

KAONIC ATOMS X-RAY SPECTROSCOPY: AN AMAZING TOOL TO STUDY FUNDAMENTAL INTERACTIONS



M E S O N
2 0 2 6

18th International Workshop
on Meson Physics
25th - 30th June 2026, Kraków, Poland

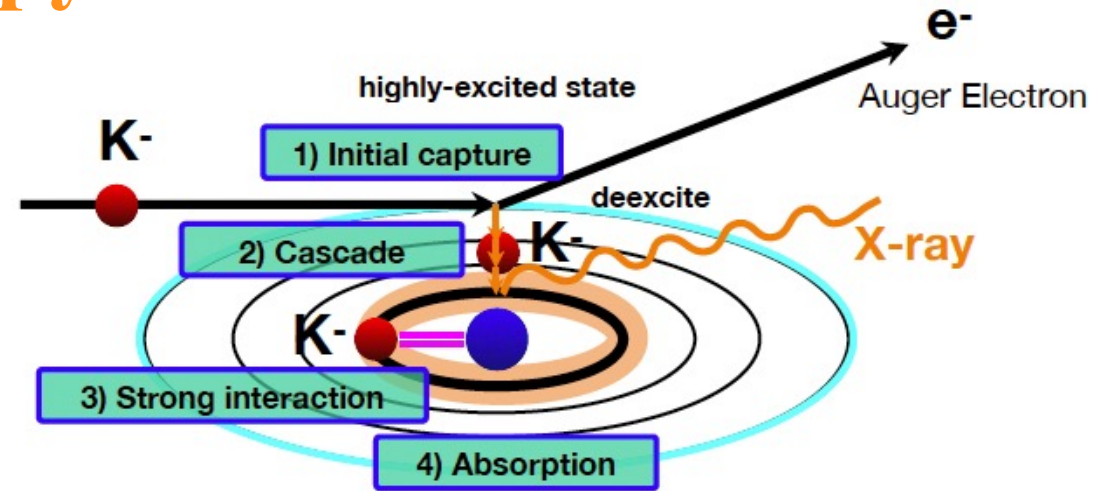
Francesco Sgaramella INFN-LNF
on behalf of the SIDDHARTA-2 collaboration

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2 20

Kaonic Atoms X-ray Spectroscopy

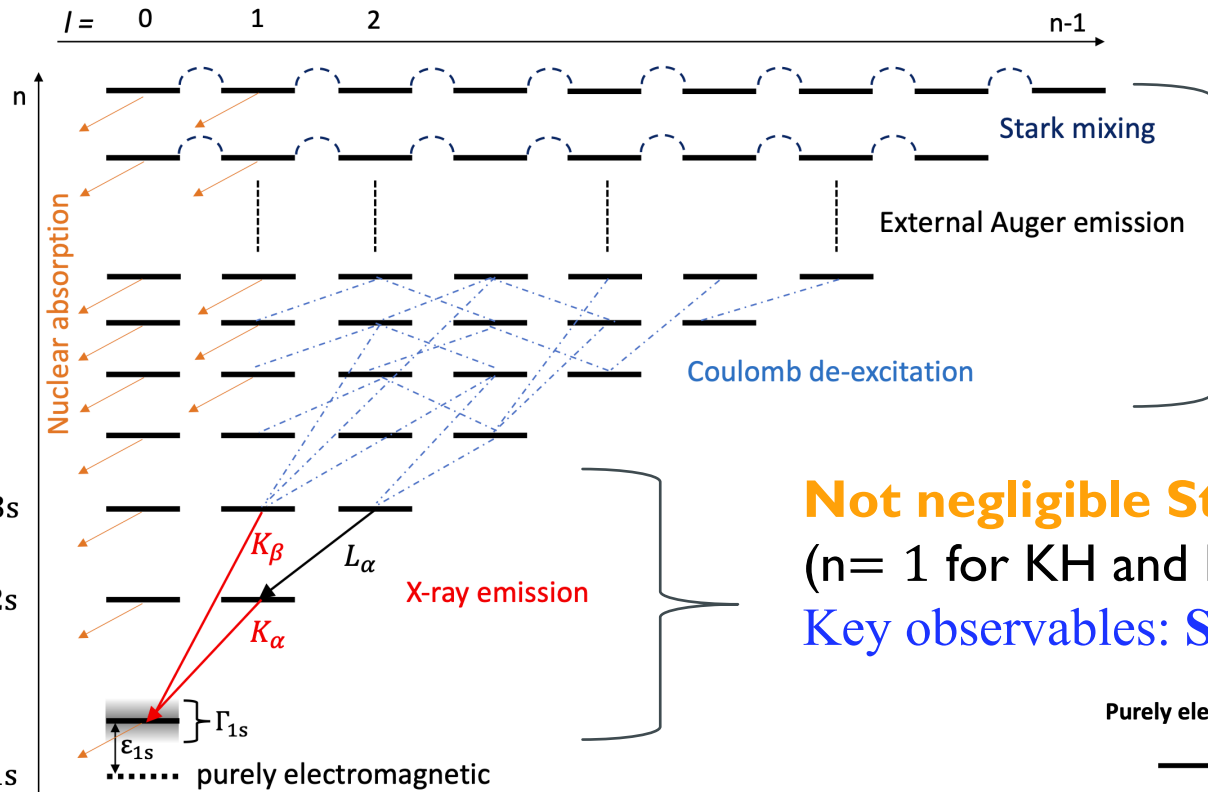
Kaonic atoms X-ray spectroscopy to investigate the kaon nucleus interaction: from QED to QCD



Pure QED transition

QED key observables: **Energy** and **X-ray Yield**

High precision test of BSQED

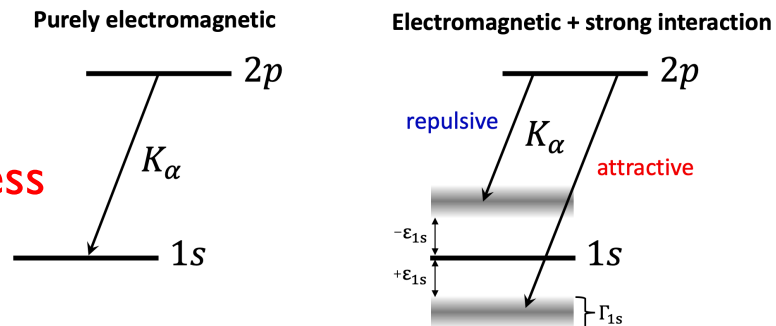


Not negligible Strong interaction effect

($n = 1$ for KH and Kd)

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

Low-energy QCD with strangeness



Why Kaonic Atom?

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

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

Fundamental physics
New Physics

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

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

Dark Matter and BSM

Probing new hadronic forces with heavy exotic atoms
(2025) *arXiv:2502.03537v1*
On self-gravitating strange dark matter halos around
galaxies *Phys.Rev.D* 102 (2020) 8, 083015

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

Astrophysics
EOS Neutron Stars

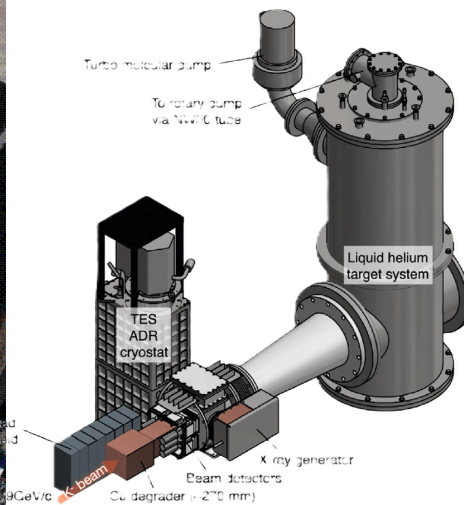
Low
Energy
QCD

Strong
Field QED

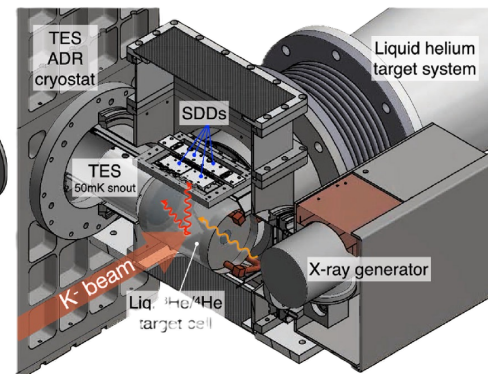
Kaon
Mass



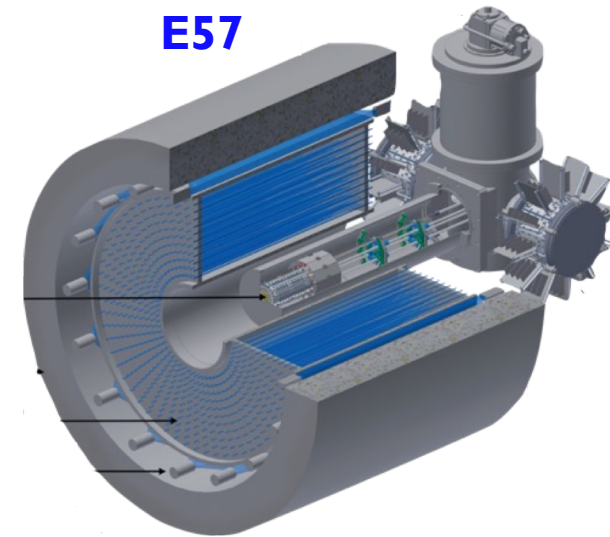
J-PARC



E62



E57



Light kaonic atoms as probes of fundamental interactions in strange systems

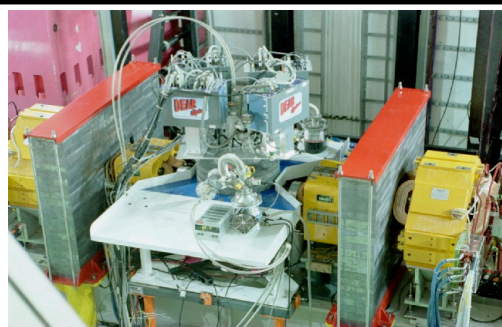
[Progress in Particle and Nuclear Physics 147 \(2026\) 104226](#)

Catalina Curceanu, Francesco Sgaramella, Massimiliano Bazzi, Tadashi Hashimoto, Mihail Iliescu, Alessandro Scordo, Diana Sirghi, Florin Sirghi

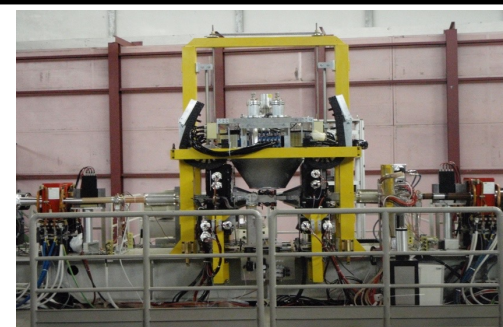


DAFNE

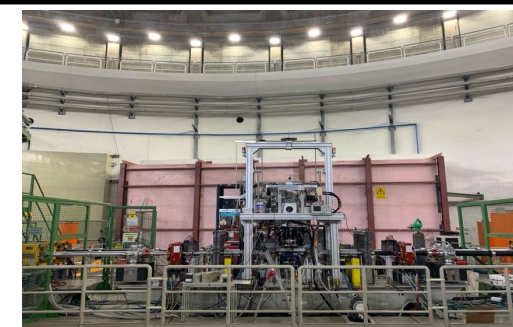
DEAR
2002



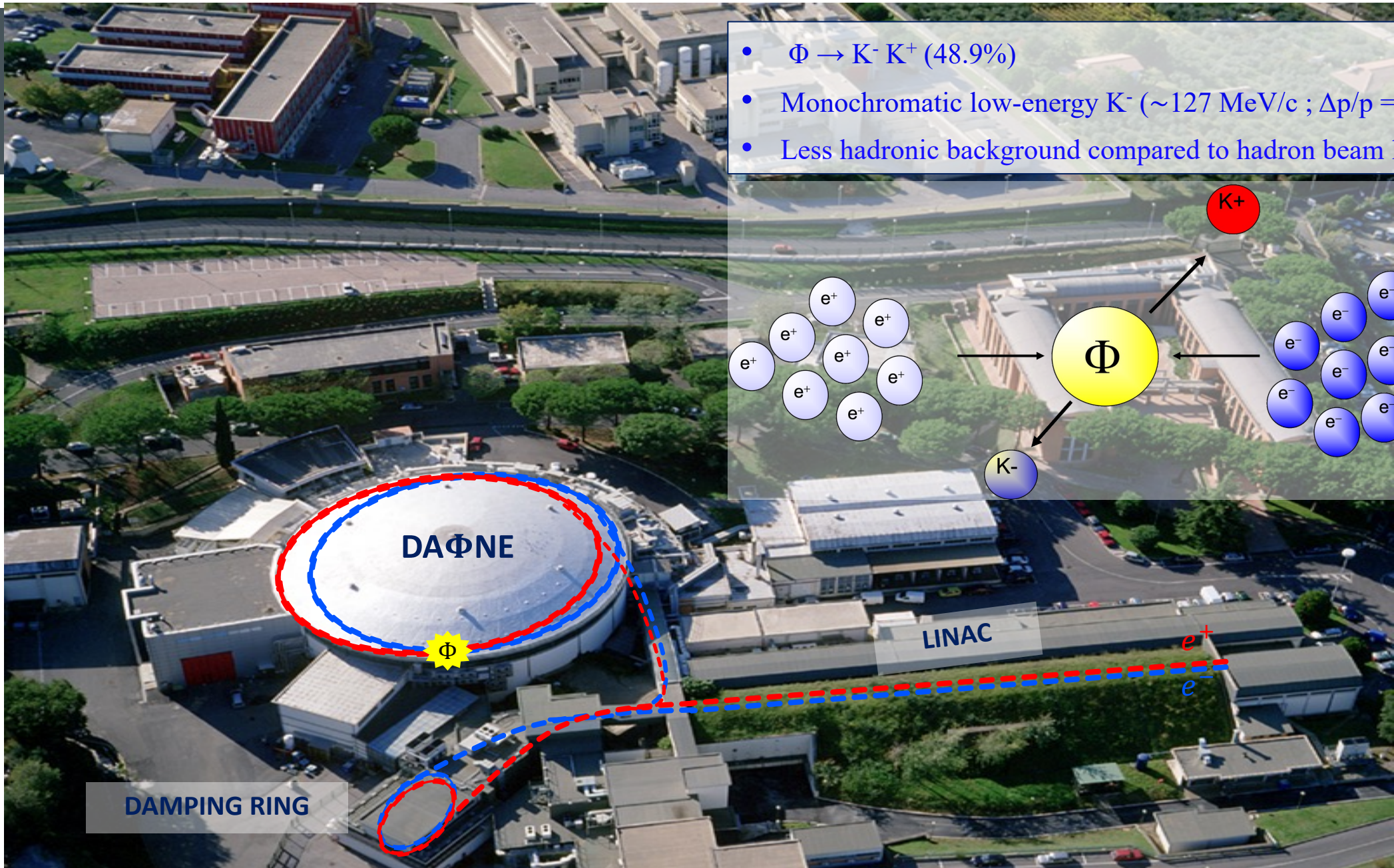
SIDDHARTA
2009



SIDDHARTA-2
2022



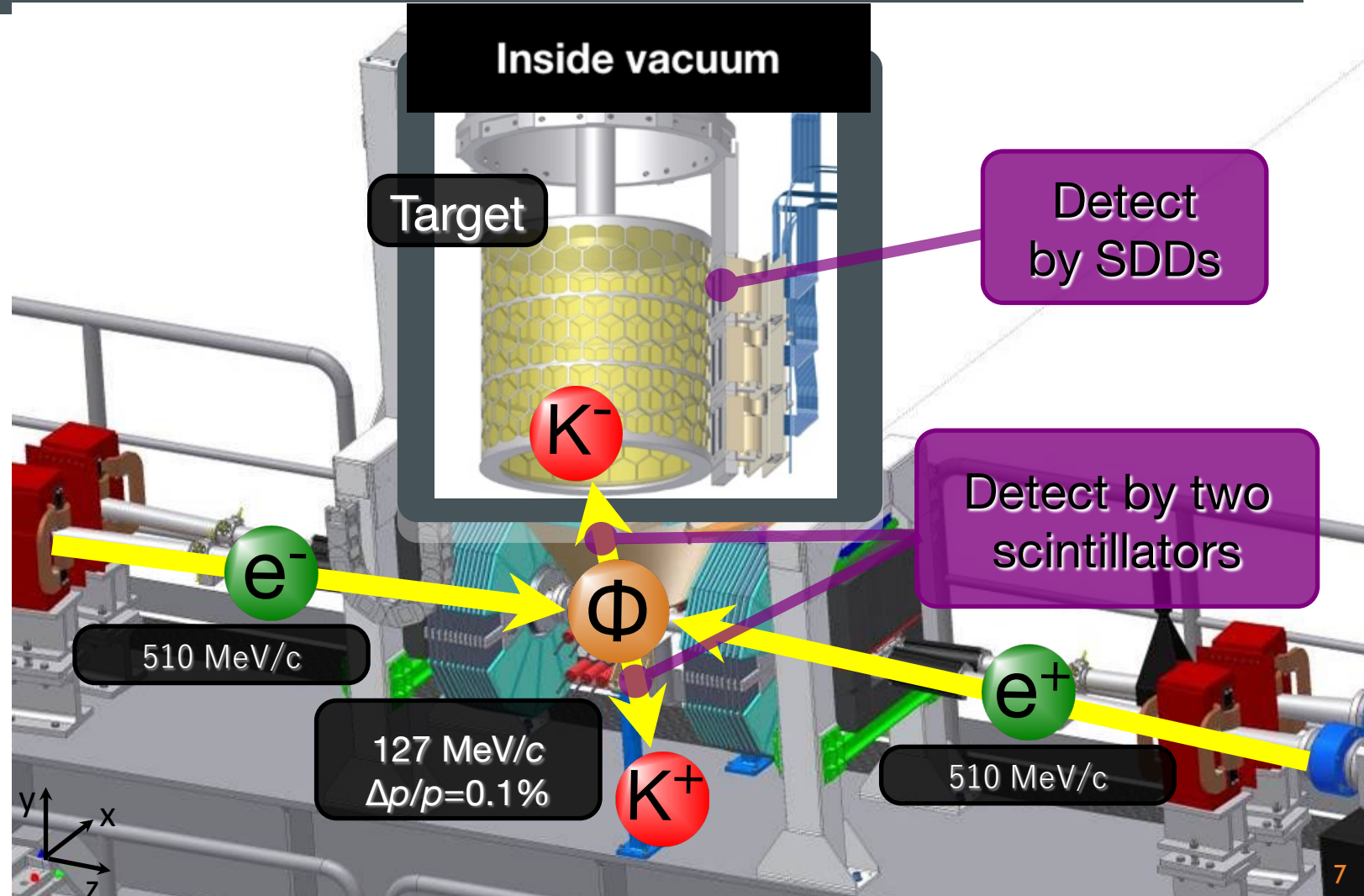
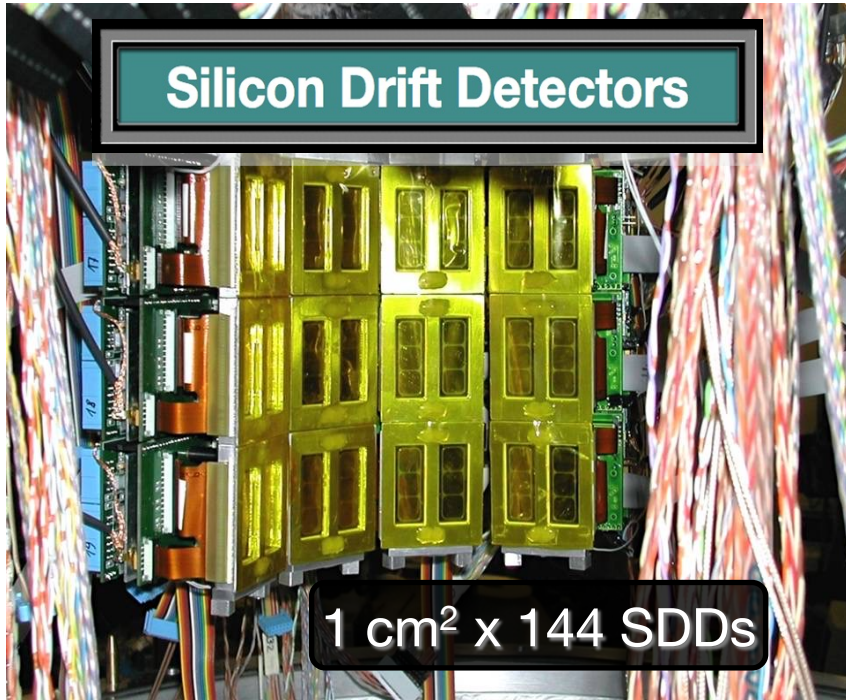
The DAΦNE collider of INFN-LNF



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

The SIDDHARTA Experiment (2009)

A cryogenic gaseous target and Silicon Drift Detectors to perform the kaonic hydrogen measurement

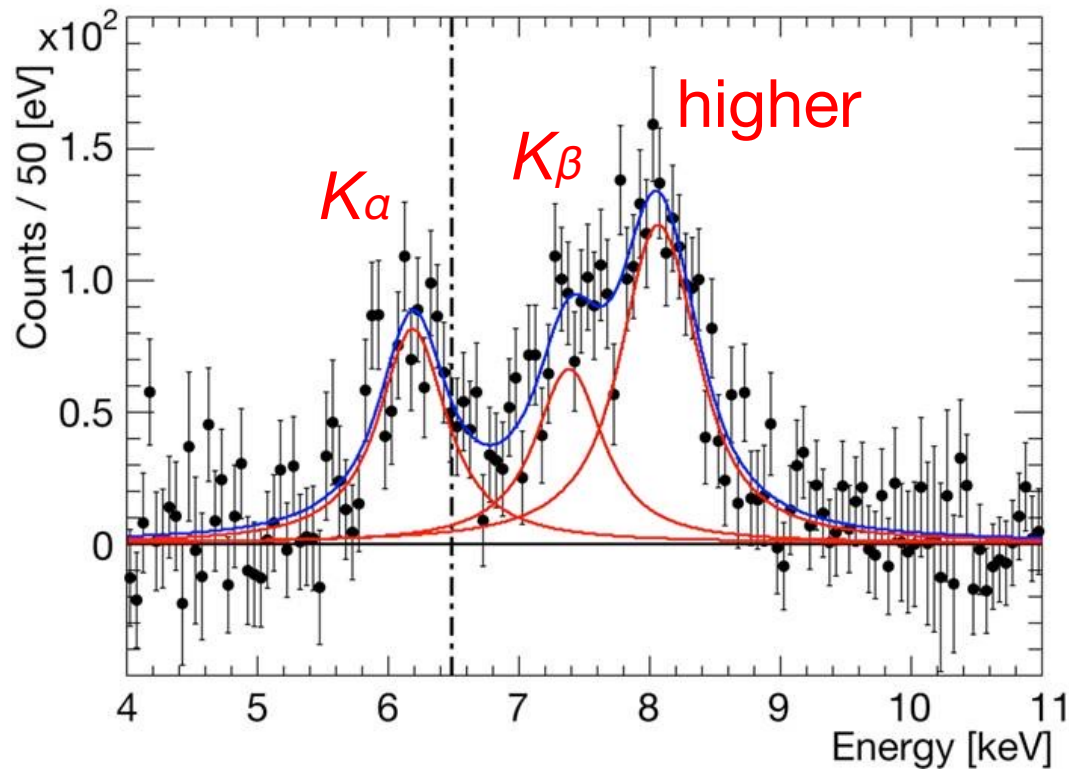


The SIDDHARTA Experiment (2009)

The most precise measurement of kaonic hydrogen 1s shift and width performed by SIDDHARTA was fundamental to constrain the description of the K-p interaction at threshold

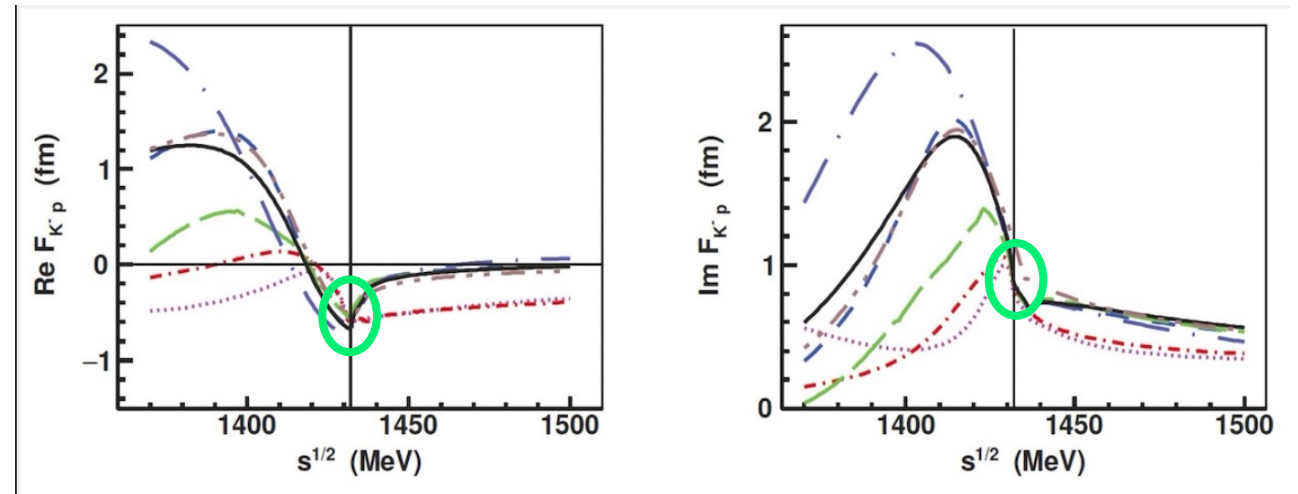
$$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst}) \text{ eV}$$

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



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

K-p scattering amplitudes generated by recent chirally motivated approaches. The vertical lines mark the threshold energy



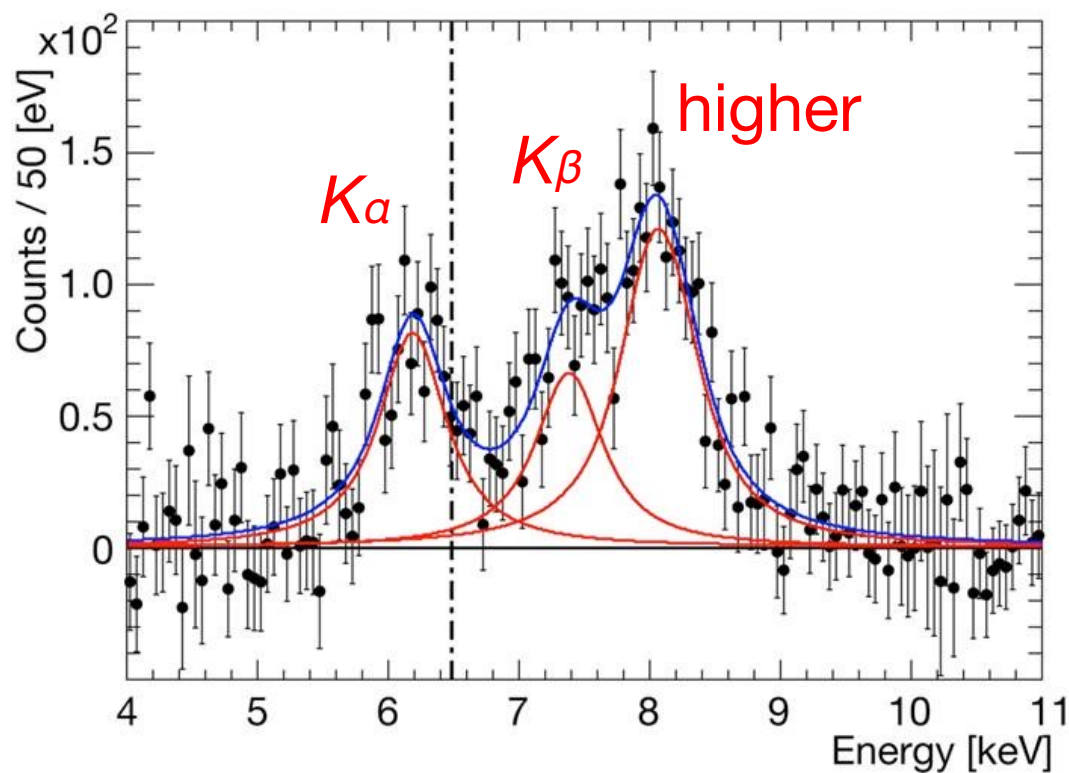
Ciepl y,A. et al. From *KN interactions to K-nuclear quasi-bound states*. *AIP Conf. Proc.* 2249, 030014 (2020).

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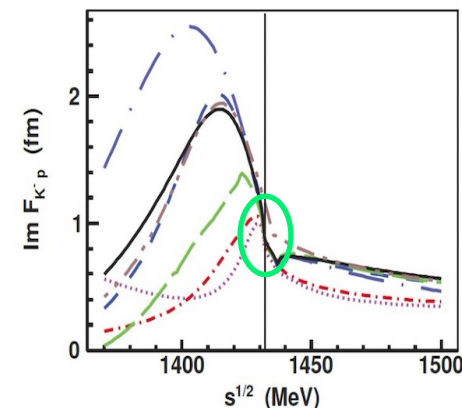
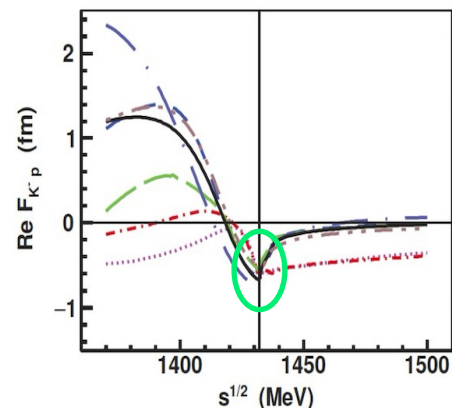
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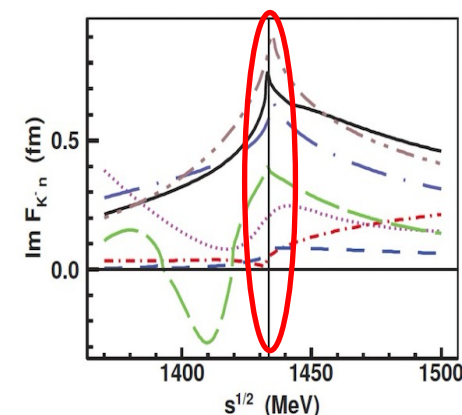
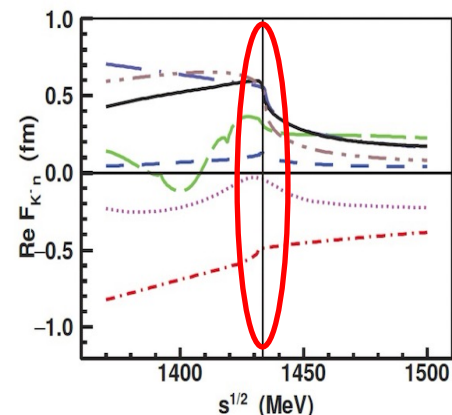
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C. Curceanu et al., *Phys. Lett. B* **704** (2011) 113



K-p: agreement



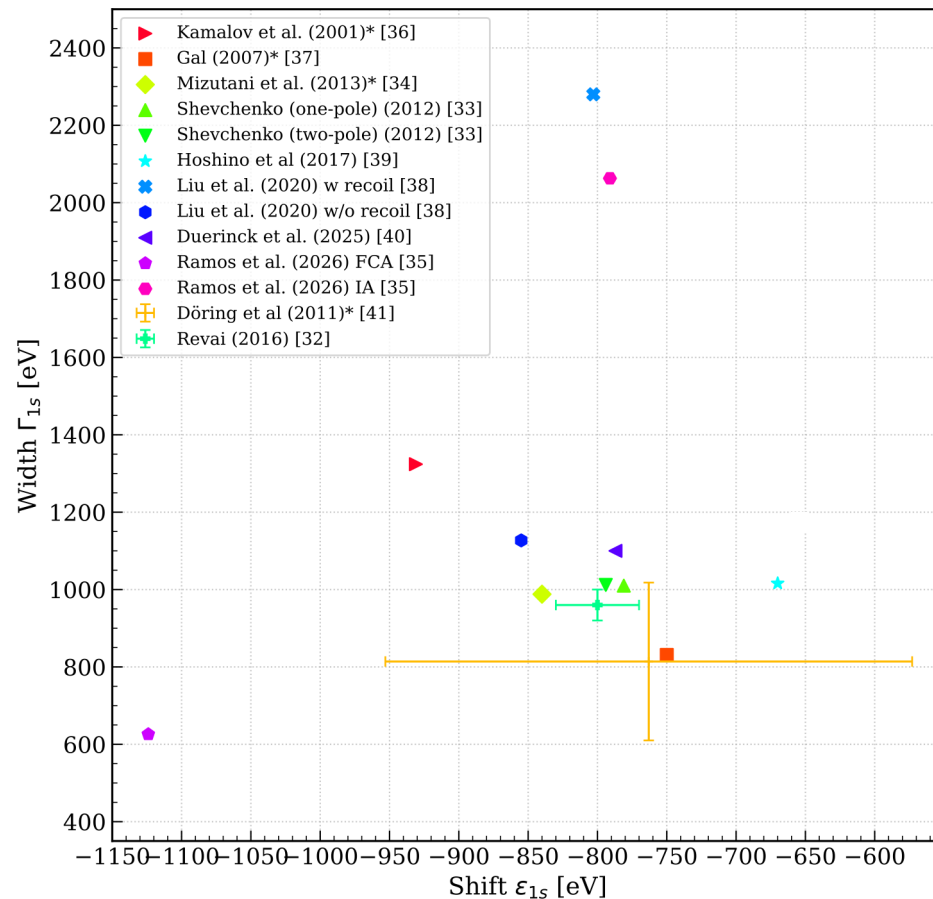
K-n: disagreement

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

The SIDDHARTA-2's experiment main aim

Main 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 strong interaction**, providing unique data to investigate the **QCD in the non-perturbative regime** with strangeness.

Kaonic deuterium 1s level shift and width: **theoretical prediction**



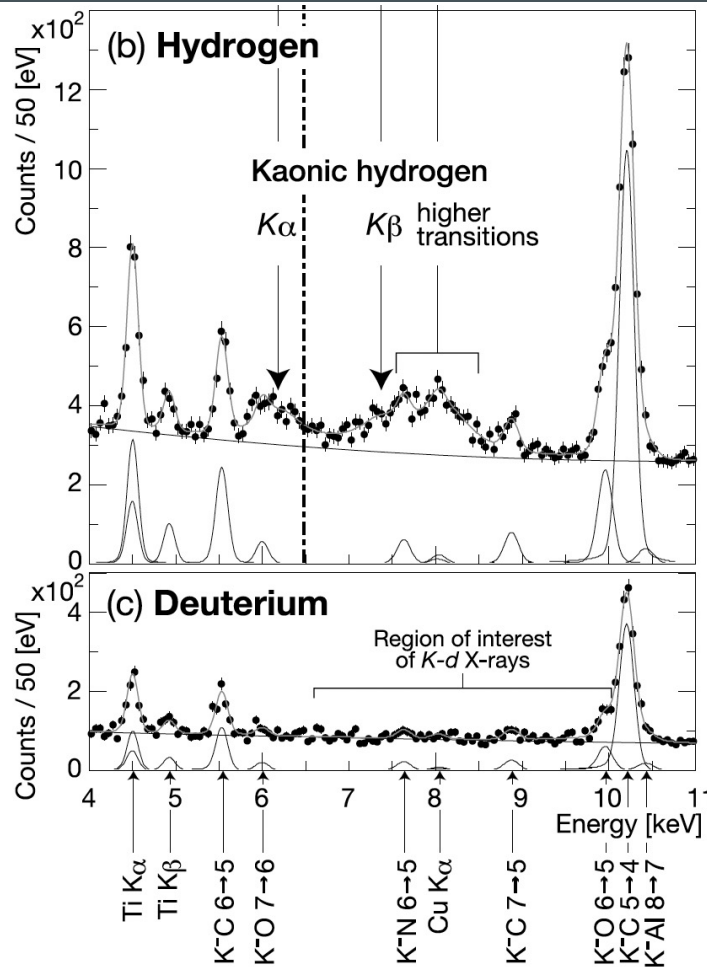
“The most important experiment to be carried out in low energy K-meson physics today is the **definitive determination of the energy level shifts in the K-p and K-d atoms**, because of their direct connection with the physics of $\bar{K}N$ interaction and their complete independence from all other kinds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

R.H. Dalitz (1982)

* The energy shift and width are extracted from scattering length using the Deser-Trueman resummed formula

The kaonic deuterium challenge

The measurement of Kaonic deuterium $2p \rightarrow 1s$ is a true challenge: SIDDHARTA performed an exploratory run in 2009, collecting 100 pb^{-1} of data but without observing a visible signal.



