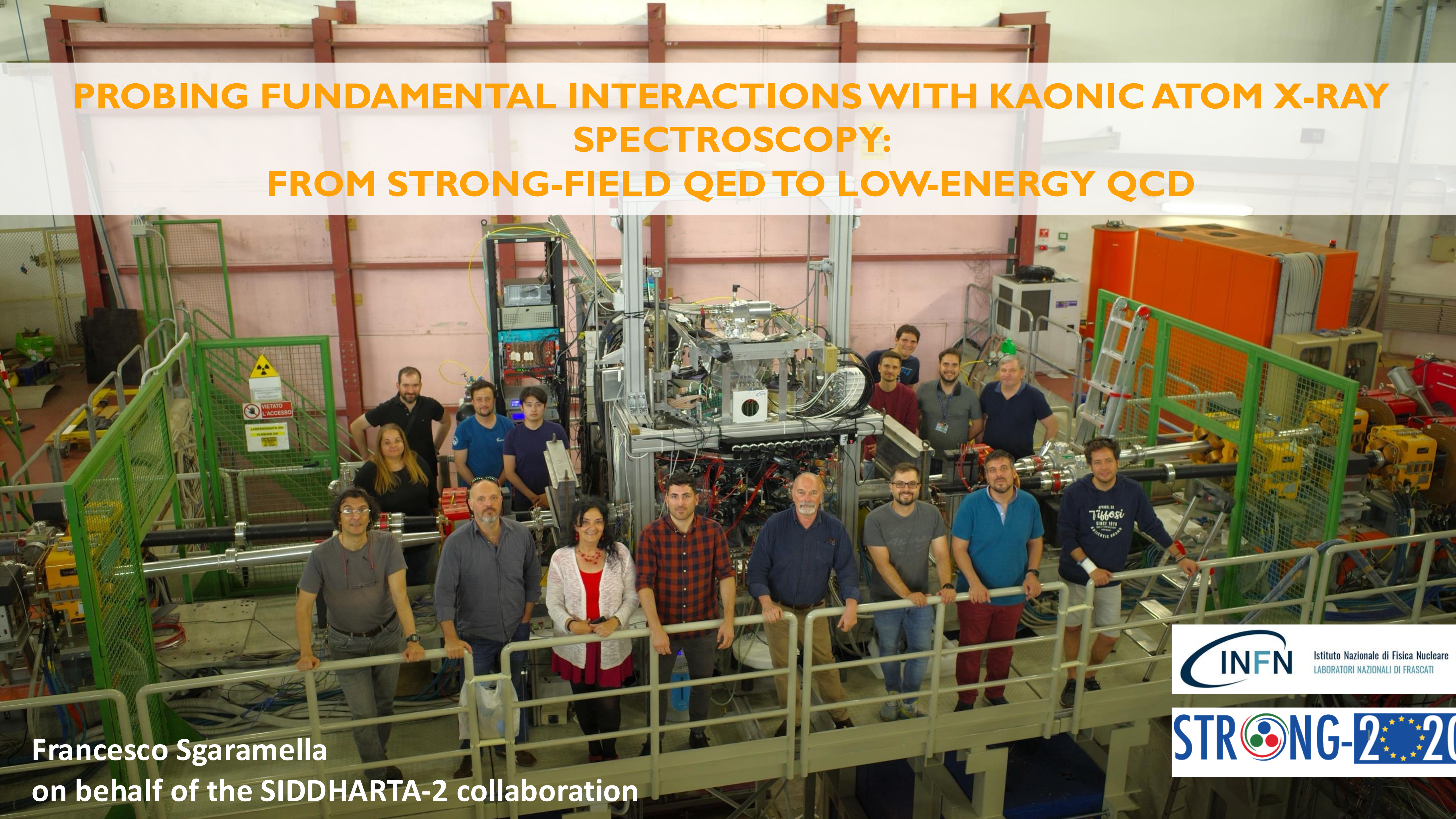
PROBING FUNDAMENTAL INTERACTIONS WITH KAONIC ATOM X-RAY SPECTROSCOPY: FROM STRONG-FIELD QED TO LOW-ENERGY QCD



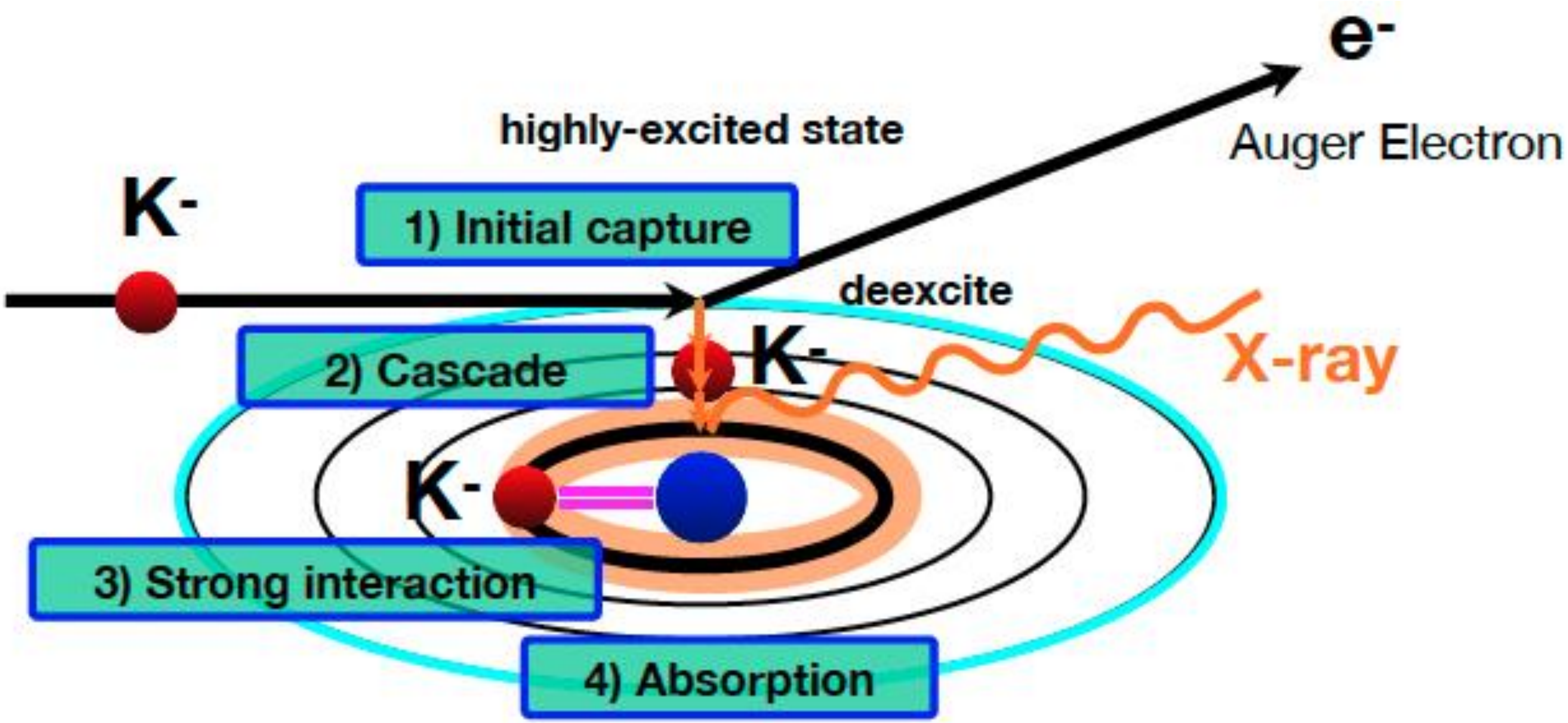
Francesco Sgaramella
on behalf of the SIDDHARTA-2 collaboration

INFN 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



Why Kaonic Atom?

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

Dark Matter studies

Fundamental physics
New Physics

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

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

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

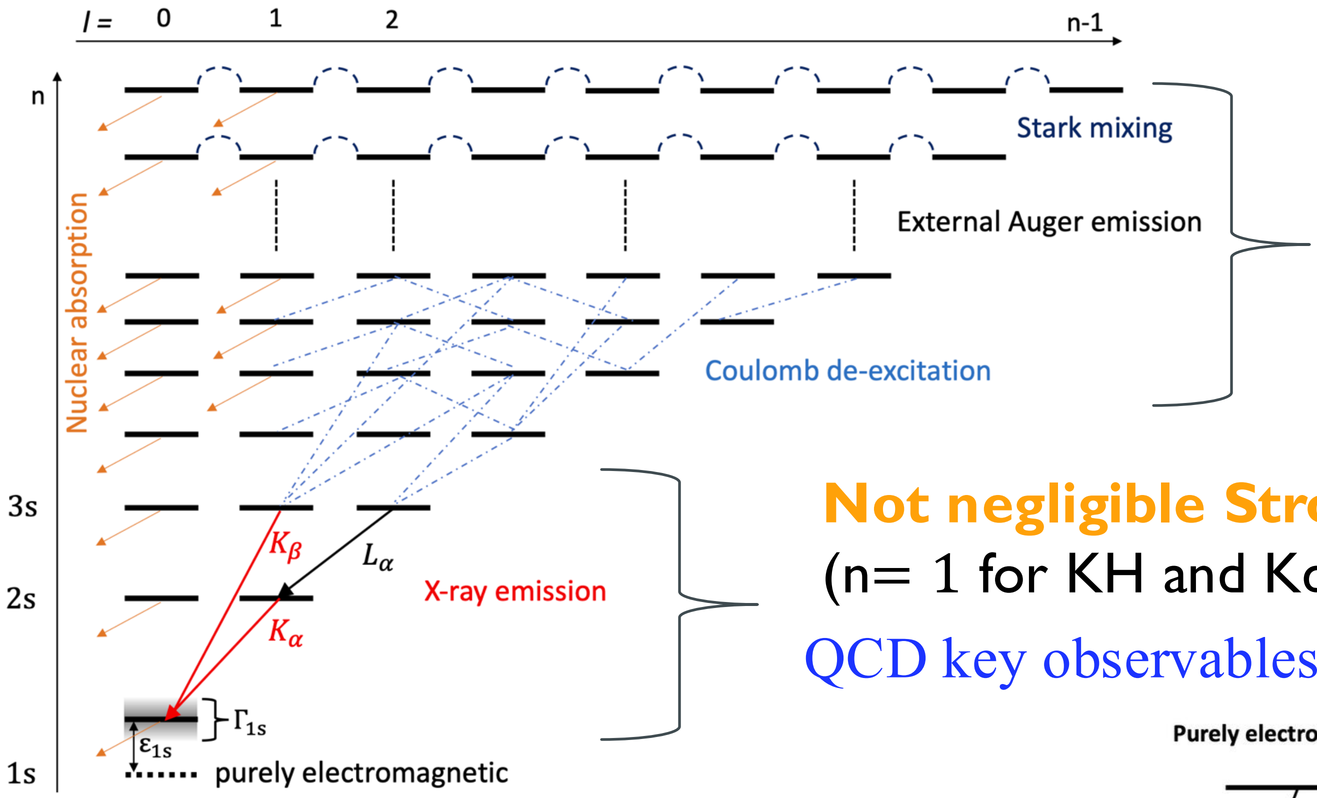
The equation of state of dense matter: Stiff, soft, or both? Astron.Nachr. 340 (2019) 1-3, 189

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

Astrophysics
EOS Neutron Stars

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)

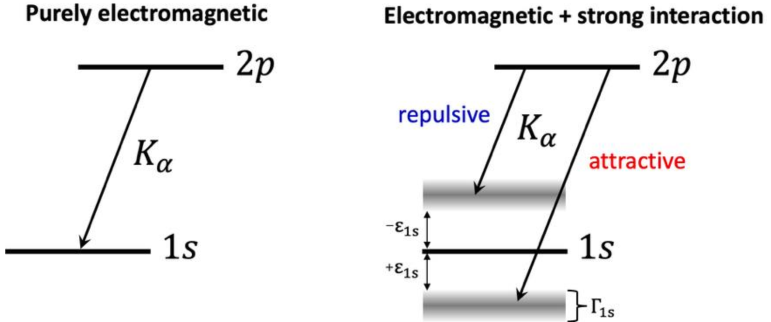
QED key observables: **Energy** and **X-ray Yield**

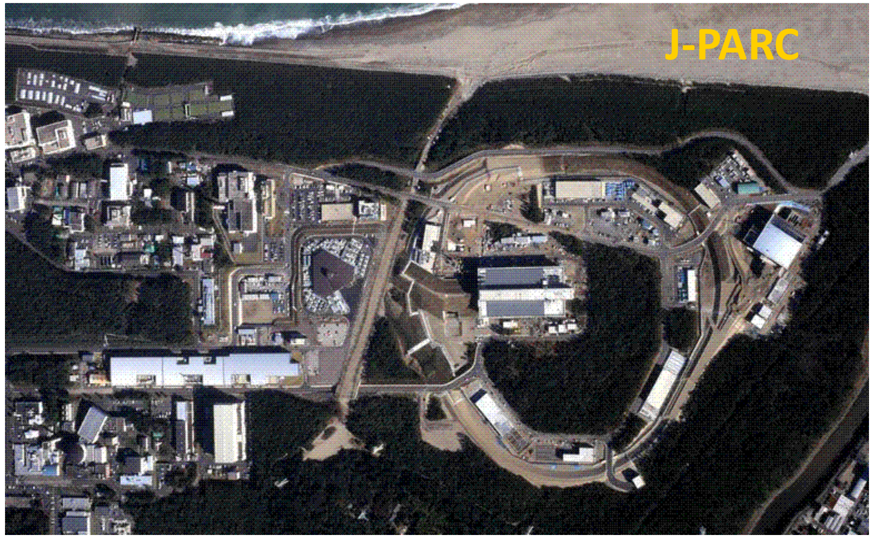
High precision test of BSQED

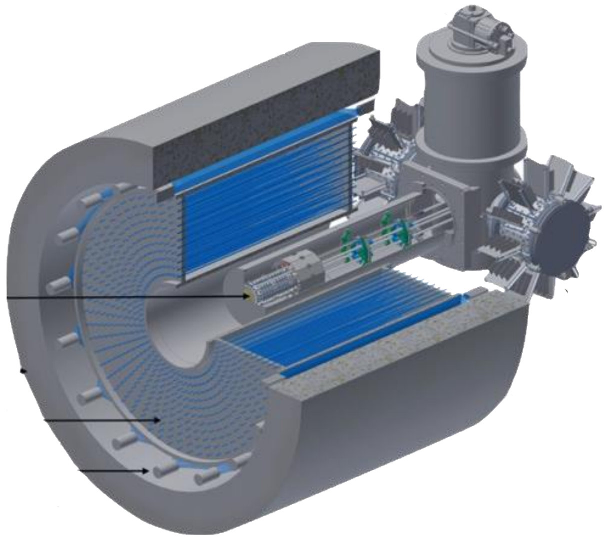
Not negligible Strong interaction effect

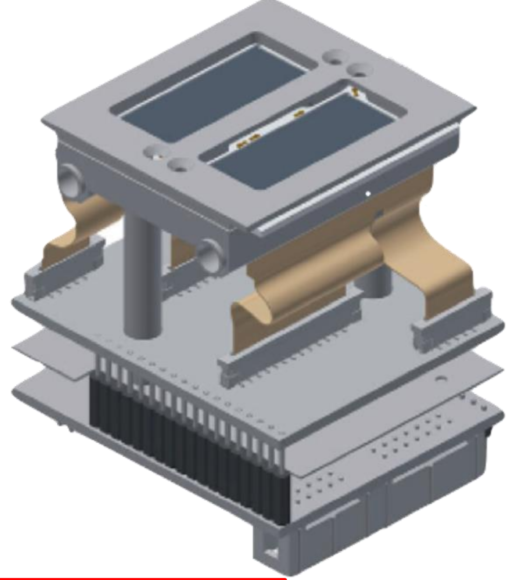
(n= 1 for KH and Kd)

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









The modern era of light kaonic atom experiments

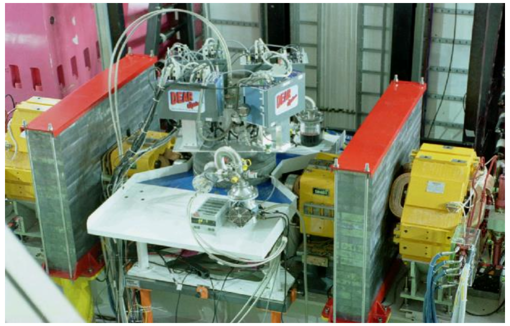
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

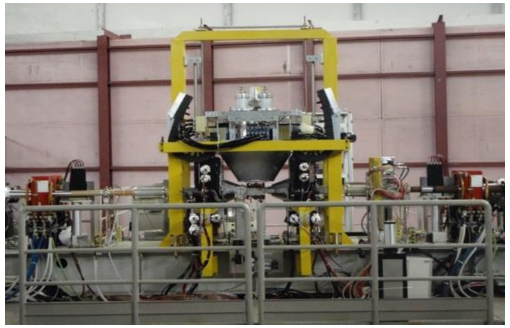
Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

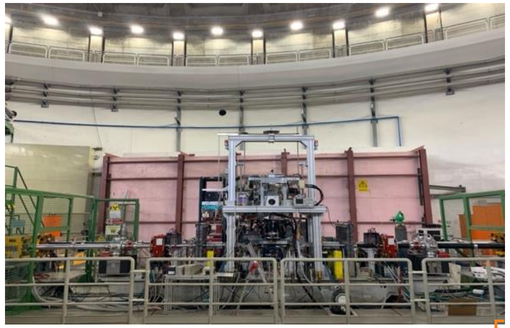
DEAR
2002

SIDDHARTA
2009

SIDDHARTA-2
2022



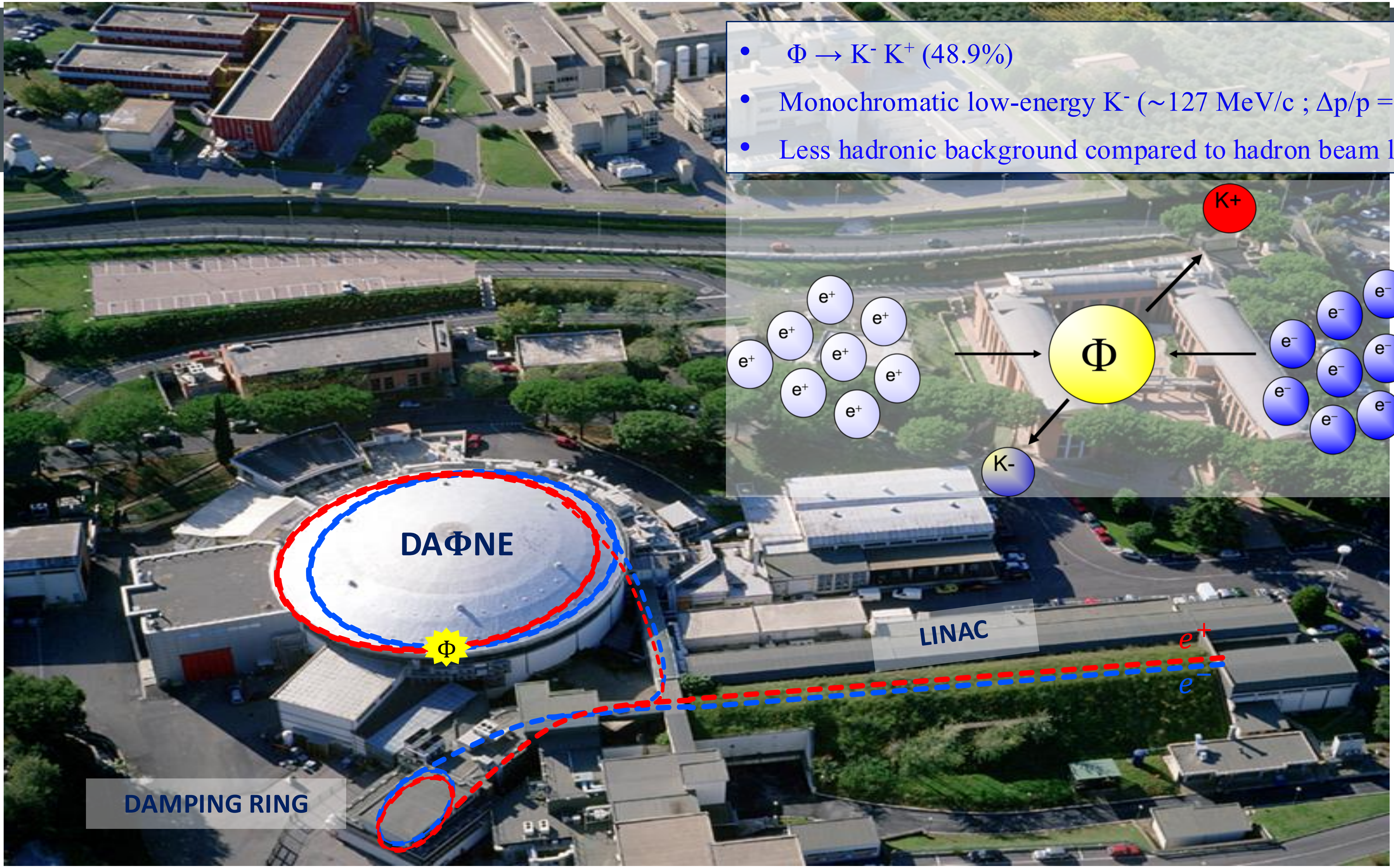




Probing the low energy QCD in the strangeness sector

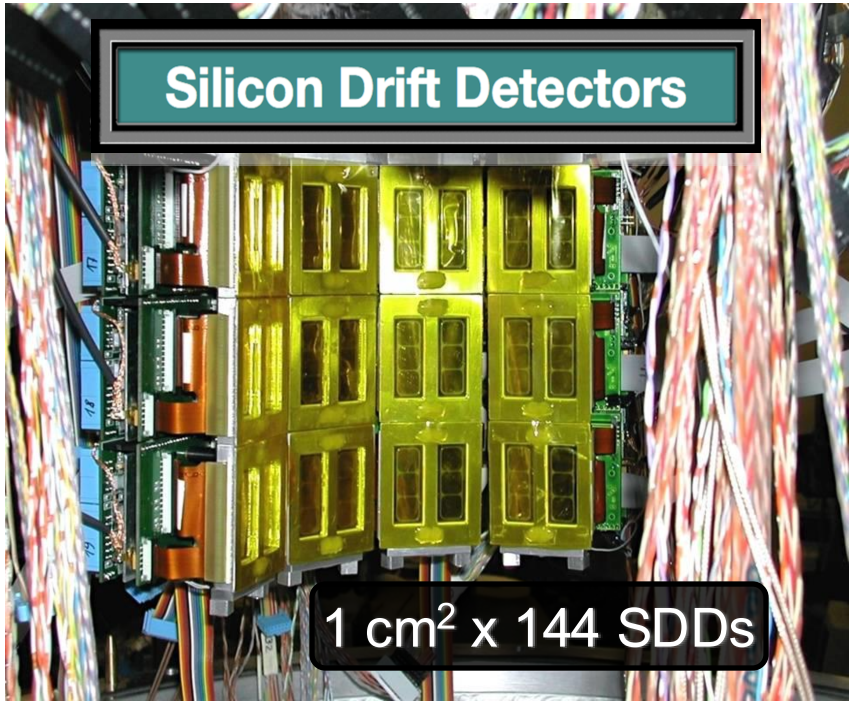
The DAΦNE collider of INFN-LNF

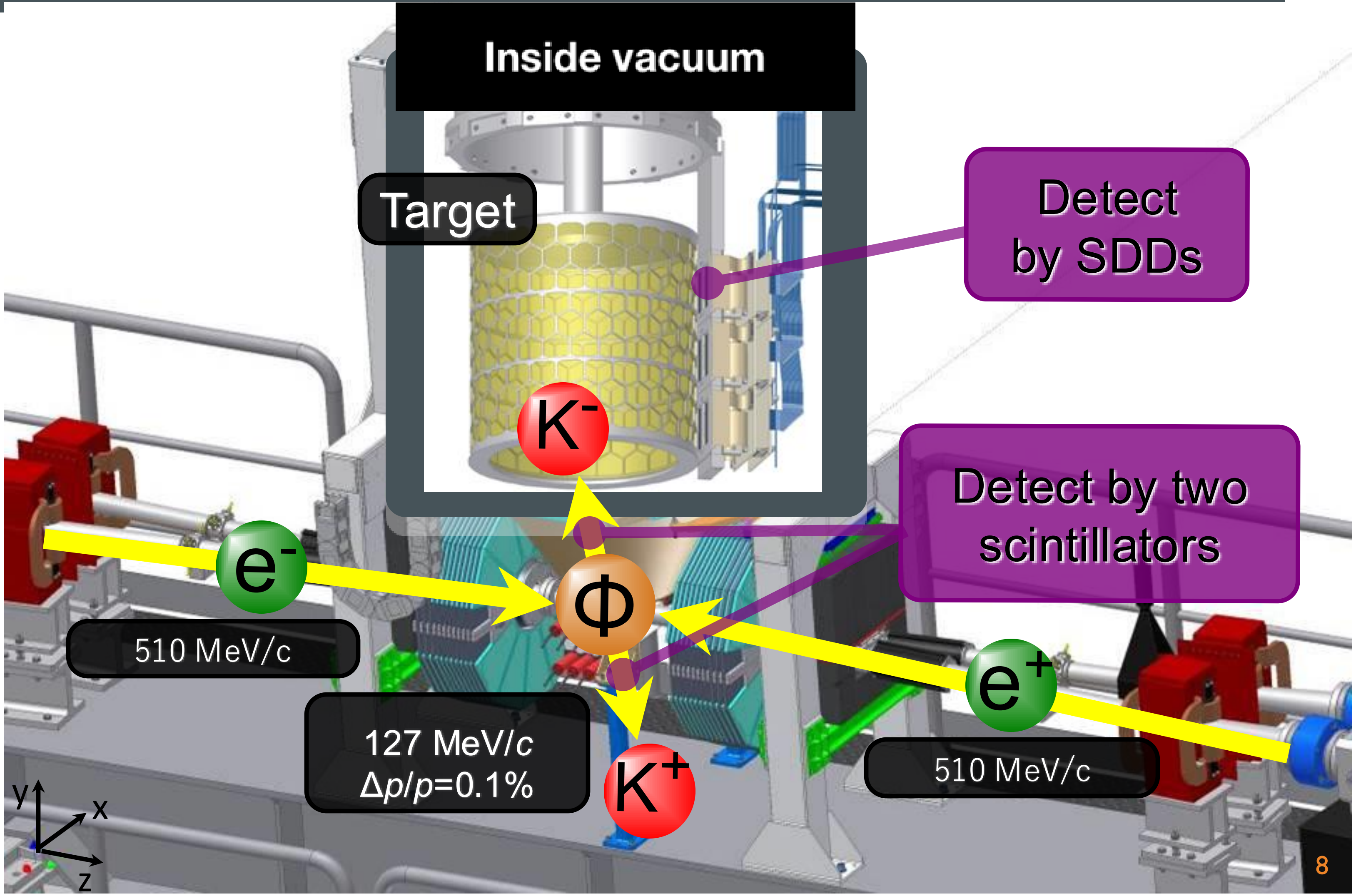
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p = 0.1\%$)
- Less hadronic background compared to hadron beam line



The SIDDHARTA Experiment (2009)

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



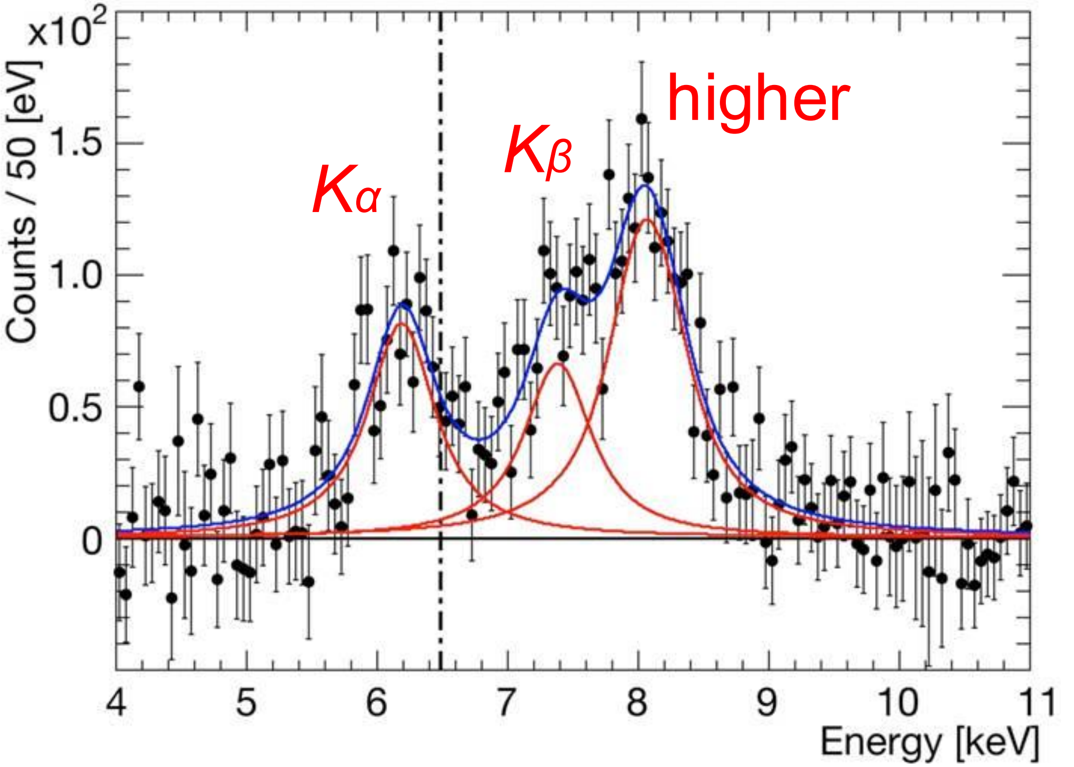


The SIDDHARTA Experiment (2009)

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

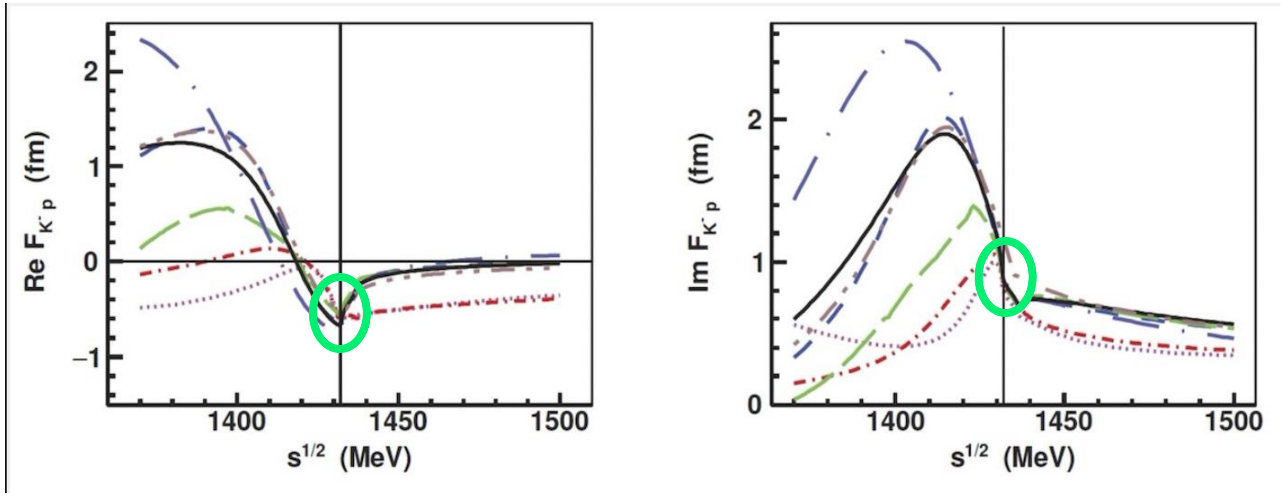
$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})$ eV

