Studying strong interaction at DAΦNE and J-PARC

Johann Zmeskal

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OUTLINE

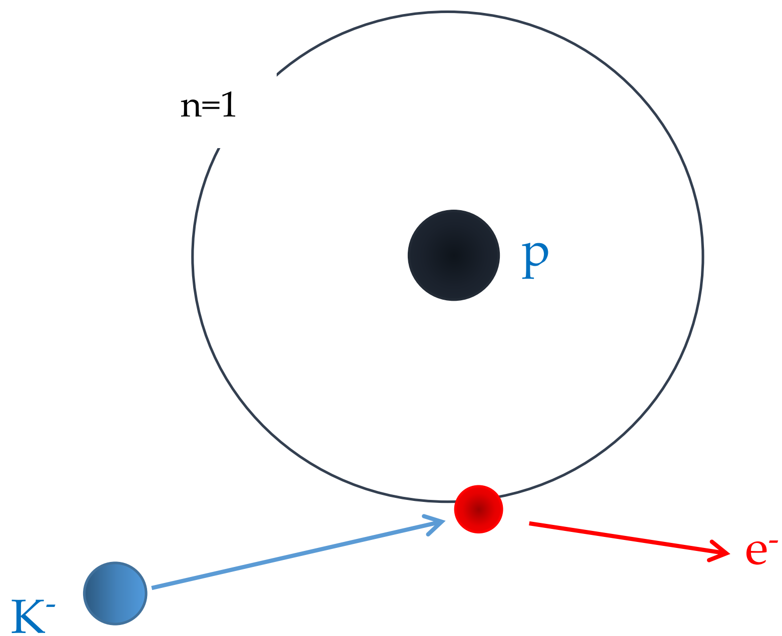
- Motivation
- Charged kaon production
- Status kaonic hydrogen
- Towards kaonic deuterium
  - SIDDHARTA-2
  - E57
- Summary

Motivation to study hadronic atoms

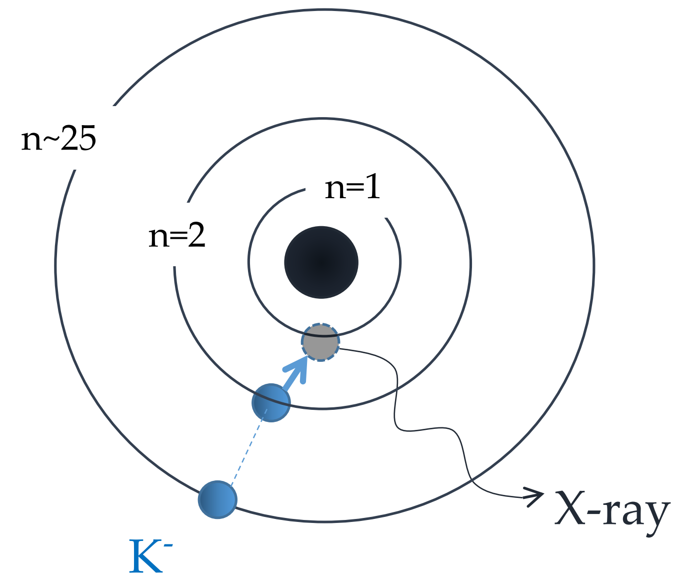
- exotic hadronic atoms are bound by Coulomb force - QED
- e.g. $\pi^+\pi^-$, π^-p, π^-d, K^-p, K^-d, …
- Bohr radii > as the typical scale of strong interaction, but..
  - observable effects of QCD
    - energy shift from pure Coulomb value
    - decay width
  - **access to scattering at zero energy**
- these scattering lengths are sensitive to chiral and isospin symmetry breaking in QCD
- can be analysed systematically in the framework of low-energy Effective Field Theory

Forming "exotic" atoms

"normal" hydrogen



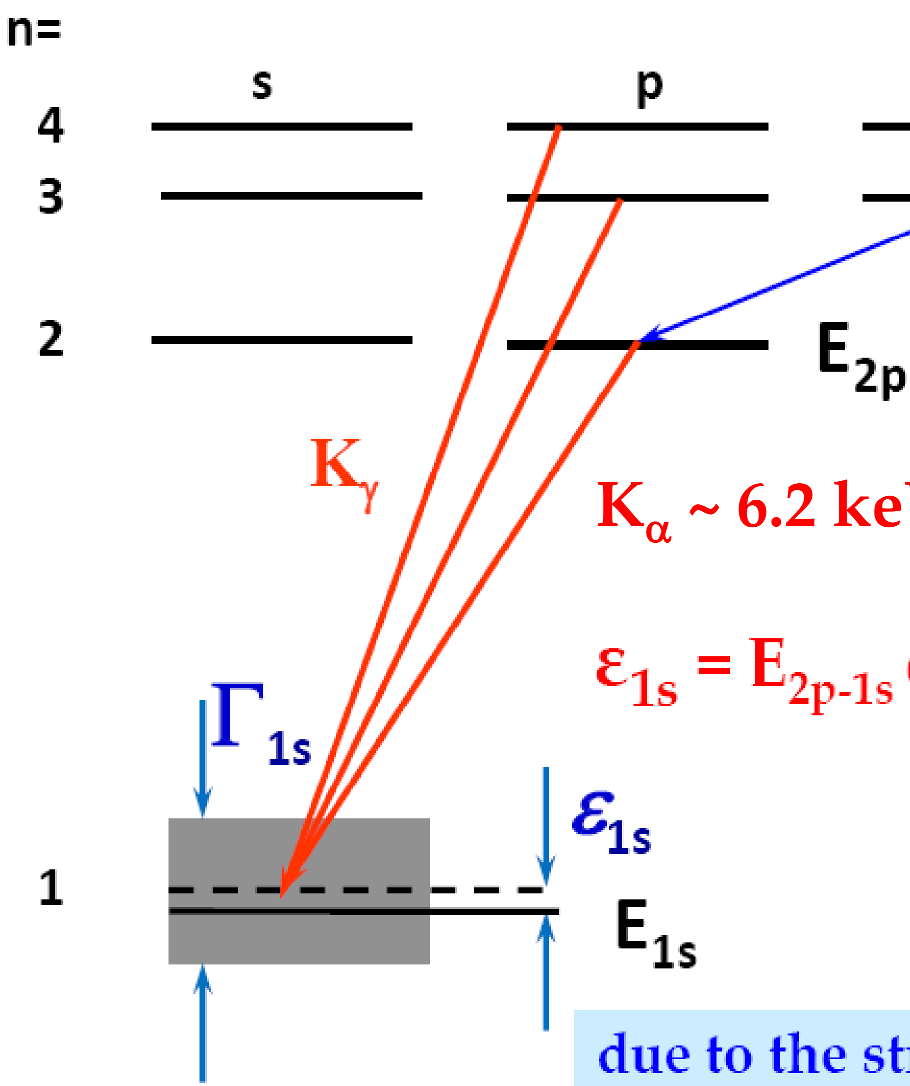
"exotic" (kaonic) hydrogen



2p $\rightarrow$ 1s
K_α transition

$$n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e$$

X-ray transitions to the 1s state



shift and width of states
n > 1 are negligible

$\varepsilon_{1s} = E_{2p\text{-}1s}\,(\text{meas.}) - E_{2p\text{-}1s}\,(\text{e.m.})$

$E_{2p \to 1s}$ (e.m.) (K-p) = 6480 ± 1 eV

$E_{2p \to 1s}$ (e.m.) (K-d) = 7820 ± 1 eV

due to the strong interaction kaon-proton
the 1s level is shifted and broadened

Scattering lengths

Deser-type relation connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of $a_{K\text{-}p}$

$$\epsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu \boldsymbol{a_{K^-p}}$$

(μ .. reduced mass of the K^-p system, α .. fine-structure constant)

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

$\Leftrightarrow$

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

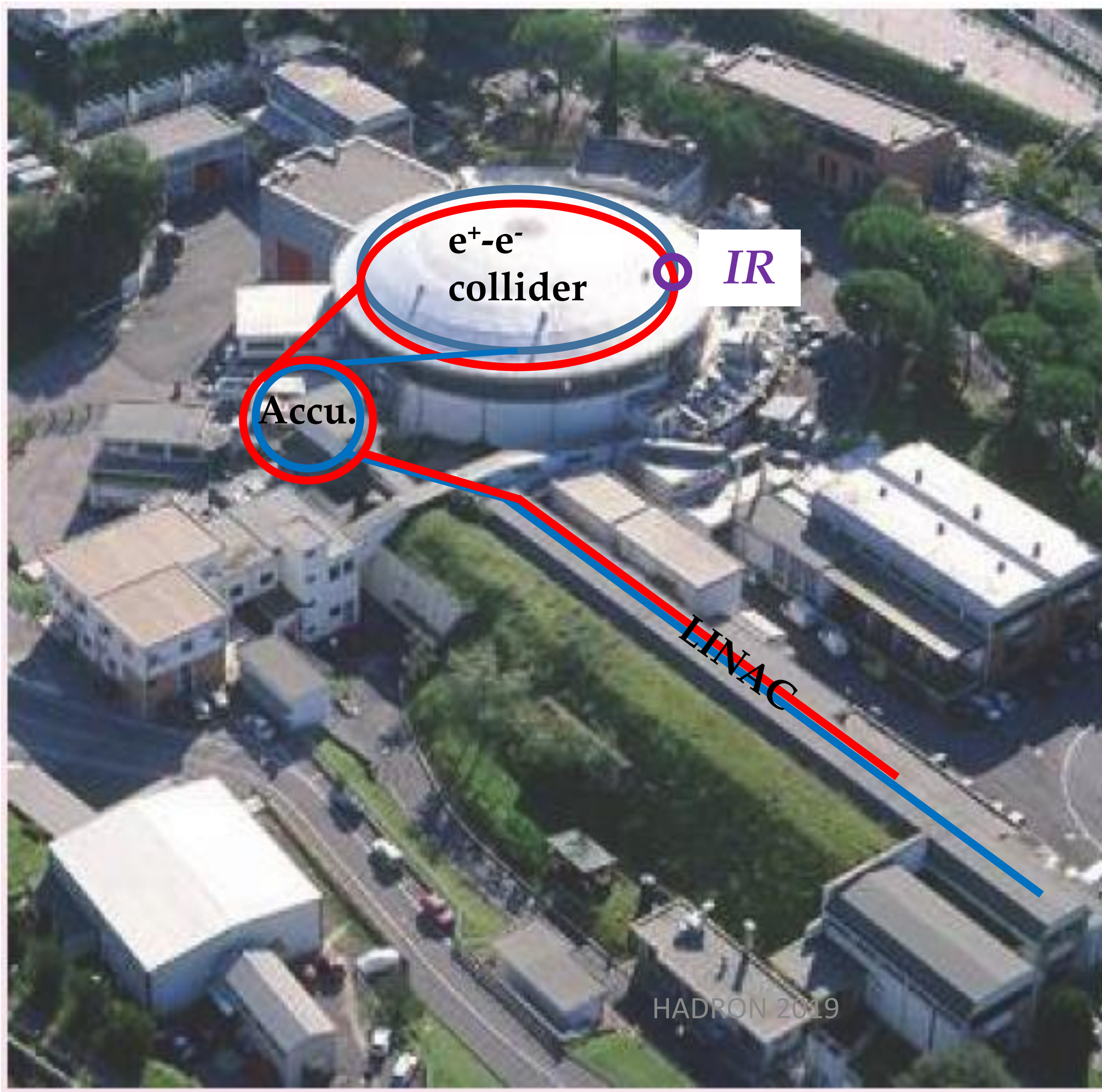
- **the measurement of kaonic deuterium**

  will allow to extract antikaon-nucleon isospin dependent scattering lengths

Charged kaon production

- DAΦNE at Laboratori Nazionali di Frascati
- J-PARC - Japan Proton Accelerator Research Complex

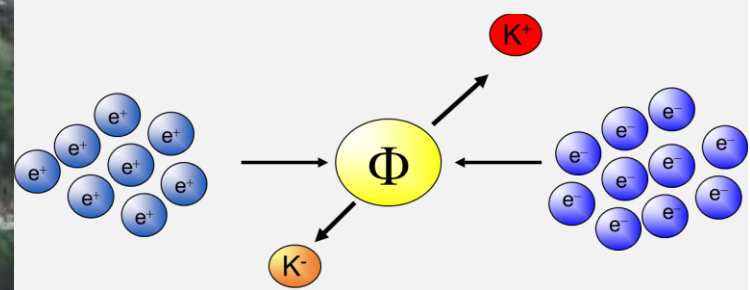
Low energy charged kaons at DAΦNE



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

mass $m = 1019.413 \pm .008$ MeV

width $\Gamma = 4.43 \pm 0.06$ MeV

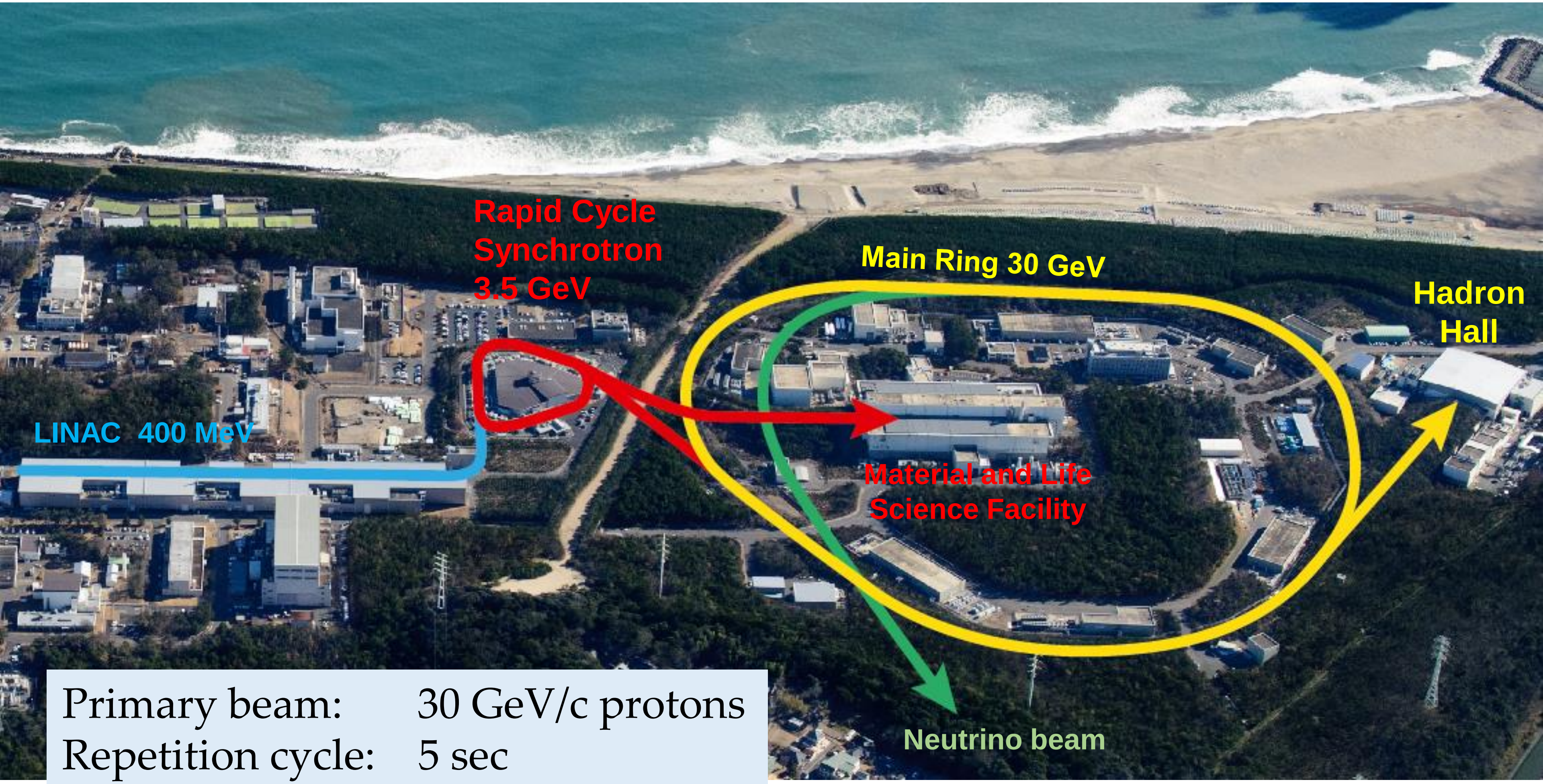


Φ produced via e^+e^- collision

$\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$

→ monochromatic kaon beam (127 MeV/c)

