ROCK STAR: Towards a ROadmap of the Crucial measurements of Key observables in Strangeness reactions for neutron sTARs equation of state

The kaonic helium-4 measurement with SIDDHARTA-2 experiment at DAΦNE accelerator

ROCKSTAR

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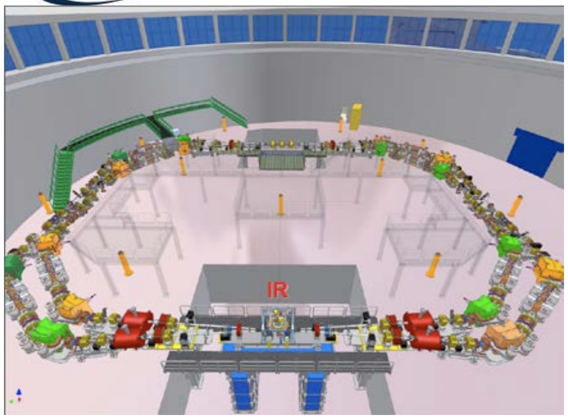
INFN-LNF

on behalf of SIDDHARTA-2 collaboration

9-13 October 2023
Trento

DAΦNE: low-momentum kaon beam

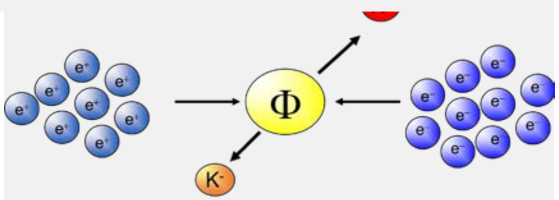
INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

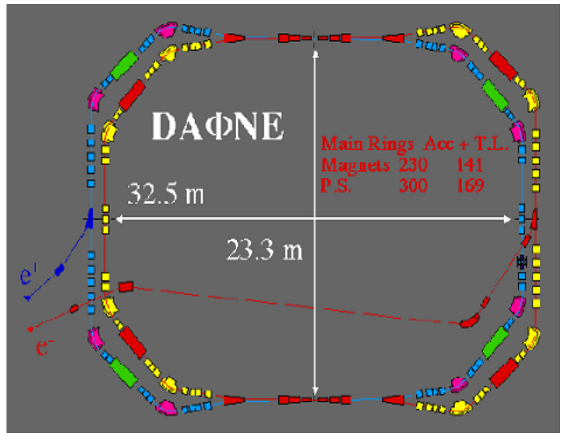


operates at the centre-of-mass energy of the Φ meson

mass m = 1019.413 ± .008 MeV

width Γ = 4.43 ± 0.06 MeV





- $e^+ e^-$ at 510 MeV
- Φ ($\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$) resonance decays at 49.2 % in **$K^+ K^-$ back-to-back pair**
- **Very low momentum (≈ 127 MeV) K^- beam**
- Flux of produced kaons: about 1000/second

Best low momentum K^- factory in the world

Ideal beam to be stopped in the gaseous target and form, with high efficiency, kaonic atoms

Suitable for low-energy kaon physics:
→ Kaonic atoms (DEAR/ SIDDHARTA/ SIDDHARTA-2)

The scientific aim

SIDDHARTA-2 measures the X-ray transitions occurring in the cascade processes of kaonic atoms

Fundamental study of strong interaction between anti-K & nucleus at low energy limit

Importance of kaonic atoms studies

Atomic binding energies of light systems the keV range →tens of MeV in the low-energy scattering experiments

	m (MeV/c^2)	μ (MeV/c^2)	B_{1s} (keV)	r_B (fm)	Accessible interaction
ep	0.511	0.511	13.6×10^{-3}	53 000	Electroweak
μp	105.7	95.0	2.53	279	Electroweak
πp	139.6	121.5	3.24	216	Electroweak + strong
Kp	493.7	323.9	8.61	81	Electroweak + strong
$\bar{p}p$	938.3	469.1	12.5	58	Electroweak + strong

Kaonic atoms: the unique opportunity to perform experiments equivalent to scattering at vanishing relative energies

Special role played by **lightest Kaonic atoms**

determination of the antikaon-nucleon/nucleus interaction at "threshold", without the need of extrapolation to zero relative energy.

Determined isospin dependent KN scattering lengths are key ingredients for all models and theories dealing with low-energy QCD in systems with strangeness

- **Explicit and spontaneous chiral symmetry breaking (mass of nucleons)**
- **Dense baryonic matter structure**
- **Neutron (strange?) stars EOS**

Kaonic Helium atoms

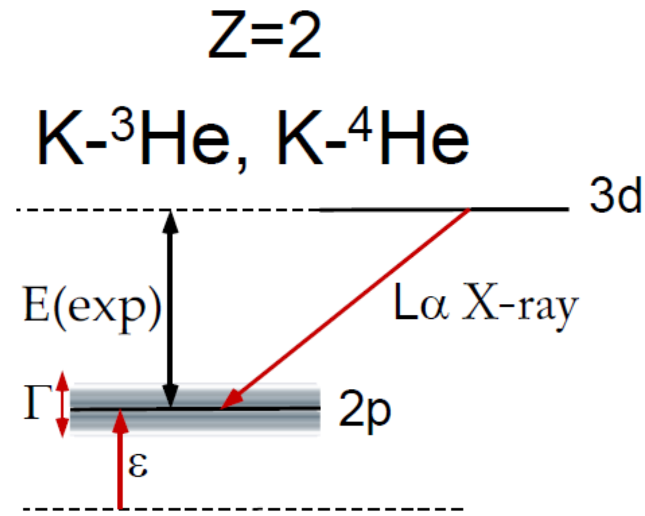
$$\varepsilon = E_{3d \rightarrow 2p}\,(\text{exp}) - E_{3d \rightarrow 2p}\,(\text{e.m.})$$

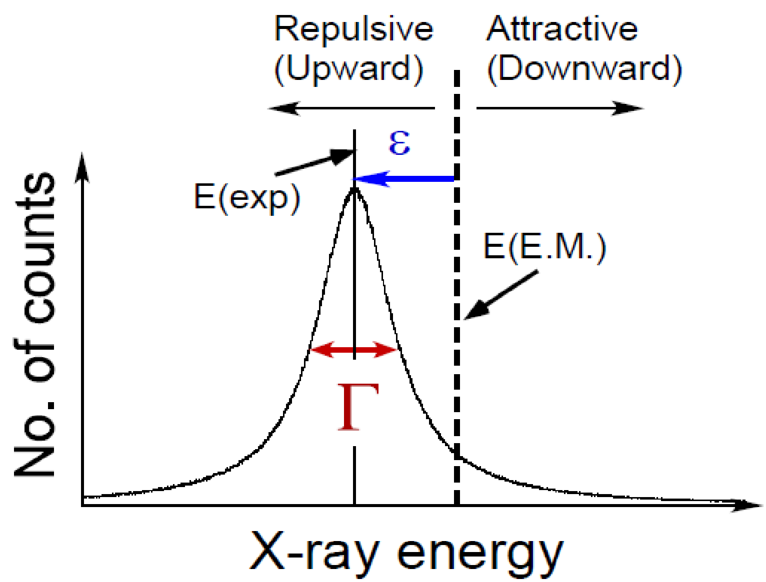
The most suitable transition to observe the strong interaction effects

Most kaons are absorbed without radiative transition to *1s* state.

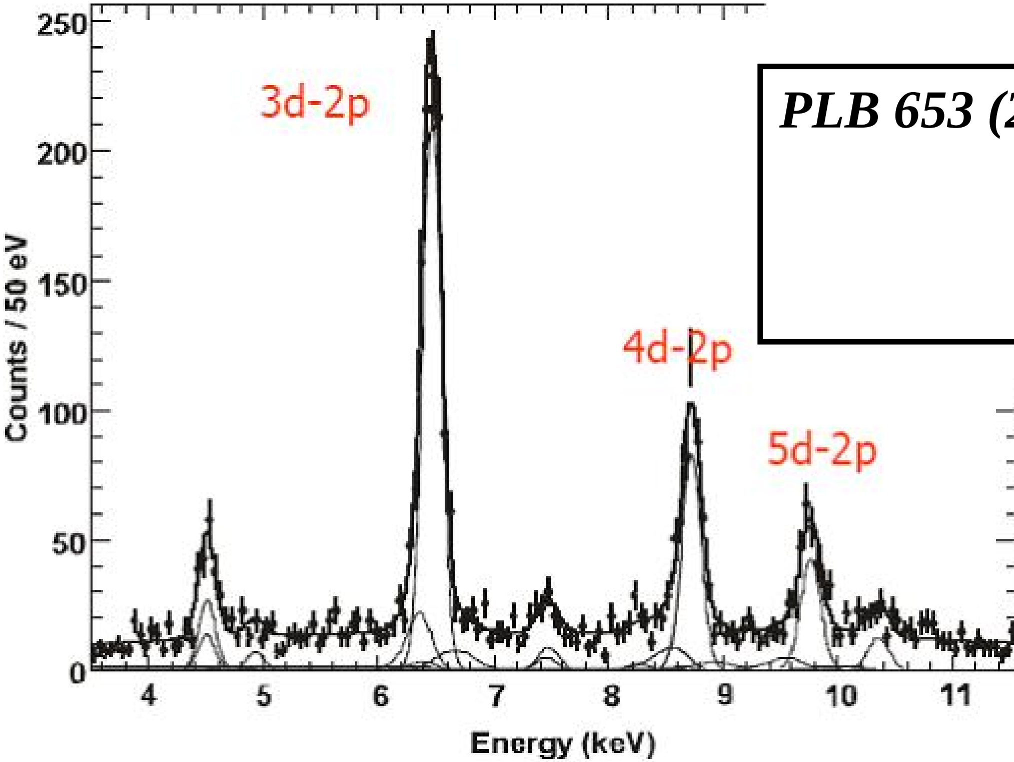
$$E(e.m.) \approx -\frac{1}{2}\mu c^2 (Z\alpha)^2 \cdot \left[\frac{1}{n_i^{\,2}} - \frac{1}{n_f^{\,2}}\right]$$

$$\varepsilon = E(\exp) - E(e.m.)$$
$$\varepsilon < 0\,(\text{repulsive})$$
$$\varepsilon > 0\,(\text{attractive})$$



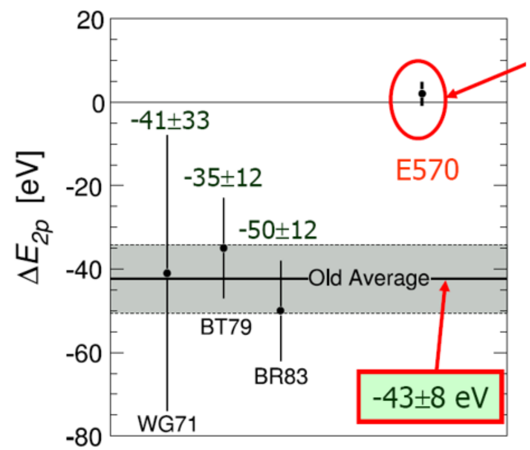


K^4He results by KEK PS E570



PLB 653 (2007) 387

	$3d \rightarrow 2p$	$4d \rightarrow 2p$	$5d \rightarrow 2p$
)	6466.7 ± 2.5	8723.3 ± 4.6	9760.1 ± 7.7
15]	6463.5	8721.7	9766.8



K^4He 3d→2p: 1500 events

3x higher statistics
2x better Energy resolution
6x better S/N

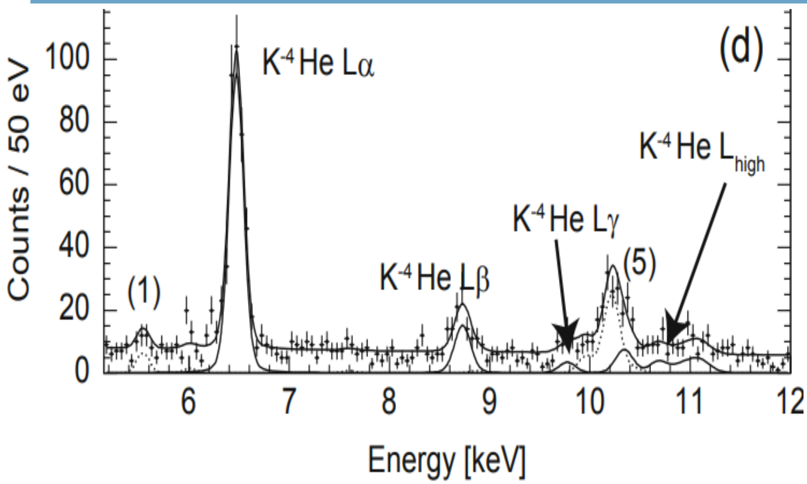
ΔE_{2p} =2±2(stat.)±2(syst.) eV)

Liquid target for ^4He

K^4He results by SIDDHARTA

Kaonic 4-Helium

K-4He (3d-2p)
E_{exp} = 6468.5±3 (stat.)±3.5(syst.) eV



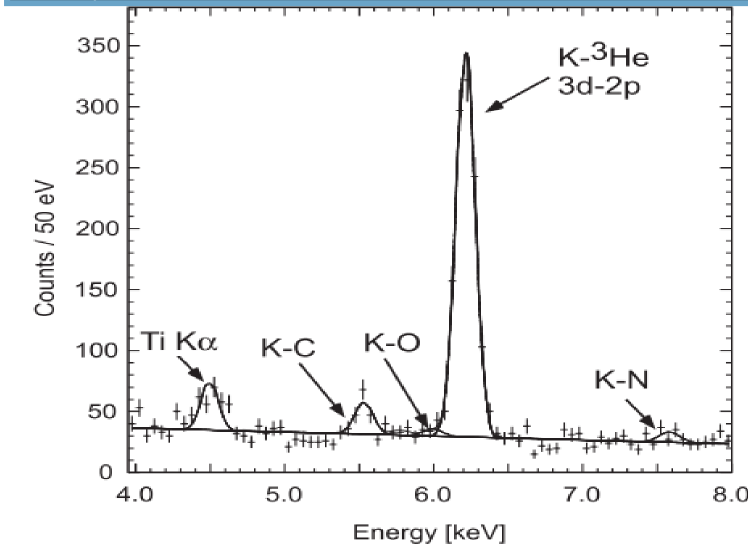
$$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys) \text{ eV}$$

Phys. Lett. B 681 (2009) 310

for first time in a gaseous target for ^4He

Kaonic 3-Helium

K-3He (3d-2p)
E_{exp}=6223.0±2.4(stat)±3.5(syst.) eV



$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys) \text{ eV}$$

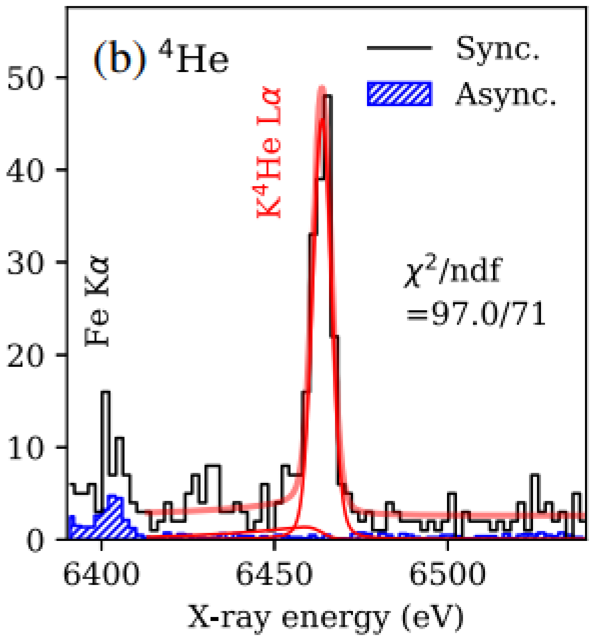
Phys. Lett. B 697 (2011) 199

for first time for ^3He

K^4He results by E62 J-PARC

Kaonic 4-Helium

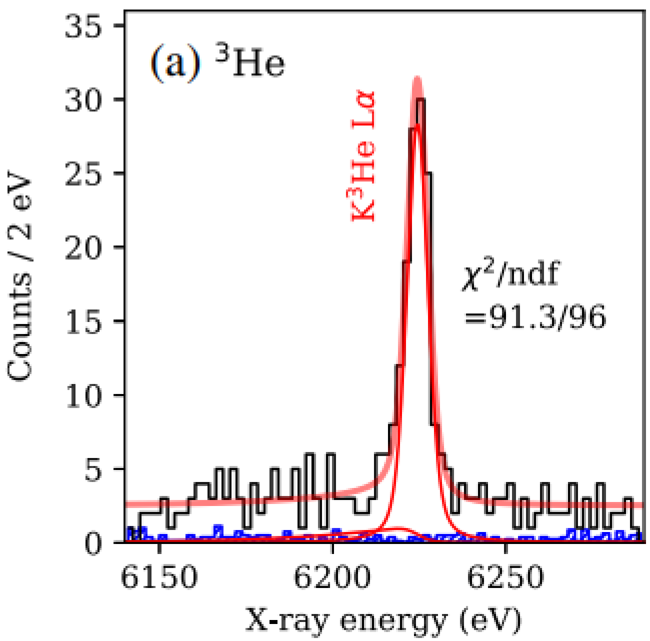
$$E^{K^-\,^4\mathrm{He}}_{3d\to 2p} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$



$$\Delta E^{K^-\,^4\mathrm{He}}_{2p} = 0.2 \pm 0.3(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}$$

Kaonic 3-Helium

$$E^{K^-\,^3\mathrm{He}}_{3d\to 2p} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}$$

