Kaonic atoms experiments at the DAΦNE collider

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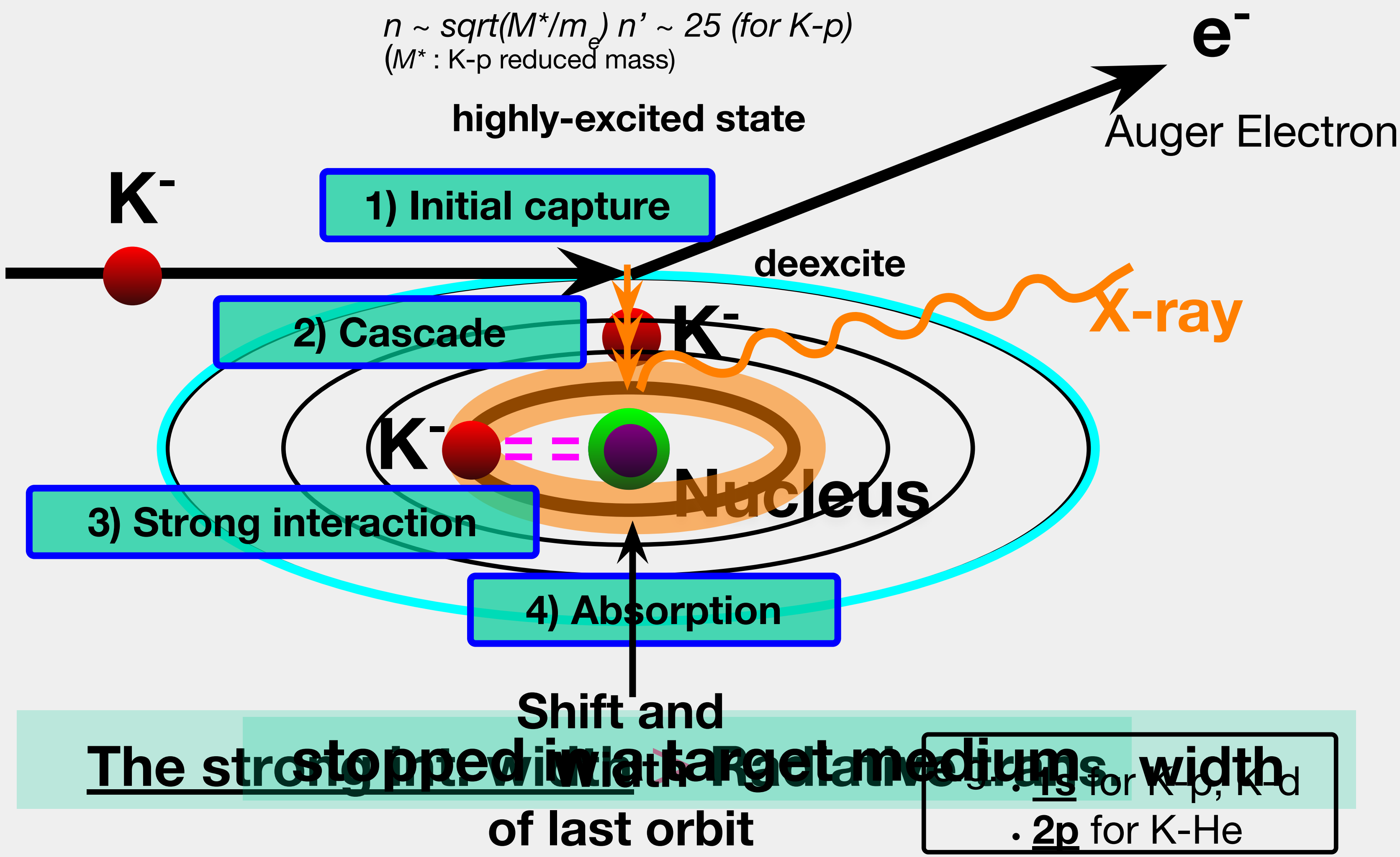
LNF

24th European Conference on Few-Body Problems in Physics

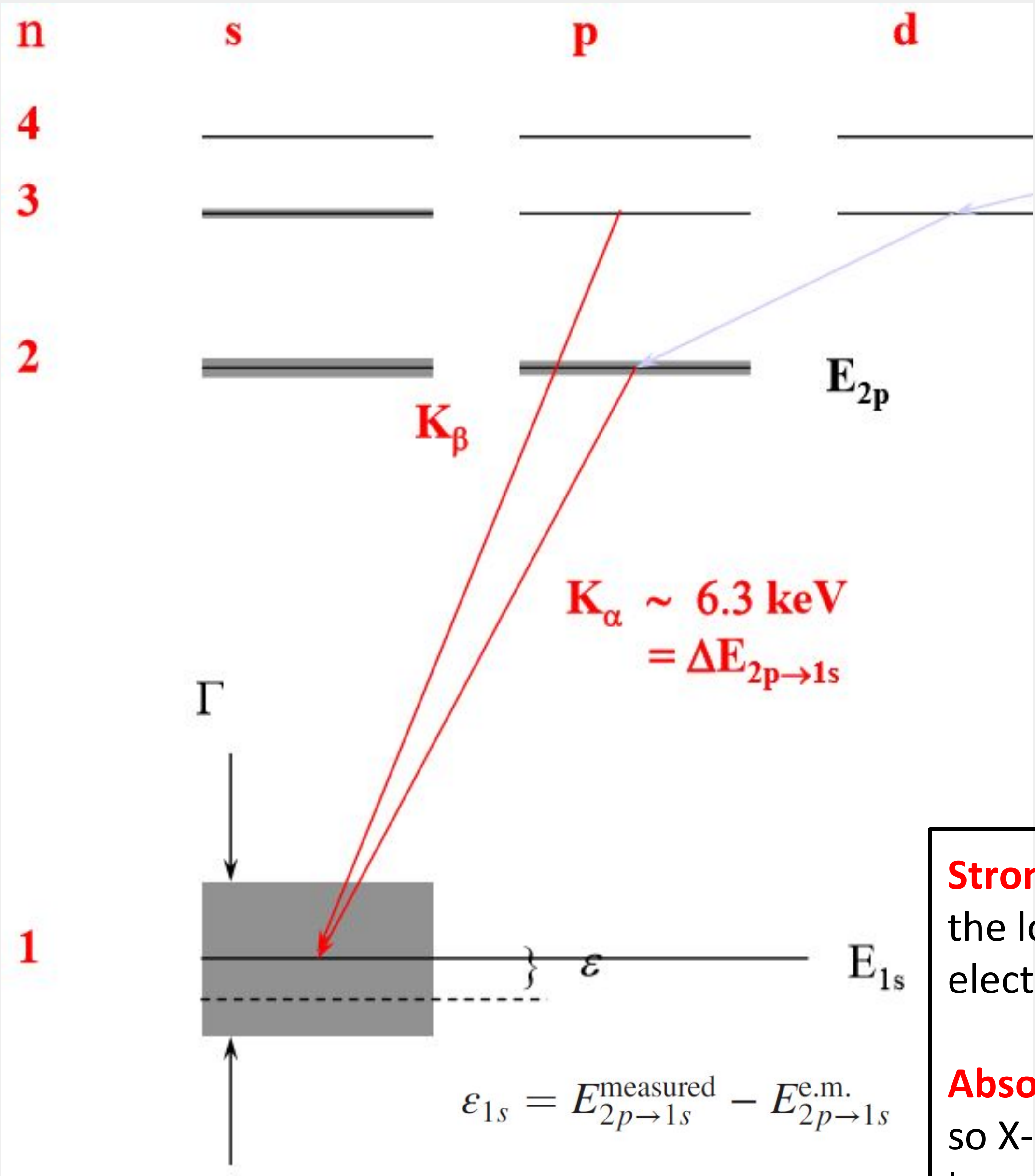
Outlook

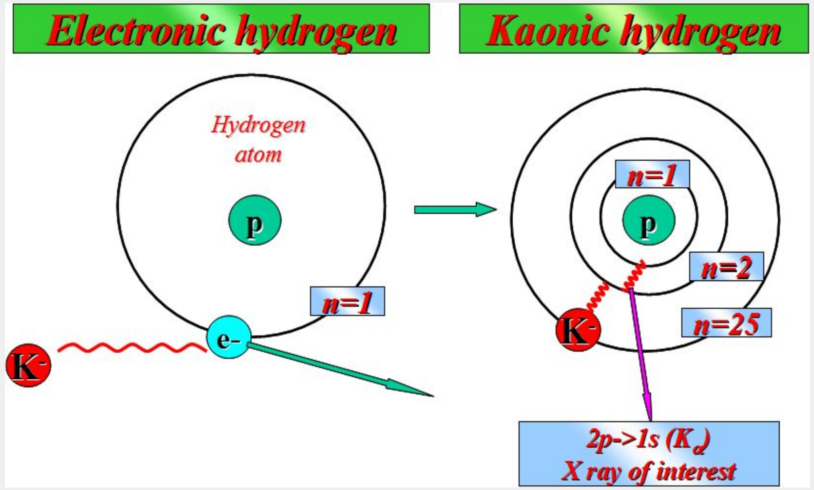
- Introduction and motivation
- DAΦNE-Φ factory @ LNF
- SIDDHARTA experiment - results
- SIDDHARTA-2 experiment - new measurement
- Summary

Kaonic atom formation



KAONIC CASCADE





$$E_{1s} \simeq m_{red}c^2 \frac{\alpha^2 Z^2}{2}$$

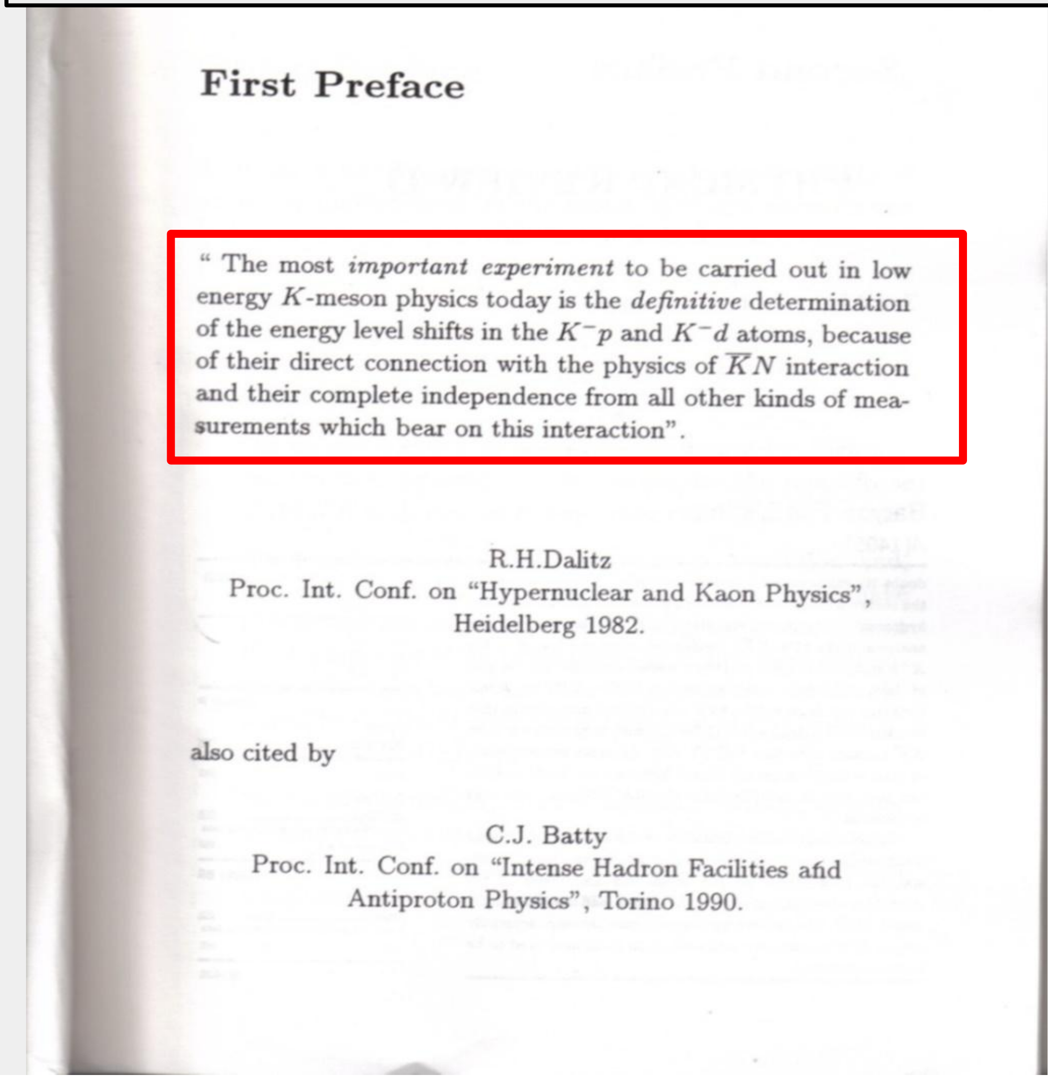
$$n \simeq \sqrt{\frac{m_{red}}{m_e}} n_e$$

Strong interaction -> shifting of the energy of the lowest atomic level from its purely electromagnetic value

Absorption -> reduces the lifetime of the state, so X-ray transitions to this final atomic level are broadened

The main scientific aim

To perform **precision measurements of kaonic atoms** X-ray transitions -> **unique** info about the QCD in non-perturbative regime in the strangeness sector **not obtainable otherwise**



First Preface

" The most *important experiment* to be carried out in low energy K-meson physics today 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 $\overline{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H.Dalitz
Proc. Int. Conf. on "Hypernuclear and Kaon Physics",
Heidelberg 1982.

also cited by

C.J. Batty
Proc. Int. Conf. on "Intense Hadron Facilities and Antiproton Physics", Torino 1990.

Precision *measurement of the shift* and *of the width*

➔ of the 1s level of kaonic hydrogen (SIDDHARTA)
C. Curceanu, et al., Rev. Mod. Phys. 91, 025006 (2019)

➔ the first measurement of the 1s level of kaonic deuterium (SIDDHARTA-2)

⬇

extract the **antikaon-nucleon isospin dependent scattering lengths**

The main scientific aim

To perform **precision measurements of the width** and **shift** for **kaonic hydrogen** and **deuterium**

Energy shift ε and **line width** Γ **of 1s state** are related to real and imaginary part of the S-wave scattering length (Deser-Trueman formula) :

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-p}[1 - 2\alpha\mu(ln\alpha - 1)a_{K-p} + \ldots]$$

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-d}[1 - 2\alpha\mu(ln\alpha - 1)a_{K-d} + \ldots]$$

Scattering lengths can be expressed in terms of $\bar{K}N$ isospin dependent isoscalar a_0 and isovector a_1 scattering lengths:

$$a_{K-d} = \frac{4[m_N + m_K]}{[2m_N + m_K]}Q + C$$

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

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

$$Q = \frac{1}{2}[a_{K-p} + a_{K-n}] = \frac{1}{4}[a_0 + 3a_1]$$

⇓

the determination of the ***isospin dependent*** $\bar{K}N$ ***scattering lengths*** with a ***precision of few %*** !

