KLOE-2 activity report

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on behalf of the KLOE-2 collaboration

LNF Scientific Committee meeting
Frascati, 14 November 2022

Status of offline activities

Data Reconstruction

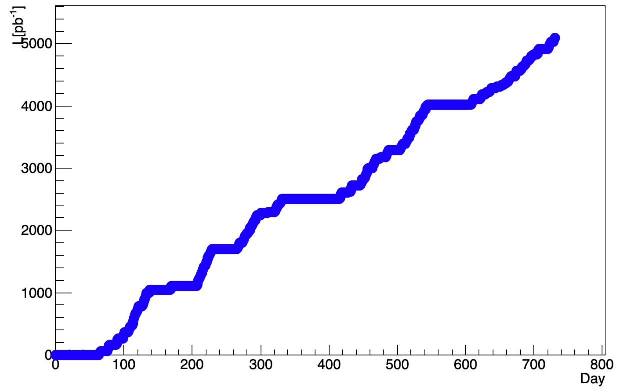
- Second round of Data reconstruction DBV-40 => completed
- Total integrated luminosity L = 5.1 fb^{-1}

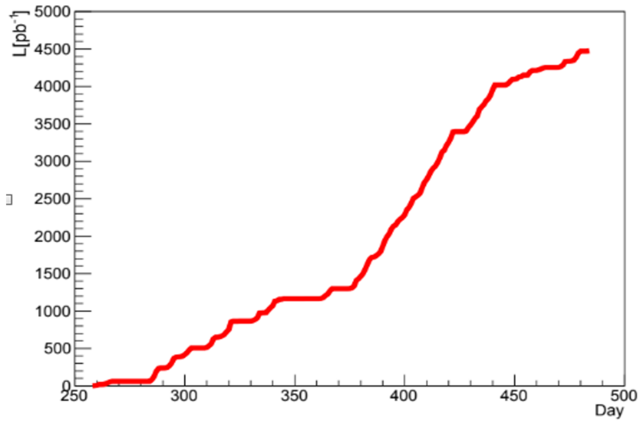
MC production

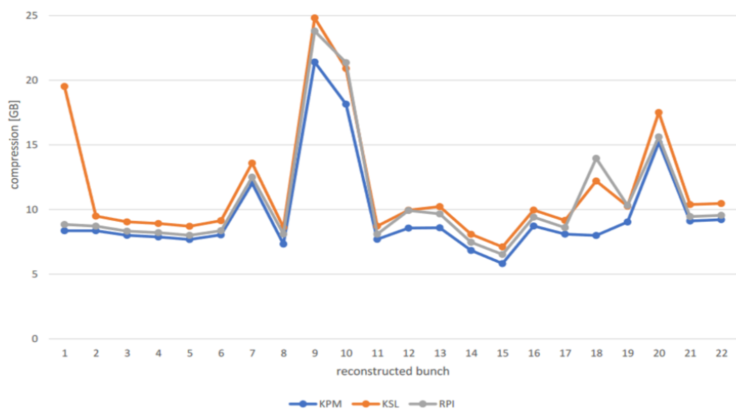
- Simulation of the main ϕ(1020) decays with Luminosity Scale Factor = 1 => completed
- Total integrated luminosity L = 4.7 fb^{-1}

ROOT output production

- Compression factor (ratio Datarec/ROOT) ~ 8 depending on run conditions
- => in progress
- DATA L = 4.1 fb^{-1}
- MC L = 0.3 fb^{-1}
- Goal: keep all ROOT files on disk for faster accessibility => 400 TB needed
- (already funded by INFN-CSN1)



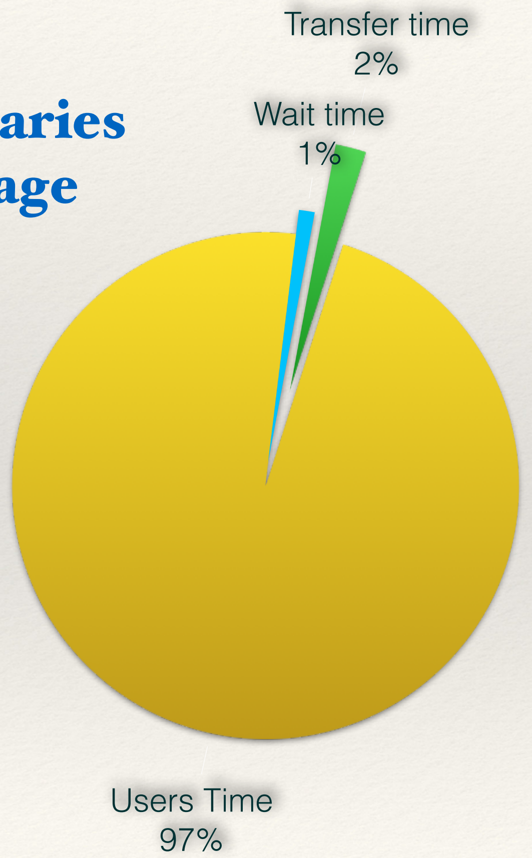


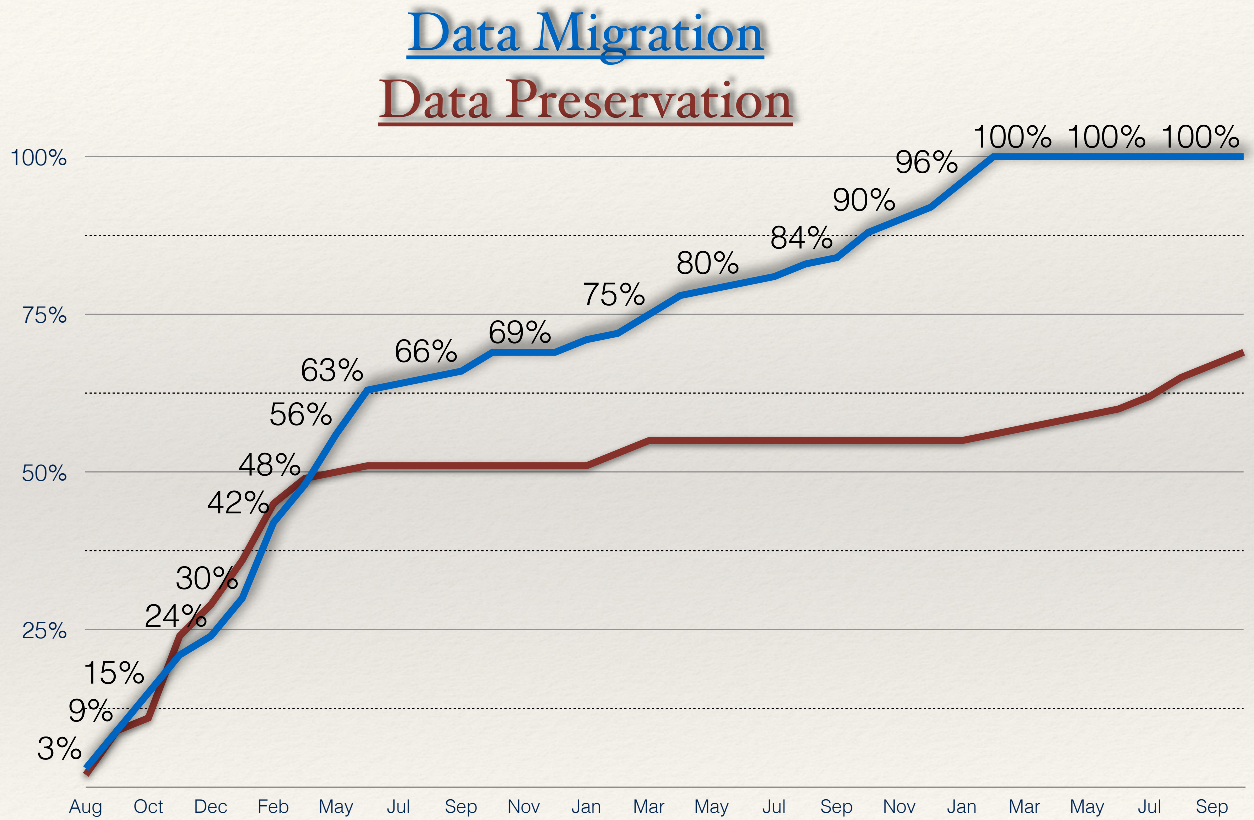


Status of offline activities

Status of Data Migration

Libraries usage



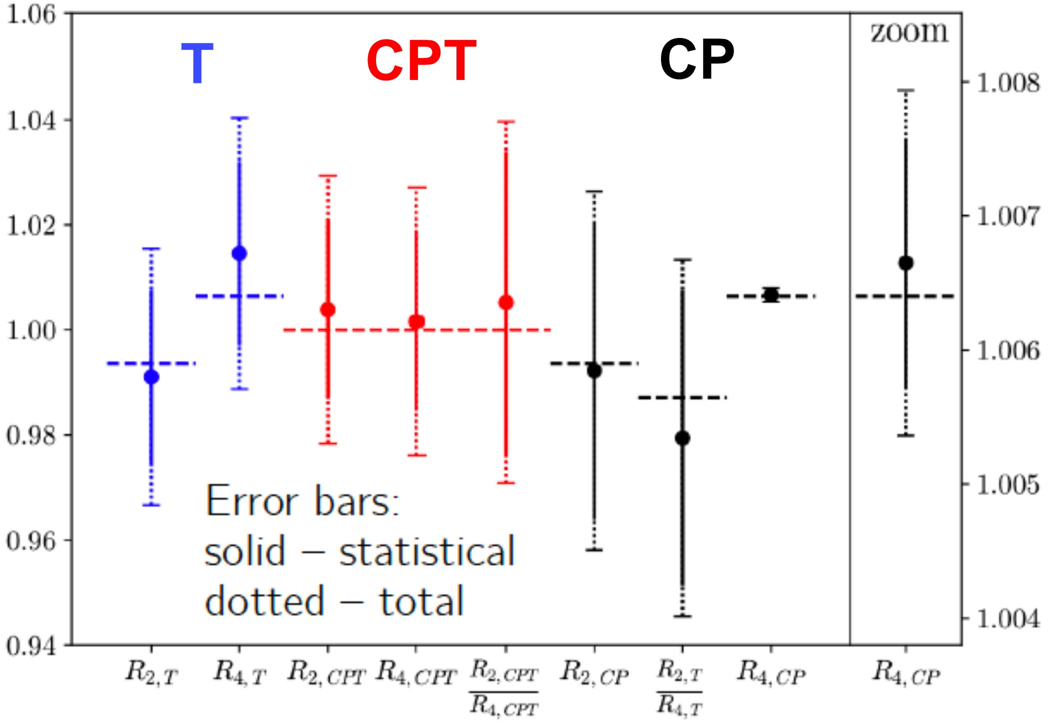


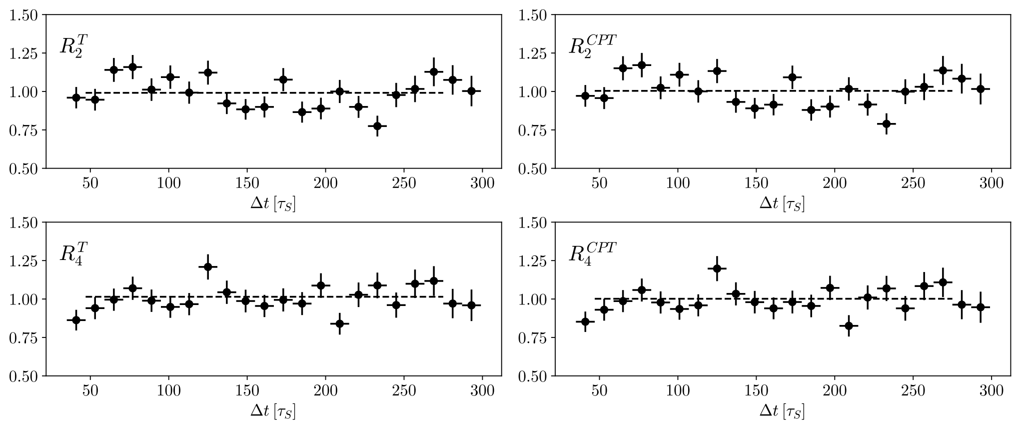
Recent results with entangled neutral kaons

