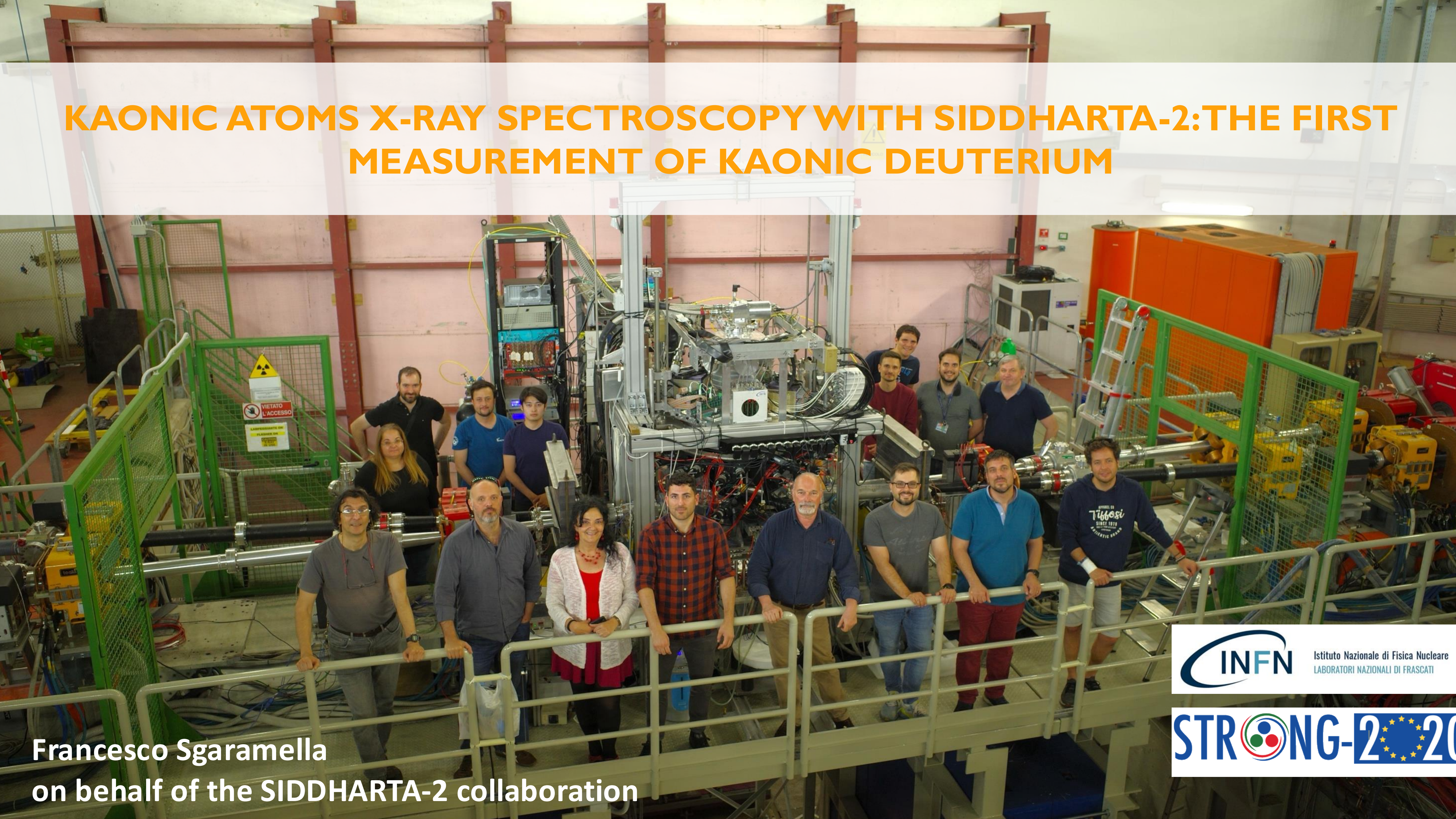
KAONIC ATOMS X-RAY SPECTROSCOPY WITH SIDDHARTA-2: THE FIRST MEASUREMENT OF KAONIC DEUTERIUM



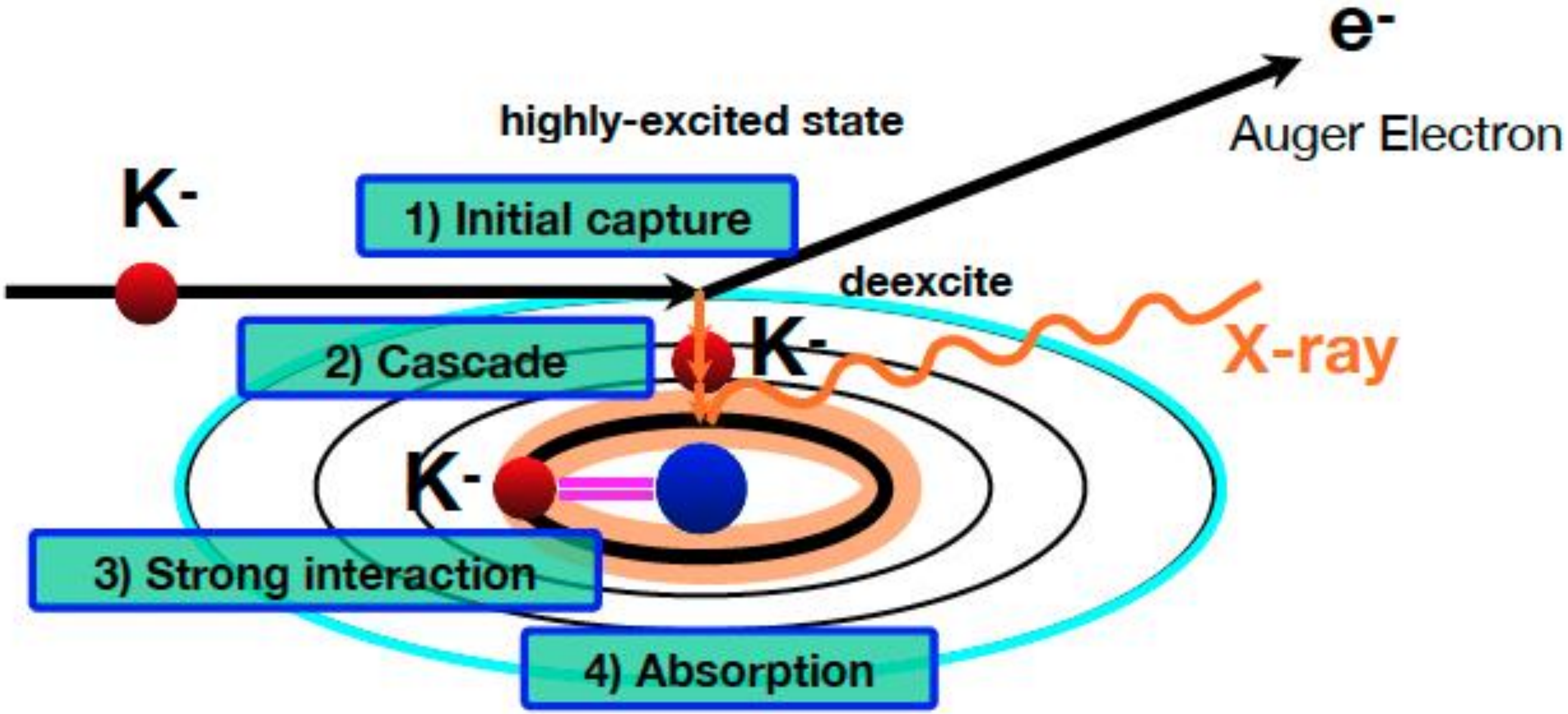
Francesco Sgaramella
on behalf of the SIDDHARTA-2 collaboration

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

Kaonic Atoms X-ray Spectroscopy

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



Kaonic Atoms X-ray Spectroscopy

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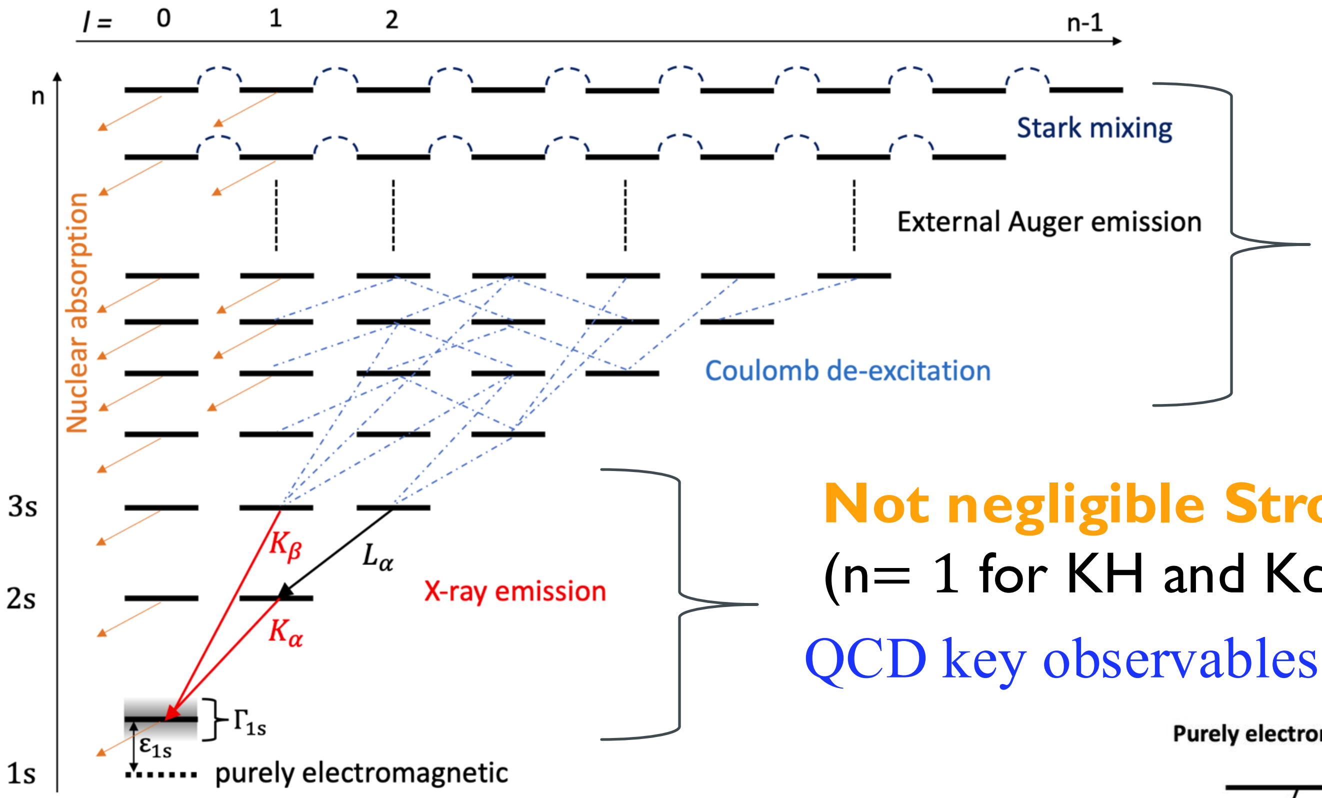


Pure QED transition (n>4)

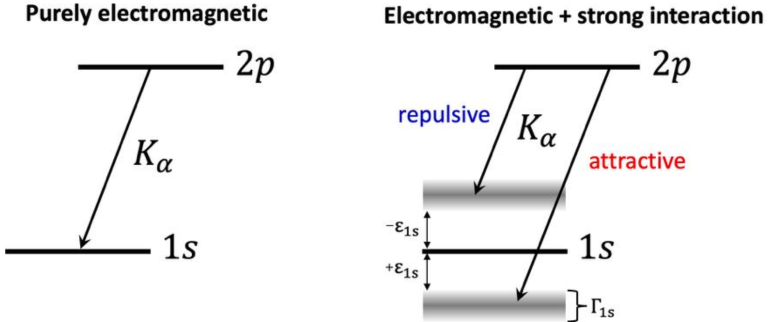
QED key observables: **Energy** and **X-ray Yield**

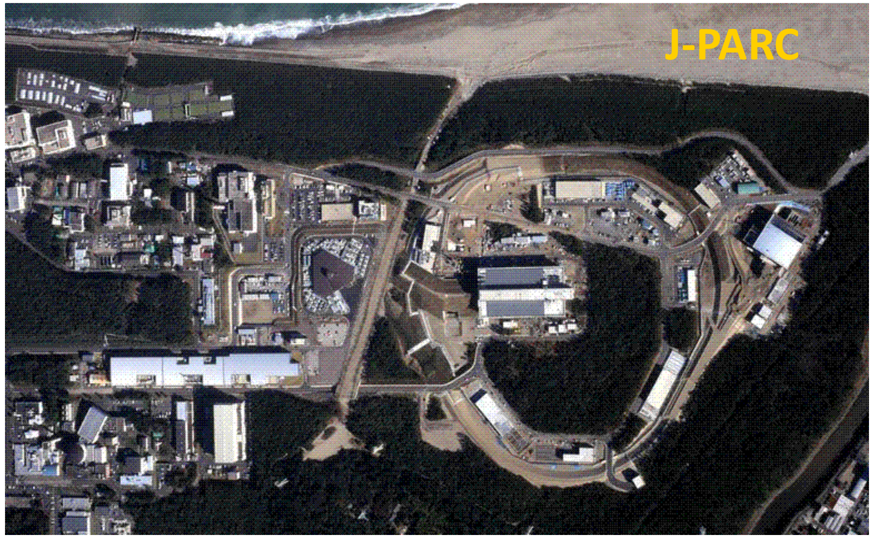
High precision test of BSQED

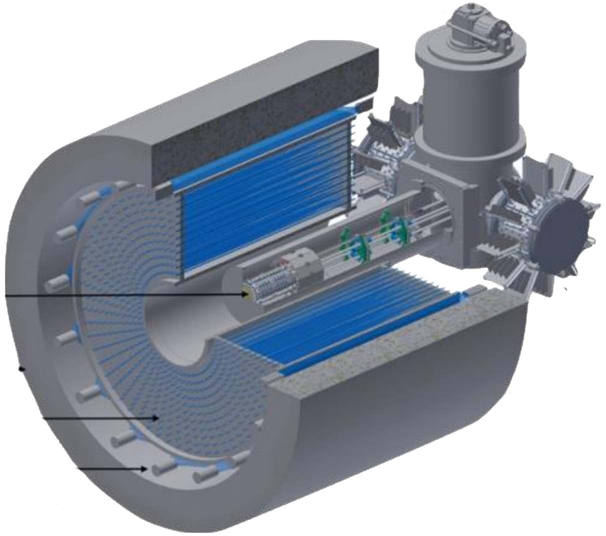
Not negligible Strong interaction effect

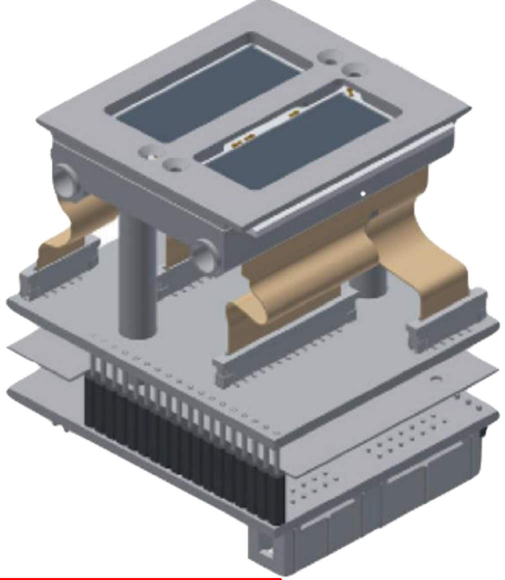
(n= 1 for KH and Kd)

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









The modern era of light kaonic atom experiments

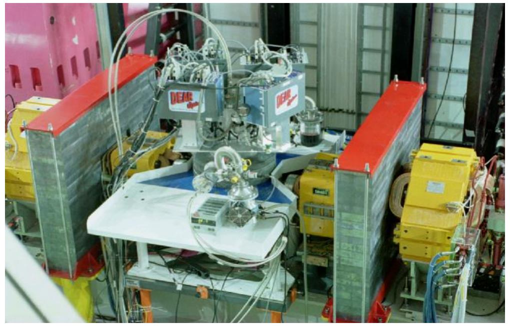
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

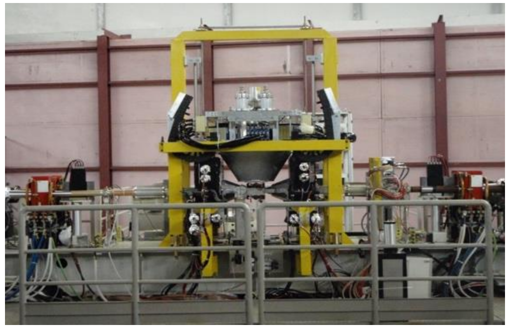
Rev. Mod. Phys. **91**, 025006 – Published 20 June 2019

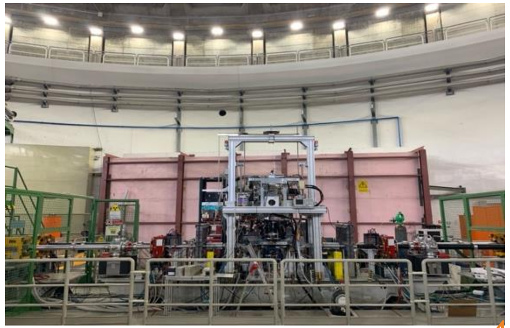
DEAR
2002

SIDDHARTA
2009

SIDDHARTA-2
2022

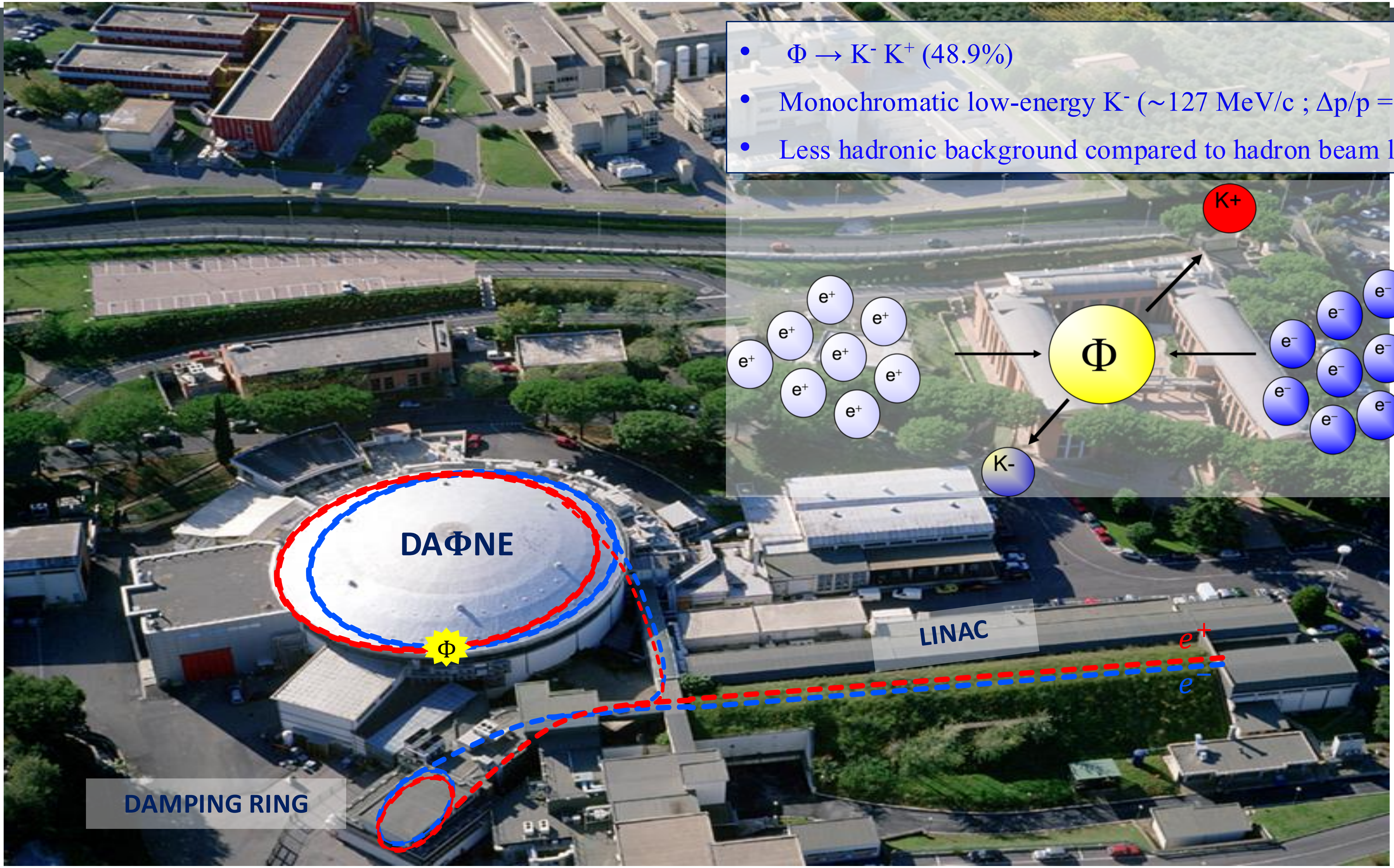






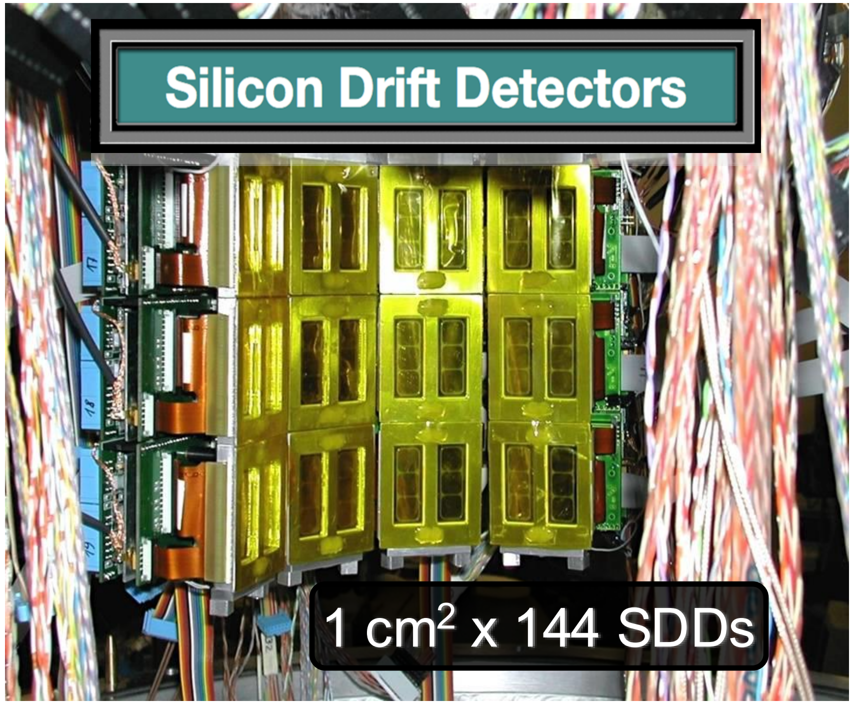
The DAΦNE collider of INFN-LNF

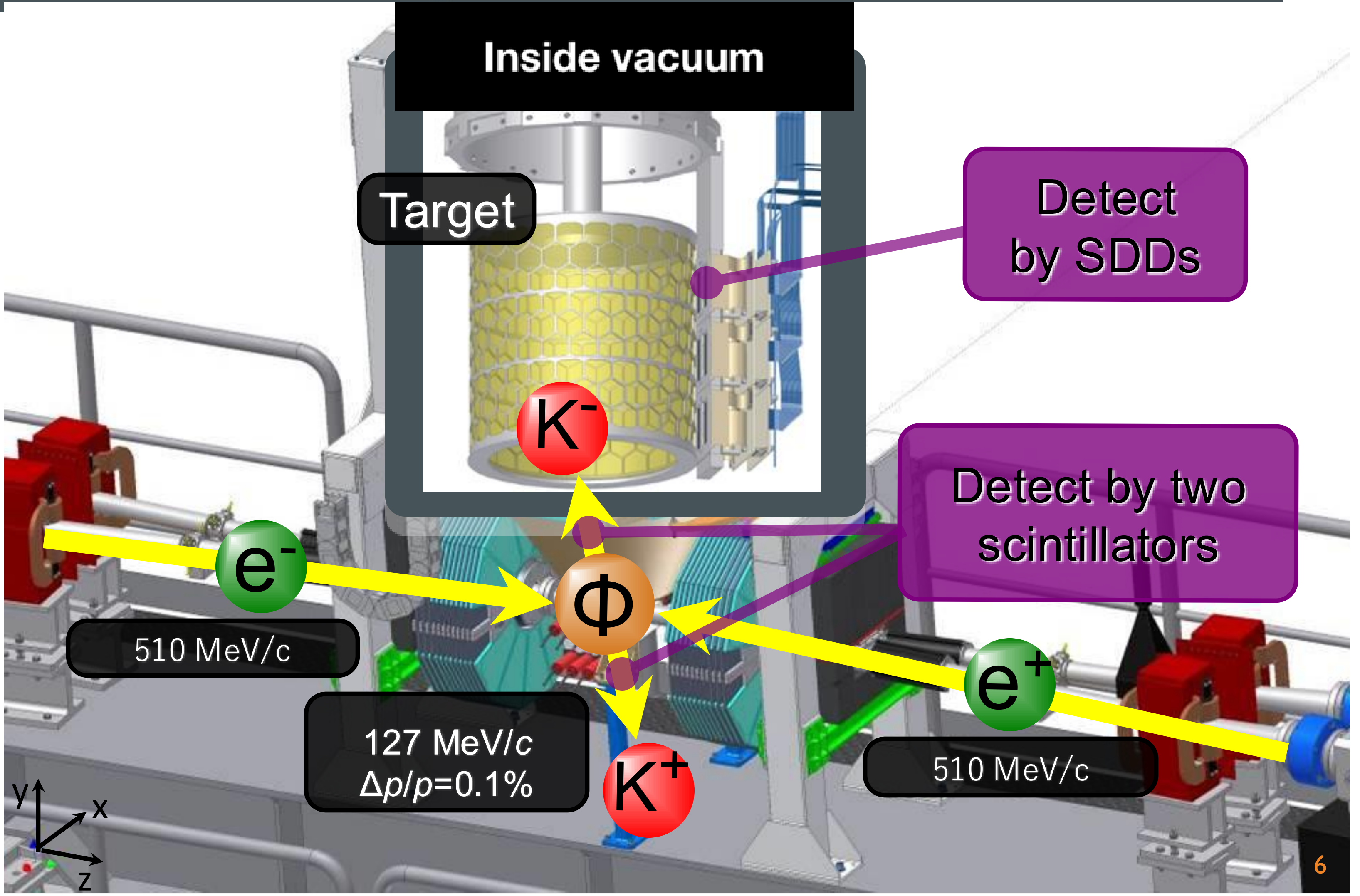
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- ($\sim$127 MeV/c ; $\Delta p/p = 0.1\%$)
- Less hadronic background compared to hadron beam line



The SIDDHARTA Experiment (2009)

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



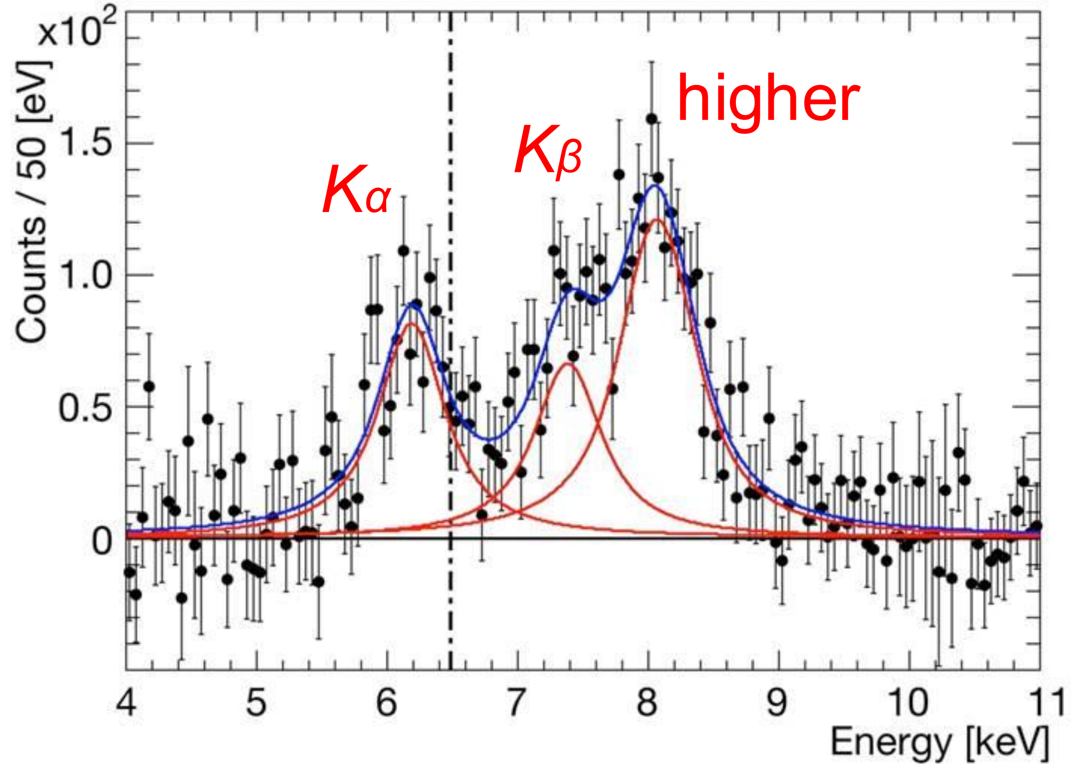


The SIDDHARTA Experiment (2009)

