EXPLORING THE STRANGENESS FRONTIERS: KAONIC ATOMS X-RAY SPECTROSCOPY AT DAFNE WITH SIDDHARTA-2

HYP2025
TOKYO

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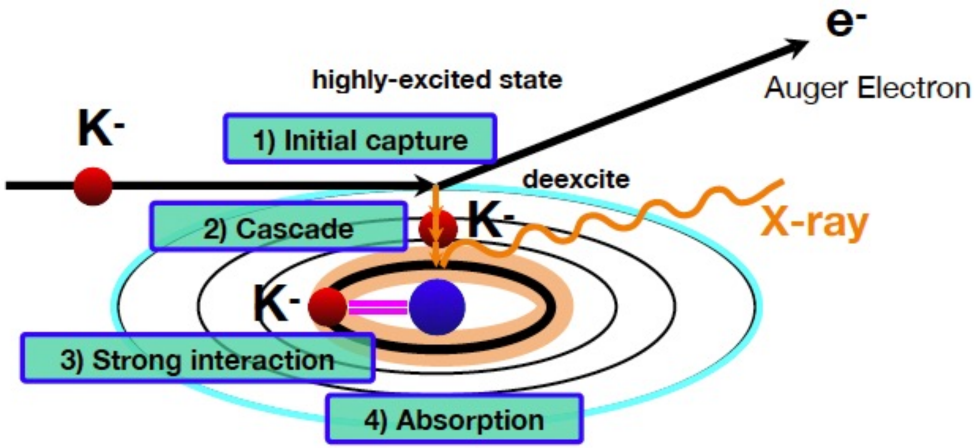
on behalf of the SIDDHARTA-2 collaboration

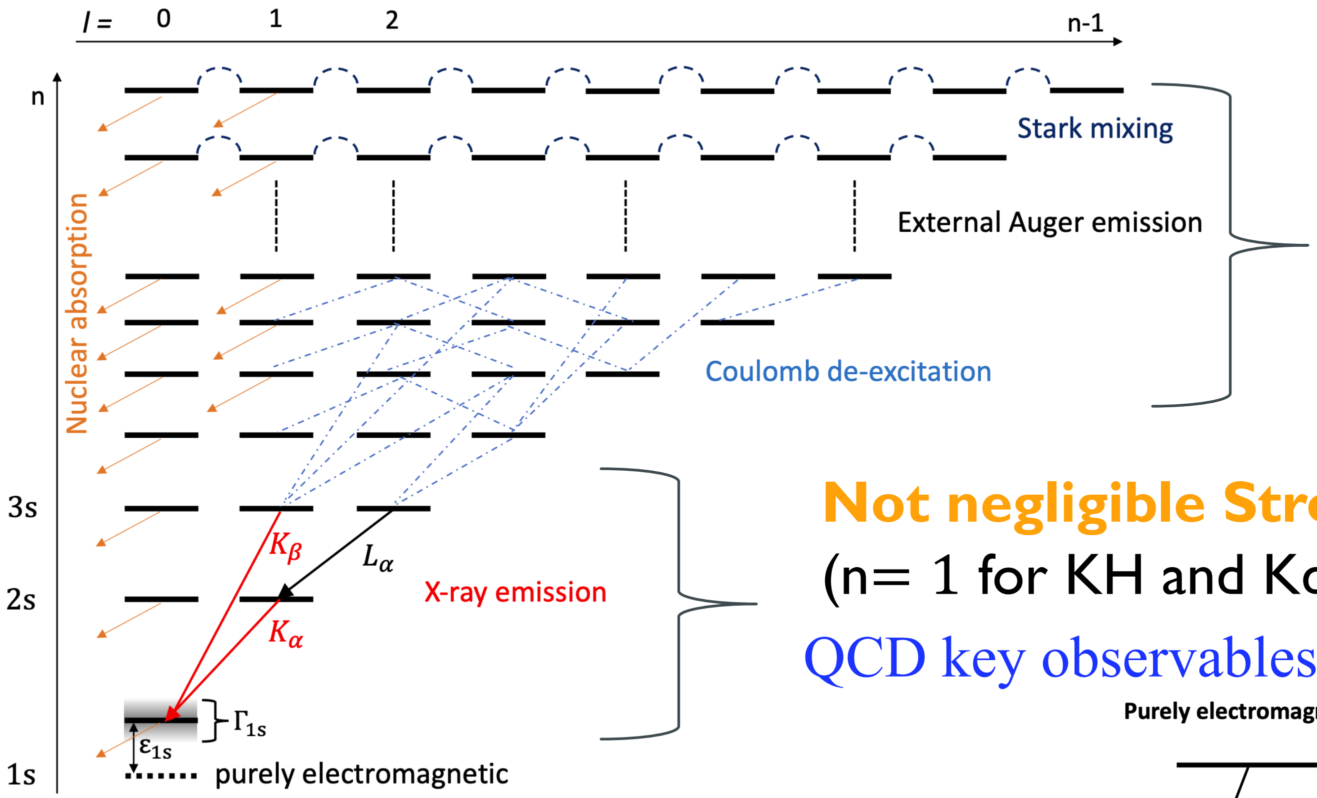
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

Kaonic Atoms X-ray Spectroscopy

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





Pure QED transition (n>4)

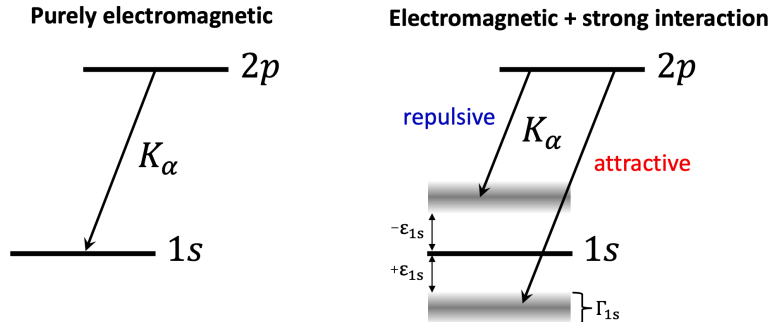
QED key observables: **Energy** and **X-ray Yield**

High precision test of BSQED

Not negligible Strong interaction effect

(n= 1 for KH and Kd)

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



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

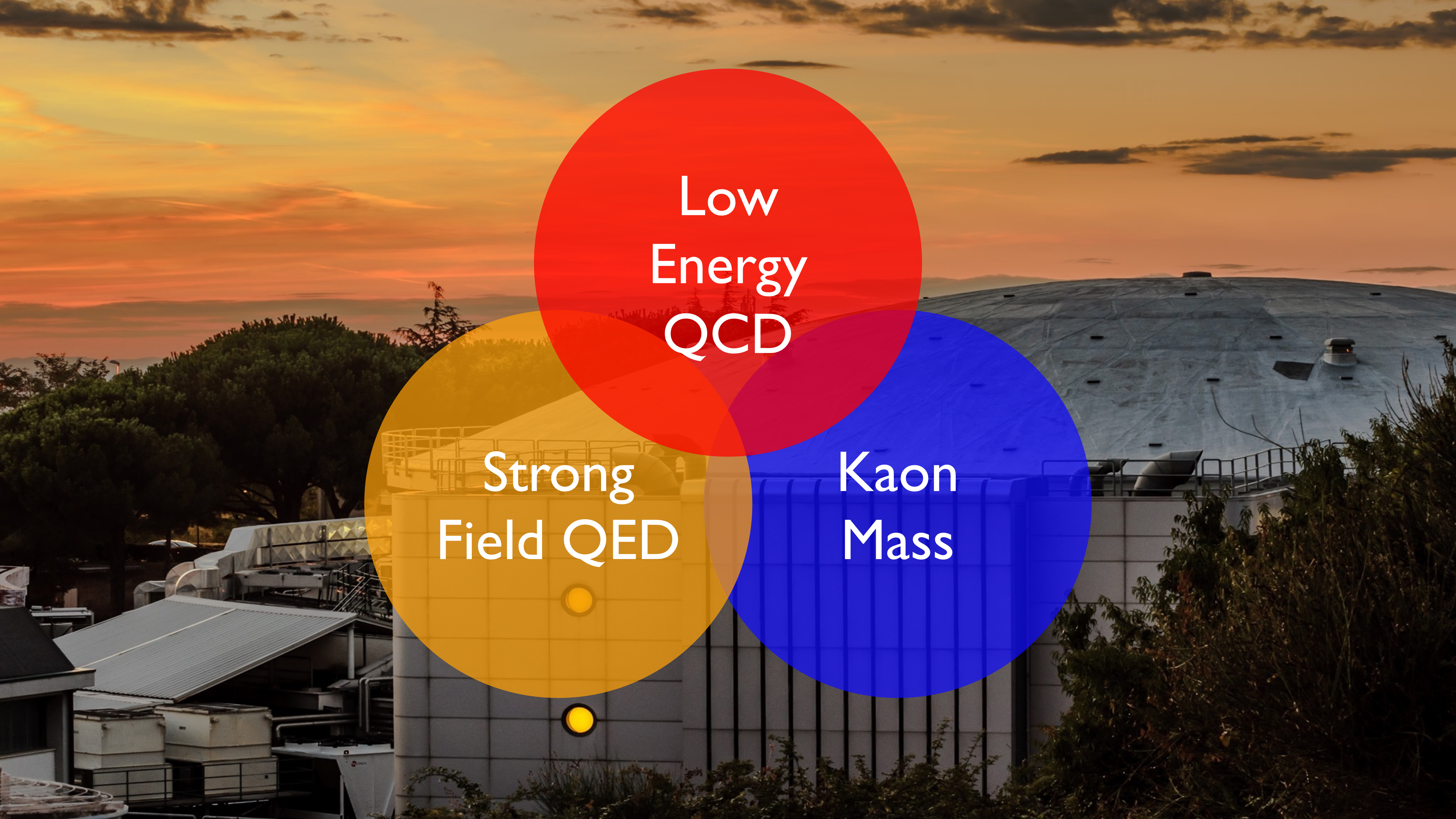
Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

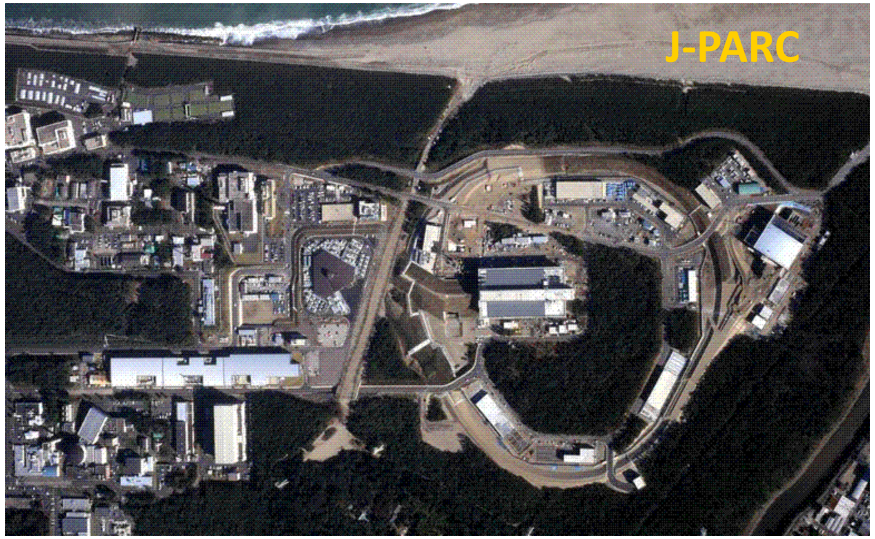
Dark Matter and BSM

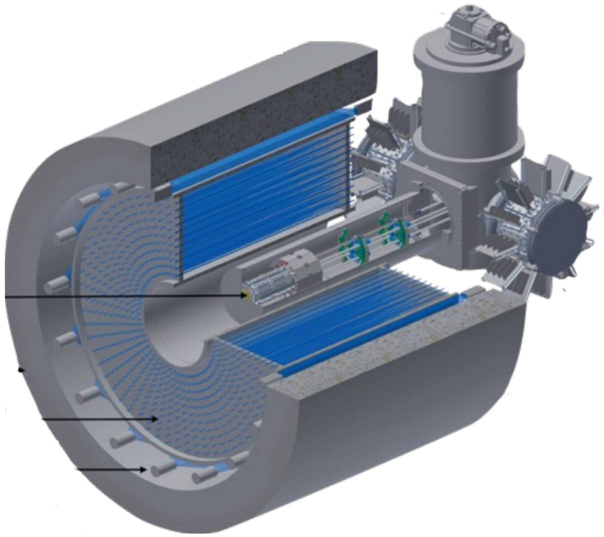
Probing new hadronic forces with heavy exotic atoms (2025) arXiv:2502.03537v1
On self-gravitating strange dark matter halos around galaxies Phys.Rev.D 102 (2020) 8, 083015

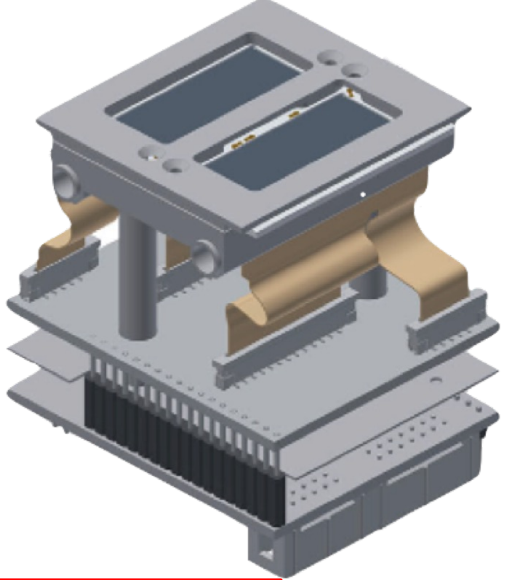
The equation of state of dense matter: Stiff, soft, or both? Astron.Nachr. 340 (2019) 1-3, 189

Astrophysics
EOS Neutron Stars


Low Energy QCD
Strong Field QED
Kaon Mass







The modern era of light kaonic atom experiments

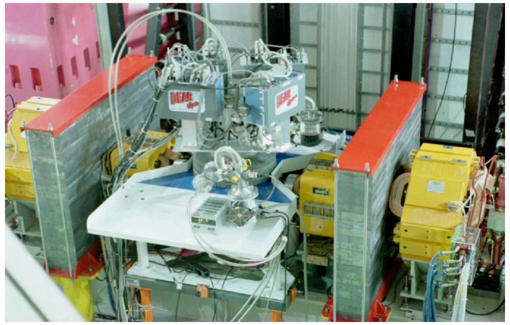
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

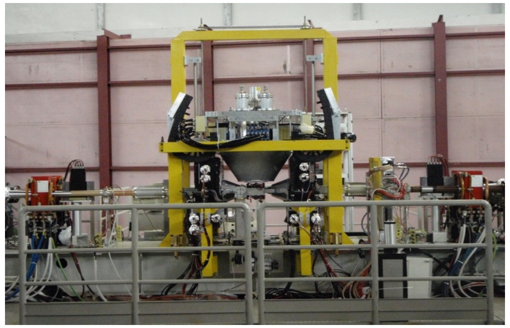
Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

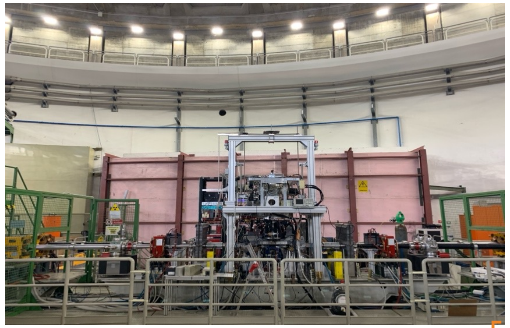
DEAR
2002

SIDDHARTA
2009

SIDDHARTA-2
2022

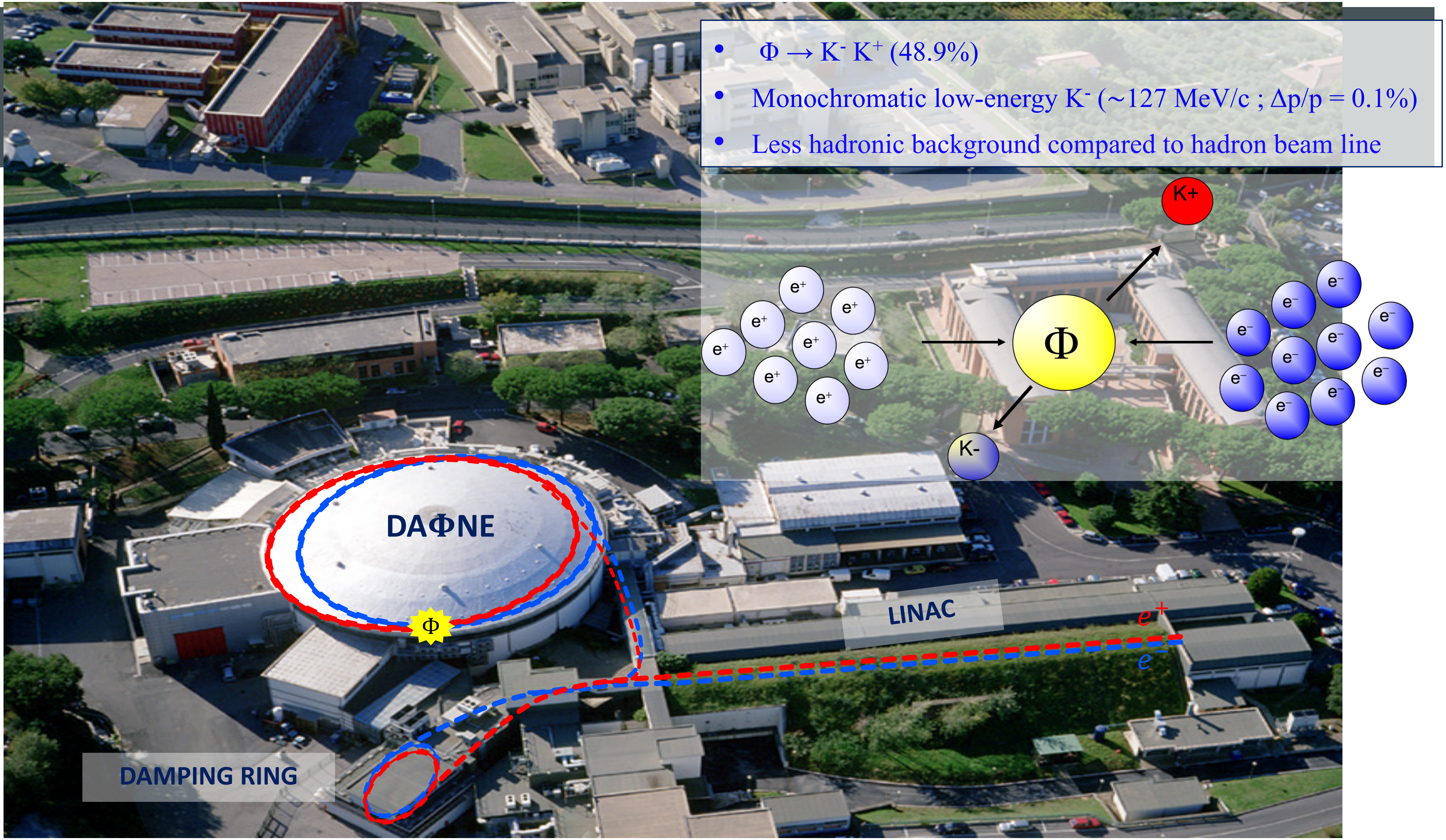






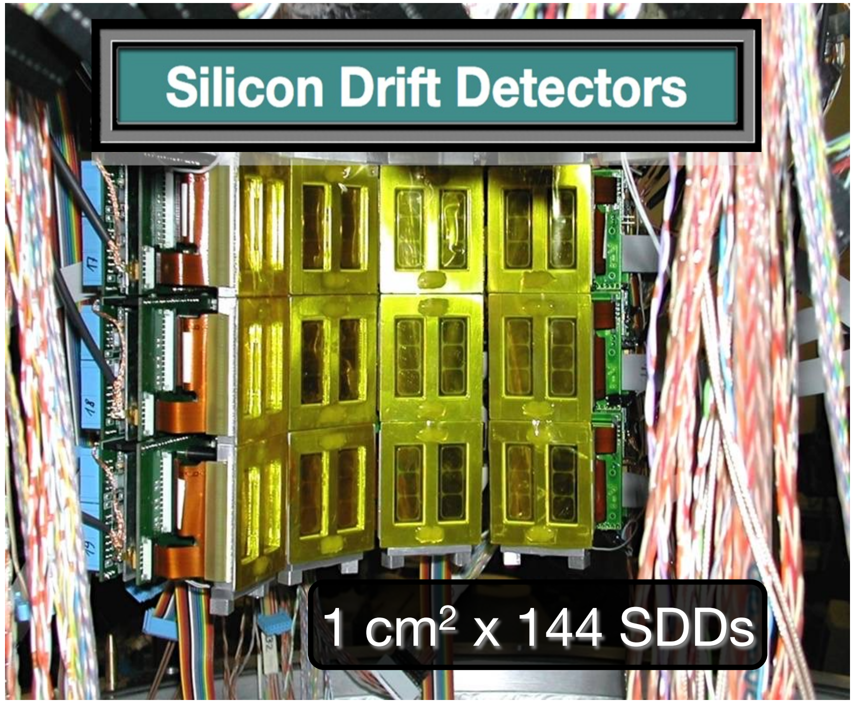
The DAΦNE collider of INFN-LNF

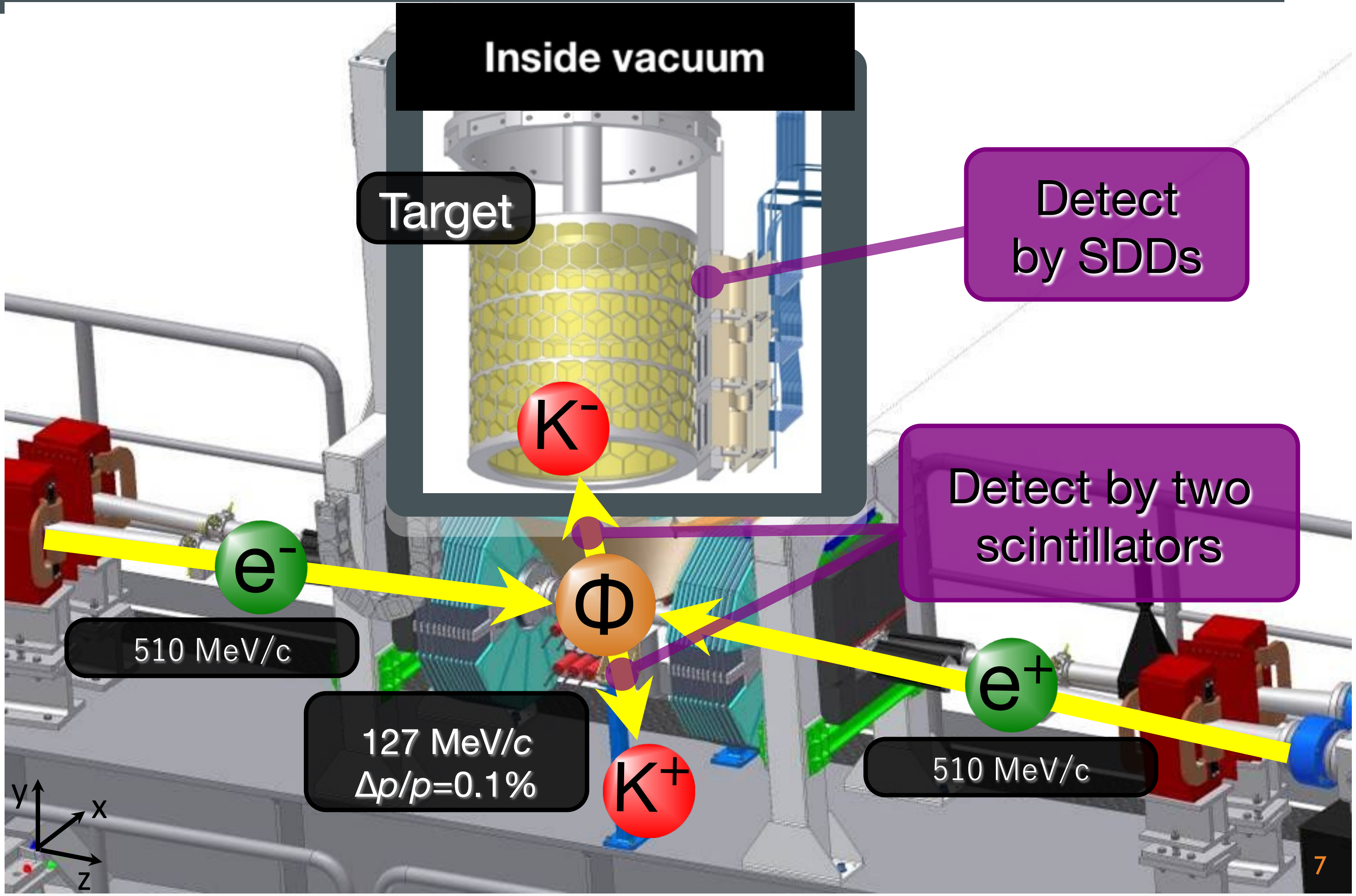
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p = 0.1\%$)
- Less hadronic background compared to hadron beam line



The SIDDHARTA Experiment (2009)

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



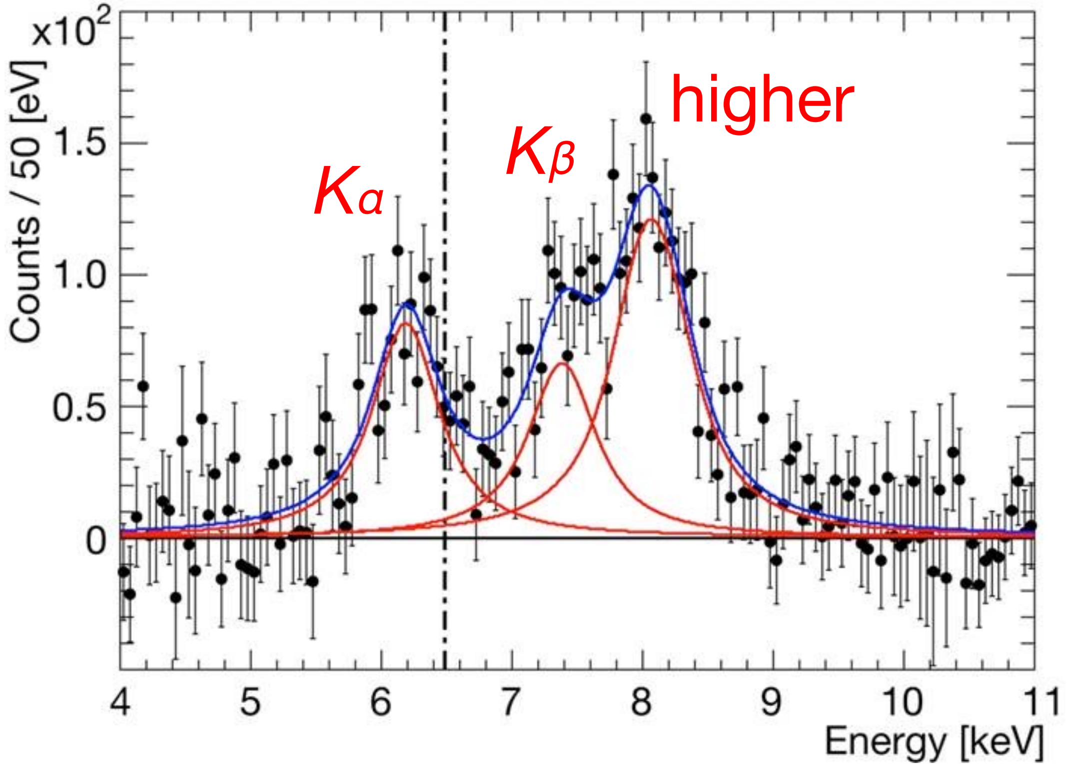


The SIDDHARTA Experiment (2009)

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

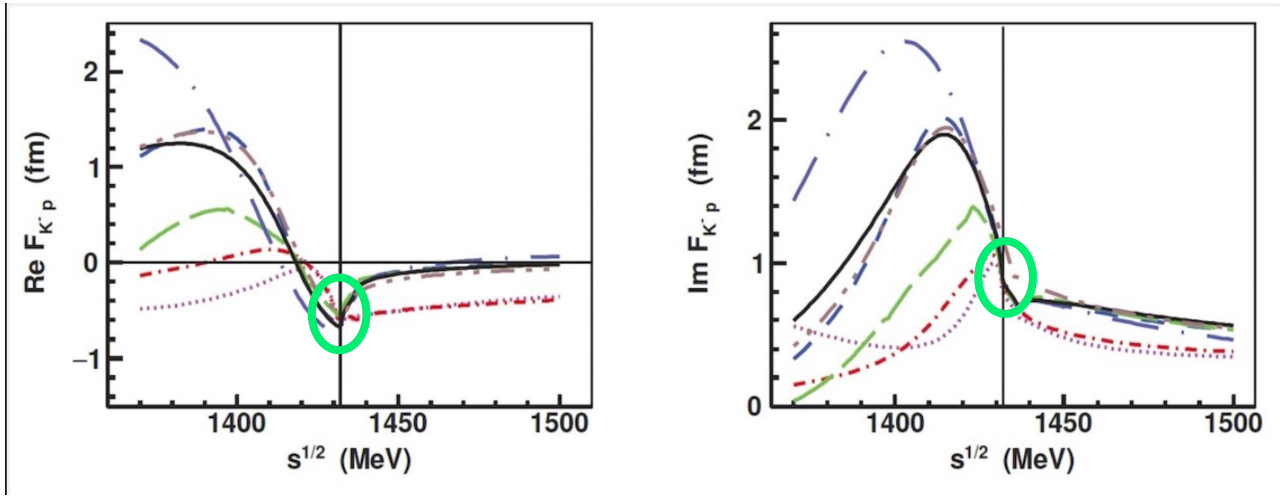
$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})$ eV

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

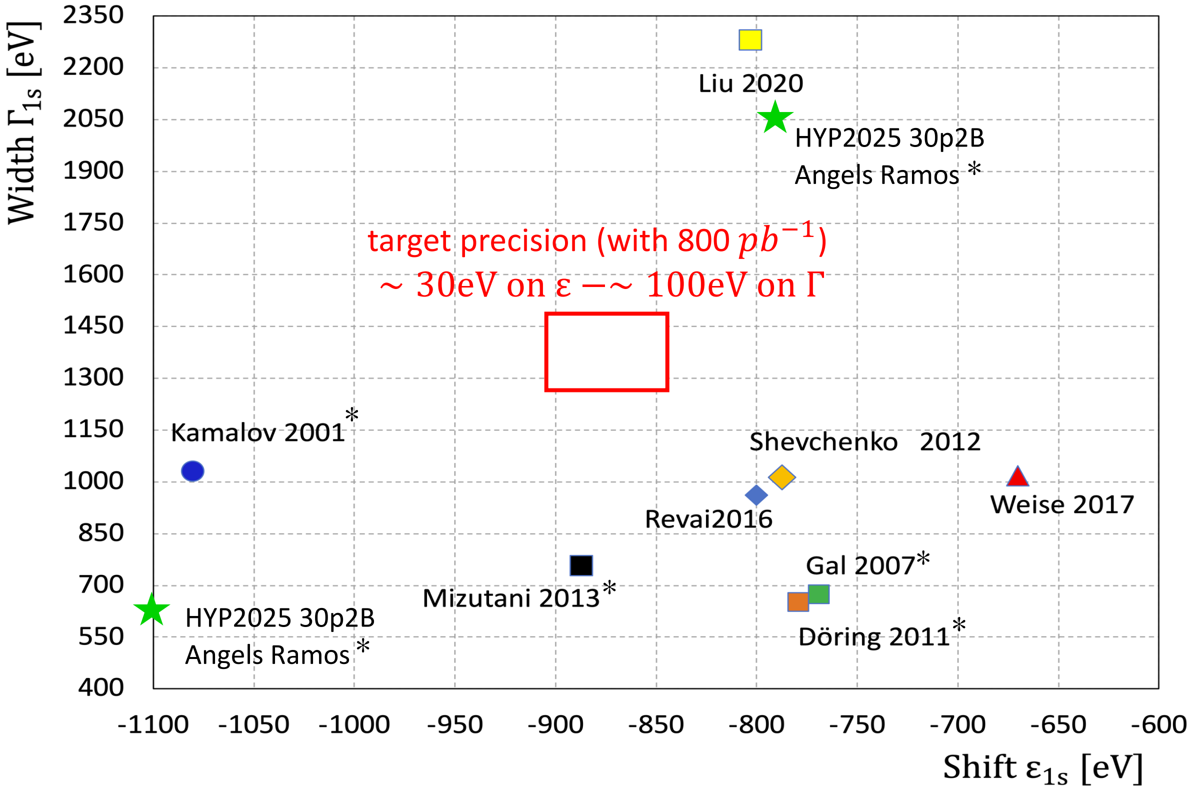


Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

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.

