Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SIlicon **D**rift
Detectors for
HAdronic **A**tom
Research by
Timing **A**pplication

The quest for kaonic atoms' measurements: technological challenges and future perspectives

Alessandro Scordo
on behalf of the SIDDHARTA-2 Collaboration,
Laboratori Nazionali di Frascati INFN

Kaonic atoms

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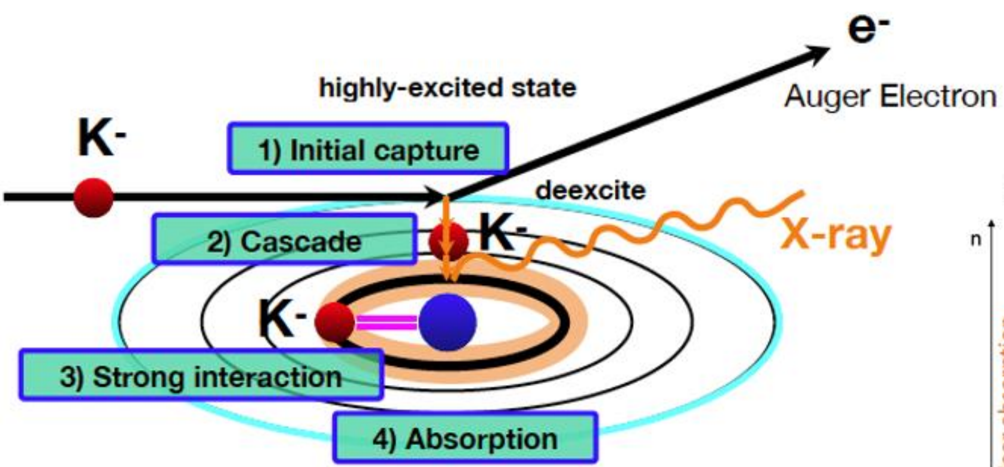
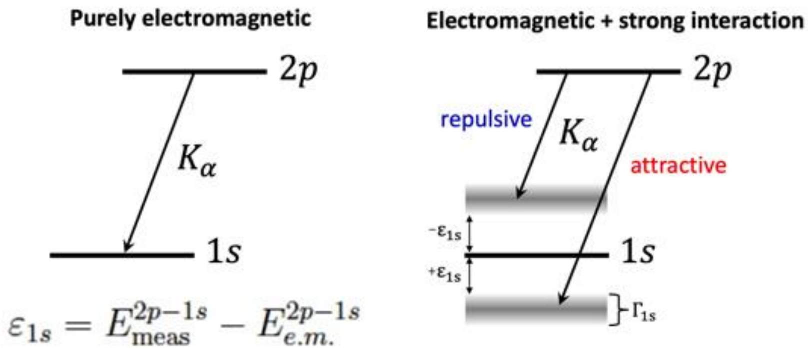
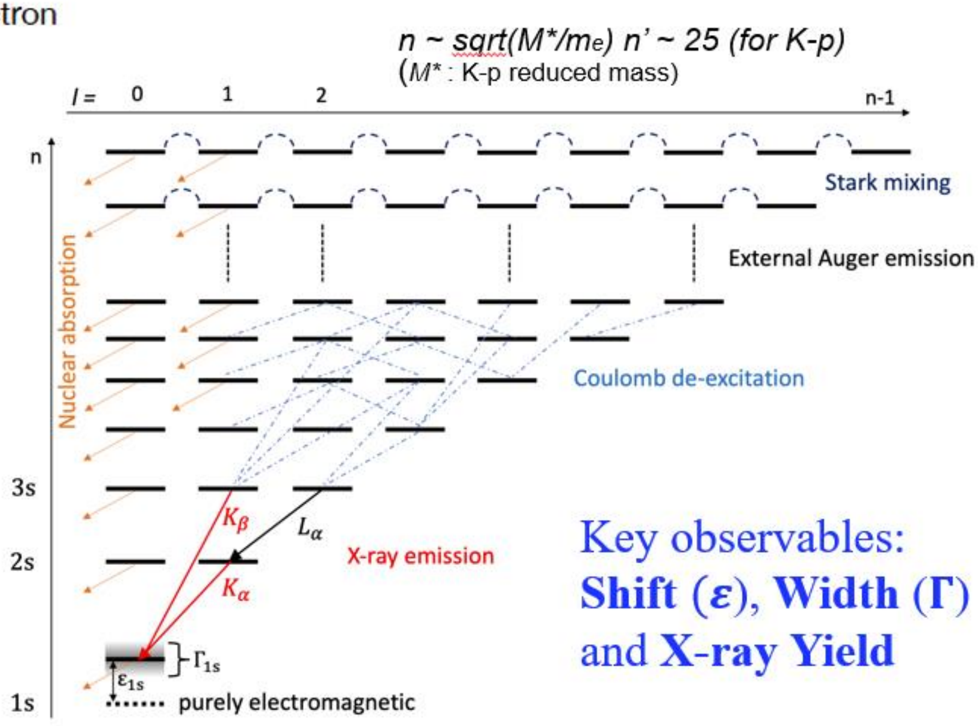
K(n)N interaction AT REST (or at threshold) can't be investigated in collision experiments

It can't be inferred by extrapolation at zero energy due to the presence of the Λ(1405?) resonance a few MeV below Kp threshold

How can we then obtain reliable information on low energy K(n)N interaction?







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

KH and Kd

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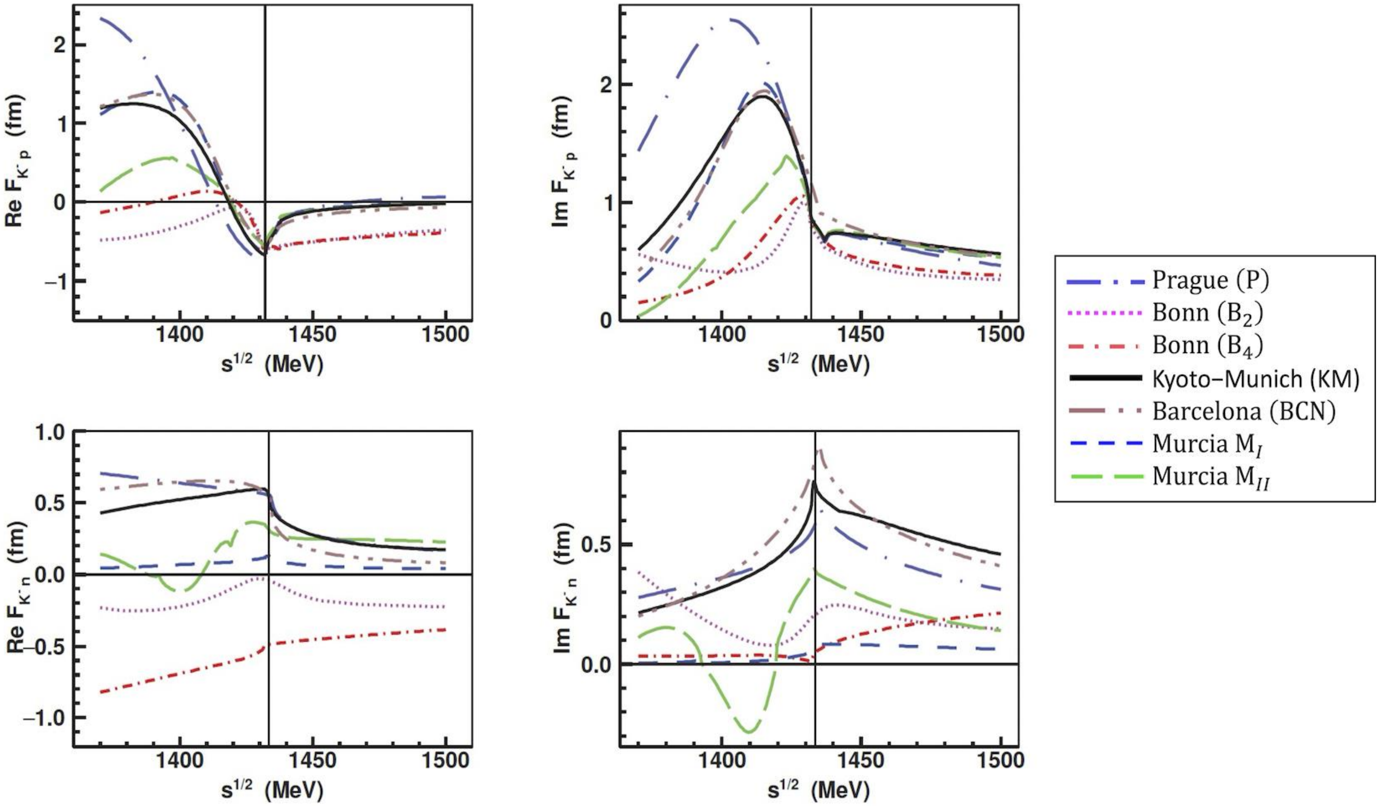

Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

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KH and Kd

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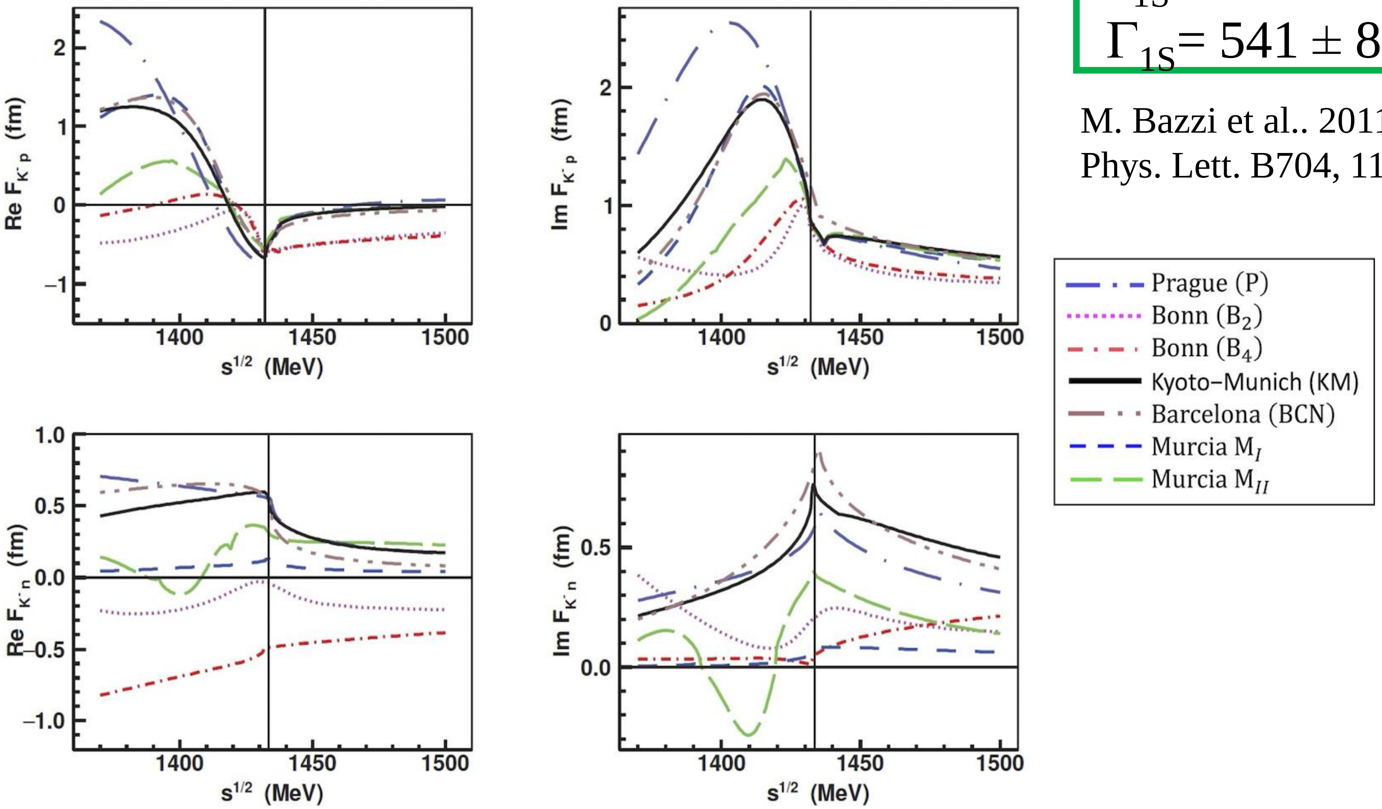
K-p: agreement

$$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$
$$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV}$$

M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113



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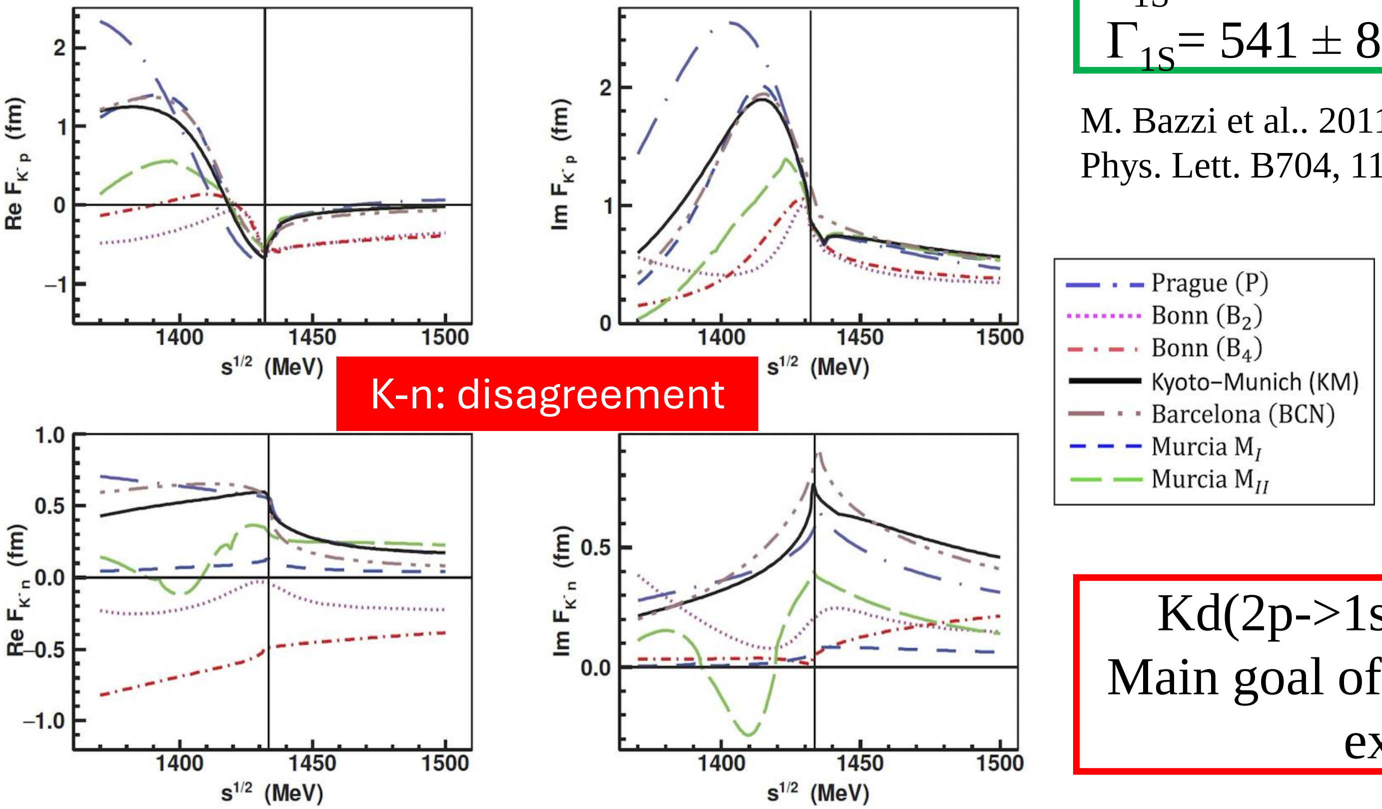

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Kd(2p->1s) never measured: Main goal of the SIDDHARTA-2 experiment

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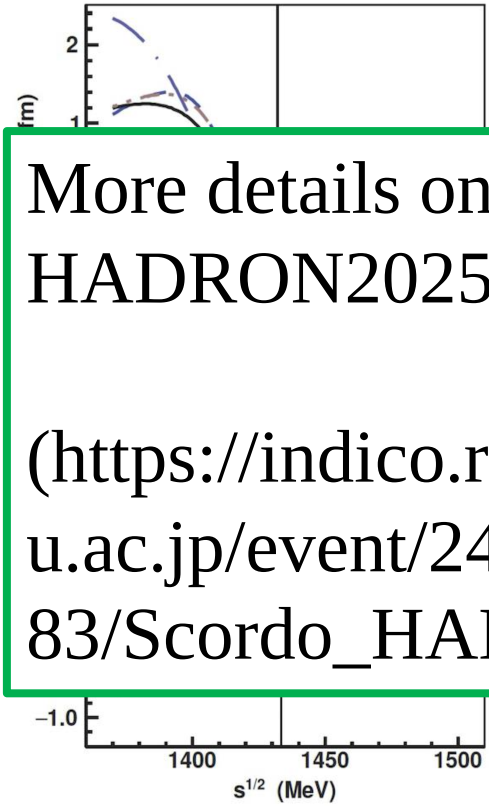
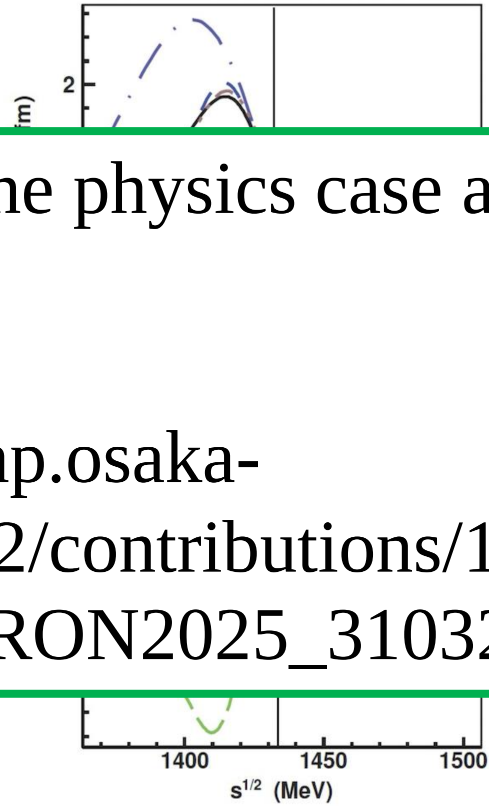
KH and Kd

K-p: agreement





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M. Bazzi et al., 2011, (SIDDHARTA Coll.).

More details on the physics case and state of art given at HADRON2025

(https://indico.rcnp.osaka-u.ac.jp/event/2402/contributions/14966/attachments/9380/12583/Scordo_HADRON2025_31032025.pdf

experiment

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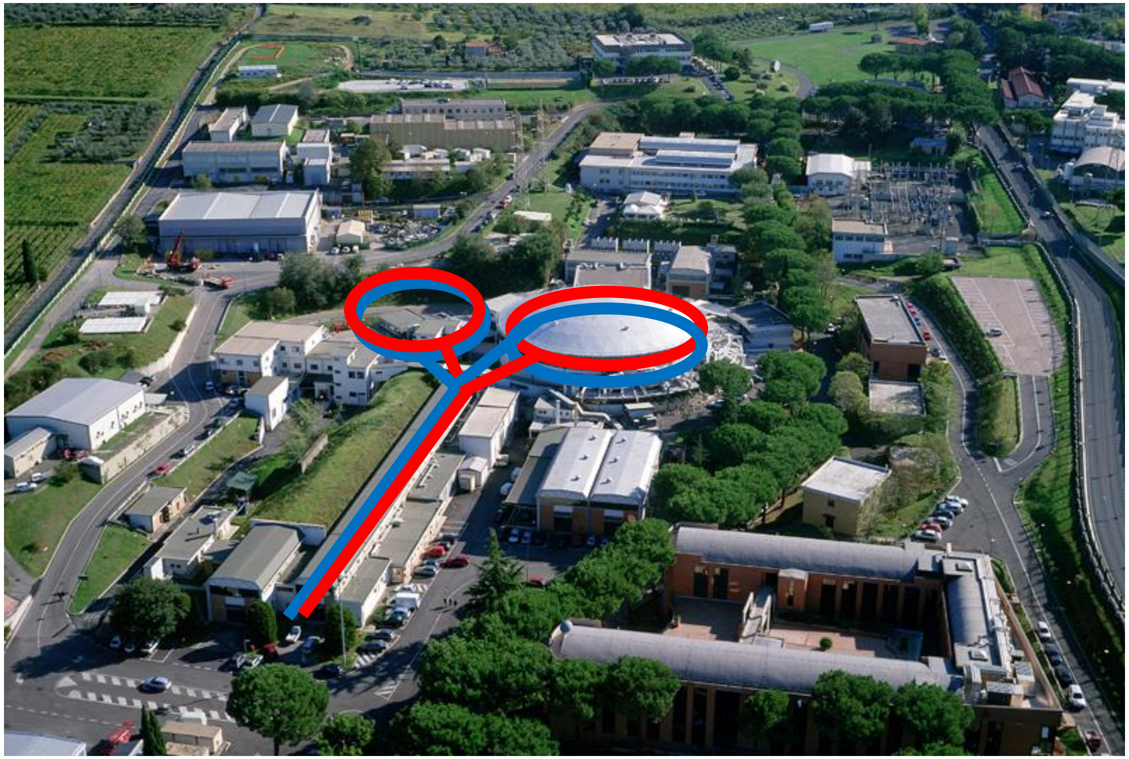

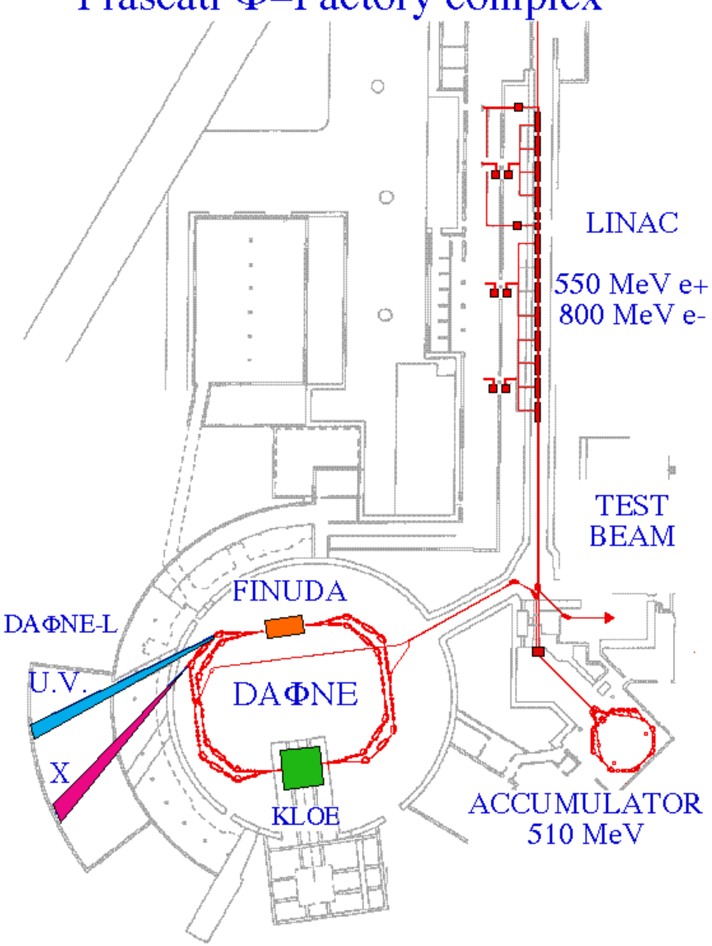

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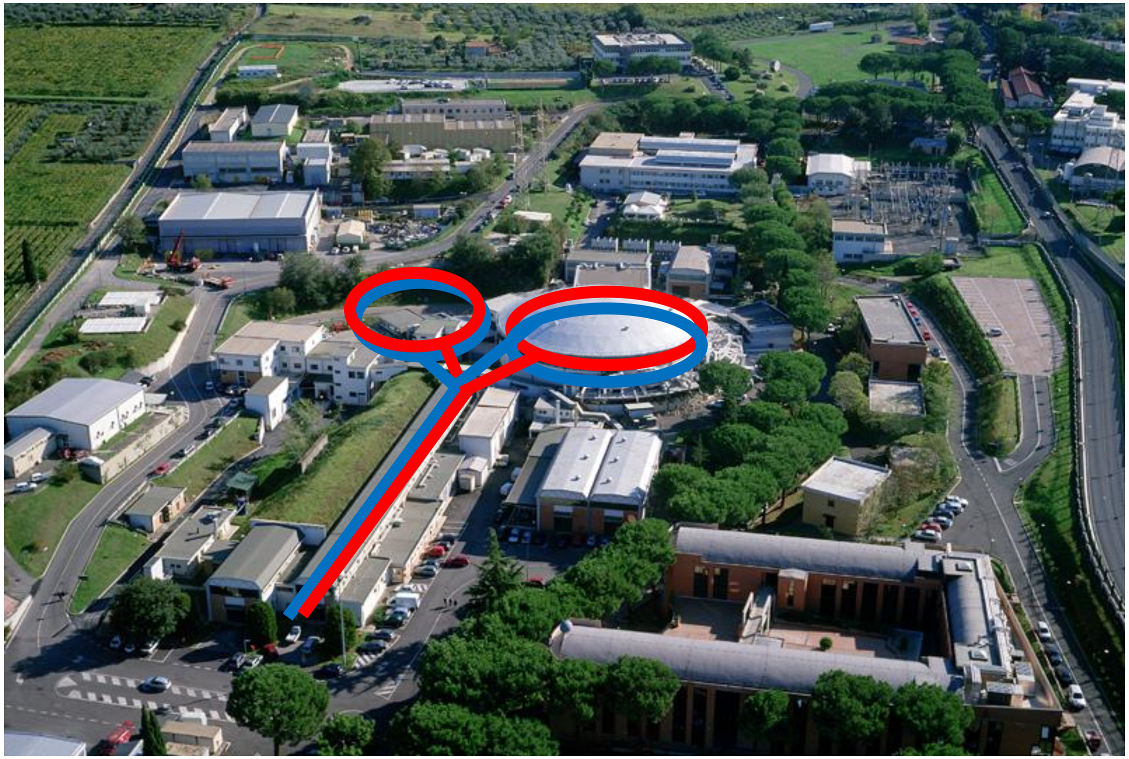
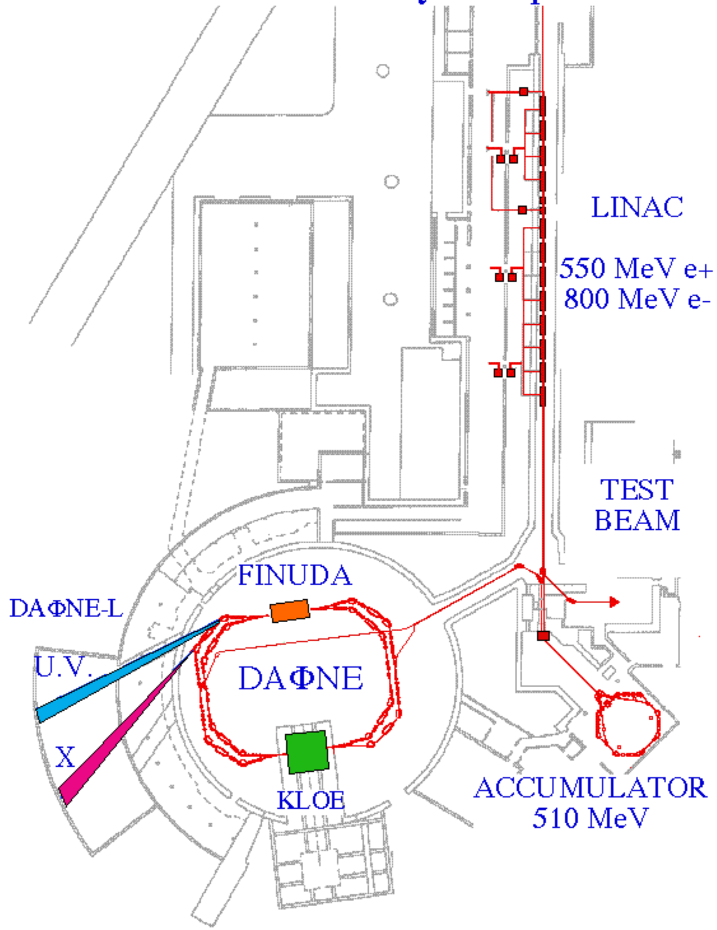
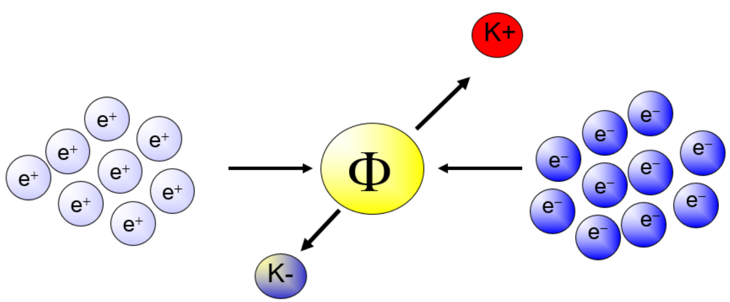


Frascati Φ–Factory complex





B.R ($\phi \rightarrow K^+ K^-$) = 48,9 %

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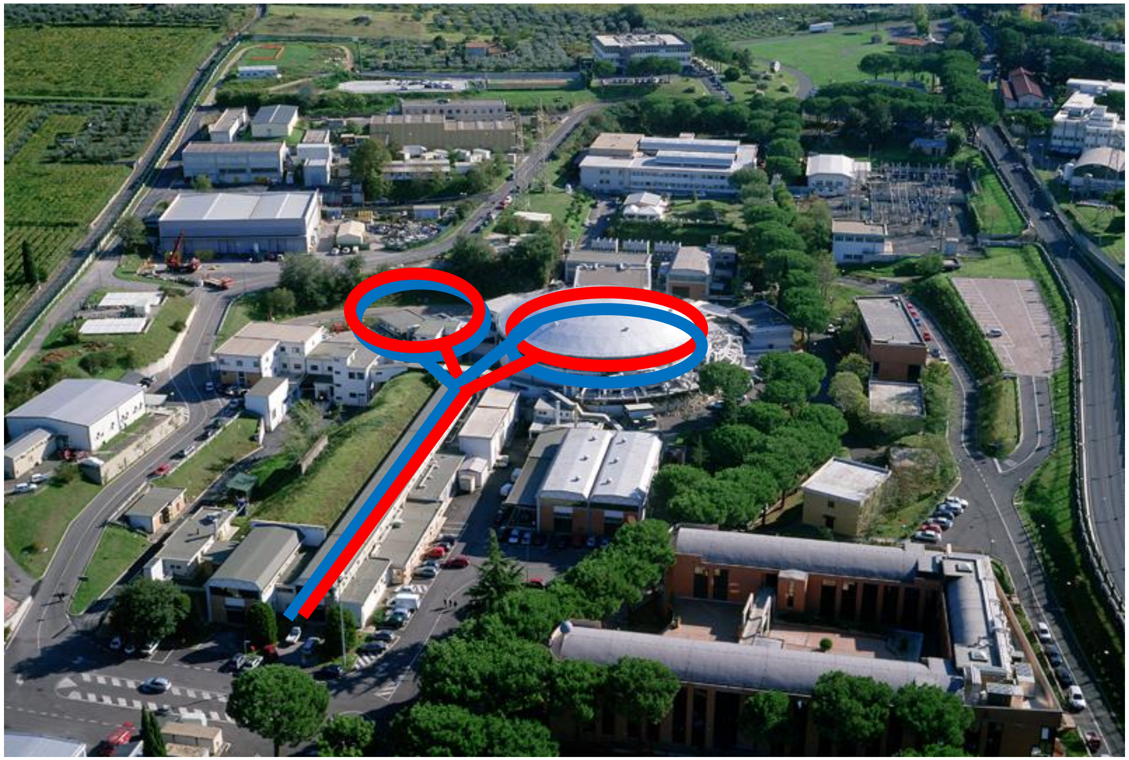

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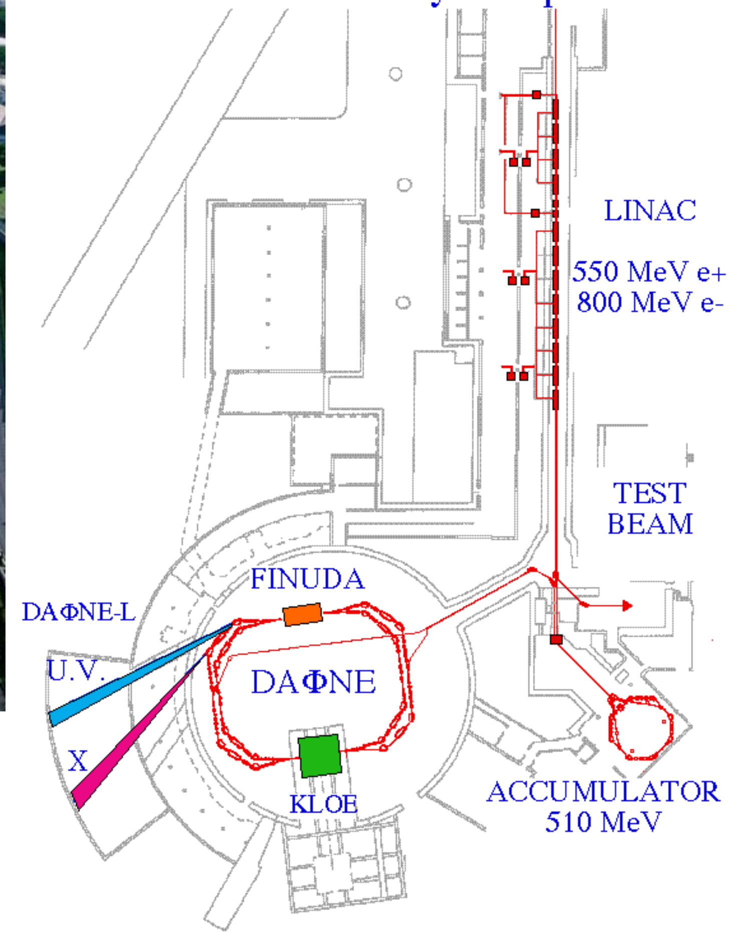

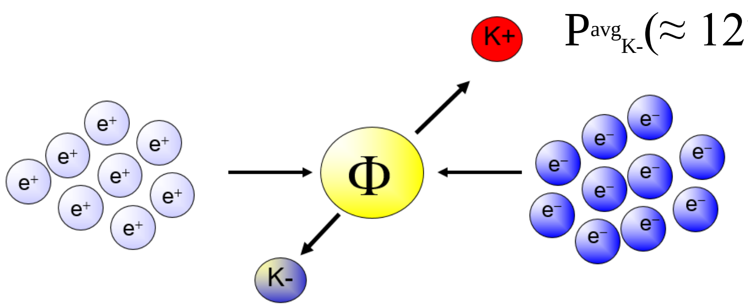

P^{avg}_{K-} (≈ 127 MeV)

B.R (ϕ -> $K^+ K^-$) = 48,9 %

Kaonic atoms measurements @ DAΦNE

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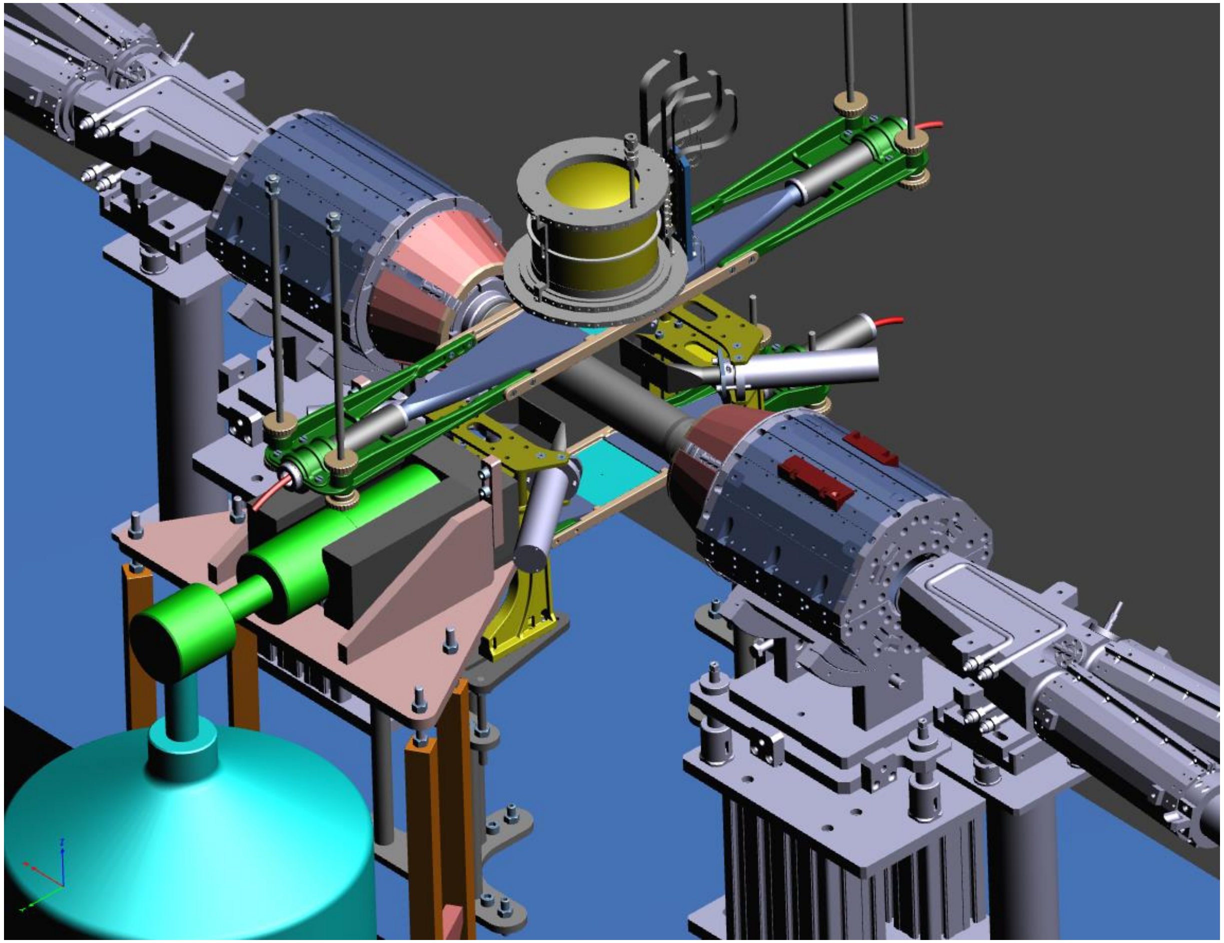

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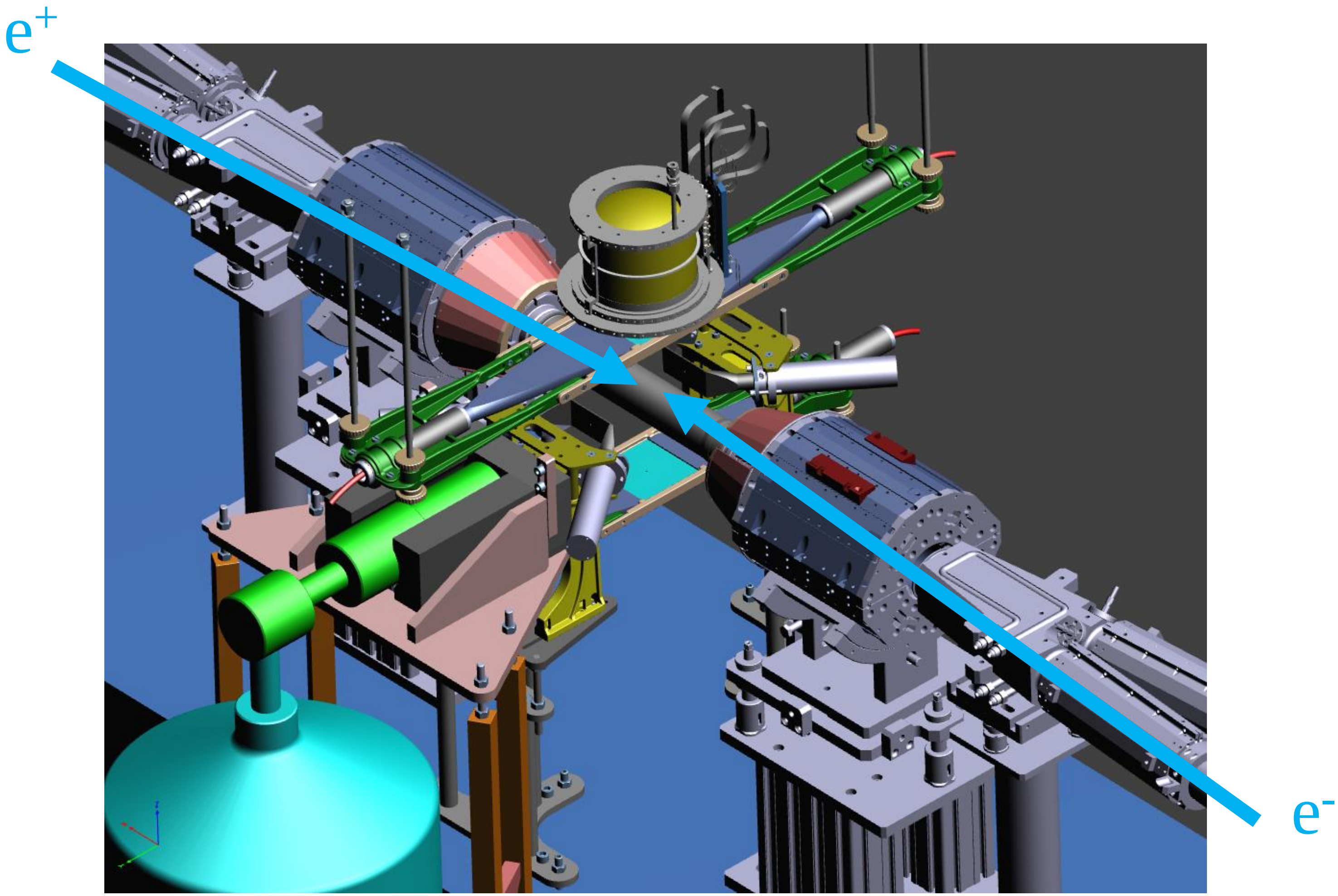

