KLOE-2 Collaboration - LNF Group

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1 Introduction

The KLOE-2 experiment at the upgraded e^+e^- DAϕNE collider of the INFN Laboratori Nazionali di Frascati completed its data taking campaign in Mach 2018 collecting more than 5 fb^{-1} at the center of mass energy of the ϕ-meson. 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 $\phi(1020)$ meson peak at e$^+$e$^-$ colliders. The physics program is mainly focused on $\mathrm{K_S}$ and η 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. KLOE-2 collaboration activities are now focused on data reconstruction and analysis towards precise measurements in both kaon and hadron sectors. The first round of data reconstruction is being completed exploiting features of the newly equipped CED which has been expanded for Data Consolidation. Also a plan for long-term Data Preservation is being prepared and first tests for ROOT compatible output are already available, exploiting contacts with CERN experts.

Latest physics results achieved in 2019 are: i) the first measurement ever of the $K_S \to \pi\mu\nu$ branching ratio [1)] allowing an independent determination of the CKM matrix element $|V_{us}|$ and the first test of the lepton-flavour universality with K_S decays ii) the final result on the $\eta \to \pi^+\pi^-$ upper limit [2)] on the nature of CP violation in strong interactions iii) the statistical evidence of correlated coincidence events between the HET tagger station and the central calorimeter [3)] in the search for candidates of single-π^0 production from $\gamma\gamma$ scattering and iv) preliminary invariant mass distributions from $\phi \to \eta B \to \eta\pi^0\gamma$ and $\eta \to B\gamma \to \pi^0\gamma\gamma$ decays to search for the B-boson, a leptophobic mediator between the dark sector and the Standard Model particles [4)].

2 Data Reconstruction and MC simulation

The first round of data processing has been completed with a reconstruction average rate of about 20 pb^{-1}/day and 30 pb^{-1}/day peak rate achieved. Concerning Monte Carlo simulation, this has been produced in parallel with data reconstruction with about 15 pb^{-1}/day average production rate. The consolidation activities on KLOE CED played a fundamental role (Sec.3) in achieving these results together with the cooperation of all KLOE-2 collaboration colleagues taking offline shifts. Simultaneously significant progress was made in the development of the new version of the official reconstruction software. Major advances have been: improved detector material description and background suppression together with an improved signal event yield from revised event selection algorithms. For Data Preservation purposes a ROOT output has been integrated in official reconstruction, after having optimized processing time and data compression configuration.

3 CED

During the last year, beside the usual tasks, KLOE CED developed and started some significant consolidation activities. First of all *Data Preservation*. We installed and designed an architectural scheme for dumping the precious KLOE and KLOE-2 raw data from both the old IBM3494 and new TS4500 tape libraries to a disaster recovery LTO tape library, using a different tape architecture (Fig.3). The copy task runs in background condition to avoid interference with the data reconstruction and simulation and with users analysis. The consolidation procedure includes also emptying the old tape library in order to have the new one as main tape library. Preparatory work to start these tasks has been finished just before the end of November and the procedure has been working uninterruptedly since December, dumping data as fast as possible, reaching in few month the 23% of the whole dataset. So we are confident to complete the tasks before the end of the year.