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

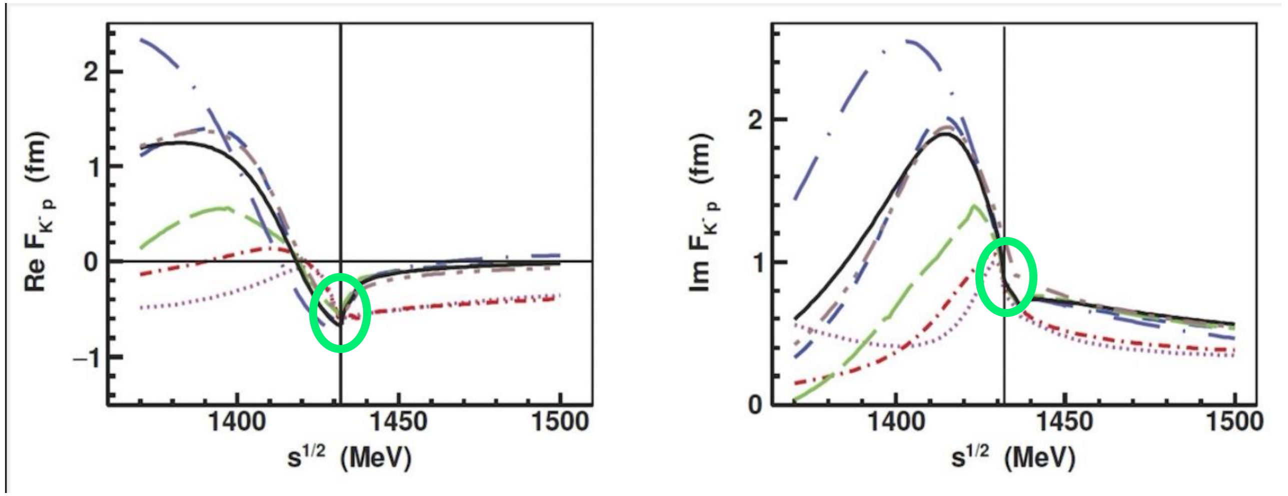
$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})$ eV

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



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

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

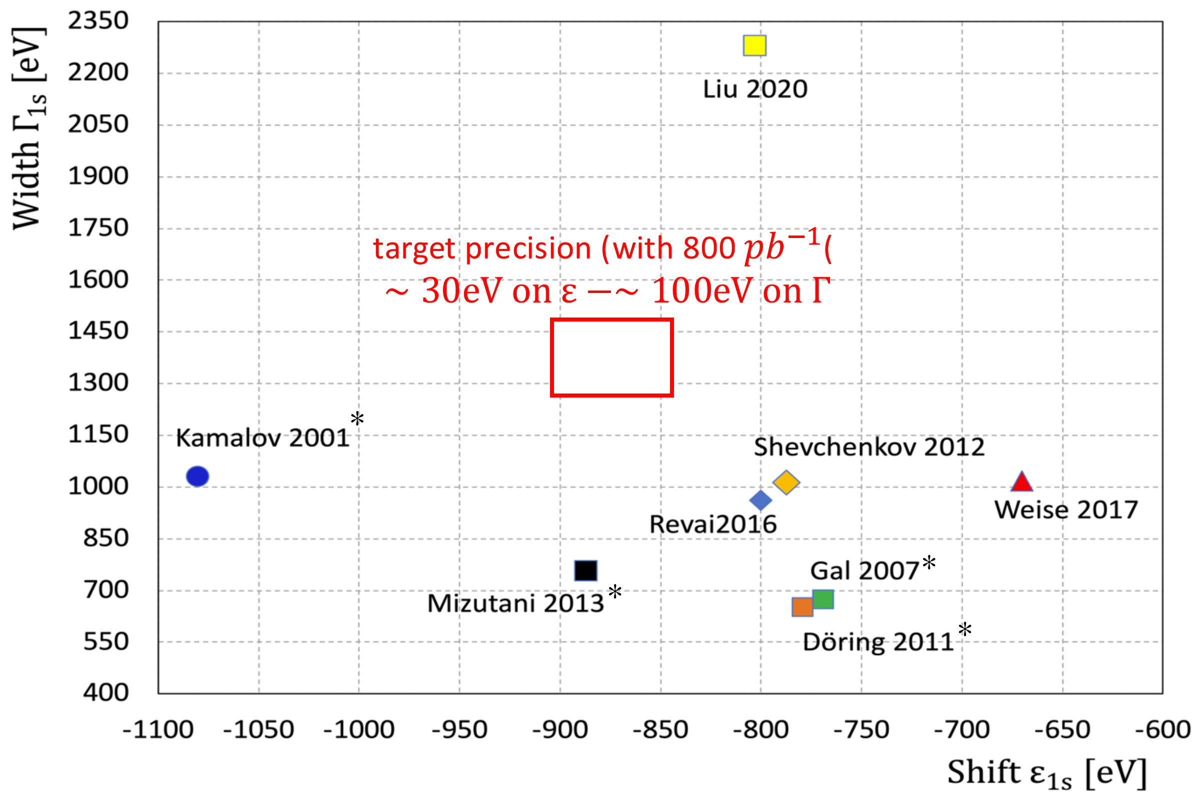


Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

The SIDDHARTA-2's experiment main aim

Main scientific goal: **first measurement ever of kaonic deuterium X-ray transition** to the ground state (1s-level) such as to determine its **shift and width induced by the strong interaction**, providing unique data to investigate the **QCD in the non-perturbative regime** with strangeness.

Kd theoretical prediction



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

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

R.H. Dalitz (1982)

The SIDDHARTA-2's experiment main aim

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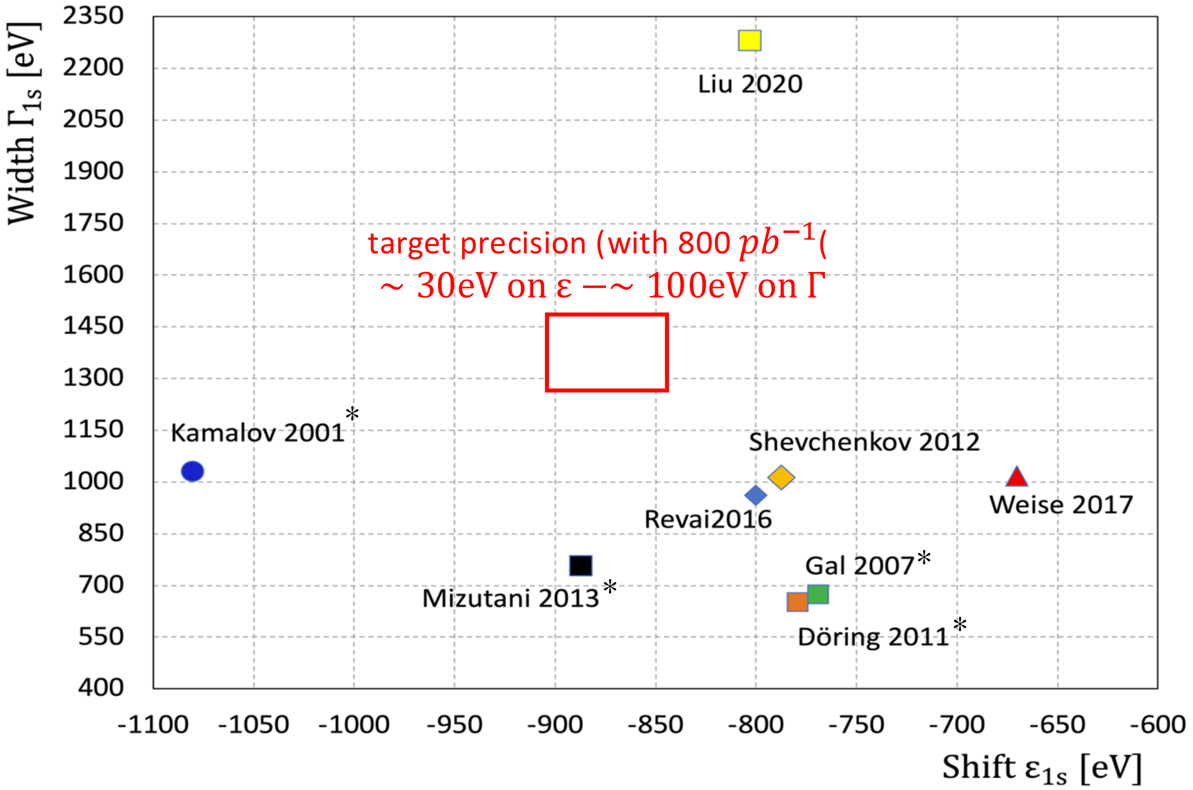
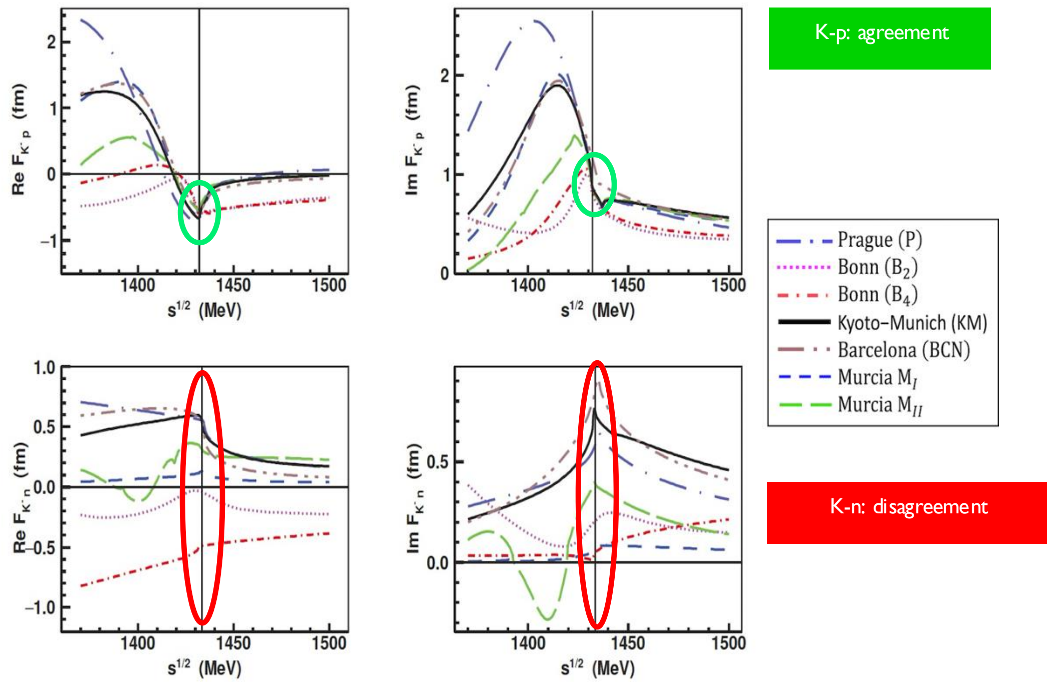


*The energy shift and width are extracted from scattering length using the Deser-Trueman formula

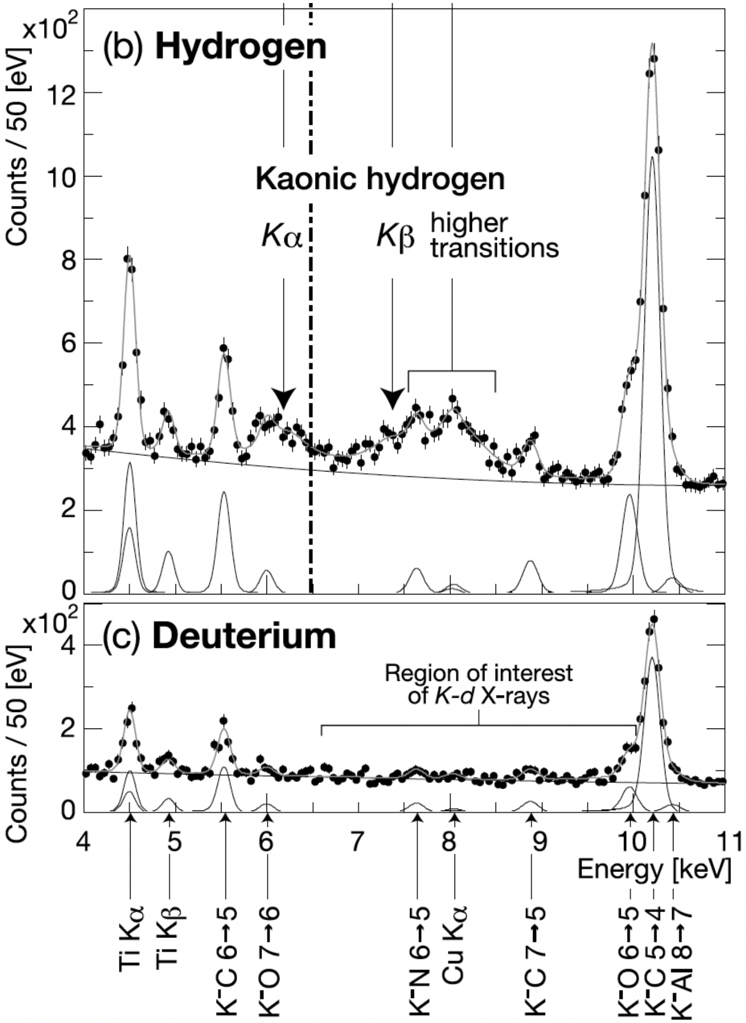
Combined analysis of the kaonic deuterium and kaonic hydrogen measurements to determine the isospin-dependet $\overline{K}N$ scattering lengths



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

The kaonic deuterium challenge

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



Physics factors:

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

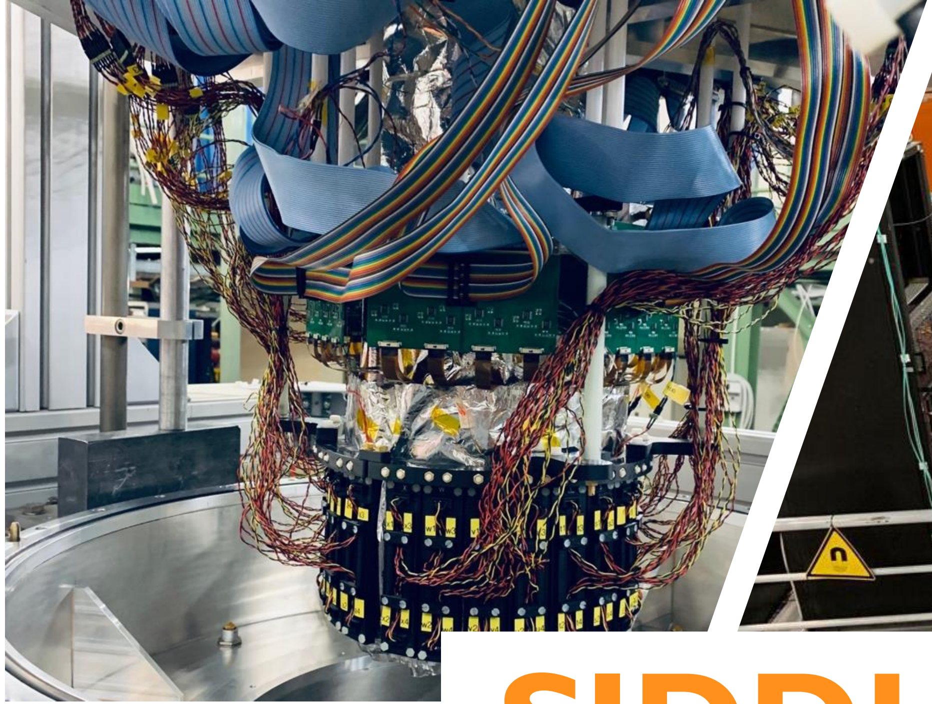
➢ Kd requires a higher integrate luminosity ~800 pb^{-1}

Background:

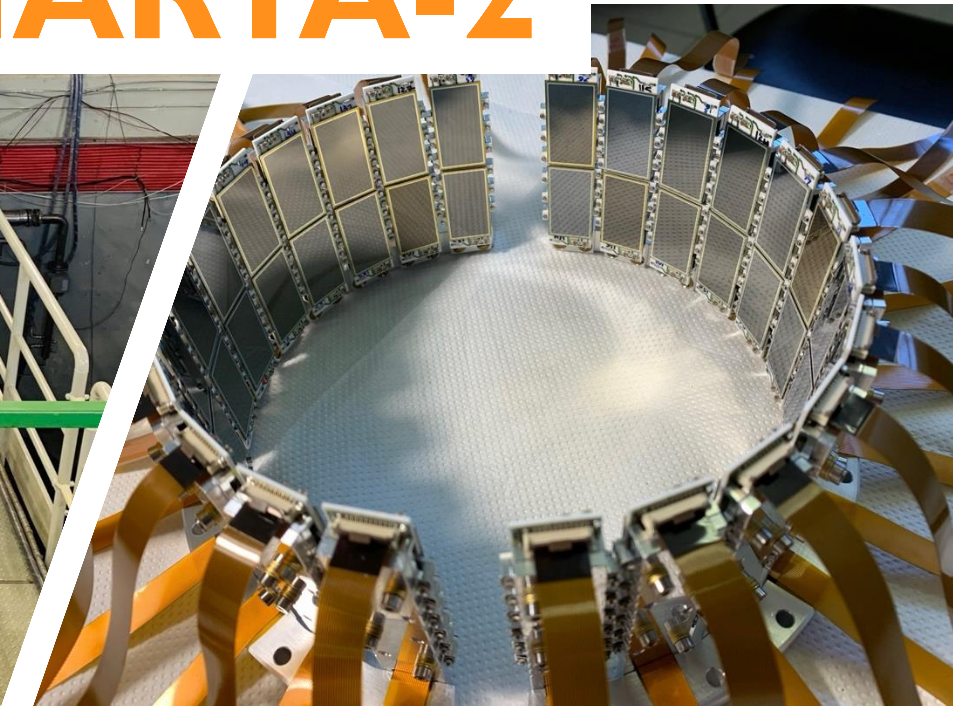
- The Kd measurement requires an improvement in signal/background ratio by a factor 10

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

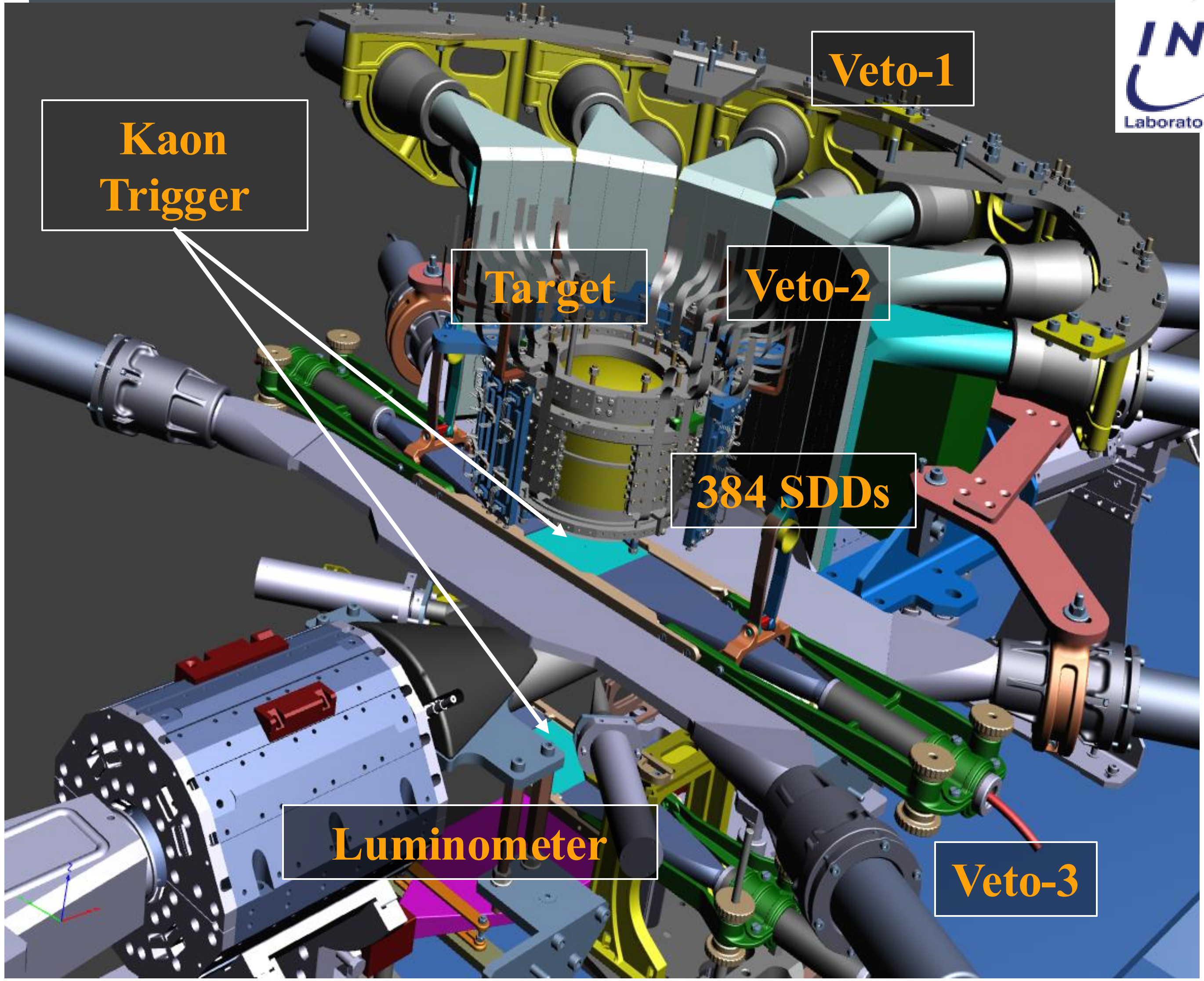
➢ Larger detection area



SIDDHARTA-2



The SIDDHARTA-2 setup and DAΦNE collider



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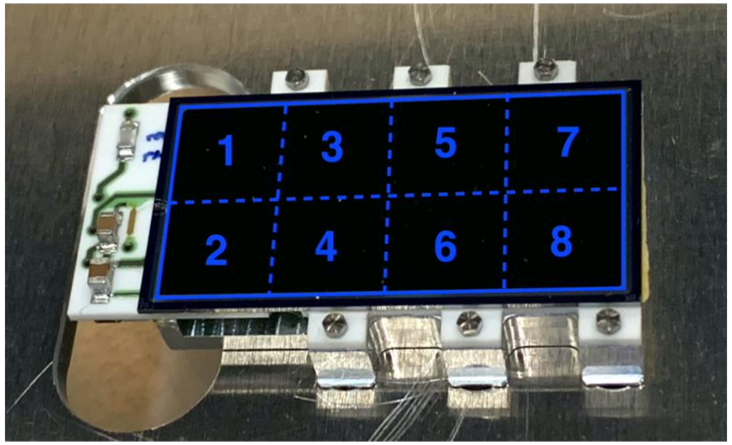
POLITECNICO MILANO 1863

FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

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

The thickness of 450 μm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV



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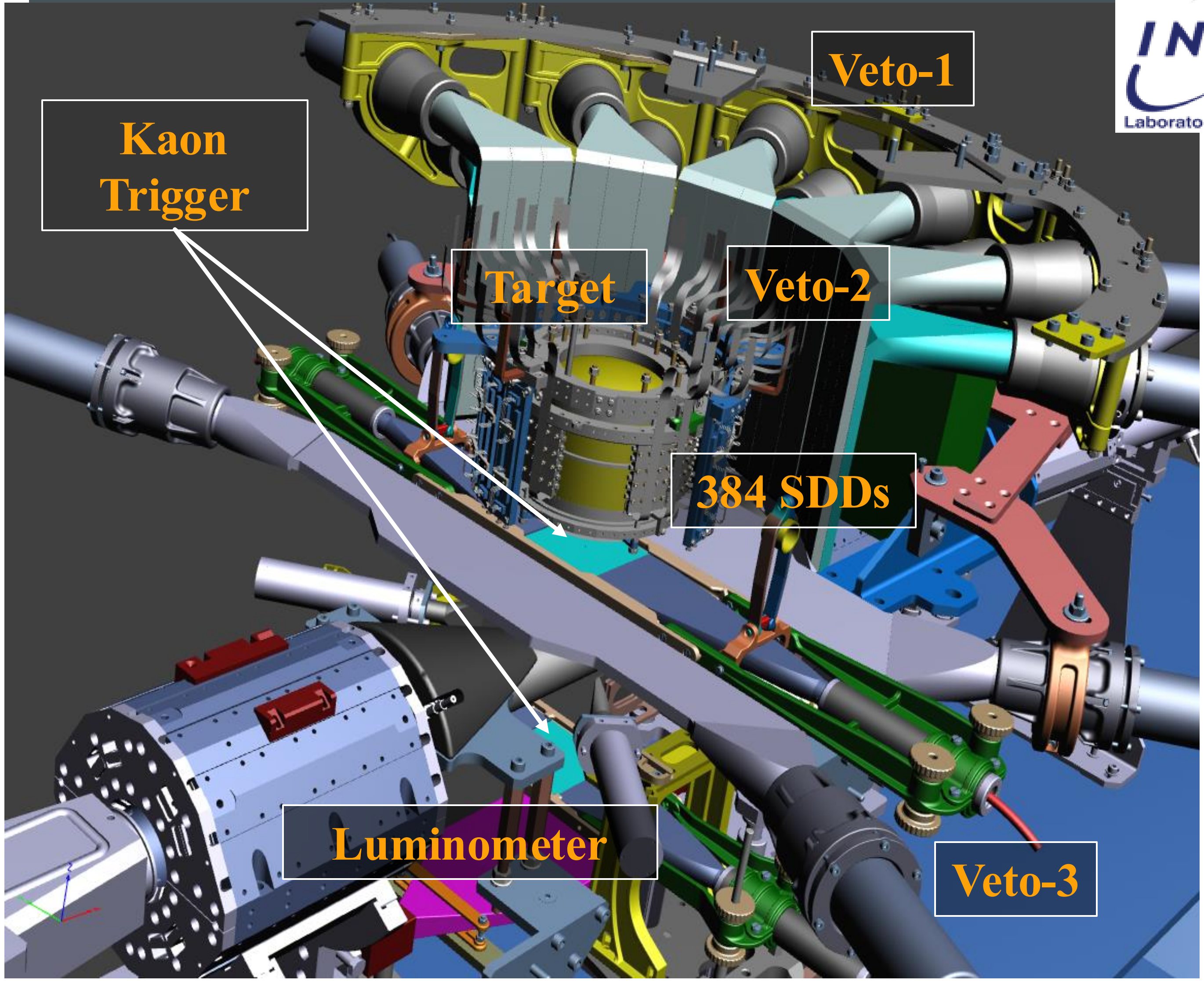

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POLITECNICO MILANO 1863

FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

Improvements compared to SIDDHARTA setup:

