SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms

KAONIC ATOMS MEASUREMENTS WITH SIDDHARTA-2 AT THE DAΦNE COLLIDER

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on behalf of the SIDDHARTA-2 collaboration

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Why Kaonic Atom?

On self-gravitating strange dark matter halos around galaxies Phys.Rev.D 102 (2020) 8, 083015

Dark Matter studies

Fundamental physics
New Physics

The modern era of light kaonic atom experiments Rev.Mod.Phys. 91 (2019) 2, 025006

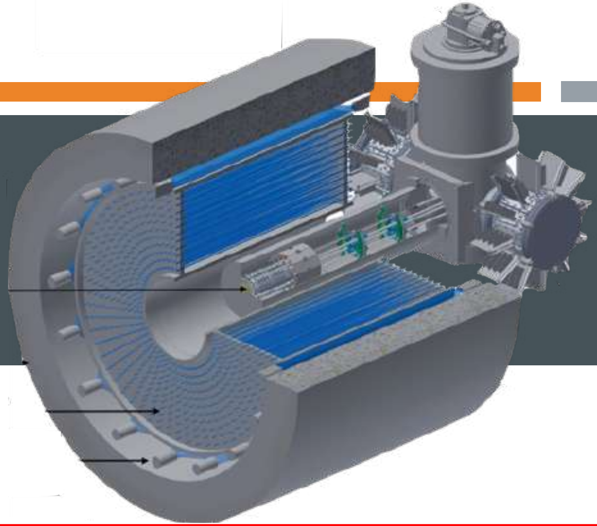
Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

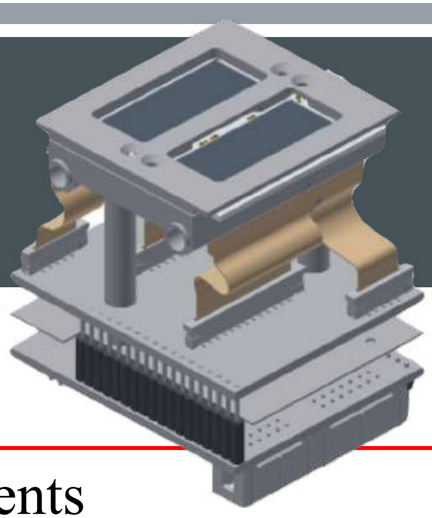
Kaonic Atoms to Investigate Global Symmetry Breaking Symmetry 12 (2020) 4, 547

The equation of state of dense matter: Stiff, soft, or both? Astron.Nachr. 340 (2019) 1-3, 189

Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

Astrophysics
EOS Neutron Stars





The modern era of light kaonic atom experiments

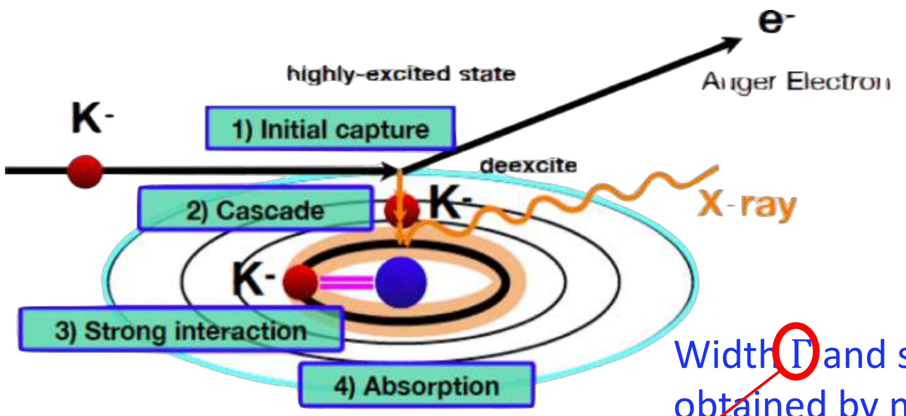
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

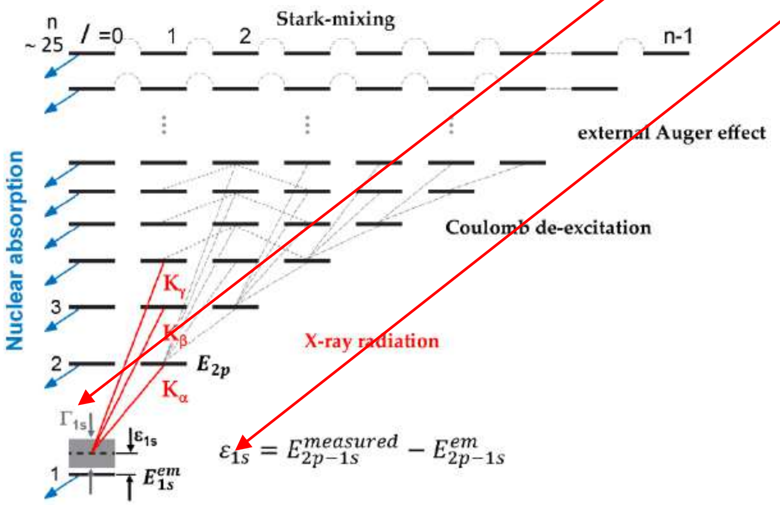
DEAR 2002 — **SIDDHARTA 2009** — **SIDDHARTA-2 2022**

The SIDDHARTA-2 experiment

Scientific goal: *first measurement ever of kaonic deuterium X-ray* transition to the ground state (1s-level) such as to determine its shift and width induced by the presence of the strong interaction, providing unique data to investigate the QCD in the non-perturbative regime with strangeness.



Width Γ and shift ε obtained by measuring the X-rays emitted



$$\varepsilon_{1s} = E^{measured}_{2p-1s} - E^{em}_{2p-1s}$$

Combined analysis of the kaonic deuterium and kaonic hydrogen measurements

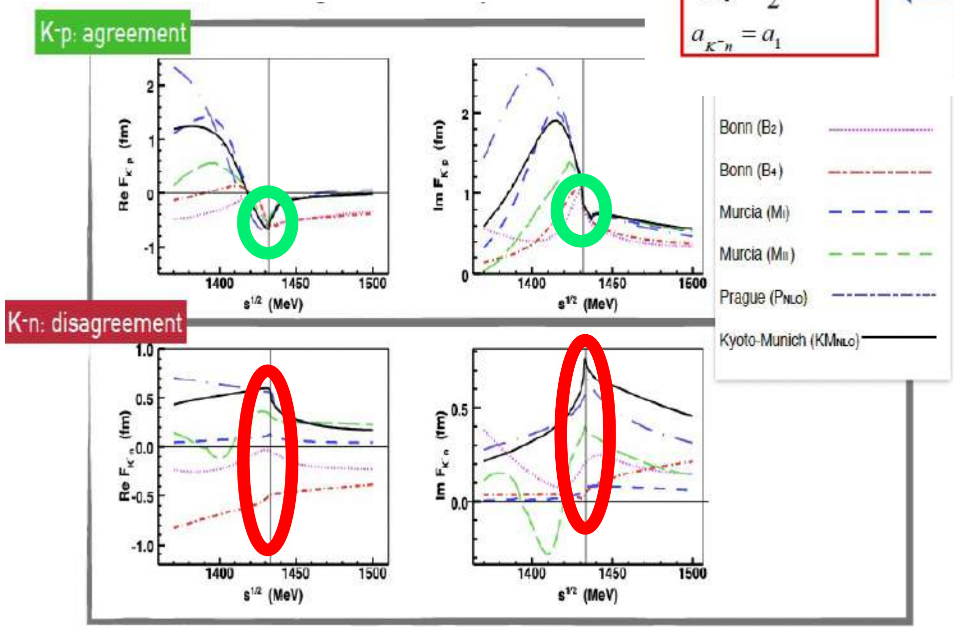
$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_{K^-p}(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p})$$

(μ_c reduced mass of the K⁻p system, α fine-structure constant)

U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

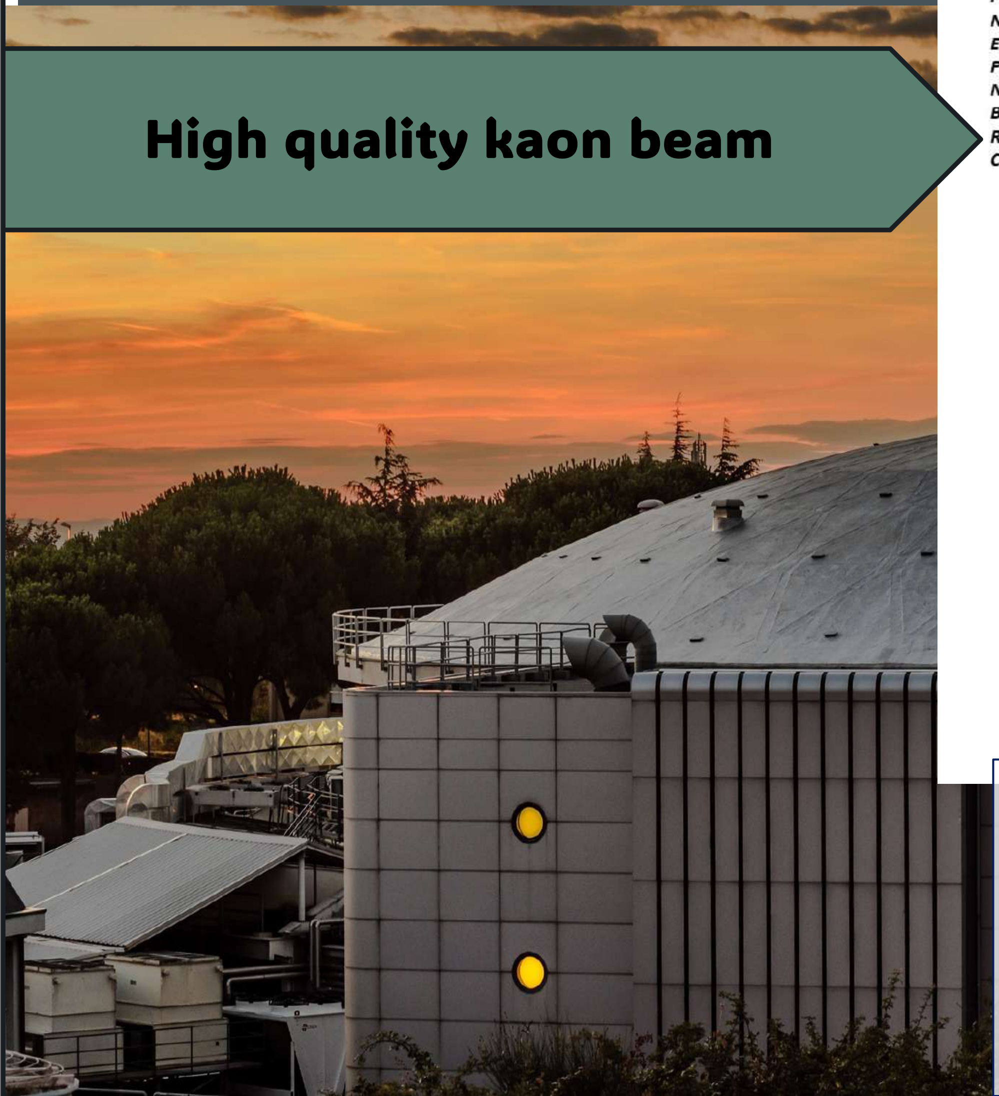
$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$
$$a_{K^-n} = a_1$$

$$a_{K^-d} = \frac{k}{2}[a_{K^-p} + a_{K^-n}] + C = \frac{k}{4}[a_0 + 3a_1] + C$$
$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

