High precision kaonic atoms X-ray spectroscopy with the SIDDHARTA-2 experiment at the DAΦNE collider

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on behalf of the SIDDHARTA-2 Collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

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

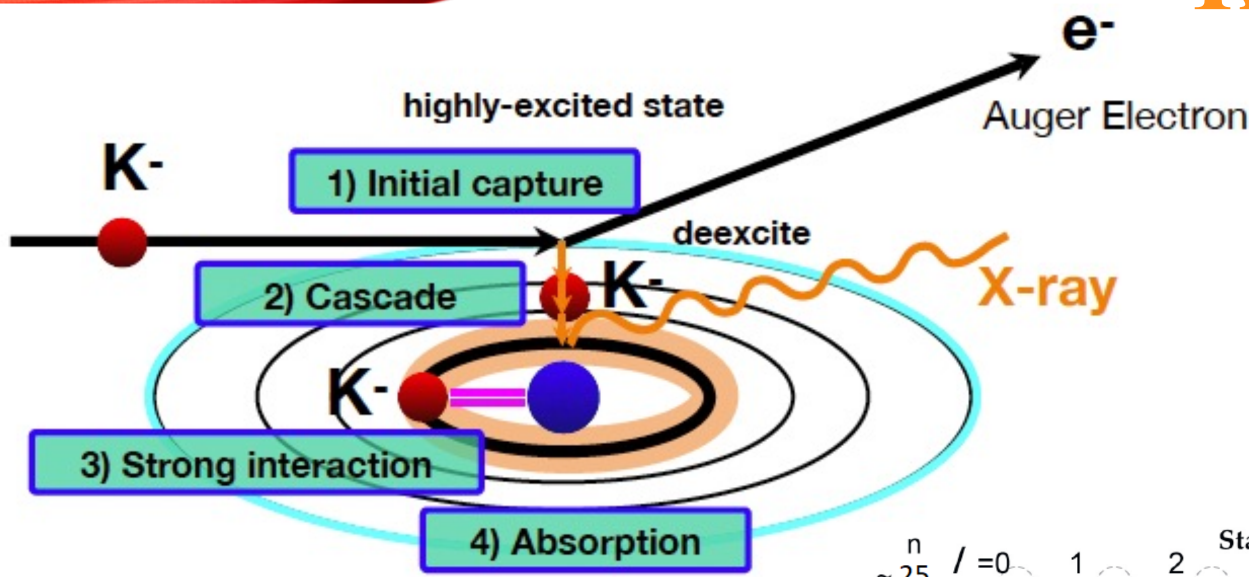
Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

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

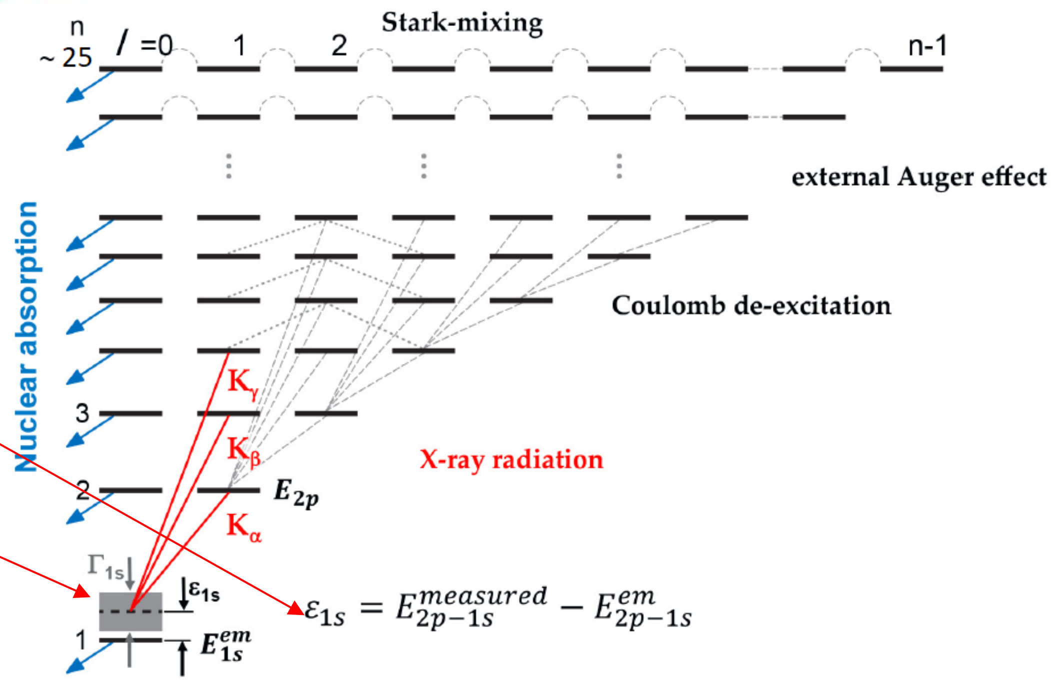
Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

Astrophysics
EOS Neutron Stars

Kaonic Atom



Strong interaction induced width Γ and shift ε obtained by measuring the emitted X-rays



SIDDHARTA-2 COLLABORATION

Silicon **D**rift **D**etectors for **H**adronic **A**tom
Research by **T**iming **A**pplication

LNF-INFN, Frascati, Italy
SMI-ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN –HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Univ. Jagiellonian Krakow, Poland
ELPH, Tohoku University

Scientific Goal

To perform the *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.

↓

Analysis of the combined measurements of kaonic deuterium and kaonic hydrogen

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

(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

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

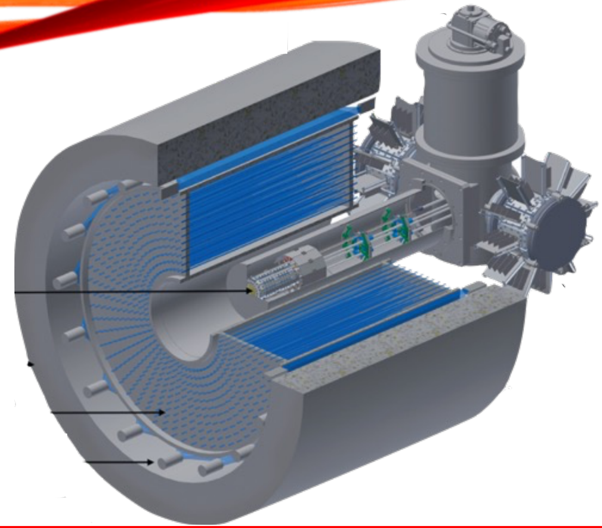
$$a_{K^-n} = a_1$$

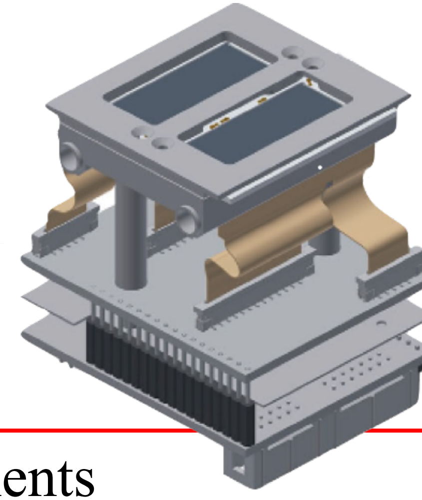
←

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

$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

Experimental determination of the isospin-dependent K-N scattering length





The modern era of light kaonic atom experiments

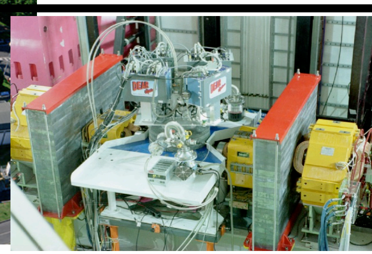
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

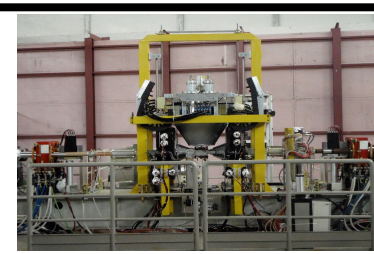
Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

DEAR 2002

SIDDHARTA 2009

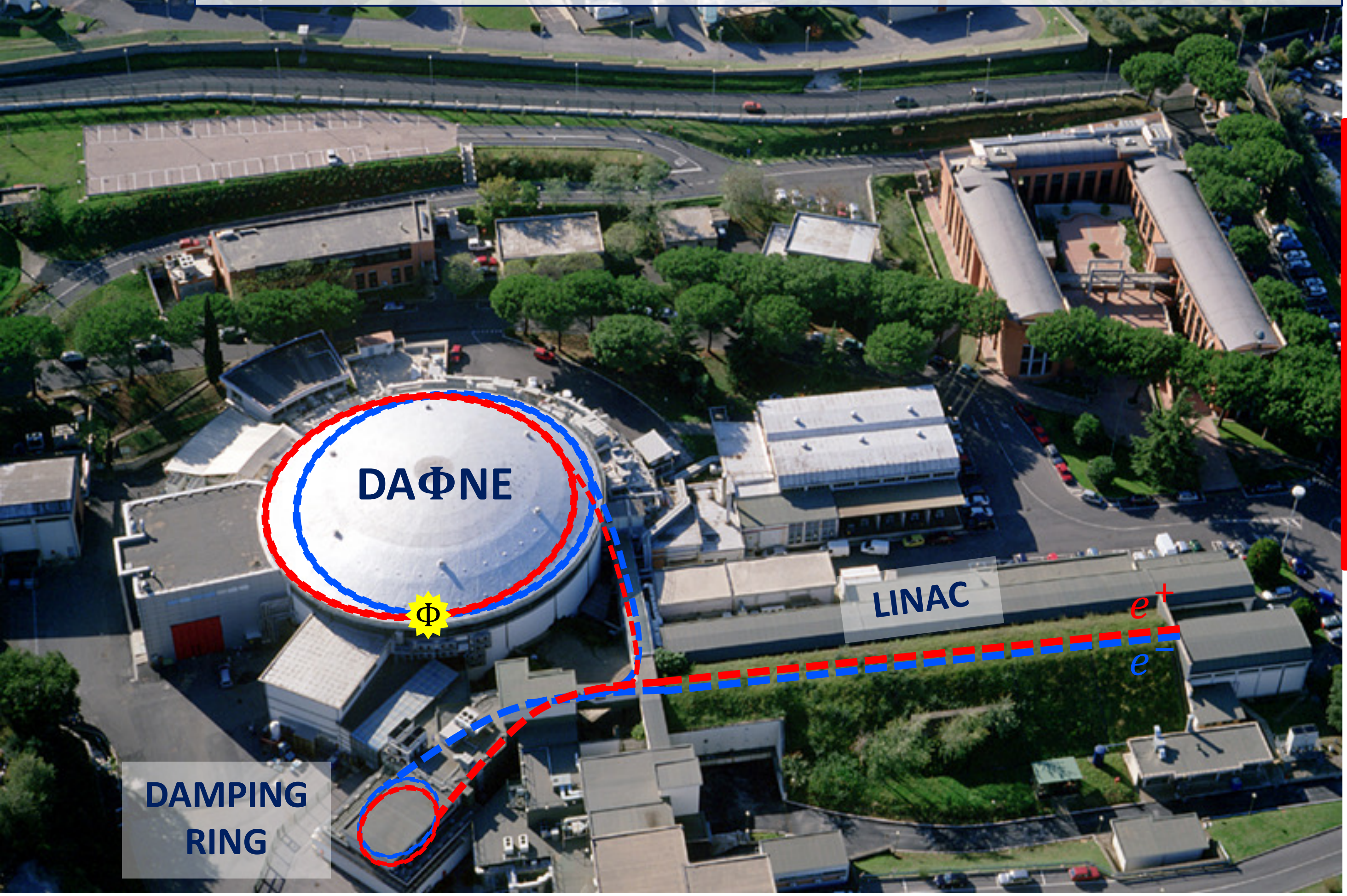
SIDDHARTA-2 2022





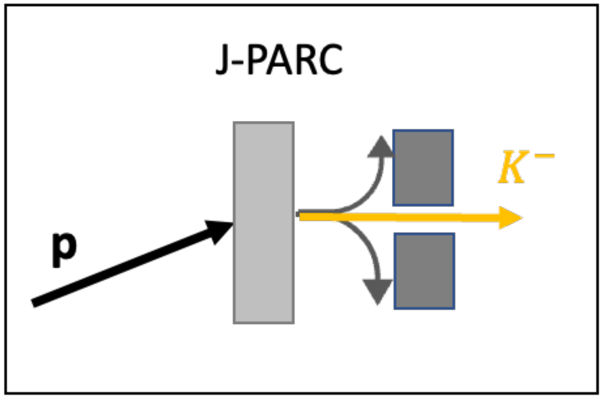
LNF – e^+e^- Accelerator Complex

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



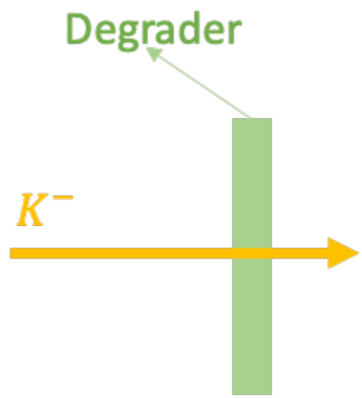
Suitable for low-energy kaon physics: kaonic atoms Kaon-nucleons/nuclei interaction studies