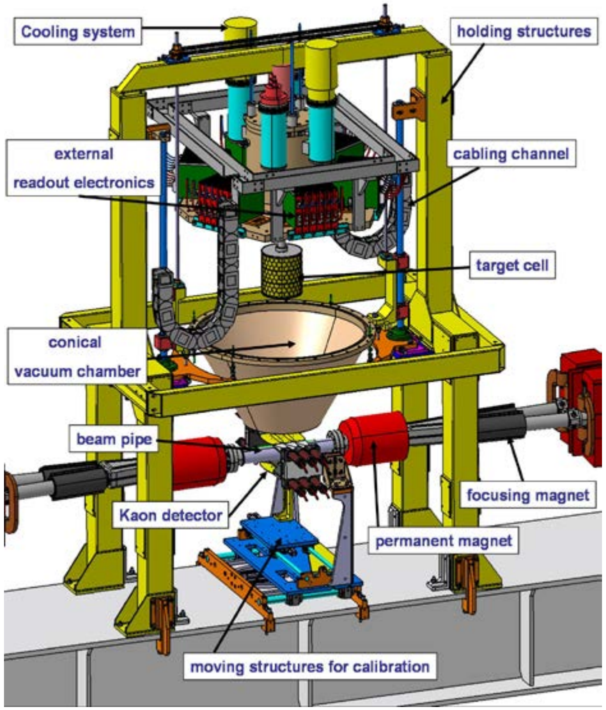


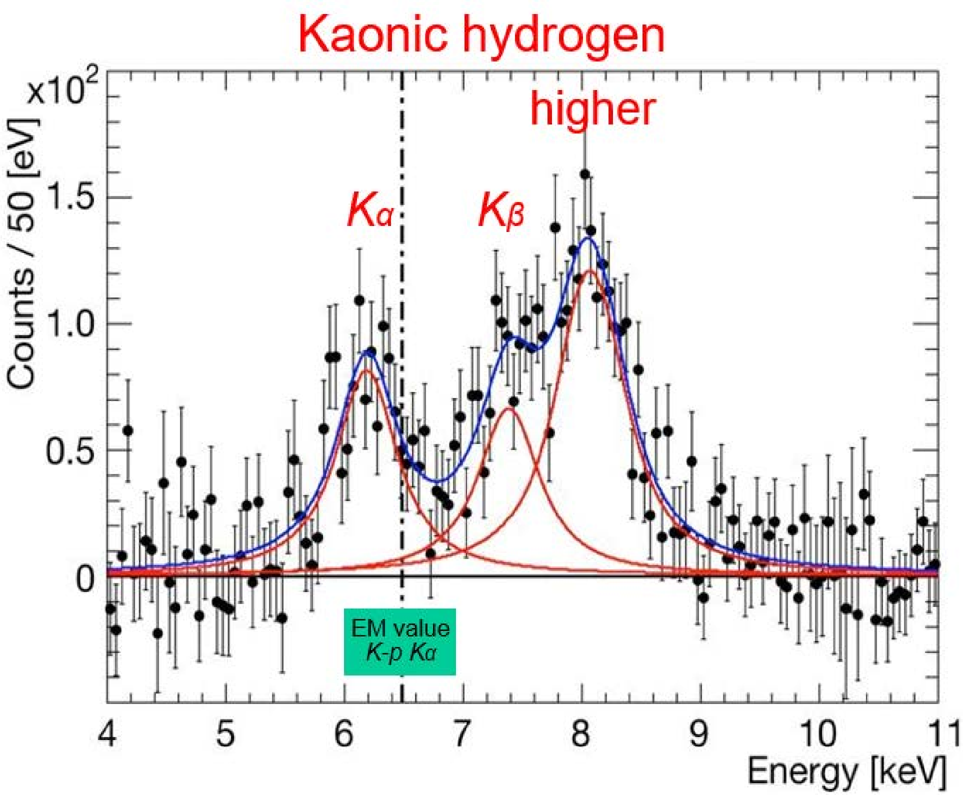
$$\Delta E^{K^-\,^3\mathrm{He}}_{2p} = -0.2 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV}$$

Phys. Rev. Lett. 128 (2022) 112503

Liquid target for $^{3,4}He$

KH results by SIDDHARTA





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

most reliable and precise measurement ever

Phys. Lett. B704 (2011), 113

SIDDHARTA-2 Scientific Goal

To perform the *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.

Analysis of the combined measurements of kaonic deuterium and kaonic hydrogen

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

(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

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

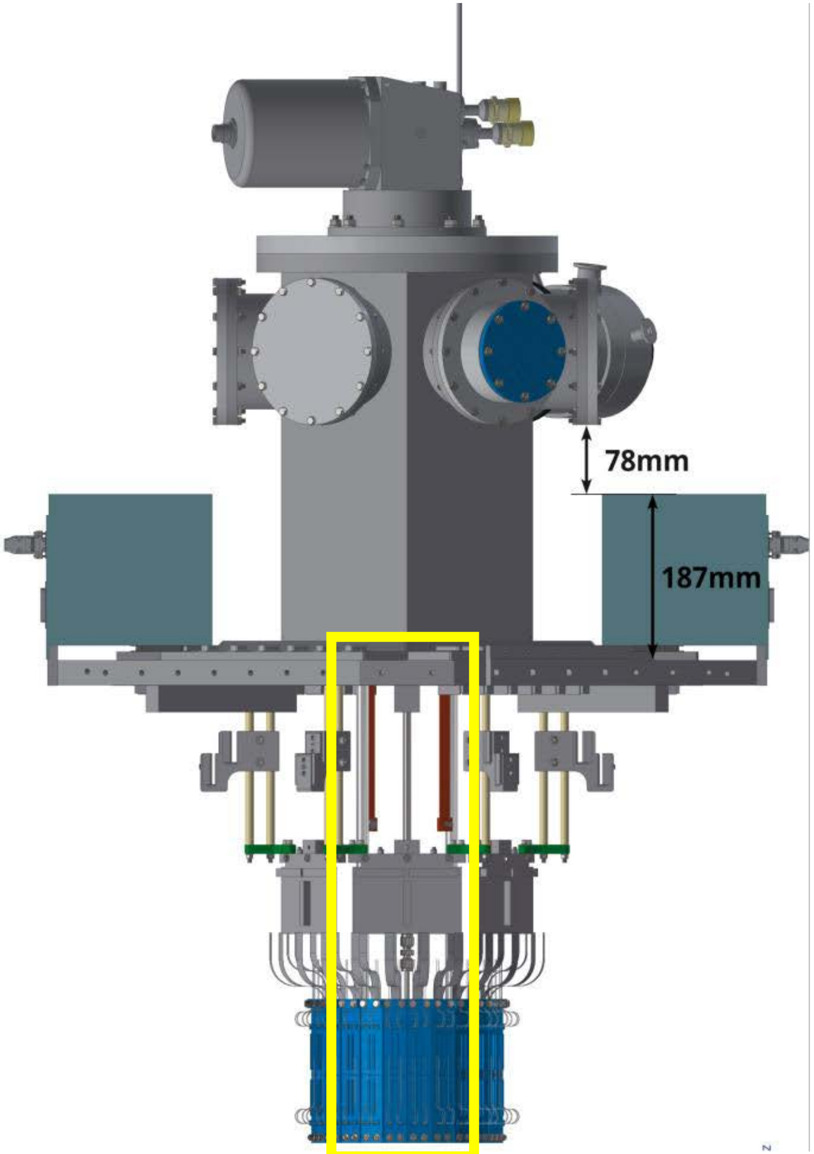
$$a_{K^-n} = a_1$$

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

$$k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$

completely solve Isospin-dependent K-N scattering length

SIDDHARTINO

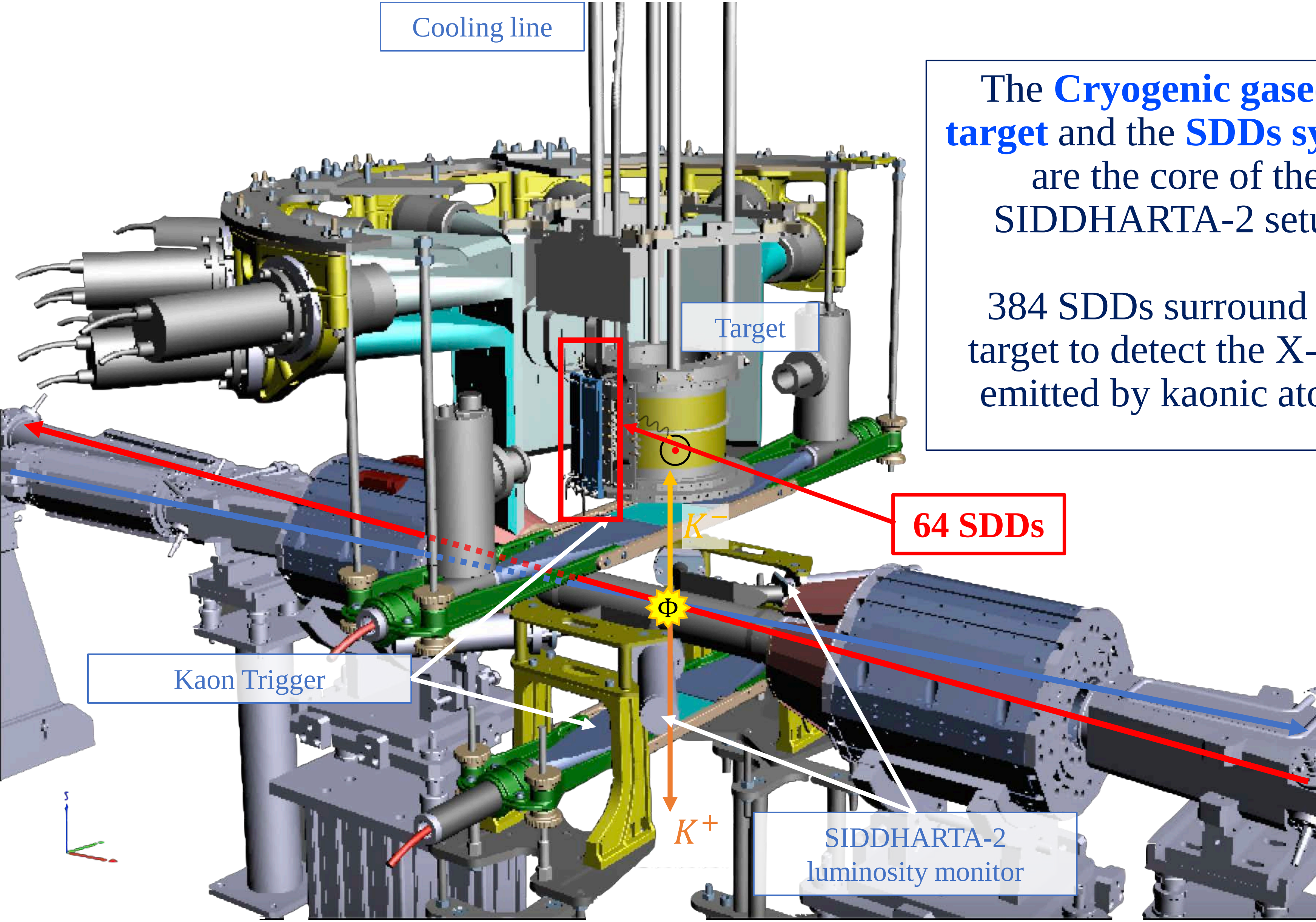


SIDDHARTINO: pilot run of SIDDHARTA-2
1/6 of SIDDHARTA-2 performed during accelerator commissioning

Optimization of the machine background during the DAΦNE beams commissioning phase in preparation for the K-d run through the **measurement of K-^{4}He 3d->2p transition**

- **Detector tuning for SIDDHARTA-2:**
  - ➢ **SDDs**
  - ➢ **Kaon Trigger**
- **Degrader (optimization of the kaons stopped in the target)**
- **Concluded in 2021**

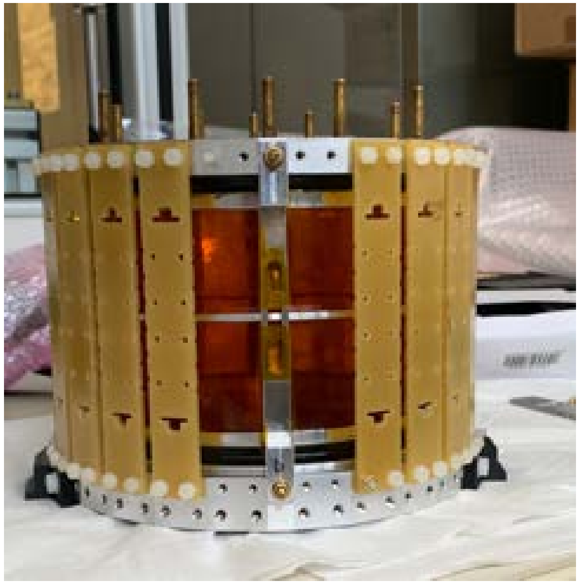
SIDDHARTA-2 setup

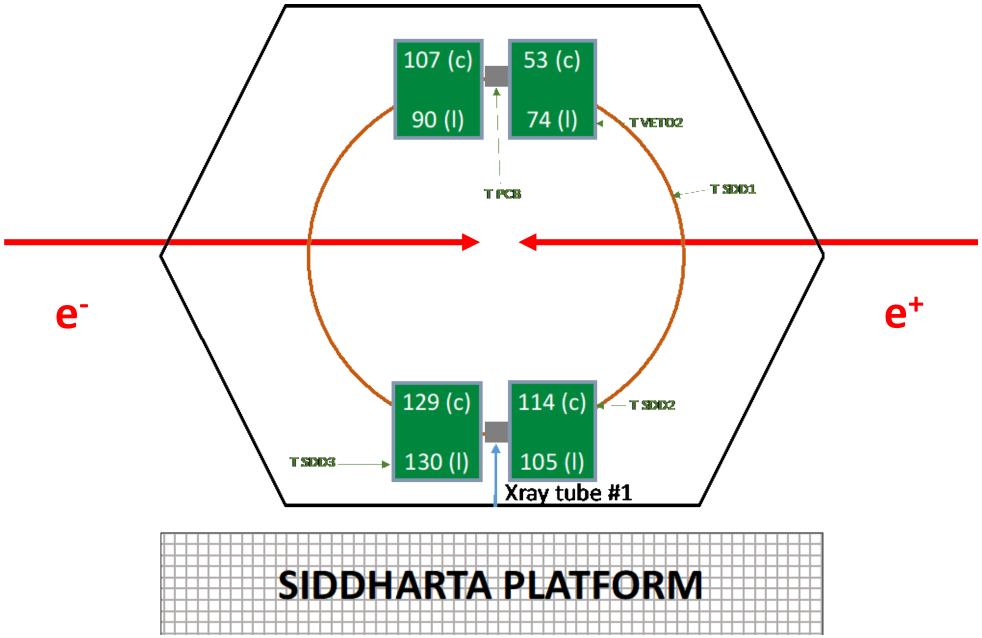


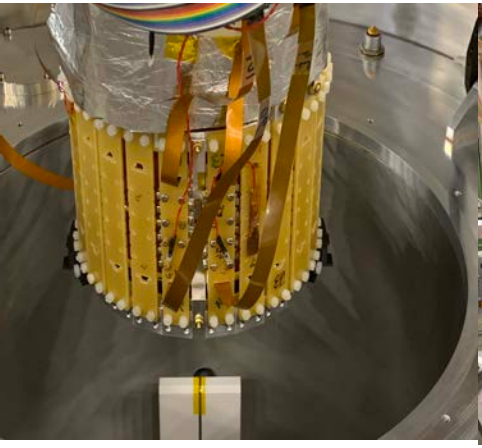
The **Cryogenic gaseous target** and the **SDDs system** are the core of the SIDDHARTA-2 setup.

