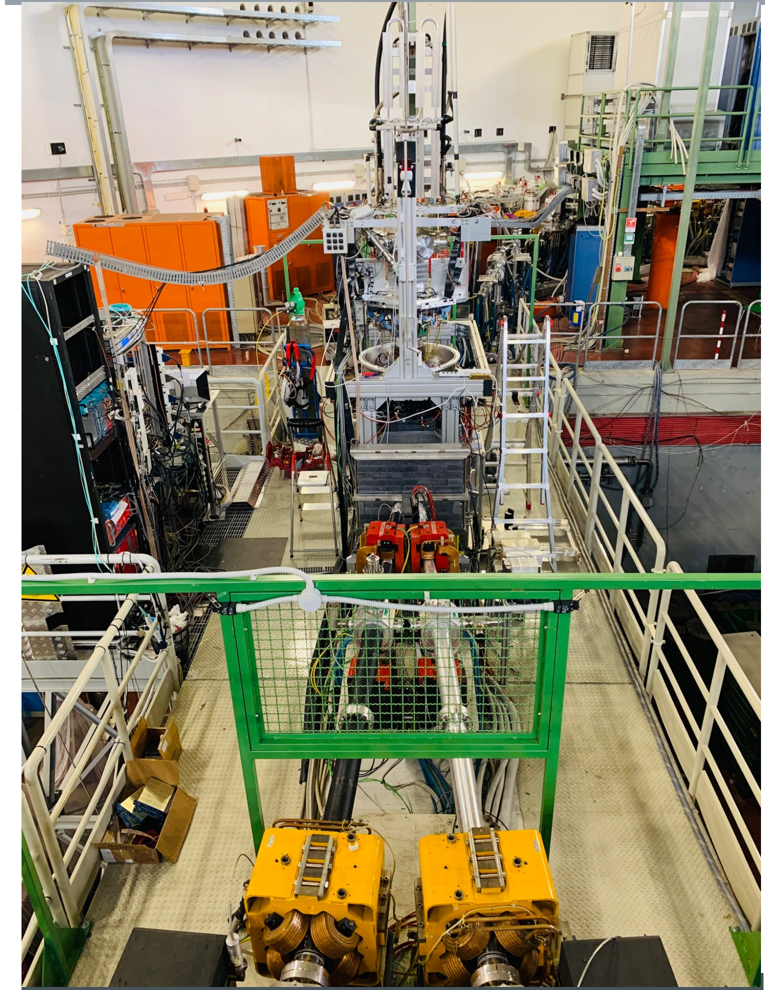
Symposium on new trends in Nuclear and Medical Physics

October 18 – 20, 2023

“ KAONIC ATOM AT DAFNE COLLIDER IN ITALY: A STRANGENESS ODYSSEY ”

Francesco Sgaramella

on behalf of the SIDDHARTA-2 collaboration



INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

SIDDHARTA-2 COLLABORATION

Silicon **D**rift **D**etectors for **H**adronic **A**tom **R**esearch 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

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Laboratori Nazionali di Frascati

HadronPhysics2
Study of Strongly Interacting Matter

STRONG-2020

HadronPhysics I3
Study of Strongly Interacting Matter

HRZZ
Croatian Science Foundation

FWF Der Wissenschaftsfonds.

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

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

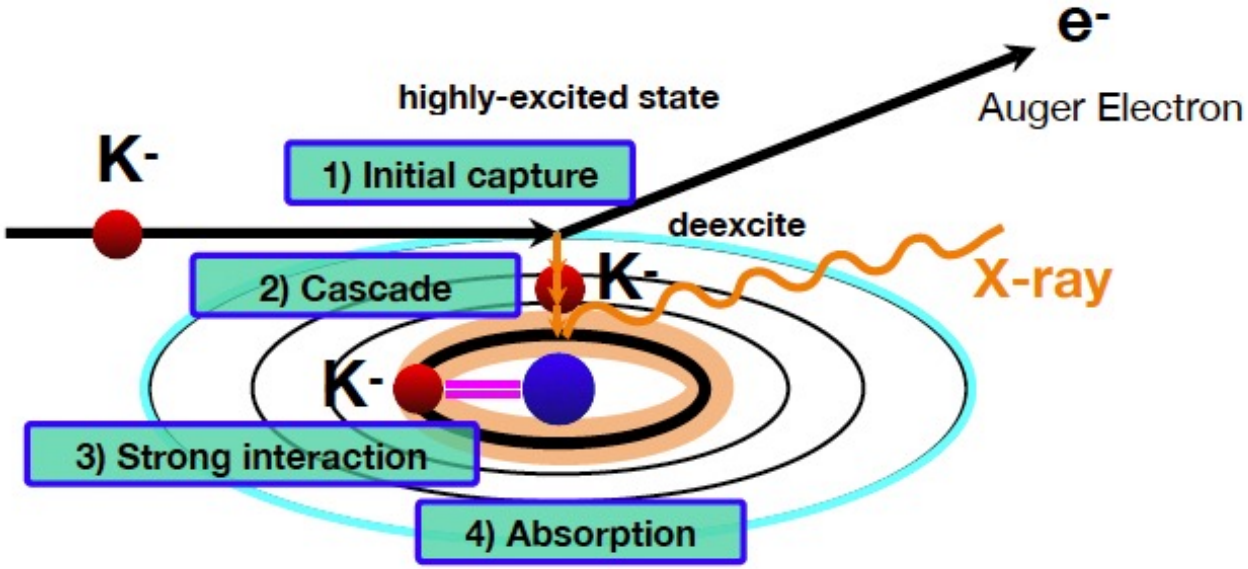
Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

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

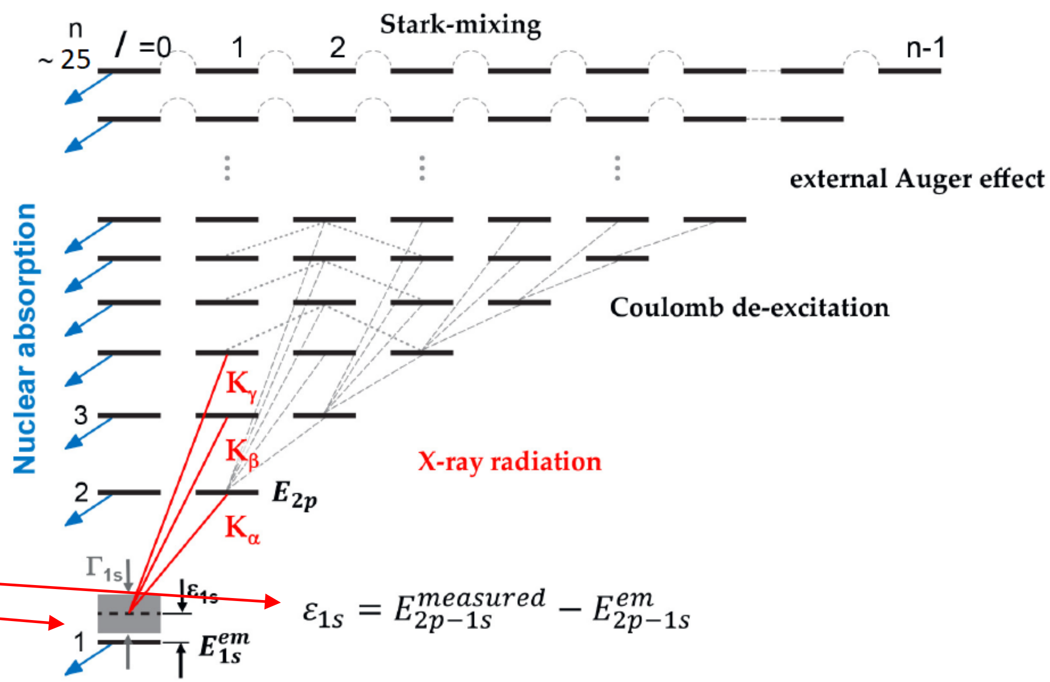
Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

Astrophysics
EOS Neutron Stars

Kaonic Atom



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



Scientific Goal

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.

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)

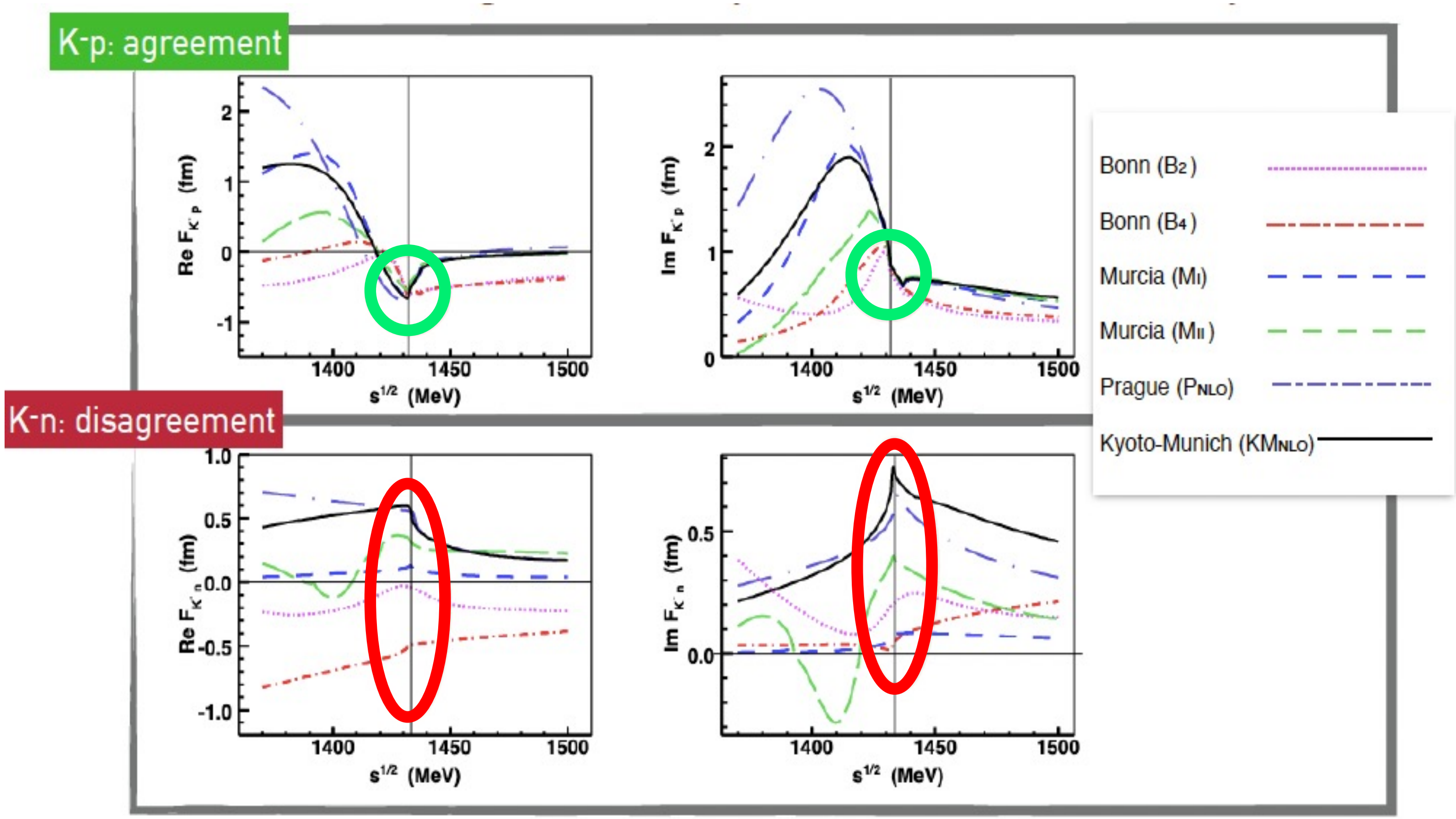
U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

