

JAGIELLONIAN UNIVERSITY
IN KRAKOW



Overview of **KLOE results on kaon physics and KLOE-2 perspectives**

Eryk Czerwiński on behalf of the KLOE-2 Collaboration

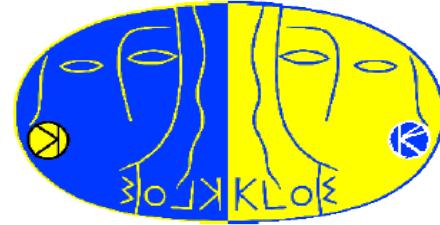
KLOE-2 Workshop on e+e- collision physics at 1 GeV

Frascati, October 26-28, 2016



NATIONAL SCIENCE CENTRE
POLAND

Outline



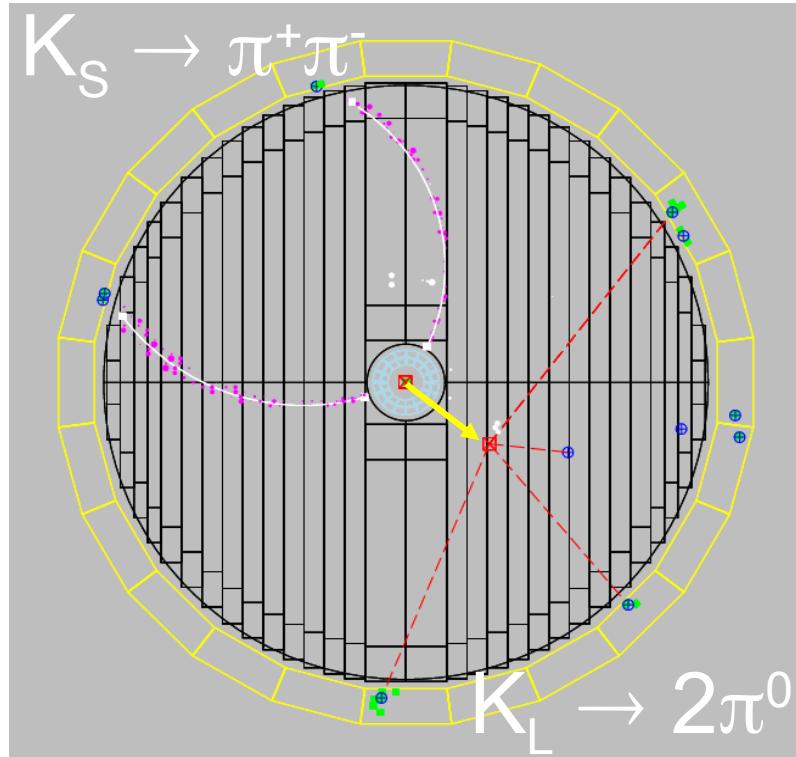
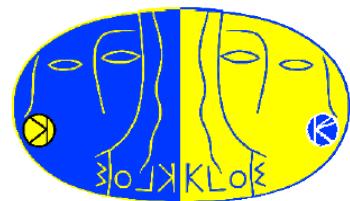
CKM matrix

Charge asymmetry of K_s

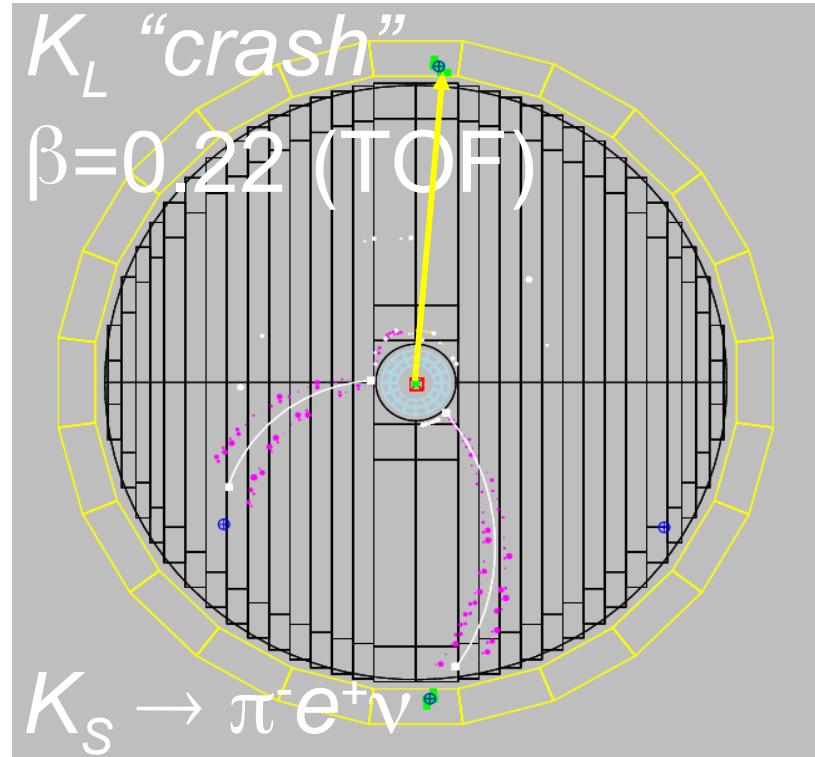
Rare K_s decays

Quantum Mechanics and CPT symmetry tests

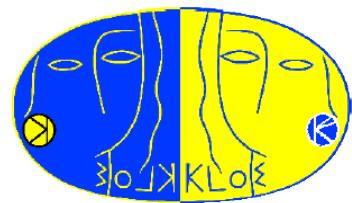
Neutral kaons beams



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



K_S tagged by
 K_L interaction in EmC



CKM unitarity

The most precise test of CKM unitarity by $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

$|V_{ud}|$ from superallowed β decay, $|V_{ub}|$ negligible ($\sim 10^{-5}$),
 $|V_{us}|$ from the measurements of the semileptonic decay rates

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{Kl}(\{\lambda\}_{Kl}) (1 + 2\Delta_K^{SU(2)} + 2\Delta_{Kl}^{EM})$$

with $K \in \{K^+, K^0\}$; $l \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+ , 1 for K^0

Inputs from theory:

S_{EW} Universal short distance EW correction (1.0232)

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element at zero momentum transfer ($t=0$)

$\Delta_K^{SU(2)}$ Form factor correction for strong SU(2) breaking

Δ_{Kl}^{EM} Long distance EM effects

Inputs from experiment:

$\Gamma(K_{l3(\gamma)})$ Branching ratios with well determined treatment of radiative decays; lifetimes

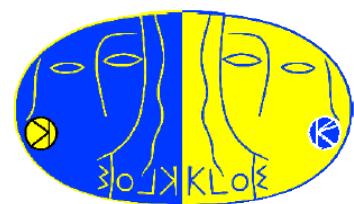
$I_{Kl}(\lambda)$ Phase space integral: λ s parameterize form factor dependence on t :

K_{e3} : only λ_+ (or $\lambda_+', \lambda_''$)

$K_{\mu 3}$: need λ_+ and λ_0

KLOE has measured all relevant inputs for charged and neutral kaons:

BR's, lifetimes (K_L, K^\pm), form factors (FFs)



V_{us} from neutral kaons

$BR(K_{e3}) = 0.4008(15)$ $BR(K_{\mu 3}) = 0.2699(14)$	Based on $13 \times 10^6 K_L$ decays tagged by $K_s \rightarrow \pi^+ \pi^-$	PLB 632 (2006)
$\tau_L = 50.92(30) \text{ ns}$	Fit the time dependence over $0.4\tau_L$ of $8.5 \times 10^6 K_L \rightarrow \pi^0 \pi^0 \pi^0$ decays tagged by $K_s \rightarrow \pi^+ \pi^-$	PLB 626 (2005)
$\lambda_+' = (25.5 \pm 1.8) \times 10^{-3}$ $\lambda_+'' = (-1.4 \pm 0.8) \times 10^{-3}$	Based on $2 \times 10^6 K_L e3$ decays tagged by $K_s \rightarrow \pi^+ \pi^-$	PLB 636 (2006)
$BR(K_s \rightarrow \pi e \nu) = 7.046(91) \times 10^{-4}$	From tagged K_s beam 1.2×10^8 events (20% of full data sample)	PLB 636 (2006)
$\lambda_+' = (25.6 \pm 1.5_{\text{stat}} \pm 0.9_{\text{syst}}) \times 10^{-3}$ $\lambda_+'' = (-1.5 \pm 0.7_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}$ $\lambda_0 = (15.4 \pm 1.8_{\text{stat}} \pm 1.3_{\text{syst}}) \times 10^{-3}$	Based on $1.8 \times 10^6 K_L \mu 3$ decays tagged by $K_s \rightarrow \pi^+ \pi^-$ and from combined fit with $K_L e3$ data	JHEP 12 (2007)



