Low-energy kaon-nuclei interaction studies at the DAΦNE collider: a strangeness Odyssey

Catalina Curceanu, INFN-LNF , Frascati (Italy)
on behalf of the SIDDHARTA-2 Collaboration

I dedicated this talk to my dear colleagues and friends Prof **Carlo Guaraldo and Dr. Johann Zmeskal who passed away in 2024**
you’ll be very much missed!

Odyssey

SIDDHARTA-2

SIlicon **D**rift **D**etector for **H**adronic **A**tom **R**esearch by **T**iming **A**pplications

HadronPhysics2 – Study of Strongly Interacting Matter

HadronPhysics I3 – Study of Strongly Interacting Matter

FWF Der Wissenschaftsfonds.

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
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
ELPH, Tohoku University

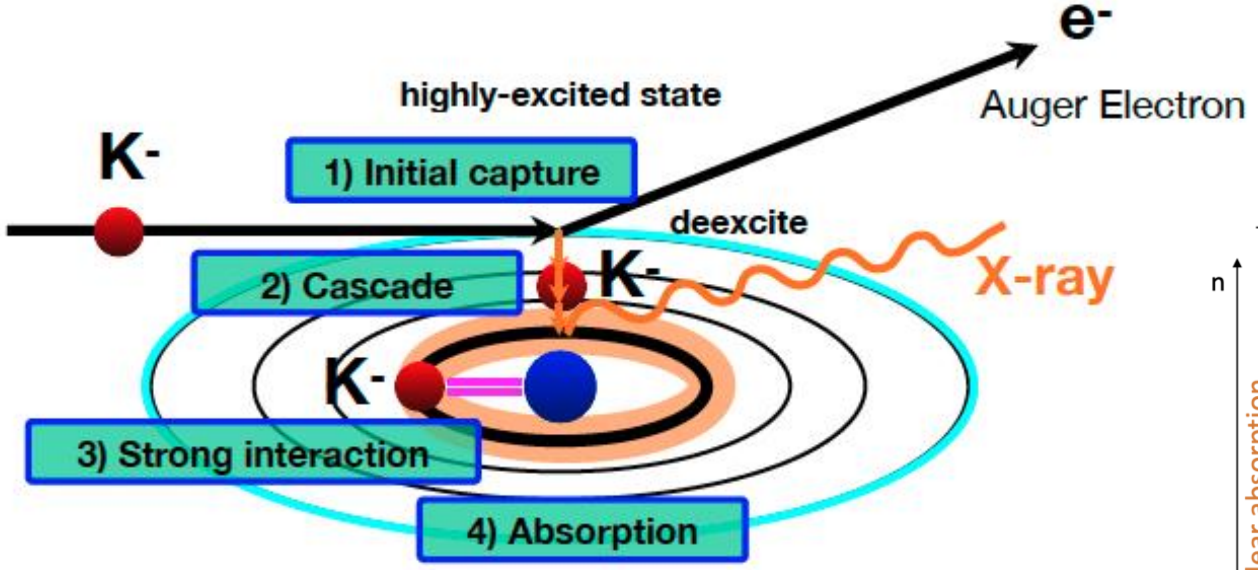
STRONG-2020

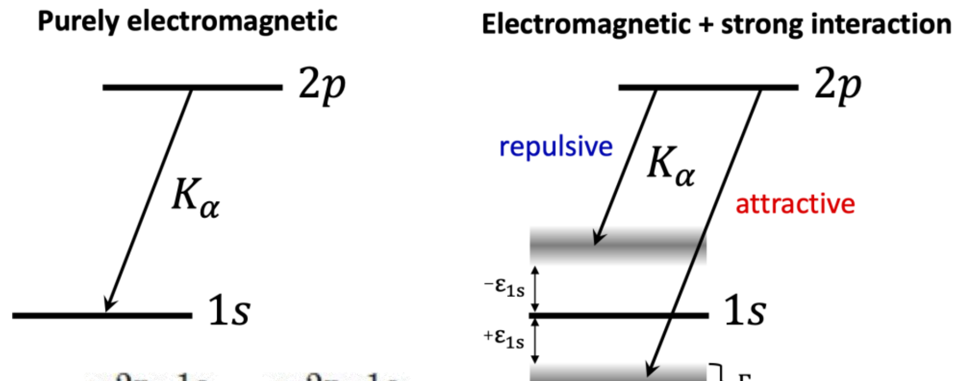
HRZZ Croatian Science Foundation

Farnesina Ministero degli Affari Esteri e della Cooperazione Internazionale

Kaonic Atoms X-ray Spectroscopy

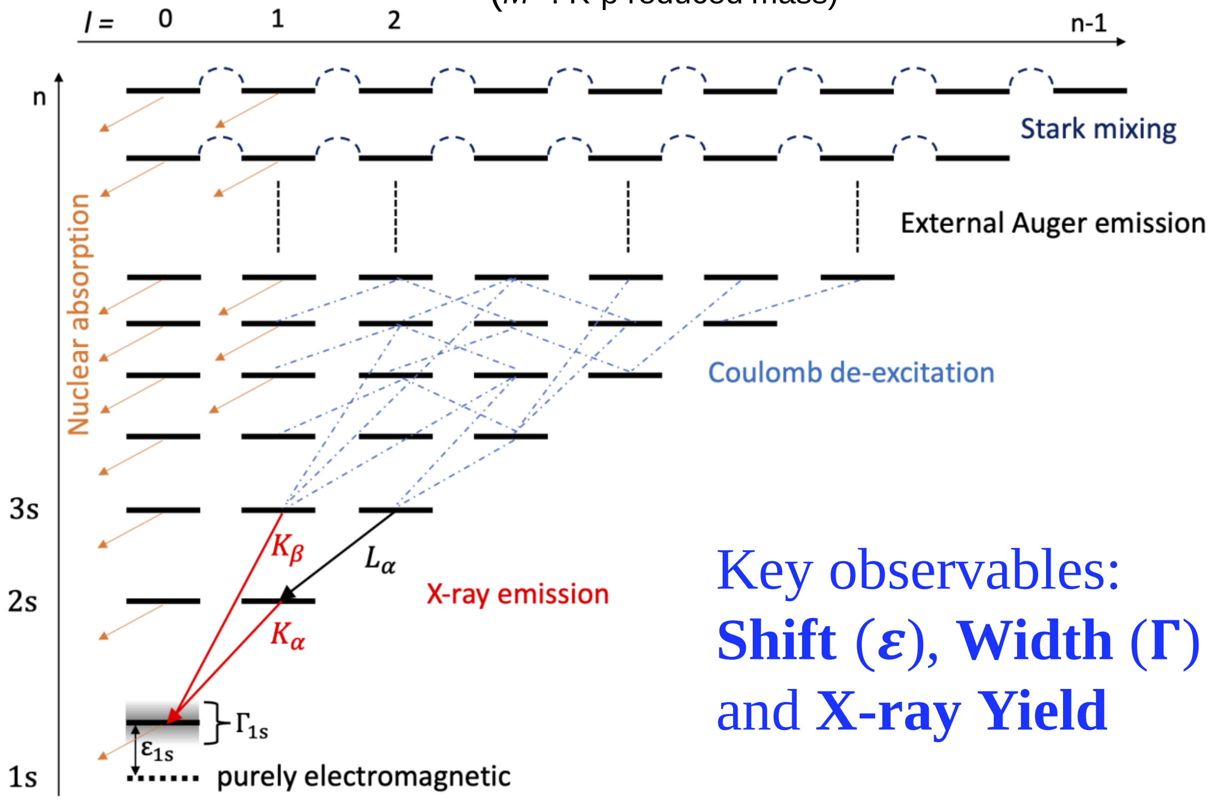
Kaonic atom formation





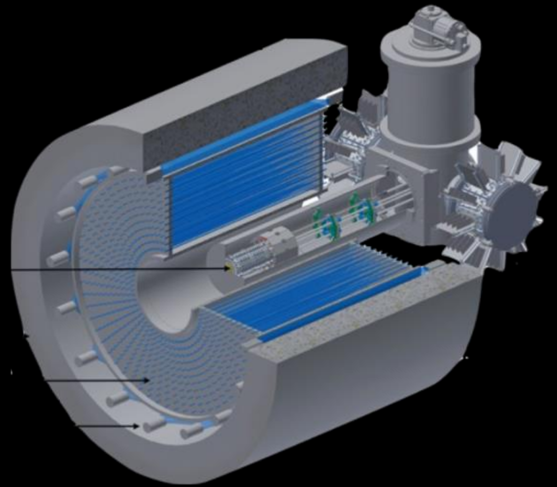
$$\varepsilon_{1s} = E^{2p-1s}_{\text{meas}} - E^{2p-1s}_{e.m.}$$

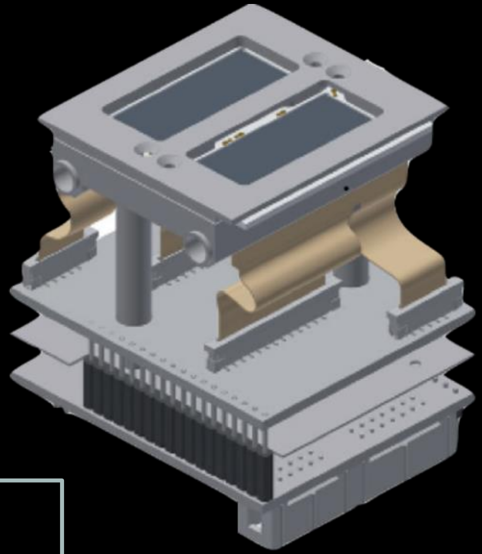
n ~ sqrt(M/mₑ) n' ~ 25 (for K-p)*
(*M** : K-p reduced mass)



Key observables:
Shift (ε), Width (Γ)
and **X-ray Yield**

A long journey





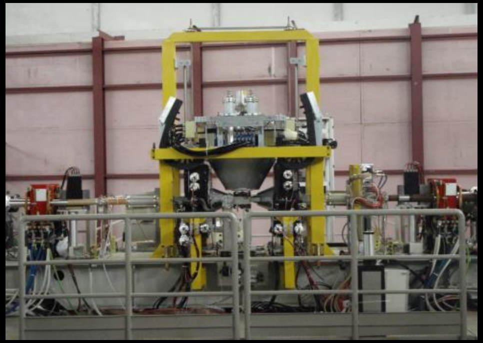
The modern era of light kaonic atom experiments

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

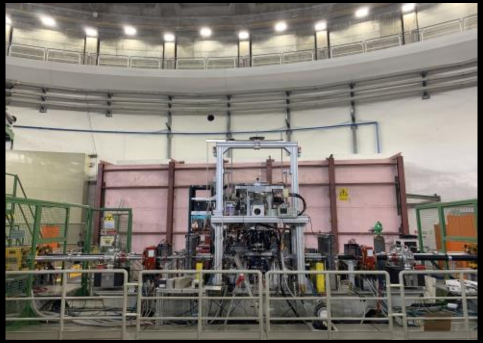
Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

DEAR 2002

SIDDHARTA 2009



SIDDHARTA-2 2022



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

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

Dark Matter studies

Fundamental physics, QED
New Physics

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

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

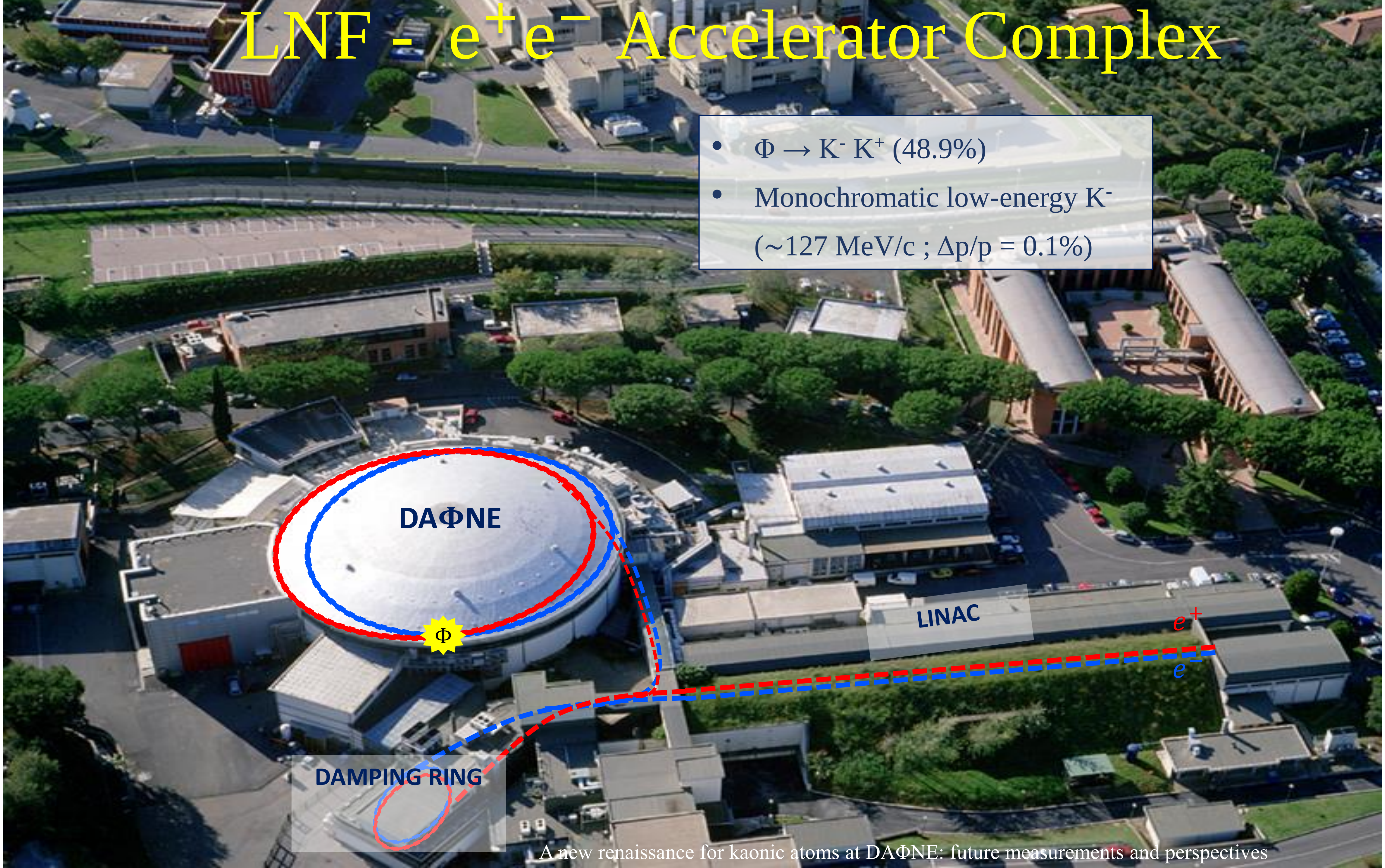
Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

Astrophysics
EOS Neutron Stars

The equation of state of dense matter

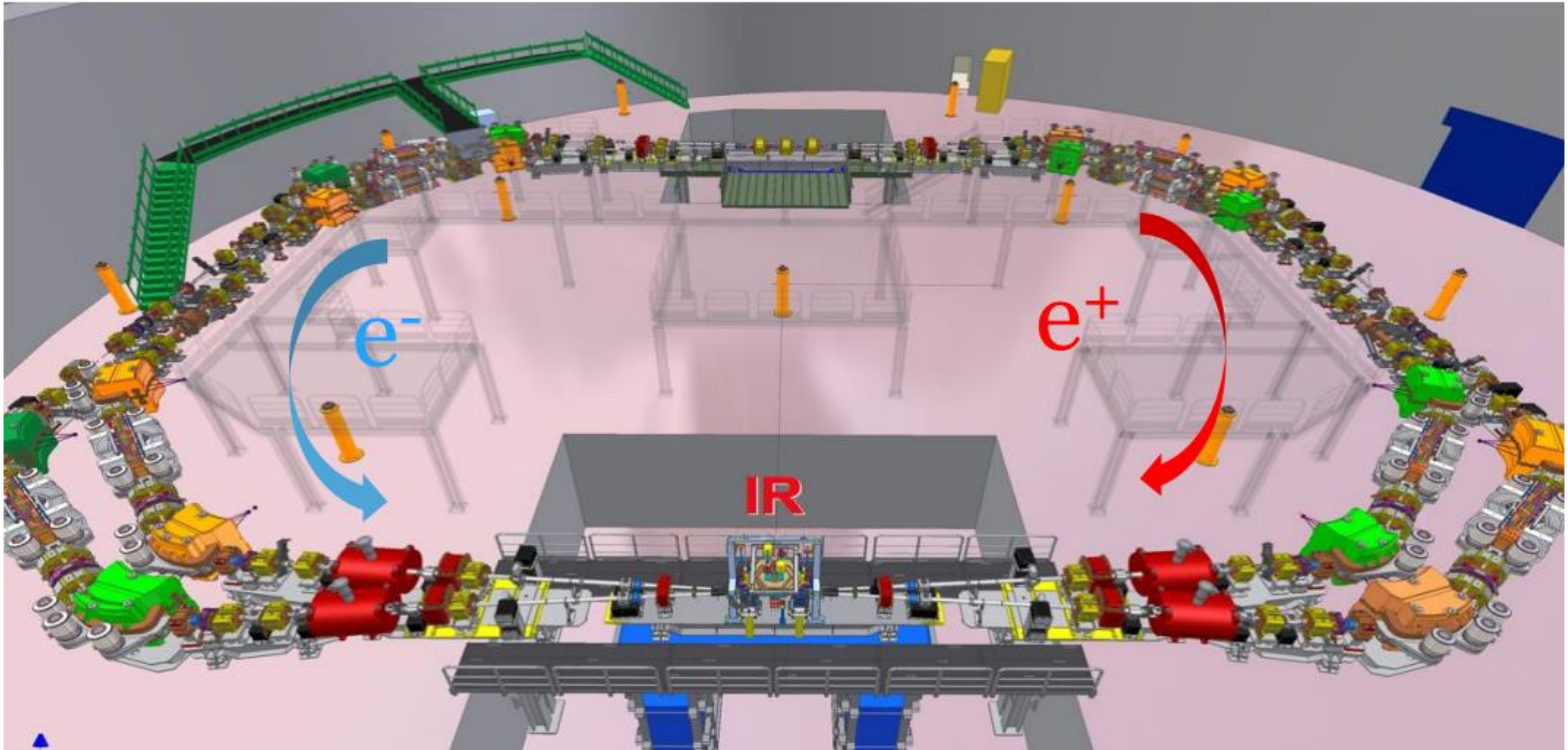
LNF - e^+e^- Accelerator Complex

- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)

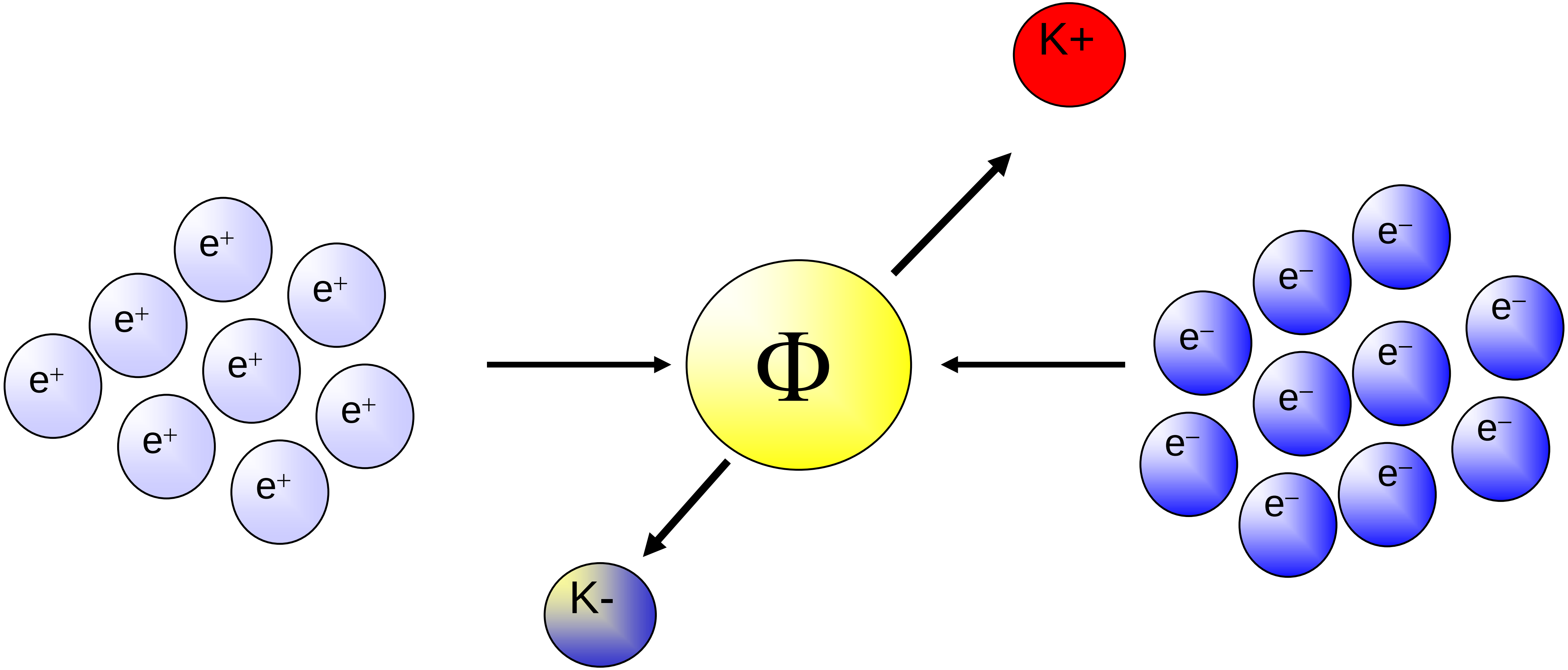


Laboratori Nazionali di Frascati (LNF-INFN)

- $\Phi \rightarrow K^- K^+$ (49.1%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)



The DAFNE principle



Flux of produced kaons: about 1000/second

DAFNE

$e^- e^+$ collider

- **$\Phi \rightarrow K^- K^+$** (49.1%)
- **Monochromatic low-energy K^-** (~127MeV/c)
- **Less hadronic background due to the beam**

