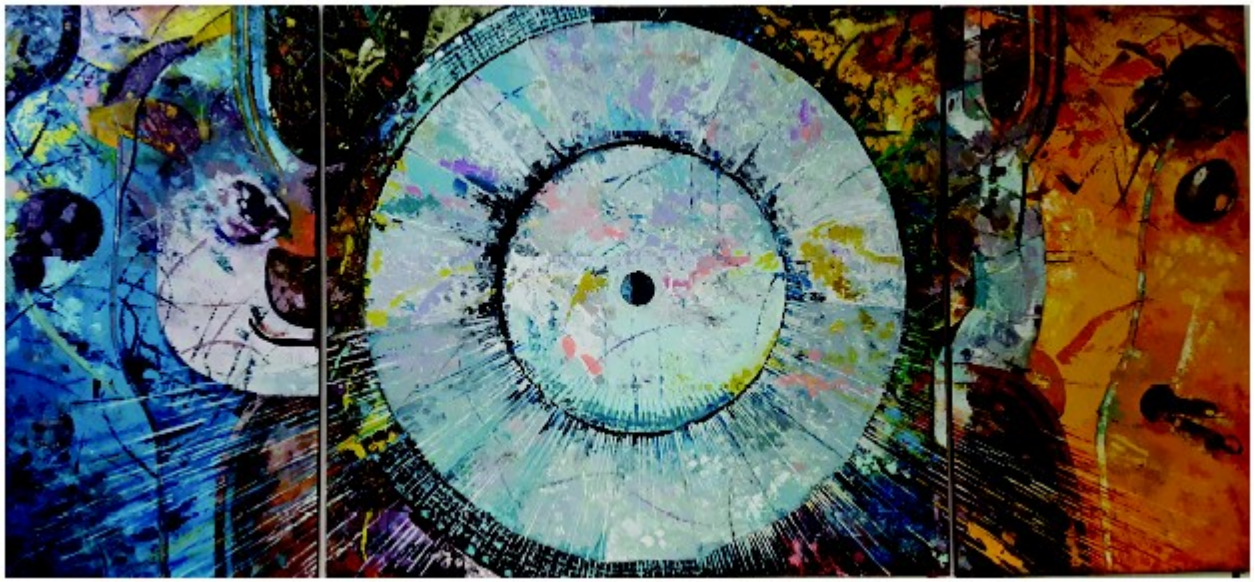
# Status of the KLOE-2 Experiment



**Veronica De Leo**
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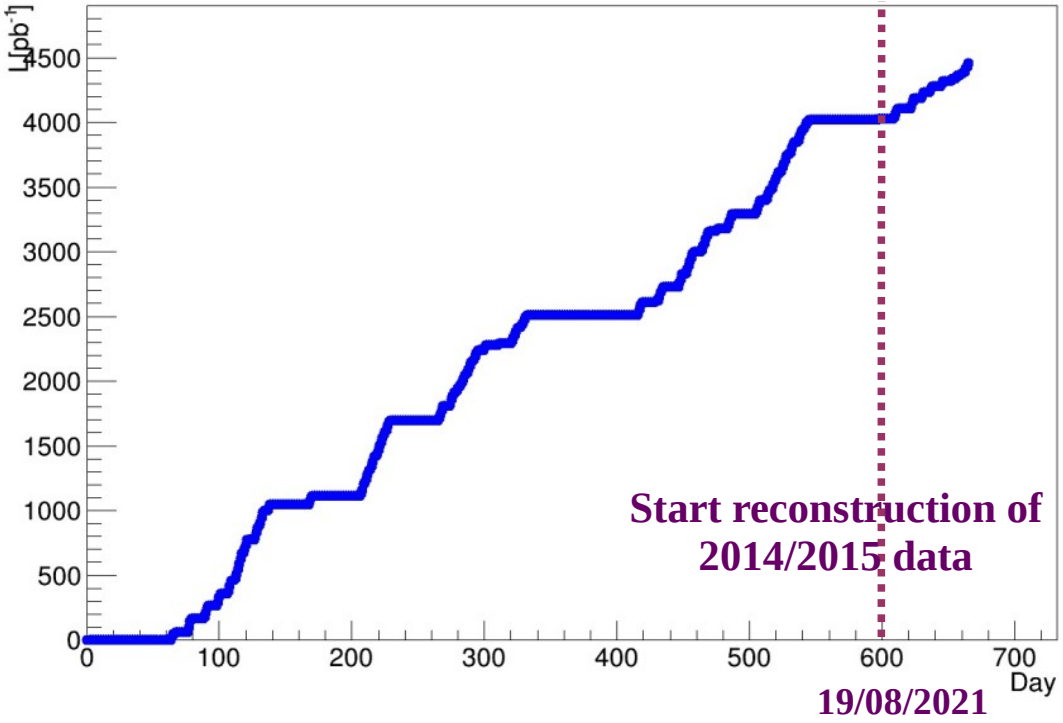
**Sezione INFN Roma 1**
**on behalf of the KLOE-2 Collaboration**

LNF Scientific Committee Meeting
Frascati, November 8th 2021

# Data recontruction & MC status

- **Second round of the reconstruction with the final DBV-40 started in March 2020:**
  - **sample of 2016-2018 data completed in June 2021 (~4fb$^{-1}$) → average (peak) reconstruction rate ~25 (30) pb$^{-1}$/day (without considering dead time);**
  - **reconstruction of the 2014/2015 dataset ongoing (not reconstructed with the previous DBV-38 due to huge background conditions). Slight decrease of the rate for the current sample (more files of smaller size)**

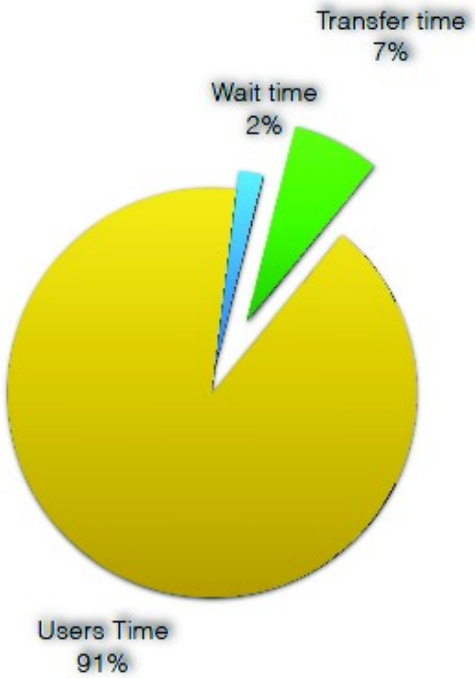


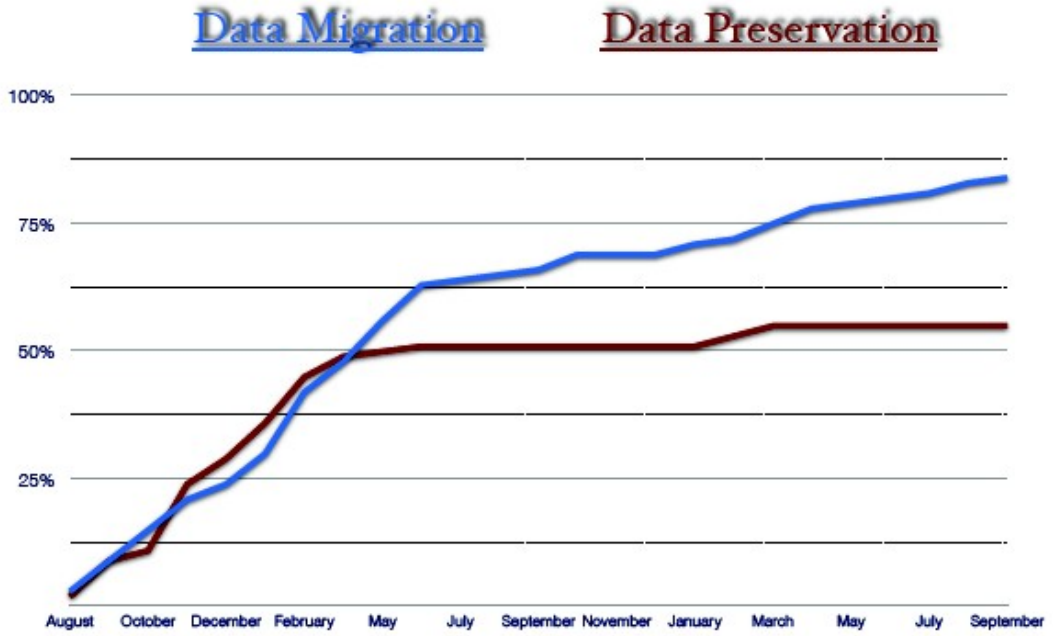

***$L_{int}$ = 4.5 fb$^{-1}$ reconstructed with DBV-40***

- **Massive MC production with the final DBV-40 started: 518 pb$^{-1}$ available for the $\varphi \rightarrow$ *all* process and LSF=1:**
  - **average production rate ~27 pb$^{-1}$/day (performed in parallel with the data reconstruction) → increase with respect to the previous one with DBV-38 (~15 pb$^{-1}$/day)**
  - **first massive MC production with DBV-38 already used in the $K_S \rightarrow 3\pi^0$ analysis**
- **Start of the massive ROOT output production**