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

Present total error:

- value from KLOE	0.28%	<i>JHEP 0804 (2008) 059</i>
- world average	0.19%	

Expected at KLOE-2 with 5fb^{-1} 0.14% with world average

World average
M.Moulson
at CKM14

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

	$f_+(0) V_{us} $	%err	BR	τ	δ	I_{KI}	%err	BR	τ	δ	I_{KI}
$K_L e3$	0.2163(6)	0.26	0.09	0.20	0.11	0.05	0.20	0.09	0.13	0.11	0.06
$K_L \mu 3$	0.2166(6)	0.28	0.15	0.18	0.11	0.06	0.24	0.15	0.13	0.11	0.08
$K_S e3$	0.2155(13)	0.61	0.60	0.02	0.11	0.05	0.32	0.30	0.03	0.11	0.06
$K^\pm e3$	0.2172(8)	0.36	0.27	0.06	0.23	0.05	0.48	0.25	0.05	0.40	0.06
$K^\pm \mu 3$	0.2170(11)	0.51	0.45	0.06	0.23	0.06	0.48	0.27	0.05	0.39	0.08
Aver	0.2165(4)	0.19					0.14				

Charge asymmetry test for K_S

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

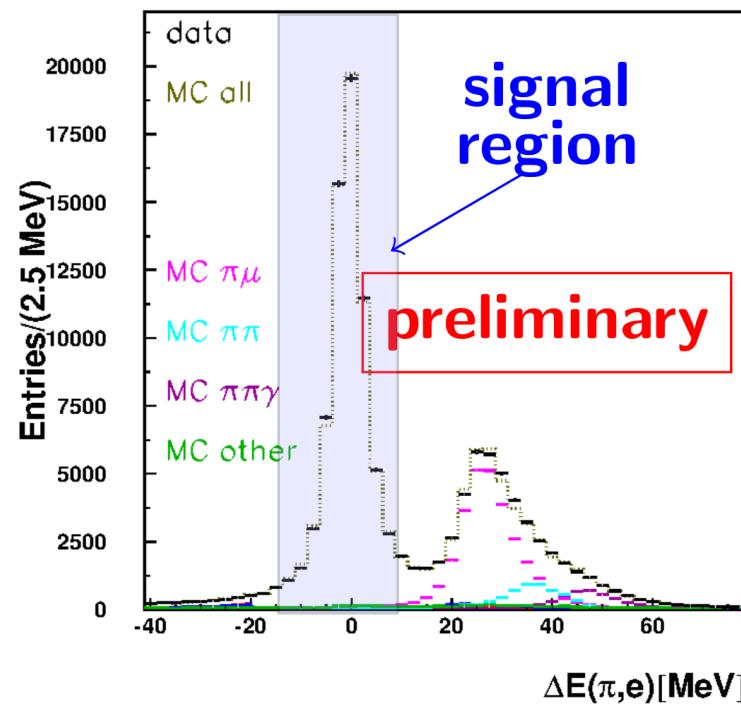
Assuming CPT invariance: $A_S = A_L = 2R\text{e}(\varepsilon_K) \approx 3 \times 10^{-3}$

$A_L = (3.332 \pm 0.058_{\text{stat}} \pm 0.047_{\text{syst}}) \times 10^{-3}$ KTeV collaboration, Phys. Rev. Lett. 88 (2002)

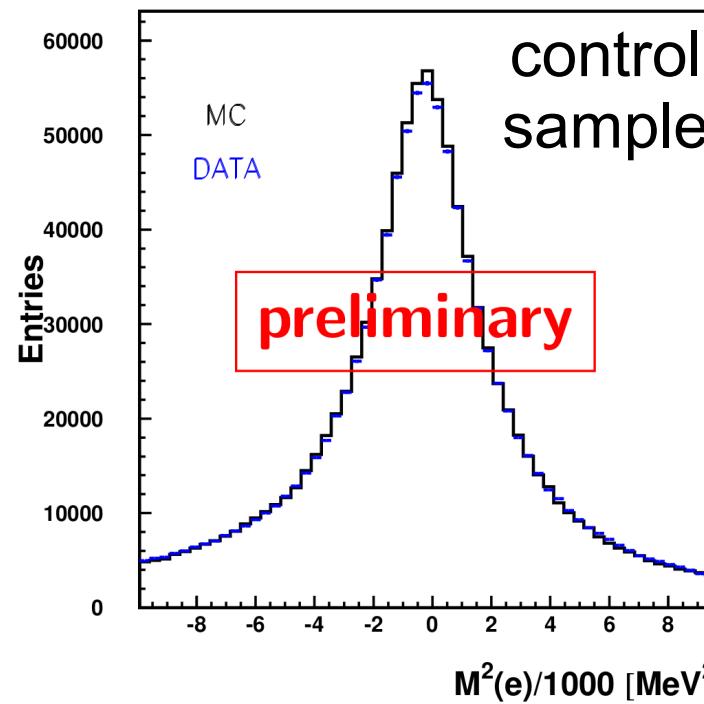
$A_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \times 10^{-3}$ KLOE collaboration, PLB 636 (2006) 173

Determination of charge assymmetries values for K_L and K_S tests fundamental assumptions of Standard Model.

↓ $K_L(\text{crash})\pi e \nu$



↓ $\pi^0 \pi^0 \pi e \nu$



Finalization of new KLOE analysis with ~2 times improved statistical accuracy (1.7fb^{-1} data sample).

With 5fb^{-1} at KLOE-2 accuracy of $\pm 3 \times 10^{-3}$ expected.

$$\Delta E(\pi, e) = E_{\text{miss}} - p_{\text{miss}}$$

$$M^2(e) = (E_{K_S} - E(\pi) - p_{\text{miss}}(\pi, e))^2 - p^2(e)$$



Rare K_S decays

$K_S \rightarrow \pi^0 \pi^0 \pi^0$: unambiguous sign of CP violation

$K_S \rightarrow \pi^+ \pi^- \pi^0$: CPV for L=0,2, but contains also conserving amplitude

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

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

$$Im(\eta_{+-0}) = -0.002 \pm 0.009 \quad Im(\eta_{000}) = (-0.1 \pm 1.6) \times 10^{-2}$$

KLOE set the best upper limit on $|\eta_{000}|$,

D. Babusci et al., Phys Lett. B 723 (2013) 54

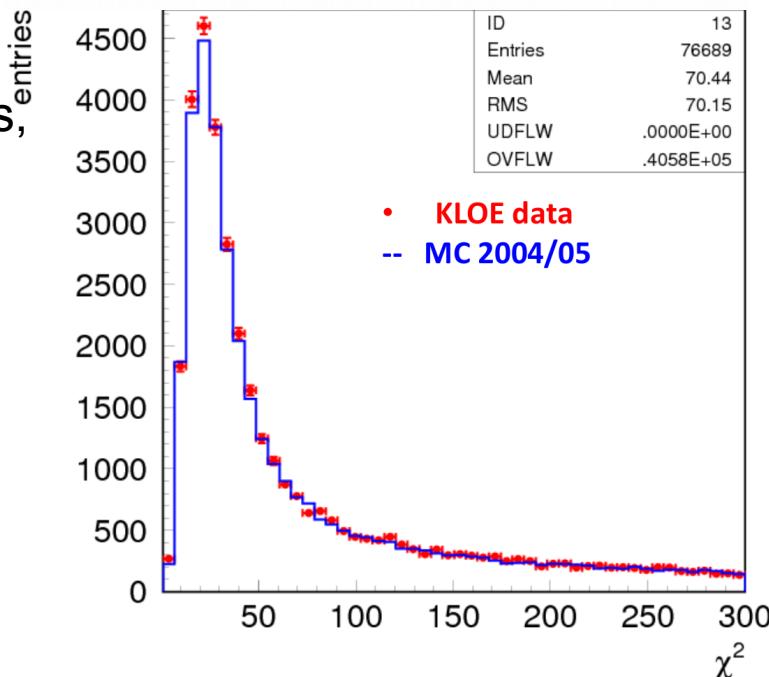
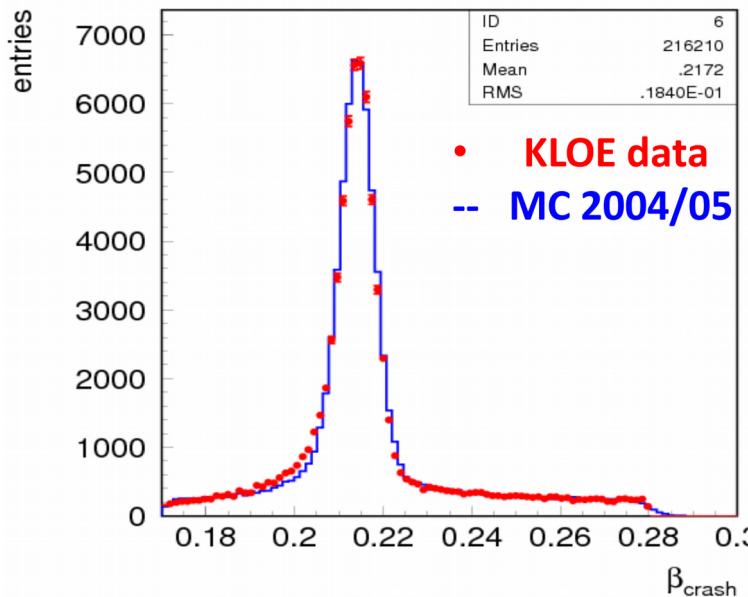
$$BR(K_S \rightarrow 3\pi^0) < 2.6 \times 10^{-8} \Rightarrow |\eta_{000}| \sqrt{\frac{\tau_L BR(K_S \rightarrow 3\pi^0)}{\tau_S BR(K_L \rightarrow 3\pi^0)}} \leq 0.0088 \text{ @ 90% C.L.}$$