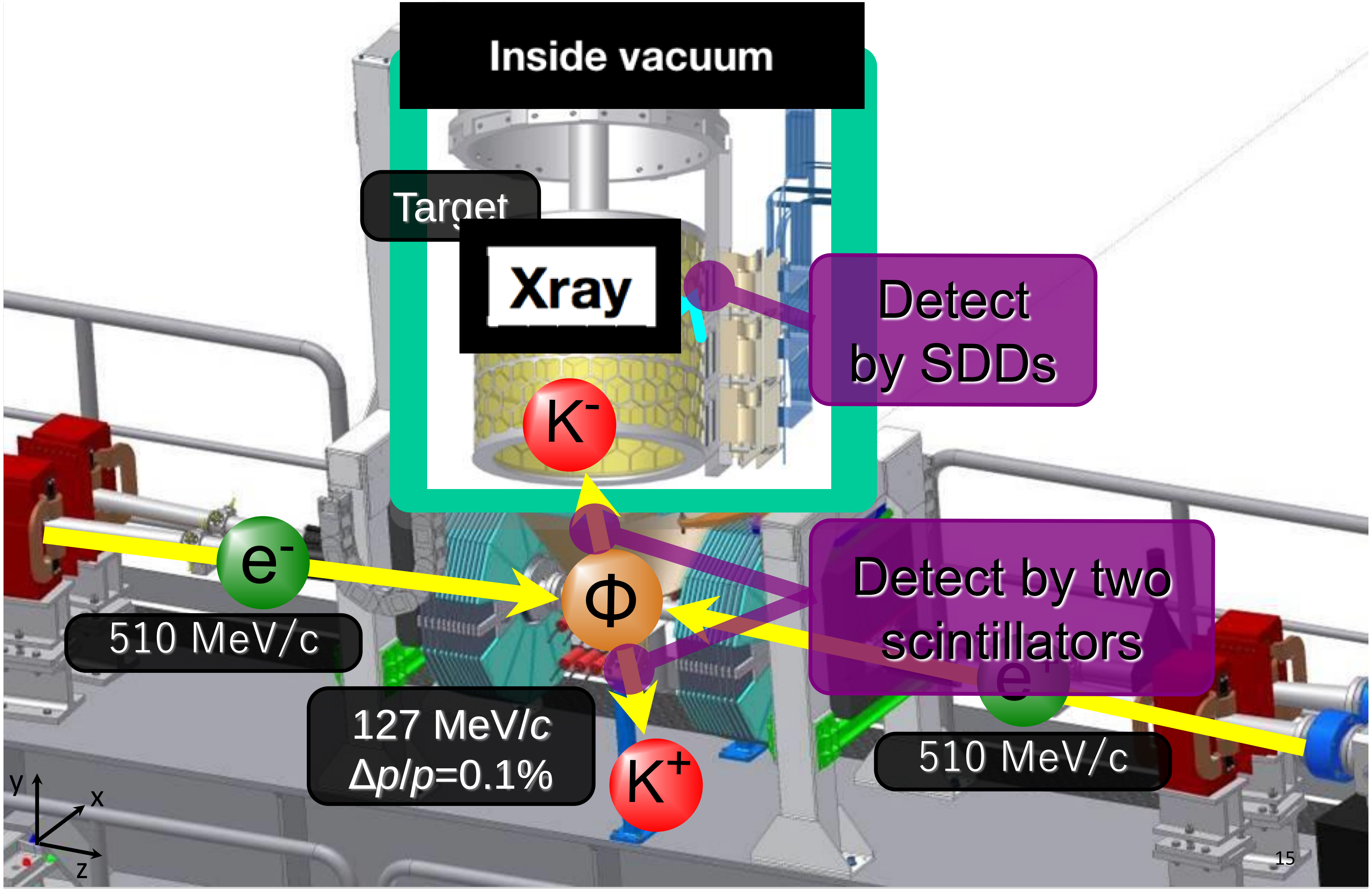
(comparing to hadron beam line : e.g. KEK /JPARC)

Suitable for low-energy kaon physics:

kaonic atoms

Kaon-nucleons/nuclei interaction studies

SIDDHARTA overview



SIDDHARTA - 2009

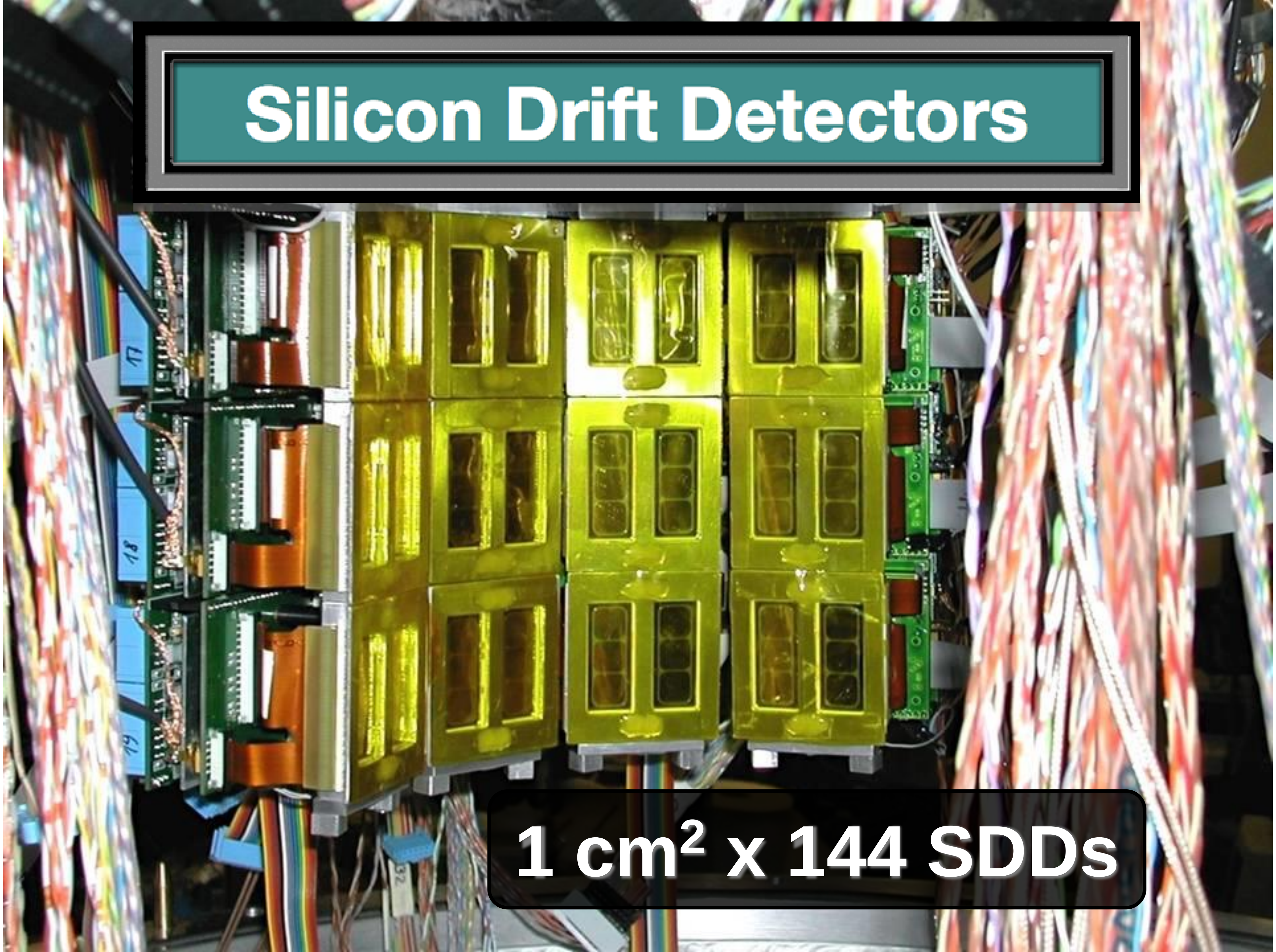
SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

- LNF- INFN, Frascati, Italy
- SMI- ÖAW, Vienna, Austria
- IFIN – HH, Bucharest, Romania
- Politecnico, Milano, Italy
- MPE, Garching, Germany
- PNSensors, Munich, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada

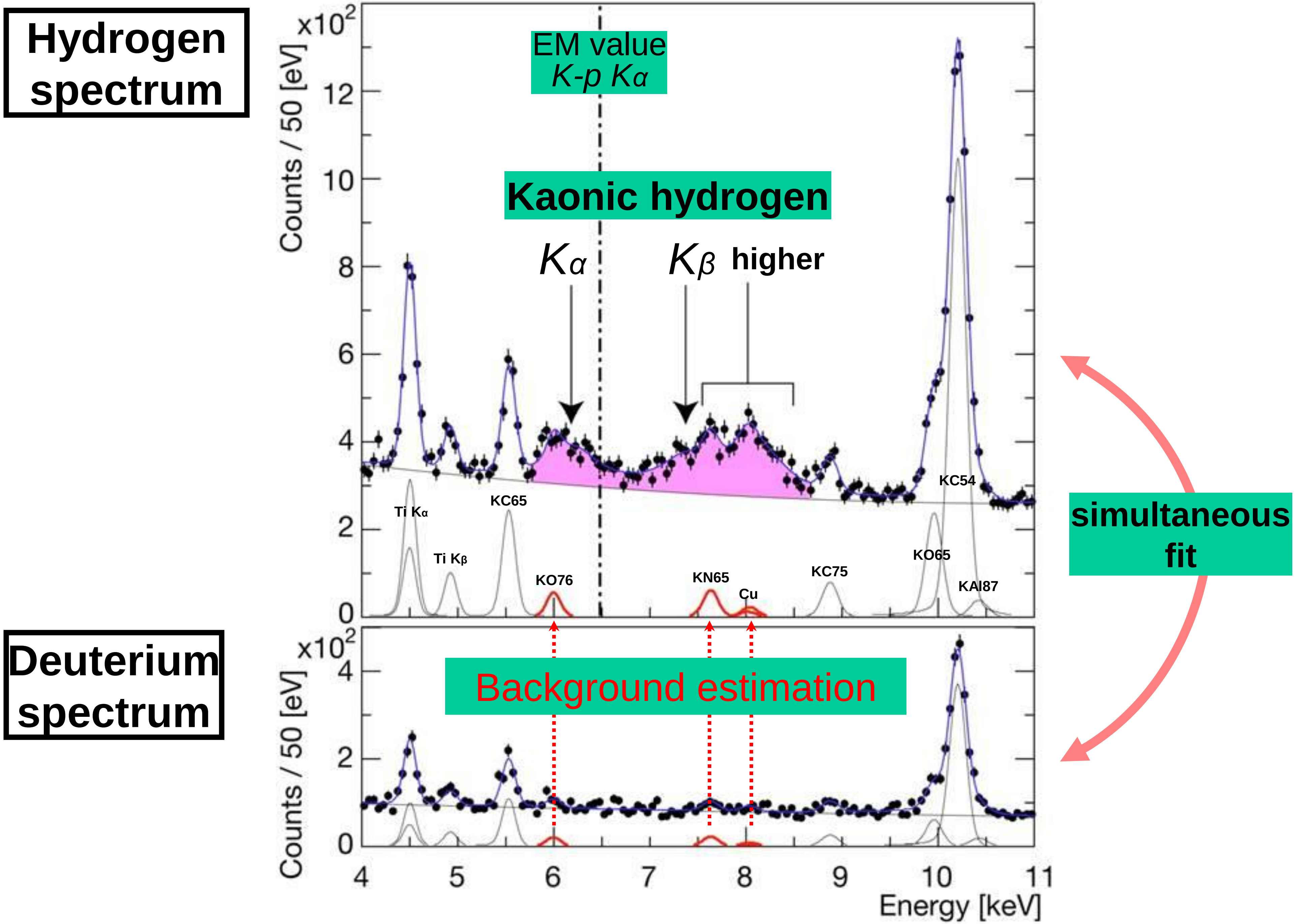
EU Fundings: JRA10 – FP6 - I3H
FP7- I3HP2

Rev.Mod.Phys. 91 (2019) 2, 025006

Silicon Drift Detectors



1 cm^2 x 144 SDDs



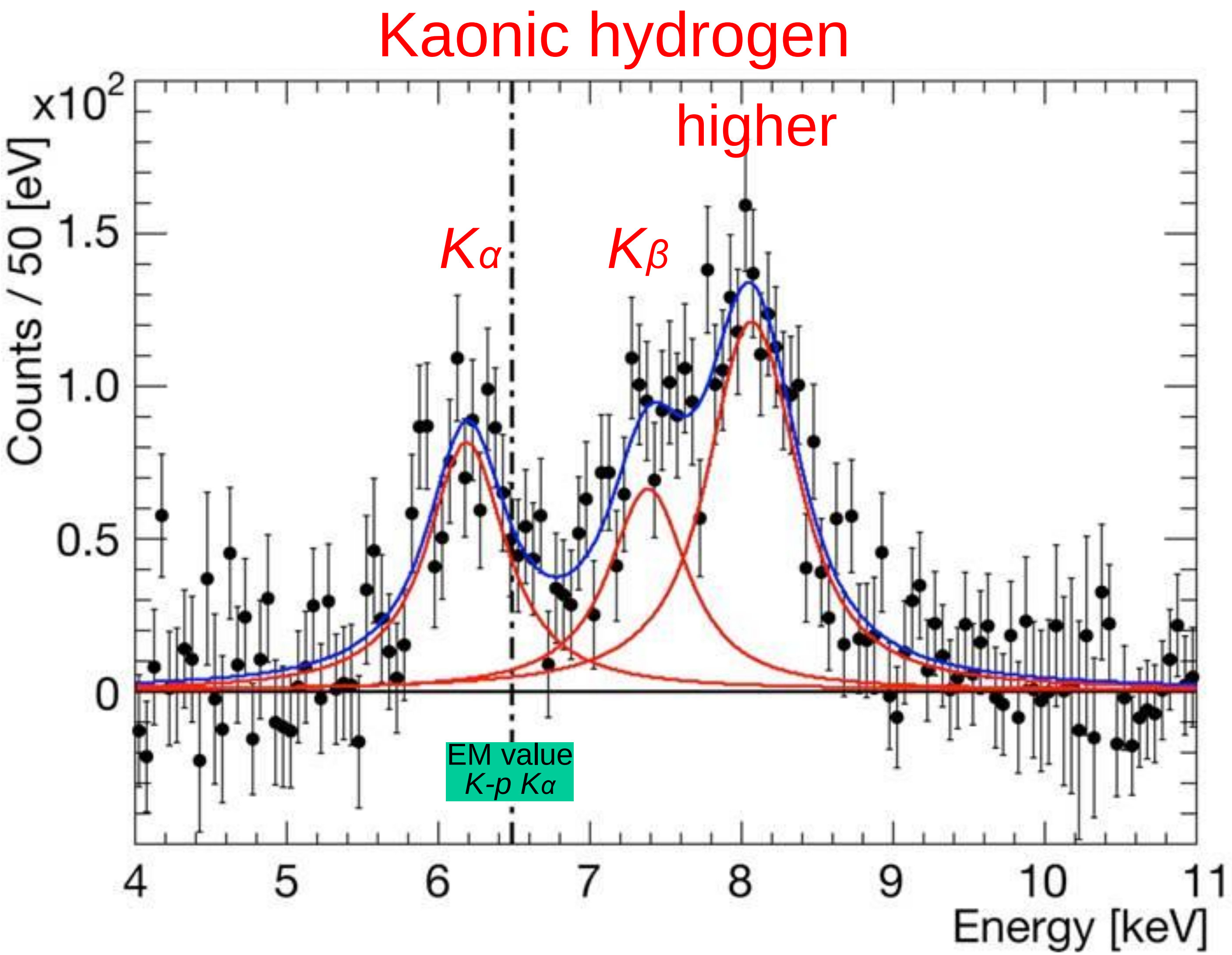
Hydrogen spectrum
Deuterium spectrum
x10^2
Counts / 50 [eV]
EM value
K-p Kα
Kaonic hydrogen
Kα
Kβ
higher
Ti Kα
Ti Kβ
KC65
KO76
KN65
Cu
KC75
KO65
KC54
KAl87
Background estimation
simultaneous fit
Energy [keV]

Residuals of K-p x-ray spectrum after subtraction of fitted background

$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})$ eV

$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})$ eV

>400 citations



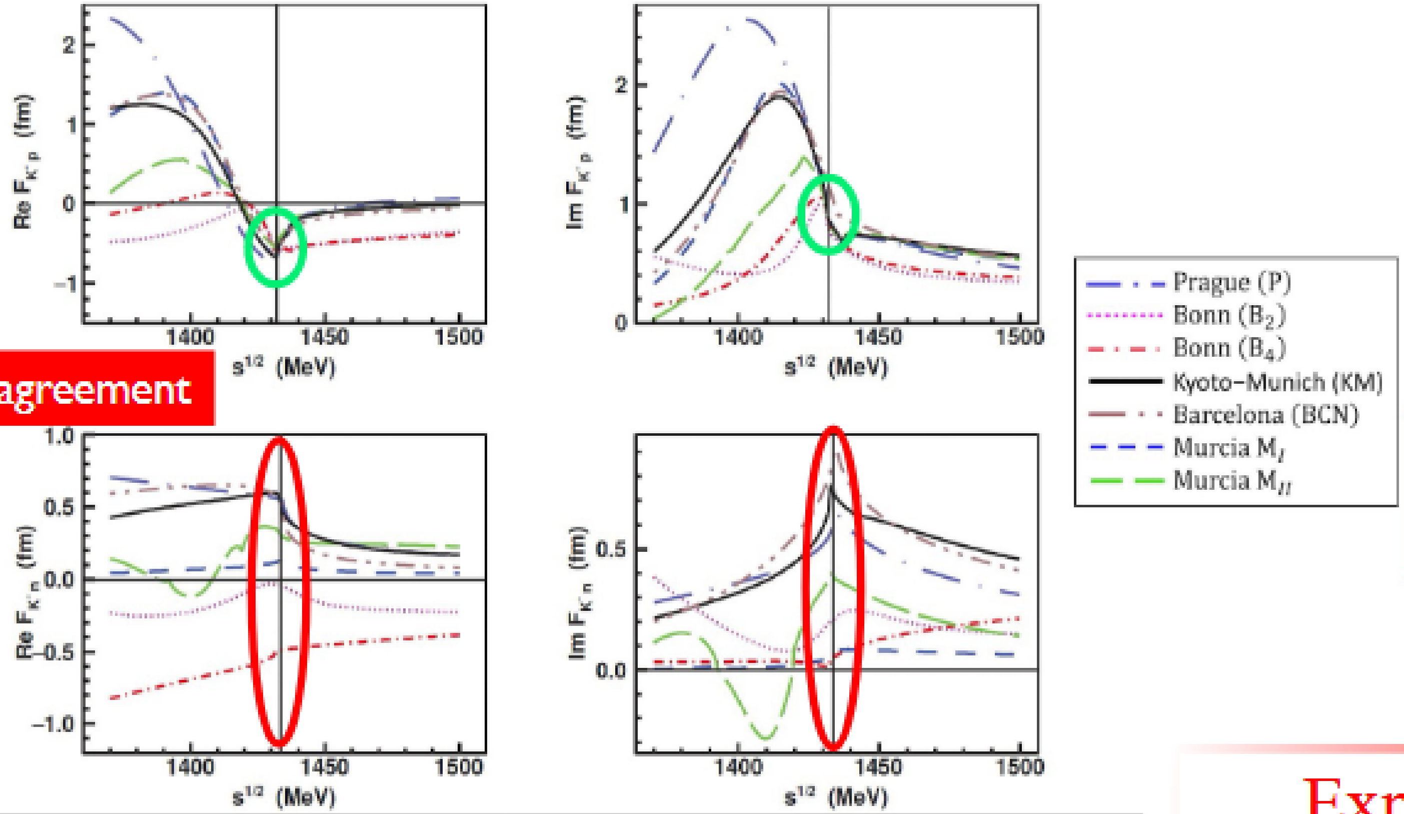
Phys. Lett. B 704 (2011) 113

The SIDDHARTA-2 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.

K-p: agreement

K-n: disagreement



Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

Combined analysis of the kaonic deuterium and kaonic hydrogen measurements

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

(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

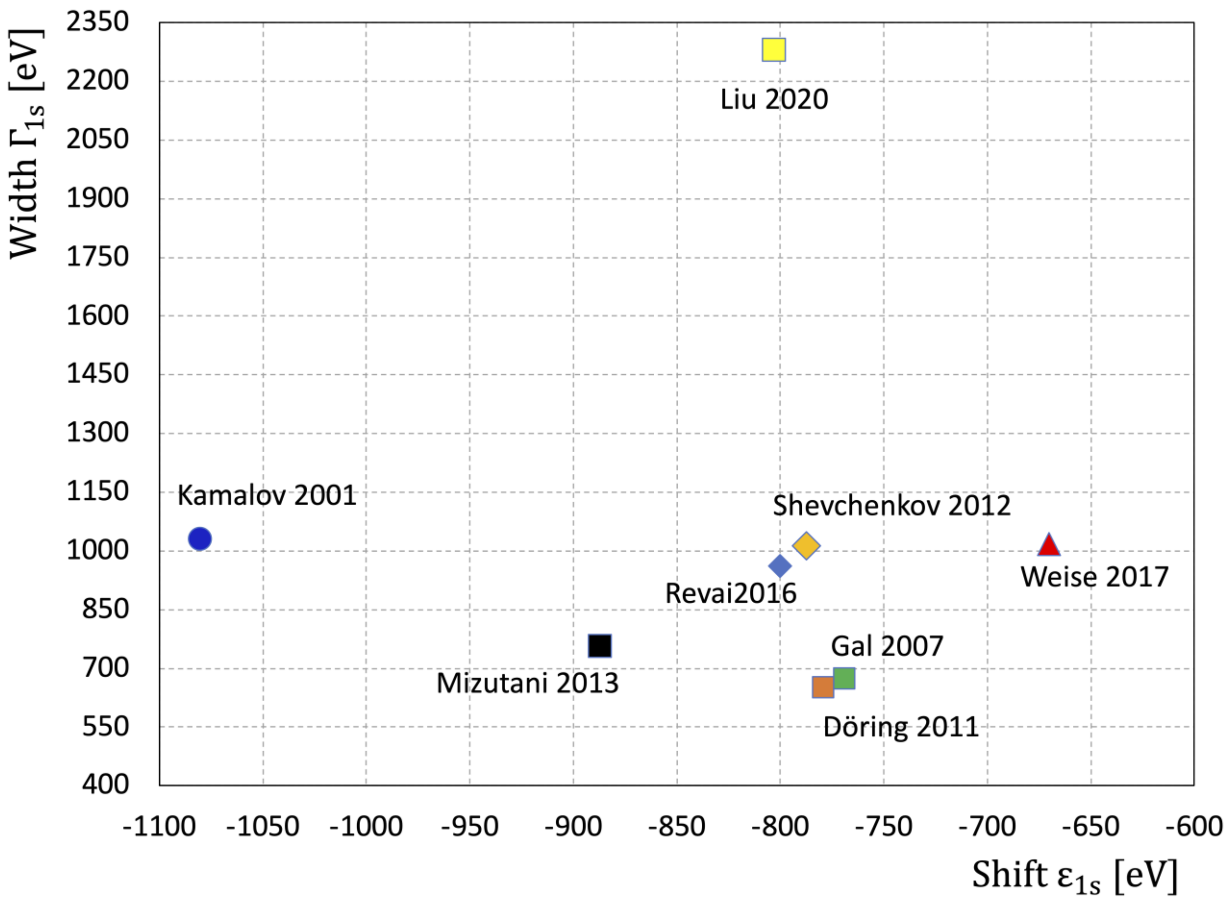
$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$
$$a_{K^-n} = a_1$$

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

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

The SIDDHARTA-2 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.