Kd theoretical prediction



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

"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 $\overline{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)

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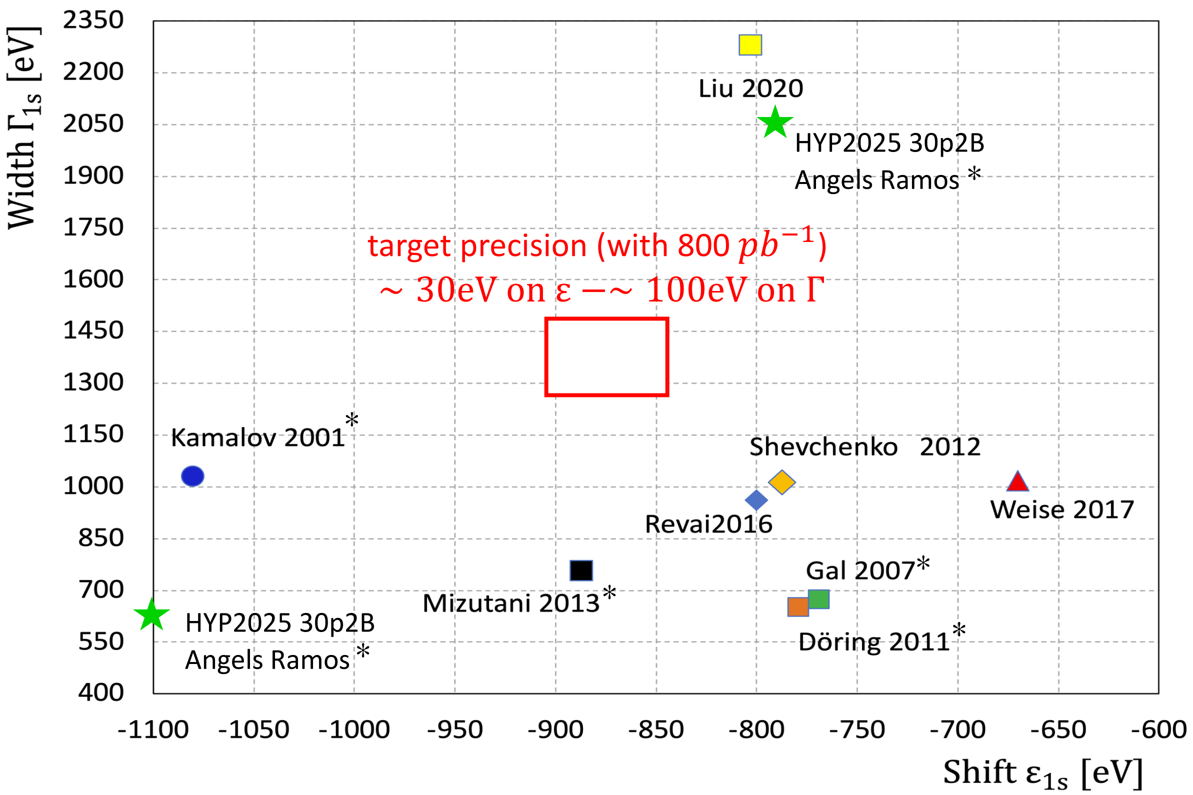

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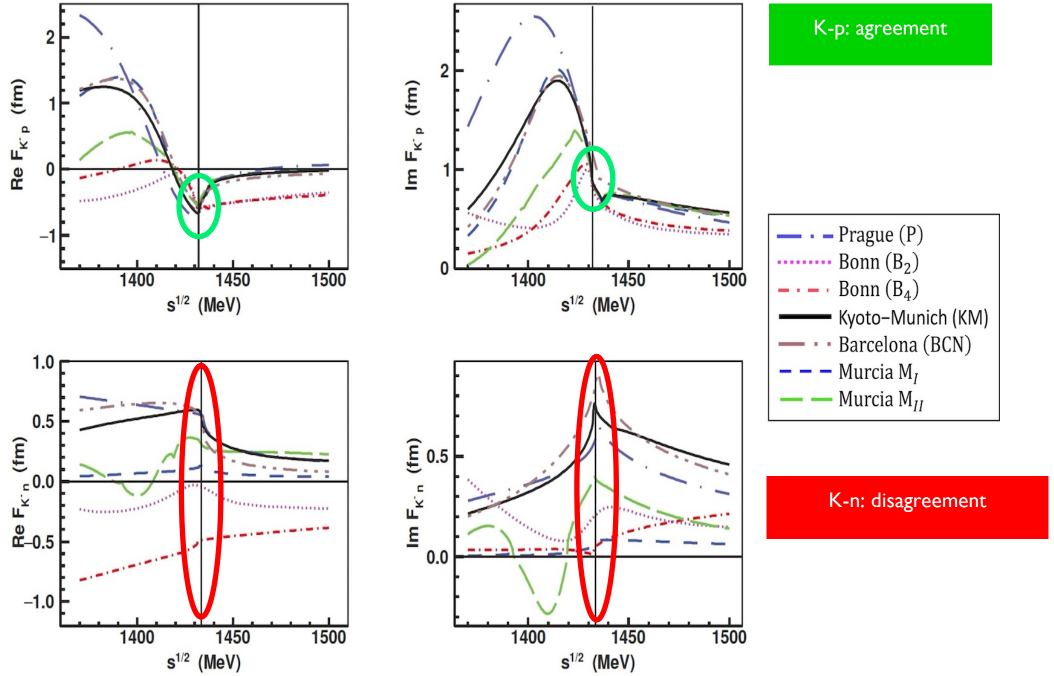
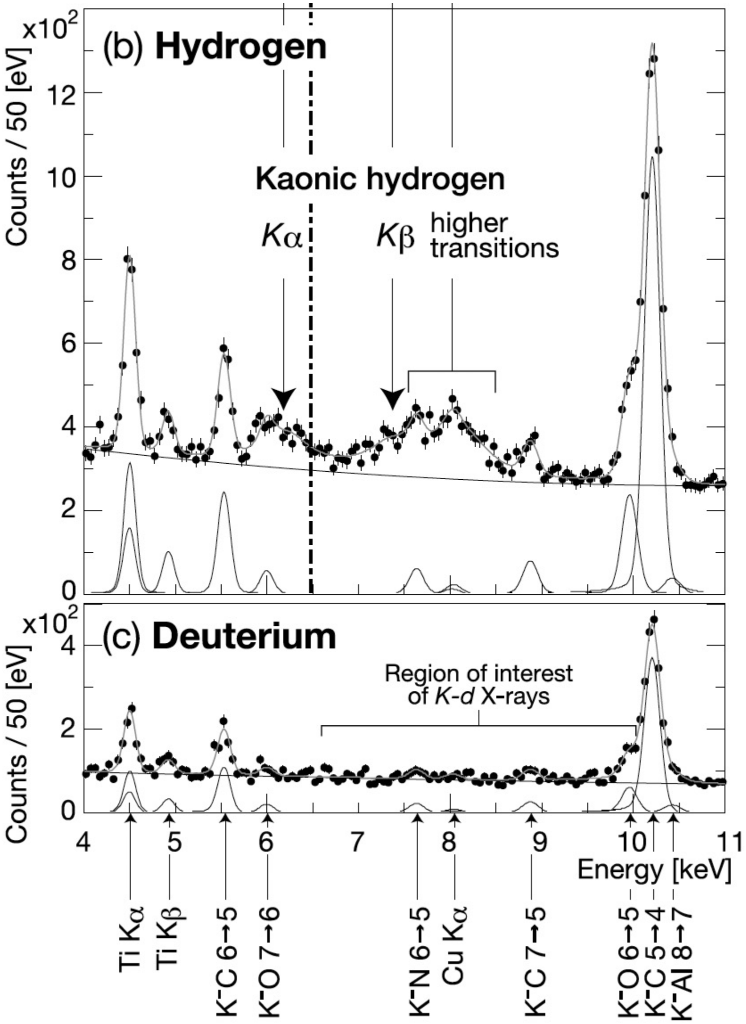
Combined analysis of the kaonic deuterium and kaonic hydrogen measurements to determine the isospin-dependet $\overline{K}N$ scattering lengths



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

The kaonic deuterium challenge

The measurement of Kaonic deuterium 2p → 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→ 1s

See K. Toho Poster

➢ Kd requires a higher integrate luminosity ~800 pb^{-1}

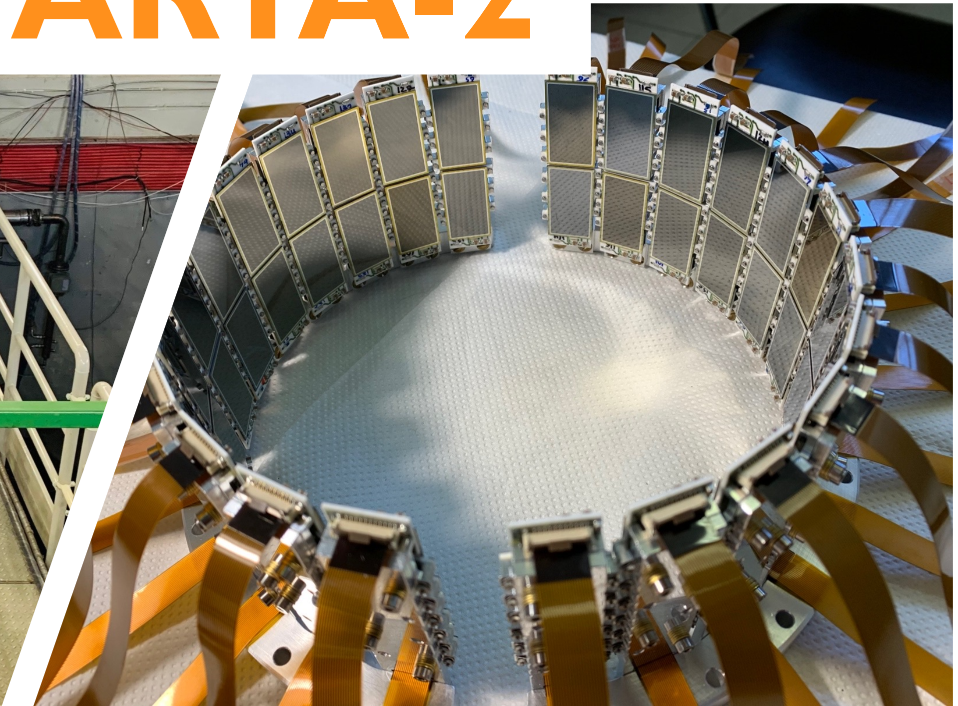
Background:

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

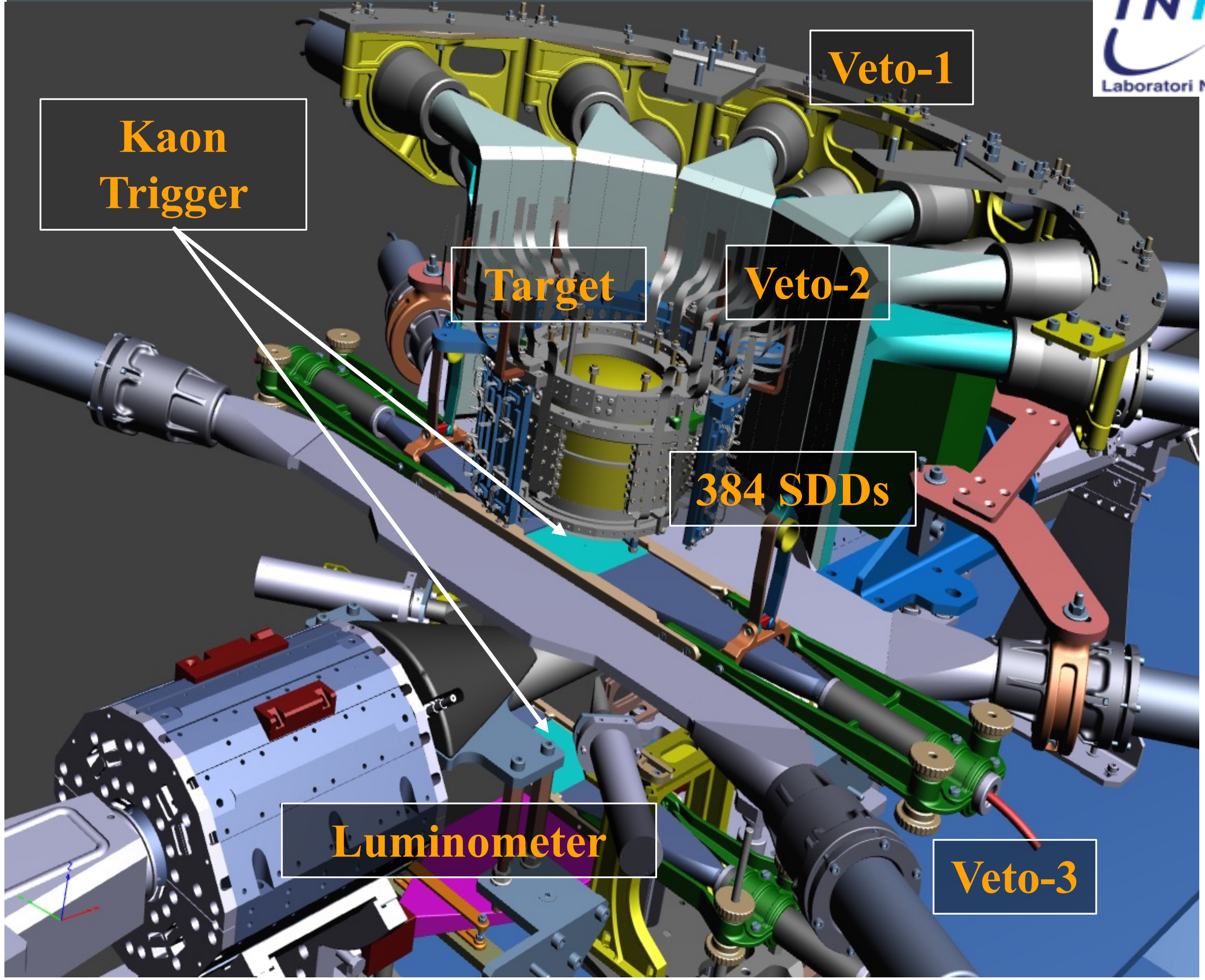
➢ New experimental apparatus with improved SDDs, trigger and Veto systems

➢ Larger detection area

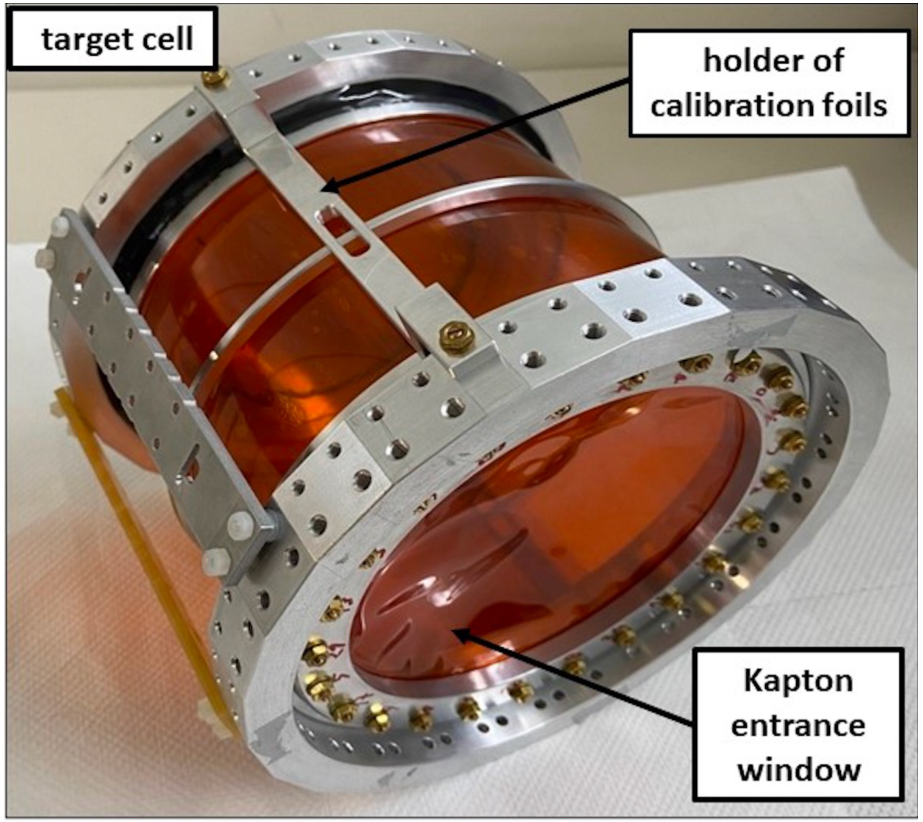
SIDDHARTA-2



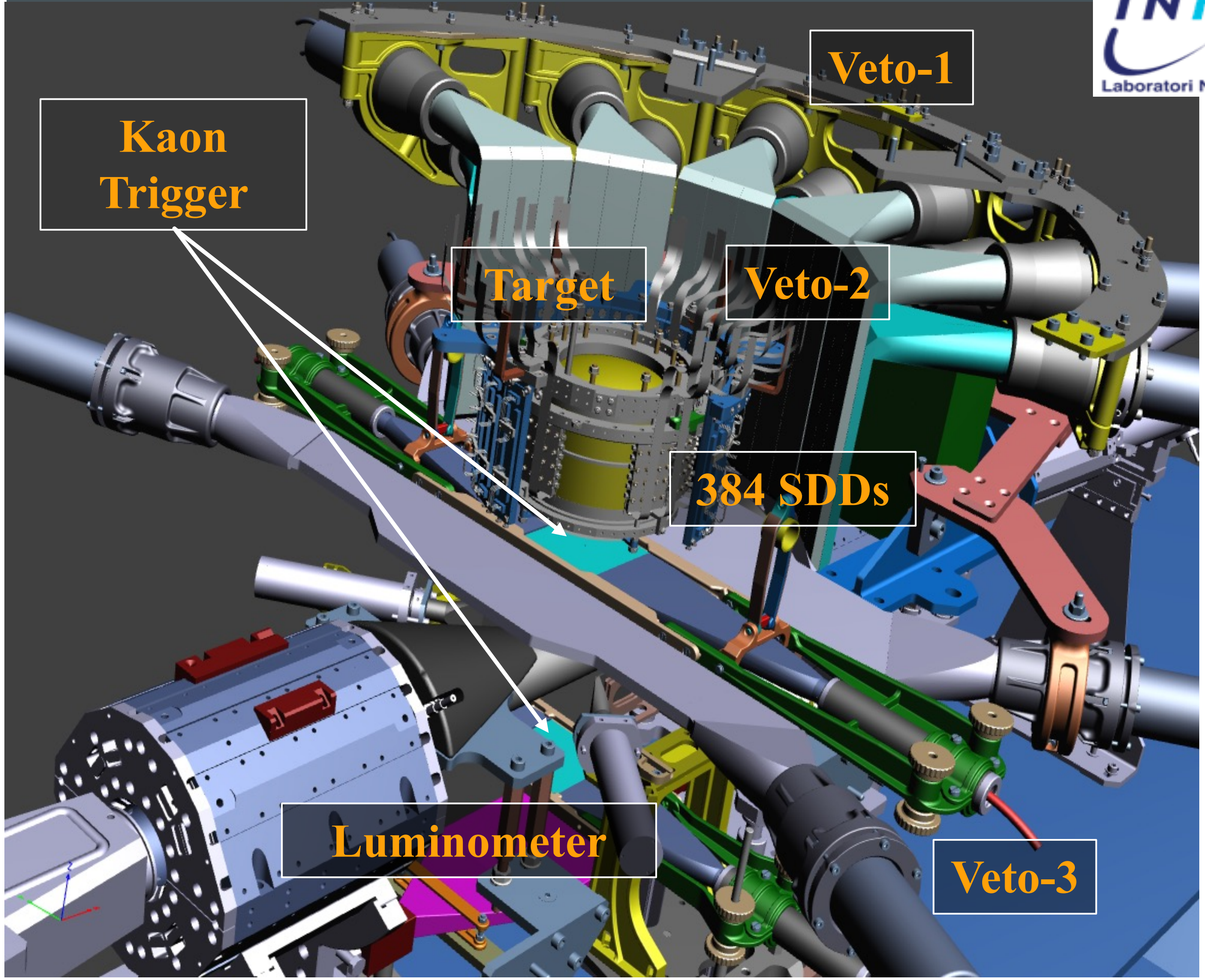
The SIDDHARTA-2 setup



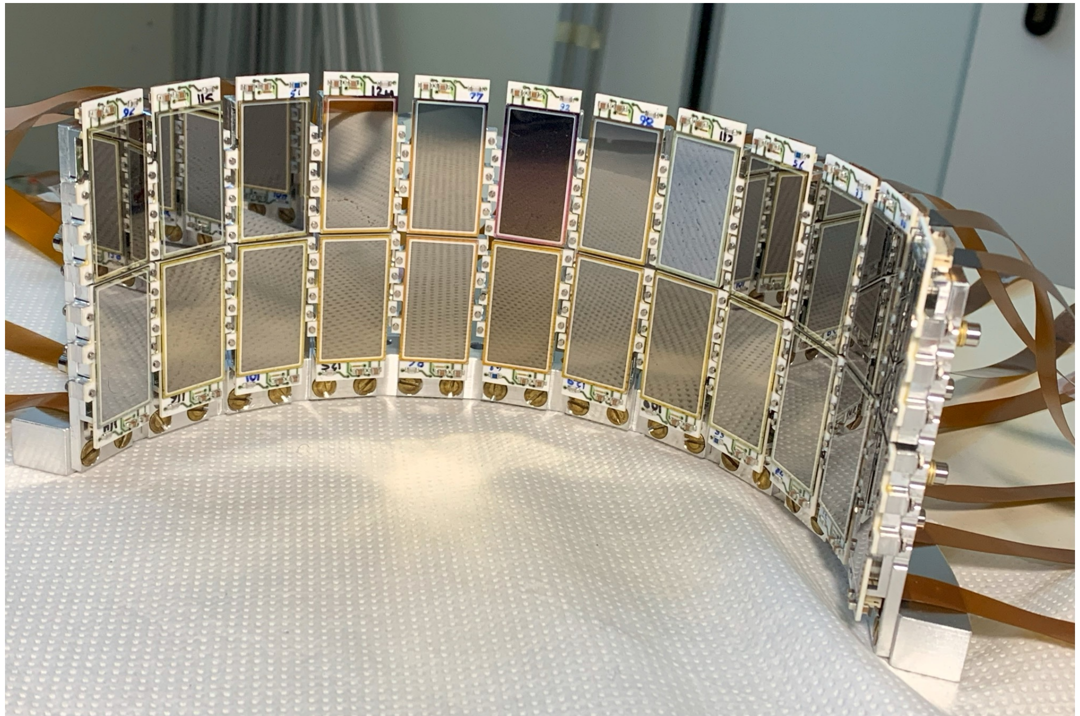
Cryogenic gaseous target cell



The SIDDHARTA-2 setup



384 Silicon Drift Detector
for a total active area of 246 cm^2
The thickness of 450 µm ensures a high collection efficiency for X-rays of energy in the 5-12 keV range



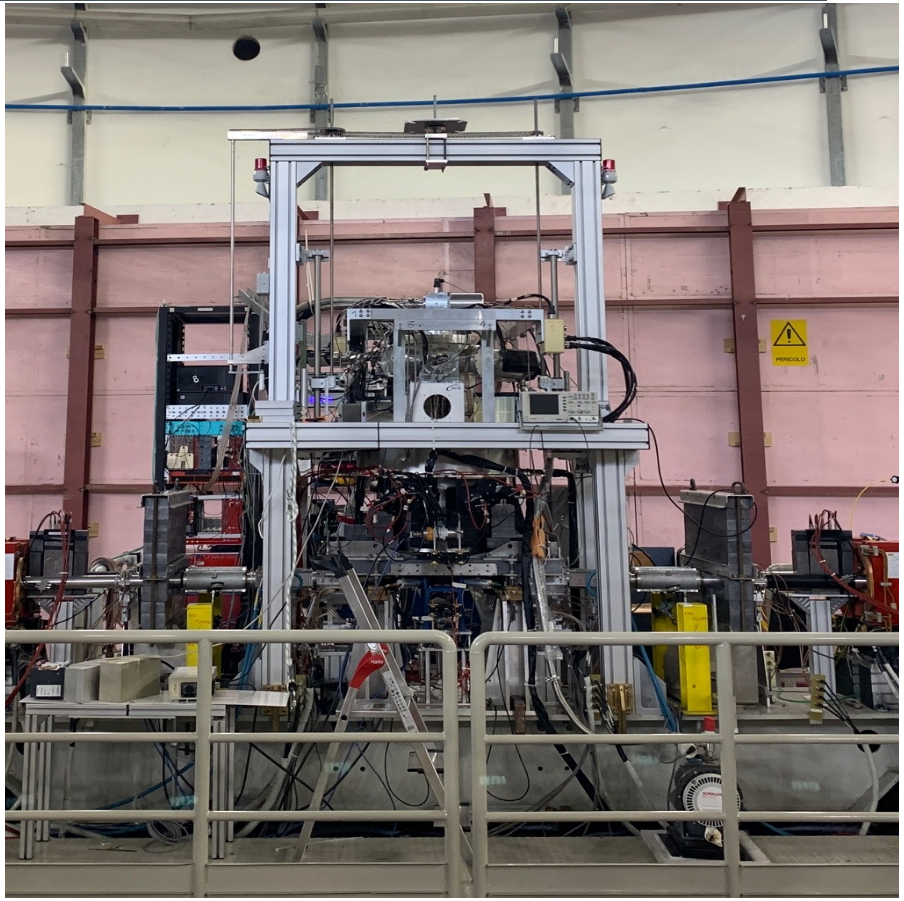
Kaonic Deuterium Data Taking Summary

- *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

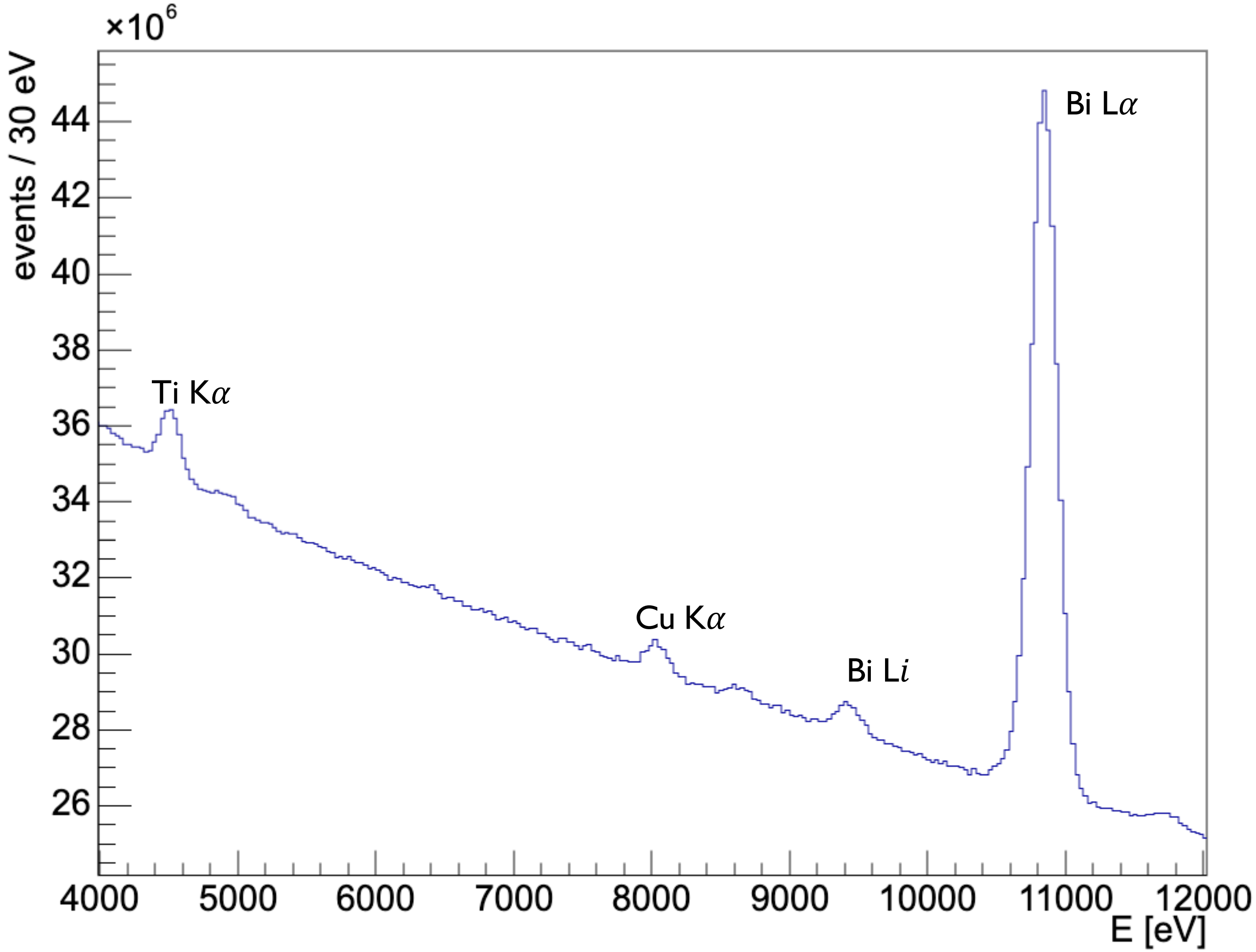
- *Low density run: int. luminosity 184 pb^{-1}* (May – July 2024)
- *Post Kd calibration run* (July 2024) – 20 pb^{-1} *with solid targets (B and F)*



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



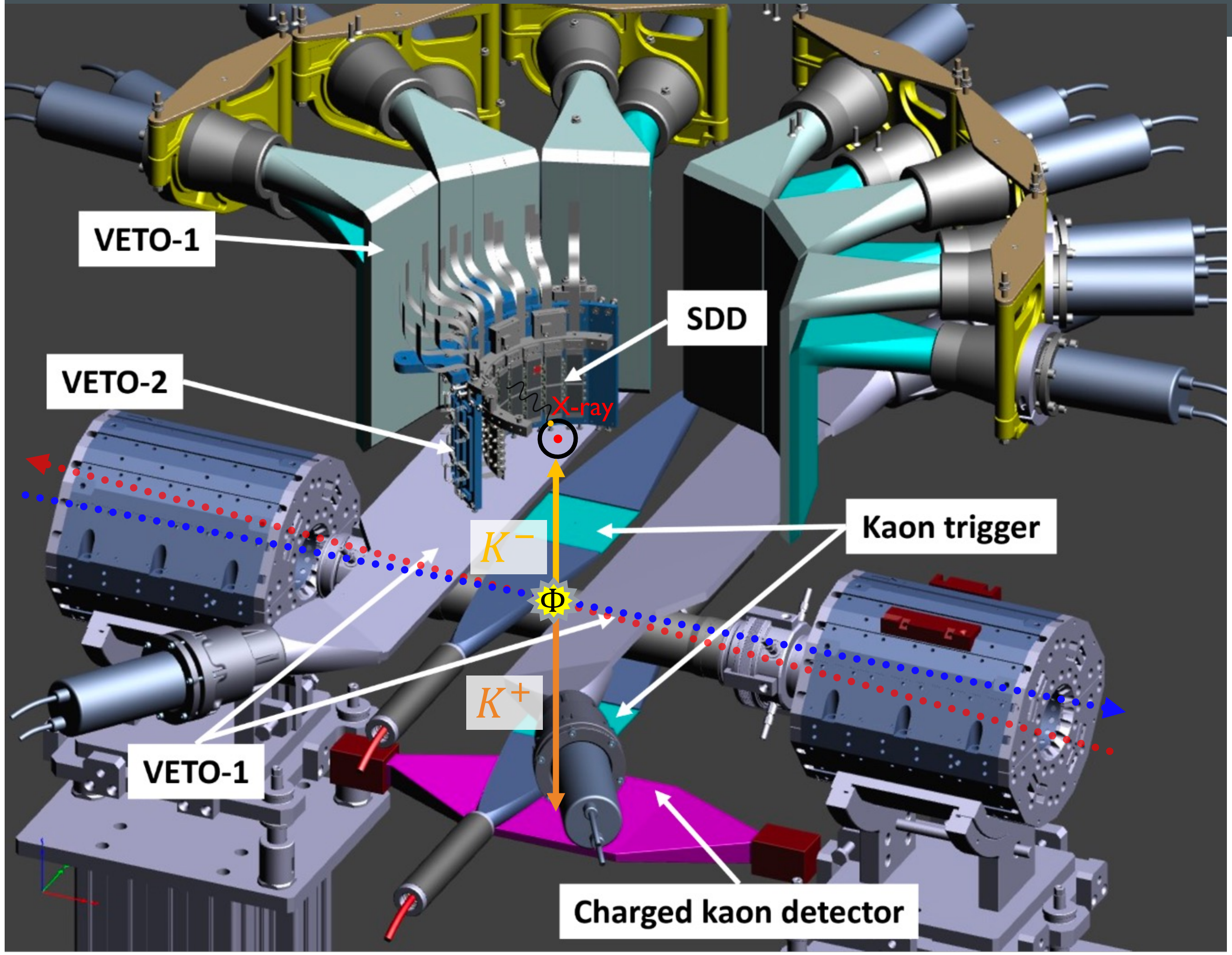
- Electromagnetic (asynchronous) background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect → Kaon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

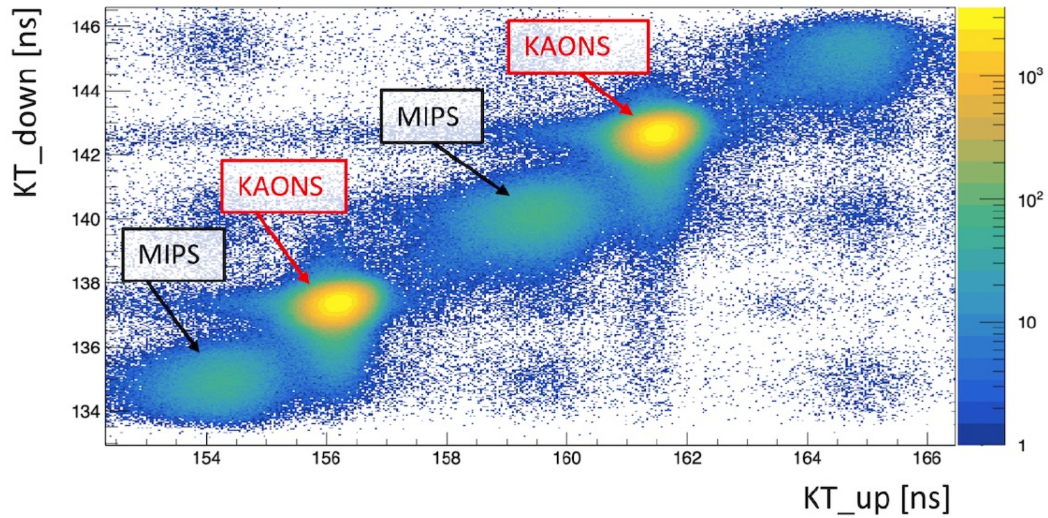
-Hadronic (synchronous) background: associated to kaon absorption on materials nuclei, or to other Φ decay channels. It can be considered a hadronic background.

