HADRON 2023

Genova 5 – 9 June 2023

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

Francesco Sgaramella
on behalf of the SIDDHARTA-2 Collaboration

STRONG-2020

INFN
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

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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HadronPhysics2
Study of Strongly Interacting Matter

STRONG-2020

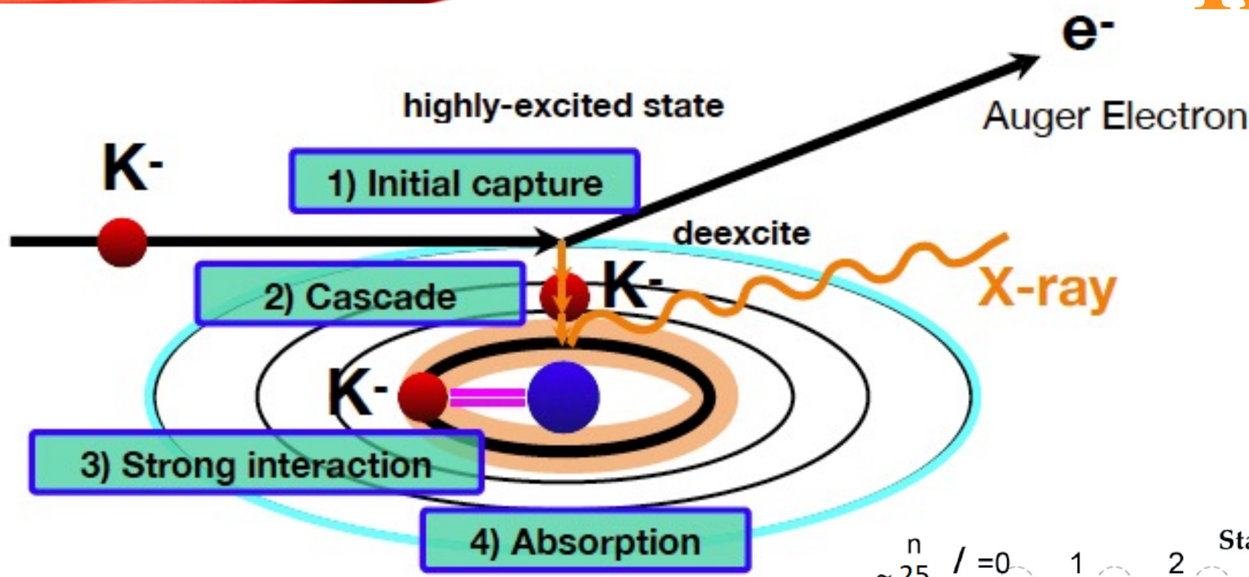
HadronPhysics I3
Study of Strongly Interacting Matter

HRZZ
Croatian Science Foundation

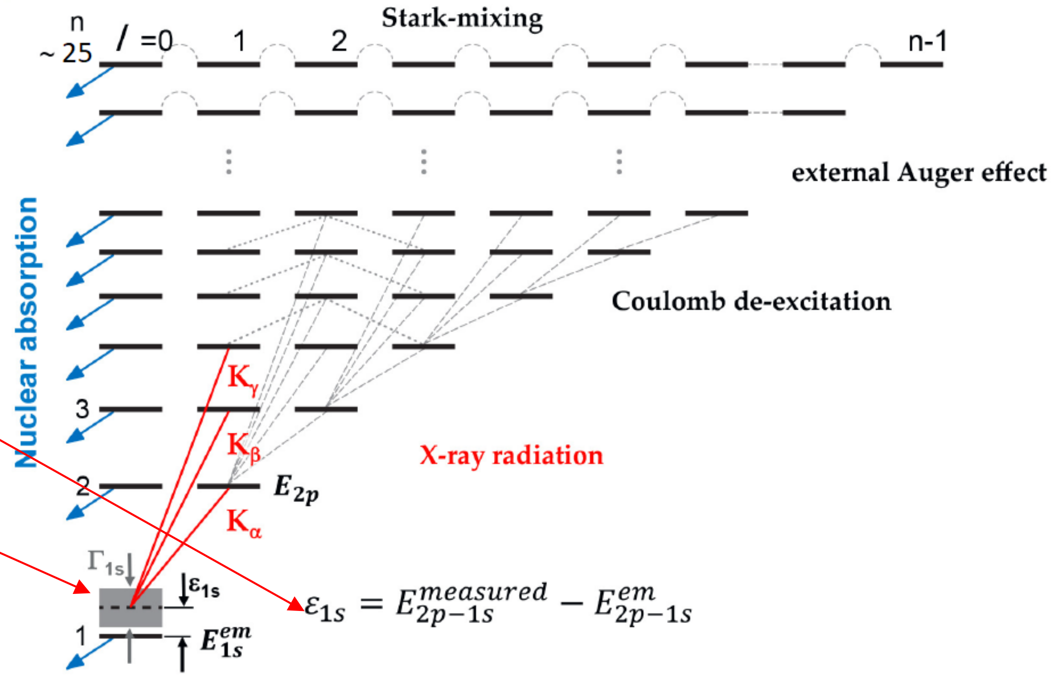
FWF Der Wissenschaftsfonds.

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

Kaonic Atom



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



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

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

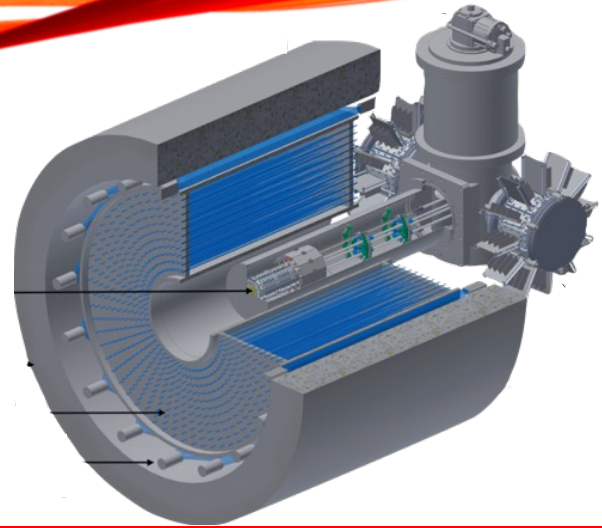
(μ_c reduced mass of the K⁻p system, α fine-structure constant)

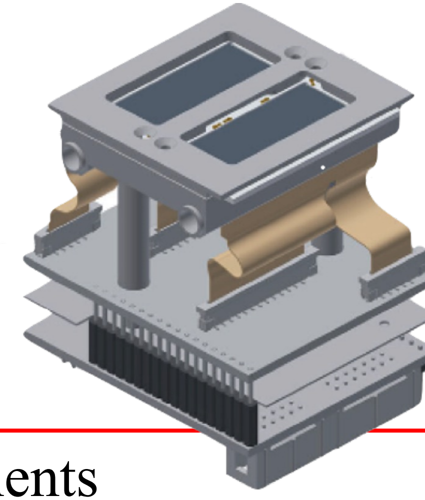
U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

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

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

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



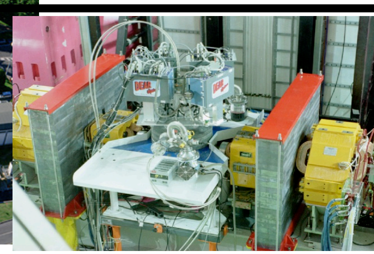


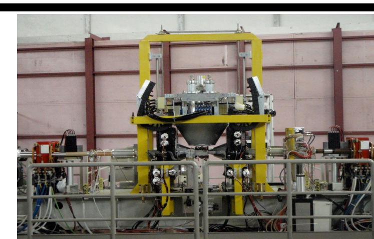
The modern era of light kaonic atom experiments

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**



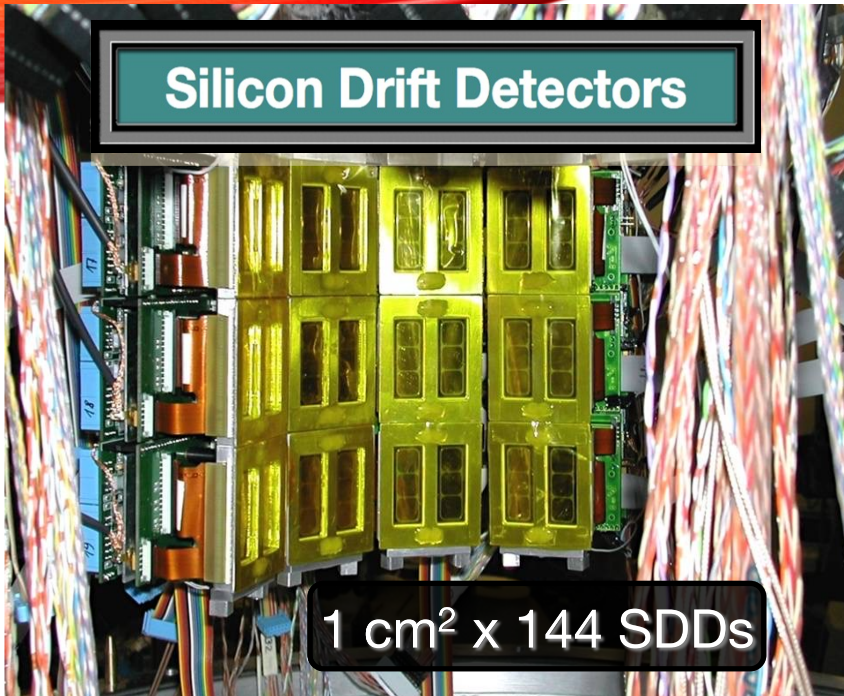


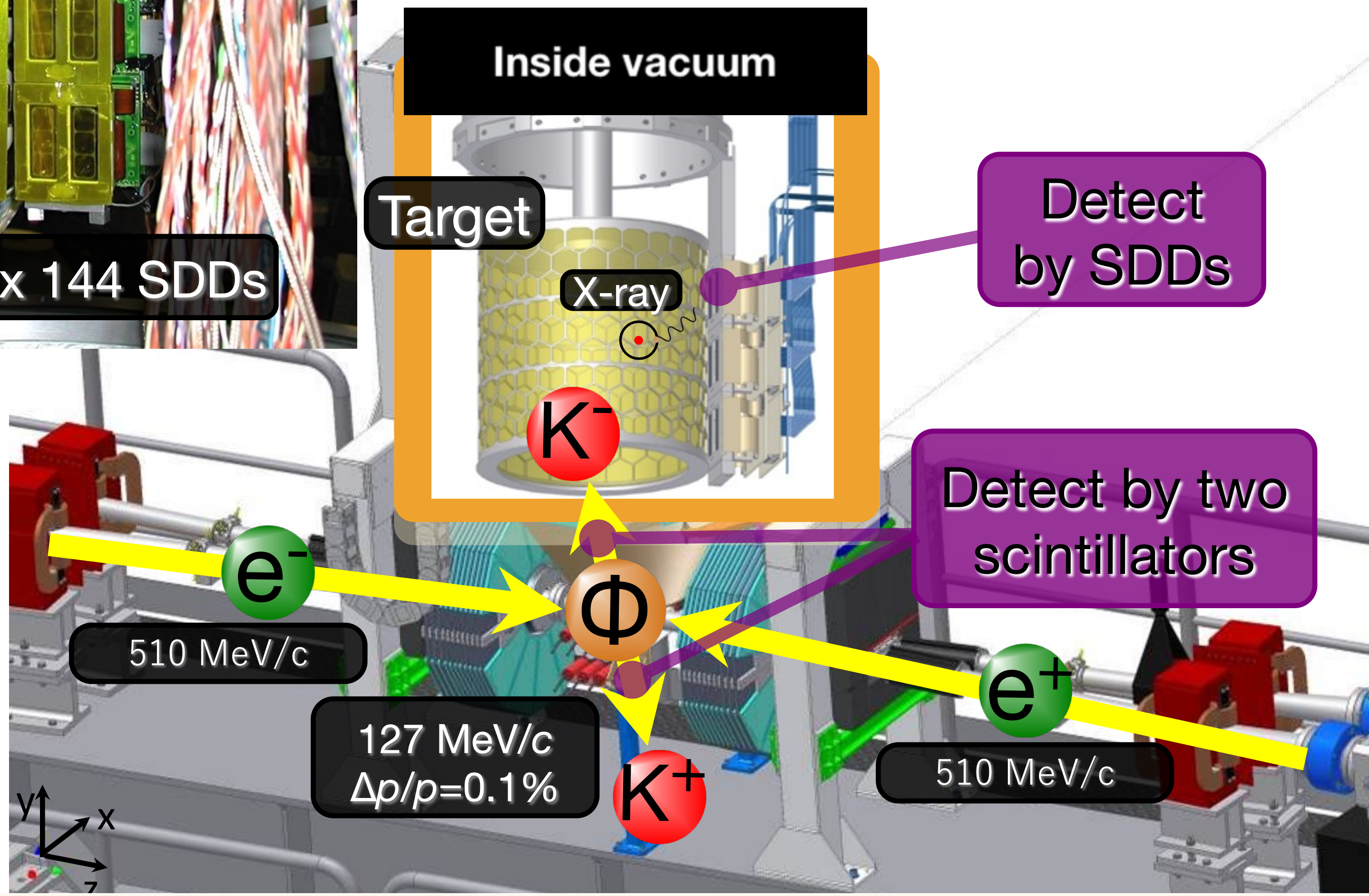
LNF – e^+e^- Accelerator Complex

- $\Phi \rightarrow K^- K^+$ (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