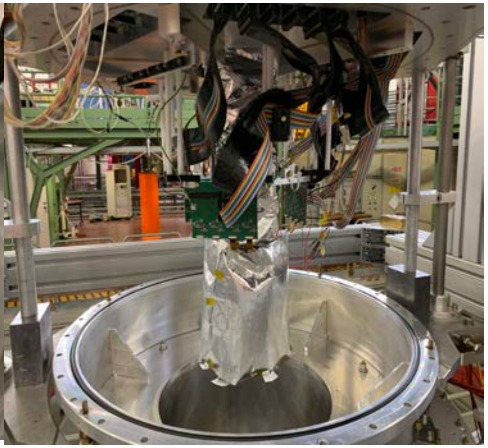
384 SDDs surround the target to detect the X-rays emitted by kaonic atoms

SIDDHARTINO setup – ^{4}He run









SIDDHARTINO cryogenic target:

Target : ^{4}He gas

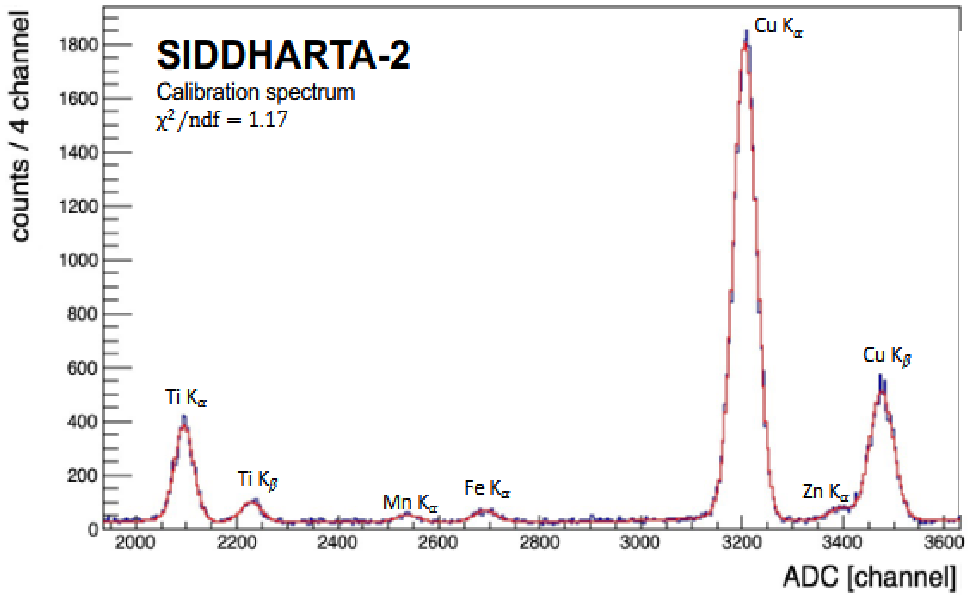
Working temperature : 25K

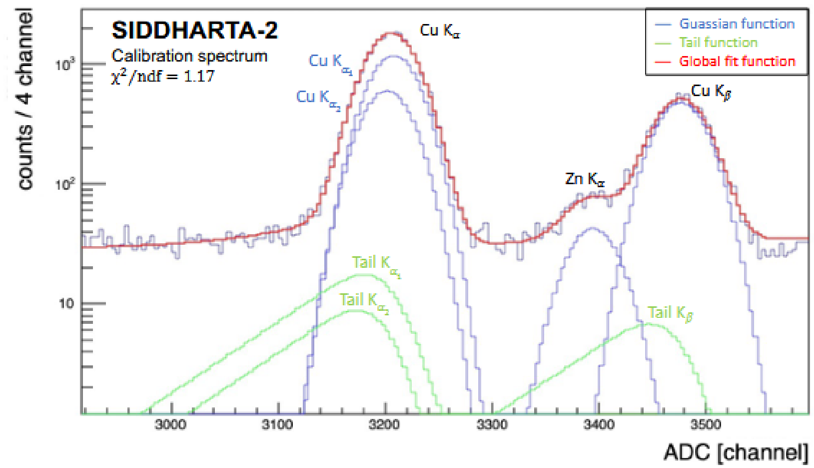
Working pressure: 1 bar

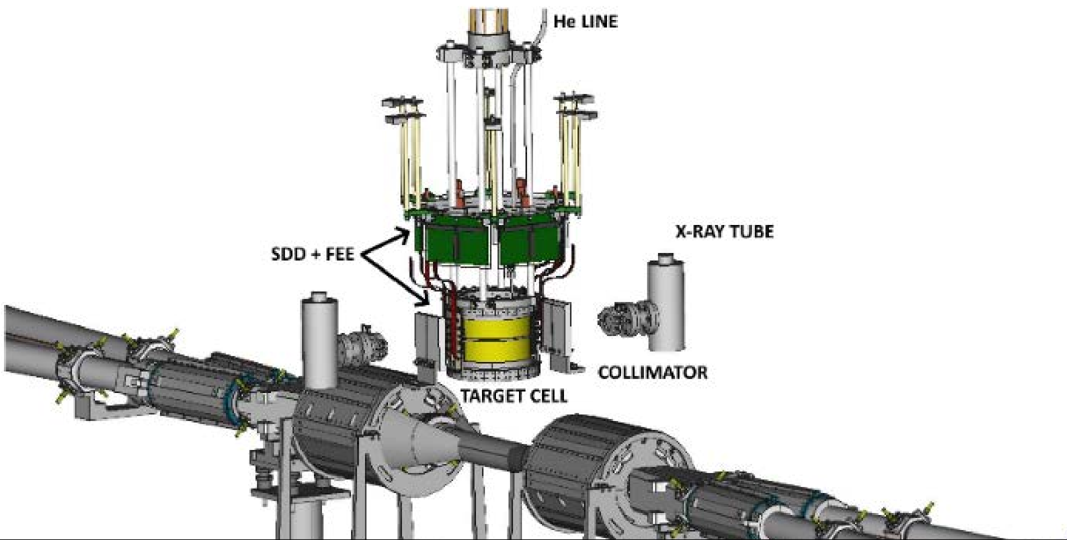
1.5% of liquid helium density (LHeD)

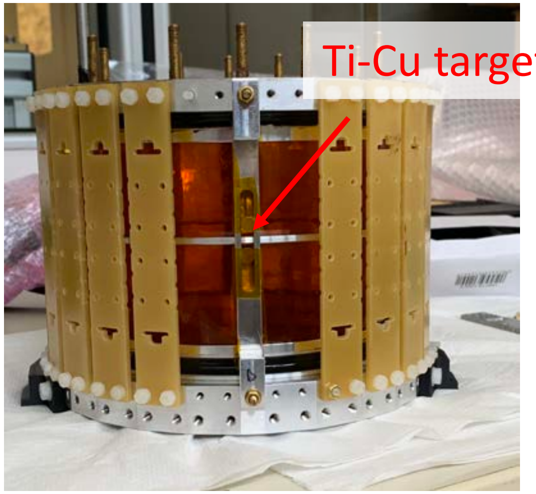
0.66% of liquid helium density (LHeD)

SDD Calibration





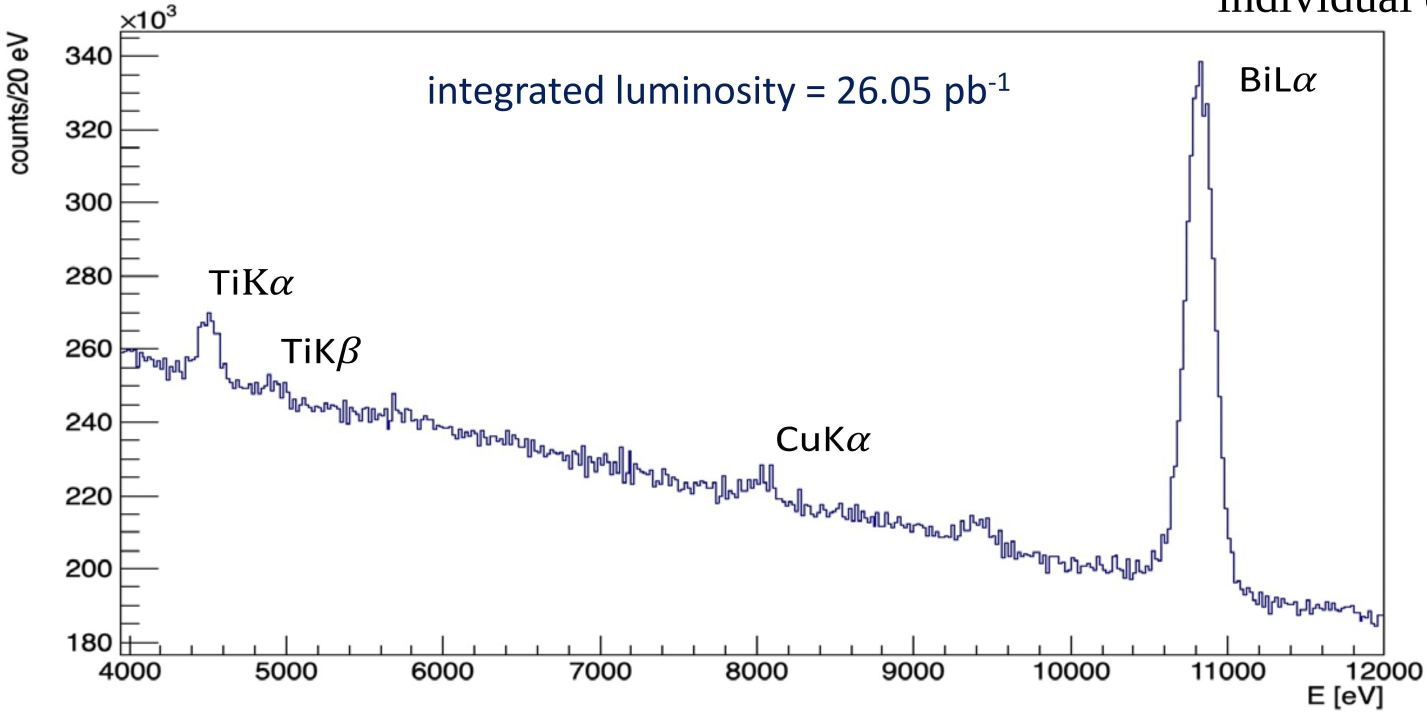


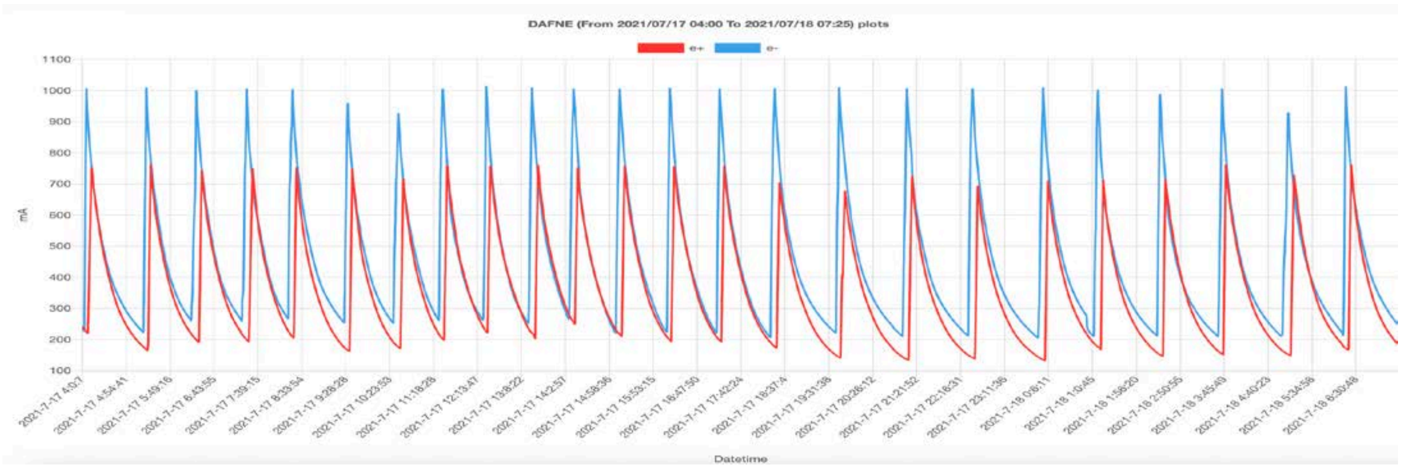


Energy resolution: FWHM (@6.4 keV): 157 ± 1 eV

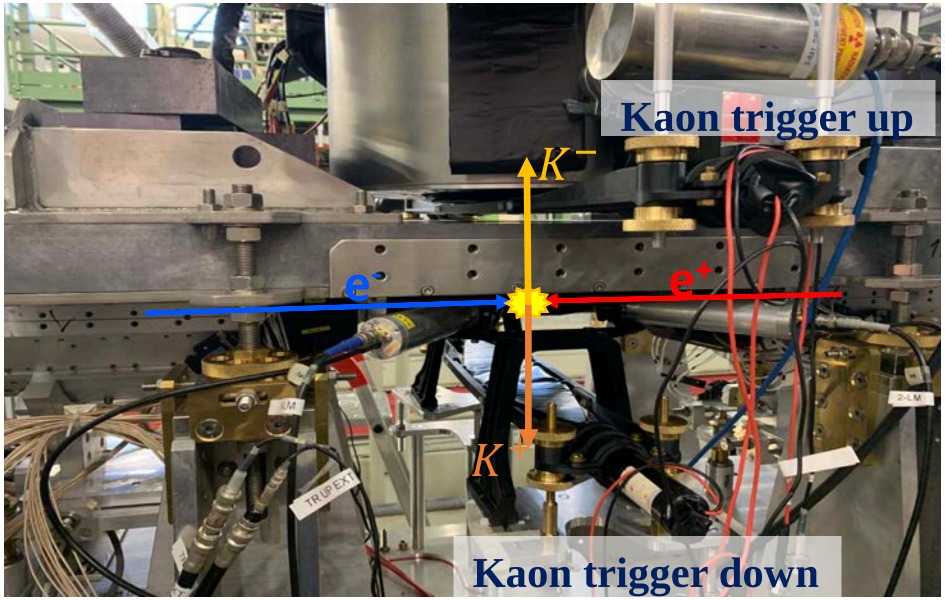
Kaonic ^{4}He 3d → 2p measurement

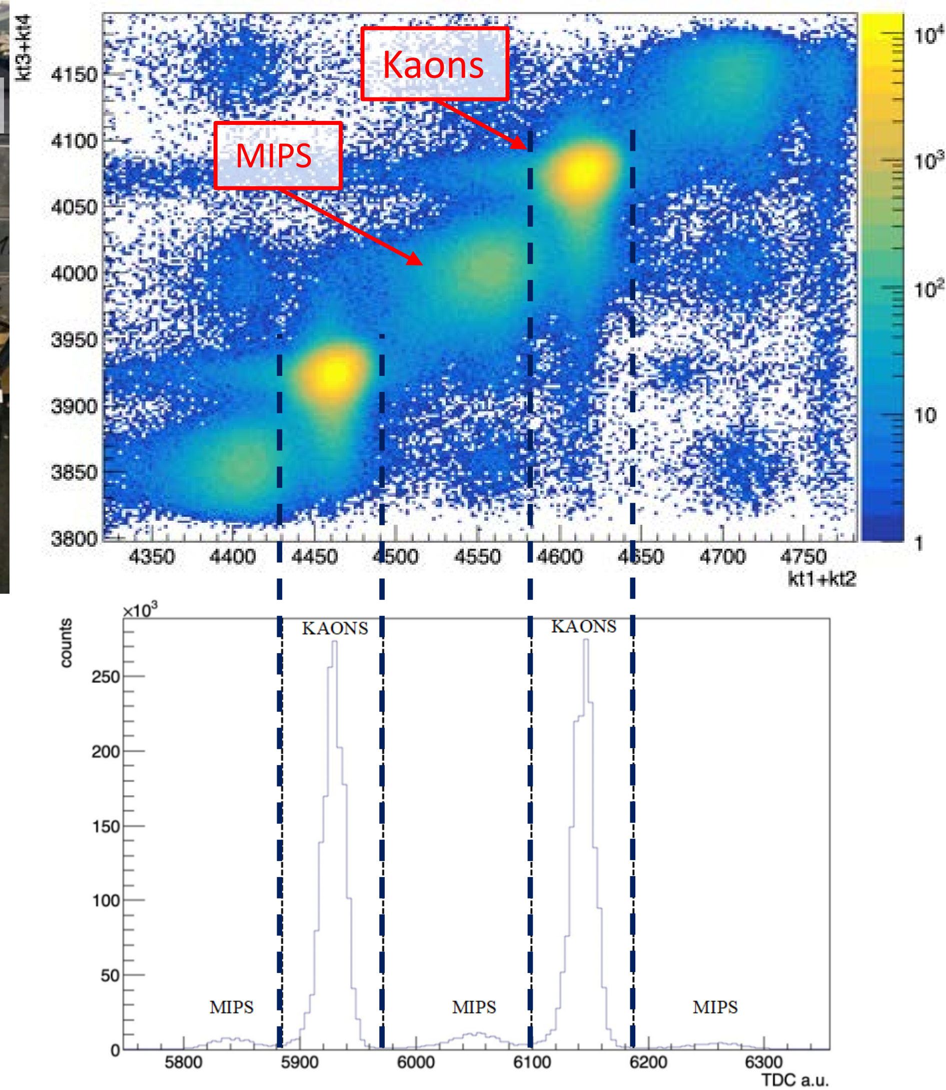
Sum of all SDDs after individual calibration