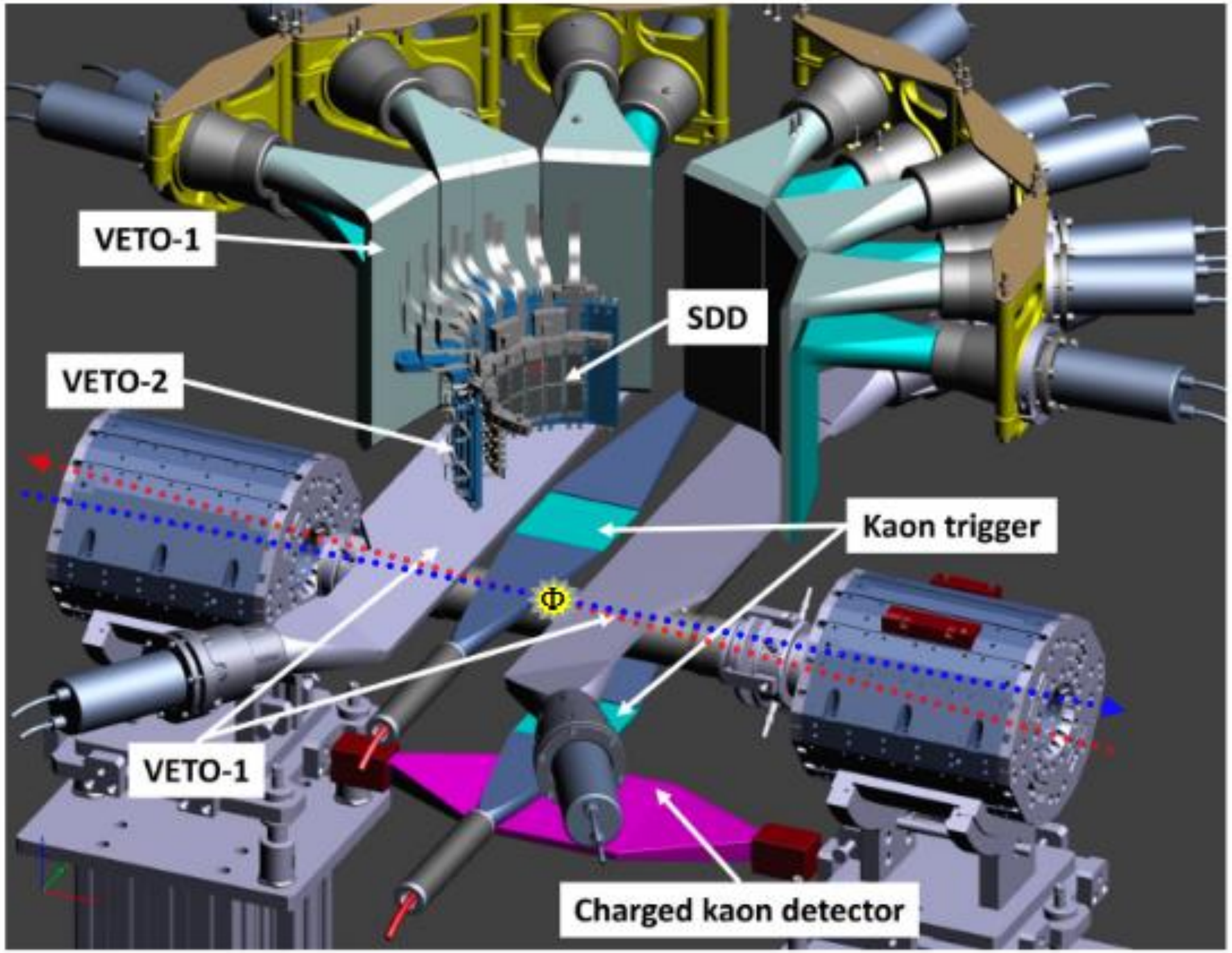


K-d transition energies predicted by QED (eV)					
K_α	K_β	$K_{complex}$			
2→1	3→1	4→1	5→1	6→1	7→1
7834.0	9280.2	9786.2	10020.4	10147.6	10224.3

Theoretical predictions for the kaonic deuterium 1s level shift and width

Reference	ε_{1s} (eV)	Γ_{1s} (eV)
Kamalov *et al.* (2001) [55]	-1080	1030
Gal (2007) [56]	-769	674
Döring *et al.* (2011) [57]	-779	650
Shevchenkov (2012) [58]	-787	1011
Mizutani *et al.* (2013) [59]	-887	757
Revai (2016) [60]	-800	960
Weise *et al.* (2017) [61]	-670	1016
Liu *et al.* (2020) [62]	-803	2280

The SIDDHARTA-2 apparatus

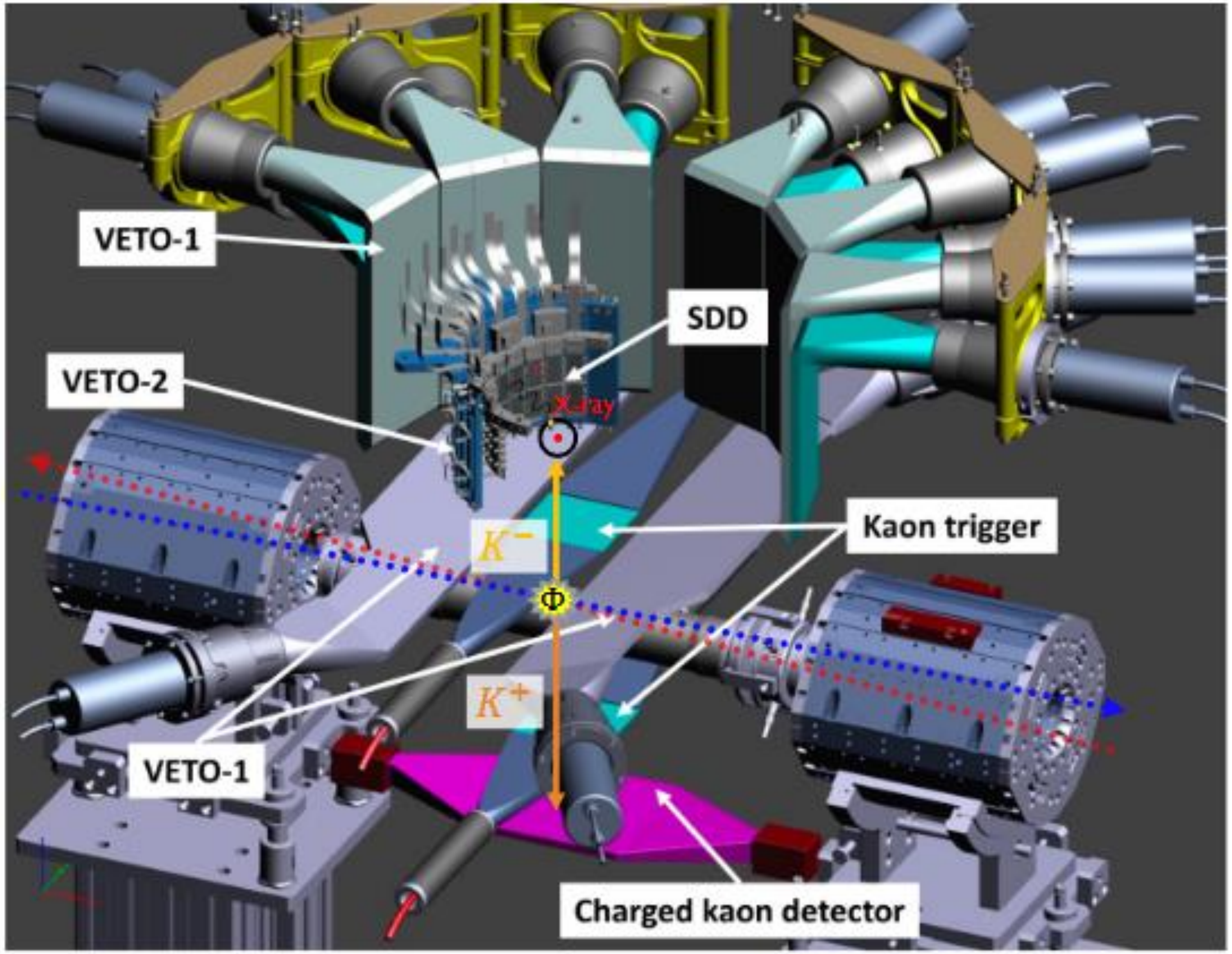


-Asynchronous background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect. → Kaon Trigger and SDDs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

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

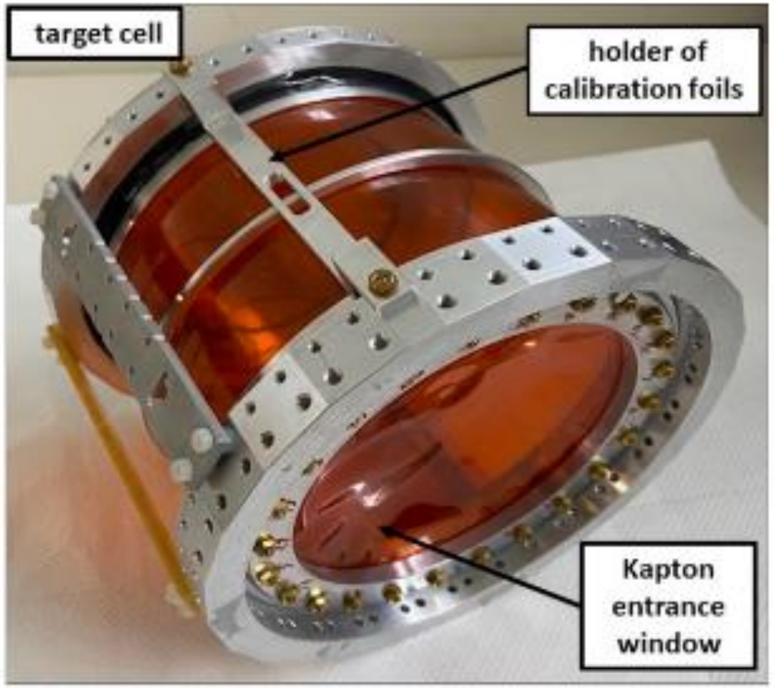
-Spectra contamination by Xray fluorescence or by X-rays produced in higher transitions of other kaonic atoms, formed in the setup materials; → Veto systems

The SIDDHARTA-2 apparatus



Kaon Trigger: two plastic scintillators read by photomultipliers placed above and below the interaction region.

Cryogenic gaseous target cell surrounded by **384 SDDs**

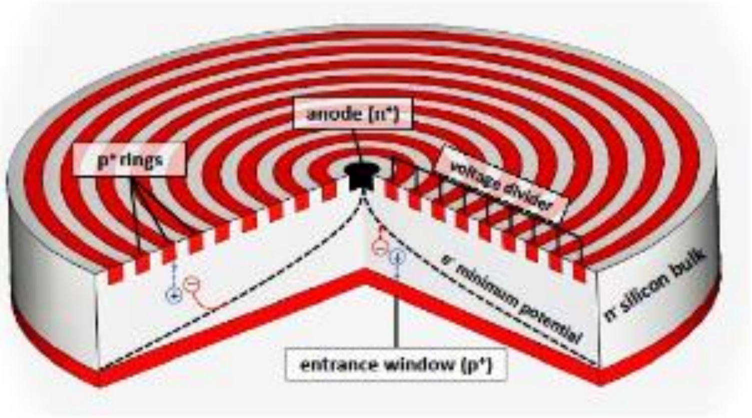


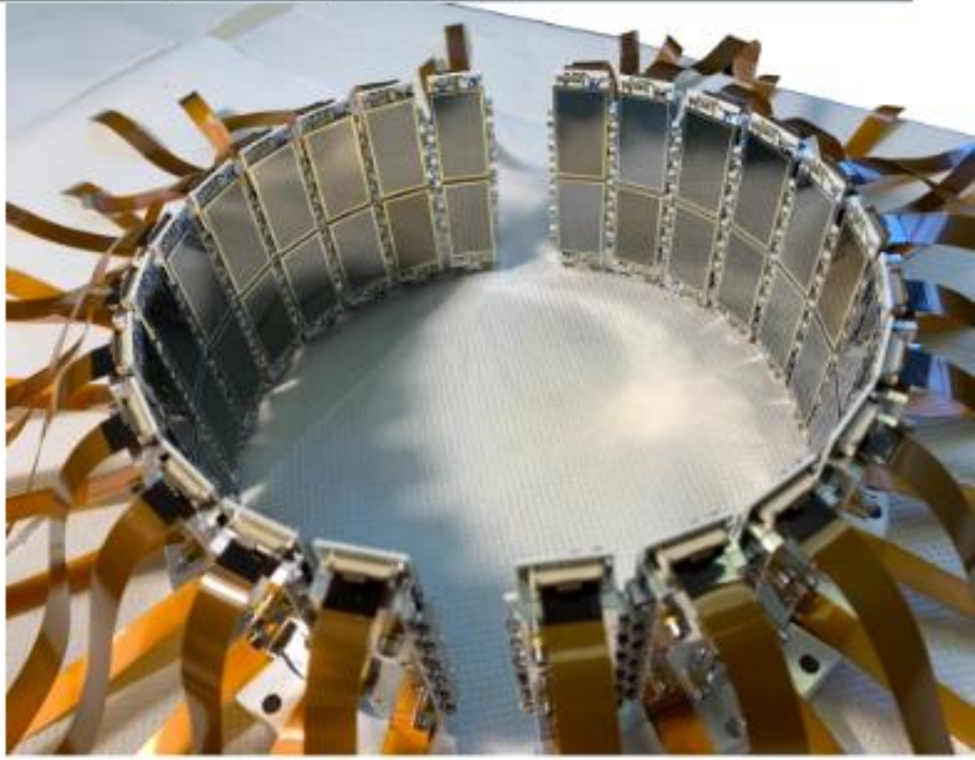
Silicon Drift Detectors (2020-2021)

Large area Silicon Drift Detectors (SDDs) have been developed to perform high precision kaonic atoms X-ray spectroscopy

8 SDD units (0.64 cm^2) for a total active area of 5.12 cm^2

Thickness of 450 µm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV



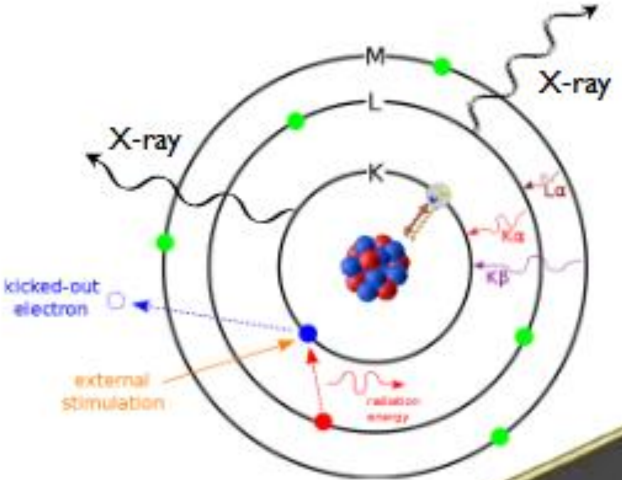


The spectroscopic response of 384 SDDs has been characterized before the installation in the SIDDHARTA-2 setup

SIDDHARTA-2 installed on DAFNE

KAONIC ATOMS MEASUREMENTS

First kaonic deuterium measurement (2023 -2024)



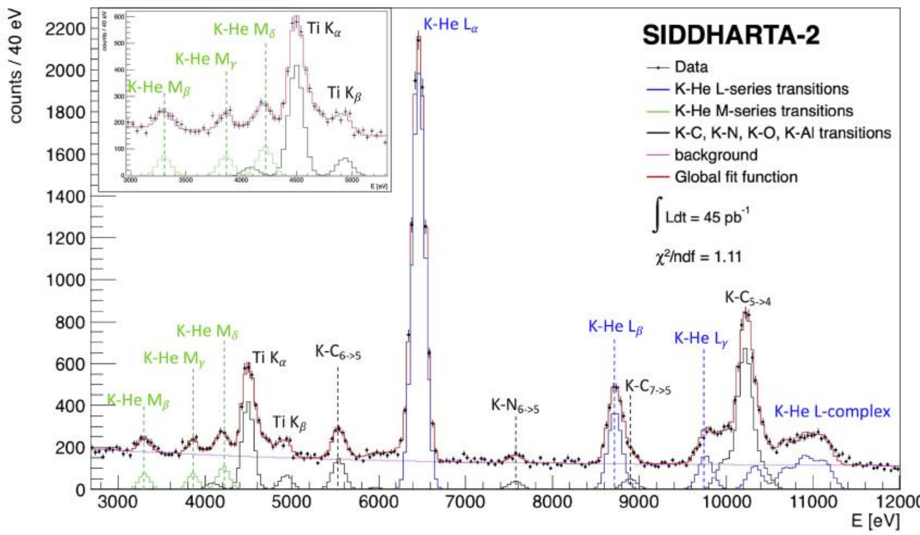
Kaonic Neon (2023)

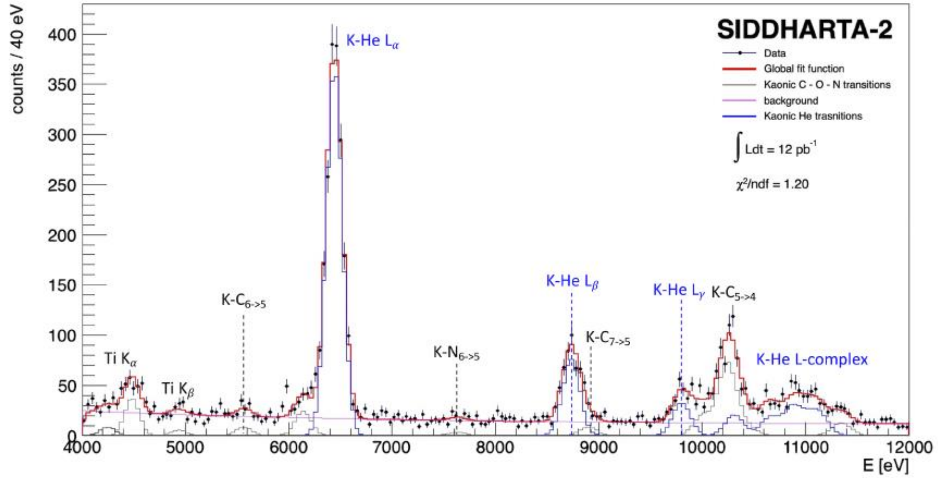
Kaonic Helium-4 (2021-2022)

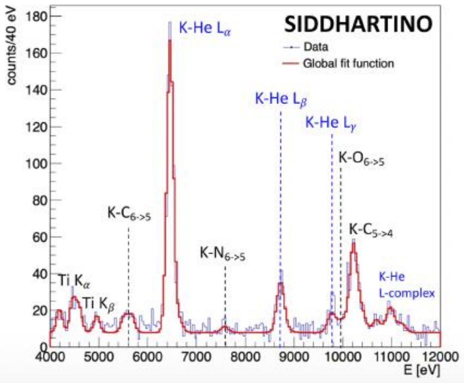
The SIDDHARTA-2 commissioning

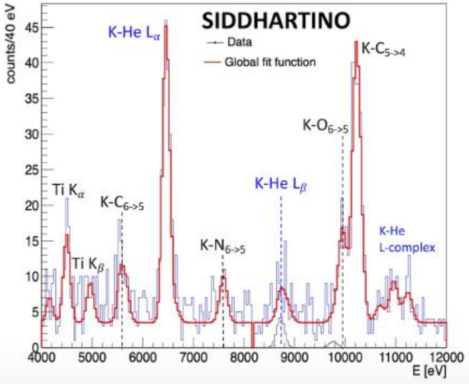
Optimization and debug of the trigger, SDDs and Veto systems through the kaonic helium 3d → 2p (L_α) measurement (high X-ray yield)

Apparatus	Helium-4 target density	Degrader thickness	Integrated luminosity (pb^{-1})
SIDDHARTINO	1.90 g/l	350 μm	5.2
		425 μm	4.6
		550 μm	6.4
		750 μm	4.8
	0.82 g/l	550 μm	9.5
sum			30.5
SIDDHARTA-2	1.37 g/l	350 μm	4.7
		475 μm	35.3
		600 μm	5.6
	2.25 g/l	475 μm	12.0
sum			57.6