Japan Proton Accelerator Research Complex - J-PARC

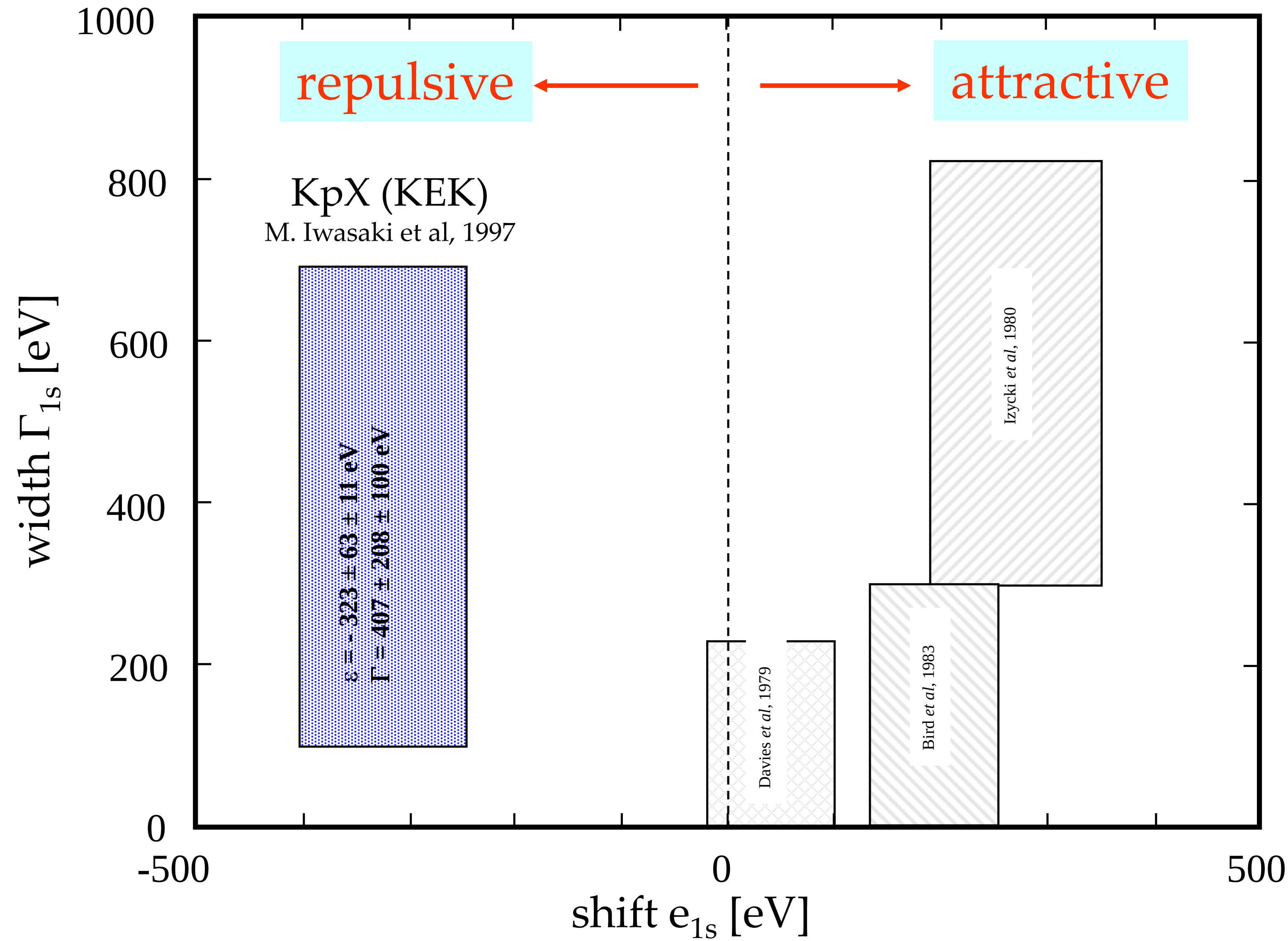


Primary beam:	30 GeV/c protons
Repetition cycle:	5 sec
Flat top:	3 sec
Production target:	Au
Kaon momentum:	1.2 GeV/c (max.)

Status kaonic hydrogen

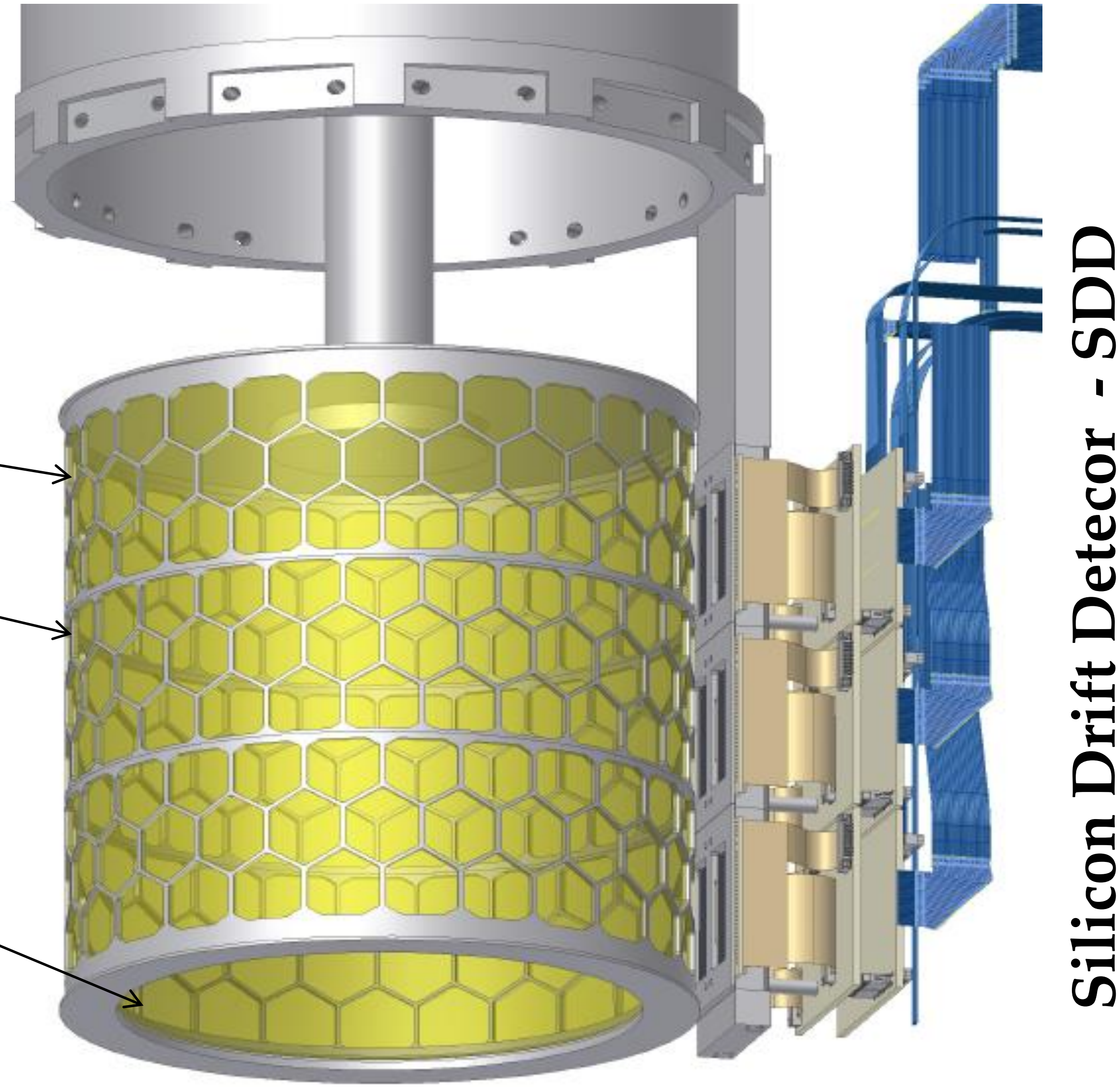
- SIDDHARTA at DAΦNE

Kaonic hydrogen “puzzle”

