The antikaon deuterium experiment at J-PARC studying strong interaction

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for the E57 Collaboration

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Motivation

- exotic hadronic atoms are bound by the Coulomb force – QED
- e.g. $\pi^+\pi^-$, $\pi^- p$, $\pi^- d$, $K^- p$, $K^- d$, …
- Bohr radii >> as the typical scale of strong interaction
- observable effects of QCD
  - energy shift ε 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

The scientific goal of E57 at J-PARC

To perform a precision measurement of **kaonic deuterium X-ray transitions**

- unique information about QCD in the non-perturbative regime in the strangeness sector, not obtainable otherwise

- **the measurement of kaonic deuterium**
  will allow to extract the antikaon-nucleon isospin dependent scattering lengths
  $\rightarrow$ kaon-neutron scattering

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

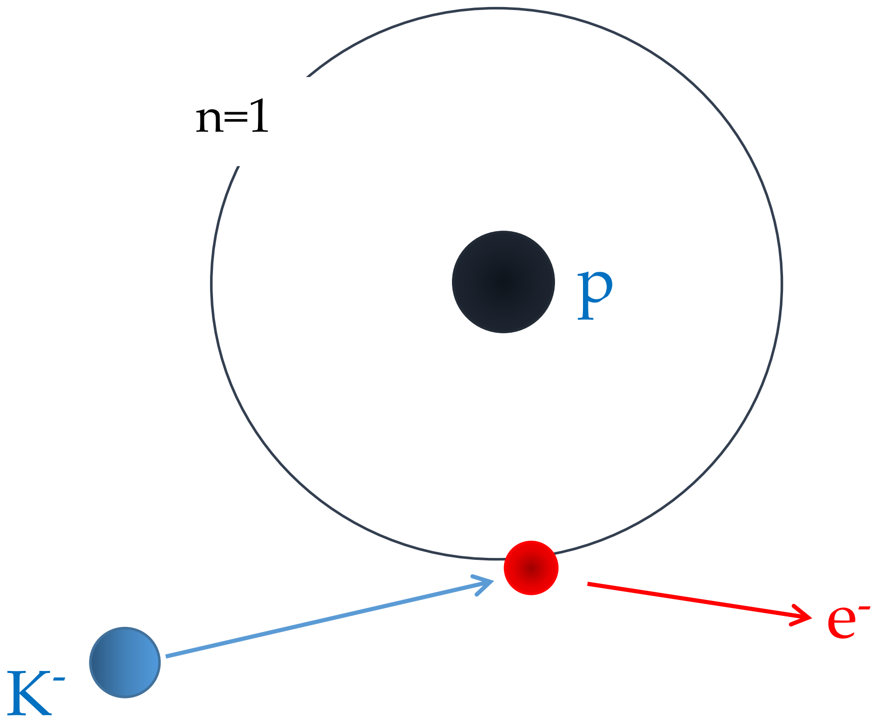
$$a_{K^- n} = a_1$$

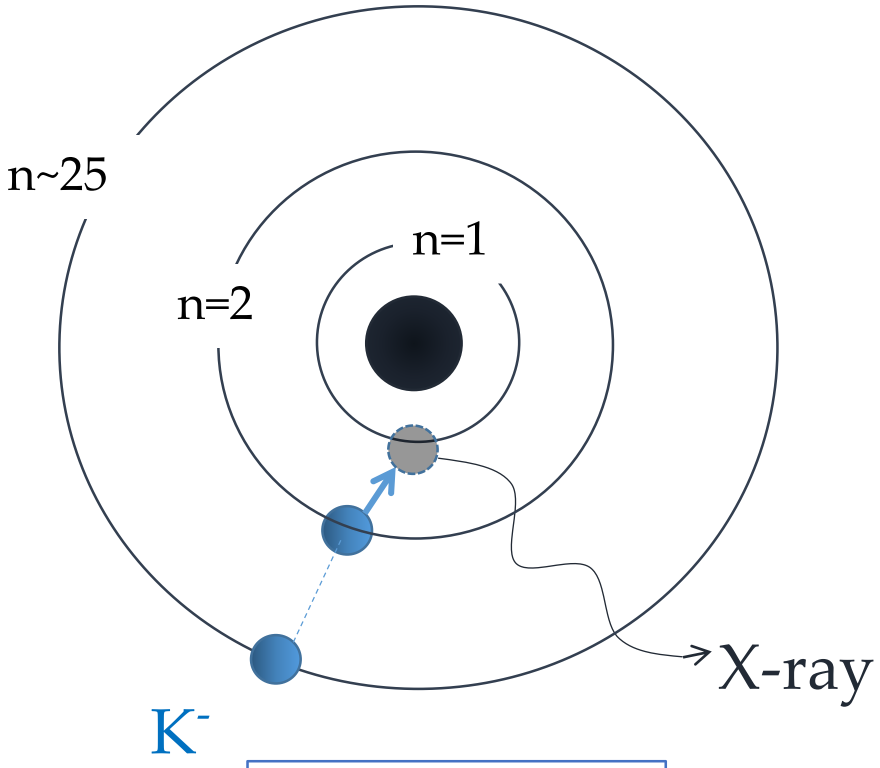
$$a_{K^- d} = \frac{k}{2}\left[a_{K^- p} + a_{K^- n}\right] + C = \frac{k}{4}\left[a_0 + 3a_1\right] + C$$