Physics factors:

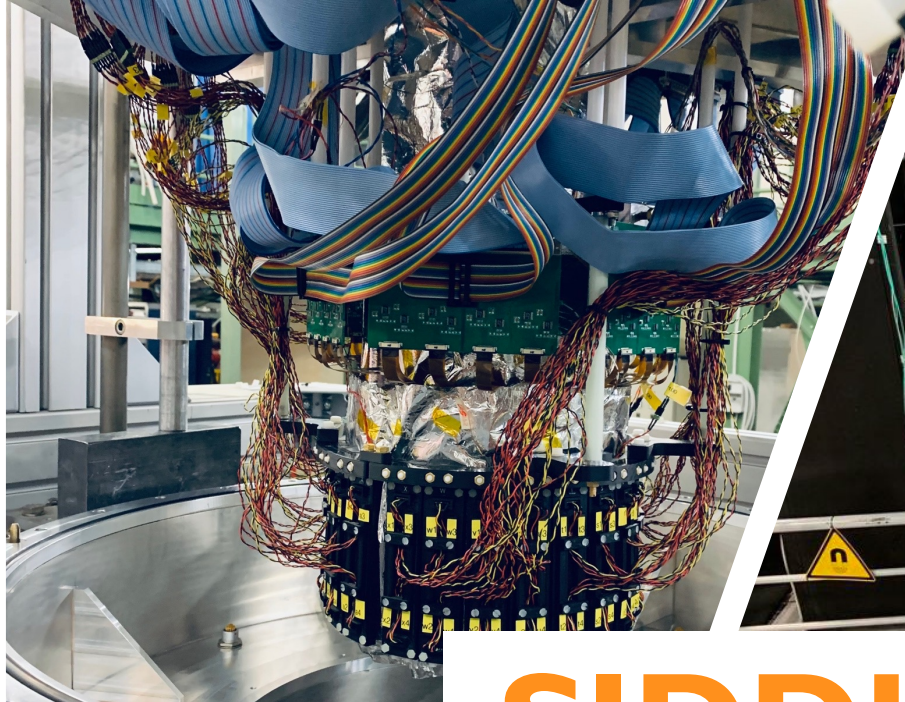
- Low X-ray yield (~ 10 times lower than KH)
- Transition width broader than KH $2p \rightarrow 1s$

➤ K-d requires a **higher (x8) integrated luminosity** $\sim 800 \text{ pb}^{-1}$

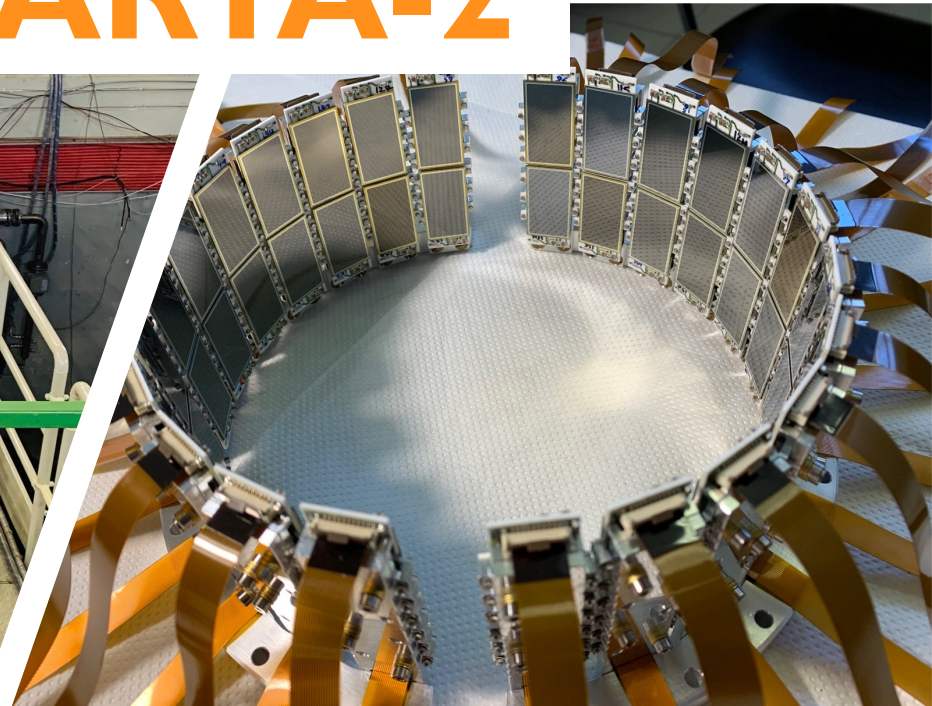
Background:

- The K-d measurement requires an improvement in signal/background ratio by a factor 10

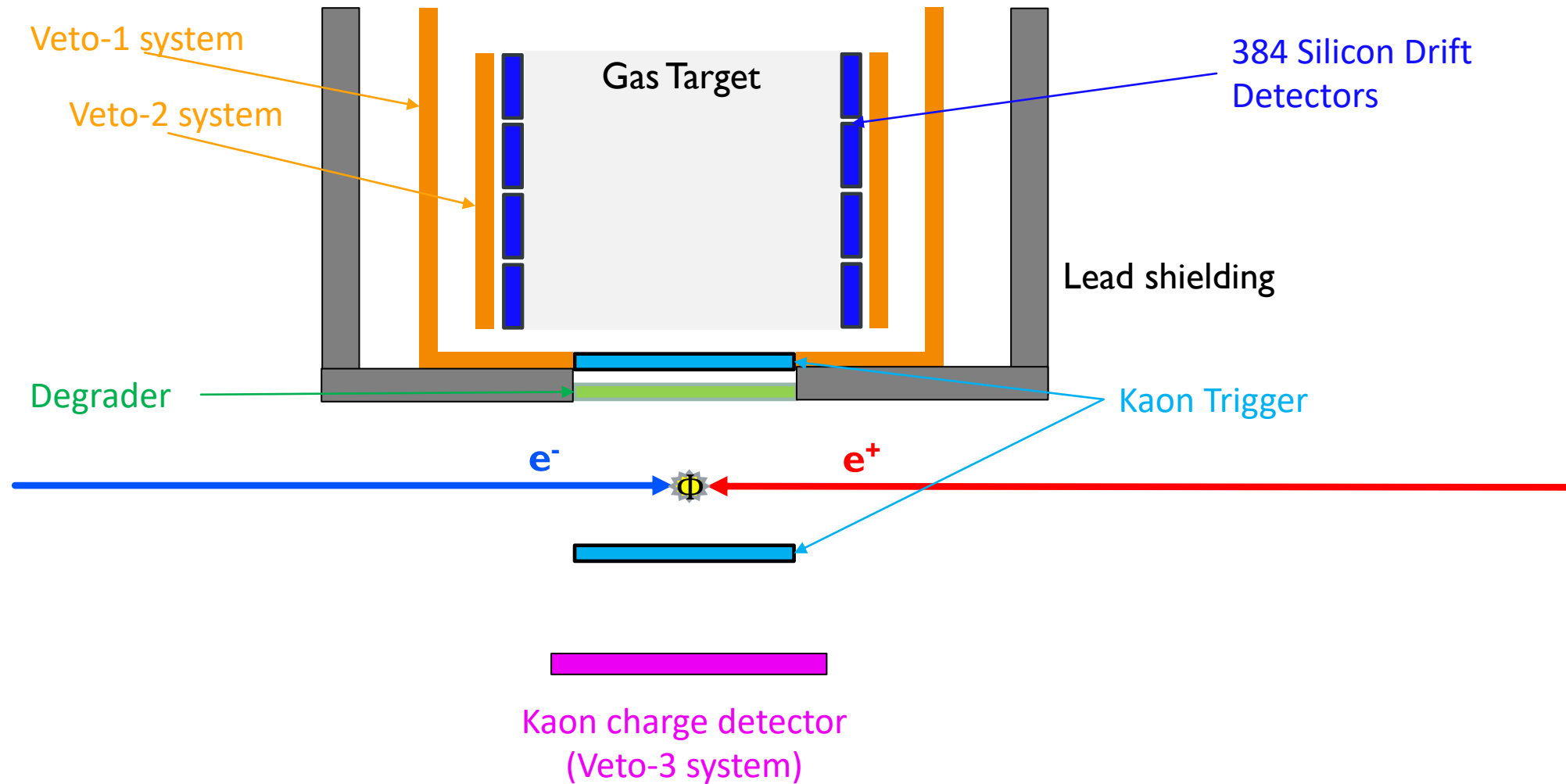
➤ **New experimental apparatus** with improved Silicon Drift Detectors, trigger system, Veto systems, DAΦNE optics and collision scheme



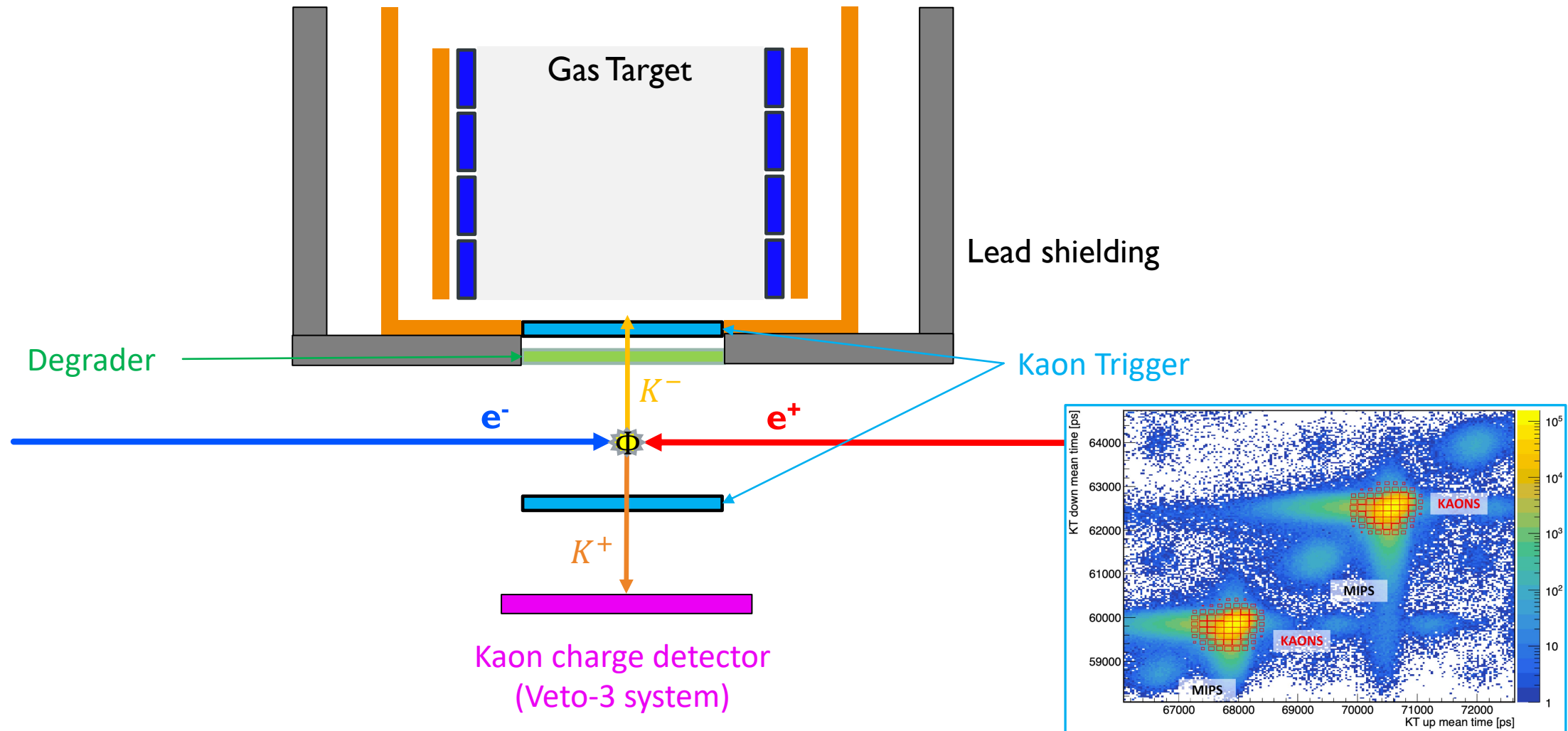
SIDDHARTA-2



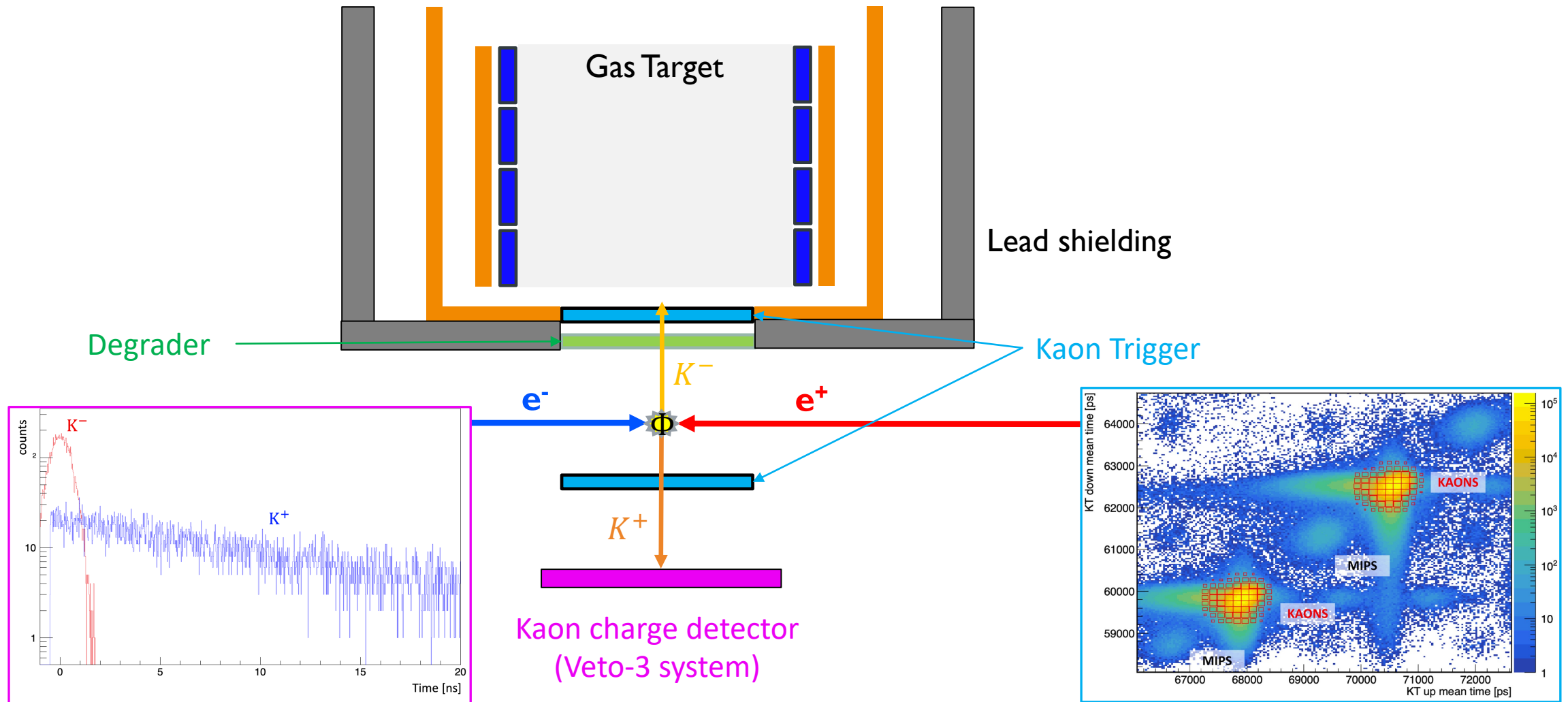
The SIDDHARTA-2 experiment



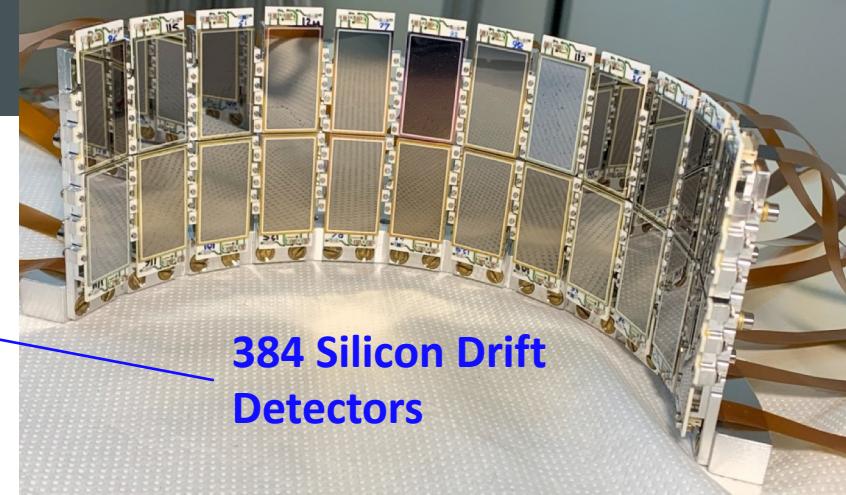
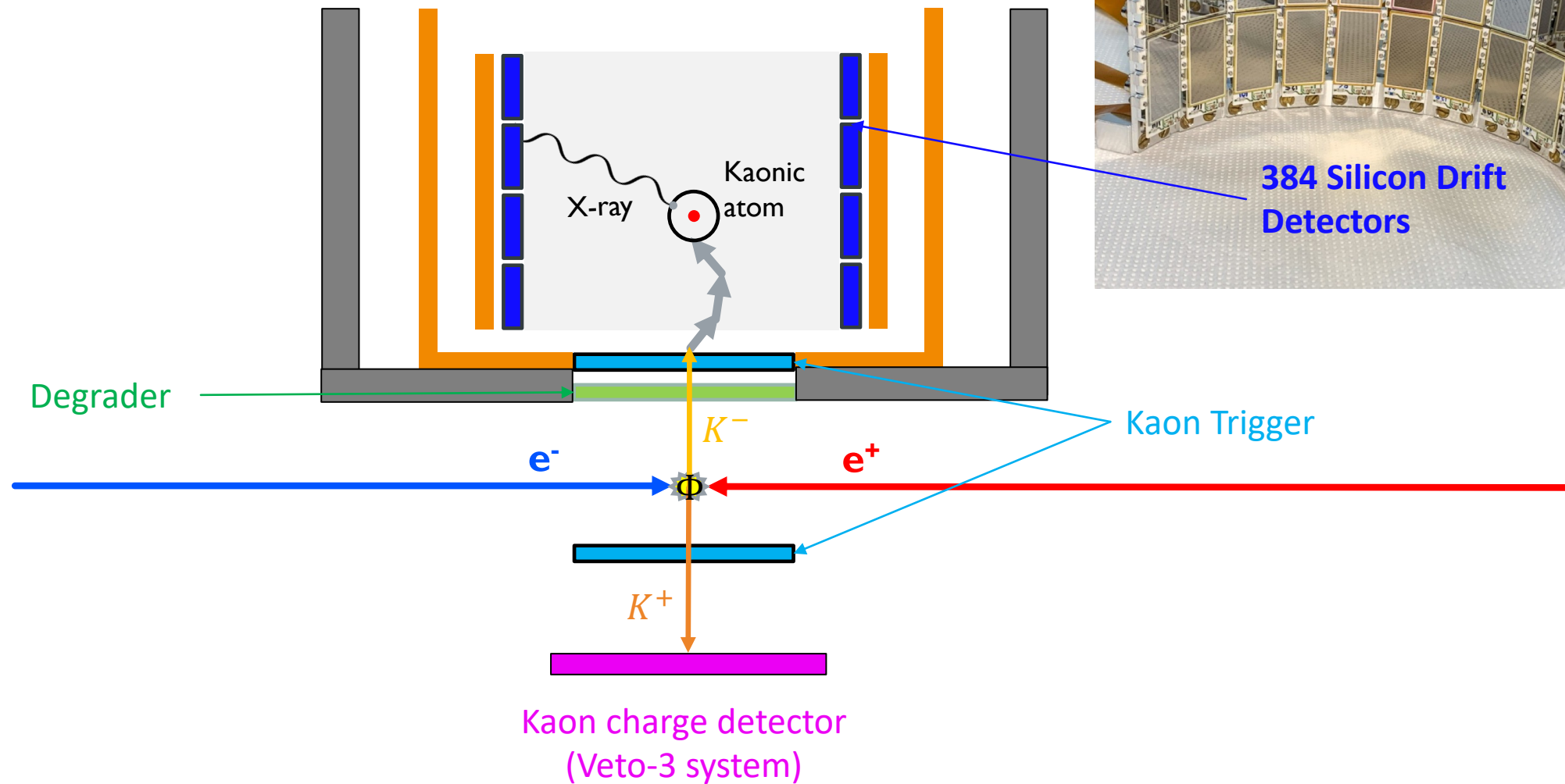
The SIDDHARTA-2 experiment



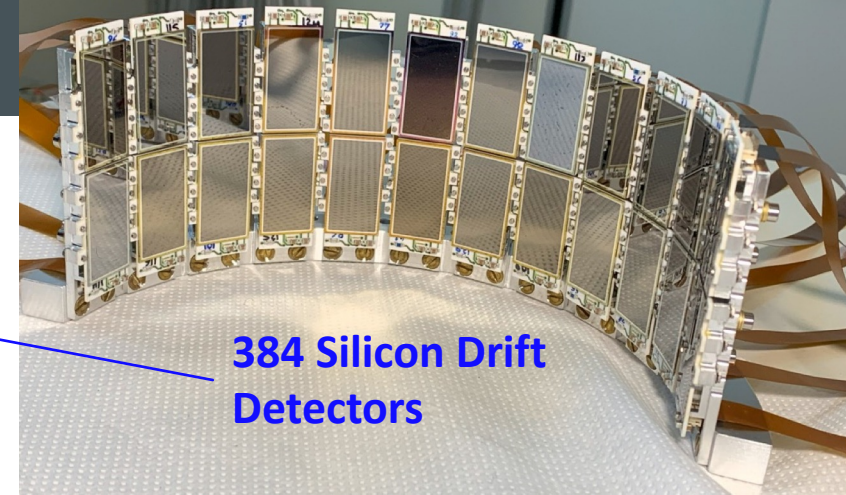
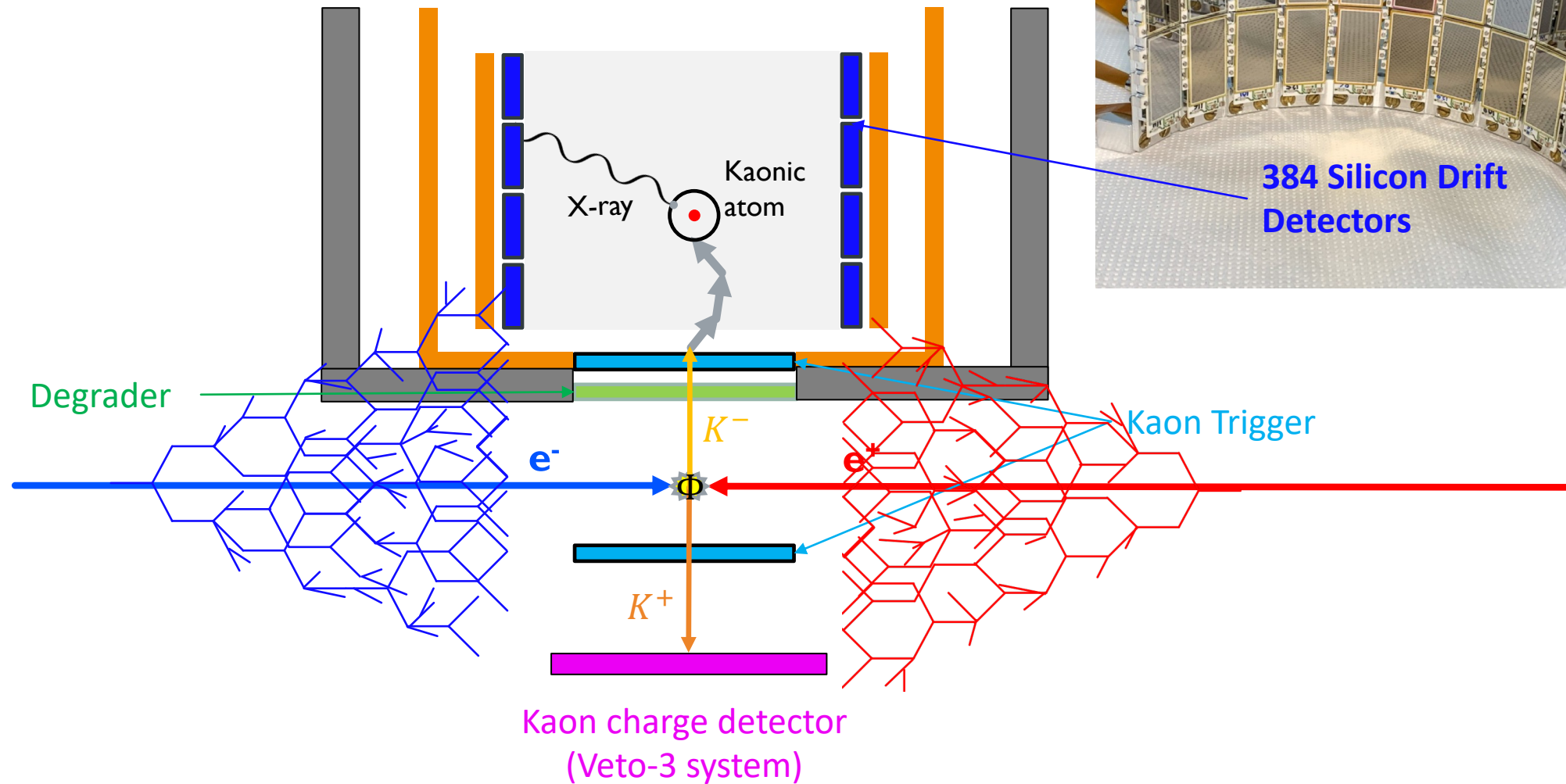
The SIDDHARTA-2 experiment



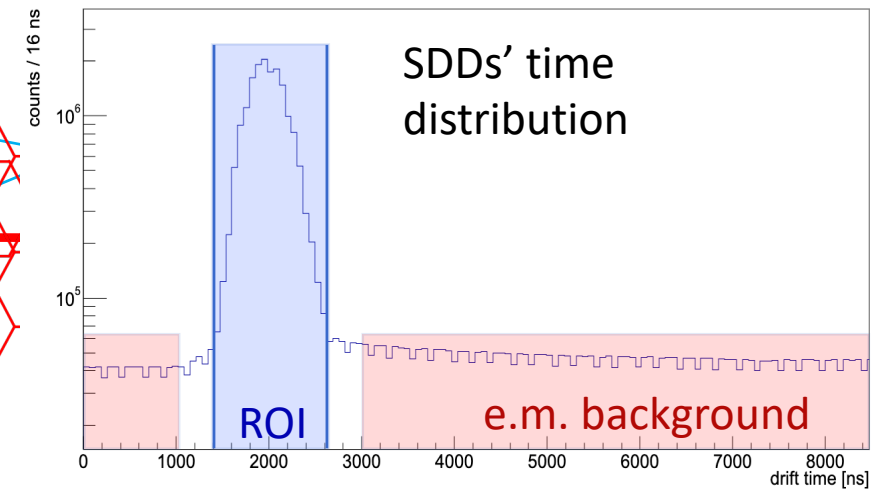
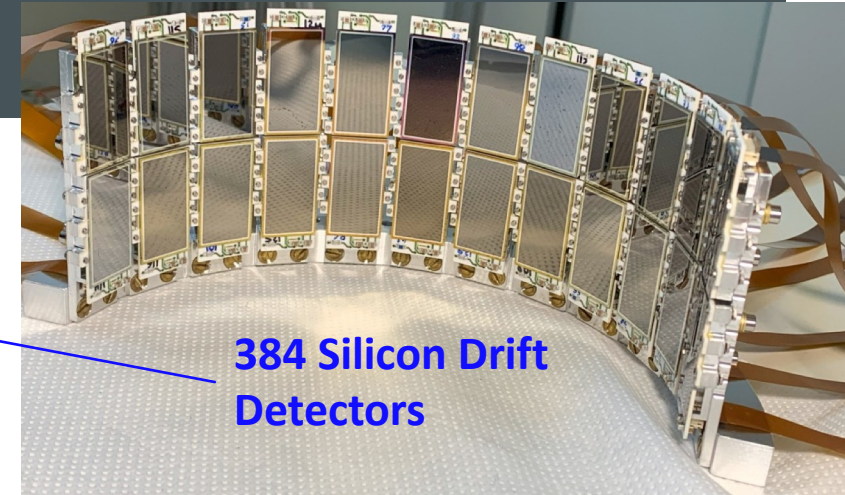
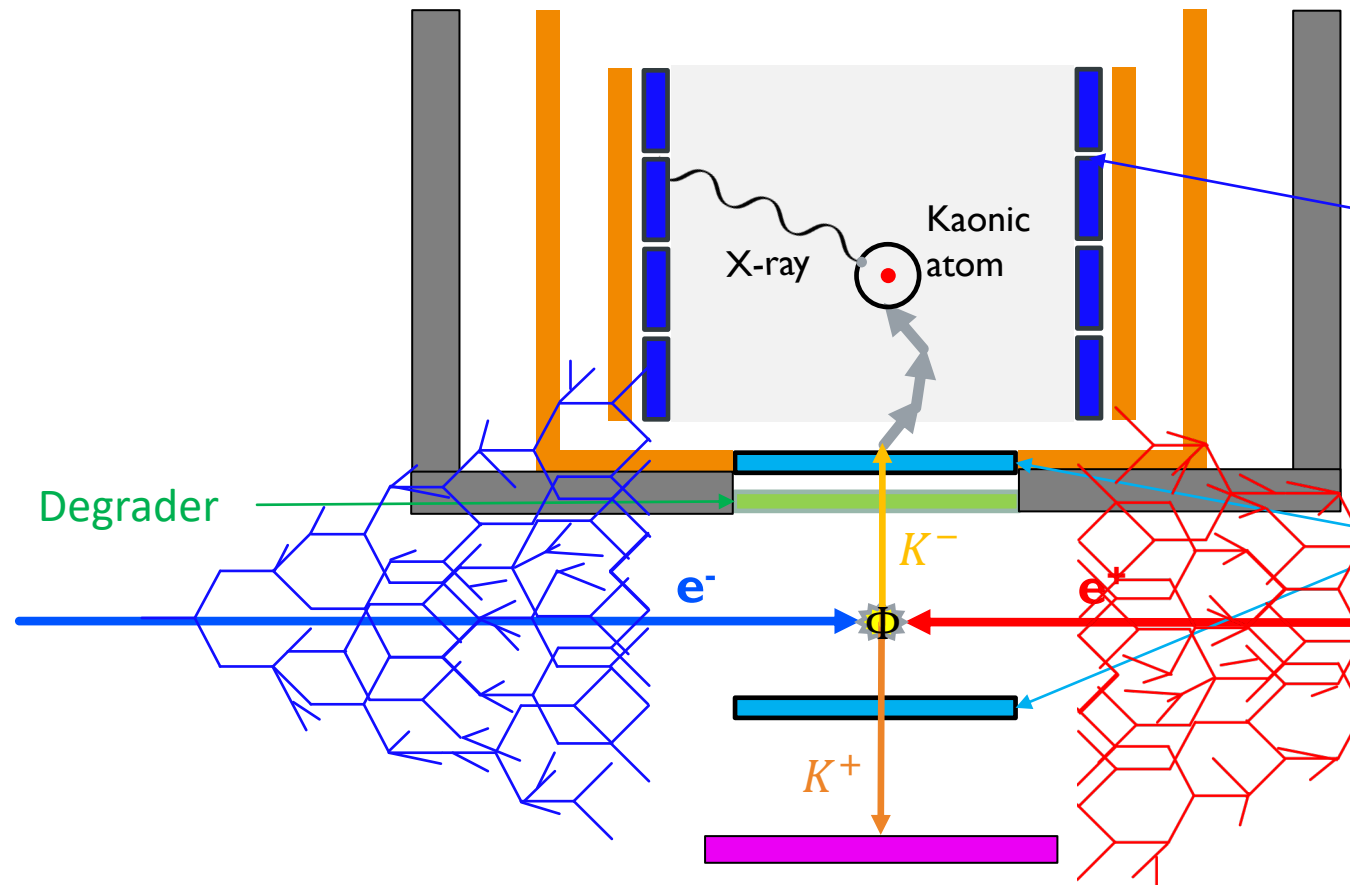
The SIDDHARTA-2 experiment



The SIDDHARTA-2 experiment

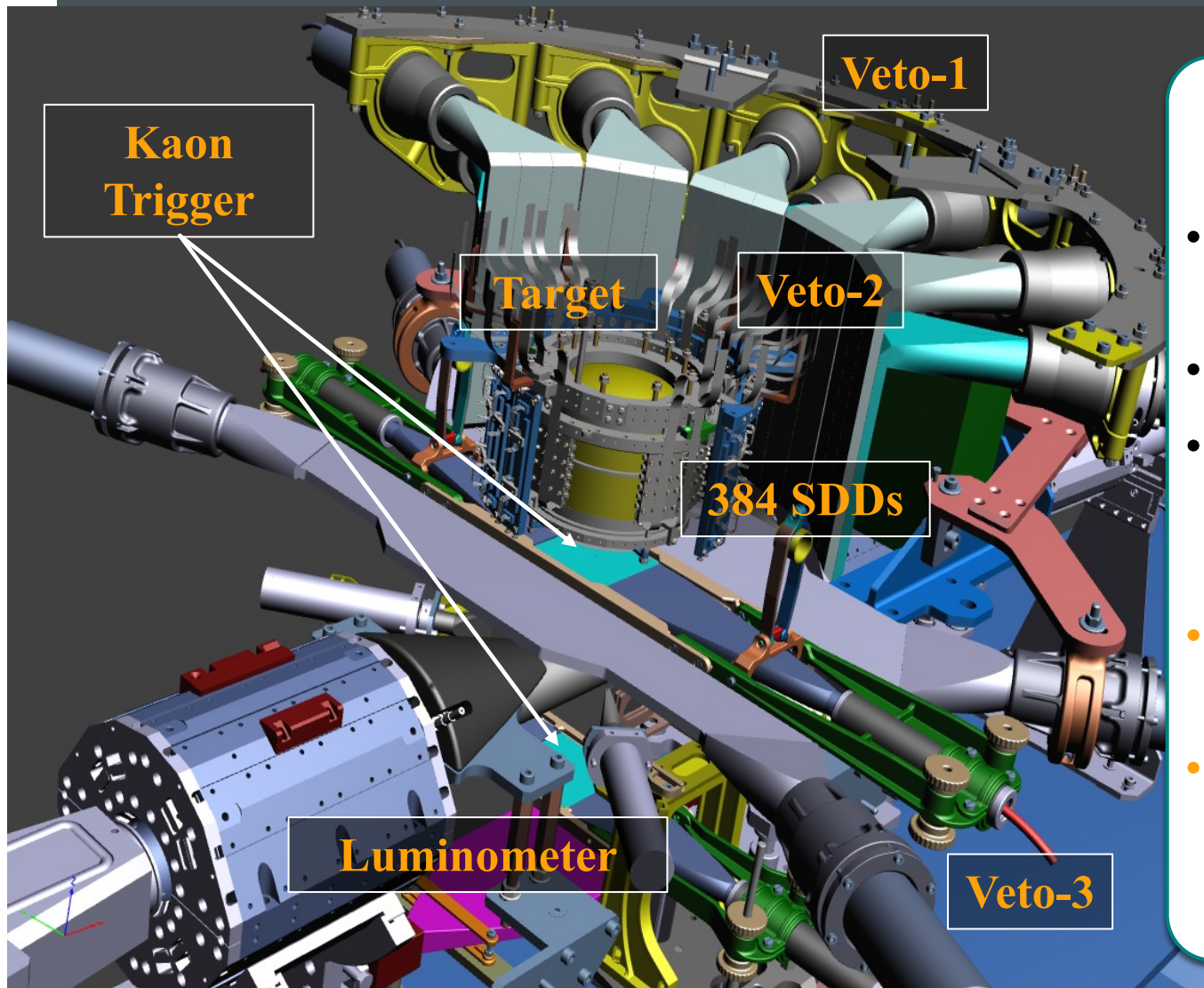


The SIDDHARTA-2 experiment



**Kaon charge detector
(Veto-3 system)**

The SIDDHARTA-2 setup



Key upgrades

- New generation of **Silicon Drift Detectors** and read-out electronics
- SDD active area **2 times larger**
- SDD **time resolution 450 ns** (instead of 800 ns in SIDDHARTA), **background rejection improved by a factor of 2**
- **New trigger, lead shielding and DAΦNE optics: background reduced by a factor of 3**
- **3 veto systems** for hadronic background suppression: **background reduced by an additional factor of 2**

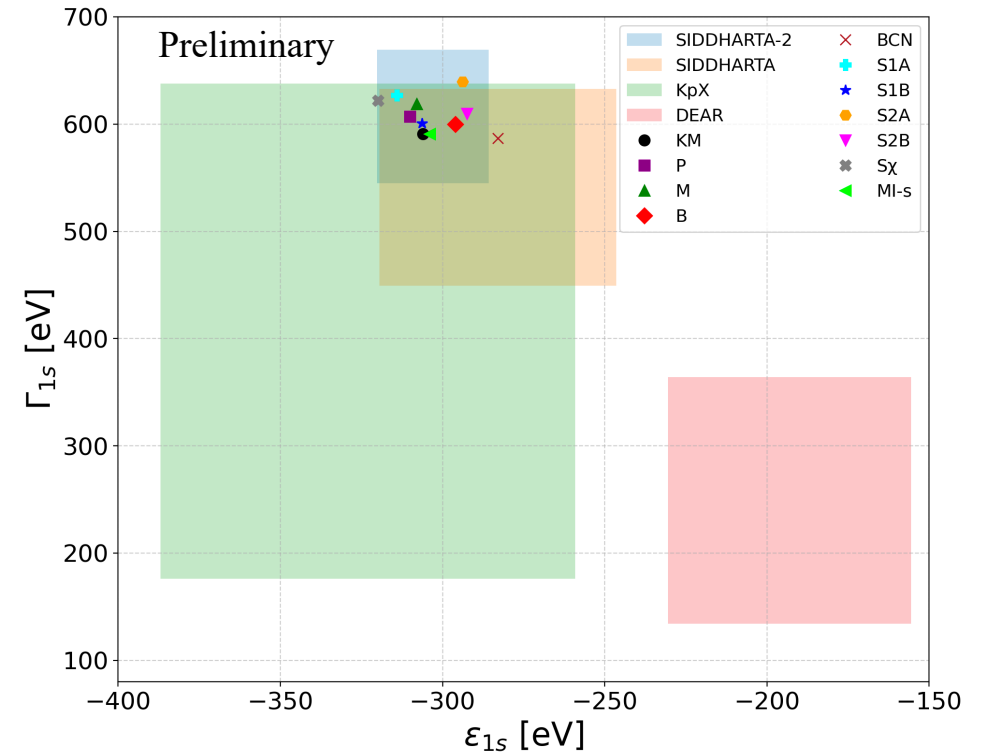
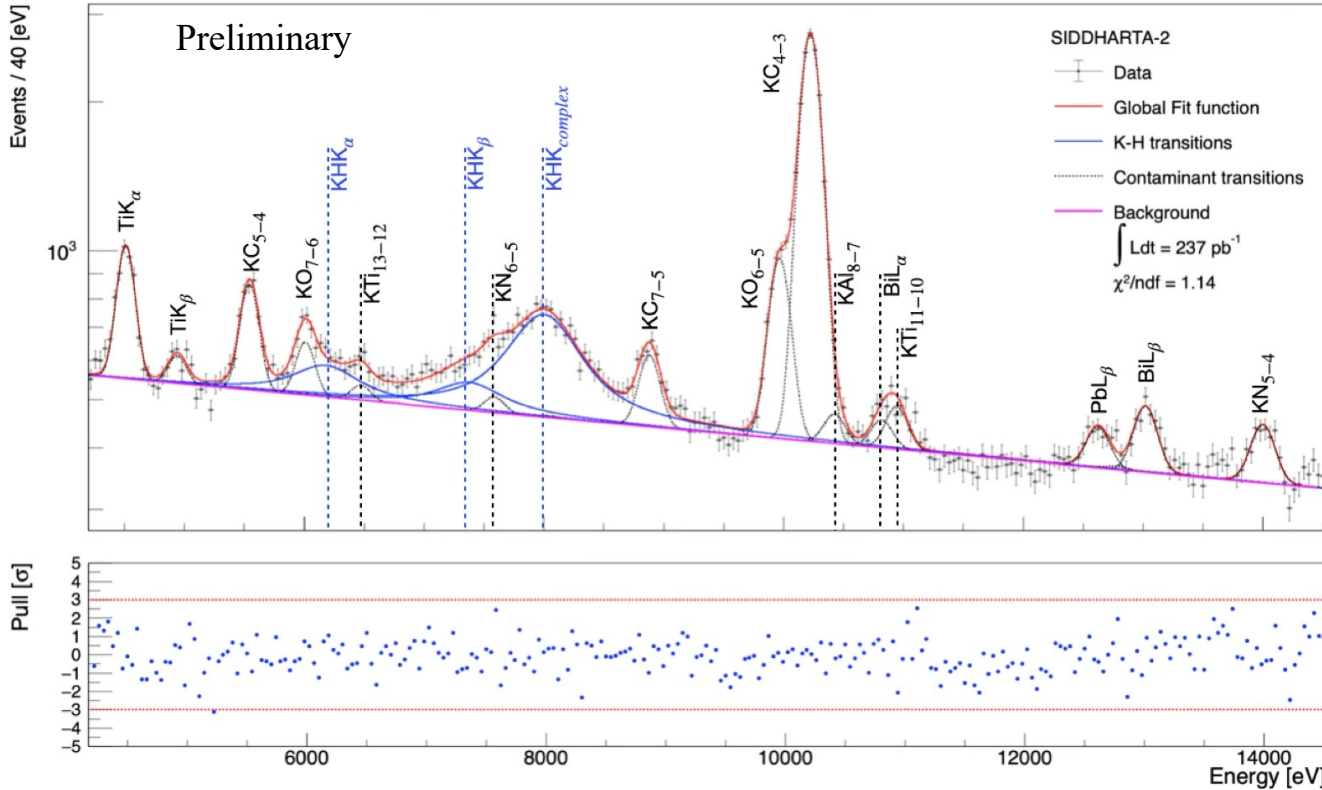
The road to the first Kaonic Deuterium measurement