Importance of kaonic atoms studies

- **Kaonic atoms are fundamental tools for understanding the low-energy quantum chromodynamics QCD in strangeness sector**

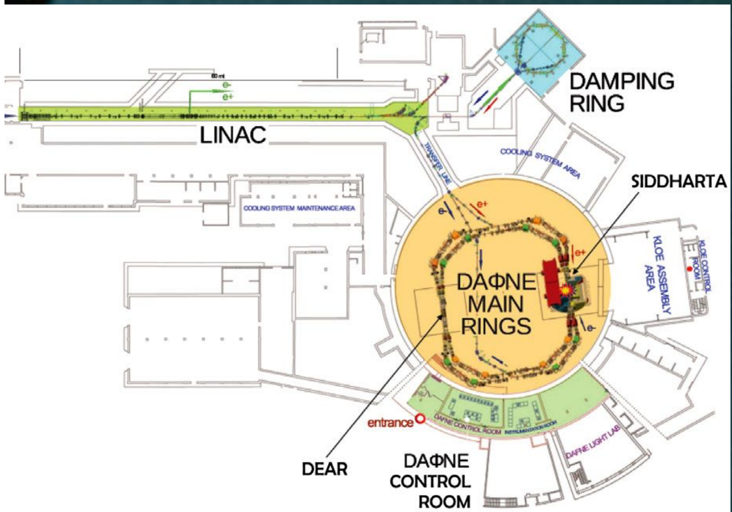
Determined isospin dependent $\bar{K}$N scattering lengths are key ingredients for all models and theories dealing with low-energy QCD in systems with strangeness

⬇

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

Role of Strangeness in the Universe from particle and nuclear physics to astrophysics

DAΦNE, Laboratori Nazionali di Frascati

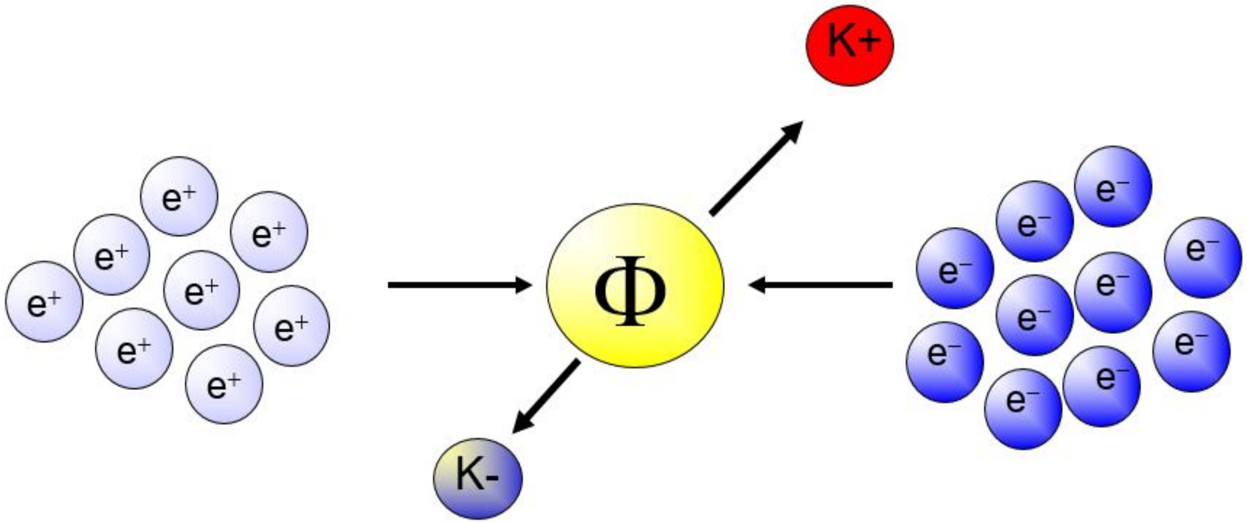


DAFNE @ LNF

Best low momentum K- factory in the world

- $\phi \rightarrow K^- K^+$ (49.2%), ≈1000 ϕ/s
- monochromatic **low momentum** Kaons ≈127 Mev/c $\Delta p/p$=0.1%
- **back to back** $K^- K^+$ topology
- **small hadronic background** due to the beam

Suitable for low-energy kaon physics: kaonic atoms kaon-nucleons/nuclei interaction studies



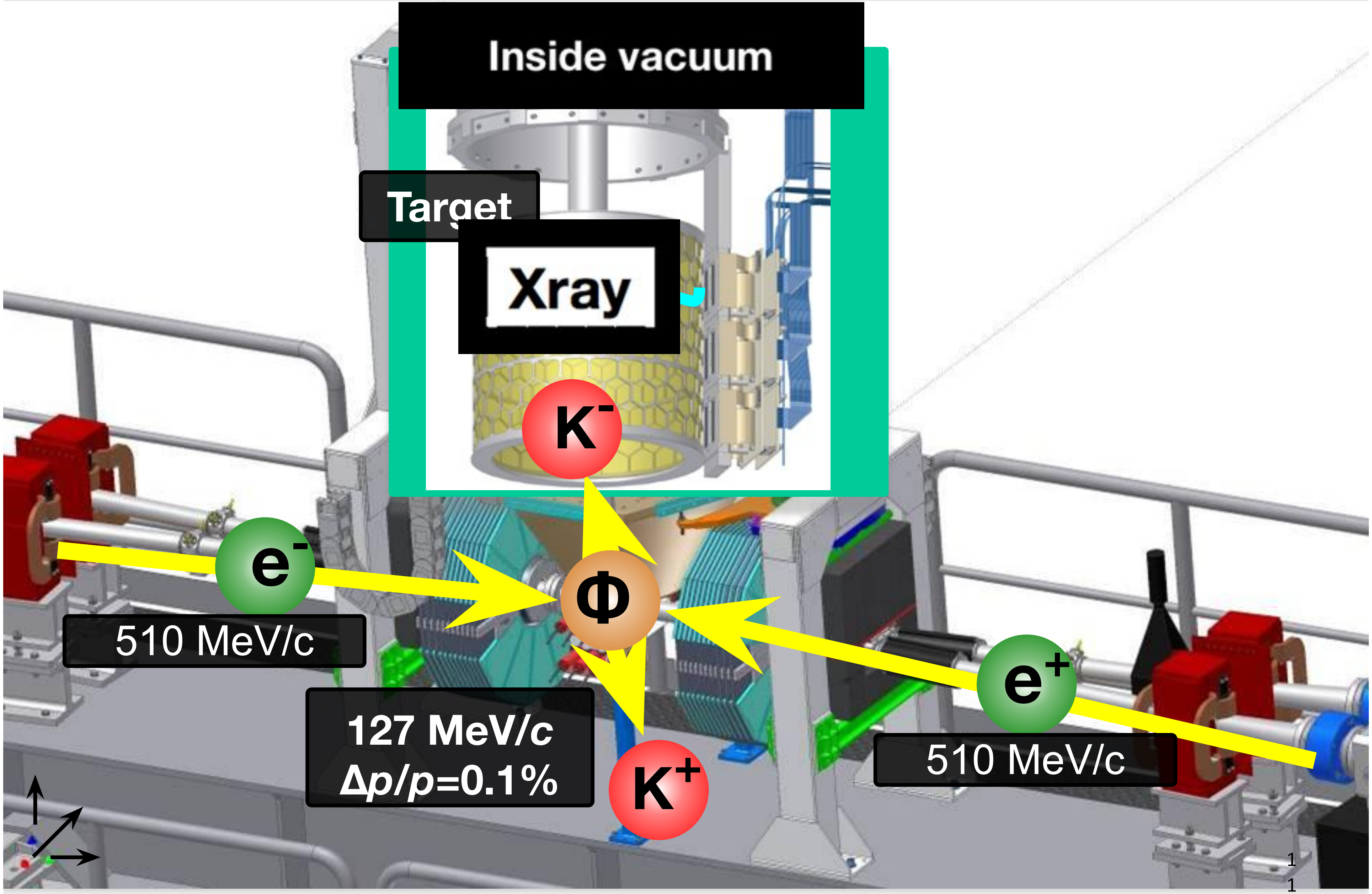
SIDDHARTA

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

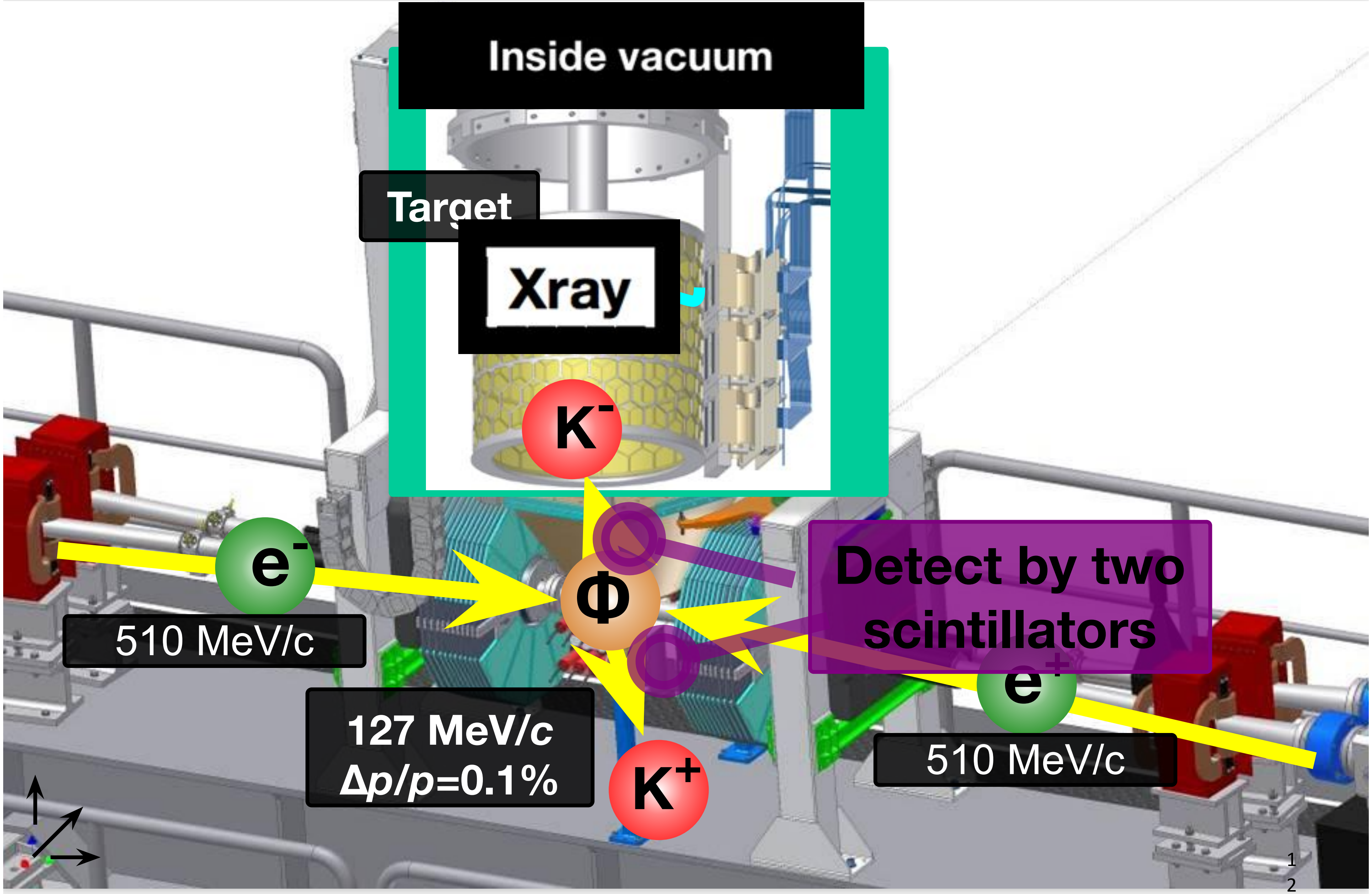
- **LNF- INFN, Frascati, Italy**
- **SMI- ÖAW, Vienna, Austria**
- **IFIN – HH, Bucharest, Romania**
- **Politecnico, Milano, Italy**
- **MPE, Garching, Germany**
- **PNSensors, Munich, Germany**
- **RIKEN, Japan**
- **Univ. Tokyo, Japan**
- **Victoria Univ., Canada**