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

- ❑ chiral symmetry breaking (mass problem)
- ❑ EOS for neutron stars

Forming "exotic" atoms

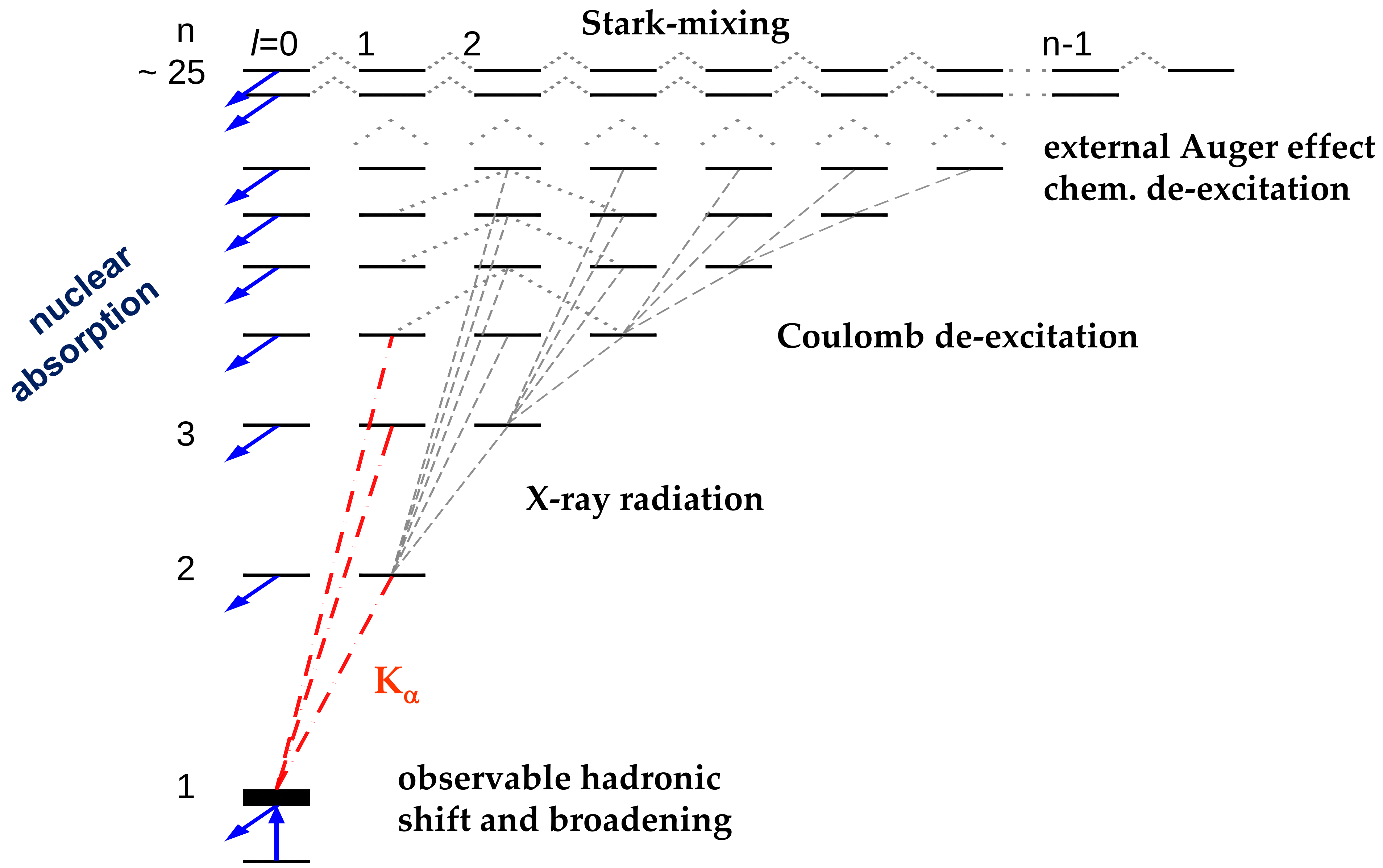




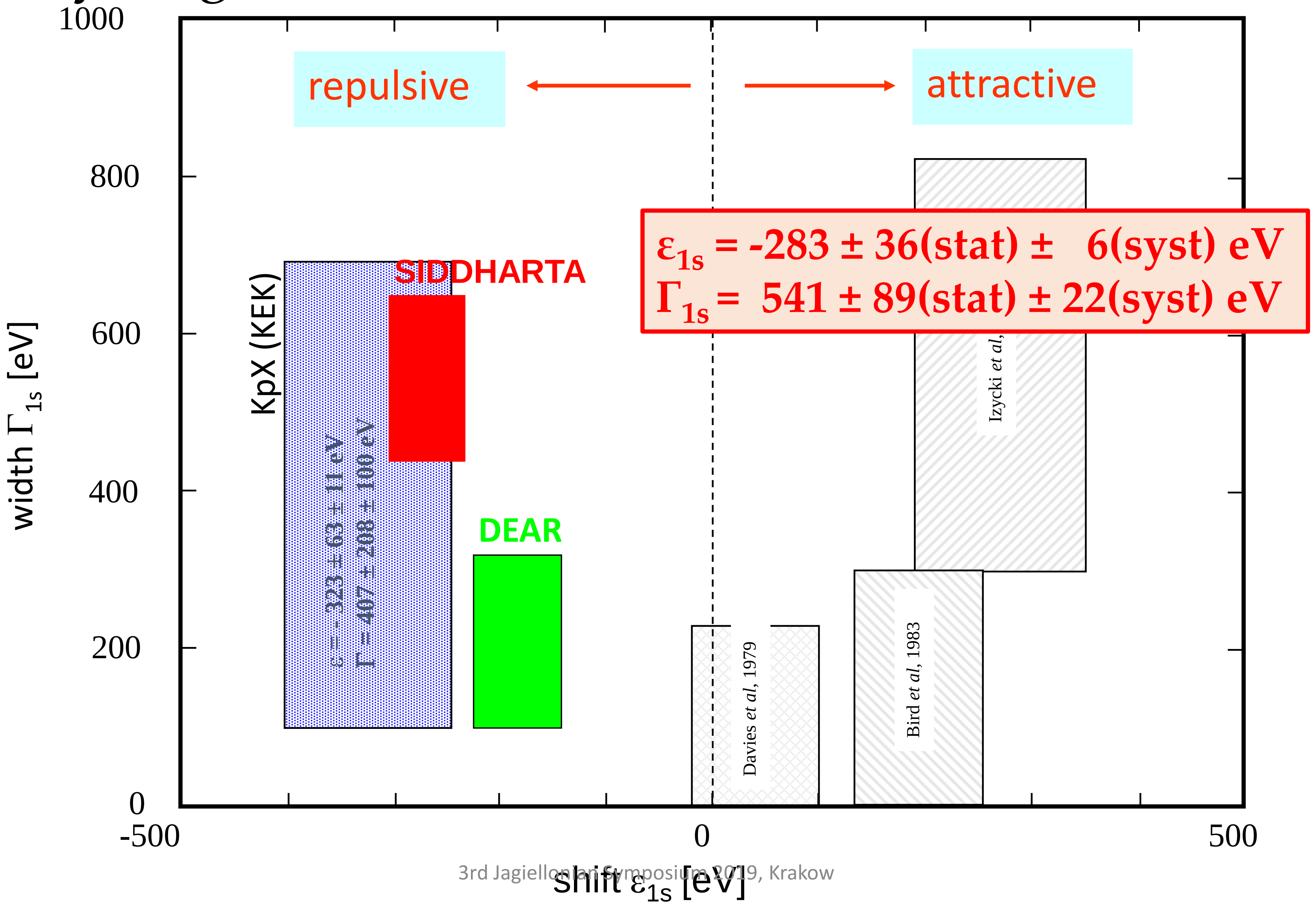
$$n \approx \sqrt{\frac{m_{\mathrm{red}}}{m_e}} \cdot n_e$$

2p → 1s
K_α transition

Cascade Processes



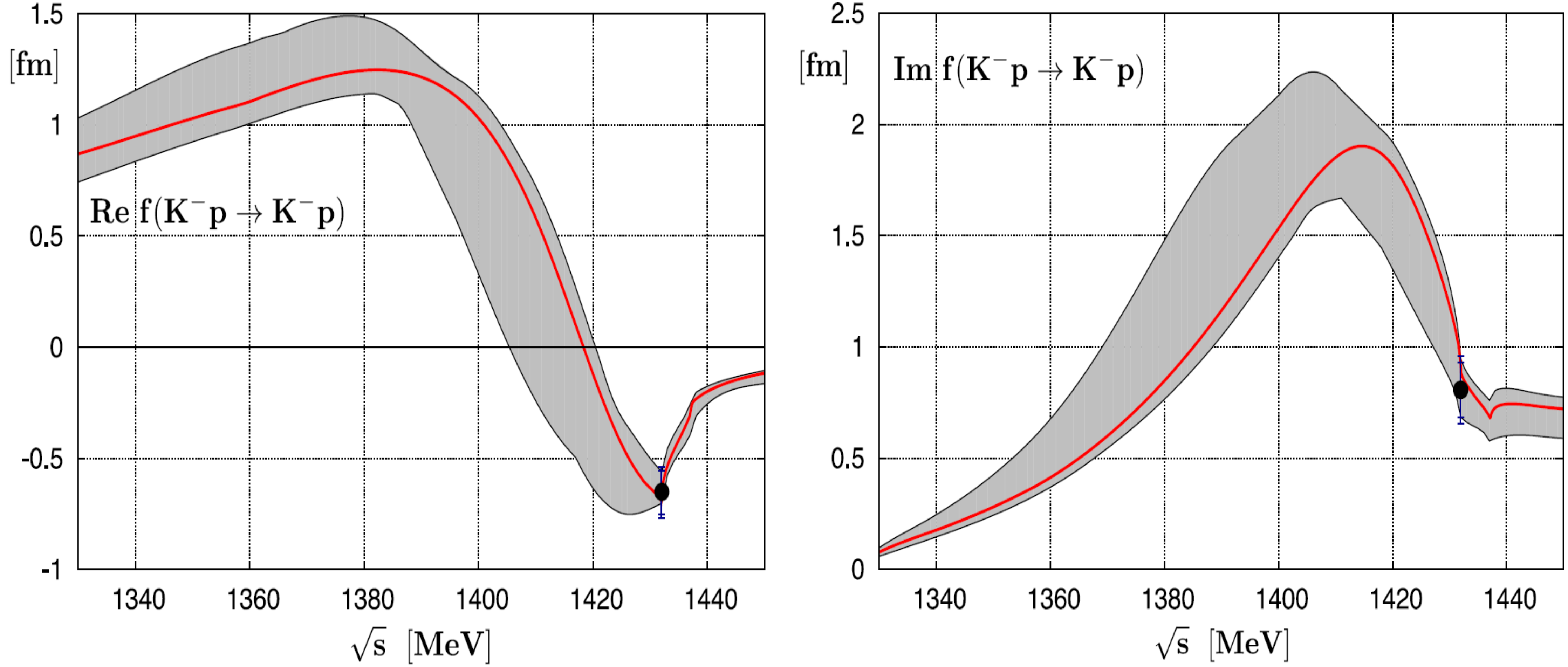
Kaonic hydrogen:



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

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

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



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

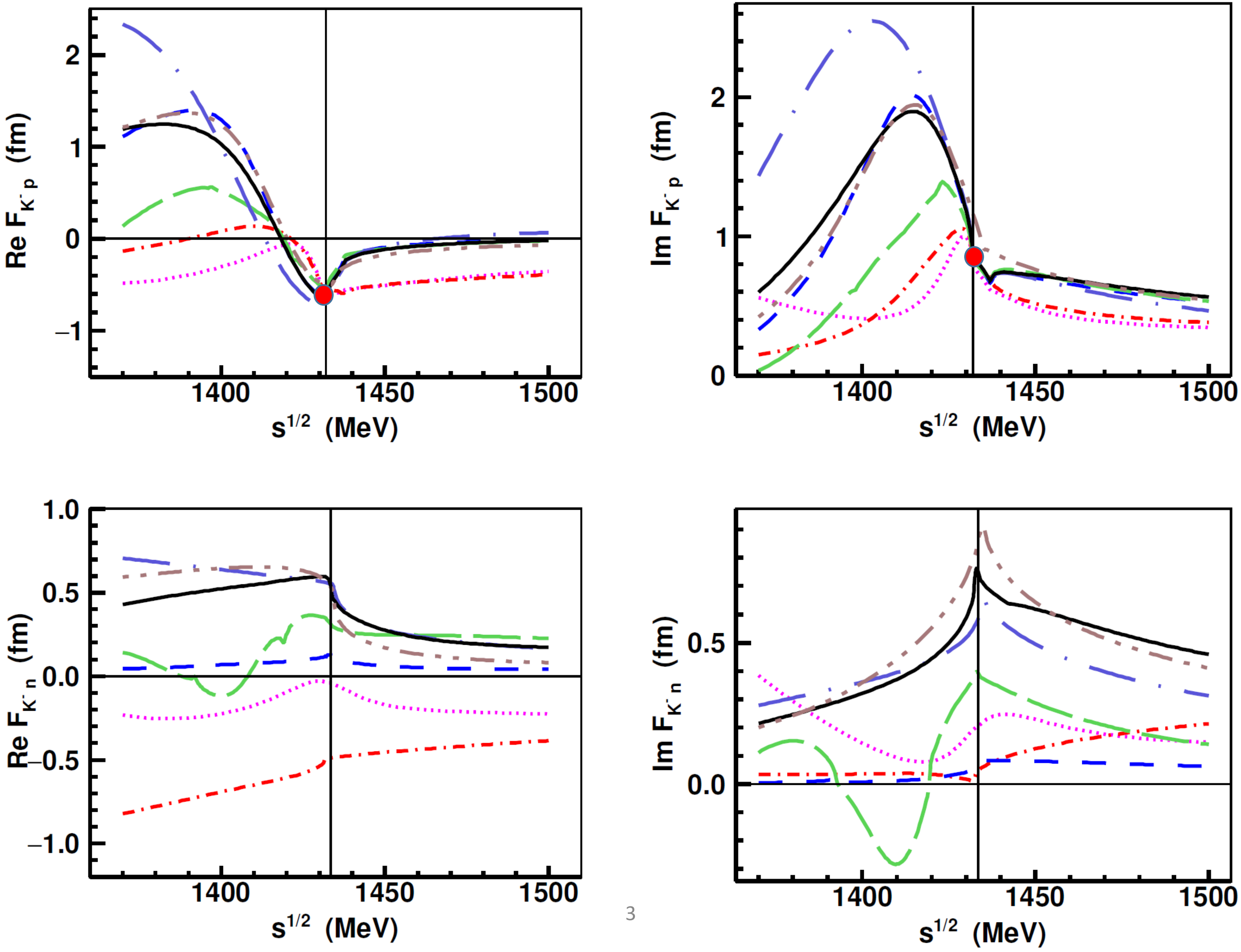
Chirally motivated K^-N approaches

A. Cieplý
MENU 2019

- Kyoto-Munich (KM)
  Y. Ikeda, T. Hyodo, W. Weise, Nucl. Phys. A 881 (2012) 98
- Murcia (M_I, M_{II})
  Z. H. Guo, J. A. Oller, Phys. Rev. C 87 (2013) 035202
- Bonn (B_2, B_4)
  M. Mai, U.-G. Meißner - Eur. Phys. J. A 51 (2015) 30
- Prague (P)
  A. C., J. Smejkal, Nucl. Phys. A 881 (2012) 115
- Barcelona (BCN)
  A. Feijoo, V. Magas, À. Ramos, Phys. Rev. C 99 (2019) 035211

Model parameters (couplings, inverse interaction ranges or subtraction constants) fixed in fits to low energy K^-p data (and more in some cases).

Comparative analysis of the first four approaches presented in
A. C., M. Mai, U.-G. Meißner, J. Smejkal - Nucl. Phys. A 954 (2016) 17



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Kyoto-Munich (KM)

KM.. solid black

Murcia (M_I , M_{II})

M_I ..dashed blue

M_{II}..dashed green

Bonn (B2, B4)

B_2..dotted purple

B_4..dot-dashed red

Prague (P)