T, CP, CPT tests in neutral kaon transitions at KLOE

horizontal dashed lines denote expected values:
CPT invariance and TV extrapolated from observed CPV (PDG)

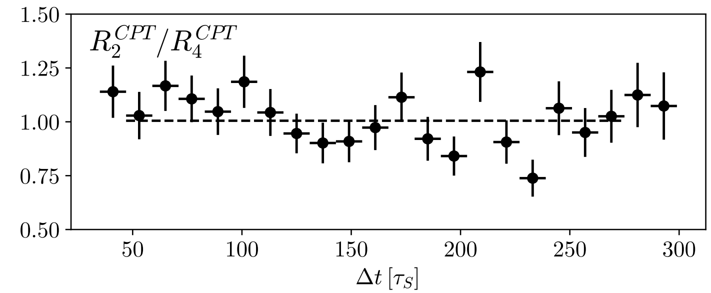
	reference	T	CPT	CP
e.g.	$K^0 \to K_-$	$K_- \to K^0$	$K_- \to \overline{K}^0$	$\overline{K}^0 \to K_-$





KLOE-2 result (2022)

$$
\begin{aligned}
R_2^T &= 0.991 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D, \\
R_4^T &= 1.015 \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_D, \\
R_2^{CPT} &= 1.004 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D, \\
R_4^{CPT} &= 1.002 \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_D, \\
R_2^{CP} &= 0.992 \pm 0.028_{stat} \pm 0.019_{syst}, \\
R_4^{CP} &= 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst}, \\
R_2^T/R_4^T &= 0.979 \pm 0.028_{stat} \pm 0.019_{syst}, \\
R_2^{CPT}/R_4^{CPT} &= 1.005 \pm 0.029_{stat} \pm 0.019_{syst}.
\end{aligned}
$$



First direct T and CPT tests in kaon transitions

Direct tests of T, CP, CPT symmetries in transitions of neutral K mesons with the KLOE experiment

Abstract

Tests of the T, CP and CPT symmetries in the neutral kaon system are performed by the direct comparison of the probabilities of a kaon transition process to its symmetry-conjugate. The exchange of *in* and *out* states required for a genuine test involving an anti-unitary transformation implied by time-reversal is implemented exploiting the entanglement of $K^0\overline{K}^0$ pairs produced at a ϕ-factory.

A data sample collected by the KLOE experiment at DAΦNE corresponding to an integrated luminosity of about 1.7 fb^{-1} is analysed to study the Δt distributions of the $\phi \to K_S K_L \to \pi^+\pi^- \, \pi^\pm e^\mp \nu$ and $\phi \to K_S K_L \to \pi^\pm e^\mp \nu \, 3\pi^0$ processes, with Δt the difference of the kaon decay times. A comparison of the measured Δt distributions in the asymptotic region $\Delta t \gg \tau_S$ allows to test for the first time T and CPT symmetries in kaon transitions with a precision of few percent, and to observe CP violation with this novel method.

Keywords: Discrete and Finite Symmetries, Kaon Physics, CP violation

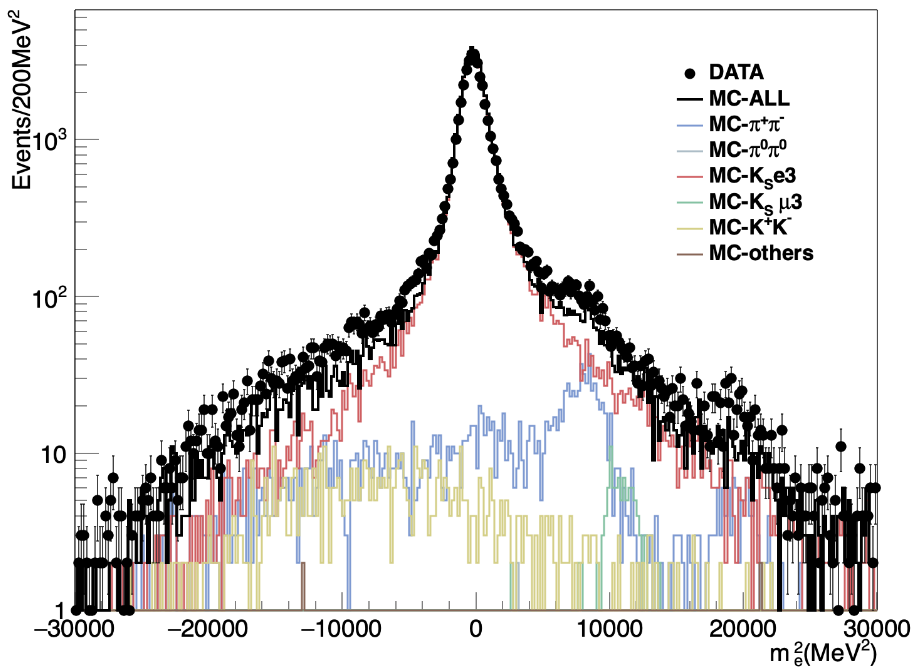
Paper reviewed by the collaboration
=> ready to be submitted to PLB by this week.

Measurement of the $K_S \to \pi e \nu$ branching ratio

- Analysed L=1.63 fb^{-1}
- $K_S \to \pi^+\pi^-$ as normalization sample
- K_S semileptonic signal selection
- Signal count from fit to $M^2(e)$ distribution

$$m_e^2 = (E_{K_S} - E_\pi - p_{\mathrm{miss}})^2 - p_e^2$$

- 49647±316 K_{Se3} events
- Selection efficiency from $K_S \to \pi^+\pi^-$ K_{Le3} close to IP data control sample
- ε =(19.38±0.04)%



$$\mathrm{BR}(K_S \to \pi e \nu) = (7.211 \pm 0.046_{stat} \pm 0.052_{syst}) \times 10^{-4}$$

$$\mathcal{B}(K_S \to \pi \ell \nu) = \frac{G^2 (f_+(0)|V_{us}|)^2}{192\pi^3} \tau_S m_K^5 I_K^\ell S_{\mathrm{EW}} (1 + \delta_{\mathrm{EM}}^{K\ell})$$

- Combination with the previous KLOE result (0.41 fb^{-1}):

$$\mathrm{BR}(K_S \to \pi e \nu) = (7.153 \pm 0.037_{stat} \pm 0.043_{syst}) \times 10^{-4}$$

=> 0.8% precision

- From BR we derive:

$$f_+(0)\,|V_{us}| = 0.2170 \pm 0.0009$$

Prepared for submission to JHEP

Measurement of the $K_S \to \pi e \nu$ branching fraction with the KLOE experiment *

arXiv:2208.04872v2 [hep-ex] 10 Aug 2022

The KLOE-2 Collaboration

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* **Dedicated to the memory of Paolo Franzini**

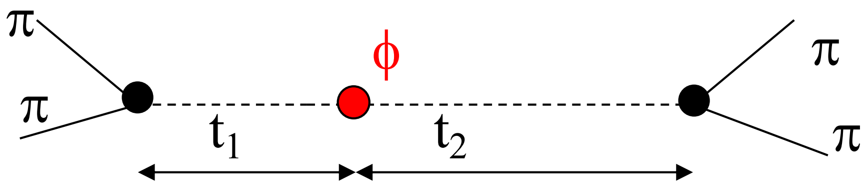
KLOE-2 result (2022)

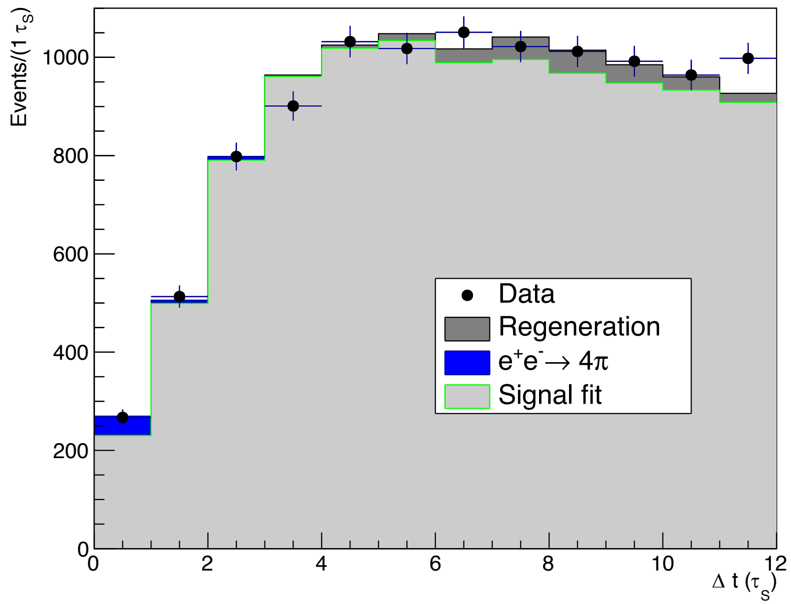
arXiv :2208.04872v2 [hep-ex]

(submitted to JHEP, received positive reports from referees => replying to the comments)

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: summary of results

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





Several parameters defining possible decoherence and CPT violation effects in the entangled neutral kaons are measured

$$\zeta_{0\bar{0}} = (-0.5 \pm 8.0_{stat} \pm 3.7_{syst})\times 10^{-7}$$
$$\zeta_{SL} = (0.1 \pm 1.6_{stat} \pm 0.7_{syst})\times 10^{-2}$$
$$\gamma = (1.3 \pm 9.4_{stat} \pm 4.2_{syst})\times 10^{-22}\ \mathrm{GeV}$$
$$\Re\omega = \left(-2.3^{+1.9}_{-1.5}{}_{stat} \pm 0.6_{syst}\right)\times 10^{-4}$$
$$\Im\omega = \left(-4.1^{+2.8}_{-2.6}{}_{stat} \pm 0.9_{syst}\right)\times 10^{-4}$$
$$|\omega| = (4.7 \pm 2.9_{stat} \pm 1.0_{syst})\times 10^{-4}$$
$$\phi_\omega = -2.1 \pm 0.2_{stat} \pm 0.1_{syst}\ \ \mathrm{rad}$$

$$\lambda \cong \frac{\zeta_{SL}}{\Gamma_S} = (0.1 \pm 1.2_{stat} \pm 0.5_{syst})\times 10^{-16}\ \mathrm{GeV}$$

$$\mathrm{BR}(\phi \rightarrow K_S K_S, K_L K_L) < 2.4\times 10^{-7}$$
at 90% C.L.