EU Fundings: JRA10 – FP6 - I3H
FP7- I3HP2

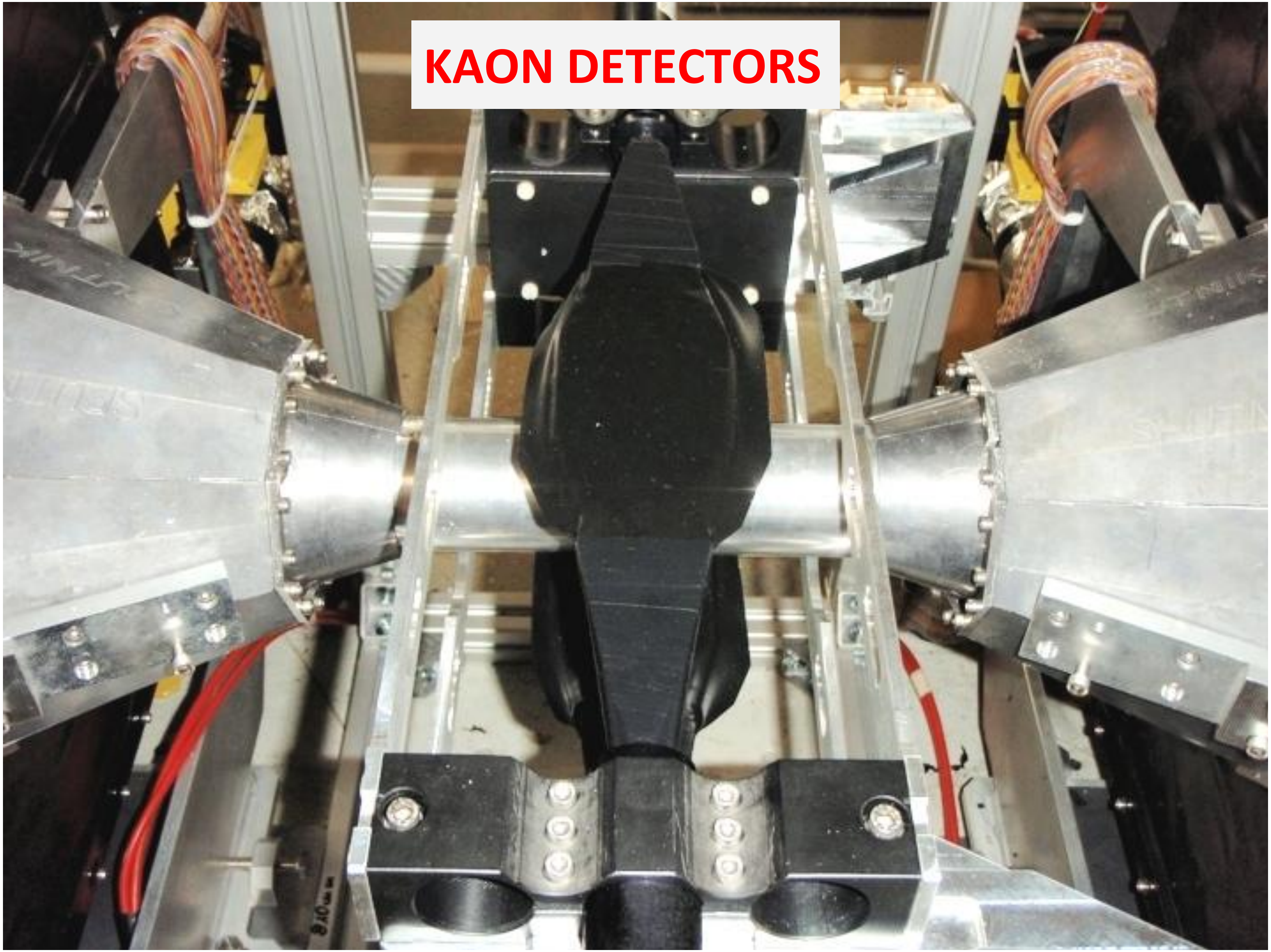
SIDDHARTA Setup



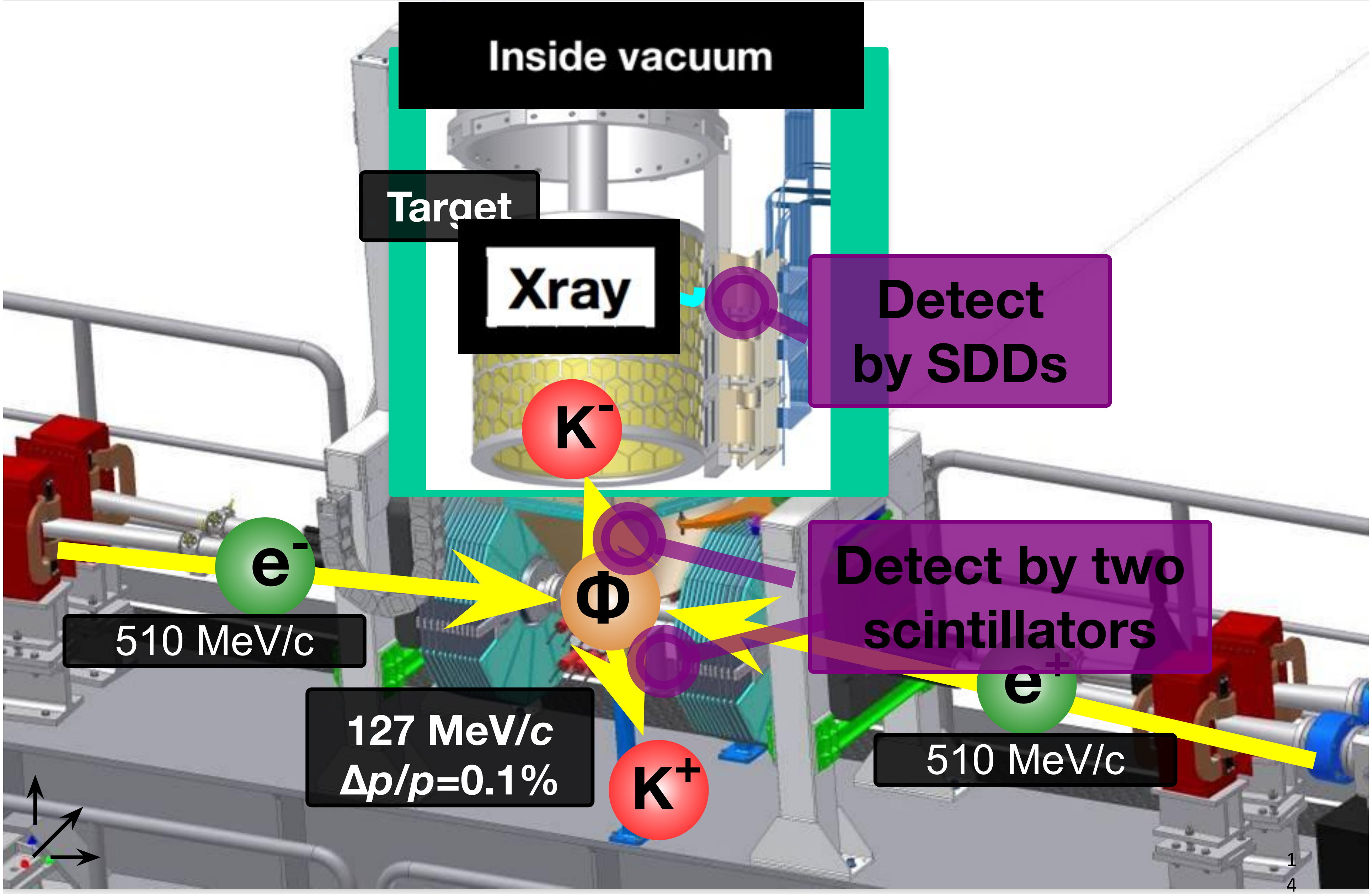
SIDDHARTA Setup



KAON DETECTORS

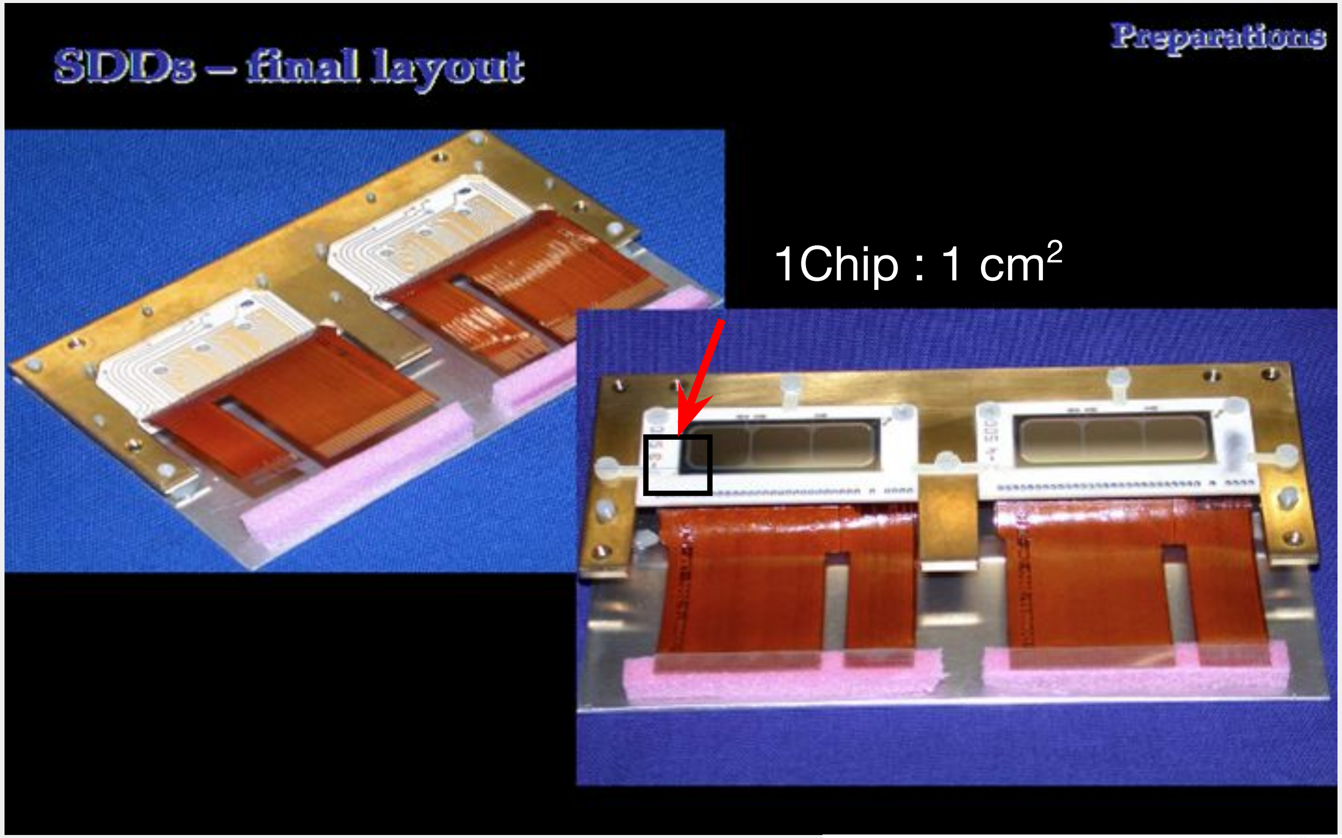


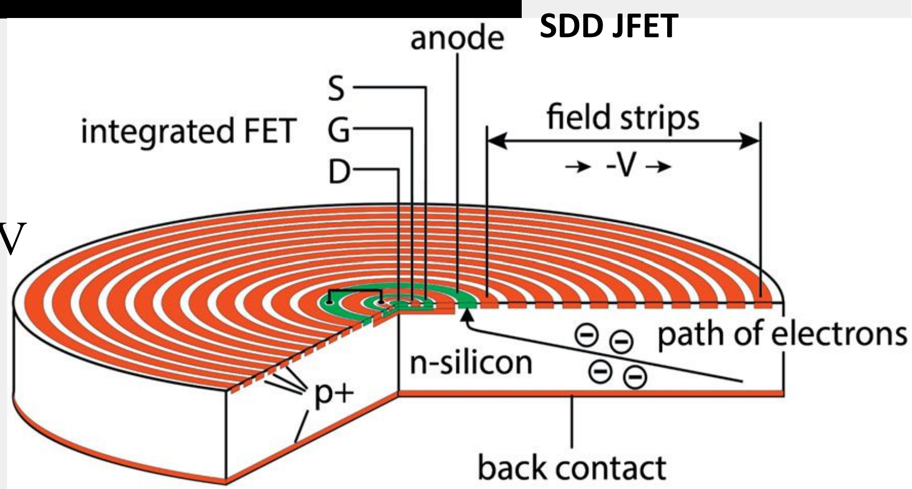
SIDDHARTA Setup



SILICON DRIFT DETECTORS
1 cm² x 144 SDDs

Silicon Drift Detector - SDD





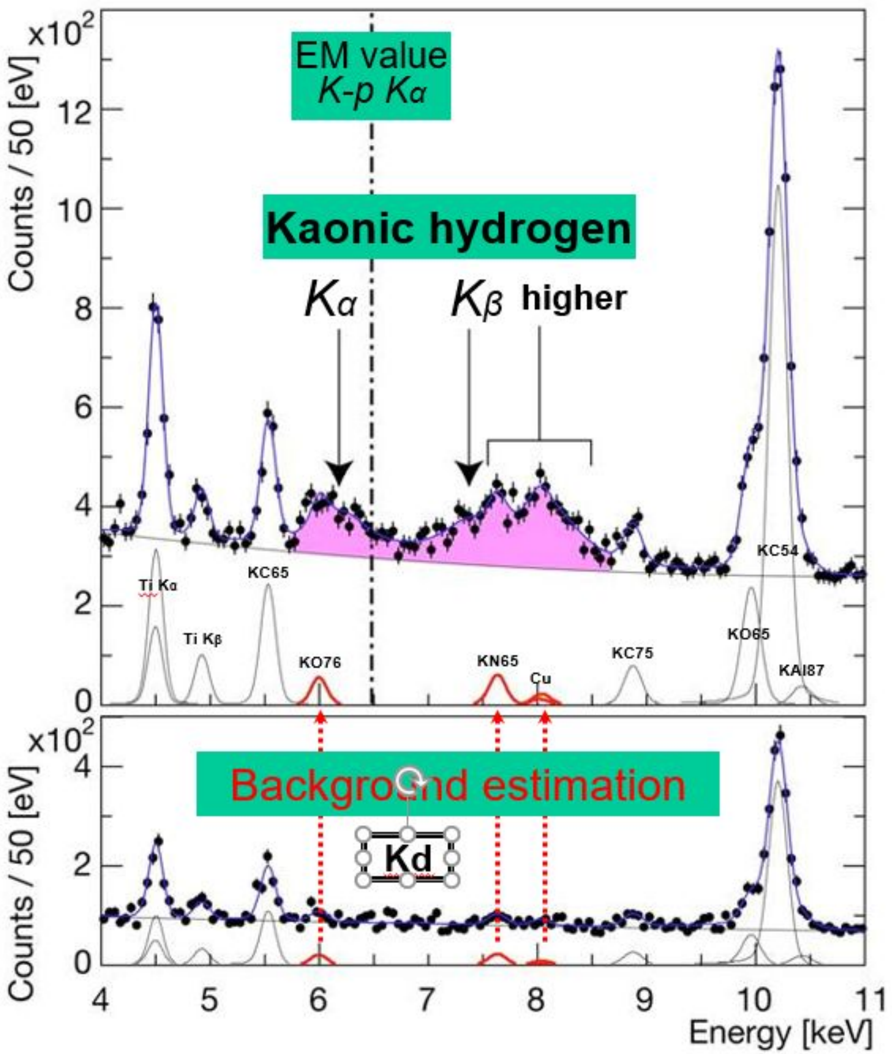
Used for the first time as energy detectors

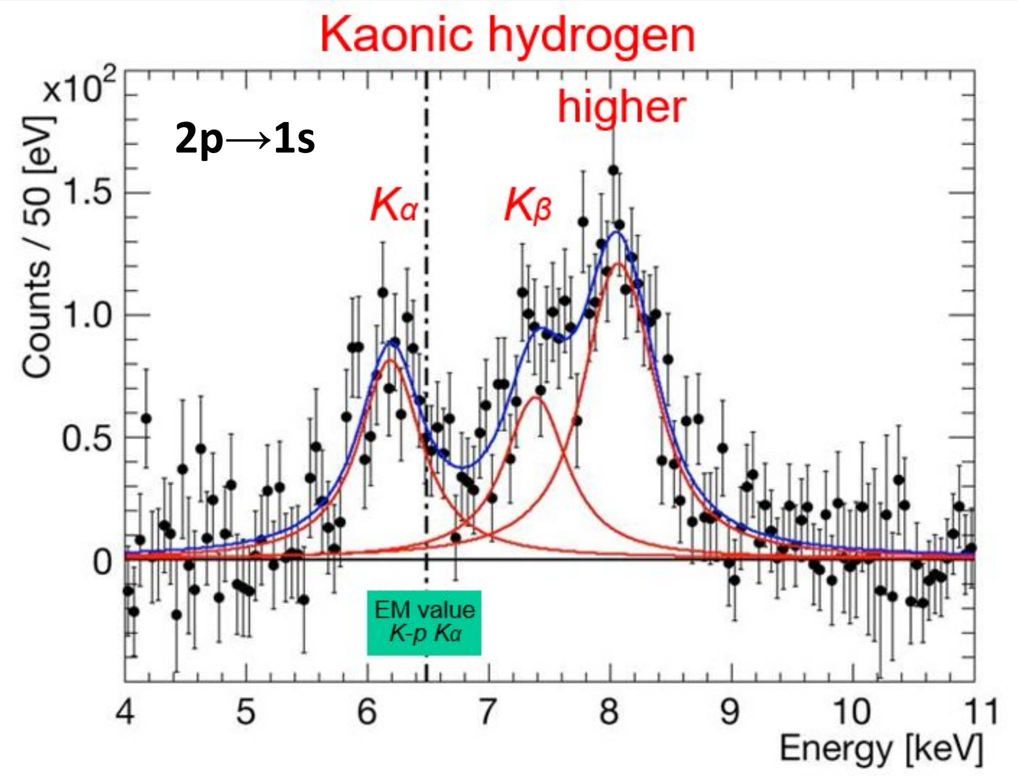
- very fast and triggerable
- energy resolution of 160 eV (FWHM) at 6 keV
- drift time (timing resolution) below 1 μs
- 48 SDDs, each with 3×1 cm^2 cells
- thickness of 450 μm

SIDDHARTA INSTALLATION

SIDDHARTA INSTALLATION

Results for Kaonic Hydrogen





Residuals of K-p x-ray spectrum after subtraction of fitted background

ε_{1S}= −283 ± 36(stat) ± 6(syst) eV

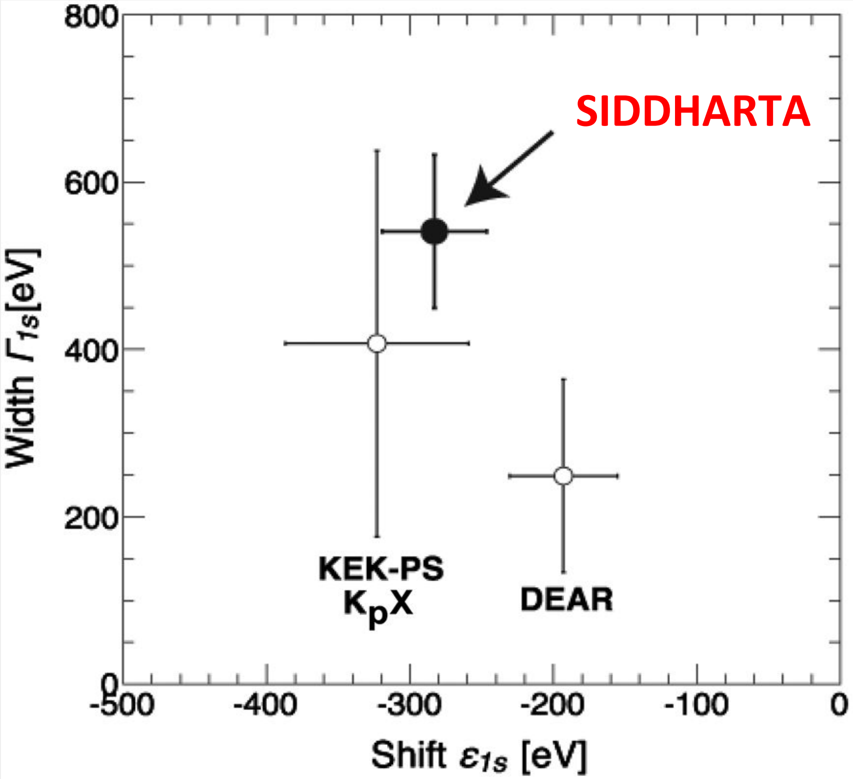
Γ_{1S}= 541 ± 89(stat) ± 22(syst) eV

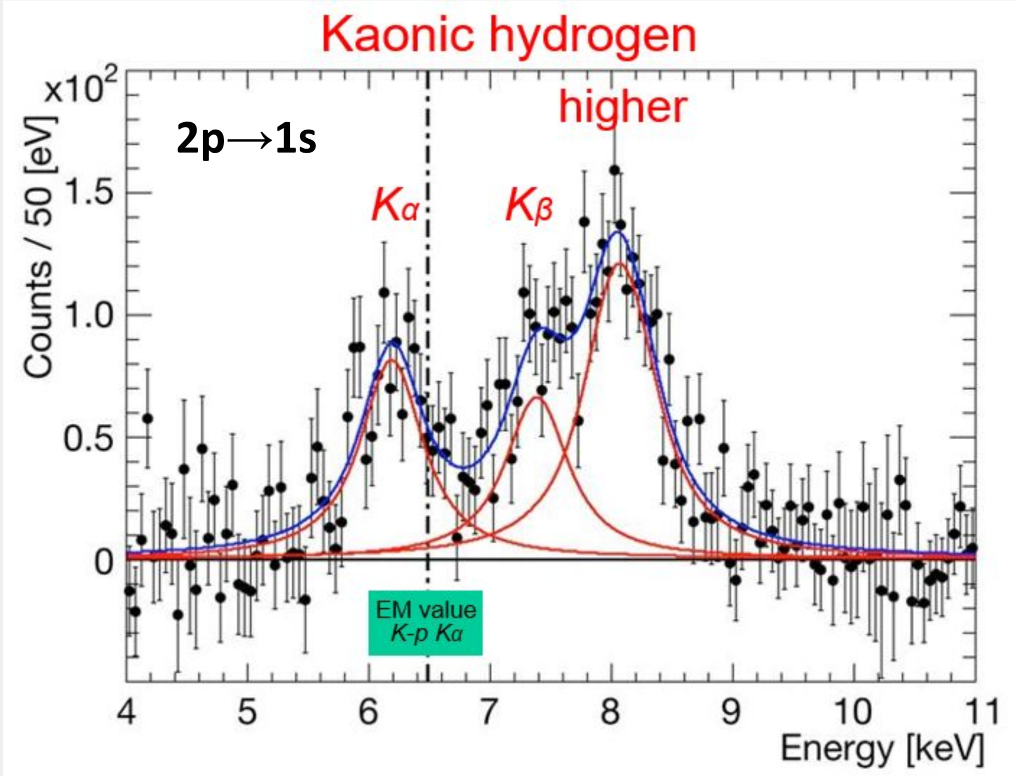
(400pb^{-1})

Only **exploratory first measurement for Kd**, no measured ε, Γ values obtained (100pb^{-1})

M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113

Results for Kaonic Hydrogen





Residuals of K-p x-ray spectrum after subtraction of fitted background

The most precise measurement for kaonic hydrogen

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

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

M. Bazzi et al., 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113

Results for Kaonic Helium

SIDDHARTA result – kaonic helium-4

The first measurement ever in gaseous target

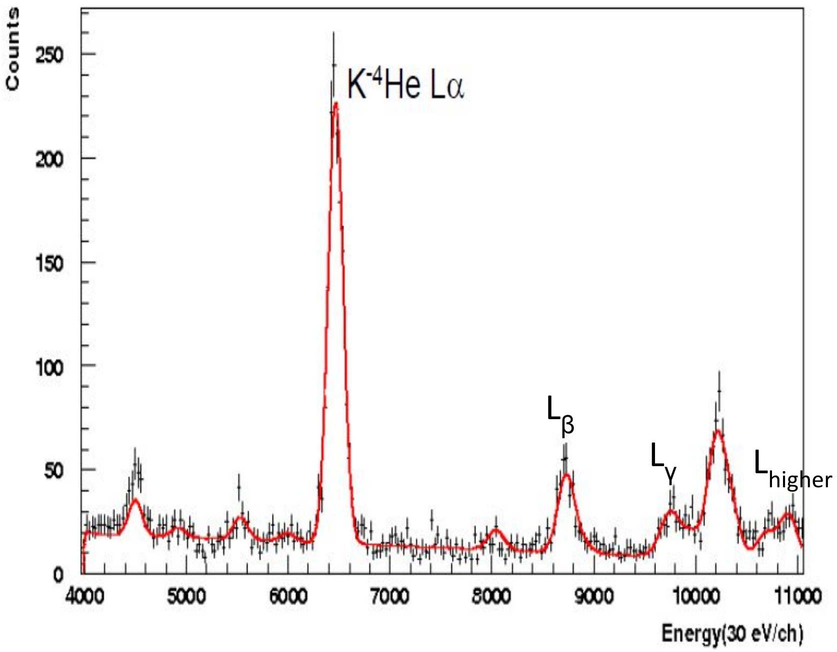
Available online at www.sciencedirect.com

