KLOE-2

KLOE-2 Collaboration - LNF Group

D. Babusci, M. Berlowski (PostDoc), C. Bloise, F. Bossi, G. Capon (Ass.), P. Ciambrone, F. Curciarello (PostDoc), E. Dané (Art. 23), E. De Lucia (Resp.), A. De Santis (Art.36), P. De Simone, A. Di Cicco (PostDoc), D. Domenici, G. Felici, P. Fermani (PostDoc), G. Fortugno (Tec.), S. Giovannella, X. Kang (PostDoc), M. Martini (Ass)*, S. Miscetti, E. Perez del Rio (Art.36), P. Santangelo, F. Sborzacchi (Tec.), F. Sirghi.

In collaboration with "LNF-SEA"
P. Albicocco, A. Balla, M. Beretta, M. Carletti, S. Ceravolo, G. Corradi, U. Denni, M. Gatta, R. Lenci, G. Papalino, B. Ponzio

**Also Dipartimento di Scienze e Tecnologie applicate,"Guglielmo Marconi" University, Rome, Italy*

1 DAΦNE Operation and KLOE-2 Run

KLOE-2 data taking campaign ended successfully on March 30^{th} 2018, with the total acquired luminosity milestone of at least 5 fb^{-1} fulfilled thanks to the combined effort of both KLOE-2 and DAΦNE teams (Fig.1). A total delivered luminosity of 6.8 fb^{-1} was achieved with a total acquired luminosity of 5.5 fb^{-1}, a daily record of 13.7 (11.1) pb^{-1} delivered (acquired) and a peak luminosity of 2.28×10^{32} cm^{-2} s^{-1} . Together with the data set of its predecessor KLOE, the acquired data sample of 8 fb^{-1} corresponds to 2.4×10^{10} ϕ-meson produced: the largest sample ever collected at the $\phi(1020)$ at e^+e colliders.

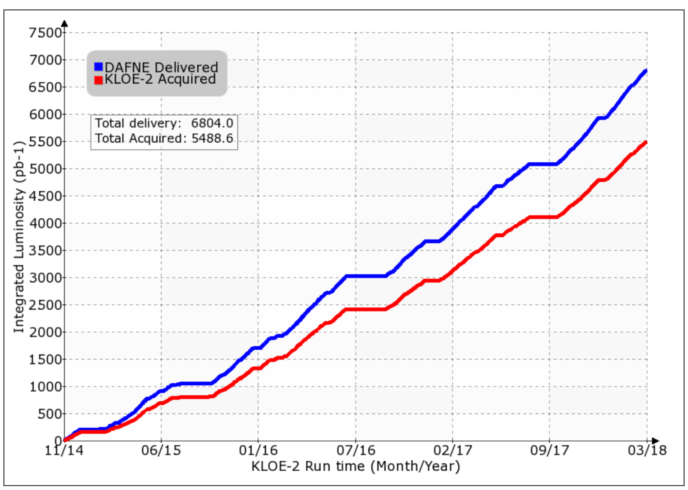

Figure 1: Total integrated luminosity: the blue curve shows DAΦNE delivered luminosity and the red curve KLOE-2 acquired luminosity respectively.

Data Quality was continuously monitored along the KLOE-2 run with benchmark analysis (e.g. $\phi \to \eta\gamma$ with $\eta \to 3\pi^0$, K_S lifetime with $K_S \to \pi^+\pi^-$, K_L invariant mass etc.). While the whole data offline reconstruction is being completed, a plan for data preservation is being prepared and first tests for ROOT compatible output are already available, exploiting contacts with CERN experts.

KLOE-2 collaboration activities are now focused on data reconstruction and analysis towards Precise Measurements in both kaon and hadron sectors. The physics program is mainly focused on K_S, η and $\eta^{'}$ meson rare decays as well as on kaon interferometry, fundamental symmetry tests and physics beyond the Standard Model, including searches for new exotic particles that could constitute the dark matter.

Latest results published in 2018 are: i) Combination of KLOE $\sigma(e^+e \to \pi^+\pi^-\gamma(\gamma))$ measurements and determination of $a_\mu(\pi^+\pi^-)$ in the energy range $0.10 < s < 0.95$ GeV^2 [1] ii) Combined limit on the production of a light gauge boson decaying into $\mu^+\mu^-$ and $\pi^+\pi^-$ [2] and iii) Measurement of the charge asymmetry for the $K_S \to \pi e \nu$ decay and test of CPT symmetry with the KLOE detector [3].