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

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

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

Kaon-nucleon scattering length



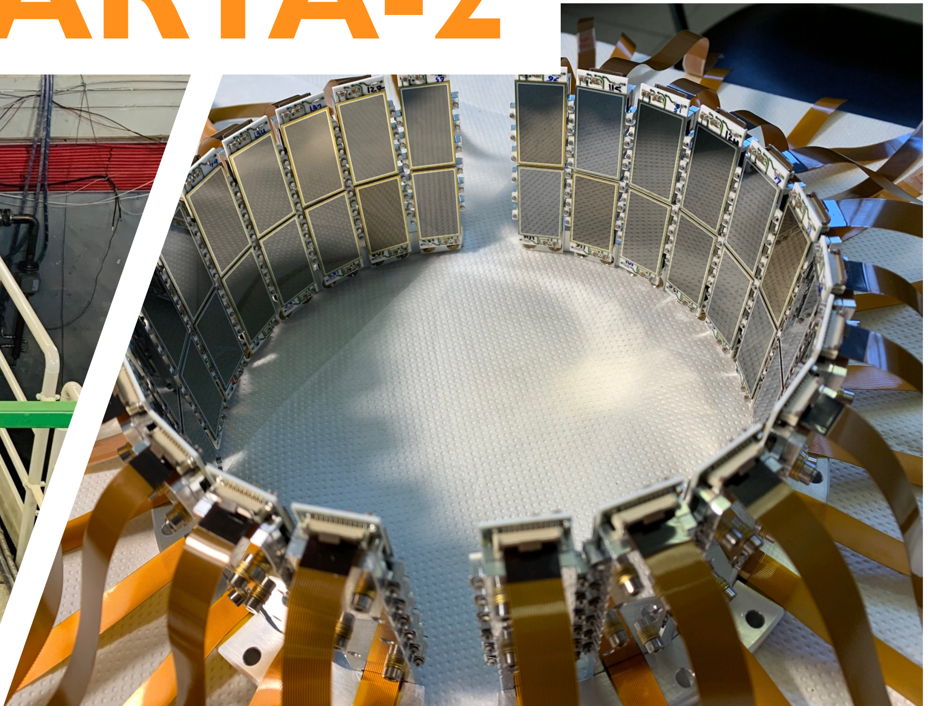
A. Ciepլý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

DAΦNE – e^+e^- collider

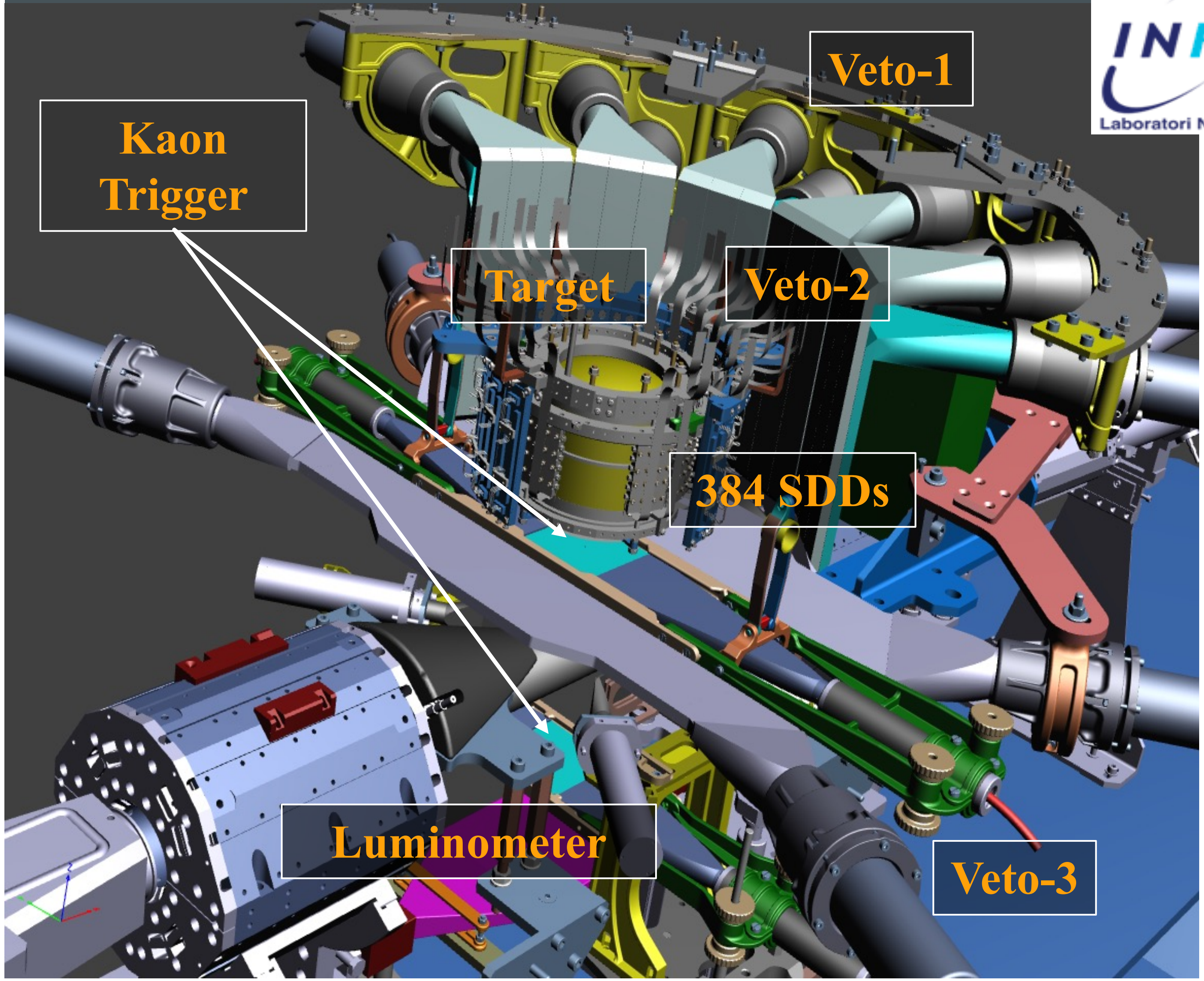
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)
- Less hadronic background compared to hadron beam line

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

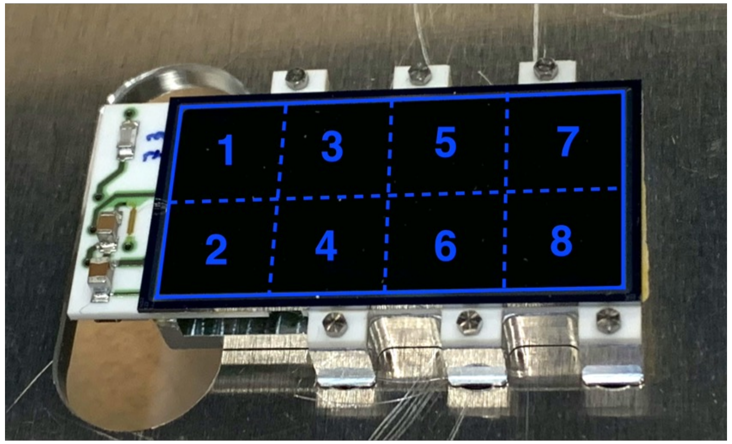
SIDDHARTA-2



The SIDDHARTA-2 setup and DAΦNE collider

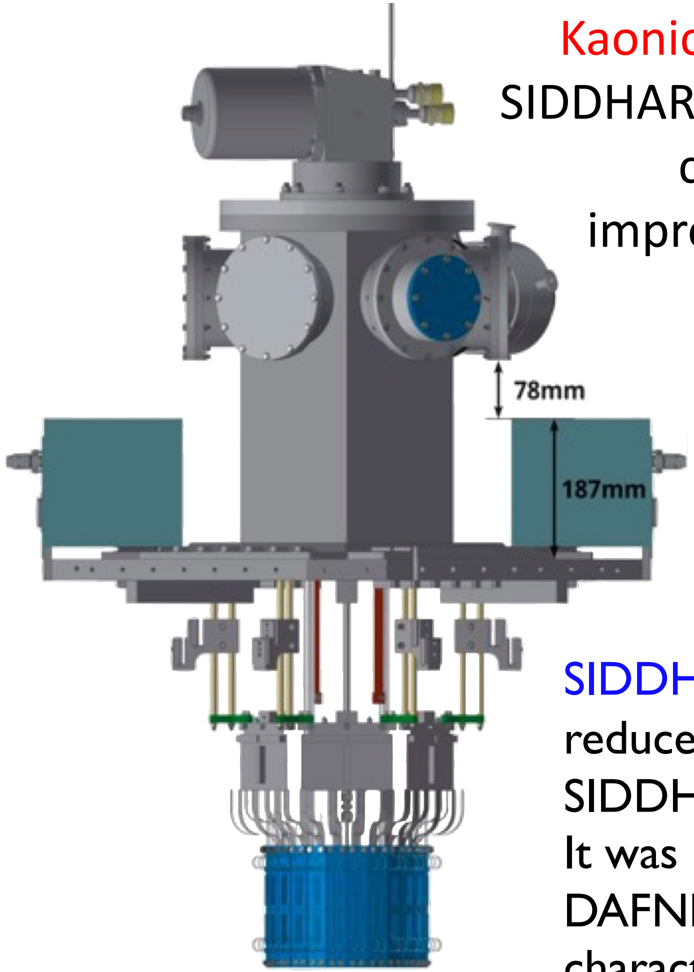


48 Silicon Drift Detector arrays with 8 SDD units (0.64 cm^2) for a total active area of 246 cm^2
The thickness of 450 μm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV



SIDDHARTINO - The kaonic ^{4}He 3d->2p measurement

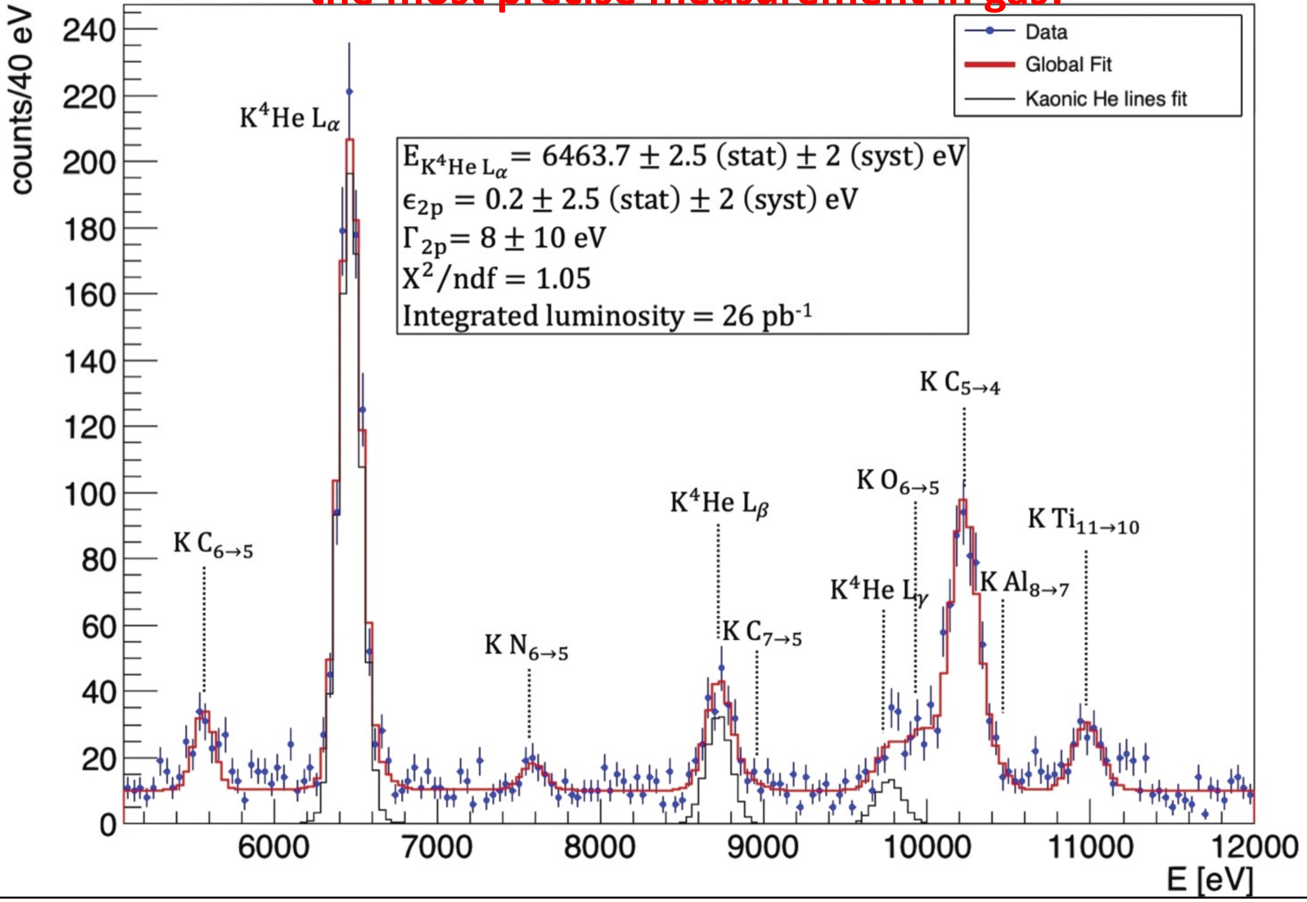
Characterization of the SIDDAHRTA-2 apparatus and optimization of DAΦNE background through the kaonic helium measurement



Kaonic Helium puzzle:
SIDDHARTA and KEK results confirmed,
improving accuracy

SIDDHARTINO:
reduced version of the SIDDHARTA-2 apparatus
It was used to optimize the DAFNE background and characterize the SDDs

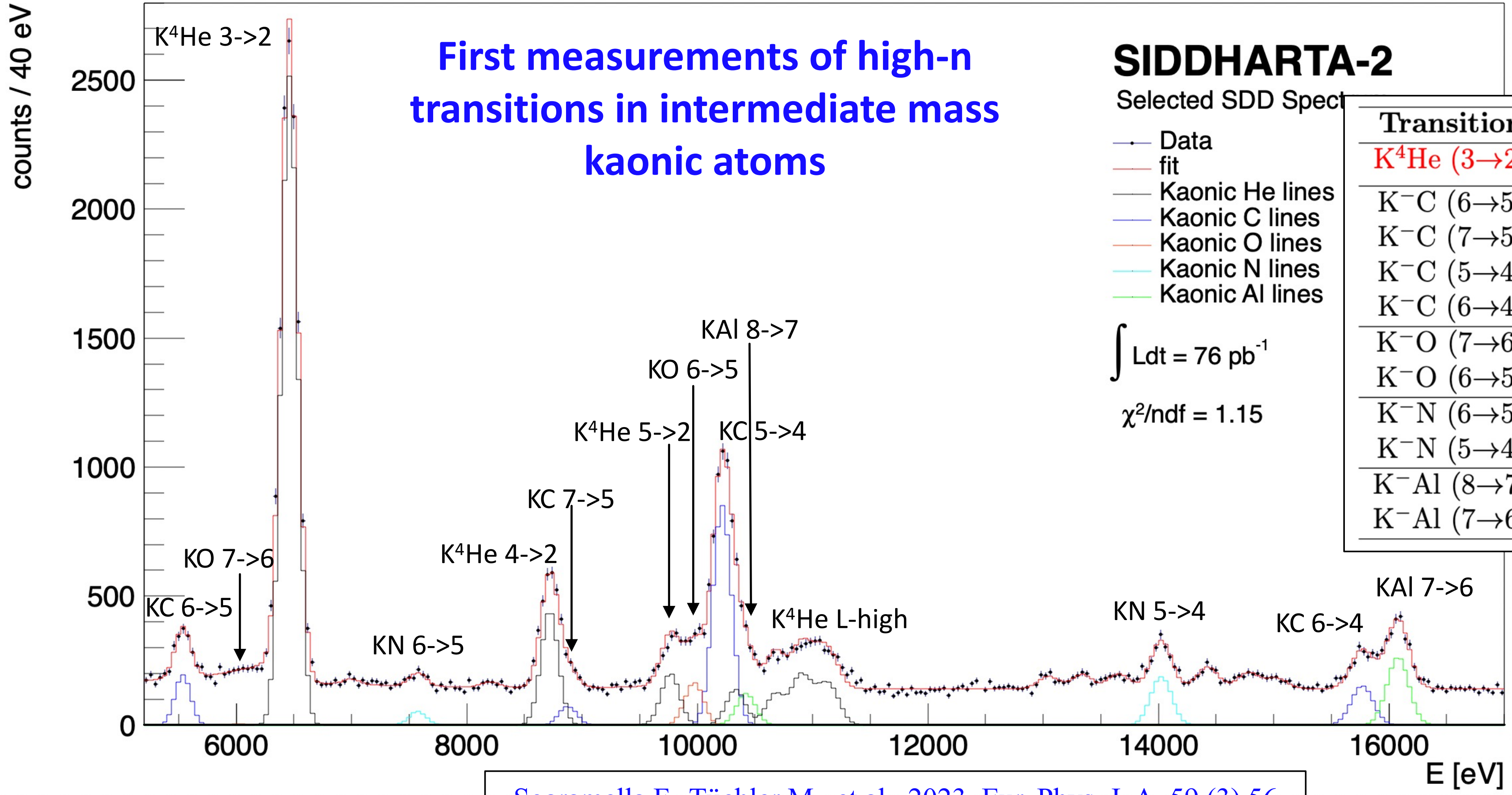
K-^{4}He 3d->2p shift and width:
the most precise measurement in gas!



Sirghi D., Sirghi F., Sgaramella F., et al., 2022, J. Phys. G Nucl. Part. Phys., 49 (5) 55106

The Kaonic ^{4}He measurement

- Kaonic He measurement with the full SIDDHARTA-2 setup
- Improved accuracy on the Lα energy shift width
- Measurement of kaonic carbon – nitrogen – oxygen and aluminium

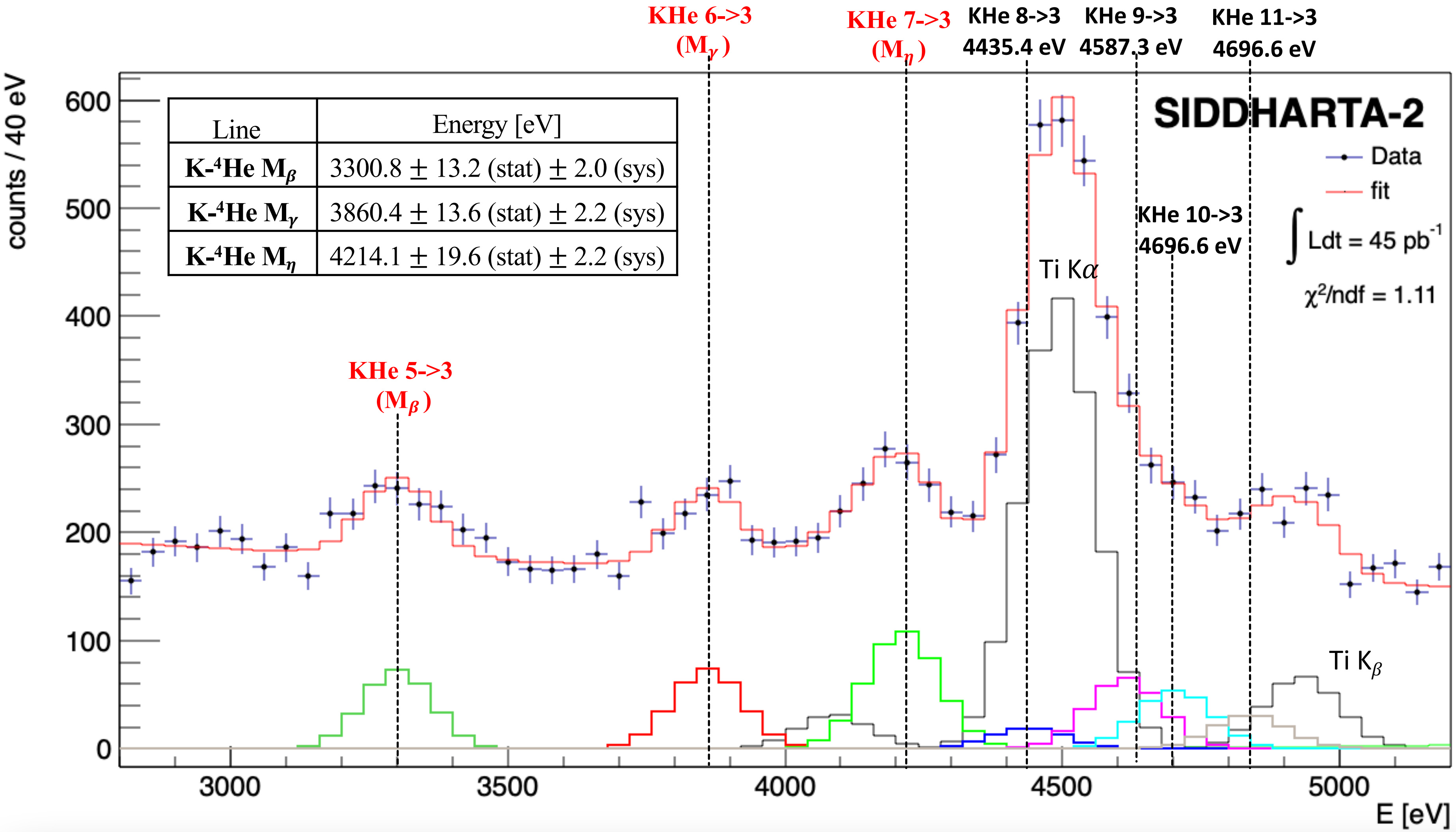


Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 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., 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 ± 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)