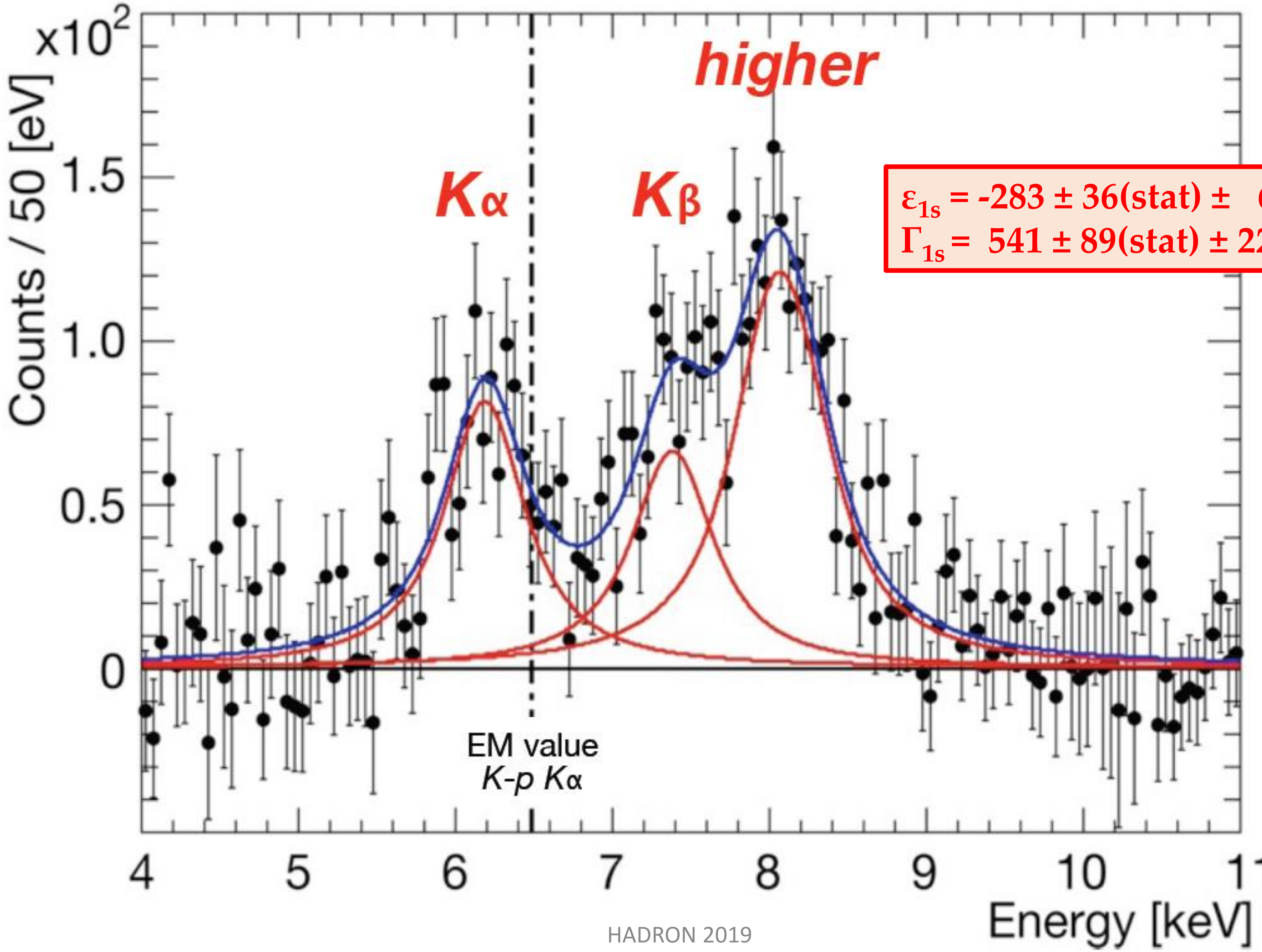


SIDDHARTA: cryogenic target + X-ray detector

working T 25 K
working P 1.5 bar

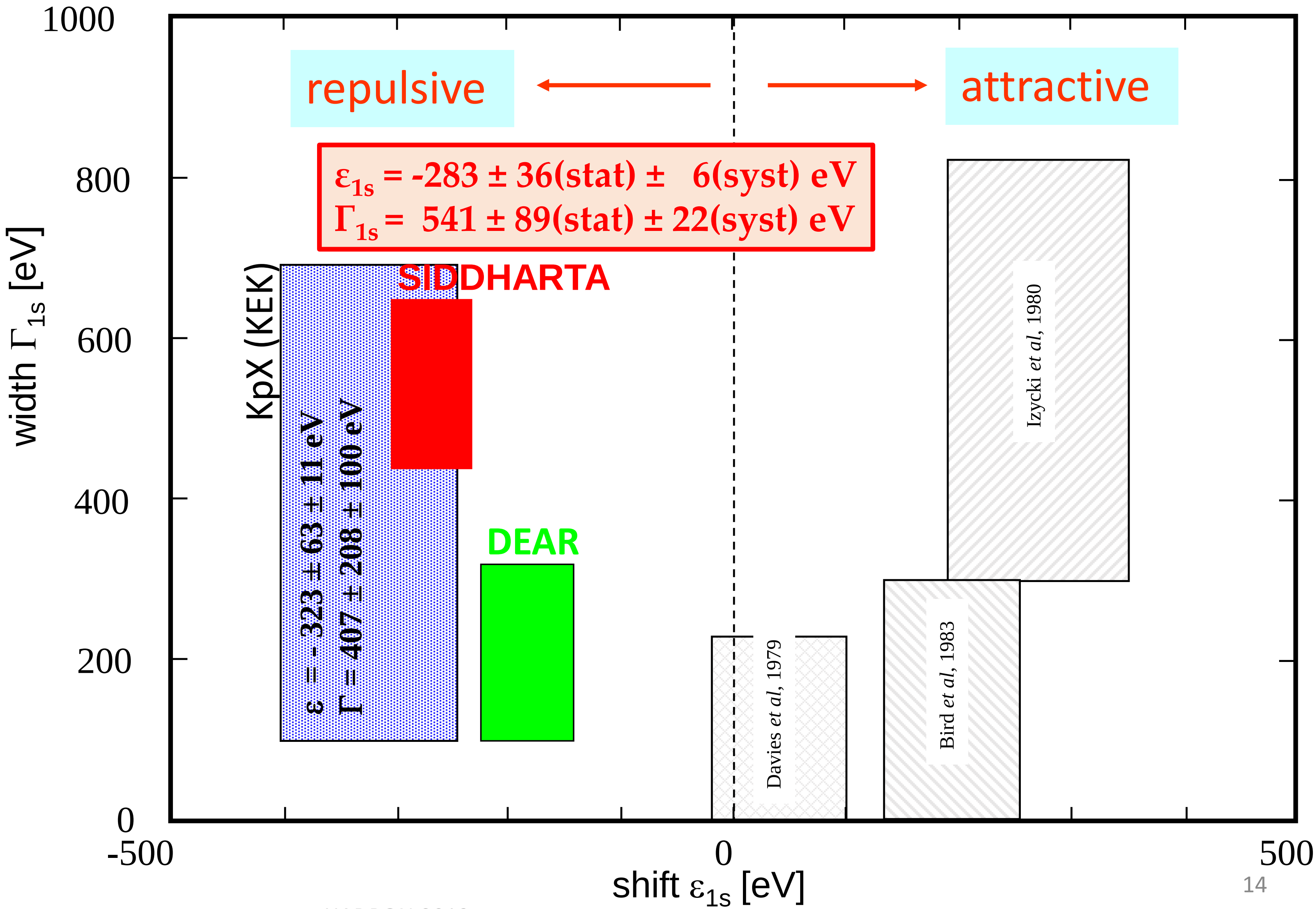


$K^{-}p$ spectrum, BG subtracted



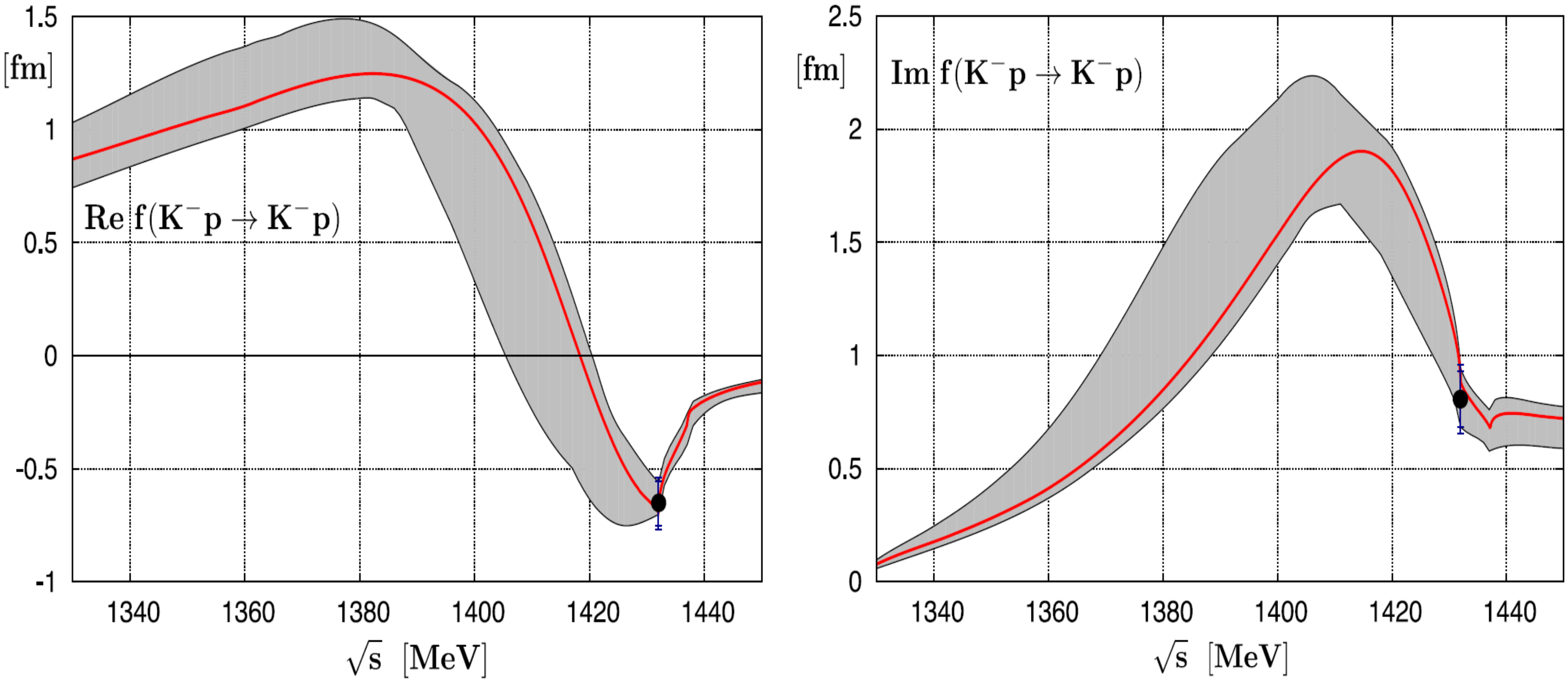
ε_{1s} = -283 ± 36(stat) ± 6(syst) eV
Γ_{1s} = 541 ± 89(stat) ± 22(syst) eV

Kaonic hydrogen results



Improved constraints on chiral SU(3) dynamics from kaonic hydrogen

Y. Ikeda, T. Hyodo and W. Weise, PLB 706 (2011) 63



Real part and imaginary part of the $K^{-}p \rightarrow K^{-}p$ forward scattering amplitude extrapolated to the subthreshold region, deduced from the SIDDHARTA kaonic hydrogen measurement.

Chiral EFT motivated K^-N approaches

Kyoto-Munich

Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98

Murcia (MI , MII)

Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202

Bonn (B2, B4)

M. Mai, U.-G. Meiner - Eur. Phys. J. A 51 (2015) 30

Prague

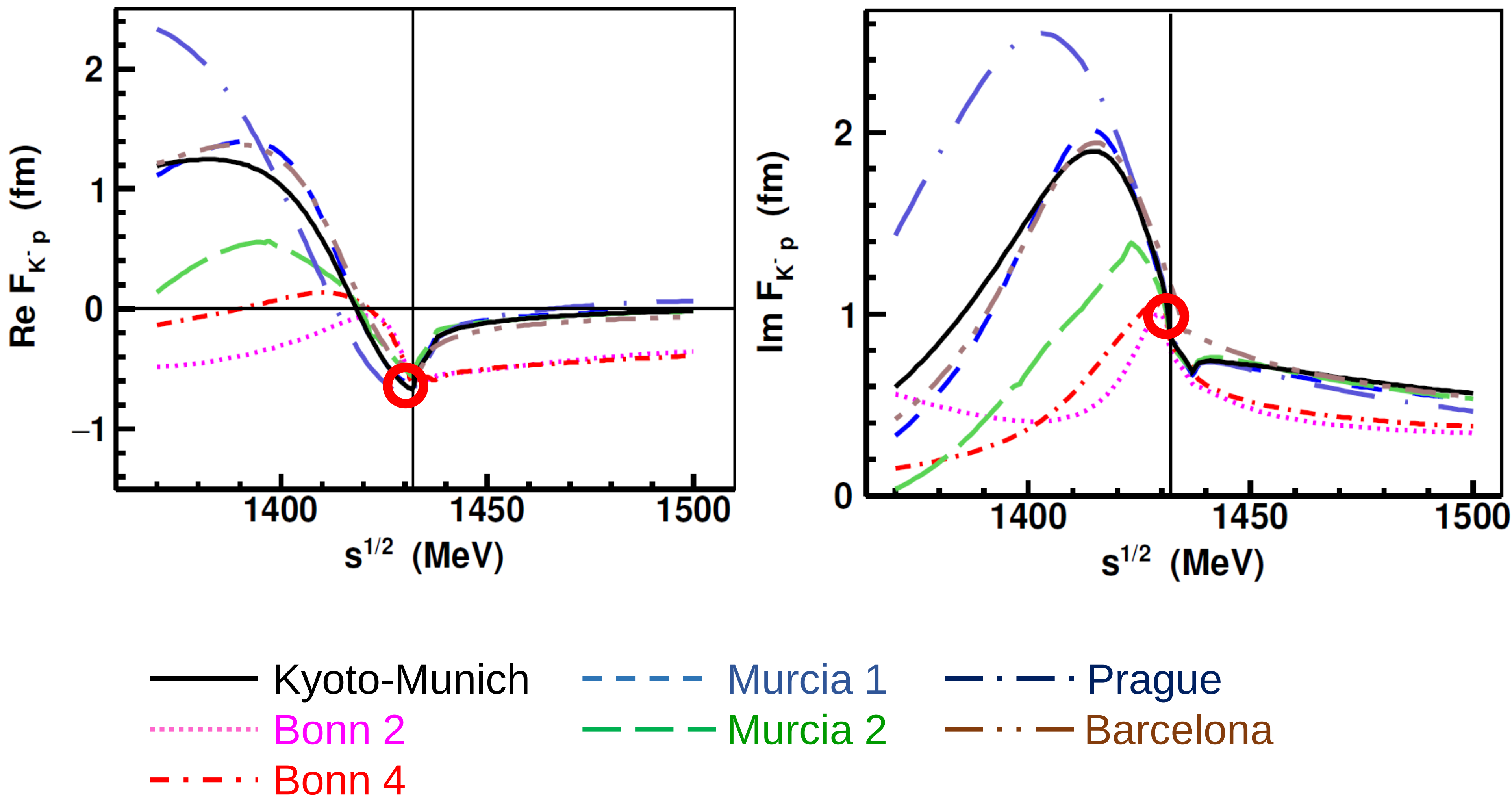
A. Cieplý, J. Smejkal, Nucl. Phys. A 881 (2012) 115

Barcelona

A. Feijoo, V. Magas, A. Ramos, Phys. Rev. C 99 (2019) 035211

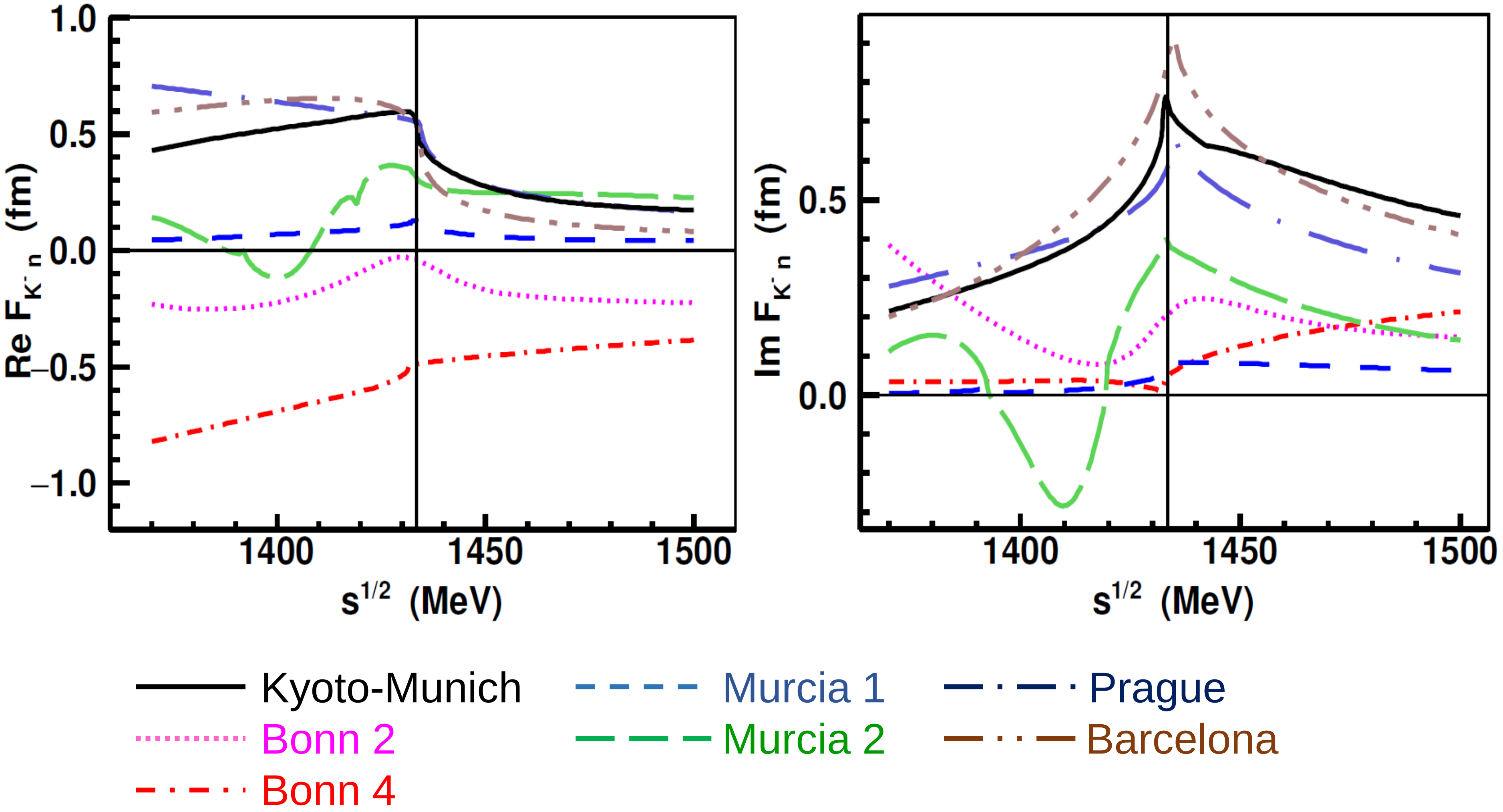
$K^-p \to K^-p$ forward scattering amplitude

