Kaonic atoms research at the DAΦNE collider:

THE SIDDHARTA-2 EXPERIMENT

and future perspectives

LUCA DE PAOLIS

on behalf of the SIDDHARTA-2 collaboration

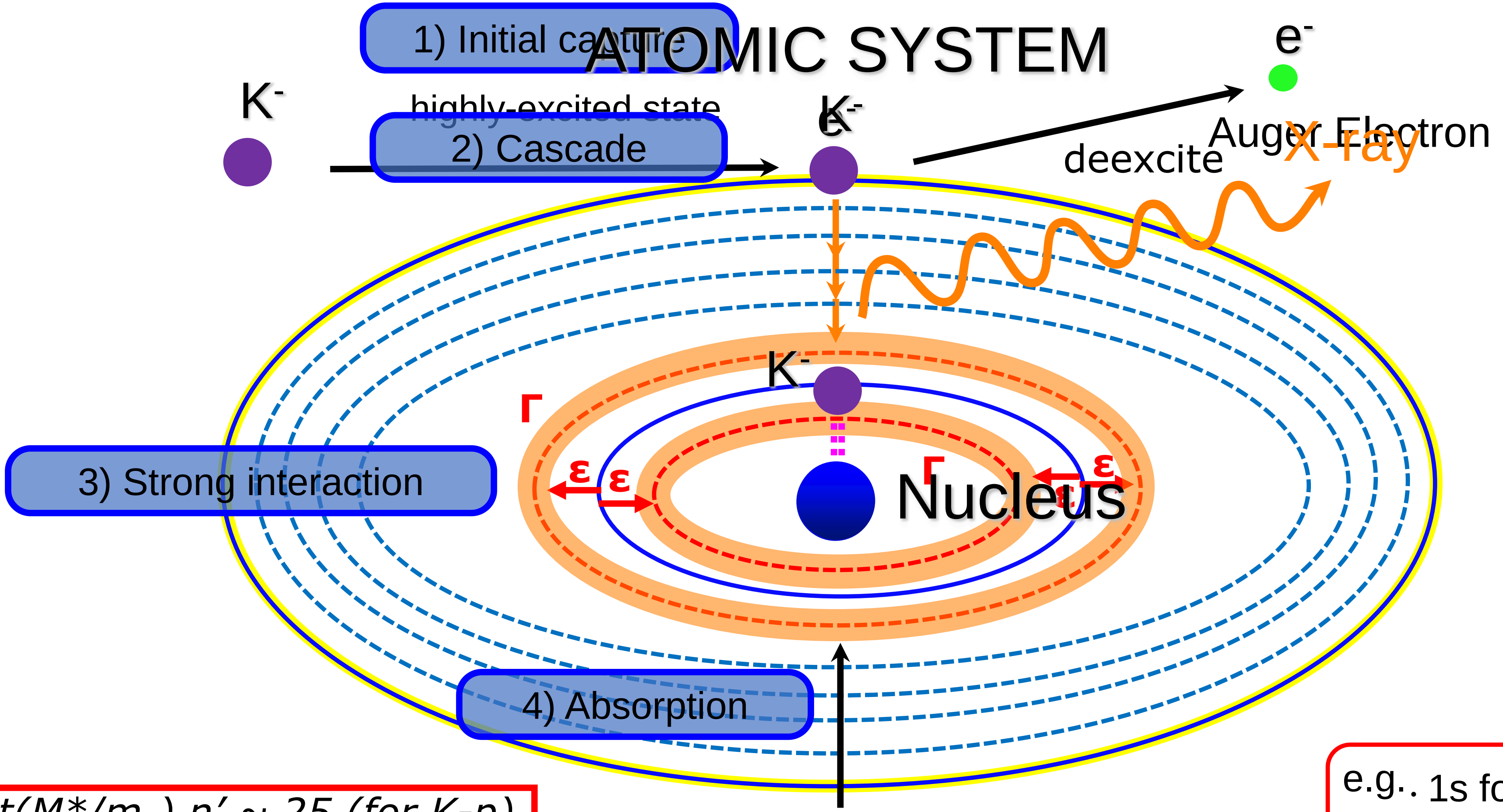
STRONG-2020

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

XI International Conference on New Frontiers of Physics, 30 August – 11 September 2022

Kaonic atoms formation

Kaonic atoms are formed by stopping a negatively charged kaon in a target medium



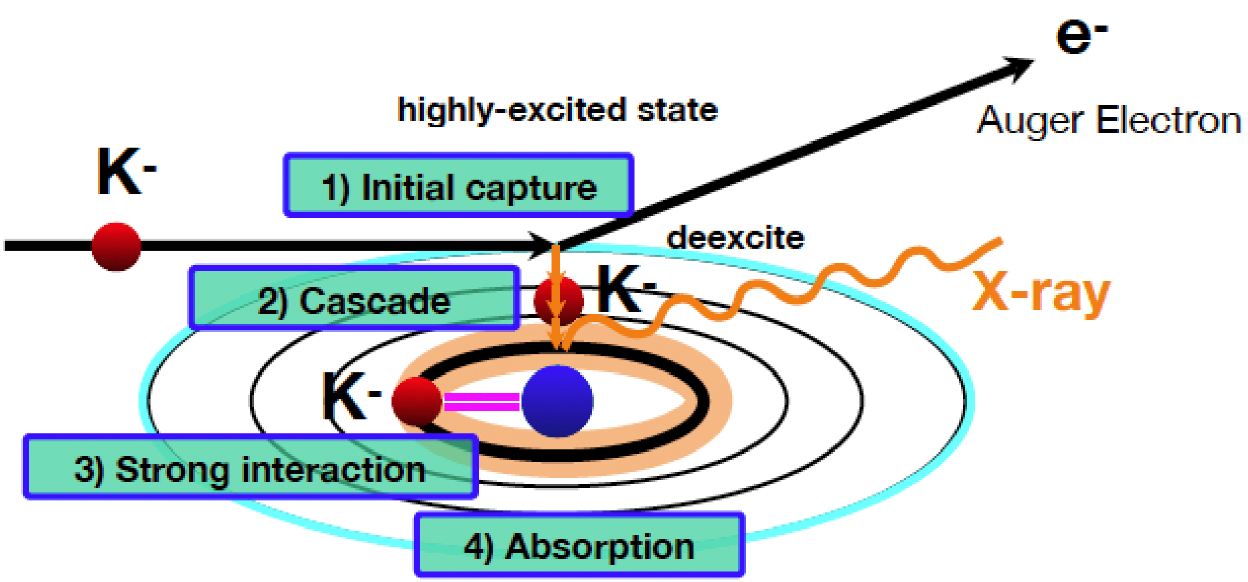
Shift (ε) and width (Γ) of the last orbit

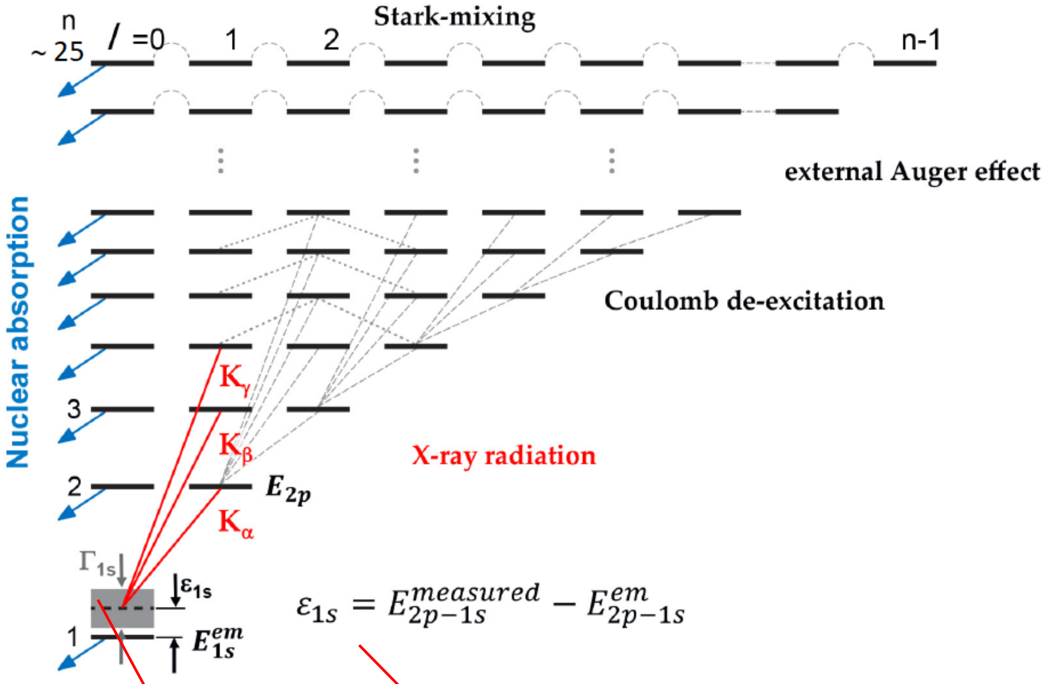
n ~ sqrt(M/mₑ) n′ ~ 25 (for K-p)*
(M : K-p reduced mass)*

e.g.. 1s for K-p, K-d
. 2p for K-He

Kaonic atoms formation

In kaonic atoms, part of the shift (ε) and width (Γ) of the innermost atomic levels is due to the strong kaon-nucleus interaction, thus allowing the study of the strong interaction at low energy (keV) in the *strange* sector.





$$\varepsilon_{1s} = E_{2p-1s}^{measured} - E_{2p-1s}^{em}$$

The measurement of shift and width of the 1S orbital in **Kaonic Hydrogen** and **Kaonic Deuterium**, provides fundamental and unique information on kaon-proton and kaon-neutron strong interaction at low energies.

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

The Scientific Goal

The $\bar{K}p$ and $\bar{K}d$ scattering lengths $(a_{\bar{K}p}, a_{\bar{K}d})$ are connected to to shift and width of kaonic hydrogen $(\varepsilon_{1s}^{H}, \Gamma_{1s}^{H})$ and kaonic deuterium $(\varepsilon_{1s}^{D}, \Gamma_{1s}^{D})$ by the Deser-Trueman Formula, improved by Meissner et al., taking into account the isospin breaking connections:

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

$$\varepsilon_{1s}^{D} + \frac{i}{2}\Gamma_{1s}^{D} = 2\alpha^3\mu_{\bar{K}d}^2 a_{\bar{K}d}(1 - 2\alpha\mu_{\bar{K}d}^2(\ln\alpha - 1)a_{\bar{K}d})$$

α is the fine-structure constant and $\mu_{\bar{K}p}$ and $\mu_{\bar{K}d}$ are the reduced masses of $\bar{K}p$ and $\bar{K}d$systems

U.-G. Meißner, U. Raha, A. Rusetsky, *Eur. J. Phys. C* **35** (2004) 349

Next-to-leading order

$$a_{\bar{K}p} = \frac{1}{2}(a_0 + a_1)$$
$$a_{\bar{K}n} = a_1$$
$$a_{\bar{K}d} = \frac{k}{4}(a_0 + 3a_1) + C = \frac{k}{2}\left(a_{\bar{K}p} + a_{\bar{K}n}\right) + C$$

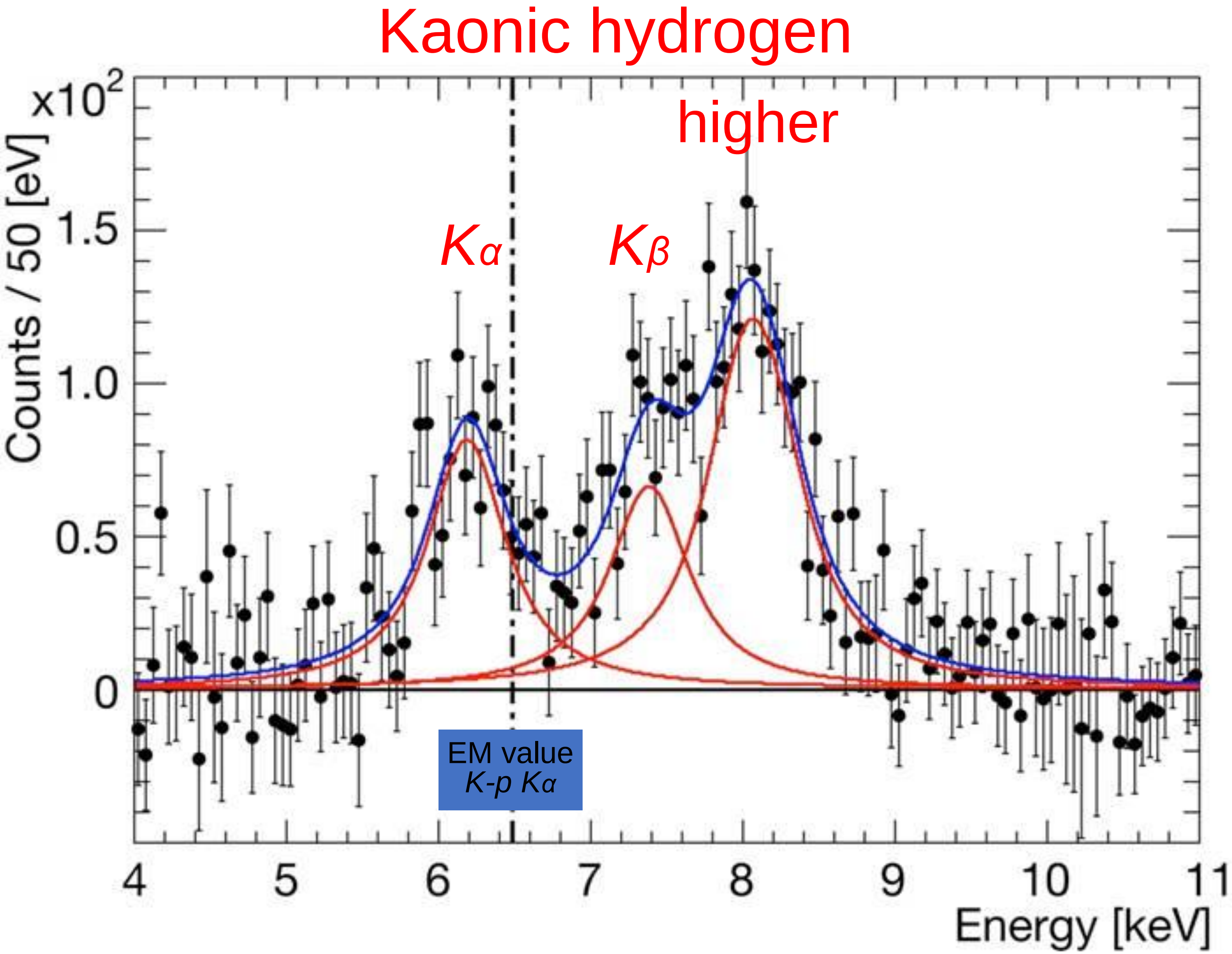
Where:

- a_0 and a_1 are $\bar{K}N$ isospin-dependent $(I = 0{,}1)$ lengths,
- $k = \frac{4(m_N+m_K)}{2m_N+m_K}$, with m_N and m_K respectively Nucleon and Kaon masses
- C is a term including all higher orders.

completely solve Isospin-dependent K-N scattering length

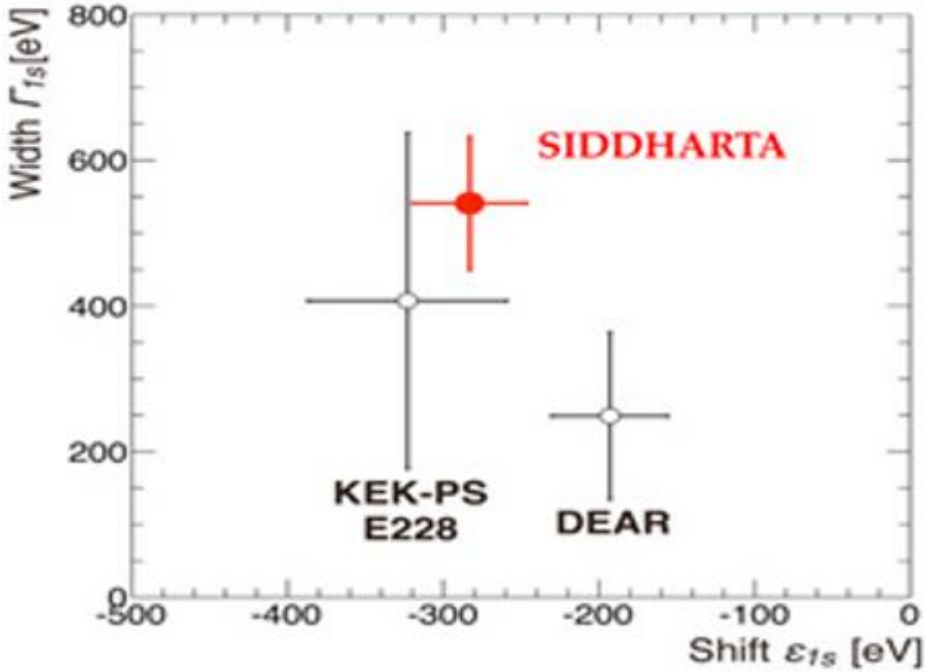
The SIDDHARTA experiment

The SIDDHARTA experiment performed the first measurements of shift and width of kaonic hydrogen in 2011 at National Laboratories of Frascati (LNF-INFN).



$$\varepsilon_{1s}^{H} = -283 \pm 36(stat) \pm 6(syst)eV$$

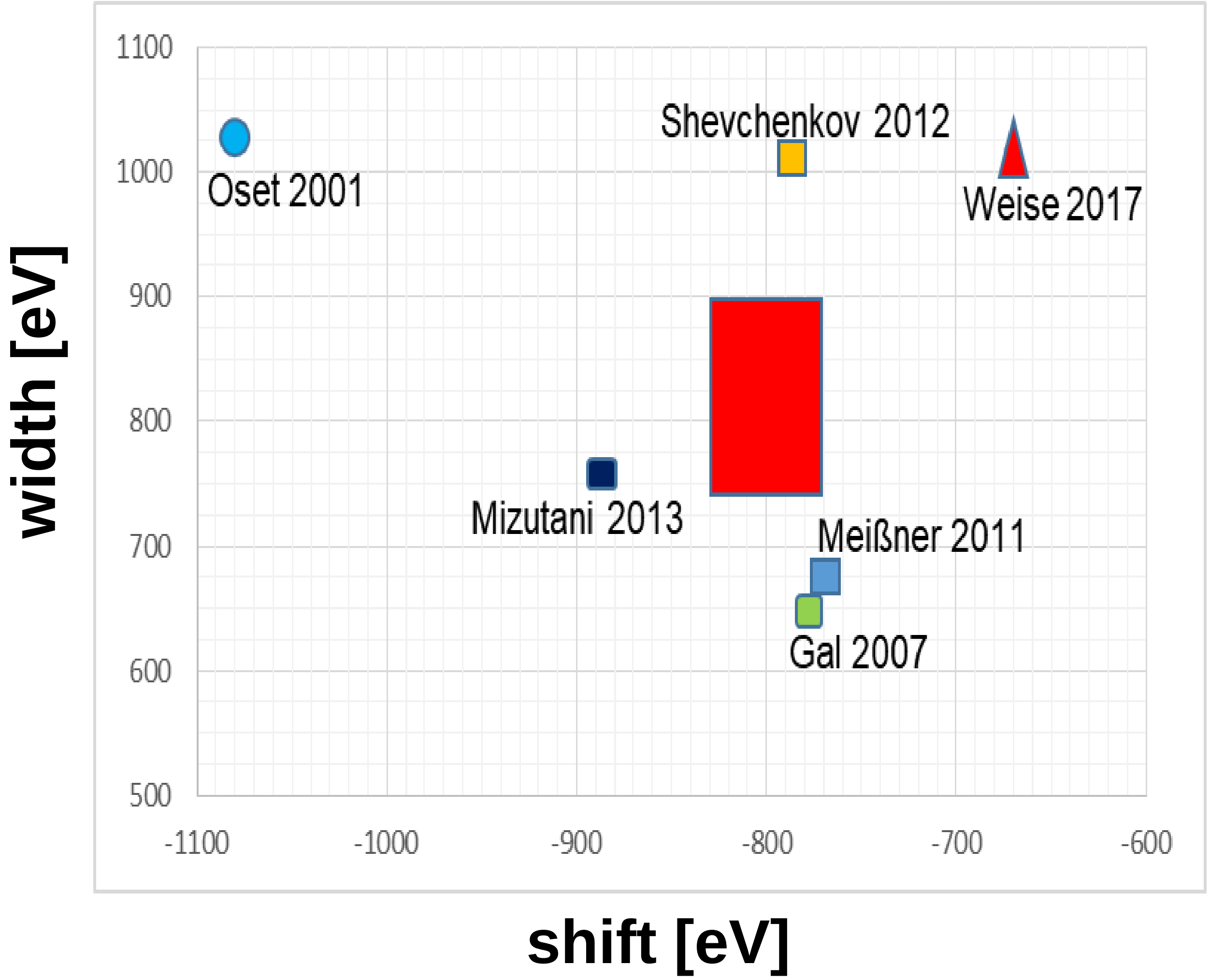
$$\Gamma_{1s}^{H} = 541 \pm 89(stat) \pm 22(syst)eV$$



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

The SIDDHARTA-2 scientific goal

The SIDDHARTA-2 experiment aims to perform the first measurement of shift and width of kaonic deuterium at the DAΦNNE e+e- collider at LNF-INFN.



ISOSPIN-DEPENDENT K-N SCATTERING LENGTH WILL BE COMPLETELY SOLVED

SIDDHARTA-2

SIlicon **D**rift **D**etector for **H**adronic **A**tom **R**esearch by **T**iming **A**pplications

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

HadronPhysics2 Study of Strongly Interacting Matter

HadronPhysics I3 Study of Strongly Interacting Matter

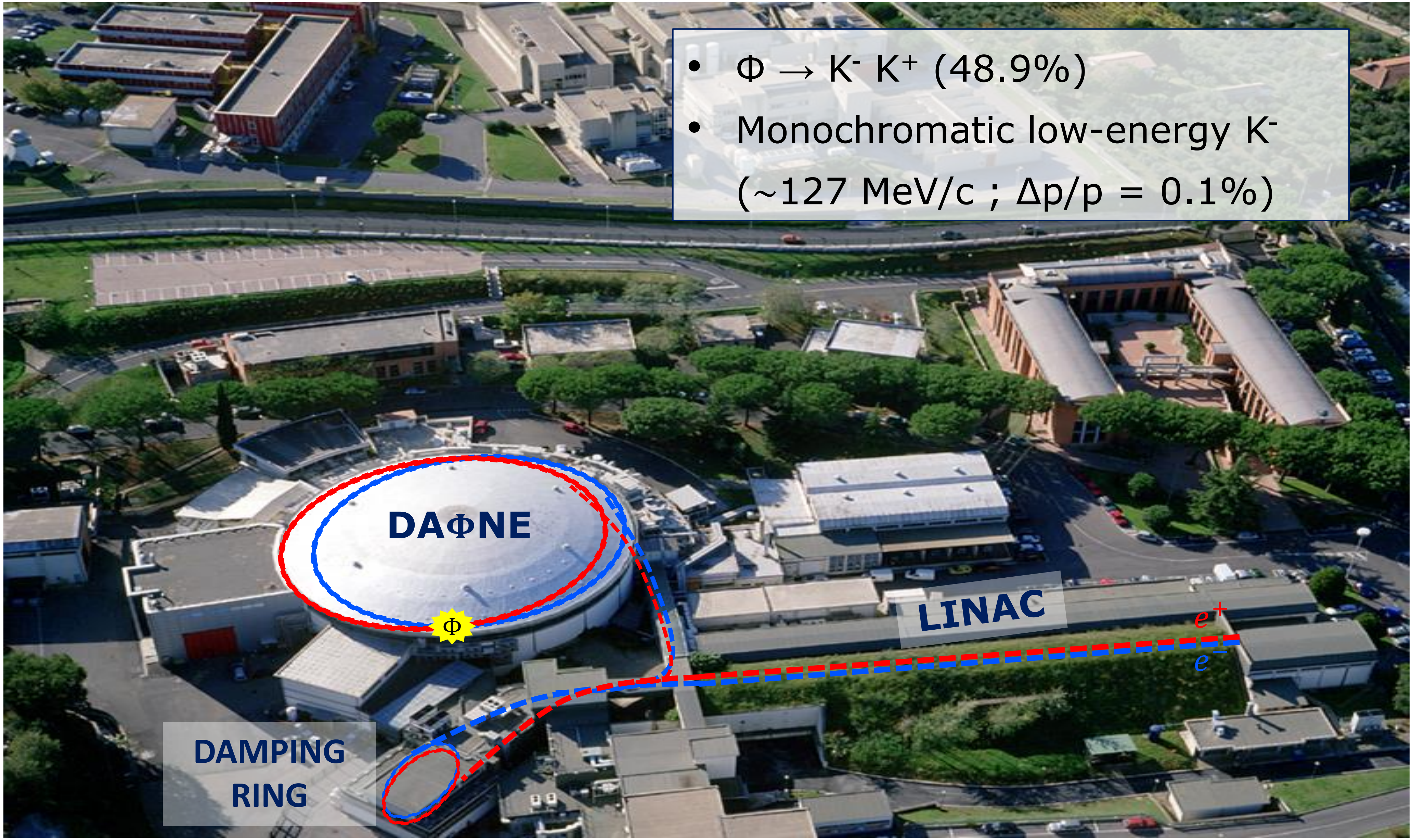
FWF Der Wissenschaftsfonds.

STRONG-2020

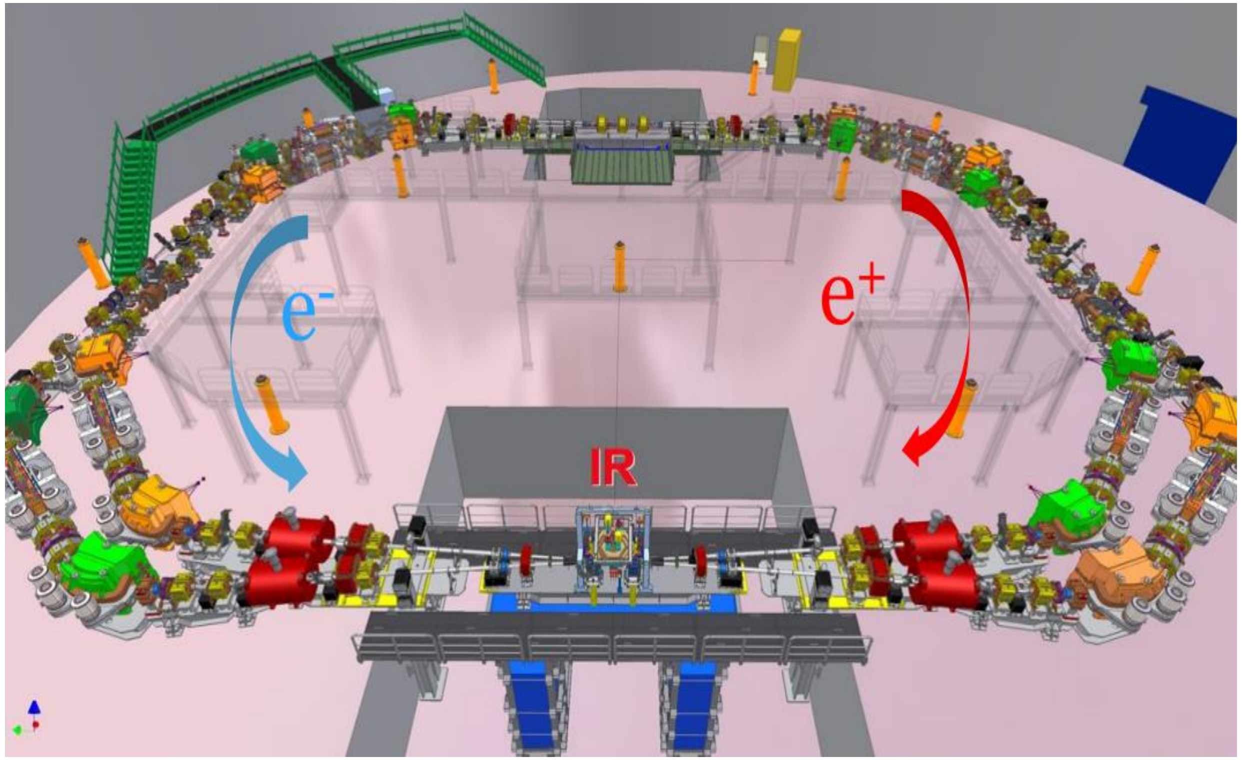
HrZZ Croatian Science Foundation

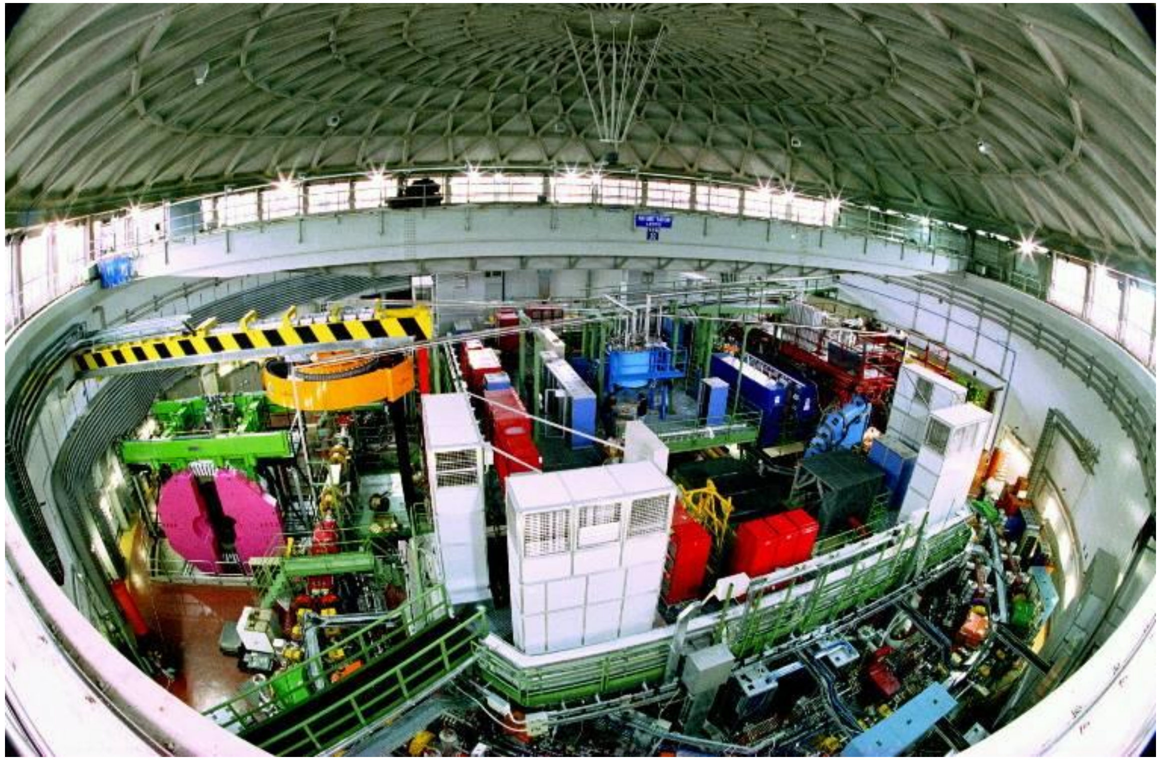
Farnesina Ministero degli Affari Esteri e della Cooperazione Internazionale