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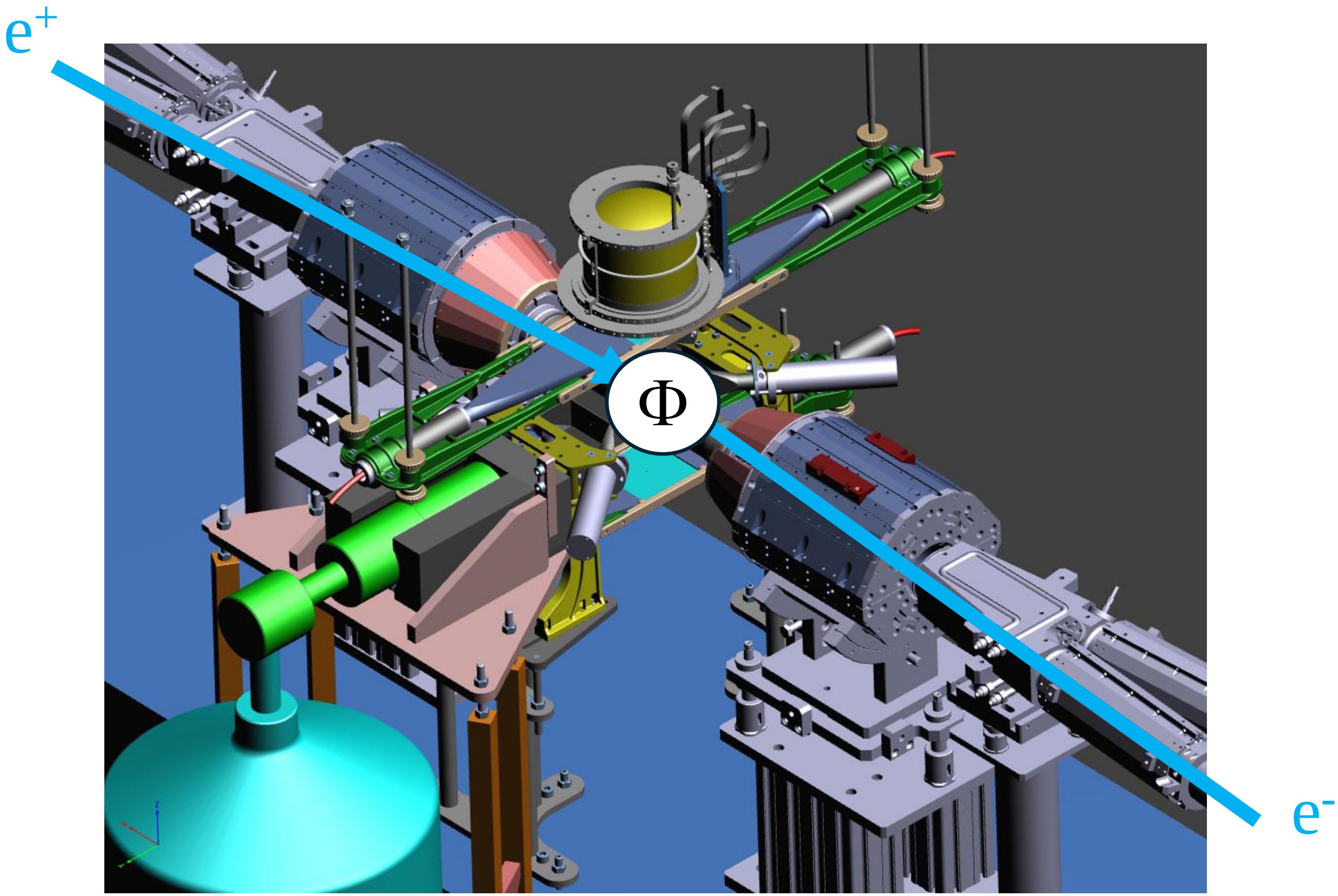

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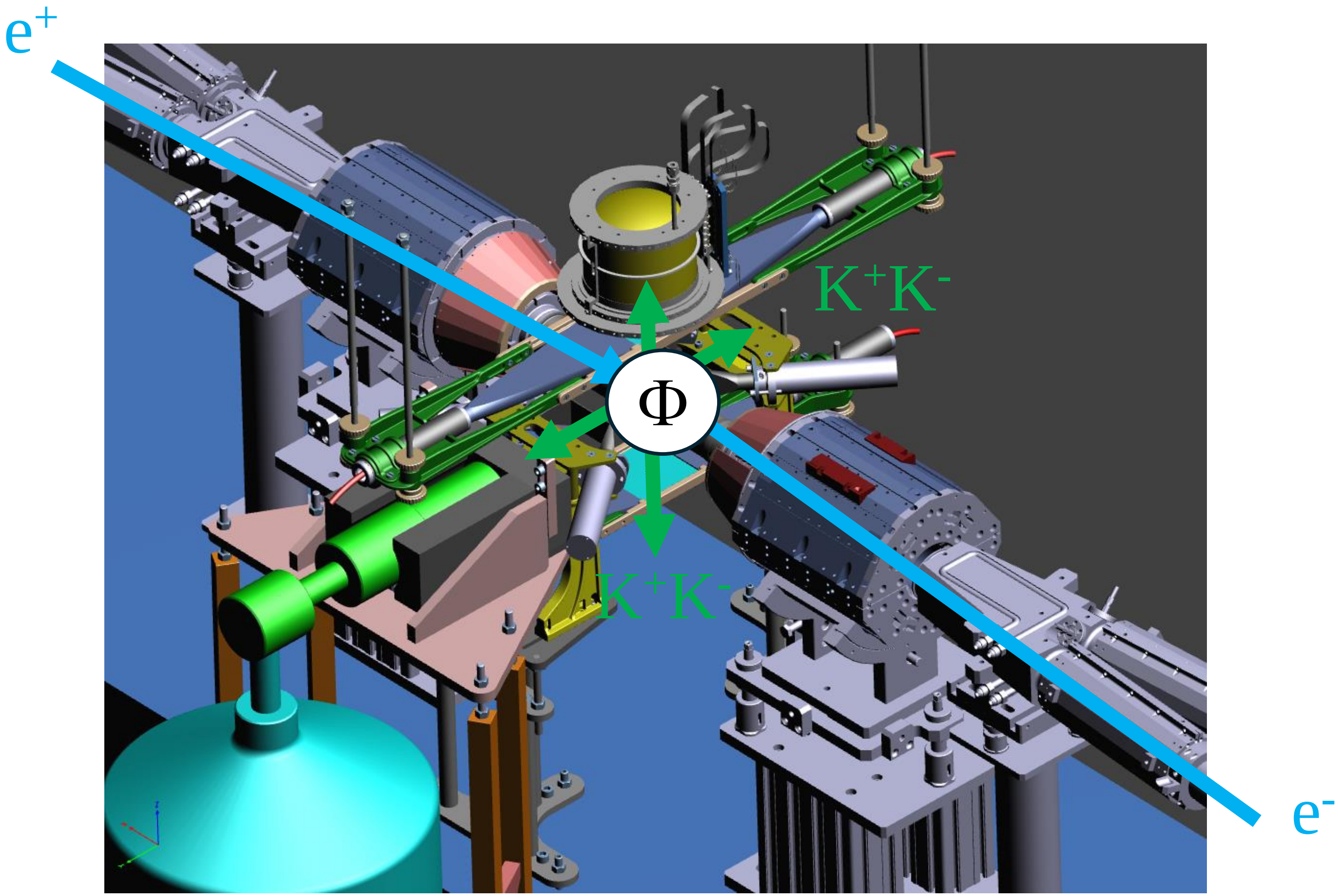

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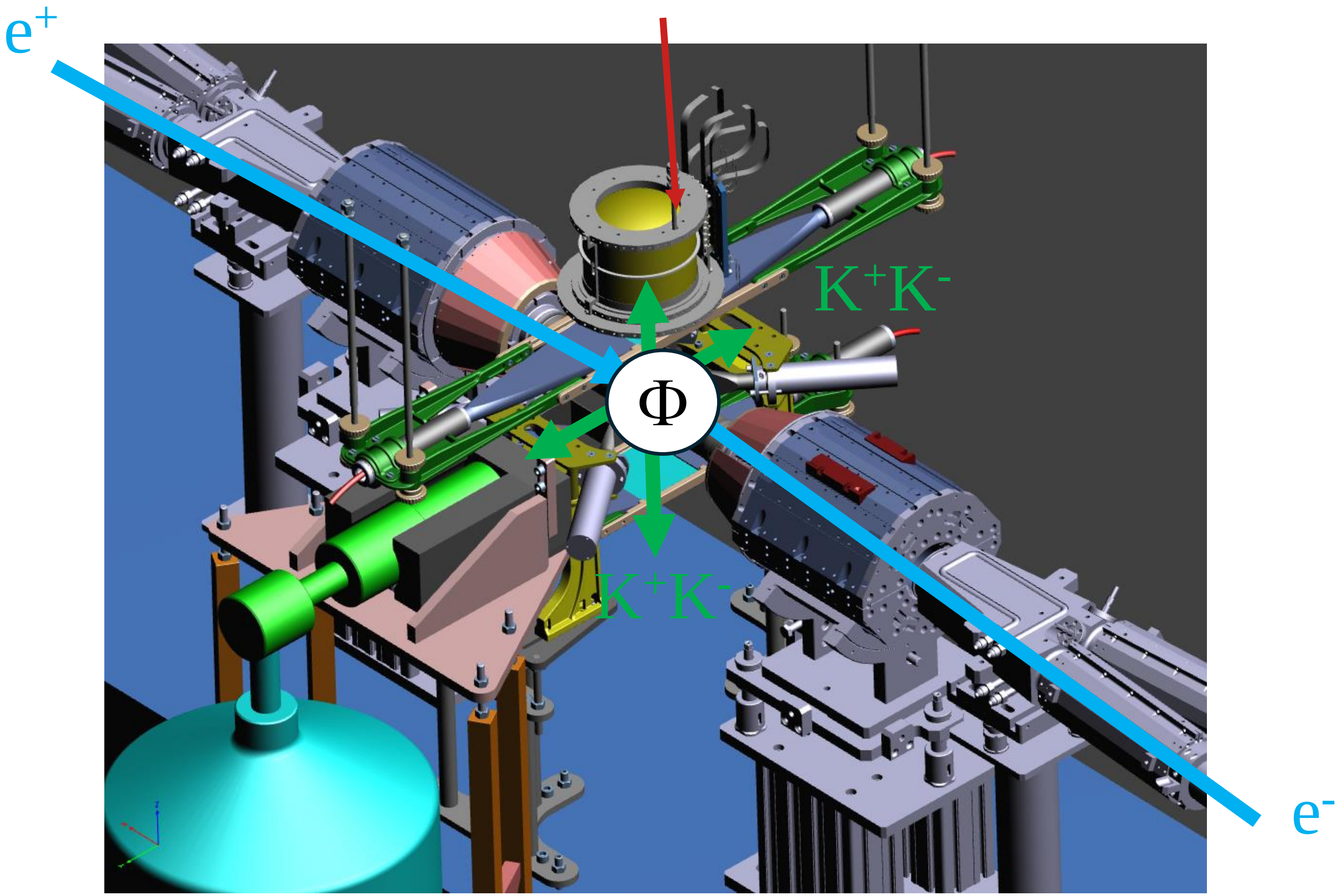
SDDs (4-30 keV) - Light Kaonic Atoms



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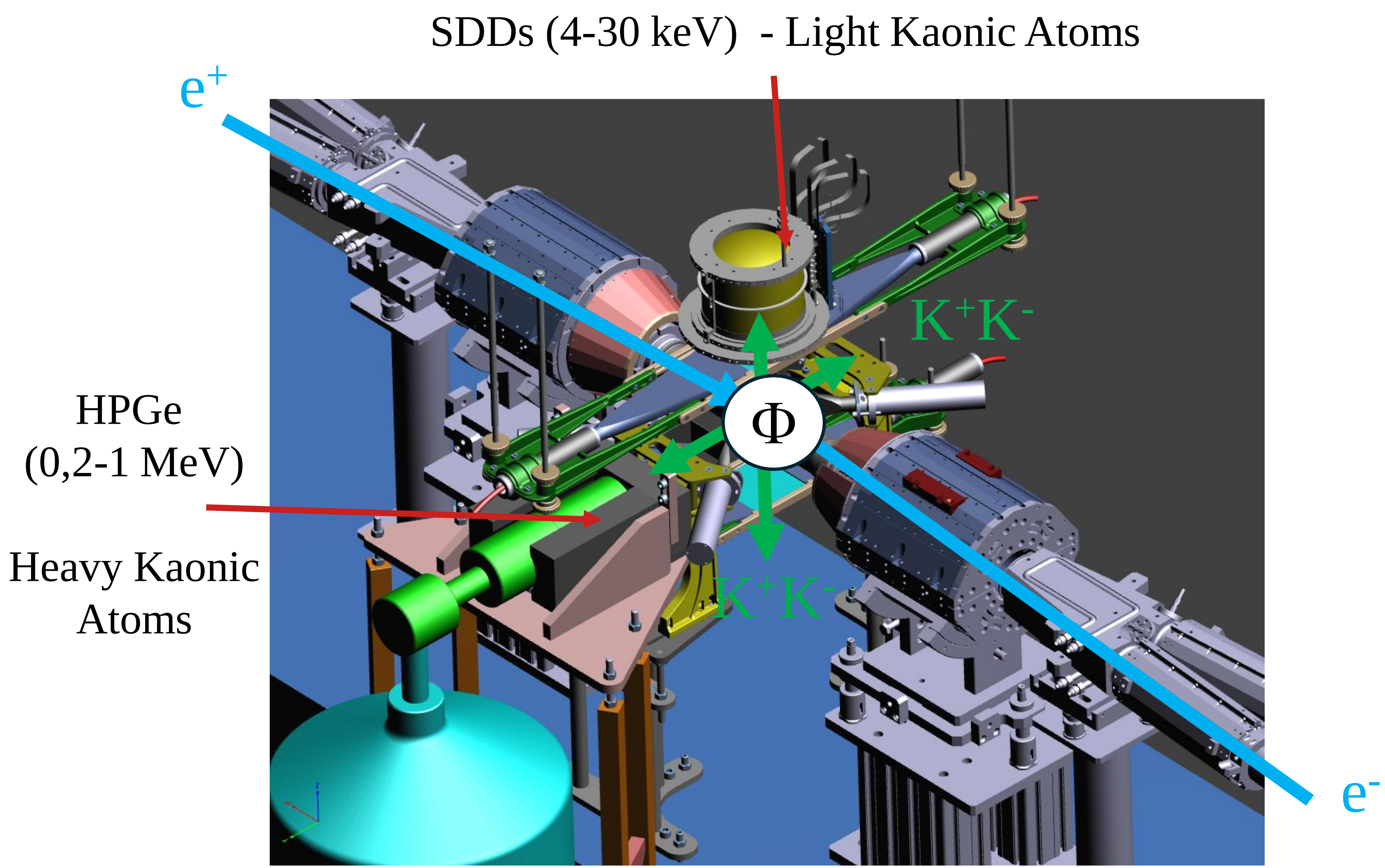

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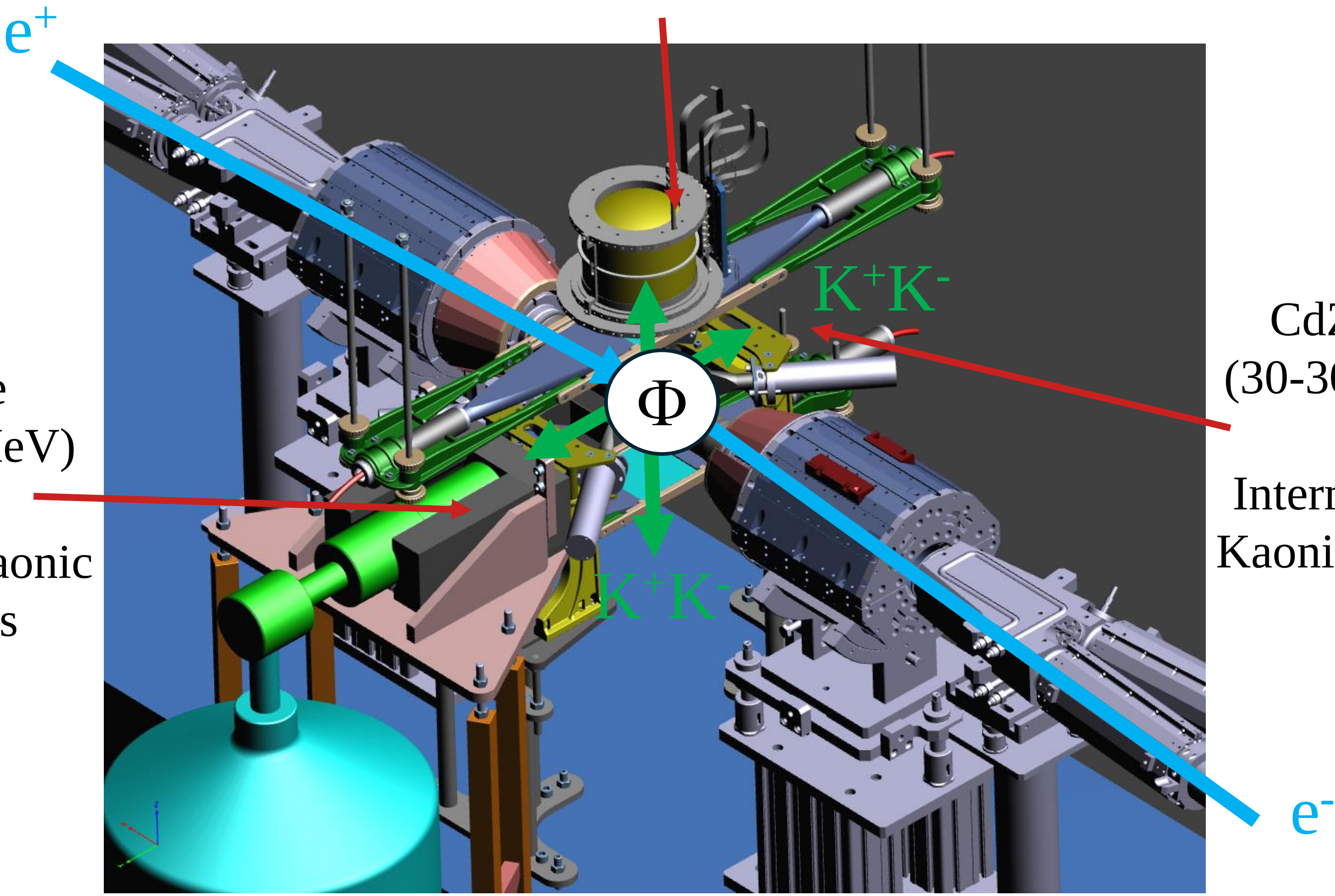

CdZnTe (30-300 keV)

Intermediate Kaonic Atoms

HPGe (0,2-1 MeV)

Heavy Kaonic Atoms

Kaonic atoms measurements @ DAΦNE

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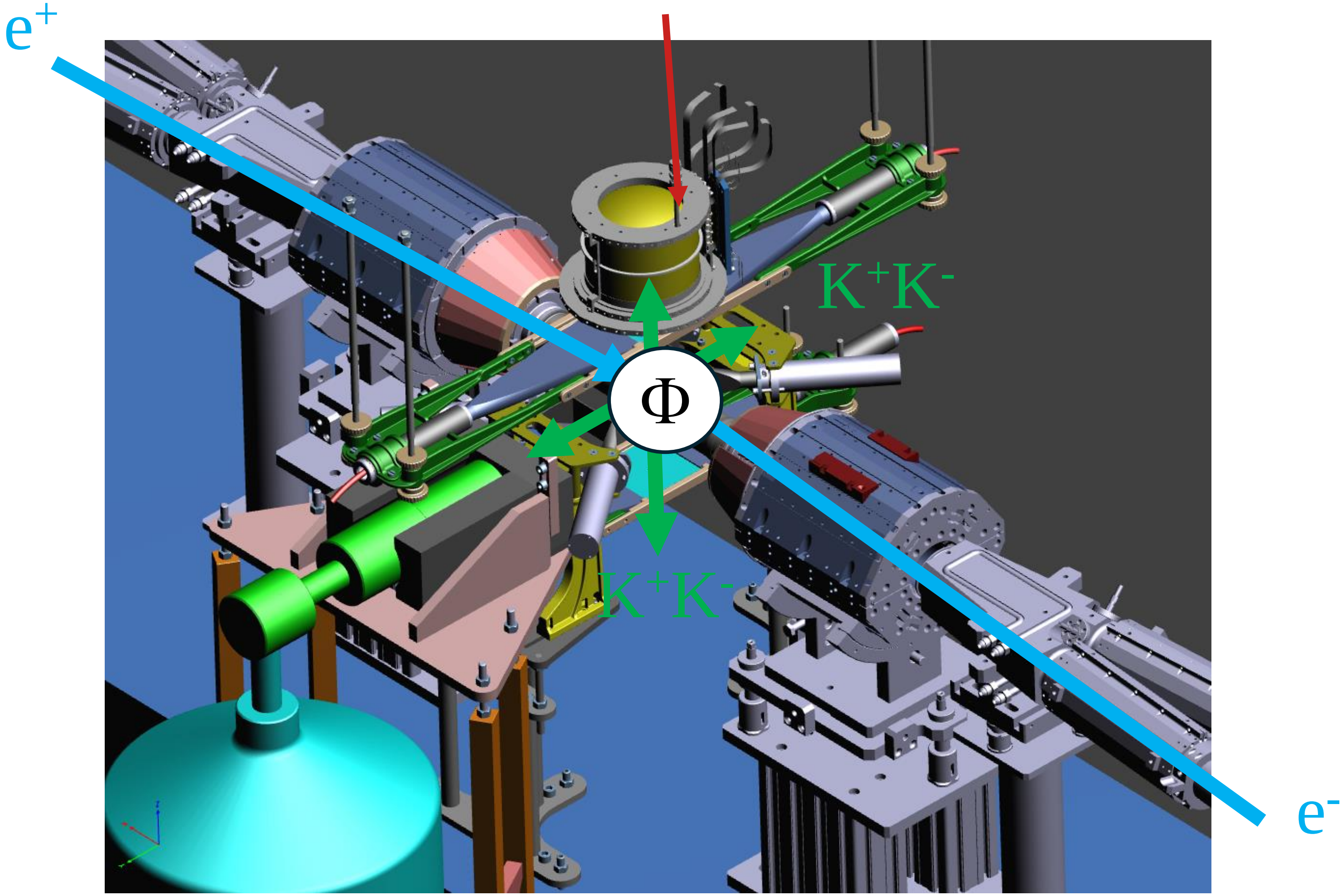
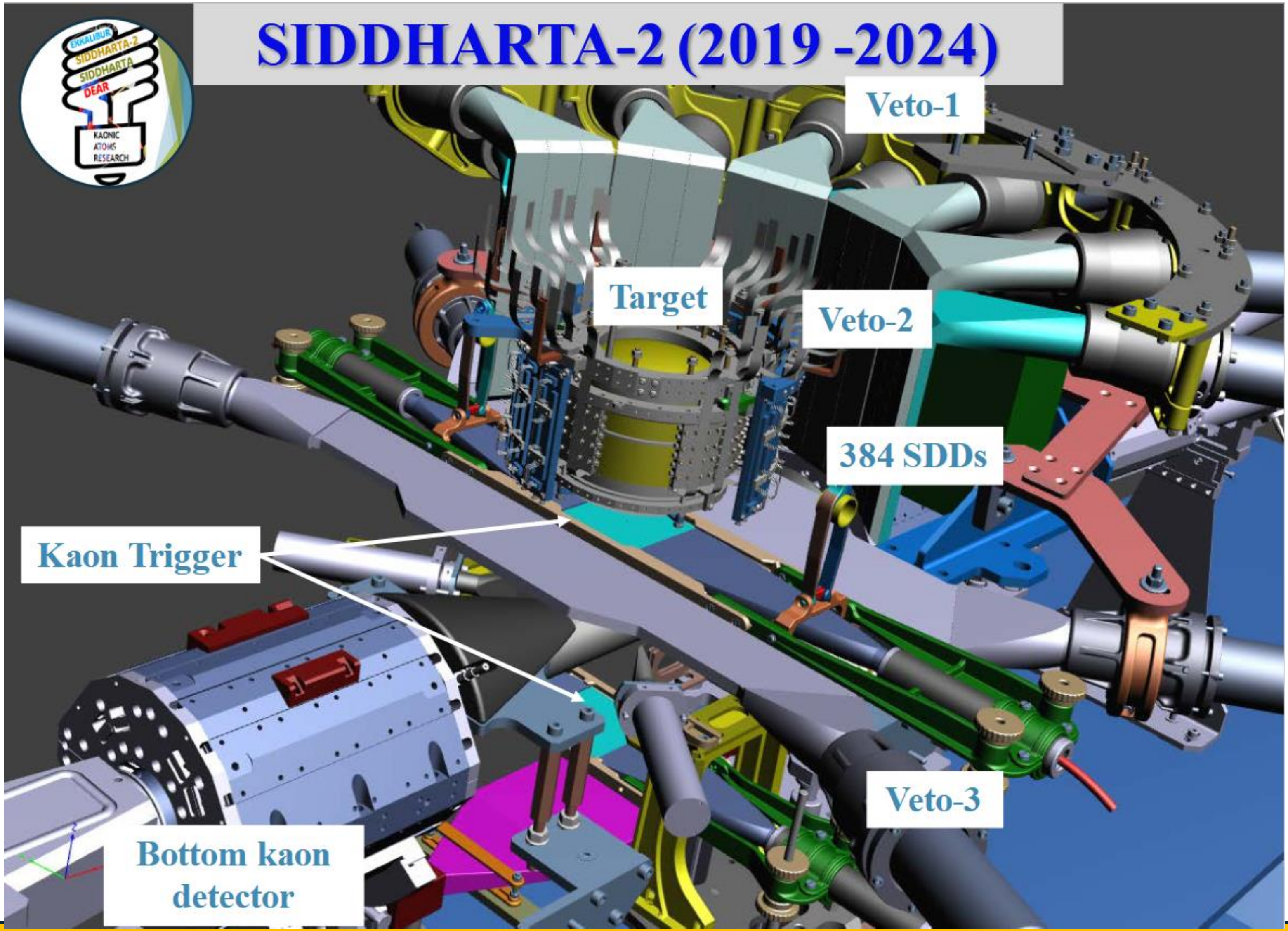


Gaseous Targets Measurements

SIlicon Drift Detectors for HAdronic Atom Research by Timing Application



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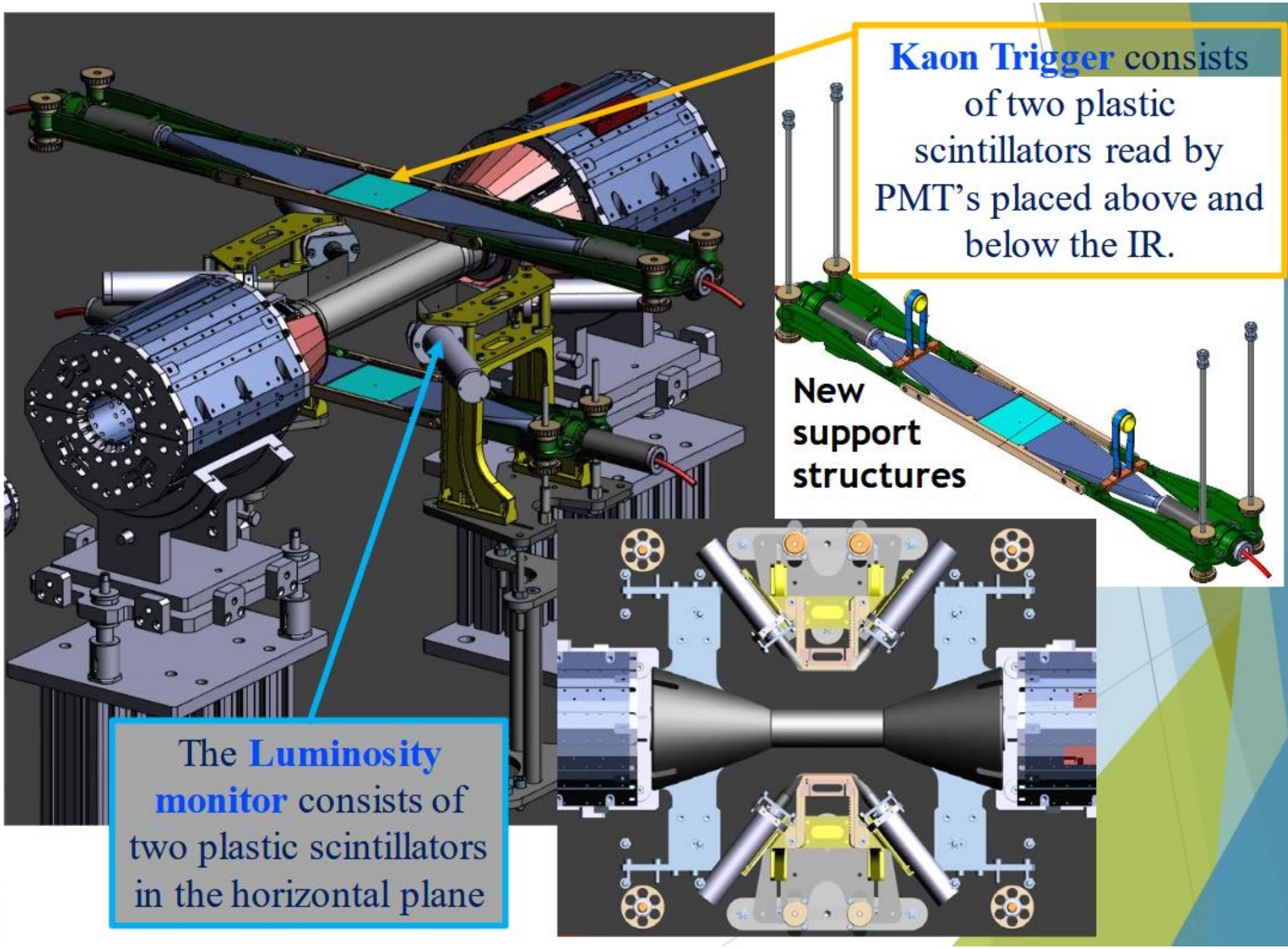

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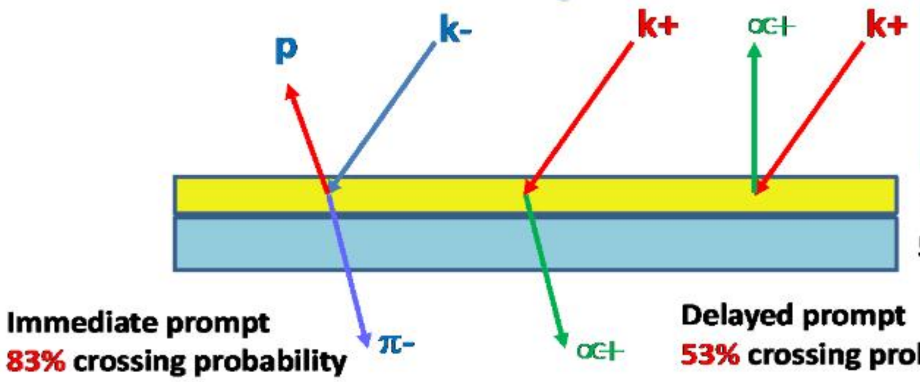
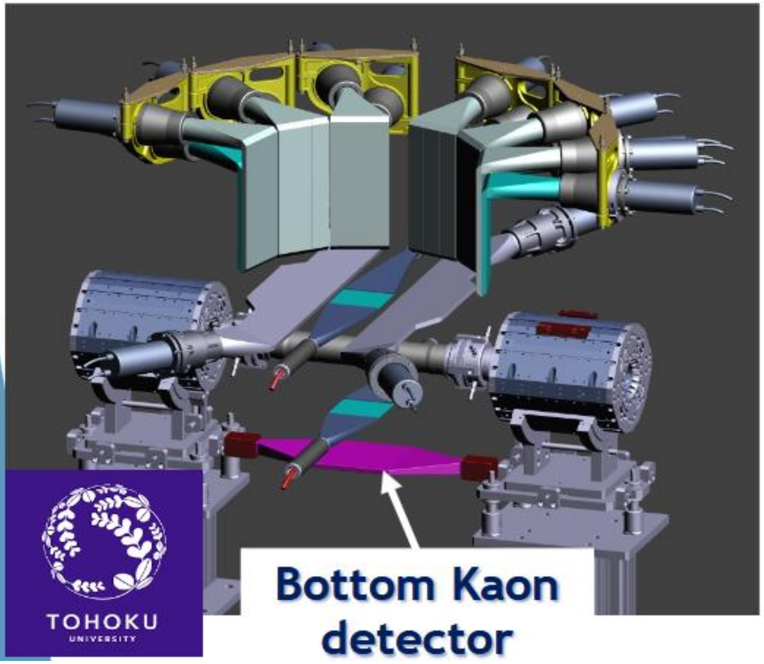
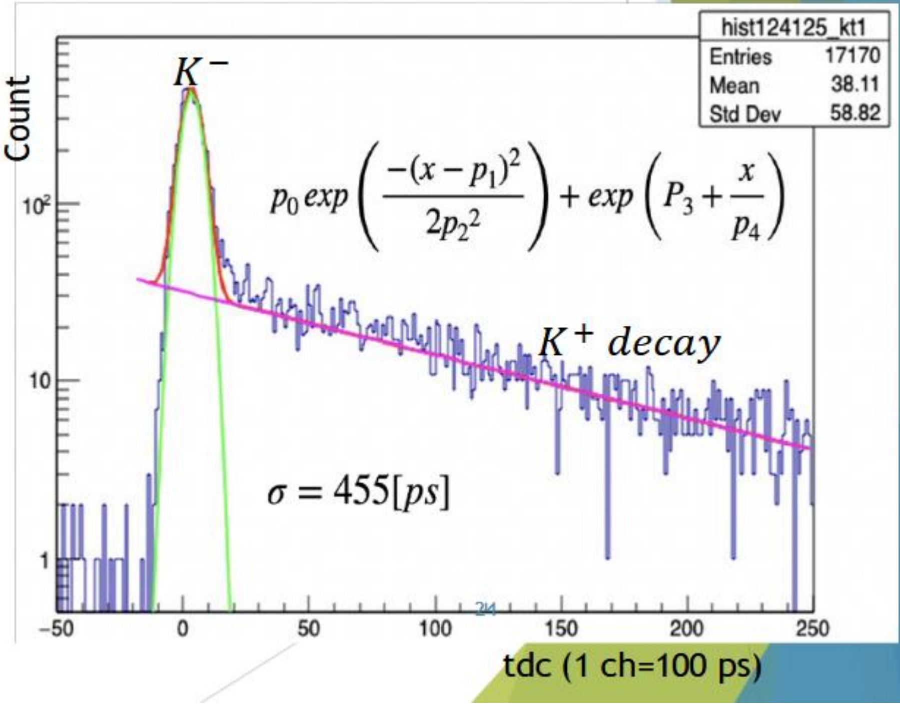
Stop both K^+ and K^- in a passive layer (Teflon) and detect secondaries in a scintillator







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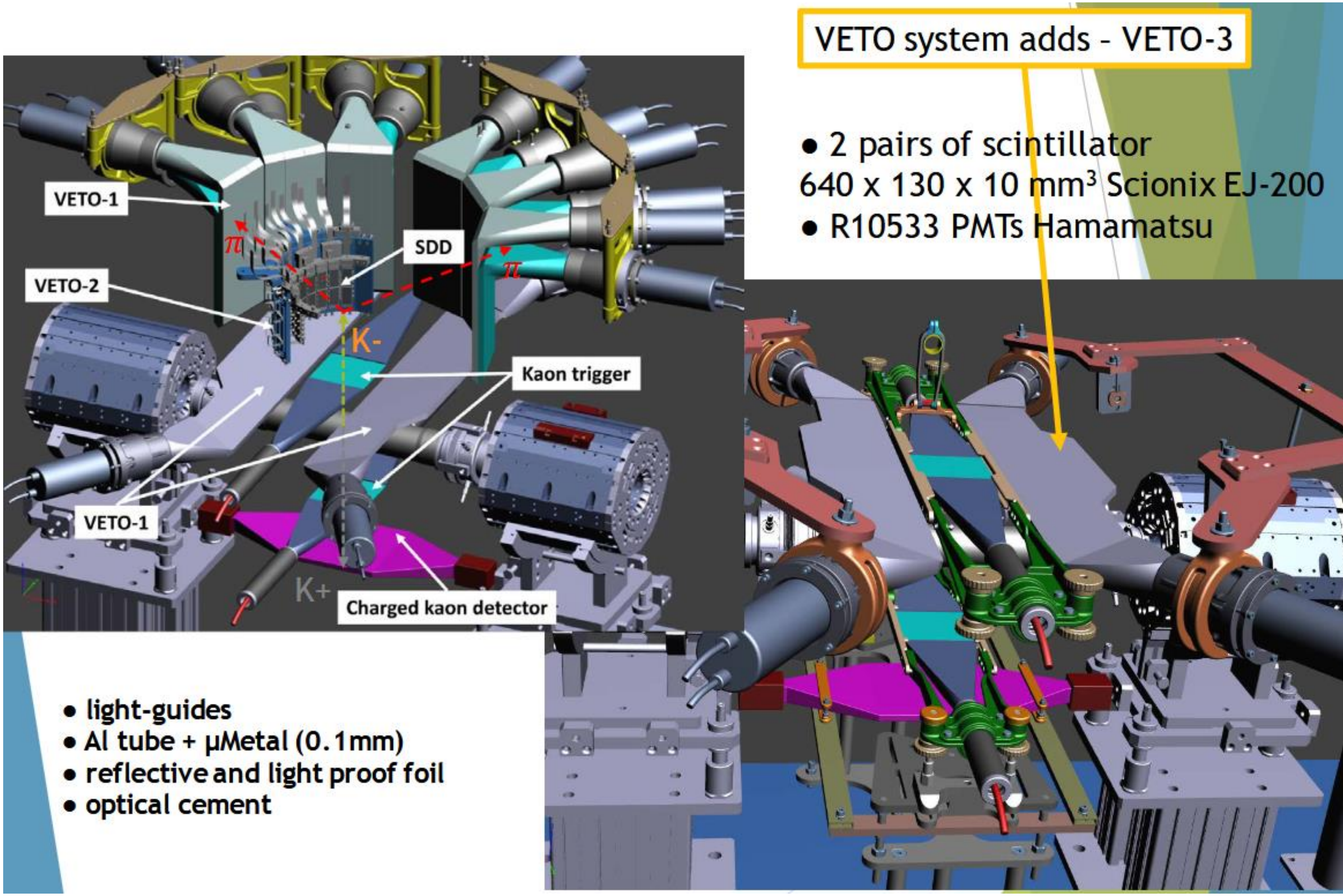

Kaonic atoms measurements @ DAΦNE

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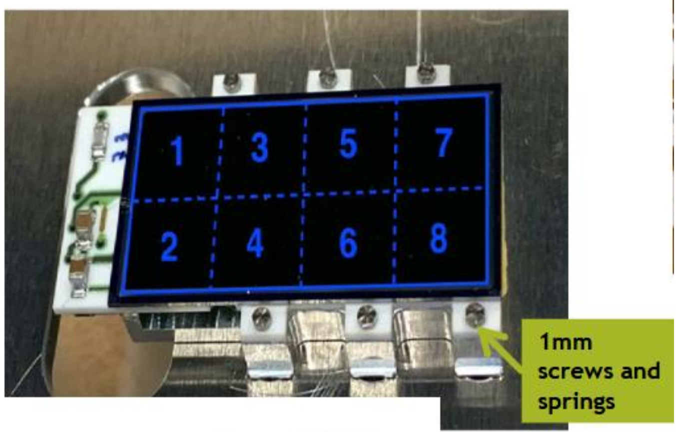
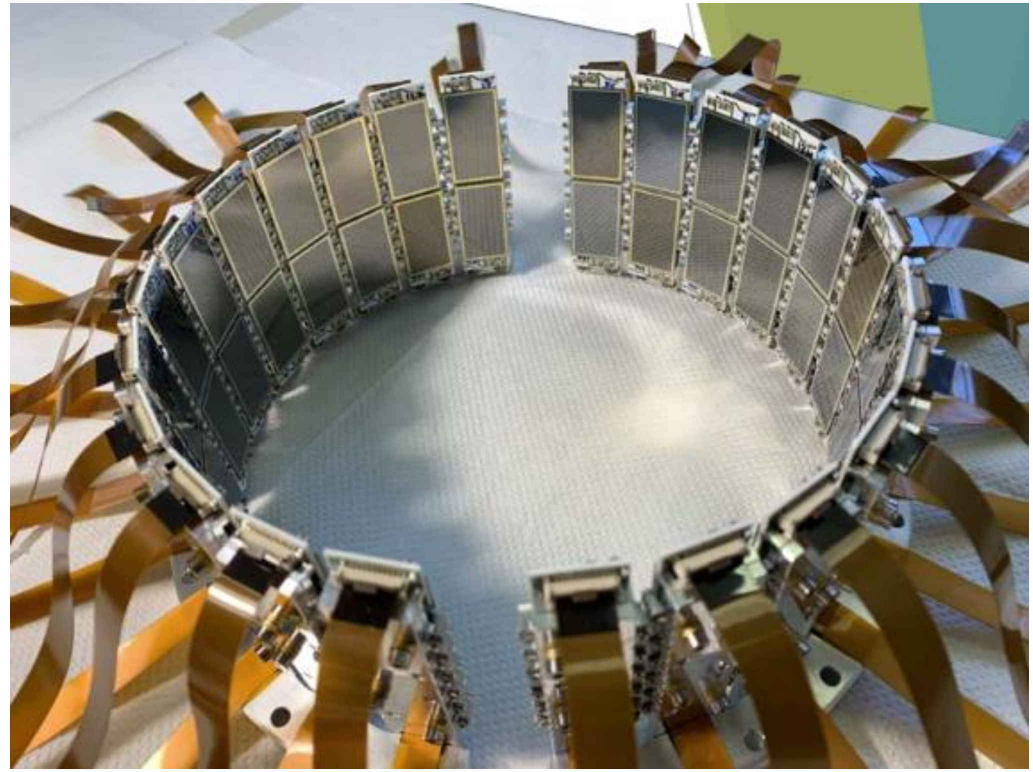
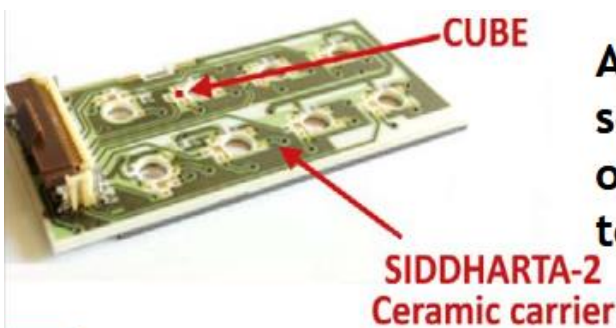
New monolithic SDDs arrays have been developed by Fondazione Bruno Kessler

new technology, lower production cost
- 2x4 matrix SDD units (0.64 cm^2)
- active/total surface ratio of 0.75







A CMOS low-noise charge sensitive preamplifier (CUBE operate at lower cryogenic temperature (up to 50k)

Total: 246 cm2
(384 SDDs)