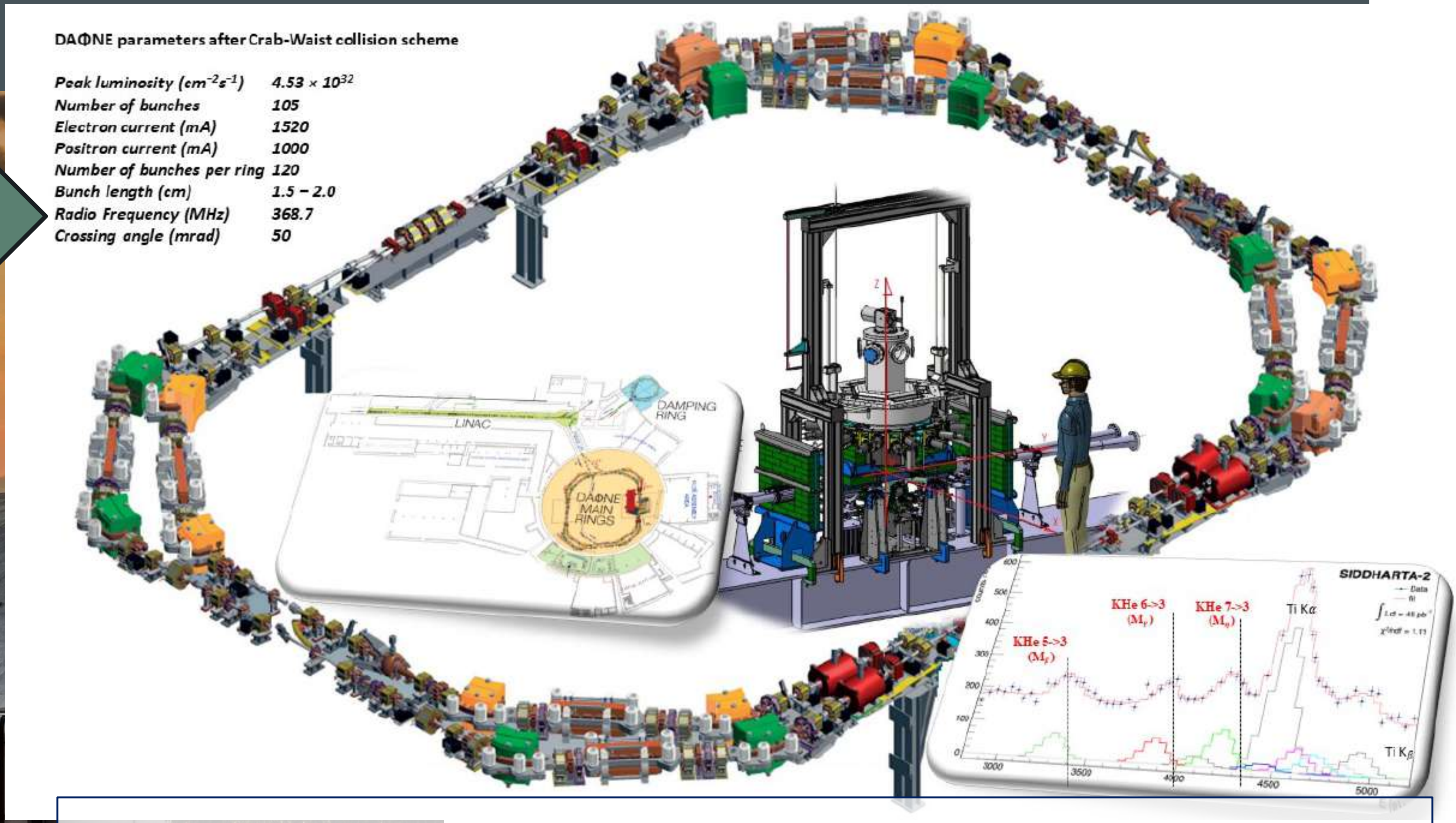


A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

The DAΦNE collider



High quality kaon beam

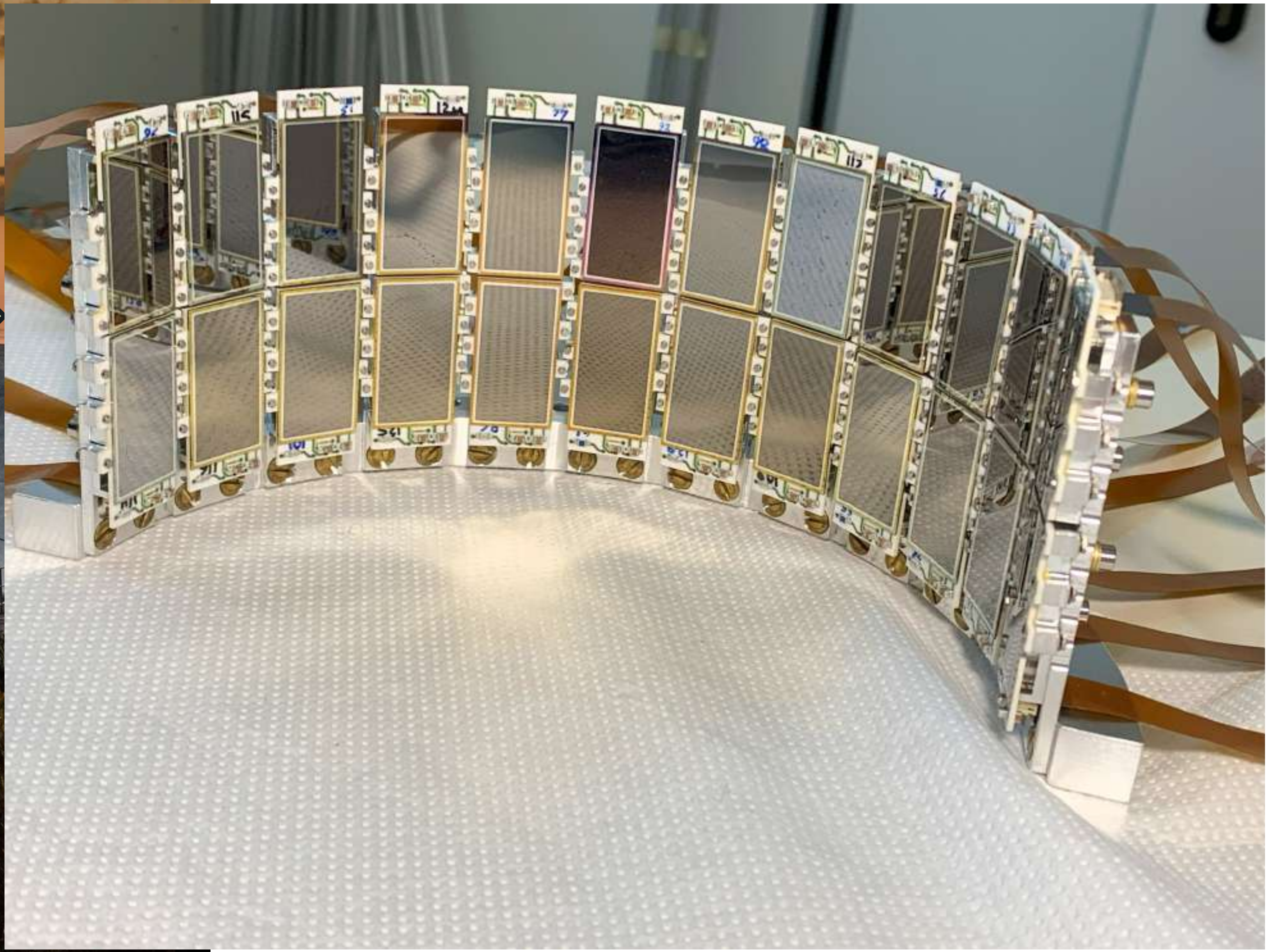


- $\Phi \to K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)
- Less hadronic background compared to hadron beam line

Silicon Drift Detectors

High quality kaon beam

Efficient x-ray detector system and trigger – veto systems



Powerful analysis tools

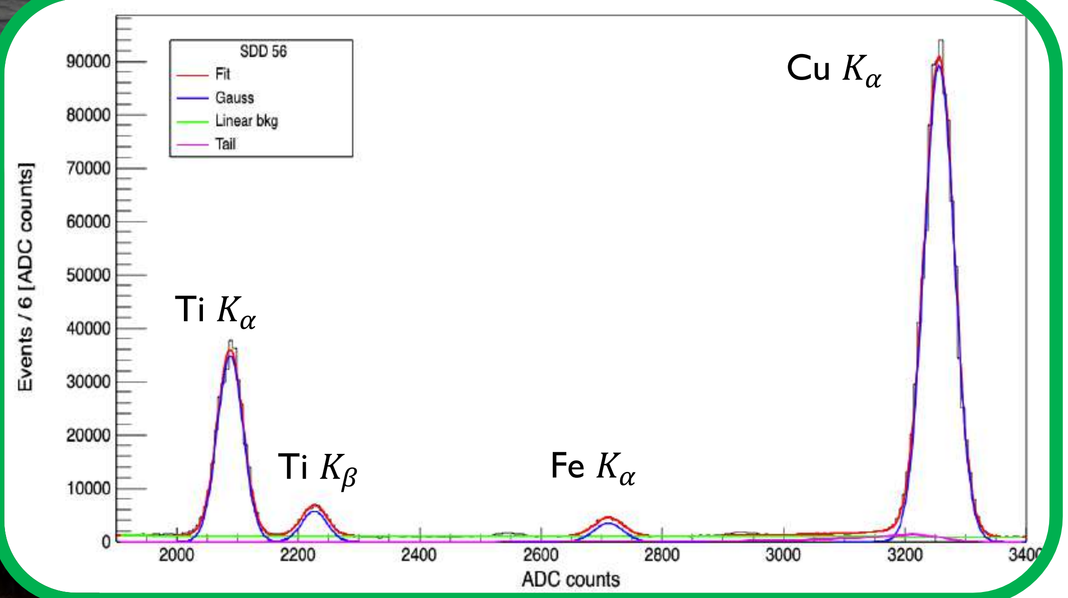
High quality kaon beam

Efficient x-ray detector system and trigger – veto systems

Powerful analysis tools

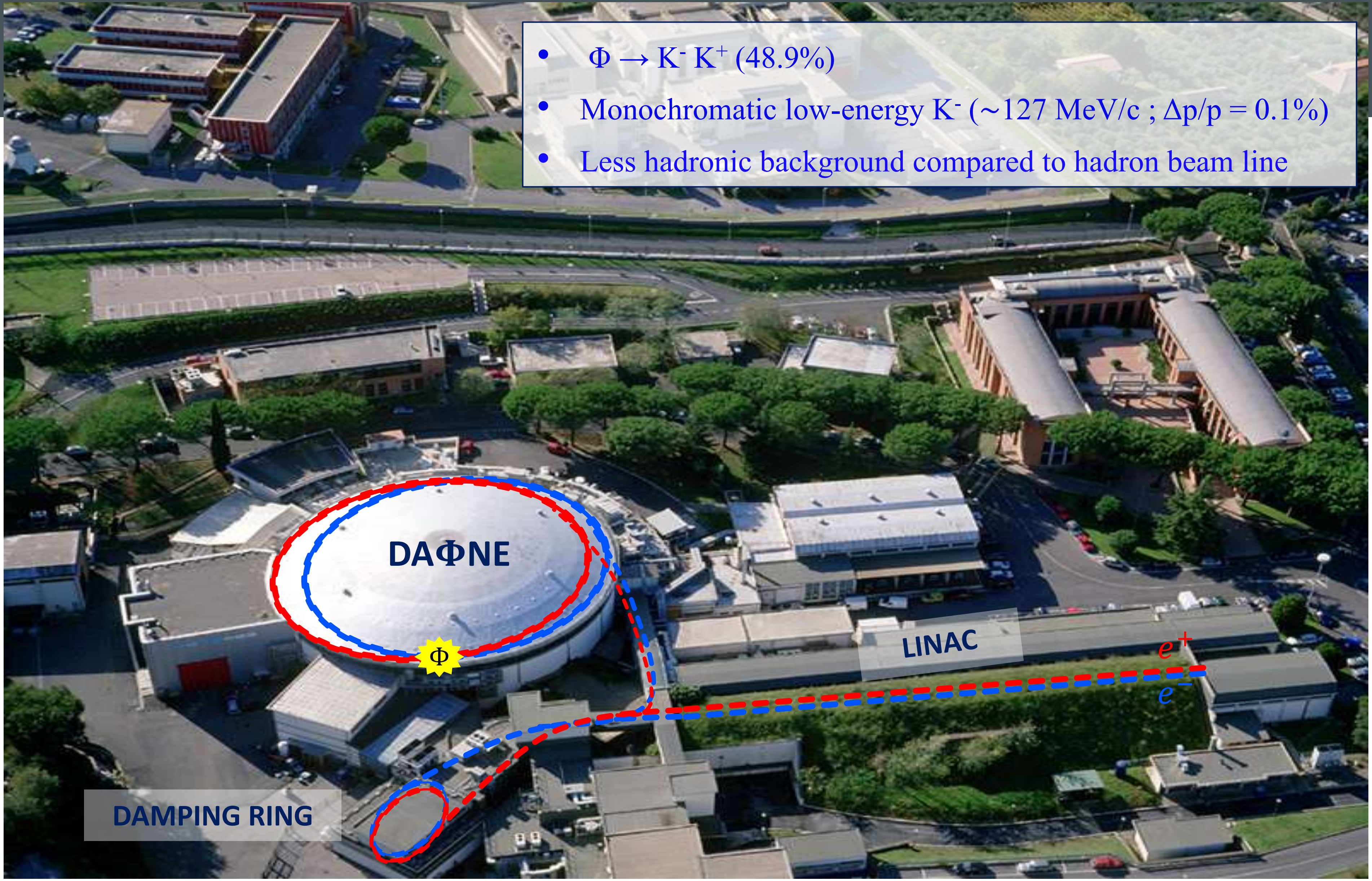
Monte Carlo simulations, modern algorithms and machine learning techniques

Optimization of the setup and detectors response (trigger, SDDs, veto, …)

