: search for a CP violating decay

Observation of $K_S \to 3\pi^0$ signals CP violation in mixing and/or in decay

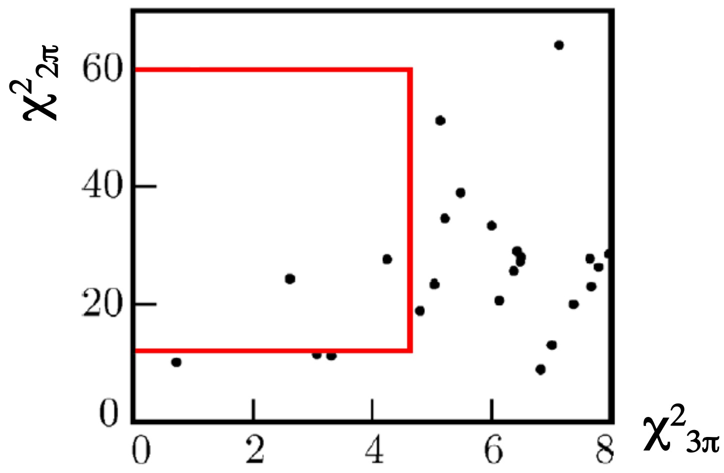
- $\Gamma(K_S \to 3\pi^0) = \Gamma(K_L \to 3\pi^0)\, |\eta_{000}|^2 = \Gamma(K_L \to 3\pi^0)\, |\varepsilon + \varepsilon'_{000}|^2$

  $\Rightarrow$ BR~ 2×10^{-9}

Direct search at KLOE

- K_L interactions in the calorimeter to tag K_S decay
- 6 prompt γ's required
- Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
- Dominant background from $K_S \to 2\pi^0$ + 2 split or 2 accidental clusters
- After all analysis cuts ($\varepsilon_{3\pi}$ = 24.4%)
  – 2 candidate events found
  – 3.13±0.82stat±0.37syst expected background

2005 analysis



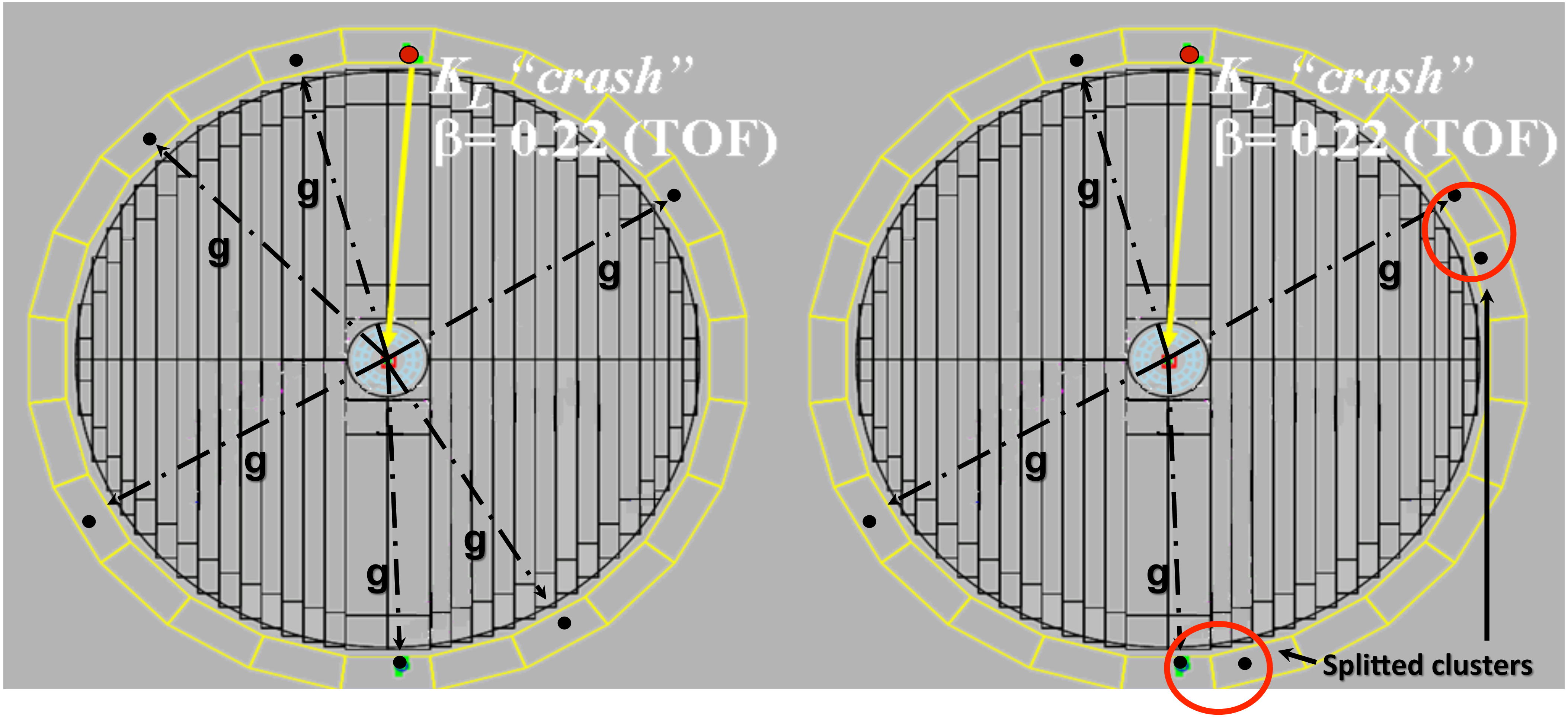
Best sensitivity from KLOE [PLB619(2005)61] with 450 pb^{-1} $\Rightarrow$

$BR(K_S \to 3\pi^0) < 1.2 \times 10^{-7}$ @ 90% CL

$|\eta_{000}| < 0.018$ @ 90% CL

$K_S \to \pi^0\pi^0\pi^0$: search for a CP violating decay

SIGNAL **BACKGROUND**



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

$K_S \to 2\pi^0$ + accidental/splitted clusters

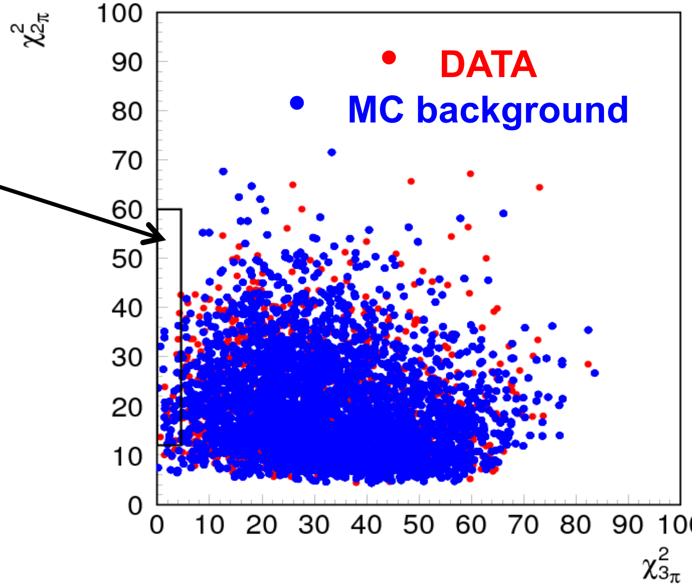
$K_L \to 3\pi$, $K_S \to \pi^+ \pi^-$ („fake K_L-crash")

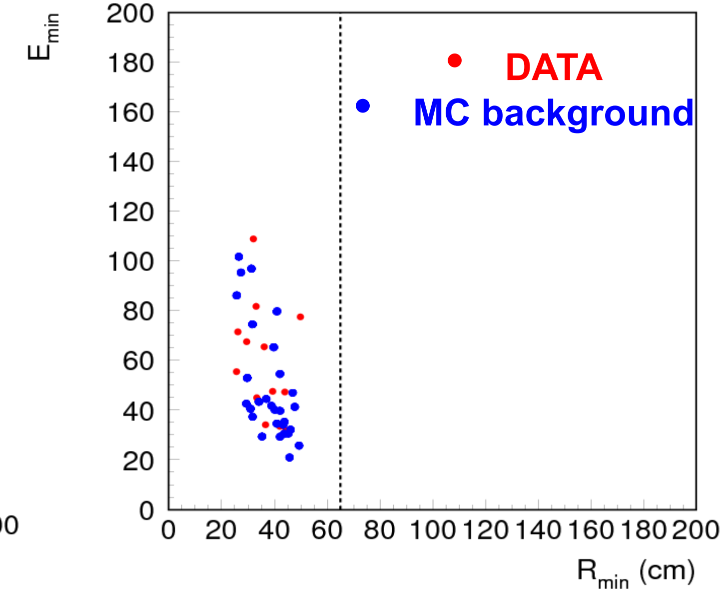
$K_S \to \pi^0\pi^0\pi^0$: search for a CP violating decay

- The analysis has been updated
  - improving clustering procedure to reduce split clusters
  - hardening the $\beta^*(K_L)$ cut for tagging the Ks decays
  - processing the entire data set (~8×10^7 tagged $K_S K_L$ pairs)

- N_{obs} =0 evts. in data
- N_{exp}=0 evts. in MC
- 0.12 evts expected in SM

- signal box
- R_{min} > 65 cm
- $\varepsilon_{3\pi} = 0.19(1)$
- $N_{3\pi 0} \leq 2.44/\varepsilon_{3\pi 0}$ = 12.84 at 90% C.L.
- Normalized to $N_{2\pi 0}$ = $90062000/\varepsilon_{2\pi 0}$=136457576





$BR(K_S \to 3\pi^0) < 2.9 \times 10^{-8}$ @ 90% CL

KLOE preliminary

$|\eta_{000}| < 0.009$ @ 90% CL

This result points to the feasibility of the first observation at KLOE-2

The light quark masses: study of η→3π decay

- Quark masses are fundamental parameters of the SM known only through their impact on hadronic interactions and hadron properties
- Changing perspective, the SM predictions of any process involving hadrons are affected by the knowledge of the quark masses
- Precision measurements combining isospin-symmetric results from LQCD with isospin-breaking study in ChPT

• η→πππ decay ⇒ Isospin violation
(e.m. contribution strongly suppressed)

$$\mathcal{L}_I = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

In ChPT:

$$A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$$

where $Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ and, at lowest order $M(s,t,u) = \frac{3s - 4m_\pi^2}{m_\eta^2 - m_\pi^2}$

$$\hat{m} = (m_d + m_u)/2$$

$$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$$

$$\Gamma_{LO}(\eta \to \pi^+\pi^-\pi^0) = 66 \text{ eV}$$

$$\Gamma_{NLO}(\eta \to \pi^+\pi^-\pi^0) = 167 \text{ eV}$$

$$\Gamma_{exp}(\eta \to \pi^+\pi^-\pi^0) = 296 \text{ eV}$$

• Large final state interactions
•In order to improve on the light quark masses precision, recent theoretical works use a dispersive relations approach and experimental inputs: η→πππ Dalitz plot

$\eta \to \pi^+\pi^-\pi^0$ at KLOE

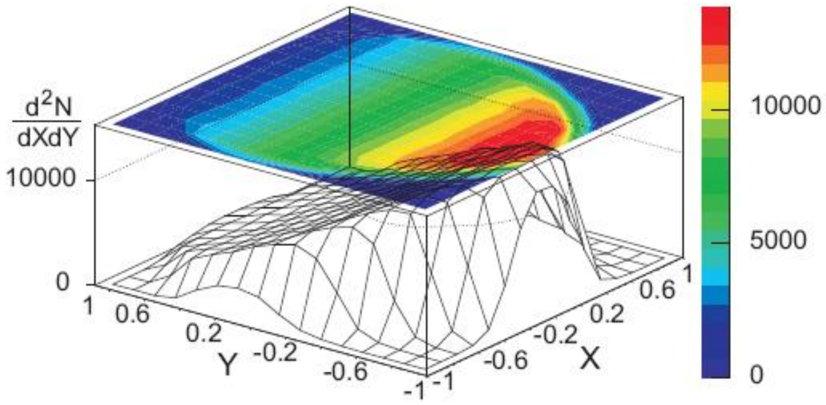
$$X = \sqrt{3}\frac{E_+ - E_-}{\Delta}$$

$$Y = 3\frac{E_0 - m_0}{\Delta} - 1$$

$$(\Delta = m_\eta - 2m_{\pi^\pm} - m_0)$$

$\phi \to \eta\gamma$ ($E_{\gamma rec}$ = 363 MeV)
$\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$

450 $pb^{-1} \Rightarrow 1.34 \times 10^6$ events in the Dalitz plot



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

a	$-1.090 \pm 0.005 ^{+0.008}_{-0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006 ^{+0.007}_{-0.016}$
e	$-0.006 \pm 0.007 ^{+0.005}_{-0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
$P(\chi^2)$	73%

[JHEP0805(2008)006]

- ***c, e*** **compatible with zero (C violation)**
- **fit without cubic term (fY^3) $\Rightarrow P(\chi^2) \sim 10^{-6}$**

$\eta \to \pi^+\pi^-\pi^0$ at KLOE

A new analysis is in progress with:

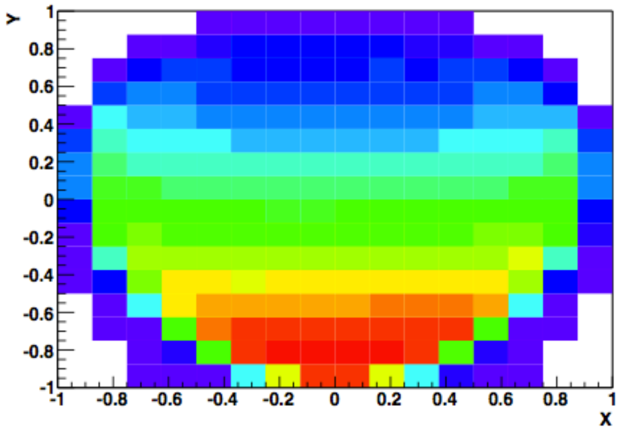
- larger data sample: 2 fb-1
- improved analysis strategy
- reduced main systematic uncertainty due to event classification efficiency (evaluated from min. bias data)

After cuts have:

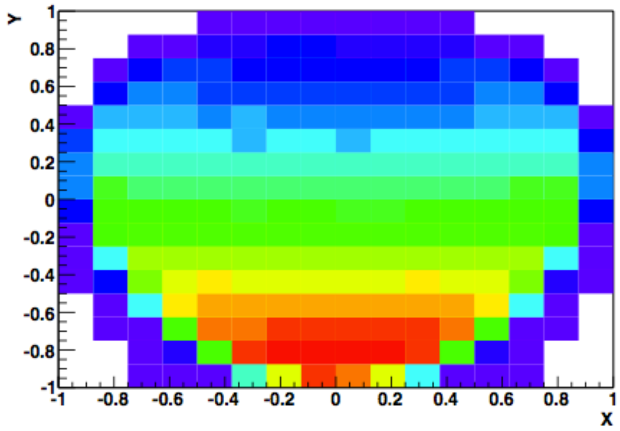
- MC signal $1.7275 \cdot 10^6$
- MC background $1.63 \cdot 10^4$

Background at $\sim 1\%$

Data



MC



$\eta \to \pi^0\pi^0\pi^0$ at KLOE

- Symmetric Dalitz plot:

  $|A|^2 \propto 1 + 2\,\alpha\,Z$ $\Rightarrow$ only one parameter

$$Z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - M_\eta}{M_\eta - 3M_\pi}\right)^2 = \frac{\rho^2}{\rho^2_{max}}$$

(ρ = distance from the Dalitz plot center)

- **450 pb^{-1} ; 7 prompt photons $\Rightarrow$ 6.5 $\times 10^5$ events**

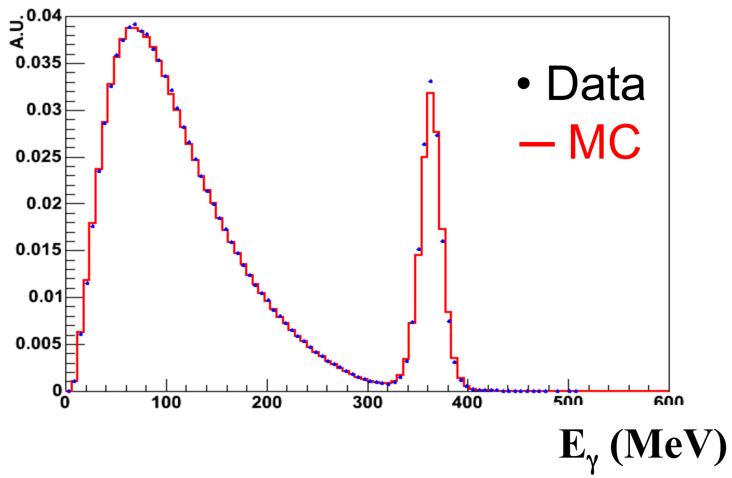
$$\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$$

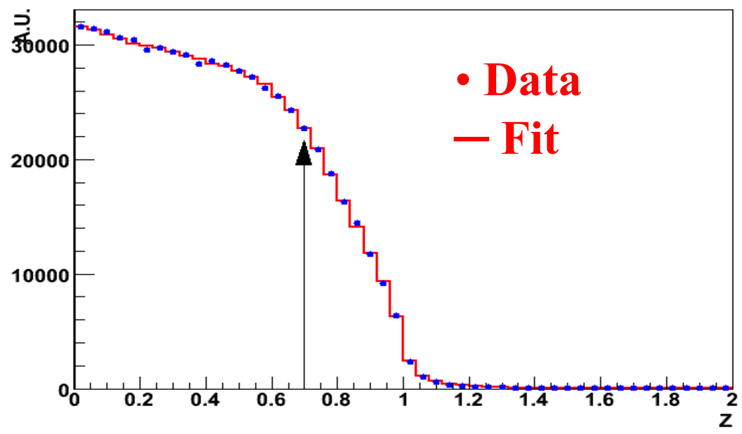
[PLB 694 (2010) 16]

Strong interactions correlate the two amplitudes $A(\eta\to\pi^+\pi^-\pi^0)$ and $A(\eta\to\pi^0\pi^0\pi^0)$: from the Dalitz plot of $\eta\to\pi^+\pi^-\pi^0$

$$\Rightarrow \quad \alpha = -0.038 \pm 0.003^{+0.012}_{-0.008}$$

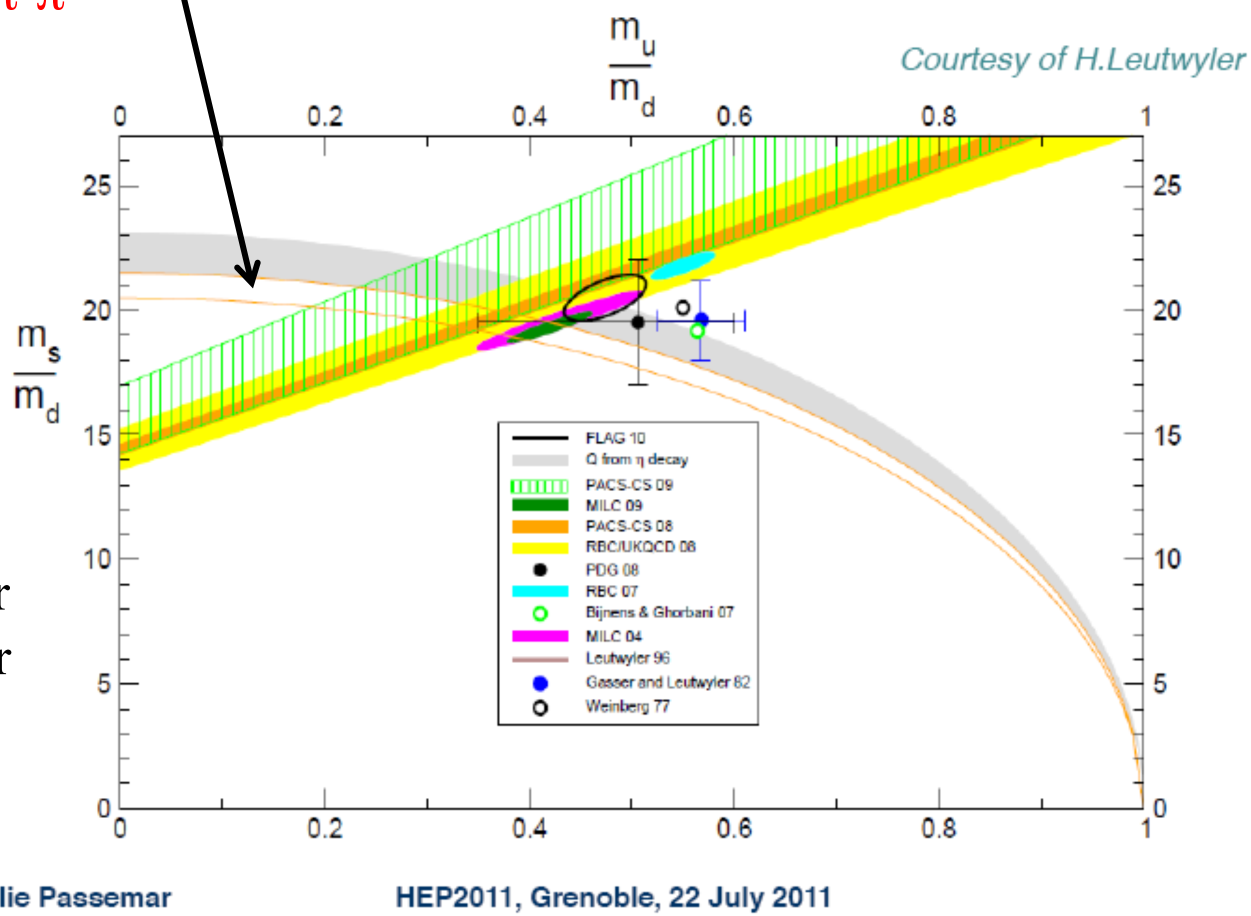
[JHEP0805(2008)006]





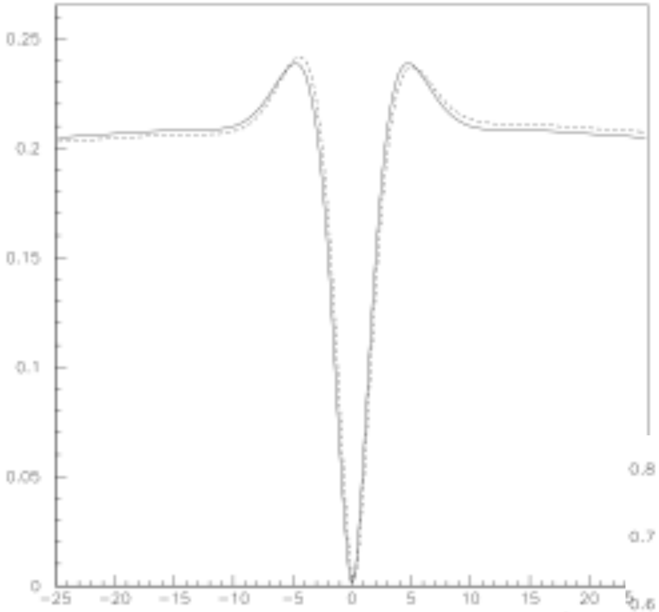
The light quark masses: study of $\eta \to 3\pi$ decay

- Using dispersive relations and the fit to the $\eta \to \pi^+\pi^-\pi^0$ data a reasonable agreement with precise experimental analyses of the $\eta \to \pi^0\pi^0\pi^0$ channel, is obtained.
- The Q value obtained with this procedure provides useful information on quark masses.
- New more precise data on $\eta \to \pi^+\pi^-\pi^0$ important in order to reduce systematics on Q^2 associated to the residual mismatch with the neutral channel.
- New analysis of the whole KLOE dataset (~2fb^{-1}) with new analysis strategy to reduce systematics
- At KLOE-2 with the inner tracker and more data we expect a further significant improvement



Neutral kaon interferometry: main observables

$I(\Delta t)$ (a.u)



$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^0\pi^0$

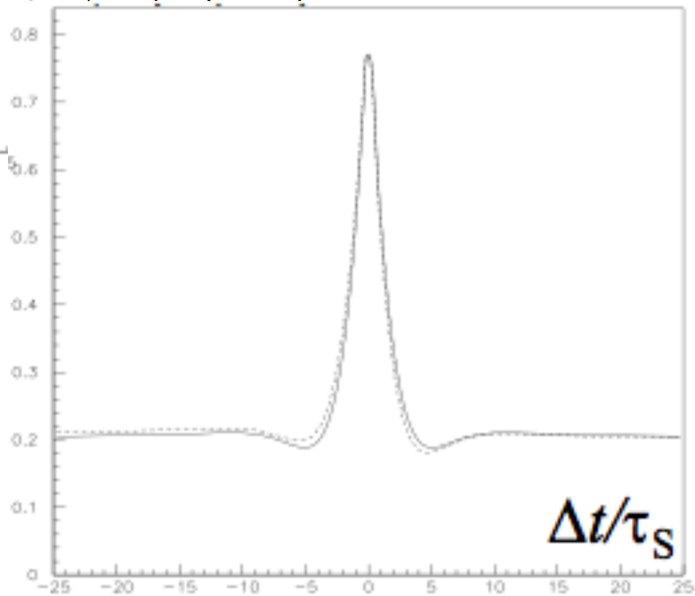
$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$\Re\delta + \Re x_-$$

$$\Im\delta + \Im x_+$$

$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \;\; \pi^-\ell^+\nu$

$I(\Delta t)$ (a.u)



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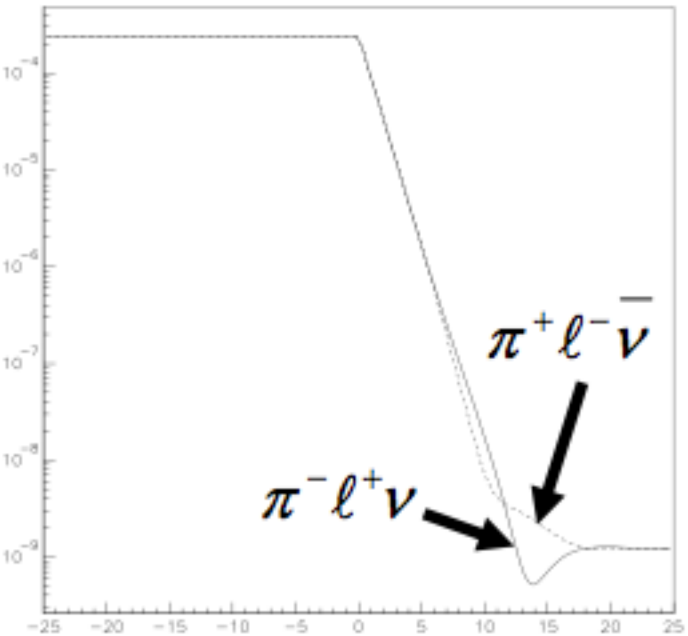


$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi\pi \;\; \pi\ell\nu$

$$A_L = 2\Re\varepsilon - \Re\delta - \Re y - \Re x_-$$

$\phi_{\pi\pi}$

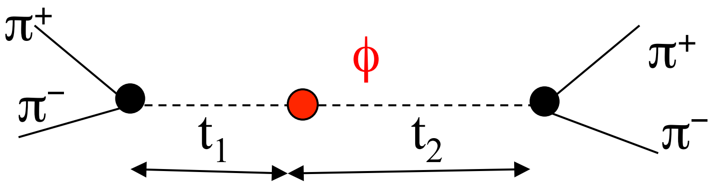
Prospects for KLOE-2 at upgraded DAΦNE

Param.	Present best published measurement	KLOE-2 $L=5\ fb^{-1}$	KLOE-2 $L=10\ fb^{-1}$	KLOE-2 $L=20\ fb^{-1}$
A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 2.7 \times 10^{-3}$	$\pm 1.9 \times 10^{-3}$	$\pm 1.4 \times 10^{-3}$
A_L	$(332.2 \pm 5.8 \pm 4.7) \times 10^{-5}$	$\pm 8.9 \times 10^{-5}$	$\pm 6.3 \times 10^{-5}$	$\pm 4.5 \times 10^{-5}$
$Re(\varepsilon'/\varepsilon)$	$(1.65 \pm 0.26) \times 10^{-3}$ (*)	$\pm 0.72 \times 10^{-3}$	$\pm 0.51 \times 10^{-3}$	$\pm 0.36 \times 10^{-3}$
$Im(\varepsilon'/\varepsilon)$	$(-1.2 \pm 2.3) \times 10^{-3}$ (*)	$\pm 9.4 \times 10^{-3}$	$\pm 6.7 \times 10^{-3}$	$\pm 4.7 \times 10^{-3}$
$Re(\delta)+Re(x_-)$	$Re(\delta) = (0.25 \pm 0.23) \times 10^{-3}$ (*) $Re(x_-) = (-4.2 \pm 1.7) \times 10^{-3}$ (*)	$\pm 0.7 \times 10^{-3}$	$\pm 0.5 \times 10^{-3}$	$\pm 0.4 \times 10^{-3}$
$Im(\delta)+Im(x_+)$	$Im(\delta) = (-0.6 \pm 1.9) \times 10^{-5}$ (*) $Im(x_+) = (0.2 \pm 2.2) \times 10^{-3}$ (*)	$\pm 9 \times 10^{-3}$	$\pm 7 \times 10^{-3}$	$\pm 5 \times 10^{-3}$
Δm	$(5.288 \pm 0.043) \times 10^{9}\ s^{-1}$	$\pm 0.096 \times 10^{9}\ s^{-1}$	$\pm 0.068 \times 10^{9}\ s^{-1}$	$\pm 0.048 \times 10^{9}\ s^{-1}$

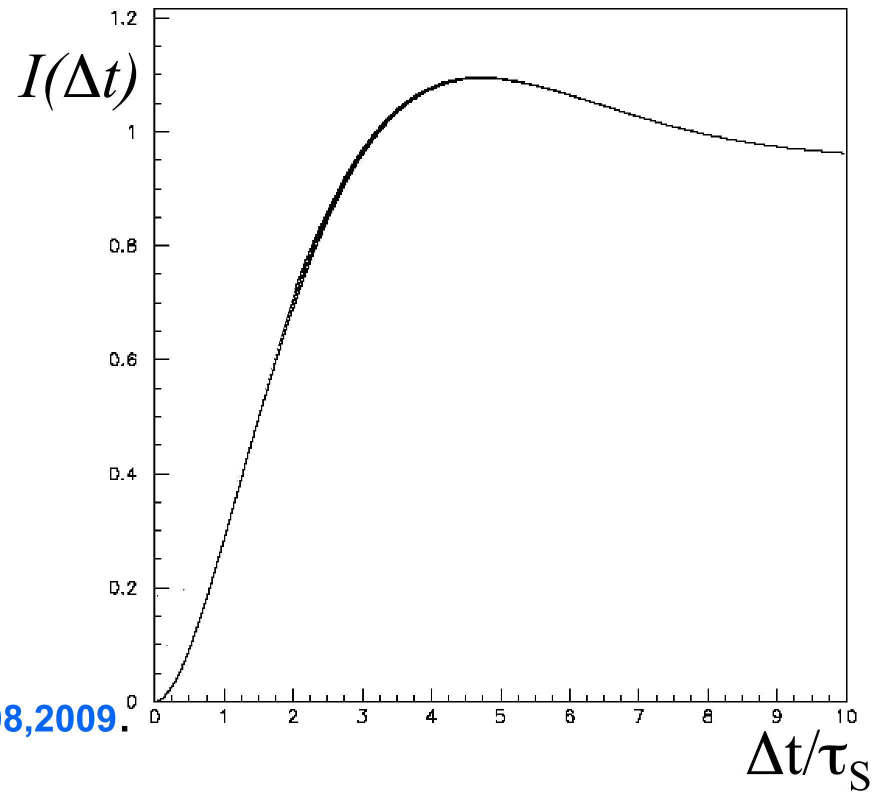
(*) = PDG 2010 fit

Neutral kaon interferometry: $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$



$\Delta t = |t_1 - t_2|$



Most precise test of quantum coherence in an entangled system:

$$\zeta_{0\bar{0}} = \left(1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}\right) \times 10^{-7}$$

ζ decoherence parameter (QM predicts $\zeta=0$)

PLB 642(2006) 315 L=1.5 fb^{-1} : J.Phys.Conf.Ser.171:012008,2009.