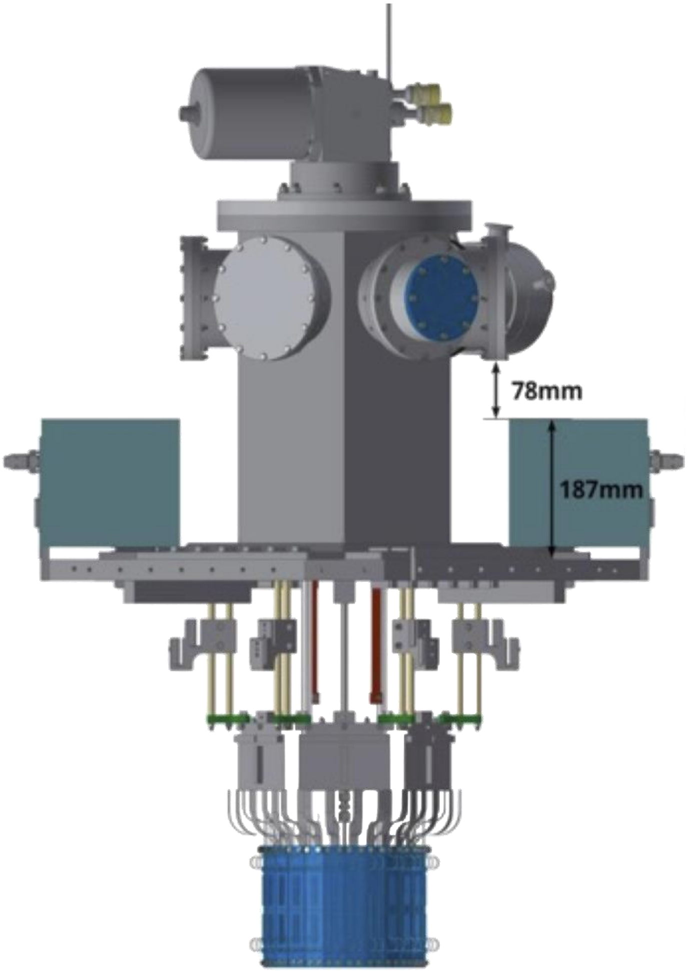




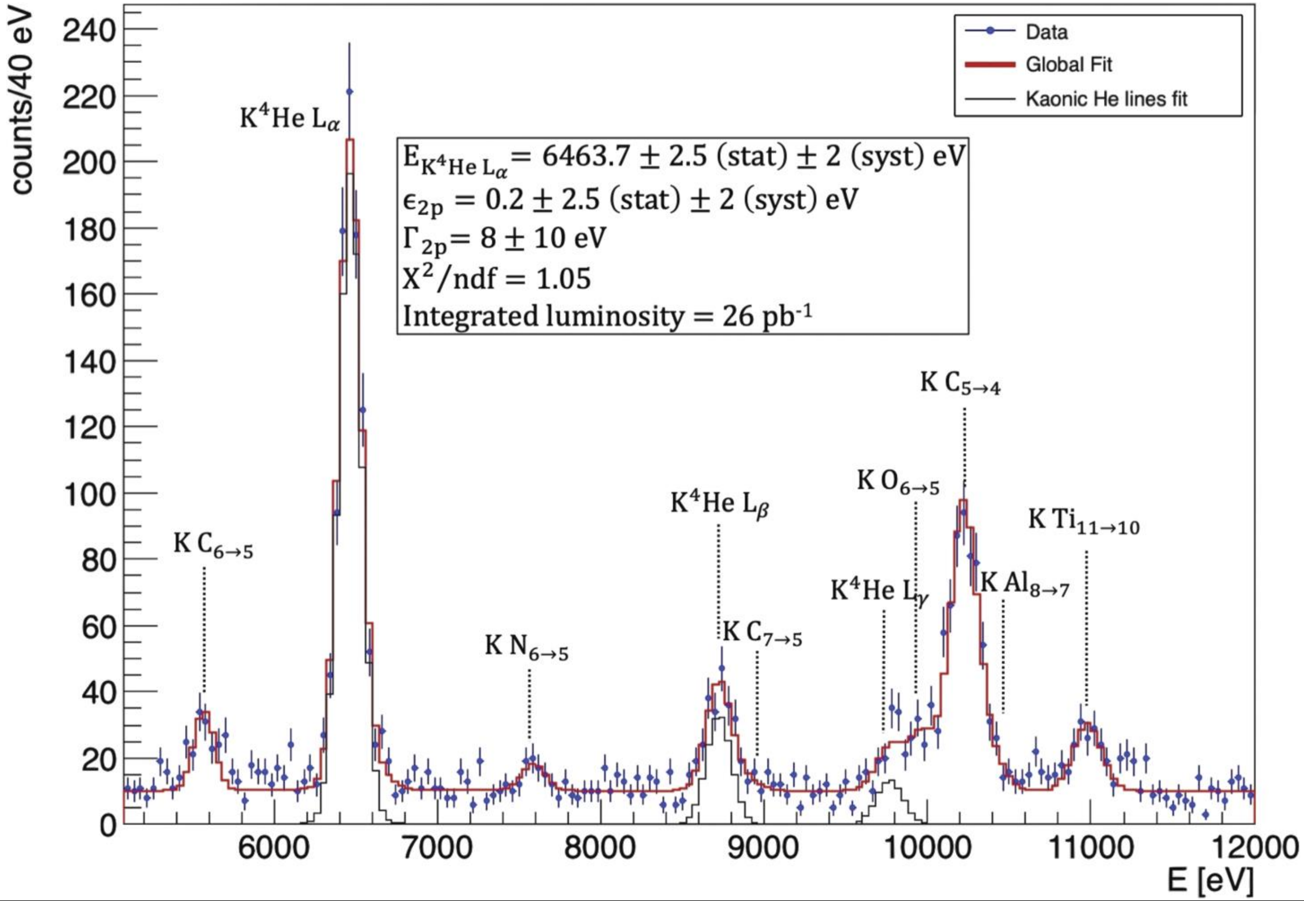


SIDDHARTINO - The kaonic ^{4}He 3d->2p measurement

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



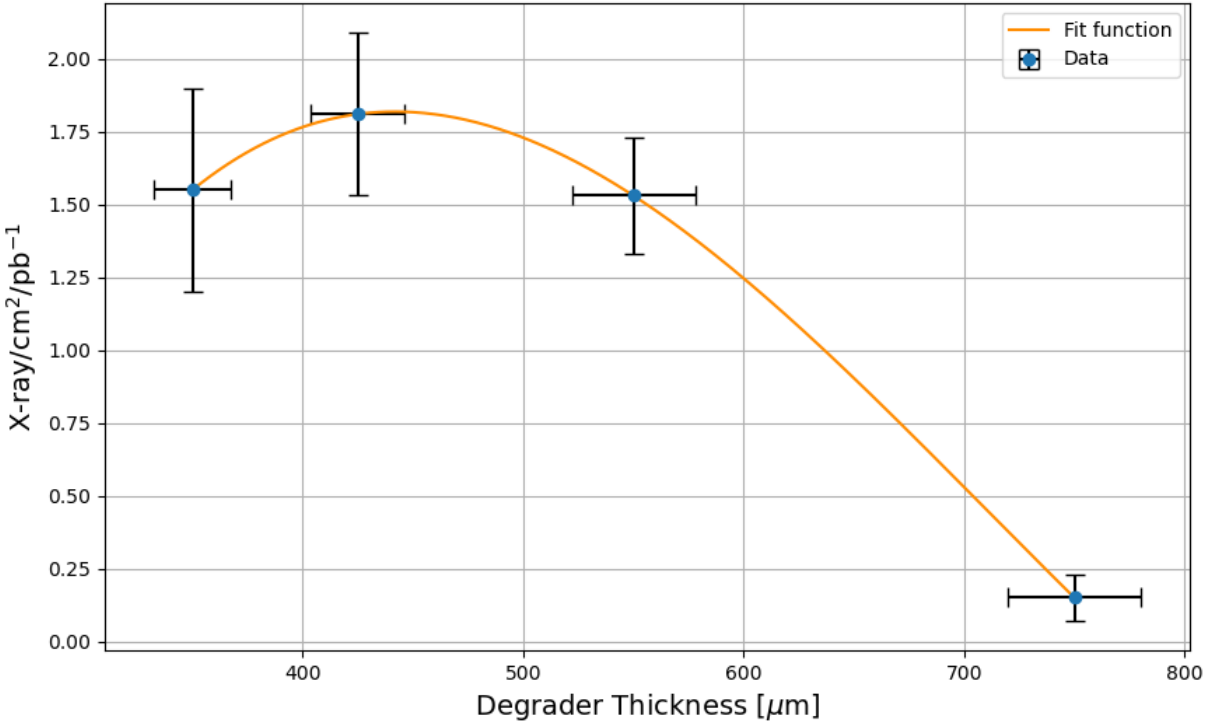
SIDDHARTINO: reduced version of the SIDDHARTA-2 apparatus (64 SDDs) It was used to optimize the DAFNE background and characterize the SDDs

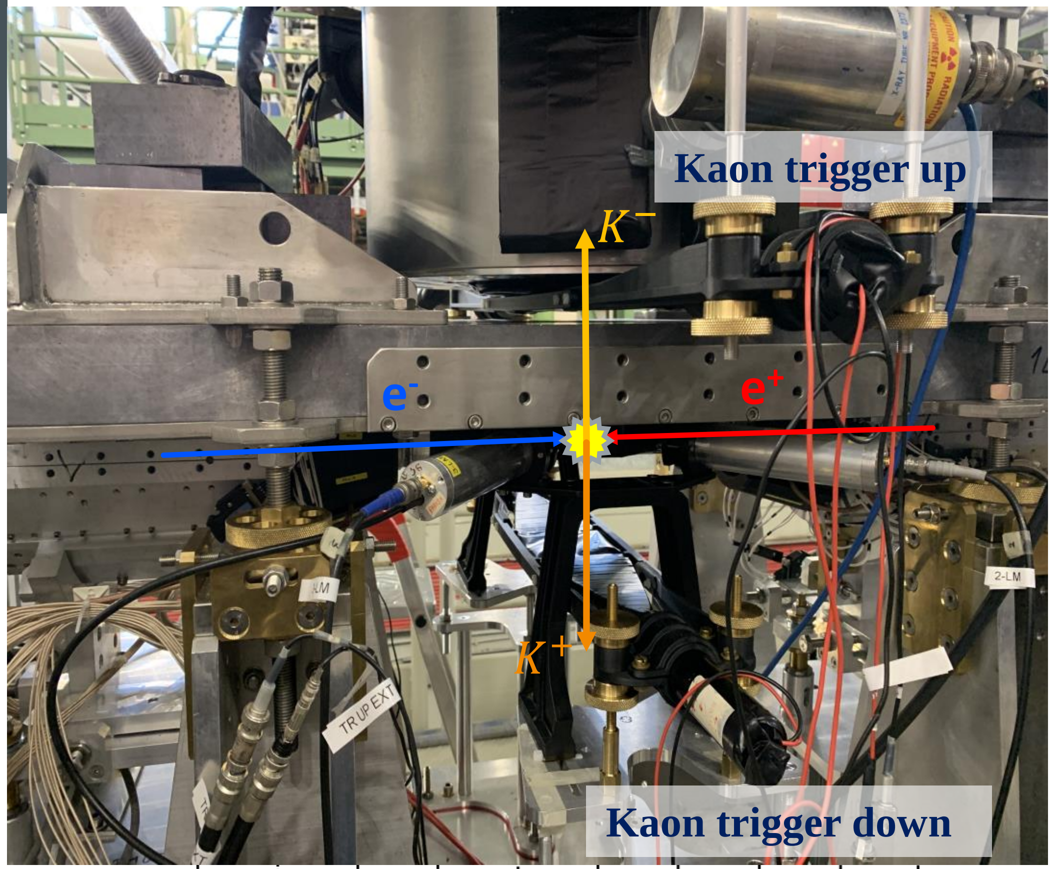


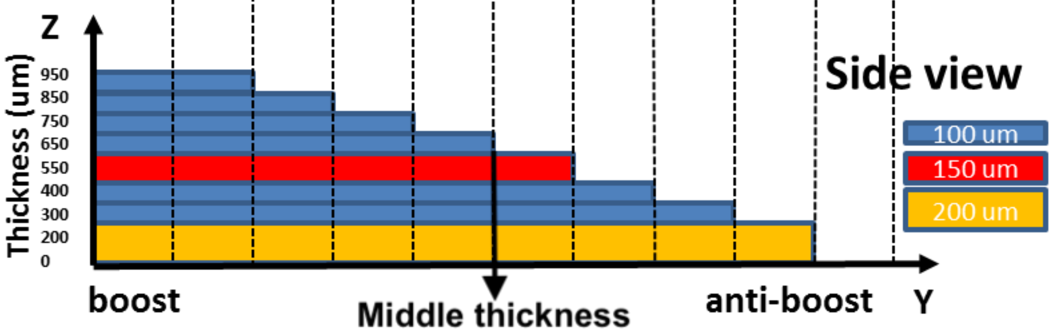
Sirghi D., Sirghi F., **Sgaramella F.**, et al., 2022, J. Phys. G Nucl. Part. Phys., 49 (5) 55106

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

Optimization of the degrader through the kaonic helium 3d → 2p (L_α) measurement
An error of approximately 200 μm in the degrader thickness, can reduce the kaonic atoms X-rays almost to zero.





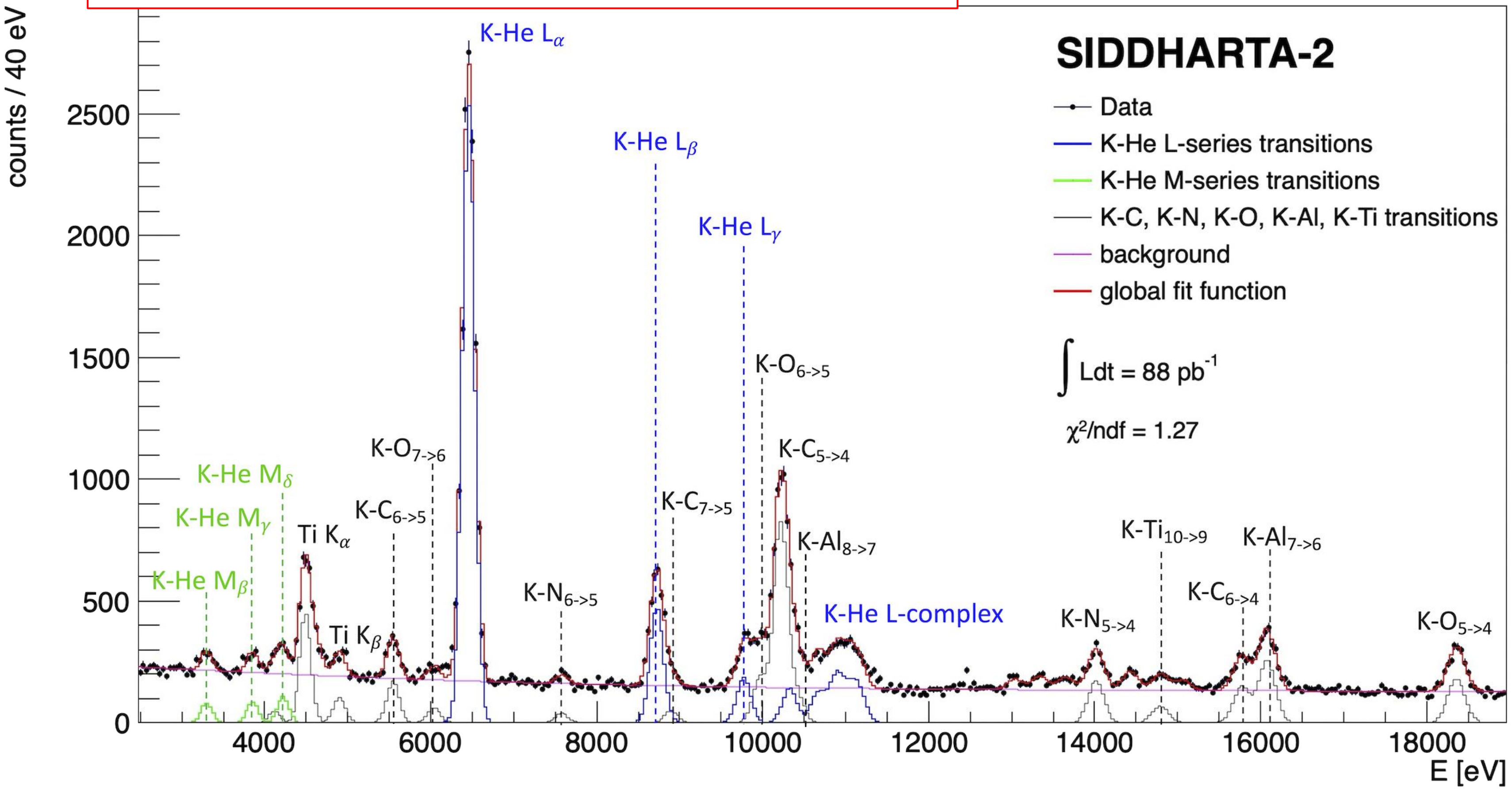


The Kaonic ^{4}He measurement (2021-2022)

- Most precise measurement of kaonic helium-4 Lα in gas: 2p level energy shift and width
- First observation of kaonic helium-4 M-series transition (n→3d)
- First Measurement of high-n transition in kaonic carbon – nitrogen – oxygen and aluminium

$$\varepsilon_{2p} = E^{exp}_{3d\to 2p} - E^{e.m}_{3d\to 2p} = -1.9 \pm 0.8\,(\text{stat}) \pm 2.0\,(\text{sys})\ \text{eV}$$
$$\Gamma_{2p} = 0.01 \pm 1.60\,(\text{stat}) \pm 0.36\,(\text{sys})\ \text{eV}$$

→ *no sharp effect of the strong interaction on the 2p level*



new data to enrich the kaonic atoms transitions database

Transition	Energy [eV]
$K^-C\ (6\to5)$	5546.0 ± 5.4 (stat) ± 2.0 (syst)
$K^-C\ (7\to5)$	8890.0 ± 13.0 (stat) ± 2.0 (syst)
$K^-C\ (5\to4)$	10216.6 ± 1.8 (stat) ± 3.0 (syst)
$K^-C\ (6\to4)$	15760.3 ± 4.7 (stat) ± 12.0 (syst)
$K^-O\ (7\to6)$	6014.8 ± 8.4 (stat) ± 2.0 (syst)
$K^-O\ (6\to5)$	9965.1 ± 6.9 (stat) ± 2.0 (syst)
$K^-O\ (5\to4)$	18361.1 ± 5.4 (stat) ± 12.0 (syst)
$K^-N\ (6\to5)$	7581.1 ± 16.0 (stat) ± 2.0 (syst)
$K^-N\ (5\to4)$	14008.0 ± 6.0 (stat) ± 9.0 (syst)
$K^-Al\ (8\to7)$	10441.0 ± 8.5 (stat) ± 3.0 (syst)
$K^-Al\ (7\to6)$	16083.4 ± 3.8 (stat) ± 12.0 (syst)
$K^-Ti\ (10\to9)$	14790.3 ± 16.6 (stat) ± 9.0 (syst)

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

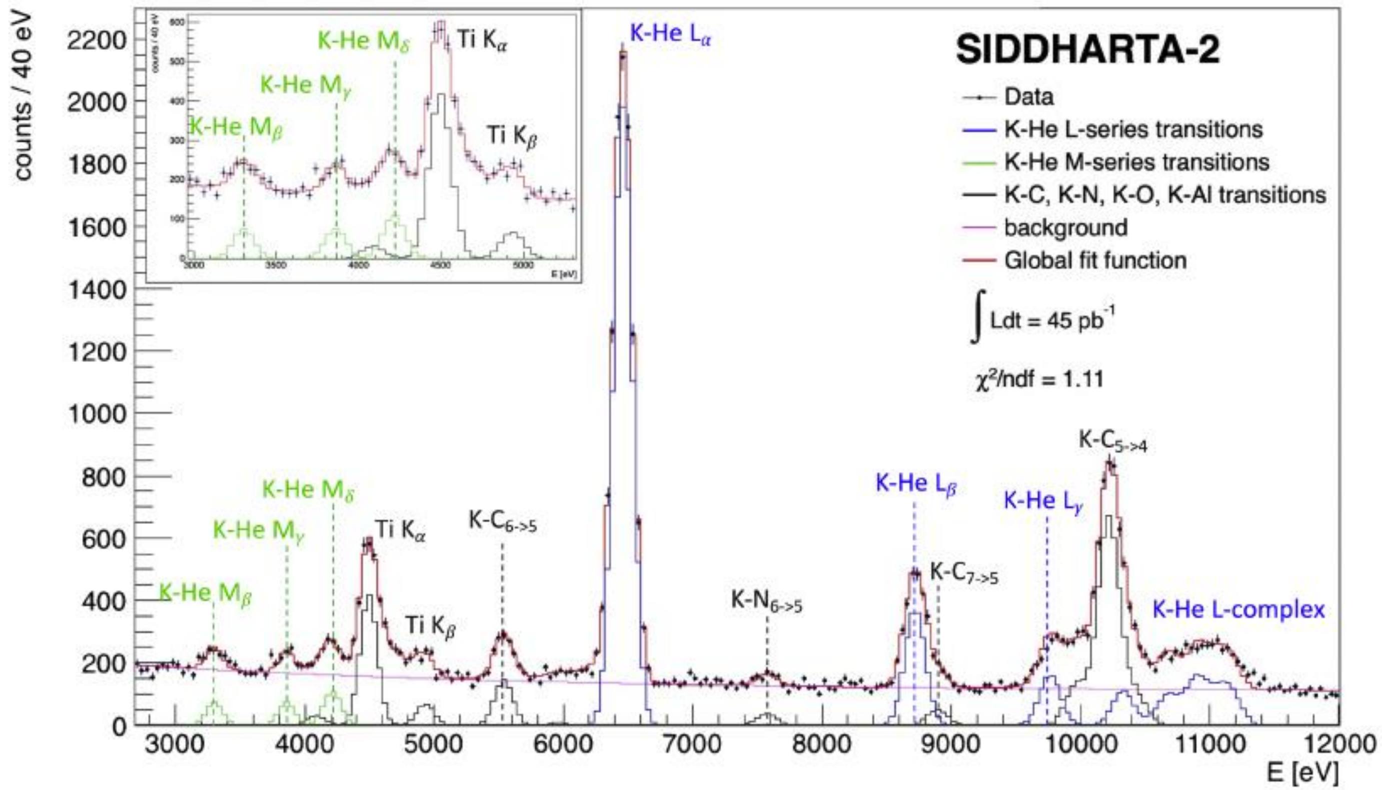
The Kaonic ^{4}He X-ray Yield (2021-2022)

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



The Kaonic ^{4}He X-ray Yield (2021-2022)

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.

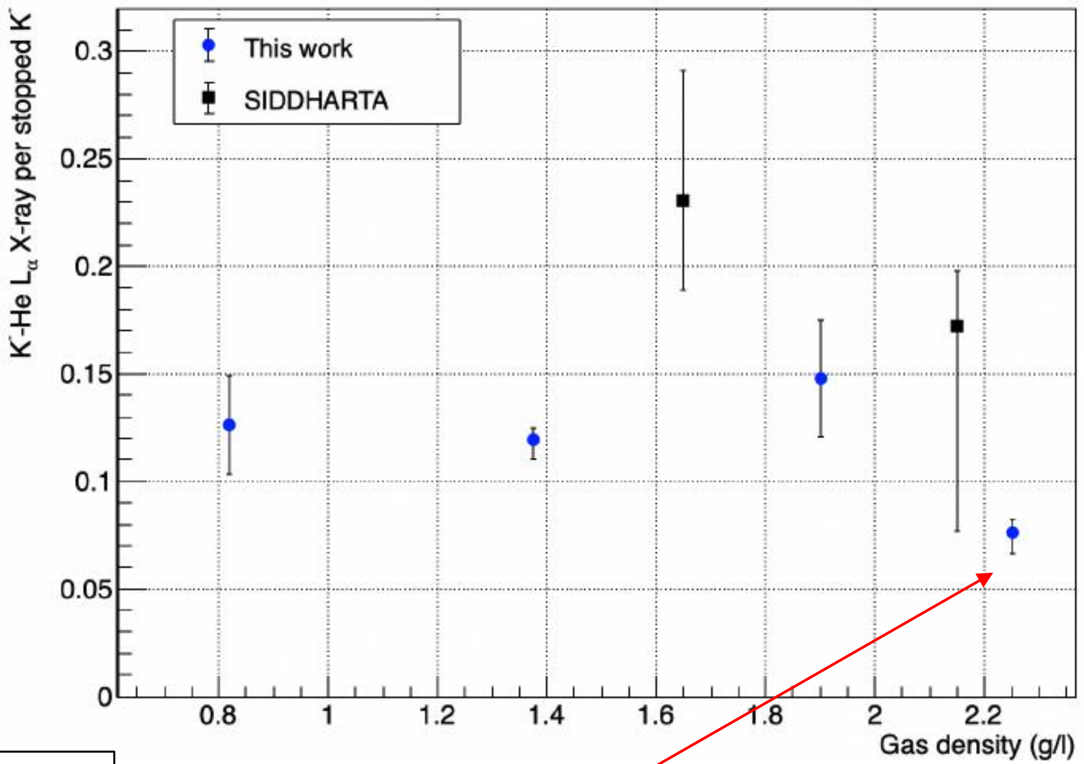
Density	2.25 ± 0.11 g/l
L_α yield	$0.075 \pm 0.003\,(\text{stat})^{+0.006\,(\text{syst})}_{-0.009\,(\text{syst})}$
L_β / L_α	$0.190 \pm 0.027\,(\text{stat})$
L_γ / L_α	$0.082 \pm 0.012\,(\text{stat})$

Density	1.90 ± 0.10 g/l	0.82 ± 0.08 g/l
L_α yield	$0.148 \pm 0.027\,(\text{stat})^{+0.006\,(\text{syst})}_{-0.009\,(\text{syst})}$	$0.126 \pm 0.023\,(\text{stat})^{+0.006\,(\text{syst})}_{-0.009\,(\text{syst})}$
L_β / L_α	$0.193 \pm 0.042\,(\text{stat})$	$0.133 \pm 0.037\,(\text{stat})$
L_γ / L_α	$0.0035 \pm 0.015\,(\text{stat})$	not detected