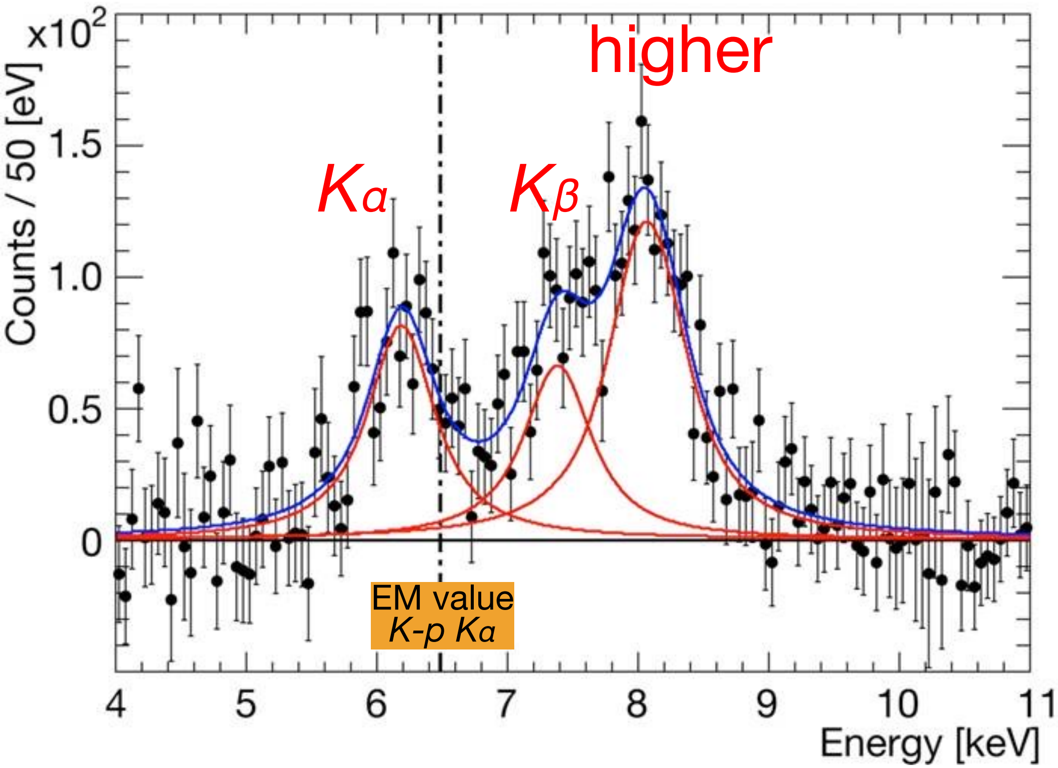
The SIDDHARTA Experiment (2009)





The SIDDHARTA Experiment (2009)

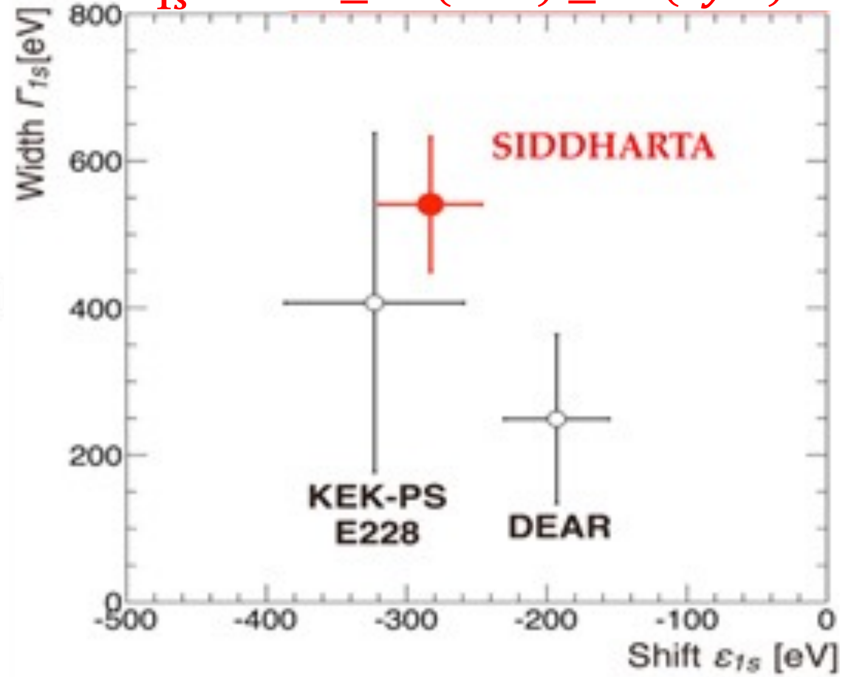
Kaonic hydrogen



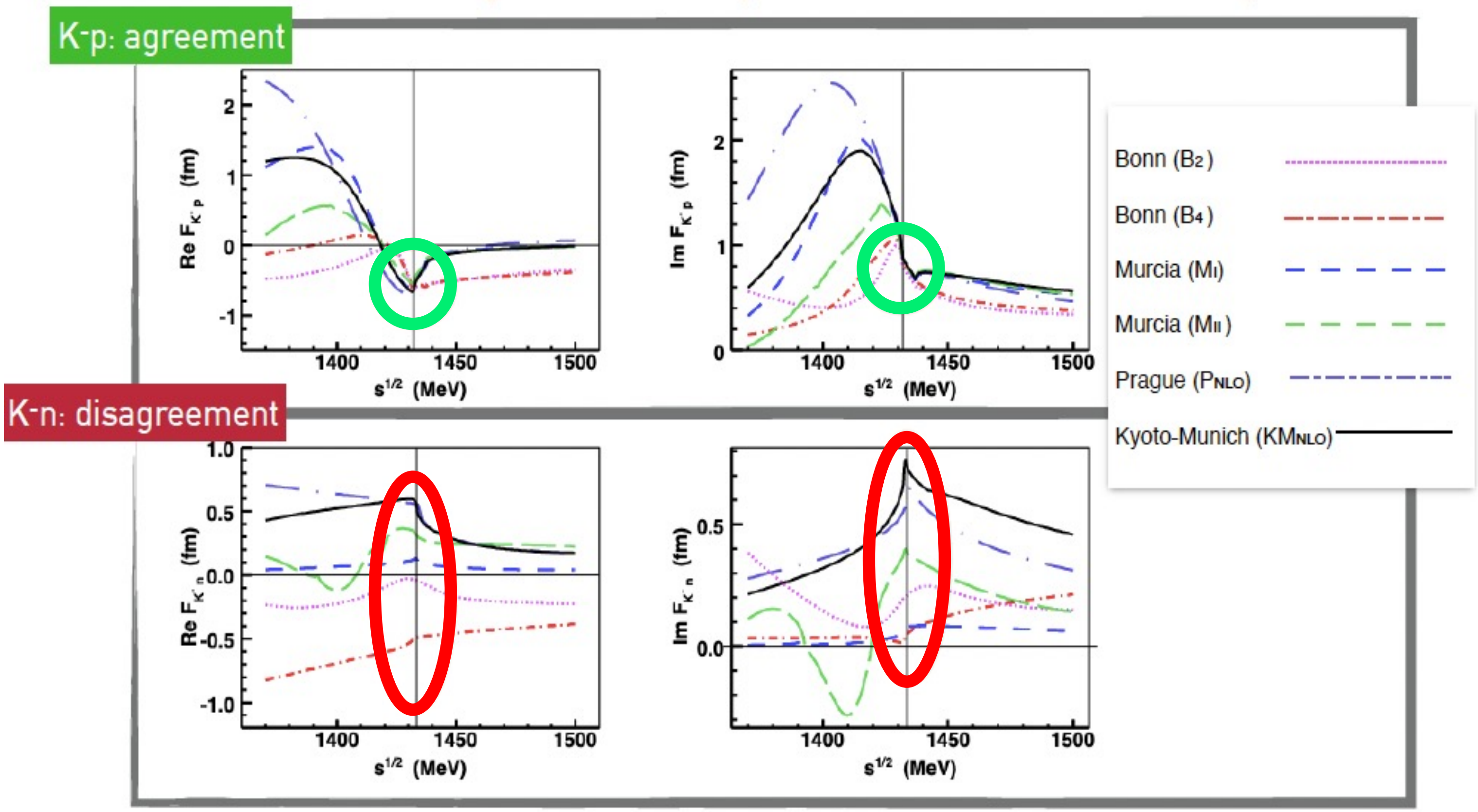
C. Curceanu et al., *Phys. Lett. B* **704** (2011) 113