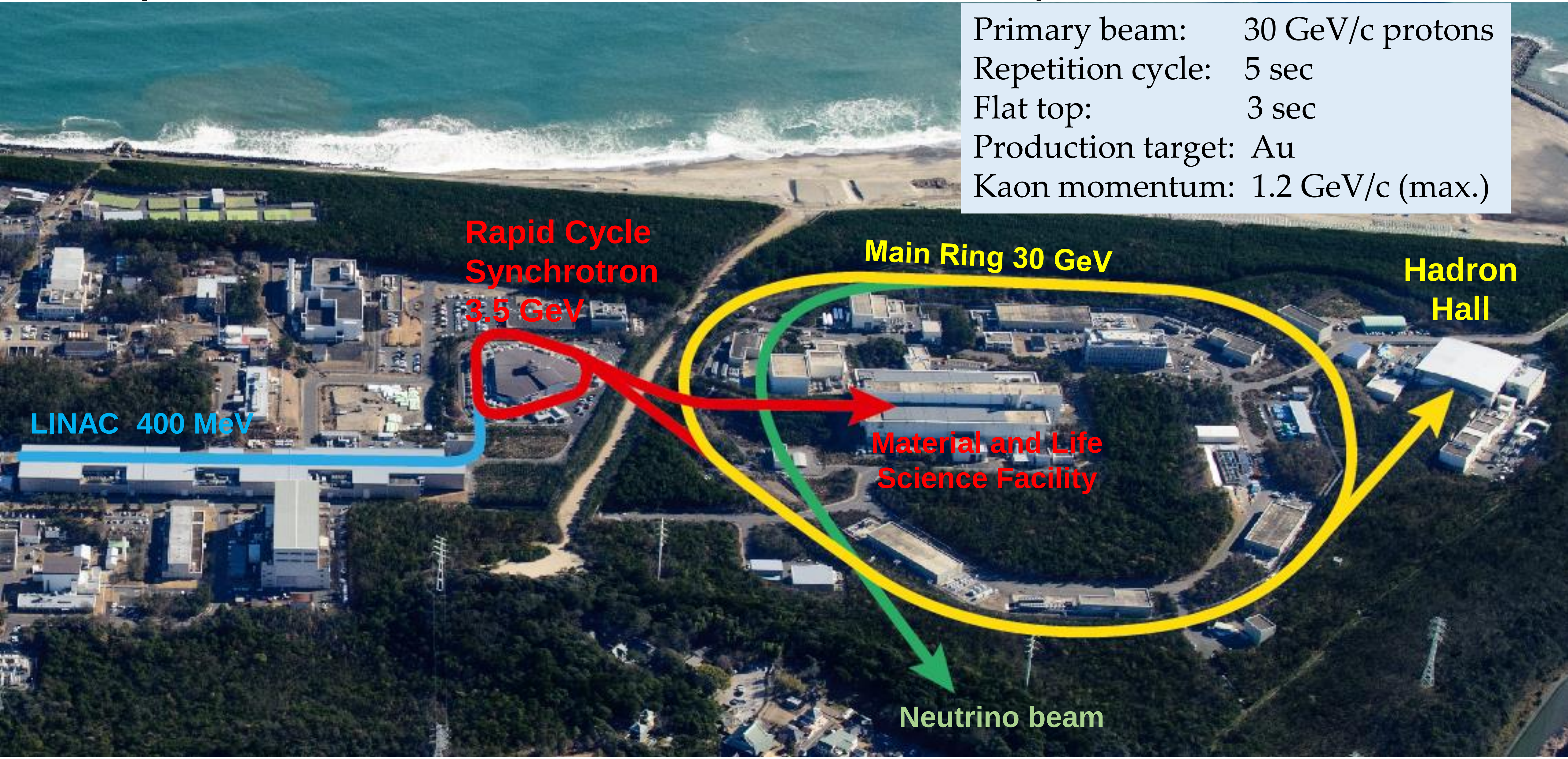
P…dot-long dashed blue

Barcelona (BCN)

BCN..dot-dot-dashed brown

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.)



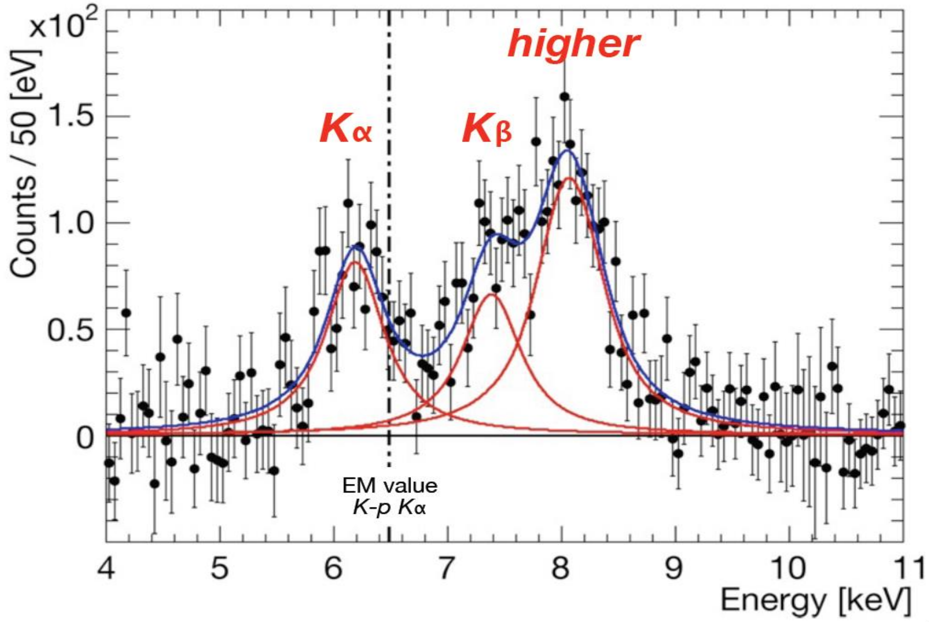
J-PARC
K–d collaboration

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

Experimental challenge towards a K^-d measurement

- X-ray yield: K^-p ~ 1 %
  K^-d ~ 0.1 %
- 1s state width: K^-p ~ 540 eV
  K^-d ~ 800 – 1000 eV