Quantum gravity effects might induce:

1)decoherence and CPT violation (at most $\gamma=O(m_K^2/M_{Planck})\sim 2\times10^{-20}$ GeV) →

$$\gamma = \left(0.7 \pm 1.2_{STAT} \pm 0.3_{SYST}\right) \times 10^{-21}\ \text{GeV}$$

2) decoherence and CPT violation induce modification of the initial correlation of the kaon pair (at most $\omega=O(m_K^2/M_{Planck}/\Delta\Gamma)\sim 1\times10^{-3}$) →

$$|i\rangle \propto \left(K^0\bar{K}^0 - K^0\bar{K}^0\right) + \omega\left(K^0\bar{K}^0 + K^0\bar{K}^0\right)$$

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

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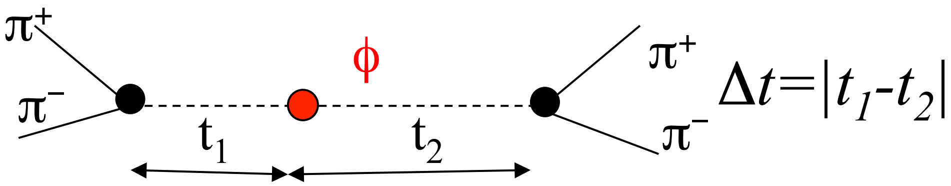

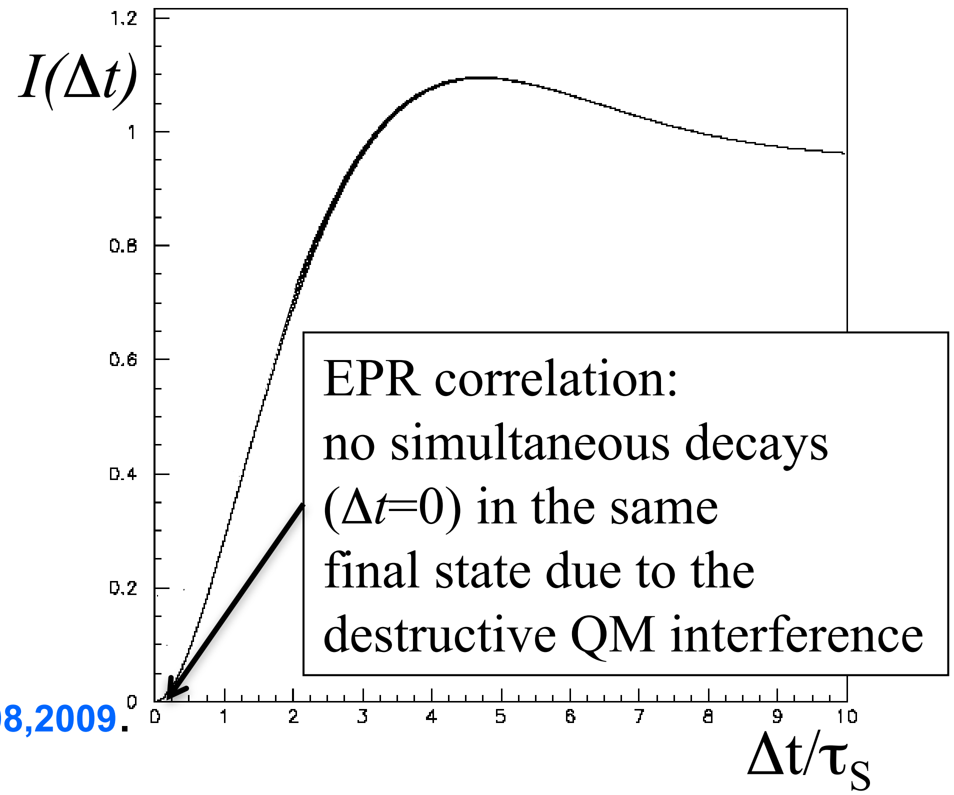

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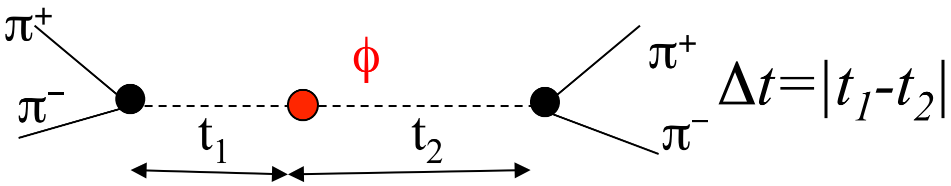

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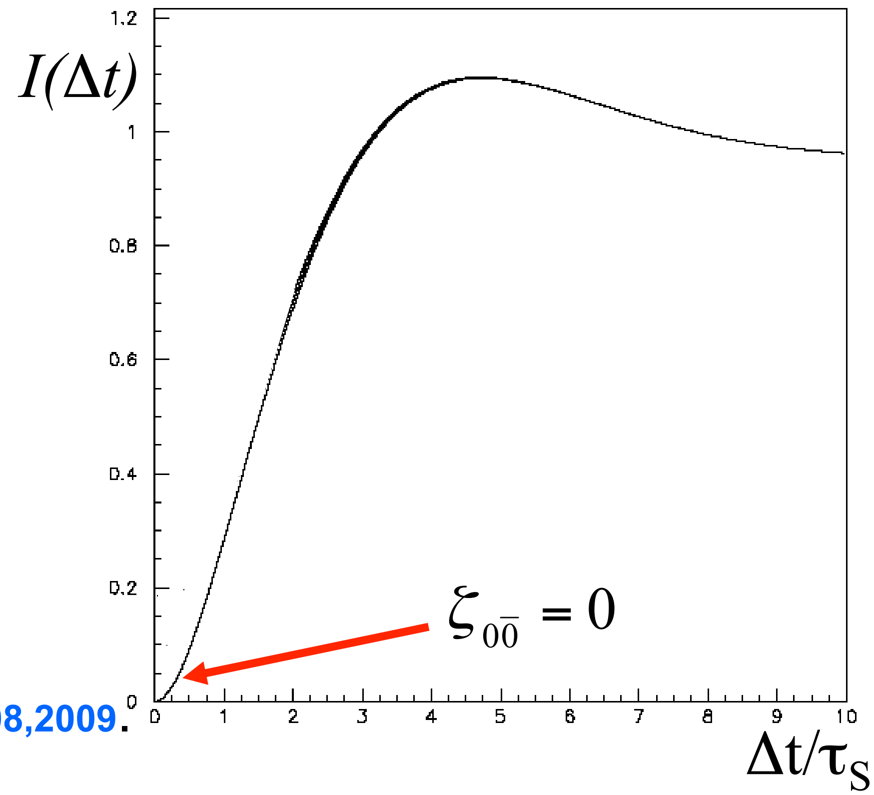

PLB 642(2006) 315 L=1.5 fb^{-1} : J.Phys.Conf.Ser.171:012008,2009.

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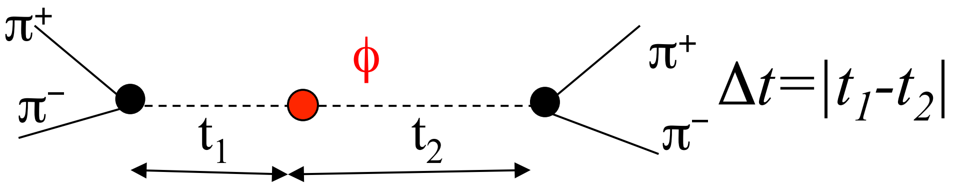

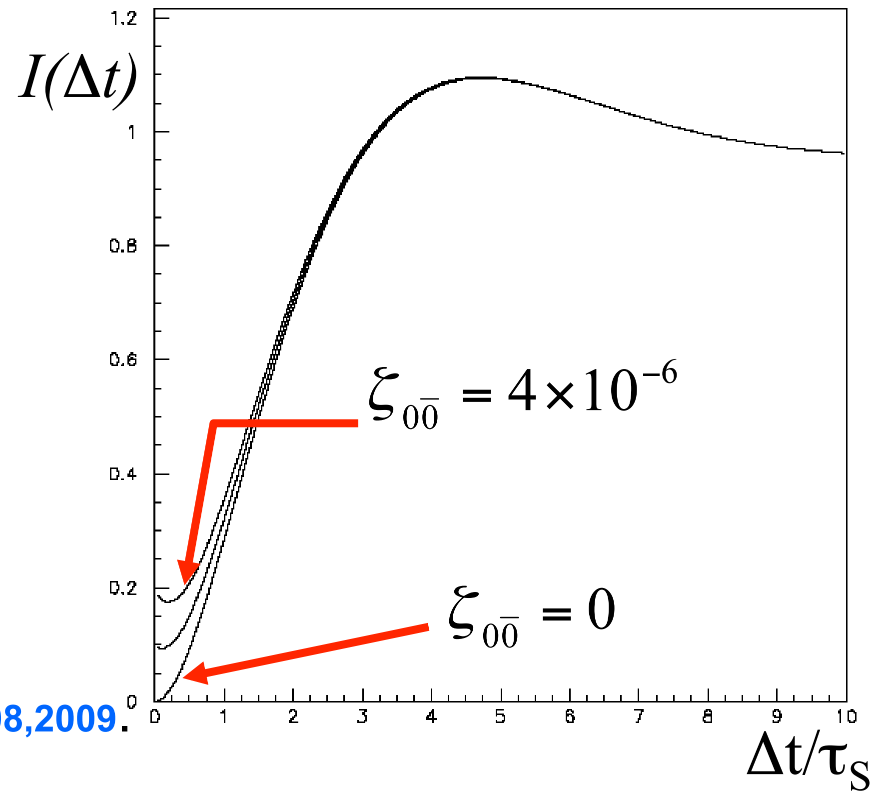

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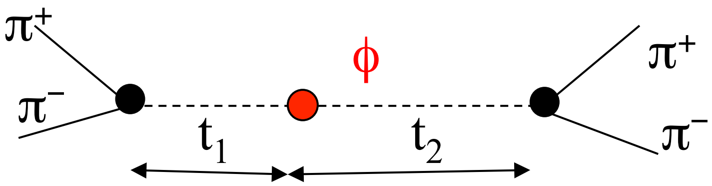

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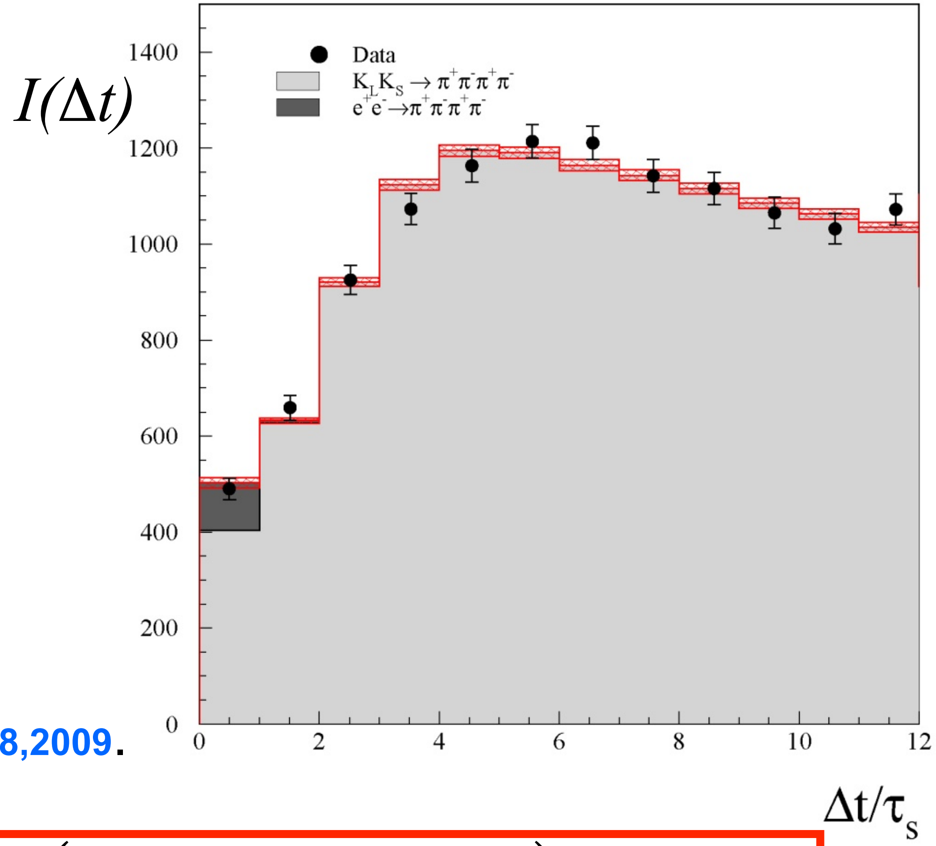

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CPT and Lorentz invariance violation (SME)

Kostelecky et al. developed a phenomenological effective model providing a framework for CPT and Lorentz violations, based on spontaneous breaking of CPT and Lorentz symmetry, which might happen in quantum gravity (e.g. in some models of string theory)

Standard Model Extension (SME) [Kostelecky PRD61, 016002, PRD64, 076001]

CPT violation in neutral kaons according to SME:

- CPTV only in mixing, not in decay, at first order (i.e. $B_I = y = x_- = 0$)
- δ cannot be a constant (momentum dependence)

$$\varepsilon_{S,L} = \varepsilon \pm \delta$$

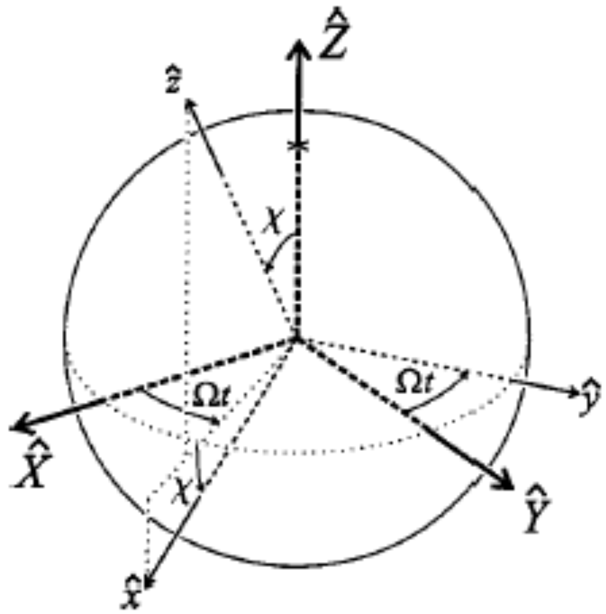
$$\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) / \Delta m$$

where Δa_μ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation.