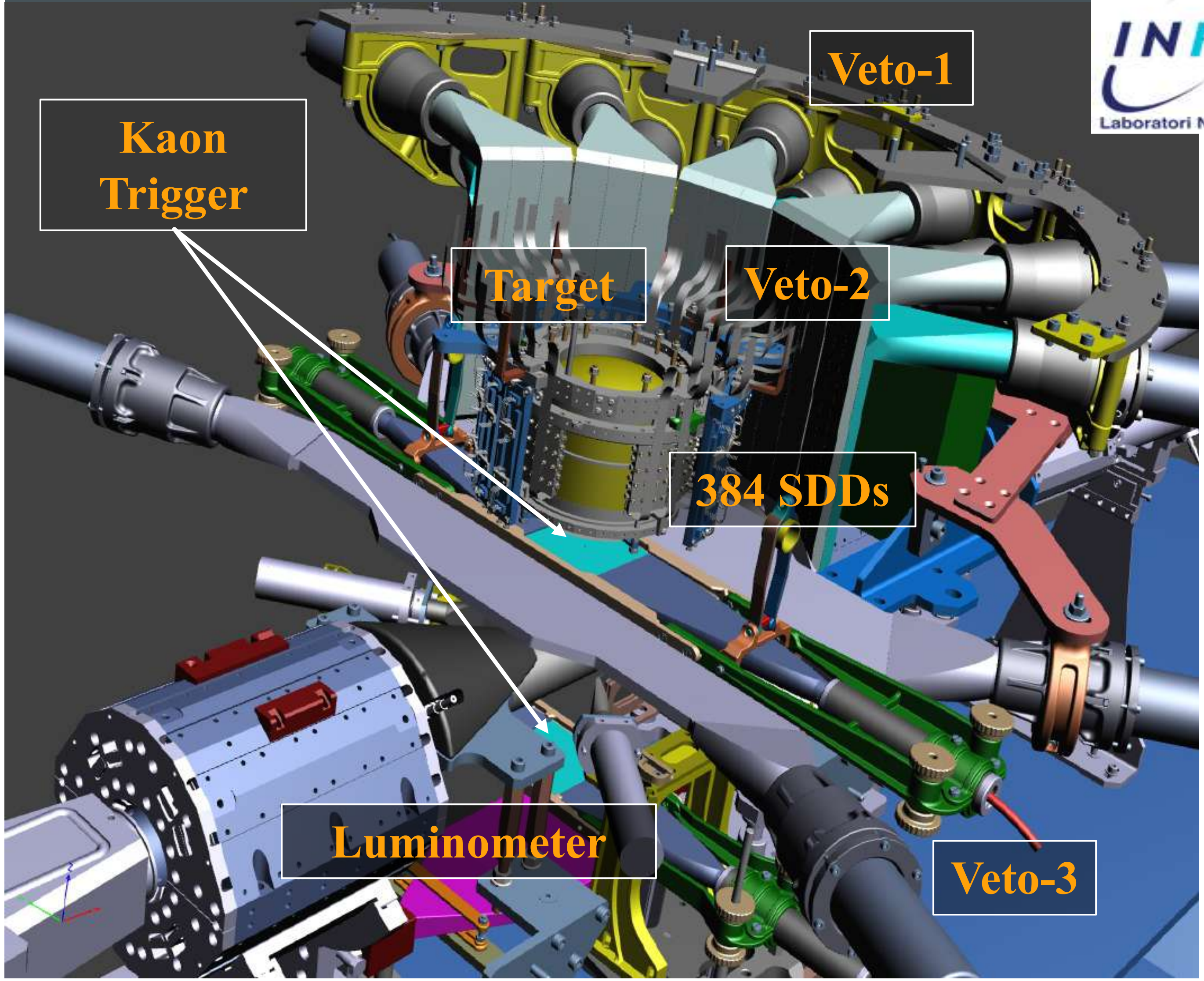


The DAΦNE collider of INFN-LNF

- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)
- Less hadronic background compared to hadron beam line



The SIDDHARTA-2 setup and DAΦNE collider

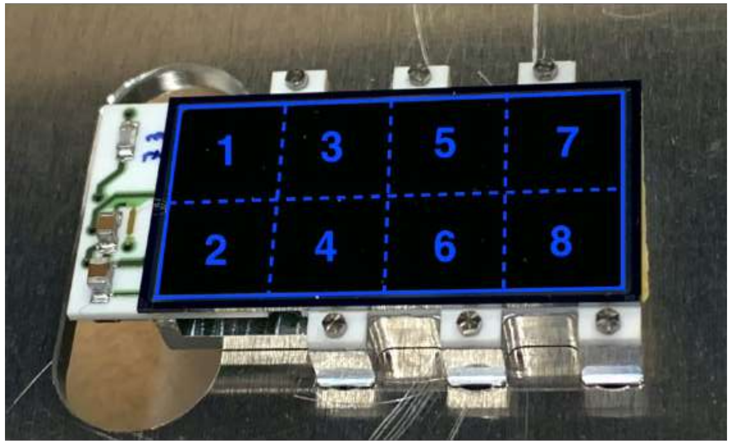


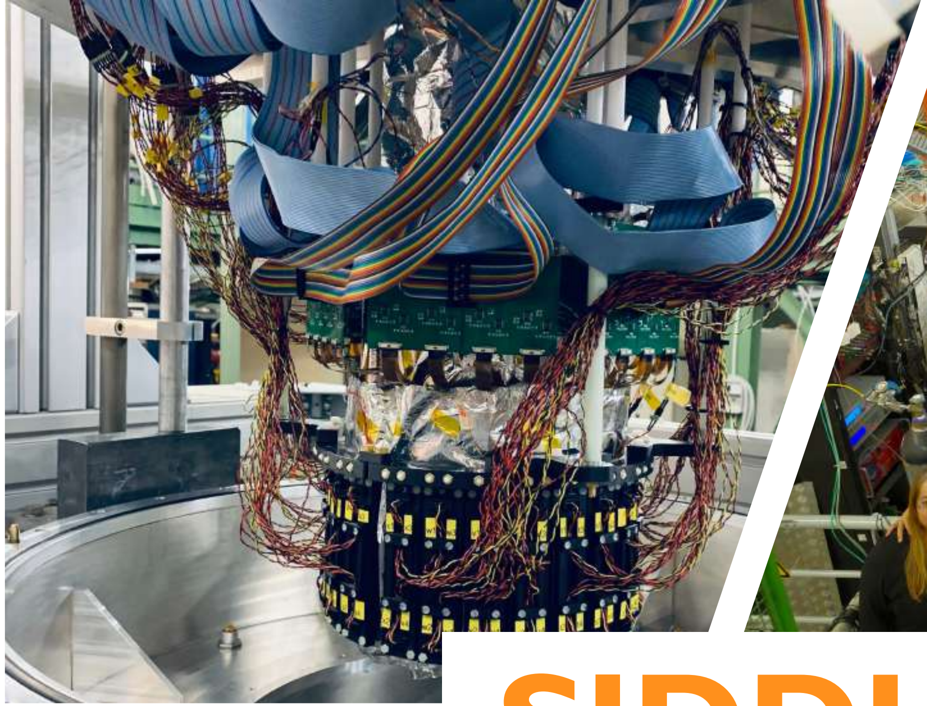
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

POLITECNICO MILANO 1863

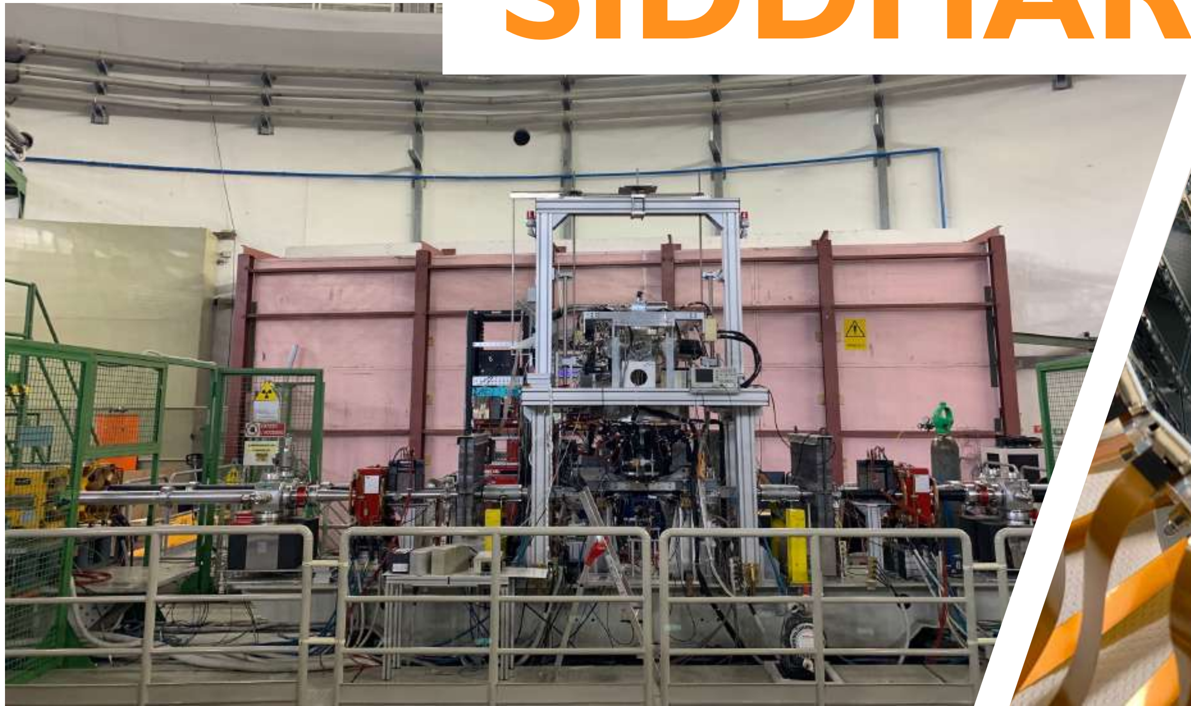
FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

48 Silicon Drift Detector arrays with 8 SDD units (0.64 cm^2)
for a total active area of 246 cm^2
The thickness of 450 μm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV



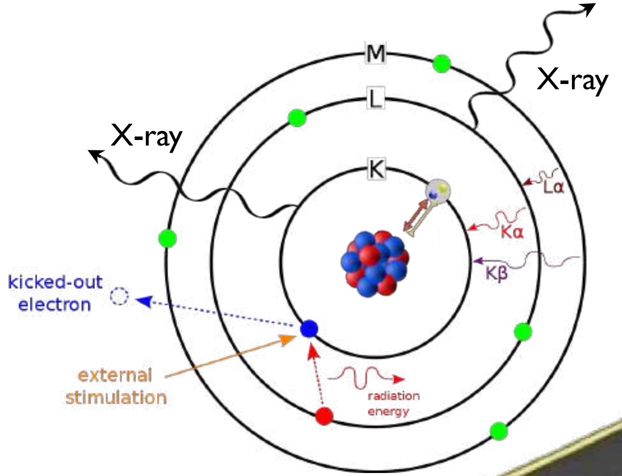


SIDDHARTA-2



First kaonic deuterium measurement (2023 -2024)

KAONIC ATOMS MEASUREMENTS



Kaonic Neon (2023)

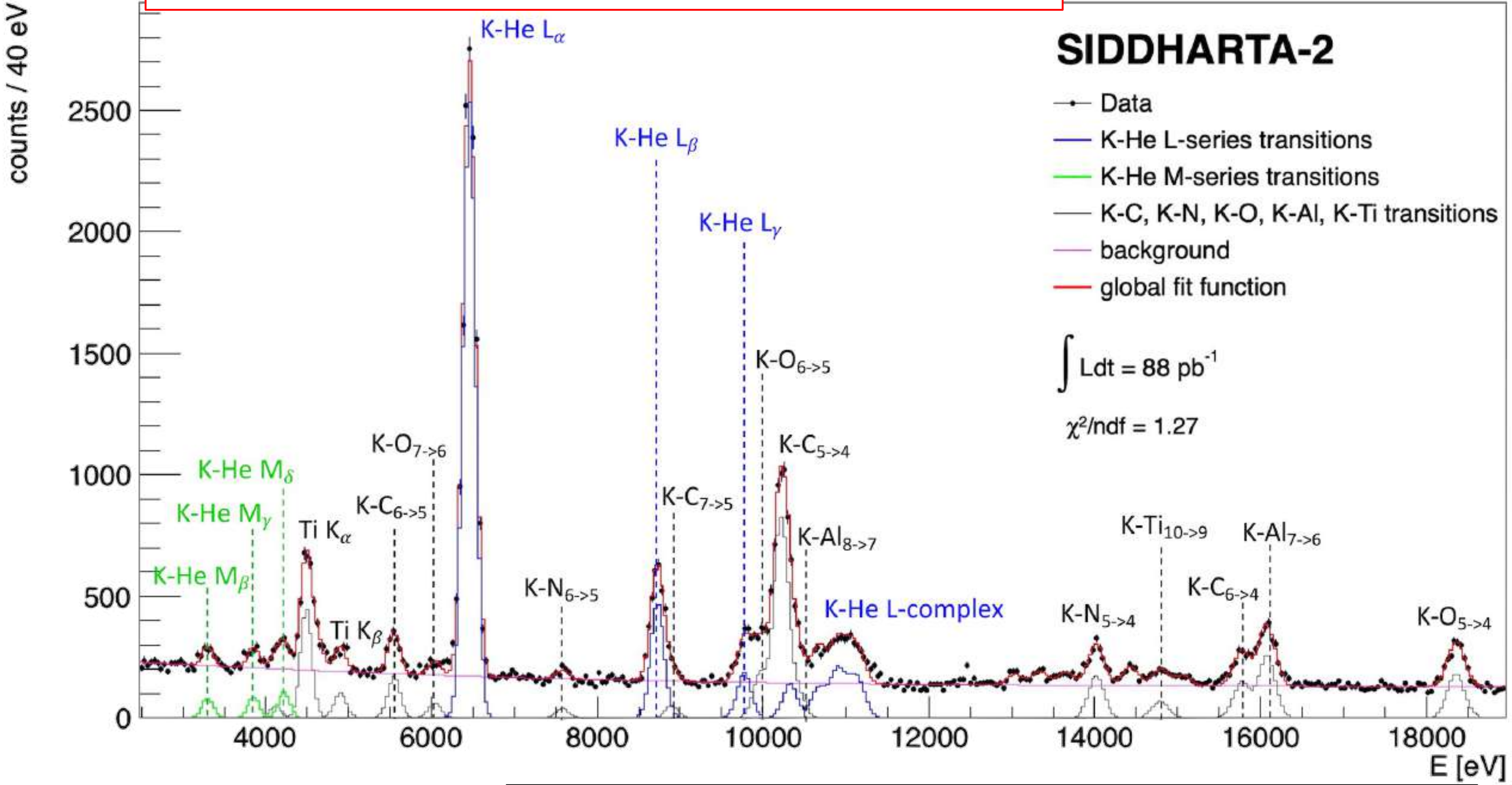
Kaonic Helium-4 (2022)