# Computing – Data consolidation

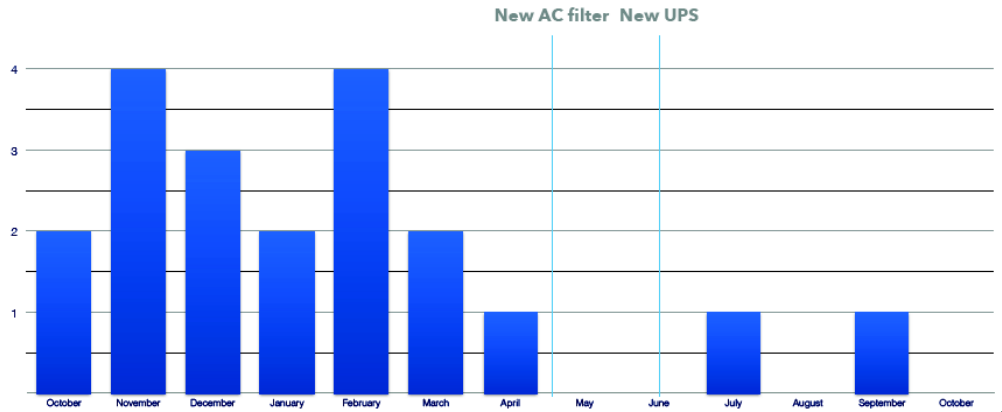
## DATA CONSOLIDATION




- **Priority to data reconstruction, MC production and analyses → data preservation in backgroud**
- **Transfer from old to new library: ~85%**
- **NFS system off; GPFS protocol is the only in use**
- **New UPS unit installed in June 2021**

## FAILURES



# Publications/Ongoing Analyses

## Last Publications

| | |
|---|---|
| • Measurement of the branching fraction for the decay $K_S \to \pi\mu\nu$ with the KLOE detector | Physics Letters B 804 (2020) |
| • $\eta \to \pi^+\pi^-$ (P and CP viol.) | JHEP 10 (2020) 047 |

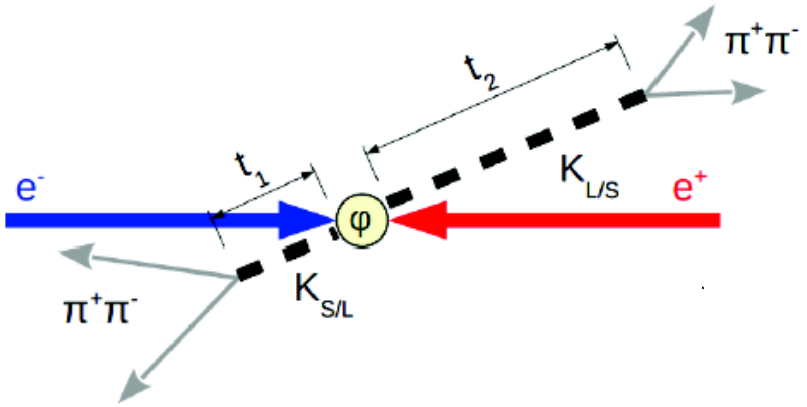
**Both results included in the Particle Data Group**

## Ongoing analyses

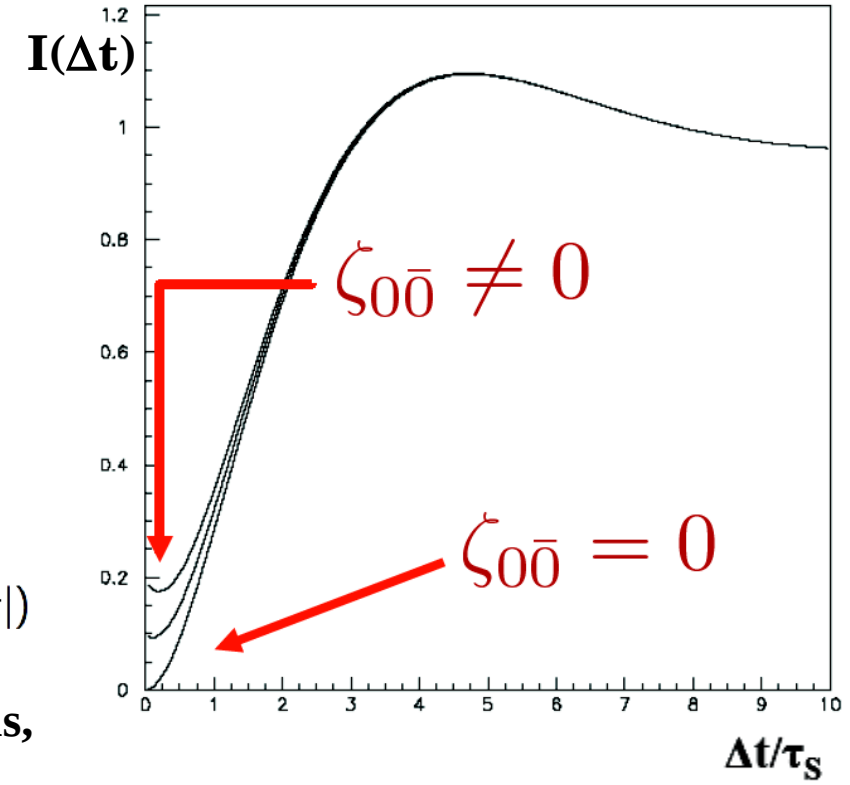
| | | |
|---|---|---|
| • T/CPT tests with $\phi \to K_S K_L \to 3\pi^0$ $\pi e\nu$, $\pi\pi$ $\pi e\nu$ | KLOE data | Pres. at EPS-HEP 2021 |
| • $K_S \to \pi^+\pi^-\pi^0$ | KLOE data | |
| • $K_S \to 3\pi^0$ (CP viol.) | KLOE-2 data | Pres. at EPS-HEP 2021 |
| • Search for decoherence and CPTV in $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ | KLOE data | Pres. at EPS-HEP 2021<br>Paper submitted to JHEP |
| • $K_S \to \pi e\nu$ | KLOE data | |
| • $\pi^0 \to \gamma\gamma$ | KLOE-2 data | Pres. at EPS-HEP 2021<br>Hadron 2021, Panic 2021 |
| • $\eta \to \pi^0\gamma\gamma$ - $\chi$PT golden mode | KLOE/KLOE-2 data | Pres. at EPS-HEP 2021<br>Hadron 2021, Panic 2021 |
| • B-boson search in $\phi \to \eta\pi^0\gamma$, $\eta \to \gamma\gamma$ | KLOE/KLOE-2 data | Pres. at EPS-HEP 2021<br>Hadron 2021, Panic 2021 |
| • $\phi \to \eta\pi^+\pi^-/\mu^+\mu^-$ | KLOE data | |
| • $e^+e^- \to \omega\, \gamma_{ISR}$ | KLOE data | Pres. at EPS-HEP 2021<br>Hadron 2021, Panic 2021 |

# Search for decoherence and CPTV in $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

$$|i\rangle = \frac{1}{\sqrt{2}}\{|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\} = \frac{\mathcal{N}}{\sqrt{2}}\{|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\}$$




$$I(|\Delta t|) \propto e^{-\Gamma_S|\Delta t|} + e^{-\Gamma_L|\Delta t|} - 2\,(1-\zeta_{SL})\, e^{-\frac{\Gamma_S+\Gamma_L}{2}|\Delta t|}\cos(\Delta m|\Delta t|)$$




**$\zeta_{0\bar{0}}$ or $\zeta_{SL}$ decoherence parameter dependig on the basis, $K_0\bar{K}_0$ or $K_SK_L$**

Decoherence effects might arise in a quantum gravity picture necessarily entailing CPT violation [Ellis et. al, NP B241 (1984) 381; Ellis, Mavromatos et al. PRD53 (1996)3846 ]:

1)in this case the relevant parameter in the modified time evolution of neutral kaons is the $\gamma$ parameter (at most $\gamma = O(m_K^2/M_{Planck}) \sim 2\times10^{-20}$ GeV)

2) the initial entangled state is modified adding a tiny symmetric part -> $\omega$ effect (at most $\omega = O(m_K^2/M_{Planc}/\Delta\Gamma) \sim 1\times10^{-3}$)