- subthreshold amplitudes not yet well determined



A. Cieplý
MENU 2019

$K^- n \rightarrow K^- n$ forward scattering amplitude



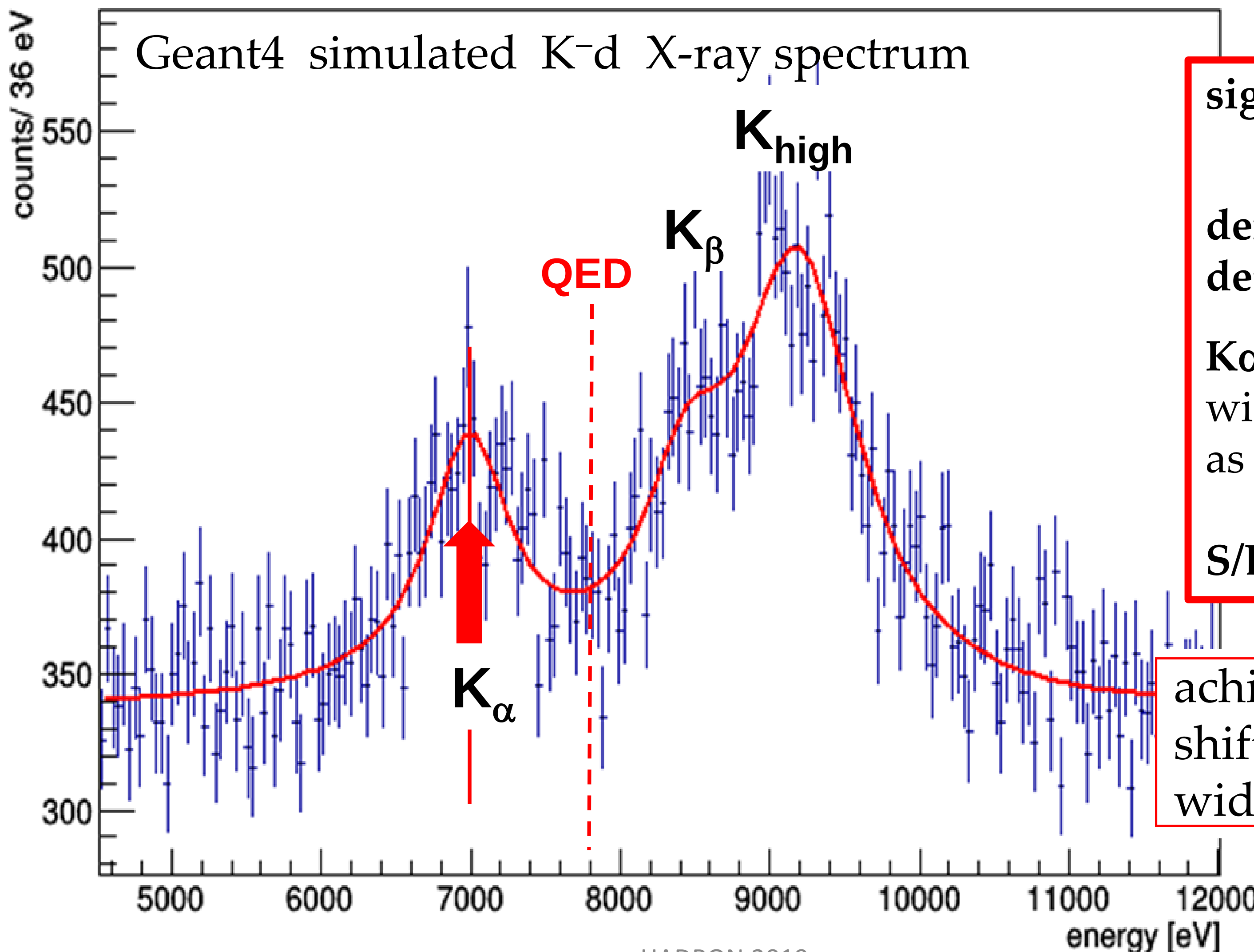
A. Cieplý
MENU 2019

Towards kaonic deuterium

- SIDDHARTA-2 at DAΦNE
- E57 at J-PARC
  - Kaonic hydrogen pilot run

The scientific goal of SIDDHARTA-2 and E57

- **a first measurement of kaonic deuterium**
  to extract the $\bar{K}N$ isospin dependent scattering lengths



INPUT

signal: shift - 800 eV
width 800 eV

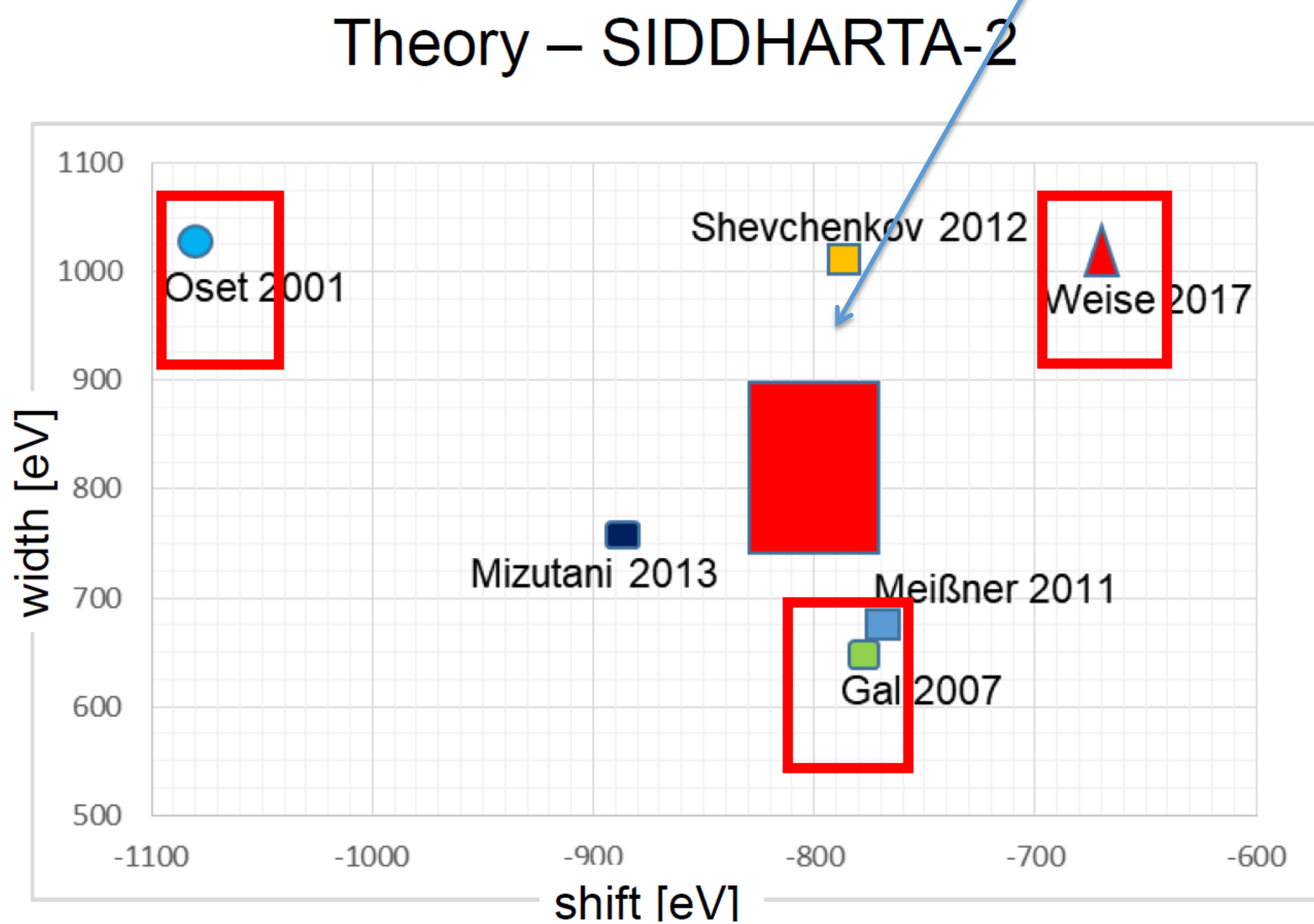
density: 5% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
with the yield ratio
as in K$^-$p

S/B ~ 1 : 4

achievable precision:
shift: 30 eV
width: 75 eV

E57 / SIDDHARTA-2 targeted precision



Experimental challenges towards $K^{-}d$

- X-ray yield: $K^{-}p$ ~ 1 %
  $K^{-}d$ ~ 0.1 %

- 1s state width: $K^{-}p$ ~ 540 eV
  $K^{-}d$ ~ 800 – 1000 eV

BG sources: asynchronous BG $\rightarrow$ timing
synchronous BG $\rightarrow$ spatial correlation

SIDDHARTA-2

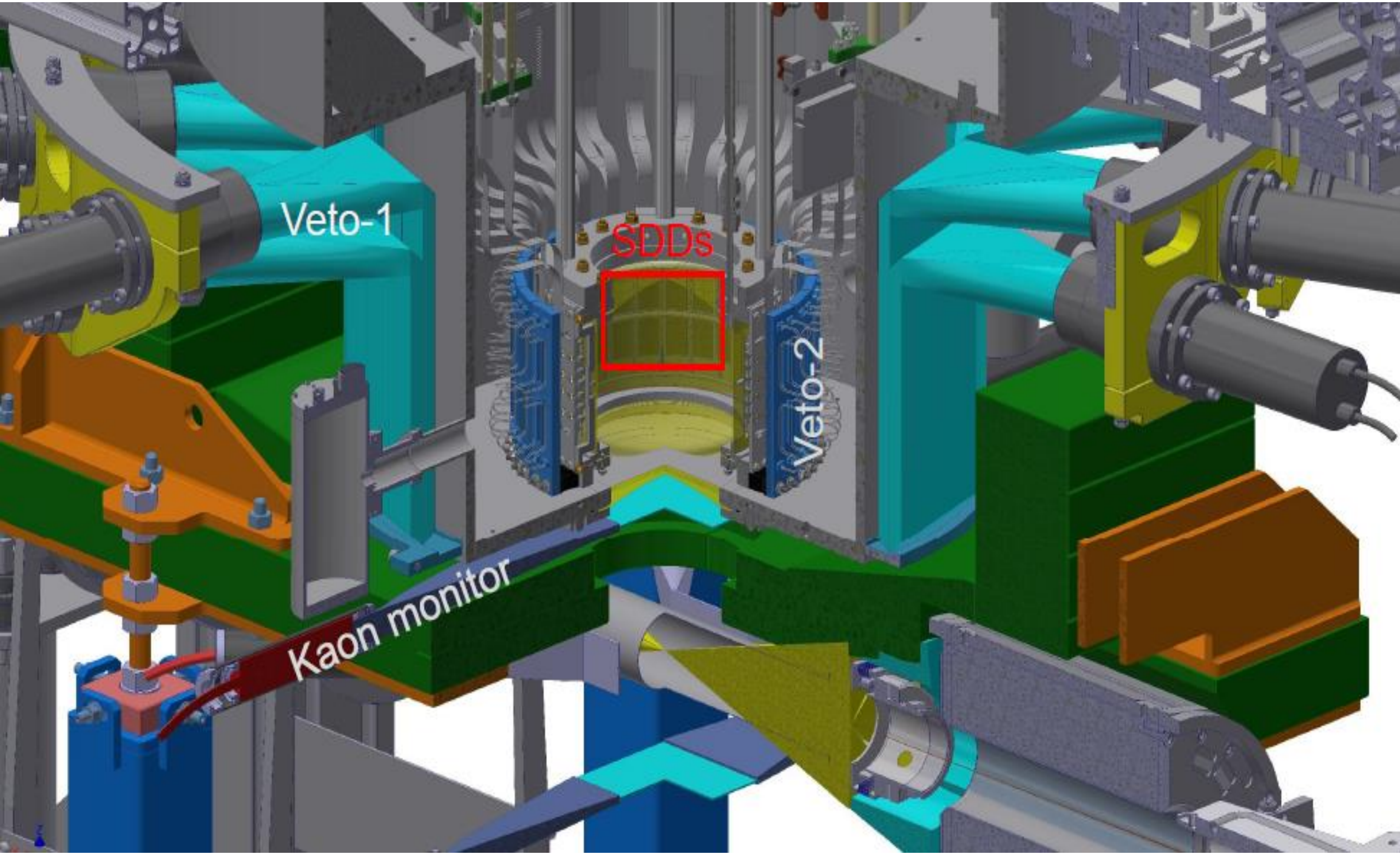
SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