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

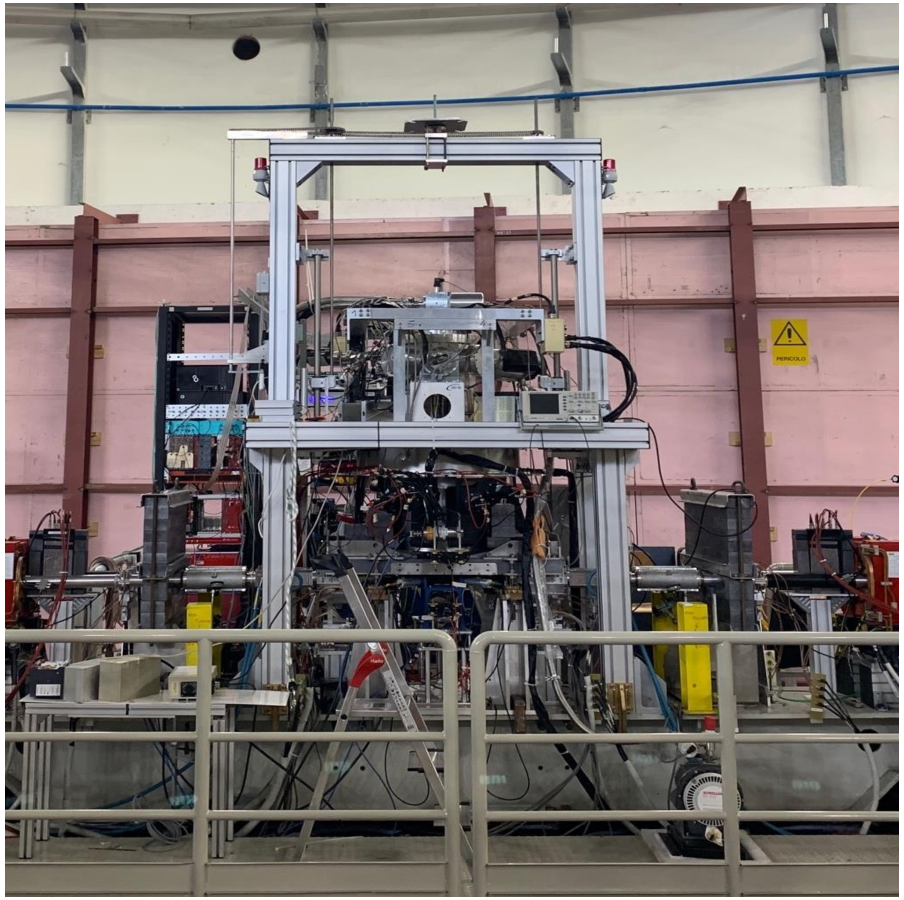
Data Taking Summary

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

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

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

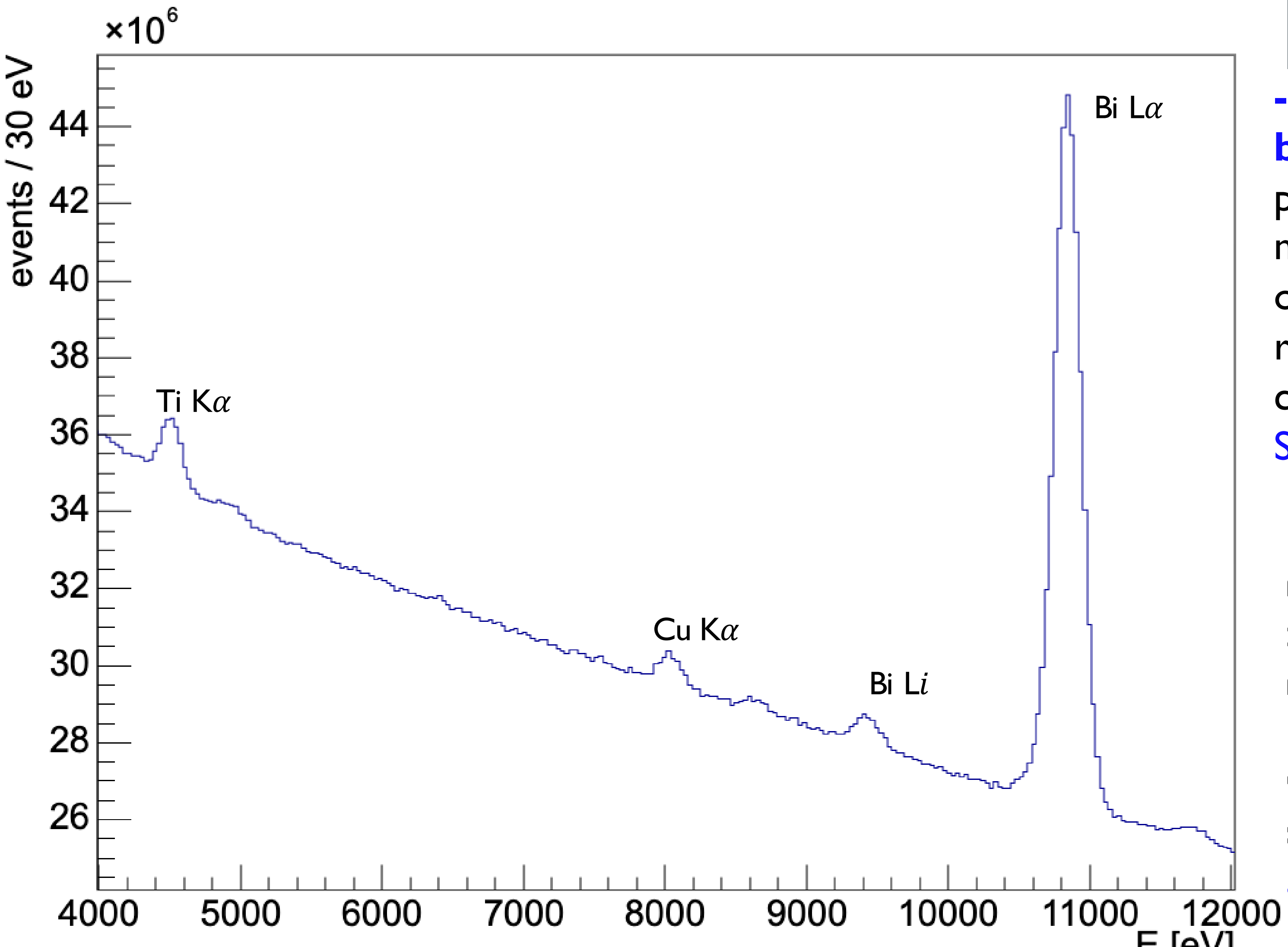
- *Low density run: int. luminosity 184 pb^{-1}* (May – July 2024)
- *Post Kd calibration run* (July 2024) – 20 pb^{-1} *with solid targets (B and F)*



K-d total integrated luminosity good for physics : 1143 pb^{-1}

Kaonic deuterium analysis

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

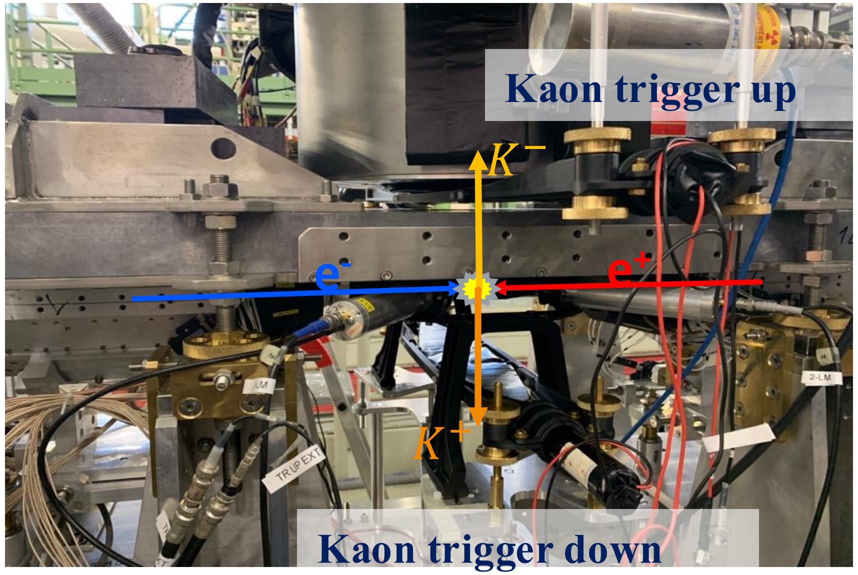


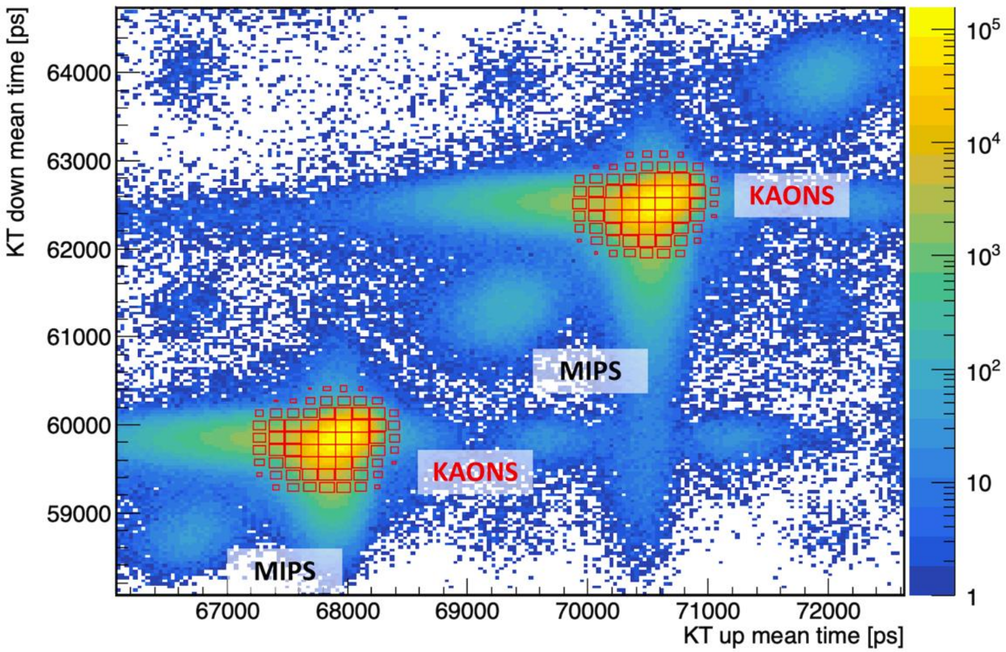
- Electromagnetic (asynchronous) background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect → Kaon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

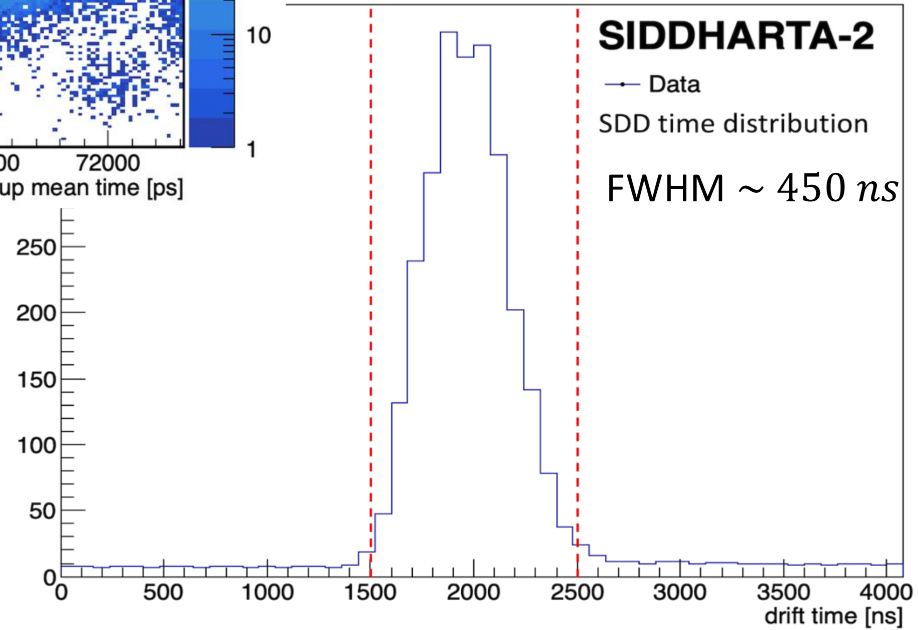
Hadronic (synchronous) background: ıssociated to kaon absorption on materials nuclei, ɔr to other Φ decay channels. It can be considered ı hadronic background.
Spectra contamination by Xray fluorescence or by <-rays produced in higher transitions of other ƙaonic atoms, formed in the setup materials →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

Kaonic deuterium analysis

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







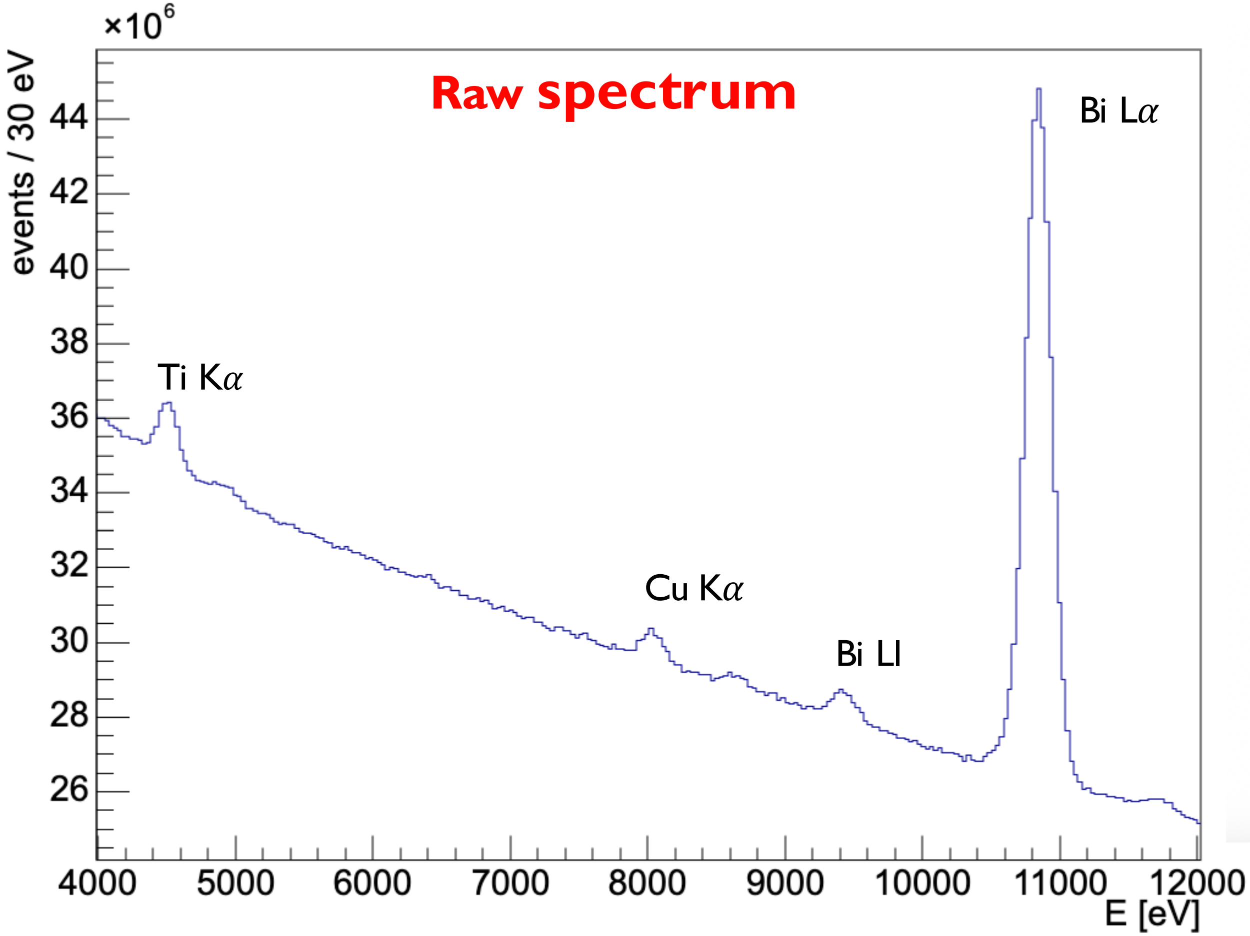
The trigger is generated by the coincidence of 2 back-to-back scintillators

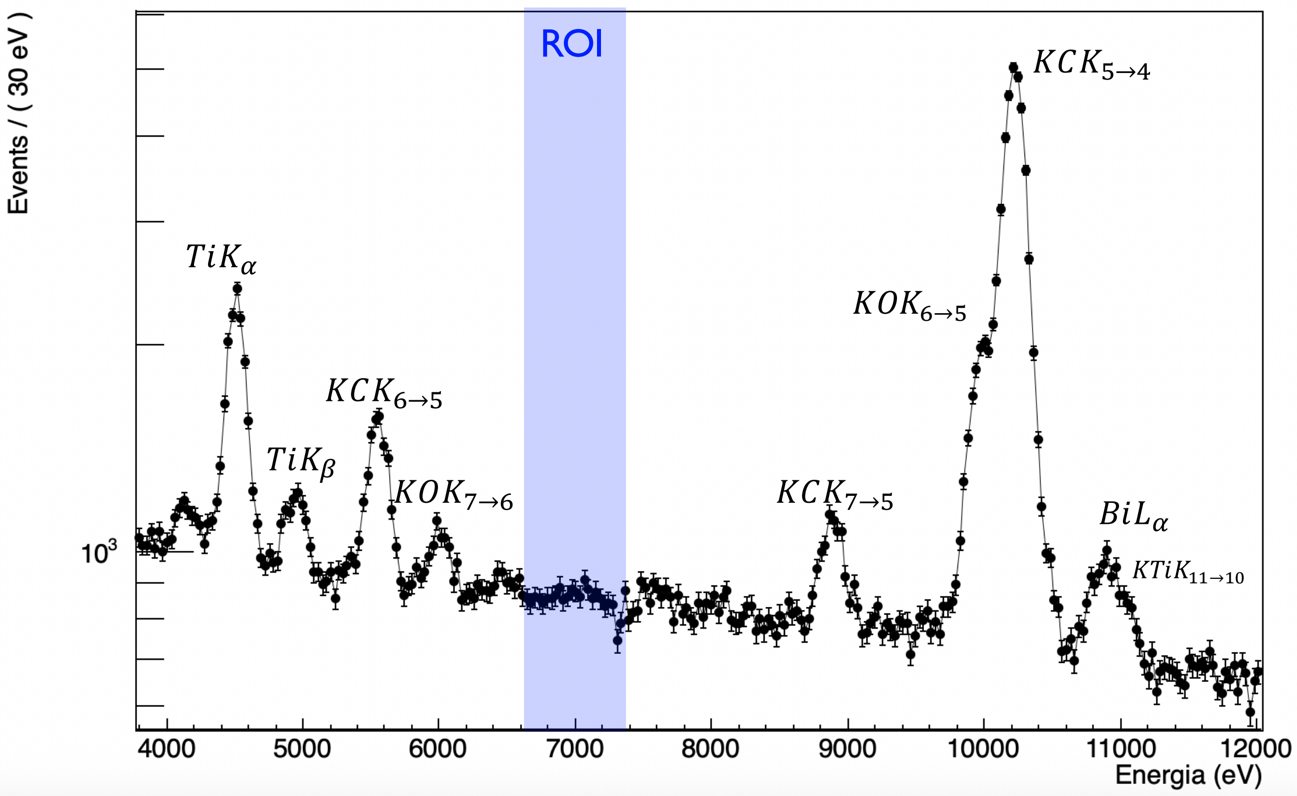
The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles

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

Can efficiently discriminate by ToF Kaons and MIPs!

Kaonic Deuterium Energy Spectrum

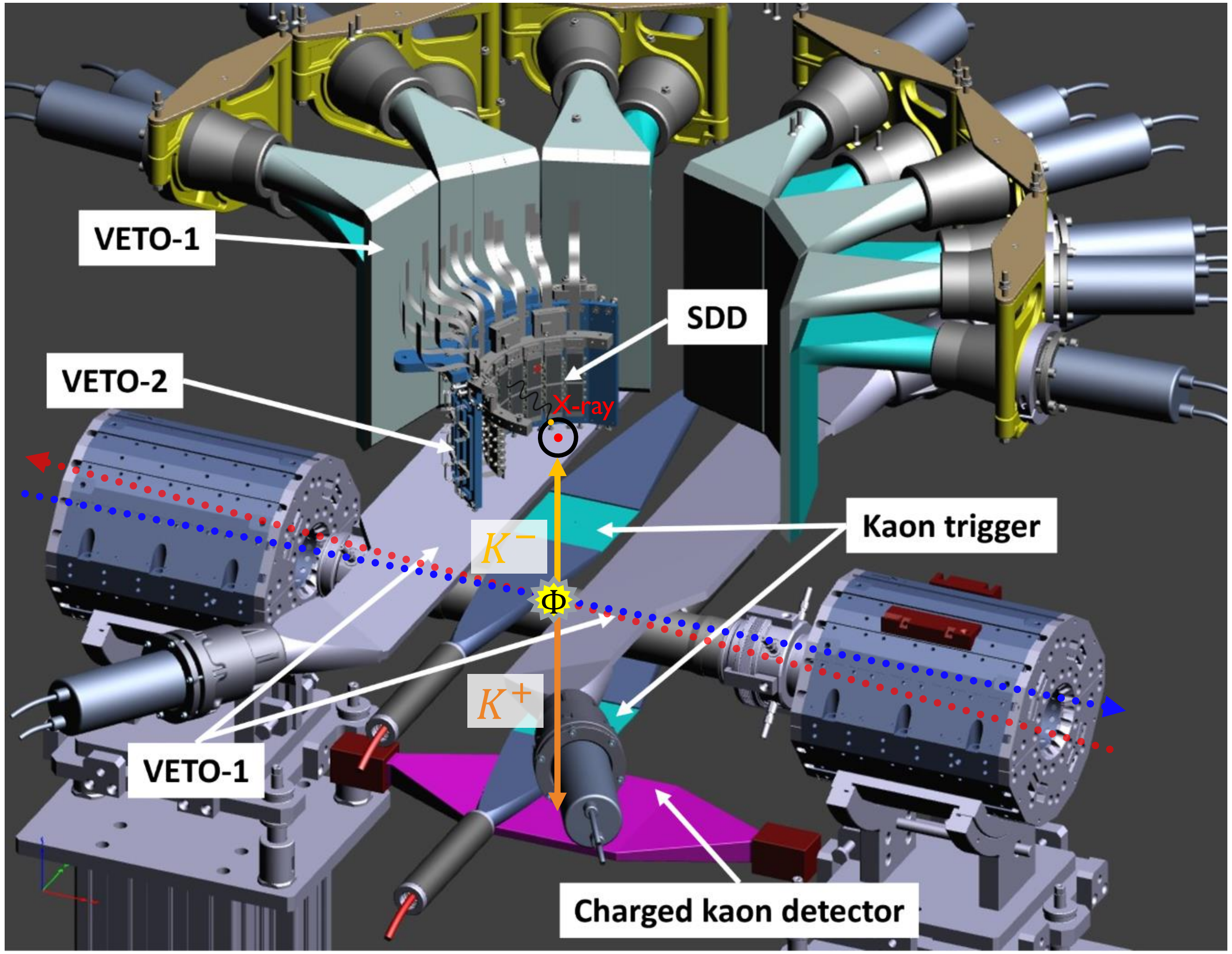




Background reduced by a factor 3×10^4

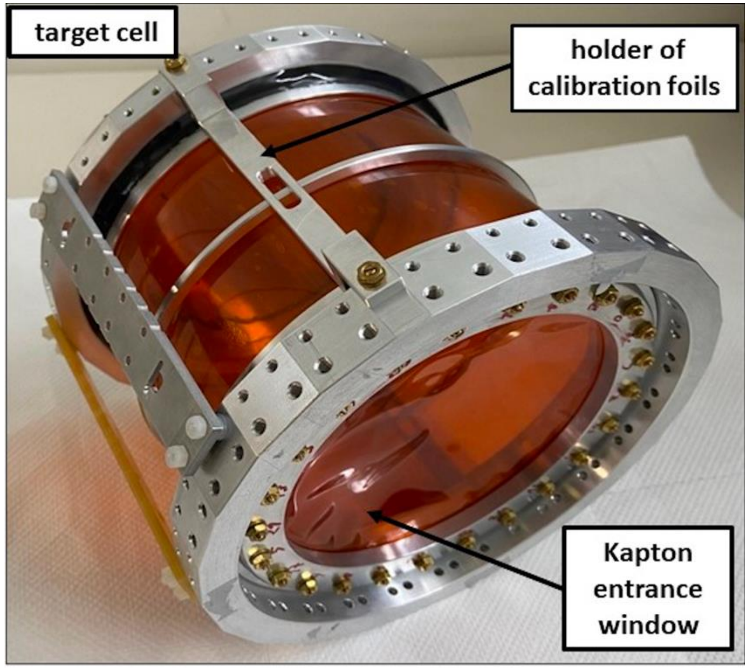
Is the excess of events consistent with a deuterium signal, or could it be explained by other sources (kaonic carbon) ?

The SIDDHARTA-2 apparatus



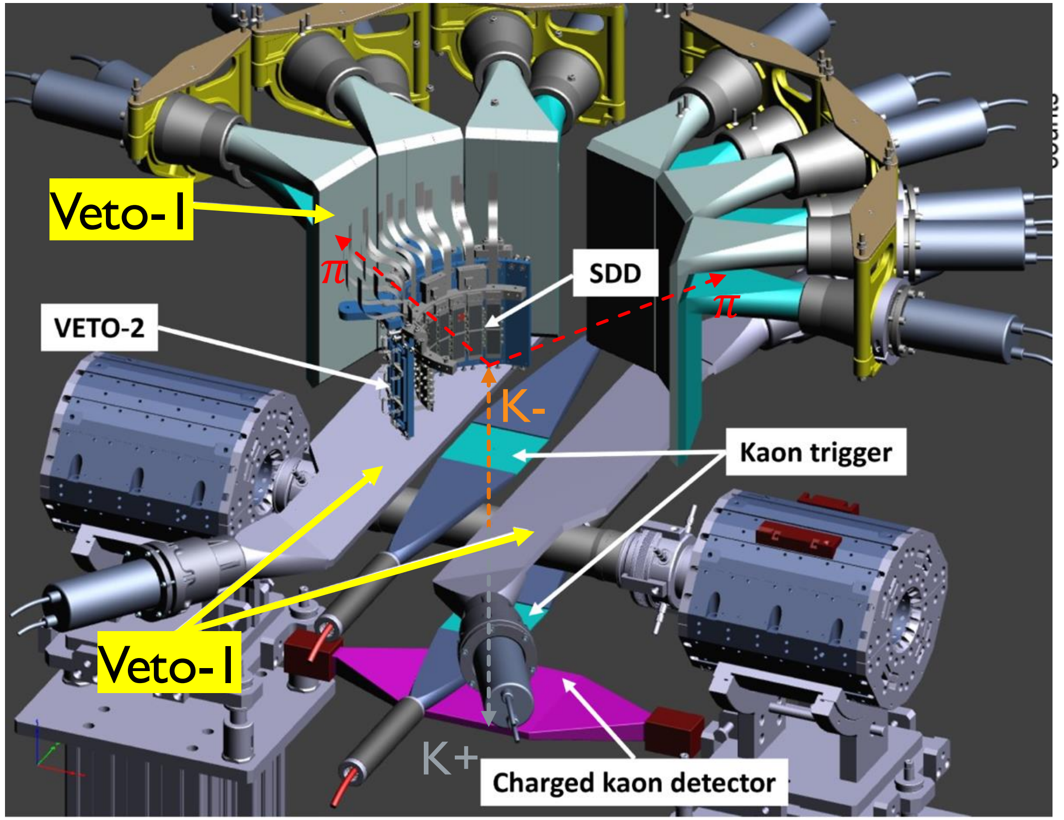
Kaon Trigger: two plastic scintillators read by photomultipliers placed above and below the interaction region.

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

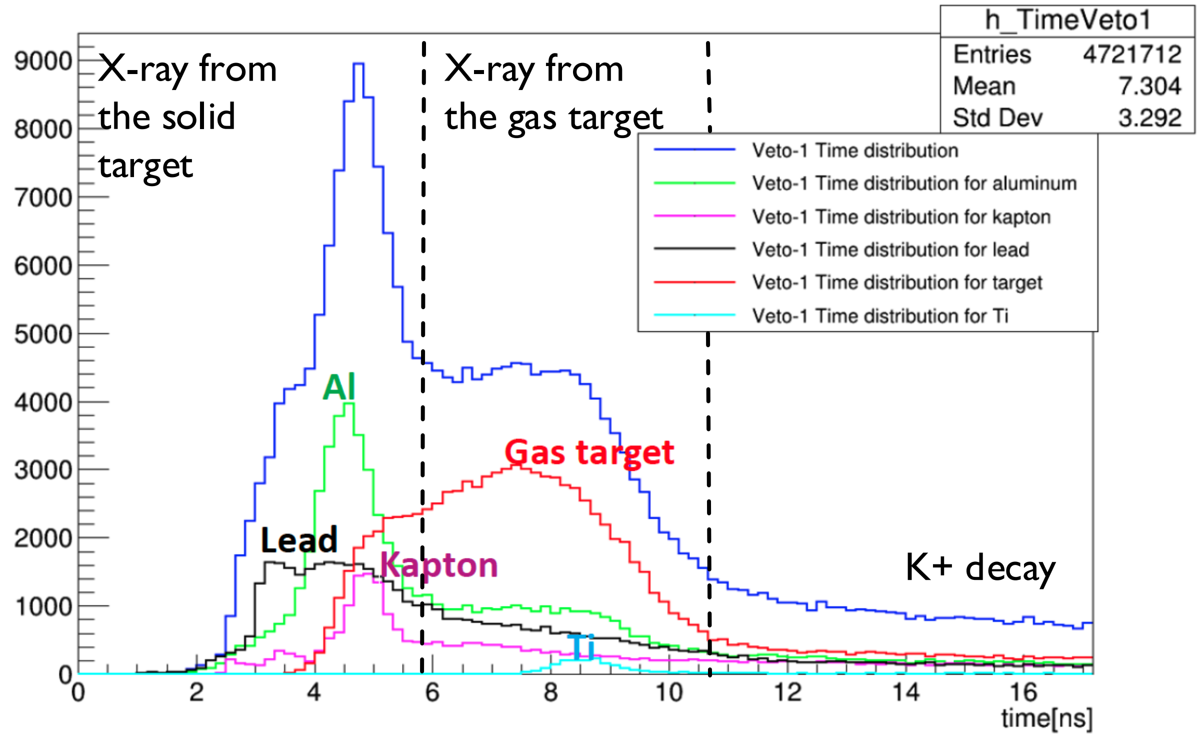


Kaonic deuterium analysis – Veto1 system

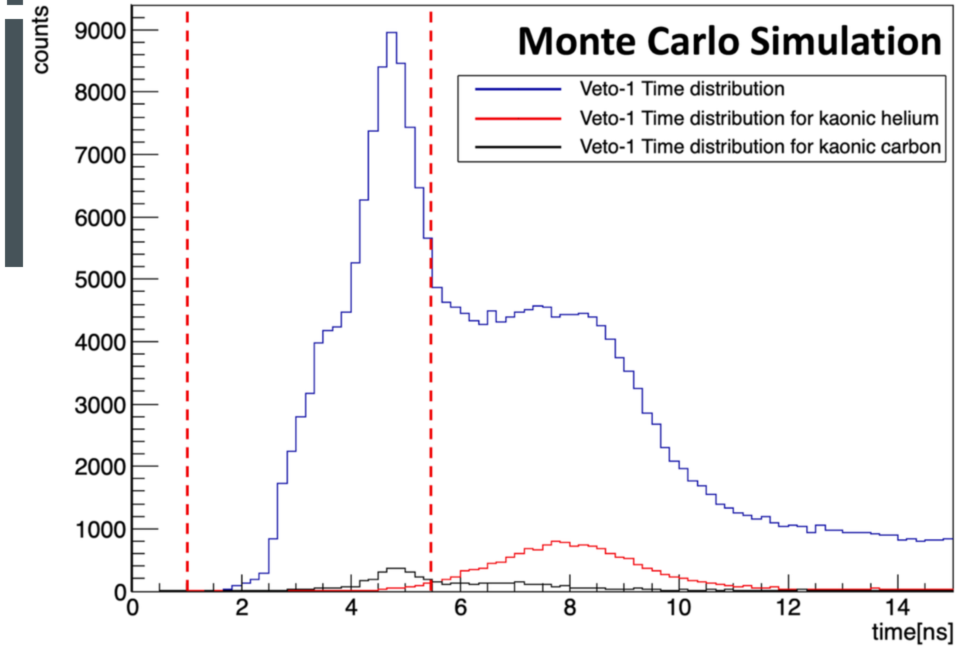
Veto-1 for hadronic background reduction: it measures the arrival time of charged particles emitted by the kaon-nucleus absorption to determine the origin of the signal — whether it comes from the deuterium gas target or from surrounding solid materials.