Uncertainties of both η_{000} and η_{+-0} contribute to phase of ε

Current experimental accuracy on $BR(K_S \rightarrow \pi^+ \pi^- \pi^0)$ is 30% (CPLEAR, NA48 and E621)

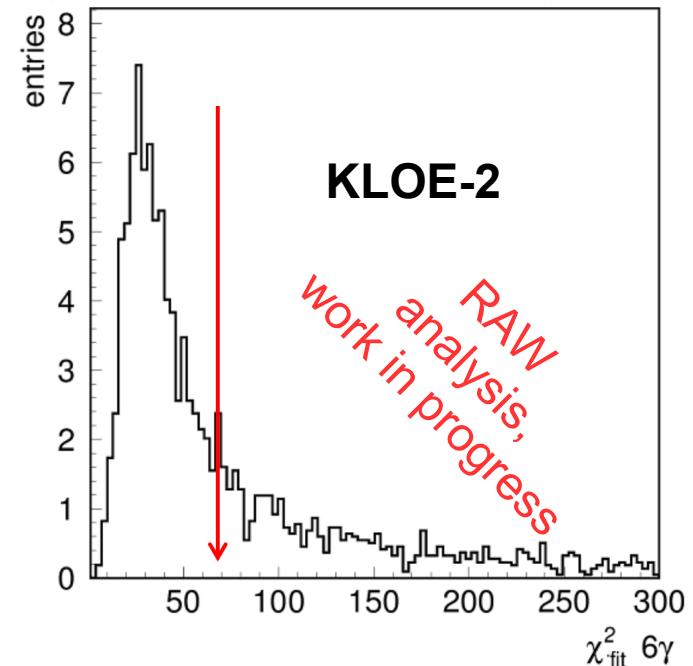
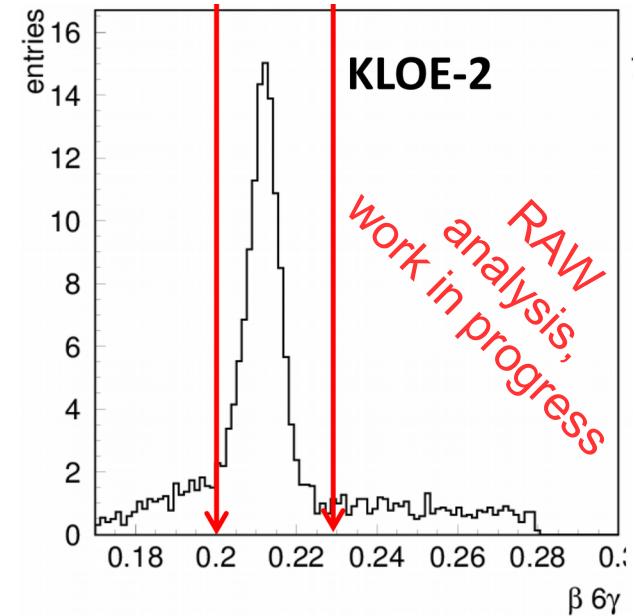
First direct search for $K_S \rightarrow \pi^+ \pi^- \pi^0$ is ongoing with the 1.7 fb^{-1} KLOE data set (with expected accuracy lower than 20%)

$K_S \rightarrow 3\pi^0$



Kinematic fit: K_S mass,
total 4-momentum
conservation,
consistency between
the measured time
and position of each
cluster.

26-28.10.2016



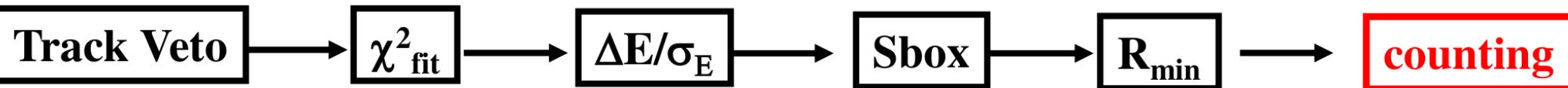
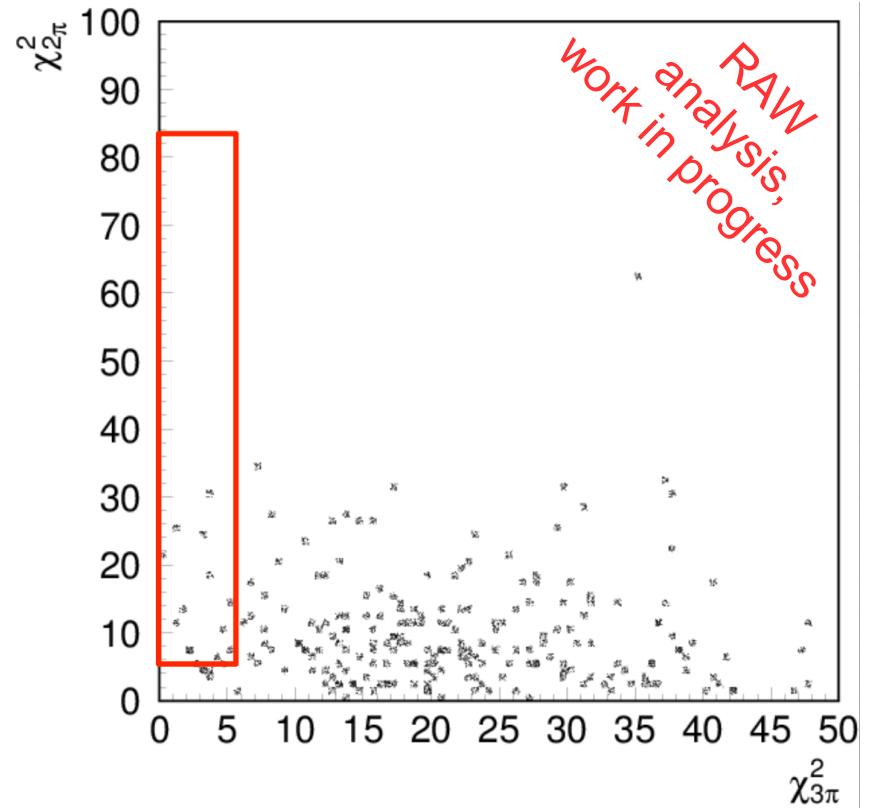
$K_S \rightarrow 3\pi^0$



Signal region definition:

$\chi^2_{2\pi}$: pairing of 4 out of 6 photons
(π^0 masses, E_{KS} , P_{KS} ,
angle between π^0 's)

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



With old analysis chain and cuts values we obtain $N_{obs} = 0$ events
selected as signal,

which translates into $O(10^{-6})$ upper limit on $BR(K_S \rightarrow 3\pi^0)$ with 20pb^{-1}