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

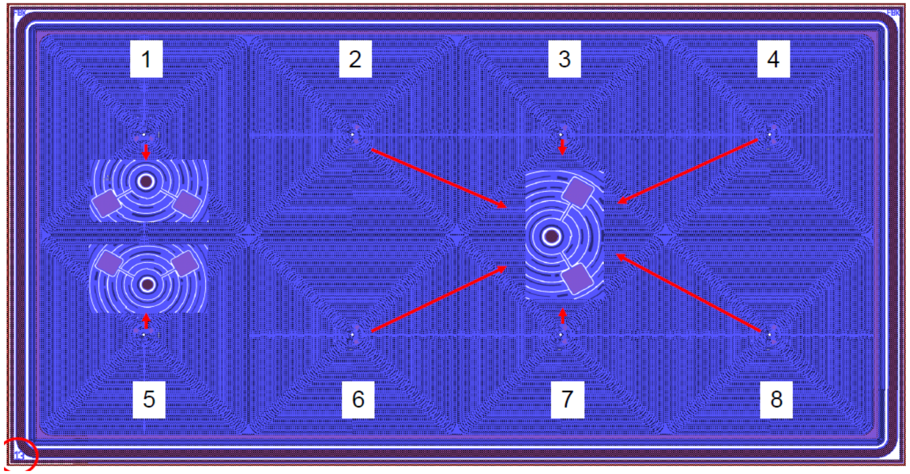
STRONG-2020

Croatian Science Foundation, research project 8570

SIDDHARTA-2

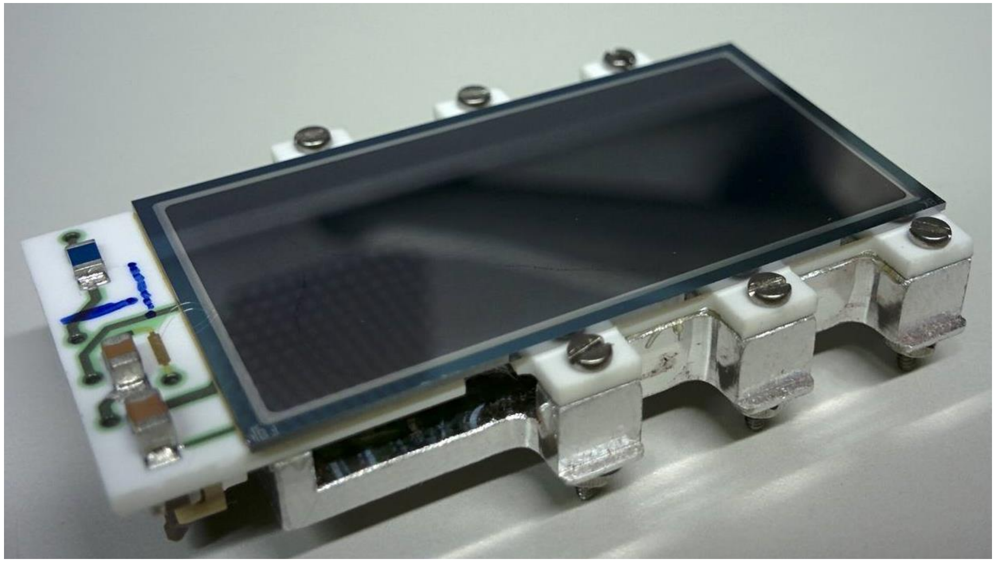


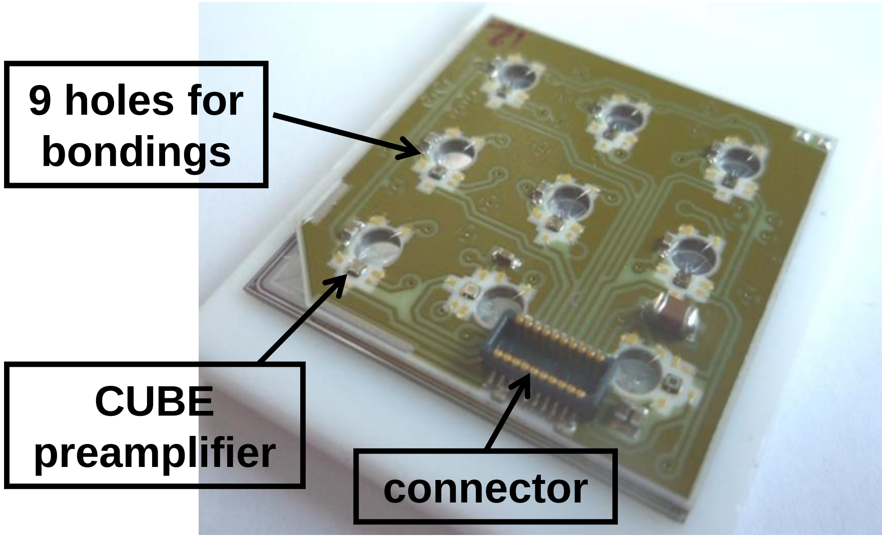
The new 4x2 SDD array for K⁻d



SDD-chip back side with bonding pads

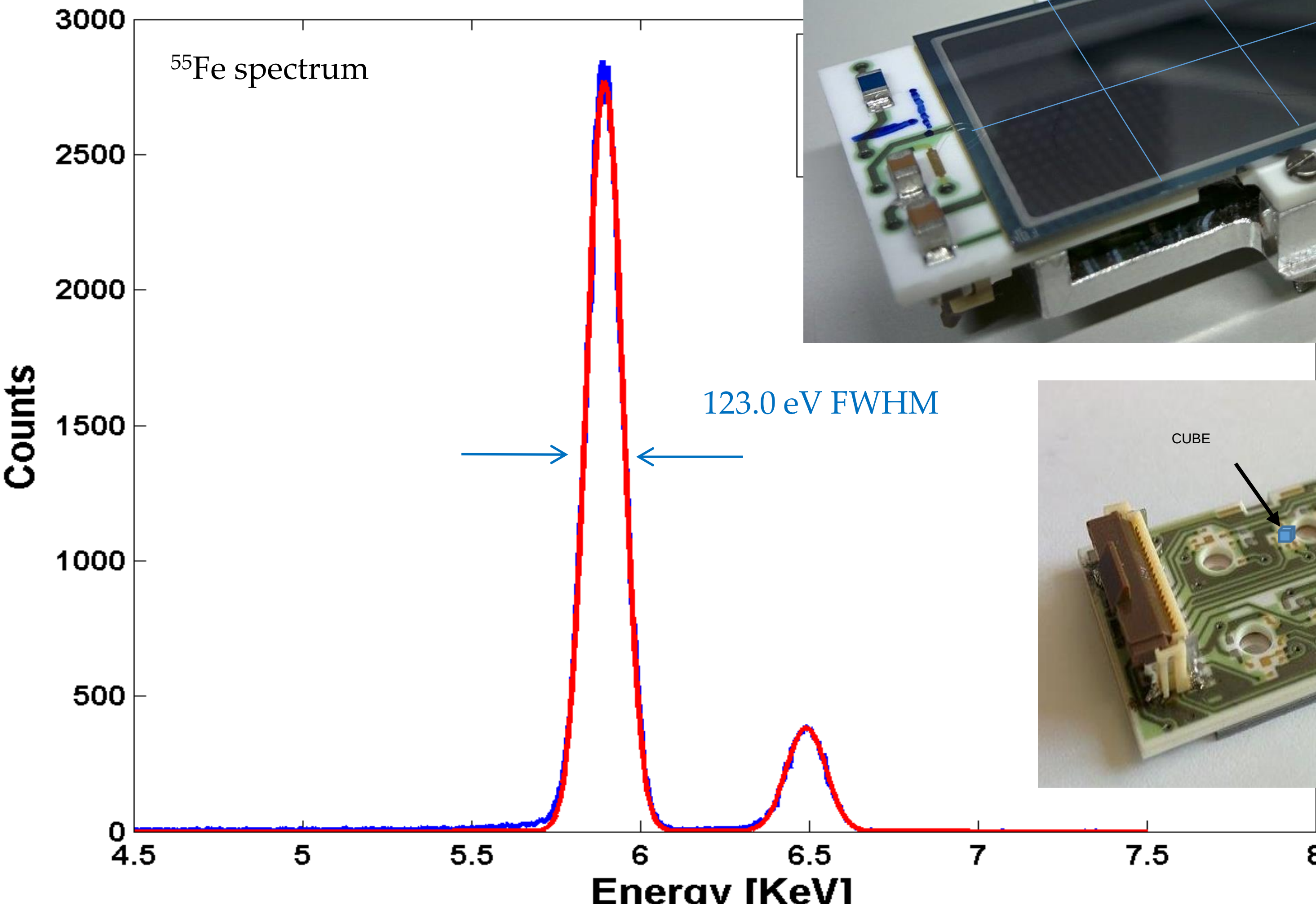
SDD-chip glued to ceramic board, bonded to CUBE preamplifier

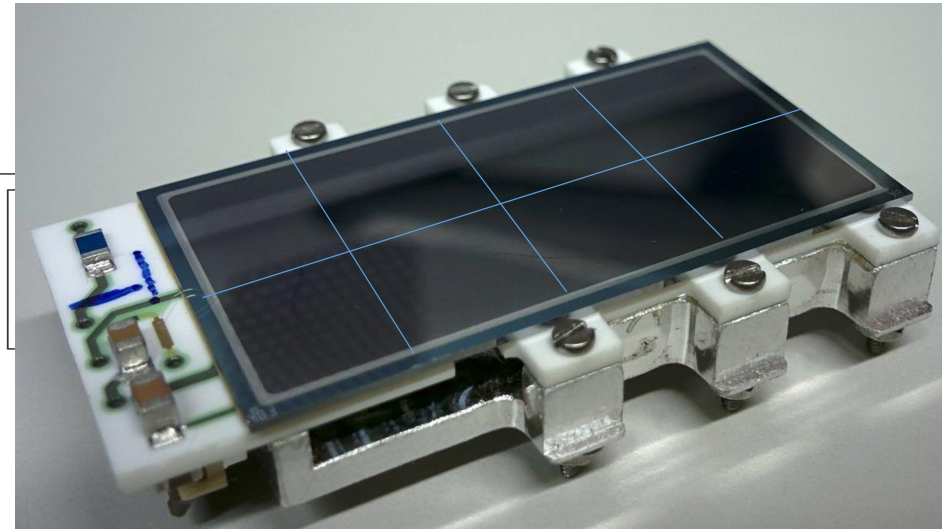


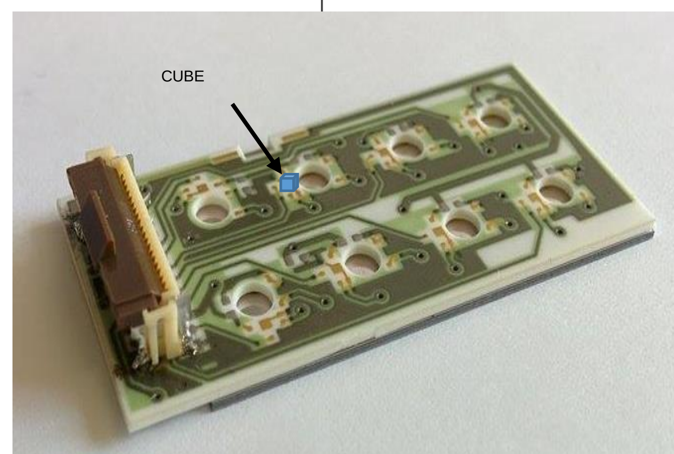


X-ray detector for SIDDHARTA-2 and E57

New SDD technology with
CUBE preamplifier







SIDDHARTA – 2 successfully installed at DAΦNE in April 2019

more details:
Session 4,
Aug. 20 at 9:15

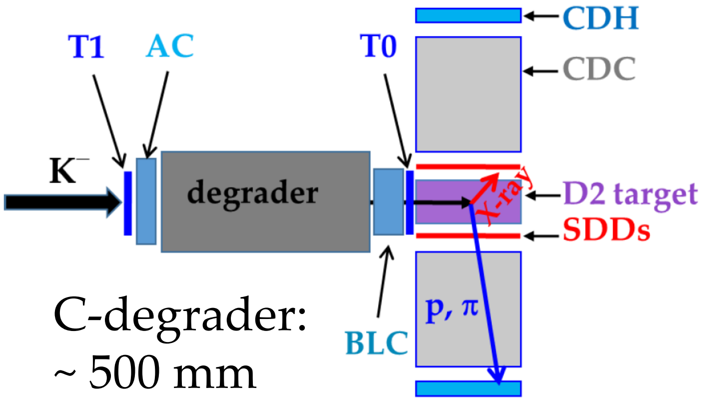
Towards kaonic deuterium

- SIDDHARTA-2 at DAΦNE
- E57 at J-PARC
  - Kaonic hydrogen pilot run

K–d collaboration

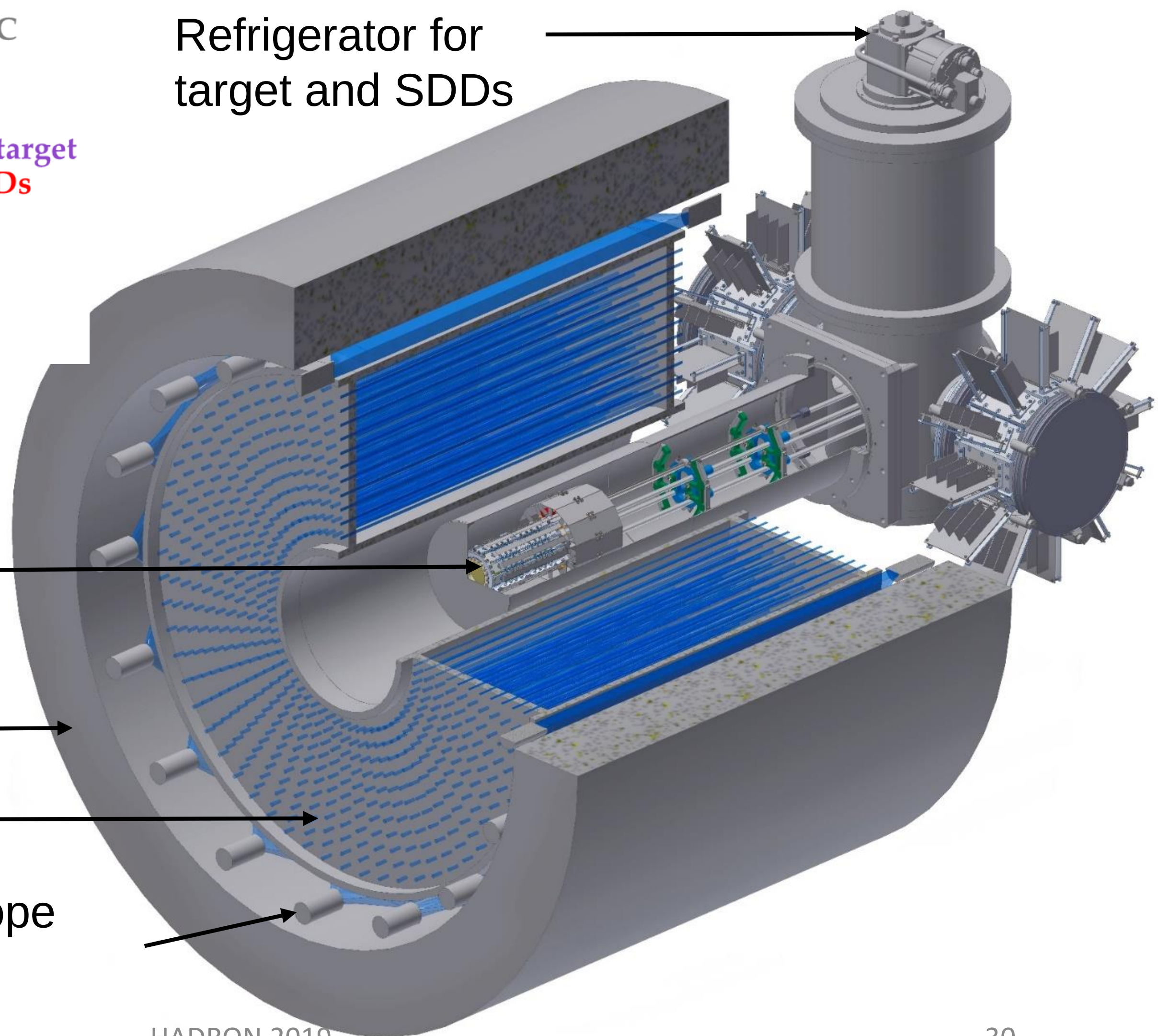
LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
IFIN – HH, Bucharest, Romania
Politecnico, Milano, Italy
RIKEN, Japan
Tokyo Univ., Japan
Victoria Univ., Canada
KEK, Tsukuba, Japan
RCNP, Osaka, Japan
Seoul Univ., South Korea
Zagreb Univ., Croatia
INFN, Torino, Italy
Osaka Univ., Japan
TUM, Garching, Germany
Kyoto Univ., Japan
Jagiellonian Univ., Poland
RCJ, Juelich, Germany
Santiago de Compostela Univ., Spain
Tohoku Univ., Japan
KIRAMS, Seoul, South Korea

E57 within E15 spectrometer (CDS)