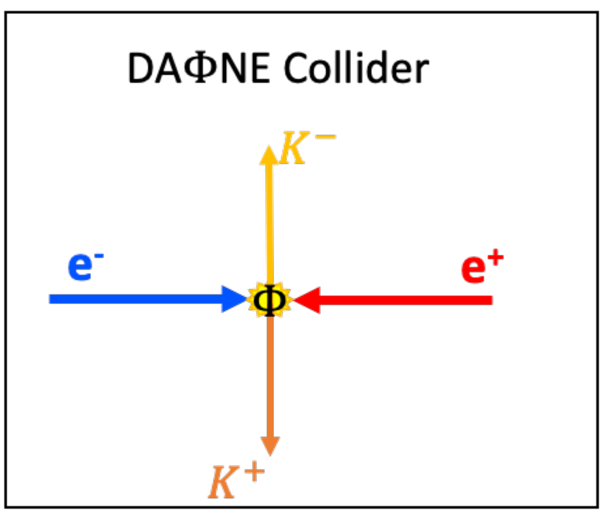
Experimental Principle



High intensity

High background



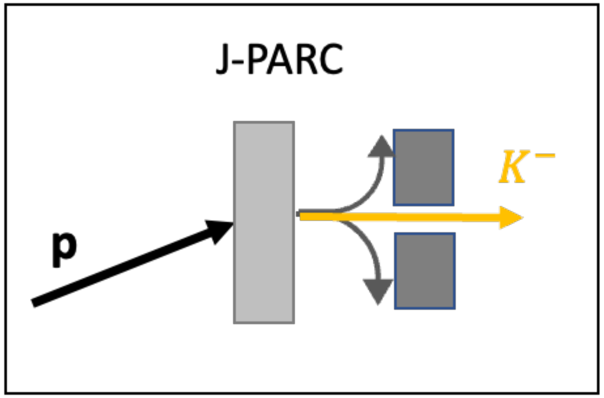


Monochromatic

Low energy kaons

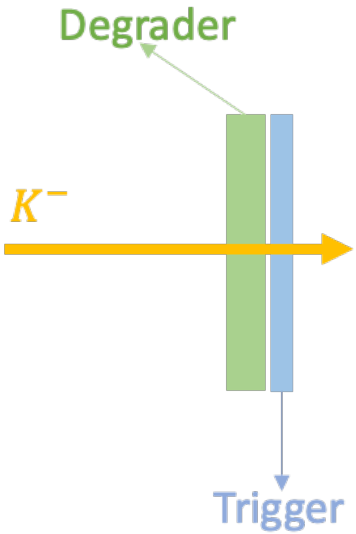
Solid angle

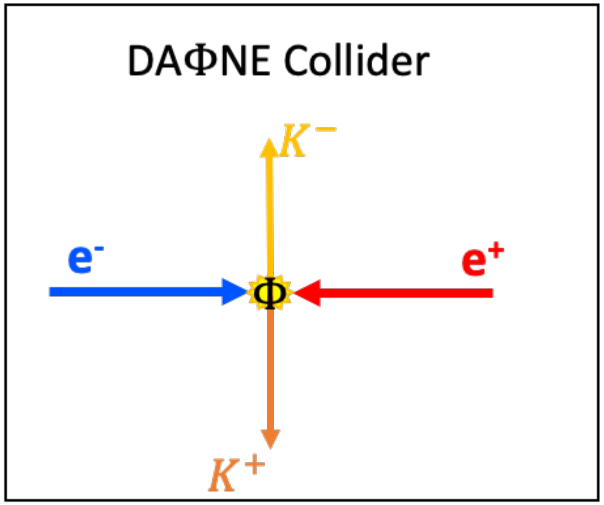
Experimental Principle



High intensity

High background





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Solid angle

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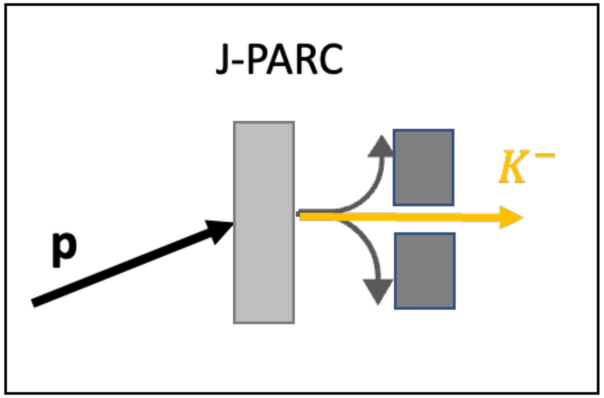
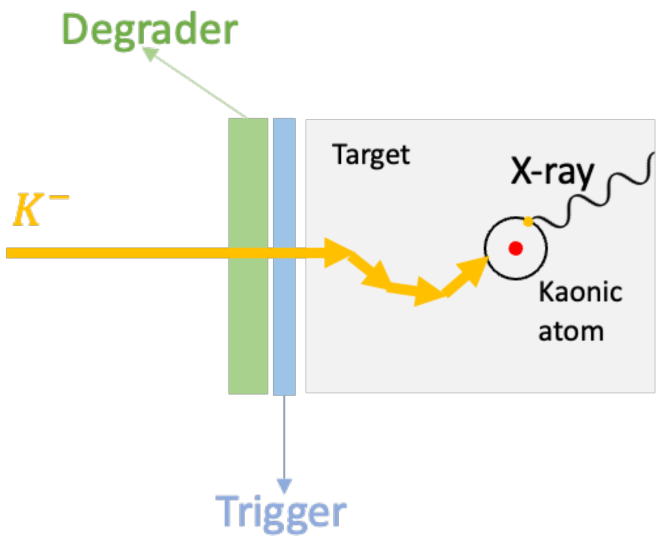
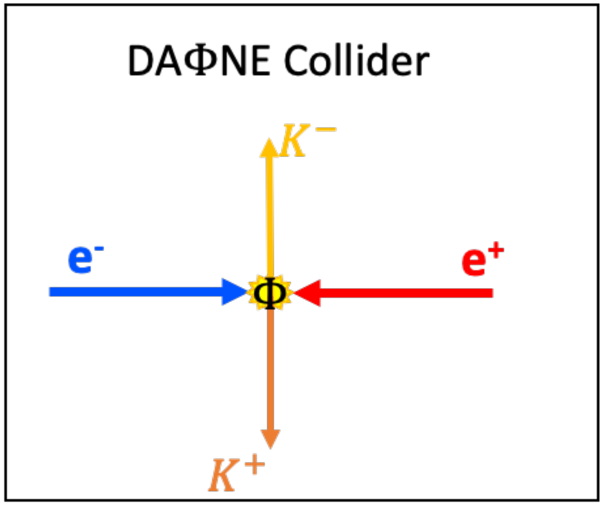


High intensity

High background



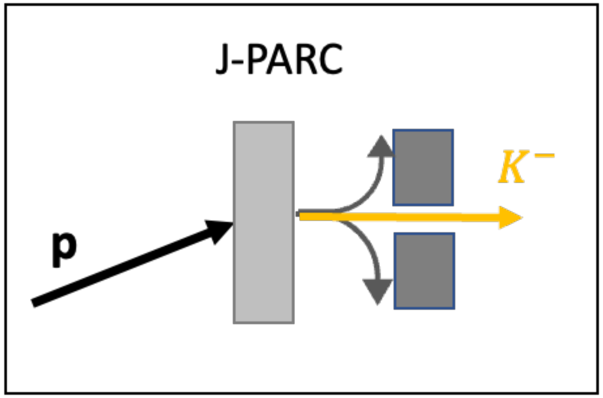


Monochromatic

Low energy kaons

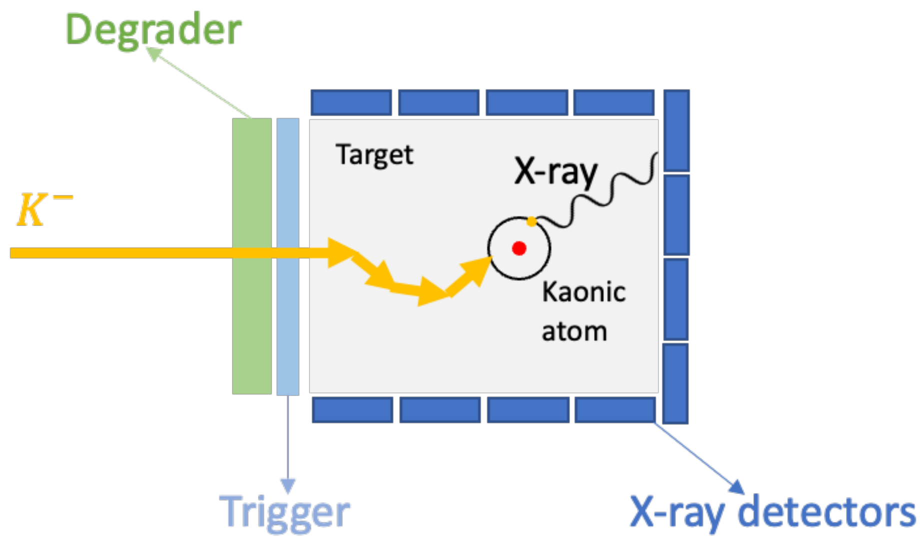
Solid angle

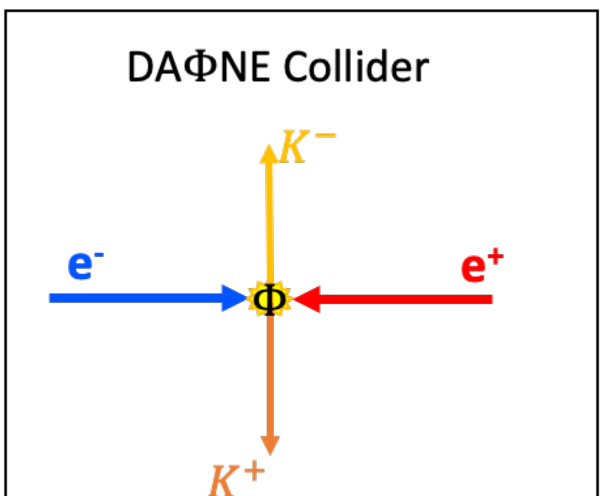
Experimental Principle



High intensity

High background



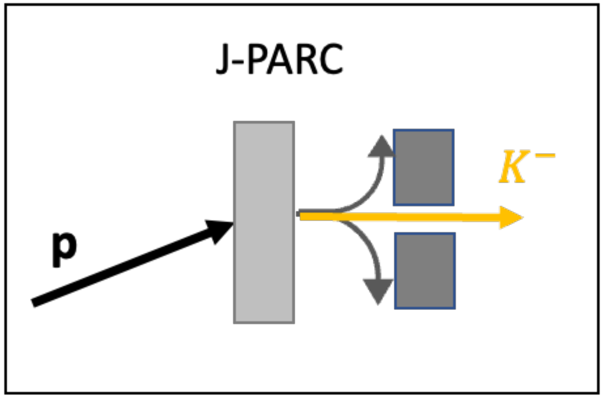


Monochromatic

Low energy kaons

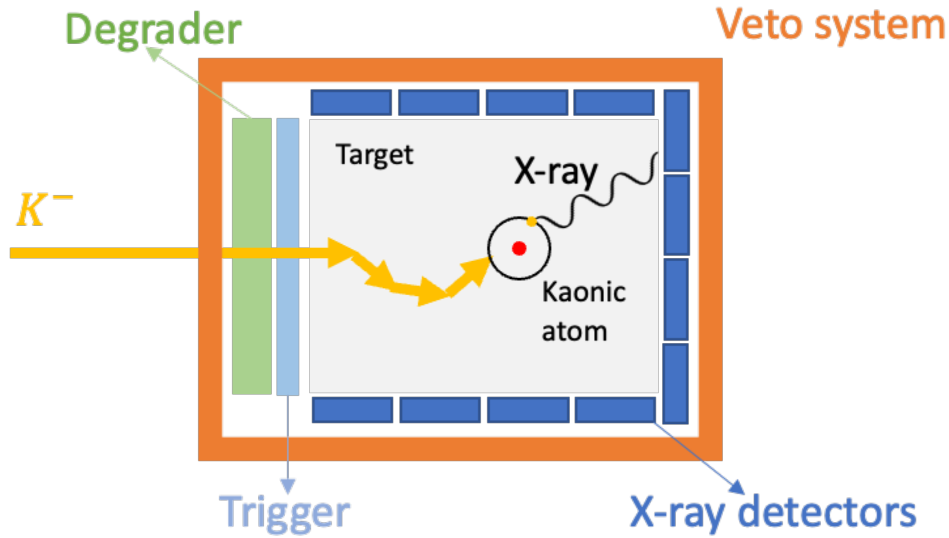
Solid angle

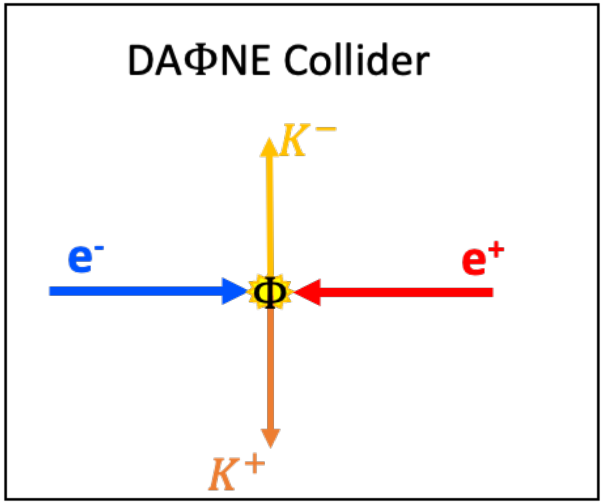
Experimental Principle



High intensity

High background



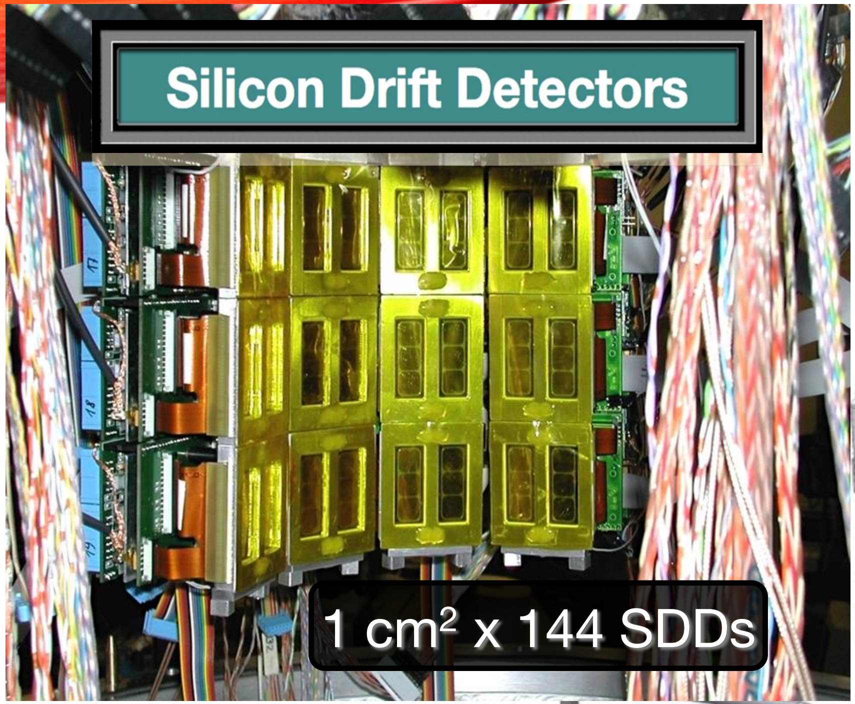


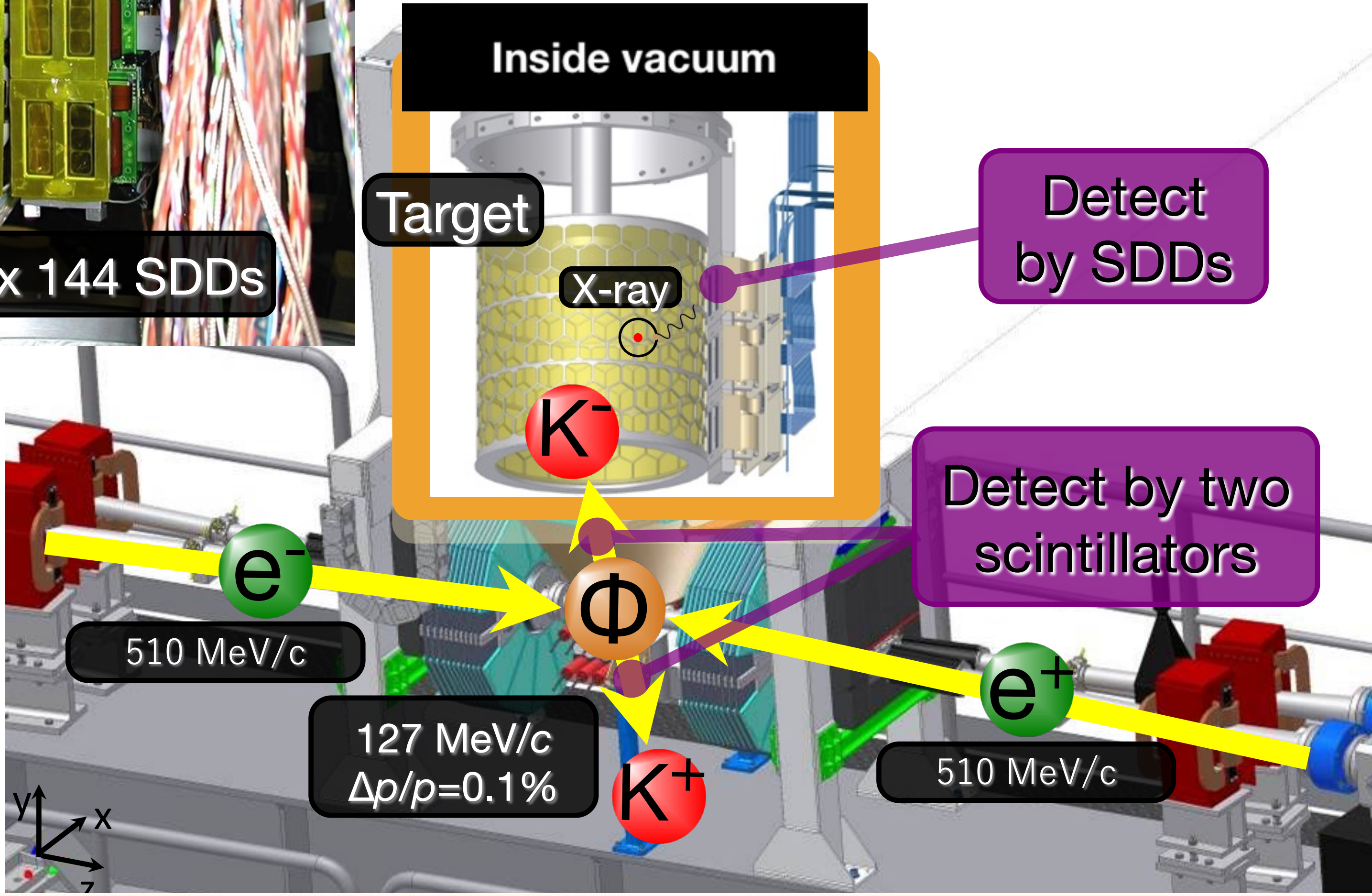
Monochromatic

Low energy kaons

Solid angle

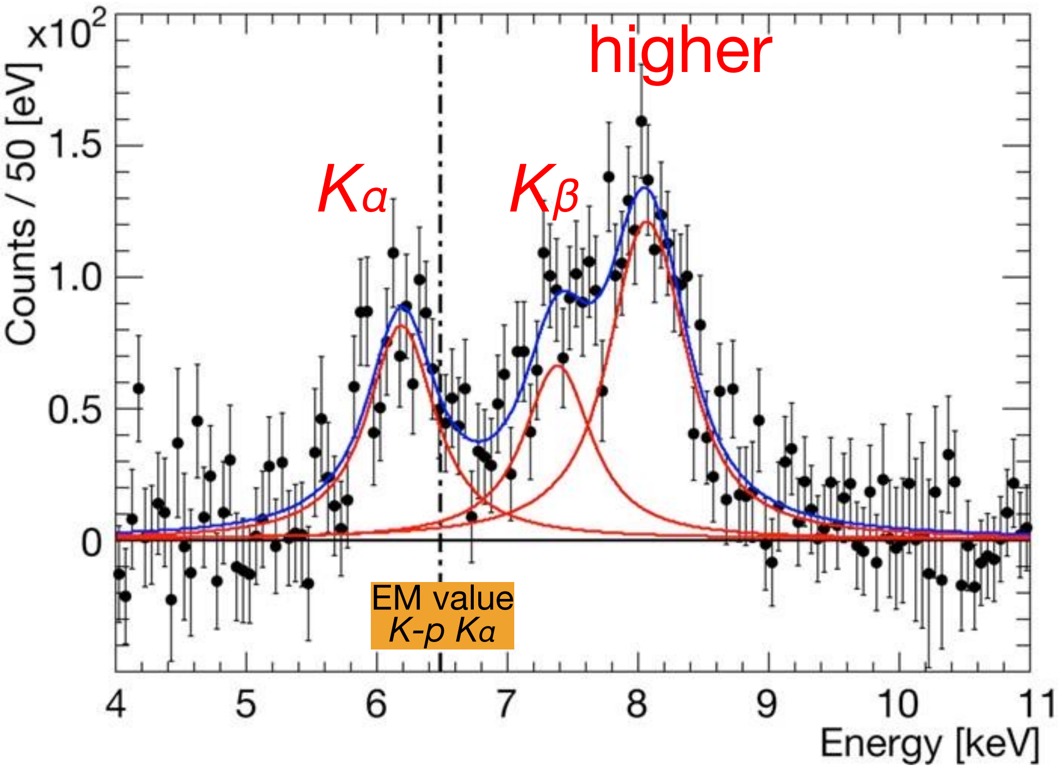
The SIDDHARTA Experiment (2009)