KLOE-2 JHEP 04 (2022) 059

[improvement x2 wrt KLOE PLB 642(2006) 315]

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: summary of results

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

π

Sev
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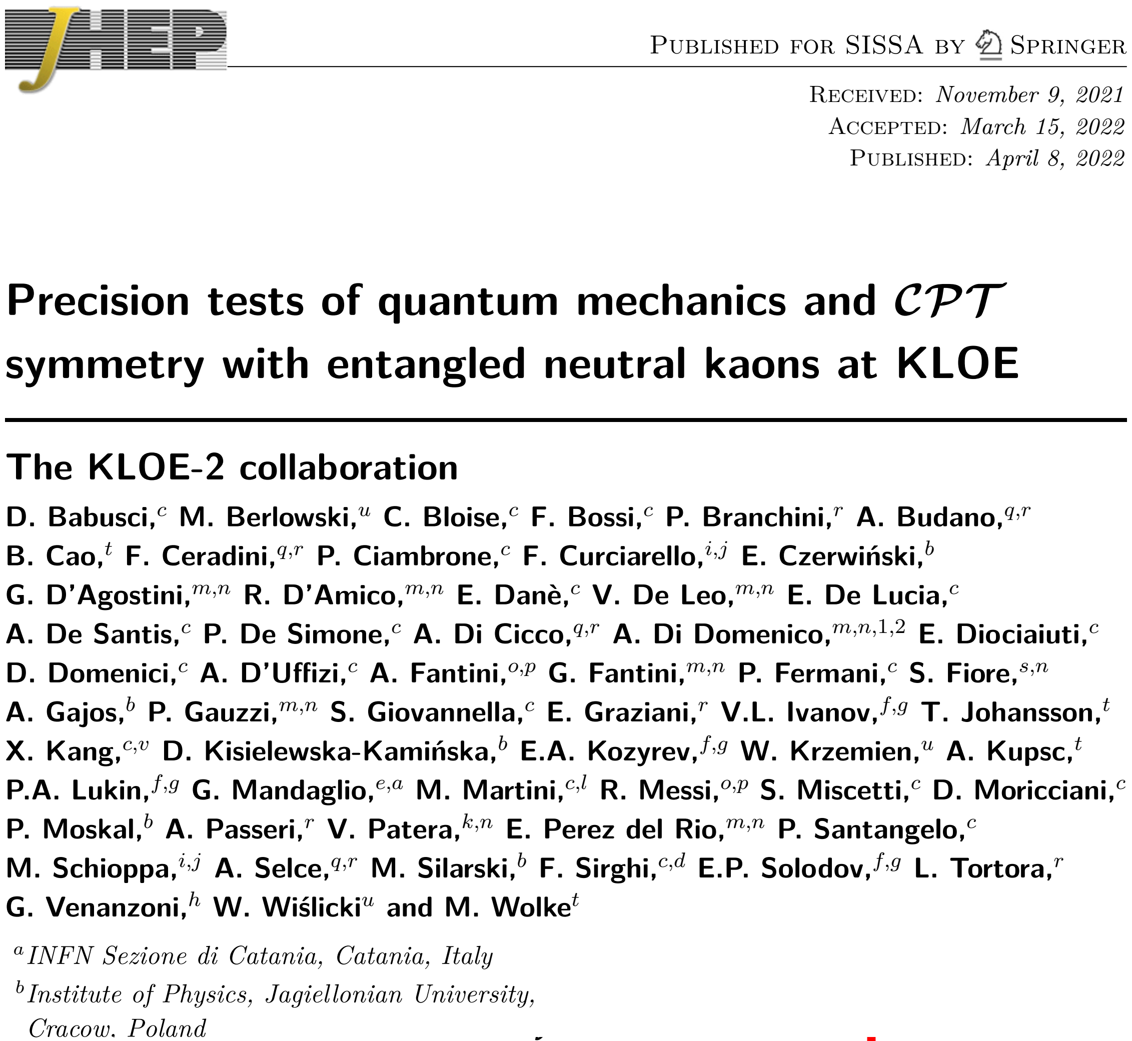

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Precision tests of quantum mechanics and $\mathcal{CPT}$ symmetry with entangled neutral kaons at KLOE

The KLOE-2 collaboration

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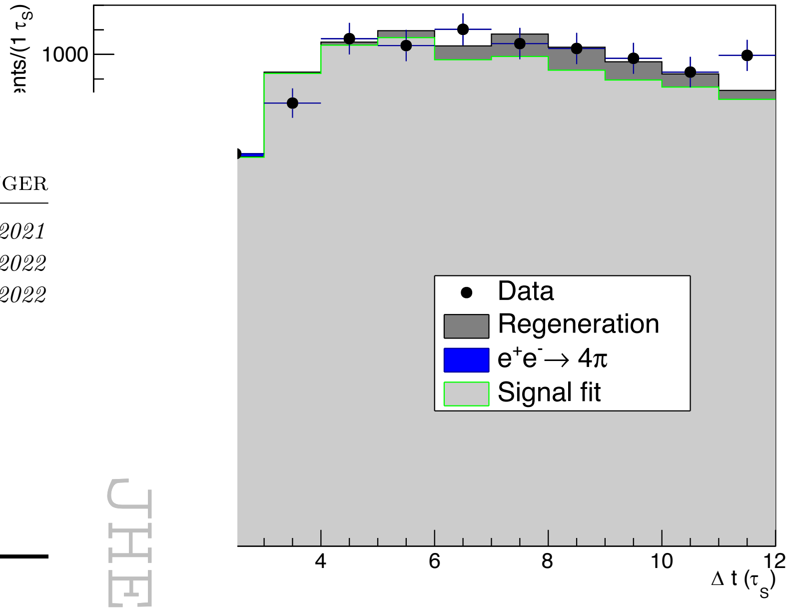
JHEP04(2022)059

ζ_0
ζ_S
γ
$\Re$
$\Im$
$|\alpha$
ϕ

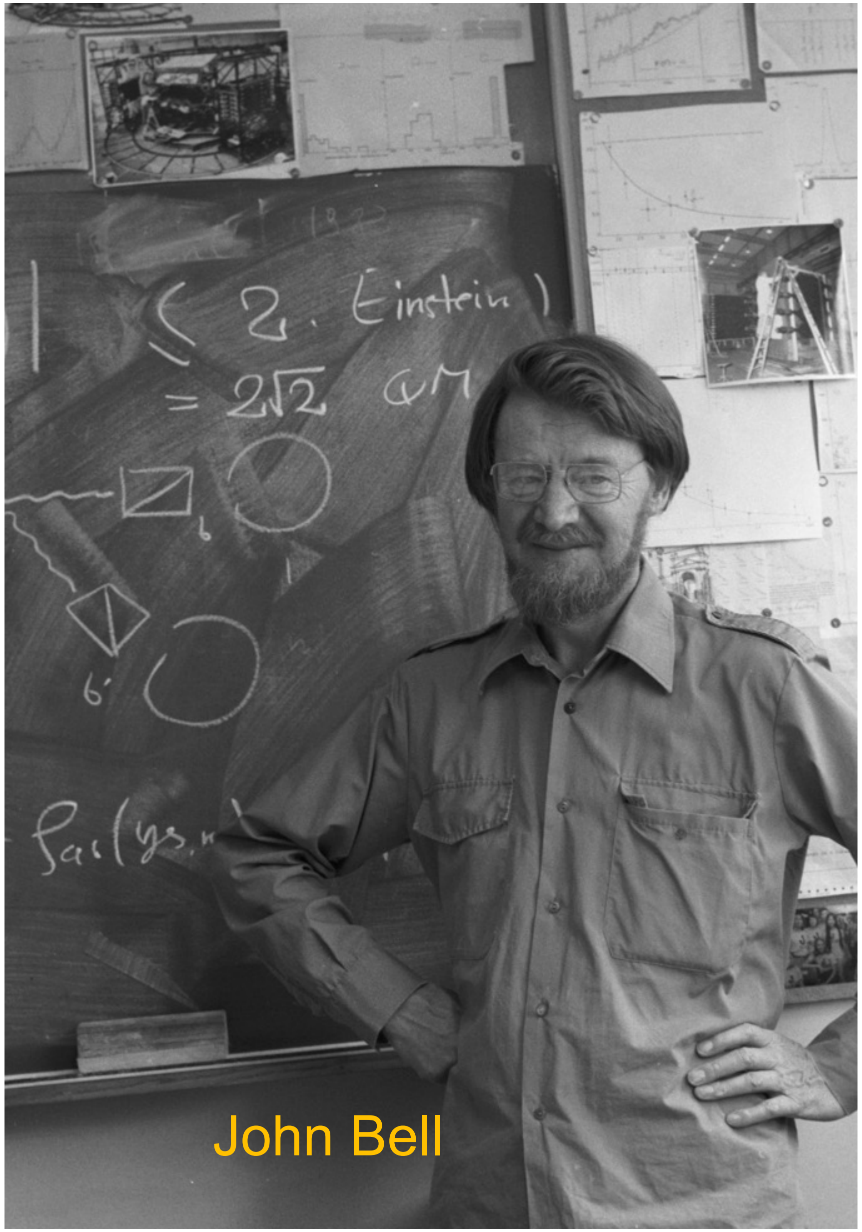


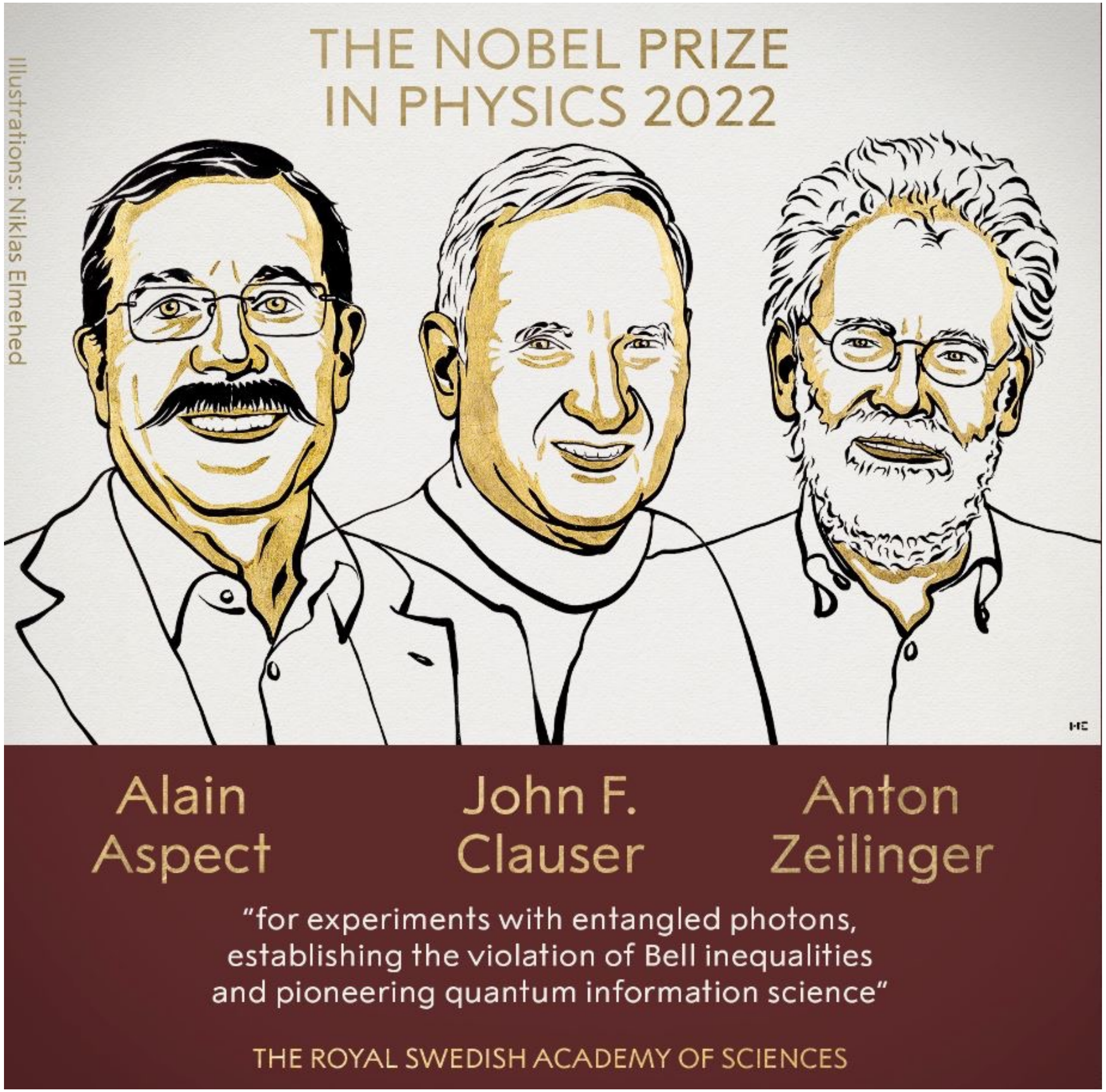
$1.2_{stat} \pm 0.5_{syst})\times10^{-16}$ GeV