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

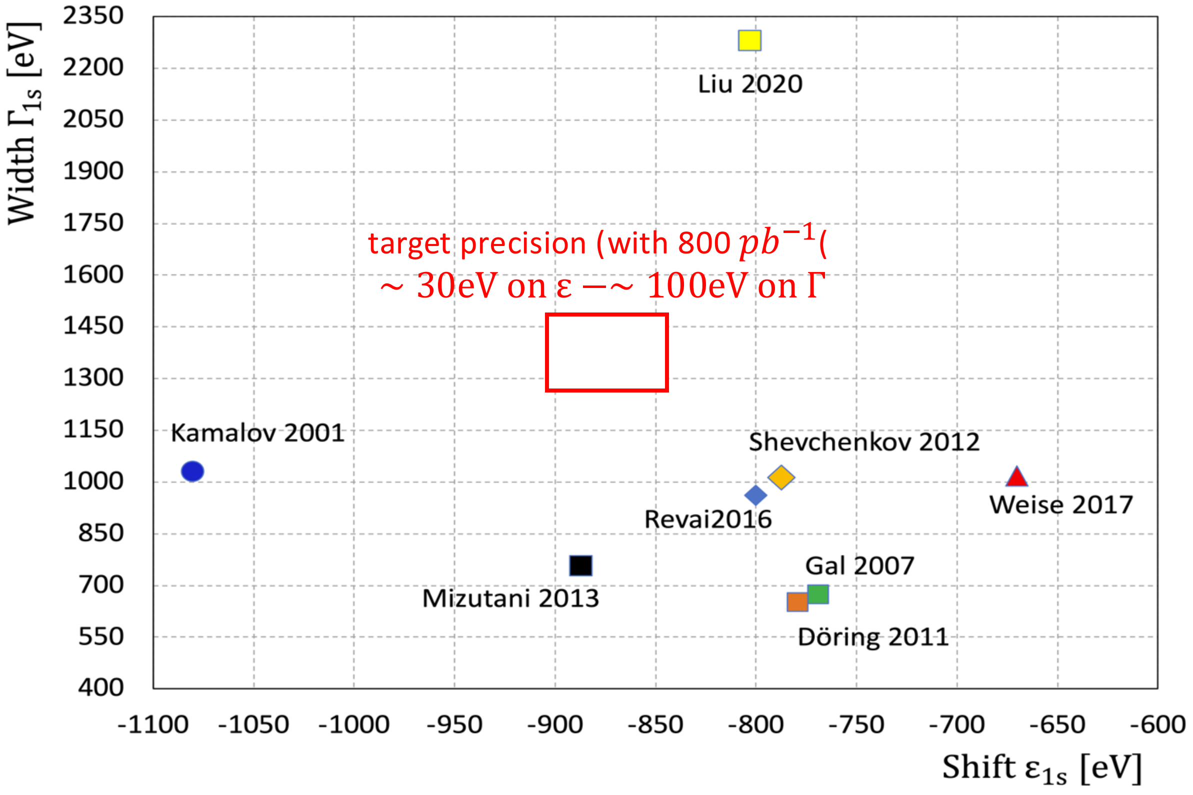


Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

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

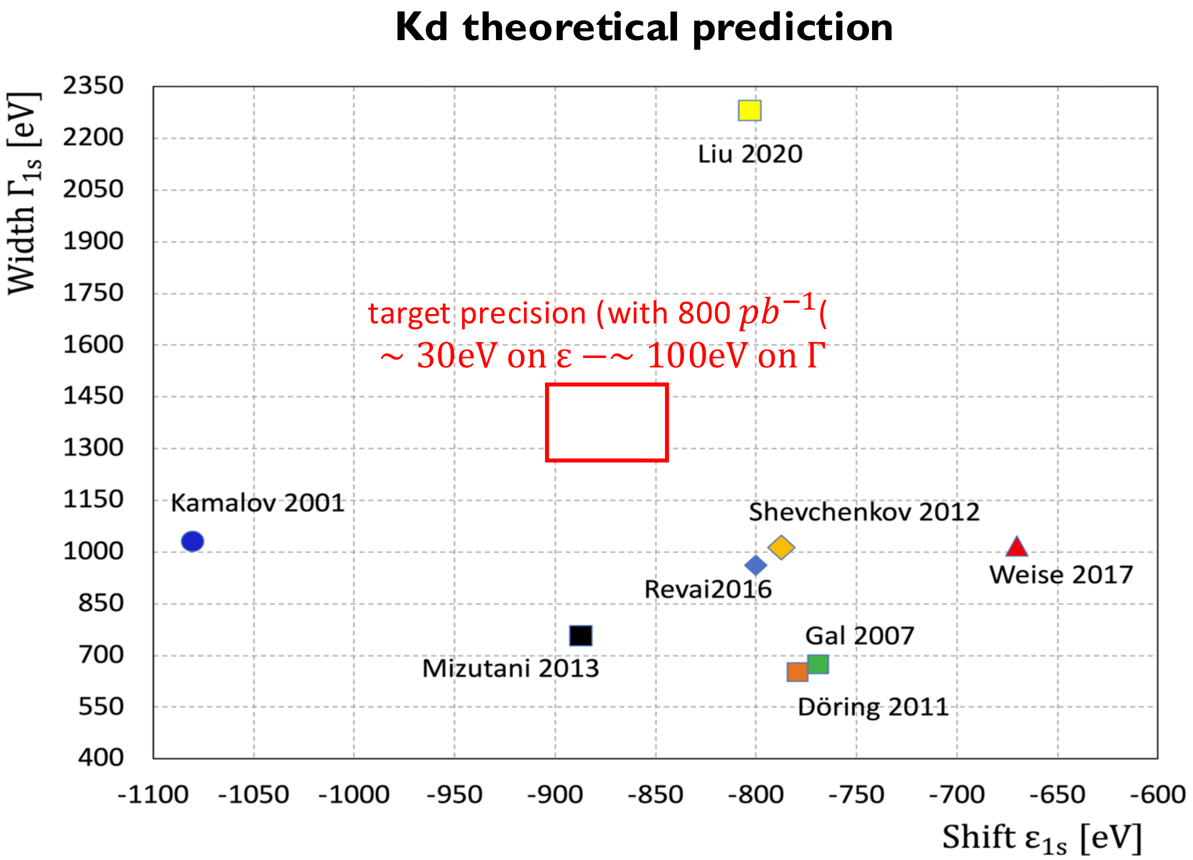


"The **<u>most important experiment to be carried out in low energy K-meson physics today</u>** is the **definitive determination of the energy level shifts in the K−p and K−d atoms**, because of their direct connection with the physics of $\overline{K}N$ interaction and their complete independence from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

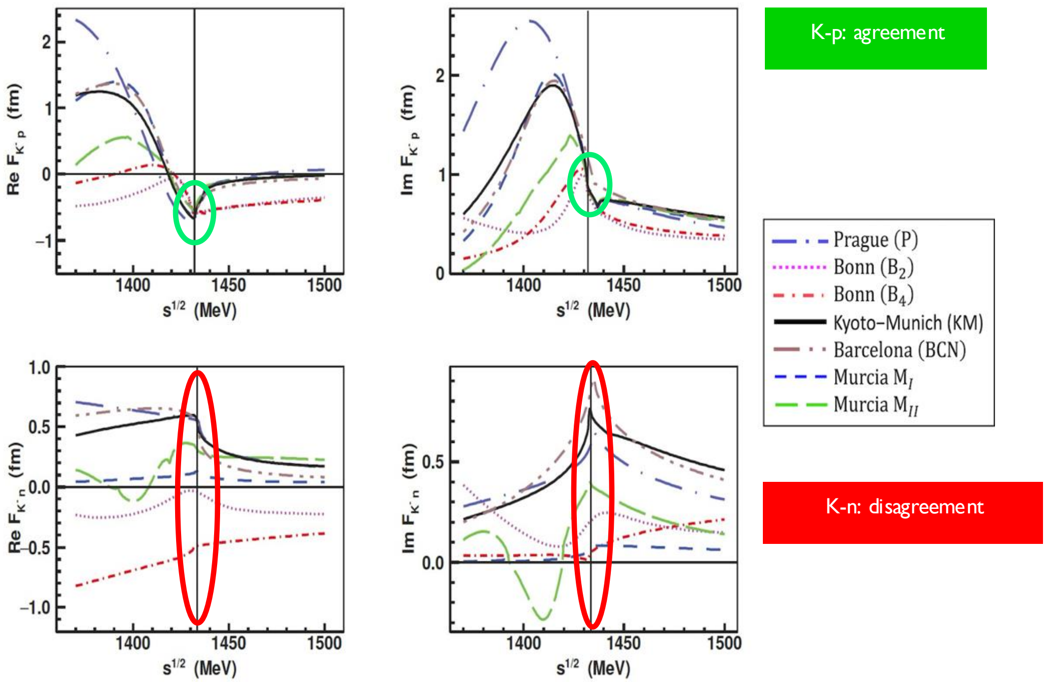
R.H. Dalitz (1982)

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.



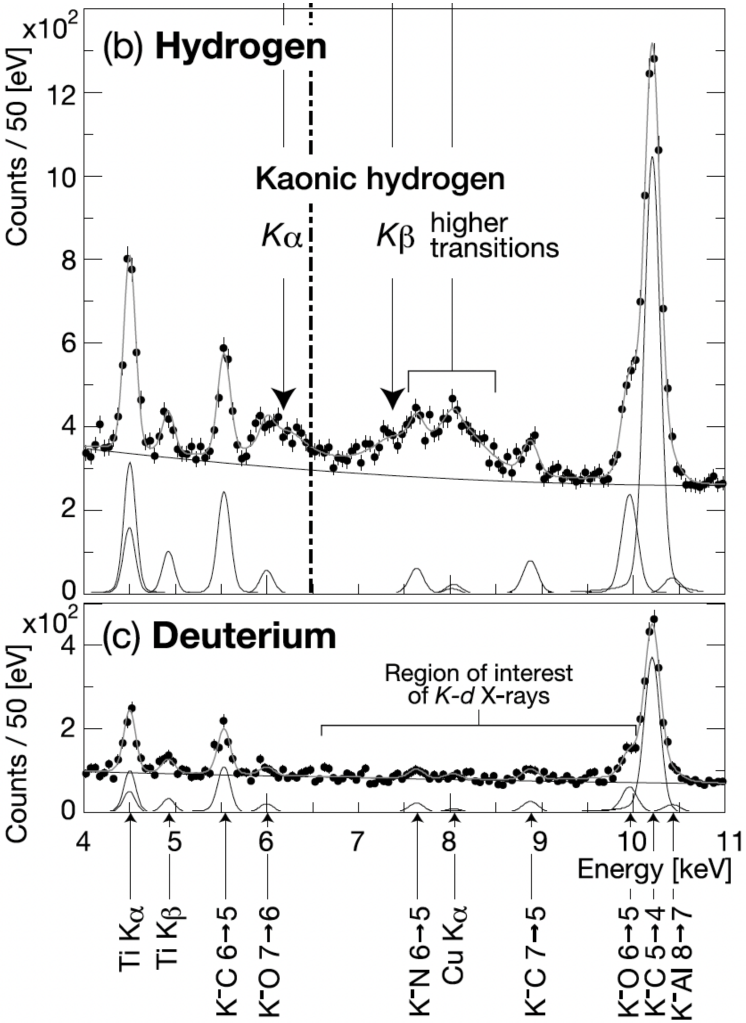
Combined analysis of the kaonic deuterium and kaonic hydrogen measurements to determine the isospin-dependet $\overline{K}N$ scattering lengths



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

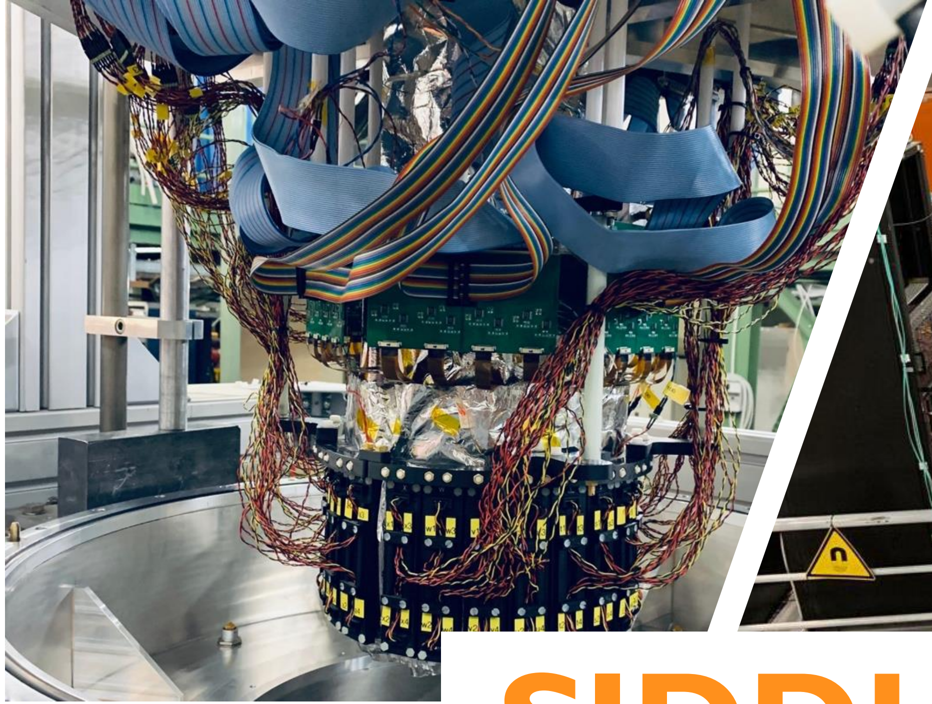
➢ Kd requires a higher integrate luminosity ~800 pb^{-1}

Background:

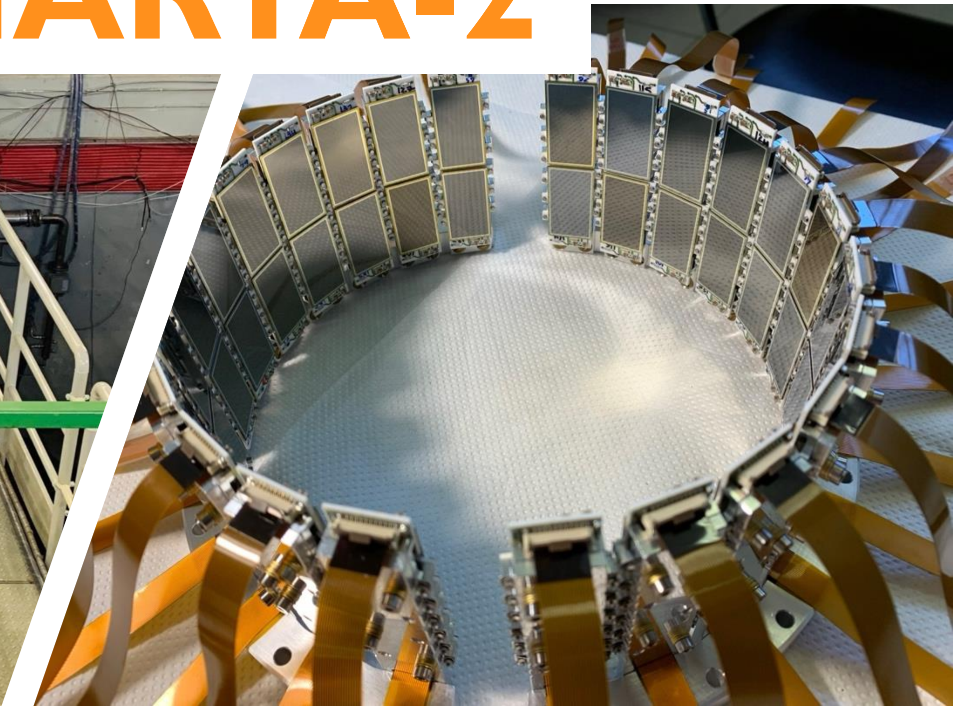
- The Kd measurement requires an improvement in signal/background ratio by a factor 10

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

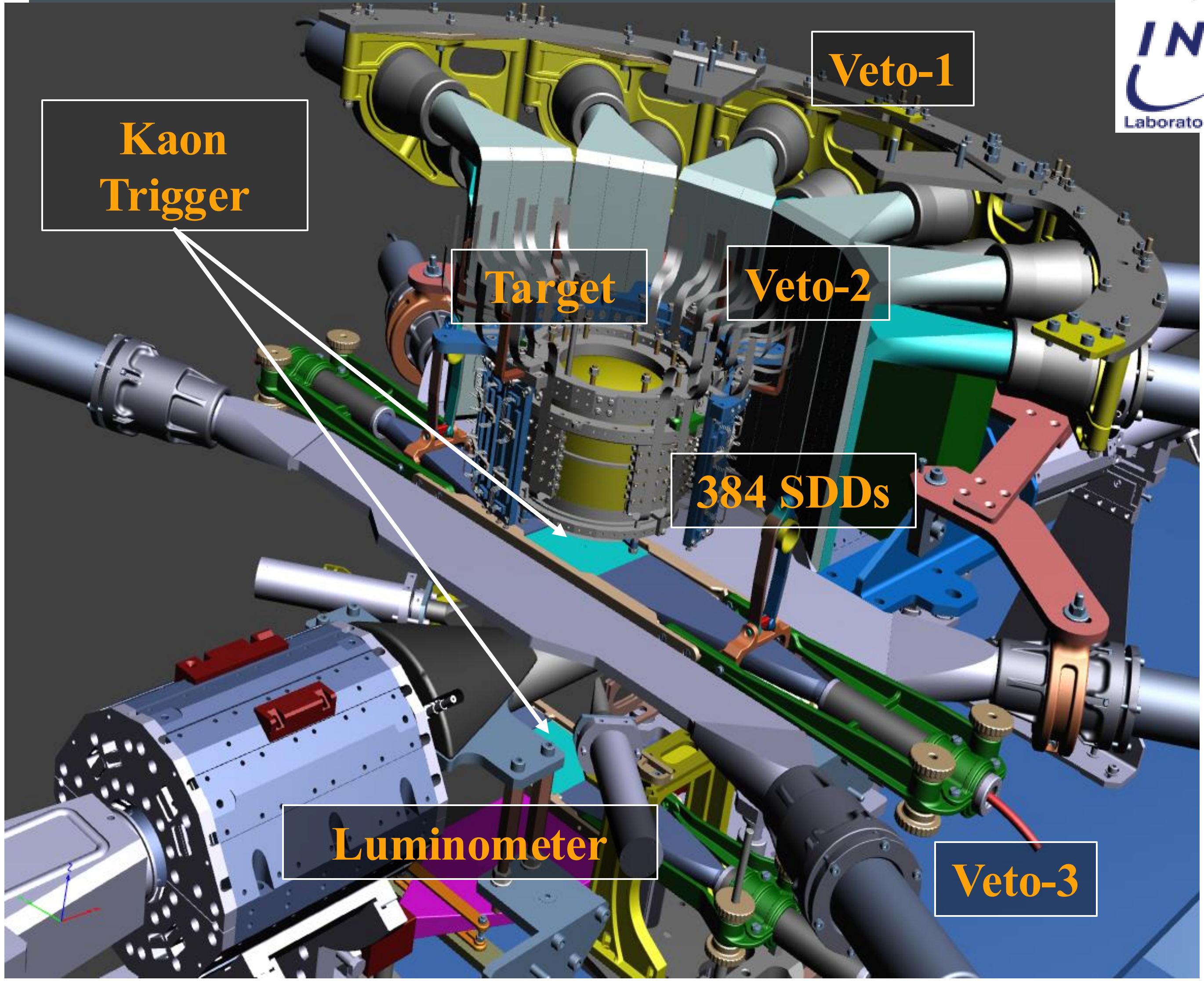
➢ Larger detection area



SIDDHARTA-2



The SIDDHARTA-2 setup and DAΦNE collider



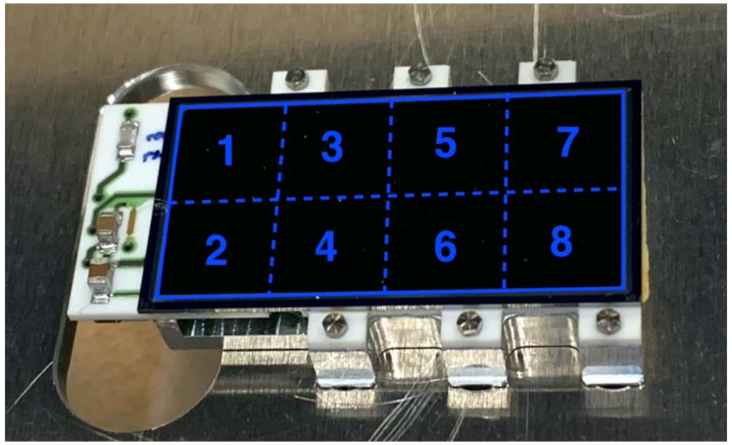
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

POLITECNICO MILANO 1863

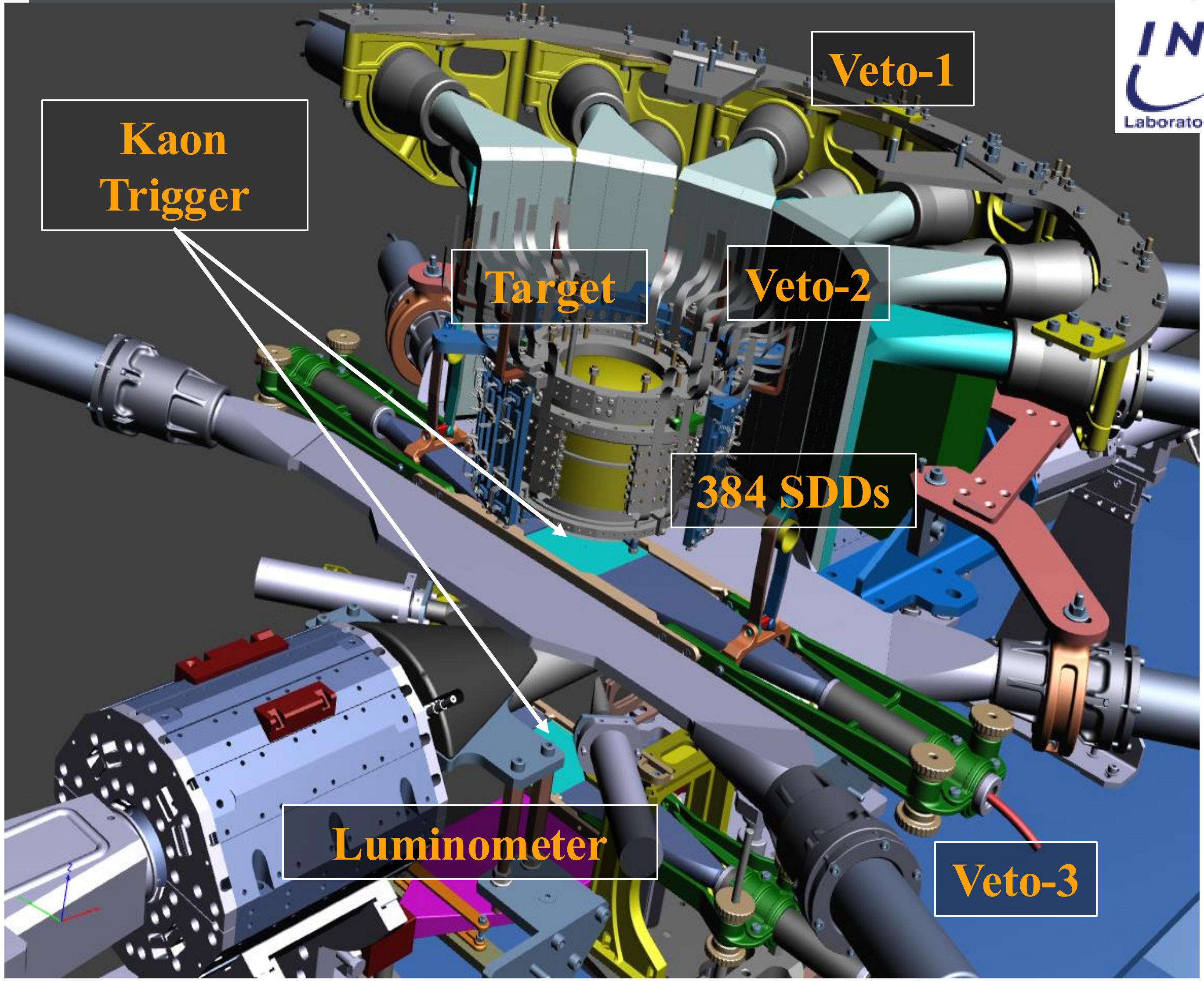
FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

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 between 5 keV and 12 keV



The SIDDHARTA-2 setup and DAΦNE collider

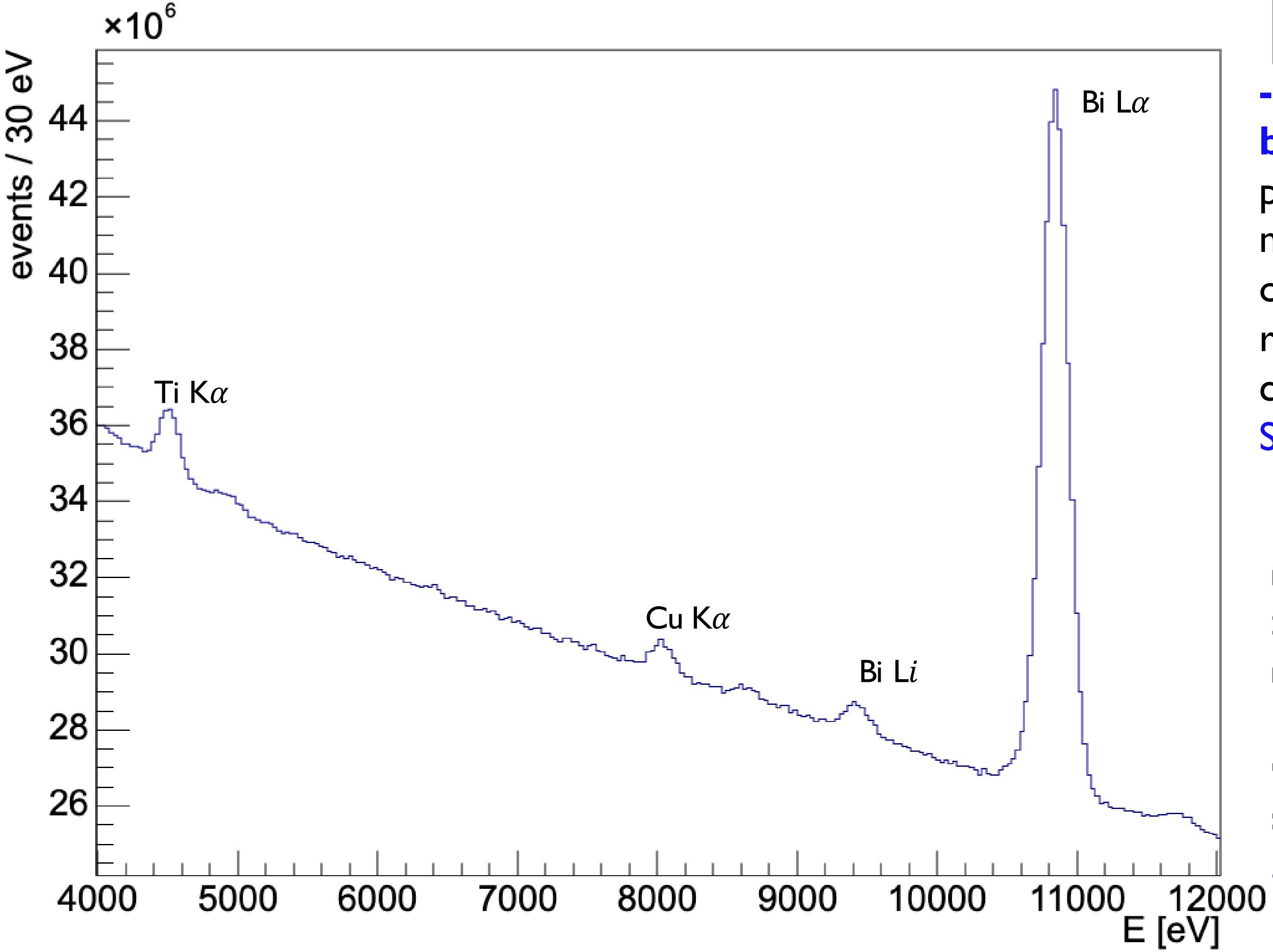


Improvements compared to SIDDHARTA setup:

- New generation of Silicon Drift Detectors and read-out electronics
- Active area 2 times larger
- SDDs drift time 450 ns (instead of 800 ns as in SIDDHARTA) → e.m. background rejection improved by a factor of 2
- 3 veto system for hadronic background suppression
- New vacuum chamber and lead shield design for better background reduction

Kaonic deuterium analysis

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

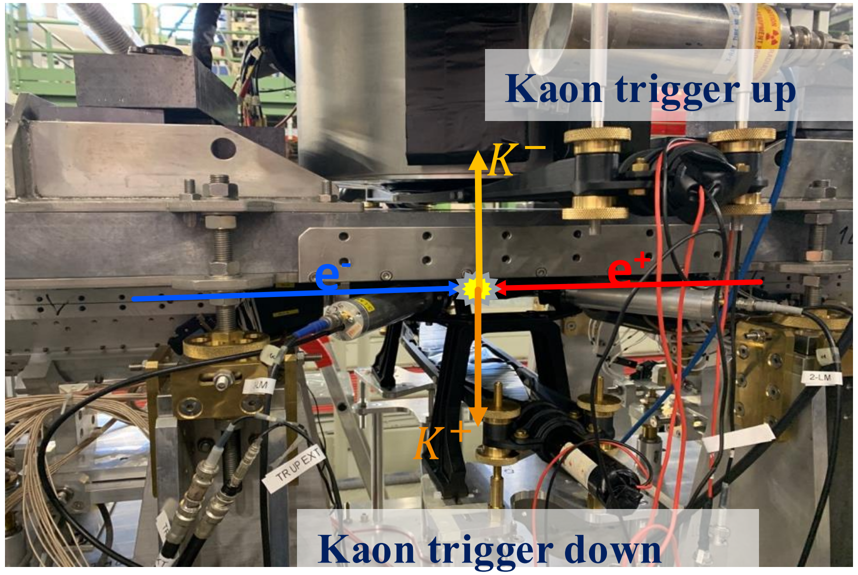


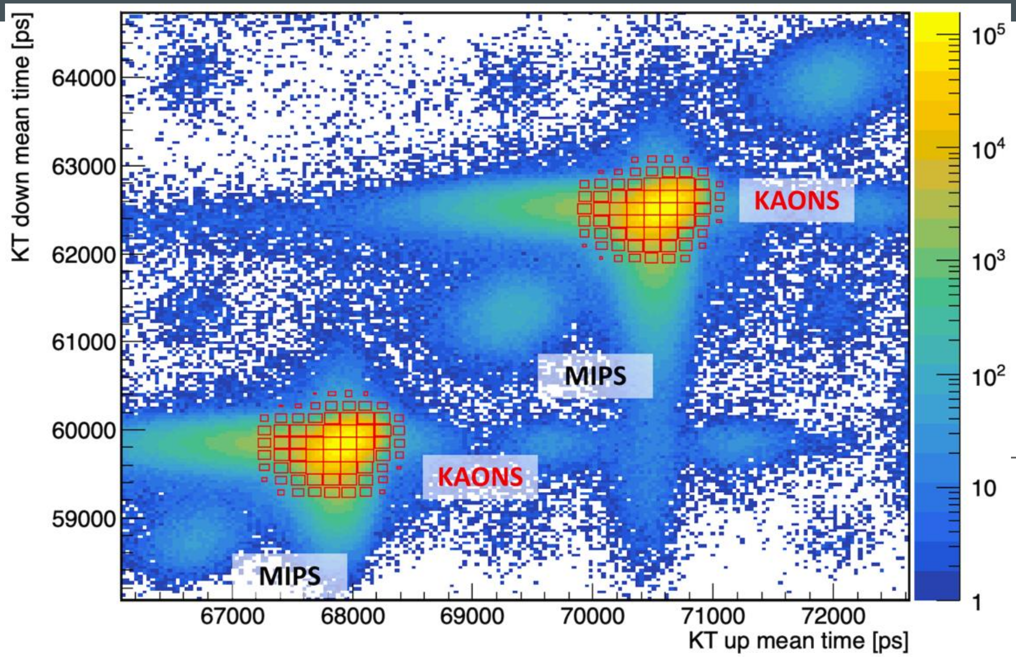
- Electromagnetic (asynchronous) background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect → Kaon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

