

European Nuclear Physics Conference 2022 (EuNPC2022)

24–28 Oct 2022

University of Santiago de Compostela

Kaonic Atoms with SIDDHARTA-2 at the DAFNE Collider



*Francesco Sgaramella
on behalf of the SIDDHARTA-2 Collaboration*

STRONG-2 20

INFN
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

Why Kaonic Atoms?

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

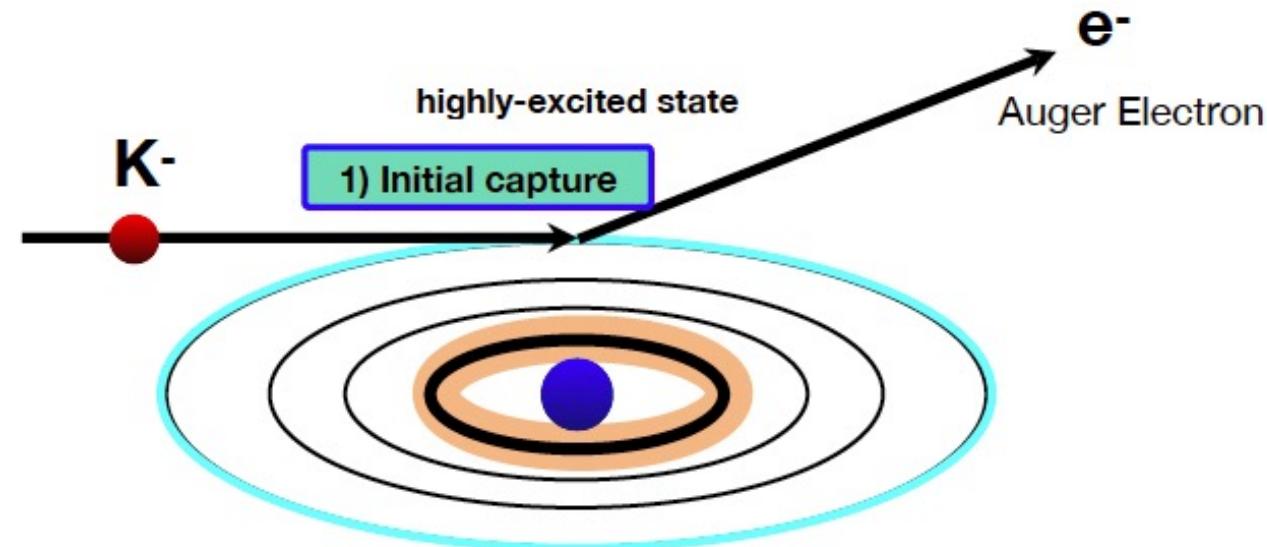
Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

Astrophys. J. 881 (2019) 2, 122

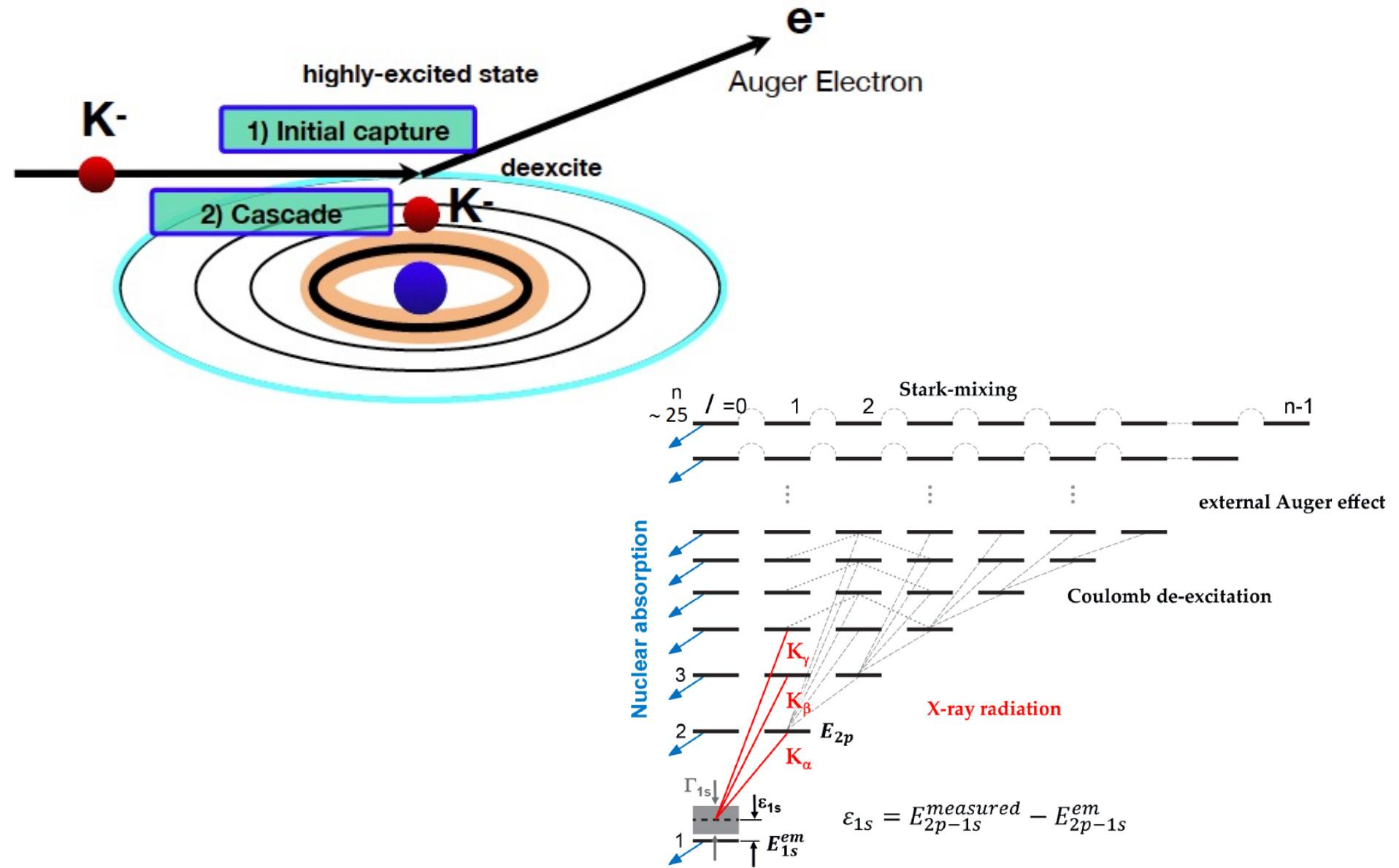
Astrophysics
EOS Neutron Stars

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

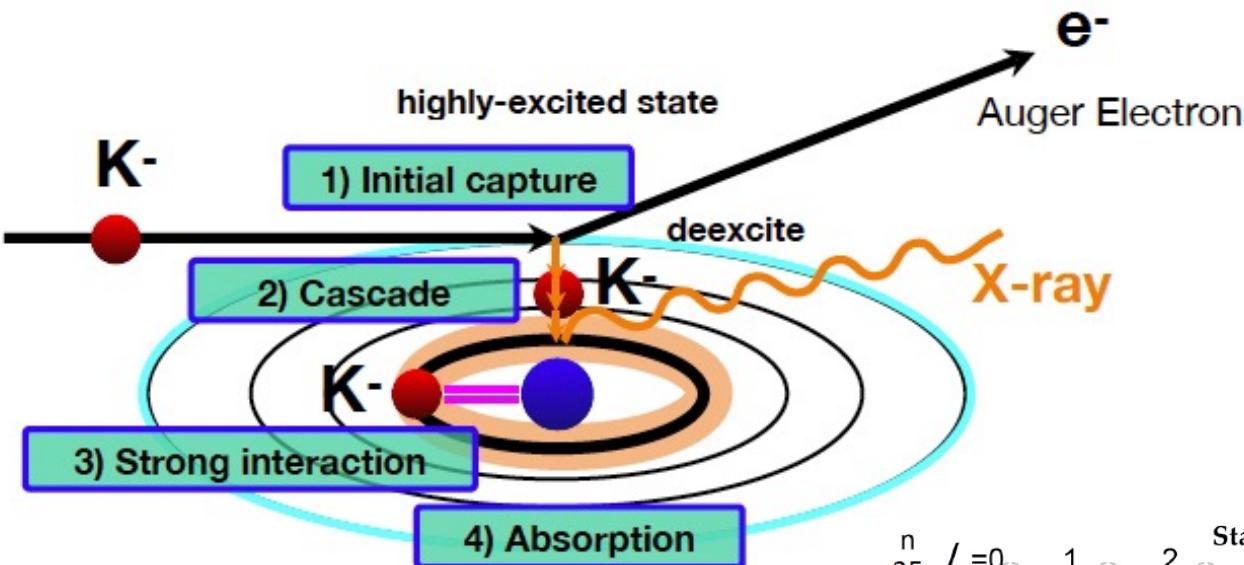
Kaonic atom Formation



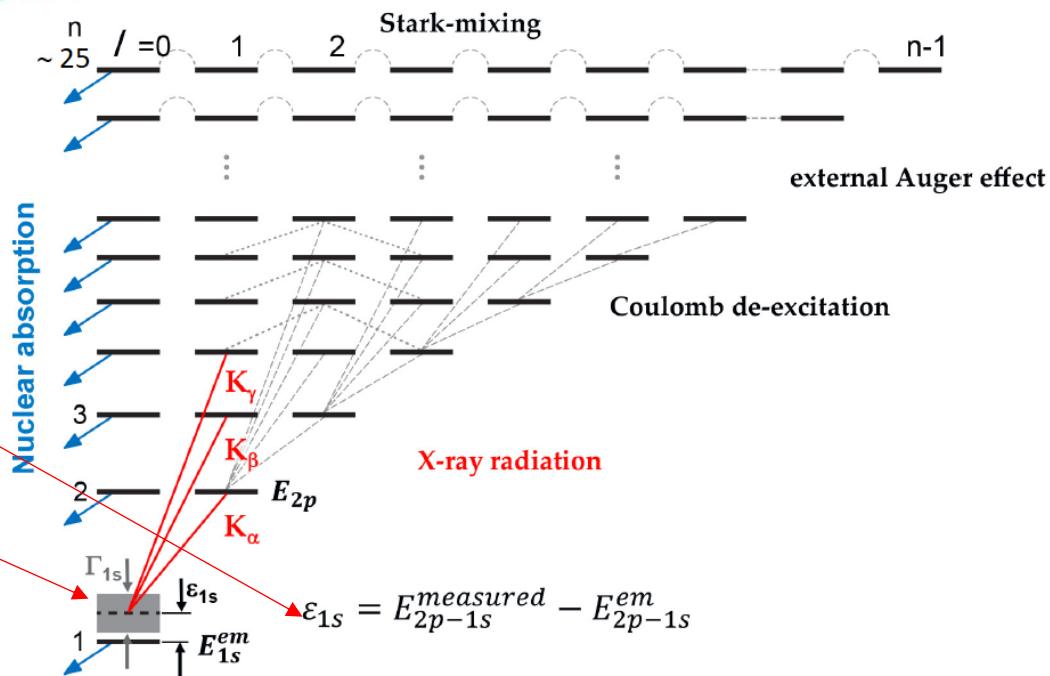
Kaonic atom Formation



Kaonic atom Formation

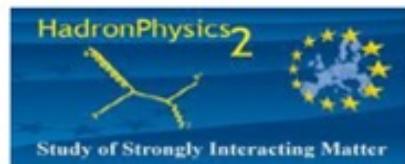


Width Γ and shift ε
obtained by measuring
the X-rays emitted



SIDDHARTA-2

Siilicon Drift Detector for Hadronic Atom Research by Timing Applications



FWF
Der Wissenschaftsfonds.

LNF-INFN, Frascati, Italy

SMI-ÖAW, Vienna, Austria

Politecnico di Milano, Italy

IFIN –HH, Bucharest, Romania

TUM, Munich, Germany

RIKEN, Japan

Univ. Tokyo, Japan

Victoria Univ., Canada

Univ. Zagreb, Croatia

Helmholtz Inst. Mainz, Germany

Univ. Jagiellonian Krakow, Poland

ELPH, Tohoku University

CERN, Switzerland



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.