$_S, K_L K_L) < 2.4\times10^{-7}$

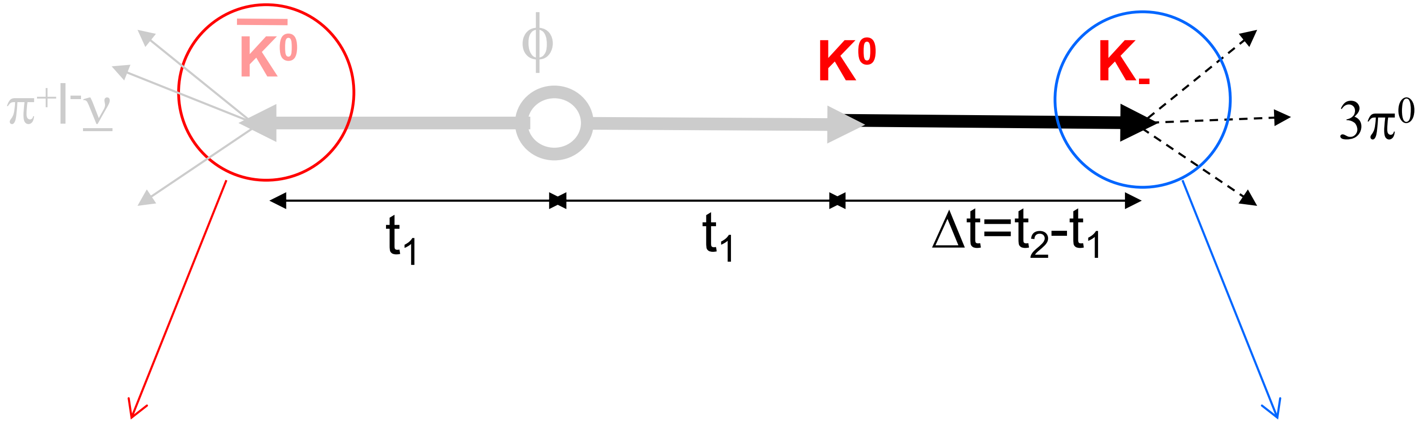
04 (2022) 059
[improvement x2 wrt KLOE PLB 642(2006) 315]

Entanglement





Can Future post-tag the Past?

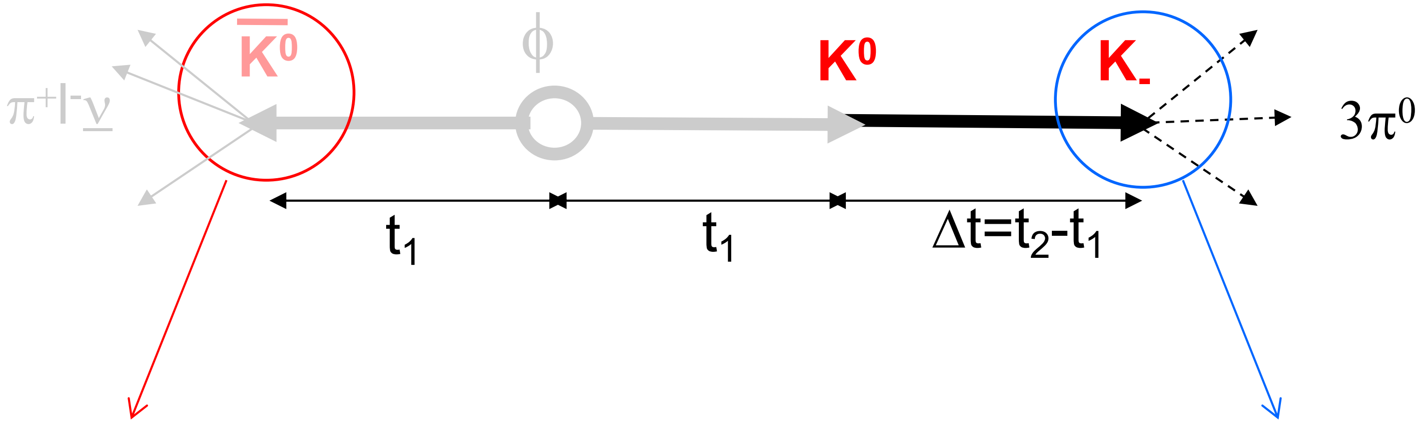


PAST

FUTURE

The past (kaon decay at t_1) tags the future partner kaon state at t_2 **before its decay**

Can Future post-tag the Past?



PAST

FUTURE

The future (kaon decay at t_2) post-tags the past partner kaon state at t_1, **before the decay**, when it was entangled !

The past (kaon decay at t_1) tags the future partner kaon state at t_2 **before its decay**

In maximally entangled systems the complete knowledge of the system as a whole is encoded in the entangled state, the single subsystems are undefined.

$$
\begin{aligned}
|K^{(1)}(t=t_1)\rangle &= \langle f_2|T|i_{t_1,t_2}\rangle \\
&= \frac{\mathcal{N}}{\sqrt{2}}\{\langle f_2|T|\mathrm{K_L}\rangle e^{-i\lambda_L t_2} e^{-i\lambda_S t_1}|\mathrm{K_S}\rangle - \langle f_2|T|\mathrm{K_S}\rangle e^{-i\lambda_S t_2} e^{-i\lambda_L t_1}|\mathrm{K_L}\rangle\} \\
&= \frac{\mathcal{N}}{\sqrt{2}}\langle f_2|T|\mathrm{K_S}\rangle\{e^{-i\lambda_S t_1}\left[\eta_2\, e^{-i\lambda_L t_2}|\mathrm{K_S}\rangle\right] - e^{-i\lambda_L t_1}\left[e^{-i\lambda_S t_2}|\mathrm{K_L}\rangle\right]\}\ .
\end{aligned}
$$

PAST

FUTURE

"Future post-tags the Past" effect: summary

Exploiting the Lee-Yang formalism:

From past to future:

The state of the last decaying particle (particle-2) - due to the decay of its entangled partner **in the past** - is prepared at $t = t_1$ as:

$$|K^{(2)}(t = t_1)\rangle = N_2[|K_L\rangle - \eta_1 |K_S\rangle]$$

a state which depends on η_1 of particle-1.

From future to past:

The state of the first decaying particle (particle-1) - due to the decay of its entangled partner **in the future** - is prepared at $t = 0$ as:

$$|K^{(1)}(t = 0)\rangle = N_1\{\eta_2 e^{-i\lambda_L t_2} |K_S\rangle - e^{-i\lambda_S t_2} |K_L\rangle\}$$

a state which depends on η_2 **and t_2** of particle-2.

This effect naturally leads to the definition of new observables, that e.g. could be exploited in discrete symmetries tests.

Details in:

PHYSICAL REVIEW D **105,** 116004 (2022)

Can future observation of the living partner post-tag the past decayed state in entangled neutral *K* mesons?

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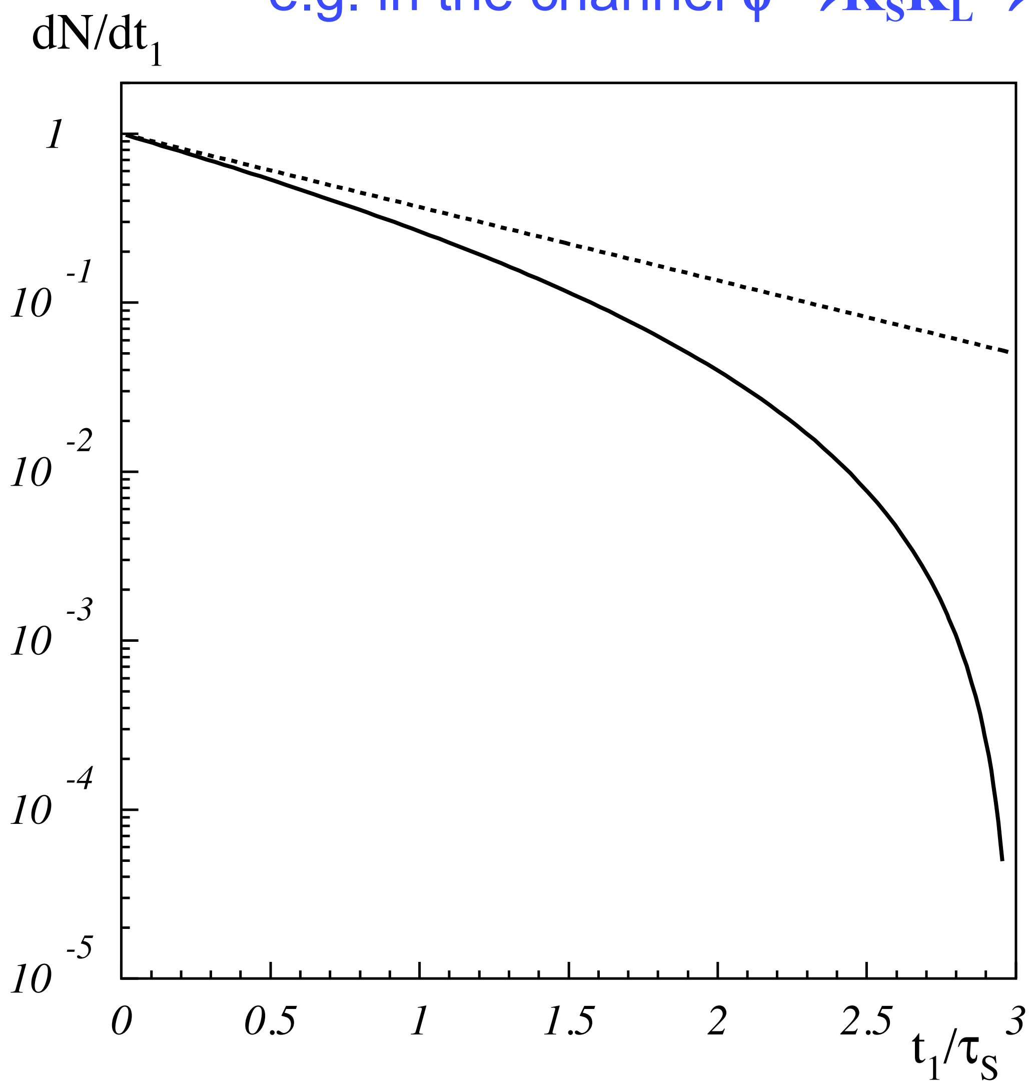
From this the K_S tagging condition is derived:

$$\frac{e^{-\frac{\Delta\Gamma\Delta t}{2}}}{|\eta_2|} \ll 1 \qquad [K_S\text{-tag}]$$

"Future post-tags the past": observable effects

This quantum effect is directly observable at KLOE/KLOE-2
e.g. in the channel $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ to maximize the effect