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

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

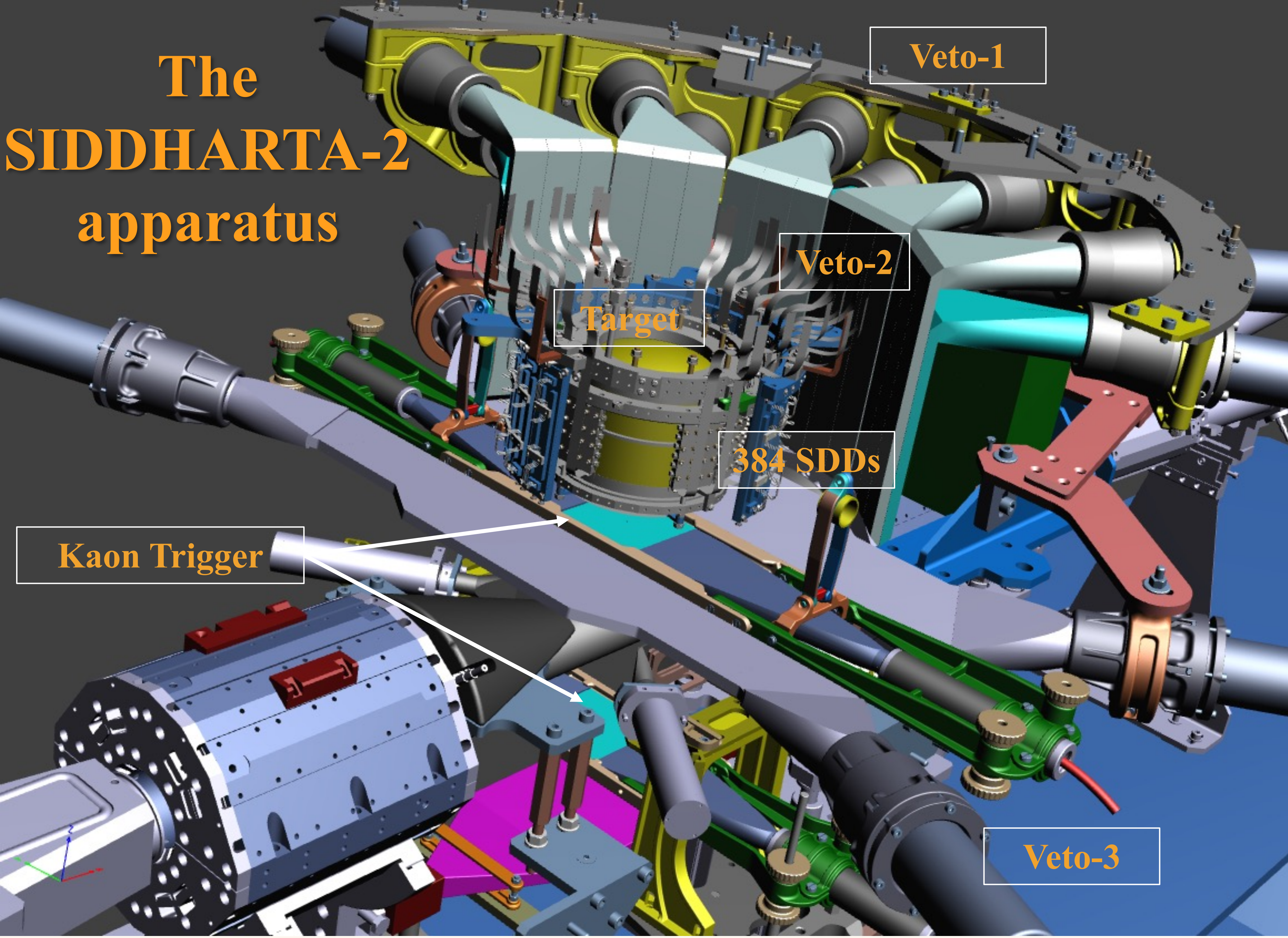


Kaon nucleon scattering amplitude

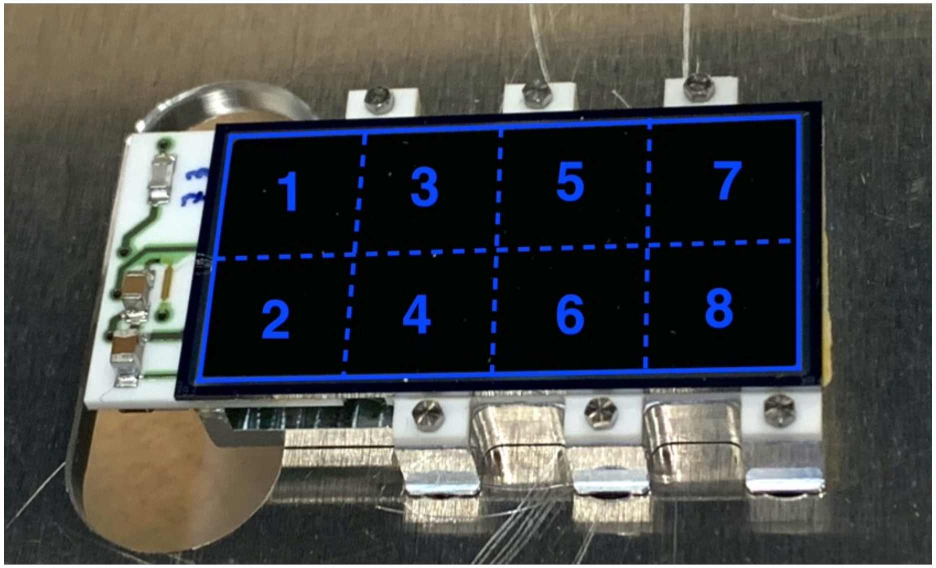


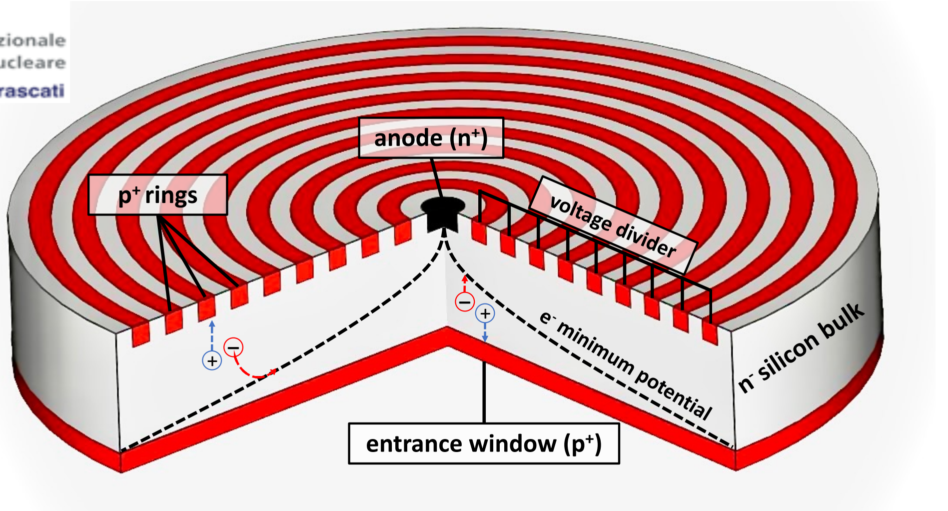
A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

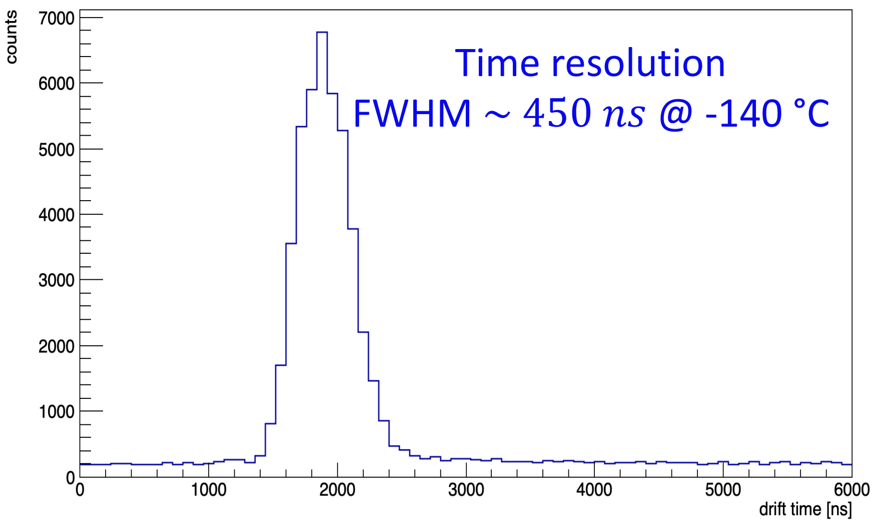
The SIDDHARTA-2 apparatus



Silicon Drift Detectors







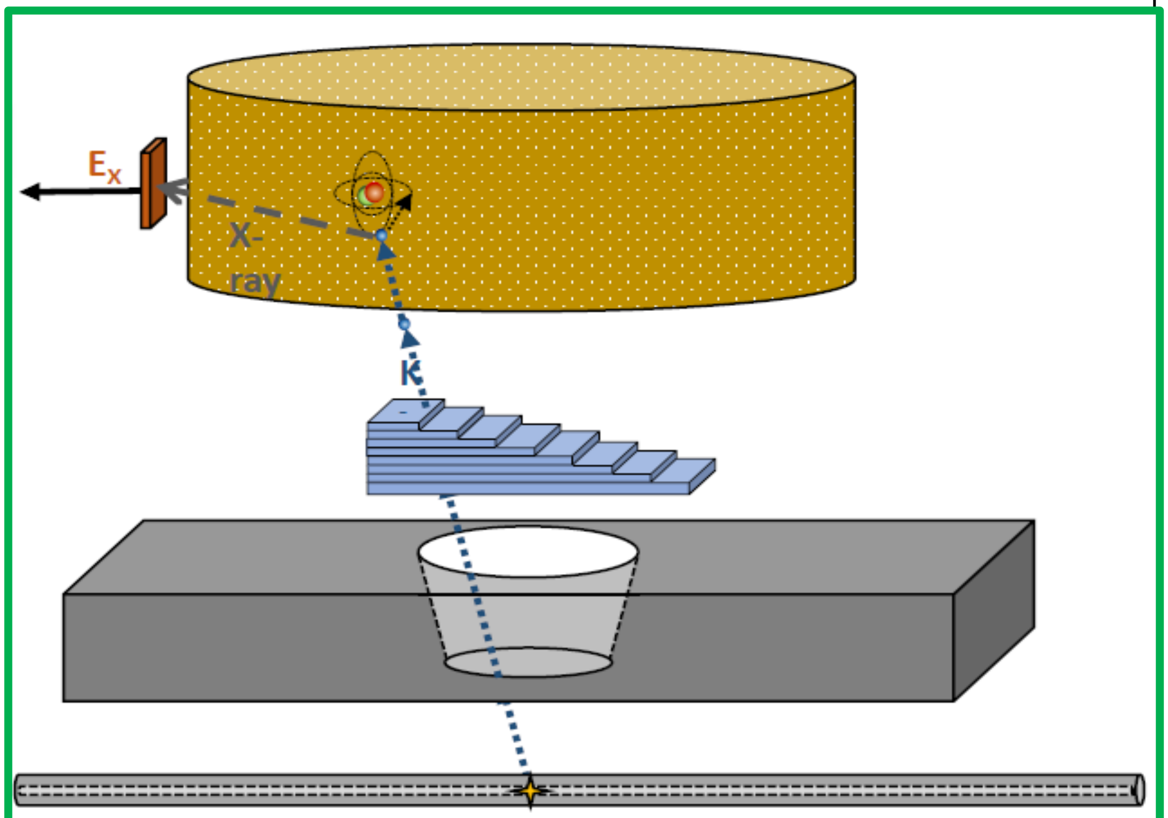
48 arrays with 8 SDD units (0.64 cm^2) for a total active area of 246 cm^2
The thickness of 450 μm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

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

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

SIDDHARTINO (2021)
The degrader optimization

Degrader optimization: sensitivity to 100 microns over all material budget (about 4 mm materials of various densities)! – a very delicate and fundamental operation (knowledge of material budget at 2.5 % level)