C-degrader:
~ 500 mm

Refrigerator for
target and SDDs



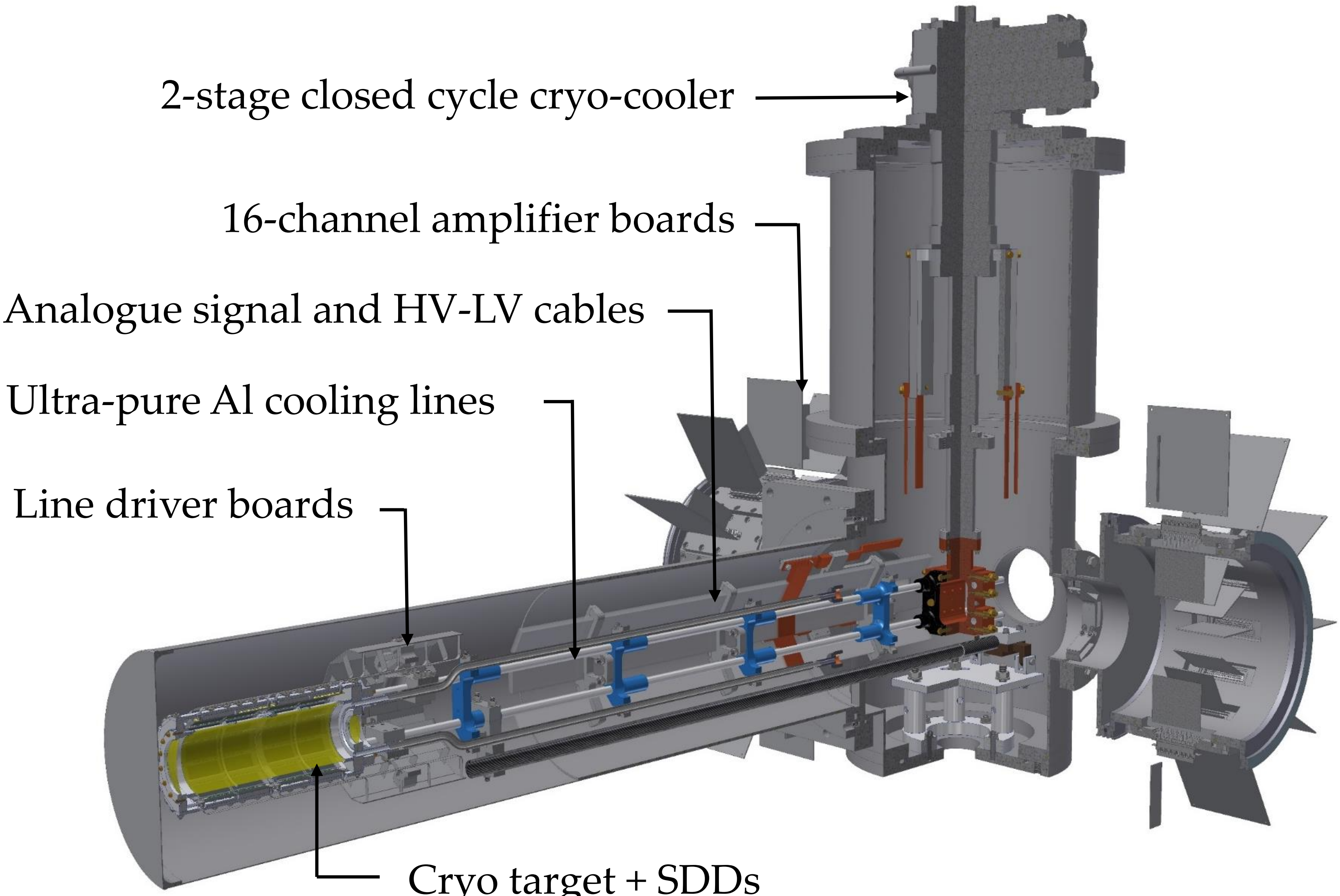
Cryogenic target cell
surrounded by SDDs

Solenoid

Cylindrical drift chamber

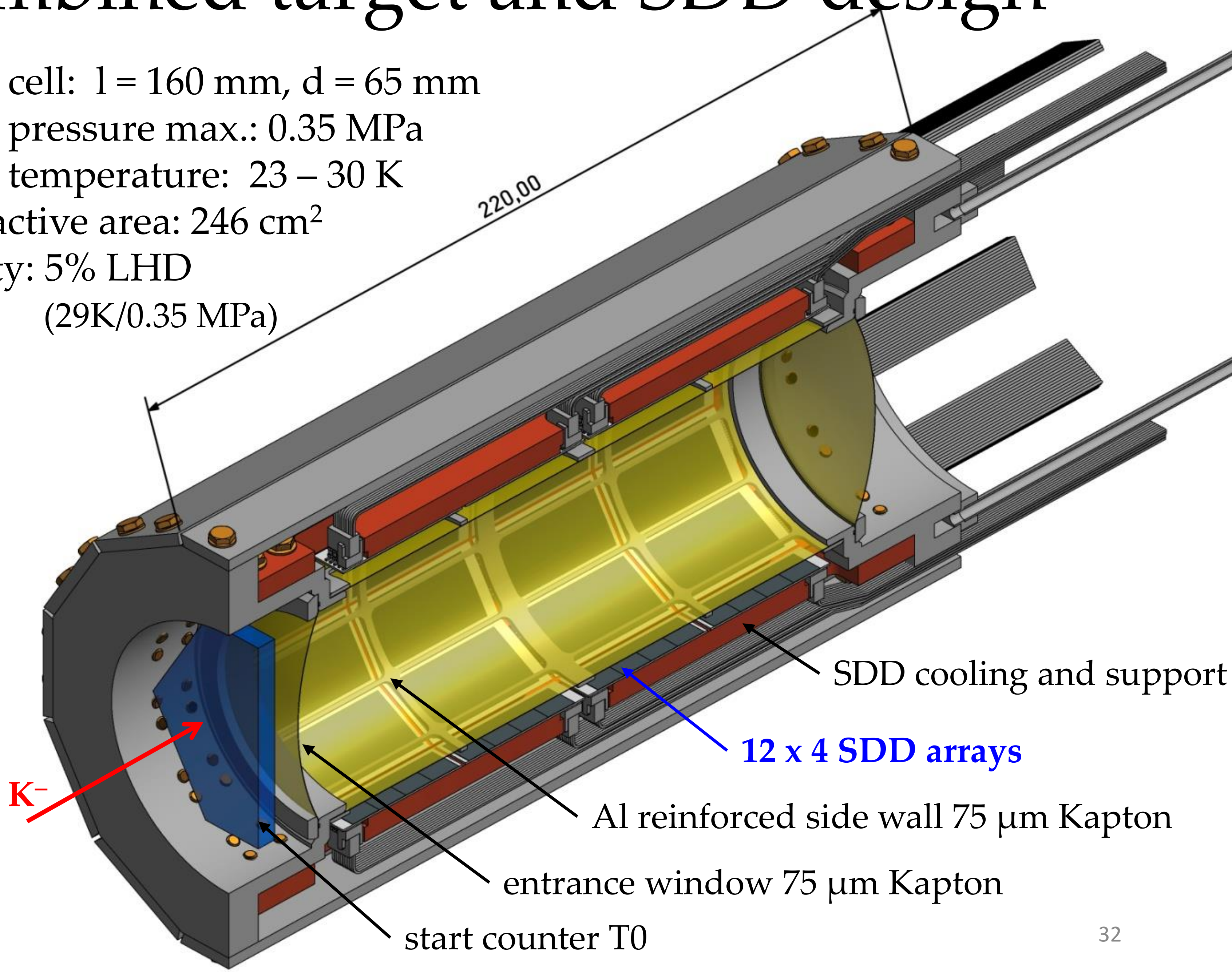
Cylindrical detector hodoscope

K$^-$d cryogenic target and SDD setup



Combined target and SDD design

target cell: l = 160 mm, d = 65 mm
target pressure max.: 0.35 MPa
target temperature: 23 – 30 K
SDD active area: 246 cm^2
density: 5% LHD
(29K/0.35 MPa)



