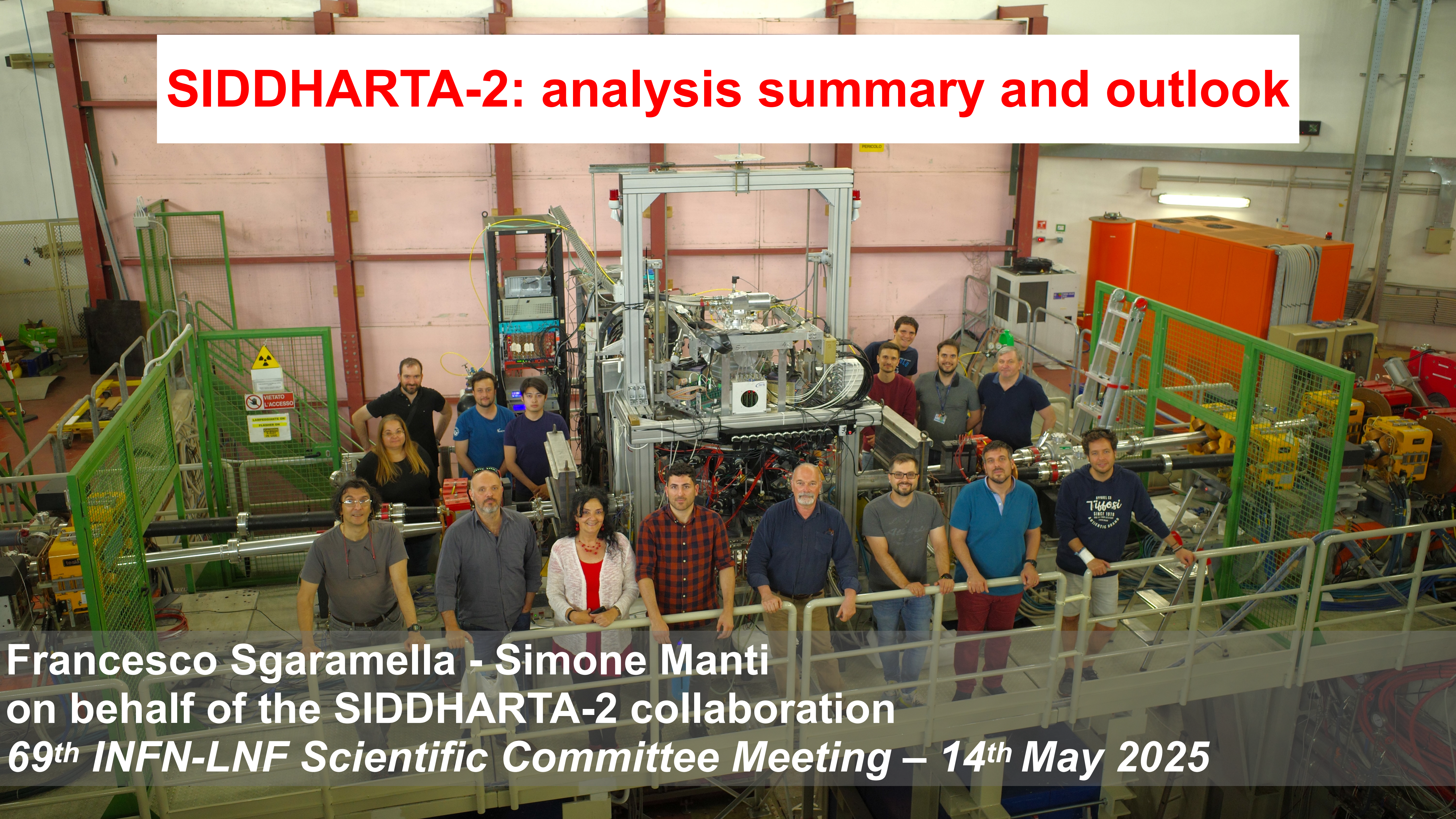


SIDDHARTA-2: analysis summary and outlook

Francesco Sgaramella - Simone Manti
on behalf of the SIDDHARTA-2 collaboration

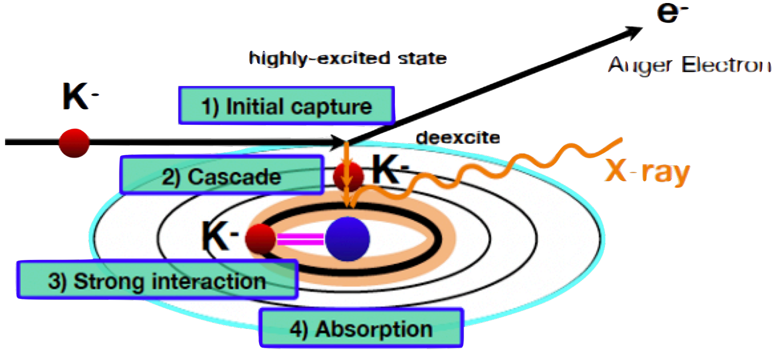
69th INFN-LNF Scientific Committee Meeting – 14th May 2025

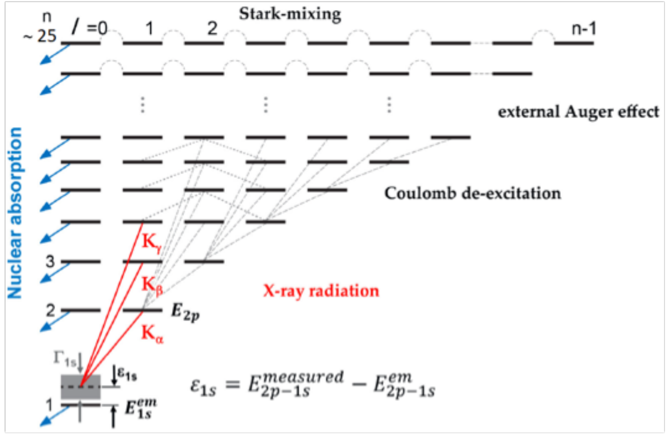
Contents

- **SIDDHARTA-2 data analysis - status and results**
- Recent Theoretical Developments (Simone Manti)
- Revised EXKALIBUR first module and experimental activities
- Scientific output and conferences
- Summary and requests

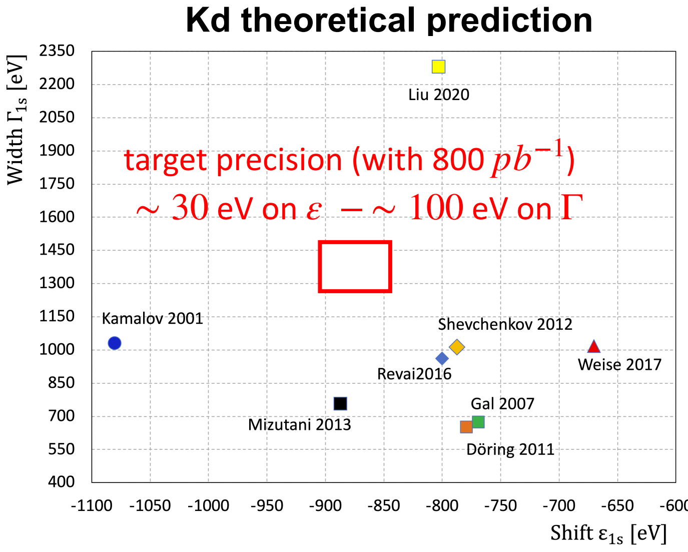
The SIDDHARTA-2's experiment main aim (reminder)

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





Kaonic deuterium X-ray spectroscopy to measure the shift (ε) and width(Γ) of 1s-level

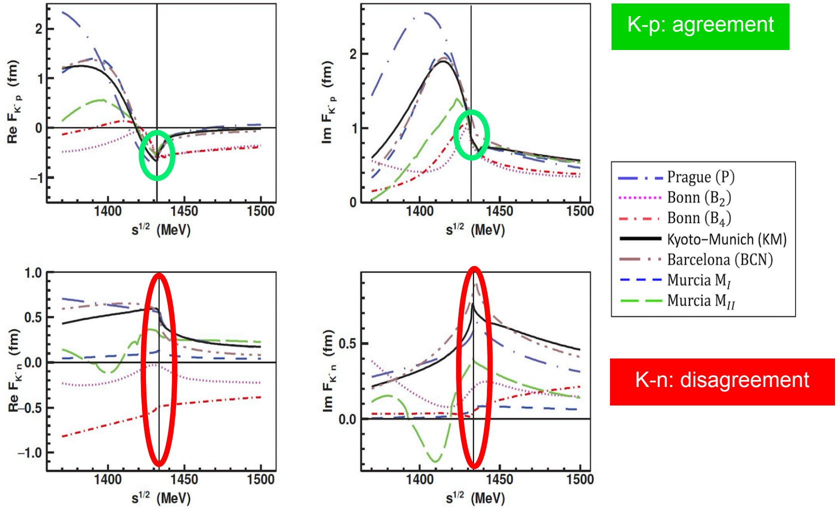


Determine the kaonic deuterium scattering length through the"summed up" Deser-Truman like formula

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-d} / [1 + 2\alpha\mu(\ln\alpha - 1)a_{K^-d}]$$

Shevchenko, N. V. Few Body Syst. 63, 22 (2022).

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).

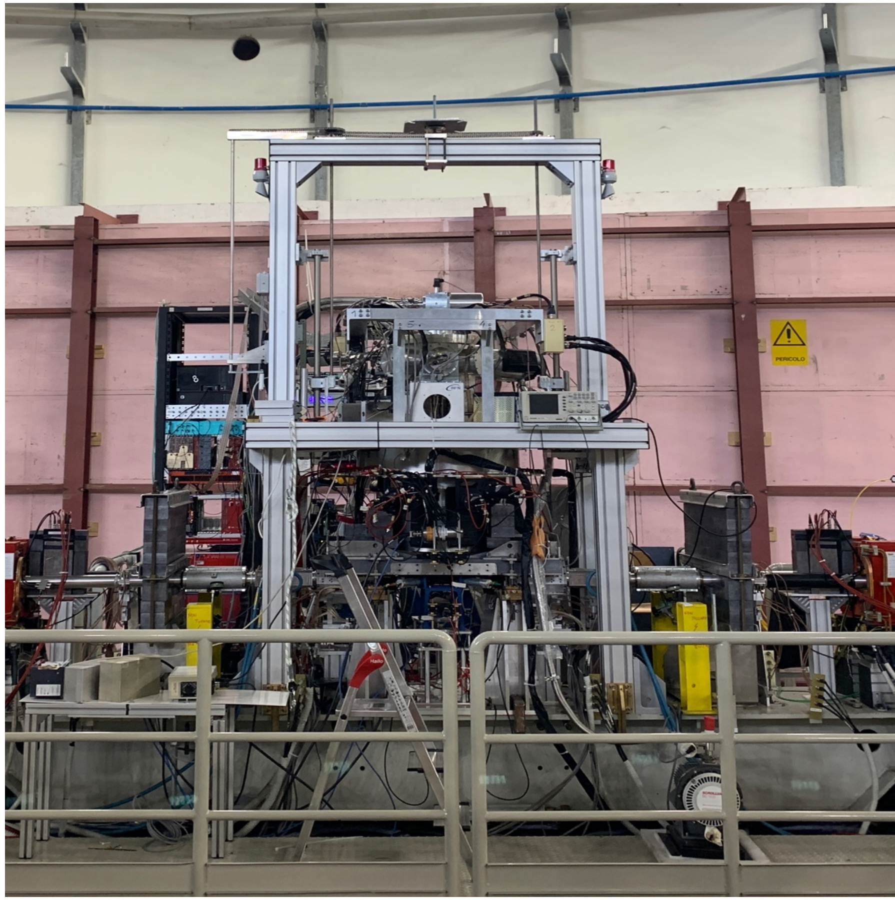
Data Taking Summary

- *Kaonic neon*: initial calibration and optimization of the setup, int. lumi $\sim 125\ \mathrm{pb}^{-1}$ (April 2023)
- *K-d Run-1: int. luminosity 164 pb^{-1} (May – July 2023)*
- *Kaonic helium-4*: final calibration of the setup , int. lumi $\sim 40\ \mathrm{pb}^{-1}$ (July 2023)

- *Kaonic neon*: initial calibration of the setup, int. lumi $\sim 36\ \mathrm{pb}^{-1}$ (Sept 2023)
- *K-d Run-2: int. luminosity 276 pb^{-1} (October – December 2023)*
- *Kaonic hydrogen*: final calibration of the setup , int. lumi $\sim 26\ \mathrm{pb}^{-1}$ (Dec 2023)

- *Kaonic hydrogen*: initial calibration of the setup, int. lumi $\sim 70\ \mathrm{pb}^{-1}$ (Jan 2024)
- *K-d Run-3: int. luminosity 375 pb^{-1} (February – April 2024)*
- *Kaonic hydrogen*: final calibration of the setup , int. lumi $\sim 150\ \mathrm{pb}^{-1}$ (April 2024)

- *Low density run: int. luminosity 185 pb^{-1}* (May – July 2024)
- *Post Kd calibration run* (July 2024) – 20 pb^{-1} *with solid targets (B and F)*



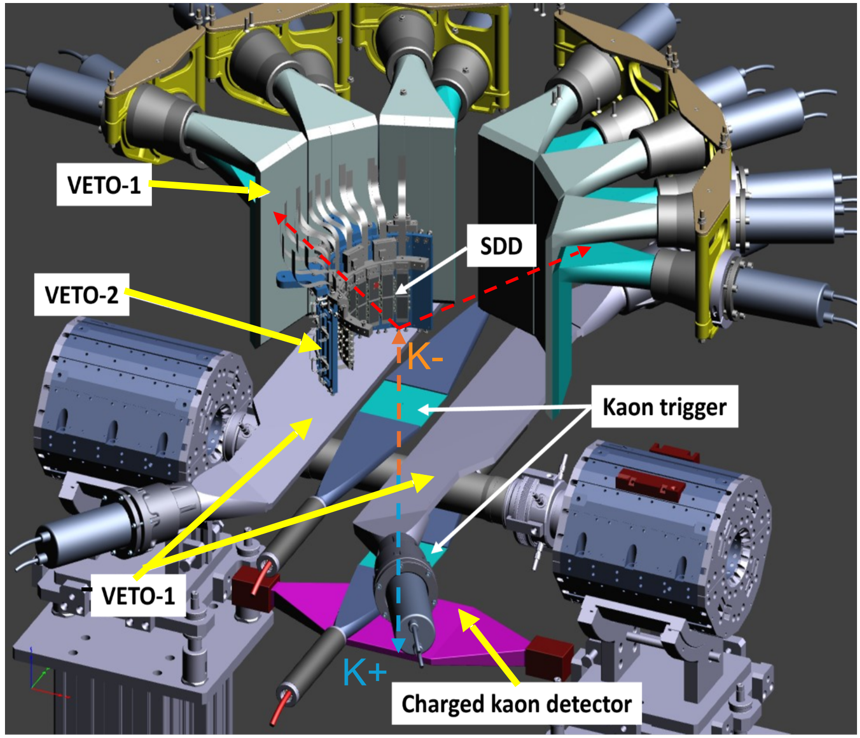
Total 1467 pb^{-1} of good data (April 2023 - July 2024; about 13 months)

K-d total integrated luminosity good for physics : 1000 pb^{-1}

Other kaonic atoms: 467 pb^{-1}

Kaonic deuterium data analysis highlights

1. **Data calibration (discussed in 68th Sci Com):**
   - ~ 20 000 calibration spectra acquired during the kaonic deuterium data taking
   - Run1, Run2, Run3, low density Run, calibration data analysis completed
     - ✓ Energy calibration accuracy ~ 1-3 eV @ 4 -10 keV range
     - ✓ Energy resolution 170 eV @ 6.4 keV
     - ✓ Long-term stability ~ 0.5 eV



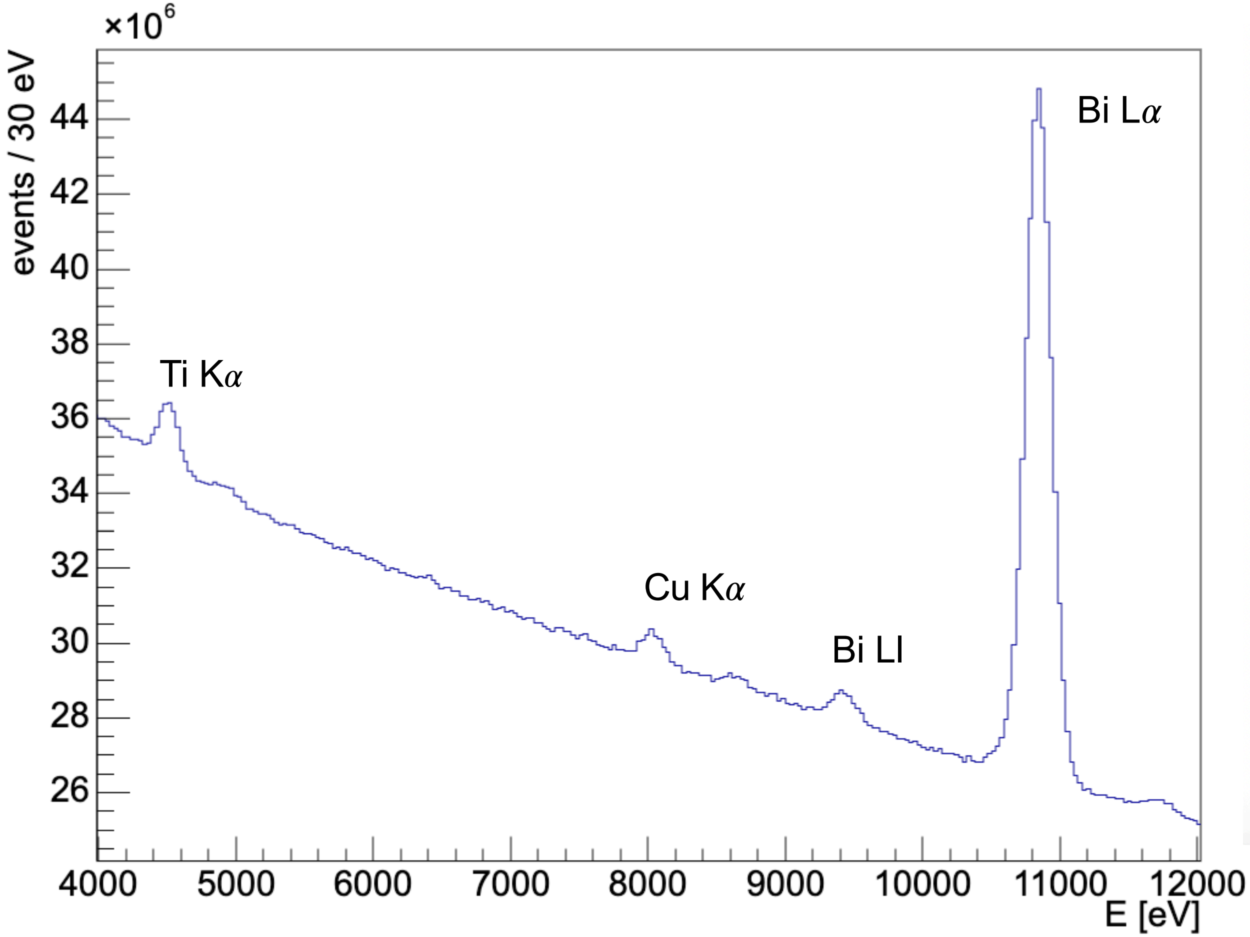
2. **Data selection: Trigger and Veto Systems (details in spare slides)**

3. **Background identification by selecting events outside the signal window:**
   - Electromagnetic background (asynchronous wrt kaons) → trigger and SDD
   - Hadronic background (synchronous wrt kaons) → Veto-2

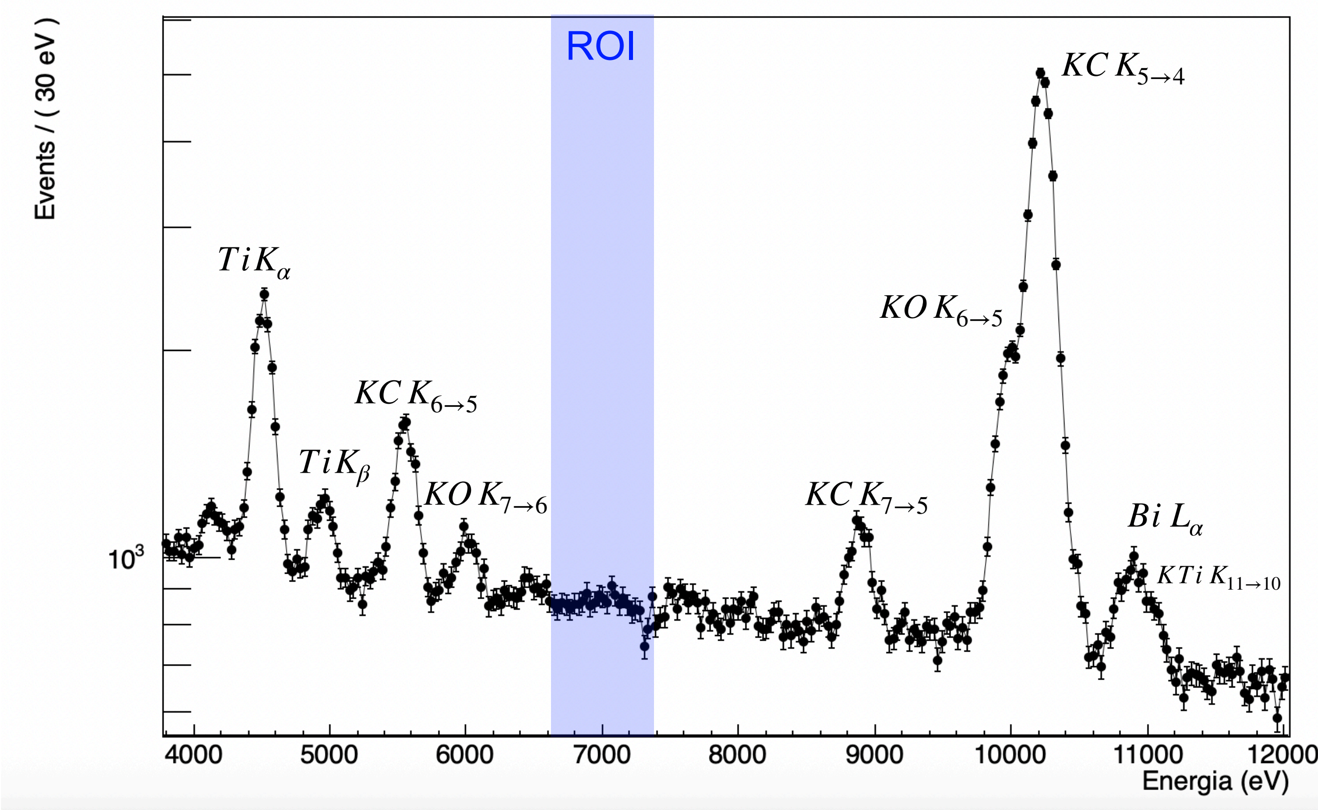
4. **Shift and Width extraction**

Kaonic deuterium energy spectrum

Raw spectrum



Data selected energy spectrum



Background reduced by a factor 3x10^4

Kaonic deuterium data analysis highlights

1. **Data calibration (discussed in 68th Sci Com):**
   - ~ 20 000 calibration spectra acquired during the kaonic deuterium data taking
   - Run1, Run2, Run3, low density Run, calibration data analysis completed
     - ✓ Energy calibration accuracy ~ 1-3 eV @ 4 -10 keV range
     - ✓ Energy resolution 170 eV @ 6.4 keV
     - ✓ Long-term stability ~ 0.5 eV

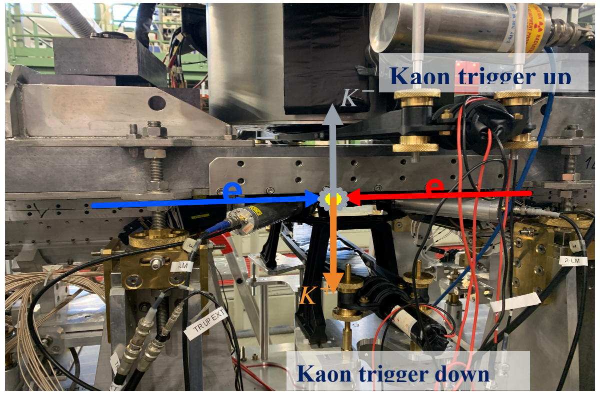
2. **Data selection: Trigger and Veto Systems (details in spare slides)**

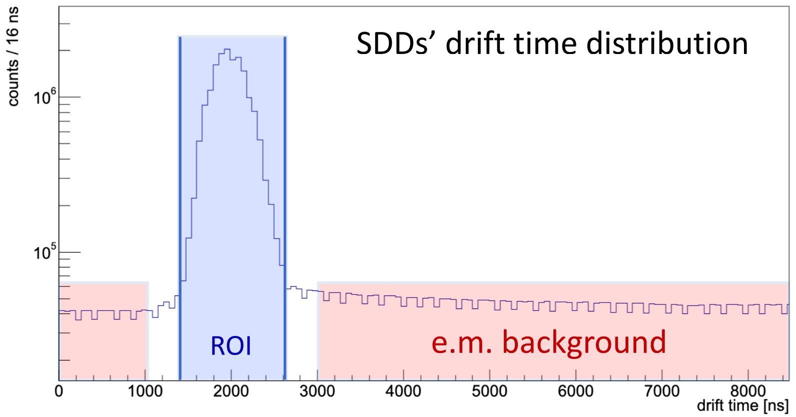
3. **Background identification by selecting events outside the signal window:**
   - Electromagnetic background (asynchronous wrt kaons) → trigger and SDD timing
   - Hadronic background (synchronous wrt kaons) → Veto-2

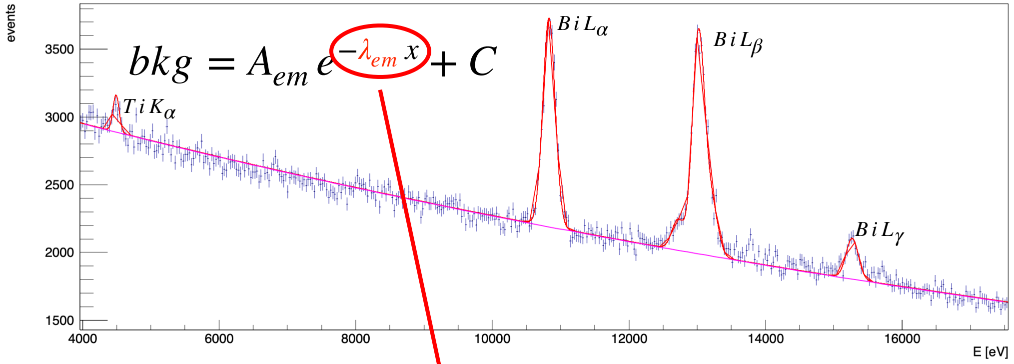
4. **Shift and Width extraction**

Background identification (outside the signal window)

Electromagnetic (asynchronous) background

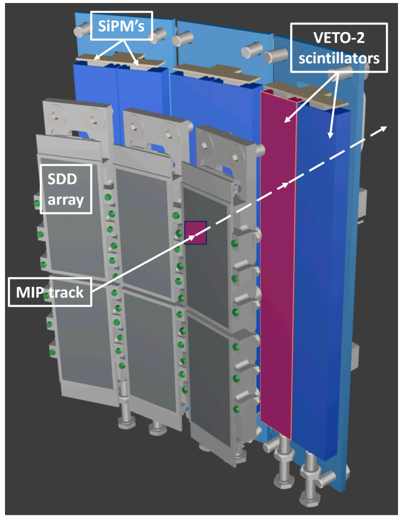


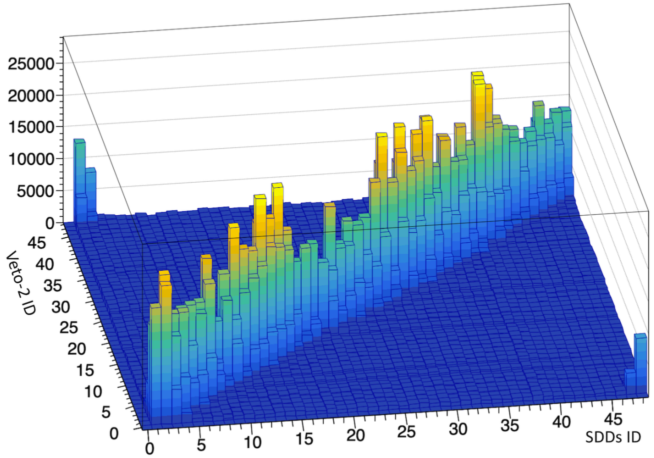




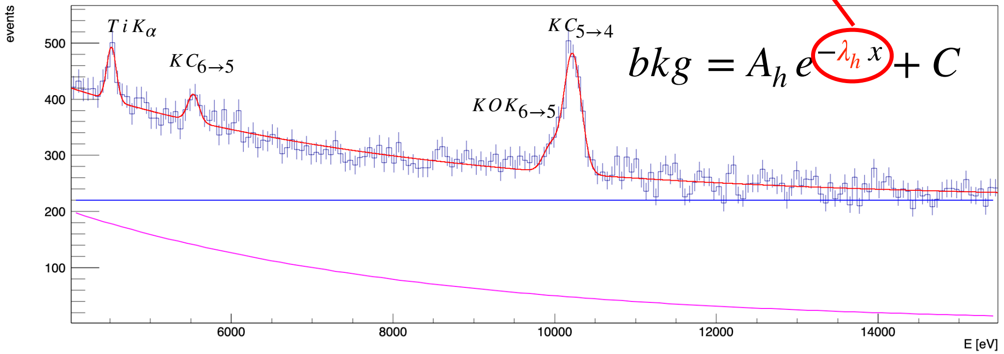
Input values for background description

Hadronic (synchronous) background





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



Kaonic deuterium data analysis highlights

1. **Analysis of the calibration data:**
   - $\sim$ 20 000 calibration spectra acquired during the kaonic deuterium data taking
   - Run1, Run2, Run3, low density Run, calibration data analysis completed
     - ✓ Energy calibration accuracy $\sim$ 1-3 eV @ 4 -10 keV range
     - ✓ Energy resolution 170 eV @ 6.4 keV
     - ✓ Long-term stability $\sim$ 0.5 eV