SIDDHARTA-2 Scientific Goal

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Analysis of the combined measurements of kaonic deuterium and kaonic hydrogen

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

(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

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

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



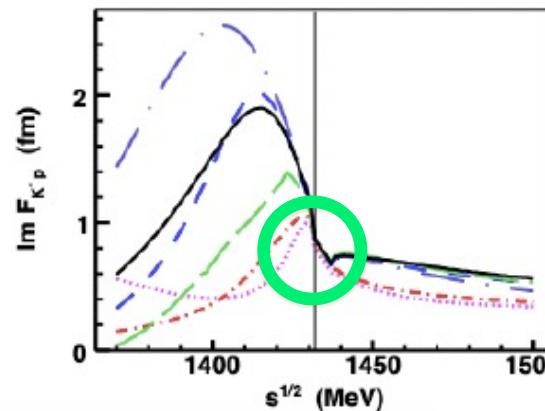
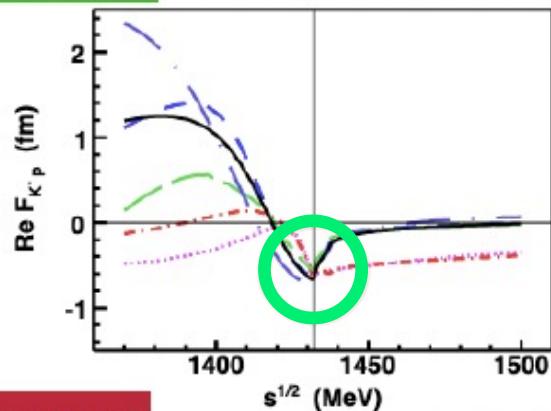
$$a_{K^- d} = \frac{k}{2} [a_{K^- p} + a_{K^- n}] + C = \frac{k}{4} [a_0 + 3a_1] + C$$

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

completely solve Isospin-dependent K-N scattering length

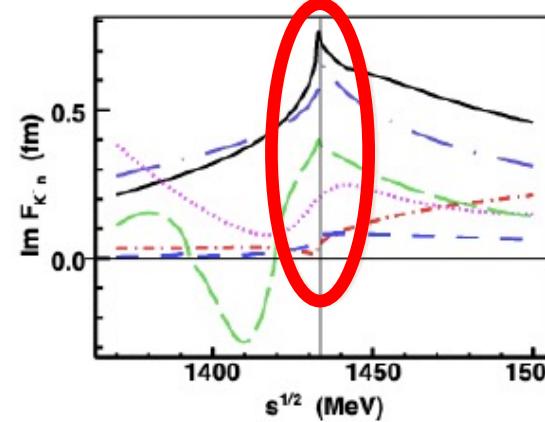
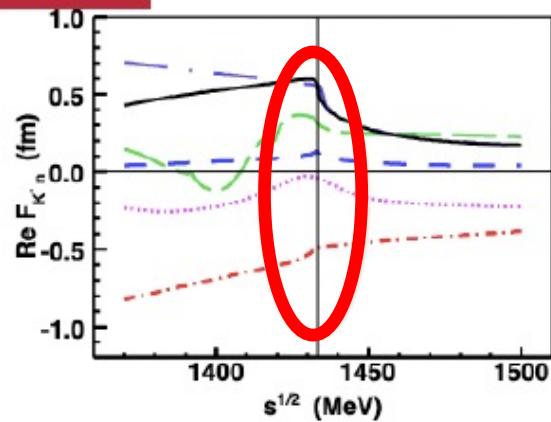
Kaonic atoms – scattering amplitudes

K-p: agreement



Bonn (B_2)
Bonn (B_4)
Murcia (M_I)
Murcia (M_{II})
Prague (P_{NLO})
Kyoto-Munich (KM_{NLO})

