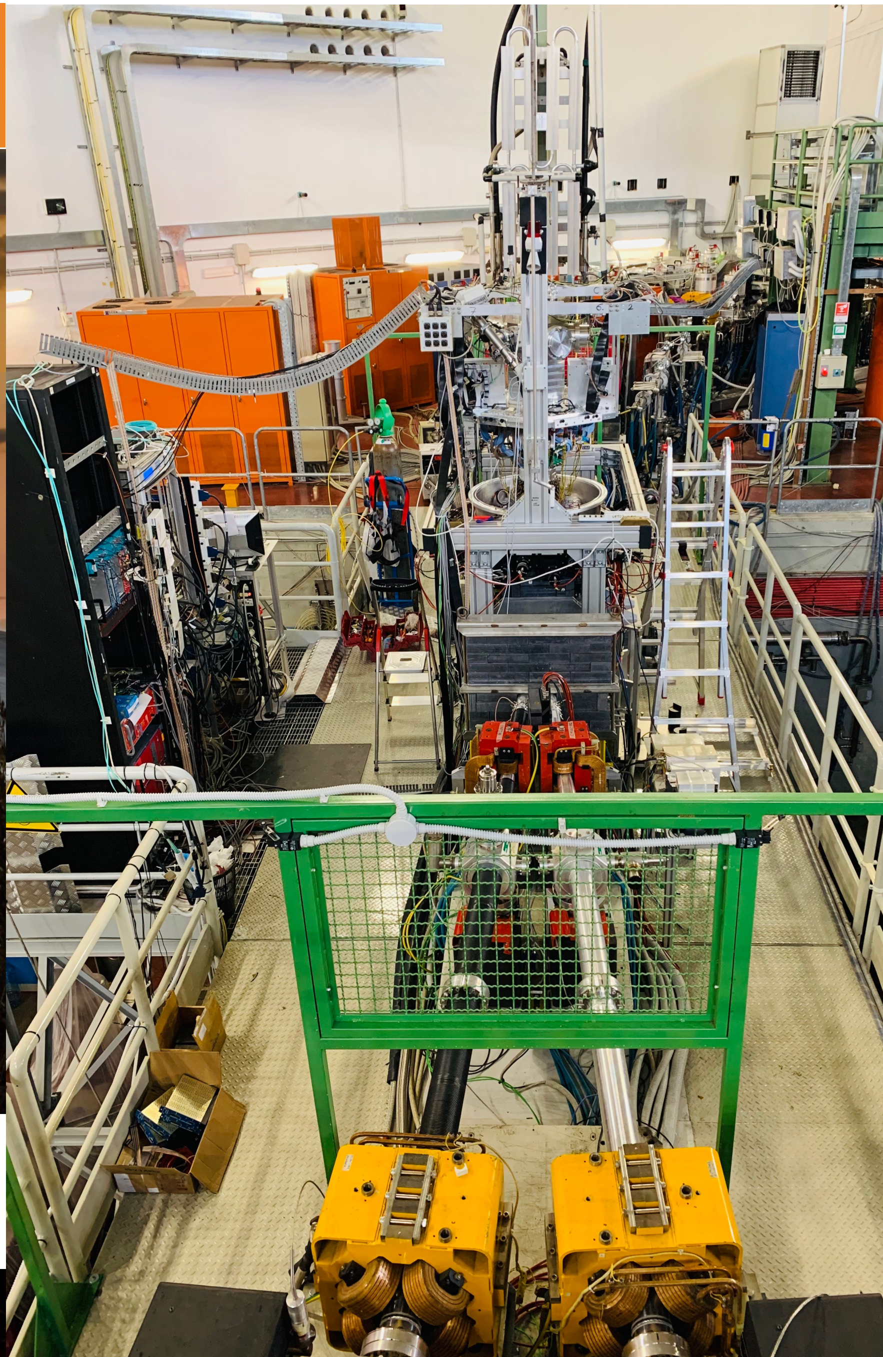
RIKEN, 14 December 2023

"THE SIDDHARTA-2 EXPERIMENT"

Francesco Sgaramella
on behalf of the SIDDHARTA-2 collaboration

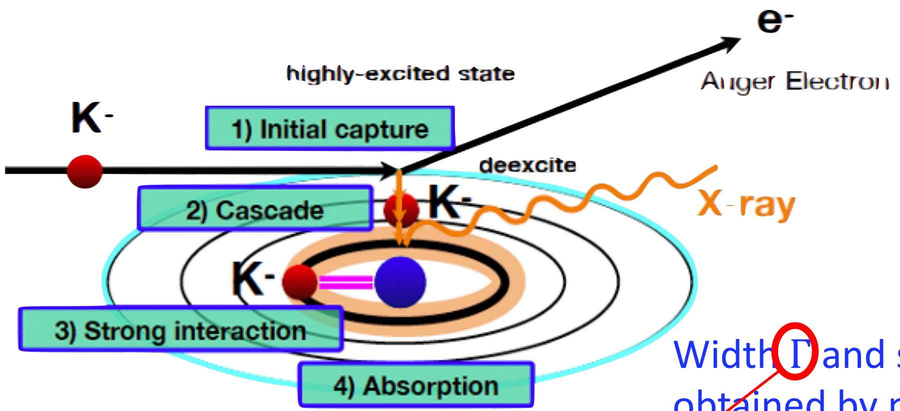
INFN
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

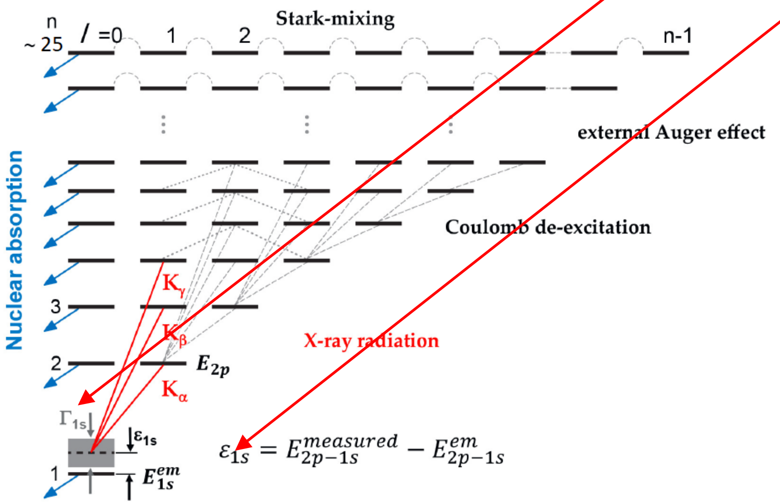


The SIDDHARTA-2 experiment

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



Width Γ and shift ε obtained by measuring the X-rays emitted



Combined analysis of the kaonic deuterium and kaonic hydrogen measurements

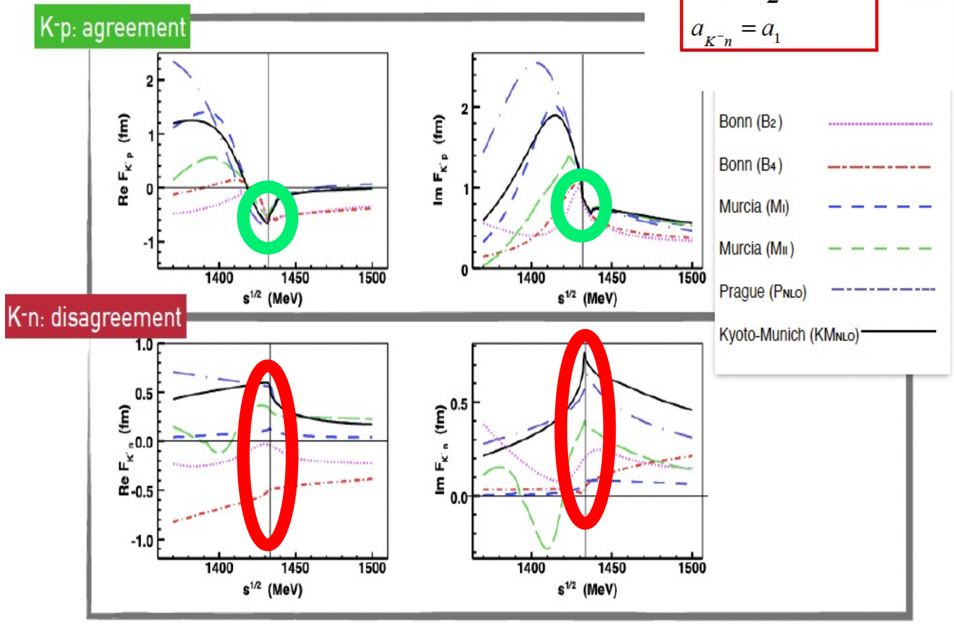
$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_{K^-p}\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}\right)$$

(μ_c reduced mass of the K⁻p system, α fine-structure constant)

U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

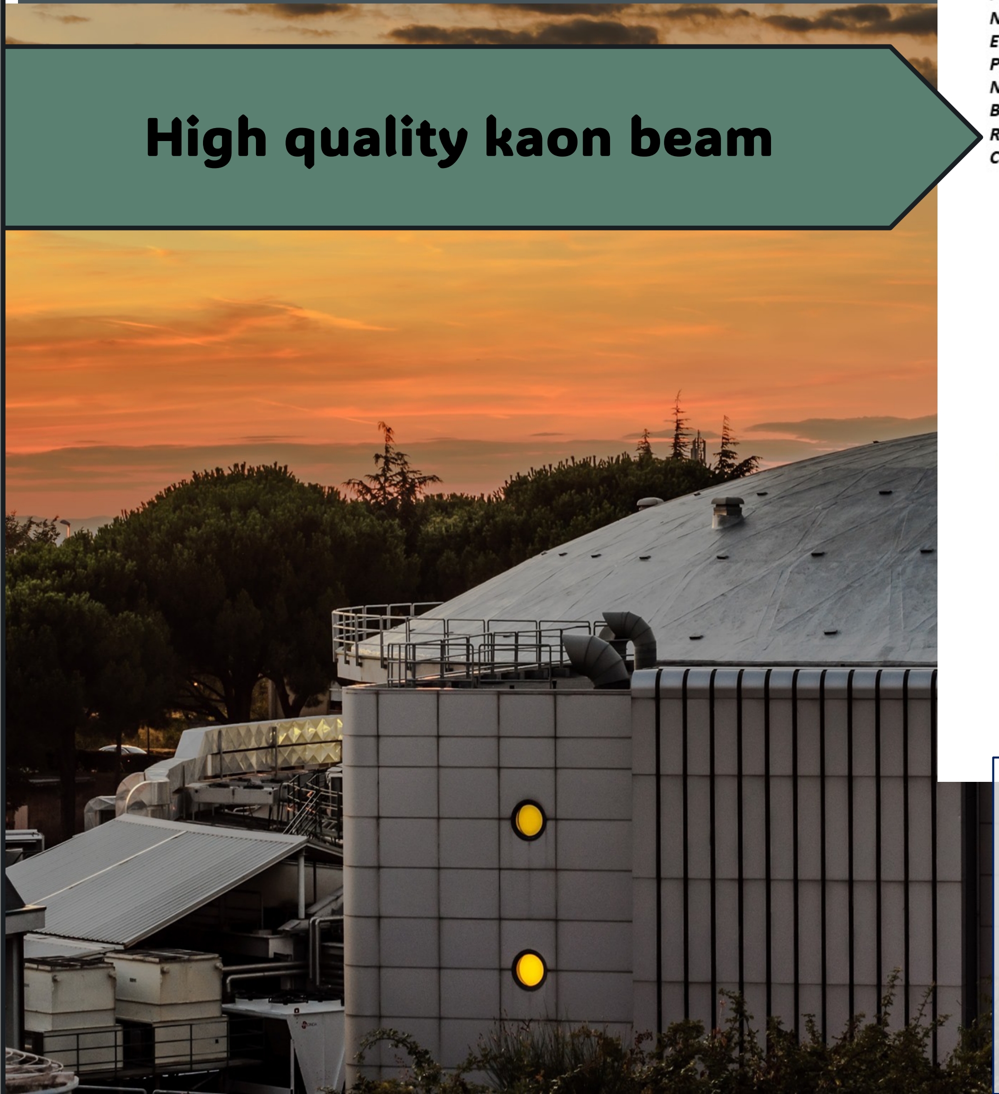
$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$
$$a_{K^-n} = a_1$$

$$a_{K^-d} = \frac{k}{2}[a_{K^-p} + a_{K^-n}] + C = \frac{k}{4}[a_0 + 3a_1] + C$$
$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

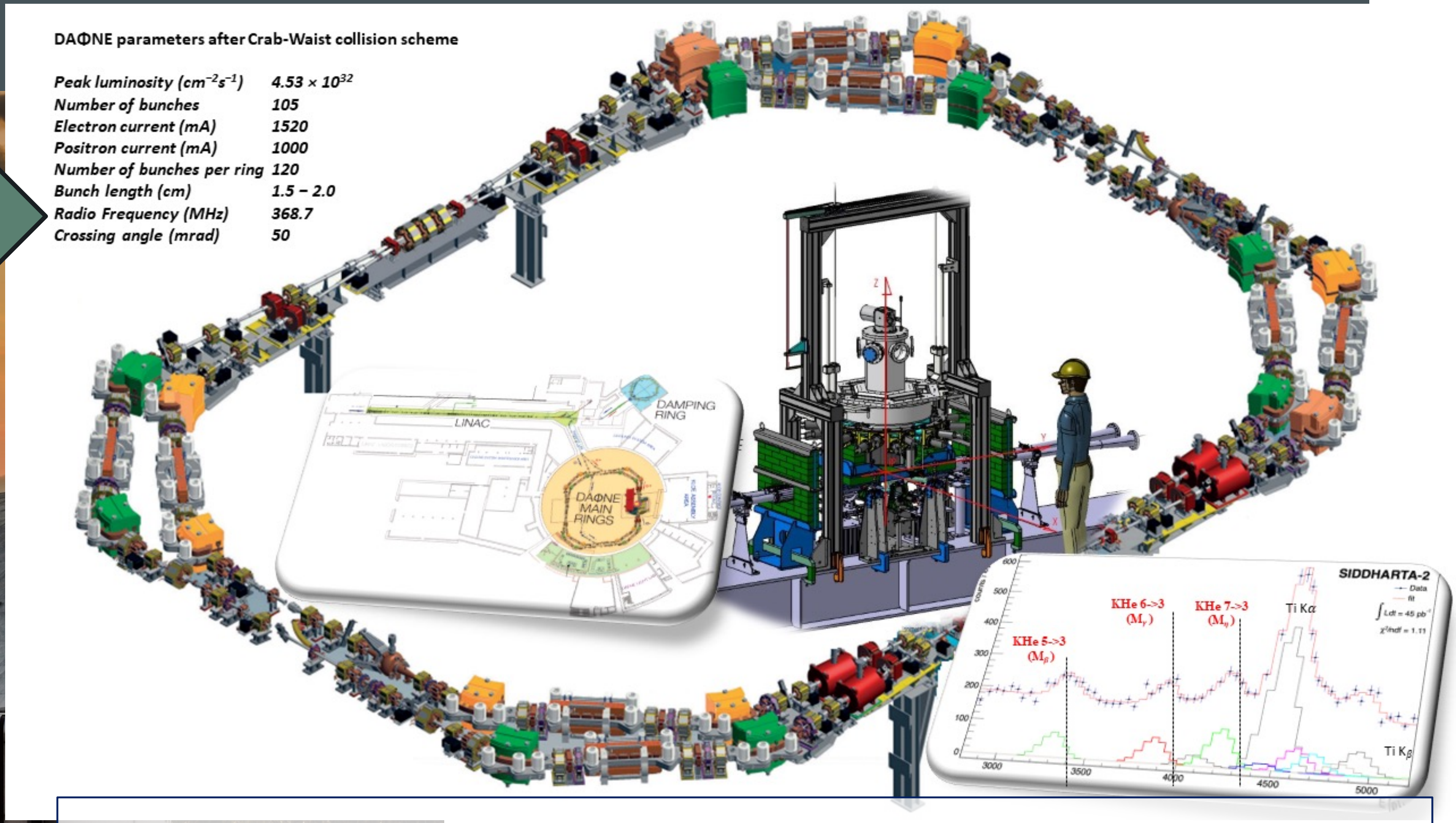


A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

The DAΦNE collider



High quality kaon beam

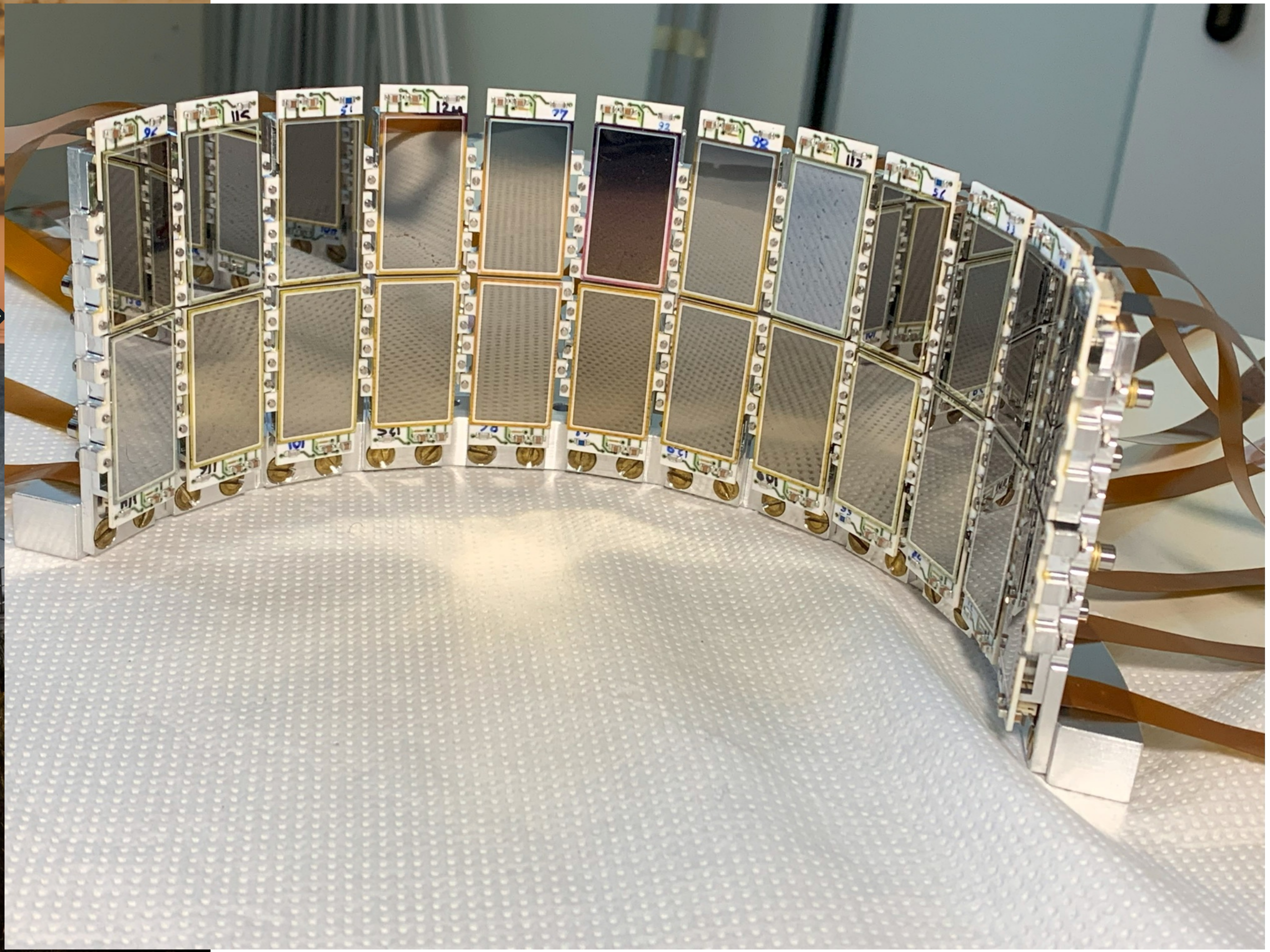


- $\Phi \rightarrow K^- K^+$ (48.9%)
- **Monochromatic low-energy K^-**
  ($\sim$127 MeV/c ; $\Delta p/p$ = 0.1%)
- **Less hadronic background compared to hadron beam line**