2. **Optimisation of the Veto Systems cuts based on MC simulations:**
   - Veto-1 timing for the reduction of contamination lines
   - Veto-2 topological cut for MIPs rejection
   - K-plus detector for suppression of K+ related background

3. **Background study by selecting events outside the signal window:**
   - Electromagnetic background (asynchronous wrt kaons) → trigger and SDD timing
   - Hadronic background (synchronous wrt kaons) → Veto-2

4. **Shift and Width extraction**

Extended maximum-likelihood fit

- **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**

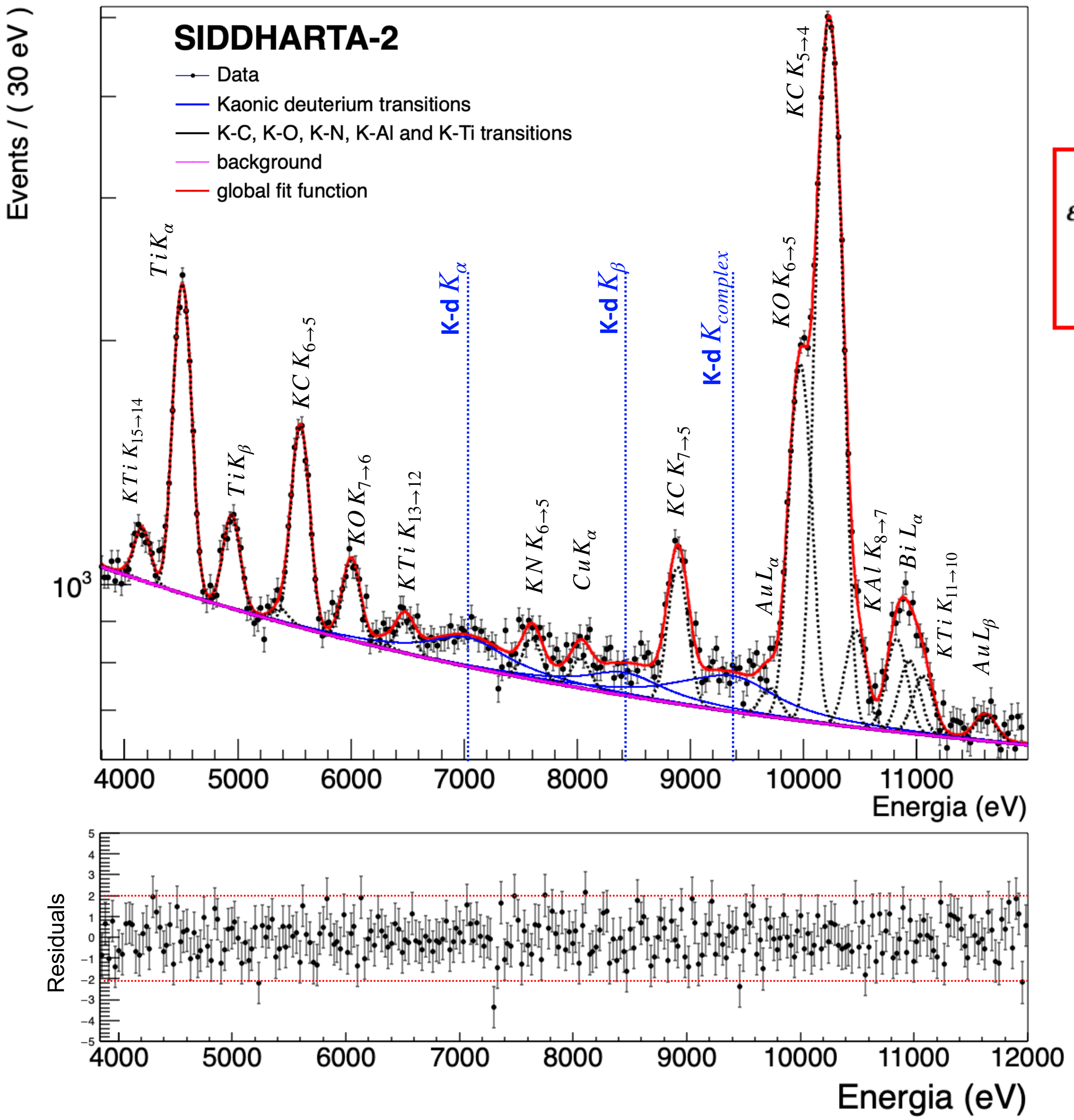
$$f(E;\theta) = \underbrace{\sum_{n=0}^{18} y_n G_n(E;\mu,\sigma)}_{\text{X-ray transitions from known sources (Eur. Phys. J. A (2023) 59 3, 56)}} + \underbrace{y_{2p\to 1s} V_{2p\to 1s}(E;\mu,\sigma,\Gamma) + \sum_{n=3}^{7} y_{n\to 1s} V_{n\to 1s}(E;\mu,\sigma,\Gamma^*)}_{\text{Kaonic deuterium lines}} + \underbrace{y_{em}\, e^{\lambda_{em} E} + y_{had}\, e^{\lambda_{had} E} + C}_{\text{Background E.M and hadronic}}$$

- **The total negative log-likelihood is:** $-2ln\mathscr{L}_{tot} = -2ln\mathscr{L}_{ext} - 2ln\mathscr{L}_{nuisance}$

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

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

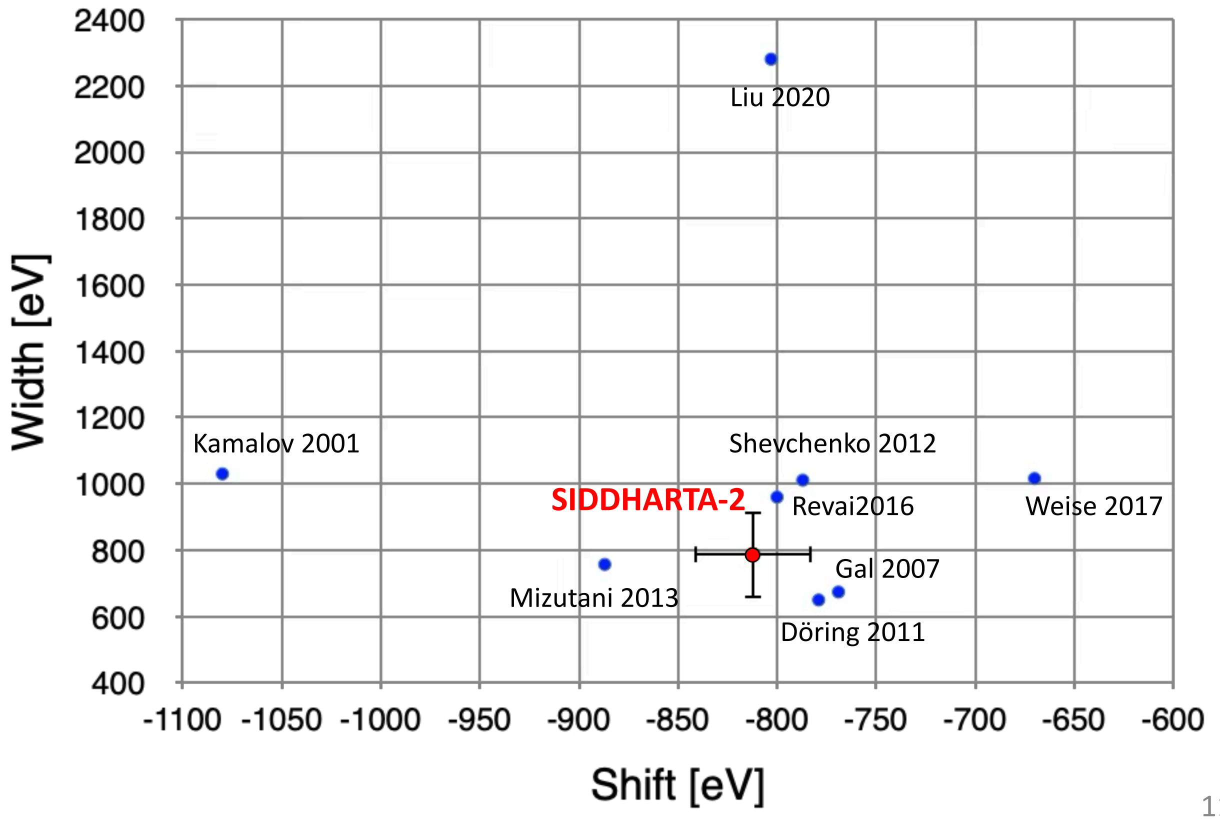
Kaonic Deuterium Results



$$\varepsilon_{1s} = E^{exp}_{2p\to1s} - E^{QED}_{2p\to1s} = 7021.9 - 7834.0 = -812.1 \pm 29.8\,(stat) \pm 2.1\,(syst)\ \text{eV}$$

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

Targeted precision achieved!



Kaonic Deuterium analysis: next steps

Recommendations for SIDDHARTA-2:
- *The SC reiterates the recommendation to aim for a very high-impact physics journal, not only for the publication of their full Kd 1s energy shift and width, but also for the yields, and their collaboration with theoreticians to determine the Kd scattering lengths and isospin-definite scattering lengths.*

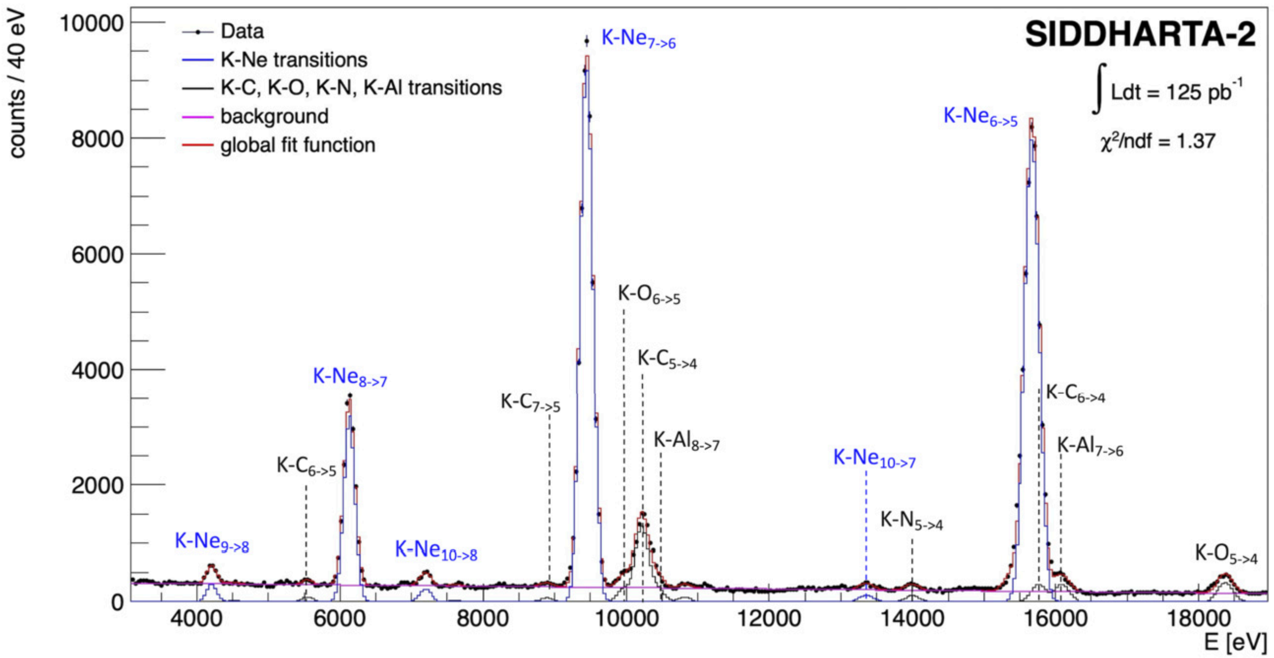
Short-term goals:

- Finalise the data analysis (calibration and events selection of the entire data set) ~ 6 month
  - ➢ **Evaluation of the 1s level energy shift and width and implications for the low energy QCD with strangeness**
- **Submission of an article on Kd shift and width in a very high-impact physics journal**

Medium-long term goals:

- Evaluation of the **kaonic deuterium X-ray yields** (high and low density runs)
- Evaluation of the **kaonic deuterium scattering length** (in collaboration with theoreticians)
- **Combined analysis of kaonic hydrogen and deuterium** to determine the **isospin dependent antikaon-nucleon scattering lengths** (in collaboration with theoreticians) and implication for theory

Kaonic Neon: update



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Physics Letters B

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

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Letter

High precision X-ray spectroscopy of kaonic neon ☆

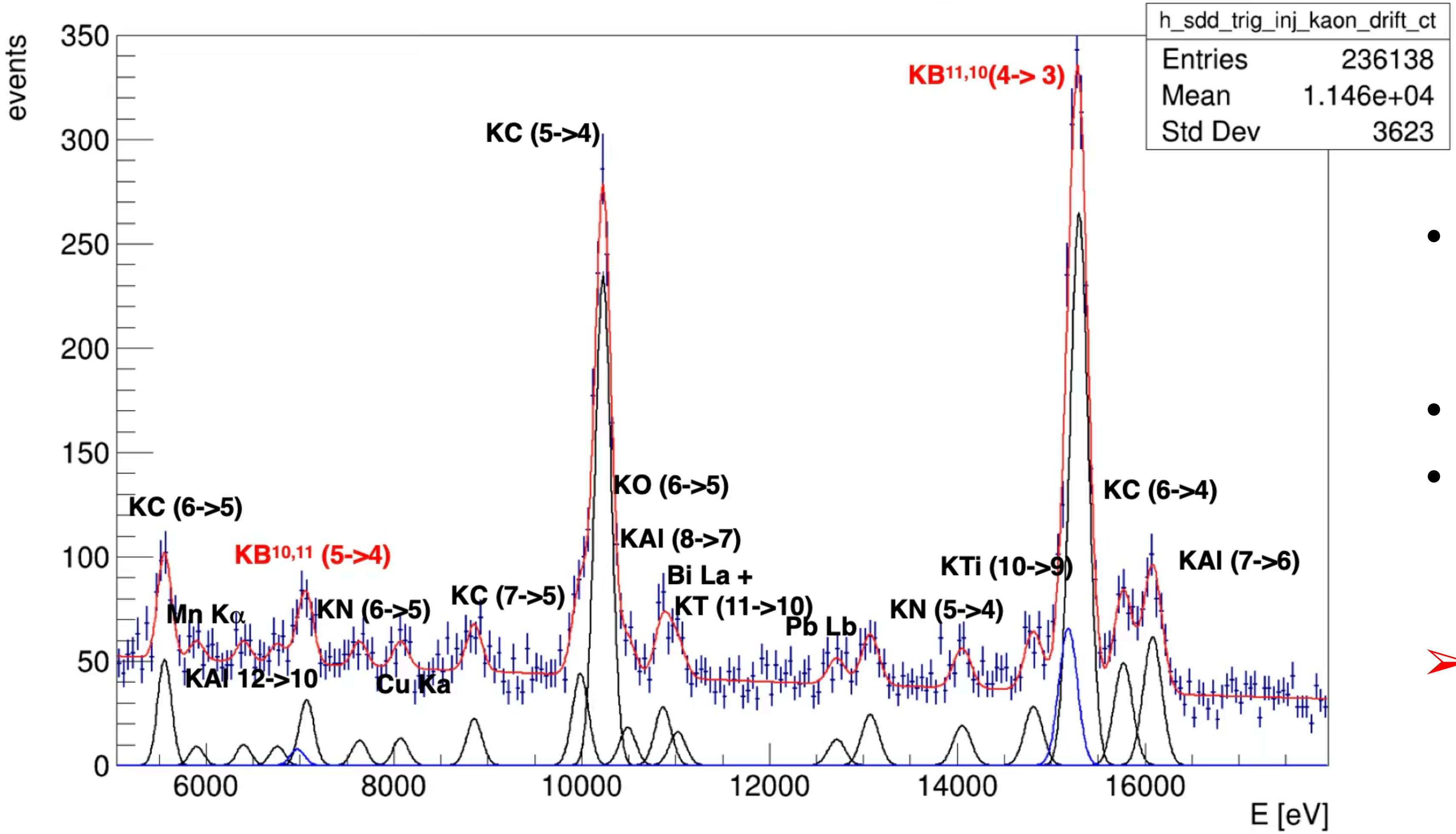
F. Sgaramella [a,*], D. Sirghi [b,a,c,**], K. Toho [d], F. Clozza [a], L. Abbene [e], C. Amsler [f], F. Artibani [a,g], M. Bazzi [a], G. Borghi [h,i], D. Bosnar [j], M. Bragadireanu [c], A. Buttacavoli [e], M. Cargnelli [f], M. Carminati [h,i], A. Clozza [a], R. Del Grande [k,a], L. De Paolis [a], K. 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]

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)

First kaonic boron high-n transition measurement



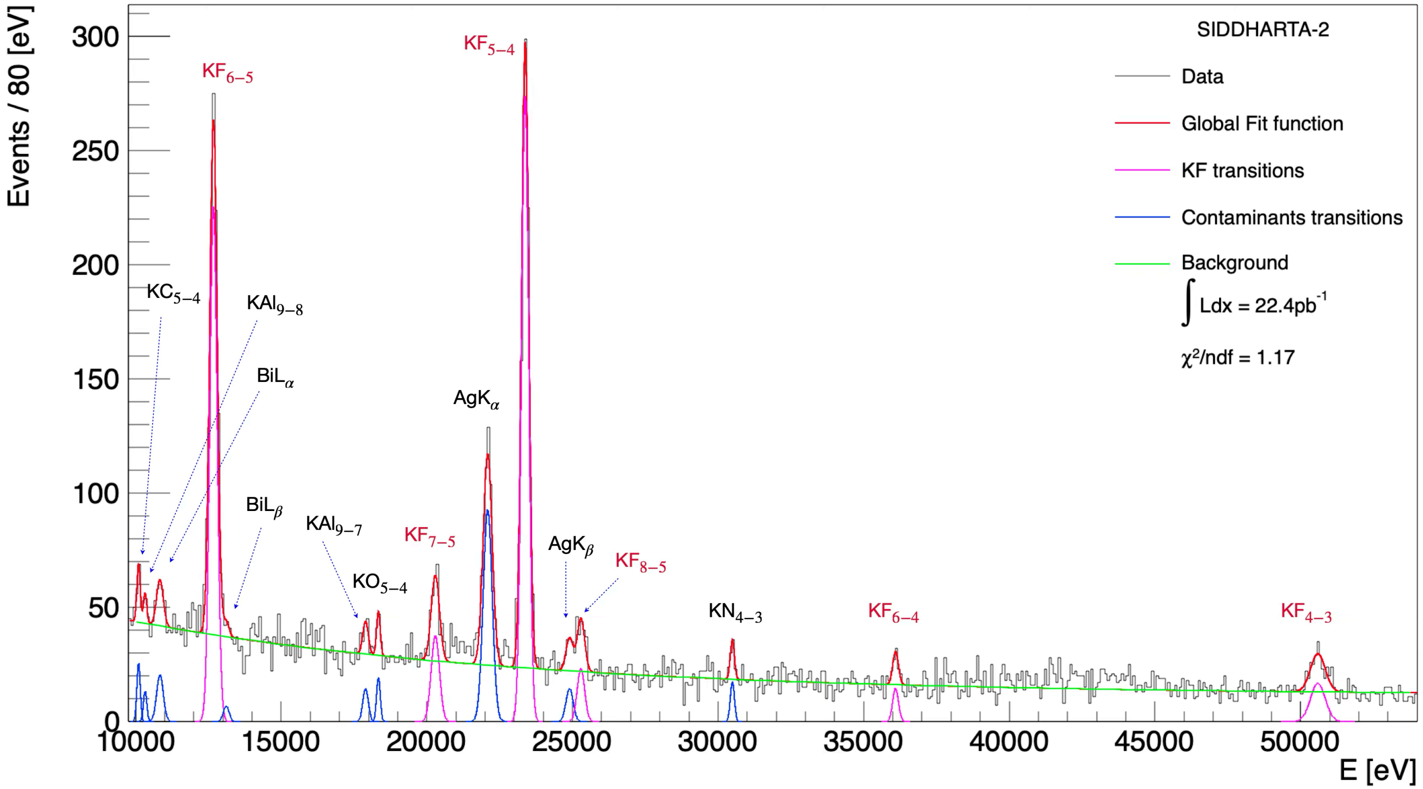
- 2 mm thick boron sheet placed in front of the window of the vacuum chamber
- Integrated luminosity 20 pb^{-1}
- Feasibility test for solid target experiment with SDDs

➢ Article in preparation

$K^{11}B$(5->4): 7064.62 ± 16.93 (eV)
$K^{10}B$(5->4): 6920.96 ± 58.23 (eV)

$K^{11}B$(4->3): 15293.33 ± 4.8 (eV)
$K^{10}B$(4->3): 15180.11 ± 20.86 (eV)

Kaonic Fluorine measurement - toward a revolution



- **The n=4 energy level of kaonic fluorine exceeds the Schwinger limit, offering a unique opportunity to study strong-field QED.**
- For the first time SDDs have been used to perform kaonic atoms spectroscopy at high energy (up 50 keV)
- The KF 4→3 is influenced by **strong interaction effect**

➢ 2 Articles in preparation

Transition	Energy [eV]	Yield[%]
KF6-5	12676.2 +- 5.1(stat) +- 6.3(syst)	6.96 +- 0.56
KF7-5	20294.1 +- 20(stat) +- 6(syst)	1.60 +- 0.46
KF5-4	23378.8 +- 4.4(stat) +- 5.9(syst)	13.91 +- 0.74
KF6-4	36096.8 +- 29(stat) +- 36(syst)	2.06 +- 0.75
KF4-3	50596.3 +- 34(stat) +- 9(syst)	12.9 +- 3.5

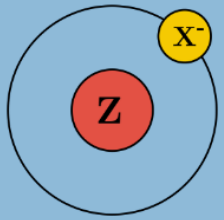
Contents

- SIDDHARTA-2 data analysis - status and results
- **Recent Theoretical Developments (Simone Manti)**
- Revised EXKALIBUR first module and experimental activities
- Scientific output and conferences
- Summary and requests

Recent Theoretical Developments: Now Running Ab Initio Calculations!

- We **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).**

Ab Initio Input



- **Ab Initio Approach:** based only on **Physical Laws** and **Fundamental Constants.**
- Supports **Normal, Exotic,** or **Mixed Atomic Systems.**
- Supported **Exotic Particles:**
  - K^- : Kaons
  - μ^- : Muons
  - π^- : Pions
  - Σ^- : Sigmas
  - $\bar{p}^-$: Antiprotons
  - X^- : Test Particles

MCDF Framework

Basis Wavefunctions:

- Dirac Equation (spin-½ particles)

$$\left[c\boldsymbol{\alpha}\cdot\mathbf{p}+\beta mc^2+V(\mathbf{r})\right]\psi_i(\mathbf{r})=\varepsilon_i\psi_i(\mathbf{r})$$

- Klein-Gordon Equation (spin-0 particles)

$$\left[-\hbar^2c^2\nabla^2+m^2c^4\right]\phi(\mathbf{r})=\left[E-V(\mathbf{r})\right]^2\phi(\mathbf{r})$$

Multi-Configuration Dirac-Fock:

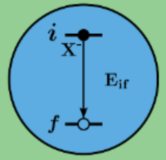
$$\Psi=\sum_{v=1}^{NCF}W_v\phi^v(1,2,...,N;J,J_z)$$

$$\mathrm{E_{tot}}=\sum_{\nu\mu}W_\nu W_\mu\langle\phi^\nu|H|\phi^\mu\rangle/\sum_\nu W_\nu^2$$

Total Energies Contributions:

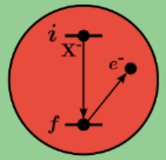
- QED
- Breit Interaction
- Recoil Effect
- Nuclear Finite Size
- Screening Effect

Output Quantities

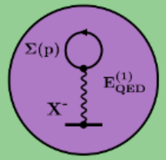


Energy Levels & Transitions

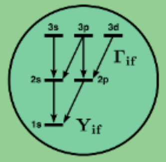
Radiative Transition Probabilities



Auger Decay Rates



QED Self-Energy & Vacuum Polarization



Parameters for Atomic Cascade

Recent Theoretical Developments: Applications to Kaonic Atoms

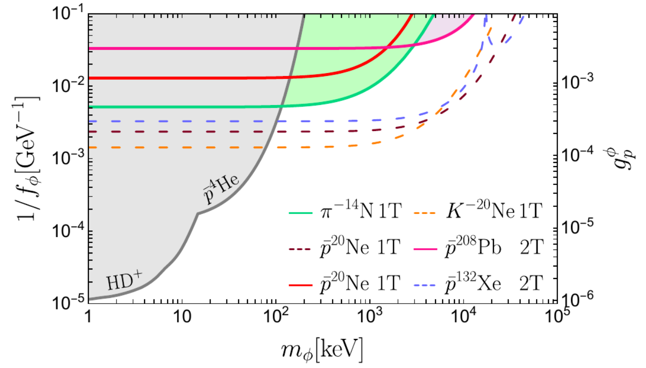
- **Validating *ab initio* QED predictions** at intermediate atomic number Z

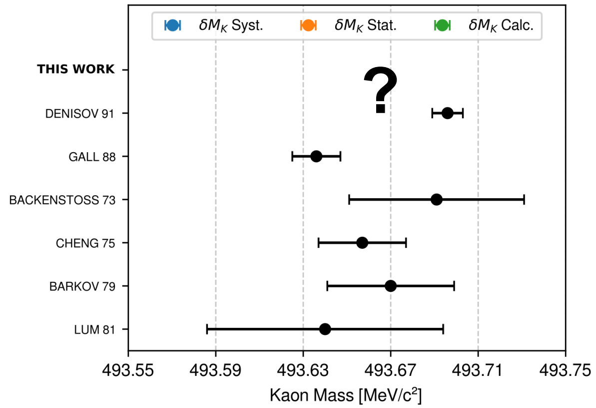
- **Enabling** precision tests of **Bound-State QED (BSQED)** in high-n circular transitions in Kaonic Atoms, where nuclear effects are minimized

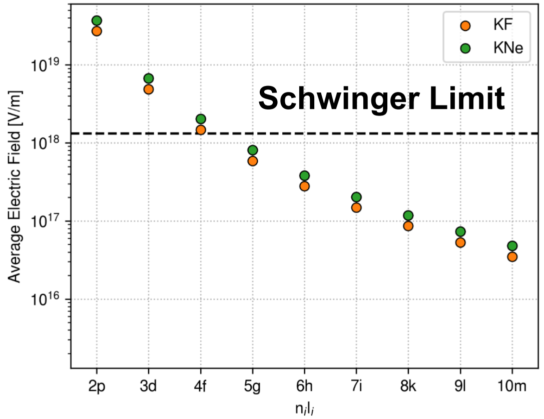
- **Testing** for deviations hinting at **Beyond Standard Model (BSM)** physics

- **Determining** the **Kaon Mass** accurately through High-n transitions with intense yields

- **Exploring** QED behavior in ultra-high Electric Fields (above the **Schwinger limit**)