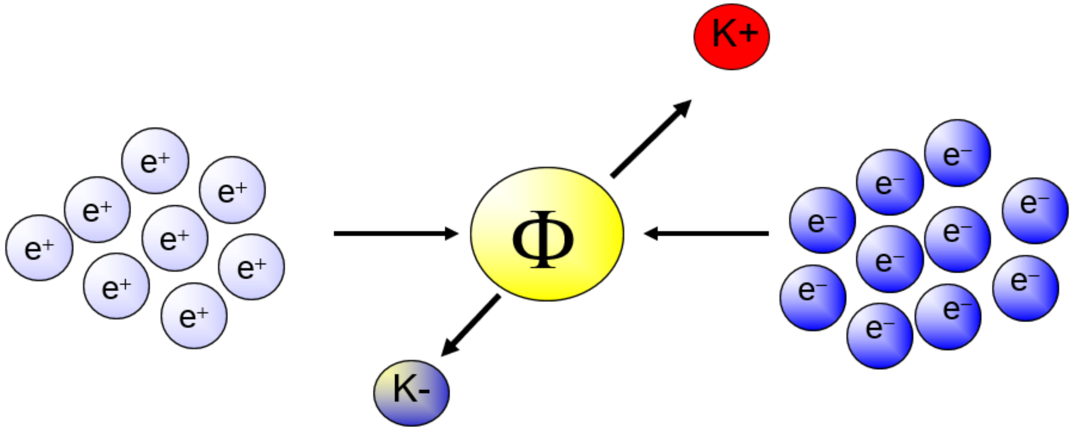
LNF e^+e^- Accelerators complex



The DAΦNE e^+e^- Collider



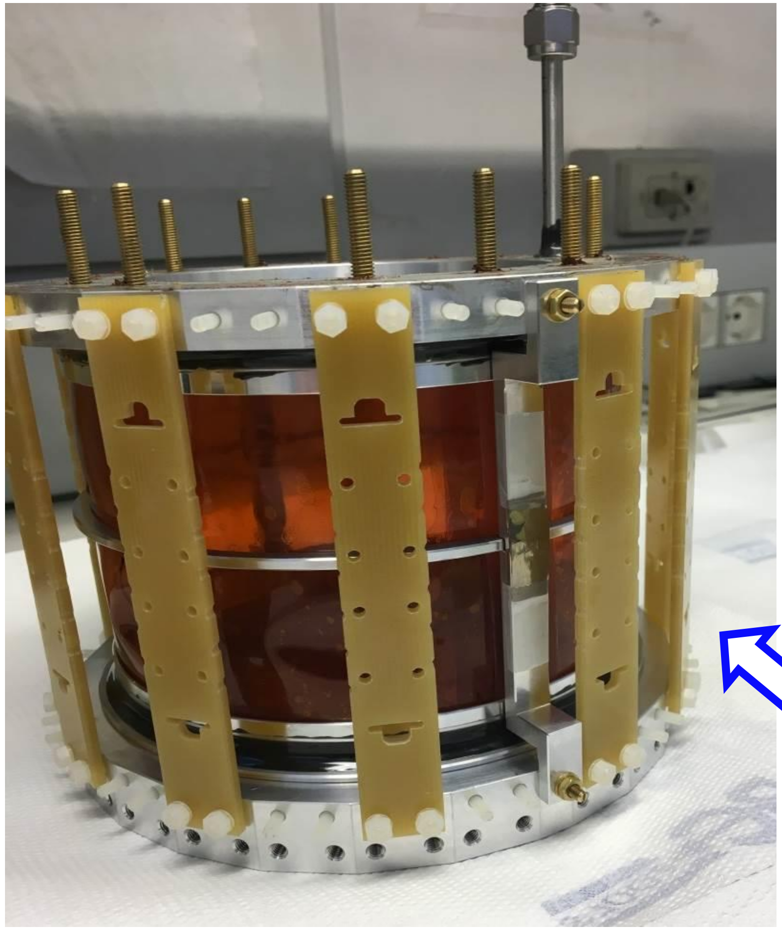


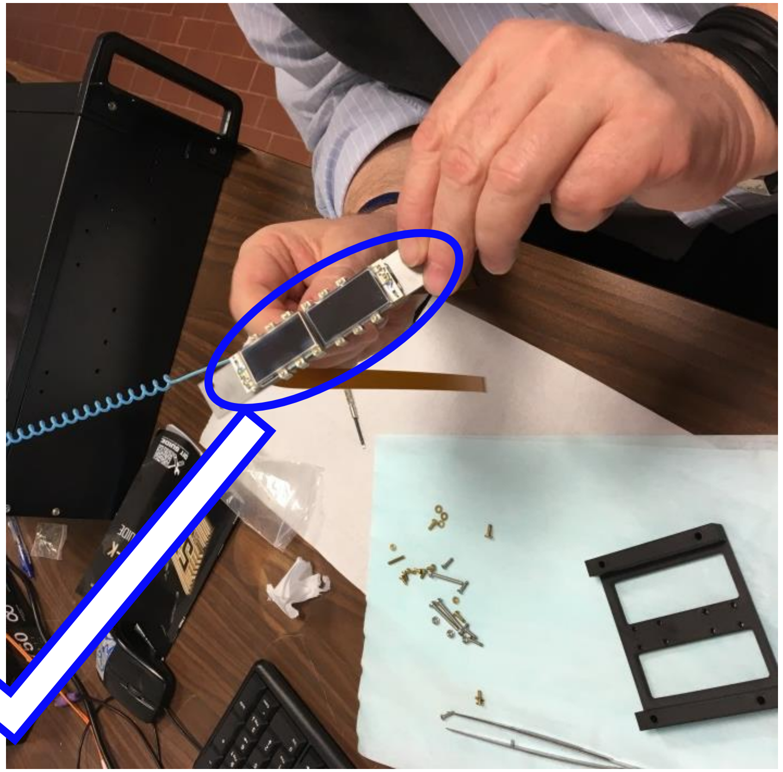


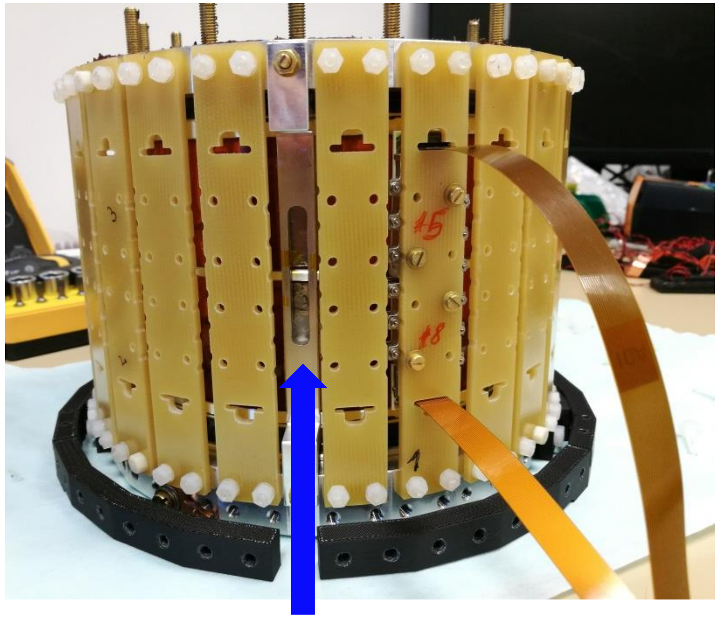
- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p$ = 0.1%)
- **Flux of produced kaons: about 1000/second**

The SIDDHARTA-2 target

The cylindric target cell consists of a wall made of a 2-Kapton layer structure (75 μm + 75 μm + Araldit), placed on aluminum support.







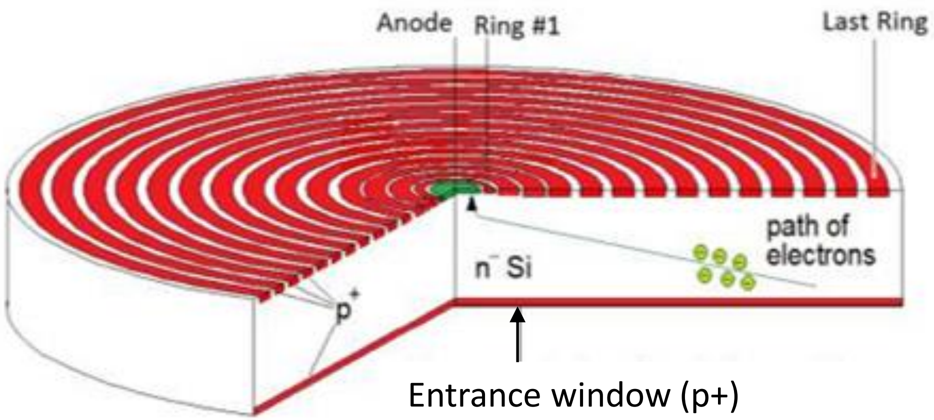
calibration foils inserted near to the SDD are activated by the X-ray tubes

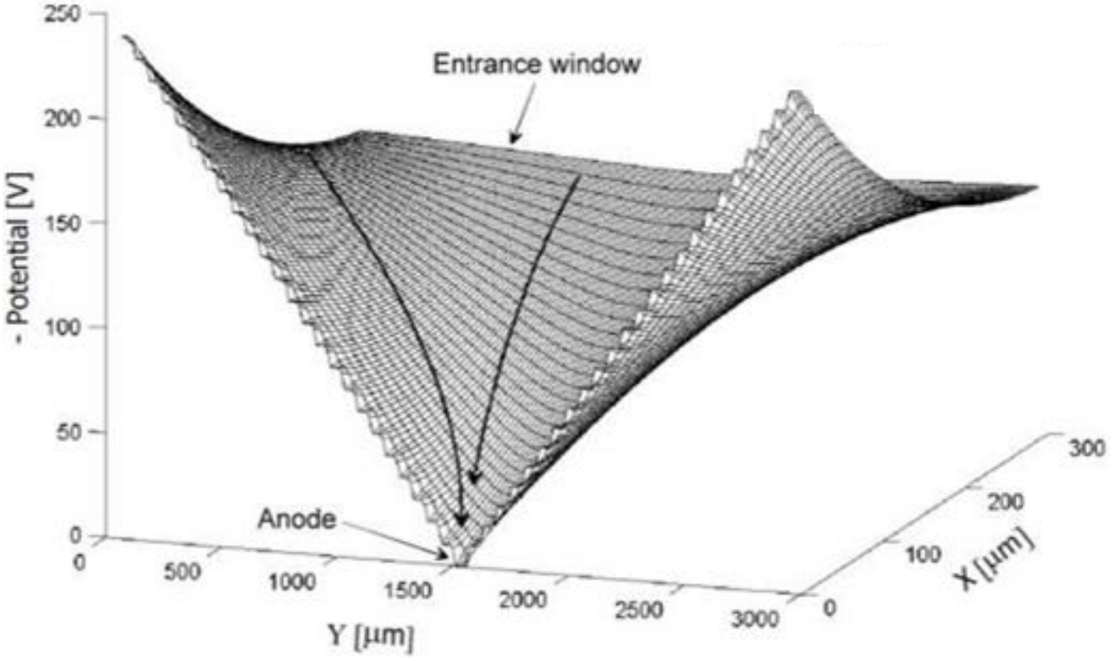
Silicon Drift Detectors (SDDs) are placed 5 mm from the target wall for the x-ray spectroscopy

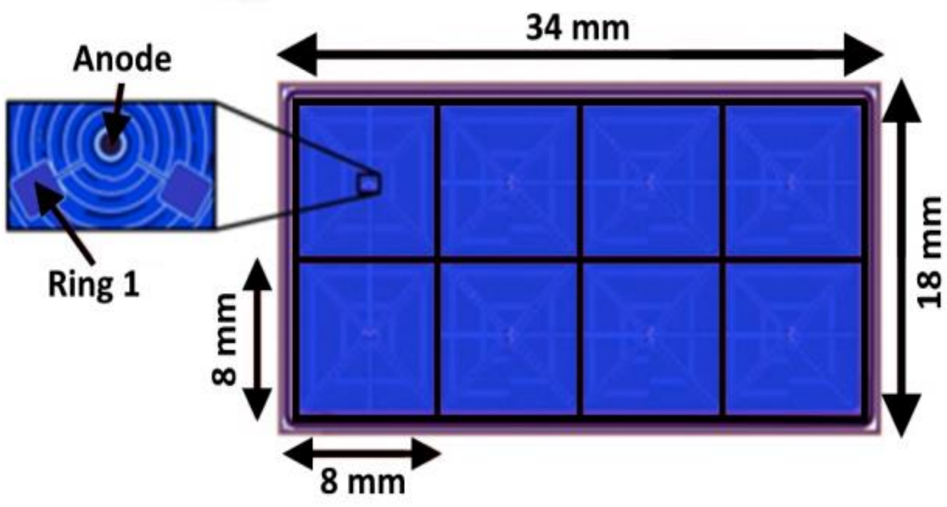
GASEOUS DEUTERIUM IS FLUXED WITHIN THE TARGET CELL