Distributions normalized to unity at t_1=0

“Future post-tags the past”: observable effects

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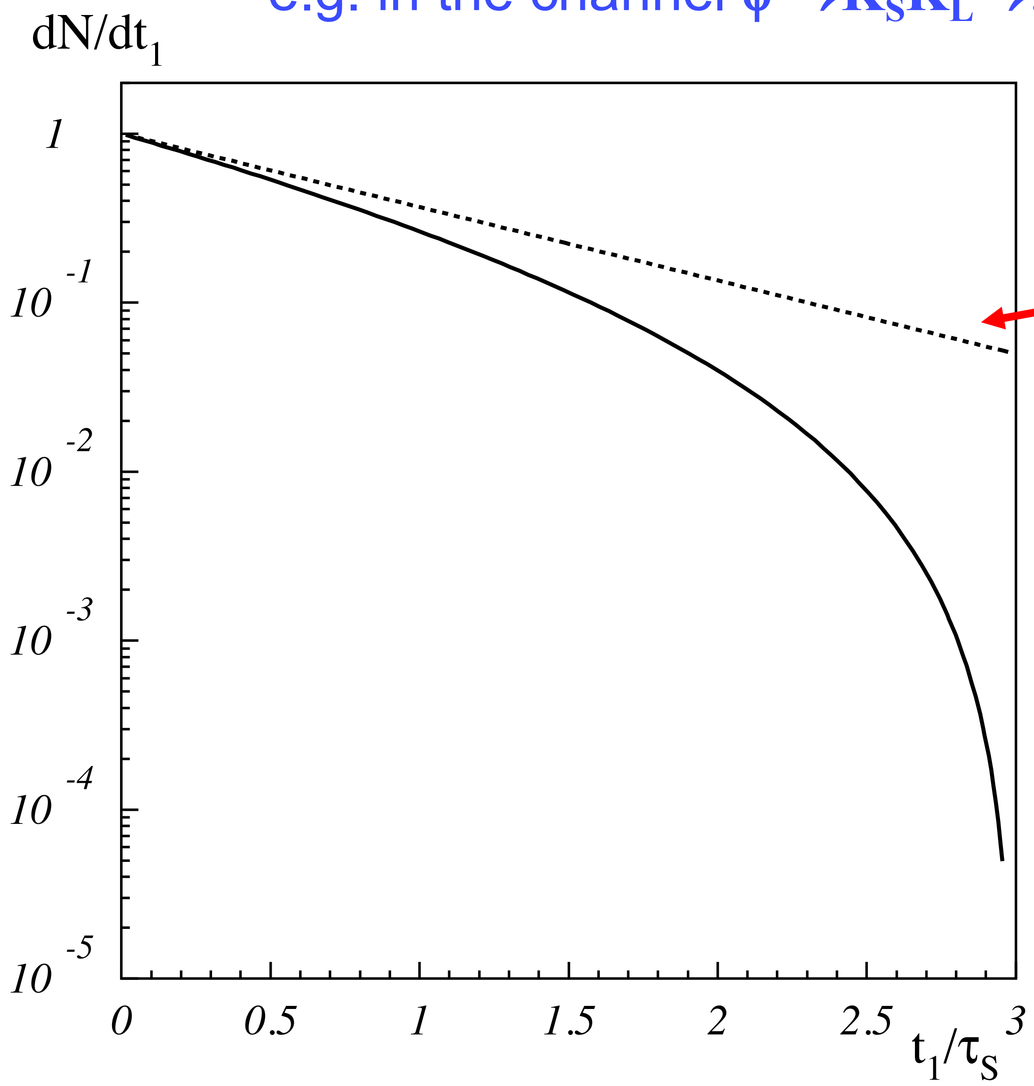


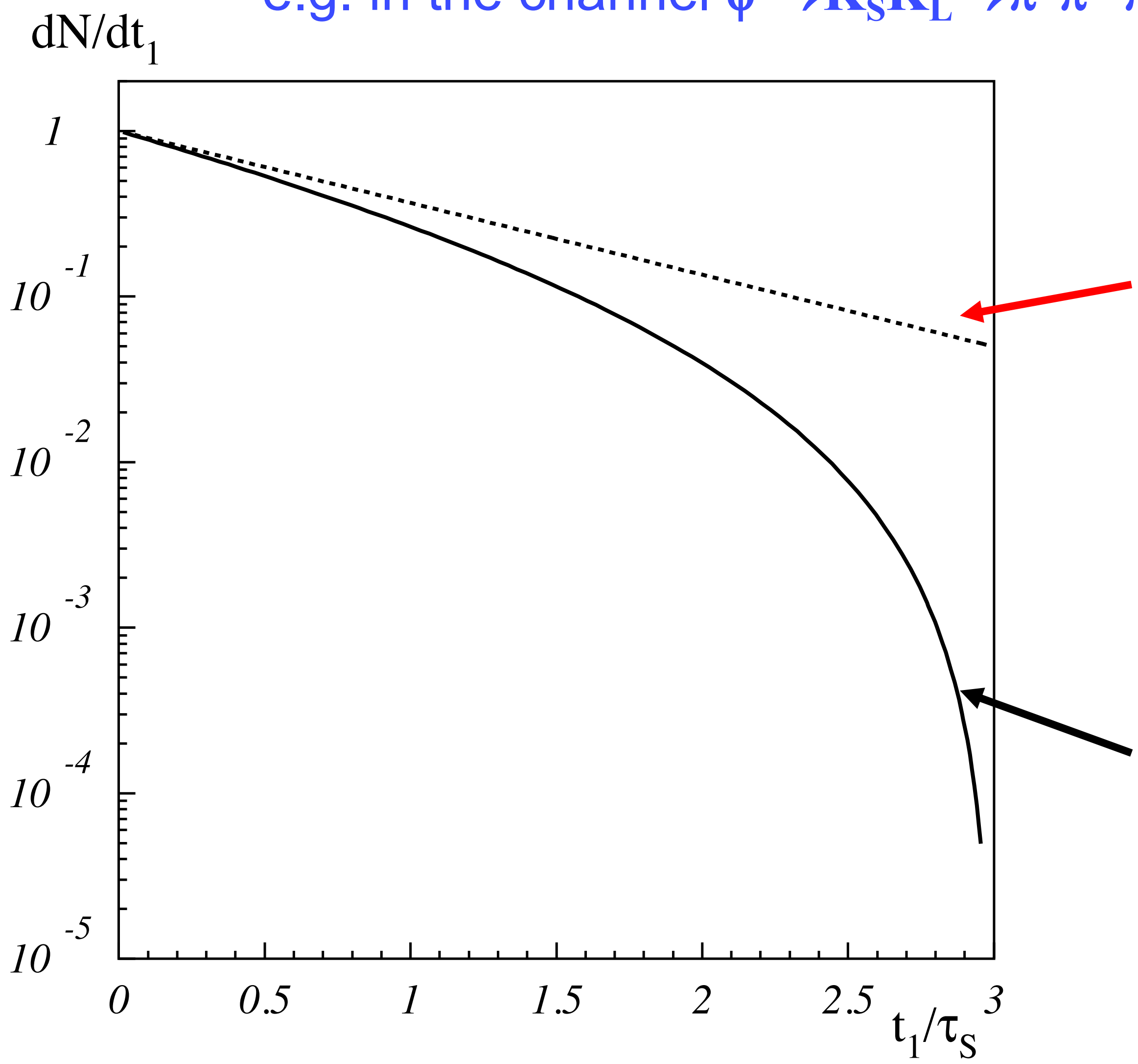
DECOHERENCE REGIME

$I(t_1)$ with $t_2 >> t_1$ and $|\eta_{+-}|, \Delta\Gamma$
such that the K_S post-tag condition is fulfilled =>
definite width: Γ_S i.e. a K_S state

Distributions normalized to unity at t_1=0

"Future post-tags the past": observable effects

This quantum effect is directly observable at KLOE/KLOE-2
e.g. in the channel $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$ to maximize the effect



DECOHERENCE REGIME

$I(t_1)$ with $t_2 >> t_1$ and $|\eta_{+-}|, \Delta\Gamma$
such that the K_S post-tag condition
is fulfilled =>
definite width: Γ_S i.e. a K_S state

INTERFERENCE REGIME

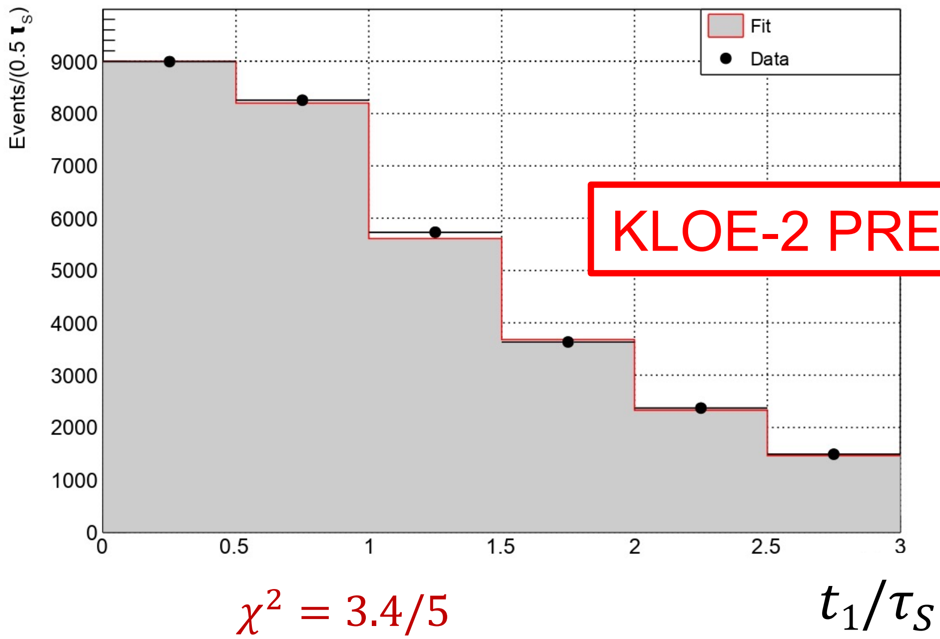
$I(t_1)$ with $t_2=3\tau_S$ (> t_1)
K_S post-tag condition
is NOT fulfilled => no definite width

Distributions normalized to unity at $t_1=0$

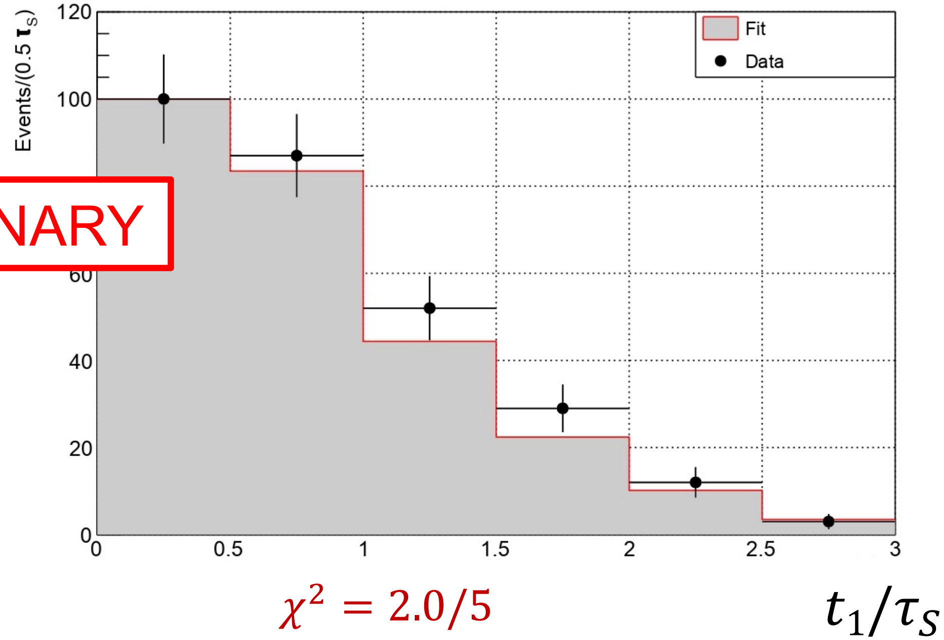
“Future post-tags the past” effect at KLOE-2

- Analysed data: 1.7 fb^{-1} (same data set used to search for decoherence and CPT violation – see previous slides)
- Fit of t_1 distribution with QM theory taking into account resolution and efficiency through a 4-dimensional smearing matrix $(t_{1,true}\ , t_{1,reco}, t_{2\ true}\ , t_{2,reco})$
- Negligible background from $e^+e^- \to 4\pi$ process and regeneration on beam pipe.
- histogram normalization as fit parameter.