CPT and Lorentz invariance violation (SME)

$$\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) / \Delta m$$

δ depends on sidereal time t since laboratory frame rotates with Earth.
For a ϕ-factory there is an additional dependence on the polar and azimuthal angle θ, ϕ of the kaon momentum in the laboratory frame:



(in general z lab. axis is non-normal to Earth's surface)

$$\bar{\delta}\left(|\vec{p}|, \theta, t\right) = \frac{1}{2\pi}\int_0^{2\pi} \delta\left(\vec{p}, t\right) d\phi$$

$$= \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \left[\underline{\Delta a_0} + \beta_K \underline{\Delta a_Z} \cos\chi\cos\theta + \beta_K \underline{\Delta a_Y} \sin\chi\cos\theta\sin\Omega t + \beta_K \underline{\Delta a_X} \sin\chi\cos\theta\cos\Omega t\right]$$

Ω: Earth's sidereal frequency
χ : angle between the z lab. axis and the Earth's rotation axis

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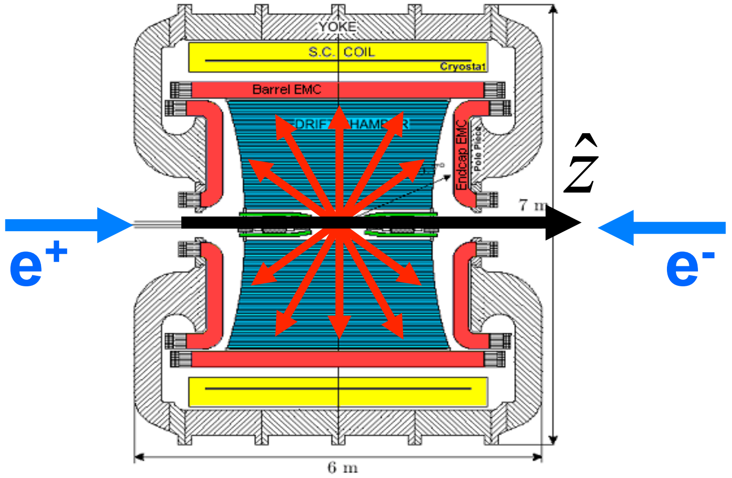
δ depends on sidereal time t since laboratory frame rotates with Earth.
For a ϕ-factory there is an additional dependence on the polar and azimuthal angle θ, ϕ of the kaon momentum in the laboratory frame:

At DAΦNE K mesons are produced with angular distribution $dN/d\Omega \propto \sin^2\theta$



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Ω: Earth's sidereal frequency
χ : angle between the z lab. axis and the Earth's rotation axis

Measurement of Δa_μ at KLOE

Δa_0 from $K_{S,L}$ semileptonic asymmetries $A_{S,L}$ (with symmetric polar angle θ and sidereal time t integration)

$$A_S - A_L \cong \frac{4\Re\left(i \sin\phi_{SW} e^{i\phi_{SW}}\right)\gamma_K}{\Delta m} \Delta a_0$$

with L=400 pb^{-1} (**preliminary**):

$$\Delta a_0 = (0.4 \pm 1.8) \times 10^{-17} \text{ GeV}$$

with L=2.5 fb^{-1} : $\sigma(\Delta a_0) \sim 7 \times 10^{-18}$ GeV

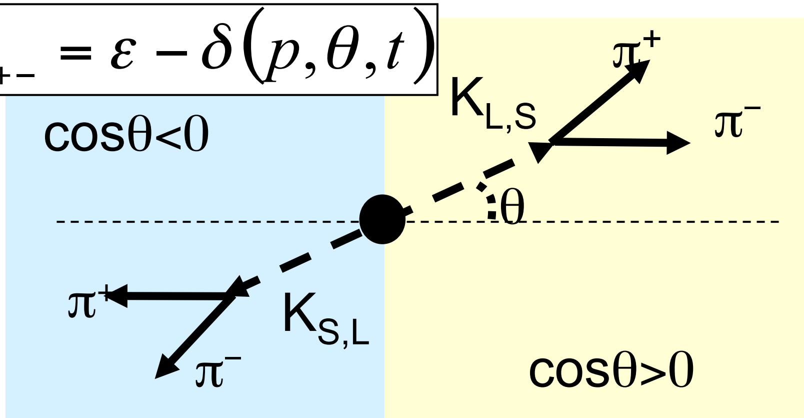
$\Delta a_{X,Y,Z}$ from $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

(analysis vs polar angle θ and sidereal time t)

Fit to: $I[\pi^+\pi^-(\cos\theta>0), \pi^+\pi^-(\cos\theta<0); \Delta t]$

- at $\Delta t \sim \tau_s$ sensitive to Im(δ/ε)

$$\eta_{+-} = \varepsilon - \delta(p, \theta, t)$$



With L=1 fb^{-1} (**preliminary**):

$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18} \text{ GeV}$$

KTeV : Δa_X, $\Delta a_Y < 9.2 \times 10^{-22}$ GeV @ 90% CL

BABAR $\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\, \Delta a^B_Z) \sim O(10^{-13}$ GeV)
[PRL 100 (2008) 131802]

Measurement of Δa_μ at KLOE

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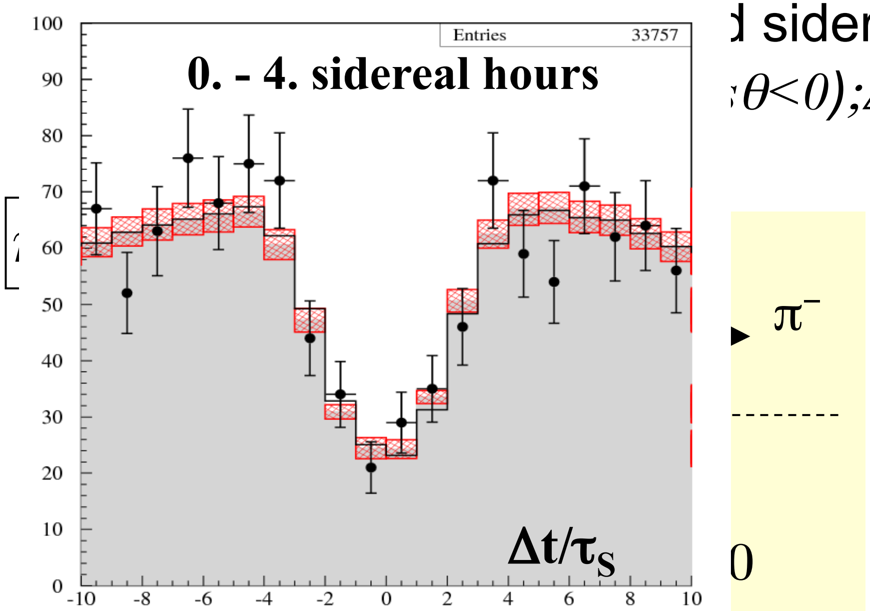
$\Delta a_{X,Y,Z}$ **from** $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

d sidereal time t)

θ<0);Δt]



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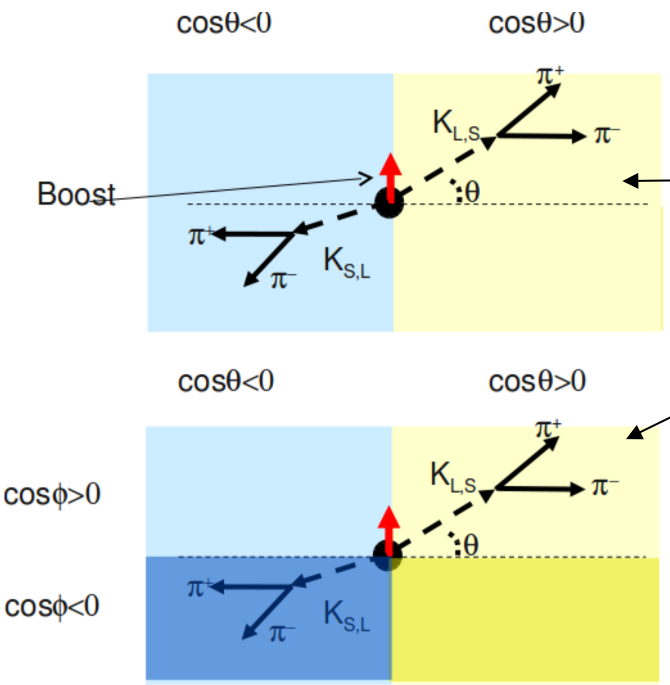
[PRL 100 (2008) 131802]

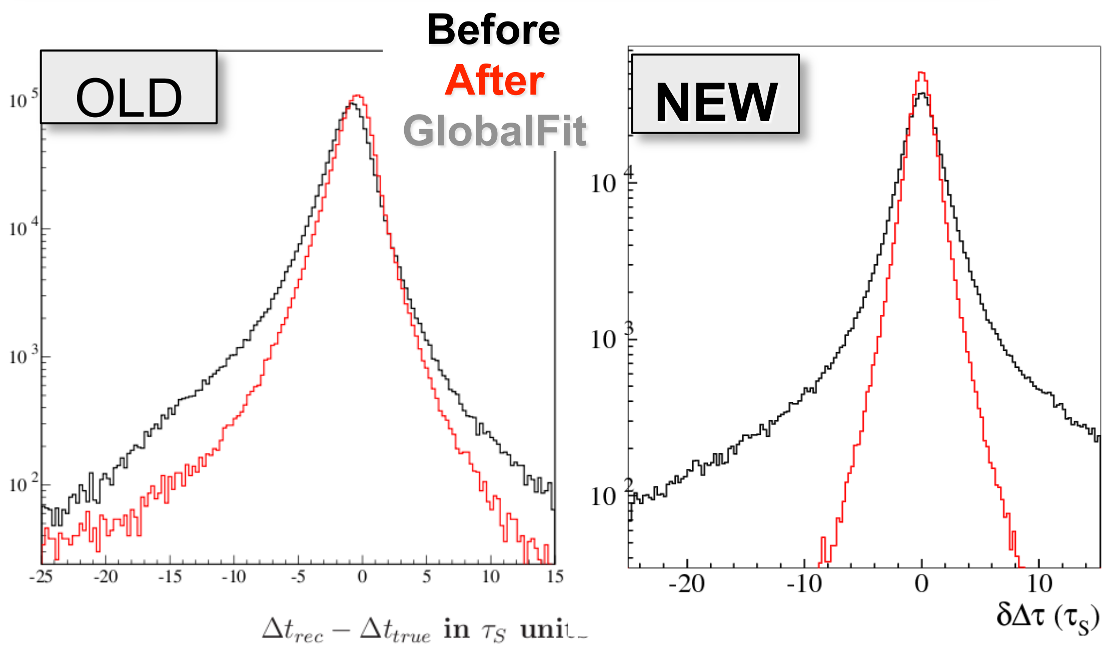
New method & refined techniques



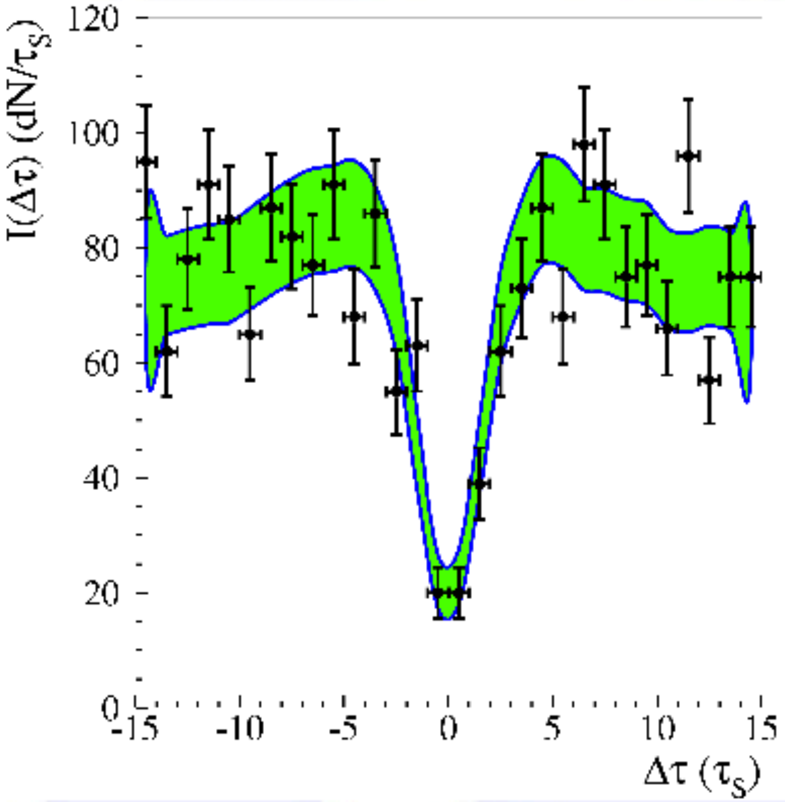
Possible effects due to $\Delta \mathbf{a}_0$ ($\sim\gamma_K$) are washed out in the old approach: forward ($\cos\theta>0$) - backward ($\cos\theta<0$) analysis.