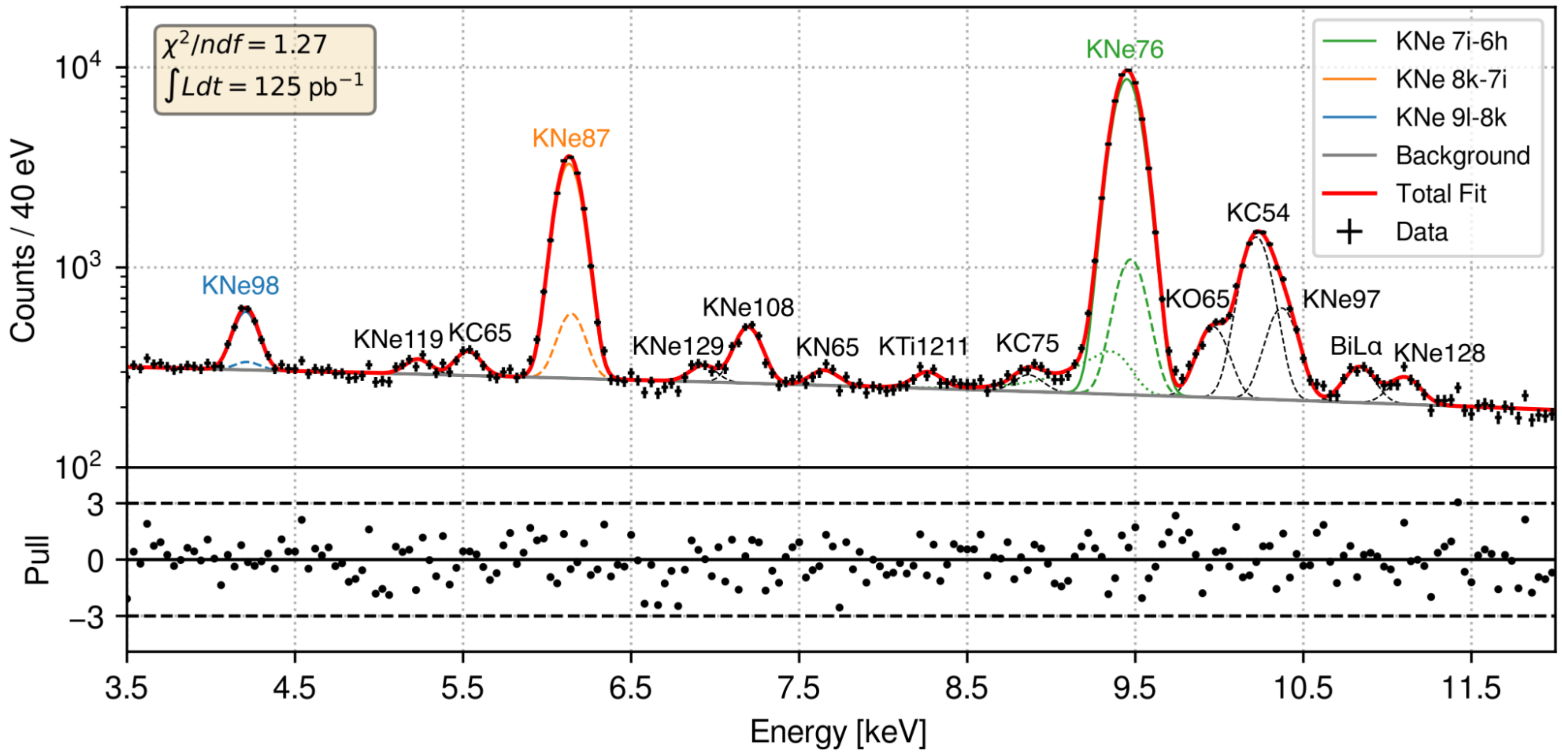




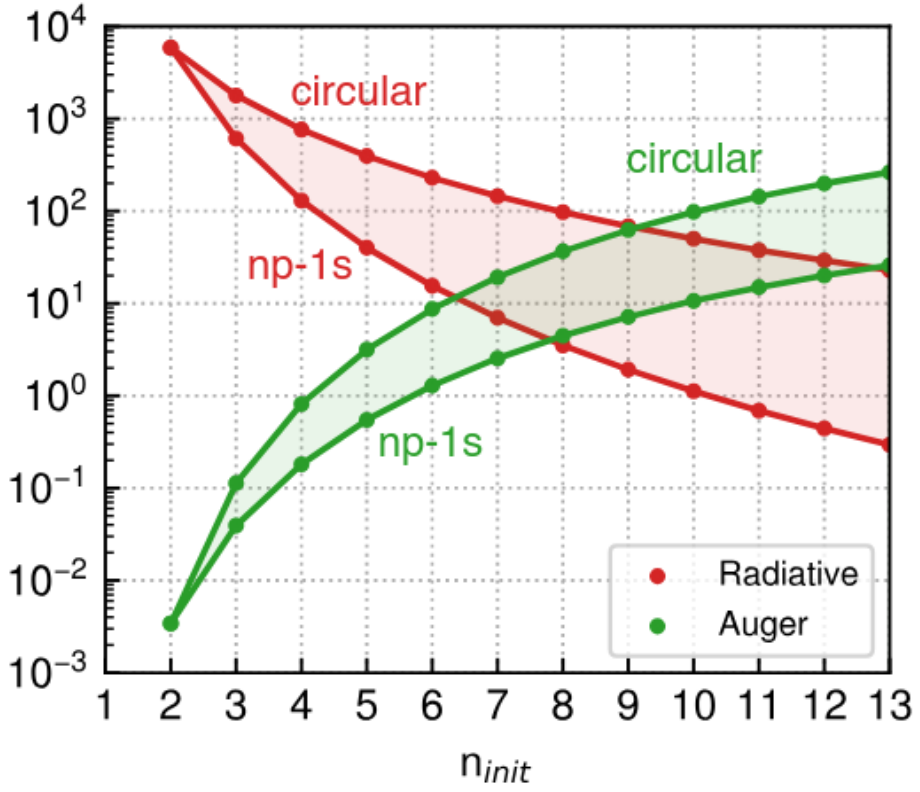


Calculations to Reveal the Cascade Mechanism: Application to KNe

- **Qualitative trends** in **kaonic X-ray Yields** can be explained by the interplay between **Radiative** and **Auger decay** rates:
  → **X-ray emission dominates for n<10**
- **Quantitative predictions** require:
  → **Cascade Calculations** (in development)



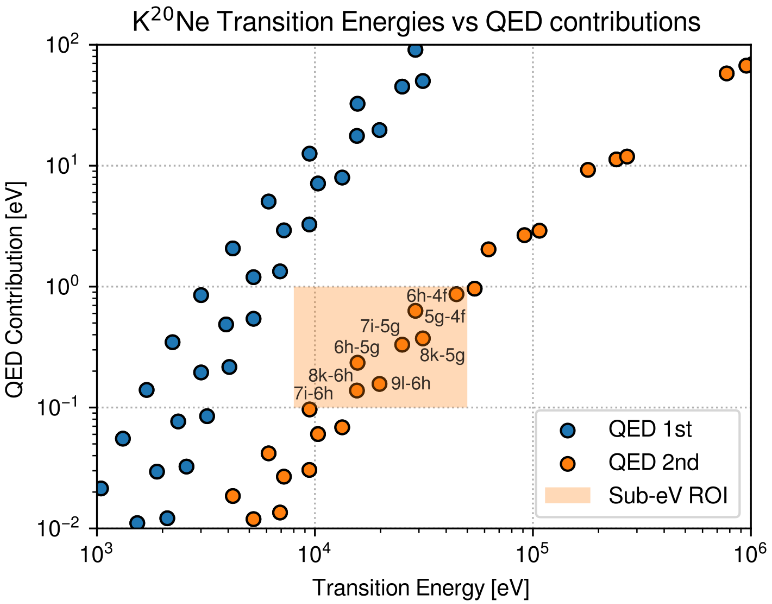
Scaled Hydrogenic Rates formulas



Burbidge, G.R., de Borde, A.H., 1953. Phys. Rev. 89, 189–193.

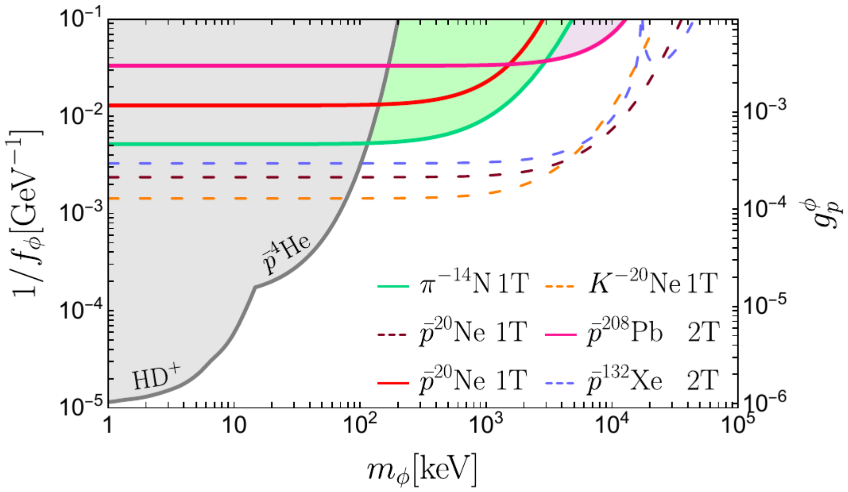
BSQED and Beyond Standard Model (BSM) Physics: Application to KNe

Transition	$E_{if}^{(\mathrm{exp.})}$	$\delta E_{if}^{(\mathrm{stat.})}$	$\delta E_{if}^{(\mathrm{sys.})}$	$E_{if}^{(\mathrm{calc.})}$	$E_{if}^{(\mathrm{QED1})}$	$E_{if}^{(\mathrm{QED2})}$	$\Delta E_{if}^{(e^-)}$	$\Delta E_{if}^{(\mathrm{isot.})}$
6h-5g	15673.30	0.52	9.00	15685.39	32.51	0.24	-0.11	37.01
7i-6h	9449.78	0.42	1.50	9450.28	12.56	0.10	-0.18	22.28
8k-7i	6129.62	0.72	1.50	6130.31	5.05	0.04	-0.27	14.45
9l-8k	4205.85	3.73	2.00	4201.45	2.07	0.02	-0.38	9.90



- **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:** 9449.78 ± 0.42 (stat) ± 1.50 (syst) eV
  - **Theory:** 9450.28 ± 0.18 (calc) ± 0.21 (pdg) eV

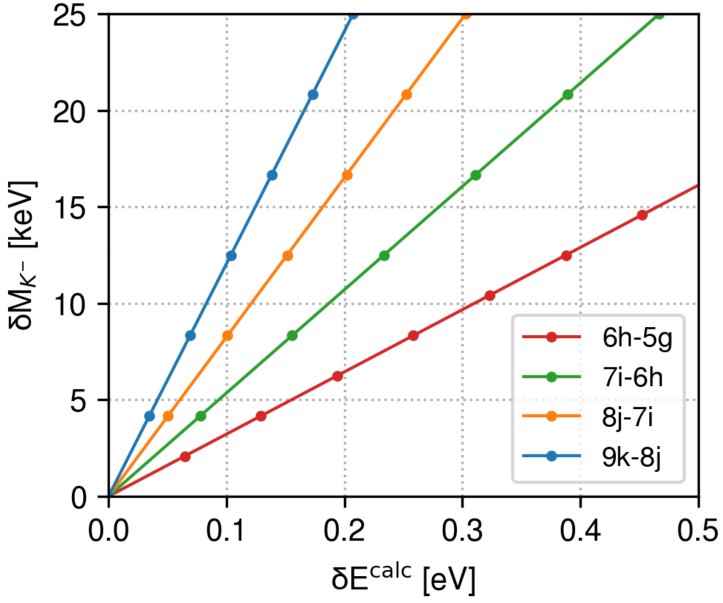
  → Useful for validating **BSQED predictions**.
- Kaonic Neon offers a clean system to test **QED calculations** and constrain **BSM scenarios**.



Exotic atoms constrain uds-scalar [arXiv:2502.03537]

Precision Kaon Mass Determination: Application to KNe

Transition	$E_{if}^{(\mathrm{exp.})}$	$\delta E_{if}^{(\mathrm{stat.})}$	$\delta E_{if}^{(\mathrm{sys.})}$	$E_{if}^{(\mathrm{calc.})}$	$E_{if}^{(\mathrm{QED1})}$	$E_{if}^{(\mathrm{QED2})}$	$\Delta E_{if}^{(e^-)}$	$\Delta E_{if}^{(\mathrm{isot.})}$
6h-5g	15673.30	0.52	9.00	15685.39	32.51	0.24	-0.11	37.01
7i-6h	9449.78	0.42	1.50	9450.28	12.56	0.10	-0.18	22.28
8k-7i	6129.62	0.72	1.50	6130.31	5.05	0.04	-0.27	14.45
9l-8k	4205.85	3.73	2.00	4201.45	2.07	0.02	-0.38	9.90

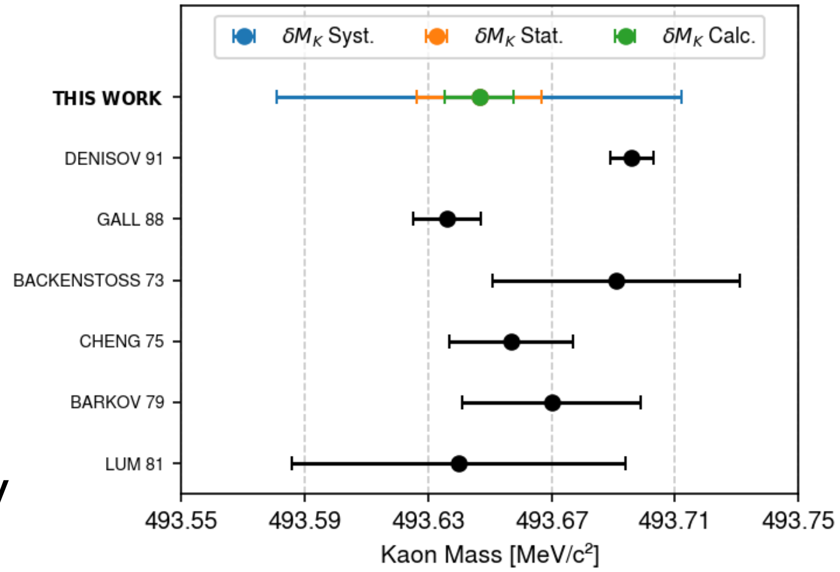


- **MCDF calculations** are used to iteratively extract the Kaon Mass from measured transitions as in **GAL88:**

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

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

Transition	M_{K^-}	$\delta M_{K^-}^{\mathrm{stat.}}$	$\delta M_{K^-}^{\mathrm{syst.}}$	$\delta M_{K^-}^{\mathrm{calc.}}$
7i-6h	493.650	0.022	0.078	0.009
8k-7i	493.619	0.058	0.121	0.021
9l-8k	494.208	0.439	0.235	0.044



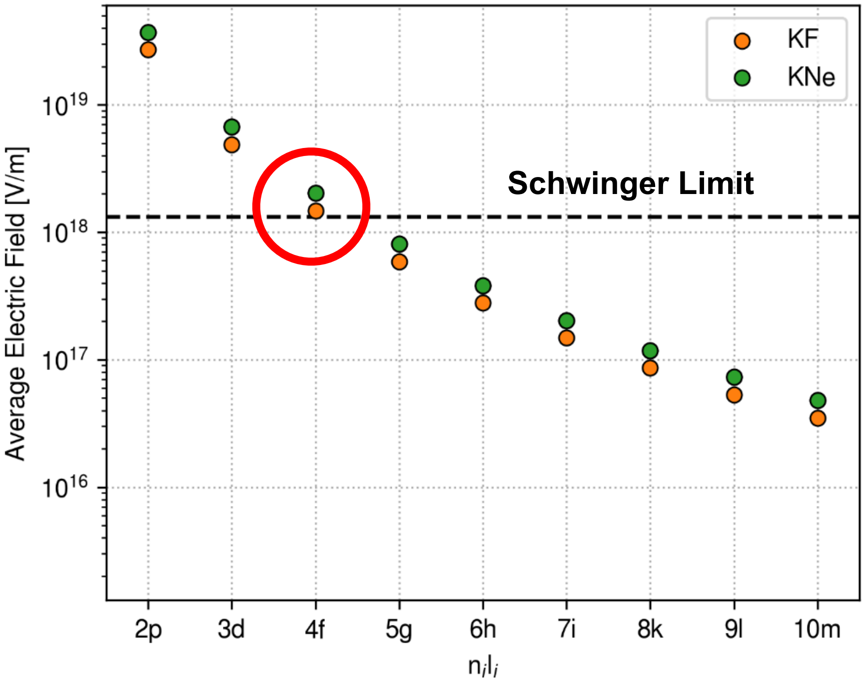
- M_{K^-} = 493.647 + 0.0203 (stat) + 0.0657 (syst) + 0.0112 (calc) MeV

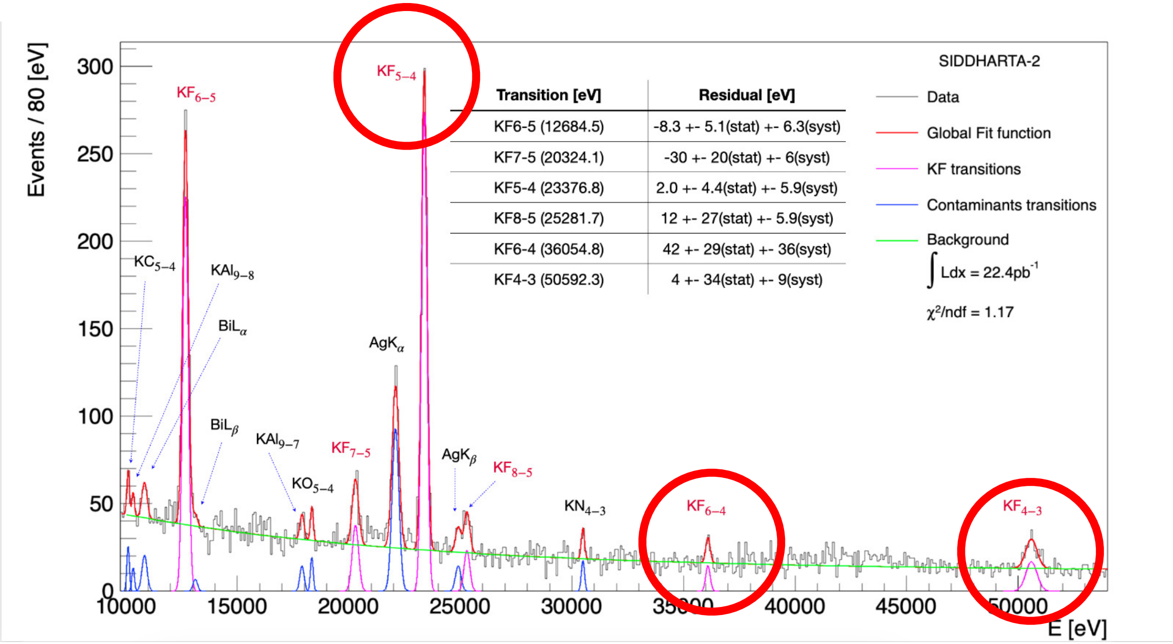
Kaonic Atoms as Probes of Strong Fields QED: Schwinger Limit for KF

- **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:

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

- The transition **KF 4f → 3d**, **E = 50.6 keV**, the **Average Electric Field** in kaonic orbitals approaches Ec





Contents

- SIDDHARTA-2 data analysis - status and results
- Recent Theoretical Developments (Simone Manti)
- **Revised EXKALIBUR first module and experimental activities**
- Scientific output and conferences
- Summary and requests

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

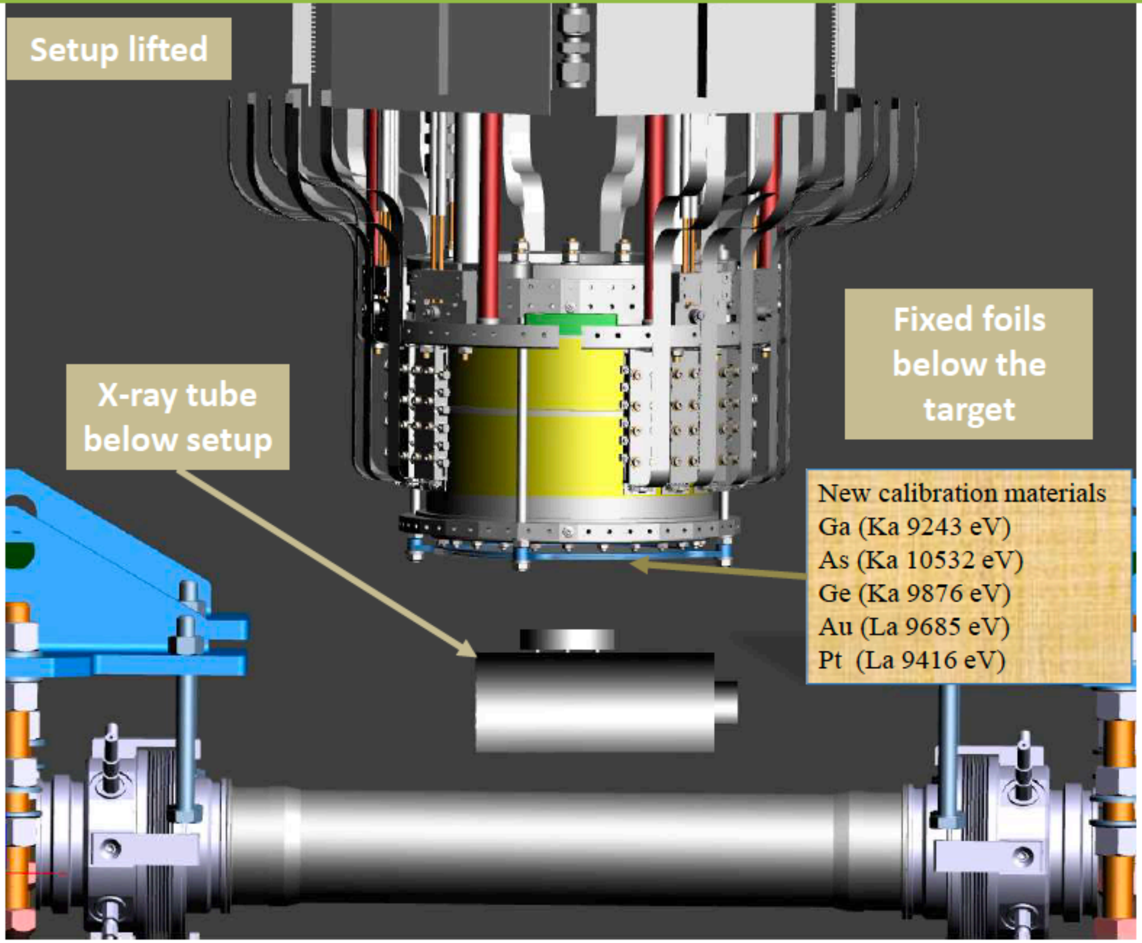
- 200 -300 pb^{-1} of integrated luminosity/target

- **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

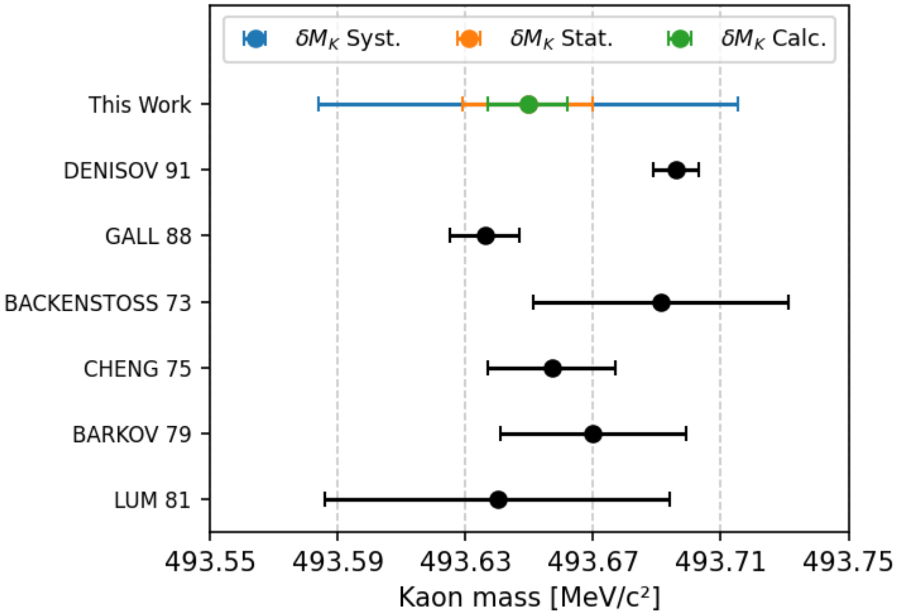
1.1 - High precision kaonic neon measurement

- Goal: systematic uncertainty ~0.2 eV
- new calibration system financed and under construction

Upgraded calibration system for offline period (KNe existent measurements) under construction – to be tested in DAFNE (off) within end 2025 - improve syst errors < 1 eV

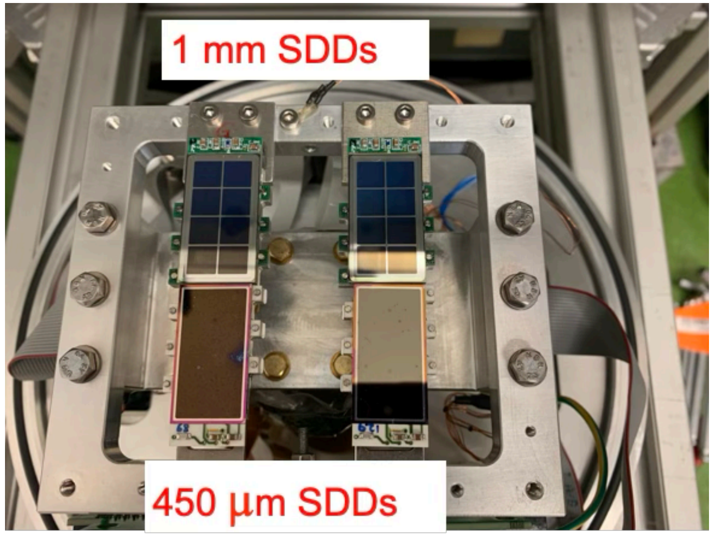


Limited by systematic uncertainty on energy calibration



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

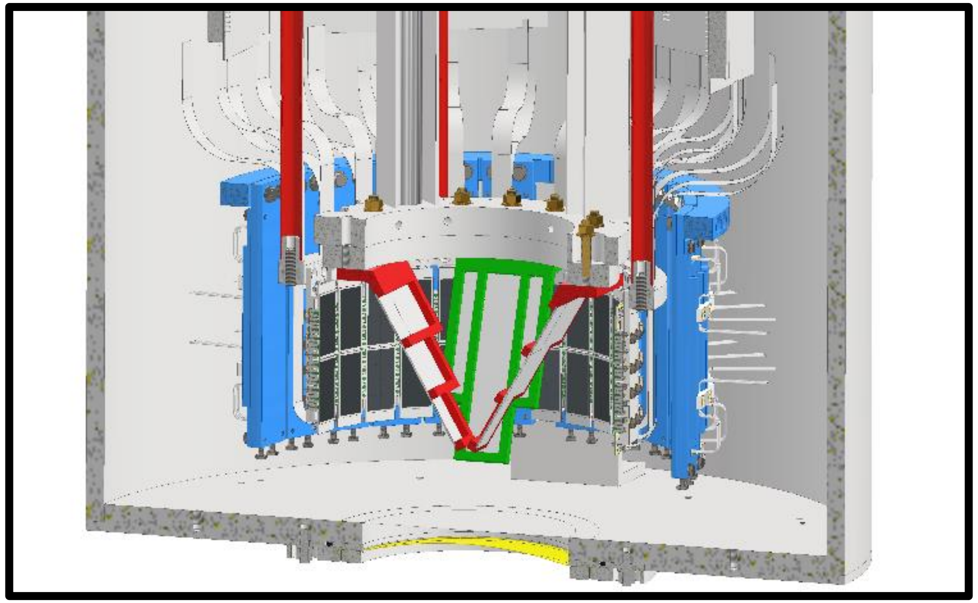
Lithium-6		Lithium-7		Beryllium-9	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**15.085**	**3 → 2**	**15.261**	**3 → 2**	**27.560**
4 → 2	**20.365**	**4 → 2**	**20.603**	**4 → 3**	**9.646**
5 → 2	**22.809**	**5 → 2**	**23.075**	**5 → 3**	**14.111**
4 → 3	5.280	4 → 3	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		