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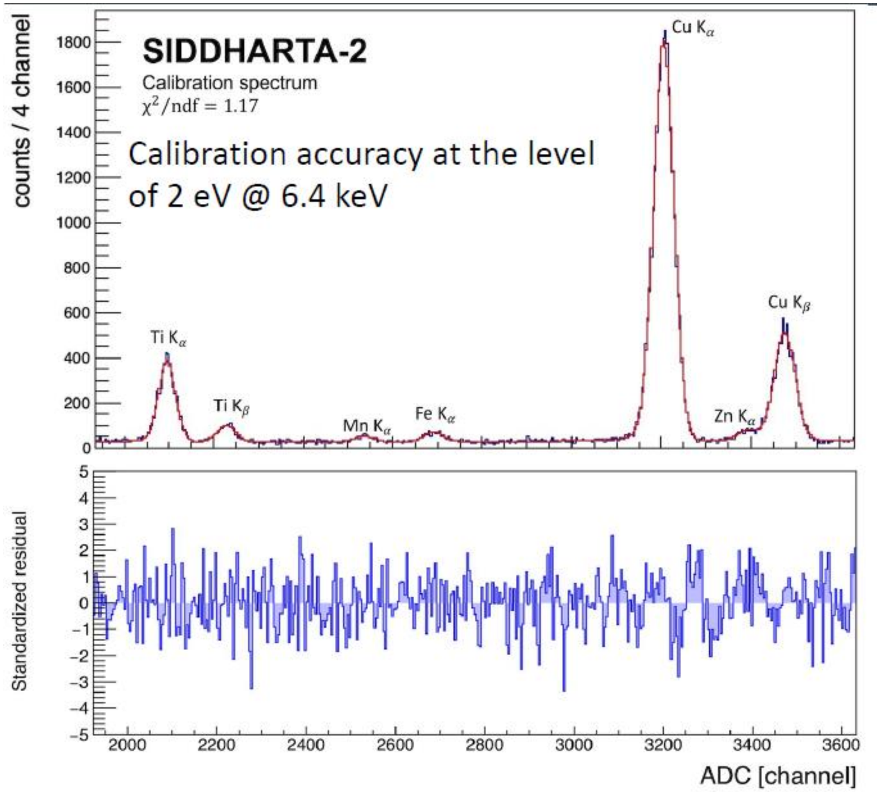

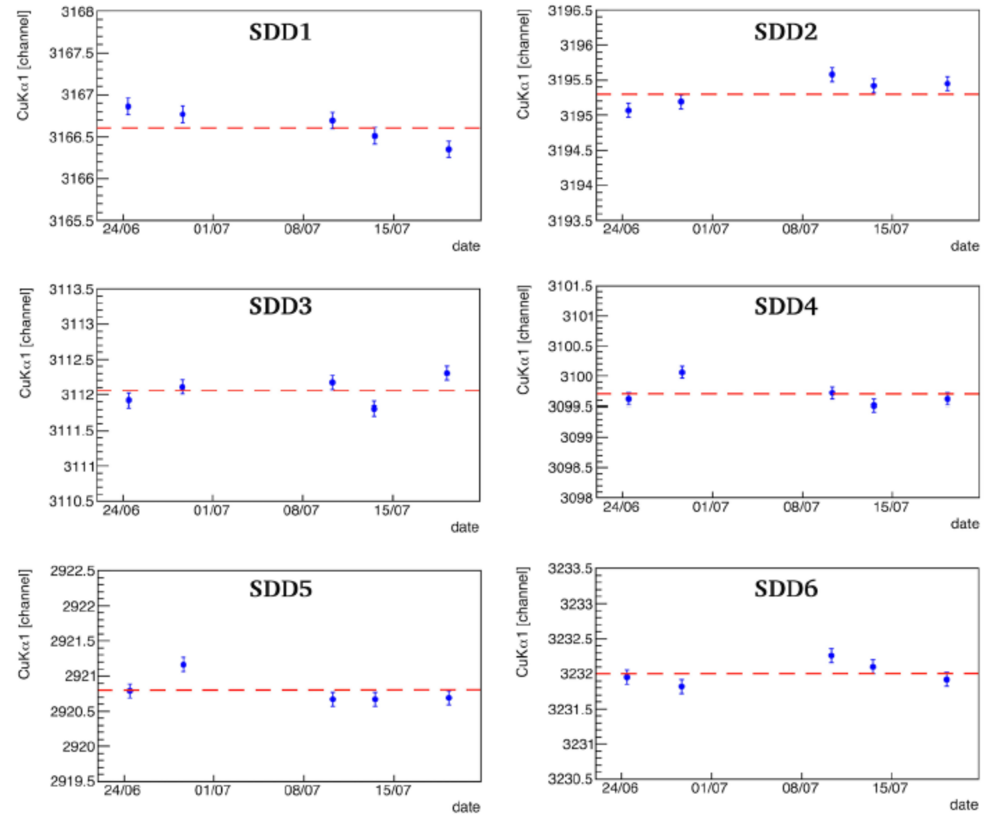

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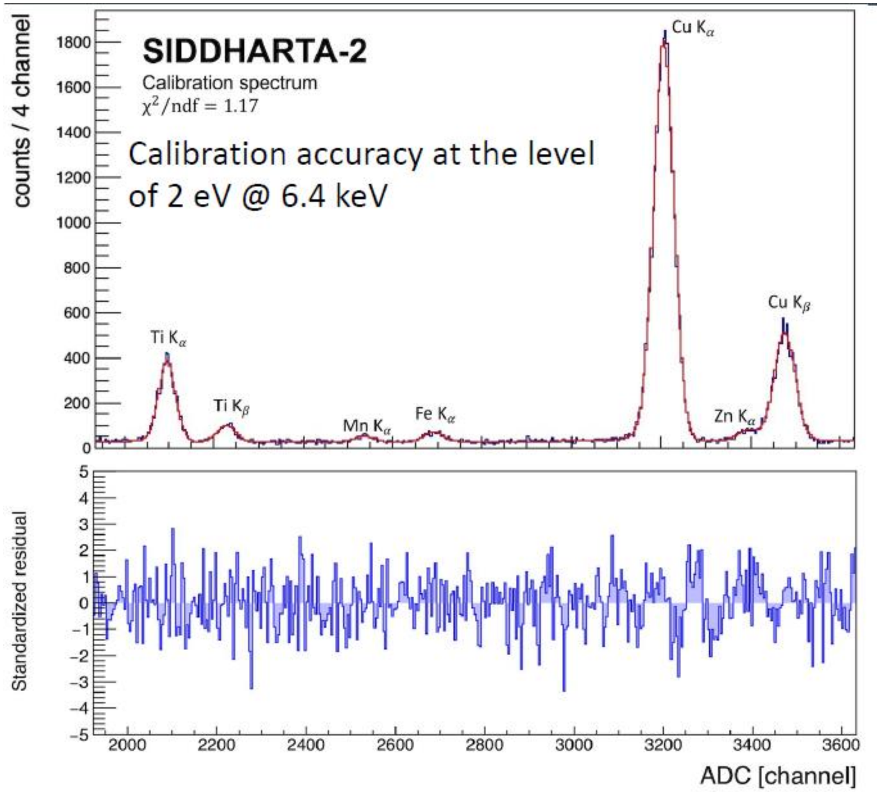

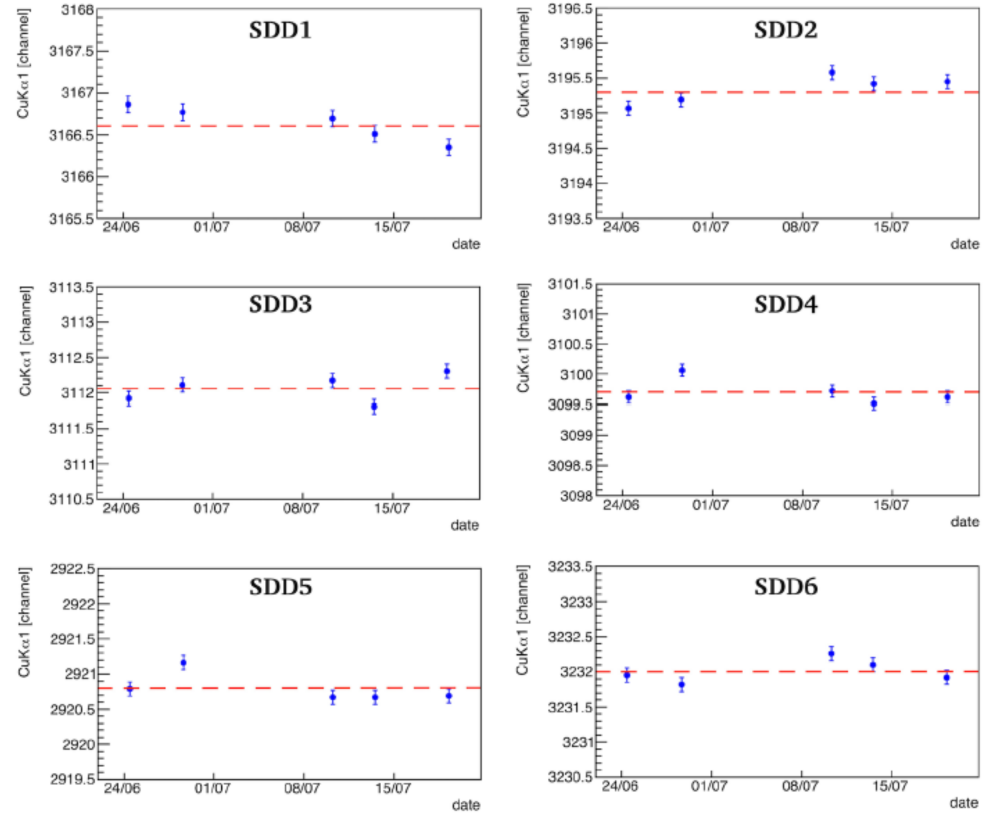

Calibration runs taken on a weekly base (or even more) -> Thousands of spectra to fit
(Very long and time consuming analysis, crucial for systematics)

Kaonic atoms measurements @ DAΦNE

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

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

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

Kaonic atoms measurements @ DAΦNE

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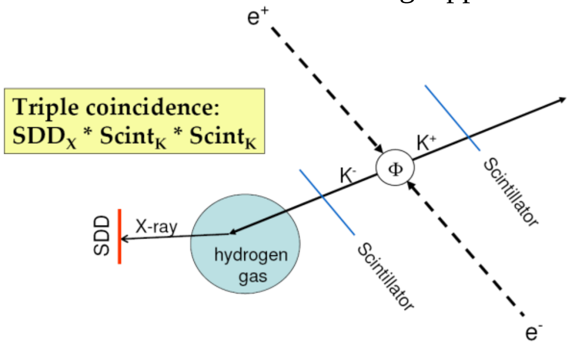

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The combined used of Kaon Trigger and SDDs drift time allows to reduce the asynchronous background by a factor $\sim 2 \cdot 10^4$

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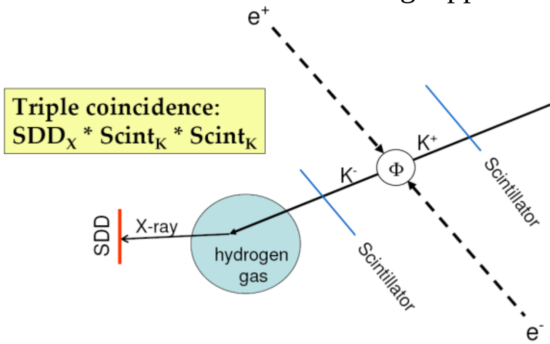

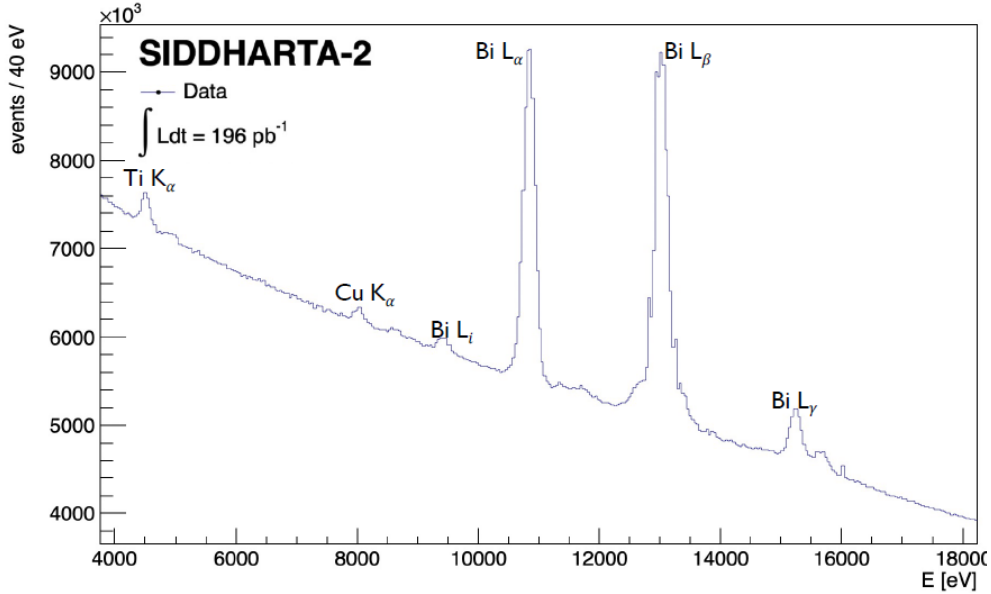

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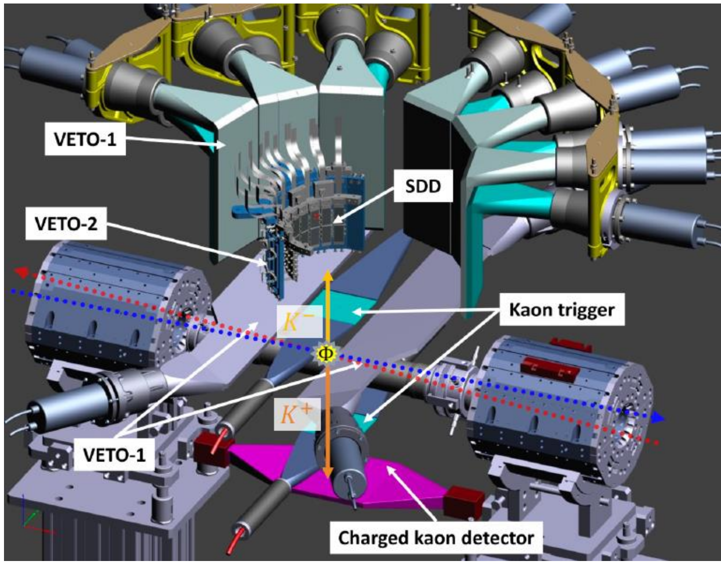
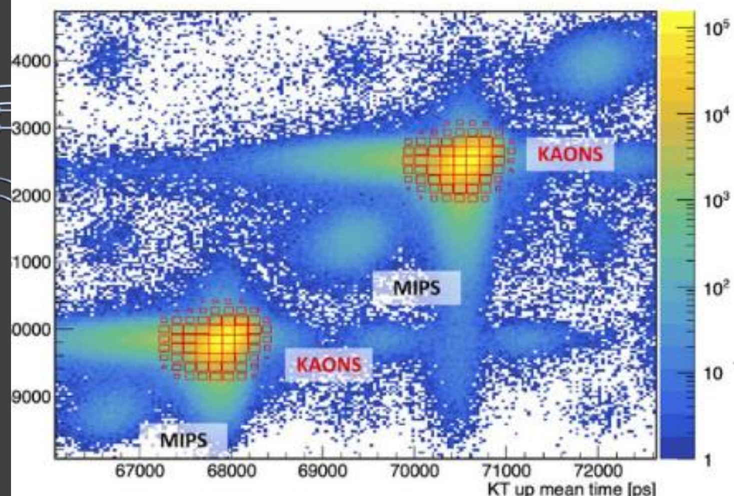
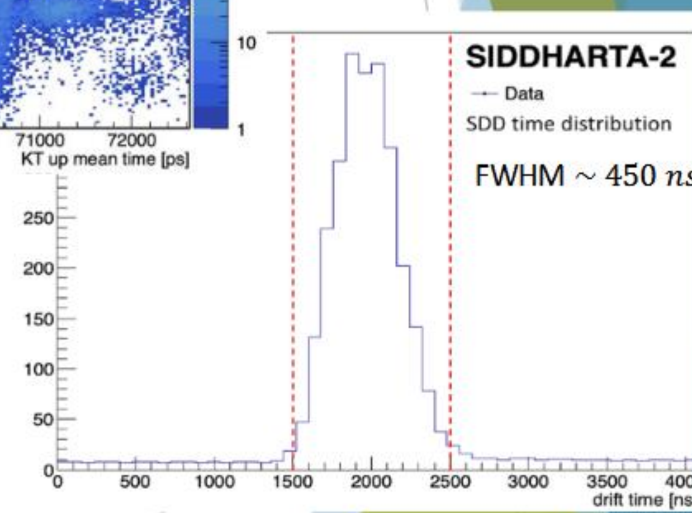




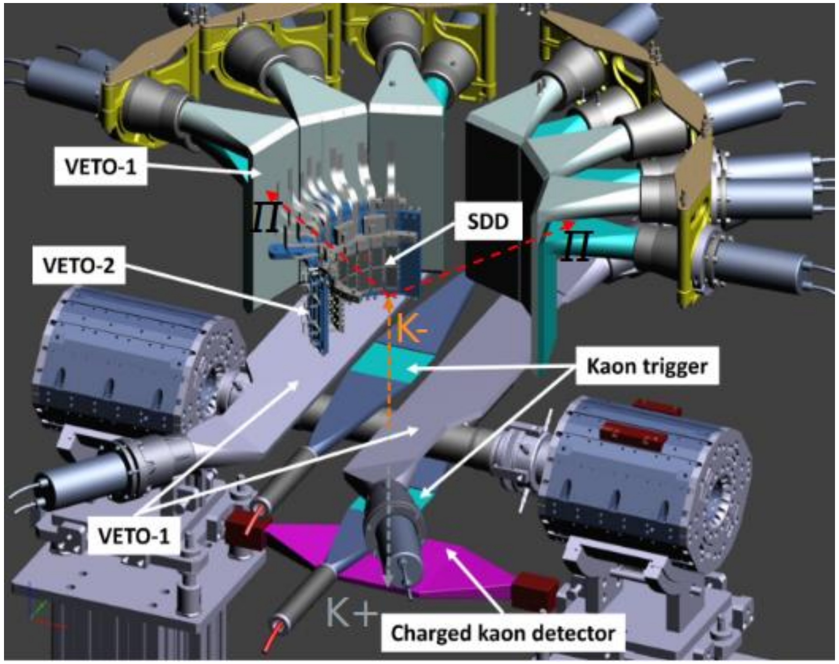


The trigger is generated by the coincidence of 2 back-to-back scintillators

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 VETO-1 system for signal identification



SIDDHARTA-2 is equipped with a VETO system that measure the arrival time of charged particles produced after the K^- absorption.

It can be used to asses if a K^- is stopped in a solid or gaseous target

The VETO-1 system for signal identification

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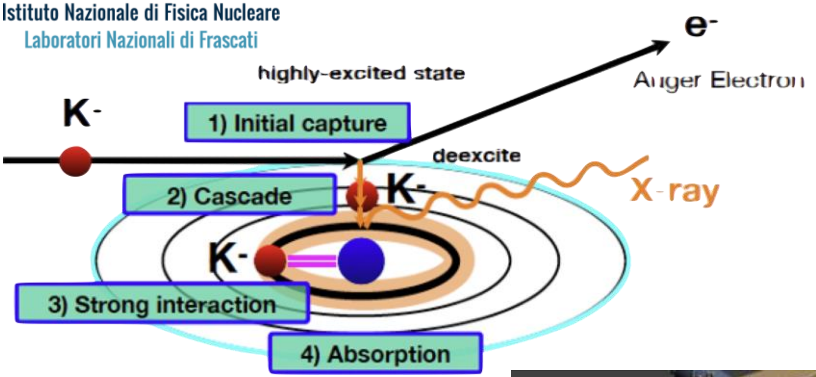

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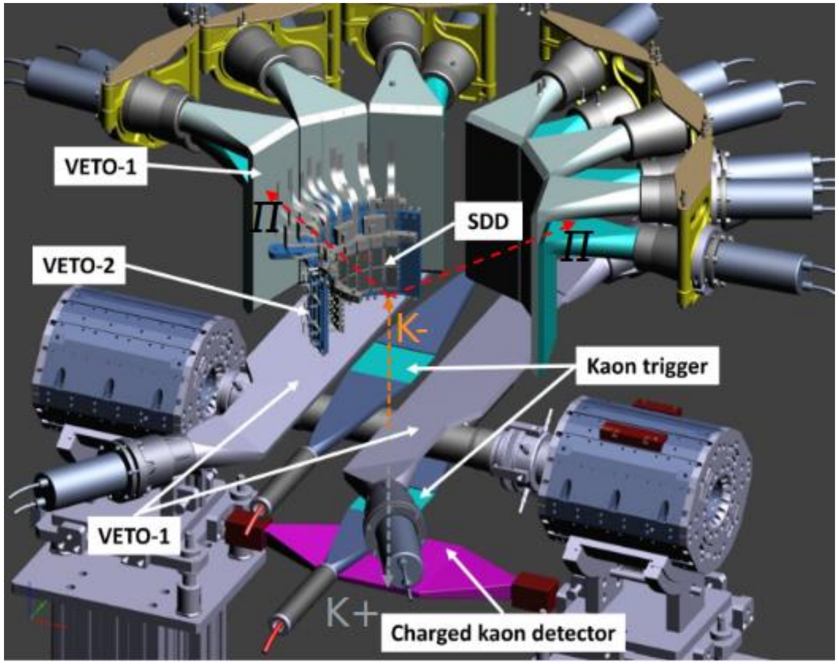

The VETO-1 system takes advantage of the difference of the moderation time of the K- between solid and gaseous targets

The VETO-1 system for signal identification

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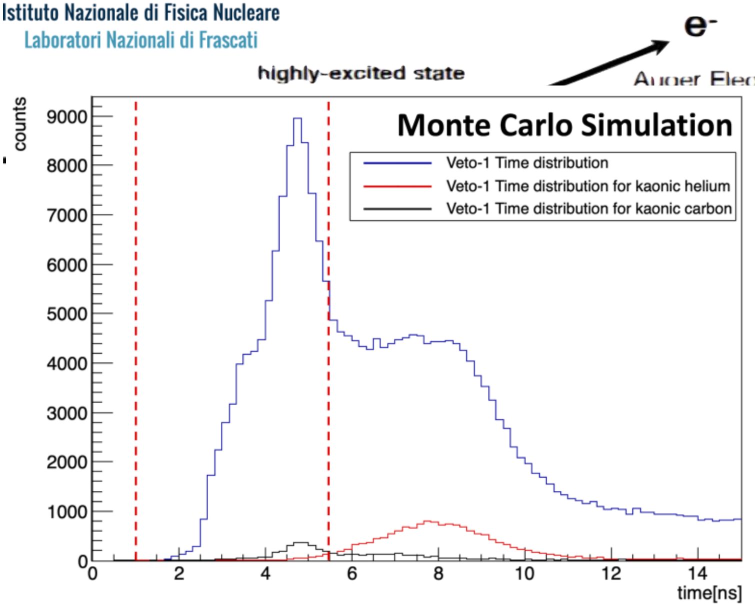
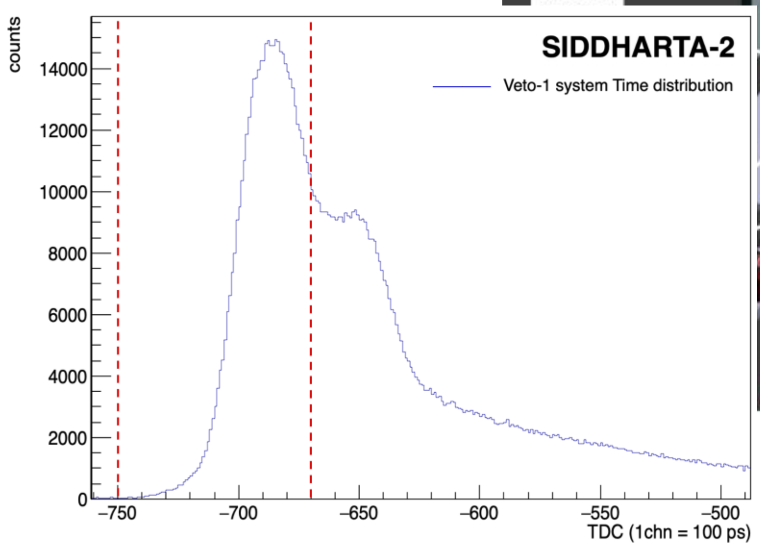
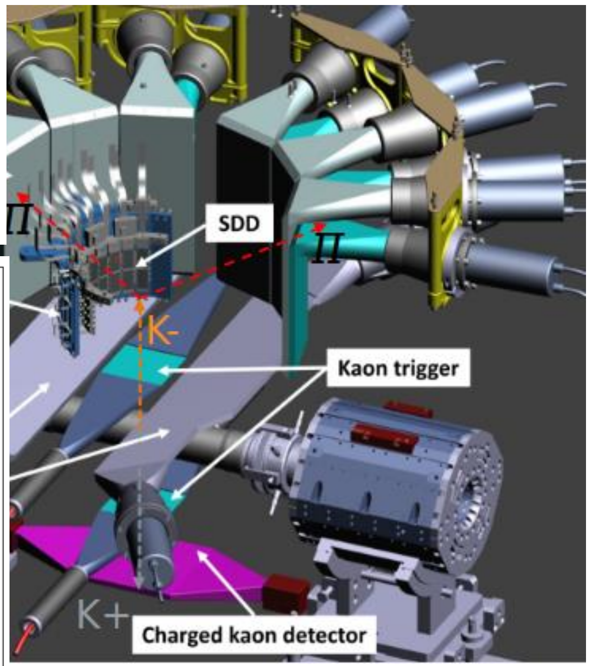




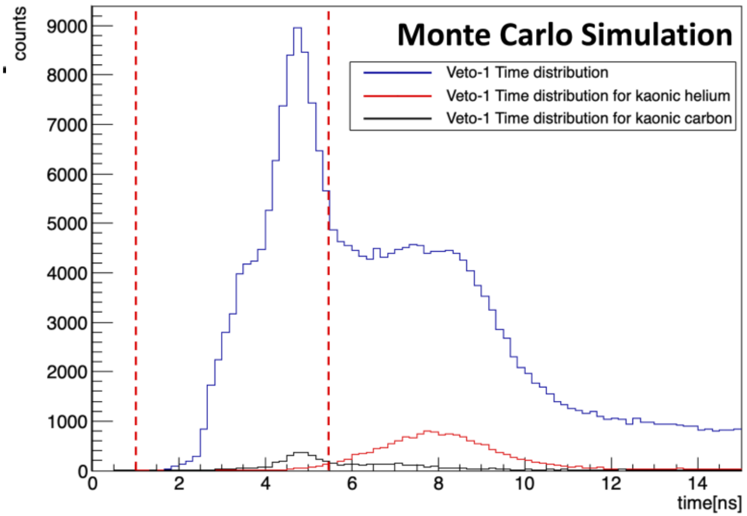


SIDDHARTA-2 is equipped with a VETO system that measure the arrival time of charged particles produced after the K^- absorption.

It can be used to asses if a K^- is stopped in a solid or gaseous target

The VETO-1 system for signal identification

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



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

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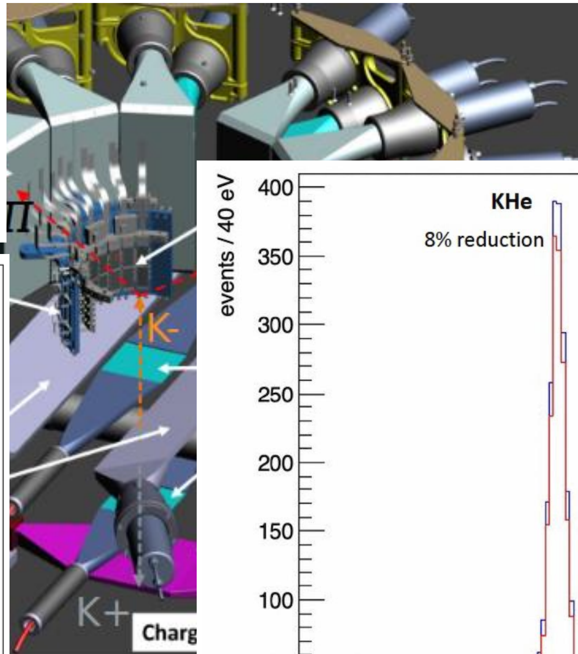

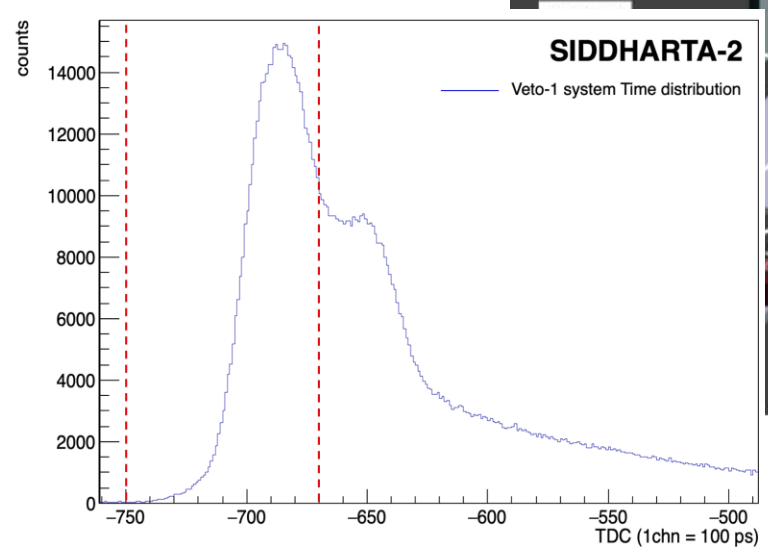

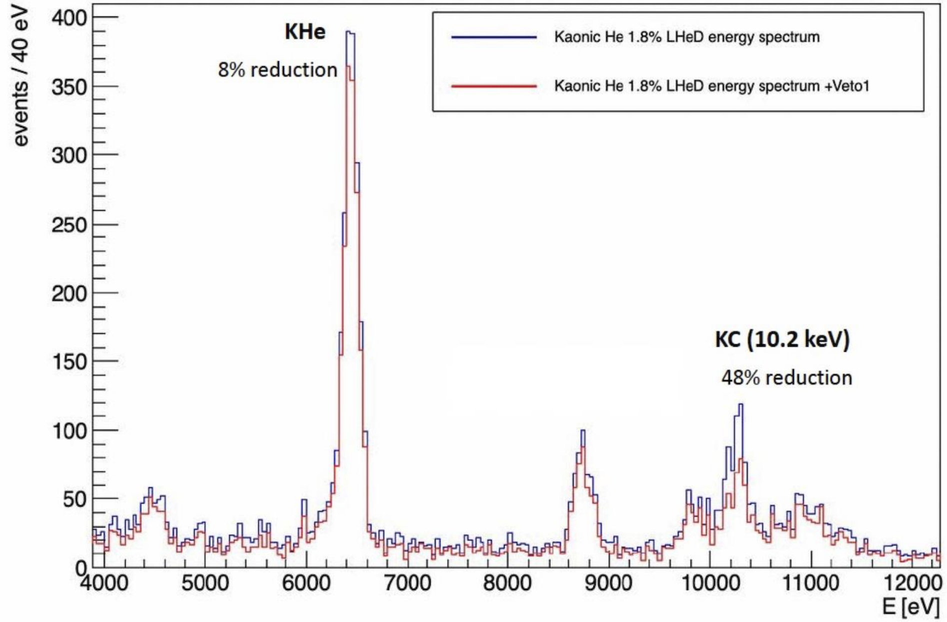

KNe measurement with SDDs

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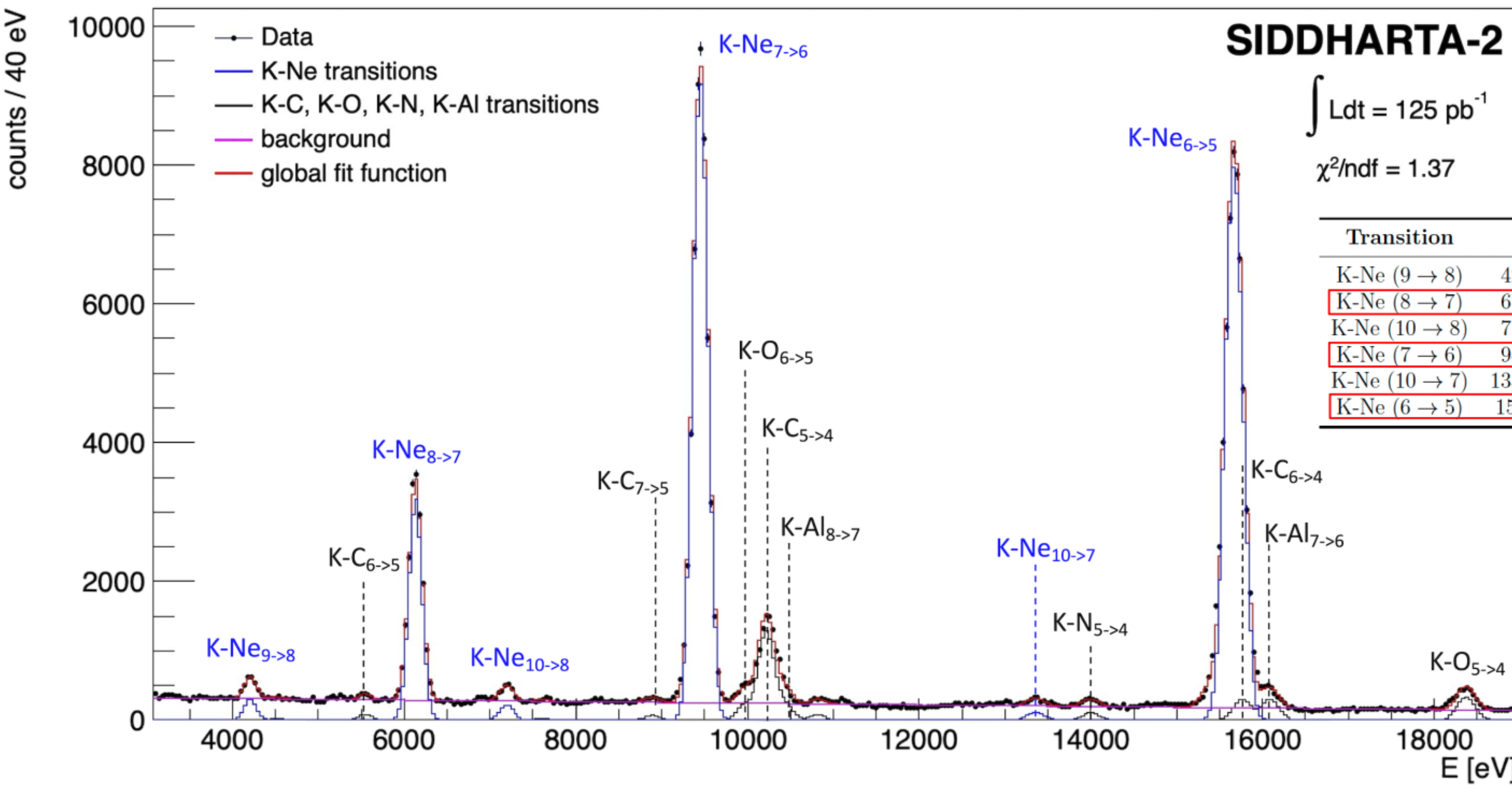
Detectors for
HAdronic **A**tom
Research by
Timing **A**pplication

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

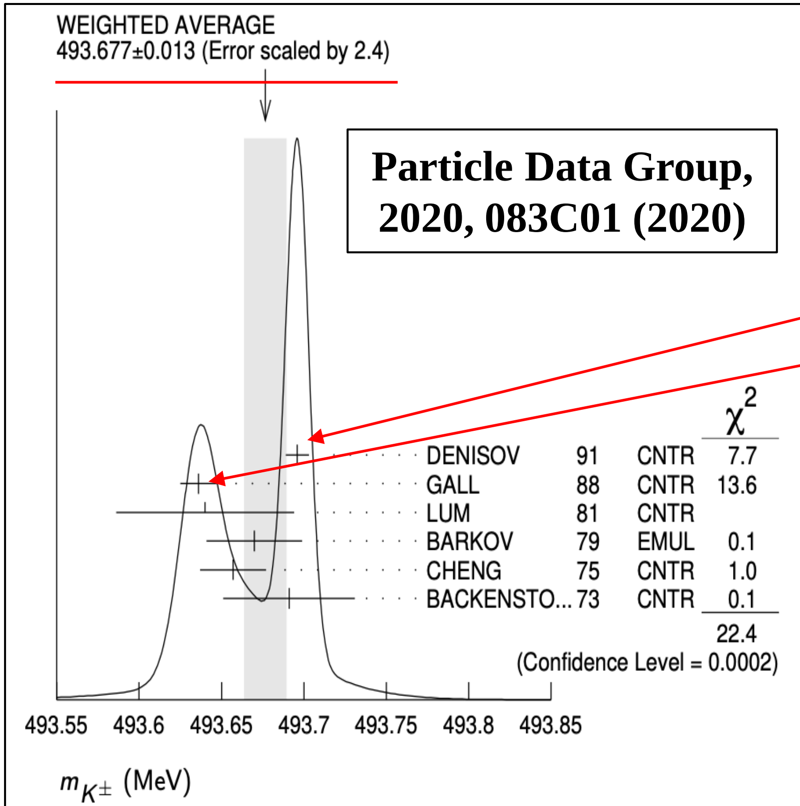


Transition	Energy [eV]
K-Ne $(9 \to 8)$	4206.35 ± 3.75 (stat) ± 2.00 (syst) eV
K-Ne $(8 \to 7)$	6130.86 ± 0.71 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 8)$	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV
K-Ne $(7 \to 6)$	9450.08 ± 0.41 (stat) ± 1.50 (syst) eV
K-Ne $(10 \to 7)$	13352.20 ± 10.07 (stat) ± 3.00 (syst)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

Paper submitted and under review

The K$^-$ mass problem

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



Large uncertainty → 26 p.p.m, compared to charged pion:

$m_\pi = 139.57061 \pm 0.00023$ MeV, 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	±	$e^+ e^- \rightarrow K^+ K^-$
493.657±0.020	[2] CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	−	Kaonic atoms

60 keV discrepancy between the two most accurate measurements

Kaon mass precision is still a crucial open issue in strangeness nuclear physics

Kaon mass puzzle can be addressed with HPGe detectors on solid targets (to repeat GALL KPb measurement)

Kaon mass puzzle can be addressed with SDD detectors on gaseous targets (attempt with KNe transitions)

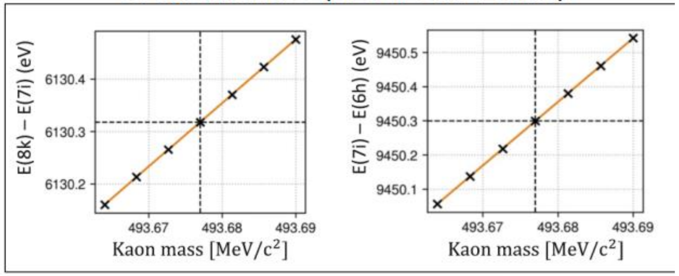
m_{K^-} with KNe

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

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

Less/different systematic uncertainty with respect to DENISOV 91 and GALL 88 measurements, thanks to the use of a low Z gas target

Kaonic Ne energy transition as function of kaon mass (MCDFGME code)



Santos, J. & Parente, F. & Indelicato, Paul & Desclaux, J.. (2005). X-ray energies of circular transitions and electron screening in kaonic atoms. Physical Review A. 71.10.1103/PhysRevA.71.032501.

m_{K^-} with KNe

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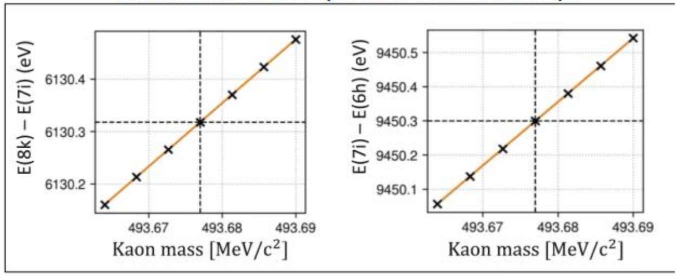

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$$K - Ne(8 \rightarrow 7) = \frac{A_G}{\sqrt{2\pi}\sigma} \cdot e^{\frac{-(E-E_0)^2}{2\sigma^2}} \quad E_0 = (m_{8\rightarrow 7} \cdot K_{mass} + q_{8\rightarrow 7})$$

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

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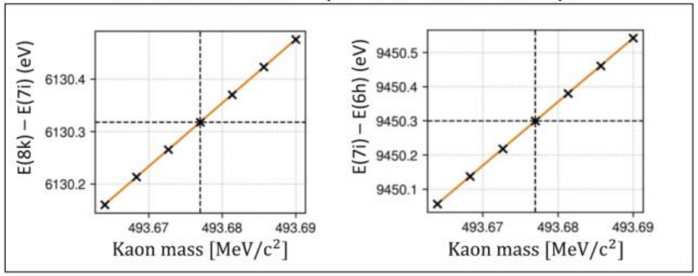

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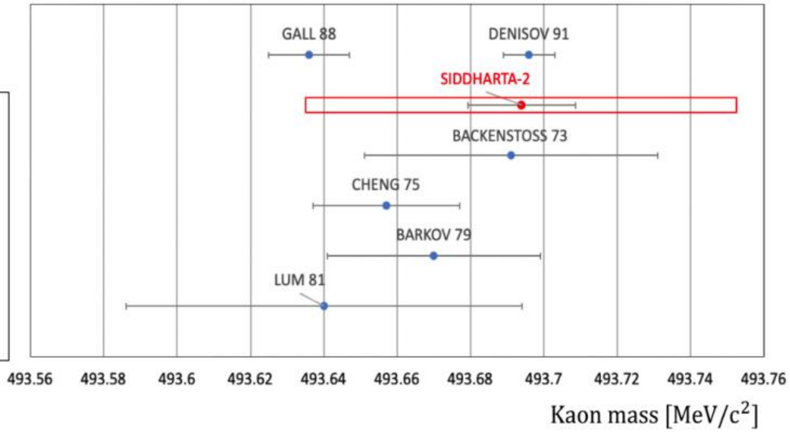

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Measurement	Kaon mass [MeV]
DENISOV 91 [23]	493.696 ± 0.007
GALL 88 [22]	493.636 ± 0.011
LUM 81 [114]	493.640 ± 0.054
BARKOV 79 [115]	493.670 ± 0.029
CHENG 75 [116]	493.657 ± 0.020
BACKENSTOSS 73 [117]	493.691 ± 0.040
This work	493.694 ± 0.015 (stat) ± 0.060 (syst)

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Kd (2p->1s) measurement with SDDs

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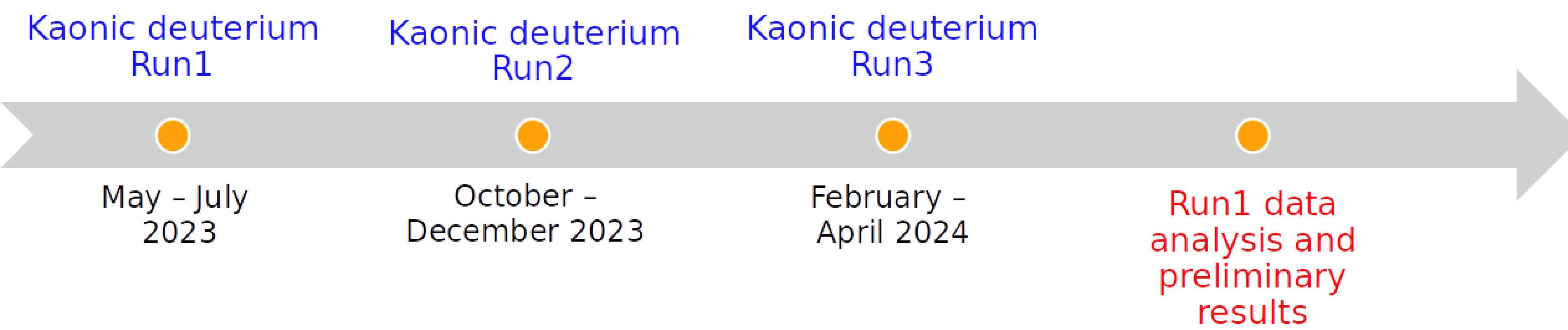
The SIDDHARTA-2 collaboration aims **to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state with similar precision as K-p !**