The Kaonic ^{4}He measurement (2022)

- Kaonic He measurement with the full SIDDHARTA-2 setup
- Measurement of kaonic helium-4 Lα transition: 2p level energy shift and width
- First Measurement of high-n transition in kaonic carbon – nitrogen – oxygen and aluminium

$$\varepsilon_{2p} = E^{exp}_{3d\to 2p} - E^{e.m}_{3d\to 2p} = -1.9 \pm 0.8\,(stat) \pm 2.0\,(sys)\ eV$$

$$\Gamma_{2p} = 0.01 \pm 1.60\,(stat) \pm 0.36\,(sys)\ eV$$

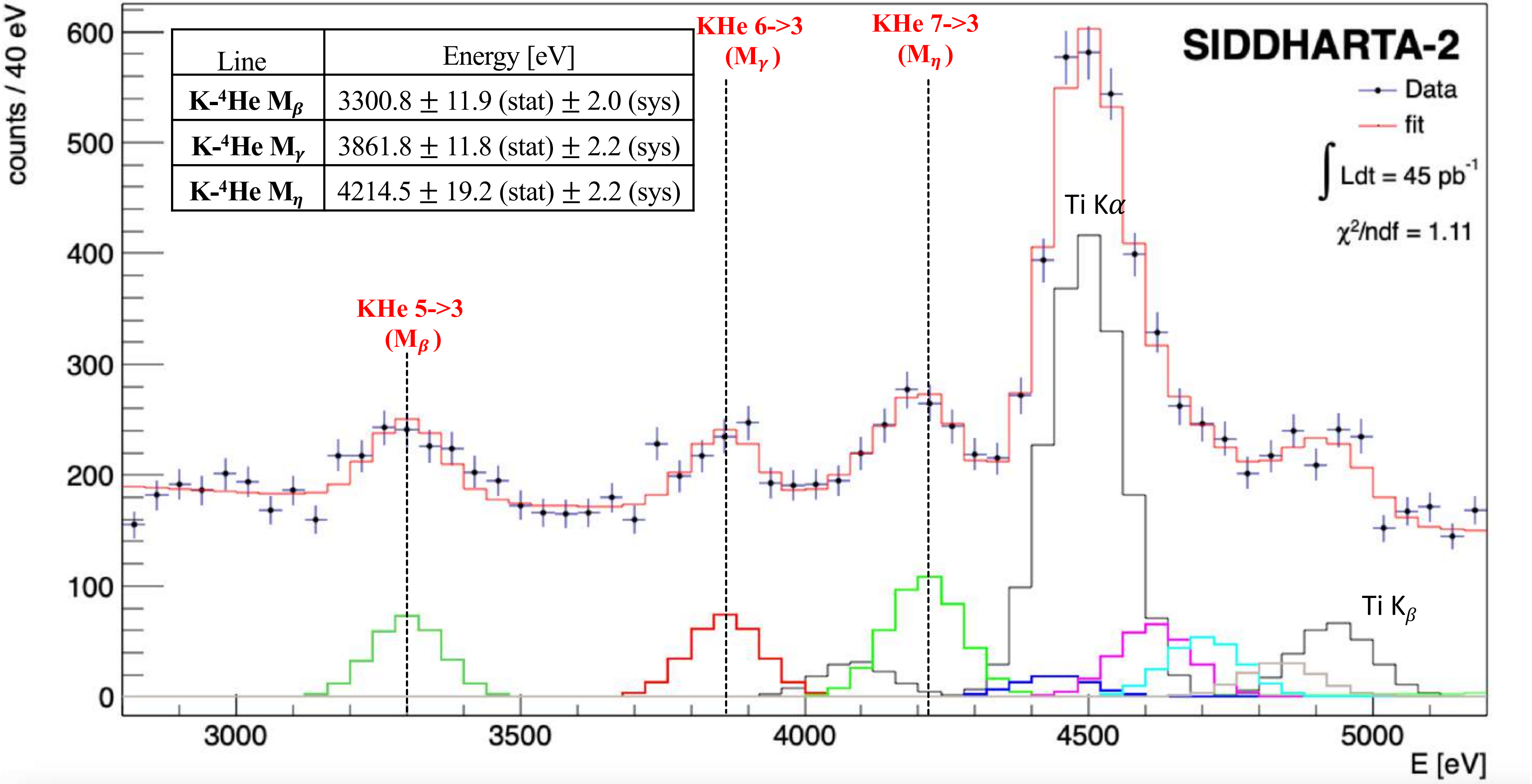


Transition	Energy [eV]
K^-C (6→5)	5546.0 ± 5.4 (stat) ± 2.0 (syst)
K^-C (7→5)	8890.0 ± 13.0 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6014.8 ± 8.4 (stat) ± 2.0 (syst)
K^-O (6→5)	9965.1 ± 6.9 (stat) ± 2.0 (syst)
K^-O (5→4)	18361.1 ± 5.4 (stat) ± 12.0 (syst)
K^-N (6→5)	7581.1 ± 16.0 (stat) ± 2.0 (syst)
K^-N (5→4)	14008.0 ± 6.0 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)
K^-Ti (10→9)	14790.3 ± 16.6 (stat) ± 9.0 (syst)

Sgaramella F., Tüchler M., et al., 2023, Eur. Phys. J. A, 59 (3) 56

The Kaonic ^{4}He – M-series transitions

First observation and measurement of kaonic helium M-series transition, with implication on kaonic helium cascade models



Line	Energy [eV]
K-^{4}He M_β	3300.8 ± 11.9 (stat) ± 2.0 (sys)
K-^{4}He M_γ	3861.8 ± 11.8 (stat) ± 2.2 (sys)
K-^{4}He M_η	4214.5 ± 19.2 (stat) ± 2.2 (sys)

Sgaramella F., et al, 2024, *J. Phys. G: Nucl. Part. Phys.* **51** 055103

The Kaonic ^{4}He yield

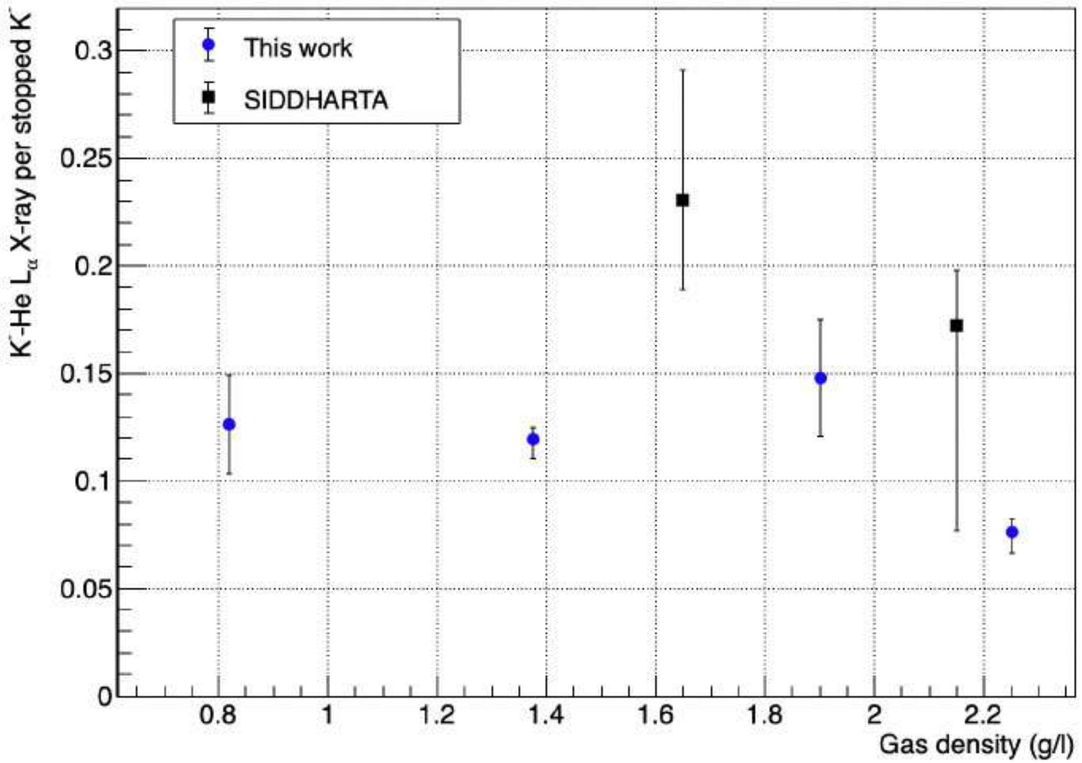
New experimental data for cascade models calculations
The X-ray yield is the key observable to understand the de-excitation mechanism in kaonic atoms and develop more accurate models.

First measurement of K-^{4}He M-series transition

Density	1.37 ± 0.07 g/l
L_α yield	$0.119 \pm 0.002\,(\text{stat})^{+0.006\,(\text{syst})}_{-0.009\,(\text{syst})}$
M_β yield	$0.026 \pm 0.003\,(\text{stat})^{+0.010\,(\text{syst})}_{-0.001\,(\text{syst})}$
L_β / L_α	0.172 ± 0.008 (stat)
L_γ / L_α	0.012 ± 0.001 (stat)
M_β / L_α	0.218 ± 0.029 (stat)
M_γ / M_β	0.48 ± 0.11 (stat)
M_δ / M_β	0.43 ± 0.12 (stat)

Sgaramella F., et al, 2024, *J. Phys. G: Nucl. Part. Phys.* **51** 055103

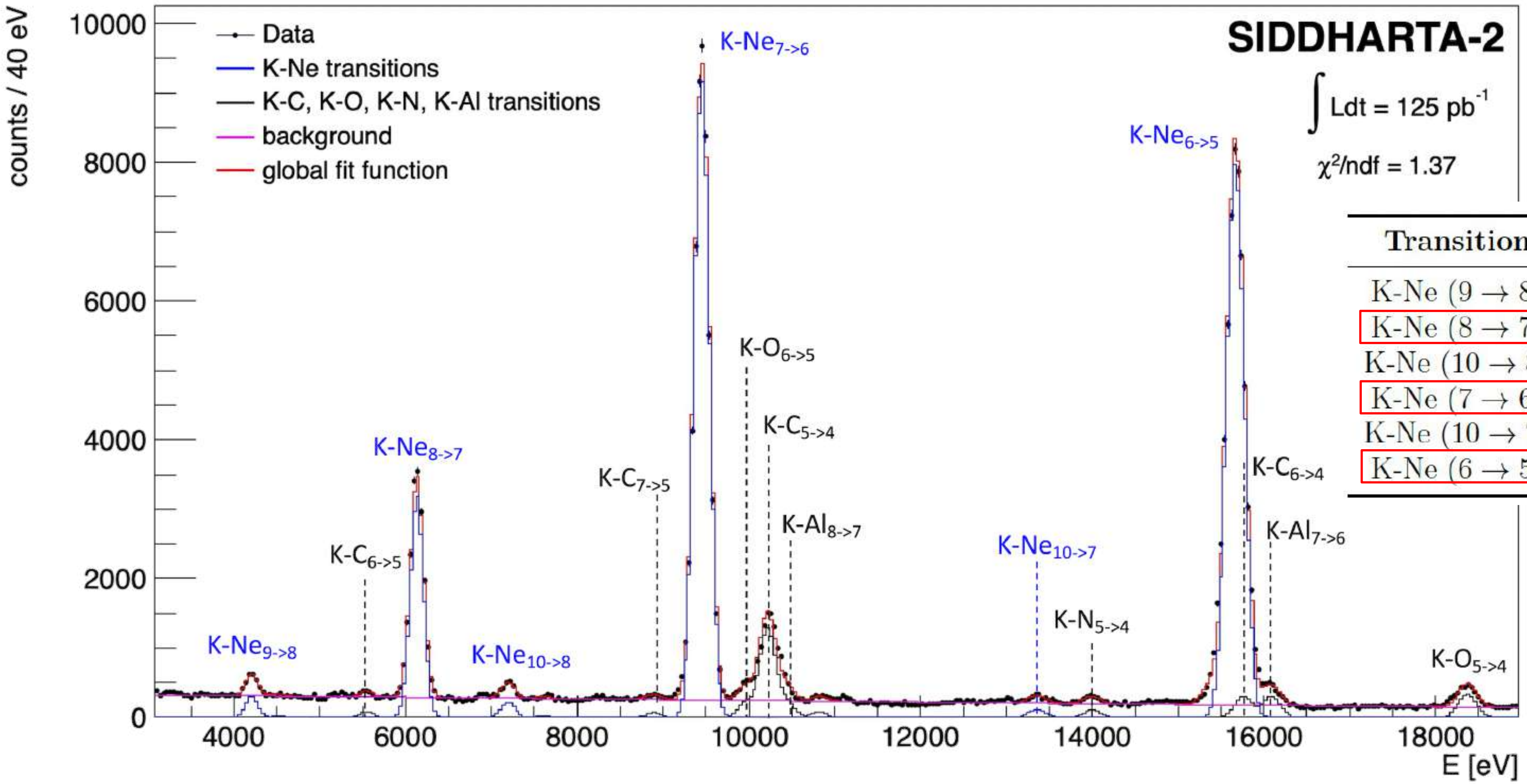
Study of yield density dependence for the K-^{4}He Lα transition