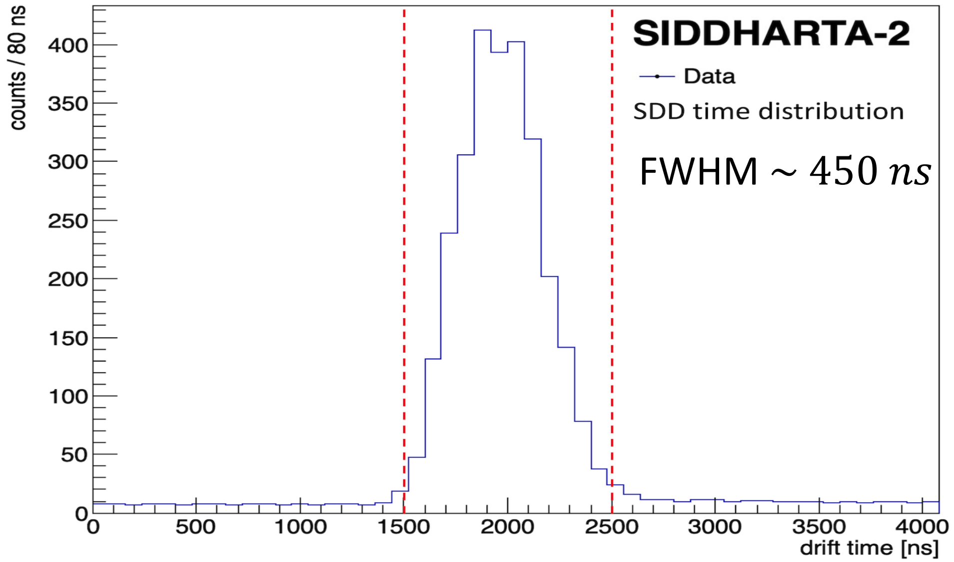
-Spectra contamination by Xray fluorescence or by X-rays produced in higher transitions of other kaonic atoms, formed in the setup materials → Veto systems

Kaonic deuterium analysis

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







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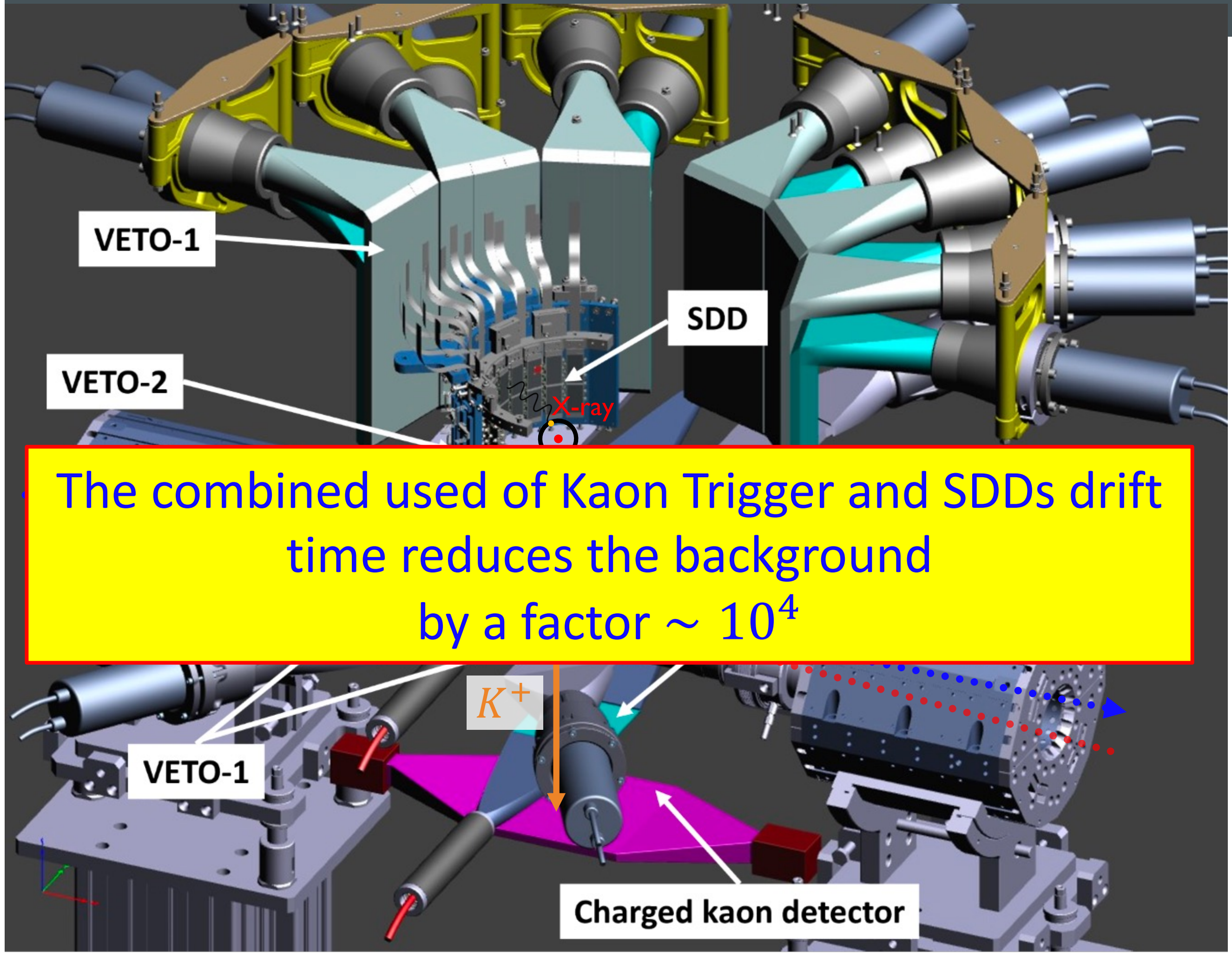
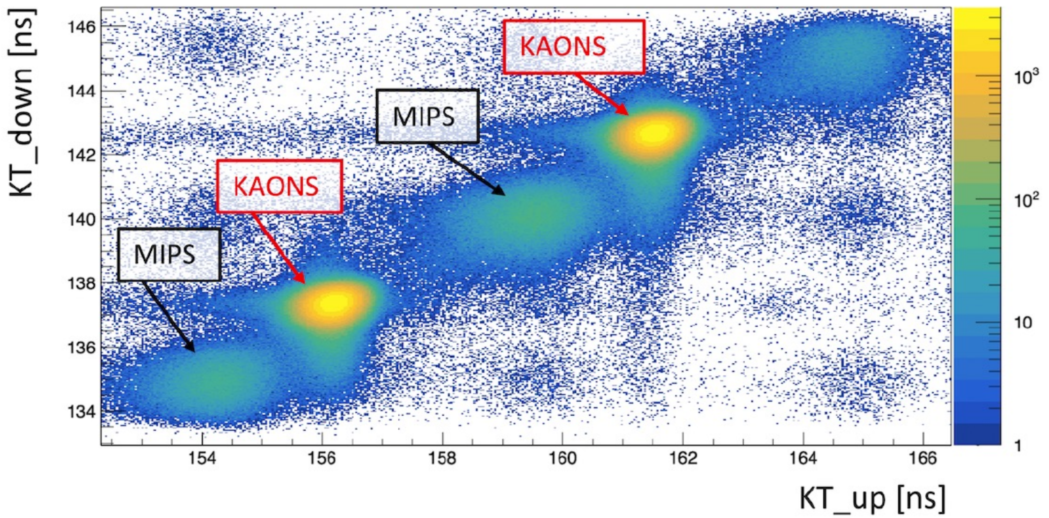
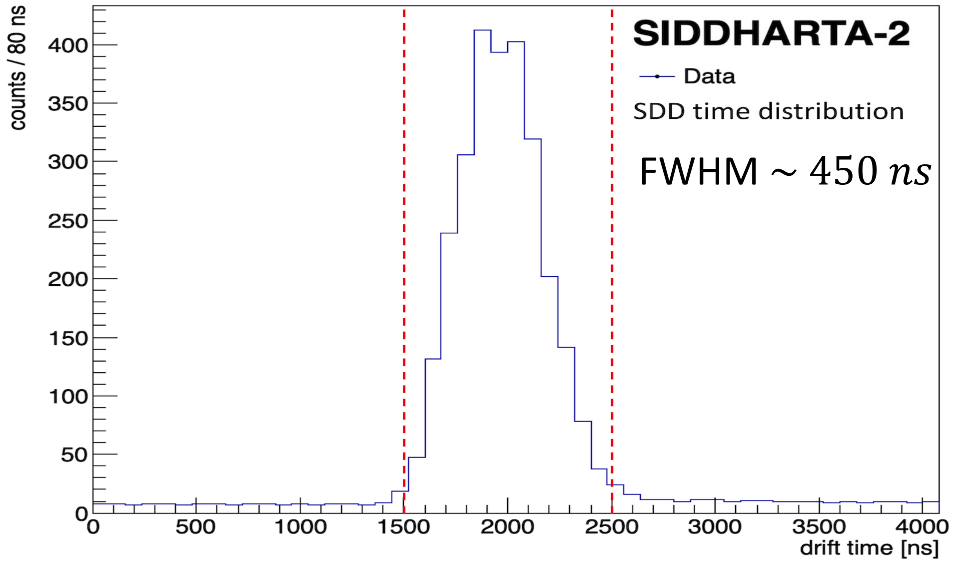


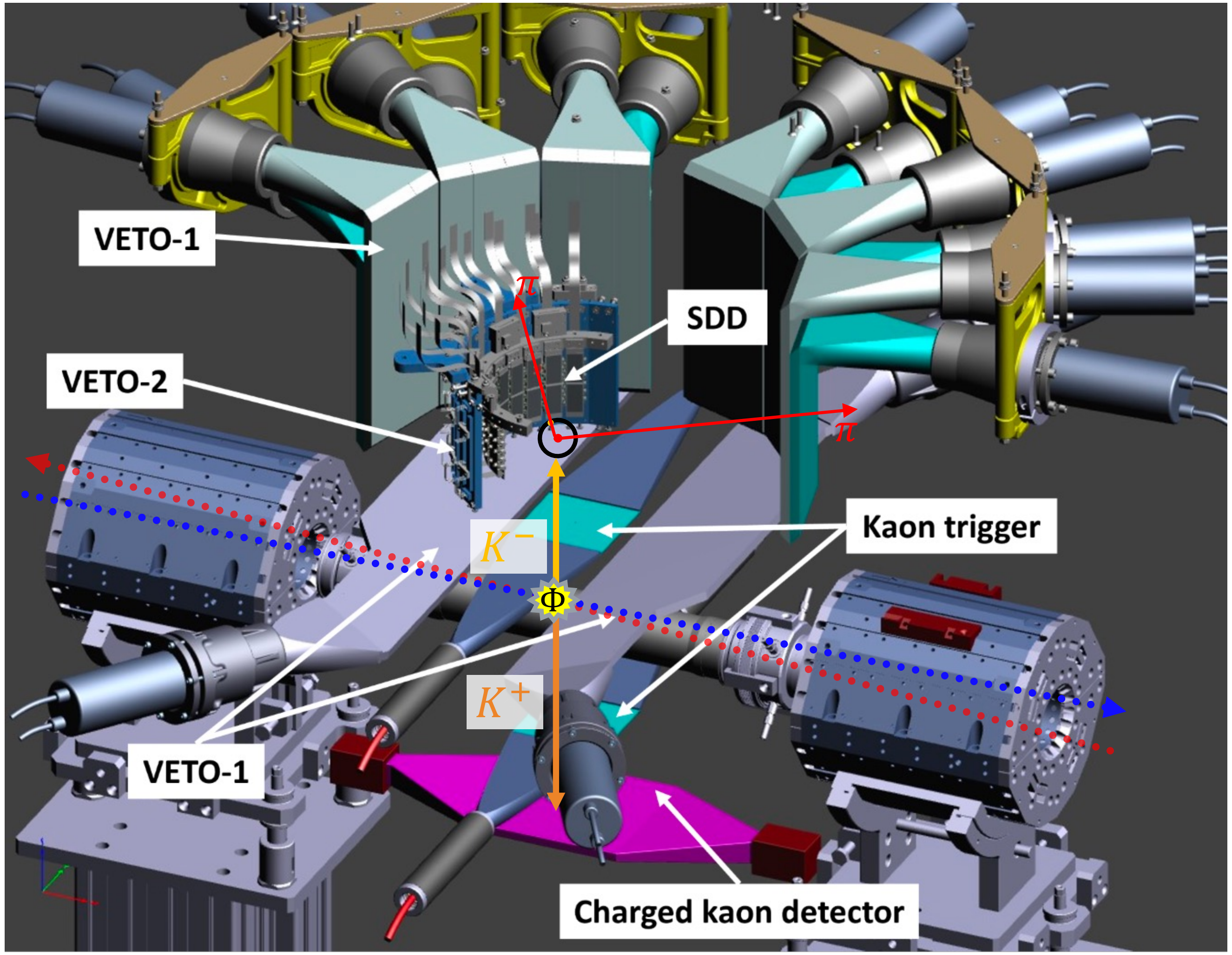
The combined used of Kaon Trigger and SDDs drift time reduces the background by a factor $\sim 10^4$





Kaonic deuterium analysis

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

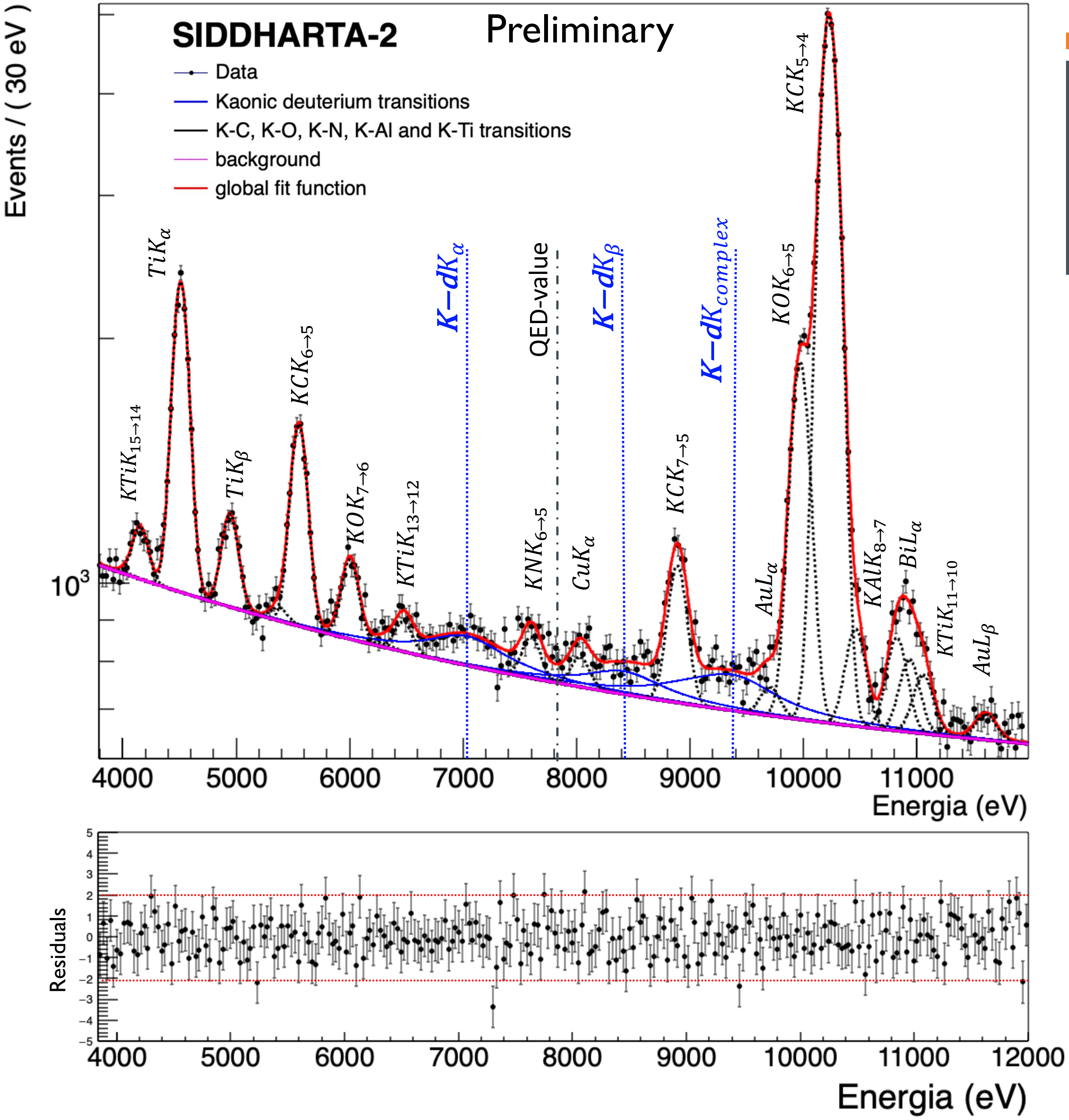


Veto-1 (fiducial volume selection): to select the events occurring in the gas target, rejecting the X-ray background corresponding to K- stopped in the solid elements of the setup.

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.

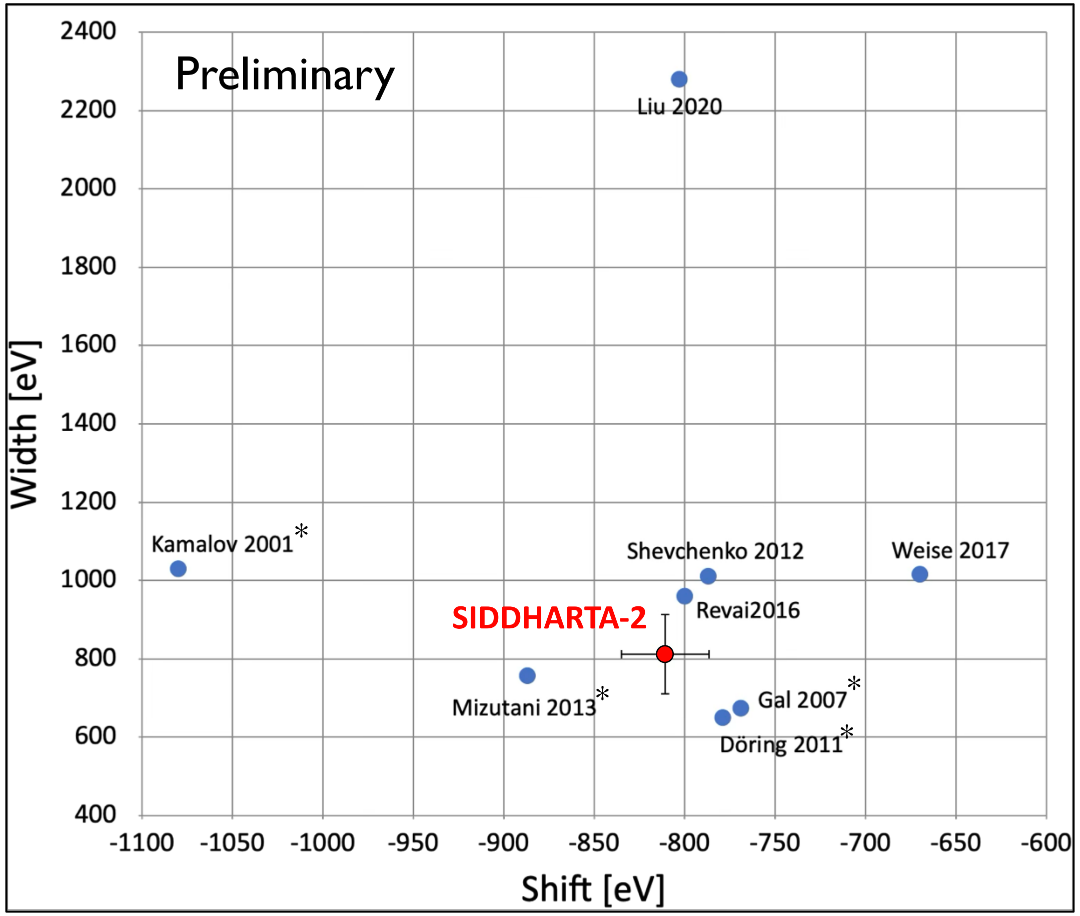
Kaonic Deuterium Results



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

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

Targeted precision achieved!



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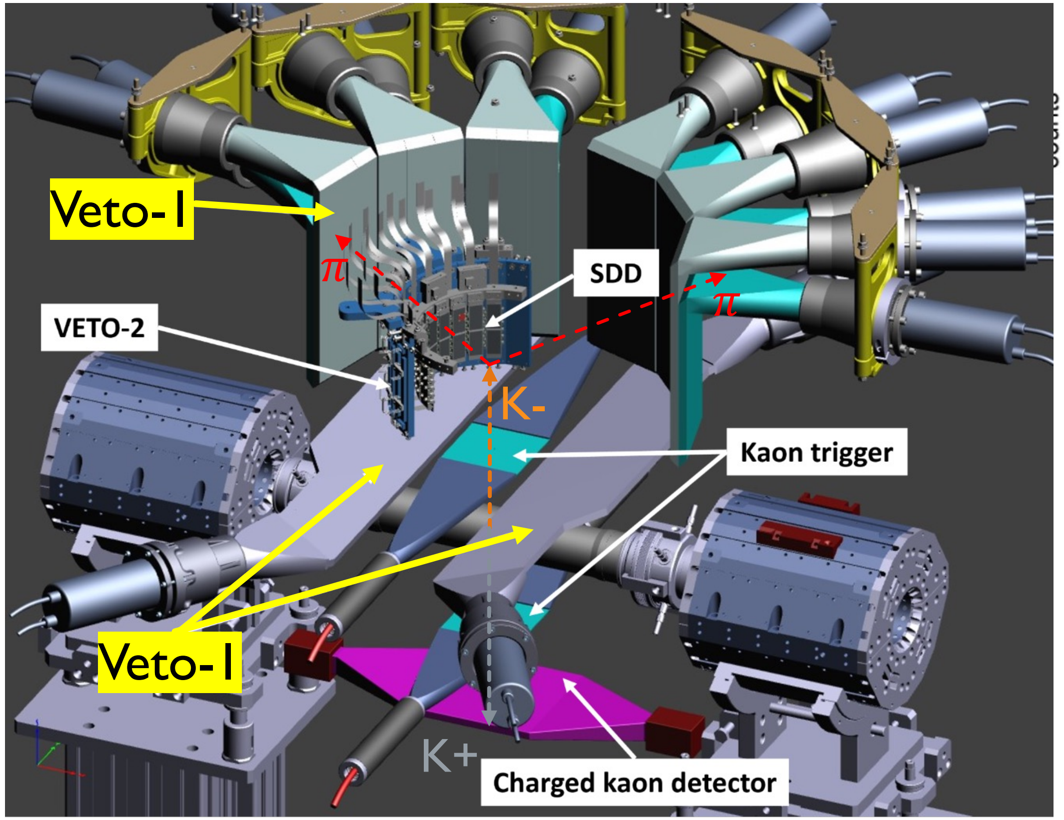
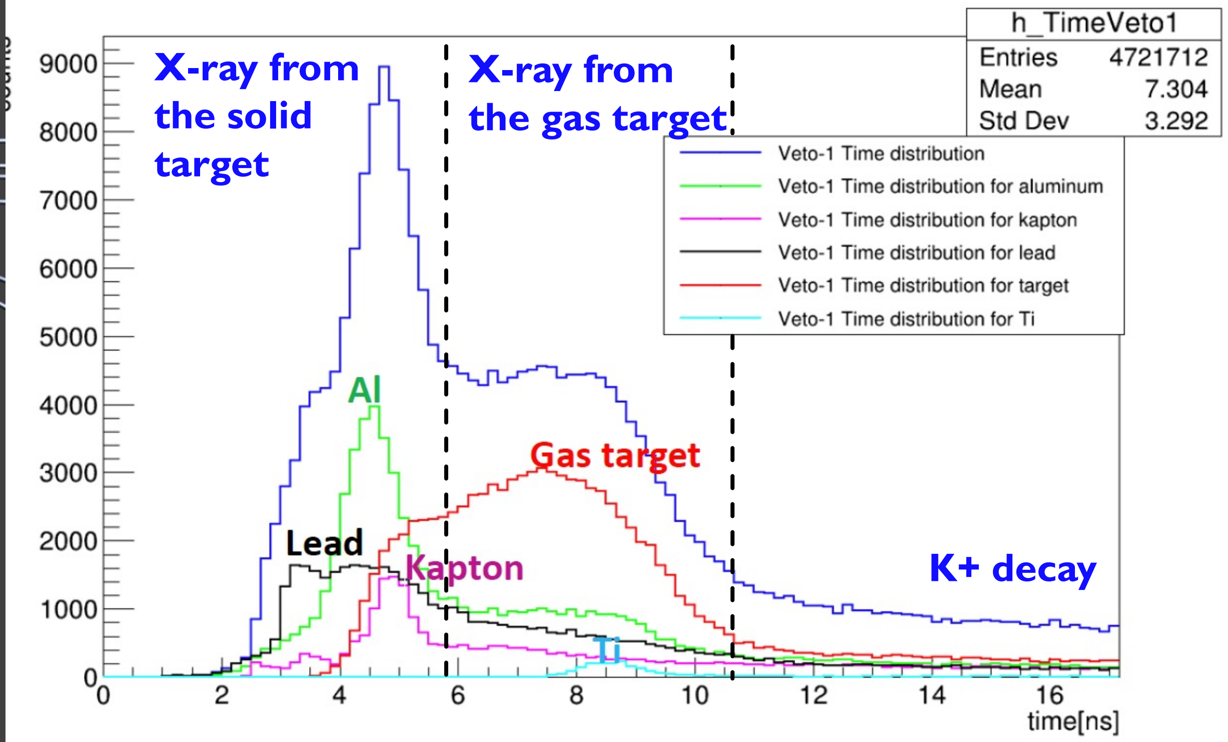
Kaonic deuterium analysis – Veto1 system

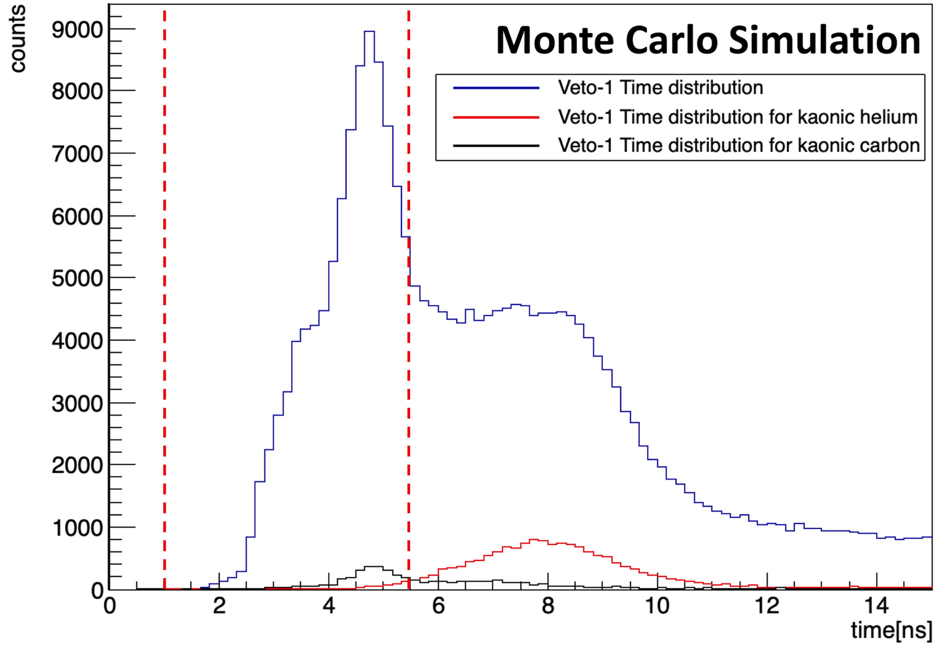
Veto-1 for hadronic background reduction: it measures the arrival time of charged particles emitted by the kaon-nucleus absorption to determine the origin of the signal — whether it comes from the deuterium gas target or from surrounding solid materials.

