KAONNIS

M. Bazzi, M. Cargnelli (Ric. Str.), A. Clozza, C. Curceanu (Resp. Naz.),
R. Del Grande (Ric. Str.), L. De Paolis (Ass.), S. Dabagov, C. Guaraldo,
D. Hampai, P. Levi Sandri, M. Iliescu, M. Merafina (Assoc.),
M. Miliucci (Ass.), S. Niedźwiecki (Ric. Str.), E. Pace, A. Scordo,
F. Sgaramella (Dott.), D. Sirghi (Ass.), F. Sirghi (Ass.), M. Skurzok (Post. Doc.),
A. Spallone (Assoc.), M. Tuechler (Assoc.), O.Vazquez Doce (Bors.), J. Zmeskal (Ric. Str.)

1 KAONNIS: the scientific program

KAONNIS represents an integrated initiative in the field of experimental low-energy kaon-nucleon/nuclei interaction studies. Under KAONNIS the following activities are performed:

- kaonic atoms measurements by the SIDDHARTA-2 experiment
- studies of kaon-nuclei interactions at low-energies in the framework of the AMADEUS Collaboration
- participation at experiments at J-PARC (Japan) dedicated to strangeness studies
- future kaonic atoms measurements program at the DAΦNE collider

We present in what follows these scientifc lines, together with the 2021 activities and plans for 2022.

The KAONNIS activities are partially financed within the STRONG-2020 European project (grant agreement No. 824093).

2 The SIDDHARTA-2 experiment

The objective of the SIDDHARTA-2 (Silicon Drift Detector for Hadronic Atom Research by Timing Application) experiment is to perform high precision measurements of X-ray transitions in exotic (kaonic) atoms at the DAΦNE collider.

The precise measurement of the shift and width of the 1s level, with respect to the purely electromagnetic calculated values, in kaonic hydrogen and kaonic deuterium, induced by the strong interaction, through the measurement of the X-ray transitions to this level, will allow the first precise experimental determination of the isospin-dependent antikaon-nucleon scattering lengths, fundamental quantities for the understanding of the low-energy QCD in strangeness sector.

The accurate determination of the scattering lengths will place strong constraints on the low-energy K^- N dynamics, which, in turn, constraints the SU(3) description of chiral symmetry breaking in systems containing the strange quark. The implications go from particle and nuclear physics to astrophysics (the equation of state of neutron stars).

The SIDDHARTA collaboration performed the most precise measurement of kaonic hydrogen and the first exploratory study of kaonic deuterium. Moreover, the kaonic helium 4 and 3 transitions to the 2p level were measured, for the first time in gas in He^4 and for the first time ever in He^3. Presently, the SIDDHARTA-2 experiment , is under way, with the aim to measure kaonic deuterium and, as well, other types of kaonic atoms.

2.1 Before SIDDHARTA-2: the SIDDHARTA experiment

In the first decade of this century, SIDDHARTA represented a new phase in the study of kaonic atoms at DAΦNE. The previous DEAR experiment's precision was limited by a signal/background ratio of about 1/70 for the kaonic hydrogen measurement, due to the high machine background. To significantly improve this ratio, an experimental breakthrough was necessary. An accurate study of the background sources at DAΦNE was done. The background includes two main sources:

- *synchronous background*: coming from the K^- interactions in the setup materials and Φ-decay processes; it can be defined as *hadronic background*;
- *asynchronous background*: final products of electromagnetic showers in the machine pipe and in the setup materials, originating from particles lost from primary circulating beams either due to the interaction of particles in the same bunch (Touschek effect) or due to the interaction with the residual gas.