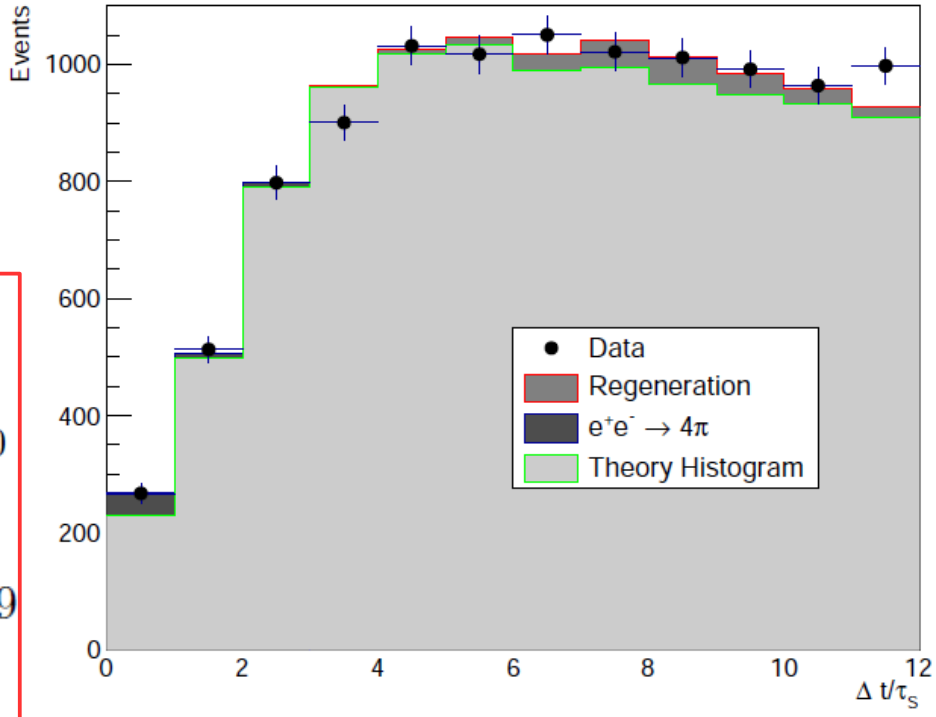
$$|i>= \frac{1}{\sqrt{2}}\left(|K^0>|\bar{K}^0> - |\bar{K}^0>|K^0>\right) + \omega\left(|K^0>|\bar{K}^0> + |\bar{K}^0>|K^0>\right)$$

# Search for decoherence and CPTV in $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

- **Fit including Δt resolution and efficiency effects + regeneration;**
- **Statistical uncertainty reduced by slightly more than half wrt old KLOE analysis with $L_{int}=380pb^{-1}$ (PLB 642 (2006) 315)**
- **Central values consistent with zero**

$$\zeta_{SL} = (0.1 \pm 1.6_{\rm stat} \pm 0.7_{\rm syst}) \cdot 10^{-2} \text{ with } \chi^2/\text{dof} = 11.2/10 ,$$
$$\zeta_{00} = (-0.05 \pm 0.80_{\rm stat} \pm 0.37_{\rm syst}) \cdot 10^{-6} \text{ with } \chi^2/\text{dof} = 11.2/10 ,$$
$$\gamma = (0.13 \pm 0.94_{\rm stat} \pm 0.42_{\rm syst}) \cdot 10^{-21} \text{ GeV with } \chi^2/\text{dof} = 11.2/10$$
$$\Re\omega = (-2.3^{+1.9}_{-1.5{\rm stat}} \pm 0.6_{\rm syst}) \cdot 10^{-4} ,$$
$$\Im\omega = (-4.1^{+2.8}_{-2.6{\rm stat}} \pm 0.9_{\rm syst}) \cdot 10^{-4} \text{ with } \chi^2/\text{dof} = 9.2/9$$
$$|\omega| = (4.7 \pm 2.9_{\rm stat} \pm 1.0_{\rm syst}) \cdot 10^{-4},$$
$$\phi_\omega = -2.1 \pm 0.2_{\rm stat} \pm 0.1_{\rm syst} \text{ (rad) with } \chi^2/\text{dof} = 9.2/9$$

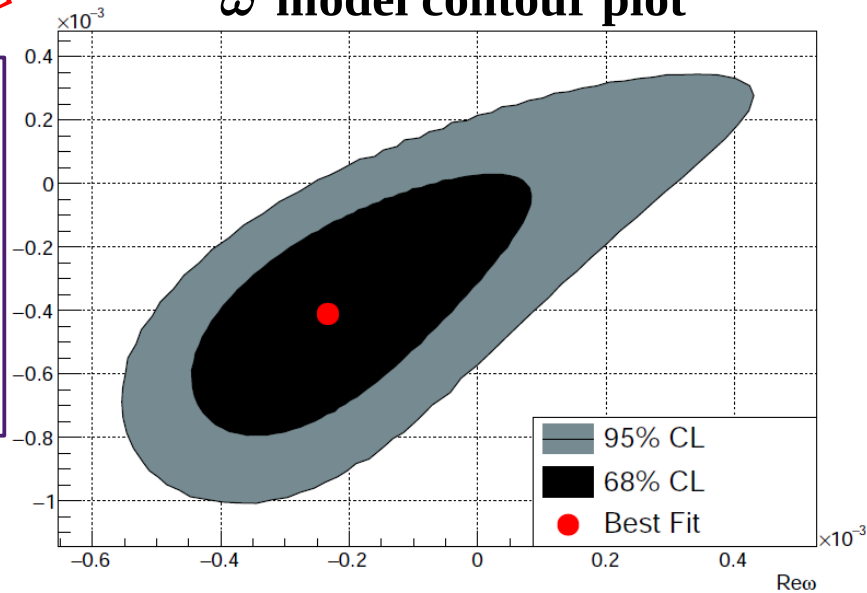
**Fit for the $\zeta_{SL}$ model**




FINAL

$$\zeta_{SL} < 0.030 \text{ (90\% C.L.)},$$
$$\zeta_{00} < 1.4 \cdot 10^{-6} \text{ (90\% C.L.)} ,$$
$$\gamma < 1.8 \cdot 10^{-21} \text{ GeV (90\% C.L.)}$$
$$\text{BR}(\phi \to K_S K_S, K_L K_L) < 2.4 \cdot 10^{-7} \text{ at 90\% C.I}$$

**$\omega$ model contour plot**




**Submitted to JHEP**

# T/CPT Test with $\phi \to K_S K_L \to 3\pi^0 \pi\nu e, \pi\pi \pi\nu e$

**Concept:**

First such measurement with kaons

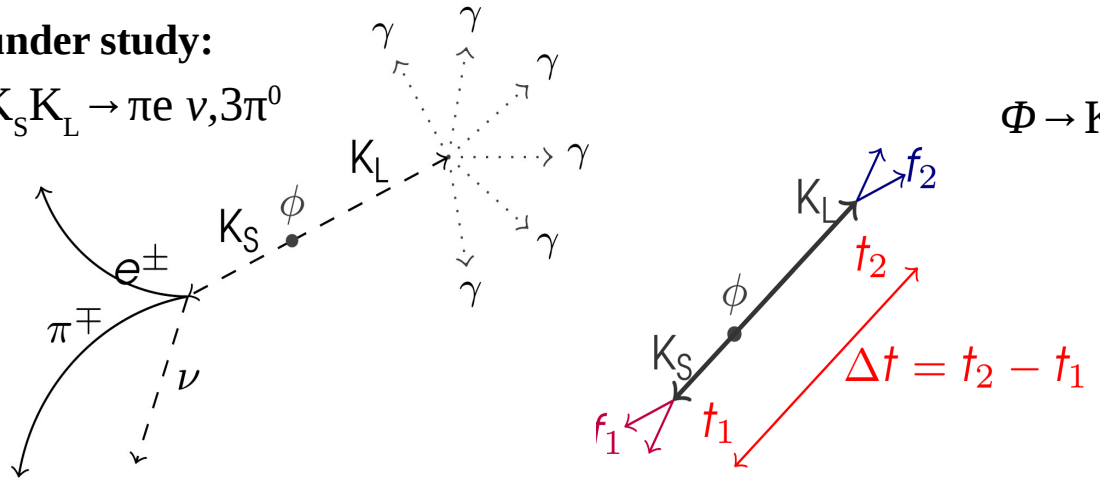
Model independent test

J. Bernabeu, A. Di Domenico and P. Villanueva-Perez,
*Direct test of time-reversal symmetry in the entangled neutral kaon system at a Φ factory*, Nucl. Phys. B 868 (2013) 102