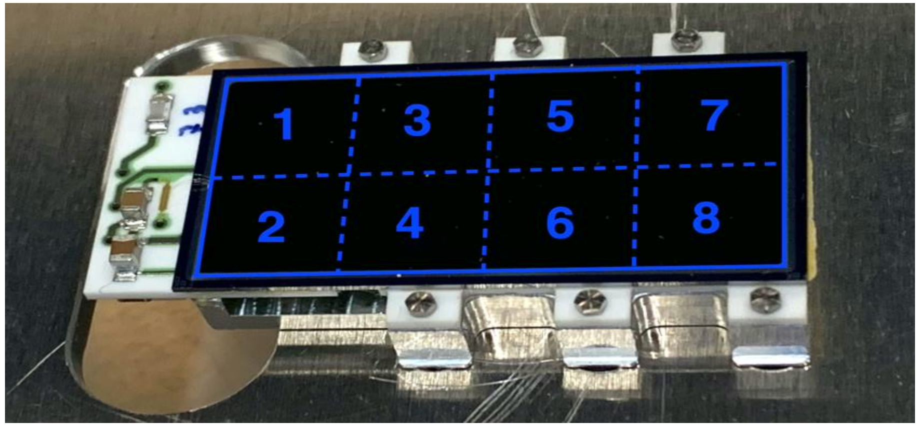
The Silicon Drift Detectors

SDD CELL CROSS SECTION









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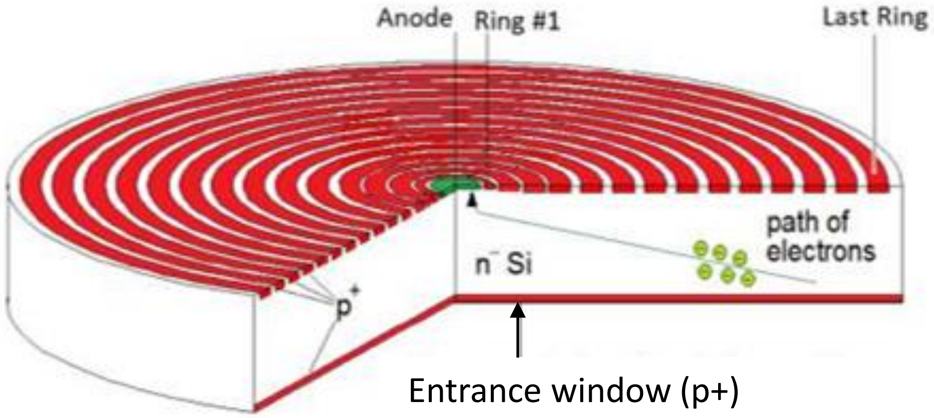
FONDAZIONE BRUNO KESSLER

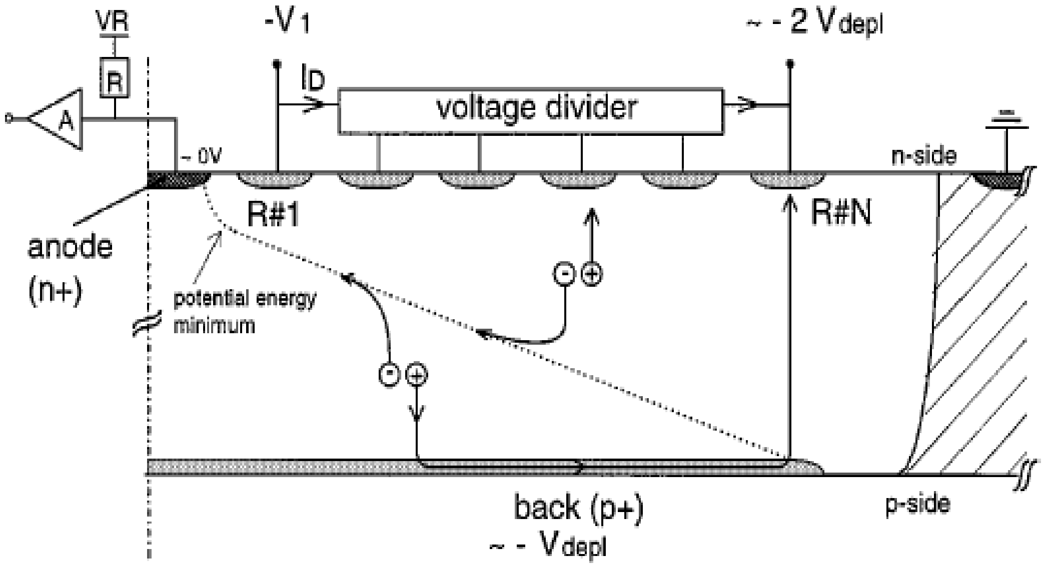
FUTURE BUILT ON KNOWLEDGE

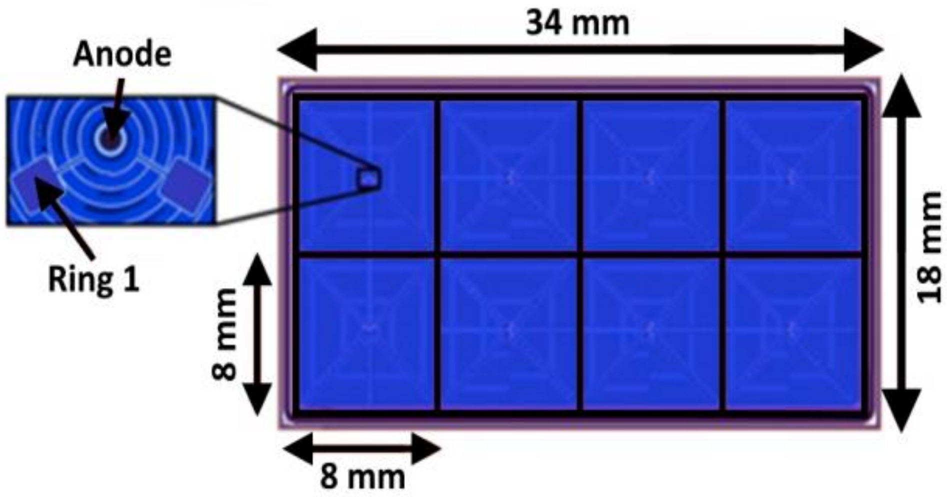
Each array consists of 8 SDD cells with 0.64 cm^2 of active area and 450 μm thickness each, which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

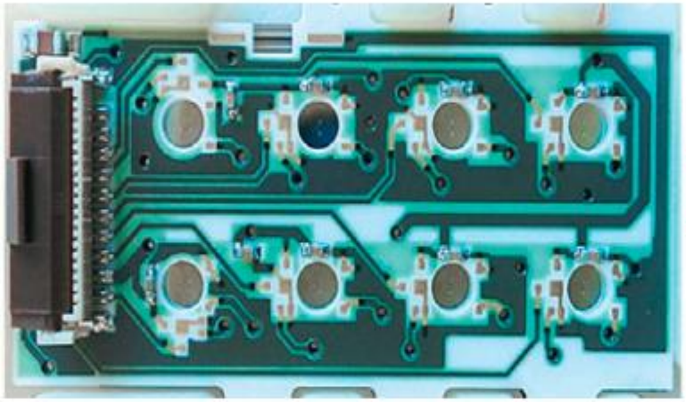
The Silicon Drift Detectors

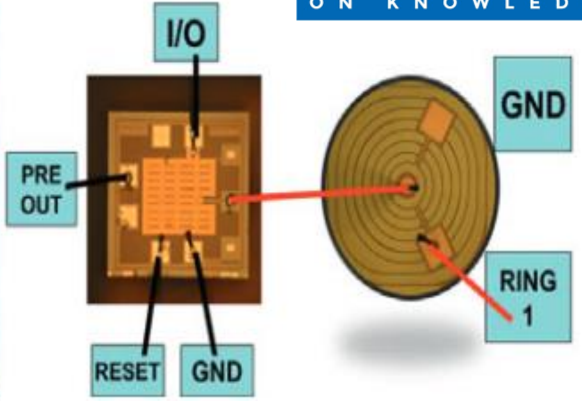
SDD CELL CROSS SECTION







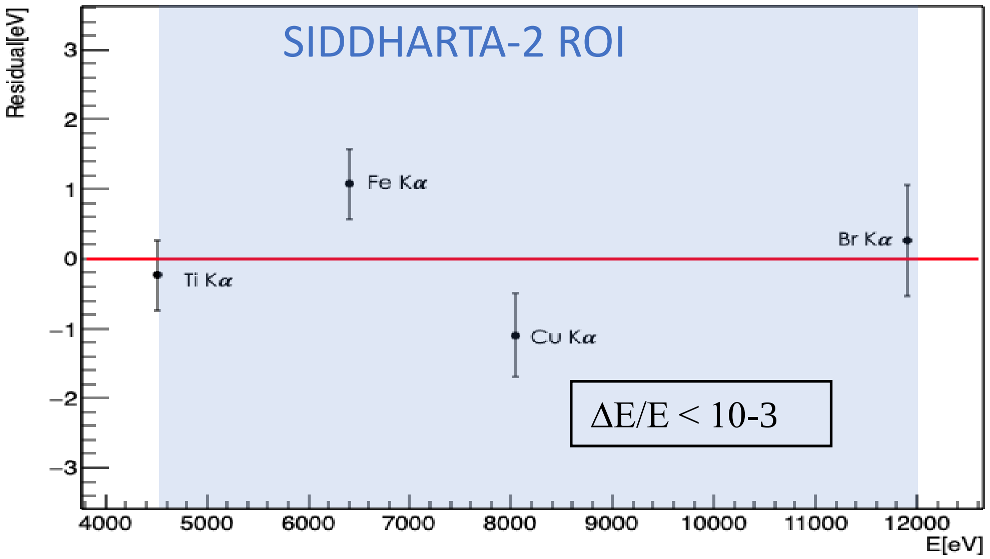




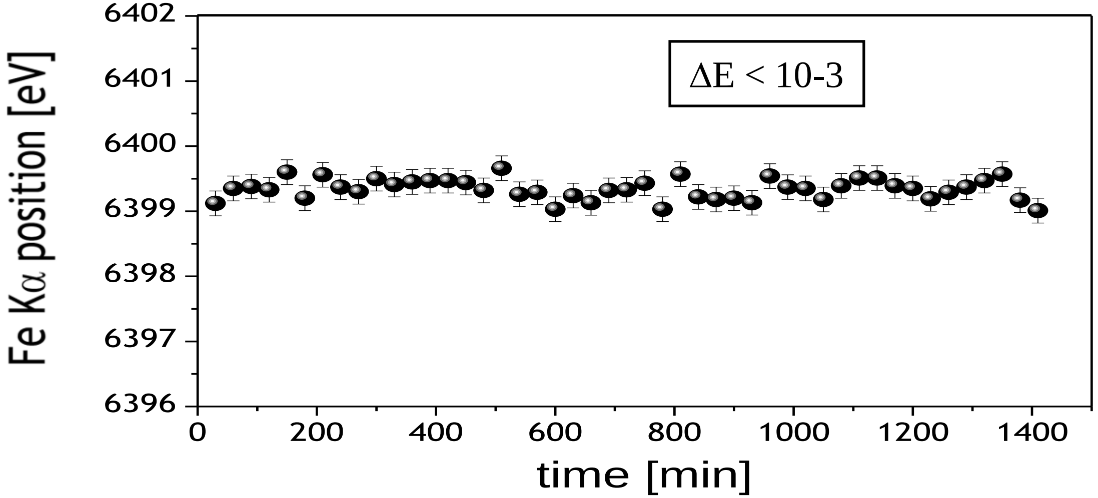
The SIDDHARTA-2 experiment equips 48 SDD arrays, for a total of 384 SDD cell detectors. Each SDD array has a total active area of 5.12 cm^2