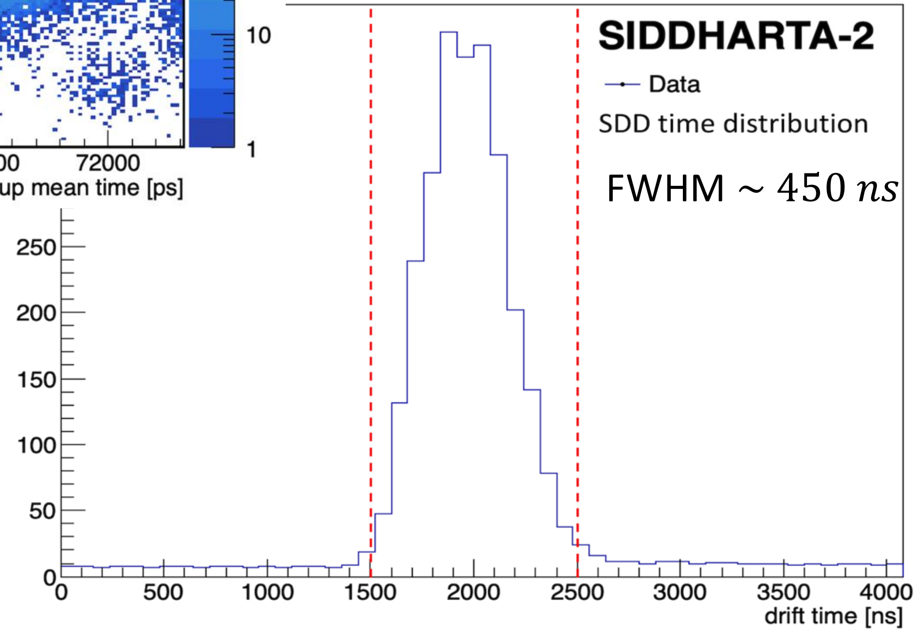
Hadronic (synchronous) background: ıssociated to kaon absorption on materials nuclei, ɔr to other Φ decay channels. It can be considered ı hadronic background.
Spectra contamination by Xray fluorescence or by ‹-rays produced in higher transitions of other ‹aonic atoms, formed in the setup materials → Veto ıystems

Kaonic deuterium analysis

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

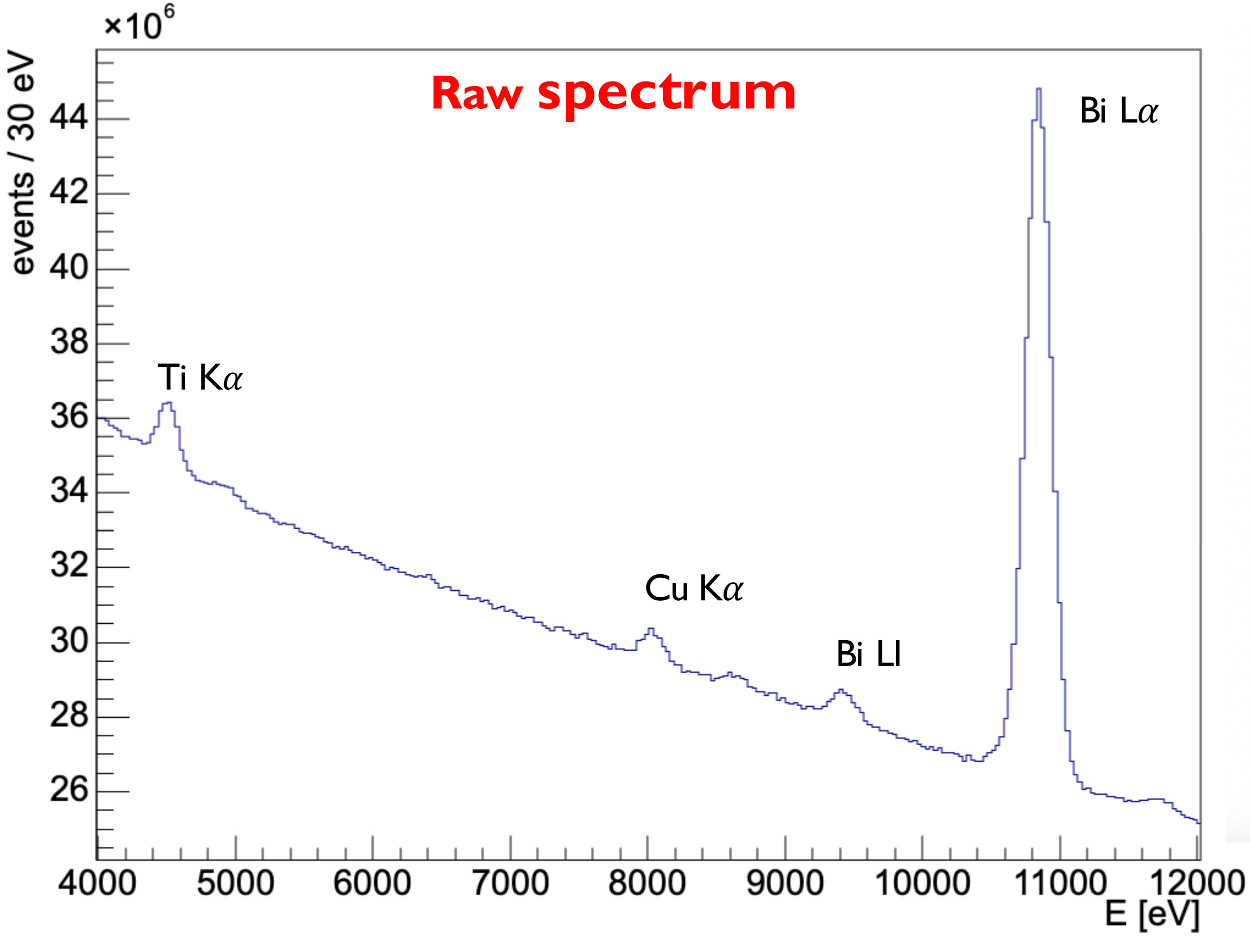


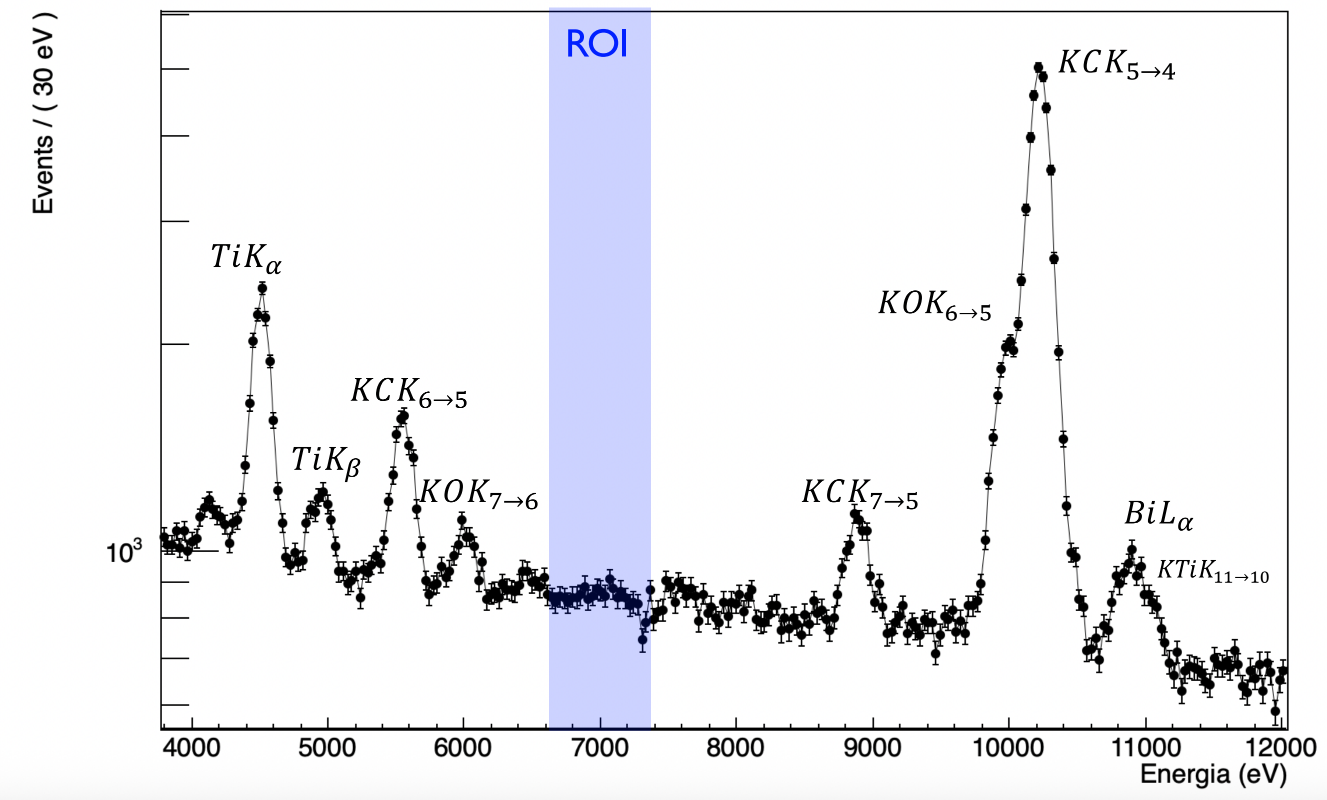




The trigger is generated by the coincidence of 2 back-to-back scintillators
The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles
originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

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

$$f(E;\theta) = \sum_{n=0}^{18} y_n G_n(E;\mu,\sigma) + y_{2p\to1s}V_{2p\to1s}(E;\mu,\sigma,\Gamma) + \sum_{n=3}^{7} y_{n\to1s}V_{n\to1s}(E;\mu,\sigma,\Gamma^*) + y_{em}e^{\lambda_{em}E} + y_{had}e^{\lambda_{had}E} + C$$

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

Kaonic deuterium lines

Background: E.M and hadronic

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

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

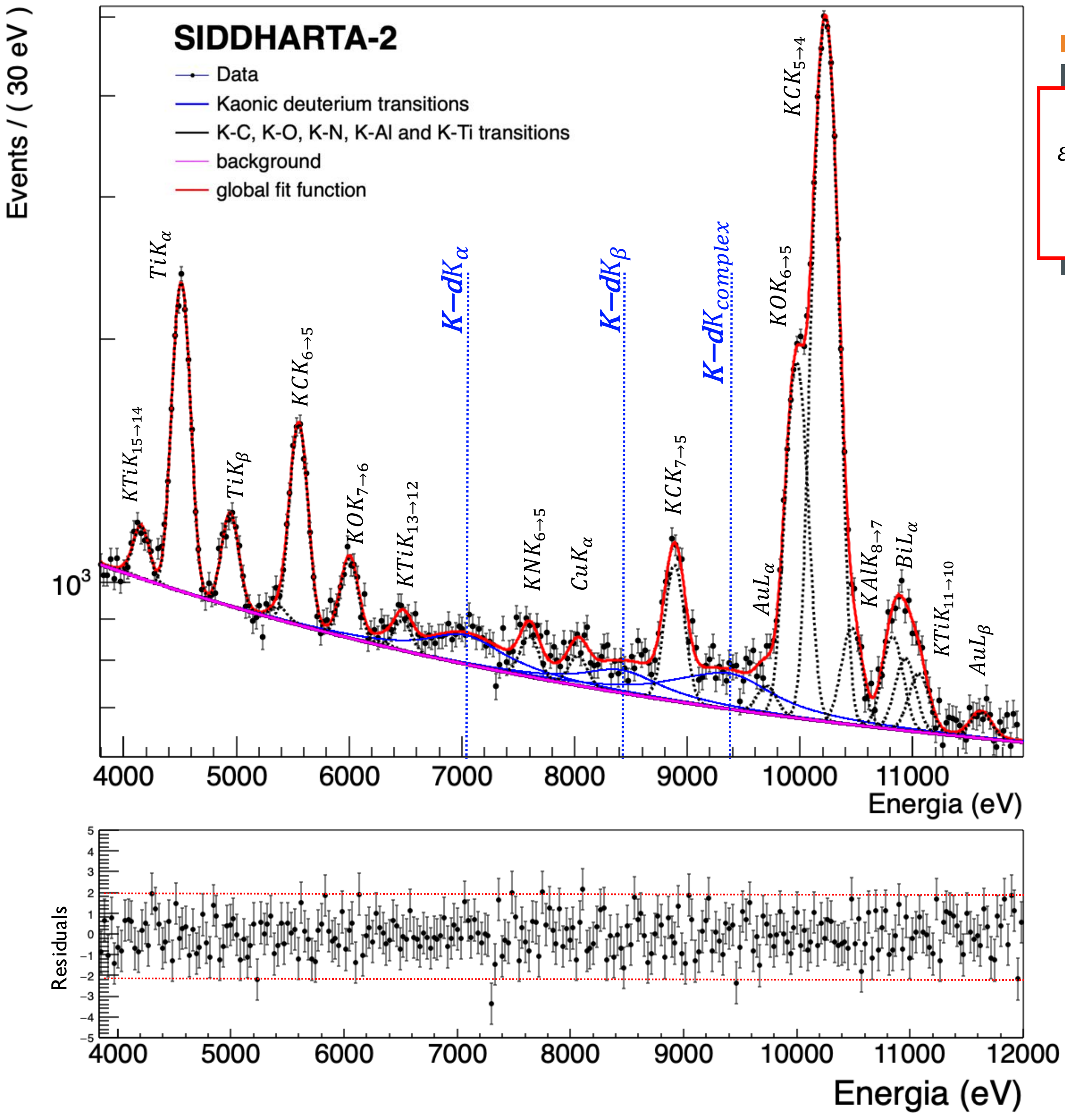
Systematic uncertainty on SDDs energy calibration and stability

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)

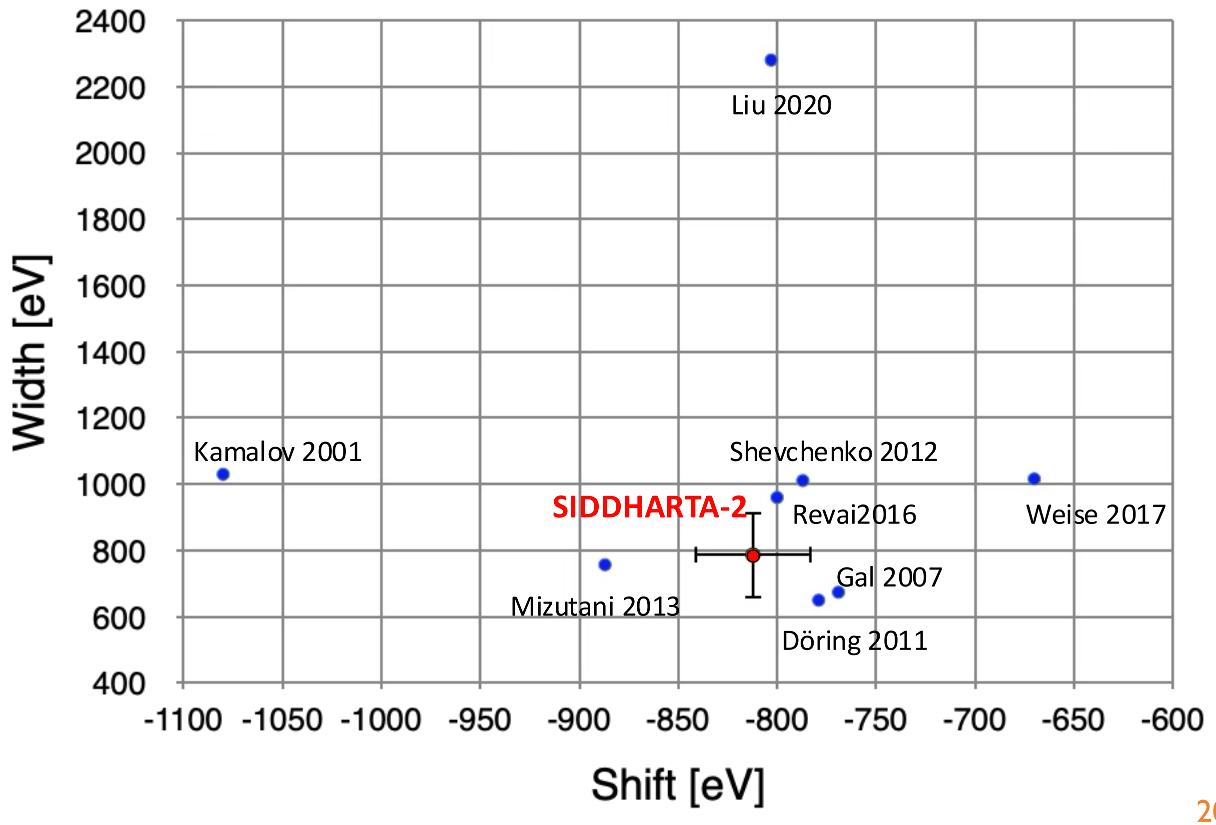
Kaonic Deuterium Results



$$\varepsilon_{1s} = E^{exp}_{2p\to 1s} - E^{QED}_{2p\to 1s} = 7021.9 - 7834.0 = -812.1 \pm 29.8(stat) \pm 2.1(syst)\ \text{eV}$$

$$\Gamma_{1s} = 787 \pm 126(stat) \pm 33(syst)\ \text{eV}$$

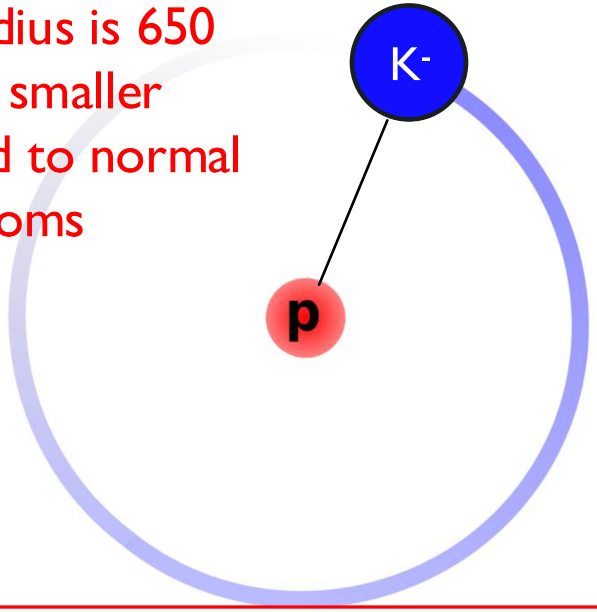
Targeted precision achieved!



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 normal atoms

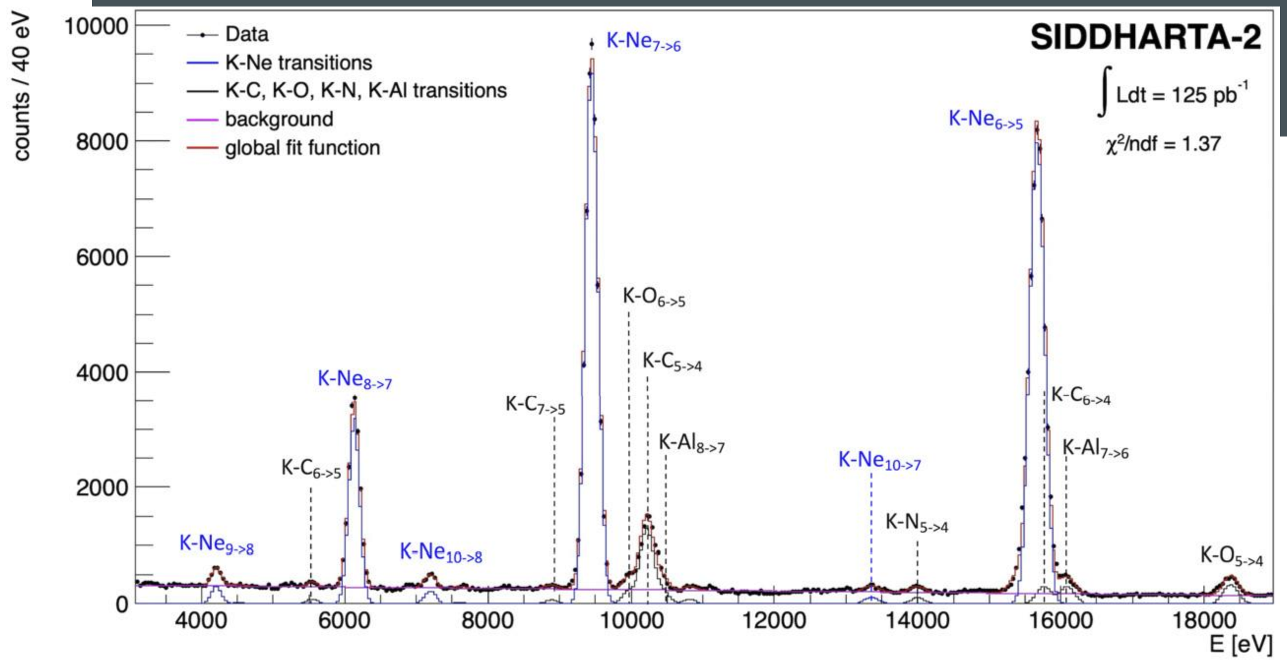


Particle	m [MeV/c^2]	B_{1s} [keV]	r_B [10^{-15} m]	Accessible interactions
ep	0.511	13.6 x 10^{-3}	0.53 x 10^5	Electro-weak
μp	105.7	2.53	279	Electro-weak
πp	139.6	3.24	216	Electro-weak + strong
Kp	493.7	8.61	81	Electro-weak + strong
$\bar{p}$p	938.3	12.5	58	Electro-weak + strong

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

Study of QED under strong field

Kaonic neon X-ray spectroscopy



Phys. Lett. B 865 (2025) 139492

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journal homepage: www.elsevier.com/locate/physletb

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,l], 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,l], C. Curceanu [a]

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

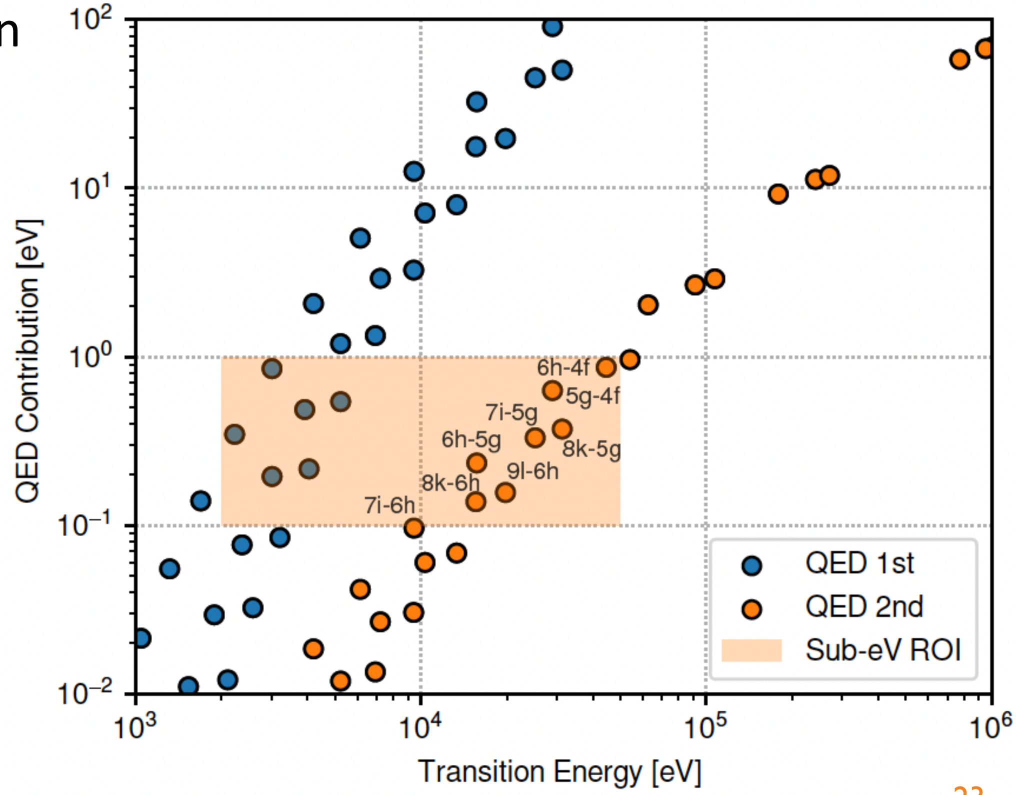
The kaonic neon measurement demonstrates the feasibility of precision studies in the field of QED with kaonic atoms (BSQED)

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	$E_{if}^{(\text{exp.})}$	$\delta E_{if}^{(\text{stat.})}$	$\delta E_{if}^{(\text{sys.})}$	$E_{if}^{(\text{calc.})}$	$E_{if}^{(\text{QED})}$	$E_{if}^{(\text{QED1})}$	$E_{if}^{(\text{QED2})}$	$\Delta E_{if}^{(\text{isot.})}$	$\Delta E_{if}^{(\text{screen.})}$	$\Delta E_{if}^{(\text{PDG})}$
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, Electron 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



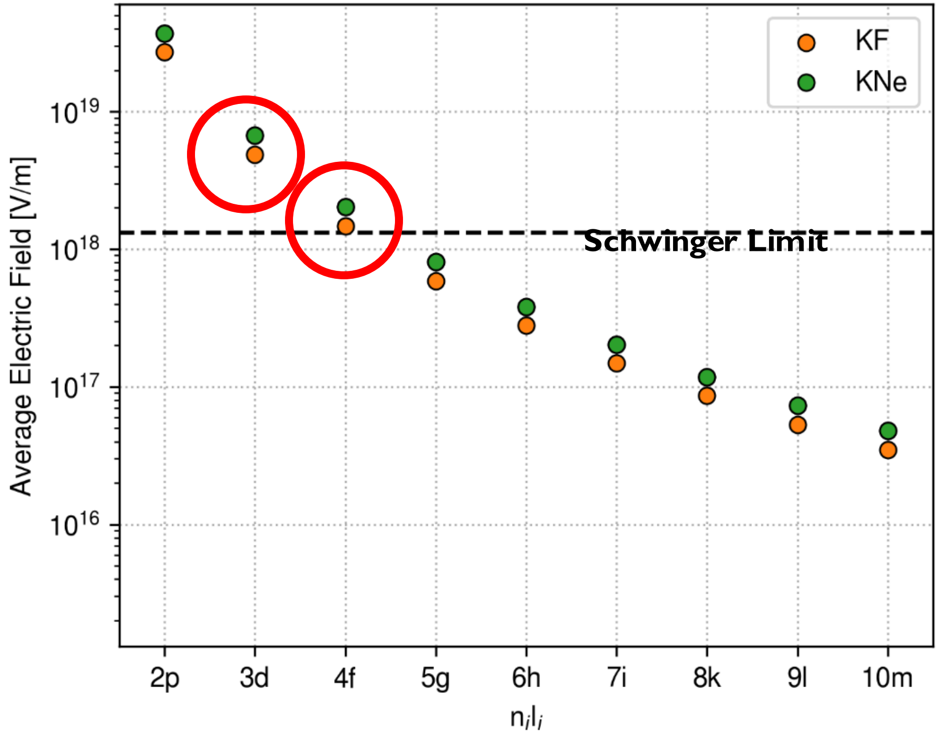
- Kaonic Neon offers a clean system to test **QED calculations**

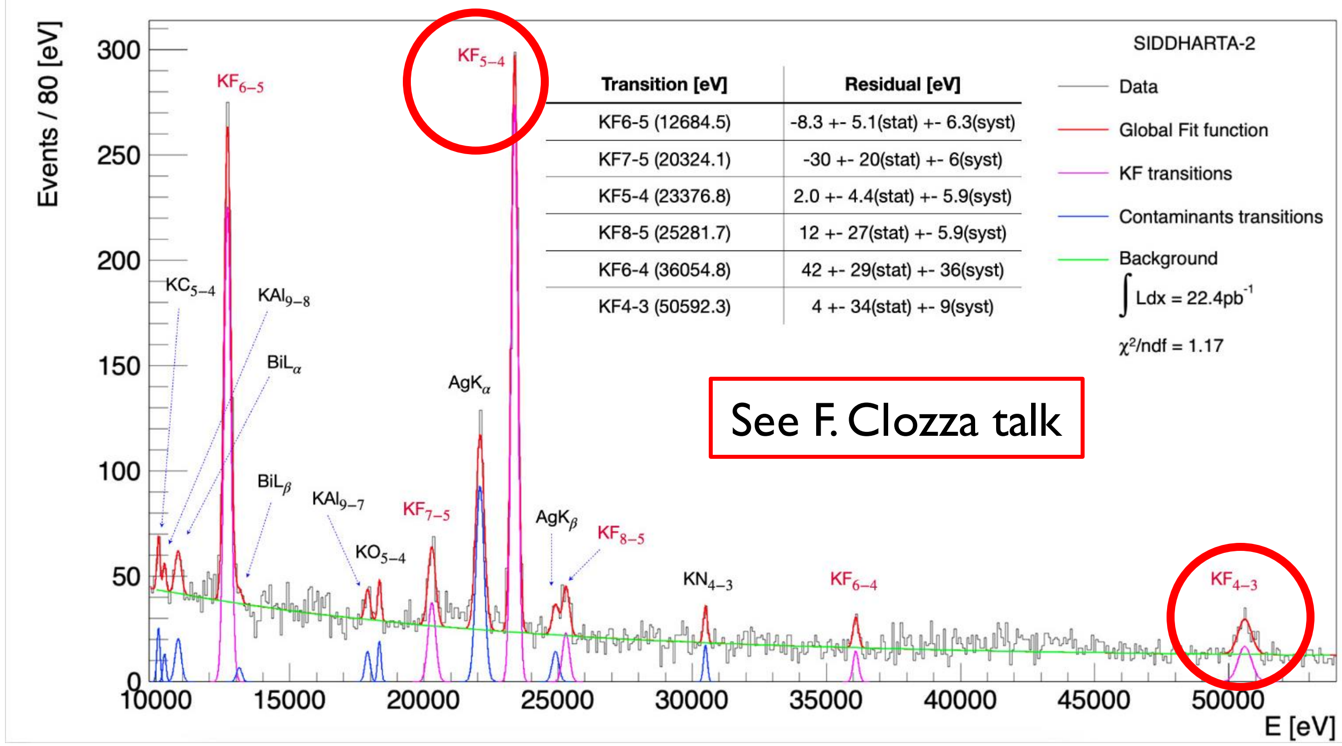
Kaonic Atoms as Probes of Strong Fields QED: Schwinger Limit for KF

- **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





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^-)

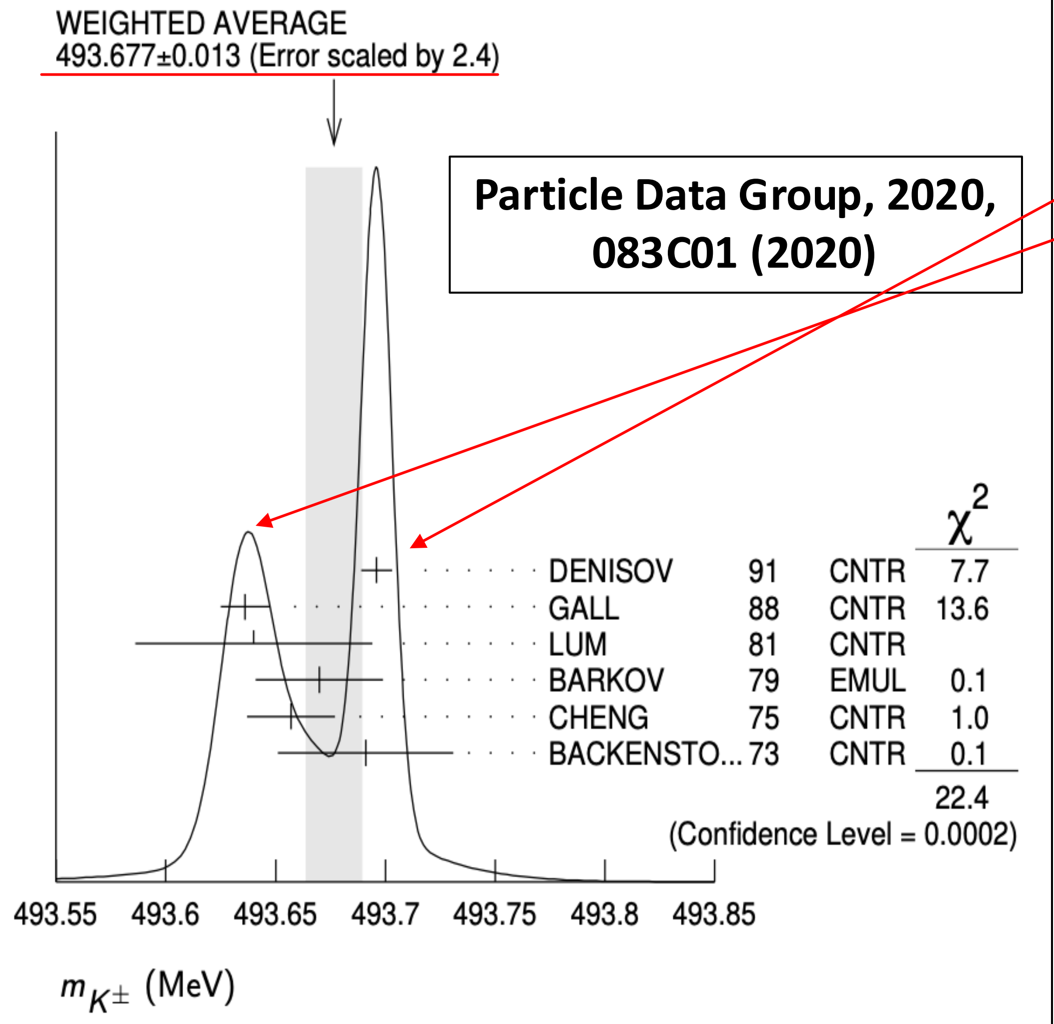
~~493.677 ± 0.013 MeV~~

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)