Manti S., et al. *Phys. Rev. A* 113, 022815 (2026)
Sgaramella F., et al. *Phys. Lett. B* 865 139492(2025)
Sgaramella F., et al. *J. Phys. G: Nucl. Part. Phys.* 51 (2024) 055103
Bosnar D., et al. *NIM A* 1069 (2024) 169966
Sgaramella F., et al. *Eur. Phys. J. A* (2023) 59:56
Sirghi D., et al. *J. Phys. G: Nucl. Part. Phys.* 49 (2022) 055106

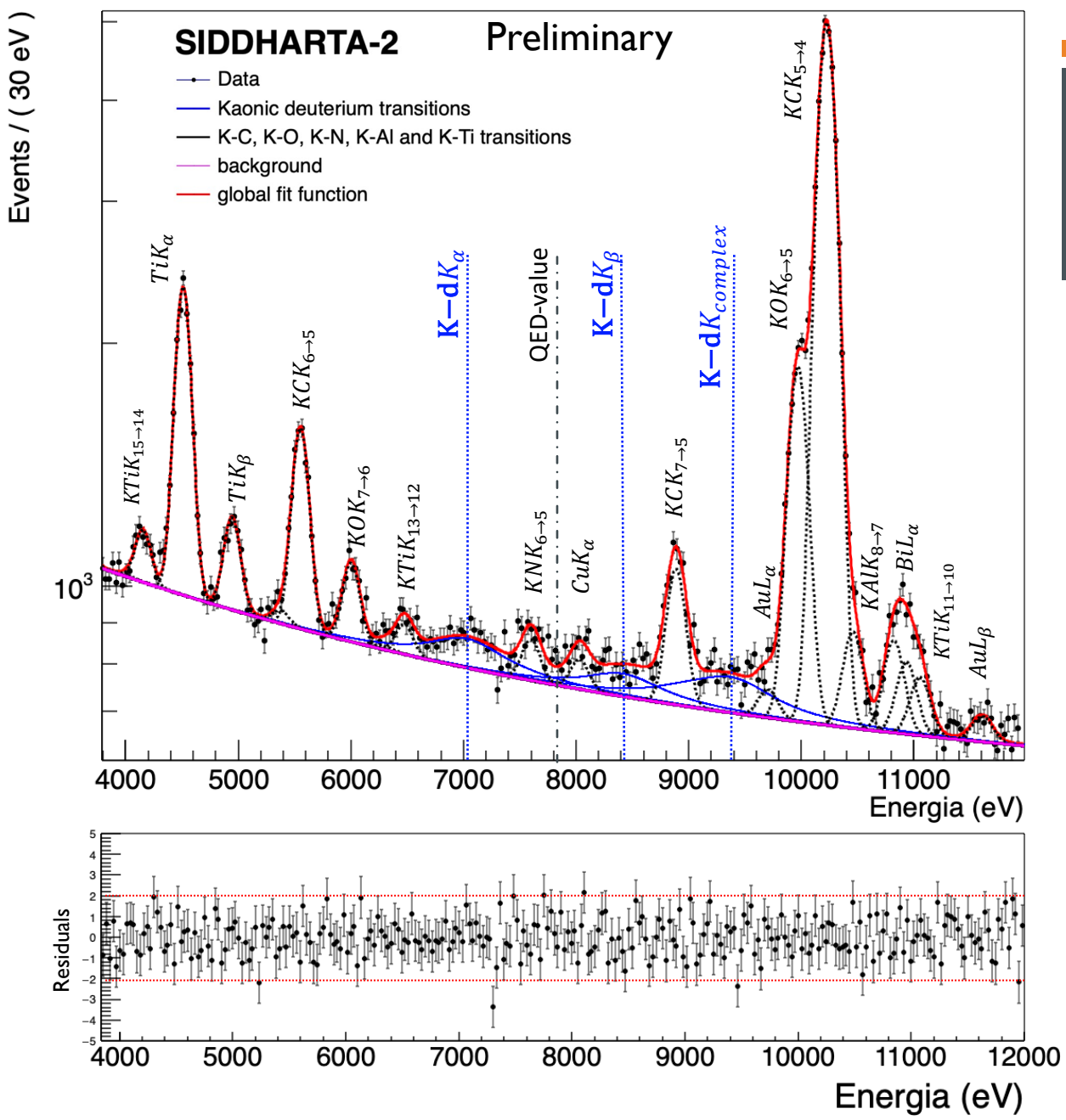
A new Kaonic Hydrogen Measurement

- The most precise determination to date
- An improvement in the $(\varepsilon_{1s}, \Gamma_{1s})$ parameter space by a factor-of-three with respect to SIDDHARTA
- Impact on theoretical models describing the low-energy $\bar{K}N$ interaction and $\Lambda(1405)$



Experiment	ε_{1s} [eV]	Γ_{1s} [eV]	a_{K-p} [fm]
SIDDHARTA-2 (this work)	-303.0 ± 17.0 (stat.) ± 2.5 (syst.)	607 ± 62 (stat.) ± 6 (syst.)	$(-0.715 \pm 0.054) + i(0.905 \pm 0.091)$
SIDDHARTA [20]	-283 ± 36 (stat.) ± 6 (syst.)	541 ± 89 (stat.) ± 22 (syst.)	$(-0.68 \pm 0.11) + i(0.80 \pm 0.13)$
KpX [18]	-323 ± 63 (stat.) ± 11 (syst.)	407 ± 208 (stat.) ± 100 (syst.)	$(-0.883 \pm 0.20) + i(0.62 \pm 0.35)$
DEAR [19]	-193 ± 37 (stat.) ± 6 (syst.)	249 ± 111 (stat.) ± 30 (syst.)	$(-0.49 \pm 0.10) + i(0.35 \pm 0.16)$

Kaonic Deuterium Measurement

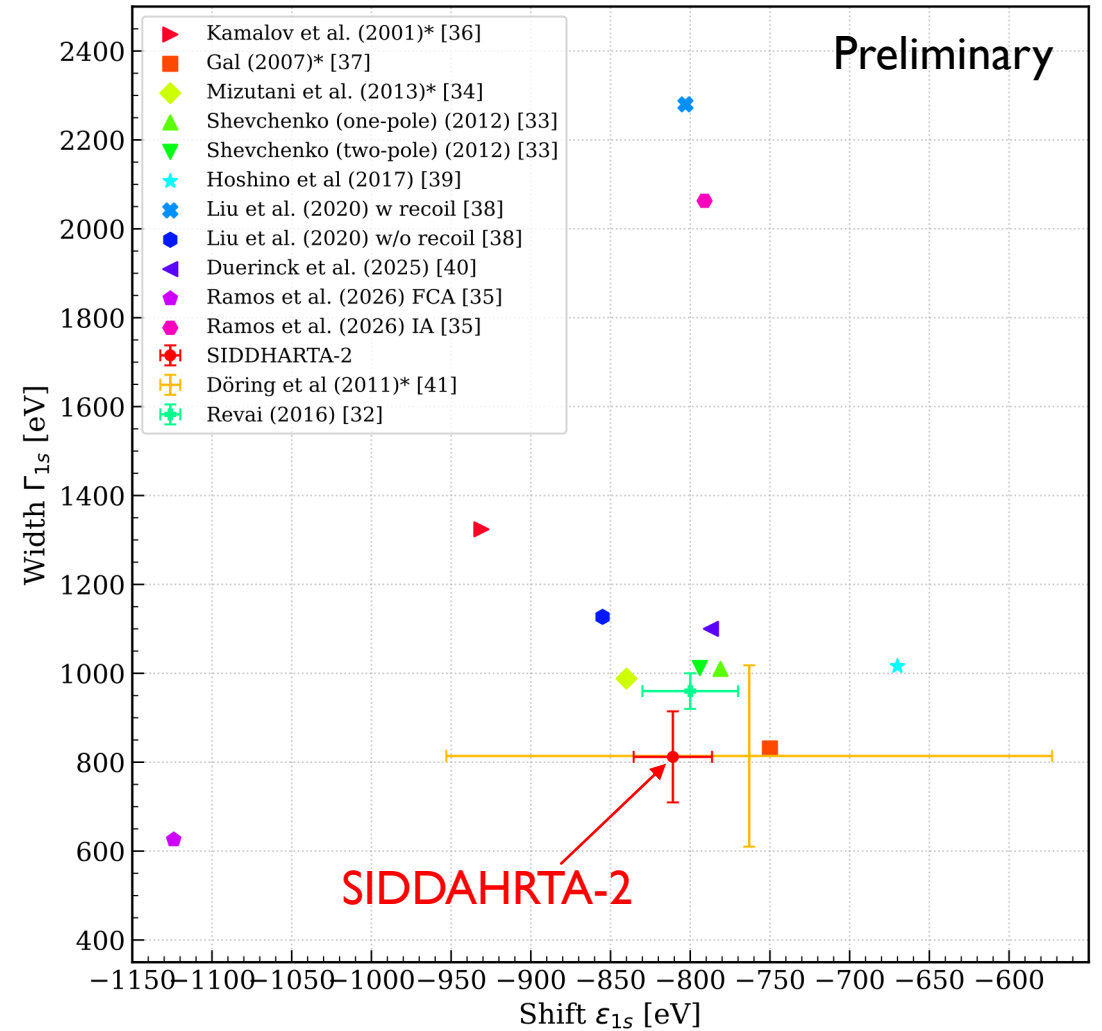
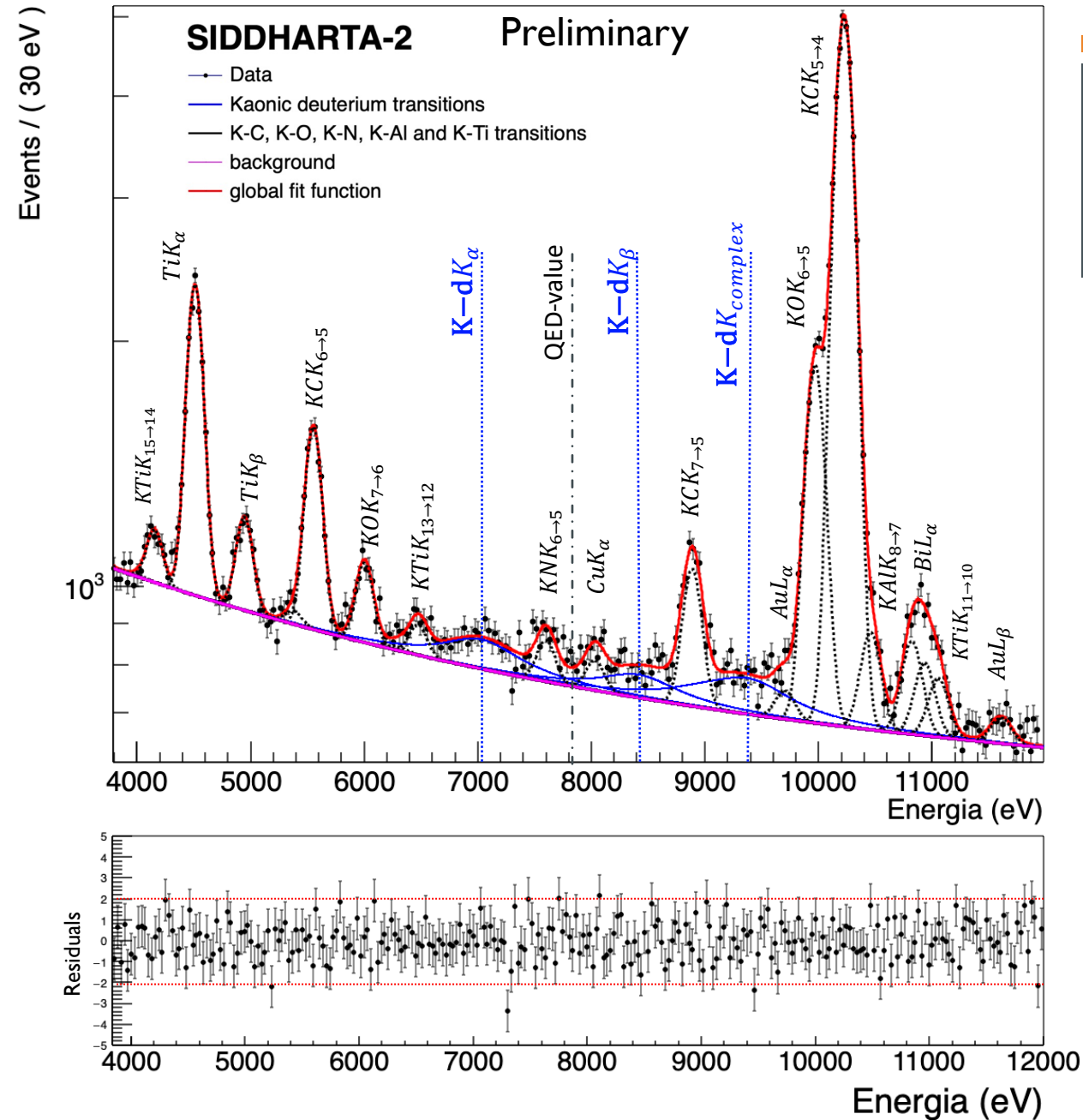


* The energy shift and width are extracted from scattering length using the Deser-Trueman formula

Kaonic Deuterium Measurement

$$\varepsilon_{1s} = -810.9 \pm 24.5(\text{stat}) \pm 2.1(\text{syst}) \text{ eV}$$

$$\Gamma_{1s} = 812 \pm 97(\text{stat}) \pm 33(\text{syst}) \text{ eV}$$



* The energy shift and width are extracted from scattering length using the Deser-Trueman formula

Low
Energy
QCD

Strong
Field QED

Kaon
Mass

How to Test Strong Field QED?

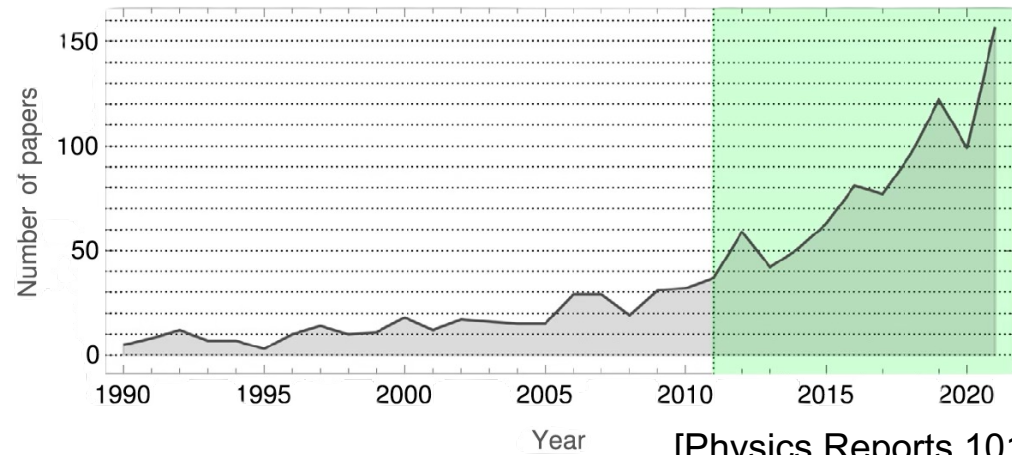
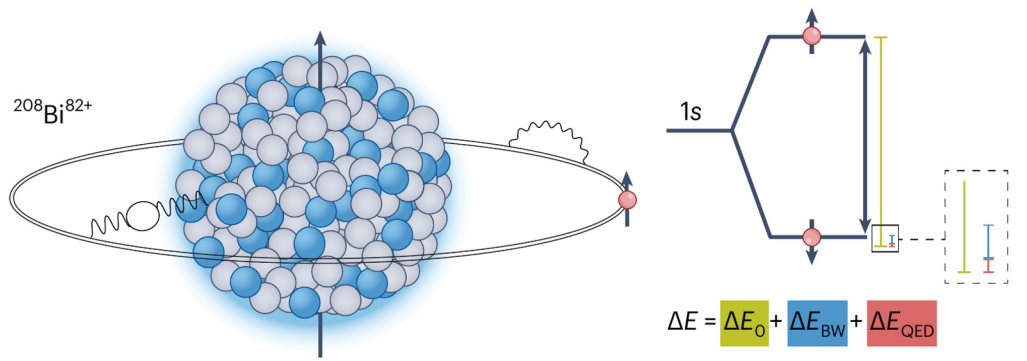


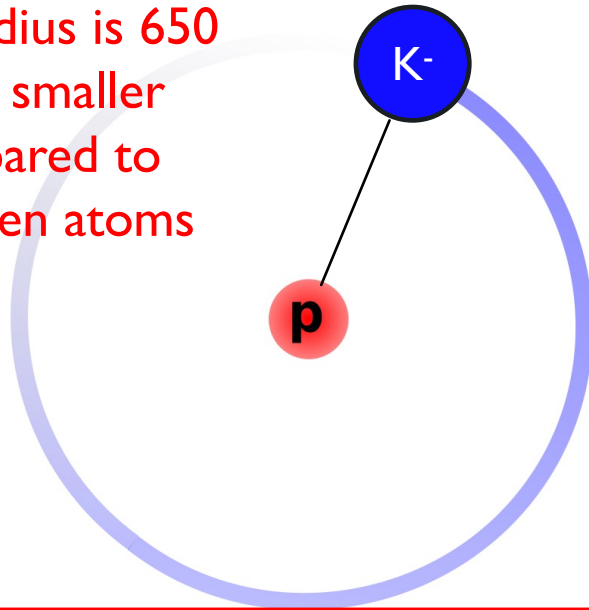
Fig. 1. Indicative bibliometric search using NASA-ADS, for at least one of the following terms occurring in the abstract: “strong field QED”, “nonlinear QED”, “nonlinear Compton”, “nonlinear Breit-Wheeler”, “locally constant field”, “Schwinger effect”, “Schwinger pair”. The shaded region is the last decade, on which the current review is focussed.

- **Laser:** High power lasers reach very intense fields suitable for **strong field studies**.
- **Highly Charged Ions:** Few electron **high-Z ions generate extreme electric fields**
- **Exotic Atoms:** Atoms where an electron is replaced by a heavier particle such as a **muon (J-PARC)**, **pion, kaon, or antiproton (PAX@CERN)** providing clean systems for precision QED tests.

Probing strong field QED with kaonic atoms

Exotic atoms are extremely compact, resulting in very strong electric fields that allow access to the strong-field regime of QED in bound system (BSQED)

Bohr radius is 650
times smaller
compared to
hydrogen atoms



Particle	m [MeV/c ²]	B_{1s} [keV]	r_B [10^{-15} m]	Accessible interactions
$e p$	0.511	13.6×10^{-3}	0.53×10^5	Electro-weak
μp	105.7	2.53	279	Electro-weak
πp	139.6	3.24	216	Electro-weak + strong
$K p$	493.7	8.61	81	Electro-weak + strong
$\bar{p} p$	938.3	12.5	58	Electro-weak + strong

The electric field between the kaon and the nucleus is 430 000 times higher than that of hydrogen atom



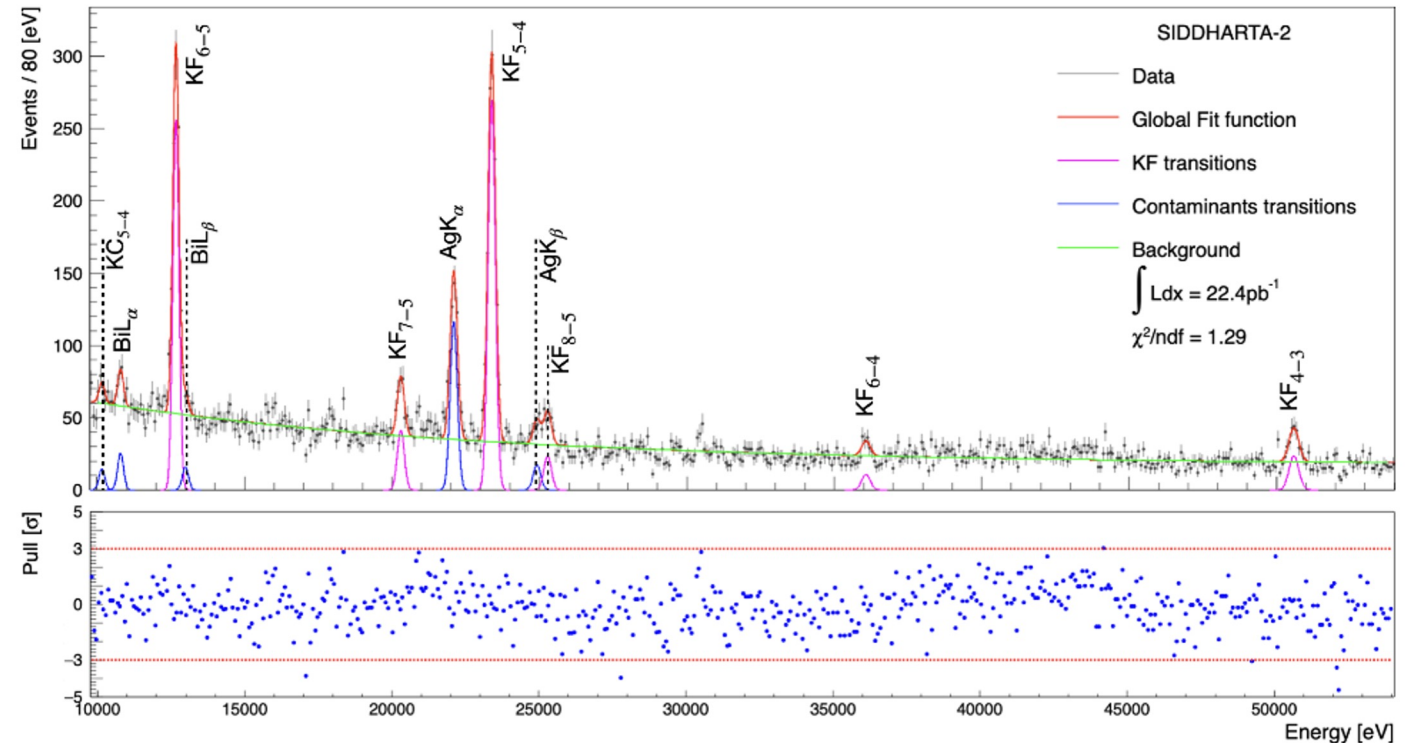
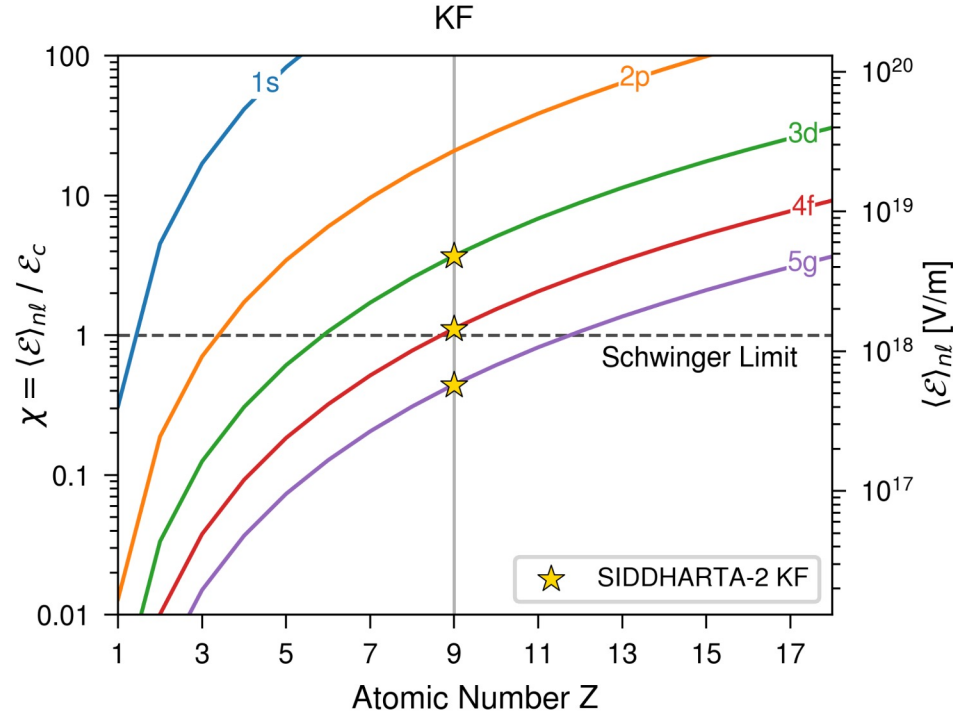
Study of QED under strong field

Strong Fields QED with Kaonic Fluorine

- **Exotic atoms** enable experimental access to **Strong Electric Fields** [Paul *et al.*, PRL 126, 173001 (2021)]
- For the transition $5 \rightarrow 4$ and $4 \rightarrow 3$ the Average Electric Field approaches the Schwinger limit

$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18} \text{ V/m}$$

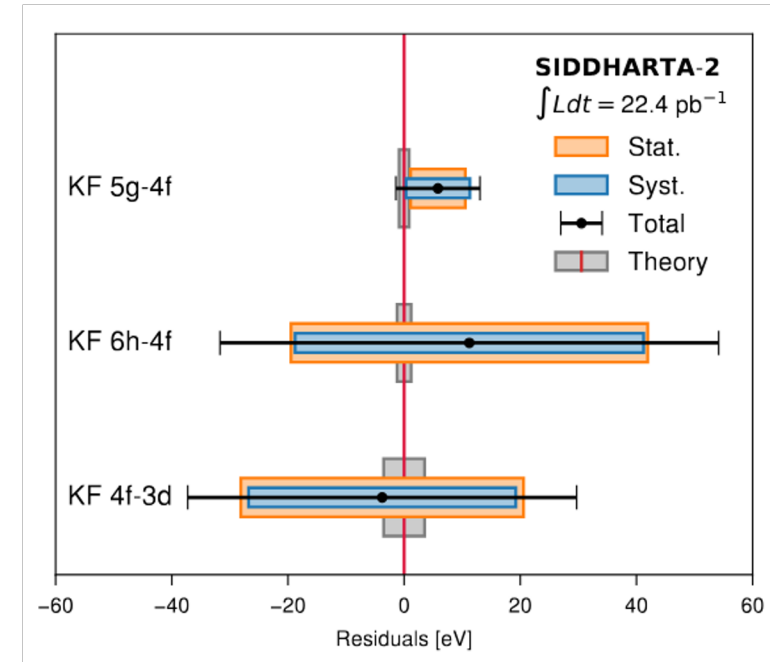
$$\langle E \rangle_{nl} = \int d^3r |\psi_{nl}(\mathbf{r})|^2 E(\mathbf{r})$$



Clozza, F., (2026). Bound-state QED test above the Schwinger limit with kaonic fluorine. *arXiv preprint arXiv:2604.19387*.

Strong Fields QED with Kaonic Fluorine

Line	$E_{if}^{(\text{exp.})} \pm (\text{stat.}) \pm (\text{sys.})$	$E_{if}^{(\text{calc.})} \begin{matrix} +\delta_{if}^+ \\ -\delta_{if}^- \end{matrix}$	$E_{if}^{(\text{QED})}$
6h-5g	$12673.9 \pm 5.9 \pm 7.1$	$12684.69 \begin{matrix} +0.42 \\ -0.43 \end{matrix}$	23.49
7i-5g	$20298.8 \pm 16.3 \pm 6.0$	$20327.49 \begin{matrix} +0.59 \\ -0.64 \end{matrix}$	32.26
5g-4f	$23383.2 \pm 4.7 \pm 5.5$	$23377.38 \begin{matrix} +1.06 \\ -1.06 \end{matrix}$	67.54
8k-5g	$25279.6 \pm 36.2 \pm 5.0$	$25285.56 \begin{matrix} +0.70 \\ -0.85 \end{matrix}$	35.65
6h-4f	$36073.3 \pm 30.7 \pm 30.0$	$36062.07 \begin{matrix} +1.27 \\ -1.28 \end{matrix}$	91.02
4f-3d	$50586.7 \pm 24.3 \pm 23.0$	$50590.48 \begin{matrix} +4.36 \\ -4.36 \end{matrix}$	222.99



Significant BSQED contribution due to the Nonlinear Dependence of **Vacuum Polarization Diagrams** on the Electric Field Strength
($\sim 9\sigma$ for 5g-4f with only $22.4 \text{ pb}^{-1} \sim 2 \text{ days}$)

Can Strong Field QED tests be made with Kaonic Atoms?

YES! Among different exotic particles **Kaons** provide some advantages:

- **Larger reduced mass** than muons and pions, leading to stronger QED effects
- **Spin zero**, so no **hyperfine splitting** as in muonic or antiprotonic atoms

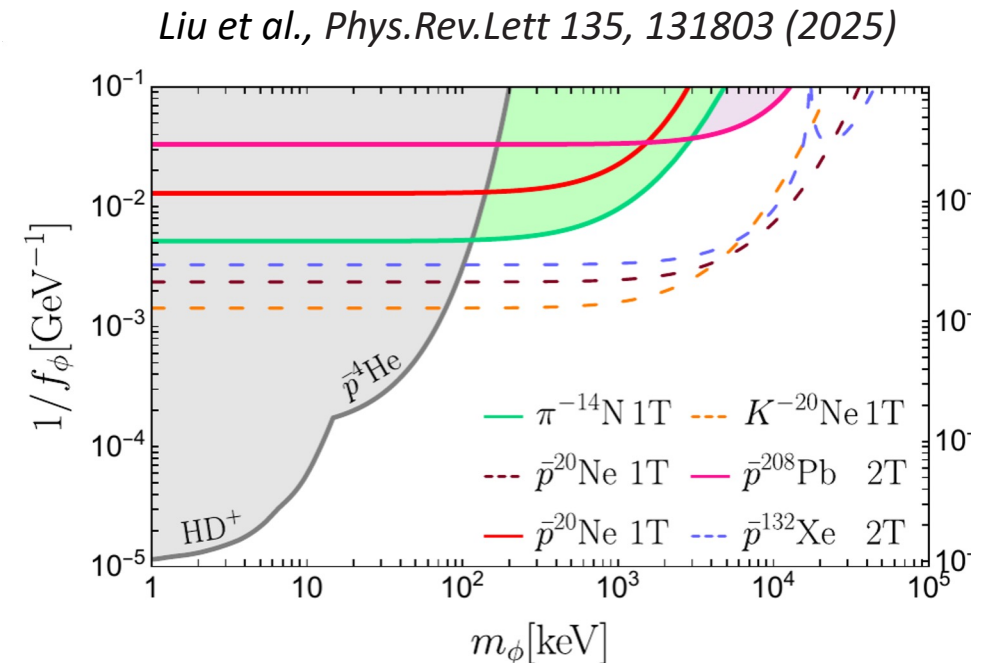
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Beyond Standard Model:

- BSQED with kaonic atoms allows stringent exclusion limits to be set on new hadronic interactions, providing a unique probe of **physics beyond the Standard Model in the strangeness sector**



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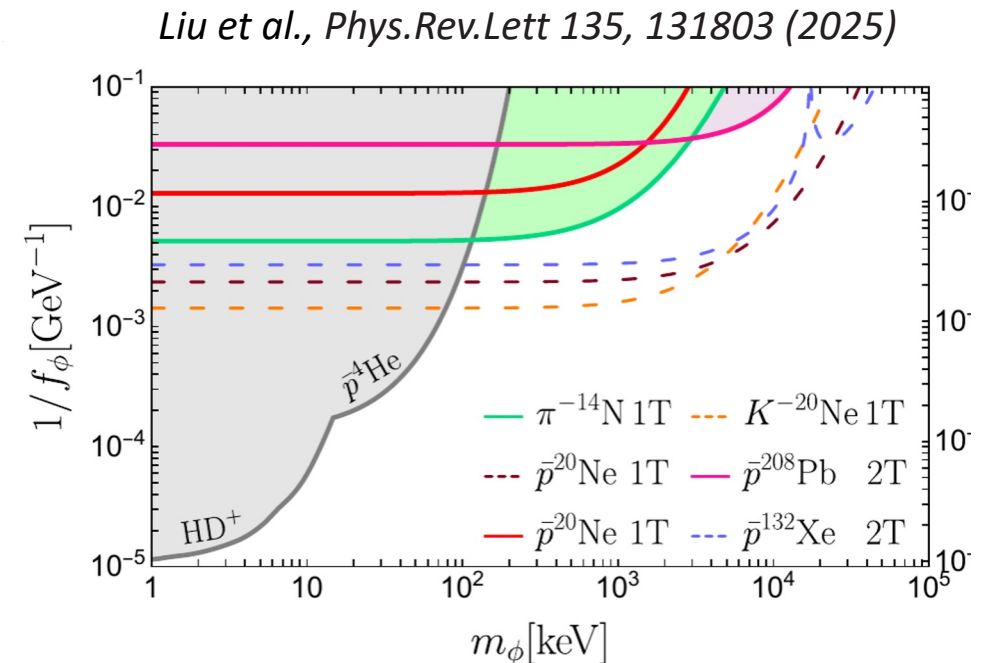
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Remaining limitation:

- The current uncertainty on the kaon mass still affects the predicted transition energies



The charged kaon mass puzzle

Charged kaon mass (K^+ , K^-)

$$493.677 \pm 0.013 \text{ MeV}$$

P.a. Zyla et al. (Particle Data Group), Prog.Theor. Exp. Phys. 2020, 083C01 (2020)

The charged kaon mass puzzle

Charged kaon mass (K^+ , K^-)

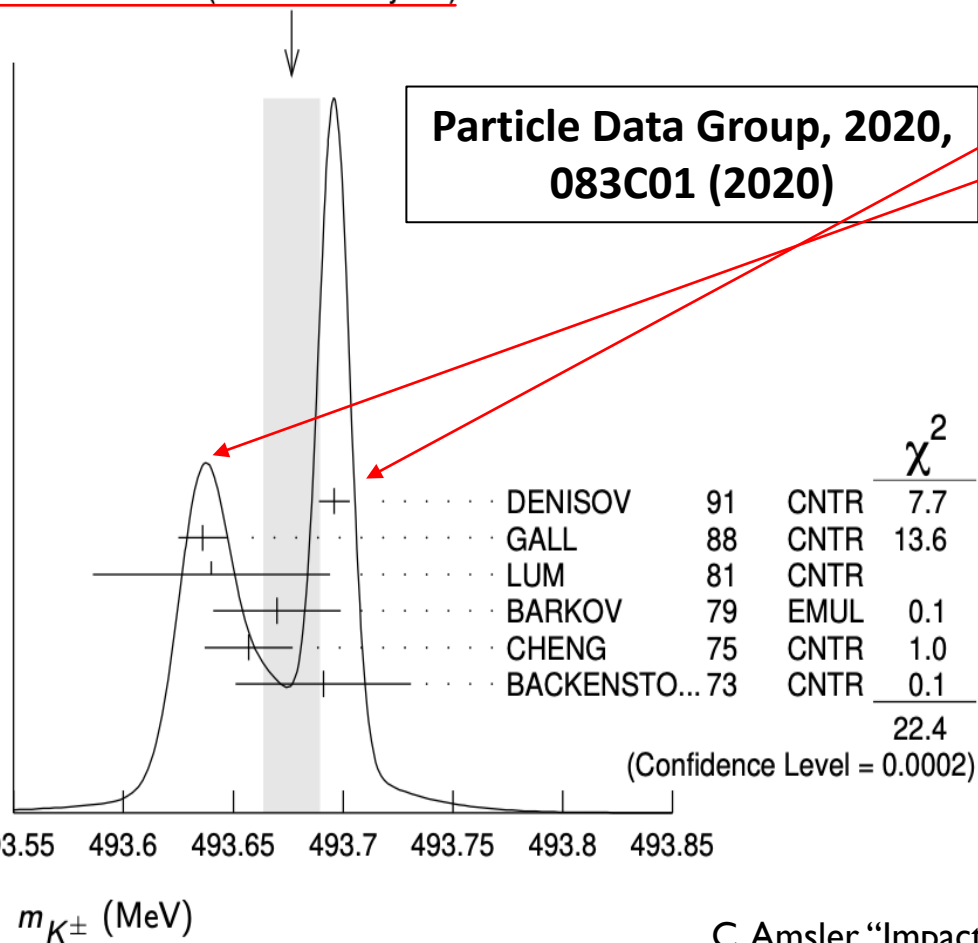
~~493.677 ± 0.013 MeV~~

Pa. Zyla et al. (Particle Data Group), Prog.Theor. Exp. Phys. 2020, 083C01 (2020)

The charged kaon mass puzzle

60 keV discrepancy between the two most accurate measurement
 Large uncertainty → 26 p.p.m, compared to charged pion (1.6 p.p.m)

WEIGHTED AVERAGE
 493.677 ± 0.013 (Error scaled by 2.4)



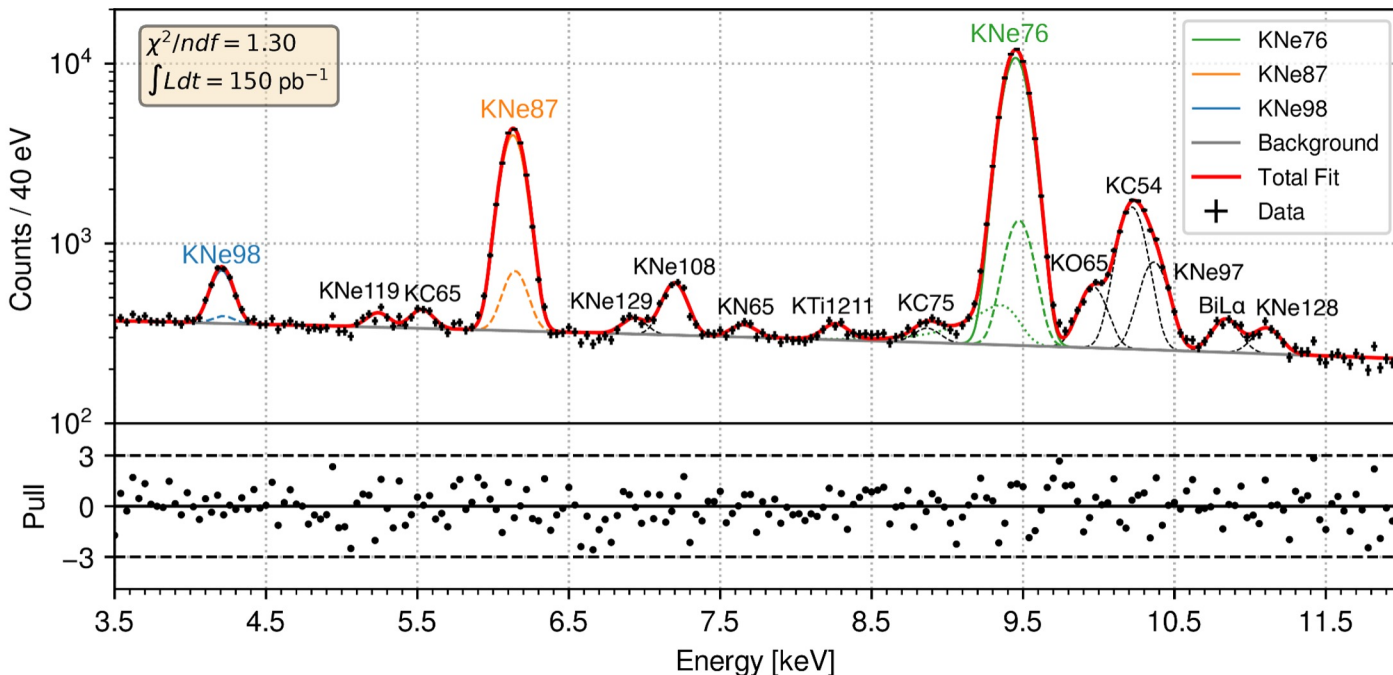
VALUE (MeV)	DOCUMENT ID	TECN	CHG	COMMENT
493.677 ± 0.016 OUR FIT	Error includes scale factor of 2.8.			
493.677 ± 0.013 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.			
493.696 ± 0.007	¹ DENISOV	91	CNTR	- Kaonic atoms
493.636 ± 0.011	² GALL	88	CNTR	- Kaonic atoms
493.640 ± 0.054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

- 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 $D^0 \bar{D}^{*0}$ 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.