Kaonic hydrogen - SIDDHARTA

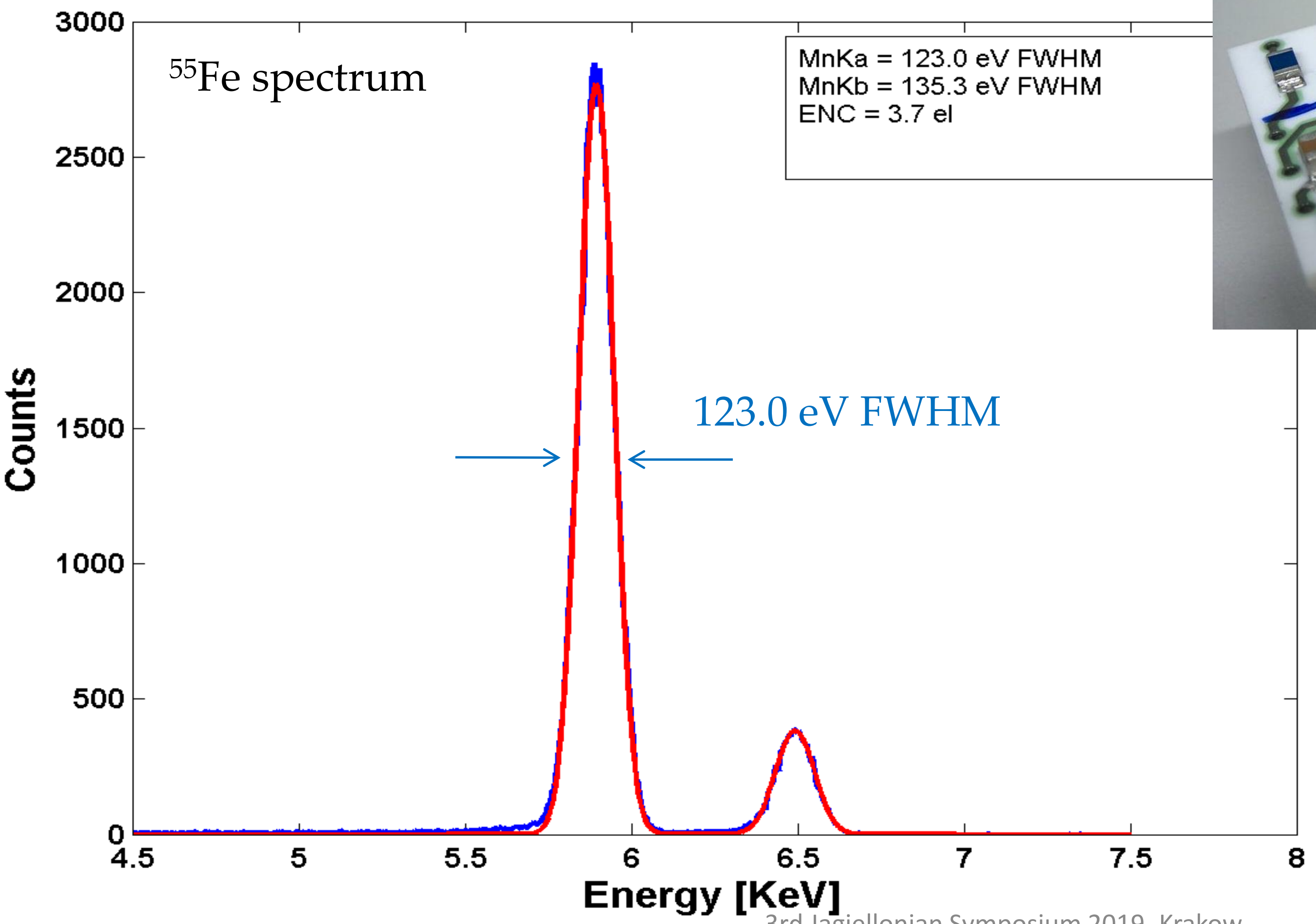


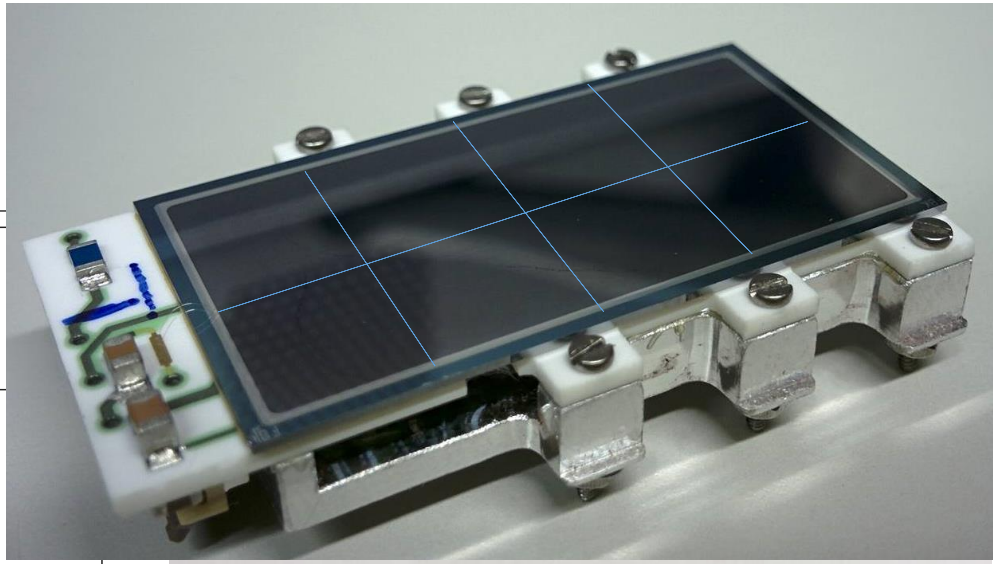
BG sources: asynchronous BG → timing
synchronous BG → spatial correlation

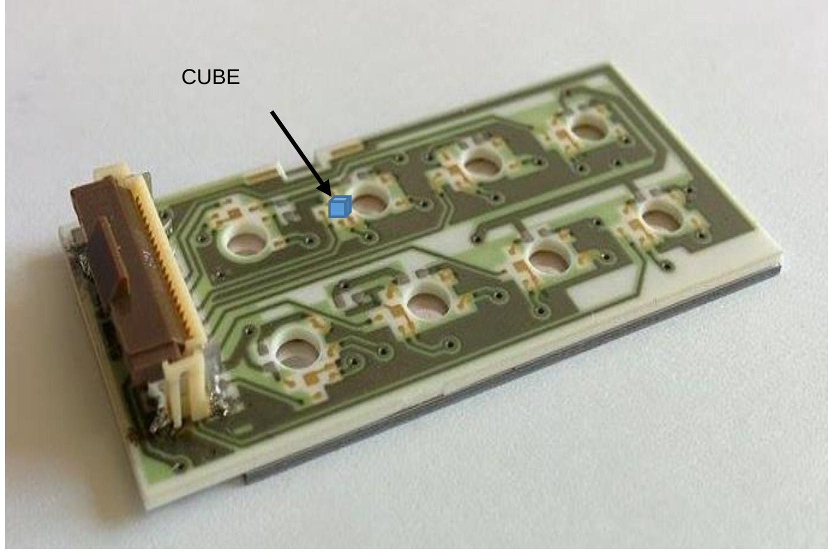
- ➢ X-ray detector system
- ➢ Lightweight cryogenic target
- ➢ Charged particle veto