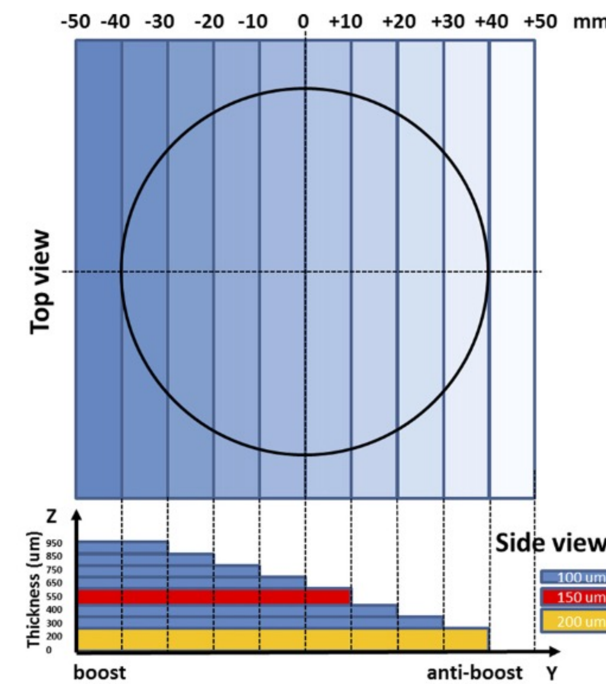
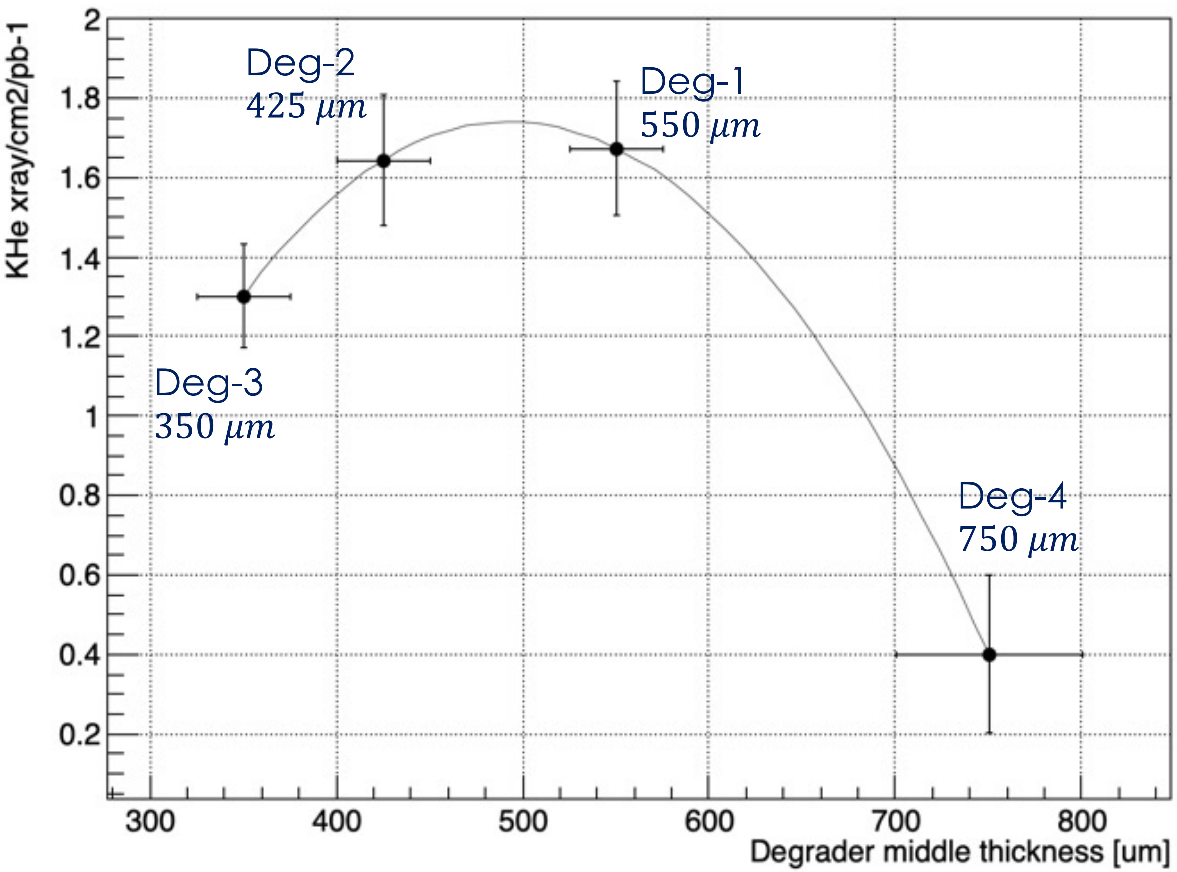
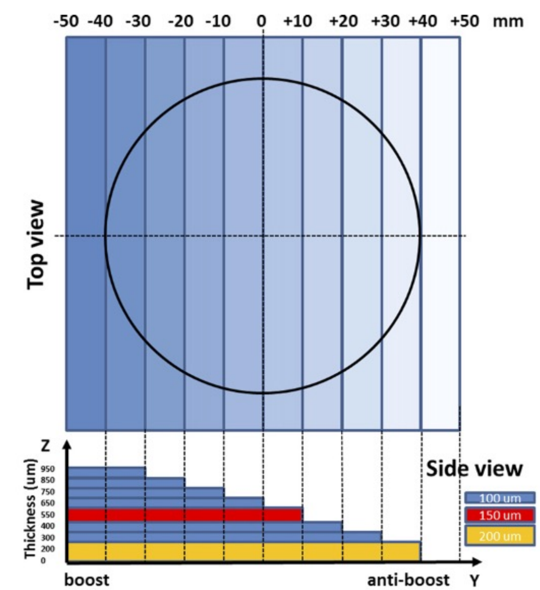


Figure 6. Nearest to optimal configuration of the Mylar degrader: the circle represents the size of the entrance window of the vacuum chamber; direction '*Y*' points to the outer side of the DAΦNE ring, corresponding to the anti-boost side for kaons. The degrader has eight steps to compensate for the boost effect, with thicknesses shown in the lower part of the figure.

SIDDHARTINO

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





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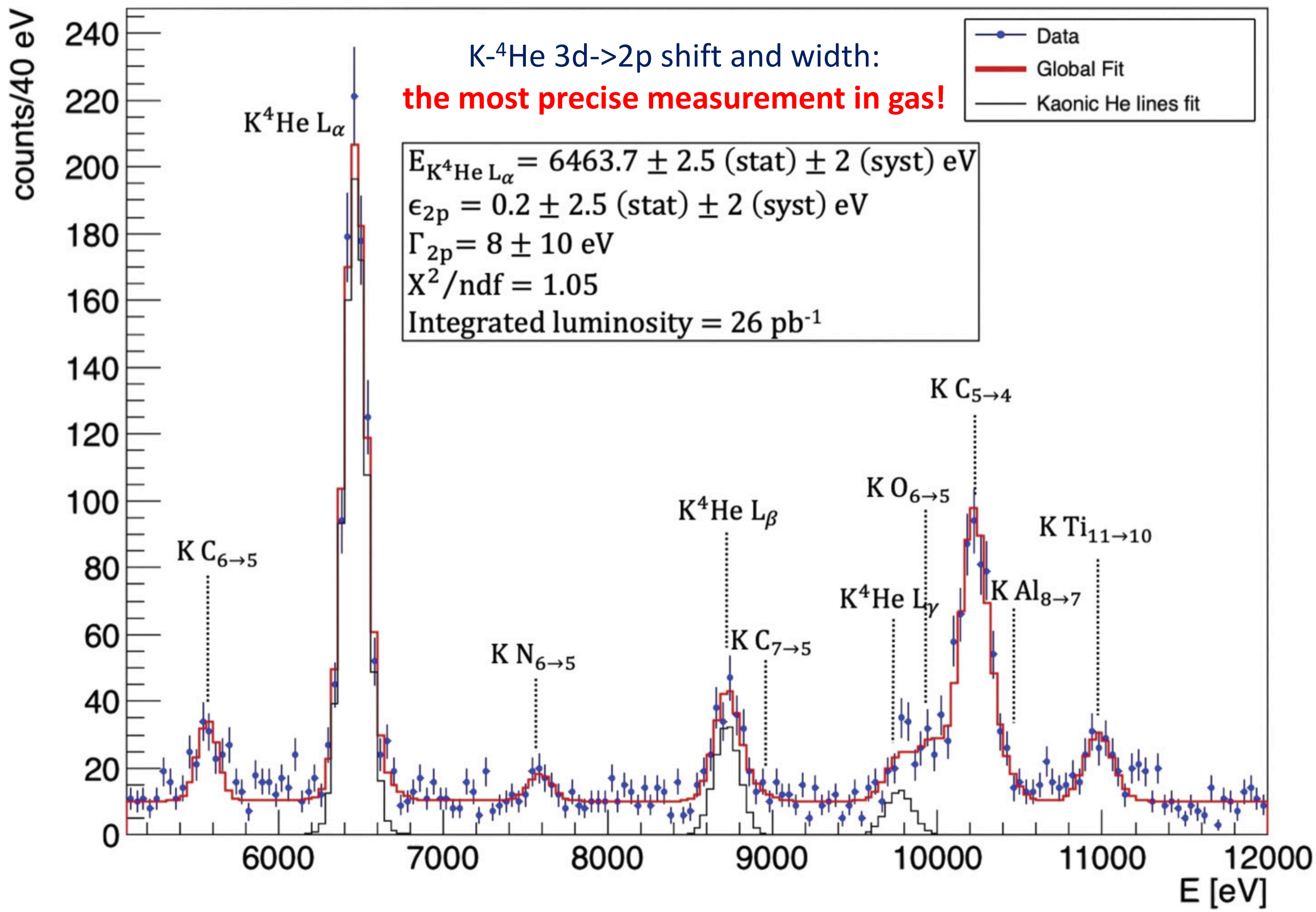
OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **49** (2022) 055106 (14pp)
https://doi.org/10.1088/1361-6471/ac5dac

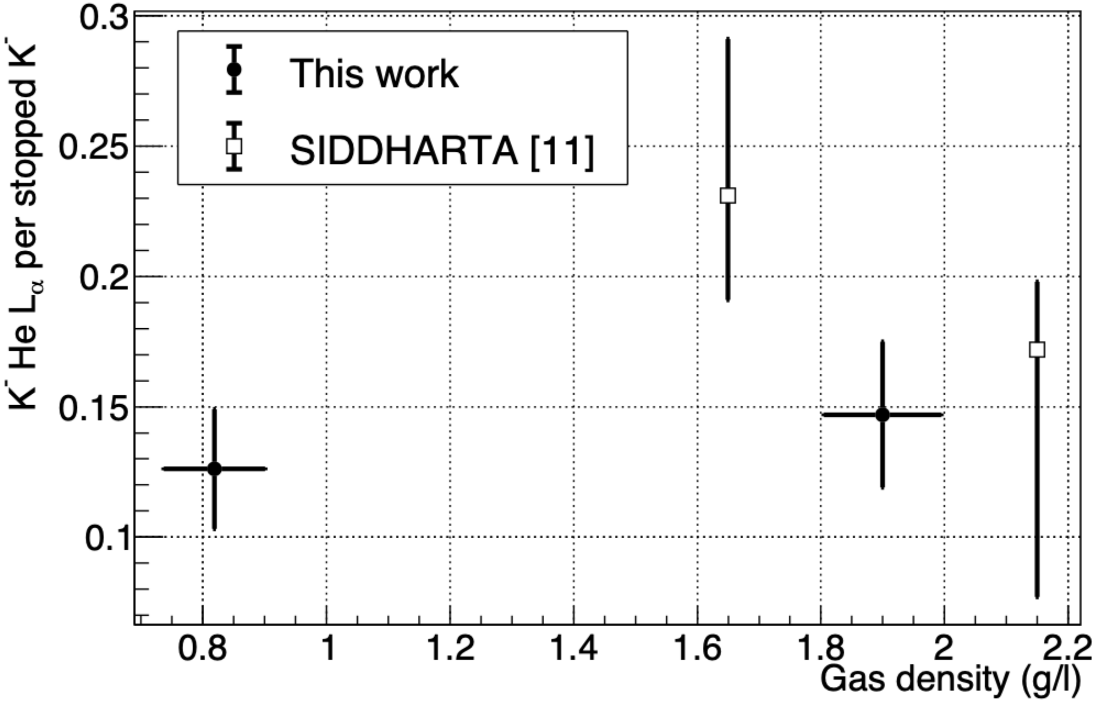
A new kaonic helium measurement in gas by SIDDHARTINO at the DAΦNE collider*