The Kaonic ^{4}He yield

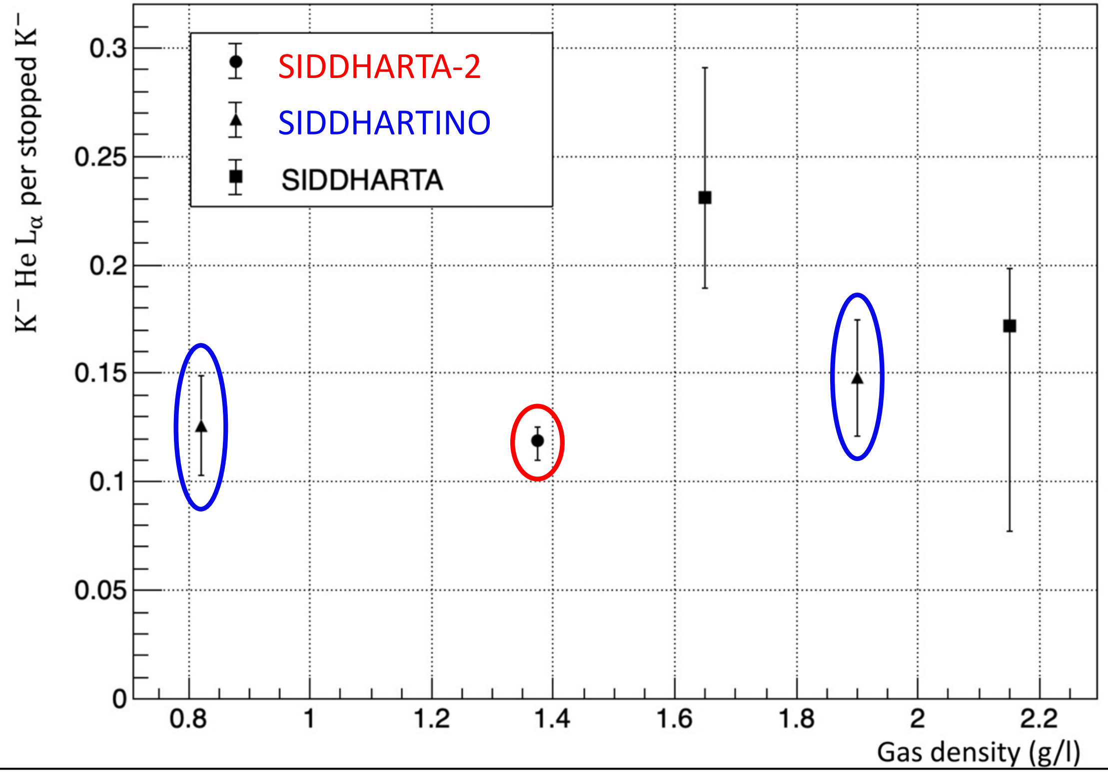
New experimental data for cascade models calculations
The X-ray yield is the key observable to understand the de-excitation mechanism in kaonic atoms and develop more accurate models.

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

Density	1.375 g/l
L_α *yield*	$0.119 \pm 0.002\,(\text{stat})^{+0.006\,(\text{sys})}_{-0.009\,(\text{sys})}$
M_β *yield*	$0.026 \pm 0.003\,(\text{stat})^{+0.010\,(\text{sys})}_{-0.001\,(\text{sys})}$
L_β / L_α	$0.172 \pm 0.008\,(\text{stat})$
L_γ / L_α	$0.012 \pm 0.001\,(\text{stat})$
L_β / M_β	$0.91 \pm 0.14\,(\text{stat})$
M_γ / M_β	$0.48 \pm 0.11\,(\text{stat})$
M_δ / M_β	$0.43 \pm 0.12\,(\text{stat})$

Sgaramella F., et al, submitted to J. Phys. G Nucl. Part. Phys

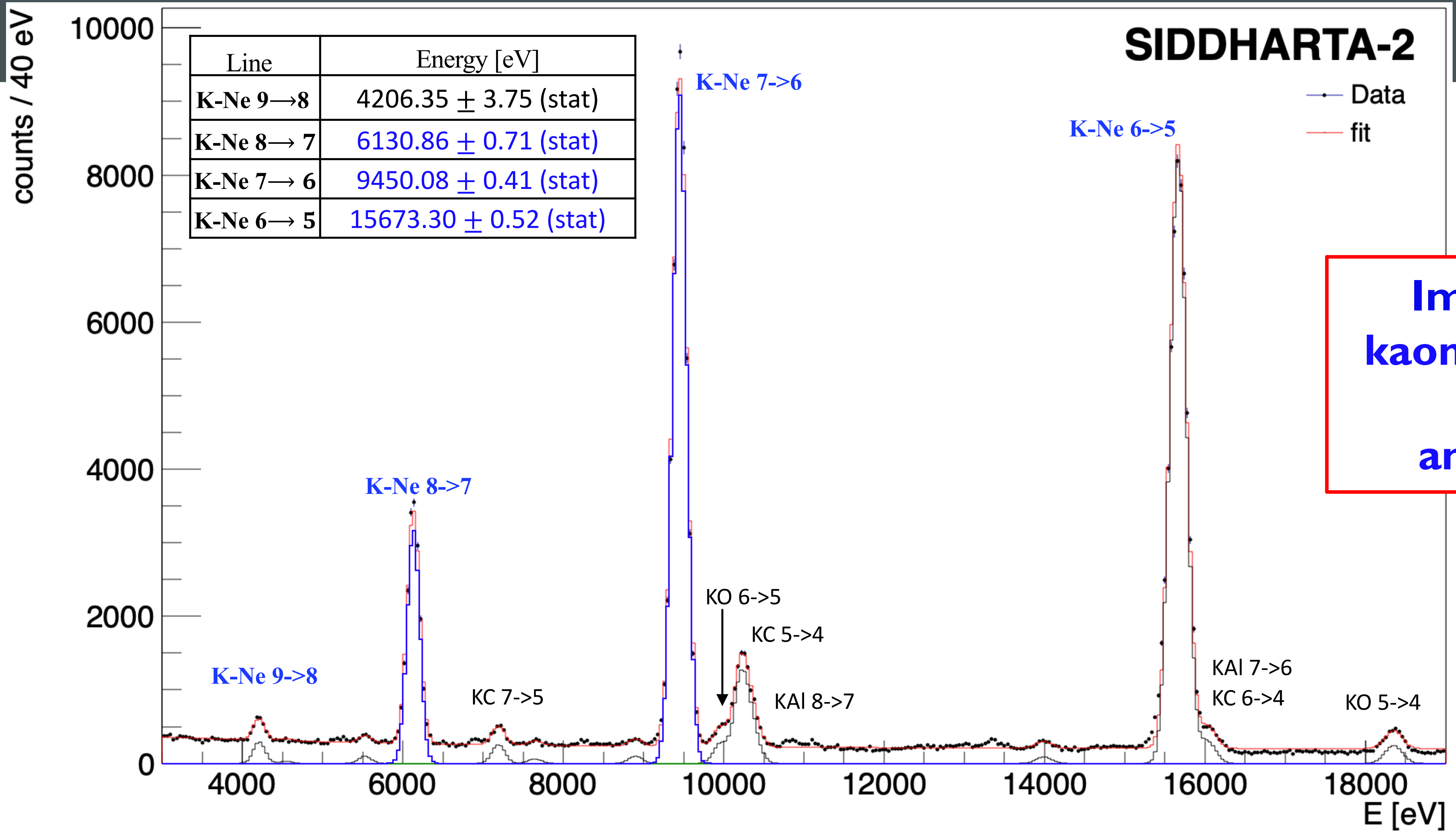
Study of yield density dependence for the K-^{4}He Lα transition



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

The Kaonic Neon measurement

First measurement of kaonic neon X-ray transitions (record of precision < 1 eV)



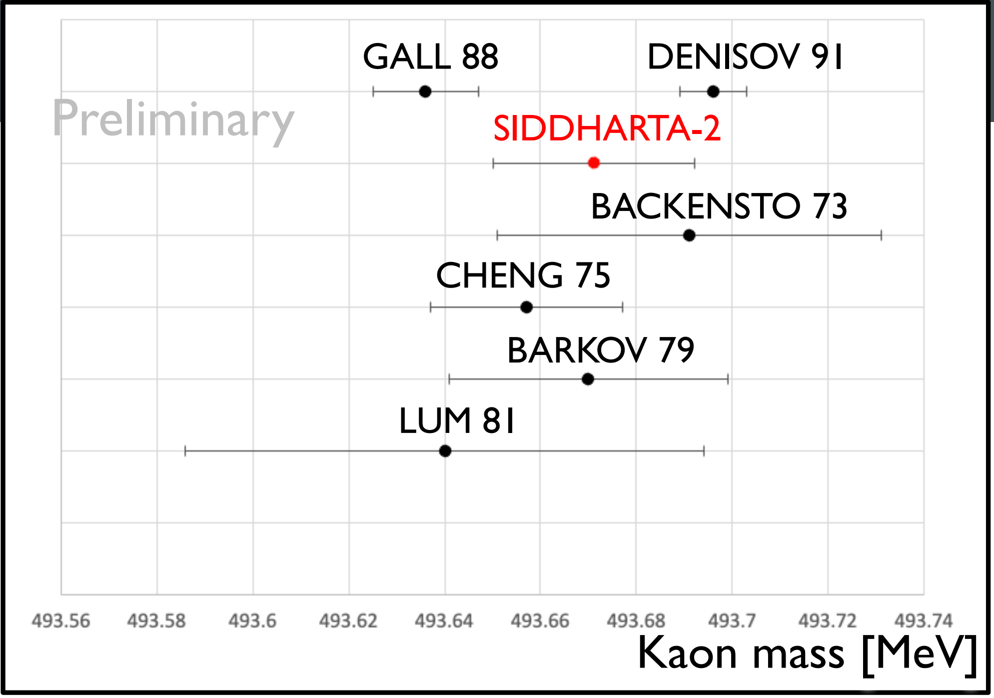
Line	Energy [eV]
K-Ne 9⟶8	4206.35 ± 3.75 (stat)
K-Ne 8⟶ 7	6130.86 ± 0.71 (stat)
K-Ne 7⟶ 6	9450.08 ± 0.41 (stat)
K-Ne 6⟶ 5	15673.30 ± 0.52 (stat)

Implications on kaon - multinucleon interaction and kaon mass

The (charged) Kaon mass puzzle

Kaon mass (K-Ne 8 ⟶ 7and K-Ne 7 ⟶ 6) = 493.671 ± 0.021 (stat) MeV

(stat. error ~ 15 keV including the K-Ne 6 ⟶ 5)



