KLOE-2 Collaboration - LNF Group

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1 Introduction

Fundamental symmetry tests and physics beyond the Standard Model, including kaon interferometry and searches for new exotic particles that could constitute the dark matter, together with K_S and η meson rare decays are the focus of the KLOE-2 collaboration, exploiting the uniqueness of the largest sample ever collected at the $\phi(1020)$ meson peak at e^+e^- colliders, corresponding to about 2.4×10^{10} ϕ-meson produced.

Latest physics results achieved on the experimental study of $K^0 - \bar{K^0}$ quantum entanglement and tests of discrete symmetries via Kaon transitions were presented at conferences in 2024 [1, 2], together with the developments of a blind technique applied to the new analysis for the hadronic cross-section measurement with the radiative return method [12].

2 Data Preservation

The ROOT output of the KLOE-2 data and MC productions has been completed, according to the KLOE-2 long-term Data Preservation plan. Neutral kaons, charged kaons, radiative decays and $\rho\pi$ streams were produced with a compression factor of about 8 depending on run conditions. The efforts are presently focused on the production of the ROOT output for both KLOE data and MC, started with events from Neutral Kaons and Minimum Bias streams. To facilitate analysis, the ROOT files will be kept on disk. Data reprocessing dedicated to the new hadronic cross-section measurement is being planned, to modify the criteria used for the signal sample selection. The long-term plan is to move to CNAF the ROOT output files presently stored on disk at LNF and perform there the data analysis using CPU time granted by CSN1.

3 Data Distribution Upgraded with AI Revolutionary and Transparent Support

During the last year, besides the usual management activities, KLOE-2 CED carried on some important planning operations. Several cornerstone devices were upgraded and renewed, increasing speed and bandwidth aimed to make more and more analyses simultaneously. The Fibre Channel is now our first protocol to deploy data around the cluster, overcoming every issue related to Ethernet protocols together with the traditional client-server architecture, for a better and more efficient peer-to-peer distribution.

These results were achieved with the steps hereafter described.

i) Introduction of a new high-capacity SSD disk on top of the tiering level besides the memory buffer of the top in/out devices, the only visible by the running programs and prone to answer back in a few microseconds.

ii) A redundant fiber channel network with an auto-balanced throughput carries on data in and out of the disk array systems, aggregating multichannel fiber networks.

iii) The AI manages the data moving from a very fast RAM memory buffer to a fast SSD disk to the last level built with slow but capacious technologies disk array like SAS, SATA, and Ultra SATA disk. There are no rules pre-inserted on the tiering model but the AI adapts the rules to our kinds of jobs every second we are working on. This allows more than 800 reconstruction

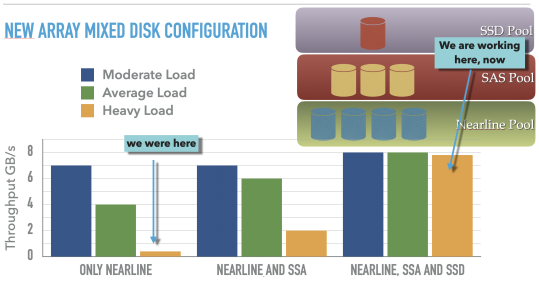

Figure 1: Disk Arrays Speed and Bandwidth.

The gained bandwidth is a top score for our computer cluster and its continuously improving every time we increase the number of parallel components in the fiber channel network. Every computer has reached the full bandwidth available on its devices or on its cards. The IO state close to zero is our best result: programs never wait for data from disk devices, these are always available for the software code and the computing times (CPU Time) is the only waiting time of the programs.

jobs to be afforded with more the 120000 files opened simultaneously. 24/7 there is an AI working to organize and optimize the access to files belonging to the array. The AI is moving files in and out from the three caching levels with the purpose of minimizing the access time and, as shown in Fig.2 panels, the results are very good before the SSD upgrade and outstanding after the upgrade.