SIDDHARTINO
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**

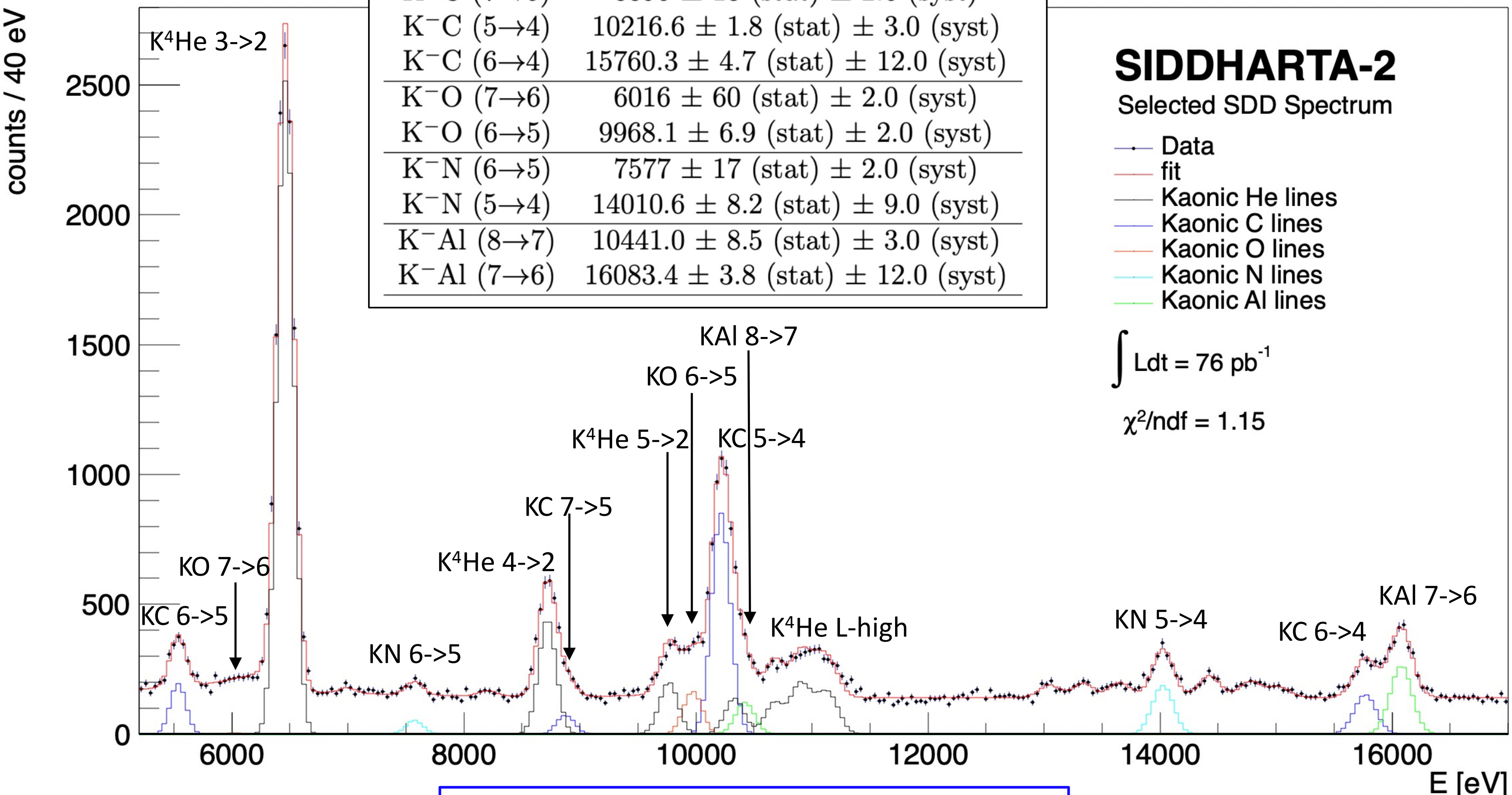
Density	1.90 g/l	0.82 g/l
L_α yield	0.148 ± 0.027	0.126 ± 0.023
L_β/L_α	0.193 ± 0.042	0.133 ± 0.037
L_γ/L_α	0.035 ± 0.015	not detected

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)

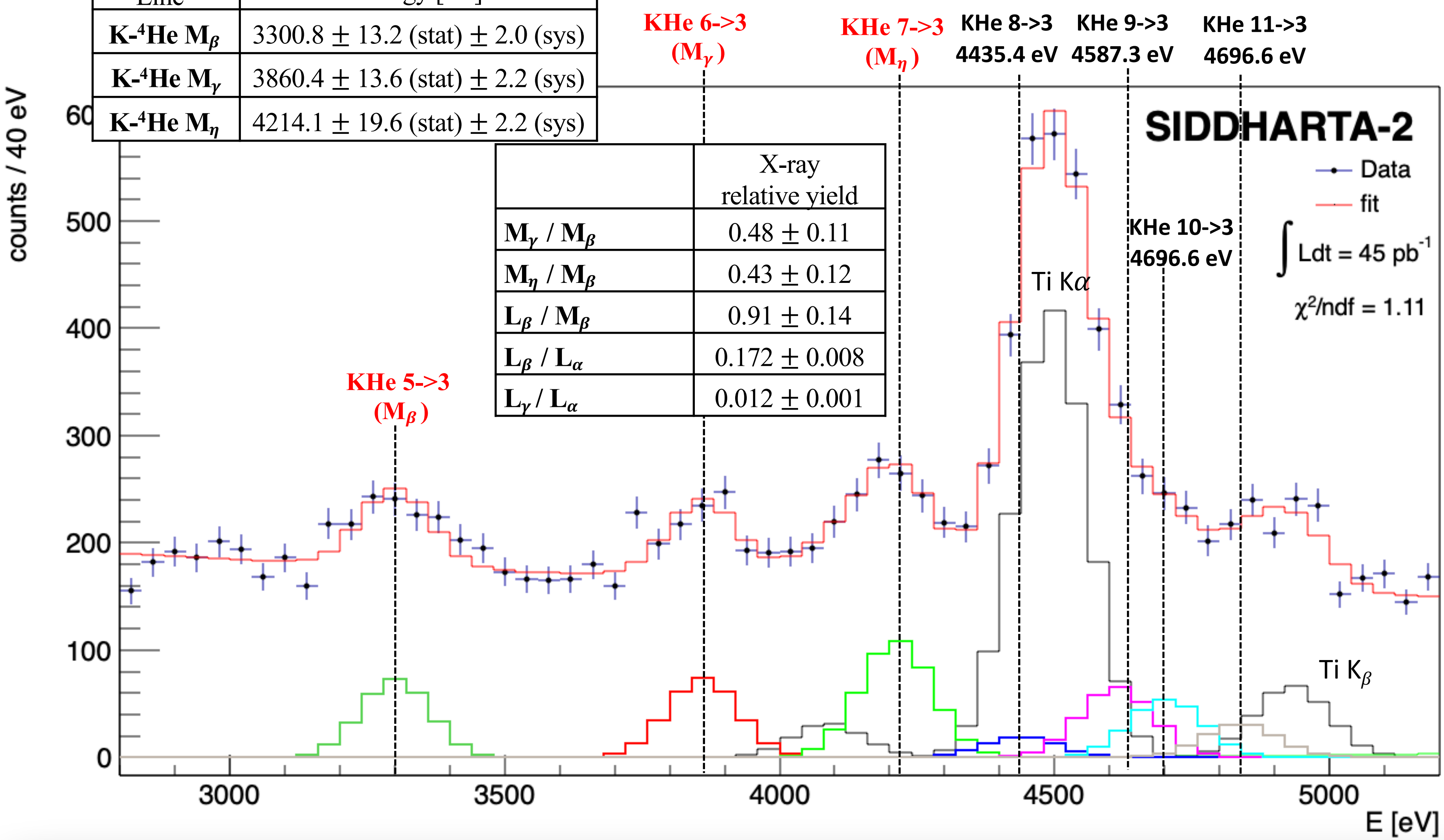


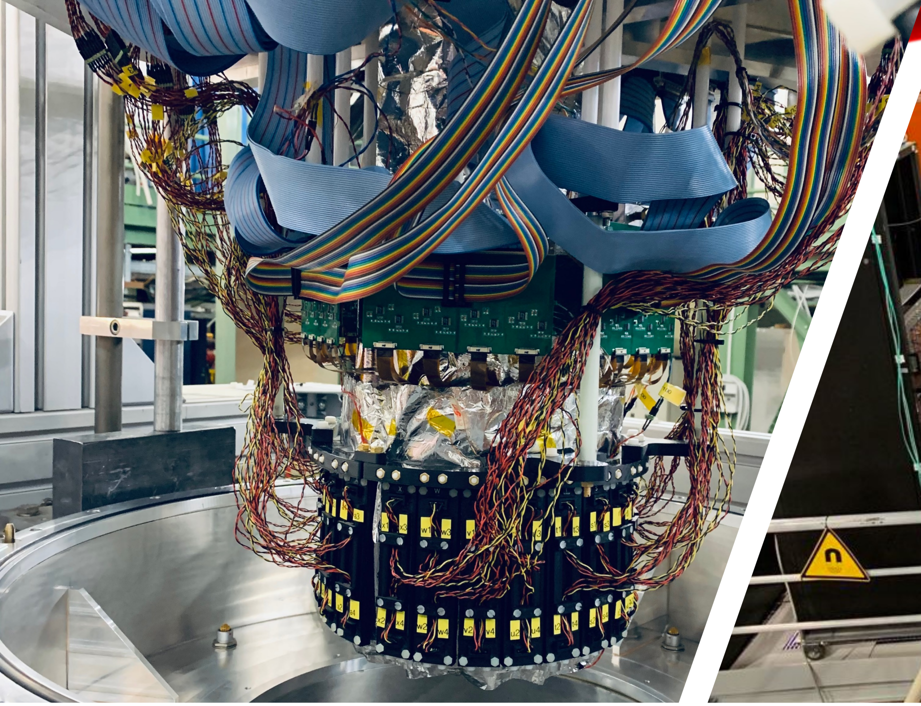
Sgaramella, F., *al. Eur. Phys. J. A* **59**, 56 (2023)

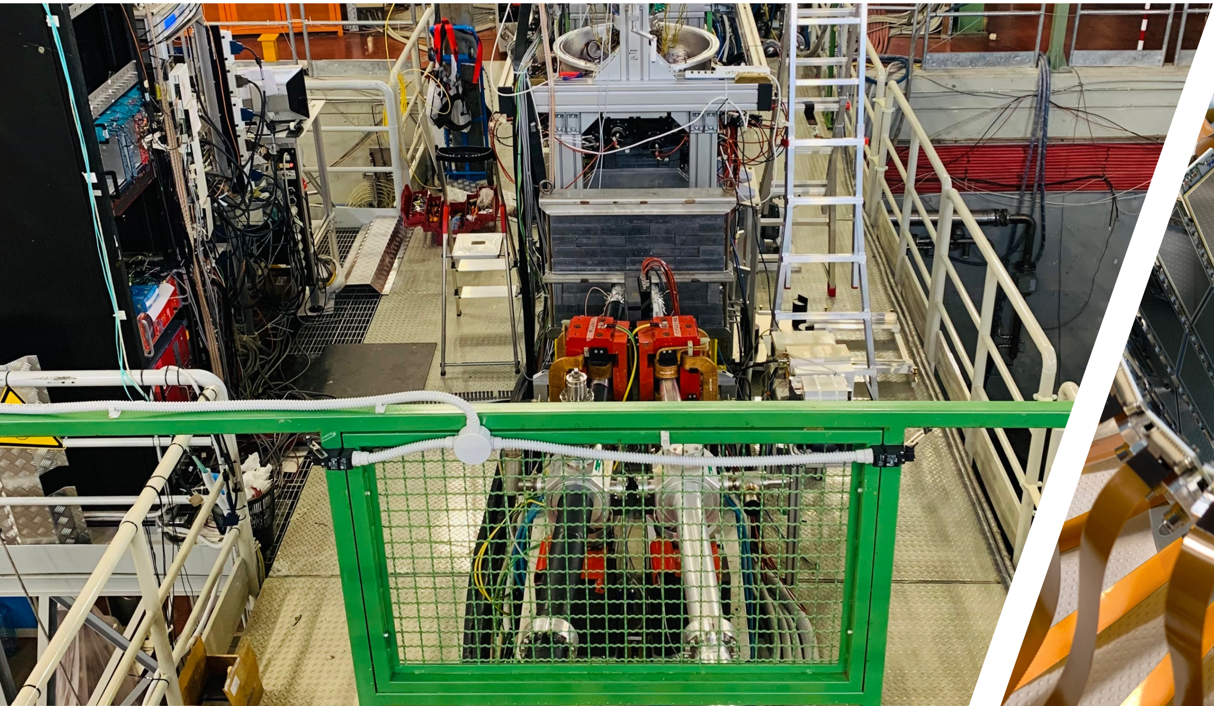
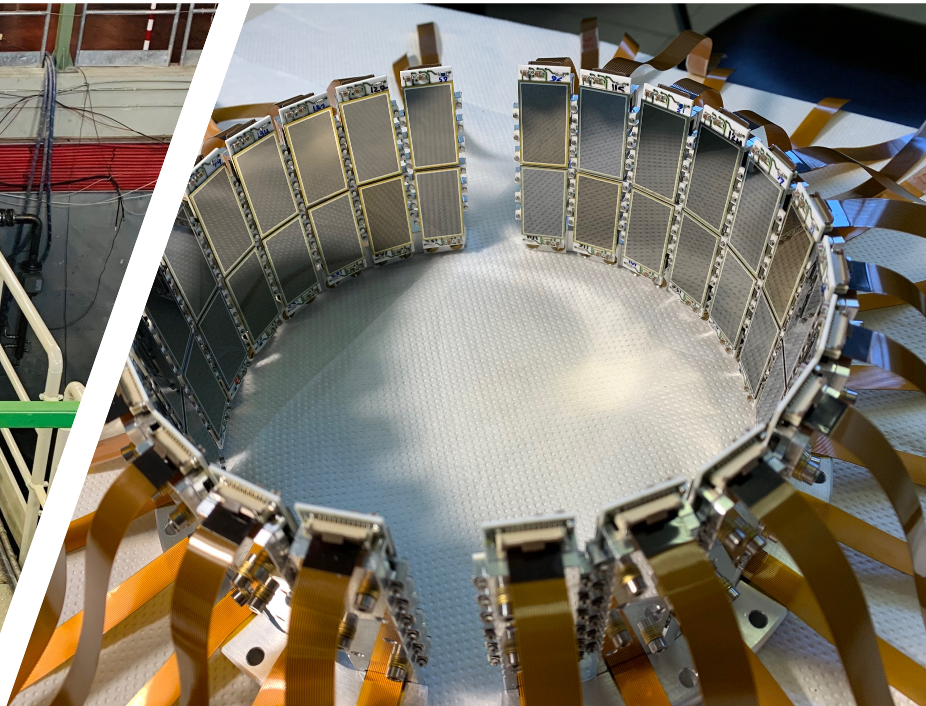
SIDDHARTA-2
Kaonic ^{4}He – M-type transitions