2 Physics achievements

The integrated luminosity collected by KLOE and KLOE-2 experiments represents a unique data sample which is very rich in physics and will allow the deep investigation and exploitation of one of the most peculiar character of neutral kaons produced at a ϕ-factory, the strange entanglement specific to two neutral kaon systems in a coherent quantum state, together with light mesons to be studied and tested with unprecedented statistics.

2.1 K_S semileptonic charge asymmetry

A test of CPT symmetry can be performed by comparing the value of the lepton charge asymmetry $A_{S,L}$ for short- and long-lived neutral kaons. The KLOE-2 Collaboration has recently published a new measurement [3] based on a data sample corresponding to an integrated luminosity of 1.7 fb^{-1}: $A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}$, which improves the statistical accuracy of previous KLOE determination [7] by almost a factor of two. The best separation between signal and background components is obtained with the variable:

$$M^2(e) = [E_{K_S} - E(\pi) - E_\nu]^2 - p^2(e), \qquad (1)$$

with E_{K_S} computed from the kinematics of $\phi \to K_S K_L$ two-body decay, knowing the ϕ-meson momentum (from Bhabha scattering events) and the reconstructed K_L direction, $E(\pi)$ evaluated from the measured track momentum in the pion mass hypothesis, and $E_\nu = |\vec{p}_{K_S} - \vec{p}(e) - \vec{p}(\pi)|$. $M^2(e)$ is calculated according to the TOF particle identification and for the signal events peaks to zero. Fig.2 shows the $M^2(e)$ distribution used for signal counting.

The combination of KLOE and KLOE-2 results is $A_S = (-3.8 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}$, taking into account the correlation between both measurements, and represents the most precise measurement of A_S up to date. This value, combined with KTeV result on A_L [4] and is also providing Re(δ) [5] and Re(ϵ) [6] as external inputs, allows to extract the CPT -violating parameters [10]: Re(x_-) = (A_S - A_L)/4 - Re(δ) = (-2.0 $\pm$1.4) $\times 10^{-3}$ and Re(y)=Re(ϵ)-(A_S + A_L)/4=(1.7 $\pm$1.4) $\times 10^{-3}$ which are consistent with CPT invariance and improve by almost a factor of two the previous results [7]. With the analysis of the full KLOE-2 data set, the uncertainty on A_S can be further reduced at the level of $\sim 3\times10^{-3}$.

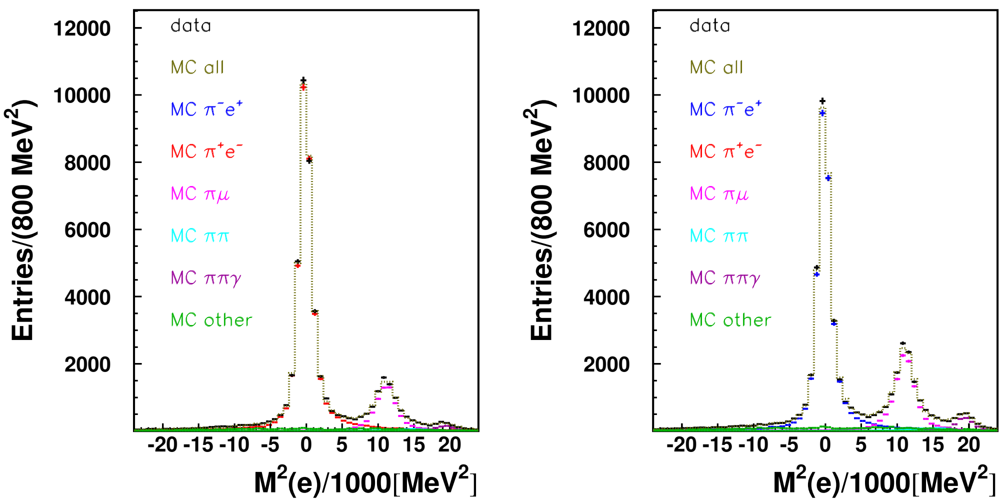

Figure 2: $M^2(e)$ distribution for data (black points) and MC simulation (dotted histogram) for both final charge states (π^+e^- – left side, π^-e^+ – right side) after the fit. Individual MC contributions are shown. Bottom row: corresponding data-MC residual distributions after the fit.