Accurate studies showed that the main background source in DAΦNE is of the second type, which points to the procedure to reduce it. A fast trigger correlated to the kaons entering into the target cut the main part of the asynchronous background. X rays were detected by DEAR using CCDs (Charge-Coupled Devices), which are excellent X-ray detectors, with very good energy resolution (about 140 eV FWHM at 6 keV), but having the drawback of being non-triggerable devices (since the read-out time per device is at the level of 10 s). A new device, which preserves all good features of CCDs (energy resolution, stability and linearity), but additionally is triggerable - i.e. fast (at the level of 1 μs), was implemented. The new detector was a large area Silicon Drift Detector (SDD), specially designed for SIDDHARTA. The development of the new 1cm^2 SDD device, together with its readout electronics and very stable power supplies, was partially performed under the Joint Research Activity JRA10 of the I3 project "Study of strongly interacting matter (HadronPhysics)" within FP6 of the EU.

The trigger in SIDDHARTA was given by a system of scintillators which recognized a kaon entering the target making use of the back-to-back production mechanism of the charged kaons at DAΦNE from Φ decay:

$$\Phi \rightarrow K^+K^- \tag{1}$$

The SIDDHARTA setup contained 144 SDD chips, 1cm^2 each, placed around a cylindrical target, filled with high density cryogenic gaseous hydrogen (deuterium or helium). The target was made of kapton, 75μm thick, reinforced with aluminium grid.

The SIDDHARTA setup was installed on DAΦNE in late summer 2008, and the period till the end of 2008 was used to debug and optimize the setup performances (degrader optimization included). The kaonic atoms measurements were done in 2009 and data analysis followed in the coming years, which produced the most precise measurement of kaonic hydrogen [1] and measurements of kaonic helium 3 [2] and kaonic helium 4 [3], [4]. Kaonic deuterium could not be measured by SIDDHARTA, since signal/background was too small.

2.2 The SIDDHARTA-2 setup

The upgrade from SIDDHARTA to SIDDHARTA-2 is relying on the following essential modifications:

- *Trigger geometry and target density*: By placing the upper kaon-trigger detector in front of the target entrance window the probability that a triggered kaon really enters the gas and is stopped there is improved. Making the detector smaller than the entry area gives away

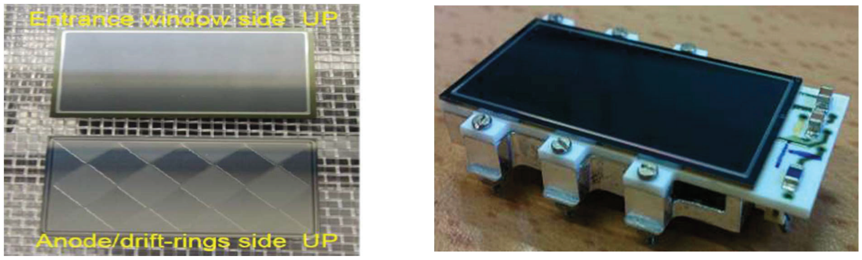

Figure 1: *The new 2 x 4 SIDDHARTA-2 SDD array together with the readout electronics.*

some signal, but suppresses efficiently the kaonic lines from "wall-stops" (kaons entering the gas volume, but passing from the inside of the target to the cylindrical walls). The number "signal per trigger" goes up, which also reduces the accidental background coming along with every trigger. We will also plan to double the gas density which enhances the gas stops and further reduces the wall-stops.

- *Active shielding*: The scintillators surrounding the target will also be used in prompt anti-coincidence if the spatial correlation of SDD and scintillator hits indicates that it originated from a pion ("charged particle veto"). An anticoincidence covering the SDD time window of about 600 ns (with the exception of the 4 ns of the gas stopping time) will reduce the accidental background. Although the scintillators have low efficiency for gammas, the abundance of secondaries from the electromagnetic showers allows a relevant reduction of accidental ("beam") background. The upper trigger scintillator has 2 functions, it is also used as an anticoincidence counter: after the kaon and eventual prompt kaon-absorption secondaries pass, it vetos beam background.
- *New SDD detectors*, produced by FBK, having a much better active/total surface ratio (about 85%, with respect to 40% in SIDDHARTA SDDs) (see Figure 1).
- *Operating SDDs at a lower temperature*: tests indicate that an improvement of the timing resolution by a factor of 1.5 is feasible by more cooling. The signal enhancement by a factor 2 to 3 is due to moving the target cell closer to the IP, by changing its shape, by a better solid angle of the SDDs and by the higher gas density. In such conditions, with an integrated luminosity of 800 pb^{-1} a precision similar to that obtained for kaonic hydrogen is reachable.