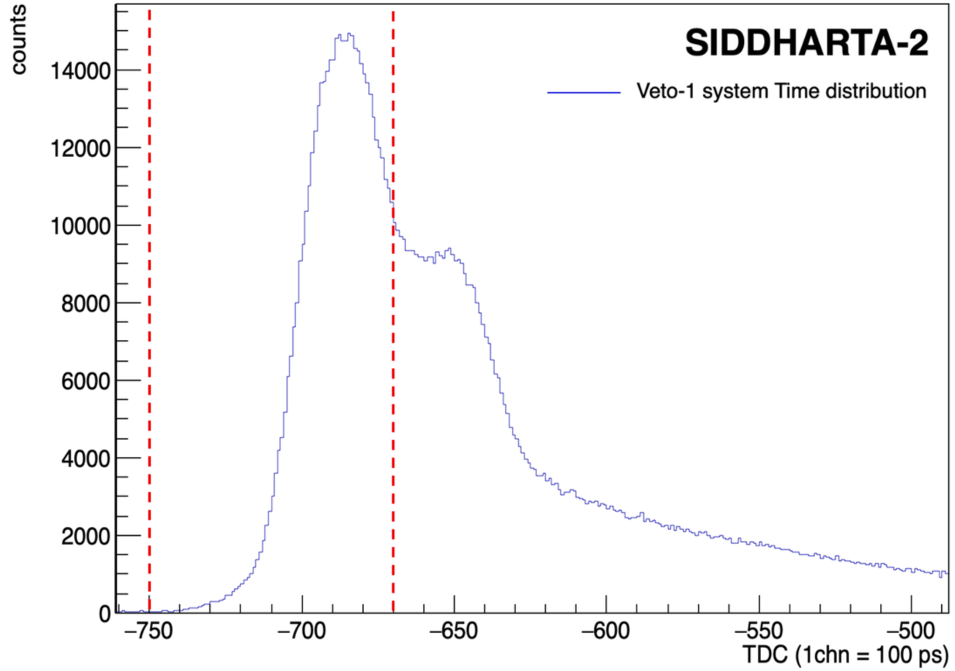


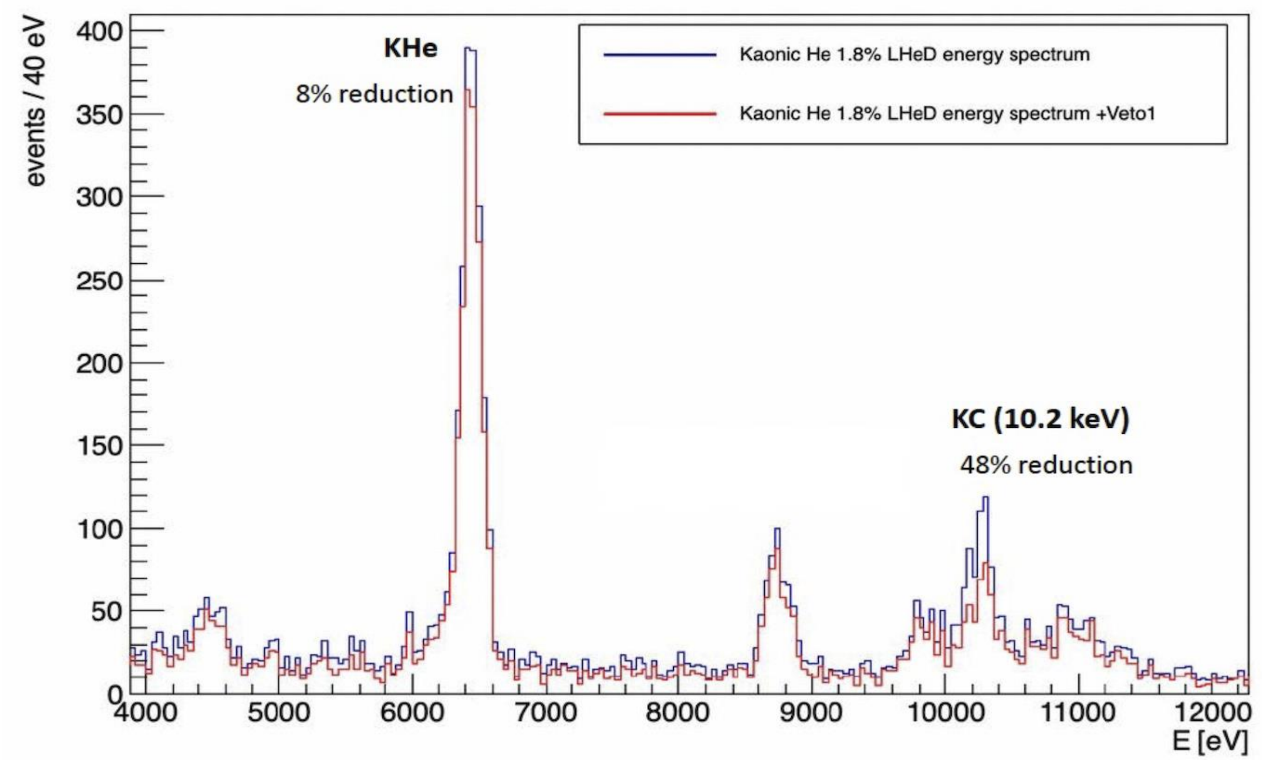
Veto-1: 14 plastic scintillators placed around and below the vacuum chamber



Veto-1 system optimization with kaonic He





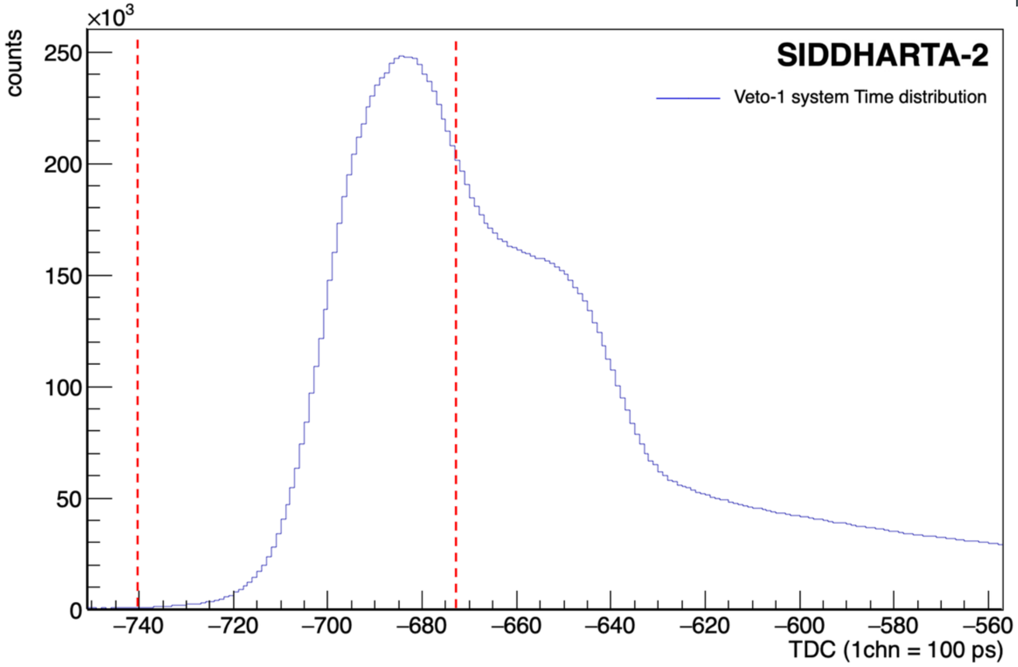


	SIDDHARTA-2 Veto-1 reduction factor	Monte Carlo Veto-1 reduction factor
K-^{4}He L_α	$(8 \pm 1)\%$	4%
K-$C_{5\to4}$	$(48 \pm 4)\%$	44%

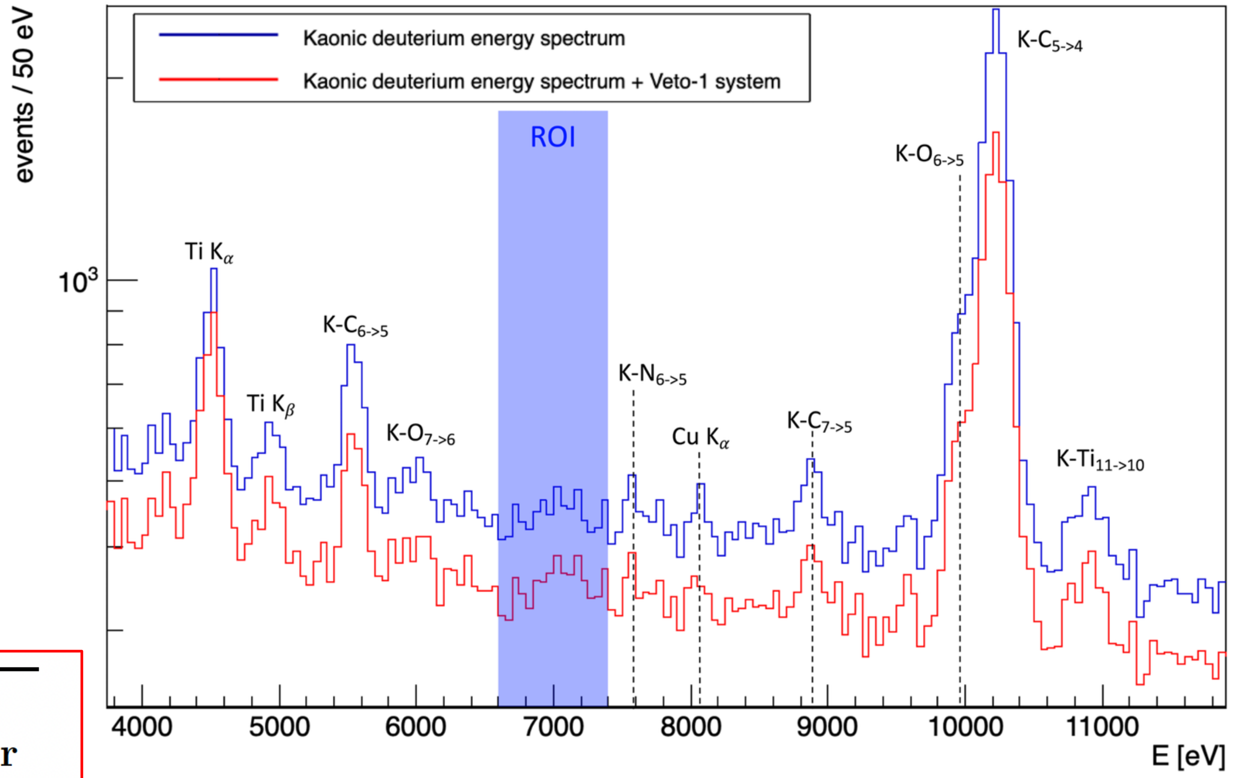
$$\text{reduction factor} = 1 - \frac{\#\text{events(with veto1)}}{\#\text{events}}$$

Kaonic Deuterium (run1): veto-1 system analysis

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



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



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

Kaonic Deuterium: veto-1 system analysis

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

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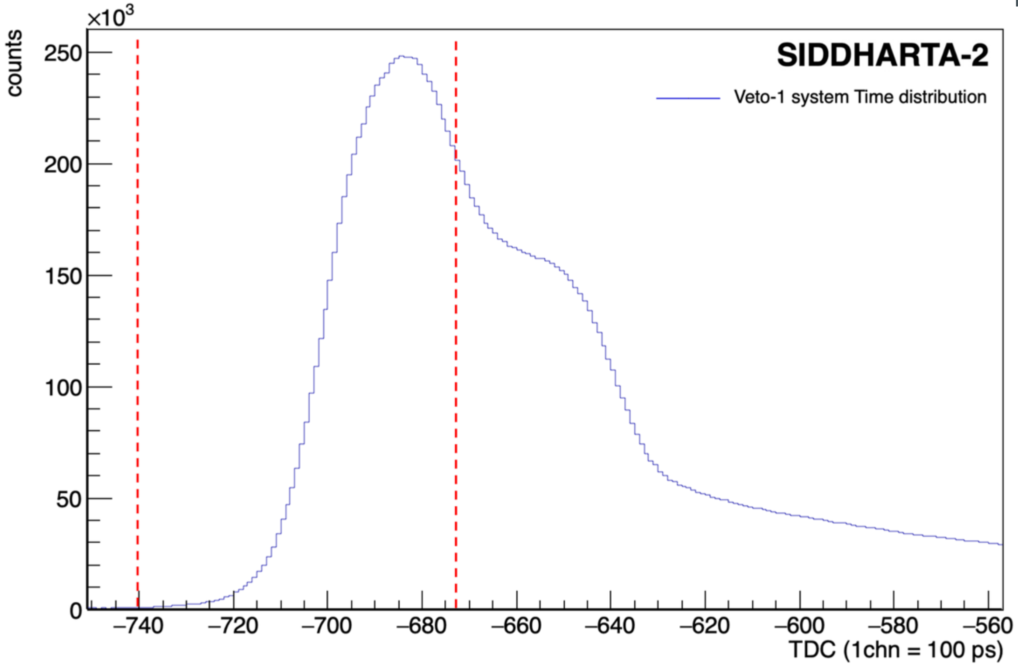

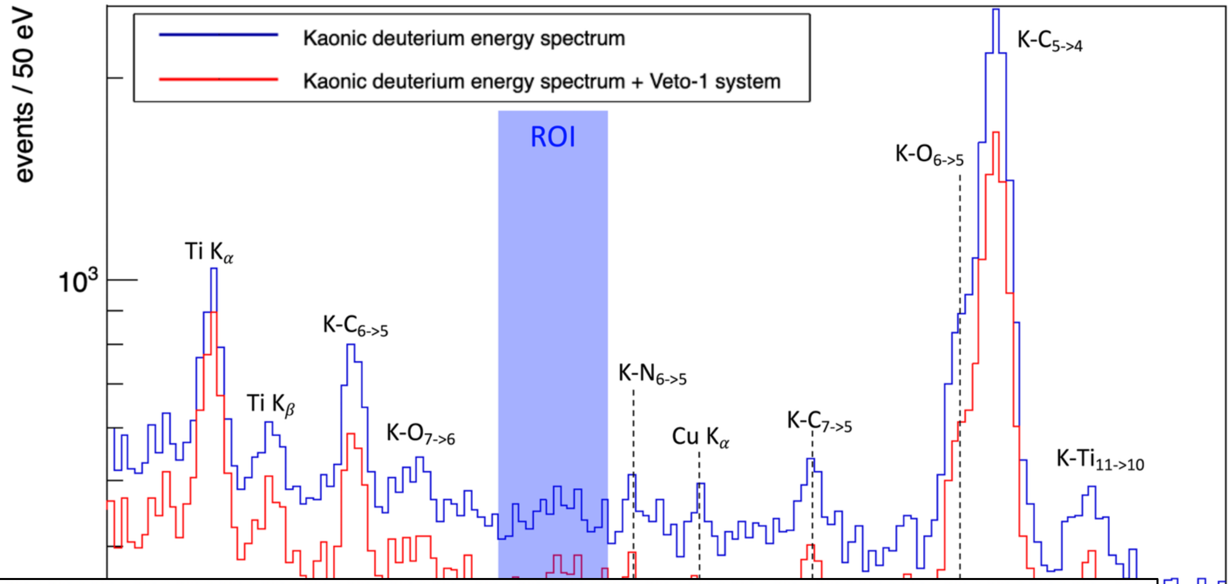

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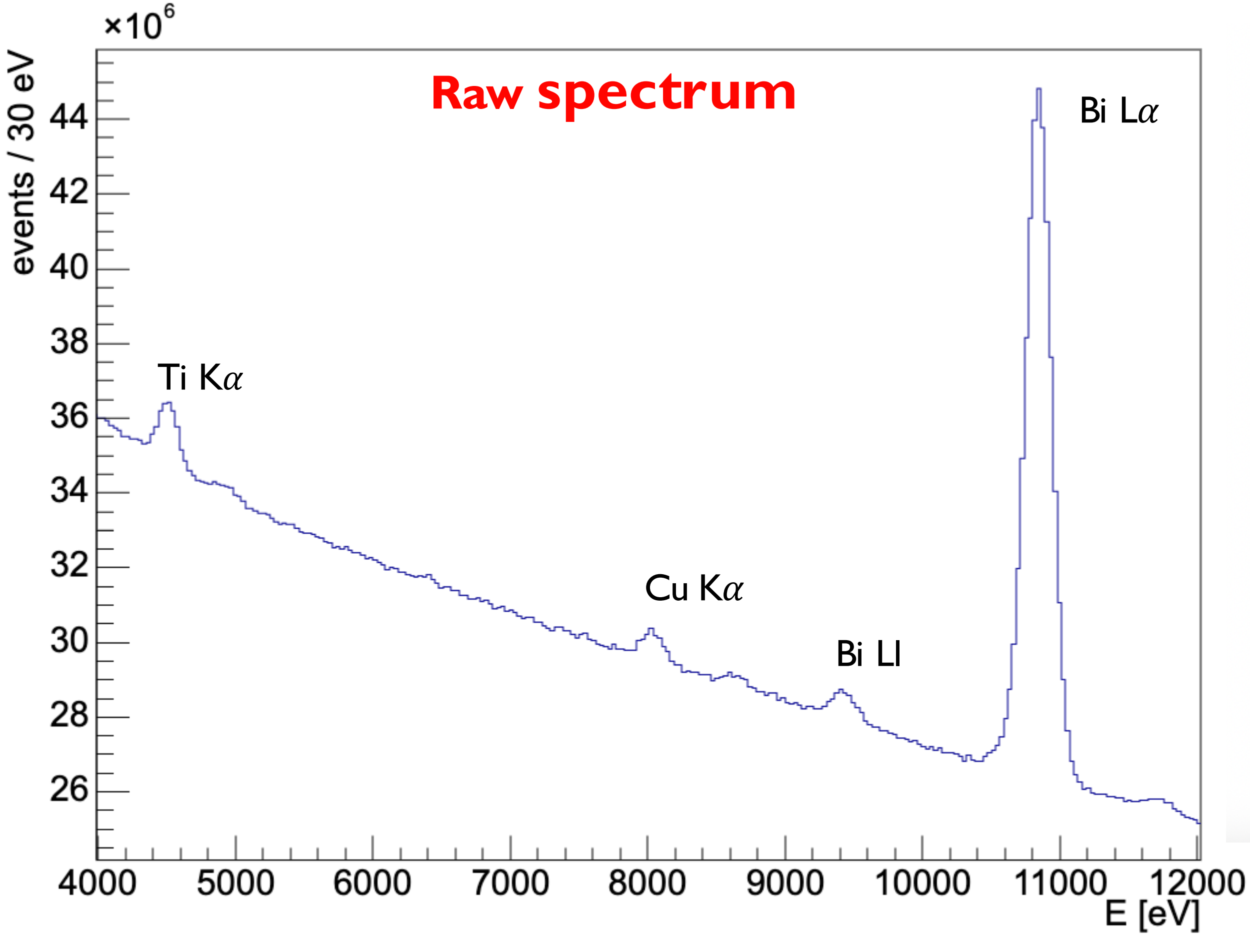
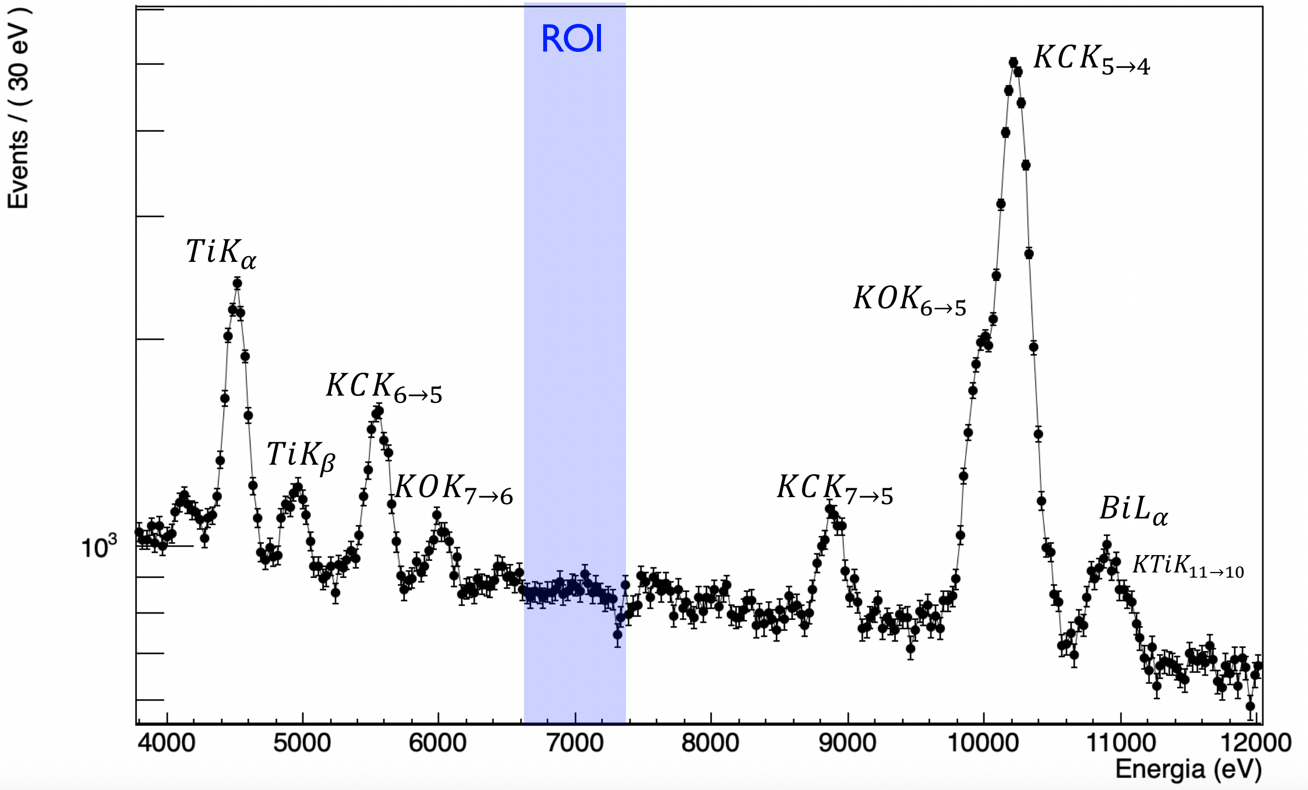
Kaonic Deuterium Energy Spectrum



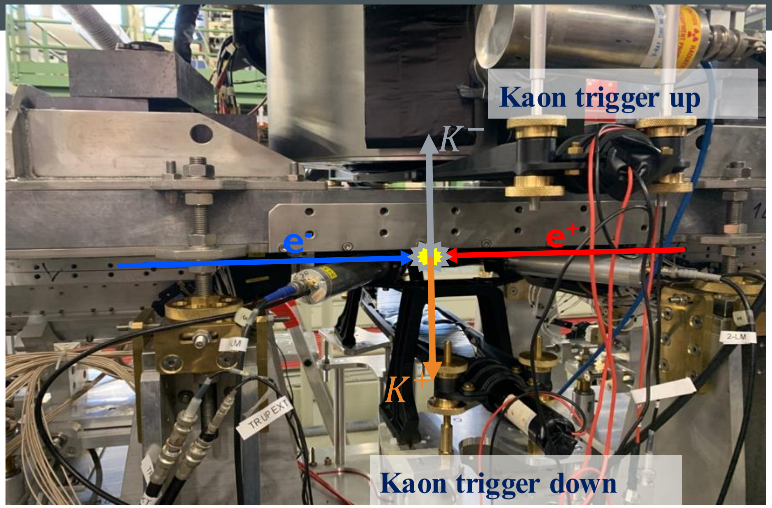


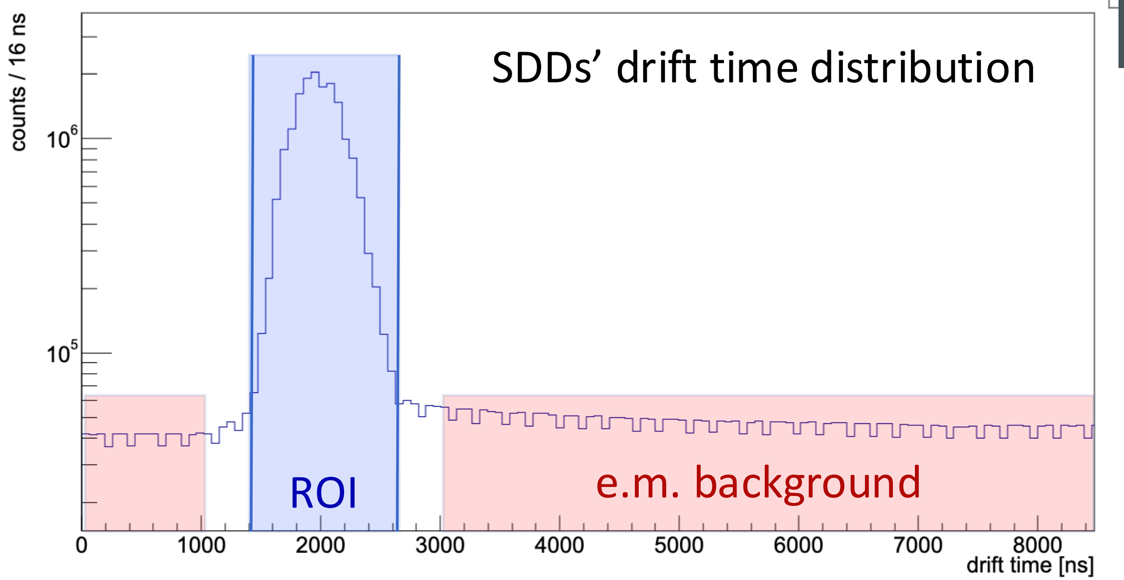
Background reduced by a factor $3x10^4$

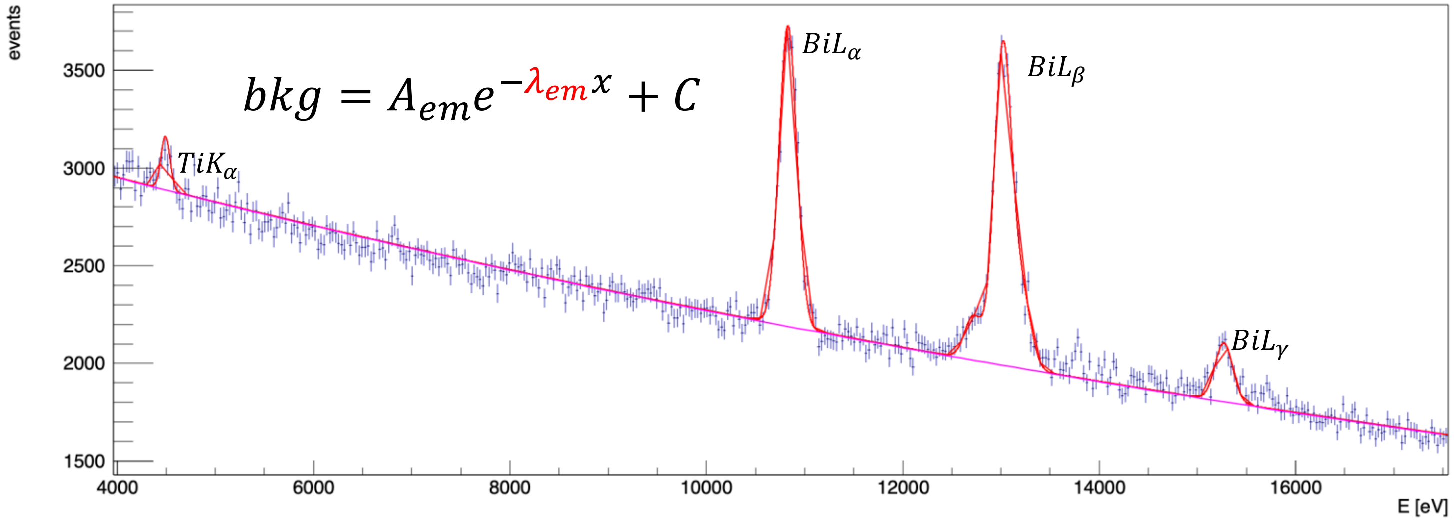
Background Analysis

Electromagnetic background (asynchronous wrt kaons)

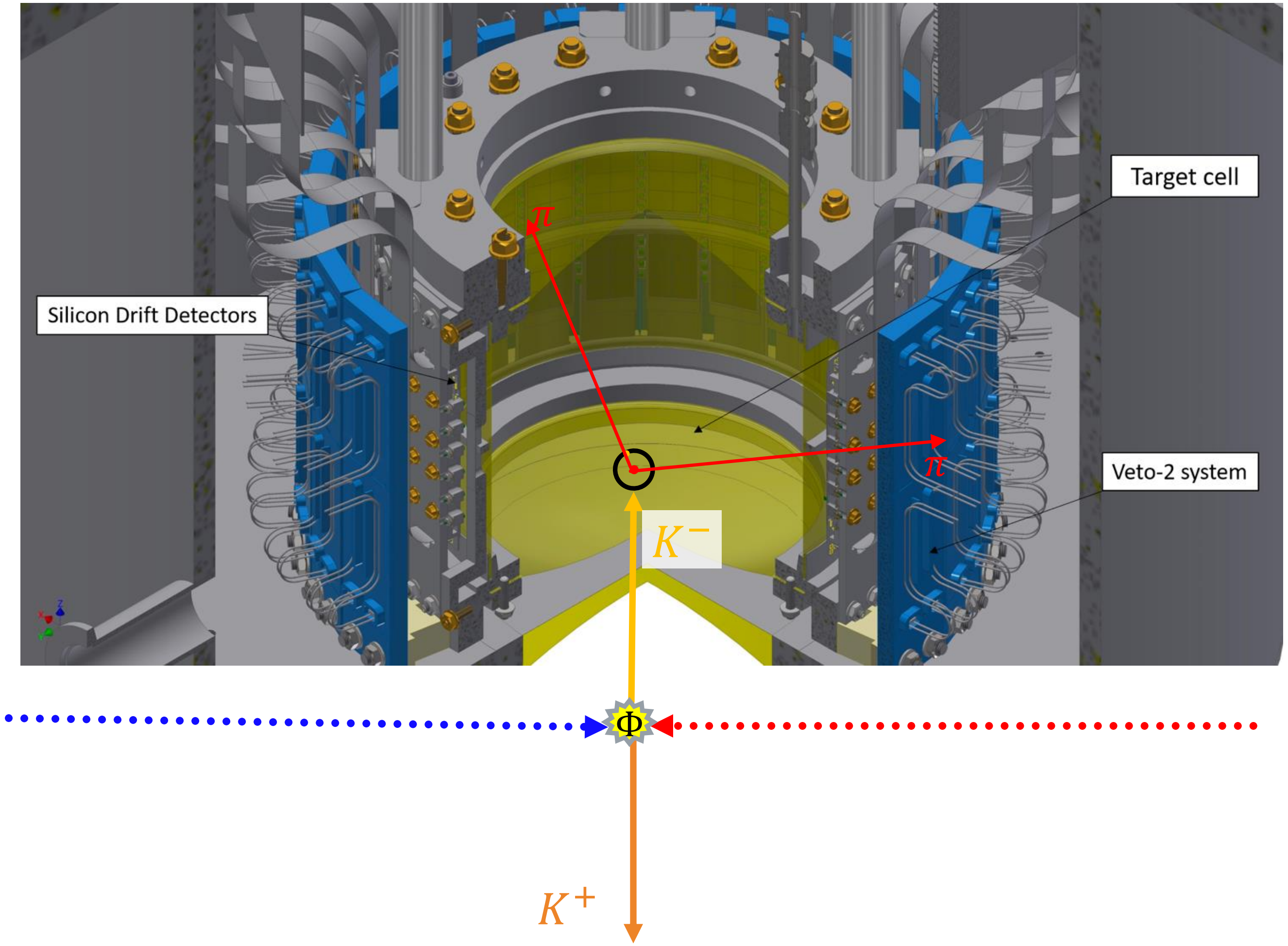
By exploiting the trigger and drift time of the SDDs, we can isolate a pure electromagnetic background spectrum by selecting events uncorrelated with kaon production.