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

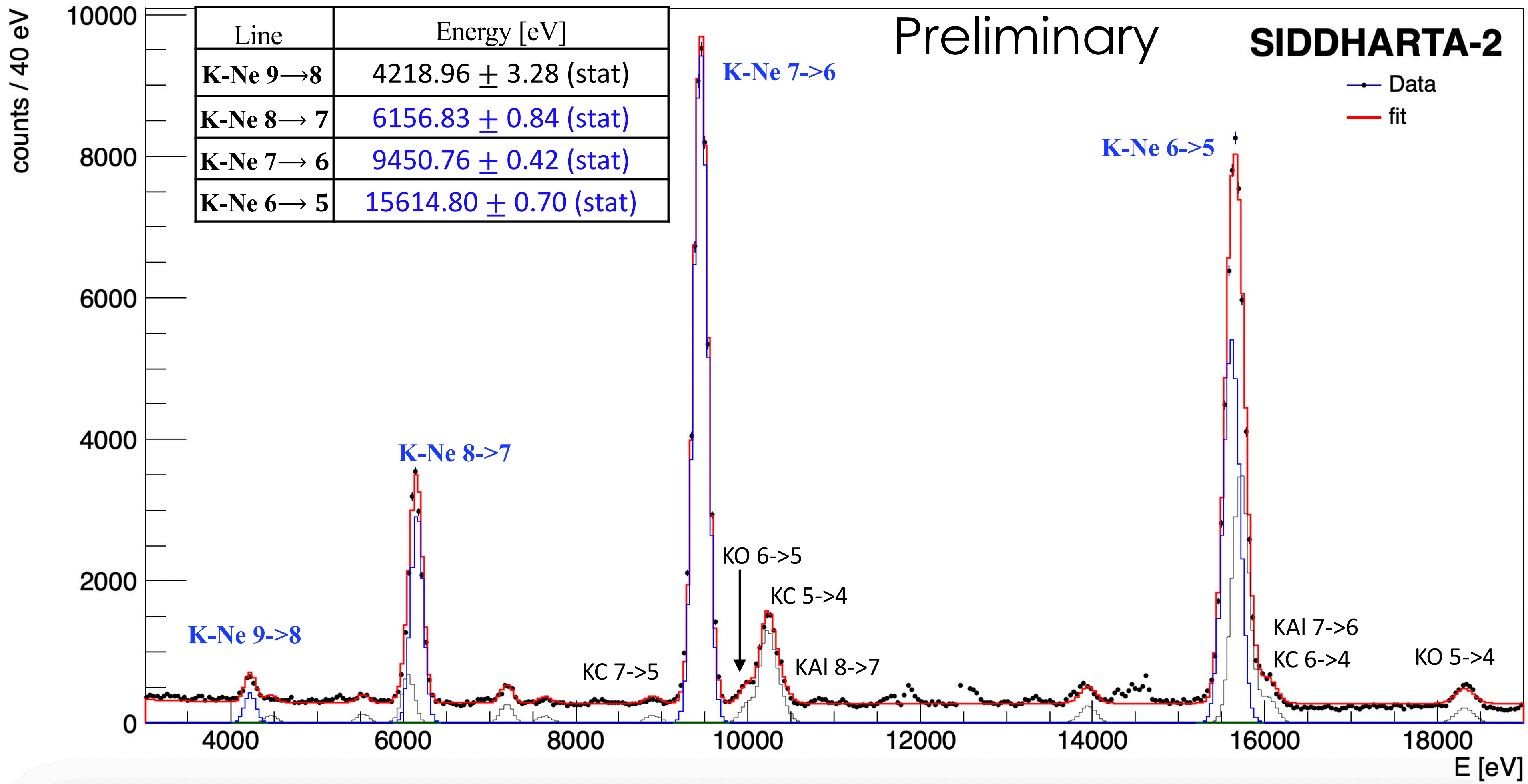
	X-ray relative yield
M_γ / M_β	0.48 $\pm$ 0.11
M_η / M_β	0.43 $\pm$ 0.12
L_β / M_β	0.91 $\pm$ 0.14
L_β / L_α	0.172 $\pm$ 0.008
L_γ / L_α	0.012 $\pm$ 0.001





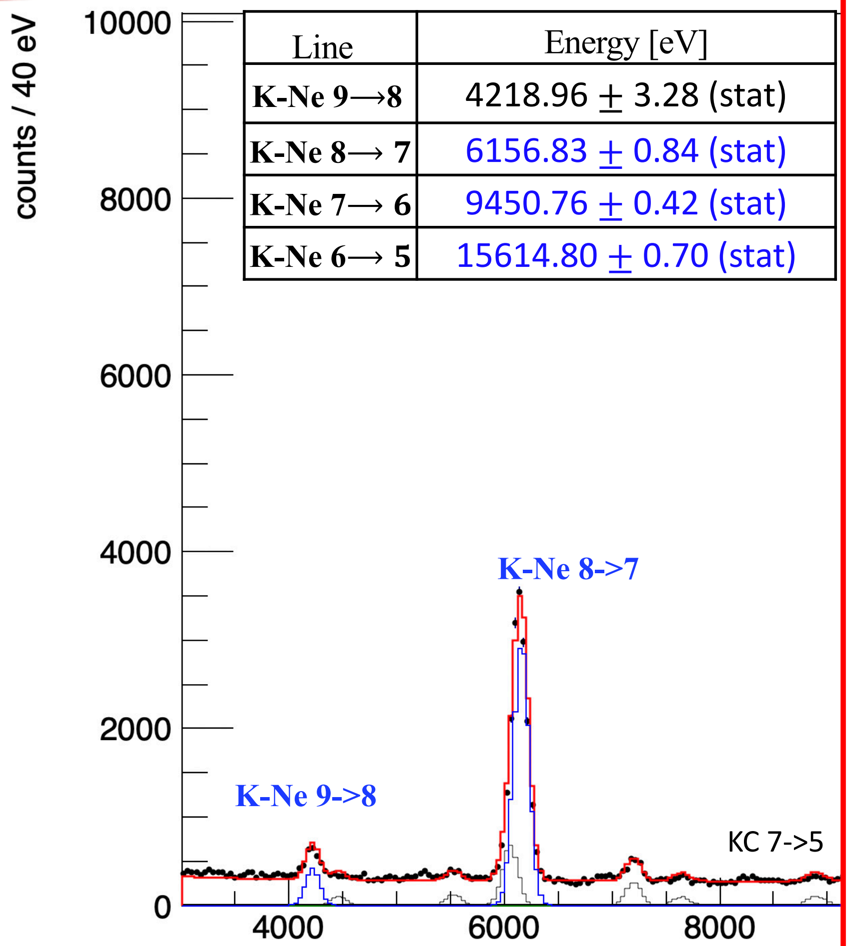
SIDDHARTA-2 Kaonic Neon (2023)



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)



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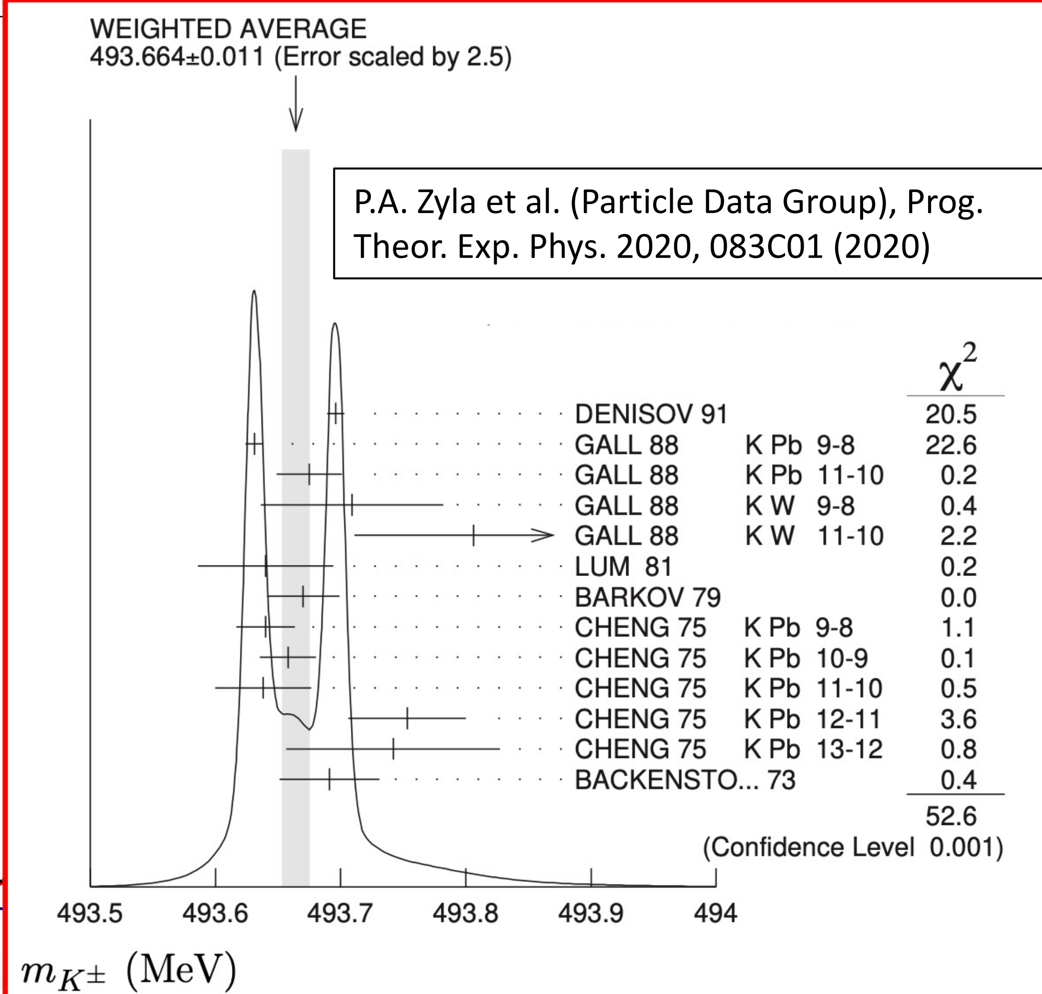
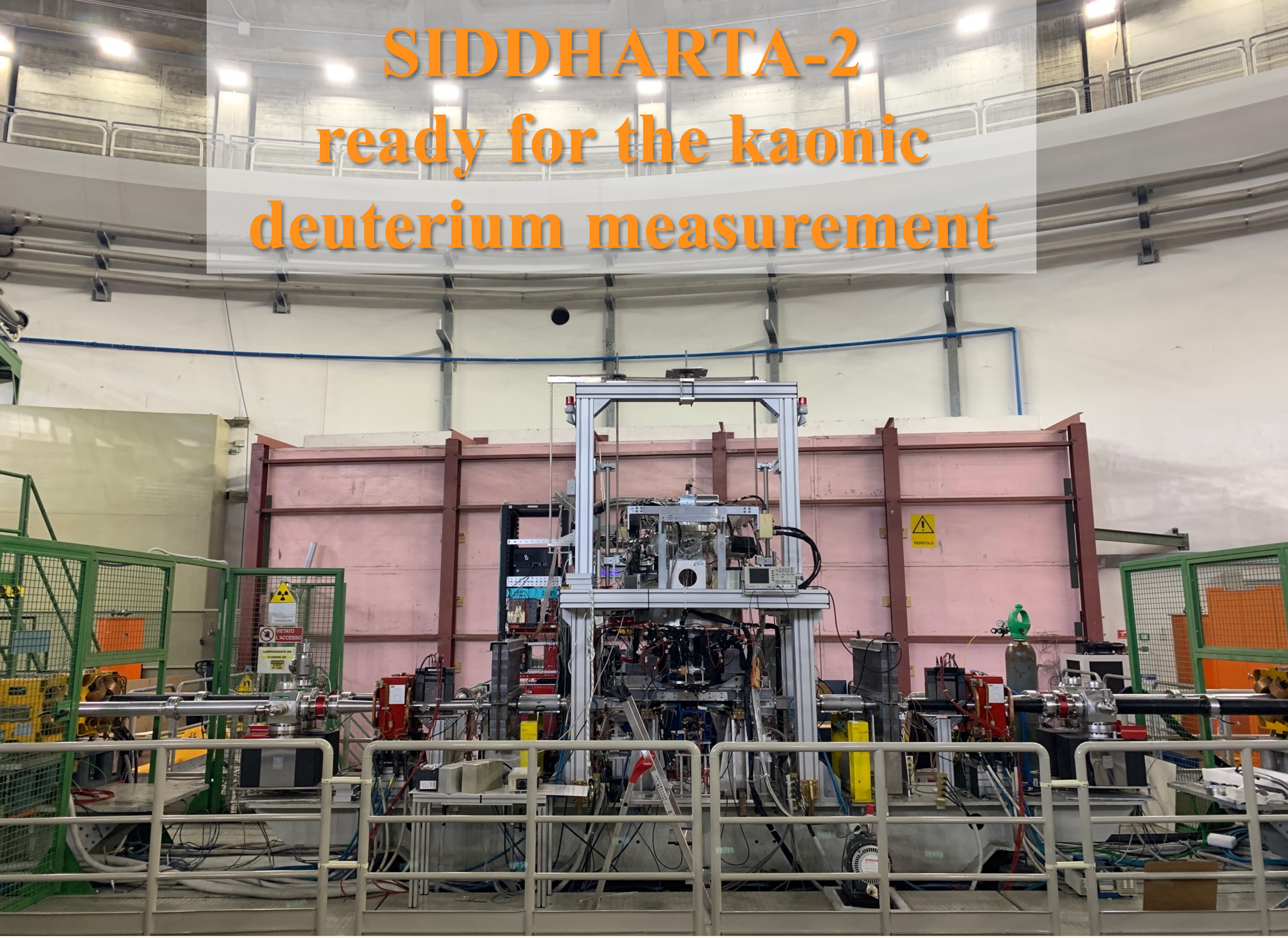