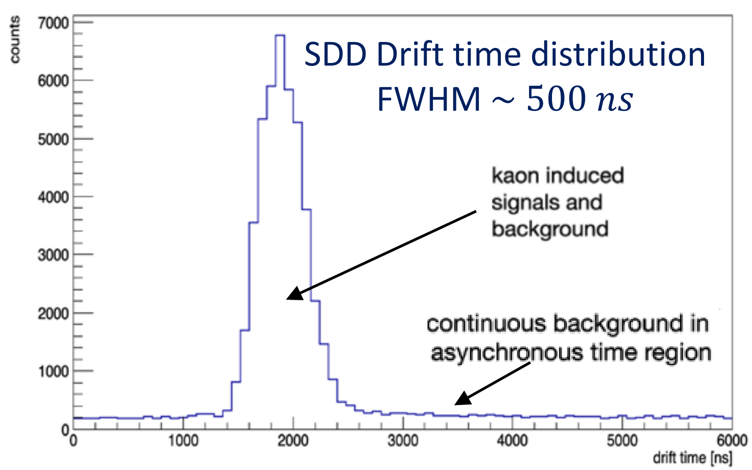




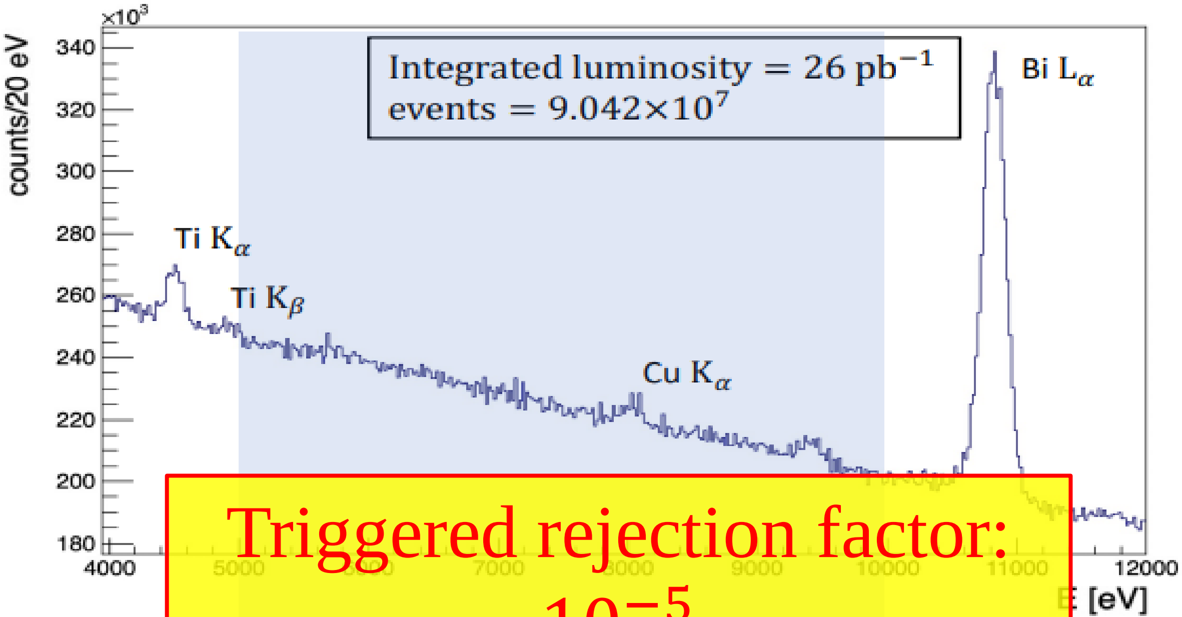
Kaon Trigger





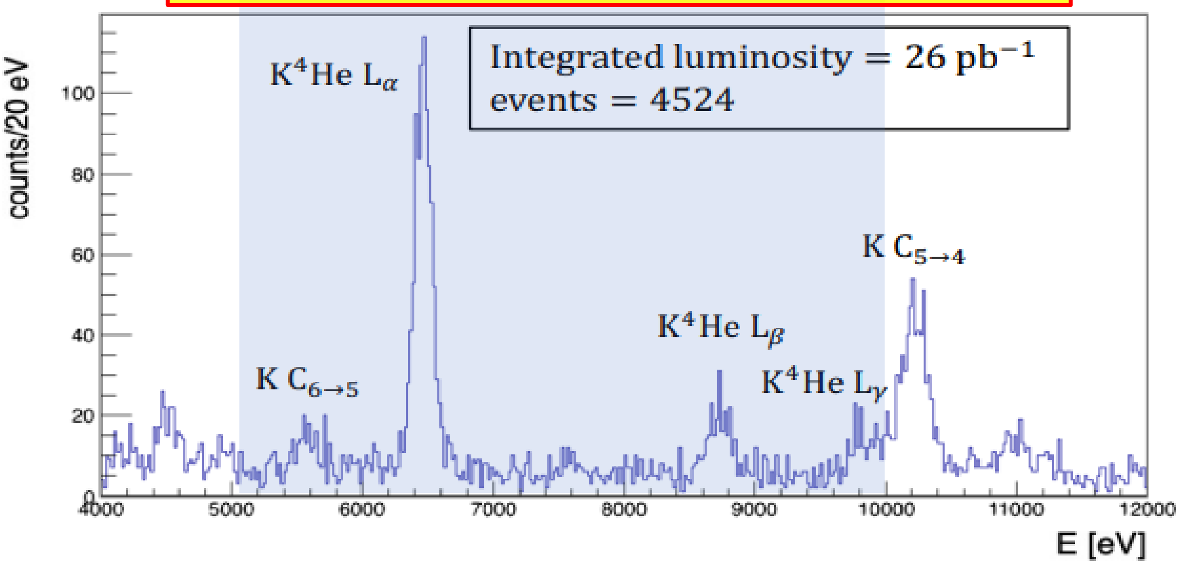


Trigger rejection factor



Sum of all SDDs after individual calibration

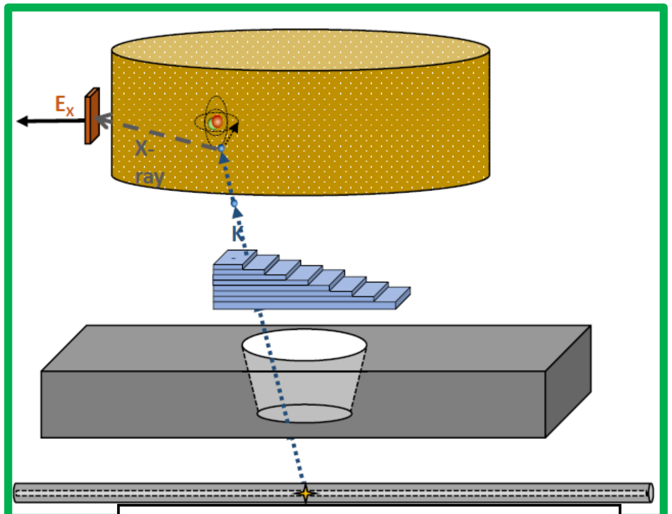
Triggered rejection factor: 10^{-5}



Sum of all SDDs after individual calibration and trigger cut

Degrader optimization

- to compensate assymetry in the kaon^{-} momentum distribution (50 mrad crossing angle of the beams)
- to optimize the numbers of the stopped kaons inside the target



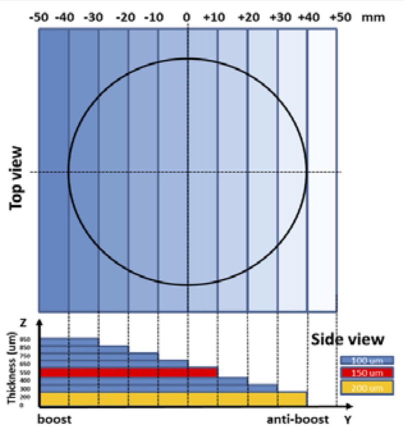
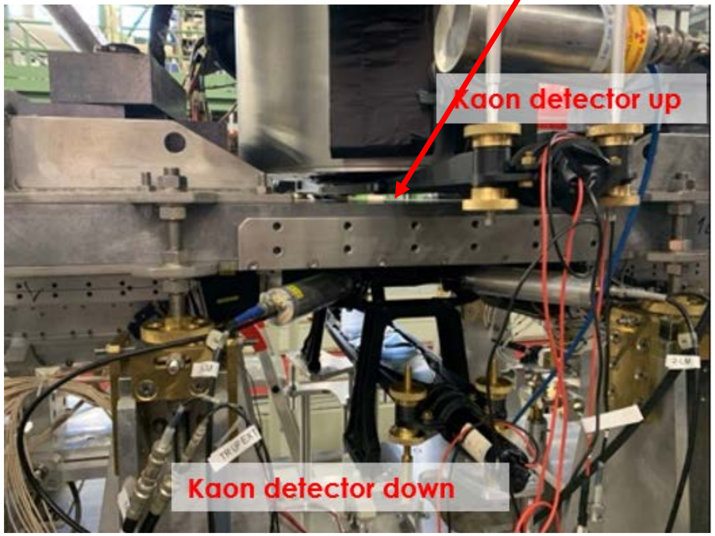
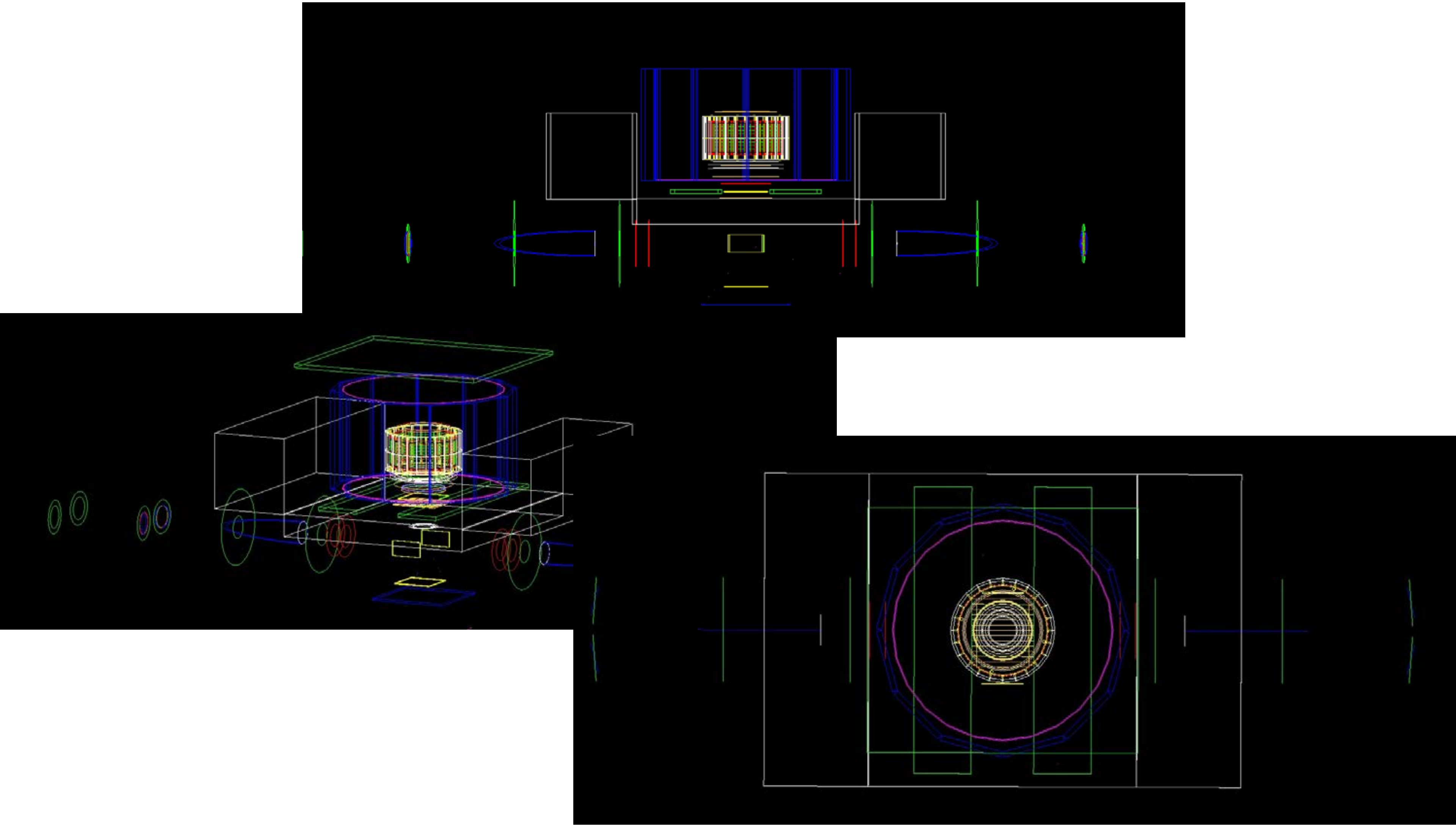


Figure 6. Nearest to optimal configuration of the Mylar degrader: the circle represents the size of the entrance window of the vacuum chamber; direction '*Y*' points to the outer side of the DAΦNE ring, corresponding to the anti-boost side for kaons. The degrader has eight steps to compensate for the boost effect, with thicknesses shown in the lower part of the figure.

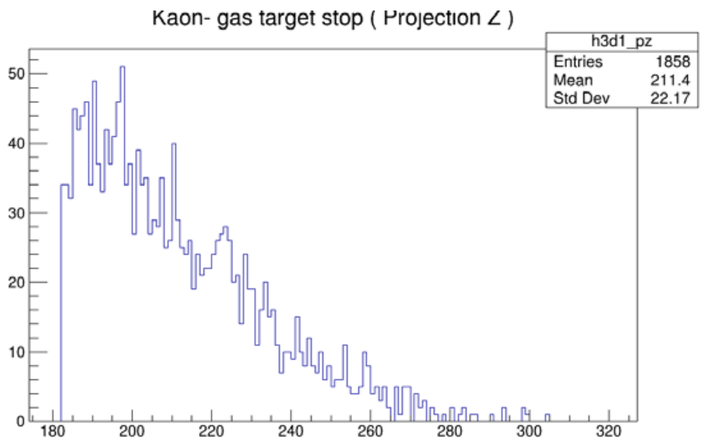


SIDDHARTA-2 Monte Carlo simulation

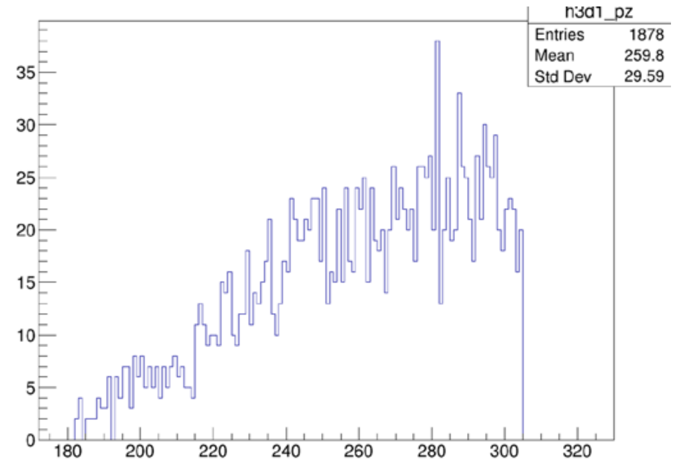


SIDDHARTA-2 Monte Carlo simulation

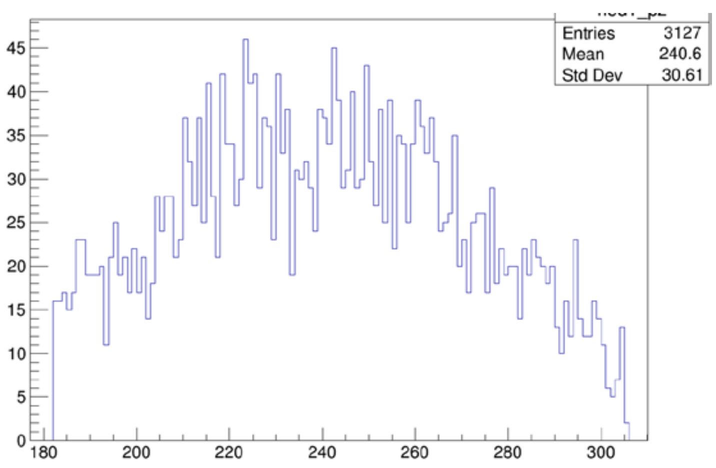
KHe 1.5% LHeD



Degrader : 600 um



Degrader : 350 um

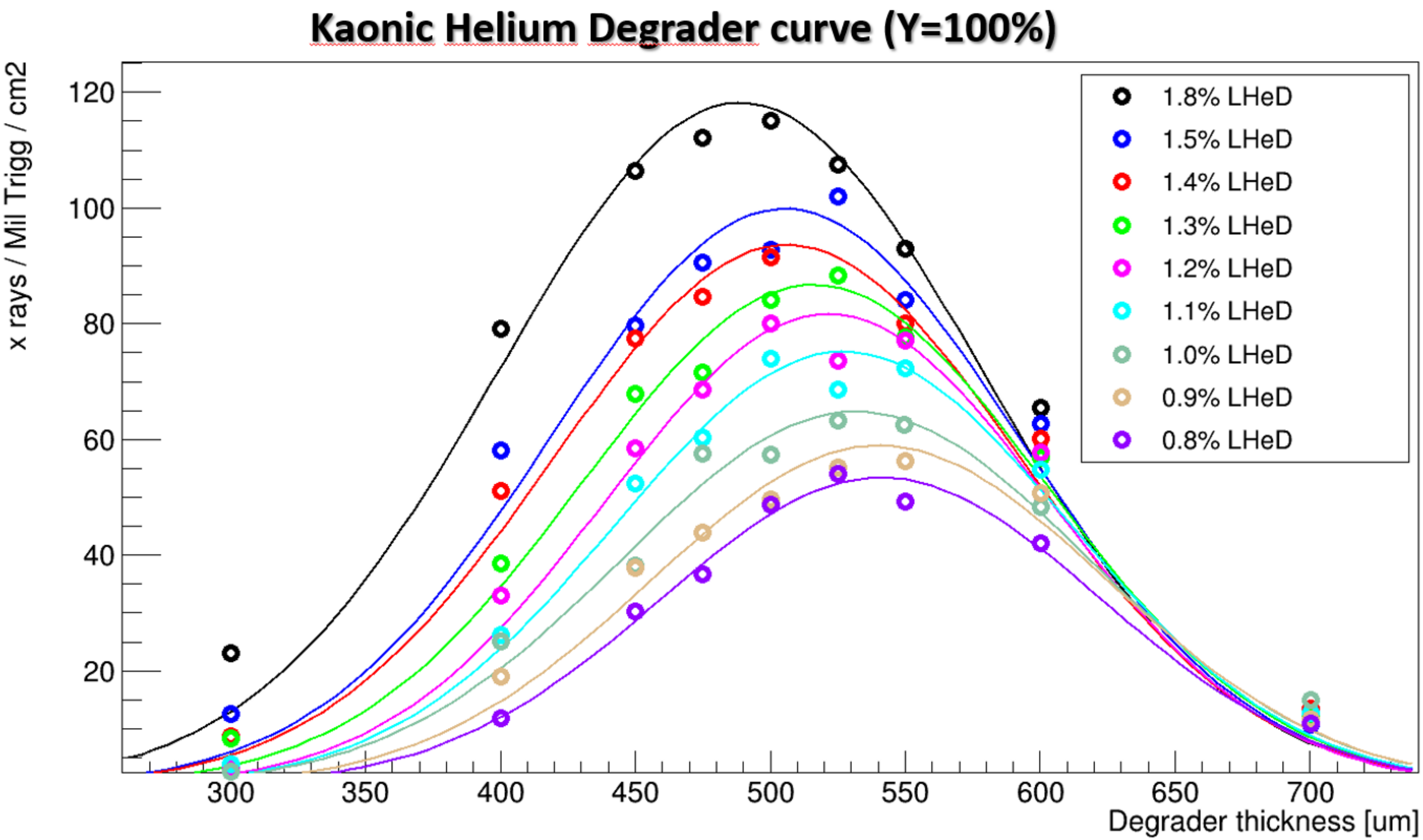


Best Degrader : 500 um

Efficiency of kaon stopped in the target

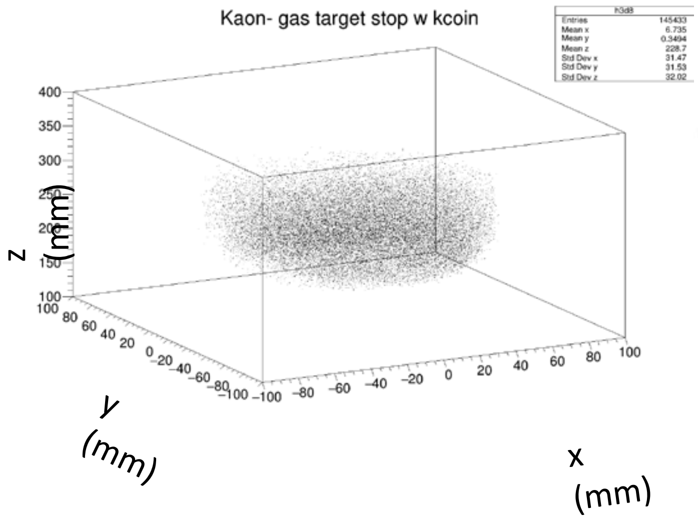
$$\frac{\text{No of kaons (stopped in the target)}}{\text{No of triggered kaons}} \quad \textbf{16,64\%}$$