Sgaramella F., et al., 2024, Acta Phys. Pol.B Proc. Suppl. 17, 1-A8

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

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

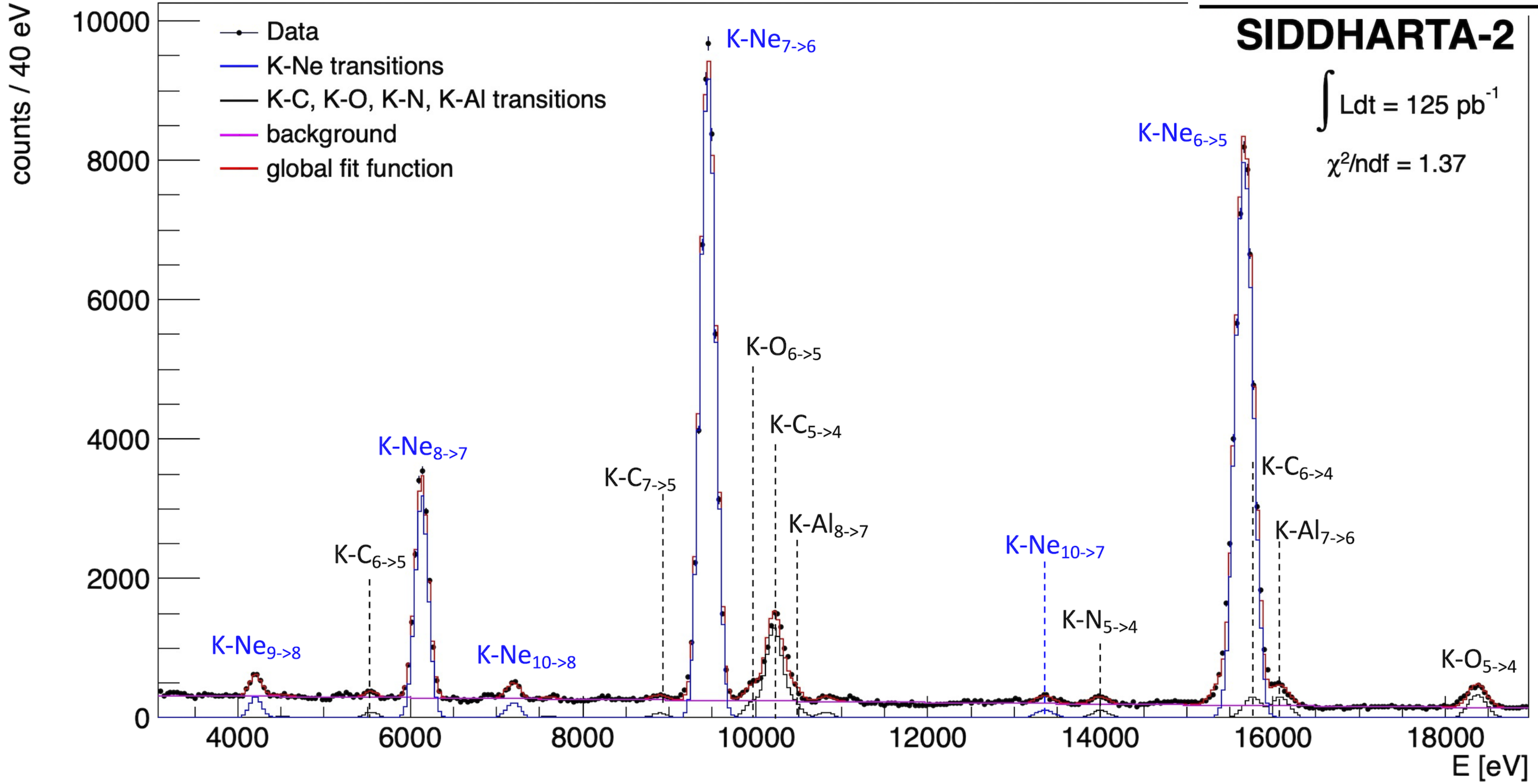


First observation of the stark effect in kaonic helium-4

The Kaonic Neon measurement (2023)

First measurement of kaonic neon X-ray transitions (sub eV statistical accuracy)

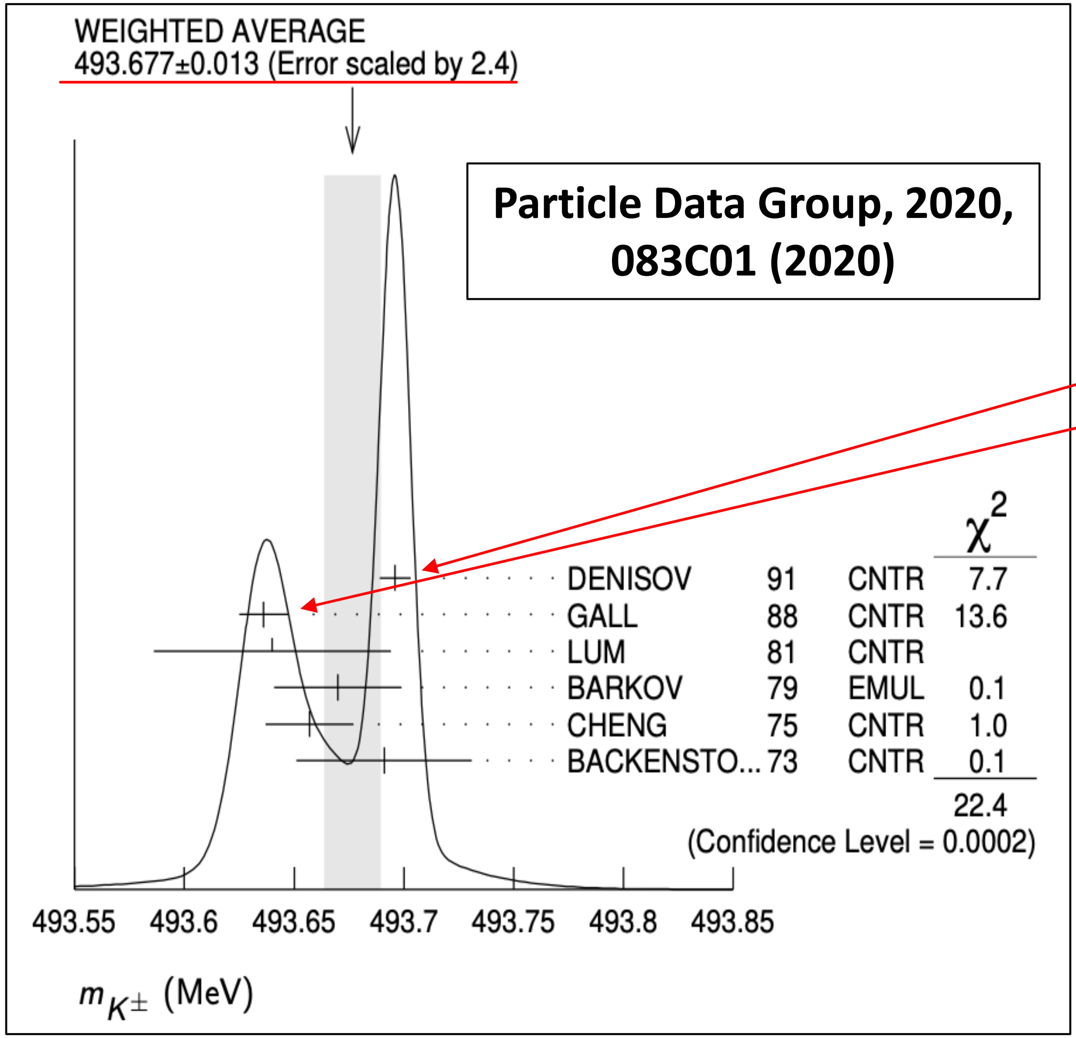
Transition	Energy [eV]
K-Ne $(9 \to 8)$	4206.35 ± 3.75 (stat) ± 2.00 (syst) eV
K-Ne $(8 \to 7)$	6130.86 ± 0.71 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 8)$	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV
K-Ne $(7 \to 6)$	9450.08 ± 0.41 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 7)$	13352.20 ± 10.07 (stat) ± 3.00 (syst)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



[Article in preparation]

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	→ Carbon
493.636±0.011	[2]	GALL	88	CNTR	–	Kaonic atoms	→ Lead
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	

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 discrepancy

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

- Implications for studies in Bound State QED (BSQED)

Testing Quantum Electrodynamics with Exotic Atoms
N. Paul, G. Bian, T. Azuma, S. Okada, and P. Indelicato, Phys. Rev. Lett. 126 (2021), 173001

The charged kaon mass puzzle

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

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

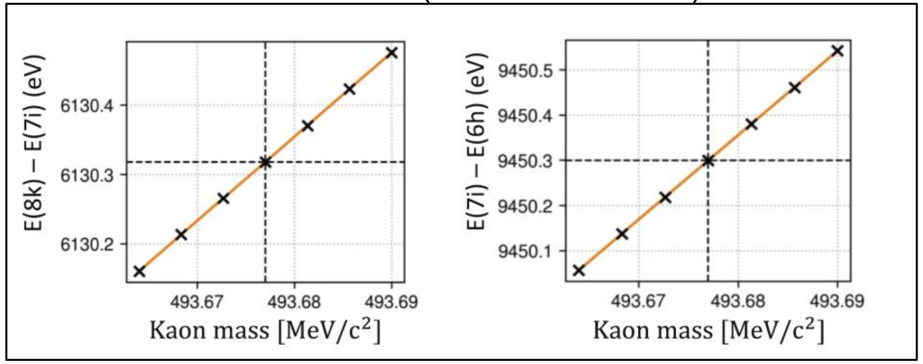
$$K - Ne(7 \rightarrow 6) = \frac{A_G}{\sqrt{2\pi}\sigma} \cdot e^{\frac{-(E-E_0)^2}{2\sigma^2}} \quad E_0 = (m_{7\rightarrow 6} \cdot K_{mass} + q_{7\rightarrow 6})$$

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

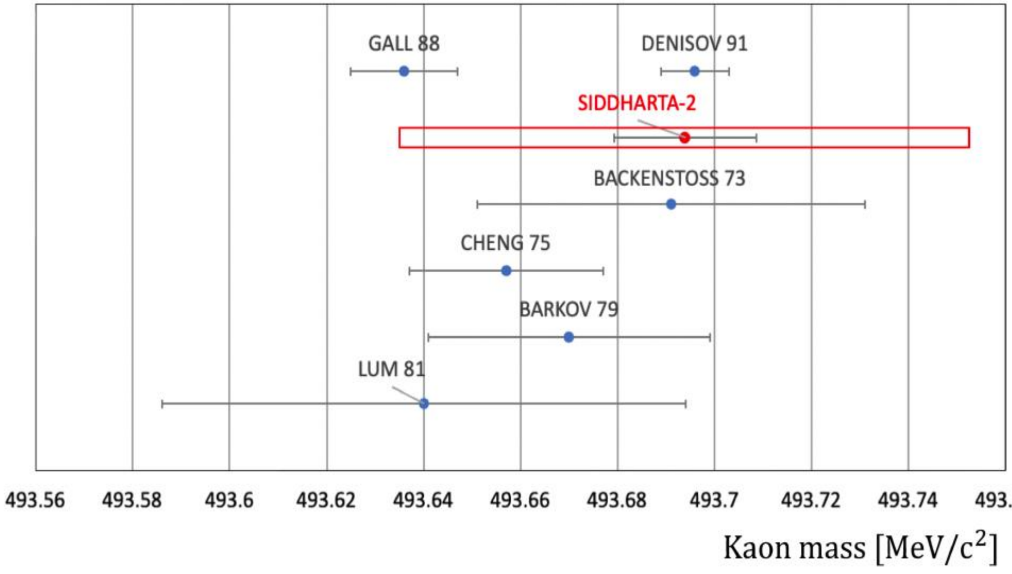
↓

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.



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 first kaonic deuterium measurement (2023-2024)

My contribution to kaonic deuterium measurement and SIDDHARTA-2 experiment:

- **Run coordinator**
- **Technical responsible for the SDDs system (performance, maintenance and calibration)**
- **Data analysis**

	Date	Gas density [g/l]	Integrated Luminosity [pb^{-1}]
Run-1	May 2023 - July 2023	1.41% LDD	196
Run-2	October 2023 - December 2023	1.46% LDD	340
Run-3	February 2024 - ongoing	1.41% LDD	300 (target)

Kaonic deuterium Run1

May – July 2023

Kaonic deuterium Run2

October – December 2023

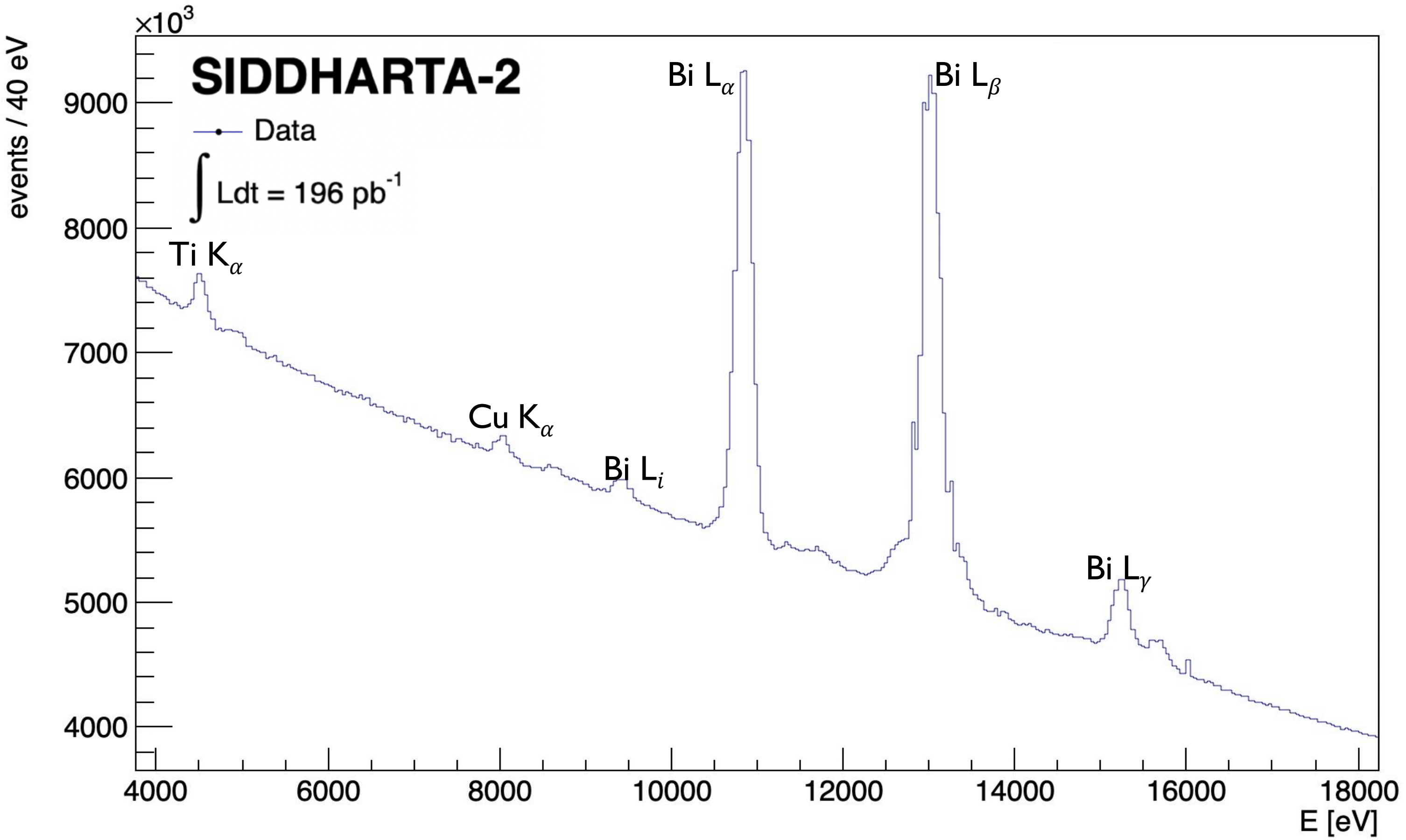
Kaonic deuterium Run3

February – April 2024

Run1 data analysis and preliminary results

The first kaonic deuterium measurement

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



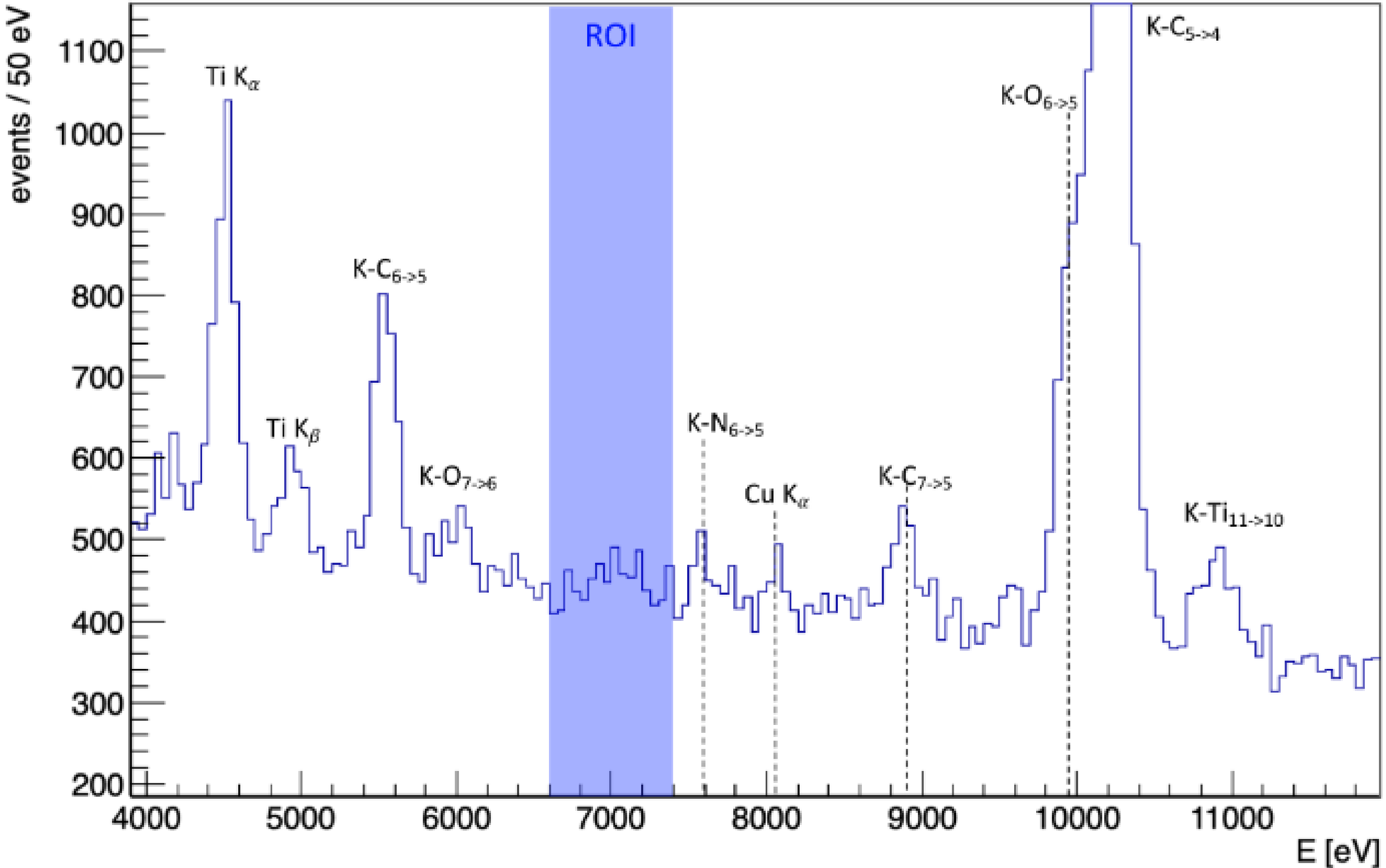
-Asynchronous background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect. → Kaon Trigger and SDDs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

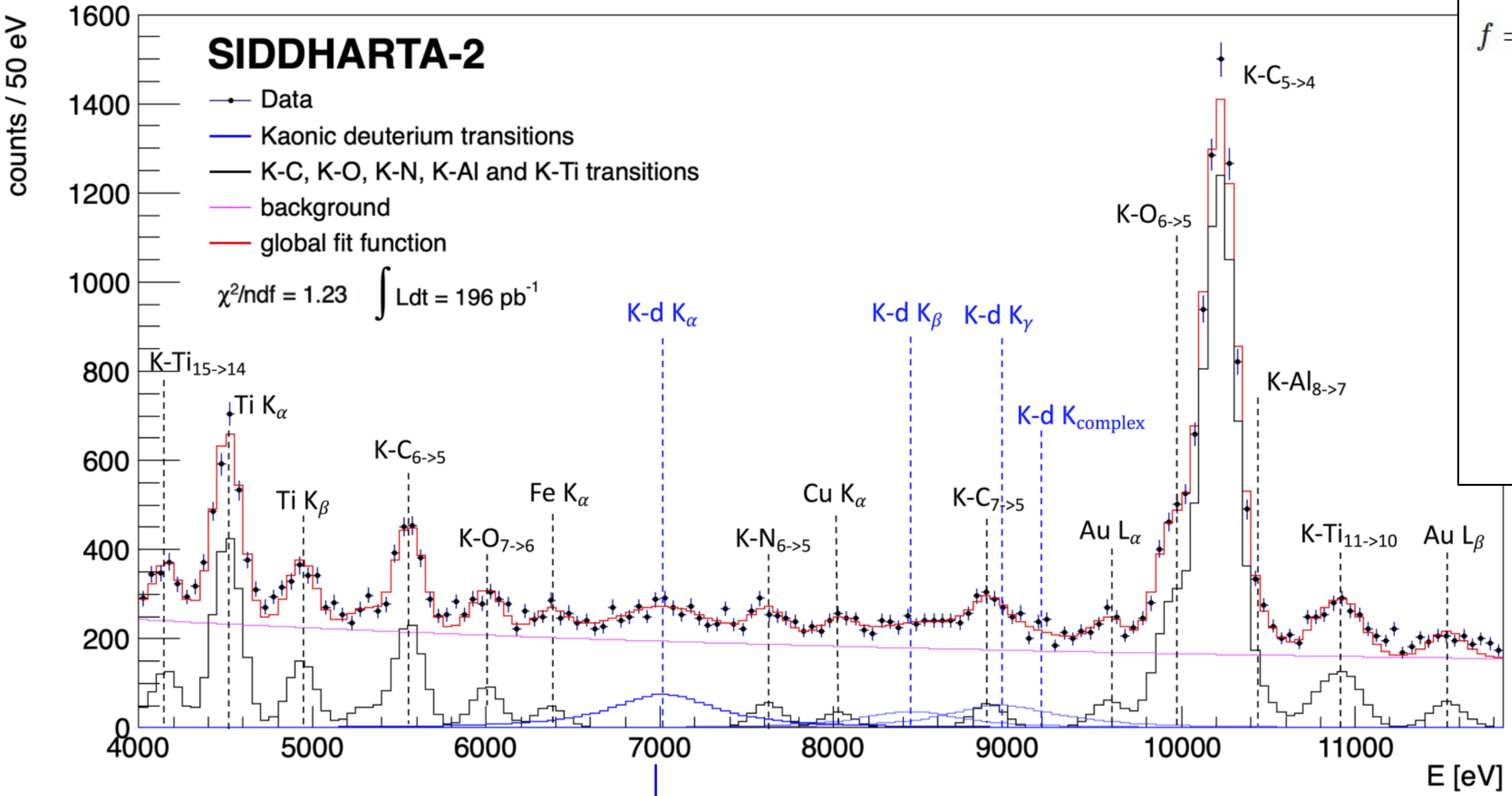
The first kaonic deuterium measurement

Energy spectrum after the asynchronous background rejection procedure



The first kaonic deuterium measurement

Very preliminary!