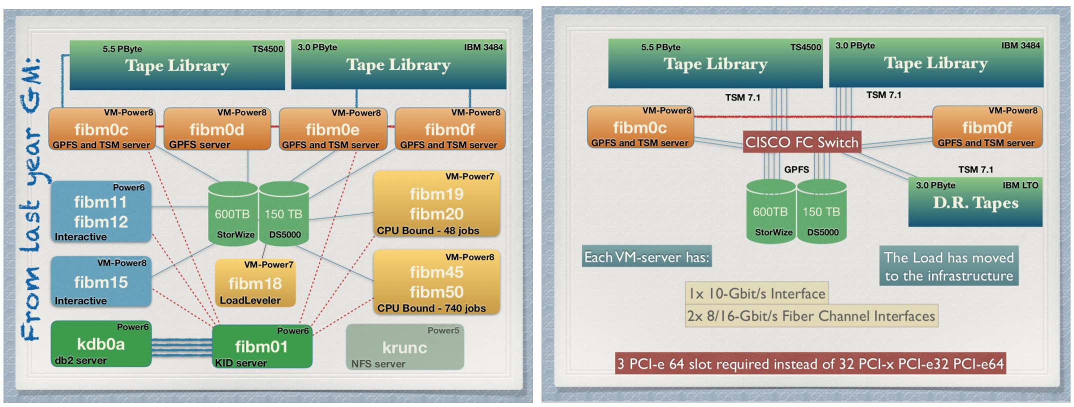

Figure 1: KLOE CED Scheme before and after consolidation

At the same time the KLOE CED infrastructure became stronger by completing the GPFS migration from the AFS protocol, now obsolete and slow. The migration to GPFS started in 2016 when it was used for KLOE-2 online DAQ. Presently GPFS protocol moves data through the entire CPU-cluster reaching the highest rate in data moving we have ever had with the sustained throughput level of 800 Gbyte per second. This high throughput rate deploys to our users the possibility to elaborate their data faster and reliably. Additional cartridges were also mounted in the main library, 200 cartridges with 10 TB capacity each, thus allowing to start the copy of the entire dataset stored in the old library into the new library. Also this task should be completed before the end of the year. A new job submission system substituted the old one that was compatible with AFS file systems. The old job submission never missed a single job, but AFS has always introduced a huge slow down in managing the system. Presently the new job submission carried by GPFS file servers is able to manage and dispatch more efficiently the daily load generated by users and to carry on the task even with thousands jobs enqueued. After the change, happened at the beginning of December the cluster has already dispatched and accomplished more than one hundred thousand different jobs.

4 Physics achievements

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

4.1 First measurement ever of $\mathcal{B}(K_S \to \pi\mu\nu)$

Measurements of the branching fraction for semileptonic decays of charged and neutral kaons together with their lifetimes are used to determine the $|V_{us}|$ Cabibbo–Kobayashi–Maskawa quark mixing matrix element. The relation among the matrix elements of the first row, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, provides the most stringent test of the unitarity of the quark mixing matrix. Different factors contribute to the uncertainty in determining $|V_{us}|$ from kaon decays [5, 6, 7] and among the six semileptonic decays the contribution of the lifetime uncertainty is smallest for the K_S meson. Nevertheless, given the lack of pure high-intensity K_S meson beams contrary to the case of $K^\pm$ and K_L mesons, the $K_S \to \pi e\nu$ decay provides the least precise determination of $|V_{us}|$, and the branching fraction $\mathcal{B}(K_S \to \pi\mu\nu)$ has not yet been measured. Measurement of this decay mode allows an independent determination of $|f_+(0)V_{us}|$, with $f_+(0)$ being the hadronic form factor at zero momentum transfer, and to extend the test of lepton-flavour universality to K_S semileptonic decays by comparison with the expected value of $(4.69 \pm 0.06) \times 10^{-4}$ [8] derived from $\mathcal{B}(K_S \to \pi e\nu)$.

A sample of 300 million K_S mesons produced in $\phi \to K_L K_S$ decays recorded by the KLOE experiment at the DAΦNE e^+e^- collider has been analyzed to measure the branching fraction for the decay $K_S \to \pi\mu\nu$. In the analysis K_S mesons are identified by the interaction of K_L mesons in the detector and $K_S \to \pi\mu\nu$ decays are selected by a boosted decision tree built with kinematic variables and by a time-of-flight measurement. Signal efficiencies are evaluated with data control samples of $K_L \to \pi\mu\nu$ decays. A fit to the reconstructed muon mass distribution (Fig.2) finds 7223 ± 180 signal events. Normalising to the $K_S \to \pi^+\pi^-$ decay events the result for the branching fraction is $\mathcal{B}(K_S \to \pi\mu\nu) = (4.56 \pm 0.11_{\mathrm{stat}} \pm 0.17_{\mathrm{syst}}) \times 10^{-4}$ [1].