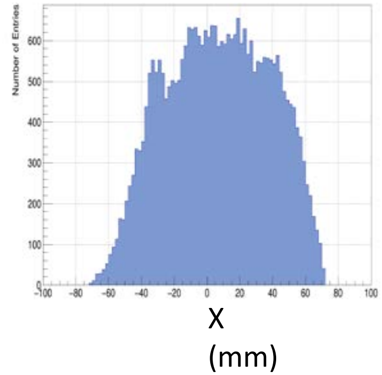
Monte Carlo simulation degrader curve for different degrader configurations

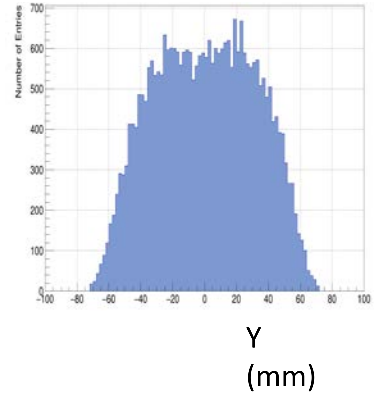


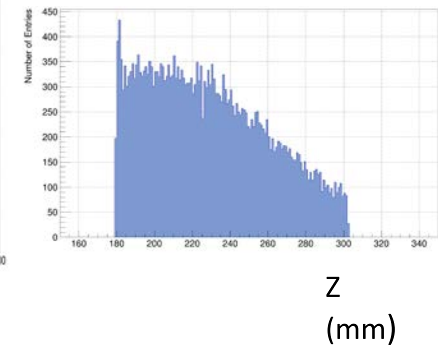
Degrader thickness optimization is fundamental to maximize the number of stopped kaons in the target

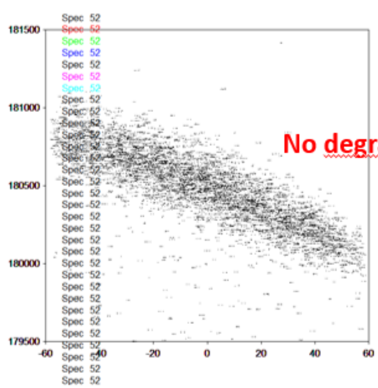
Results for Helium with density 1.5% LDD for the best degrader (500 um thickness)





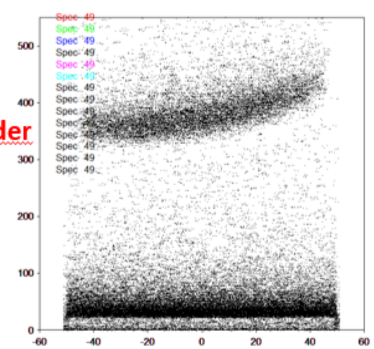




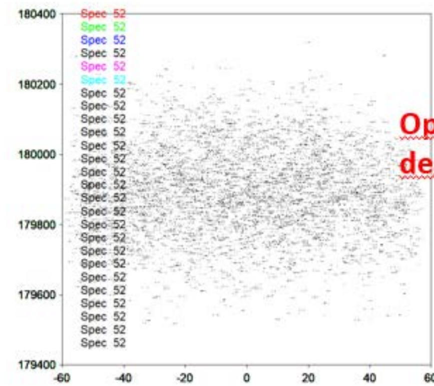


K stopped in the target:
Z vs Y position (boost direction)

No degrader

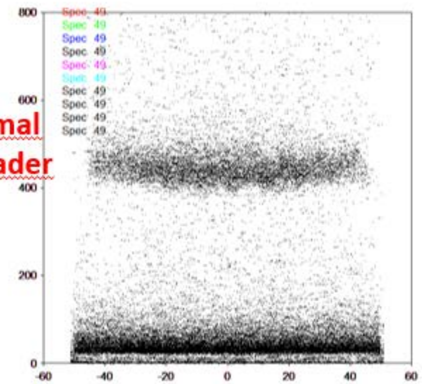


dE in Kaon Monitor Top vs Y (boost direction)



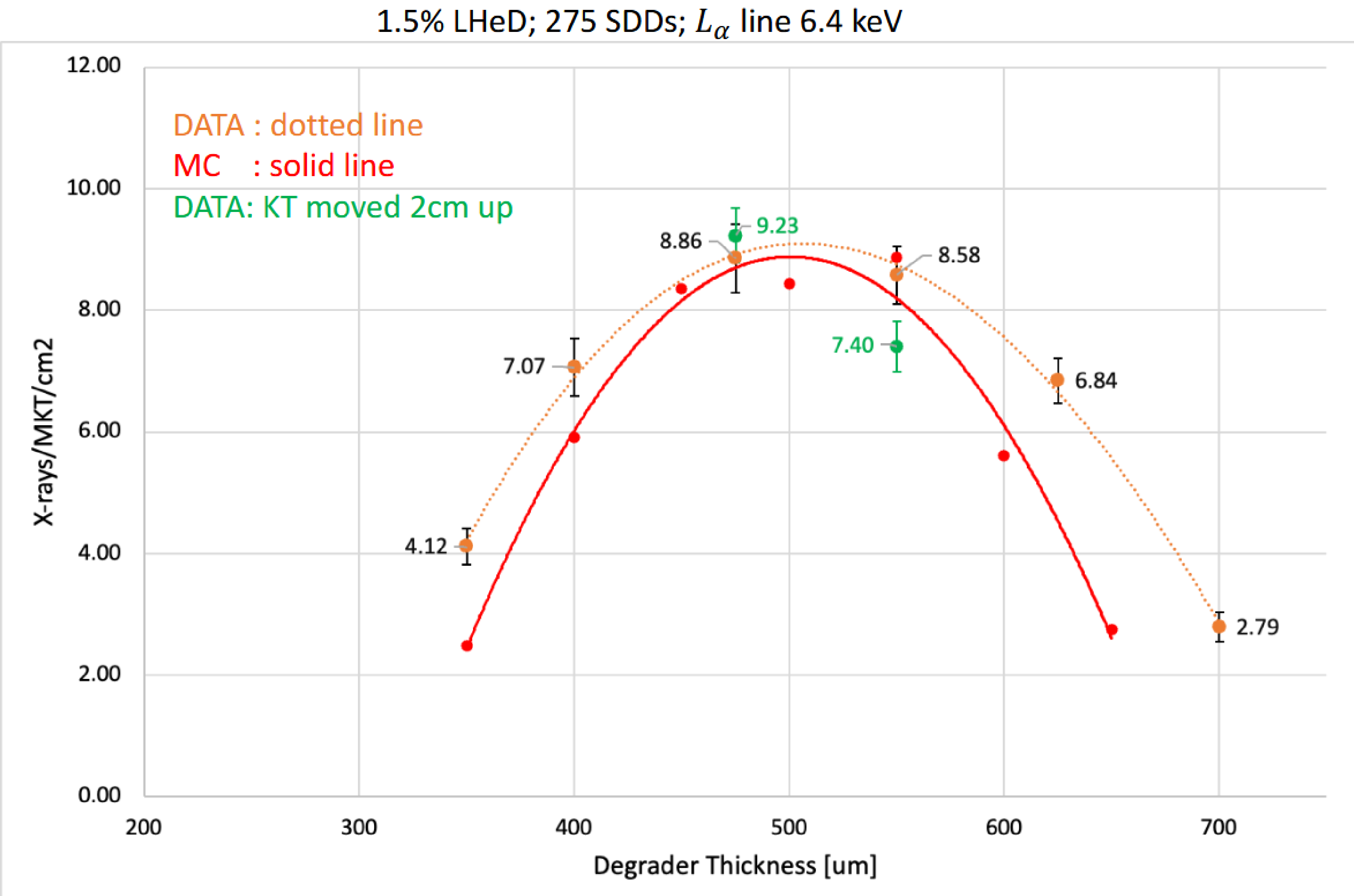
K stopped in the target:
Z vs Y position (boost direction)

Optimal degrader



dE in Kaon Monitor Top vs Y (boost direction)

SIDDHARTA-2 Kaonic Helium – degrader scan

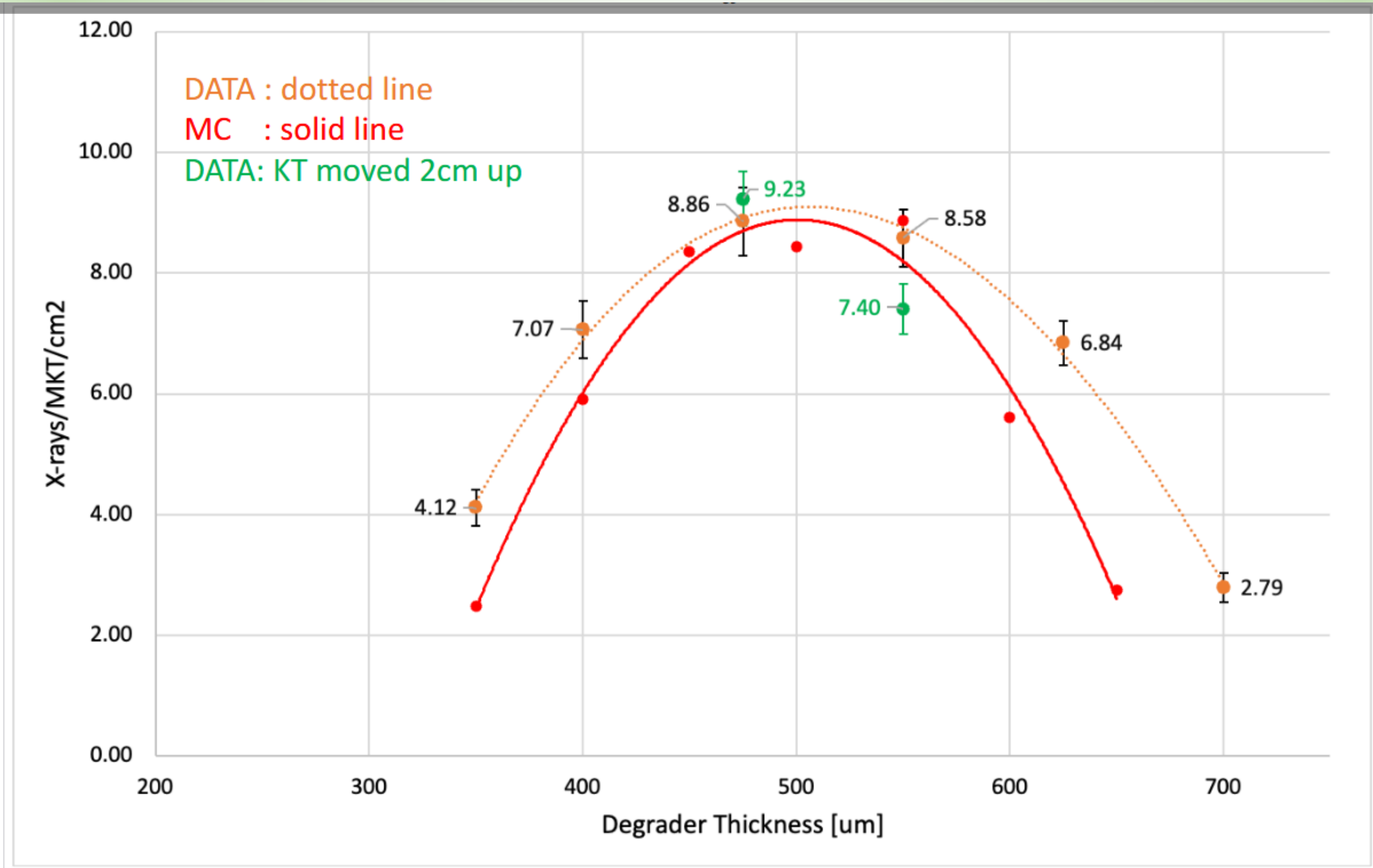


The degrader curve was used to verify the compatibility of the simulation data with the experimental data.

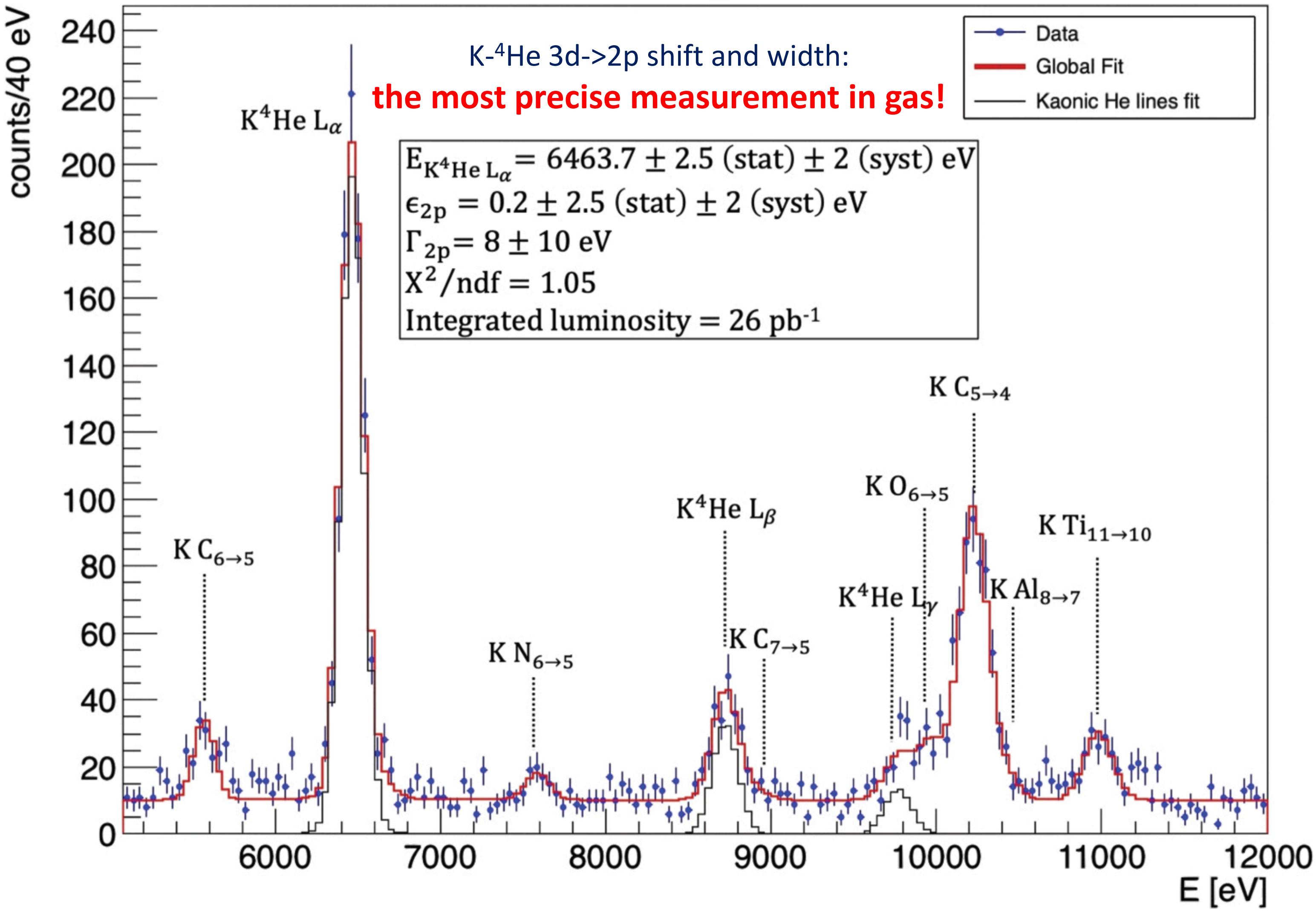
Degrader optimization: sensitivity to 100 microns over all material budget (about 4 mm materials of various densities)!

a very delicate and fundamental operation

(knowledge of material budget at 2.5 % level)



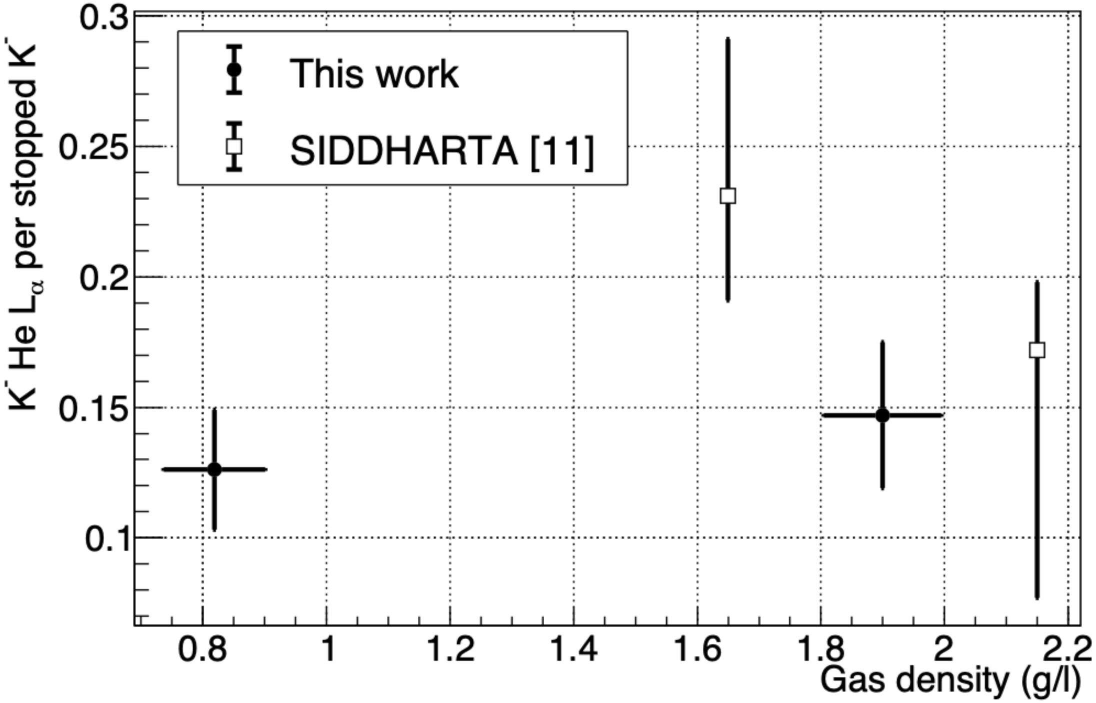
SIDDHARTINO
The kaonic ^{4}He 3d->2p (L_α) measurement