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

- 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

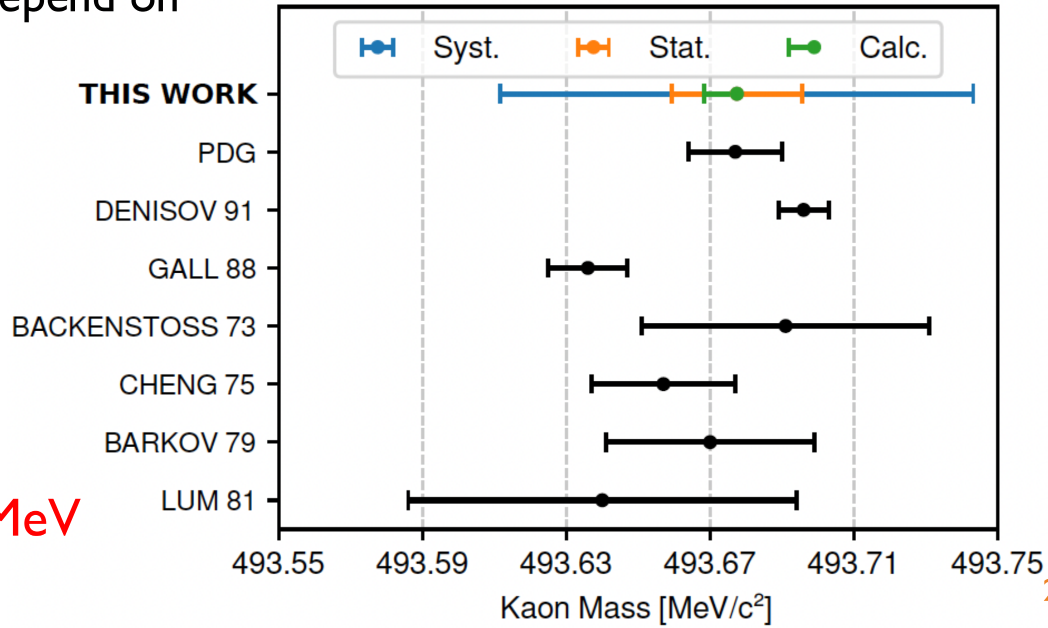
Transition	$E_{if}^{(exp.)}$	$\delta E_{if}^{(stat.)}$	$\delta E_{if}^{(sys.)}$	$E_{if}^{(calc.)}$	$E_{if}^{(QED)}$	$E_{if}^{(QED1)}$	$E_{if}^{(QED2)}$	$\Delta E_{if}^{(isot.)}$	$\Delta E_{if}^{(screen.)}$	$\Delta E_{if}^{(PDG)}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02	9.90	-0.38	0.11
8k-7i	6130.57	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** are used to iteratively extract the Kaon Mass from measured transitions as in **GAL88:**

$$M'_{K^-} = M_{K^-}\frac{E^{exp}}{E^{calc}} \qquad \delta M_{K^-} = M_{K^-}\frac{\delta E^{exp}}{E^{exp}}$$

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

Transition	M_{K^-} [MeV]	$\delta M_{K^-}^{stat.}$ [keV]	$\delta M_{K^-}^{syst.}$ [keV]	$\delta M_{K^-}^{calc.}$ [keV]
7i-6h	493.674	19	78	9
8k-7i	493.699	52	121	21
7i-6h + 8k-7i	493.677	18	66	11



- M_{K^-} = 493.647 + 0.0203 (stat) + 0.0657 (syst) + 0.0112 (calc) MeV

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

Table 1
Compilation of K^- atomic data

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

Beyond SIDDHARTA-2

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

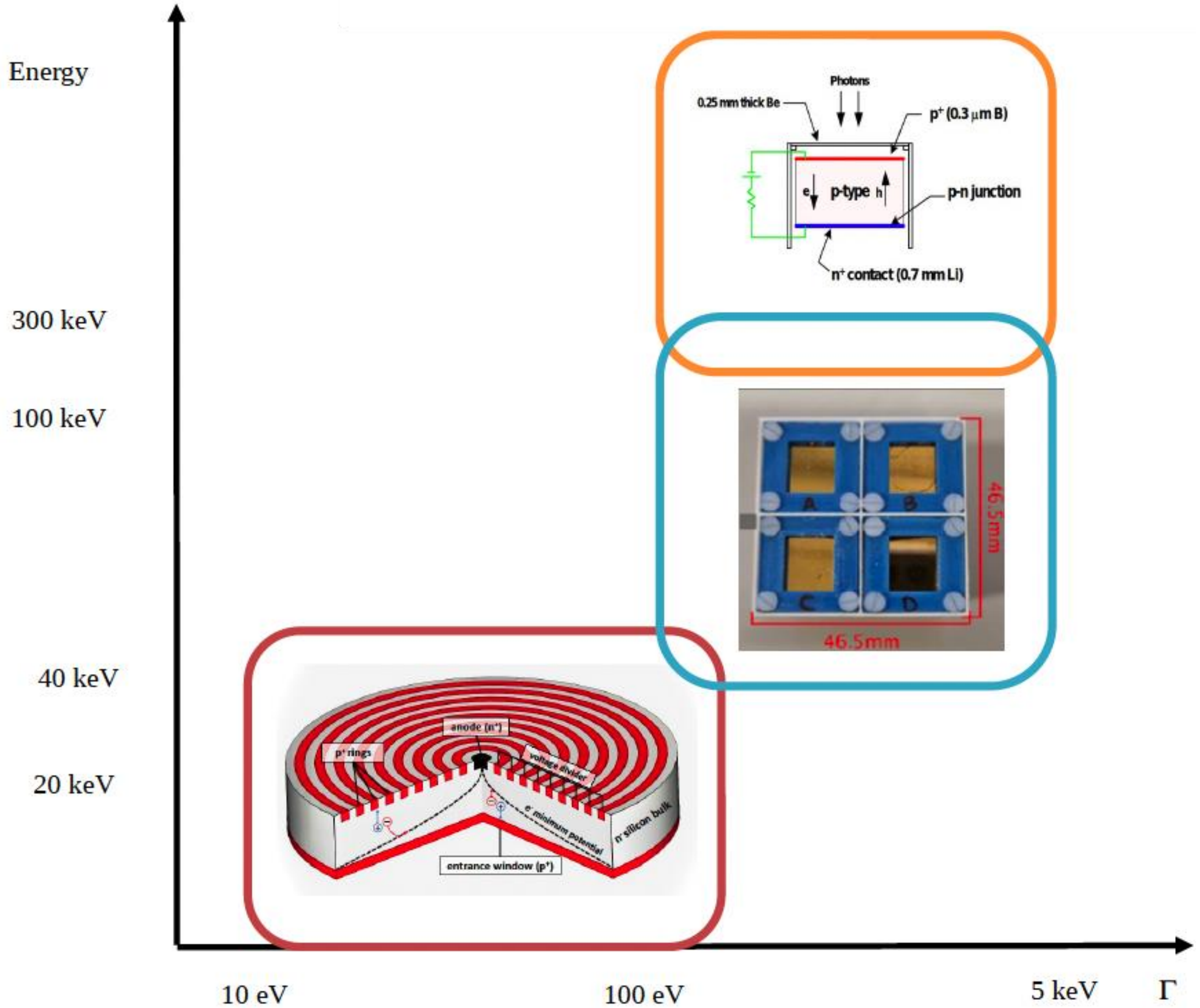
See F. Clozza talk

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

See F.Artibani talk

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

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



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

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)

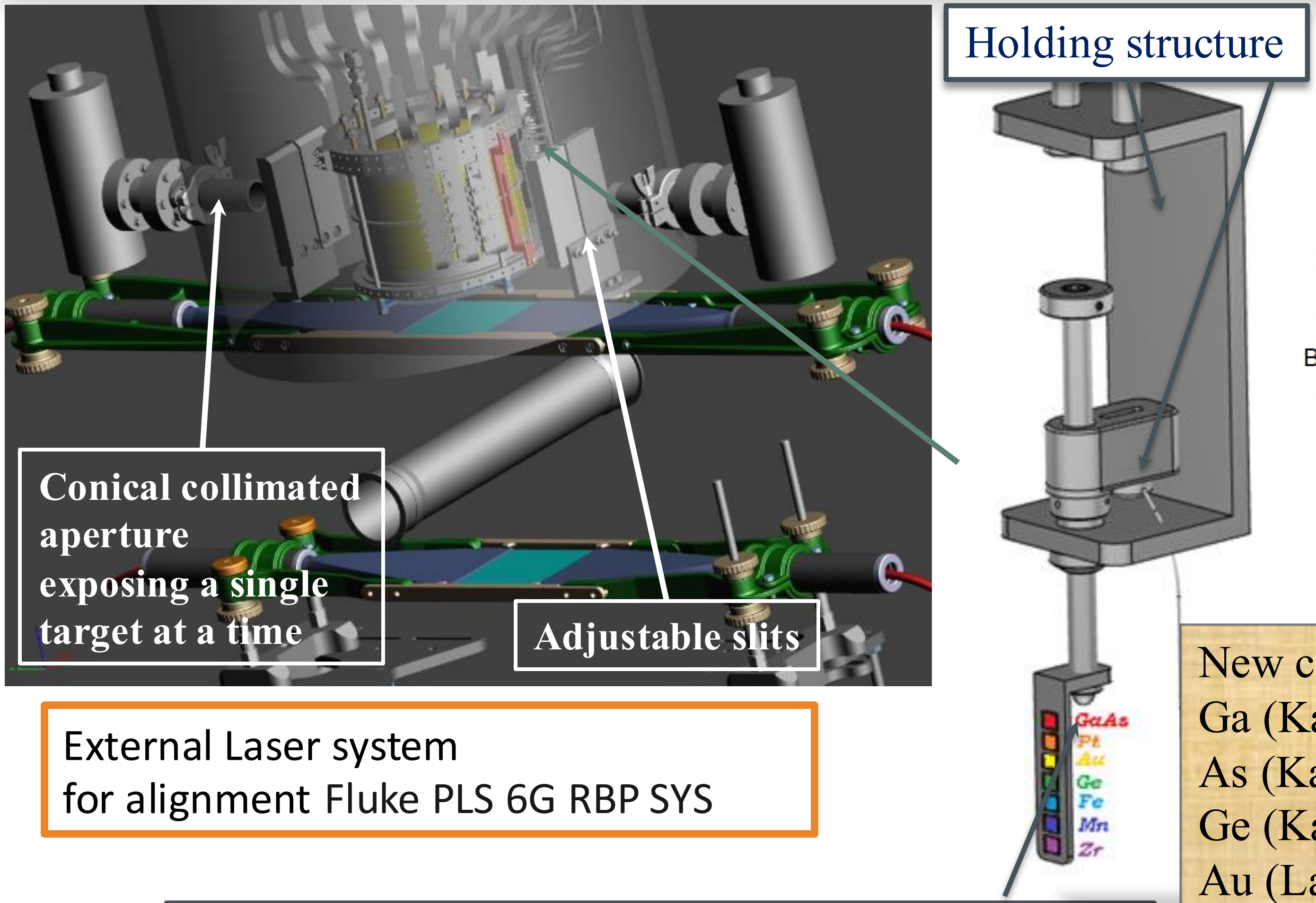
In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with CdZnTe detectors

- 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

1.1 - High precision kaonic neon measurement
- **Goal: systematic uncertainty ~0.1 eV - 0.2 eV**
- **new calibration system financed and under construction**

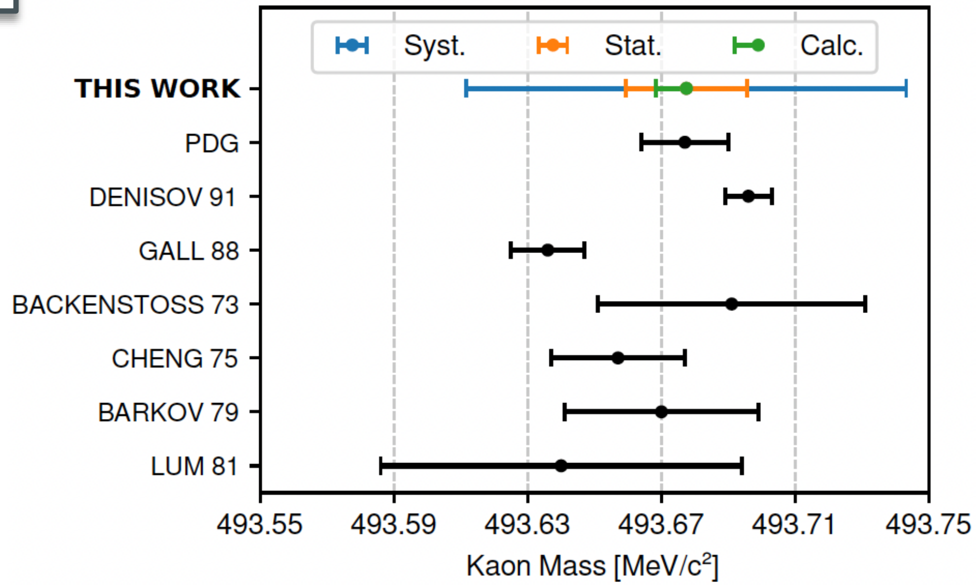
Modifying the calibration target system from 3 fixed to 7 movable fluorescent foils



External Laser system
for alignment Fluke PLS 6G RBP SYS

Movable targets arm inserted behind the collimator.

Limited by systematic uncertainty on energy calibration

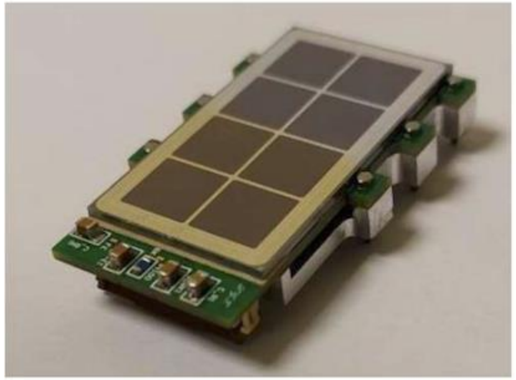


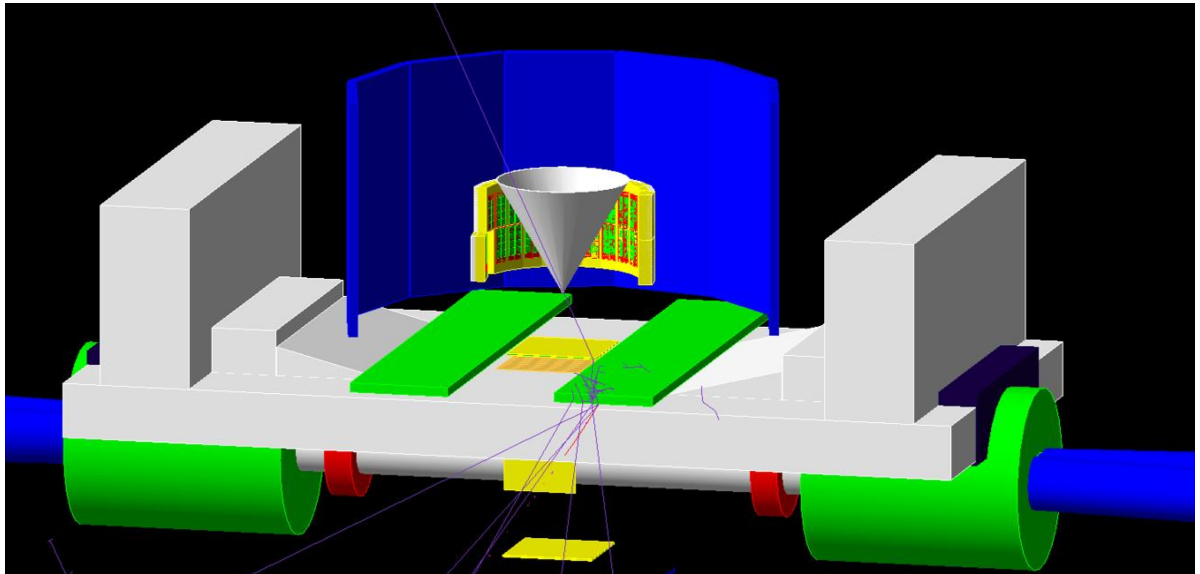
New calibration materials
Ga (Ka 9243 eV)
As (Ka 10532 eV)
Ge (Ka 9876 eV)
Au (La 9685 eV)
Pt (La 9416 eV)

Beyond SIDDHARTA-2: EXKALIBUR

LIGHT MASS (LOW-Z) KAONIC ATOMS (LHKA)

- After the kaonic neon, measurement of **light mass (Li, Be, B)** kaonic atoms **high and low-n transitions**, **to study in detail the strong interaction between kaon and few nucleons (many body).**
- Now precise measurements for these kaonic atoms of the shifts, widths and yields will result in a **significative improvement on the knowledge of the interactions of kaons in matter**, with a great impact on the **low energy QCD and astrophysics** (equation of state for neutron stars).





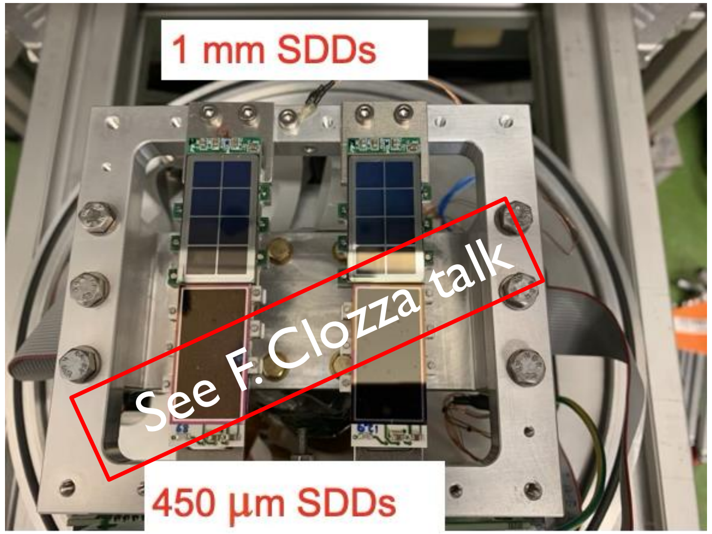
Replacing the gaseous target with a multi-element (Li-Be-B) solid target and new 1 mm thick SDDs for higher detection efficiency up to 50 keV

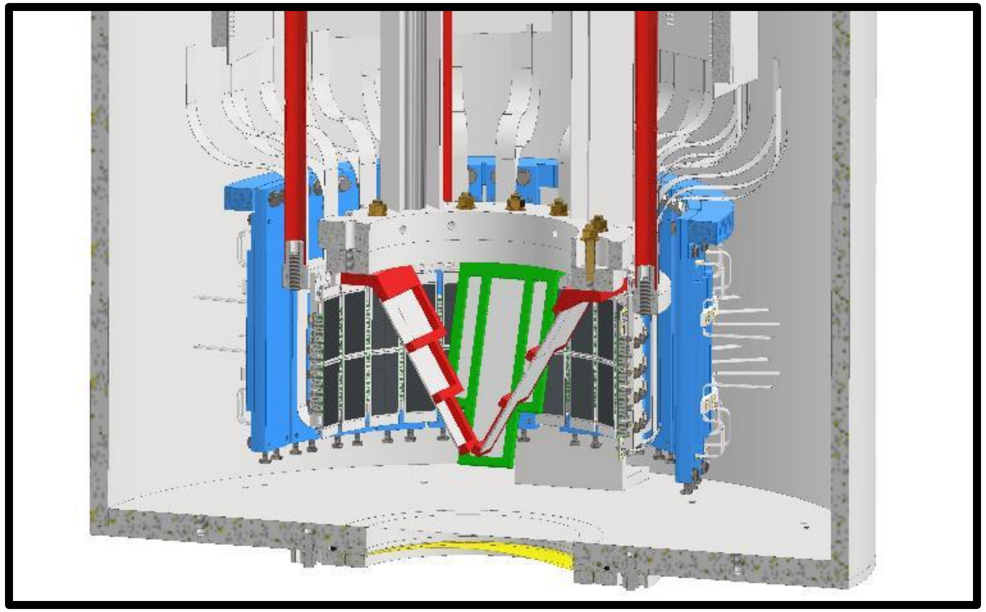
1.2 - Light kaonic atoms (LHKA)
– solid target Li, Be, B
– integration of 1mm SDD

Solid targets system

- Kaonic boron test measurement successfully achieved
- Construction of new support system
- conical shape to maximise the solid angle
- MC simulations ongoing

Lithium-6		Lithium-7		Beryllium-9	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**15.085**	**3 → 2**	**15.261**	**3 → 2**	**27.560**
4 → 2	**20.365**	**4 → 2**	**20.603**	**4 → 3**	**9.646**
5 → 2	**22.809**	**5 → 2**	**23.075**	**5 → 3**	**14.111**
4 → 3	5.280	4 → 3	5.341	5 → 4	4.465
5 → 3	7.724	5 → 3	7.814	6 → 4	6.890
5 → 4	2.444	5 → 4	2.472	6 → 5	2.425
6 → 4	3.771	6 → 4	3.815		



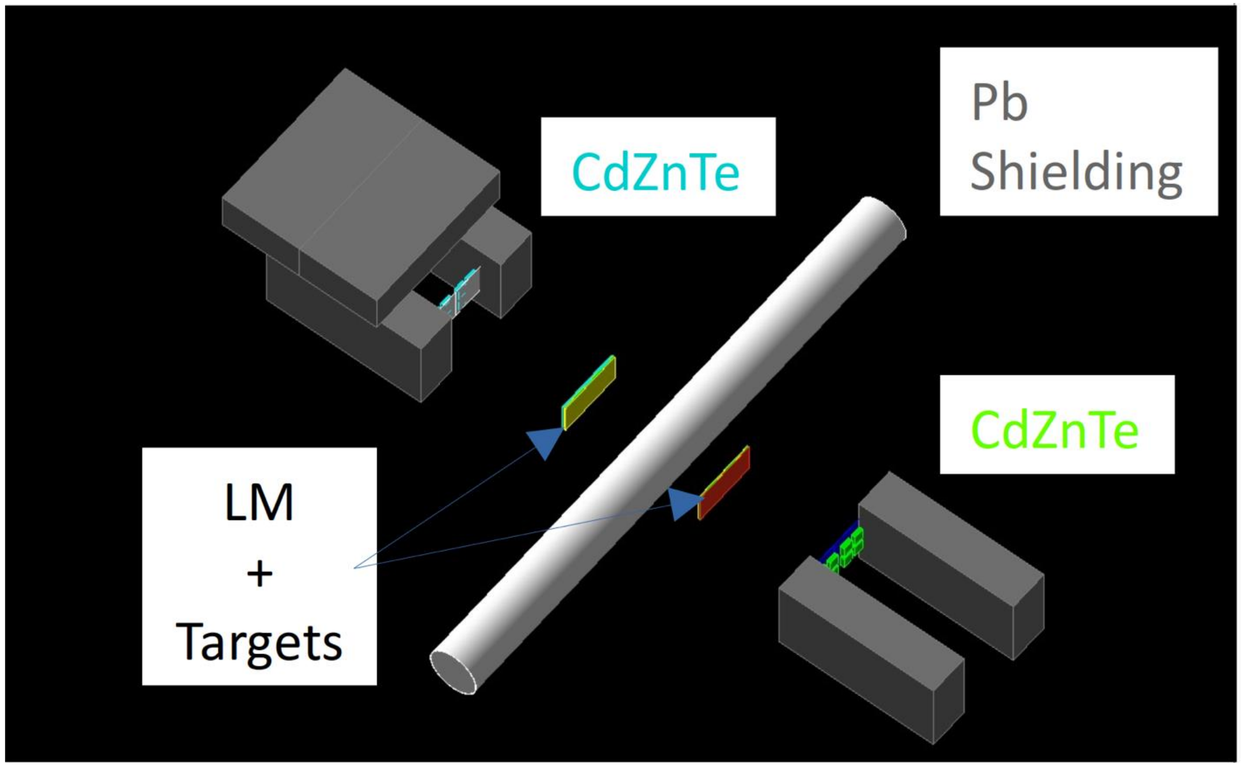


Boron-10		Boron-11	
Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**43.568**	**3 → 2**	**43.768**
4 → 3	**15.156**	**4 → 3**	**15.225**
5 → 3	**22.171**	**5 → 3**	**22.273**
5 → 4	7.015	5 → 4	7.047
6 → 4	10.826	6 → 4	10.875
6 → 5	3.811	6 → 5	3.828

1mm thick SDDs: enhanced efficiency above 15 keV

Beyond SIDDHARTA-2: EXKALIBUR

Intermediate-mass kaonic atoms measurements with CdZnTe setups (in parallel with the LHKA measurement)



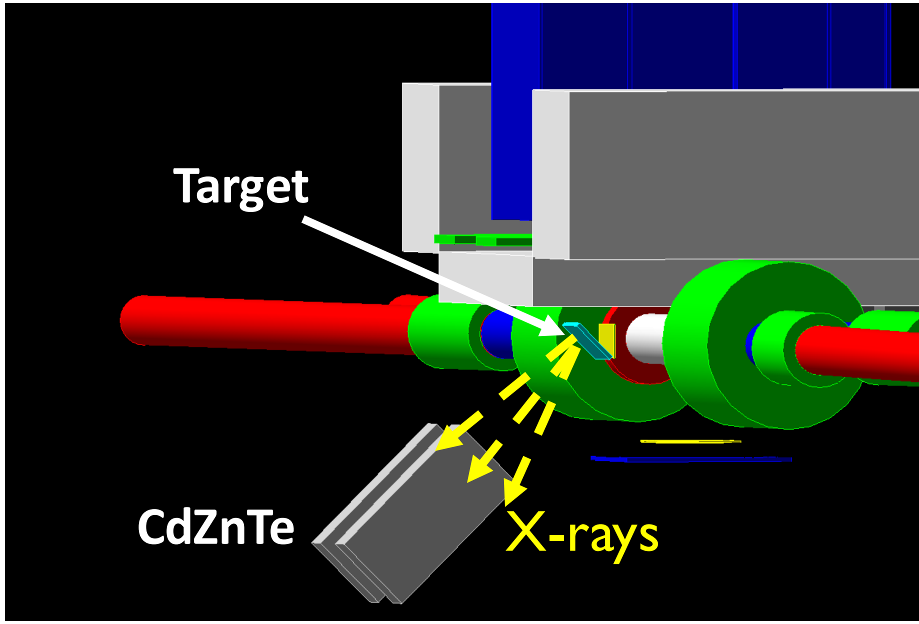
See F. Artibani talk for more details

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

Intermediate kaonic atoms (IMKA)

In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with different types of detectors: CdZnTe detectors

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



Scientific goals

- ❑ The energy and width of the **KAl(3->2) and KO(3->2)** transitions;
- ❑ The energies (E) and widths (W) of the **KO(4->3), KS(4->3) and KAl(4->3)** with precisions better than the present ones;
- ❑ **The first measurements ever of the absolute yields** of the Δn=1,2 transitions towards n=2,3 levels in KO, n=3,4,5 in KS and KAl

We are developing an optimised CdZnTe based setup

- **Larger active area:** 32 detectors instead of 8
- **Optimised geometry and shielding** to reduce the background

MC simulation: estimated precision for 300 pb^{-1}

$K^{32}S(4 \rightarrow 3)$ @ 160 keV : $\delta E = 41$ eV, $\delta\Gamma = 81$ eV (91 eV and 181 in the S/B = 1/10 case) for 16 cm^2

$K^{32}S(4 \rightarrow 3)$ @ 160 keV : $\delta E = 19$ eV, $\delta\Gamma = 37$ eV (42 eV and 83 in the S/B = 1/10 case) for 2% FWHM

Conclusions

- **First measurement of strong-interaction effects in kaonic deuterium:** implication for low-energy QCD

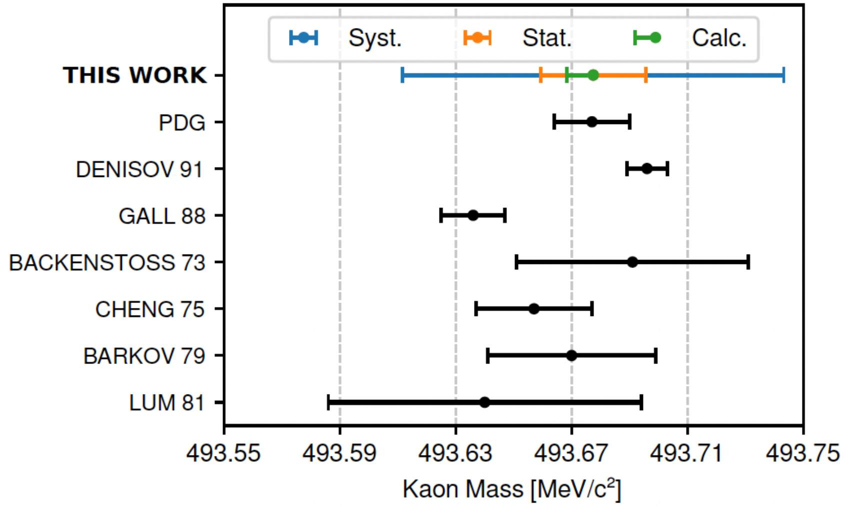
$$\varepsilon_{1s} = E^{exp}_{2p\rightarrow 1s} - E^{QED}_{2p\rightarrow 1s} = 7021.9 - 7834.0 = -812.1 \pm 29.8(stat) \pm 2.1(syst)\ \text{eV}$$

$$\Gamma_{1s} = 787 \pm 126(stat) \pm 33(syst)\ \text{eV}$$

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

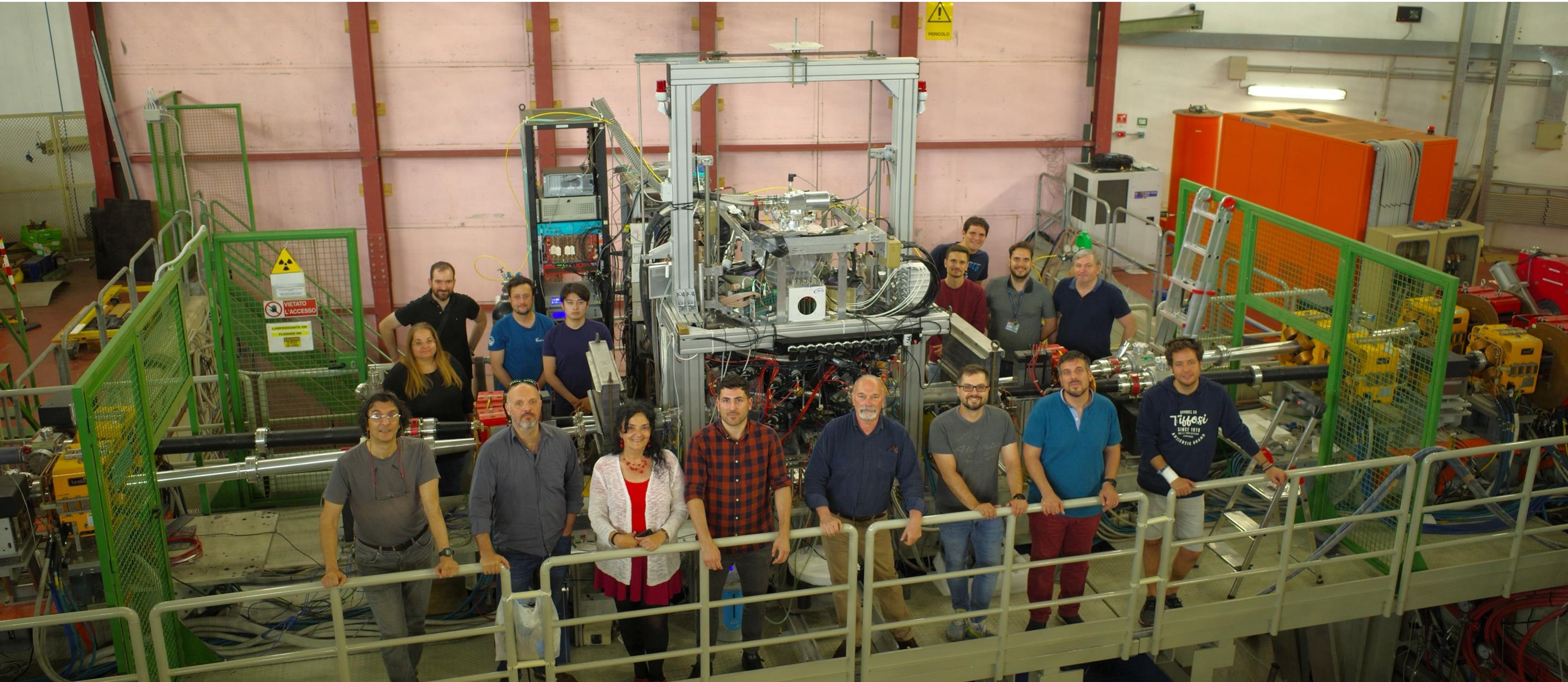
Transition	$E_{if}^{(\text{exp.})}$	$\delta E_{if}^{(\text{stat.})}$	$\delta E_{if}^{(\text{sys.})}$	$E_{if}^{(\text{calc.})}$	$E_{if}^{(\text{QED})}$	$E_{if}^{(\text{QED1})}$	$E_{if}^{(\text{QED2})}$	$\Delta E_{if}^{(\text{isot.})}$	$\Delta E_{if}^{(\text{screen.})}$	$\Delta E_{if}^{(\text{PDG})}$
9l-8k	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