Kaon mass discrepancy

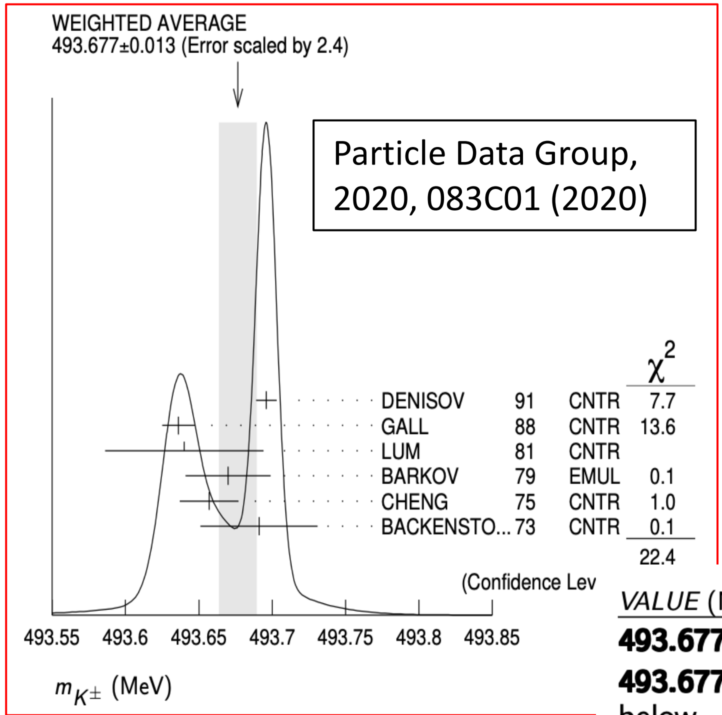
The kaonic Neon measurement to determine the K^- (K^+)

⬇

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

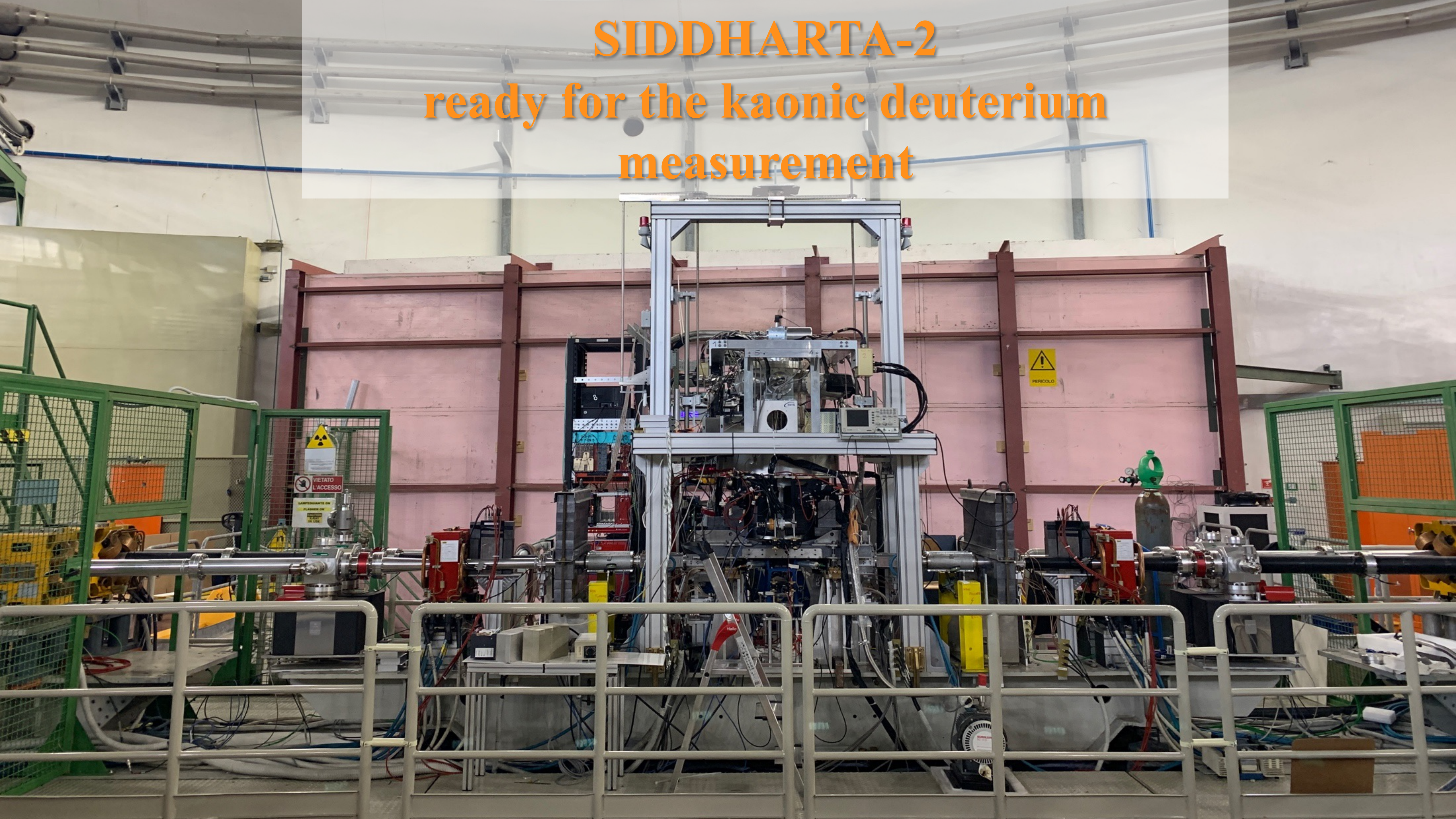
⬇

It could solve the kaon mass discrepancy issue ➡ Impact on the charmonium spectrum and on all processes in which charged kaons are involved



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	±	$e^+e^- \to K^+K^-$
493.657±0.020	[2] CHENG	75	CNTR	–	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	–	Kaonic atoms

SIDDHARTA-2 ready for the kaonic deuterium measurement



The kaonic deuterium measurement

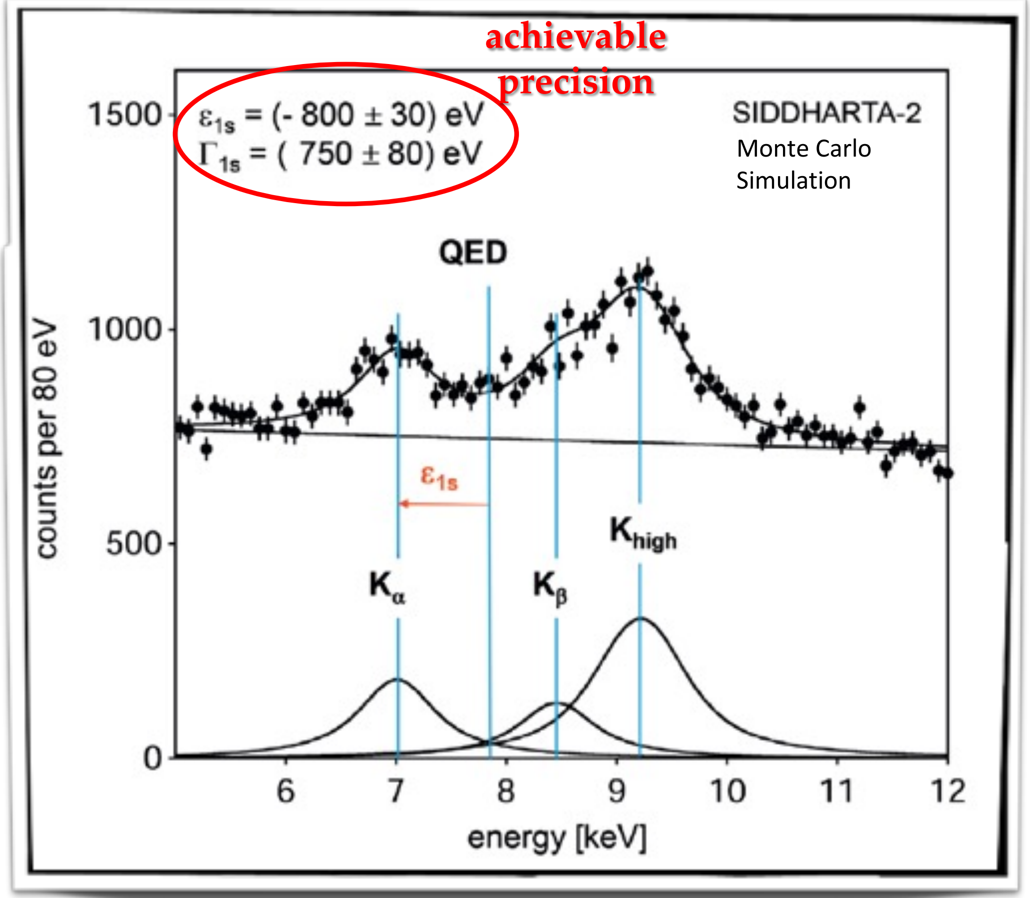
- First run with SIDDHARTA-2 optimized setup for 200 pb^{-1} integrated luminosity: May – July 2023 - completed
- Second run Autumn – Winter 2023 goal: 300 pb^{-1} on going
- Third run 2024 – goal: 300 pb^{-1}
- Calibration runs: Kaonic He; Kaonic Ne; Kaonic H;