D Sirghi *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* 49 055106

SIDDHARTINO

The kaonic ^{4}He yield measurement



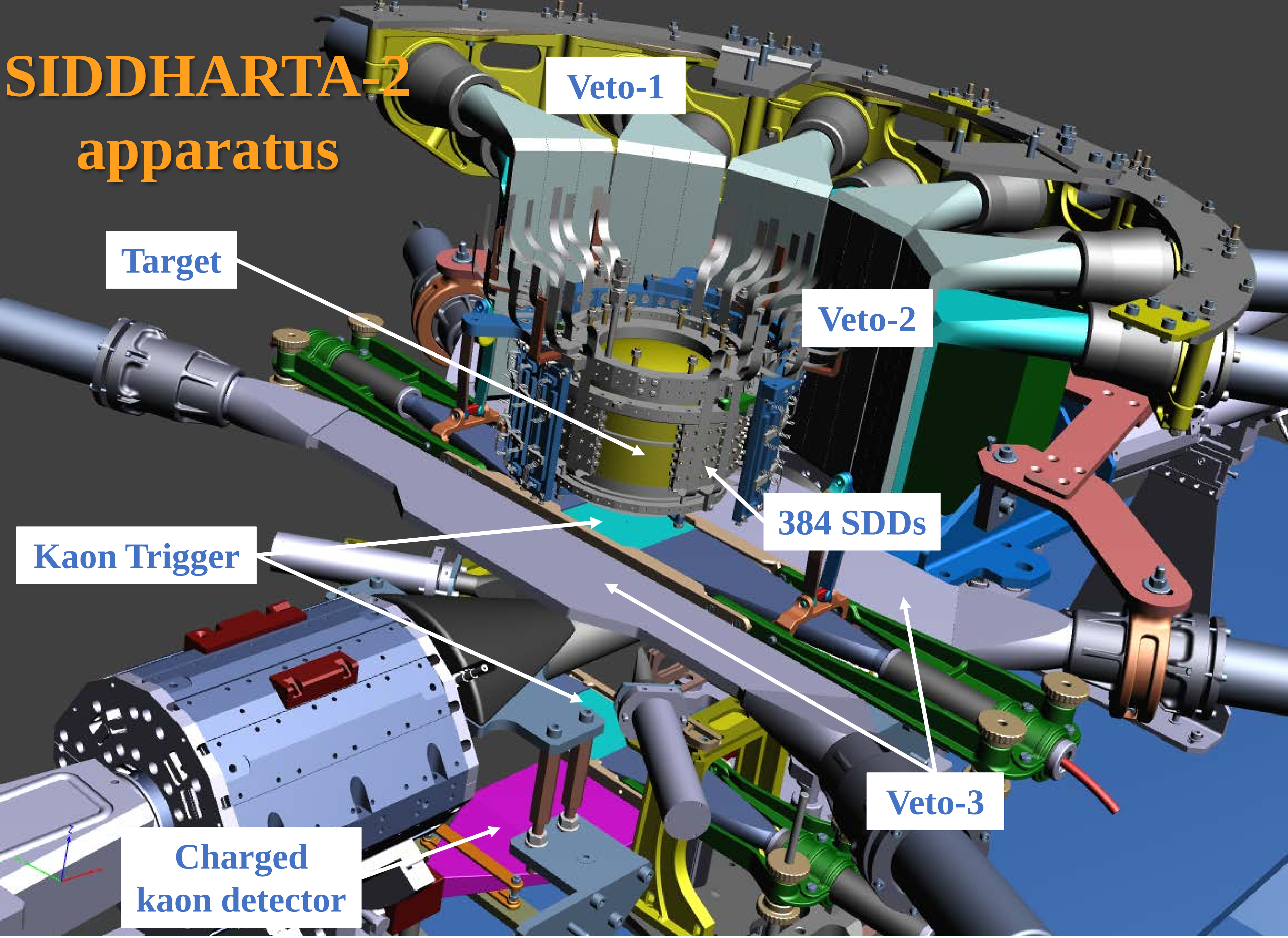
K-^{4}He low density run: 0.75% liquid helium density -> **yields at lowest measured density**

Input of the cascade calculations for exotic atoms

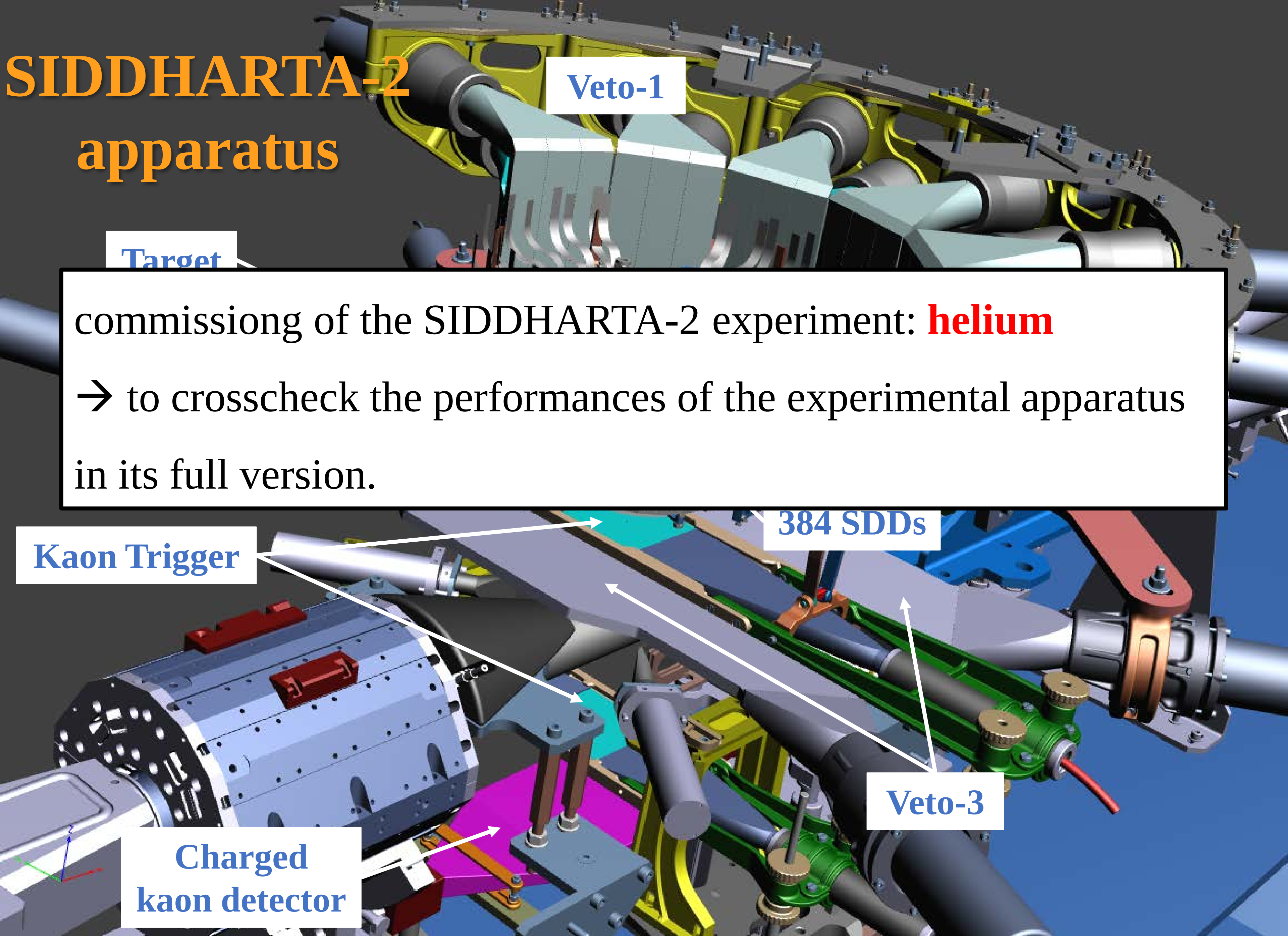
Density	1.90 g/l	0.82 g/l
L_α yield	0.148 ± 0.027	0.126 ± 0.023
L_β/L_α	0.193 ± 0.042	0.133 ± 0.037
L_γ/L_α	0.035 ± 0.015	not detected

D.L. Sirghi, et al. Nuclear Physics A 1029 (2023) 122567

SIDDHARTA-2 apparatus



SIDDHARTA-2 apparatus



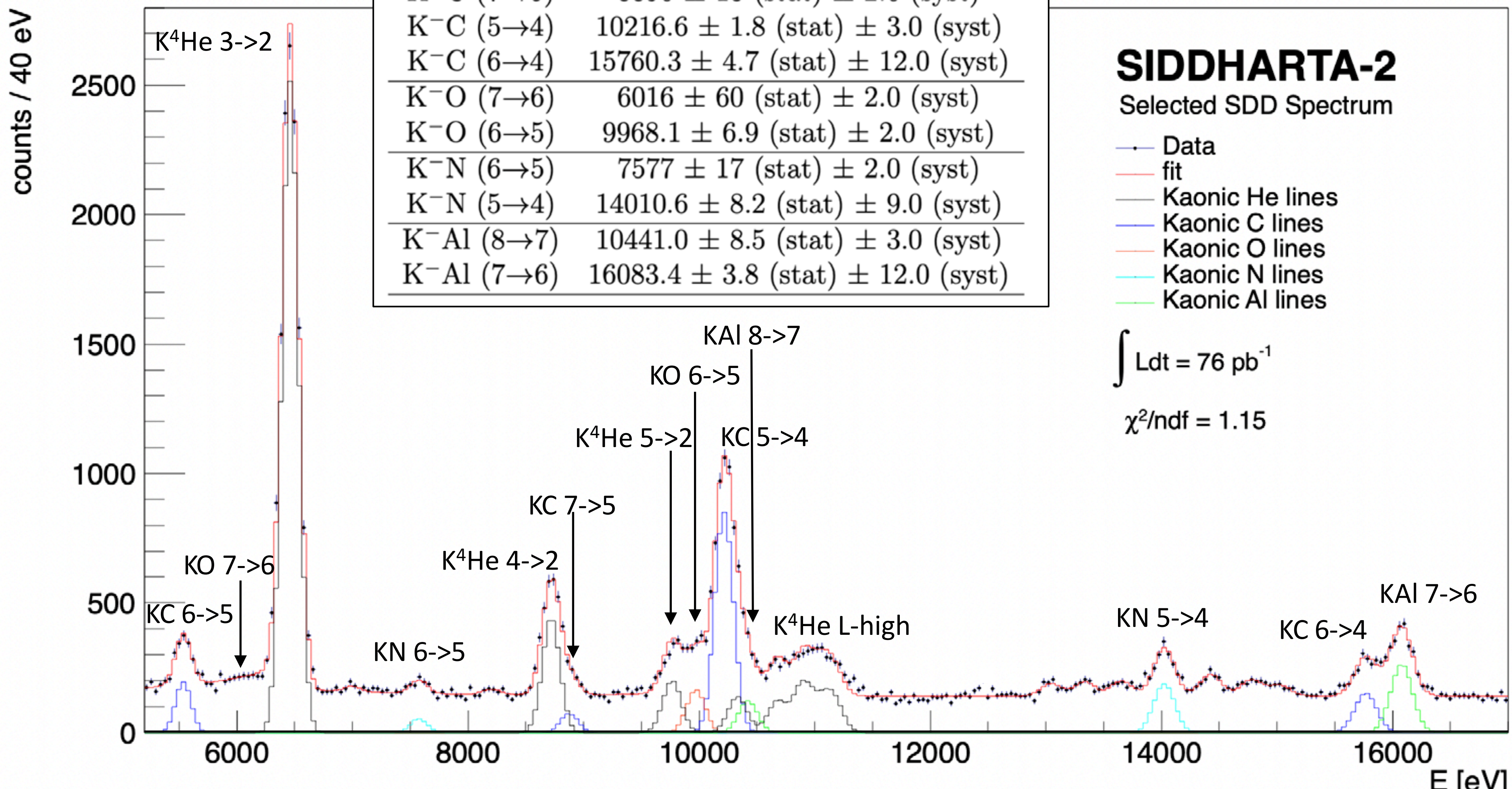
commissiong of the SIDDHARTA-2 experiment: **helium**

→ to crosscheck the performances of the experimental apparatus in its full version.

Measurements of high-n transitions in intermediate mass kaonic atoms

SIDDHARTA-2 (2022)

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., al. Eur. Phys. J. A 59, 56 (2023)

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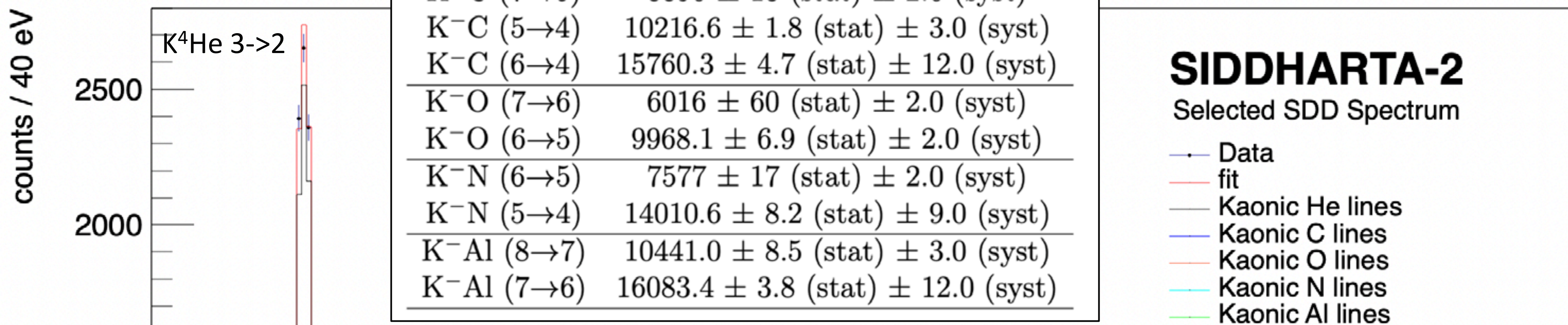
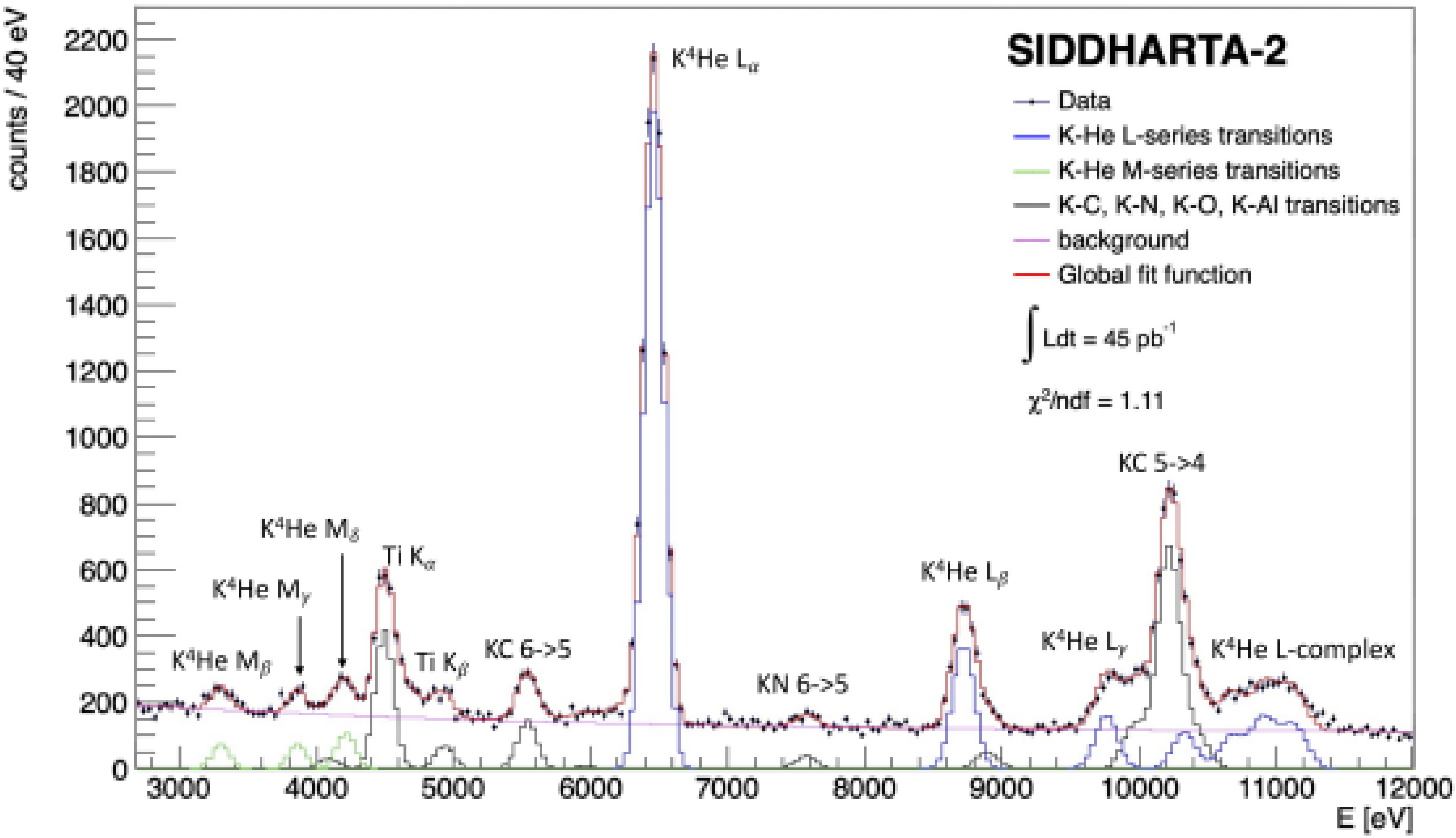