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



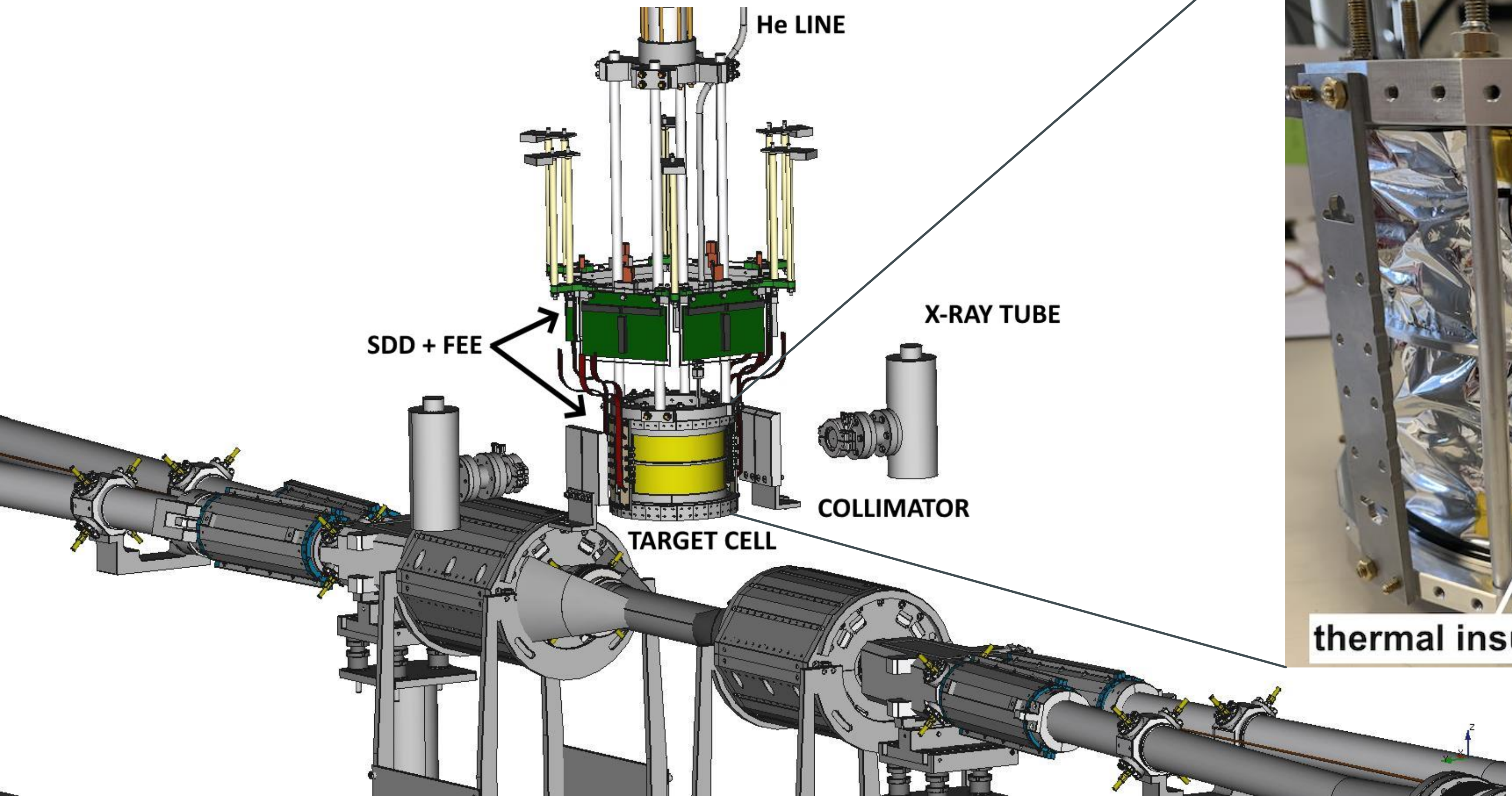
- **EXKALIBUR:** new X-ray detectors (**SDDs – CZT - HPGe**) have been developed/tested to perform **kaonic atoms measurements along the periodic table** providing new experimental data to probe the **kaon-nucleus interaction – kaon mass - BSQED**

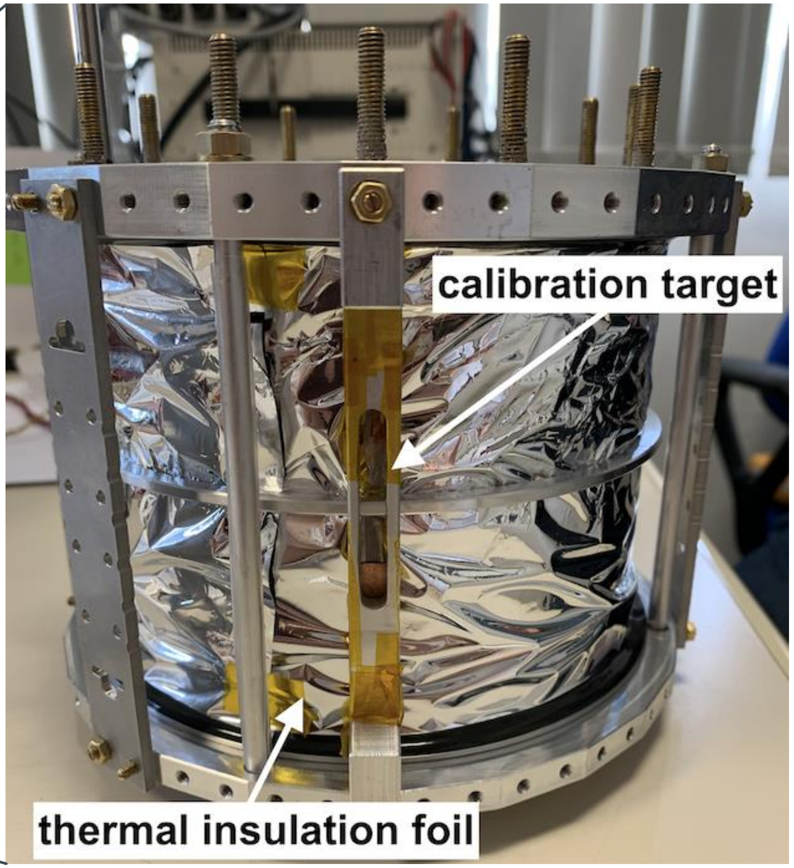
THANK YOU



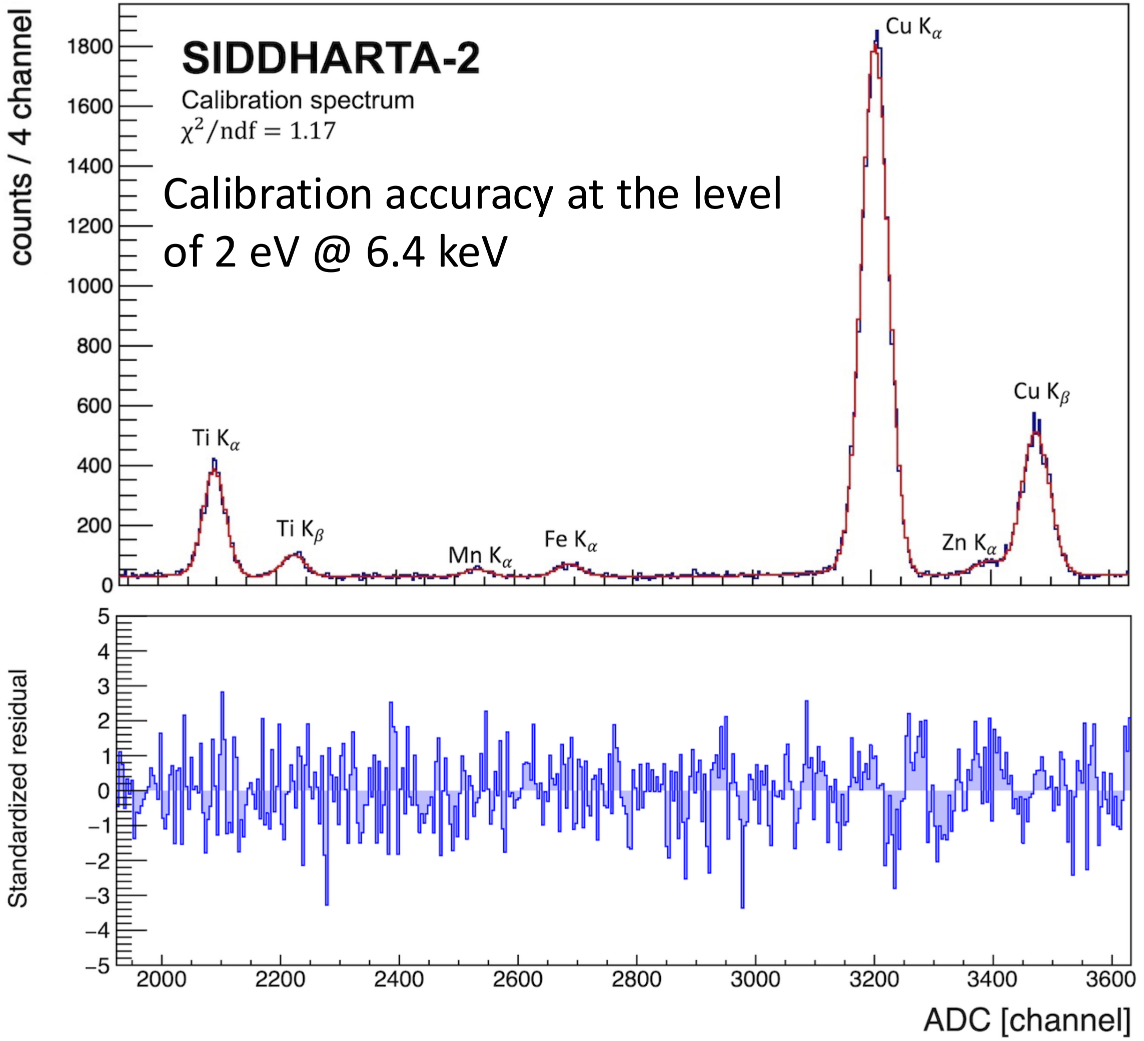
SPARE

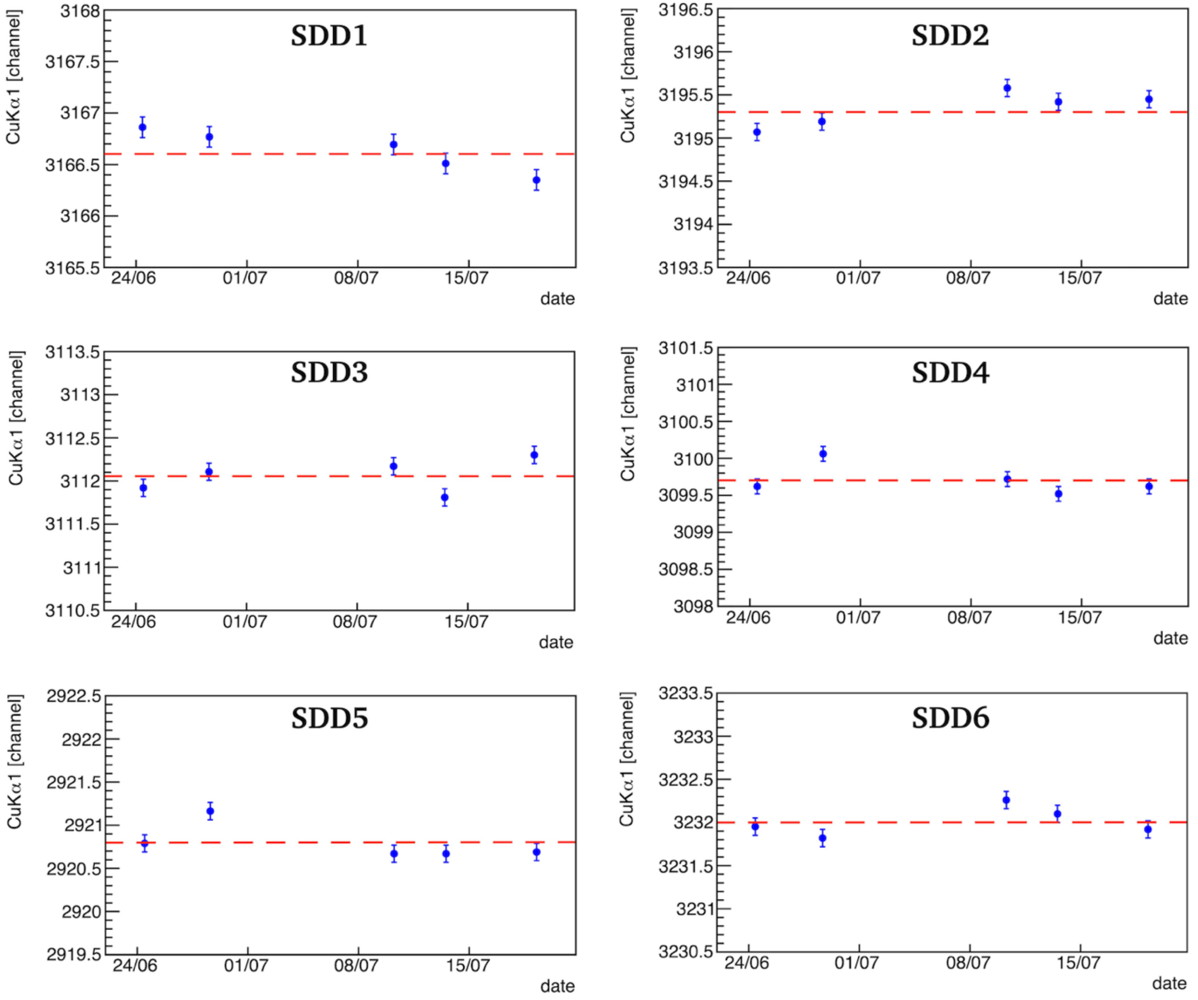
SDDs Calibration Procedure in DAΦNE





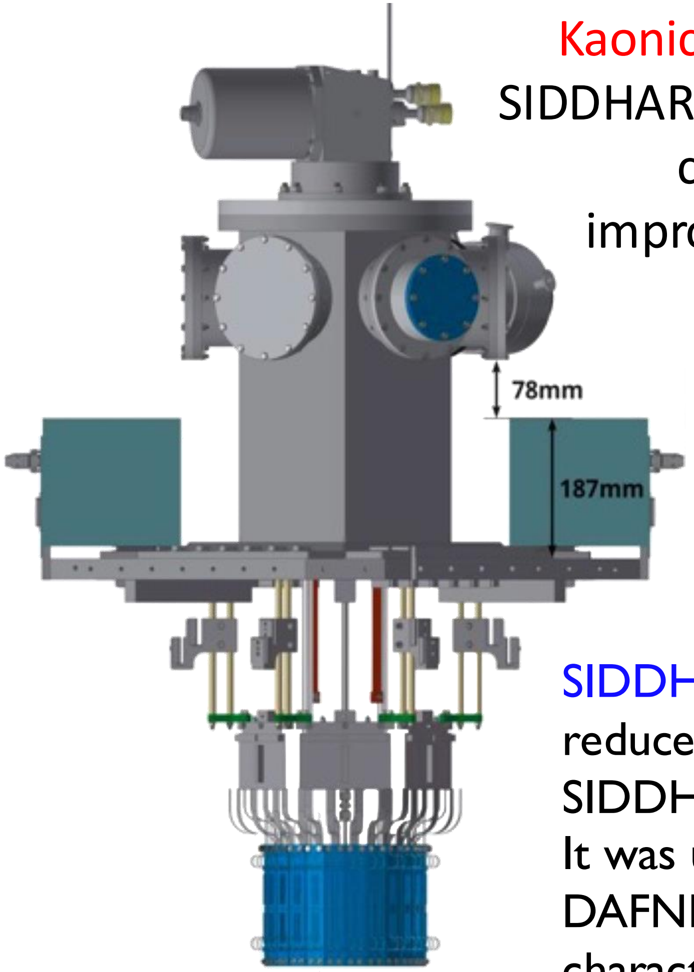
SDDs Calibration Procedure in DAΦNE





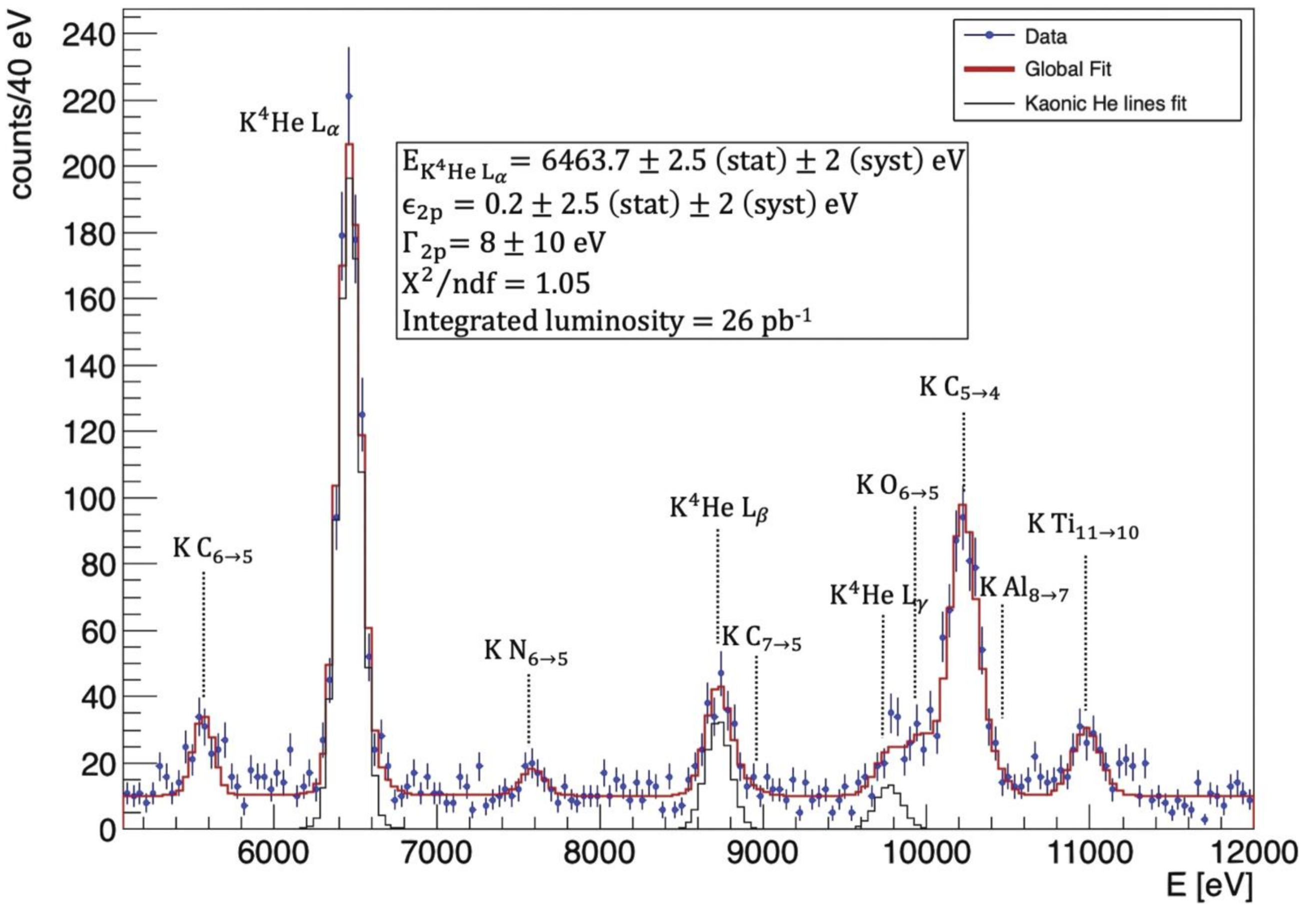
SIDDHARTINO - The kaonic ^{4}He 3d->2p measurement

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



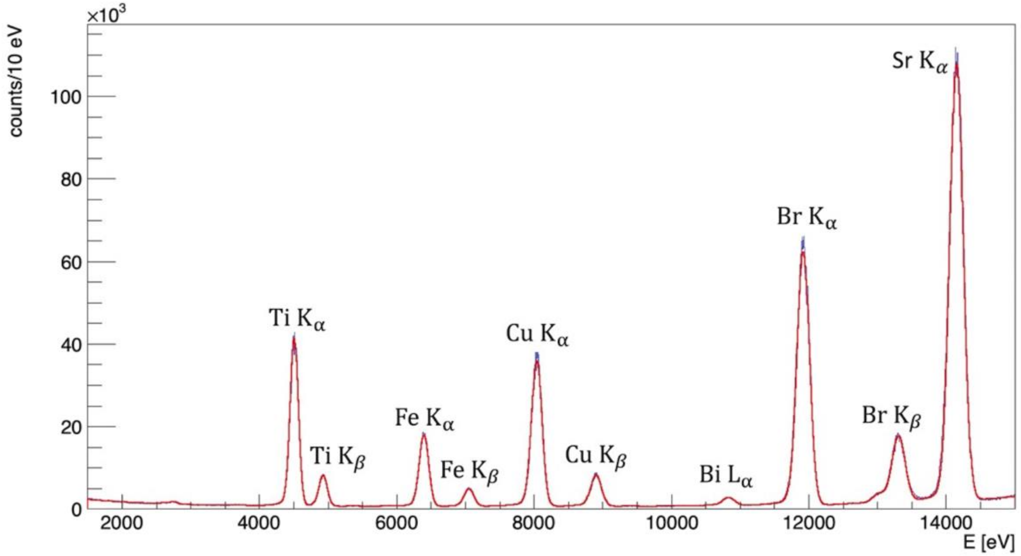
Kaonic Helium puzzle:
SIDDHARTA and KEK results confirmed,
improving accuracy

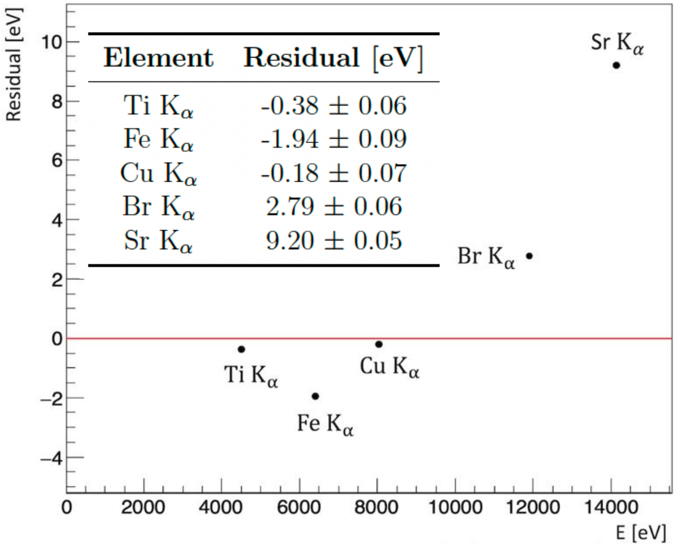
SIDDHARTINO:
reduced version of the SIDDHARTA-2 apparatus
It was used to optimize the DAFNE background and characterize the SDDs



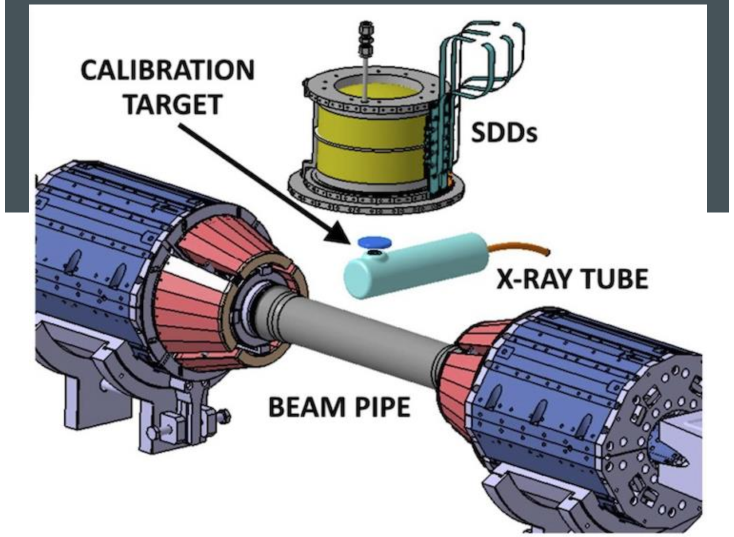
Sirghi D., Sirghi F., **Sgaramella F.**, et al., 2022, J. Phys. G Nucl. Part. Phys., 49 (5) 55106

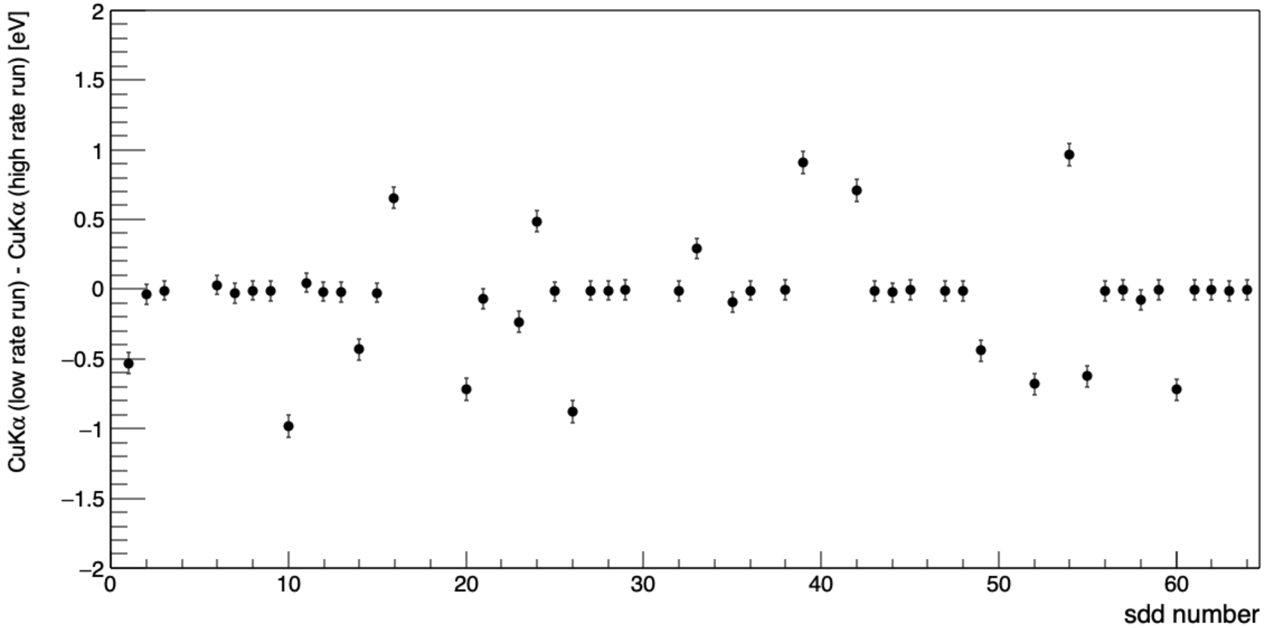
Spectroscopy Response in a High Background Environment

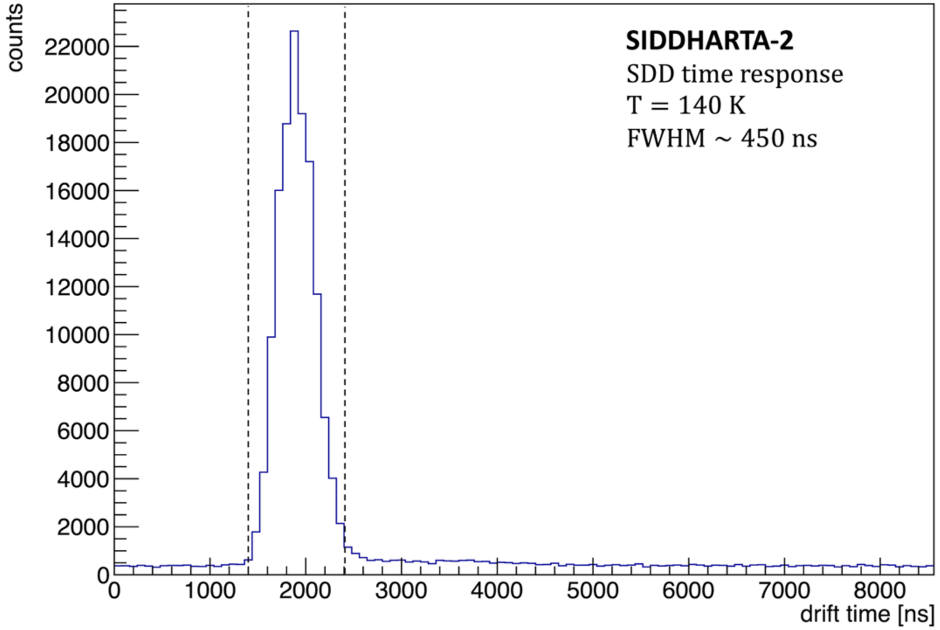




Element	Residual [eV]
Ti K_α	-0.38 ± 0.06
Fe K_α	-1.94 ± 0.09
Cu K_α	-0.18 ± 0.07
Br K_α	2.79 ± 0.06
Sr K_α	9.20 ± 0.05