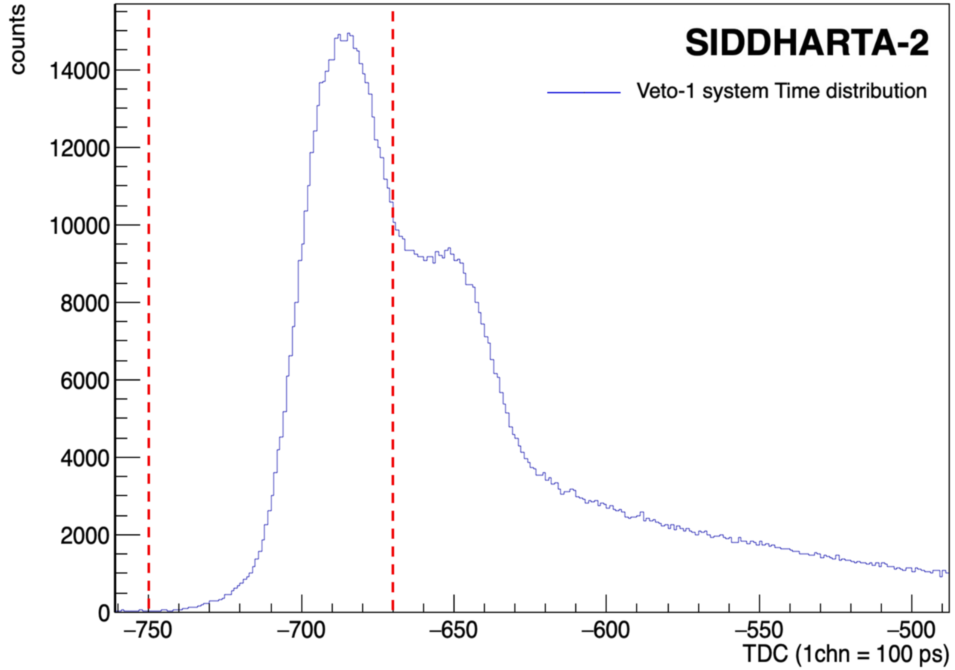


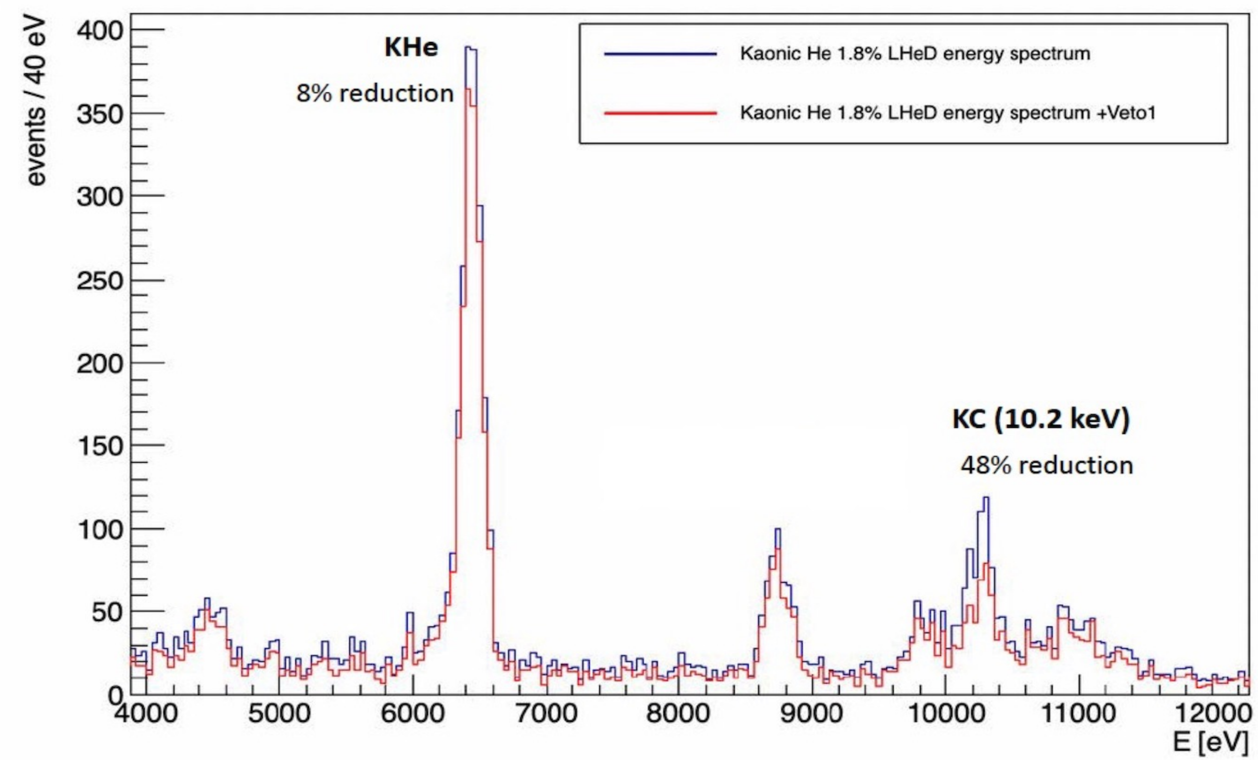


Veto-1: 14 plastic scintillators placed around and below the vacuum chamber

Veto-1 system optimization with kaonic He





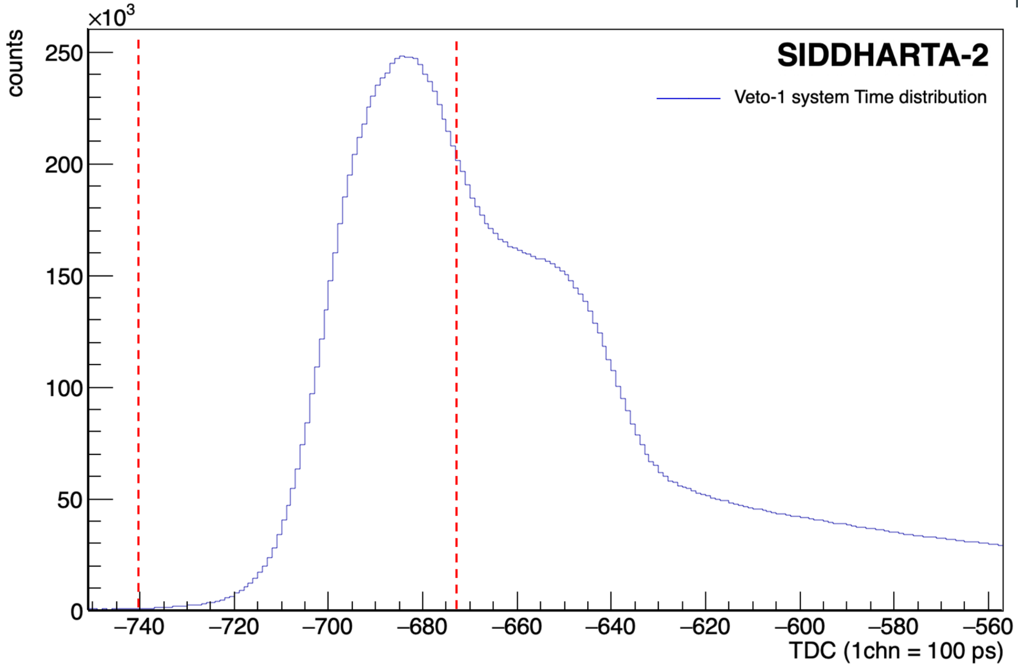


	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-^{4}He L_α	$(8 \pm 1)\%$	4%
K-$C_{5\to4}$	$(48 \pm 4)\%$	44%

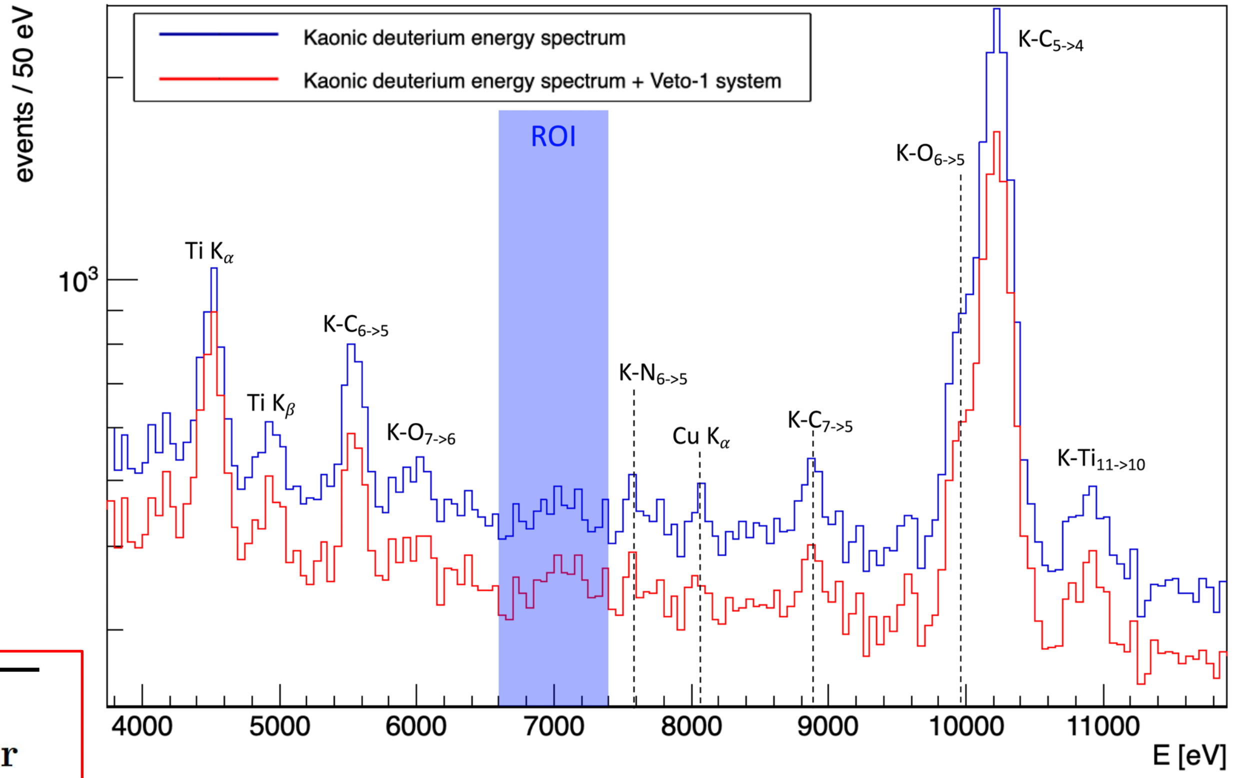
$$\text{reduction factor} = 1 - \frac{\#\text{events(with veto1)}}{\#\text{events}}$$

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-$C_{5\to4}$	$(44 \pm 4)\%$	46%
K-$C_{6\to5}$	$(39 \pm 5)\%$	45%
K-$C_{7\to5}$	$(48 \pm 4)\%$	46%

Kaonic Deuterium: veto-1 system analysis

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

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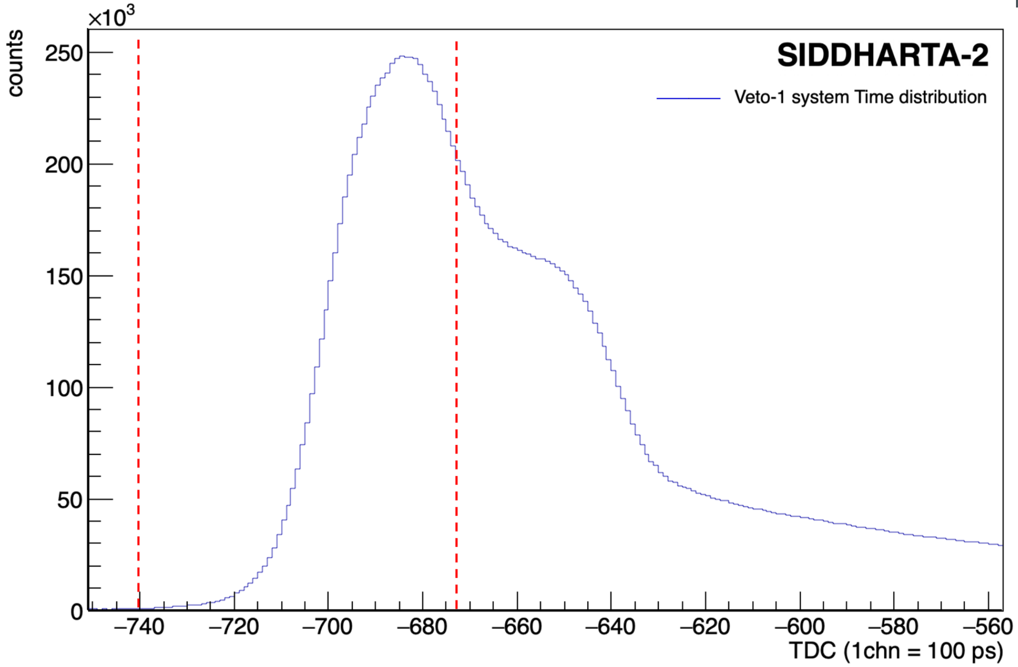

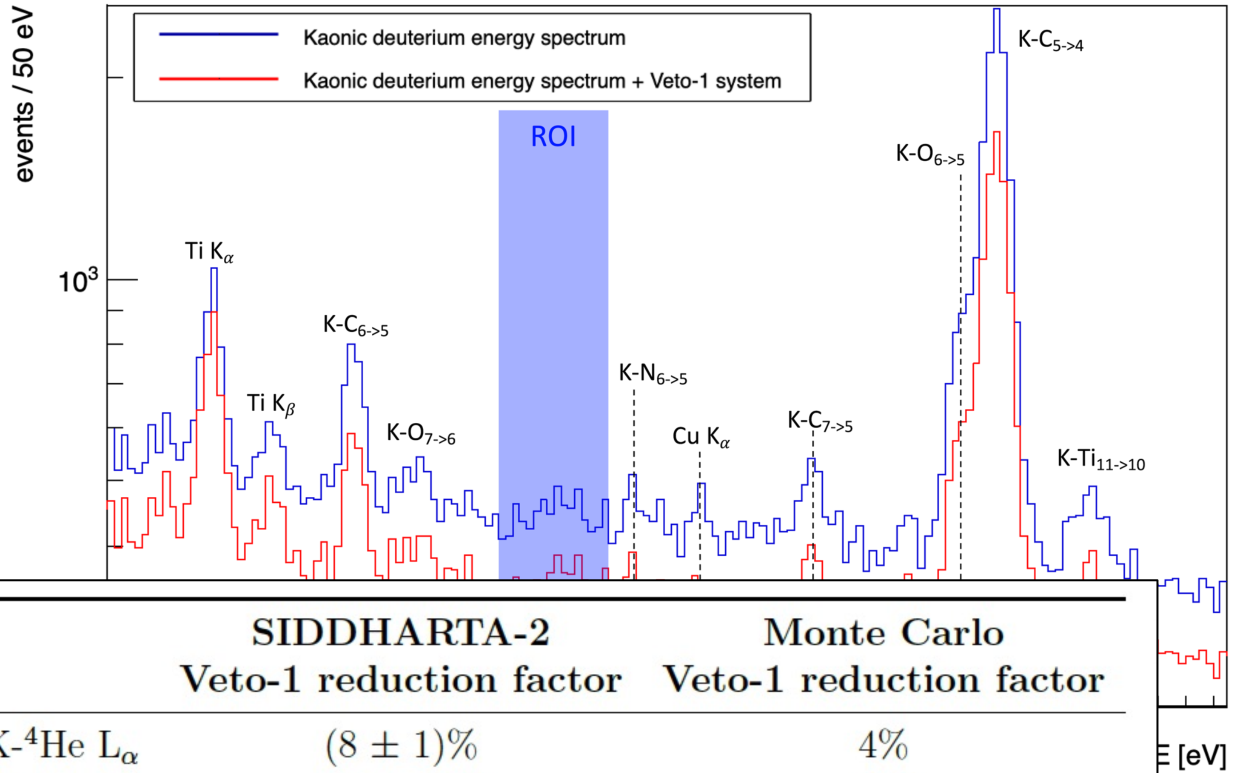

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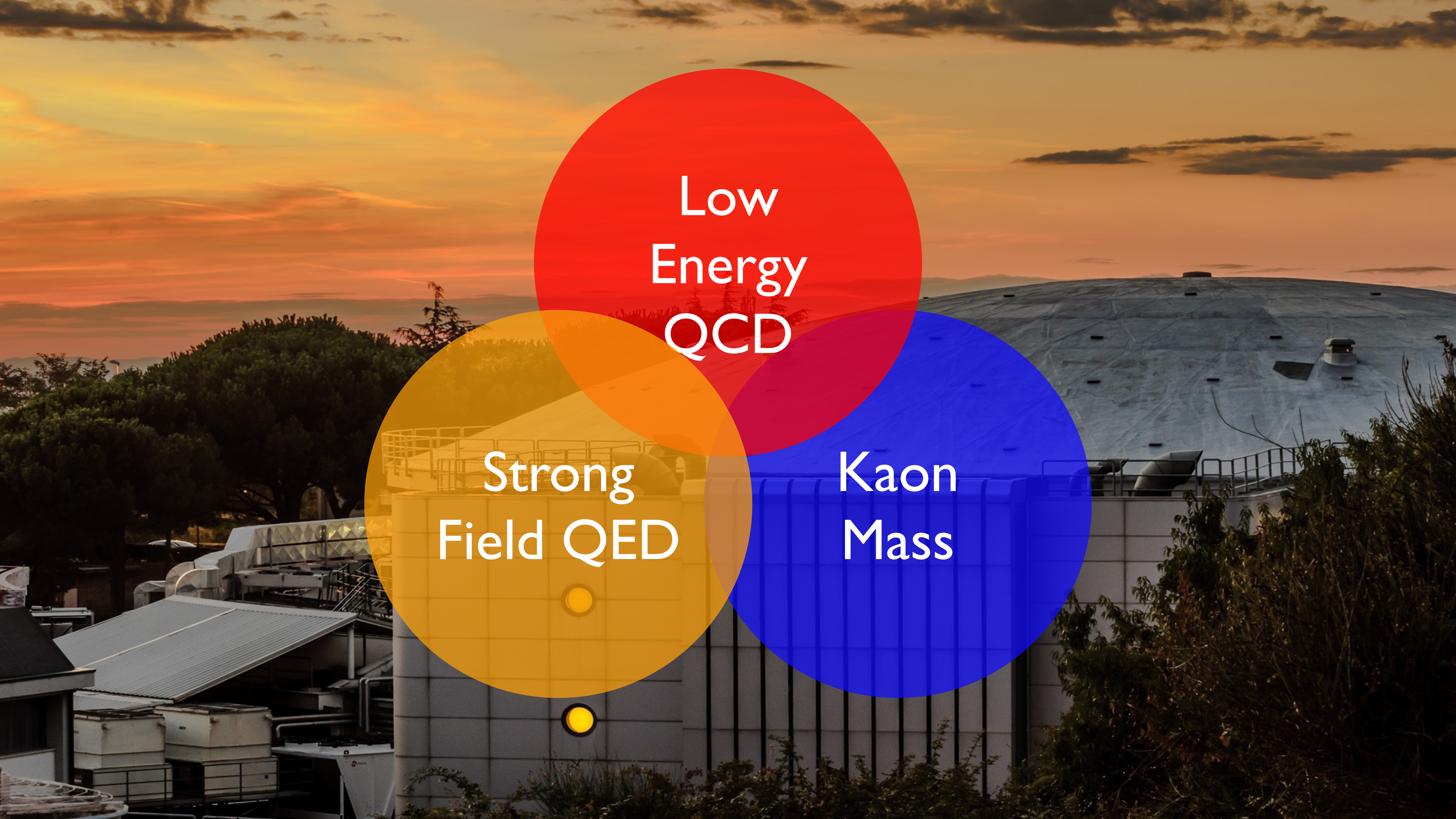
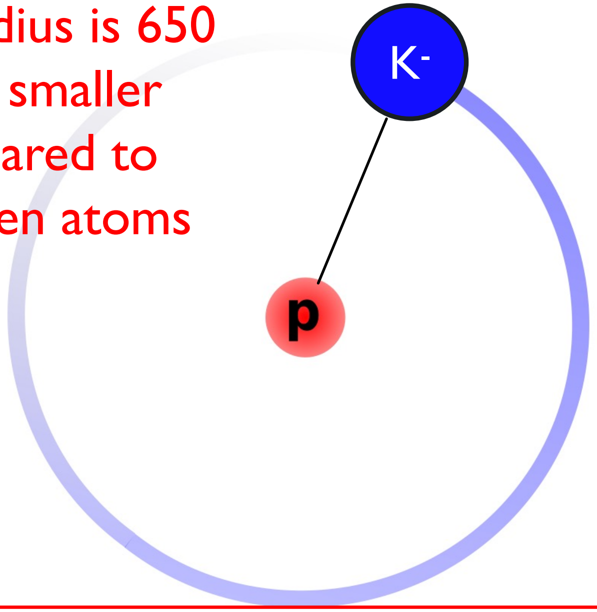


Low
Energy
QCD
Strong
Field QED
Kaon
Mass

Probing strong field QED with kaonic atoms

Kaonic atoms are extremely compact, resulting in very strong electric fields that allow access to the strong-field regime of QED

Bohr radius is 650 times smaller compared to hydrogen atoms

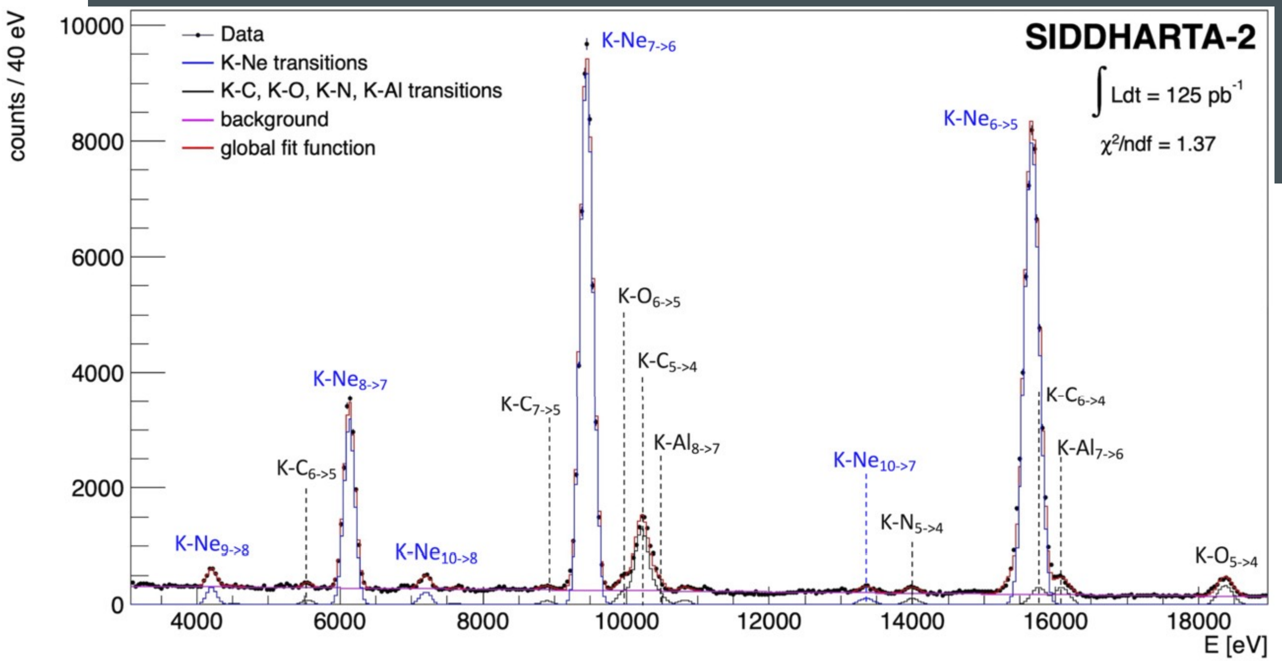


Particle	m [MeV/c^2]	B_{1s} [keV]	r_B [10^{-15} m]	Accessible interactions
ep	0.511	13.6 x 10^{-3}	0.53 x 10^5	Electro-weak
μp	105.7	2.53	279	Electro-weak
πp	139.6	3.24	216	Electro-weak + strong
Kp	493.7	8.61	81	Electro-weak + strong
$\bar{p}$p	938.3	12.5	58	Electro-weak + strong

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

Kaonic neon X-ray spectroscopy



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 ± 4.91 ±2.00	0.010 ± 0.001 ± 0.001
K-Ne (10 → 7)	13352.20 ± 10.07 ±3.00	0.004 ± 0.002 ± 0.001
K-Ne (9 → 8)	4206.35 ± 3.75 ±2.20	0.137 ± 0.012 ± 0.010
K-Ne (8 → 7)	6130.86 ± 0.71 ±1.50	0.228 ± 0.004 ± 0.011
K-Ne (7 → 6)	9450.08 ± 0.41 ±1.50	0.277 ± 0.002 ± 0.014
K-Ne (6 → 5)	15673.30 ± 0.52 ±9.00	0.308 ± 0.003 ± 0.015

Phys. Lett. B 865 (2025) 139492

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Letter

High precision X-ray spectroscopy of kaonic neon ☆

F. Sgaramella [a,*], D. Sirghi [b,a,c,**], K. Toho [d], F. Clozza [a], L. Abbene [e], C. Amsler [f], F. Artibani [a,g], M. Bazzi [a], G. Borghi [h,i], D. Bosnar [j], M. Bragadireanu [c], A. Buttacavoli [e], M. Cargnelli [f], M. Carminati [h,i], A. Clozza [a], R. Del Grande [k,a], L. De Paolis [a], K. Dulski [a,l,m], L. Fabbietti [k], C. Fiorini [h,i], I. Friščić [j], C. Guaraldo [a,1], M. Iliescu [a], M. Iwasaki [n], A. Khreptak [l,m], S. Manti [a], J. Marton [f], P. Moskal [l,m], F. Napolitano [a], S. Niedźwiecki [l,m], H. Ohnishi [d], K. Piscicchia [b,a], F. Principato [e], A. Scordo [a], M. Silarski [l], F. Sirghi [a,c], M. Skurzok [l,m], A. Spallone [a], L.G. Toscano [h,i], M. Tüchler [f], O. Vazquez Doce [a], E. Widmann [f], J. Zmeskal [f,1], C. Curceanu [a]

The kaonic neon measurement demonstrates the feasibility of precision studies in the field of QED with kaonic atoms (BSQED)

Kaonic atoms offer high sensitivity to BSQED corrections thanks to their large reduced mass compared to muonic atoms. Unlike antiprotonic and muonic atoms, they lack hyperfine structure effects, simplifying measurement and analysis.

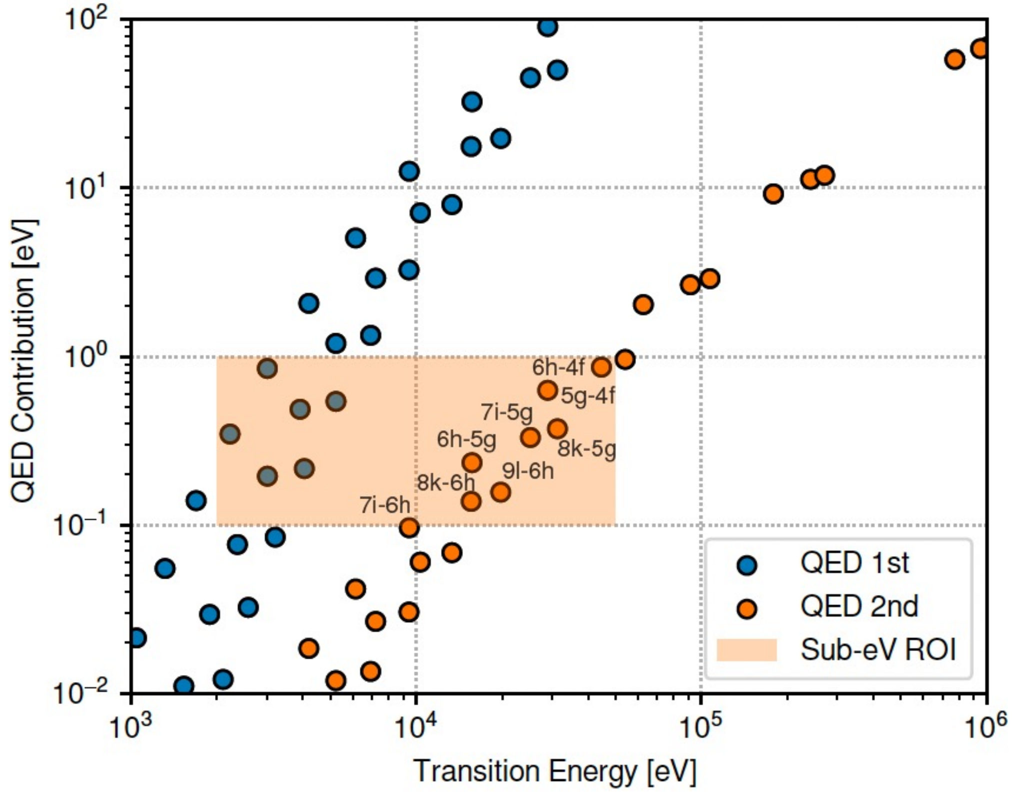
Bound State QED with kaonic atoms

We (S. Manti) **Run**, **Test**, and **Contribute** to the **MCDF code** for Ab Initio Atomic Calculations, including Relativistic and QED effects, in collaboration with **Prof. Paul Indelicato (Paris–CNRS).**

Transition	$E_{if}^{(exp.)}$	$\delta E_{if}^{(stat.)}$	$\delta E_{if}^{(sys.)}$	$E_{if}^{(calc.)}$	$E_{if}^{(QED)}$	$E_{if}^{(QED1)}$	$E_{if}^{(QED2)}$	$\Delta E_{if}^{(isot.)}$	$\Delta E_{if}^{(screen.)}$	$\Delta E_{if}^{(PDG)}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02	9.90	-0.38	0.11
8k-7i	6130.57	0.65	1.50	6130.31	5.09	5.05	0.04	14.45	-0.27	0.16
7i-6h	9450.23	0.37	1.50	9450.28	12.66	12.56	0.10	22.28	-0.18	0.24
6h-5g[a]	15673.30	0.52	9.00	15685.39	32.75	32.51	0.24	37.01	-0.11	0.40

- **MCDF Calculations** include transition energies, QED effects, Electro Screening, and Isotopic Shifts (K^{20}Ne,K^{22}Ne)
- **Sub-eV Statistical Uncertainties** match the scale of **Second-Order QED corrections** (e.g., **Vacuum Polarization**).
- **K^{20}Ne 7i → 6h transition:**
  - **Exp:** 9450.23 ± 0.37 (stat) ± 1.50 (syst) eV
  - **Theory:** 9450.28 (with the QED contribution to the transition energy is 12.66 eV)

    → Excellent agreement between Theory and Experiment



- Kaonic Neon offers a clean system to test **QED calculations**

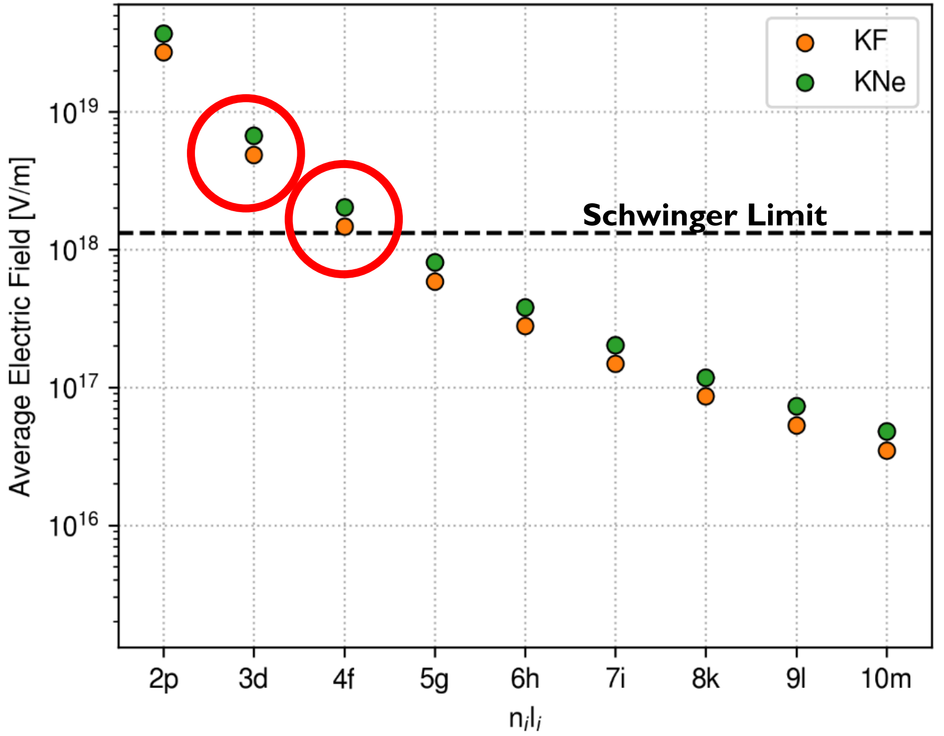
Under review in PRL arXiv:2508.08161

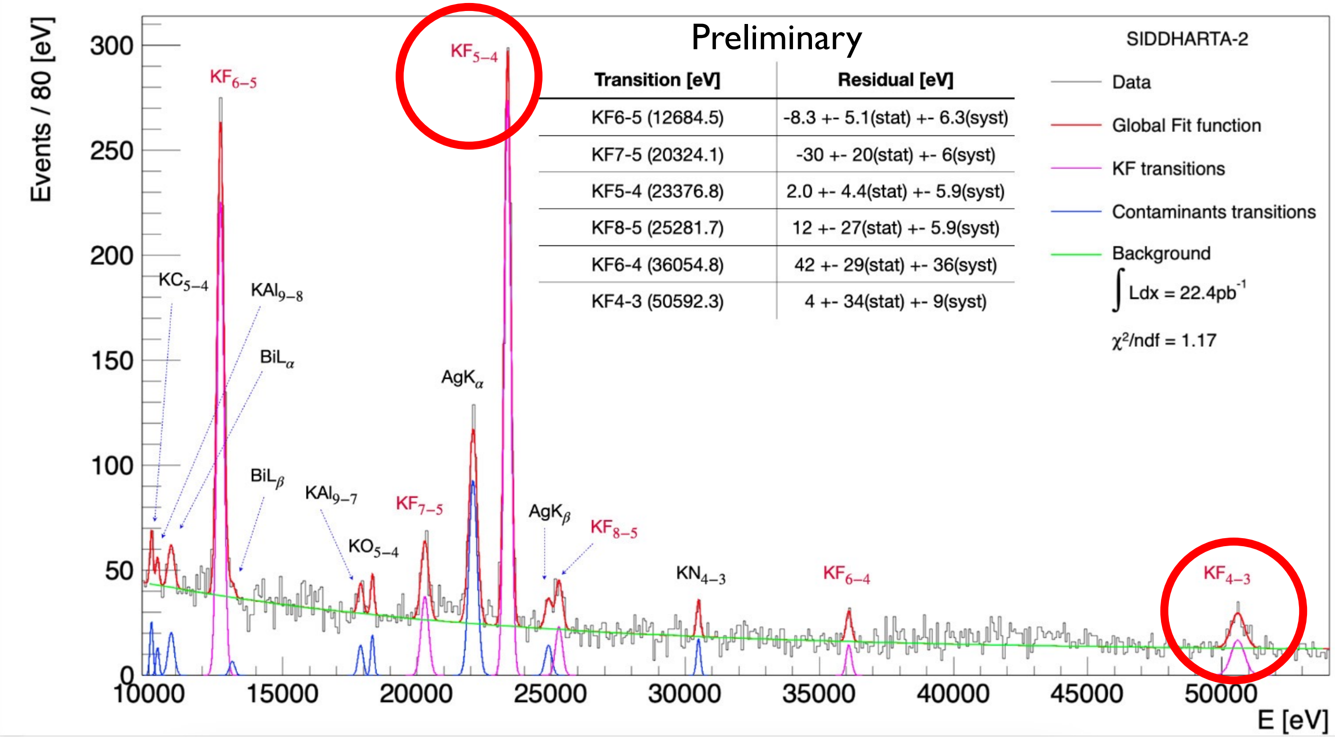
Kaonic Atoms as Probes of Strong Fields QED: Schwinger Limit for KF