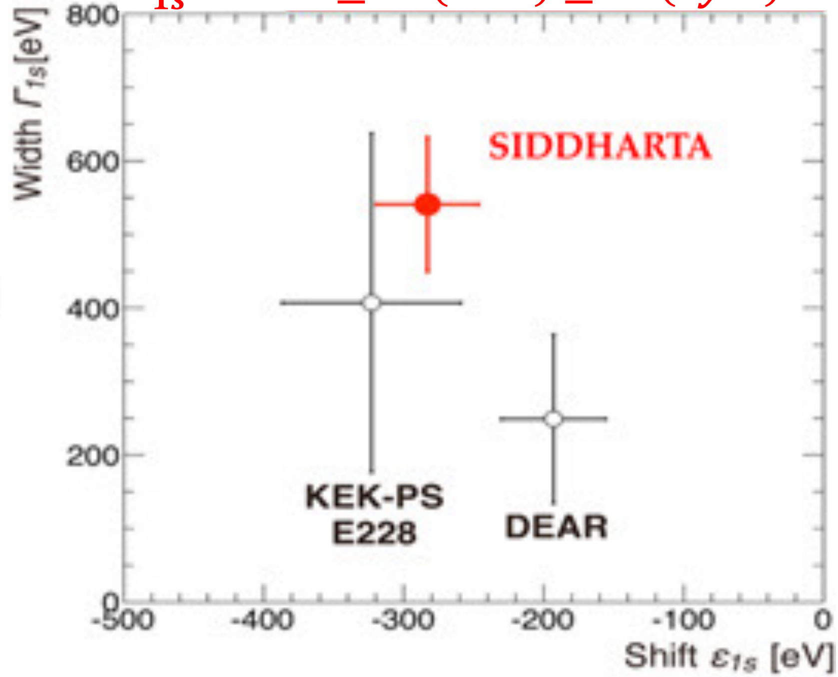
The SIDDHARTA Experiment (2009)

Kaonic hydrogen



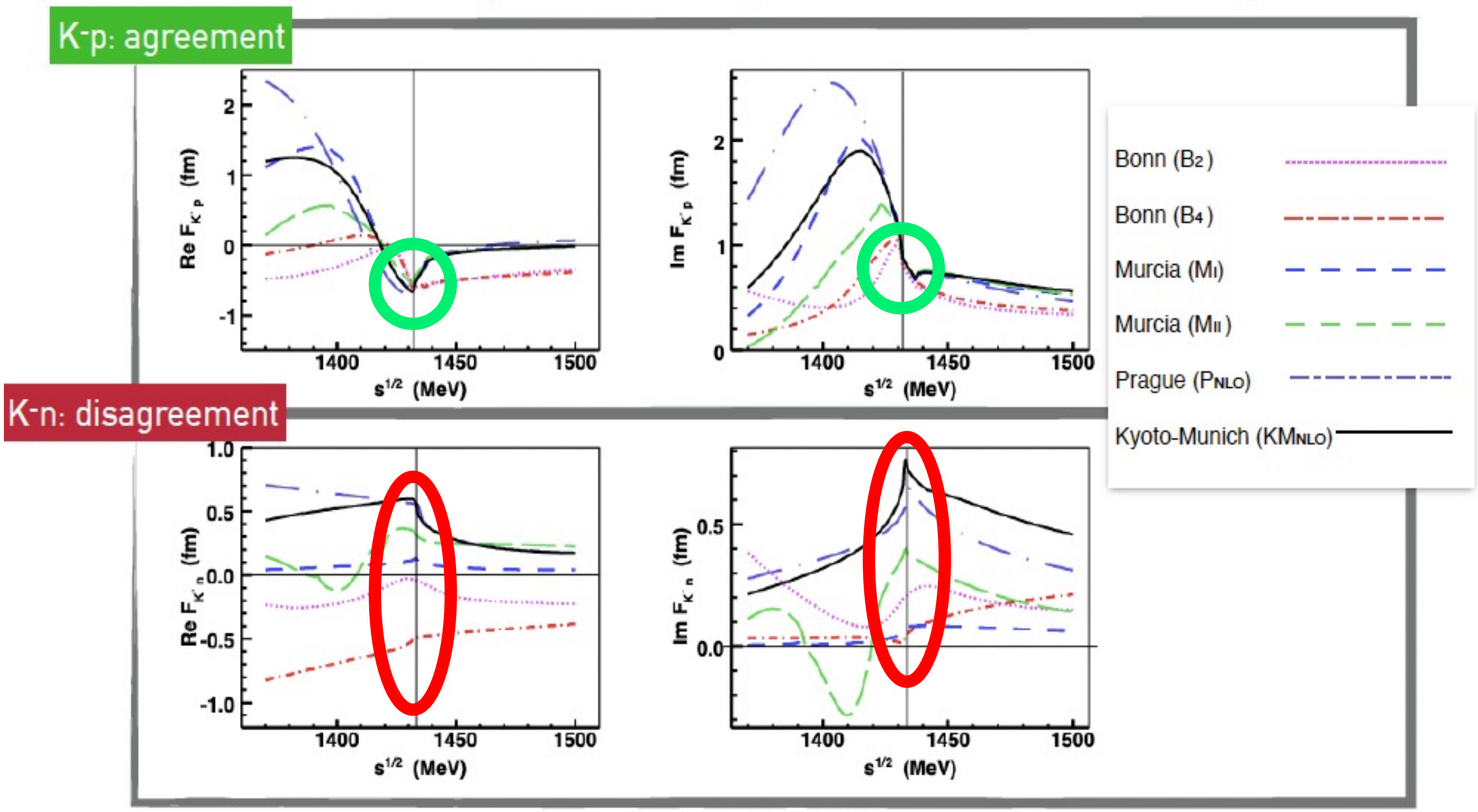
$$\varepsilon_{1s}^{H} = -283 \pm 36(stat) \pm 6(syst)eV$$

$$\Gamma_{1s}^{H} = 541 \pm 89(stat) \pm 22(syst)eV$$



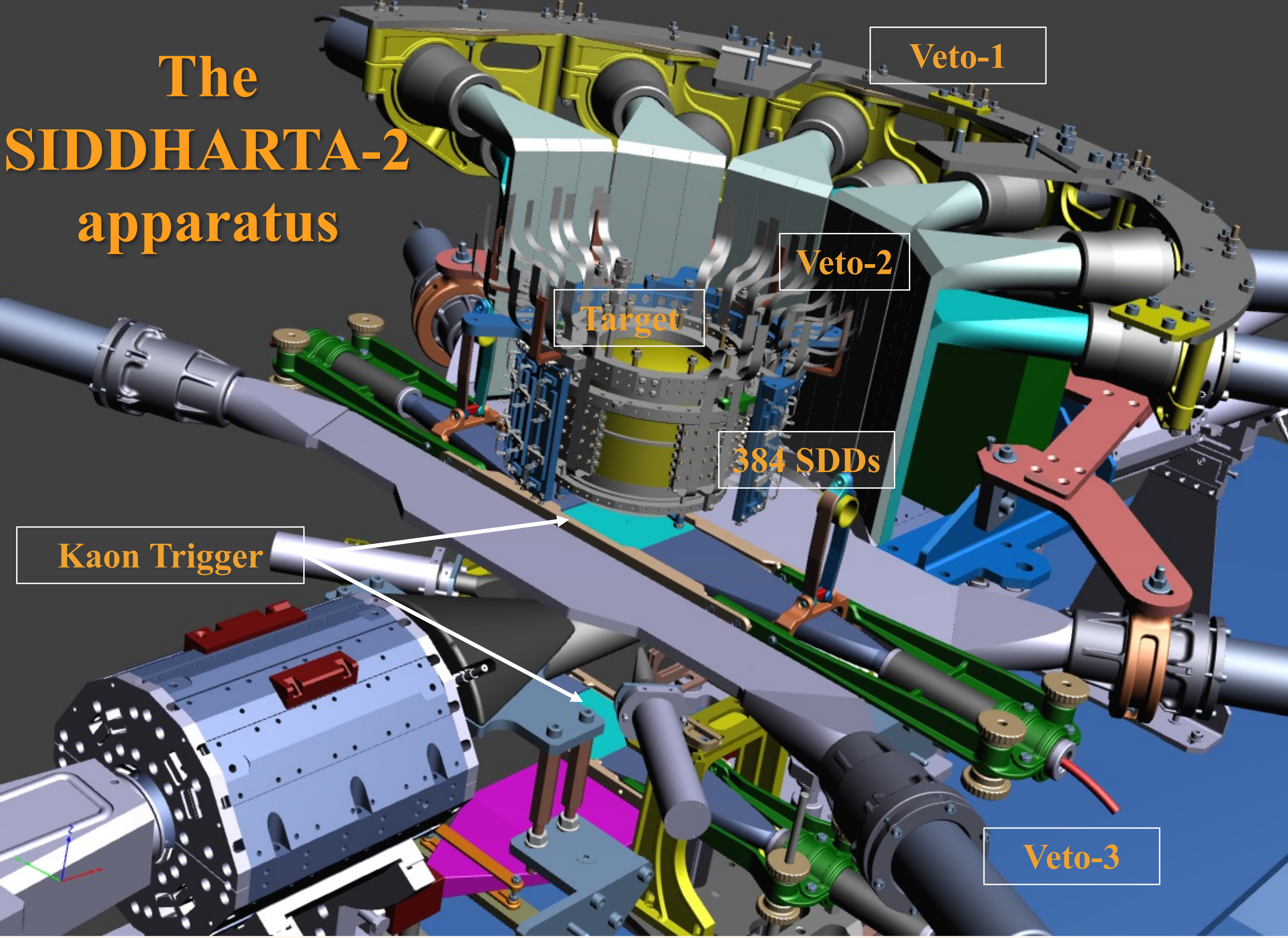
C. Curceanu et al., *Phys. Lett. B* **704** (2011) 113

Kaon nucleon scattering amplitude

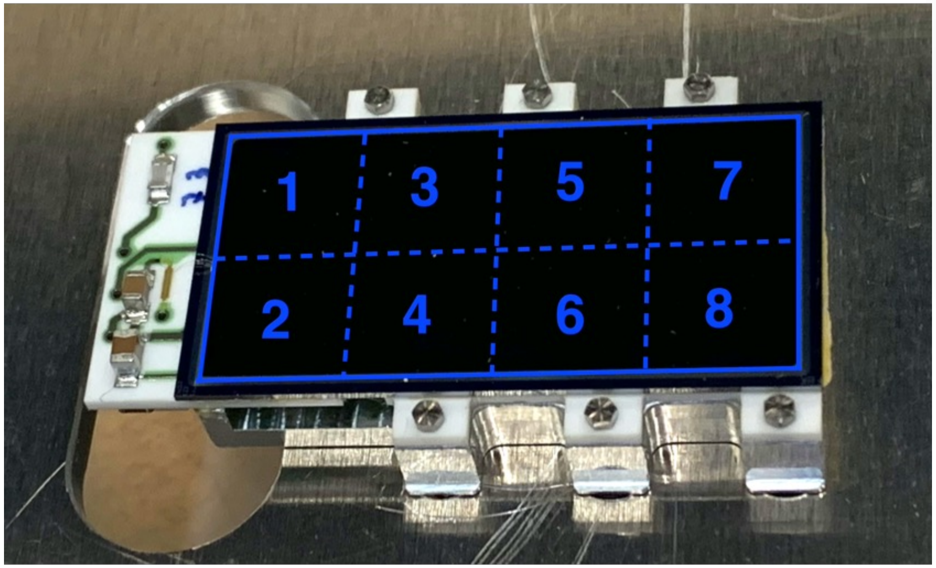


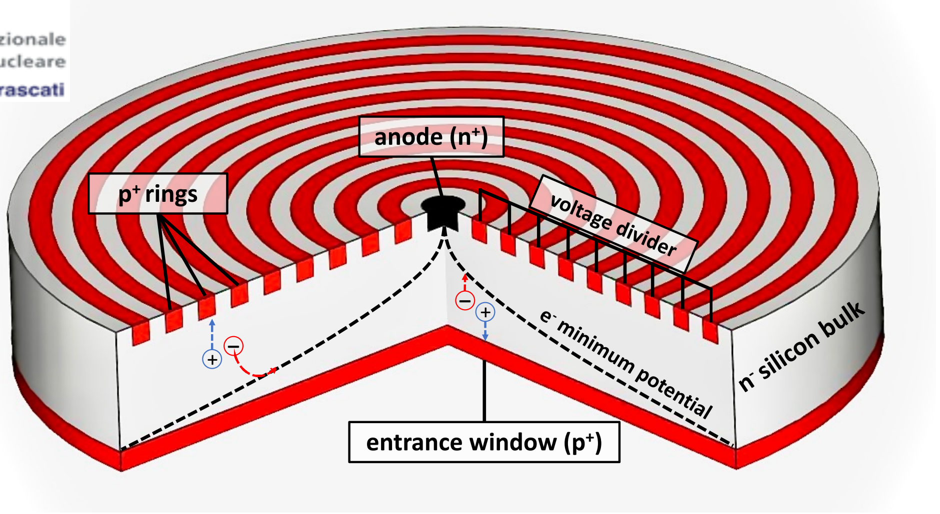
A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

The SIDDHARTA-2 apparatus



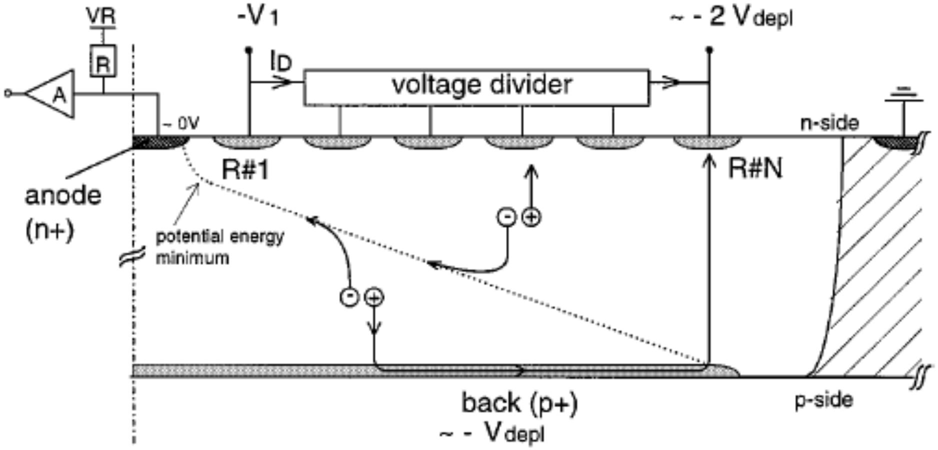
Silicon Drift Detectors





48 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

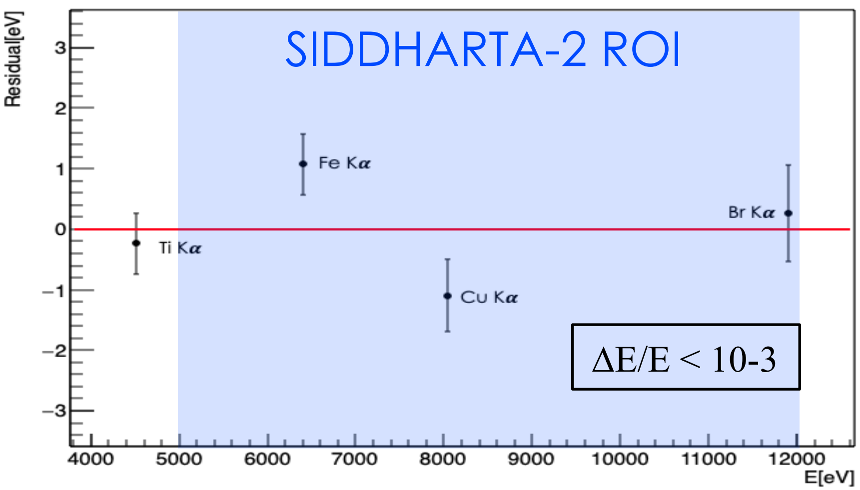


M Miliucci *et al* 2021 *Meas. Sci. Technol.* **32** 095501

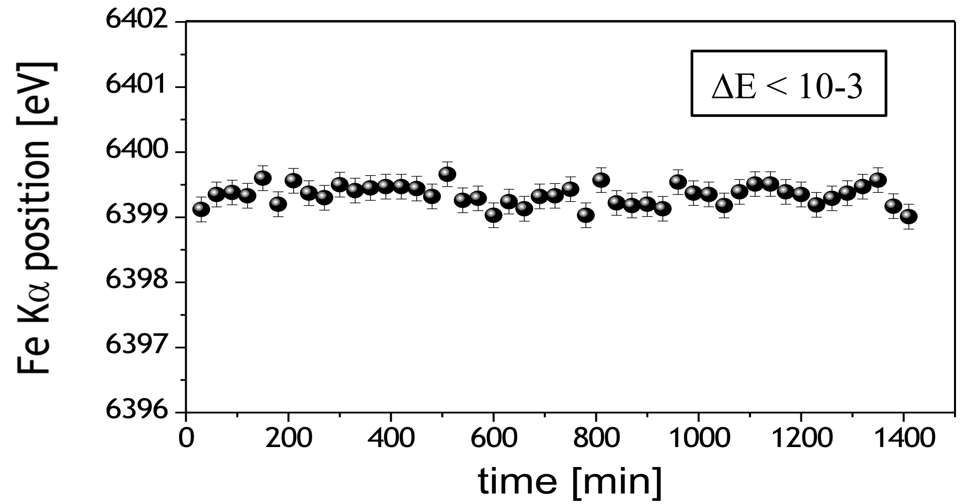
F Sgaramella *et al 2022 Phys. Scr. 97 114002*