- **First run** with SIDDHARTA-2 optimized setup for **200 pb^{-1}** integrated luminosity: May – July 2023
- **Second run** - October – December 2023: **344 pb^{-1}**
- **Third run** 2024 - February – April 2024: **435 pb^{-1}**



Kd (2p->1s) measurement with SDDs

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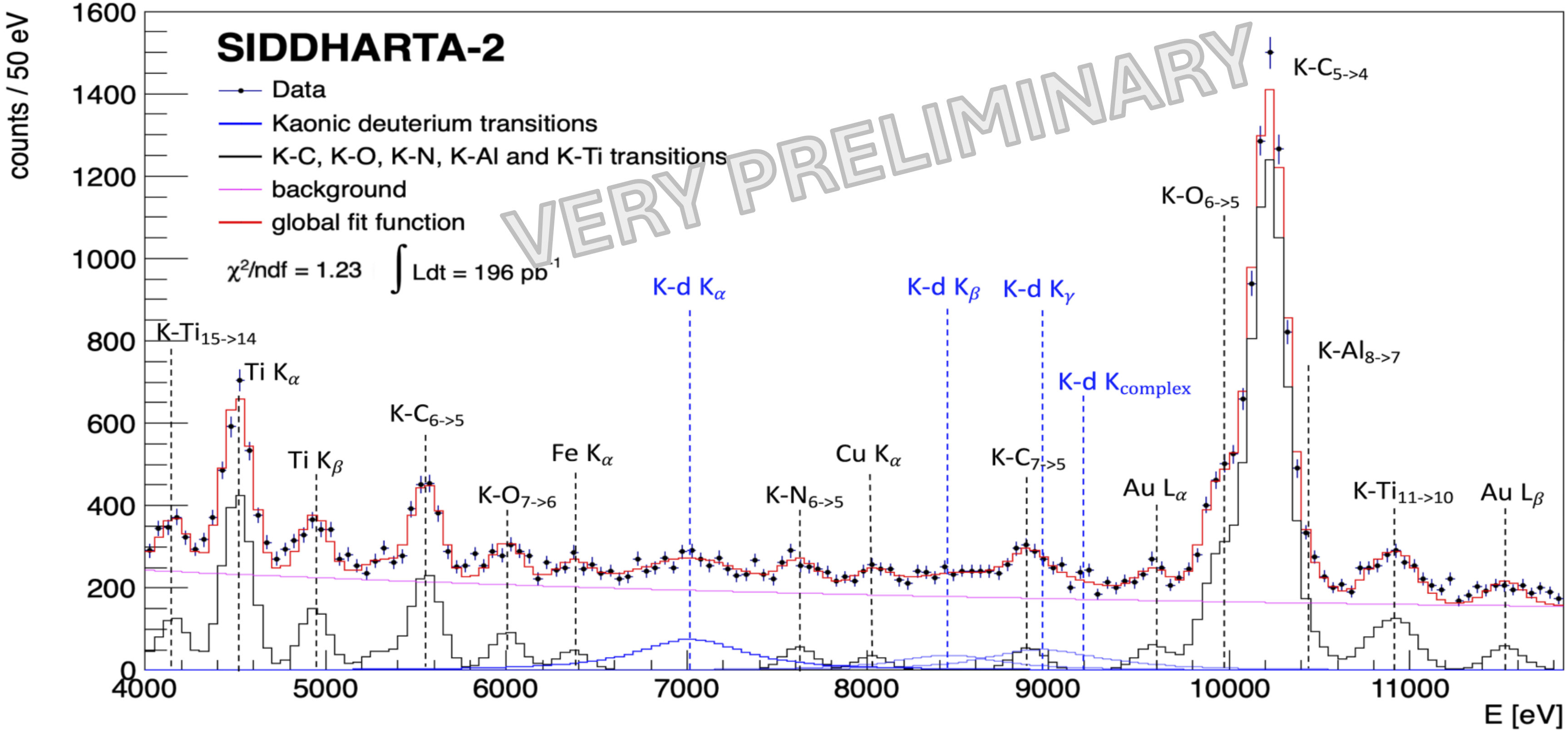

From 2p->1s transition (Kα):

ε_{1s}: -816 ± 53 (stat) ± 2(syst) eV
Γ_{1s}: 756 ± 271 (stat)

From (n>2)->1s transition:

ε_{1s}: -813 ± 56 (stat) ± 2(syst) eV
Γ_{1s}: 751 ± 280 (stat)

Kd (2p->1s) measurement with SDDs

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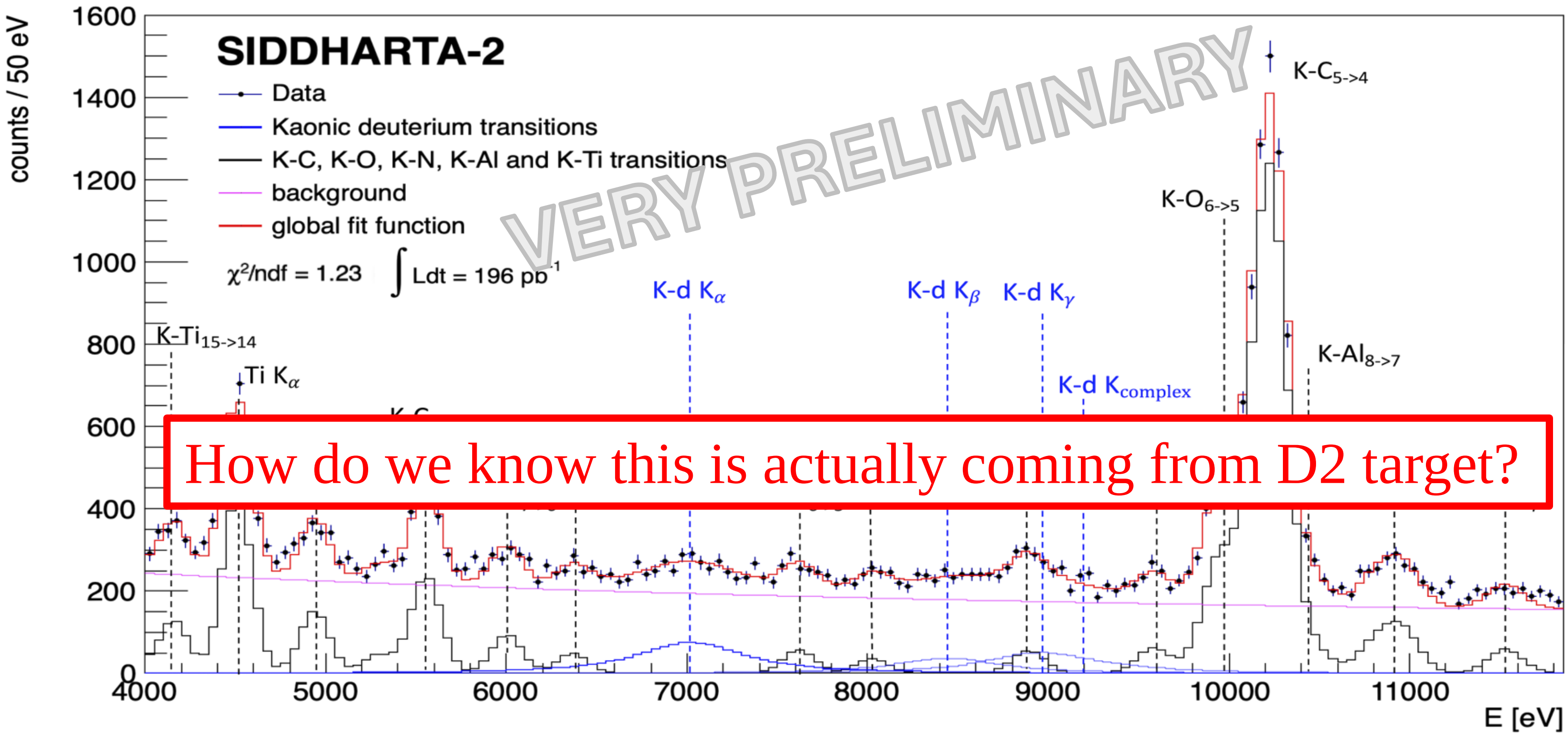

How do we know this is actually coming from D2 target?

From 2p->1s transition (Kα):

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Kd (2p->1s) measurement

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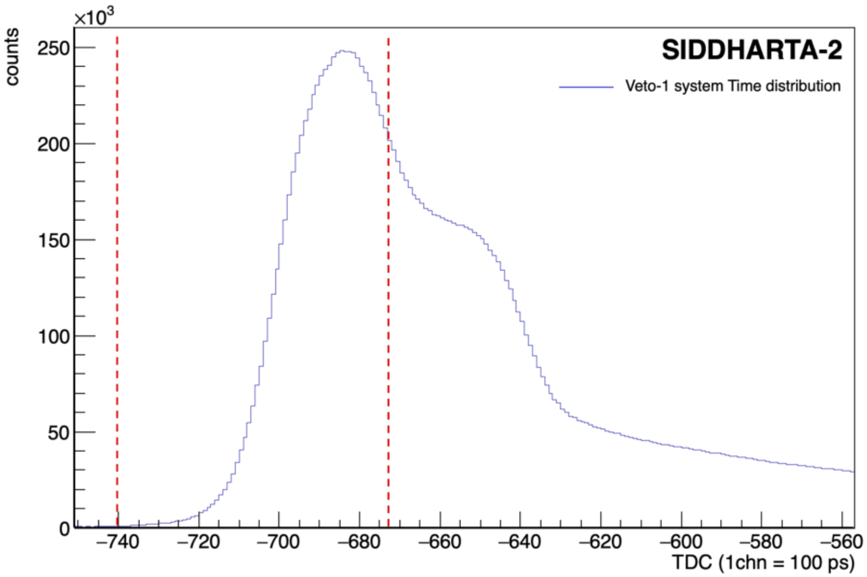

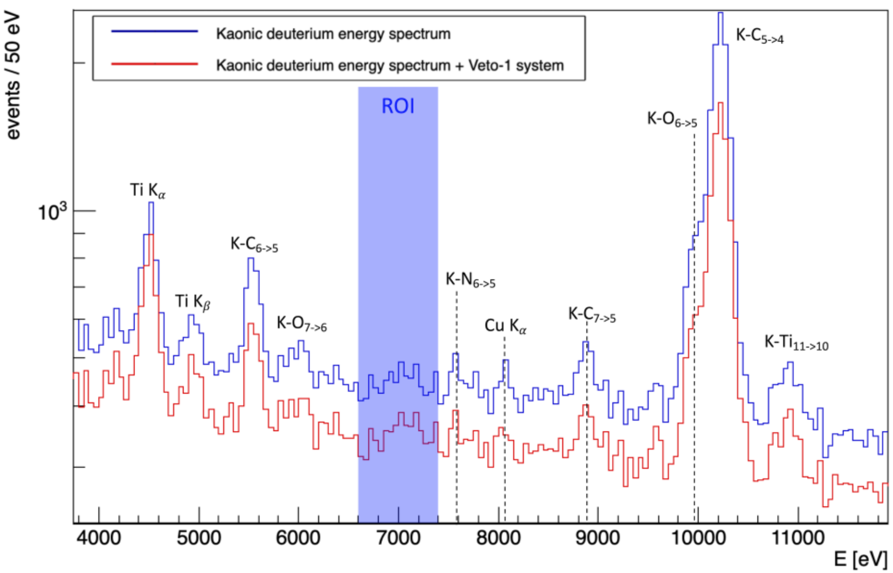

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Kd (2p->1s) measurement

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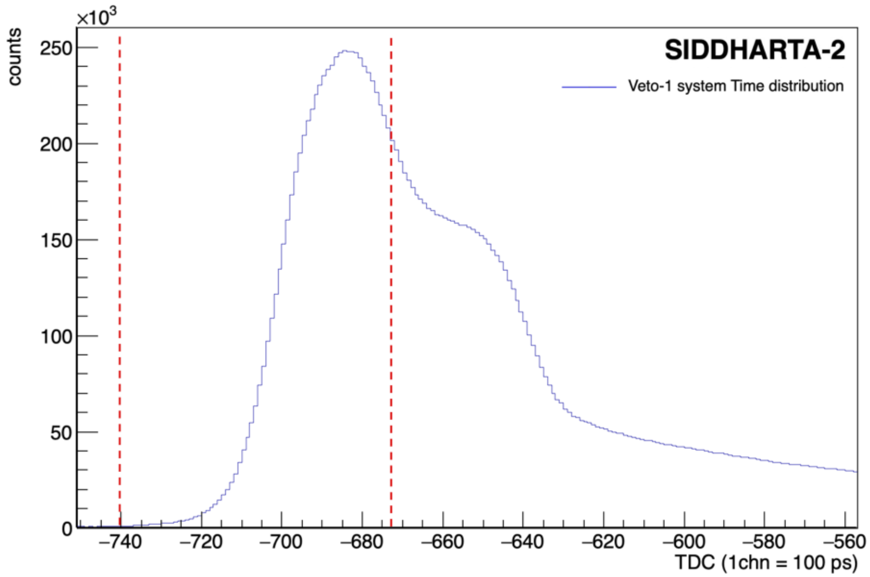

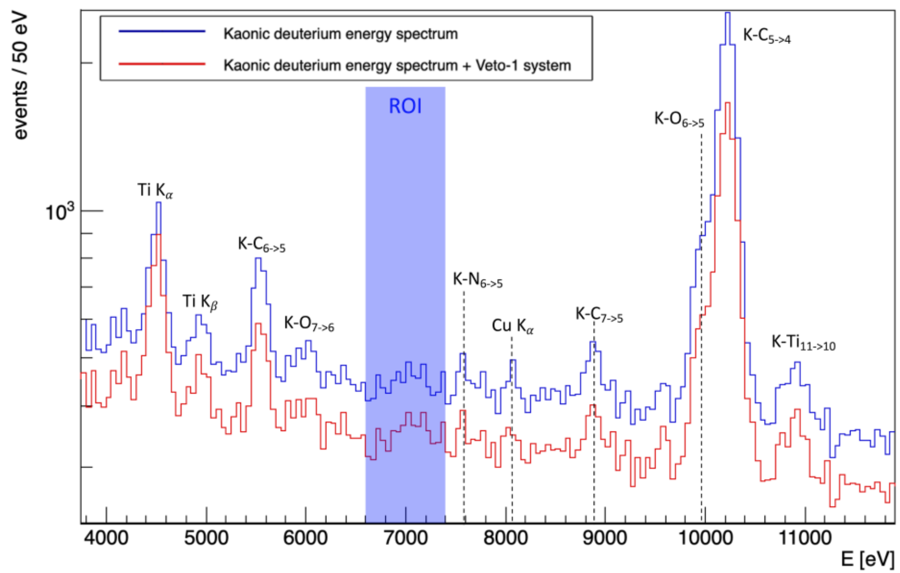

	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-d K_α	$(11 \pm 3)\%$	4%
K-$C_{5\to4}$	$(44 \pm 4)\%$	46%
K-$C_{6\to5}$	$(39 \pm 5)\%$	45%
K-$C_{7\to5}$	$(48 \pm 4)\%$	46%

Kd (2p->1s) measurement

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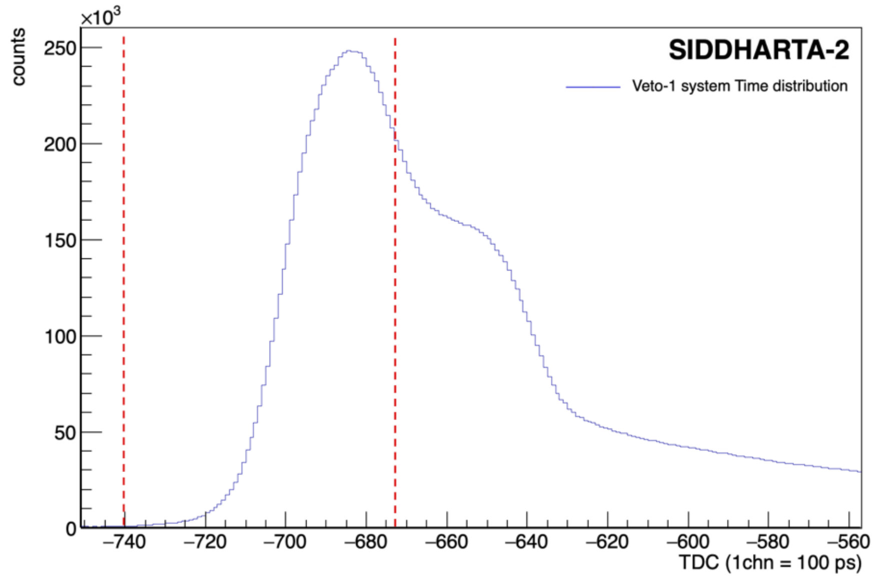

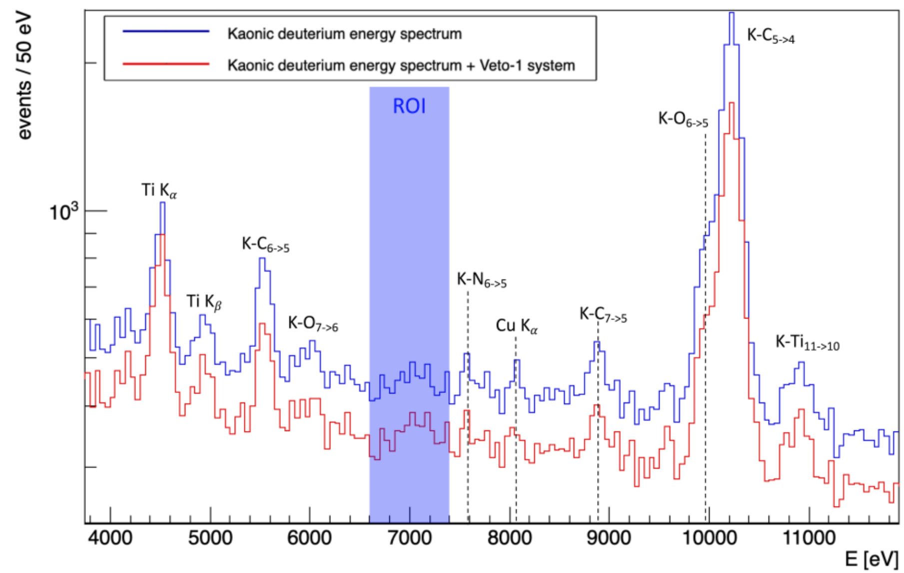

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Kd (2p->1s) measurement

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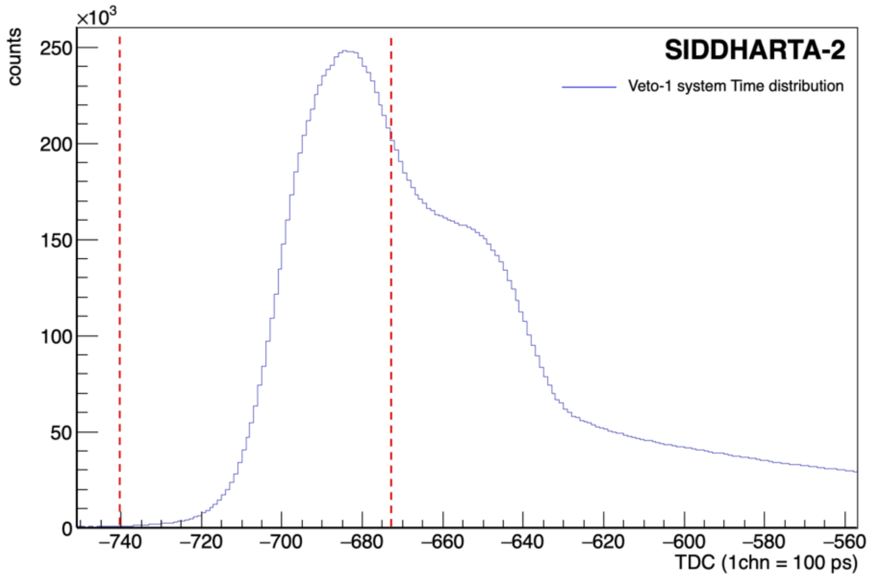

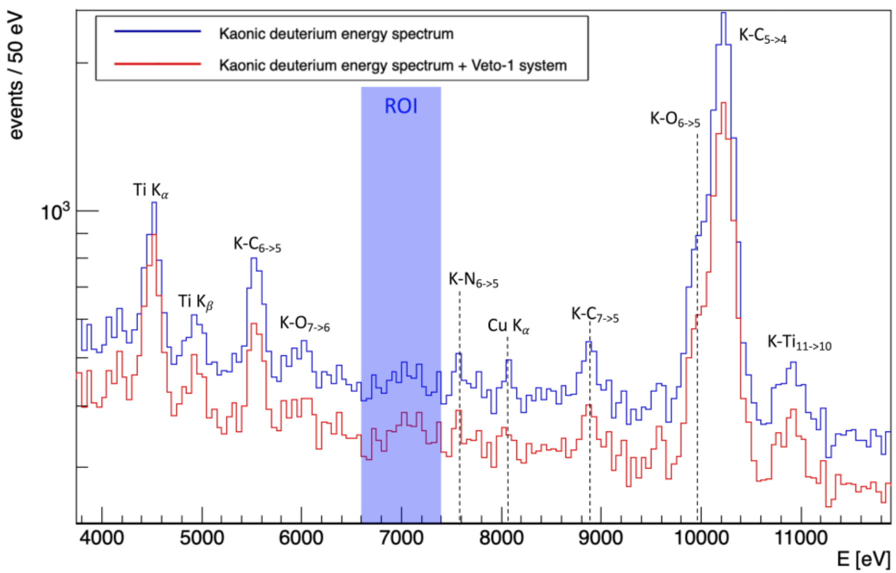

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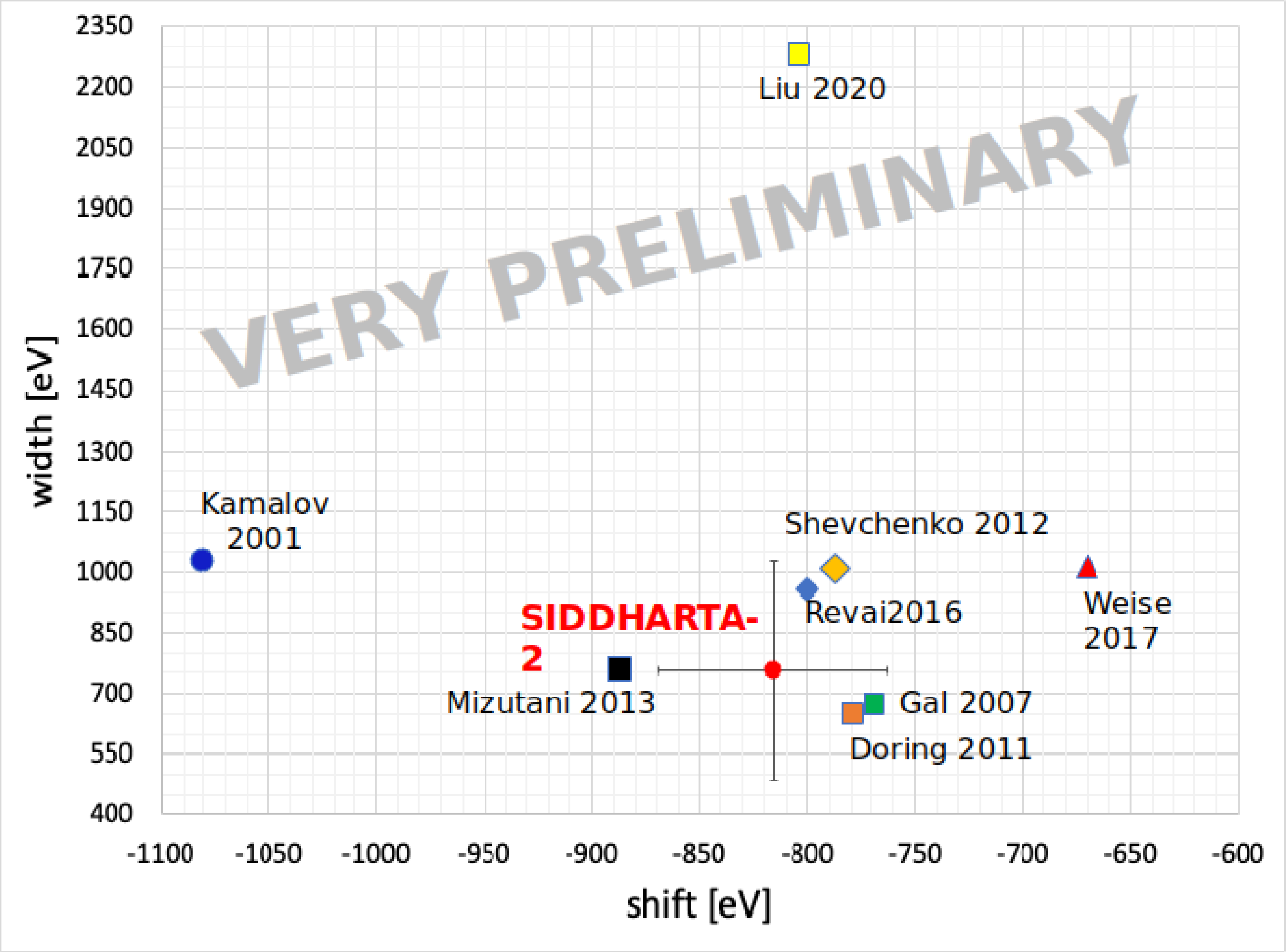
Signals in the ROI are actually produced in the D_2 gaseous target

Kd (2p->1s) measurement with SDDs

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



Kd (2p->1s) measurement with SDDs

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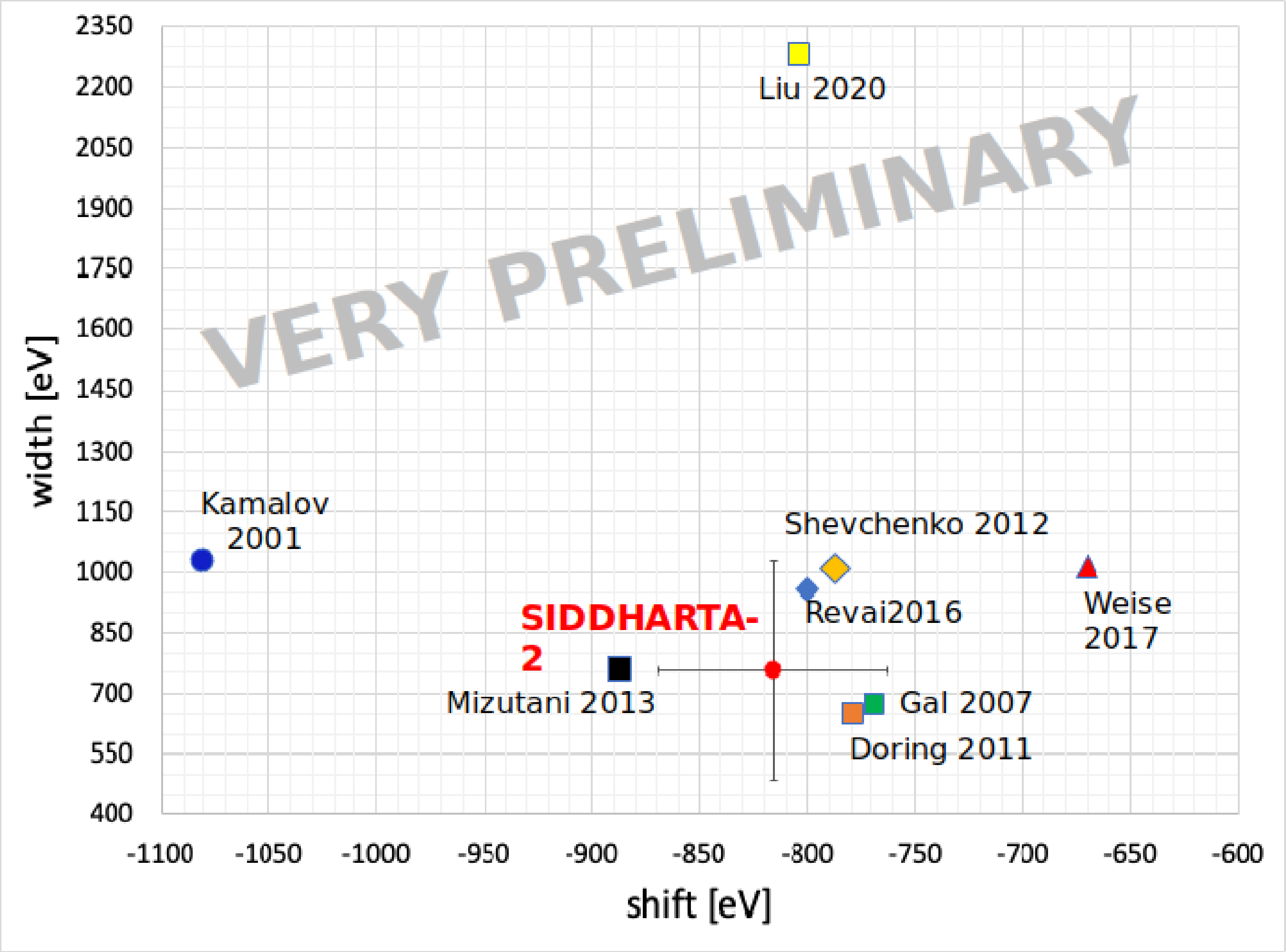


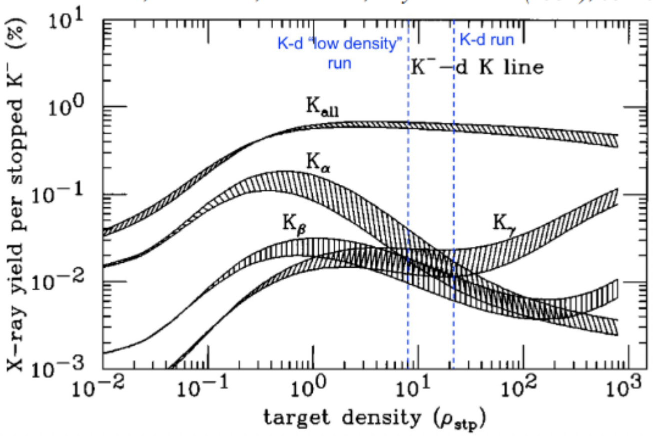
The analysis of the full dataset can potentially improve the statistical accuracy by a factor 2

(precision similar to kaonic hydrogen measurement)

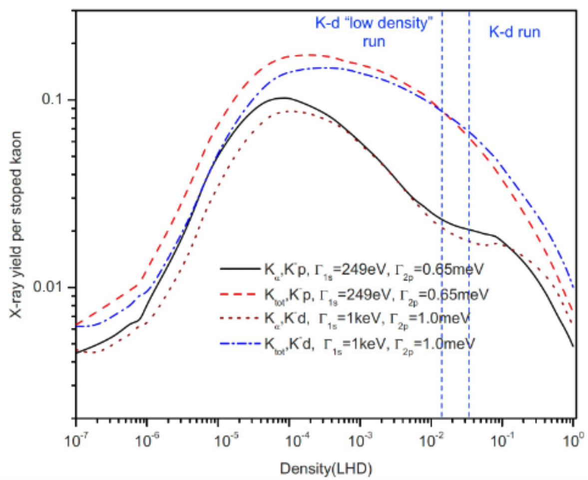
Kd (2p->1s): the yield puzzle

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

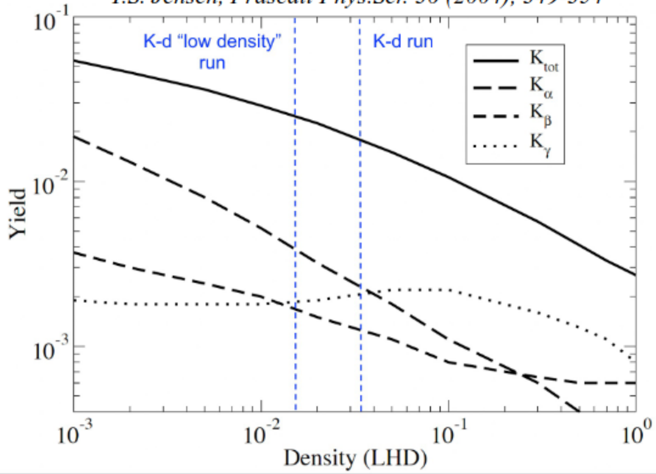
T. Koike, T. Harada, Y. Akaishi, Phys.Rev.C 53 (1996), 79-87



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



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



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

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Kd (2p->1s): the yield puzzle

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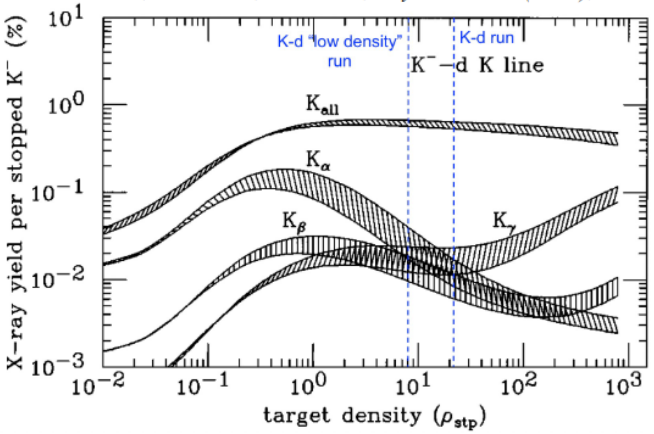

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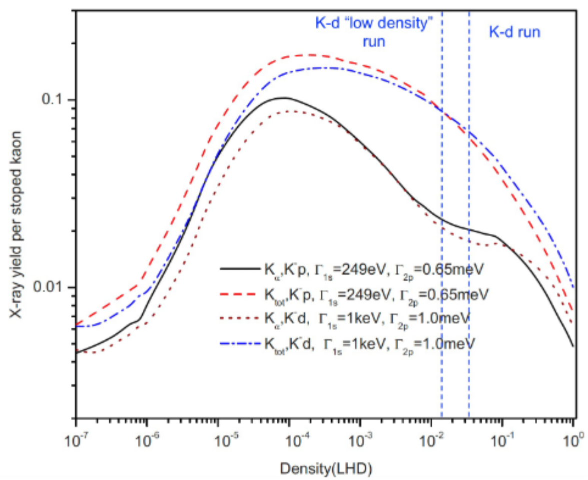
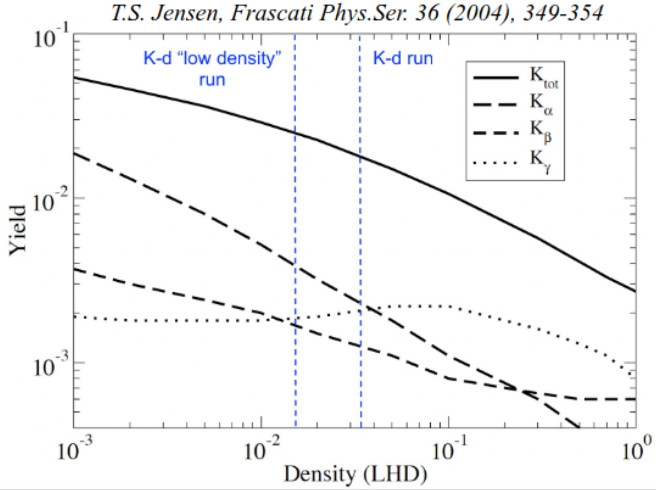


T.S. Jensen, Frascati Phys.Ser. 36 (2004), 349-354



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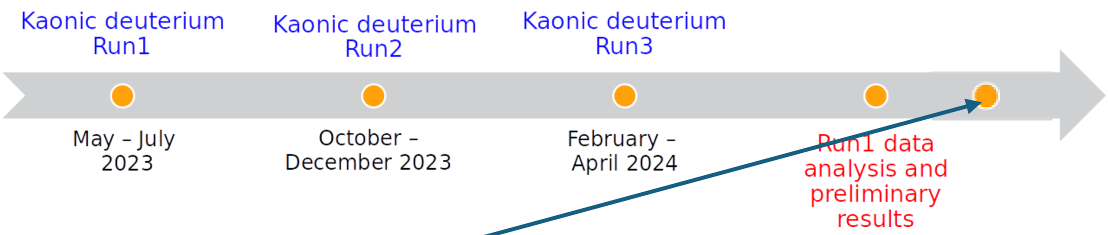

Additional Run (Run4) : April-July 2024, ~ 200 pb-1, 0.8% LDD

Goal: provide a second point to disentangle between cascade models

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Results (1)

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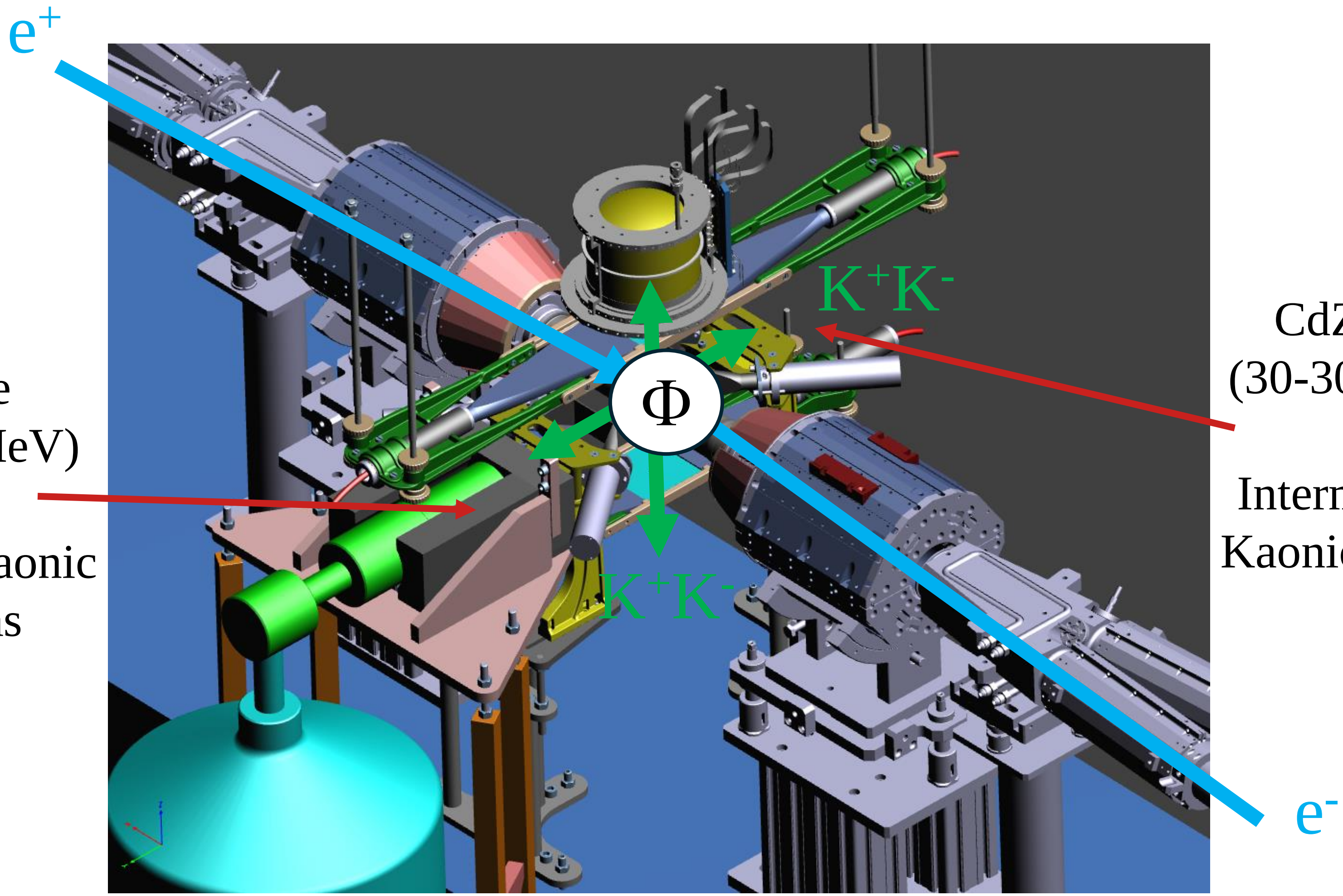
KHe L-transition measurement in gas : *J. Phys. G 49 (2022) 5, 055106*
Kaonic helium-4 yields L-lines in gas : *Nucl. Phys. A 1029 (2023) 122567*
First measurement of intermediate mass kaonic atoms: *Eur. Phys. J. A 59(2023)3, 56*
First Measurement of KHe M-lines : *J. Phys. G (2024) 51 055103*
First Measurement of kaonic Neon (stat. precision < 1 eV) *Paper submitted and under review*
First measurement of Kaonic Deuterium: preliminary analysis

Kaonic atoms measurements @ DAΦNE

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



HPGe (0,2-1 MeV)

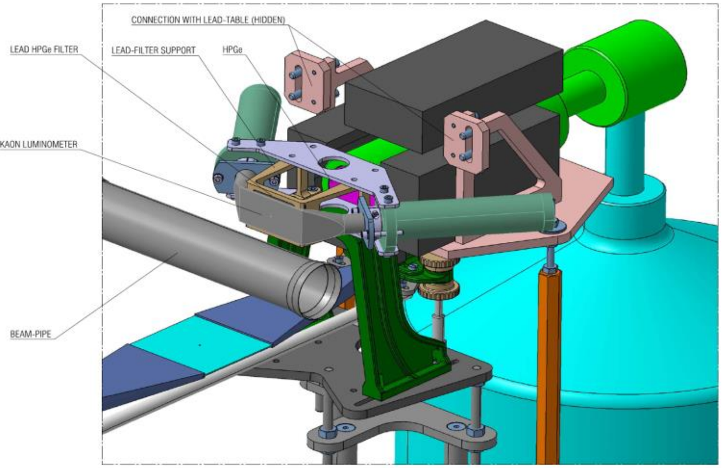
Heavy Kaonic Atoms

CdZnTe (30-300 keV)