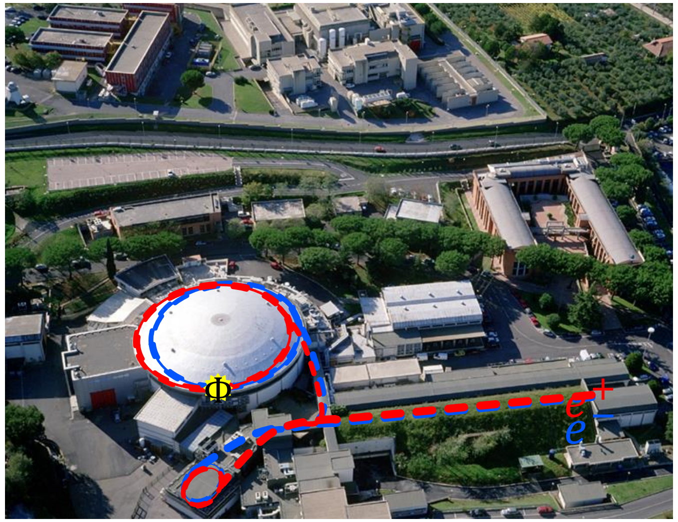


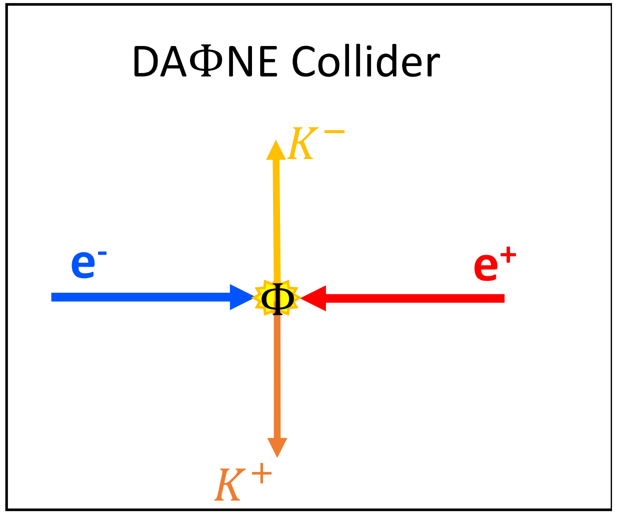


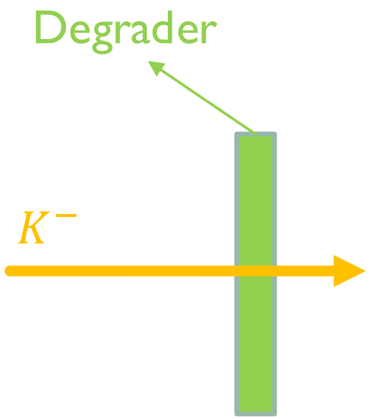


Sgaramella F., Miliucci M., et al., 2022, Phys Scr, 97 (11) 114002

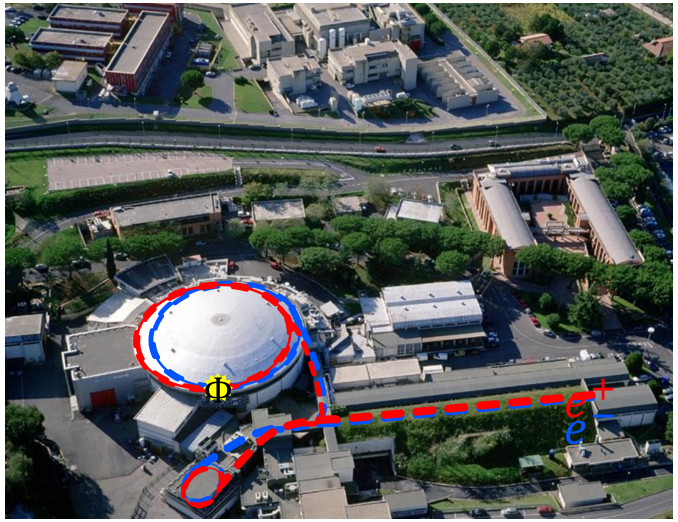
The SIDDHARTA-2 experiment - Layout

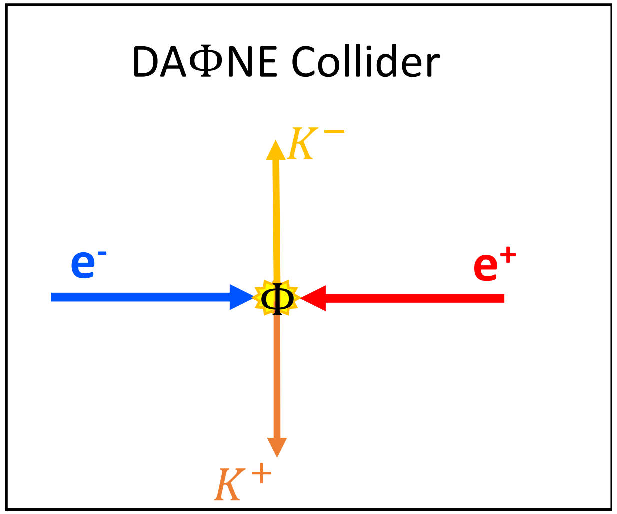


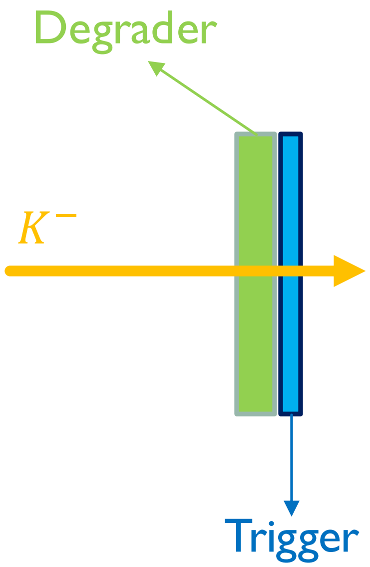




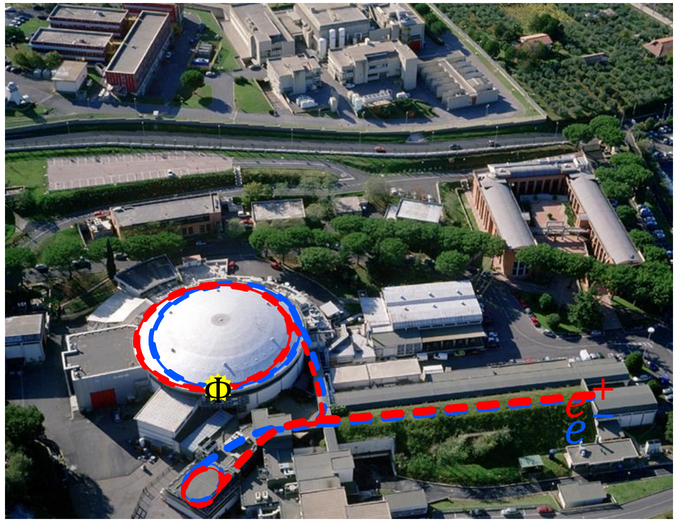
The SIDDHARTA-2 experiment - Layout

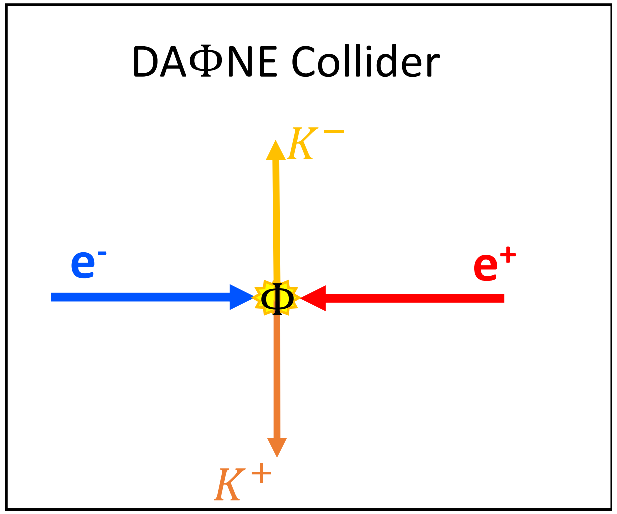


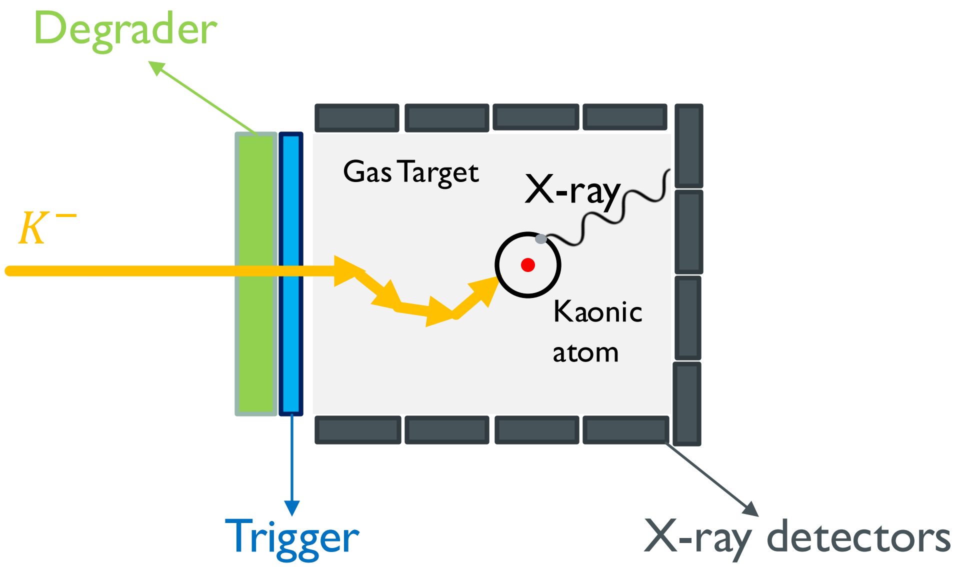




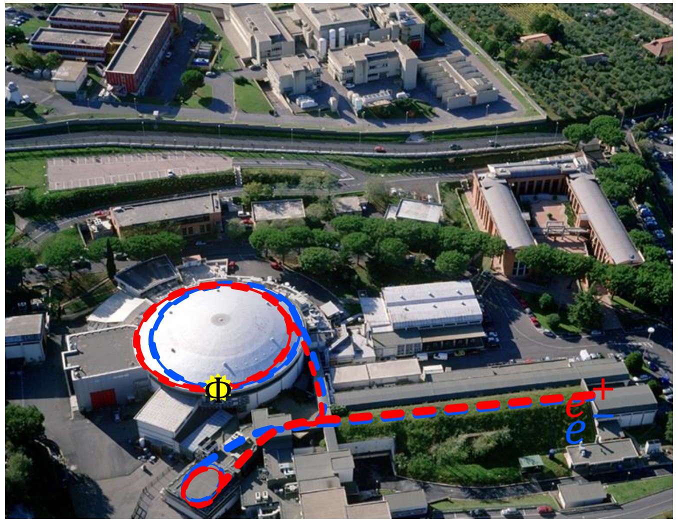
The SIDDHARTA-2 experiment - Layout

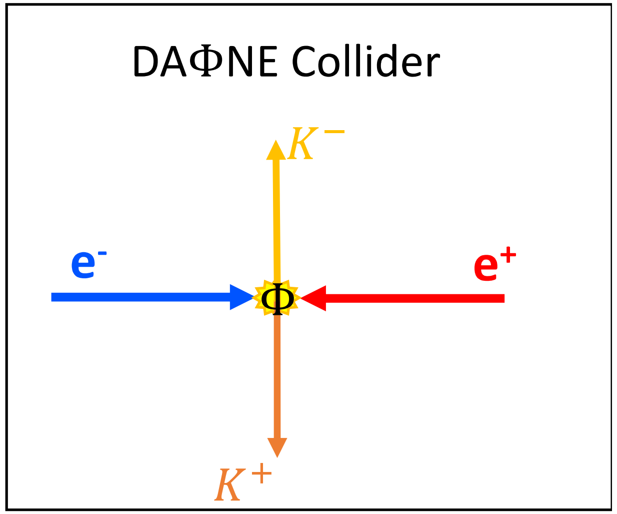


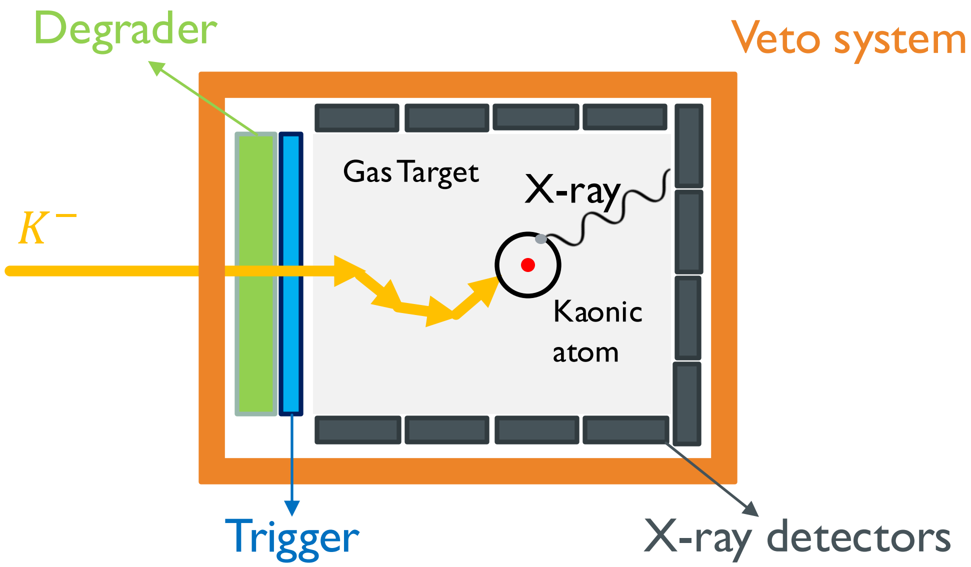




The SIDDHARTA-2 experiment - Layout







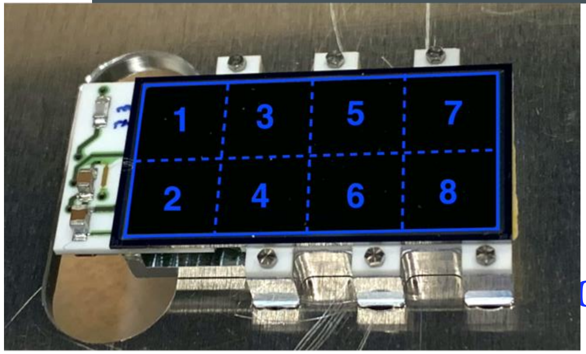
Silicon Drift Detectors

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

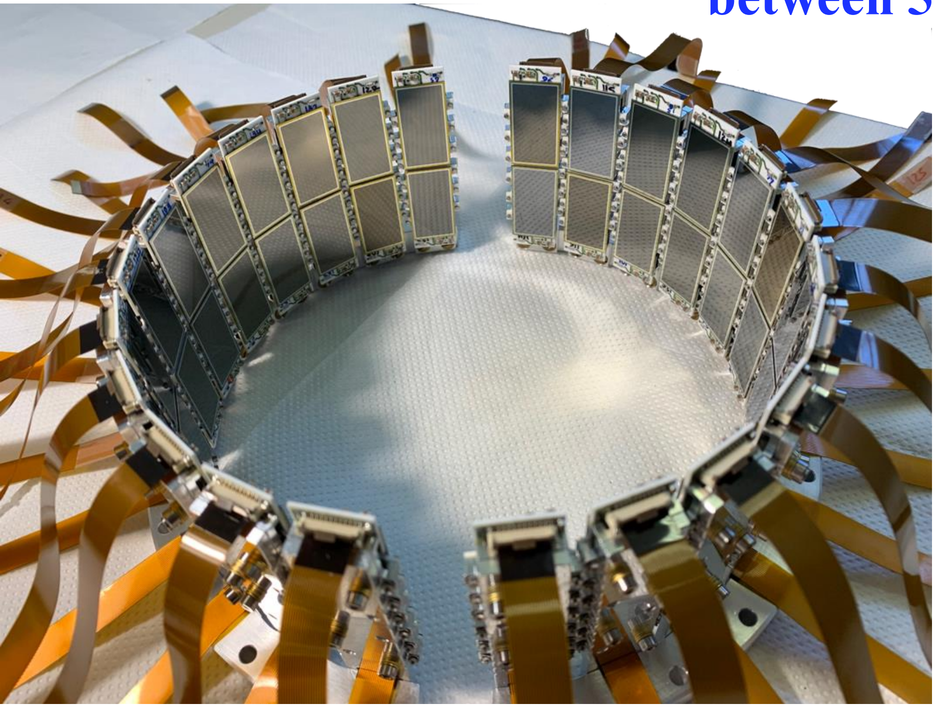
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

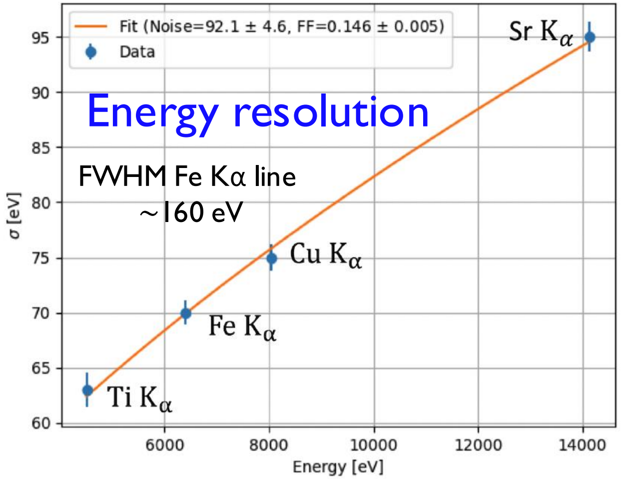
FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

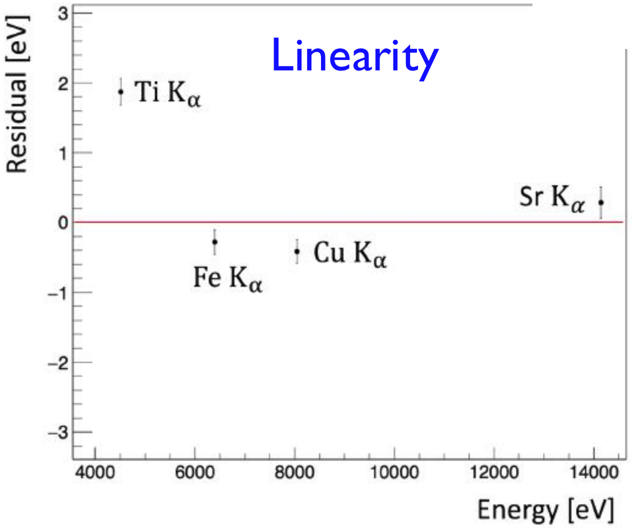
POLITECNICO MILANO 1863

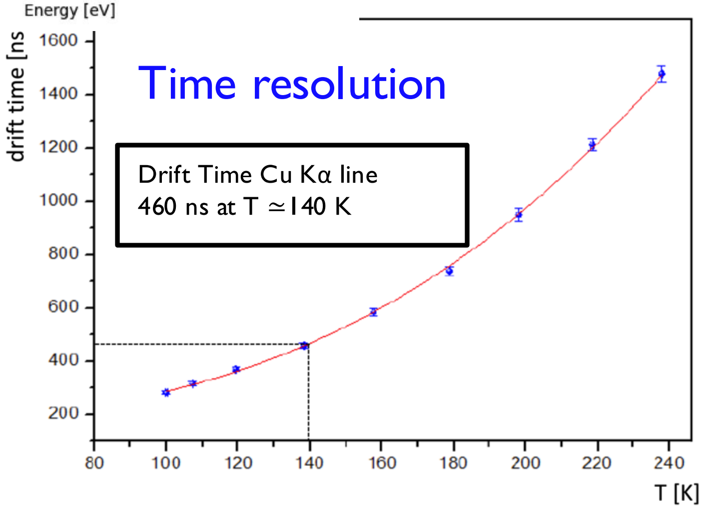


8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of 450 μm ensures a high
ollection efficiency for X-rays of energy
between 5 keV and 12 keV

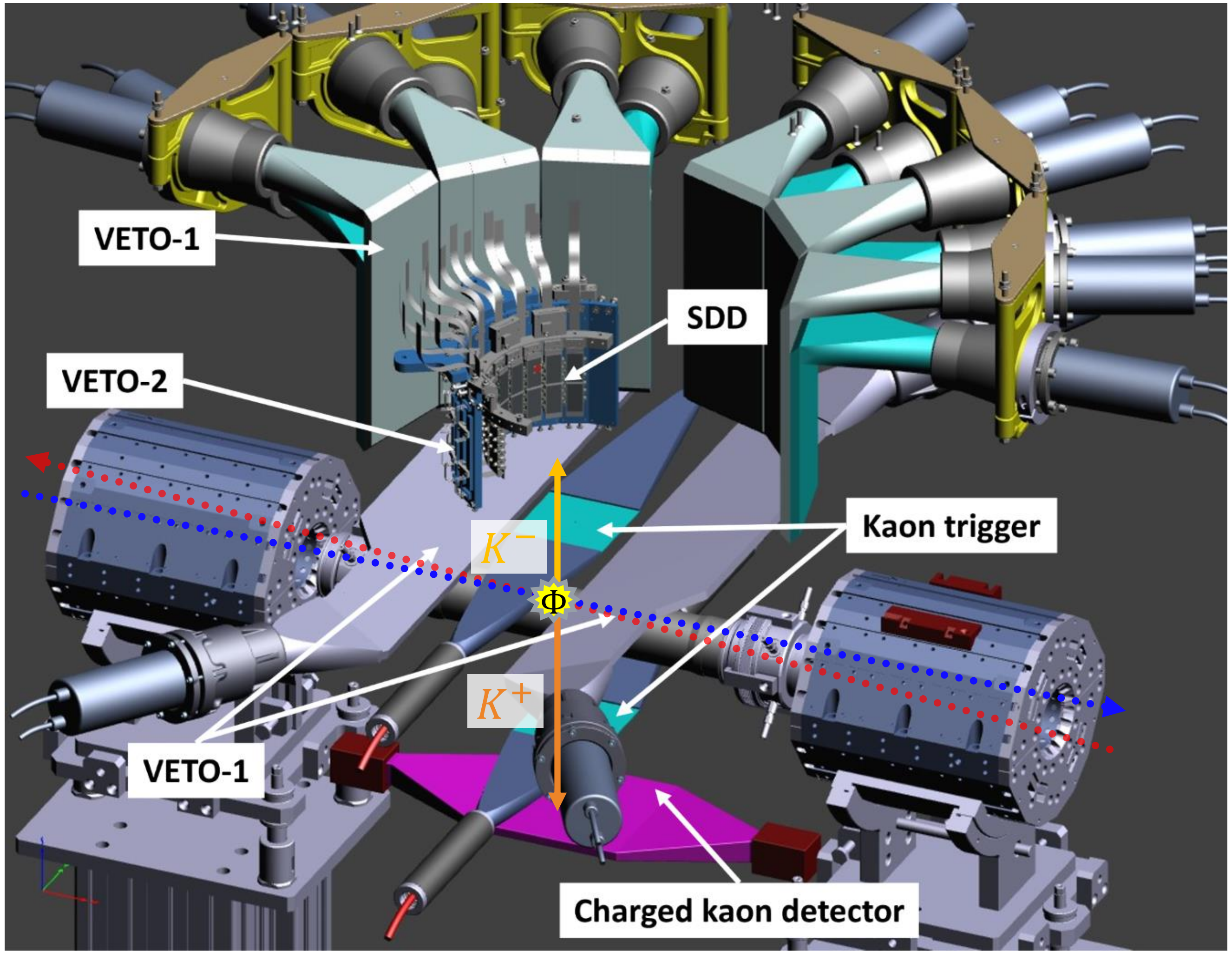




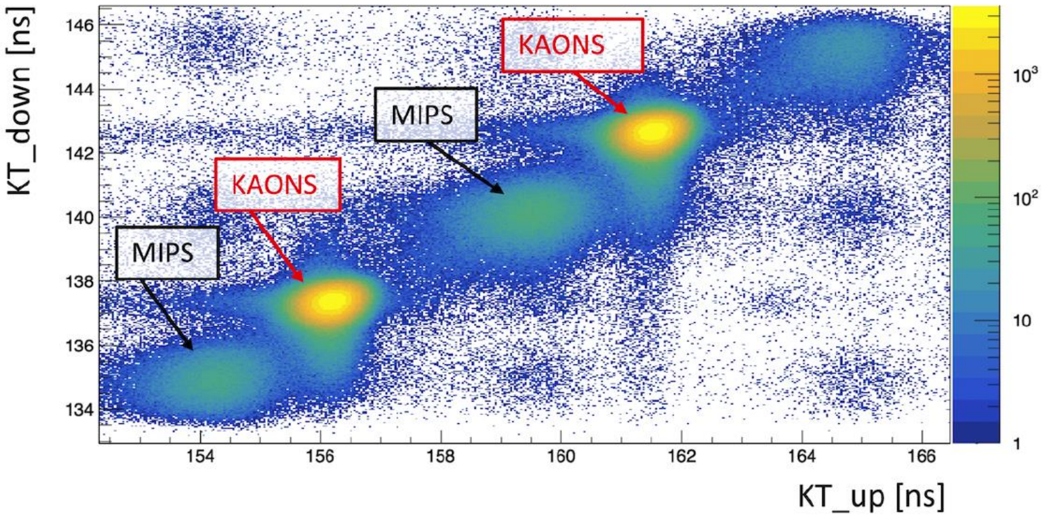




The SIDDHARTA-2 apparatus



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

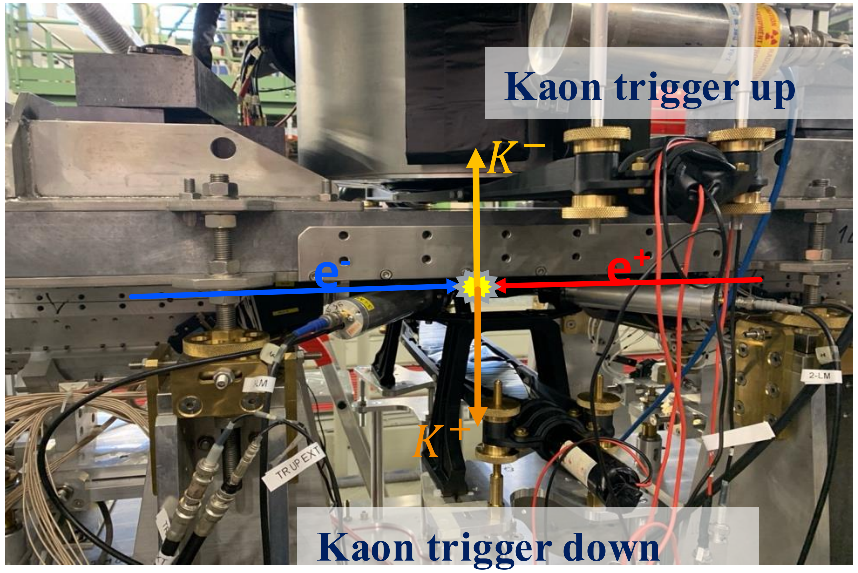


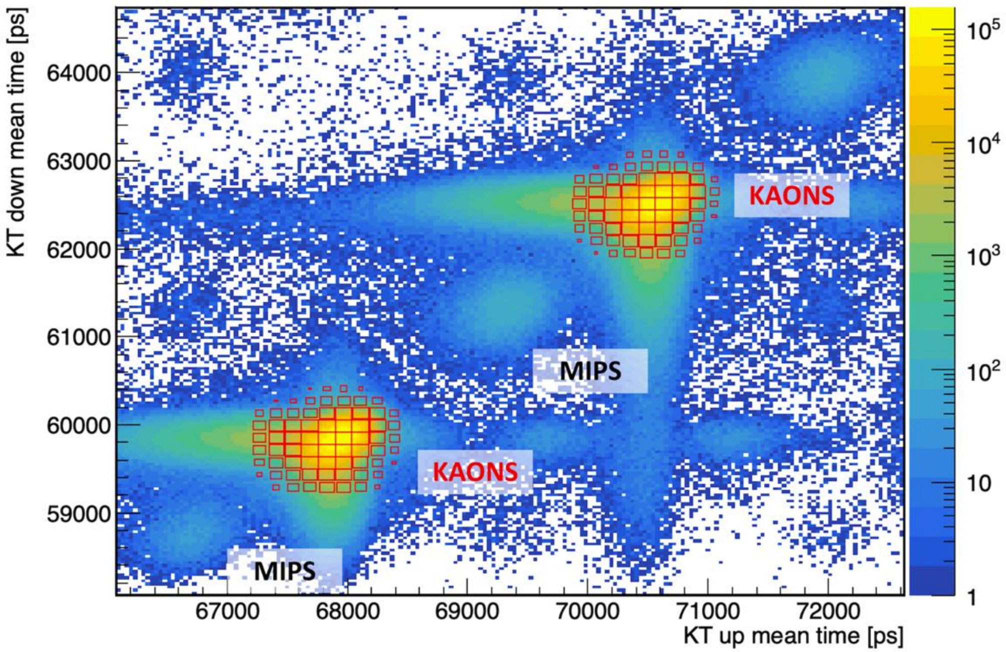
The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

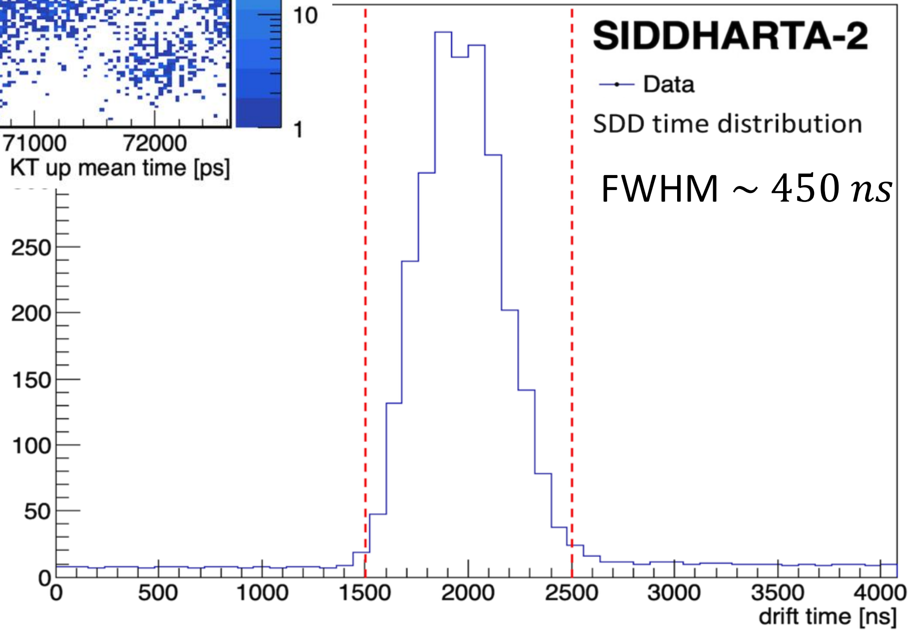
Can efficiently discriminate by ToF Kaons and MIPs!