1mm thick SDDs: enhanced efficiency above 15 keV

Solid targets system

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

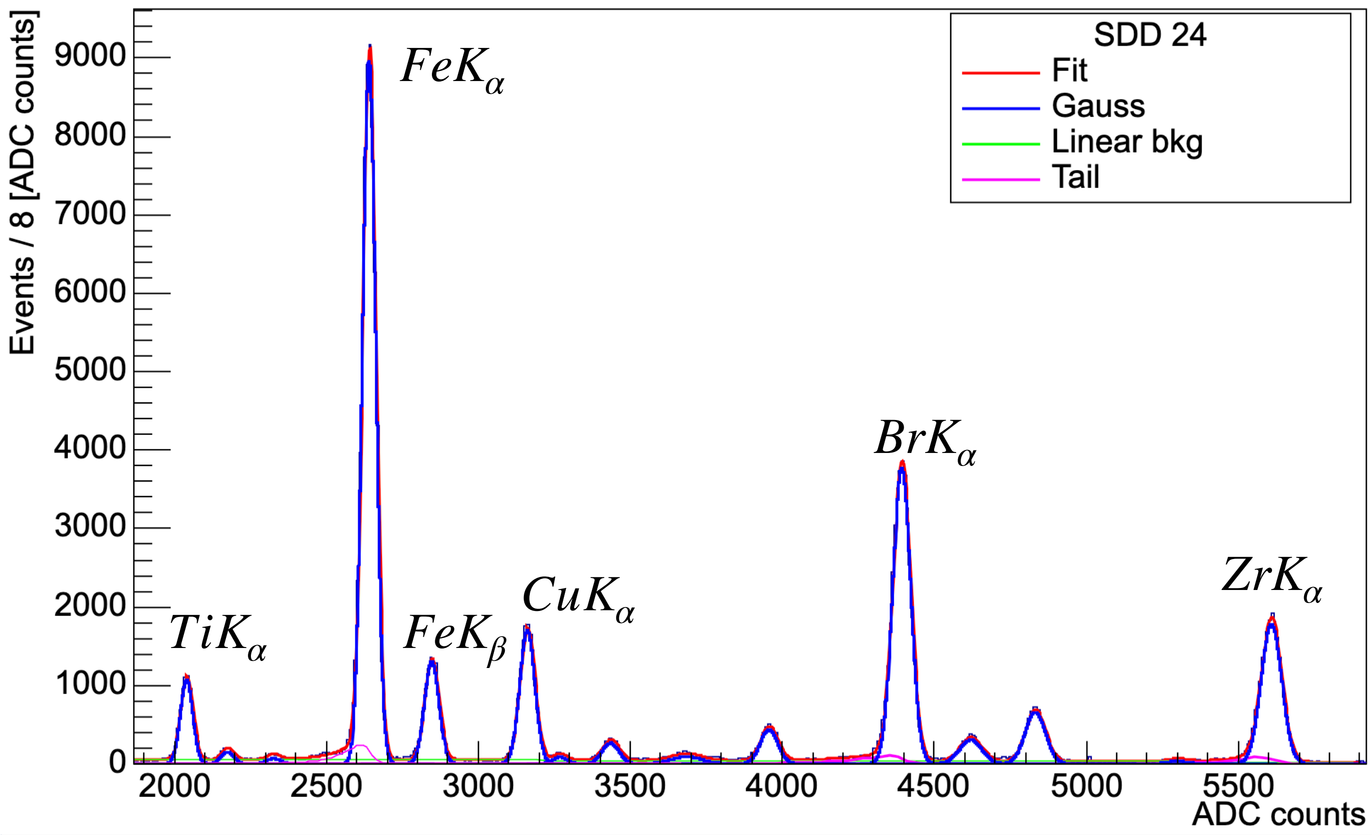


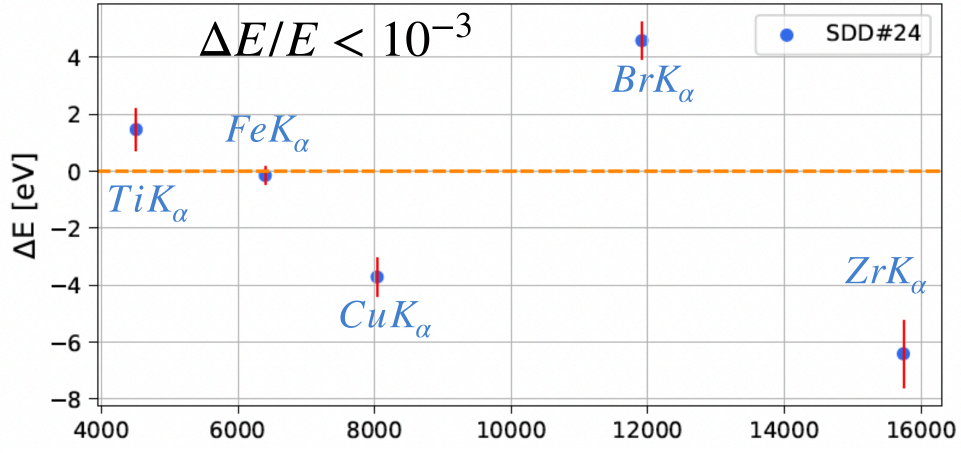
Boron-10		Boron-11	
Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**43.568**	**3 → 2**	**43.768**
4 → 3	**15.156**	**4 → 3**	**15.225**
5 → 3	**22.171**	**5 → 3**	**22.273**
5 → 4	7.015	5 → 4	7.047
6 → 4	10.826	6 → 4	10.875
6 → 5	3.811	6 → 5	3.828

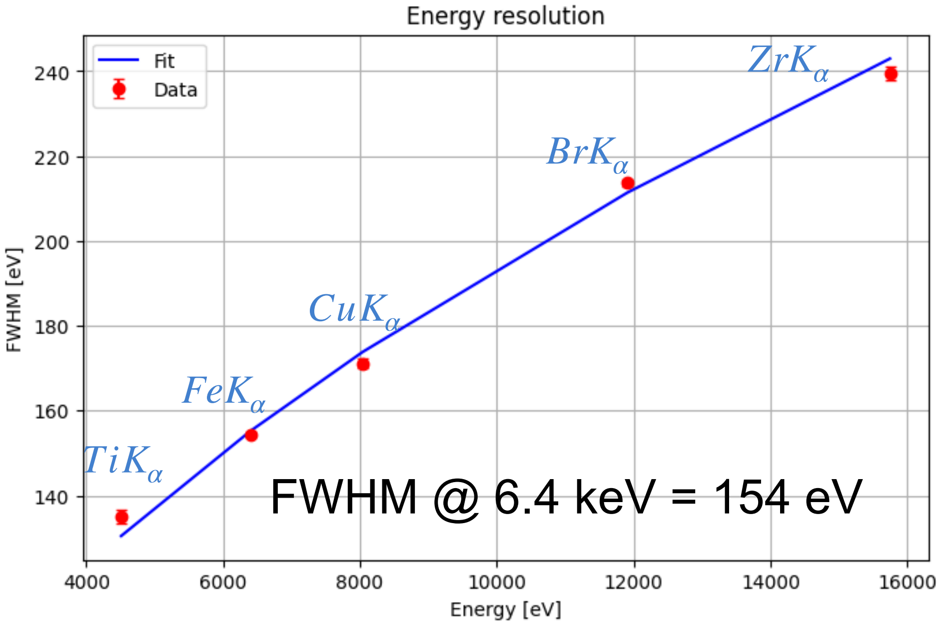
1 mm thick Silicon Drift Detectors: Optimisation of the Energy response

The optimisation of the detectors' energy response has led to excellent energy resolution and linearity

Typical spectrum acquired with a 1 mm thick SDD using an X-ray tube and a multi-element target to study its spectroscopic response





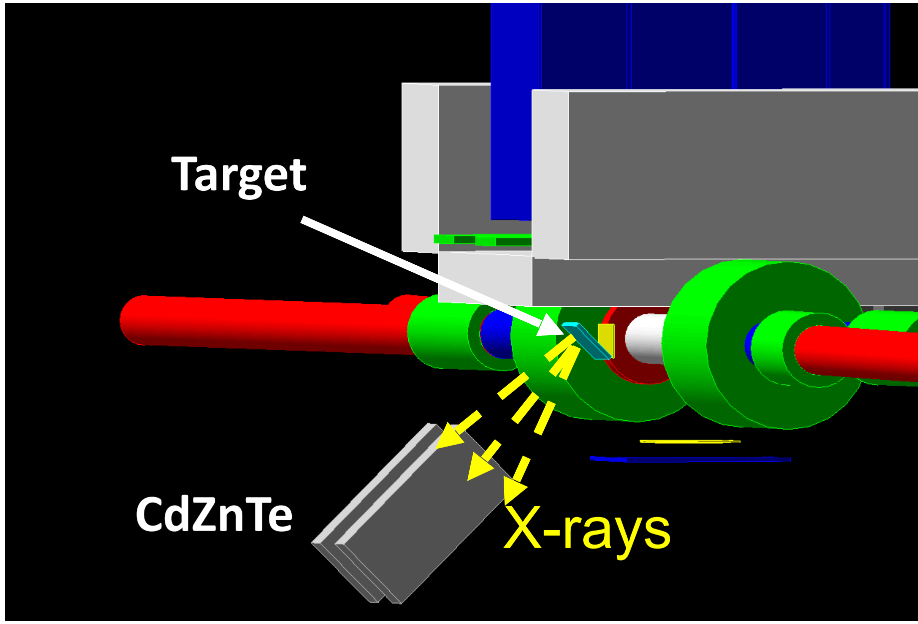


➢ Article in preparation

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

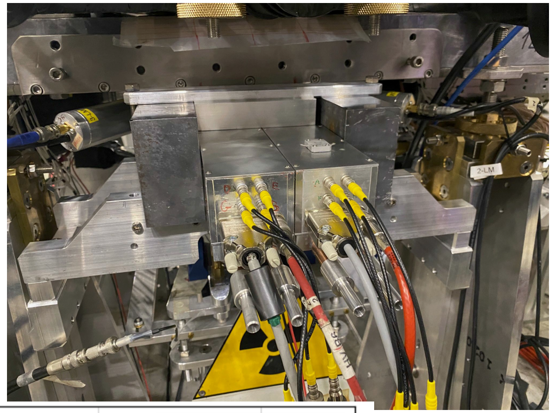
- **Larger active area:** 32 detectors instead of 8
- **Optimised geometry and shielding** to reduce the background

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

$K^{32}S(4\to3)$ @ 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

$K^{32}S(4\to3)$ @ 160 keV : $\delta E = 19$ eV, $\delta\Gamma = 37$ eV (42 eV and 83 in the S/B = 1/10 case) for 2% FWHM

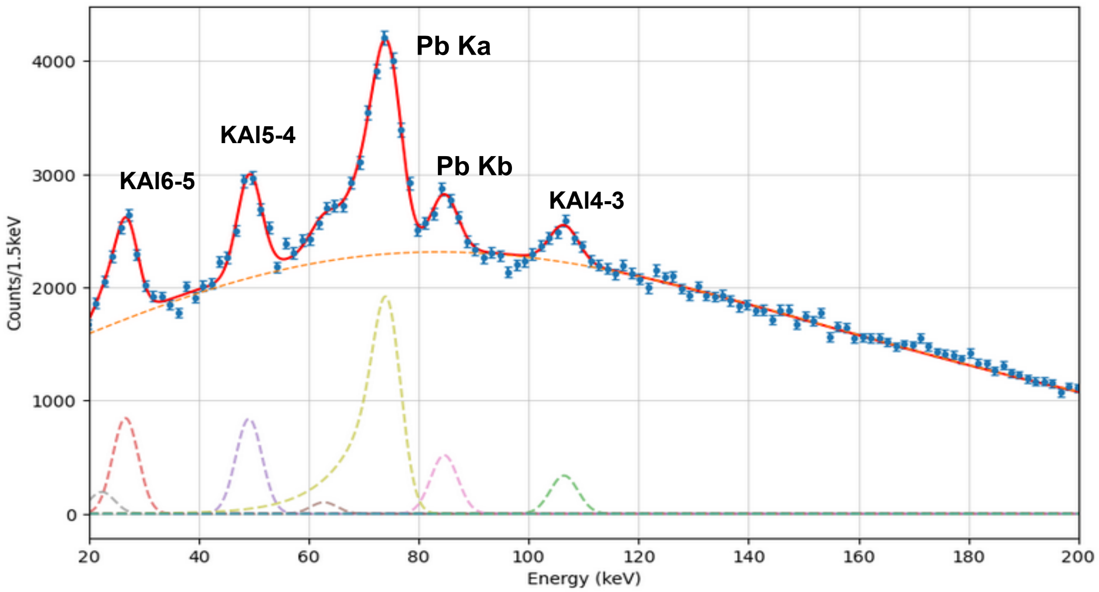
Kaonic atoms measurements with CdZnTe



First kaonic atoms' spectra measured with CZT detectors

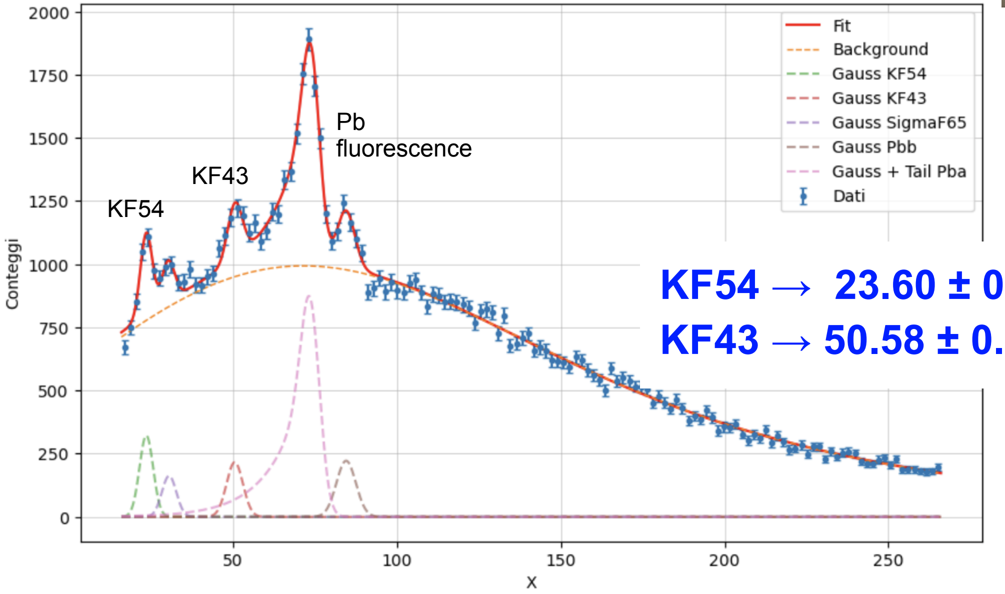
➢ 2 Articles in preparation

Kaonic Aluminium Results



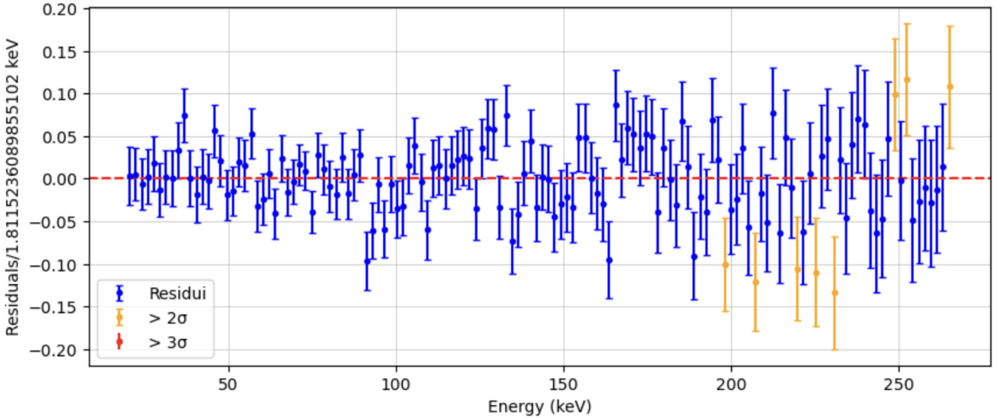
Transition	Energy (keV)	Th. Energy (keV)	Yield
KAl 4-3	106.44 ± 0.22	106.57	6.4 ± 0.4 %
KAl 5-4	49.128 ± 0.092	49.23	12.6 ± 0.5 %
KAl 6-5	26.67 ± 0.16	26.707	15.0 ± 0.9 %

Kaonic Fluorine Results



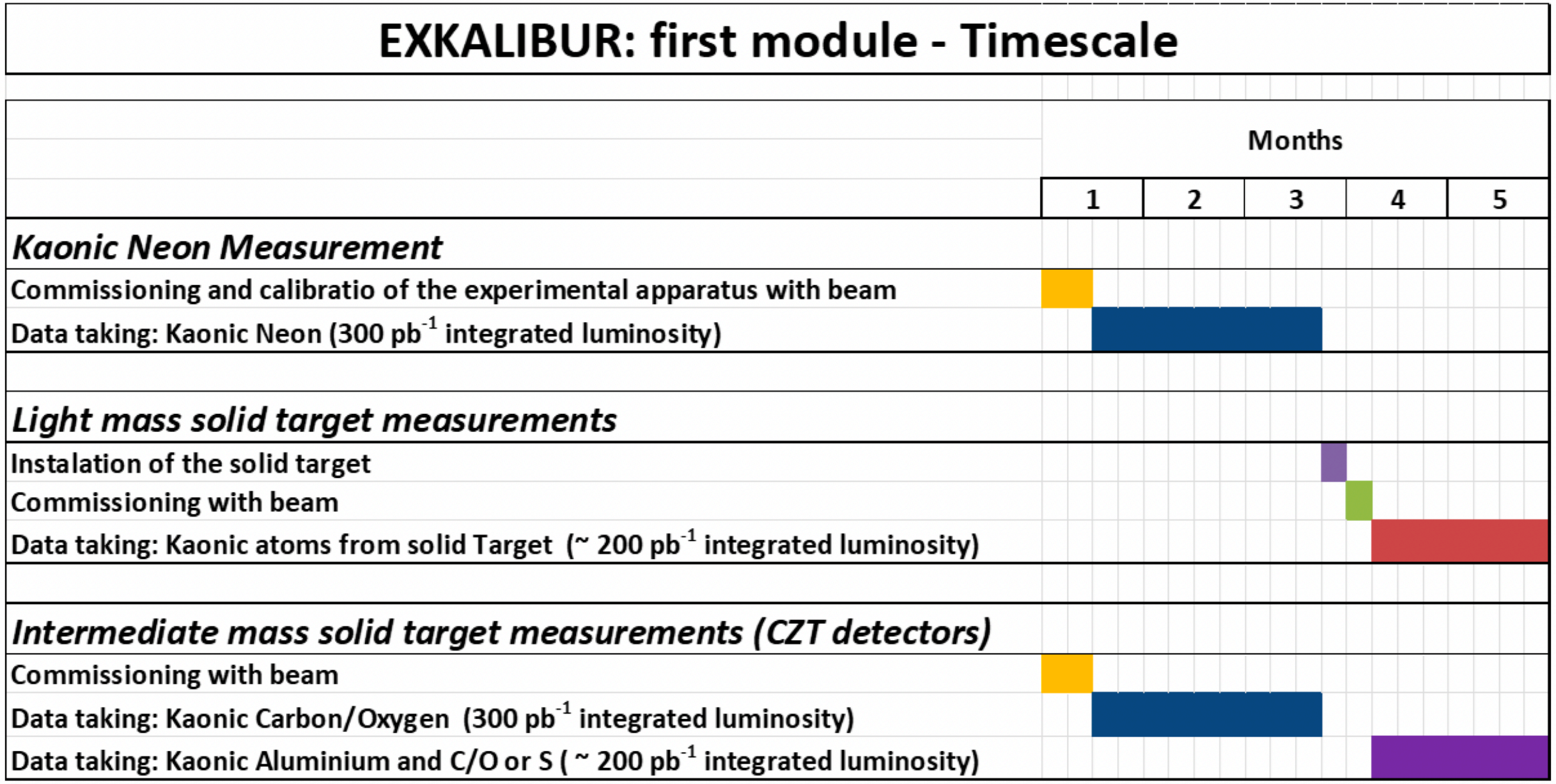
KF54 → 23.60 ± 0.15 keV

KF43 → 50.58 ± 0.29 keV



EXKALIBUR: first module - Timescale

- New calibration system and 1mm thick SDDs financed by INFN Gr3
    - Construction of the new calibration system → **under construction - to be tested in DAFNE (off) within end 2025**
    - Construction of 3 buses of 1mm thick SDDs (192 detectors) ongoing
    - Construction of the multi element solid target ongoing
- **Requested luminosity: 300 pb^{-1} + 200 pb^{-1} (about 4 months in SIDDHARTA2-like condition)**



Publications since last SciCom – November 2024

1. F. Sgaramella, D. Sirghi, et al., “High precision X-ray spectroscopy of kaonic neon”, Phys. Lett. B 856 (2025) 139492

2. A. Scordo, F. Artibani et al., “Kaonic atoms studies with the SIDDHARTA-2 experiment”, POS QNP2024, (2025) 465.

3. F. Artibani, L. Abbene et al., “Tests of New CZT detectors at DAΦNE collider for Kaonic Atoms Measurements”, POS DISCRETE2024, (2025) 031.

4. Nuclear Physics Midterm Plan in Italy - Physics perspectives, accepted for publication in EPJ D (with a section on kaonic atoms)

5. T. Yamaga et al., “Measurement of the mesonic decay branch of the $\bar{K}NN$ quasibound state”, Phys.Rev.C 110 (2024) 1, 014002
6. H. Noumi et al., “Measurement of KN scattering below the KN mass threshold”, Acta EPJ Web Conf. 291 (2024) 05011
7. F. Sakuma et al., “Light Kaonic Nuclei at J-PARC”, PoS QNP2024 (2025) 211

Article in preparation:

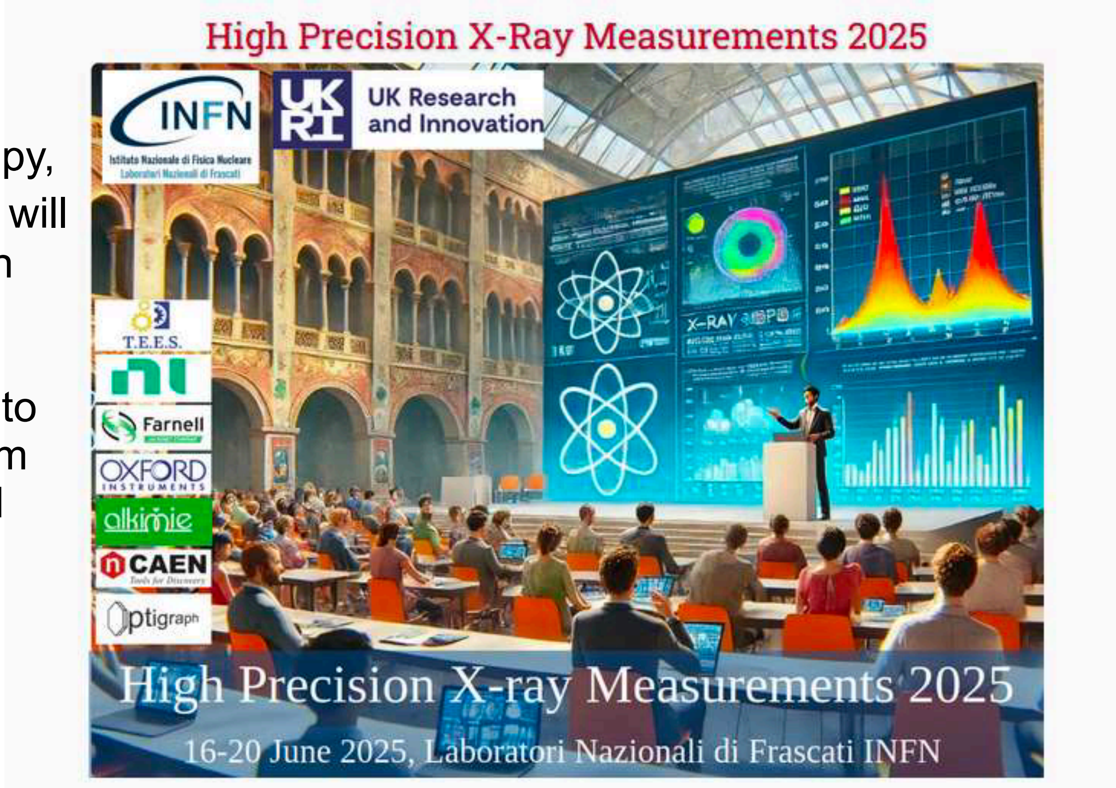
- “Timing Application of Quasi-Hemispherical CZT Detectors for Kaonic Atoms Spectroscopy”
- “High precision Kaonic Aluminium X-ray spectroscopy with CZT detectors”
- “Characterization of the SIDDHARTA-2 Silicon Drift Detectors’ energy response up to 50keV”
- The kaonic neon measurement: theoretical implications for BSQED and a precise determination of the kaon mass
- First measurement of Kaonic deuterium 1s level shift and width

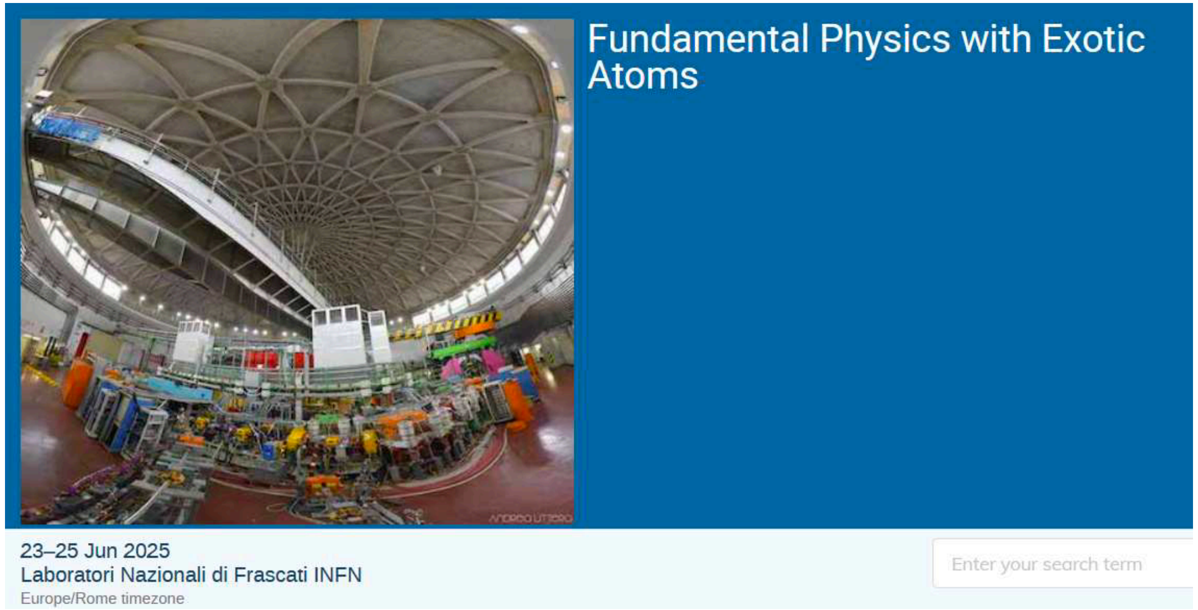
Workshops and Conferences

We planned two conferences to be held in Frascati in June:

- ***High Precision X-ray Measurement***, will focus on X-ray spectroscopy, advanced techniques, new detectors, and future opportunities →We will present the new 1 mm-thick SDDs along with recent developments in the use of CZT detectors at particle colliders.

- ***Fundamental Physics with Exotic Atoms***, will offer an opportunity to present to the scientific community the results of the kaonic deuterium measurement, along with recent findings on kaonic neon, boron, and fluorine for BSQED studies.





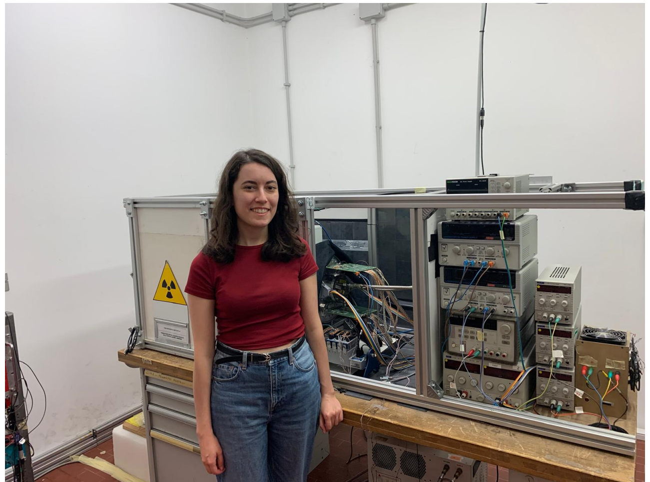
You are all invited!

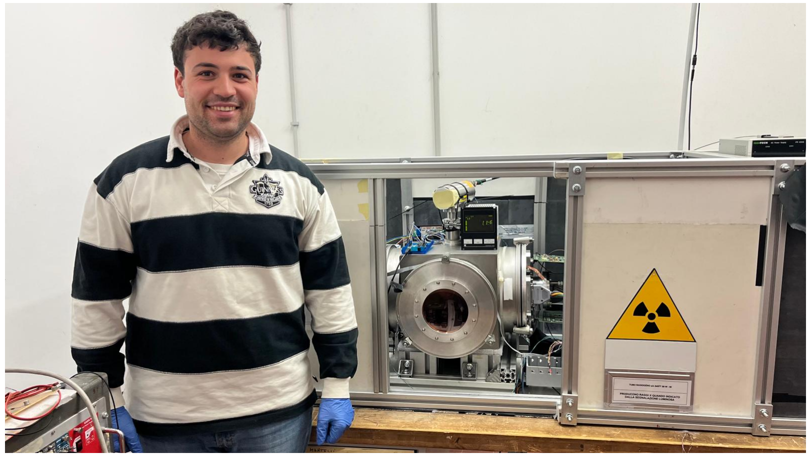
Recommendations for SIDDHARTA-2:

- *The collaboration is encouraged to continue their development of X-ray detectors and to foster the formative aspects of this research beyond the kaonic atoms program, incorporating younger researchers, as a strategic opportunity for LNF.*

Young students involved:

- **Francesco Clozza – Ph.D. at University of Rome Tor Vergata**
- **Francesco Artibani - Ph.D. at University of Rome-3**
- **Kairo Toho - Ph.D. at Tohoku University**
- **Livia Modesti - master degree student at University of Rome La Sapienza**
- **Riccardo Gasbarrini – bachelor degree student at University of Rome Tor Vergata**
- **Erasmus student from November**
- **+1 summer student**





Summary and requests

- The SIDDHARTA-2 Kd data taking (Runs 1, 2, 3 and 4) **has been successfully completed**, integrating 815 pb^{-1} + 185 pb^{-1} of data;

- **Data analyses of total Kd statistics completed; the shift and width of the ground state of kaonic deuterium have been determined with excellent precision; article in preparation**

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

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

- **Kaonic Neon article published Phys. Lett. B 856 (2025) 139492**
- **Kaonic Boron and Fluorine data analyses in advance phase**
- **Data analyses for kaonic aluminium and fluorine with CZT setup completed** (article in preparation);

- **Huge progress in theoretical activities: mastering ab initio calculations -> much enriched scientific outcome**

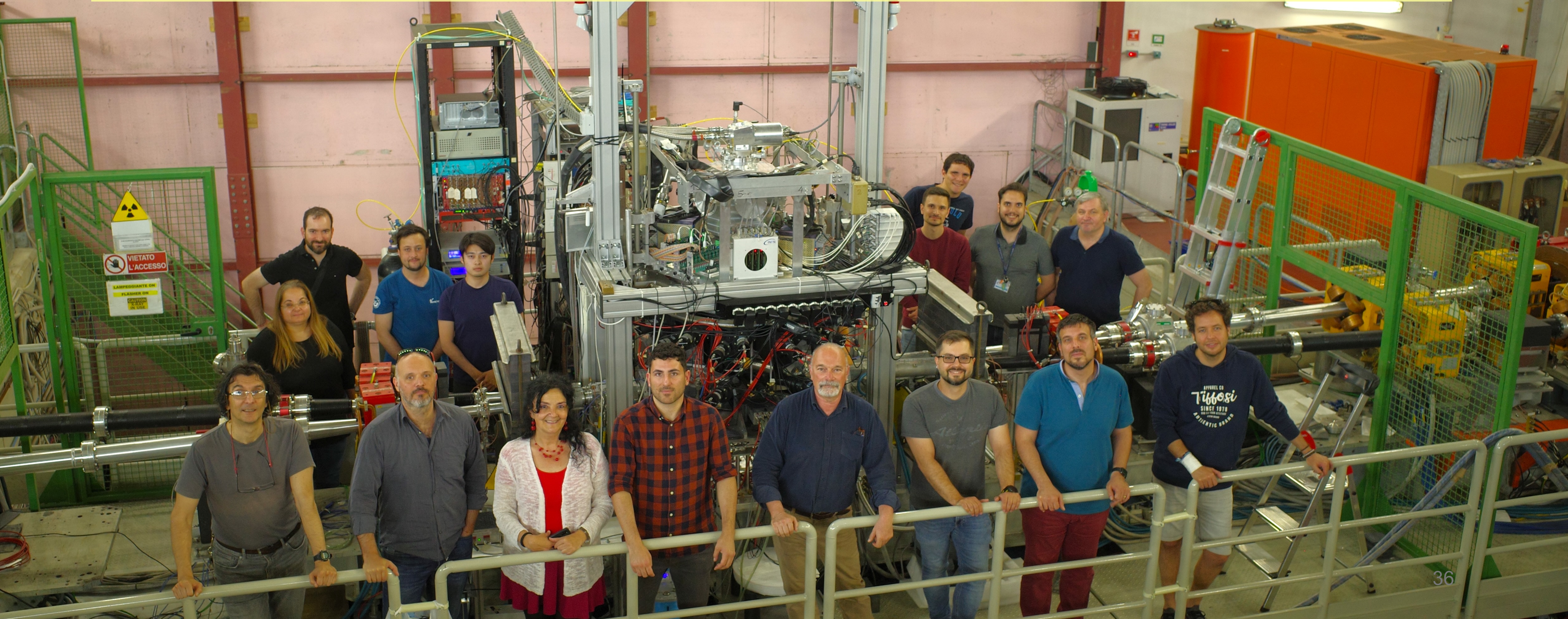
- **For the first EXKALIBUR measurements module:**
  - **Enriched scientific program (BSQED - physics beyond the Schwinger limit)**
  - **realisation of refined calibration system ongoing: request for test in DAFNE (off)**
  - **successful optimisation of 1 mm SDDs energy response - production of 3 buses ongoing;**
  - **ready to start as soon as possible: requested 300 pb^{-1} + 200 pb^{-1}**

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!