A scheme of the SIDDHARTA-2 internal region of the setup is shown in Figure 2.

In 2020 the first setup, SIDDHARTINO, see Figure 3, containing 8 SDDs units, aiming to measure kaonic helium to quantify the background in the new DAΦNE configuration, previous to the kaonic deuterium measurement, installed on DAΦNE in 2019 was partially tested on DAΦNE (Figure 4).

In 2021 runs, lasting till July 2021, SIDDHARTINO was able to perform a kaonic helium 4 measurement and optimize the setup.

In summer-autumn the full SIDDHARTA-2 setup was installed on DAΦNE, tested in November-December and ready for kaonic deuterium runs in 2022/2023.

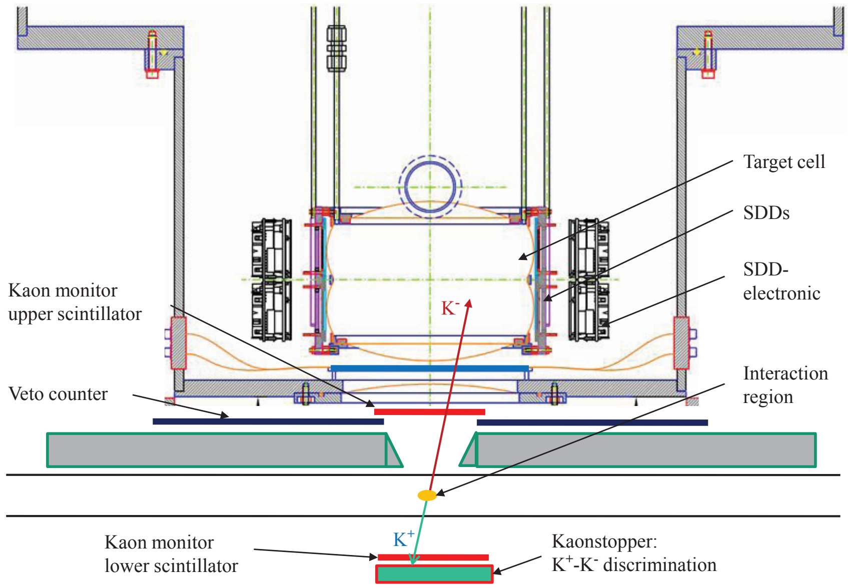

Figure 2: *Schematic view of the SIDDHARTA-2 setup.*

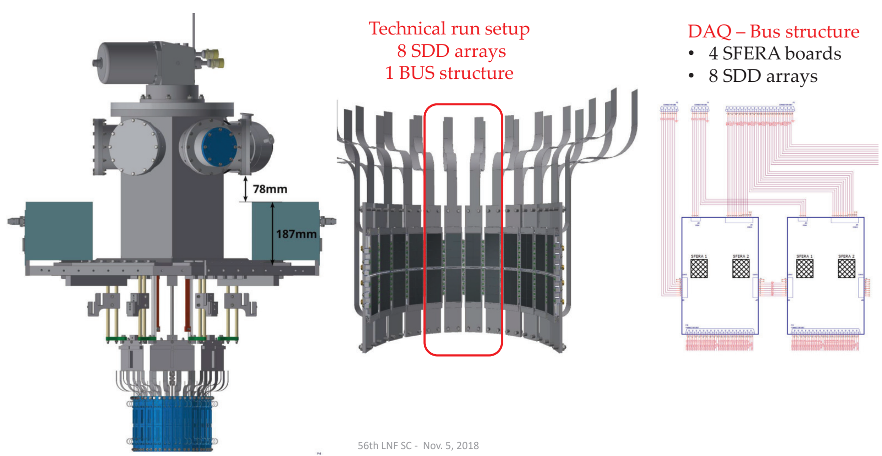

Figure 3: *The SIDDHARTINO setup.*

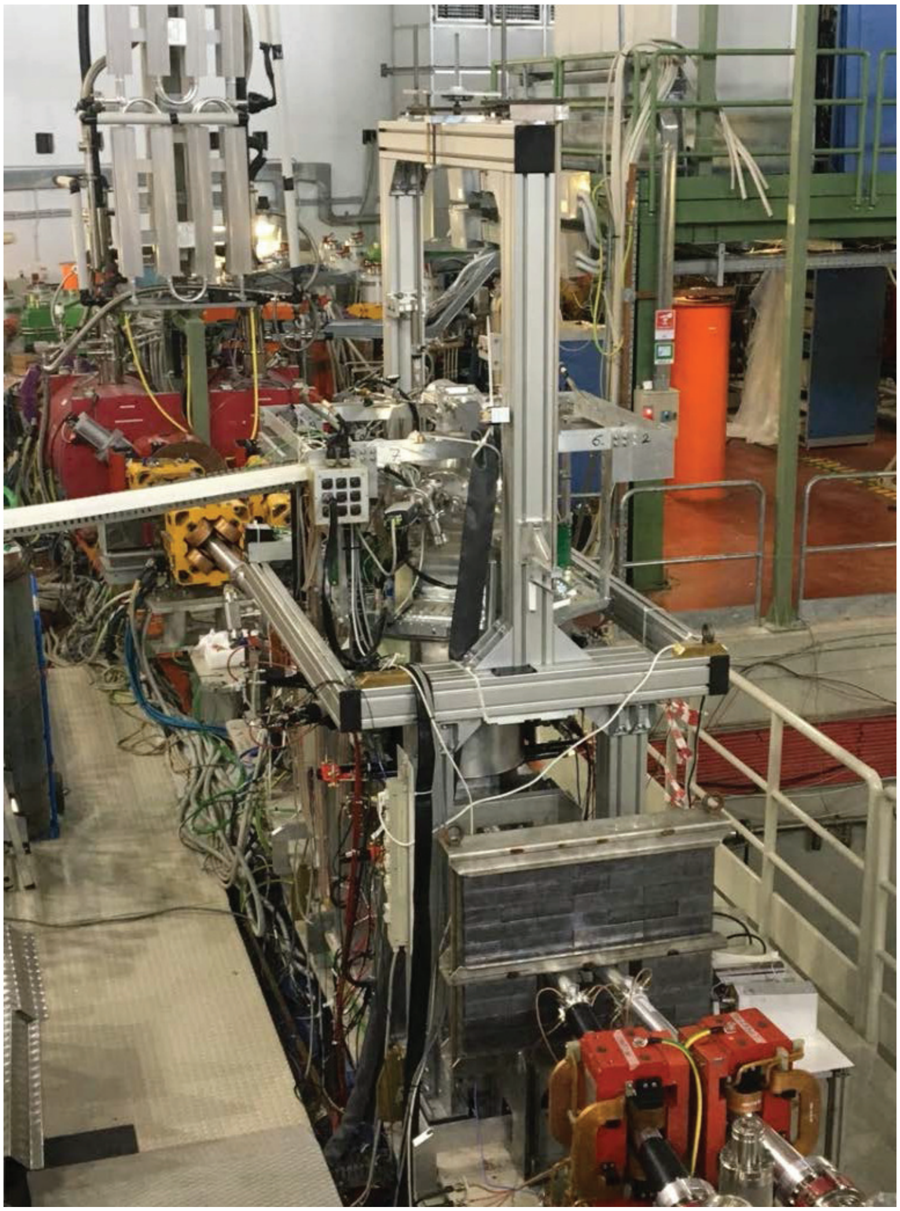

Figure 4: *Photo of SIDDHARTINO setup installed in DAΦNE.*

2.3 More details on 2021 SIDDHARTINO activities

SIDDHARTINO took data on DAΦNE until July 2021 and was performimg kaonic helium-4 runs, for the optimization of the running