SIDDHART-2 new X-ray detector

New SDD technology with
CUBE preamplifier

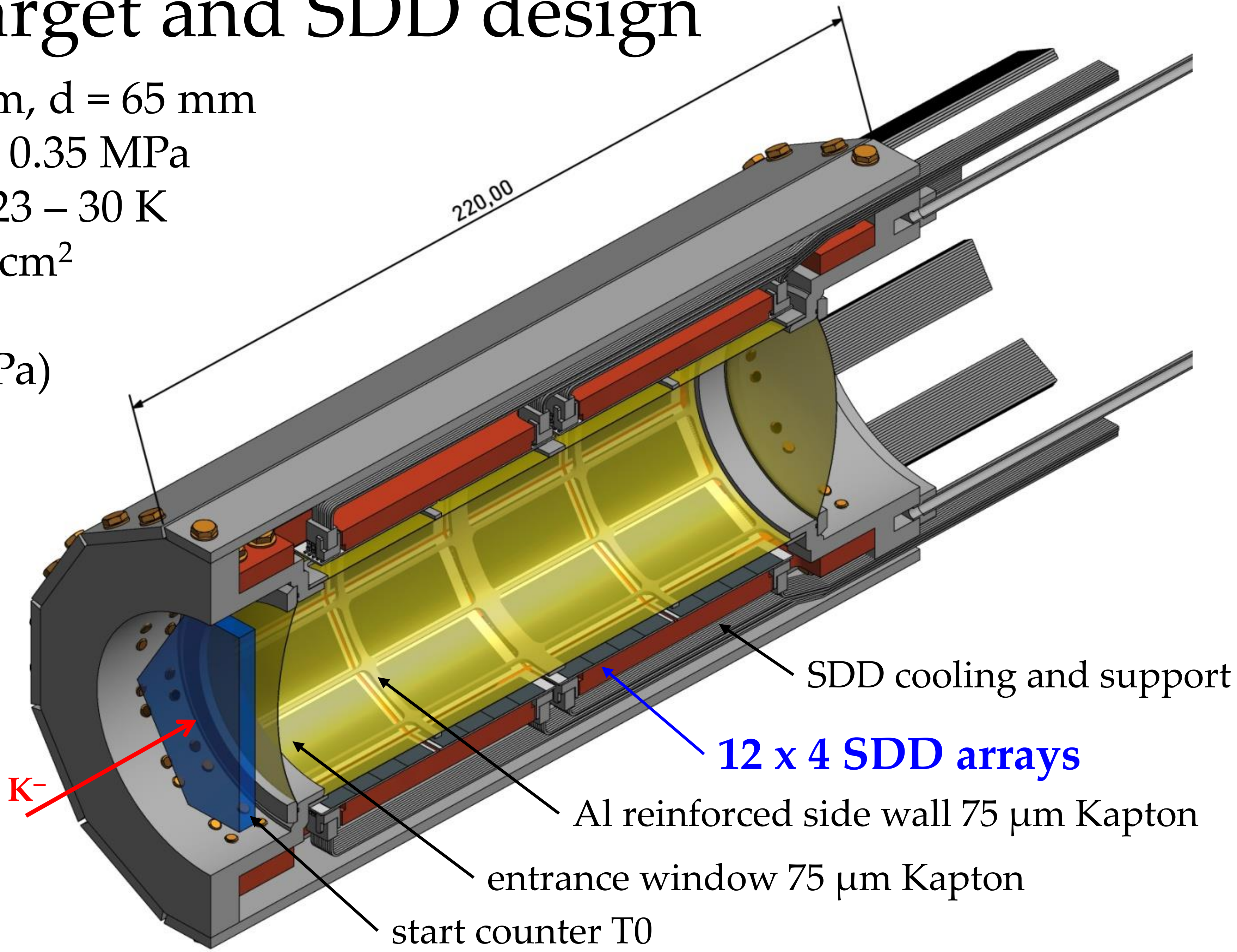




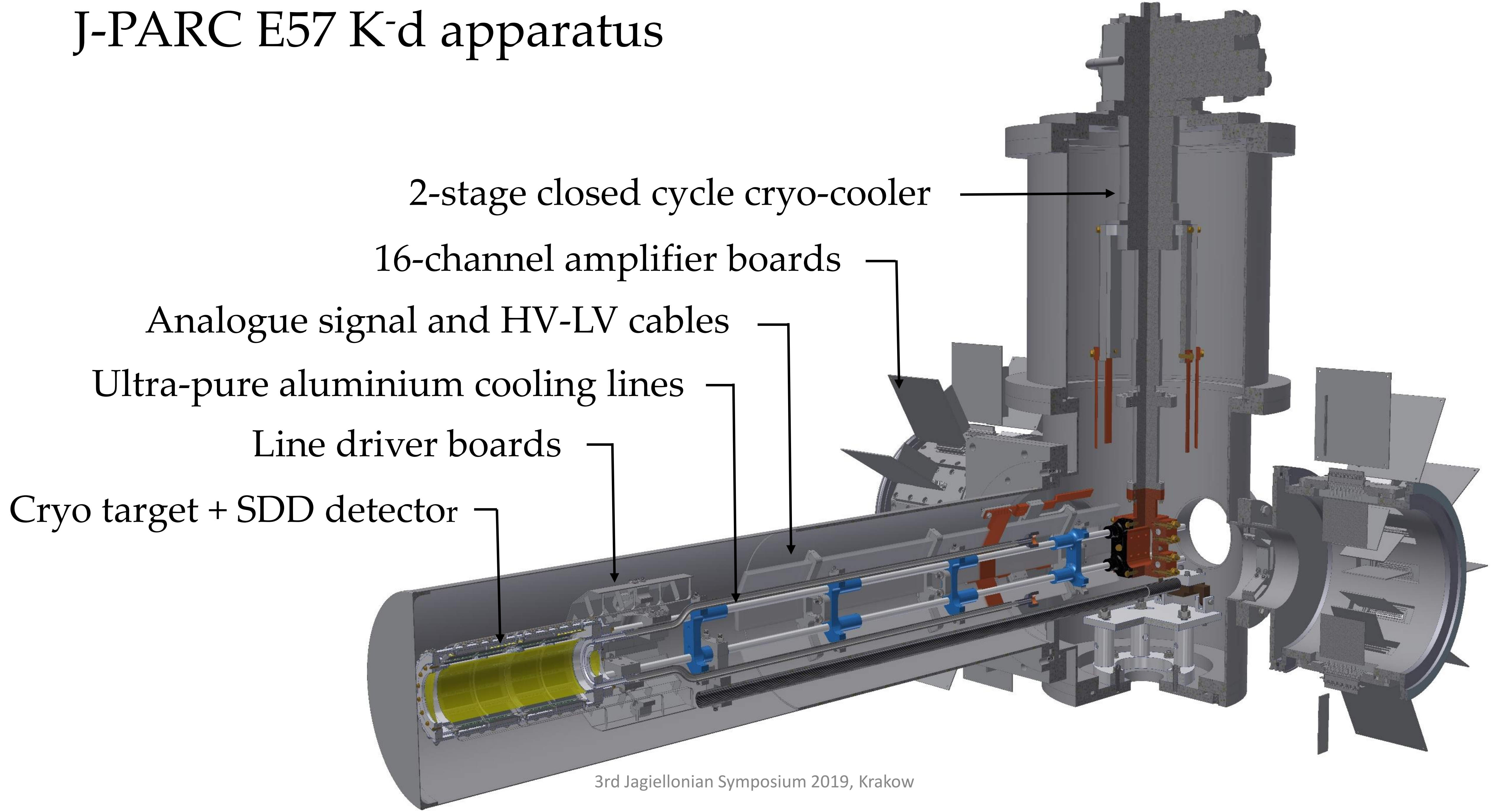


Combined target and SDD design

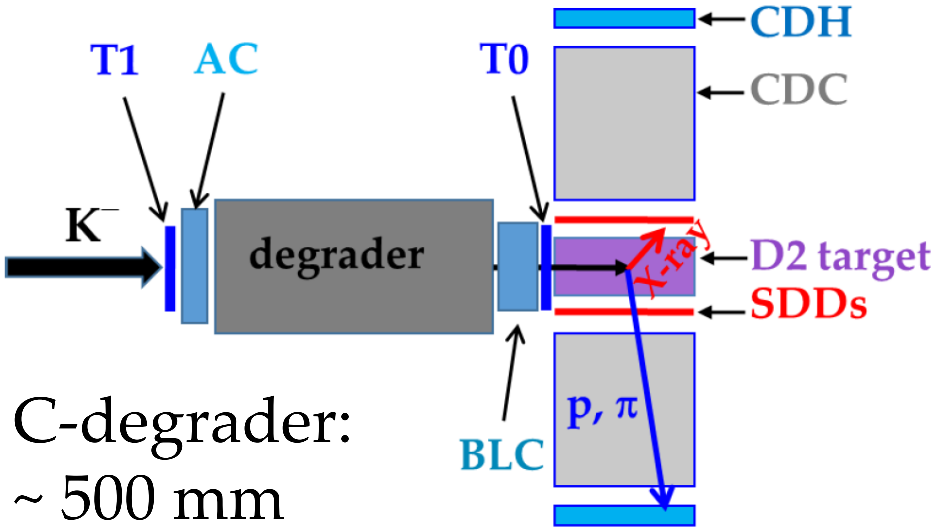
target cell: l = 160 mm, d = 65 mm
target pressure max.: 0.35 MPa
target temperature: 23 – 30 K
SDD active area: 246 cm^2
density: 5% LHD
(29K/0.35 MPa)