SciVerse ScienceDirect

Nuclear Physics A 914 (2013) 305–309

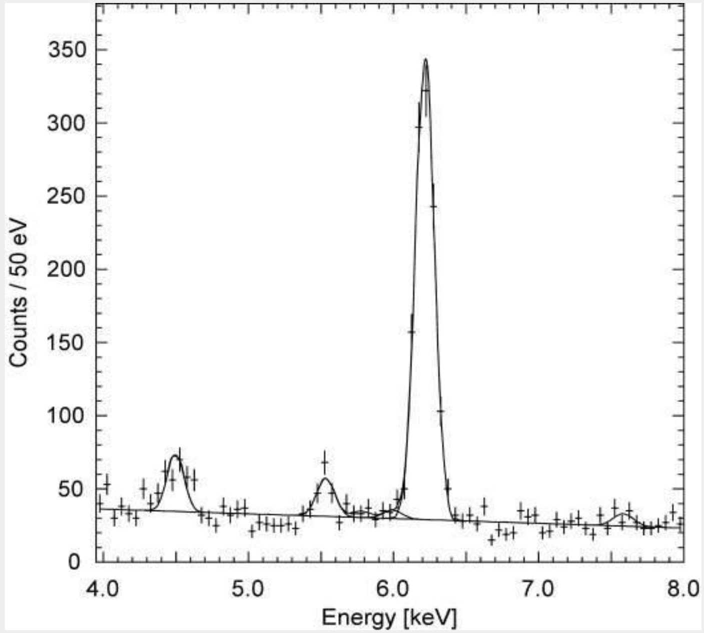
kaonic helium-4
about 28 pb^{-1}
S/B about 1 to 10

3d→2p



55th LNF SC - May 14, 2018

Kaonic helium-3



ε_{2p} = +5 ± 3(stat) ± 4(syst) eV

Γ_{2p} = 14 ± 8(stat) ± 5(syst) eV

ε_{2p} = -2 ± 2(stat) ± 4(syst) eV

Γ_{2p} = 6 ± 6(stat) ± 7(syst) eV

M. Bazzi et al., 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113
M. Bazzi et al., 2012. (SIDDHARTA Coll.), Phys. Lett. B714, 40

Kaonic Deuterium

SIDDHARTA-2

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

HadronPhysics2 – Study of Strongly Interacting Matter

HadronPhysics I3 – Study of Strongly Interacting Matter

FWF Der Wissenschaftsfonds.

Farnesina – Ministero degli Affari Esteri e della Cooperazione Internazionale

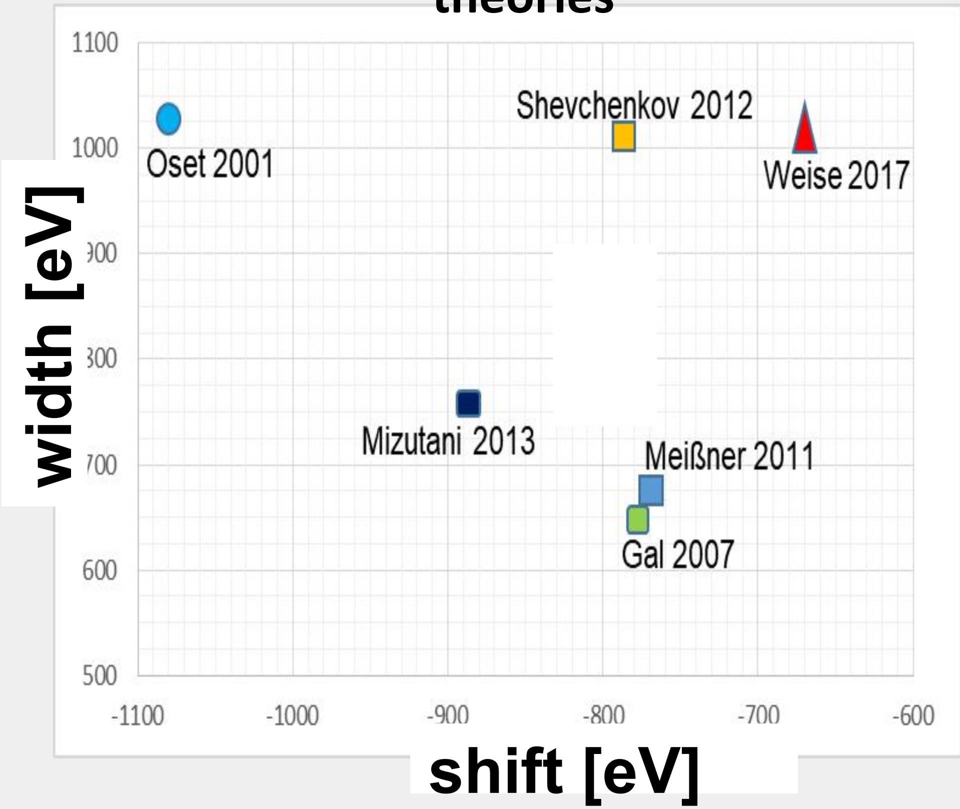
LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN – HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
Research Center for Electron Photon Science (ELPH), Tohoku University
CERN, Switzerland

STRONG-2020

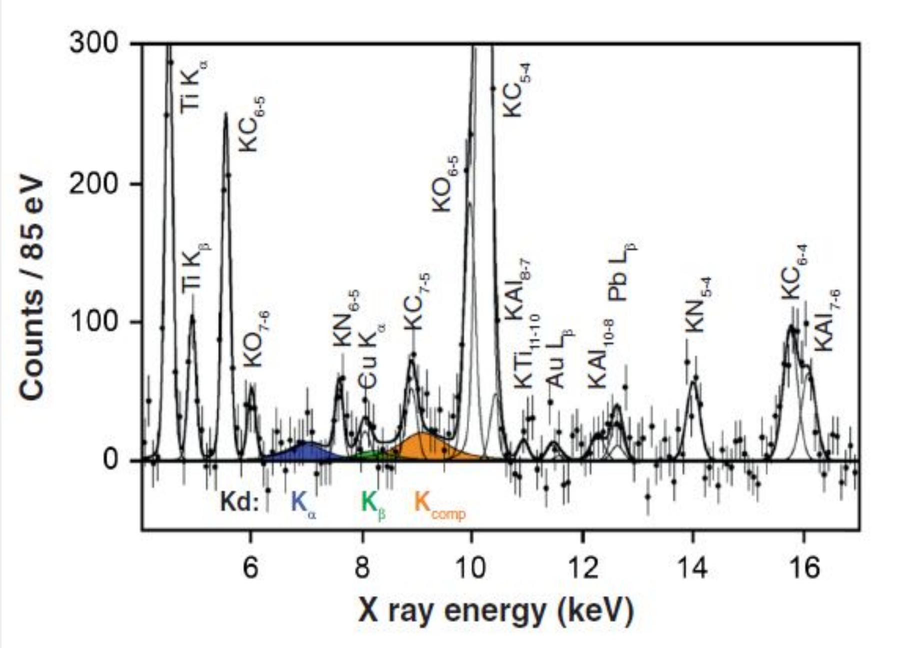
Croatian Science Foundation, research project 8570

Kaonic Deuterium

theories



First exploratory measurement for Kd by SIDDHARTA (100pb^{-1})



Upper limits of yields (90% C.L.):

Y(K$_{tot}$) <0.0143

Y(K$_\alpha$) <0.0039

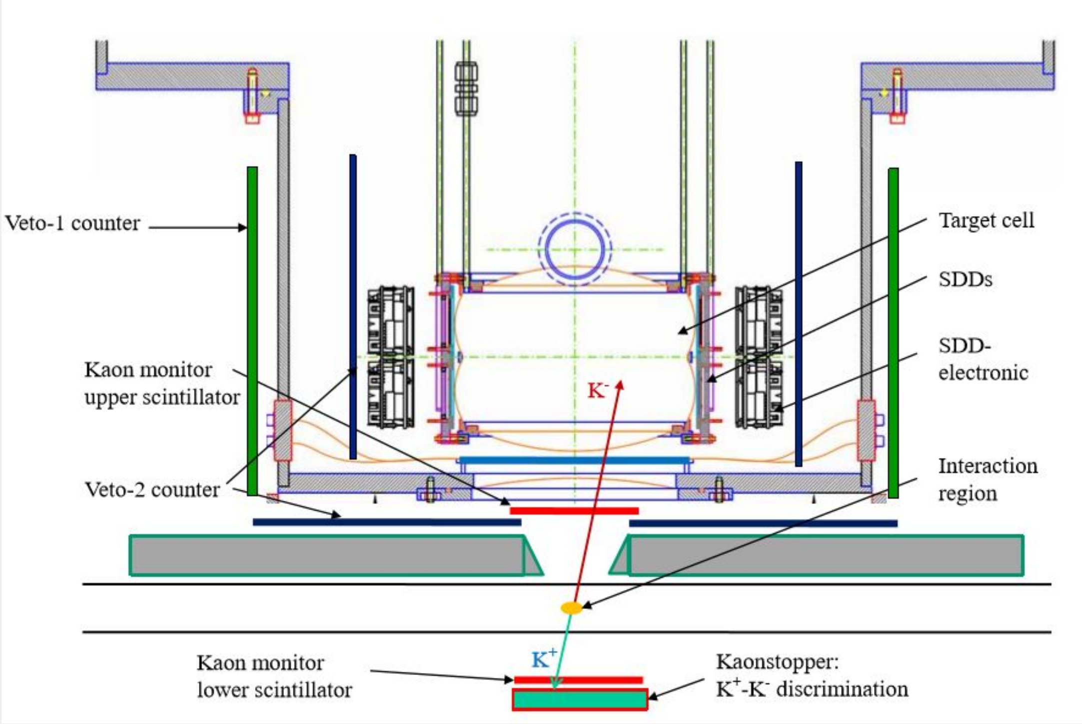
Yield of a factor about **10 times smaller** than for KH (estimated to be from **1 to 2%** for K$_\alpha$)

SIDDHARTA-2: enhancement by one order of magnitude of the S/B ratio

- **Mizutani, T., C. Fayard, B. Saghai, and K. Tsushima, 2013, arXiv: 1211.5824.**
- **Shevchenko, N., 2012, Nucl. Phys. A 890–891, 50.**
- **Doring, M., and U. G. Meißner, 2011, Phys. Lett. B 704, 663.**
- **Gal, A., 2007, Int. J. Mod. Phys. A 22, 226.**
- **Hoshino, T., S. Ohnishi, W. Horiuchi, T. Hyodo, and W. Weise, 2017, Phys. Rev. C 96, 045204.**

From SIDDHARTA to SIDDHARTA-2 improvements

	signal	hadronic BG	machine BG	S/B	K_α events
SIDDHARTA	1.00	1.00	1.00	1:40	
IP - target	1.38	1.33		1:11	6075
3% LHD	1.64	1.08			
geometry	1.25	0.56	0.25		
Trigger 1	0.71	0.48		1:7.6	4320
Trigger 2	0.79	0.59	0.33	1:5.7	3415
Trigger 3	0.98	0.73		1:4.2	3350
K+ discrimination	0.70	0.78		1:3.3	2345
drift time 400ns			0.49	1:3.0	2345
SIDDHARTA-2	**1.09**	**0.12**	**0.04**	**1:3**	**2345**

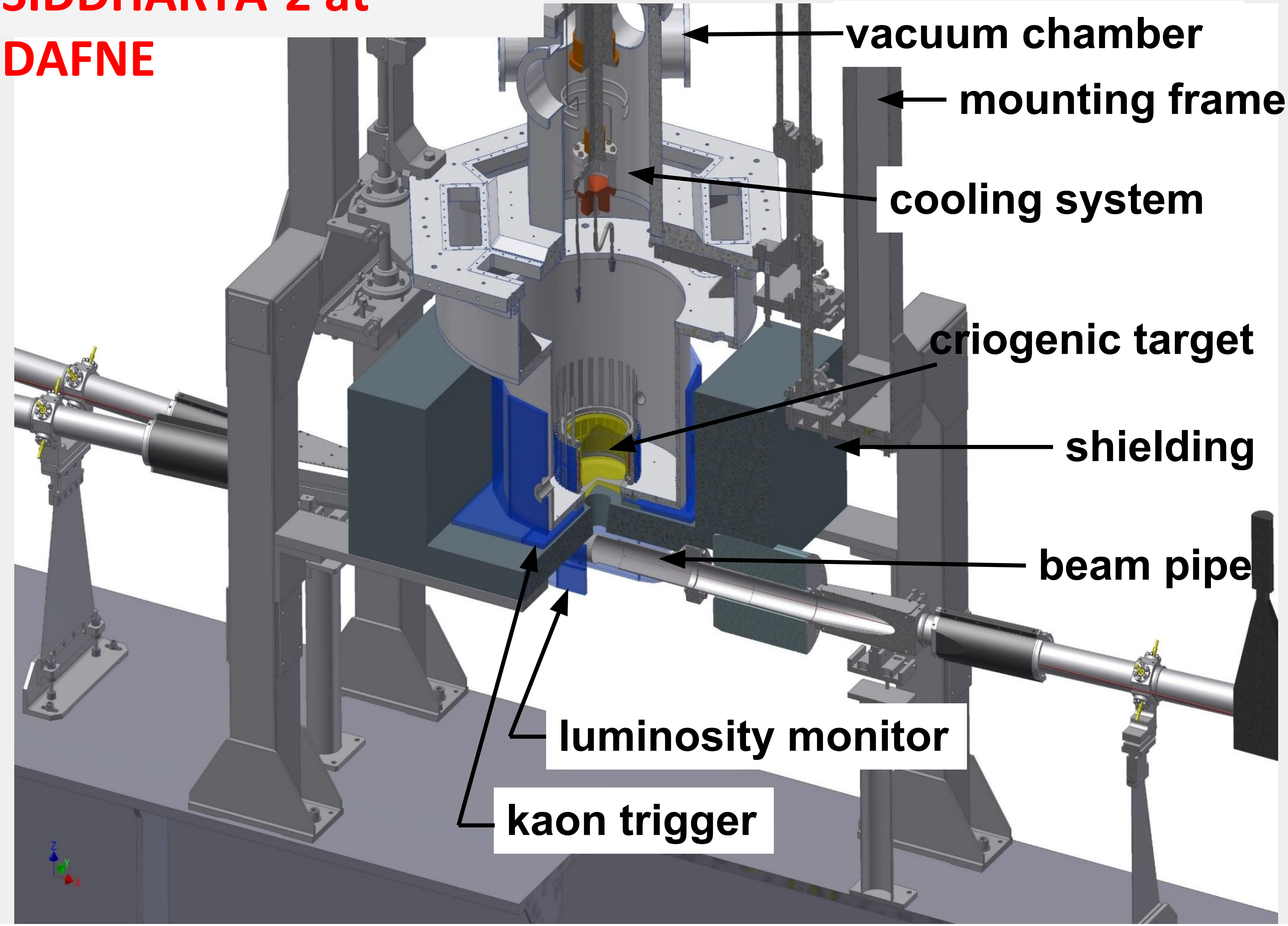


NEW SETUP

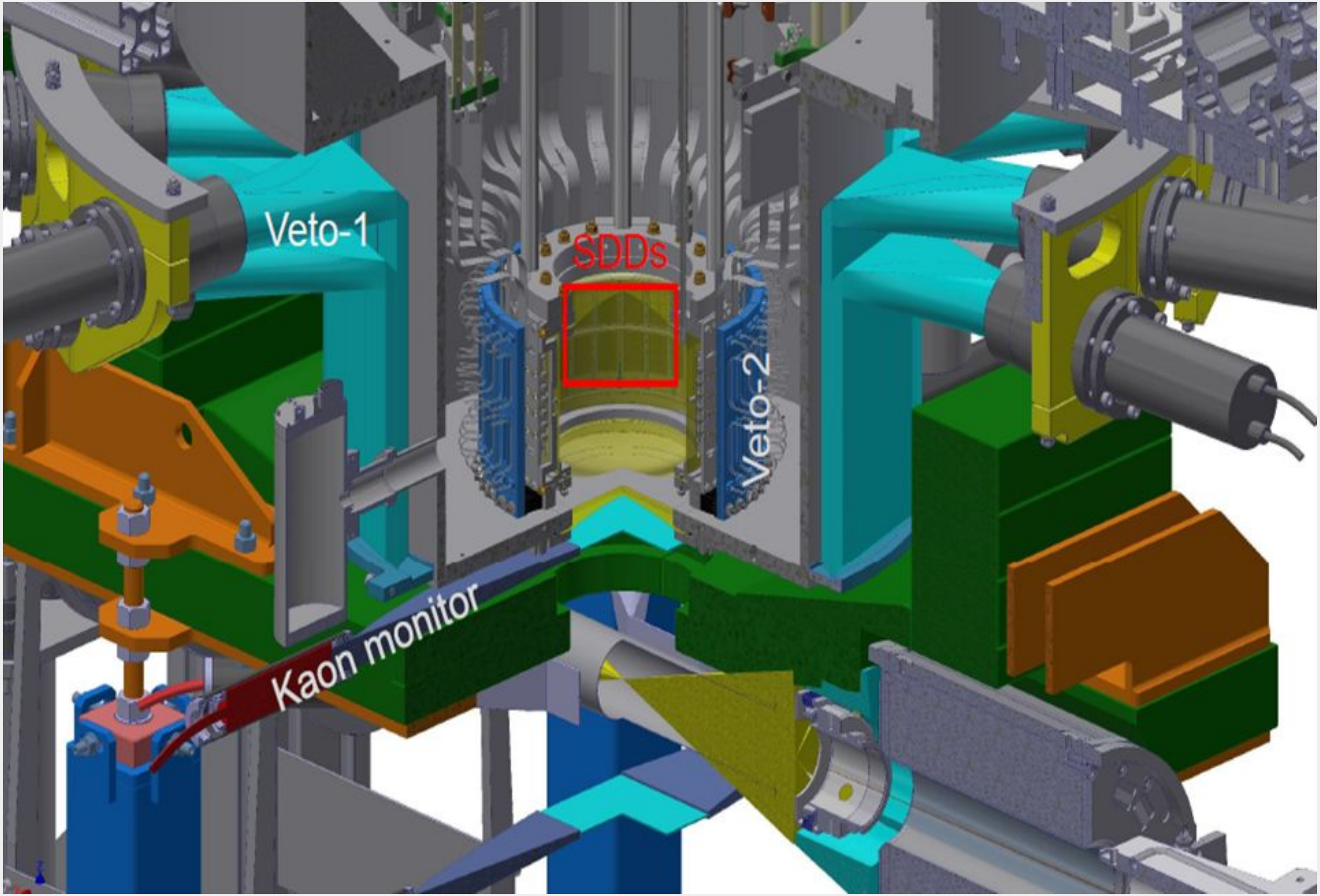
- new cooling system
- new vacuum chamber
- new target design
- new SDD detectors
- improved kaon monitor/trigger scheme
- new shielding structure
- two veto systems
- new luminosity detector