New method exploiting the quadrant ($\cos\theta>0$ $\cos\phi>0$) -($\cos\theta<0$ $\cos\phi<0$) analysis is under way.
=> consistent and independent determination of all four $\Delta \mathbf{a}_\mu$

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



New method & refined techniques



Data are black points

Green band is the fit result

Statistical error only

Summary:
4 bins of sidereal time (times)
2 sample according to the direction of first kaon (times)
30 bin of $\Delta\tau$ (τ_S)

27 Mar 2012 A. De Santis – K2GM – CPT&Lorentz Invariance 24

Prospects for KLOE-2 at upgraded DAΦNE

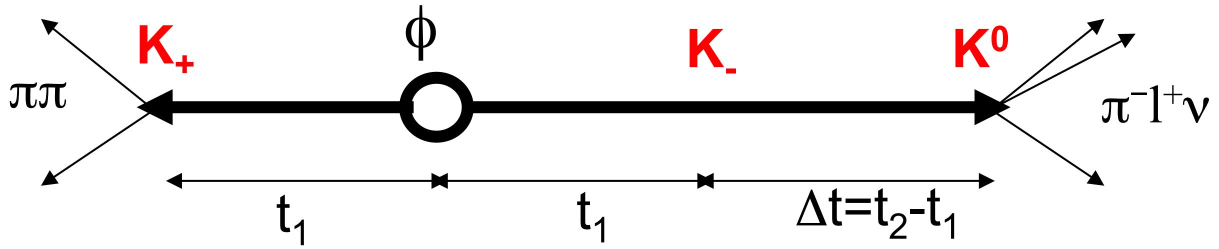
Param.	Present best published measurement	KLOE-2 (IT) $L=5\ fb^{-1}$	KLOE-2 (IT) $L=10\ fb^{-1}$	KLOE-2 (IT) $L=20\ fb^{-1}$
ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$	$\pm 0.13 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$	$\pm 0.35 \times 10^{-2}$	$\pm 0.25 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ GeV	$\pm 2.5 \times 10^{-17}$ GeV
β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.50 \times 10^{-19}$ GeV	$\pm 0.35 \times 10^{-19}$ GeV	$\pm 0.25 \times 10^{-19}$ GeV
γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV	$\pm 0.75 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.33 \times 10^{-21}$ GeV	$\pm 0.53 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.23 \times 10^{-21}$ GeV	$\pm 0.38 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.16 \times 10^{-21}$ GeV
Re(ω)	$(-1.6 \pm 2.6) \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$	$\pm 0.49 \times 10^{-4}$	$\pm 0.35 \times 10^{-4}$
Im(ω)	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$	$\pm 0.43 \times 10^{-4}$
Δa_0	[$(0.4 \pm 1.8) \times 10^{-17}$ GeV]	$\pm 0.52 \times 10^{-17}$ GeV	$\pm 0.36 \times 10^{-17}$ GeV	$\pm 0.26 \times 10^{-17}$ GeV
Δa_Z	[$(2.4 \pm 9.7) \times 10^{-18}$ GeV]	$\pm 2.2 \times 10^{-18}$ GeV	$\pm 1.5 \times 10^{-18}$ GeV	$\pm 1.1 \times 10^{-18}$ GeV
$\Delta a_{X,Y}$	[$<10^{-21}$ GeV]	$\pm 1.3 \times 10^{-18}$ GeV	$\pm 0.95 \times 10^{-18}$ GeV	$\pm 0.67 \times 10^{-18}$ GeV

[….] = preliminary

Direct test of Time Reversal symmetry with neutral kaons

- A direct evidence for T violation would mean an experiment that, considered by itself, clearly shows T violation INDEPENDENT and unconnected to the results for CP violation and CPT invariance (see Bernabeu's talk)

- The Kabir asymmetry $K^0 \to \bar{K}^0$ vs. $\bar{K}^0 \to K^0$ has been measured in CPLEAR with non-vanishing value. But $K^0 \to \bar{K}^0$ is a CPT-even transition, so $CP \equiv T$ in this case !
- EPR correlations at a ϕ-factory can be exploited to study other transitions involving also "CP states" K_+ and K_-



$$|i> = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+\rangle|K_-\rangle - |K_-\rangle|K_+\rangle\right]$$

$$I(\pi\pi, l^+; \Delta t) = C(\pi\pi, l^+) \times P[K_-(0) \to K^0(\Delta t)]$$

Direct test of Time Reversal symmetry with neutral kaons

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\bar{K}^0 \to K_-$	$(\ell^+, \pi^0\pi^0\pi^0)$	$K_- \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_+ \to K^0$	$(\pi^0\pi^0\pi^0, \ell^+)$	$K^0 \to K_+$	$(\ell^-, \pi\pi)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_- \to K^0$	$(\pi\pi, \ell^+)$	$K^0 \to K_-$	$(\ell^-, \pi\pi)$

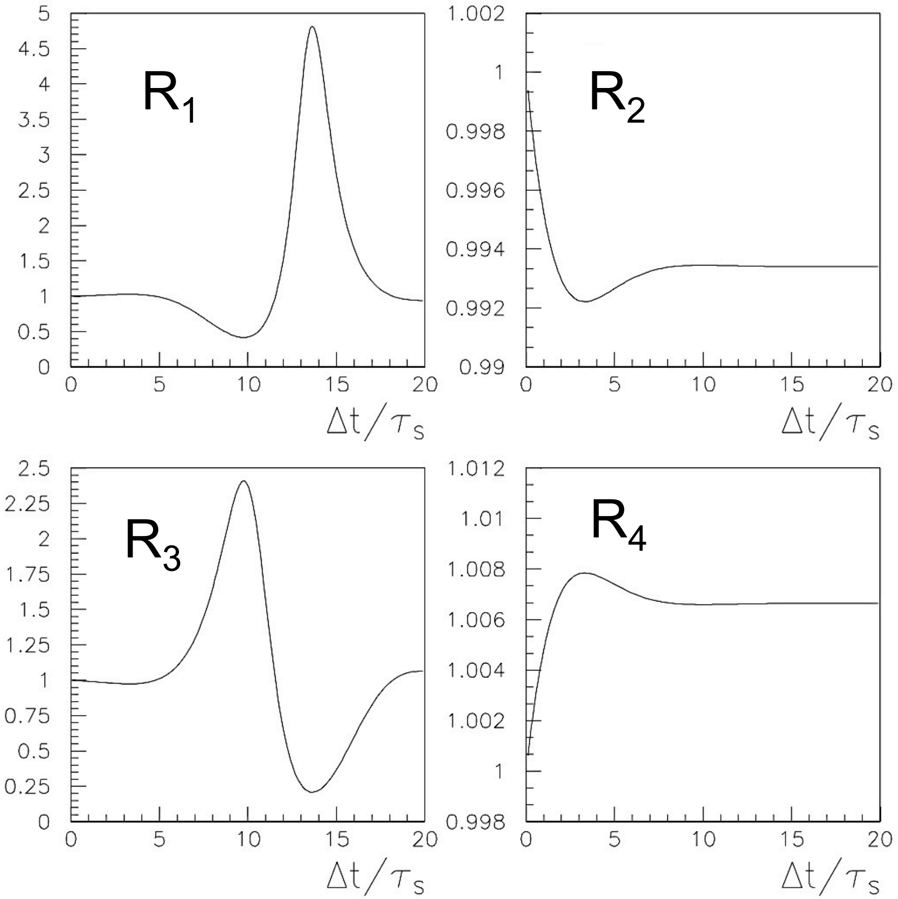
One can define the following ratios of probabilities:

$$
\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \ .
\end{aligned}
$$

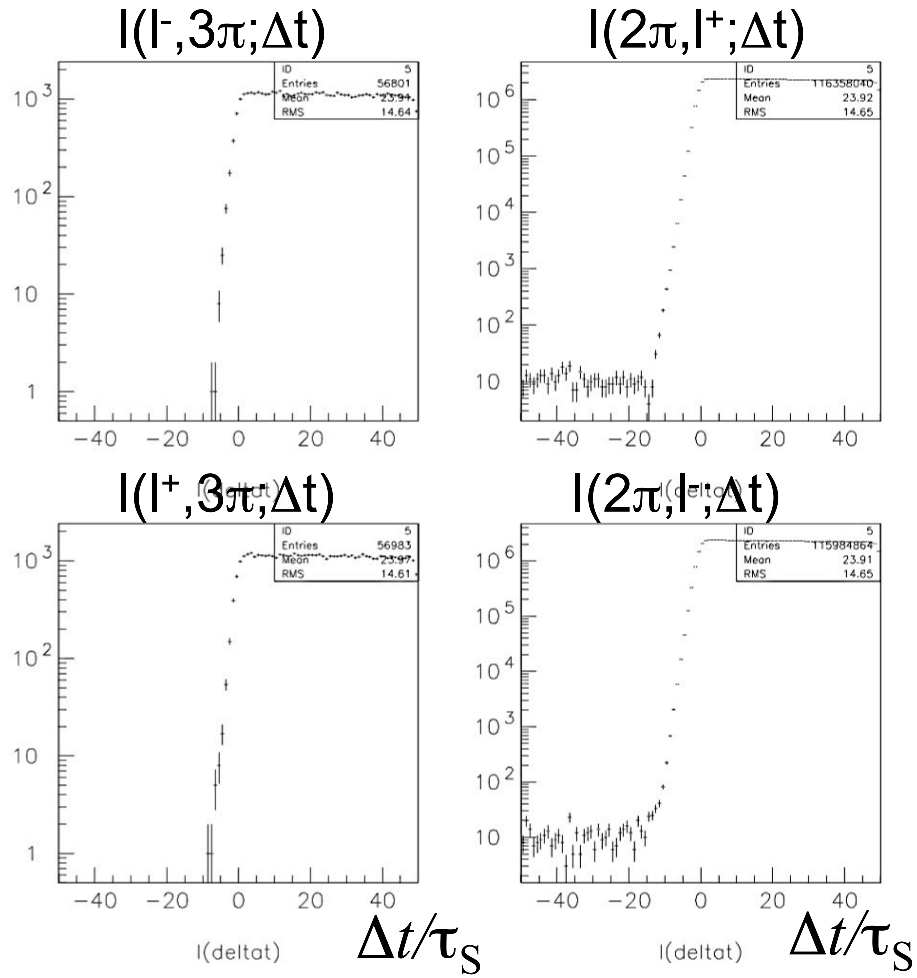
Any deviation from R_i=1 constitutes a violation of T-symmetry

(study with J. Bernabeu, P. Villanueva: in preparation)

Direct test of Time Reversal symmetry at KLOE-2



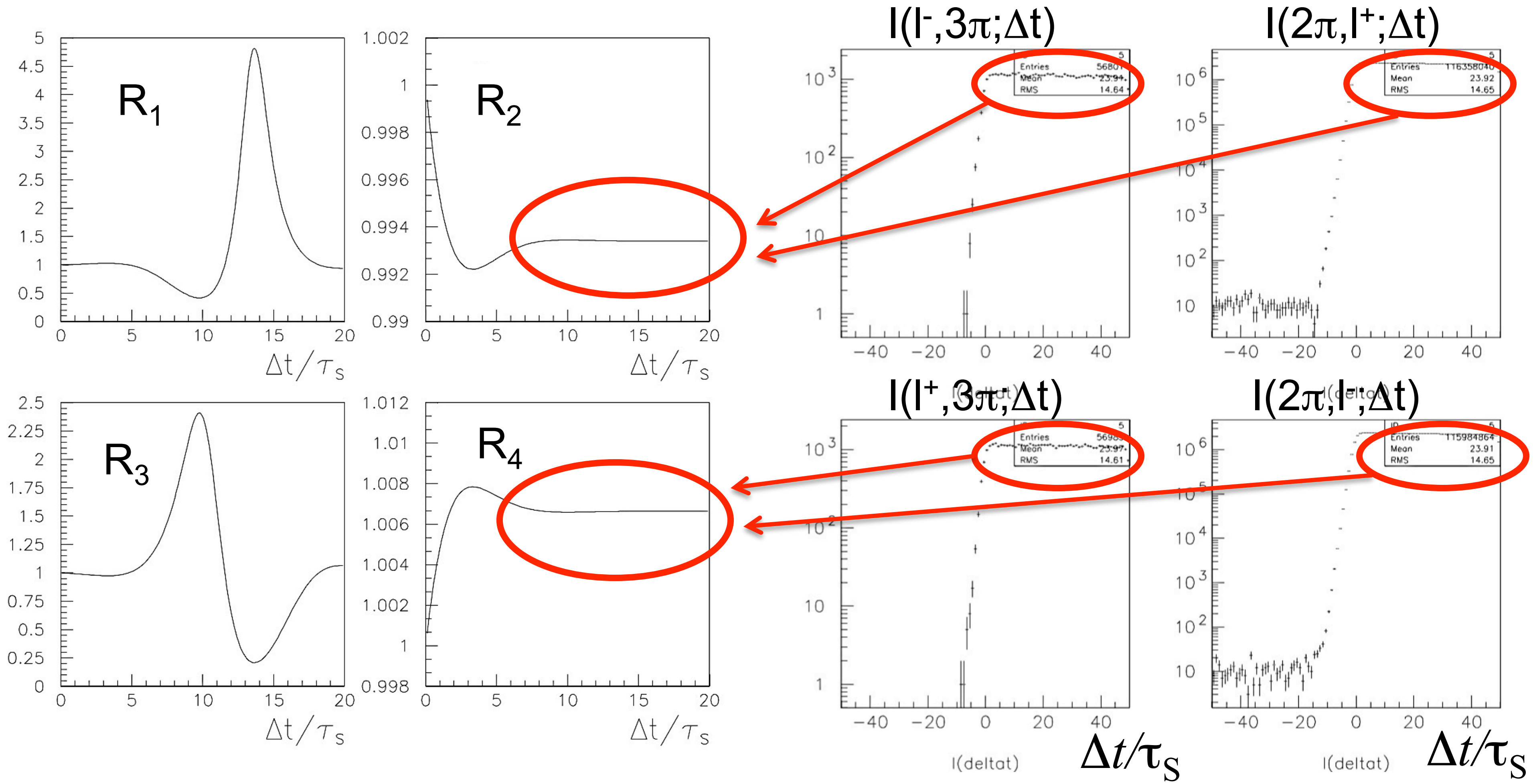
toy MC with L=10 fb^{-1}



measurement of $R_{2,4} \neq 1$ in the region $\Delta t >> \tau_S$ feasible at KLOE-2 with L=O(10 fb^{-1})

Direct test of Time Reversal symmetry at KLOE-2

toy MC with $L=10\ fb^{-1}$



measurement of $R_{2,4} \neq 1$ in the region $\Delta t >> \tau_S$ feasible at KLOE-2 with $L=O(10\ fb^{-1})$

Conclusions

•KLOE-2 physics program described in EPJC 68 (2010) 619-681

•Several interesting topics related directly or indirectly to flavor physics can be addressed by KLOE-2 at DAΦNE, e.g.:

- •$|V_{us}|$ and CKM unitarity
- •CP violation in the K_S sector
- •Light quark masses
- •Neutral kaon interferometry ("standard" CP and CPT observables and "non-standard" CPT violation and Lorentz symmetry breaking)
- •Direct time reversal test

•DAΦNE commissioning in progress
•KLOE detector fully operational
•KLOE-2 upgrades are being completed

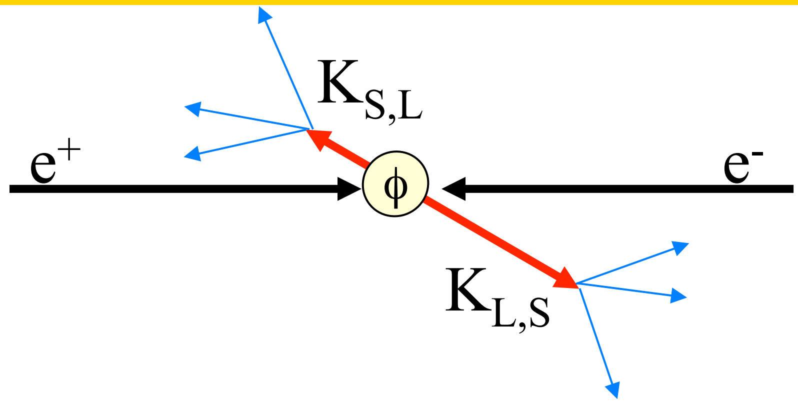
SPARE SLIDES

Neutral kaons at a ϕ-factory

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \to \phi$ $\quad \sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- $BR(\phi \to K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:

$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\quad \lambda_L = 3.5$ m

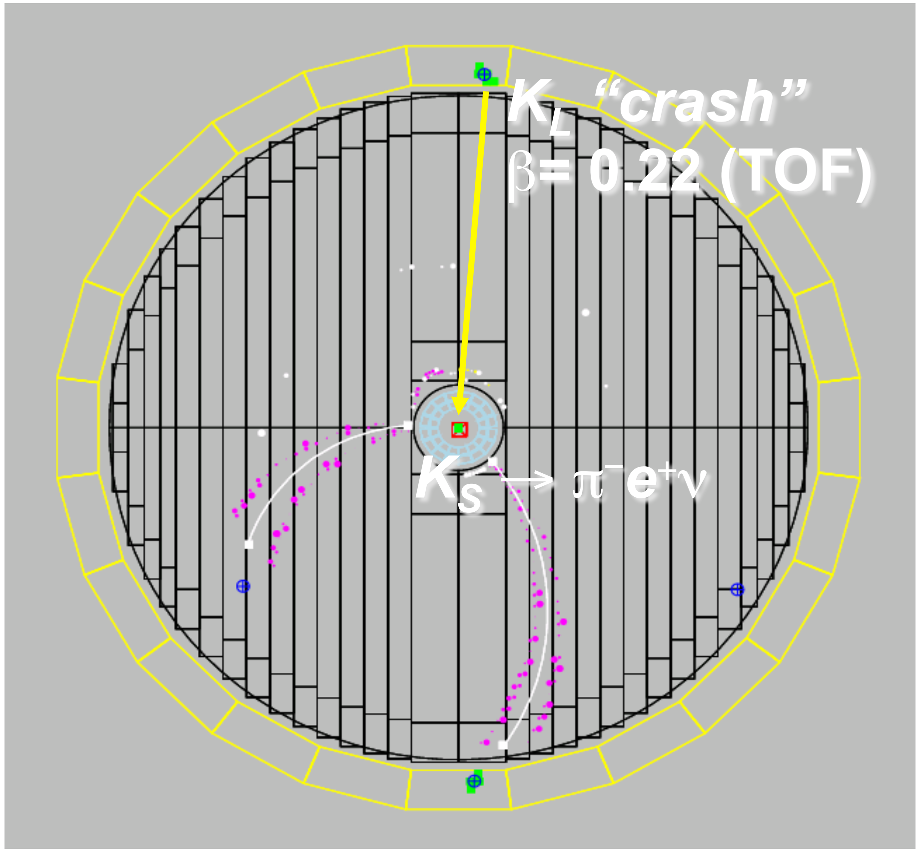


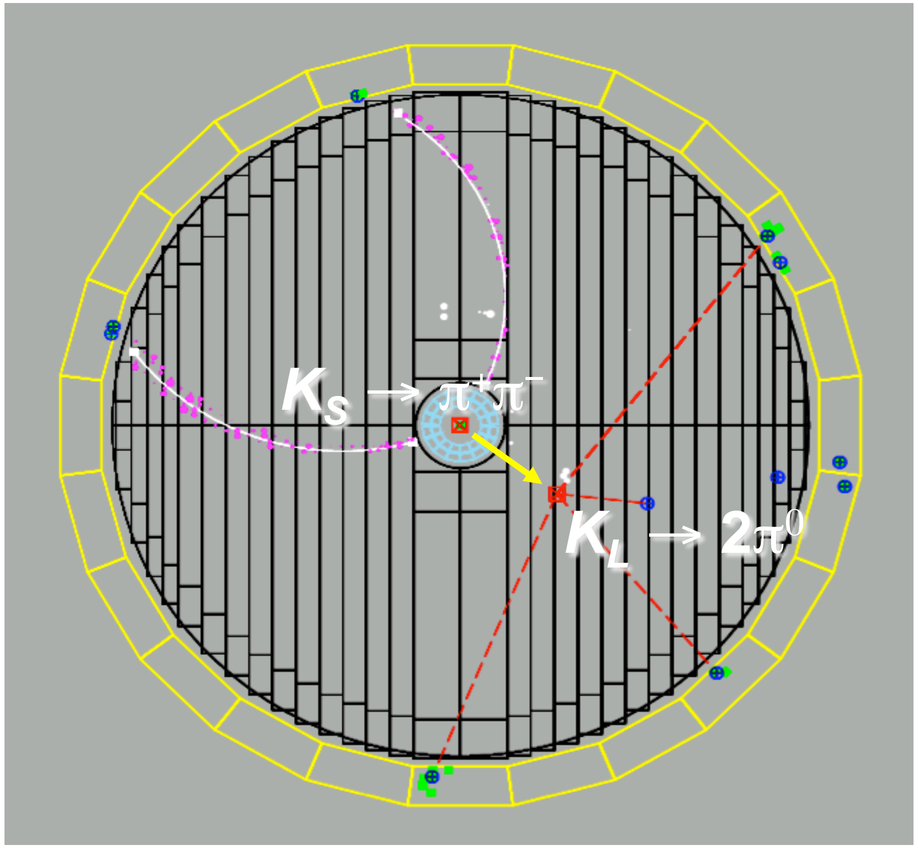
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

The detection of a kaon at large (small) times tags a K_S (K_L)
$\Rightarrow$ possibility to select a pure K_S beam (**unique** at a ϕ-factory, not possible at fixed target experiments)

K_S and K_L Tagging





***K_S* tagged by *K_L* interaction in EmC**

Efficiency ~ 30% (largely geometrical)

K_S angular resolution: ~ 1° (0.3° in ϕ)

K_S momentum resolution: ~ 2 MeV

***K_L* tagged by *K_S* $\rightarrow \pi^+\pi^-$ vertex at IP**

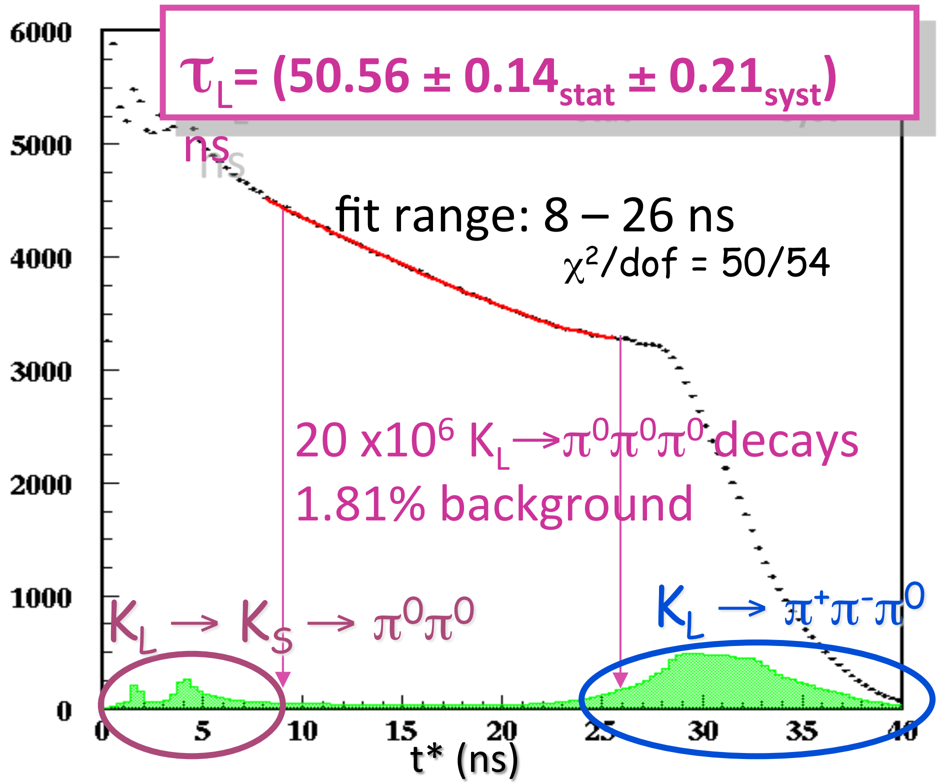
Efficiency ~ 70% (mainly geometrical)

K_L angular resolution: ~ 1°

K_L momentum resolution: ~ 2 MeV

Improving $K_{L,S}$ & $K^{\pm}$ lifetime: $\tau_{L,S}, \tau_{\pm}$

Preliminary result from L=1.1 fb^{-1}



i. 0.38% is expected with whole KLOE data
ii. 0.27% adding 5 fb^{-1} from KLOE-2/step-0
iii. < 0.2%. inserting QCALT improving photon reconstruction & control of the systematics

Systematic errors in KLOE are partially statistical in nature: efficiencies are measured with data control samples. Then also these contributions to the total uncertainty decrease with statistics

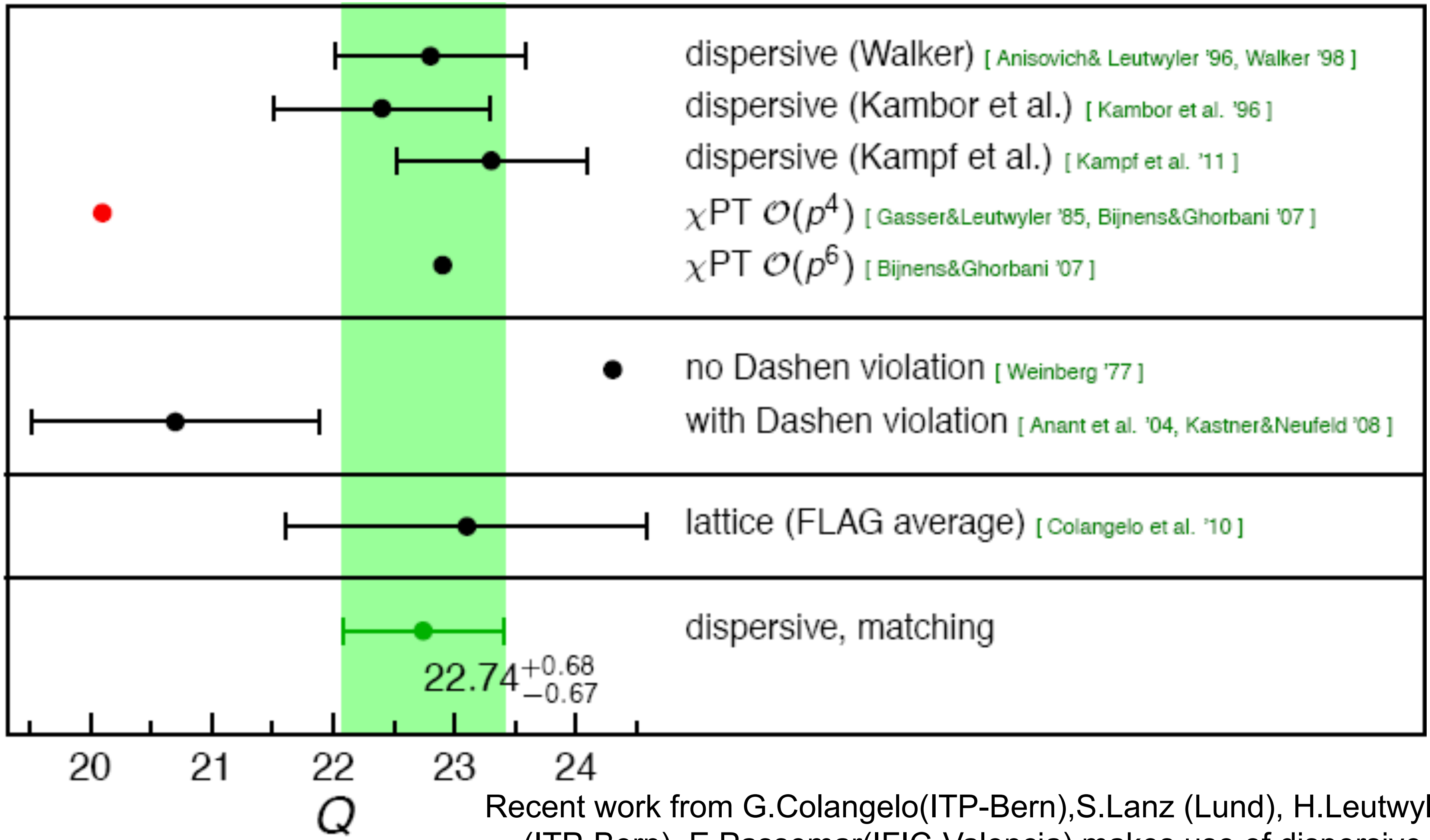
$\tau_{\pm}$

i. 0.1% is expected with KLOE + 5 fb^{-1} KLOE-2 /step-0
ii. x2 inserting Inner Tracker,allowing detection of $K^{\pm}$ tracks closer to the IP, improves accuracy of the decay length technique

τ_S

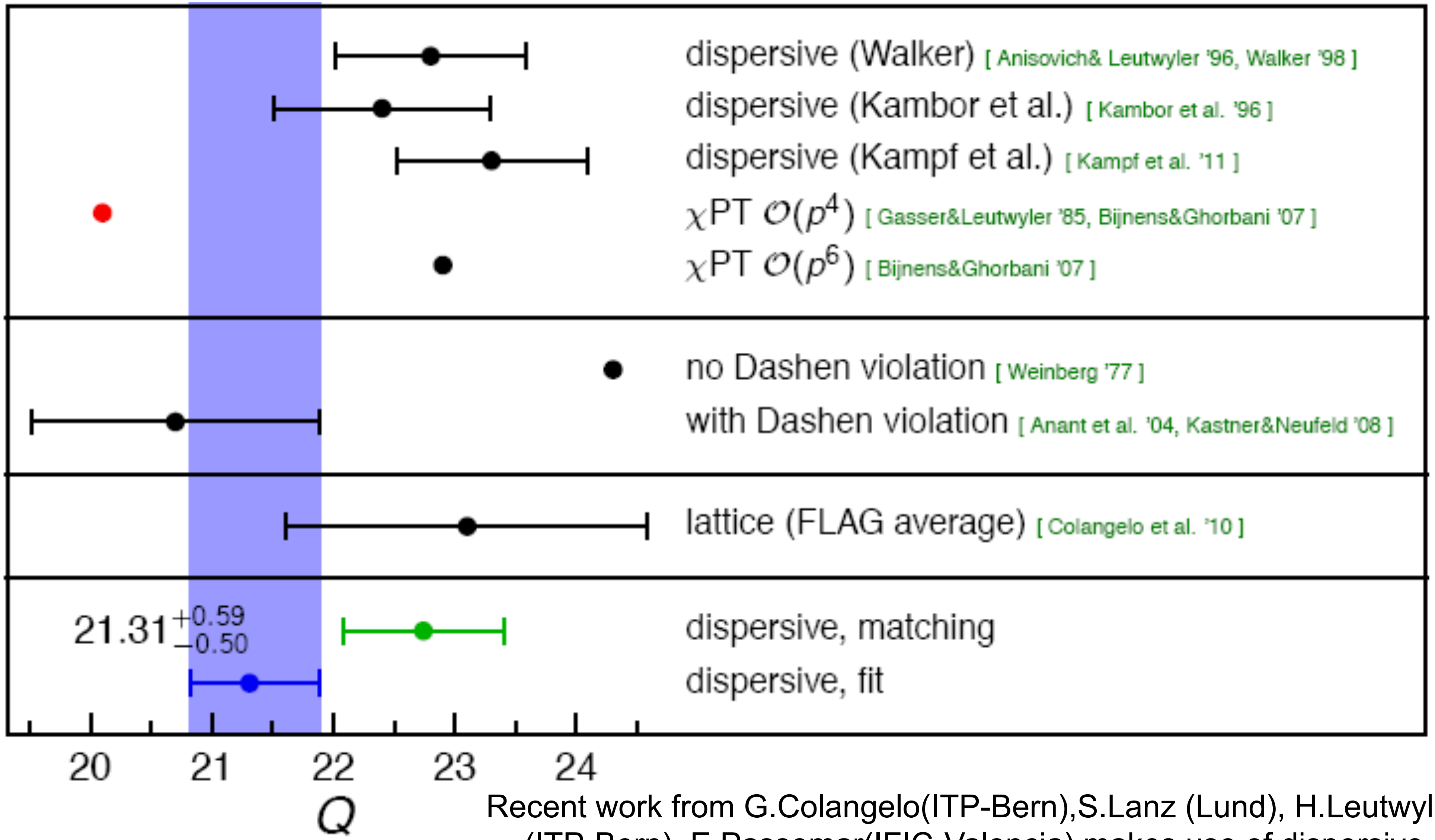
0.03% is expected adding 5 fb^{-1} from KLOE-2/step-0 .