conditions, including SDDs background and degrader. The run allowed to obtain the most precise measurement of kaonic helium-4 L-lines in gas (see Figure 5), and the results were sent for publication [8].

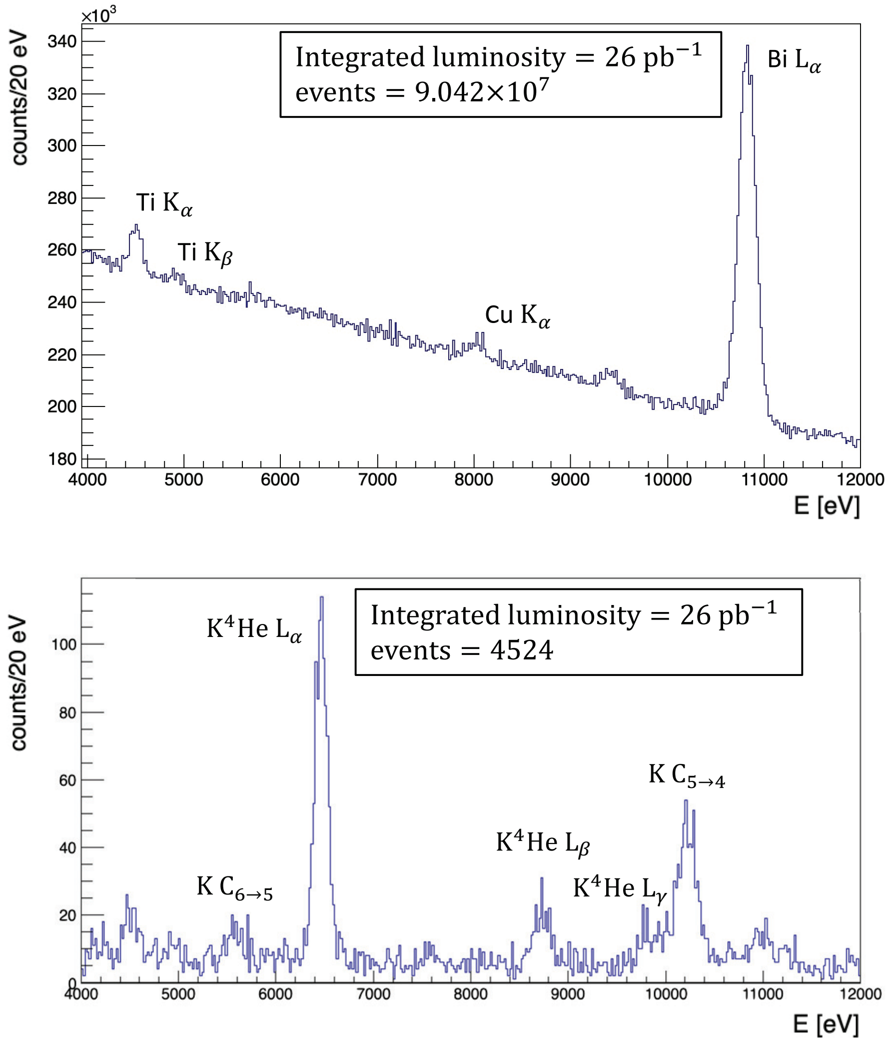

Figure 5: *Spectra without (top) and with (bottom) KT selections, from which the* $\simeq 10^{-5}$ *rejection factor can be obtained (bottom).*

Also, in 2021 a proposal for future kaonic atoms measurements beyond SIDDHARTA-2 was put forward (Figure 6): for more details see arXiv:2201.09735 [nucl-ex].