The charged kaon mass puzzle: Kaonic neon measurement

Kaonic neon is the ideal system to precisely determine the kaon mass:

- **fully ionized:** no electron screening as for kaonic lead (*K.P. Gall et al. Phys. Rev. Lett. 60 (1988)186*)
- **low-density gas target:** negligible electron refill compared to solid targets like lead and carbon (*K.P. Gall et al. Phys. Rev. Lett. 60 (1988)186; Denisov et al. JEPT Lett. 54 (1991)558*)



Kaonic neon energy transitions and absolute yields at the density of 3.60 ± 0.18 g/l. The first error is statistical, the second systematic.

Transition	Energy [eV]	Yield
K-Ne (10 → 8)	$7191.21 \pm 4.91 \pm 2.00$	$0.010 \pm 0.001 \pm 0.001$
K-Ne (10 → 7)	$13352.20 \pm 10.07 \pm 3.00$	$0.004 \pm 0.002 \pm 0.001$
K-Ne (9 → 8)	$4206.35 \pm 3.75 \pm 2.20$	$0.137 \pm 0.012 \pm 0.010$
K-Ne (8 → 7)	$6130.86 \pm 0.71 \pm 1.50$	$0.228 \pm 0.004 \pm 0.011$
K-Ne (7 → 6)	$9450.08 \pm 0.41 \pm 1.50$	$0.277 \pm 0.002 \pm 0.014$
K-Ne (6 → 5)	$15673.30 \pm 0.52 \pm 9.00$	$0.308 \pm 0.003 \pm 0.015$

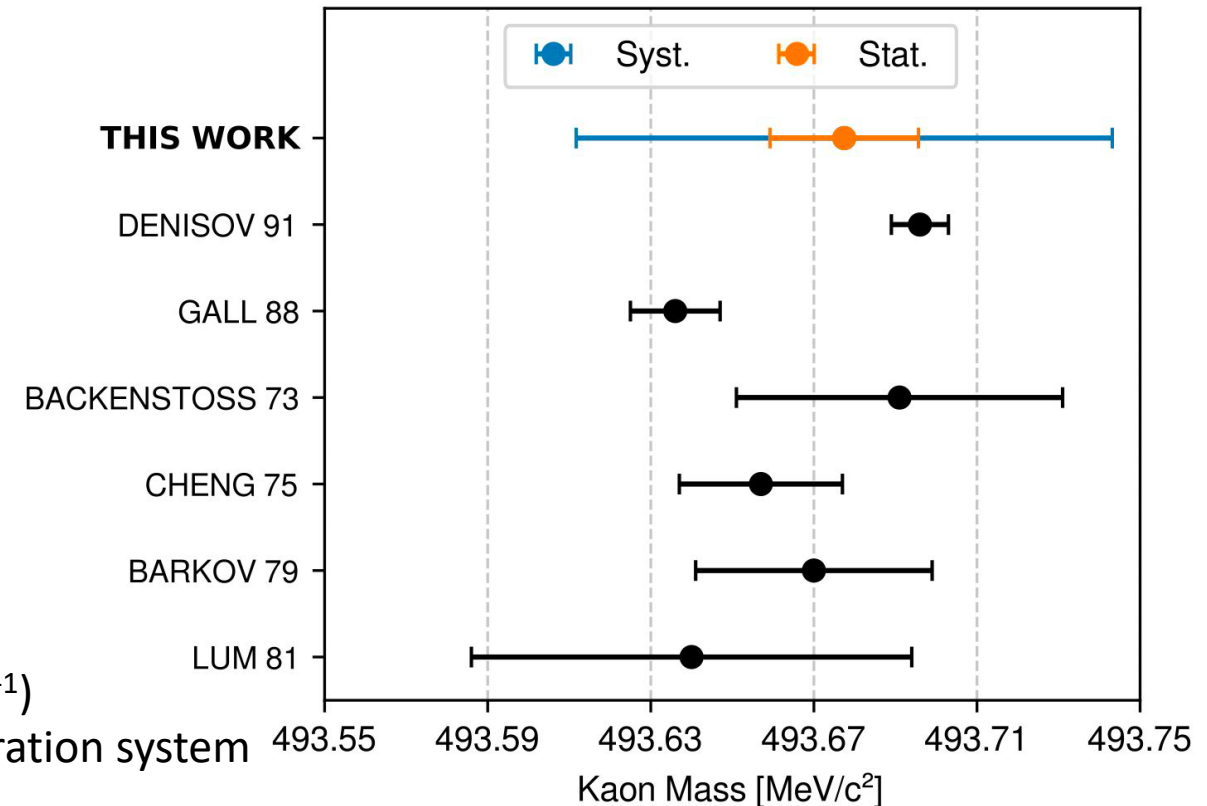
The charged kaon mass puzzle: Kaonic neon measurement

- $M_{K^-} = 493.677 + 0.018 \text{ (stat)} + 0.066 \text{ (syst)} \text{ MeV}$

Transition	M_{K^-} [MeV]	$\delta M_{K^-}^{\text{stat.}}$ [keV]	$\delta M_{K^-}^{\text{syst.}}$ [keV]
7i-6h	493.674	19	78
8k-7i	493.699	52	121
7i-6h + 8k-7i	493.677	18	66

- Transitions with **Sub-eV Statistical Precision** already provide a **Statistical Uncertainty of 18 keV** on the Kaon Mass

- **A KNe Dedicated Optimized Run can reach < 10 keV via:**
 - × 2 improvement by Doubling Statistics ($150 \text{ pb}^{-1} \rightarrow 300 \text{ pb}^{-1}$)
 - × 2 improvement by Optimized Gas Target Design and calibration system (lower statistical and systematic uncertainty)



Beyond SIDDHARTA-2

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 measurements are the basis for all the theoretical model used for: $\bar{K}N$, $\bar{K}NN$ interaction at threshold, Kaon mass, Kaonic atoms cascade models

Present status:

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

5. Absolute yields are unknown (except for few transitions)

**This situation is a proper justification
for a new era of kaonic atoms
measurements**

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

521

Table 1
Compilation of K^- atomic data

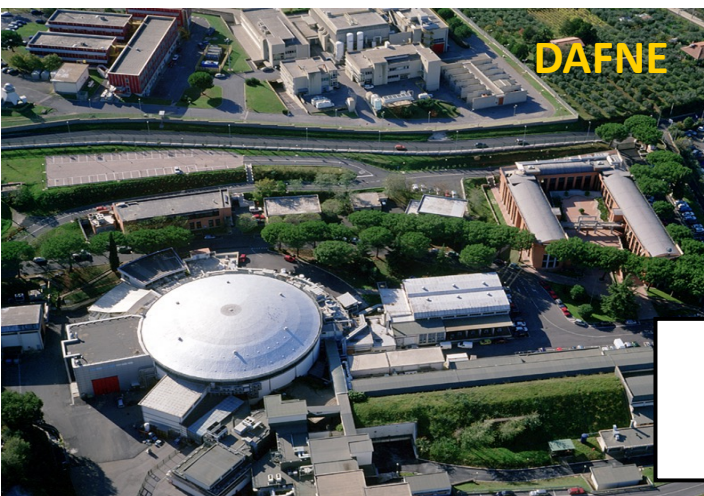
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3 → 2	-0.04 ± 0.03	–	–	–	[15]
		-0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	3 → 2	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	3 → 2	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	3 → 2	-0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	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]
P	4 → 3	-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06	[19]
		-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]

1.1 - High precision kaonic neon measurement
To extract the charged kaon mass with a precision of about 5 keV

BSQED and Physics beyond Standard Model

1.2 - Light kaonic atoms (LHKA)
– solid target **Li, Be, B**

**Low energy strong interaction –
kaon multi-nucleon interaction**



DAFNE

EXKALIBUR

C. Curceanu et al., Front.in Phys. 11 (2023) 1240250

EXtensive **K**aonic **A**toms research:
from **L**ithium and **B**eryllium to **U**Ranium



J-PARC

Intermediate kaonic atoms (IMKA)

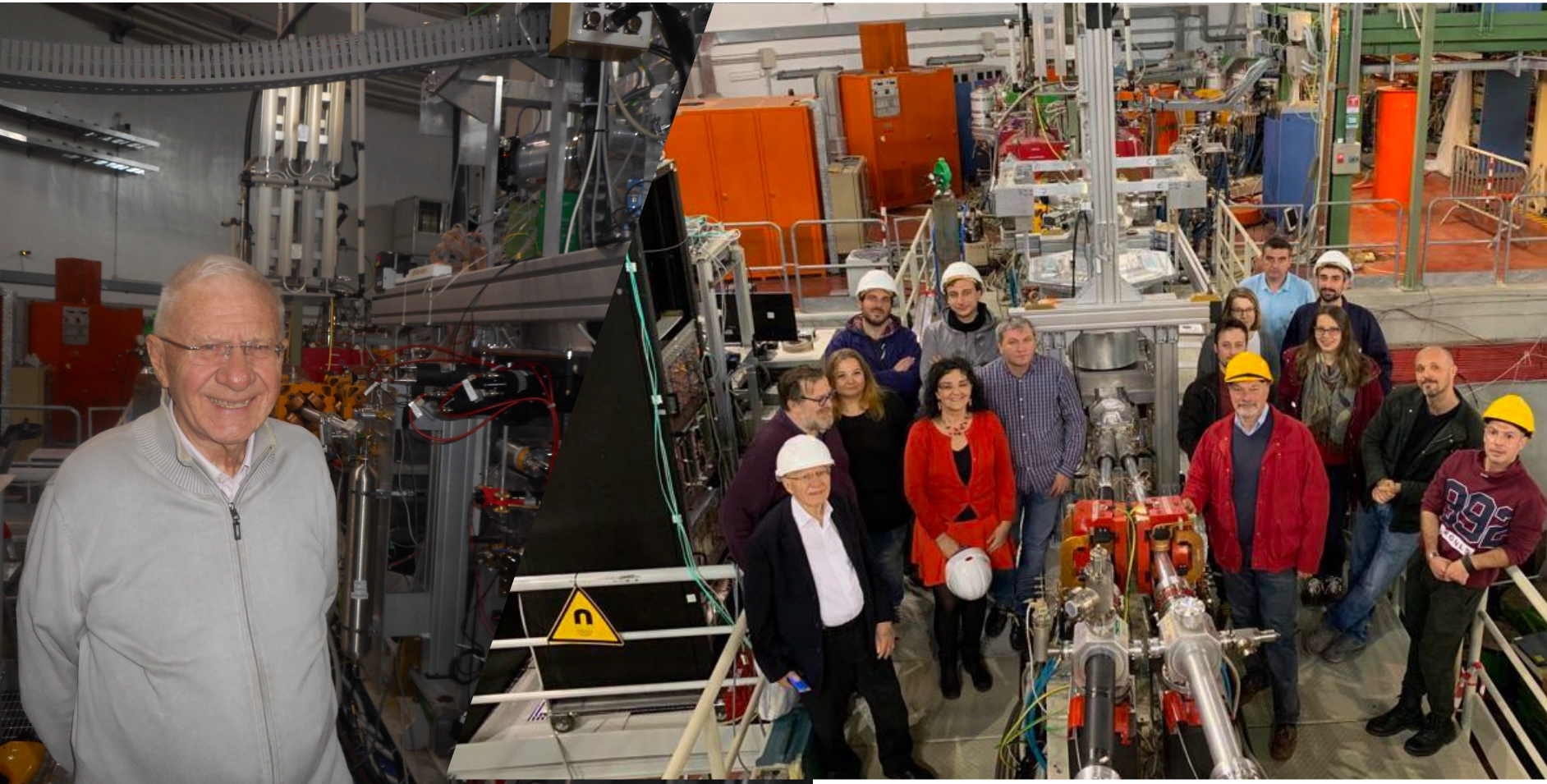
In parallel we plan dedicated runs kaonic atoms such as *O, Al, S*
with CdZnTe detectors

- 200 -300 pb⁻¹ of integrated luminosity/target

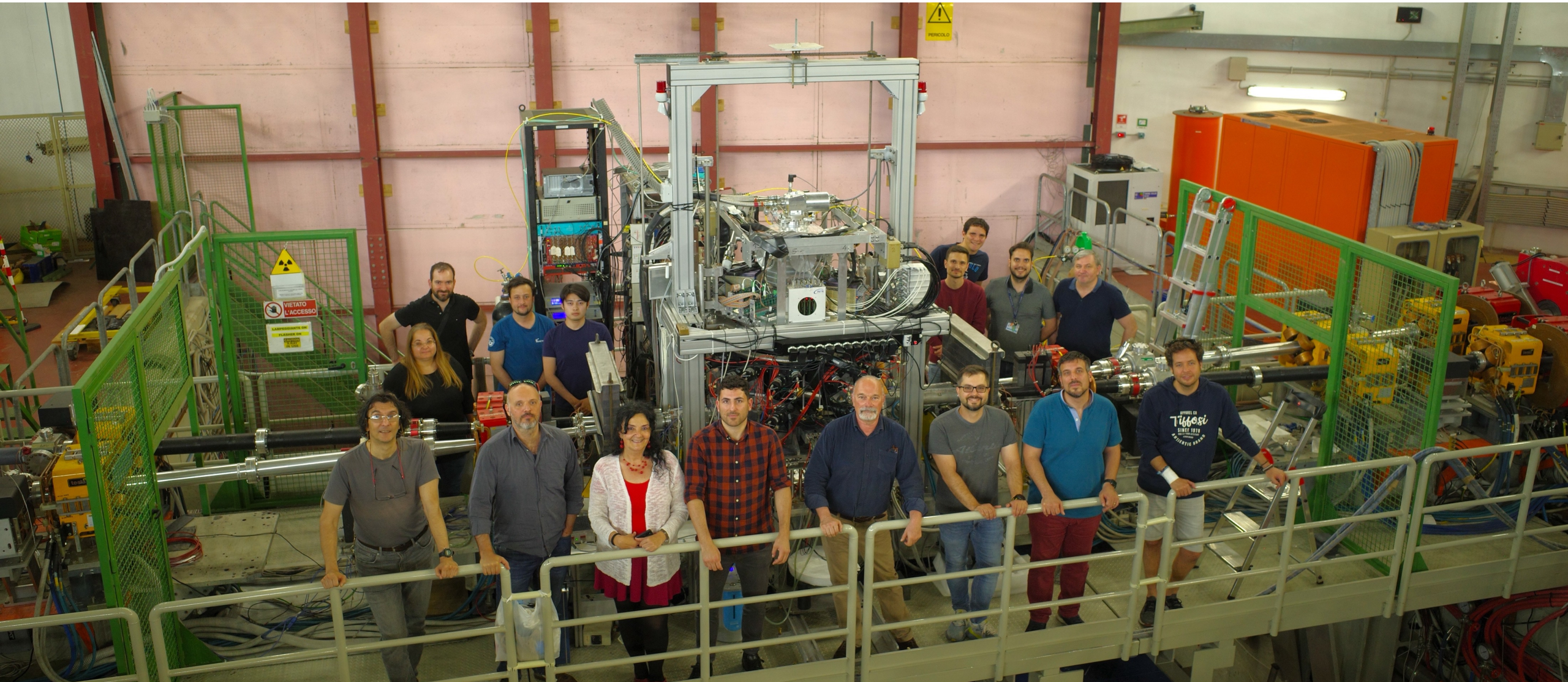
Conclusions

- Kaonic atoms provide **a unique tool to test fundamental interactions**, in particular **low-energy strong interaction with strangeness**.
 - **The first measurement of kaonic deuterium**—awaited for more than 40 years—will significantly improve our understanding of the $\bar{K}N$ interaction.
 - A **new and more precise measurement of kaonic hydrogen**: implications for the $\bar{K}N$ interaction and the $\Lambda(1405)$
 - **Feasibility study of kaonic fluorine** opens the way to tests of **strong-field QED with kaonic atoms** and to searches for **physics beyond the Standard Model**.
 - Exploratory measurements of **kaonic neon demonstrated the feasibility of resolving the kaon mass–charge puzzle**
- These results lay the foundation for a **new era of precision kaonic atom spectroscopy at DAΦNE and J-PARC** within the **EXKALIBUR project**, aimed at exploring fundamental interactions from low-energy strong QCD to strong-field QED.

We dedicate these results to our dear friends and colleagues
Prof Carlo Guaraldo and Dr. Johann Zmeskal
who passed away in 2024. You are very much missed!



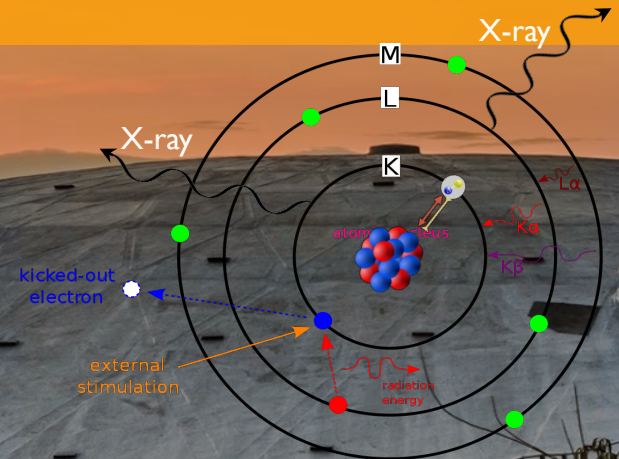
THANK YOU





SPARE

KAONIC ATOMS X-RAY SPECTROSCOPY: AN AMAZING TOOL TO STUDY FUNDAMENTAL INTERACTIONS



M E S O N
2 0 2 6

18th International Workshop
on Meson Physics
25th - 30th June 2026, Kraków, Poland

Francesco Sgaramella INFN-LNF
on behalf of the SIDDHARTA-2 collaboration

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2 2020

Kaonic Atoms as Precision Probes: Experimental Challenges

Significant Technical and scientific requirements for kaonic atoms experiments:



New kaon beams with excellent characteristics are the first necessary ingredient for precision kaonic-atom experiments.

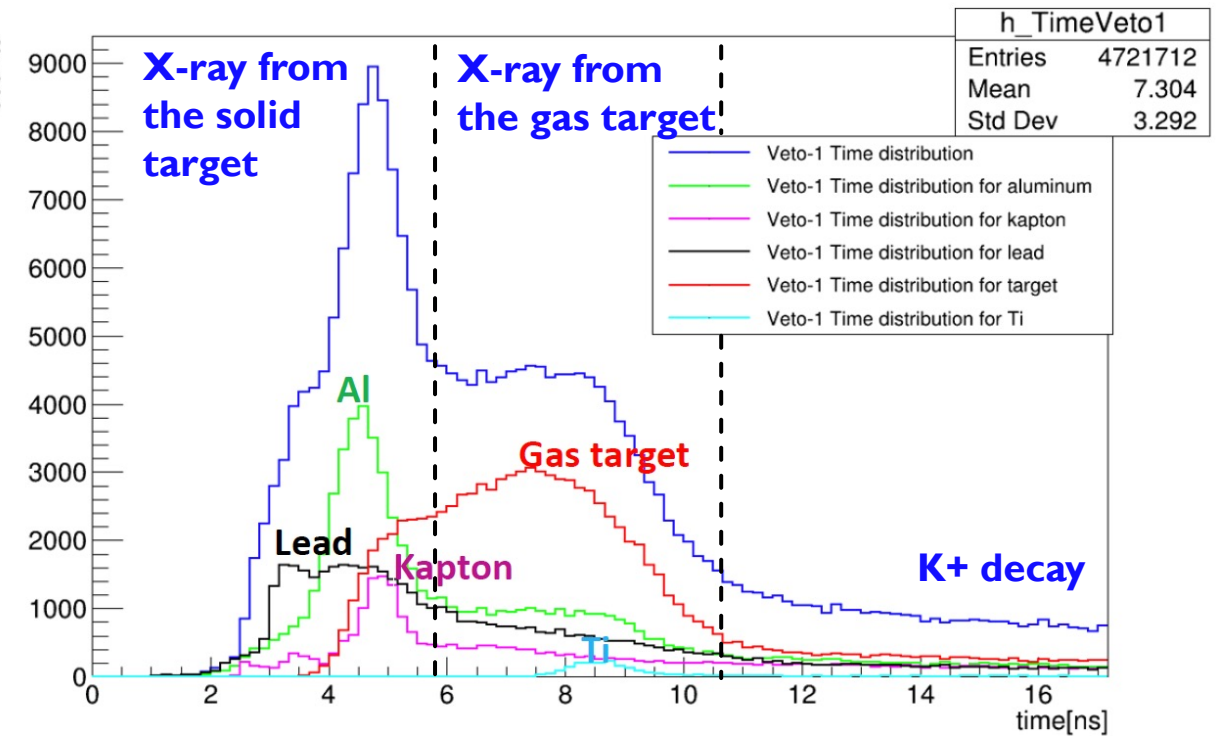
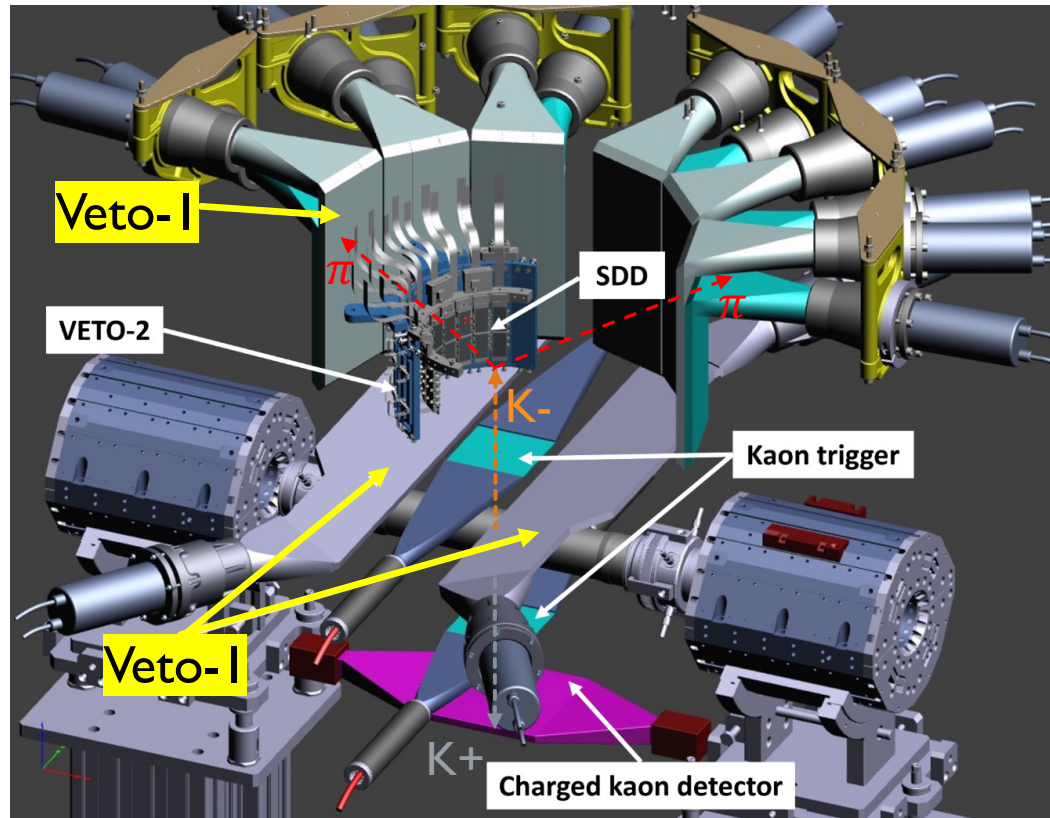
New technological developments in the accelerators delivering kaon beams:

DAΦNE collider **LNF-INFN, Italy**
Low-momentum, almost
monochromatic K^- beams from $\phi \rightarrow K^+K^-$
decays; ideal for stopping kaons in
gaseous targets. **Low intensity**

KEK, J-PARC Hadron Hall **Japan**
High intensity; High energy Extracted kaon
beam lines provide complementary
conditions for stopped-kaon and kaonic-
atom measurements.

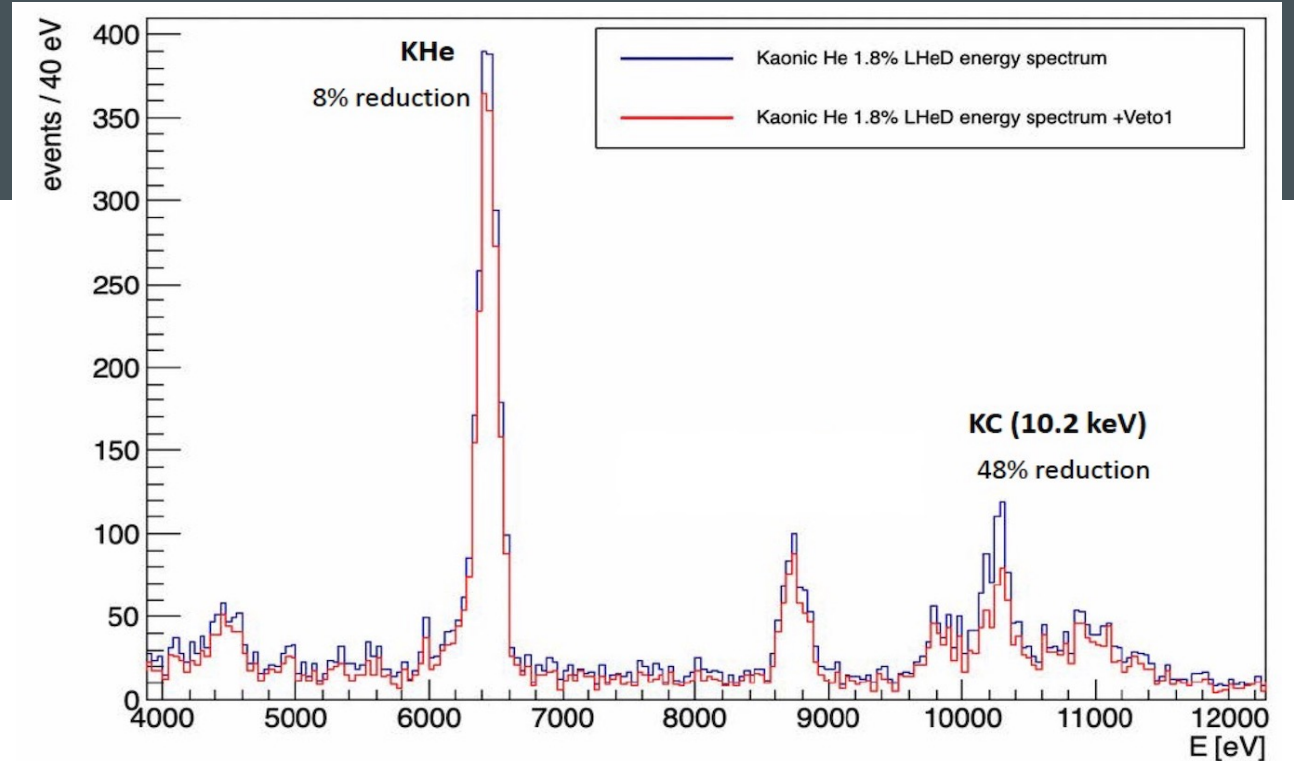
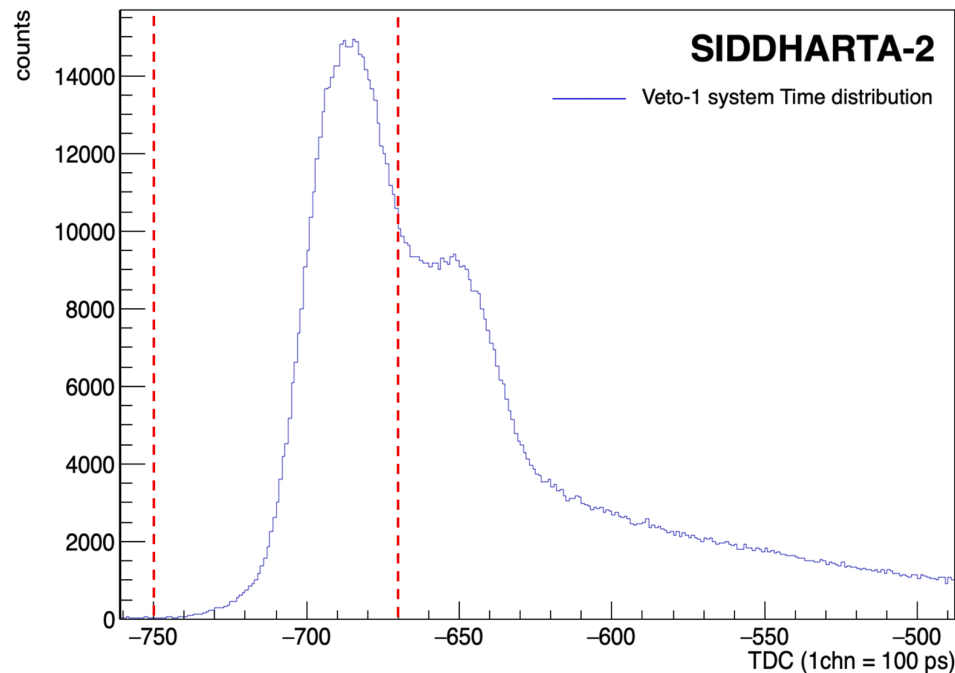
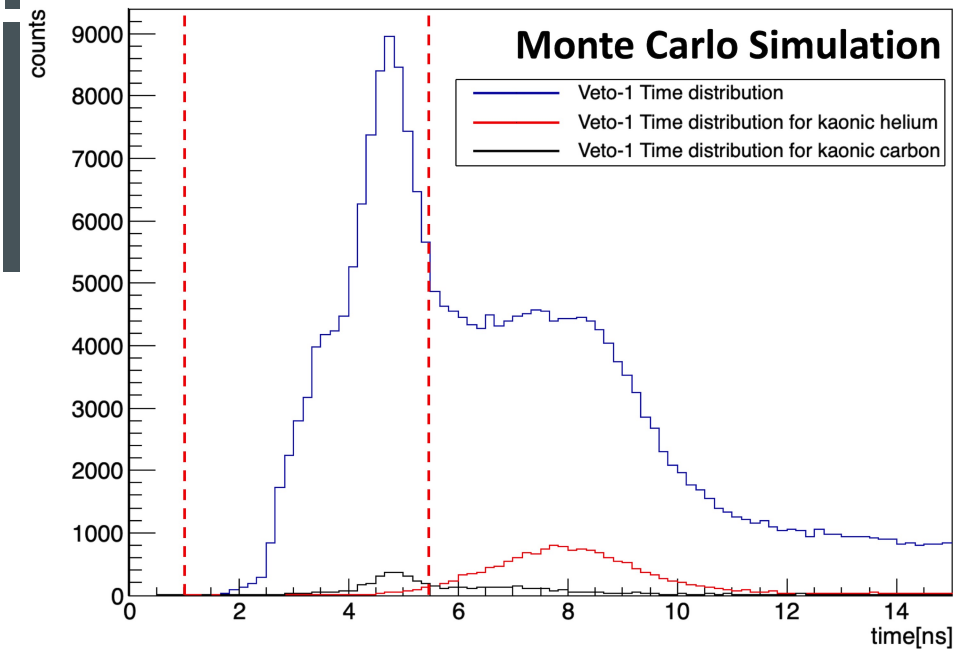
Kaonic deuterium analysis – Veto1 system

Veto-1 for hadronic background reduction: it measures the arrival time of charged particles emitted by the kaon-nucleus absorption to determine the origin of the signal — whether it comes from the deuterium gas target or from surrounding solid materials.



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

Veto-1 system optimization with kaonic He

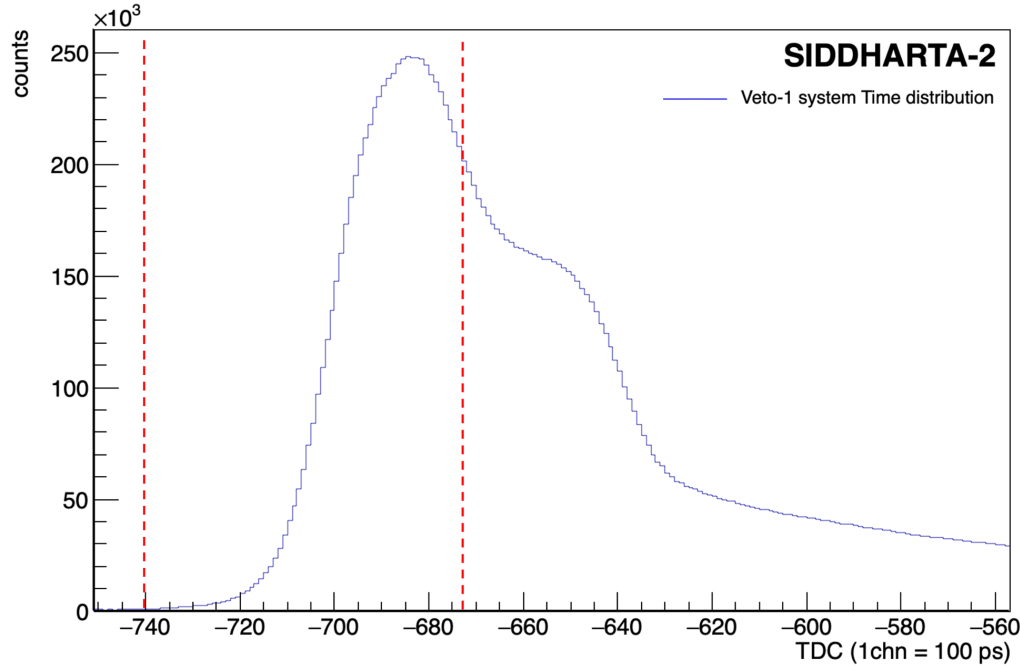


	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K- ⁴ He L _α	(8 ± 1)%	4%
K-C _{5→4}	(48 ± 4)%	44%

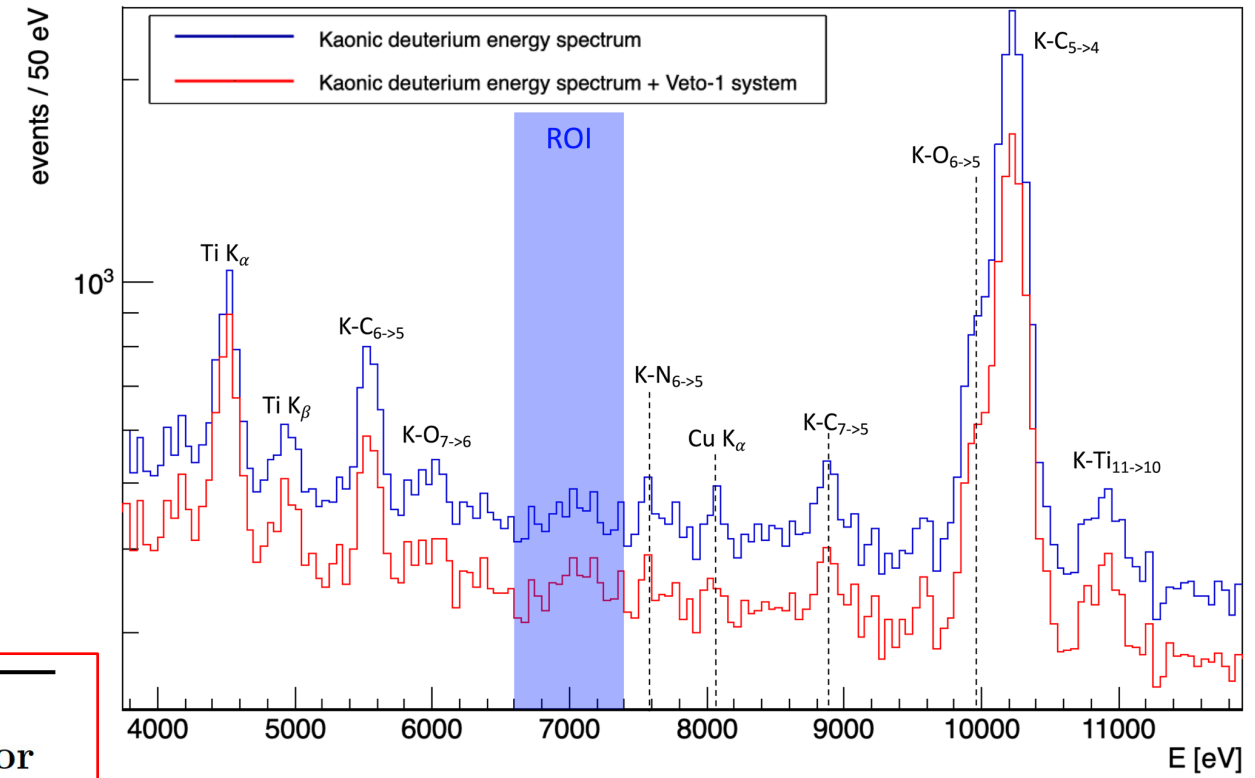
$$\text{reduction factor} = 1 - \frac{\text{\#events(with veto1)}}{\text{\#events}}$$