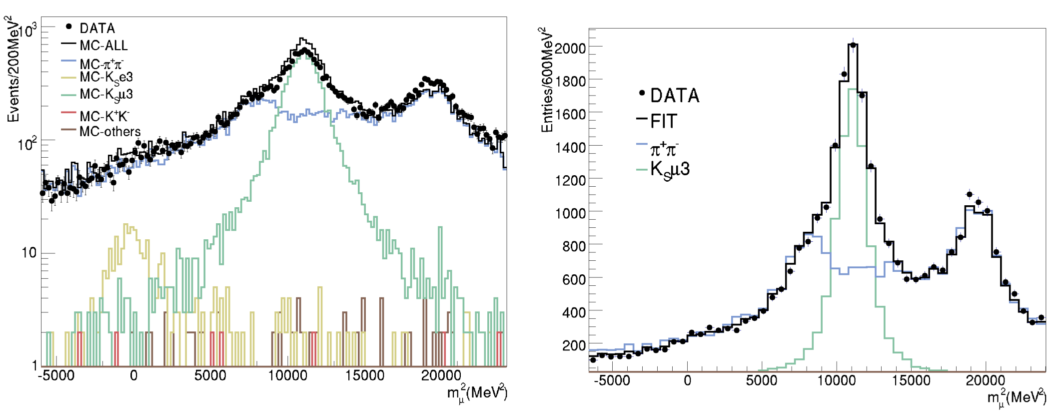

Figure 2: Left panel: The reconstructed muon mass m_μ^2 distribution for data, MC signal and background components. Right panel: Data comparison with the fit result using MC shapes.

This is the first measurement of this decay mode and the result allows an independent determination of $|f_+(0)V_{us}|$ and a test of the lepton-flavour universality. Using $I_K^\mu = 0.10262 \pm 47$ [7] for the phase space integral, we derive $|f_+(0)V_{us}|_{K_S\to\pi\mu\nu} = 0.2126 \pm 0.0046$ [1] and the ratio to the value obtained for $K_S \to \pi e\nu$ decay, $|f_+(0)V_{us}|_{K_S\to\pi e\nu} = 0.2153 \pm 14$ [7], allows to confirm the assumption of kaon–lepton coupling universality for the first time with K_S semileptonic decays [1)]

$$r_{\mu e} = \frac{|f_+(0)V_{us}|^2_{K_S\to\pi\mu\nu}}{|f_+(0)V_{us}|^2_{K_S\to\pi e\nu}} = 0.975 \pm 0.044.$$

These results are consistent with those determined for the other kaon semileptonic decays [5, 7)] though less precise.

4.2 $\eta \to \pi^+\pi^-$ 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_S meson and has a branching ratio $Br(\eta \to \pi^+\pi^-) \leq 2 \times 10^{-27}$ [9, 10)]. This upper limit (UL) can increase of an order of magnitude by introducing a possible QCD-violating term contribution to the decay [9, 10)] and reach 10^{-15} if CP violation is allowed also in an extended Higgs sector [9, 10)]. 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: $Br(\eta \to \pi^+\pi^-) \leq 1.3 \times 10^{-5}$ at 90% CL [11)].

A new 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 $45° < \theta < 135°$ 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