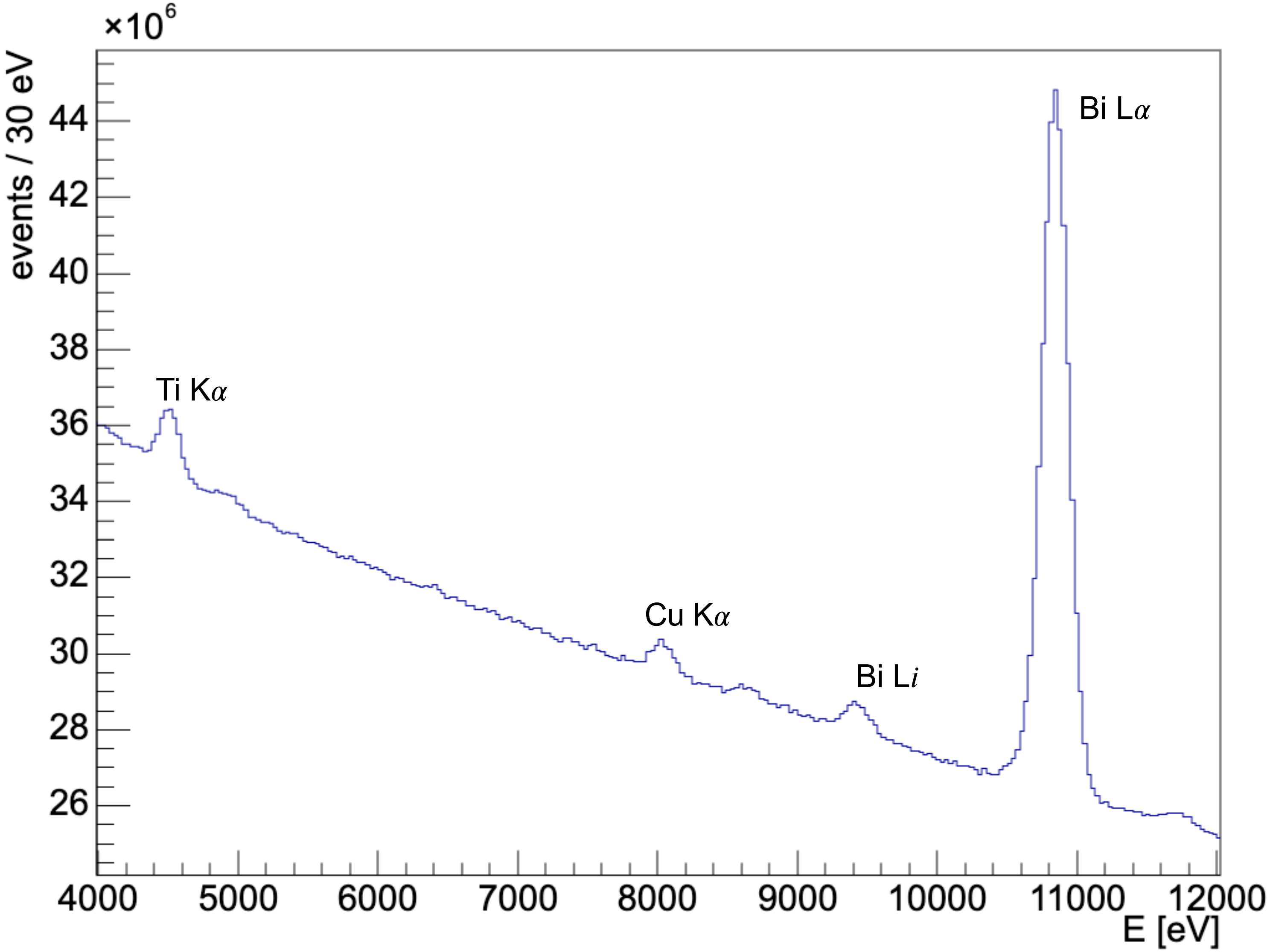
Special thanks to the accelerator, research and technical divisions, to the DAΦNE staff, in particular to Catia Milardi, the LNF former and present Directors, to the Gruppo 3-INFN and to all those who made this possible!



SPARE

Determination of the background (outside the signal window)

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



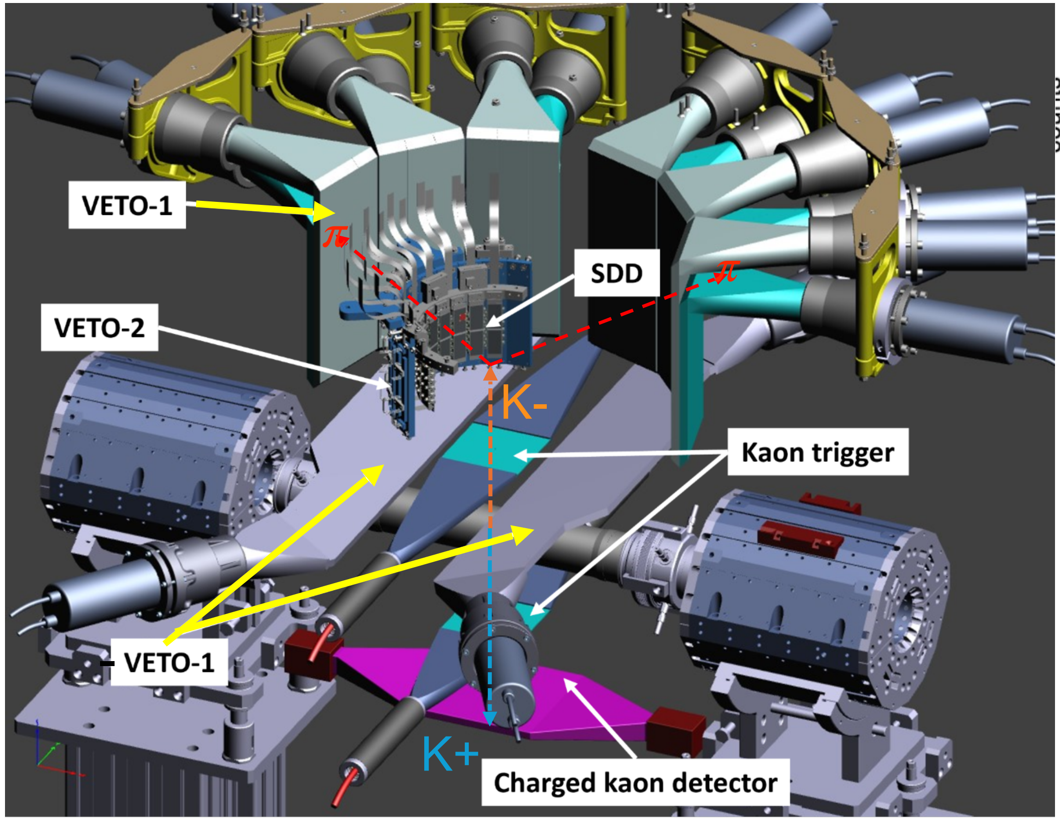
- Electromagnetic (asynchronous) background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect → Kaon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

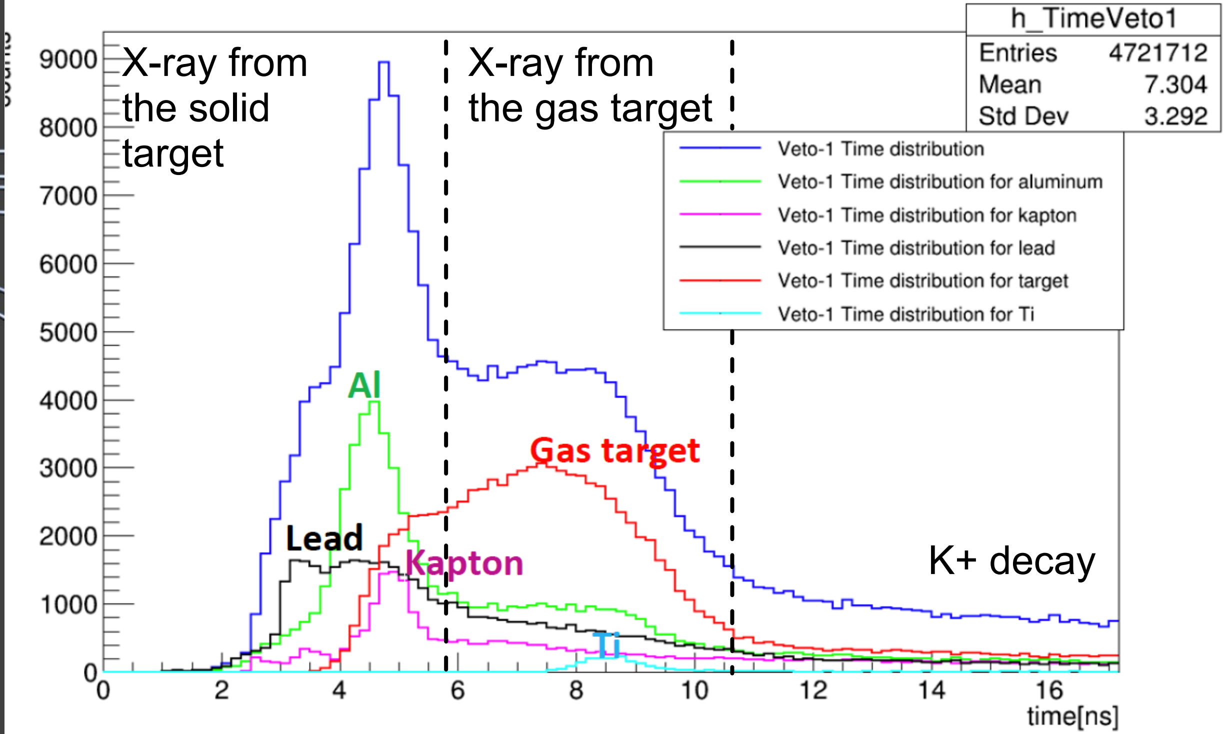
-Spectra contamination by Xray fluorescence or by X-rays produced in higher transitions of other kaonic atoms, formed in the setup materials → Veto systems

Optimisation of the Veto Systems cuts - Veto 1

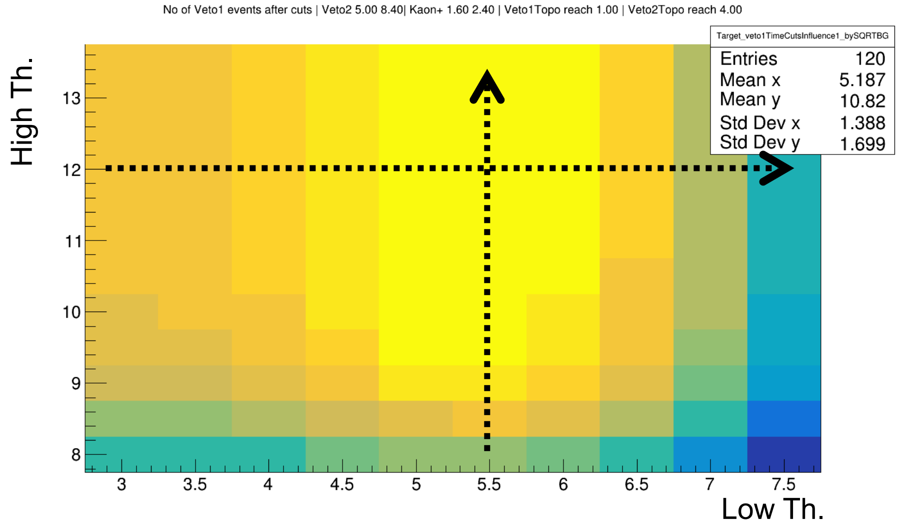
Veto-1 for hadronic (synchronous) background reduction: measure the arrival time of the charged particles emitted by the kaon-nucleus absorption to determine the origin of the signal: deuterium gas target or solid elements

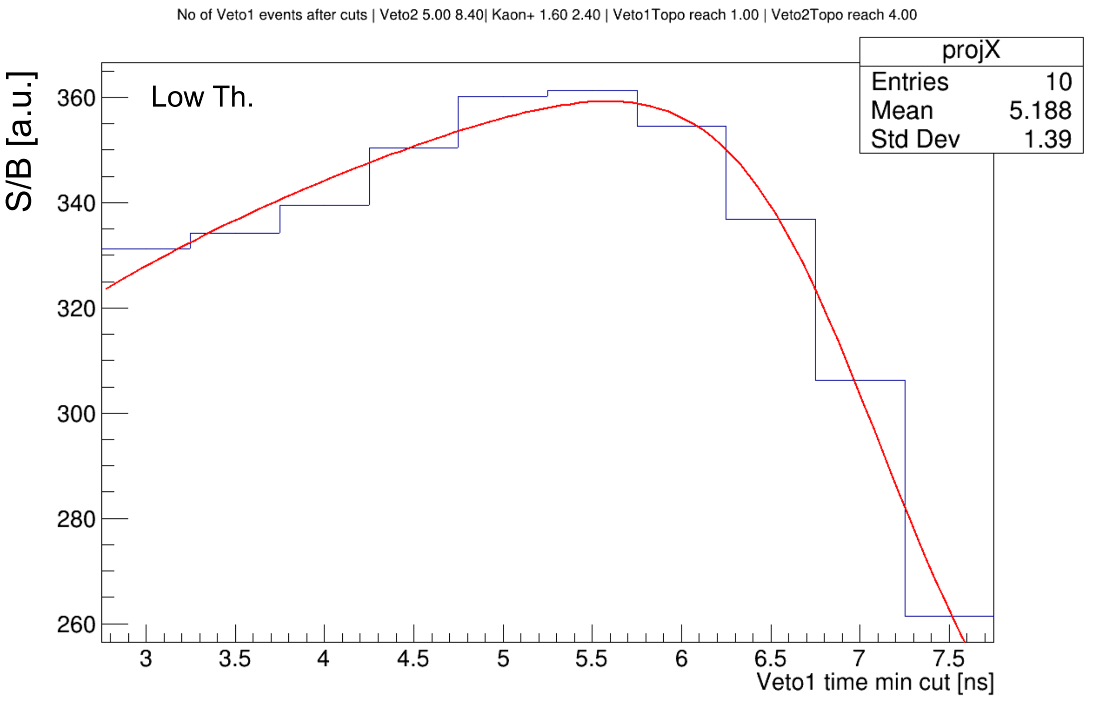


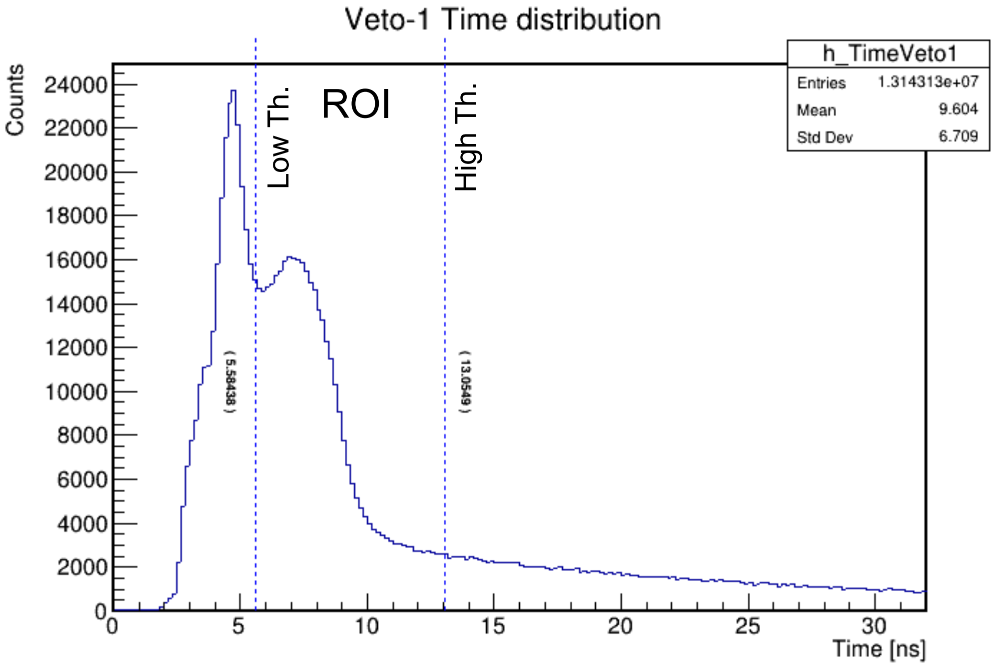
Veto-1: 14 plastic scintillators placed around and below the vacuum chamber