Silicon Drift Detectors

High quality kaon beam

Efficient x-ray detector system and trigger – veto systems



Powerful analysis tools

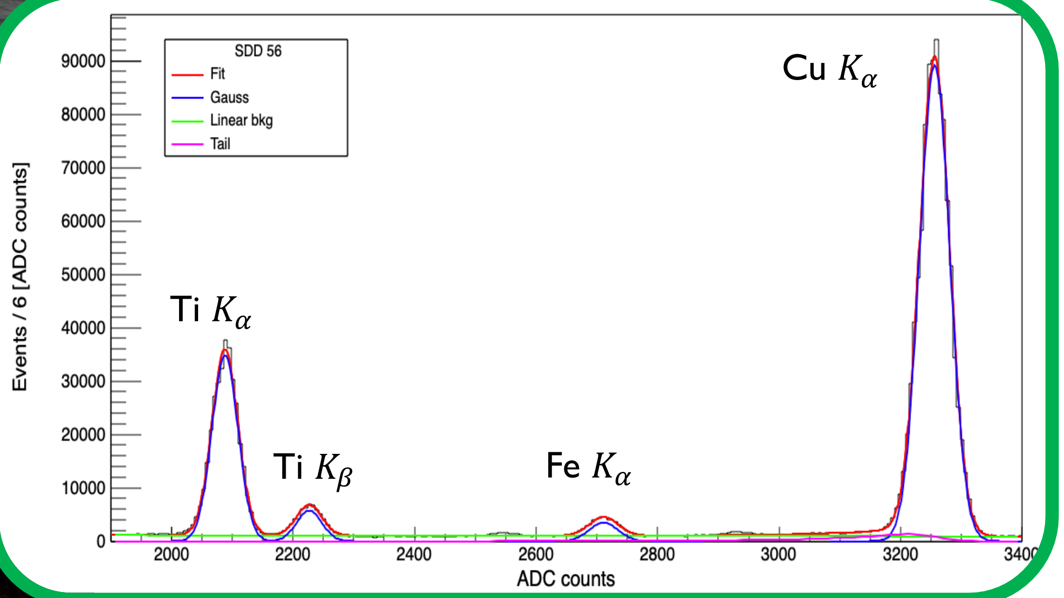
High quality kaon beam

Efficient x-ray detector system and trigger – veto systems

Powerful analysis tools

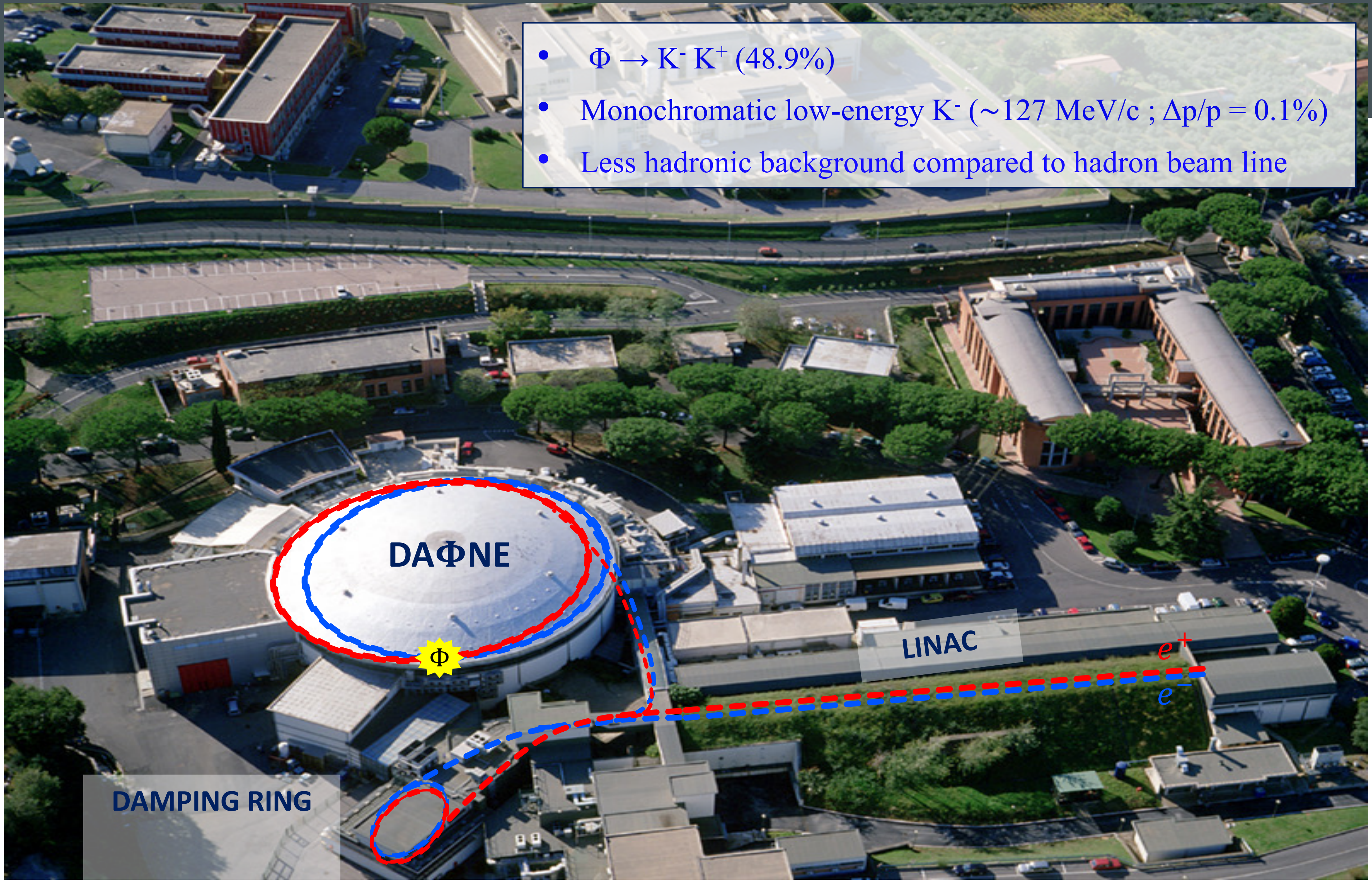
Monte Carlo simulations, modern algorithms and machine learning techniques

Optimization of the setup and detectors response (trigger, SDDs, veto, …)

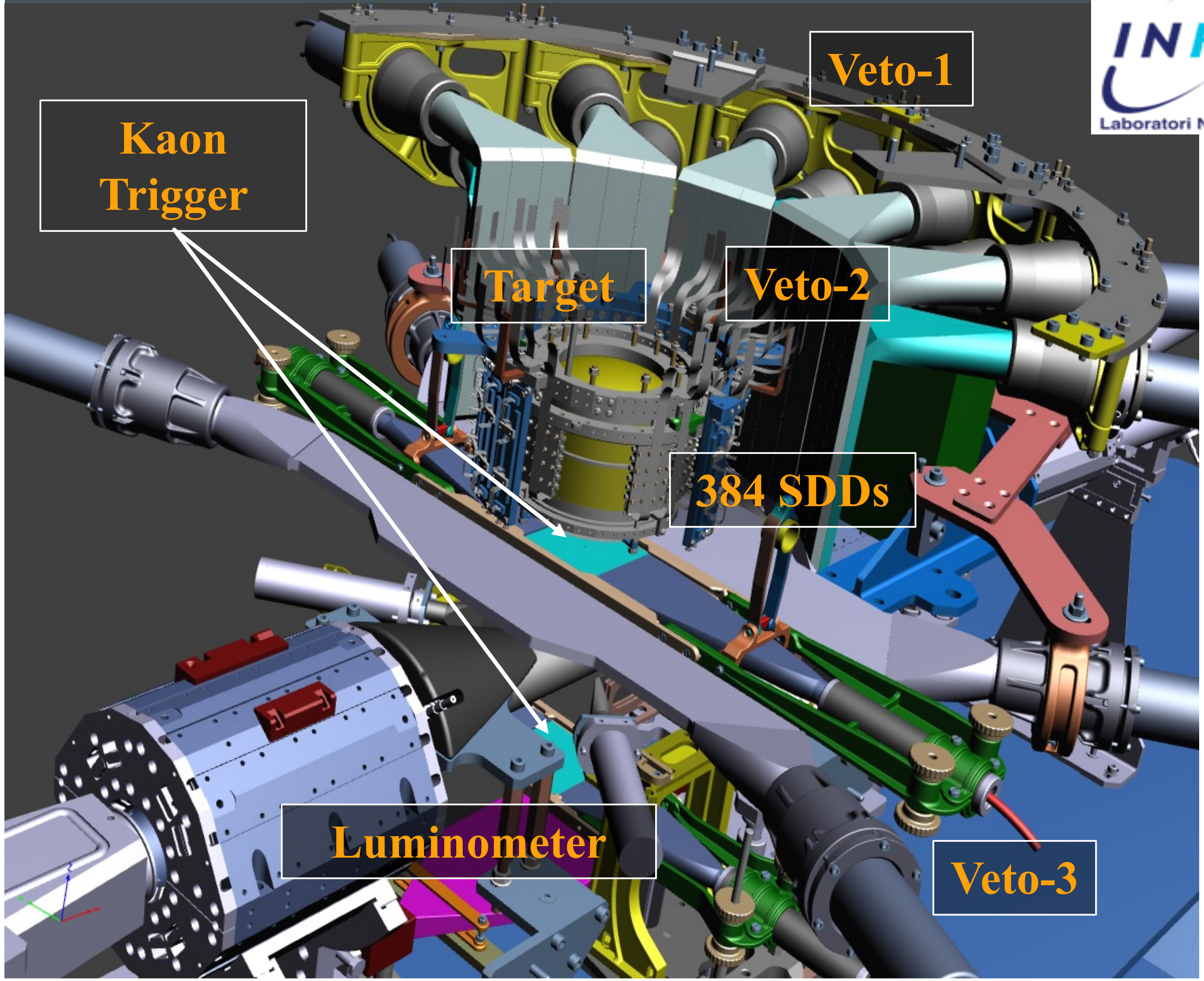


The DAΦNE collider of INFN-LNF

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



The SIDDHARTA-2 setup and DAΦNE collider



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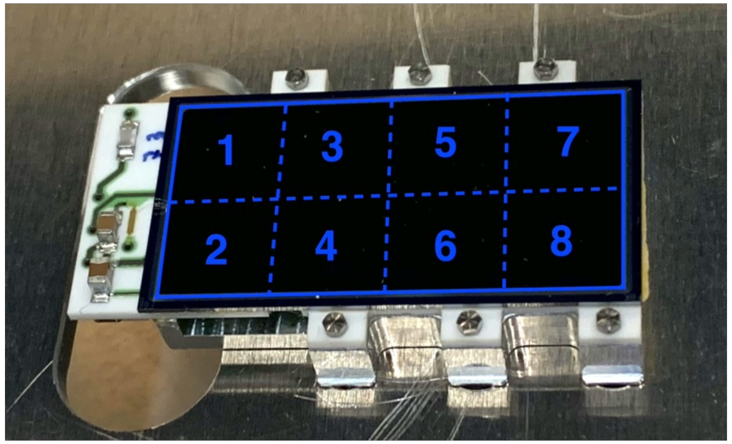
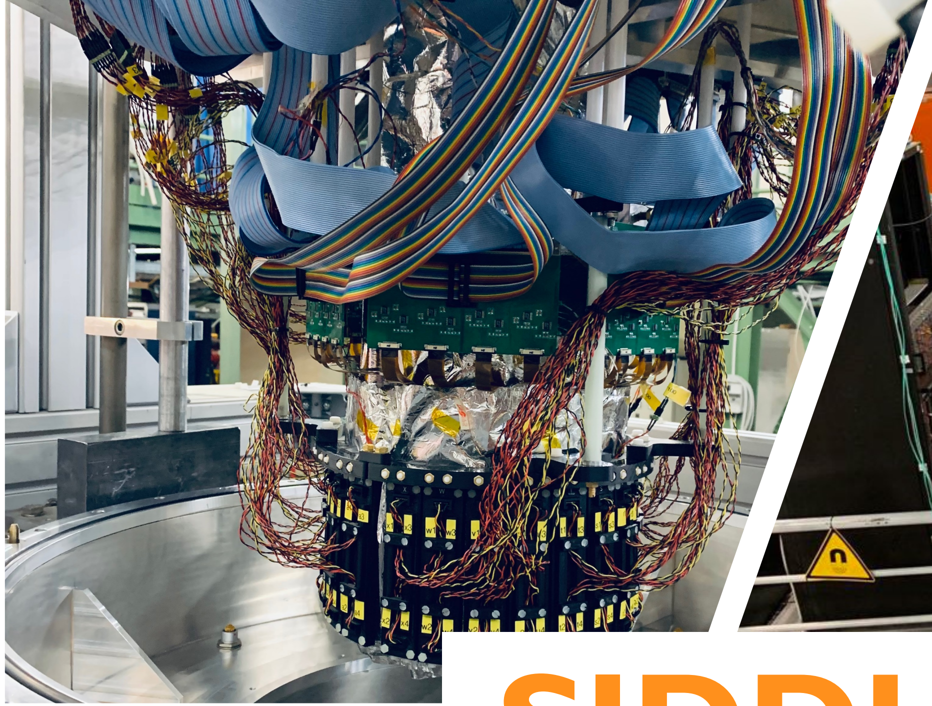
POLITECNICO MILANO 1863

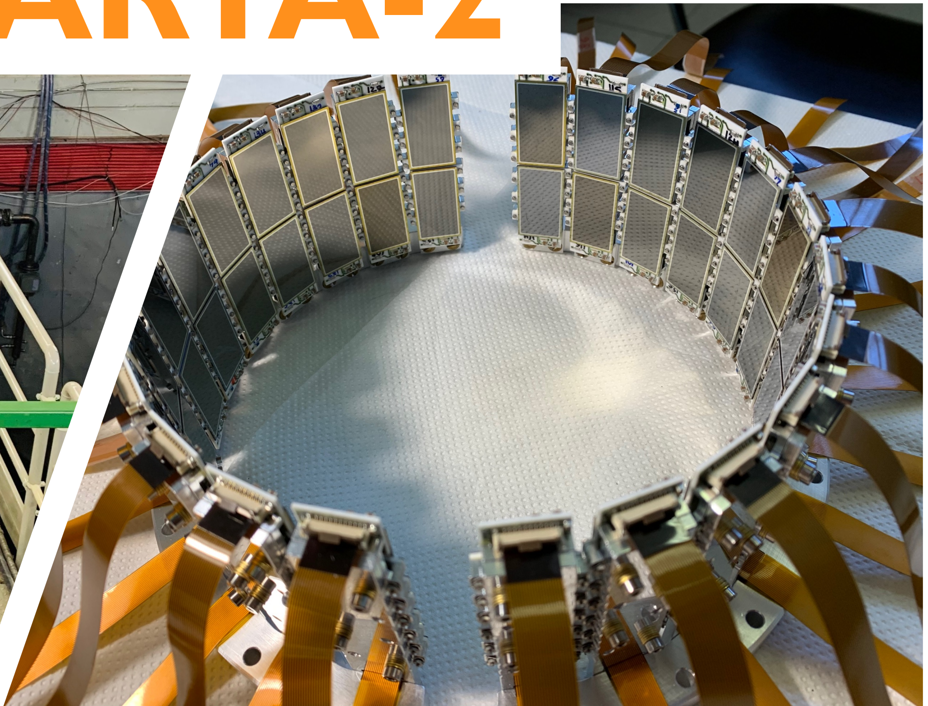
FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