Kaonic deuterium run ongoing

2023/24

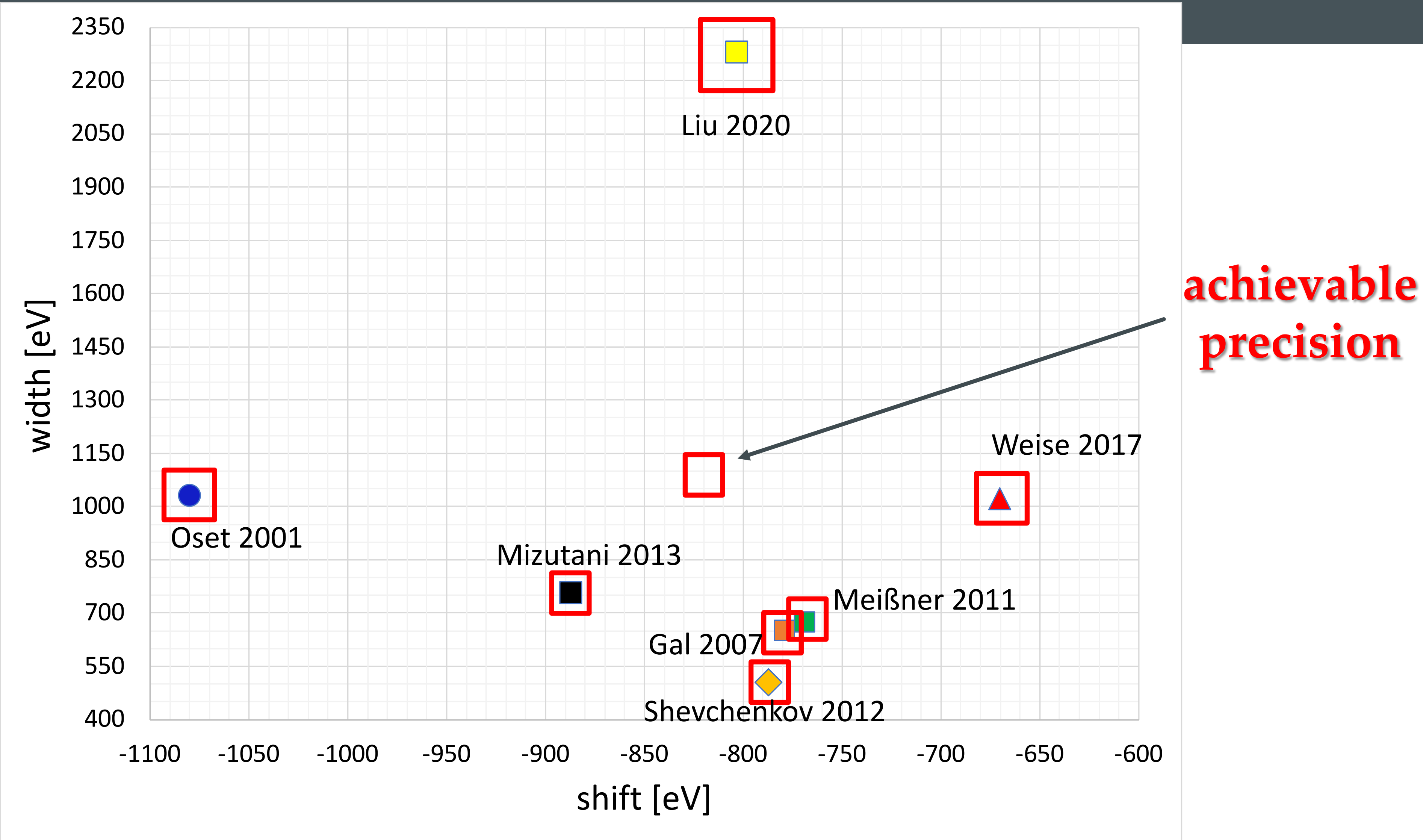
Monte Carlo for an integrated luminosity of 800 pb^{-1}

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 (theoretical predictions)



Beyond SIDDHARTA-2: why still kaonic atoms?

Except for the most recent measurements at DAFNE 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

402 C.J. Batty et al. / Physics Reports 287 (1997) 385–445

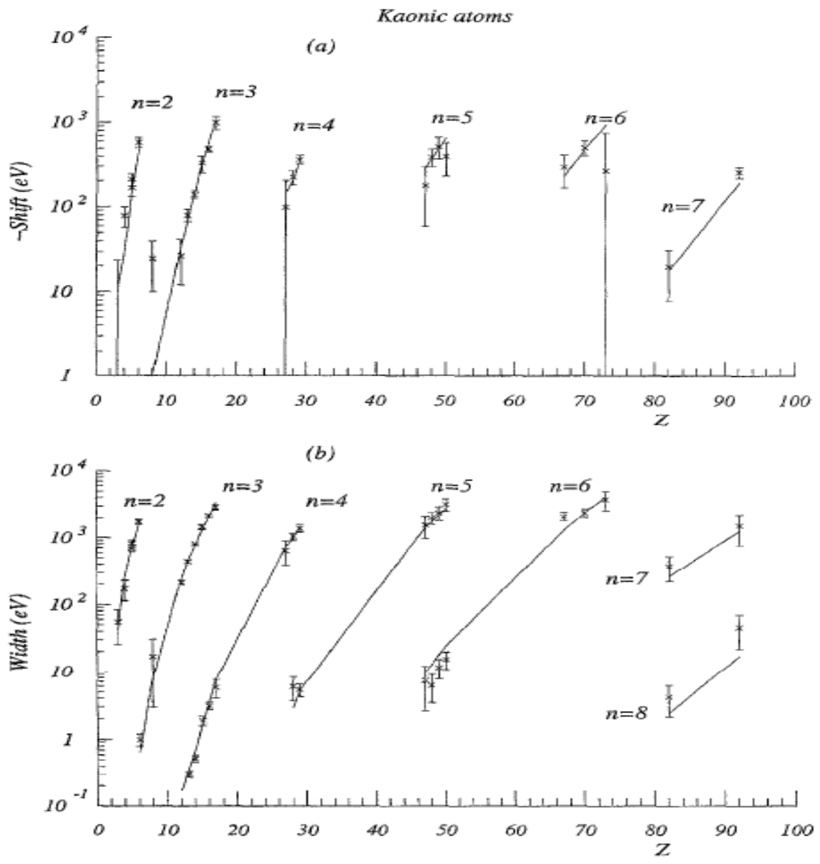


Fig. 7. Shift and width values for kaonic atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 4.2.

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

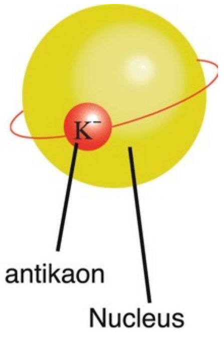
E. Friedman et al. / Nuclear Physics A579 (1994) 518–538 521

Table 1
Compilation of K^- atomic data

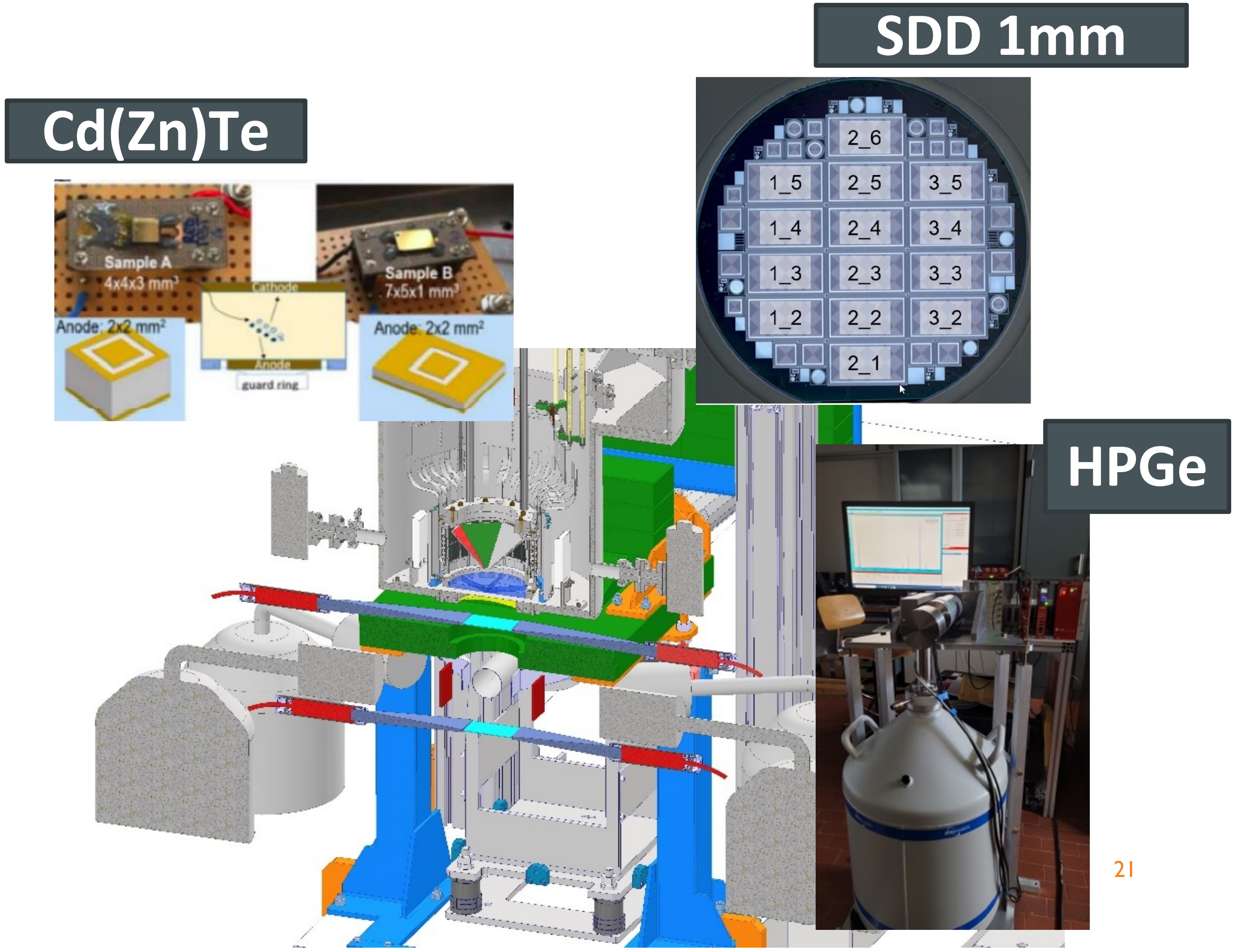
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3 → 2	−0.04 ± 0.03	–	–	–	[15]
		−0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	3 → 2	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	3 → 2	−0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	3 → 2	−0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	3 → 2	−0.167 ± 0.035	0.700 ± 0.080	–	–	[18]
C	3 → 2	−0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20	[18]
O	4 → 3	−0.025 ± 0.018	0.017 ± 0.014	–	–	[19]
Mg	4 → 3	−0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03	[19]
Al	4 → 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 → 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 → 3	−0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30	[18]
S	4 → 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 → 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 → 4	−0.099 ± 0.106	0.64 ± 0.25	–	–	[19]
Ni	5 → 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 → 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 → 5	−0.18 ± 0.12	1.54 ± 0.58	0.51 ± 0.16	7.3 ± 4.7	[19]
Cd	6 → 5	−0.40 ± 0.10	2.01 ± 0.44	0.57 ± 0.11	6.2 ± 2.8	[19]
In	6 → 5	−0.53 ± 0.15	2.38 ± 0.57	0.44 ± 0.08	11.4 ± 3.7	[19]
Sn	6 → 5	−0.41 ± 0.18	3.18 ± 0.64	0.39 ± 0.07	15.1 ± 4.4	[19]
Ho	7 → 6	−0.30 ± 0.13	2.14 ± 0.31	–	–	[23]
Yb	7 → 6	−0.12 ± 0.10	2.39 ± 0.30	–	–	[23]
Ta	7 → 6	−0.27 ± 0.50	3.76 ± 1.15	–	–	[23]
Pb	8 → 7	–	0.37 ± 0.15	0.79 ± 0.08	4.1 ± 2.0	[24]
		−0.020 ± 0.012	–	–	–	[25]
U	8 → 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 DAΦNE (Italy) and JPARC (Japan)
Kaonic atoms data are the experimental basis for all the theoretical models used to derive:
KN, KNN interaction at threshold, Kaon mass, cascade models, possible existence of kaon condensates



EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium



Precision measurements along the periodic table at for:

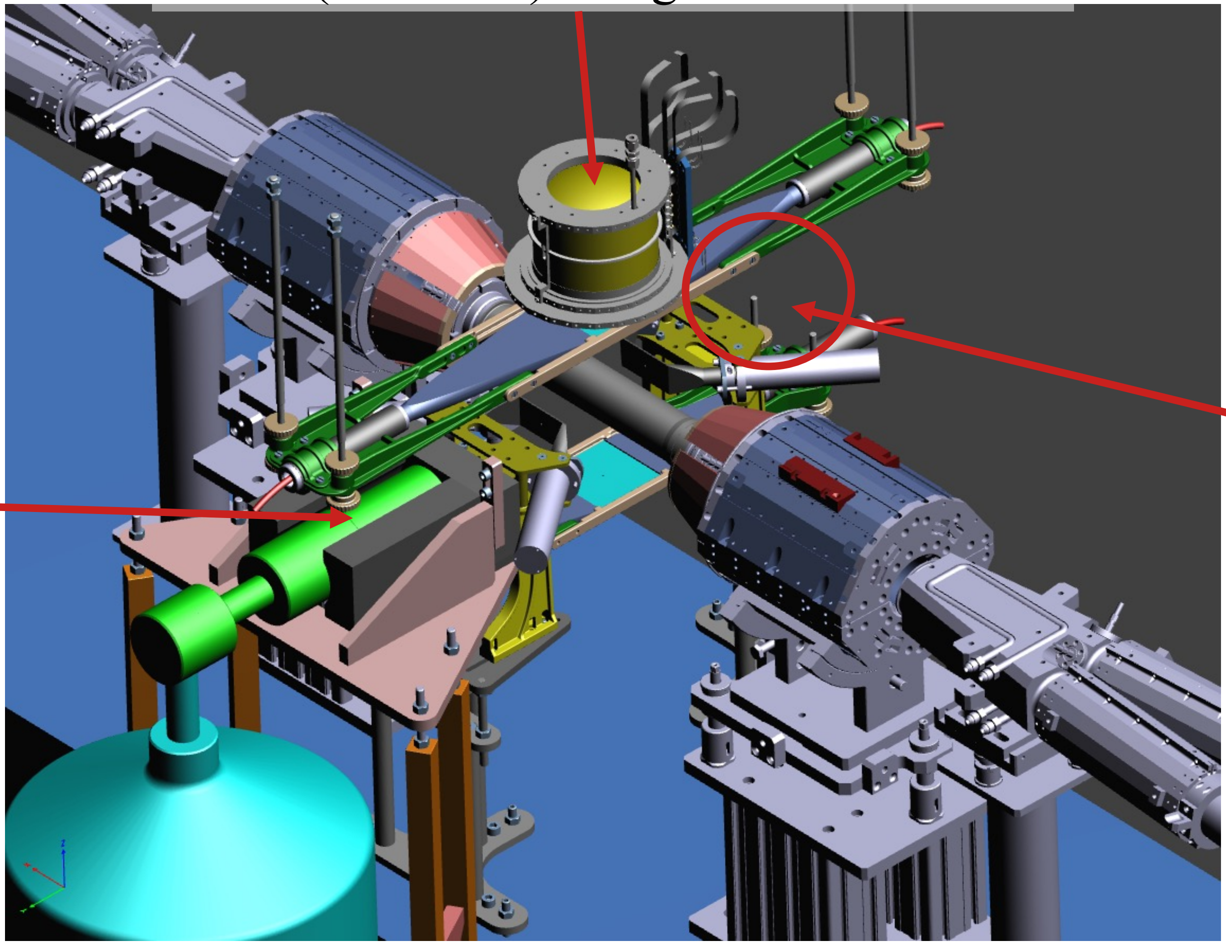
- **Kaonic Hydrogen: 200 pb^{-1} – with SIDDHARTA-2 setup – to get a precision < 10 eV (KH)**
- **Selected light kaonic atoms (LHKA) – Li, Be, B**
- **Selected intermediate and heavy kaonic atoms charting the periodic table (IMKA) – Pb, C, Al**
- **Ultra-High precision measurements of Kaonic Atoms (UHKA)**

Kaonic atoms at DAΦNE collider: a strangeness adventure
C. Curceanu et al.,
doi.org/10.3389/fphy.2023.1240250

Exploiting DAΦNE

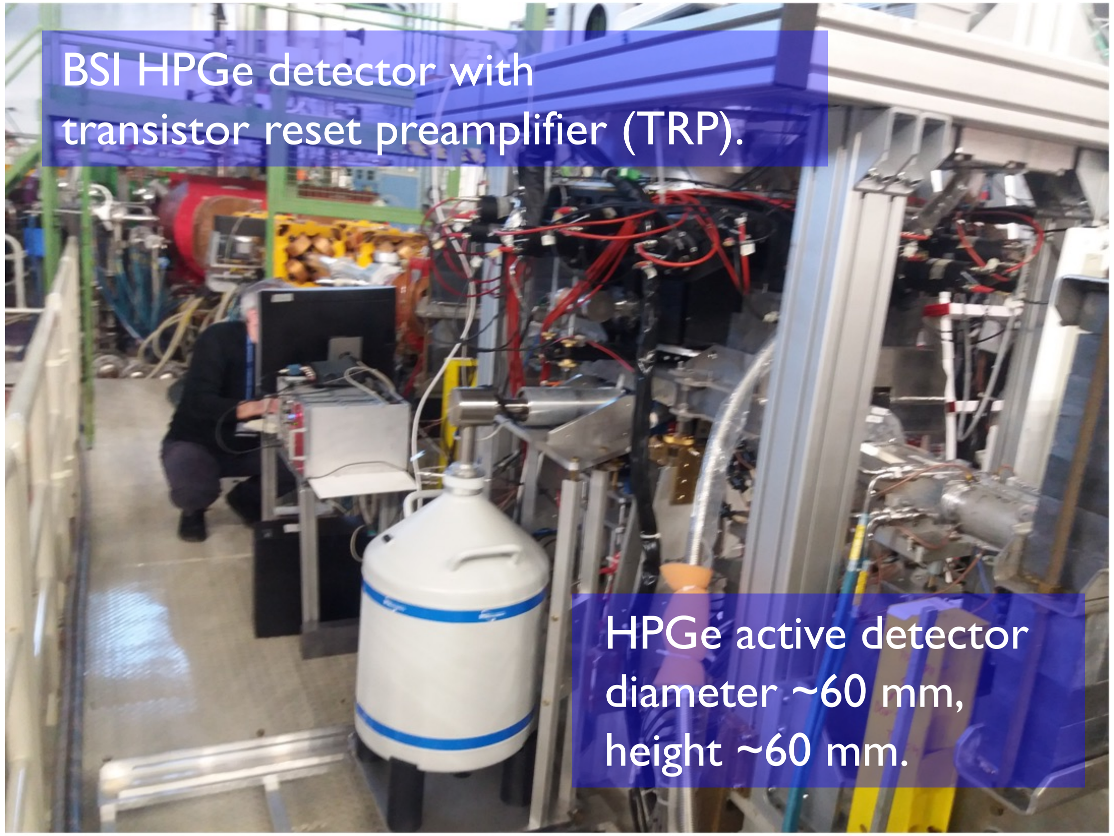
DAΦNE delivers almost 4π K^-

We want to exploit this unique beam as much as possible to perform important physics measurements



Kaonic Lead Measurement at DAΦNE with HPGe

HPGe provided by Zagreb University (Croatian Science Foundation project 8570)
to perform the kaonic lead measurement
in parallel with the SIDDHARTA-2 kaonic deuterium measurement



3.1. Detection unit GCD-30185 characteristics

#	Parameter	Value
1.	Relative efficiency (with respect to 3'' x 3'' NaI detector and Co-60 source mounted 25 cm above the detector) at 1.33 MeV γ-photon	> 30 %
2.	Energy resolution* at • 122 keV • 477.6 keV • 1.33 MeV **Measured with spectrometric device MS Hybrid at input count rate 1000 pulses/sec, shaping time constant = 6 μsec*	875 eV 1400 eV 1850 ± 30 eV
3.	Peak shape: • FWTM/FWHM • FW.02M/FWHM	< 1.9 < 2.65
4.	Spectral Broadening of FWHM up to 100,000 counts/sec for 1.33 Mev	< 8 %
5.	Peak position shift	< +/- 0.018 %
6.	Peak to Compton ratio, not worse	58 : 1
7.	Energy range of detector operation	40 keV – 3 MeV
8.	Material of input window	Al
9.	Cooling time	< 8 hours
10.	Liquid nitrogen holding time in Dewar vessel	> 15 days
11.	Dewar volume	30 l
12.	Preamplifier (built – in detector capsule) with cooled FET and transistor reset preamplifier (TRP) • Preamplifier power supply is ±12 V with 9 pin connector compatible with NIM standards • TTL signal to shut down the HV: - detector warm -0V; - detector cold: +5V • HV INHIBIT – BNC	

The Kaonic Lead Measurement

First run performed in June - July 2023 (109 pb^{-1})

Preliminary

- (10 -> 9) : 906 events in peak (integration of fitting function gaus+linear)

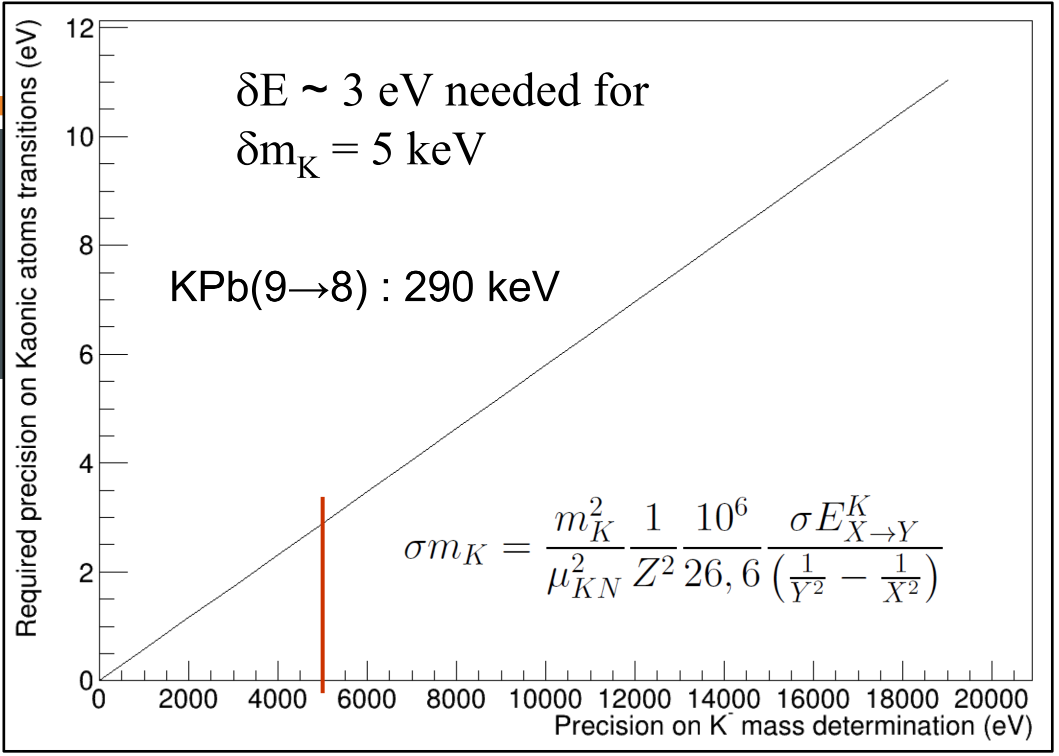
  position 209.191 ± 0.171 keV; $\sigma/\sqrt{N}$ = 0.0057 keV