- **Exotic atoms** (like **KNe** and **KF**) enable experimental access to **Strong Electric Fields** [Paul *et al.*, PRL 126, 173001 (2021)]
- The **Schwinger Limit** for spontaneous **e⁺- e⁻ Pair Creation** is:

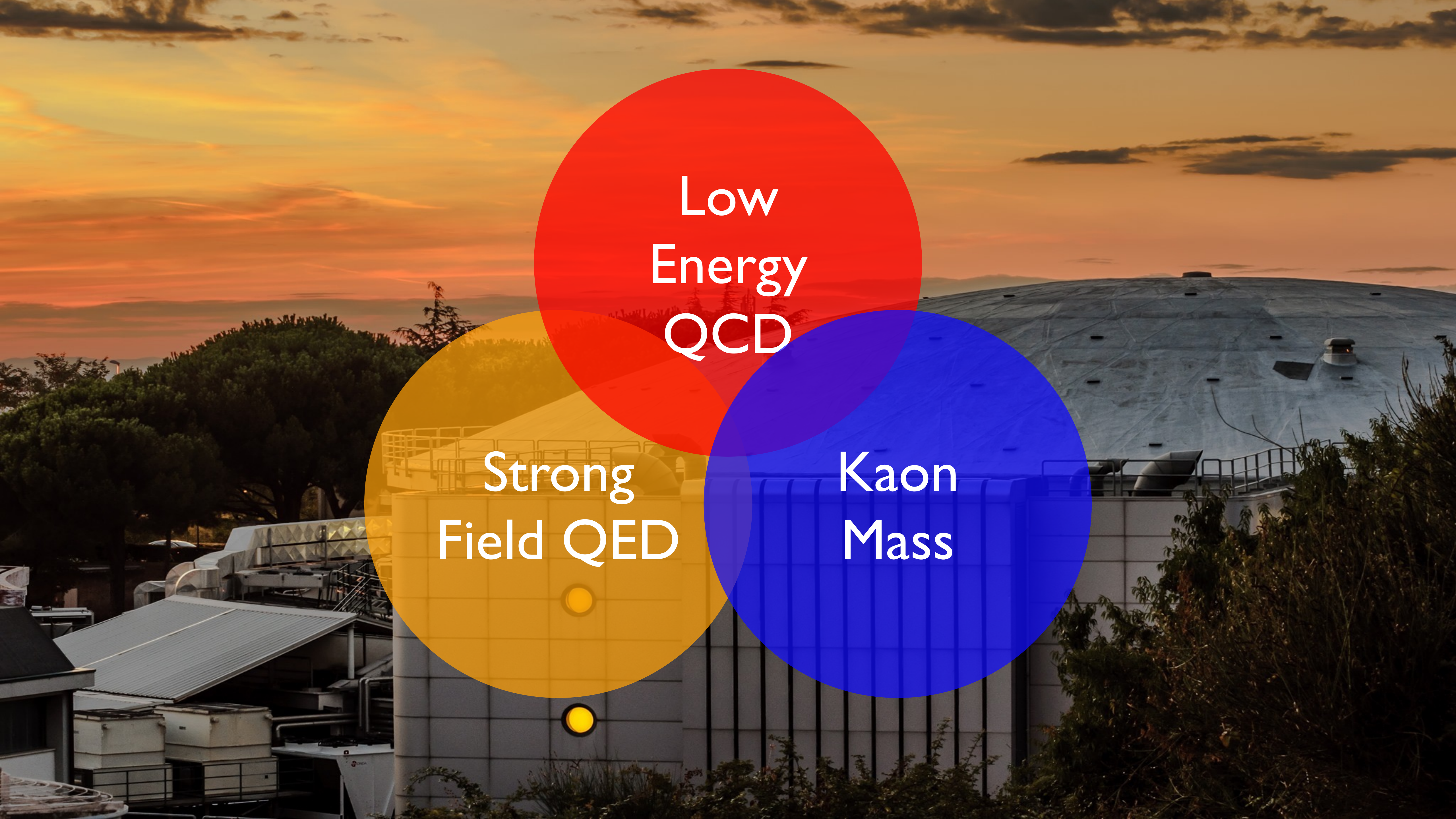
$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18} V/m \qquad \langle E \rangle_{nl} = \int d^3r \, |\psi_{nl}(\mathbf{r})|^2 E(\mathbf{r})$$

For the transition **KF 5 → 4, and 4 → 3**, the **Average Electric Field** in kaonic orbitals approaches the **Schwinger limit** and the **BSQED contribution are enhanced by the Nonlinear Electric-Field dependence of Vacuum Polarization**





Transition [eV]	Residual [eV]
KF6-5 (12684.5)	-8.3 +- 5.1(stat) +- 6.3(syst)
KF7-5 (20324.1)	-30 +- 20(stat) +- 6(syst)
KF5-4 (23376.8)	2.0 +- 4.4(stat) +- 5.9(syst)
KF8-5 (25281.7)	12 +- 27(stat) +- 5.9(syst)
KF6-4 (36054.8)	42 +- 29(stat) +- 36(syst)
KF4-3 (50592.3)	4 +- 34(stat) +- 9(syst)


Low
Energy
QCD
Strong
Field QED
Kaon
Mass

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^-)

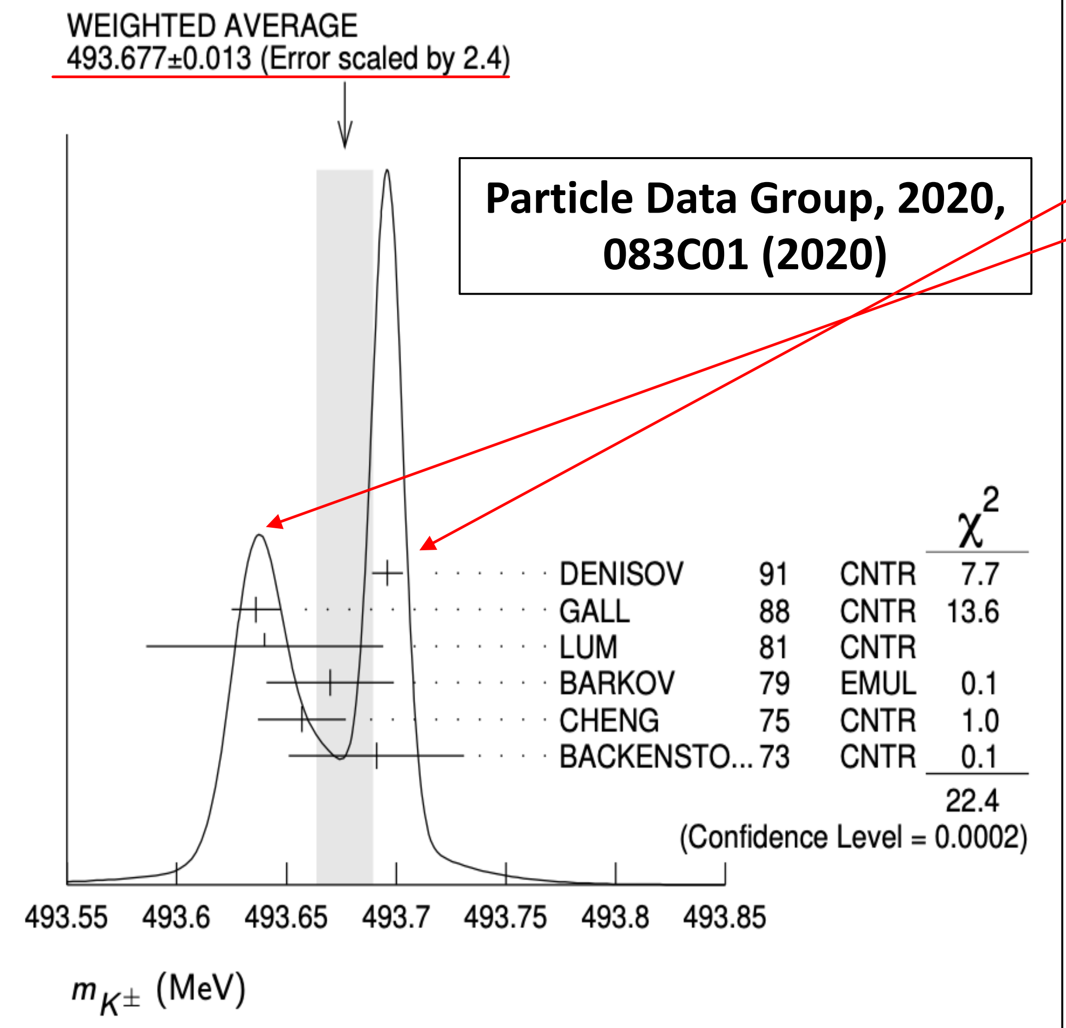
$$\cancel{493.677 \pm 0.013 \text{ MeV}}$$

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

The charged kaon mass puzzle

60 keV discrepancy between the two most accurate measurement

Large uncertainty → 26 p.p.m, compared to charged pion (1.6 p.p.m)



Particle Data Group, 2020, 083C01 (2020)

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.				
493.677±0.013 OUR AVERAGE	Error includes scale factor of 2.4. See the ideogram below.				
493.696±0.007	[1] DENISOV	91	CNTR	−	Kaonic atoms
493.636±0.011	[2] GALL	88	CNTR	−	Kaonic atoms
493.640±0.054	LUM	81	CNTR	−	Kaonic atoms
493.670±0.029	BARKOV	79	EMUL	±	$e^+e^- \rightarrow K^+K^-$
493.657±0.020	[2] CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	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 $D^0\overline{D}^{*0}$ 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.

Kaon Mass Determination: Application to KNe

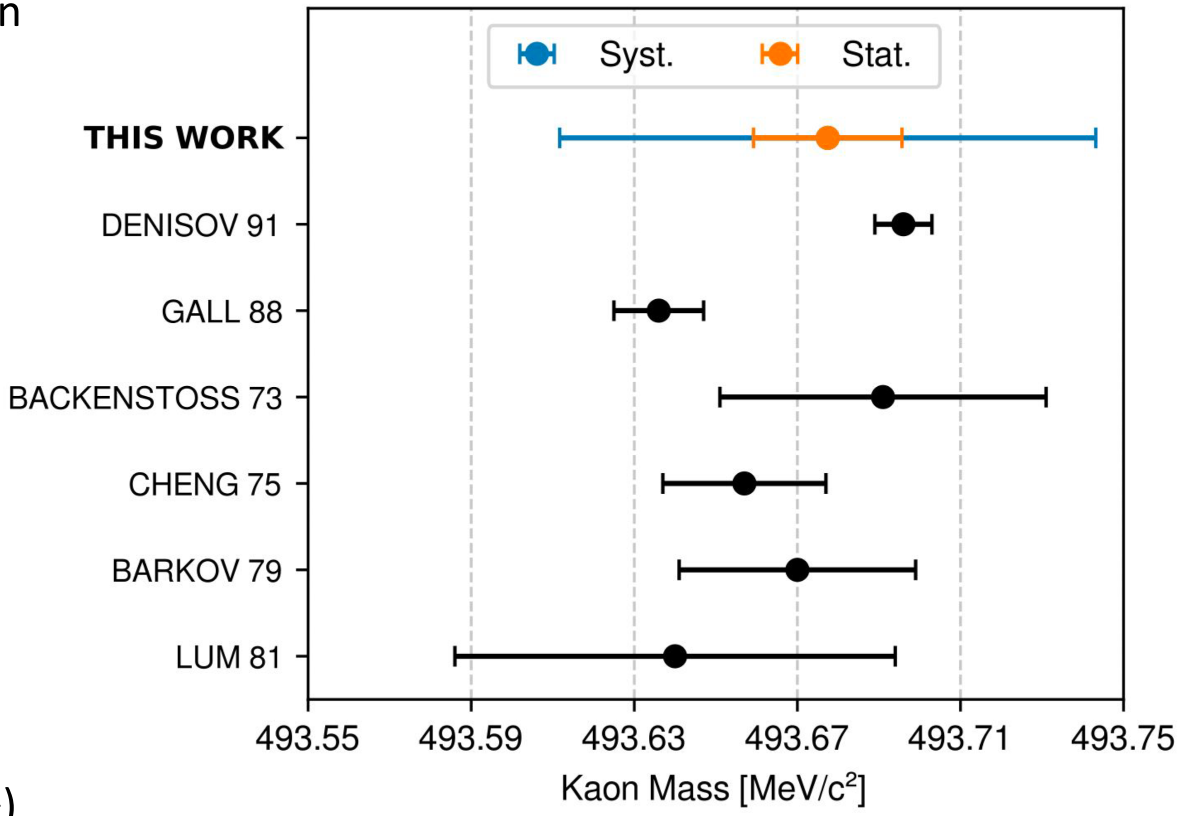
Kaonic neon is the ideal system to precisely determine the kaon mass:

- **fully ionized** :no electron screening as in kaonic lead
- **low-density gas target**: negligible electron refill compared to solid targets like Pb and C

- **Theoretical Uncertainties** stem from **Electron Screening** and depend on occupation of a **K-shell** electron in the 1s during the transition

- M_{K^-} = 493.677 + 0.018 (stat) + 0.066 (syst) 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 pb^{-1} → 300 pb^{-1})
  x 2 improvement by Optimized Gas Target Design and calibration system
    (lower statistical and systematic ->0)

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

BSQED and Physics beyond Schwinger limit

1.2 - Light kaonic atoms (LHKA)
– solid target Li, Be, B
– integration of 1mm SDD

Low energy QCD – kaon multi-nucleon interaction

EXKALIBUR

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

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

- **Feasibility** with **minimal modifications/addings** of the already existent SIDDHARTA-2
  - ➢ New calibration system (0.2 eV accuracy)
  - ➢ New 1mm thick SDDs
  - ➢ New and improved CZT setup
- **Impact**: i.e. the **maximal scientific outcome:** KN and KNN interaction at threshold; Nuclear density distributions; Kaonic atoms cascade models; kaon mass; BSQED; Physics beyond Schwinger limit

Conclusion

- **First measurement of kaonic deuterium 1s level shift and width**

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

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

Preliminary

- **First proof-of-concept for QED studies with kaonic atoms** from an experimental and theoretical perspective.

Transition	$E_{if}^{(exp.)}$	$\delta E_{if}^{(stat.)}$	$\delta E_{if}^{(sys.)}$	$E_{if}^{(calc.)}$	$E_{if}^{(QED)}$	$E_{if}^{(QED1)}$	$E_{if}^{(QED2)}$	$\Delta E_{if}^{(isot.)}$	$\Delta E_{if}^{(screen.)}$	$\Delta E_{if}^{(PDG)}$
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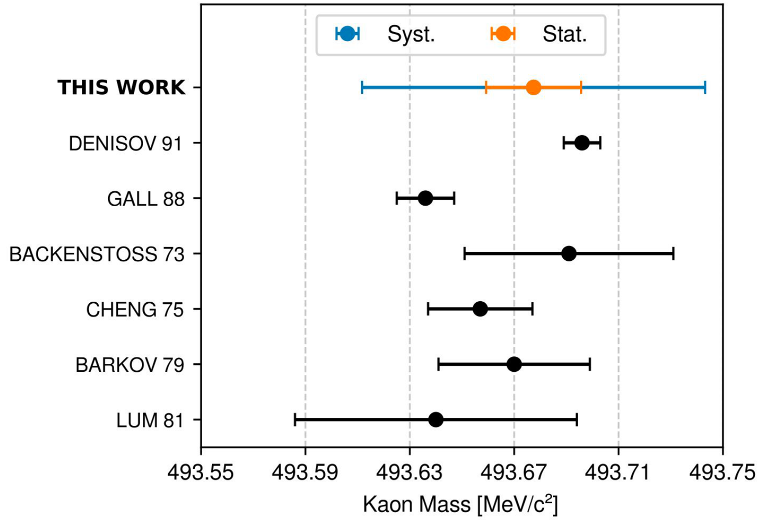
6h-5g[a]	15673.30	0.52	9.00	15685.39	32.75	32.51	0.24	37.01	-0.11	0.40

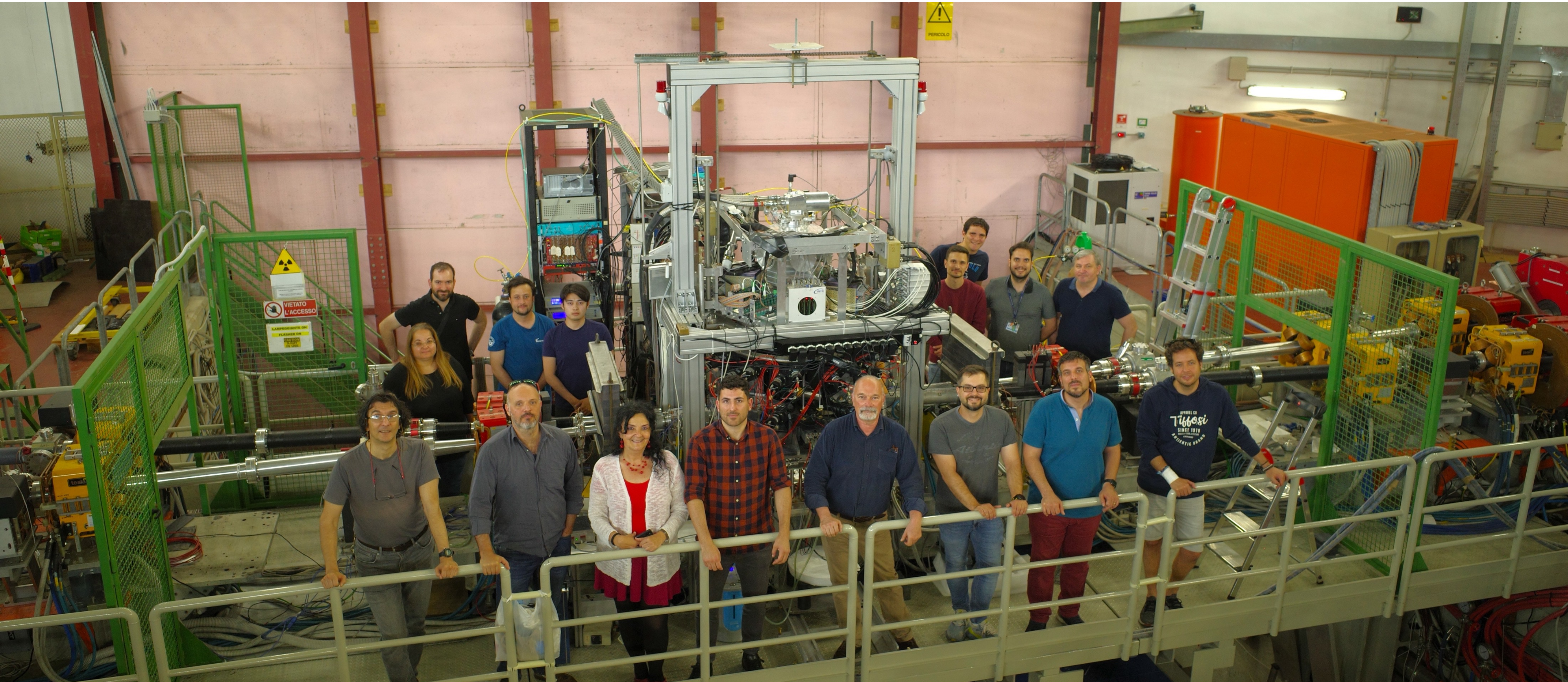
- **Kaonic neon X-ray spectroscopy ideal candidate to solve the kaon mass discrepancy**



- **EXKALIBUR:** new X-ray detectors (**SDDs – CZT - HPGe**) have been developed/tested to perform **kaonic atoms measurements along the periodic table** providing new experimental data to probe the **kaon-nucleus interaction – kaon mass - BSQED**

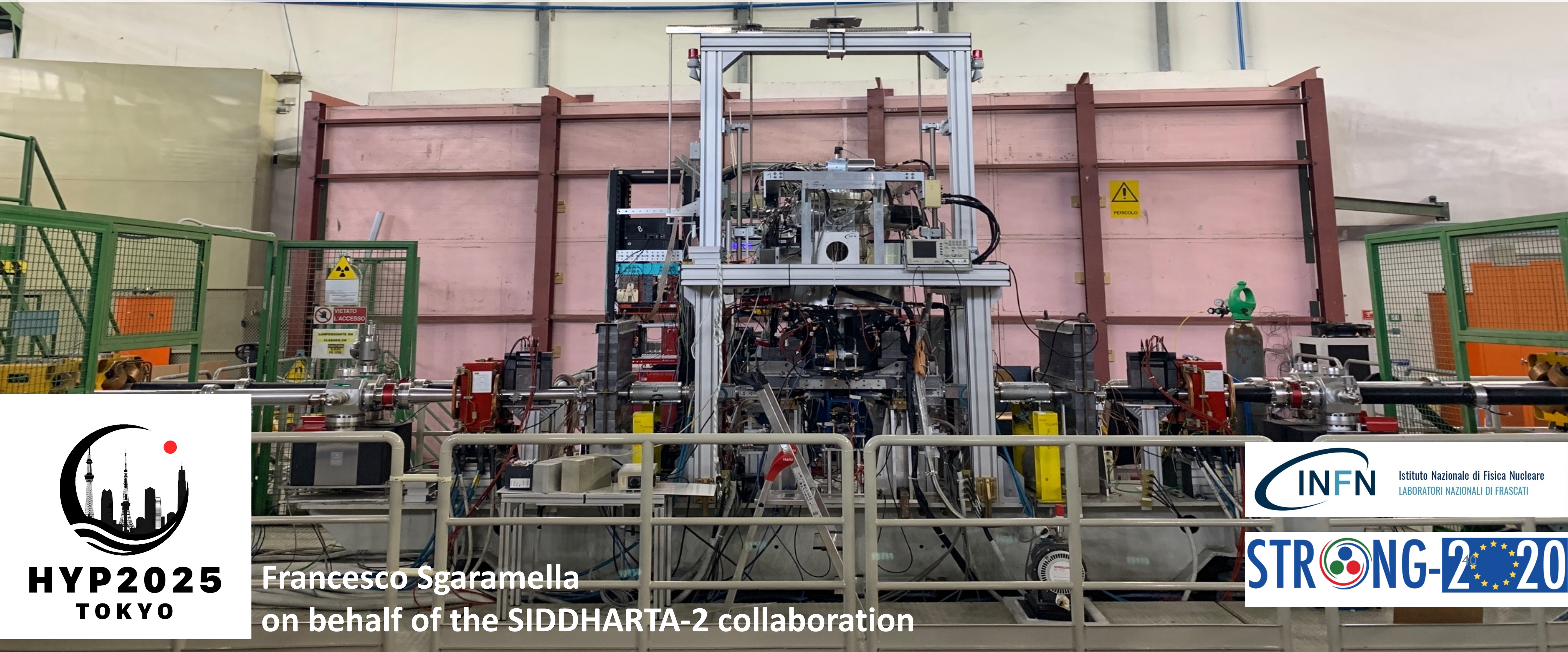
We dedicate these results to our dear friends and colleagues **Prof Carlo Guaraldo and Dr. Johann Zmeskal** who passed away in 2024. You are very much missed!

THANK YOU



SPARE

EXPLORING THE STRANGENESS FRONTIERS: KAONIC ATOMS X-RAY SPECTROSCOPY AT DAFNE WITH SIDDHARTA-2



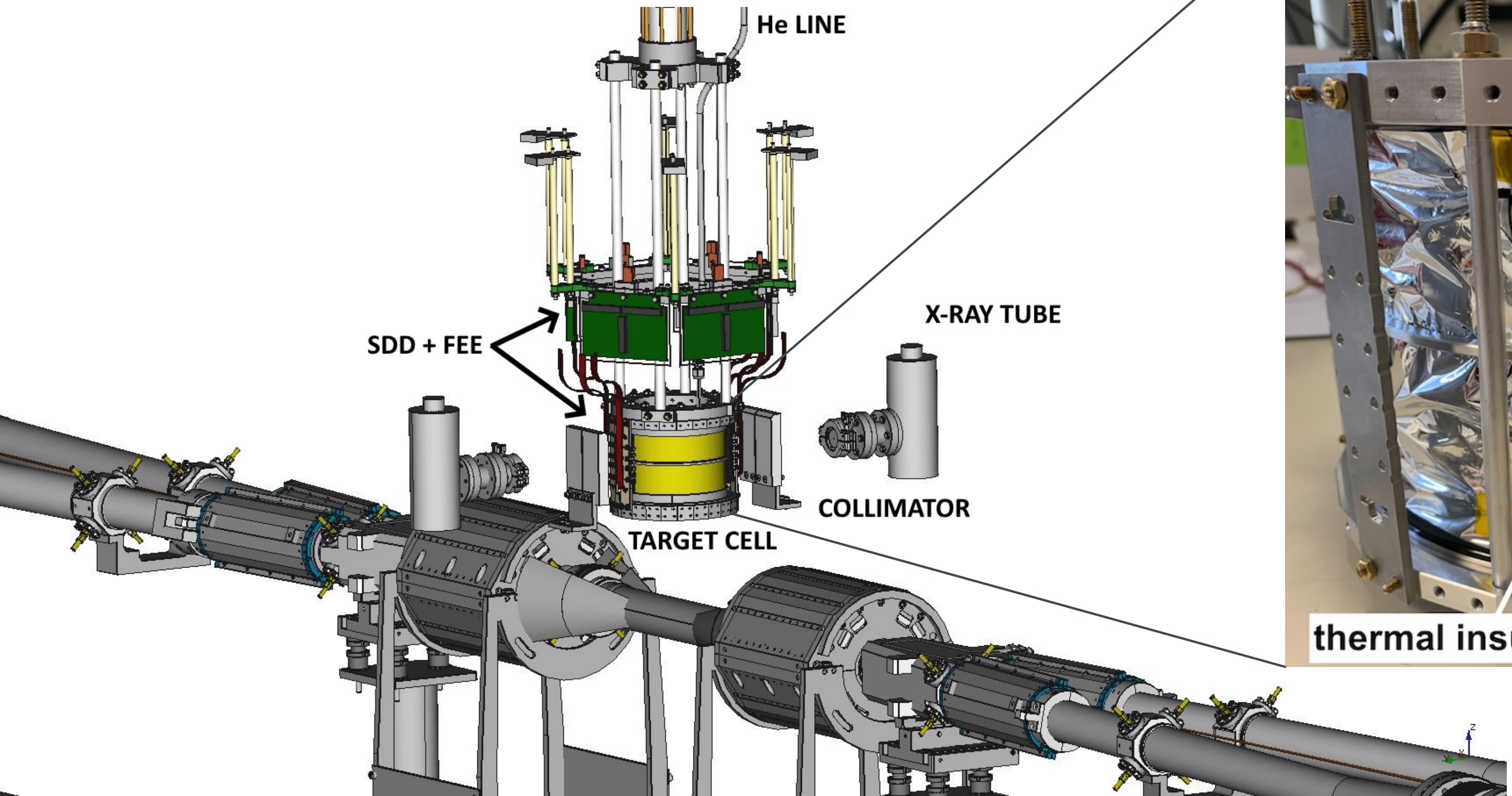
HYP2025
TOKYO

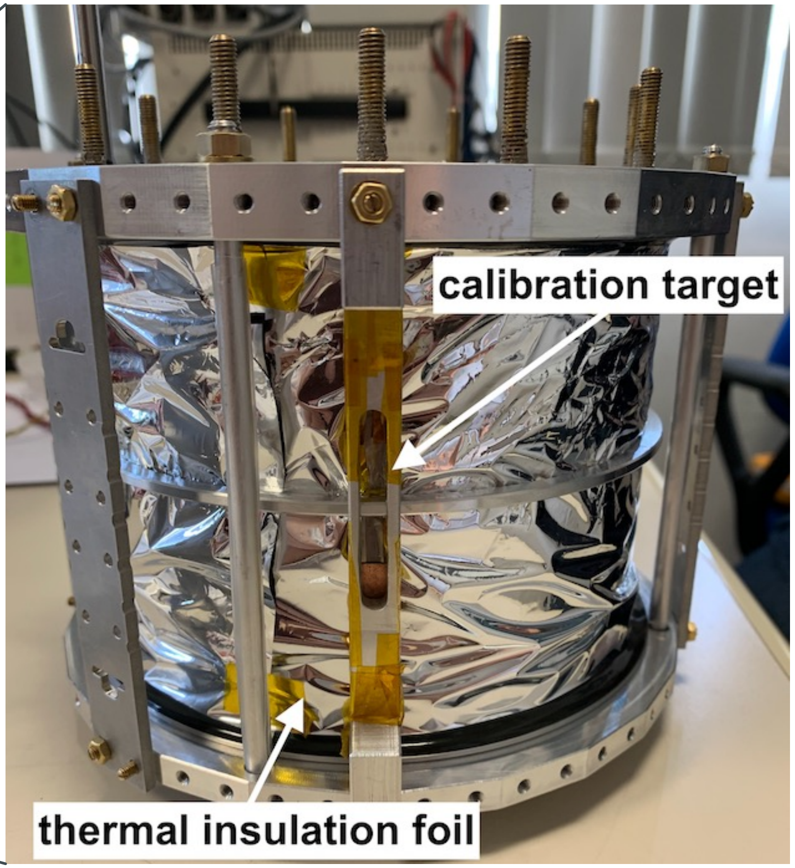
Francesco Sgaramella
on behalf of the SIDDHARTA-2 collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