48 Silicon Drift Detector arrays with 8 SDD units (0.64 cm^2)
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

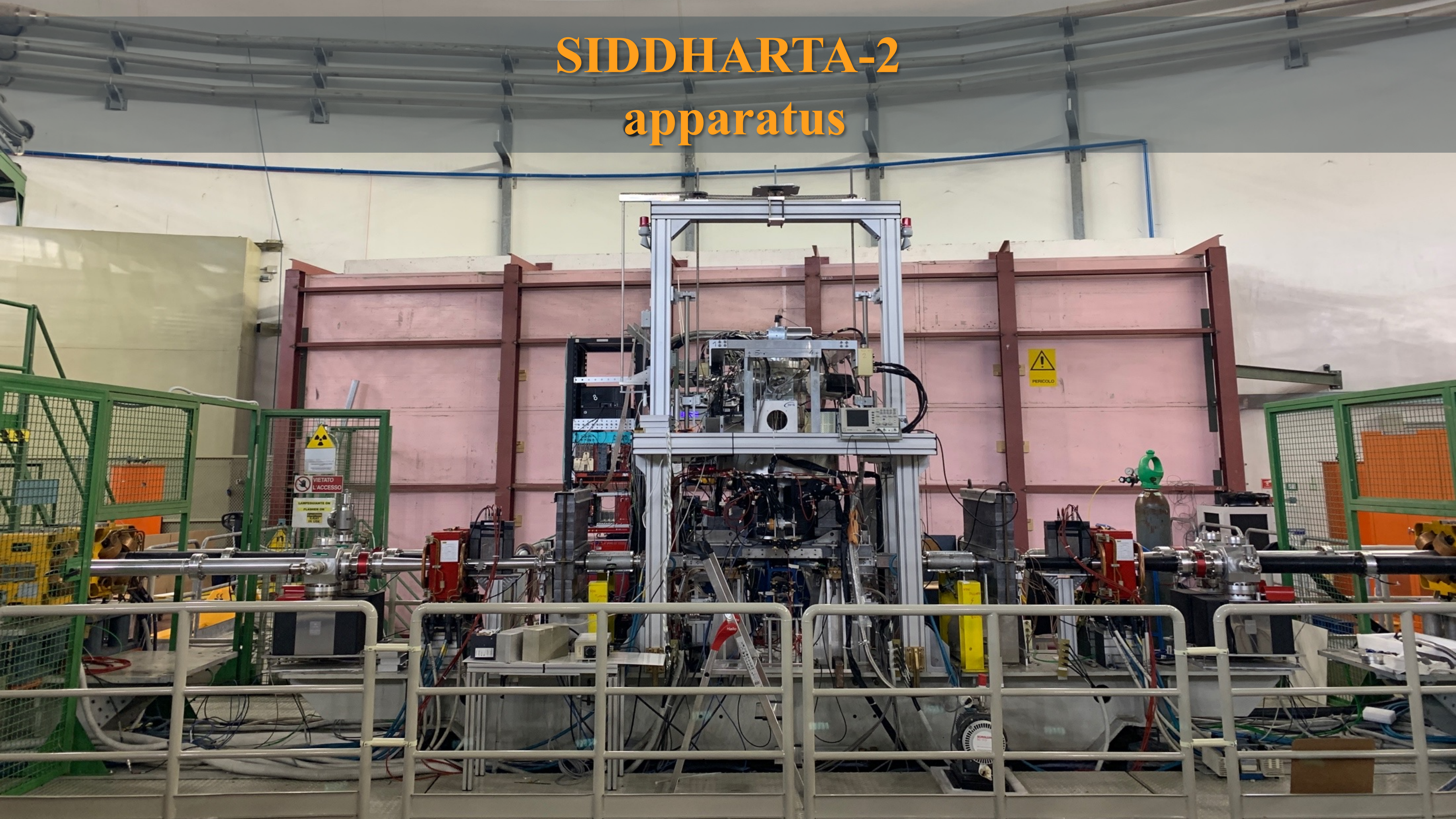




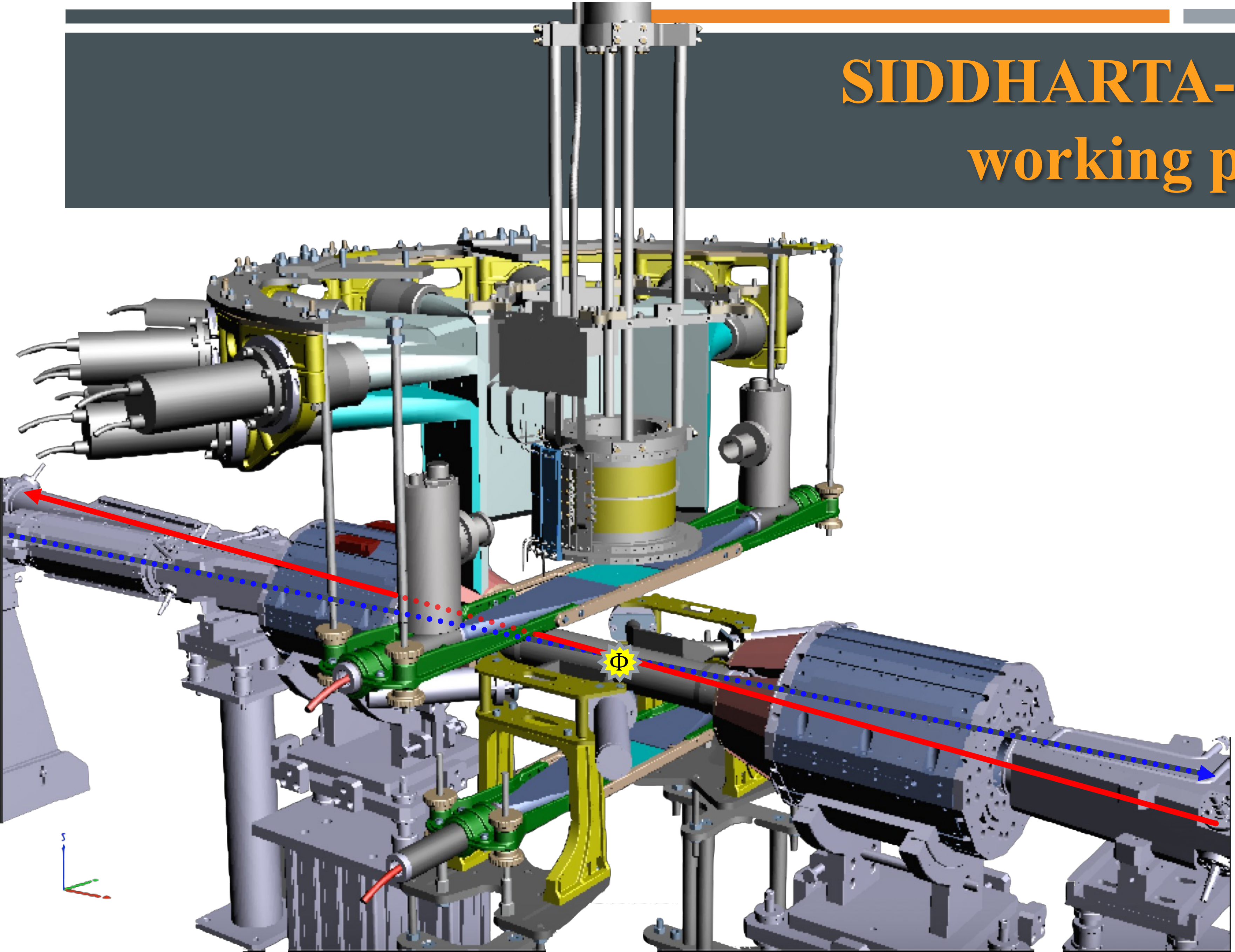
SIDDHARTA-2



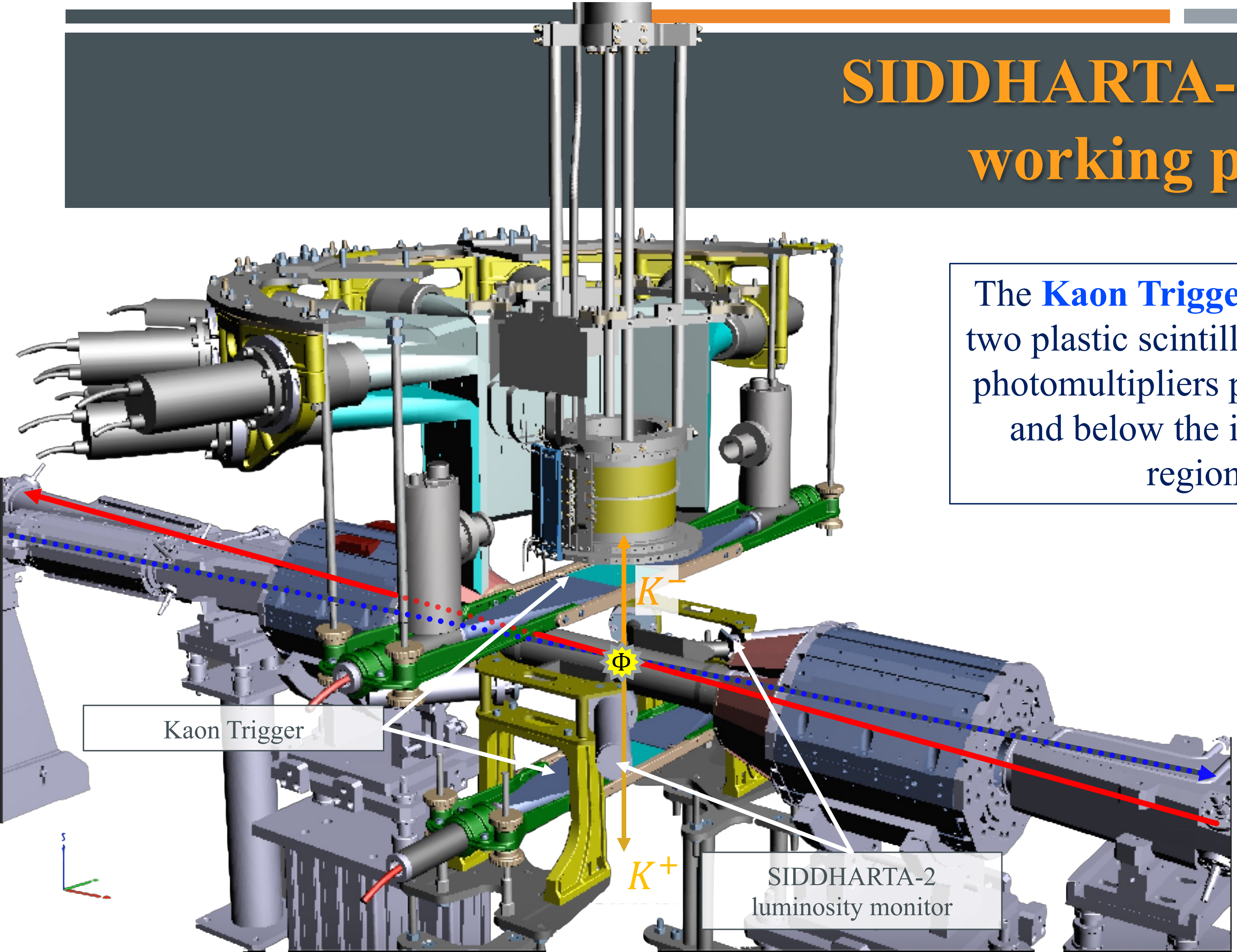
SIDDHARTA-2 apparatus



SIDDHARTA-2 apparatus: working principle

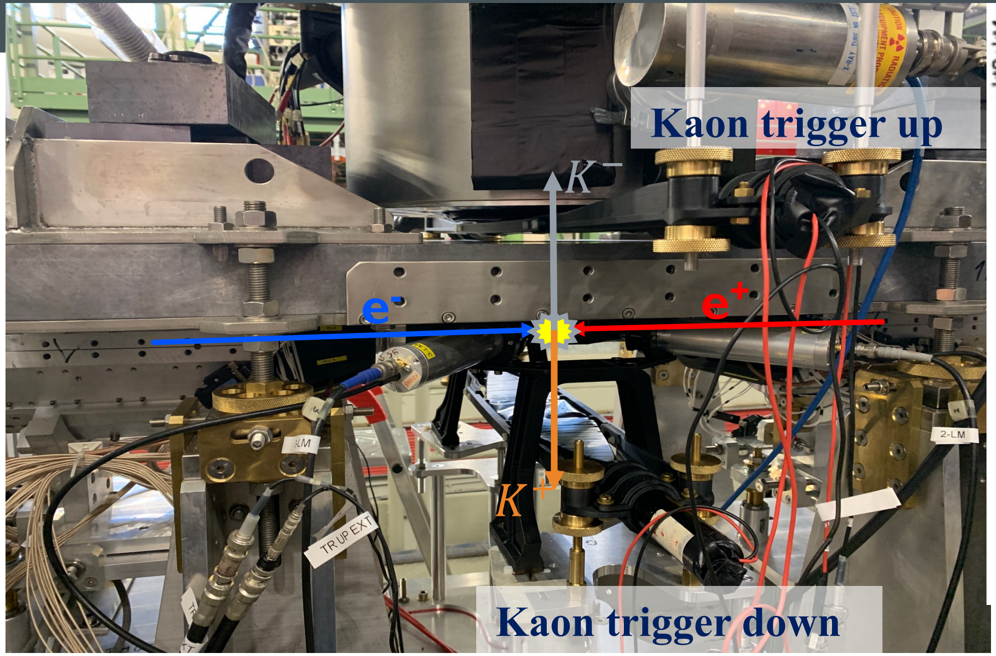


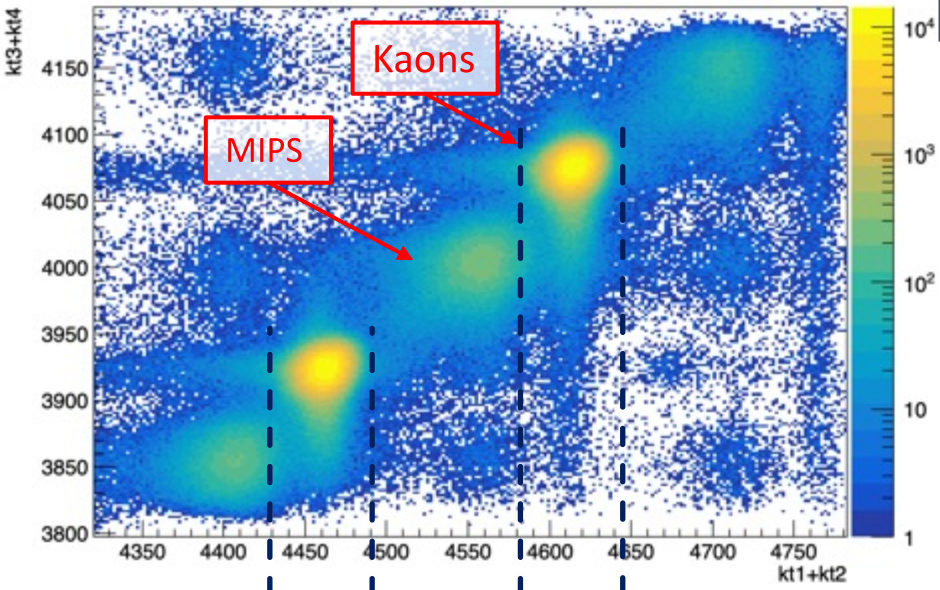
SIDDHARTA-2 apparatus: working principle

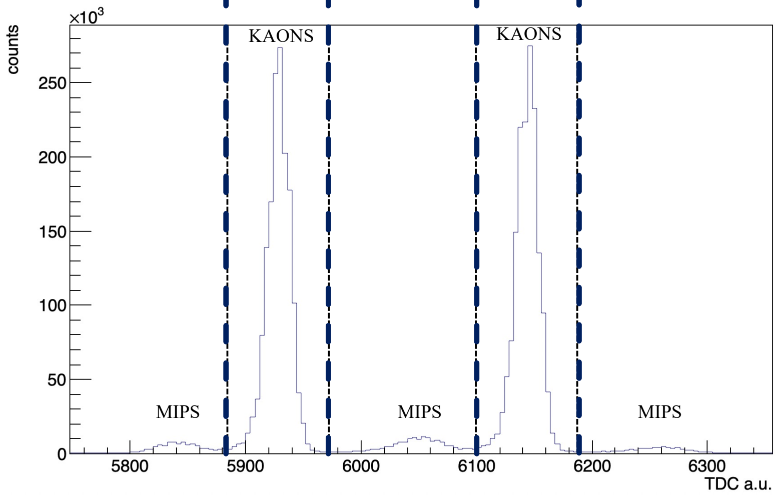


The **Kaon Trigger** consists of two plastic scintillators read by photomultipliers placed above and below the interaction region.

The Kaon Trigger – Time of Flight

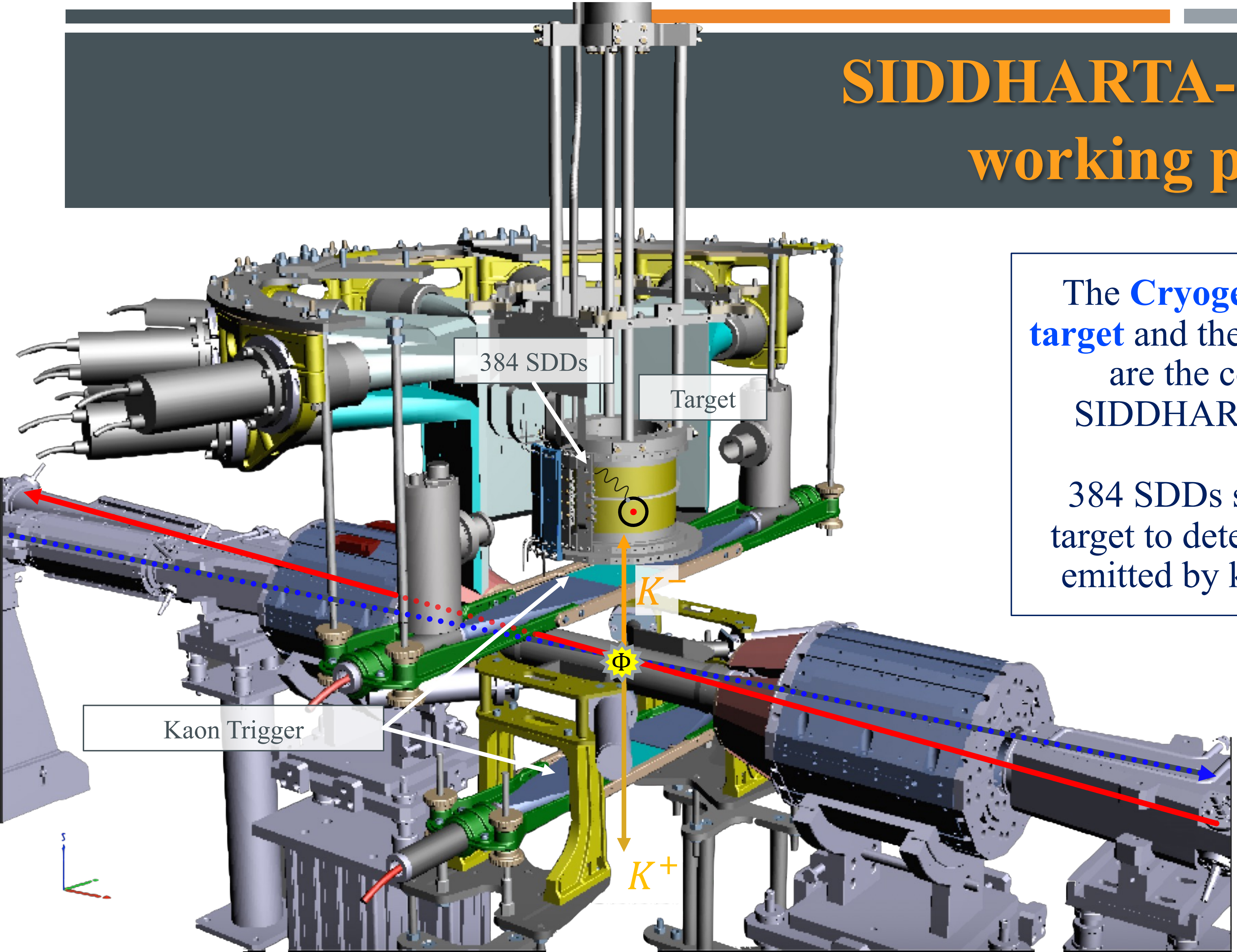






The ToF is different for Kaons, m(K)~ 500 MeV/c^2
and light particles
originating from beam-beam and beam-environment
interaction (MIPs).
Can efficiently discriminate by ToF Kaons and
MIPs!

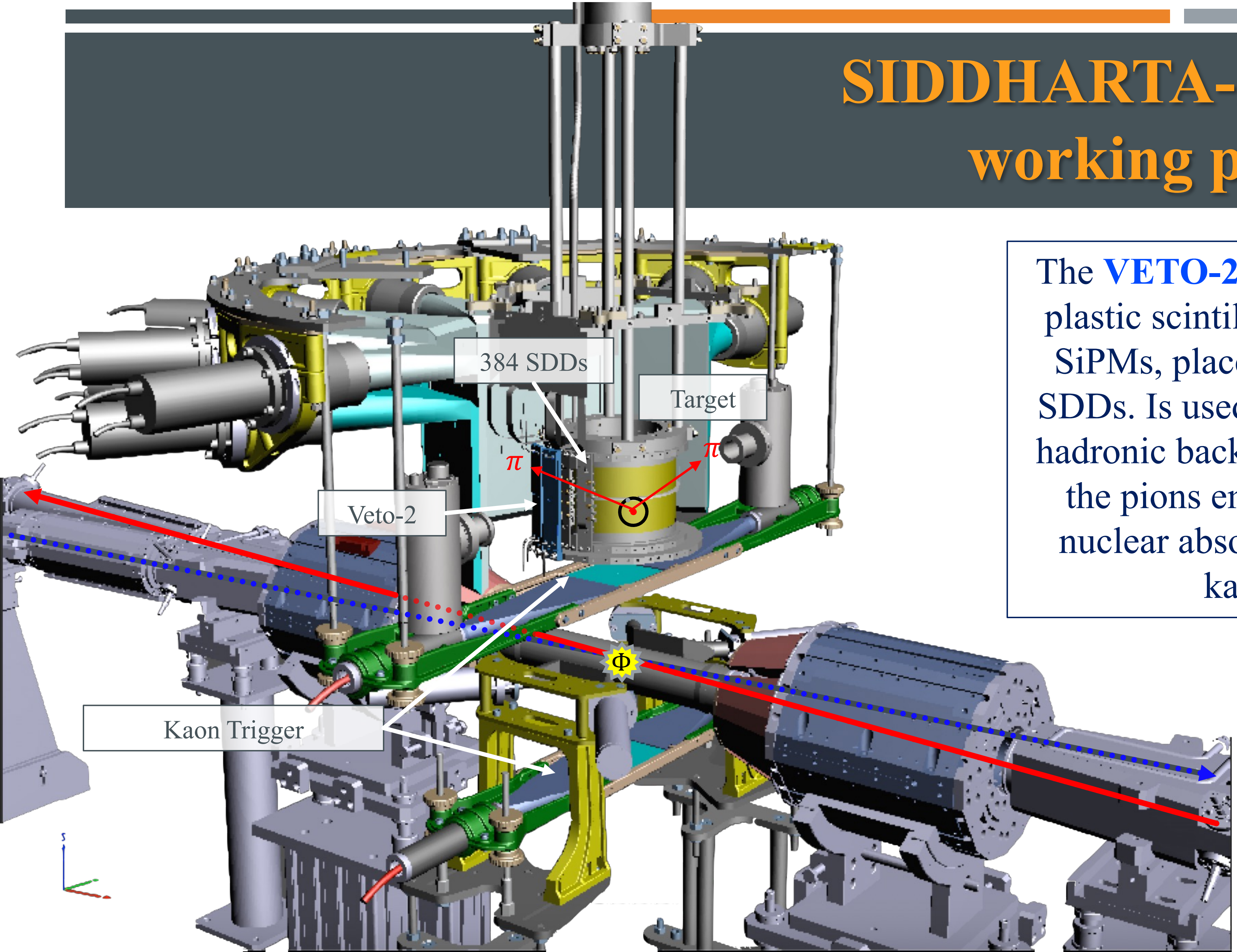
SIDDHARTA-2 apparatus: working principle



The **Cryogenic gaseous target** and the **SDDs system** are the core of the SIDDHARTA-2 setup.

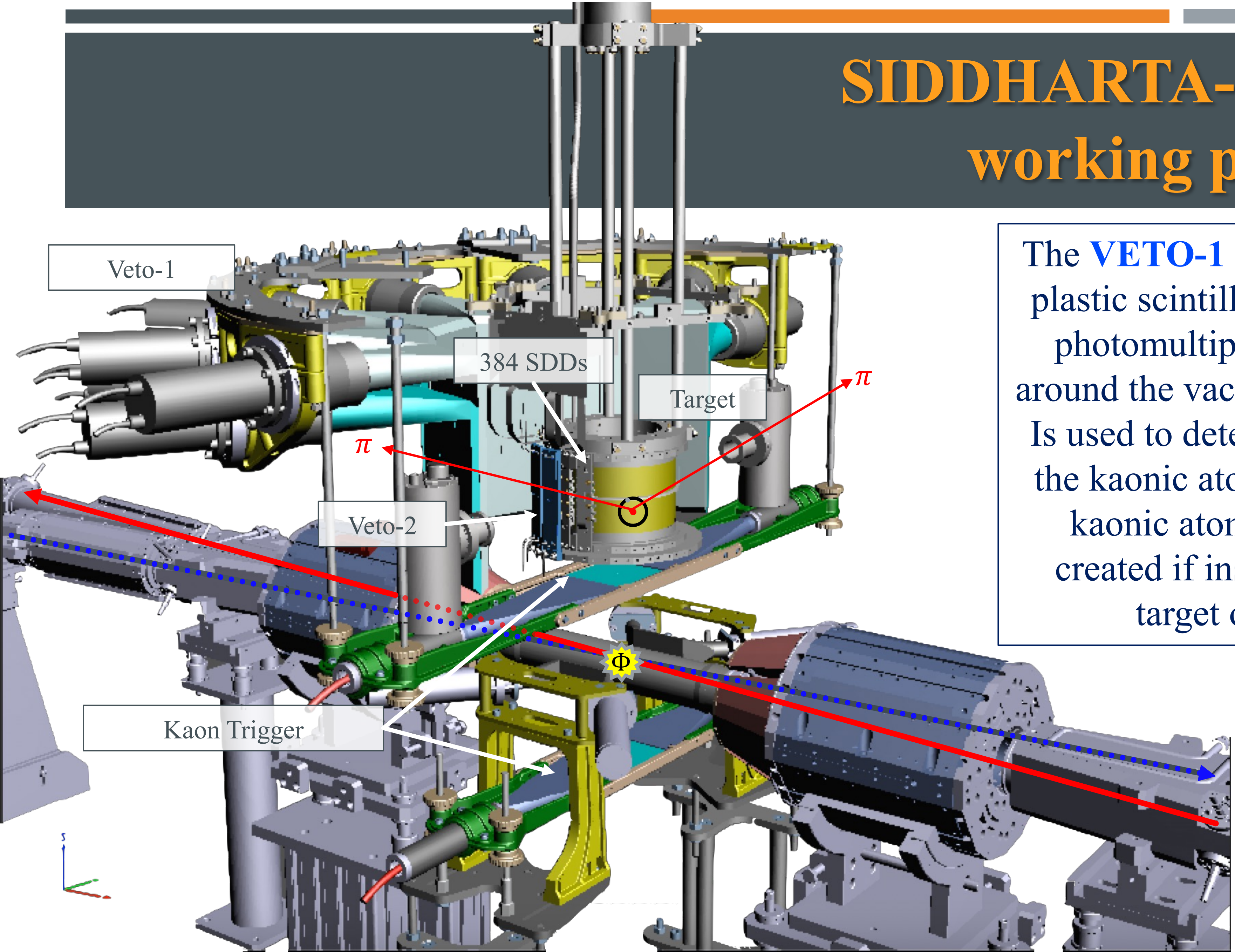
384 SDDs surround the target to detect the X-rays emitted by kaonic atoms

SIDDHARTA-2 apparatus: working principle



The **VETO-2** consists of 96 plastic scintillators read by SiPMs, placed behind the SDDs. Is used to reduce the hadronic background due to the pions emitted by the nuclear absorption of the kaon.