With the new S/B, Kd measurement will be possible

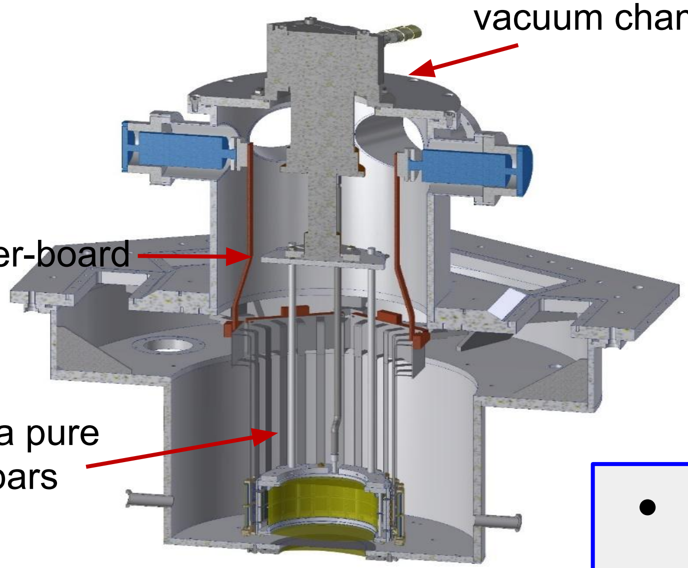
SIDDHARTA-2 at DAFNE



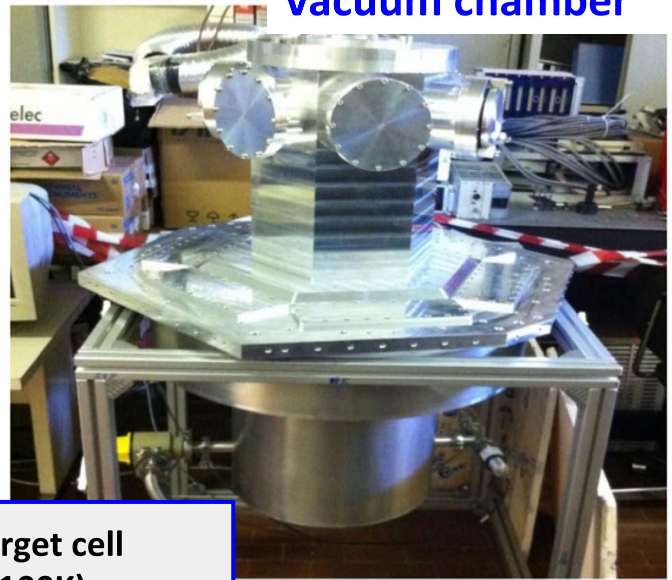
SIDDHARTA-2 at DAFNE



cooling system

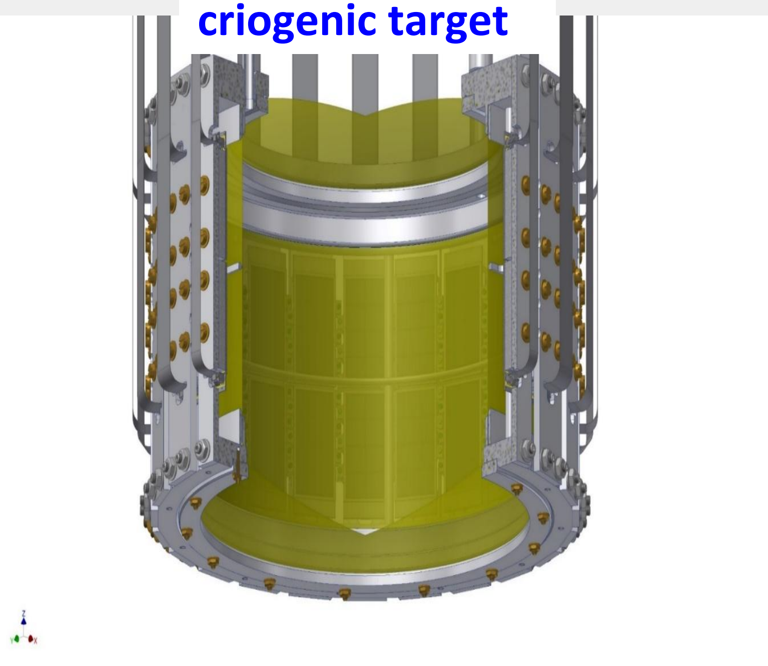


vacuum chamber



- ultra pure Al bars to cool target cell (T_{TC} = 30K) and SDDs (T_{SDD}= 100K)

criogenic target



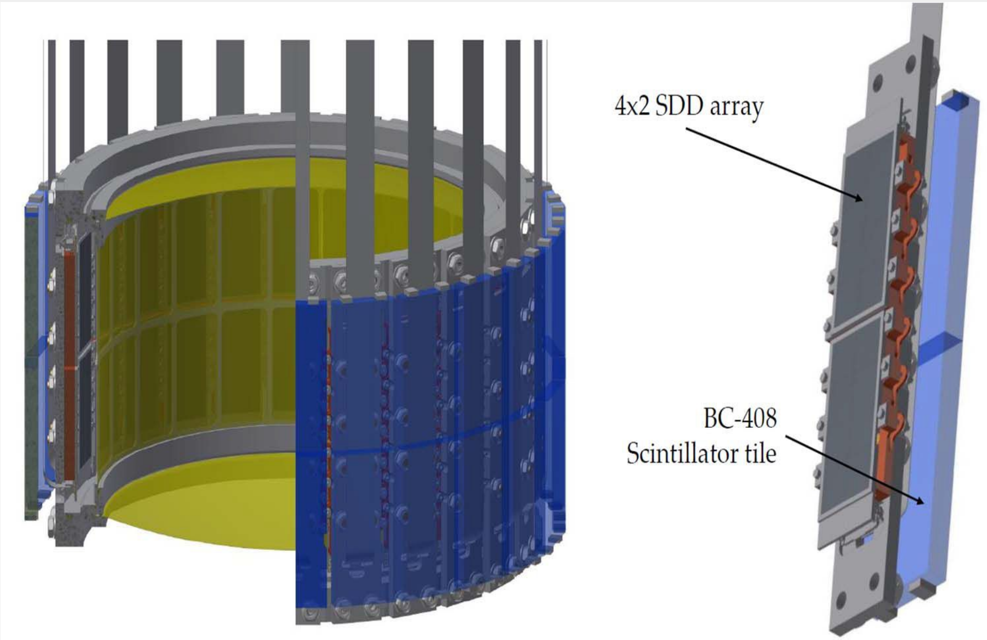
- Working temp. and pressure : 30 K and 0.3 MPa
- Target cell wall is made of a 2-Kapton layer structure (<100μm)
- HPH Deuterium generator and heavy water
- almost double gas density with respect to SIDDHARTA (3% LHD)
- X-ray transmission 85% at 7keV

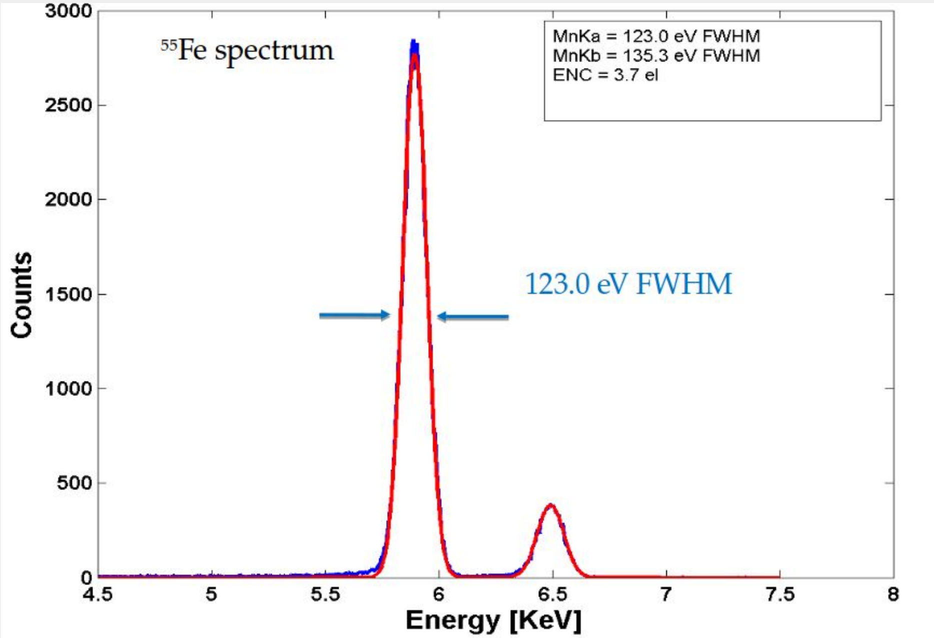
SDD detectors

covering a solid angle for stopped kaons in the gaseous target of ~ 2π, 5mm from the target

48 monolithic SDD arrays will be around the target with a total area of about **246 cm^2**

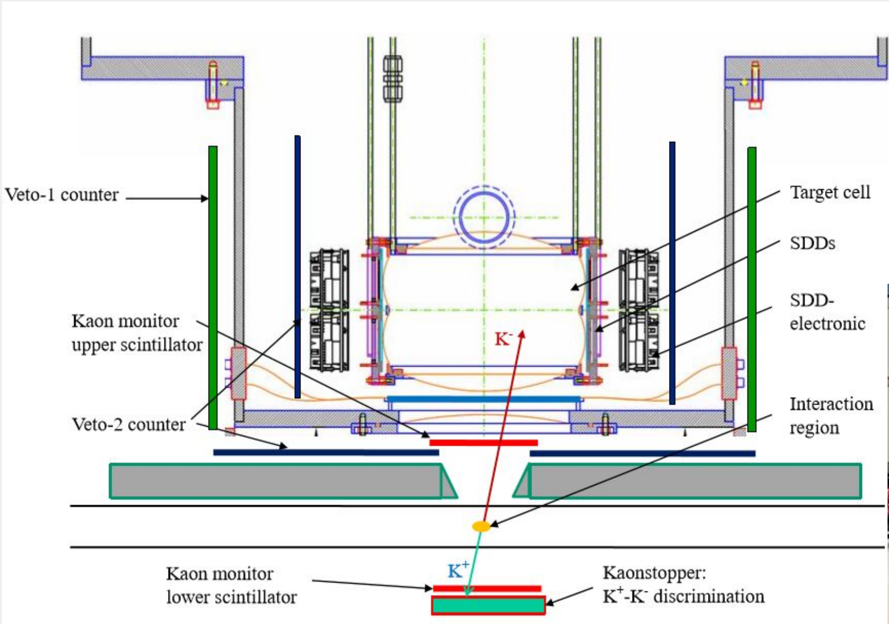
the large active to total area of about 75% (compared to 20% for the SIDDHARTA SDDs)





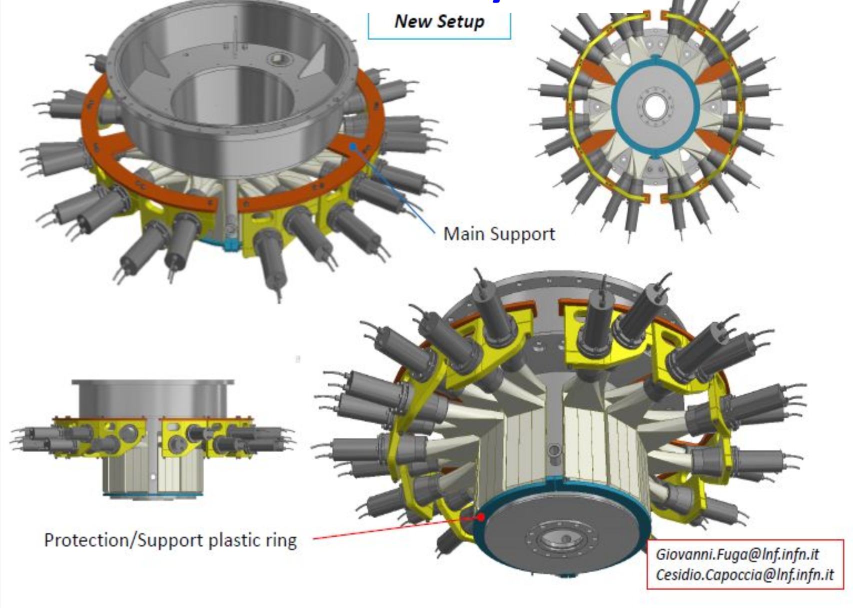
- **single unit: 4x2 SDD array (48 units in total)**
- **SDD**
  - **external CUBE preamplifier (MOSFET input transistor)**
  - **larger total anode capacitance**
  - **better than FET performances**
  - **standard SDD technology**
  - **area/cell = 64mm^2**
  - **T=100 K**
  - **Thickness 0.45 mm**
  - **drift time<500ns**

kaon monitor

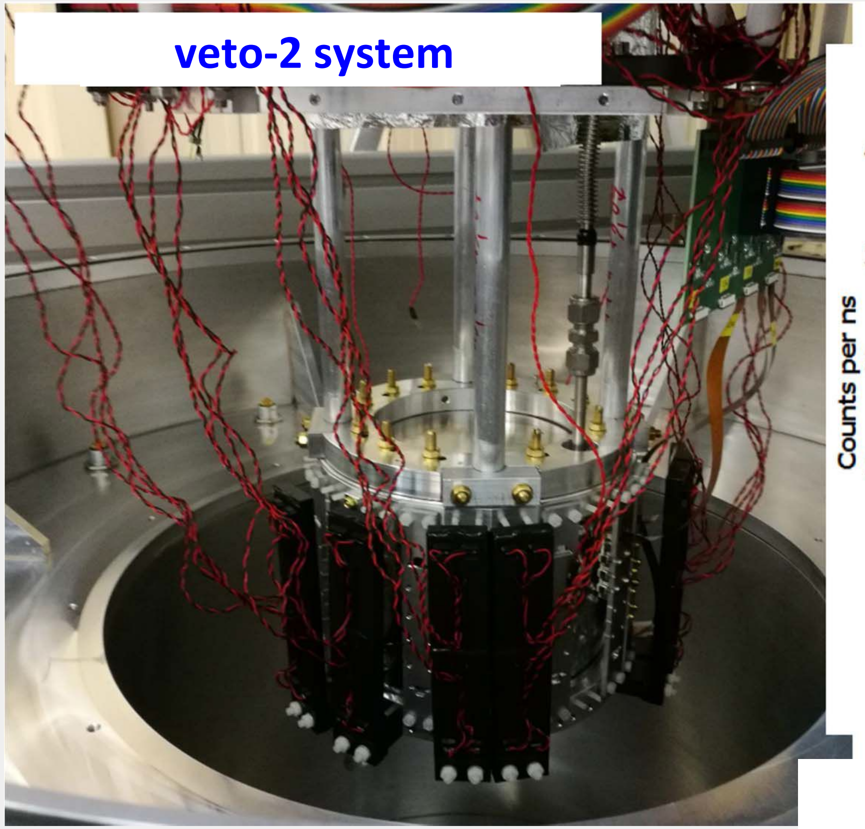


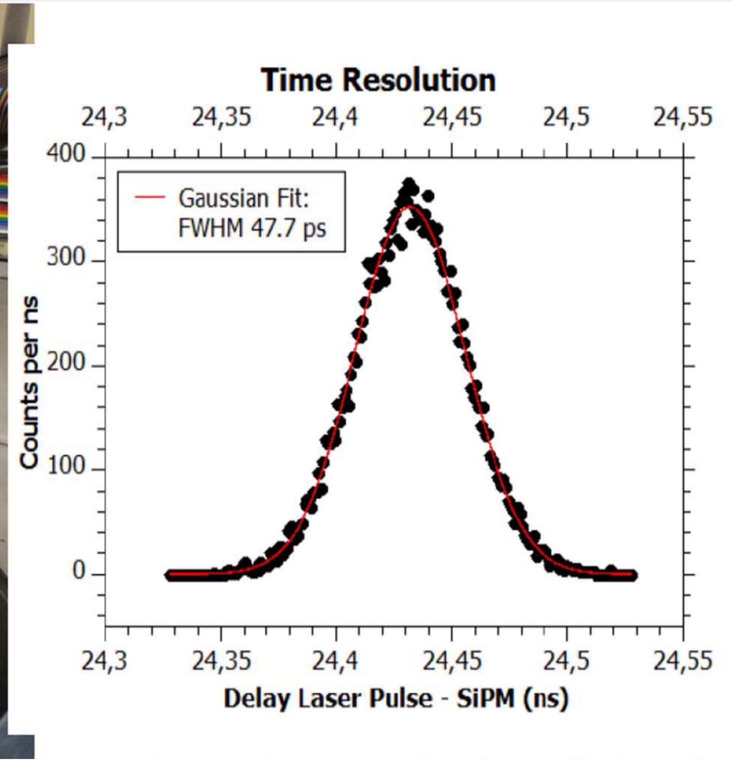
- with the new position only those kaons which are reaching directly the entrance flange of the vacuum chamber will be selected
- reduction of the hadronic and e. m. background is expected comparing to old geometry