Intermediate Kaonic Atoms

KPb measurement with HPGe detector

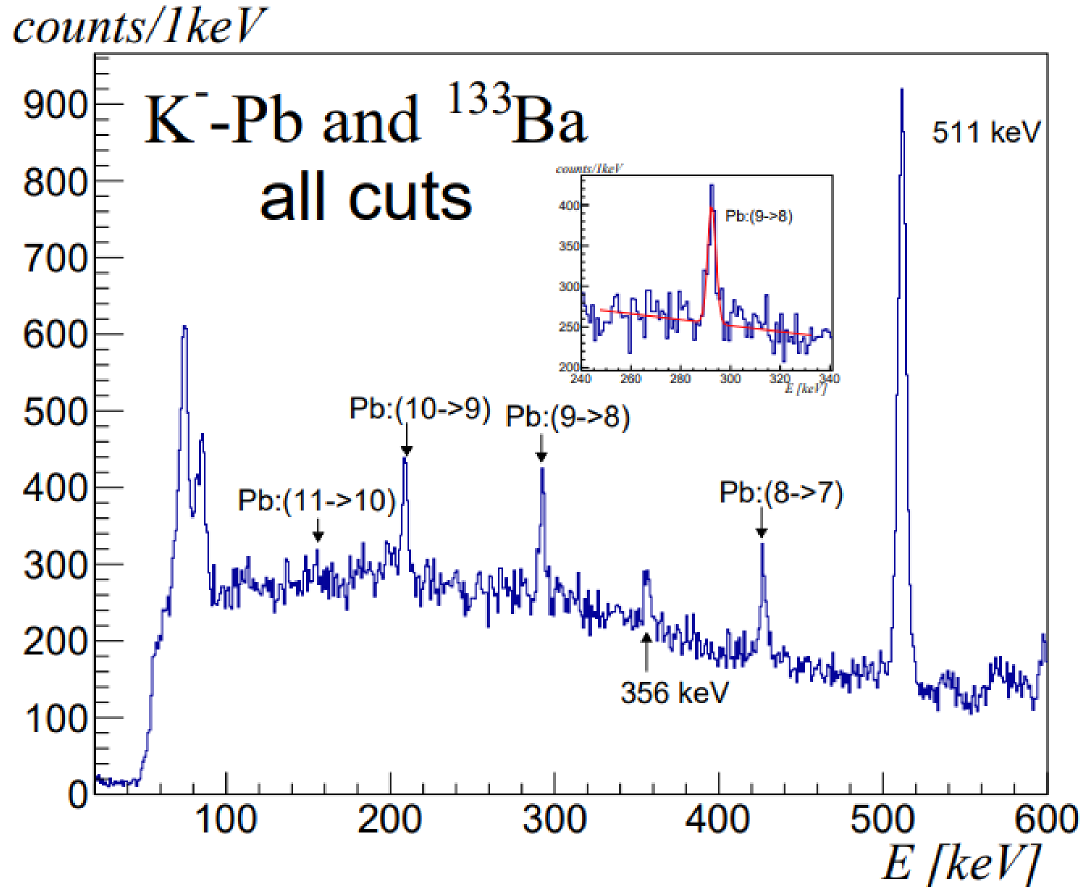
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



Feasibility test measurement of KPb transitions, including the GALL 88 one

First technical paper published

Nucl.Instrum.Meth.A 1069 (2024) 169966



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

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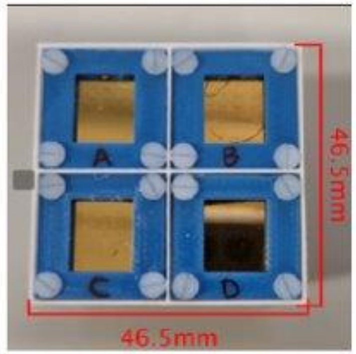
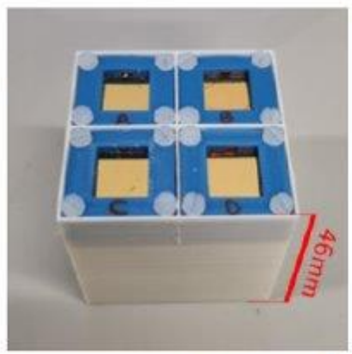
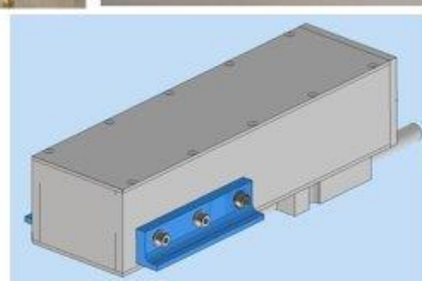
Intermediate mass Kaonic (only?) Atoms with CdZnTe

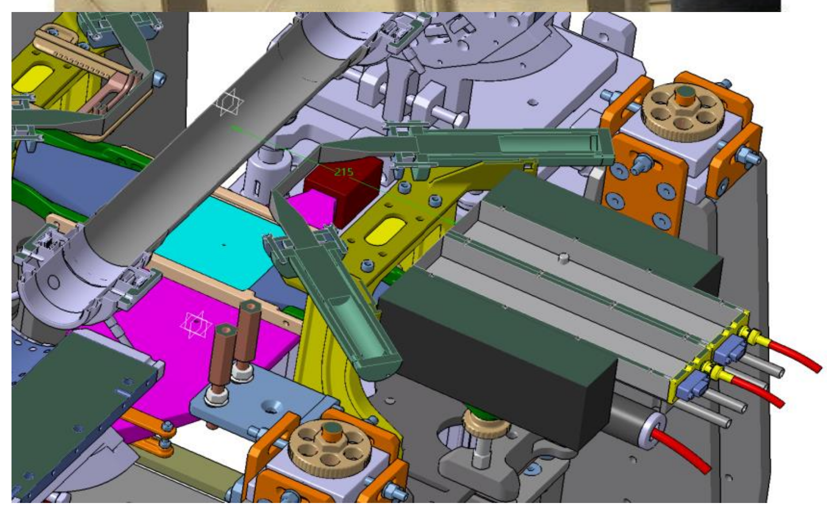
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication





8 (4+4)
1,3x1,5x0,5 cm^3
CZT hemispherical
detectors

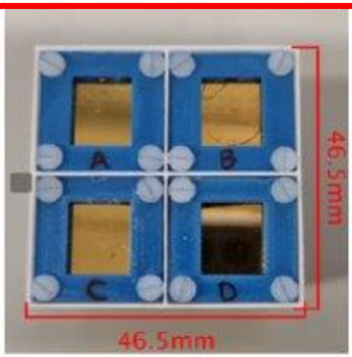


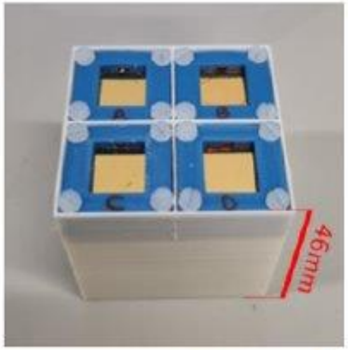


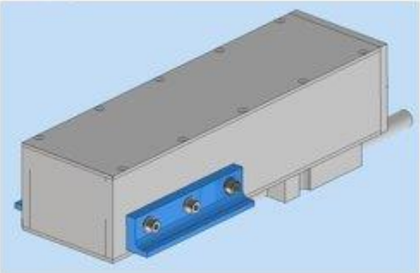
Intermediate mass Kaonic (only?) Atoms with CdZnTe

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

Feasibility test: CdZnTe detectors first use in particle accelerators or colliders







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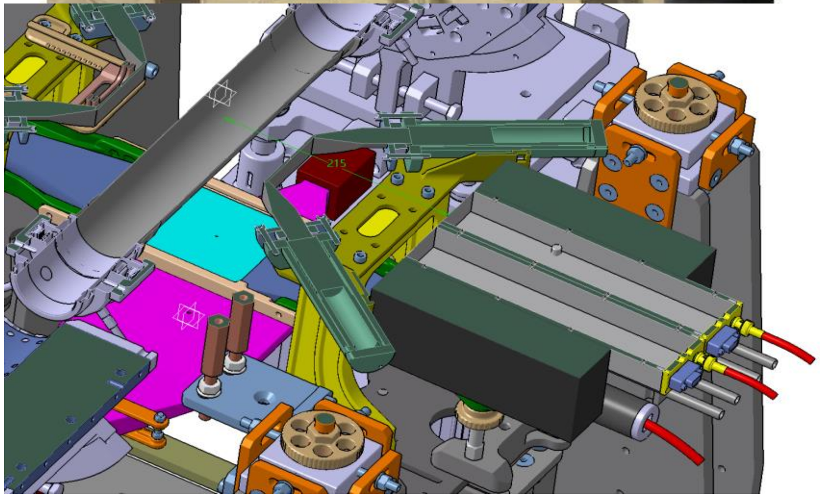
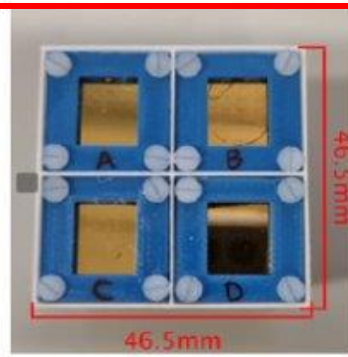


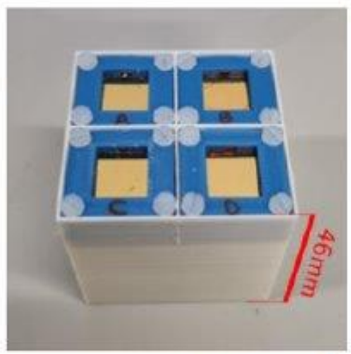
Intermediate mass Kaonic (only?) Atoms with CdZnTe

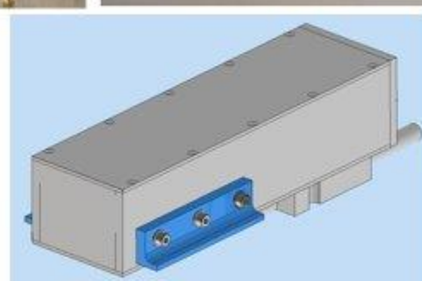
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

Feasibility test: CdZnTe detectors first use in particle accelerators or colliders

CZT
- FWHM / E ~ %
- ~ 10 ns time resolution
- Working T ~ 300 K
- keV – MeV wide energy range







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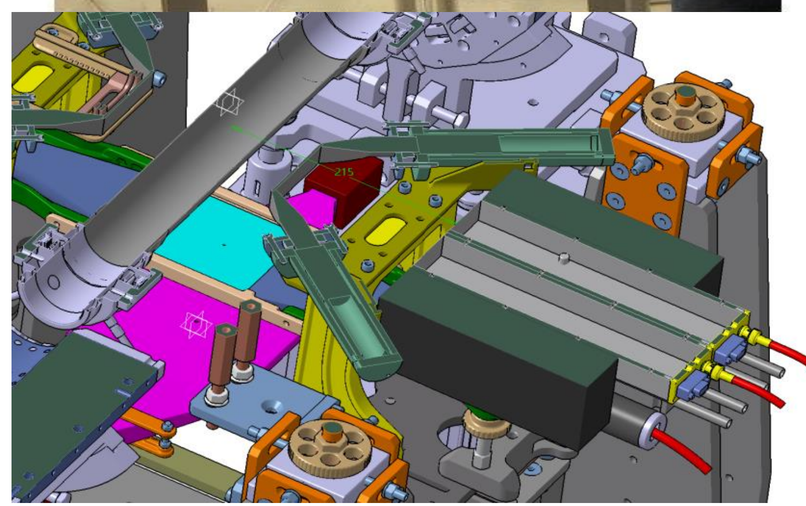
CZT hemispherical detectors



Intermediate mass Kaonic (only?) Atoms with CdZnTe

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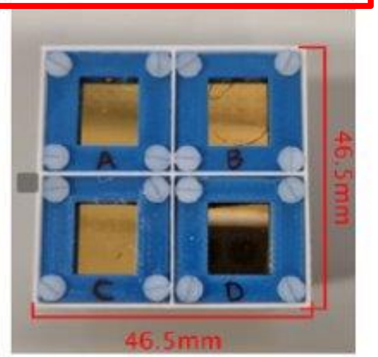
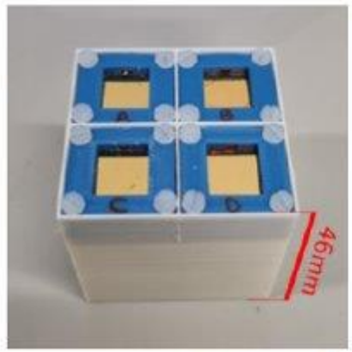
CZT
- FWHM / E ~ %
- ~ 10 ns time resolution
- Working T ~ 300 K
- keV – MeV wide energy range

Work in collaboration between

LNF: Setup Assembly and data analysis
IMEM-CNR: Detectors production
UniPa: Front-end and digital electronics
SMI: Mechanical supports and detectors' box





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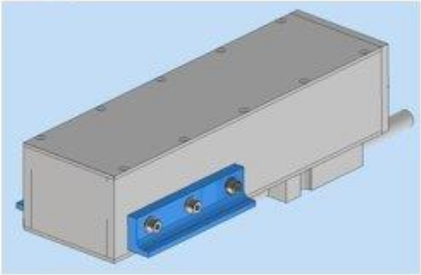
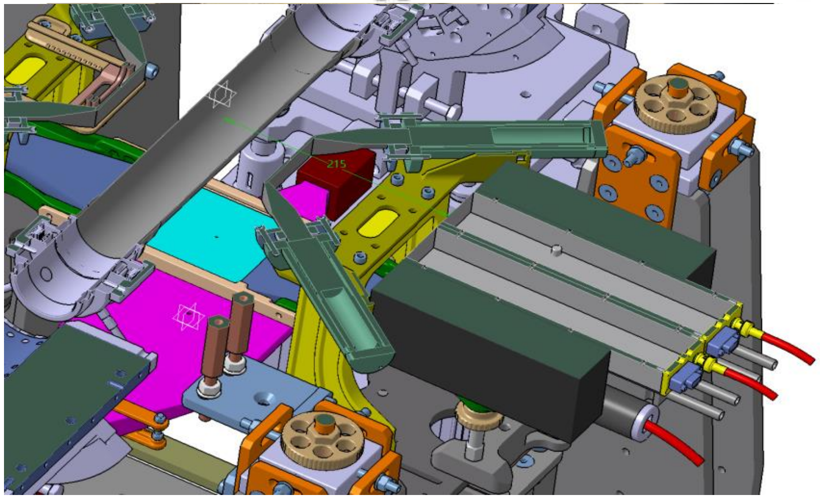
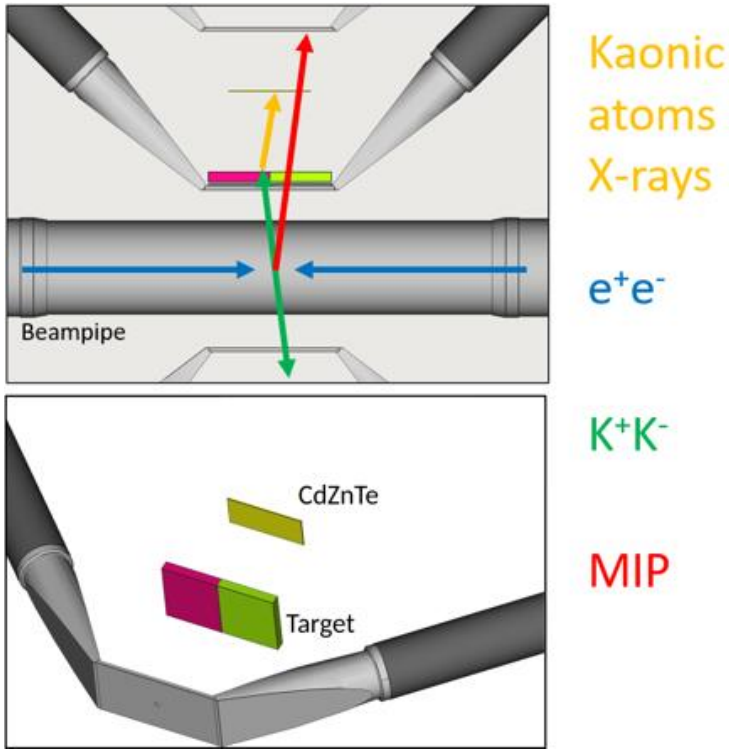




Intermediate mass Kaonic (only?) Atoms with CdZnTe



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Intermediate mass Kaonic (only?) Atoms with CdZnTe

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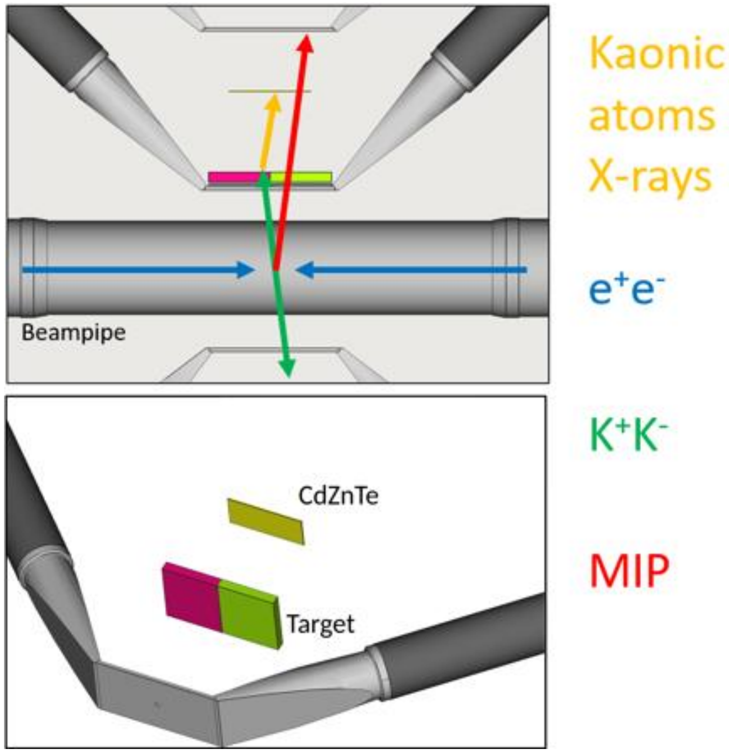

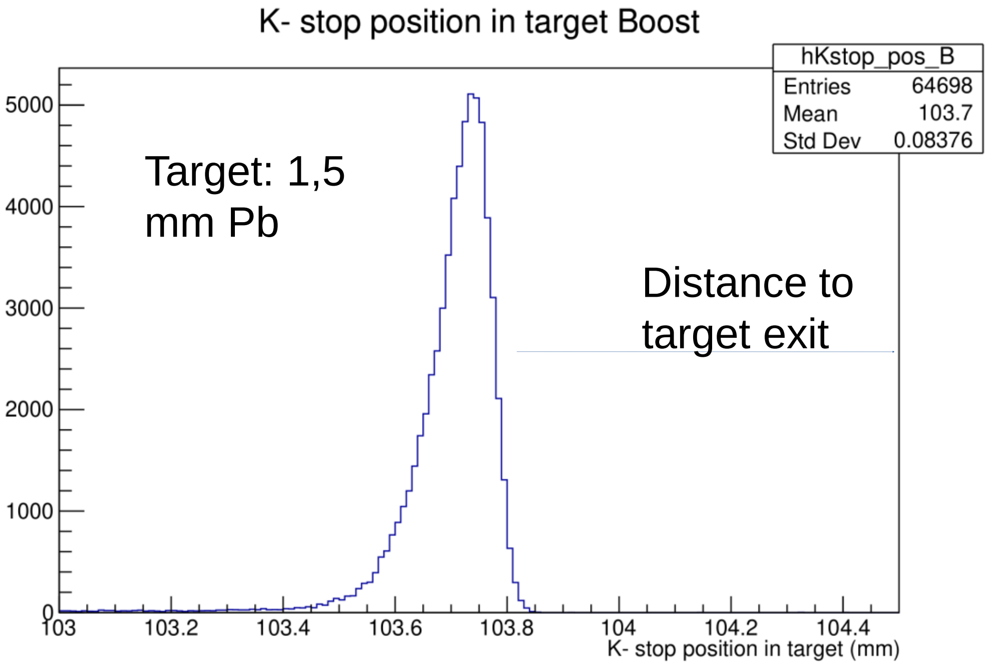

Kaons enter in the target with an average momentum of 99 MeV/c and are stopped in the first 0,7 mm

Generated X-rays must travel through additional 0,7-1 mm

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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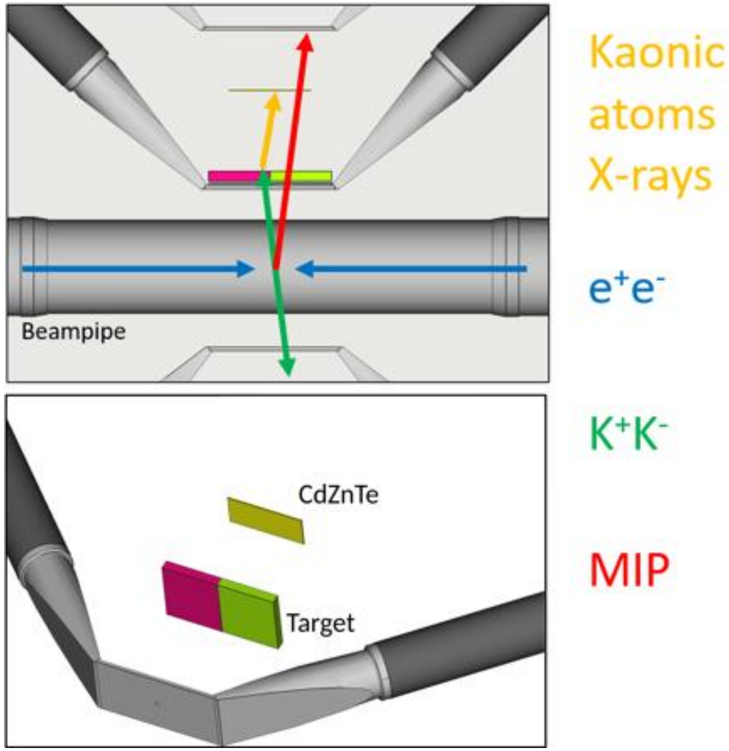

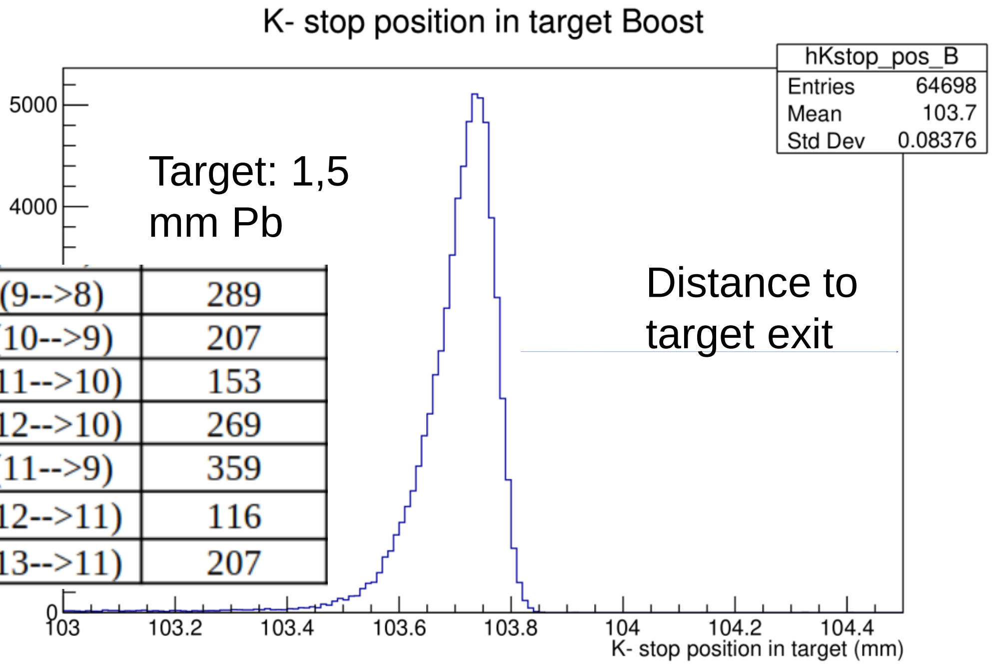

KPb(9-->8)	289
KPb(10-->9)	207
KPb(11-->10)	153
KPb(12-->10)	269
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Pb

Energy (keV)	μ/ρ (cm2/g)	μ (cm-1)	μ (mm-1)	I/I0 1 mm	I/I0 2 mm
100	5,55E+00	62,981	6,298	0,002	0,000
150	2,01E+00	22,859	2,286	0,102	0,010
200	9,99E-01	11,333	1,133	0,322	0,104
300	4,03E-01	4,575	0,458	0,633	0,401

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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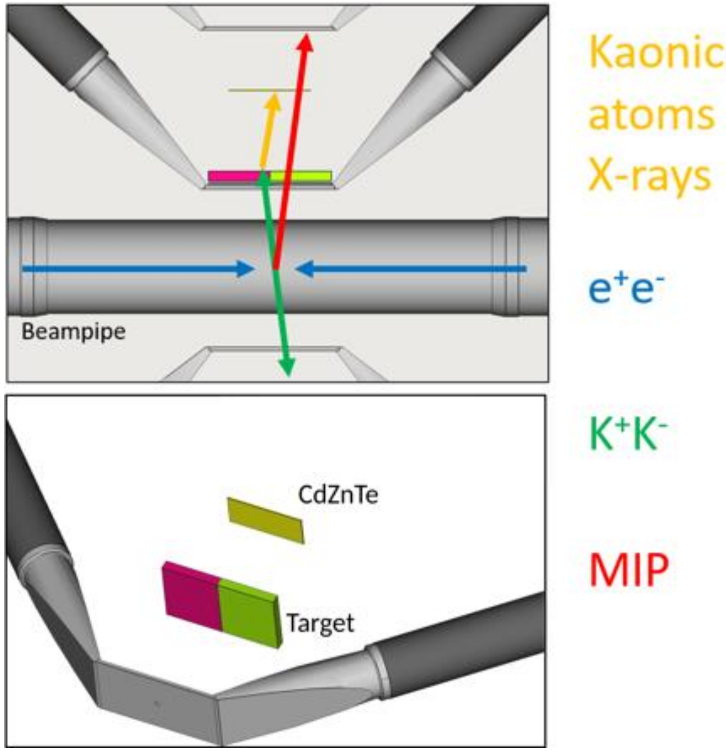
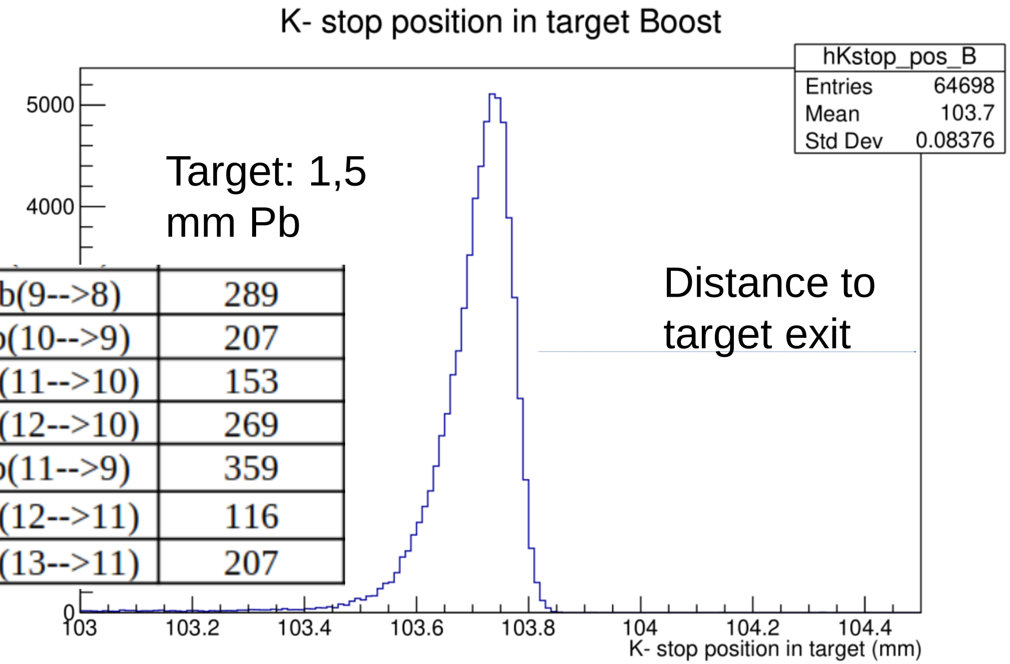
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication





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Pb transmission would be too low to see signals in CZT range

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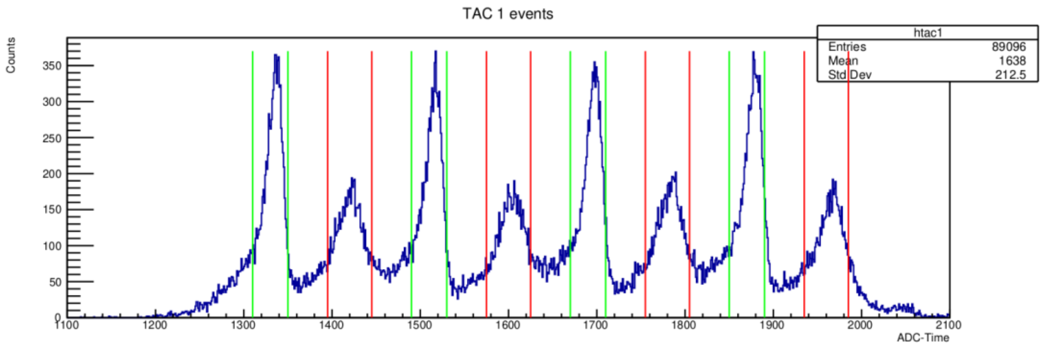

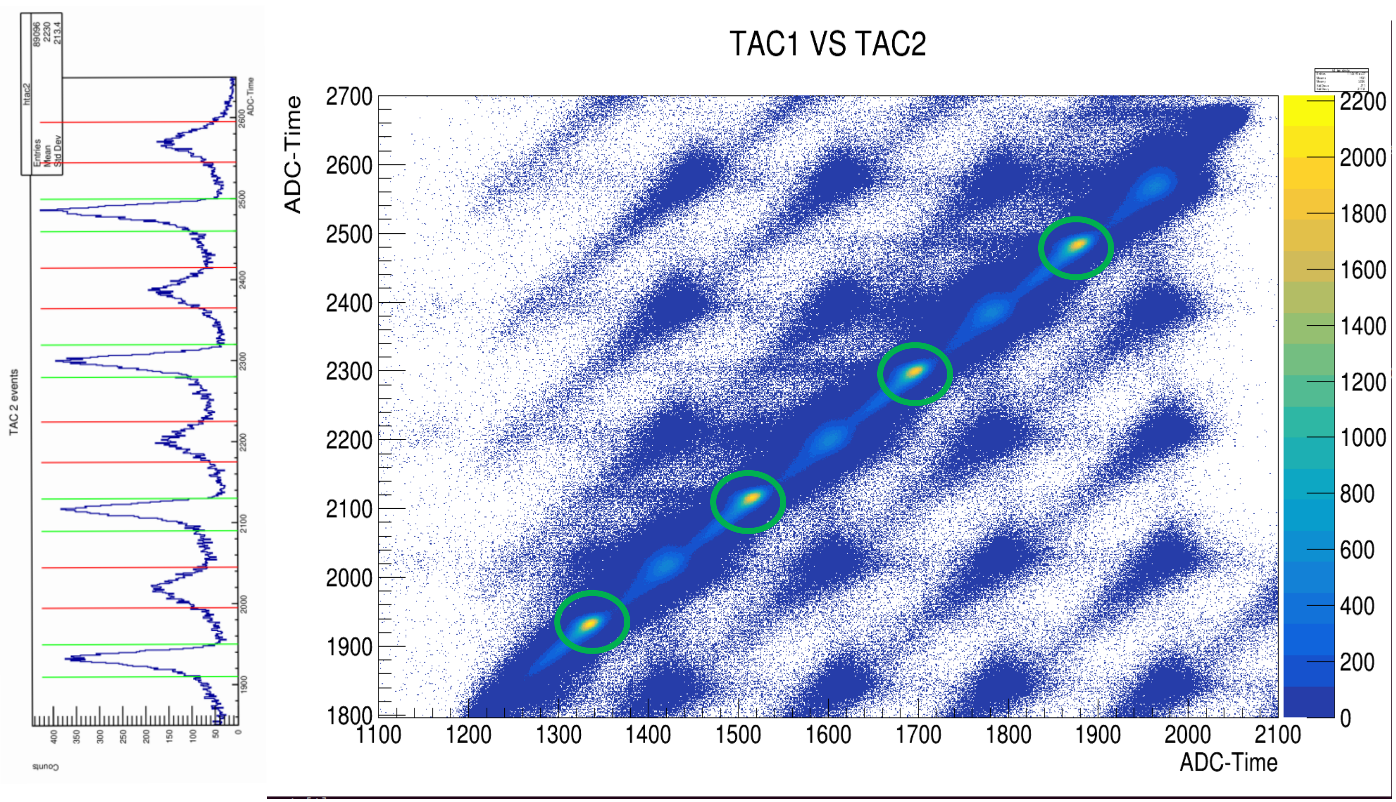

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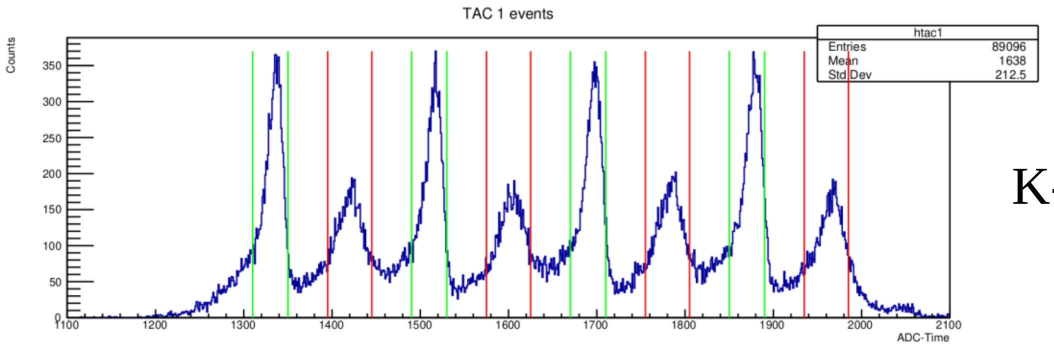
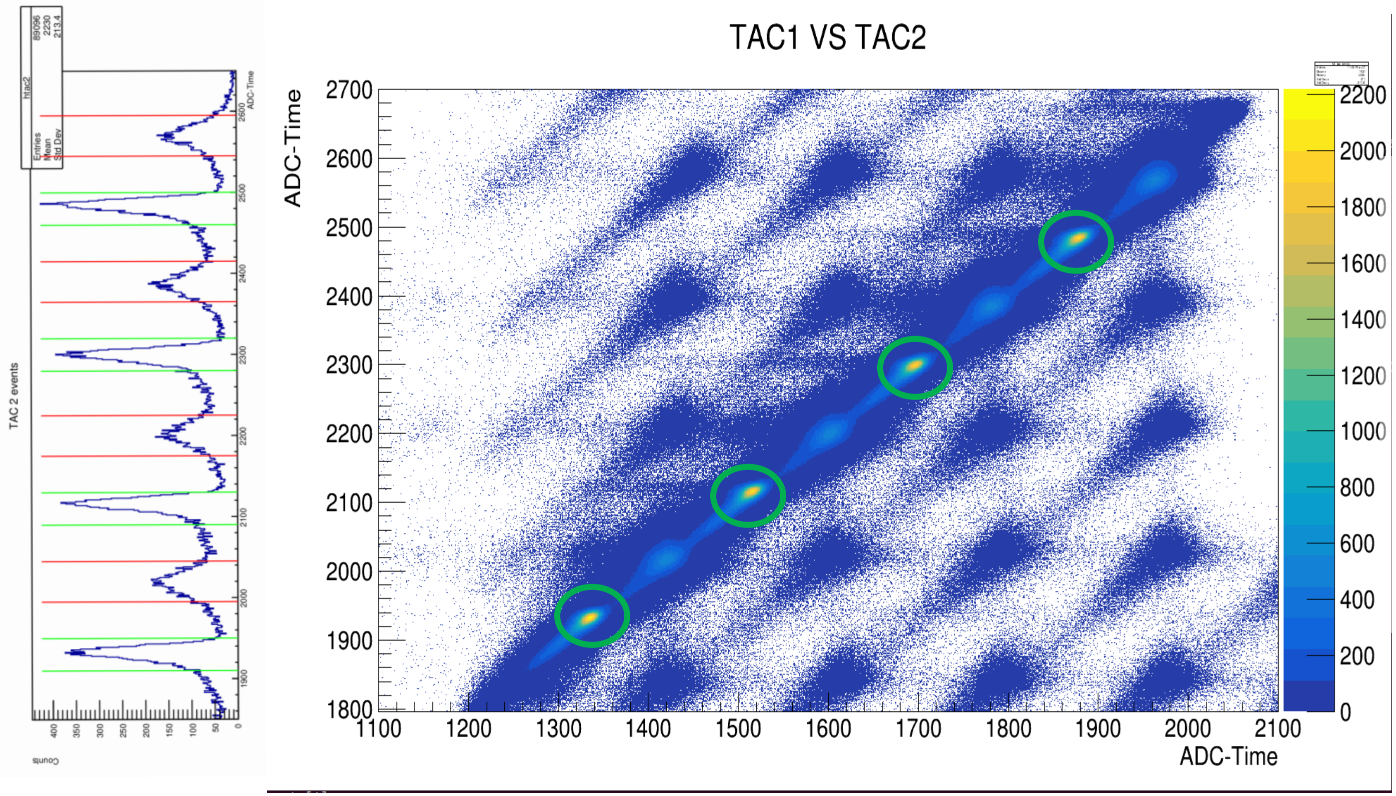


K- are monochromatic and slower than relativistic MIPs



TOF information can be used to deduce that a K- is heading towards the target

Intermediate mass Kaonic (only?) Atoms with CdZnTe

Once a collision occurs, the K- flights through the LM Scintillator and then the target with a very specific timing

The kaonic atom’s formation and radiative deexcitation process is order of magnitudes faster than the K- TOF

X-rays fly towards the CZT at speed c with a very specific timing

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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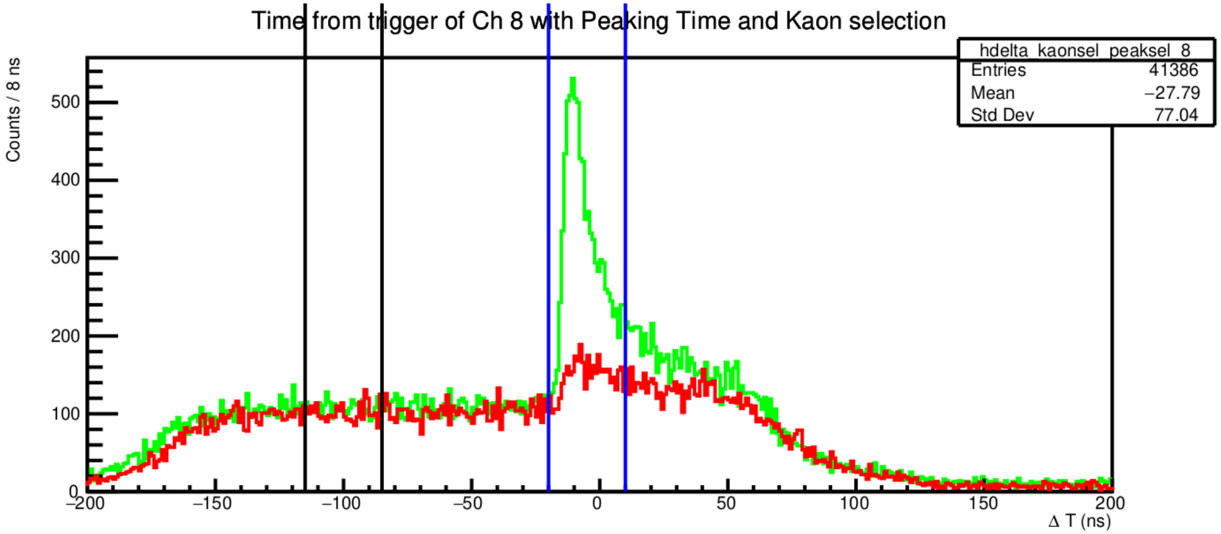

Kaonic atoms’s X-rays in the CZT detectors have then a clear time peak wrt to the collision

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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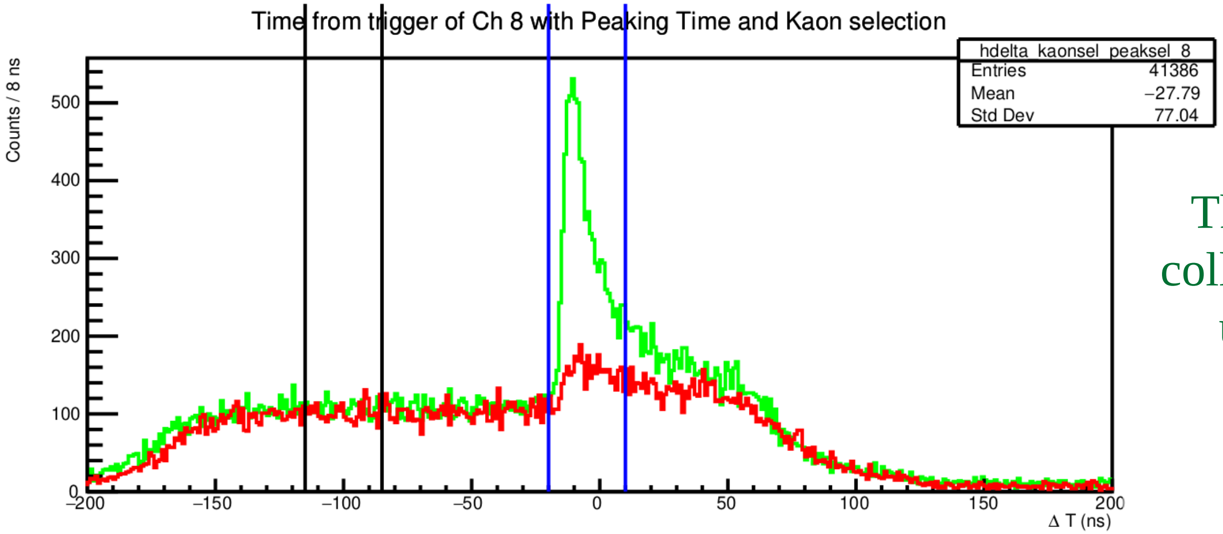

The time difference between the collision and the CZT signal can be used to further clean the final spectrum

Kaonic atoms’s X-rays in the CZT detectors have then a clear time peak wrt to the collision

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Intermediate mass Kaonic (only?) Atoms with CdZnTe

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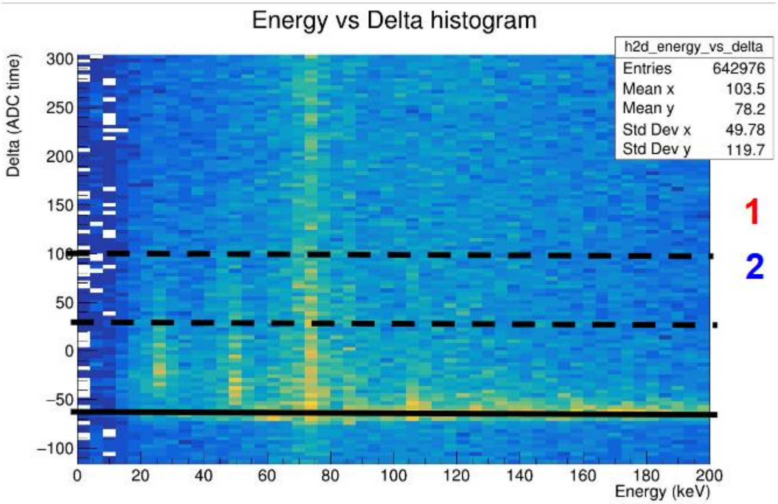