The first kaonic deuterium measurement

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

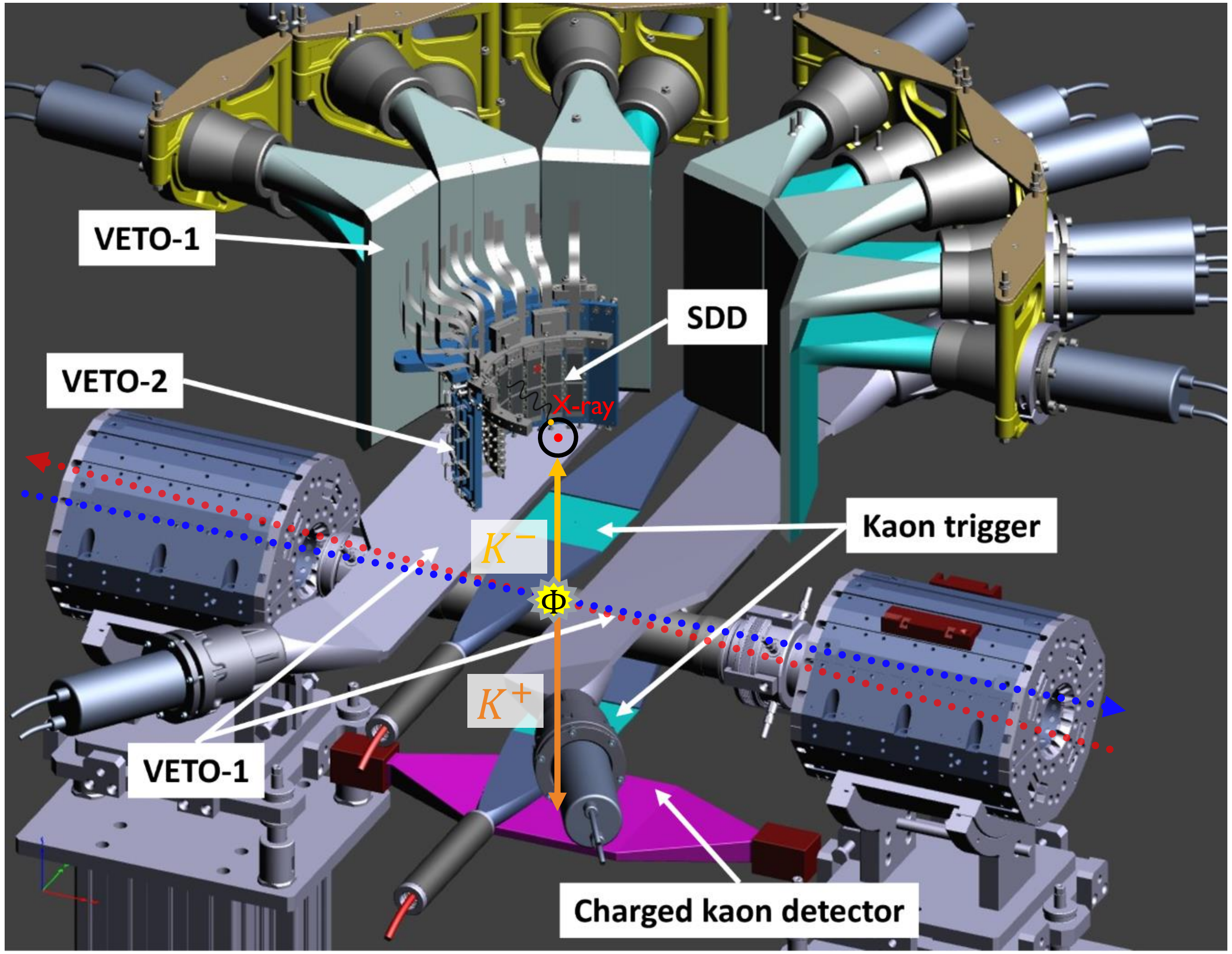






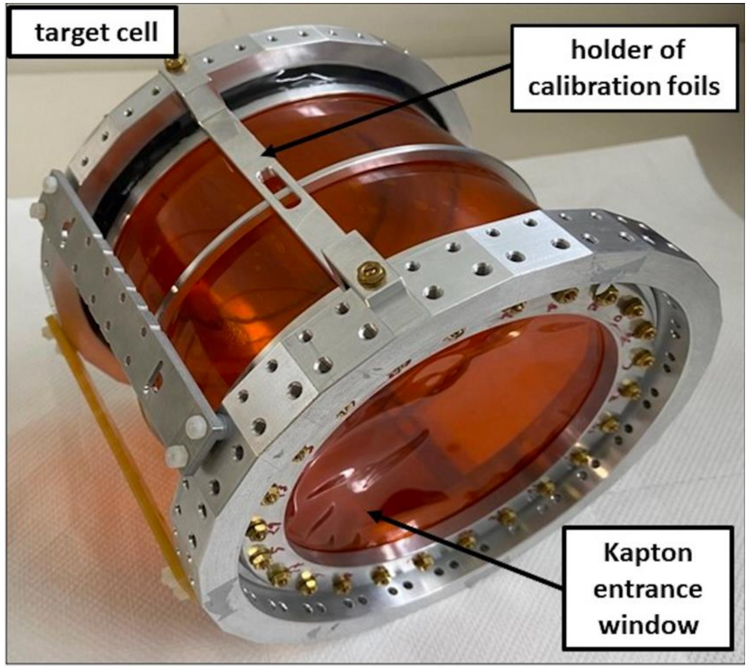
The trigger is generated by the coincidence of 2 back-to-back scintillators
The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles
originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

The SIDDHARTA-2 apparatus

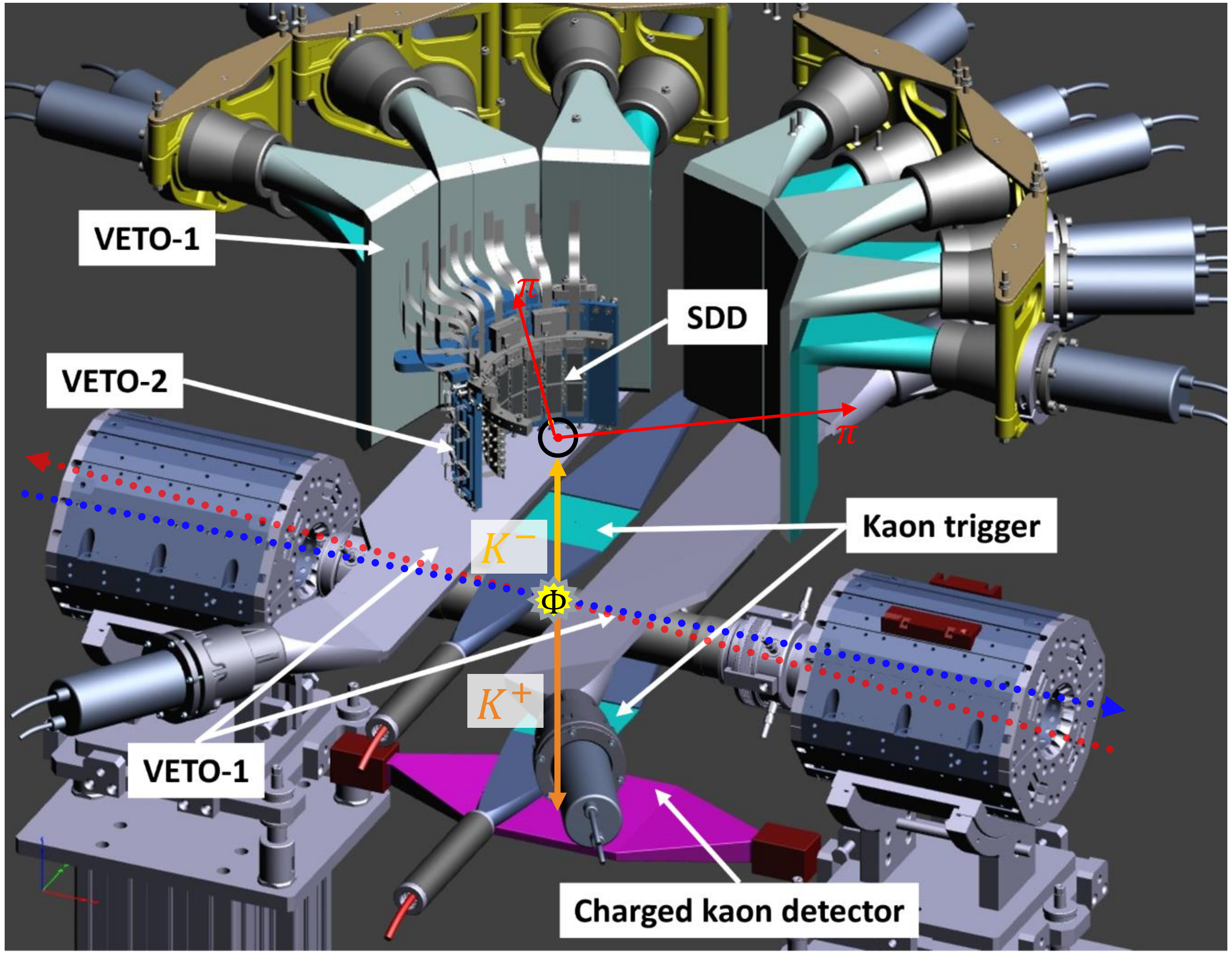


Kaon Trigger: two plastic scintillators read by photomultipliers placed above and below the interaction region.

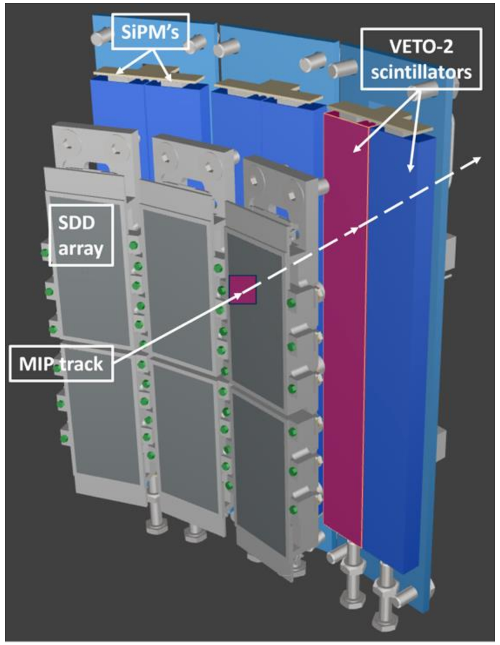
Cryogenic gaseous target cell surrounded by **384 SDDs**

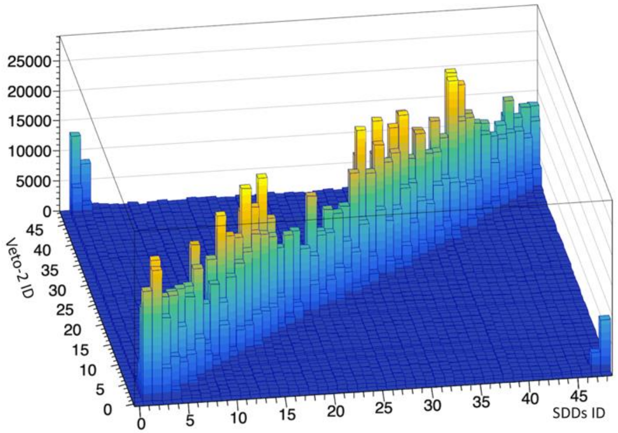


The SIDDHARTA-2 apparatus

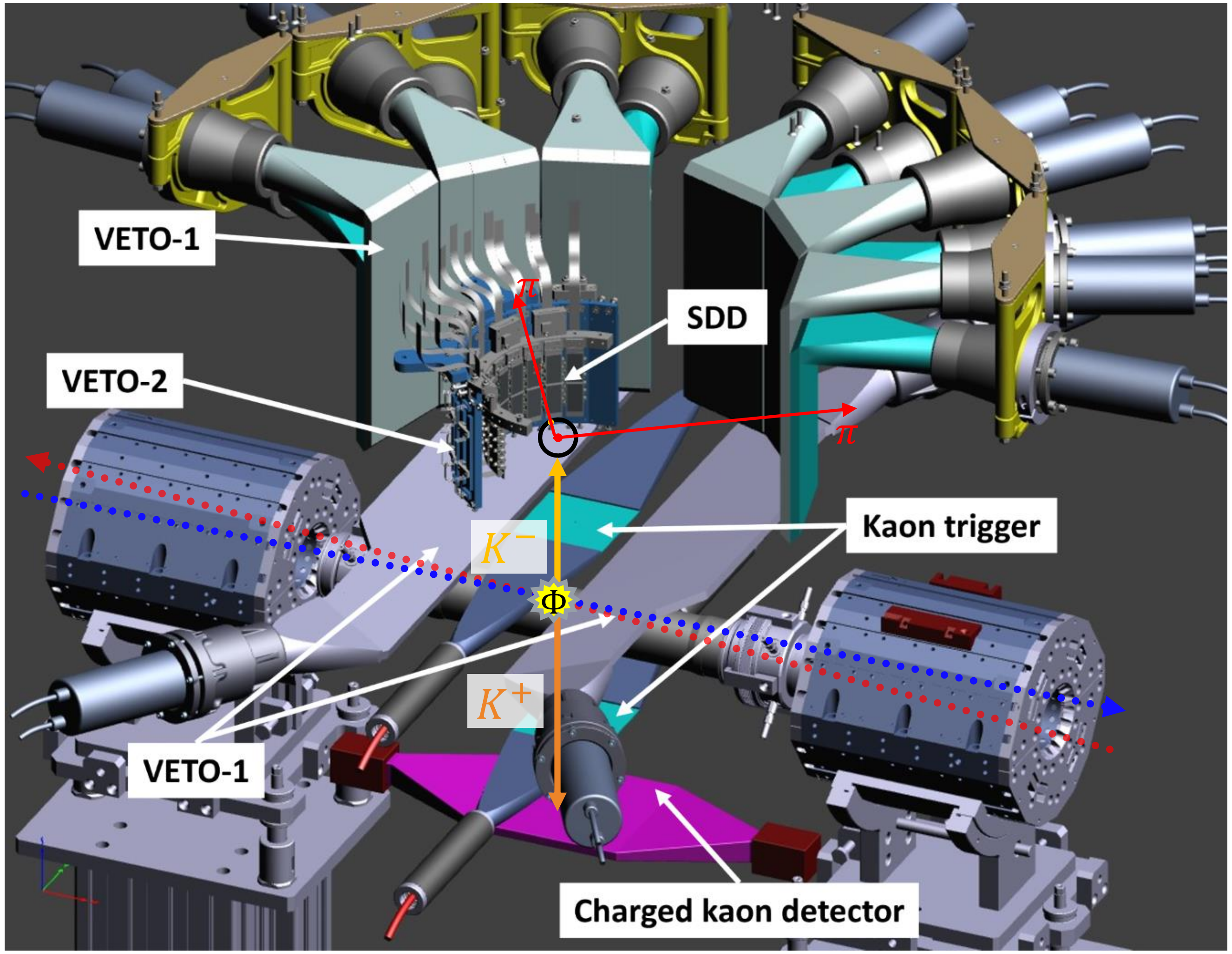


Veto-2 48 plastic scintillator read by SiPMs to suppress the background induce by particles produced by kaon absorption, passing through the SDDs.

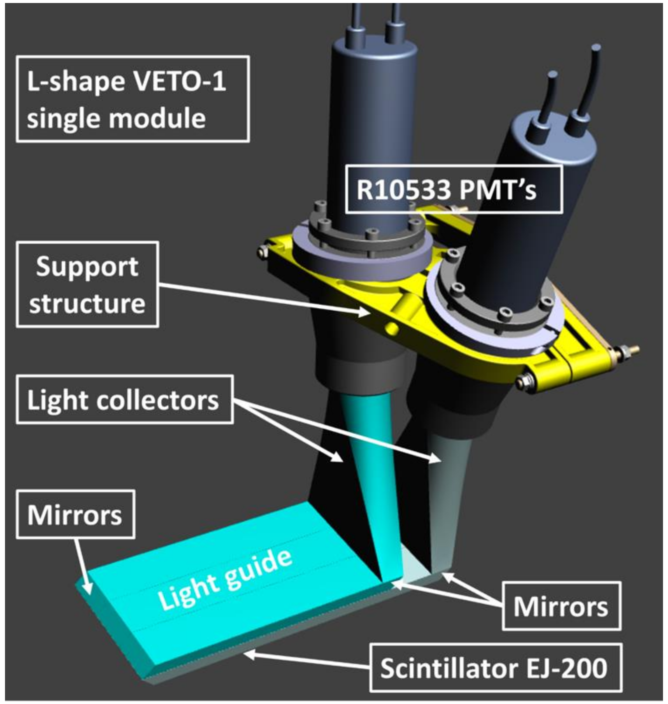




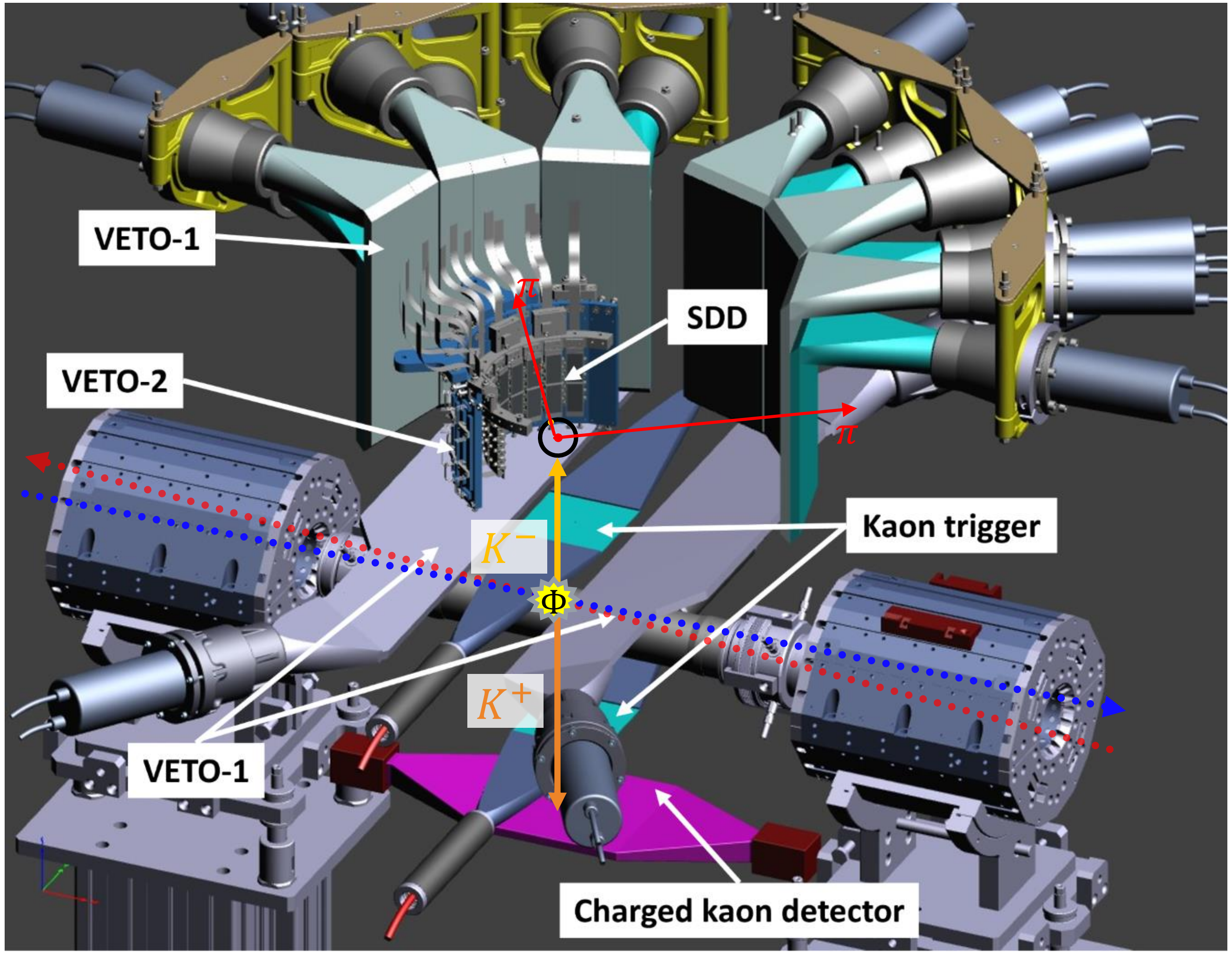
The SIDDHARTA-2 apparatus



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

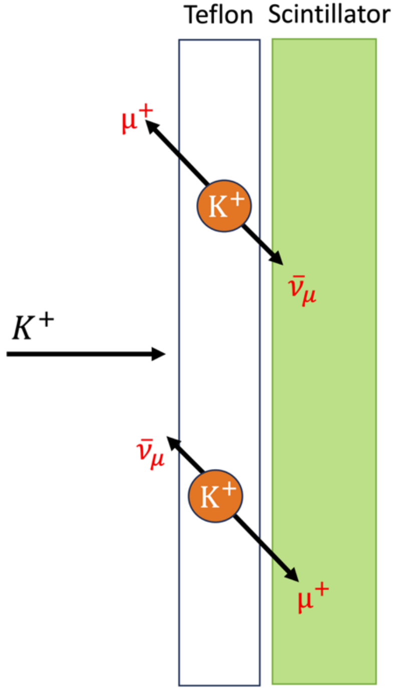


The SIDDHARTA-2 apparatus

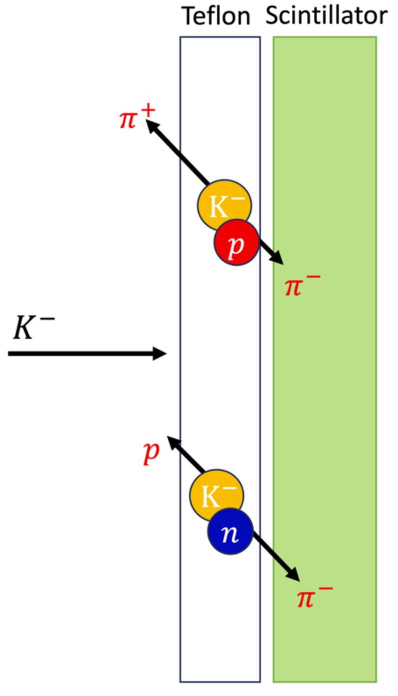


Charged Kaons Veto

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

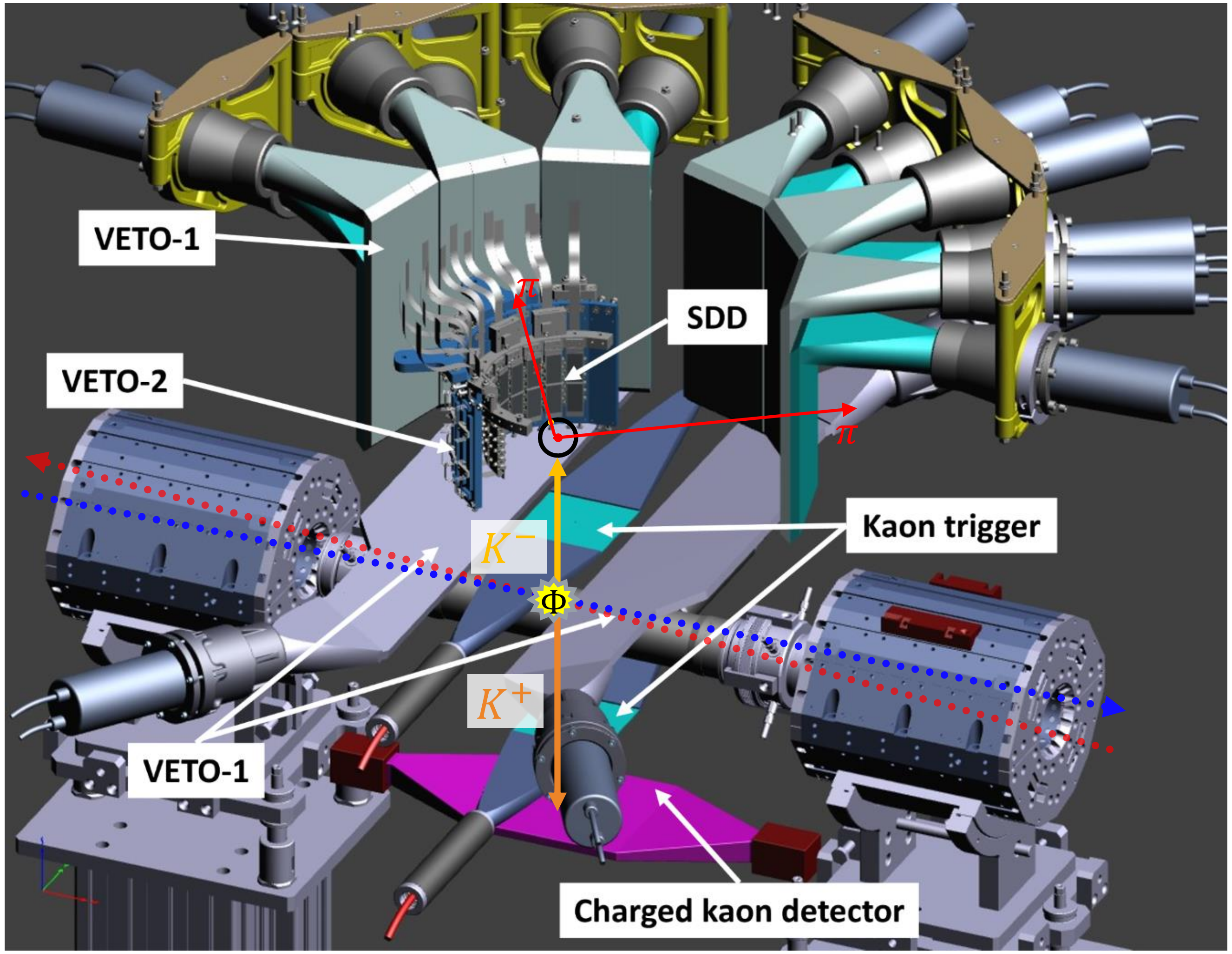


K^+ decay



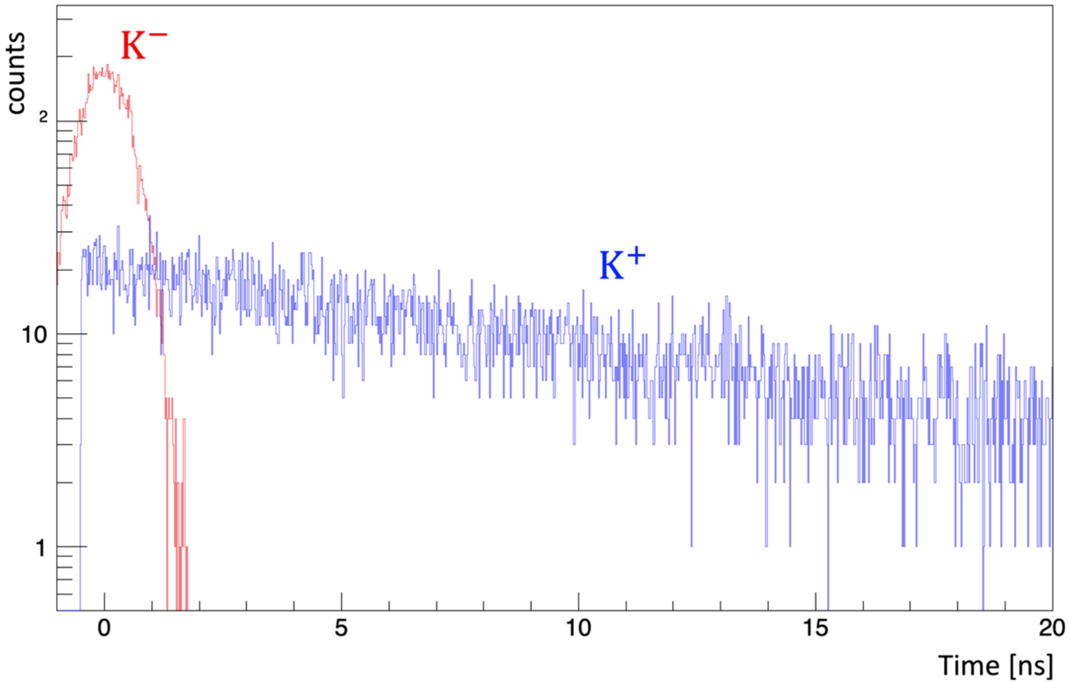
K^- nuclear absorption

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



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

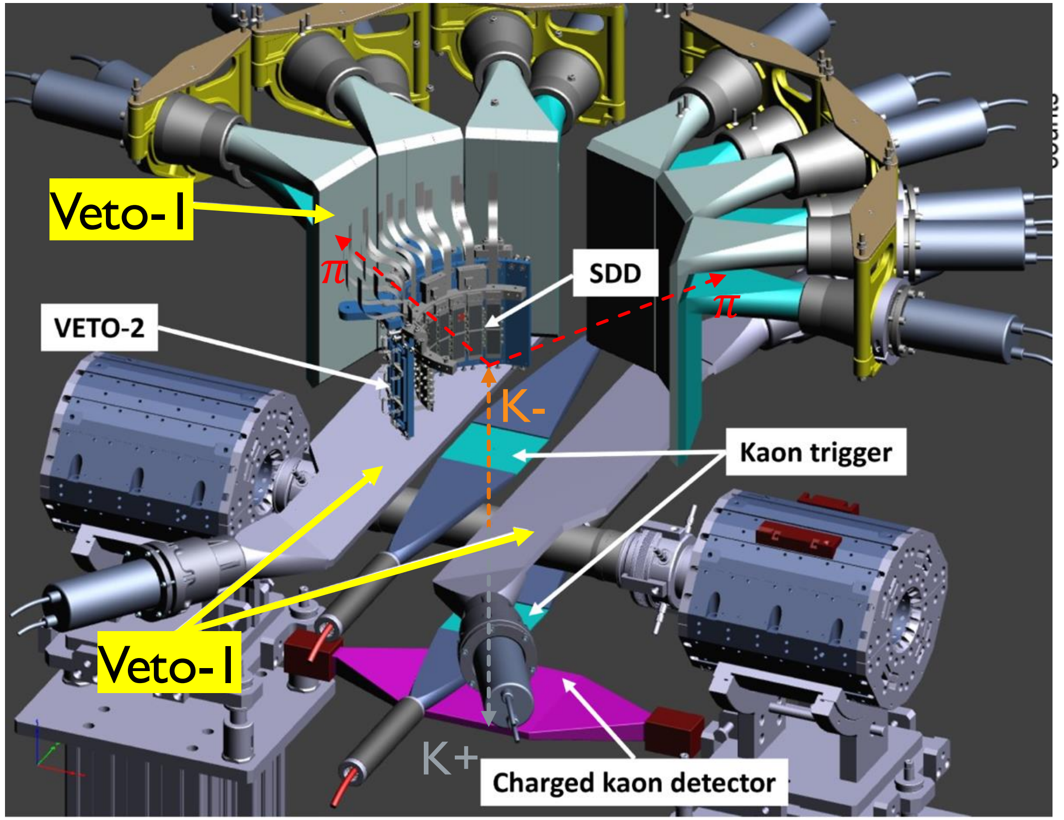
This situation would already be a proper justification for new measurements

Table 1
Compilation of K^- atomic data

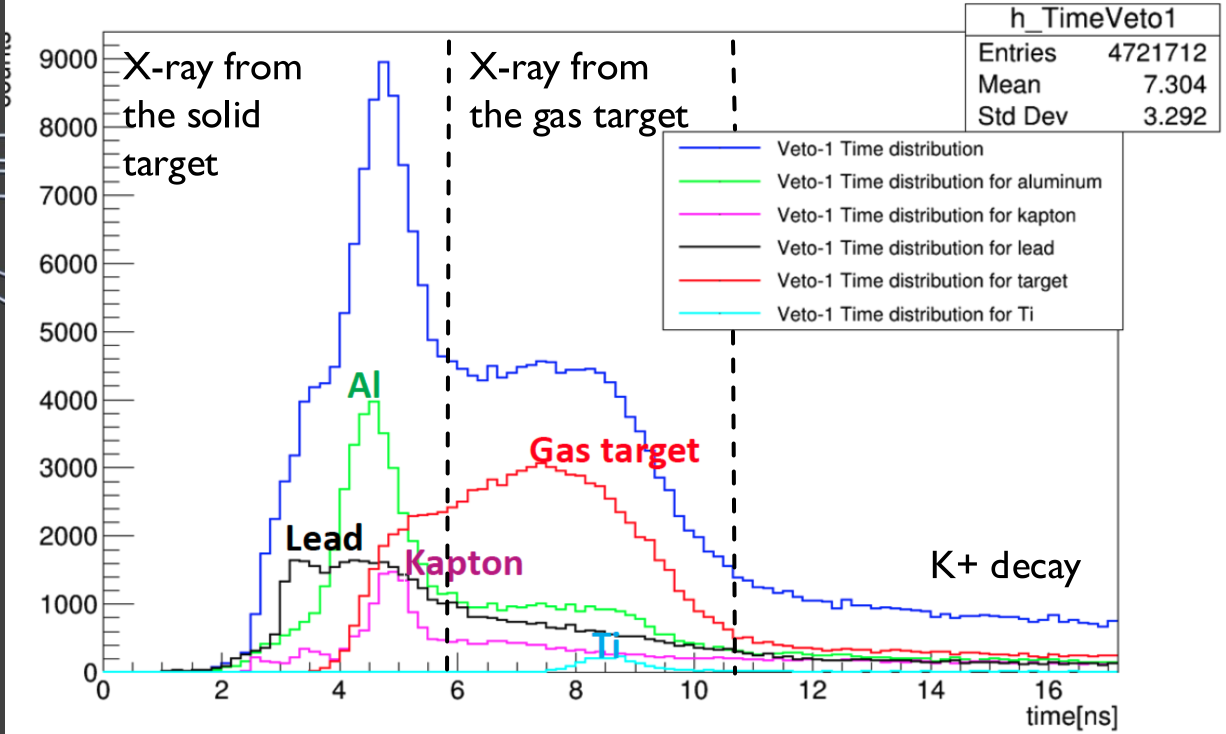
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3→2	−0.04 ±0.03	–	–	–	[15]
		−0.035±0.012	0.03 ±0.03	–	–	[16]
Li	3→2	0.002±0.026	0.055±0.029	0.95±0.30	–	[17]
Be	3→2	−0.079±0.021	0.172±0.58	0.25±0.09	0.04±0.02	[17]
^{10}B	3→2	−0.208±0.035	0.810±0.100	–	–	[18]
^{11}B	3→2	−0.167±0.035	0.700±0.080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

Kaonic deuterium analysis – Veto1 system

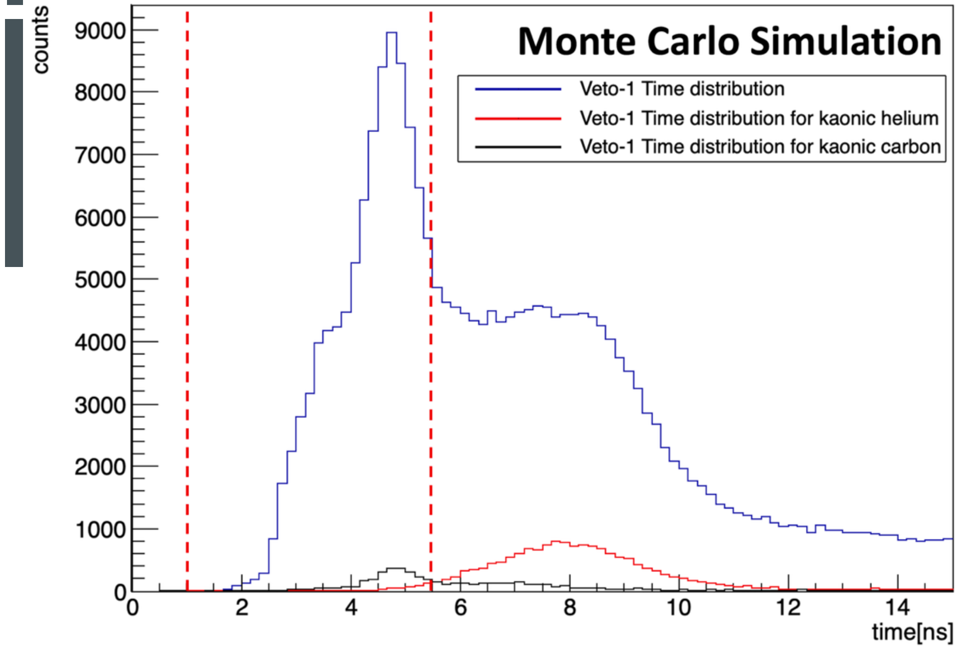
Veto-1 for hadronic background reduction: it measures the arrival time of charged particles emitted by the kaon-nucleus absorption to determine the origin of the signal — whether it comes from the deuterium gas target or from surrounding solid materials.