Silicon Drift Detectors

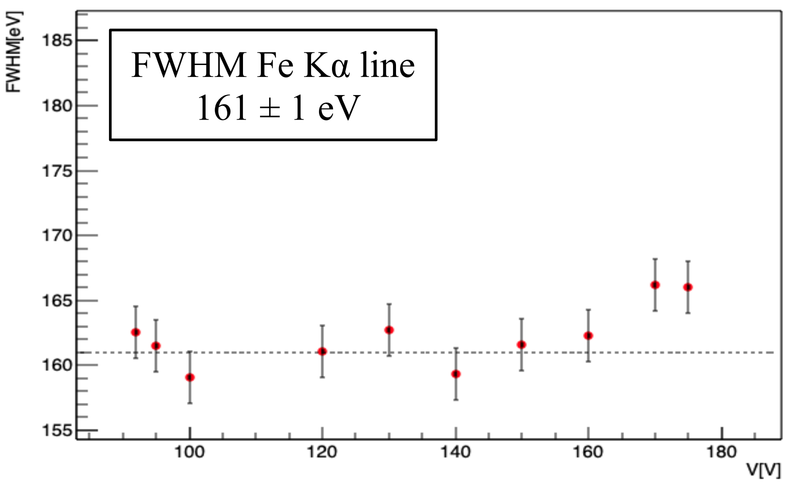
Linearity



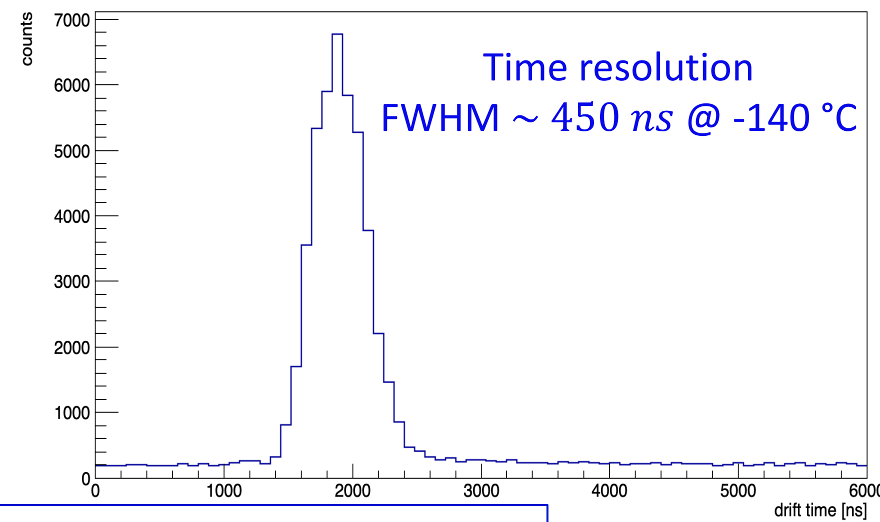
Stability



Energy Resolution

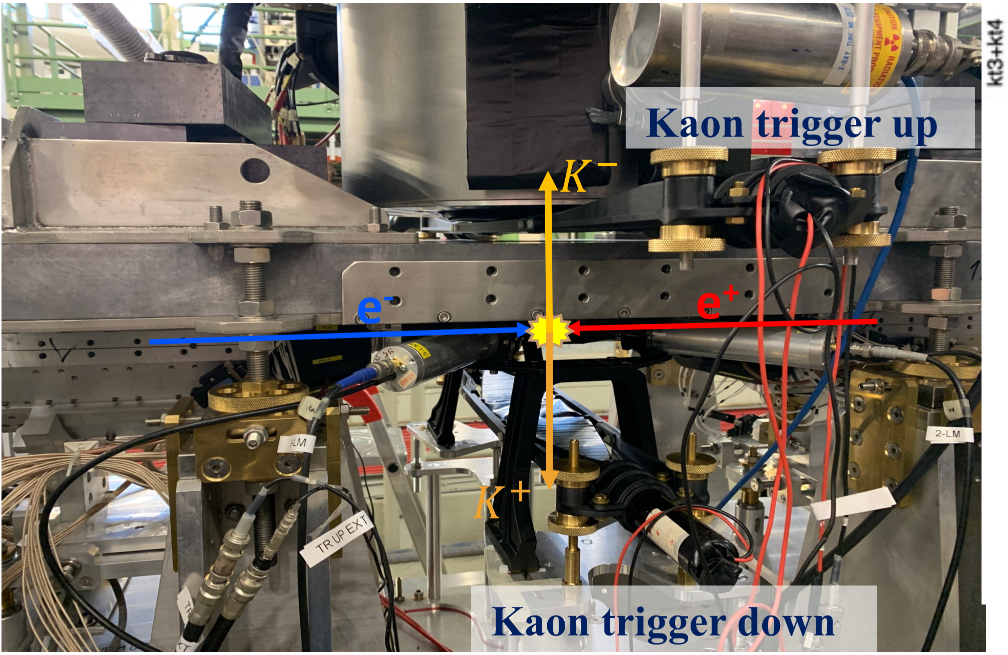


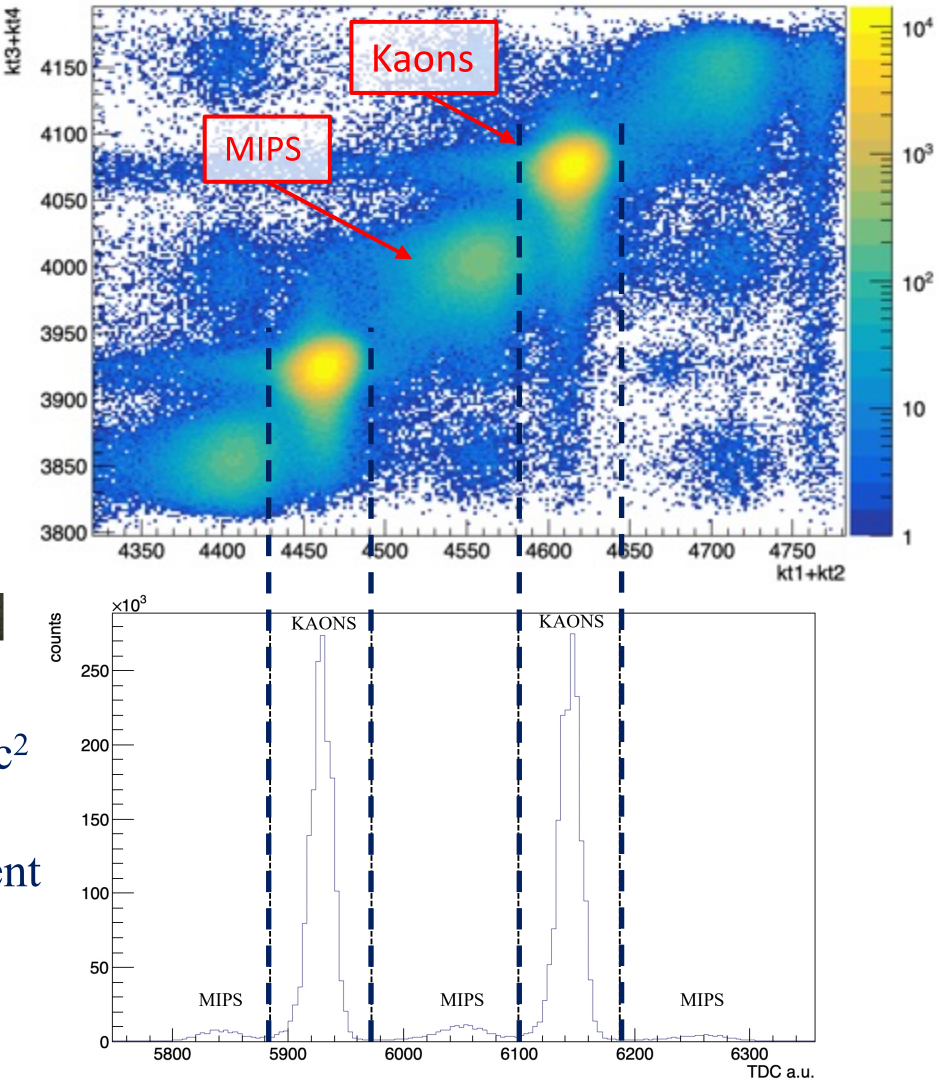
Time Resolution



M Miliucci *et al* 2021 *Meas. Sci. Technol.* **32** 095501

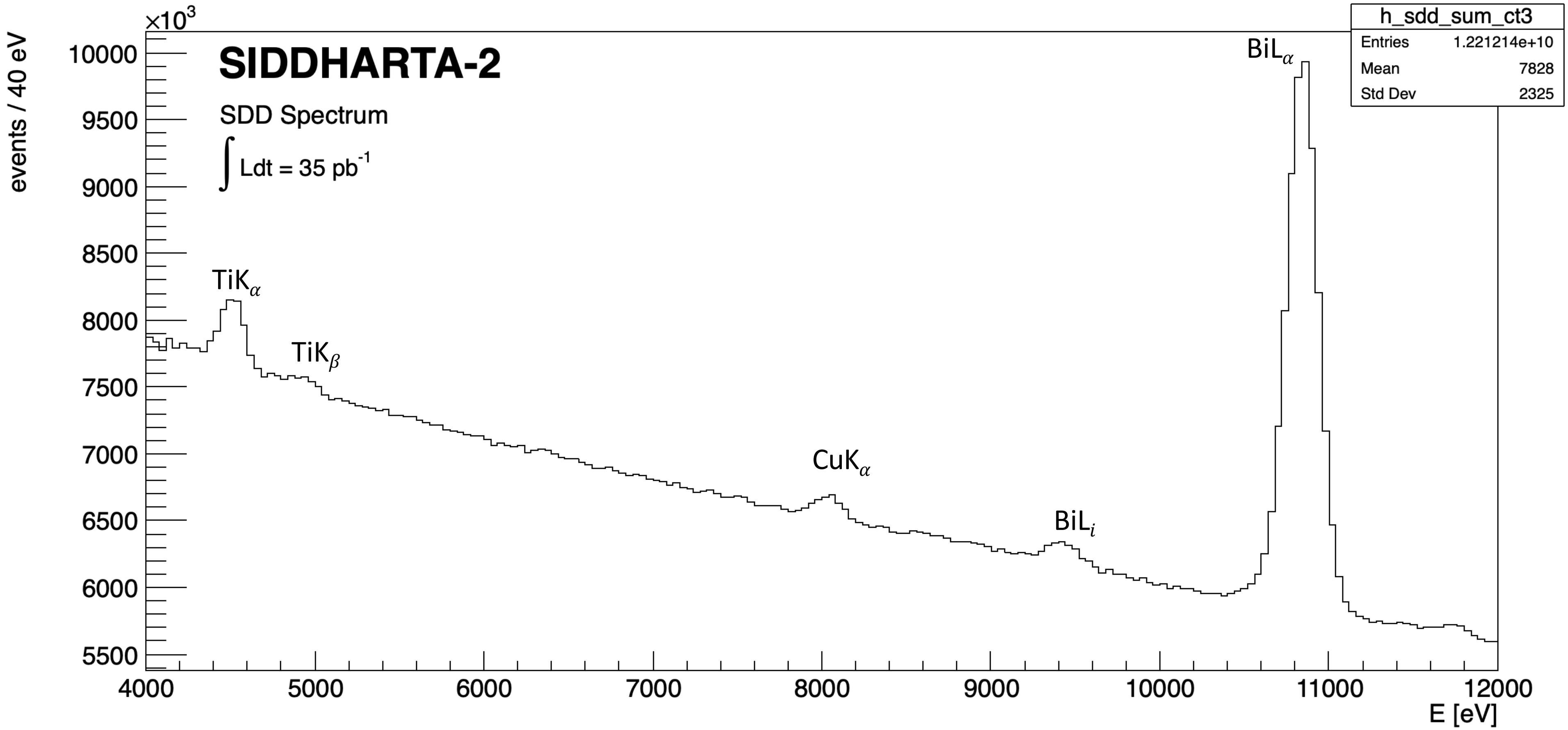
The Kaon Trigger



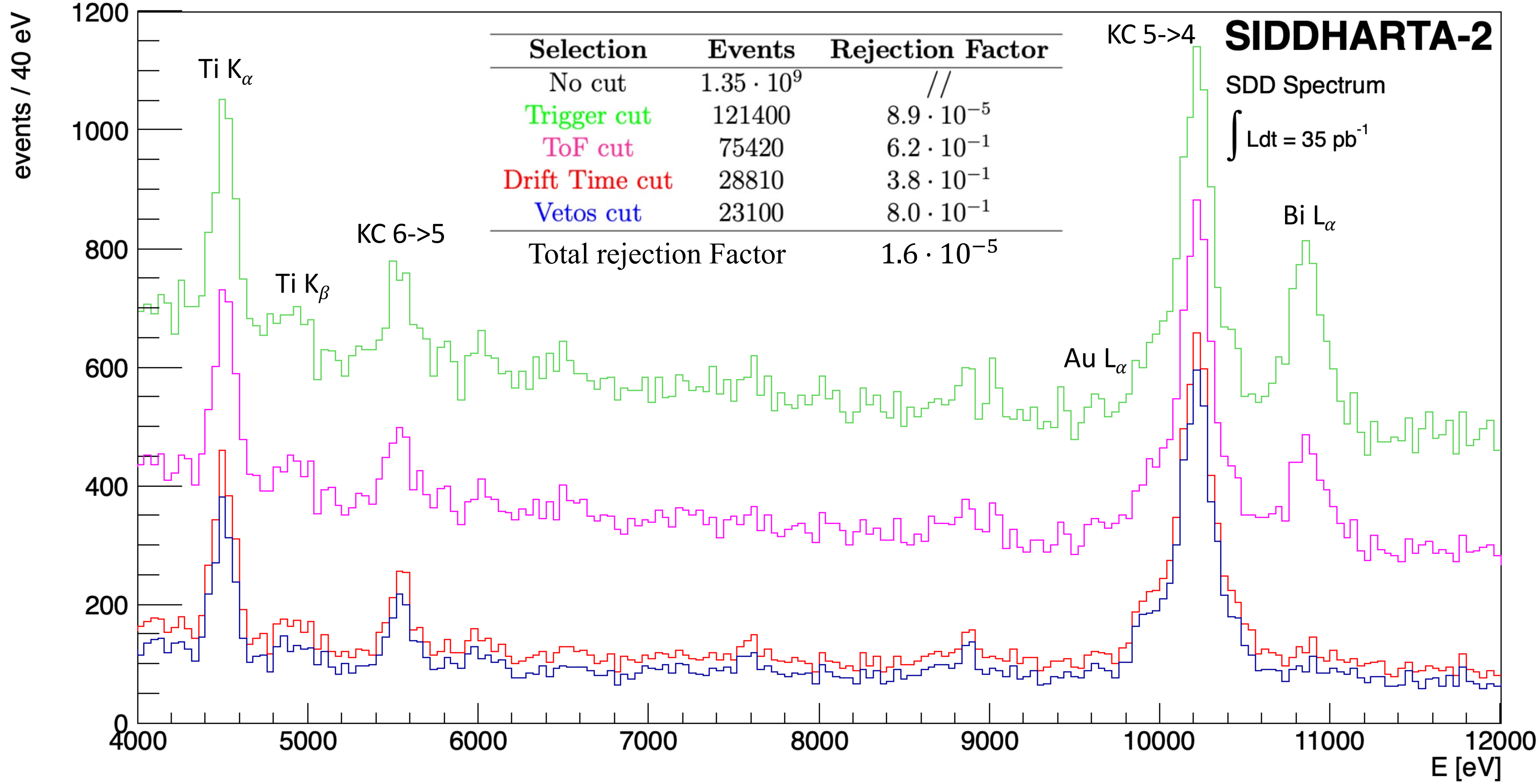


The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

SIDDHARTA-2
Background rejection



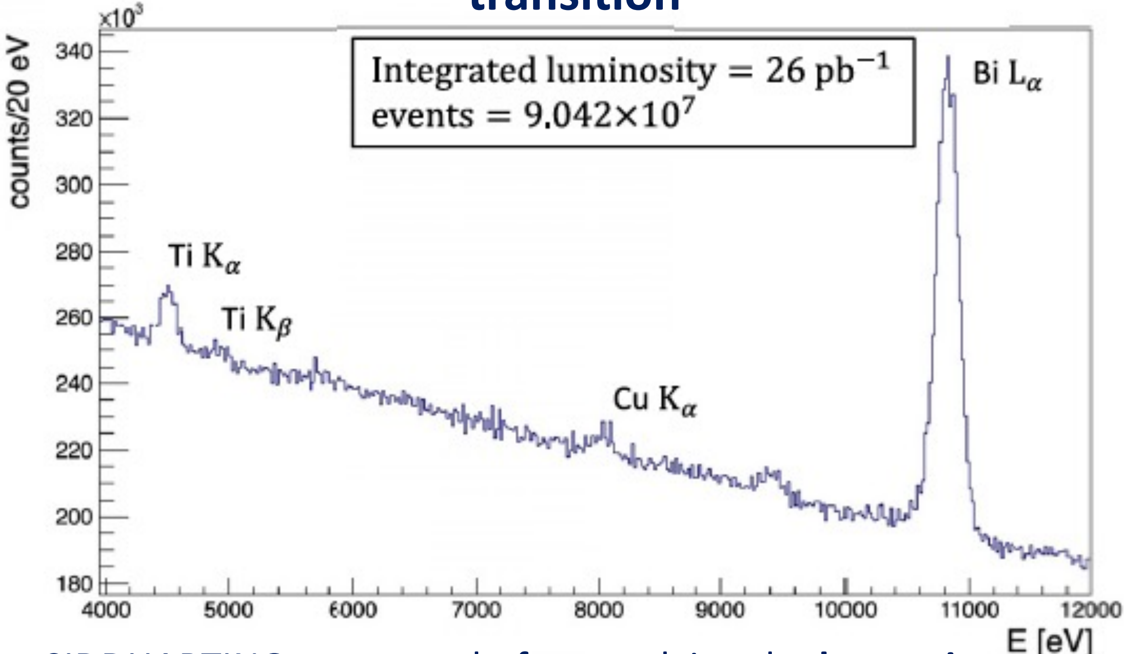
SIDDHARTA-2
Background rejection



Selection	Events	Rejection Factor
No cut	$1.35 \cdot 10^9$	//
Trigger cut	121400	$8.9 \cdot 10^{-5}$
ToF cut	75420	$6.2 \cdot 10^{-1}$
Drift Time cut	28810	$3.8 \cdot 10^{-1}$
Vetos cut	23100	$8.0 \cdot 10^{-1}$
Total rejection Factor		$1.6 \cdot 10^{-5}$

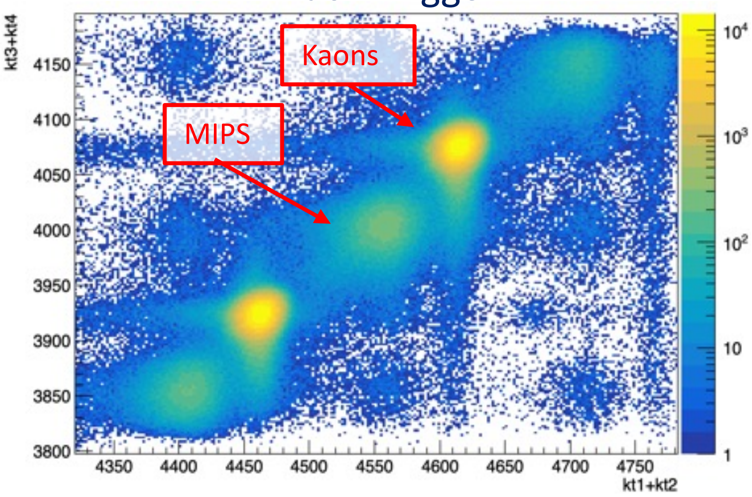
SIDDHARTINO (2021)
The kaonic ^{4}He 3d->2p (L_α) measurement

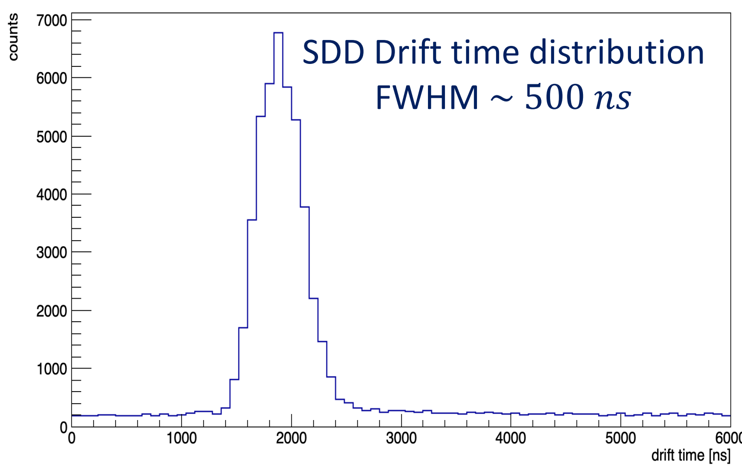
Optimization of the trigger and SDDs during the DAΦNE beams commissioning phase in preparation for the K-d run through the **measurement of K-^{4}He 3d->2p transition**