1: More signal, 2: Better SNR (especially for KAl 4-3 at ~106 keV)

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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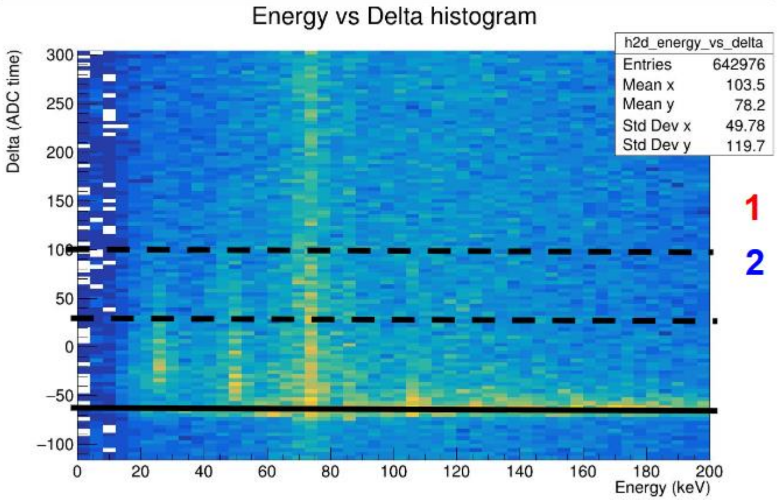

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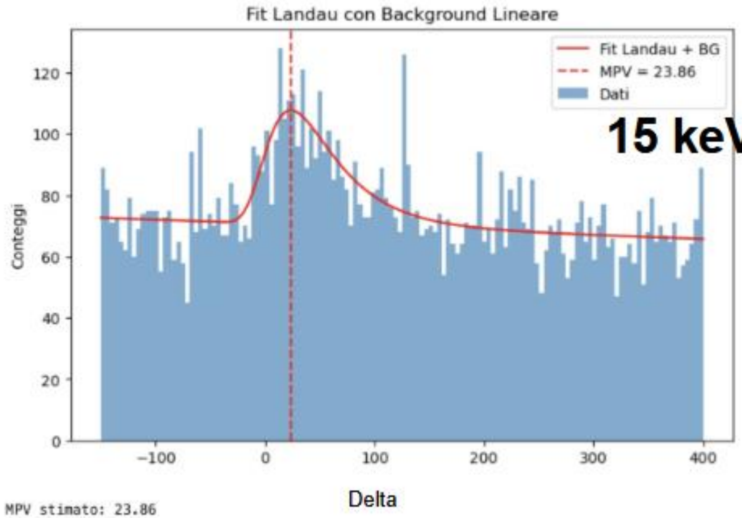

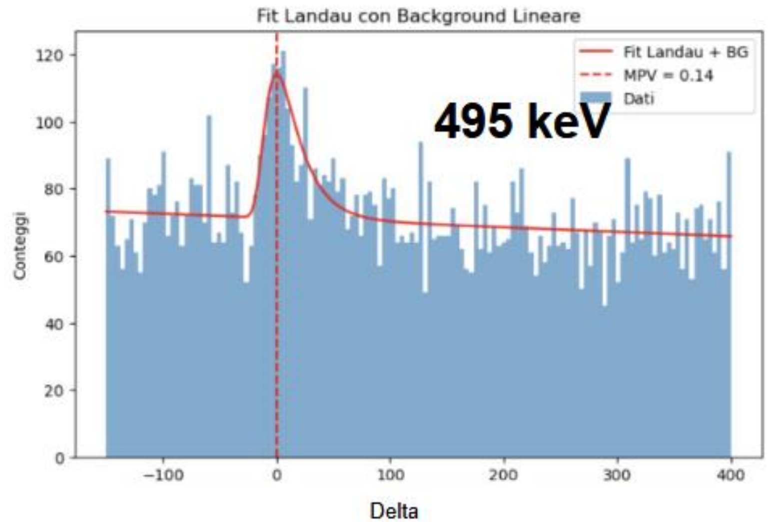

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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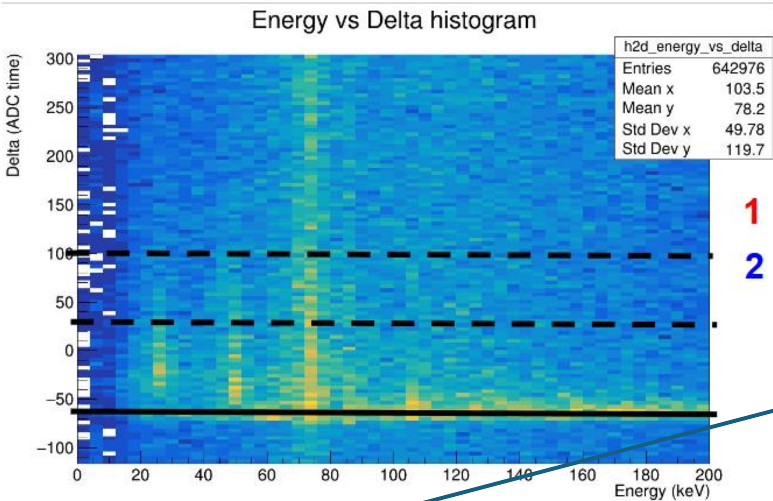
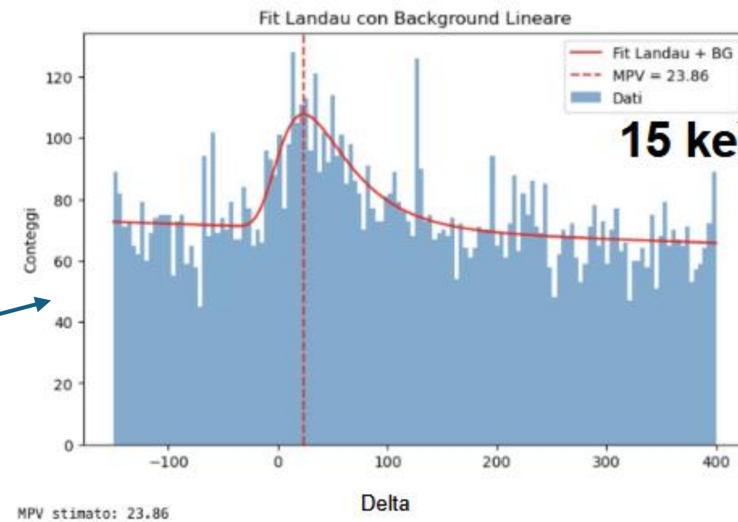
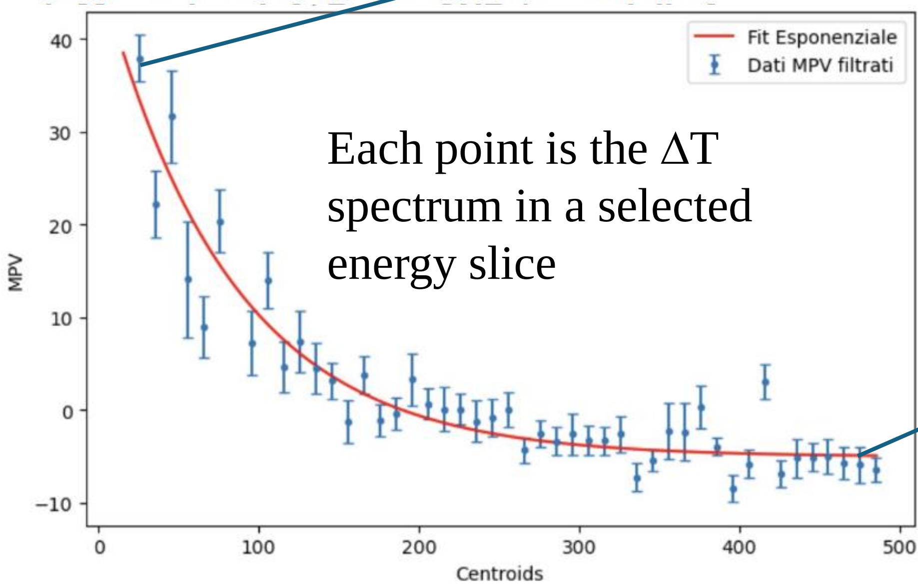
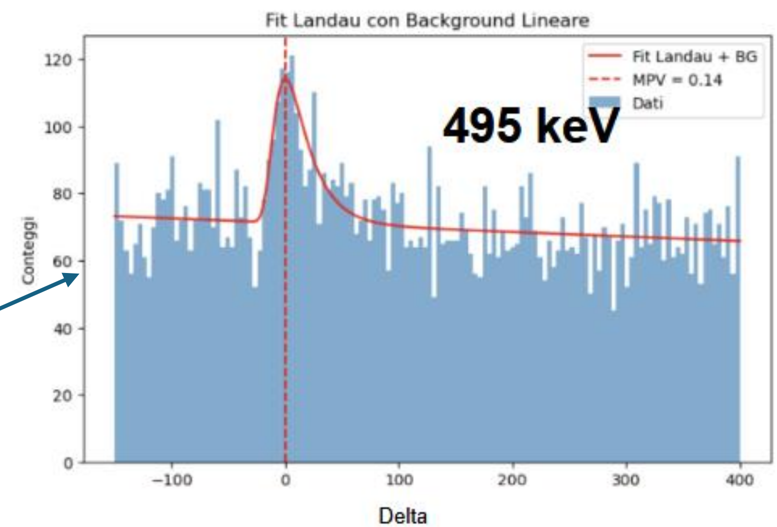






Each point is the ΔT spectrum in a selected energy slice



Intermediate mass Kaonic (only?) Atoms with CdZnTe

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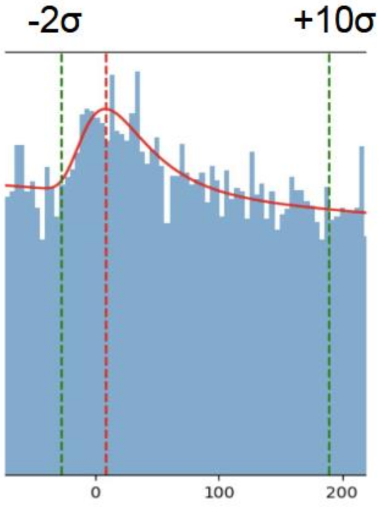

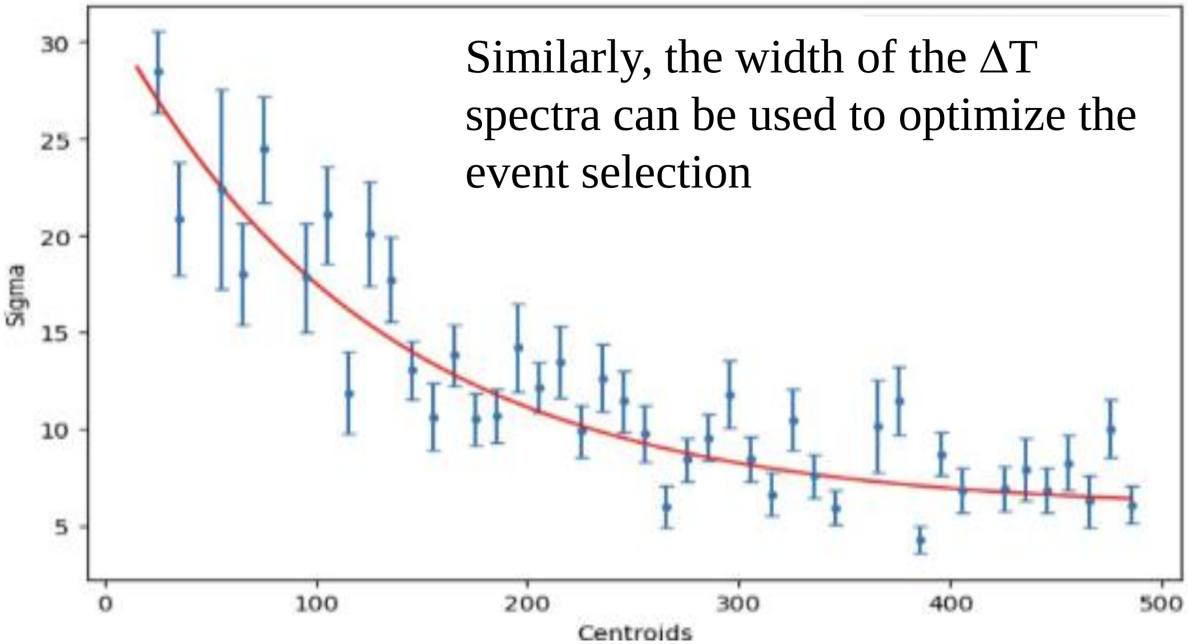

Similarly, the width of the ΔT spectra can be used to optimize the event selection

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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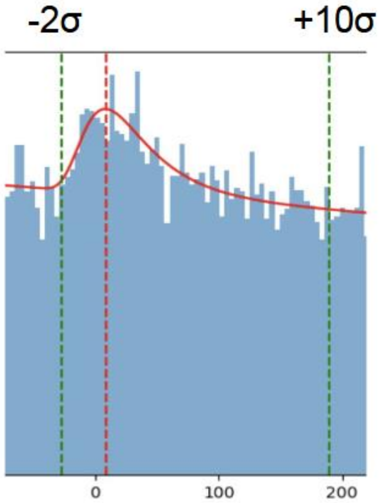

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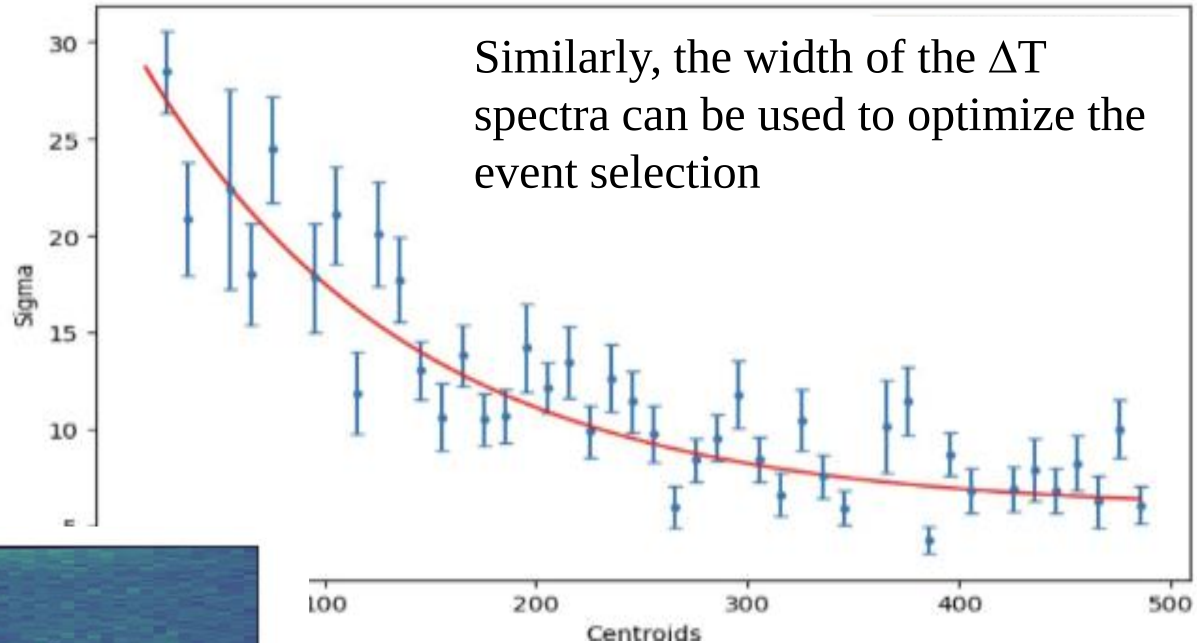
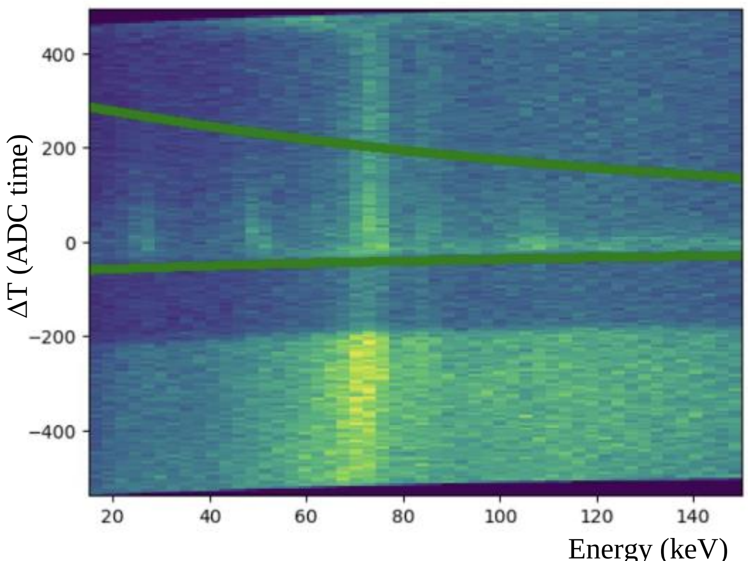


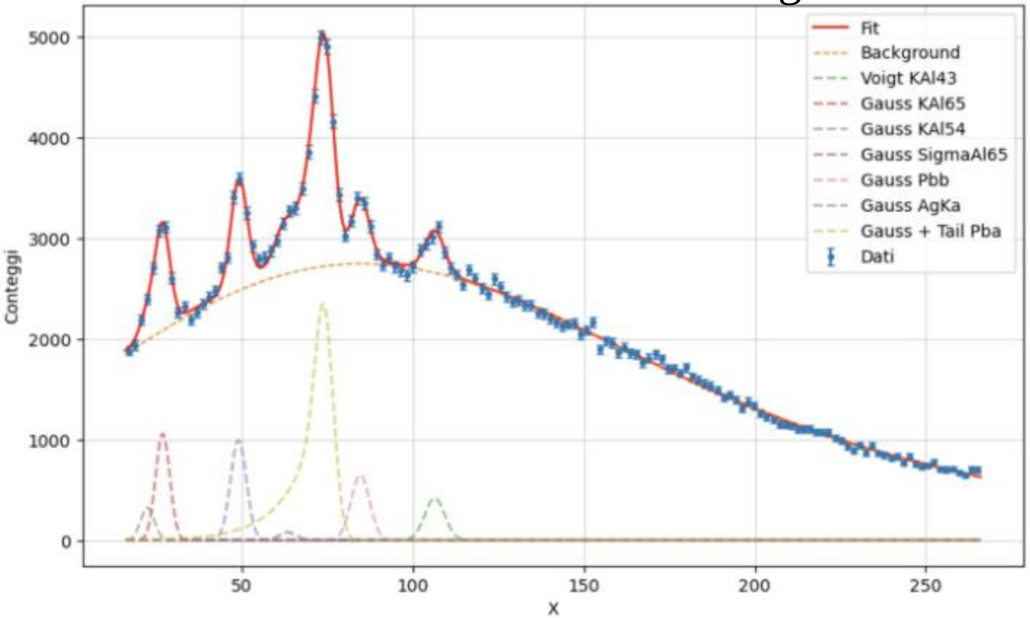


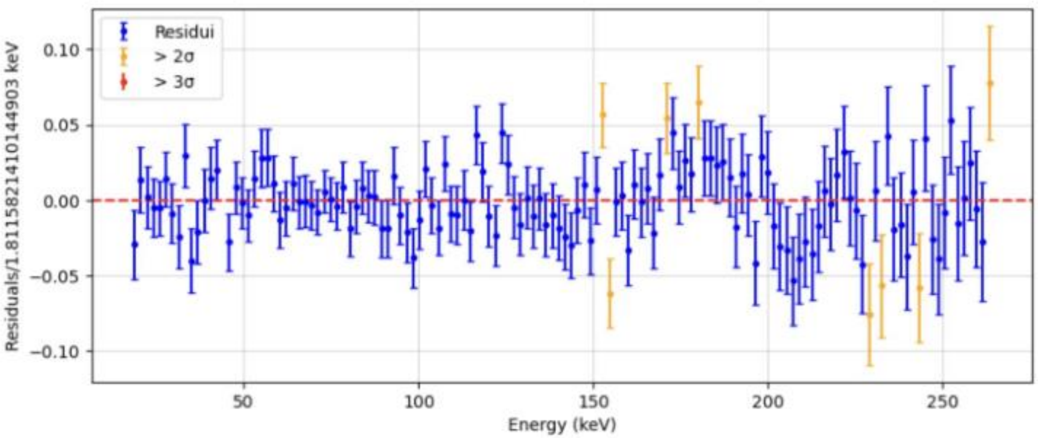
Optimized NON-linear 2D event selection for Signal/Background improvement

Intermediate mass Kaonic (only?) Atoms with CdZnTe

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

2 mm thick Al target





KAl43 → 106.44 ± 0.22 keV

KAl65 → 26.92 ± 0.12 keV

KAl54 → 49.067 ± 0.090 keV

ΣAl65 → 63.5 ± 1.1 keV

AgKα → 22.46 ± 0.37 keV

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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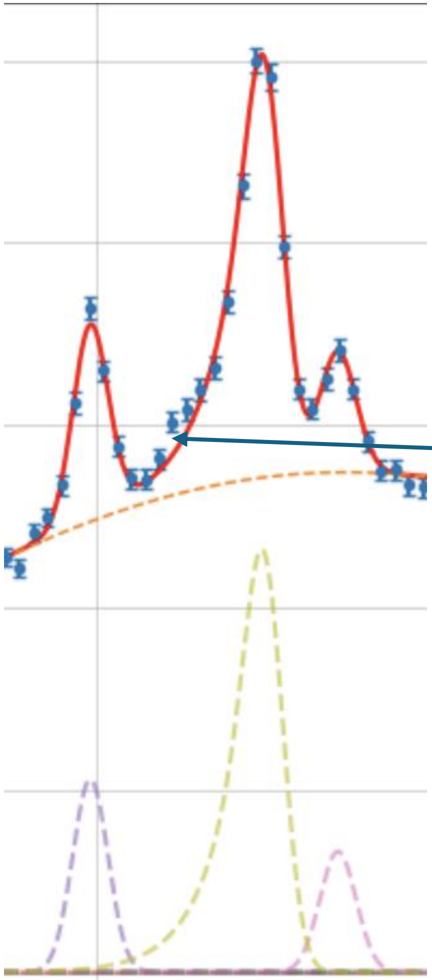

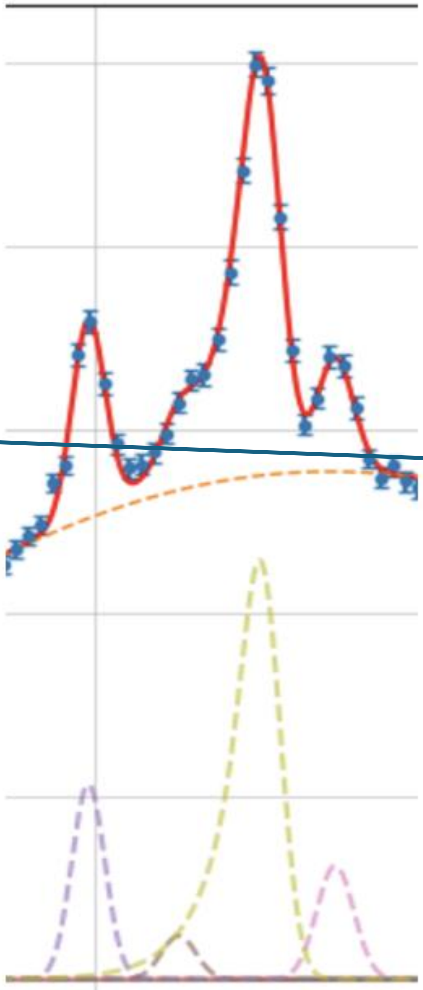

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NOT WELL FITTED without the ΣAl65 peak

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Intermediate mass Kaonic (only?) Atoms with CdZnTe

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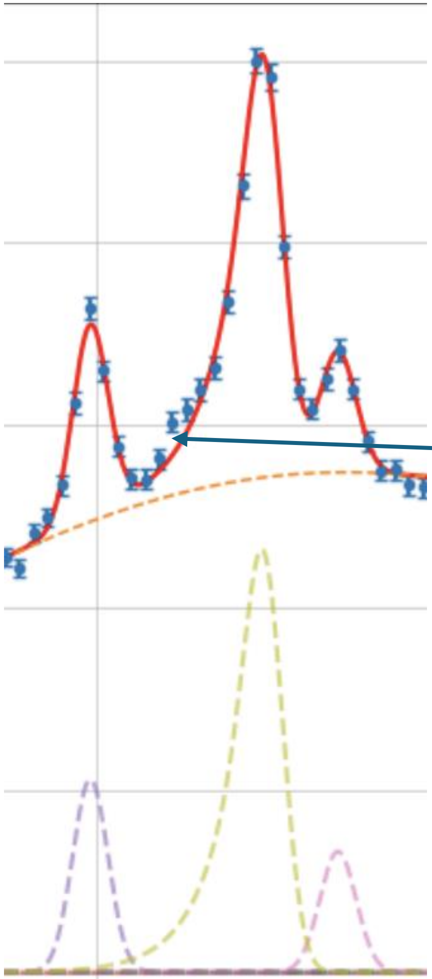

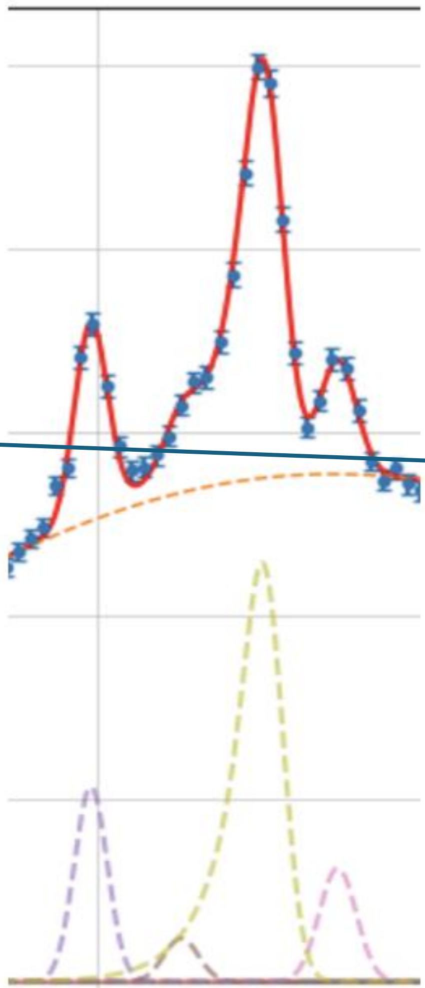

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First kaonic (and sigmonic?) atoms' spectra measured with CZT detectors

Others under analysis (F, Cu, Pb)

New perspectives opening

Intermediate mass Kaonic (only?) Atoms with CdZnTe

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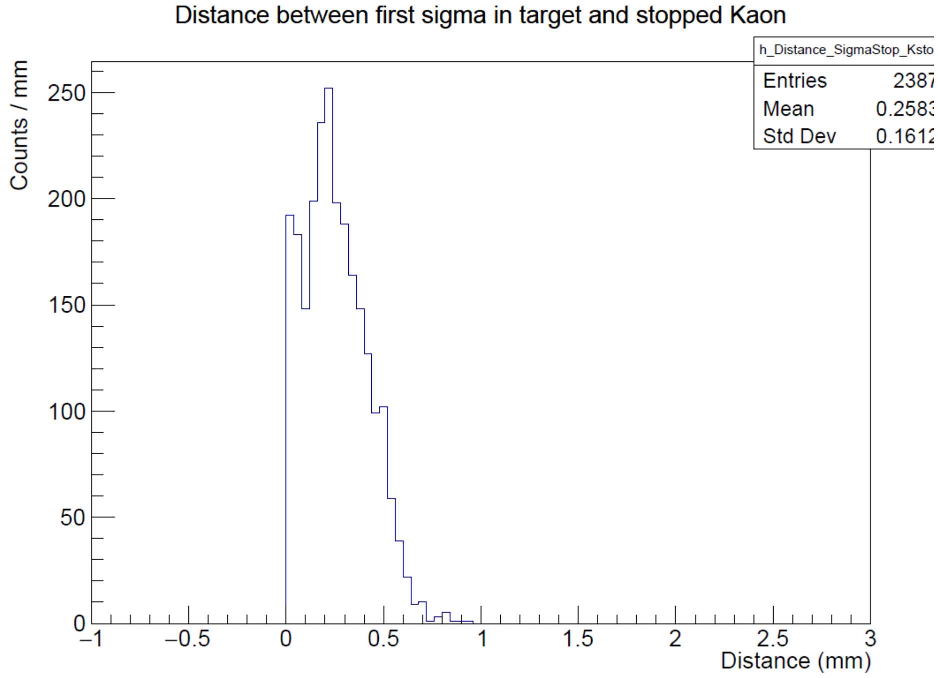
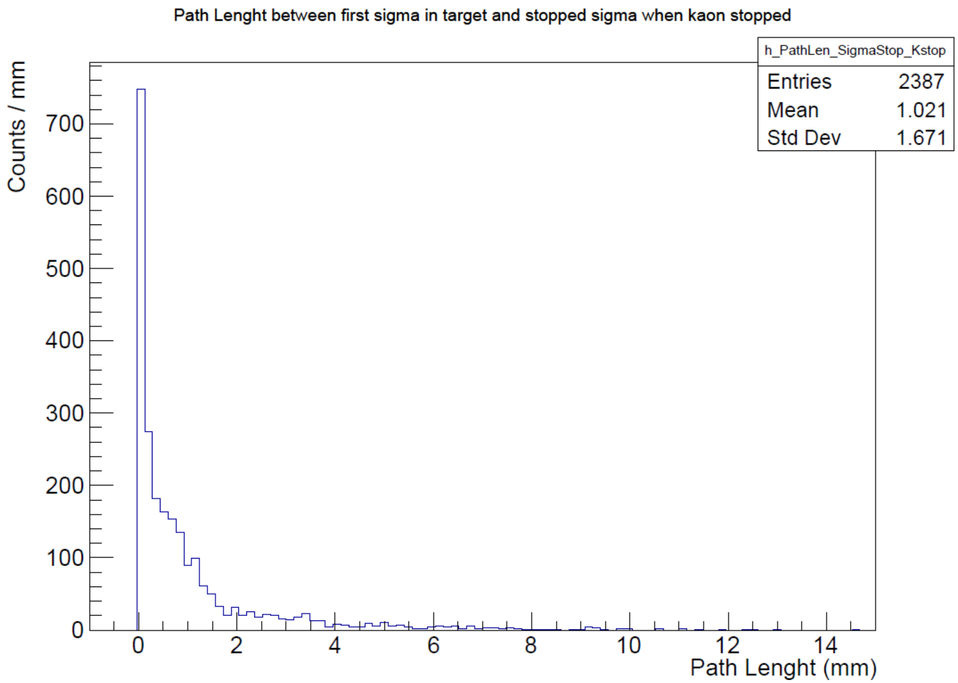
K^- stopped in the target: 69260

Σ^- stopped in target when K^- stopped in target: 2387



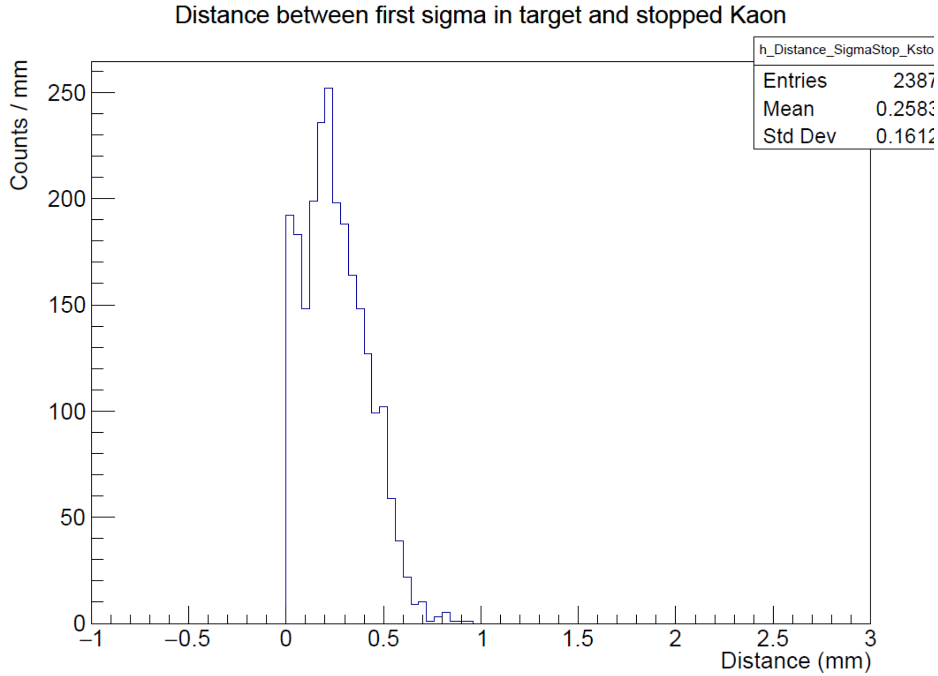


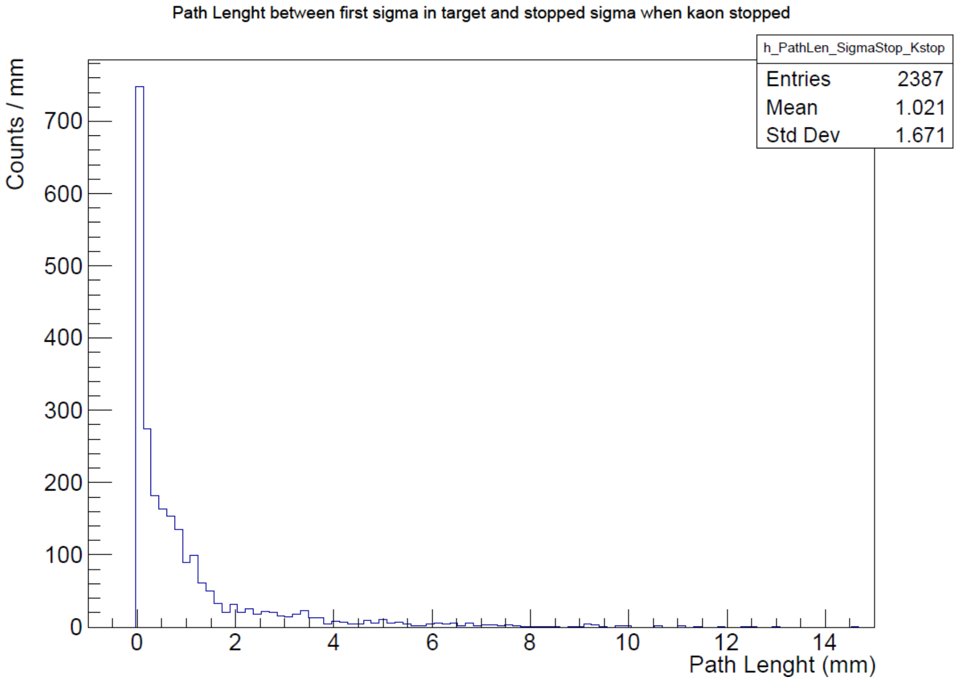
Intermediate mass Kaonic (only?) Atoms with CdZnTe

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

K^- stopped in the target: 69260

Σ^- stopped in target when K^- stopped in target: 2387





Σ- path length compatible with PDG-based calculations

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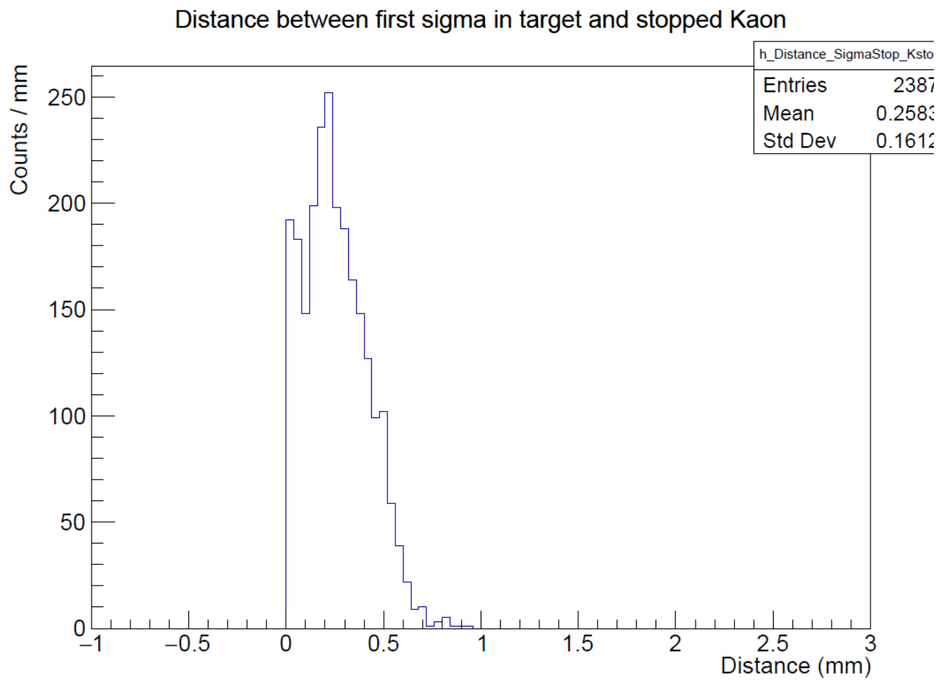
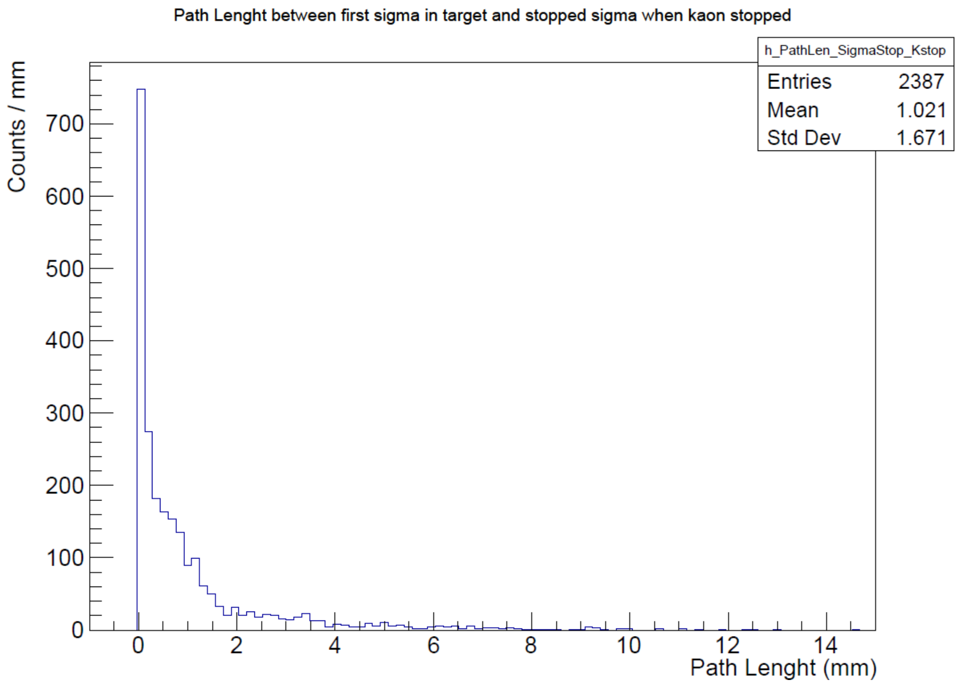




Σ- atoms formation possibility confirmed by MC simulations

Σ- path length compatible with PDG-based calculations

Further refinement and analysis is ongoing (GEANT4 physics)

Results (2)

KHe L-transition measurement in gas : *J. Phys. G 49 (2022) 5, 055106*

Kaonic helium-4 yields L-lines in gas : *Nucl. Phys. A 1029 (2023) 122567*

First measurement of intermediate mass kaonic atoms: *Eur. Phys. J. A 59(2023)3, 56*

First Measurement of KHe M-lines : *J. Phys. G (2024) 51 055103*

First Measurement of kaonic Neon (stat. precision < 1 eV) *Paper submitted and under review*

First measurement of Kaonic Deuterium: preliminary analysis

KPb pure E.M. transitions measurements with HPGe: *Nucl.Instrum.Meth.A 1069 (2024) 169966*

Feasibility tests & exploratory measurements with CdZnTe detectors @ DAFNE:

Eur.Phys.J.ST 232 (2023) 10, 1487-1492

Sensors 23 (2023) 17, 7328

Nucl.Instrum.Meth.A 1060 (2024) 169060

Front.in Phys. 11 (2023) 1240250

Sensors 2024, 24(23), 7562

Proposal(s) for future measurements @ DAΦNE

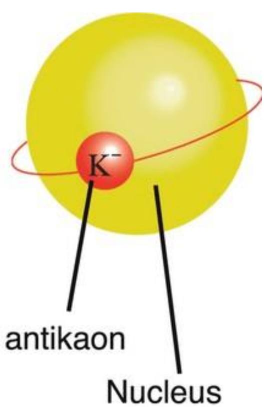
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

Proposal for future extensive kaonic atoms measurements @ DAFNE to be performed exploiting:

- 450 mm SDD (light KA, up to 15 keV)
- 1-2 mm SDD (light KA, up to 40 keV)
- CdZnTe detectors (Intermediate mass KA)
- HPGe detectors (Heavy KA)
- Crystal Spectrometer (High-Res light KA)

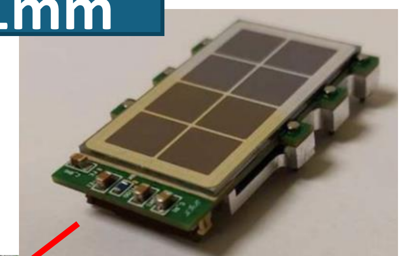
Kaonic atoms at DAΦNE collider: a strangeness adventure
C. Curceanu et al., doi.org/10.3389/fphy.2023.1240250

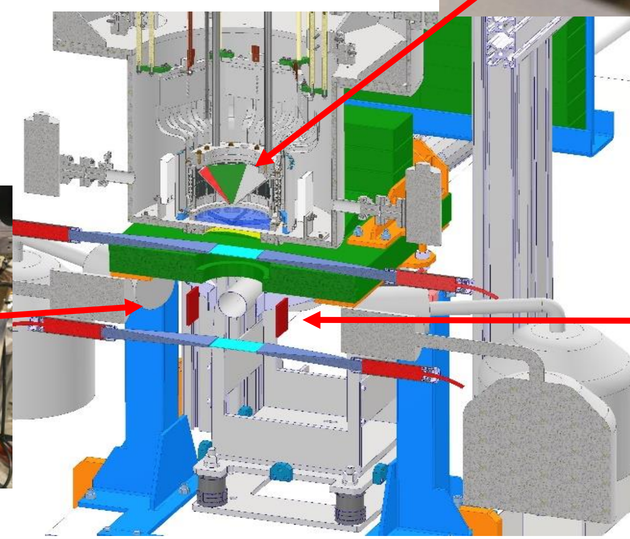
Extensive **K**aonic **A**toms research: from **LI**thium and **B**eryllium to **UR**anium



Cd(Zn)Te

SDD 1mm





HPGe

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Proposal(s) for future measurements @ DAΦNE

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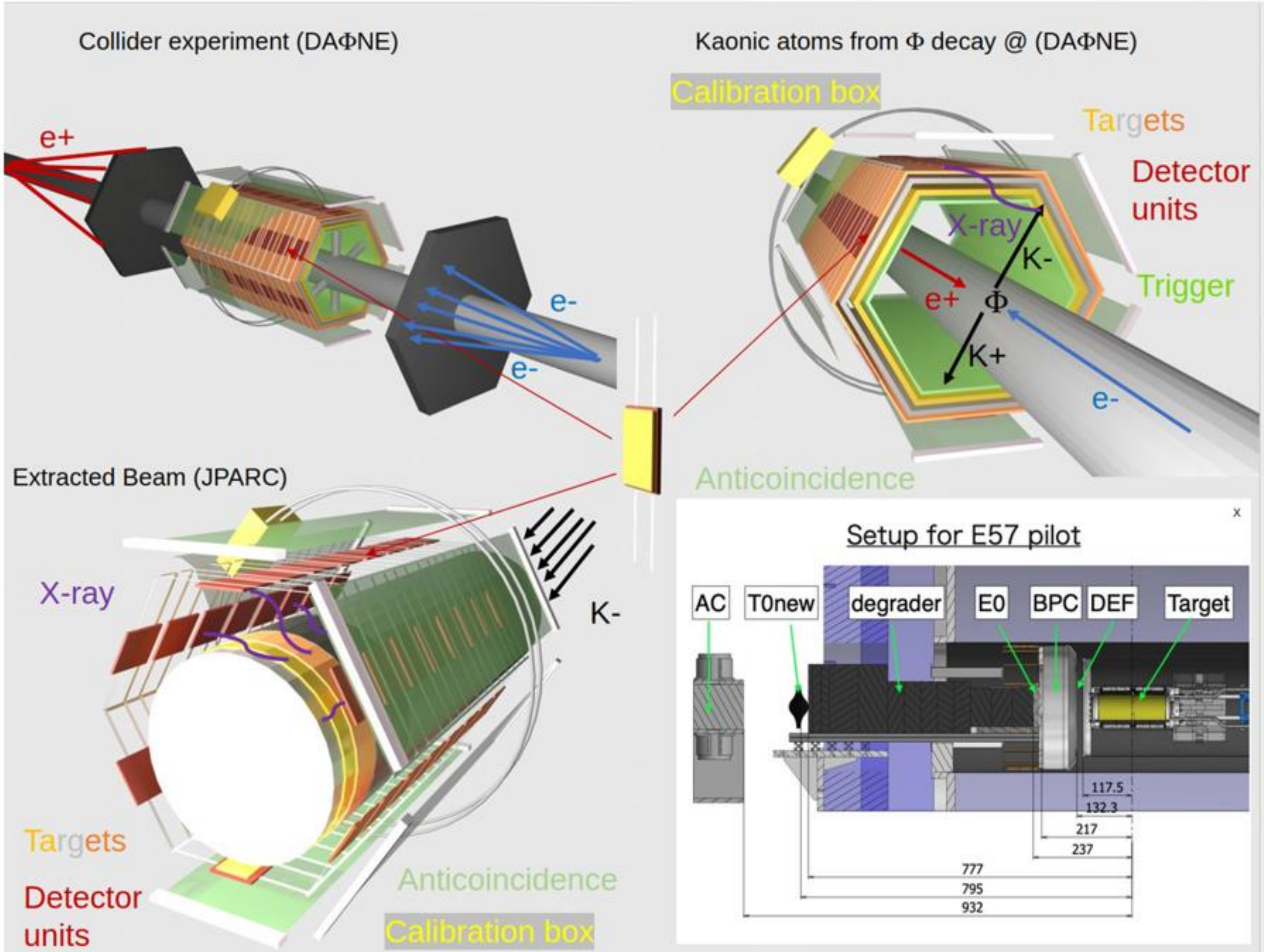

At J-PARC, the 10^{7-8} K^-/s stopping in the target/degrader will ensure a statistic of orders of magnitude higher than that collectable at DAFNE.