2.2 Direct test of T and CPT symmetries in neutral kaon transitions

Comparing neutral meson transition rates between flavour and CP eigenstates allows direct and model independent tests of time-reversal T and CPT symmetries [8] to be performed. Quantum entangled kaon pairs are used to identify the initial state of a particle transition by the decay of its entangled partner, while the final state is tagged by semileptonic and hadronic decays into two and three pions. Two T-violating observables are determined as ratios of the rates of two classes of processes identified in the dataset $K_SK_L \to \pi^\pm e^\mp \nu, 3\pi^0$ and $K_SK_L \to \pi^+\pi^-, \pi^\pm e^\mp \nu$:

$$\mathrm{R}_2(\Delta t) = \frac{\mathrm{P}[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{\mathrm{P}[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} \sim \frac{\mathrm{I}(\pi^+e^-\bar{\nu}, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^-e^+\nu; \Delta t)}, \tag{2}$$

$$\mathrm{R}_4(\Delta t) = \frac{\mathrm{P}[\bar{\mathrm{K}^0}(0) \to \mathrm{K}_-(\Delta t)]}{\mathrm{P}[\mathrm{K}_-(0) \to \bar{\mathrm{K}^0}(\Delta t)]} \sim \frac{\mathrm{I}(\pi^-e^+\nu, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^+e^-\bar{\nu}; \Delta t)}, \tag{3}$$

where $\mathrm{I}(f_1,f_2;\Delta t)$ denotes the number of recorded events characterized by a time-ordered pair of kaon decays f_1 and f_2 separated by an interval of proper kaon decay times Δt [8]. A deviation of the asymptotic level of these ratios from unity for large transition times would be a T-violation manifestation.

Moreover CPT symmetry can be tested through the determination of the asymptotic level of the following double ratio:

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{\mathrm{P}[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]/\mathrm{P}[\mathrm{K}_-(0) \to \bar{\mathrm{K}^0}(\Delta t)]}{\mathrm{P}[\bar{\mathrm{K}^0} \to \mathrm{K}_-(\Delta t)]/\mathrm{P}[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} \overset{\Delta t \gg \tau_S}{=} 1 - 8\Re\delta_K - 8\Re x_-, \tag{4}$$

where the δ_K and x_- are parameters violating the CPT symmetry in $\mathrm{K}^0\bar{\mathrm{K}^0}$ mixing and the $\Delta S = \Delta Q$ rule, respectively. This double ratio represents a robust CPT-violation sensitive observable [8] which has never been measured to date. A percent level accuracy was obtained on the double ratio measurement with 1.7 fb1 KLOE data sample and presented st ICHEP 2018 conference.The accuracy is expected to be reduced down to the 10^{-3} level of precision adding KLOE-2 data set.

2.3 π^0 production from $\gamma\gamma$ scattering

The precision measurement of the $\pi^0 \to \gamma\gamma$ width allows to gain insights into the low-energy QCD dynamics. A way to achieve the $\mathcal{O}(1\%)$ precision needed in order to test theory predictions is to study the π^0 production through $\gamma\gamma$ fusion in the $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ reaction. KLOE-2 has the possibility to perform this measurement [9]. In order to reduce the background coming from ϕ-meson decays, two High Energy Tagger (HET) stations [10] are used to measure the deviation of final state leptons from their main orbit by determining their position and timing.

The HET detectors composed of 28 plastic scintillators are placed in roman pots just at the exit of the DAΦNE dipole magnets, 11 m away from the IP, both on positron and electron sides. The measured time resolution of 550 ps allows the identification of the correct bunch crossing ($\Delta T_{bunch} \sim 2.7$ ns). The counting rate is dominated by low-angle radiative Bhabha scattering events and their effective cross-section as a function of the data-taking period has been used to determine the detector acceptance×efficiency and for data quality purposes. An effective cross section of the order of 10 mb has been measured, with big fluctuations for the scintillators closest to the beam.