The Silicon Drift Detectors

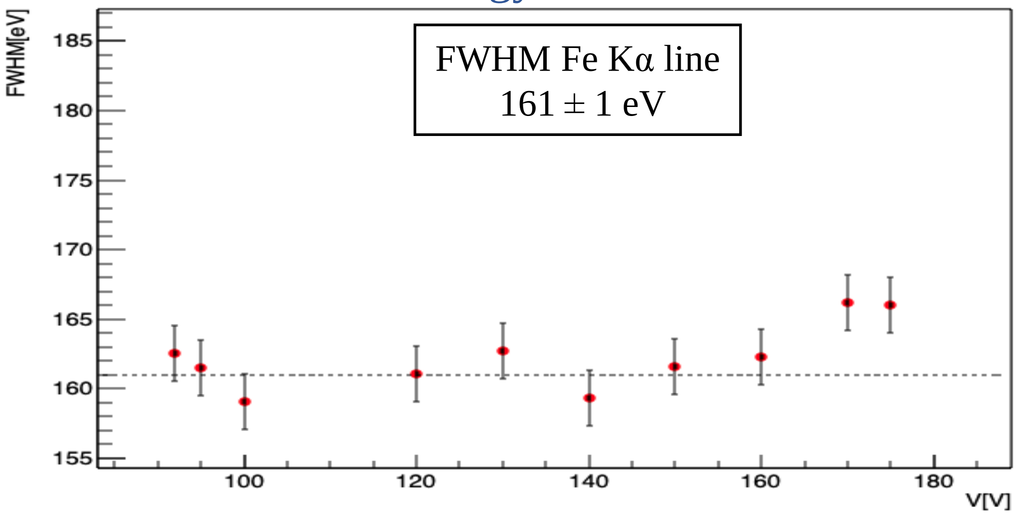
Linearity



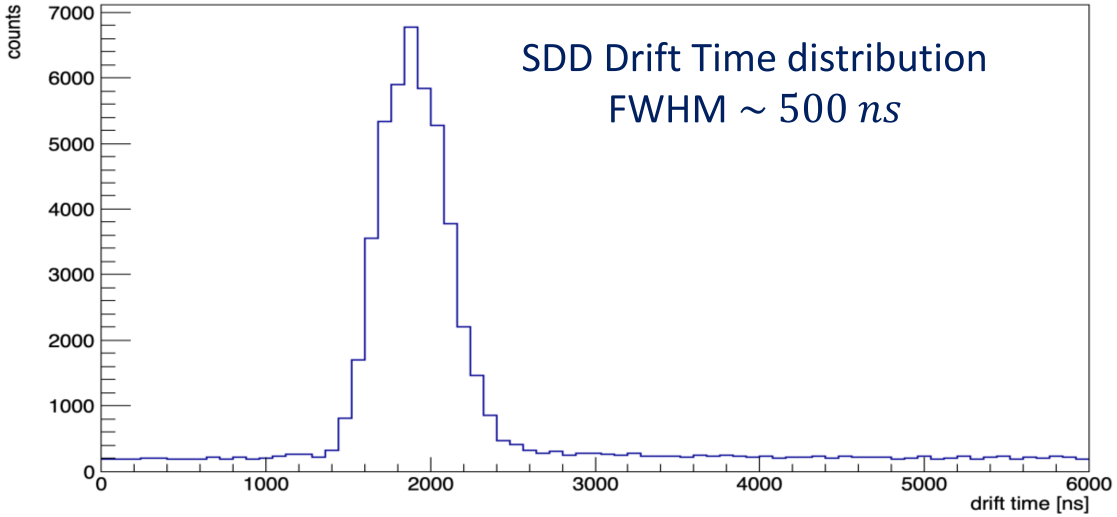
Stability



Energy Resolution

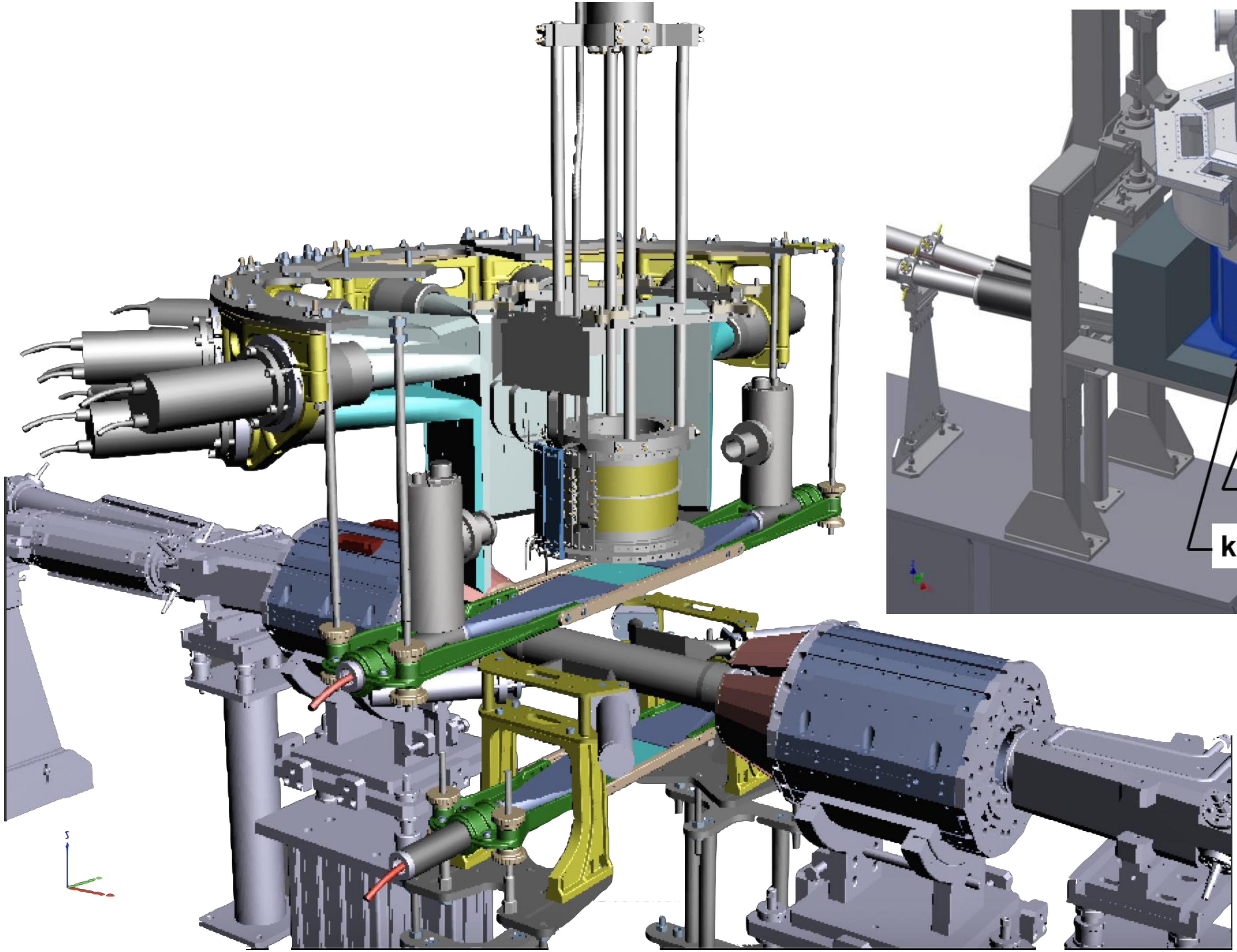


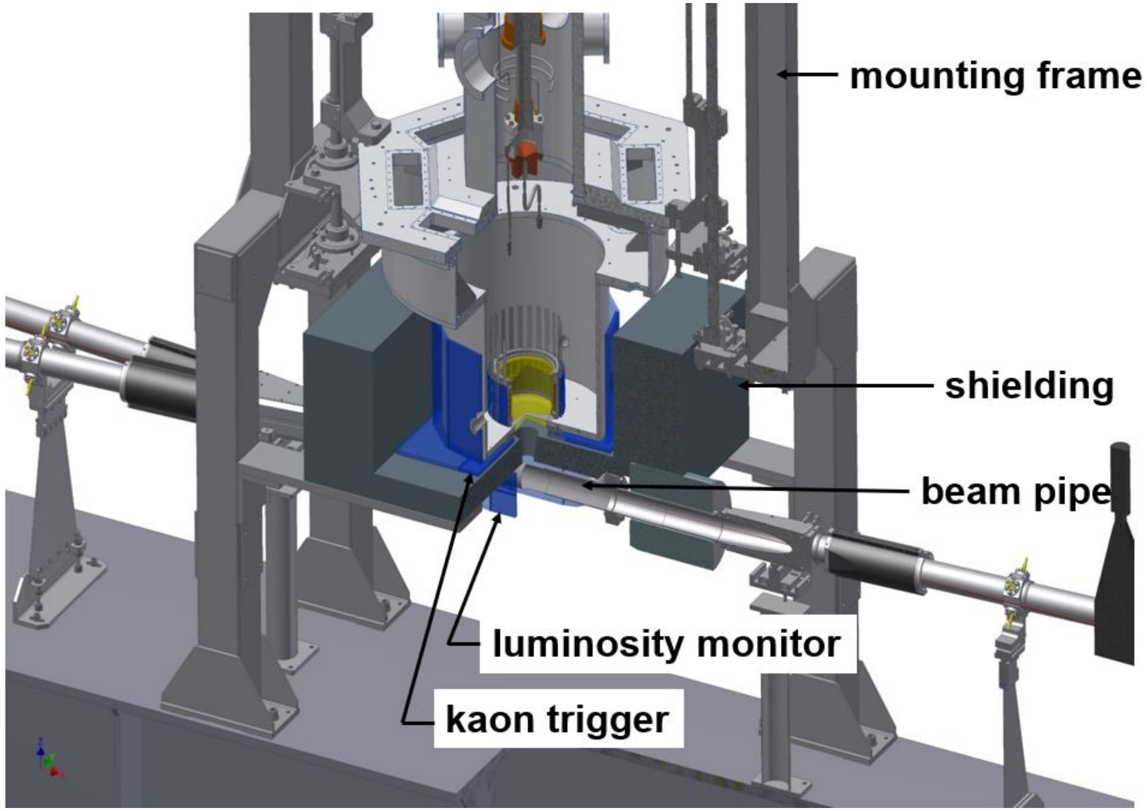
Timing Resolution



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

The SIDDHARTA-2 setup



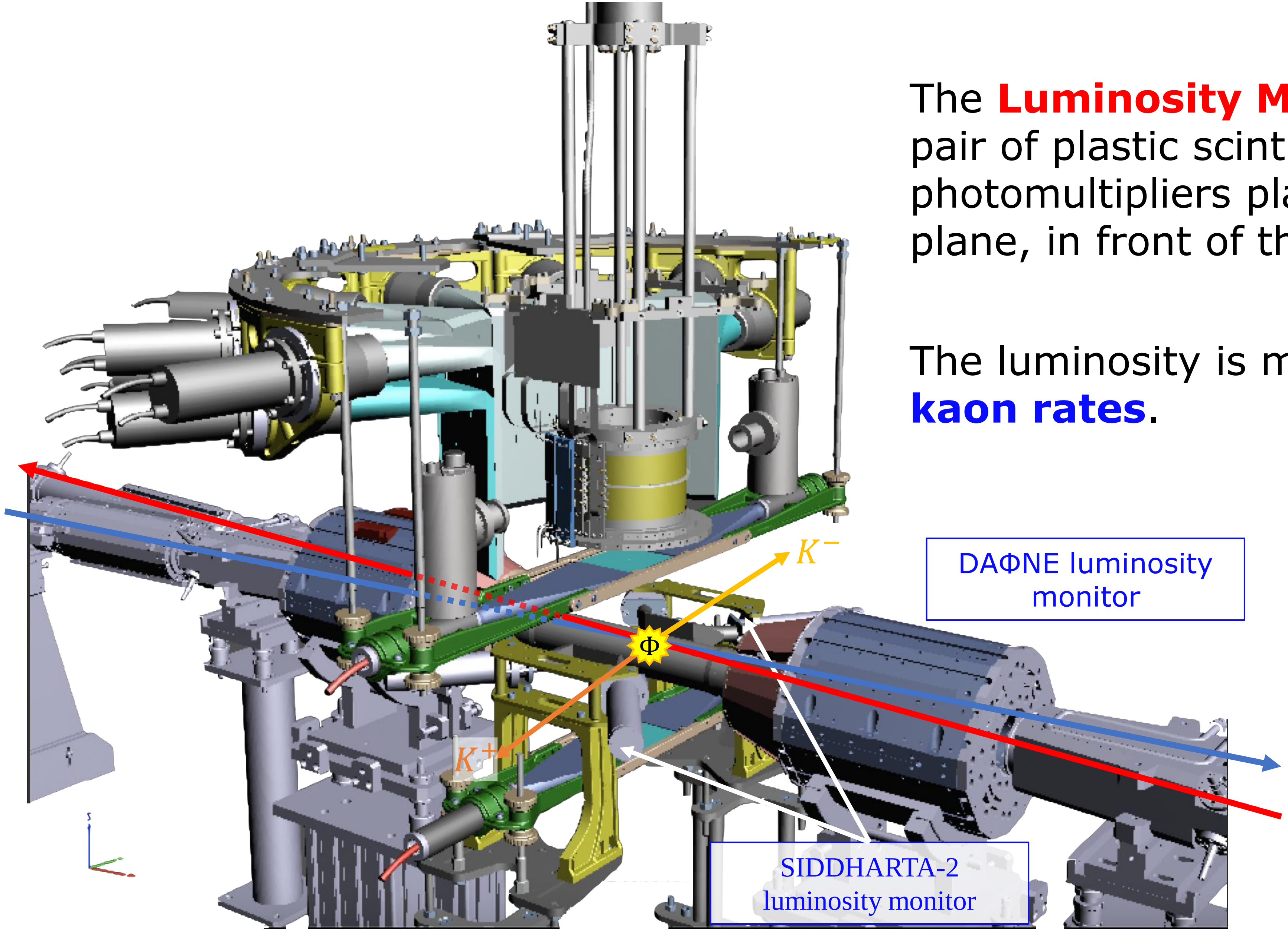


The SIDDHARTA-2 experiment is actually installed in the DAΦNE collider at LNF.

The SIDDHARTA-2 setup

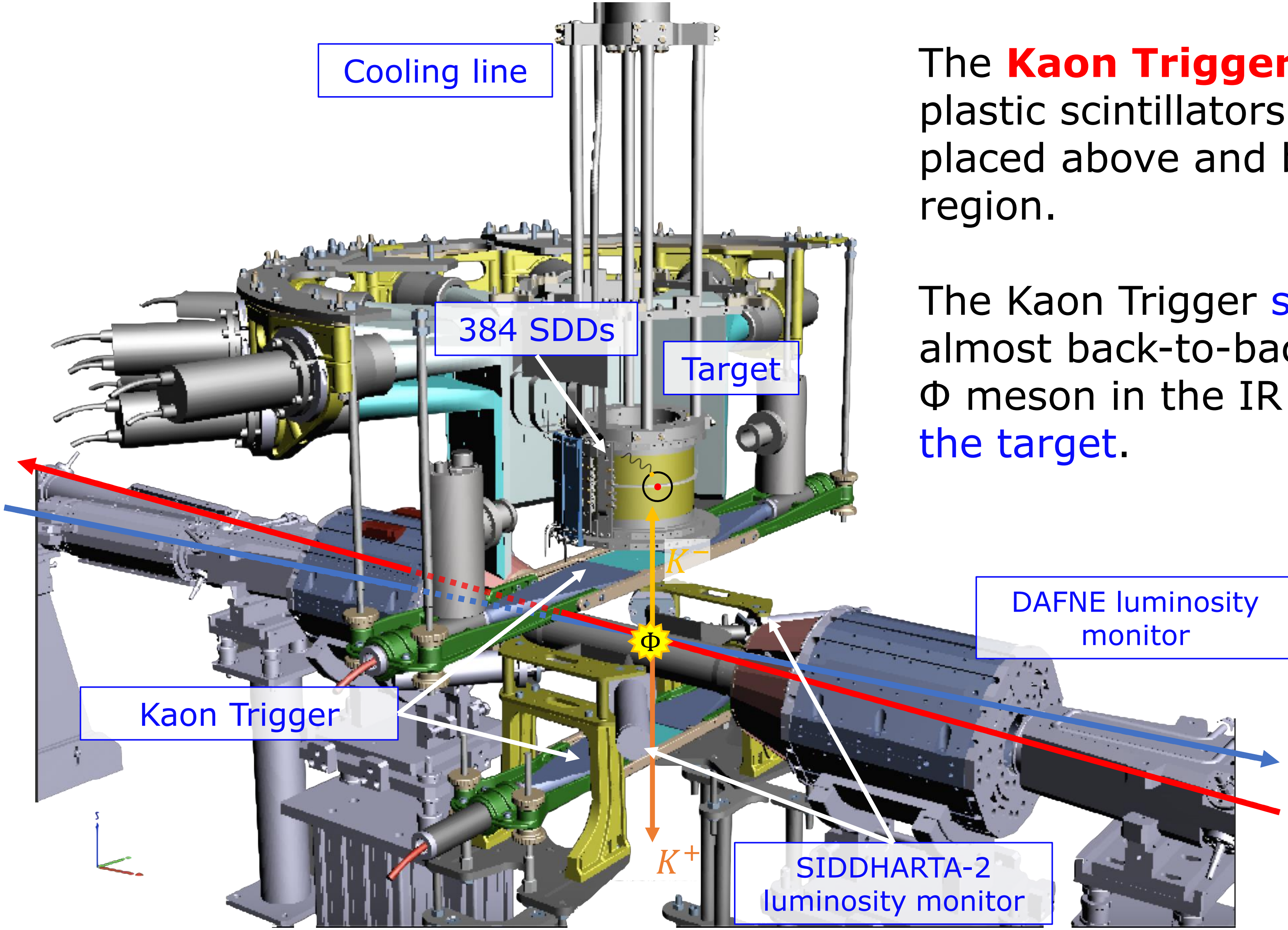
The **Luminosity Monitor** consists of a pair of plastic scintillators read by photomultipliers placed on the longitudinal plane, in front of the interaction region.

The luminosity is measured using the **kaon rates**.