Decoherence regime: $t_2 > 30\tau_S$



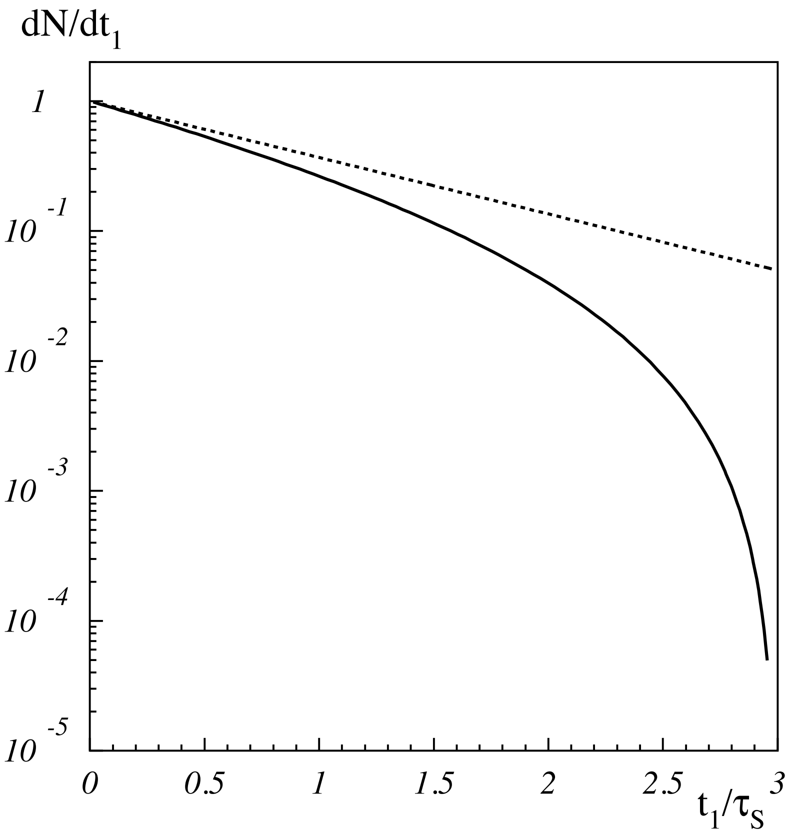
Interference regime: $2.5\tau_S < t_2 < 3\tau_S$

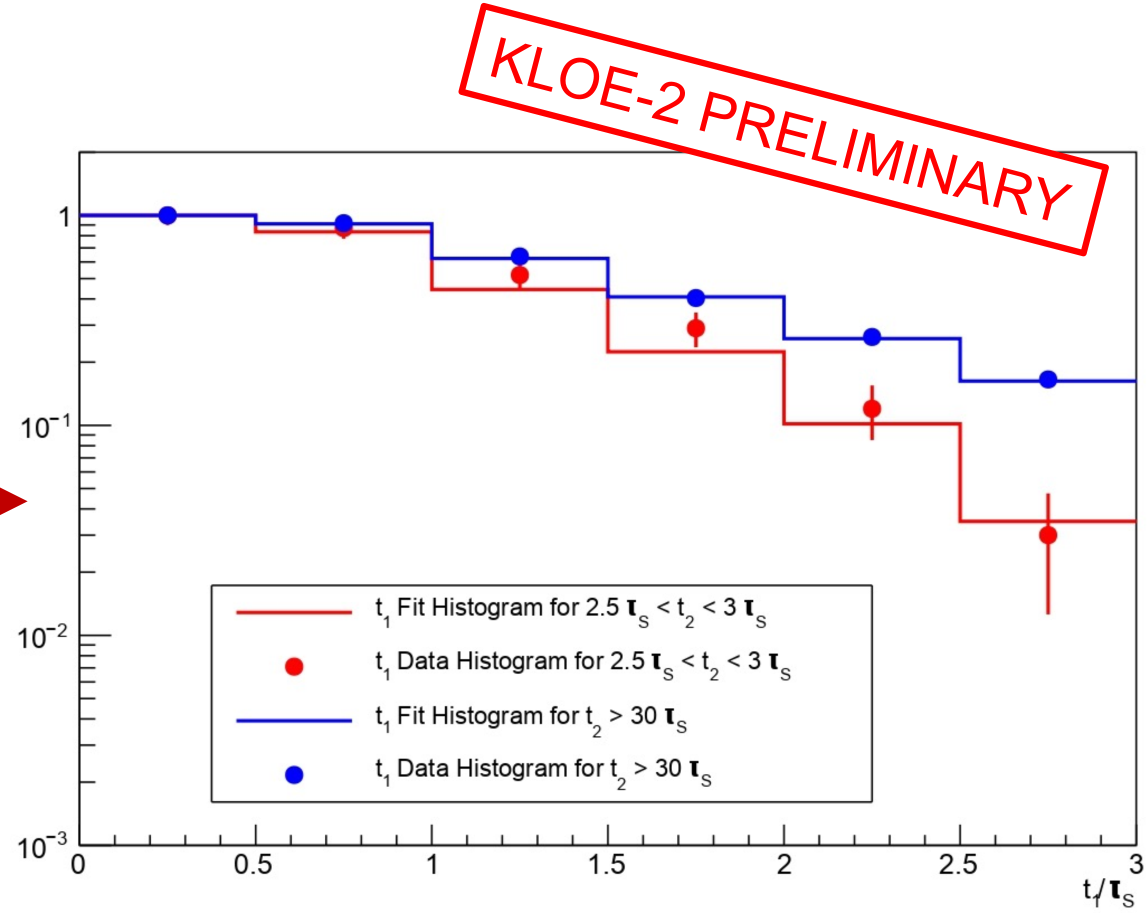


KLOE-2 PRELIMINARY

"Future post-tags the past" effect at KLOE-2

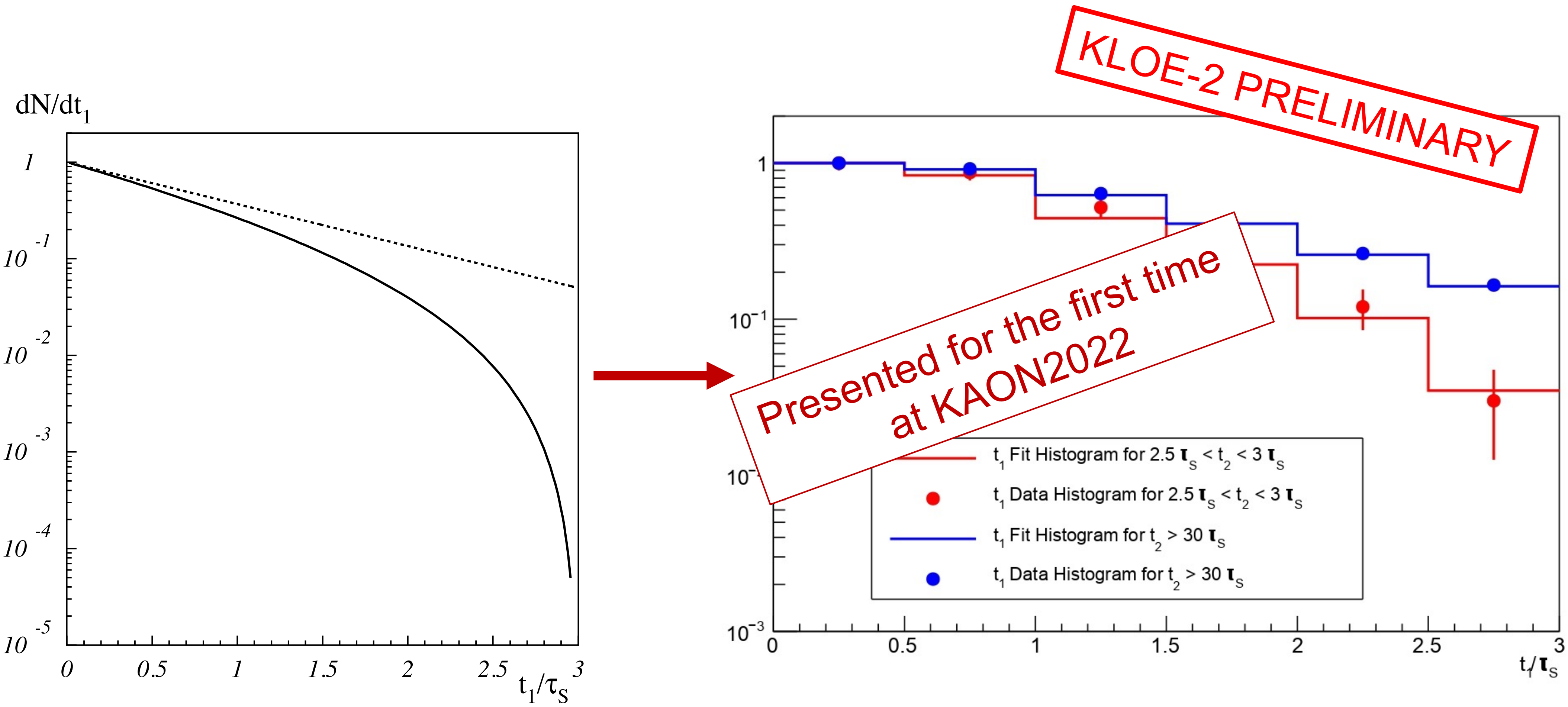
- normalizing the distributions to unity at t_1=0, we get a first evidence of the effect





"Future post-tags the past" effect at KLOE-2

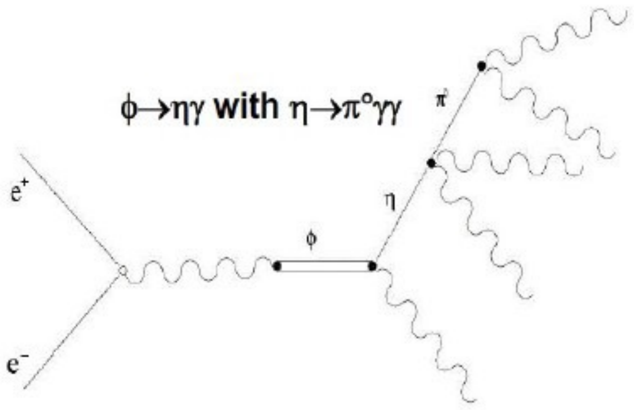
• normalizing the distributions to unity at $t_1=0$, we get a first evidence of the effect

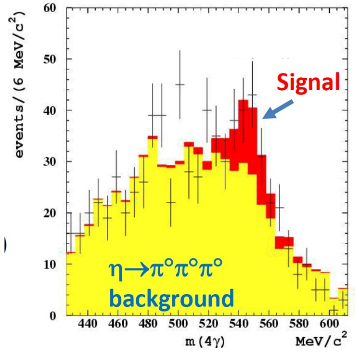


Hadron physics results

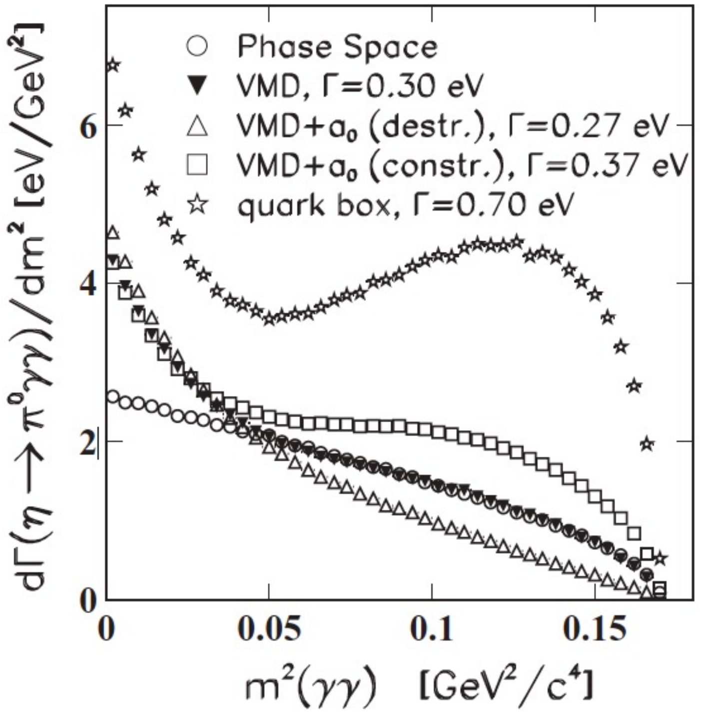
$\eta \to \pi^0\gamma\gamma$ decay

- $\eta\to\pi^0\gamma\gamma$ (from $\phi\to\eta\gamma$): χPT golden mode,
  $O(p^2)$ null, $O(p^4)$ suppressed
  $\Rightarrow$ sensitive to $O(p^6)$
  Br = $(2.21 \pm 0.24 \pm 0.47)\times 10^{-4}$ CB@AGS(2008)
  [PRC 78 (2008) 015206]
  Br = $(2.52\pm0.25)\times 10^{-4}$ CB@MAMI (2014)
  [PRC 90 (2014) 025206]
  Old KLOE preliminary: $(8.4\pm2.7\pm1.4)\times 10^{-5}$
  (L = 450 pb^{-1} ~ 70 signal events)
  [Acta Phys.Slov.56(2006)403]