2.4 Plan for the SIDDHARTA-2 activities in 2022

The LNF group main activities in SIDDHARTA-2 for 2022 will be the following ones:

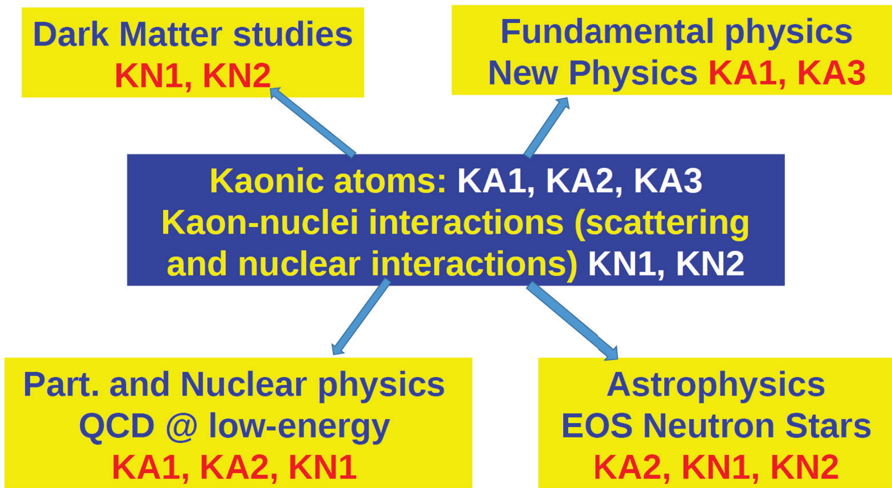

Figure 6: *Impact of the Fundamental Physics at the Strangeness Frontier at DAΦNE studies in various sectors.*

- optimization, debug and run with SIDDHARTA-2 setup for kaonic deuterium measurement
- Monte Carlo simulations for SIDDHARTA-2 setup and physics;
- data analysis
- run with a High Purity Germanium detector for testing the feasibility of other kaonic atoms measurements, as kaonic lead.
- consolidation of the proposal for kaonic atoms measurements beyond SIDDHARTA-2

In Figure 7 we show the kaonic deuterium simulated spectrum and expected results for an integrated luminosity of 800 pb^{-1}.

3 AMADEUS: 2021

The low-energy kaon-nuclei interaction studies represent the main aim of AMADEUS. The negatively charged kaons from DAΦNE can stop inside the target or interact at low energies, giving birth of a series of processes we plan to study. Among these, a key-role is played by the production of $\Lambda(1405)$ which can decay into: $\Sigma^0\ \pi^0$, $\Sigma^+\ \pi^-$ or $\Sigma^-\ \pi^+$. We study all these three channels in the same data taking. Another important item is represented by the debated case of the "kaonic nuclear clusters", especially the and K^-pp and K^-ppn ones. We study these channels by measuring their decays to Λp and to Λd. In the same time, many other kaon-nuclei processes are investigated, either for the first time, or in order to obtain more accurate results than those actually reported in literature. Cross sections, branching ratios, rare hyperon decay processes are investigated, taking advantage of the unique kaon-beam quality delivered by DAΦNE.