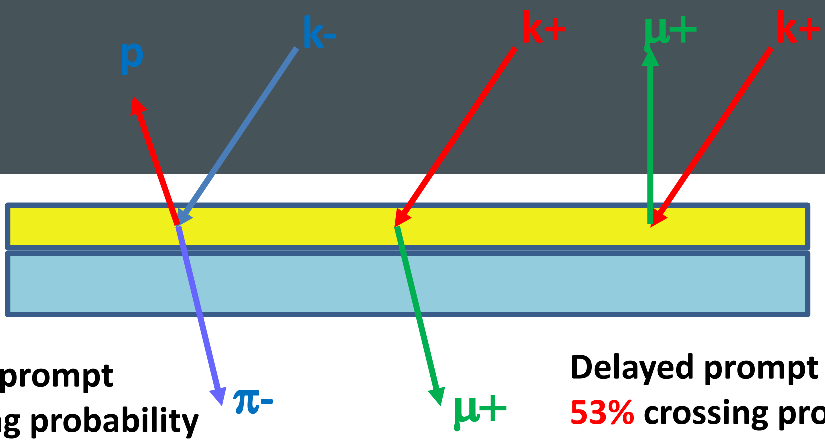
SIDDHARTA-2 apparatus: working principle



The **VETO-1** consists of 12 plastic scintillators read by photomultipliers placed around the vacuum chamber. Is used to determine where the kaonic atom where the kaonic atom has been created if inside the gas target or not.

The Kaon charge detector

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

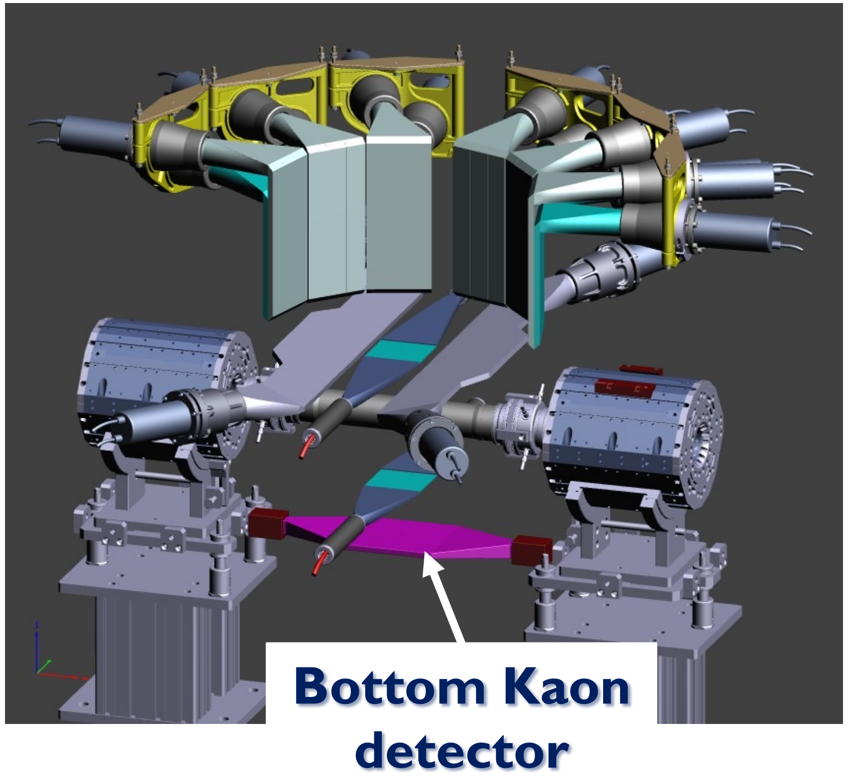


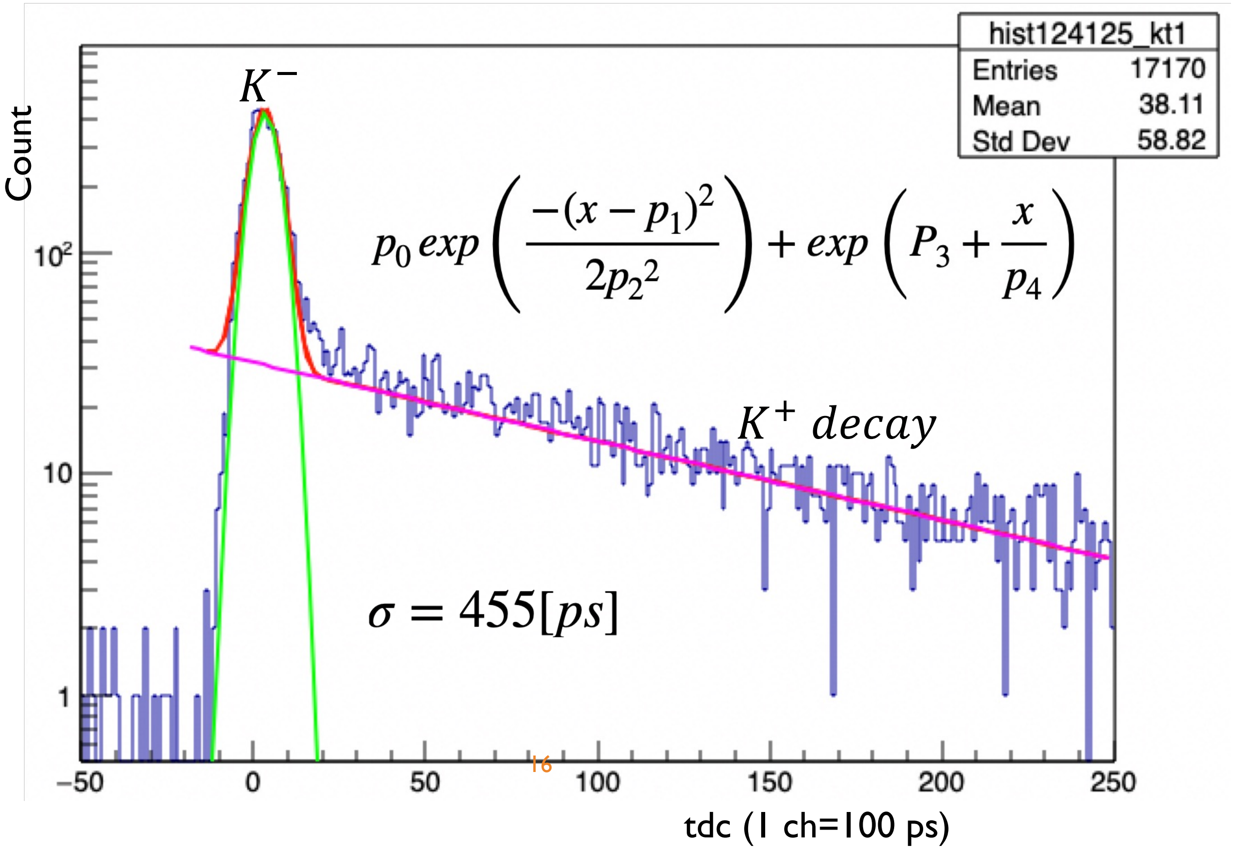
2 mm teflon or 5 mm thick scintillator

5-10 mm thick scintillator

Immediate prompt
83% crossing probability

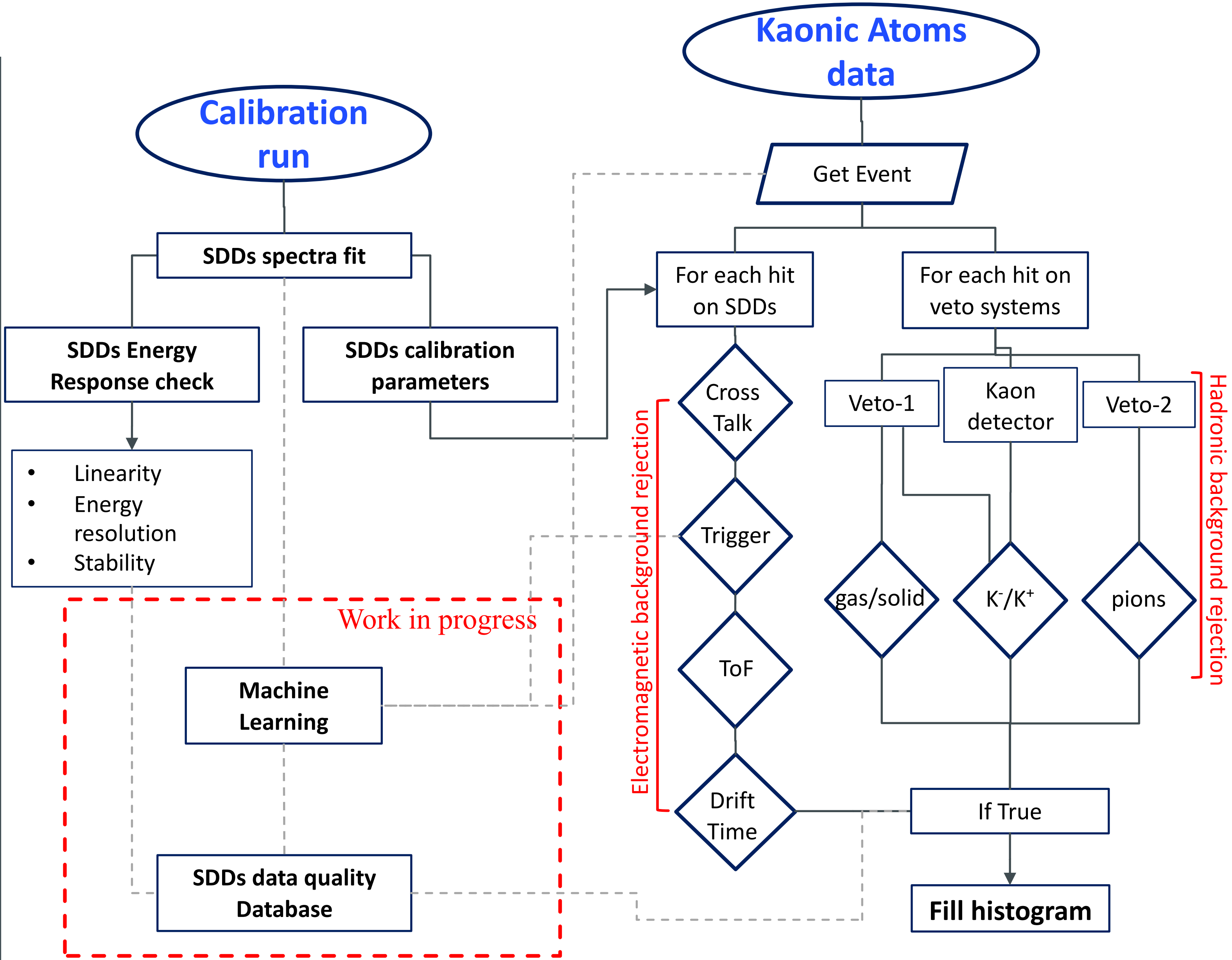
Delayed prompt
53% crossing probability



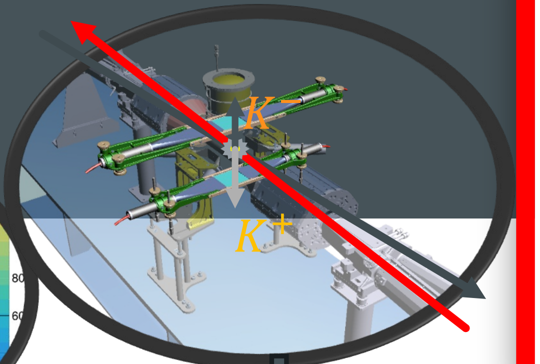


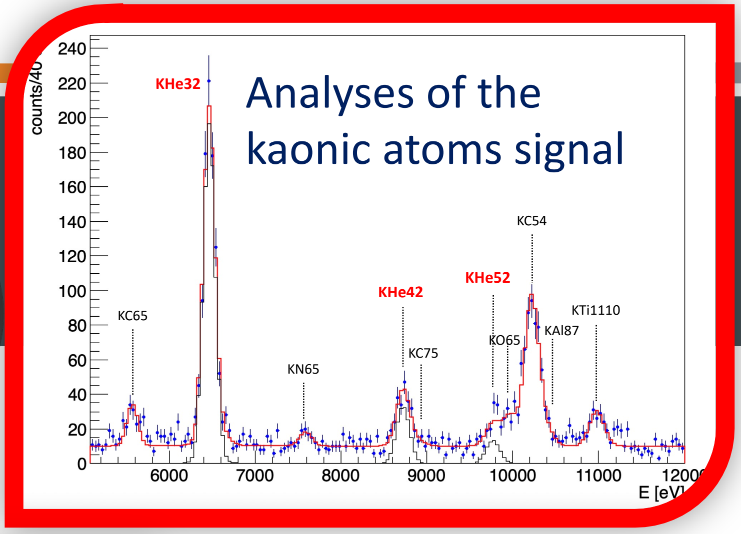
TOHOKU UNIVERSITY

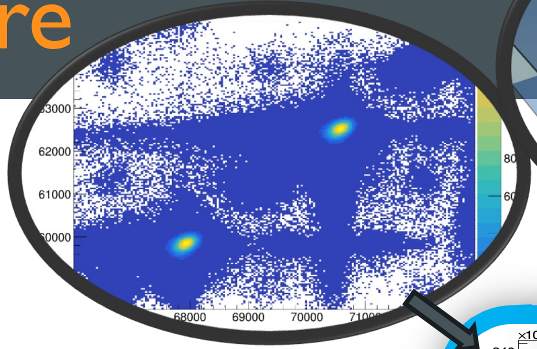
DATA ANALYSIS

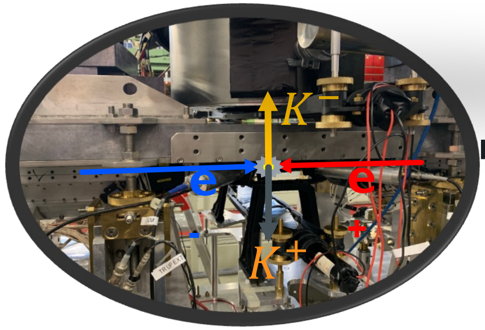


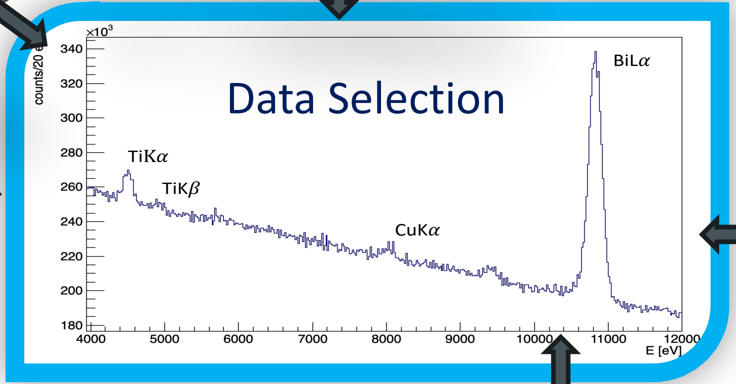
Data Analysis procedure

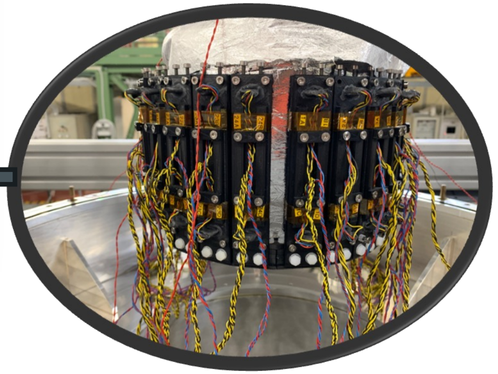


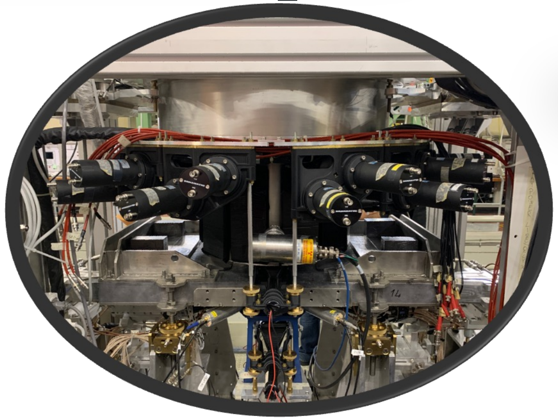


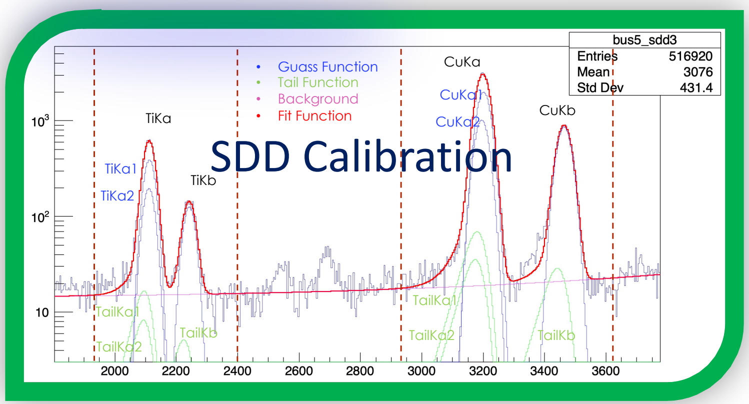










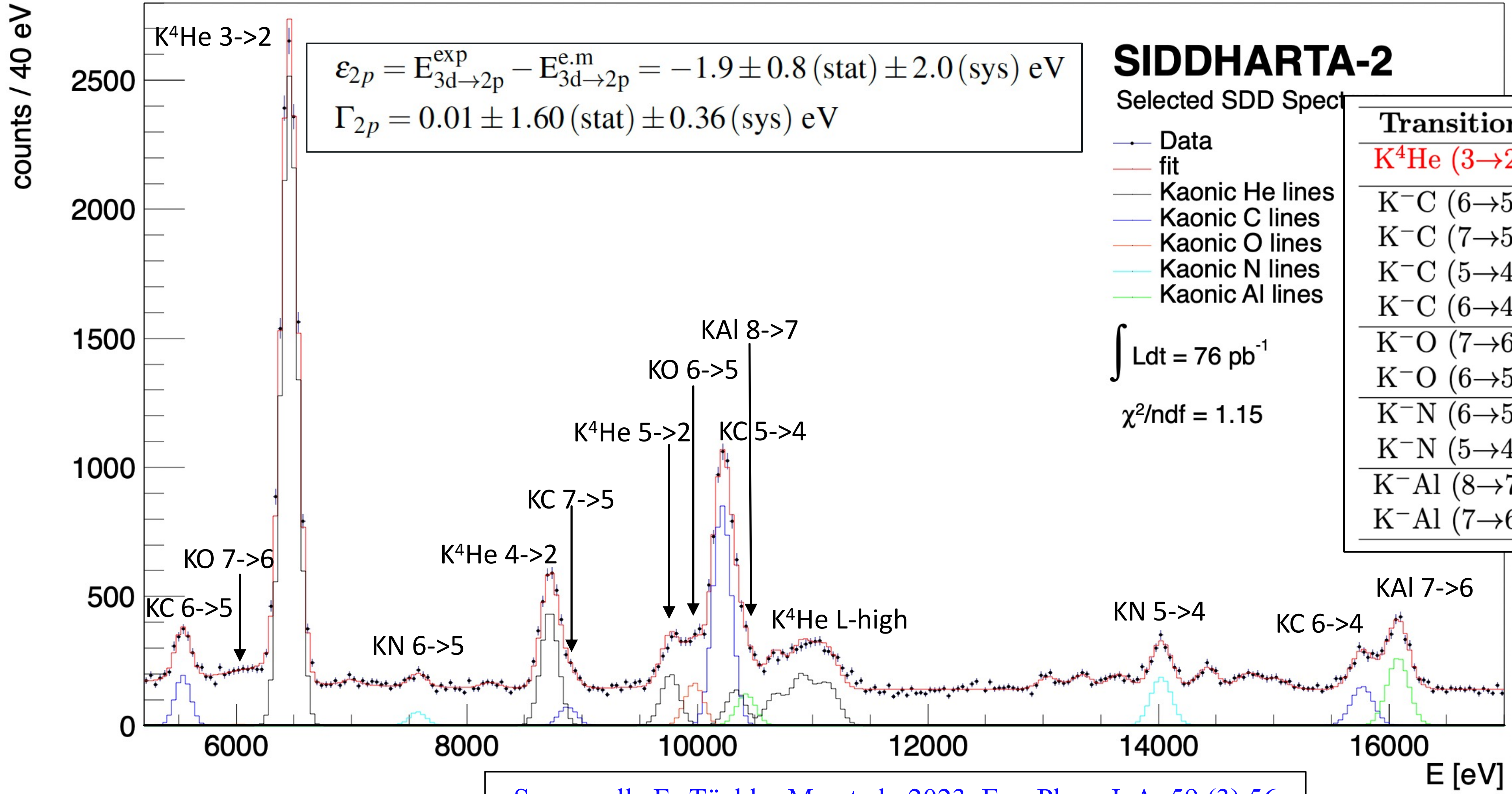



元素記号
2
He
元素名 ヘリウム Helium
113番元素ニホニウム発見のまち
元素記号
10
Ne
元素名 ネオン Neon
ū
s
Deuterium
2.01410
NA: 0.0115%