First K-Ne measurements – possible implications on K- multinucleon interaction and kaon mass

SIDDHARTA-2 ready for the kaonic deuterium measurement



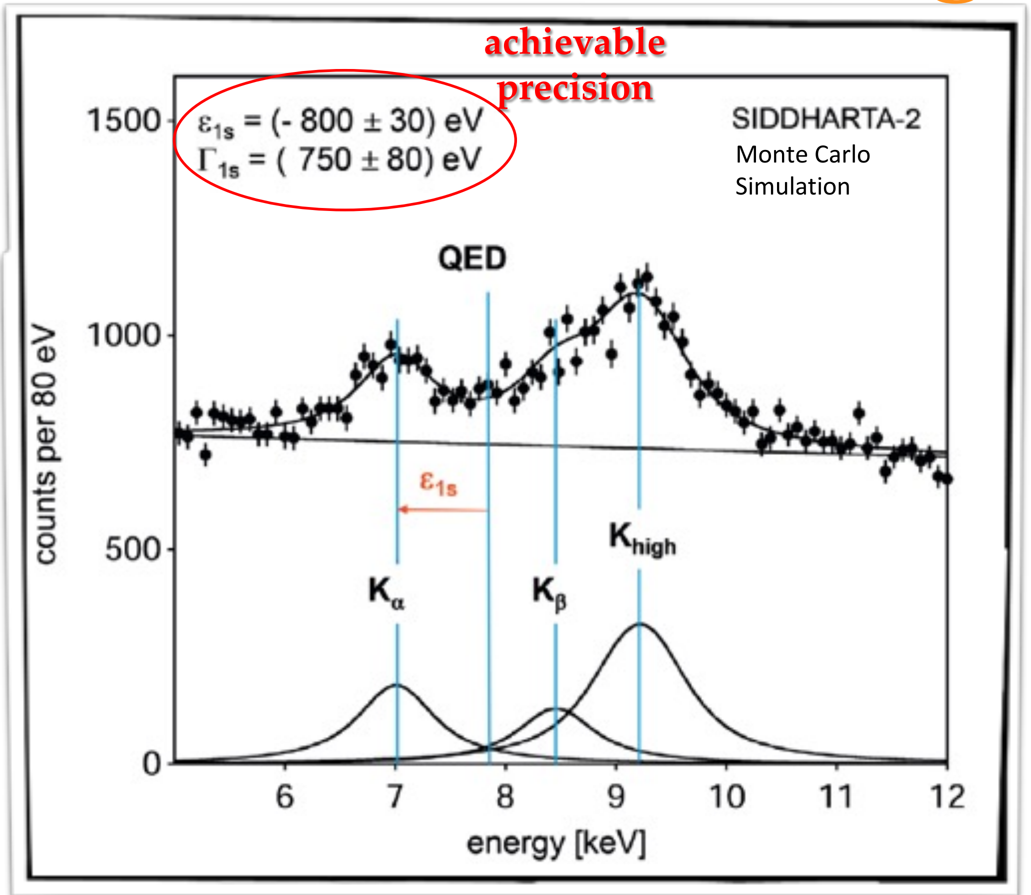
Kaonic deuterium data taking

Kaonic deuterium run ongoing

2023/24

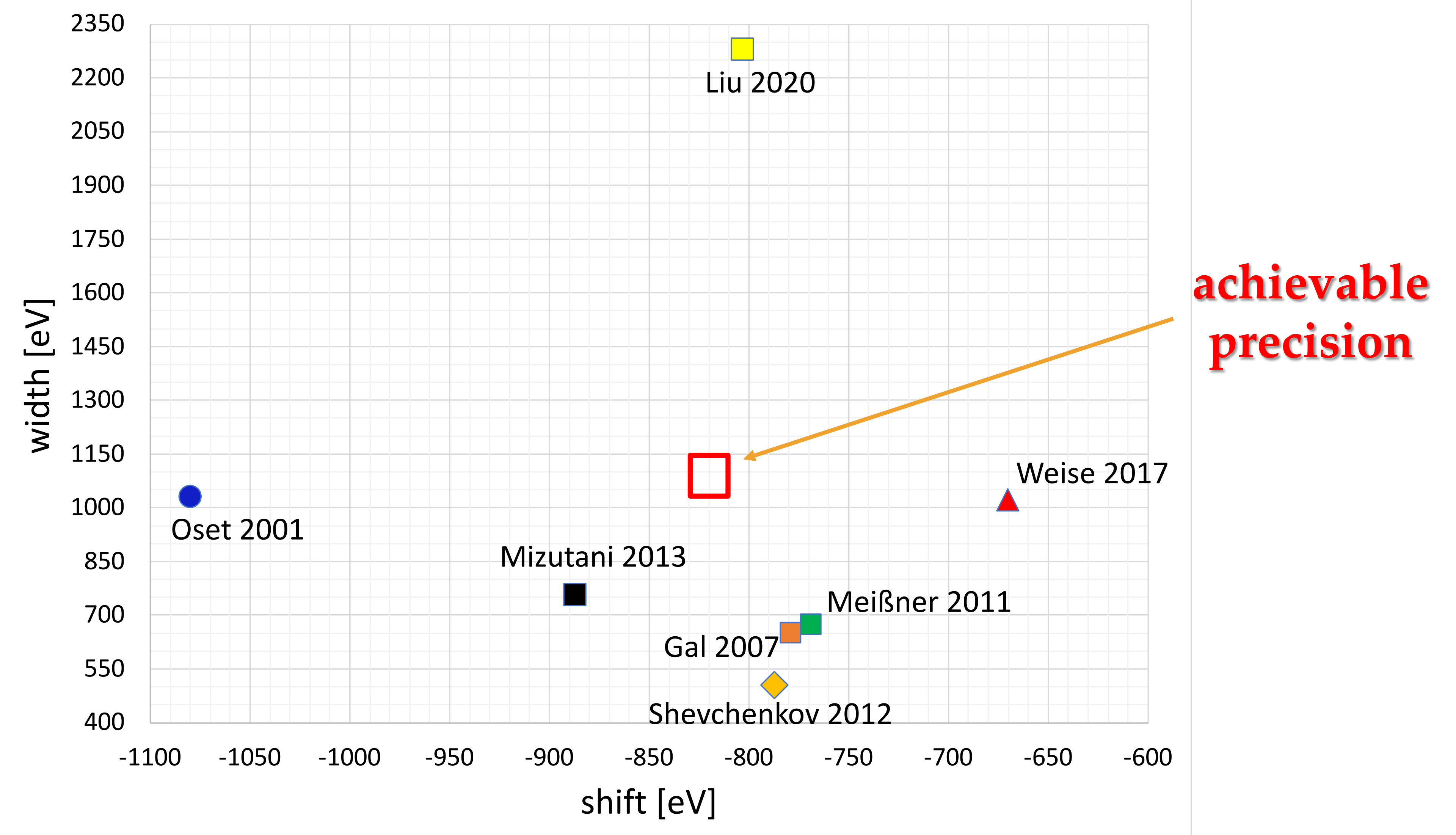
Monte Carlo for an integrated luminosity of 800 pb^{-1}

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) !