Kaonic Deuterium (run1): veto-1 system analysis

Veto-1 time distribution and time window used to reduce the background



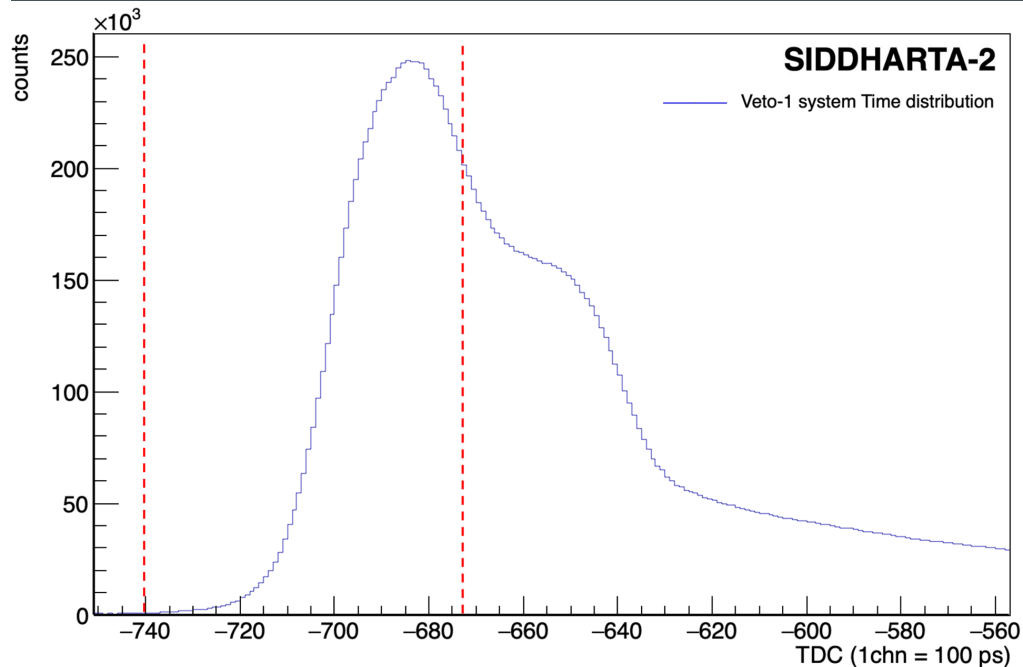
SDDs X-ray energy spectra with and without the veto-1 (be aware logarithmic scale)



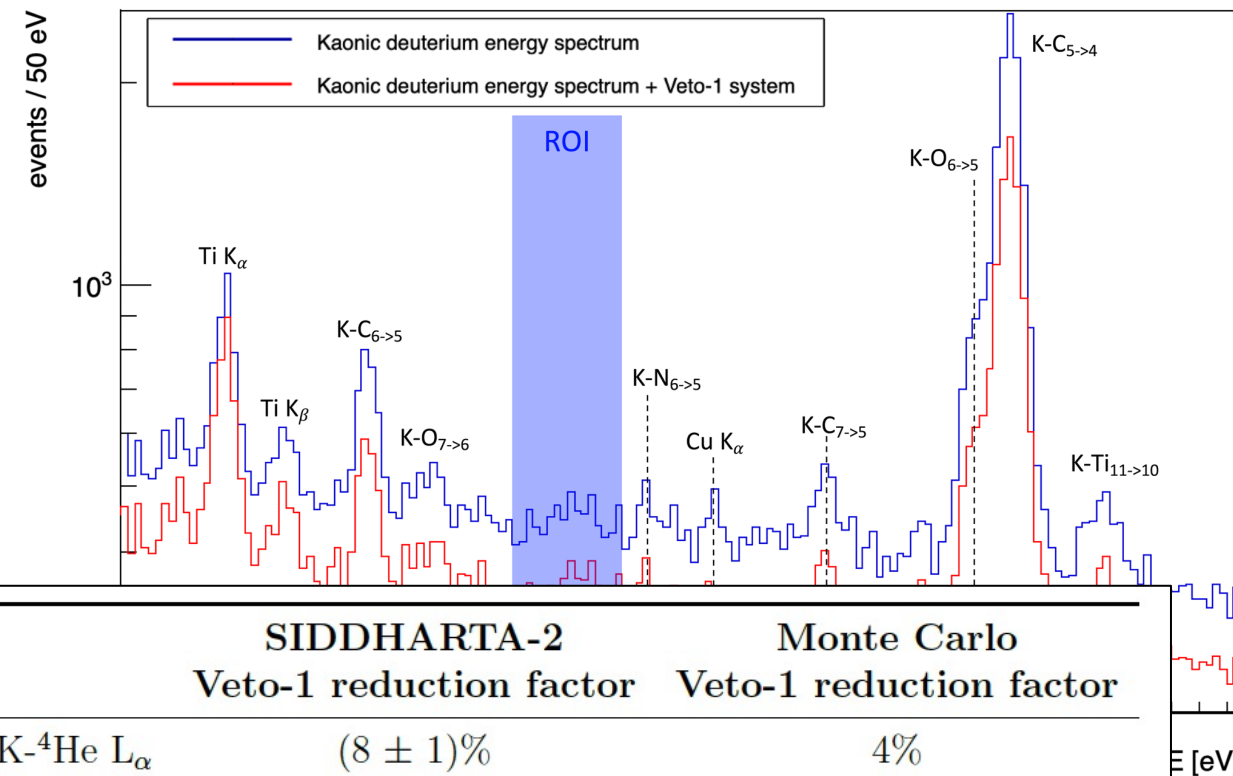
SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-d K_α	$(11 \pm 3)\%$ 4%
K-C ₅ →4	$(44 \pm 4)\%$ 46%
K-C ₆ →5	$(39 \pm 5)\%$ 45%
K-C ₇ →5	$(48 \pm 4)\%$ 46%

Kaonic Deuterium: veto-1 system analysis

Veto-1 time distribution and time window used to reduce the background



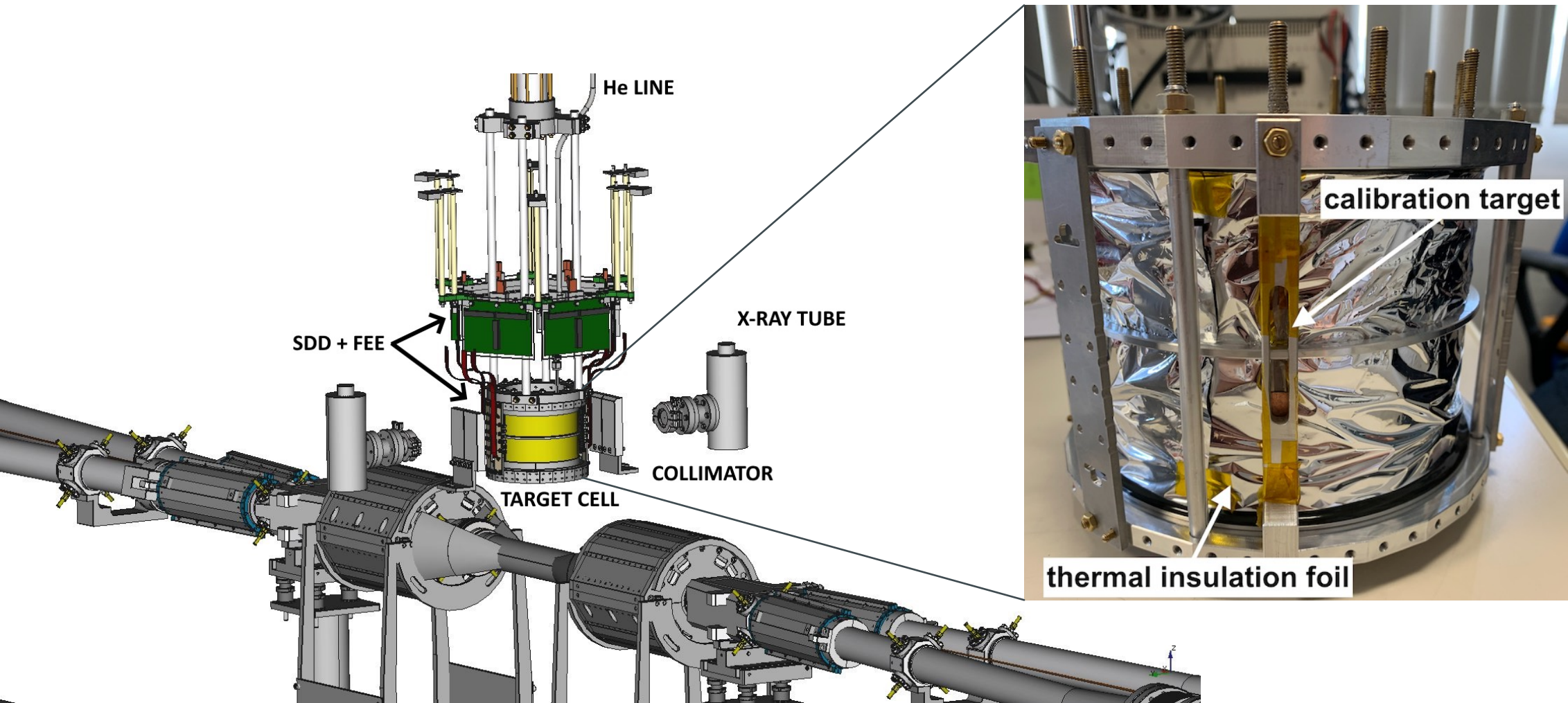
SDDs X-ray energy spectra with and without the veto-1 (be aware logarithmic scale)



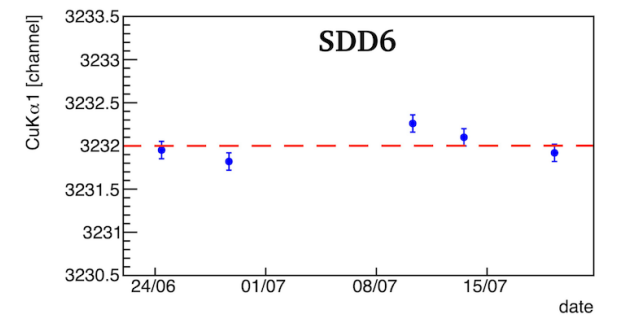
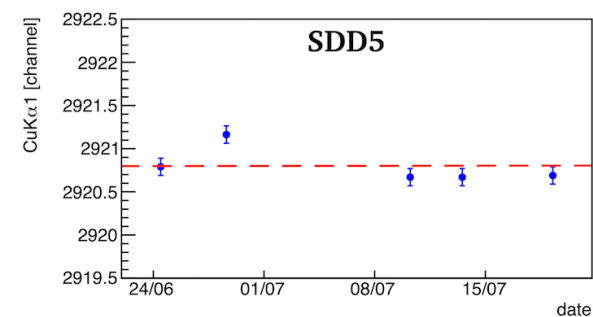
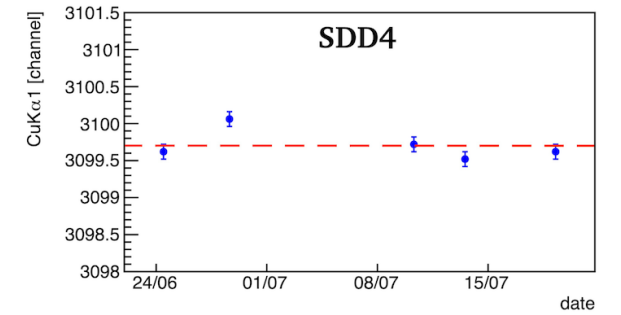
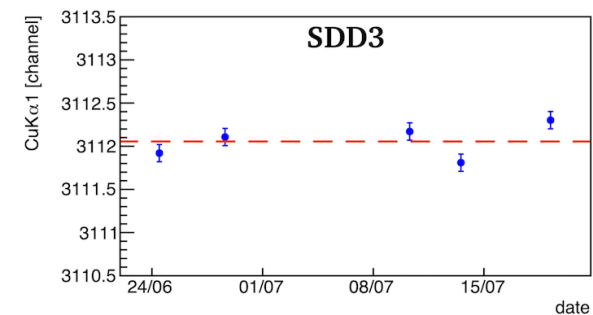
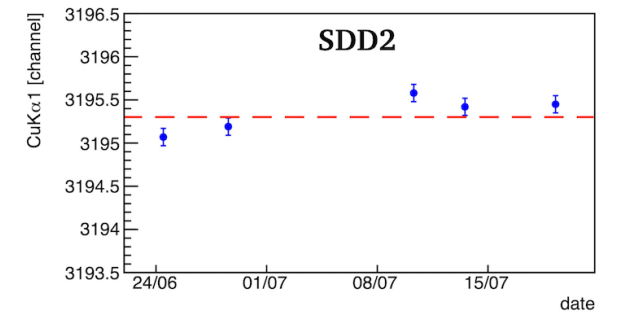
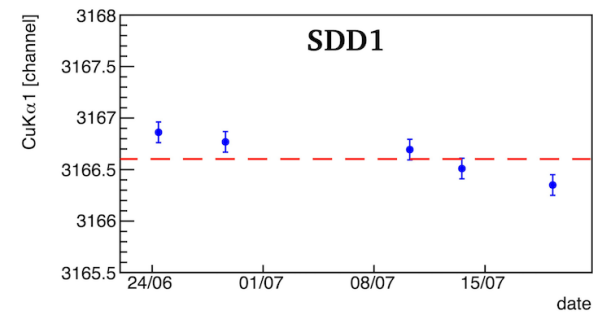
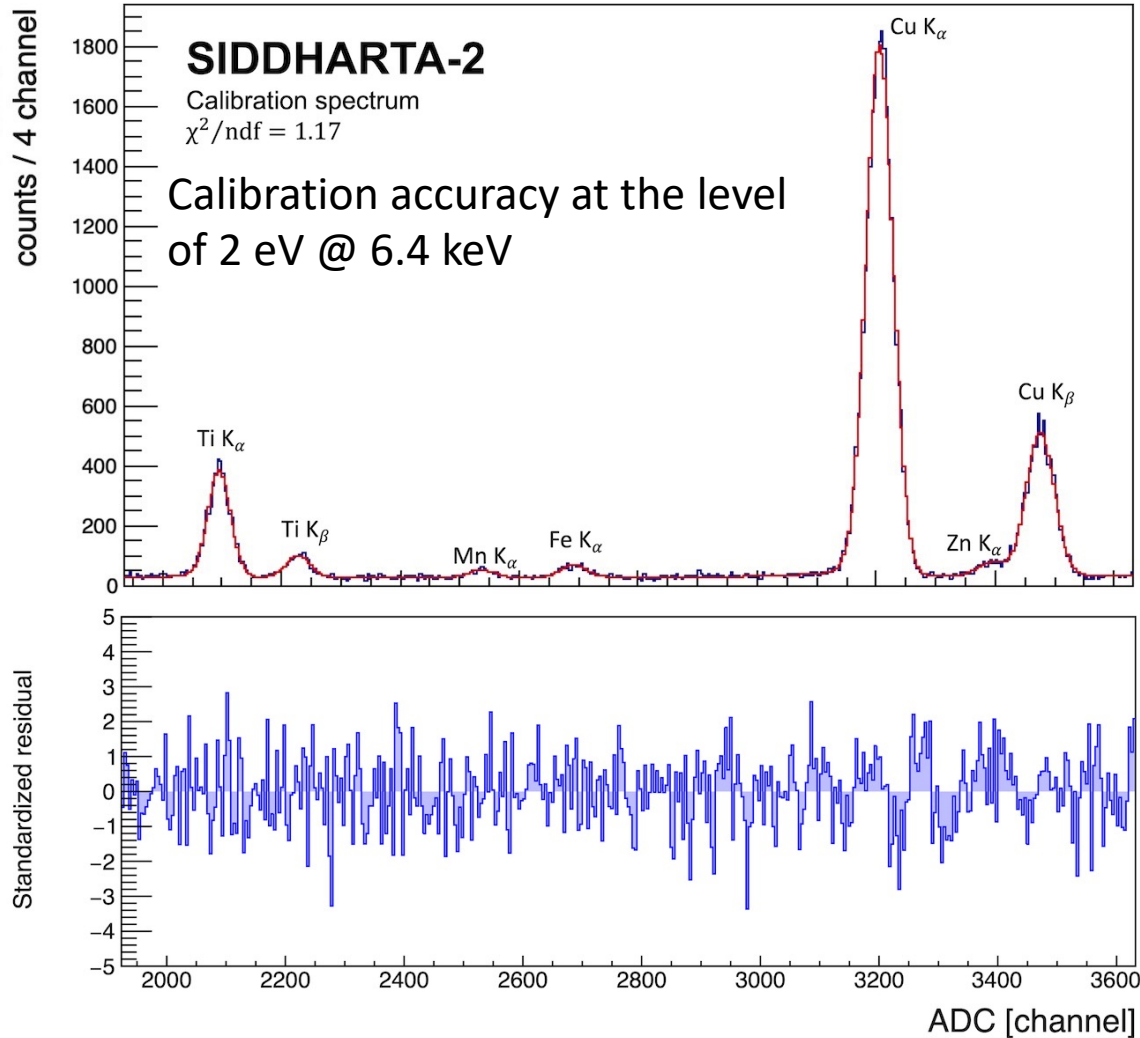
SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor	
K-d K_α	$(11 \pm 3)\%$	4%
K-C ₅ →4	$(44 \pm 4)\%$	46%
K-C ₆ →5	$(39 \pm 5)\%$	45%
K-C ₇ →5	$(48 \pm 4)\%$	46%

	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K- ⁴ He L_α	$(8 \pm 1)\%$	4%
K-C ₅ →4	$(48 \pm 4)\%$	44%

SDDs Calibration Procedure in DAΦNE



SDDs Calibration Procedure in DAΦNE



SIDDHARTINO - The kaonic ^4He $3d \rightarrow 2p$ measurement

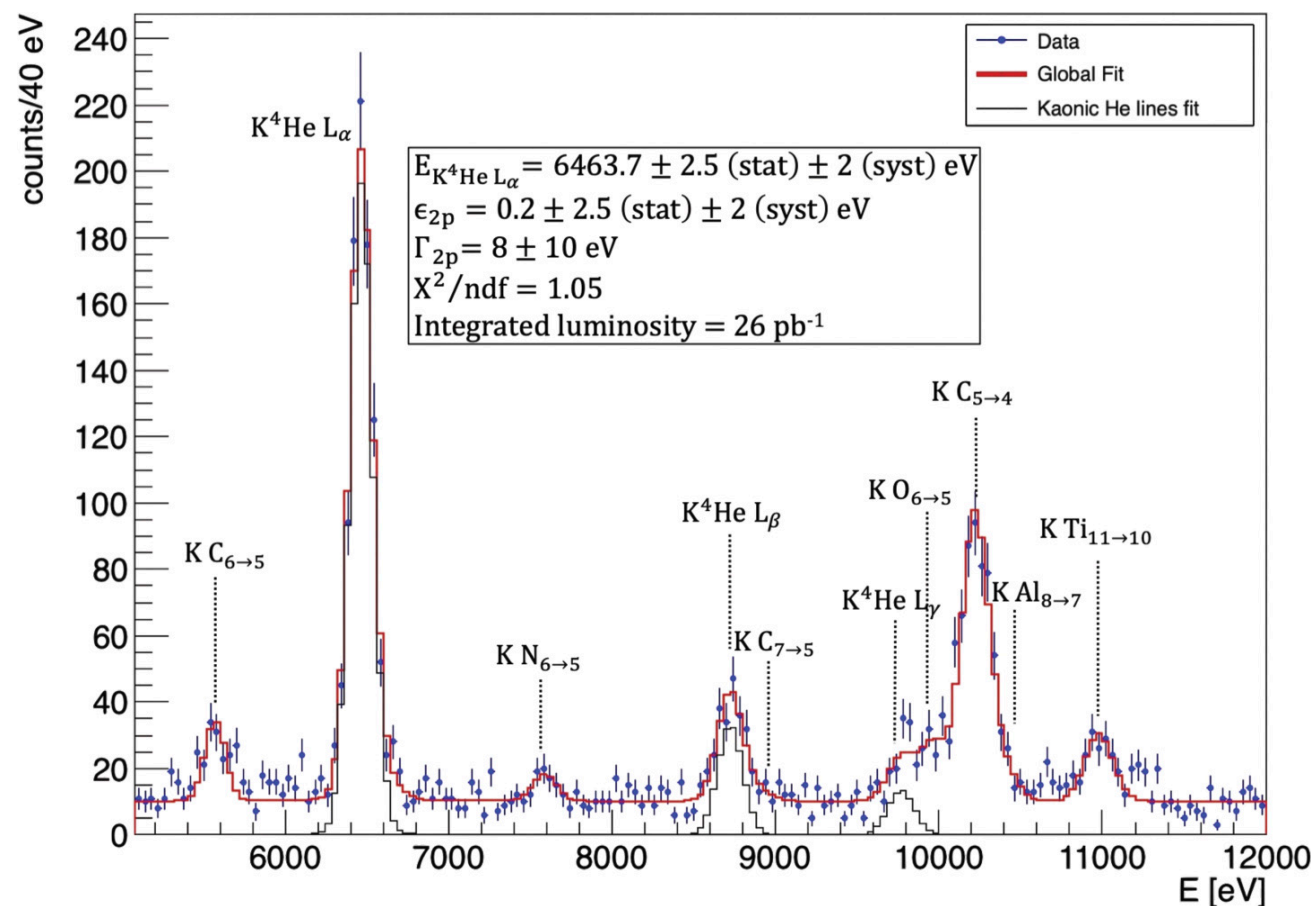
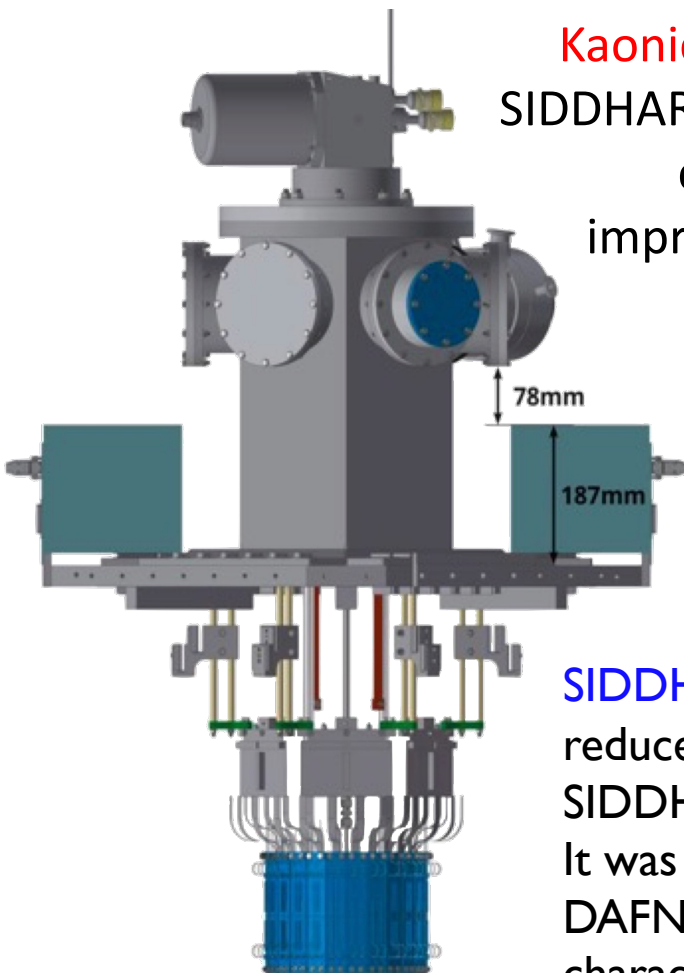
Characterization of the SIDDHARTA-2 apparatus and optimization of DAΦNE background through the kaonic helium measurement

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



SIDDHARTINO

The kaonic ${}^4\text{He } 3d \rightarrow 2p (L_\alpha)$ measurement

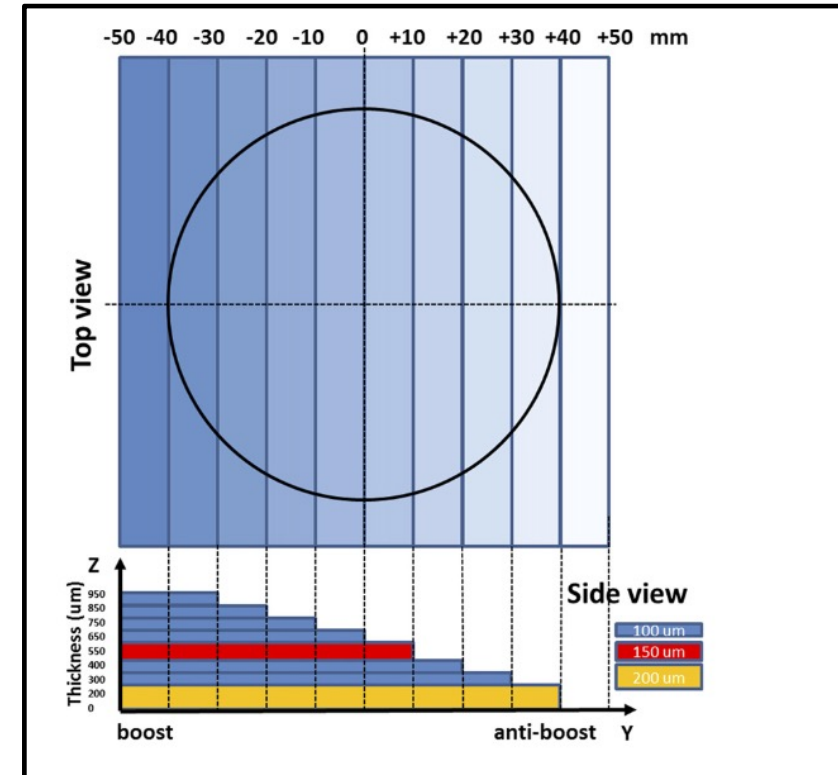
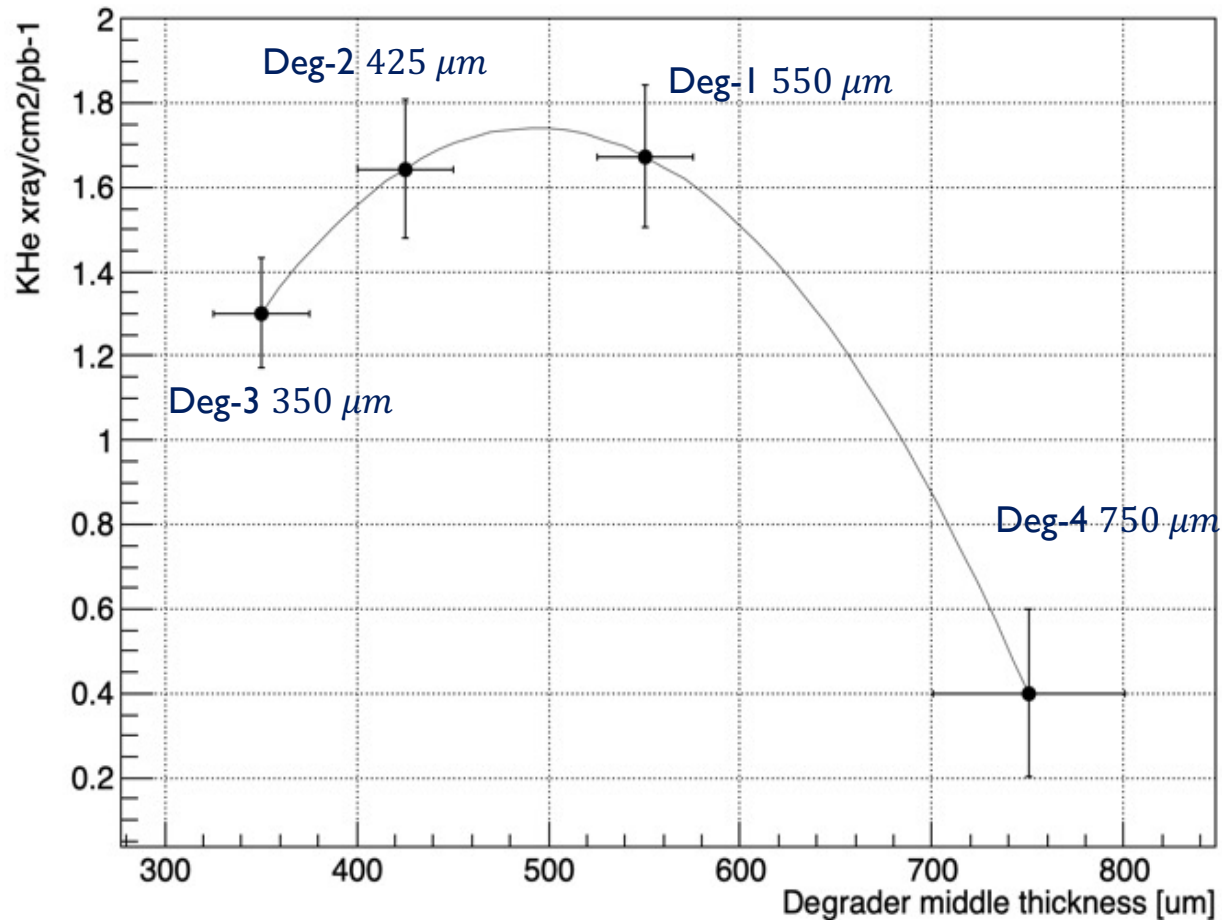


Figure 6. Nearest to optimal configuration of the size of the entrance window of the vacuum chamber side of the DAΦNE ring, corresponding to the degrader has eight steps to compensate for the boost effect part of the figure.

OPEN ACCESS

IOP Publishing

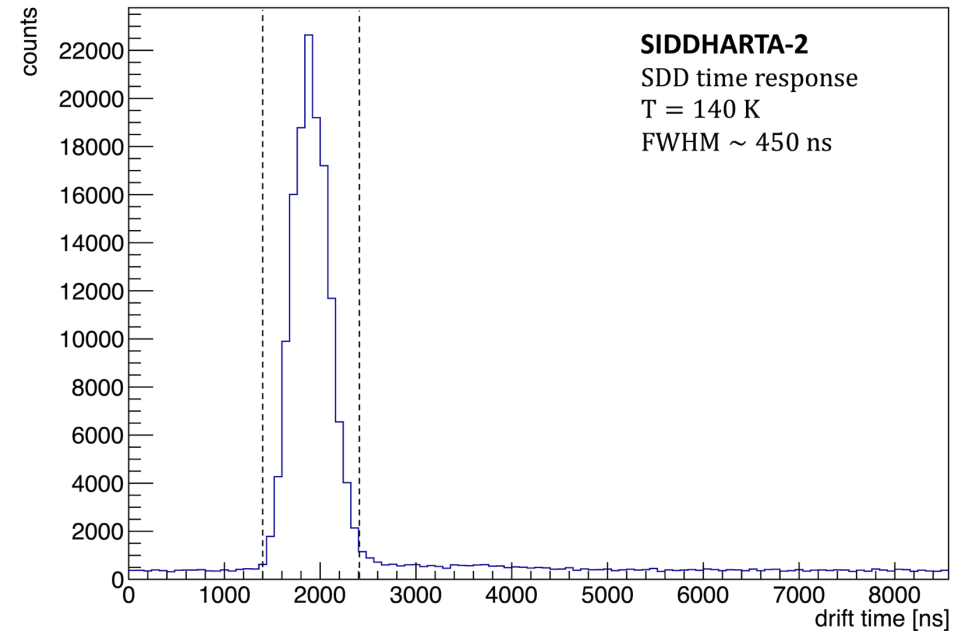
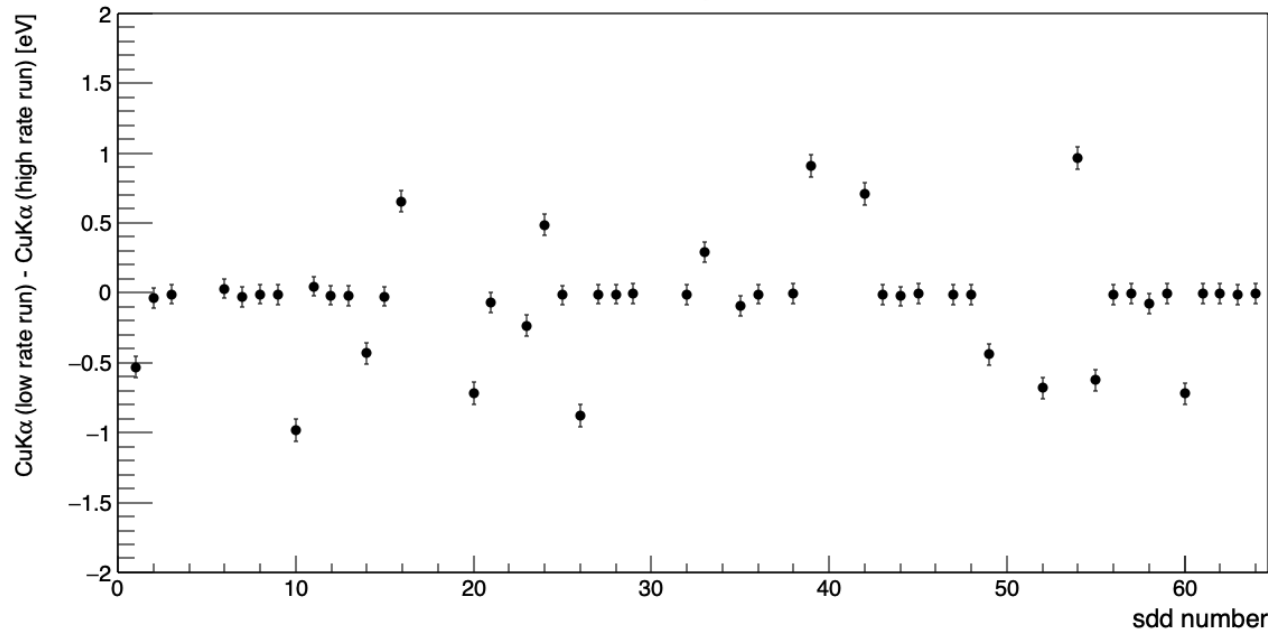
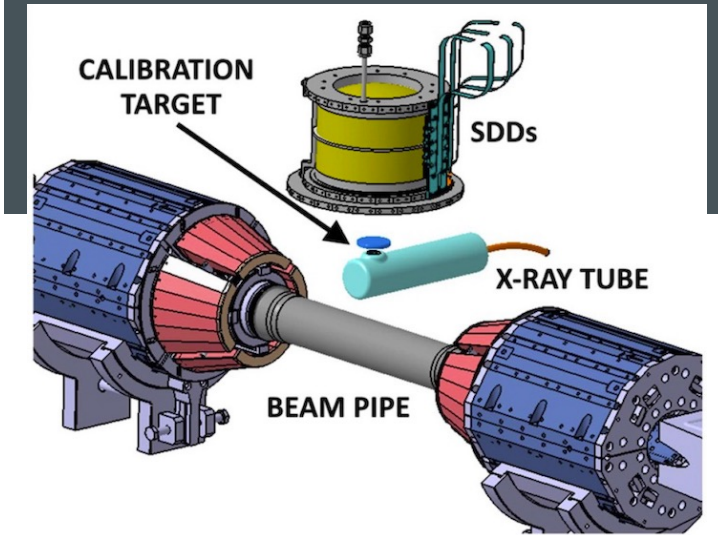
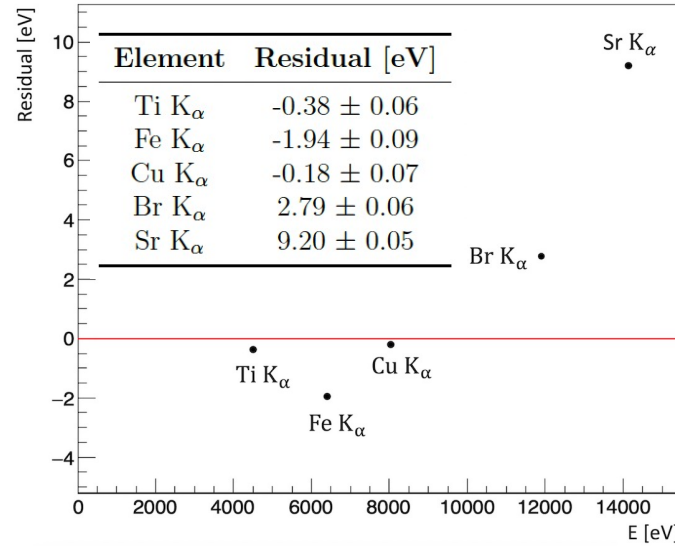
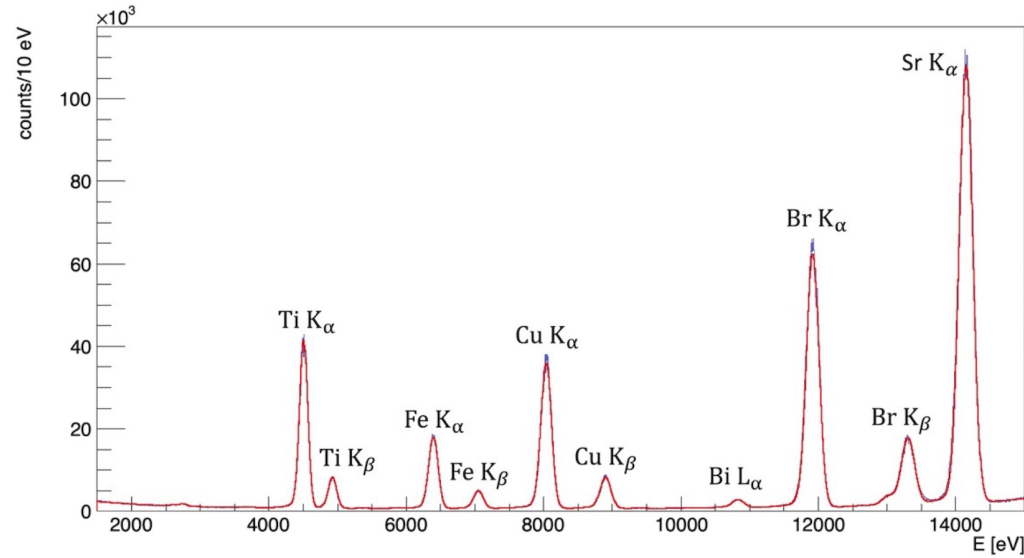
Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. 49 (2022) 055106 (14pp)

<https://doi.org/10.1088/1361-6471/ac5dac>

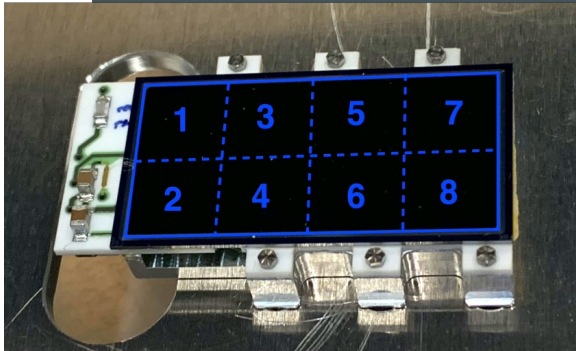
A new kaonic helium measurement in gas by SIDDHARTINO at the DAΦNE collider*