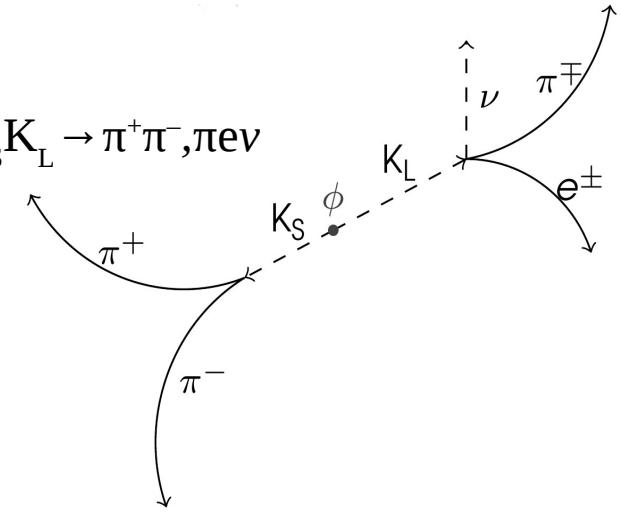
J. Bernabeu, A. Di Domenico and P. Villanueva-Perez,
*Probing CPT in transitions with entangled neutral kaons*, JHEP 1510 (2015) 139

**Processes under study:**

$\Phi \to K_S K_L \to \pi e \nu, 3\pi^0$




$\Phi \to K_S K_L \to \pi^+\pi^-, \pi e \nu$




**Observables of the tests (we focus on the asymptotic region ):**

T-violation sensitive

$$R_2^T(\Delta t) \sim \frac{I(\pi^+ e^- \nu, 3\pi^0;\ \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu;\ \Delta t)}$$

$$R_4^T(\Delta t) \sim \frac{I(\pi^- e^+ \nu, 3\pi^0;\ \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \nu;\ \Delta t)}$$

CPT-violation sensitive

$$R_2^{CPT}(\Delta t) \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$$R_4^{CPT}(\Delta t) \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

Double ratios:

$$\text{DRCP} = \frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$$

$$\frac{R_2^{CPT}}{R_4^{CPT}}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

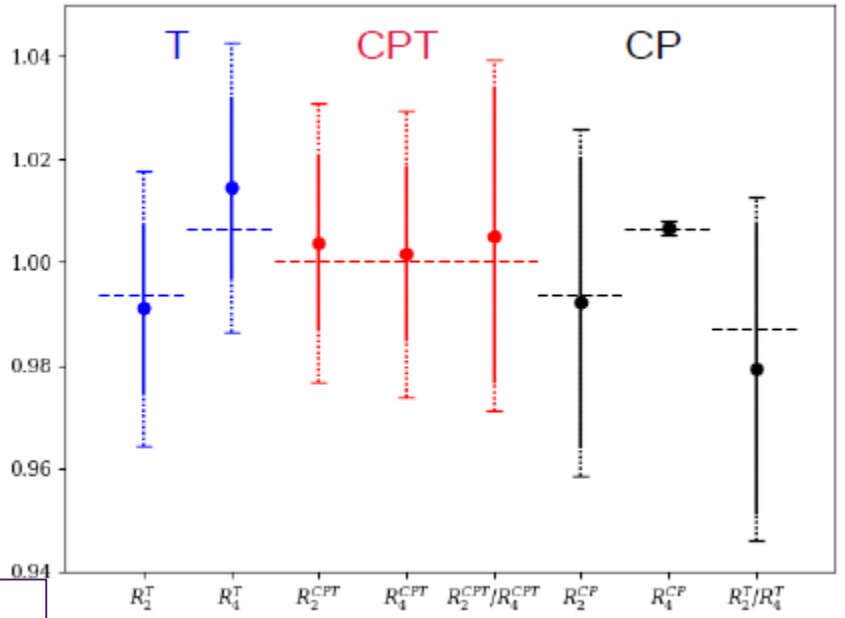
# T/CPT Test with $\phi \to K_S K_L \to 3\pi^0\pi\nu e, \pi\pi\pi\nu e$

- **Analysis is concluded – final results:**

**Uncertainty on the D factor ***

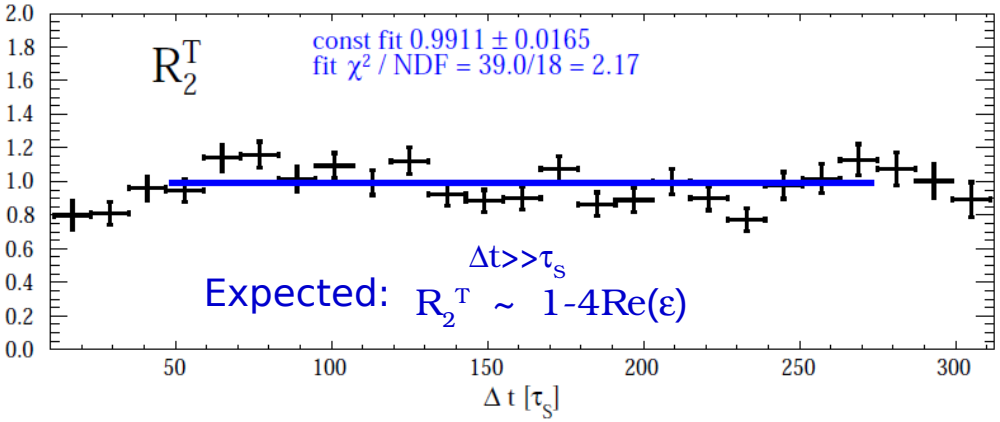
$$
\begin{aligned}
R_2^T &= 0.991 \pm 0.017_{stat} \pm 0.017_{syst} \pm 0.012,\\
R_4^T &= 1.015 \pm 0.018_{stat} \pm 0.018_{syst} \pm 0.012,\\
R_2^{CPT} &= 1.004 \pm 0.017_{stat} \pm 0.017_{syst} \pm 0.012,\\
R_4^{CPT} &= 1.002 \pm 0.017_{stat} \pm 0.018_{syst} \pm 0.012,\\
R_2^{CP} &= 0.992 \pm 0.028_{stat}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

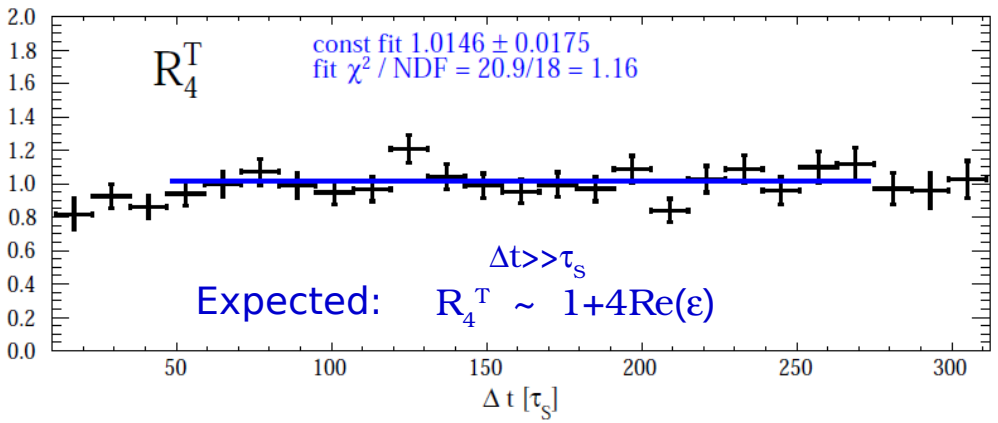
T observables -- TV from CPV+CPT | CPT observables -- CPT invariance | CP observables -- CPV PDG




Final results with both statistical (solid errorbars) and total uncertainty (dotted errobars)