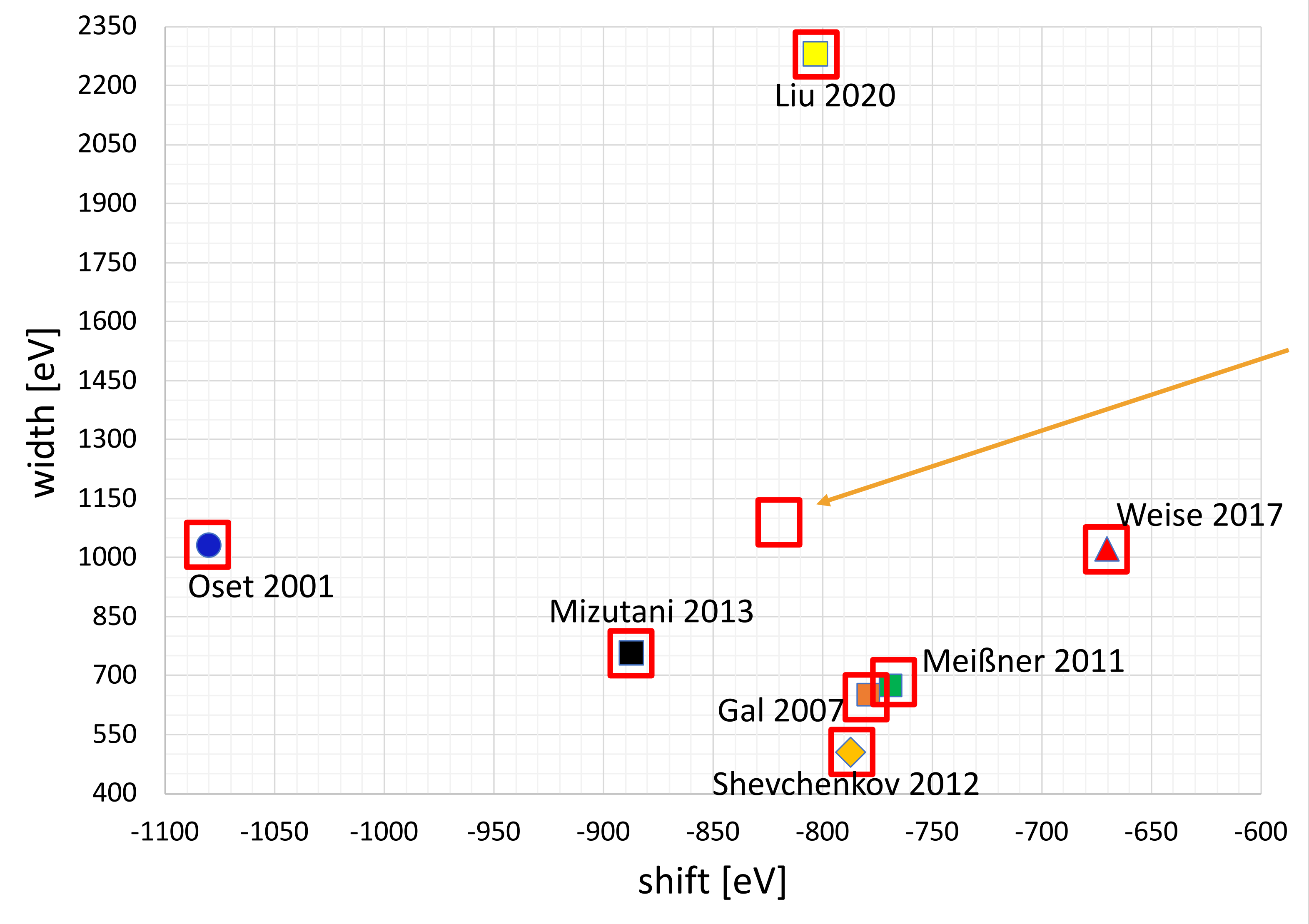


Significant impact in the theory of strong interaction with strangeness

Kaonic deuterium shift and width



Kaonic deuterium shift and width



achievable precision

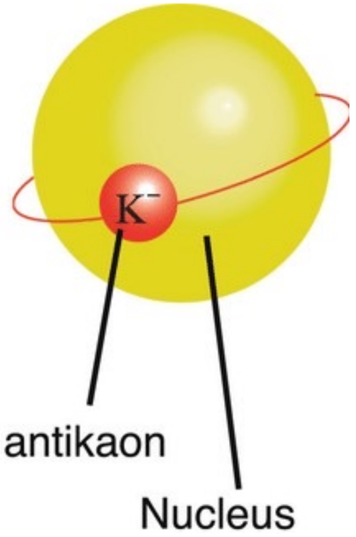
Beyond SIDDHARTA-2: EXKALIBUR

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

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

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)**



EXKALIBUR

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

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

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

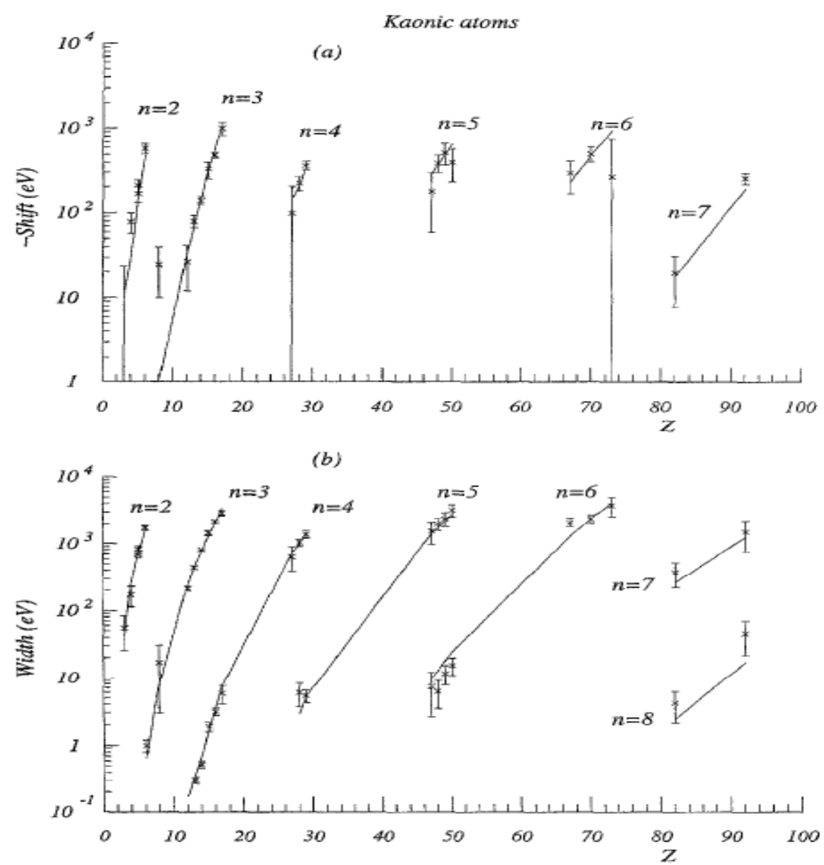


Fig. 7. Shift and width values for kaonic atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 4.2.

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

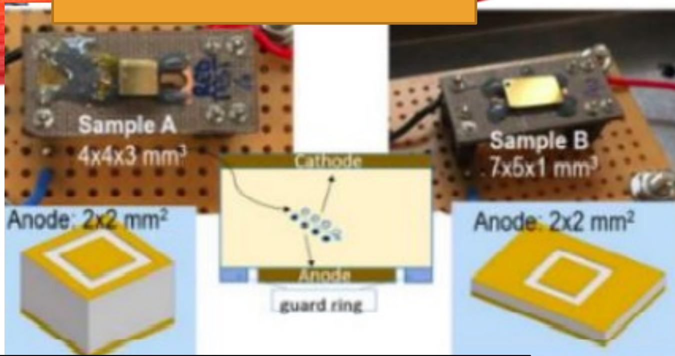
This situation would already be a proper justification for new measurements

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

Table 1
Compilation of K^- atomic data

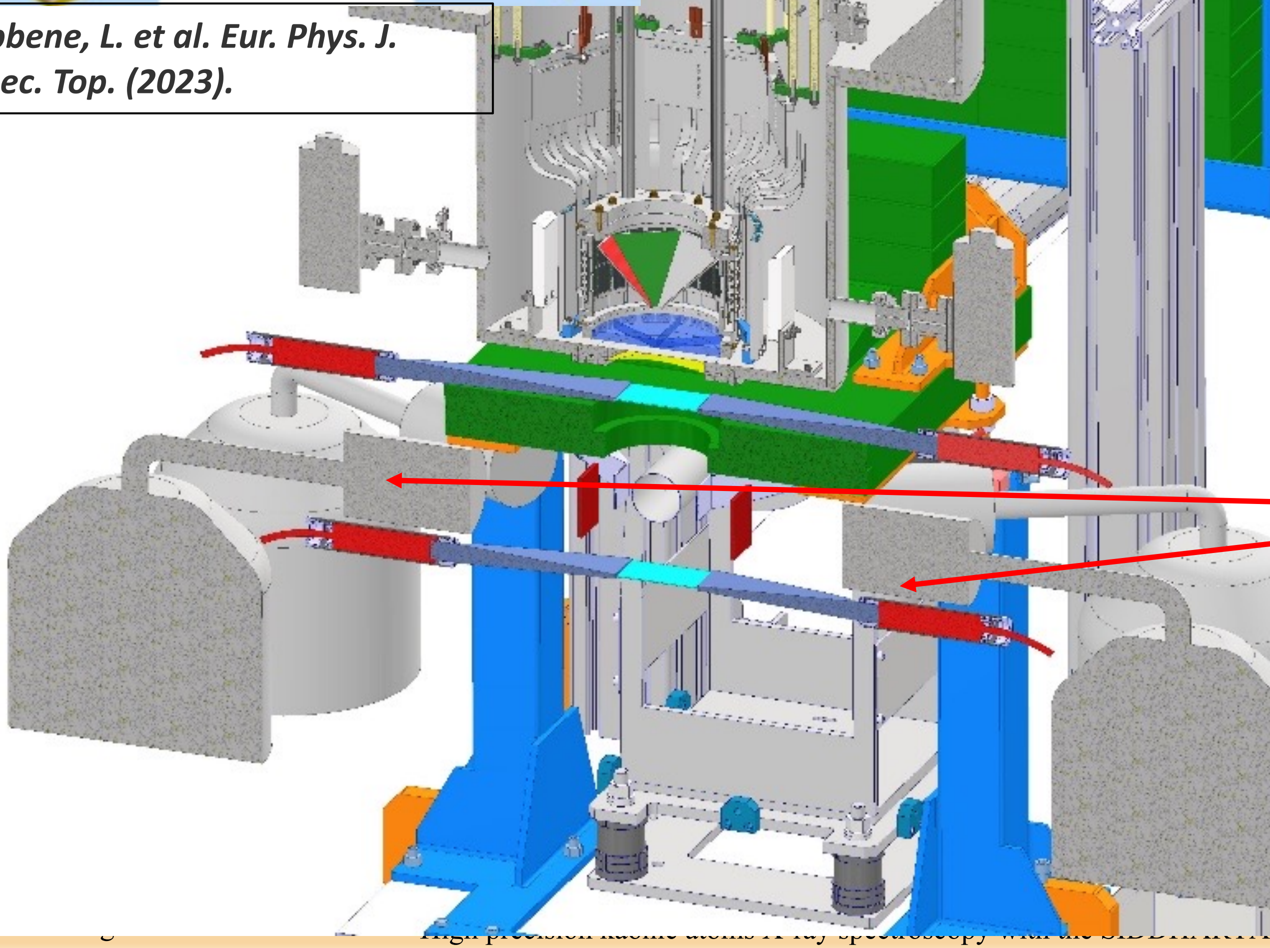
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3→2	−0.04 ±0.03	–	–	–	[15]
		−0.035±0.012	0.03 ±0.03	–	–	[16]
Li	3→2	0.002±0.026	0.055±0.029	0.95±0.30	–	[17]
Be	3→2	−0.079±0.021	0.172±0.58	0.25±0.09	0.04±0.02	[17]
^{10}B	3→2	−0.208±0.035	0.810±0.100	–	–	[18]
^{11}B	3→2	−0.167±0.035	0.700±0.080	–	–	[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]

Cd(Zn)Te

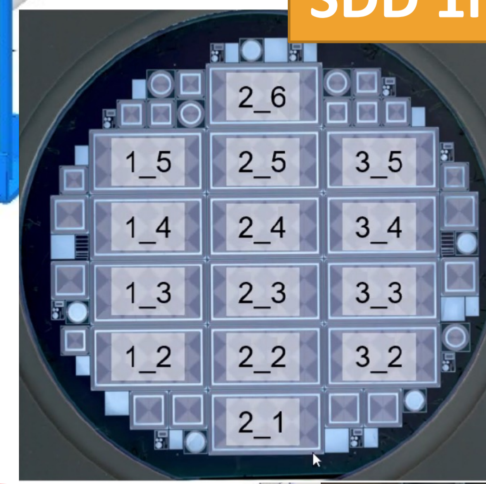


Abbene, L. et al. Eur. Phys. J. Spec. Top. (2023).

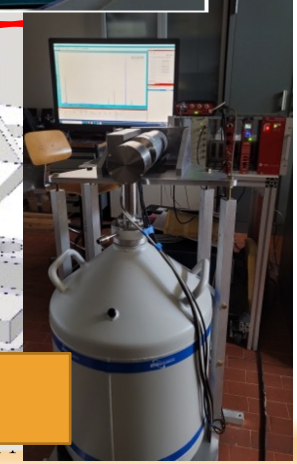
- **Feasibility studies in parallel with Siddharta-2**
- **Various setups in preparation:**
  - *HPGe*
  - *Crystal spectrometers (VOXES)*
  - *CdZnTe detectors*
  - *SDD 1mm for kaonic atoms measurement*



SDD 1mm



HPGe



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

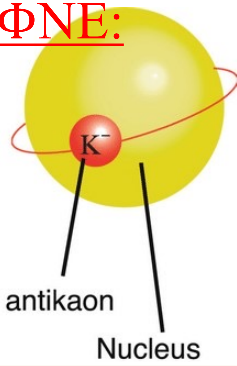
- **Measurement of Kaonic-Deuterium key to fully disentangle isospin dependence on KN scattering lengths**

- **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