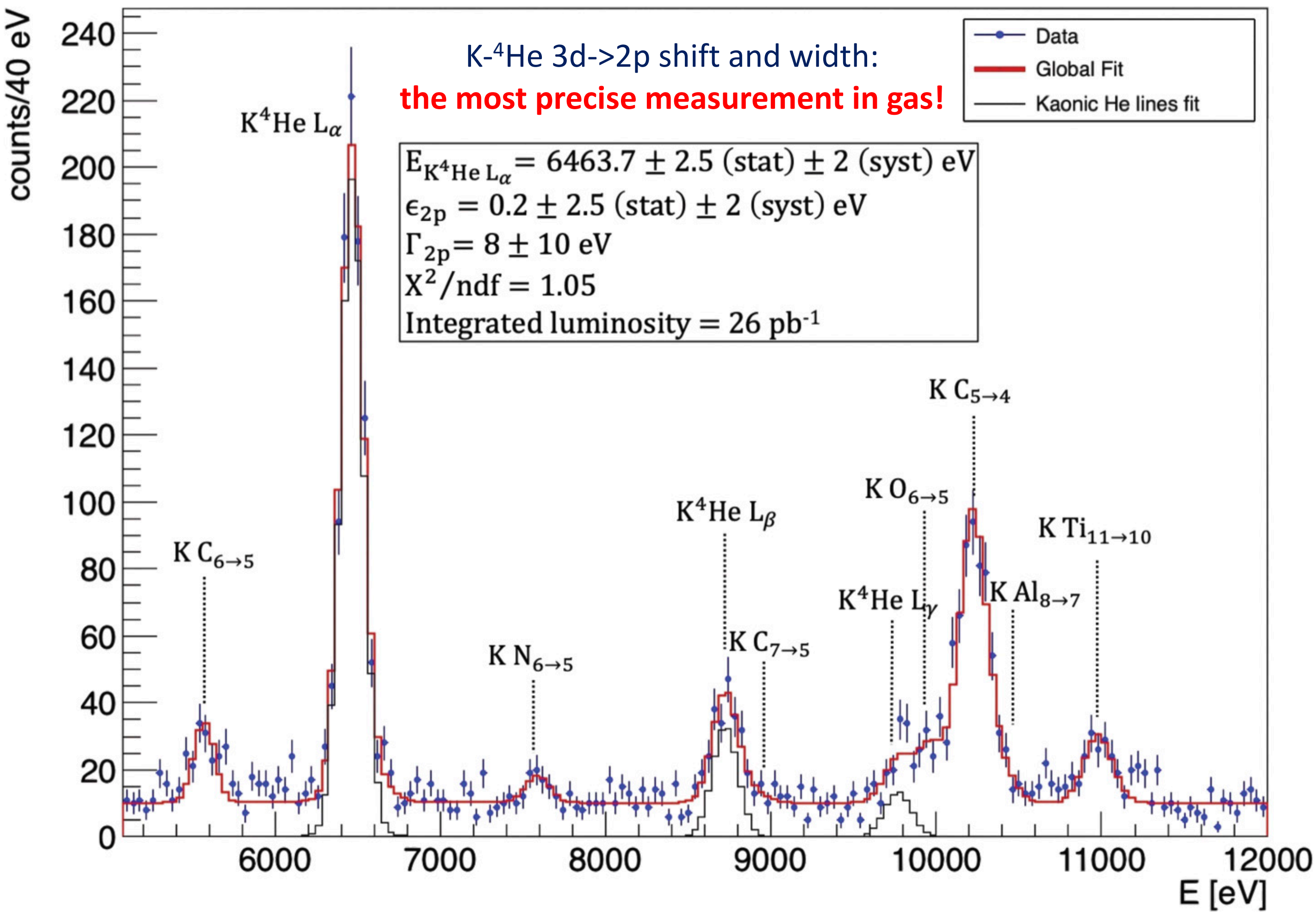
SIDDHARTINO spectrum before applying the **kaon trigger** and the **drift time rejection**

Kaon Trigger



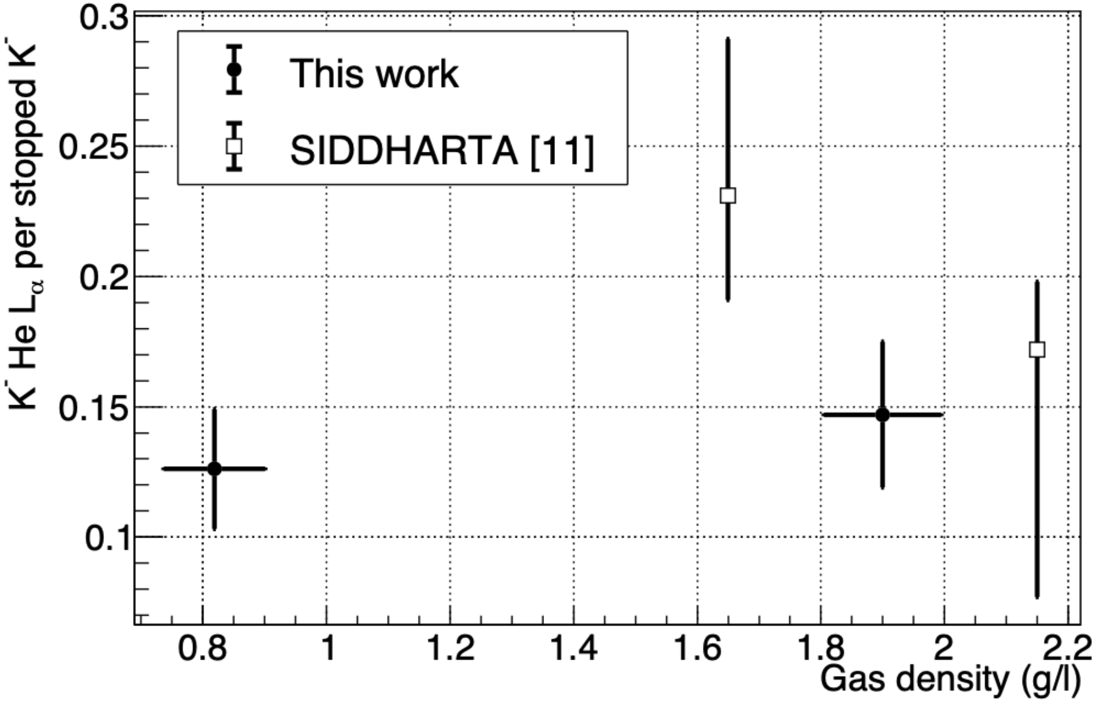


SIDDHARTINO (2021)
The kaonic ^{4}He 3d->2p (L_α) measurement



D Sirghi *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 055106

SIDDHARTINO
The kaonic ^{4}He yield measurement



K-^{4}HE LOW DENSITY RUN: 0.75% LIQUID HELIUM DENSITY -> **YIELDS AT LOWEST MEASURED DENSITY**

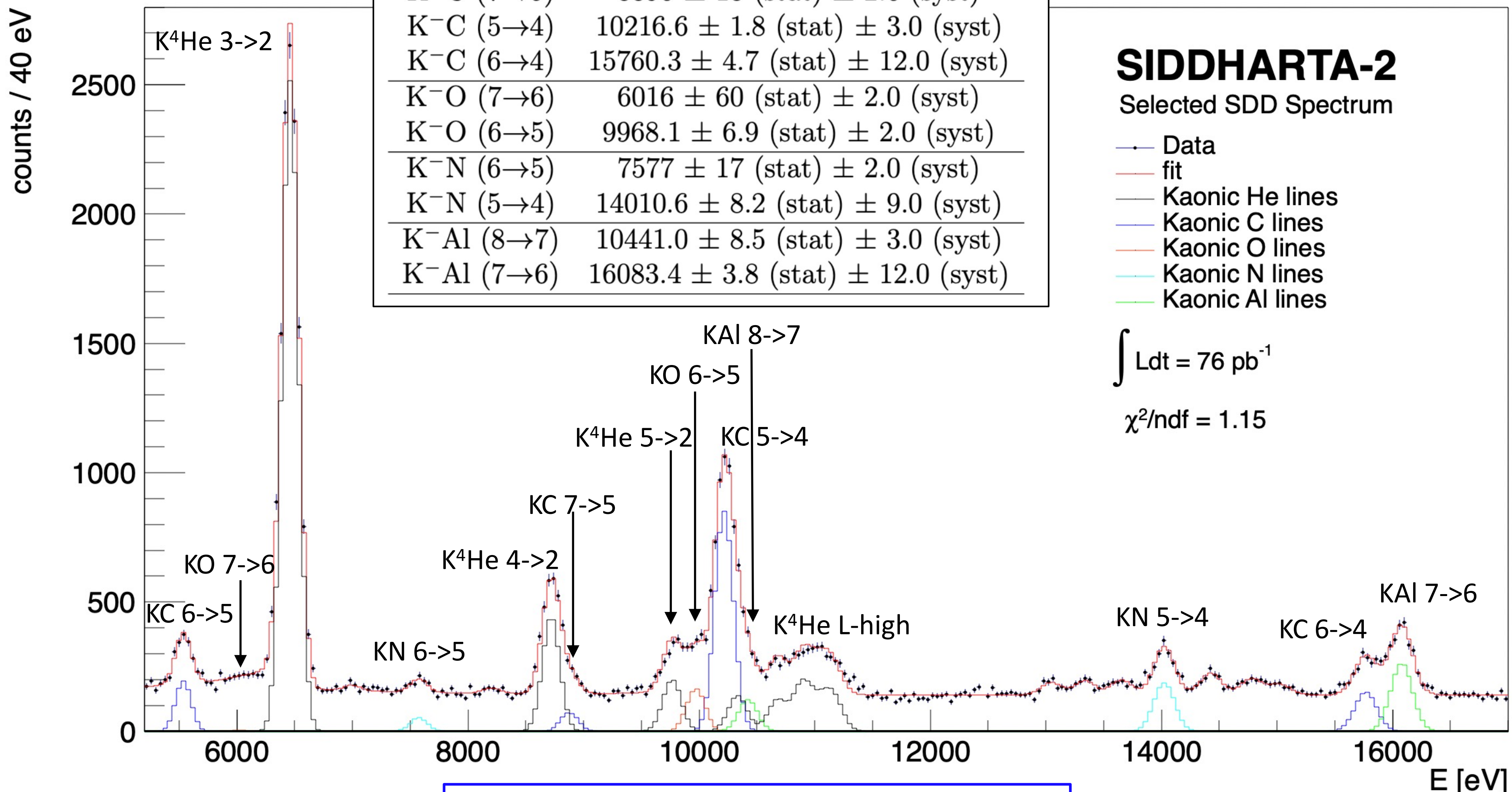
Density	1.90 g/l	0.82 g/l
L_{α} yield	0.148 ± 0.027	0.126 ± 0.023
L_{β}/L_{α}	0.193 ± 0.042	0.133 ± 0.037
L_{γ}/L_{α}	0.035 ± 0.015	not detected

D.L. Sirghi, et al. Nuclear Physics A 1029 (2023) 122567

Measurements of high-n transitions in intermediate mass kaonic atoms

SIDDHARTA-2 (2022)

Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (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)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (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)