Spectroscopy Response in a High Background Environment

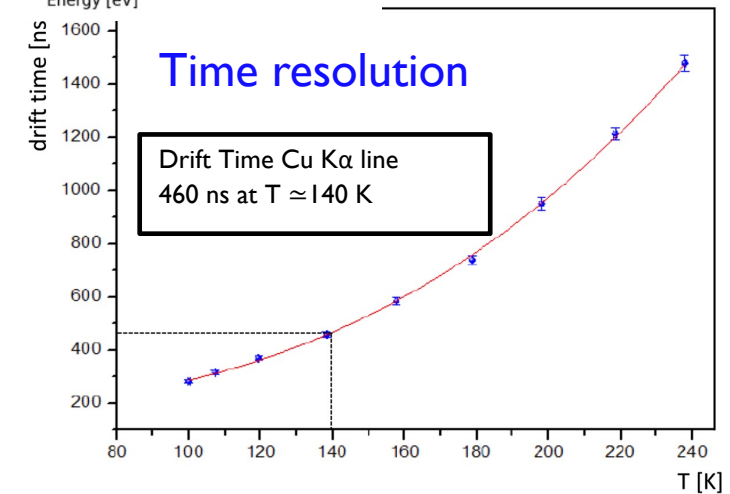
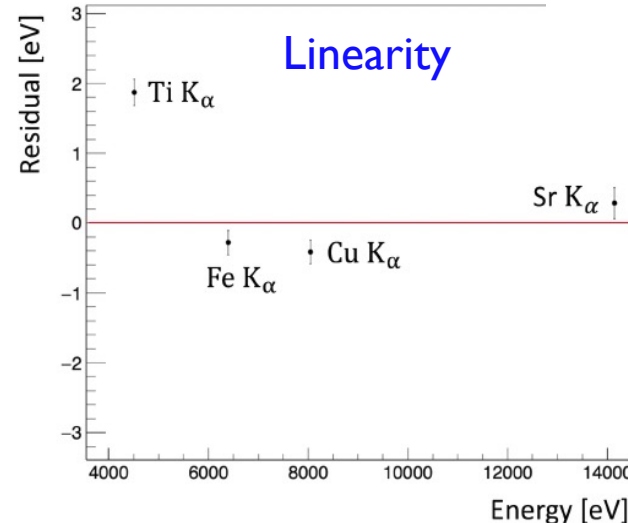
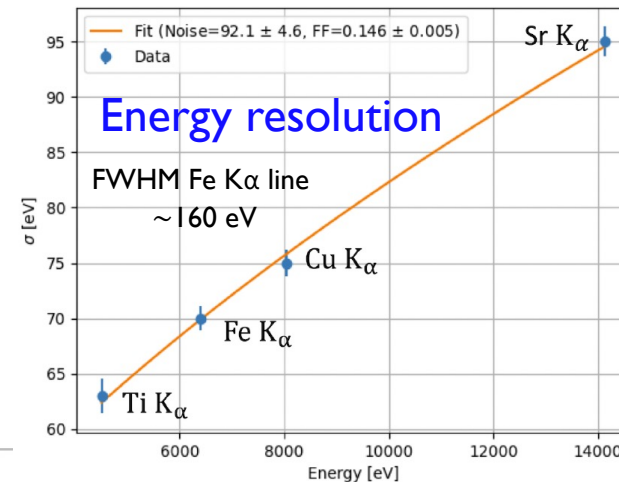
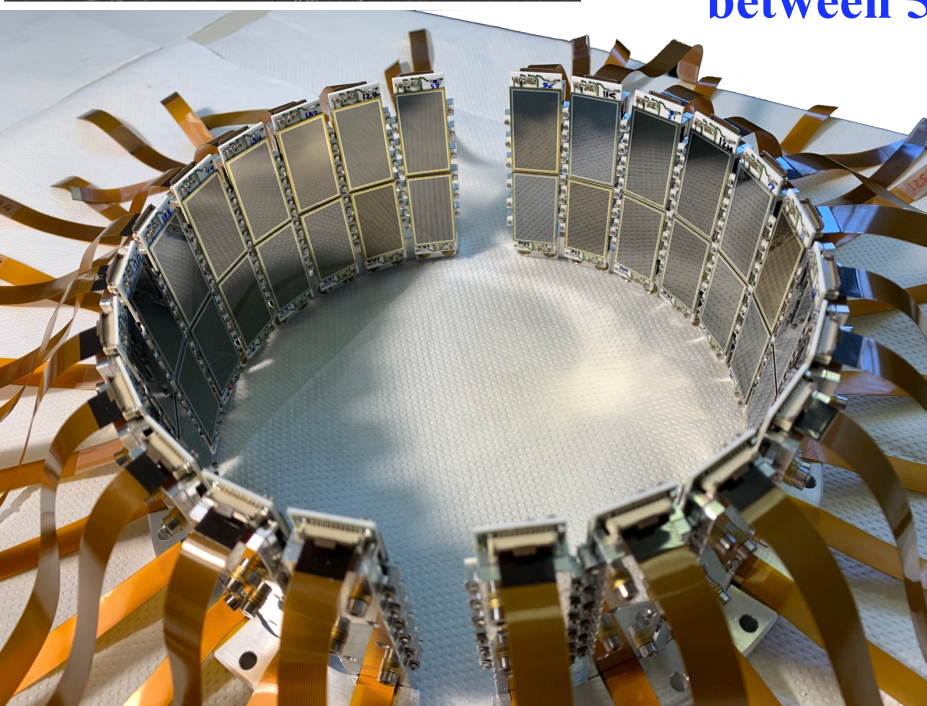


Silicon Drift Detectors

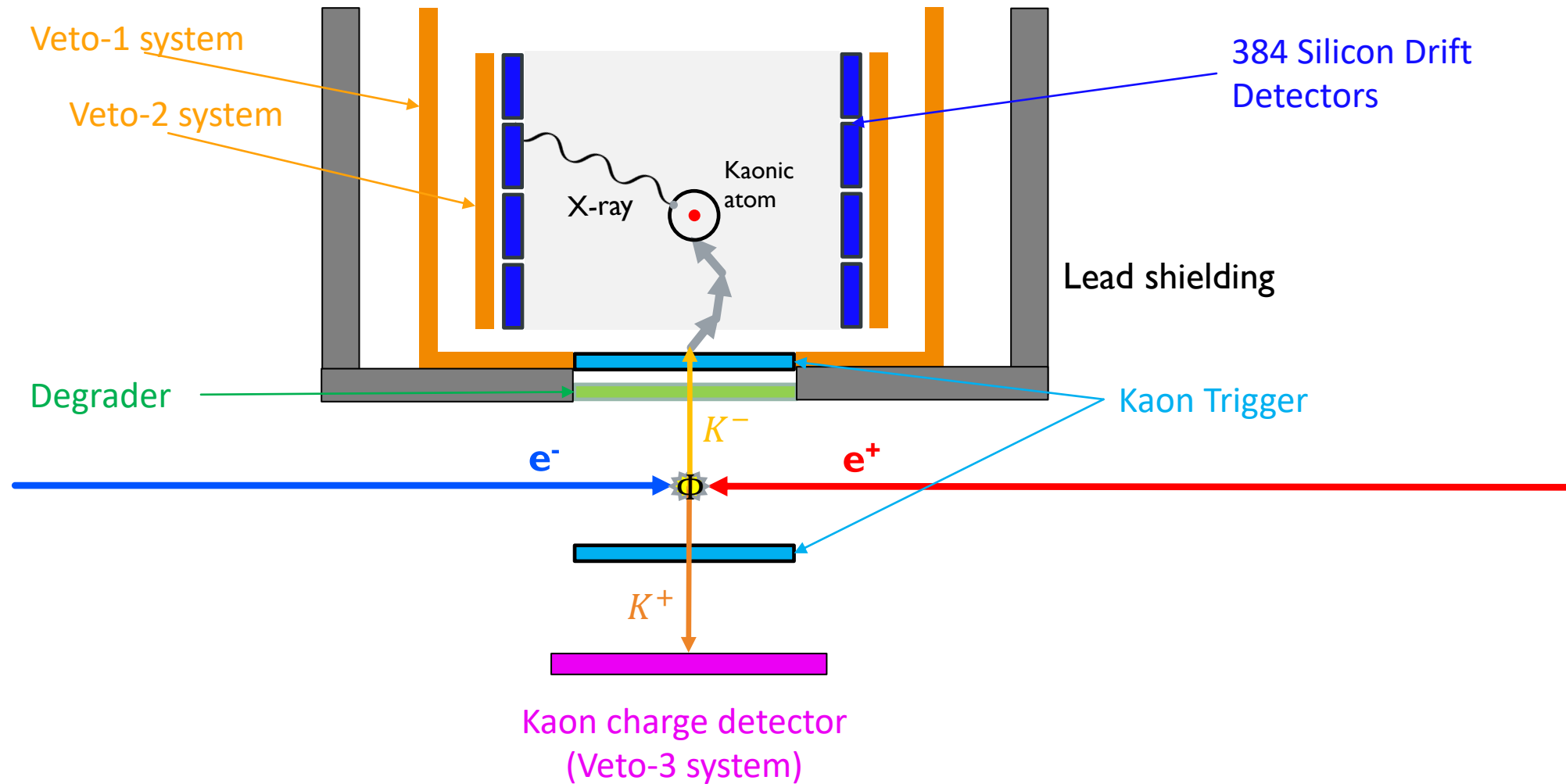
Large area Silicon Drift Detectors (SDDs) have been developed to perform high precision kaonic atoms X-ray spectroscopy



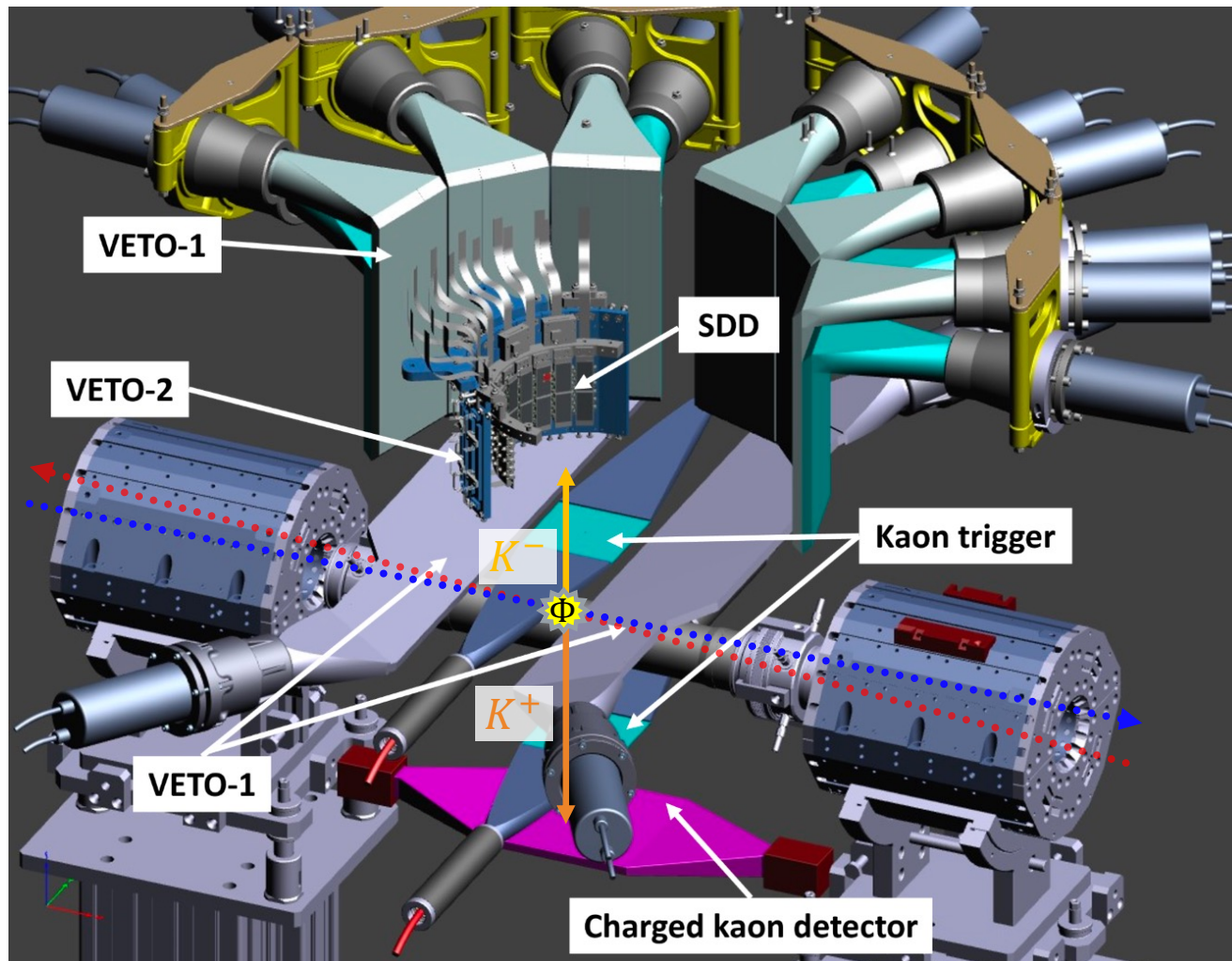
**8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of $450 \mu\text{m}$ ensures a high
collection efficiency for X-rays of energy
between 5 keV and 12 keV**



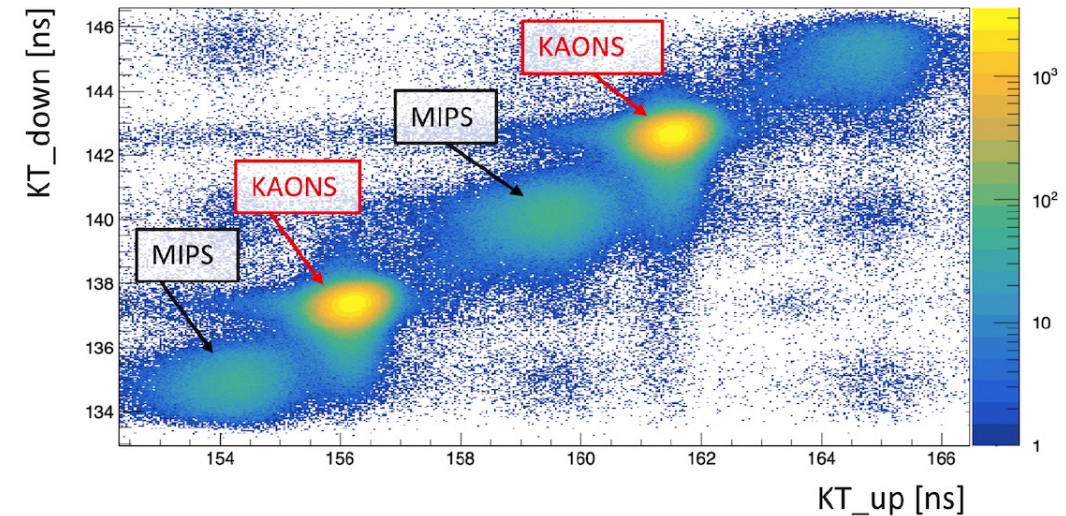
The SIDDHARTA-2 experiment



The SIDDHARTA-2 apparatus



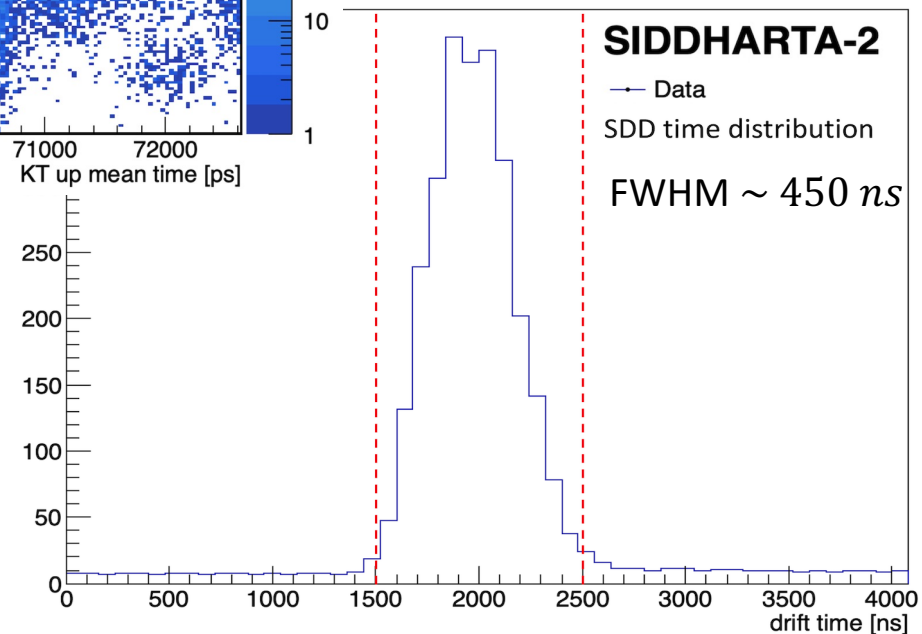
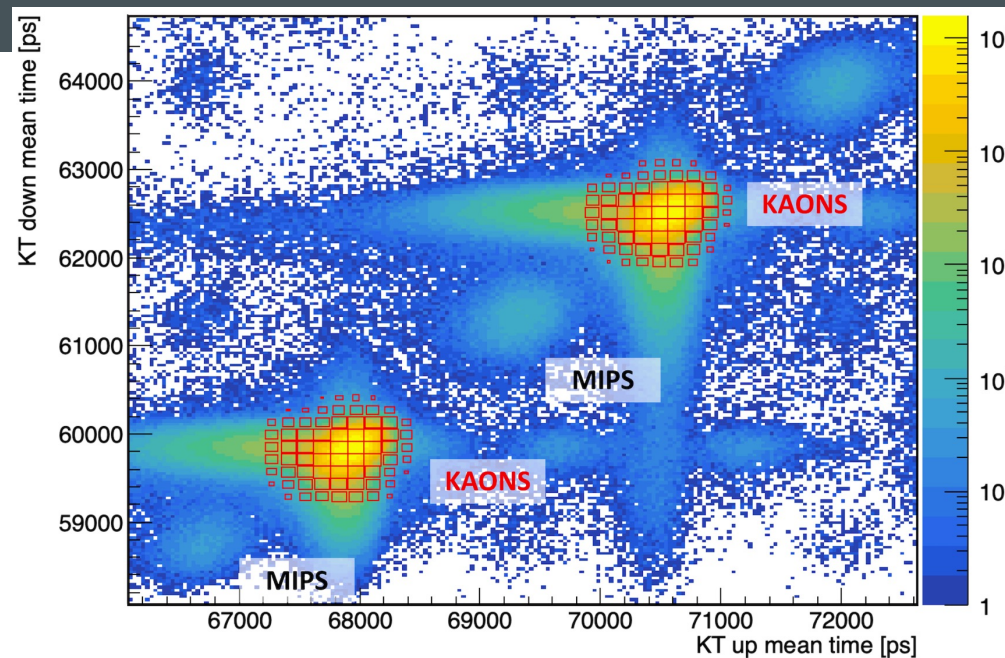
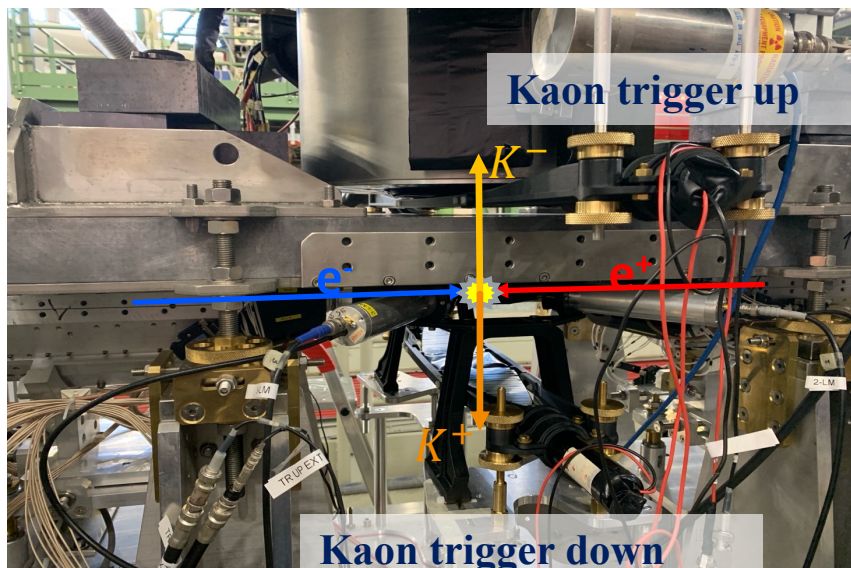
Kaon Trigger: two plastic scintillators read by photomultipliers placed above and below the interaction region.



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

The first kaonic deuterium measurement

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



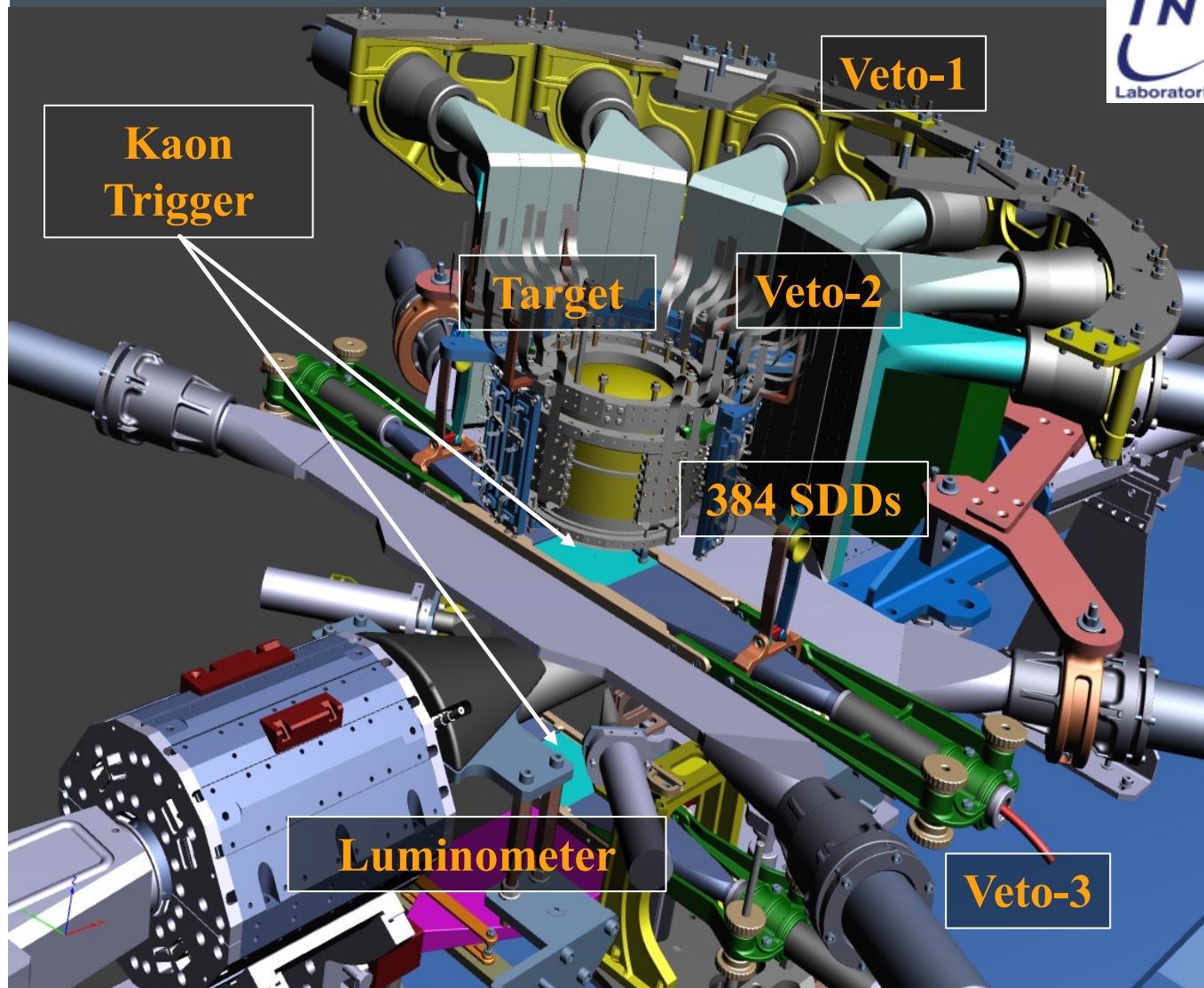
The trigger is generated by the coincidence of 2 back-to-back scintillators

The ToF is different (~ 2 ns) for Kaons, $m(K) \sim 500$ MeV/c² and light particles

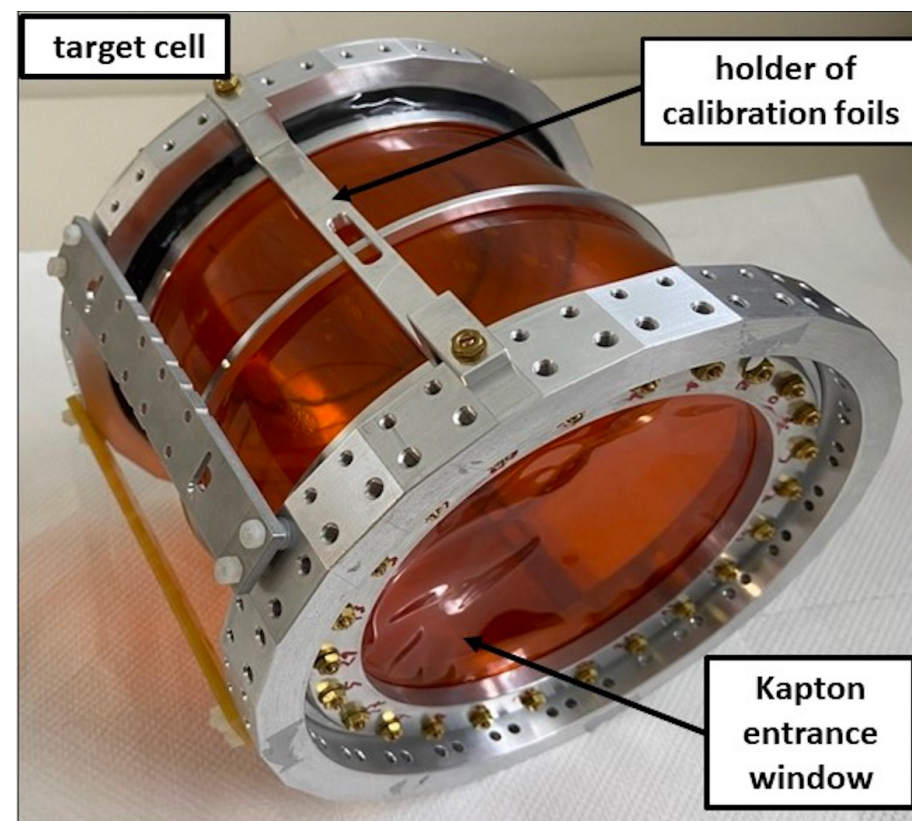
originating from beam-beam and beam-environment interaction (MIPs).

Can efficiently discriminate by ToF Kaons and MIPs!

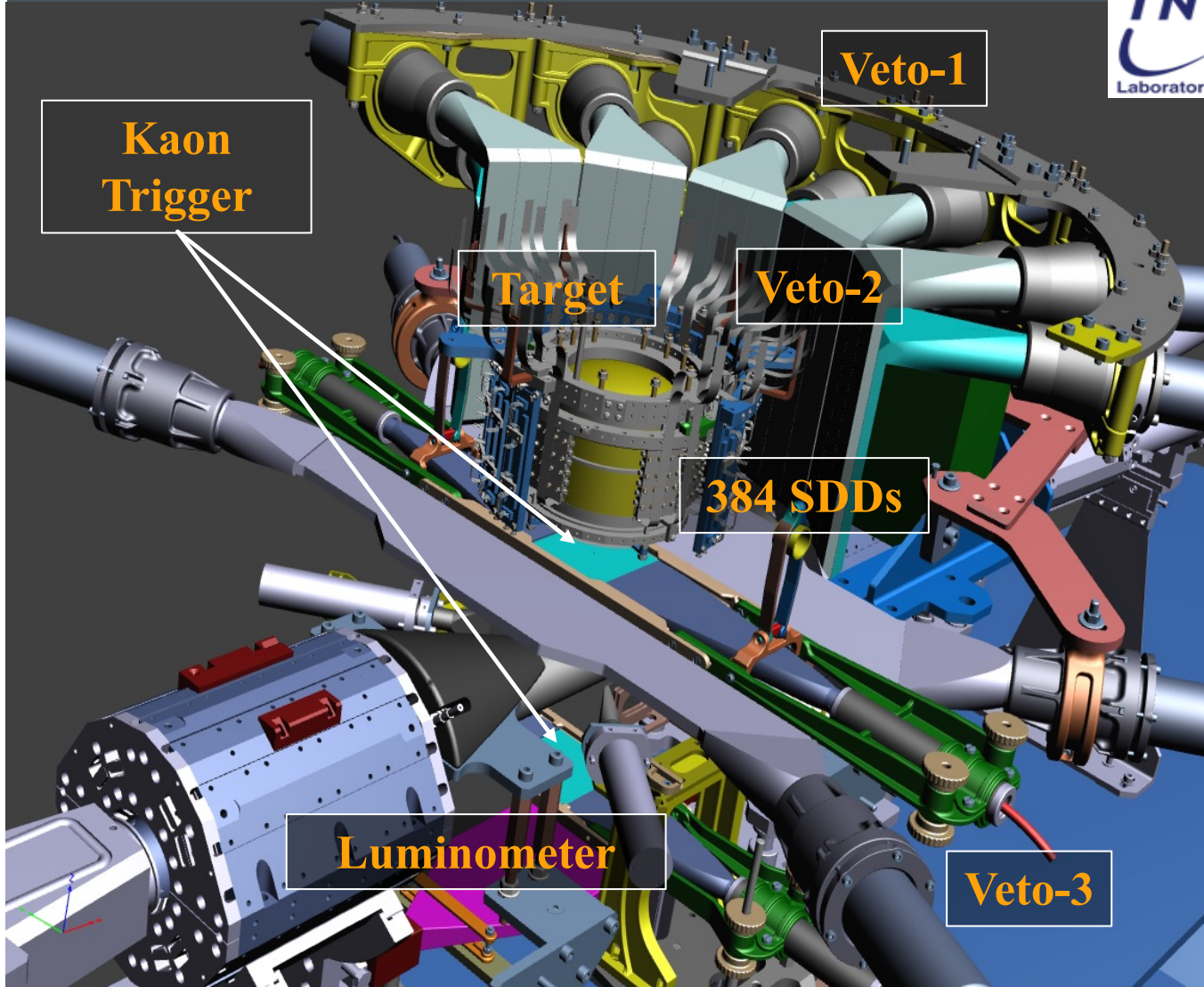
The SIDDHARTA-2 setup



Cryogenic gaseous target cell

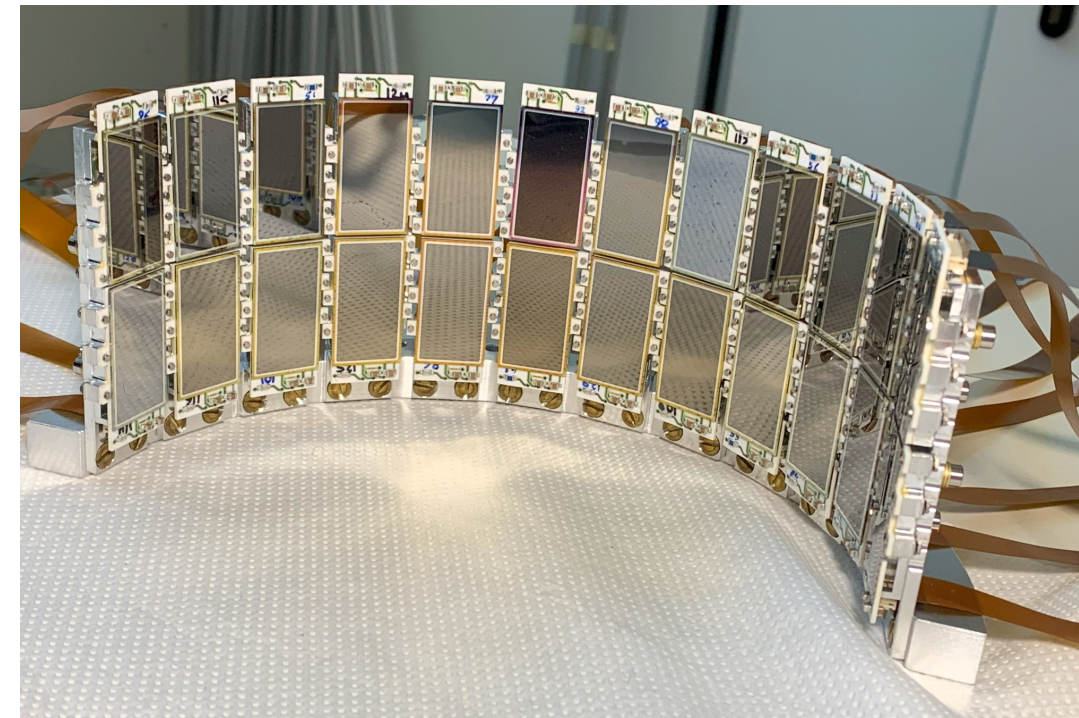


The SIDDHARTA-2 setup

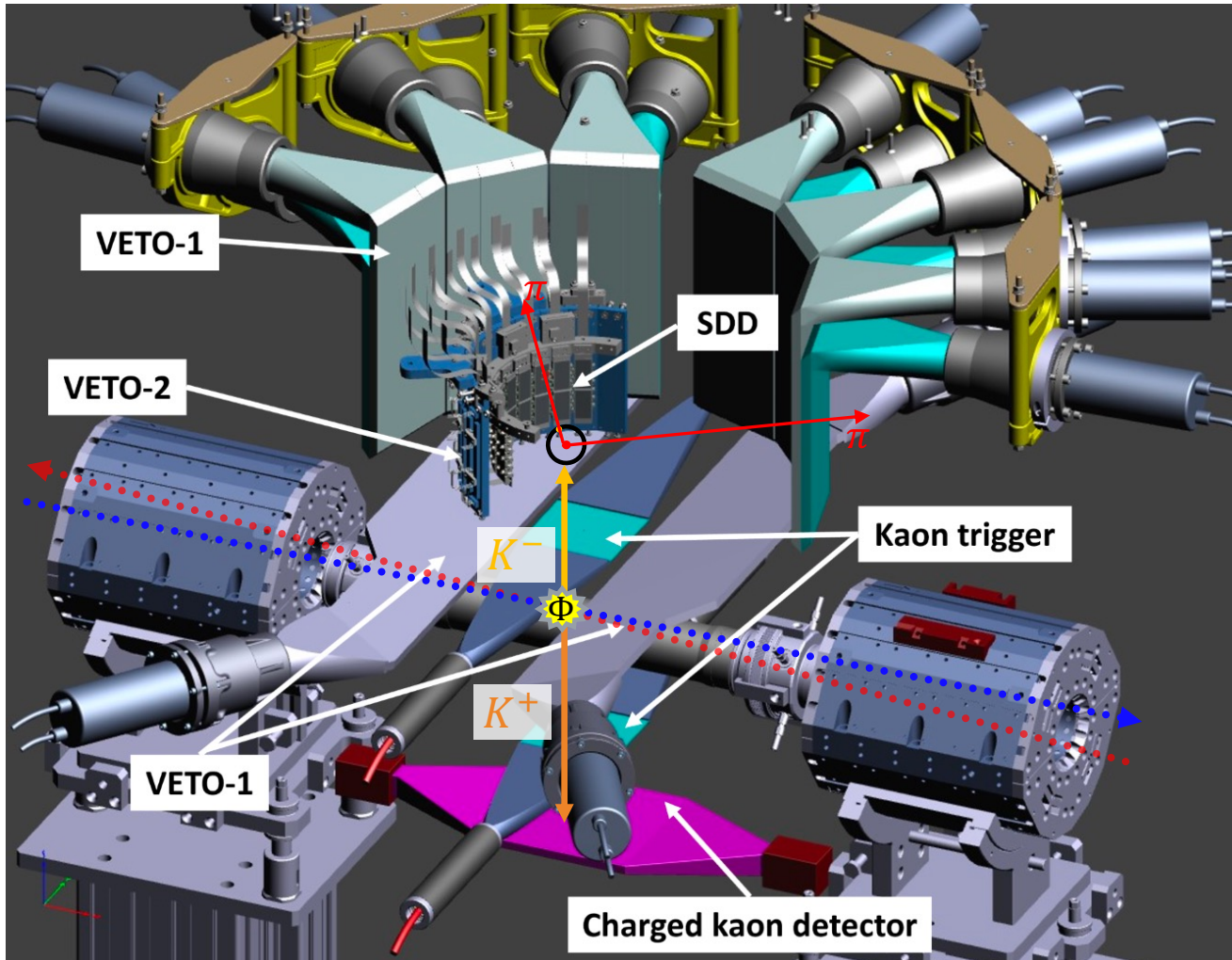


384 Silicon Drift Detector
for a total active area of 246 cm^2

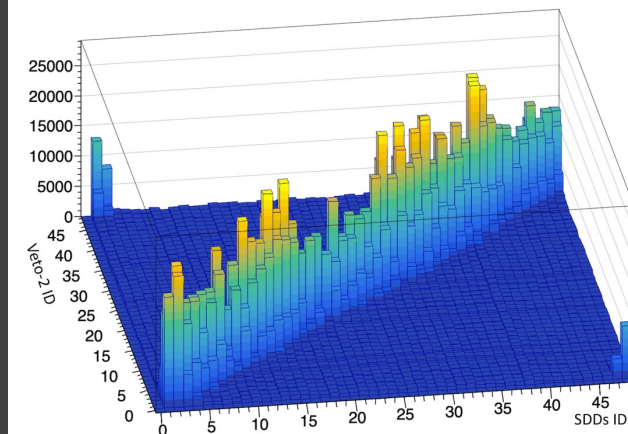
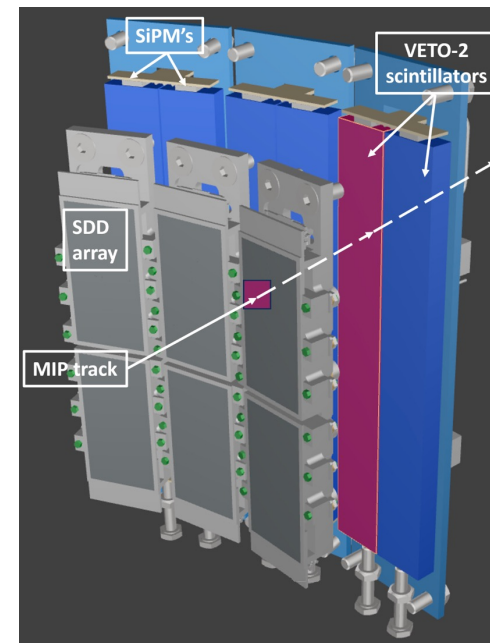
The thickness of $450 \mu\text{m}$ ensures a high collection efficiency for X-rays of energy in the 5-12 keV range



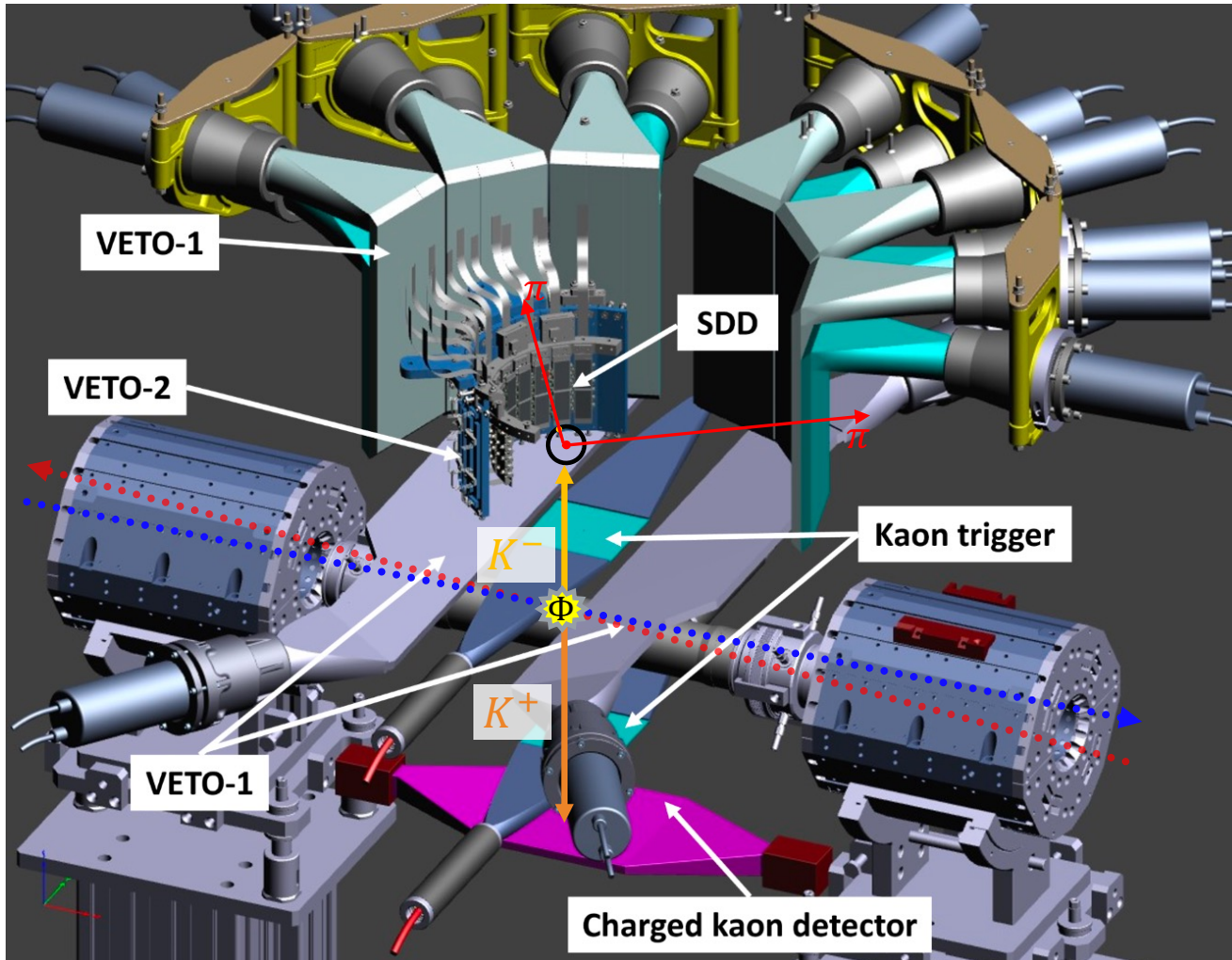
The SIDDHARTA-2 apparatus



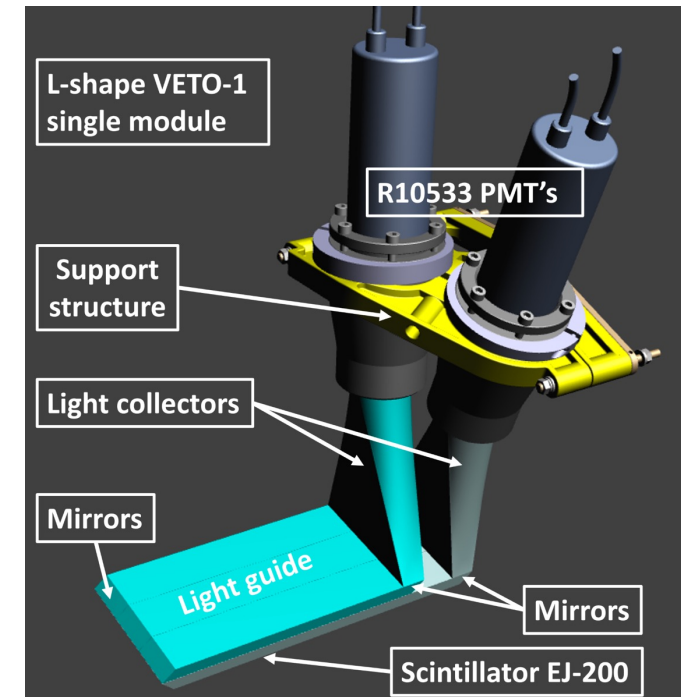
Veto-2 48 plastic scintillator read by SiPMs to suppress the background induced by particles produced by kaon absorption, passing through the SDDs.