The SIDDHARTA-2 luminosity monitor is complementary to the DAΦNE luminosity monitor, which use the Bhabha scattering $e^+e^- \rightarrow e^+e^-$

The SIDDHARTA-2 setup



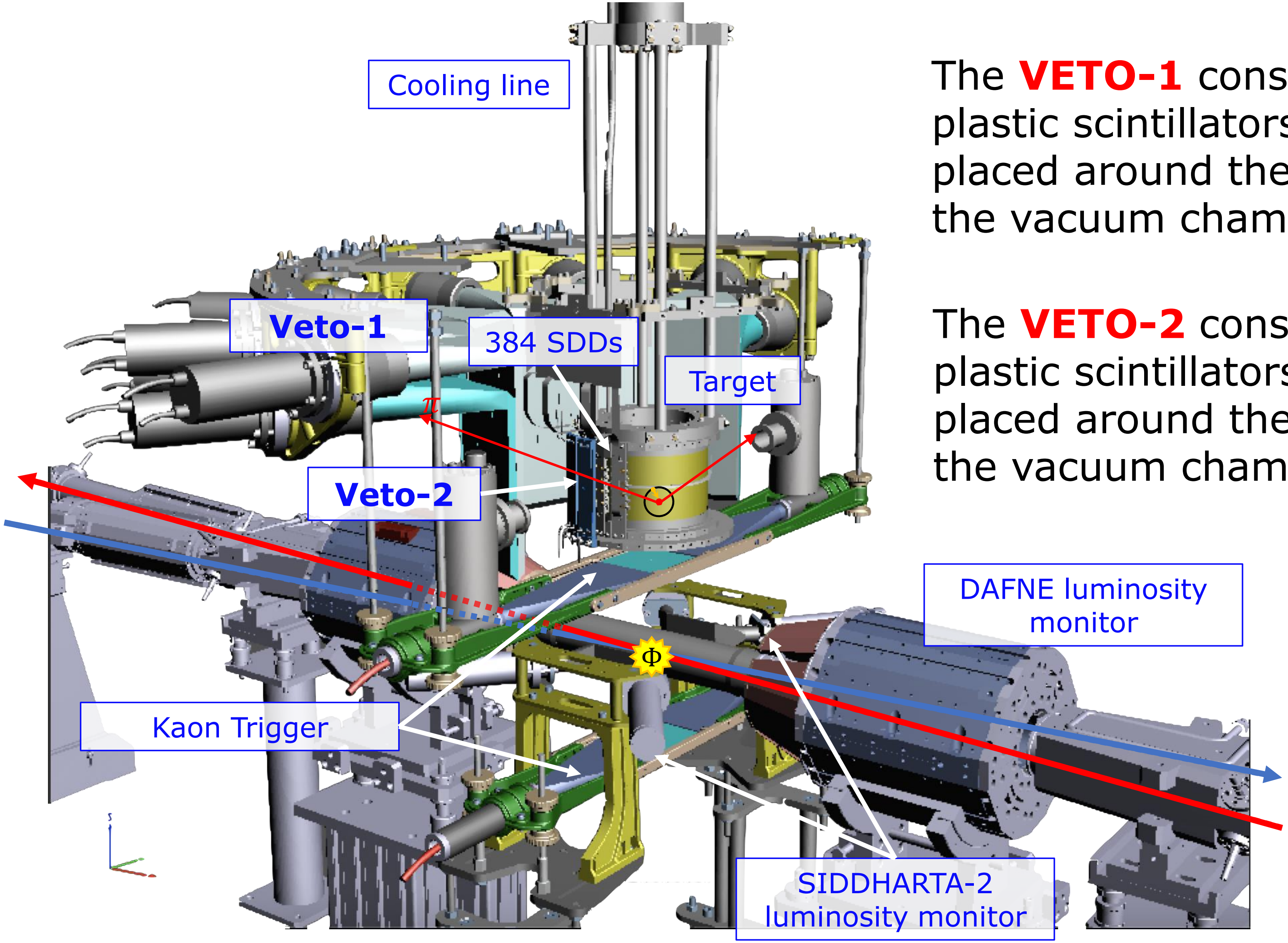
The **Kaon Trigger** consists of two pair of plastic scintillators read by photomultipliers placed above and below the Interaction region.

The Kaon Trigger selects kaons emitted almost back-to-back from the decay of the Φ meson in the IR and directed towards the target.

A cylindrical vacuum chamber is placed above the interaction point and contains target and SDDs.

SDDs are cooled to 170 K.

The SIDDHARTA-2 setup



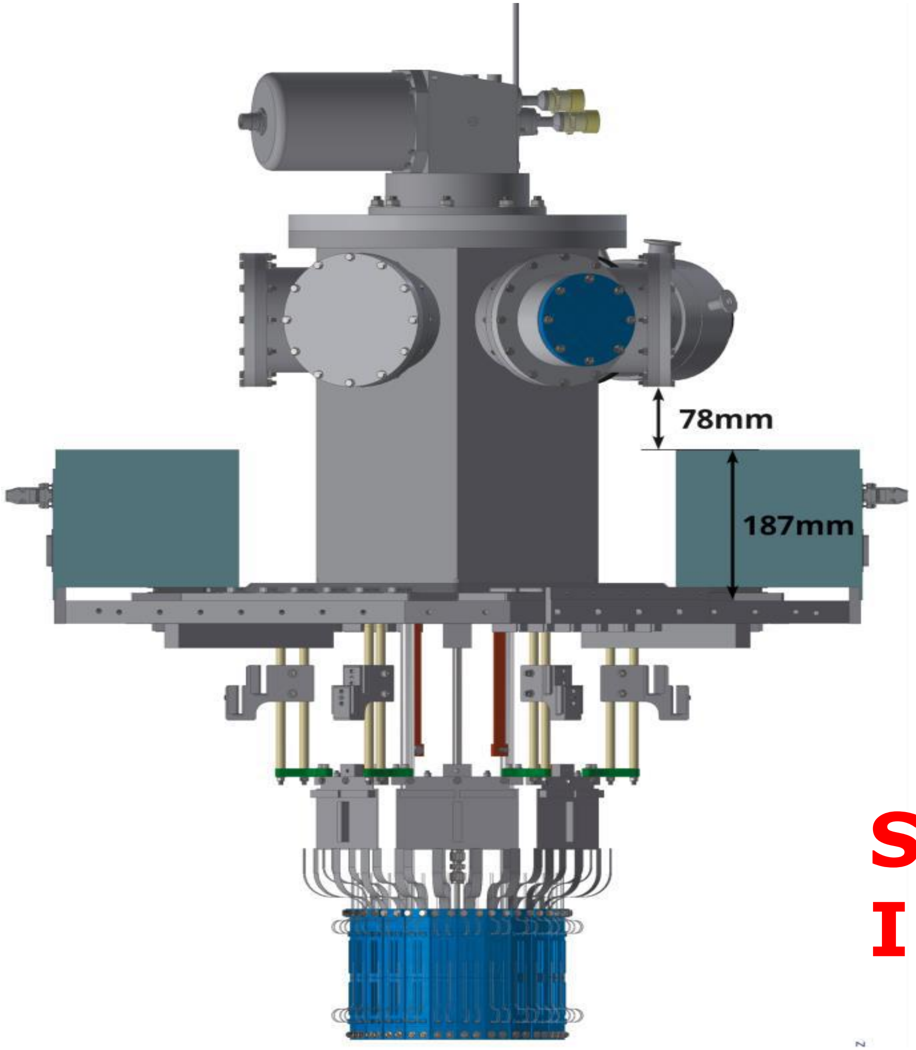
The **VETO-1** consists of twelve pair of plastic scintillators read by photomultipliers placed around the cryogenic target, outside the vacuum chamber.

The **VETO-2** consists of smaller pair of plastic scintillators read by photomultipliers placed around the cryogenic target, inside the vacuum chamber.

The Veto systems are used to suppress the synchronous and asynchronous background from the accelerator, and limit the fake signals due to minimum ionizing particles (MIPs)

SIDDHARTINO

SIDDHARTINO was the phase 1 of the SIDDHARTA-2 experiment, which consisted of 1/6 of the SIDDHARTA-2 apparatus, installed in the DAΦNE collider during the DAΦNE beams commissioning phase



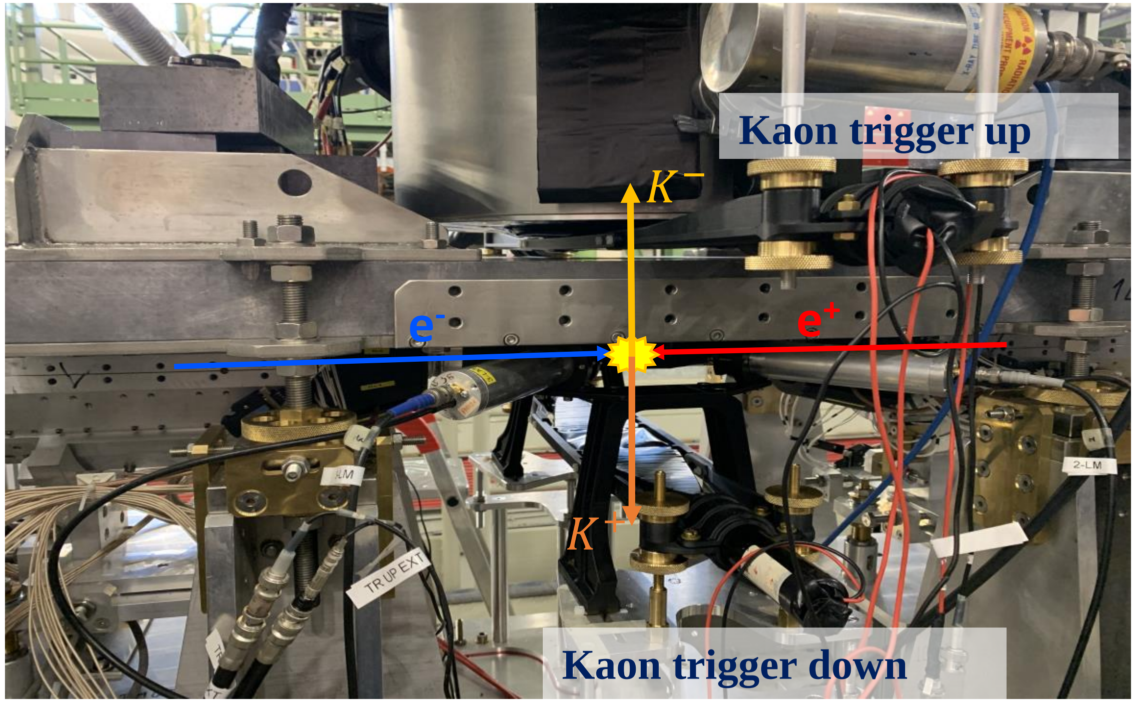
SIDDHARTINO goals:

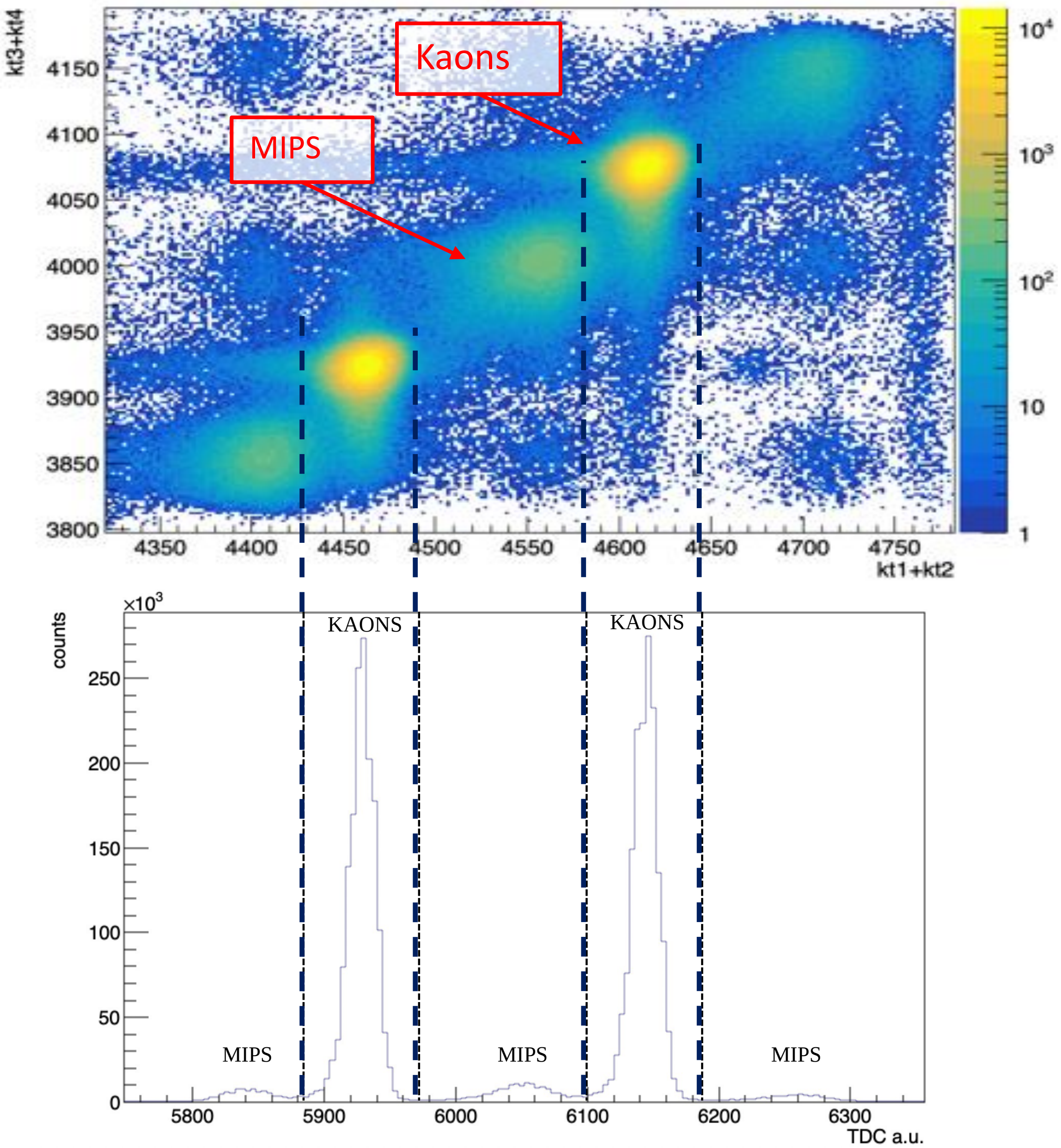
- Evaluation of the machine background (in preparation for the K-d run) through the measurement of the shift ε_{2p} and width Γ_{2p} in kaonic Helium 4