Sirghi D.L., Shi H., Guaraldo C., Sgaramella F., et al., 2023, Nucl. Phys. A,1029 122567

The Kaonic Neon measurement (2023)

First measurement of kaonic neon high-n X-ray transitions

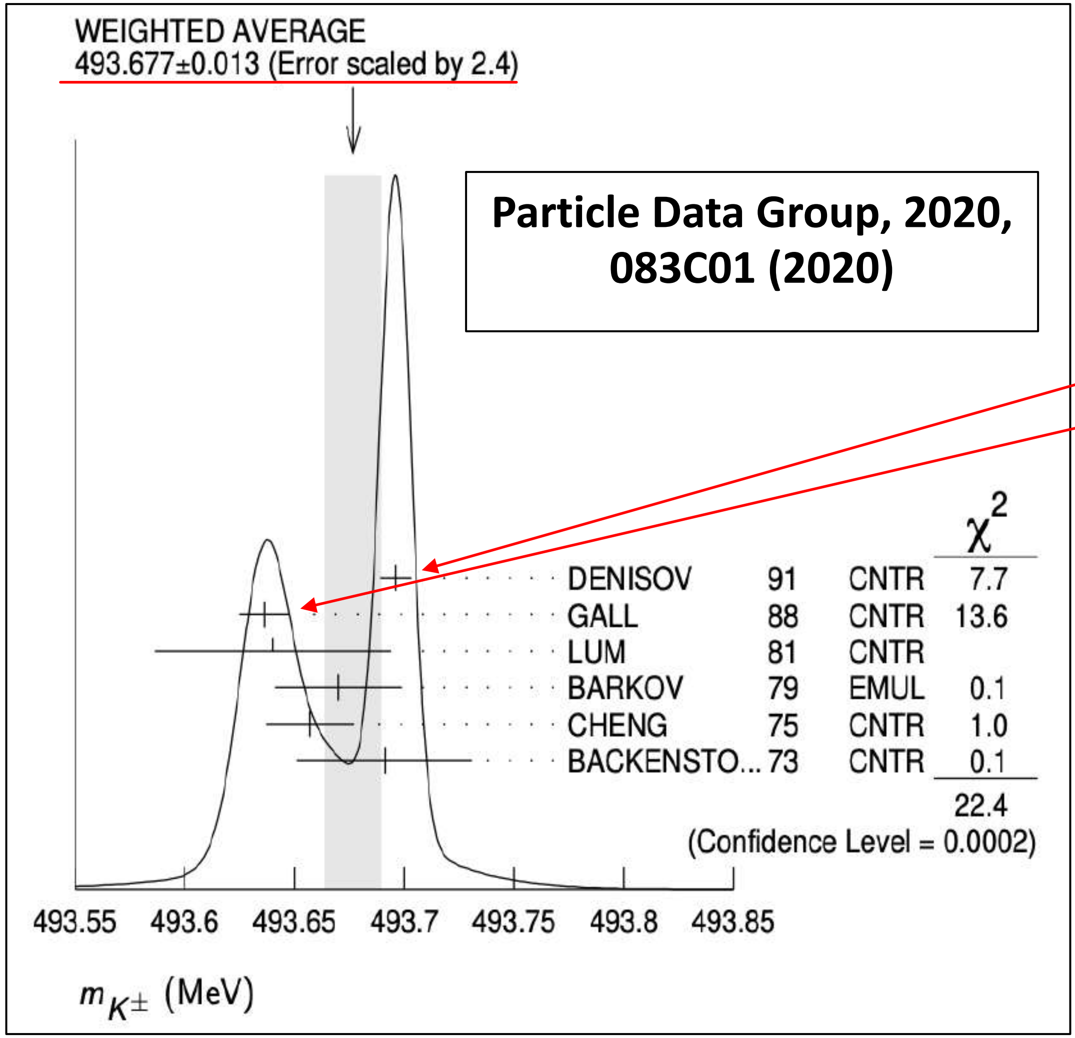


Transition	Energy [eV]
K-Ne $(9 \to 8)$	4206.35 ± 3.75 (stat) ± 2.00 (syst) eV
K-Ne $(8 \to 7)$	6130.86 ± 0.71 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 8)$	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV
K-Ne $(7 \to 6)$	9450.08 ± 0.41 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 7)$	13352.20 ± 10.07 (stat) ± 3.00 (syst) eV
K-Ne $(6 \to 5)$	15673.30 ± 0.52 (stat) ± 9.00 (syst) eV

Transition	Yield (%)
K-Ne $(8 \to 7)$	0.228 ± 0.004 (stat) ± 0.011 (sys)
K-Ne $(7 \to 6)$	0.277 ± 0.002 (stat) ± 0.014 (sys)
K-Ne $(6 \to 5)$	0.308 ± 0.003 (stat) ± 0.015 (sys)

The charged kaon mass puzzle

60 keV discrepancy between the two most accurate measurement



VALUE (MeV)		*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.					
493.677±0.013 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.					
493.696±0.007	[1]	DENISOV	91	CNTR	−	Kaonic atoms
493.636±0.011	[2]	GALL	88	CNTR	−	Kaonic atoms
493.640±0.054		LUM	81	CNTR	−	Kaonic atoms
493.670±0.029		BARKOV	79	EMUL	±	$e^+e^- \rightarrow K^+K^-$
493.657±0.020	[2]	CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040		BACKENSTO...	73	CNTR	−	Kaonic atoms

Large uncertainty → 26 p.p.m,
compared to charged pion:
$m_\pi = 139.57061 \pm 0.00023$ MeV, 1.6 p.p.m

The charged kaon mass puzzle

Severe consequences for nuclear and particle physics
and all the processes in which charged kaons are involved

- The uncertainty on the charged kaon mass leads to an error of 50 keV (σ) on the D^0 mass
- Large uncertainty on the charmonium spectrum, in particular on precise values of charm-anticharm meson thresholds
- A particular case is that of $D^0\overline{D}^{*0}$ which lies within the measured width of the best known candidate for a hadron-hadron molecule, the X(3872), an improved K-mass measurement would lead to a better interpretation of the X(3872), and of its radius.

C. Amsler, "Impact of the charged kaon mass on the charmonium spectrum", workshop, Frascati, 19 April 2021

- Impact on the K-N scattering lengths and sub eV measurement of K-nuclei interaction (kaonic atoms)

A new kaonic helium measurement in gas by SIDDHARTINO at the DAFNE collider
D. Sirghi, F. Sirghi, F. Sgaramella, et al., J.Phys.G 49 (2022) 5, 055106

Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters, J-PARC E62 Collaboration, Phys.Rev.Lett. 128 (2022) 11, 112503

Goal: solve the discrepancy and try to improve the kaon mass accuracy

The charged kaon mass puzzle

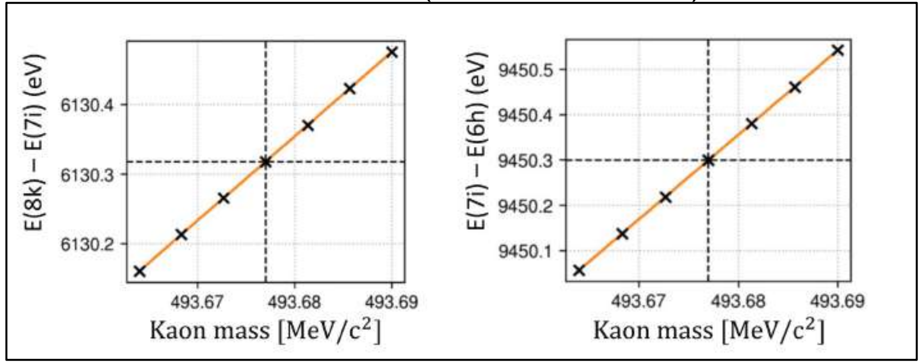
The measurement of kaonic neon high-n transitions could solve the charged kaon mass puzzle

The kaonic Neon measurement to determine the K^- (K^+) mass

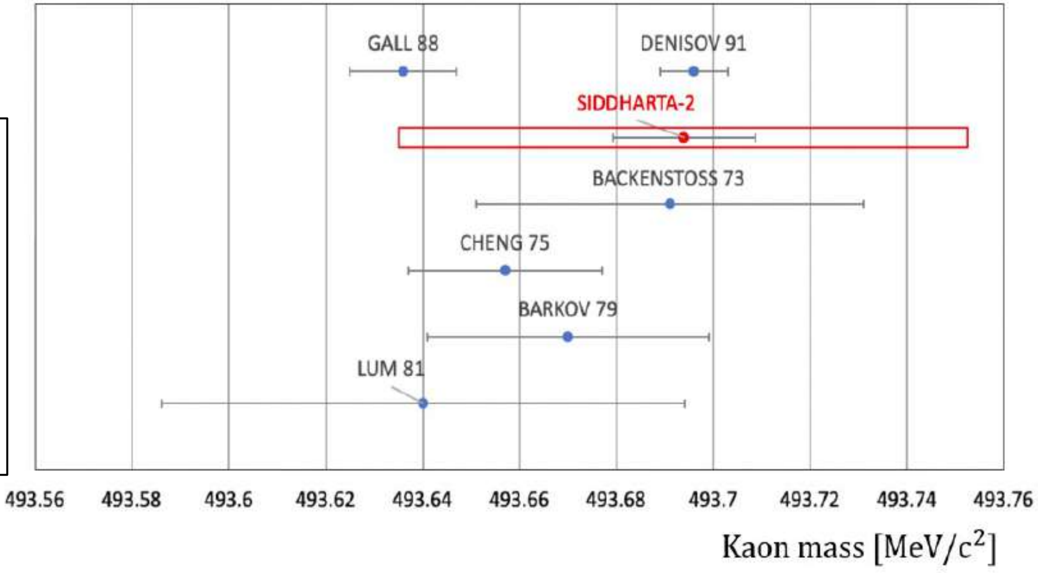
↓

Less/different systematic uncertainty with respect to DENISOV 91 and GALL 88 measurements, thanks to the use of a low Z gas target

Kaonic Ne energy transition as function of kaon mass (MCDFGME code)



Santos, J. & Parente, F. & Indelicato, Paul & Desclaux, J.. (2005). X-ray energies of circular transitions and electron screening in kaonic atoms. Physical Review A. 71.10.1103/PhysRevA.71.032501.



$$K - Ne(8 \to 7) = \frac{A_G}{\sqrt{2\pi\sigma}} \cdot e^{\frac{-(E-E_0)^2}{2\sigma^2}} \quad E_0 = (m_{8\to7} \cdot K_{mass} + q_{8\to7})$$

$$K - Ne(7 \to 6) = \frac{A_G}{\sqrt{2\pi\sigma}} \cdot e^{\frac{-(E-E_0)^2}{2\sigma^2}} \quad E_0 = (m_{7\to6} \cdot K_{mass} + q_{7\to6})$$

Measurement	Kaon mass [MeV]
DENISOV 91 [23]	493.696 ± 0.007
GALL 88 [22]	493.636 ± 0.011
LUM 81 [114]	493.640 ± 0.054
BARKOV 79 [115]	493.670 ± 0.029
CHENG 75 [116]	493.657 ± 0.020
BACKENSTOSS 73 [117]	493.691 ± 0.040
This work	493.694 ± 0.015 (stat) ± 0.060 (syst)

The kaonic deuterium measurement

Kaonic deuterium run completed

2023/24

A total integrated luminosity of 800 pb^{-1} has been acquired

to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K-p) !