For the π^0 search a sub-set of HET plastic scintillators has been used, showing operational stability over a time scale of years. Candidates of single-π^0 production from $\gamma\gamma$ scattering have been pre-filtered recording information on the hit in the tagger, trigger, DAΦNE operational parameters, clusters and tracks reconstructed in the KLOE central detector. Data are classified as single-arm (SA) or double-arm (DA) events. DA events are selected requiring the time coincidence of the two HET stations within a proper time window, while for SA events, we select hits in one HET station and at least one bunch in KLOE central detector associated with only 2 clusters in the EMC, in a given time window around the trigger signal. A statistical evidence of correlated coincidence events between the tagger station hits and KLOE calorimeter clusters has been observed for the first time, after an event-by-event subtraction of the registered amount of accidentals. New data reconstruction is ongoing in order to study in more detail the tagged sample.

2.4 $\eta \to \pi^+\pi^-$ limit

The $\eta \to \pi^+\pi^-$ decay is a P- and CP-violating process. According to SM, this decay can occur only through CP-violating weak interaction mediated by a virtual K^0_S meson and has a branching ratio $\mathrm{Br}(\eta \to \pi^+\pi^-) \leq 2 \times 10^{-27}$ [11, 12]. This upper limit (UL) can increase of an order of magnitude by introducing a possible QCD-violating term contribution to the decay [11, 12] and reach 10^{-15} if CP violation is allowed also in an extended Higgs sector [11, 12]. Any detection of a larger branching fraction would indicate a new source of CP violation in the strong interaction, beyond any considerable extension of the SM.

The collaboration already set the best UL on the branching ratio of the di-pion decay of the η meson by using $350\,\mathrm{pb}^{-1}$ of KLOE data: $\mathrm{Br}(\eta \to \pi^+\pi^-) \leq 1.3 \times 10^{-5}$ at 90% CL [13]. A new preliminary limit has been extracted by the KLOE-2 collaboration increasing the sample statistic to $1.6\,\mathrm{fb}^{-1}$ of KLOE data. The selection of $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-$ events requires: i) one vertex reconstructed in the tracking detector with two opposite charge tracks reaching the calorimeter and required to be at large polar angle $45^\circ < \theta < 135^\circ$ and ii) the prompt photon in time in order to suppress initial state radiation background. The angle Ω between the missing momentum of the di-pion system and the prompt photon direction has to be $\Omega < 0.03$ rad to reject the background from $\pi^+\pi^-\pi^0$ decays. Main background contamination originates from radiative Bhabha scattering events, $\gamma\mu^+\mu^-$ and $\rho(\pi\pi)\pi$ with a lost photon decays. Time of flight techniques are use to separate γe^+e^- from selected $\gamma\pi^+\pi^-$ events while $\gamma\mu^+\mu^-$ events can be rejected using the track-mass variable, computed assuming the ϕ-meson decays to two particles of identical mass

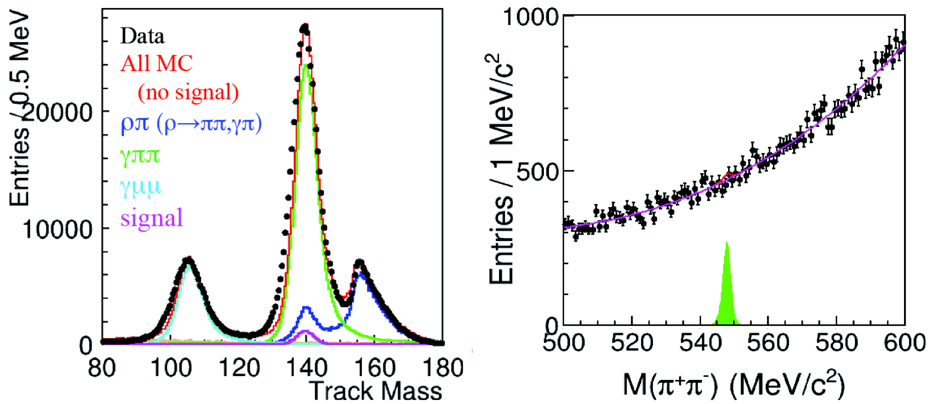

Figure 3: Left panel: track mass distributions. Data are shown in black, all MC background contributions in the hypothesis of no $\eta \to \pi^+\pi^-$ signal are in red ($\rho\pi$ in blue, $\gamma\pi^+\pi^-$ in green, $\gamma\mu^+\mu^-$ in cyan), while the expected signal is shown in violet. Right panel: $\pi^+\pi^-$ invariant mass distribution for data (black points). The curve is a third polynomial function with superimposed a MC signal shape in arbitrary units