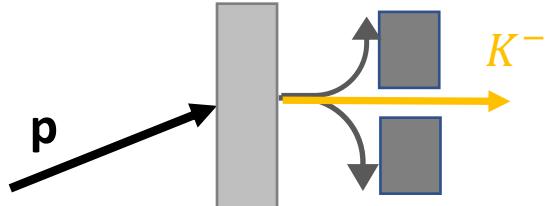
K-n: disagreement



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

Kaon Beam Source

J-PARC

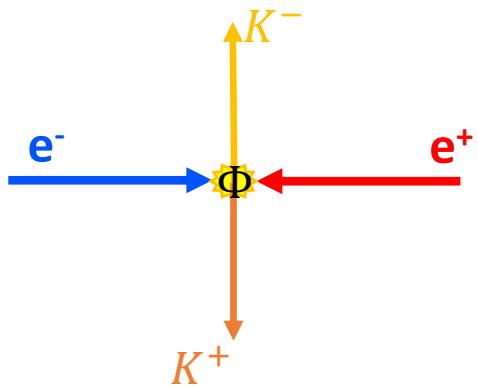


High intensity

High background



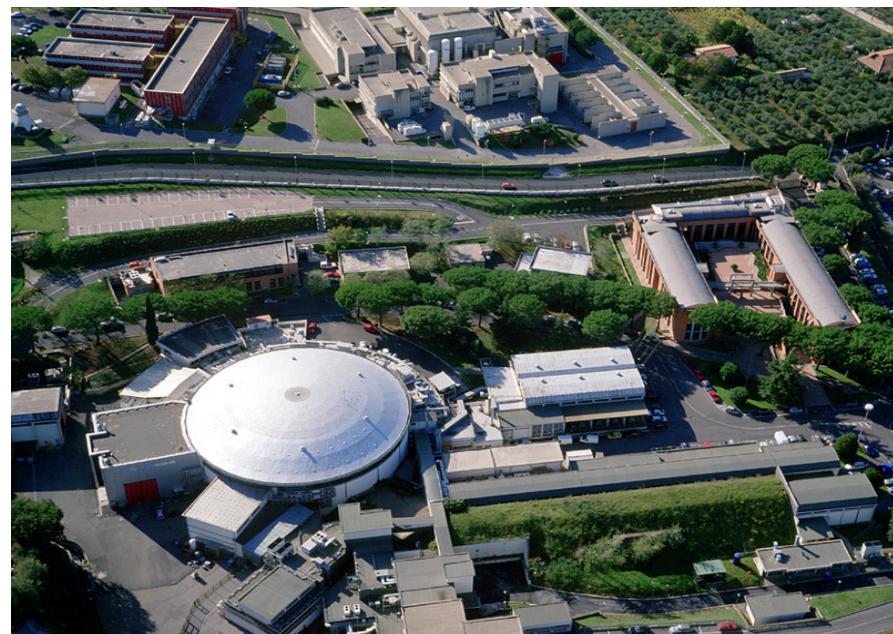
DAΦNE Collider



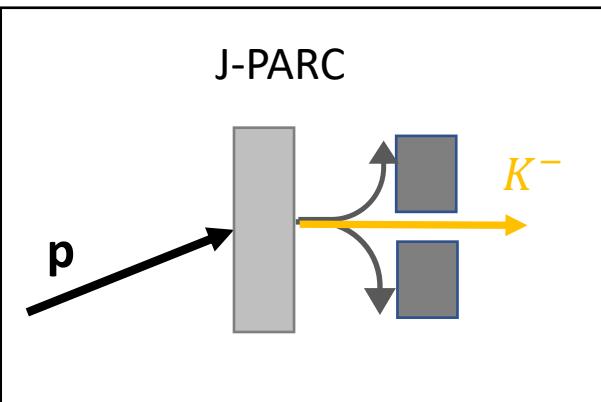
Monochromatic

Low energy kaons

Solid angle

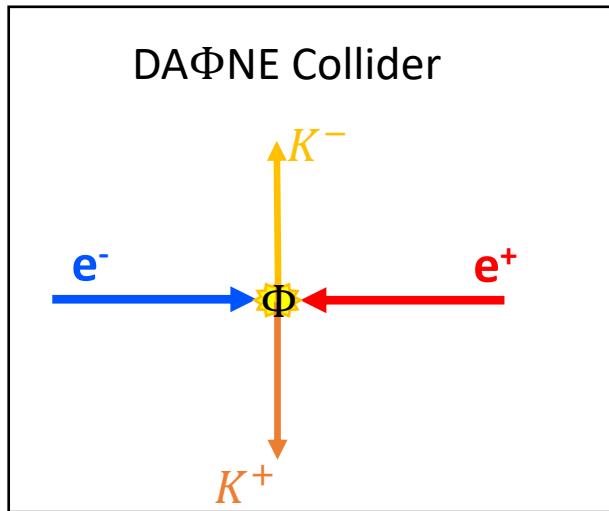


Experimental Principle



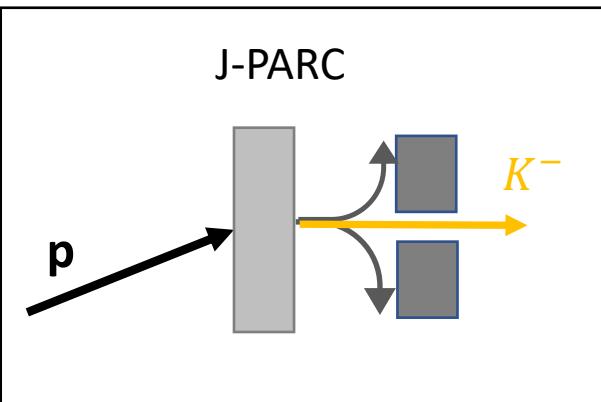
High intensity
High background

Degrader

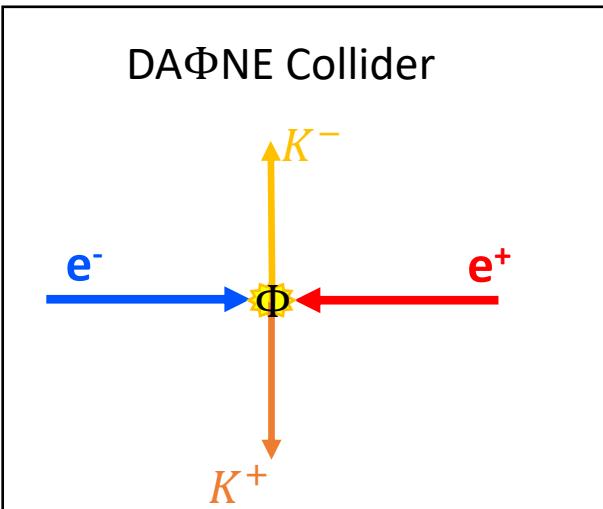


Monochromatic
Low energy kaons
Solid angle

Experimental Principle



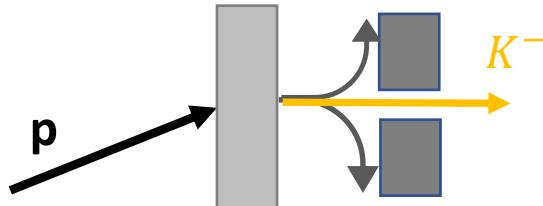
High intensity
High background



Monochromatic
Low energy kaons
Solid angle

Experimental Principle

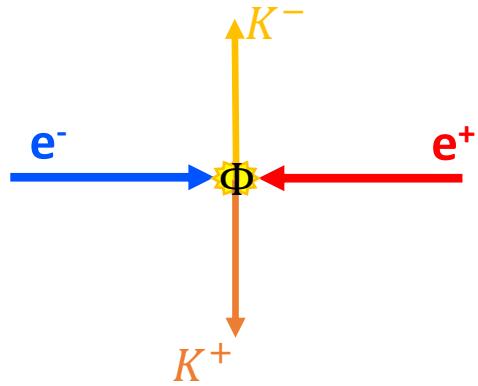
J-PARC



High intensity

High background

DAΦNE Collider



Monochromatic

Low energy kaons

Solid angle

Degrader

K^-

Target

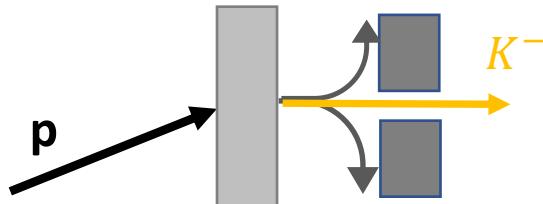
X-ray

Kaonic atom

Trigger

Experimental Principle

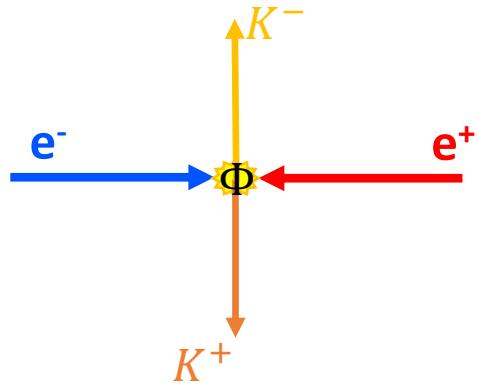
J-PARC



High intensity

High background

DAΦNE Collider



Monochromatic

Low energy kaons

Solid angle

Degrader

Target

X-ray

Kaonic atom

Trigger

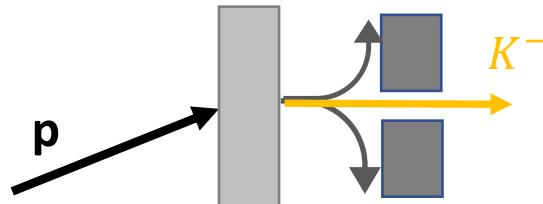
X-ray detectors

High intensity

K^-

Experimental Principle

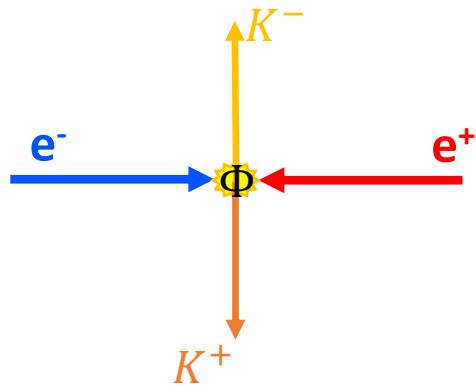
J-PARC



High intensity

High background

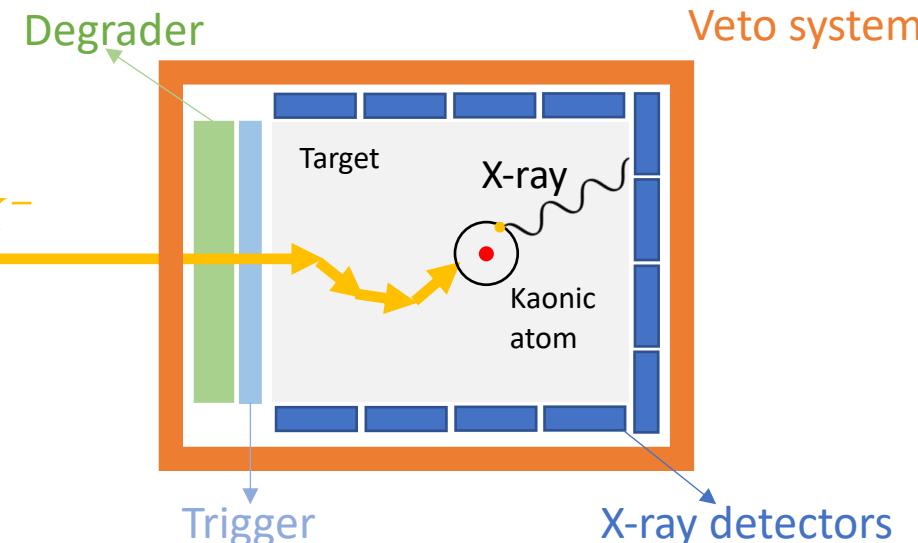
DAΦNE Collider



Monochromatic

Low energy kaons

Solid angle

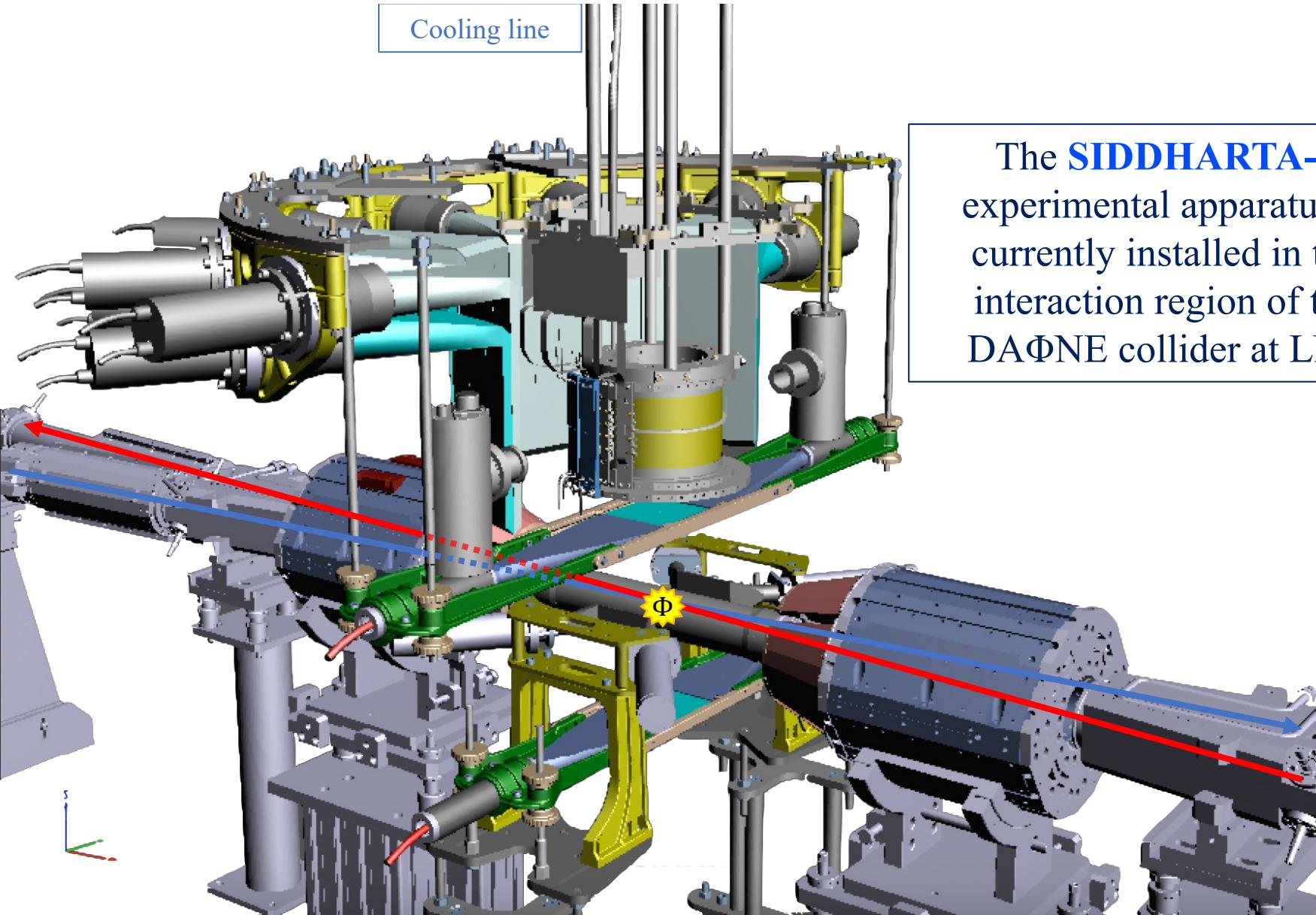


INFN-LNF e⁺e⁻ Accelerator Complex



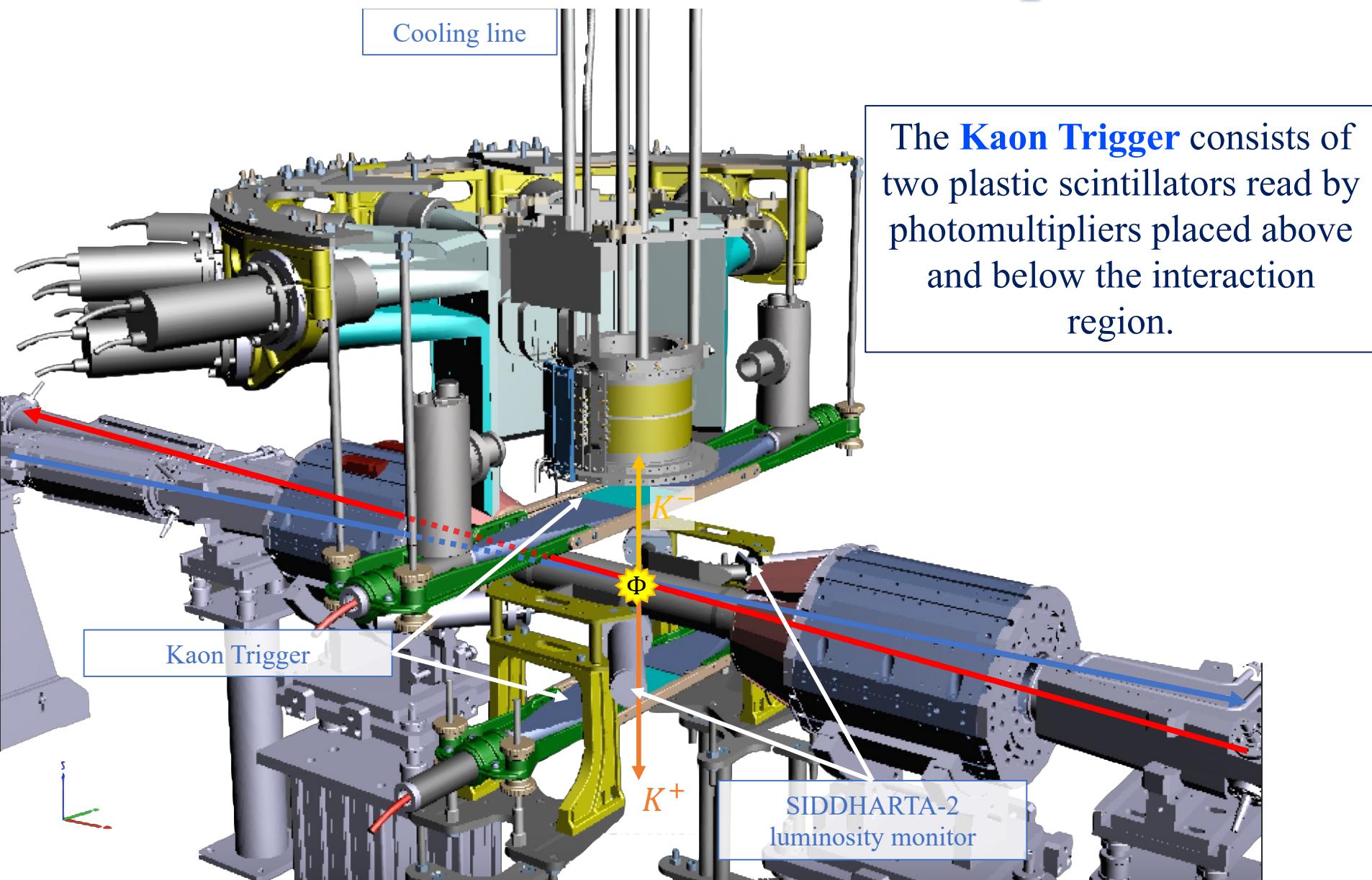
SIDDHARTA-2 setup

Cooling line

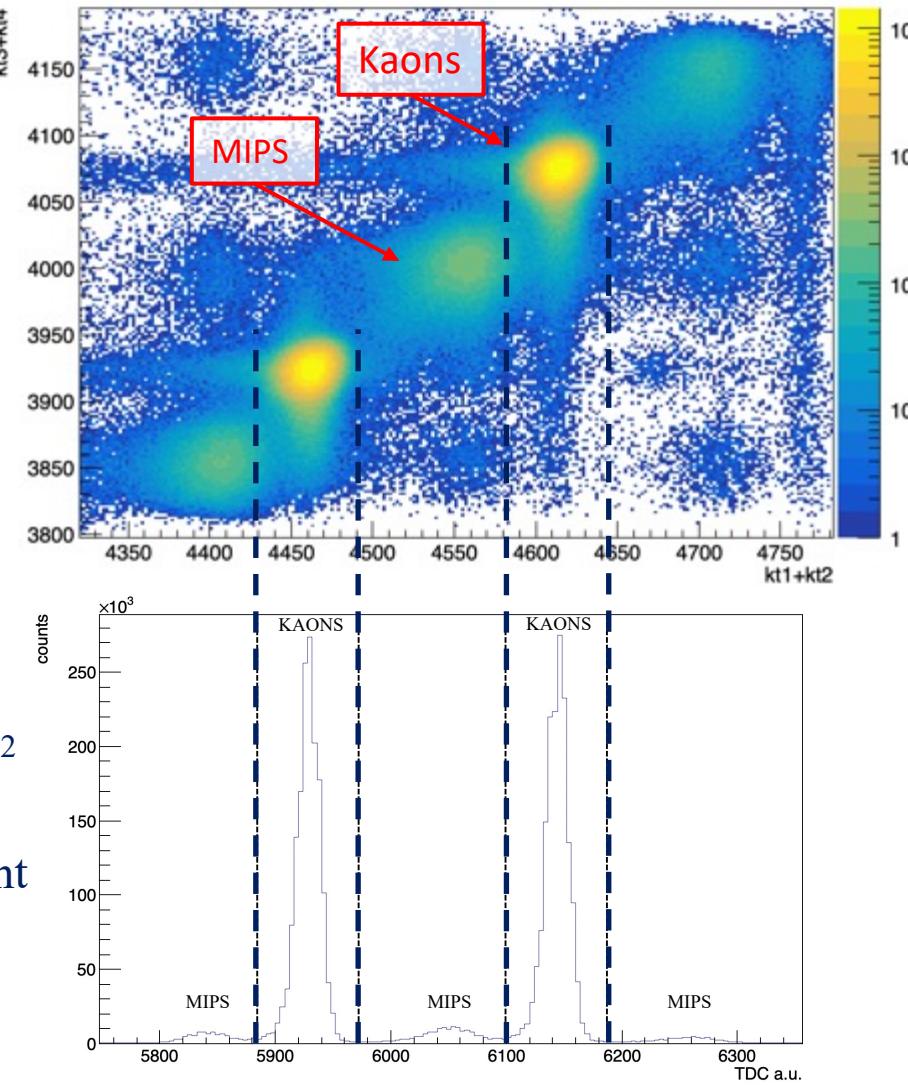
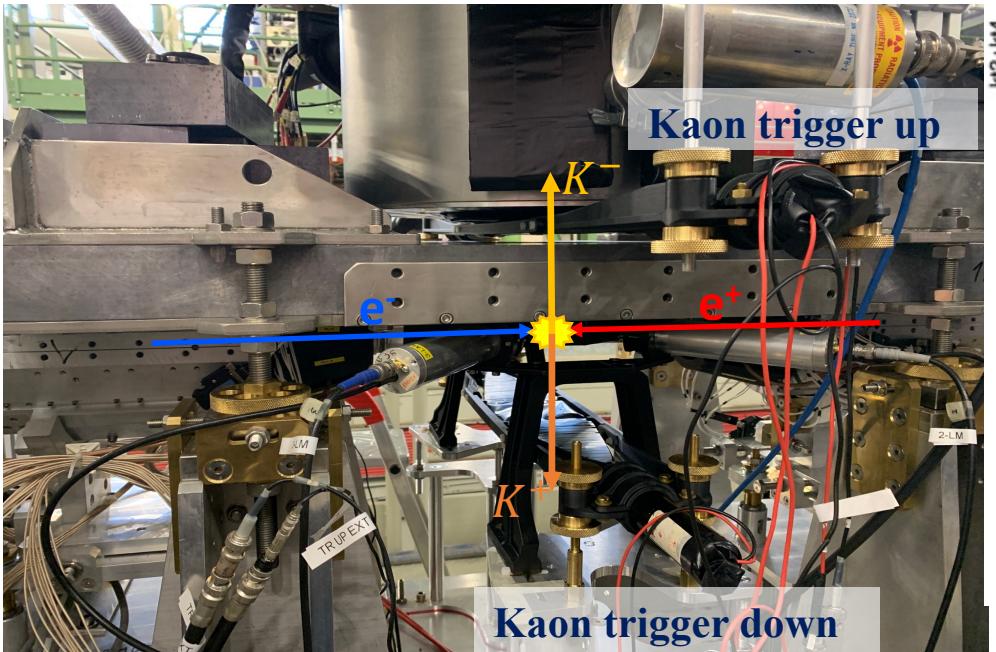