$\eta \rightarrow \pi^+\pi^-\pi^0$: evaluation of Q



Recent work from G.Colangelo(ITP-Bern),S.Lanz (Lund), H.Leutwyler (ITP-Bern), E.Passemar(IFIC-Valencia) makes use of dispersive relations, effective to account for $\pi\pi$ re-scattering in the final state

$\eta \rightarrow \pi^+\pi^-\pi^0$: evaluation of Q



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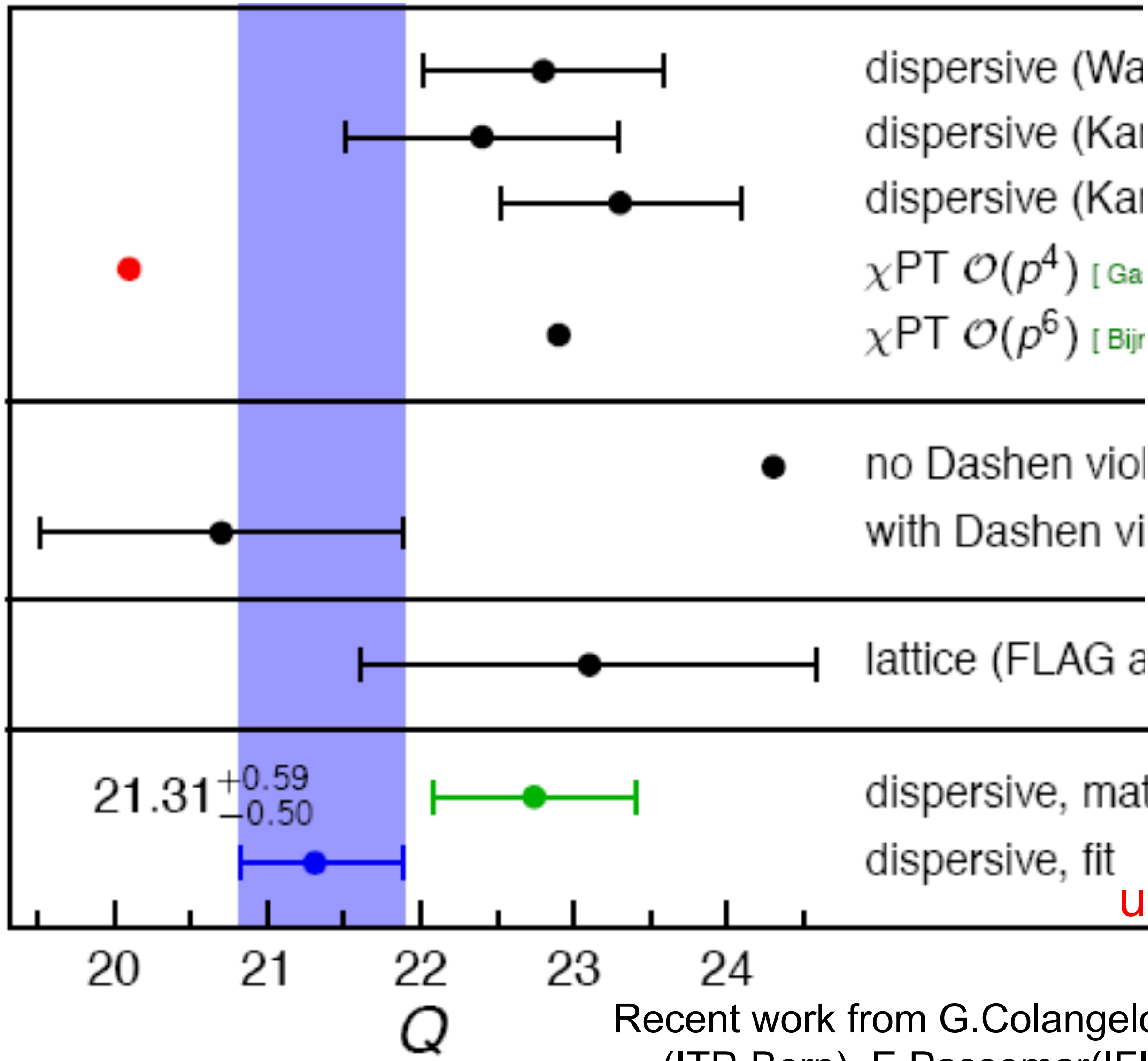

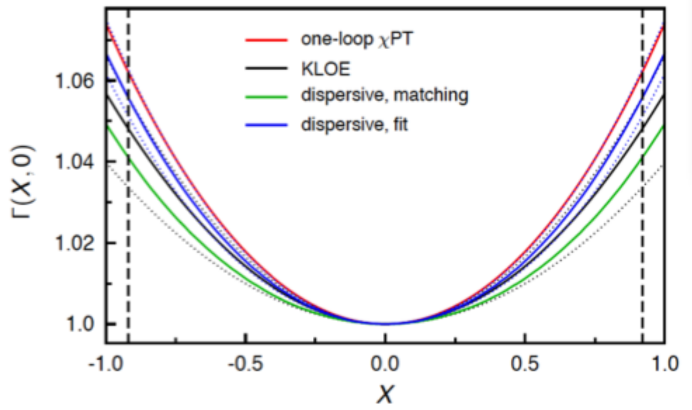

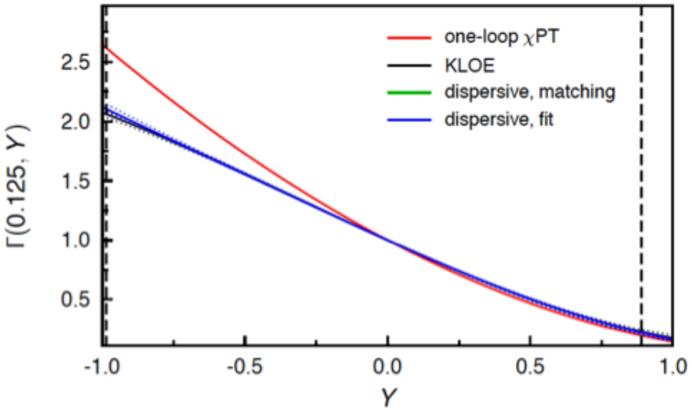

use of KLOE measurement of Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$

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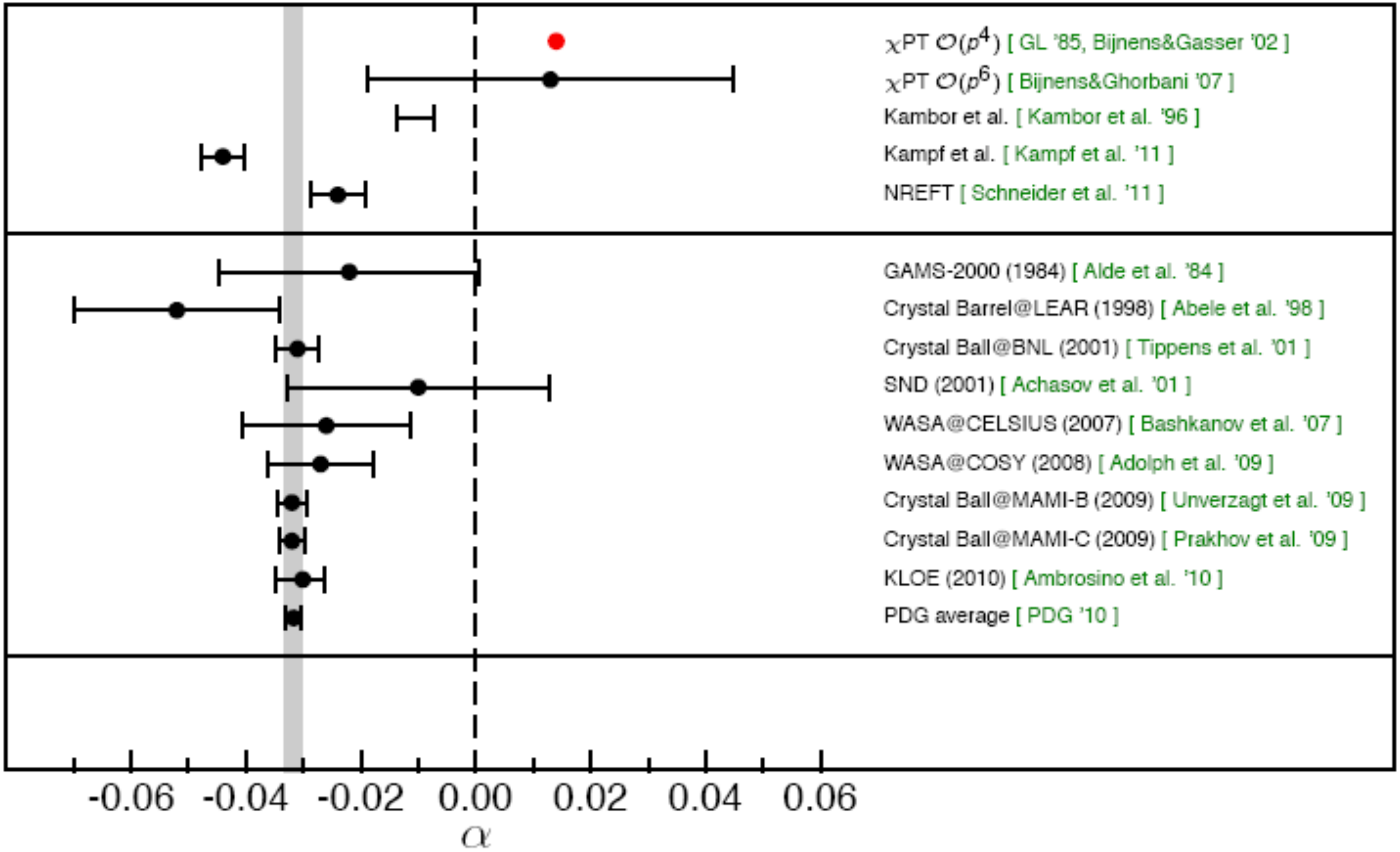
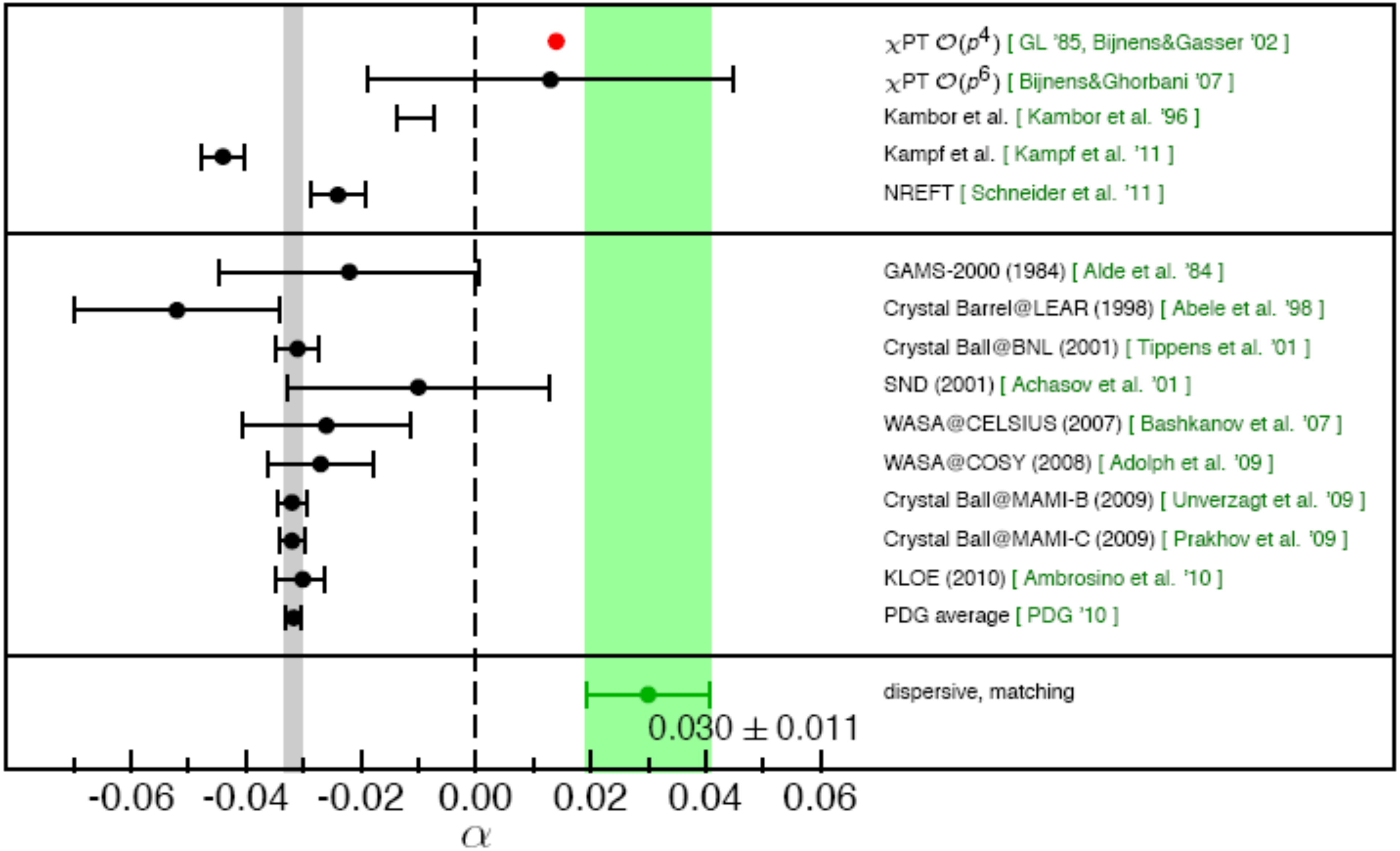
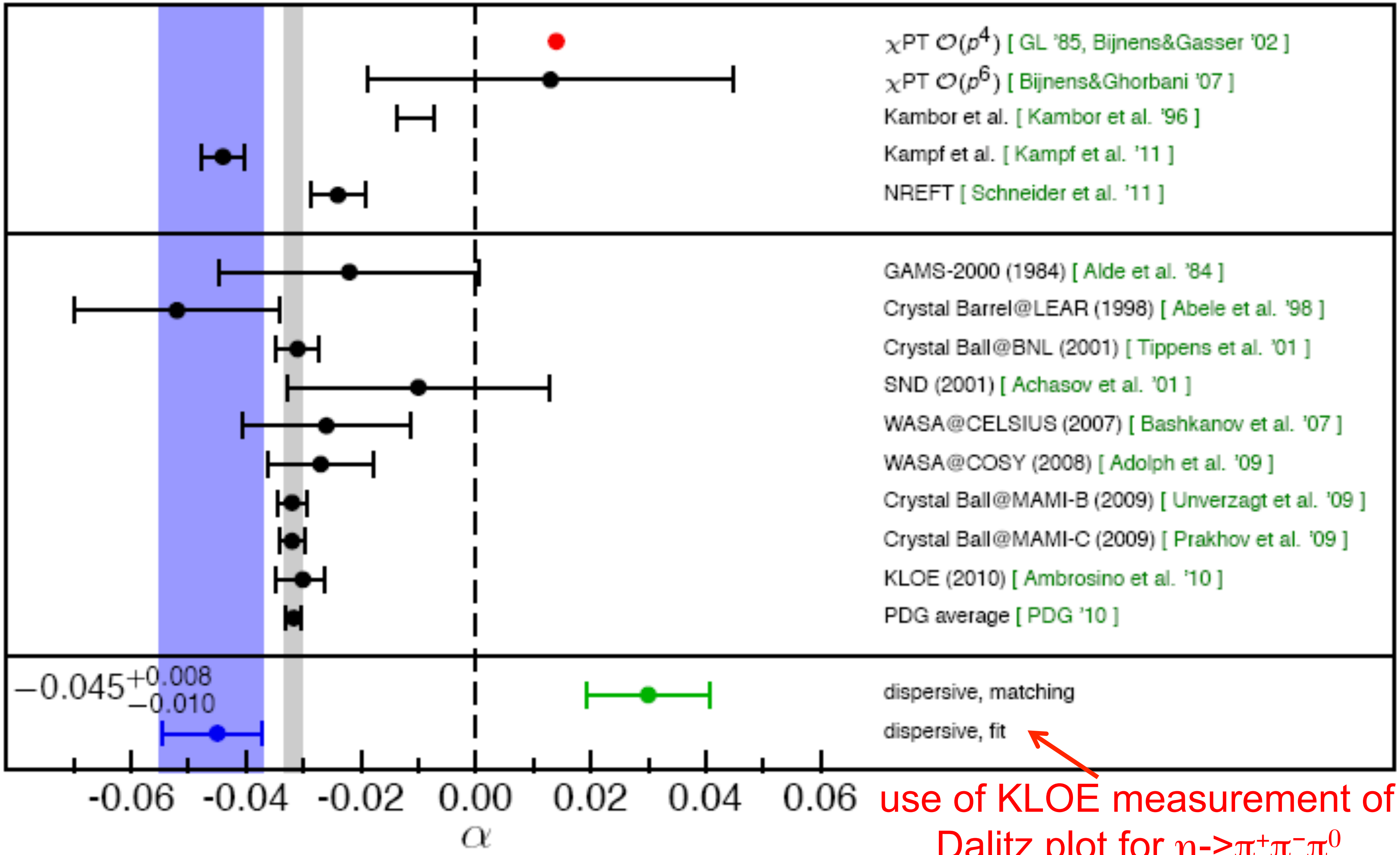
Results for $\eta \to \pi^0\pi^0\pi^0$: evaluation of α