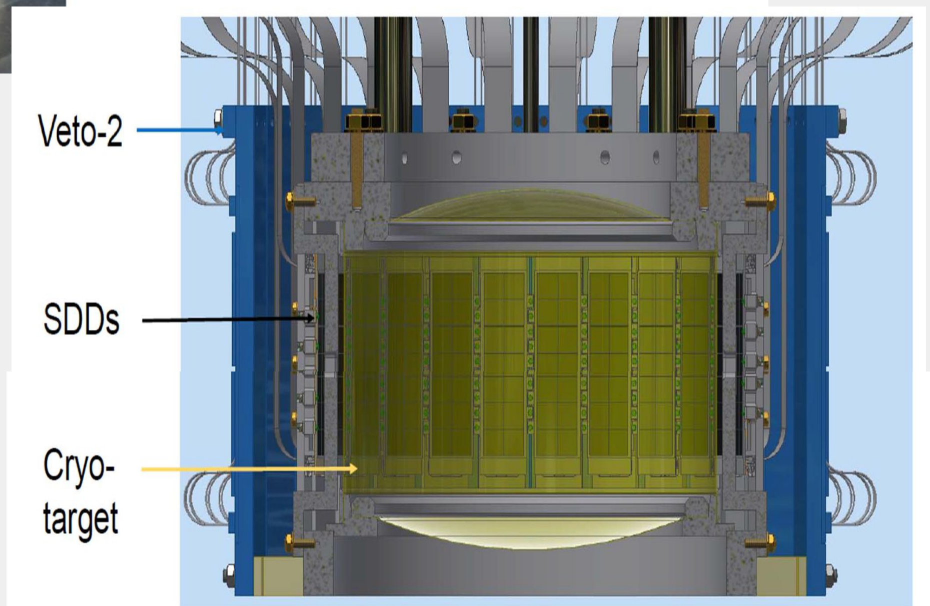
veto-1 system



- outher barrel of scintillators
- to identify the products of K^- absorption on gas nuclei

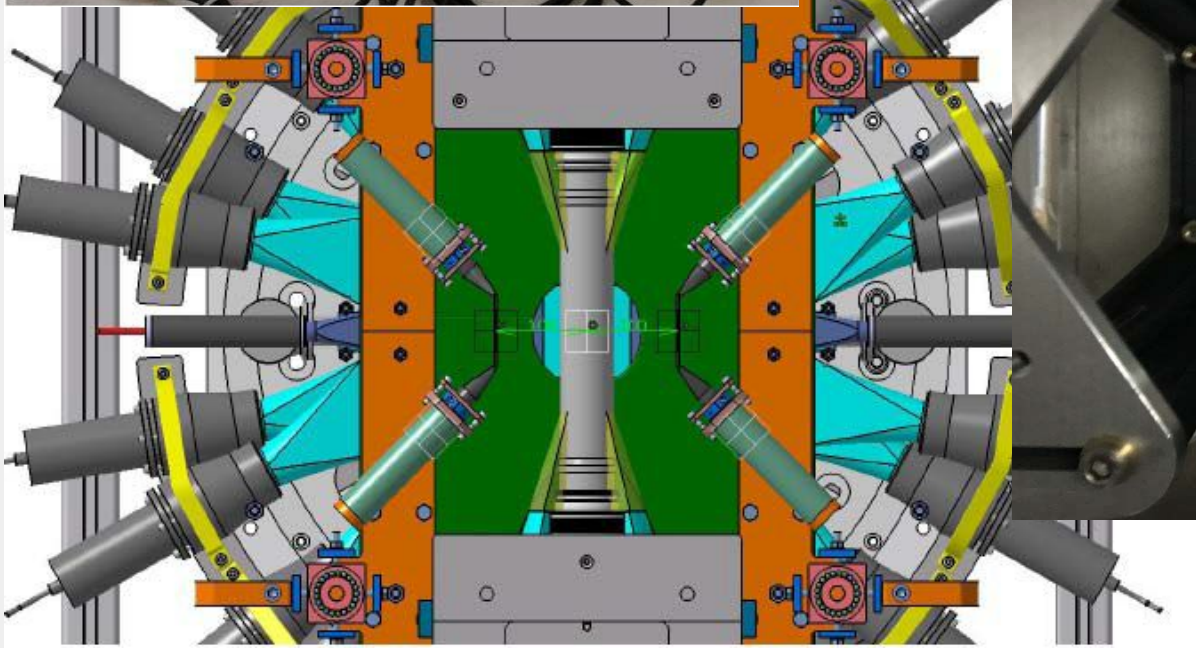




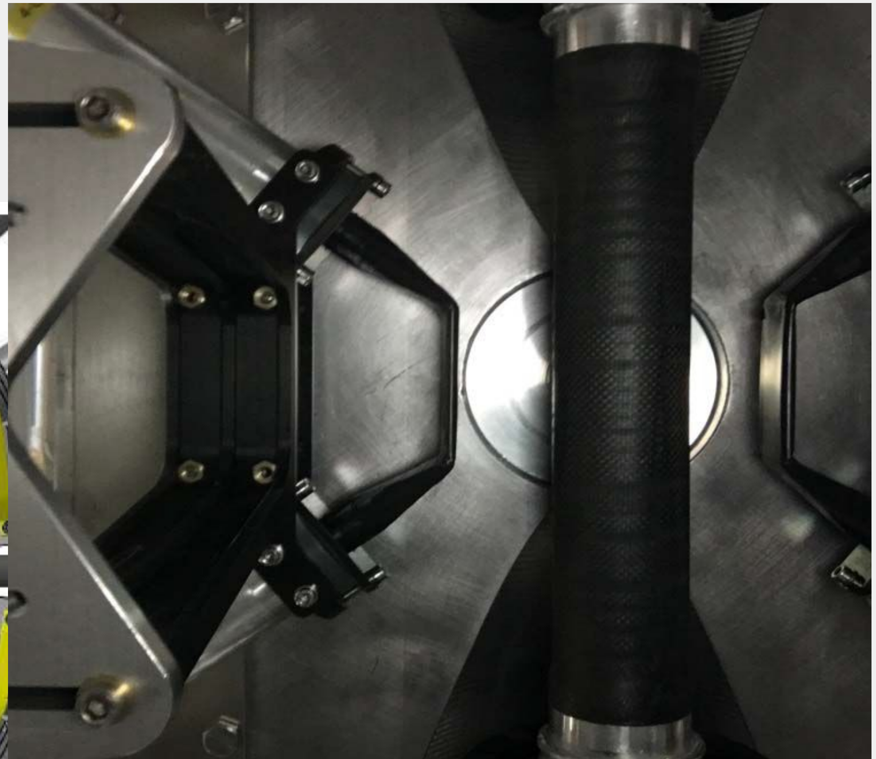


- an inner ring of scintillator tiles (SciTiles) placed as close as possible behind the SDDs
- for charge particle tracking

luminosity detector



- 2 pairs of scintillator: 80x40x2 mm^3
Scionix EJ-200
- R4998 PMTs Hamamatsu
- reflective and light proof foil, optical cement
- luminosity ~ 10^{32} cm^{-2} s^{-1}
- rate ~ 50 - 60 Hz



SIDDHARTA-2 strategy

Phase 1: during the commissioning of DAΦNE

SIDDHARTINO (K^{-} ^{4}He: 8 SDD arrays)

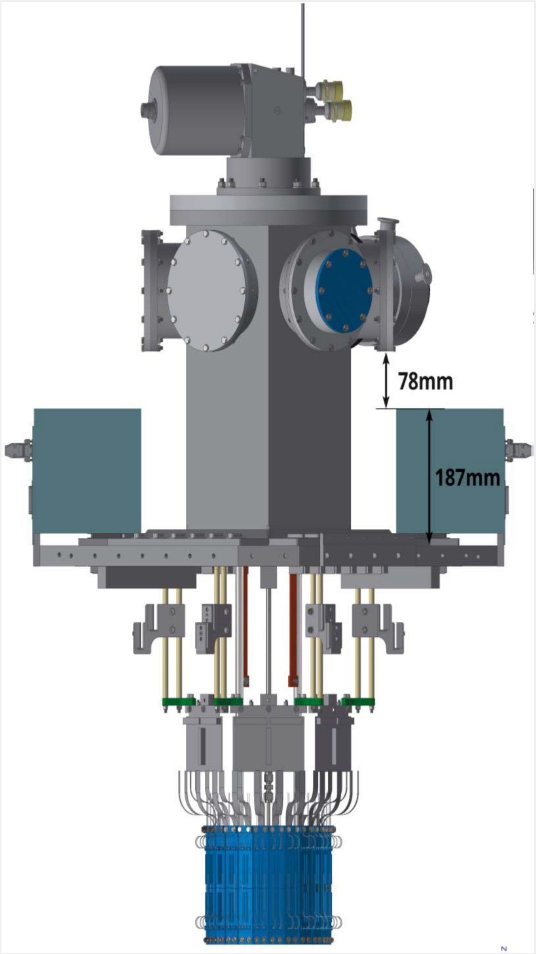
installed on DAΦNE in April 2019, run May 2019 - 1 November 2019 (?) ,

S/B adjustment to 100/1

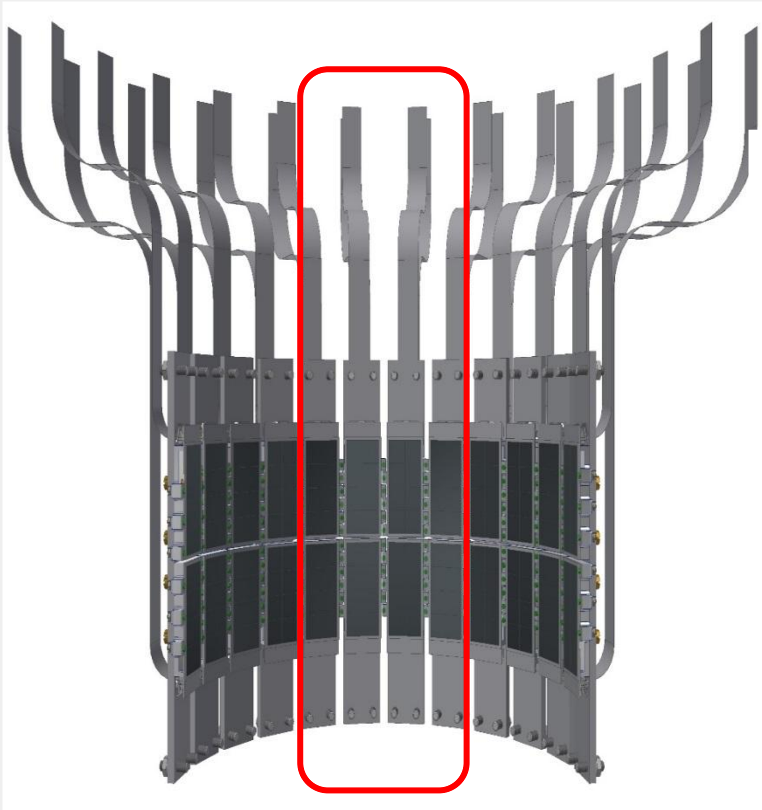
Phase 2: SIDDHARTA-2 will be installed (48 SDD arrays):