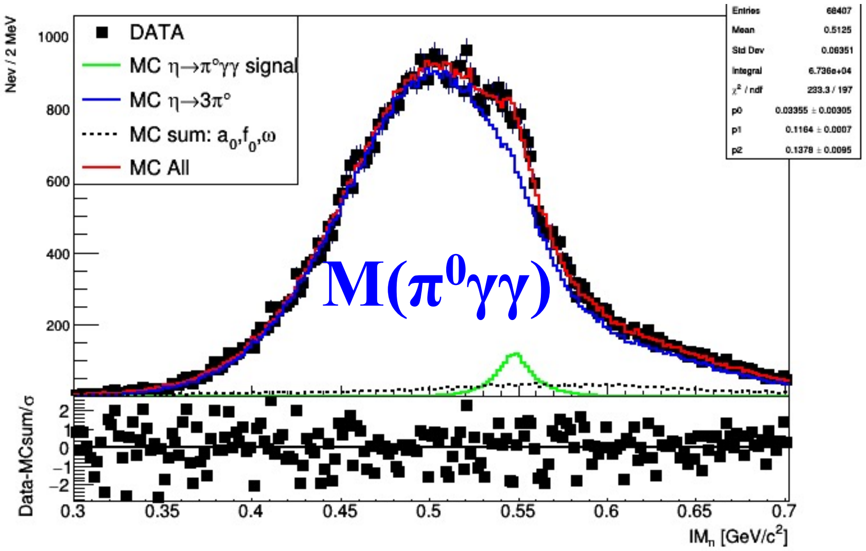


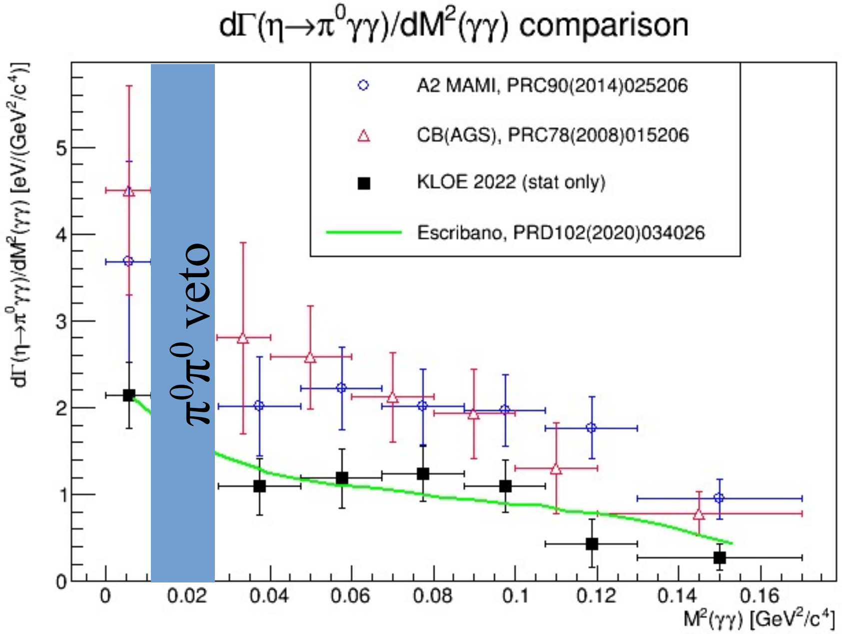


- Invariant mass of non-π^0 photons can be used to test theoretical models
- Recent theoretical prediction based on LσM + VMD
  $Br(\eta\to\pi^0\gamma\gamma) = (1.30 \pm 0.08)\times 10^{-4}$
  [R.Escribano et al., PRD 102 (2020) 034026]



$\eta \rightarrow \pi^0\gamma\gamma$ decay





- Integrated luminosity of 1.7 fb^{-1} ($\sim 7 \cdot 10^7$ η's)
- 5 prompt photons selection, no charged tracks
  ~ 1200 signal events
- Data distribution fit with MC components:

  $\eta \rightarrow 3\pi^0$, $\eta \rightarrow \pi^0\gamma\gamma$ signal, sum of non- $3\pi^0$
- Fit χ^2/(ndf=98)=1.033 (fit prob=39%)
- Normalized with $\eta \rightarrow 3\pi^0$ sample with 7 photons
- The main sources for systematic uncertainty come from 5 prompt photon selection, analysis cuts and normalization
- Last checks on systematics ongoing

$$BR(\eta \rightarrow \pi^0\gamma\gamma) = (1.21 \pm 0.13_{stat} \pm 0.25_{syst}) \cdot 10^{-4}$$

- Separate fits in bins of M2(γγ)
- Second bin missing due to the veto for π0π0 events (from φ→f0(980)γ, with f0(980) →π0π0 and e+e−→ωπ0 with ω→π0γ)

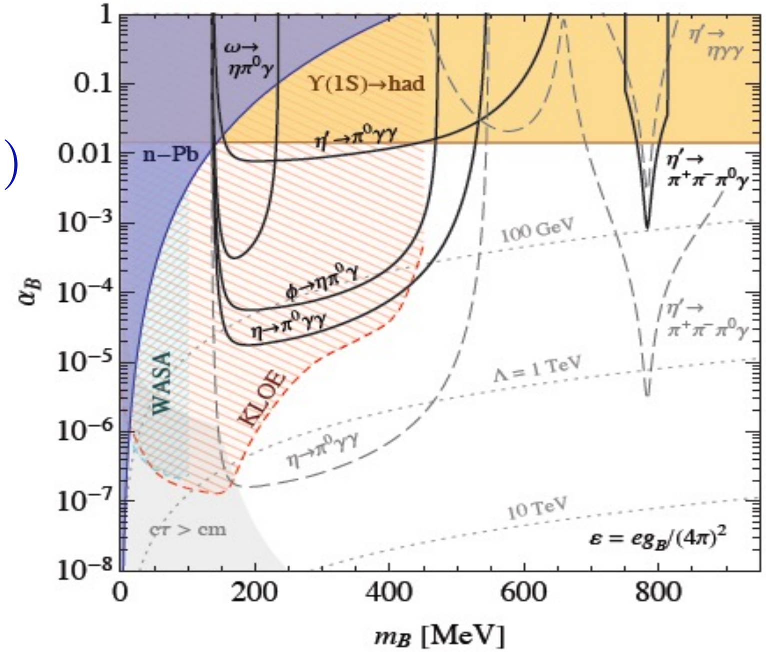
Leptophobic B boson

- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the ω(782) ⇒ $I^G=0^-$

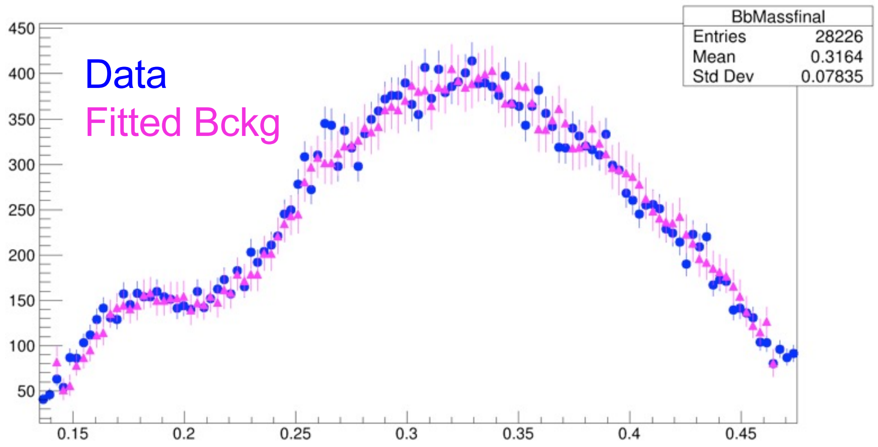
$$\mathcal{L} = \frac{1}{3} g_B \bar{q}\gamma^\mu q B_\mu \qquad \alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\,\mathrm{MeV})$$

- Dominant decay channel (m_B < 600 MeV): $B \to \pi^0\gamma$
- Can be studied in:
  $\phi \to \eta B \;\Rightarrow\; \eta\pi^0\gamma \;\Rightarrow$ 5 prompt γ final state

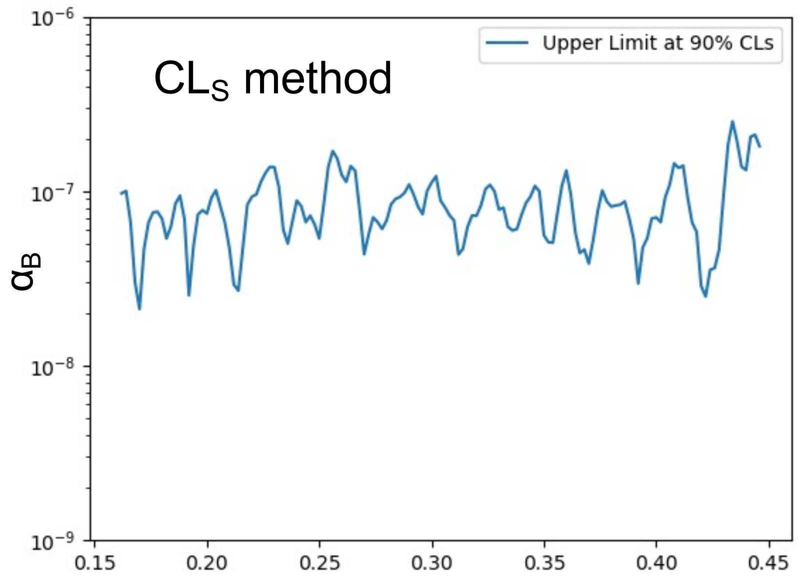
[Tulin, PRD89(2014)114008]



- L = 1.7 fb-1 analyzed
- Background evaluation from sidebands
  (fit region 5 σ with 1σ exclusion region, σ ~ 2 MeV)



$M_{\pi 0\gamma}$ [GeV]



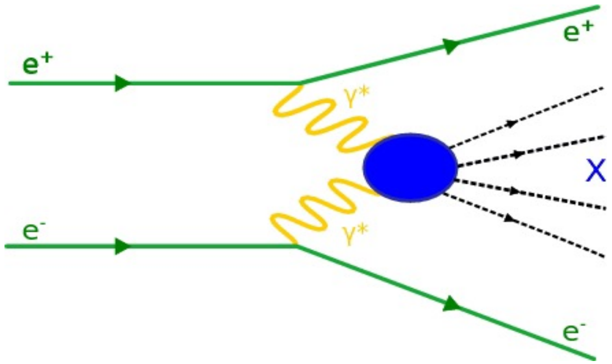
M_B [GeV]