Quantum interferometry

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**

$$|i\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle|\bar{K}_0\rangle - |\bar{K}_0\rangle|K_0\rangle) = \mathcal{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle),$$

$$I(f_1, t_1; f_2, t_2) = C_{12} \left\{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} \right\}$$

$$\left\{ -2|\eta_1||\eta_2|e^{-(\Gamma_S + \Gamma_L)(t_1 + t_2)/2} \cos(\Delta m(t_2 - t_1) + \varphi_1 - \varphi_2) \right\}$$

interference term

$$\eta_j = \frac{\langle f_j | K_L \rangle}{\langle f_j | K_S \rangle}$$

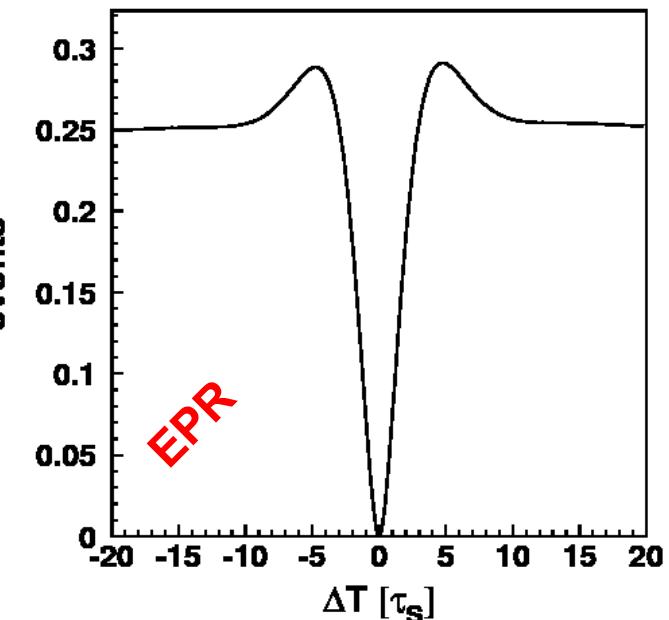
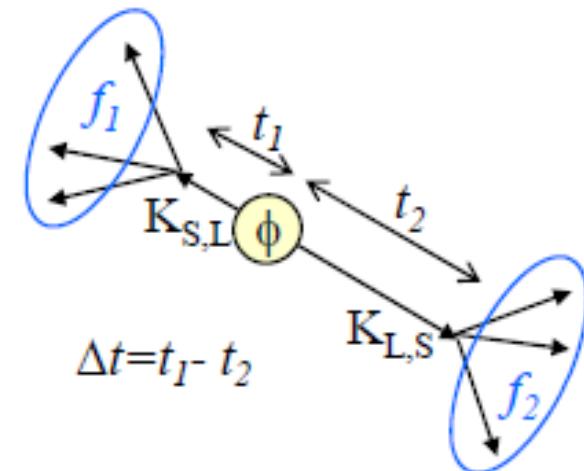
$$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \Rightarrow \frac{\varepsilon'}{\varepsilon} \text{ (CPV)}$$

$$\phi \rightarrow K_S K_L \rightarrow \pi^\pm l^\pm \nu \pi^0 \pi^0 \pi^0, \pi \pi \Rightarrow T \text{ violation}$$

$$\phi \rightarrow K_S K_L \rightarrow \pi^- l^+ \nu \pi^+ l^- \bar{\nu} \Rightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$

$$\phi \rightarrow K_S K_L \rightarrow \pi^\pm l^\mp \nu \pi \pi \Rightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$

$$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- \text{ CPT, Quantum Mechanics}$$



Decoherence

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

$$|i\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle|\bar{K}_0\rangle - |\bar{K}_0\rangle|K_0\rangle) = \mathcal{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle),$$

$$I(f_1, t_1; f_2, t_2) = C_{12} \left\{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_s t_2} + |\eta_2|^2 e^{-\Gamma_s t_1 - \Gamma_L t_2} \right\}$$

$$\left\{ -2|\eta_1||\eta_2|e^{-(\Gamma_s+\Gamma_L)(t_1+t_2)/2} \cos(\Delta m(t_2-t_1) + \varphi_1 - \varphi_2) \right\}$$

interference term

$$\eta_j = \frac{\langle f_j | K_L \rangle}{\langle f_j | K_S \rangle}$$

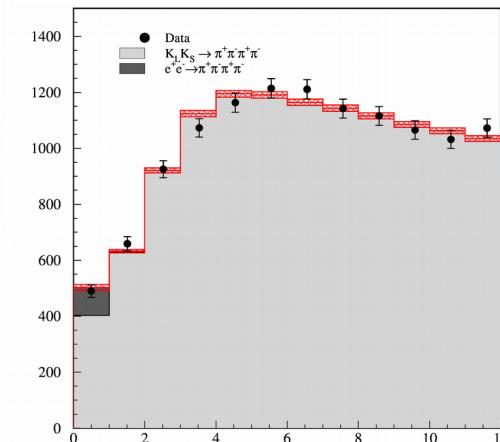
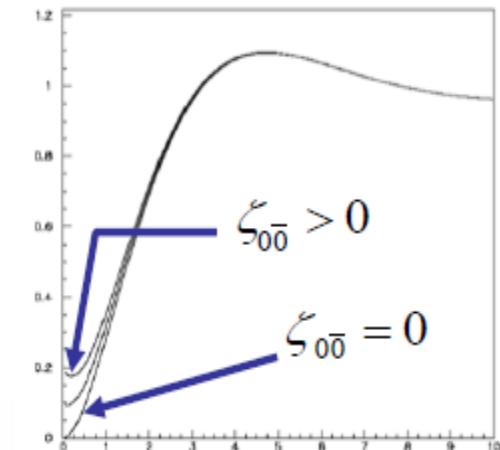
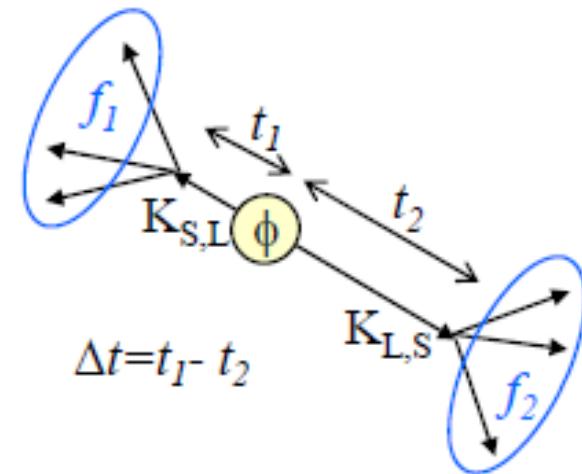
$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[\left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 - (1 - \xi_{00}) \cdot 2 \Re \left(\langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right) \right]$$

J.Phys.Conf.Ser. 171:012008 (2009)

$$\xi_{00} = (1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}}) \times 10^{-7}$$

26-28.10.2016

Overview of KLOE results on kaon physics and KLOE-2 perspectives, E.C.