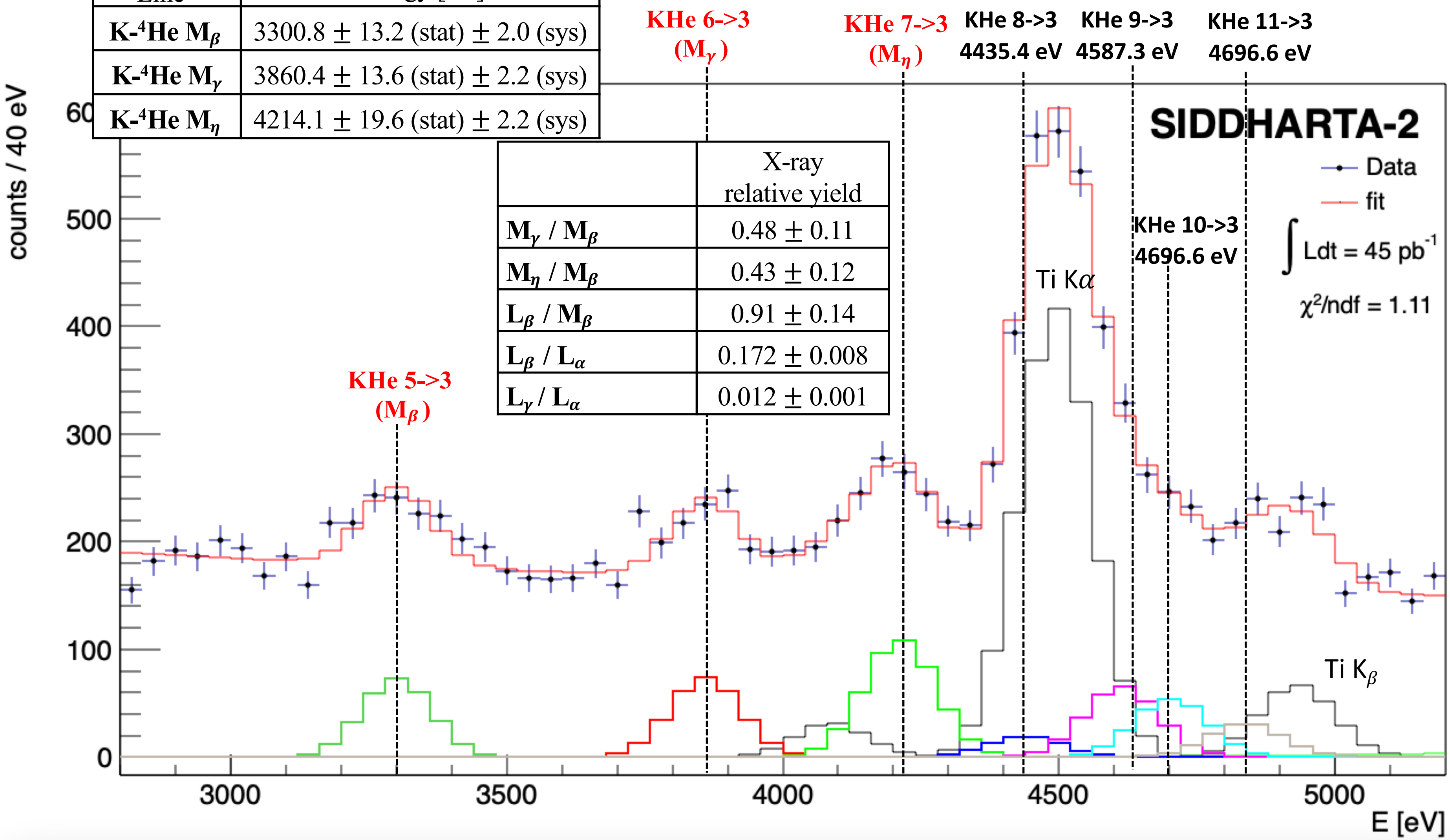


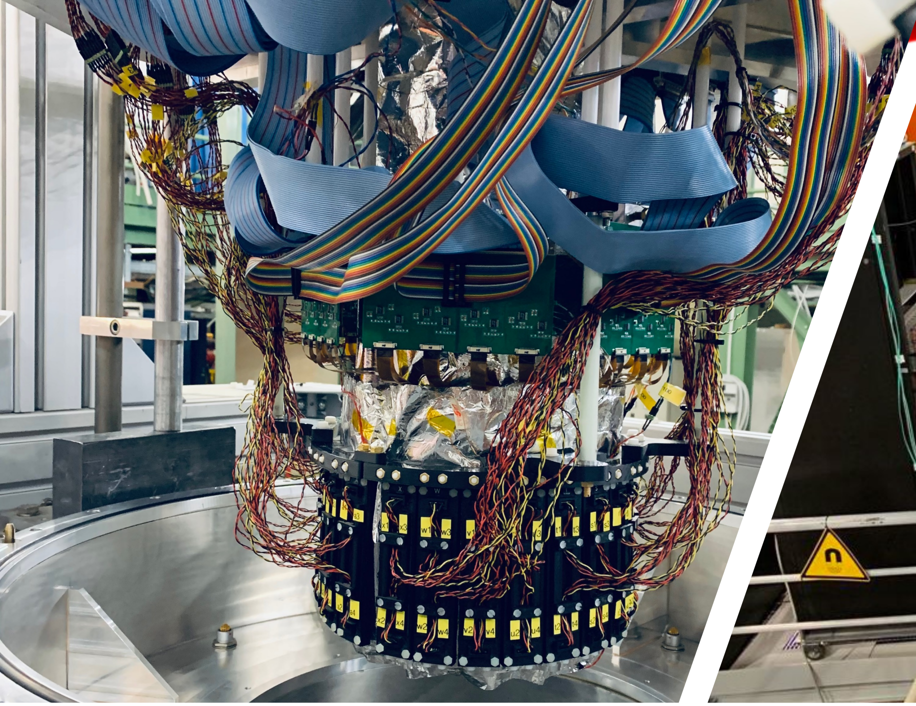
Sgaramella, F., *al. Eur. Phys. J. A* **59**, 56 (2023)

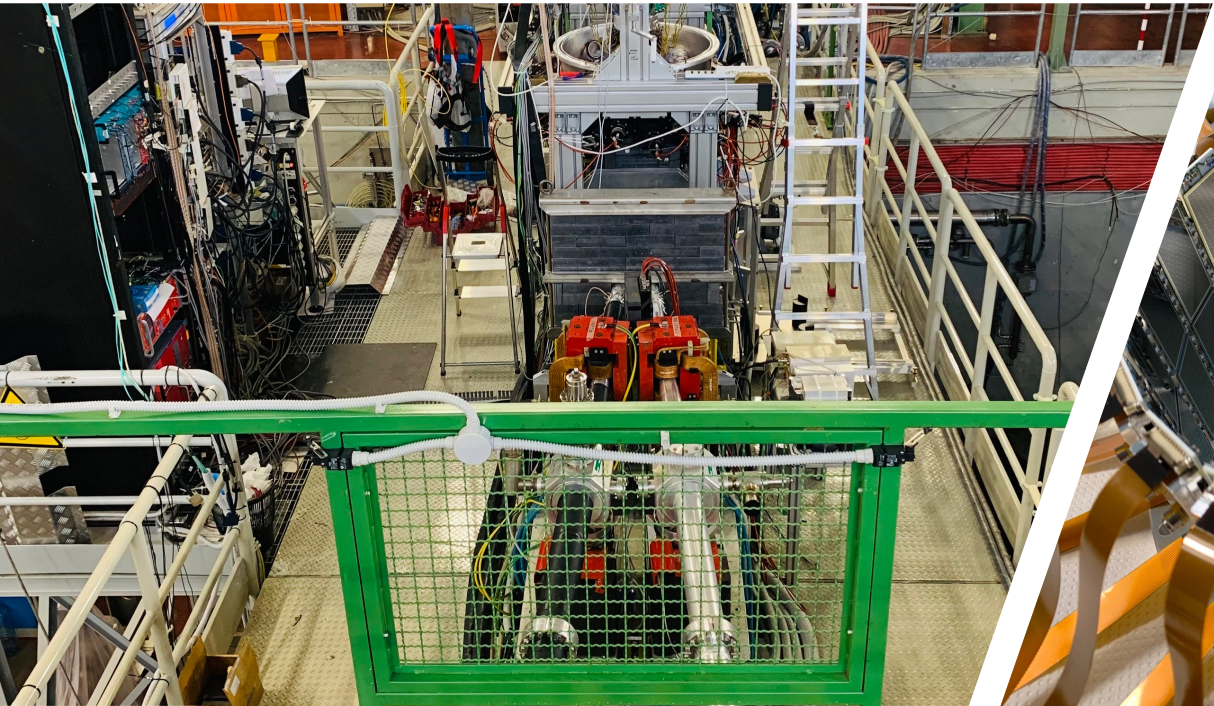
SIDDHARTA-2
Kaonic ^4He – M-type transitions

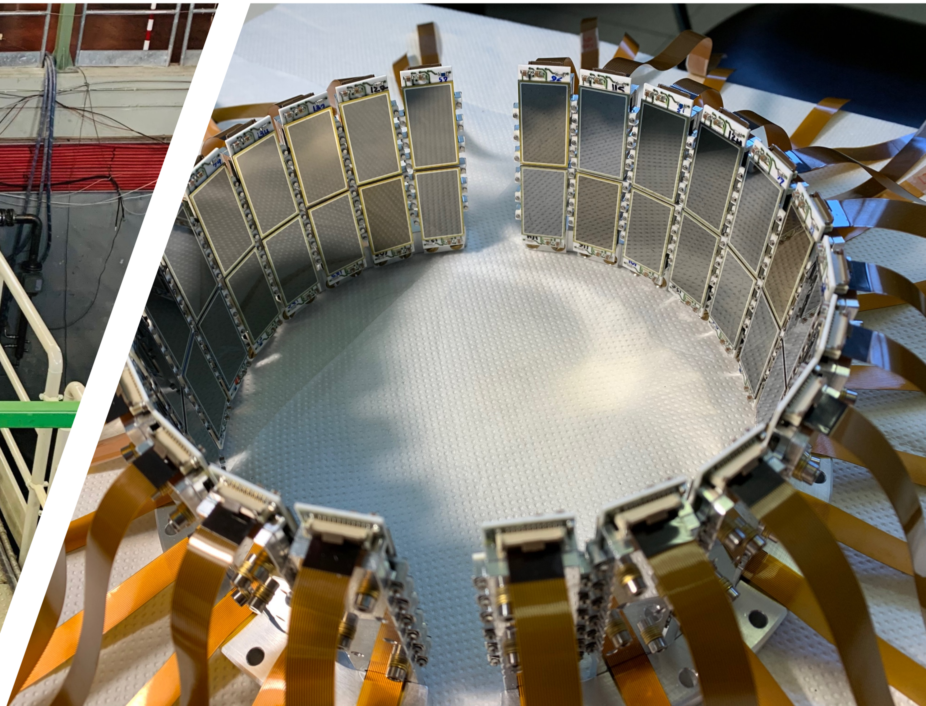
Line	Energy [eV]
K-^{4}He M_β	3300.8 ± 13.2 (stat) ± 2.0 (sys)
K-^{4}He M_γ	3860.4 ± 13.6 (stat) ± 2.2 (sys)
K-^{4}He M_η	4214.1 ± 19.6 (stat) ± 2.2 (sys)

	X-ray relative yield
M_γ / M_β	0.48 ± 0.11
M_η / M_β	0.43 ± 0.12
L_β / M_β	0.91 ± 0.14
L_β / L_α	0.172 ± 0.008
L_γ / L_α	0.012 ± 0.001

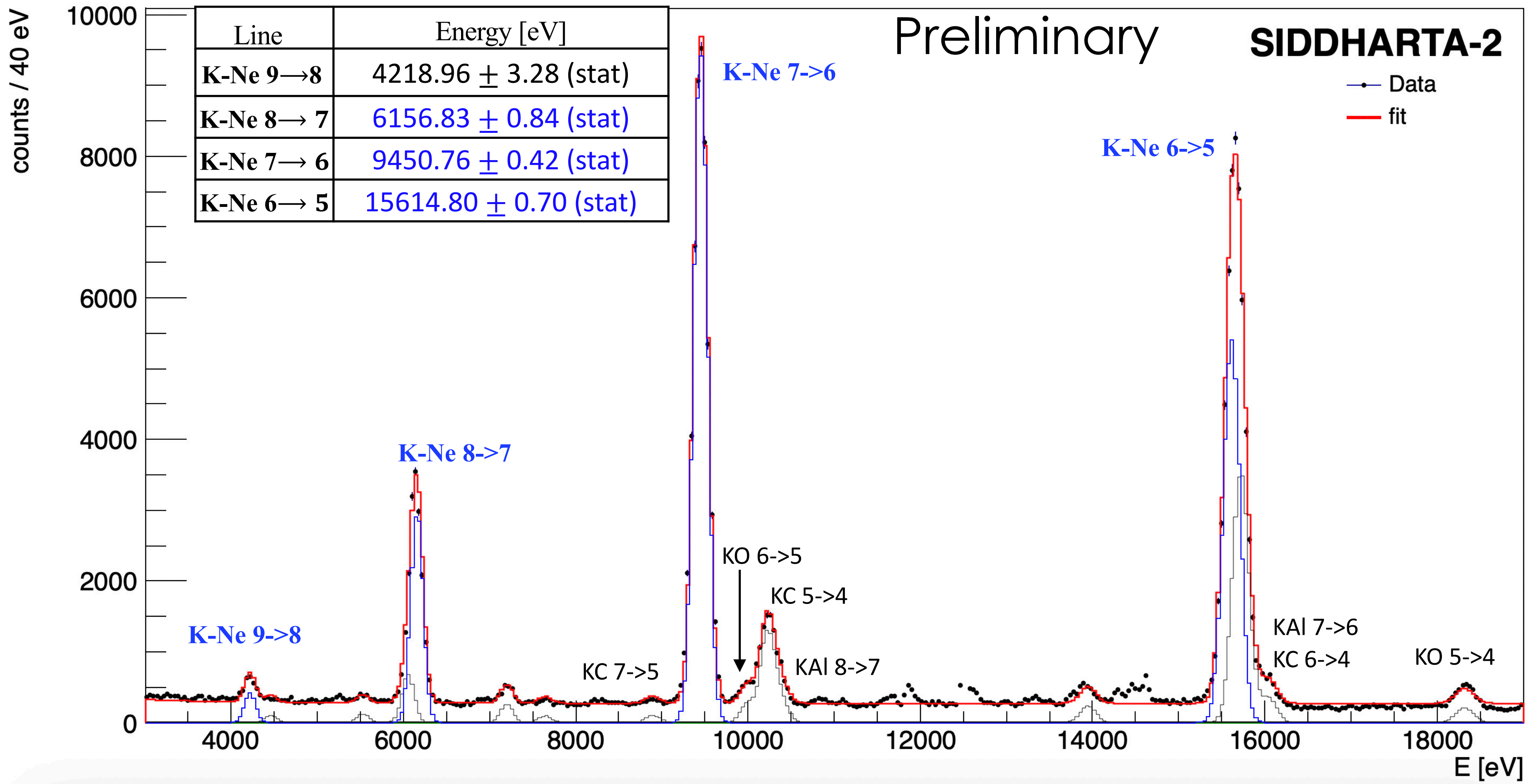








SIDDHARTA-2 Kaonic Neon (2023)