What is lost for D_2 is gained for solid targets measurements

Enhanced probability to systematically study Σ- atoms

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Conclusions

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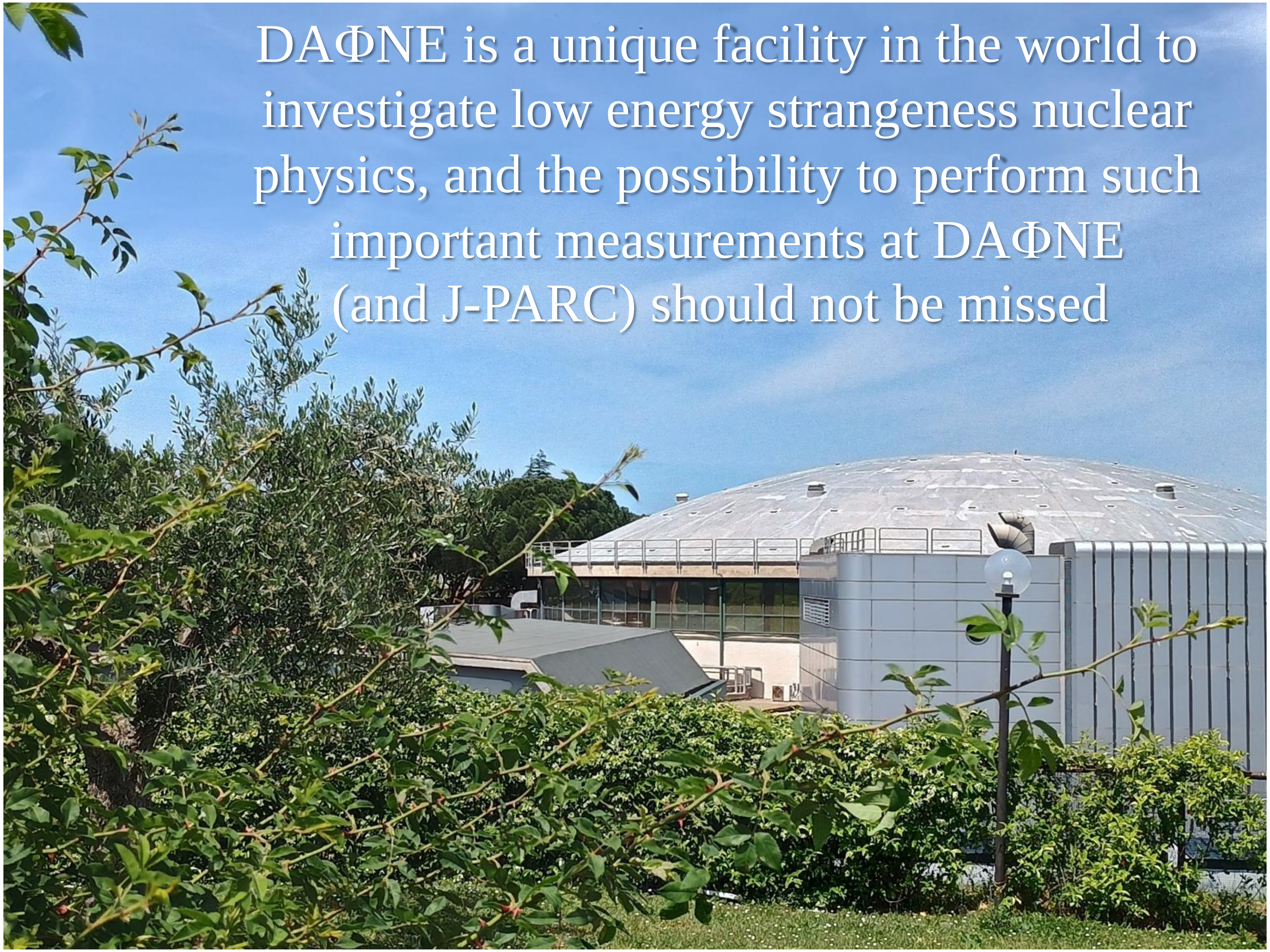
DAΦNE is a unique facility in the world to investigate low energy strangeness nuclear physics, and the possibility to perform such important measurements at DAΦNE (and J-PARC) should not be missed



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To Carlo & Hannes

SIlicon **D**rift
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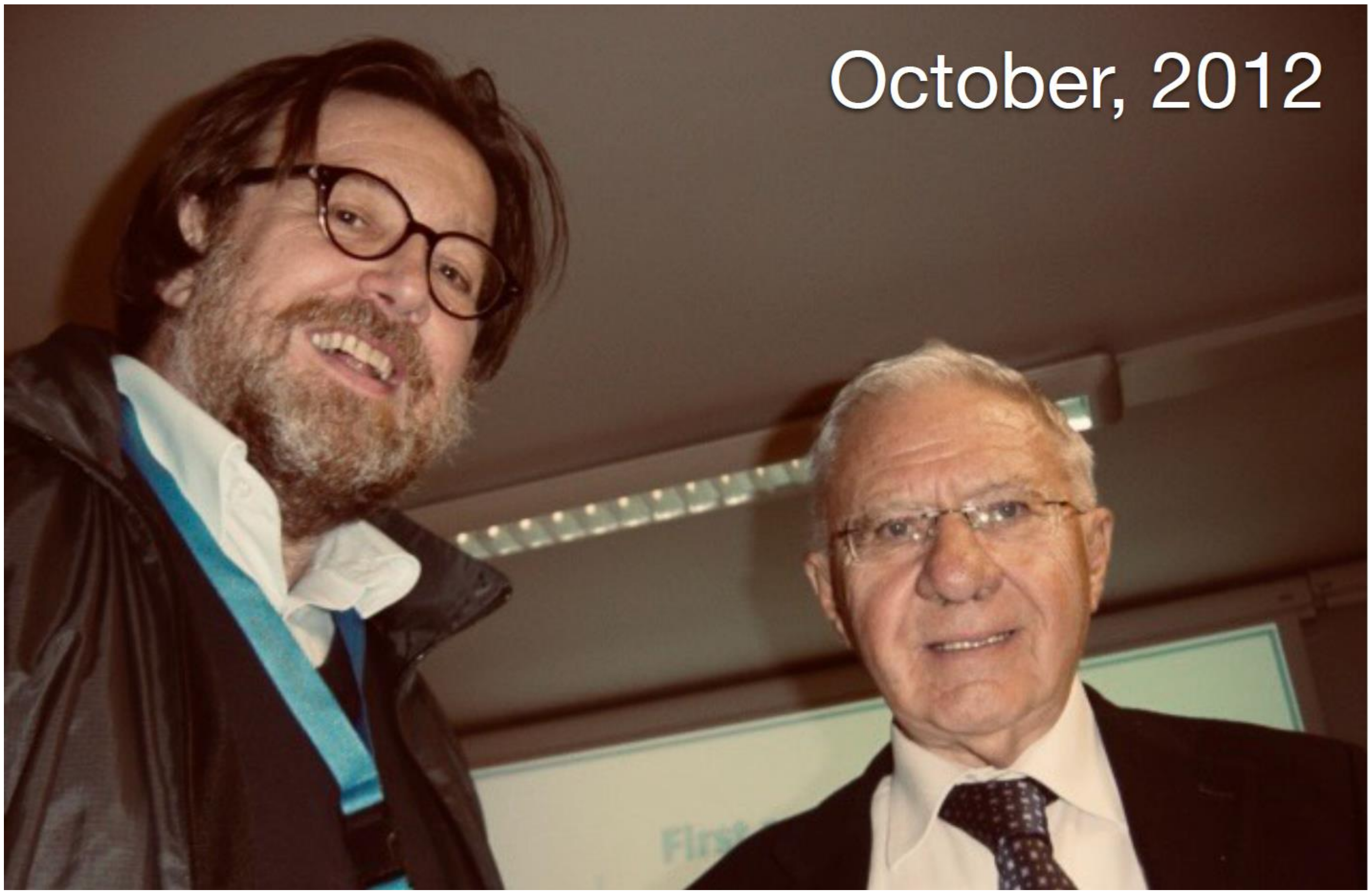
We dedicate all our efforts and results to Prof. Carlo Guaraldo and Prof. Johann Zmeskal, who conceived, designed, realized and led the DEAR, SIDDHARTA and SIDDHARTA-2 experiments, and without whom none of these results would have never been achieved.



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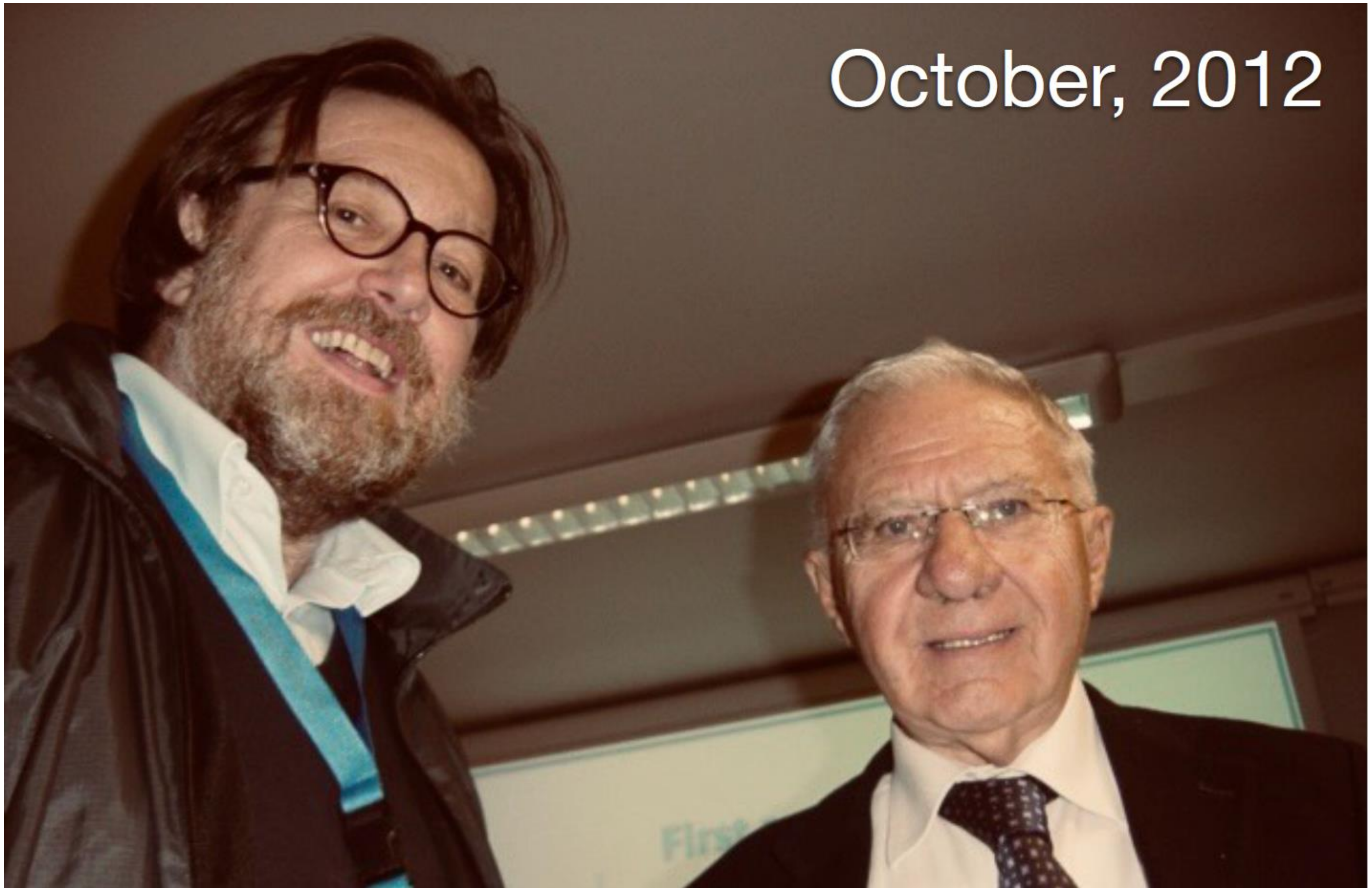

My special thanks also to prof. Yamazaki for the nice and fruitful discussions during my Ph.D and PostDoc

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Thanks for your attention

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ご清聴ありがとうございました

SPARE

KH and Kd

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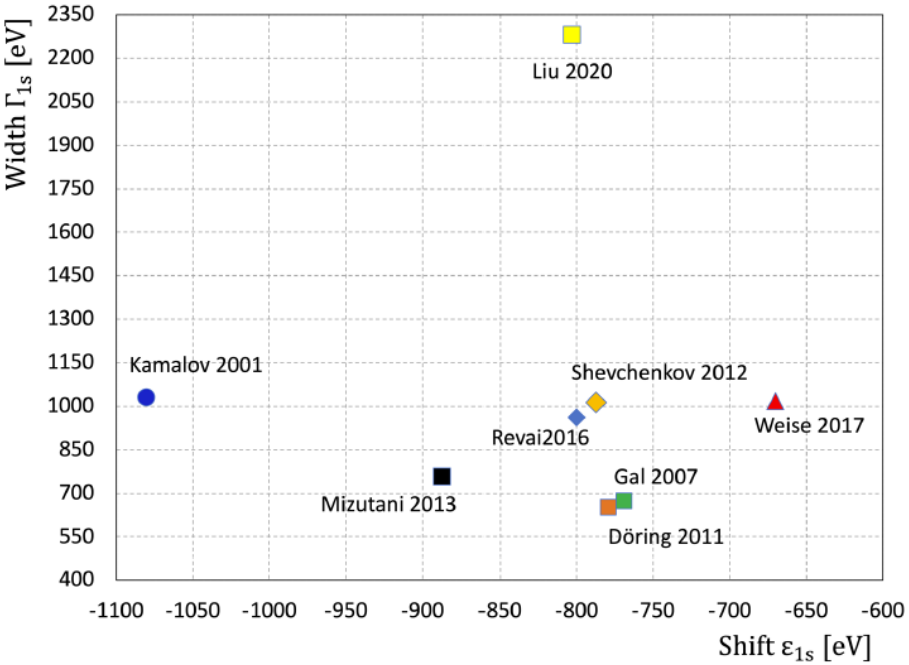

Theoretical predictions for the kaonic deuterium 1s level shift and width

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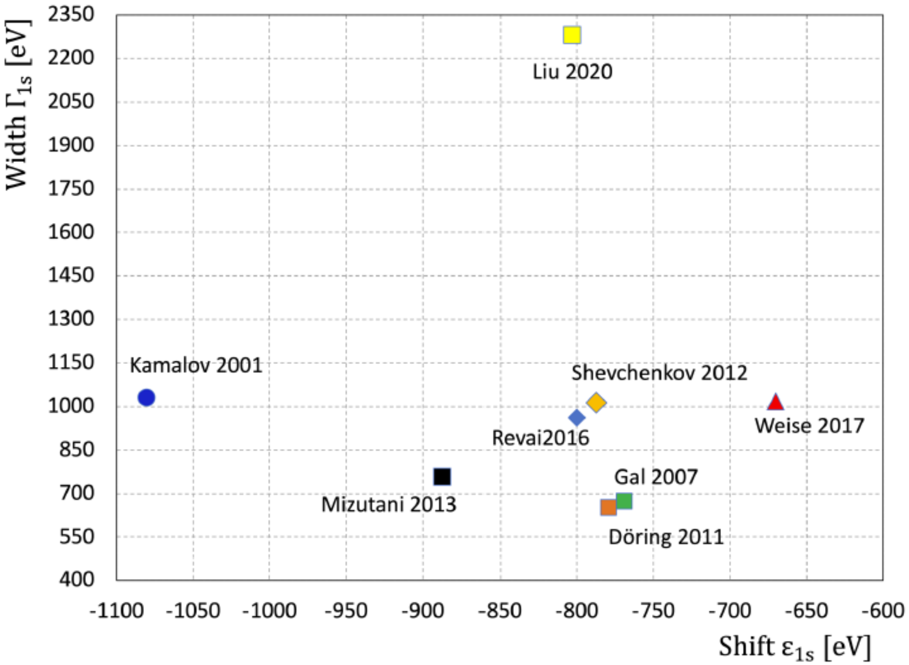
KH and Kd

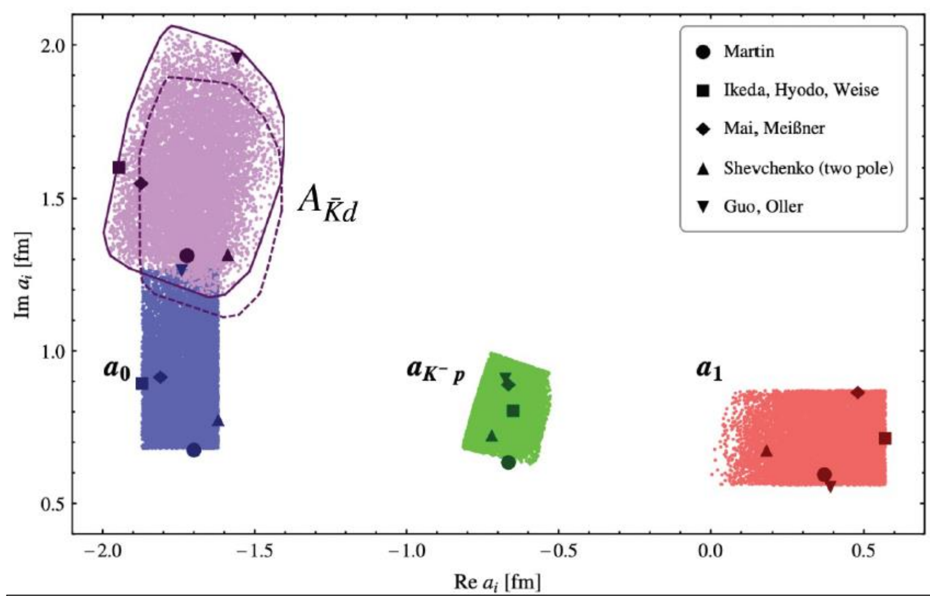


Theoretical predictions for the kaonic deuterium
1s level shift and width

Antikaon-deuteron scarring length

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

Shevchenko, N. V. Light Kaonic Atoms: From \Corrected" to \Summed Up" Deser Formula. Few Body Syst. 63, 22



Maxim Mai, Vadim Baru, Evgeny Epelbaum, and Akaki Rusetsky Phys. Rev. D **91**, 054016

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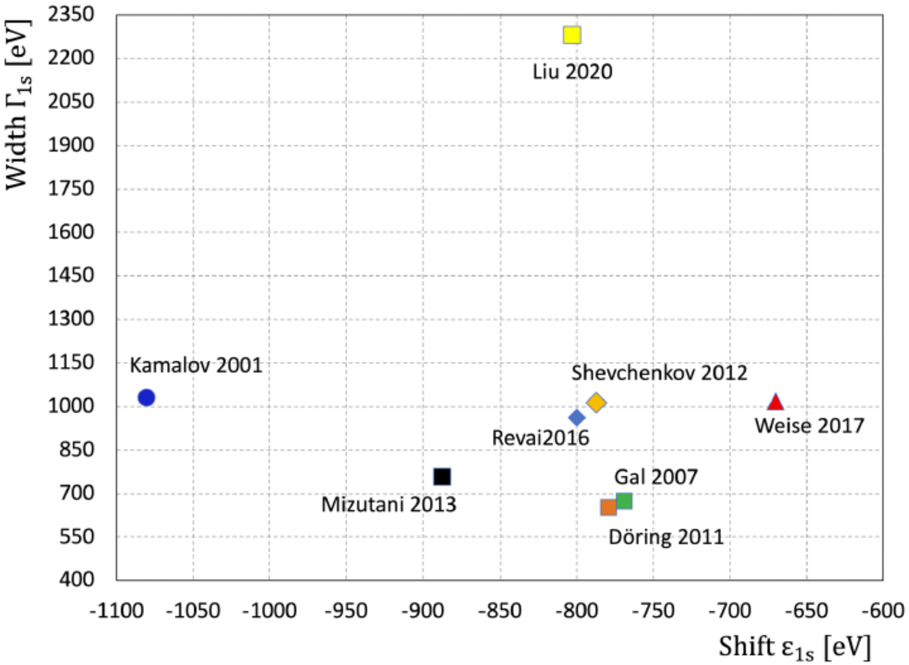
Detectors for
HAdronic Atom
Research by
Timing Application

KH and Kd



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

The low X-rays yield has, until now, prevented the observation of 1s level transitions in kaonic deuterium.

Antikaon-deuteron scarring length

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

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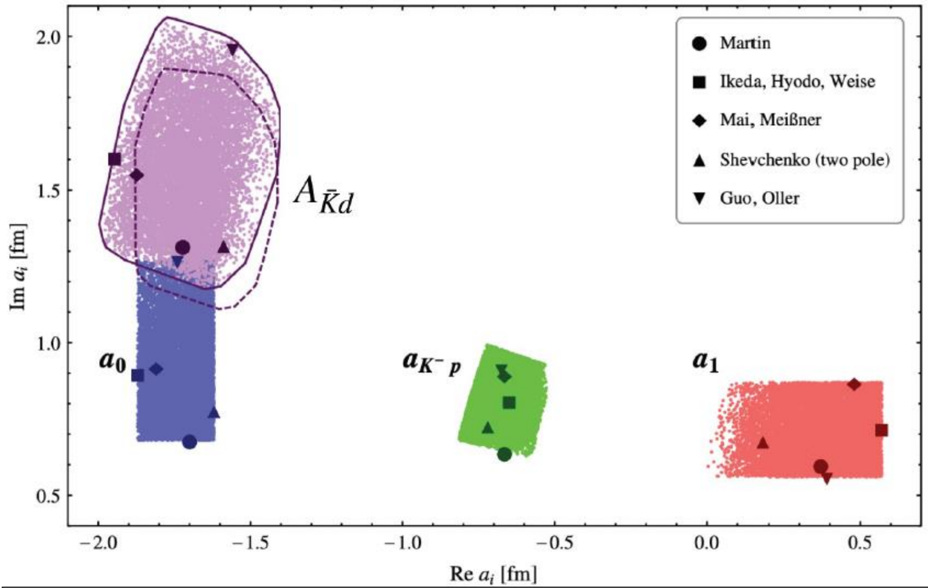

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Kaonic atoms state of art

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Antikaon absorption in nuclear medium: role of hadron self-energies and implications for kaonic atoms

Jaroslava Óbertová

Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University in Prague

in collaboration with

Àngels Ramos — University of Barcelona
Eliahu Friedman — *Hebrew University, Jerusalem*
Jiří Mareš — *NPI, Řež*

SPICE workshop, 13 - 17 May 2024, Trento, Italy

Microscopic K−N + K−N N potentials derived from K−N scattering amplitudes constructed within SU(3) chiral coupled-channels models of meson-baryon interactions

J. Obertova, E. Friedman, J. Mares
Phys. Rev. C 106 (2022) 6, 065201

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Calculations of selected kaonic atoms

Table 3: Values of χ^2 for shifts, widths and yields in selected K^- atoms, calculated with Pauli + YN, Pauli + YNK, Pauli + YNKπ BCN amplitudes and with K^-N+phen. multiN potentials based on BCN WRW amplitudes.

BCN		Pauli + YN	Pauli + YNK	Pauli + YNKpi	phen.
		$K^-N + K^-NN$	$t\rho + V^{corr}_{K^-NN}$	$t\rho + V^{corr}_{K^-NN}$	K^-N + phen. multiN
^{12}C	$\Delta(\epsilon)$	0.81	0.02	0.36	1.76
	Γ	17.48	3.15	0.00	0.70
	Γ^*	3.98	3.08	3.46	2.74
^{31}P	$\Delta(\epsilon)$	1.84	0.15	0.01	0.03
	Γ	12.85	2.49	0.18	0.24
	Γ^*	0.08	0.03	0.02	0.30
^{32}S	$\Delta(\epsilon)$	25.48	7.80	2.28	1.24
	Γ	74.33	23.85	7.05	9.24
	Γ^*	0.43	0.06	0.08	0.47
^{35}Cl	$\Delta(\epsilon)$	0.86	0.03	0.02	2.10
	Γ	12.35	1.28	0.14	0.00
	Γ^*	0.06	0.05	0.07	0.15
^{63}Cu	$\Delta(\epsilon)$	0.06	2.04	5.12	3.19
	Γ	7.73	2.71	0.98	2.25
	Γ^*	2.79	1.86	1.81	1.52
^{118}Sn	$\Delta(\epsilon)$	5.59	1.44	0.74	2.15
	Γ	1.33	0.41	0.11	0.29
	Γ^*	2.97	3.55	3.81	4.09
^{208}Pb	$\Delta(\epsilon)$	3.36	0.04	0.87	0.34
	Γ	0.49	0.39	0.33	0.39
	Γ^*	0.46	0.54	0.57	0.52
χ^2(21)	total	175.34	54.98	28.00	33.71
χ^2/d.p.	total	8.35	2.62	1.33	1.61
χ^2(18)	S^{32}out	75.10	23.27	18.60	22.76
χ^2/d.p.	S^{32}out	4.17	1.29	1.03	1.26

Microscopic K−N + K−N N potentials derived from K−N scattering amplitudes constructed within SU(3) chiral coupled-channels models of meson-baryon interactions

Further inclusion of hyperon, nucleon, kaon and pion self-energies in the model

J. Obertova, E. Friedman, J. Mares
Phys. Rev. C 106 (2022) 6, 065201

Kaonic atoms state of art

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J. Obertova dedicated talk at HIN2025

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

Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3→2	−0.04 ±0.03	–	–	–	[15]
		−0.035±0.012	0.03 ±0.03	–	–	[16]
Li	3→2	0.002±0.026	0.055±0.029	0.95±0.30	–	[17]
Be	3→2	−0.079±0.021	0.172±0.58	0.25±0.09	0.04±0.02	[17]
^{10}B	3→2	−0.208±0.035	0.810±0.100	–	–	[18]
^{11}B	3→2	−0.167±0.035	0.700±0.080	–	–	[18]
C	3→2	−0.590±0.080	1.730±0.150	0.07±0.013	0.99±0.20	[18]
O	4→3	−0.025±0.018	0.017±0.014	–	–	[19]
Mg	4→3	−0.027±0.015	0.214±0.015	0.78±0.06	0.08±0.03	[19]
Al	4→3	−0.130±0.050	0.490±0.160	–	–	[20]
		−0.076±0.014	0.442±0.022	0.55±0.03	0.30±0.04	[19]
Si	4→3	−0.240±0.050	0.810±0.120	–	–	[20]
		−0.130±0.015	0.800±0.033	0.49±0.03	0.53±0.06	[19]
P	4→3	−0.330±0.08	1.440±0.120	0.26±0.03	1.89±0.30	[18]
S	4→3	−0.550±0.06	2.330±0.200	0.22±0.02	3.10±0.36	[18]
		−0.43 ±0.12	2.310±0.170	–	–	[21]
		−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 atoms state of art

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		−0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06	[19]
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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]
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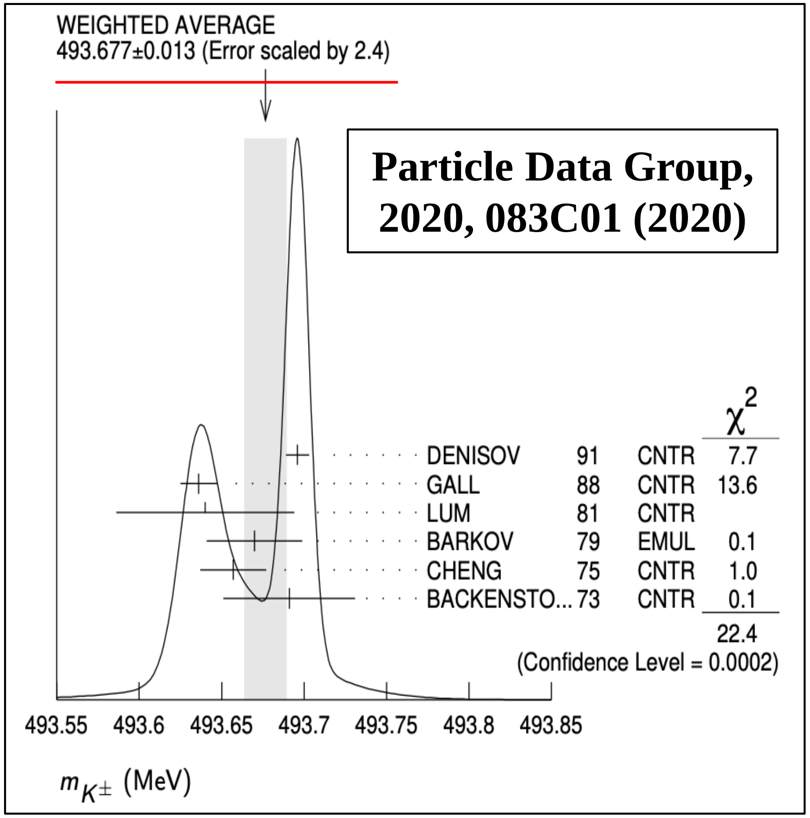
Absolute yields are basically unknown (except for few transitions)

New measurements (with improved precisions) are important to be performed

The K$^-$ mass problem

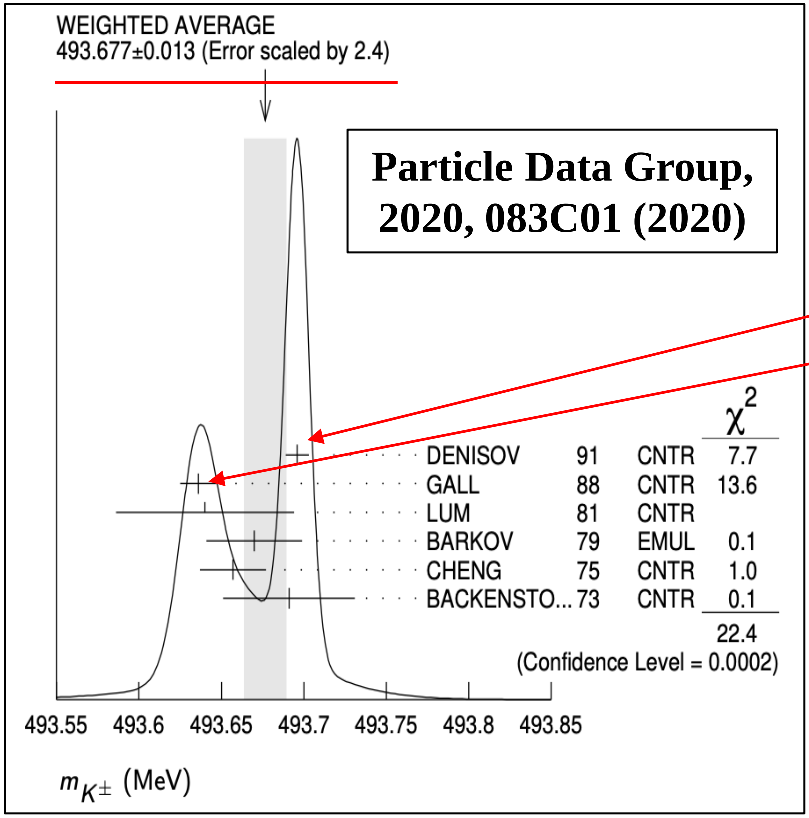
SIlicon Drift Detectors for HAdronic Atom Research by Timing Application



Large uncertainty → 26 p.p.m,
compared to charged pion:
$m_\pi = 139.57061 \pm 0.00023$ MeV, 1.6 p.p.m

The K$^-$ mass problem

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



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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

60 keV discrepancy between the two most accurate measurements

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Laboratori Nazionali di Frascati

The K$^-$ mass problem

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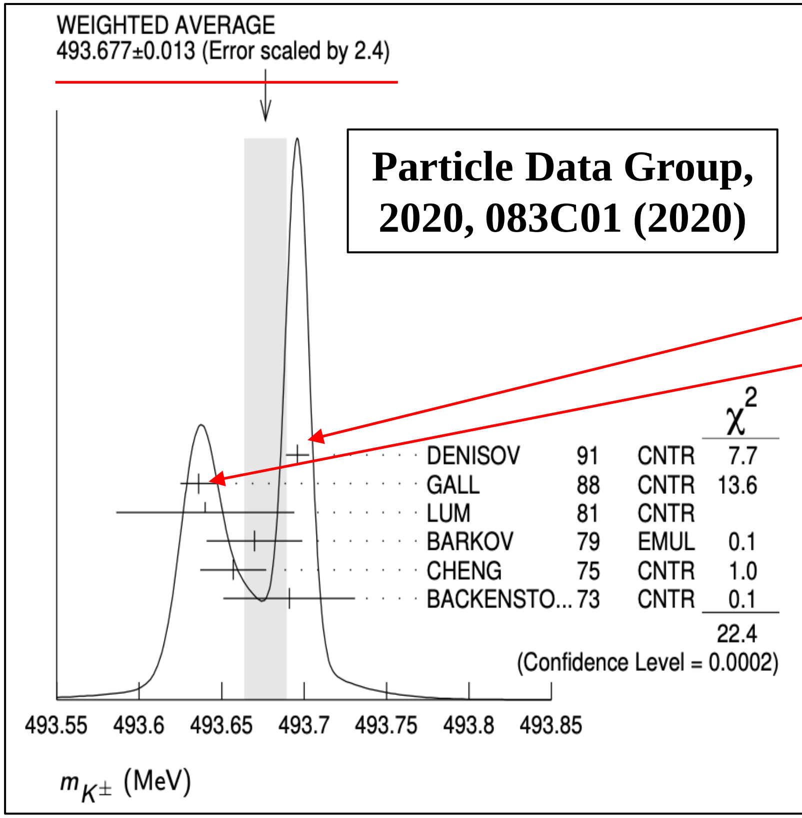

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Kaon mass precision is still a crucial open issue in strangeness nuclear physics

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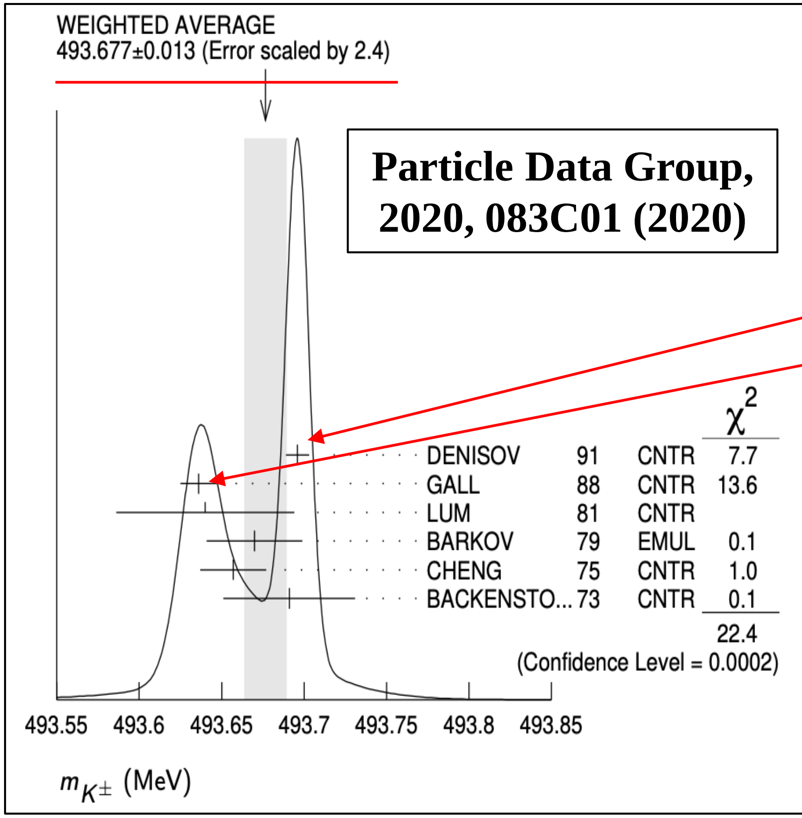

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Kaon mass puzzle can be addressed with HPGe detectors on solid targets (to repeat GALL KPb measurement)

The K⁻ mass problem

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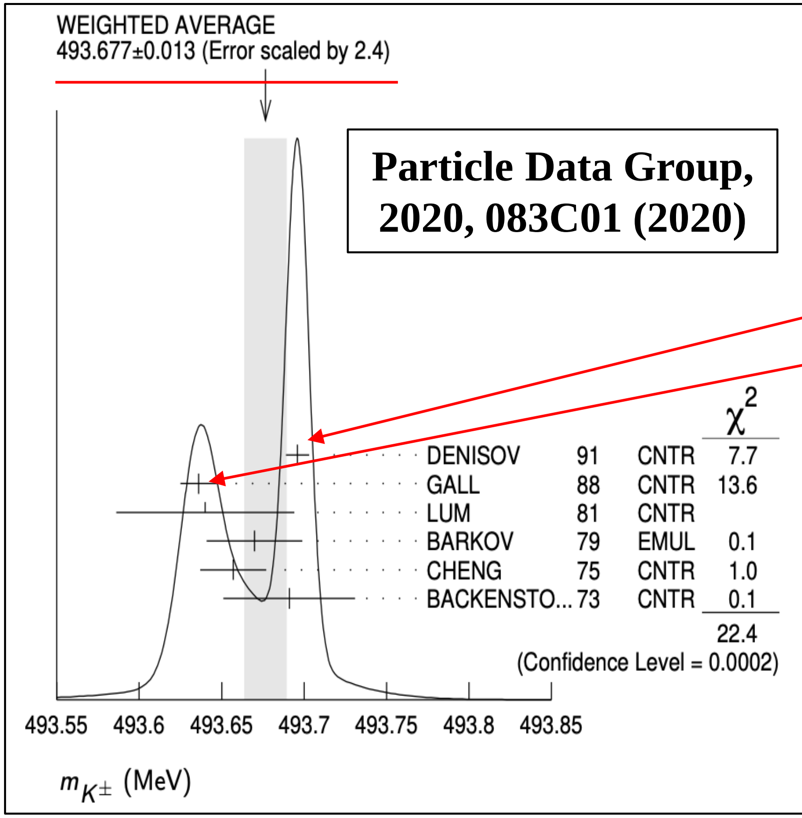

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493.657±0.020	[2] CHENG 75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...73	CNTR	−	Kaonic atoms

60 keV discrepancy between the two most accurate measurements

Kaon mass precision is still a crucial open issue in strangeness nuclear physics

Kaon mass puzzle can be addressed with HPGe detectors on solid targets (to repeat GALL KPb measurement)

Kaon mass puzzle can be addressed with SDD detectors on gaseous targets (attempt with KNe transitions)