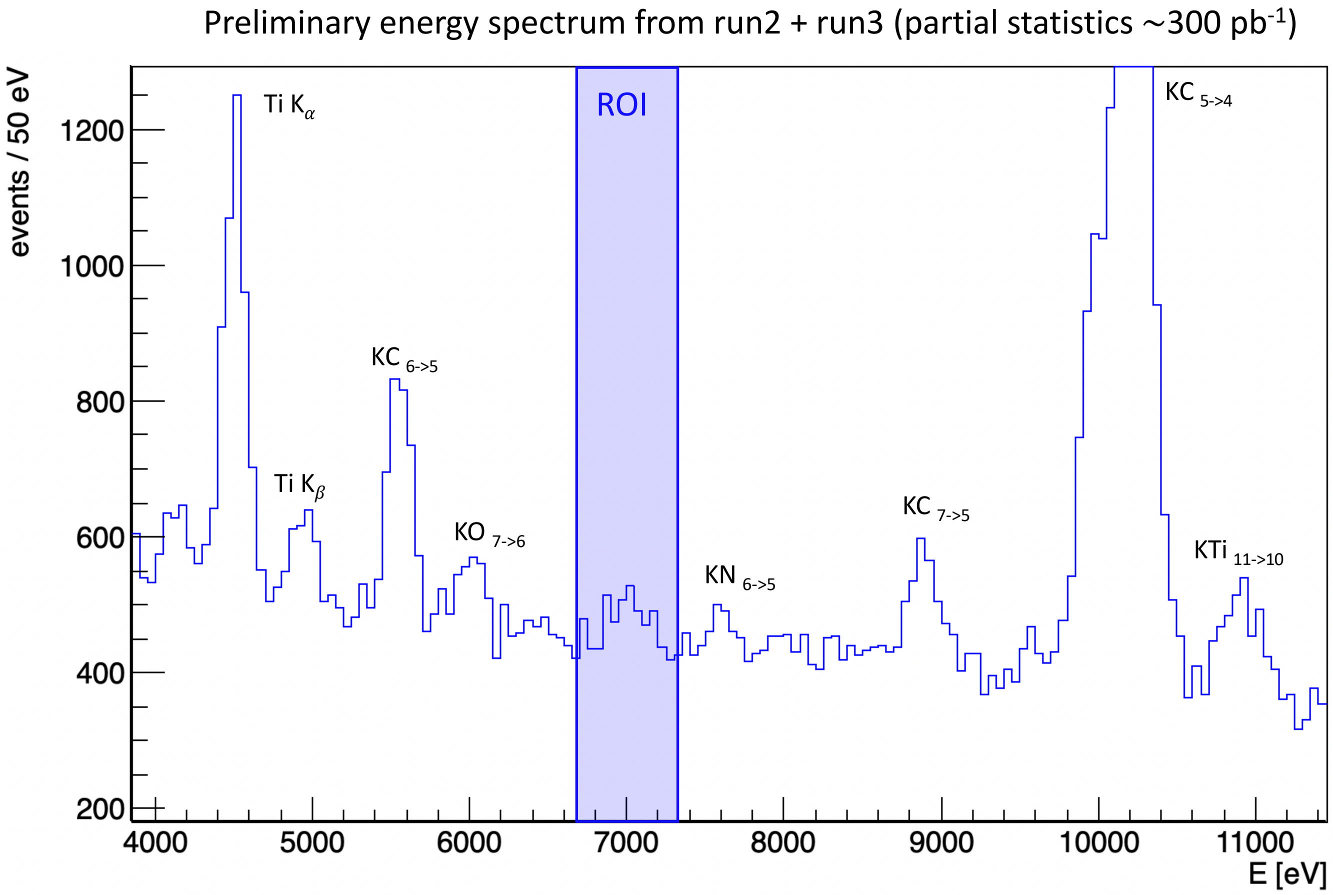
$$f = pol_1(E) + \exp(E) + \sum_i \text{Gauss}(A_{Gi}, E_i, \sigma) + \text{Tail}(A_{Ti}, E_i, \beta, \sigma) +$$
$$A_{\text{Kd}_{2\to1}} \cdot \text{Voigt}(E_{2\to1}, \sigma, \Gamma_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{3\to1}} \cdot \text{Voigt}(E^{e.m.}_{3\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot \text{Voigt}(E^{e.m.}_{4\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{5\to1}} \cdot \text{Voigt}(E^{e.m.}_{5\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{6\to1}} \cdot \text{Voigt}(E^{e.m.}_{6\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s}) +$$
$$A_{\text{Kd}_{4\to1}} \cdot A_{rel_{7\to1}} \cdot \text{Voigt}(E^{e.m.}_{7\to1} + \varepsilon^*_{1s}, \sigma, \Gamma^*_{1s})$$

$$\varepsilon_{1s} = E^{meas}_{2p\to1s} - E^{e.m.}_{2p\to1s} = -816 \pm 53 \text{ (stat)} \pm 2 \text{ (syst) eV}$$
$$\Gamma_{1s} = 756 \pm 271 \text{ (stat) eV}$$

"The **most important experiment to be carried out in low energy K-meson physics today** is the **definitive determination of the energy level shifts in the K−p and K−d atoms**, because of their direct connection with the physics of $\bar{K}$N interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)

Kaonic Deuterium Run2 and Run3: analysis ongoing



Next Step of the analysis:

- Refined calibration of Run3 data (ongoing)
- Veto-1 analysis (similar to run1 data)
- Define a proper fit function
- Fit of the energy spectrum (full dataset)

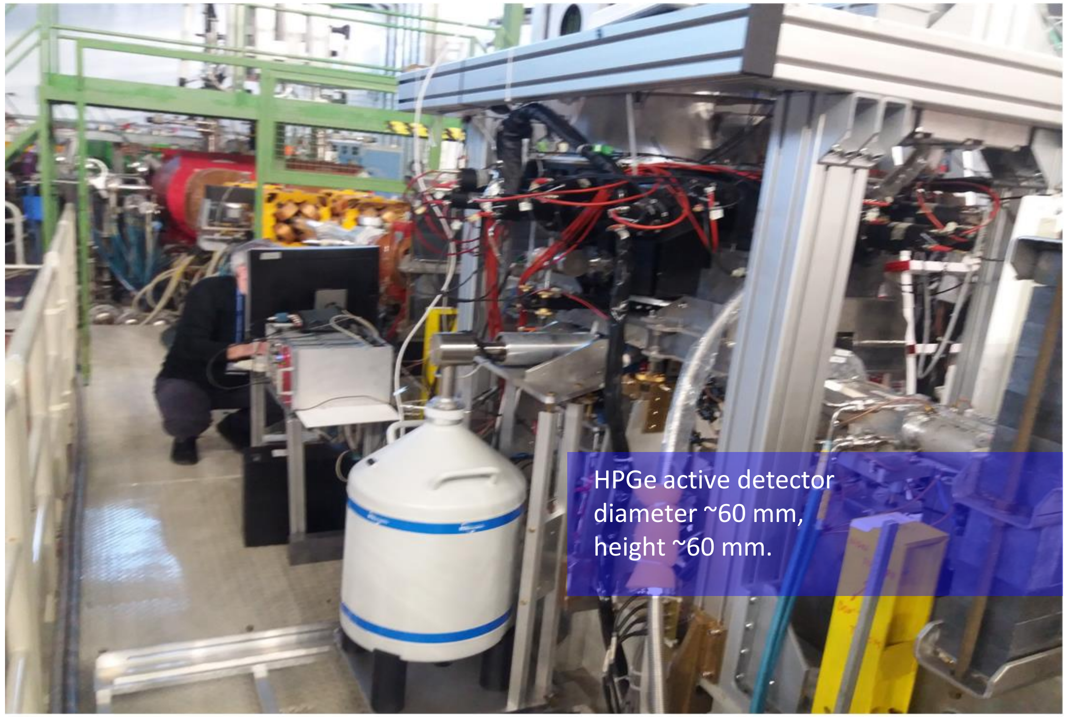
The analysis of the full dataset can potentially improve the statistical accuracy by a factor 2

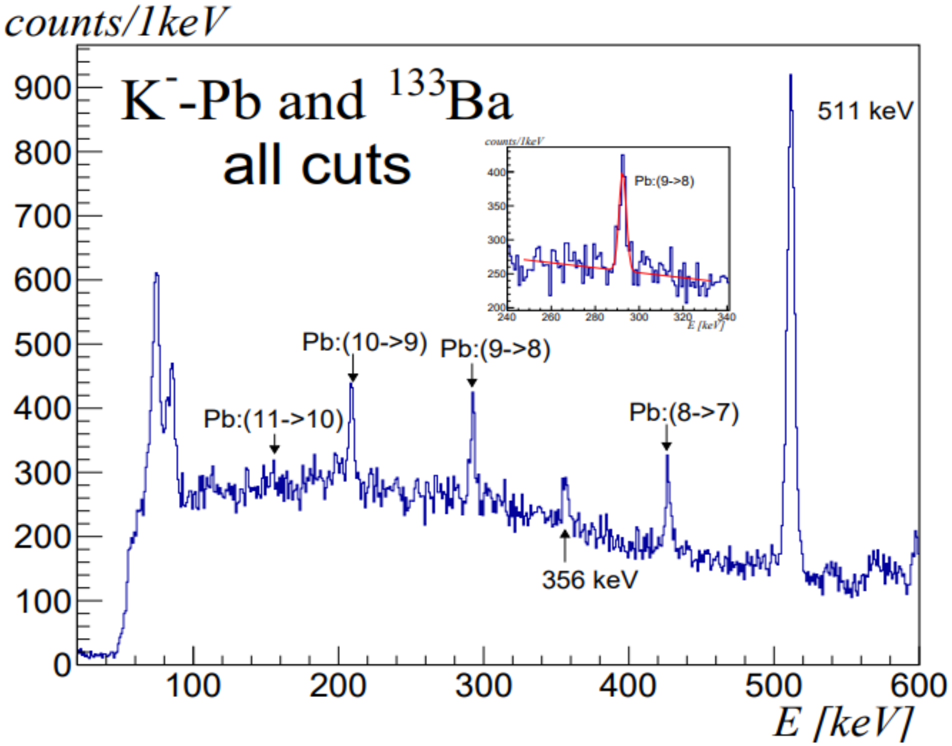
(precision similar to kaonic hydrogen measurement)

Kaonic Lead Measurement at DAΦNE with HPGe

(Zagreb Uni; Krakow, Jagiellonian Uni – Lumi)

Integrated luminosity: 109.38 pb^{-1} (June – July 2023)

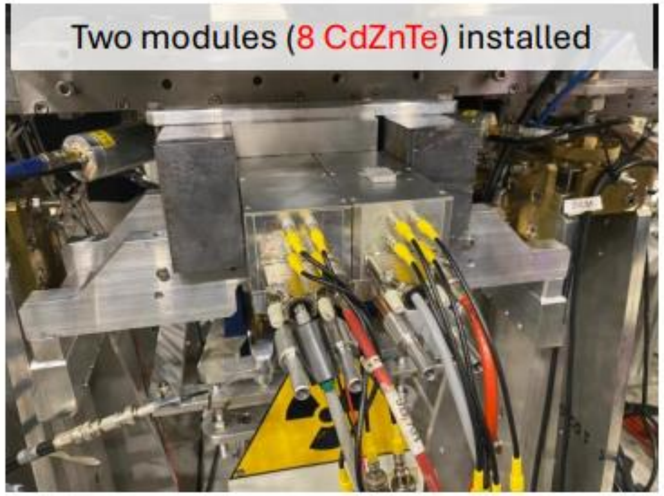


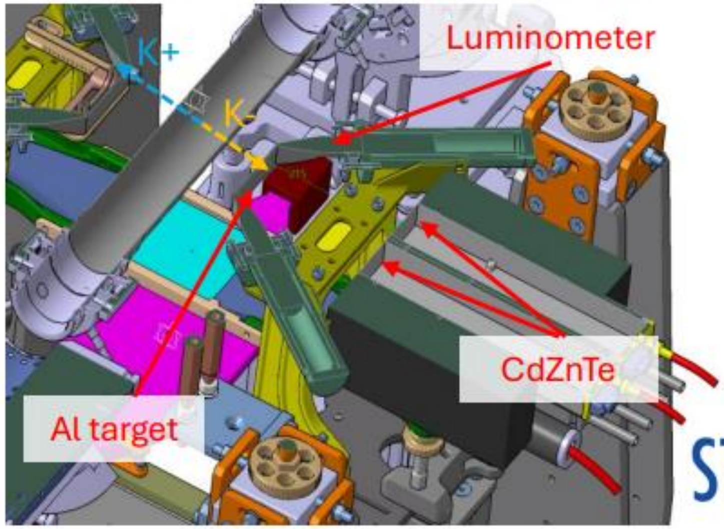


K^--Pb transition	Peak position (keV)	Resolution (FWHM) (keV)	Number of events
$10 \rightarrow 9$	208.92 ± 0.17	3.68 ± 0.42	584 ± 30
$9 \rightarrow 8$	292.47 ± 0.17	3.97 ± 0.49	770 ± 65
$8 \rightarrow 7$	427.07 ± 0.24	4.37 ± 0.54	457 ± 45

Article submitted to Nuclear Instruments and Methods A preprint: arXiv:2405.12942

CdZnTe detectors: test run with 8 detectors

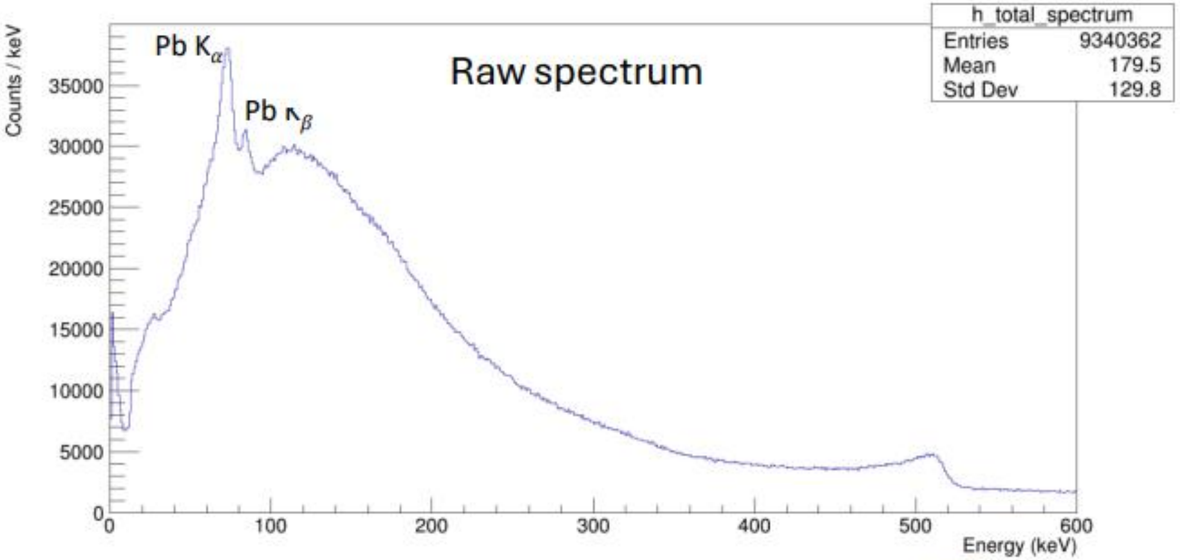




8 cm^2 CdZnTe detectors to perform X-ray spectroscopy of kaonic aluminium in parallel with SIDDHARTA-2 kaonic deuterium run (L. Abbene, A. Buttacavoli, F. Principato, A. Scordo)

Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy : ASTRA

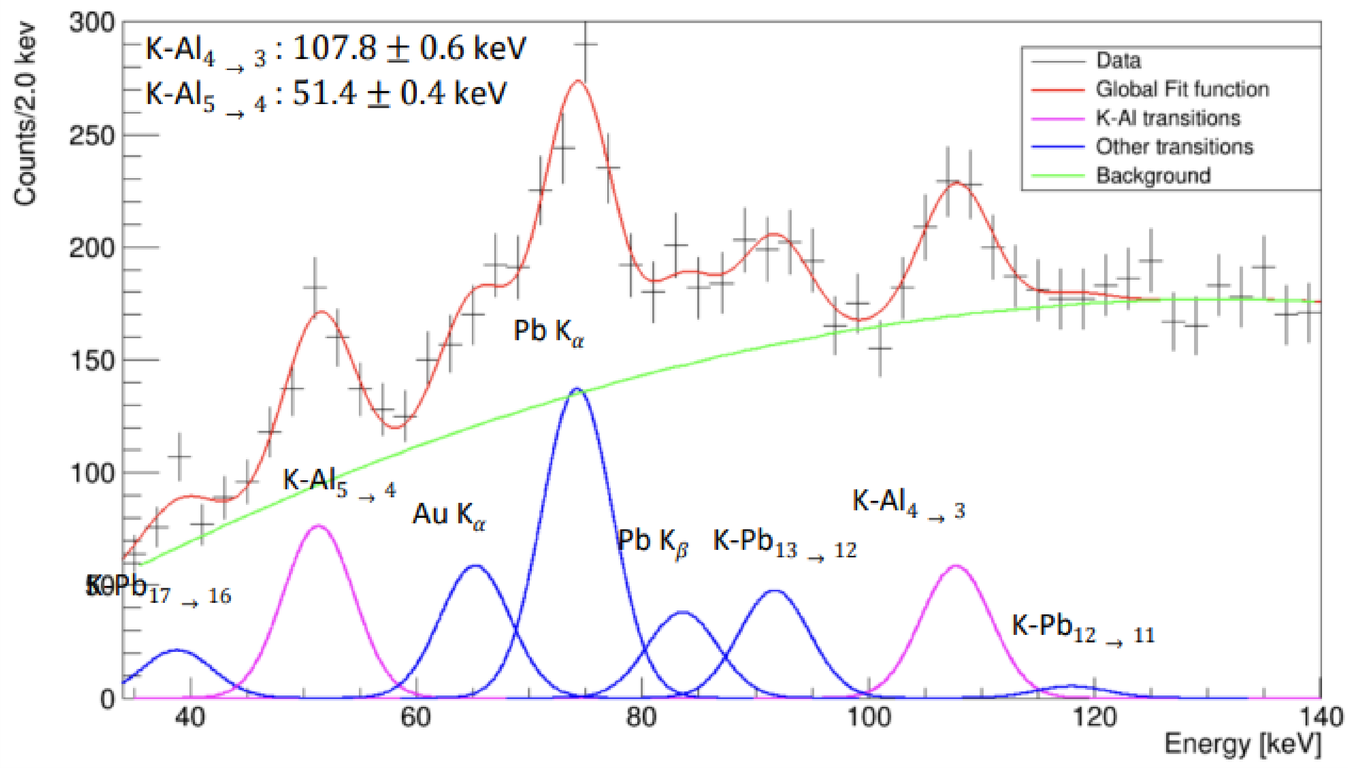
~ 60 pb^{-1} of data with a 2,2 mm Al target



STRONG-2020 Università degli Studi di Palermo unipa imem Istituto dei Materiali per l'Elettronica ed il Magnetismo Consiglio Nazionale delle Ricerche

CdZnTe detectors: test run with 8 detectors

Preliminary result from the kaonic aluminium analysis (~60 pb^{-1})



- First kaonic atoms' spectrum measured with CZT detectors
- CZT proved to be the **perfect technology for intermediate mass kaonic atoms**, with very good "in-beam" performances during preliminary tests
- CdZnTe detectors can be easily used in parallel with already existing experiments, requiring very small space and not invasive electronics.

An article is in preparation

Strangeness precision frontier at DAΦNE: a unique opportunity for measurements of kaonic atoms along the periodic table: **will represent a reference in physics with strangeness**

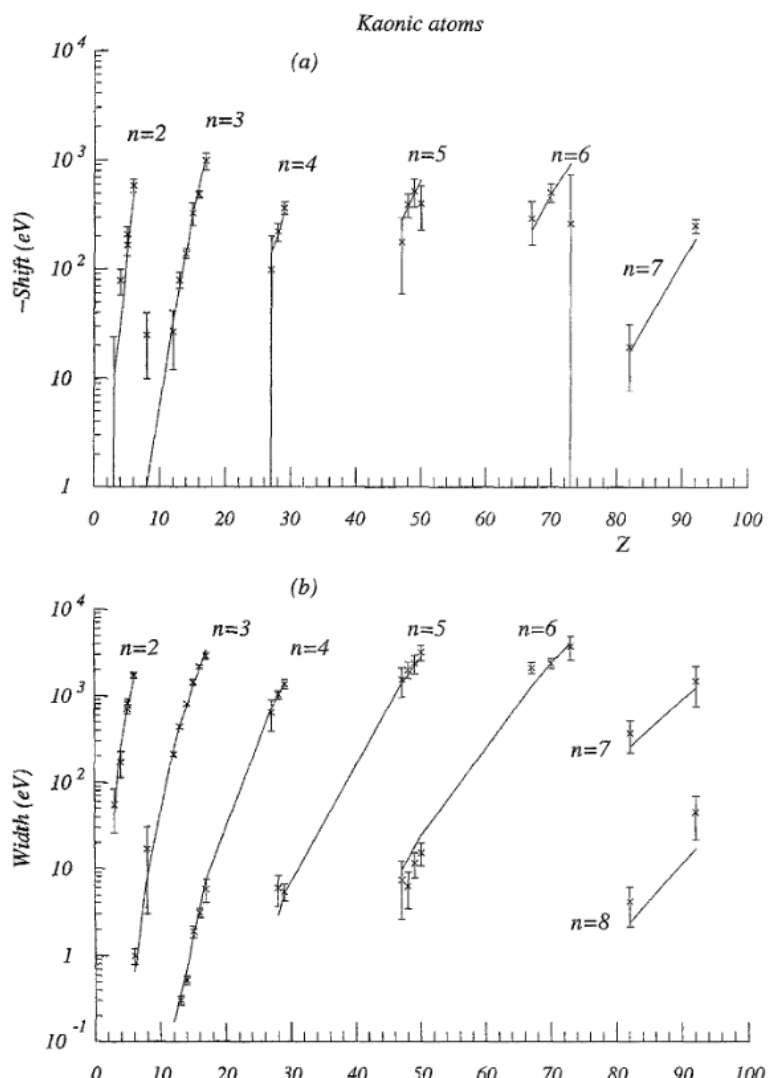
Present status: old and very old measurements with low precisison (some even wrong: kaonic helium puzzle)

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

- Selected light kaonic atoms
- Selected intermediate mass kaonic atoms
- Selected heavy kaonic atoms

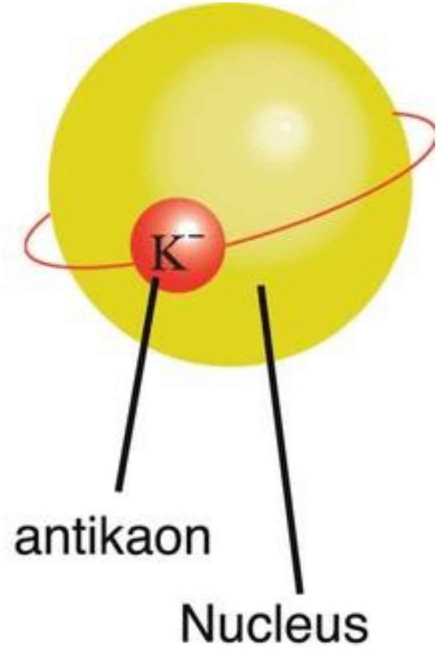
charting the periodic table

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

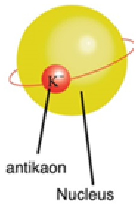


EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

EXKALIBUR



First Module of Kaonic Atoms Measurements within the EXKALIBUR scientific program



20th May 2024

By SIDDHARTA2-/EXKALIBUR Collaboration

EXtensive Kaonic Atoms research: from LIthium and Beryllium to URanium

Built up on our world-recognized expertise:

- Kaonic Hydrogen
- Kaonic Nitrogen
- Kaonic Helium
- Kaonic Neon
- Kaonic deuterium
- + more

The measurement for the **first EXKALIBUR module** were selected based on two criteria:

Feasibility with **minimal modifications/addings** of the already existent SIDDHARTA-2 setup and within a reduced timescale