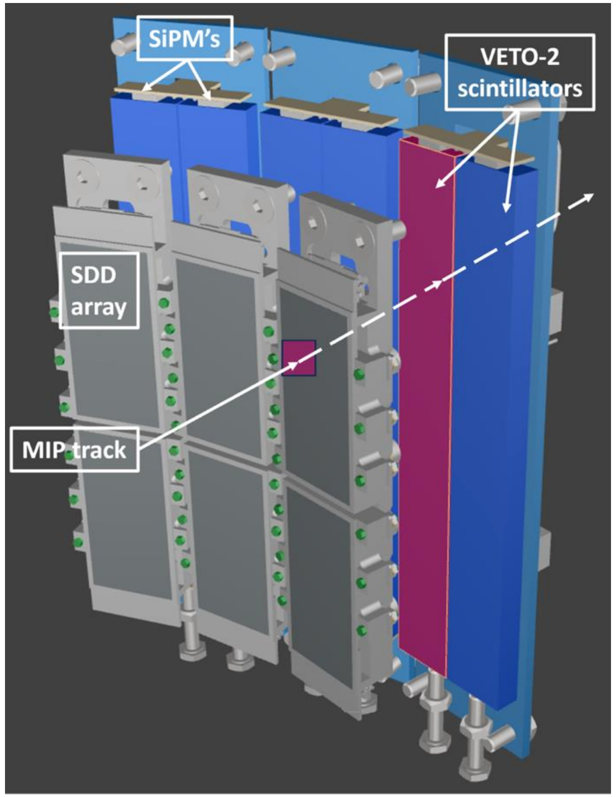




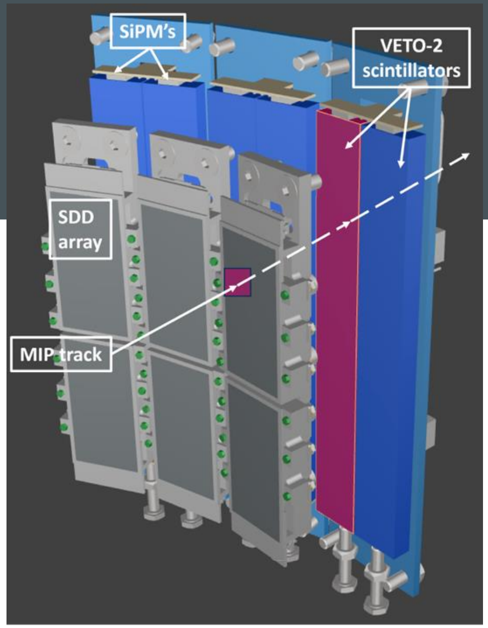
The SIDDHARTA-2 apparatus - Veto-2 system



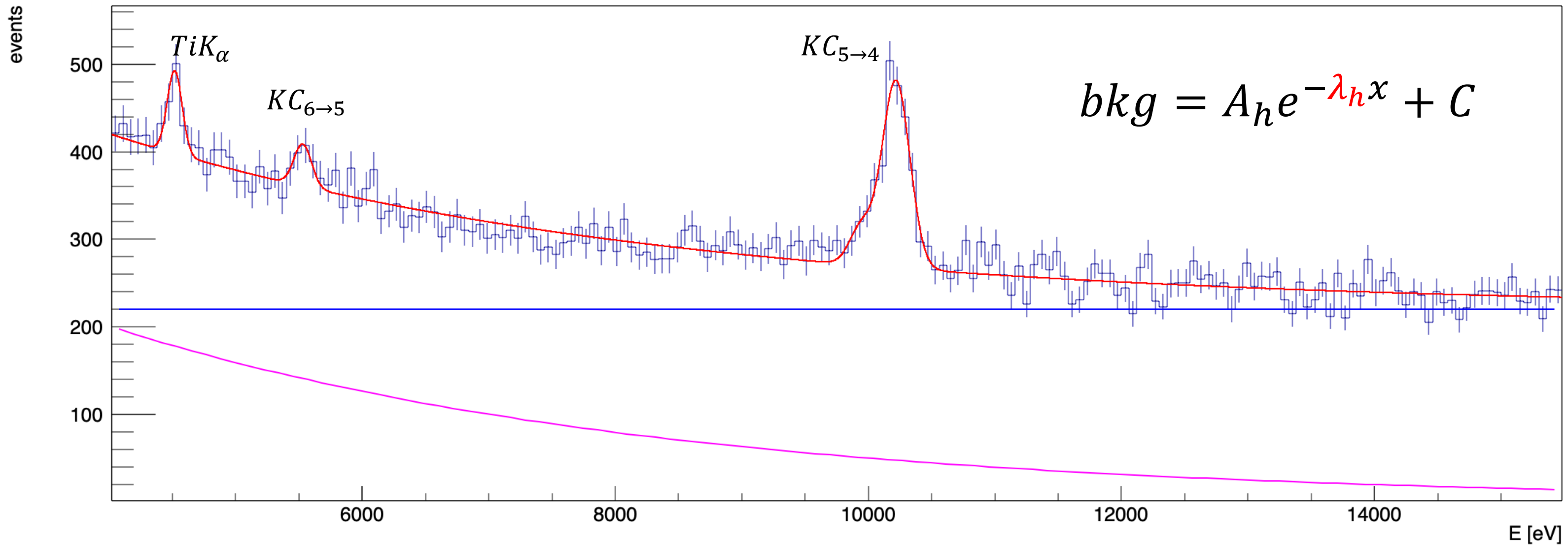
Veto-2 48 plastic scintillator read by SiPMs to suppress the background induce by particles produced by kaon absorption, passing through the SDDs.

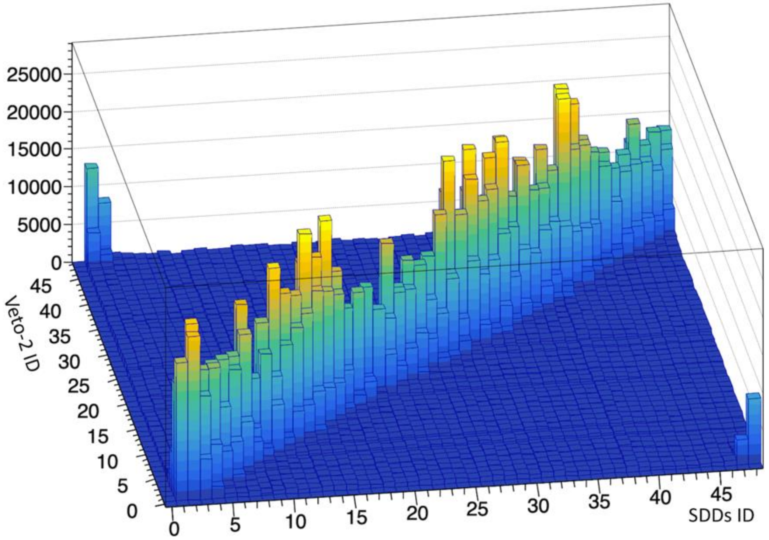


Hadronic background (synchronous wrt kaons)



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.

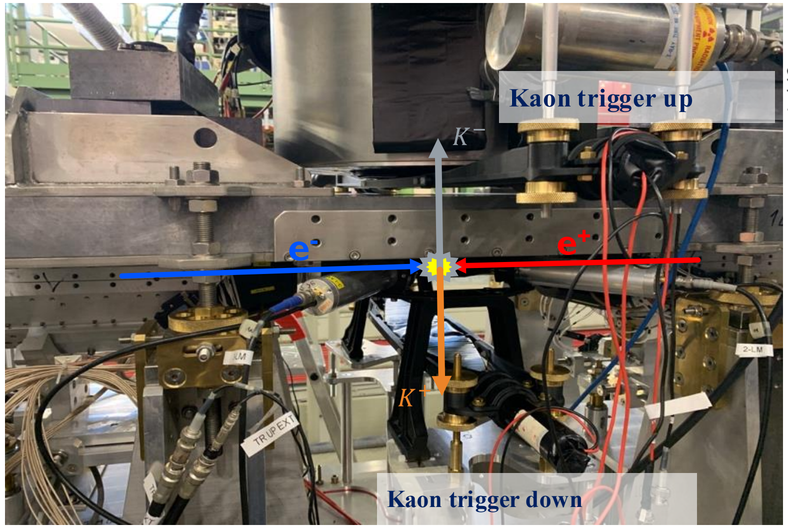


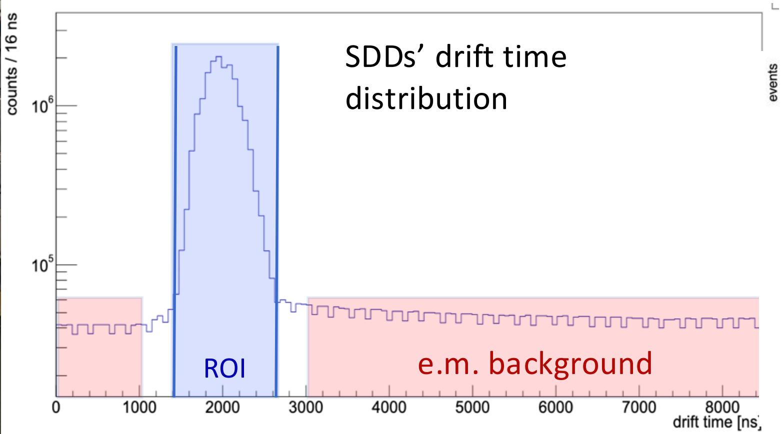


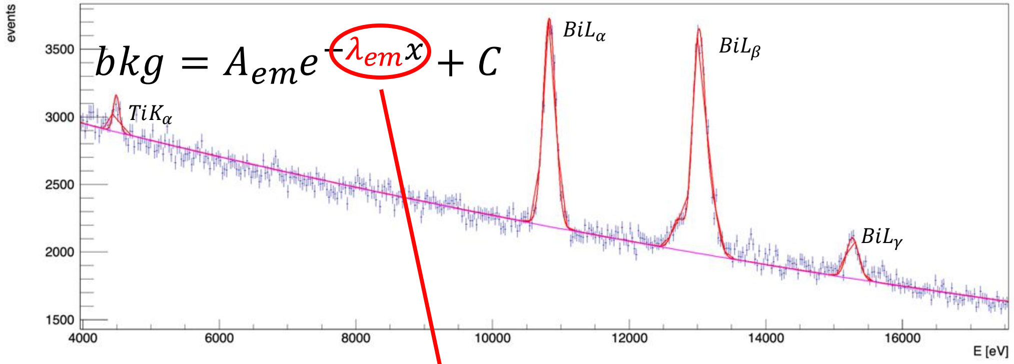
Topological correlation between Veto2's scintillators and SDDs

Study of background events (outside the signal window)

Electromagnetic (asynchronous) background



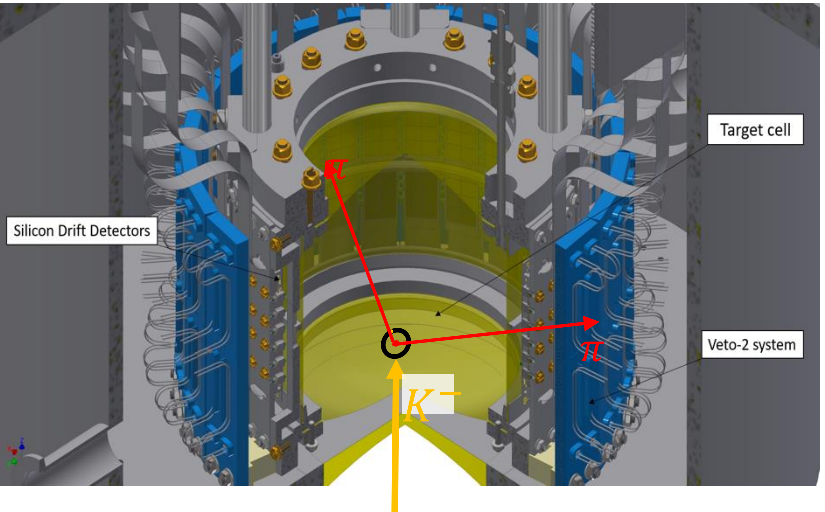


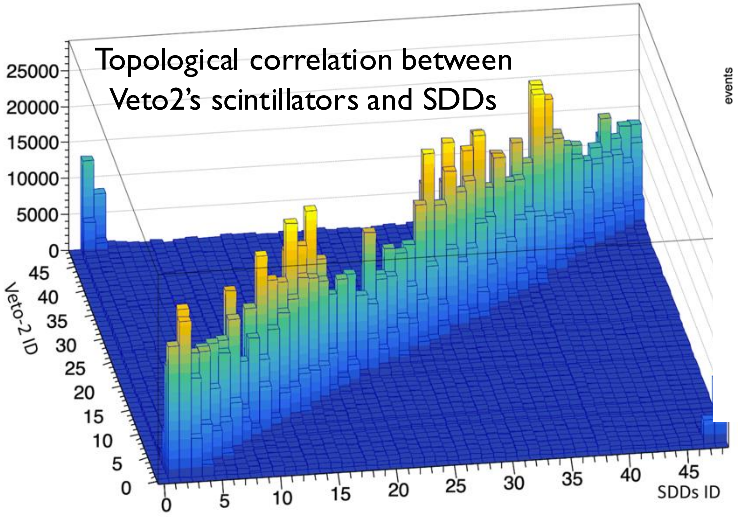


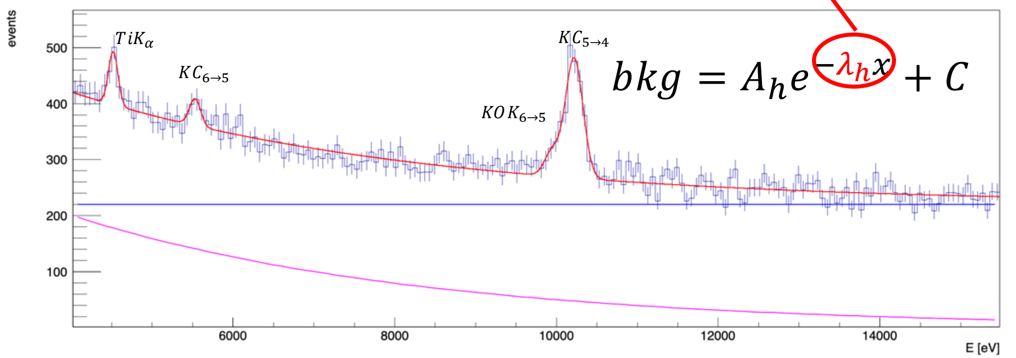
$$bkg = A_{em}e^{-\lambda_{em}x} + C$$

Input values for background description

Hadronic (synchronous) background







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

Kaonic Deuterium Energy Spectrum – Fit procedure

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

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

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

Kaonic deuterium lines

Background
E.M and hadronic

- $G_n(E;\mu,\sigma)$ Gaussian functions for X-ray transitions from known fluorescence (Ti, Cu, Bi, Au) and kaonic atoms such as kaonic C, O, N, Ti, Al
- $V_{2p\to 1s}(E;\mu,\sigma,\Gamma)$ Voigt function

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

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

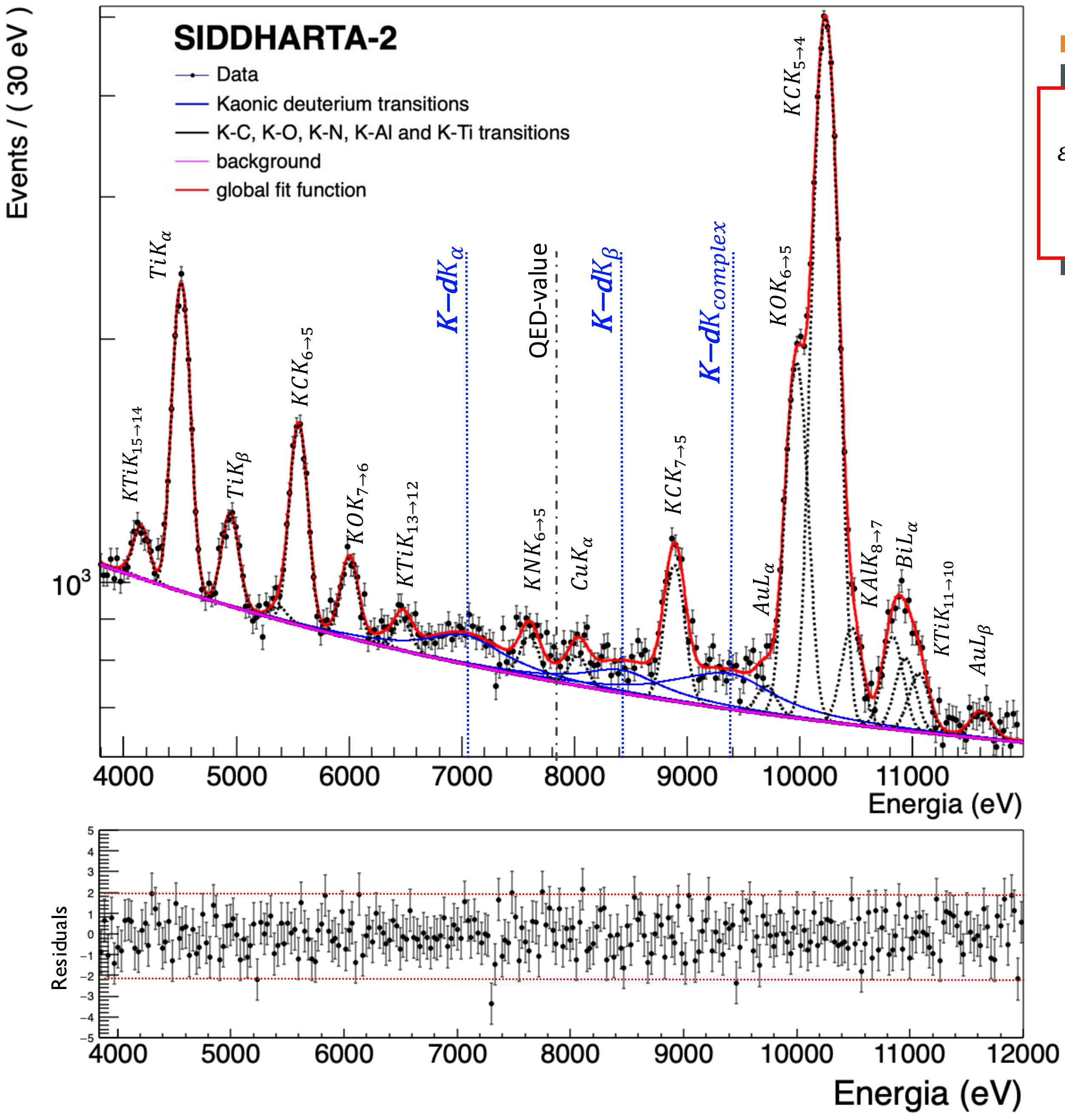
Systematic uncertainty on SDDs energy calibration and stability

Systematic uncertainty on SDDs energy resolution

Systematic uncertainty on e.m. and hadronic background

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

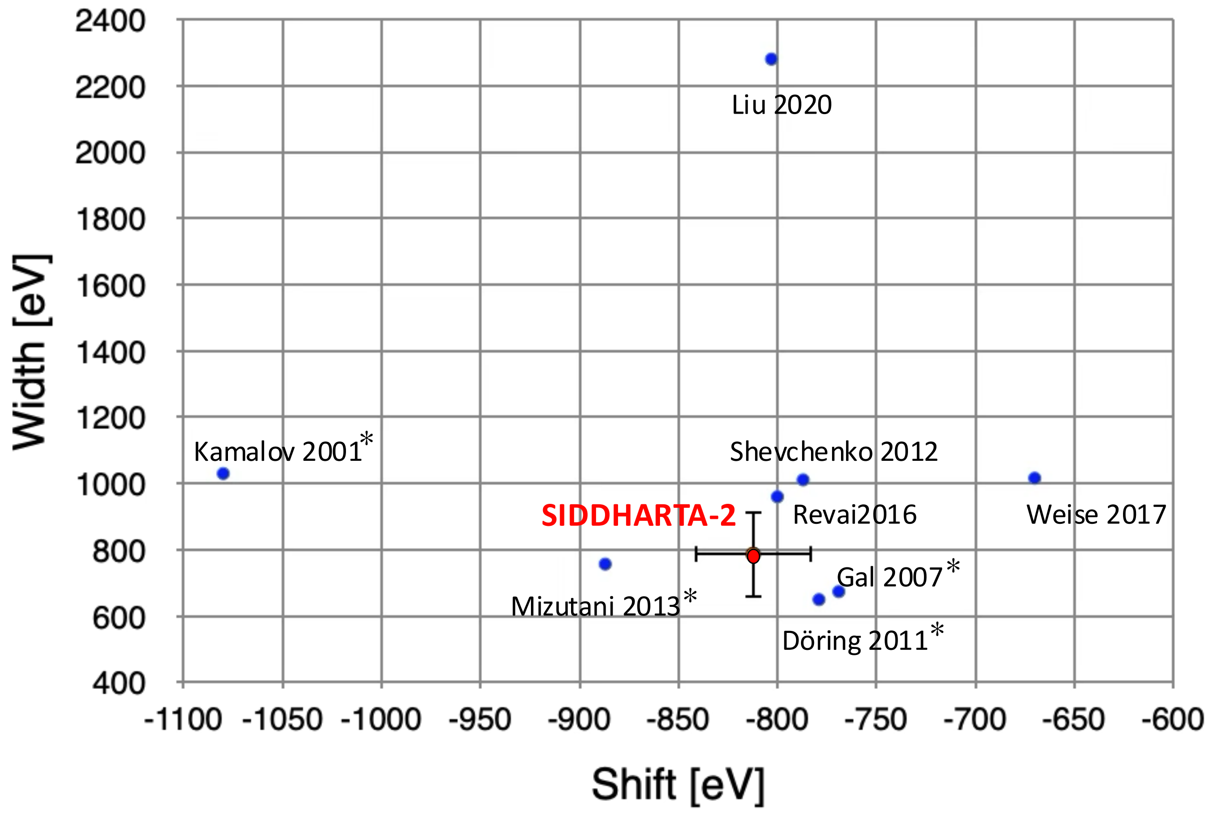
Kaonic Deuterium Results



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

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

Targeted precision achieved!



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

Data Taking Summary

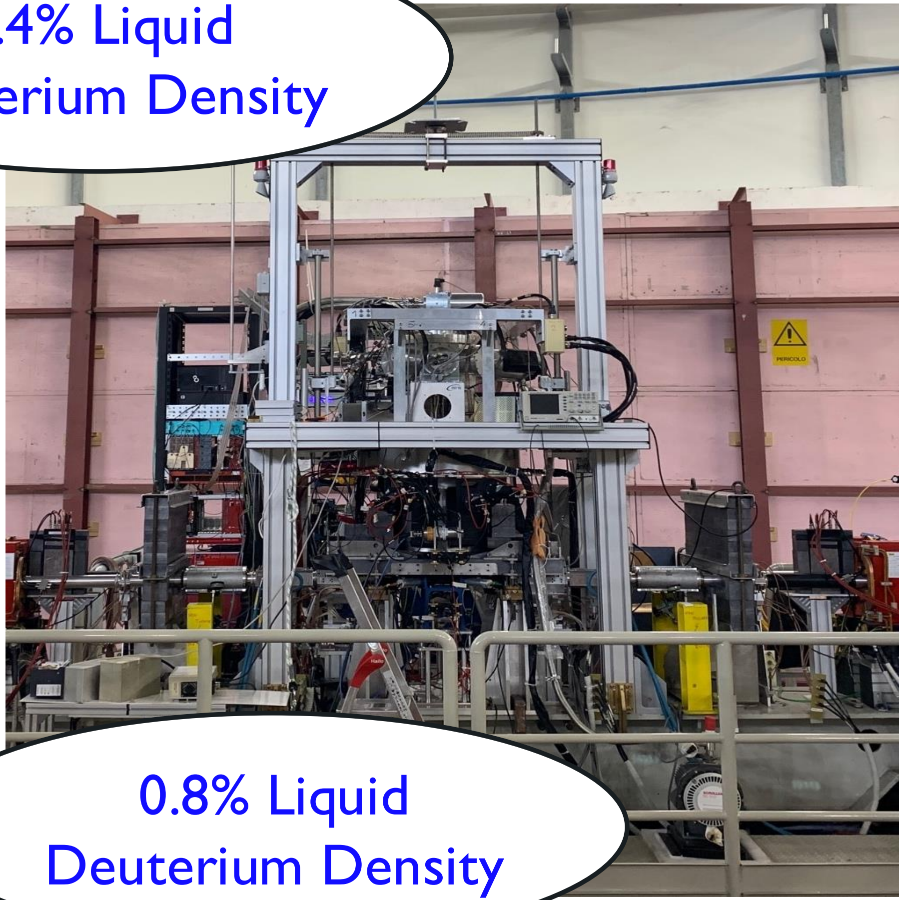
- *Kaonic neon*: initial calibration and optimization of the setup
- *K-d Run-1: int. luminosity 196 pb^{-1}* *(May – July 2023)*
- *Kaonic helium-4*: final calibration of the setup

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

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

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

1.4% Liquid Deuterium Density

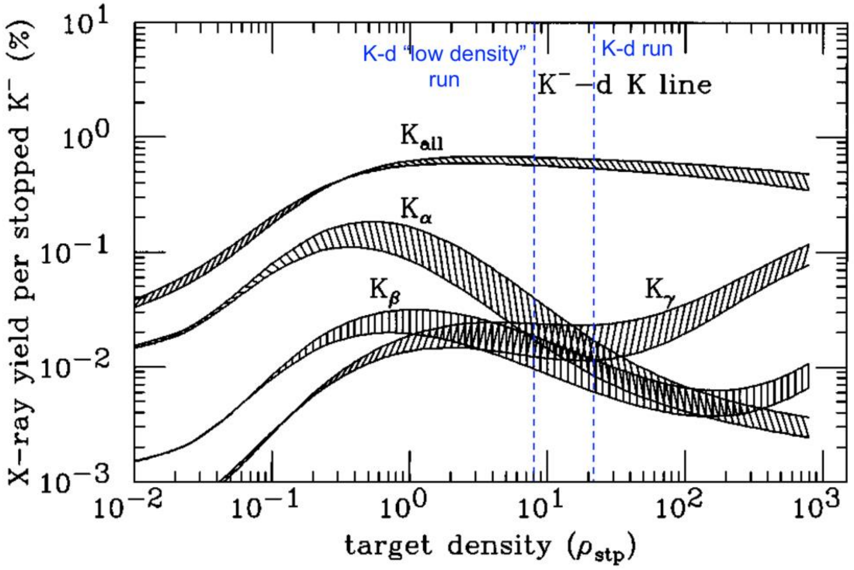


0.8% Liquid Deuterium Density

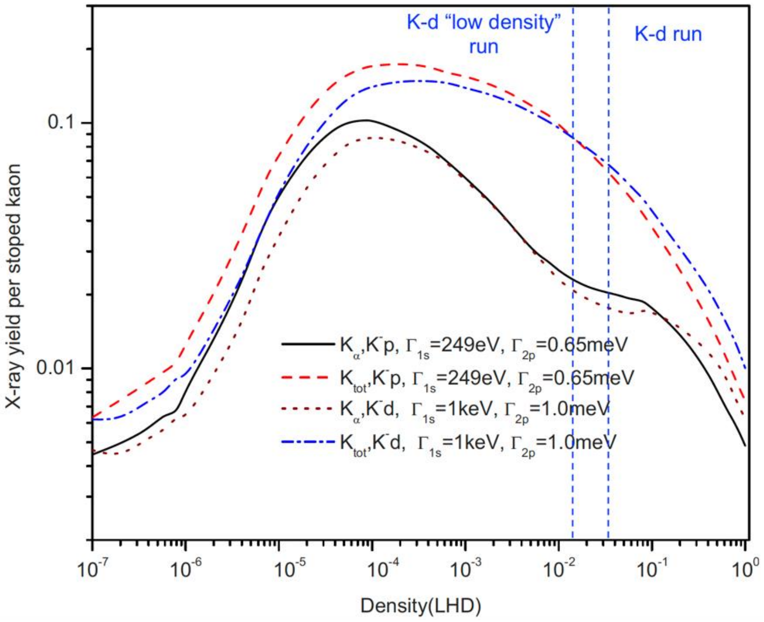
K-d total integrated luminosity good for physics : 1143 pb^{-1}