K^4He measurement with SDDs

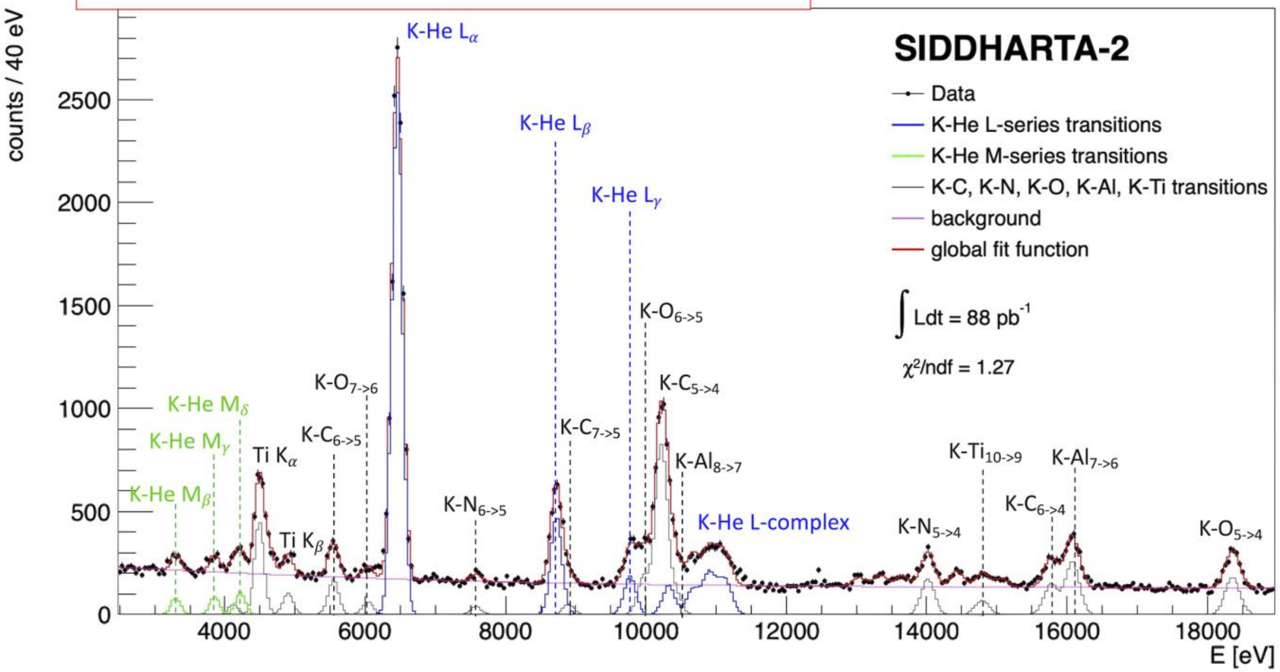
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

- Most precise measurement of kaonic helium-4 L in gas: 2p level energy shift and width
- First observation of kaonic helium-4 M-series transition (n3d)

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

$$\Gamma_{2p} = 0.01 \pm 1.60\,(\mathrm{stat}) \pm 0.36\,(\mathrm{sys})\ \mathrm{eV}$$

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



J. Phys. G (2024) 51 055103

Istituto Nazionale di Fisica Nucleare
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K^{4}He measurement with SDDs

SIlicon **D**rift
Detectors for
HAdronic **A**tom
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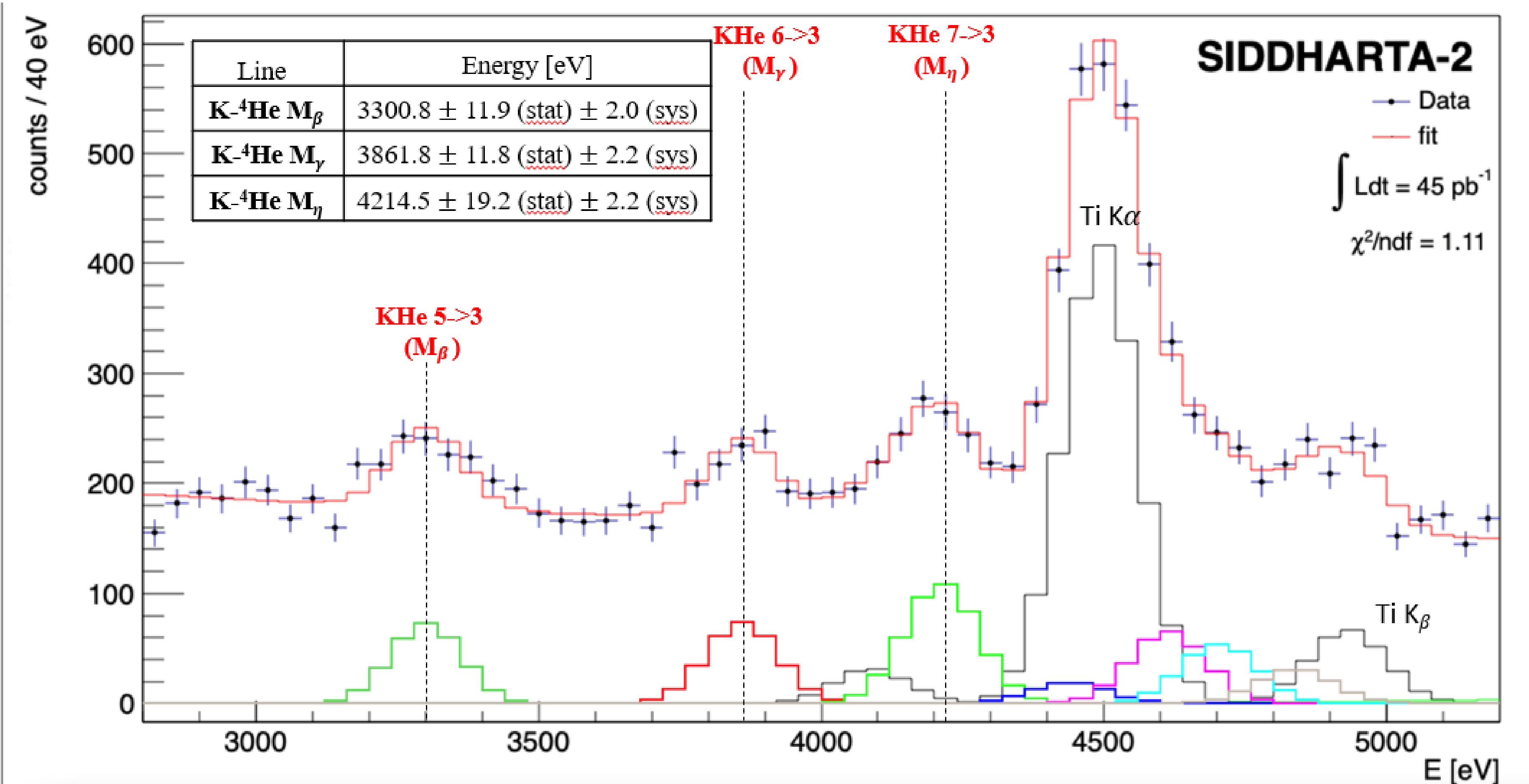

First measurement of
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K^4He measurement with SDDs

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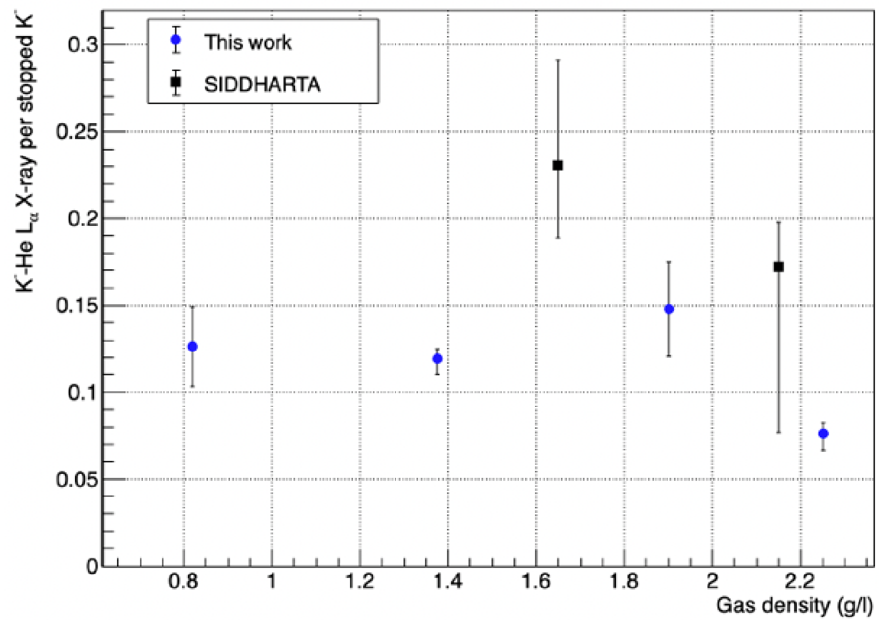
New experimental data for cascade models calculations
The X-ray yield is the key observable to understand the de-excitation mechanism in kaonic atoms and develop more accurate models.

First measurement of K-^4He M-series transition

Density	1.37 ± 0.07 g/l
L_α yield	$0.119 \pm 0.002\,(\mathrm{stat})^{+0.006\,(\mathrm{syst})}_{-0.009\,(\mathrm{syst})}$
M_β yield	$0.026 \pm 0.003\,(\mathrm{stat})^{+0.010\,(\mathrm{syst})}_{-0.001\,(\mathrm{syst})}$
L_β / L_α	0.172 ± 0.008 (stat)
L_γ / L_α	0.012 ± 0.001 (stat)
M_β / L_α	0.218 ± 0.029 (stat)
M_γ / M_β	0.48 ± 0.11 (stat)
M_δ / M_β	0.43 ± 0.12 (stat)

Sgaramella F., et al, 2024, *J. Phys. G: Nucl. Part. Phys.* **51** 055103

Study of yield density dependence for the K-^4He $L\alpha$ transition



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

K^4He measurement with SDDs

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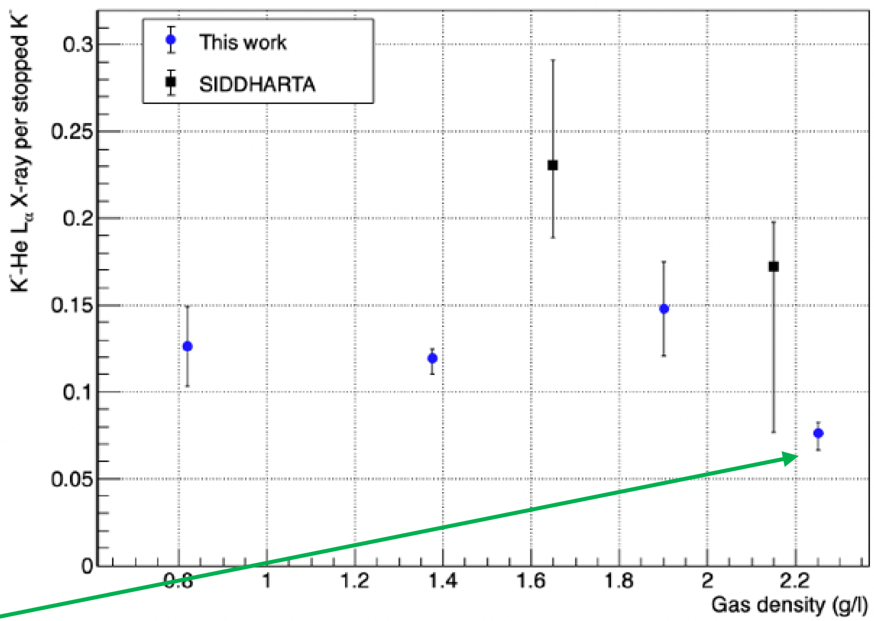


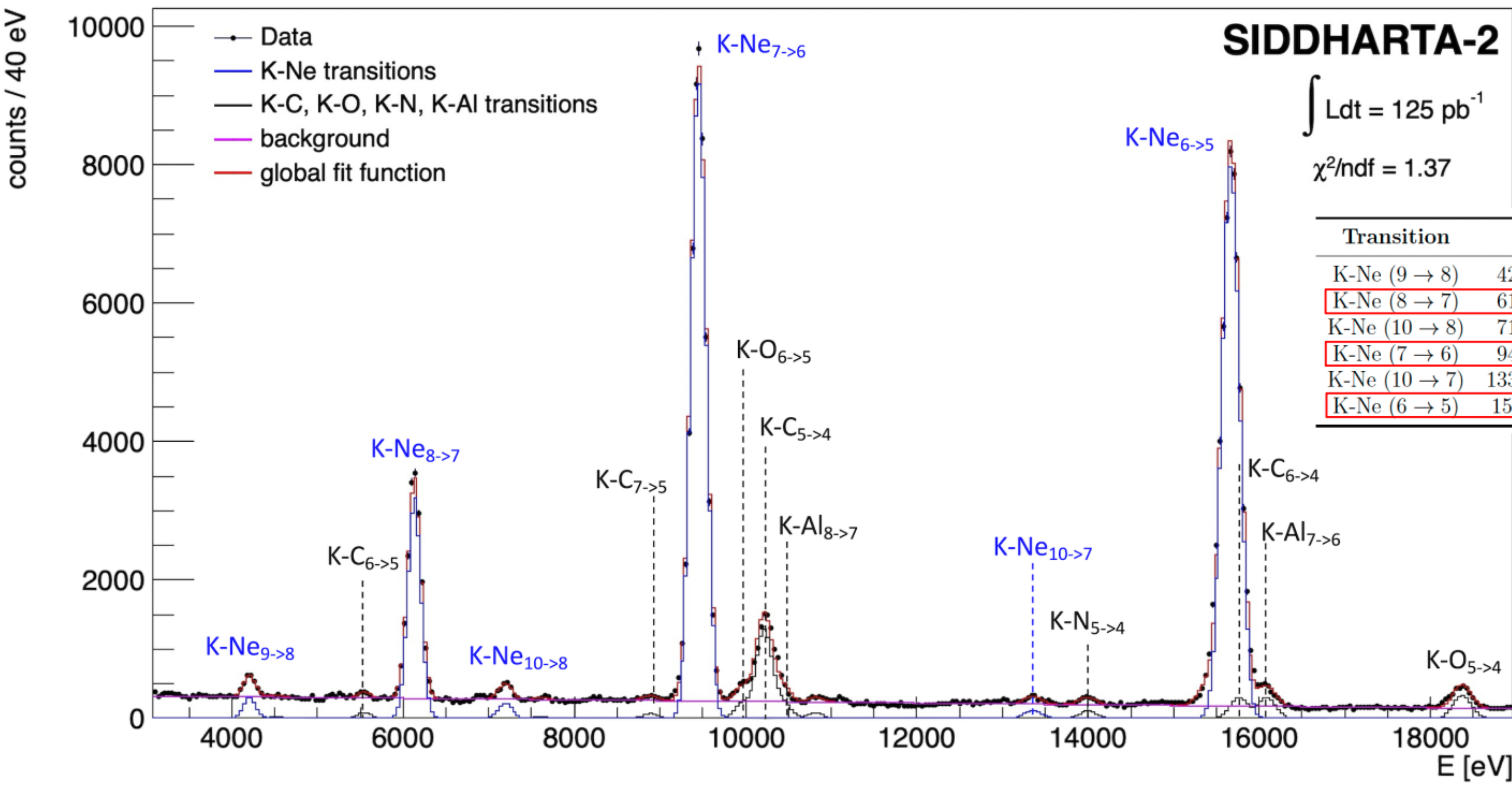
Sirghi D.L., Shi H., Guaraldo C., Sgaramella F., et al., 2023, Nucl. Phys. A,1029 122567

Stark effect observation in Helium

KNe measurement with SDDs

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

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



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

Paper submitted and under review

m_{K^-} with KNe

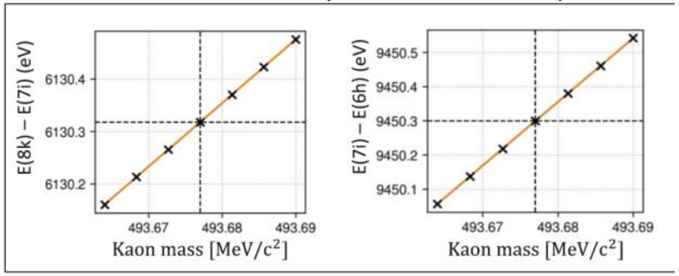
SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

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

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

Less/different systematic uncertainty with respect to DENISOV 91 and GALL 88 measurements, thanks to the use of a low Z gas target

Kaonic Ne energy transition as function of kaon mass (MCDFGME code)



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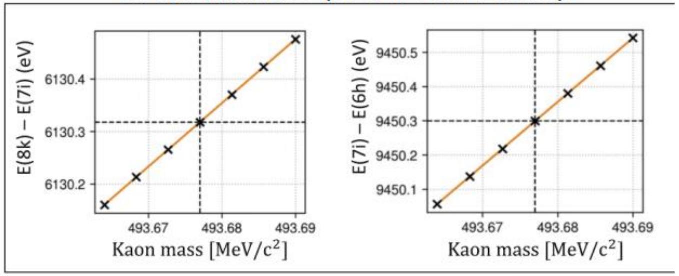

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$$K-Ne(8\rightarrow 7) = \frac{A_G}{\sqrt{2\pi}\sigma}\cdot e^{\frac{-(E-E_0)^2}{2\sigma^2}} \qquad E_0 = (m_{8\rightarrow 7}\cdot K_{mass} + q_{8\rightarrow 7})$$

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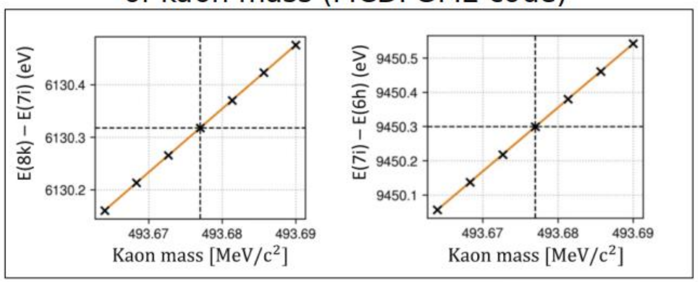

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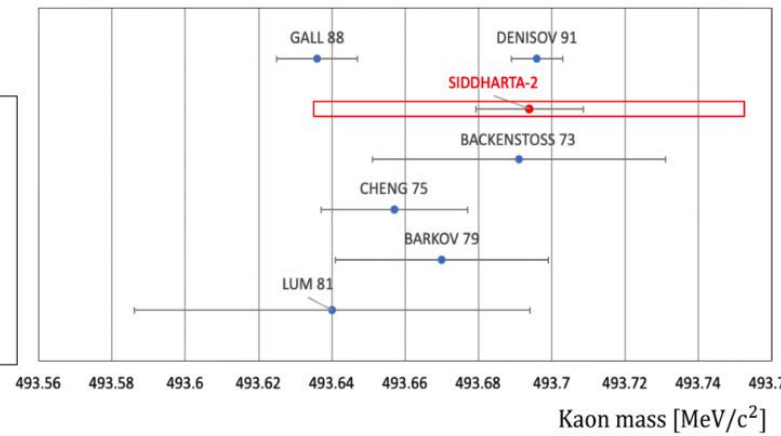

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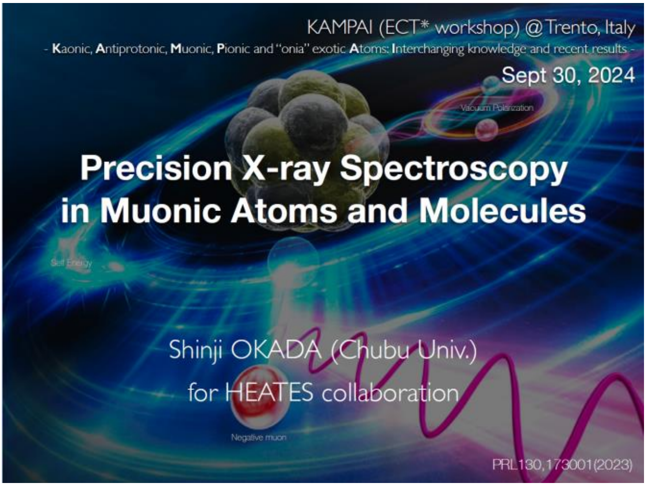
CHENG 75 [116]	493.657 ± 0.020
BACKENSTOSS 73 [117]	493.691 ± 0.040
This work	493.694 ± 0.015 (stat) ± 0.060 (syst)

Precise QED investigations with KNe

SIlicon **D**rift
Detectors for
HAdronic **A**tom
Research by
Timing **A**pplication



Precise QED investigations with KNe

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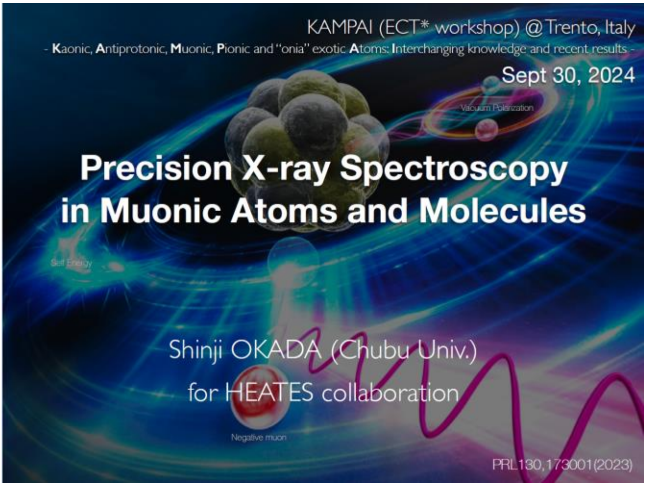

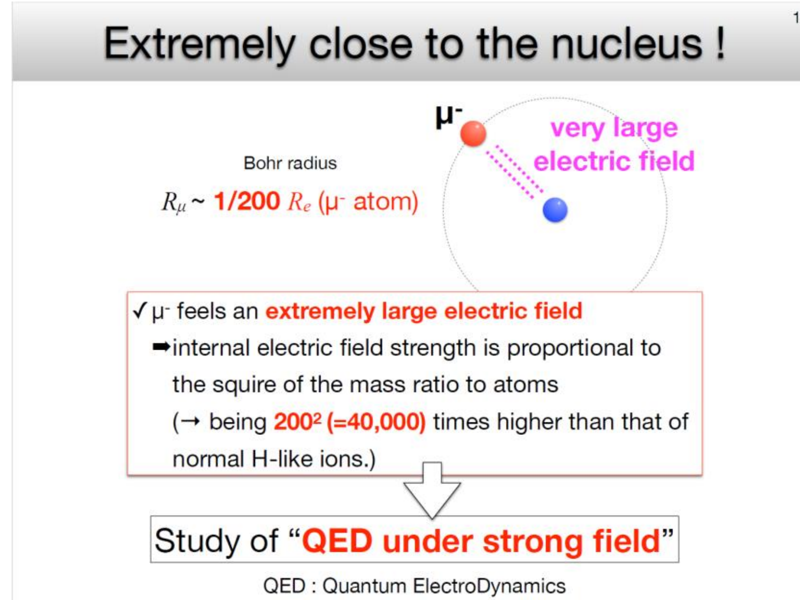

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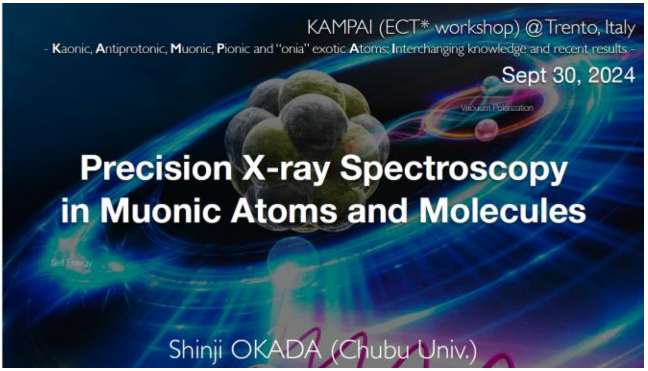
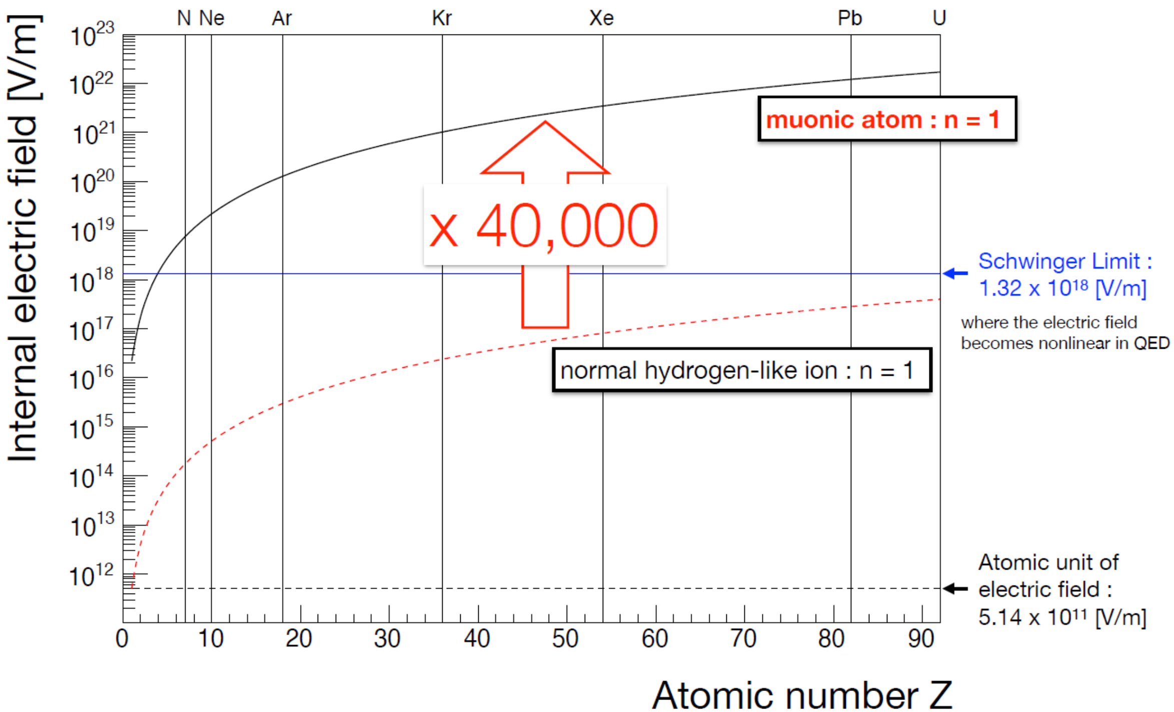


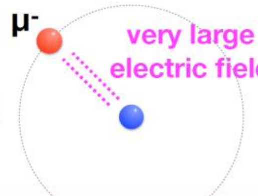


14

Extremely close to the nucleus !

Bohr radius

$R_\mu \sim$ **1/200** R_e (μ⁻ atom)



✓ μ⁻ feels an **extremely large electric field**
➡internal electric field strength is proportional to the squire of the mass ratio to atoms
(→ being **200² (=40,000)** times higher than that of normal H-like ions.)

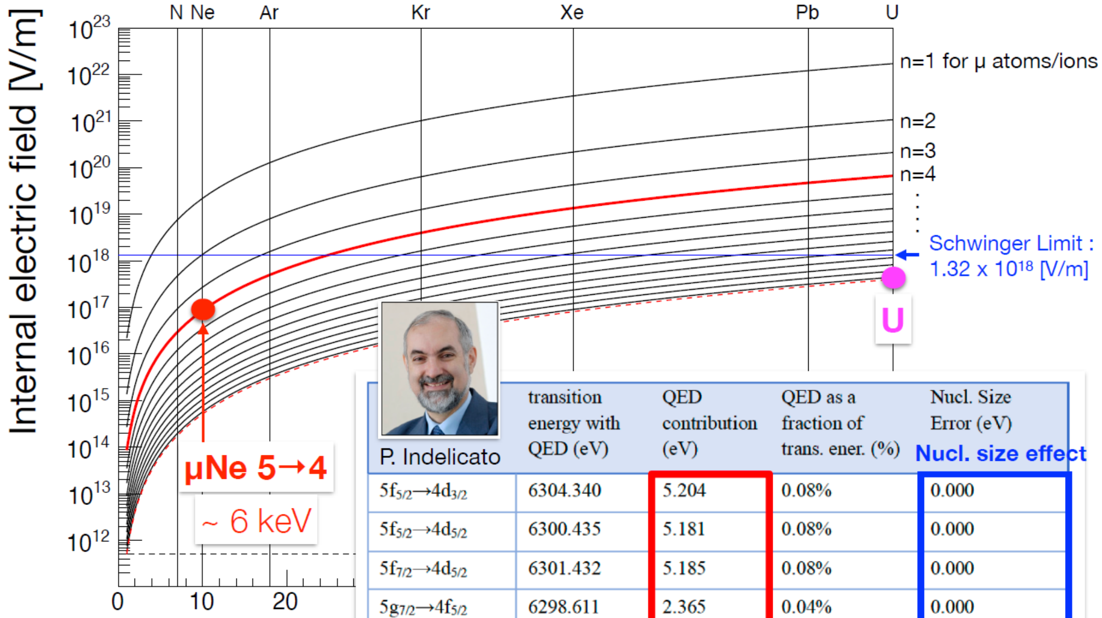
Study of "**QED under strong field**"

QED : Quantum ElectroDynamics

Precise QED investigations with KNe

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication

The first experiment (with ~10 keV X-ray region)



P. Indelicato	transition energy with QED (eV)	QED contribution (eV)	QED as a fraction of trans. ener. (%)	Nucl. Size Error (eV) Nucl. size effect
$5f_{5/2} \to 4d_{3/2}$	6304.340	5.204	0.08%	0.000
$5f_{5/2} \to 4d_{5/2}$	6300.435	5.181	0.08%	0.000
$5f_{7/2} \to 4d_{5/2}$	6301.432	5.185	0.08%	0.000
$5g_{7/2} \to 4f_{5/2}$	6298.611	2.365	0.04%	0.000
$5g_{7/2} \to 4f_{7/2}$	6296.664	2.357	0.04%	0.000
$5g_{9/2} \to 4f_{7/2}$	6297.261	2.359	0.04%	0.000

Precise QED investigations with KNe

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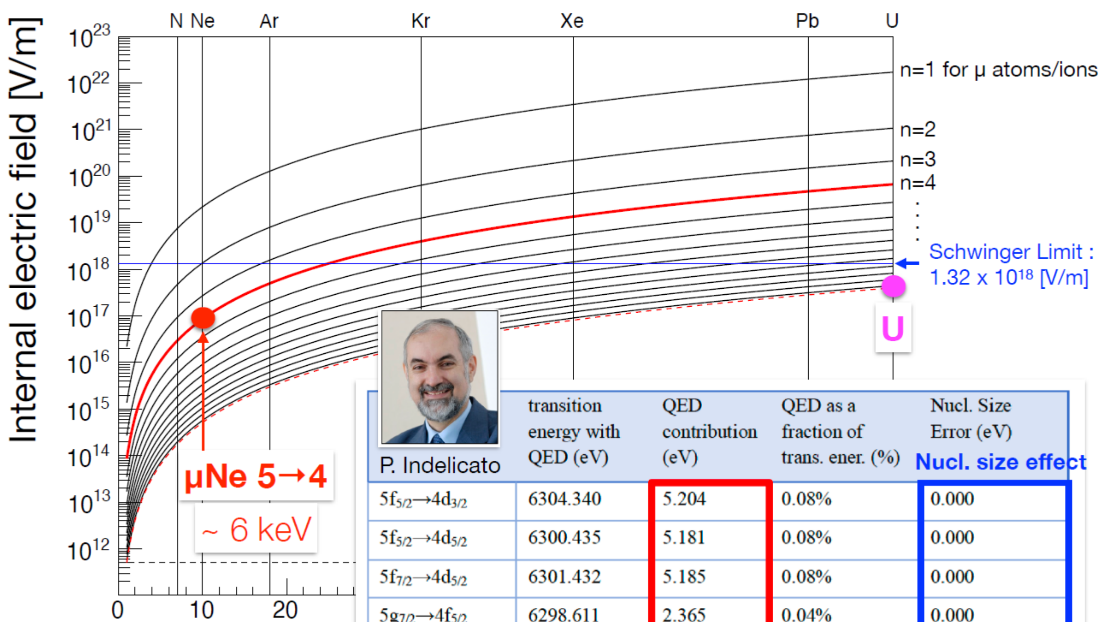

P. Indelicato

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PHYSICAL REVIEW LETTERS **126,** 173001 (2021)

TABLE I. Transition energies, QED, and finite size corrections for transitions amenable to BSQED tests in muonic atoms and antiprotonic atoms, compared to transitions of similar energies in highly charged ions. All energies are given in eV.

Particle	Element	Initial state	Final state	Theoretical transition energy	1st order QED	2nd order QED	$g-2\ \bar{p}$	FNS	FNS/QED	Exp.	Ref.
e^-	^{40}Ar	$2p_{3/2}$	$1s_{1/2}$	3322.9931	−1.1238	0.0007		−0.0090	0.804%	3322.993(14)	[6]
μ^-	^{20}Ne	$6h_{11/2}$	$5g_{9/2}$	3419.6828	0.3845	0.0042		0.0001	0.013%		
$\bar{p}$	^{40}Ar	$17v_{33/2}$	$16u_{31/2}$	3522.9850	1.2209	0.0124	0.0618	0.0002	0.014%		
e^-	^{56}Fe	$2p_{3/2}$	$1s_{1/2}$	6973.1815	−3.8873	0.0042		−0.0527	1.357%	6972.73(24)	[50]
μ^-	^{20}Ne	$5g_{9/2}$	$4f_{7/2}$	6297.2616	2.3365	0.0229		0.0003	0.013%		
e^-	^{84}Kr	$2p_{3/2}$	$1s_{1/2}$	13 508.9648	−11.4244	0.0181		−0.2963	2.594%	13 508.95(50)	[66]

Precise QED investigations with KNe

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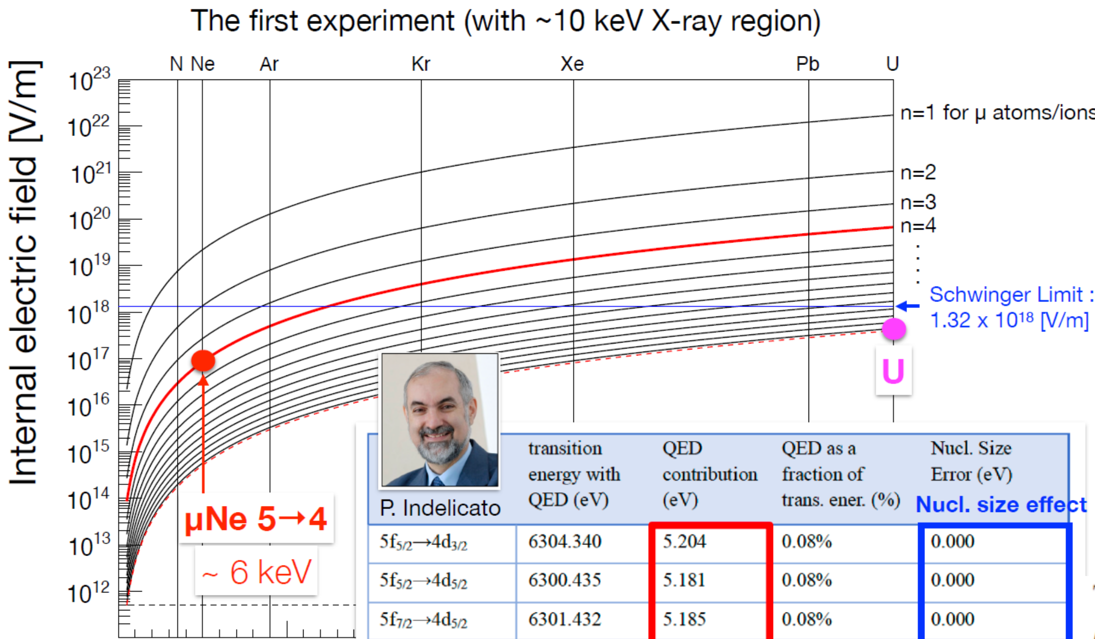

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$5f_{5/2}\to 4d_{5/2}$	6300.435	5.181	0.08%	0.000
$5f_{7/2}\to 4d_{5/2}$	6301.432	5.185	0.08%	0.000
$5g_{7/2}\to 4f_{5/2}$	6298.611	2.365	0.04%	0.000
$5g_{7/2}\to 4f_{7/2}$	6296.664	2.357	0.04%	0.000
$5g_{9/2}\to 4f_{7/2}$	6297.261	2.359	0.04%	0.000

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TABLE I. Transition energies, QED, and finite size corrections for transitions amenable to BSQED tests in muonic atoms and antiprotonic atoms, compared to transitions of similar energies in highly charged ions. All energies are given in eV.

Particle	Element	Initial state	Final state	Theoretical transition energy	1st order QED	2nd order QED	$g-2\ \bar{p}$	FNS	FNS/QED	Exp.	Ref.
e^-	^{40}Ar	$2p_{3/2}$	$1s_{1/2}$	3322.9931	−1.1238	0.0007		−0.0090	0.804%	3322.993(14)	[6]
μ^-	^{20}Ne	$6h_{11/2}$	$5g_{9/2}$	3419.6828	0.3845	0.0042		0.0001	0.013%		
$\bar{p}$	^{40}Ar	$17v_{33/2}$	$16u_{31/2}$	3522.9850	1.2209	0.0124	0.0618	0.0002	0.014%		
e^-	^{56}Fe	$2p_{3/2}$	$1s_{1/2}$	6973.1815	−3.8873	0.0042		−0.0527	1.357%	6972.73(24)	[50]
μ^-	^{20}Ne	$5g_{9/2}$	$4f_{7/2}$	6297.2616	2.3365	0.0229		0.0003	0.013%		
e^-	^{84}Kr	$2p_{3/2}$	$1s_{1/2}$	13 508.9648	−11.4244	0.0181		−0.2963	2.594%	13 508.95(50)	[66]

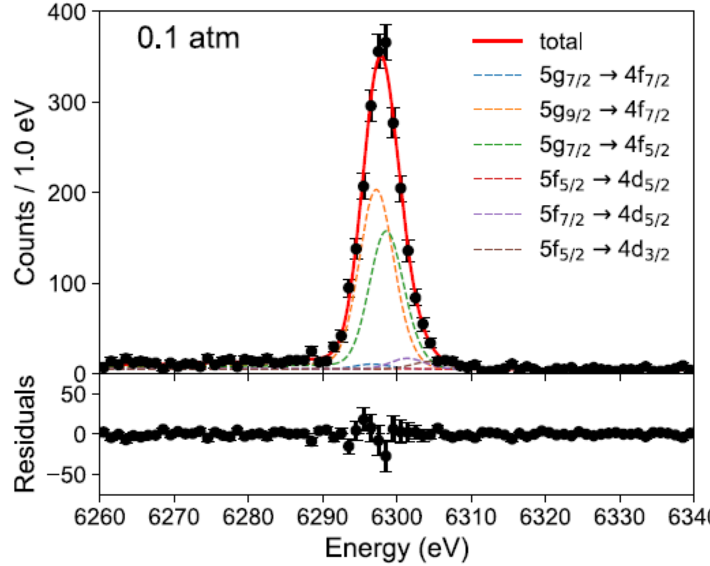

TABLE II. The experimental $5g_{9/2}$-$4f_{7/2}$ transition energies for μ^{20}Ne and associated uncertainties.

Transition energy and uncertainties (eV)	$5g_{9/2}-4f_{7/2}$ 0.1 atm	0.4 atm	0.9 atm
Measured energy	6297.13	6297.06	6297.05
Statistical error	0.07	0.06	0.06
Systematic error: Total	0.13	0.13	0.13
(1) Calibration	0.07	0.07	0.07
(2) Low-energy tail	0.01	0.02	0.01
(3) Thermal crosstalk	0.11	0.11	0.11

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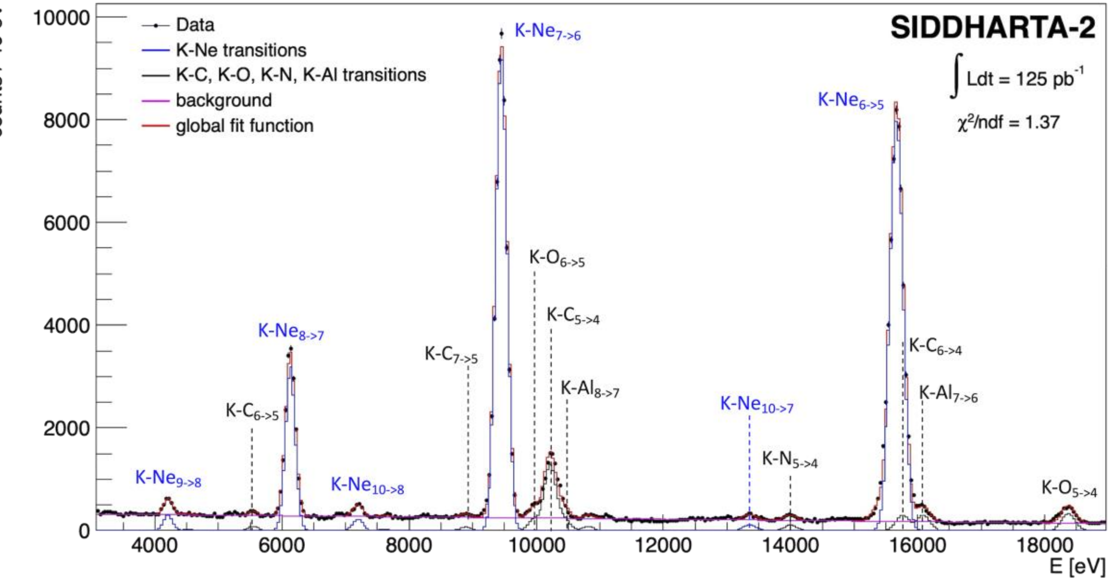
Precise QED investigations with KNe

SIlicon **D**rift **D**etectors for **HA**dronic **A**tom **R**esearch by **T**iming **A**pplication



High-n transition in kaonic atoms represents an ideal test bench for BSQED:

1. For high-n transitions, the strong interaction contribution is negligible

2. Due to the compactness of the kaonic atom the QED effects such as vacuum polarization are enhanced compared to high-Z ions

3. BSQED corrections for kaonic neon are of the order of tens of eV for first-order QED effects and order of 0.2 eV for second-order QED effects

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

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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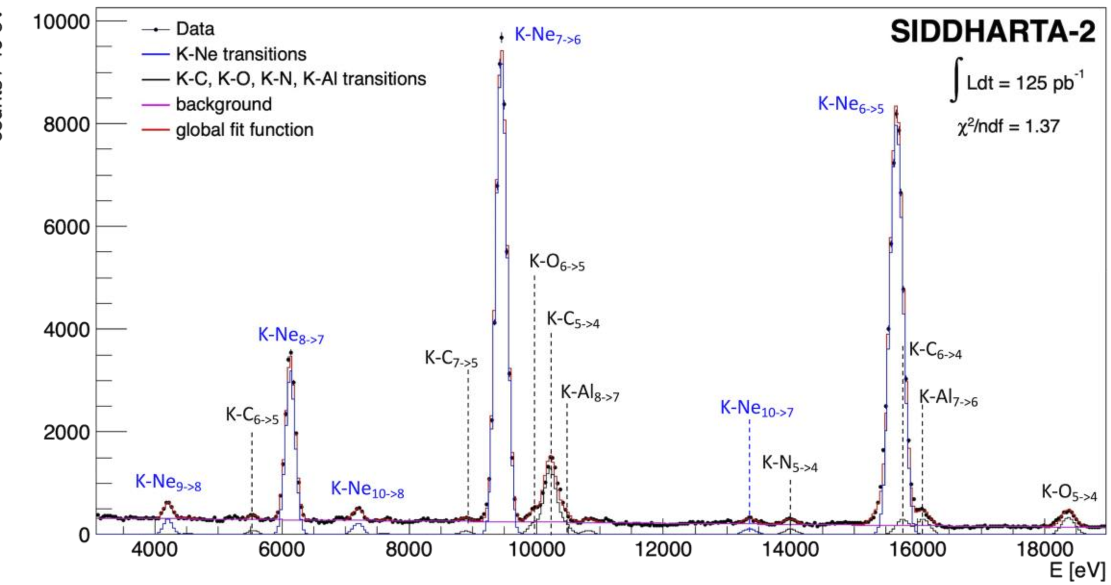

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Calculations and feasibility under evaluation