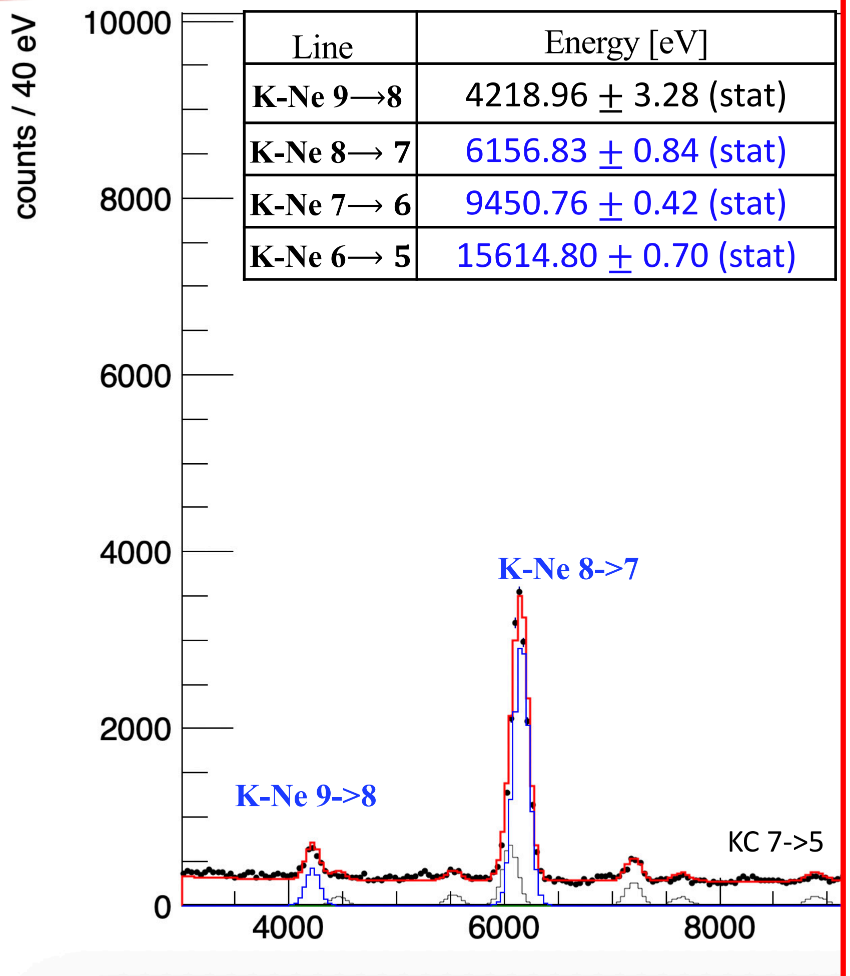


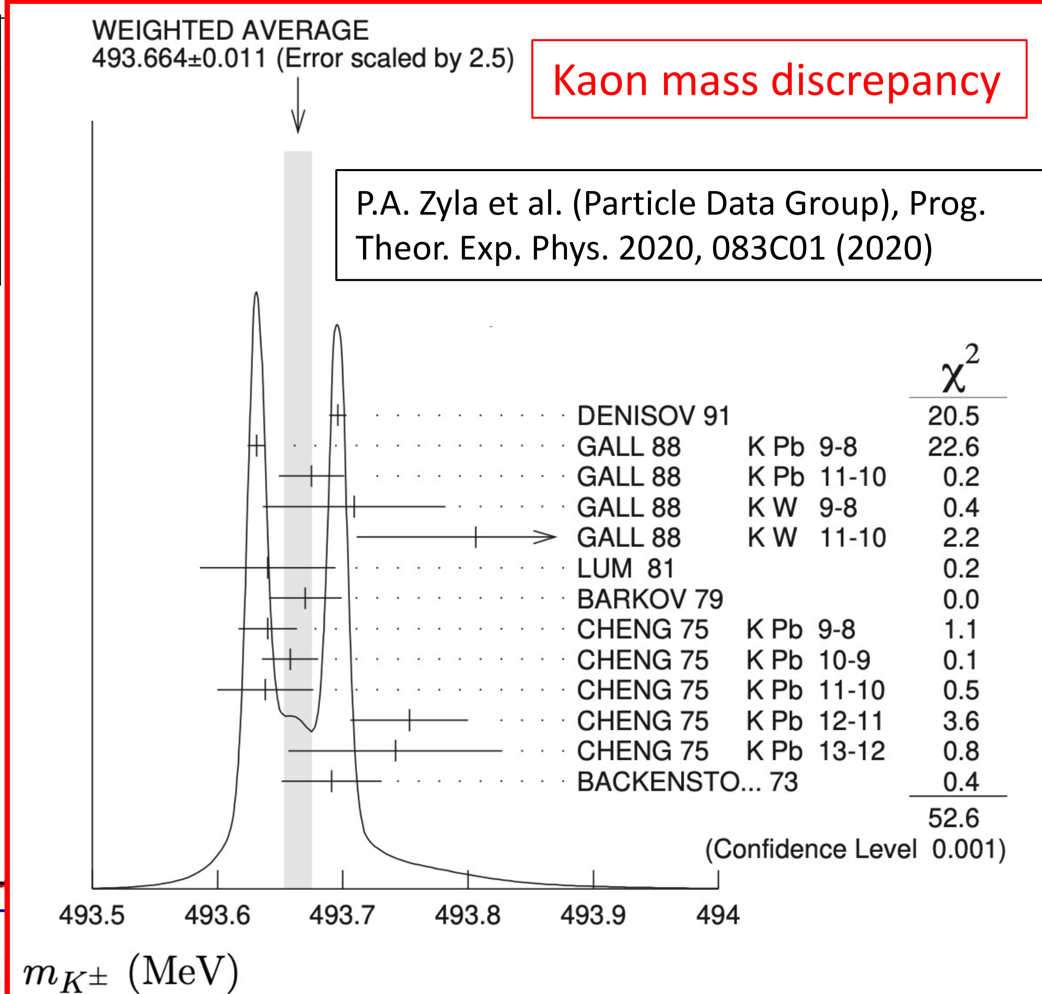
Line	Energy [eV]
K-Ne 9⟶8	4218.96 ± 3.28 (stat)
K-Ne 8⟶ 7	6156.83 ± 0.84 (stat)
K-Ne 7⟶ 6	9450.76 ± 0.42 (stat)
K-Ne 6⟶ 5	15614.80 ± 0.70 (stat)

First K-Ne measurements – possible implications on K- multinucleon interaction and kaon mass

SIDDHARTA-2
Kaonic Neon (2023)

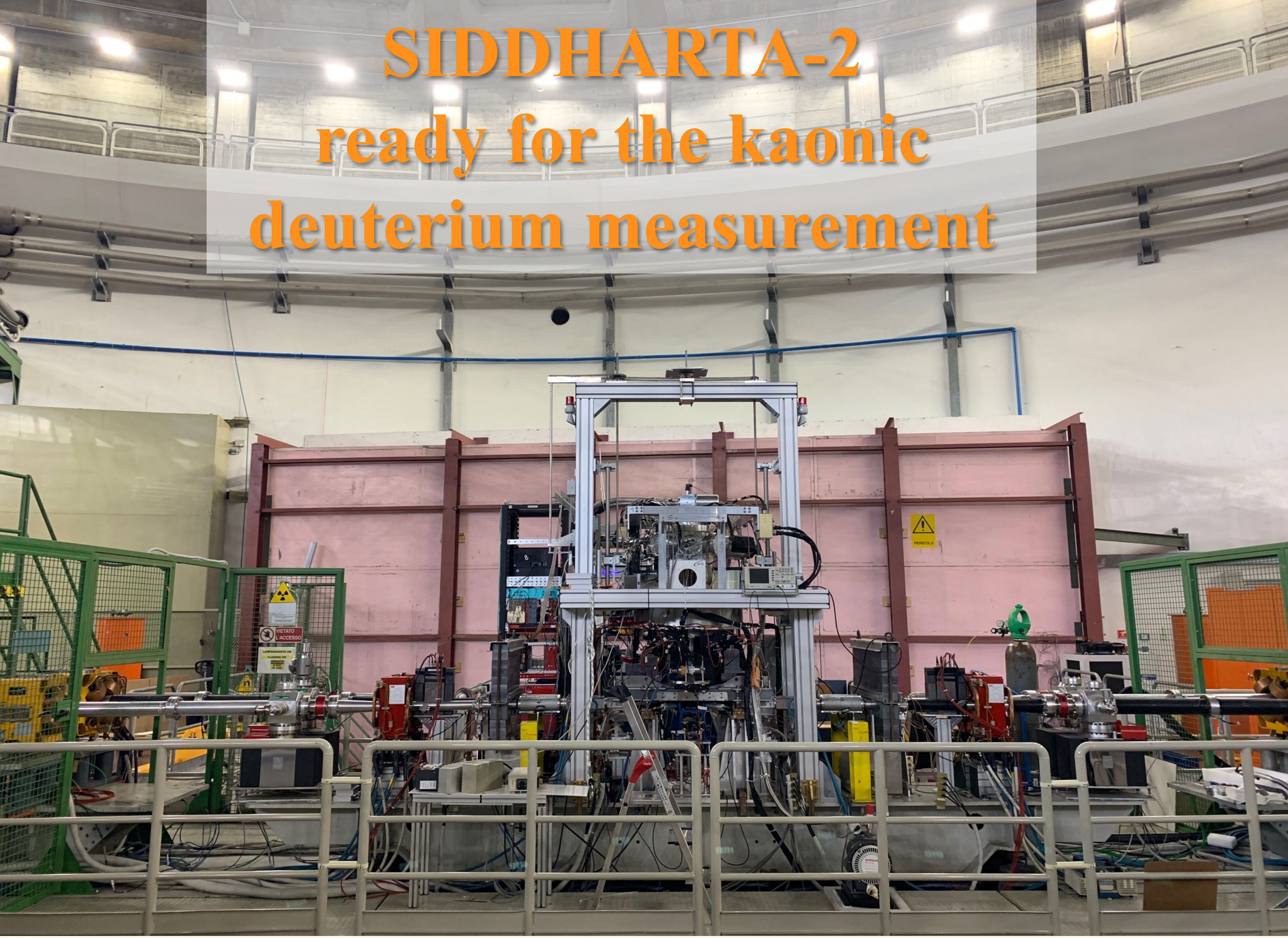
Line	Energy [eV]
K-Ne 9⟶8	4218.96 ± 3.28 (stat)
K-Ne 8⟶ 7	6156.83 ± 0.84 (stat)
K-Ne 7⟶ 6	9450.76 ± 0.42 (stat)
K-Ne 6⟶ 5	15614.80 ± 0.70 (stat)





First K-Ne measurements – possible implications on K- multinucleon interaction and kaon mass

SIDDHARTA-2 ready for the kaonic deuterium measurement



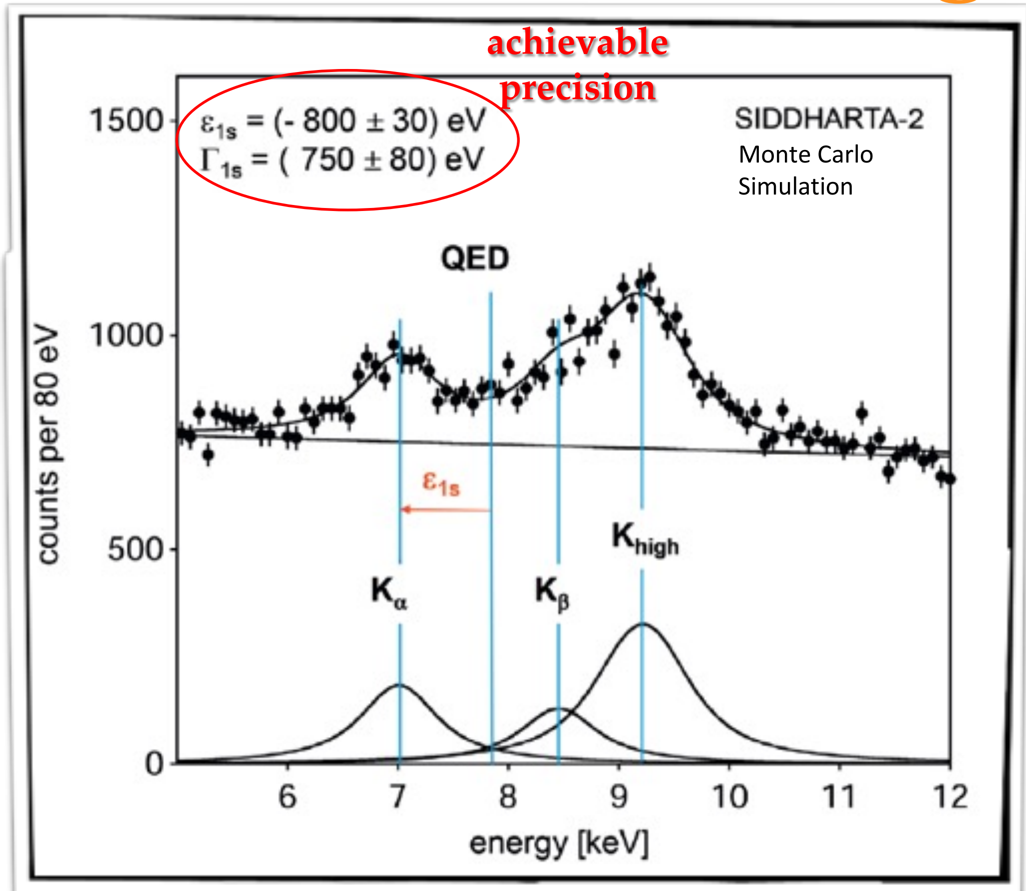
Kaonic deuterium data taking

Kaonic deuterium run ongoing

2023/24

Monte Carlo for an integrated luminosity of 800 pb^{-1}

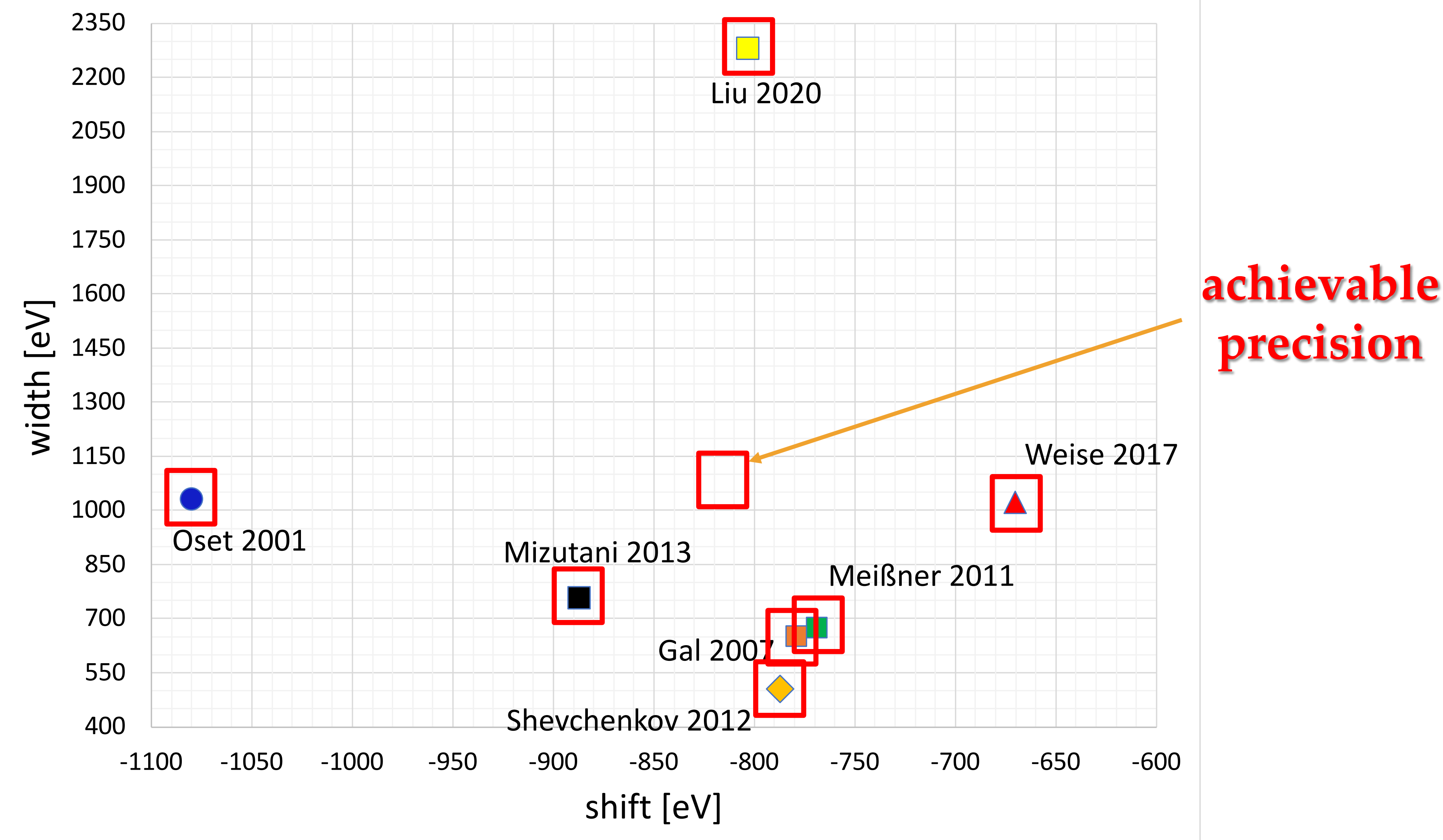
to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K-p) !



Significant impact in the theory of strong interaction with strangeness

Kaonic deuterium shift and width

Kaonic deuterium shift and width



Beyond SIDDHARTA-2: why still kaonic atoms?

Except for the most recent measurements at DAΦNE and JPARC on KHe and KH, the database on kaonic atoms dates back to 1970s and 1980s

These data are the experimental basis for all the developed theoretical models

These theoretical models are used to derive, for example:

- KN interaction at threshold
- KNN interaction at threshold
- Nuclear density distributions
- Possible existence of kaon condensates
- Kaon mass
- Kaonic atoms cascade models

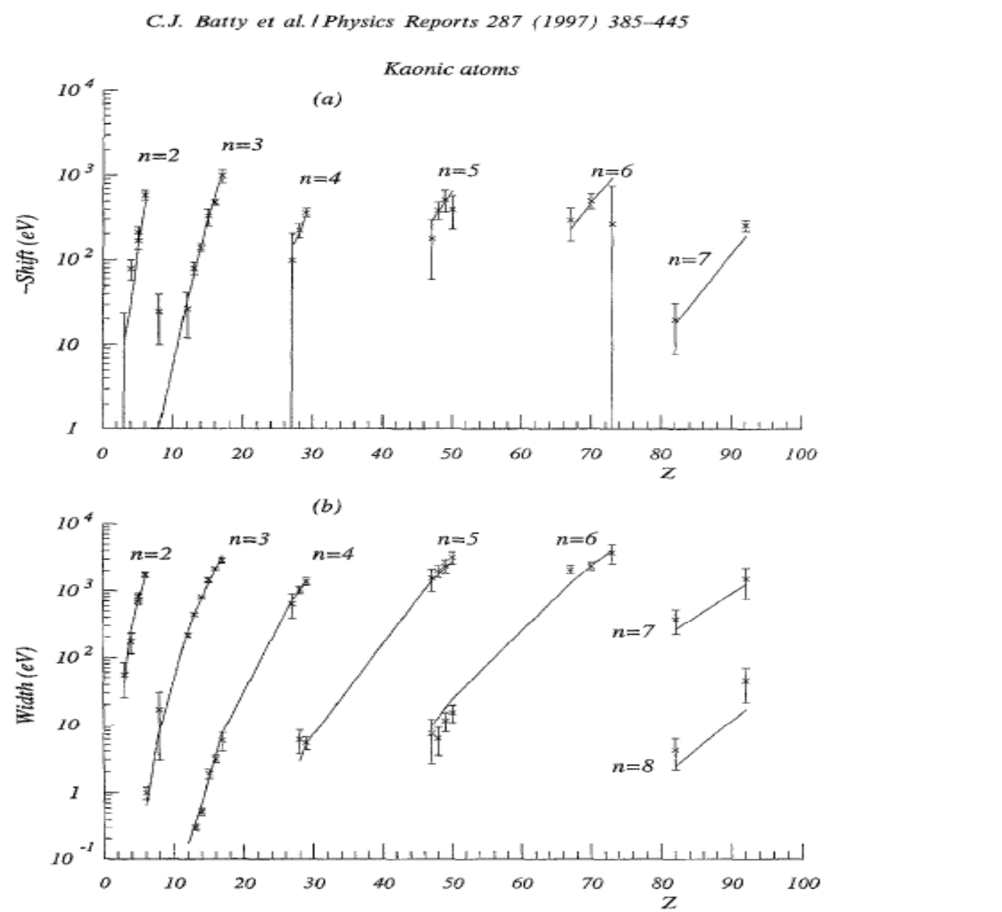


Fig. 7. Shift and width values for kaonic atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 4.2.