KAONIC HELIUM

The Kaonic ^{4}He measurement (2022)

- Kaonic He measurement with the full SIDDHARTA-2 setup
- Measurement of kaonic helium-4 Lα transition: 2p level energy shift and width
- First Measurement of high-n transition in kaonic carbon – nitrogen – oxygen and aluminium

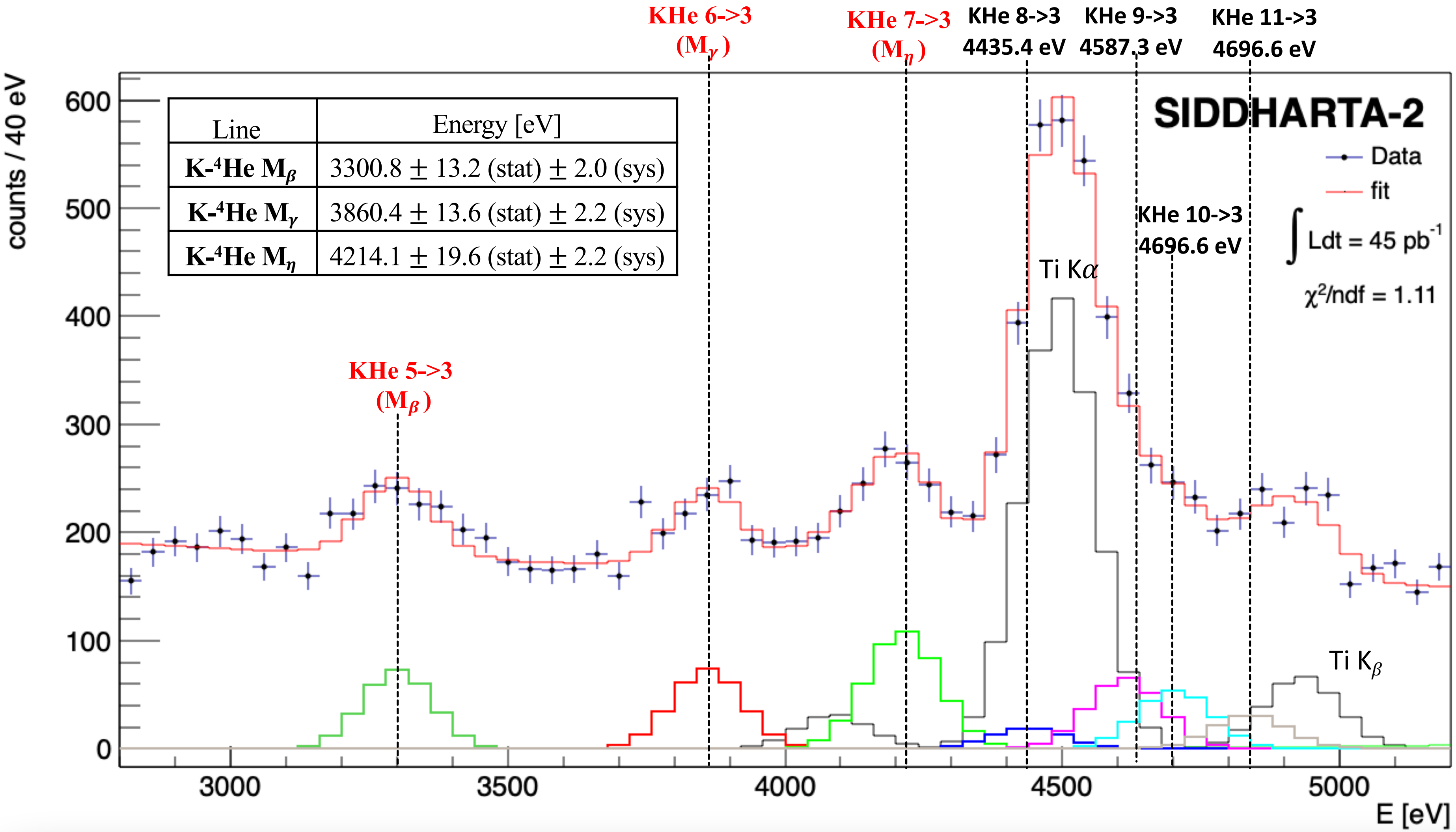


Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)

Sgaramella F., Tüchler M., et al., 2023, Eur. Phys. J. A, 59 (3) 56

The Kaonic ^{4}He – M-series transitions

First observation and measurement of kaonic helium M-series transition, with implication on kaonic helium cascade models



Line	Energy [eV]
K-^{4}He M_β	3300.8 $\pm$ 13.2 (stat) $\pm$ 2.0 (sys)
K-^{4}He M_γ	3860.4 $\pm$ 13.6 (stat) $\pm$ 2.2 (sys)
K-^{4}He M_η	4214.1 $\pm$ 19.6 (stat) $\pm$ 2.2 (sys)

The Kaonic ^{4}He yield

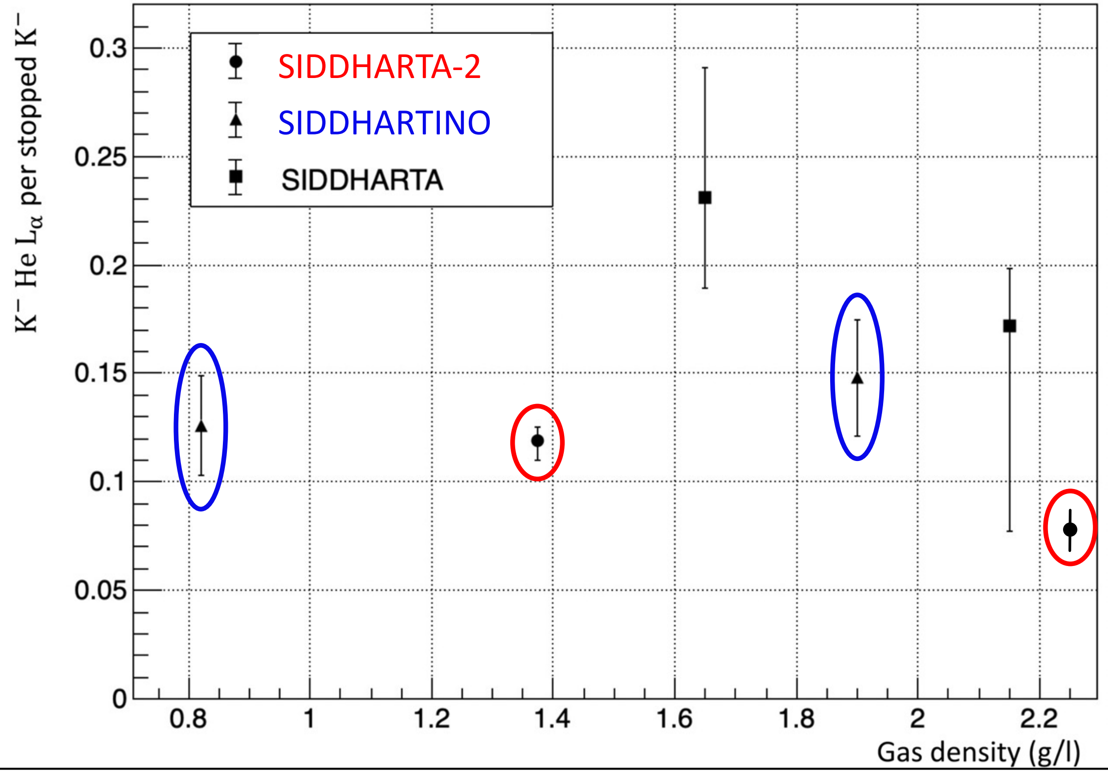
New experimental data for cascade models calculations
The X-ray yield is the key observable to understand the de-excitation mechanism in kaonic atoms and develop more accurate models.

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

Density	1.375 g/l
L_α *yield*	$0.119 \pm 0.002\,(\text{stat})^{+0.006\,(\text{sys})}_{-0.009\,(\text{sys})}$
M_β *yield*	$0.026 \pm 0.003\,(\text{stat})^{+0.010\,(\text{sys})}_{-0.001\,(\text{sys})}$
L_β / L_α	$0.172 \pm 0.008\,(\text{stat})$
L_γ / L_α	$0.012 \pm 0.001\,(\text{stat})$
L_β / M_β	$0.91 \pm 0.14\,(\text{stat})$
M_γ / M_β	$0.48 \pm 0.11\,(\text{stat})$
M_δ / M_β	$0.43 \pm 0.12\,(\text{stat})$

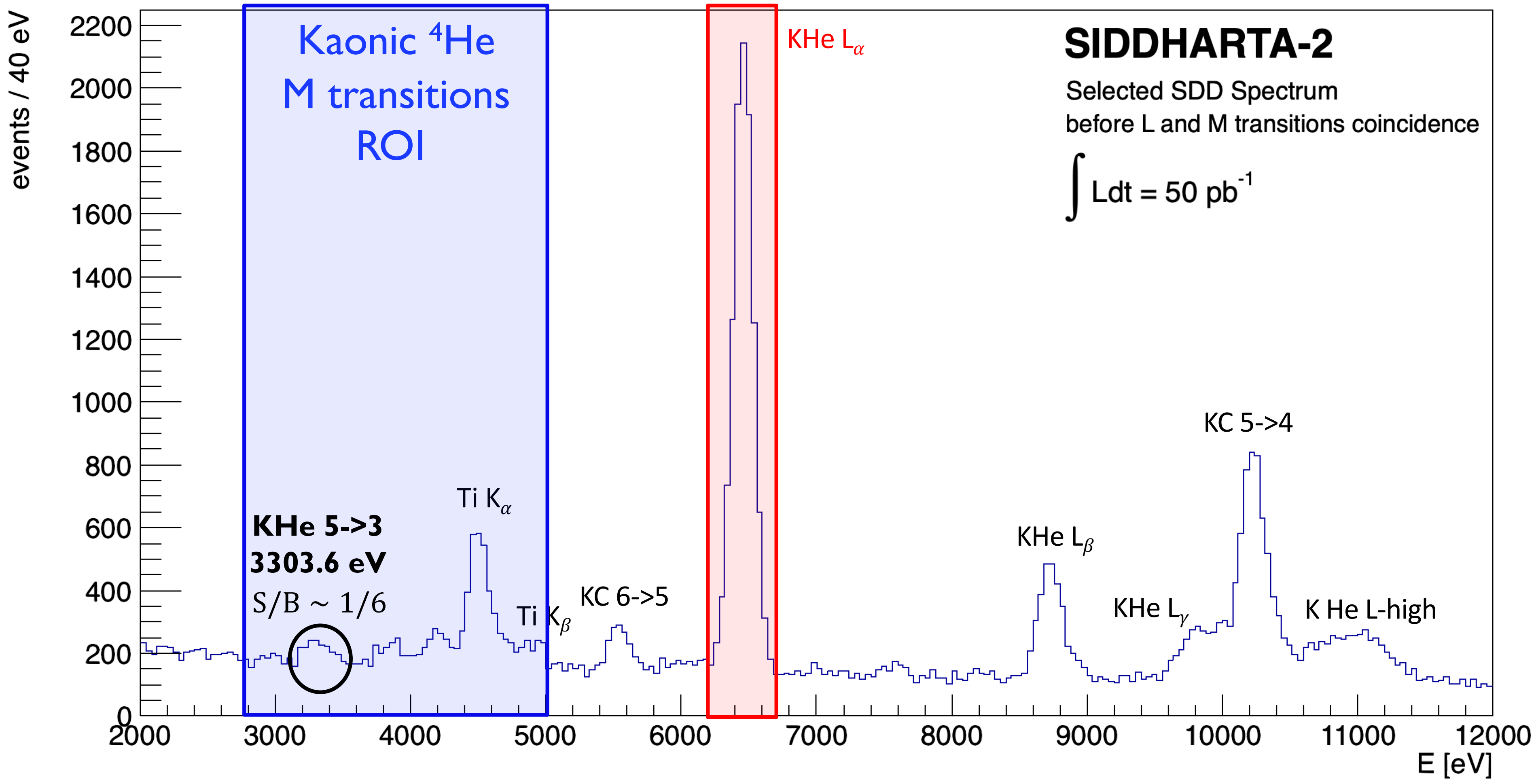
Sgaramella F., et al, submitted to J. Phys. G Nucl. Part. Phys

Study of yield density dependence
for the K-^{4}He Lα transition

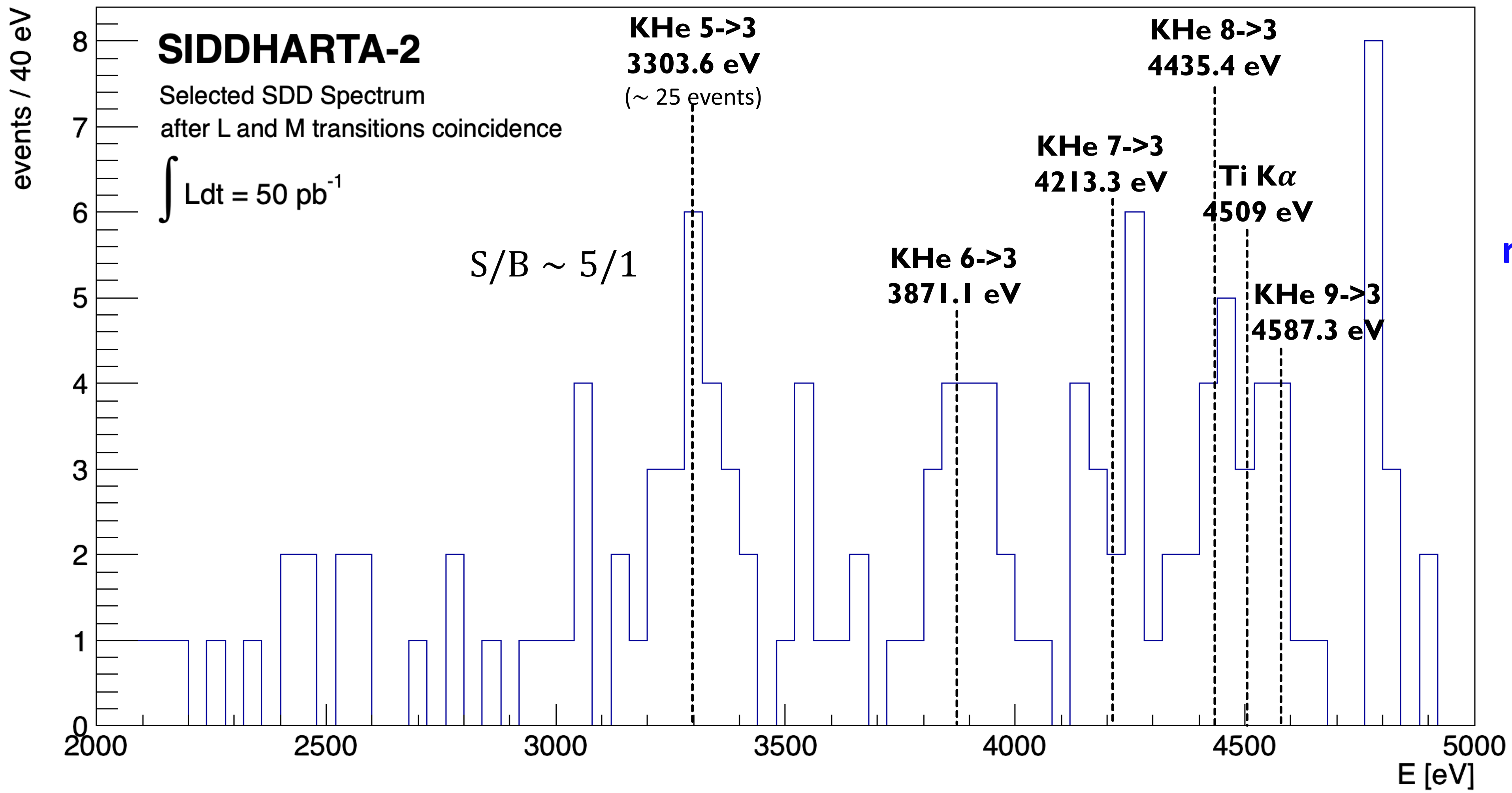


Sirghi D.L., Shi H., Guaraldo C., Sgaramella F., et al., 2023, Nucl. Phys. A,1029 122567