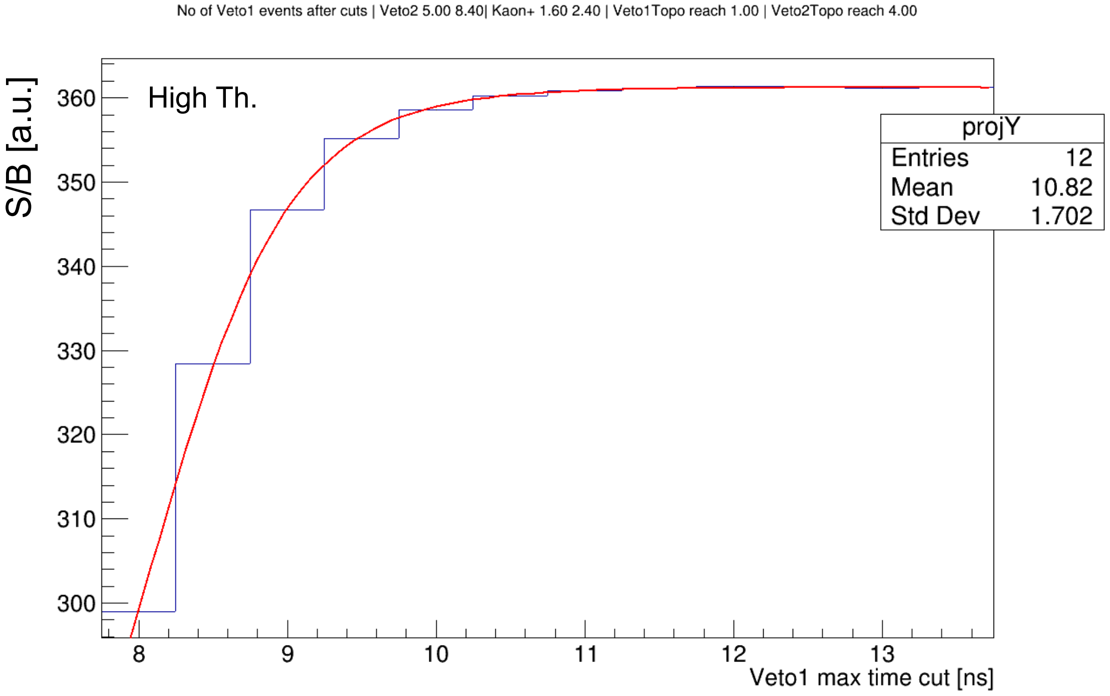


Veto1 time selection

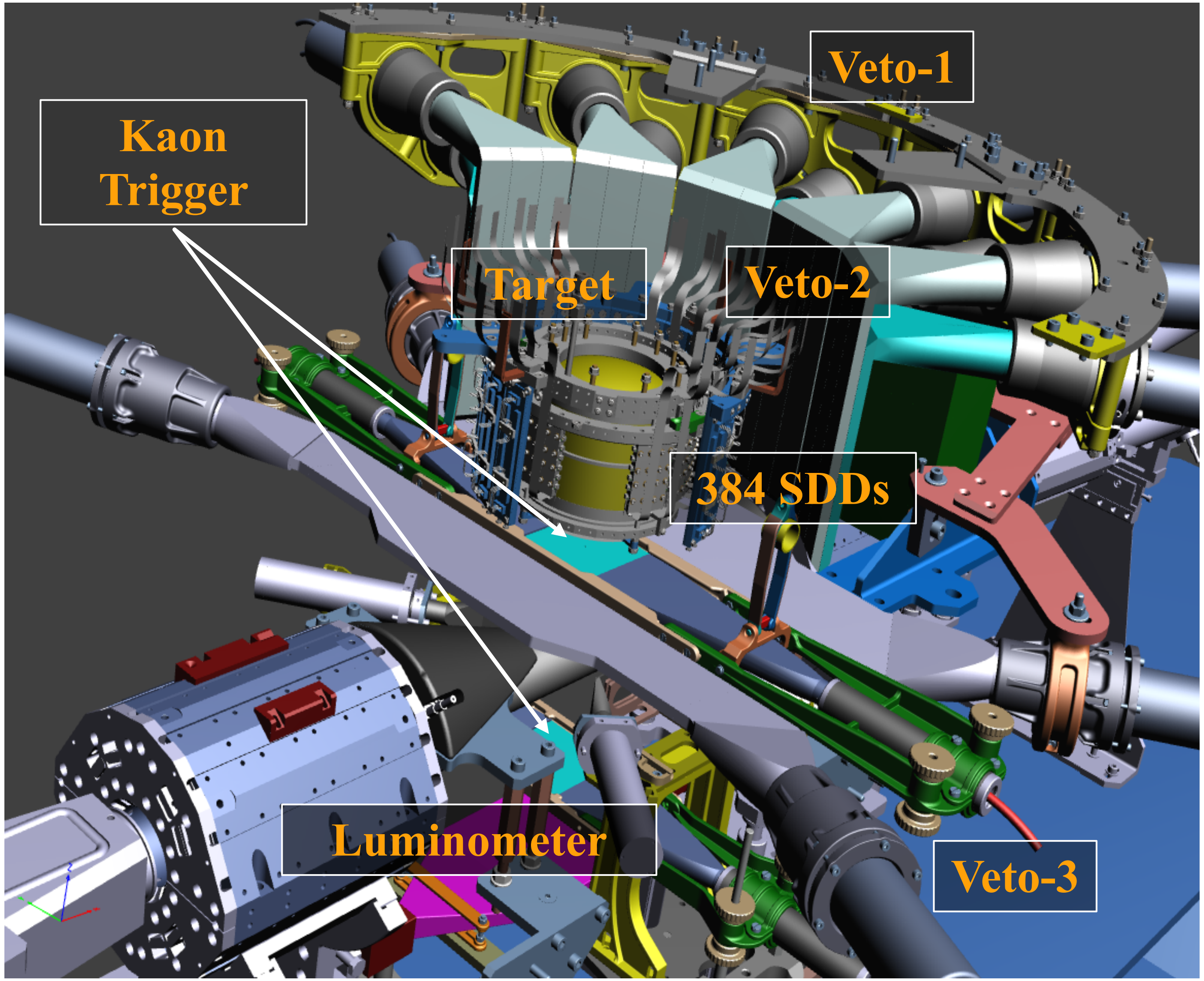


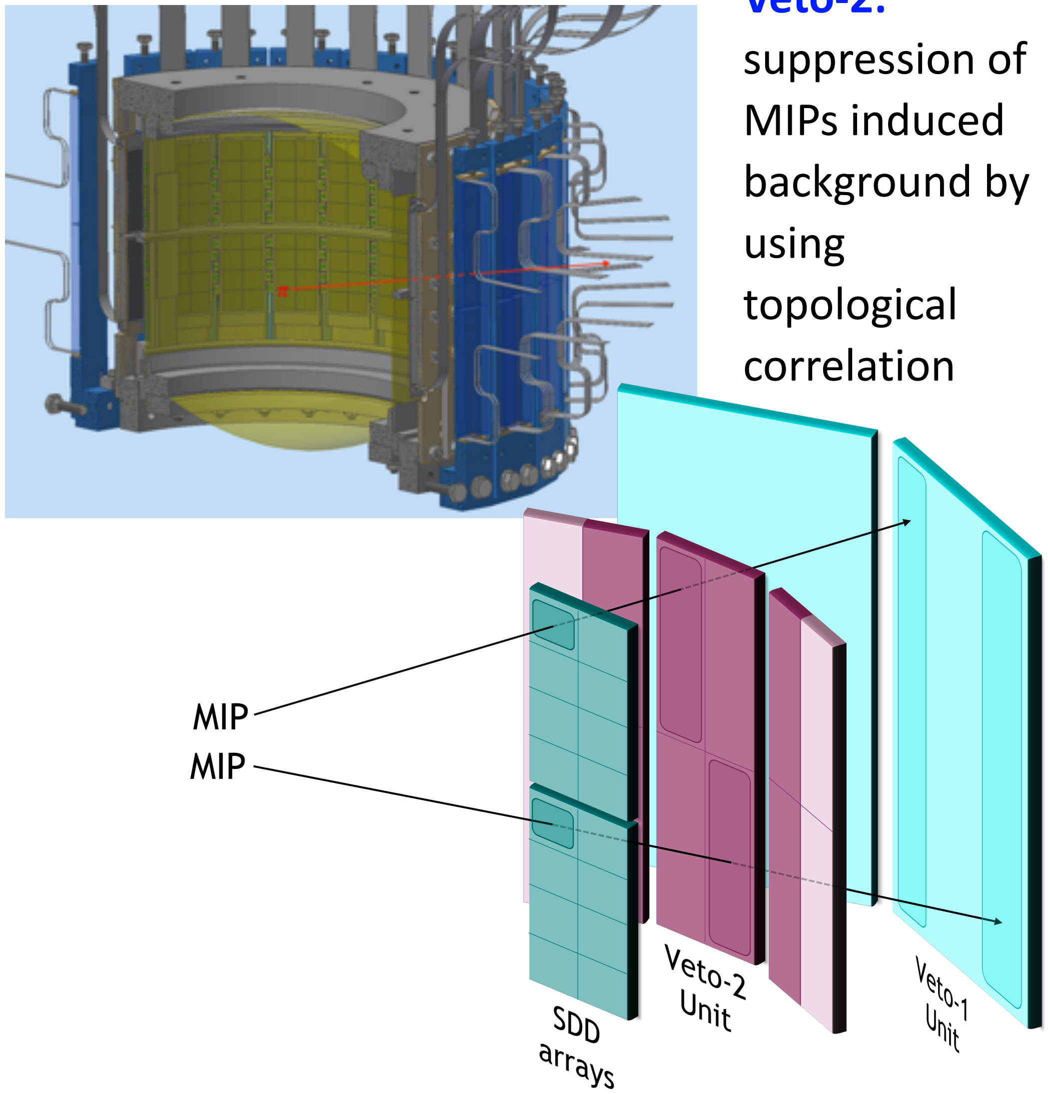






Optimisation of the Veto Systems cuts - Veto 2

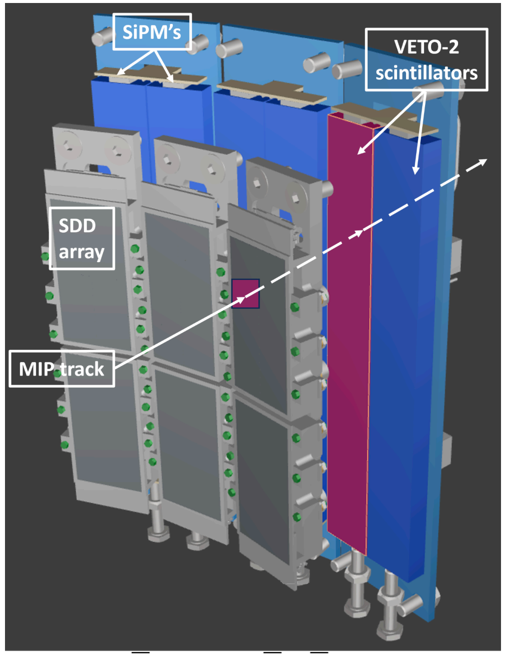


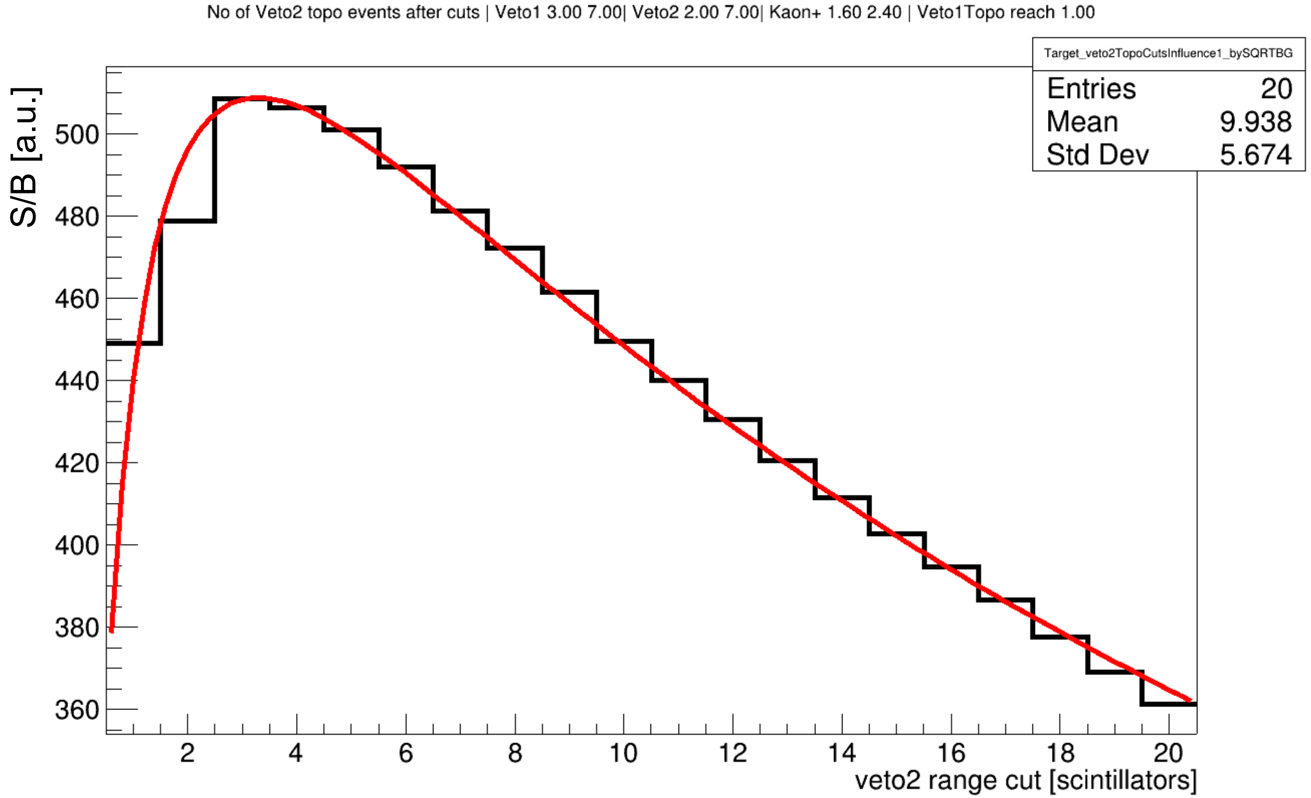


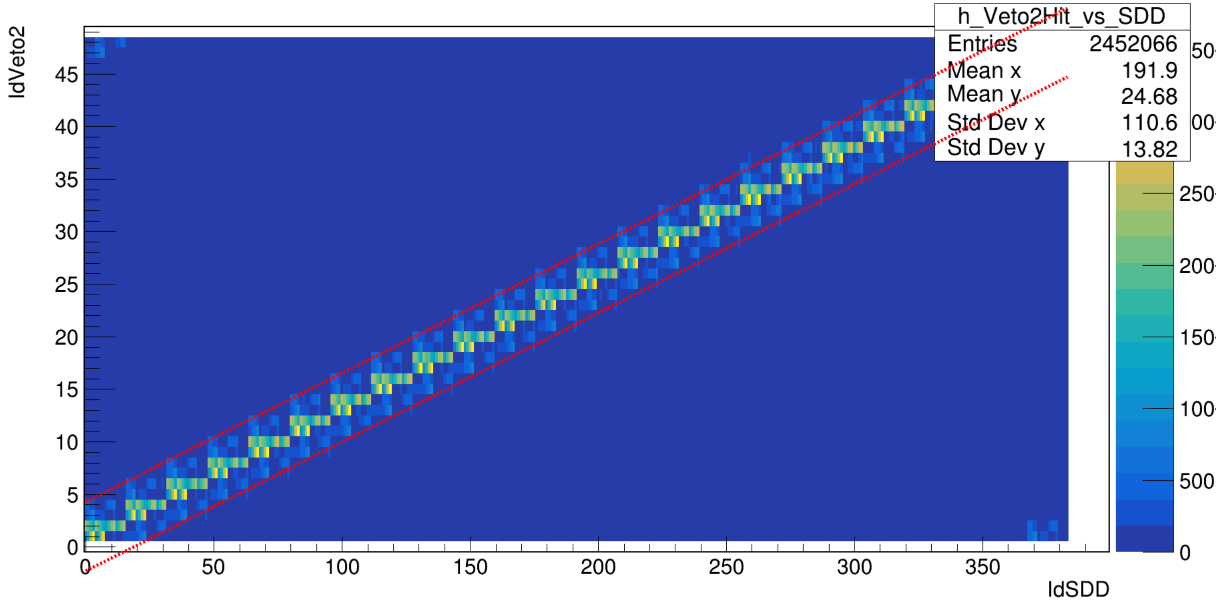
Veto-2:
suppression of MIPs induced background by using topological correlation

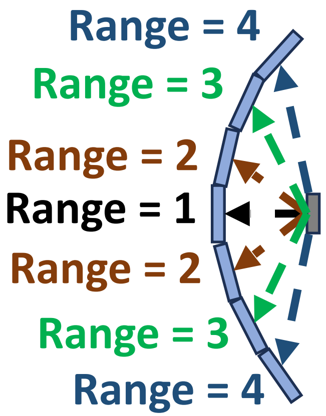
M. Tuchler et al., The SIDDHARTA-2 Veto-2 system for X-ray spectroscopy of kaonic atoms at DAΦNE, JINST, accepted

Veto2 topological cut

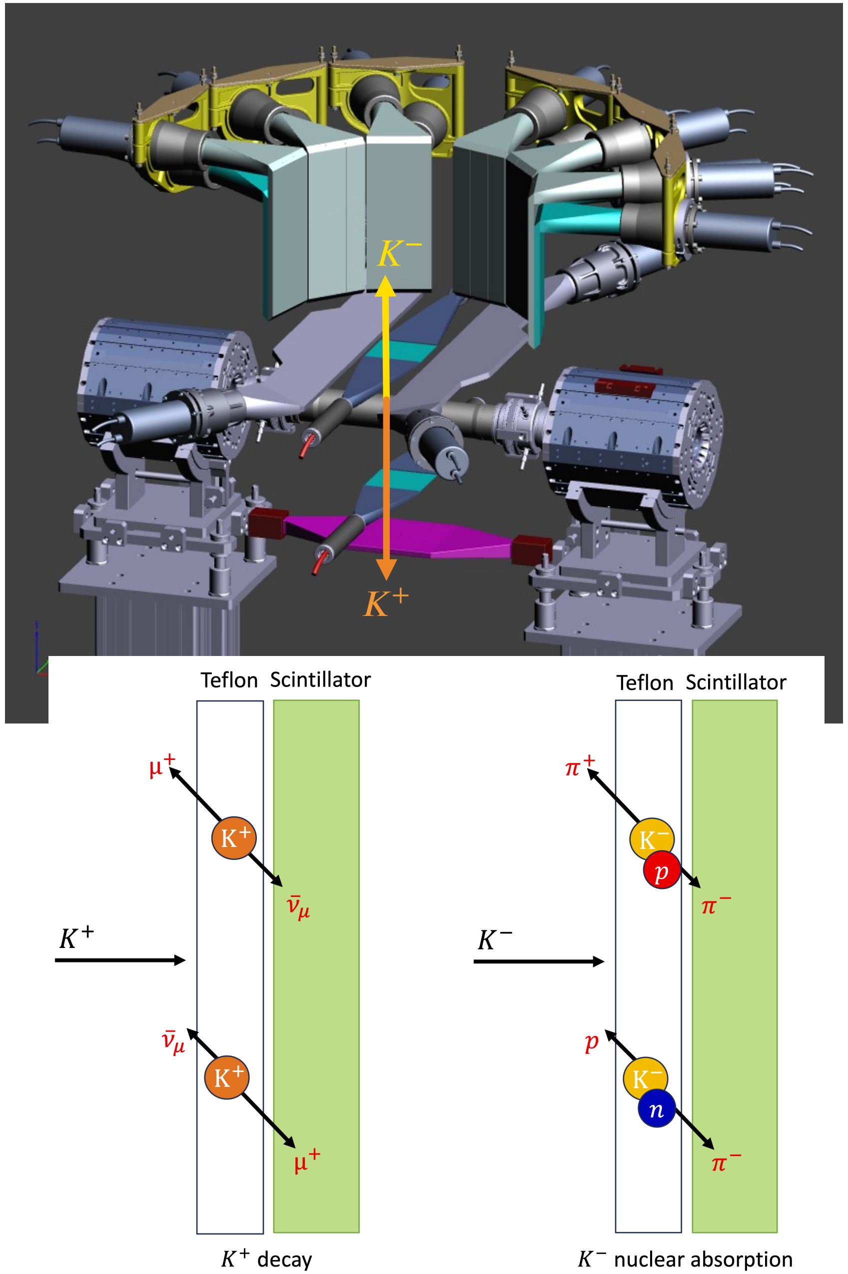




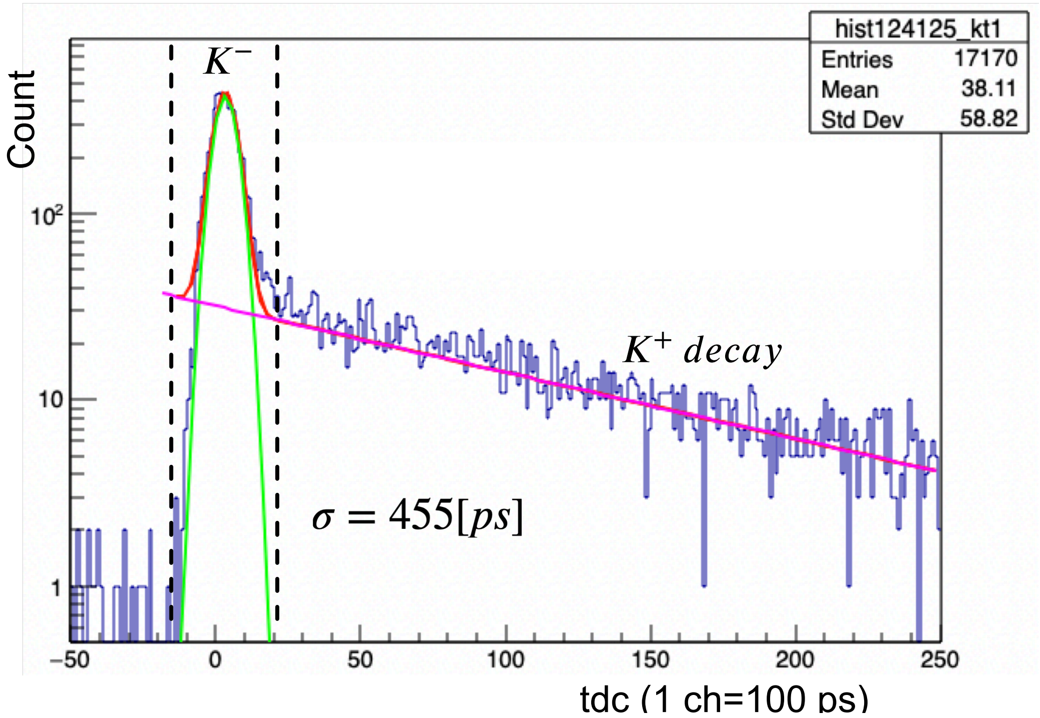




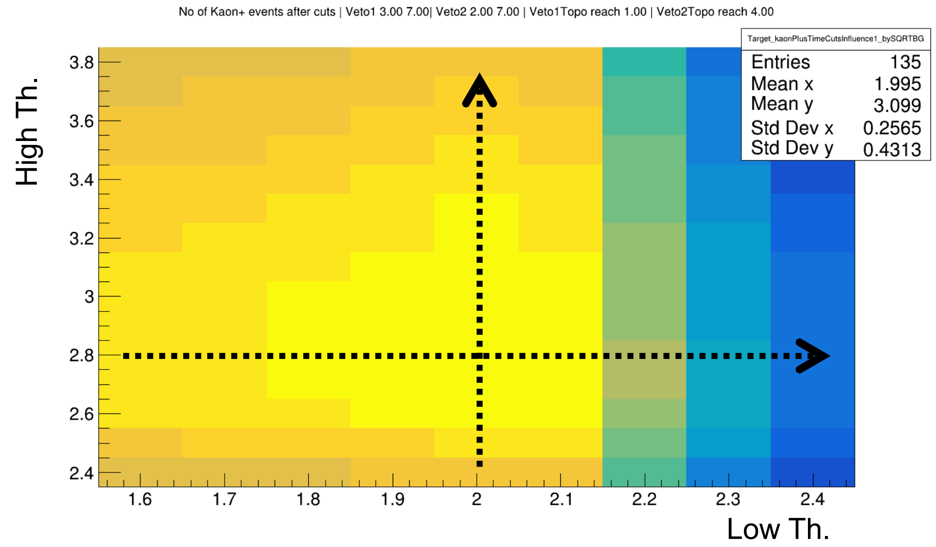
Optimisation of the Veto Systems cuts - Kaon charge detector

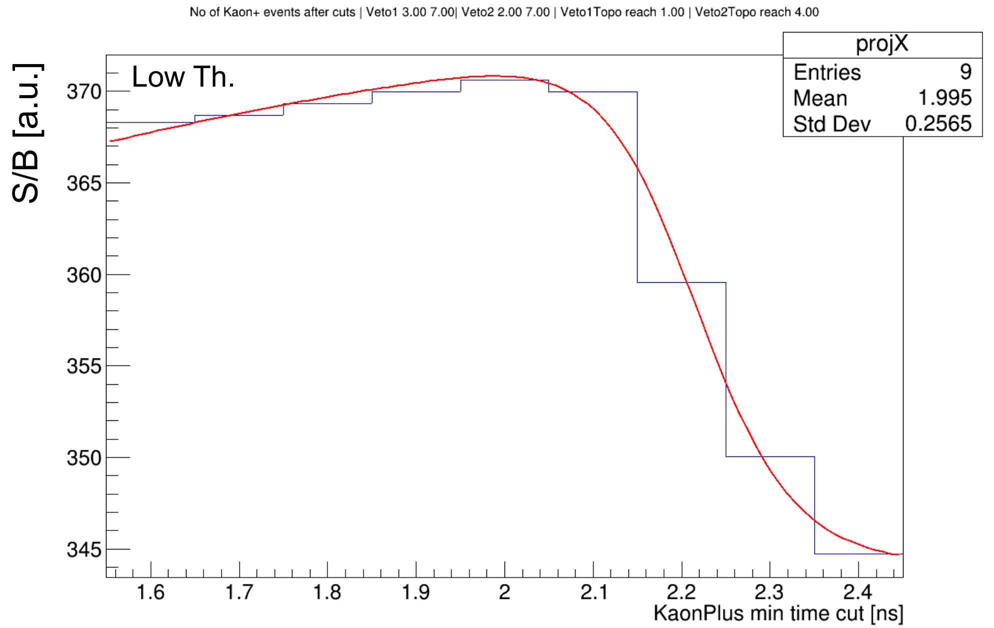


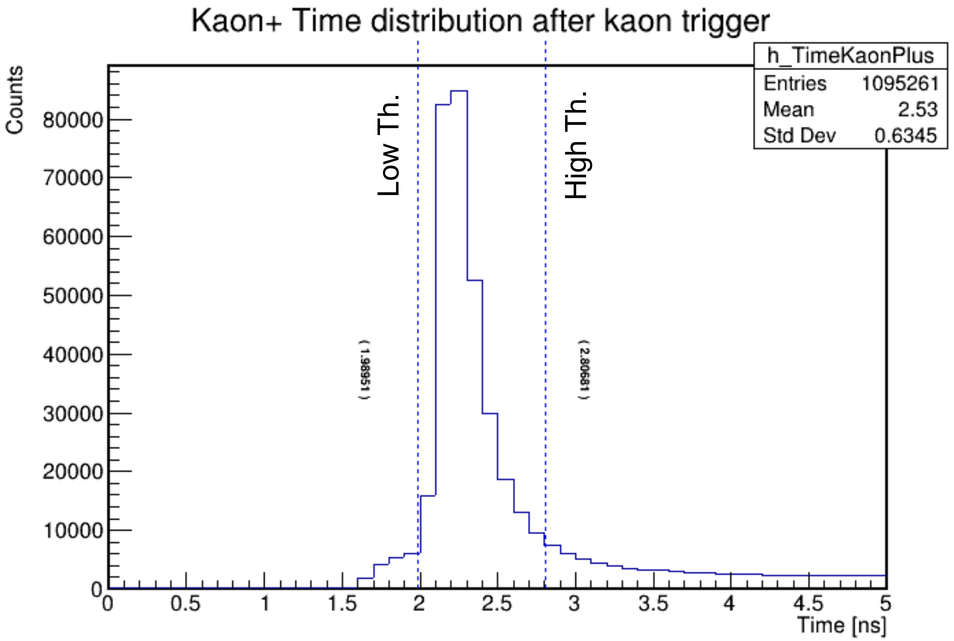
A Teflon layer to stop both $K^+$and K^- and a plastic scintillator to detect secondaries particles (pions and muons)

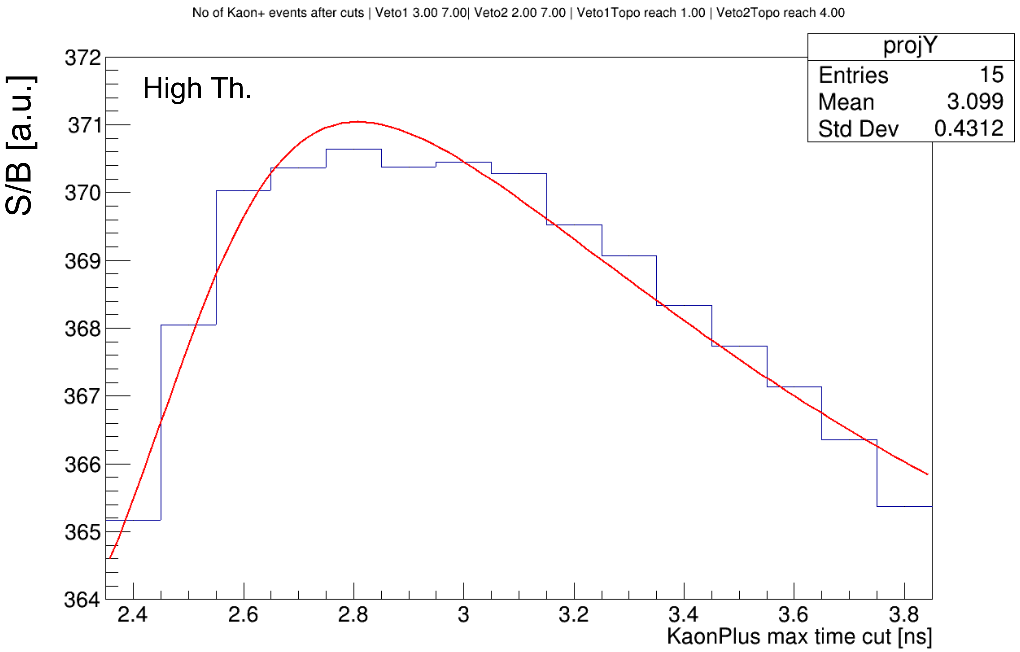


Kaon charge detector

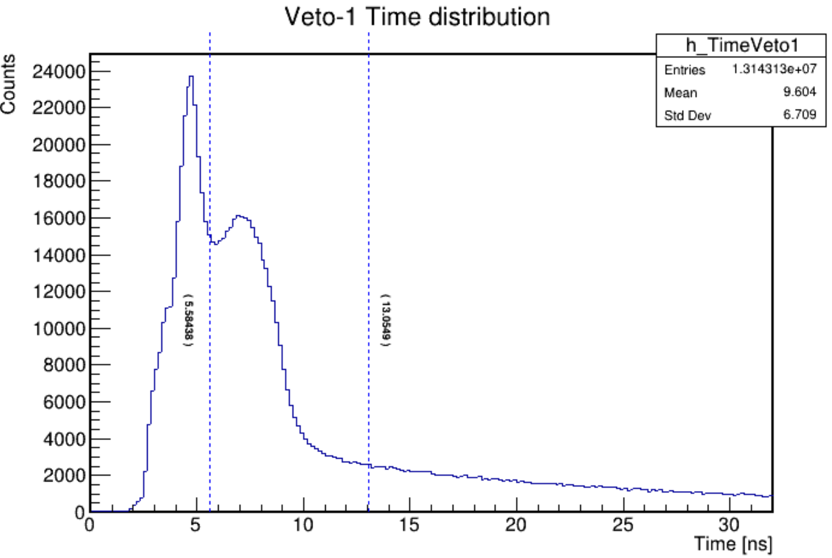




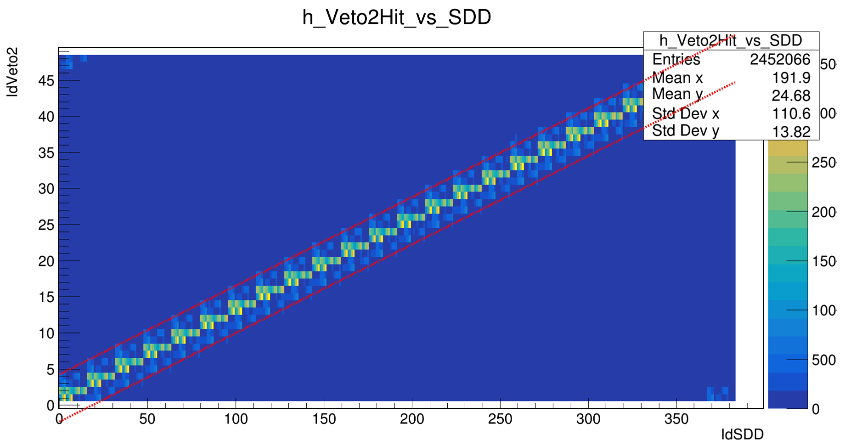


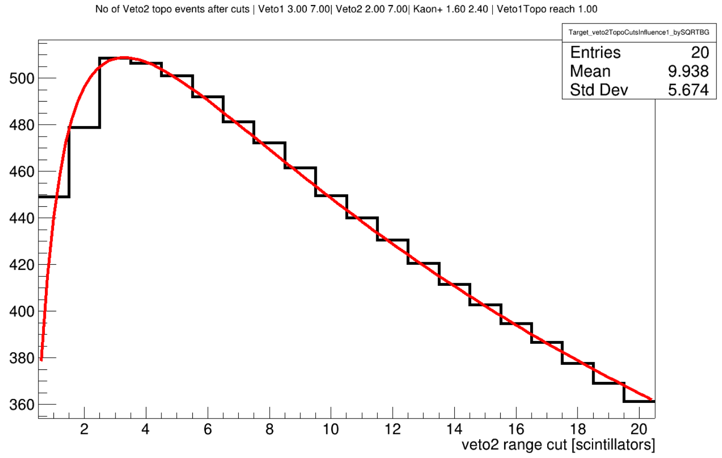


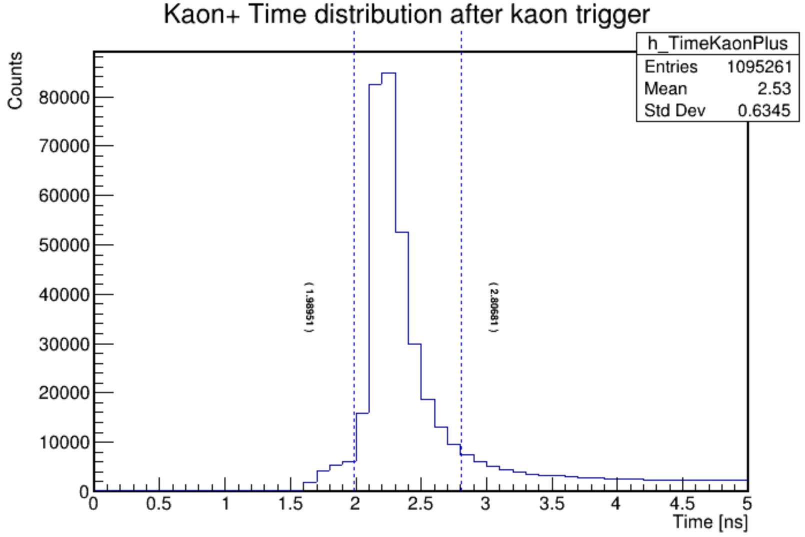
Summary - Veto systems optimised cuts



Veto1 time: 5.8 – 13.05 ns





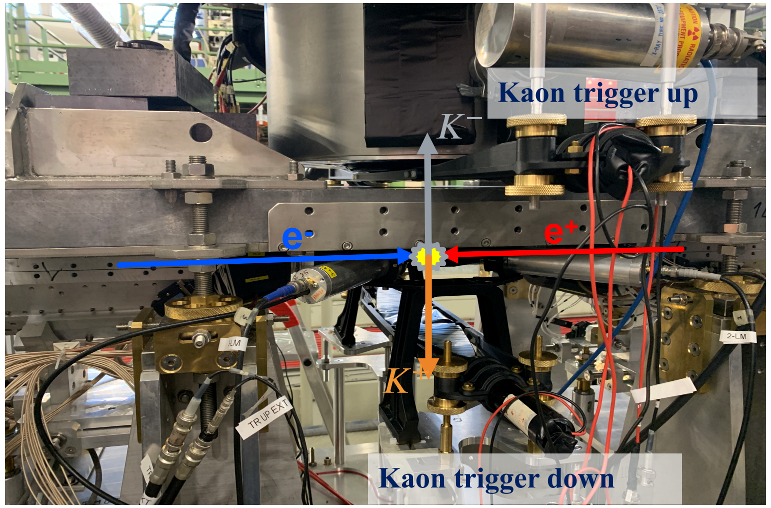


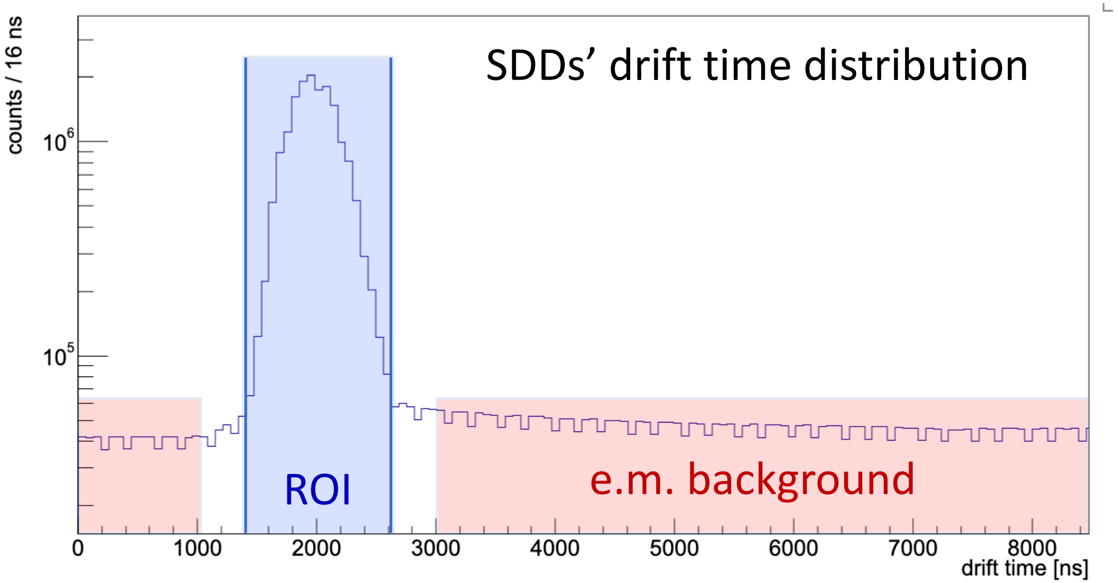
Kaon+ rejection: 2.0 - 2.8 ns

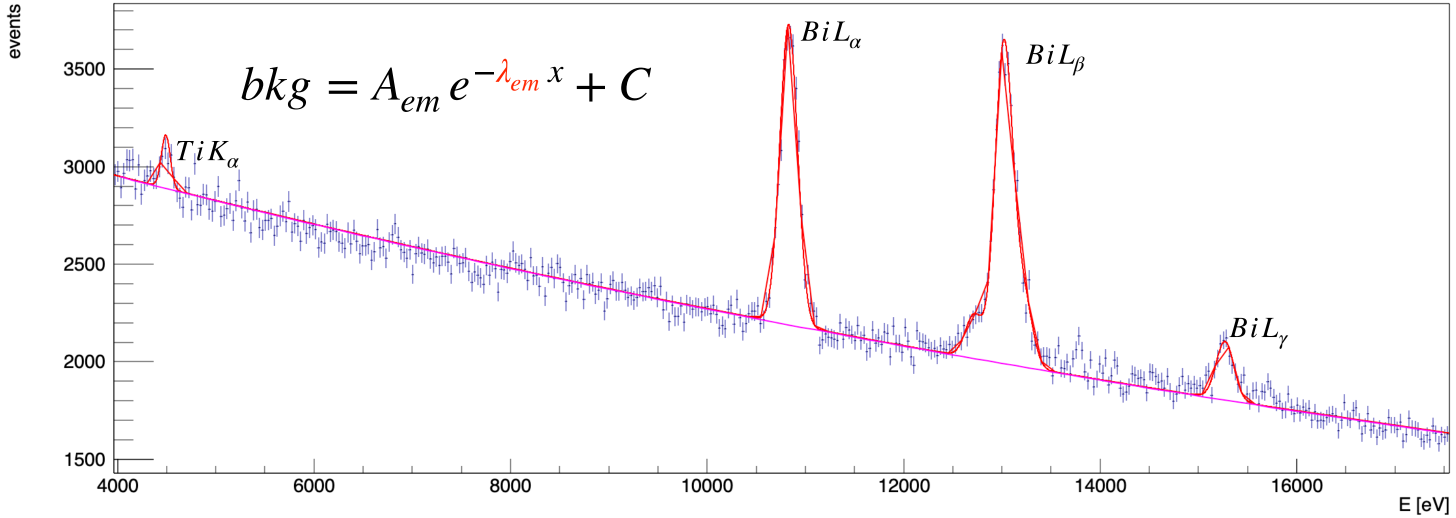
Veto2: 1 scintillator +/- 2 scintillator

Electromagnetic background (asynchronous wrt kaons)

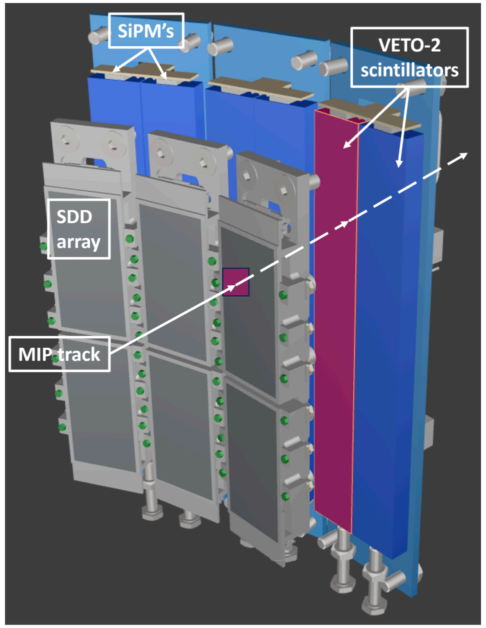
By exploiting the trigger and drift time of the SDDs, we can isolate a pure electromagnetic background spectrum by selecting events uncorrelated with kaon production.