The **SIDDHARTA-2** experimental apparatus is currently installed in the interaction region of the DAΦNE collider at LNF

SIDDHARTA-2 setup

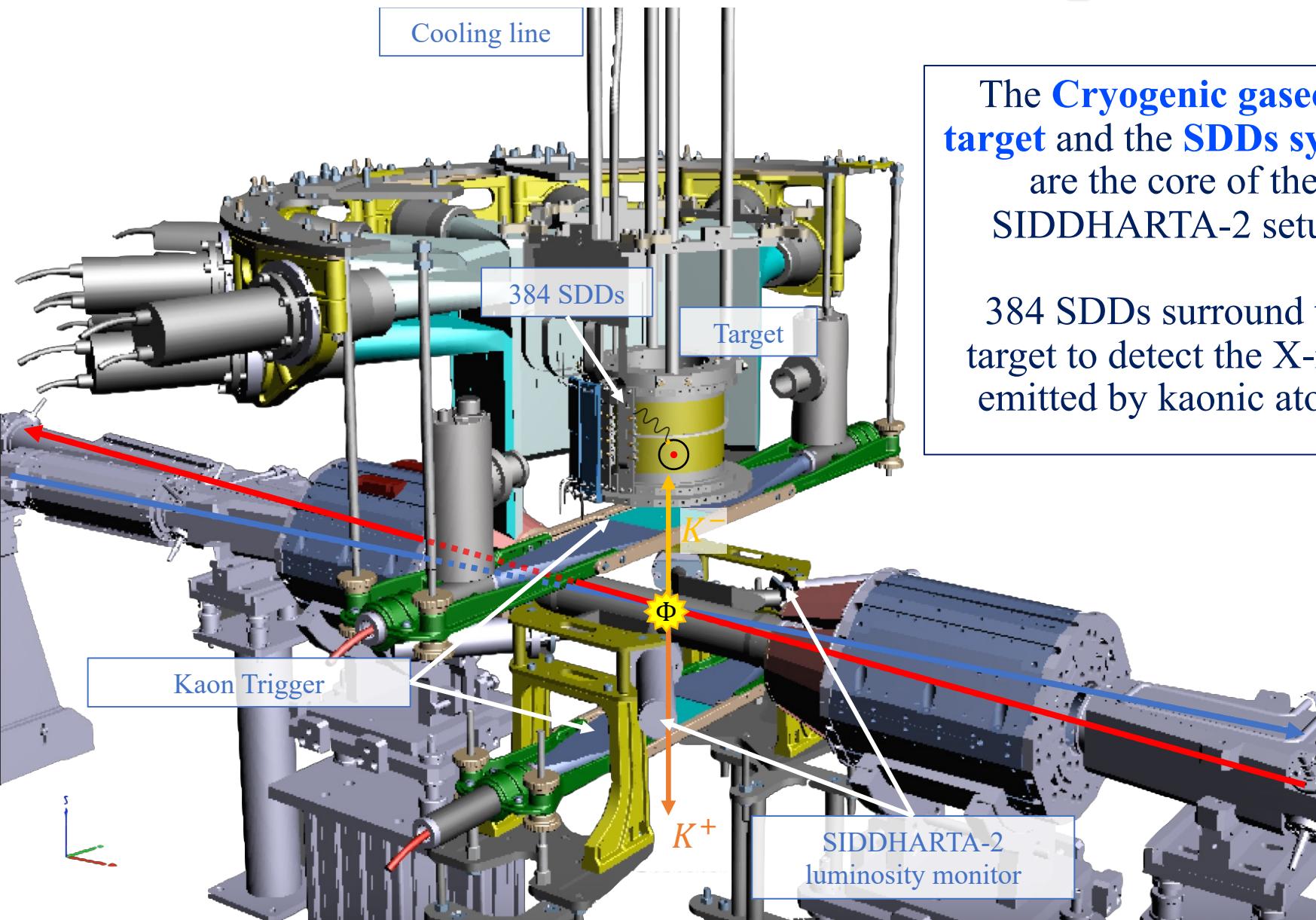


Kaon Trigger



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

SIDDHARTA-2 setup

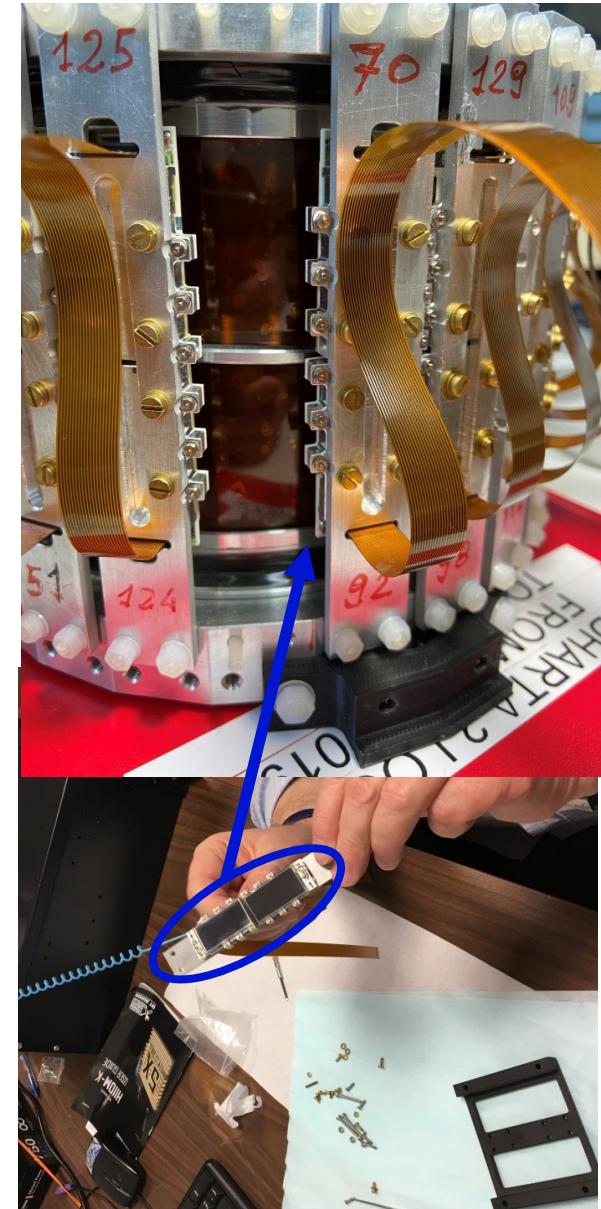
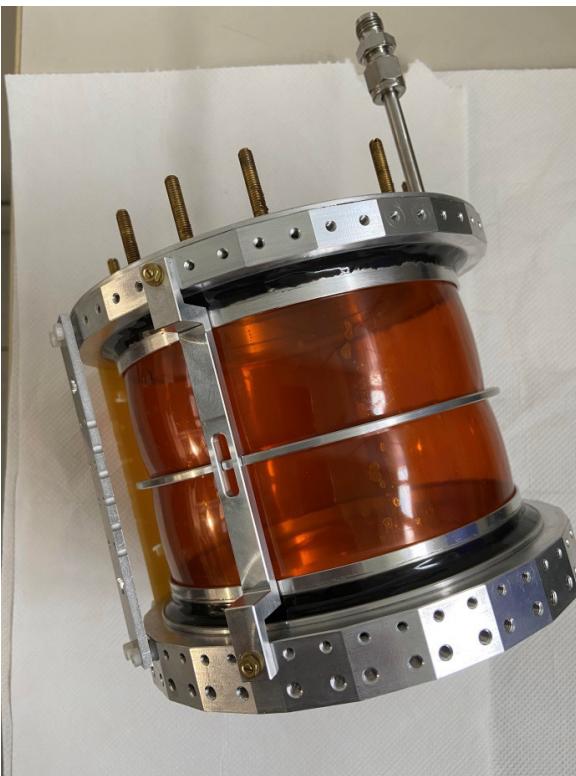


The **Cryogenic gaseous target** and the **SDDs system** are the core of the SIDDHARTA-2 setup.

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

The SIDDHARTA-2 target

Cryogenic Cylindrical target cell made of high purity aluminium frame and 150 μ m thick Kapton walls

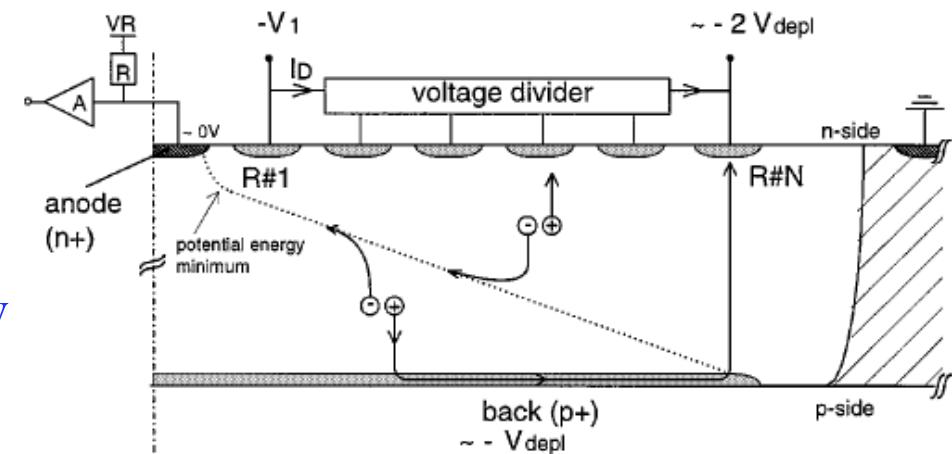
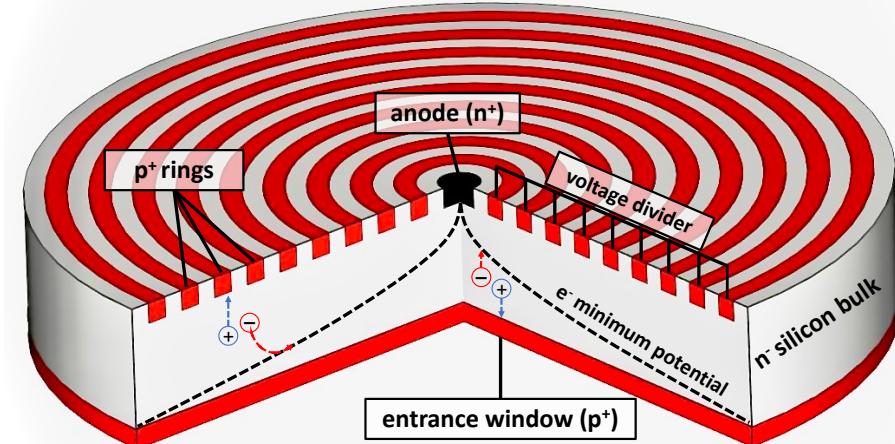
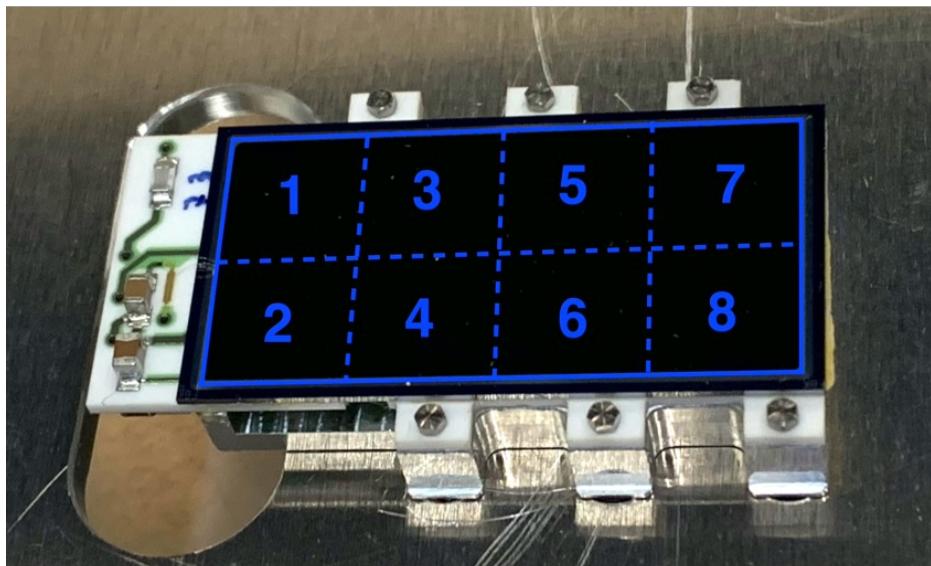