Kaonic ^{4}He – coincidence between L -type and M-type transitions

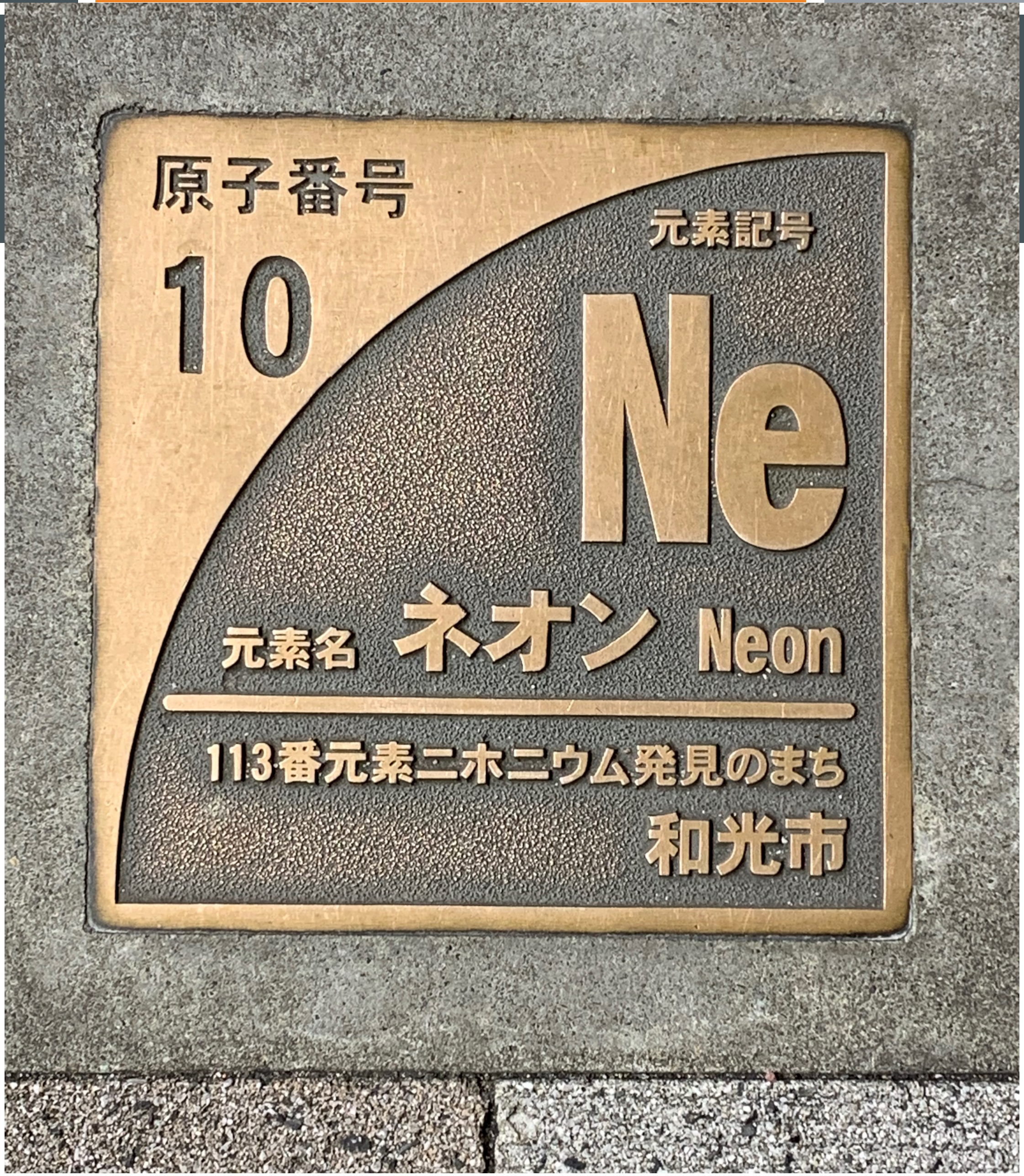


Kaonic ^{4}He – coincidence between L -type and M-type transitions



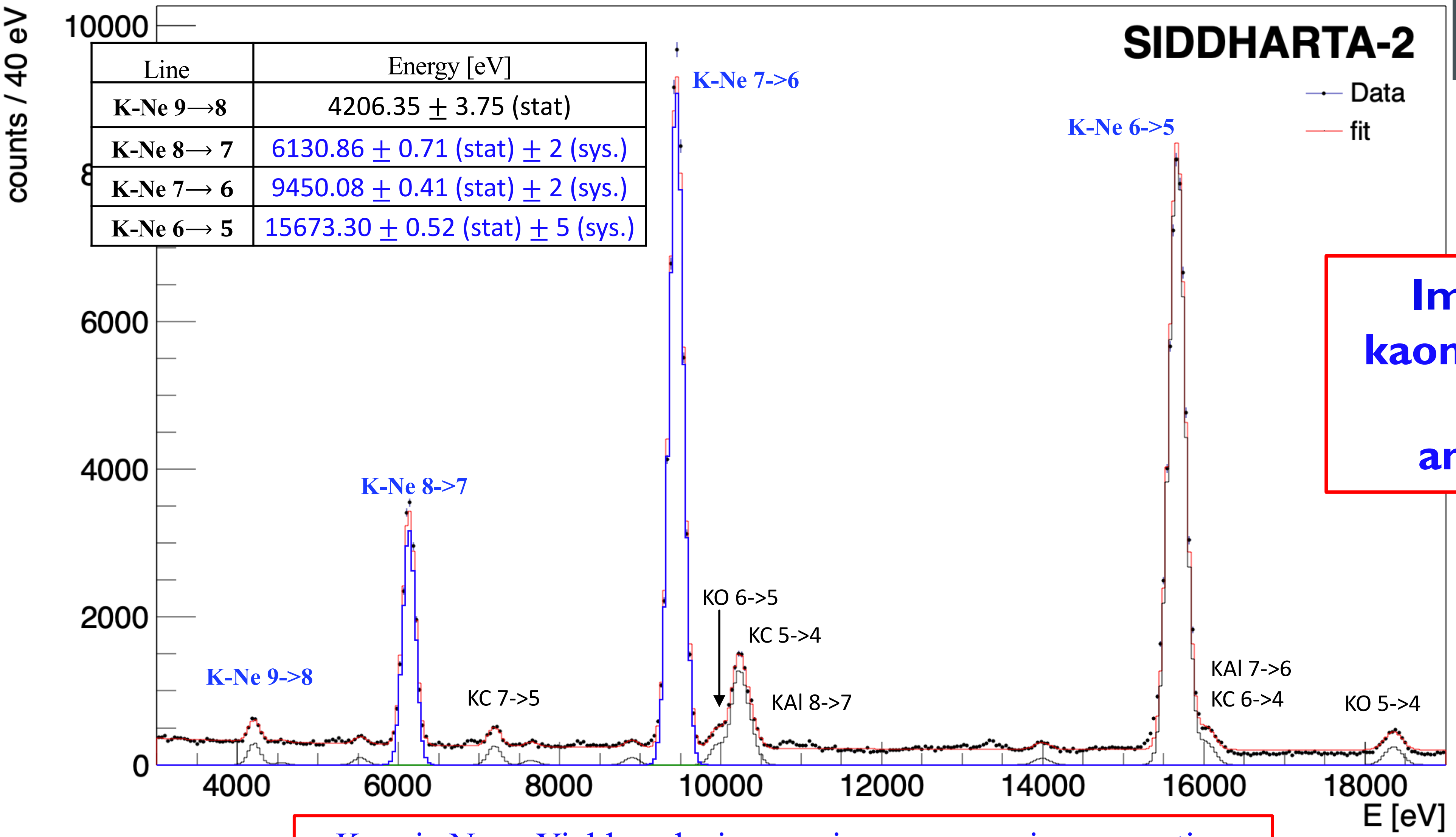
Feasibility test for future kaonic atom measurements (kaonic ^{4}He fundamental level) and kaonic deuterium at JPARC

KAONIC NEON



The Kaonic Neon measurement (2023)

First measurement of kaonic neon X-ray transitions (record of precision < 1 eV)



Line	Energy [eV]
K-Ne 9⟶8	4206.35 ± 3.75 (stat)
K-Ne 8⟶ 7	6130.86 ± 0.71 (stat) ± 2 (sys.)
K-Ne 7⟶ 6	9450.08 ± 0.41 (stat) ± 2 (sys.)
K-Ne 6⟶ 5	15673.30 ± 0.52 (stat) ± 5 (sys.)

Implications on kaon - multinucleon interaction and kaon mass

Kaonic Neon Yield analysis on going ⟶ paper in preparation

The charged Kaon mass puzzle

Kaon mass (K-Ne 8 ⟶ 7and K-Ne 7 ⟶ 6) = 493.694 ± 0.015 (stat) MeV
(syst. error ~ 50 keV to be carefully check)

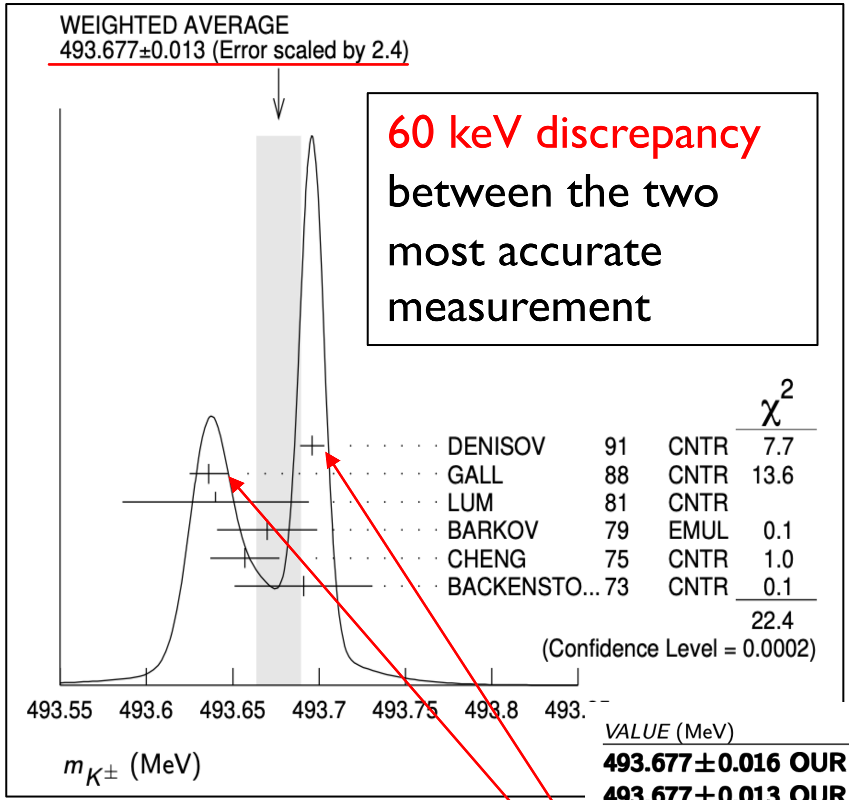
The kaonic Neon measurement to determine the K^- (K^+) mass

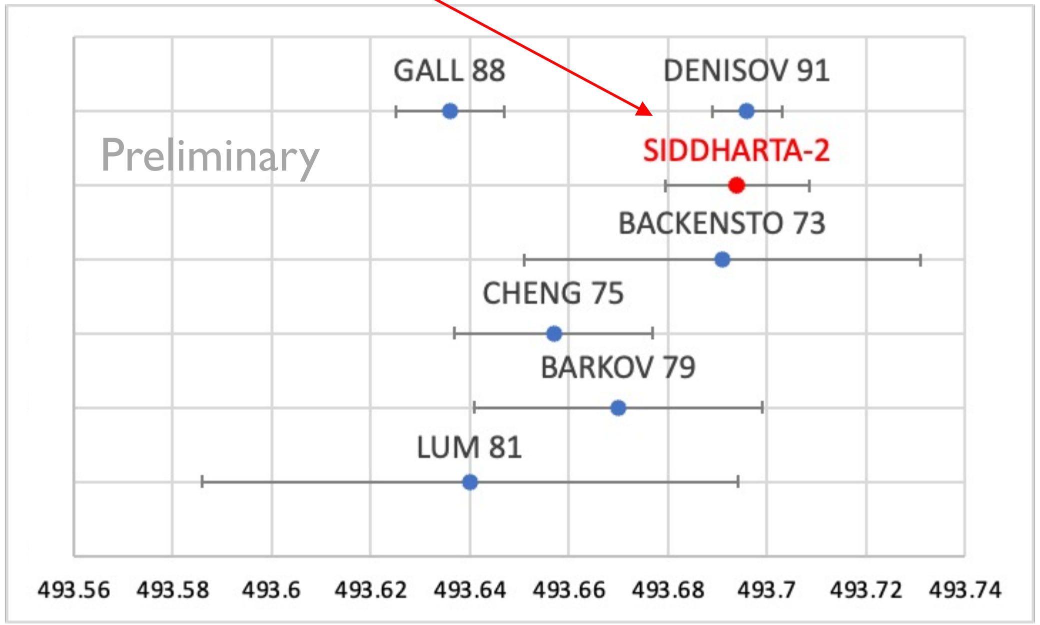
↓

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

↓

It could solve the kaon mass discrepancy issue





Kaon mass [MeV]

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

Particle Data Group, 2020, 083C01 (2020)

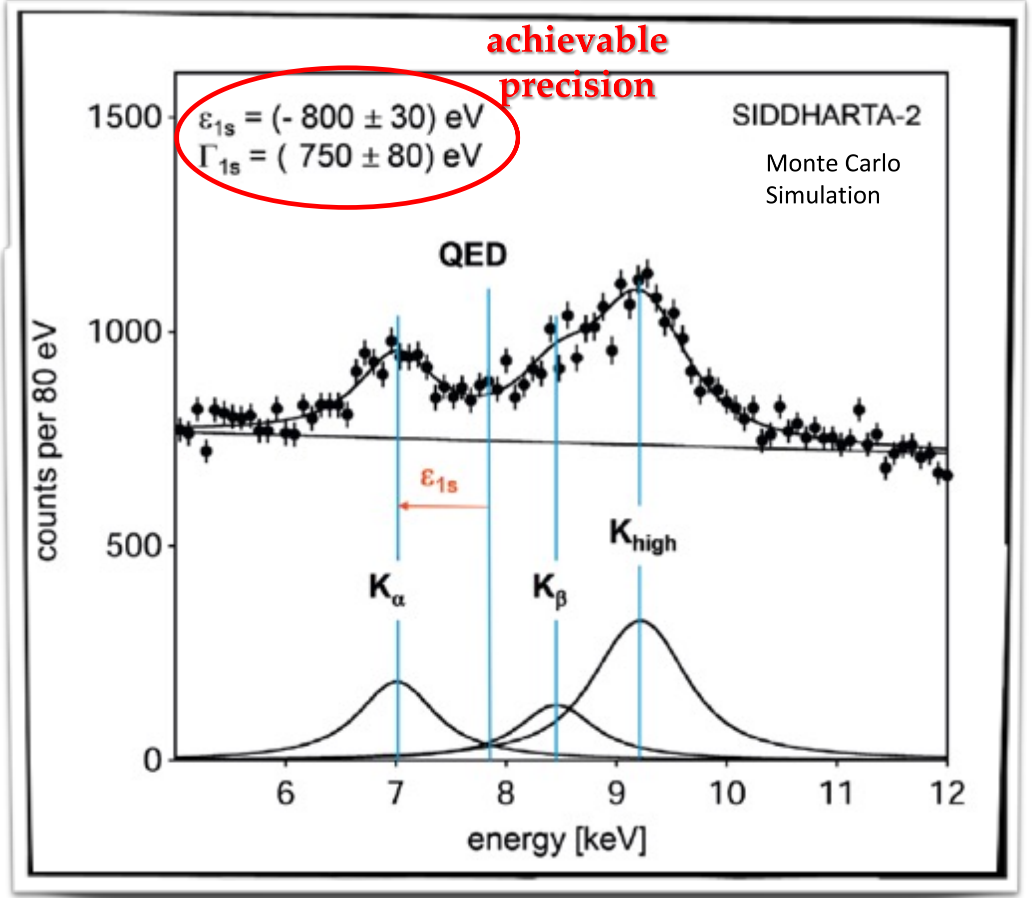
The kaonic deuterium measurement

Kaonic deuterium run ongoing

2023/24

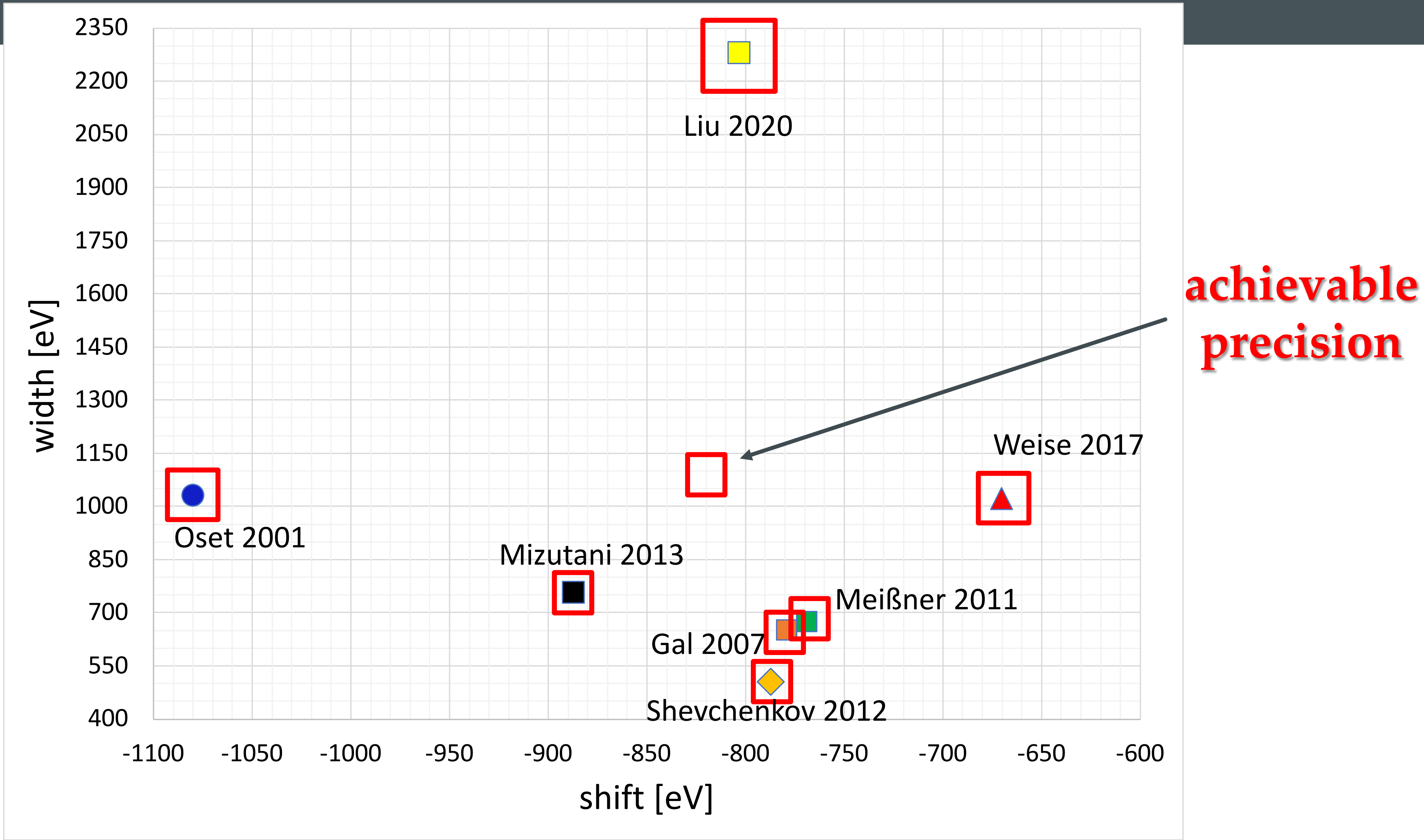
Monte Carlo for an integrated luminosity of 800 pb^{-1}

to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K-p) !