In the summer of 2012 a first dedicated target, half cylinder done in pure carbon was realized and installed inside the Drift Chamber of KLOE as a first setup towards the realization of AMADEUS. The target thickness was optimized to have a maximum of stopped kaons (about 24% of the generated ones) without degrading too much the energy of resulting charged particles

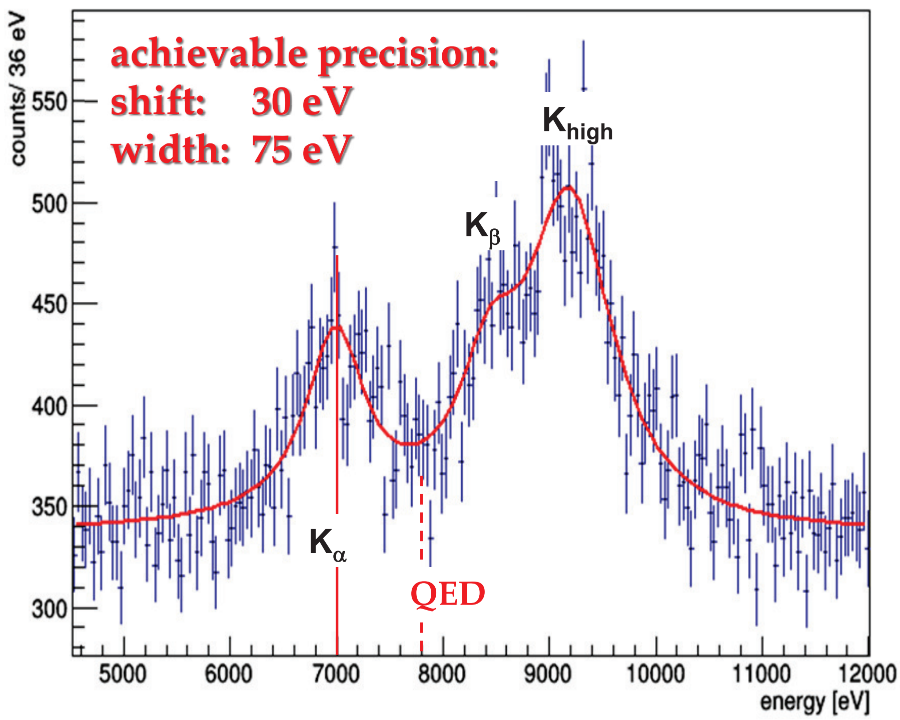

Figure 7: *Monte Carlo simulated kaonic deuterium spectrum for 800 pb^{-1}. sectors.*

inside the target material. In the period of data taking a total integrated luminosity of about 90 pb^{-1} was achieved. The ongoing analysis of these data will provide new insights in the low-energy interactions of charged kaons in the nuclear matter.

Activities done in 2021:

- analysis of 2002-2005 KLOE data searching for processes generated by negatively charged kaons interacting at rest or in- fight in the setup materials (wall of the Drift Chamber and gas inside the Drift Chamber); the analyses of the K^- absorption delivering Λd and Λt final states were finalized and results are being prepared for pubblication;
- analysis of Σ^0 π^0;
- analysis of the 2012 Carbon target data;
- Monte Carlo dedicated simulations.

3.1 AMADEUS activities in 2022

The main activities of AMADEUS in 2022 will be:

- analyses of data taken with the dedicated carbon target
- Monte Carlo dedicated simulations
- definition of the future strategy for dedicated experiment on DAΦNE and J-PARC.

3.2 Events and workshop organization

In 2021 the following events were done:

- Fundamental physics at the strangeness Frontier at DAΦNE (online), 25-26 February 2021 (LNF-INFN)
- Symphosium: Fundamental physics with exotic atoms and radiation detectors (online), 25-26 November 2021 (INFN-LNF)
- Workshop at ECT*: STRANU: Hot Topics in Strangeness Nuclear and Atomic Physics (online), 24-28 July 2021 (ECT*, Trento, Italy)

where the KAONNIS physics was discussed, were organized.

The physics results of KAONNIS were presented in 2021 in about 20 talks in International workshops and conferences.

Acknowledgements

The support from LNF Director, Dr. Fabio Bossi and from the DANE, KLOE2 and BTF-LNF teams are gratefully acknowledged.