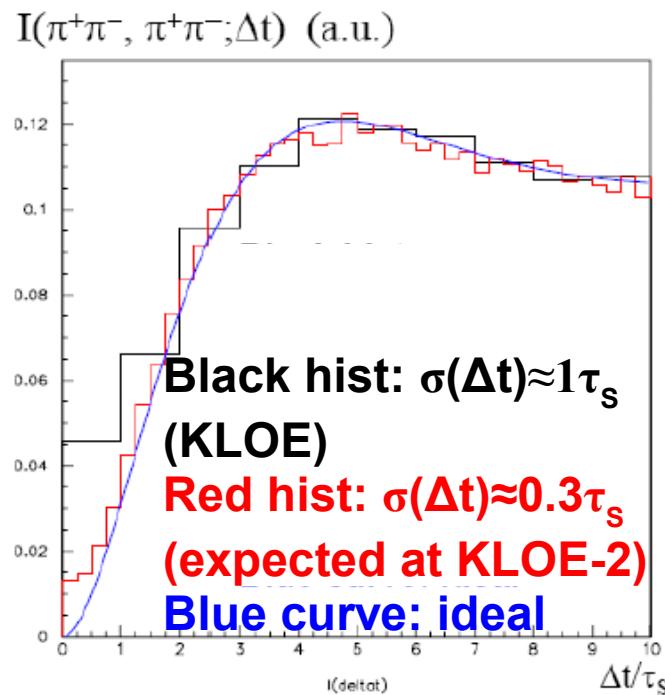


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$\Delta t / \tau_s$

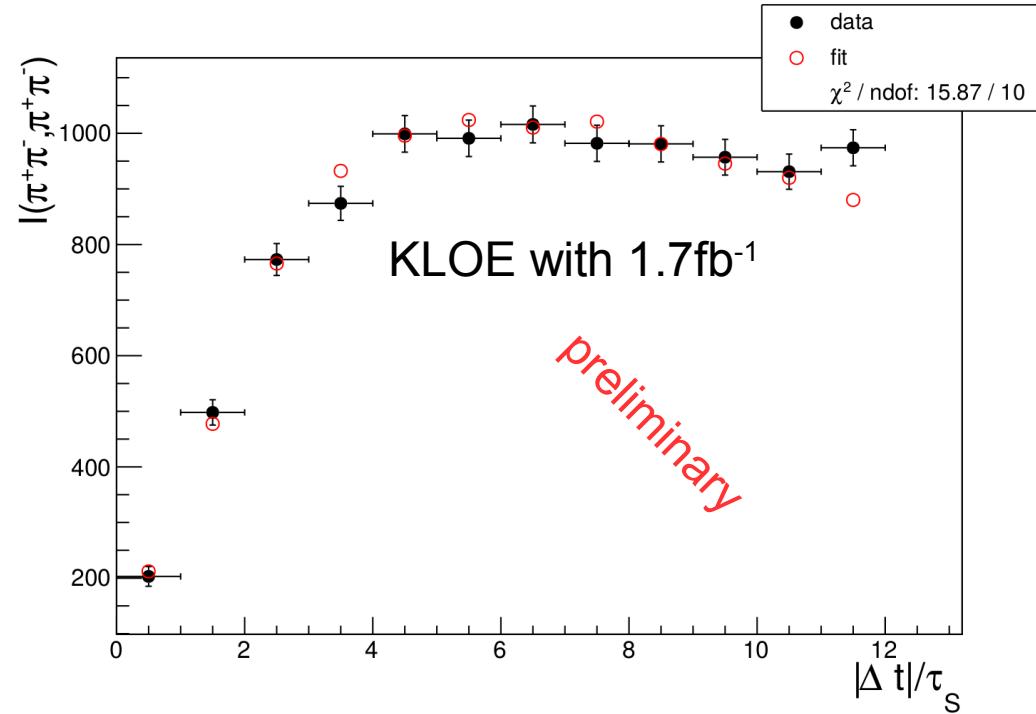
Decoherence

New analysis on the same statistics will improve sensitivity on decoherence parameter due to refined selection of $\pi^+\pi^-$ decays.



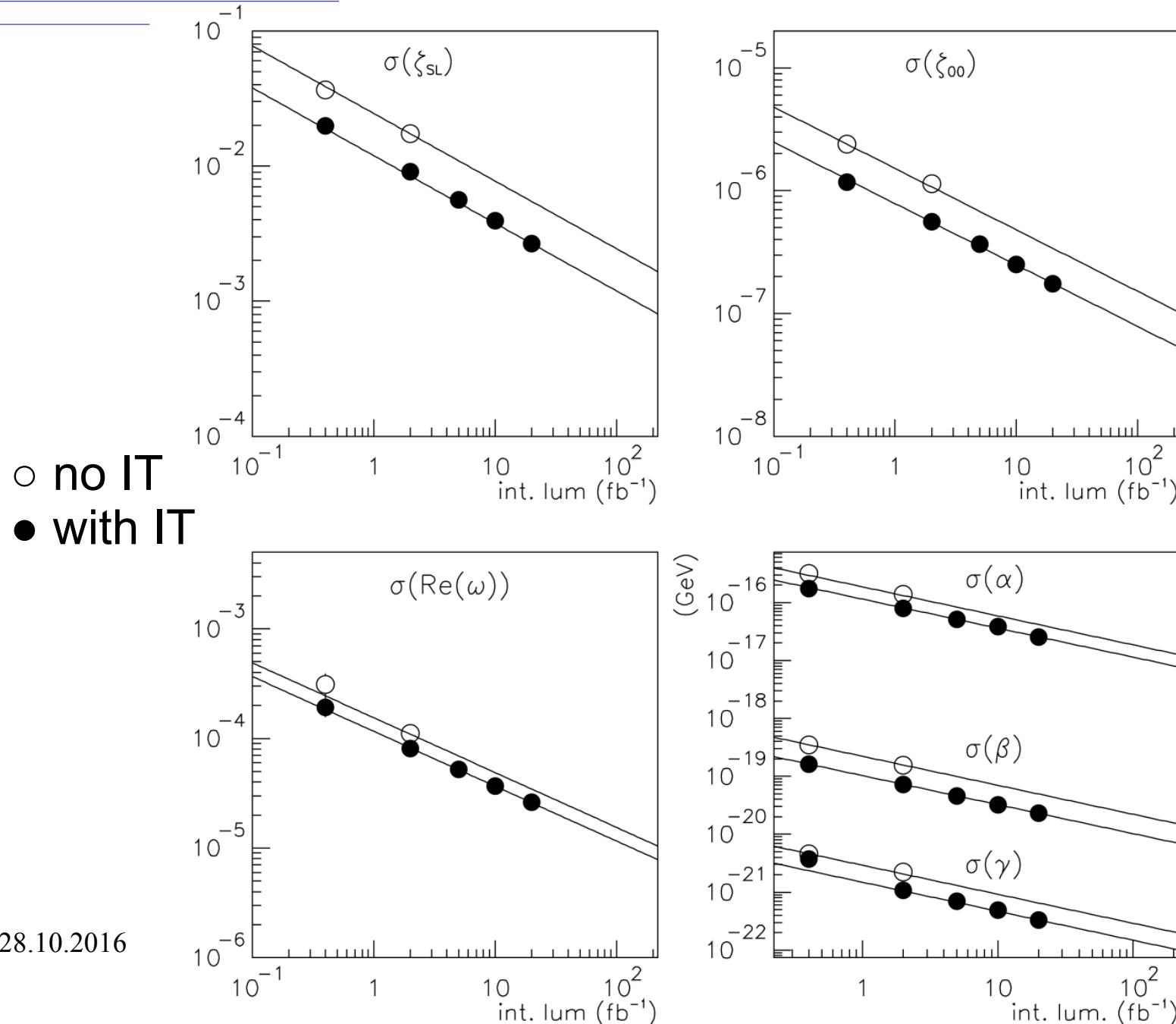
26-28.10.2016

Overview of KLOE results on kaon physics
and KLOE-2 perspectives, E.C.



Further improvement on vertex reconstruction resolution at **KLOE-2** due to insertion of **Inner Tracker**.

Prospects at KLOE-2



CPT & Lorentz invariance violation: Standard Model Extension framework

Using the same final state for both kaons ($\pi^+\pi^-$) the two decay are distinguished only by the kaon momentum direction. The decay amplitude is written as follows:

$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|} \left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_1 \eta_2^* e^{-i\Delta m \Delta\tau}\right) \right]$$

The diagram consists of two equations at the bottom: $\eta_1 = \eta_\pm = \varepsilon_K - \delta(\vec{p}_{K^1})$ and $\eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2})$. Two arrows point upwards from each equation to the corresponding terms in the decay amplitude formula above them.

δ_K is the CPT violation parameter in the Kaon system.

According to the SME (Kostelecky) [[PRD64,076001](#)] and anti-CPT theorem, CPT violation should appear together with Lorentz Invariance breaking (Greenberg) [[PRL89,231602](#)], and thus implying a direction dependent modulation.

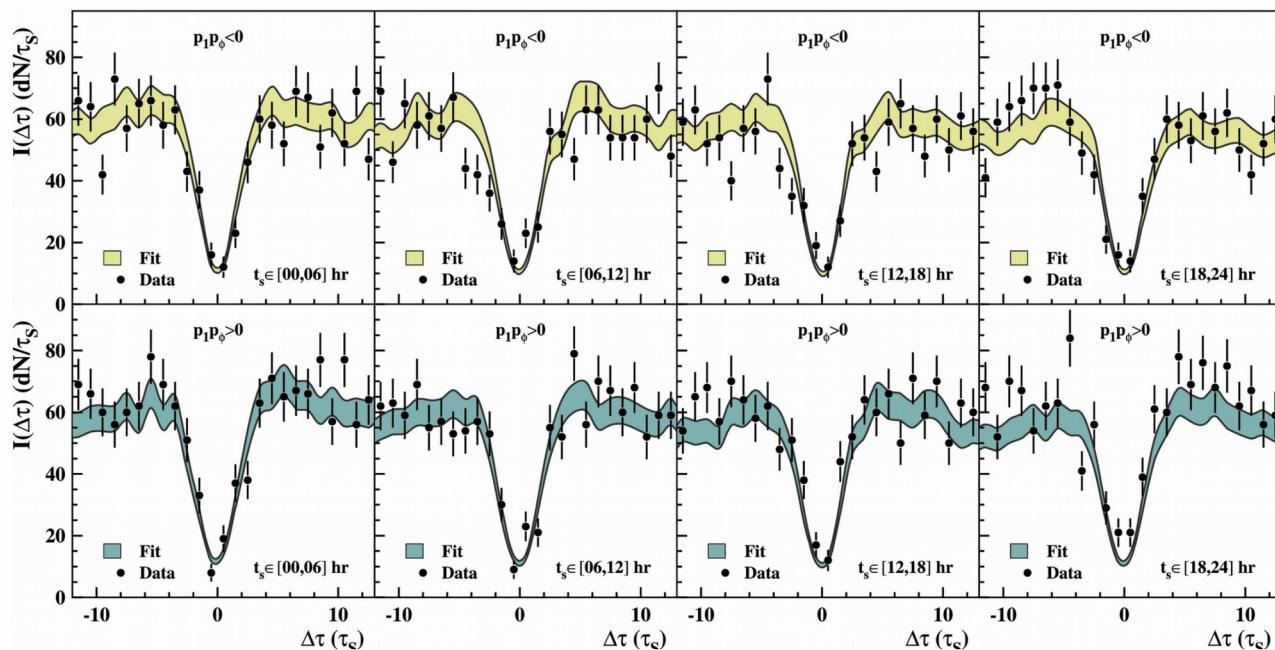
$$\delta \simeq i \sin \phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta \vec{a}) / \Delta m$$

Ordering Kaon according to their momenta it is possible to have the two η -coefficients containing two different δ_K CPT violating parameter.