- Tuning of the SDD detectors
- Test and tuning of the Kaon trigger

SIDDHARTINO WAS CONCLUDED IN 2021

The Kaon Trigger



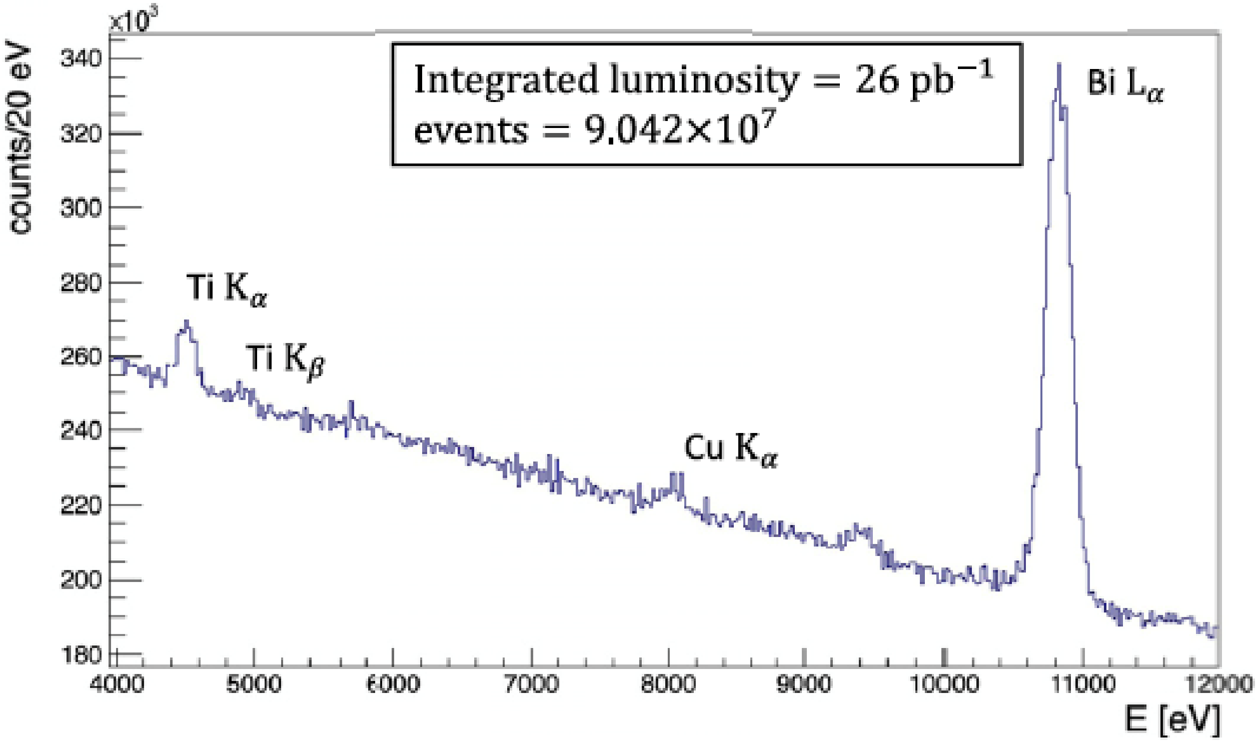


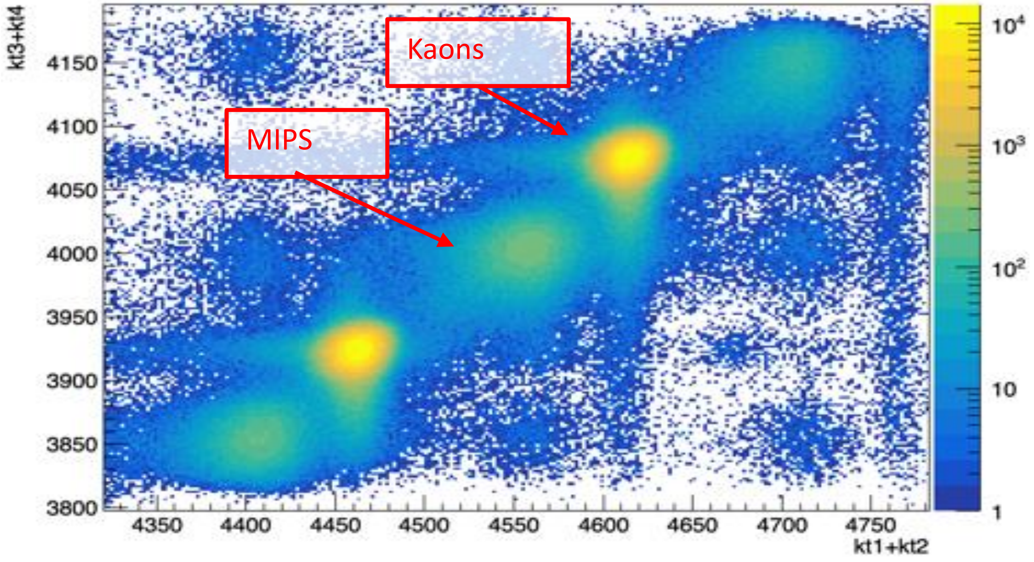
The Time of Flight (ToF) is different for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs).

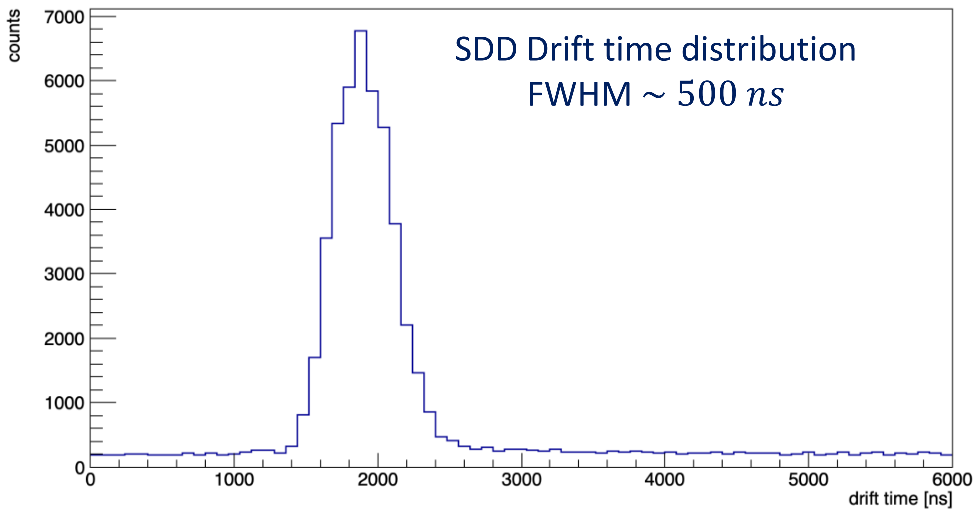
Can efficiently discriminate by ToF Kaons and MIPs!

The Kaon Trigger

SIDDHARTINO spectrum before applying the **kaon trigger** and the **drift time rejection**

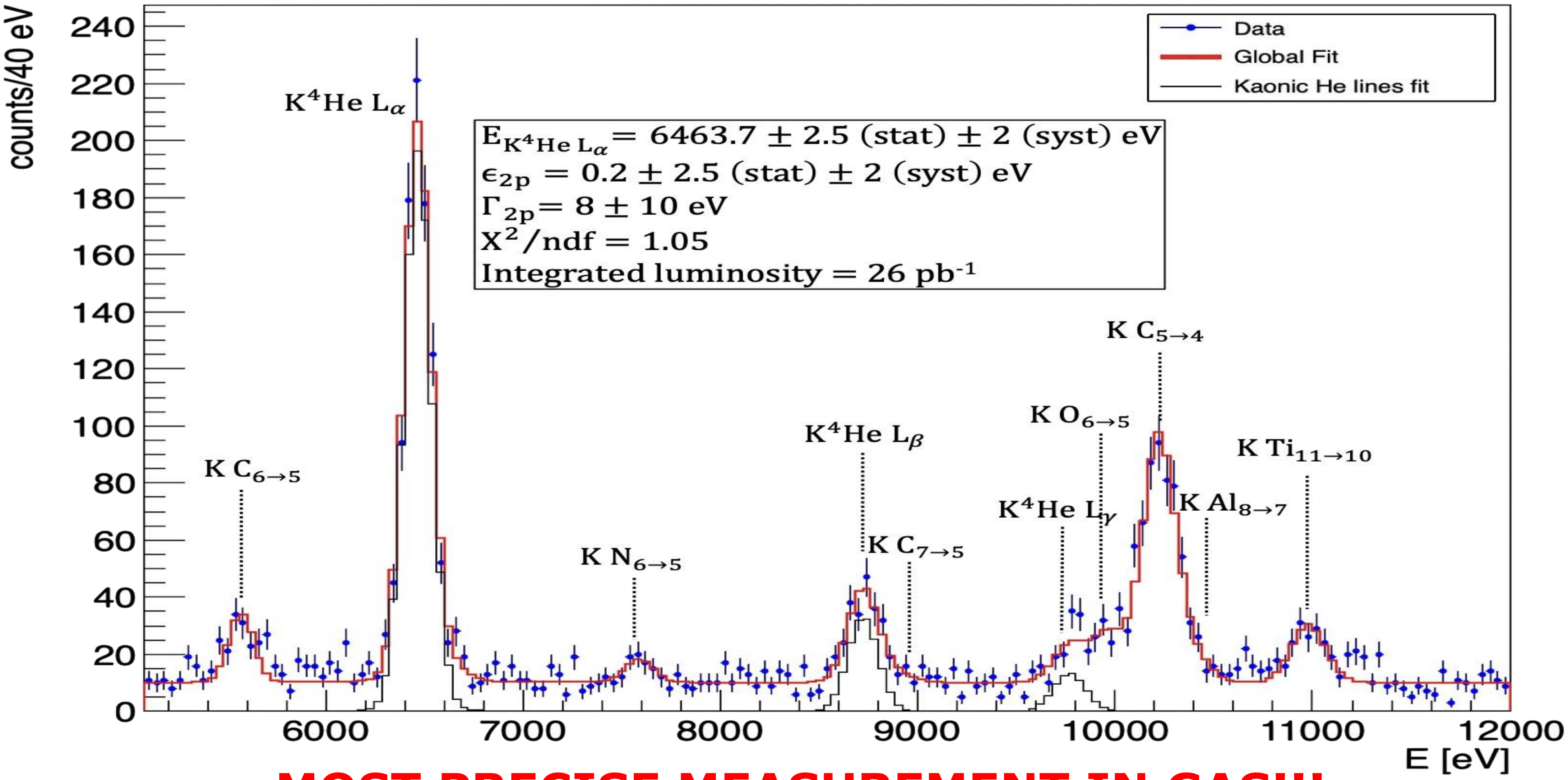






Triggered rejection factor ~ 10^{-5}

$K^{-}\,{}^4_2He$ measurement with SIDDHARTINO



MOST PRECISE MEASUREMENT IN GAS!!!

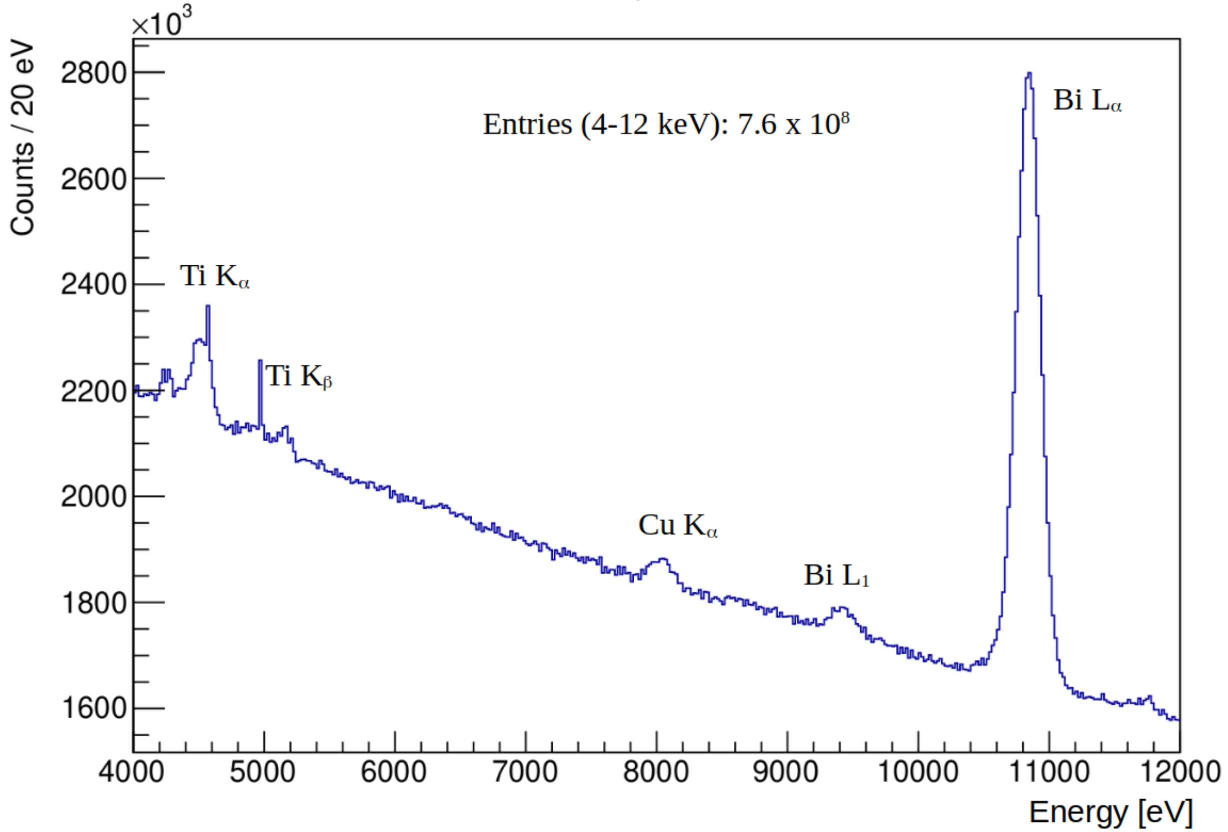
Sirghi *et al* 2022 *J. Phys. G: Nucl. Part. Phys.*