Significant impact in the theory of strong interaction with strangeness

SIDDHARTA-2 K-d strategy:

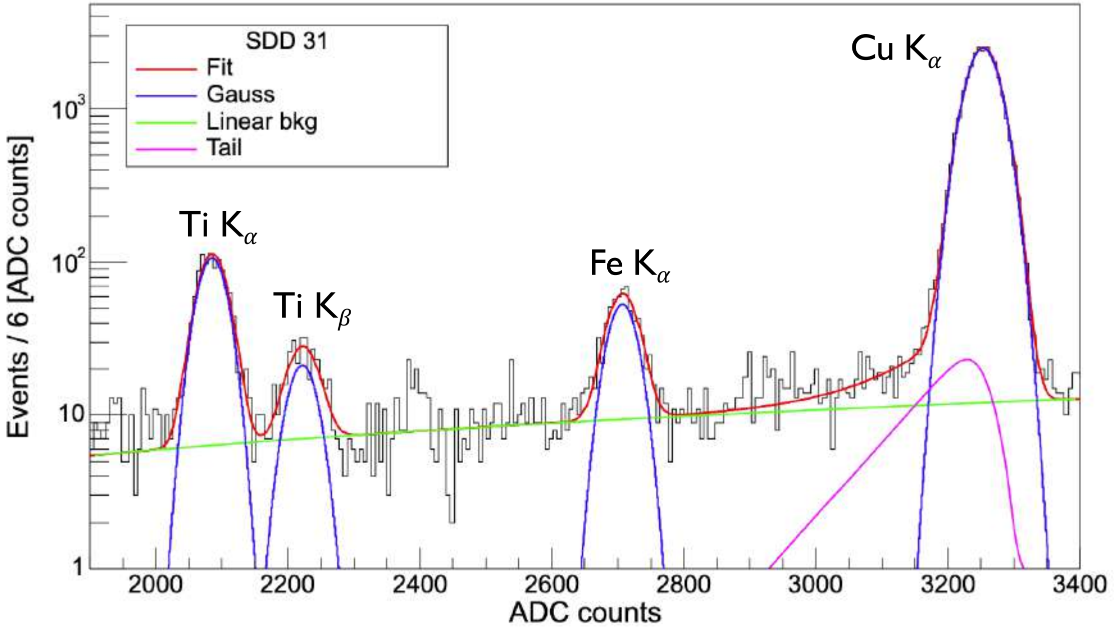
- ✓ K-d run1: May-July 2023 int. luminosity 200 pb^{-1}
  - ✓ Optimization of the setup based on run 1 results
- ✓ K-d run2: Oct - Dec 2023 int. luminosity 276 pb^{-1}
- ✓ K-d run3: Feb - Apr K-d 2024 int. luminosity 375 pb^{-1}

↓

Kaonic Deuterium Run1: a preliminary analysis

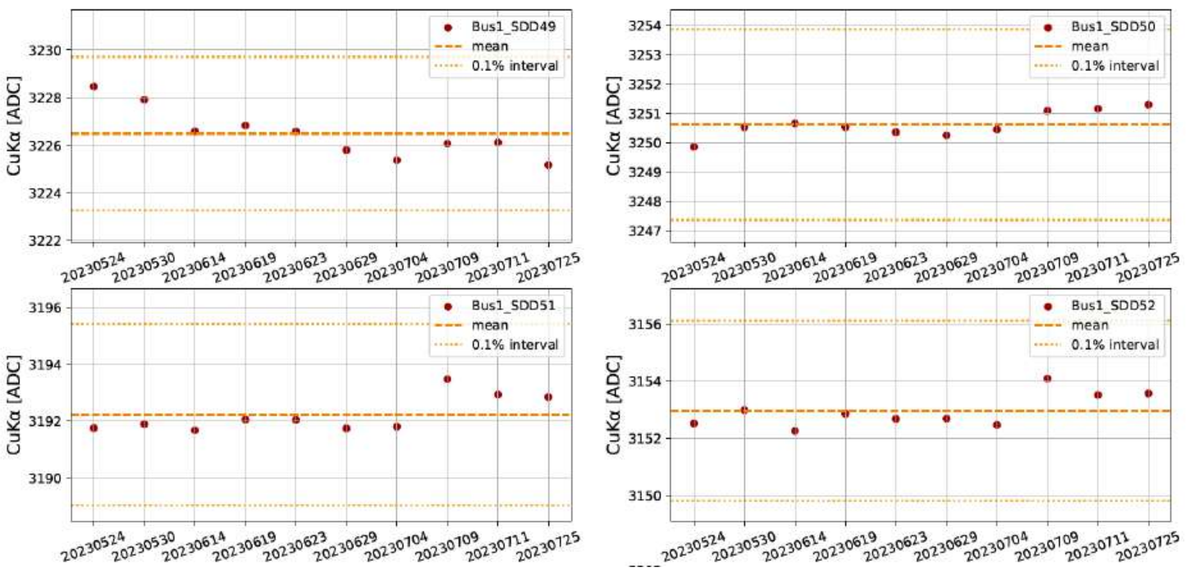
Refined calibration and check of the SDDs energy response

~ 12 000 spectra to be anlysed

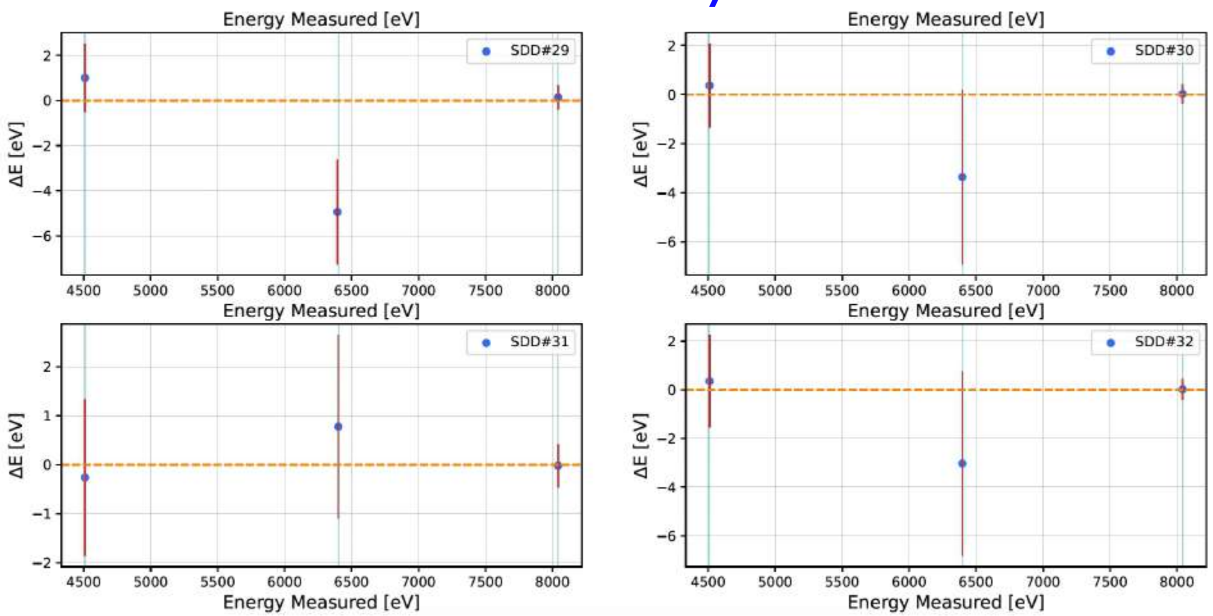


Systematic uncertainty due to energy calibration and stability at the level of 2-3 eV

Stability

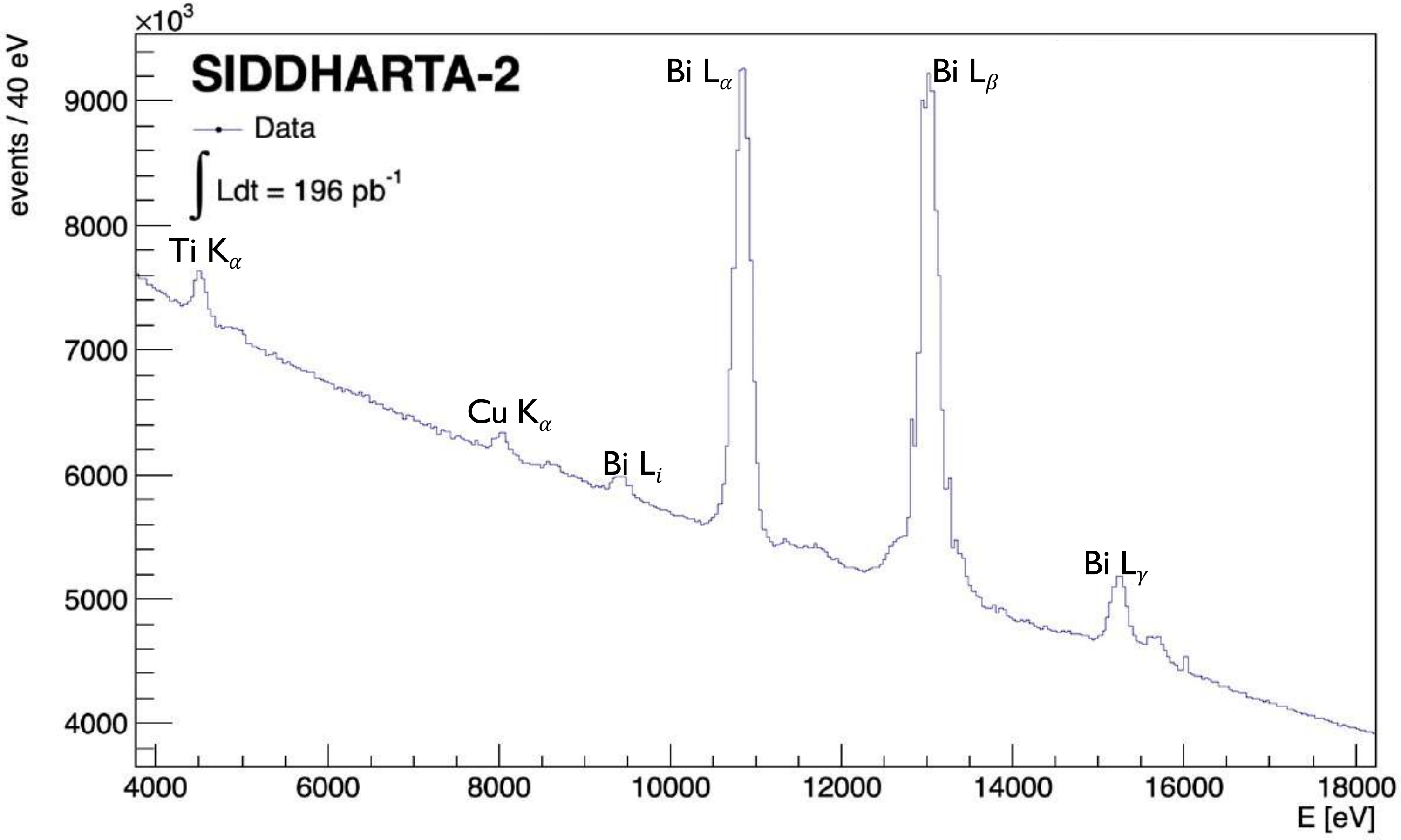


Linearity



Kaonic deuterium run1: a preliminary analysis

Inclusive energy spectrum: the continuous background and the fluorescence peaks are due to the electromagnetic (asynchronous) and hadronic (synchronous) background



-Asynchronous background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect. → Kaon Trigger and SDDs drift time

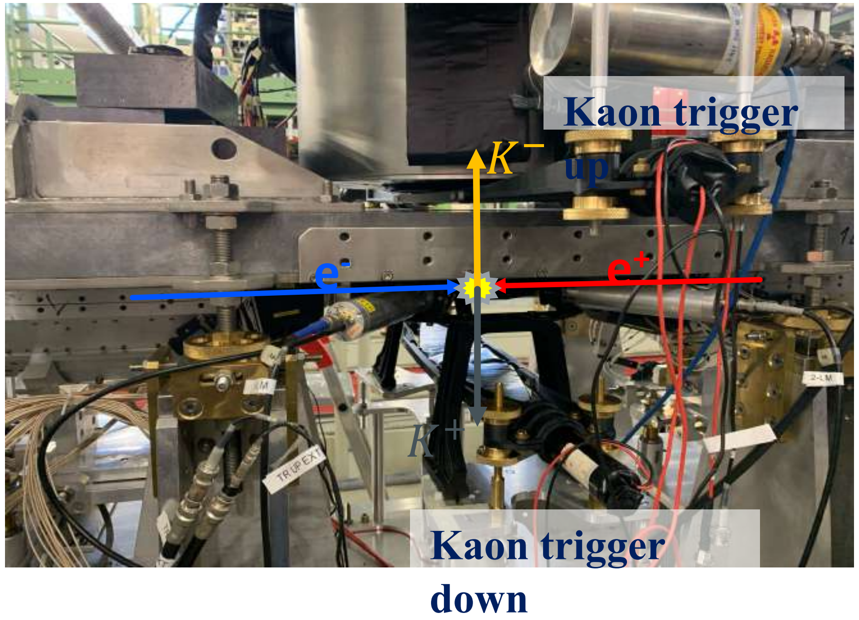
-Synchronous background, associated to kaon absorption on materials nuclei, or to other Φ decay channels. It can be considered a hadronic background.