and one photon, as shown in Fig. 3 left panel. Candidates surviving the above selection are mainly $(\gamma)\gamma\pi^+\pi^-$ events. The η-meson resonance should appear over the $(\gamma)\gamma\pi^+\pi^-$ continuum spectrum. No signal is observed around the η-meson mass in the $\pi^+\pi^-$ mass spectrum as shown in the right panel of Fig. 3. The upper limit on number of signal events is extracted by using a Bayesian approach. The irreducible background is evaluated performing a fit to the observed $\pi^+\pi^-$ mass spectrum with a third-order polynomial function while the signal is described with a dedicated MC simulated shape. The preliminary UL on the branching ratio is 6.3×10^{-6} at 90% CL and was presented at the DISCRETE 2018 conference. With the KLOE /KLOE-2 data samples the upper limit is expected to reach 2.7×10^{-6}.

3 List of Conference Talks by LNF Authors in Year 2018

1. F. Curciarello, "The KLOE-2 High Energy Taggers", CHARM 2018 , Novosibirsk, Russia
2. A. Di Cicco, "The KLOE-2 Cylindrical GEM Inner Tracker", CHARM 2018, Novosibirsk,Russia
3. F. Sirghi, "Outcome of the KLOE-2 experiment after the conclusion of the data-taking period", Pisa meeting 2018, La biodola, Italy
4. A. De Santis, "Test of discrete symmetries with neutral kaons at KLOE-2", BEACH 2018, Lisbon, Portugal
5. F. Curciarello, "KLOE-2 Status on $\gamma^*\gamma^* \to \pi^0$", Second Plenary Workshop of the Muon g-2 Theory Initiative, Mainz, Germany
6. E. Perez del Rio, "KLOE/KLOE-2 results and perspectives on dark force search", ICHEP 2018, Seoul, Corea
7. M. Berlowski, "KLOE-2 results and perspectives on hadron physics", Chiral Dymanics 2018, Durham, England
8. F. Curciarello, "Search for dark Forces with KLOE/KLOE-2", SIF 2018, Arcavacata di Rende, Italy

9. A. Di Cicco, "Study of KS semileptonic decays at KLOE/KLOE-2", SIF 2018, Arcavacata di Rende, Italy
10. X. Kang, "Study of eta-meson decays at KLOE/KLOE-2", SIF 2018, Arcavacata di Rende, Italy
11. D. Domenici Danilo, "The KLOE detector performance summary after the end of data-taking", NSS/MIC IEEE 2018, Sydney, Australia
12. A. De Santis, "Test of discrete symmetries in transitions with entangled neutral kaons at KLOE/KLOE-2", DISCRETE 2018, Vienna, Austria
13. X. Kang, "Study of eta decays at KLOE/KLOE-2", DISCRETE 2018, Vienna, Austria

References

1. A. Anastasi et al., JHEP 03 (2018) 173
2. A. Anastasi et al., Physics Letters B 784 (2018) 336-341
3. A. Anastasi et al., JHEP 09 21 (2018)
4. A. Alavi-Harati et al., Phys. Rev. Lett. 88 181601 (2002)
5. C. Patrignani, et al. (Particle Data Group), Chin. Phys. C 40 100001 (2016)
6. F. Ambrosino et al., JHEP 12 11 (2006)
7. F. Ambrosino et al., Phys. Lett. B 636 173 (2006)
8. Bernabeu, J., Di Domenico, A., Villanueva-Perez, P.: Direct test of time-reversal symmetry in the entangled neutral kaon system at a ϕ-factory. Nucl. Phys. B868, 102119 (2013). https://doi.org/10.1016/j.nuclphysb.2012.11.009 and Bernabeu, J., Di Domenico, A., Villanueva-Perez, P.: Probing CPT in transitions with entangled neutral kaons. JHEP 10, 139 (2015). https://doi.org/10.1007/JHEP10(2015)139
9. D. Babusci et al., Eur. Phys. J. C 72, 1917 (2012)
10. D. Babusci et al., Acta Phys. Pol B 46, 81 (2015)
11. C. Jarlskog, E. Shabalin, Phys. Scr. T 99, 23 (2002)
12. E. Shabalin, Phys. Scr. T 99, 104 (2002)
13. Ambrosino et al. (KLOE Collaboration), Phys. Lett. B 606, 276 (2005)