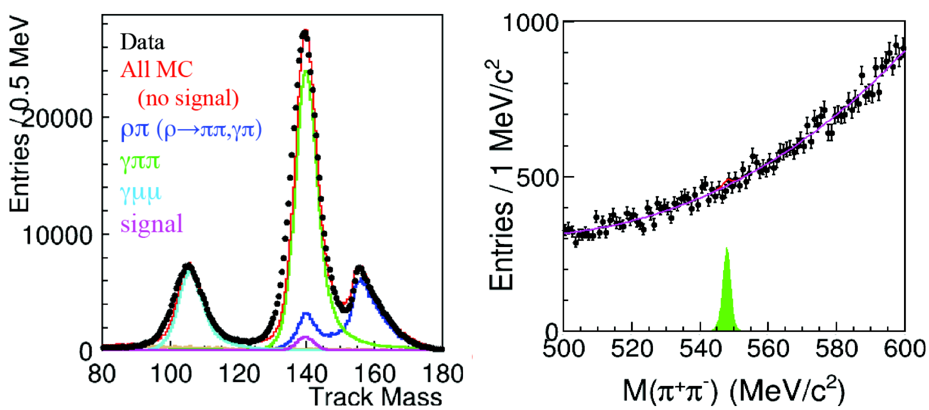

Figure 3: Left panel: track mass distributions. Data are shown in black, all MC background contributions in the hypothesis of no $\eta \to \pi^+\pi^-$ signal are in red , while the expected signal is shown in violet. Right panel: $\pi^+\pi^-$ invariant mass distribution for data (black points). The curve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

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 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 Fig. 3 right panel. The upper limit on the branching ratio, extracted by using a Bayesian approach, is 5.8×10^{-6} at 90% CL and was presented at the EPS-HEP 2019 and Hadron 2019 conferences [2]. More recently a combined UL of 4.4×10^{-6} was obtained by using the full KLOE data sample and different approaches with respect to the Bayesian first adopted. The result was shown at the open session of the 58^{th} meeting of LNF Scientific Committee in November 2019. With the KLOE /KLOE-2 data samples the upper limit is expected to reach 2.7×10^{-6}.

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

The precision measurement of the $\pi^0 \to \gamma\gamma$ width would give insight into low-energy QCD dynamics. To achieve the $\mathcal{O}(1\%)$ precision needed to test theory predictions, the π^0 production through $\gamma\gamma$ fusion in the $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ reaction can be used and KLOE-2 has the possibility to perform this measurement [12]. To reduce the background coming from ϕ-meson decays, two High Energy Tagger (HET) stations [13] 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 interaction point (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 measure the detector acceptance×efficiency and for data quality purposes. An effective cross section of the order of 10 mb has been measured, with large fluctuations for the scintillators closest to the beam (Fig. 4).

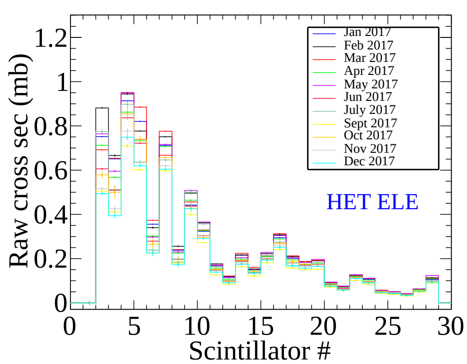

Figure 4: Effective low angle radiative Bhabha cross section per plastic as measured by the electron station. Every distribution refers to a different month of the 2017. Only plastics greater than 10 are used for the π^0 search.

For the π^0 search a sub-set of HET plastic scintillators has been used, showing operational stability over a time scale of years of data taking. Candidates of single-π^0 production from $\gamma\gamma$ scattering have been pre-filtered recording information on the hit in the tagger, the trigger signal, 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 the KLOE central detector associated with only 2 clusters in the calorimeter, in a given time window around the trigger signal. Very loose kinematic cuts are applied to this sample. A statistical evidence of correlated coincidence events between the tagger station hits and KLOE calorimeter clusters has been observed on a sample of 500 pb^{-1} and on the electron side, after an event-by-event subtraction of the registered accidentals. Fig. 5 left panel shows the bi-dimensional fit of the invariant mass of the two selected