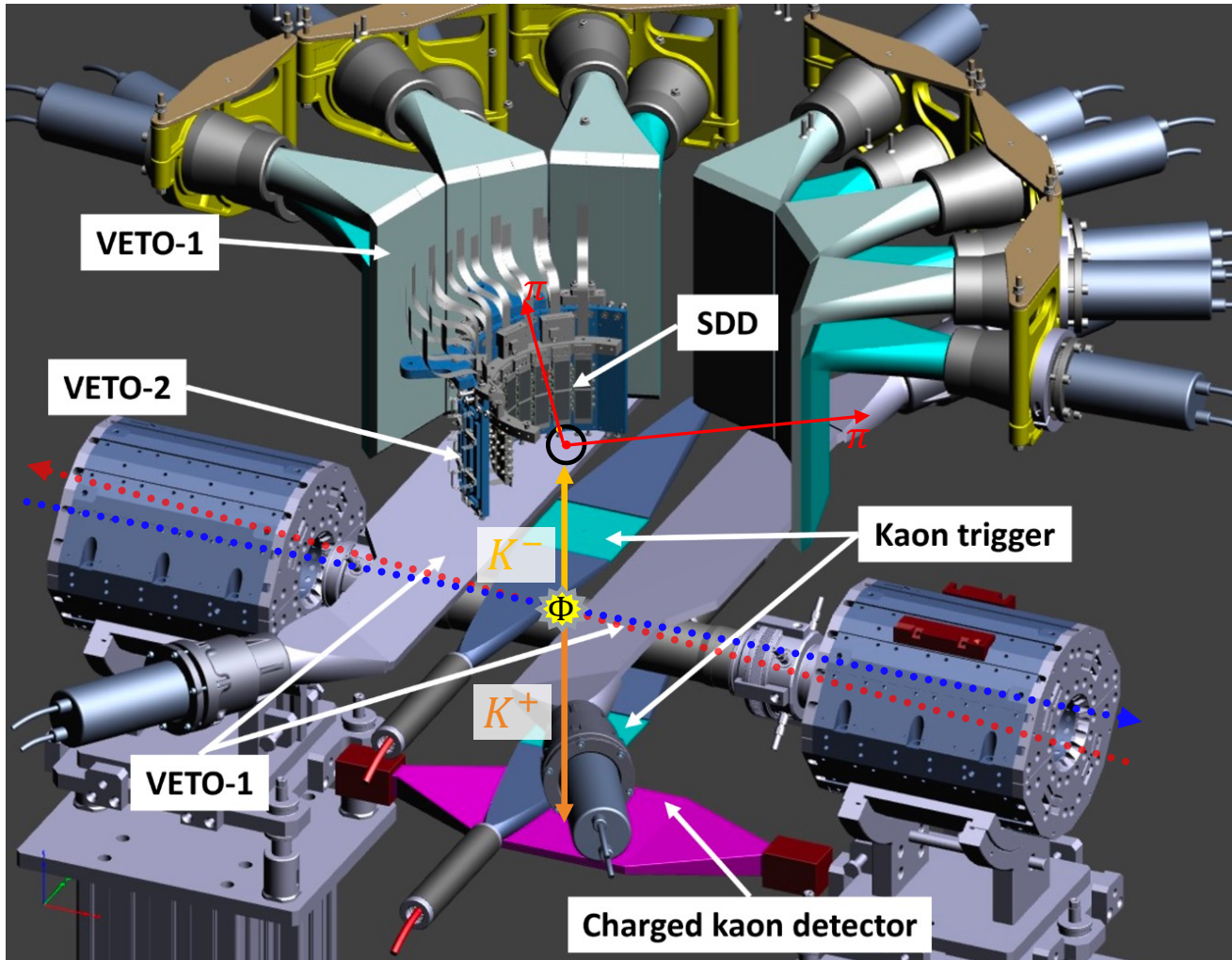
The SIDDHARTA-2 apparatus



Veto-1 14 plastic scintillator read by PMTs to select the events occurring in the gas target, rejecting the X-ray background corresponding to K- stopped in the solid elements of the setup

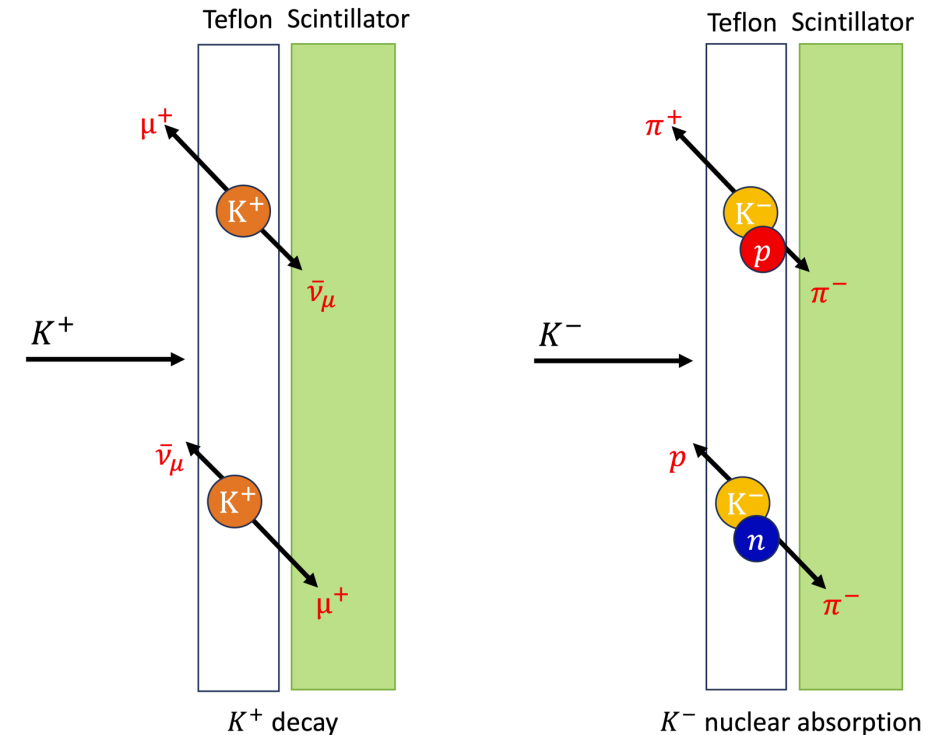


The SIDDHARTA-2 apparatus

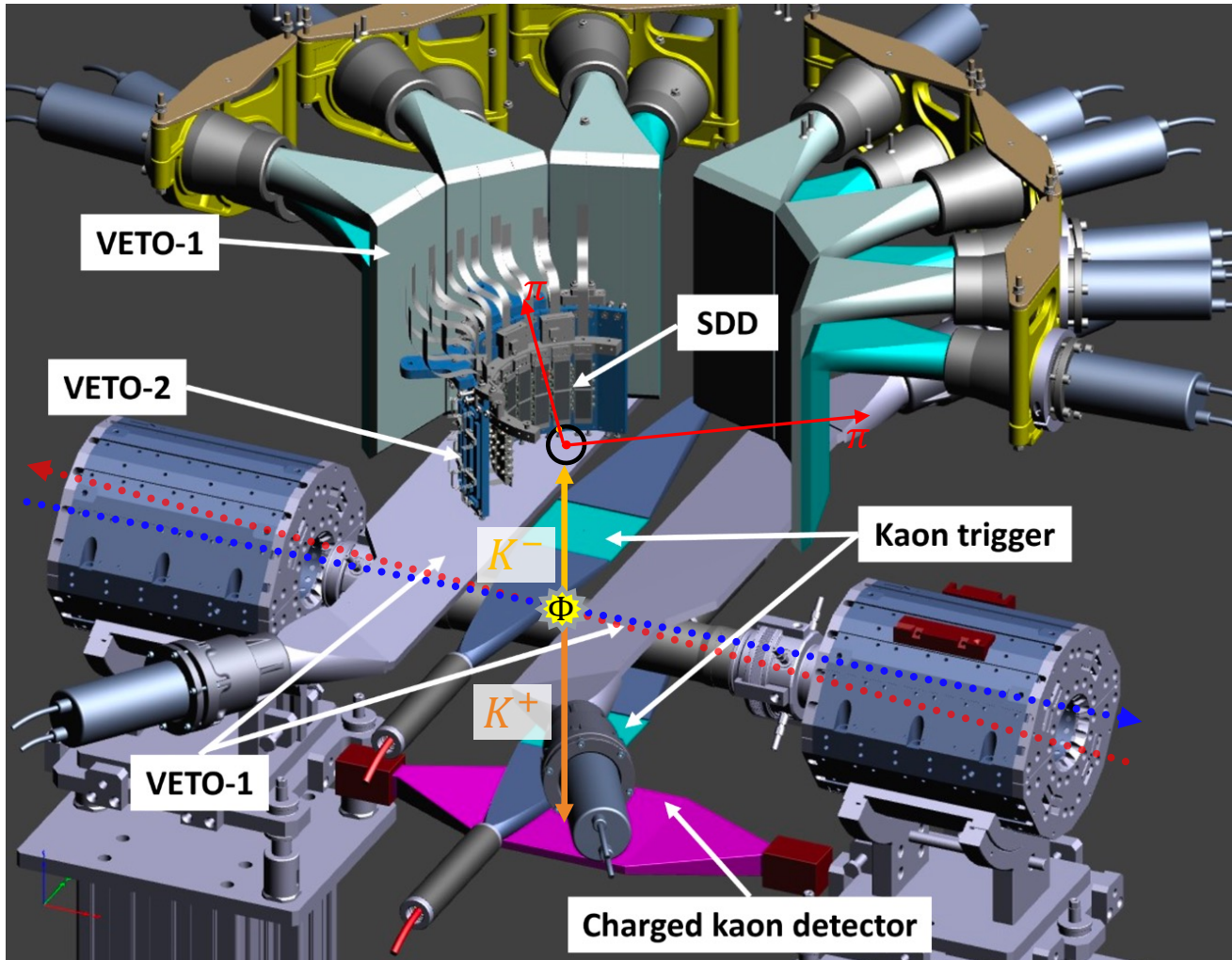


Charged Kaons Veto

Stop both K^+ and K^- in a passive layer (Teflon 3 mm) and detect secondaries charged particles using a plastic scintillator

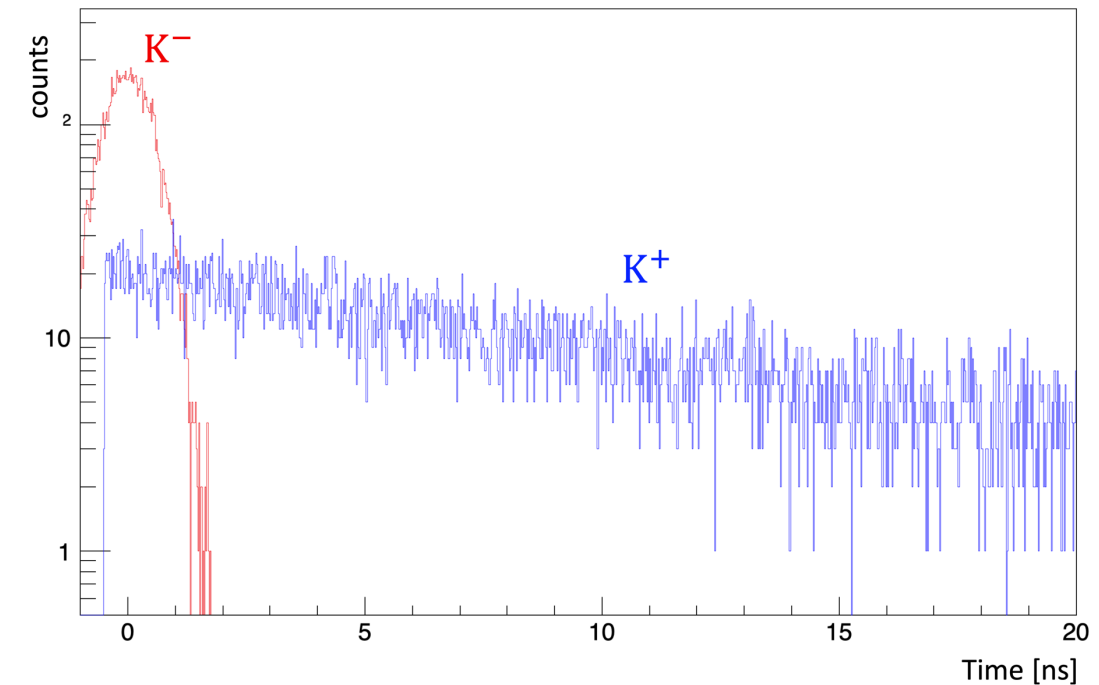


The SIDDHARTA-2 apparatus



Charged Kaons Veto

Stop both K^+ and K^- in a passive layer (Teflon 3 mm) and detect secondaries charged particles using a plastic scintillator



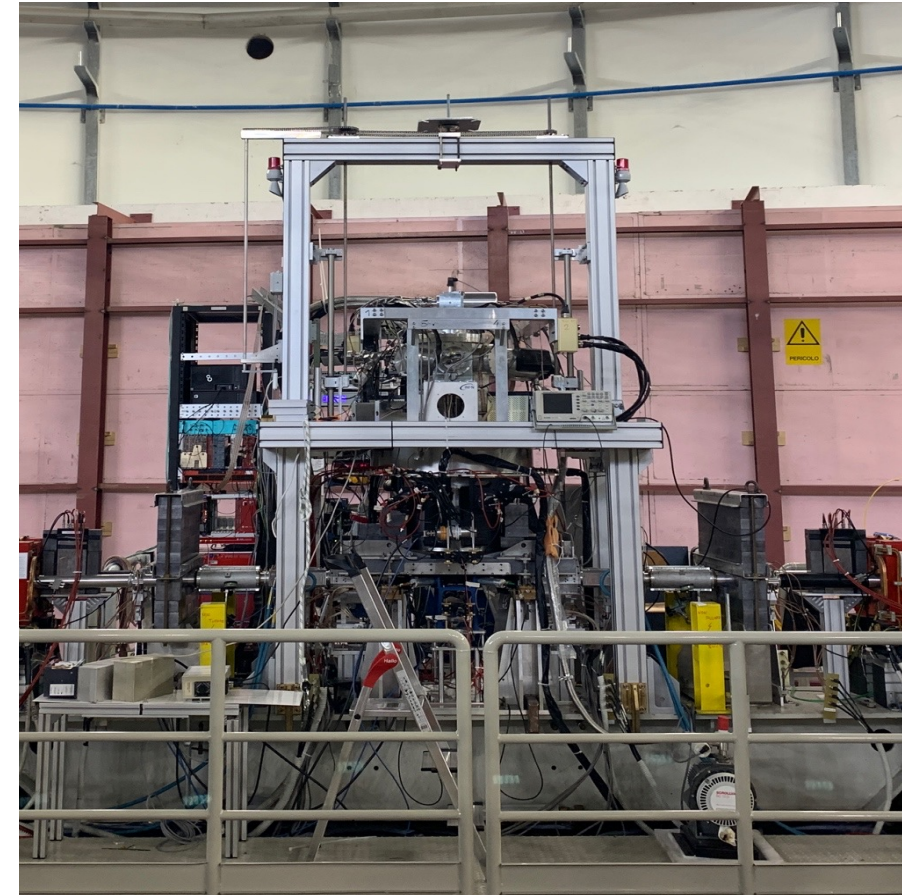
Kaonic Deuterium Data Taking Summary

- *Kaonic neon*: initial calibration and optimization of the setup
- *K-d Run-1: int. luminosity 196 pb⁻¹ (May – July 2023)*
- *Kaonic helium-4*: final calibration of the setup

- *Kaonic neon*: initial calibration of the setup
- *K-d Run-2: int. luminosity 338 pb⁻¹ (October – December 2023)*
- *Kaonic hydrogen*: final calibration of the setup

- *Kaonic hydrogen*: initial calibration of the setup
- *K-d Run-3: int. luminosity 425 pb⁻¹ (February – April 2024)*
- *Kaonic hydrogen*: final calibration of the setup

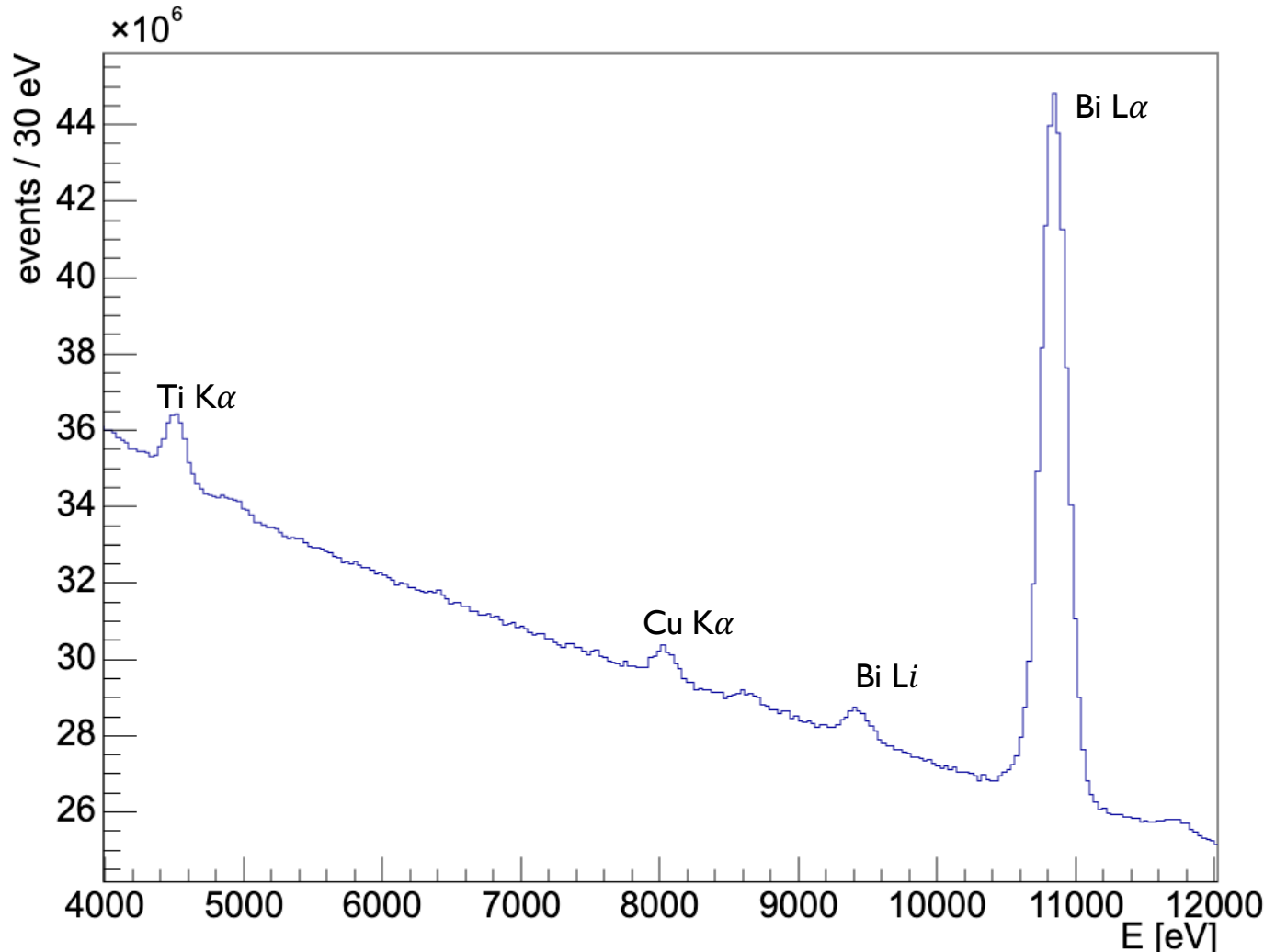
- *Low density run: int. luminosity 184 pb⁻¹ (May – July 2024)*
- *Post Kd calibration run (July 2024) – 20 pb⁻¹ with solid targets (B and F)*



K-d total integrated luminosity: 1143 pb⁻¹

Kaonic deuterium analysis

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



- Electromagnetic (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](#)

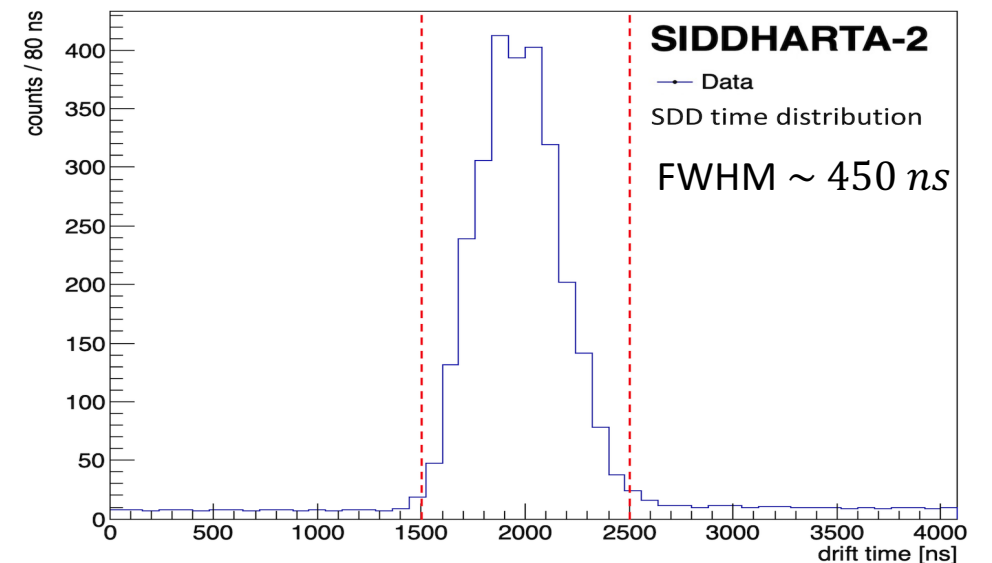
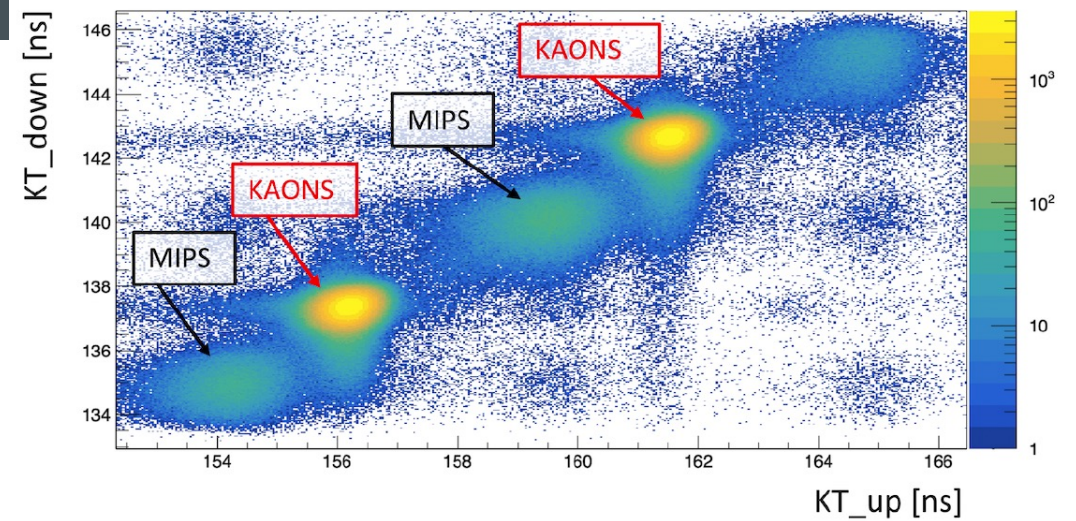
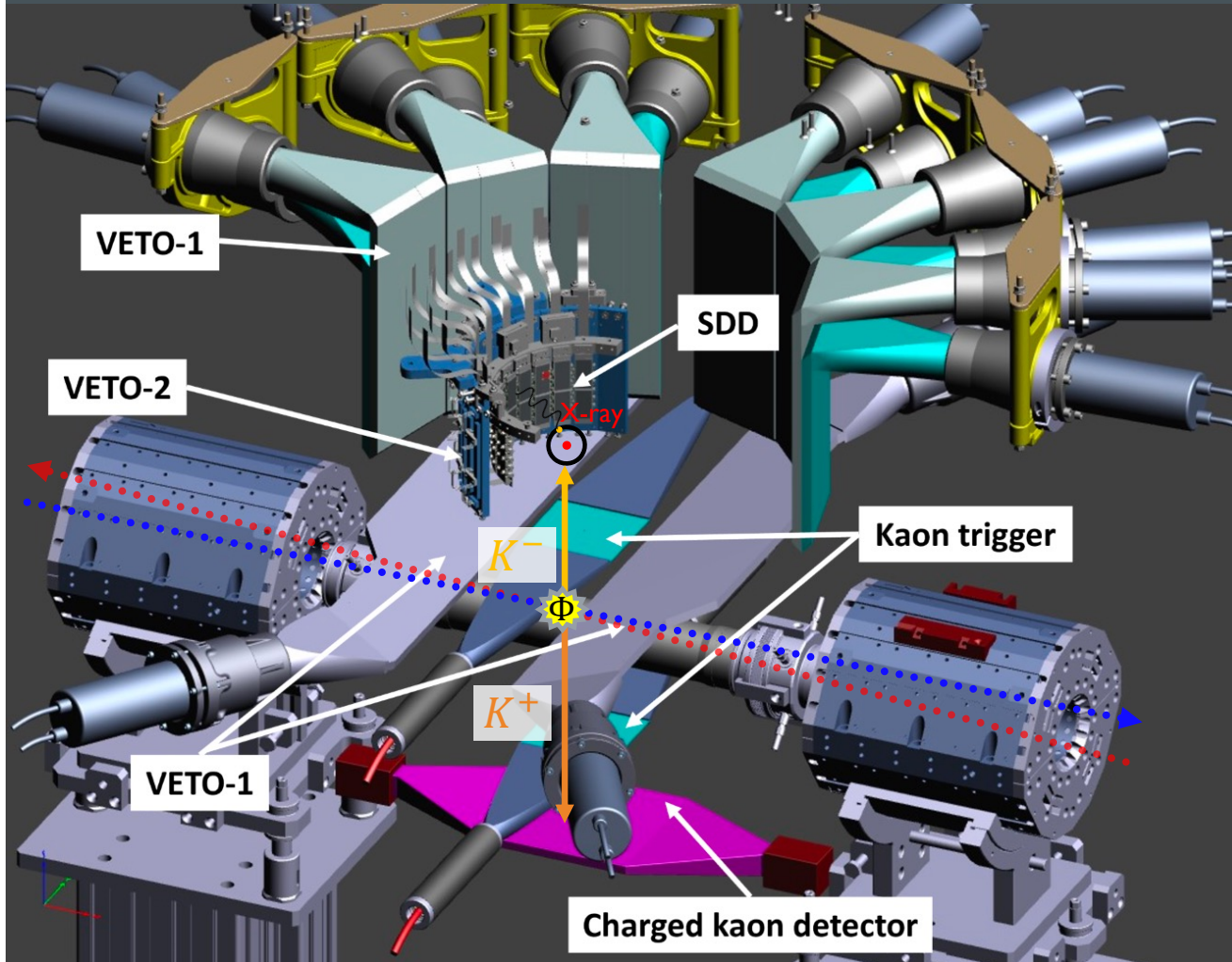
-Hadronic (synchronous) background:

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

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

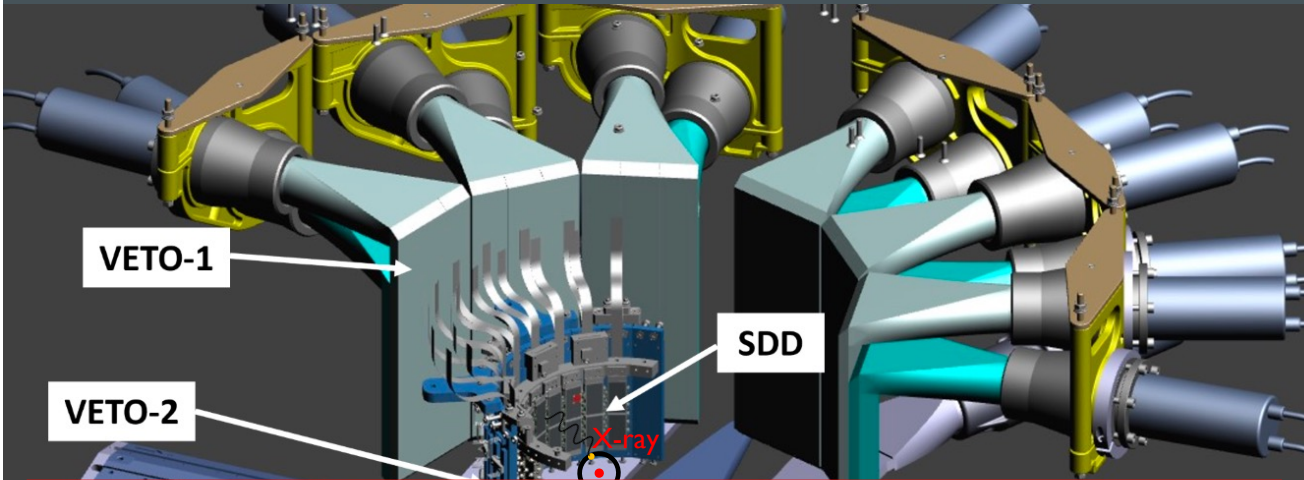
Kaonic deuterium analysis

The trigger is generated by the coincidence of 2 back-to-back scintillators. The ToF is different (~ 2 ns) for Kaons, $m(K) \sim 500$ MeV/c² and light particles originating from beam-beam and beam-environment interaction (MIPs). ToF analysis can efficiently discriminate the Kaons from MIPs!

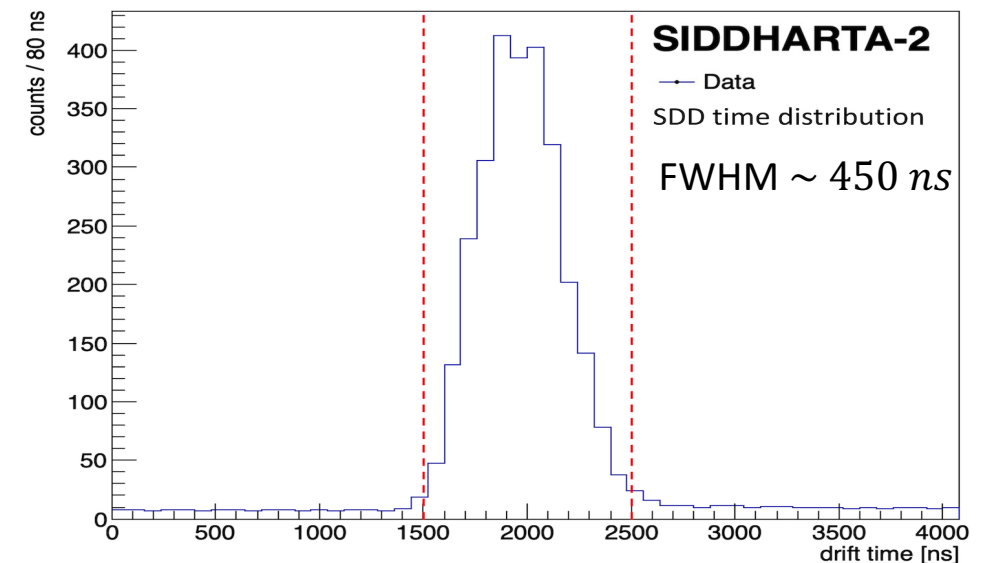
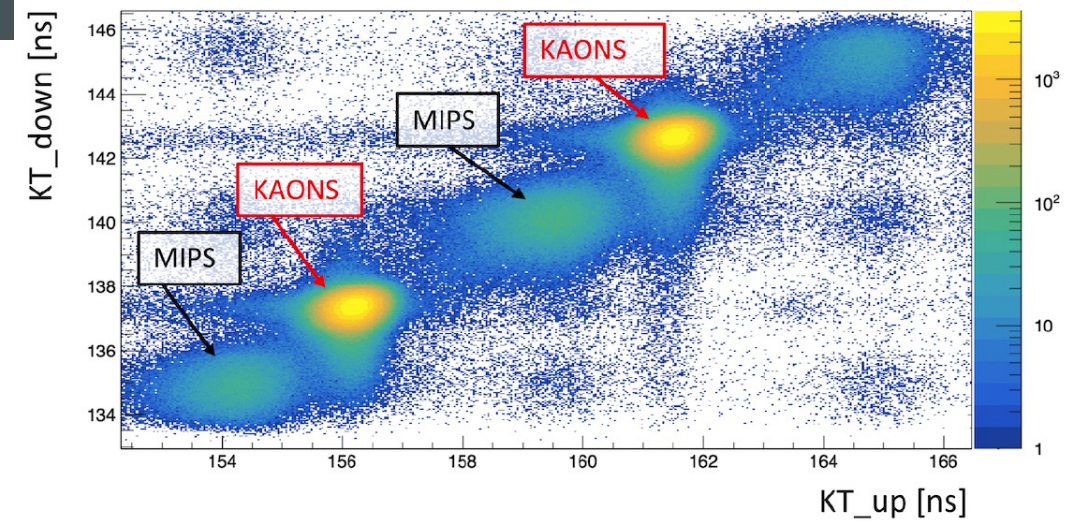
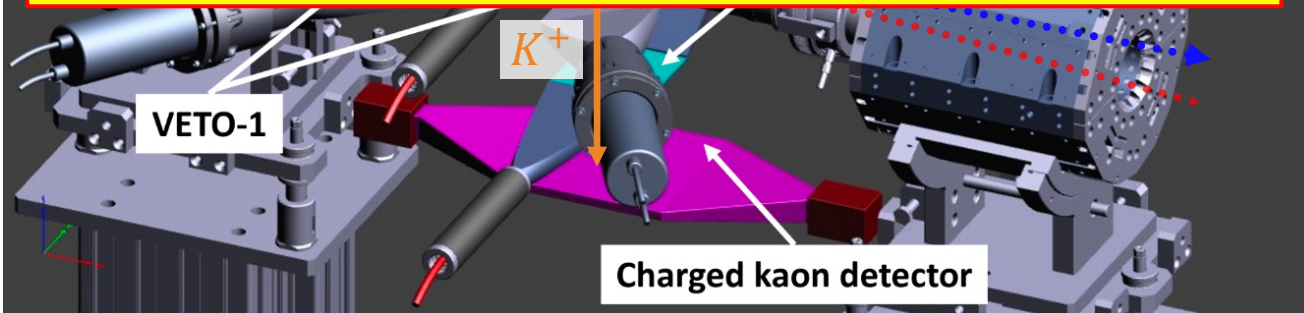


Kaonic deuterium analysis

The trigger is generated by the coincidence of 2 back-to-back scintillators. The ToF is different (~ 2 ns) for Kaons, $m(K) \sim 500$ MeV/c² and light particles originating from beam-beam and beam-environment interaction (MIPs). ToF analysis can efficiently discriminate the Kaons from MIPs!