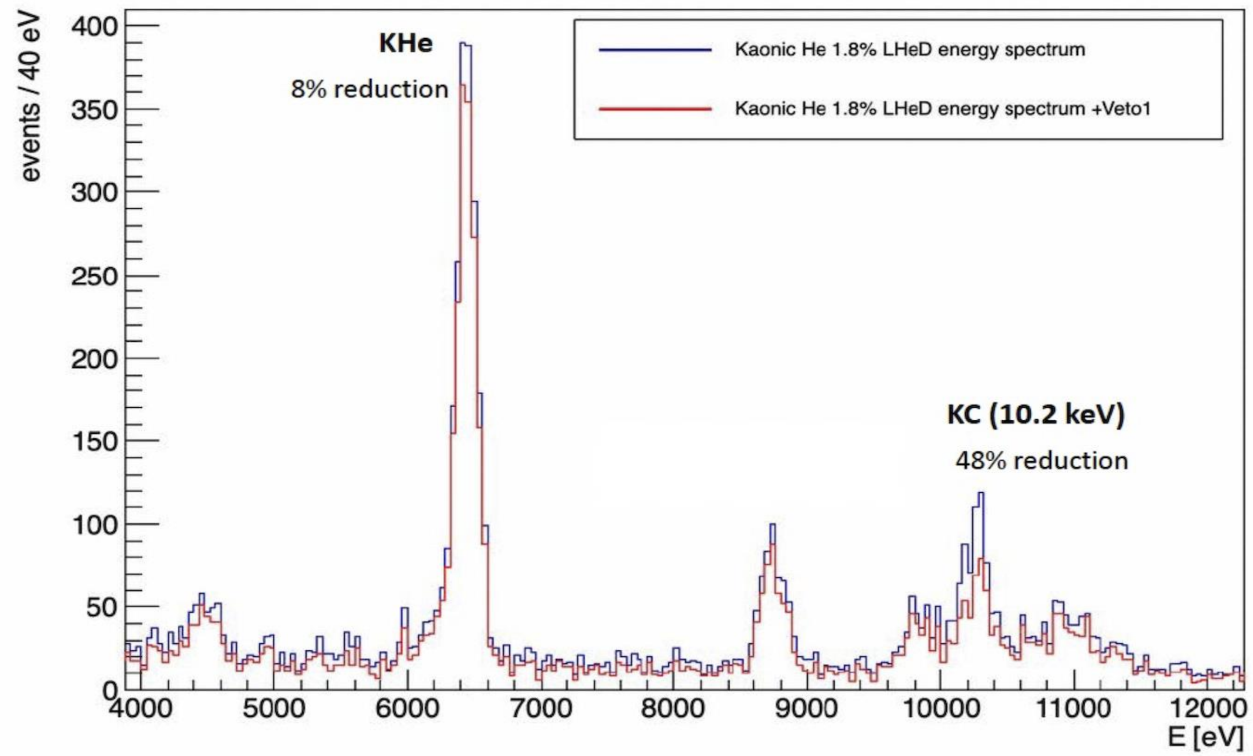


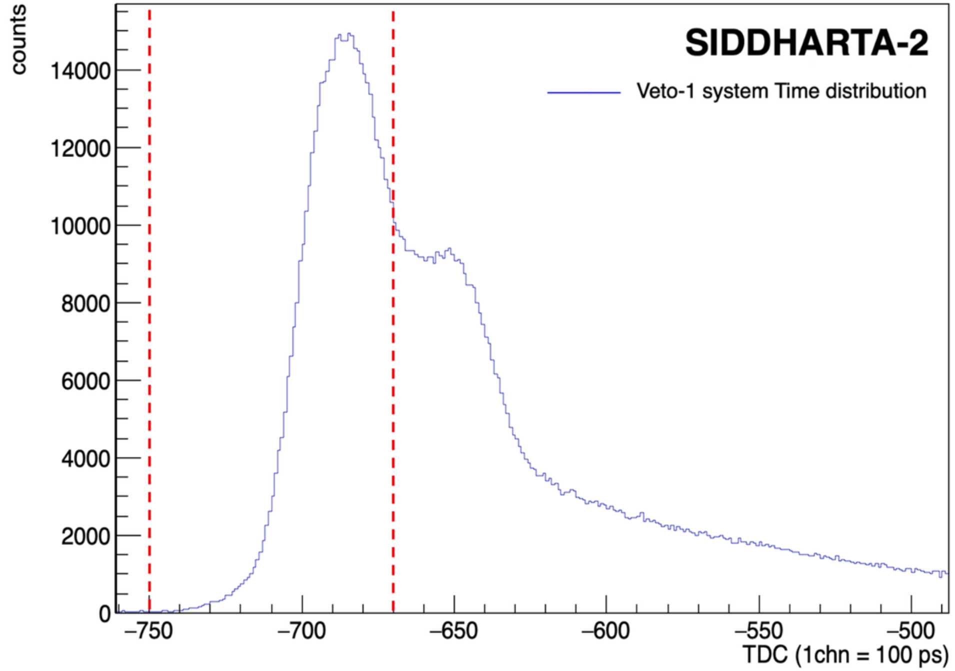
Veto-1: 14 plastic scintillators placed around and below the vacuum chamber



Veto-1 system optimization with kaonic He





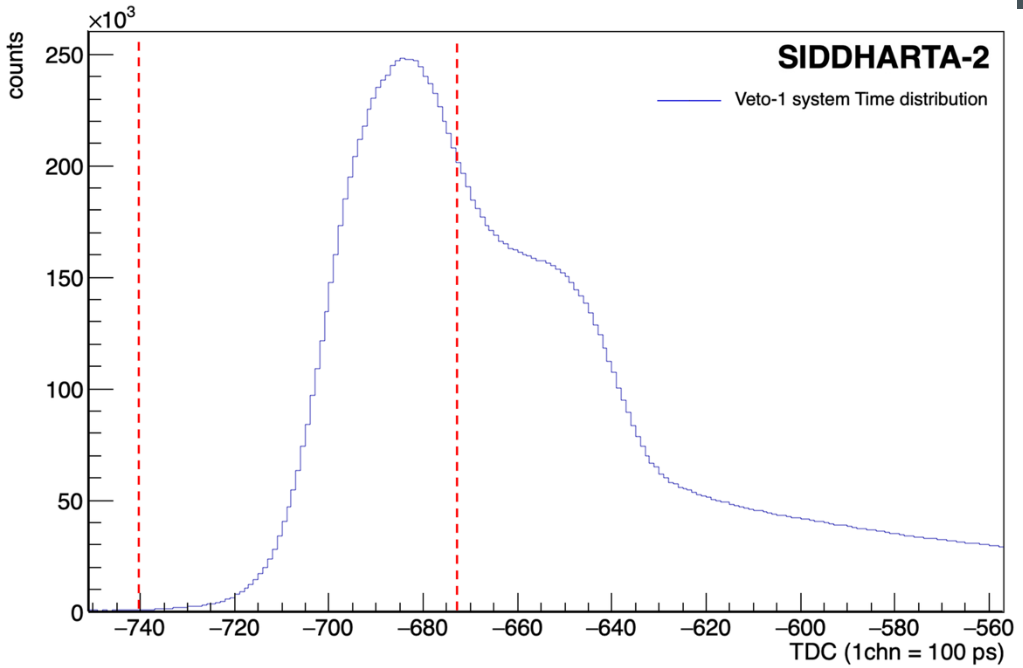


	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
$K\text{-}^4He\ L_\alpha$	$(8 \pm 1)\%$	4%
$K\text{-}C_{5\to4}$	$(48 \pm 4)\%$	44%

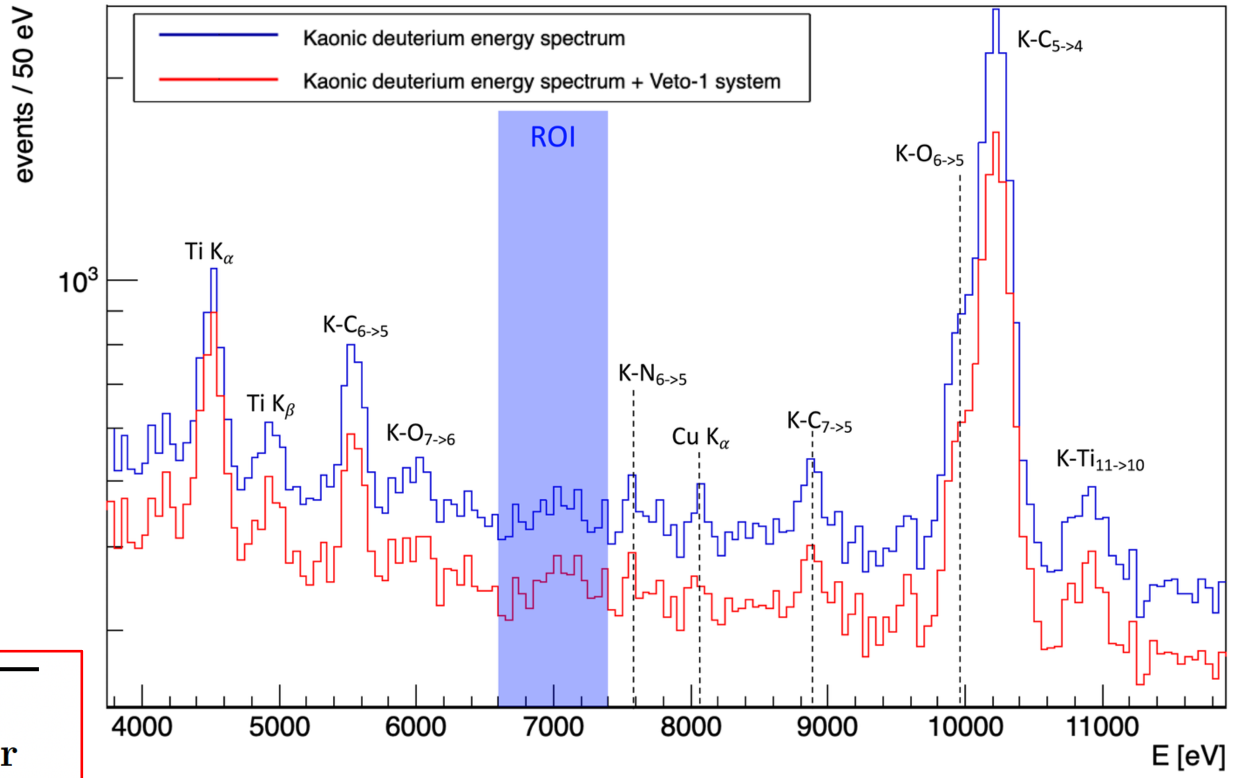
$$\text{reduction factor} = 1 - \frac{\#\text{events(with veto1)}}{\#\text{events}}$$

Kaonic Deuterium: veto-1 system analysis

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



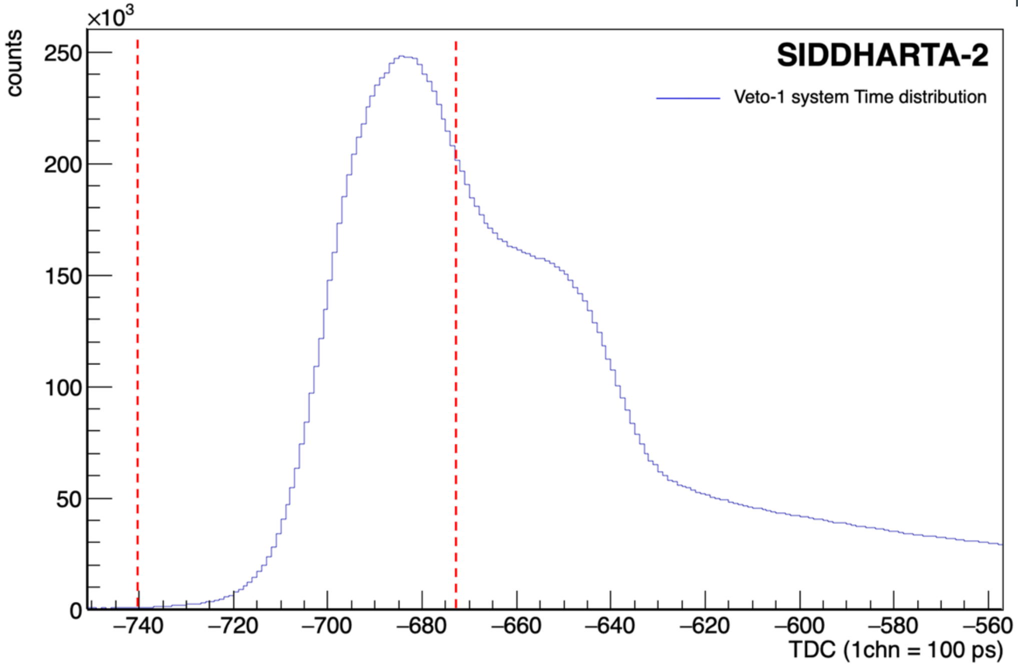
SDDs X-ray energy spectra with and without the veto-1 (be aware logarithmic scale)



	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-d K_α	$(11 \pm 3)\%$	4%
K-$C_{5\to4}$	$(44 \pm 4)\%$	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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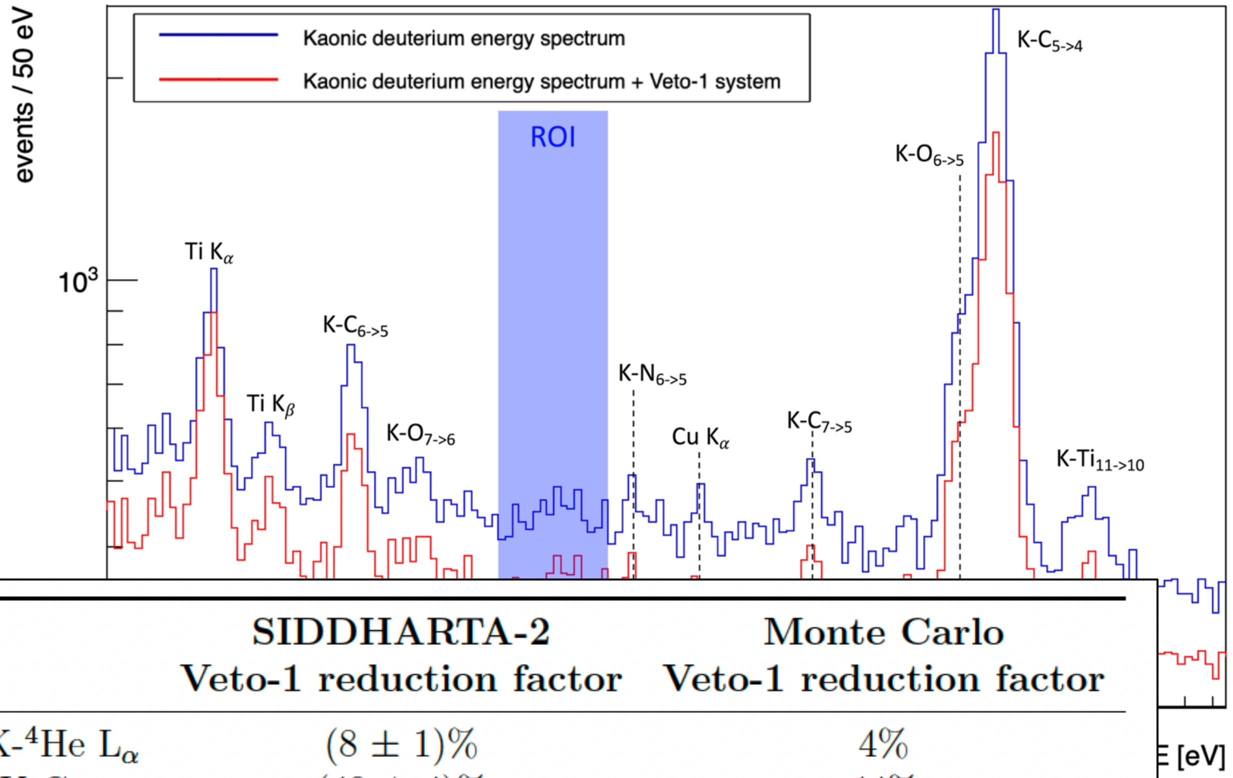

	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
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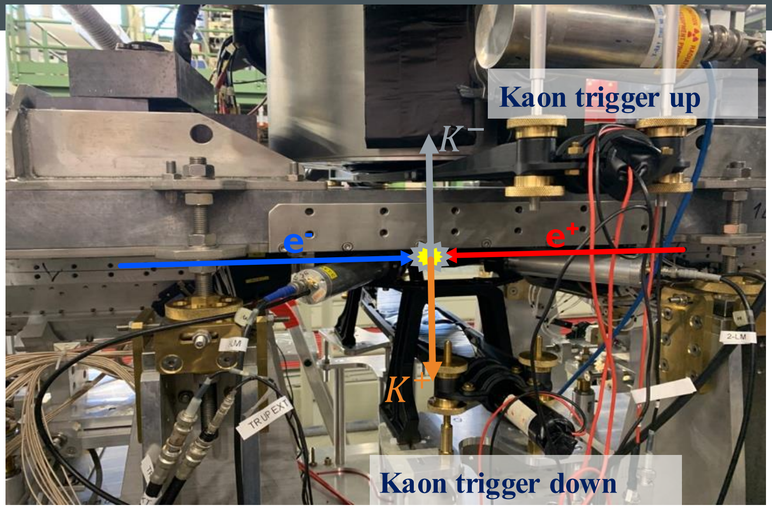
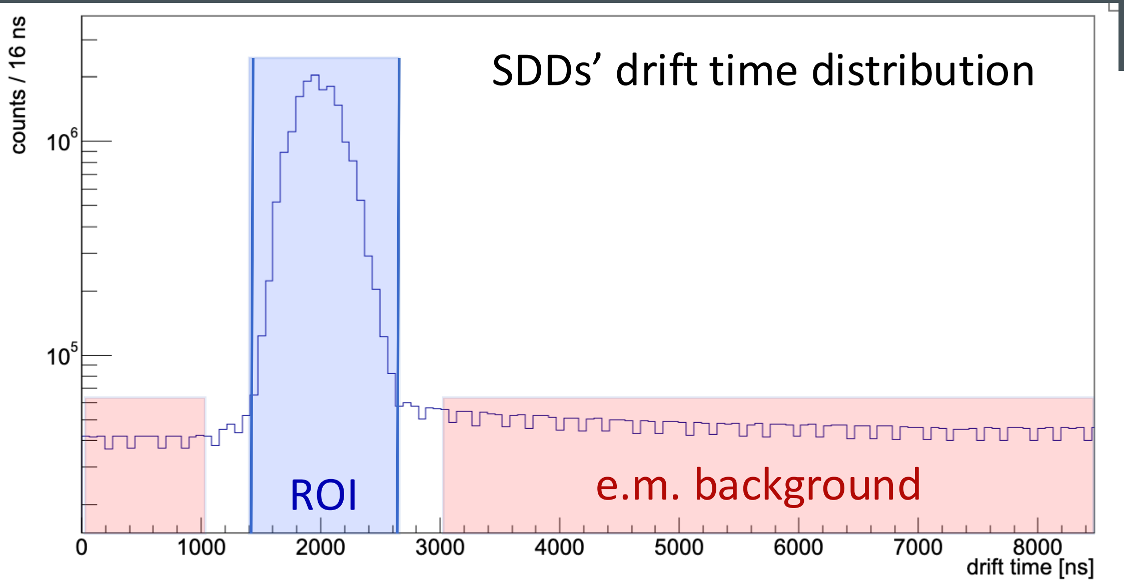
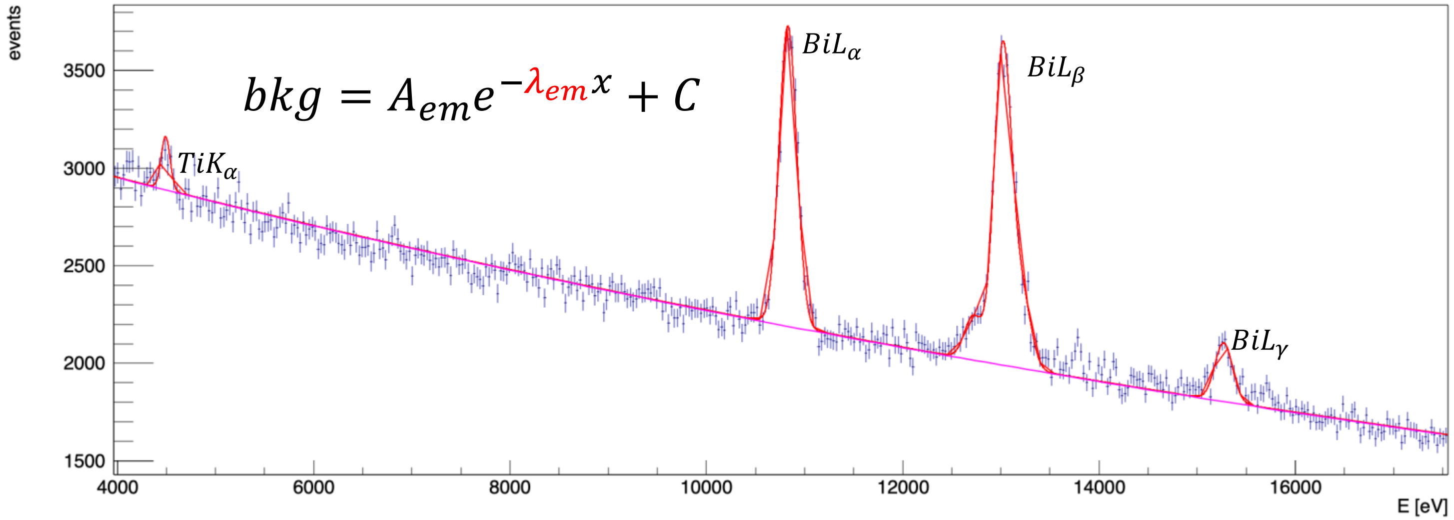
K-$C_{7\to5}$	$(48 \pm 4)\%$	46%

Electromagnetic background (asynchronous wrt kaons)

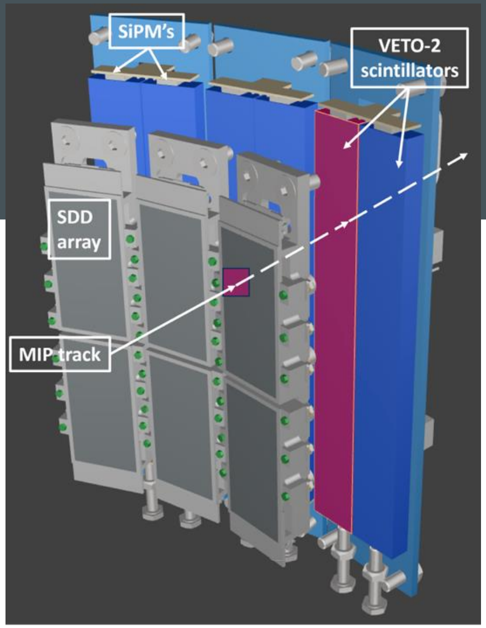
By exploiting the trigger and drift time of the SDDs, we can isolate a pure electromagnetic background spectrum by selecting events uncorrelated with kaon production.



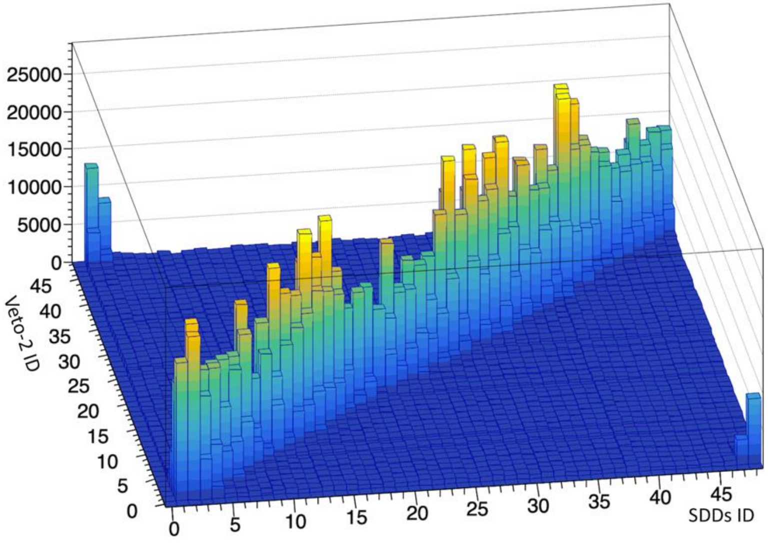




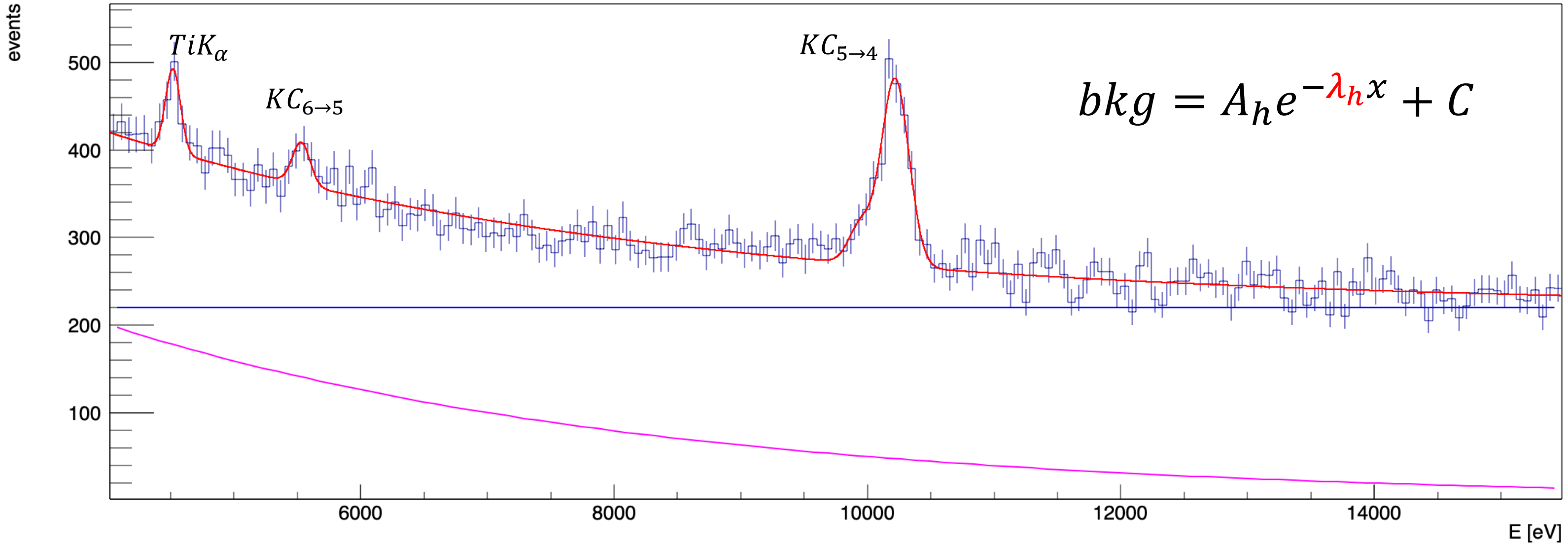
Hadronic background (synchronous wrt kaons)



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.



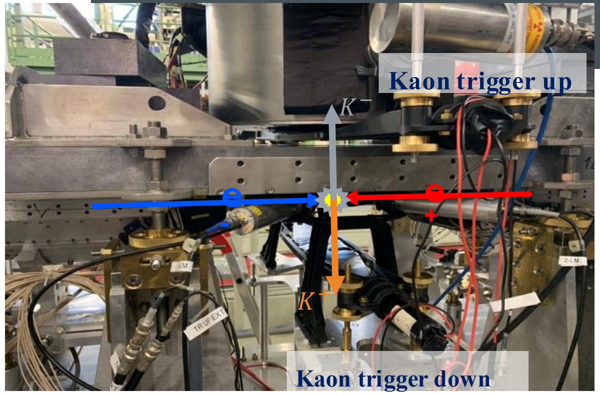
Plot of the topological correlation between Veto2's scintillators and SDDs

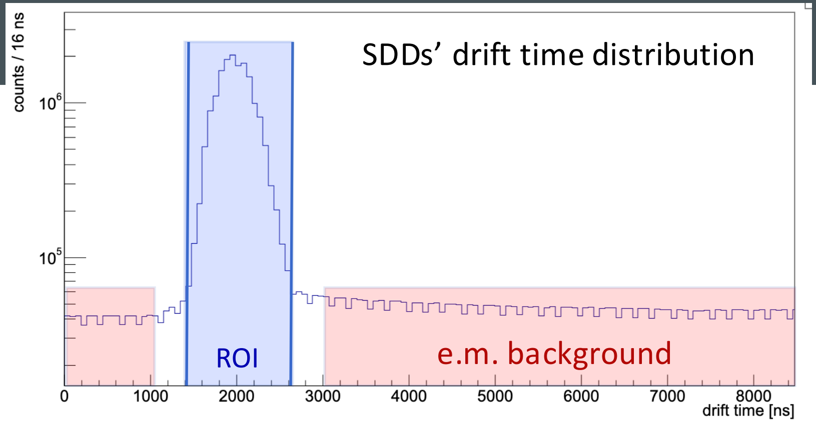


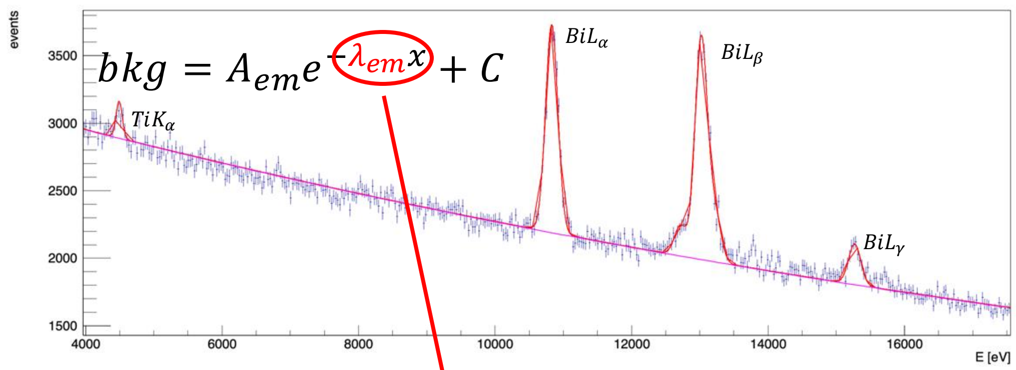
$$bkg = A_h e^{-\lambda_h x} + C$$

Study of background events (outside the signal window)

Electromagnetic (asynchronous) background

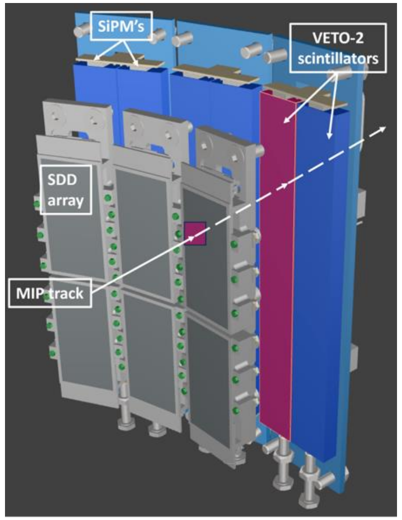


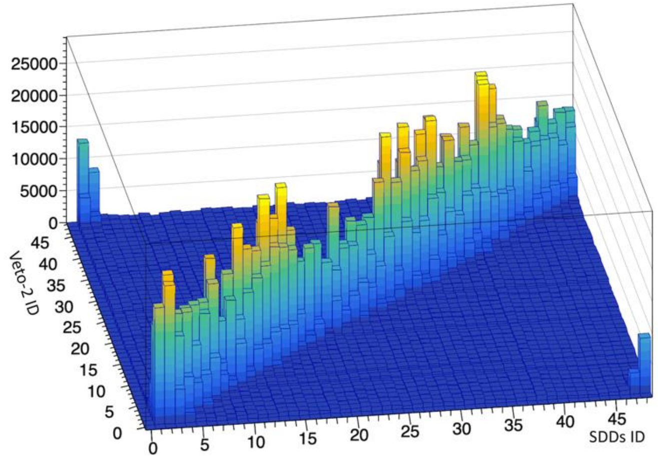




Input values for background description

Hadronic (synchronous) background





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