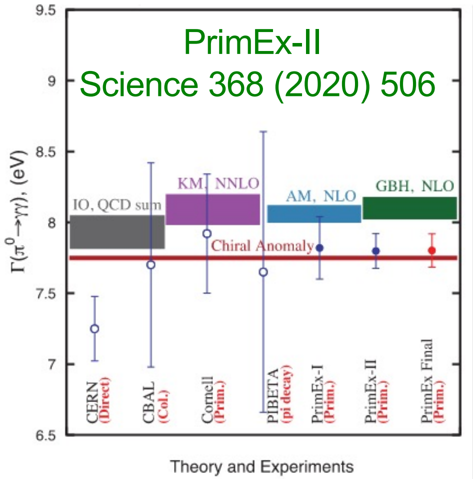
Study of $\gamma\gamma \rightarrow \pi^0$ with High Energy Tagger (HET)

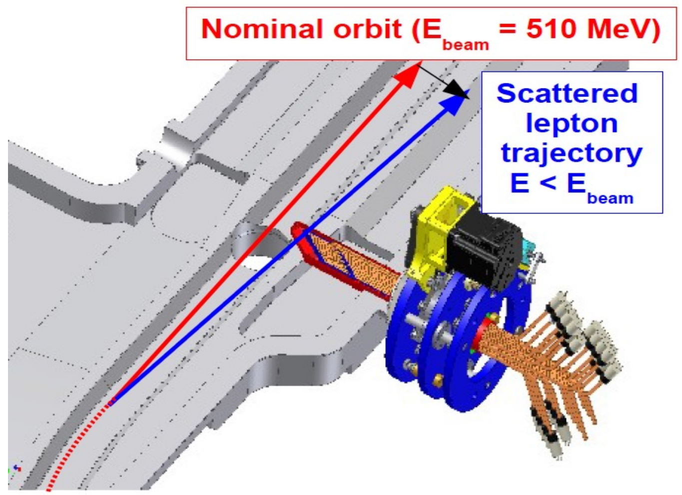
$$e^+e^- \rightarrow e^+e^-\gamma^\star\gamma^\star \rightarrow e^+e^- X$$

$$[\mathbf{C(X)} = +\mathbf{1}]$$

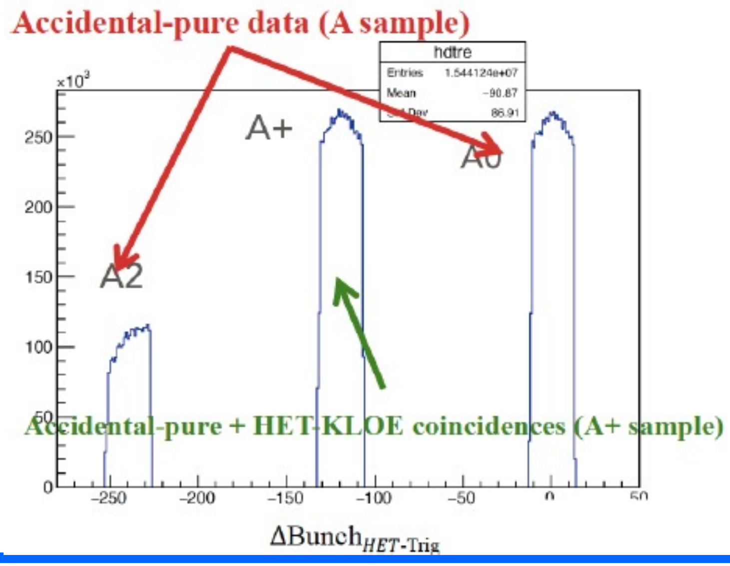
$$\mathbf{X} = \pi^0, \pi\pi, \eta$$







- Precision measurement of $\Gamma(\pi^0\rightarrow\gamma\gamma)$ (goal @ few % level)
- Transition form factor $\mathcal{F}_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2|< 0.1$ GeV^2) relevant for the Light-by-Light scattering contribution to $(g-2)_\mu$



- First bending dipoles of DAΦNE act as spectrometers for the scattered e^+/e^- (420 < E < 495 MeV)
- Strong correlation between E and trajectory
- Scintillator hodoscope + PMTs, inserted in roman pots Pitch: 5 mm, ~ 11 m from IP (σ_E~2.5 MeV σ_t~500 ps)

- Analysis based on “A+”/”A” comparison
- “A” sample used for background modelling
- Signal pdfs by MC (Ekhara) simulation, control samples and BDSIM transport MC

Search for $e^+e^- \rightarrow e^+e^- \gamma^*\gamma \rightarrow e^+e^- \pi^0$

- $\frac{\sigma_{\pi^0}}{\sigma_B} = \frac{N_{\pi^0}}{\sigma_{Bmeas}\epsilon_{analysis}\int Ldt}\frac{A_B}{A_{\pi^0}}$

- N_{π^0} obtained from a fit to the $M_{\gamma\gamma} vs \Delta T_{\gamma\gamma}$ distribution per HET channel (or data taking periods) with background and signal shapes

- Using $M_{\gamma\gamma} vs \Delta T_{\gamma\gamma}$ signal shape independent from any assumption
- Depends on KLOE calorimeter reconstruction and trigger : carefully checked on data (radiative Bhabha control sample)

- Pure background sample from data in a time region outside the coincidence interval between KLOE and HET data acquisition

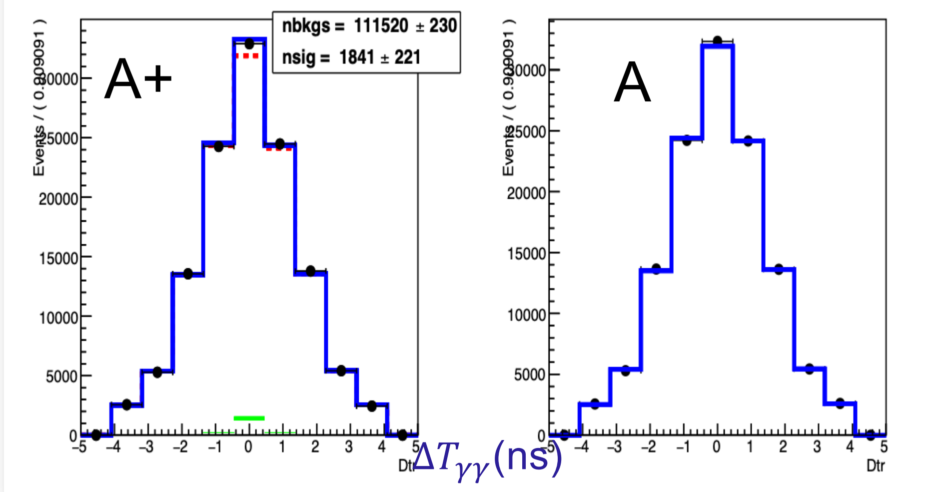
- We obtained from unweighted fits a total of 8820(570) signal events

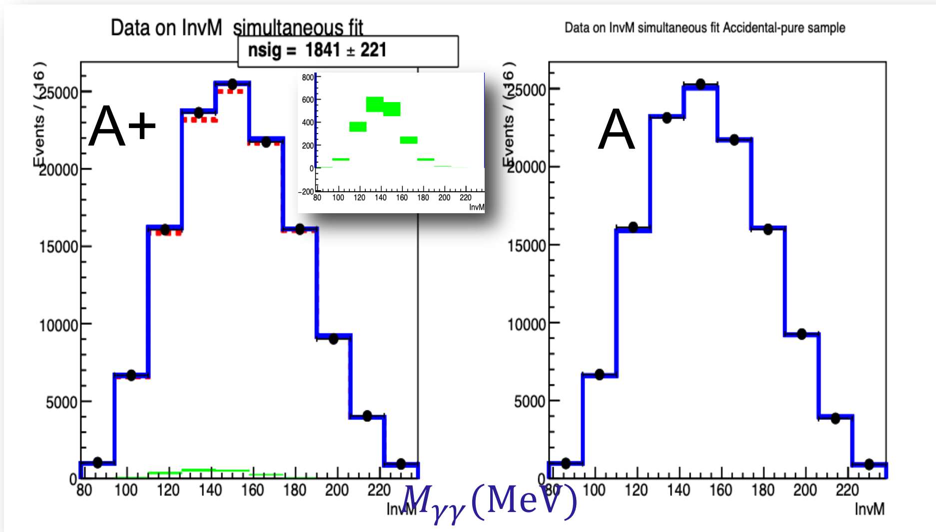
- Efficiency per period and per channel obtained using the simulation of radiative Bhabha's at very low angle (σ_B) and measuring the cross sections per channel and data taking period (σ_{Bmeas}).

- Q^2 distribution can be obtained from the tagged sample, after background subtraction. We are investigating the sensitivity with our data set to extract TFF information.

- A detailed report is in preparation for the review by the Collaboration

Fit example: ch 10-12 HET-electrons





Conclusions

- Final round of Data Reconstruction and MC production completed.
- Root output is being completed both for data and MC and will be available on disk.
- Data Consolidation in progress (in background to main offline activities).

- In 2022 we are capitalizing past efforts; three papers on kaons: one published, two submitted to journals; two analyses at final stage, $\eta \rightarrow \pi^0\gamma\gamma$ and B-boson search, with final results and paper draft expected by the end of the year.
- Several other analysis ongoing both with KLOE and KLOE-2 samples with preliminary results; ideas for new analyses.
- All these results have been recently presented at several international conferences and workshops, including ICHEP2022, QNP2022, Excited QCD, PhiPsi2022, eeFACT2022, KAON2022, DISCRETE2022 etc.

- Recently the collaboration discussed the possibility to open KLOE/KLOE-2 data:
- KLOE-2 recognize the importance of opening the data
- some of the tasks are being implemented (standard data format, i.e. ROOT output)
- however the whole operation requires a strong effort that, given the small size of the Collaboration and its commitments in data processing and analysis, cannot be completed
- KLOE-2 is anyhow willing to stimulate the collaboration with external people interested in specific analyses, and a special procedure to ease and formalize it has been set up.
- KLOE-2 is available to guide and supervise the operation of “opening the data” in case of interest and support from outside the Collaboration (for instance dedicated postdoc positions)

LNF Scientific Committee

LNF Scientific Committee after the meeting on May 16-17, 2022
From the document “Findings & Recommendations”

Recommendation KLOE:

In order to promote new analyses and attract new collaborators a dedicated workshop should be envisaged at LNF.

SPARE SLIDES

List of analyses of interest for the KLOE-2 collaboration

Ongoing Analyses:

- $\gamma\gamma\to\pi^0$
- Test of T, CP, CPT in kaon transitions ($\varphi\to K_S K_L \to 3\pi^0\ \pi e\nu$, $\pi\pi\ \pi e\nu$)
- $K_S\to 3\pi^0$
- $\eta\to\pi^0\gamma\gamma$
- Search for leptophobic B-boson
- $e^+e^-\to\pi^+\pi^-\pi^0\gamma_{ISR}$
- $\phi\to\eta\pi^+\pi^-$ / $\eta\mu^+\mu^-$
- "From future to past" effect in $\phi\to K_S K_L\to\pi^+\pi^-\pi^+\pi^-$
- $K_S\to\pi^+\pi^-\pi^0$
- Charged Kaon mass

Other analyses:

- Search for Axion Like Particles in $\gamma\gamma$
- $\varphi\to K_S K_S\gamma$
- $\varphi\to\pi^+\pi^-\pi^0$
- $K_S\to\gamma\gamma$
- $K_L\to\gamma\gamma$
- $K_S\to$invisibile
- $K_S\to\pi^0\gamma\gamma$
- Hadronic cross section ($\pi^+\pi^-$) with all data sample
- Measurement of Re(ε'/ε) and Im(ε'/ε)