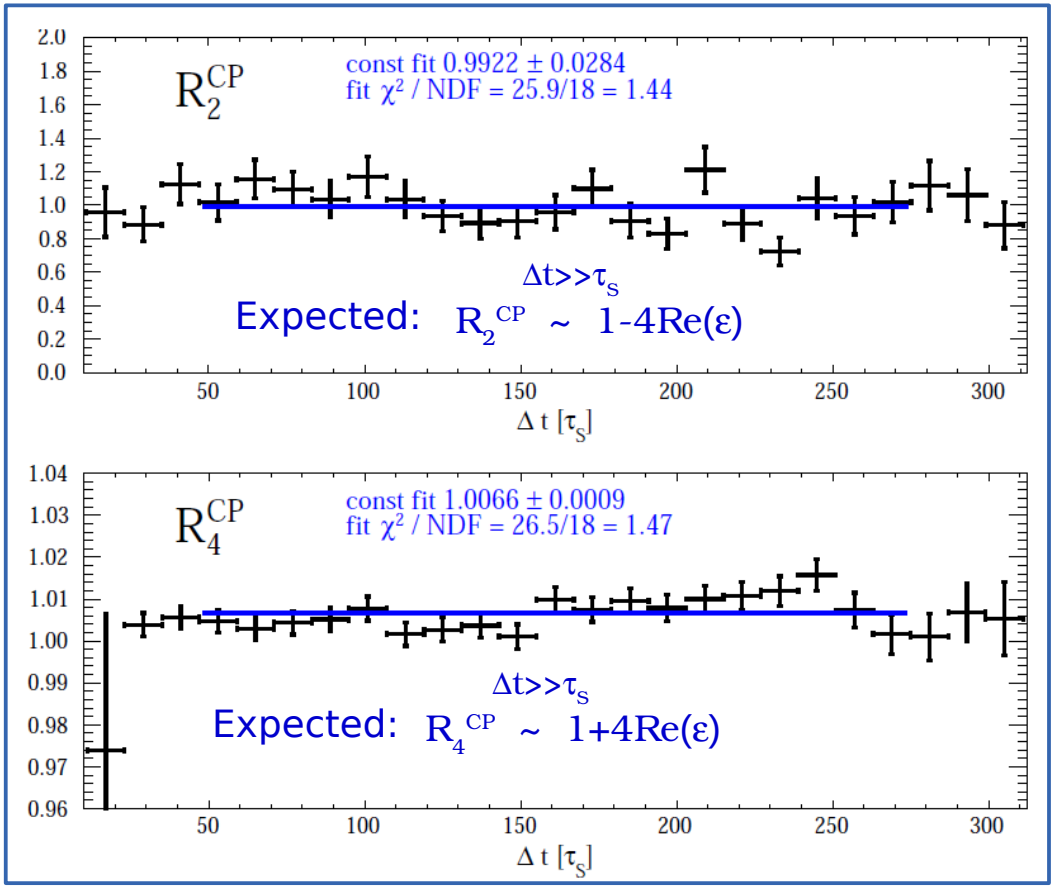
$$^*D = \frac{\mathrm{BR}(K_L \to 3\pi^0)\tau_S}{\mathrm{BR}(K_S \to \pi^+\pi^-)\tau_L}$$

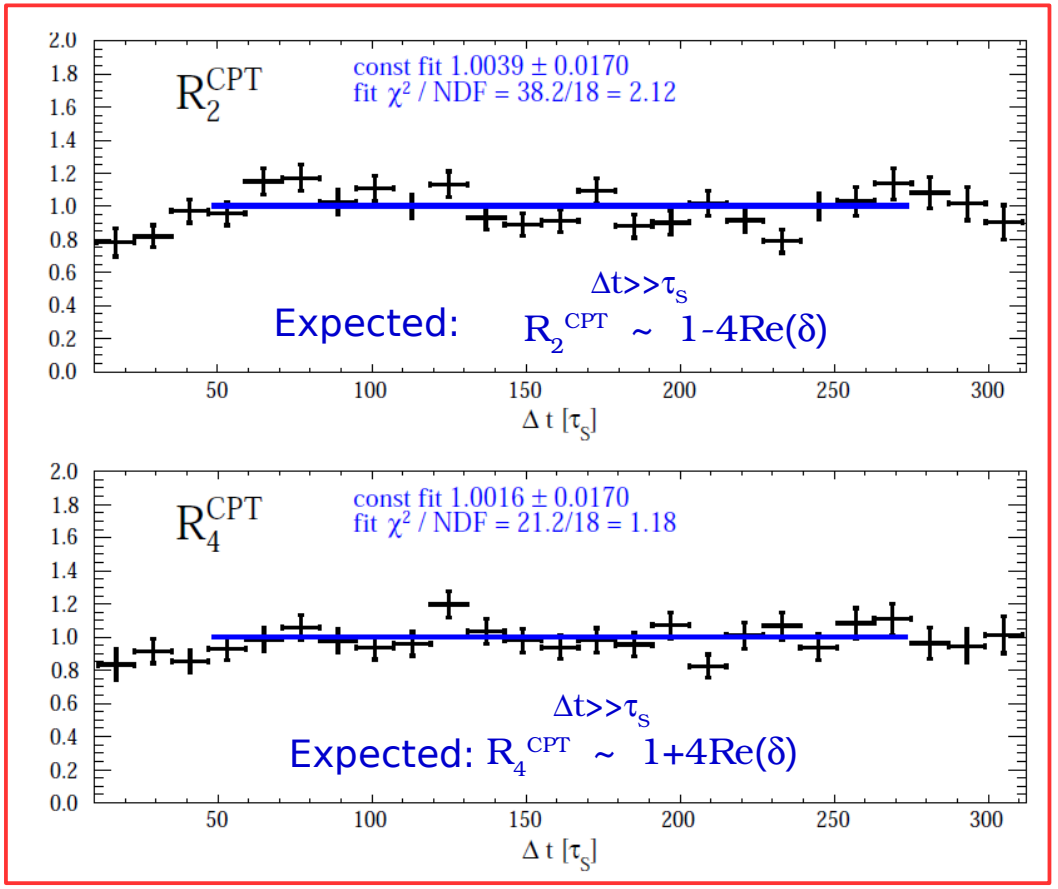


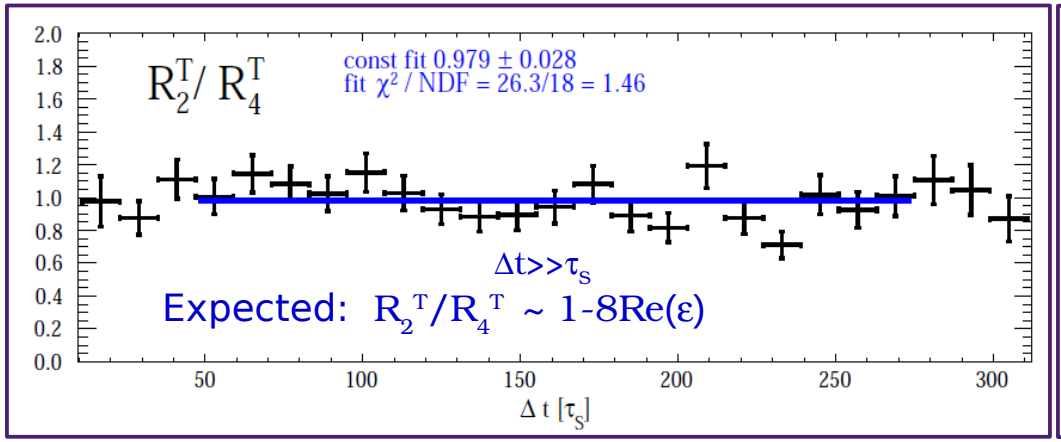



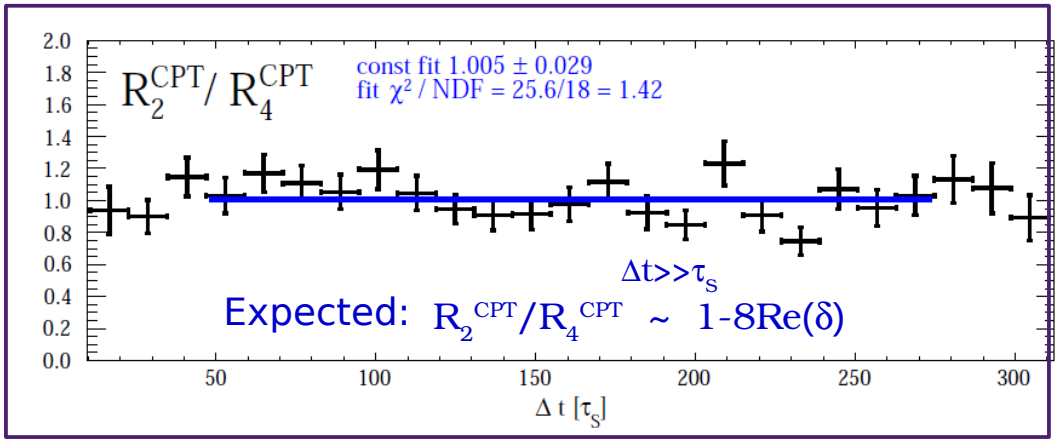

**Draft paper in preparation**

# T/CPT Test with $\phi \rightarrow K_S K_L \rightarrow 3\pi^0$ πνe, ππ πνe



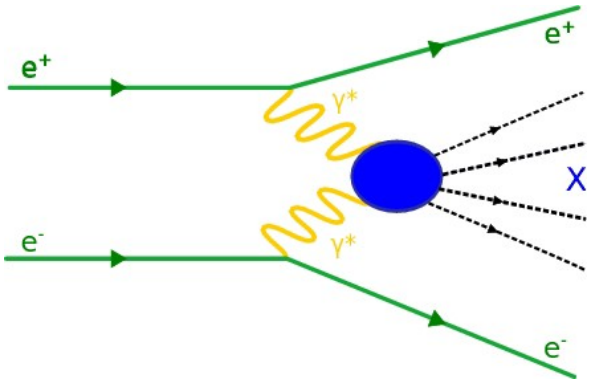



# γγ physics with High Energy Tagger (HET)

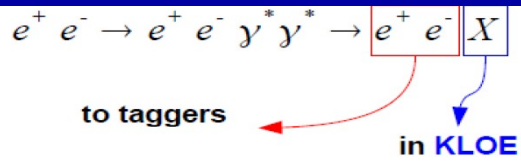
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^- X \qquad [C(X) = +1]$$