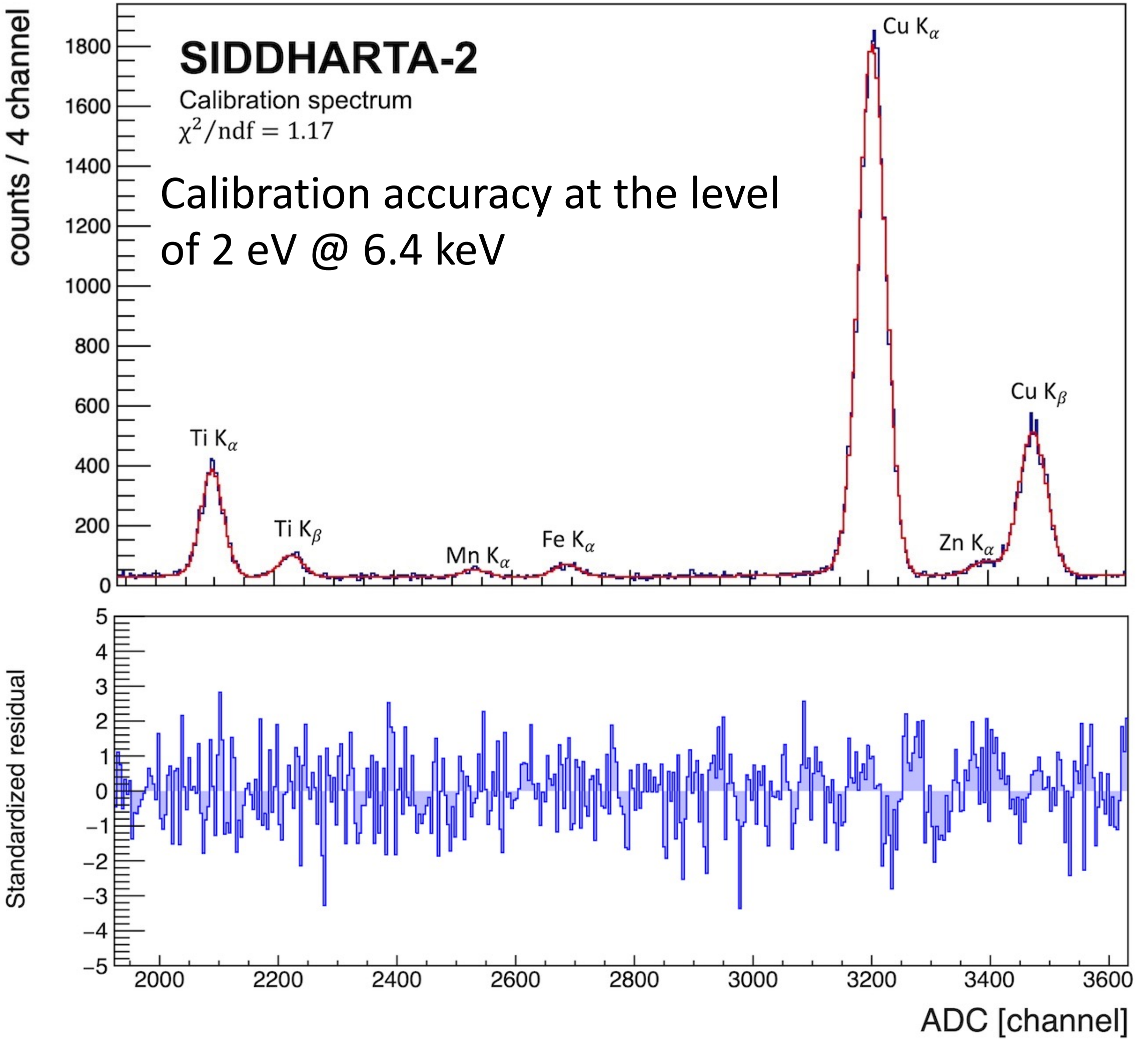
STRONG-2020

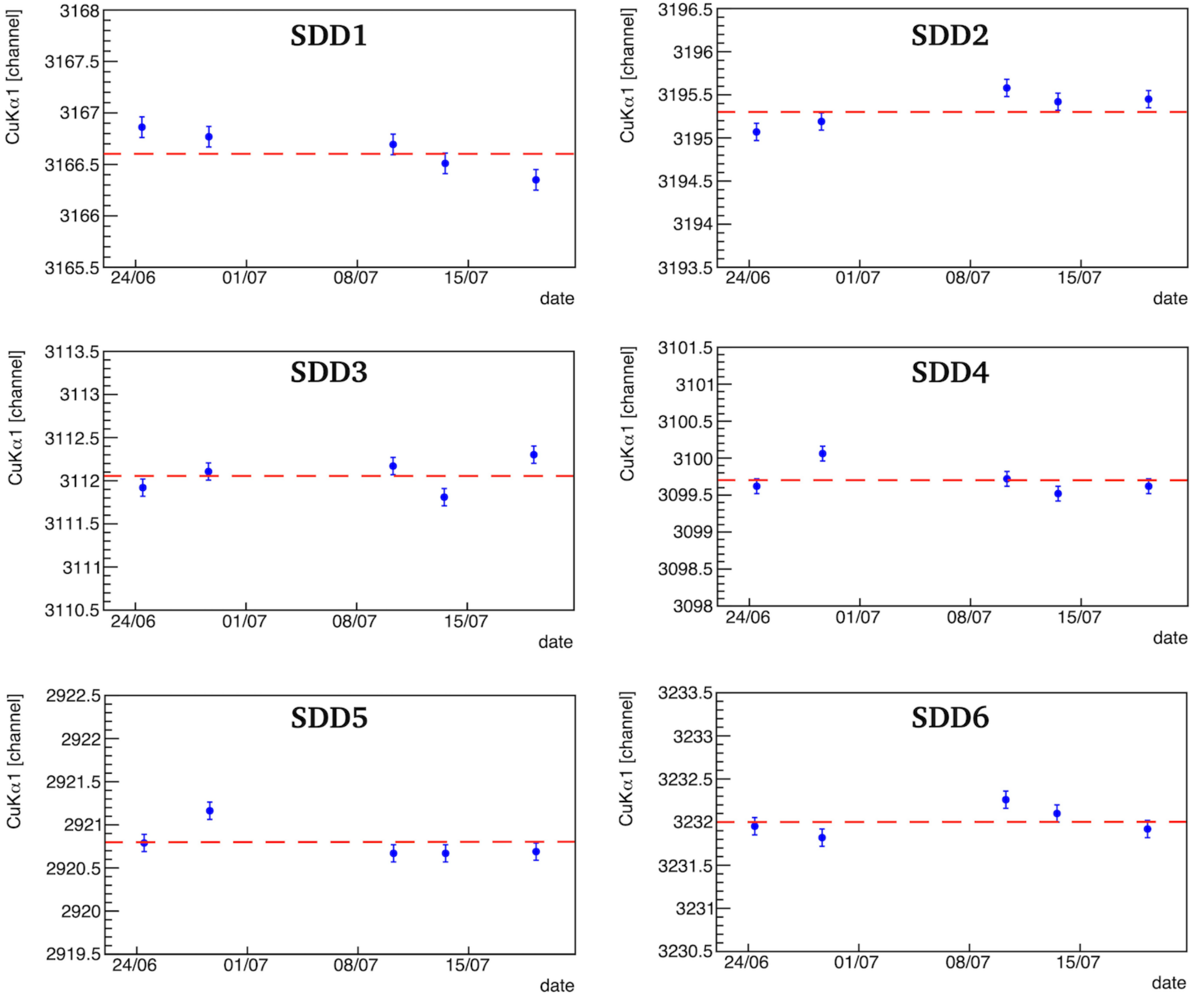
SDDs Calibration Procedure in DAΦNE





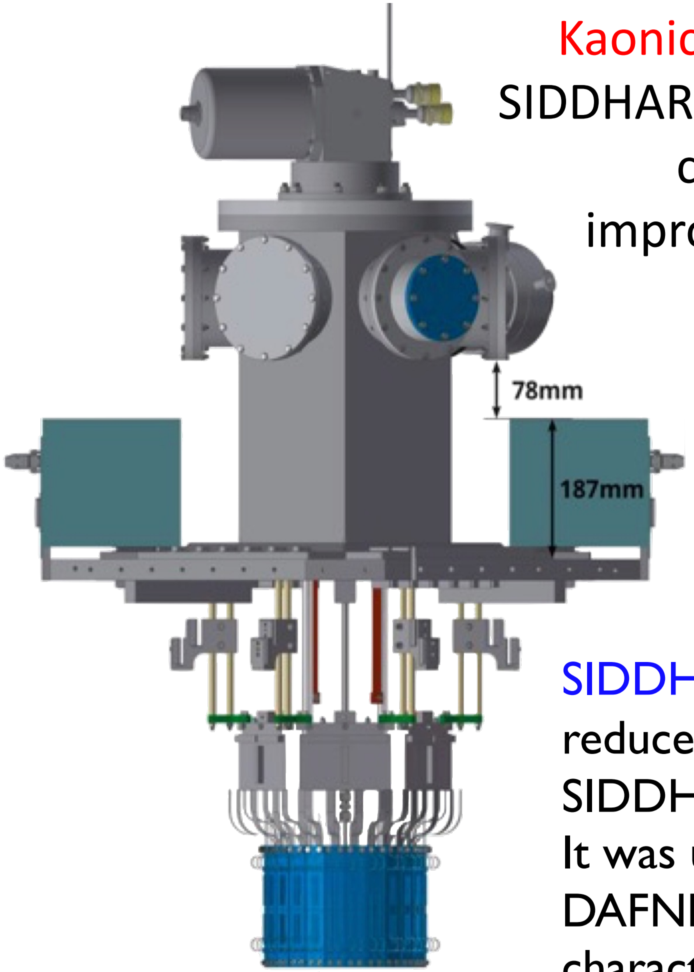
SDDs Calibration Procedure in DAΦNE





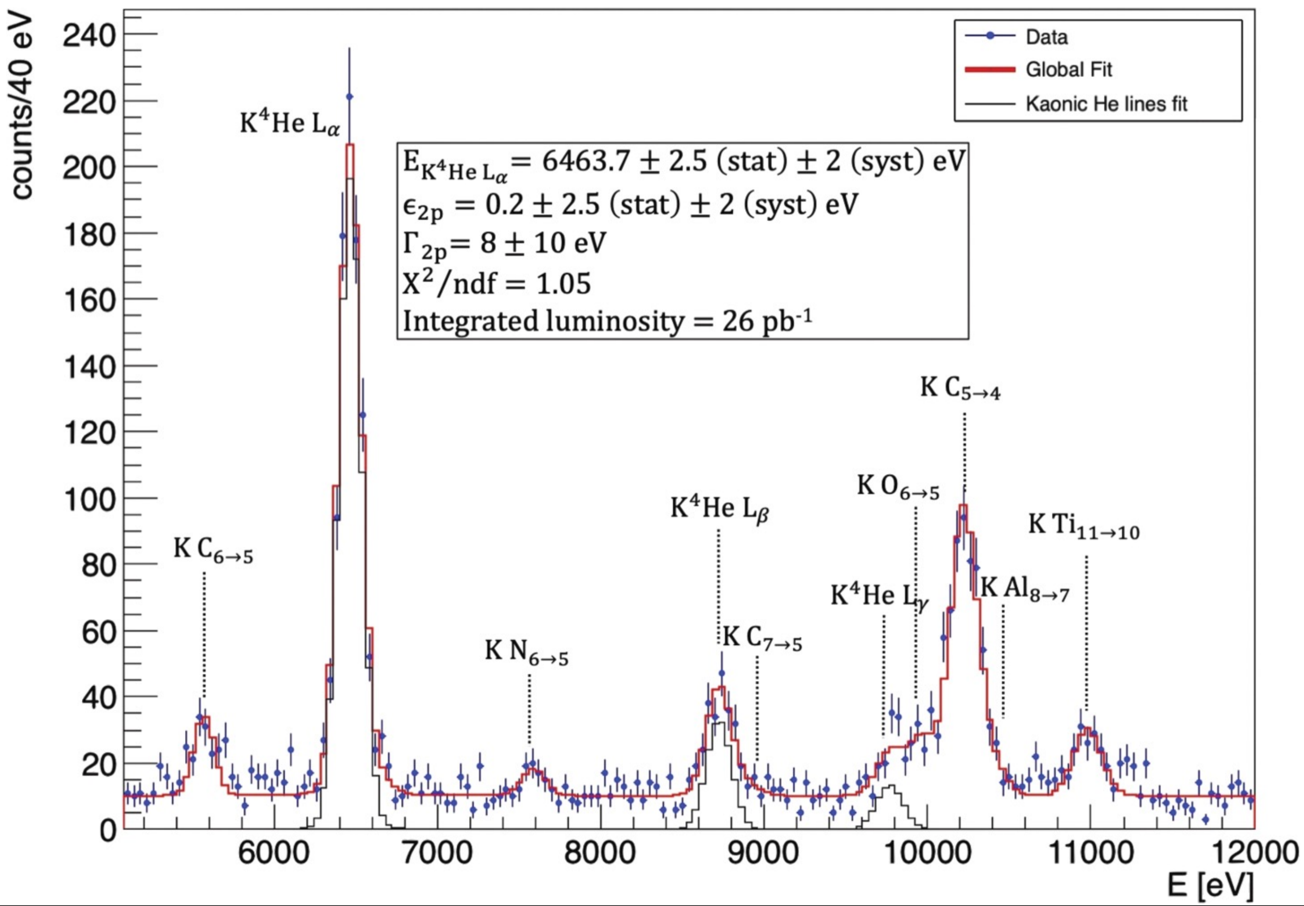
SIDDHARTINO - The kaonic ^{4}He 3d->2p measurement

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



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

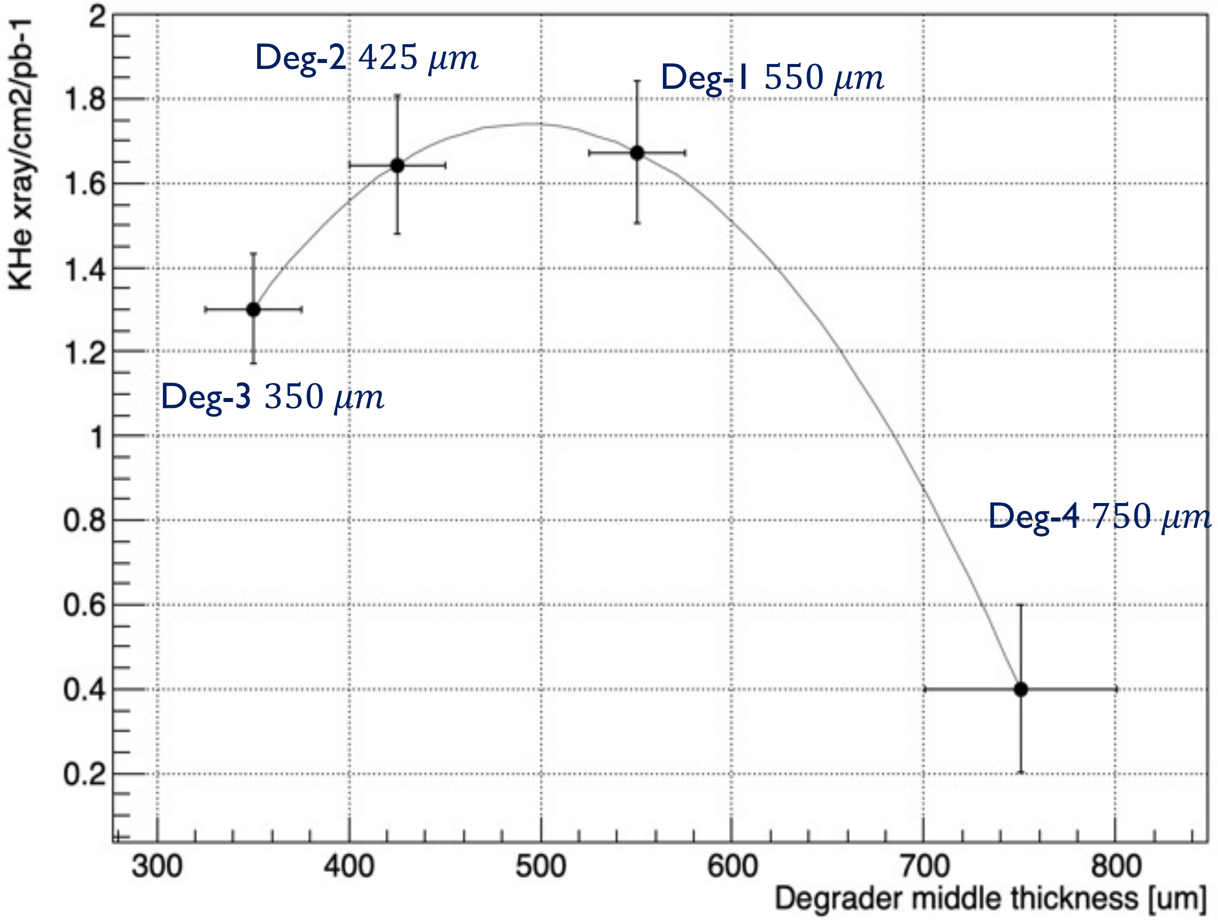
SIDDHARTINO:
reduced version of the SIDDHARTA-2 apparatus
It was used to optimize the DAFNE background and characterize the SDDs



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 (L_α) measurement



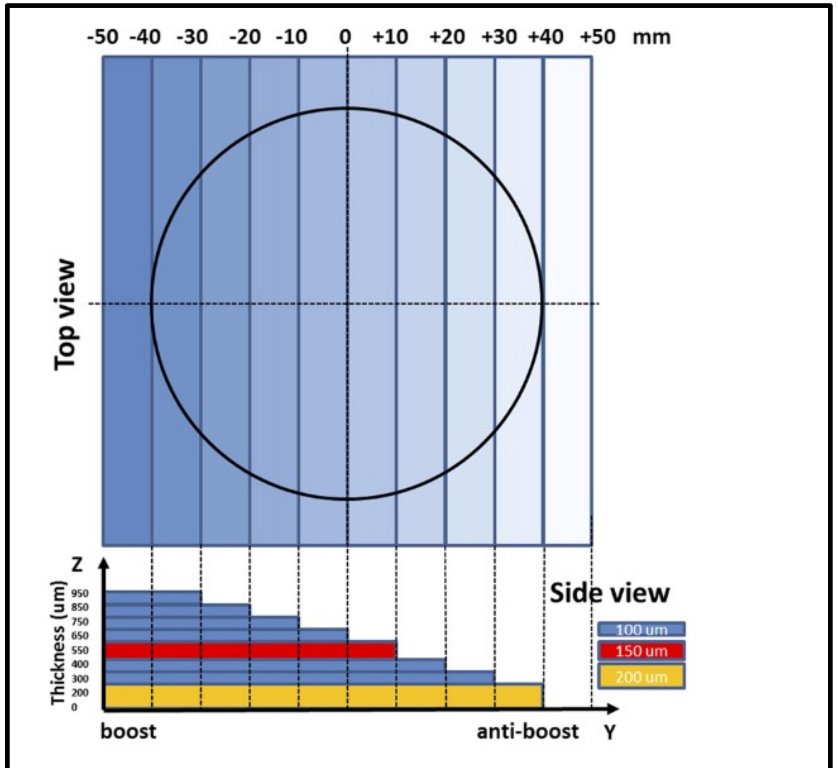
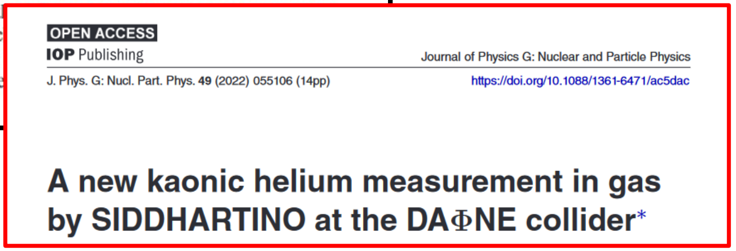


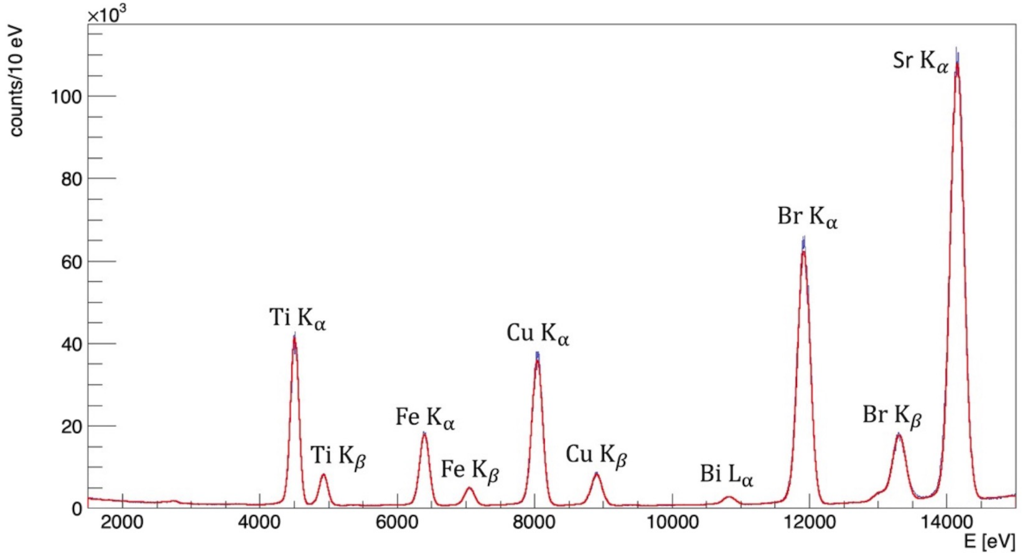
Figure 6. Nearest to optimal configuration of t
the size of the entrance window of the vacuum c
side of the DAΦNE ring, corresponding to the
has eight steps to compensate for the boost effe
part of the figure.

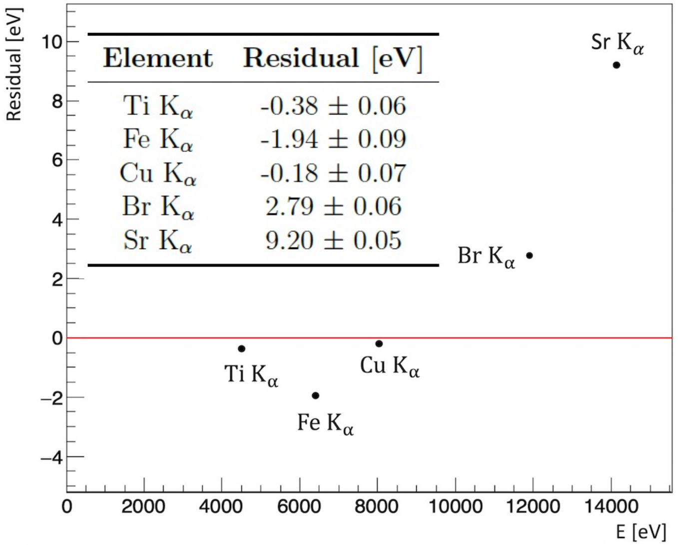


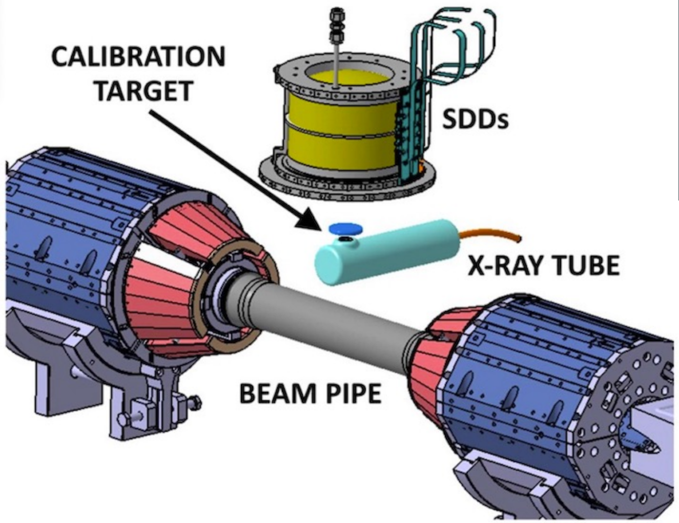
OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 49 (2022) 055106 (14pp)
https://doi.org/10.1088/1361-6471/ac5dac

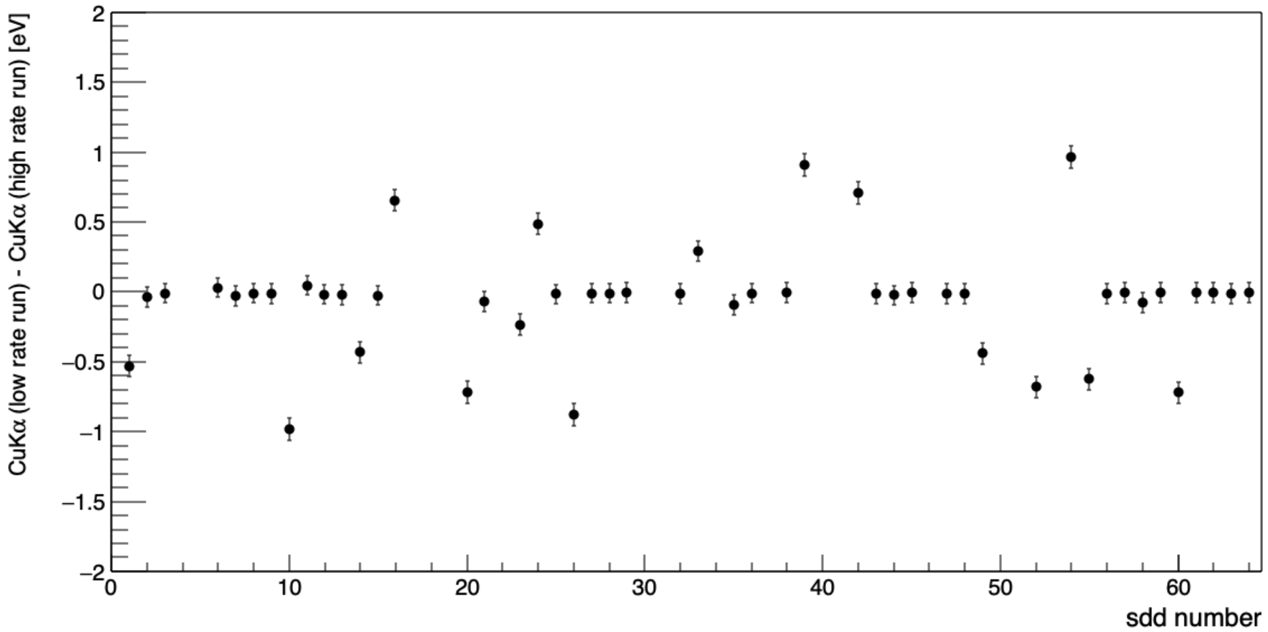
A new kaonic helium measurement in gas by SIDDHARTINO at the DAΦNE collider*

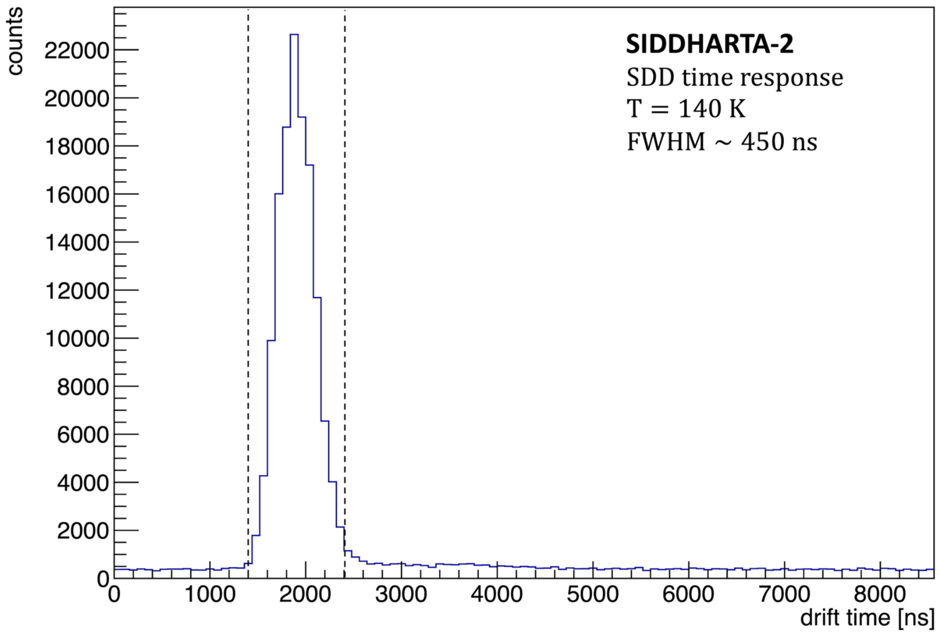
Spectroscopy Response in a High Background Environment











Sgaramella F., Miliucci M., et al., 2022, Phys Scr, 97 (11) 114002

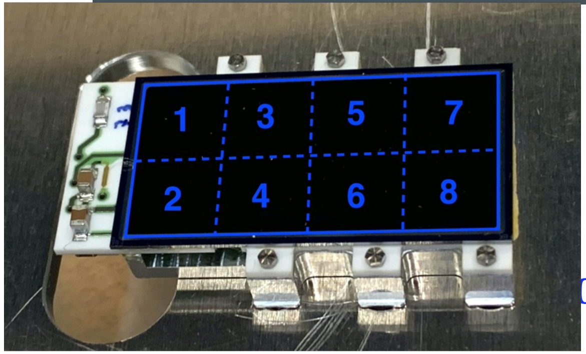
Silicon Drift Detectors

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

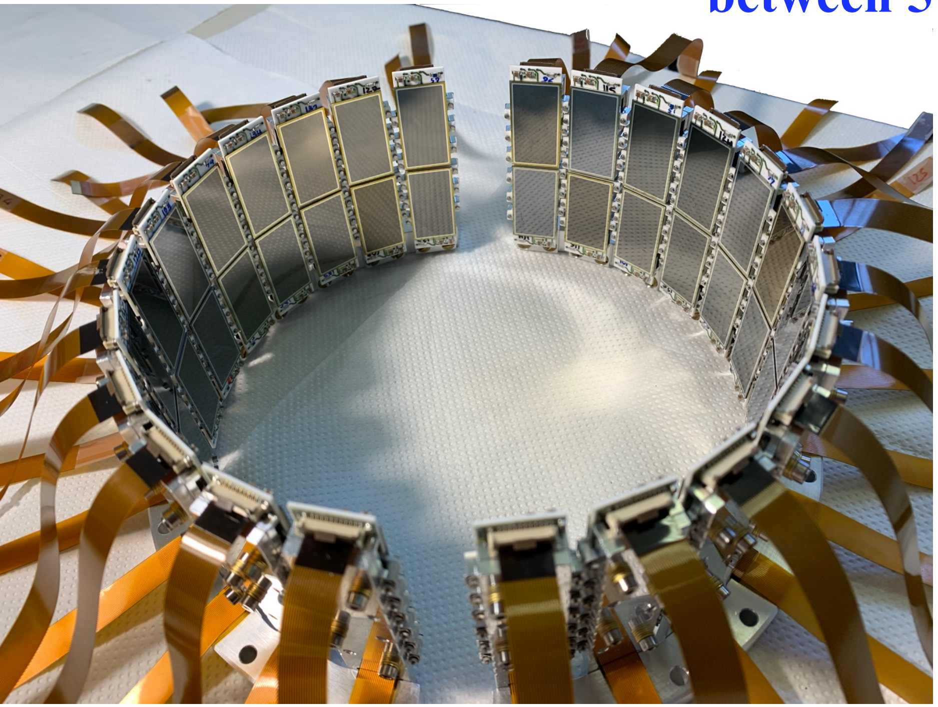
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

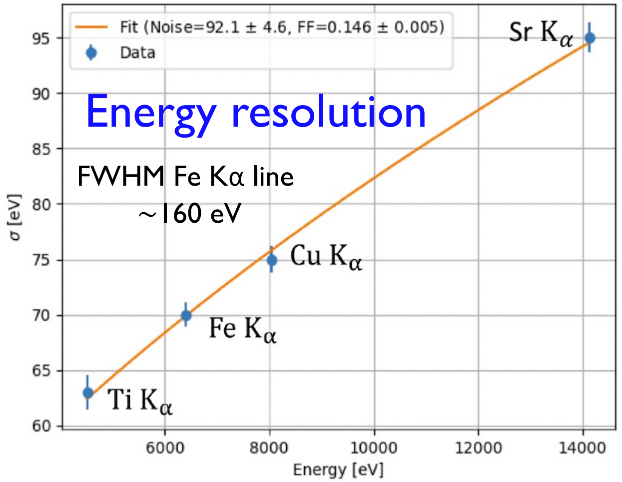
FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

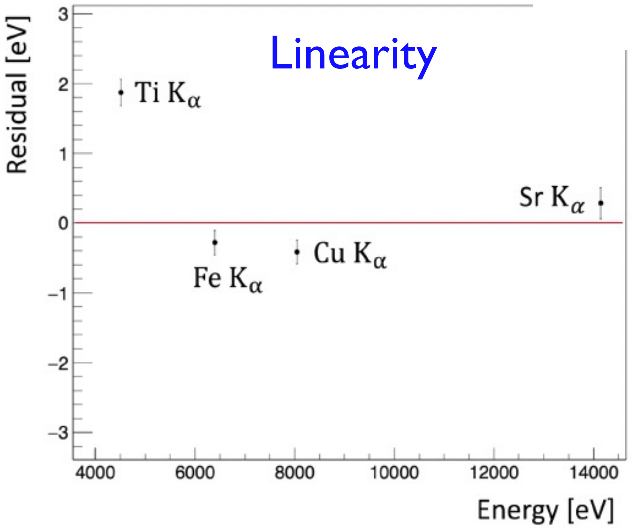
POLITECNICO MILANO 1863

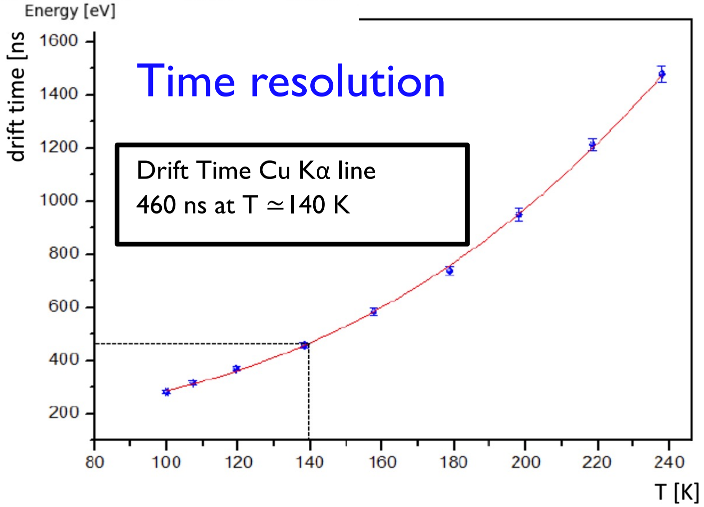


8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of 450 μm ensures a high ollection efficiency for X-rays of energy between 5 keV and 12 keV