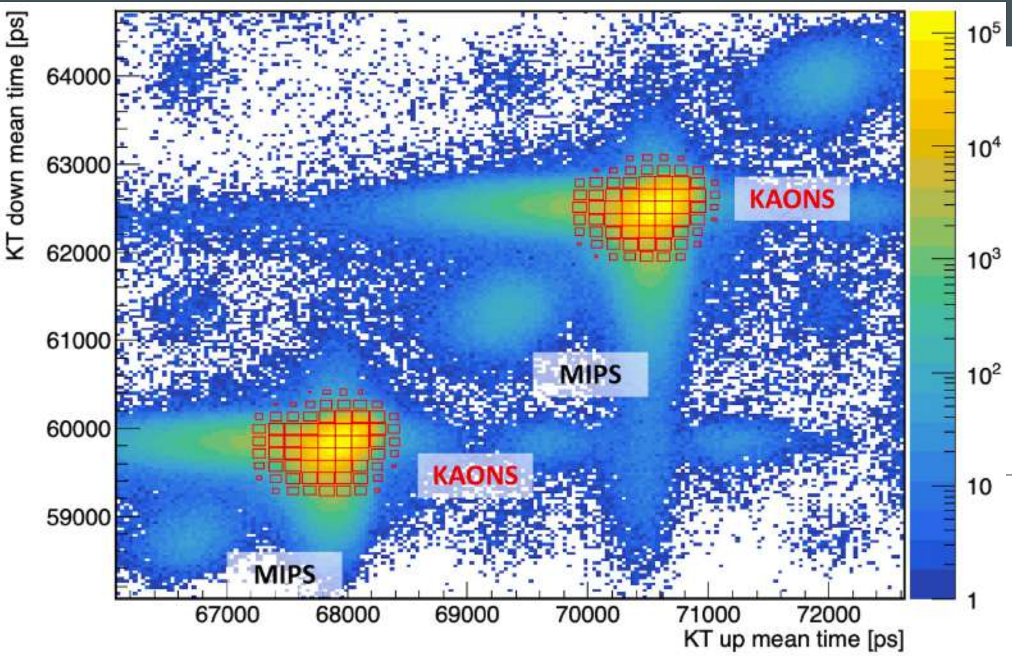
-Spectra contamination by Xray fluorescence or by X-rays produced in higher transitions of other kaonic atoms, formed in the setup materials;

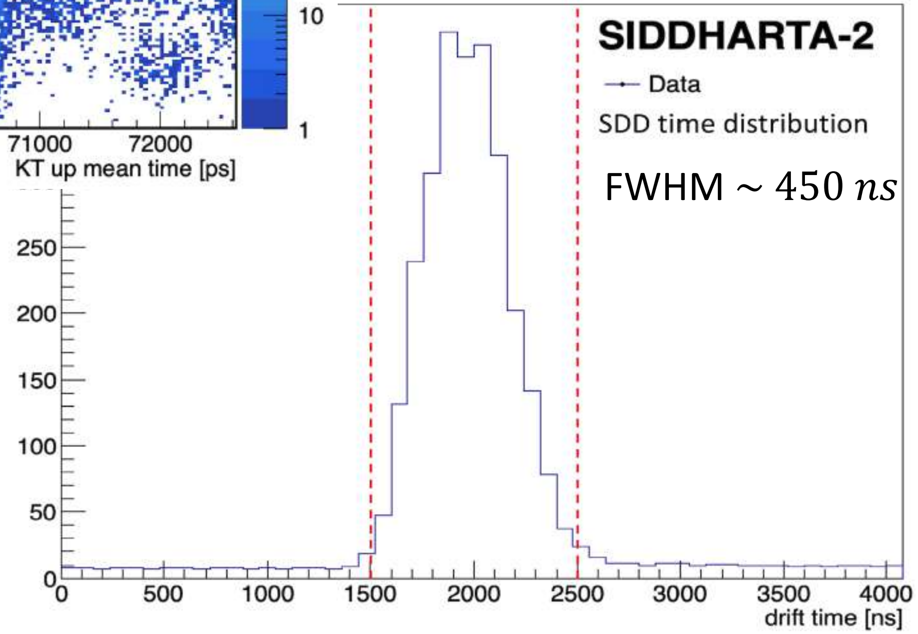
→ Veto systems

Kaonic deuterium run1: Asynchronous background rejection

The combined used of Kaon Trigger and SDDs drift time allows to reduce the asynchronous background by a factor $\sim 2 \cdot 10^4$



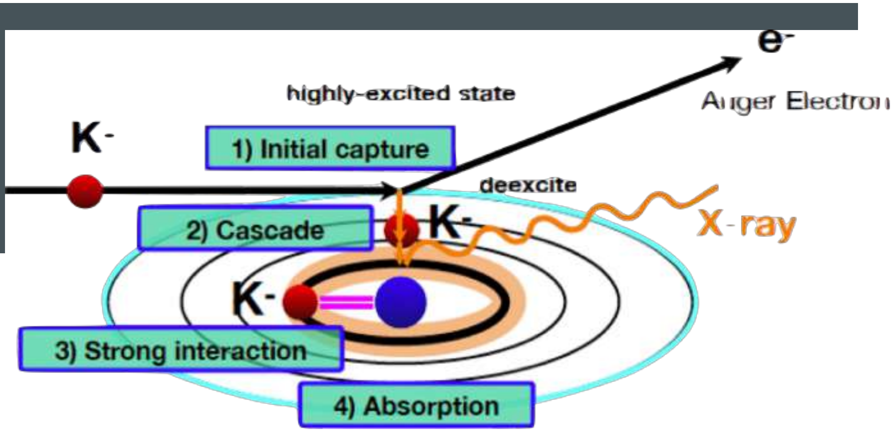


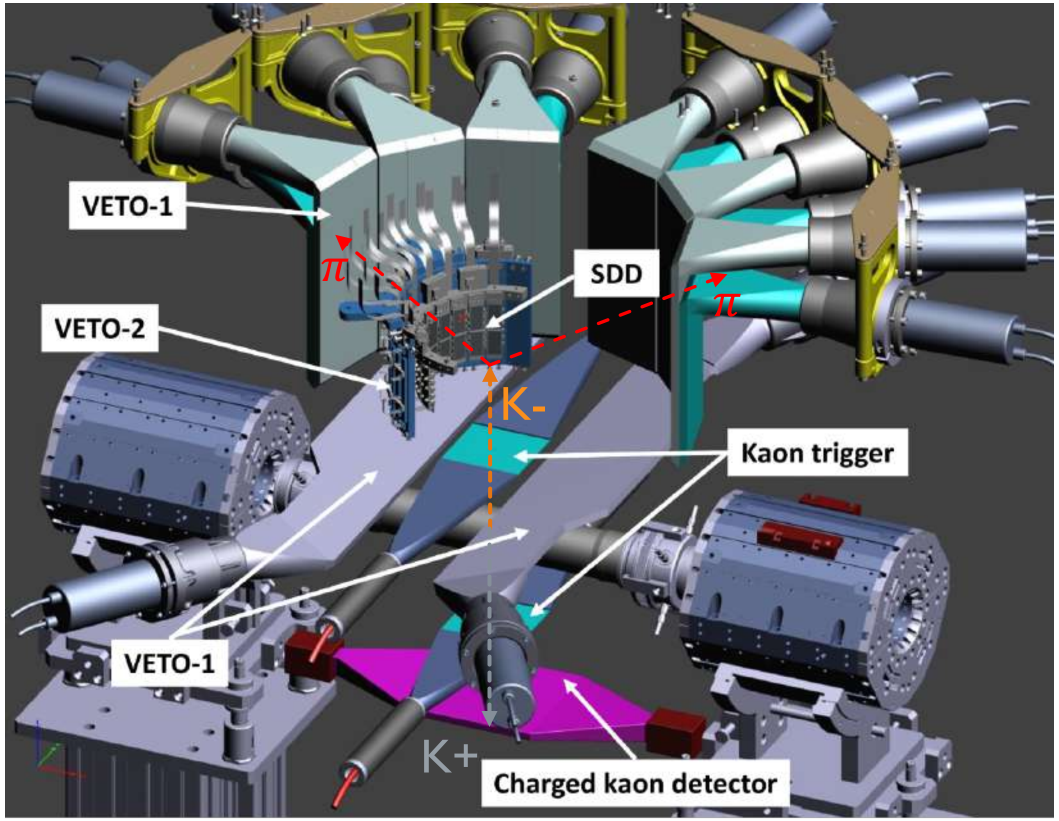


The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

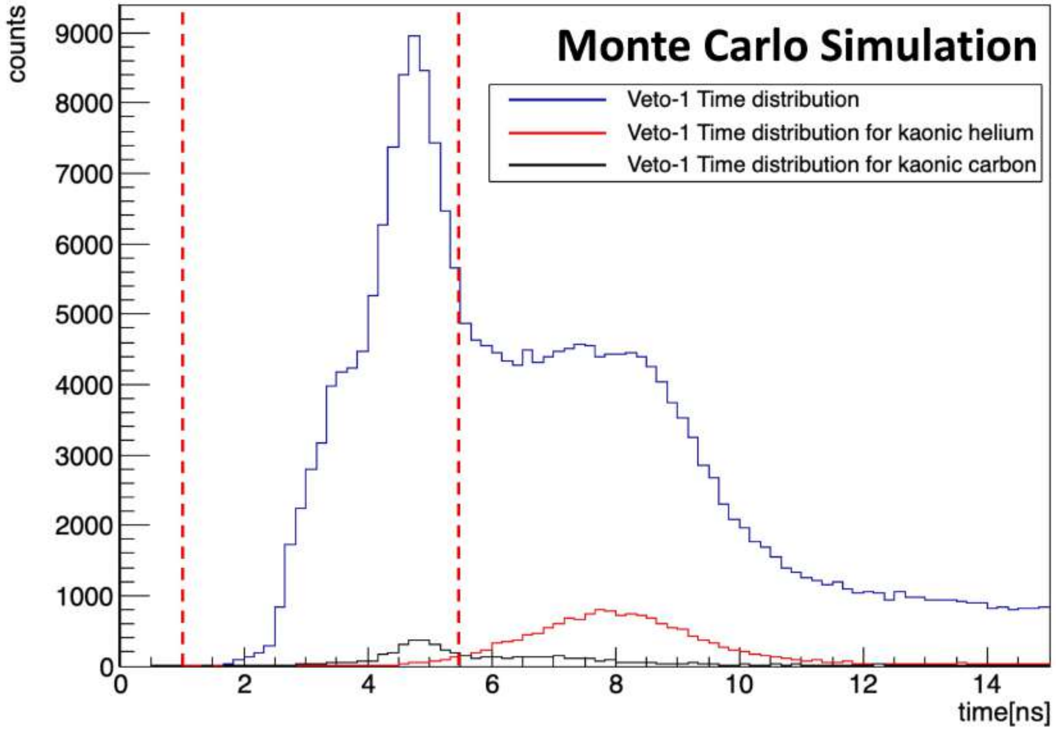
Kaonic deuterium run1: veto-1 system analysis

Veto-1 for synchronous background reduction:
measure the arrival time of the charged particles emitted by the kaon-nucleus absorption