$$X = \pi^0, \pi\pi, \eta$$

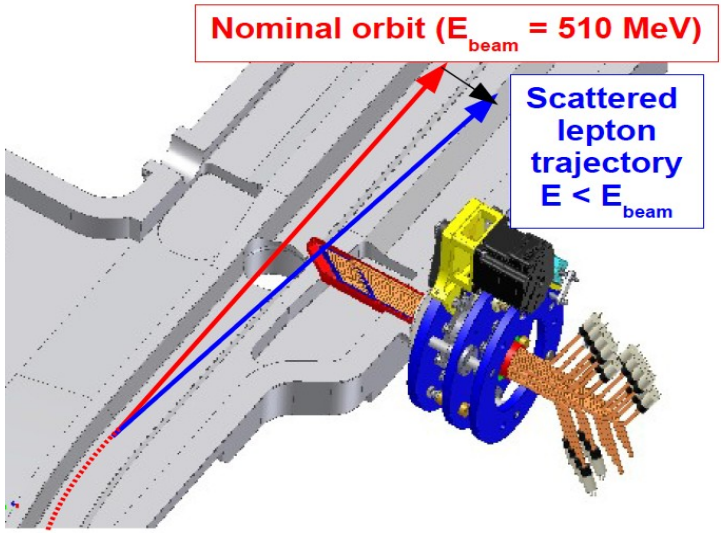



Bernstein & Holstein, Rev. Mod. Phys., 85 (2013) 49

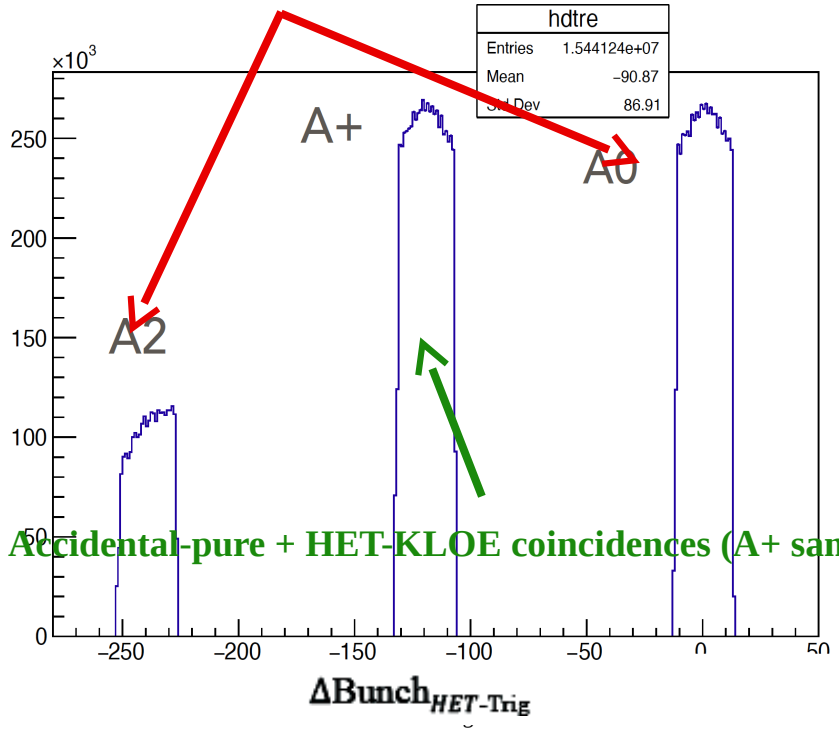
- Precision measurement of $\Gamma(\pi^0 \to \gamma\gamma)$
- Transition form factor $F_{\pi\gamma\gamma^*}(q^2,0)$ at space-like $q^2$ ($|q^2| < 0.1$ GeV2), impact on value and precision of $\alpha_\mu^{\text{LbyL};\pi 0}$




Measurement concept:
Eur. Phys. J. C 72 (2012) 1917




**Accidental-pure data (A sample)**




**Accidental-pure + HET-KLOE coincidences (A+ sample)**

First bending dipoles of DAΦNE act as spectrometers for scattered leptons (420 < E < 495 MeV)

Scintillator hodoscope + PMTs, inserted in Roman pots pitch: 5 mm, ~ 11 m from IP (E~2.5 MeV t~500 ps)

HET is acquired asynchronously w.r.t. the KLOE-2 DAQ (Xilinx Virtex 5 - FPGA),synchronization with the "Fiducial» signal from DAΦNE (each 325 ns) and the KLOE trigger

HET acquisition window corresponds to about 2.5 DAΦNE revolutions, data are recorded only when a KLOE trigger is asserted

The analysis is based on the HET-KLOE coincidences and the accidental-pure samples used for background modelling (shape and number)

# $\gamma\gamma \rightarrow \pi^0$ cross section measurement – concept and status

Measurement concept:

$$\frac{\sigma_{\pi^0}}{\sigma_{\mathrm{Bha}}} = \frac{N_{\pi^0}}{\epsilon_{\mathrm{ana}}\,\sigma^{\mathrm{meas}}_{\mathrm{Bha}} \int Ldt}\,\frac{A_{\mathrm{Bha}}}{A_{\pi^0}}$$

Status of the measurement:

$N_{\pi^0}$ → Number of $\pi^0$ tagged events. Preliminary results on the whole reconstructed data sample (electron station) obtained, 10% precision level, some improvements still possible.

$\epsilon_{\mathrm{ana}}$ → Analysis efficiency evaluation completed, only small refinement needed.

$\frac{A_{\mathrm{Bha}}}{A_{\pi^0}}$ → Full simulation of signal ($\gamma\gamma \rightarrow \pi^0$ triggering KLOE DAQ and one lepton in the HET) and normalization channel (low angle $e^+e^-\gamma$ with one lepton reaching HET) events, obtained with EKHARA/BBBREM generators + BDSIM for lepton transport, completed.

$\sigma^{\mathrm{meas}}_{\mathrm{Bha}} \int \mathrm{Ldt}$ → Obtained from the KLOE online luminosity measurement. Product independent from luminometer scale, scaling behavior checked along data-taking periods.

# Status of $\gamma\gamma \rightarrow \pi^0$ analysis

**Single-arm selection:**
-Sample of 2 clusters associated with the same bunch crossing in the KLOE barrel calorimeter
-Selected bunch crossing, and, independently selected HET signal, are in a time window of 40 ns around the KLOE trigger

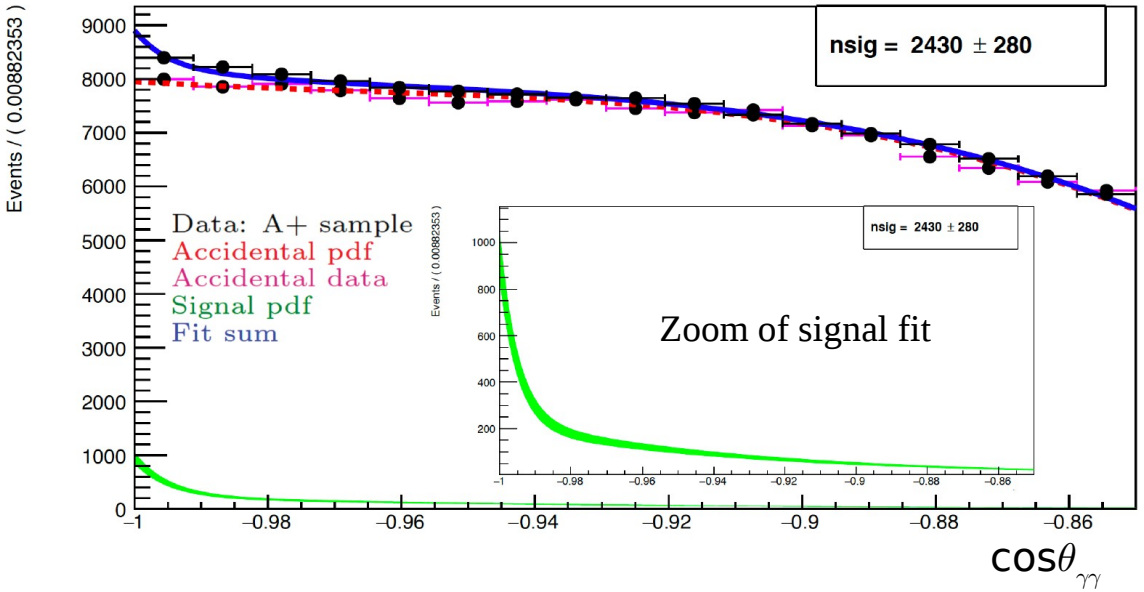
Example of ML fit, statistics: $2fb^{-1}$, HET electron data from October '16 to March '18