Kaonic Deuterium yield puzzle

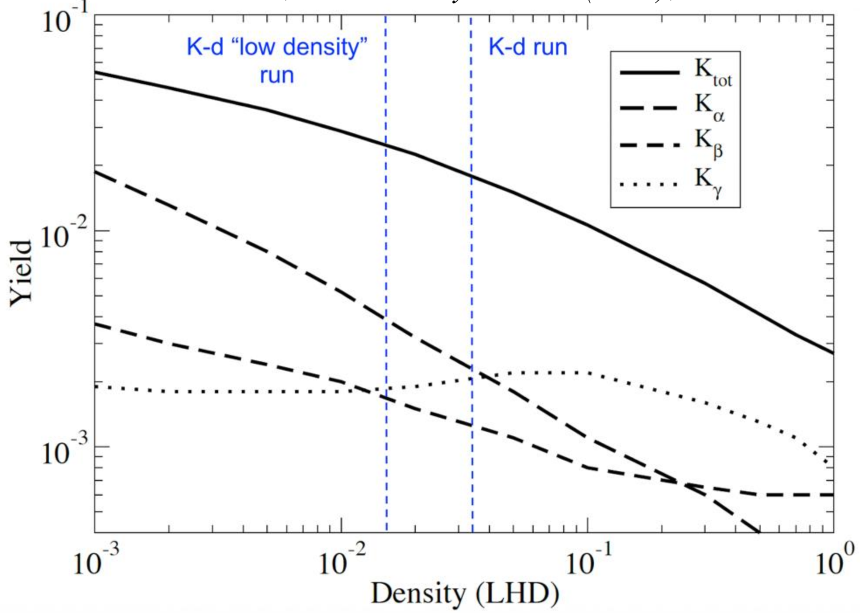
T. Koike, T. Harada, Y. Akaishi, Phys.Rev.C 53 (1996), 79-87



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

Low density kaonic deuterium measurement
(60% lower compared to the previous run)

Providing unique data to investigate the de-excitation mechanism in kaonic atoms (cascade model)

The combined analysis of the kaonic deuterium measurement performed at 1.4% LDD and the ongoing measurement at 0.8% LDD **can help to disentangle between the various theoretical cascade models**

Conclusions

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

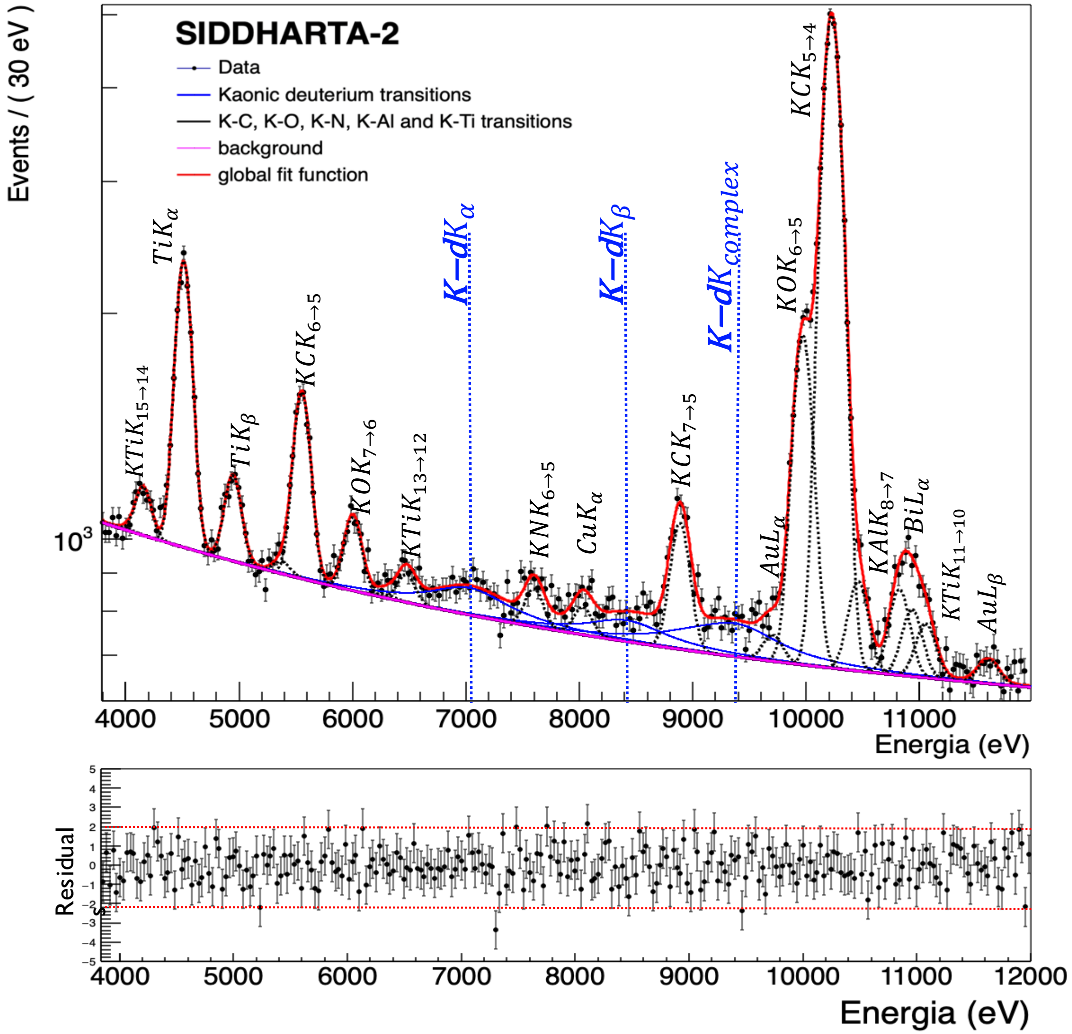
- Through a detailed analysis of the collected data, we demonstrate that the observed signal is consistent with deuterium.

- The 1s-leve shift and width were determined to be

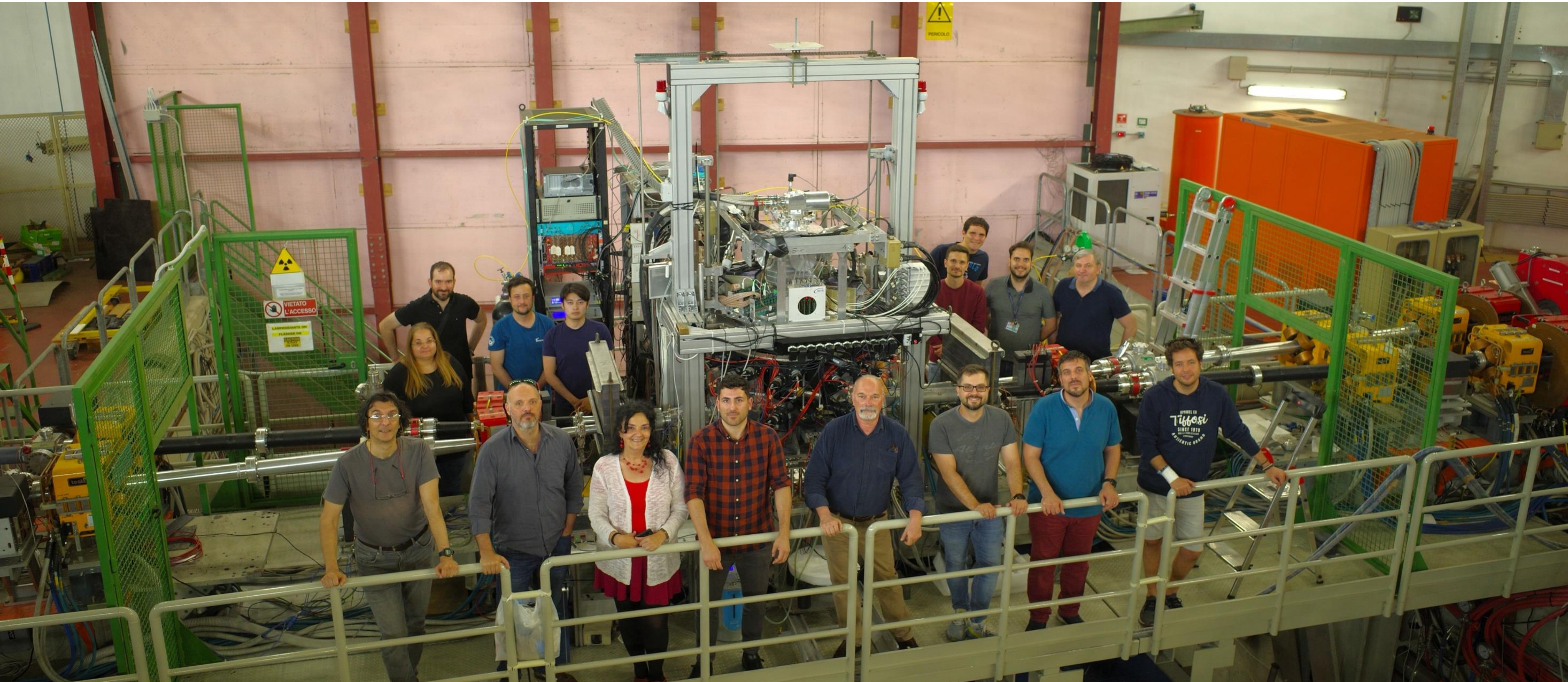
$$\varepsilon_{1s} = E_{2p\to 1s}^{exp} - E_{2p\to 1s}^{QED} = 7021.9 - 7834.0 = -812.1 \pm 29.8(stat) \pm 2.1(syst)\ \text{eV}$$

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

- Article in preparation



THANK YOU



SPARE

Why Kaonic Atom?

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

Dark Matter studies

Fundamental physics
New Physics

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

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

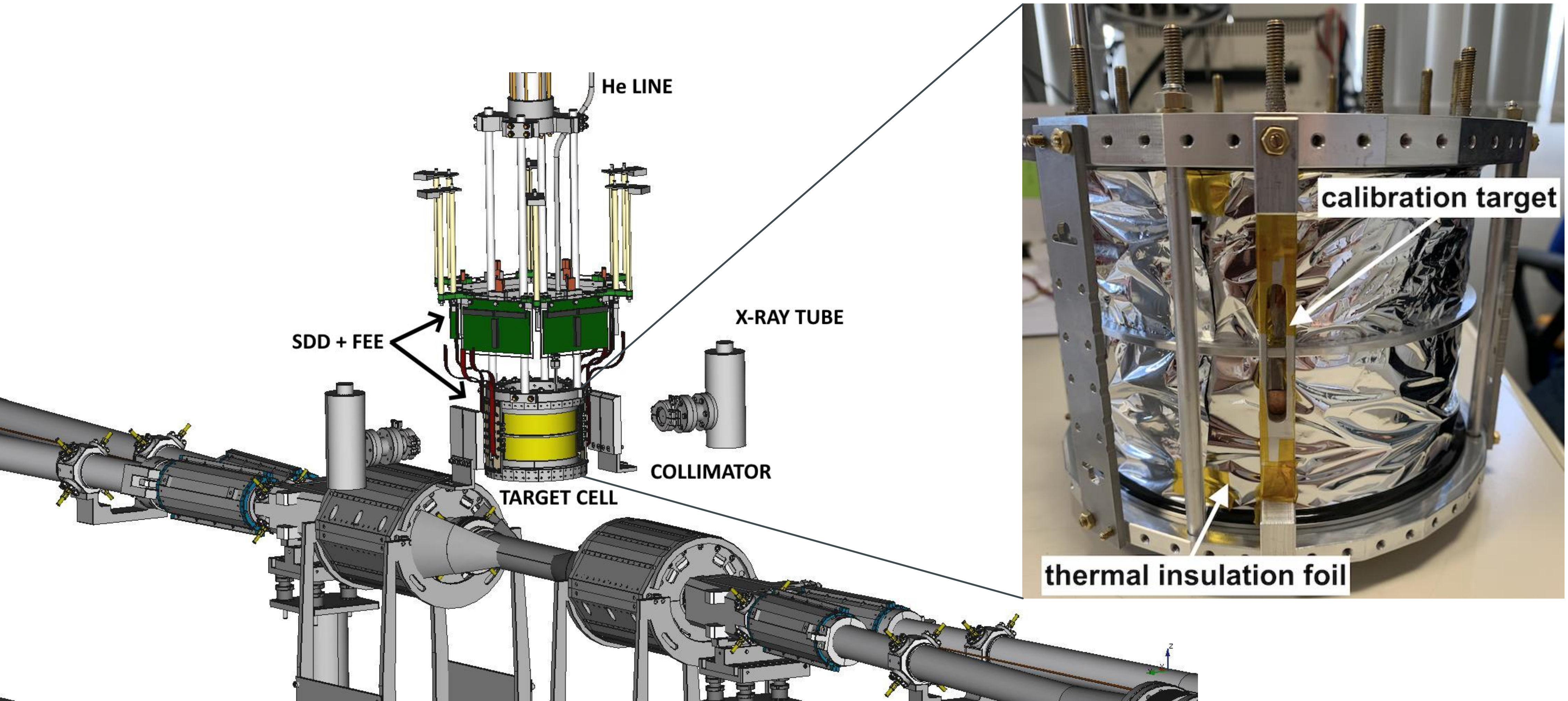
Kaonic Atoms to Investigate Global Symmetry Breaking Symmetry 12 (2020) 4, 547

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

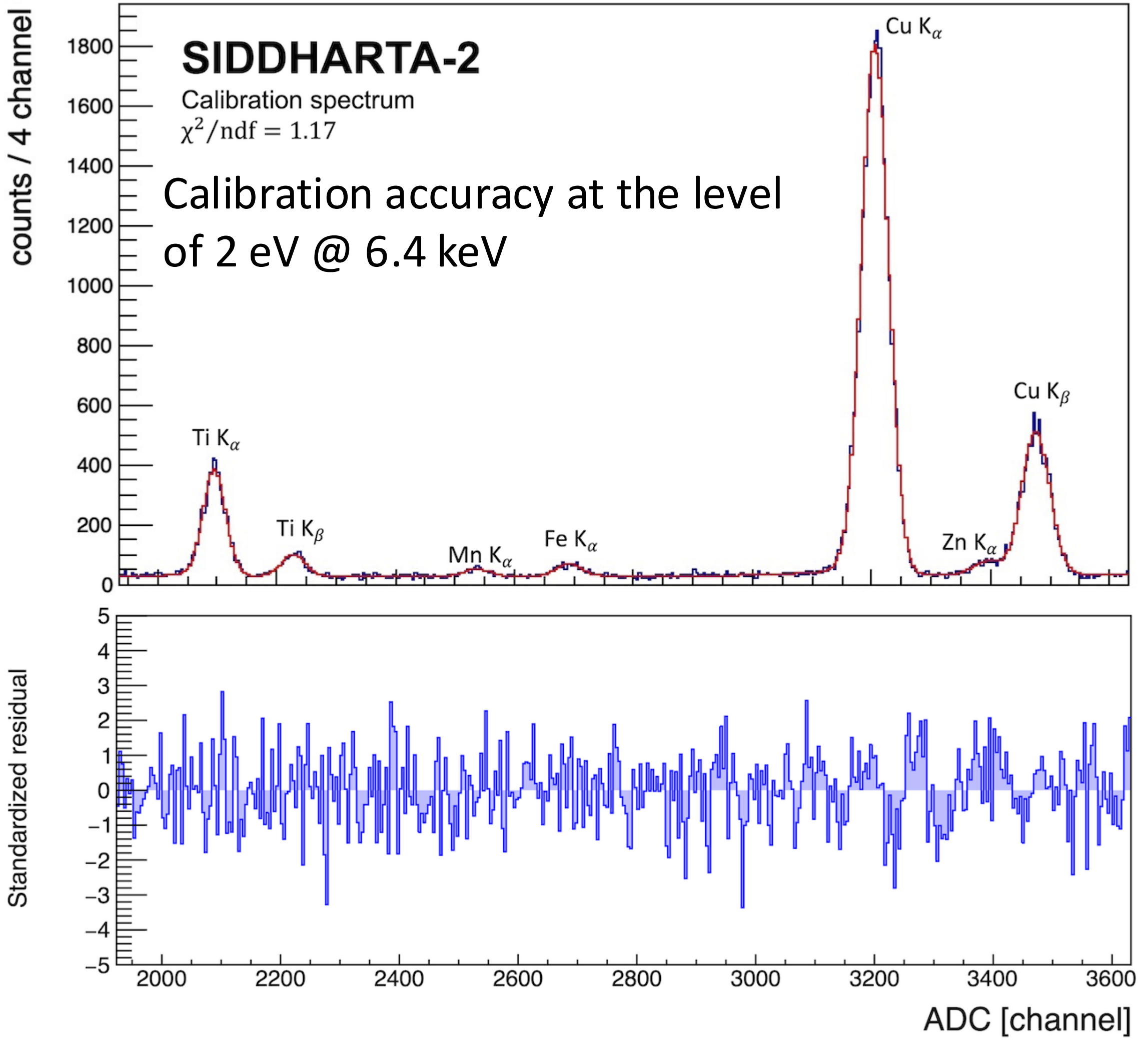
Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

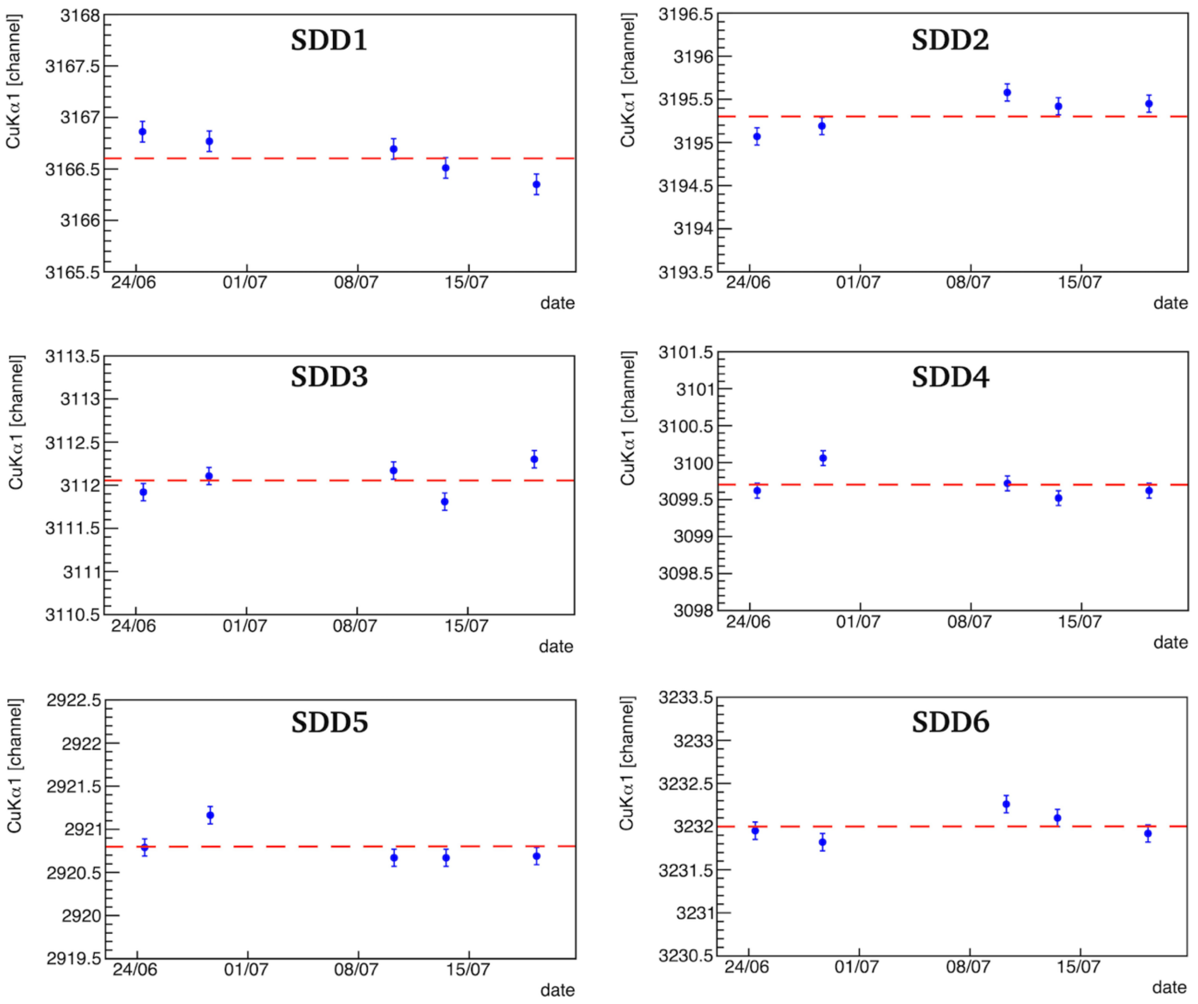
Astrophysics
EOS Neutron Stars

SDDs Calibration Procedure in DAΦNE



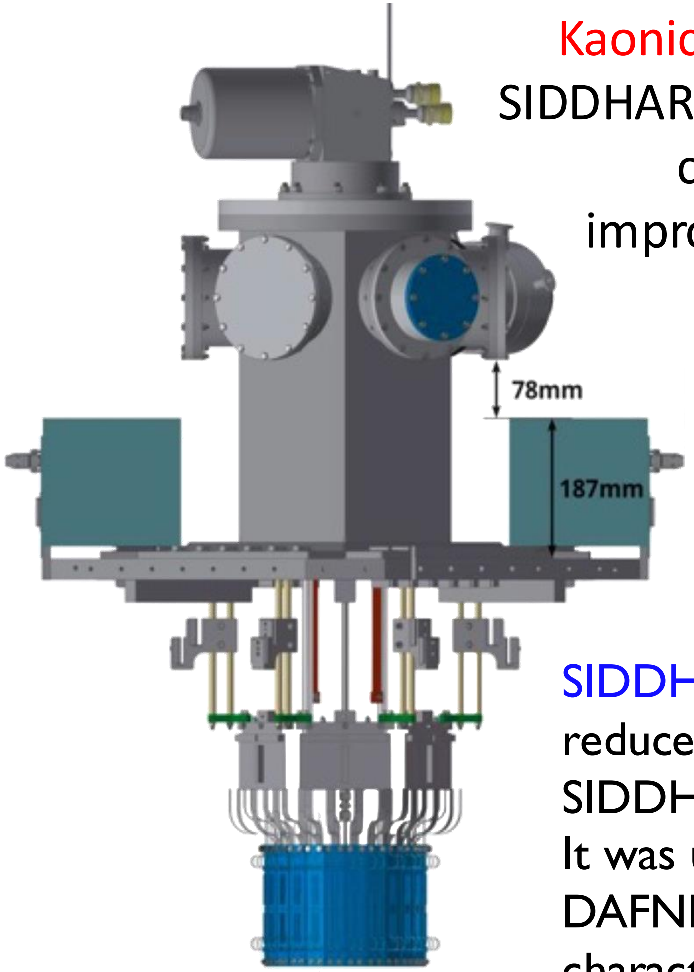
SDDs Calibration Procedure in DAΦNE





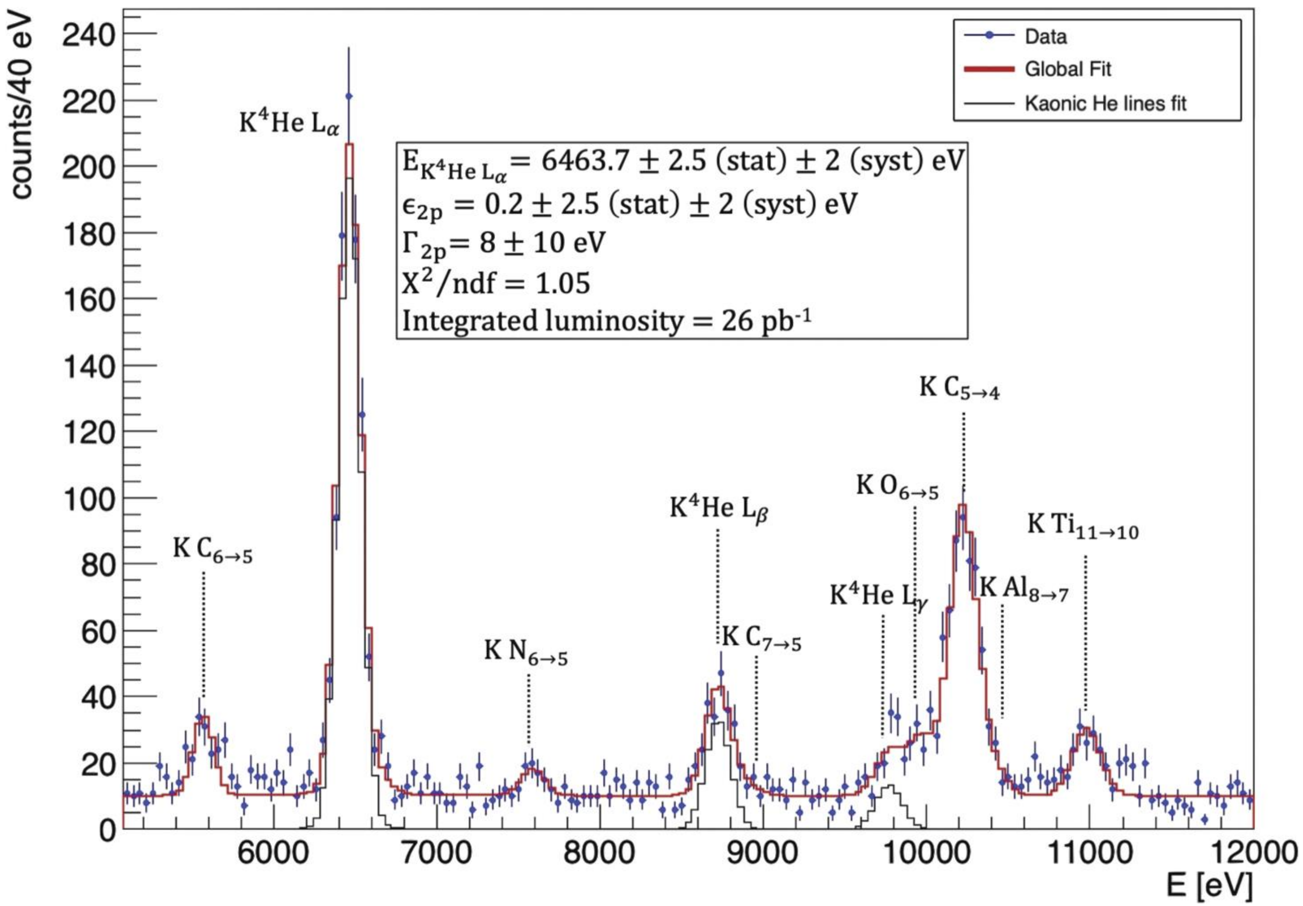
SIDDHARTINO - The kaonic ^4He 3d->2p measurement

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



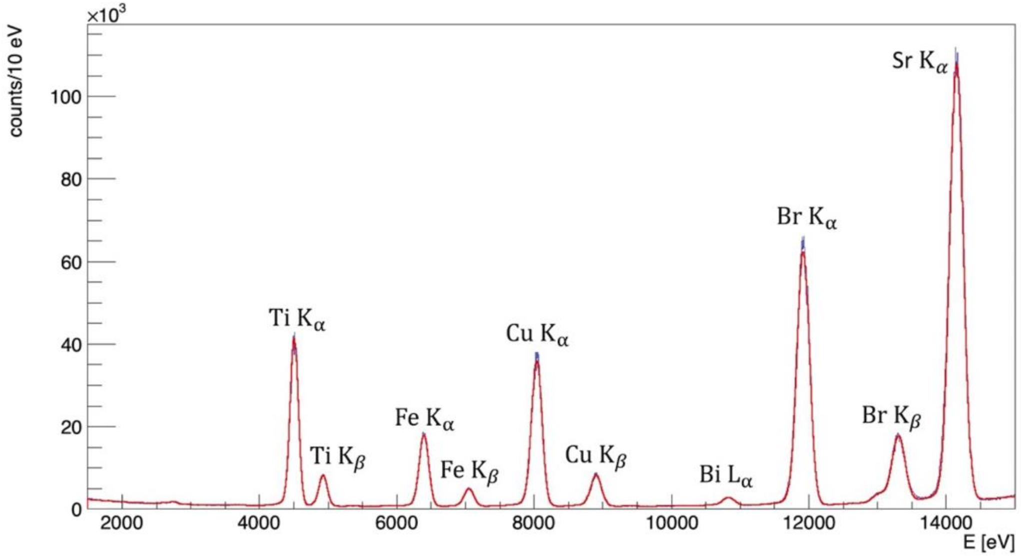
Kaonic Helium puzzle:
SIDDHARTA and KEK results confirmed, improving accuracy