The new kaonic atoms measurements:

- **add valuable input to the kaonic atoms transitions data base**, which is used as a reference for theories and models of the low-energy strong interaction between antikaon and nuclei
- pave the way for **future dedicated kaonic atoms measurements through the whole periodic table** and to a **new era for the antikaon-nuclei studies at low energy**

SIDDHARTA-2
Kaonic ^{4}He – M-type transitions



Paper ready to be submitted to *J. Phys. G: Nucl. Part. Phys.*

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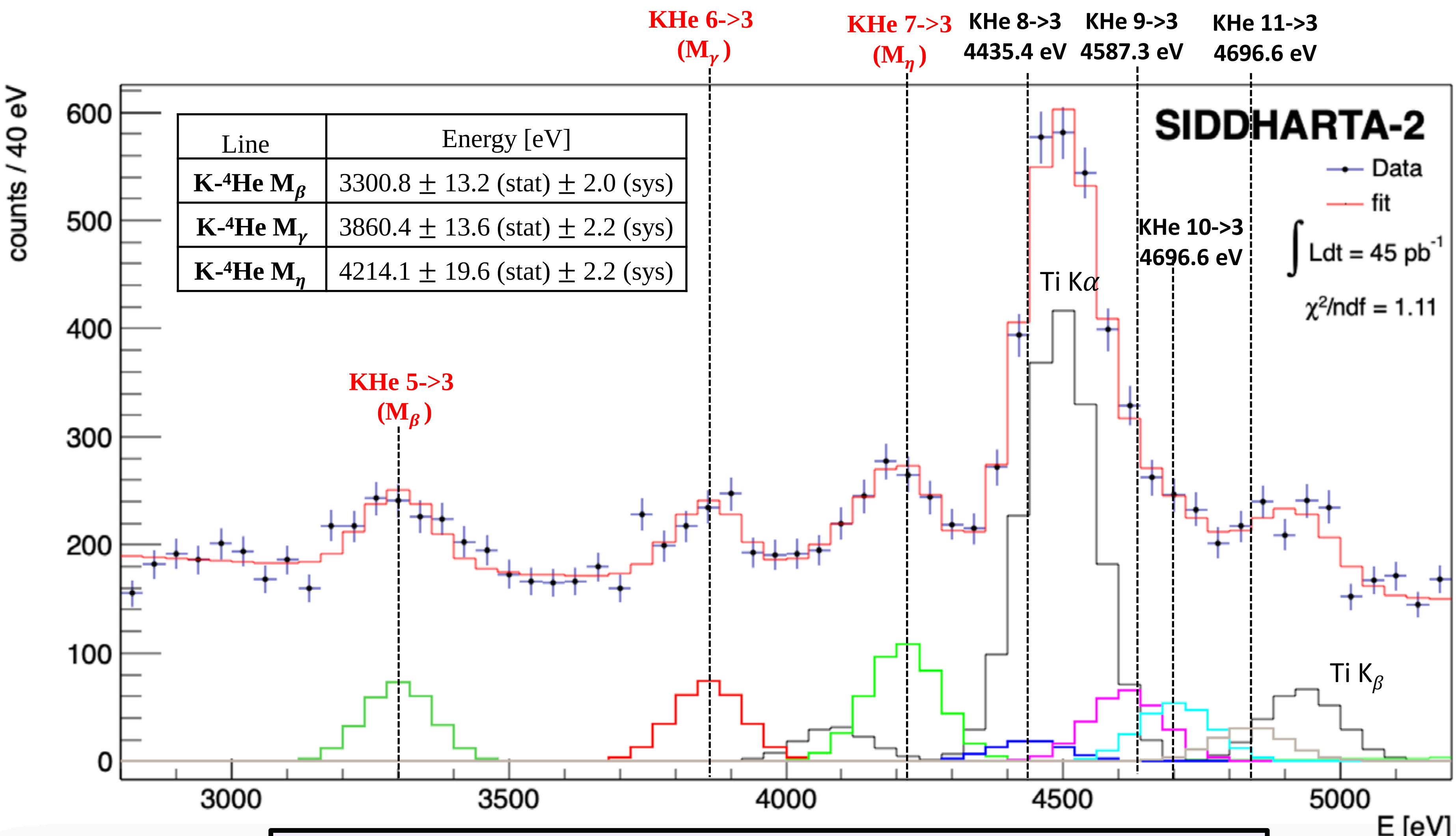


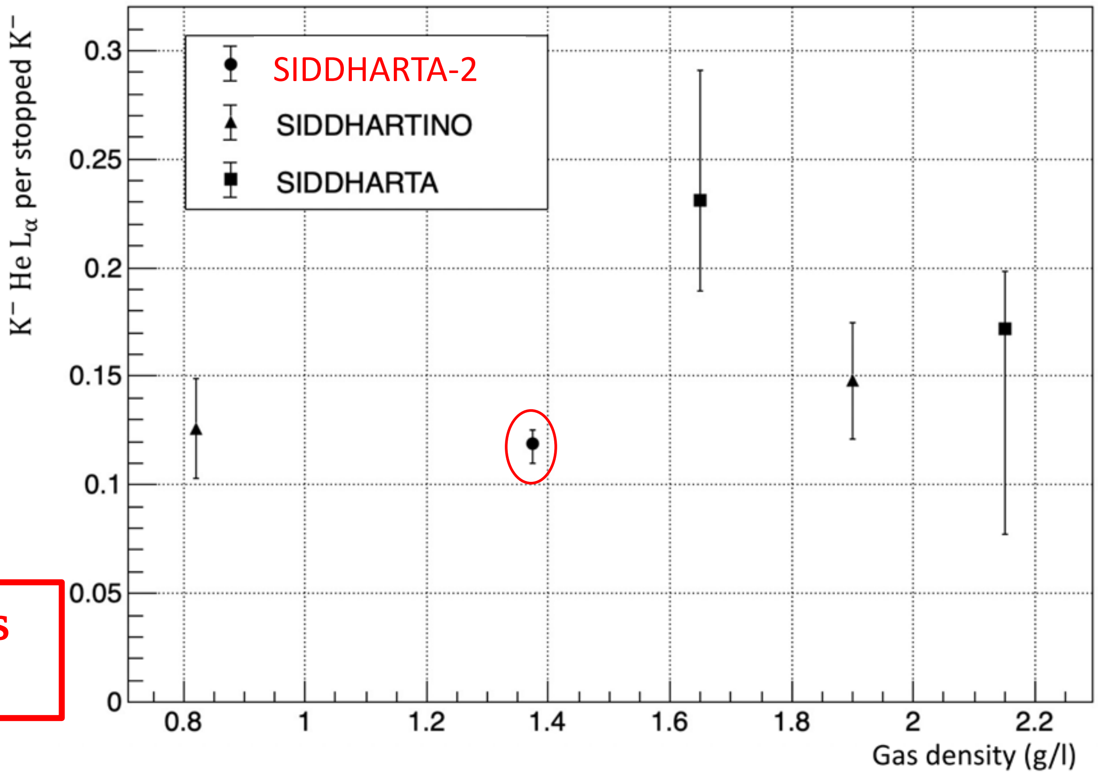
Line	Energy [eV]
K-^{4}He M_β	3300.8 ± 13.2 (stat) ± 2.0 (sys)
K-^{4}He M_γ	3860.4 ± 13.6 (stat) ± 2.2 (sys)
K-^{4}He M_η	4214.1 ± 19.6 (stat) ± 2.2 (sys)

Paper ready to be submitted to *J. Phys. G: Nucl. Part. Phys.*

SIDDHARTA-2
Kaonic ^{4}He yield

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

first experimental measurement of the M-series transitions yields, providing new experimental data to optimize the cascade models for kaonic helium



develop cascade models across the density scale

Outcomes

- **The SIDDHARTINO experiment has successfully been concluded during the commissioning phase of the collider in 2021.**

- **SIDDHARTA-2 at DAFNE**
  - Installation of the full SIDDHARTA-2 setup
  - Kaonic ^{4}He test run concluded in July 2022

✓ **Performed the most precise K-^{4}He 3d → 2p measurement in gas**
✓ **Several solid target high-n transition energies measured for the first time**
✓ **The first measurement of the M-series transitions energies and yields of the K-^{4}He**

Outcomes

The SIDDHARTINO experiment sets the ground for the kaonic deuterium measurement with the SIDDHARTA-2 experiment, which starts the data acquisition campaign in 2022 and continuing in 2023 and 2024, for an overall integrated luminosity of 800 pb^{-1}.

Other types of kaonic atom measurements with various radiation detectors are presently under consideration, to be proposed and performed after the SIDDHARTA-2 run. (see talk of F. Sgaramella)

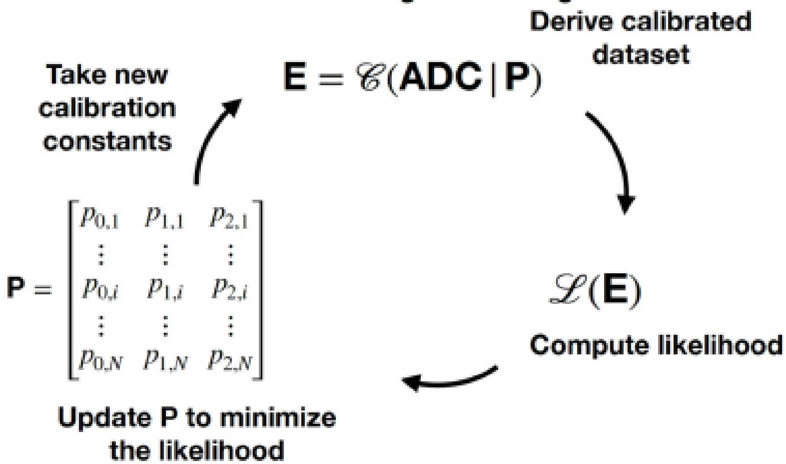
They could further contribute to a deeper understanding of the strong interaction in the low-energy regime in the strangeness sector, impacting particle and nuclear physics and also astrophysics.


THANK YOU

SPARE

SDD energy calibration with ML and Differential Programming

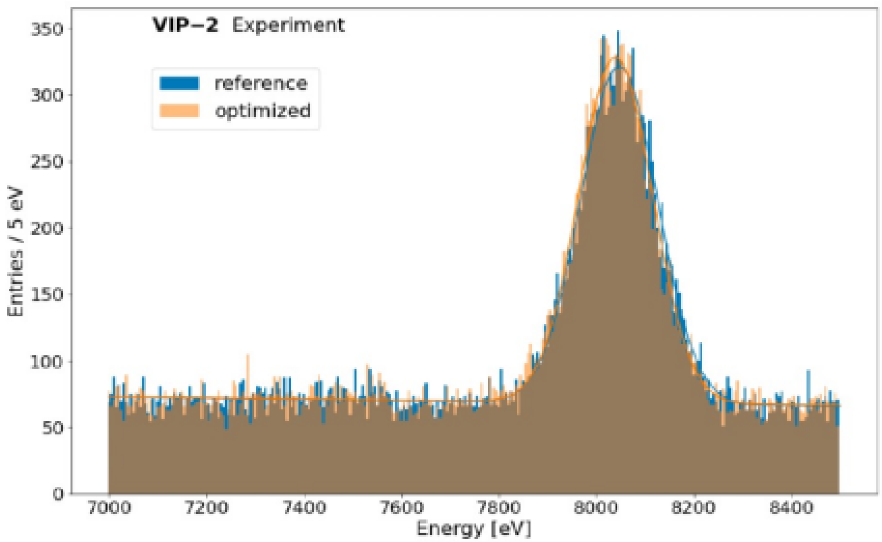
Loss function for the gradient: log likelihood



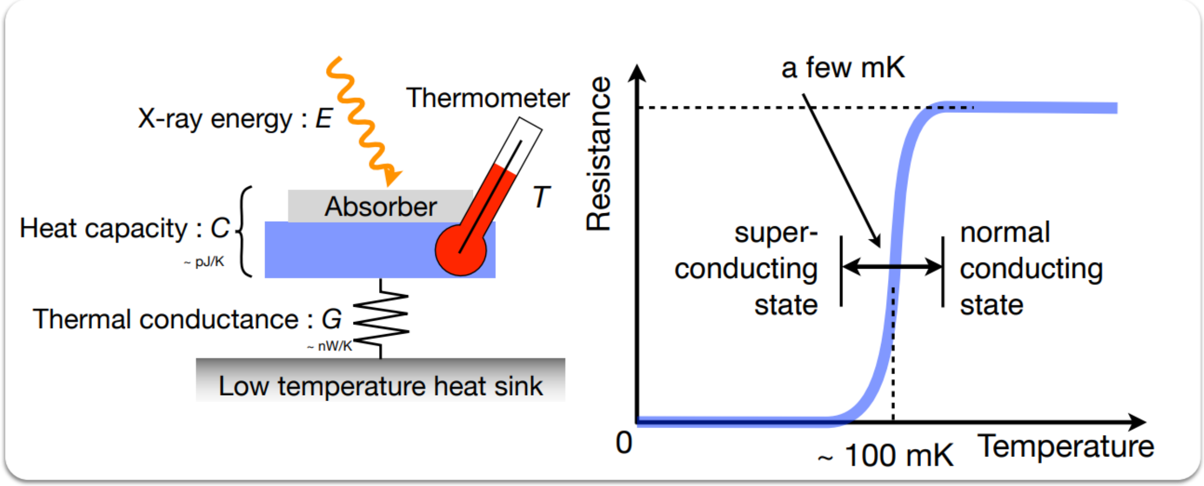
	Position [eV]	FWHM [eV]	χ^2/ndf
Reference	8050 ± 1	185 ± 2	1.64
Optimized	8048 ± 1	176 ± 2	1.25