kaonic deuterium, run for 800 pb^{-1}

SIDDHARTINO – SIDDHARTA-2 with 8 SDDs

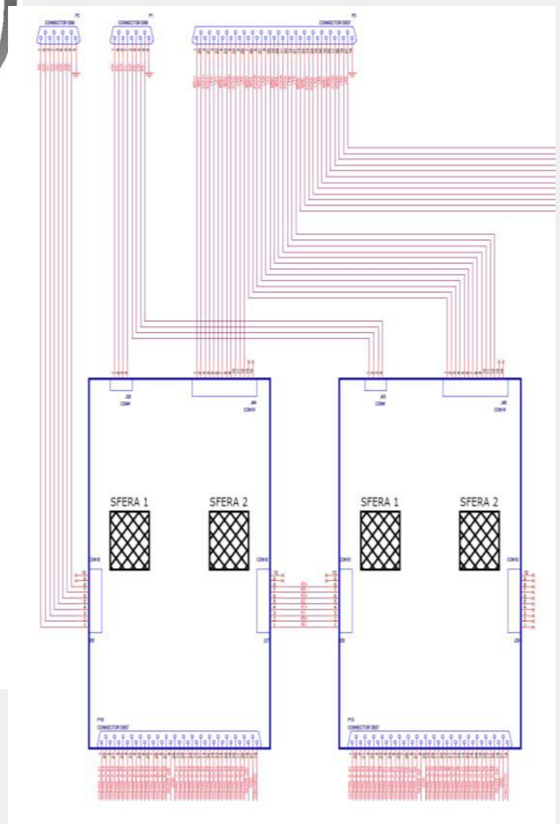


8 SDD arrays
(out of 48)
1 BUS structure

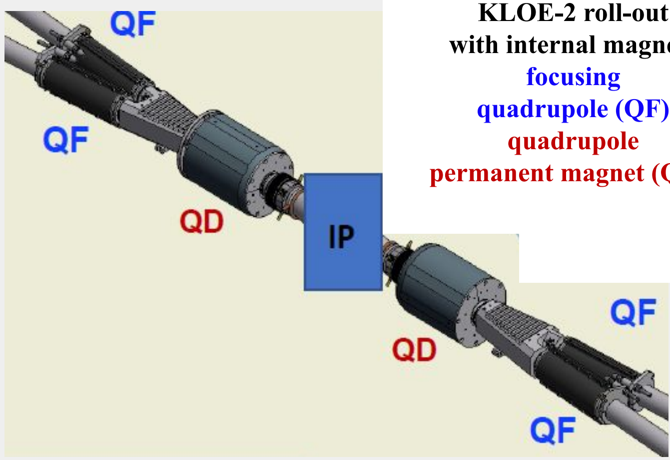


DAQ – Bus structure

- 4 SFERA boards
- 8 SDD arrays



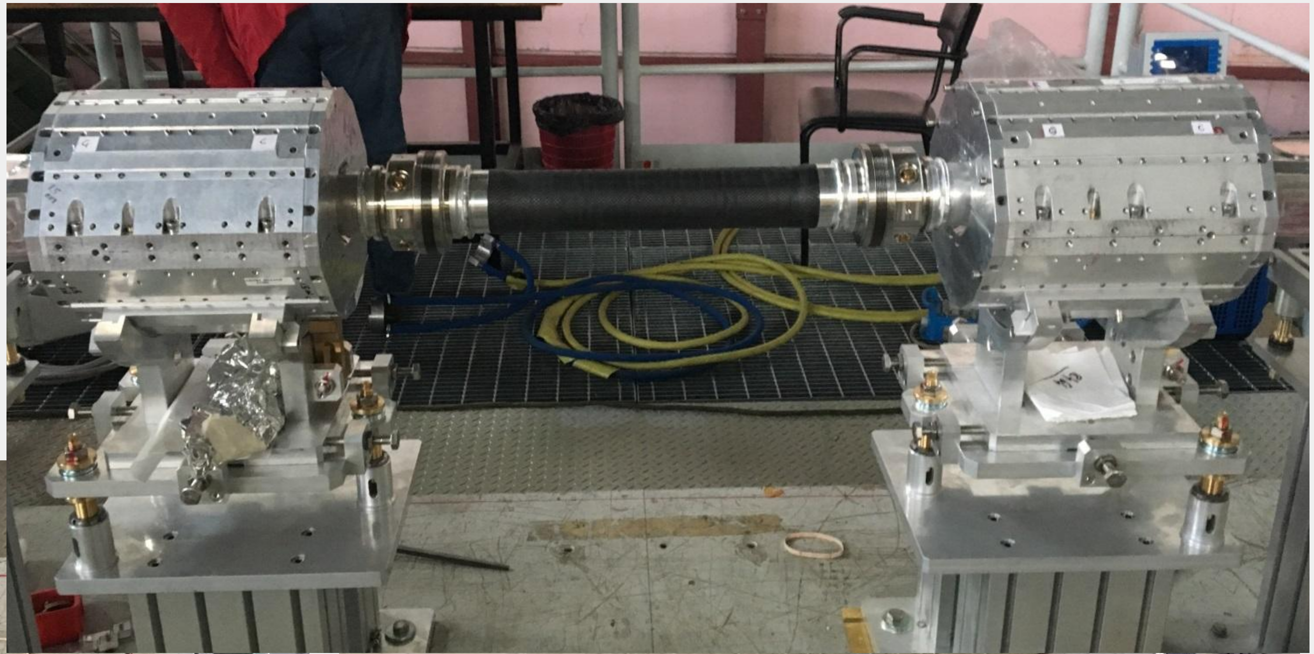
New platform near to interaction region

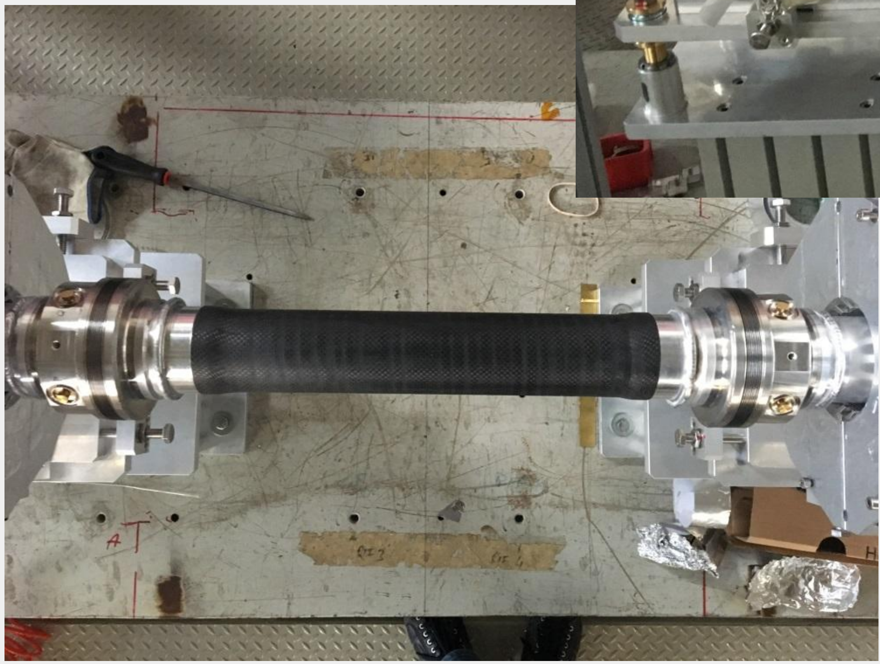


KLOE-2 roll-out
with internal magnets
focusing
quadrupole (QF)
quadrupole
permanent magnet (QD)

New beam pipe

flanges removed
major source of
asynchronous background

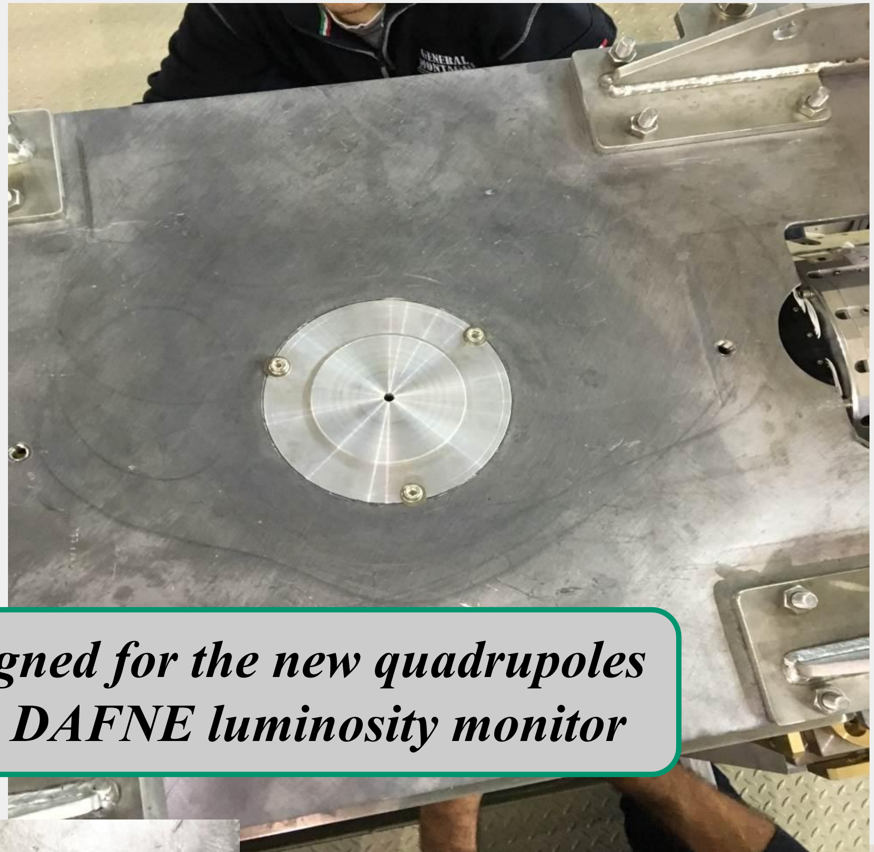




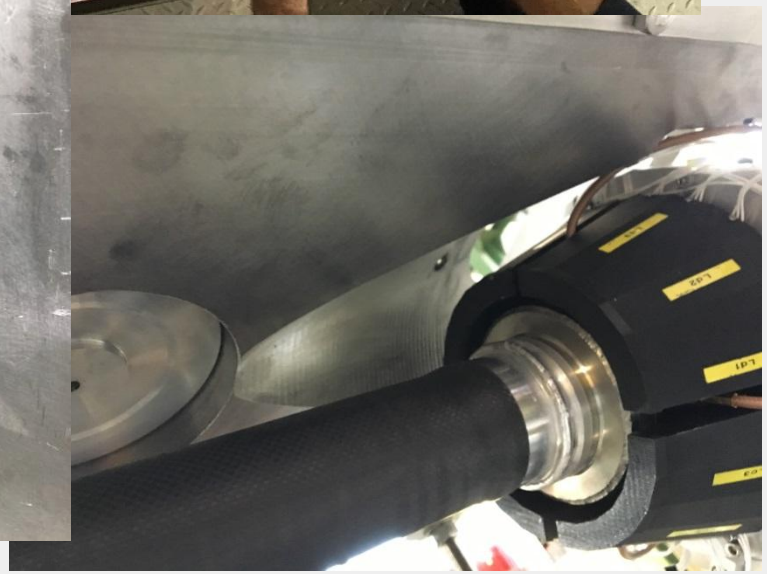
external carbon fiber jacket
ø 66 mm and **thickness ~ 500 micron**
internal ultra pure aluminum
ø 55mm and **thickness ~ 150 micron**

DAFNE luminosity monitor

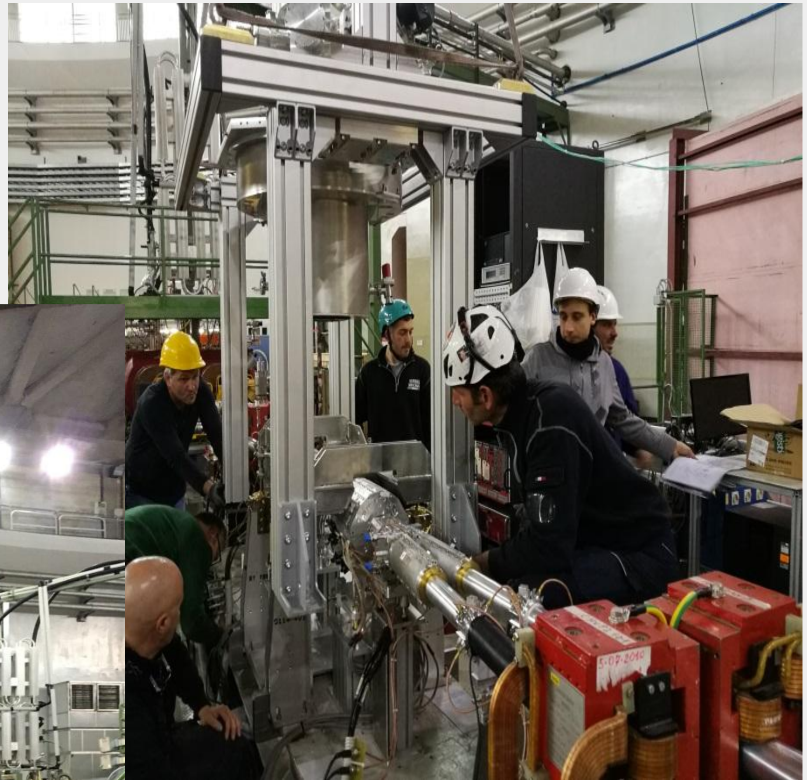
Special SIDDHARTINO designed shielding



Designed for the new quadrupoles and DAFNE luminosity monitor

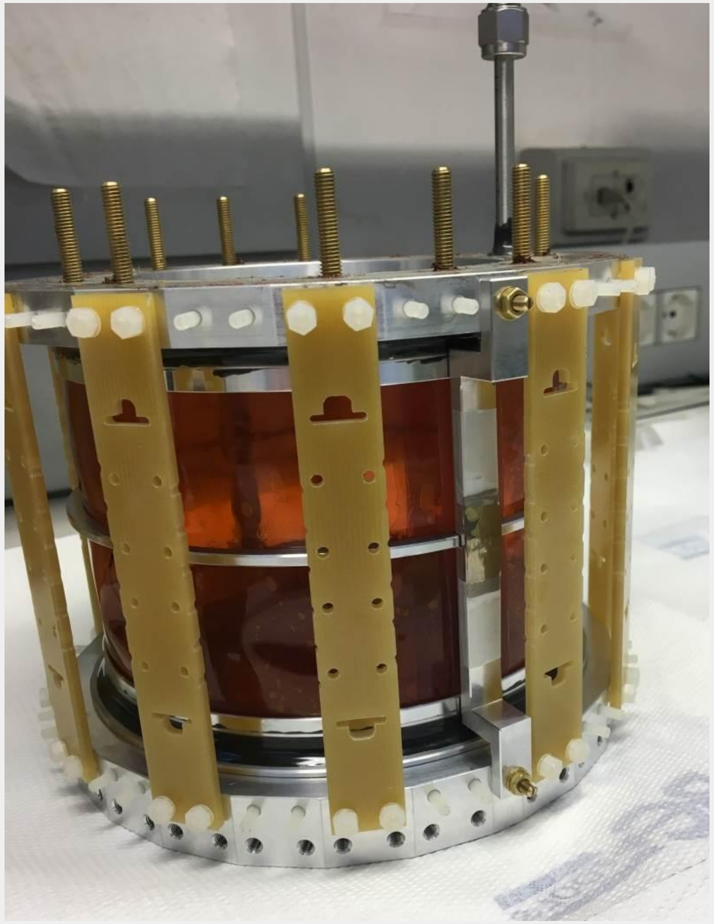


SIDDHARTA-2 aluminum support frame



With the help of DAFNE experts the setup and the shielding were aligned with the beam line axis

Light target and Silicon Drift Detector assembly

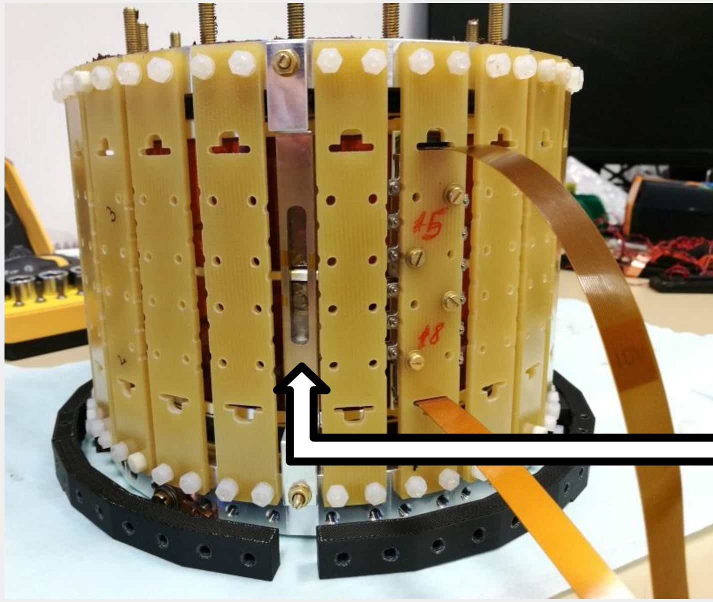


increase the target stopping power

almost double gas density with respect to SIDDHARTA (3% LHD)

SDDs placed 5 mm from the target wall

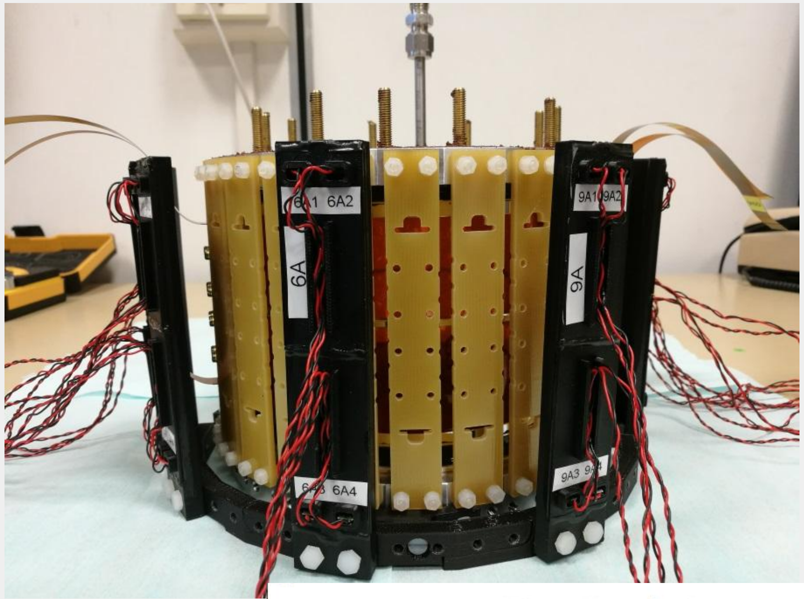
Target cell wall is made of a 2-Kapton layer structure (75 µm + 75 µm + Araldit)

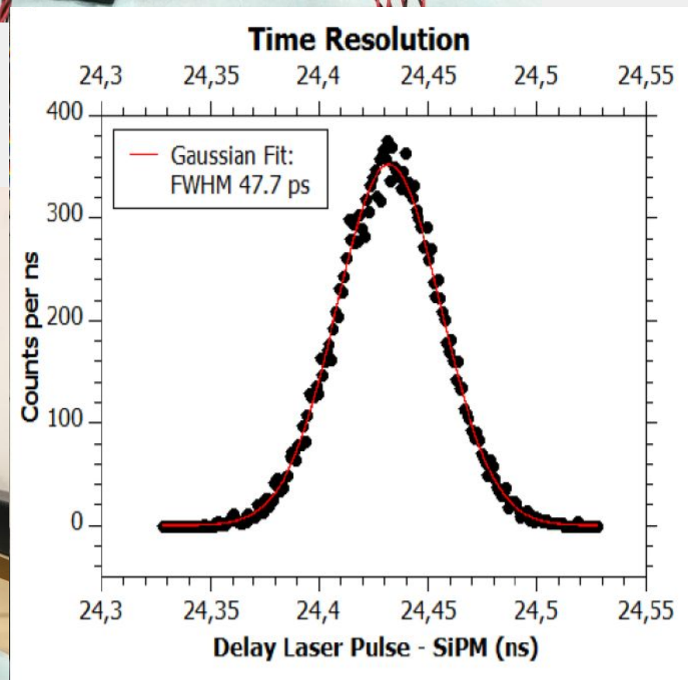


calibration foils inserted near to the SDD are activated by the X-ray tubes

Veto-2 system

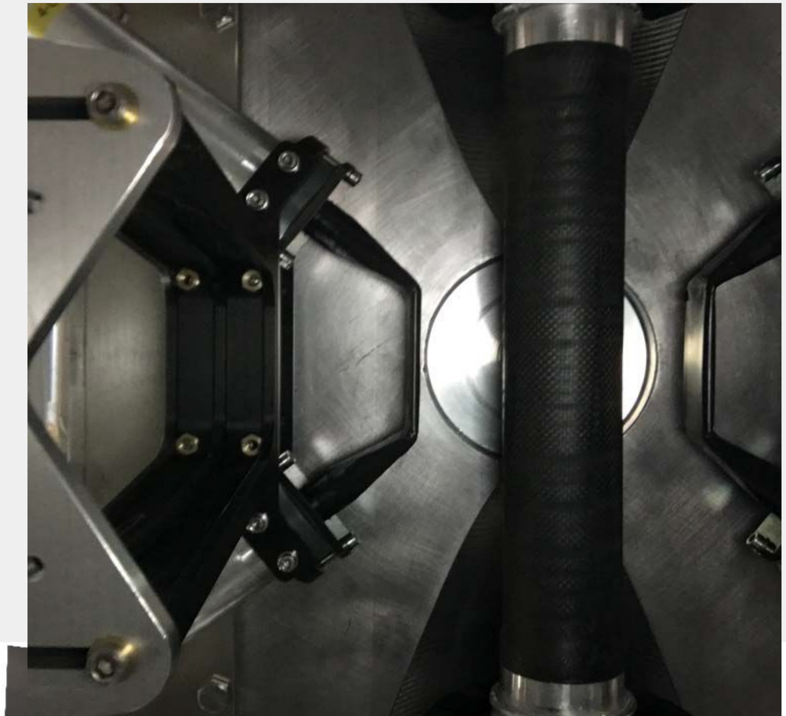
an inner ring of scintillator tiles (SciTiles) placed as close as possible behind the SDDs for charge particle tracking