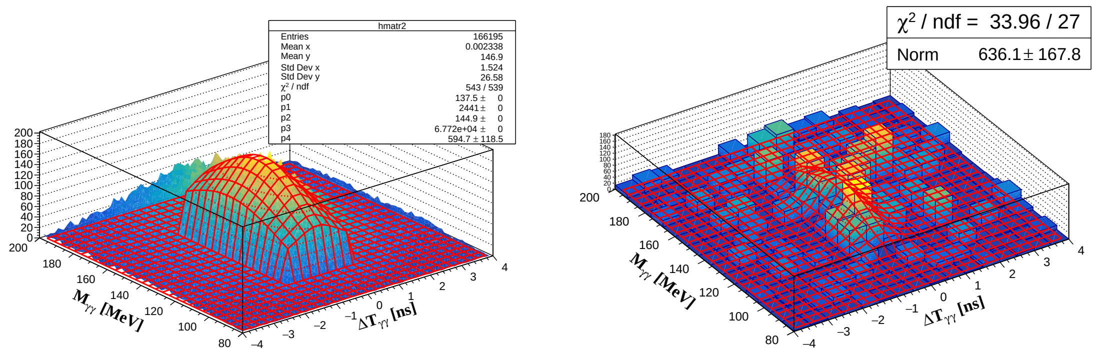

Figure 5: the invariant mass of the two selected photons $M_{\gamma\gamma}$ as function of their time difference $\Delta_{\gamma\gamma}$. Left panel: 2D-fit of signal plus accidental data sample, all parameters are fixed but signal normalization. The background function is determined by the fit of the accidental-pure sample. Signal resolution parameters are fixed to: $\sigma_{M_{\gamma\gamma}}$=20 MeV, $\sigma_{\Delta \mathrm{T}_{\gamma\gamma}}$=400 ps. Right panel: 2D-fit after accidental subtraction.

photons $M_{\gamma\gamma}$ as function of their time difference $\Delta_{\gamma\gamma}$, for the coincidence sample between KLOE and HET electron station. The background function is determined by the fit of the accidental-pure sample while signal parameters are taken from the simulation. Fig. 5 right panel shows the bi-dimensional fit of the coincidence sample after the subtraction of accidental events. The number of π^0 candidates evaluated with the two fits is in agreement within the errors. An improved rejection of accidental events is needed to improve the precision on the measurement. Some issues affecting the evaluation of the accidental events and the KLOE-HET synchronization have been found and fixed. A reprocessing of all reconstructed data is ongoing to profit from optimized calibration constants for the calorimeter cluster energy and time, in order to improve as much as possible energy and time resolutions and therefore the signal to background ratio.

4.4 Leptophobic Dark Matter search with KLOE-2

Several Dark Matter (DM) models have been searched for with the KLOE detector setup constraining the space parameters for the DM candidates [14, 15, 16, 17, 18, 19, 20]. In particular, currently, a new search based in the model presented in [21], which proposes a leptophobic mediator between the dark sector and the SM particles, the B boson, is investigated. The B boson arises from a new $U(1)_B$ gauge symmetry that couples to the baryon number as:

$$\mathcal{L} = \frac{g_B}{3}\bar{q}\gamma^\mu q B_\mu \tag{1}$$

where g_B is the $U(1)_B$ coupling, estimated to be $g_B \lesssim 10^{-2} \times (m_B/100\ \mathrm{MeV})$. With quantum numbers $I^G(J^{PC}) = 0^-(1^{--})$, the B-boson decays in a similar way as the ω-meson. It is worth to notice that, given that the decay $B \to \pi^+\pi^-$ is forbidden by G-parity, the B-boson cannot be hidden under the ρ meson.