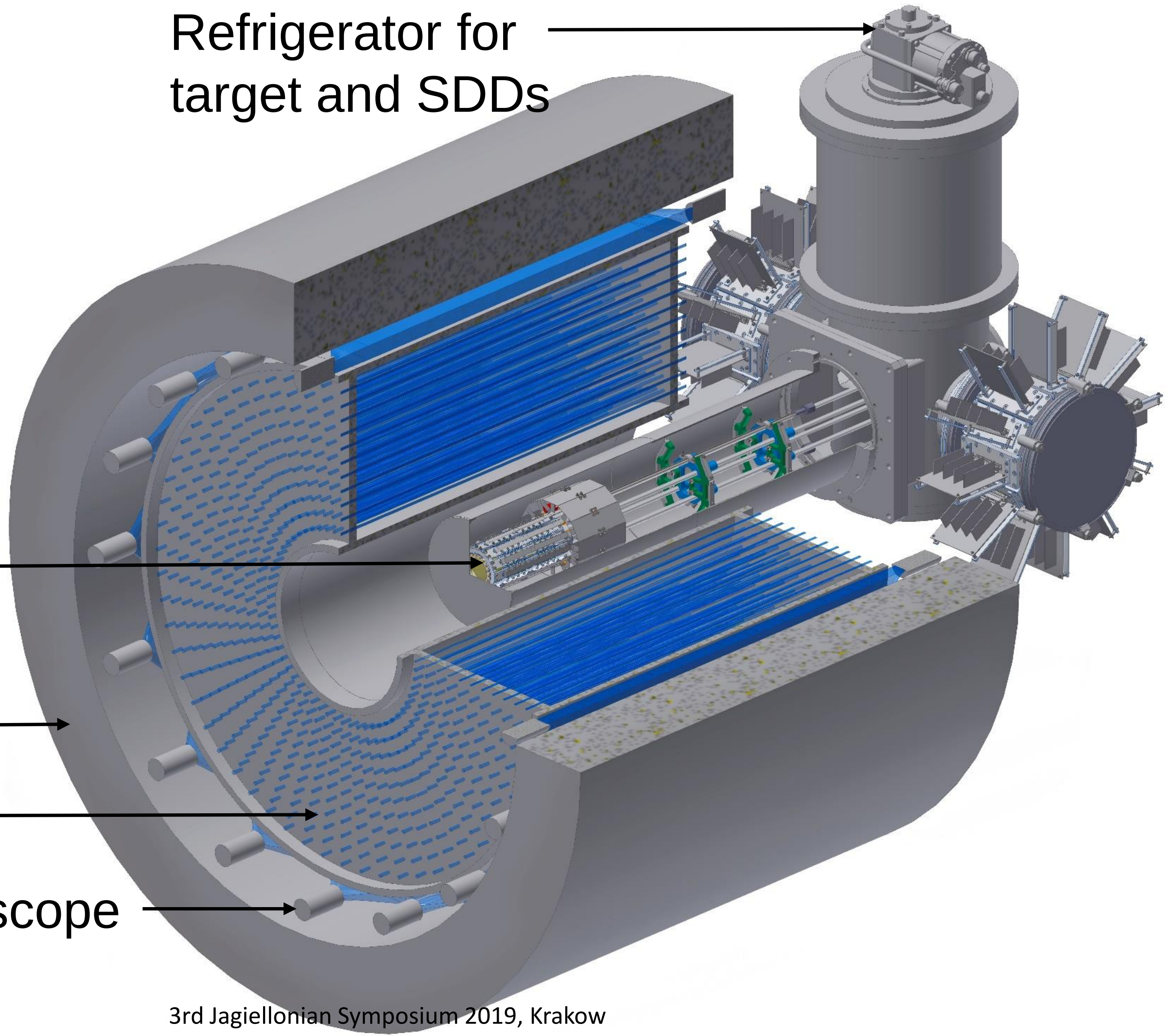
J-PARC E57 K^-d apparatus



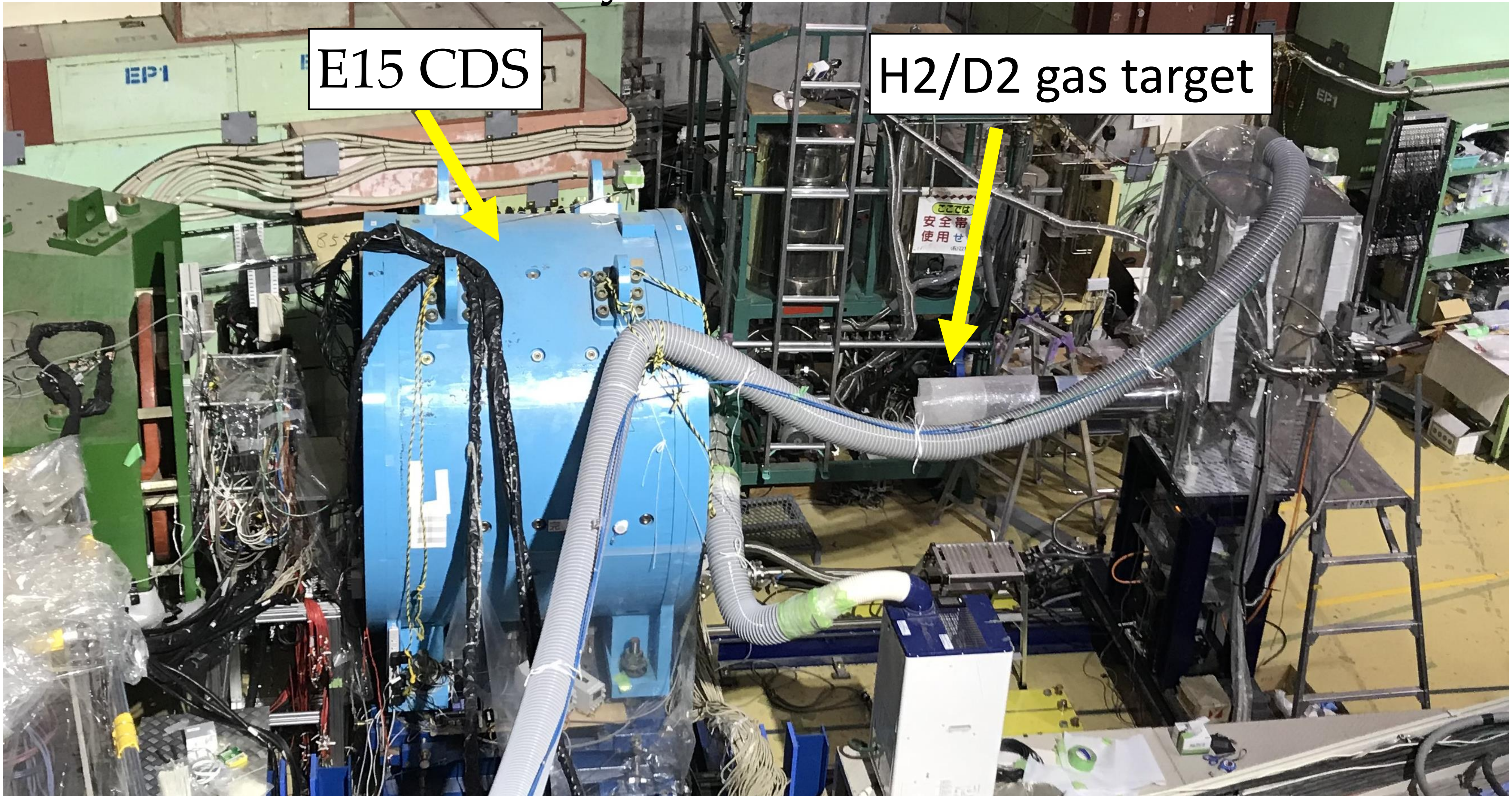
E57 within E15 spectrometer (CDS)