CPT & Lorentz invariance with SME



KLOE result with the best sensitivity ever reached in the quark sector



KLOE (1.7 fb^{-1}), PLB 730(2014)89

$$\Delta a_0 = (-6.0 \pm 7.7 \pm 3.1) \cdot 10^{-18} \text{ GeV}$$

$$\Delta a_x = (0.9 \pm 1.5 \pm 0.6) \cdot 10^{-18} \text{ GeV}$$

$$\Delta a_y = (-2.0 \pm 1.5 \pm 0.5) \cdot 10^{-18} \text{ GeV}$$

$$\Delta a_z = (3.1 \pm 1.7 \pm 0.5) \cdot 10^{-18} \text{ GeV}$$

FOCUS, PLB 556(2003)7, mixing D

$$\Delta a_{x,y,\parallel} \approx 10^{-13} \text{ GeV}$$

LHCb, PRL 116(2016)241601, 2016 mixing

$$B^0 \rightarrow J/\psi K_S$$

$$\Delta a_{x,y,\parallel} \approx 10^{-15} \text{ GeV}$$

$$\Delta a_\perp \approx 10^{-13} \text{ GeV}$$

$$B_S^0 \rightarrow J/\psi K^+ K^-$$

$$\Delta a_{x,y,\parallel} \approx 10^{-14} \text{ GeV}$$

$$\Delta a_\perp \approx 10^{-12} \text{ GeV}$$

BaBar, PRL 100(2000)131802,
entangled $\Psi(4S) \rightarrow B\bar{B} \rightarrow (Xl\nu)(Xl\nu)$

$$\Delta a_{\perp,\parallel} \approx 10^{-13} \text{ GeV}$$

QM and CPT test at KLOE-2

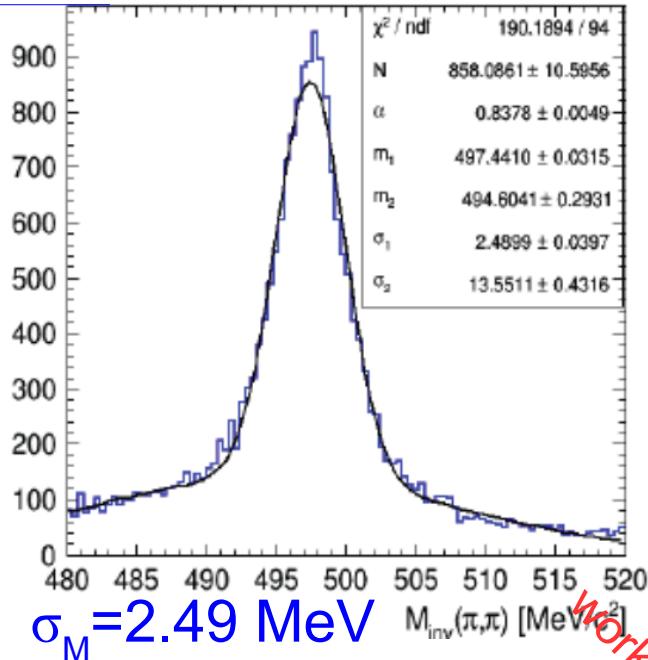


	Physics case	Physics reach
$\pi^+\pi^-\pi^+\pi^-$	QM, CPT and Lorentz invariance tests	Factor 4 improvement in sensitivity
$K_s \rightarrow 3\pi^0$	CP violation, best limit: $BR < 2.6 \times 10^{-8}$ @ 90% C.L.	$< 1 \times 10^{-8}$
$K_s \rightarrow \pi e \nu$	CP, CPT test $A_S = (1.5 \pm 11) \times 10^{-3}$ (CP viol. $A_S = 3.3 \times 10^{-3}$) (CPT : $A_S - A_L = 0$)	

Parameter	Present best measurement	KLOE-2 (5 fb^{-1})
$\zeta_{0\bar{0}}$	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17} \text{ GeV}$	$\pm 5 \times 10^{-17} \text{ GeV}$
β	$(2.5 \pm 2.3) \times 10^{-19} \text{ GeV}$	$\pm 0.5 \times 10^{-19} \text{ GeV}$
γ	$(1.1 \pm 2.5) \times 10^{-21} \text{ GeV}$ (compl. pos. hyp.) $(0.7 \pm 1.2) \times 10^{-21} \text{ GeV}$	$\pm 0.75 \times 10^{-21} \text{ GeV}$ (compl. pos. hyp.) $\pm 0.33 \times 10^{-21} \text{ GeV}$
$\text{Re}\omega$	$(-1.6^{+3.0}_{-2.1} \pm 0.4) \times 10^{-4}$	$\pm 0.7 \times 10^{-4}$
$\text{Im}\omega$	$(-1.7^{+3.3}_{-3.0} \pm 1.2) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$
Δa_0	$(-6.0 \pm 7.7 \pm 3.1) \times 10^{-18} \text{ GeV}$	$\pm 0.52 \times 10^{-17} \text{ GeV}$
Δa_Z	$(3.1 \pm 1.7 \pm 0.5) \times 10^{-18} \text{ GeV}$	$\pm 2.2 \times 10^{-18} \text{ GeV}$
$\Delta a_X, \Delta a_Y$	$(0.9 \pm 1.5 \pm 0.6) \times 10^{-18}, (-2.0 \pm 1.5 \pm 0.5) \times 10^{-18} \text{ GeV}$	$\pm 1.3 \times 10^{-18} \text{ GeV}$