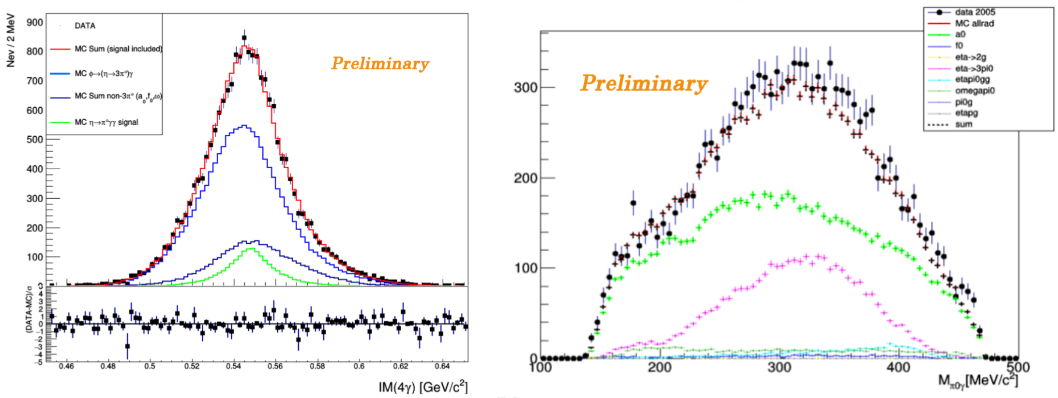

Figure 6: Left panel: Invariant mass of the $4-\gamma$ system in the decay $\eta \to B\gamma$. The dots show the data point while the solid color lines correspond to Monte Carlo simulations. Right panel: Invariant mass of the $\pi^0\gamma$ system from the channel $\phi \to \eta B \to \eta\pi^0\gamma$. Solid dots correspond to data, solid lines are Monte Carlo simulations.

In KLOE the interesting region to be explored corresponds to masses below 600 MeV, where the dominant decay is $B \to \pi^0\gamma$. In particular, two reactions are being investigated by KLOE: the $\phi \to \eta B \to \eta\pi^0\gamma$, which mimics the final state of the SM decay $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$, and the $\eta \to B\gamma \to \pi^0\gamma\gamma$, which has the same final state as χPT golden mode rare decay $\eta \to \pi^0\gamma\gamma$. Preliminary results were presented at Phi2Psi2019 [4]. Fig. 6-left shows the invariant mass of 4-γ from $\eta \to B\gamma$ obtained with 1.7 fb^{-1} and Fig. 6-right shows the $\pi^0\gamma$ invariant mass from the decay $\phi \to \eta B$ using 1.2 fb^{-1}. In case of formation of the B-boson, the signature would appear as an enhancement in the corresponding 4-γ and $\pi^0\gamma$ invariant masses. In case no signal is discovered an upper limit in the coupling of such a DM mediator to the SM will be established.

5 List of Conference Talks by LNF Authors in Year 2019

1. C. Bloise,"Hadron Physics with KLOE-2 data at the Phi-factory", invited talk at MENU 2019, Pittsburg, United States
2. F. Curciarello, "Recent Results on Hardon Physics at KLOE-2", PHIPSI2019 , Novosibirsk, Russia
3. E. De Lucia, "CPT symmetry test at KLOE-2", KAON2019, Perugia, Italia
4. A. Di Cicco, "Recent Results on Kaon Physics at KLOE-2", PHIPSI2019, Novosibirsk,Russia
5. A. Di Cicco, "The cylindrical-GEM inner tracker detector of the KLOE-2 experiment", VCI2019, Vienna, Austria
6. X. Kang, "Low energy hadron physics at KLOE/KLOE-2",EPS-HEP2019, Ghent, Belgium
7. X. Kang,"Overview of light hadron physics at KLOE/KLOE-2", Guilin, China
8. X. Kang,"Studies of the ISR process $e^+e^- \to \pi^+\pi^-\pi^0\gamma$ at the ϕ-meson mass with the KLOE and KLOE-2" (Poster), Guilin, China
9. D. Moricciani, "$\gamma\gamma$-physics at KLOE-2 ", PHOTON2019, Frascati, Italia

10. E. Perez Del Rio, ”Search for dark forces at KLOE-2”, PHIPSI2019, Novosibirsk,Russia
11. E. Perez Del Rio, P. Gauzzi, ”The KLOE-2 experiment at DAϕNE”, PHIPSI2019, Novosibirsk,Russia
12. E. Perez Del Rio,”The KLOE-2 Experiment at DAϕNE”, 3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Krakow, Poland

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