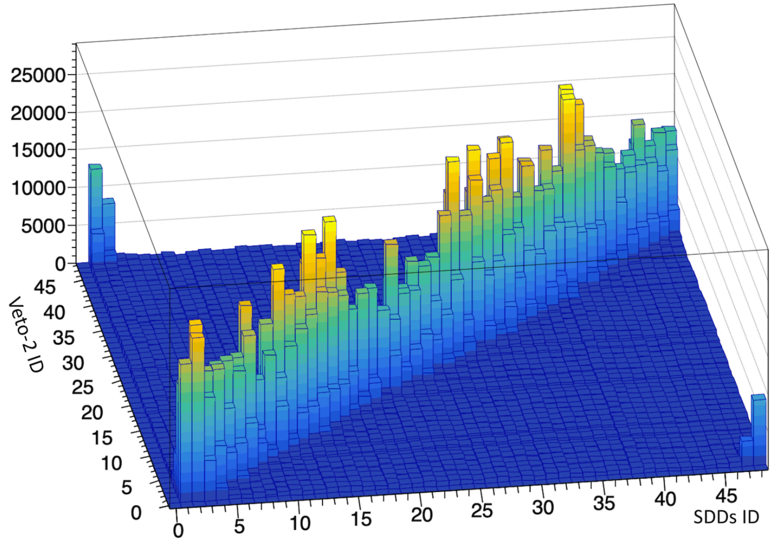


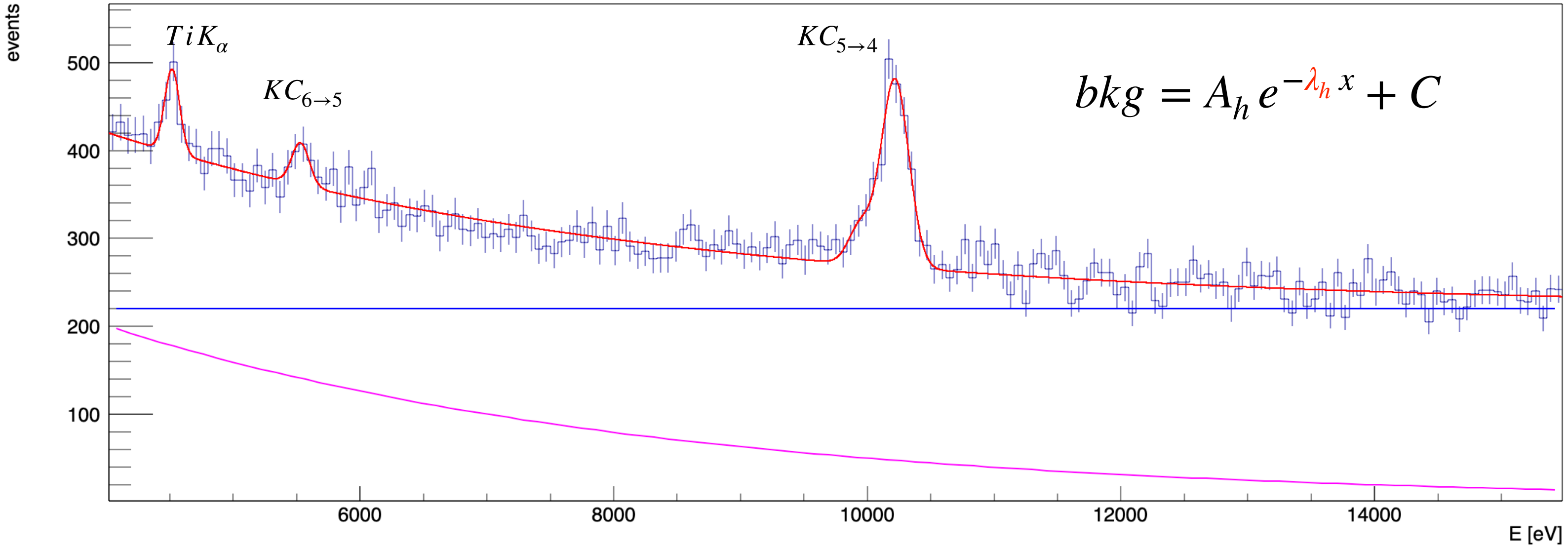


Hadronic background (synchronous wrt kaons)



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

Extended maximum-likelihood fit

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

The FF_0, $noise_0$, λ^0_{em}, and λ^0_{had} represent the expected values, while the σ_i terms represent the associated uncertainty

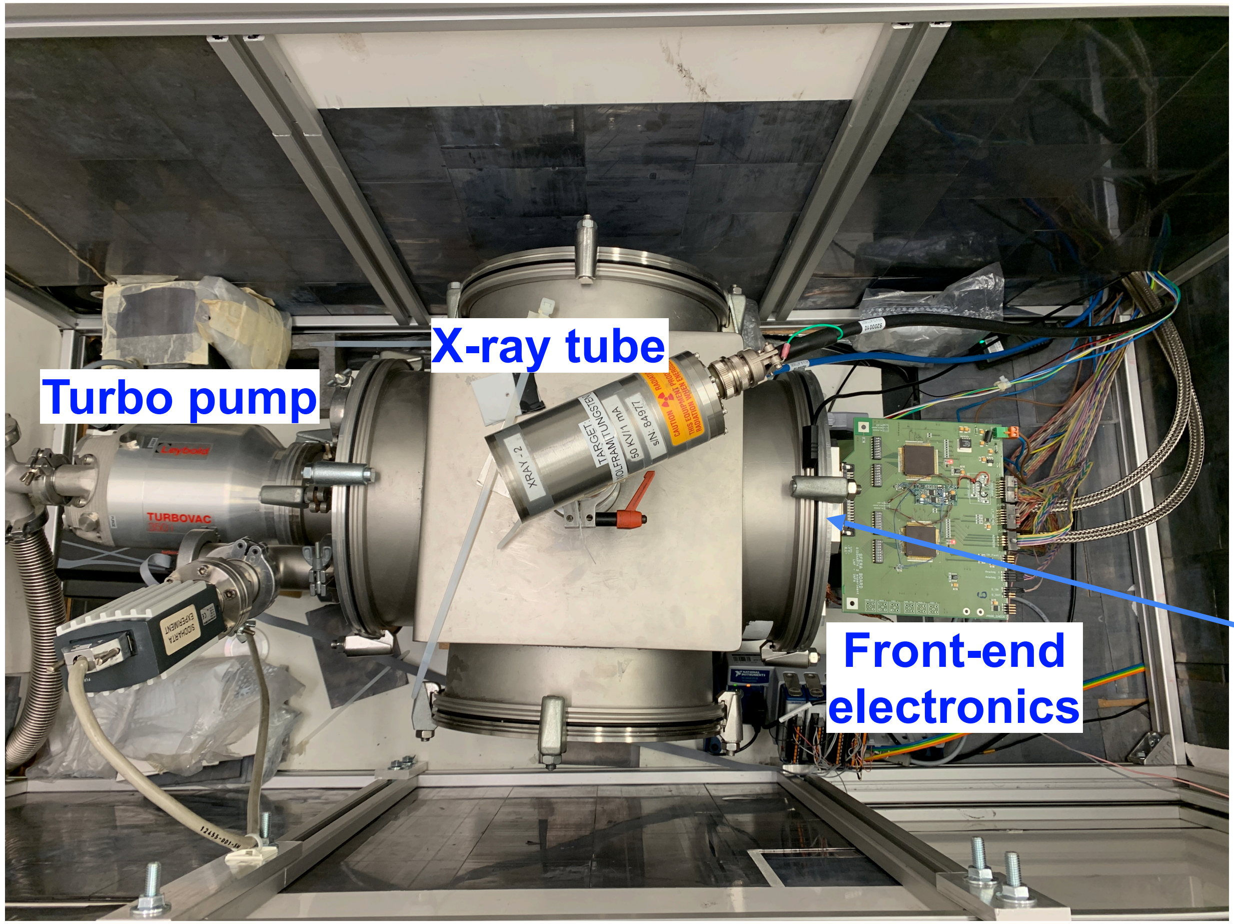
Symbol	Description	Estimated Uncertainty (σ)	References
$\delta\mu_{cal}$	Energy calibration uncertainty	$\sim$ 1-3 eV	Phys. Scr. 97 (11) 114002 Meas. Sci. Technol., 32 9 95501
$\delta\mu_{stab}$	Energy response stability over time	$\sim$0.5 eV	Phys. Scr. 97 (11) 114002 Meas. Sci. Technol. 32 9 95501
FF	Fano factor	$\sim$0.05	Meas. Sci. Technol. 33 (9) 95502 Meas. Sci. Technol. 32 9 95501
$noise$	Electronic noise	$\sim$20 eV	Meas. Sci. Technol. 33 (9) 95502 Meas. Sci. Technol. 32 9 95501
λ_{em}	Slope of electromagnetic background	$\sim 2.2 \cdot 10^{-5}$	Background modeling
λ_{had}	Slope of hadronic background	$\sim 3.9 \cdot 10^{-3}$	Background modeling

- **Fit Procedure and Systematic error:** two fits were performed
  1. fit with all nuisance terms active
  2. fit without nuisance terms

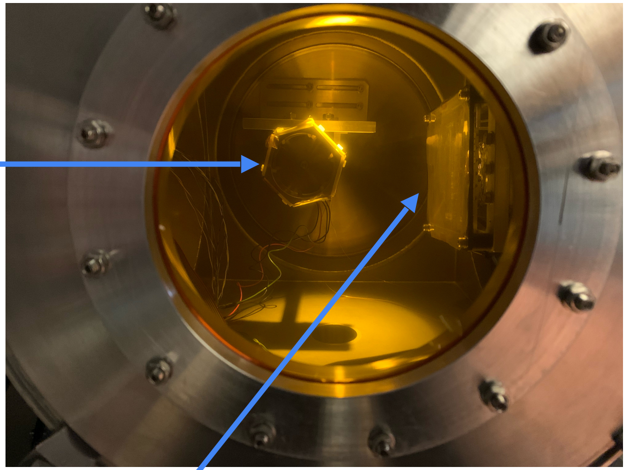
- The parameters' total uncertainty (σ_{tot}) comes from fit(1), while statistical uncertainty (σ_{stat}) from fit (2).
- The systematic uncertainties are then estimated by the difference: $\sigma^2_{syst} = \sigma^2_{tot} - \sigma^2_{stat}$ for each parameter.

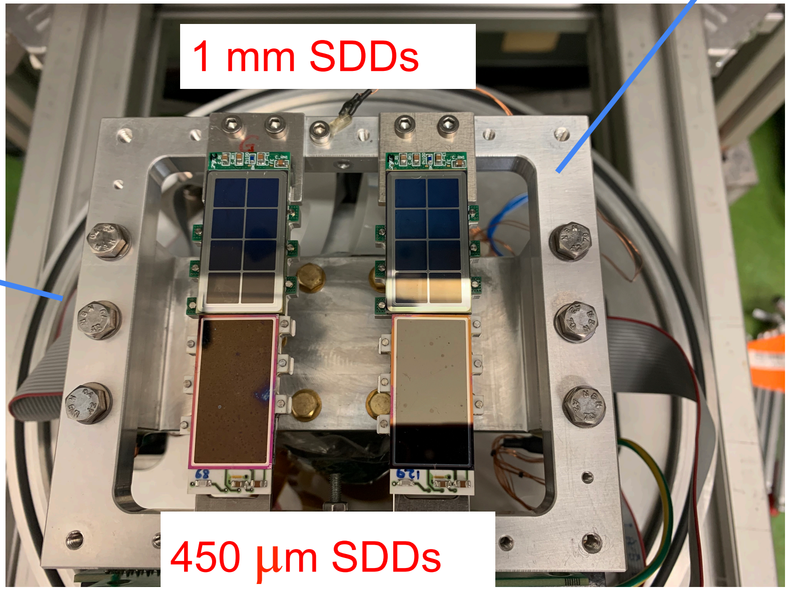
1 mm thick Silicon Drift Detectors: Optimisation of the Energy response

A dedicated experimental apparatus has been set up to optimise the energy resolution of the 1mm thick SDDs as function of the polarisation voltage



Multi-element rotating target for X-ray spectroscopy





Characterisation of 1 mm thick Silicon Drift Detectors at BTF-LNF

Spectroscopic measurement with electron and X-ray

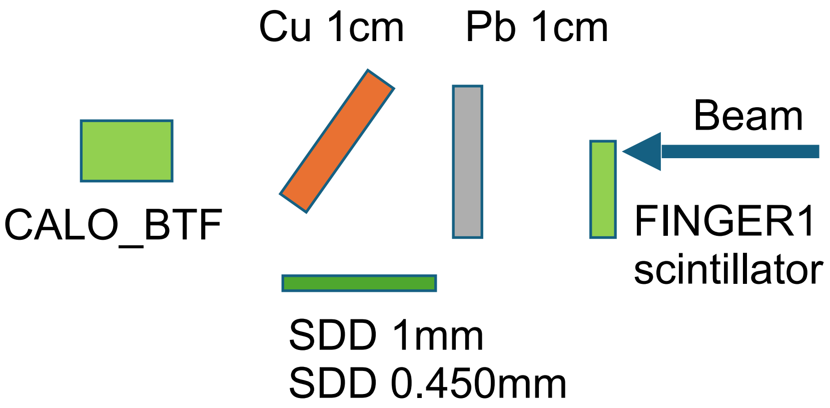
❖ Dedicated beam time in June and October 2024 at BTF

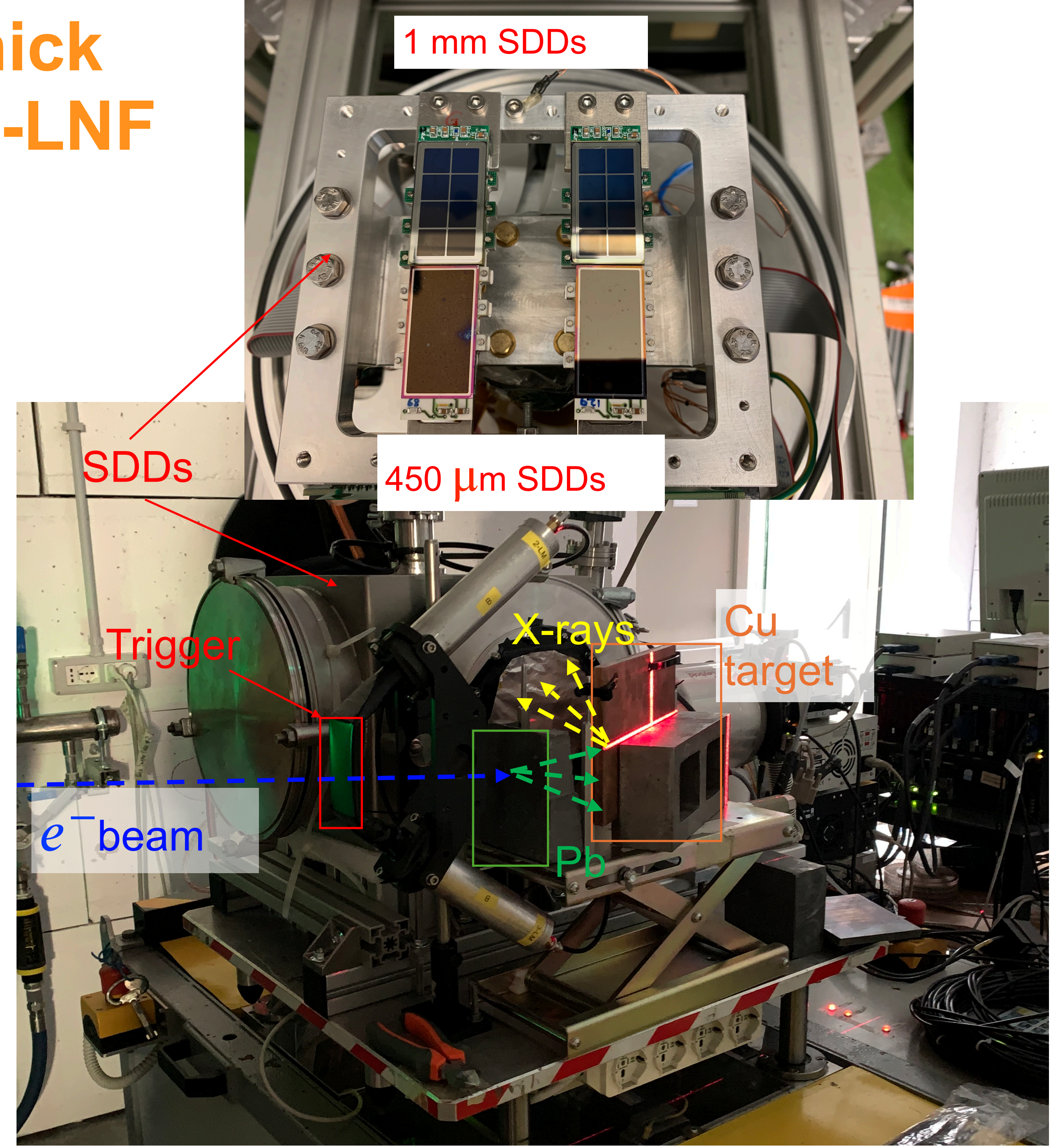
❖ Irradiation with e- beam and X-ray sources

- Characterization of the 1 mm SDDs **time response** as function of the temperature
- Characterization of the **energy response: new energy range 50 keV**
- Study of the **energy response in a high background environment** (ionizing particles and radiation)

Data analysis ongoing

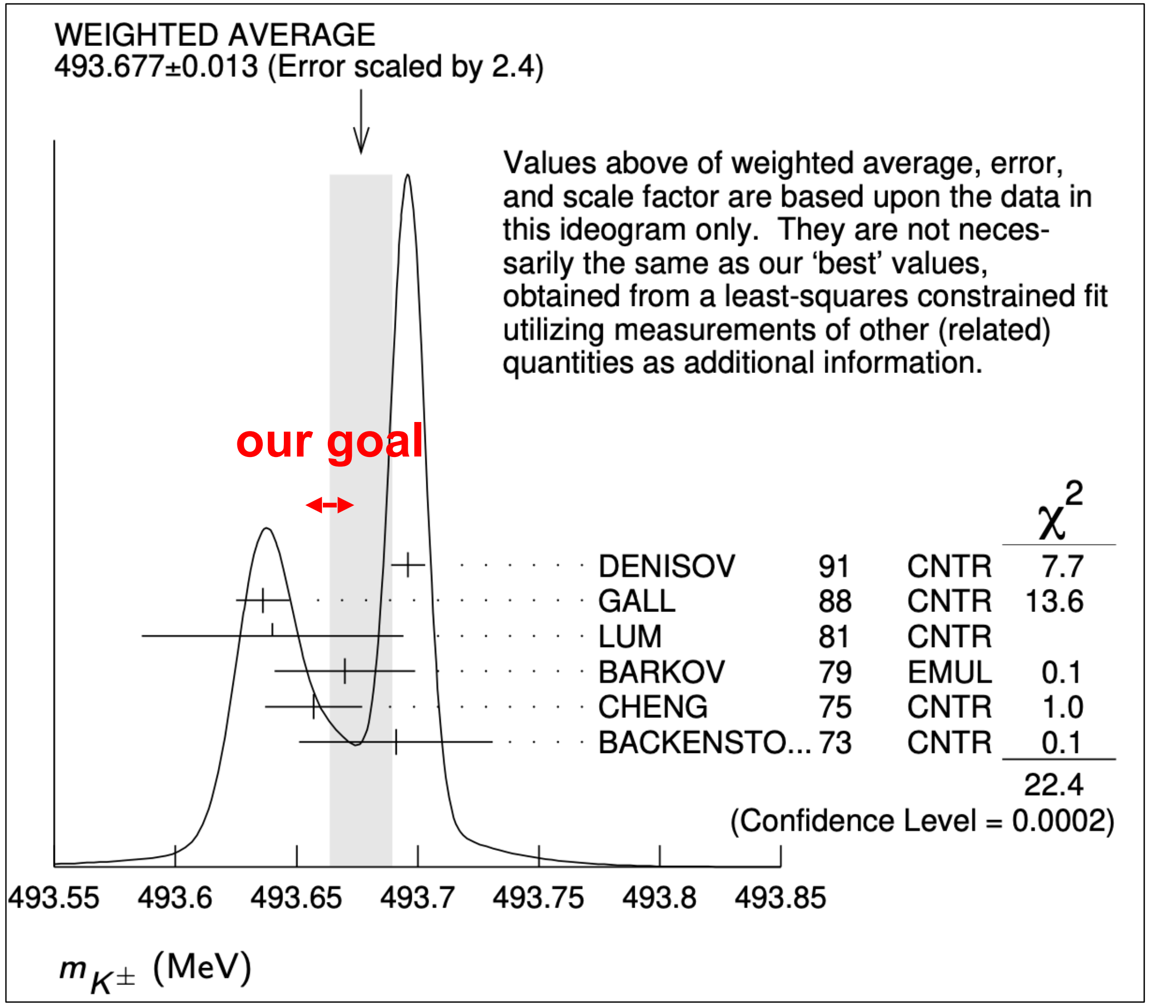
Layout of the Setup





1.1 - Kaon mass by Kaonic neon measurement
- Use the SIDDHARTA2 setup
- 300 pb^{-1} of integrated luminosity

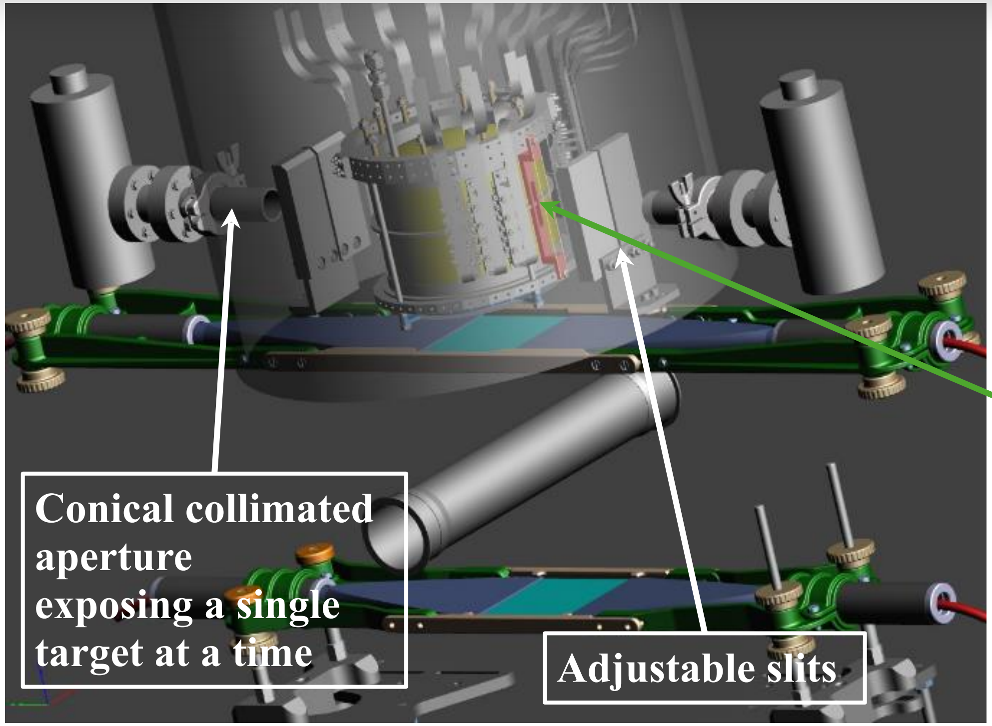
The charged kaon mass puzzle

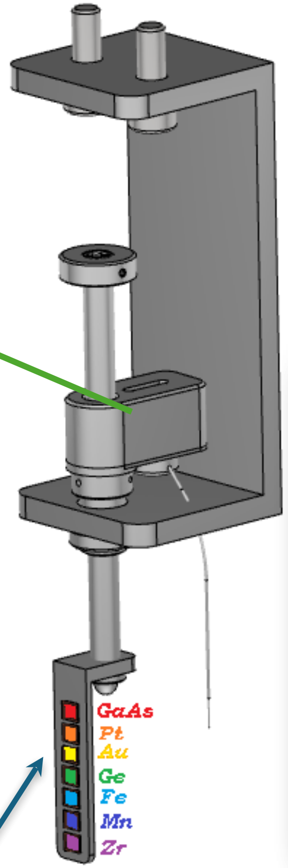


- The first measurement we plan doing is the **kaonic neon** high-n levels transition <u>with precisions below 1 eV</u>, **to extract the charged kaon mass with a precision of about 5 keV**.
- By using a **gaseous target**, we can resolve the ambiguity in the charged kaon mass de-termination, providing **a new precise value through the measurement of kaonic neon high-n transitions**. Moreover, the measurement also provides **a precision test of QED in atomic systems with strangeness** (BSQED).
- M. Hori ….