384 Silicon Drift Detectors (SDDs) are mounted on aluminium finger support for cooling (-150°C)

Silicon Drift Detectors



SDD cross section



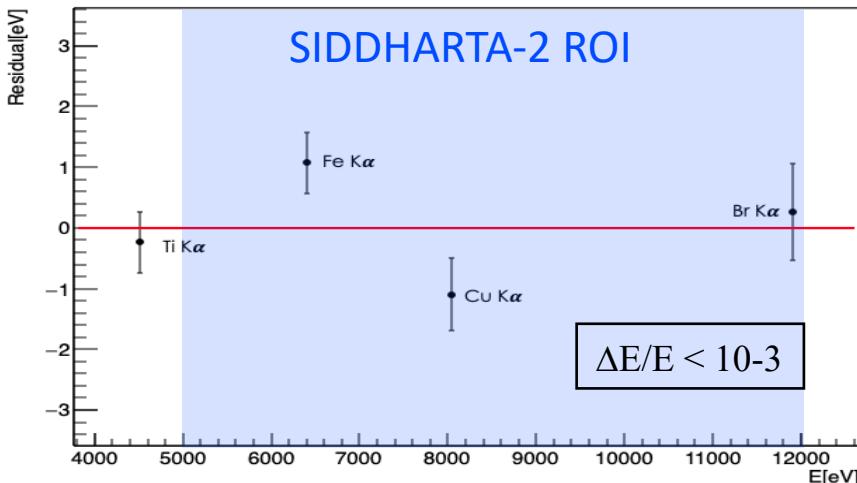
8 SDD units (0.64 cm^2)

for a total active area of 5.12 cm^2

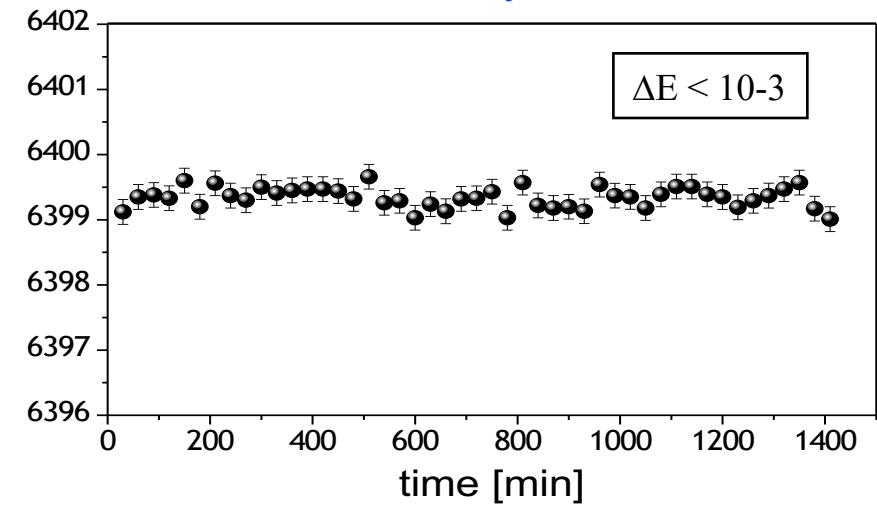
Thickness of $450 \mu\text{m}$ ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