Significant impact in the theory of strong interaction with strangeness

Kaonic deuterium shift and width (theoretical predictions)



The kaonic deuterium measurement – Timeline

- First run with SIDDHARTA-2 optimized setup for 200 pb^{-1} integrated luminosity: May – July 2023 - completed
- Second run Autumn – Winter 2023 goal: estimated 200-300 pb^{-1} ongoing
- Third run 2024 – goal: 300-400 pb^{-1}
- Calibration runs: Kaonic He; Kaonic Ne; …. 50-100 pb

Start kaonic deuterium Run1

HPGe and CdZnTe test run

2023, May

End of Run1

2023, July

Integrated luminosity $\sim$200 pb^{-1} (with injections)

Summer stop

2023, July – September

Setup maintenance and upgrade

Start kaonic deuterium Run2

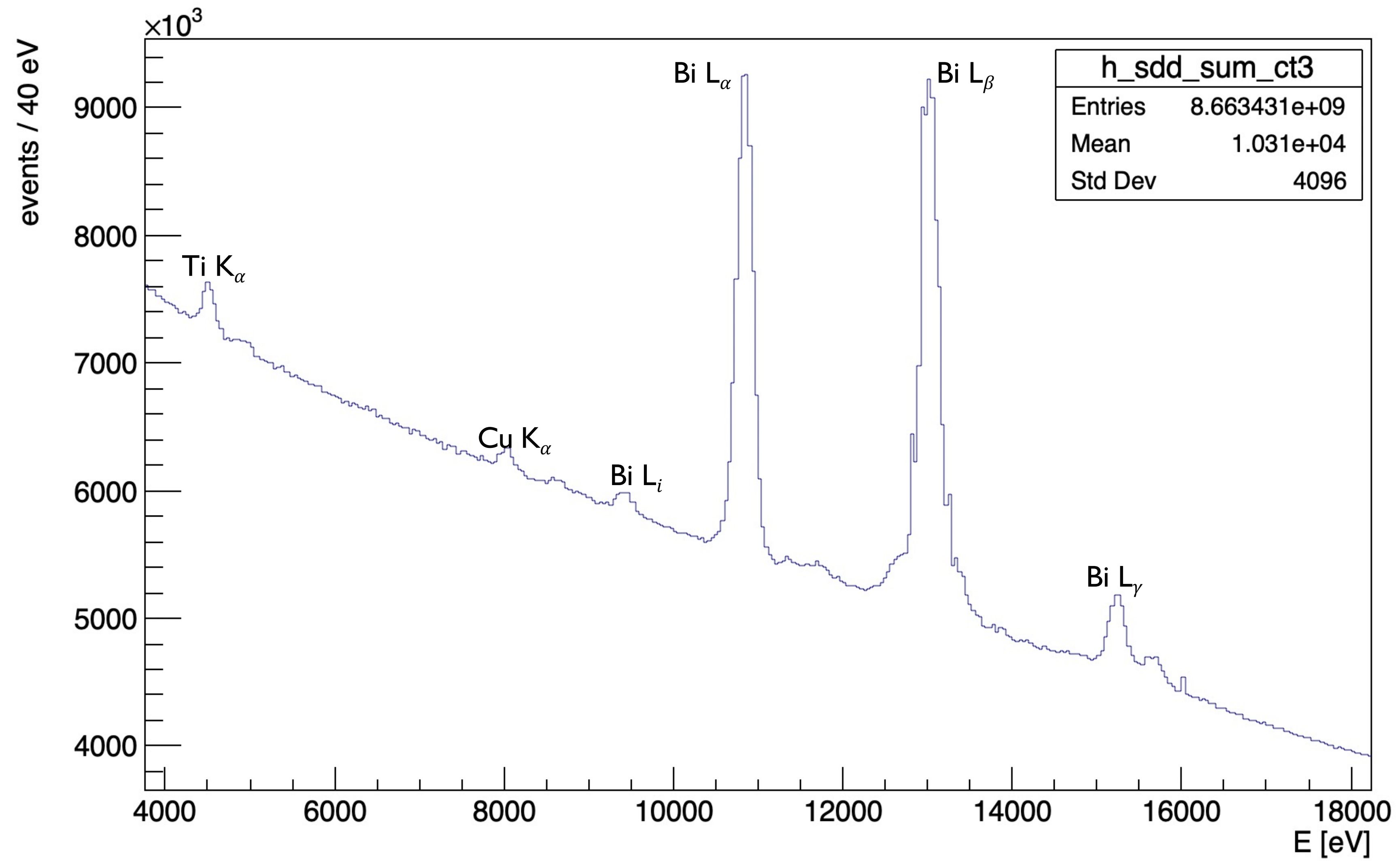
2023, October

HPGe and CdZnTe runs

Kaonic deuterium Run 2 on going

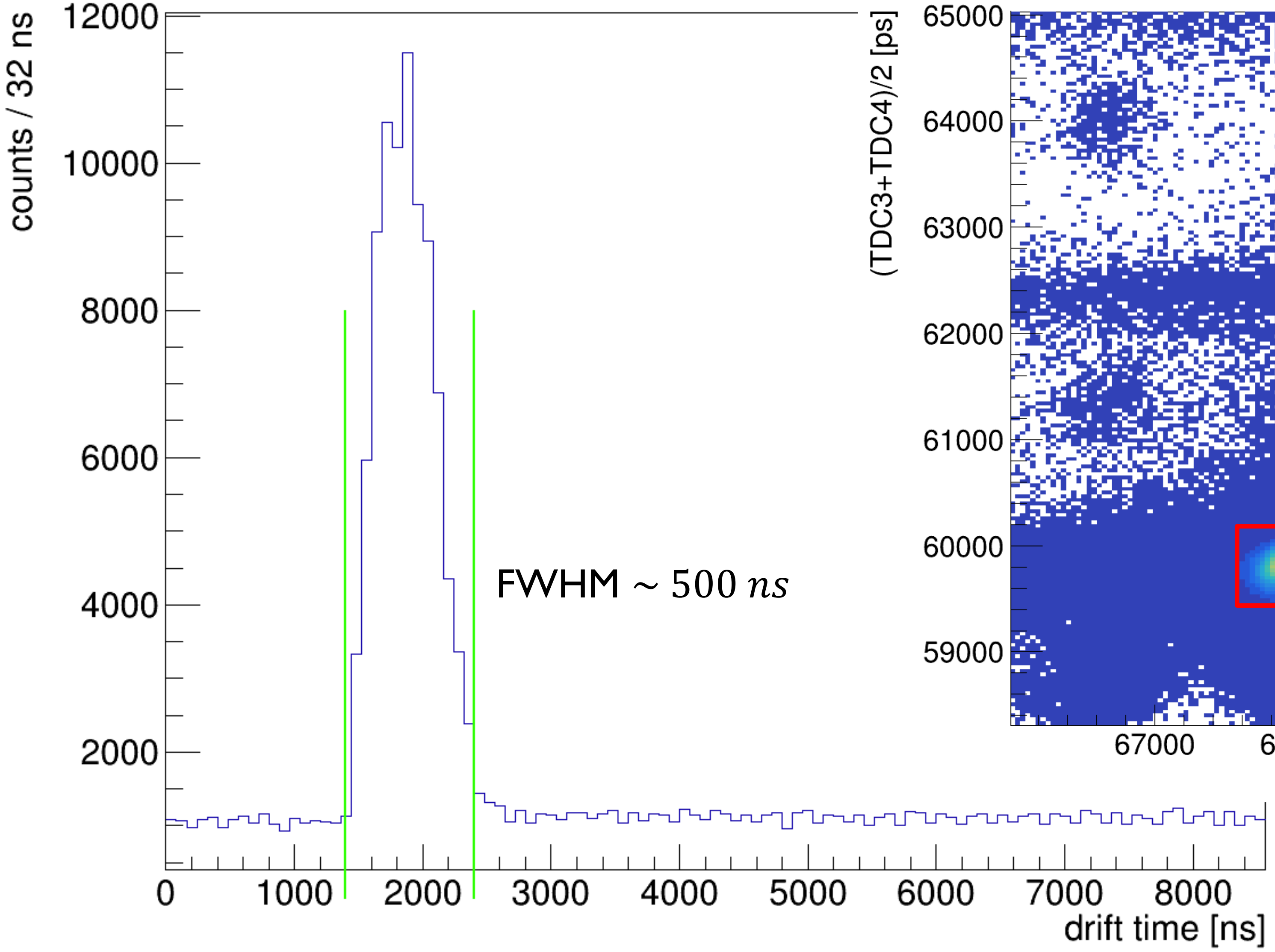
Kaonic deuterium data analysis – Run1

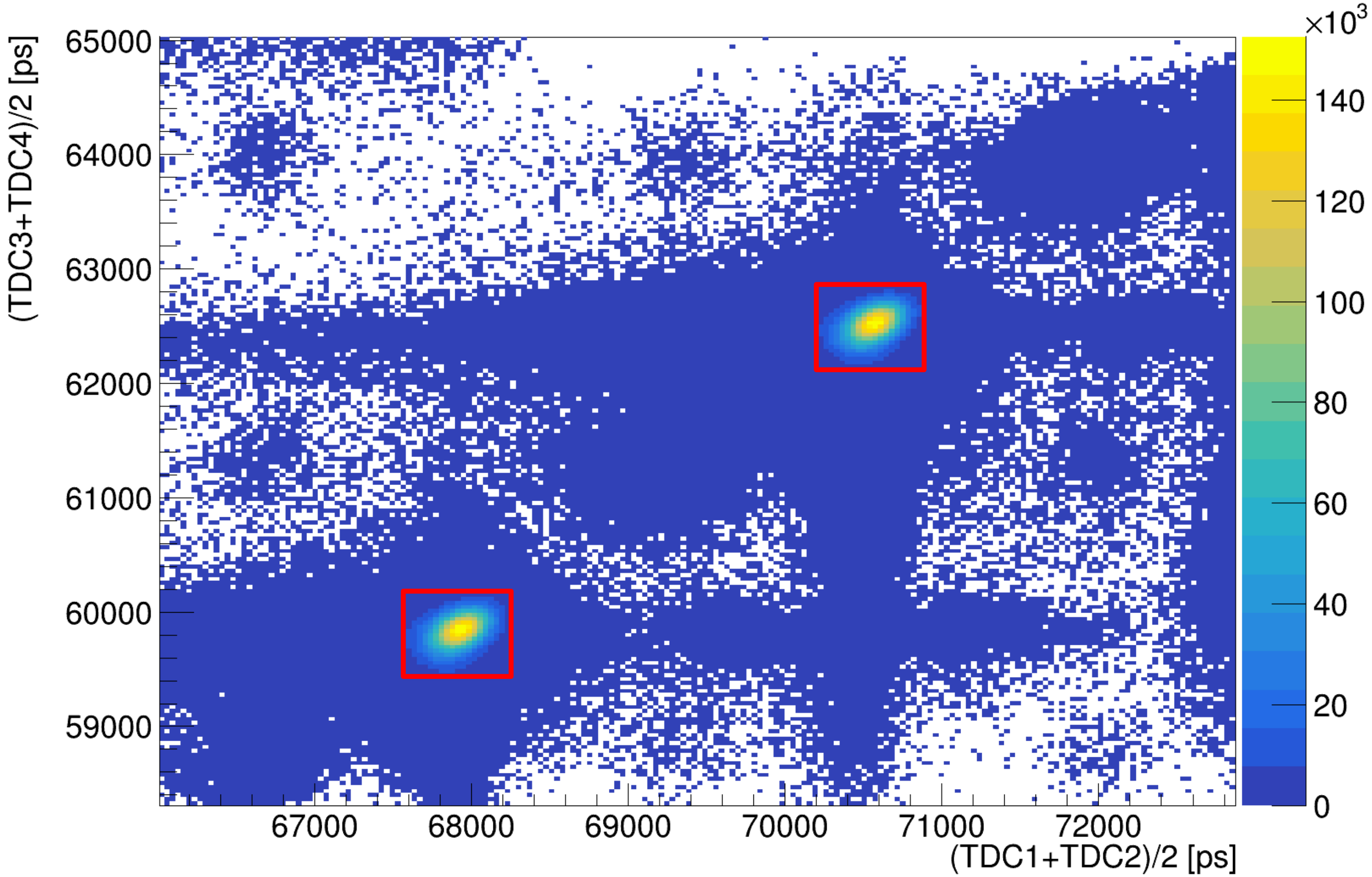
First run, May – July 2023, integrated luminosity 200 pb^{-1} (with injections)



Kaonic deuterium data analysis – Run1

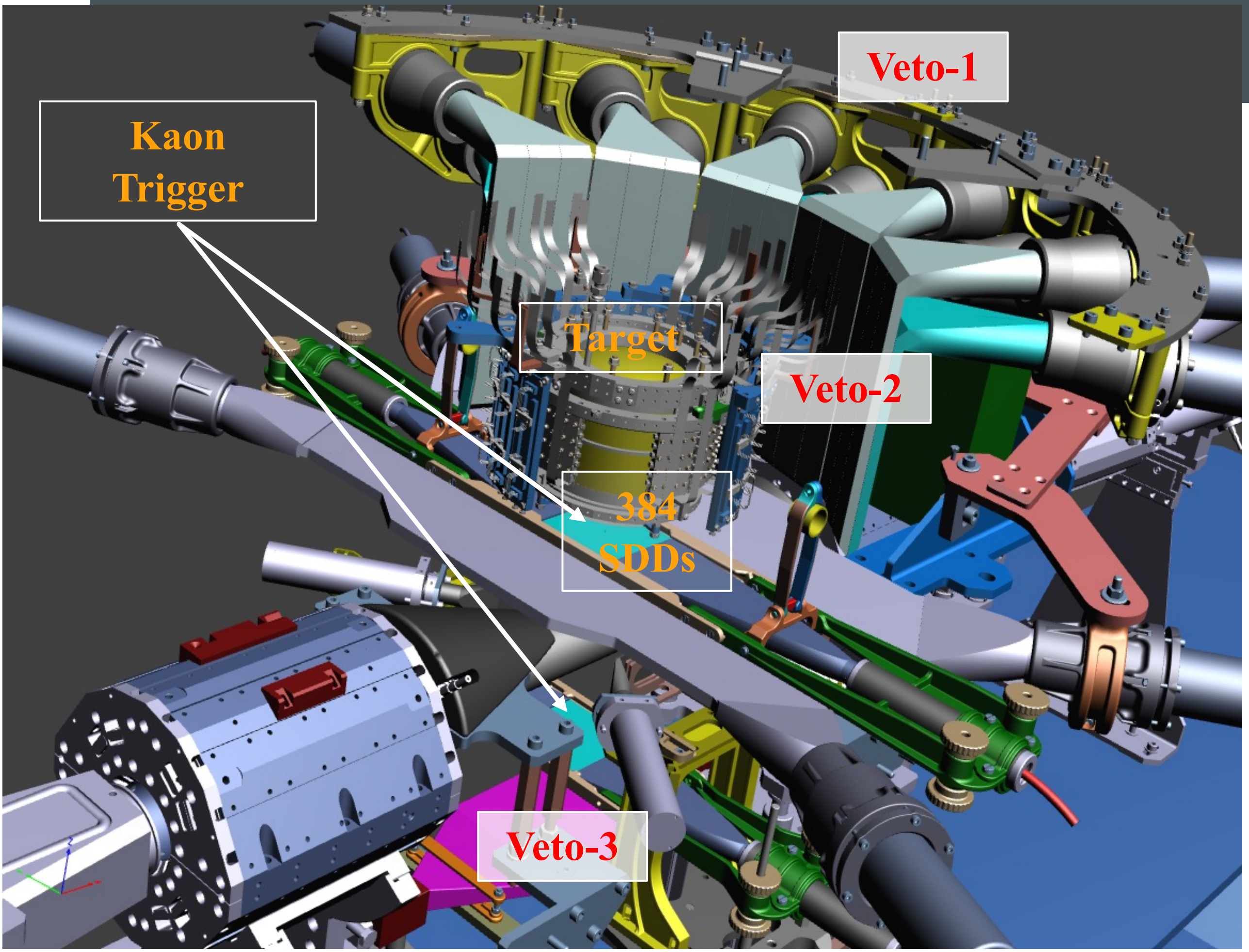
Kaon Trigger and SDDs drift time for asynchronous background reduction



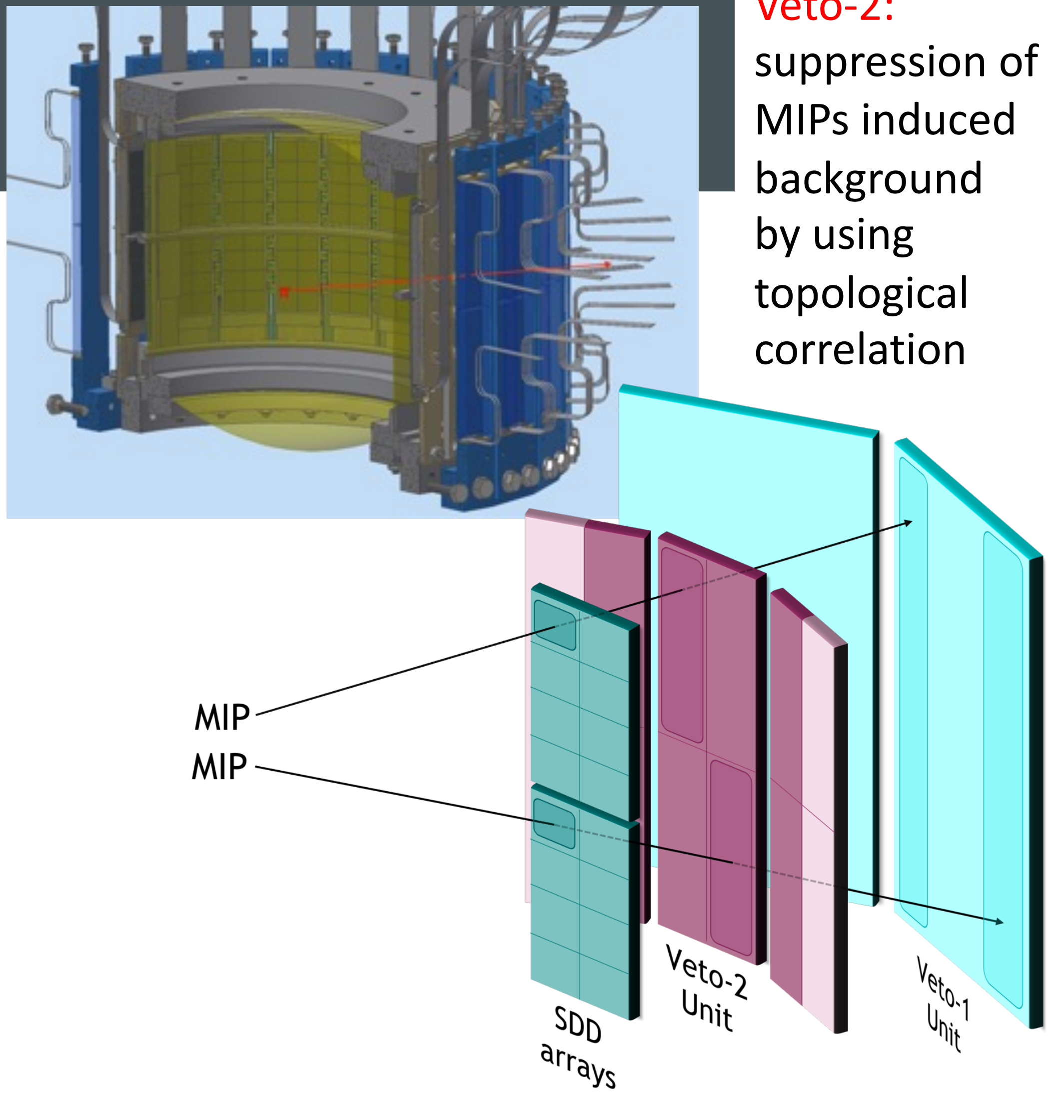


Kaonic deuterium data analysis – Run1

Veto-2 for synchronous background reduction



Three Veto systems for synchronous background reduction (M. Iliescu, J. Zmeskal, M. Tuchler…)



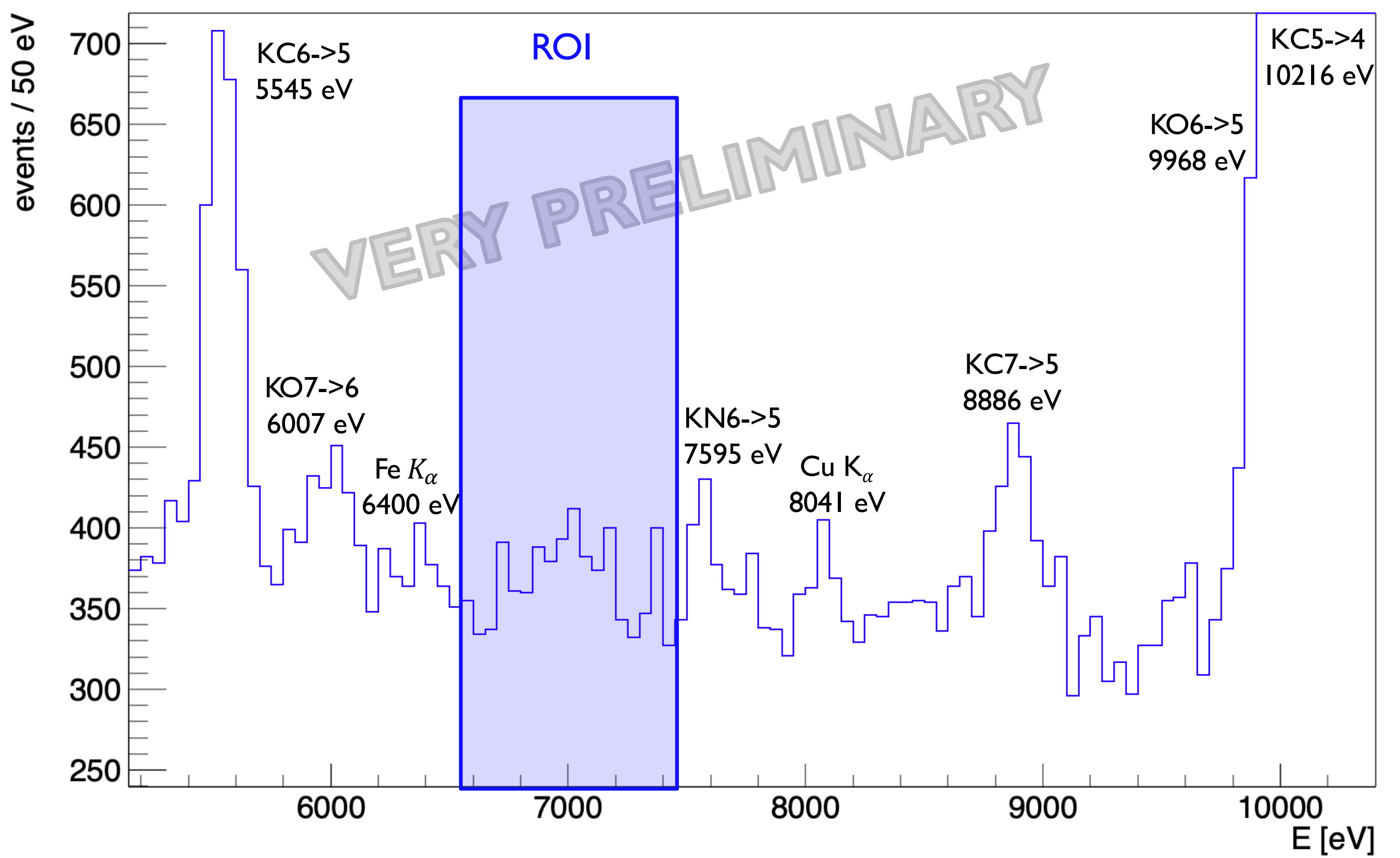
Veto-2: suppression of MIPs induced background by using topological correlation