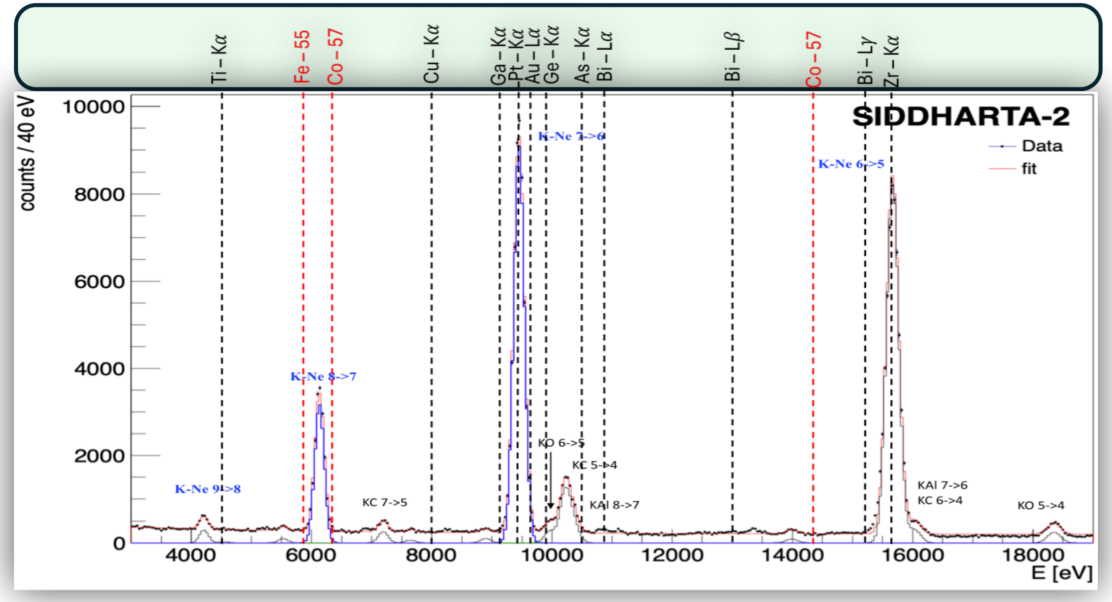
1.1 - Kaon mass by Kaonic neon measurement
- Goal: systematic uncertainty <0.2 eV
- new calibration system financed and under construction

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





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



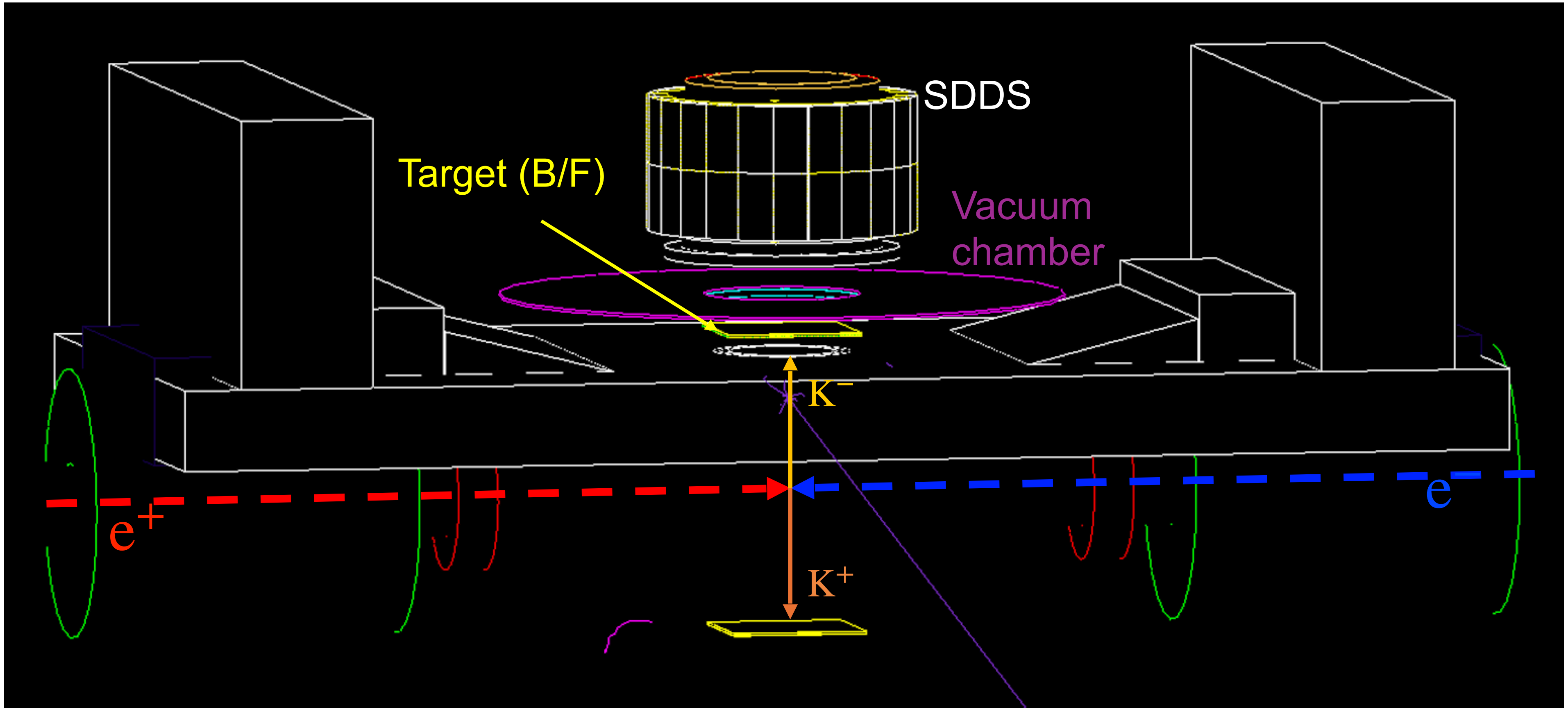
External Laser system
for alignment Fluke PLS 6G RBP SYS

Movable targets arm inserted behind the collimator.
Selected materials: GaAs, Pt, Au, Ge, Fe, Mn, Zr

Post K-d calibration run

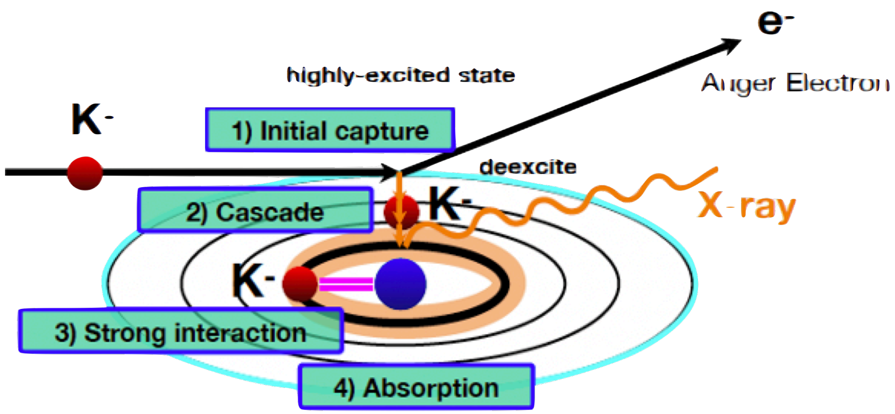
The **final calibration was performed with two solid targets Boron and Fluorine (Teflon):**

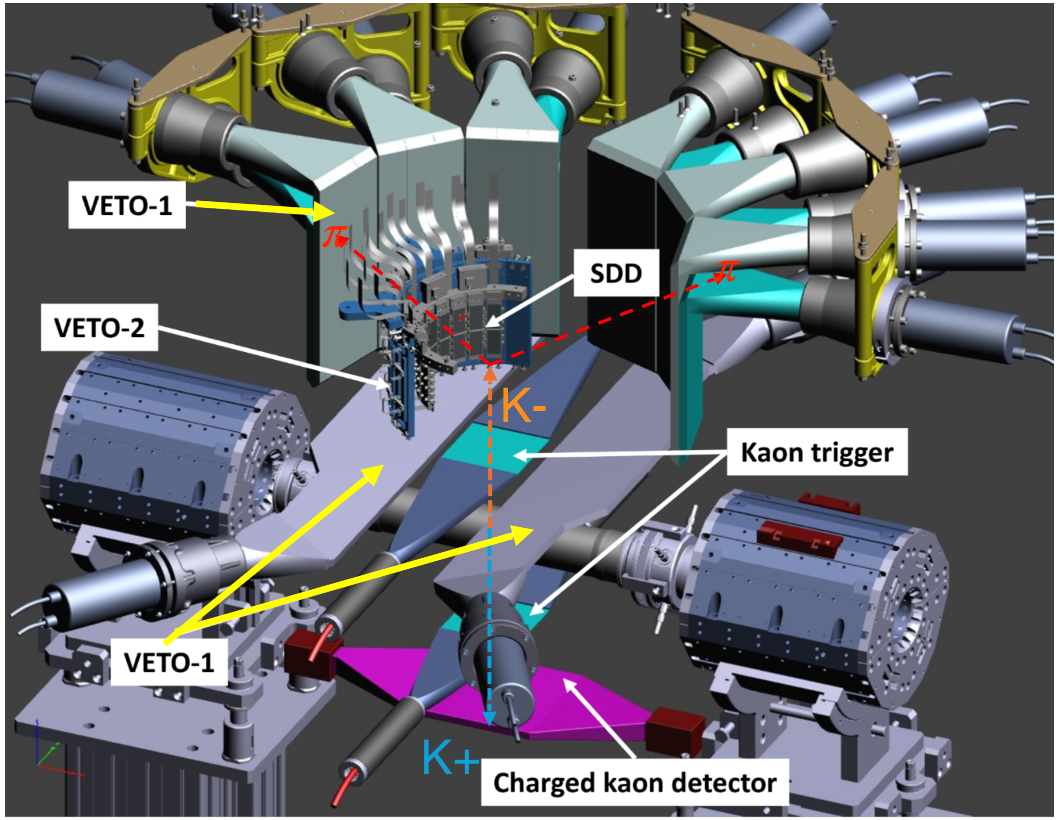
Combined with the calibration performed with the X-ray tubes this data will be used to check the performance of detectors and veto systems at the end of the data taking and to investigate the performance of the apparatus in the view of the EXKALIBUR first module



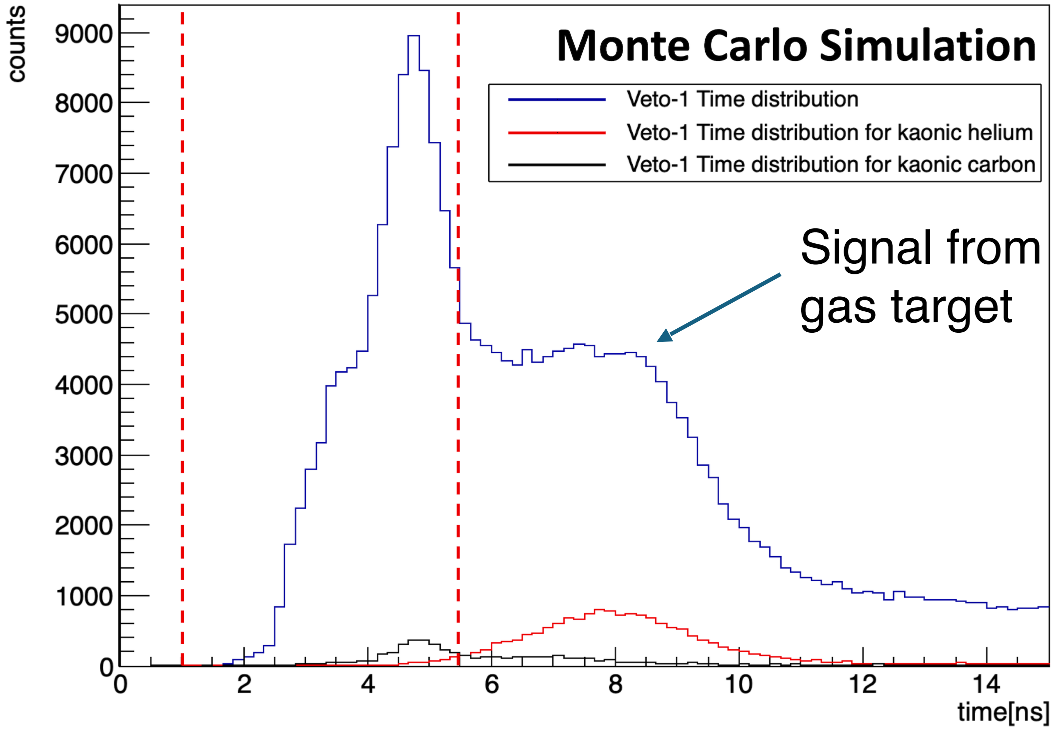
Kaonic Deuterium: veto-1 system analysis

Veto-1 for synchronous background reduction:
measure the arrival time of the charged particles emitted by the kaon-nucleus absorption

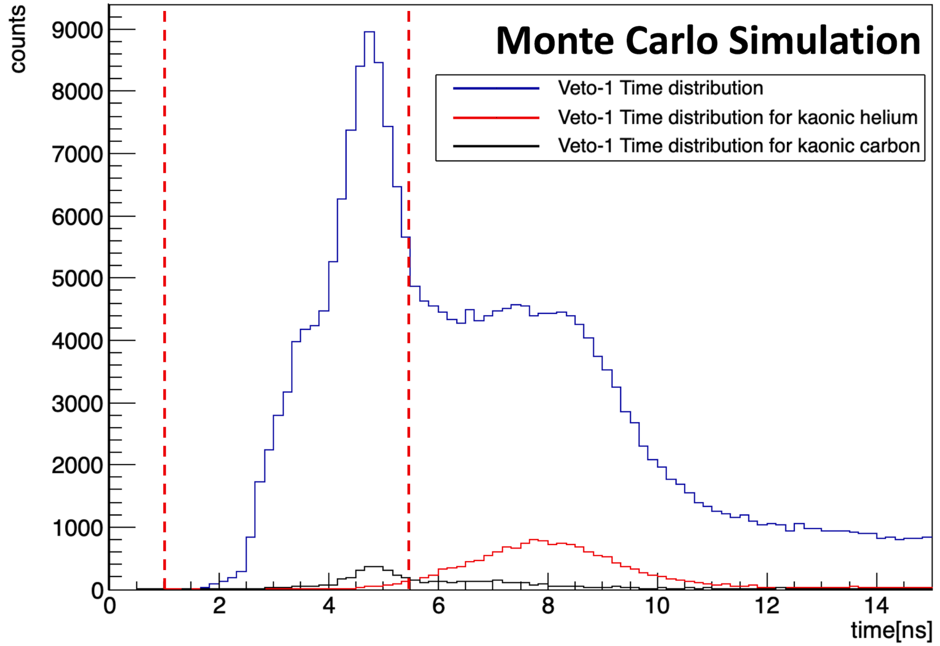


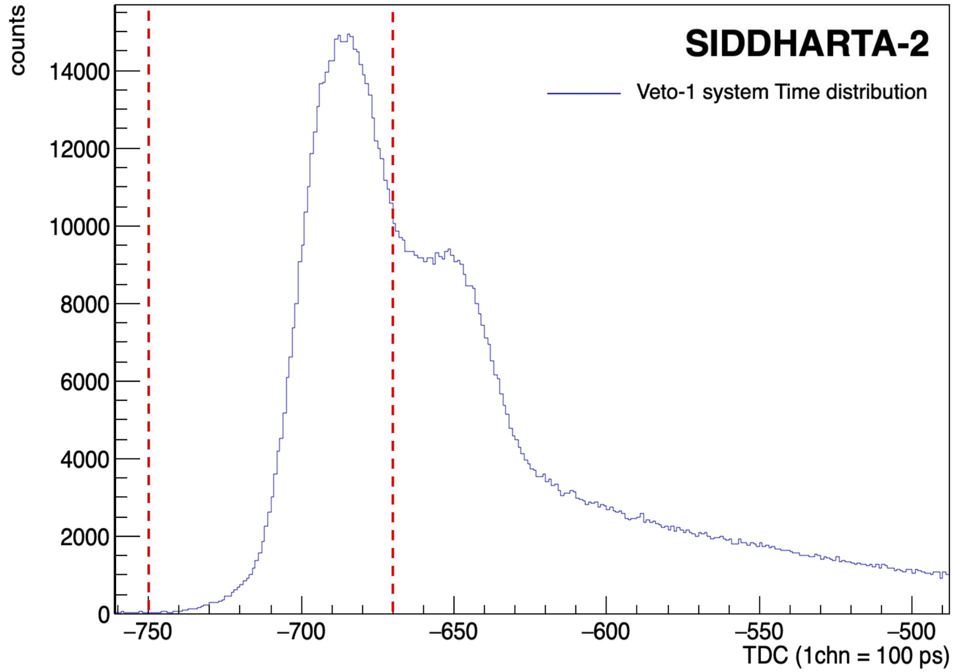


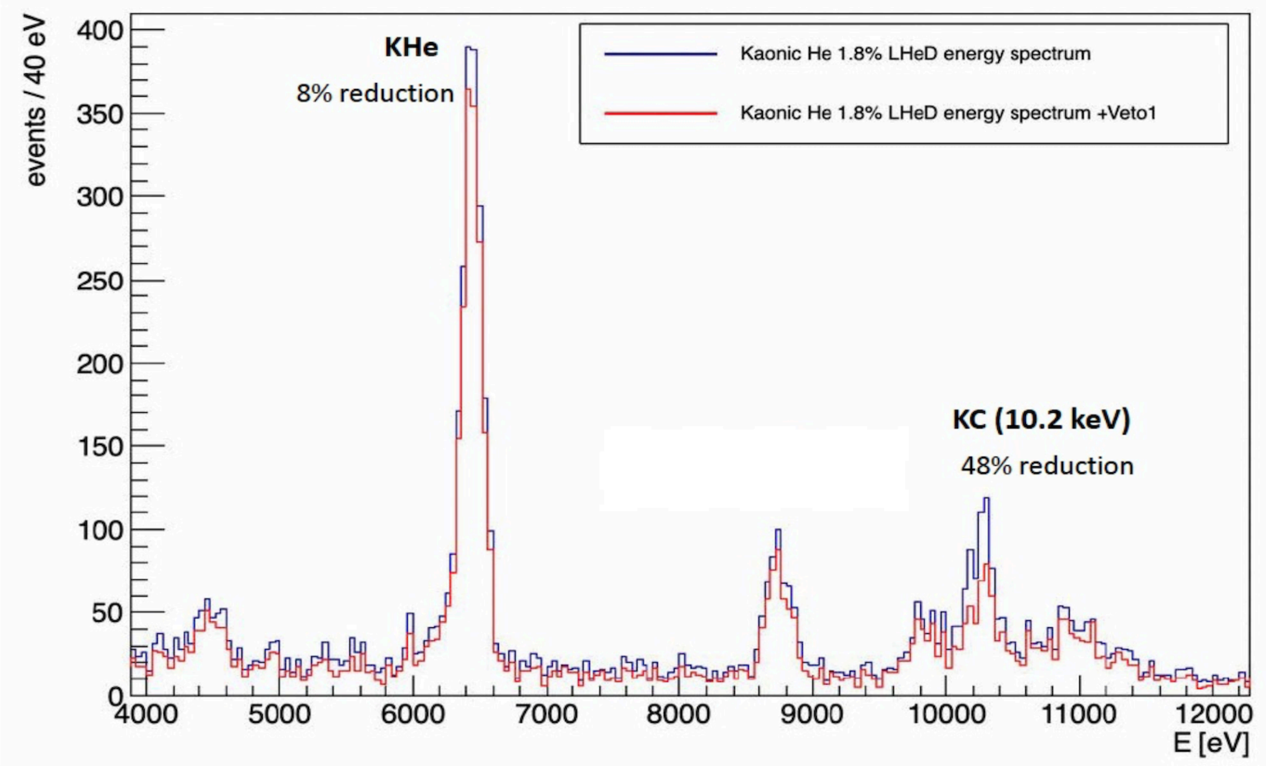
Veto-1: 14 plastic scintillators placed around and below the vacuum chamber



Veto-1 system optimisation with kaonic He





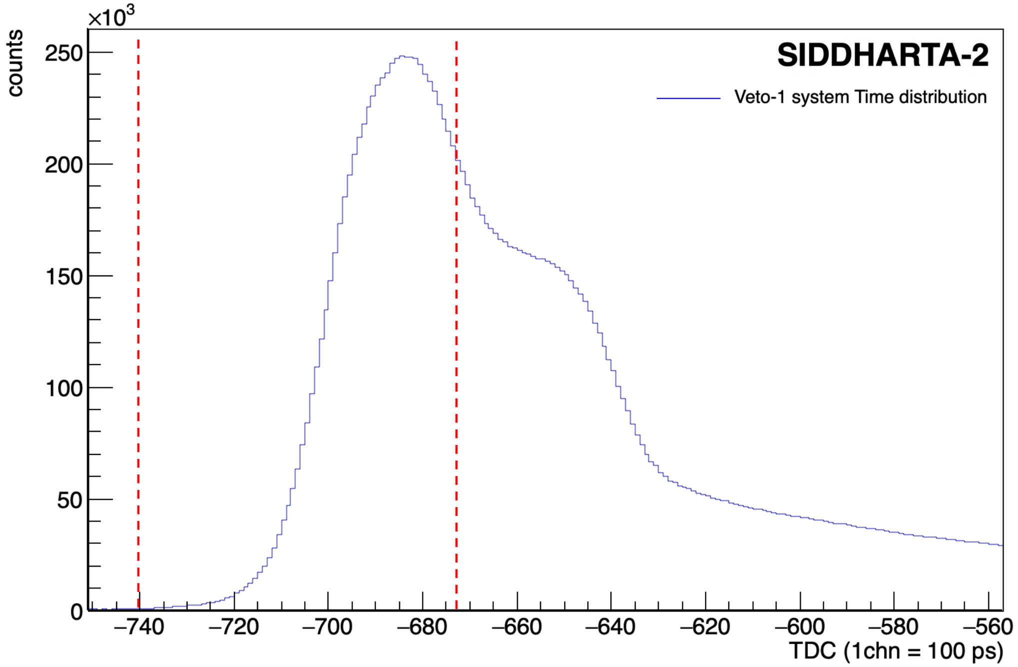


	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-^{4}He L_α	$(8 \pm 1)\%$	4%
K-$C_{5\to 4}$	$(48 \pm 4)\%$	44%

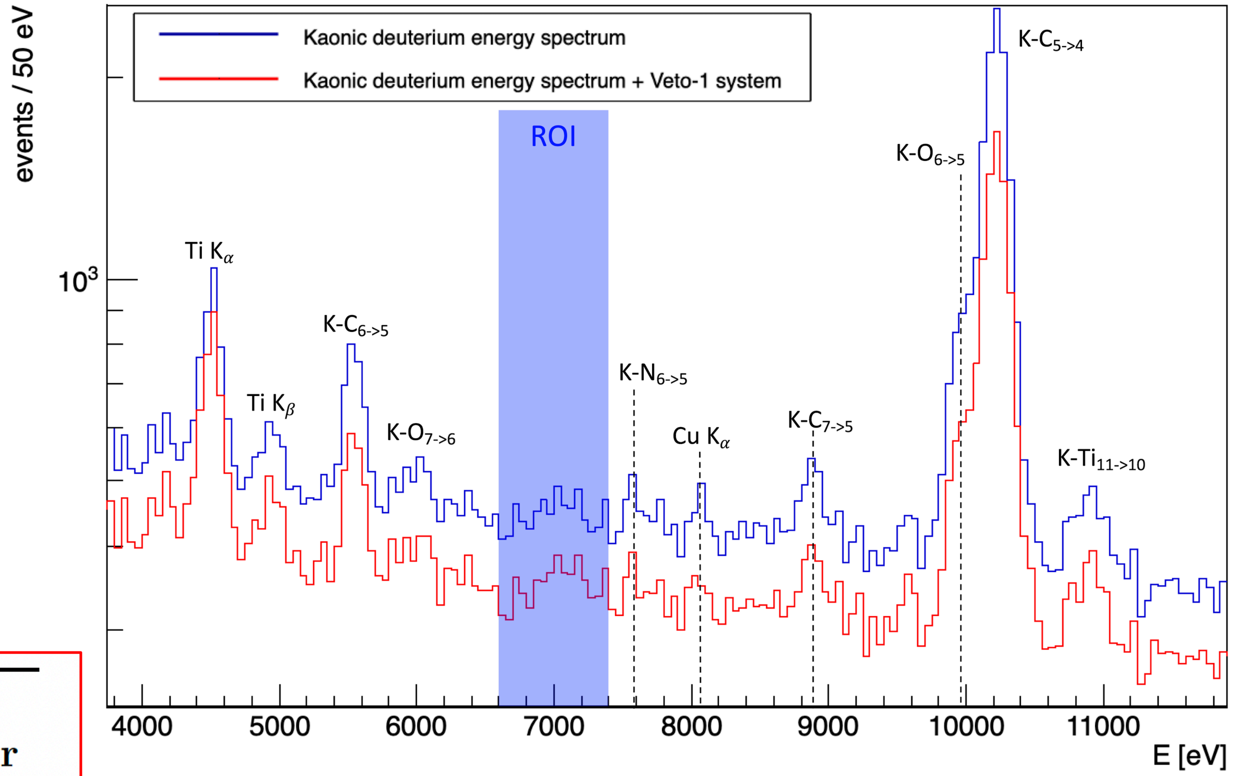
$$\text{reduction factor} = 1 - \frac{\#\text{events(with veto1)}}{\#\text{events}}$$

Kaonic Deuterium: veto-1 system analysis

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



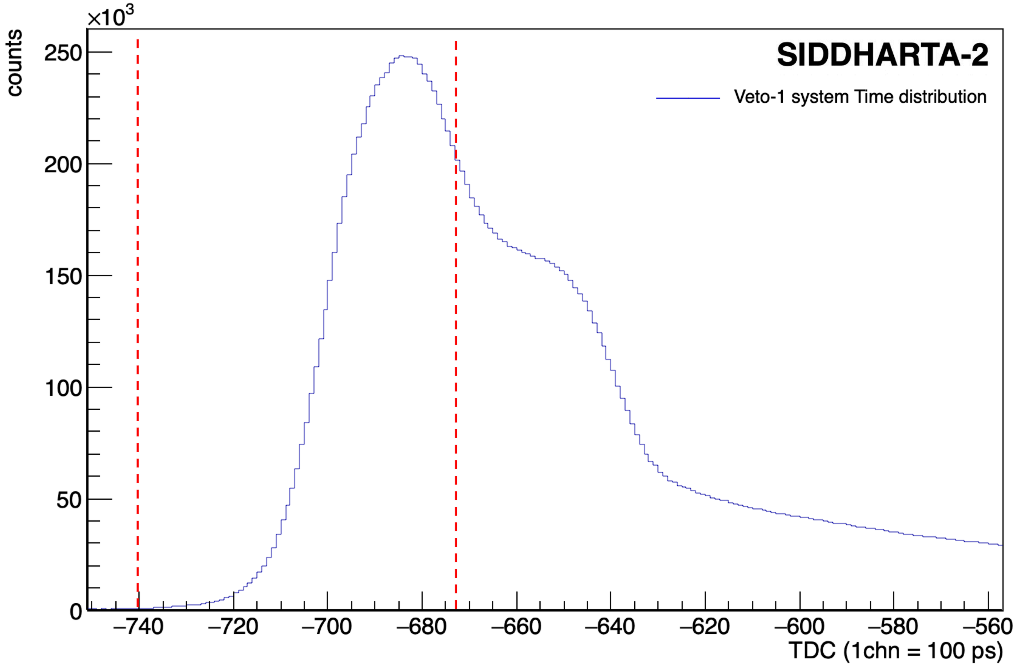
SDDs X-ray energy spectra with and without the veto-1 (be aware logarithmic scale)



	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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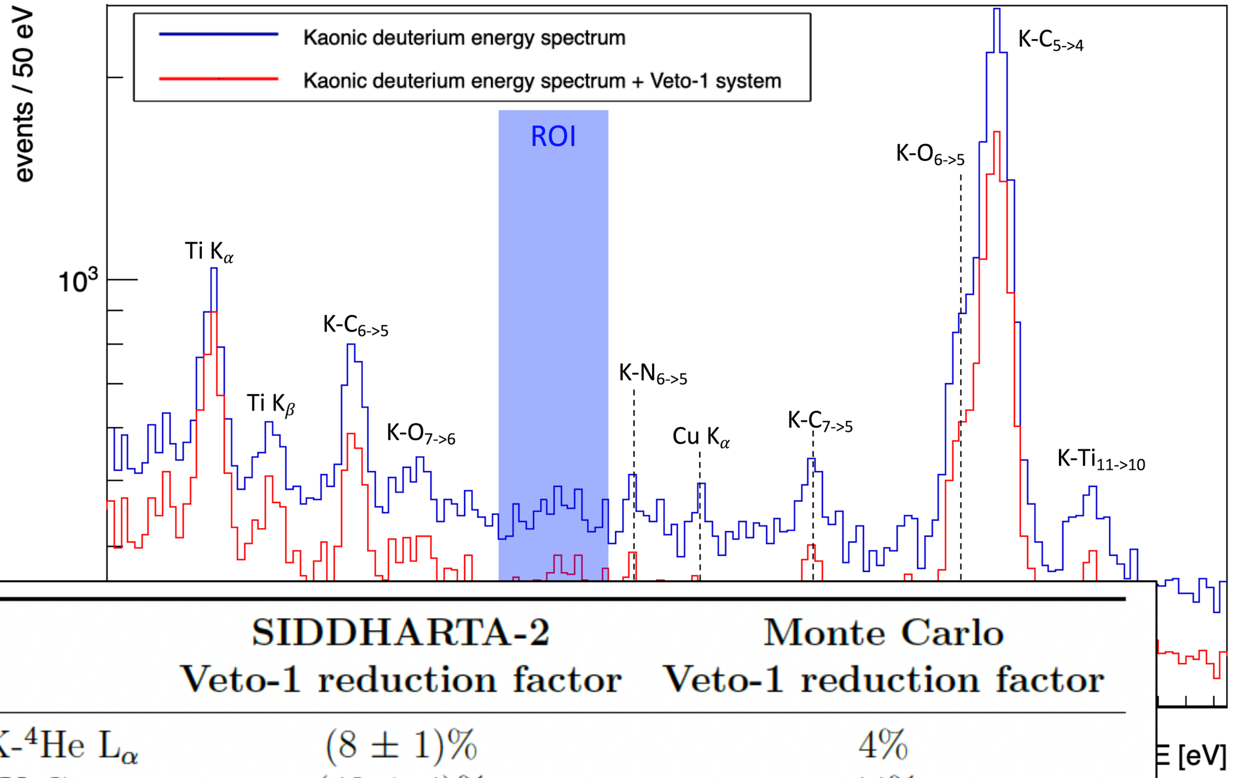

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