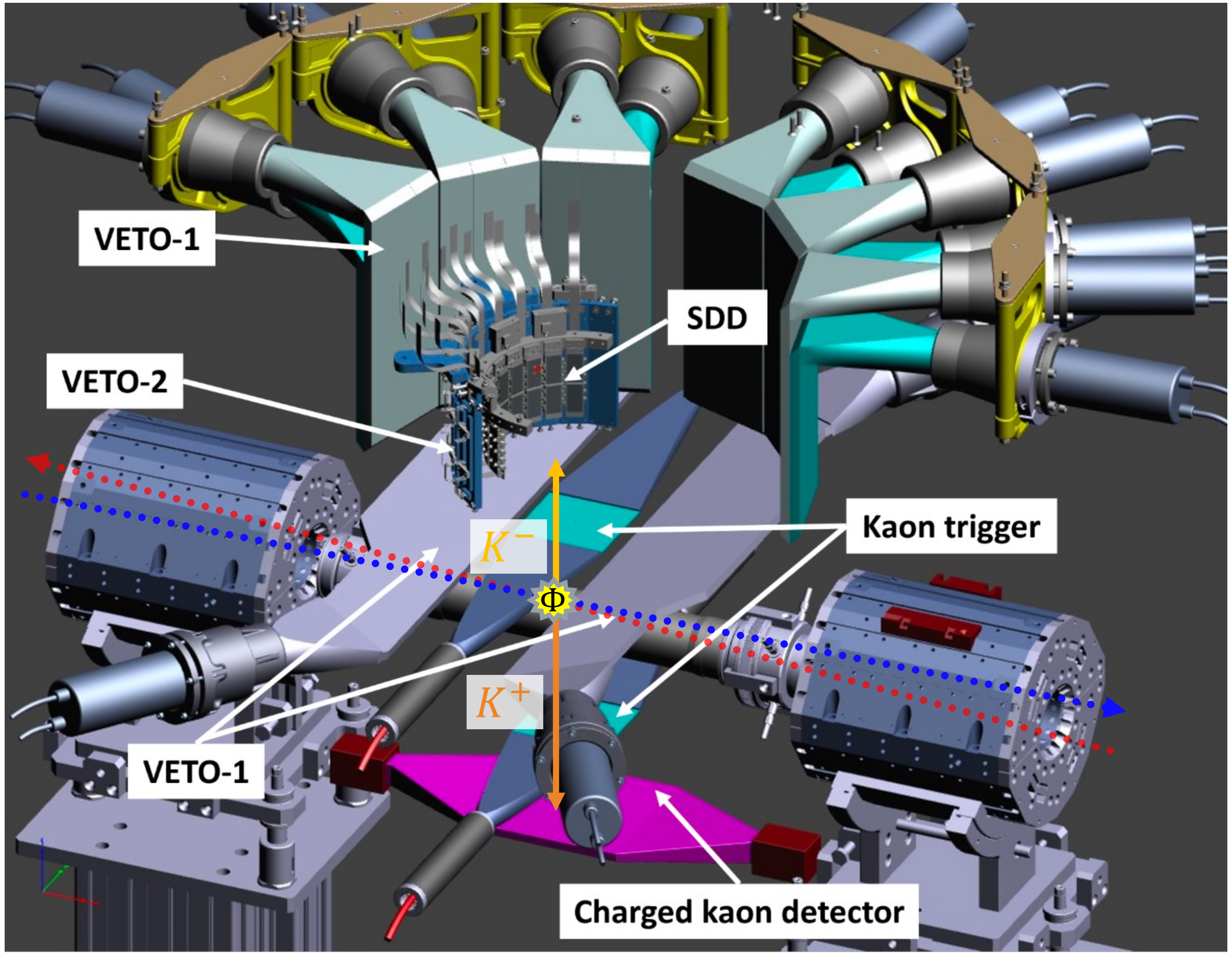




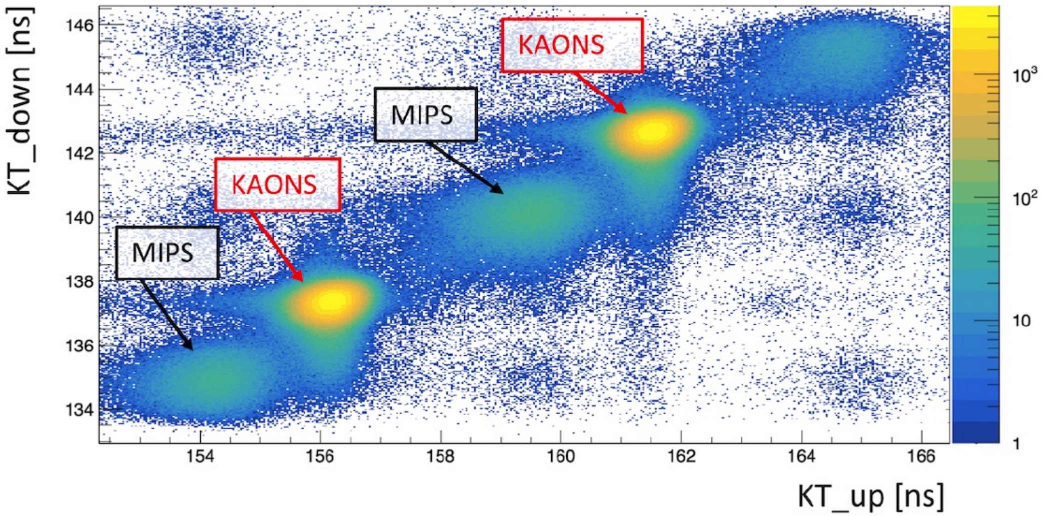




The SIDDHARTA-2 apparatus



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

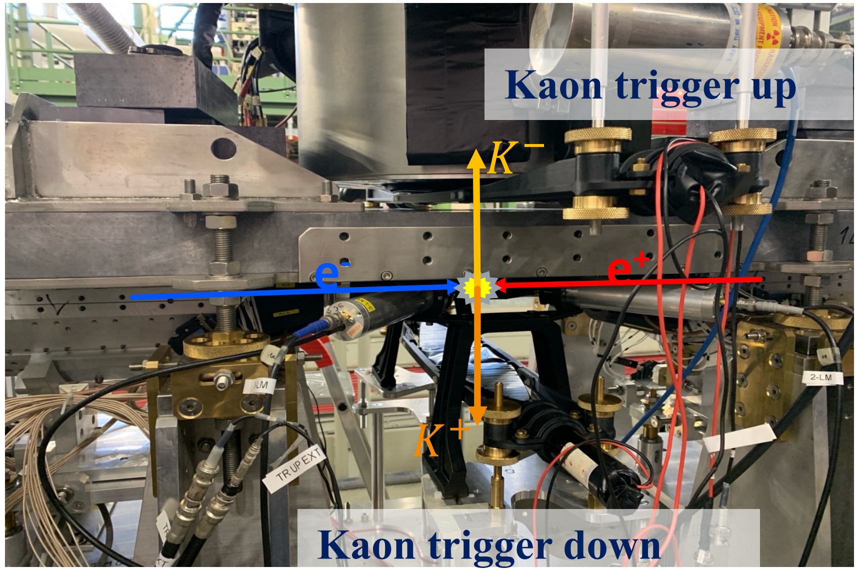


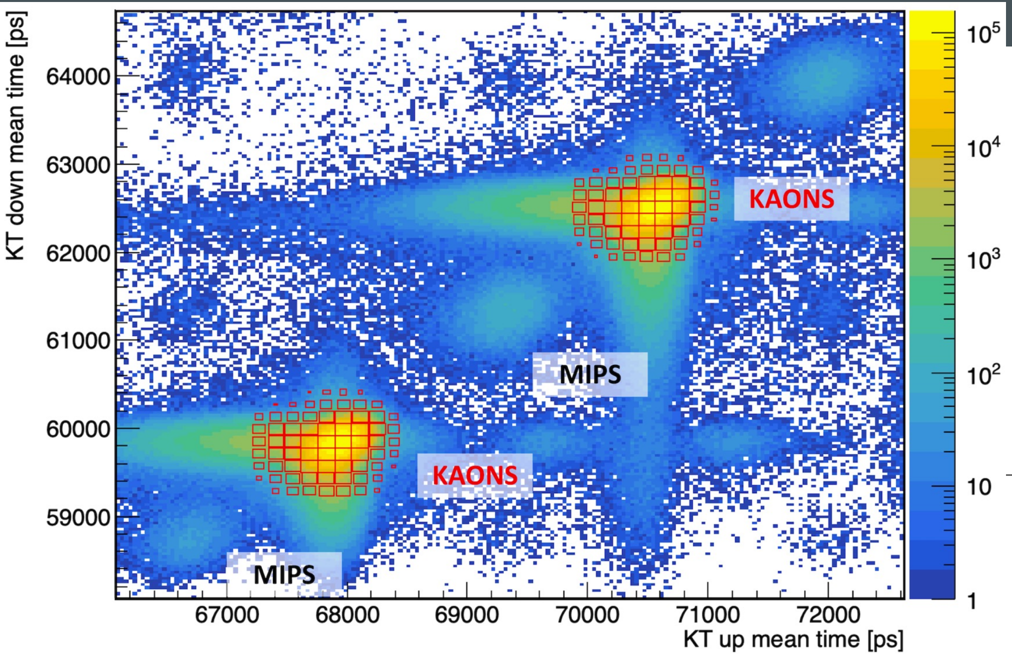
The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

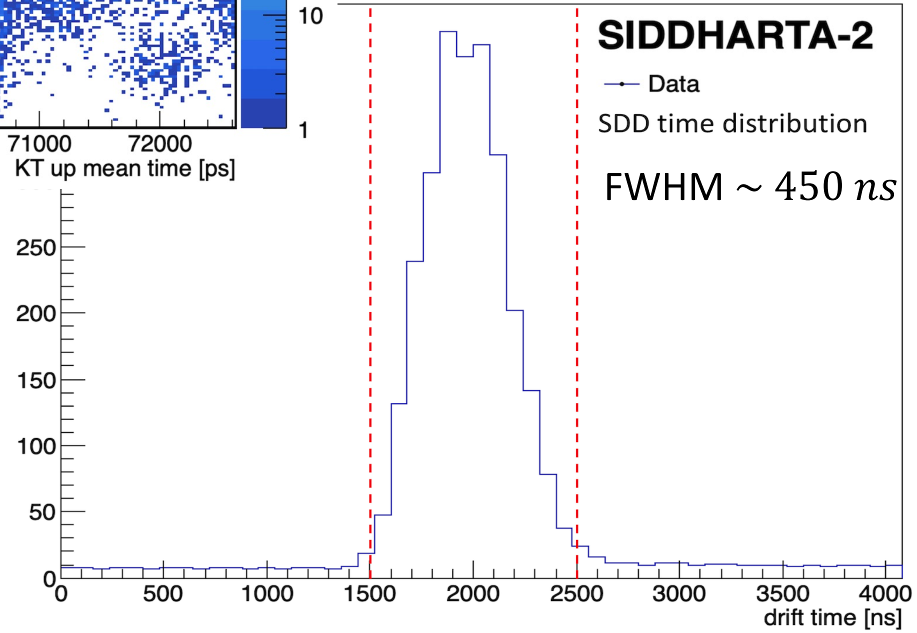
Can efficiently discriminate by ToF Kaons and MIPs!

The first kaonic deuterium measurement

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





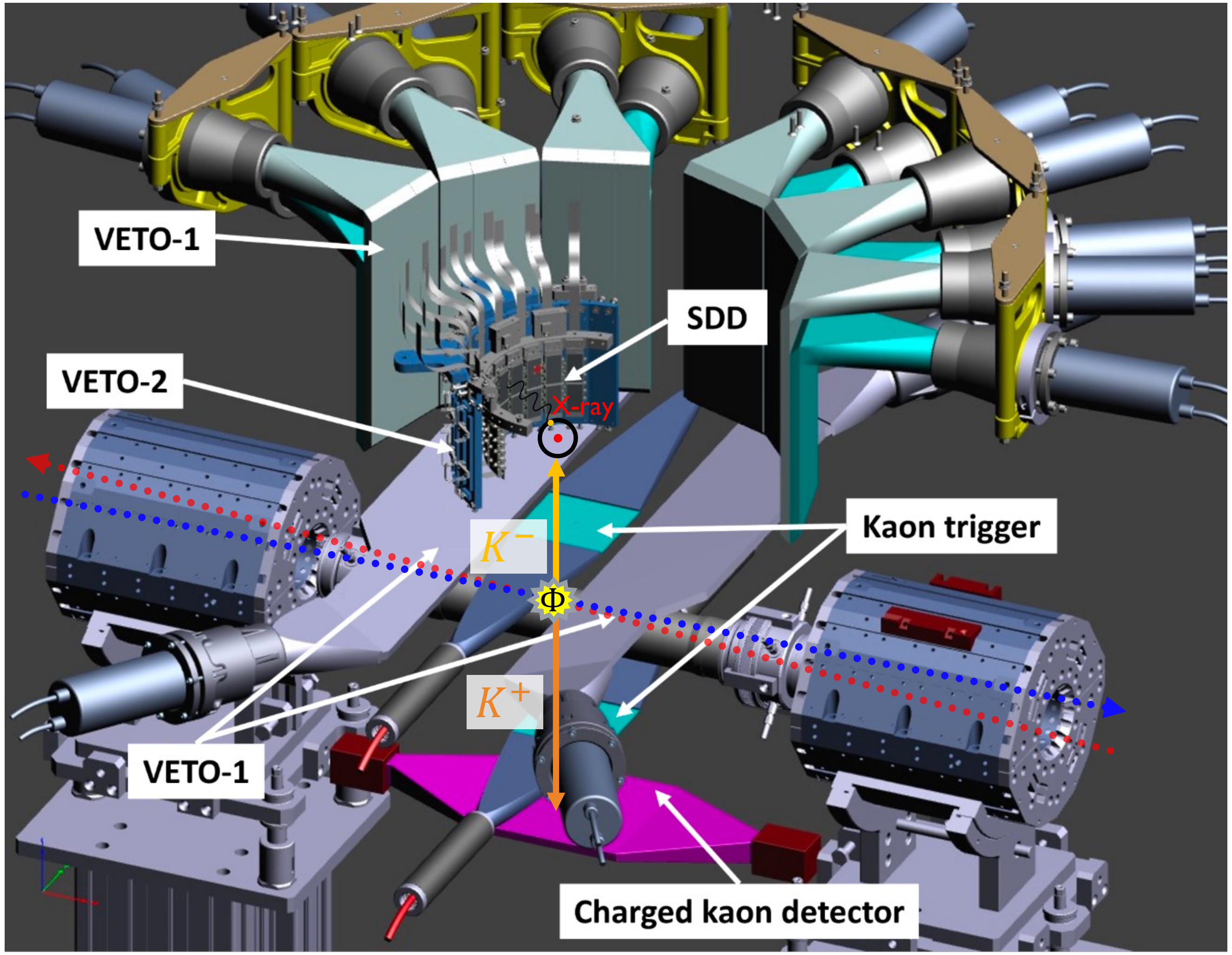


The trigger is generated by the coincidence of 2 back-to-back scintillators

The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

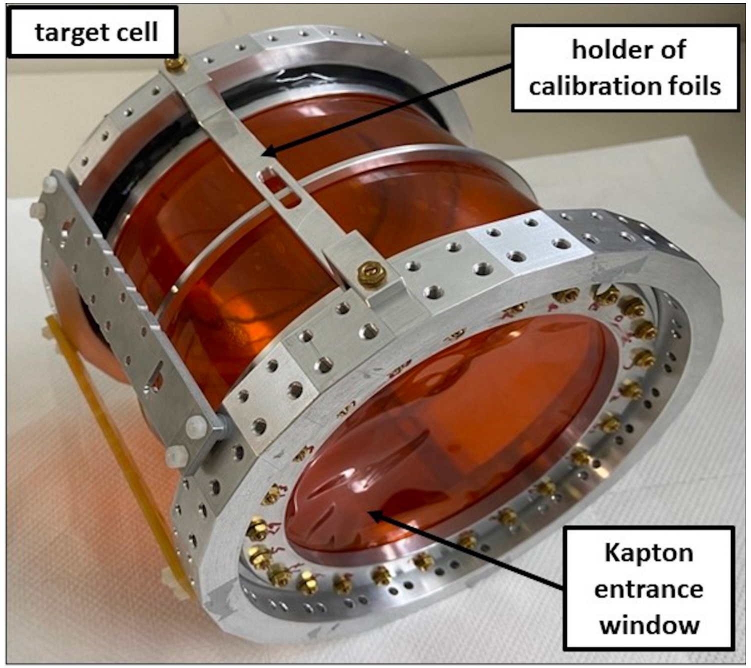
Can efficiently discriminate by ToF Kaons and MIPs!

The SIDDHARTA-2 apparatus

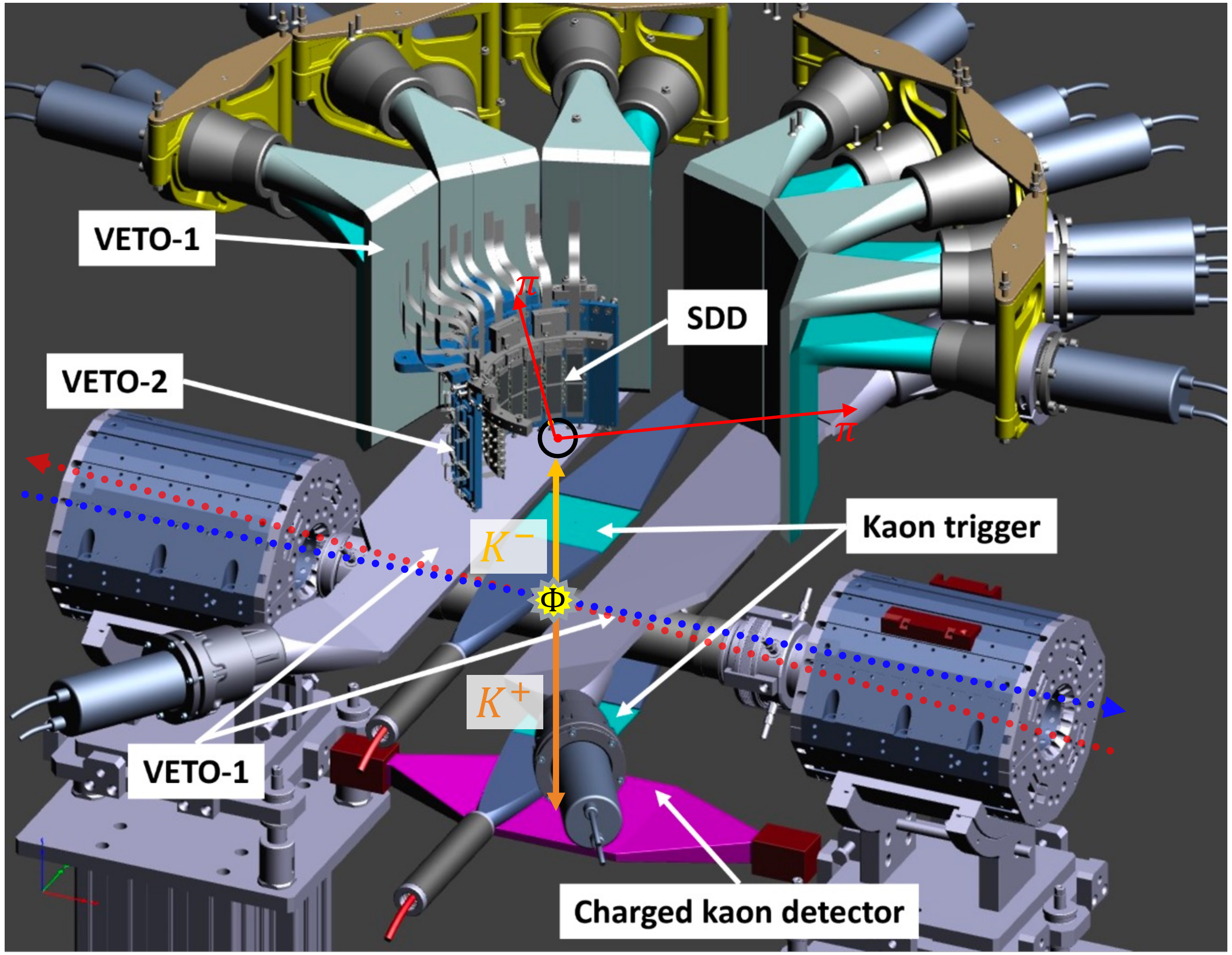


Kaon Trigger: two plastic scintillators read by photomultipliers placed above and below the interaction region.

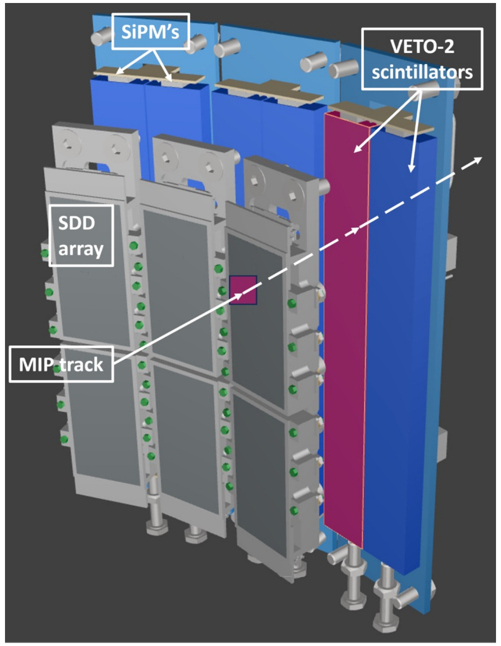
Cryogenic gaseous target cell surrounded by **384 SDDs**

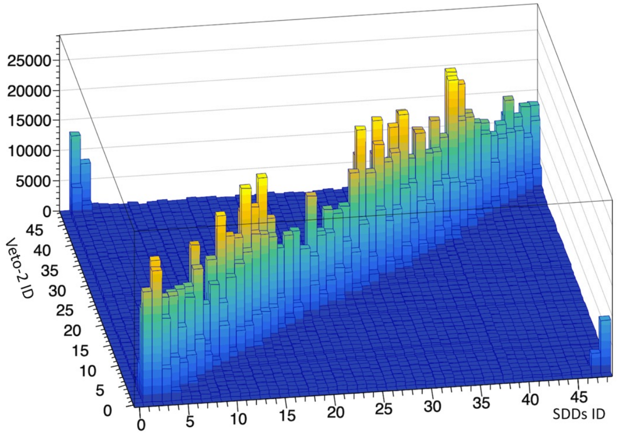


The SIDDHARTA-2 apparatus



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





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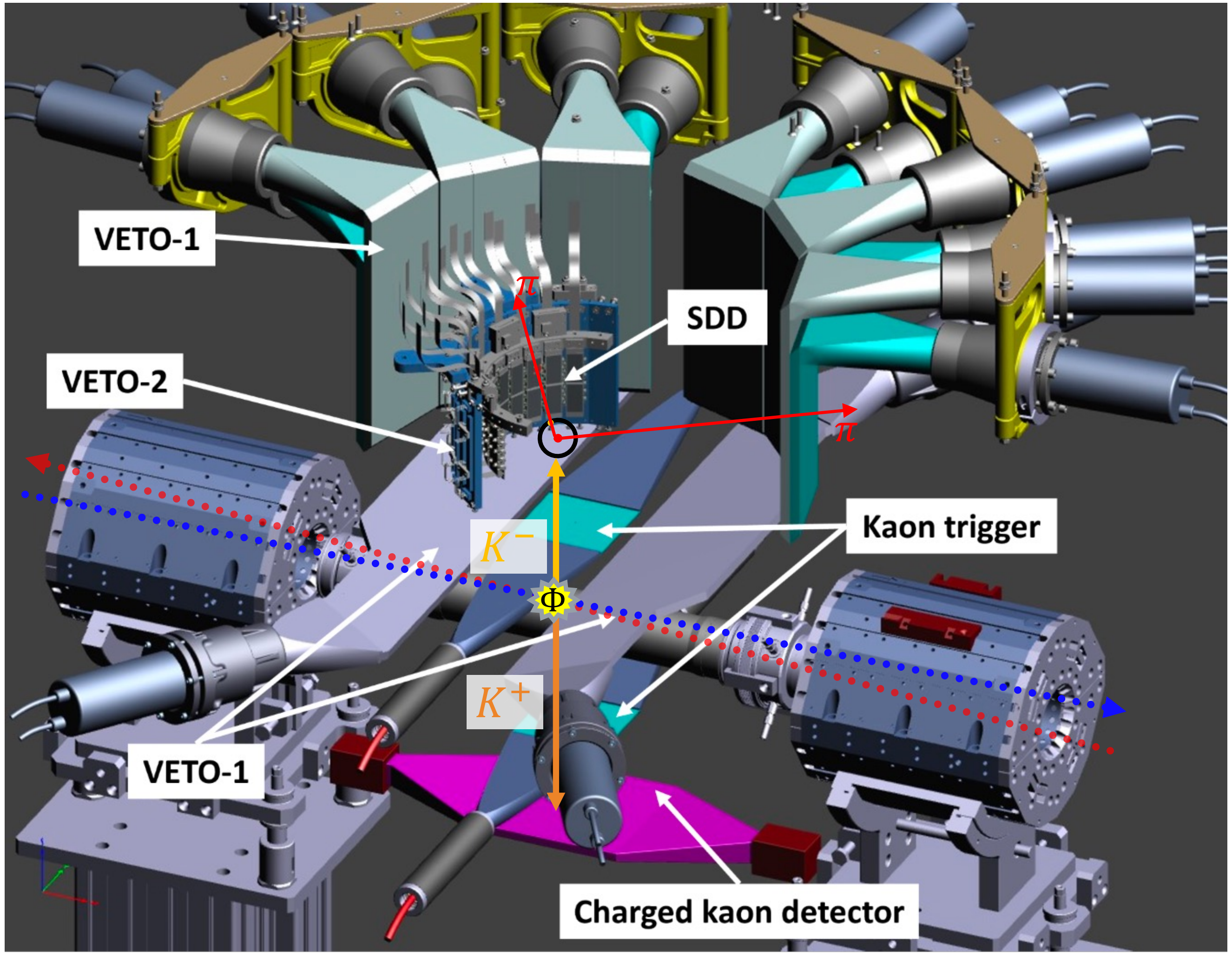
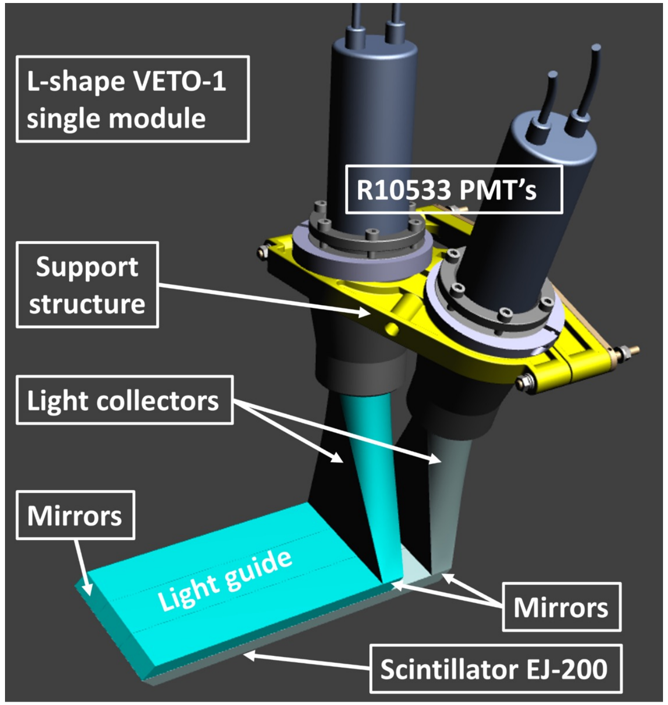
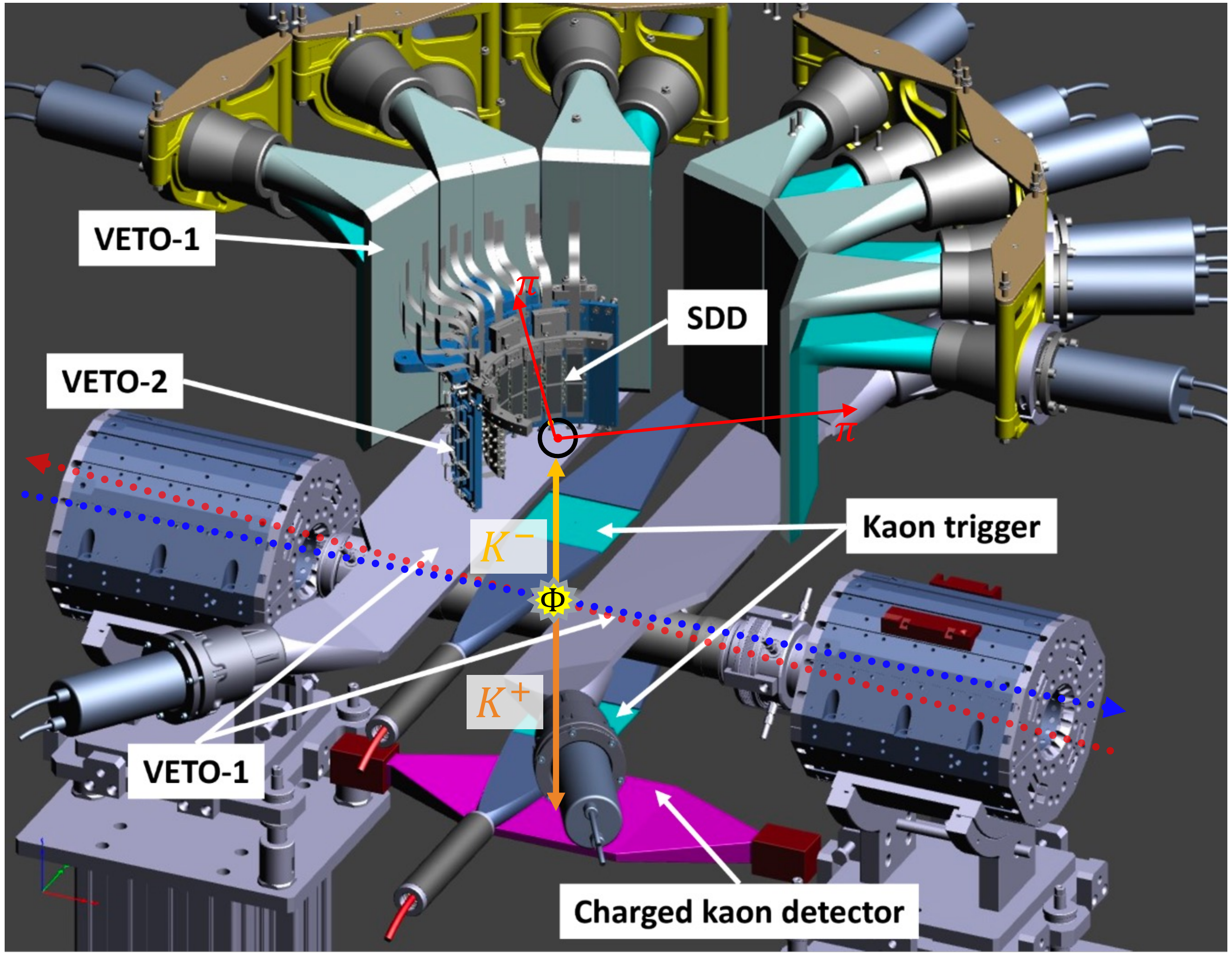


Veto-1 14 plastic scintillator read by PMTs to select the events occurring in the gas target, rejecting the X-ray background corresponding to K- stopped in the solid elements of the setup