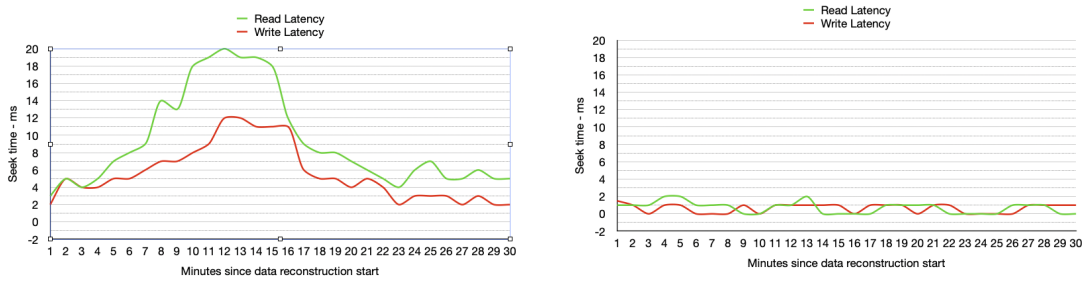

Figure 2: Disk Arrays read/write latency before (left) and after (right) the update.

iv) The algorithm of the AI, designed to satisfy the file-hungry jobs, is well suited to our typical job request and is becoming every day better in its tasks. Every time the AI model controlling the file distribution is becoming more expert in our file usage and the files necessary for jobs running into the HPC cluster are managing to increase the speed and lower the access time. Presently, every job running on the cluster works without interference from other jobs, as if it were alone in the cluster.

The job submission system, based on a Condor-derived protocol and the GPFS file system, managed more than 200.000 jobs during the last year without missing even a single job. It dispatched and managed efficiently the load into the KLOE-2 computing cluster, working as a High-Performance Computing in a parallel way with a high level of latency. This cluster with the new job submission system is the keystone of the KLOE-2 tasks, fitting the jobs to the cluster resources without over-heading even a single processor, so to keep the efficiency at the top level.

In conclusion, we managed the tasks required from KLOE-2 experiment reconstruction and analysis in a powerful environment used to face every request needed. Continuous studies for a new computational model have been developed with the not used power or during the idle time of the main tasks, because every simulation runs in a parallel environment extruded from the main one, partitioning resources and using them to bump not into one another.

4 Physics Analysis Updates

In the following sections latest updates obtained analysing the unique data sample collected by KLOE and KLOE-2 experiments will be discussed, in both kaon and hadron sectors.

4.1 "Back from the future" effect in $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$

A novel quantum time correlation phenomenon in the entangled neutral kaon system produced at a ϕ-factory has been studied at KLOE/KLOE-2: the "back from the future" effect. As discussed in [3], the past state of the first decayed kaon, when it was still entangled before its decay, is post-tagged by the result and the time of the future observation on the other kaon decay. This surprising effect is fully observable, and naturally leads to the tagging of the K_S state, an unsolved problem since the discovery of CP violation.

To study the t_1 distribution of the first decaying kaon in the $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ process [4], a data sample of about 1.7 fb^{-1} integrated luminosity has been analysed in two different cases: (i) the decoherence regime with $t_2 > 30\ \tau_S$ and the KS-tag condition satisfied, (ii) the interference regime with $2.5 < t_2 < 3\ \tau_S$.