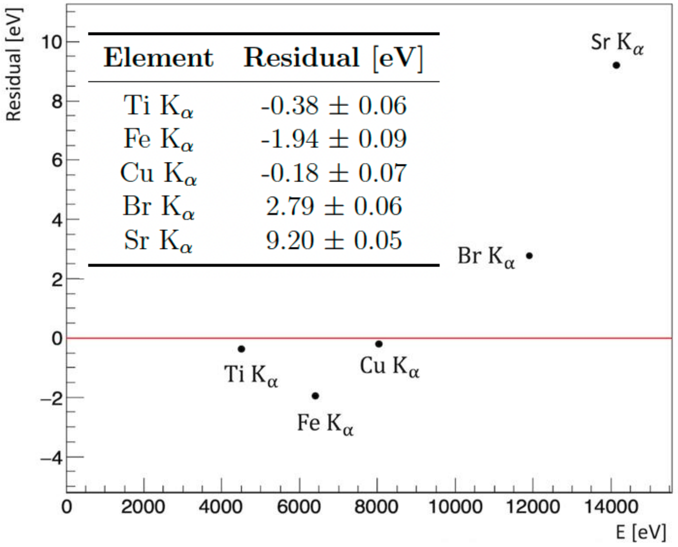
SIDDHARTINO:
reduced version of the SIDDHARTA-2 apparatus
It was used to optimize the DAFNE background and characterize the SDDs



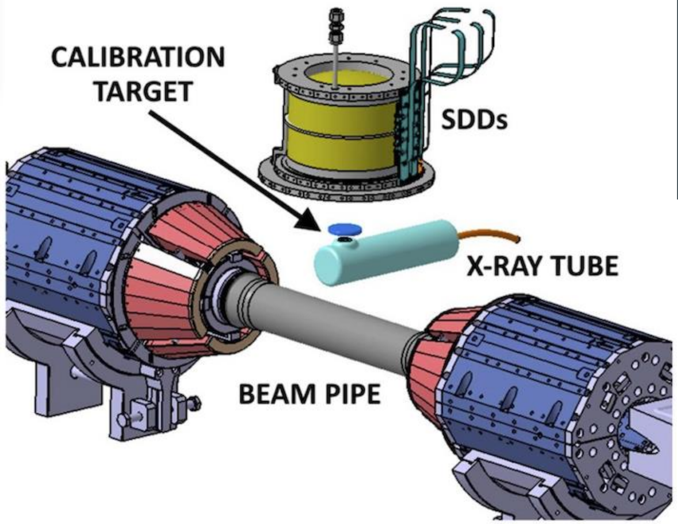
Sirghi D., Sirghi F., **Sgaramella F.**, et al., 2022, J. Phys. G Nucl. Part. Phys., 49 (5) 55106

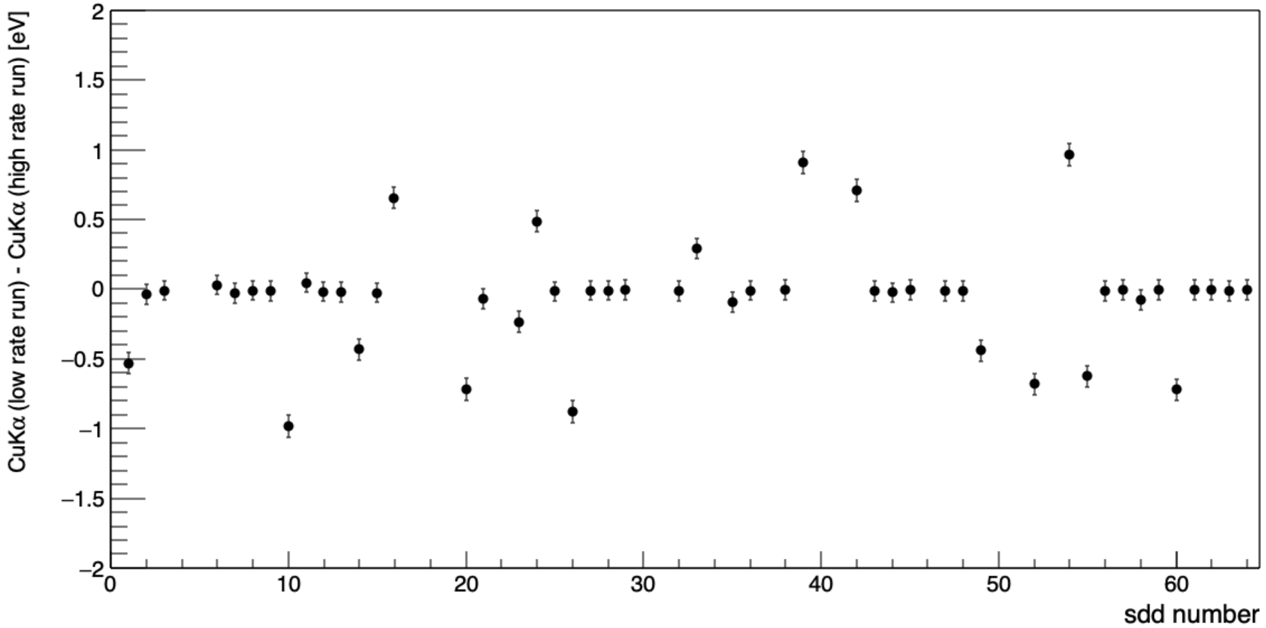
Spectroscopy Response in a High Background Environment

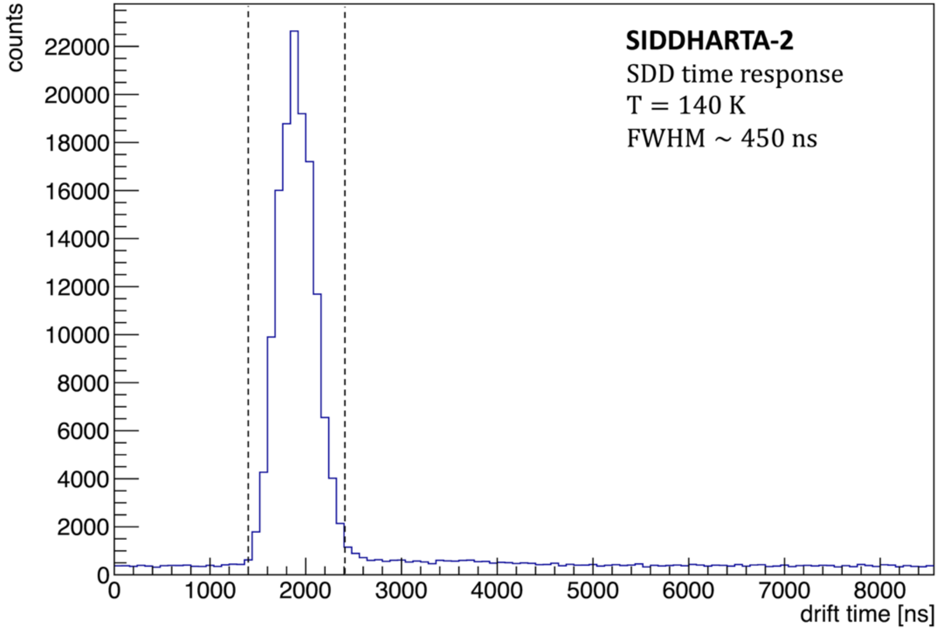




Element	Residual [eV]
Ti K_α	-0.38 $\pm$ 0.06
Fe K_α	-1.94 $\pm$ 0.09
Cu K_α	-0.18 $\pm$ 0.07
Br K_α	2.79 $\pm$ 0.06
Sr K_α	9.20 $\pm$ 0.05

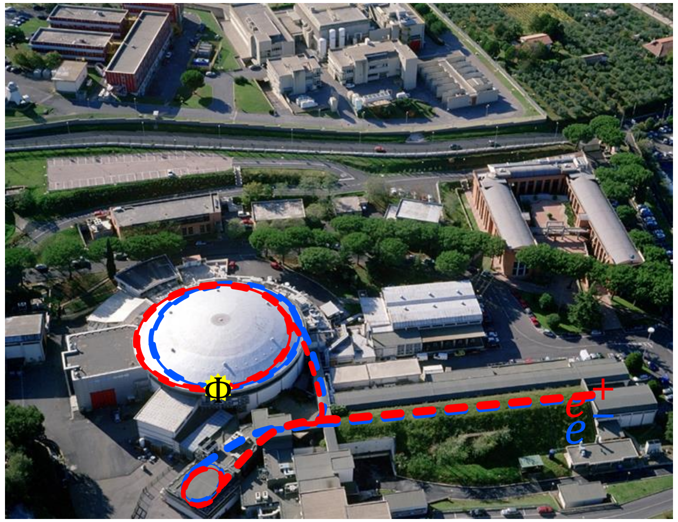


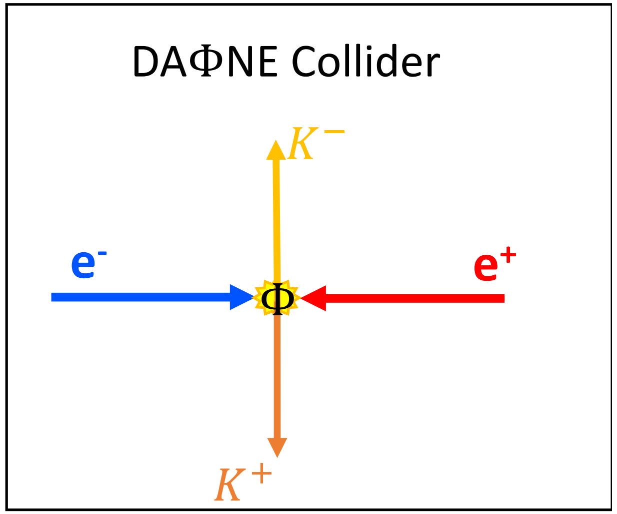


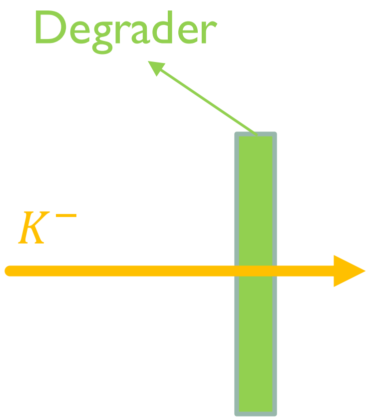


Sgaramella F., Miliucci M., et al., 2022, Phys Scr, 97 (11) 114002

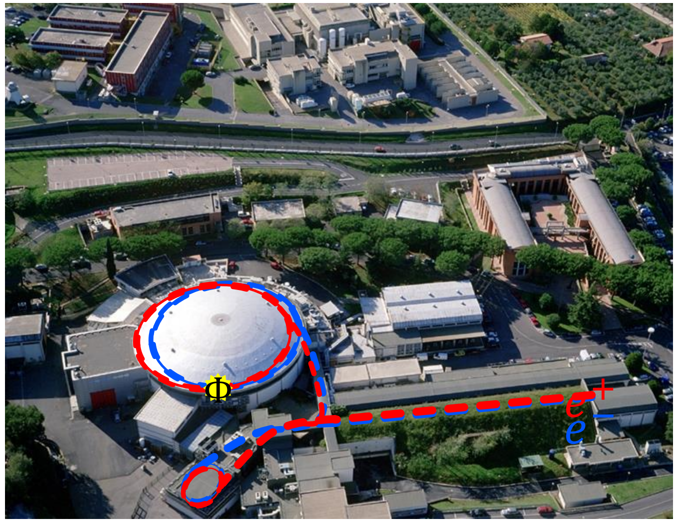
The SIDDHARTA-2 experiment - Layout

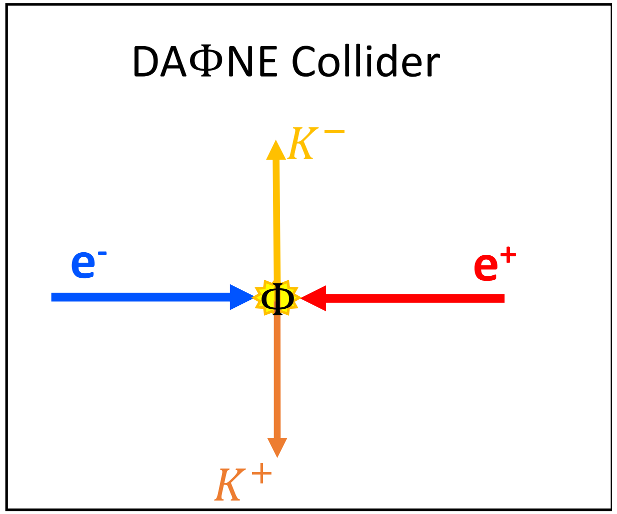


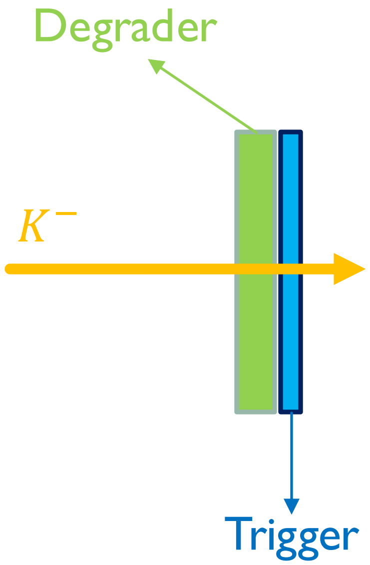




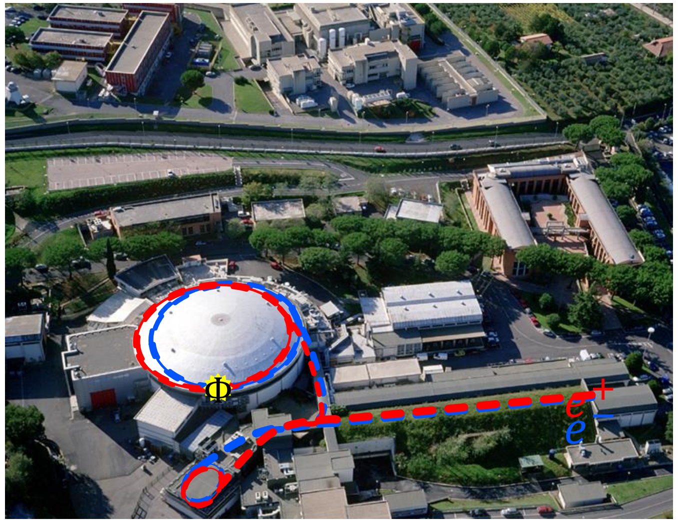
The SIDDHARTA-2 experiment - Layout

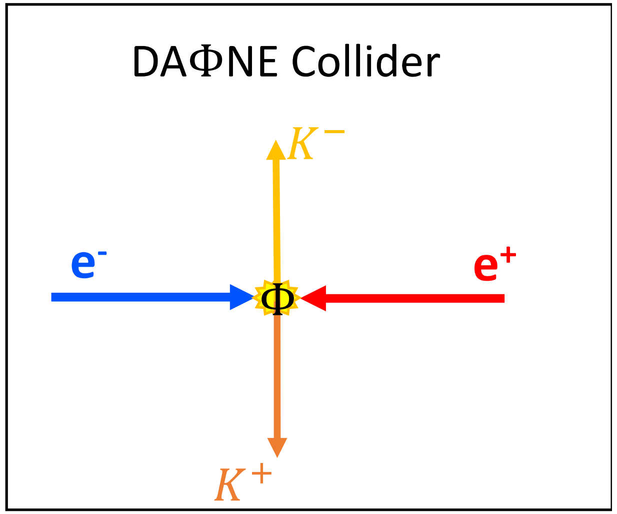


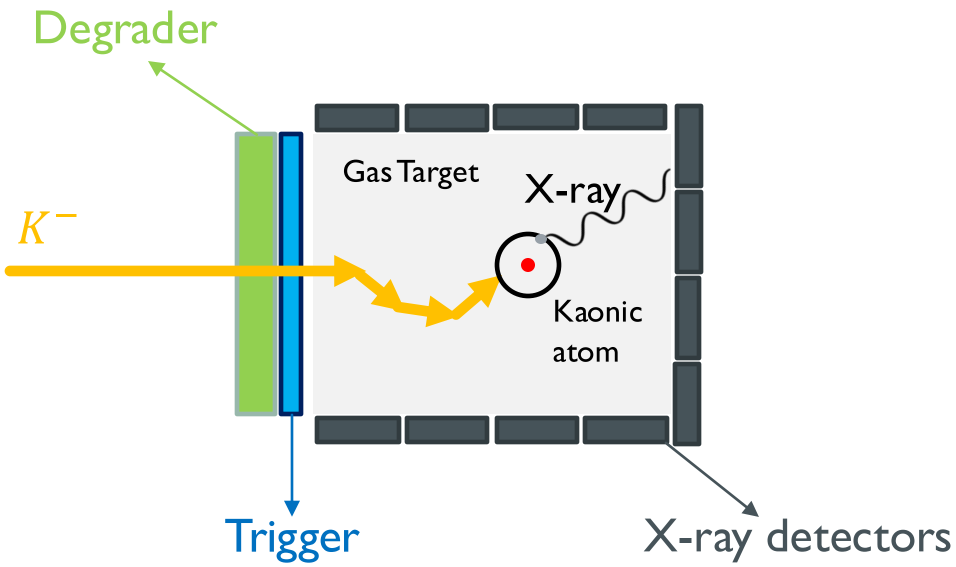




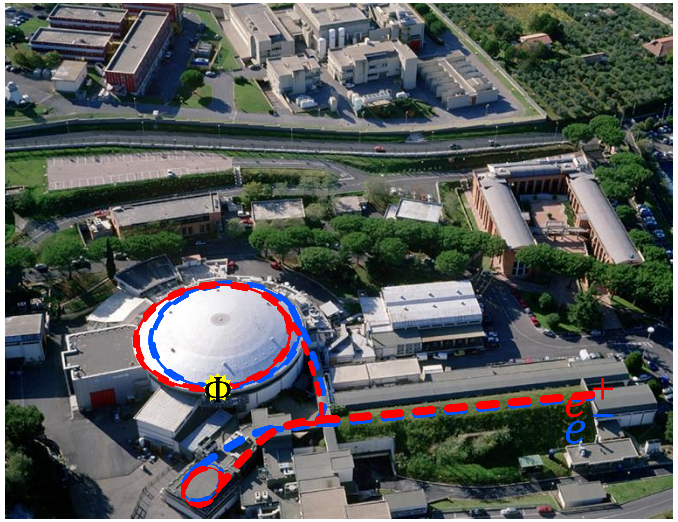
The SIDDHARTA-2 experiment - Layout

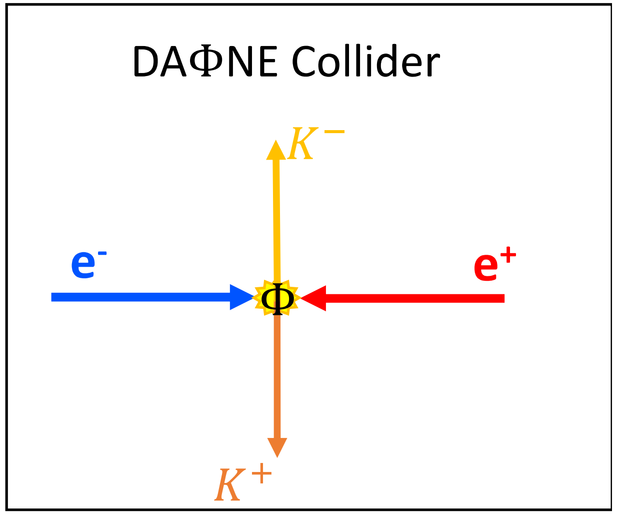


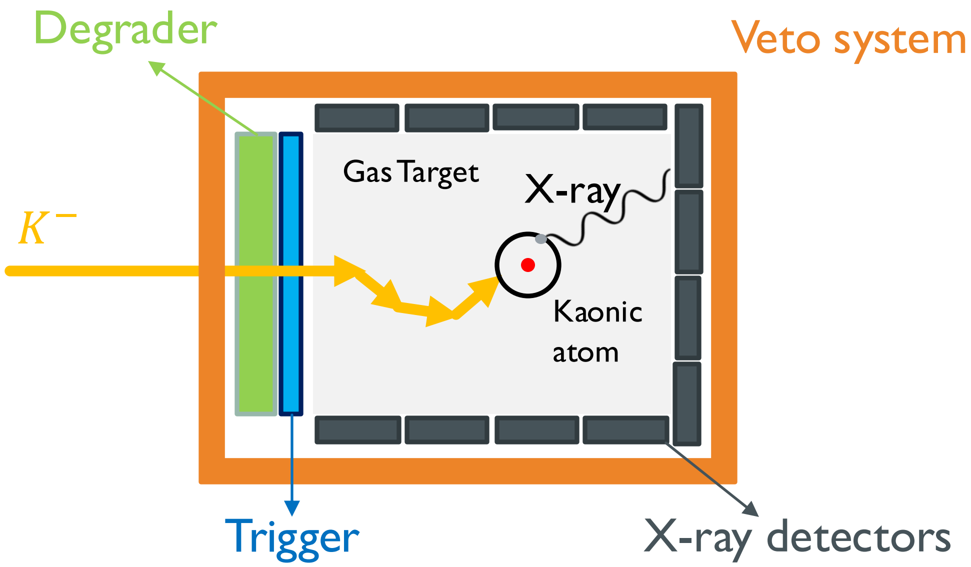




The SIDDHARTA-2 experiment - Layout







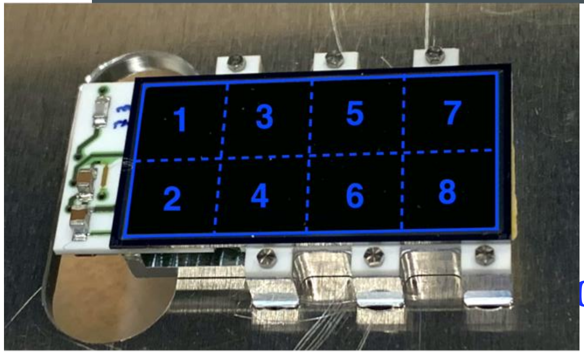
Silicon Drift Detectors

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

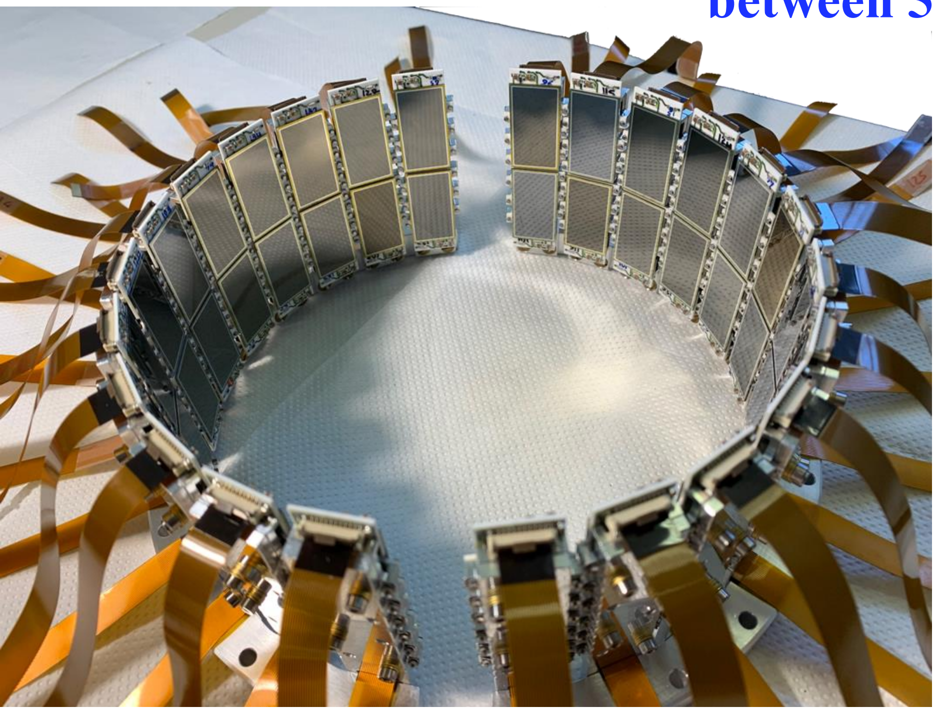
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

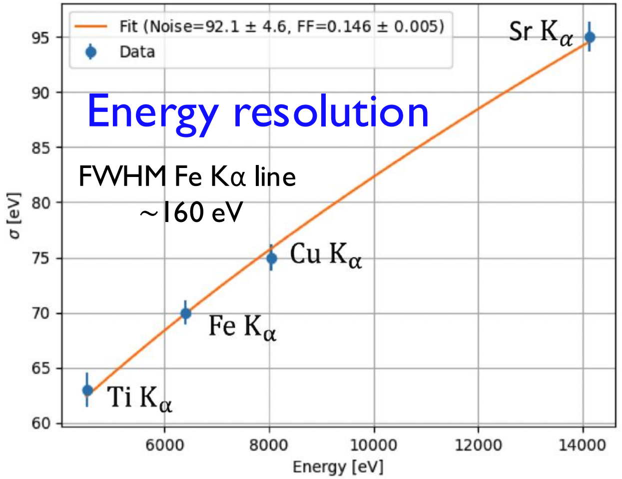
FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

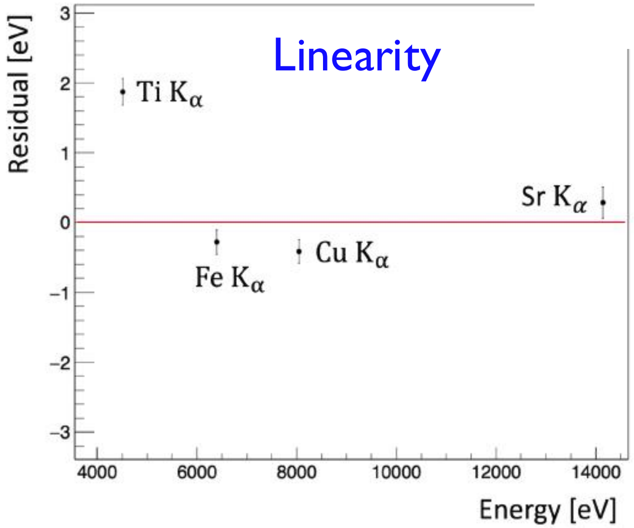
POLITECNICO MILANO 1863

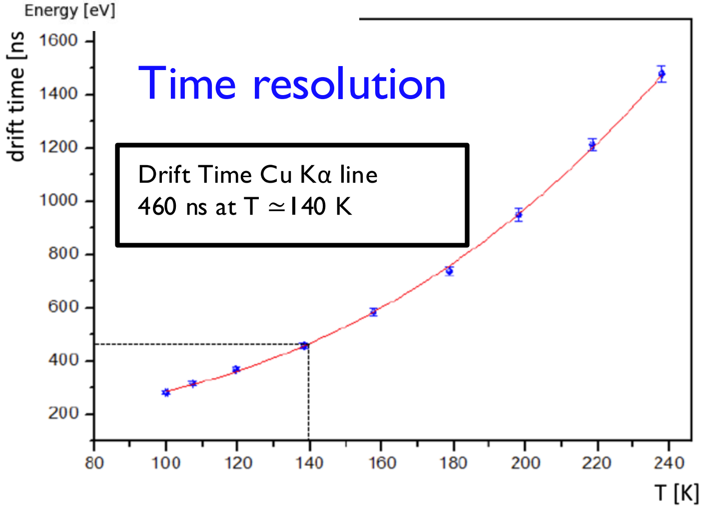


8 SDD units (0.64 cm^2)
for a total active area of 5.12 cm^2
Thickness of 450 μm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