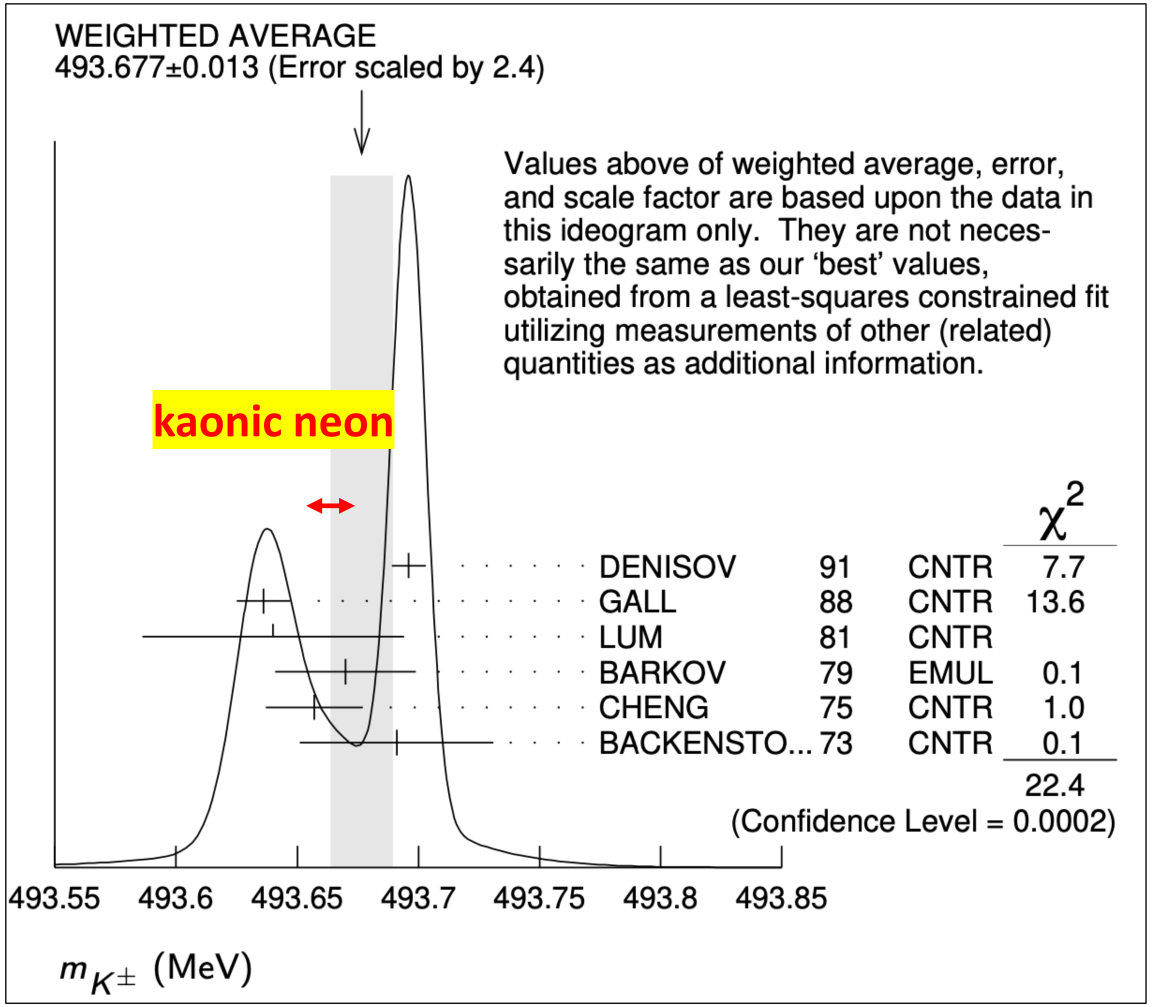
Impact: i.e. the **maximal scientific outcome:**

Kaonic Neon -> kaon mass

Light kaonic atoms (KLi; Be; B)

In parallel intermediate mass kaonic atoms

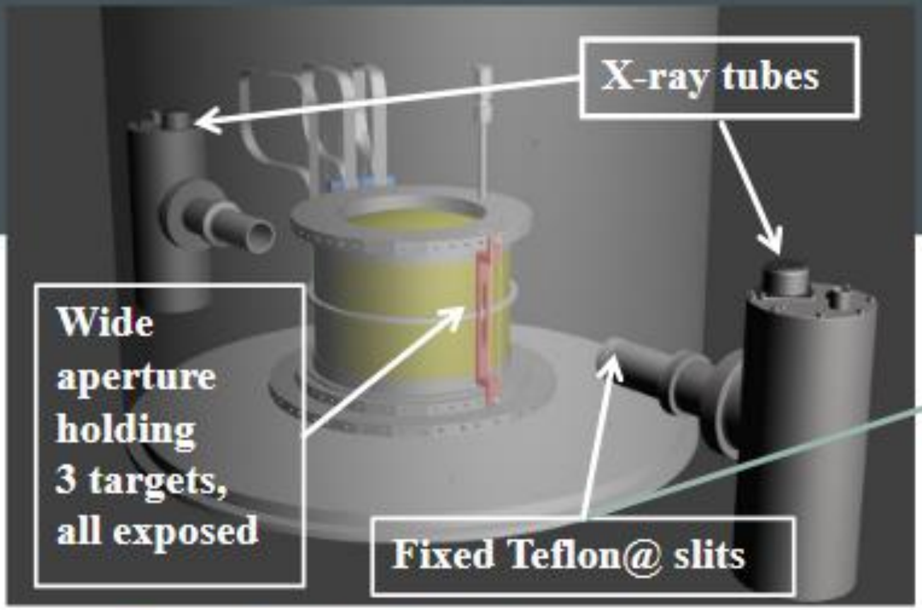
Kaonic neon for the charged kaon mass

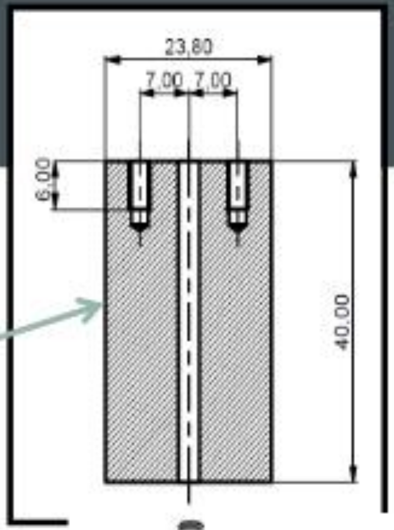


- The first measurement we plan doing is the **kaonic neon** high-n levels transition with precisions below 1 eV, **to extract the charged kaon mass**.

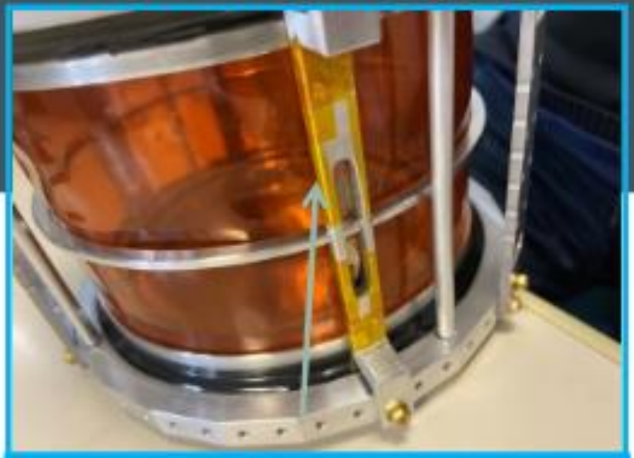
- By using a **gaseous target**, we can resolve the ambiguity in the charged kaon mass determination, providing **a new precise value through the measurement of kaonic neon high-n transitions**. Moreover, the measurement also provides **a precision test of QED in atomic systems with strangeness** (Rydberg constant, as example).

Refined calibration system : movable fluorescent foils



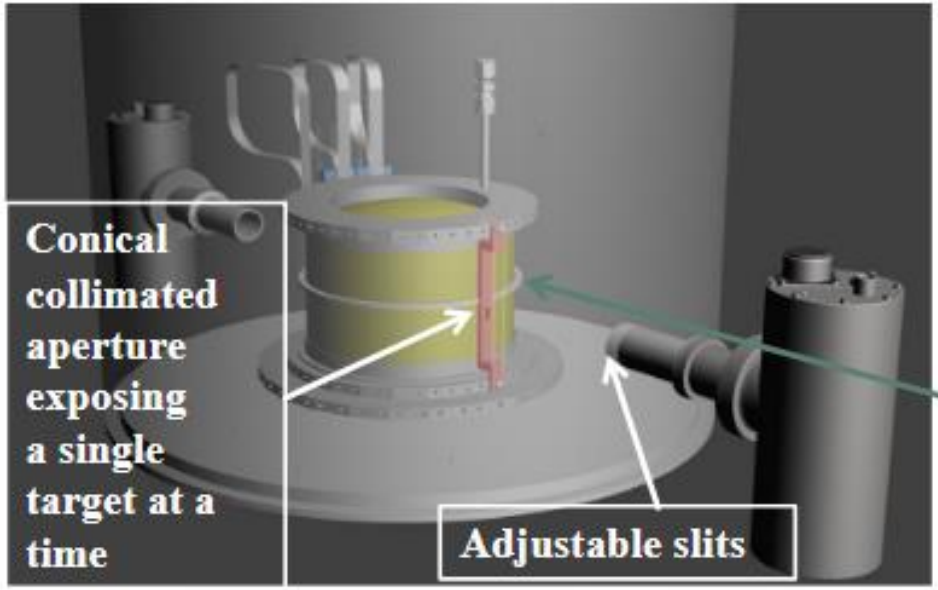


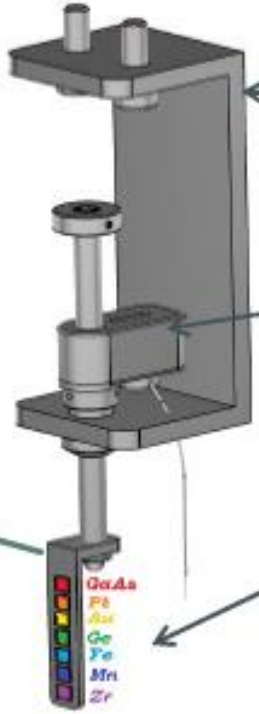
Current calibration system



Ti, Cu, Zr calibration foils holder

Upgraded calibration system





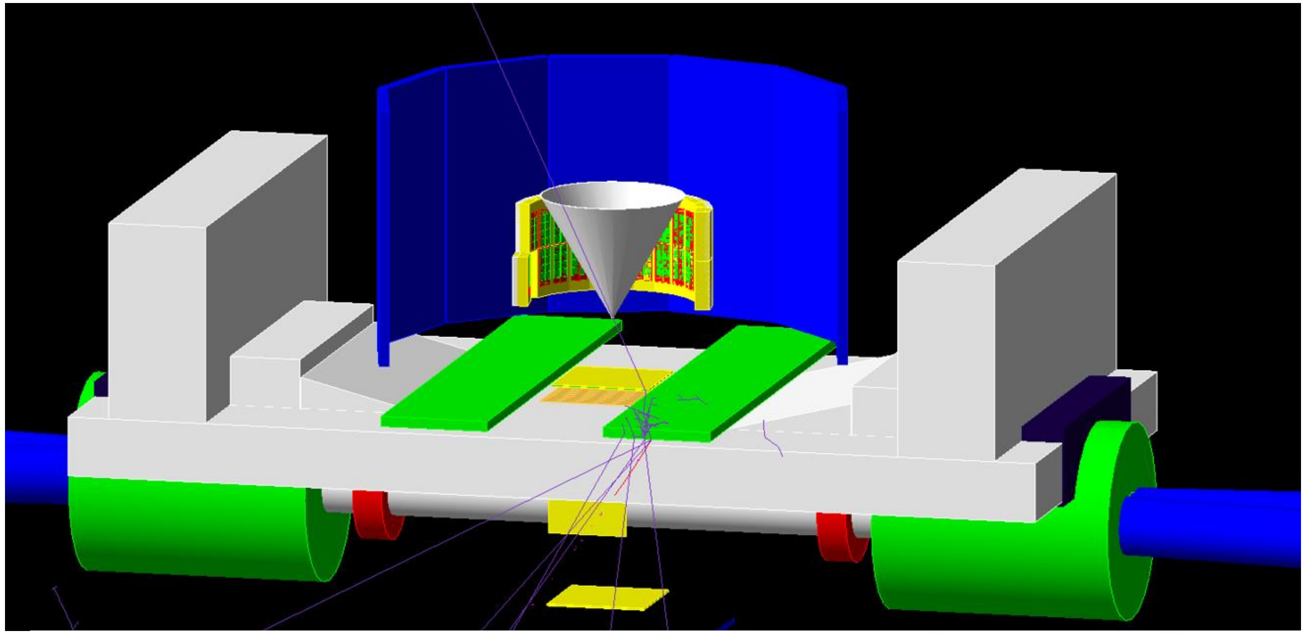
Light Mass (low-Z) Kaonic Atoms

- The second module of measurement are **light mass (Li, Be, B)** kaonic atoms **high and low-n transitions**, **to study in detail the strong interaction between kaon and few nucleons (many body).**

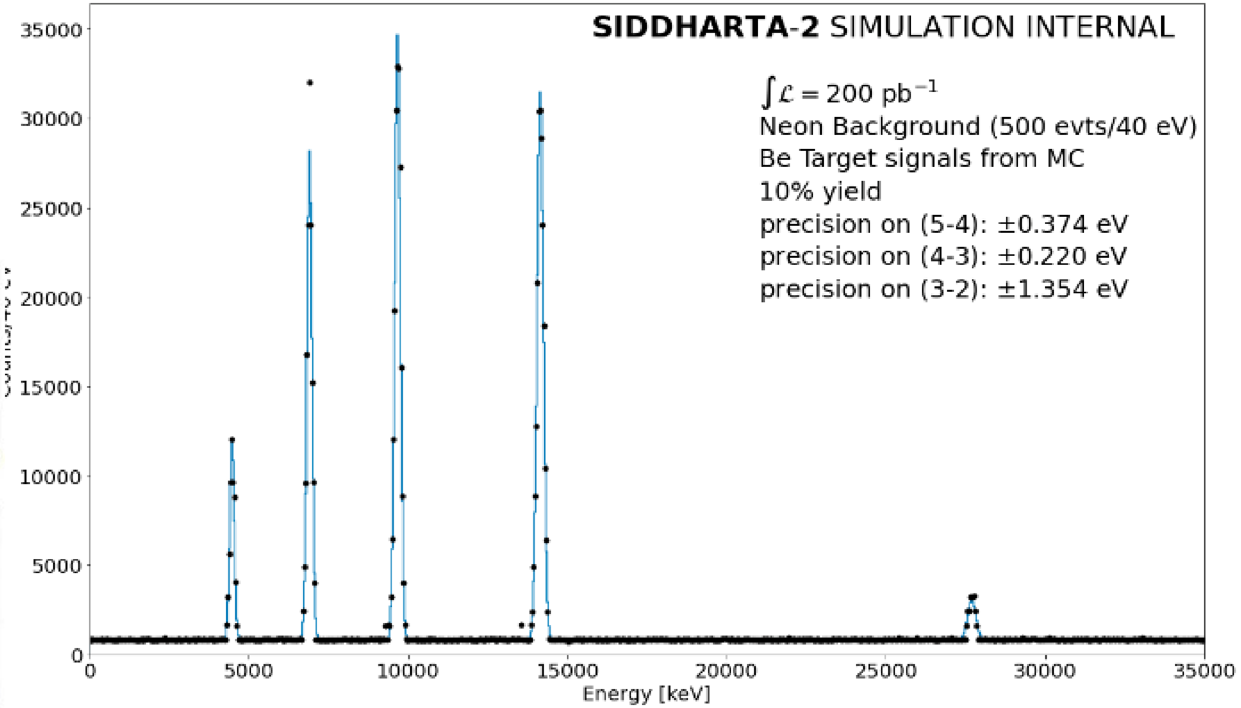
- Now precise measurements for these kaonic atoms of the shifts, widths and yields will result in a **significative improvement on the knowledge of the interactions of kaons in matter**, with a great impact on the **low energy QCD and astrophysics** (equation of state for neutron stars) .

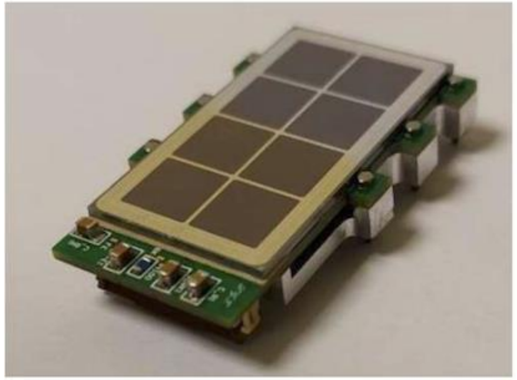
Lithium-6		Lithium-7		Beryllium-9		Boron-10		Boron-11	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**15.085**	**3 → 2**	**15.261**	**3 → 2**	**27.560**	**4 → 3**	**15.156**	**4 → 3**	**15.225**
4 → 2	**20.365**	**4 → 2**	**20.603**	**4 → 3**	**9.646**	**5 → 3**	**22.171**	**5 → 3**	**22.273**
5 → 2	**22.809**	**5 → 2**	**23.075**	**5 → 3**	**14.111**	5 → 4	7.015	5 → 4	7.047
4 → 3	5.280	4 → 3	5.341	5 → 4	4.465	6 → 4	10.826	6 → 4	10.875
5 → 3	7.724	5 → 3	7.814	6 → 4	6.890	6 → 5	3.811	6 → 5	3.828
5 → 4	2.444	5 → 4	2.472	6 → 5	2.425				
6 → 4	3.771	6 → 4	3.815						

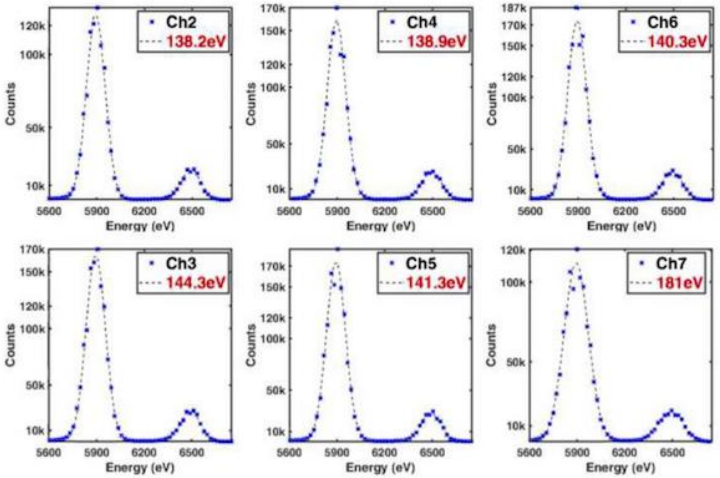
Solid targets replacing the gaseous one
and possible use of 1/2 buses of 1 mm SDDs (>20 keV)



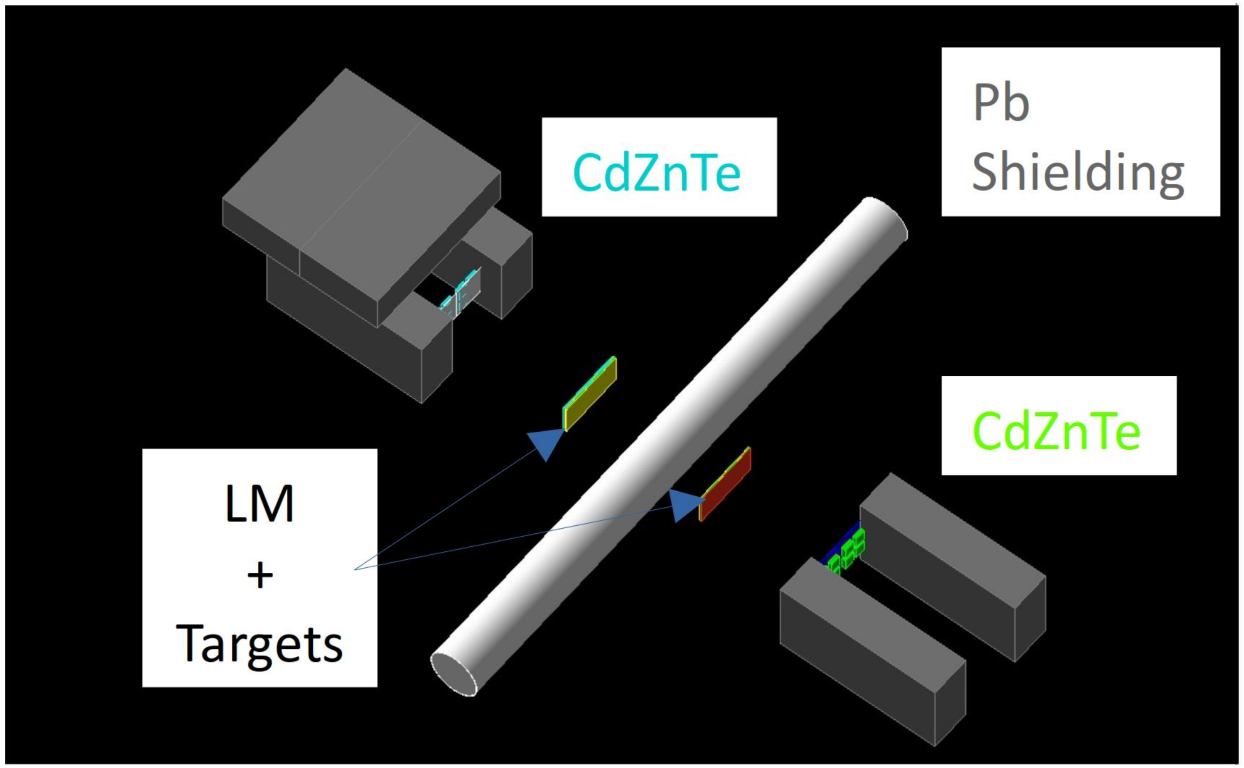
Precision measurements:
Precision below (around) eV





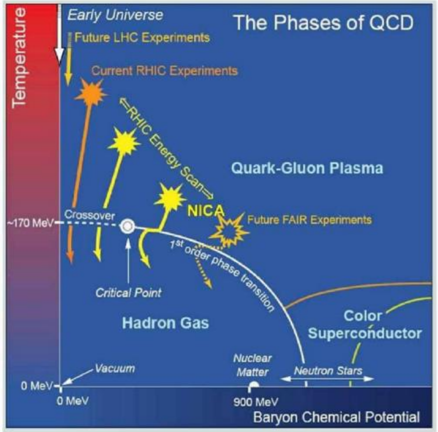


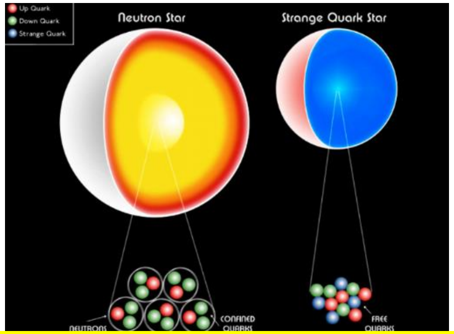
As a bonus: intermediate-mass kaonic atoms measurements with CdZnTe setups (same beam)

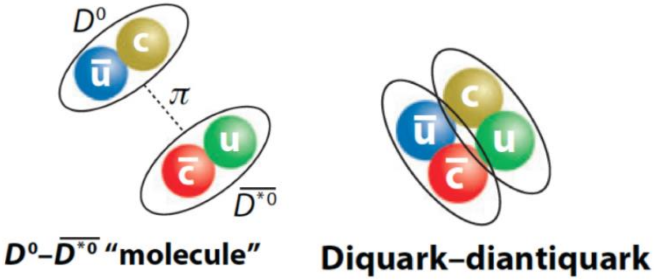


- **Kaonic Oxygen**: key role in the description of the nuclear-matter density distribution which enters in the formula for the density-dependent optical potentials
- **Kaonic Aluminium**; 3->2 QCD – never measured; 4->3 the inconsistent measurements **Kaonic Sulphur**:

S	$4 \rightarrow 3$	-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]



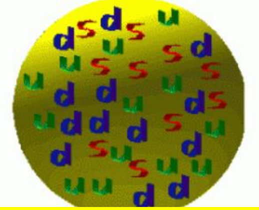




Neutron star EOS

Particles structure

Cold Dense matter

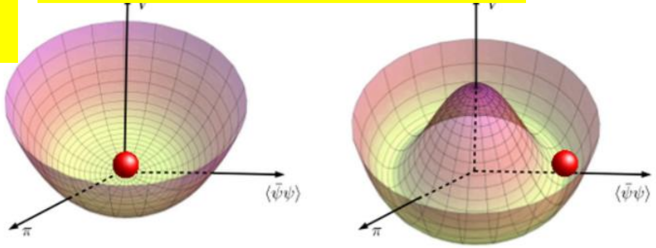


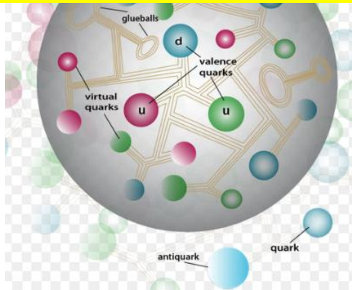
Strangeness Fundamental Physics

Mass generation, visible Universe

QCD Chiral symm.