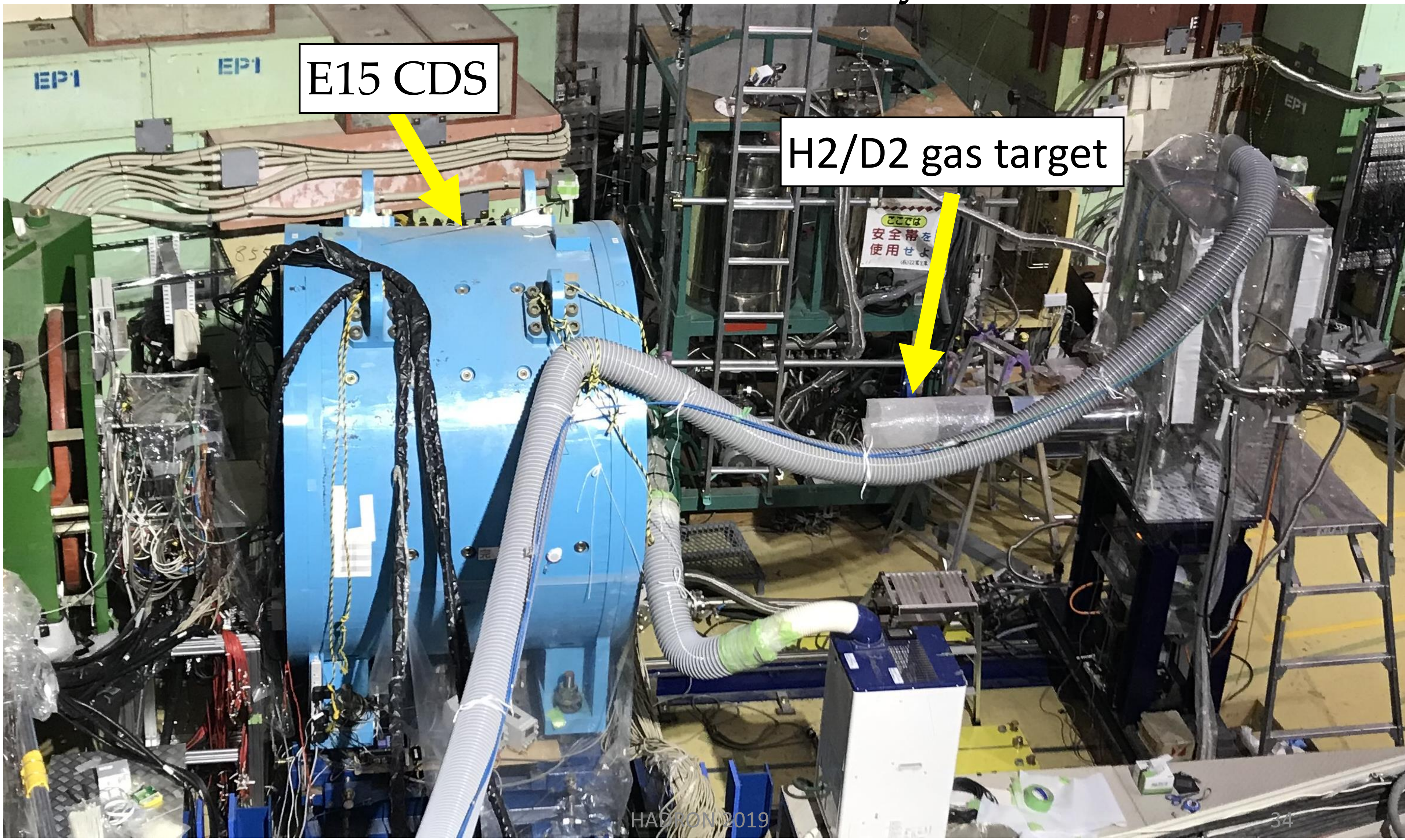
Towards kaonic deuterium

- SIDDHARTA-2 at DAΦNE

- E57 at J-PARC
  - Kaonic hydrogen pilot run

Kaonic hydrogen/helium pilot run

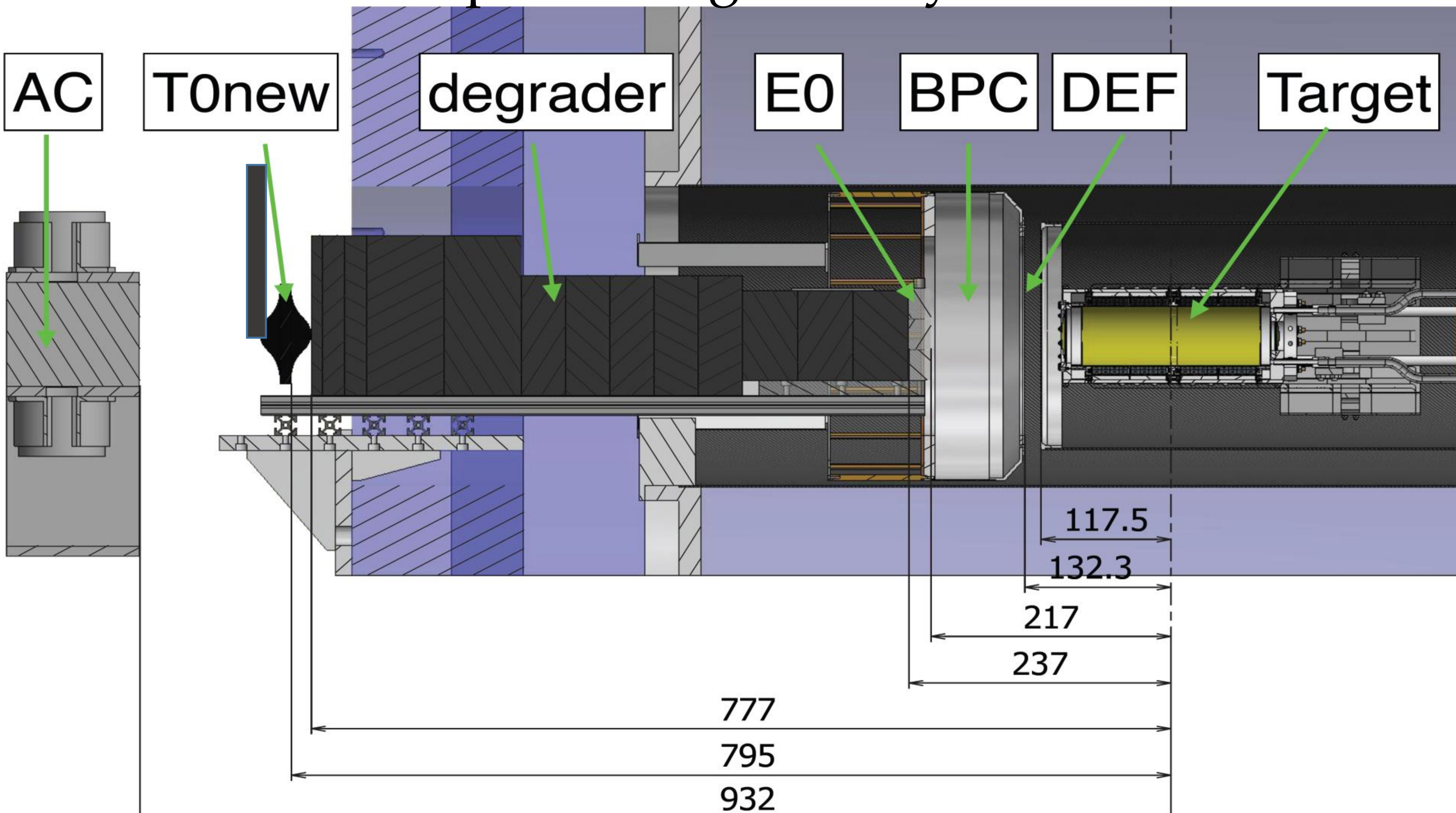
K1.8BR area February 2019



Kaonic hydrogen/helium pilot run

Feb. - April 2019 for a total of 6 days

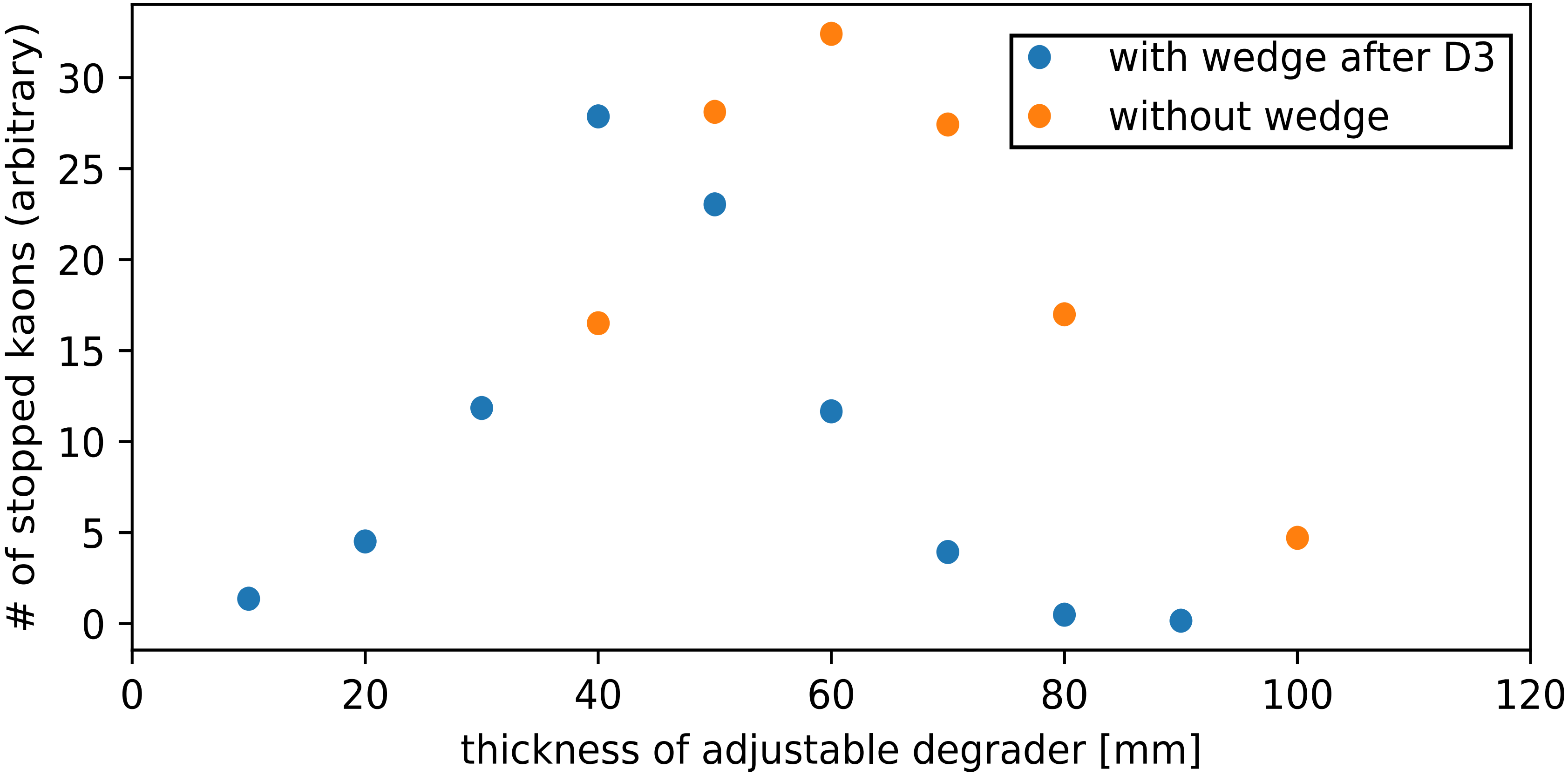
E57 pilot run geometry



Kaonic hydrogen/helium pilot run

Feb. - April 2019 for a total of 6 days

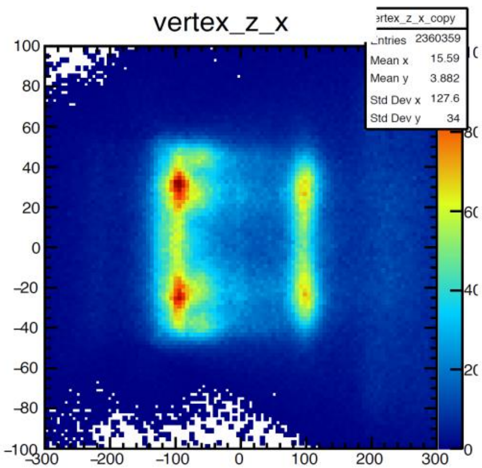
K^+ stopping tune: Range curve
kaon momentum 0.7 GeV/c



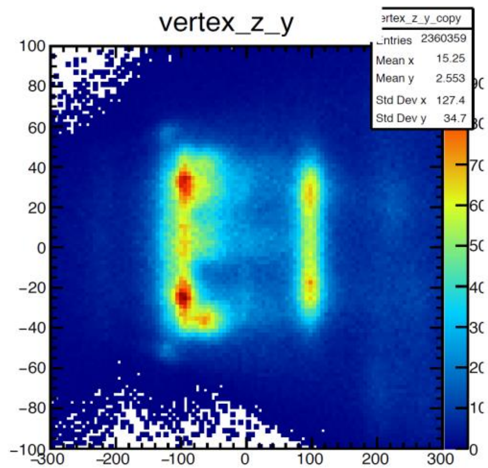
- ➢ successfully optimized kaon stop density

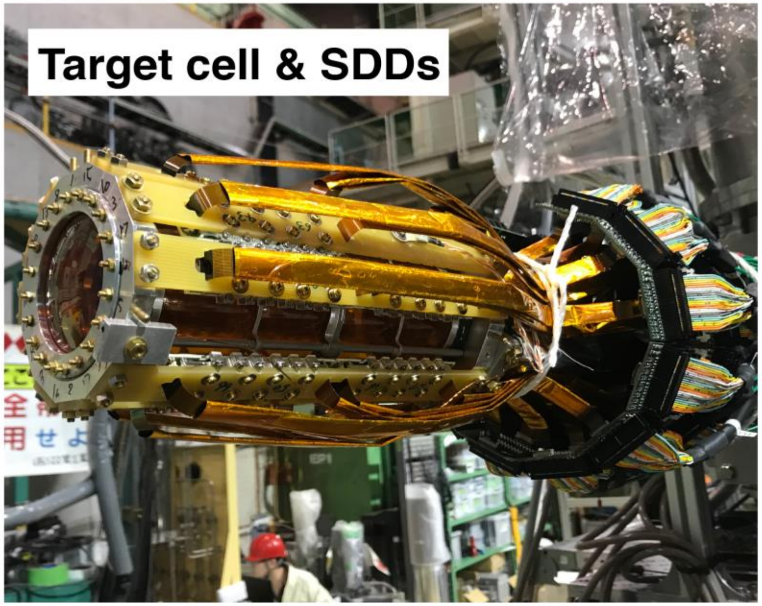
K+ run: Vertex (BPC&CDC)