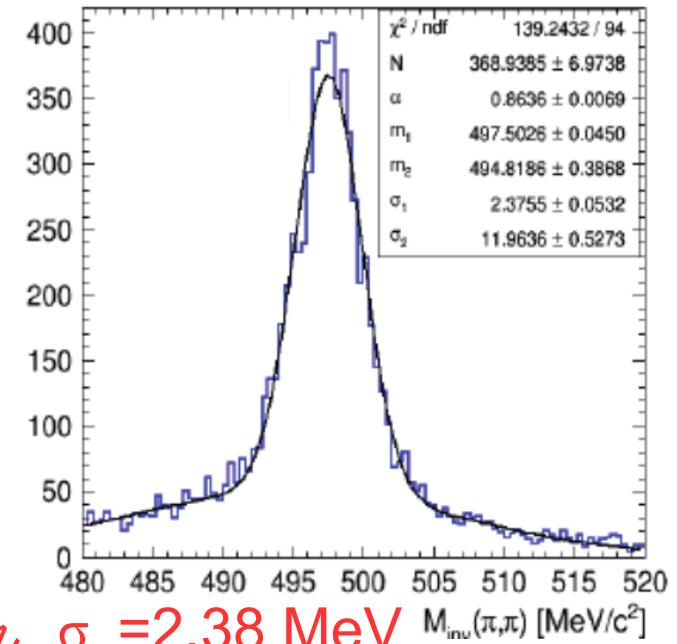
$K_{S,L} \rightarrow \pi^+ \pi^-$

KLOE



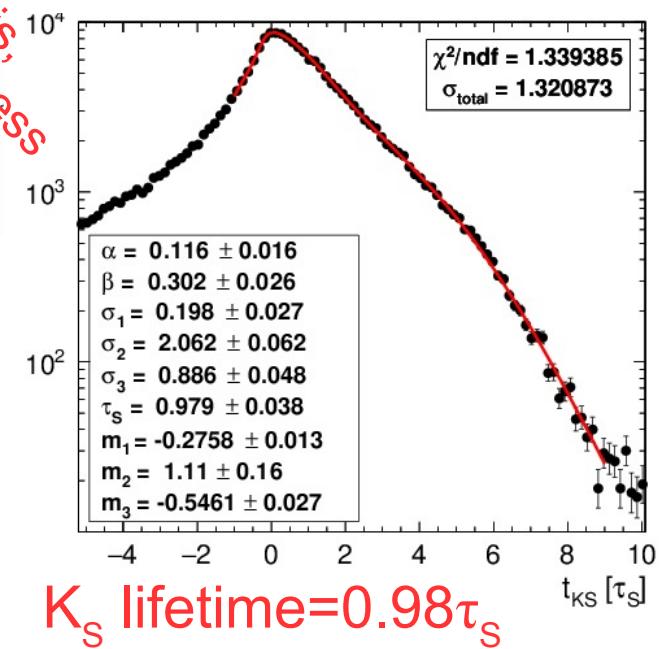
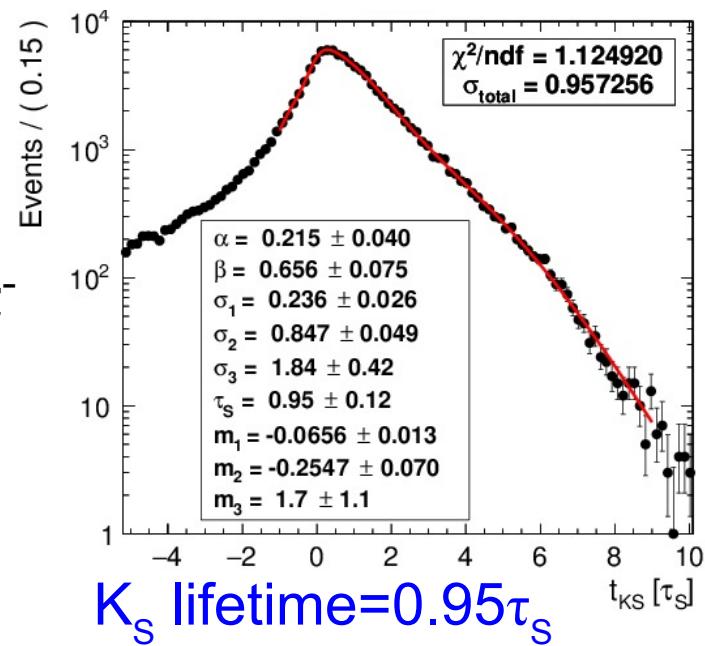
$K_L \rightarrow \pi^+ \pi^-$

KLOE-2



$K_S \rightarrow \pi^+ \pi^-$

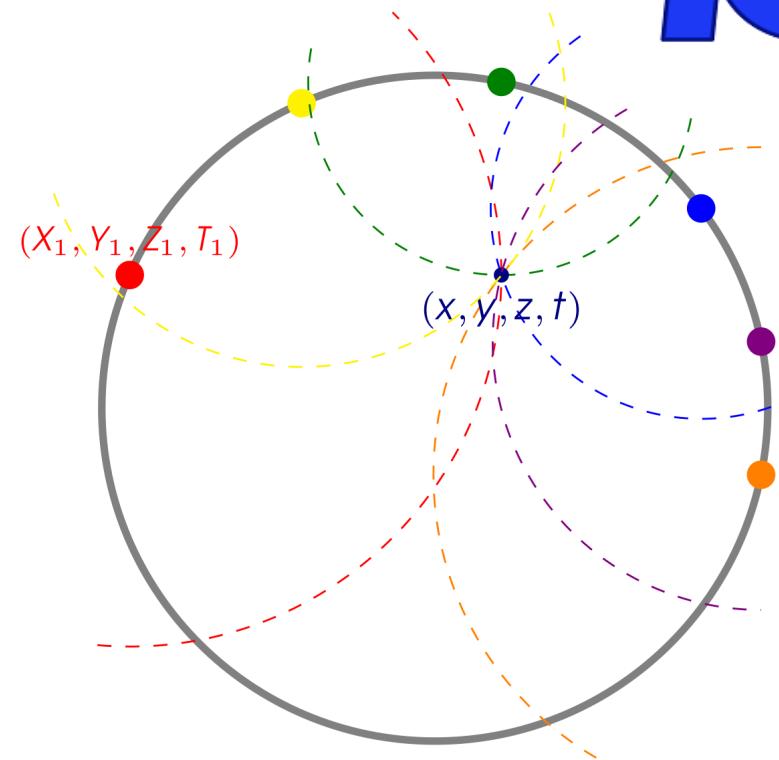
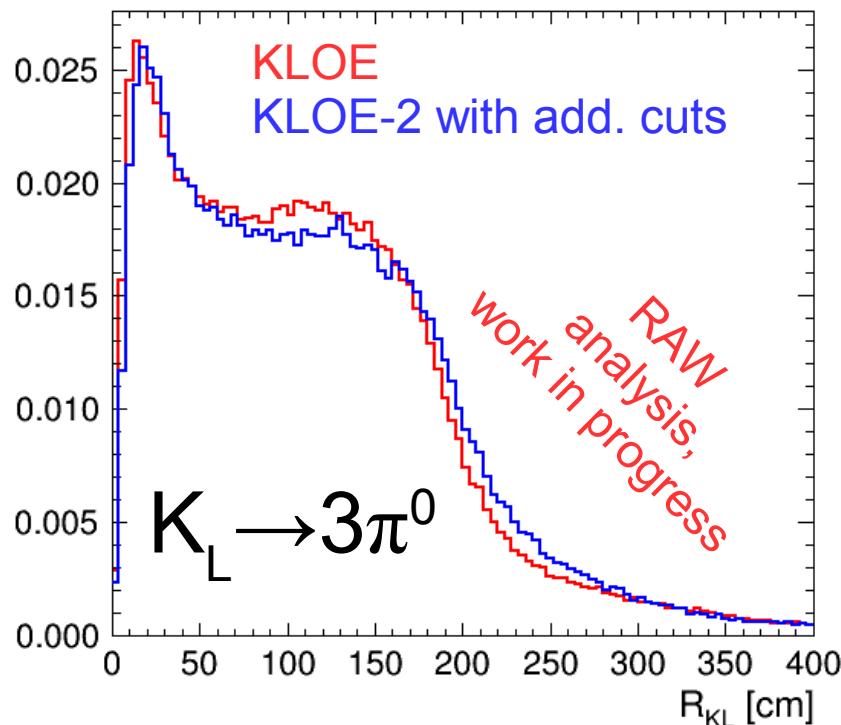
RAW analysis,
work in progress



GPS@KLOE



Reconstruction mathematically similar to GPS positioning: for each calorimeter hit - a set of possible γ origin points is a sphere
 $(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2$,
 $i=1, \dots, 6$.



Decay vertex lies on the intersection of the spheres, at least 4 of them necessary to find the $K_L \rightarrow 3\pi^0$ decay point and time, additional two γ hits can be used to improve accuracy of reconstruction with a kinematic.

This is a key ingredient for testing CPT symmetry in transition processes
 (never done before and possible only at KLOE)

J. Bernabeu, A. Di Domenico, P. Villanueva-Perez: JHEP 10 (2015) 139

CPT and T sym. test in transition

$A \leftrightarrow B$

$$S|K^0\rangle = +1|K^0\rangle$$

$$S|\bar{K}^0\rangle = -1|\bar{K}^0\rangle$$

$$\bar{K}^0 \rightarrow \pi^+ l^- \bar{\nu}_l \quad S = -1$$

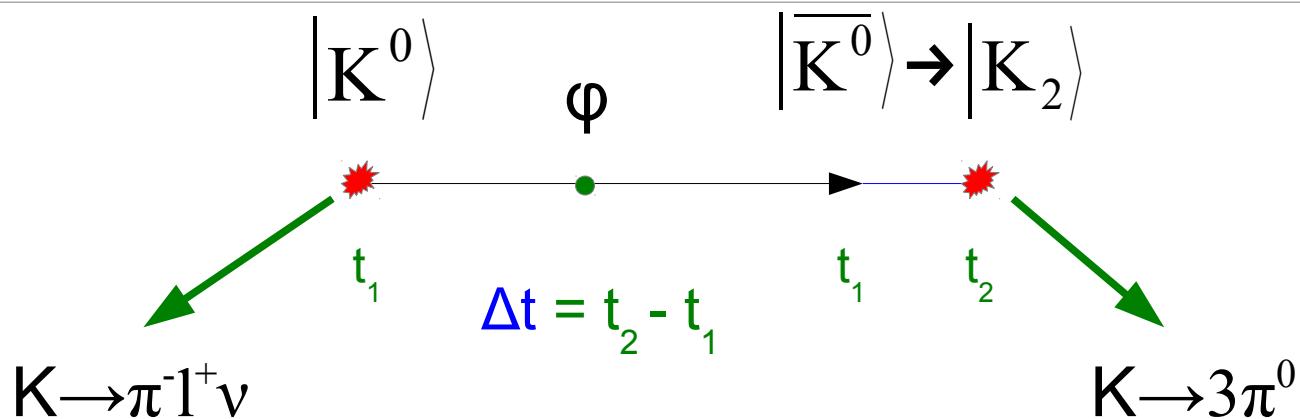
$$K^0 \rightarrow \pi^- l^+ \nu_l \quad S = +1$$

$$|K_1\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle + |\bar{K}^0\rangle] \quad CP = +1$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle - |\bar{K}^0\rangle] \quad CP = -1$$

$$K_1 \rightarrow \pi\pi \quad CP = +1$$

$$K_2 \rightarrow 3\pi^0 \quad CP = -1$$



$$|\bar{K}^0\rangle \rightarrow |K_2\rangle \xrightarrow{T} |K_2\rangle \rightarrow |\bar{K}^0\rangle$$