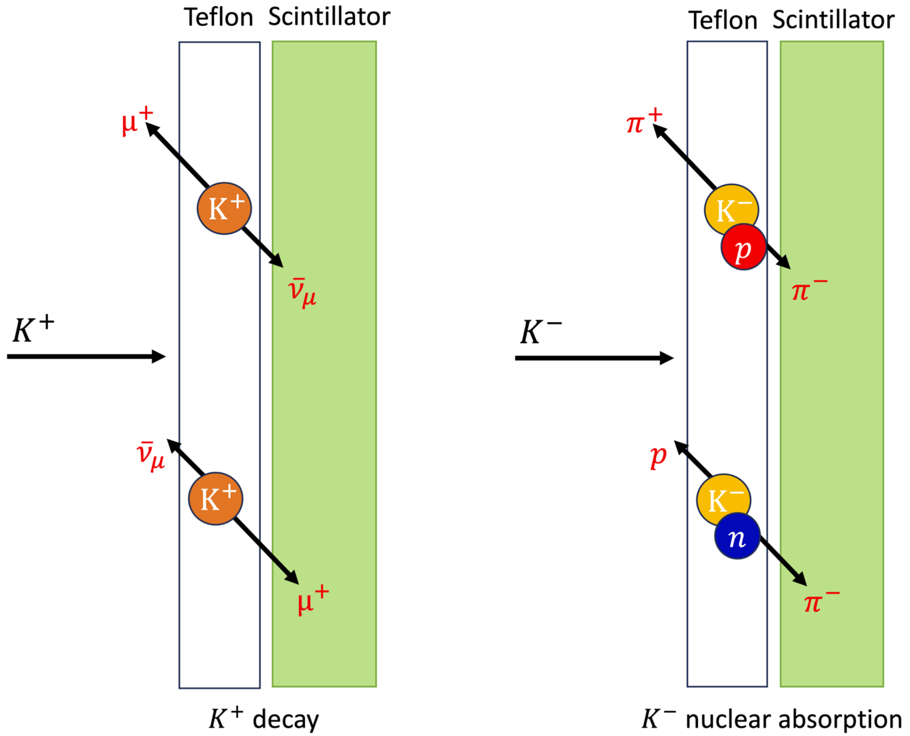


The SIDDHARTA-2 apparatus

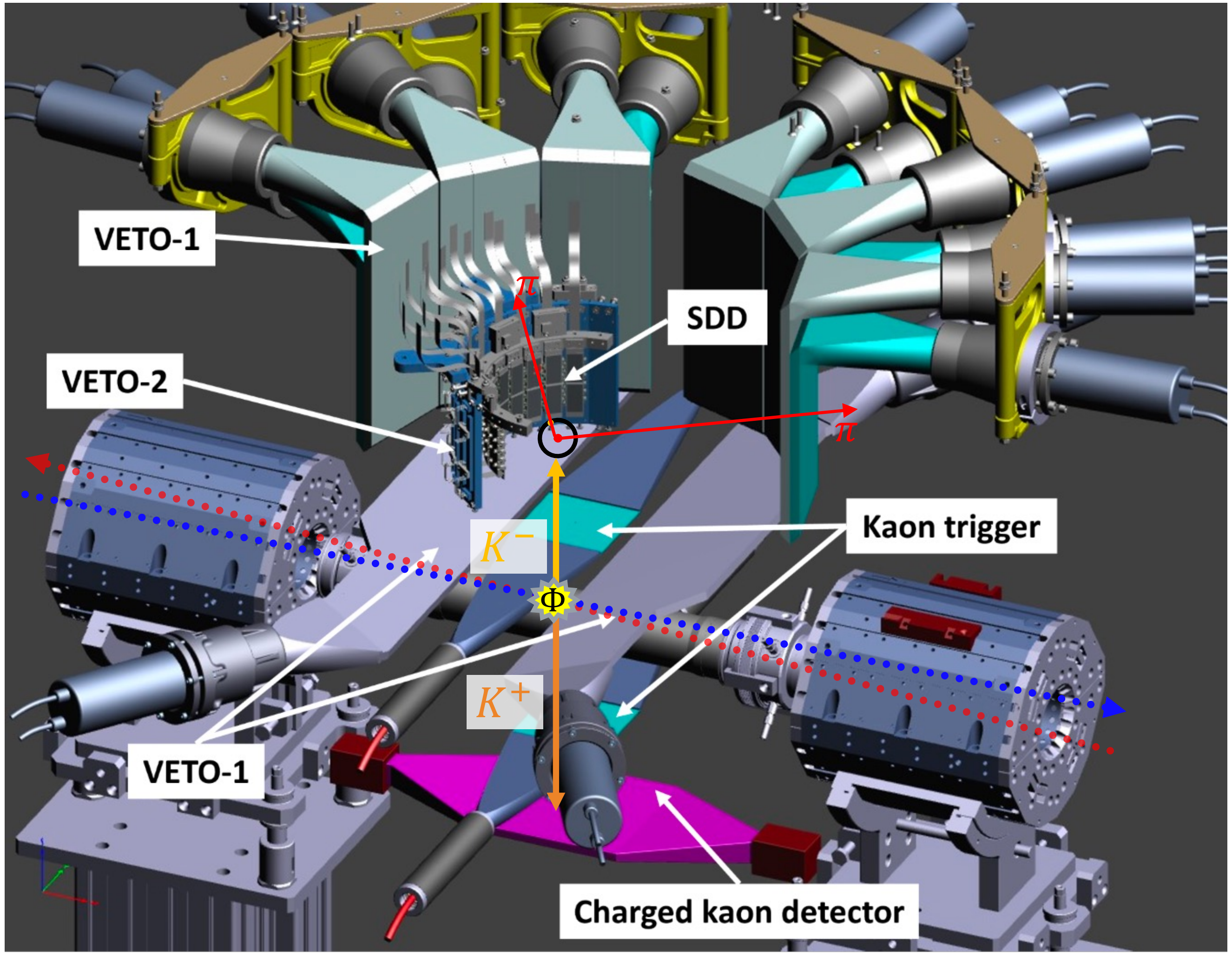


Charged Kaons Veto

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



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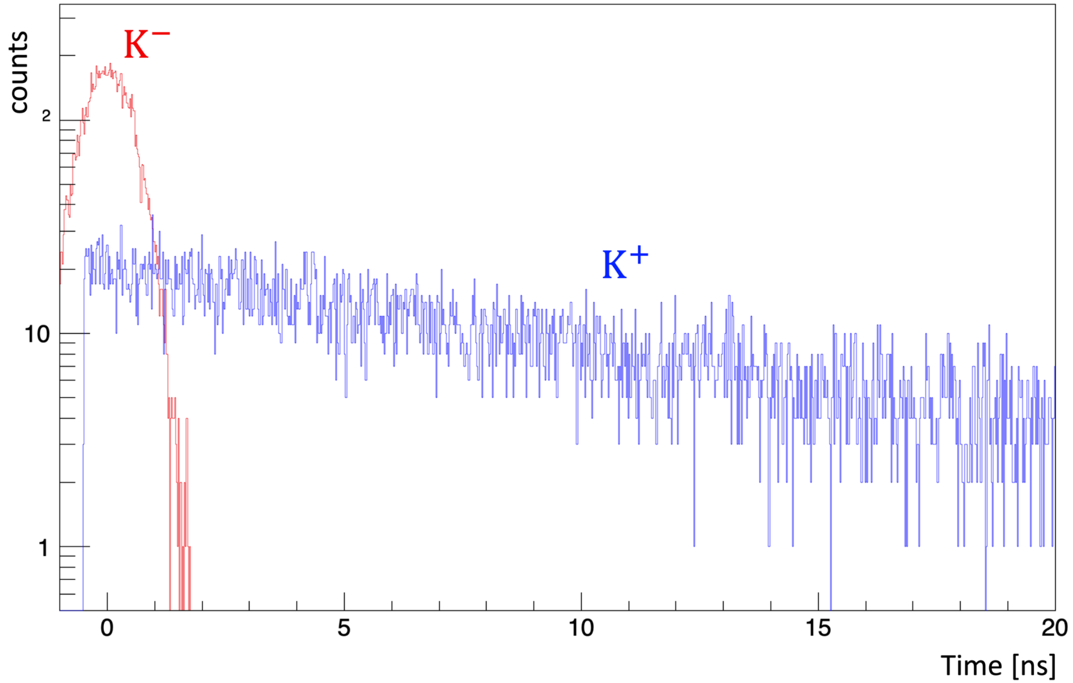


Beyond SIDDHARTA-2

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

This situation would already be a proper justification for new measurements

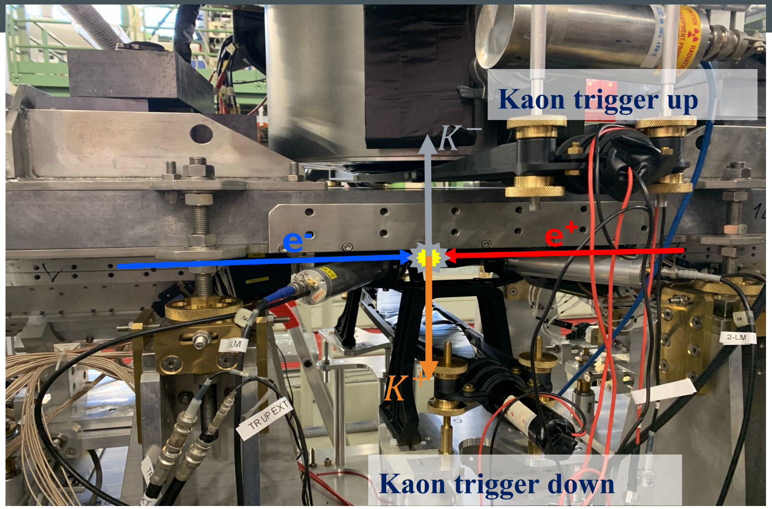
E. Friedman et al. / Nuclear Physics A579 (1994) 518–538 521

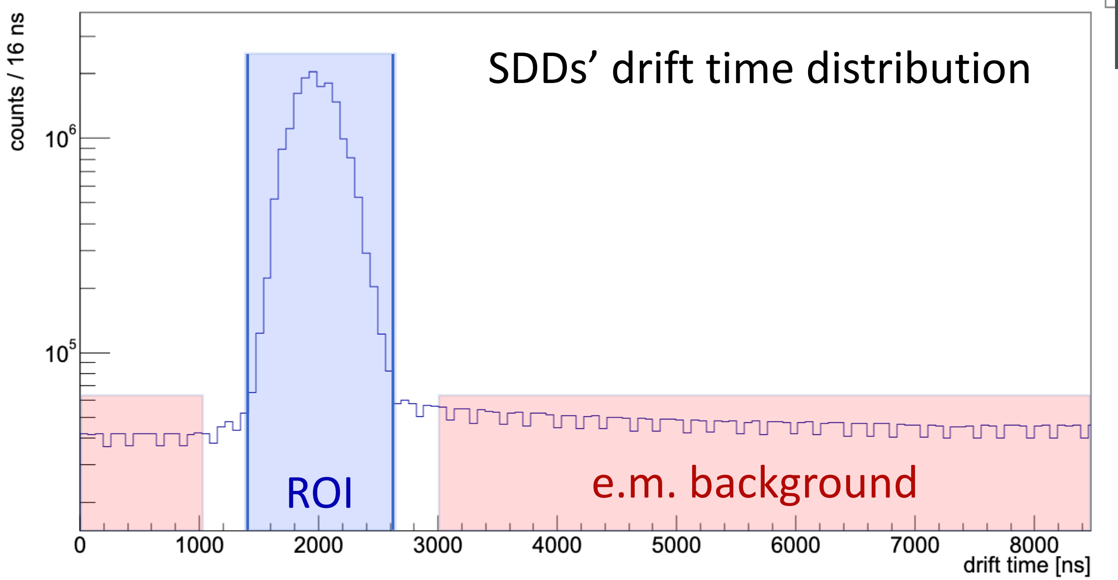
Table 1
Compilation of K^- atomic data

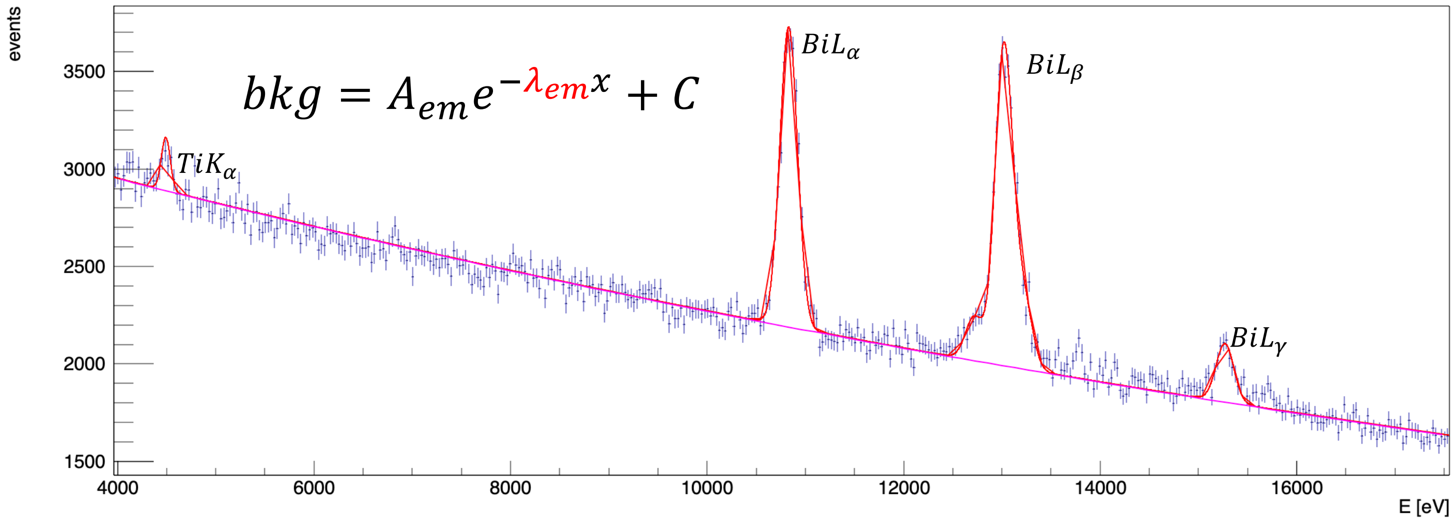
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	$3 \to 2$	-0.04 ± 0.03	–	–	–	[15]
		-0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	$3 \to 2$	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	$3 \to 2$	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	$3 \to 2$	-0.208 ± 0.035	0.810 ± 0.100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

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.

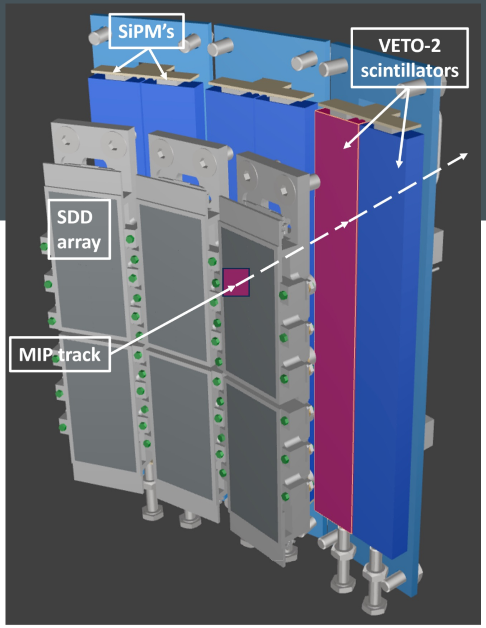


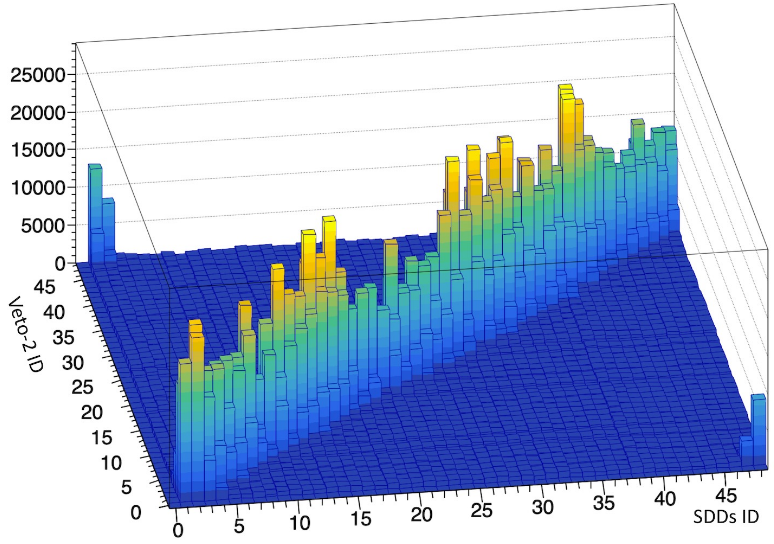




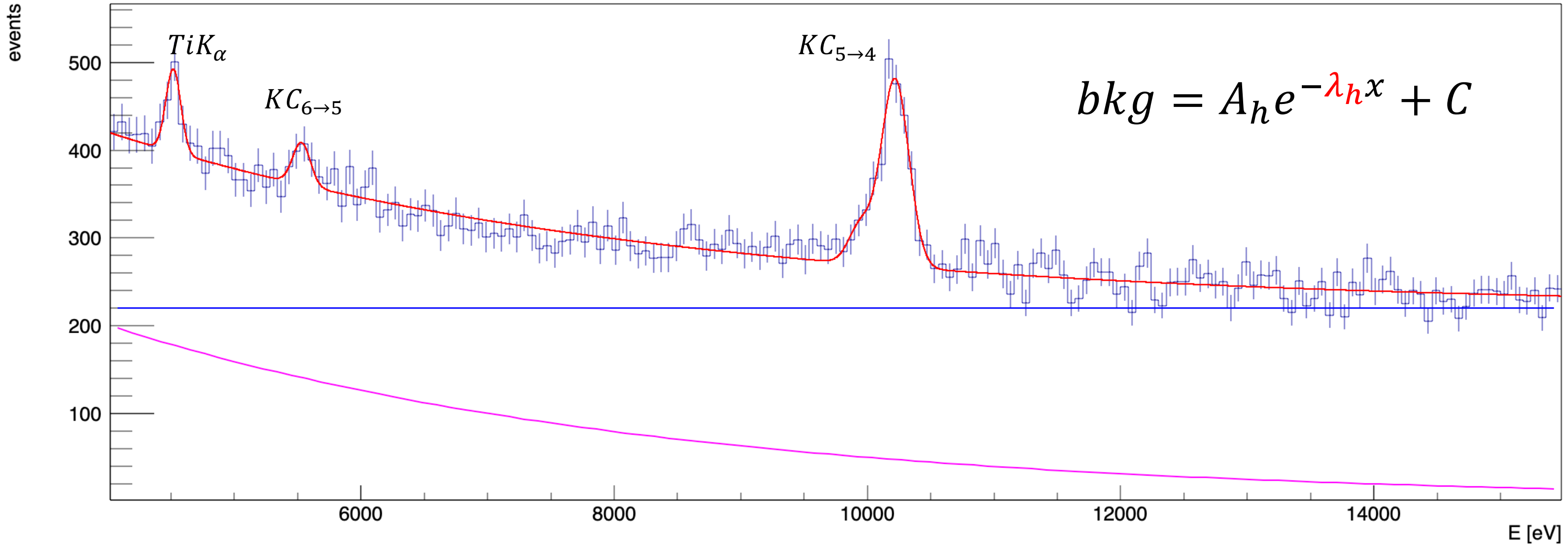
Hadronic background (synchronous wrt kaons)

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.



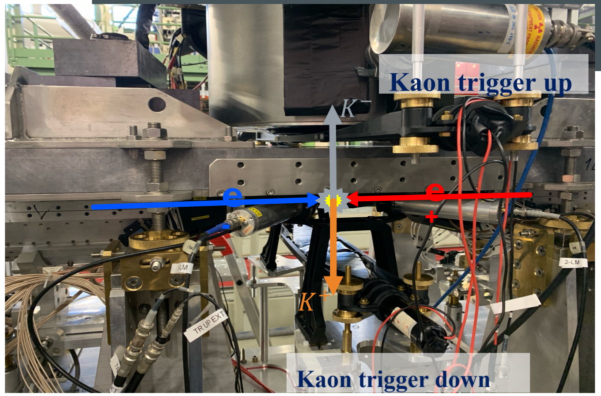


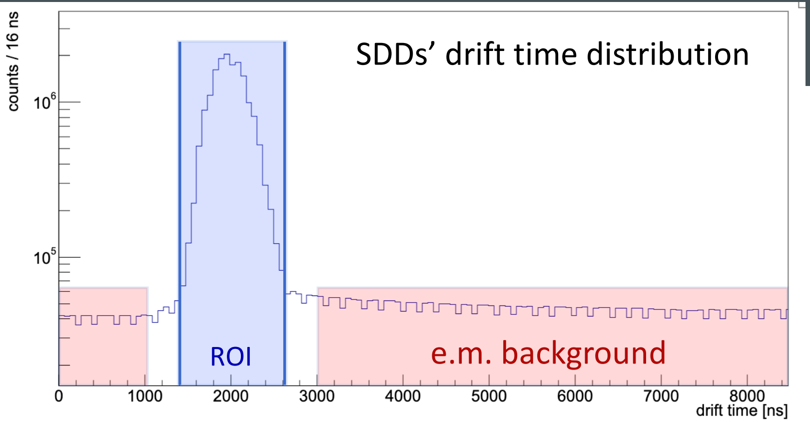
Plot of the topological correlation between Veto2's scintillators and SDDs

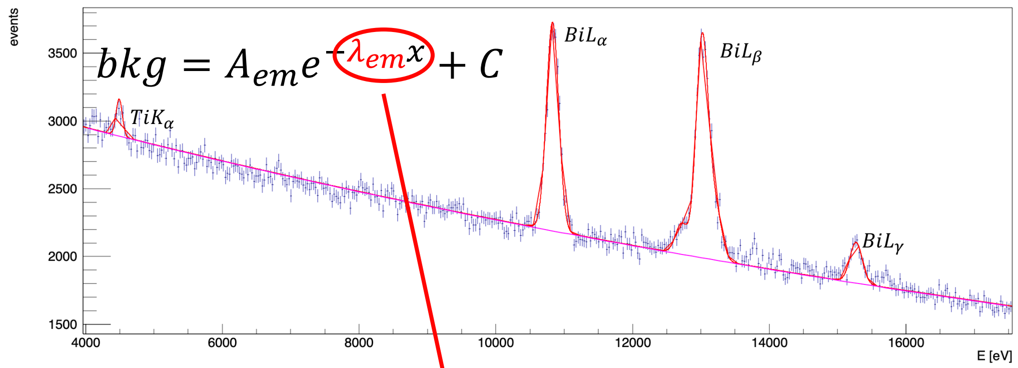


Study of background events (outside the signal window)

Electromagnetic (asynchronous) background

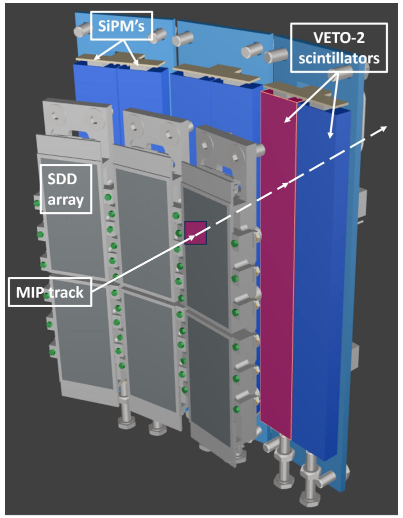


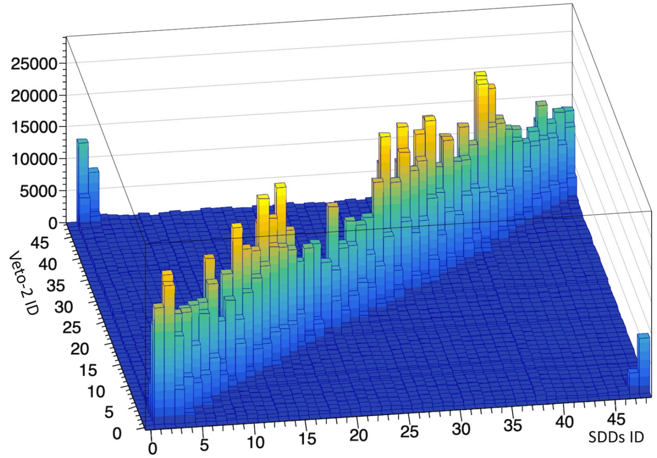




Input values for background description

Hadronic (synchronous) background





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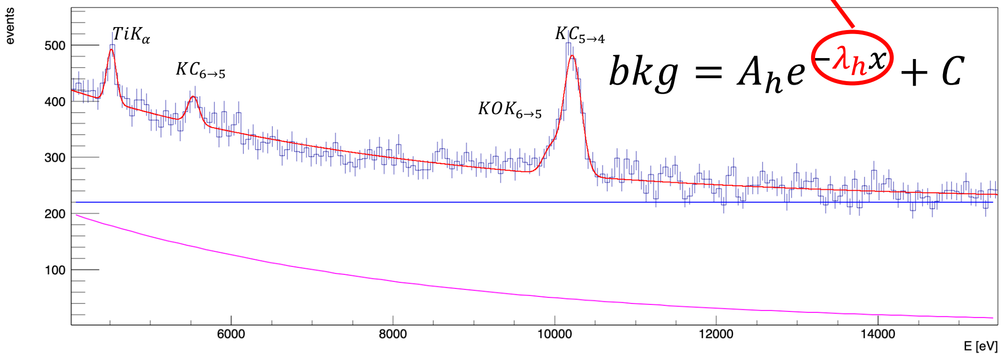
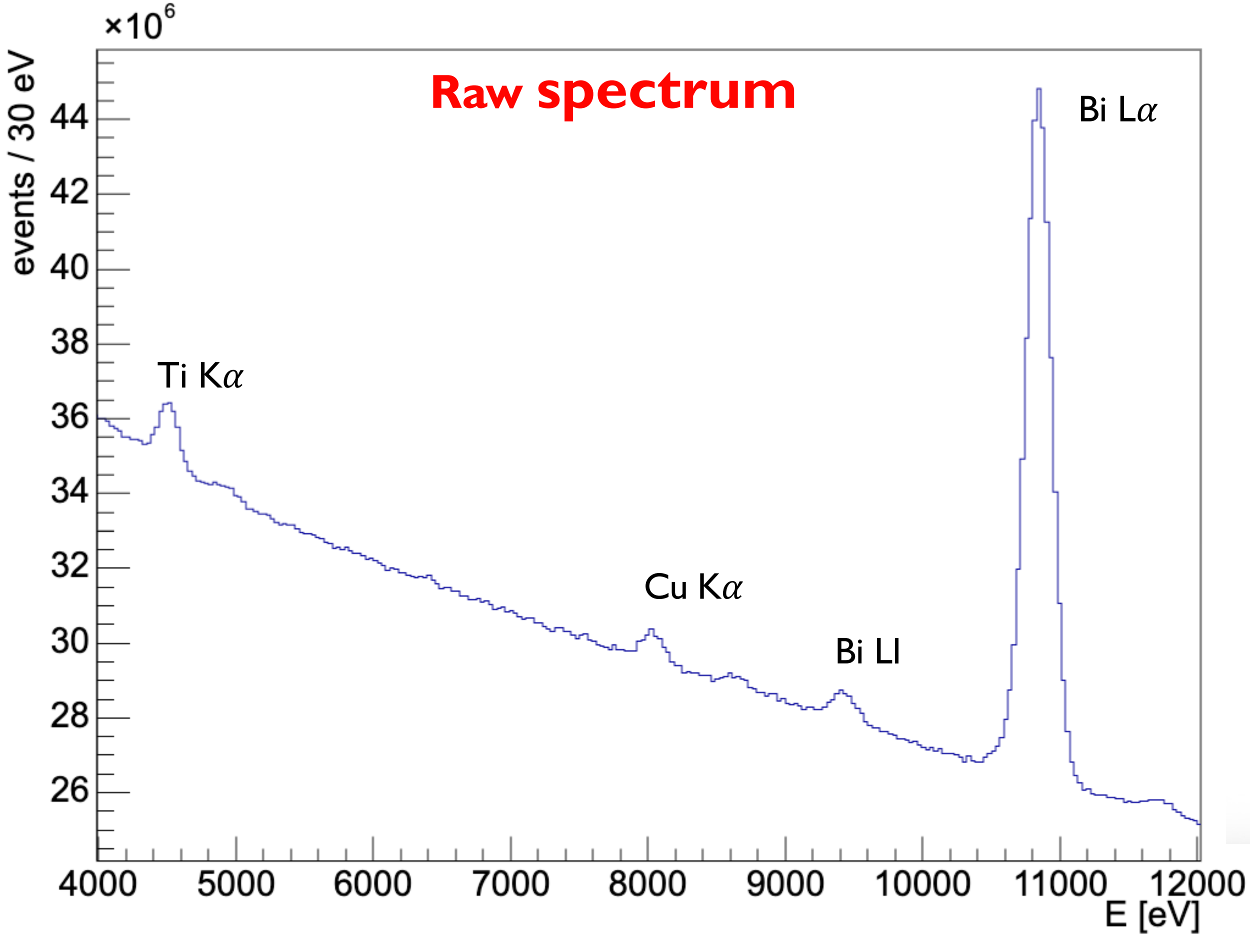
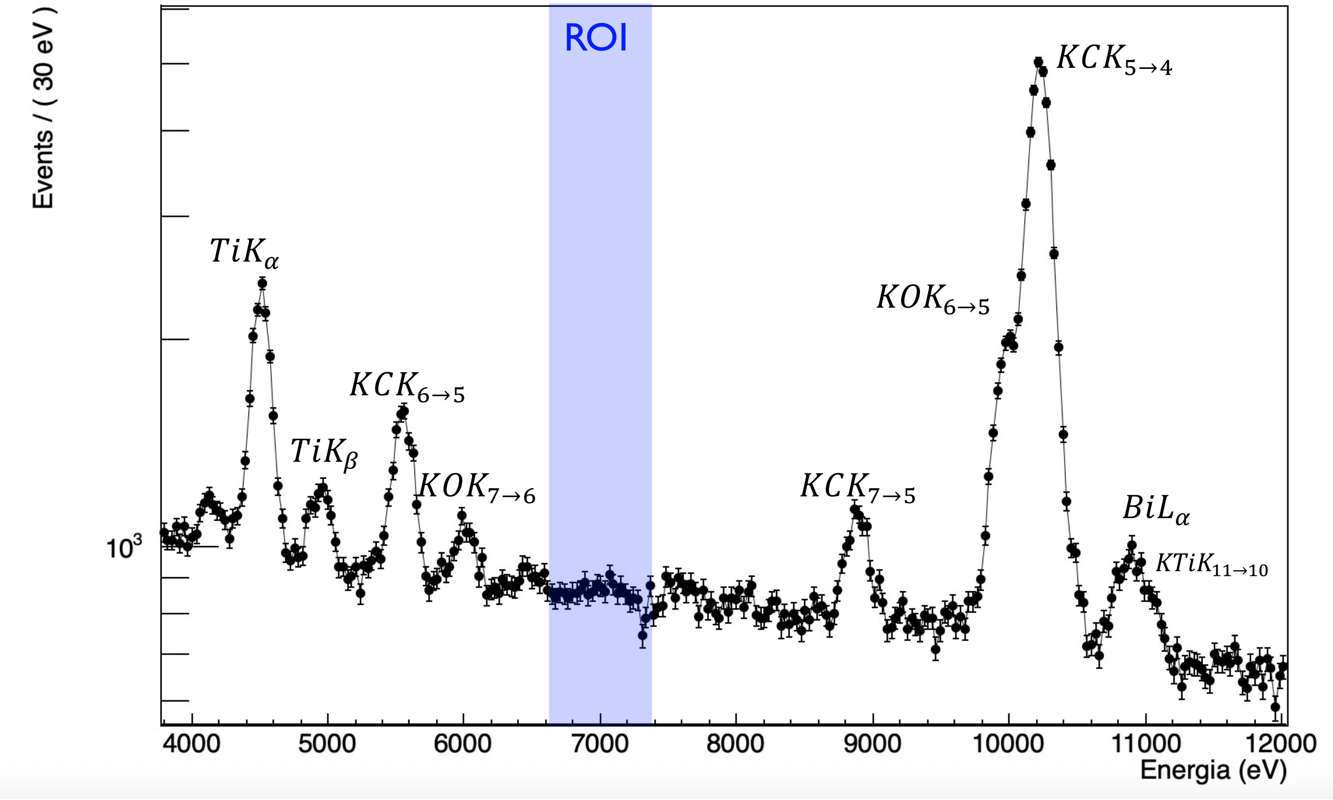


Kaonic Deuterium Energy Spectrum





Background reduced by a factor 3x10^4

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

$$f(E;\theta) = \underbrace{\sum_{n=0}^{18} y_n G_n(E;\mu,\sigma)}_{\text{X-ray transitions from known sources}} + \underbrace{y_{2p\to 1s} V_{2p\to 1s}(E;\mu,\sigma,\Gamma) + \sum_{n=3}^{7} y_{n\to 1s} V_{n\to 1s}(E;\mu,\sigma,\Gamma^*)}_{\text{Kaonic deuterium lines}} + \underbrace{y_{em} e^{\lambda_{em} E} + y_{had} e^{\lambda_{had} E}}_{\text{Background}} + C$$

X-ray transitions from known sources
(*Eur. Phys. J. A (2023) 59 3, 56)*

Kaonic deuterium lines

Background
E.M and hadronic

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

$$-2\ln\mathcal{L}_{nuisance} = \underbrace{\frac{(\delta\mu_{cal})^2}{\sigma_{cal}^2} + \frac{(\delta\mu_{stab})^2}{\sigma_{stab}^2}}_{\text{Systematic uncertainty on SDDs energy calibration and stability}} + \underbrace{\frac{(FF - FF_0)^2}{\sigma_{FF}^2} + \frac{(noise - noise_0)^2}{\sigma_{noise}^2}}_{\text{Systematic uncertainty on SDDs energy resolution}} + \underbrace{\frac{(\lambda_{em} - \lambda_{em}^0)^2}{\sigma_{\lambda em}^2} + \frac{(\lambda_{had} - \lambda_{had}^0)^2}{\sigma_{\lambda had}^2}}_{\text{Systematic uncertainty on e.m. and hadronic background}}$$

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

<u>Present status</u>:

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

<u>charting the periodic table</u>

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

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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]
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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