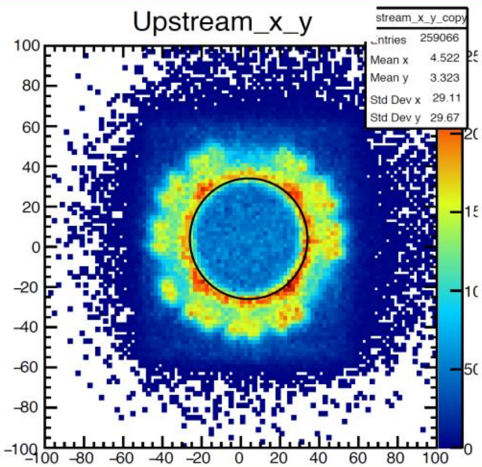
ZX



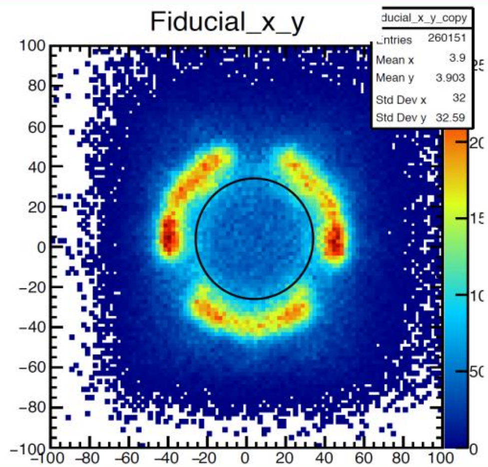
ZY



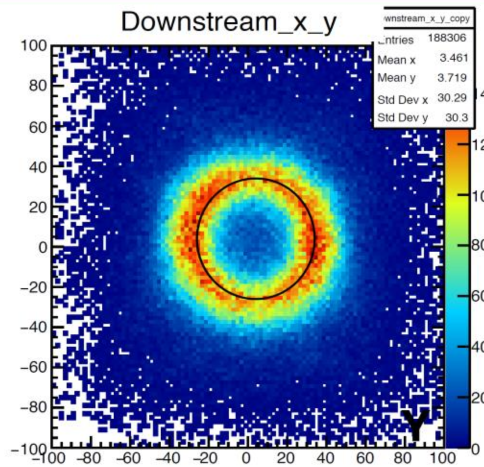




-130<Z<-70



-60<Z<60

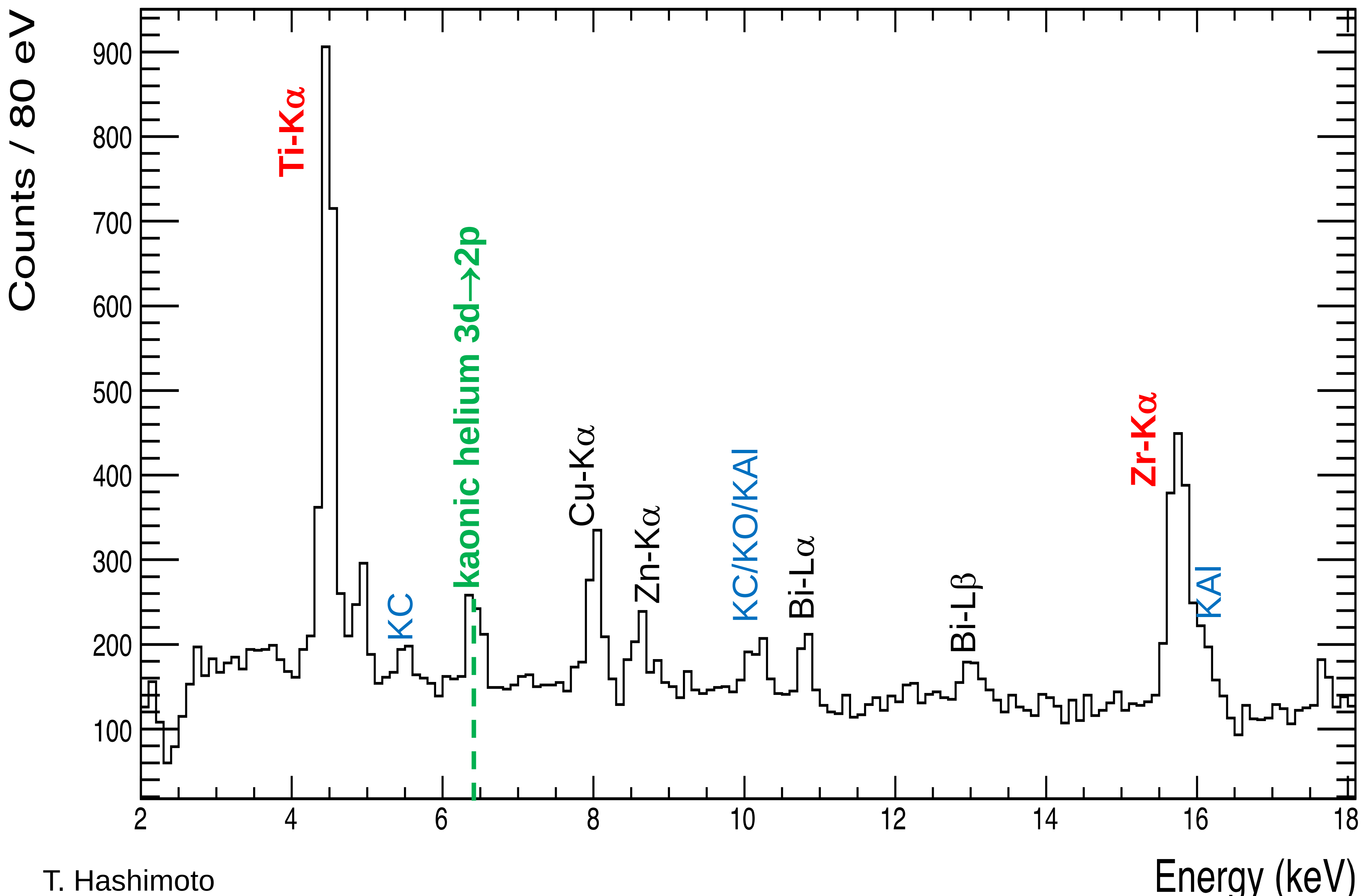


70<Z<130

XY

T. Hashimoto@20190515

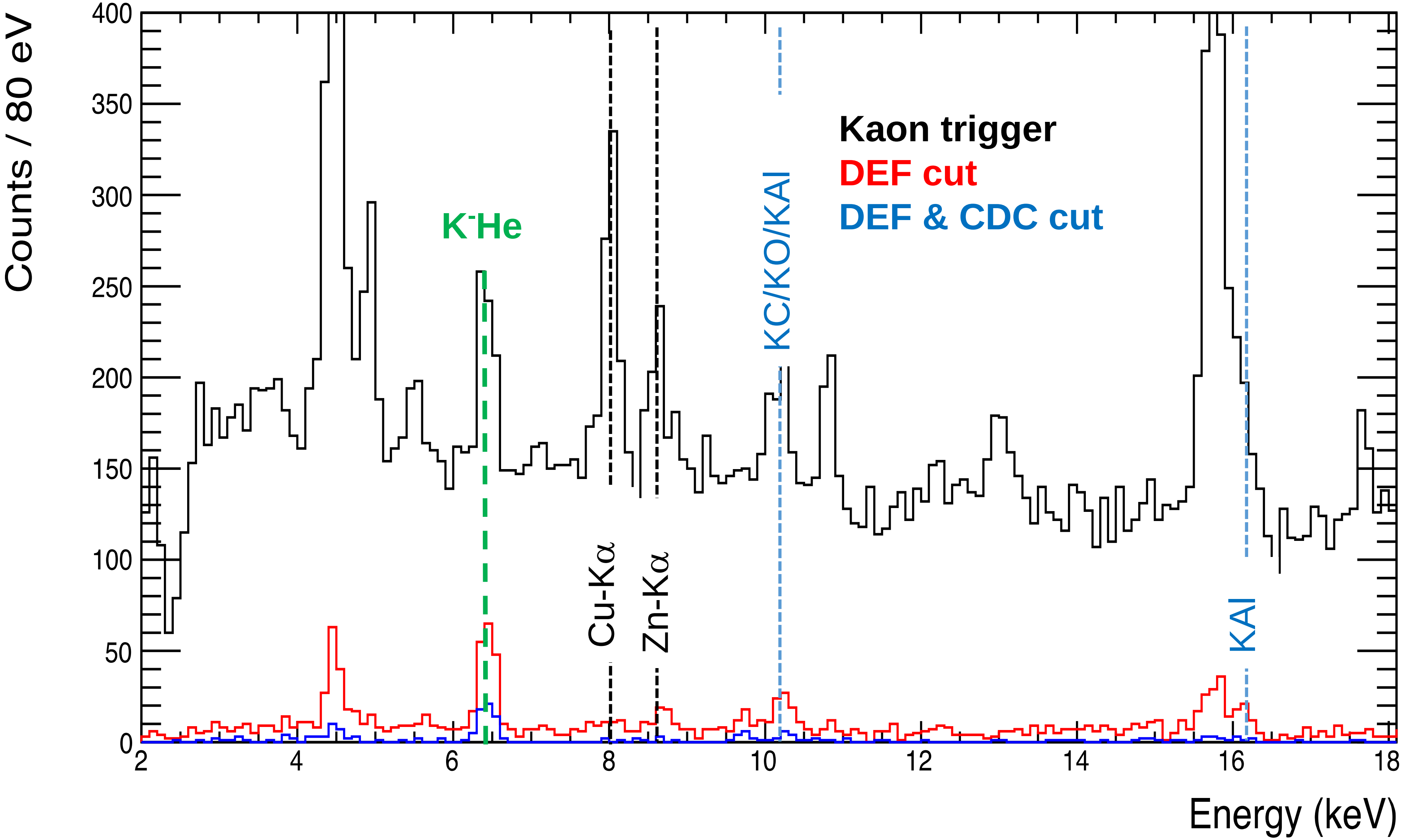
Helium-4, Stopped Kaon trigger



T. Hashimoto

Kaonic Helium-4 spectrum

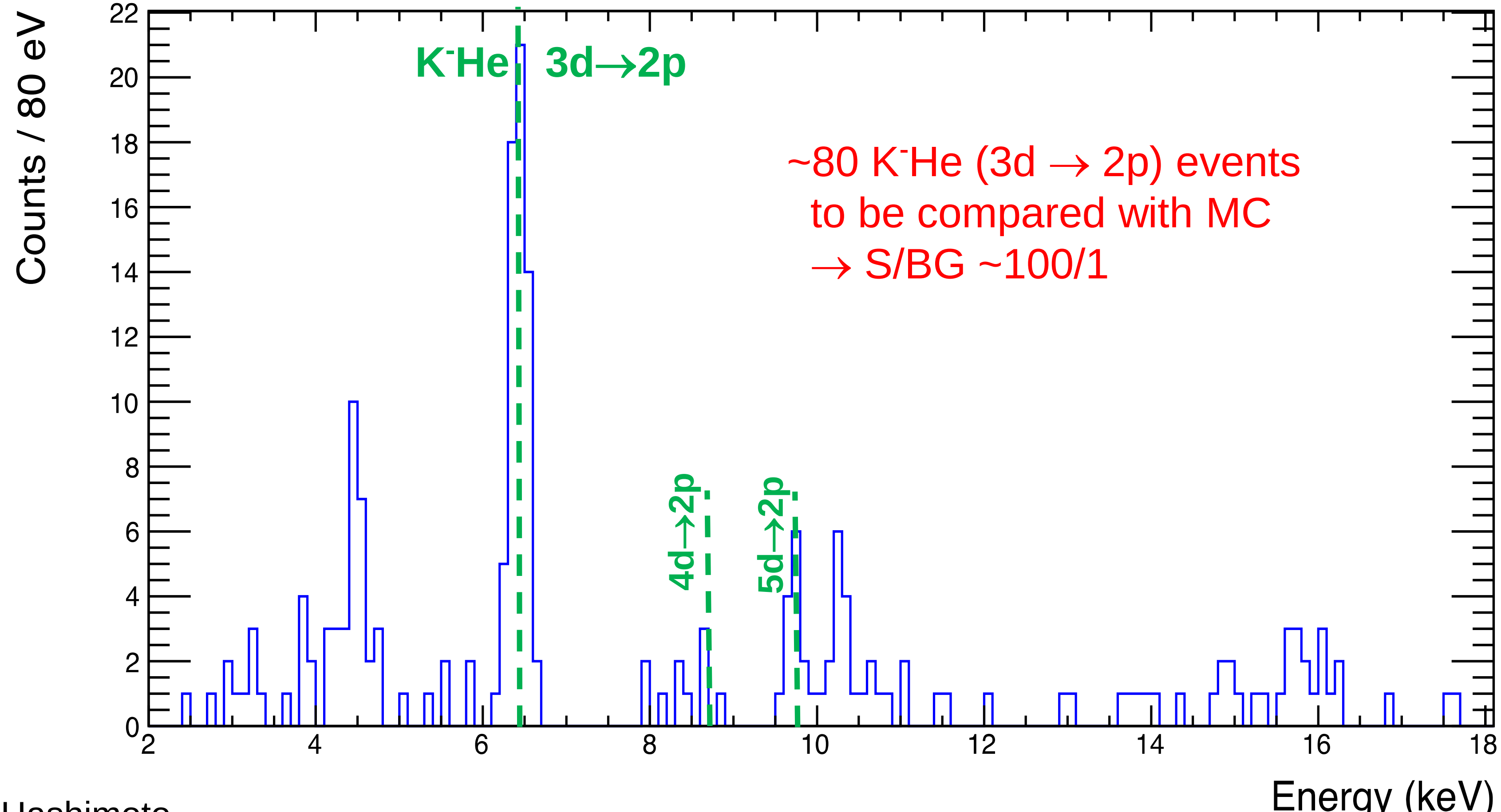
6 hour data taking



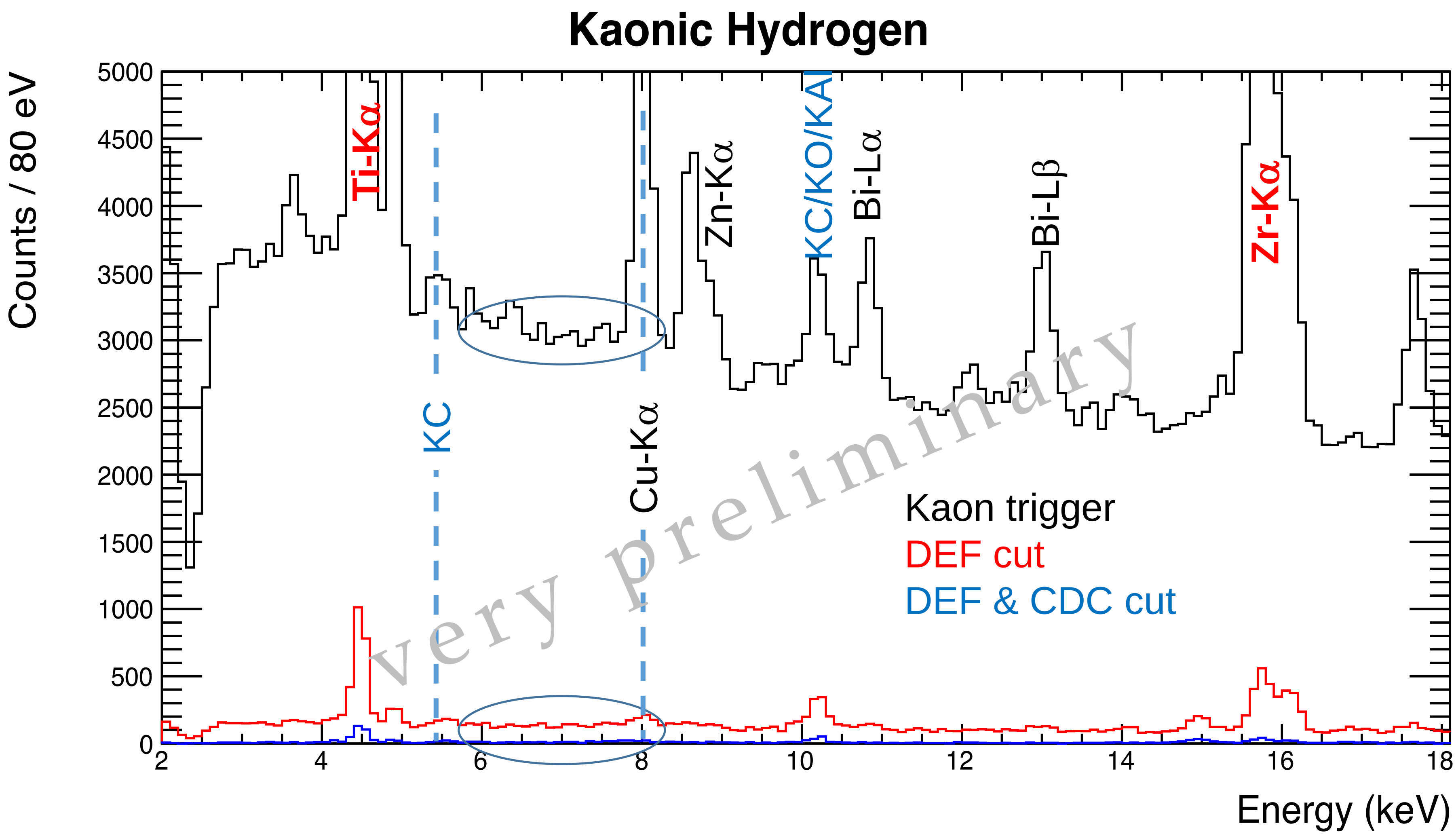
T. Hashimoto

Kaonic Helium-4 spectrum

6 hour data taking

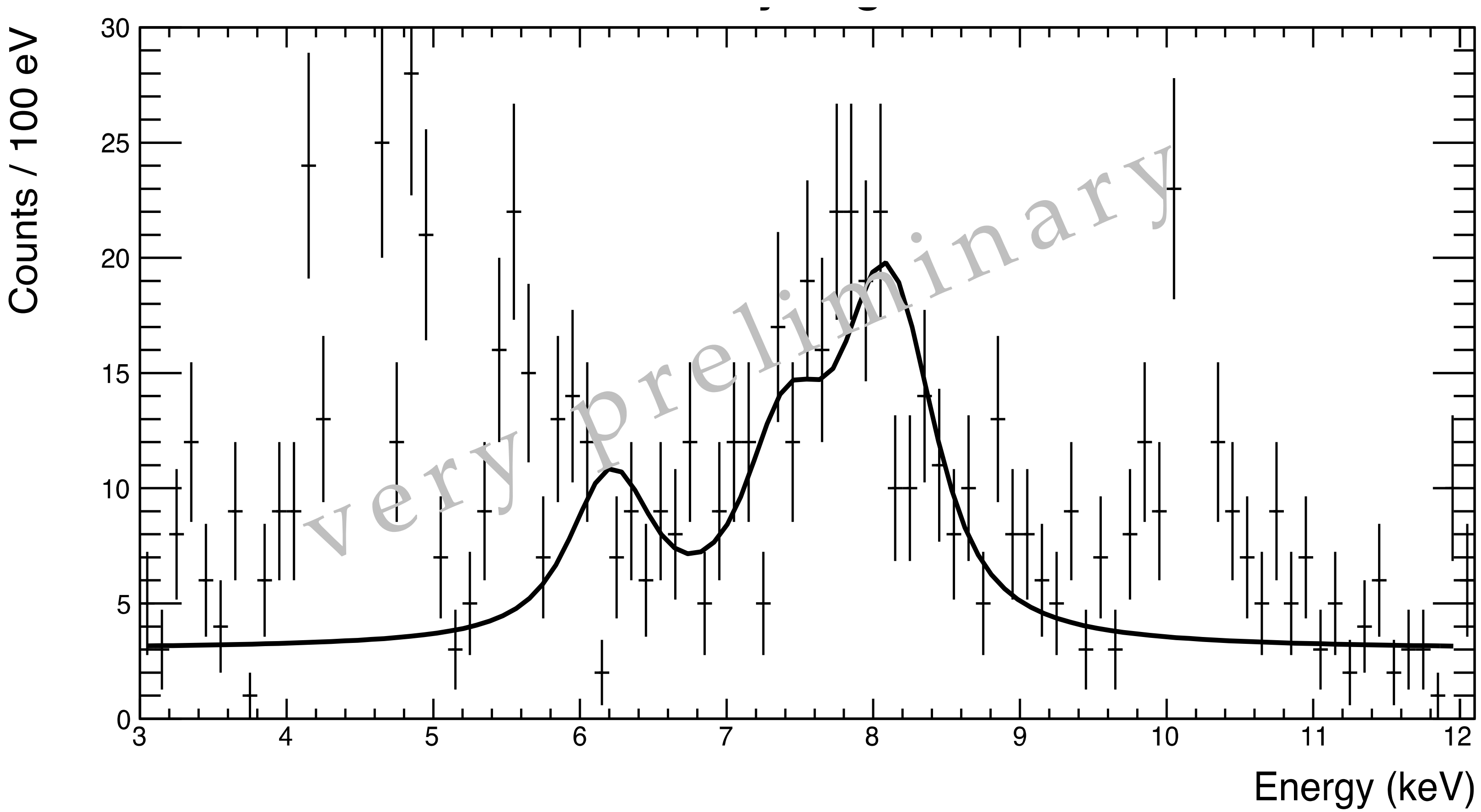


T. Hashimoto


Kaonic Hydrogen
Counts / 80 eV
Energy (keV)
Ti-Kα
KC
Cu-Kα
Zn-Kα
KC/KO/KAl
Bi-Lα
Bi-Lβ
Zr-Kα
Kaon trigger
DEF cut
DEF & CDC cut
very preliminary

Kaonic hydrogen spectrum

90 hour data taking



- Higher X-ray transitions are observed
- Kα events less than expected, analysis ongoing

Summary

- **A first measurement of kaonic deuterium is urgently needed and will be performed at DAΦNE and J-PARC**

  - SIDDHARTA-2
    - Apparatus installed at DAΦNE in April 2019
    - Commissioning until Nov. 2019
    - Data taking planned for 2020

  - E57
    - Kaonic hydrogen/helium pilot run (Feb.-April 2019)
    - Data analysis ongoing, together with improvements on the dedicated MC

For more infos:

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The modern era of light kaonic atom experiments

Rev. Mod. Phys.

Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

Accepted 8 March 2019

ABSTRACT

Thanks for your attention

ABSTRACT

This review article covers the modern era of experimental kaonic atoms studies, encompassing twenty years of activity, defined by breakthroughs in technological developments which allowed performing a series of long-awaited precision measurements. Kaonic atoms are atomic systems where an electron is replaced by a negatively charged kaon, containing the strange quark, which interacts in the lowest orbits with the nucleus also by the strong interaction. As a result, their study offers the unique opportunity to perform experiments equivalent to scattering at vanishing relative energy. This allows to study the strong interaction between the antikaon and the nucleon or the nucleus "at threshold", namely at zero relative energy, without the need of {} extrapolation to zero energy, as in scattering experiments. The fast progress achieved in performing precision light kaonic atoms experiments, which also solved

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