Silicon Drift Detectors

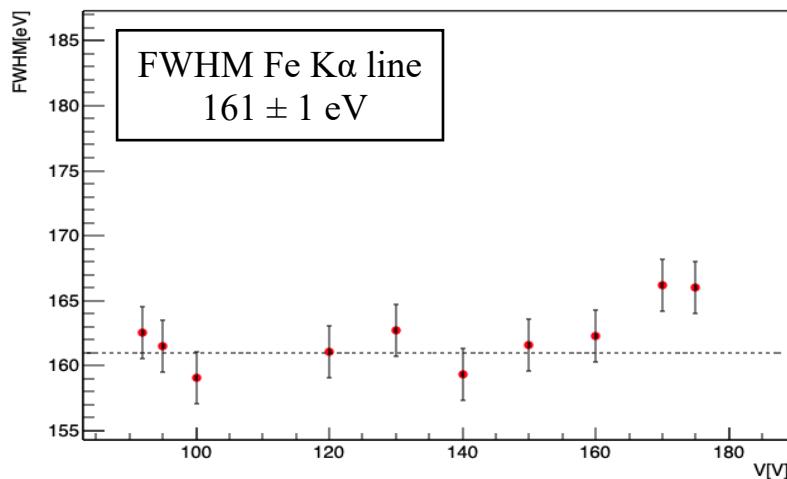
Linearity



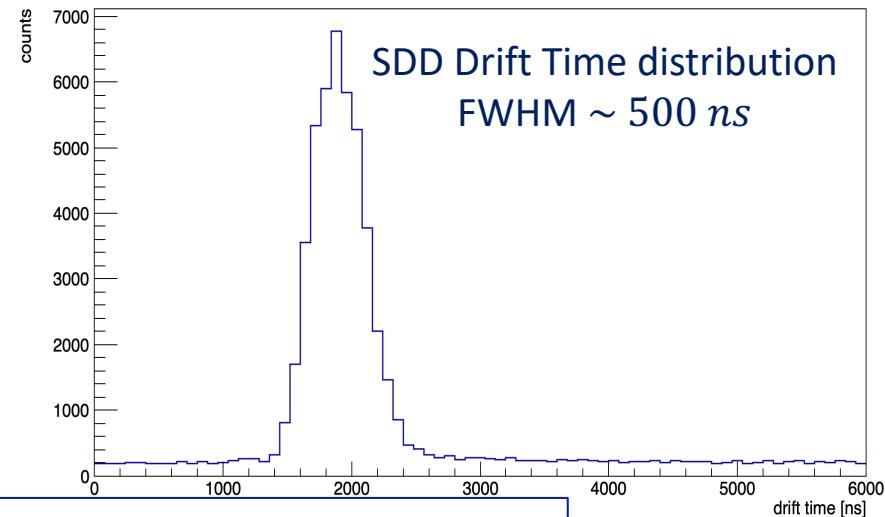
Stability



Energy Resolution

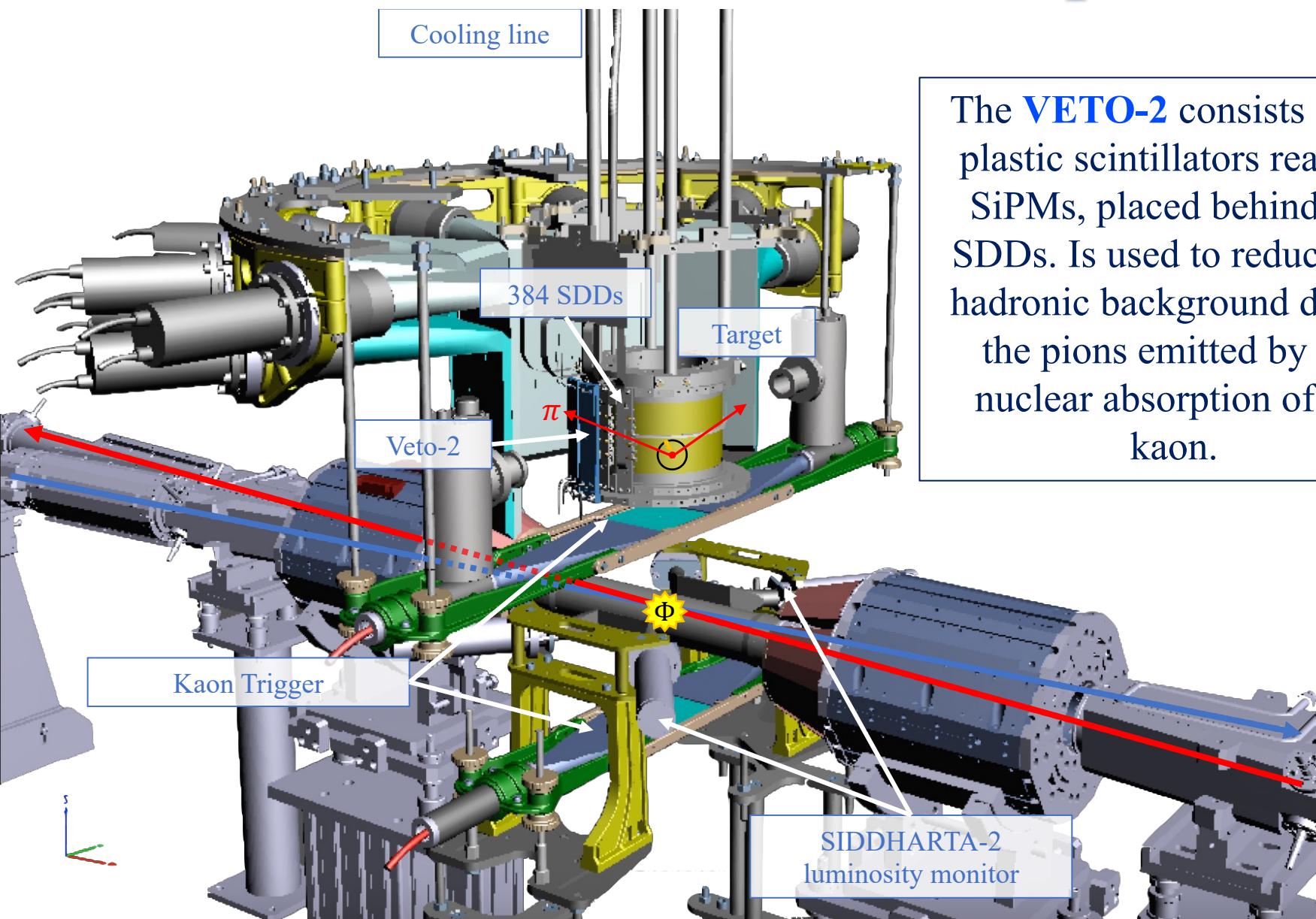


Timing Resolution

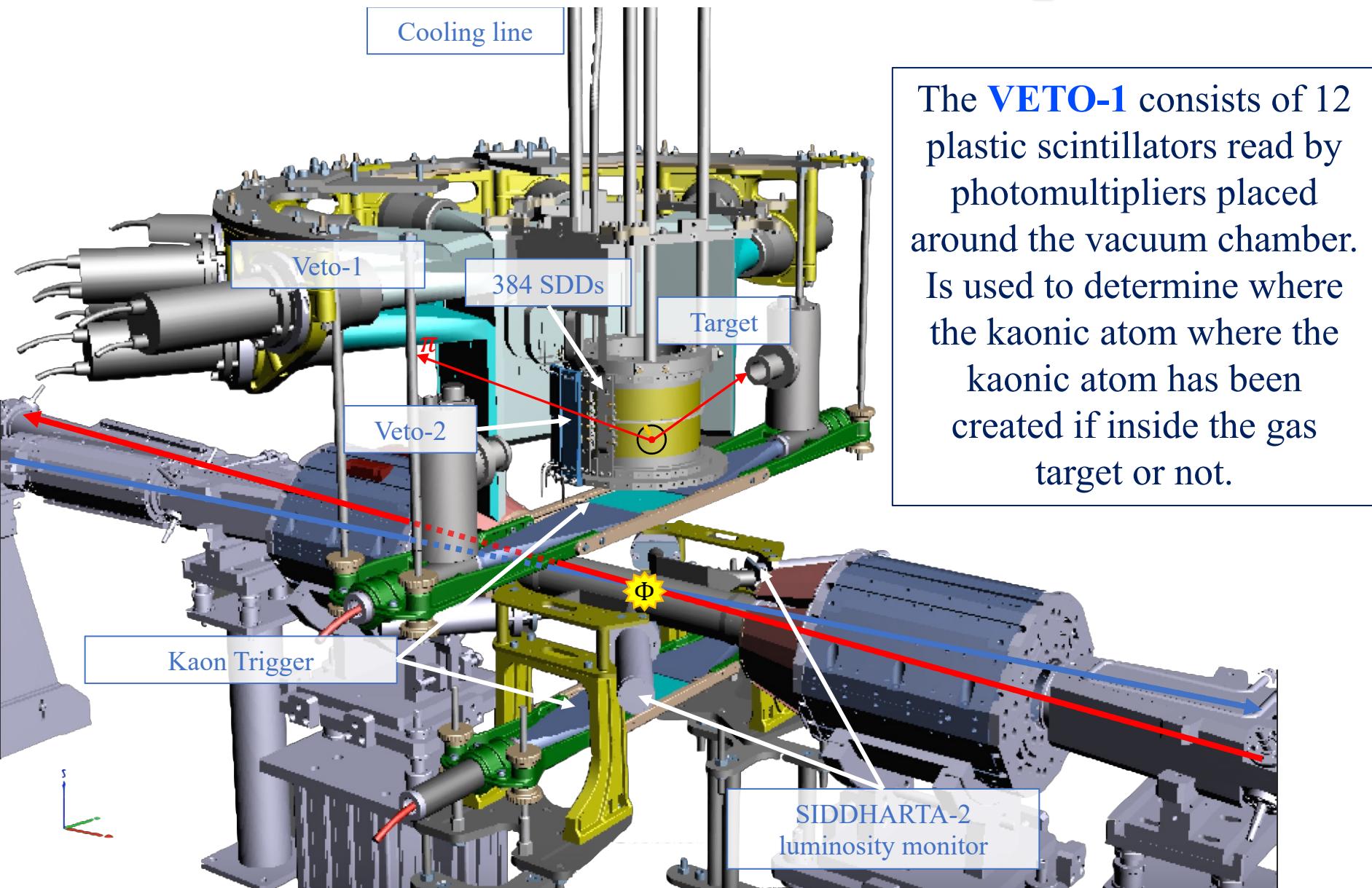


M Miliucci *et al* 2021 *Meas. Sci. Technol.* **32** 095501

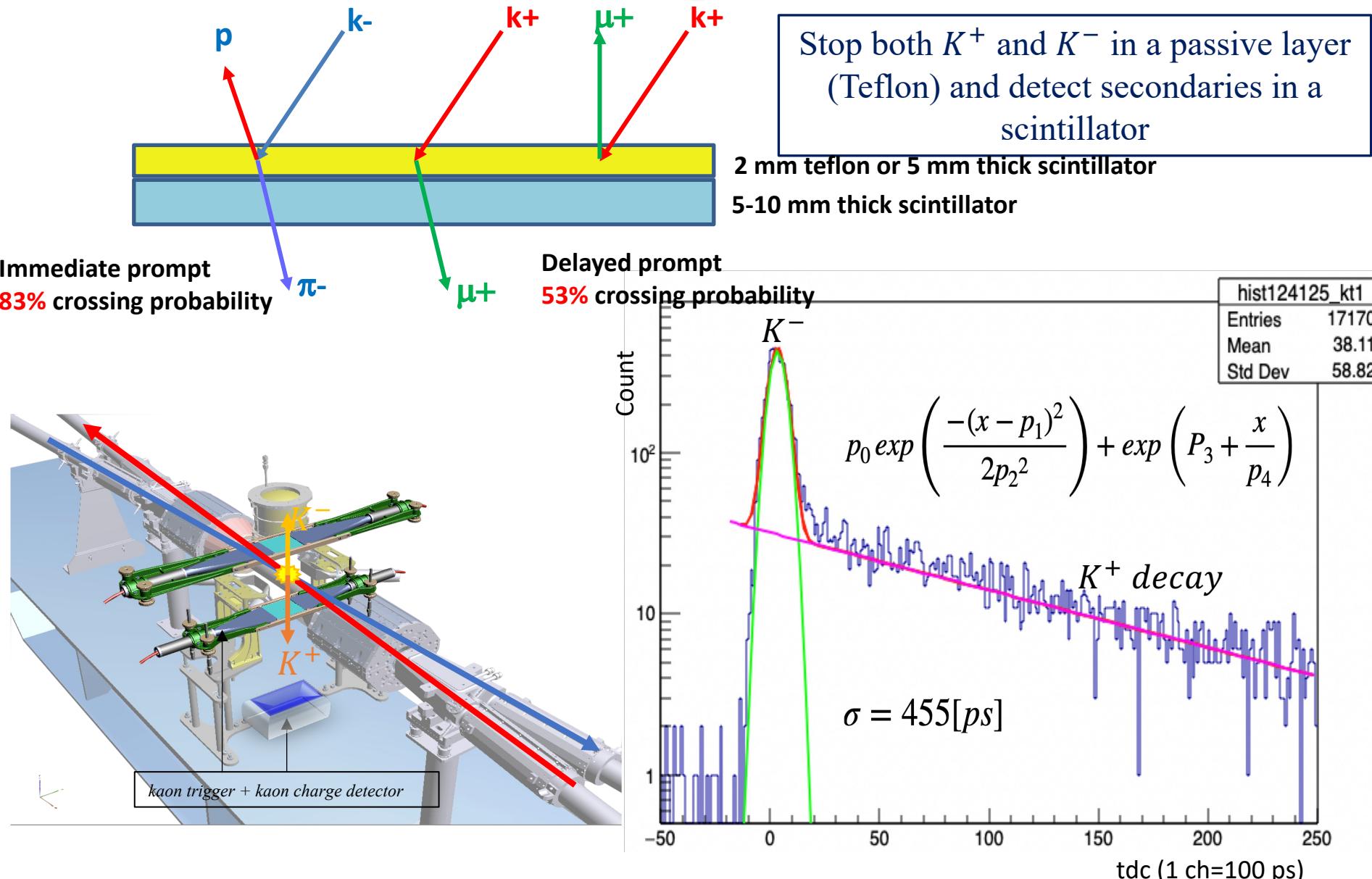
SIDDHARTA-2 setup



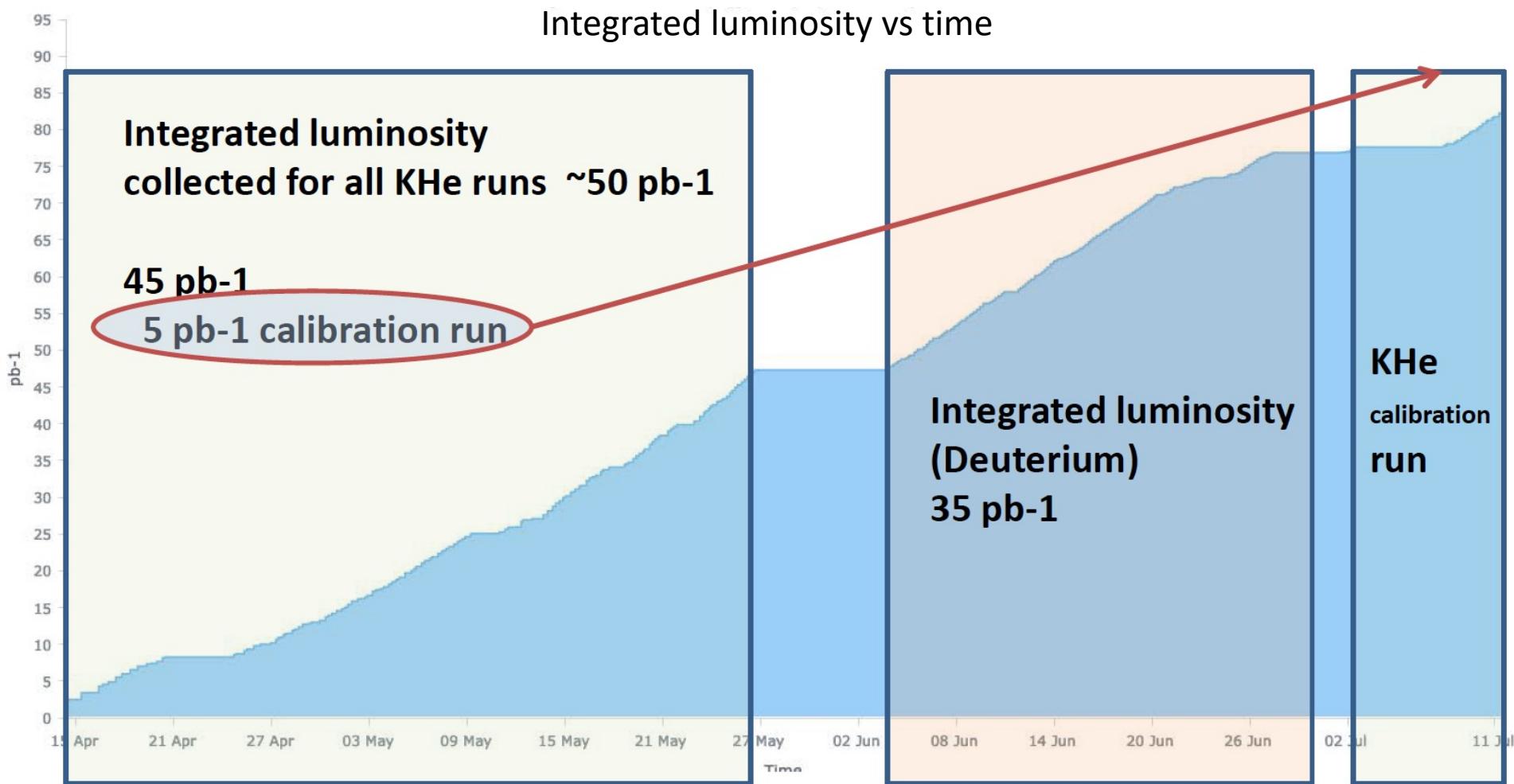
SIDDHARTA-2 setup



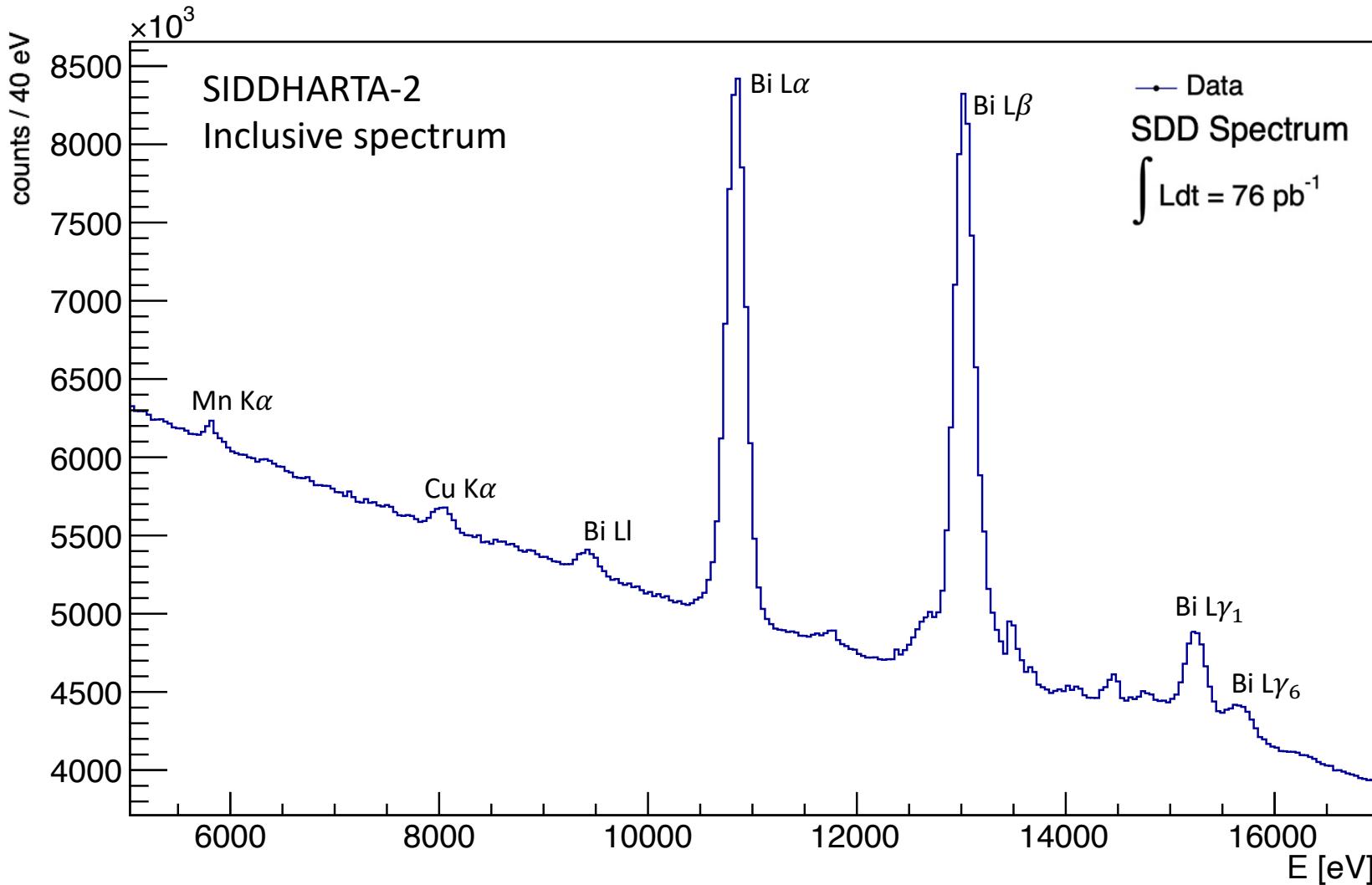
Kaon Charge Detector



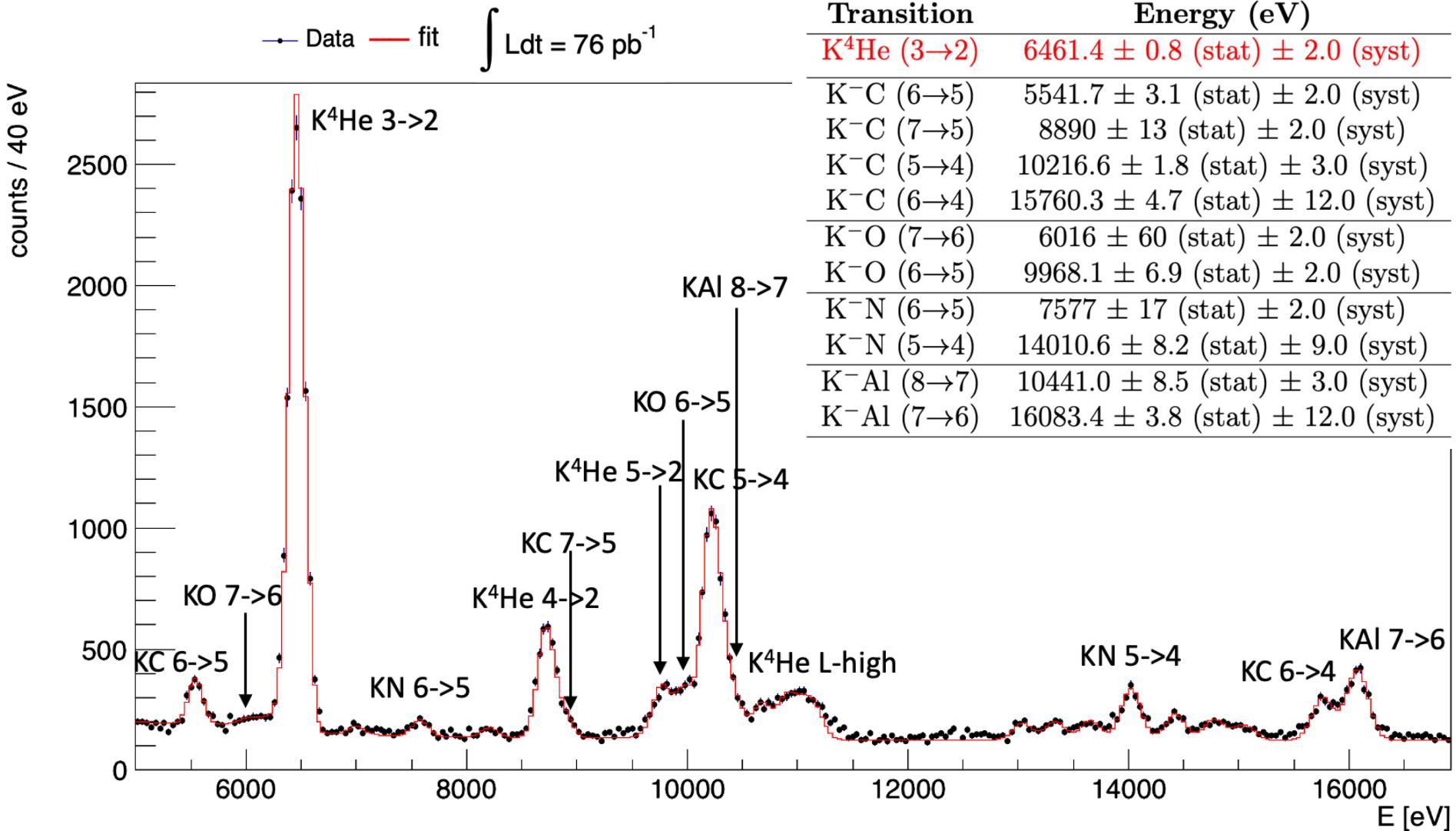
SIDDHARTA-2 First Run



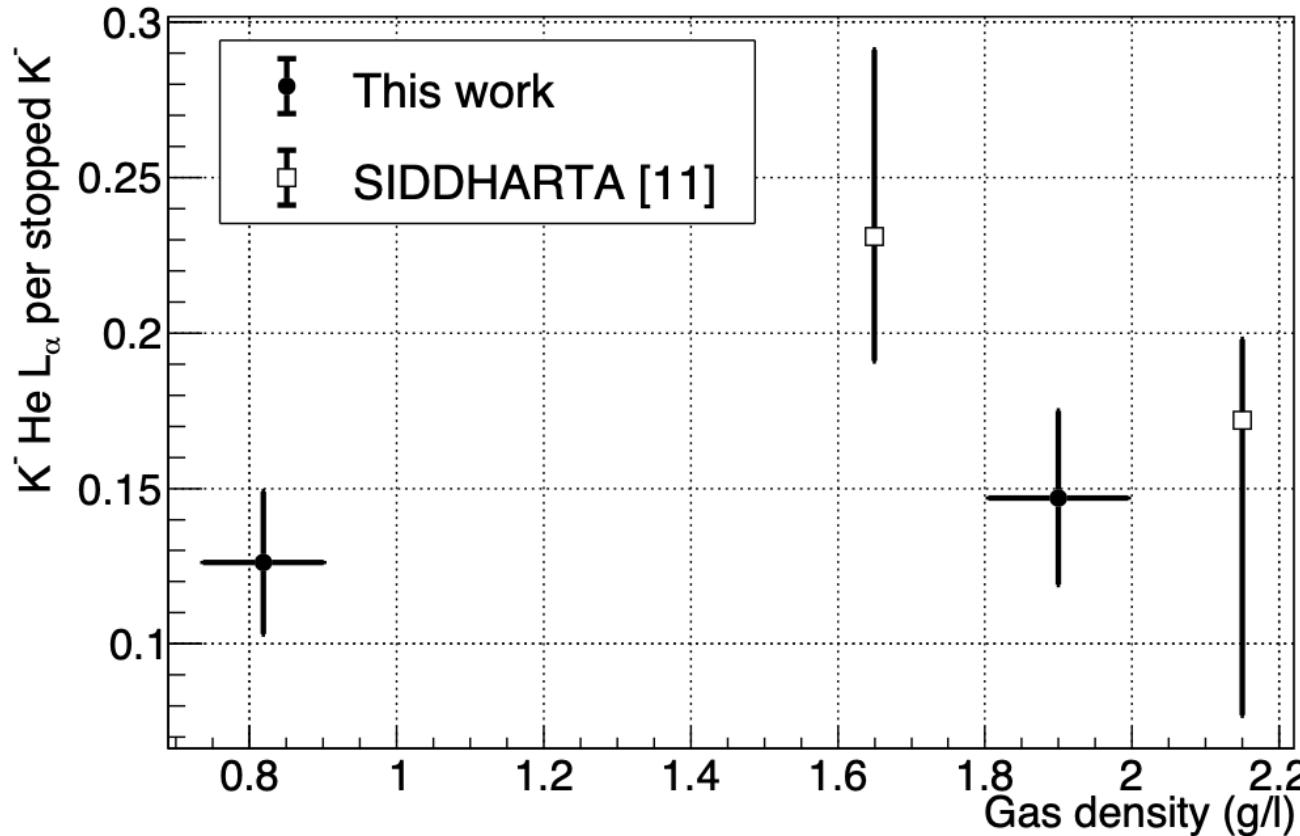
SIDDHARTA-2 Kaonic ${}^4\text{He}$



SIDDHARTA-2 Kaonic ${}^4\text{He}$



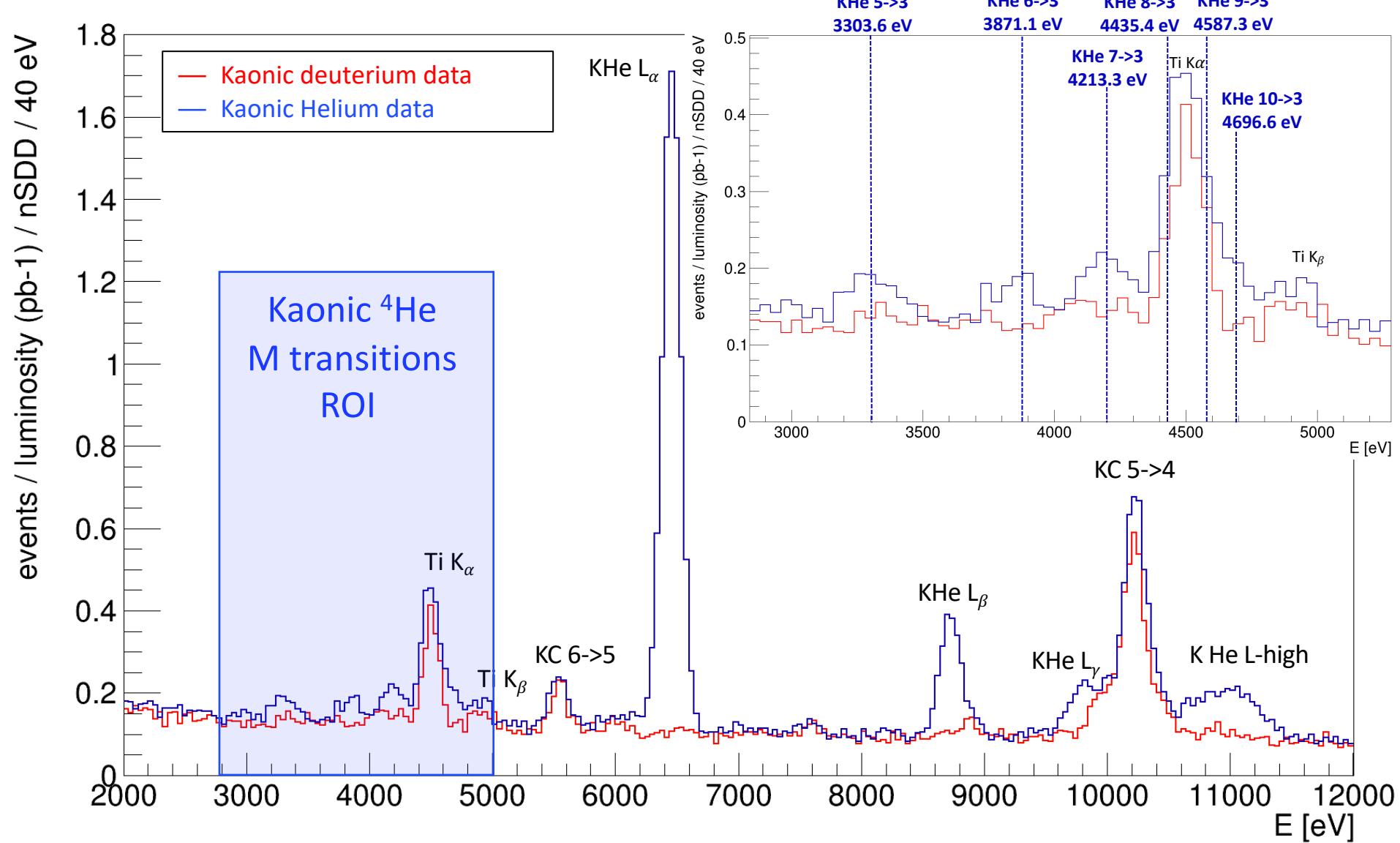
SIDDHARTA-2 Kaonic ${}^4\text{He}$