SIDDHARTA-2 setup
Ready for Run

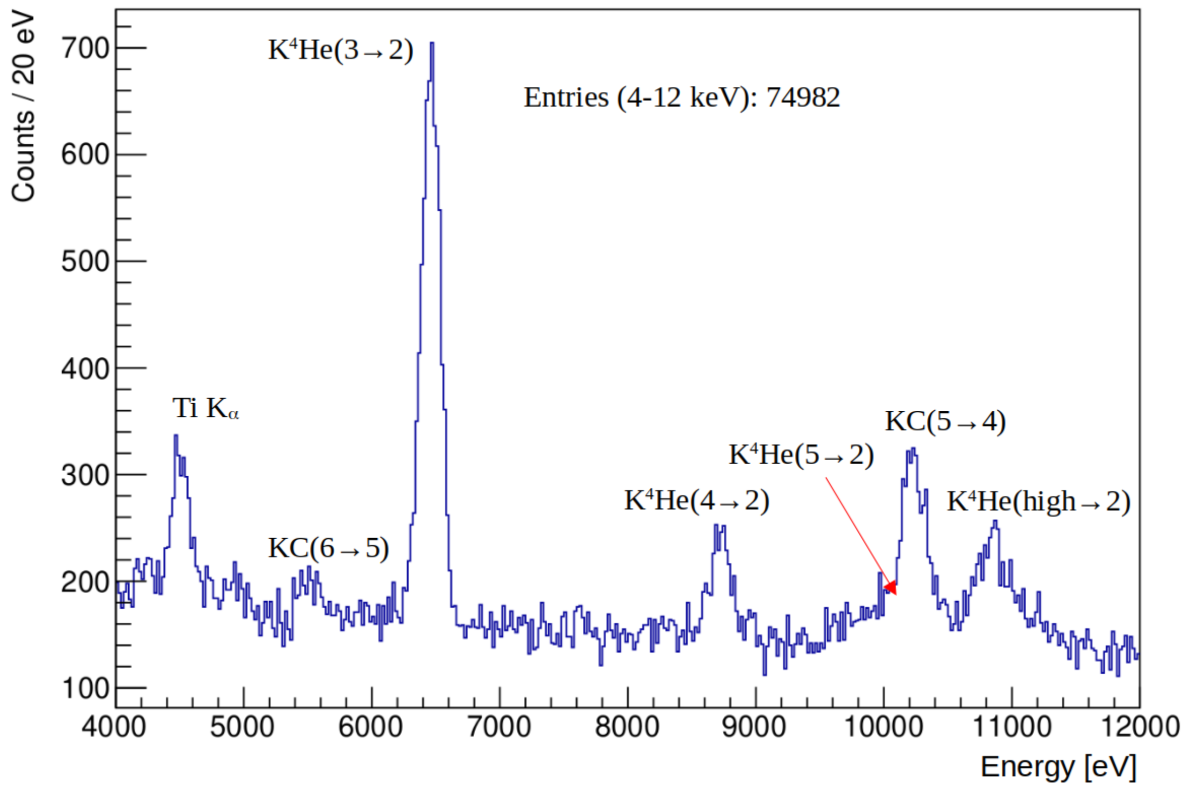
$K^-{}^4_2He$ measurement with SIDDHARTA2

The SIDDHARTA-2 installation was completed in the second half of 2021. In May 2022 a new measurement of $K^-{}^4_2He$ was performed to confirm the great performance shown by SIDDHARTINO, for the SIDDHARTA-2 apparatus.

COMPLETE SPECTRUM ACQUIRED BY SIDDHARTA-2

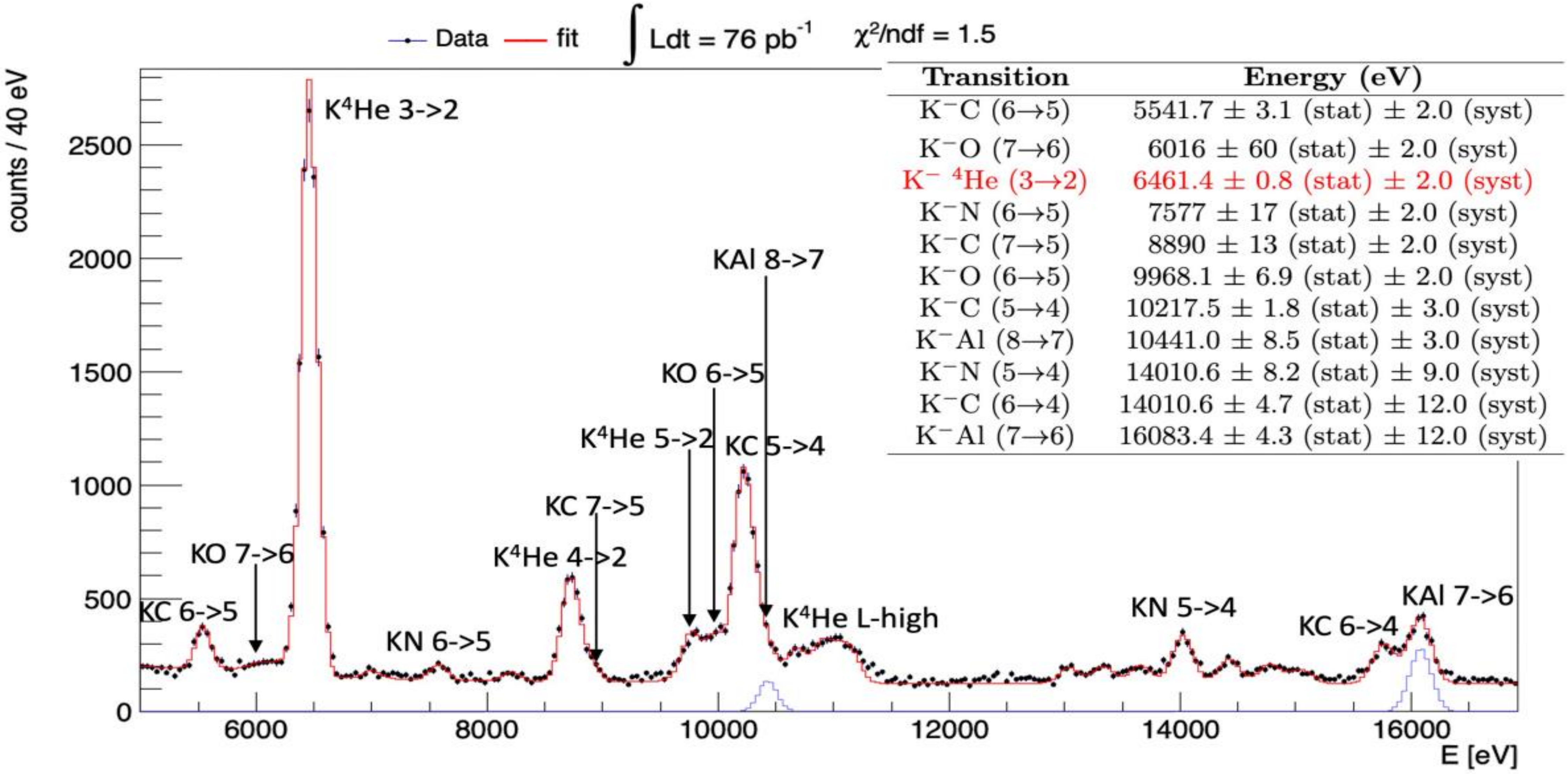


$K^-{}^4_2He$ SPECTRUM APPLYING KAON TRIGGER



Triggered rejection factor 3.15×10^{-5}

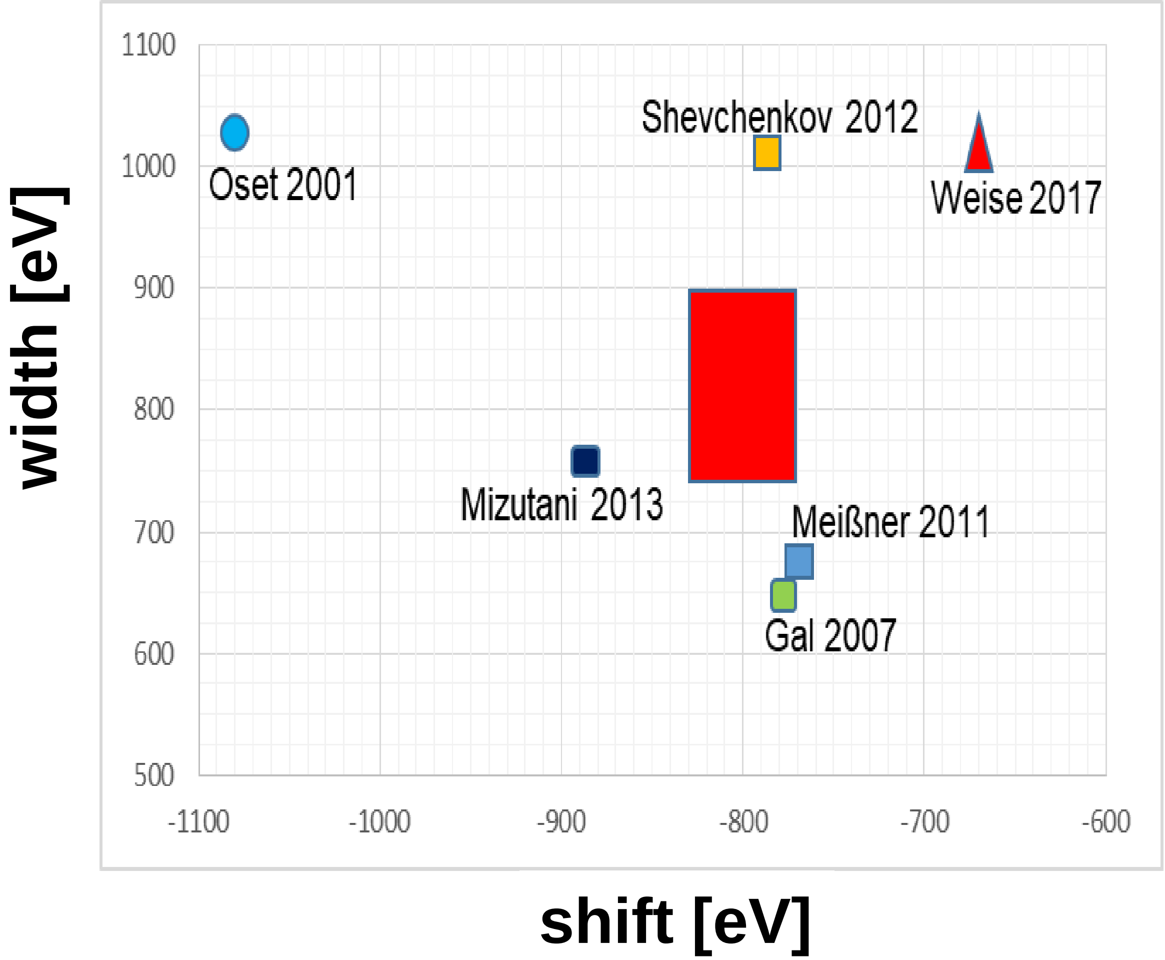
$K^-{}^4_2He$ measurement SIDDHARTINO + SIDDHARTA-2



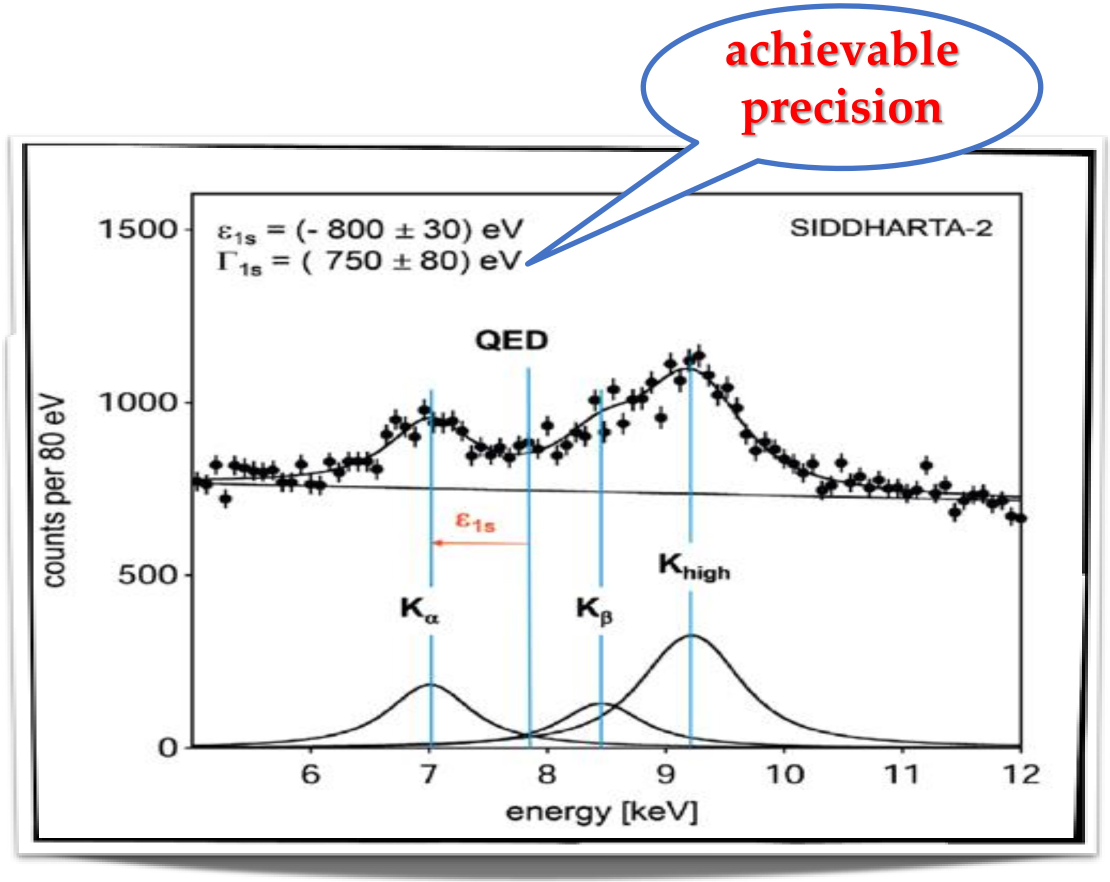
Transition	Energy (eV)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^- ^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-C (5→4)	10217.5 ± 1.8 (stat) ± 3.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-C (6→4)	14010.6 ± 4.7 (stat) ± 12.0 (syst)
K^-Al (7→6)	16083.4 ± 4.3 (stat) ± 12.0 (syst)

READY TO START KAONIC DEUTERIUM MEASUREMENT!!!

SIDDHARTA-2 $\bar{K}d$ measurement



SIDDHARTA-2 WILL RUN DURING 2023 TO PERFORM THE FIRST $\bar{K}d$ 1s ATOMI LEVEL SHIFT AND WIDTH MEASUREMENT



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) !

Beyond SIDDHARTA-2

- **Feasibility studies in parallel with Siddharta-2**

- **Various setups in preparation:**
  - *HPGe*
  - *Crystal spectrometers (VOXES)*
  - *CdZnTe detectors*
  - *SDD 1mm for kaonic atoms measurement*

- **Proposal for Extension of the Scientific Program at DAFNE:**
  - *Kaon mass - precision measurement at a level < 7 keV*
  - *Kaonic helium transitions to the 1s level*
  - *Other light kaonic atoms (K^-Bi, Li, B,, K^-C,…)*
  - *Heavier kaonic atoms (K^-Si, K^-Pb…)*
  - *Radiative kaon capture – Λ(1405) study*
  - *Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen)*
  - *Measurement of Nuclear Resonance Effects in Kaonic Molybdenum Isotopes ($^{94}_{42}Mo, ^{96}_{42}Mo, ^{98}_{42}Mo, ^{100}_{42}Mo$) with investigation on nuclear pheriphery changement adding pair of neutrons from the lightest isotope (possible implication in* neutrinoless double beta ($0\nu\beta\beta$) decay*)*

Thank you!