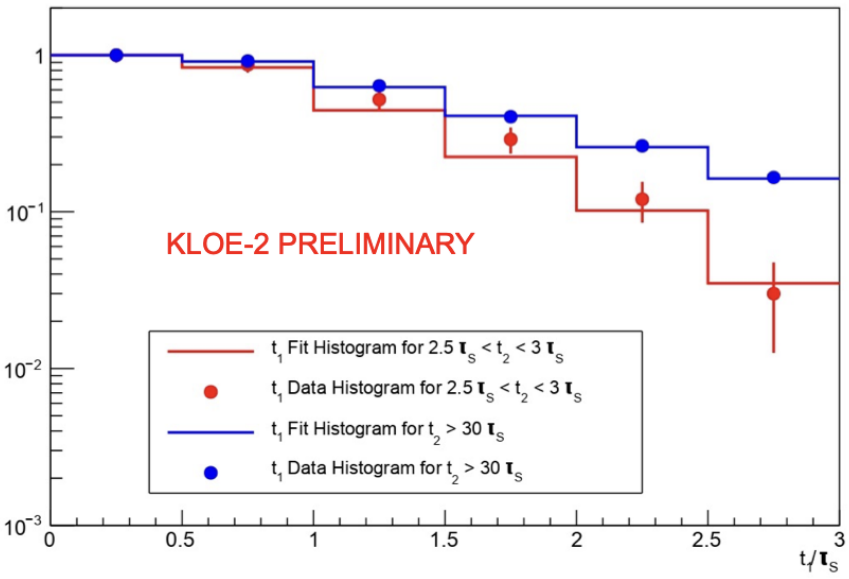

Figure 3: The measured t_1 distribution for $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ events in the case of the decoherence with $t_2 > 30\ \tau_S$ regime (blue points), and the interference regime with $2.5 < t_2 < 3\ \tau_S$ (red points). Both distributions are normalized to unity at t_1=0. The corresponding predictions of quantum mechanics, taking into account experimental resolution effects, are superimposed (blue and red histograms).

The first experimental evidence of the "Back from the future" effect obtained with $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ events from KLOE data is shown in Fig. 3. The measured t_1 distribution in the case of decoherence with $t_2 > 30\ \tau_S$ regime is represented by blue points and the interference regime with $2.5 < t_2 < 3\ \tau_S$ by the red points, with both distributions normalized to unity at

t_1=0. The corresponding predictions of quantum mechanics, taking into account the experimental resolution effects, are superimposed (blue and red histograms).

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

The analysis of the 2023 beam test of the KLOE-2 HET tagger stations conducted at the Frascati Beam Test Facility (BTF) was concluded and reported in the KLOE-2 internal document K2ID-91 [5]. The goal was the measurement of the efficiencies and relative positions of all the scintillators used in the analysis of KLOE-2 data with one neutral pion produced in $\gamma\gamma$ interactions at DAΦNE. It has been reached by the exposure of the scintillators to single-particle beams of 450 MeV electrons provided by the BTF with spatial resolution of 0.6-0.8 mm. The HET position was varied during the test in both x and y directions to obtain the response of all the scintillators in different regions, 1 mm apart. Radiative Bhabha scattering events at low angle would be used as reference process for the measurement of the $e^+e^- \to e^+e^-\gamma^{(*)}\gamma^{(*)} \to e^+e^-\pi^0$ cross section. The results of the analysis, taking into account of the clearance of the Roman Pots where the HET taggers were installed in DAΦNE, is that the effective Bhabha cross-sections measured with KLOE-2 are in agreement with MonteCarlo expectations using the efficiencies and the positions of the scintillators obtained at the BTF.

4.3 New measurement of the hadronic cross-section with the radiative return method

In recent years, there has been a lot of effort in the particle physics community to understand the long-standing discrepancy between the experimental and theoretical values of the muon anomalous magnetic moment, a_μ. The recent measurement of the Muon $g-2$ Collaboration at Fermilab [6] improves the uncertainty on a_μ by more than a factor of two with respect to the value published in 2021, confirming the previous result and increasing the discrepancy from the Standard Model evaluation based on e^+e^- data [7] to a significance of more than 5 σ's. On the other hand, recent lattice QCD calculations [8] give results which are in better agreement with the experimental measurement. Moreover, the historical tension in the results on the hadronic cross section from e^+e^- collider experiments, recently revived as the CMD-3 [9] result came out, is motivating new measurements.

The KLOE-2 Collaboration is aiming to perform a new measurement of the $e^+e^- \to \pi^+\pi^-$ cross-section with the radiative return method, exploiting a larger dataset available (roughly 7 times the statistics of the previously published KLOE 2π analyses [10]), with the goal of obtaining a 0.4% total error on a_μ, which represents a two-fold improvement in the accuracy with respect to the latest KLOE 2π measurement. Differently from previous hadronic cross-section measurements, we are developing a blind analysis procedure to avoid the possibility of a bias in the result. The blinding procedure removes a small, unknown fraction of events from the data as a function of the invariant mass: this affects the differential cross section, with a different fraction of removed events for the $\pi\pi\gamma$ and $\mu\mu\gamma$ analyses, but has no effect on the distributions in each invariant mass bin. The unblinded result will only be known to the analysis group after there has been a unanimous approval.