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

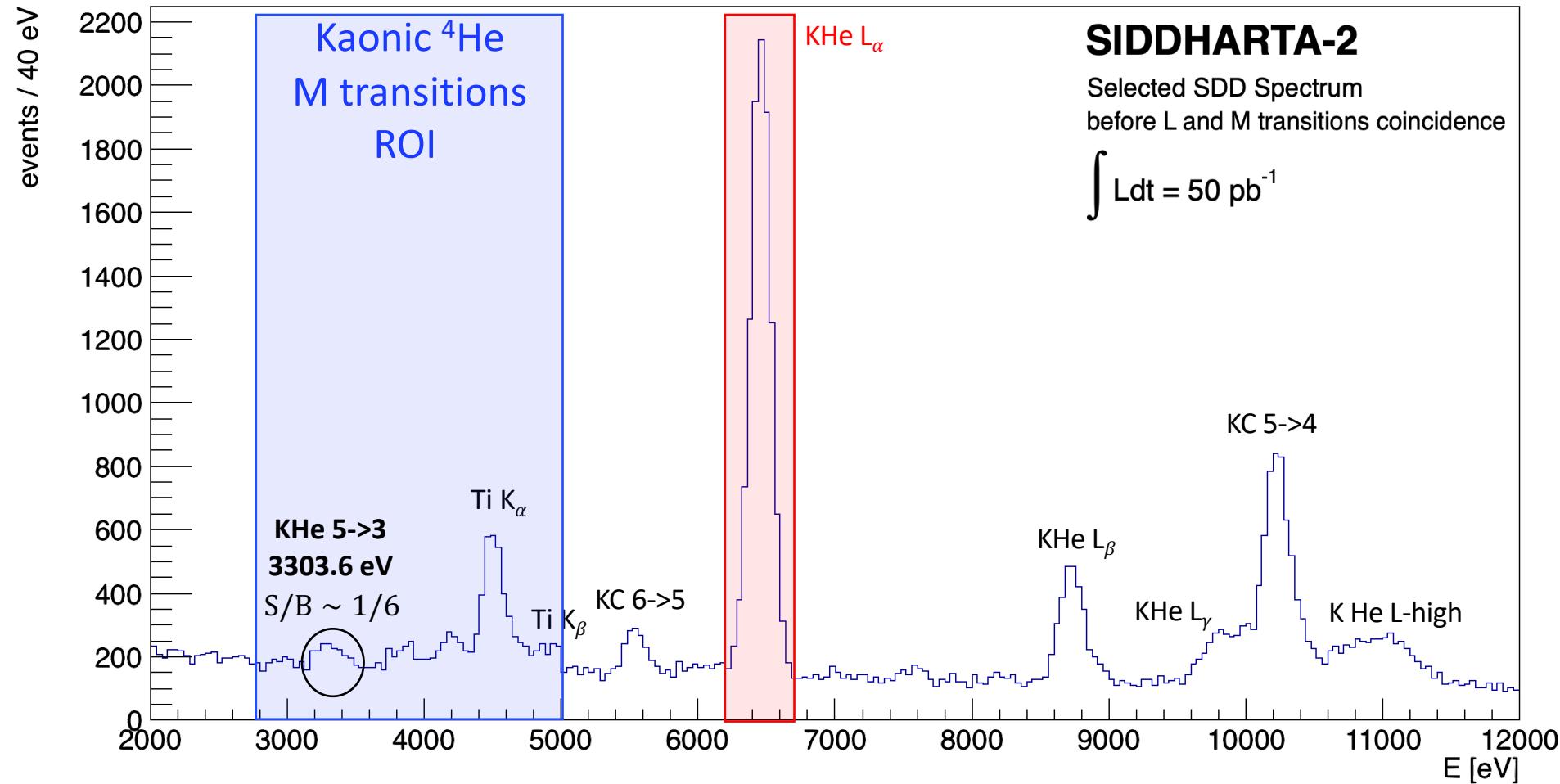
Density	1.90 g/l	0.82 g/l
L_α yield	0.148 ± 0.027	0.126 ± 0.023
L_β/L_α	0.193 ± 0.042	0.133 ± 0.037
L_γ/L_α	0.035 ± 0.015	not detected

SIDDHARTA-2 Kaonic ${}^4\text{He}$



SIDDHARTA-2 Kaonic ${}^4\text{He}$

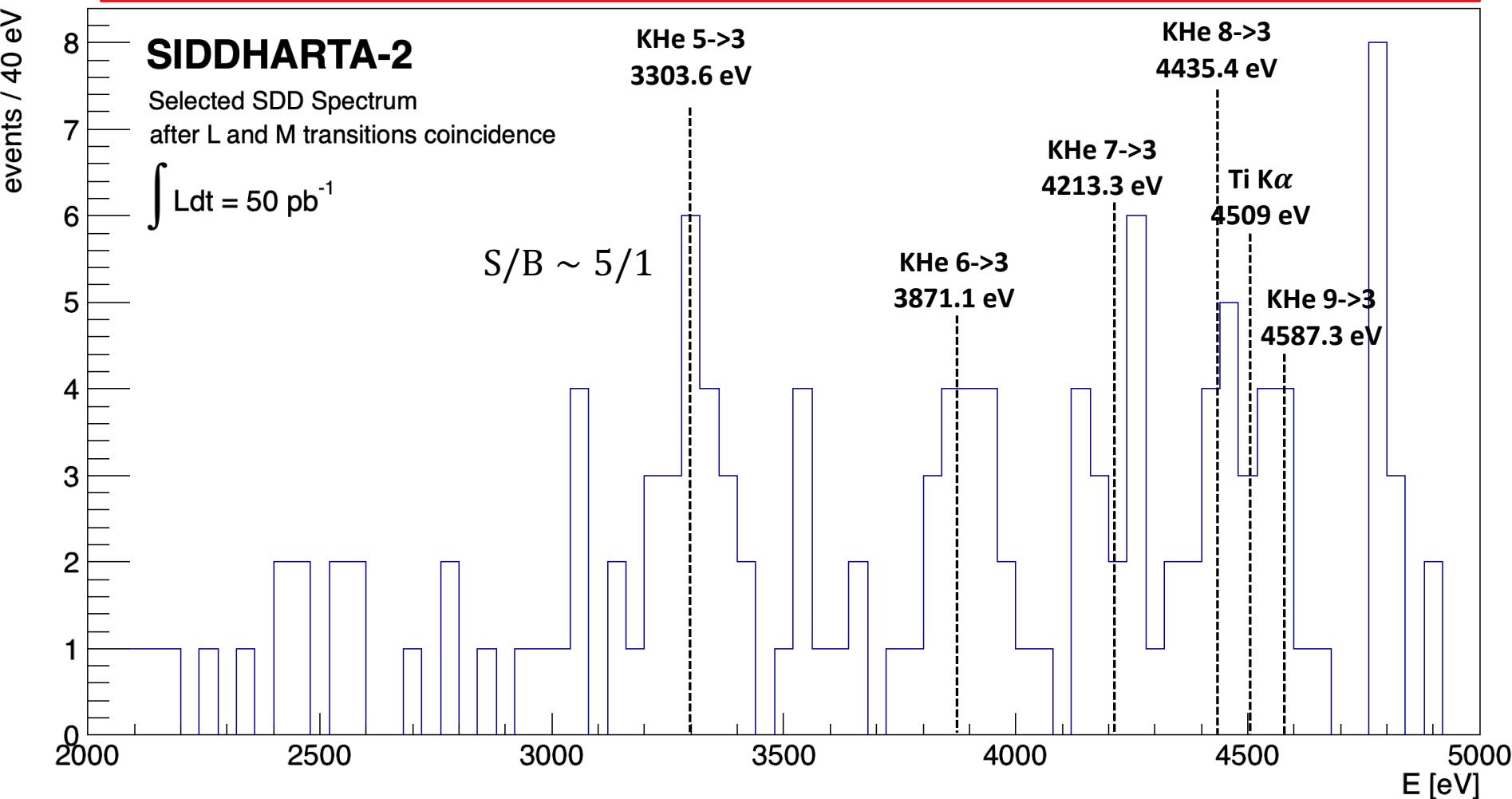
Coincidence between L ($n=2$) and M ($n=3$) transitions



SIDDHARTA-2 Kaonic ${}^4\text{He}$

Coincidence between L ($n=2$) and M ($n=3$) transitions

Feasibility test for future kaonic atom measurements (kaonic ${}^4\text{He}$ fundamental level)

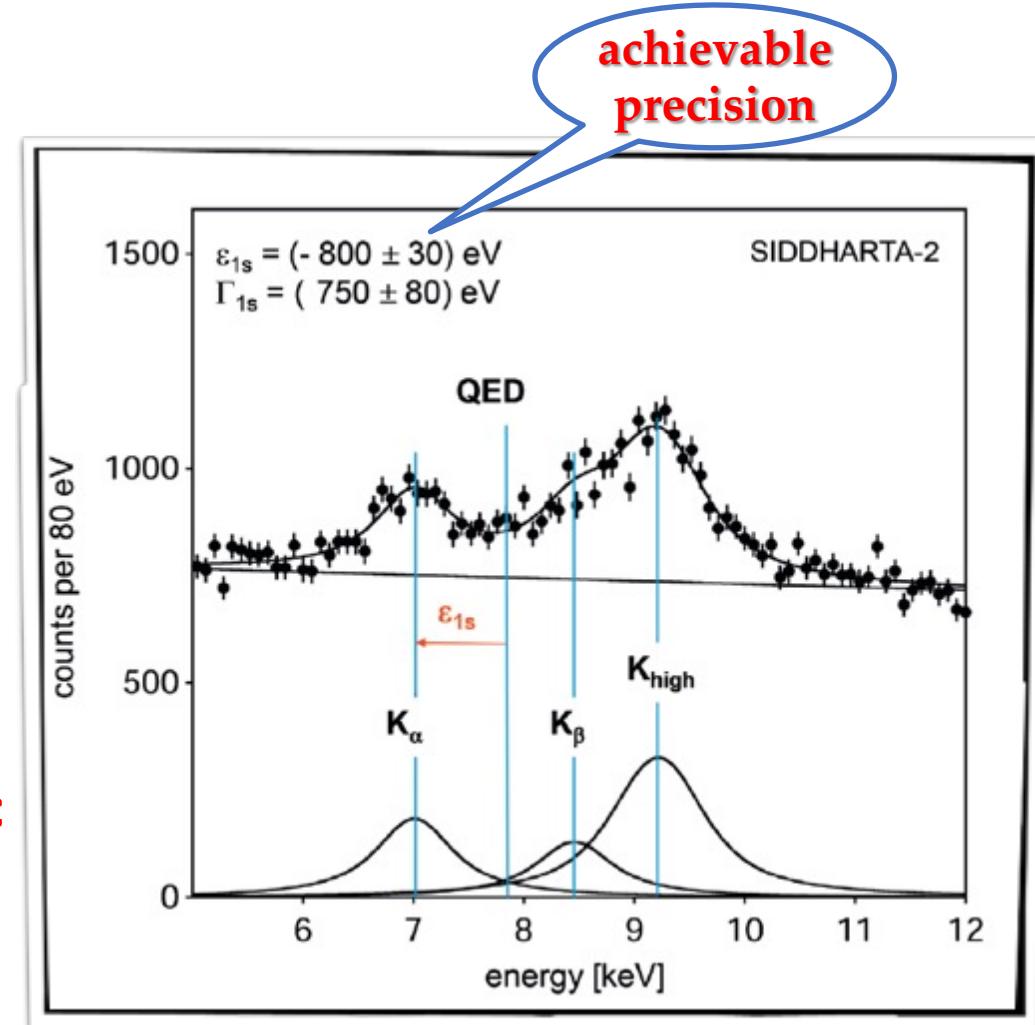


SIDDHARTA-2 K-d measurement

Kaonic deuterium run in (all)

2023

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

Outcomes

- **Kaonic Atoms bring great insights in kaon-nucleon interaction**
 - Tool to directly probe low energy QCD with strangeness



Measurement of Kaonic-Deuterium key to fully disentangle isospin dependence on KN scattering lengths

- **SIDDHARTA-2 at DAFNE**
 - Installation of the full SIDDHARTA-2 setup
 - Kaonic ${}^4\text{He}$ test run concluded in July 2022
 - **Performed the most precise K- ${}^4\text{He}$ 3d → 2p measurement in gas**
 - Energy shift and width
 - Yield at two different density 1.9 g/l and 0.82 g/l
 - **Several solid target high-n transition energies measured for the first time**
 - **First measurement of kaonic ${}^4\text{He}$ M (n=3) transitions**
 - **First kaonic deuterium test run**

SIDDHARTA-2 setup ready for Kaonic Deuterium Run



Thank You