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

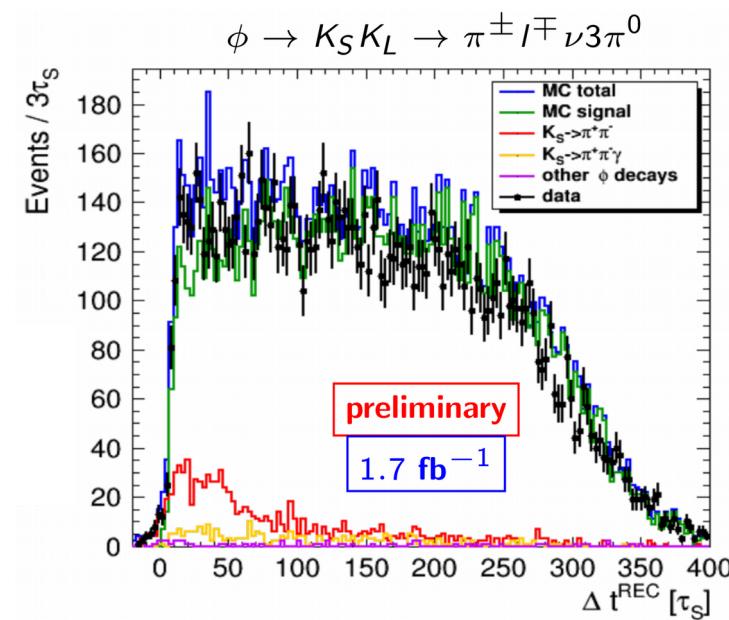
CPT and T sym. test in transition



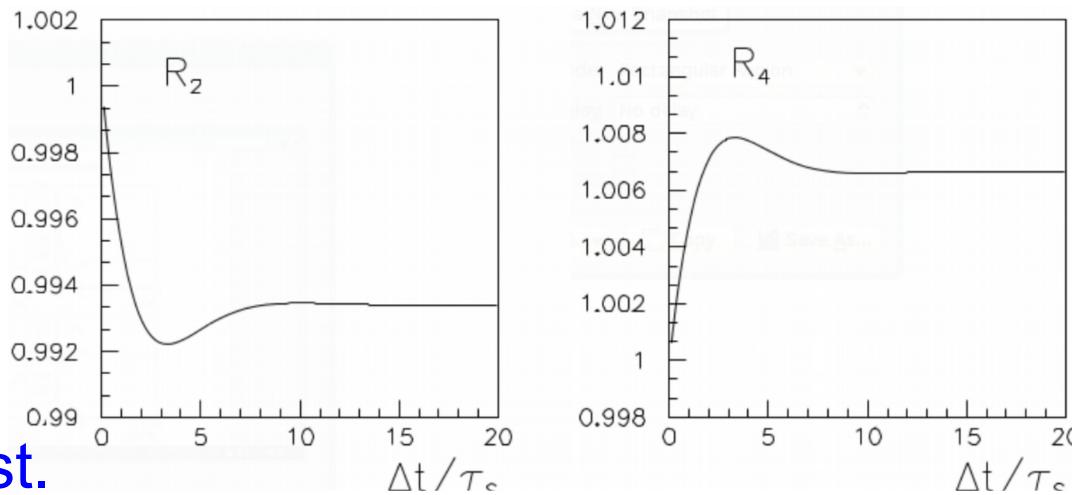
$$R_2^{\text{exp}}(\Delta t) = \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_2(\Delta t) \times \frac{C(\ell^-, 3\pi^0)}{C(\pi\pi, \ell^+)}$$

$$R_4^{\text{exp}}(\Delta t) = \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_4(\Delta t) \times \frac{C(\ell^+, 3\pi^0)}{C(\pi\pi, \ell^-)}$$

$R_{2,4} \sim 1 \pm 4\text{Re}(\delta)$ for $\Delta t > \tau_S$



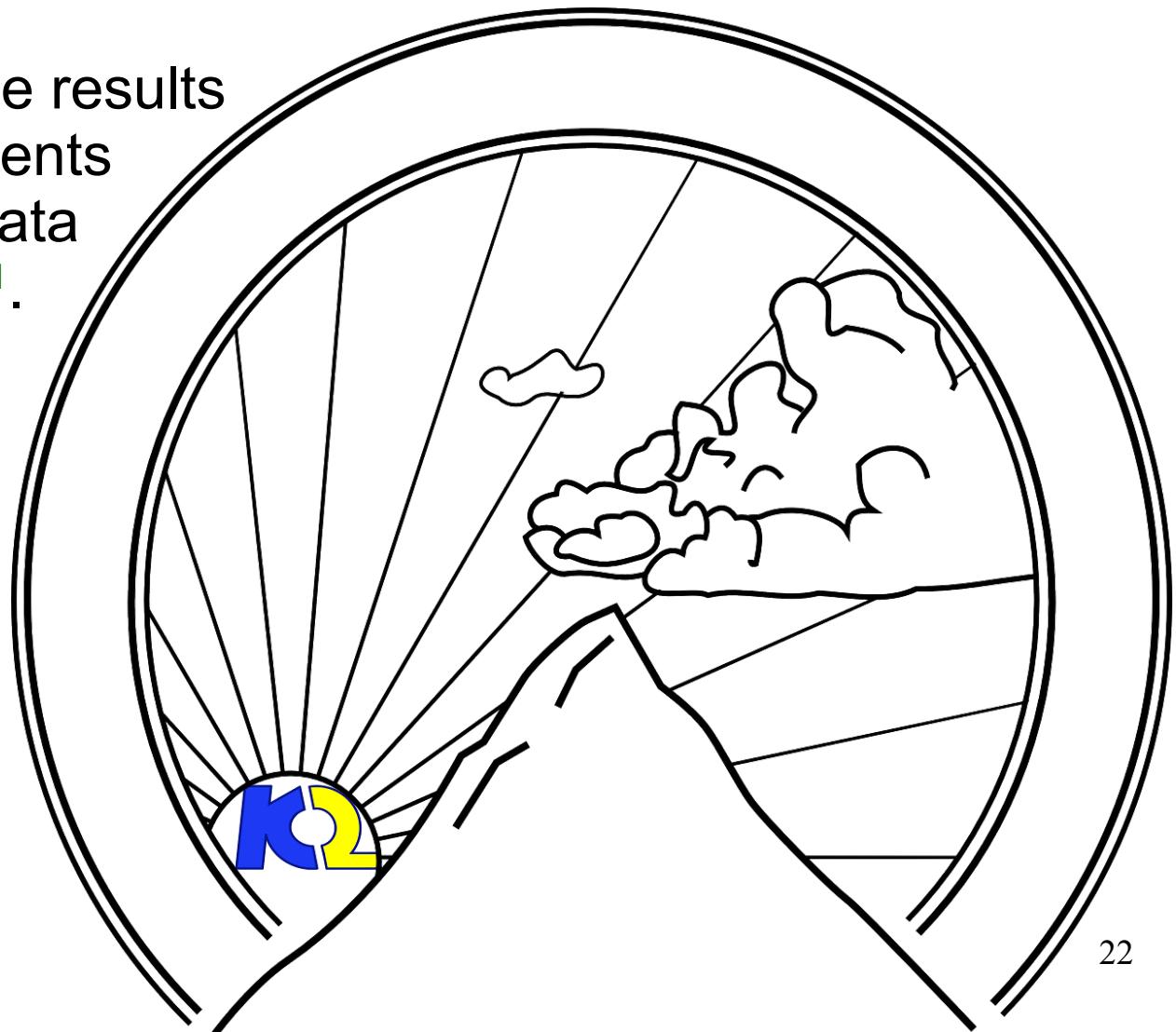
Asymptotic behaviour of $R_2(\Delta t > \tau_S)$ and $R_4(\Delta t > \tau_S)$ can be extracted and allows for T symmetry violation test, whereas double ratio R_2/R_4 constitutes one of the robust observables for CPT symmetry test.



J. Bernabeu, A. Di Domenico, P. Villanueva-Perez: JHEP 10 (2015) 139

Summary

1. Based on the **KLOE** 1.7 fb^{-1} data sample new results on A_s determination and tests of QM and CPT symmetry.
2. Dawn of more precise results and new measurements from **KLOE-2** with data sample at least 5fb^{-1} .





Thank you

Grazie

Dziękuje

Danke

Merci

ありがとう