In order to reduce systematic errors, the analysis is performed normalizing the $e^+e^- \to \pi^+\pi^-\gamma$ events with the $\mu^+\mu^-\gamma$ final state. The event selection requires two tracks at large angle ($50^\circ < \theta_{\pi,\mu} < 130^\circ$) and an un-detected small angle photon ($\theta_{miss} < 15^\circ$ or $\theta_{miss} > 165^\circ$).

The signal and background contributions are extracted fitting for each 0.02 GeV^2 bin of $Q^2_{\pi\pi}$ the trackmass variable, M_{trk}, derived from the 4-momentum conservation under the hypothesis of events with two equal-mass charged tracks and a photon. Example of fits to the M_{trk} for different

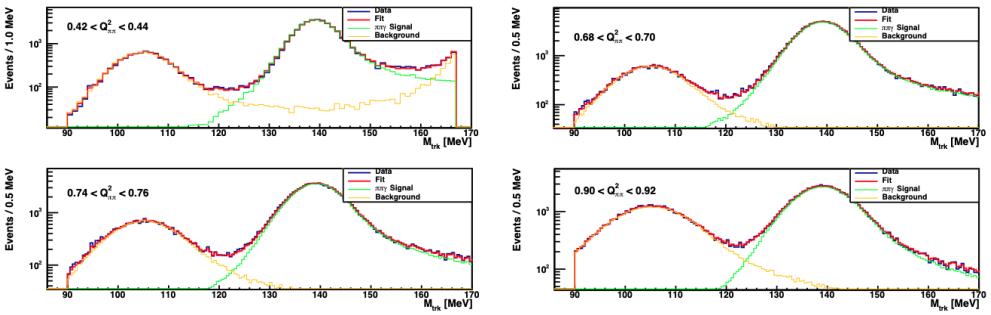

Figure 4: Fit to the track mass variable, M_{trk}, for different $Q^2_{\pi\pi}$ bins. Data (blue) are fit with Monte Carlo signal (green) and background (yellow) contributions. The fit result is reported in red.

$Q^2_{\pi\pi}$ values are reported in Fig. 4. Work is in progress to refine selection cuts, define the blinding strategy, and improve the unfolding procedure.

In the last year, comparisons between the MC generator PHOKHARA (used in previous KLOE analyses) and other MC generators were performed, in order to investigate radiative correction effects both due to missing NNLO contributions in PHOKHARA and also to test the validity of the generator at NLO, as questioned in Ref. [11]. In these studies, the cross sections as a function of the invariant mass of the two pions or two muons from PHOKHARA were compared with other generators. Vacuum polarization was switched off and detector effects (involving smearing of momenta) were not included. These preliminary studies indicated that [12]: (i) PHOKHARA is in excellent agreement with MCMULE; (ii) observed effects between PHOKHARA and other generators seem not to explain the whole difference of KLOE with the other experiments (particularly BaBar and CMD-3). Additional studies are in progress to confirm the above conclusions, specifically: enlarging the statistics; including detector effects; including more refined hadron-photon models for FSR (beyond sQED) [13] and NNLO radiative corrections; and applying the whole analysis selection.

In addition, KLOE-2 is also analyzing the three-pion cross section using the radiative return method with $1.7\,\mathrm{fb}^{-1}$ of data collected at the ϕ meson mass [14].