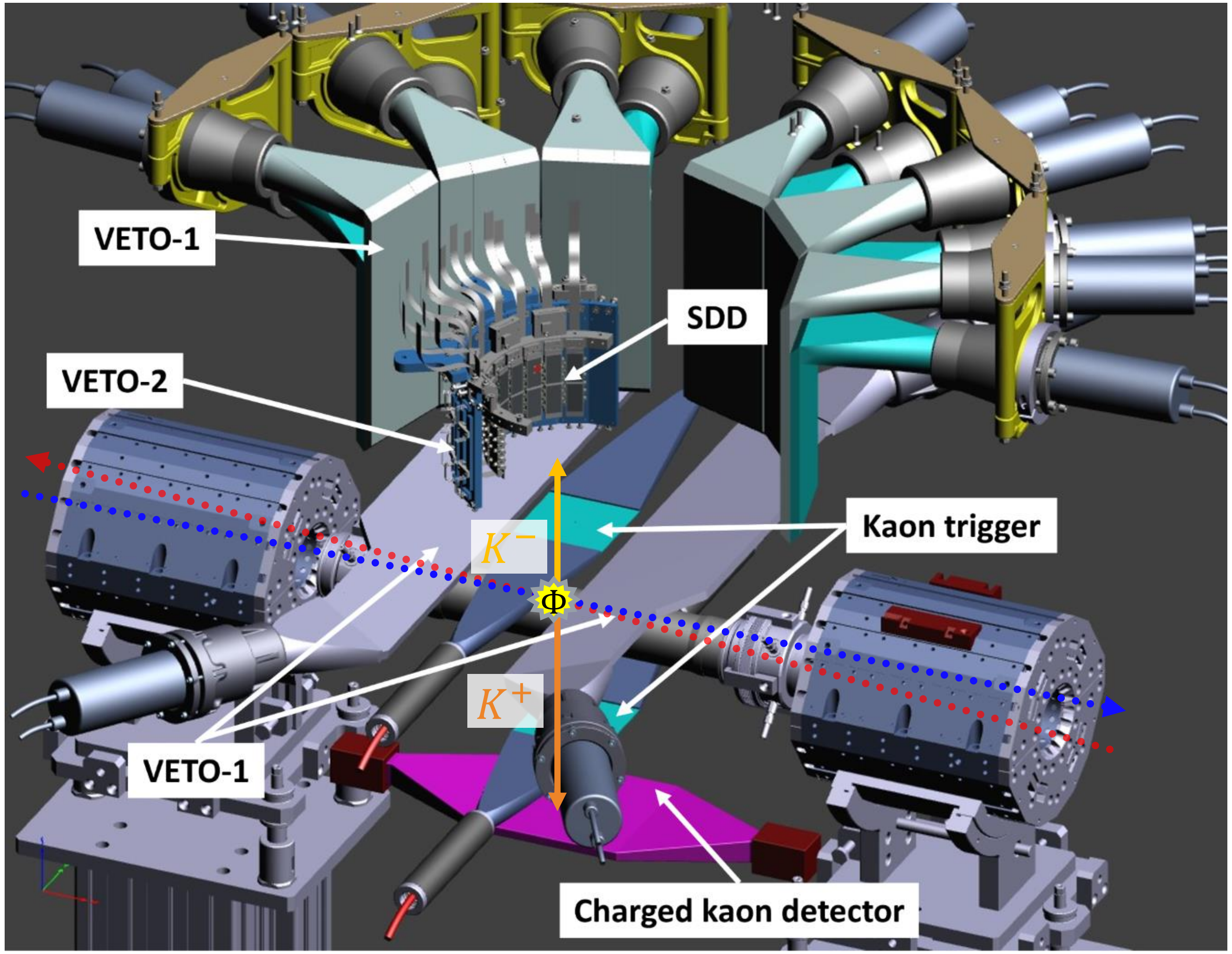




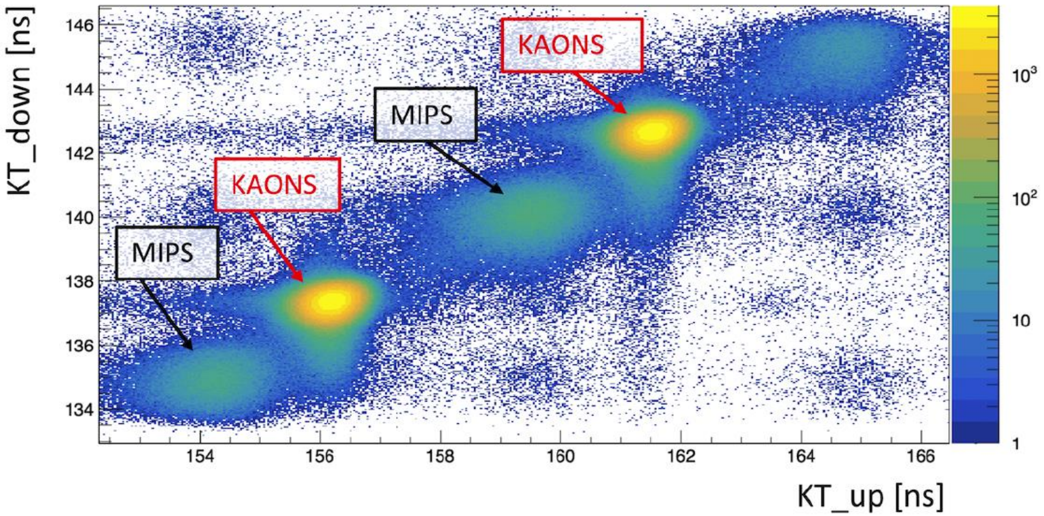




The SIDDHARTA-2 apparatus



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

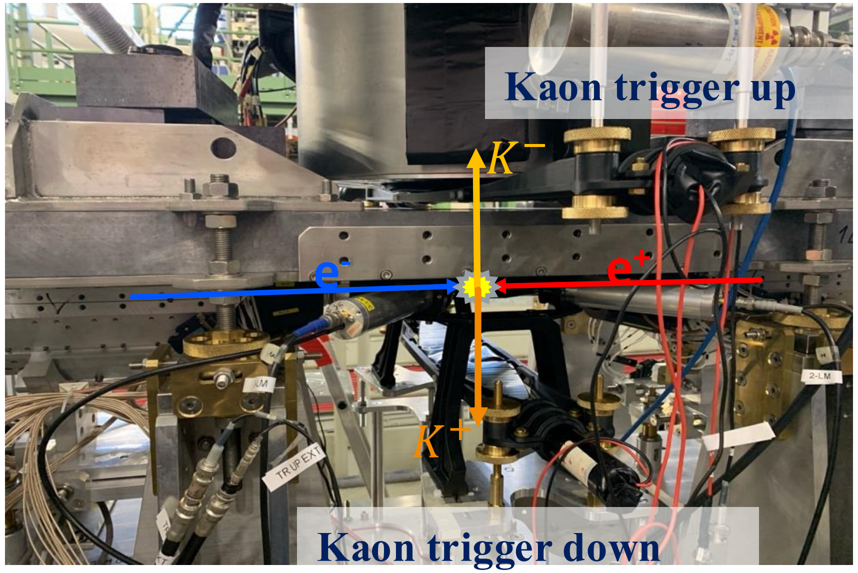


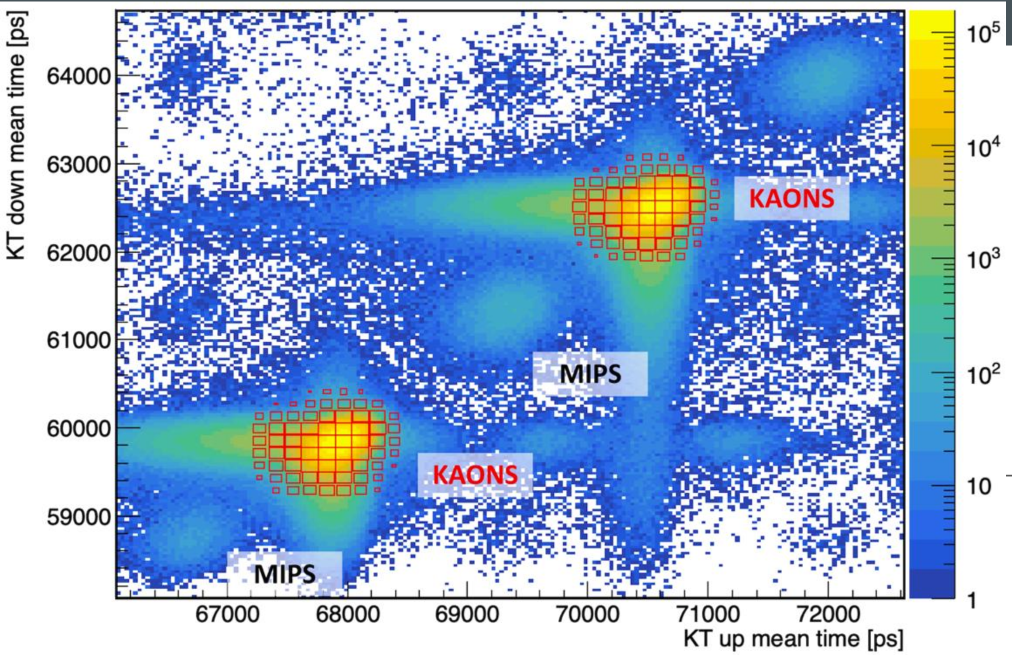
The ToF is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

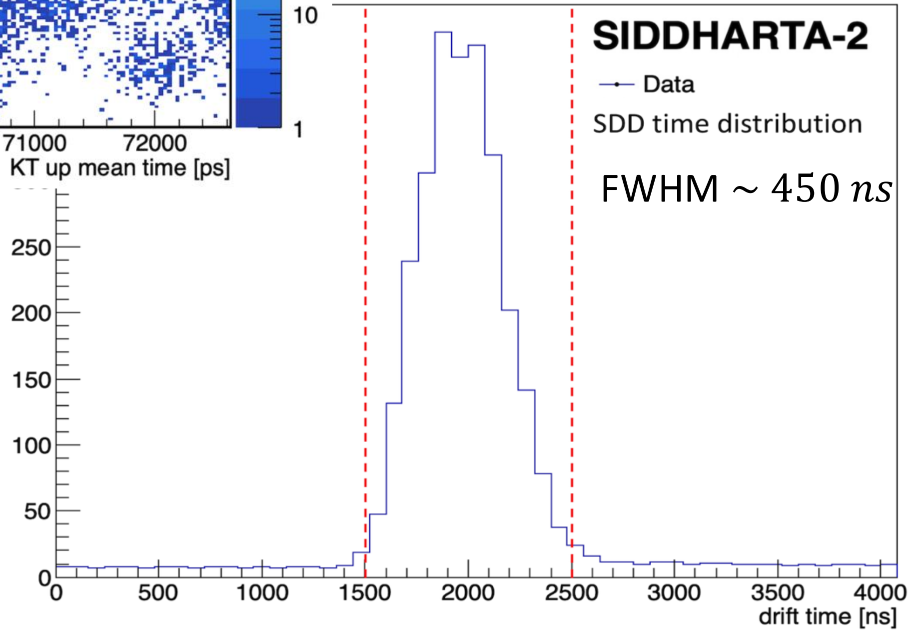
Can efficiently discriminate by ToF Kaons and MIPs!

The first kaonic deuterium measurement

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

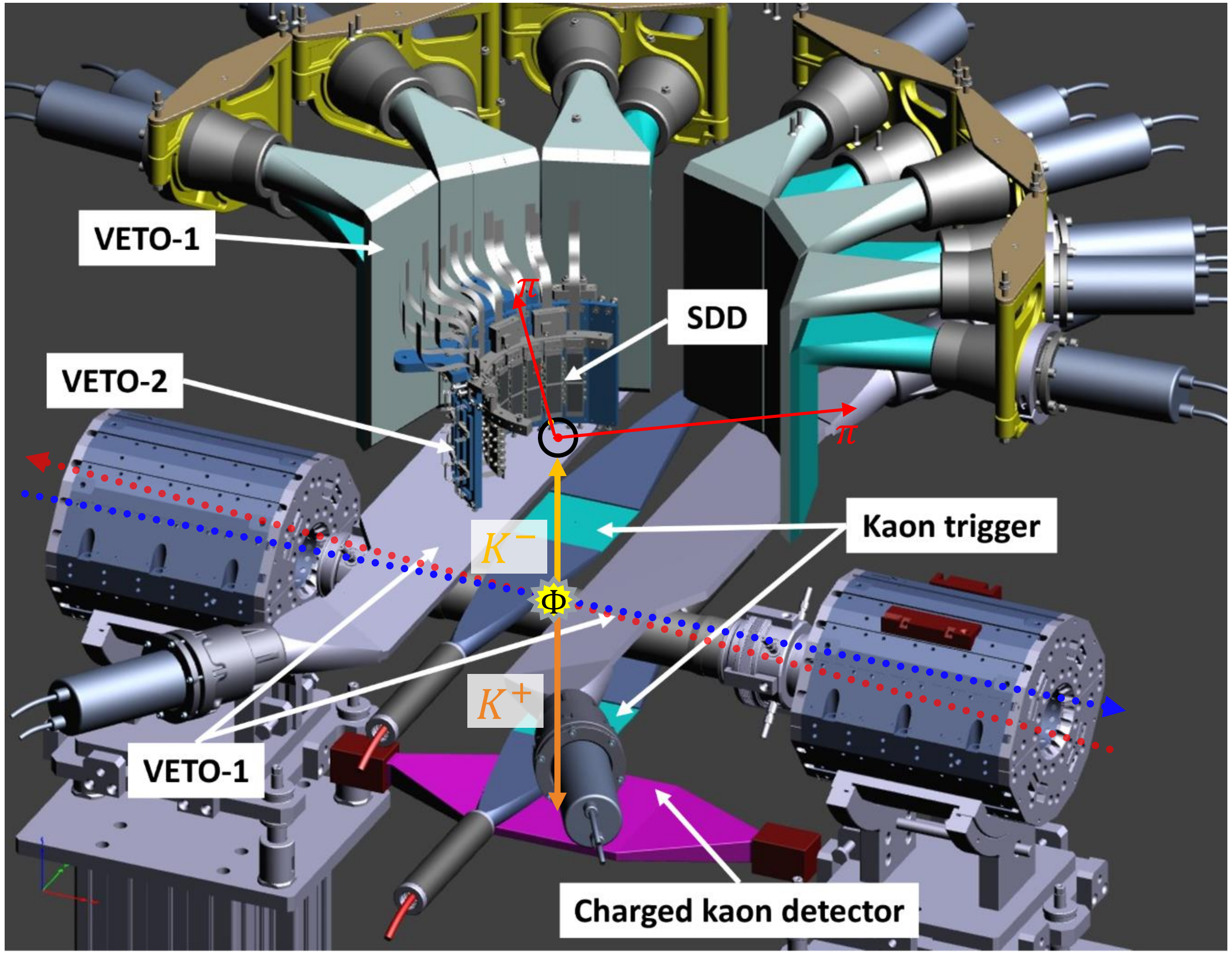




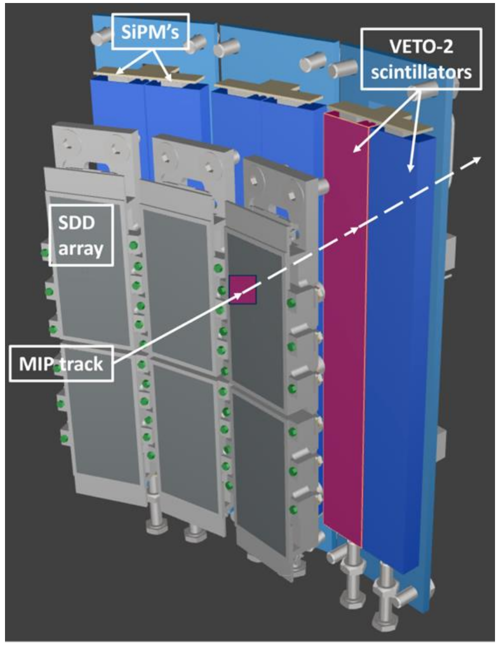


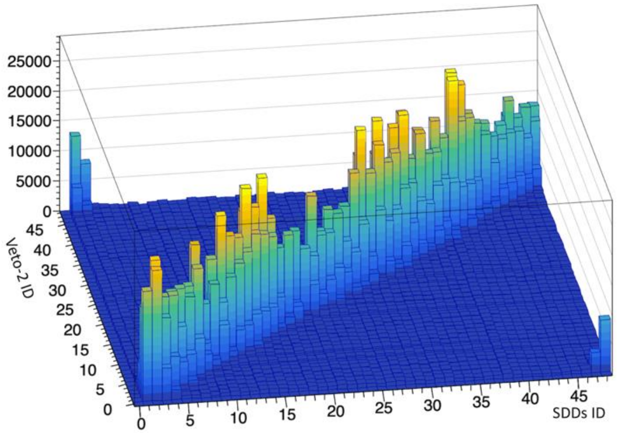
The trigger is generated by the coincidence of 2 back-to-back scintillators
The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles
originating from beam-beam and beam-environment interaction (MIPs).
Can efficiently discriminate by ToF Kaons and MIPs!

The SIDDHARTA-2 apparatus

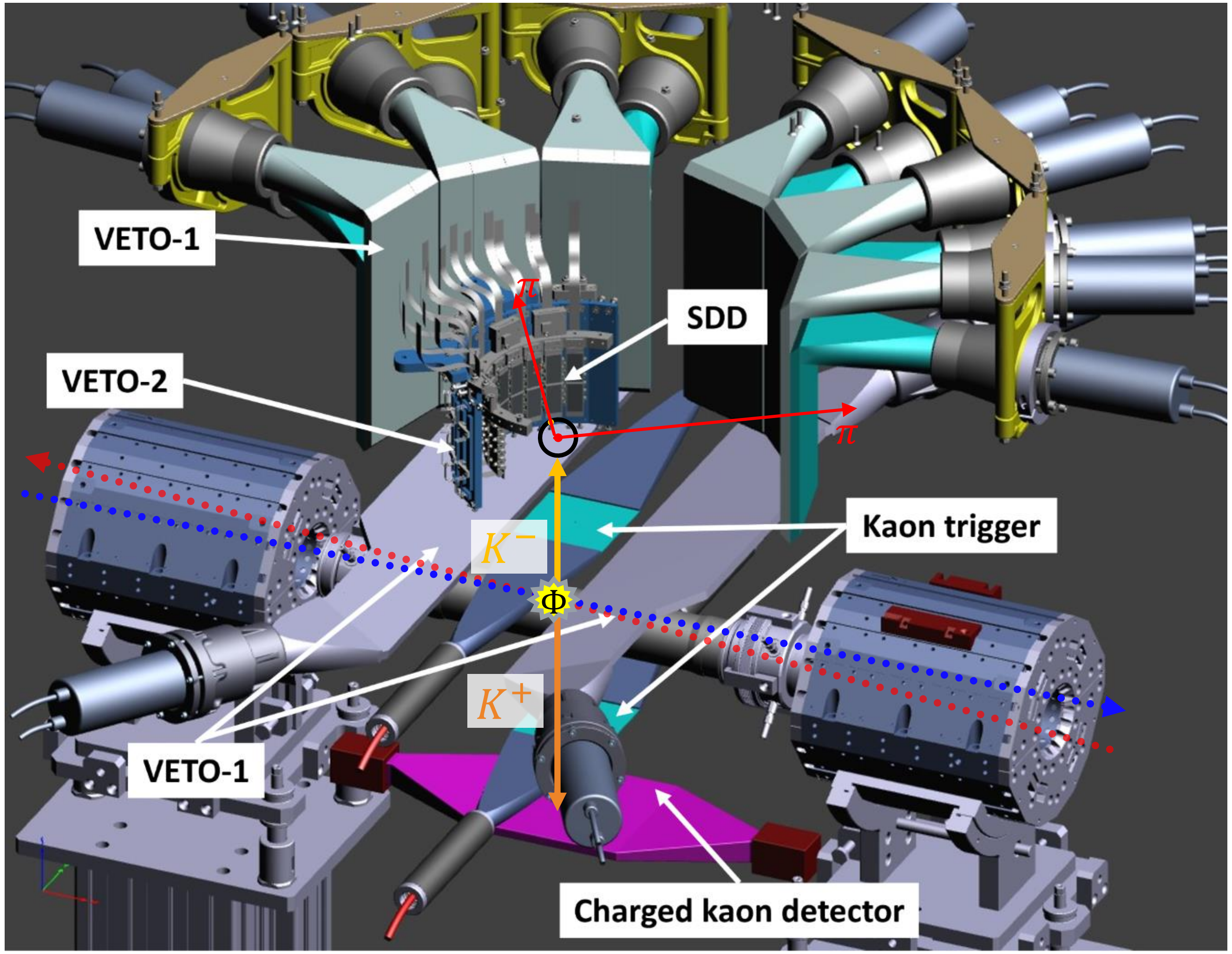


Veto-2 48 plastic scintillator read by SiPMs to suppress the background induce by particles produced by kaon absorption, passing through the SDDs.

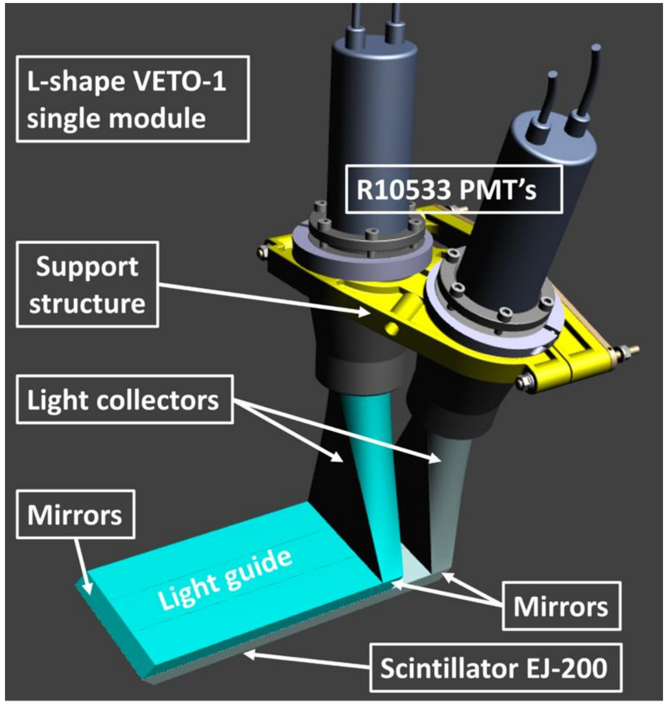




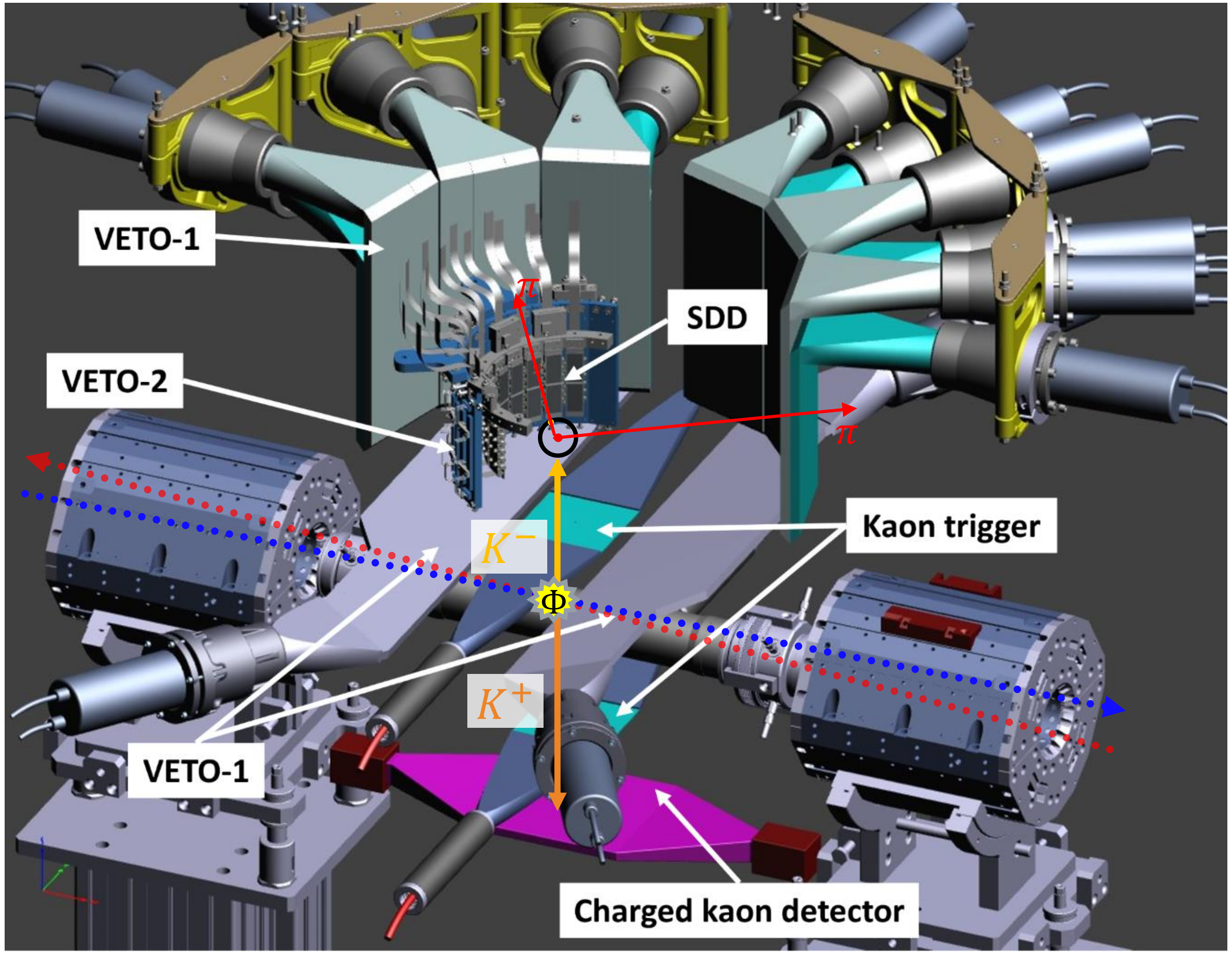
The SIDDHARTA-2 apparatus



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

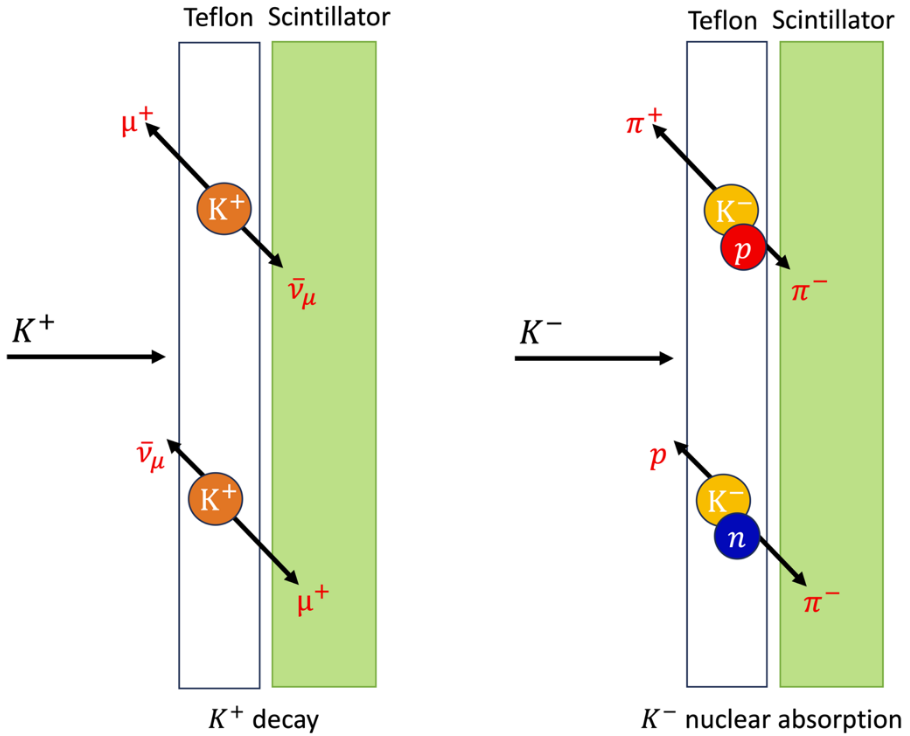


The SIDDHARTA-2 apparatus

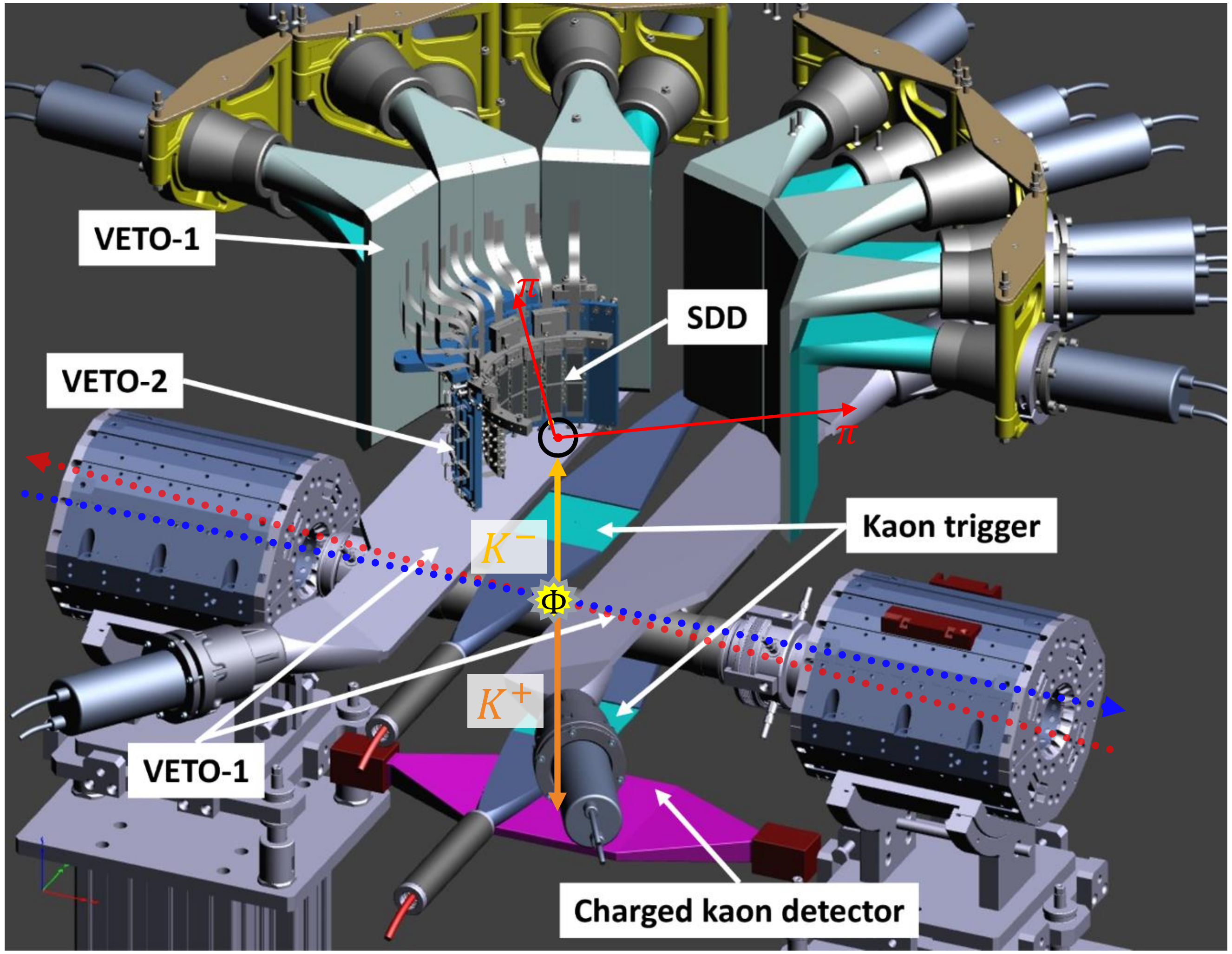


Charged Kaons Veto

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



The SIDDHARTA-2 apparatus



Charged Kaons Veto

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