F. Napolitano et al. paper accepted for publication on Meas. Sci. and Tech.

The method can correct for miscalibration improving the systematic error

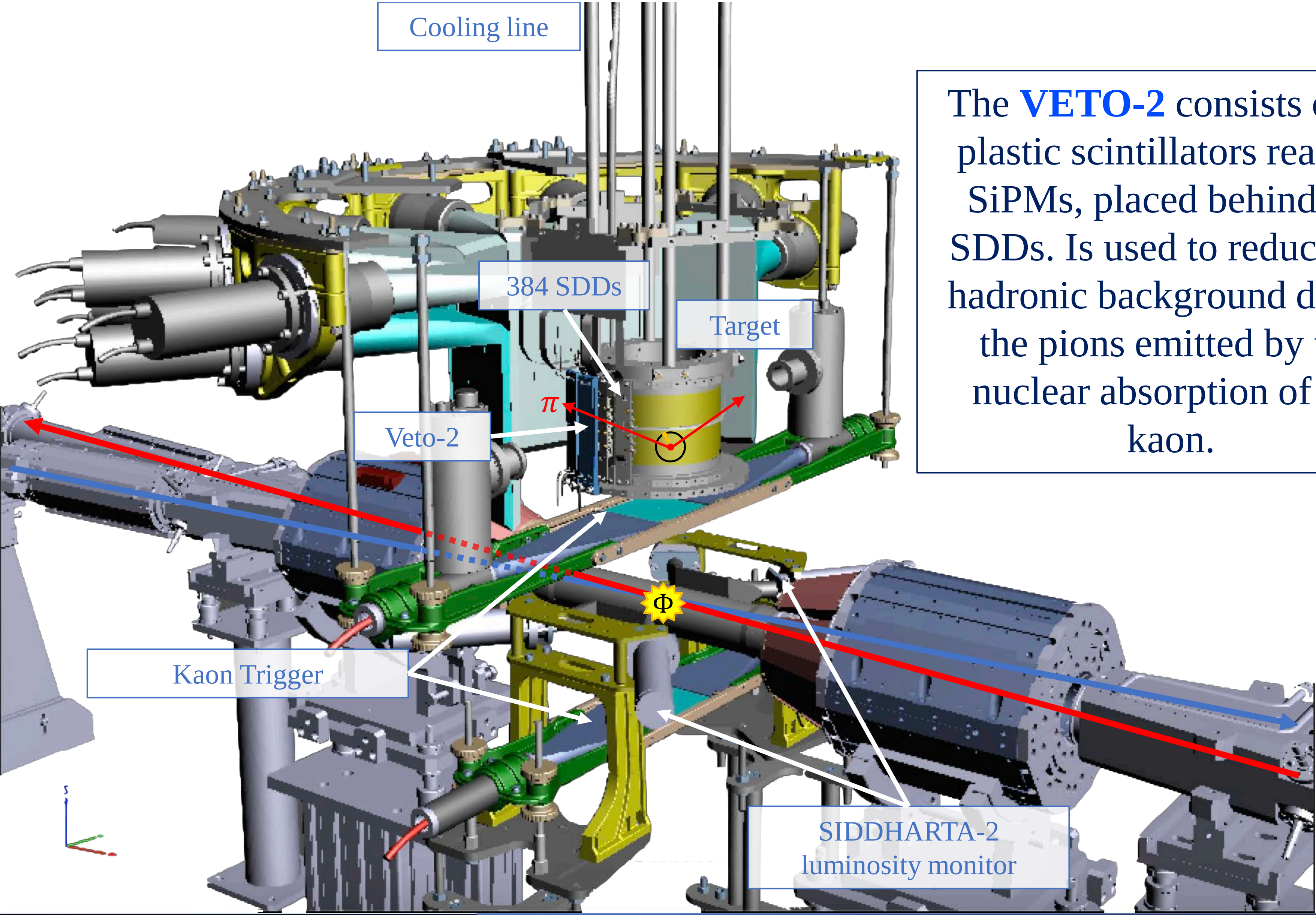


Transition-Edge-Sensor microcalorimeters



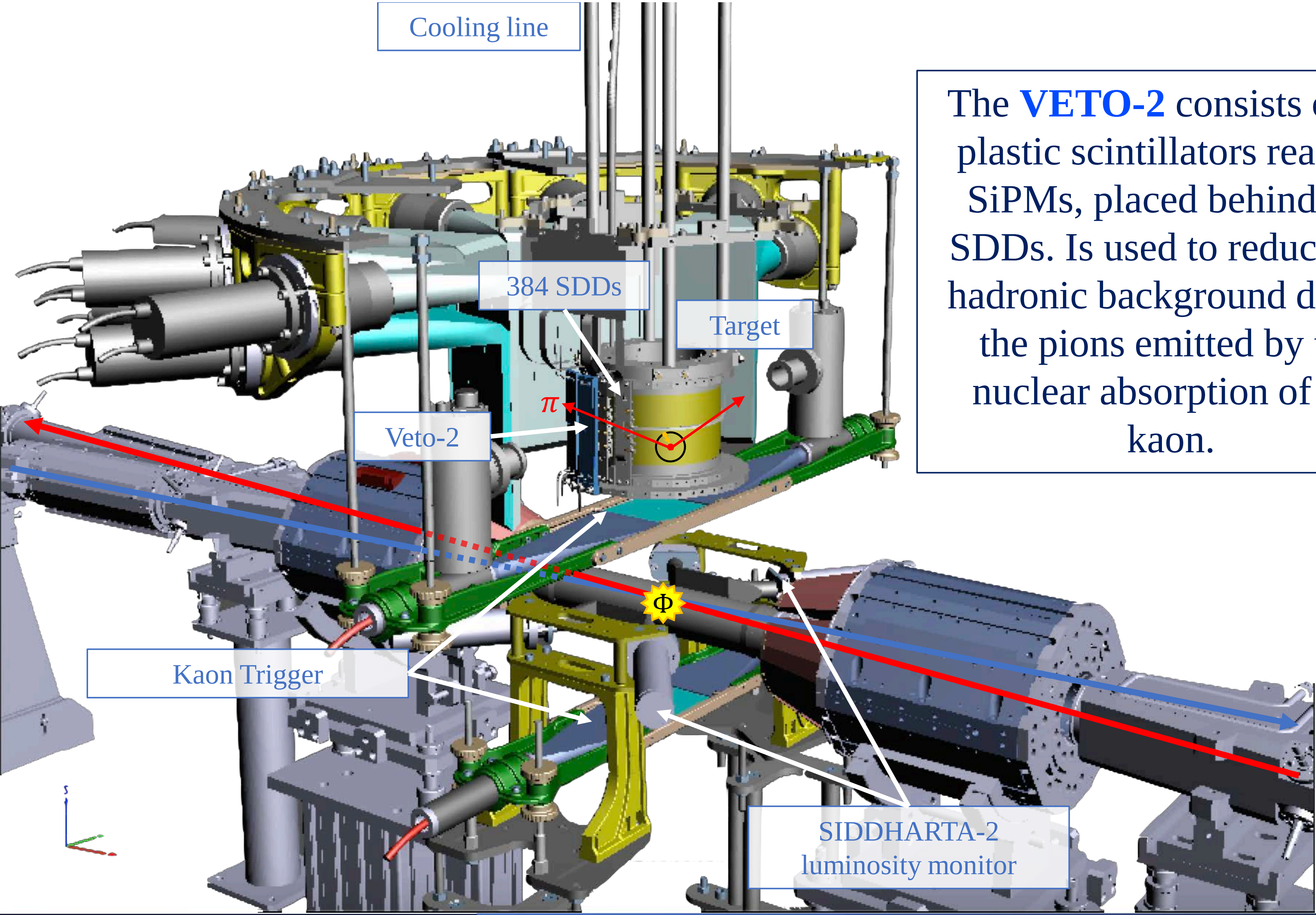
- ✓ Excellent energy resolution **~5 eV FWHM**
- ✓ Reasonable dynamic range **4-15 keV**
- ✓ Multiplexing technique using SQUID **240 pixels**

SIDDHARTA-2 setup



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 setup



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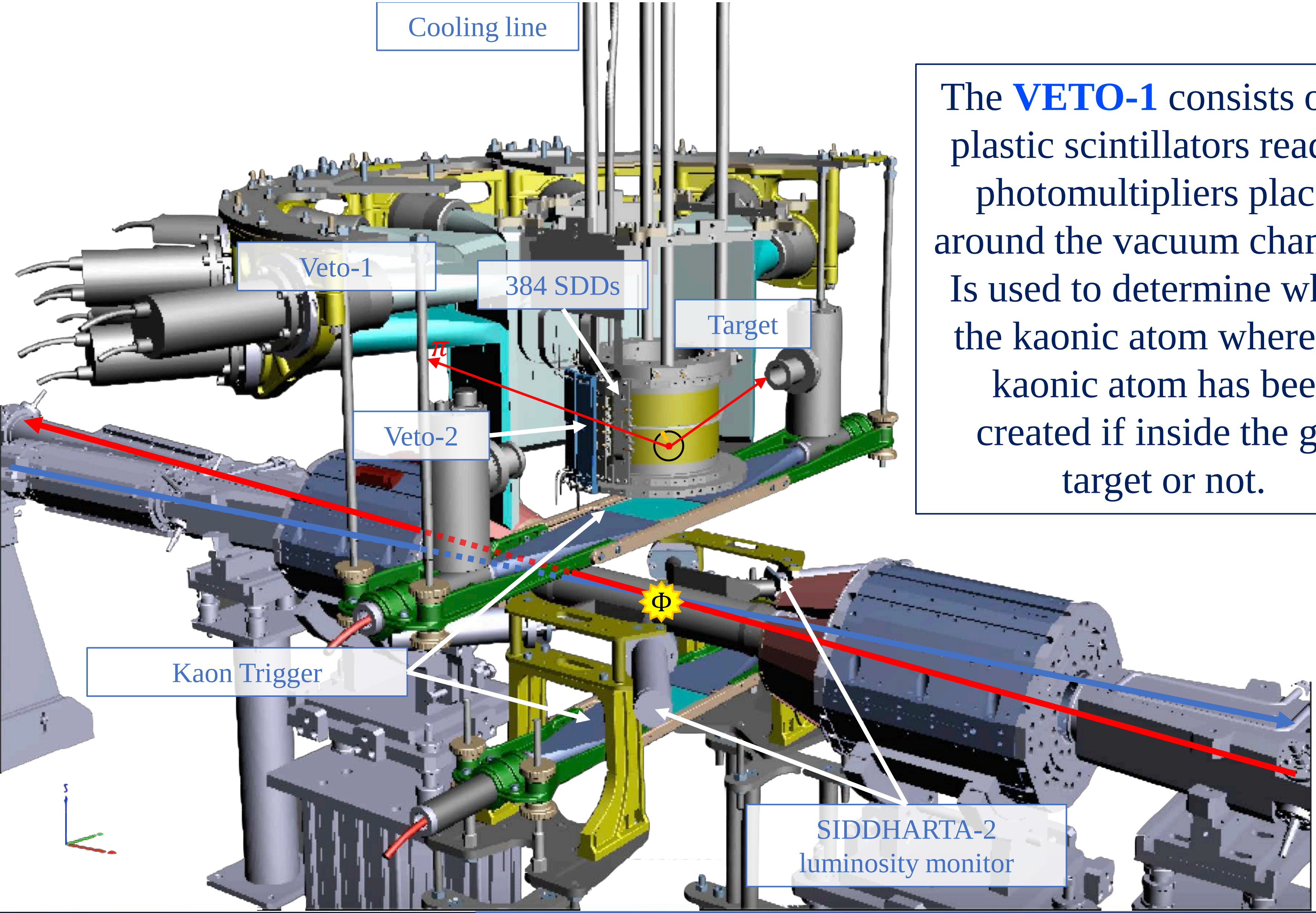
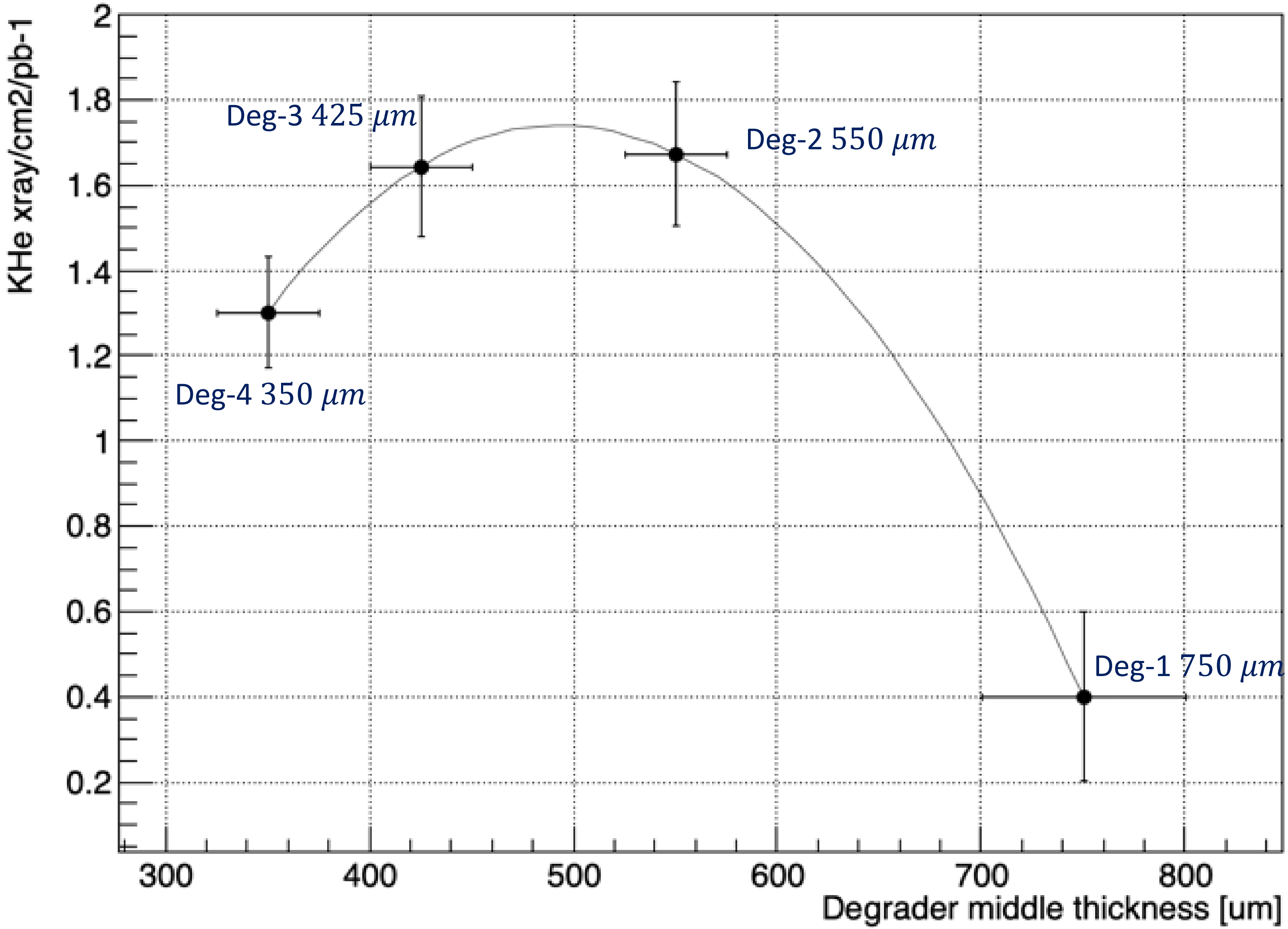


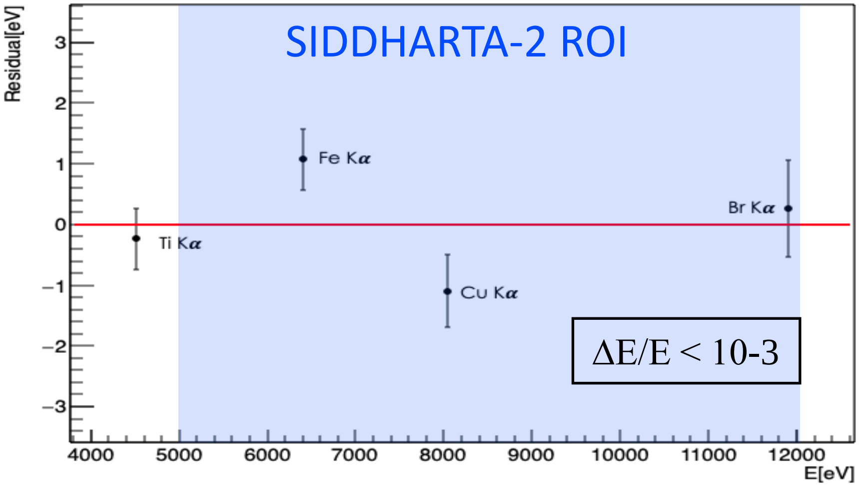
The **VETO-1** consists of 12 plastic scintillators read by photomultipliers placed around the vacuum chamber. Is used to determine where the kaonic atom where the kaonic atom has been created if inside the gas target or not.

Degrader Curve

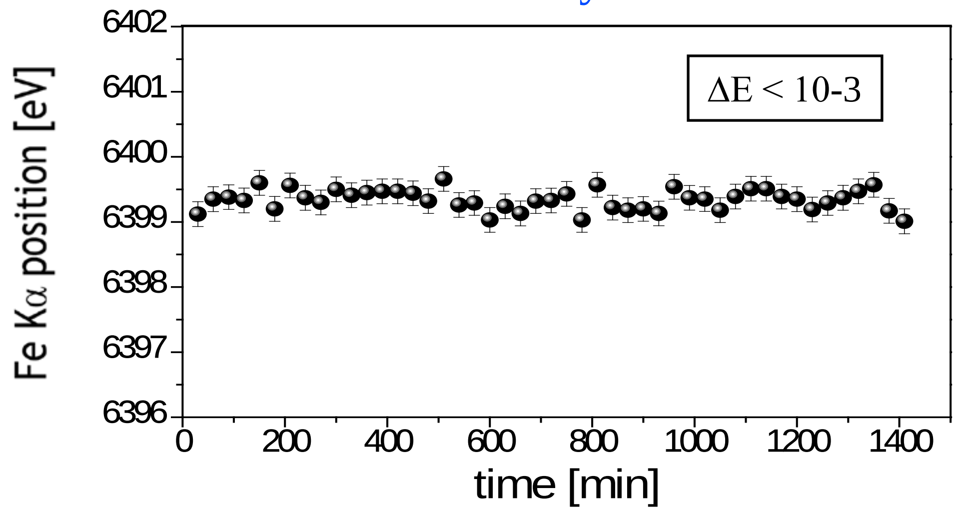


Silicon Drift Detectors

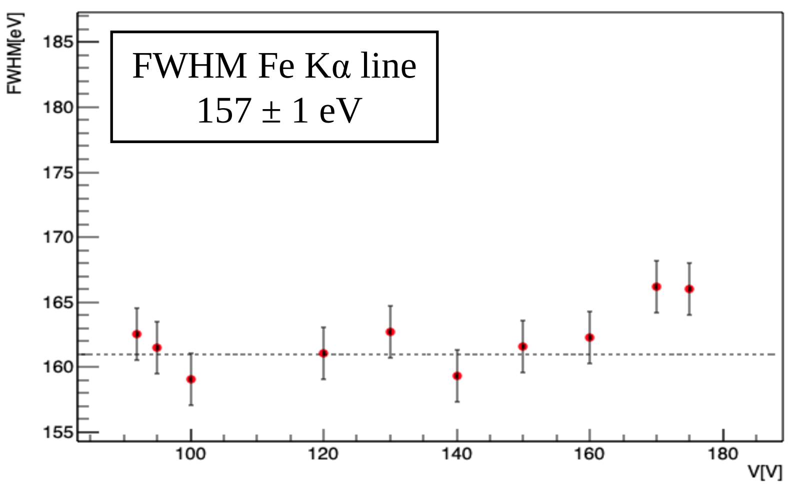
Linearity



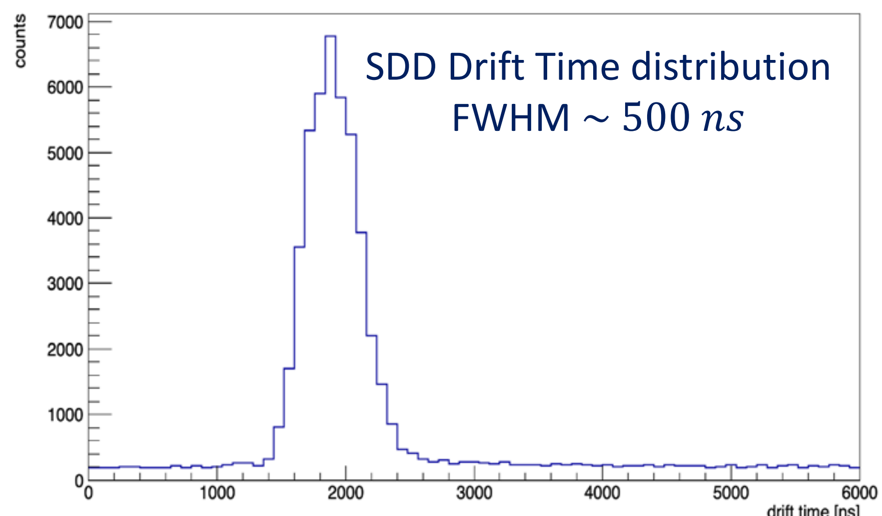
Stability



Energy Resolution



Timing Resolution



M Miliucci *et al* 2021 *Meas. Sci. Technol.* **32** 095501