Results for $\eta\rightarrow\pi^0\pi^0\pi^0$: evaluation of α

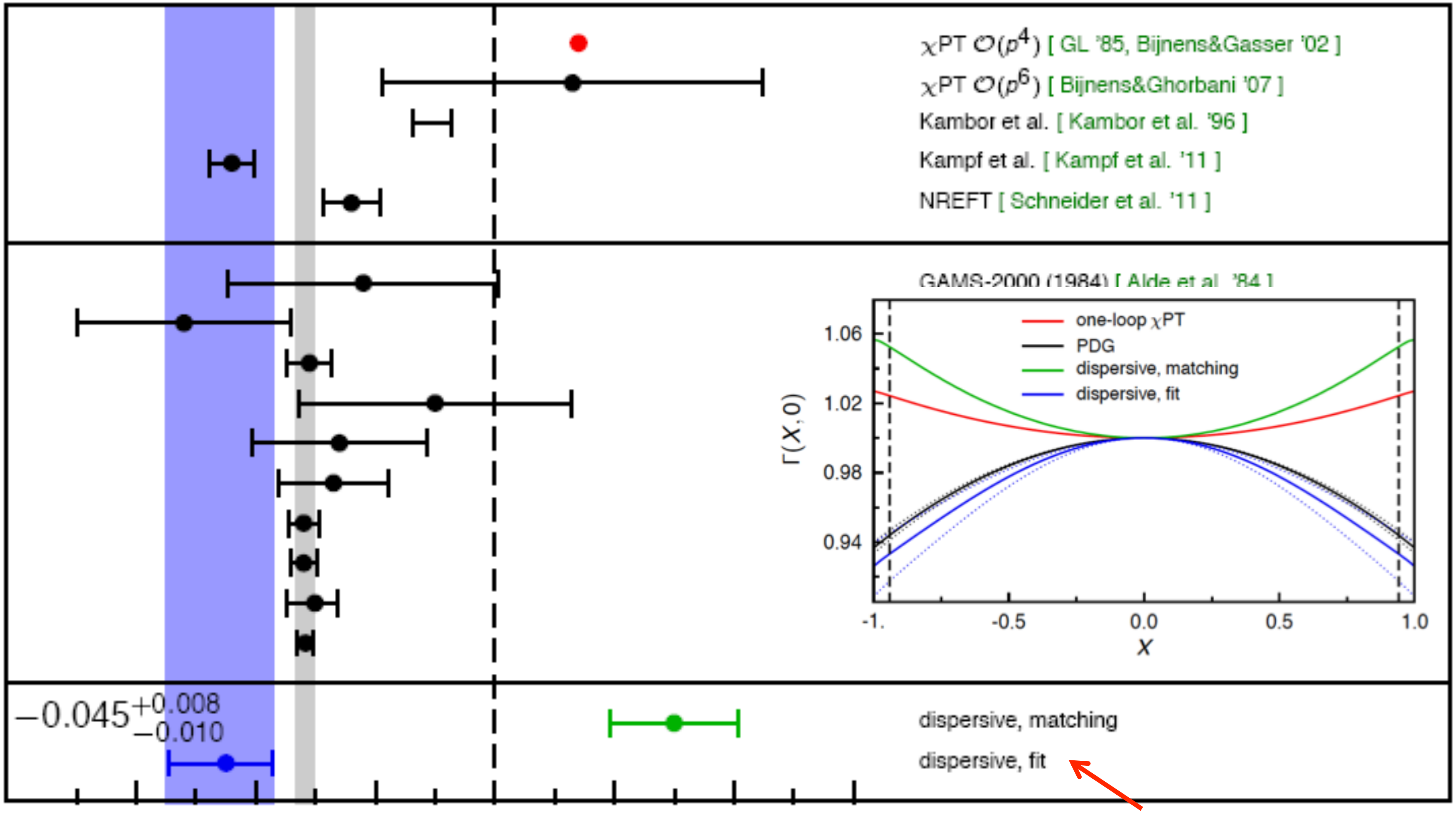


Results for $\eta \to \pi^0\pi^0\pi^0$: evaluation of α



use of KLOE measurement of Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$

Results for $\eta \rightarrow \pi^0\pi^0\pi^0$: evaluation of α

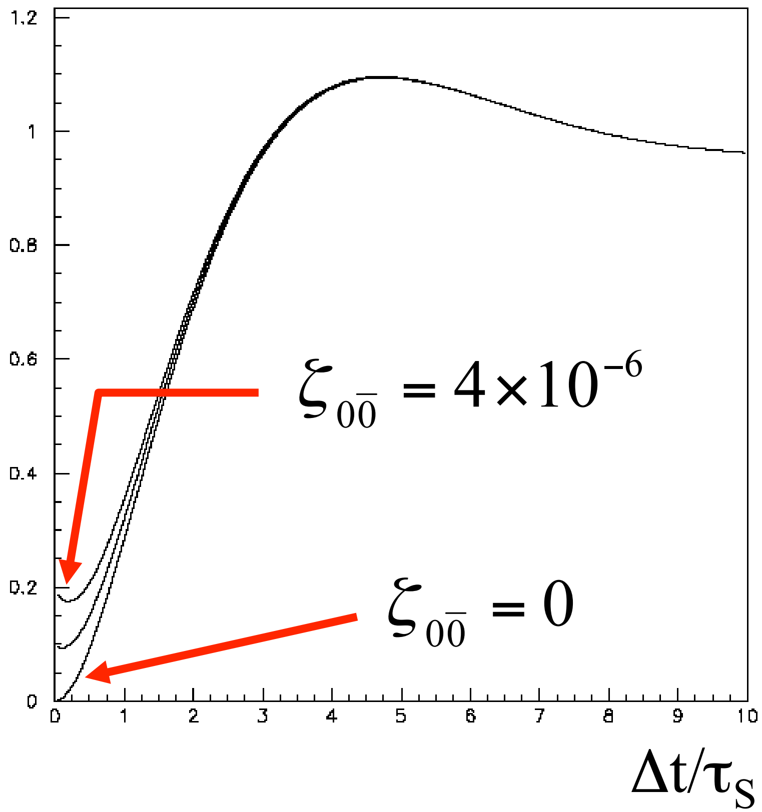


use of KLOE measurement of Dalitz plot for $\eta \text{->} \pi^+\pi^-\pi^0$

Interferometry at KLOE-2: $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

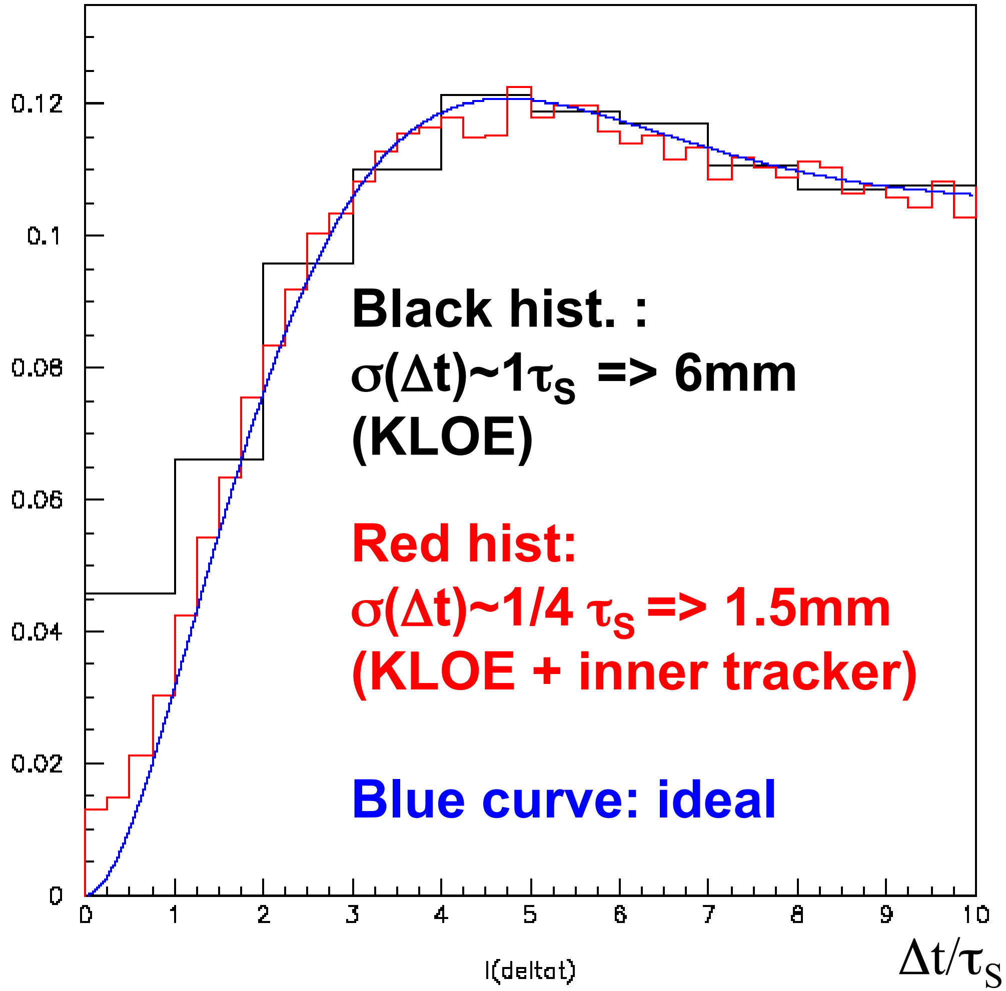
Possible signal of decoherence concentrated at very small Δt

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



Theoretical distribution

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



Reconstructed distribution (MC)

Prospects for KLOE-2 at upgraded DAΦNE

Param.	Present best published measurement	KLOE-2 (IT) $L=5\ fb^{-1}$	KLOE-2 (IT) $L=10\ fb^{-1}$	KLOE-2 (IT) $L=20\ fb^{-1}$
$\zeta_{0\bar{0}}$	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$	$\pm 0.13 \times 10^{-6}$
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α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ GeV	$\pm 2.5 \times 10^{-17}$ GeV
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γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV	$\pm 0.75 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.33 \times 10^{-21}$ GeV	$\pm 0.53 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.23 \times 10^{-21}$ GeV	$\pm 0.38 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.16 \times 10^{-21}$ GeV
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Im(ω)	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$	$\pm 0.43 \times 10^{-4}$
Δa_0	[$(0.4 \pm 1.8) \times 10^{-17}$ GeV]	$\pm 0.52 \times 10^{-17}$ GeV	$\pm 0.36 \times 10^{-17}$ GeV	$\pm 0.26 \times 10^{-17}$ GeV
Δa_Z	[$(2.4 \pm 9.7) \times 10^{-18}$ GeV]	$\pm 2.2 \times 10^{-18}$ GeV	$\pm 1.5 \times 10^{-18}$ GeV	$\pm 1.1 \times 10^{-18}$ GeV
$\Delta a_{X,Y}$	[$<10^{-21}$ GeV]	$\pm 1.3 \times 10^{-18}$ GeV	$\pm 0.95 \times 10^{-18}$ GeV	$\pm 0.67 \times 10^{-18}$ GeV

[….] = preliminary