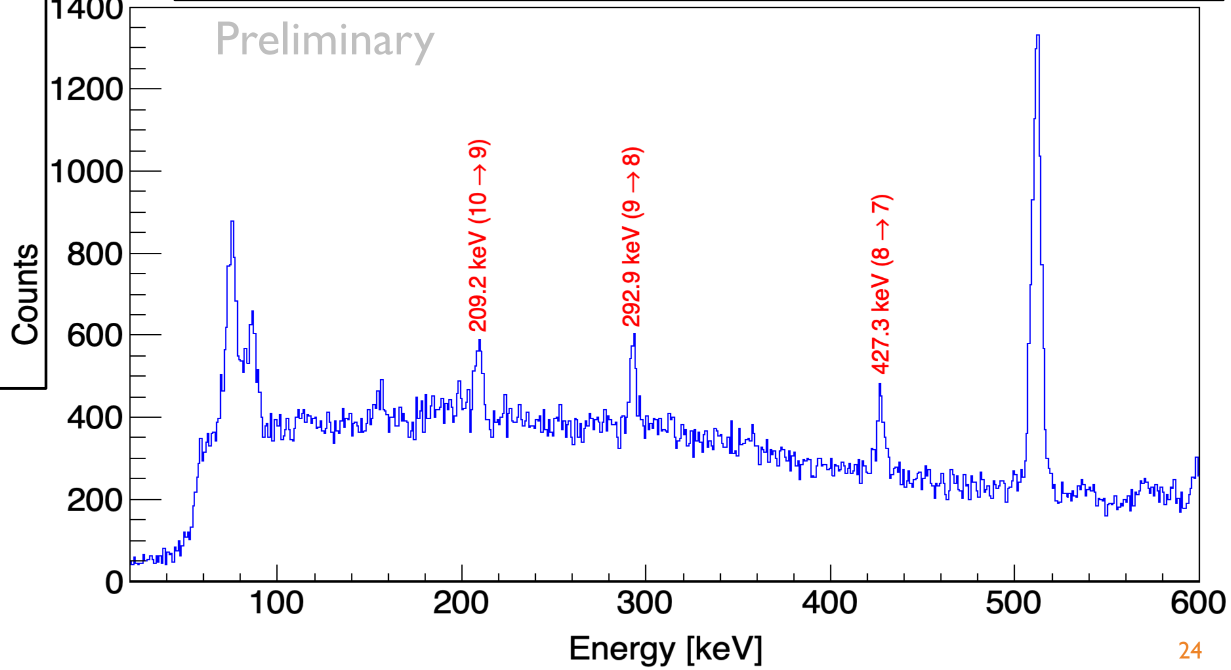
- (9 -> 8) : 947 events in peak (integration of fitting function gaus+linear)

  position 292.939 ± 0.134 keV; $\sigma/\sqrt{N}$ = 0.0044 keV

- (8 -> 7) : 943 events in peak (integration of fitting function gaus+linear)

  position 427.2 ± 0.152 keV; $\sigma/\sqrt{N}$ = 0.0049 keV





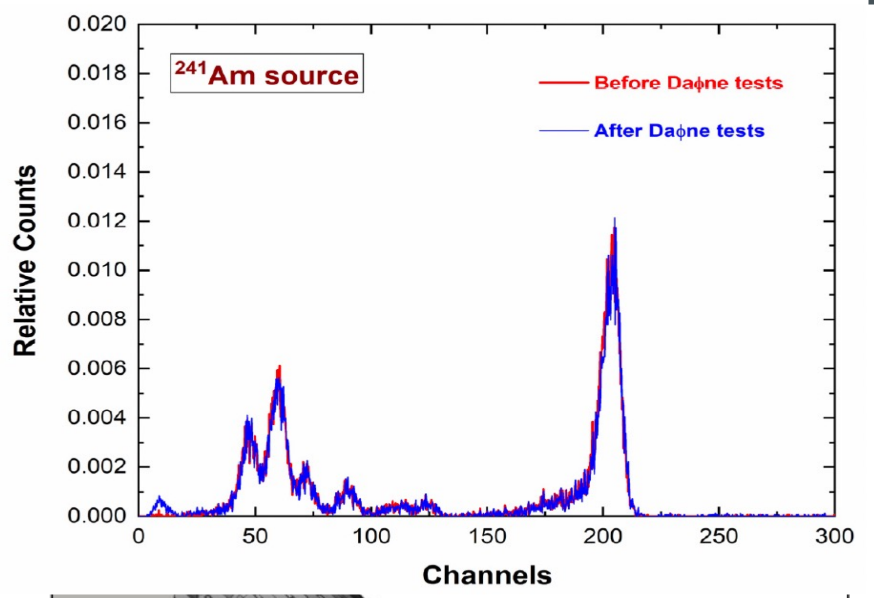
Ivica Friščić (and SIDDHARTA-2 collaboration) -
Mini workshop on kaonic atoms: present status and future plans,
18th July 2023

Heavy and medium mass kaonic atoms measurements

CdZnTe detectors,

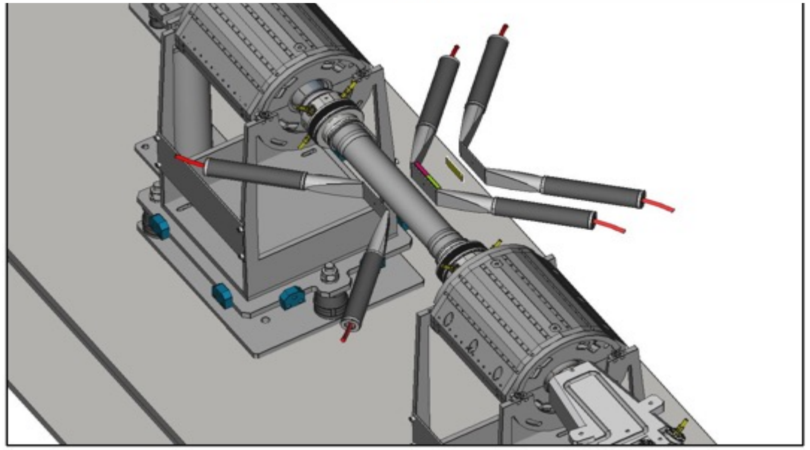
developed in collaboration with University of Palermo

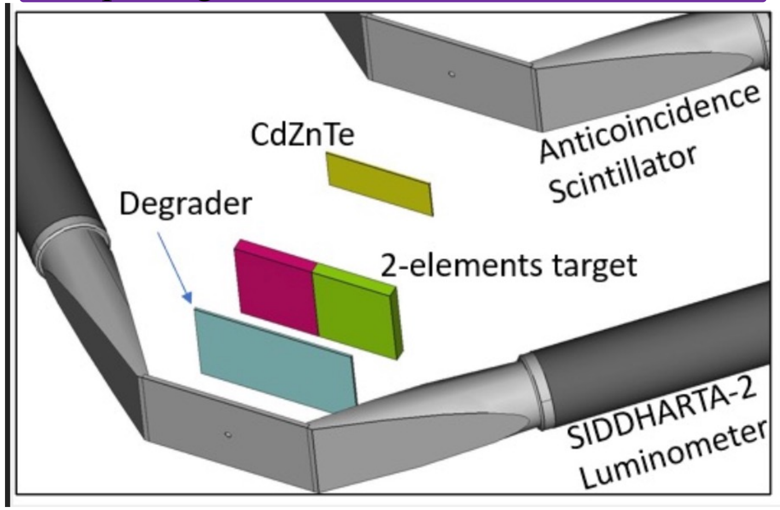
(Abbene, L.; et al. Potentialities of CdZnTe Quasi-Hemispherical Detectors for Hard X-ray Spectroscopy of Kaonic Atoms at the DAFNE Collider. Sensors 2023, 23, 7328.)

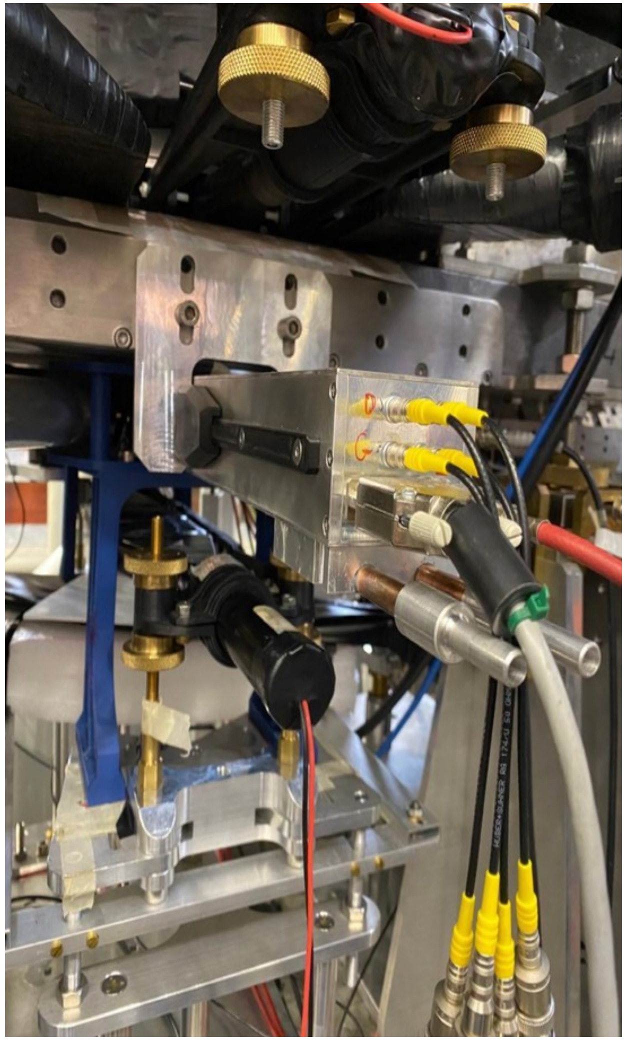


Detector Key Points:

- High efficiency in the 20-100 keV region
- Reasonable efficiencies up to 300 keV
- Good resolution (FHWM/E ~ %)
- Fast response and time resolution (< 50 ns)
- No need for cooling
- Compact readout and installation package







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**
  - ✓ **The most precise Kaonic ^{4}He $3d \rightarrow 2p$ measurement in gas**
    - Energy shift and width
    - Yield at 3 different density 1.9 g/l, 1,37, and 0.82 g/l
  - ✓ **First measurement ever of Kaonic ^{4}He M-series transitions**
  - ✓ **First measurement of several solid target high-n transition energies**
  - ✓ **First kaonic Neon measurement -> implications on kaon mass**

- **Kaonic deuterium run in going**
  - ✓ First phase completed. 200 pb^{-1} collected

- **EXKALIBUR: fundamental physics at the strangeness frontier at DAFNE**

Thank You