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

Kaonic deuterium data analysis – Run1

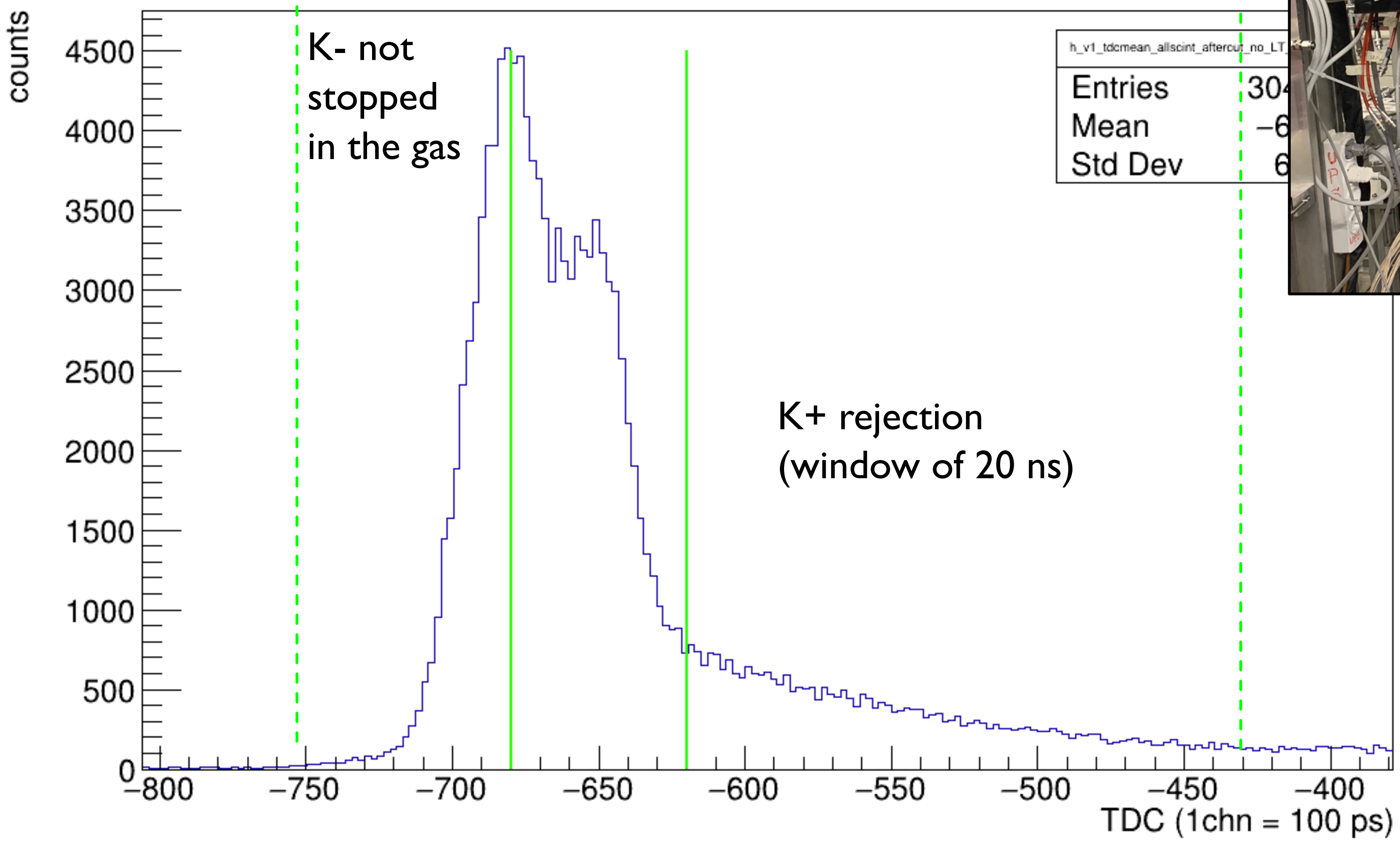
First run, May – July 2023, integrated luminosity 200 pb^{-1} (with injections)

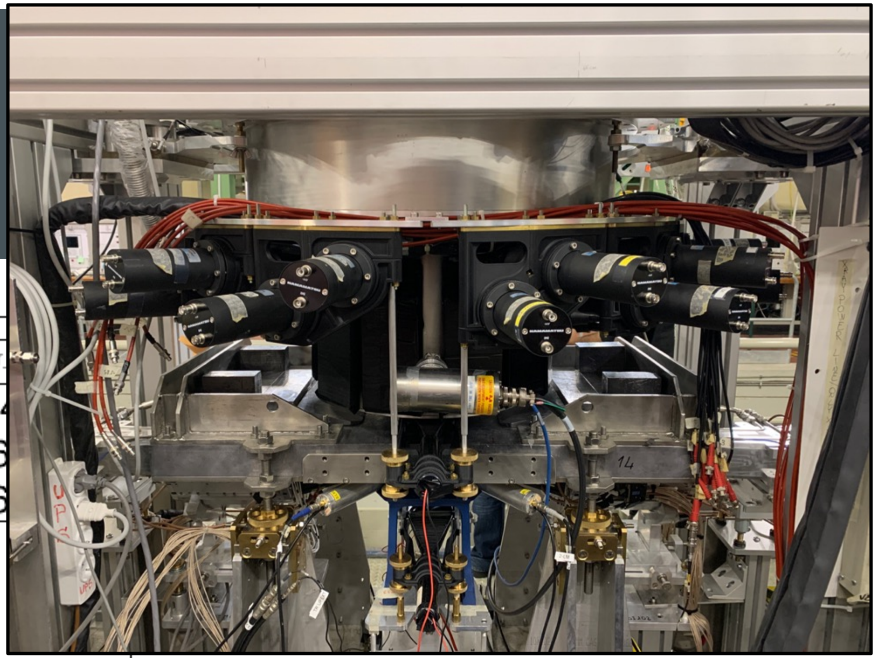
✓ Refined data calibration completed



Kaonic deuterium data analysis – Run1

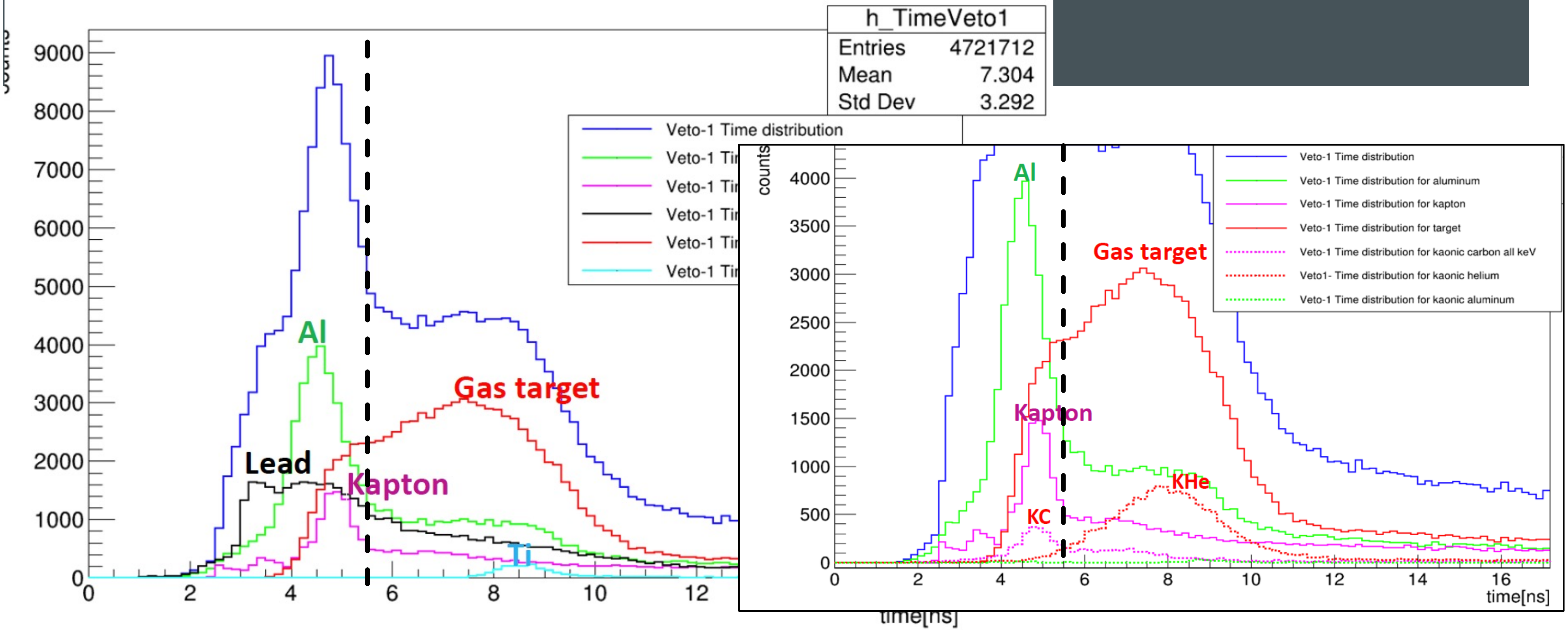
Veto-1 for synchronous background reduction





Veto-1 system optimization with kaonic He

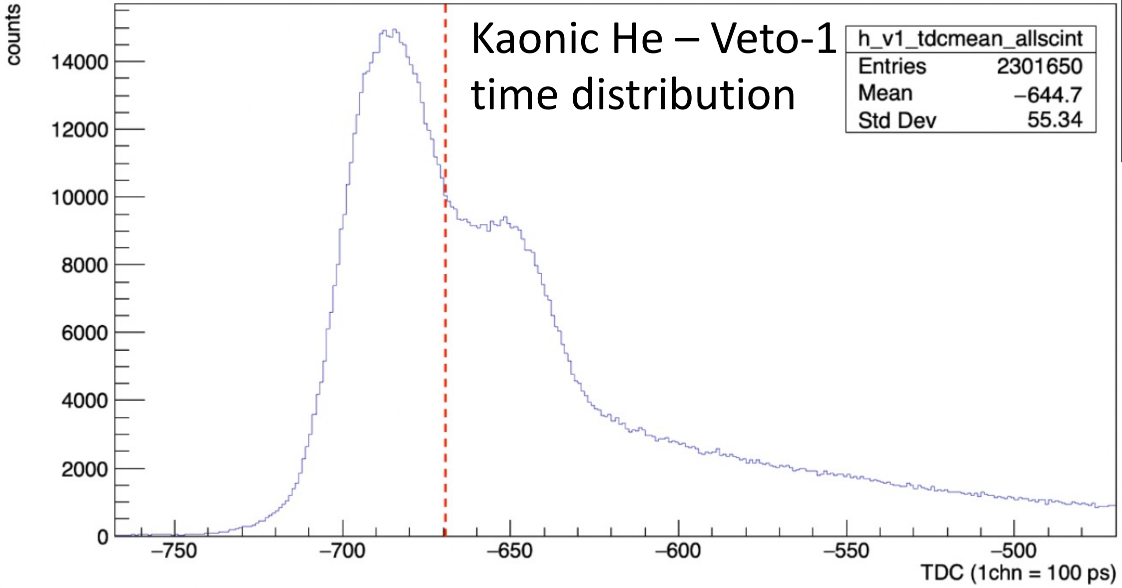
MC simulations and kaonic He data have been used to tune the Veto-1 system

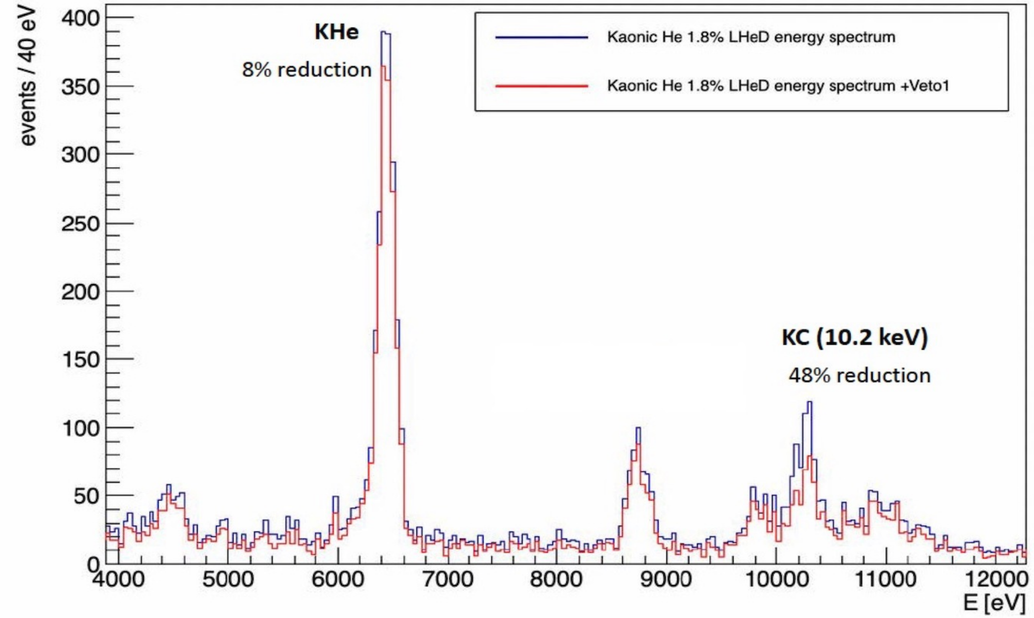


MC simulation to disentangle the several contributions and provide the right time selection cut (M. Iliescu, D. Sirghi, K. Dulski)

Veto-1 system optimization with kaonic He

MC simulations and kaonic He data have been used to tune the Veto-1 system





	SIDDAHTA-2 veto-1 reduction	MC expectation veto-1 reduction
Kaonic He Lα	8%	4%
Kaonic Carbon 5⟶4	48%	44%

Project Timeline – Future plans

- First run with SIDDHARTA-2 optimized setup for 200 pb^{-1} integrated luminosity: May – July 2023 - completed
- Second run Autumn – Winter 2023 goal: estimated 200-300 pb^{-1} ongoing
- Third run 2024 – goal: 400 pb^{-1}
- Calibration: solid targets – Li, B, Be – 100-150 pb

Run2 expected integrated luminosity ~ 200 – 300 pb^{-1} (with injections)

End of kaonic deuterium Run2

2023, December

Total: 500 pb^{-1}

Start kaonic deuterium Run3

2024, January

Goal: integrated luminosity ~400 pb^{-1}

End Run3

2024

Total: 900 pb^{-1}

(to ensure 800 pb^{-1} of useful data)

Integrated luminosity 100-150 pb^{-1} (1 month)

Light kaonic atoms Run (Li - Be - B)

Extension of the SIDDHARTA-2 run, also as post-calibration

SIDDHARTA-2 main outcomes 2022-2023

$$\epsilon_{2p} = E_{exp} - E_{e.m} = 0.2 \pm 2.5(stat) \pm 2.0(syst)\ eV$$

$$\Gamma_{2p} = 8 \pm 10\ eV\ (stat).$$

- **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 ever of intermediate mass kaonic atoms:** Eur. Phys. J. A 59(2023)3, 56
- **First Measurement of KHe M-lines :** paper ready to be submitted to J. Phys. G
- **First Measurement ever of kaonic Neon (record of precision < 1 eV) :** analysis on going with implication on the kaon mass

- **First measurement of kaonic deuterium (200 pb^{-1}) :** analysis on going

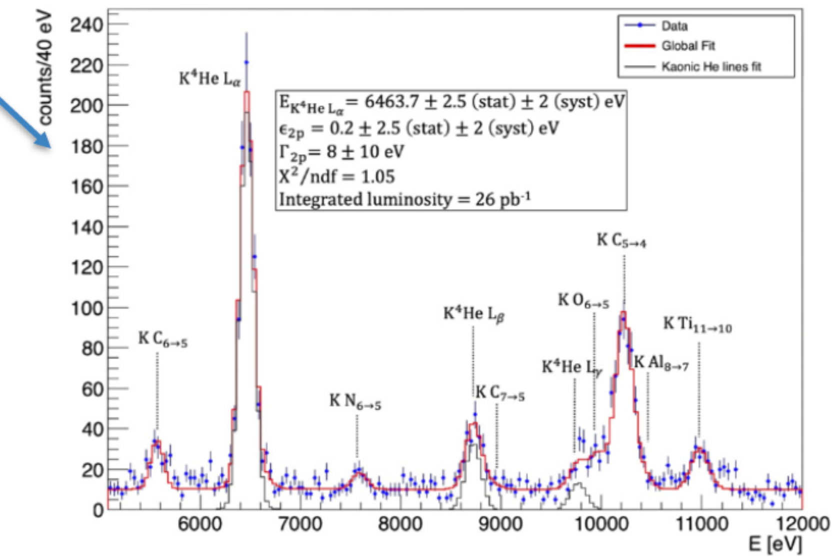


Figure 7. Fit (red line) of the K^4He energy spectrum. The $L\alpha$ peak is seen together with the $L\beta$ and $L\gamma$ ones (black lines). The peaks labeled as KN, KC, KAl, KTi (dotted lines) are the kaonic atoms lines produced by the kaons stopped in the Kapton ($C_{22}H_{10}O_5N_2$)

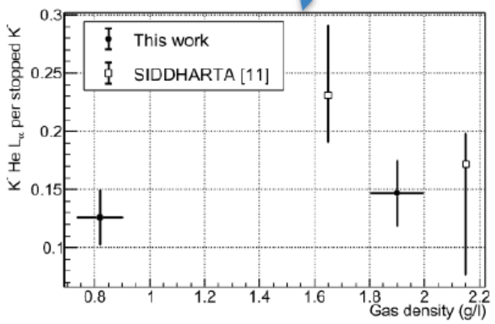


Fig. 3. The L_α X-ray yield of K^- ^{4}He as function of the target density from all gaseous target measurements: this wo (filled dots) and SIDDHARTA [16] (hollow squares).

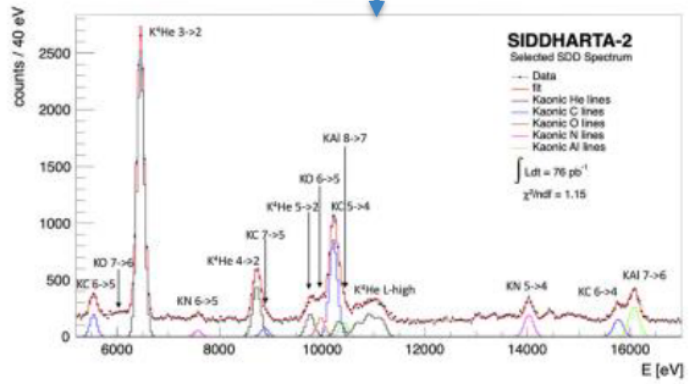
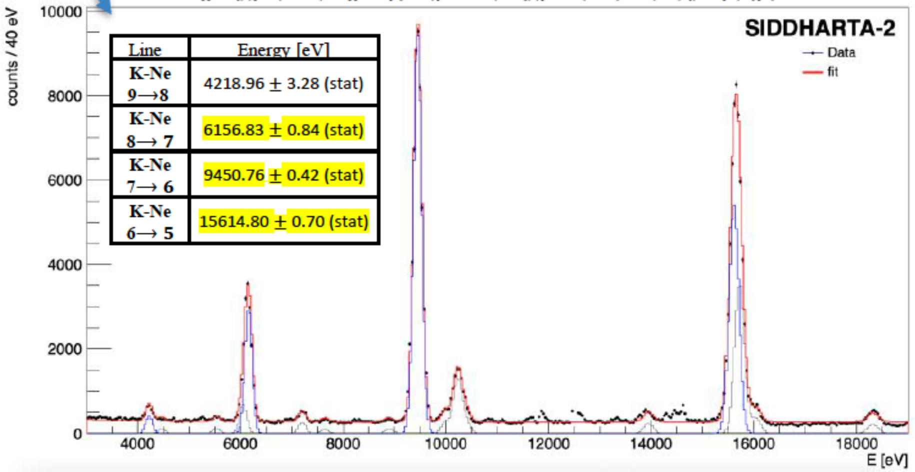


Fig. 6 SDD energy spectrum and fit of SIDDHARTA-2 and SIDDHARTINO summed data after background suppression (see text). The kaonic helium signals are seen as well as the kaonic carbon (KC), oxygen (KO), nitrogen (KN) and aluminium (KAl) peaks



Line	Energy [eV]
K-Ne 9→8	4218.96 ± 3.28 (stat)
K-Ne 8→7	6156.83 ± 0.84 (stat)
K-Ne 7→6	9450.76 ± 0.42 (stat)
K-Ne 6→5	15614.80 ± 0.70 (stat)