5 List of Conference Talks in Year 2024

- L. Cotrozzi, "Muon $g-2$ and KLOE activities in Liverpool", Particle Physics Annual Meeting, Liverpool (UK), 23-24/05/2024
- S. Gamrat, "Test of T, CP, and CPT Discrete Symmetries via Kaons Transitions at KLOE-2", 5^{th} Jagiellonian Symposium on Advances in Particle Physics and Medicine, Krakow (PL), June 29–July 7, 2024
- E. Zaid, "Status report on the KLOE $\pi\pi\gamma/\mu\mu\gamma$ analysis", Seventh Plenary Workshop of the Muon g-2 Theory Initiative at KEK, Tsukuba (JPN), 09-13/09/2024
- G. Venanzoni, "Investigation of Radiative Corrections with KLOE 2π analysis", Seventh Plenary Workshop of the Muon g-2 Theory Initiative at KEK, Tsukuba (JPN), 09-13/09/2024

- W. Torres Bobadilla, "Towards NNLO theoretical predictions to radiative return processes", Seventh Plenary Workshop of the Muon g-2 Theory Initiative at KEK, Tsukuba (JPN), 09-13/09/2024
- A. Di Domenico, "The experimental study of $K^0 - \bar{K}^0$ quantum entanglement at KLOE: from past to future or from future to past?", Workshop on "Quantum tests in collider physics", Merton College, Oxford, 1-3/10/2024
- A. Di Domenico, "Testing quantum mechanics at colliders", XXVI Roma Tre Topical Seminar on Subnuclear Physics, 3/12/2024

6 List of Publications in Year 2024

- Gauzzi P for KLOE-2 Collaboration, "Latest results from KLOE-2", EPJ Web of Conferences 303, 01010 (2024)
- Gamrat S for KLOE-2 Collaboration, "Test of T, CP, and CPT Discrete Symmetries via Kaons Transitions at KLOE-2", Acta Physica Polonica B Proceedings Supplement 17, 7-A4 (2024)

References

1. Gauzzi P for KLOE-2 Collaboration, EPJ Web of Conferences 303, 01010 (2024)
2. Gamrat S for KLOE-2 Collaboration, Acta Physica Polonica B Proceedings Supplement 17, 7-A4 (2024)
3. J. Bernabeu, A. Di Domenico, Can future observation of the living partner post-tag the past decayed state in entangled neutral K mesons?, Phys. Rev. D 105 (11) (2022) 116004. arXiv: 1912.04798, doi:10.1103/PhysRevD.105.116004.
4. Di Domenico A for KLOE-2 Collaboration, PoS(EPS-HEP2023)371
5. Babusci D *et al*, "KLOE-2 Taggers characterization at the LNF Beam Test Facility", KLOE-2 Internal Document K2ID-91 (2024)
6. D. P. Aguillard *et al* (The Muon $g-2$ collaboration), "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm", Phys. Rev. Lett. 131, 161802 (2023)
7. T. Aoyama *et al*, "The anomalous magnetic moment of the muon in the Standard Model", Phys. Rep. 887, 1 (2020)
8. Sz. Borsanyi *et al* (BMWc collaboration), "Leading hadronic contribution to the muon magnetic moment from lattice QCD", Nature 593, 51 (2021)
9. F. V. Ignatov *et al* (CMD-3 collaboration), "Measurement of the $e^+e^- \to \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector", Phys. Rev. D 109, 112002 (2024)
10. A. Anastasi *et al* (KLOE-2 collaboration), "Combination of KLOE $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ measurements and determination of $a_\mu^{\pi^+\pi^-}$ in the energy range $0.10 < s < 0.95\,\mathrm{GeV}^2$", JHEP 03, 173 (2018)
11. M. Davier *et al*, "Tensions in $e^+e^- \to \pi^+\pi^-(\gamma)$ measurements: the new landscape of data-driven hadronic vacuum polarization predictions for the muon $g-2$", Eur. Phys. J. C 84, 721 (2024)

12. G. Venanzoni, "Investigation of Radiative Corrections with KLOE 2π analysis", Seventh Plenary Workshop of the Muon $g-2$ Theory Initiative, KEK Tsukuba campus, Japan (2024)

13. R. Aliberti *et al*, "Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions", arXiv: 2410.22882, doi:10.48550/arXiv.2410.22882.

14. B. Cao and X. L. Kang for KLOE-2 Collaboration, "Study of $e^+e^- \to \pi^+\pi^-\pi^0$ process using initial state radiation at KLOE", Proceedings of 18th International Conference on Hadron Spectroscopy and Structure (2020)