Signal-enriching cut applied: $|\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c| < 0.5$ ns, cut efficiency 80% from control sample studies

**Analysis Strategy:**
-Maximum Likelihood (ML) fits of A+/A samples.
-Fit to accidental-pure samples used to constraint the number of accidentals in A+
- Time coincidence window: 4÷5 bunch crossings depending on the period

-Accidental pure sample (A) used to model background pdf

-Signal pdfs by Ekhara simulation, control samples and BDSIM transport of the leptons through the beam line

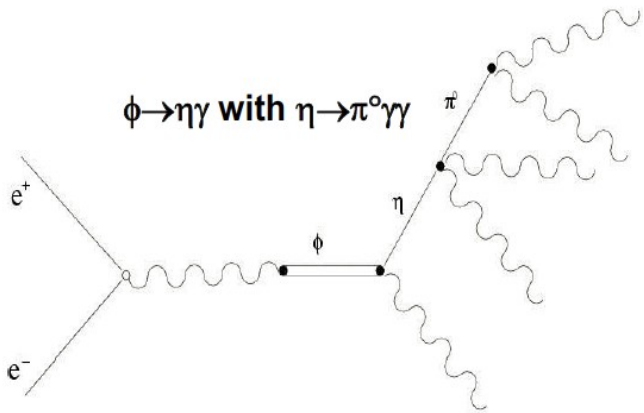


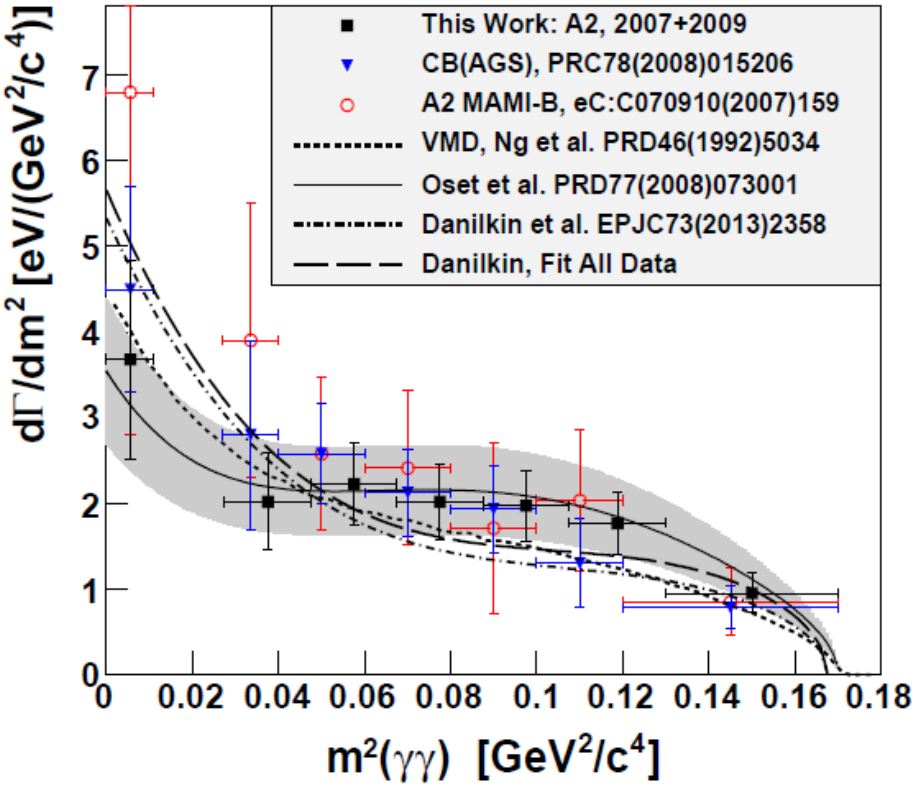

**10% precision level on signal reached.**
**Some improvements still possible.**

Signal counting and acceptance measurement under review by KLOE-2 analysis Referees

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

- $\eta \to \pi^0\gamma\gamma$ (from $\phi \to \eta\gamma$): $\chi$PT golden mode,
  $O(p2)$ null, $O(p4)$ suppressed ⇒ sensitive to $O(p6)$
- Mass of non-π° photons can be used as a test of theoretical models




**BR = (22.1 ± 2.4 ± 4.7)×10$^{-5}$ CB@AGS (2008)**
**[PRC 78 (2008) 015206]**

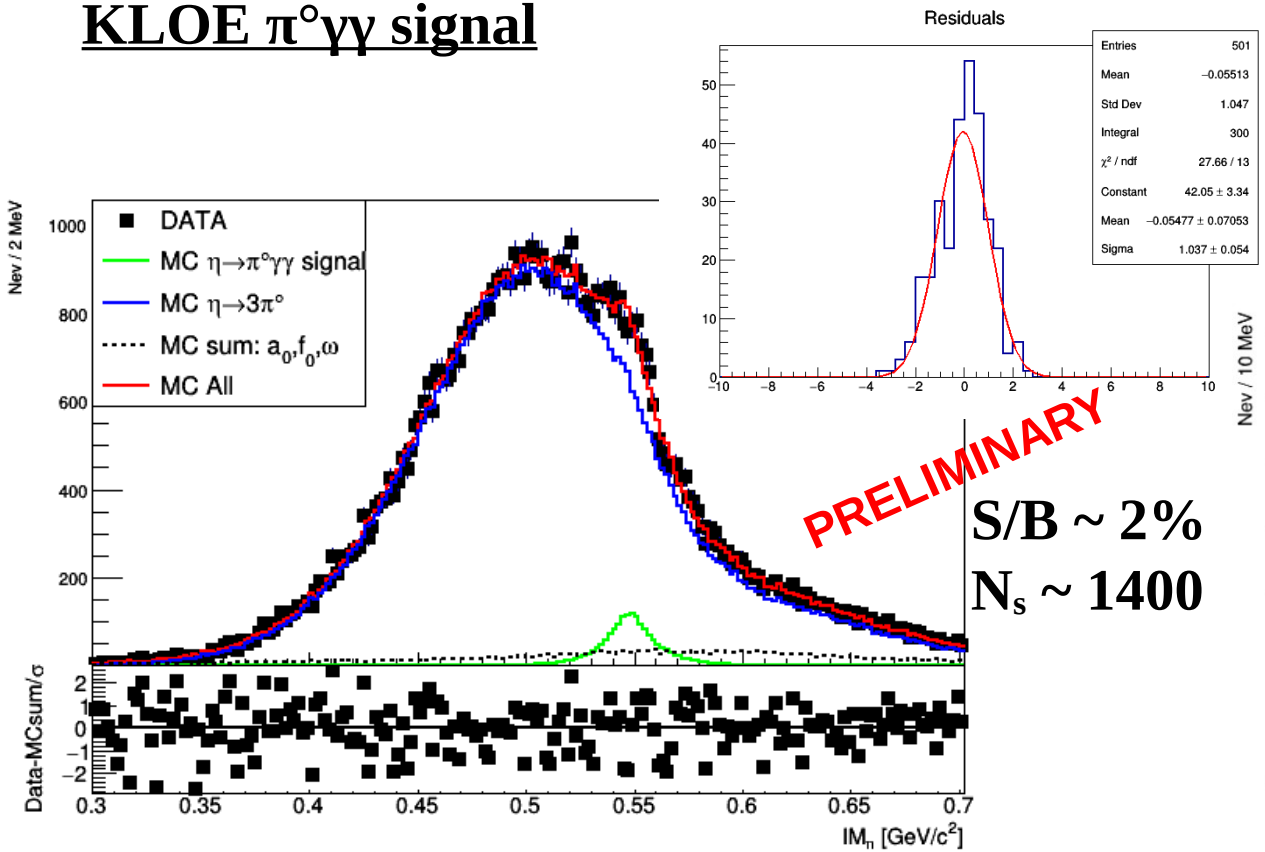
**BR = (25.6±2.4)×10$^{-5}$ CB@MAMI (2014)**
**A2 MAMI [PRC 90 (2014) 025206]**
**Sample of ~6·10$^7$ η's**
**~1200 $\eta \to \pi^\circ\gamma\gamma$ events found**

**Old KLOE preliminary: (8.4±2.7±1.4)×10$^{-5}$**
**(L = 450 pb$^{-1}$ ~ 70 signal events)**

- Latest theoretical studies by Escribano et al. PRD 90 (2020) 034026
- Calculated BR = 1.35(8) · 10$^{-4}$
- Many previous predictions differ by a factor ~2