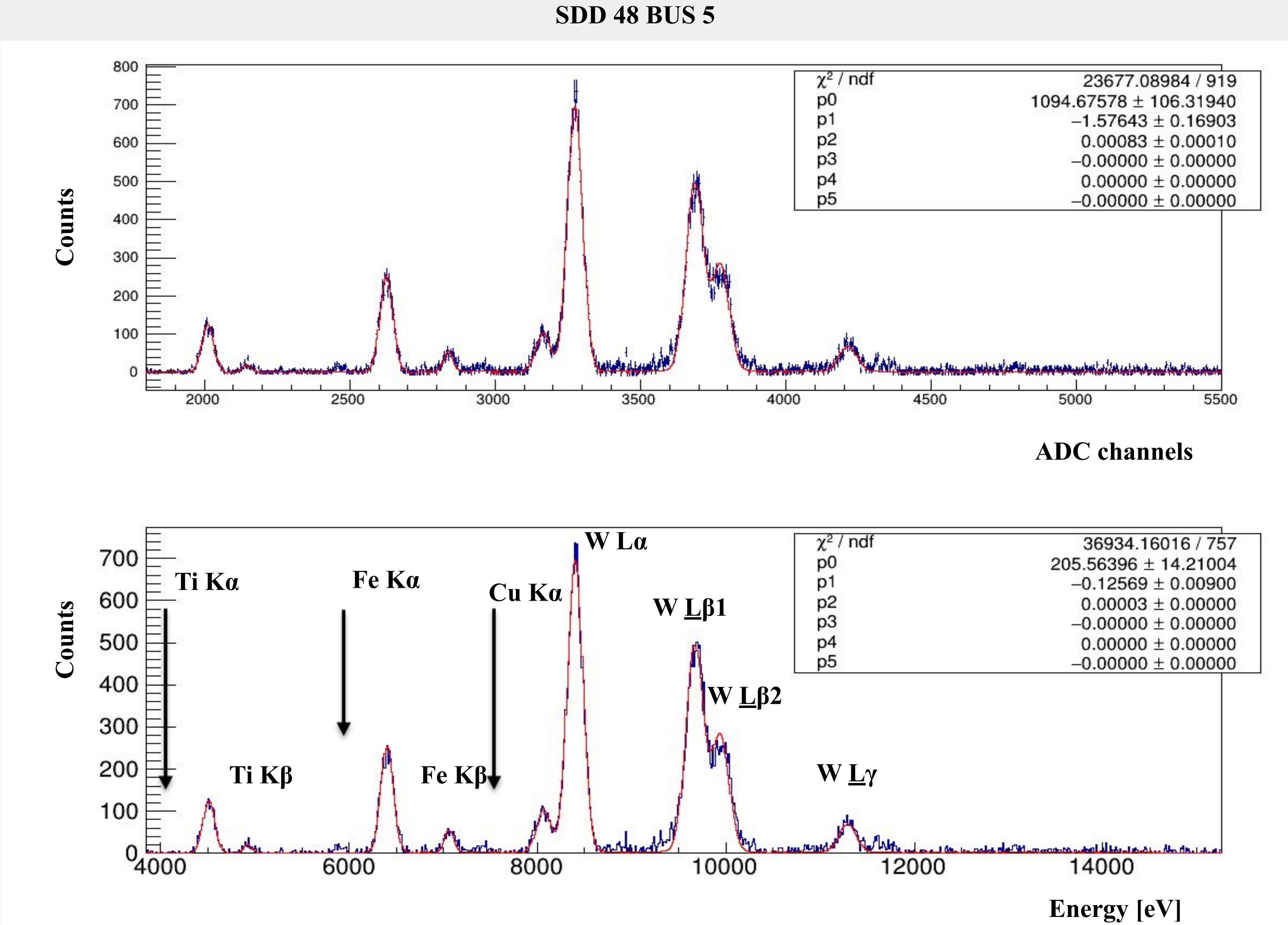
Luminosity monitor

- luminosity ~ 10^{32} cm^{-2} s^{-1}
- rate ~ 50 - 60 Hz



SIDDHARTINO installed on DAFNE (17 April 2019)

Calibration of SDDs with the X-ray tube in DAFNE



SIDDHARTA result – kaonic helium-4

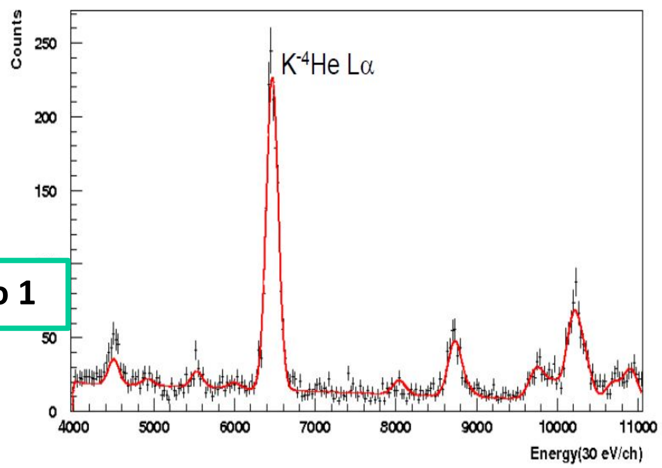
Available online at www.sciencedirect.com

SciVerse ScienceDirect

Nuclear Physics A 914 (2013) 305–309

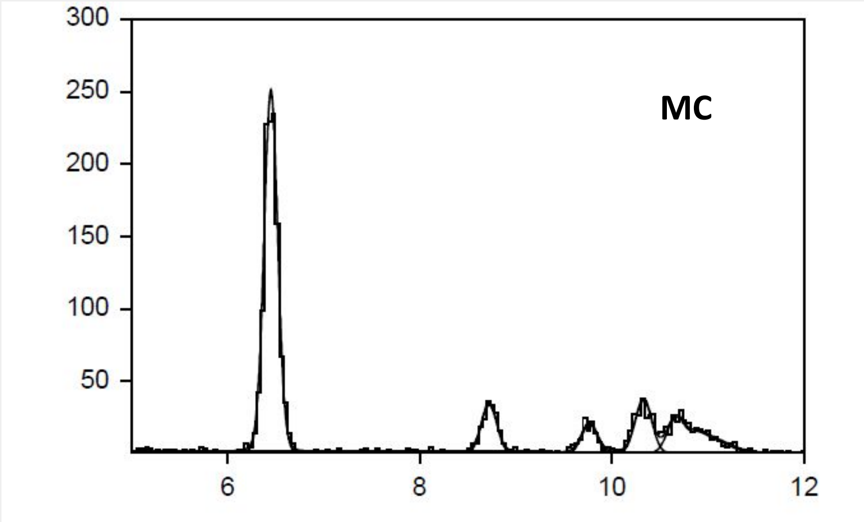
kaonic helium-4
about 28 pb^{-1}
S/B about 1 to 10

S/B about 10 to 1



55th LNF SC - May 14, 2018

Kaonic helium-4 SIDDHARTINO expected spectrum for about 50 pb^{-1} (one week of data taking in SIDDHARTA-like conditions)

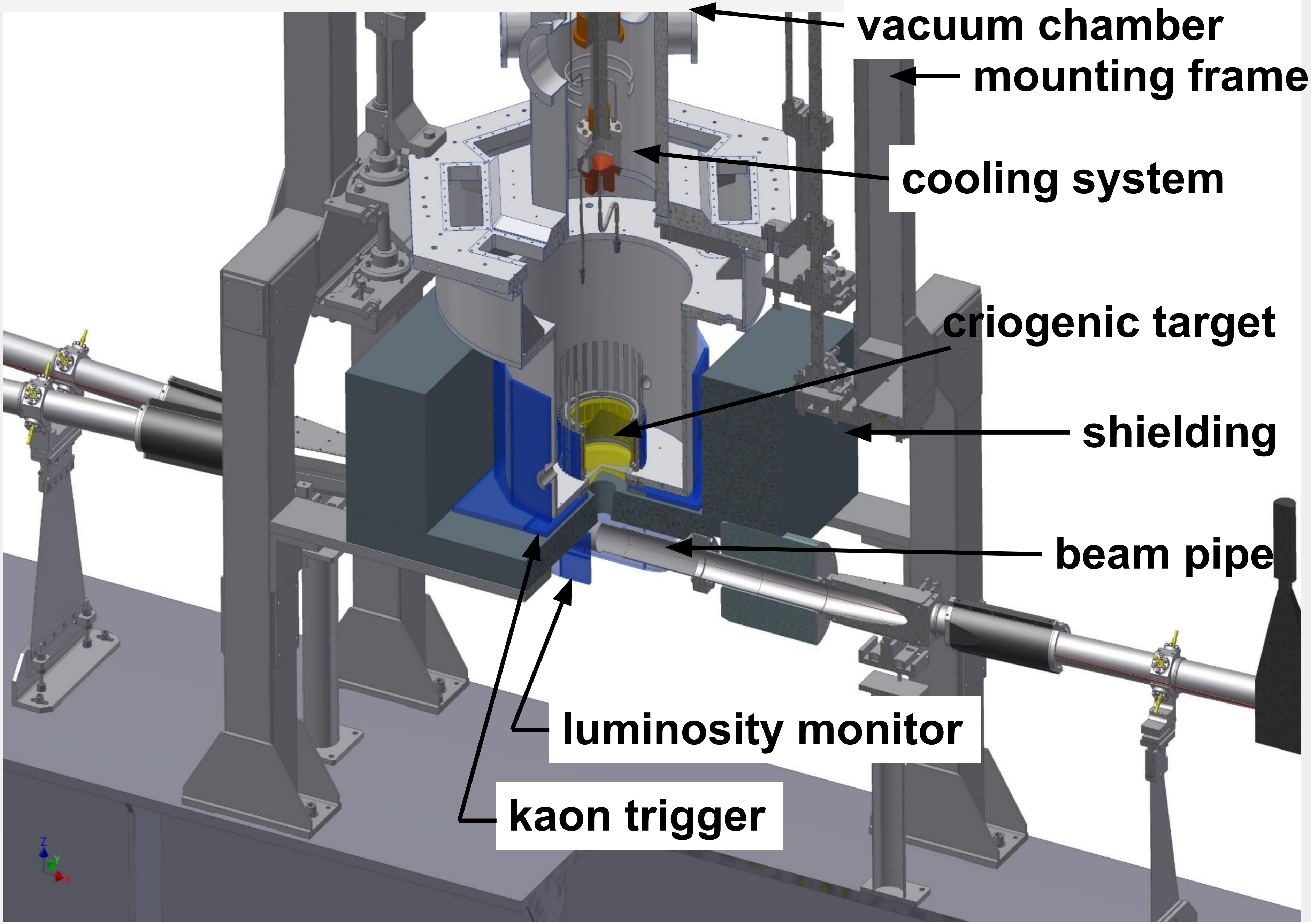


About 1000 events in Lα peak; S/B > 100/1
Position precision : 6.452 +- 0.002 (stat) keV

When Phase 1 is over (basically when S/B for KHe4 about 100/1) in 2020

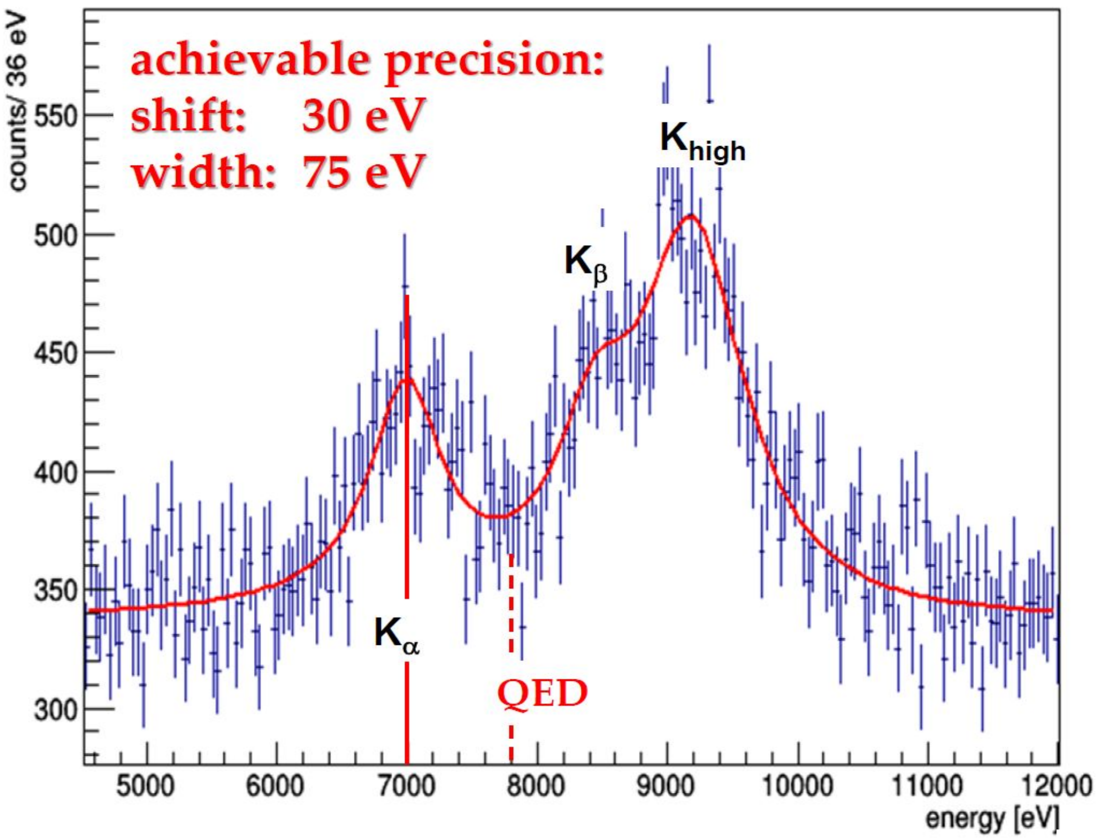
we go for SIDDHARTA-2

SIDDHARTA-2 setup - will be installed after Phase 1



SDDHARTA-2 expected result

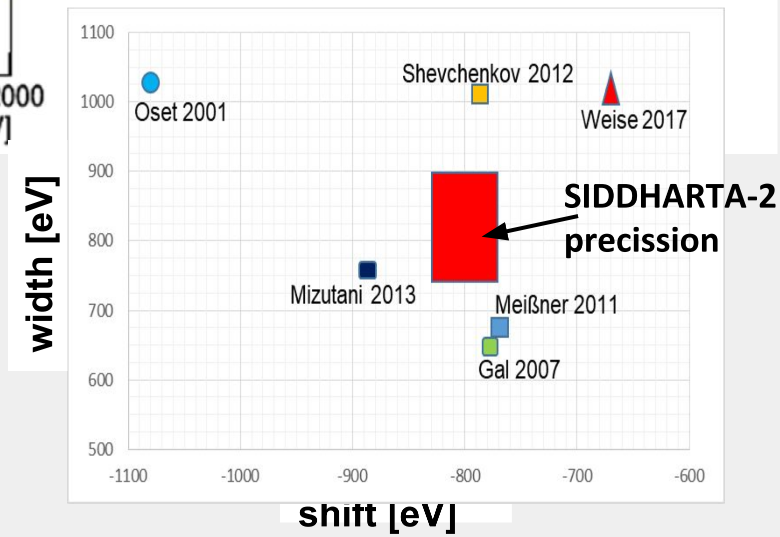
Geant4 simulated K⁻d X-ray spectrum for 800 pb^{-1}



signal: shift - 800 eV
width 800 eV
density: 3% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
yield ratio as in K⁻p
S/B ~ 1 : 3

- charged particle veto
- asynchronous BG



Kaonic deuterium puzzle, SIDDHARTA-2 will bring new constraints on theories

Summary

- Kaonic atoms, in particular KH & Kd, represent a unique tool to investigate the KN low energy interaction

- The SIDDHARTA experiment delivered fundamental results based on the kaonic hydrogen and kaonic helium (shift and width measurements)

- The SIDDHARTA-2 experiment goal is to deliver the first measurement ever of the kaonic deuterium 1s level shift and width

- SIDDHARTINO installed at DAFNE (Phase 1)

- SIDDHARTA-2 future program and perspectives involve also:

  Other light kaonic atoms (K-O, K-C,…)
  Heavier kaonic atoms (K-Si, K-Pb…)
  Kaonic He measurement with higher precision
  Kaonic helium transitions to the 1s level