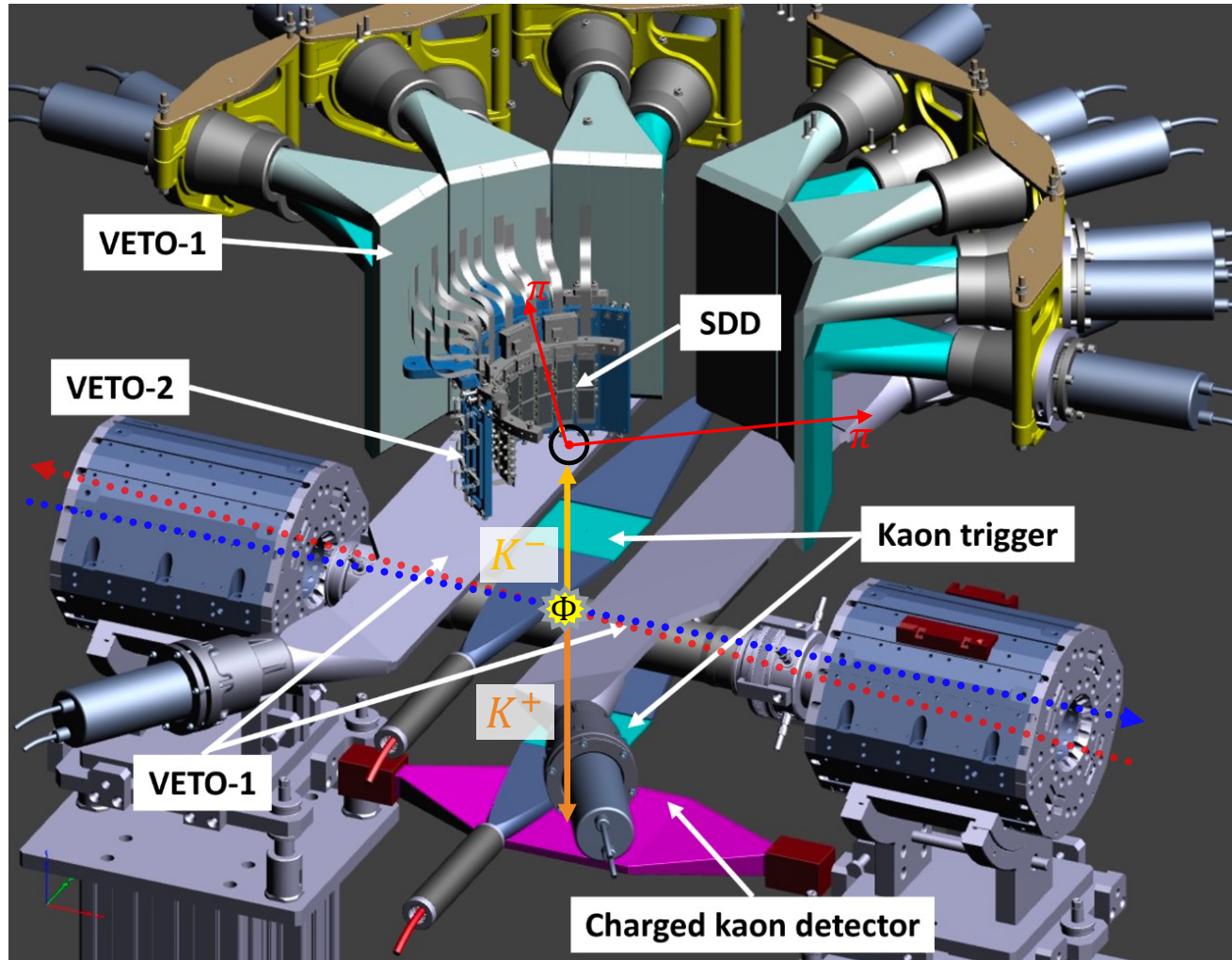


The combined use of Kaon Trigger and SDDs drift time reduces the background by a factor $\sim 10^4$



Kaonic deuterium analysis

The combined use of the veto systems further reduces the background by a factor of 3



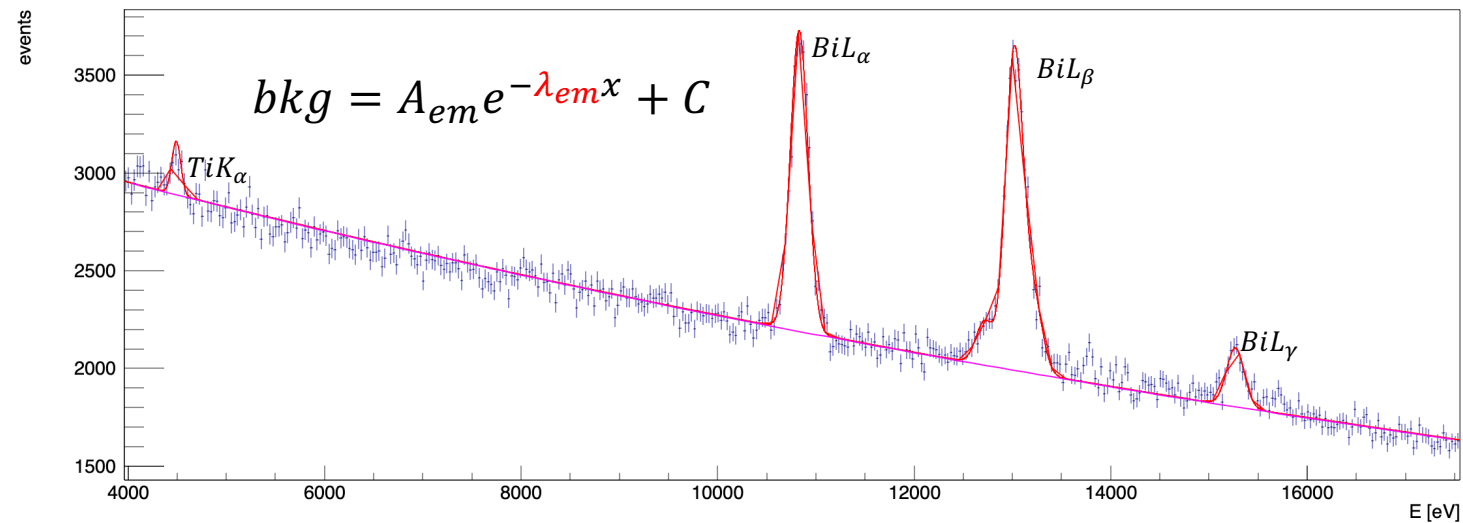
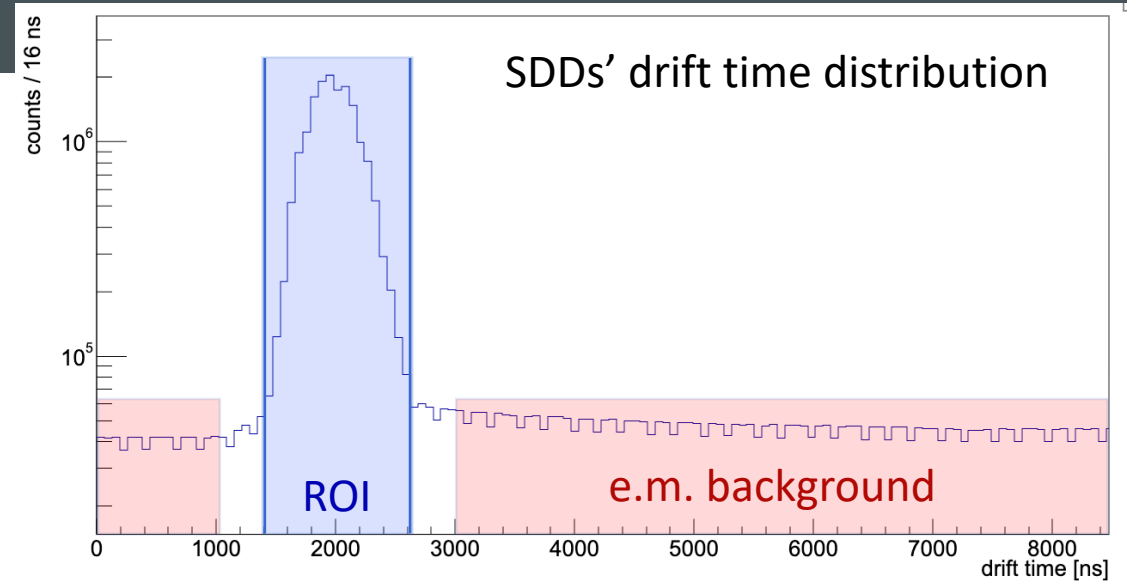
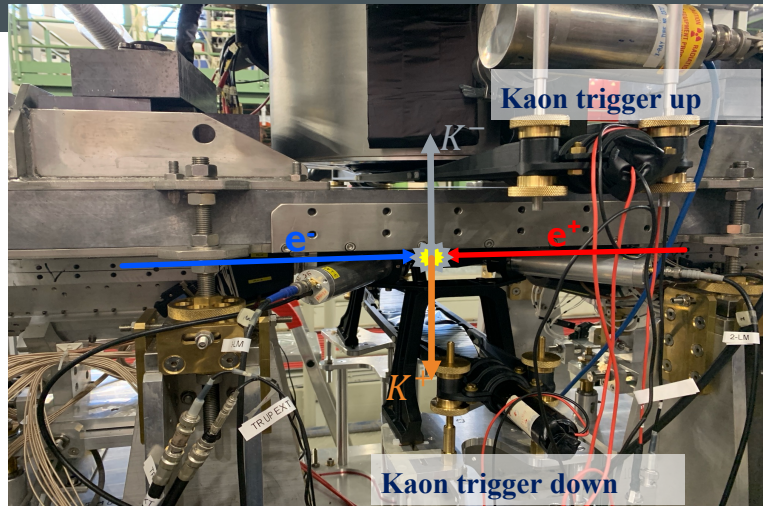
Veto-1 (fiducial volume selection): to select the events occurring in the gas target, rejecting the X-ray background corresponding to K- stopped in the solid elements of the setup.

Veto-2 (charged particle rejection): 48 plastic scintillator read by SiPMs to distinguish X-ray from charged particle by topological correlation with the SDD.

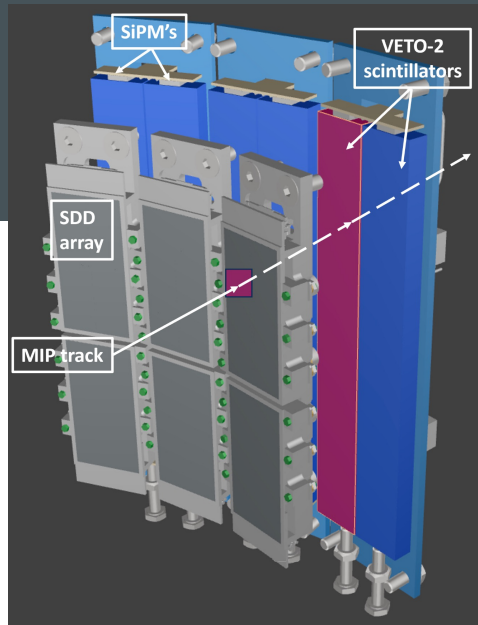
Charged kaon detector: distinguishes K^+ from K^- by exploiting their different interaction mechanisms with matter.

Electromagnetic background (asynchronous wrt kaons)

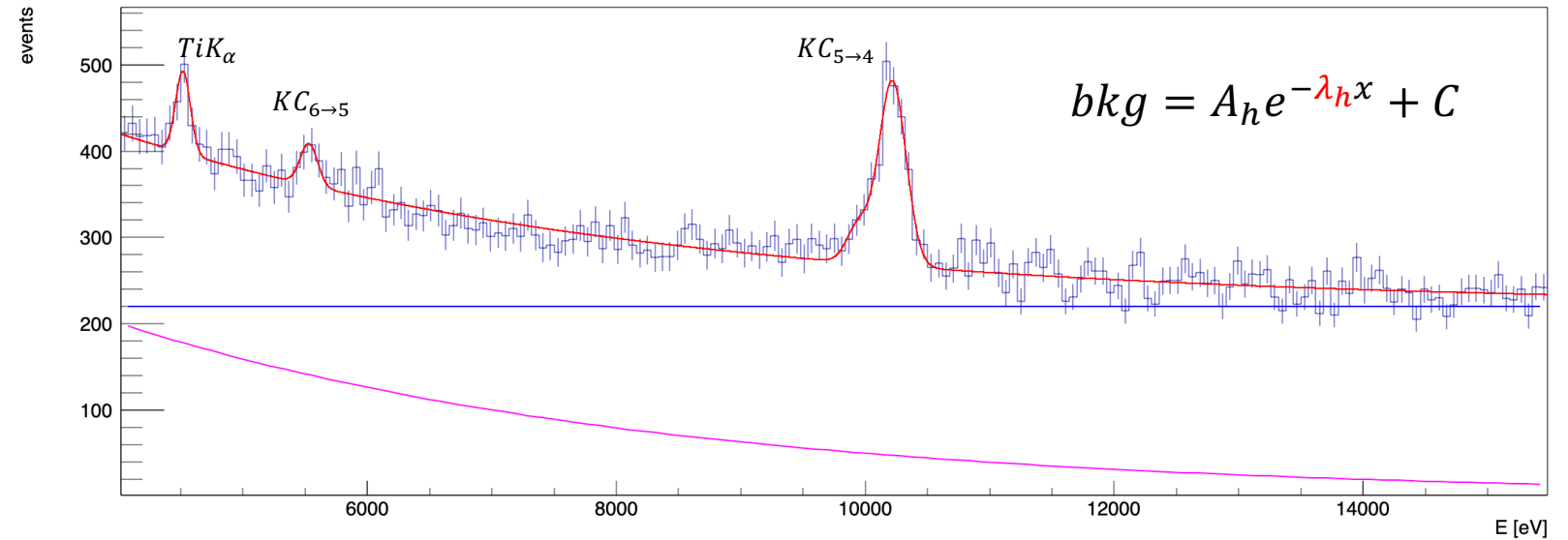
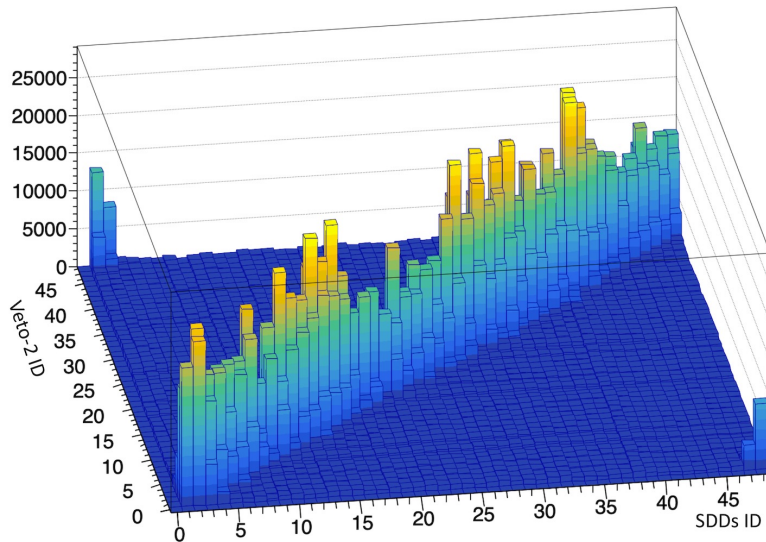
By exploiting the trigger and drift time of the SDDs, we can isolate a pure electromagnetic background spectrum by selecting events uncorrelated with kaon production.



Hadronic background (synchronous wrt kaons)



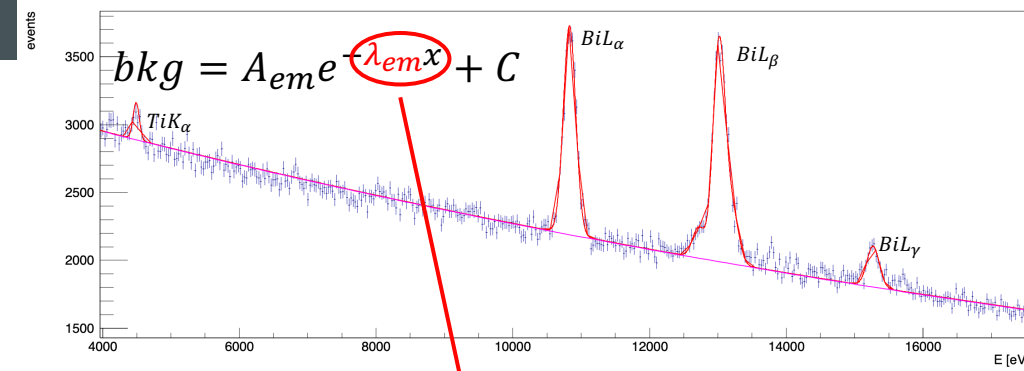
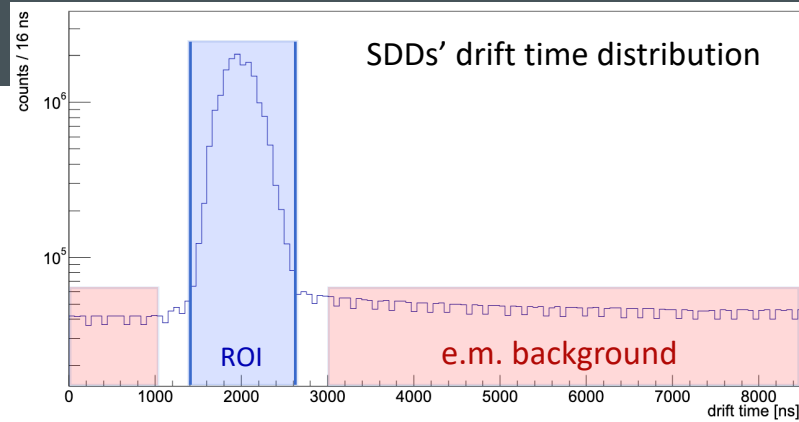
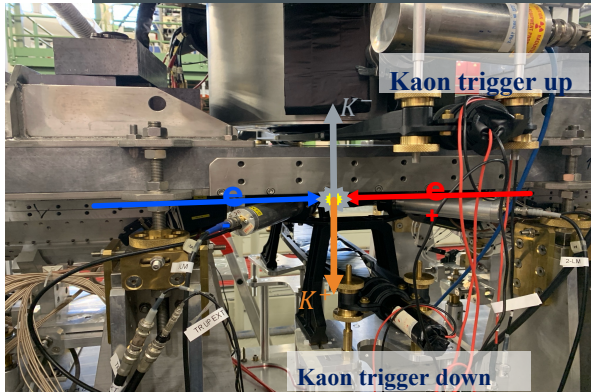
Hadronic background from MIPs (mainly pions) produced by kaon nuclear absorption can be isolated using the spatial correlation between Veto-2 and the SDDs, yielding a pure hadronic background spectrum.



Plot of the topological correlation between Veto2's scintillators and SDDs

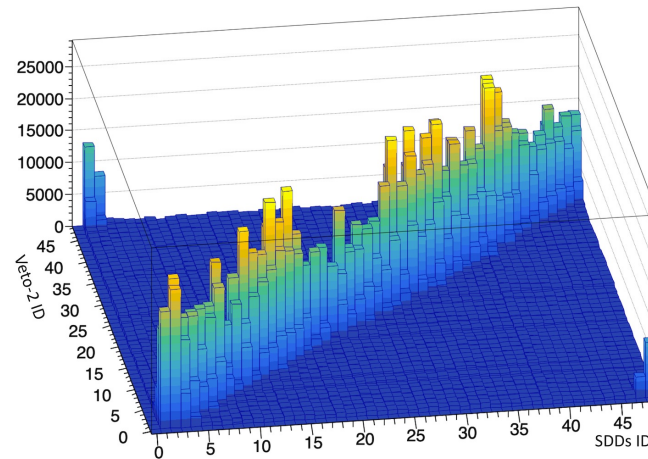
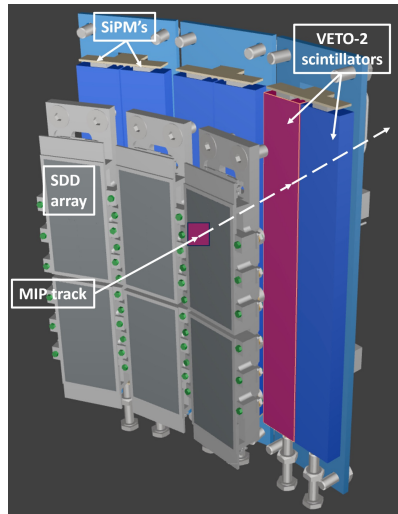
Study of background events (outside the signal window)

Electromagnetic (asynchronous) background

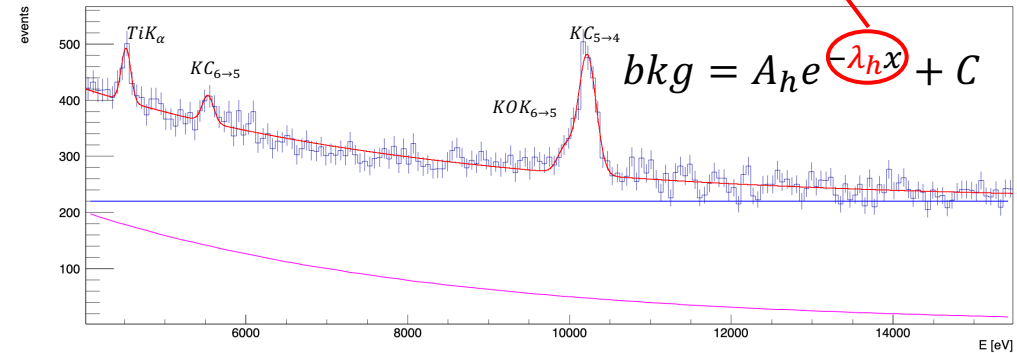


Input values for background description

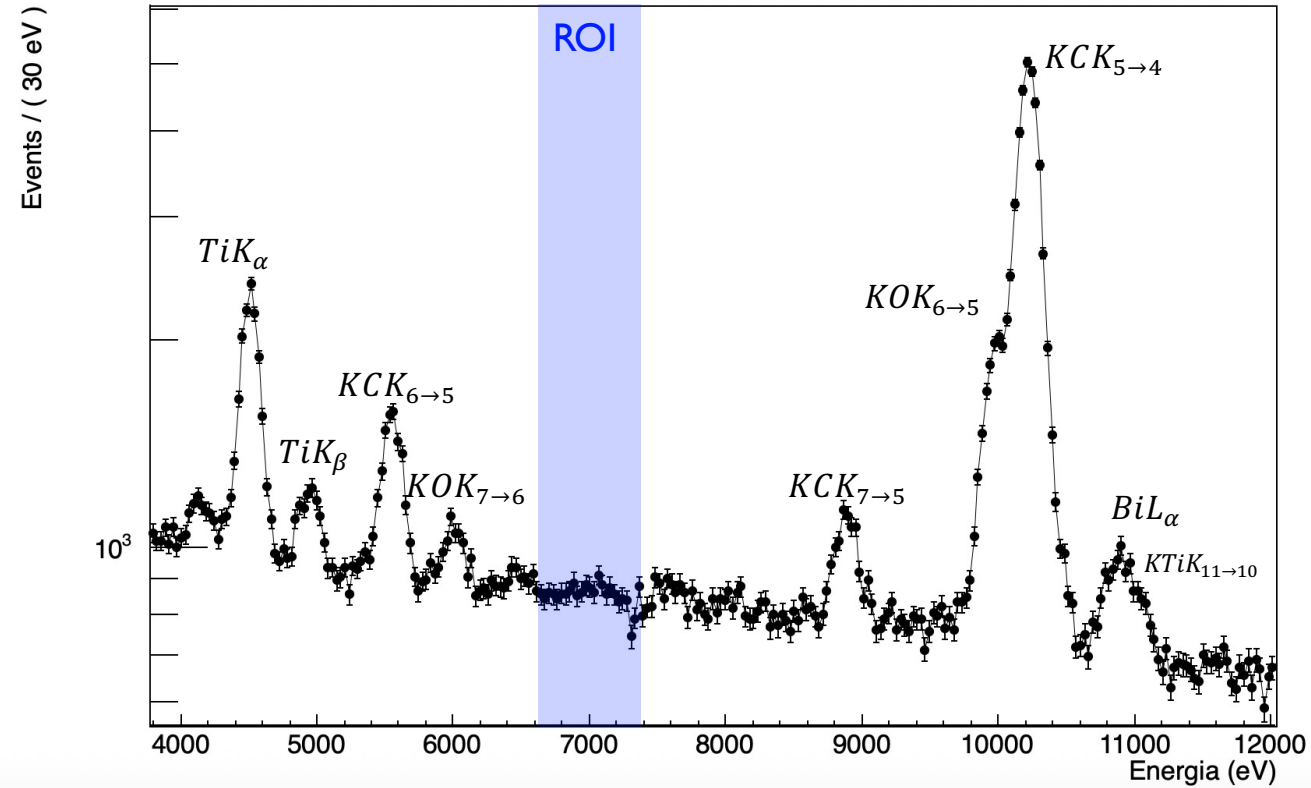
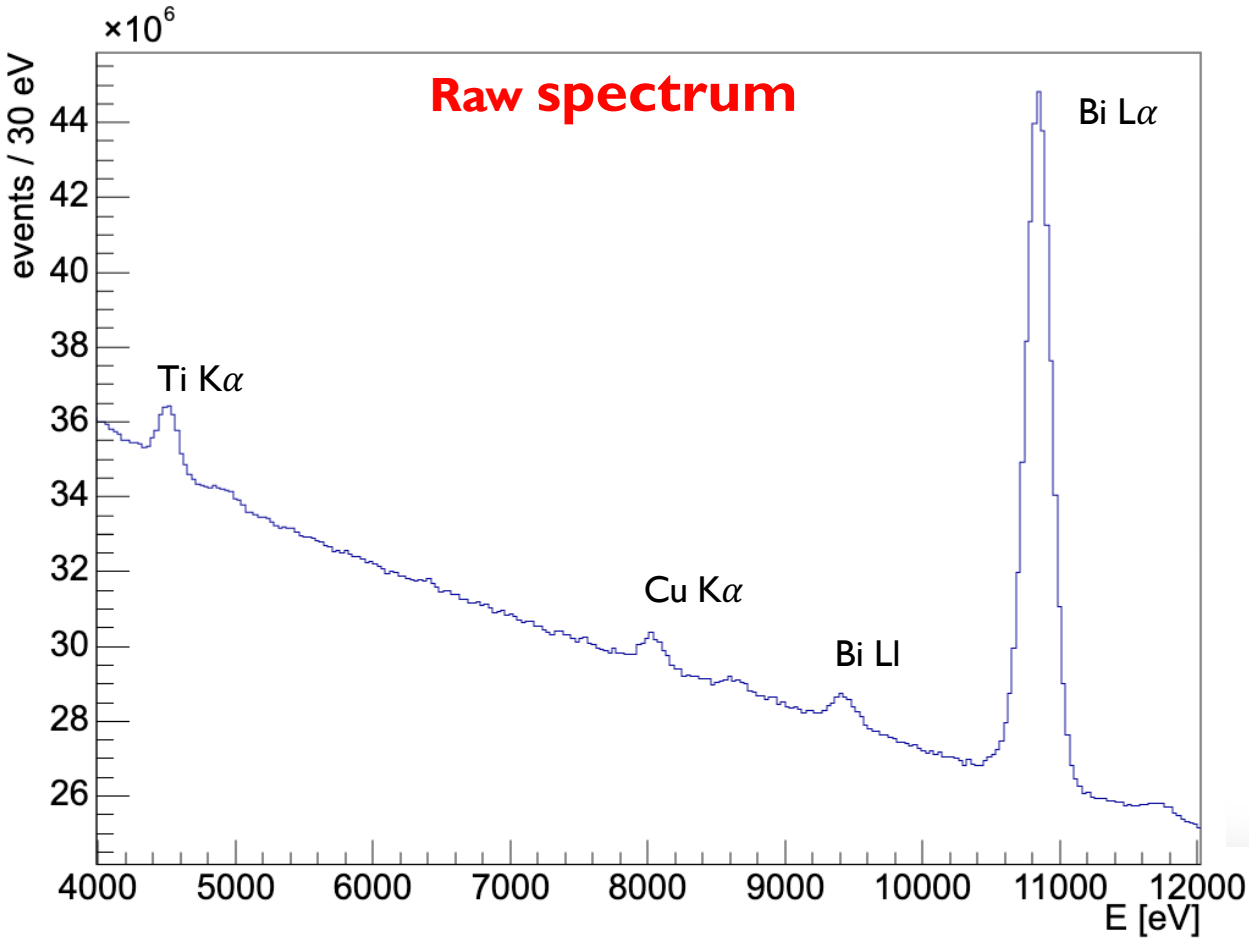
Hadronic (synchronous) background



Plot of the topological correlation between Veto2's scintillators and SDDs



Kaonic Deuterium Energy Spectrum

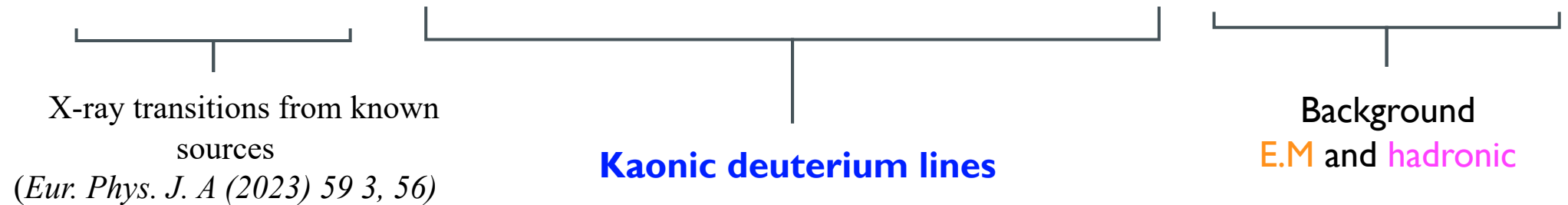


Background reduced by a factor 3×10^4

Kaonic Deuterium Energy Spectrum – Fit procedure

- We perform an extended maximum-likelihood fit to the binned spectrum, including systematic uncertainties as nuisance parameters
- The full model is implemented in ROOT/RooFit

$$f(E; \theta) = \sum_{n=0}^{18} y_n G_n(E; \mu, \sigma) + y_{2p \rightarrow 1s} V_{2p \rightarrow 1s}(E; \mu, \sigma, \Gamma) + \sum_{n=3}^7 y_{n \rightarrow 1s} V_{n \rightarrow 1s}(E; \mu, \sigma, \Gamma^*) + y_{em} e^{\lambda_{em} E} + y_{had} e^{\lambda_{had} E} + C$$



$$-2 \ln \mathcal{L}_{tot} = -2 \ln \mathcal{L}_{ext} - 2 \ln \mathcal{L}_{nuisance}$$

$$-2 \ln \mathcal{L}_{nuisance} = \frac{(\delta \mu_{cal})^2}{\sigma_{cal}^2} + \frac{(\delta \mu_{stab})^2}{\sigma_{stab}^2} + \frac{(FF - FF_0)^2}{\sigma_{FF}^2} + \frac{(noise - noise_0)^2}{\sigma_{noise}^2} + \frac{(\lambda_{em} - \lambda_{em}^0)^2}{\sigma_{\lambda_{em}}^2} + \frac{(\lambda_{had} - \lambda_{had}^0)^2}{\sigma_{\lambda_{had}}^2}$$

Systematic uncertainty on SDDs
energy calibration and stability

Systematic uncertainty on SDDs
energy resolution

Systematic uncertainty on
e.m. and hadronic background

(Phys. Scripta 97 (2022) 11, 114002; Measur.Sci.Tech. 32 (2021) 9, 095501; Measur.Sci.Tech. 33 (2022) 9, 095502)

Beyond SIDDHARTA-2

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 measurements are the basis for all the theoretical model used for: KN, KNN interaction at threshold, Kaon mass, Kaonic atoms cascade models

Present status:

1. The available data on “lower levels” have big uncertainties
2. Many of them are hardly compatible among each other
3. Many atoms are actually Unmeasured
4. Absolute yields are basically unknown (except for few transitions)

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

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

charting the periodic table

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]
Cl	4 → 3	-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5	[19]
		-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7	[18]
Co	5 → 4	-0.94 ± 0.40	3.92 ± 0.99	-	-	[22]
		-1.08 ± 0.22	2.79 ± 0.25	-	-	[21]
Ni	5 → 4	-0.099 ± 0.106	0.64 ± 0.25	-	-	[19]
		-0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3	[20]
Cu	5 → 4	-0.246 ± 0.052	1.23 ± 0.14	-	-	[19]
		-0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8	[20]
Ag	6 → 5	-0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1	[19]
		-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

A new era of kaonic atoms measurements along the periodic table requires suitable detectors to match the different transitions energies

Journal of Instrumentation, 19 (2024) P07039

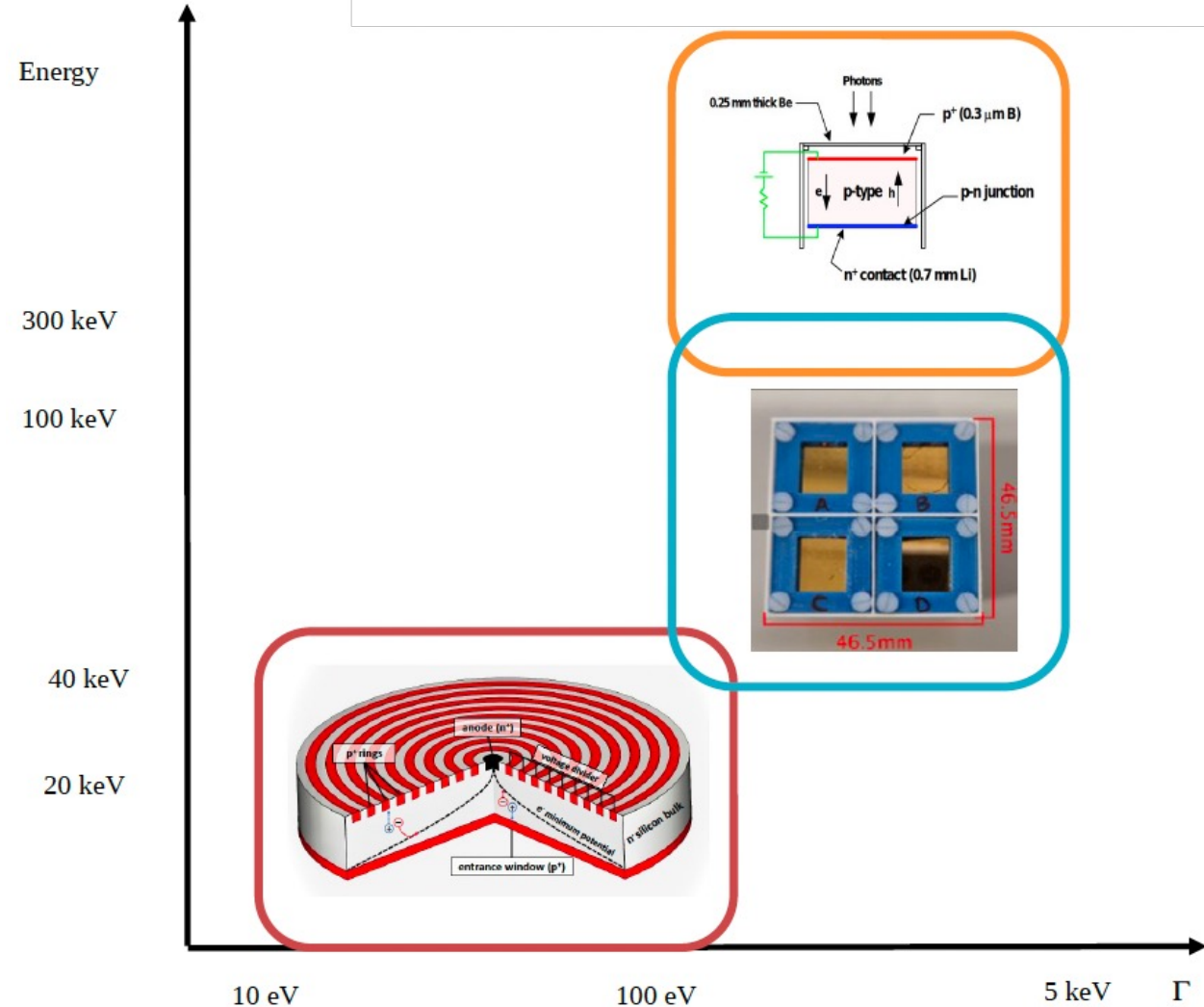
- SDDs**
- 100 eV max resolution
 - 4-40 keV range
 - High efficiency

Nuclear Instruments and Methods in Physics Research A 1060 (2024) 169060

- Cd(Zn)Te**
- 20-300 keV range
 - FWHM / E ~ %
 - High efficiency
 - Room Temperature

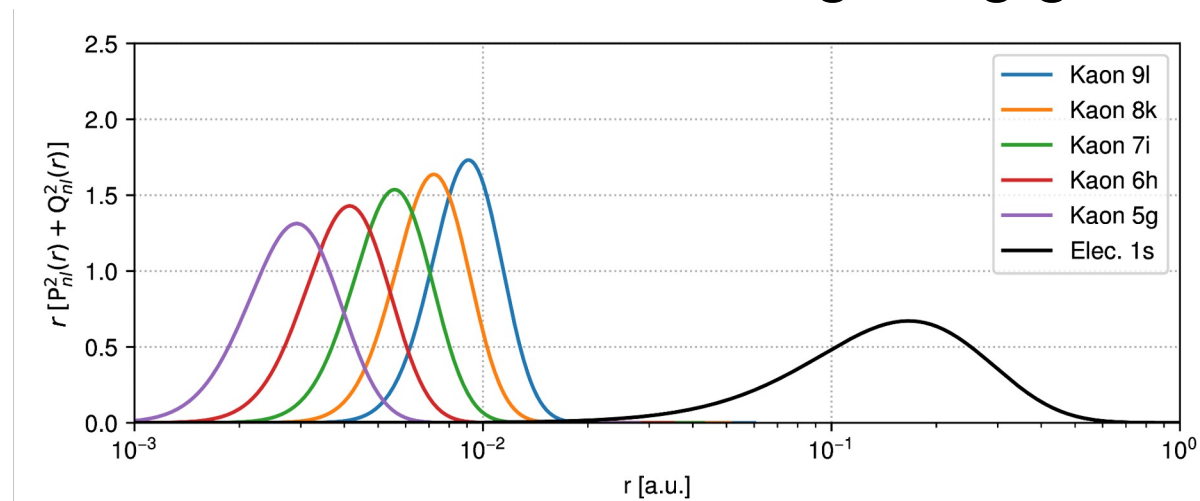
Nuclear Instruments and Methods in Physics Research A 1069 (2024) 169966

- HPGe**
- 100-1000 keV range
 - FWHM / E ~ %
 - High efficiency
 - Cooling needed



Kaonic Atoms for Bound-State QED Studies? Yes!

- Evaluation of **Electronic Screening** effects and **Uncertainty on the Kaon Mass (~ 13 keV)** on the observed lines in comparison to the size of QED contributions
- **Both Effects are Small (< 0.5 eV)** relative to the QED contributions and, moreover, electronic screening is negligible for the considered transitions.



Kaon WFs are well inside the 1s electron orbit -> Neon Fully Ionized!