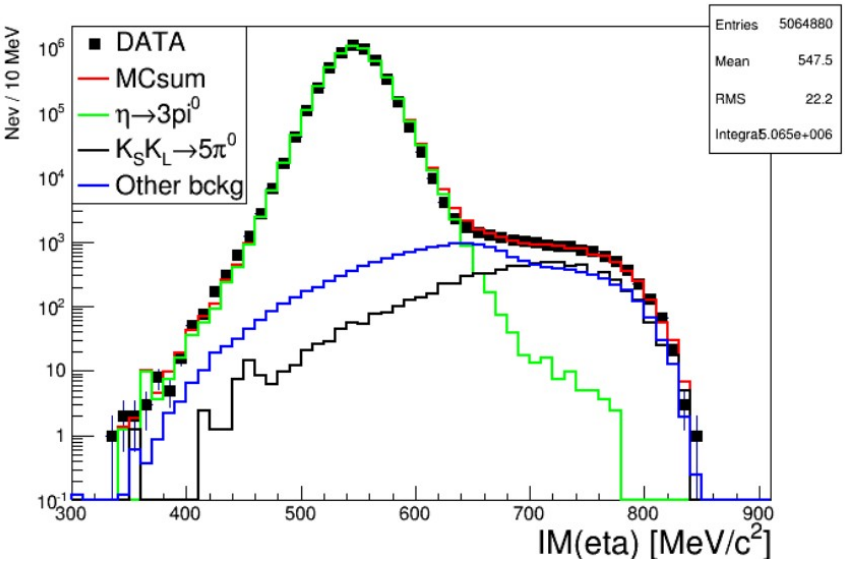
# $\eta \to \pi^0\gamma\gamma$ decay

## KLOE $\pi^\circ\gamma\gamma$ signal




- Integrated luminosity of 1730 pb$^{-1}$, around 7·10$^7$ η's
- $\eta \to 3\pi^\circ$, $\eta \to \pi^\circ\gamma\gamma$ signal and ∑ of non-3$\pi^0$ MC's fitted to data
- Fit $\chi^2$/(ndf=98)=1.033 (fit_prob=39%)

## $\phi \to \eta(\to 3\pi^\circ)\gamma$ normalization



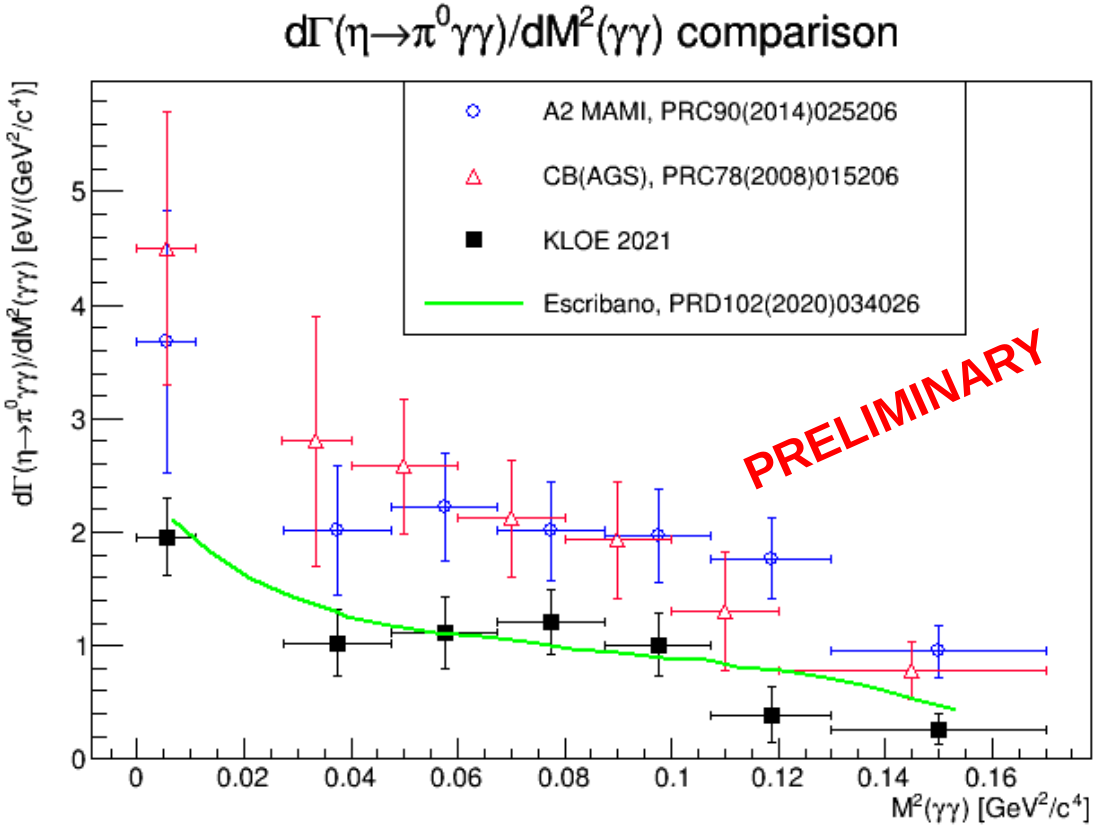

- Similar analysis as for $\eta \to \pi^0\gamma\gamma$ channel, but this time $\phi \to \eta(\to 3\pi^\circ)\gamma \to 7\gamma$ in the final state (BR~33%)
- Very pure channel, backgrounds well below 1%

$$\frac{BR(\eta \to \pi^\circ\gamma\gamma)}{BR(\eta \to 3\pi^\circ)} = \frac{N_S/\varepsilon_S}{N_{3\pi^\circ}/\varepsilon_{3\pi^\circ}}$$

Preliminary KLOE result:

**BR($\eta \to \pi^0\gamma\gamma$) = (1.21 ± 0.13$_{stat}$) · 10$^{-4}$**

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




- **Separate fits to M(eta) in $M^2(\gamma\gamma)$ slices**
- **Bin 0.011-0.0275 $GeV^2/c^4$ missing due to $\pi^\circ\pi^\circ$ veto**
- **Half with respect to previous experiments**
- **Good agreement with the latest theoretical predictions by Escribano et al. From 2020 ($BR=1.35(8)\cdot10^{-4}$)**

**From integration of $d\Gamma/dM^2$ (missing bin lineary interpolated) one can calculate KLOE preliminary:**

$$BR(\eta \to \pi^0\gamma\gamma)=(1.30 \pm 0.13_{stat})\cdot10^{-4}$$

# Conclusions

- **Data reconstruction ongoing (reconstructed 4.5 $fb^{-1}$)**

- **MC production of the whole KLOE-2 dataset with the DBV-40 in progress: more than 500 $pb^{-1}$ are already available for the $\phi \rightarrow$ *all* process**

- **About the analyses:**
  - **paper on the search for decoherence and CPTV in $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ submitted to JHEP;**
  - **draft in preparation on the T/CPT test with $\phi \rightarrow K_S K \rightarrow$ $3\pi^0$ $\pi e\nu$, $\pi\pi$ $\pi e\nu$**
  - **B boson limit, $\eta \rightarrow \pi^0\gamma\gamma$, BR($K_S e3$) almost completed, close to the final result.**

## LNF Scientific Committee after the meeting on May 6-7, 2021 (held remotely)
## From the document "Findings & Recommendations"

Introduction:
For KLOE the director informs that he had given the advice to the collaboration to put a certain focus on a small number of publications to be published soon.

### Observations KLOE:

1- KLOE presented an update with respect to the last meeting. As for the data processing, by now 3.3/fb of data have been processed, about 0.9/fb more than at the last report. The progress here was slower than expected due to problems with various aspects of computing: the hardware, the tape library and the DBV-40 release. In particular, the hardware problems were traced to sparks that were not filtered by the UPS system in place. A new unit will replace the old one and should fix these problems, and then the data processing should finish by the end of the summer. Despite the hardware problems no data were lost. MC production with DBV-38 is finished and production with DBV-40 will start soon. For the purpose of data preservation changes were made to the computing infrastructure which is expected to make the system more efficient and resilient, and to have been the last change.

2- As for data analysis, there is excellent progress. Eleven new results from KLOE and/or KLOE-2 data are expected by the end of this year, and among those five are targeting the EPS conference at the end of July. Four of the analyses include the use of KLOE-2 data. In particular, the HET-tagged search for gamma-gamma to pi0 has made excellent progress. A signal is extracted based on a multi-dimensional fit to the signal and a background template from accidental overlaps. It is projected that a statistical precision of 8% can be reached with 1.5/fb currently under analysis. Another particularly timely analysis is the measurement of e+e- \to pi+pi-pi0 plus an ISR photon as it's precision measurement constrains some of the relatively poorly known contributions to the anomalous magnetic moment of the muon. With 1.7/fb the results are expected to improve the PDG world average.

### Recommendation KLOE:

*Ensure that the new UPS system is installed and follow the proposed plan for physics analyses*

*Thank you!*