4 Publications in 2021

1. F. Sgaramella *et al*, The SIDDHARTA-2 calibration method for high precision kaonic atoms X-ray spectroscopy measurements, e-Print: 2201.12101 [physics.ins-det].
2. F. Napolitano *et al*, Kaonic Atoms at the DAΦNE Collider with the SIDDHARTA-2 Experiment, e-Print: 2201.11525 [nucl-ex].
3. D. Sirghi *et al*, A new kaonic helium measurement in gas by SIDDHARTINO at the DAΦNE collider, e-Print: 2201.09735 [nucl-ex]
4. C. Curceanu *et al*, Kaonic atoms measurements at the DAΦNE collider: the SIDDHARTA-2 experiment, EPJ Web Conf. 258 (2022) 07006.
5. M. Miliucci *et al*, Silicon drift detectors technology for high precision light Kaonic atoms spectroscopic measurements at the DAΦNE collider, AIP Conf.Proc. 2416 (2021) 1, 020009.
6. M. Miliucci *et al*, Silicon Drift Detectors' Spectroscopic Response during the SIDDHARTA-2 Kaonic Helium Run at the DAΦNE Collider, Condens.Mat. 6 (2021) 4, 47.
7. V. De Leo, A. Scordo, C. Curceanu, M. Miliucci, F, Sirghi, Reflection Efficiency and Spectra Resolutions Ray-Tracing Simulations for the VOXES HAPG Crystal Based Von Hamos Spectrometer, Condens.Mat. 7 (2021) 1, 1.
8. F.Sakuma *et al*, Recent Results and Future Prospects of Kaonic Nuclei at J-PARC, Few Body Syst. 62 (2021) 4, 103.
9. C. Curceanu *et al*, Kaonic Atoms Measurements at DAΦNE : SIDDHARTA-2 and Future Perspectives, Few Body Syst. 62 (2021) 4, 83.
10. M. Miliucci *et al*, Low energy kaon-nuclei interaction at DAΦNE: The SIDDHARTA-2 experiment, Nuovo Cim.C 44 (2021) 4-5, 152.

11. M. Miliucci *et al*, Silicon drift detectors system for high-precision light kaonic atoms spectroscopy, Measur.Sci.Tech. 32 (2021) 9, 095501.
12. C. Curceanu *et al*, Fundamental physics at the strangeness frontier at DANE. Outline of a proposal for future measurements, e-Print: 2104.06076 [nucl-ex].
13. R. Del Grande *et al*, On the K^- Absorptions in Light Nuclei by AMADEUS, Few Body Syst. 62 (2021) 1, 7.
14. K. Piscicchia *et al*, γ-ray high sensitivity tests of Collapse Models, J.Phys.Conf.Ser. 2156 (2021) 1, 012167.
15. M. Miliucci *et al*, Low-energy Kaon Nucleon/Nuclei Studies at DAΦNE: the SIDDHARTA-2 Experiment, Acta Phys.Polon.Supp. 14 (2021) 49.
16. K. Piscicchia *et al*, High Sensitivity Quantum Mechanics Tests in the Cosmic Silence, Acta Phys.Polon.Supp. 14 (2021) 151.
17. S. Donadi, K. Piscicchia, C. Curceanu *et al*, Underground test of gravity-related wave function collapse, Nature Phys. 17 (2021) 1, 74-78.

References

1. M. Bazzi *et al*, Phys. Lett. B **704** , 113 (2011).
2. M. Bazzi *et al*, Phys. Lett. B **697** , 199 (2011).
3. M. Bazzi *et al*, Phys. Lett. B **681** , 310 (2009).
4. M. Bazzi *et al*, Phys. Lett. B **714** , 40 (2012).
5. R. Del Grande *et al*, Eur. Phys. J. C **79** , 190 (2019).
6. C. Curceanu *et al*, Rev. Mod. Phys. **91** , 022006 (2019).
7. C. Curceanu *et al*, Symmetry **1** , 547 (2020).
8. arXiv:2201.09735 [nucl-ex].