Strangelets & Dark Matter





We would be very happy to collaborate with you!

Part of the SIDDHARTA-2 collaboration

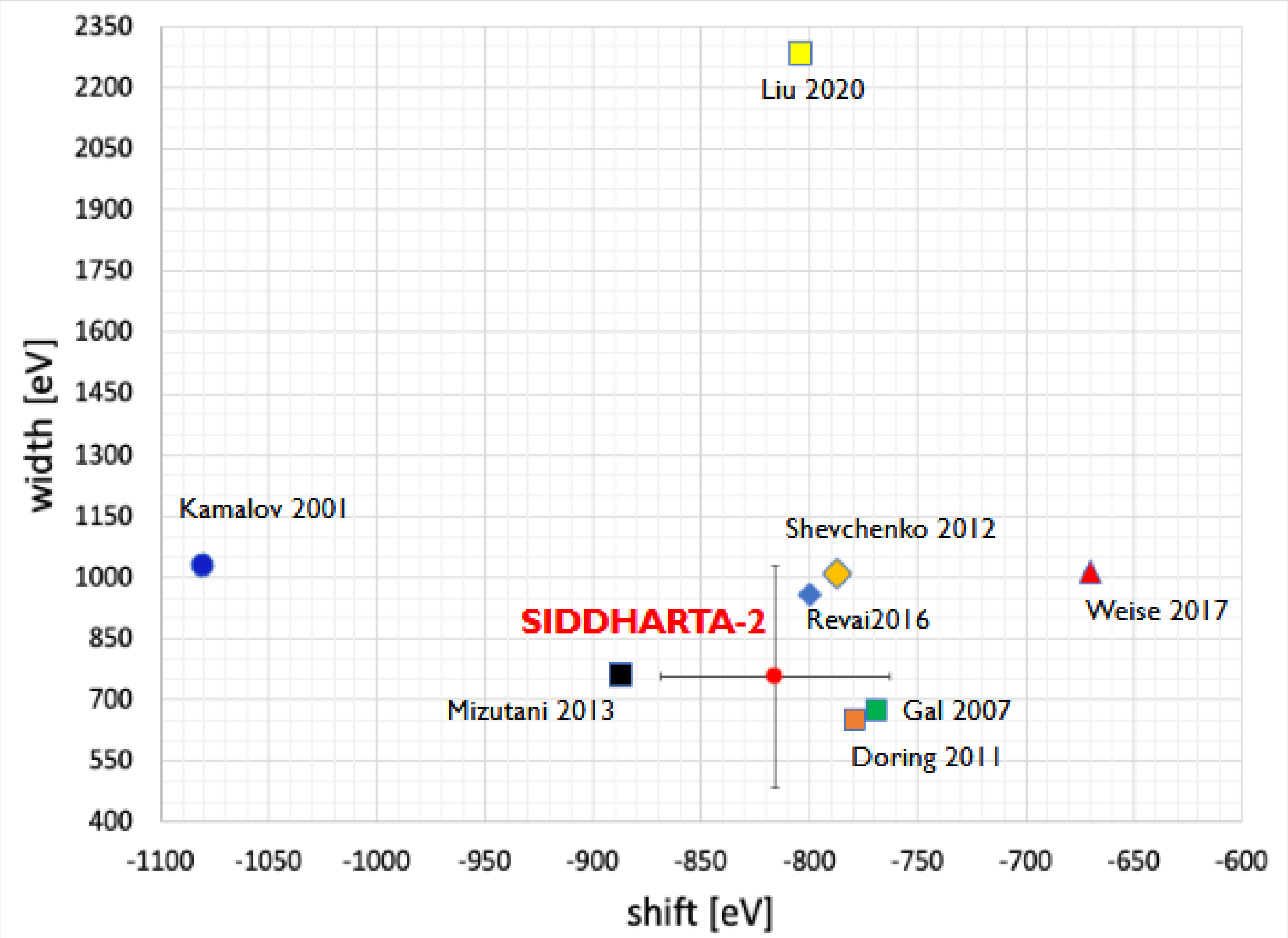
ThanK You

Immortals are never alien to one another.
— Homer, The Odyssey

Grazie Carlo, grazie Hannes!

Kaonic Deuterium Run1: preliminary result

Preliminary comparison between SIDDHARTA-2 Run1 result and the theoretical model



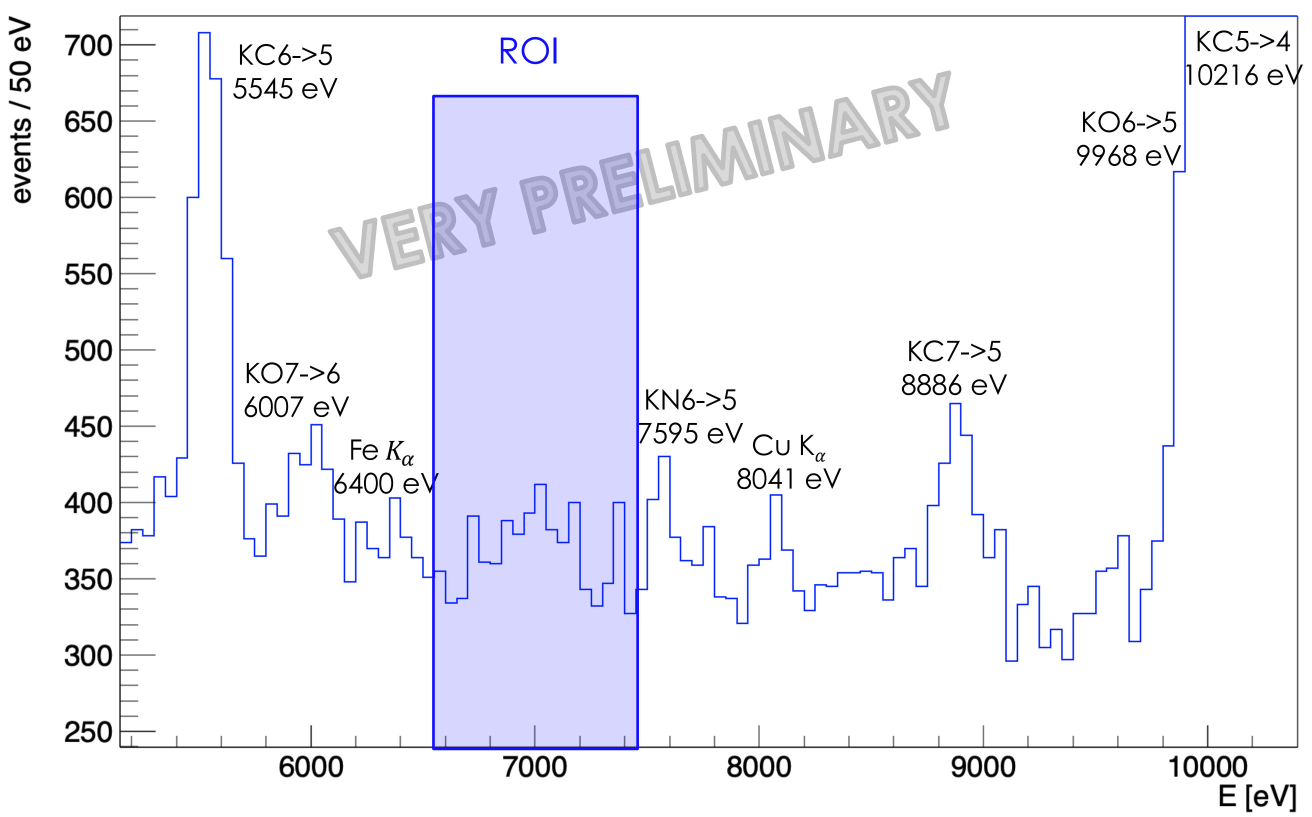
The analysis of the full dataset can potentially improve the statistical accuracy by a factor 2

(precision similar to kaonic hydrogen measurement)

Kaonic deuterium data analysis – Run1

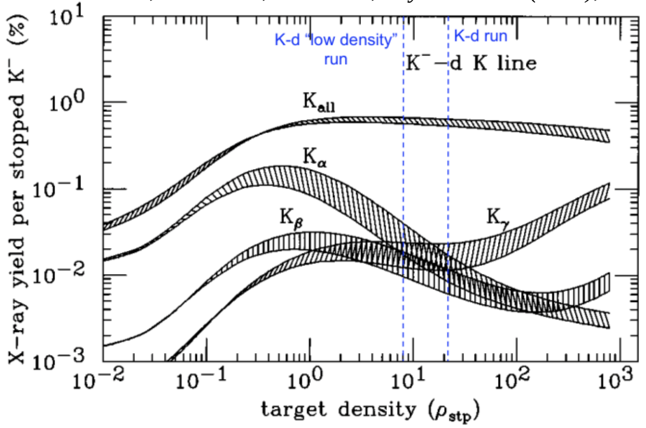
First run

200 pb^{-1}

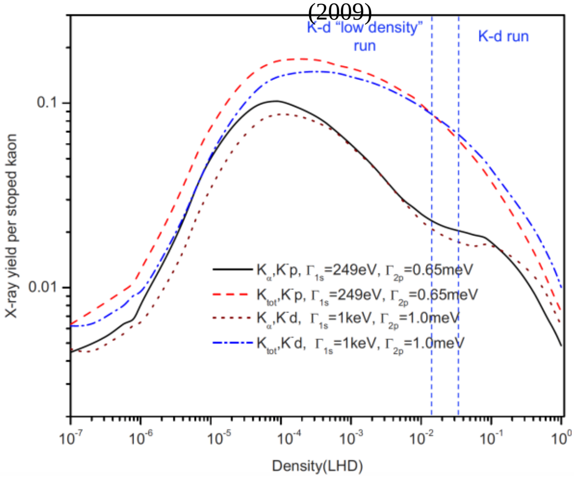


Kaonic Deuterium yield puzzle– low density run

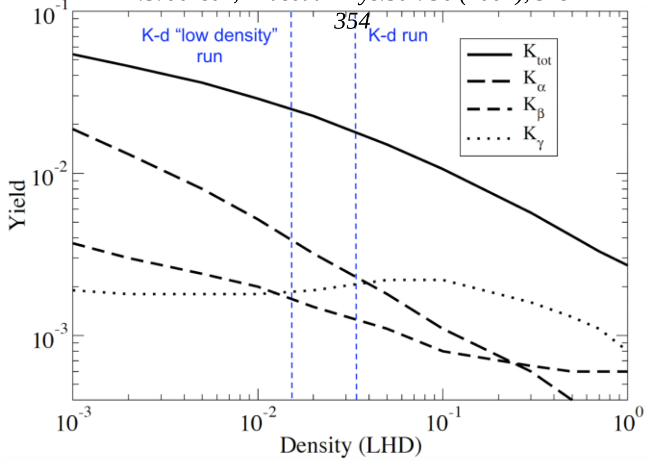
T. Koike, T. Harada, Y. Akaishi, Phys.Rev.C 53 (1996), 79-87



M Raeisi, S. Z. Kalantari, Phys.Rev.A 79, 012510 (2009)



T.S. Jensen, Frascati Phys.Ser. 36 (2004), 349-354



Several cascade model predict **completely different kaonic deuterium X-ray yields** (absolute and relative) and different trends as function of the density

Low density kaonic deuterium measurement

(60% lower compared to the previous run)

Providing unique data to investigate the de-excitation mechanism in kaonic atoms (cascade model)

The combined analysis of the kaonic deuterium measurement performed at 1.4% LDD and the ongoing measurement at 0.8% LDD **can help to disentangle between the various theoretical cascade models**

AMADEUS scientific case (with KLOE data)

AMADEUS (**A**ntikaonic **M**atter **A**t **D**AΦNE: an **E**xperiment with **U**nravelling **S**pectroscopy)
investigates **low-energy K^- absorption in nuclei** with the aim to extract information on

- K^-N interaction <u>above and below</u> threshold
  - Λ(1405) nature
  - K^-N scattering amplitudes and cross sections
- K^-NN, K^-NNN, K^-NNNN (multi-nucleon) interactions
  - K^--multi nucleon cross sections
  - essential for the determination of K^--nuclei optical potential
  - kaonic bound states
- Hyperon-nucleon/(multi-nucleons) interaction cross sections

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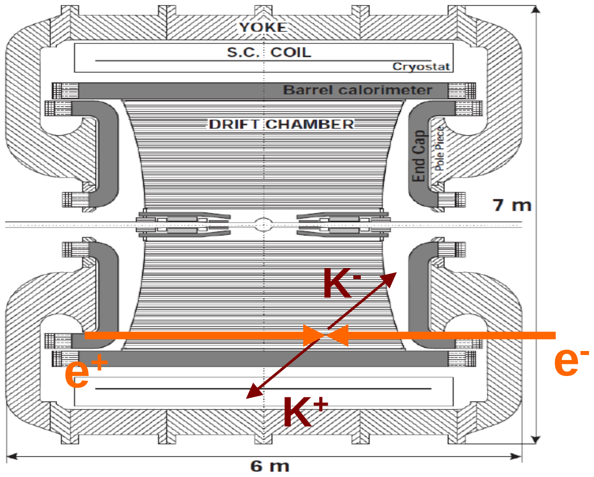
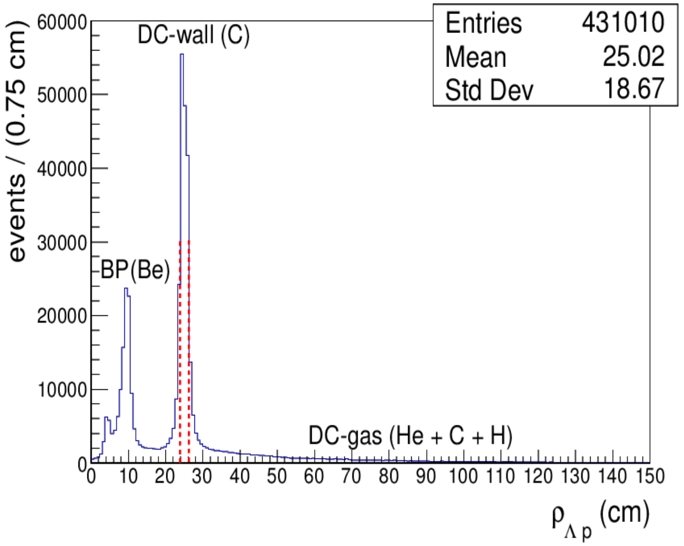
AMADEUS



The KLOE detector

Cylindrical drift chamber with a **4π geometry** and electromagnetic calorimeter, **96% acceptance**

- optimized in the energy range of all **charged particles** involved
- **good performance** in detecting **photons and neutrons** checked by kloNe group [M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)]



KLOE used as an active target

- DC wall (750 μm C foil , 150 μm Al foil);
- DC gas (90% He, 10% C_4H_{10}).

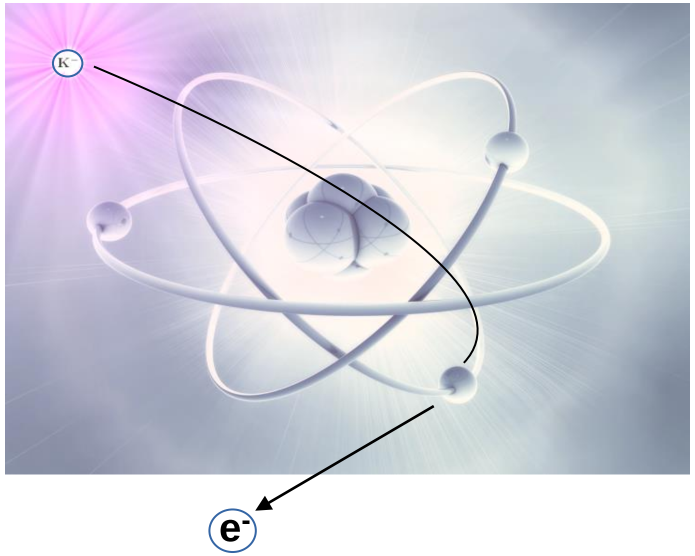
+

pure sample of K^- ^{12}C absorptions at-rest

K^- absorptions at-rest and in-flight

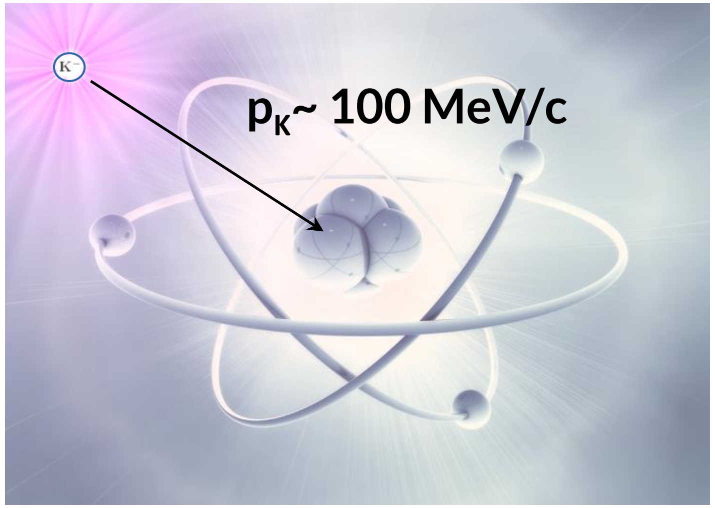
AT-REST

K^- absorbed from atomic orbitals
(p_K ~ 0 MeV/c)



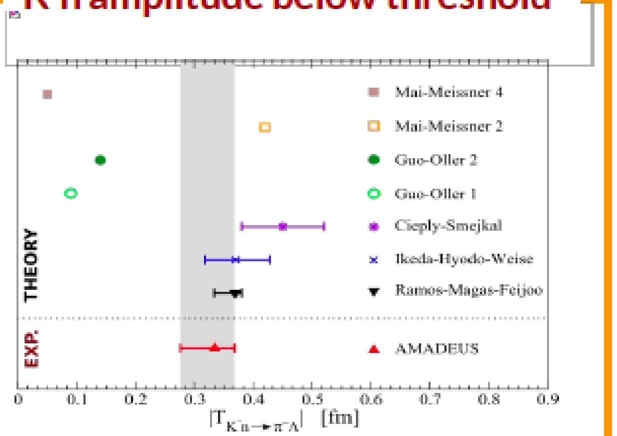
IN-FLIGHT

(p_K~ 100 MeV/c)



Highlights of AMADEUS results

K⁻n amplitude below threshold



Λp channel: 2NA, 3NA and 4NA BRs and σ

Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	0.25 ± 0.02 (stat.) $^{+0.01}_{-0.02}$(syst.)	2.8 ± 0.3 (stat.) $^{+0.1}_{-0.2}$ (syst.)	@	128 ± 29
2NA-FSI Λp	6.2 ± 1.4(stat.) $^{+0.5}_{-0.6}$(syst.)	69 ± 15 (stat.) $\pm$ 6 (syst.)	@	128 ± 29
2NA-QF Σ^0p	0.35 ± 0.09(stat.) $^{+0.13}_{-0.06}$(syst.)	3.9 ± 1.0 (stat.) $^{+1.4}_{-0.7}$ (syst.)	@	128 ± 29
2NA-FSI Σ^0p	7.2 ± 2.2(stat.) $^{+4.2}_{-5.4}$(syst.)	80 ± 25 (stat.) $^{+46}_{-60}$ (syst.)	@	128 ± 29
2NA-CONV Σ/Λ	2.1 ± 1.2(stat.) $^{+0.9}_{-0.5}$(syst.)	-		
3NA Λpn	1.4 ± 0.2(stat.) $^{+0.1}_{-0.2}$(syst.)	15 ± 2 (stat.) $\pm$ 2 (syst.)	@	117 ± 23
3NA Σ^0pn	3.7 ± 0.4(stat.) $^{+0.2}_{-0.4}$(syst.)	41 ± 4 (stat.) $^{+2}_{-5}$ (syst.)	@	117 ± 23
4NA Λpnn	0.13 ± 0.09(stat.) $^{+0.08}_{-0.07}$(syst.)	-		
Global $\Lambda(\Sigma^0)$p	21 ± 3(stat.) $^{+5}_{-6}$(syst.)	-		

The ratio between the branching ratios of the 2NA-QF in the Λp channel and in the Σ^0p is measured to be:

$$\mathcal{R} = \frac{BR(K^- pp \to \Lambda p)}{BR(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2(stat.)^{+0.2}_{-0.3}(syst.)$$

$$BR(K^- 2NA \to YN) = (21.6 \pm 2.9(stat.)^{+4.4}_{-5.6}(syst.))\%$$

K- p -> (Σ^0/Λ) π^0

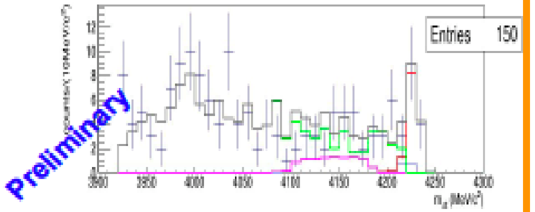
cross section at p_{K^-} = 98 ± 10 MeV/c :

- $\sigma_{K^-p\to\Sigma^0\pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)$ mb
- $\sigma_{K^-p\to\Lambda\pi^0} = 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)$ mb ,

Λt channel: 4NA BRs and σ

$BR(K^-{}^4He(4NA) \to \Lambda t) < 2.0 \times 10^{-4} / K_{stop}$ (95% c. l.)

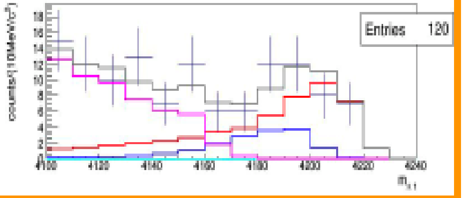
$\sigma(100 \pm 19$ MeV/c$)(K^-{}^4He(4NA) \to \Lambda t) = (0.81 \pm 0.21$ (stat) $^{+0.03}_{-0.04}$ (syst)) mb



$BR(K^-{}^{12}C(4NA) \to \Lambda t\, {}^8Be) = 1.5 \pm 0.5 \times 10^{-4}$ (stat) $/K_{stop}$

$\sigma(K^-{}^{12}C(4NA) \to \Lambda t\, {}^8Be) = 0.58 \pm 0.11$ (stat) mb

$\sigma(K^-{}^{12}C(4NA) \to \Sigma^0 t\, {}^8Be) = 1.88 \pm 0.35$ (stat) mb



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Future perspectives

- The present knowledge of total and differential cross sections of low energy kaon-nucleon reactions is very limited: below 150 MeV/c there is a "desert" - the experimental data are very scarce and with large errors and practically no data exist below 100 MeV/c.
- **Kaon-nucleon scattering/interaction data are fundamental to validate theories: chiral symmetries; lattice calculations; potential models etc.**