Beyond SIDDHARTA-2: why still kaonic atoms?

1. The available data on "lower levels" have big uncertainties
2. Many of them are actually UNmeasured
3. Many of them are hardly compatible among each other
4. Relative yields with upper levels are not always measured
5. Absolute yields are basically unknown (except for few transitions)
6. The REmeasured ones have been proved WRONG

This situation would already be a proper justification for new measurements

E. Friedman et al. / Nuclear Physics A579 (1994) 518–538 521

Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	$3 \to 2$	-0.04 ± 0.03	–	–	–	[15]
		-0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	$3 \to 2$	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	$3 \to 2$	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	$3 \to 2$	-0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	$3 \to 2$	-0.167 ± 0.035	0.700 ± 0.080	–	–	[18]
C	$3 \to 2$	-0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20	[18]
O	$4 \to 3$	-0.025 ± 0.018	0.017 ± 0.014	–	–	[19]
Mg	$4 \to 3$	-0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03	[19]
Al	$4 \to 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–	[20]
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04	[19]
Si	$4 \to 3$	-0.240 ± 0.050	0.810 ± 0.120	–	–	[20]
		-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06	[19]
P	$4 \to 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30	[18]
S	$4 \to 3$	-0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36	[18]
		-0.43 ± 0.12	2.310 ± 0.170	–	–	[21]
		-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5	[19]
Cl	$4 \to 3$	-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7	[18]
		-0.94 ± 0.40	3.92 ± 0.99	–	–	[22]
		-1.08 ± 0.22	2.79 ± 0.25	–	–	[21]
Co	$5 \to 4$	-0.099 ± 0.106	0.64 ± 0.25	–	–	[19]
Ni	$5 \to 4$	-0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3	[20]
		-0.246 ± 0.052	1.23 ± 0.14	–	–	[19]
Cu	$5 \to 4$	-0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8	[20]
		-0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1	[19]
Ag	$6 \to 5$	-0.18 ± 0.12	1.54 ± 0.58	0.51 ± 0.16	7.3 ± 4.7	[19]
Cd	$6 \to 5$	-0.40 ± 0.10	2.01 ± 0.44	0.57 ± 0.11	6.2 ± 2.8	[19]
In	$6 \to 5$	-0.53 ± 0.15	2.38 ± 0.57	0.44 ± 0.08	11.4 ± 3.7	[19]
Sn	$6 \to 5$	-0.41 ± 0.18	3.18 ± 0.64	0.39 ± 0.07	15.1 ± 4.4	[19]
Ho	$7 \to 6$	-0.30 ± 0.13	2.14 ± 0.31	–	–	[23]
Yb	$7 \to 6$	-0.12 ± 0.10	2.39 ± 0.30	–	–	[23]
Ta	$7 \to 6$	-0.27 ± 0.50	3.76 ± 1.15	–	–	[23]
Pb	$8 \to 7$	–	0.37 ± 0.15	0.79 ± 0.08	4.1 ± 2.0	[24]
		-0.020 ± 0.012	–	–	–	[25]
U	$8 \to 7$	-0.26 ± 0.4	1.50 ± 0.75	0.35 ± 0.12	45 ± 24	[24]

Beyond SIDDHARTA-2: EXKALIBUR

proposal to perform fundamental physics at the strangeness frontier at DAFNE for a 3-years period (post-SIDDHARTA-2)

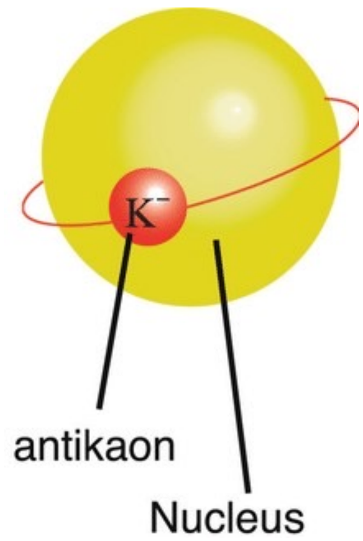
We propose to do precision measurements along the periodic table at DAFNE for:

- **Kaonic Hydrogen: 200 pb^{-1} – with SIDDHARTA-2 setup – to get a precision < 10 eV (KH)**
- **Selected light kaonic atoms (LHKA)**
- **Selected intermediate and heavy kaonic atoms charting the periodic table (IMKA)**
- **Ultra-High precision measurements of Kaonic Atoms (UHKA)**

Dedicated runs with different types of detectors: CZT detectors, HpGe, SDD 1mm, crystal HAPG spectrometer from VOXES project

Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements,
C. Curceanu et al., e-Print: 2104.06076

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

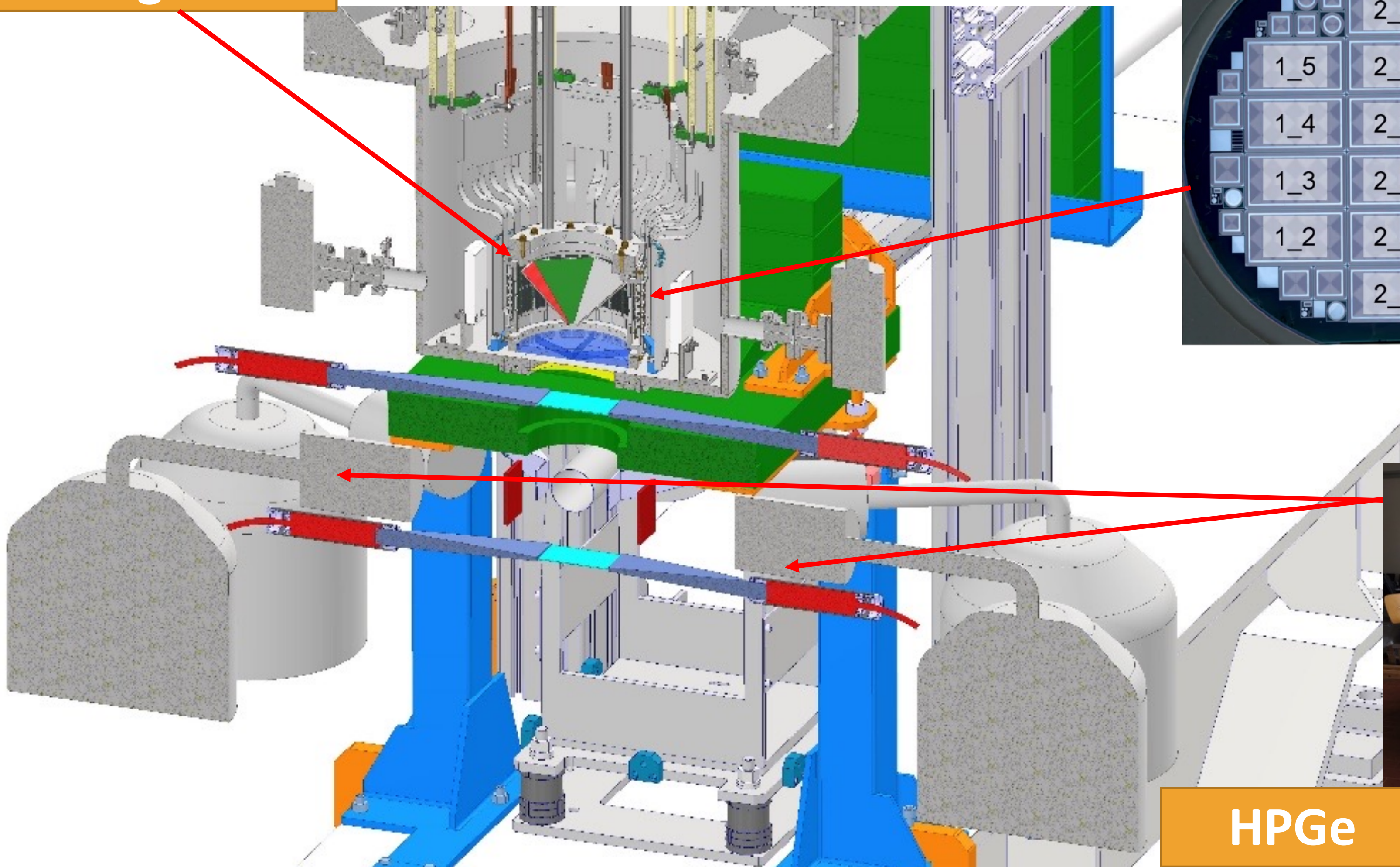


EXKALIBUR

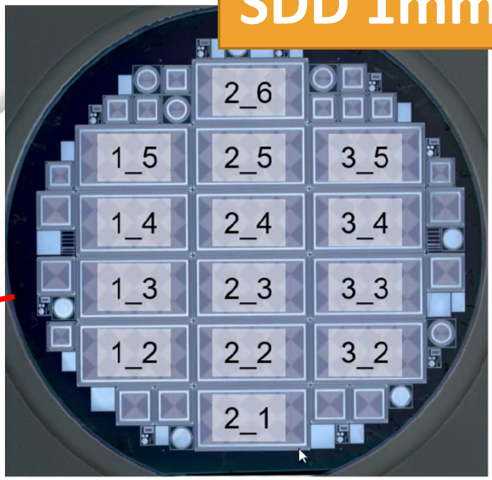
➢ **Various setups in preparation:**

- *HPGe*
- *CdZnTe detectors*
- *SDD 1mm for kaonic atoms measurement*

Li, Be, B targets

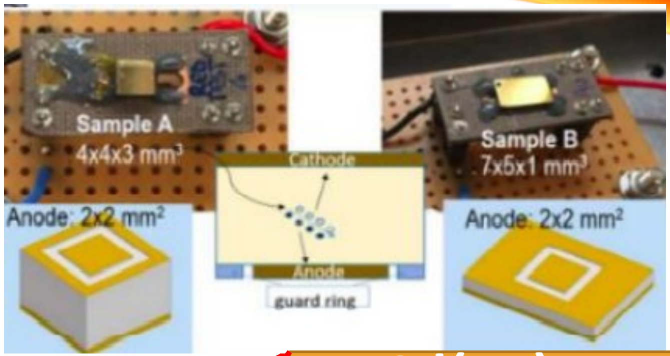


SDD 1mm

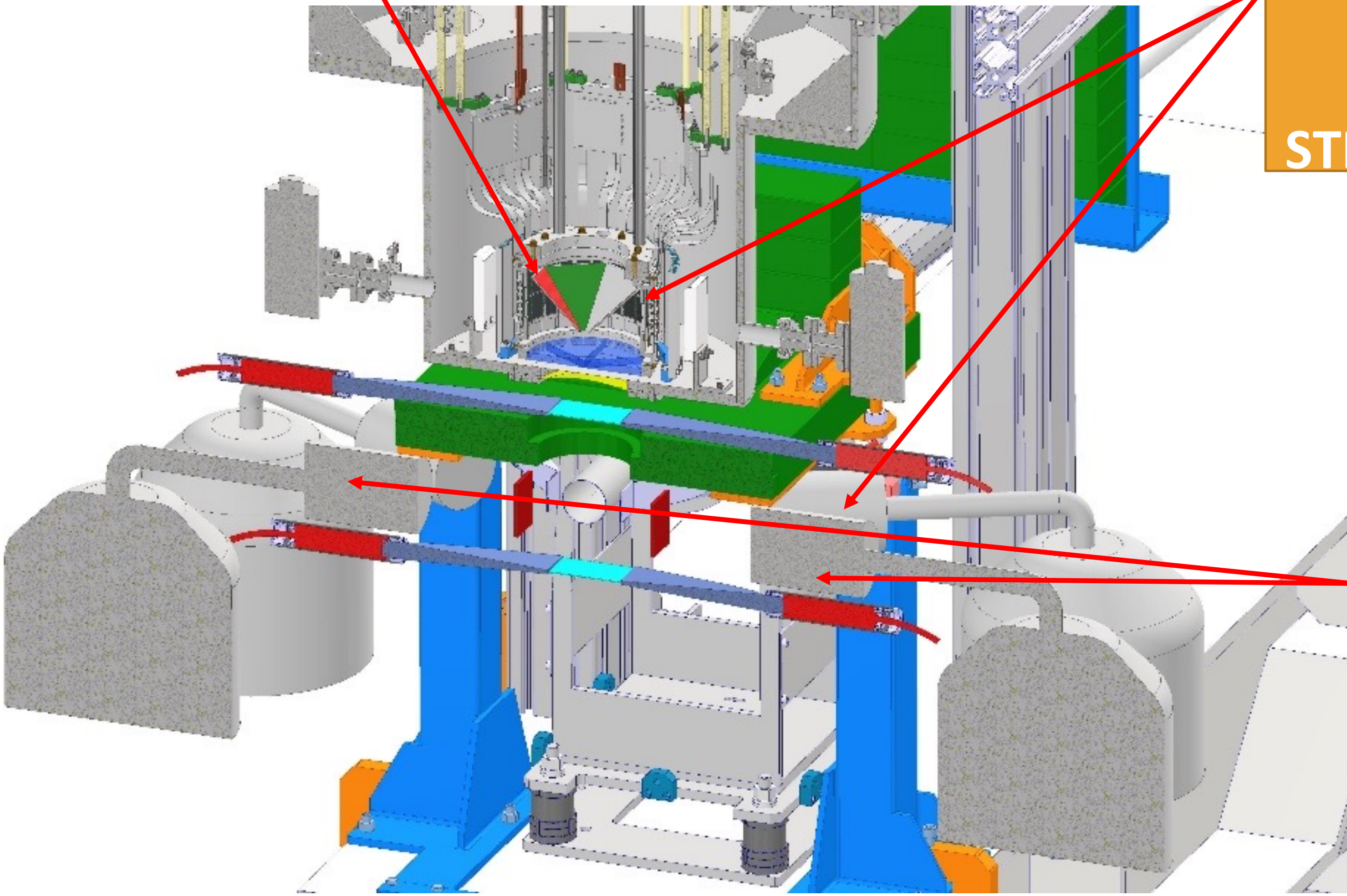


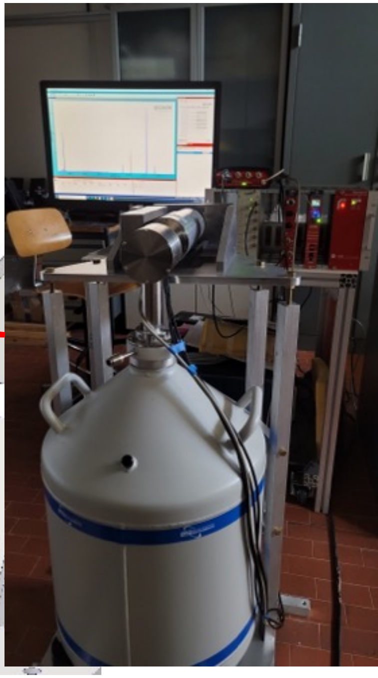
HPGe

Ti, C, Zr, Ag targets



Cd(Zn)Te
ASTRA
STRONG-2020





Conclusions

- **Kaonic Atoms are a unique tool to study the kaon-nucleon interaction**
  - Tool to directly probe low energy QCD
  - Rich of implications from nuclear and particle physics to astrophysics

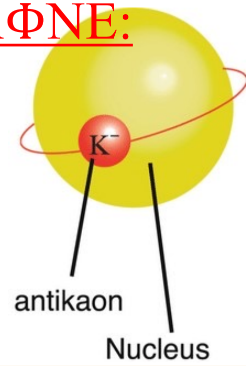
- **Measurement of Kaonic-Deuterium key to fully disentangle isospin dependence on KN scattering lengths**

- **SIDDHARTA-2 at DAFNE**
  - ✓ **Kaonic ^{4}He $3d \rightarrow 2p$ sub eV (stat) precision measurement**
    - Energy shift and width
    - Yield at two different density 1.9 g/l and 0.82 g/l
  - ✓ **Several solid target high-n transition energies measured for the first time**
  - ✓ **First kaonic Neon measurement -> implications on kaon mass**

we plan to perform fundamental Physics at the strangeness frontier at DAΦNE:

High Precision Kaonic Atoms Measurements on DAΦNE:

EXKALIBUR



Thank You