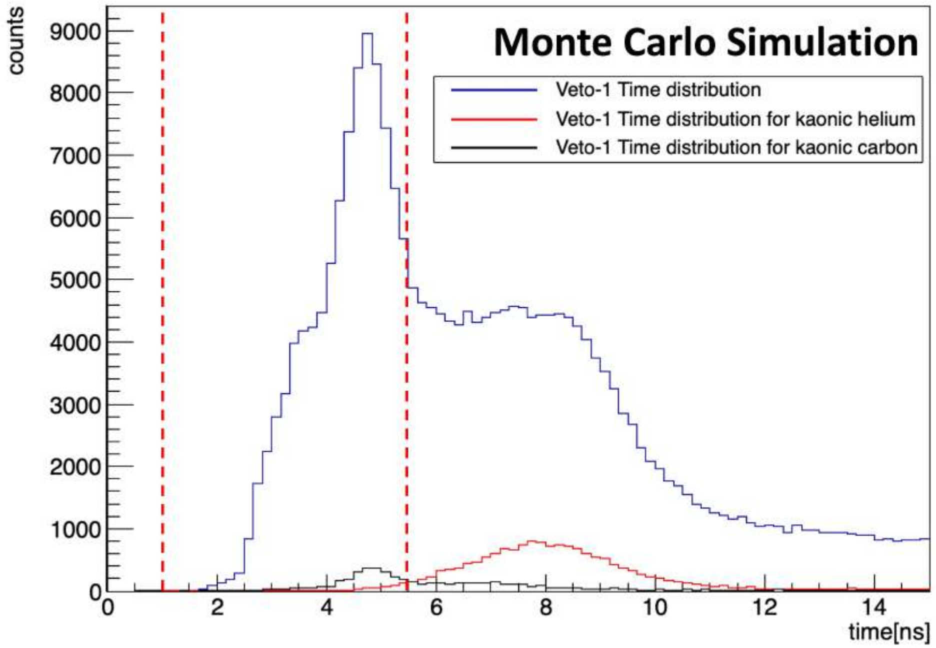


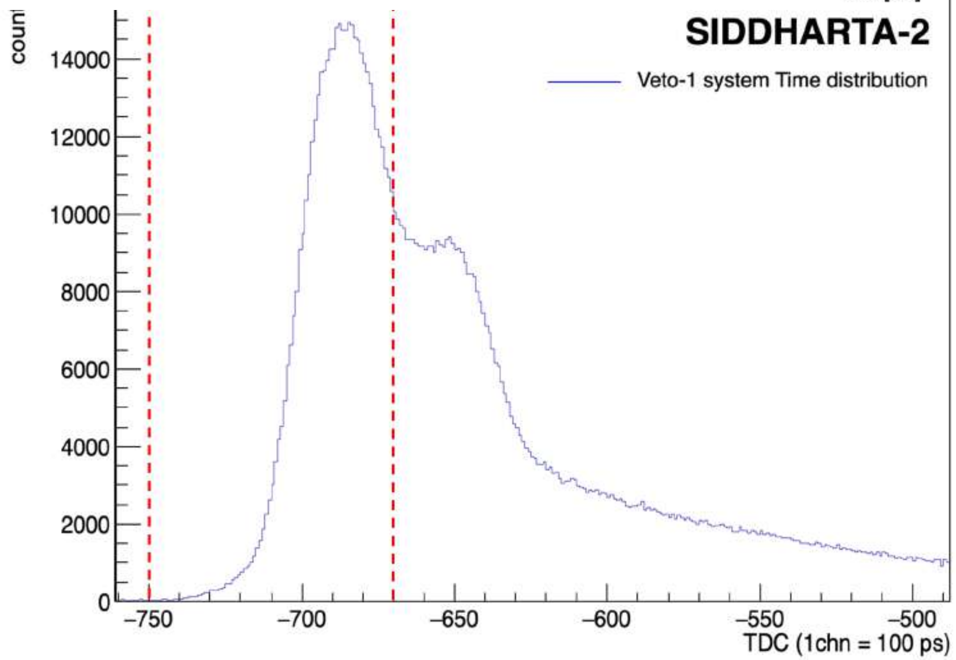


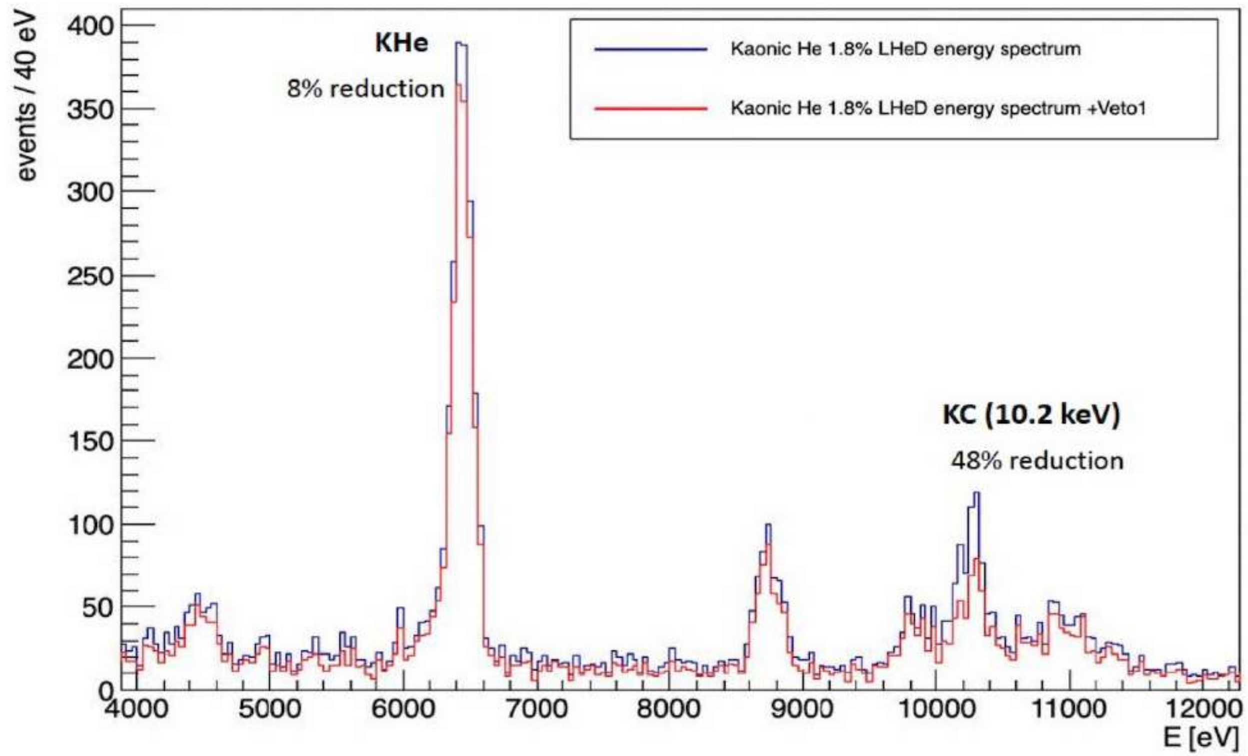
Veto-1: 14 plastic scintillators placed around and below the vacuum chamber



Veto-1 system optimization with kaonic He

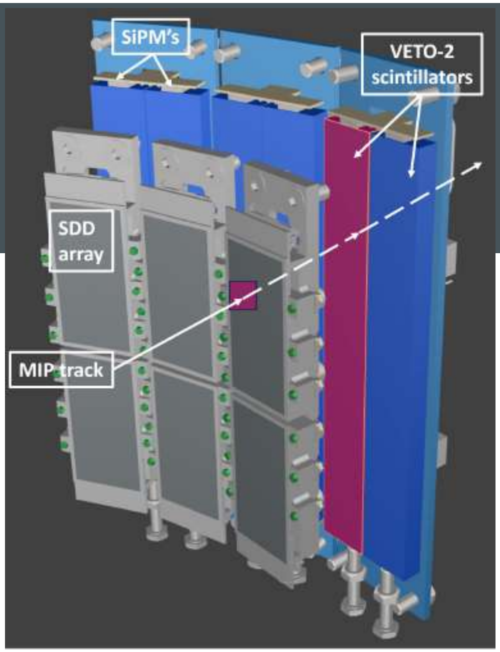


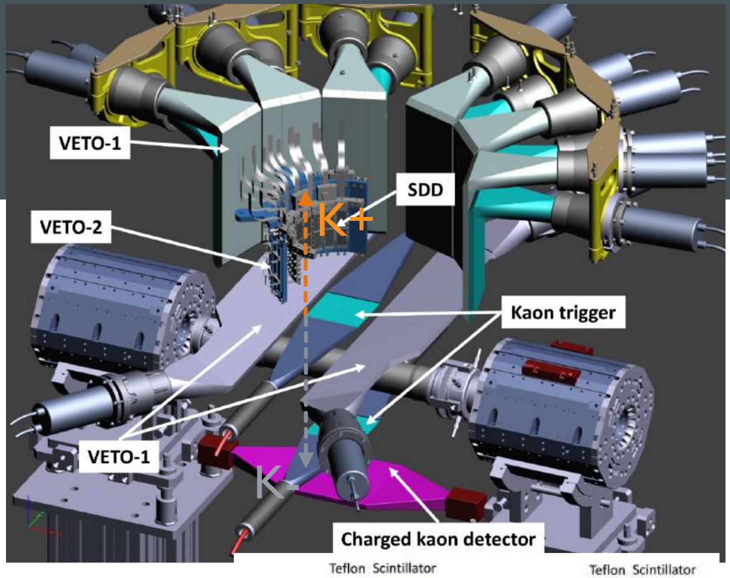


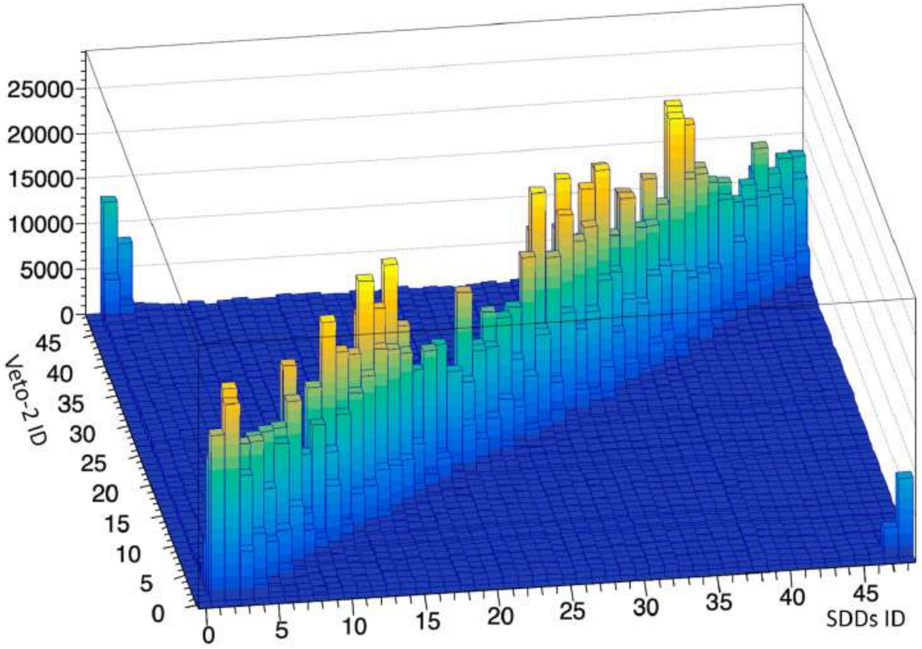


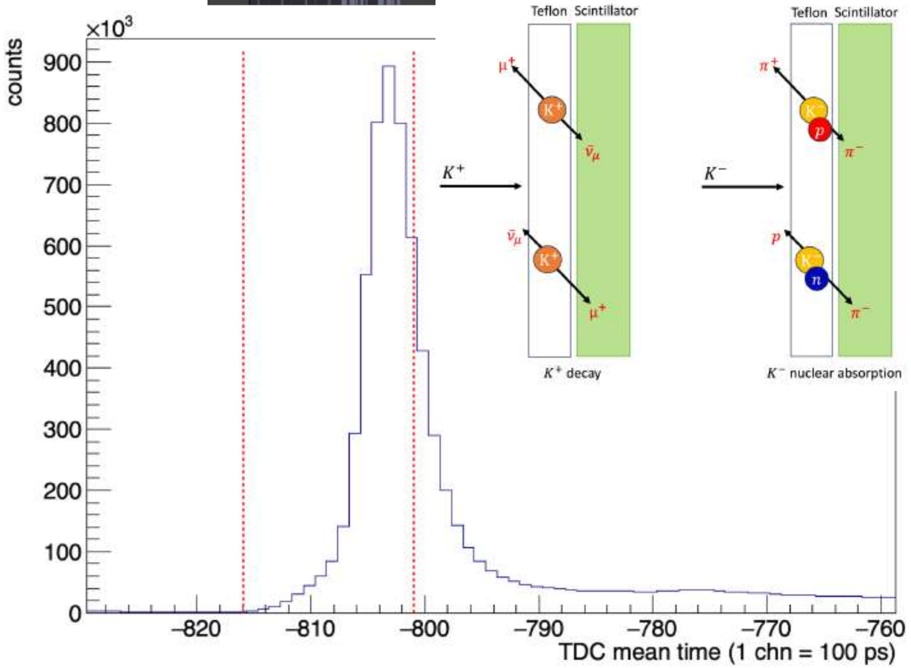
	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-^{4}He L_{α}	$(8 \pm 1)\%$	4%
K-$C_{5\to4}$	$(48 \pm 4)\%$	44%

Veto-2 and charged kaon veto system for hadronic background reduction









Conclusion

- **Kaonic Atoms bring great insights in kaon-nucleon interaction**
  - Tool to directly probe low energy QCD
  - Rich of implications from nuclear to astrophysics and cosmology
- **Measurement of kaonic helium X-ray transition**
  - **L_α** energy shift and width
  - First measurement of M-series (3d level) transitions
  - Study of the yield as function of the gas density
  - Several solid target high-n transition energies measured for the first time
- **First Measurement of kaonic neon high-n transitions**
  - Energy transitions measured with a sub-eV precision (stat)
  - Measurement of the X-ray yields
  - Exploratory estimation of the charged kaon mass
- **Measurement of Kaonic-Deuterium to fully disentangle isospin dependence on KN scattering lengths**
  - A total integrated luminosity of 800 pb^{-1} has been acquired
  - A preliminary analysis of the run 1 data shows a signal in the region of interest for K-d K_α transition
  - A more refined analysis, including the full statistic, is in progress

THANK YOU