C-degrader:
~ 500 mm

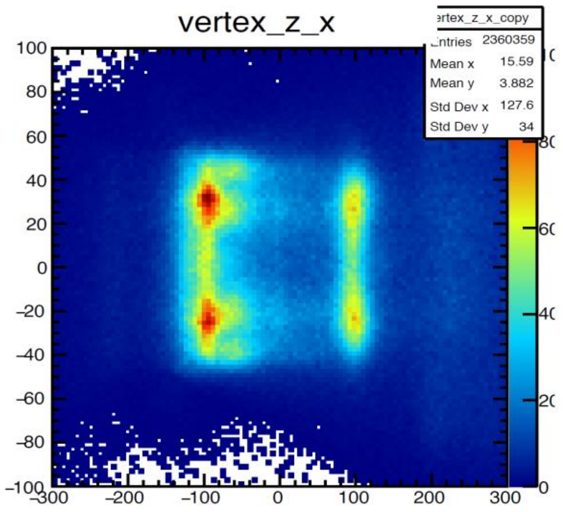


K1.8BR area February 2019

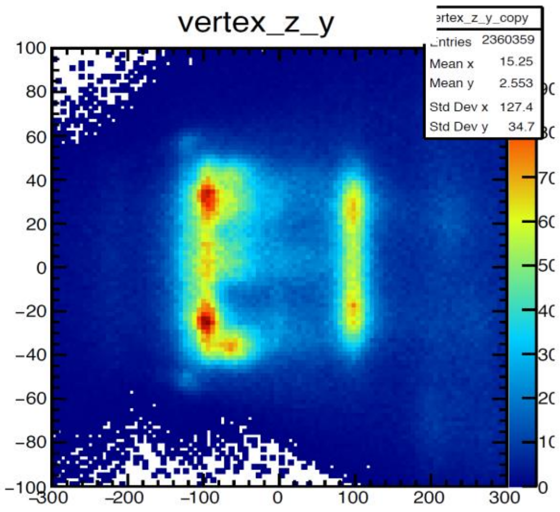


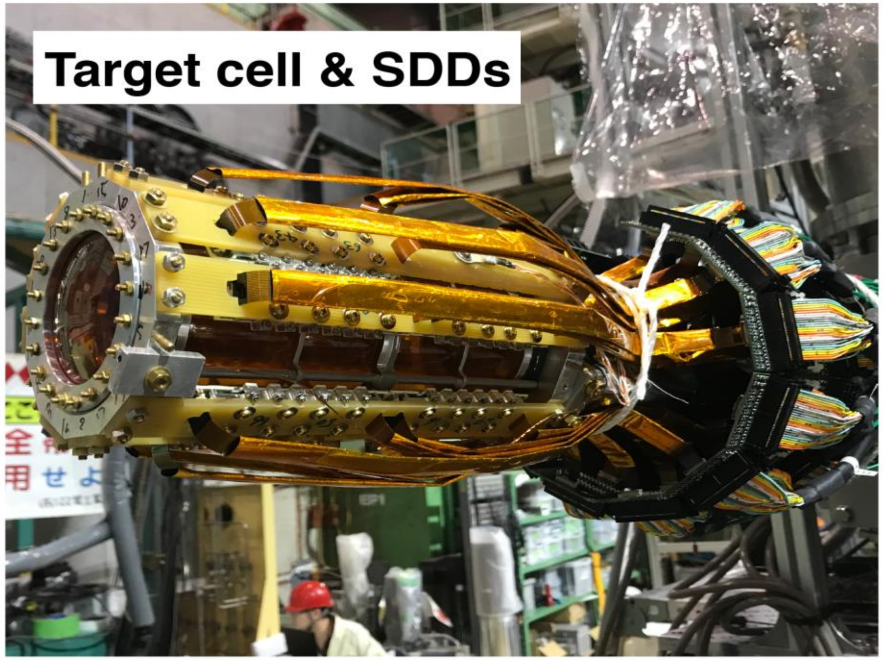
K+ run: Vertex (BPC&CDC)

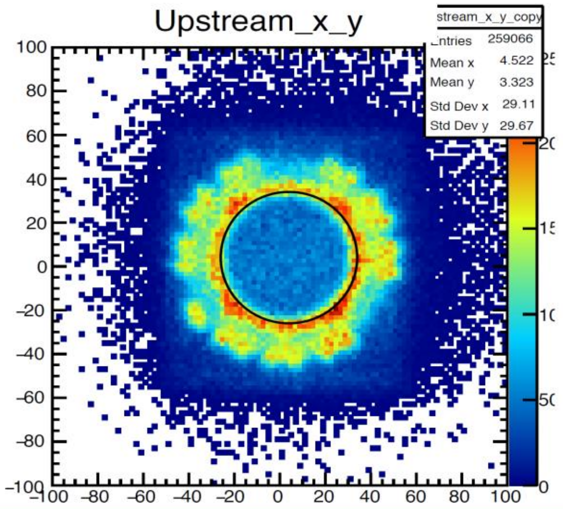
ZX



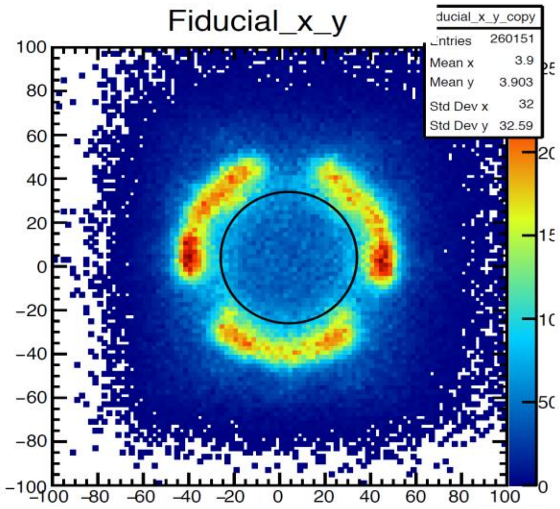
ZY



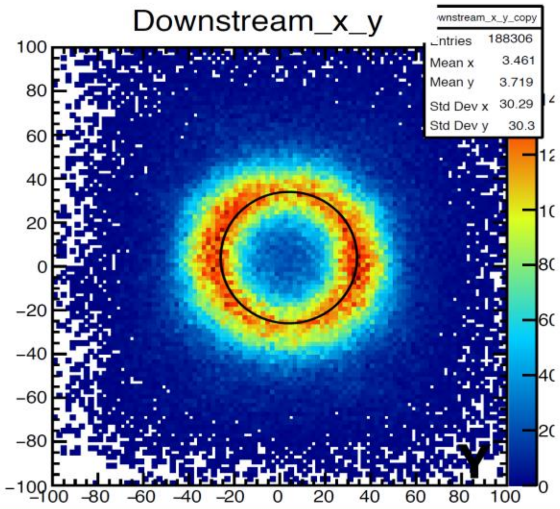




-130<Z<-70



-60<Z<60



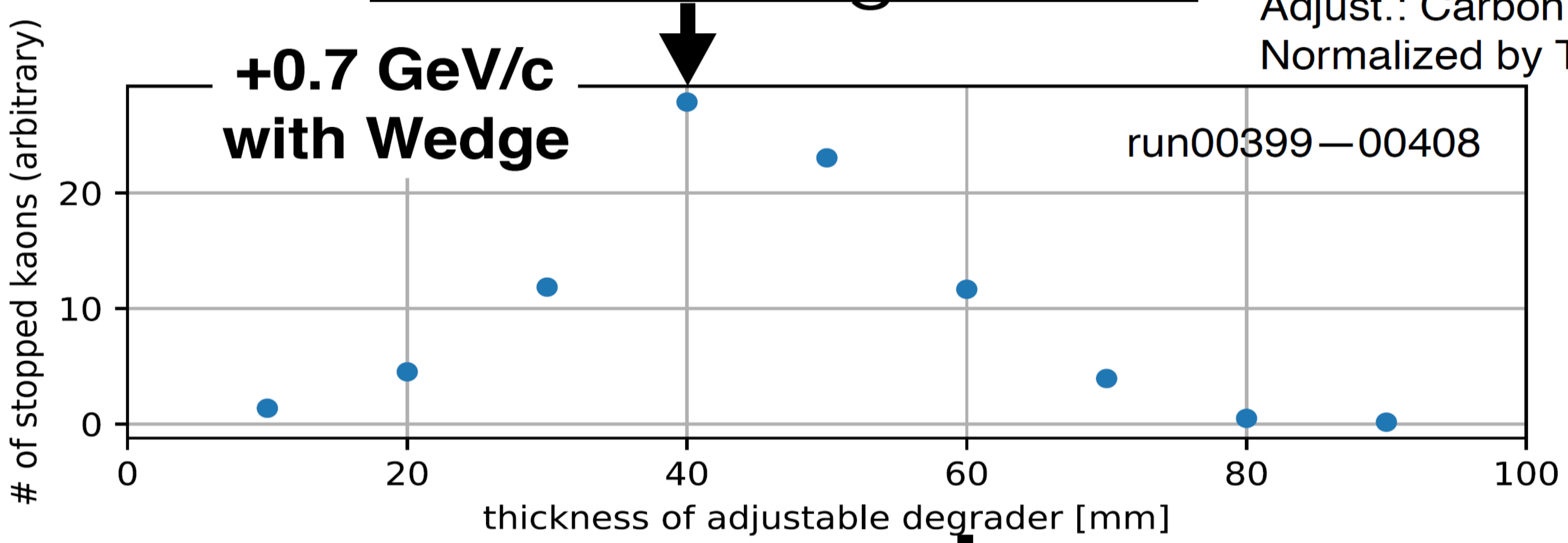
70<Z<130

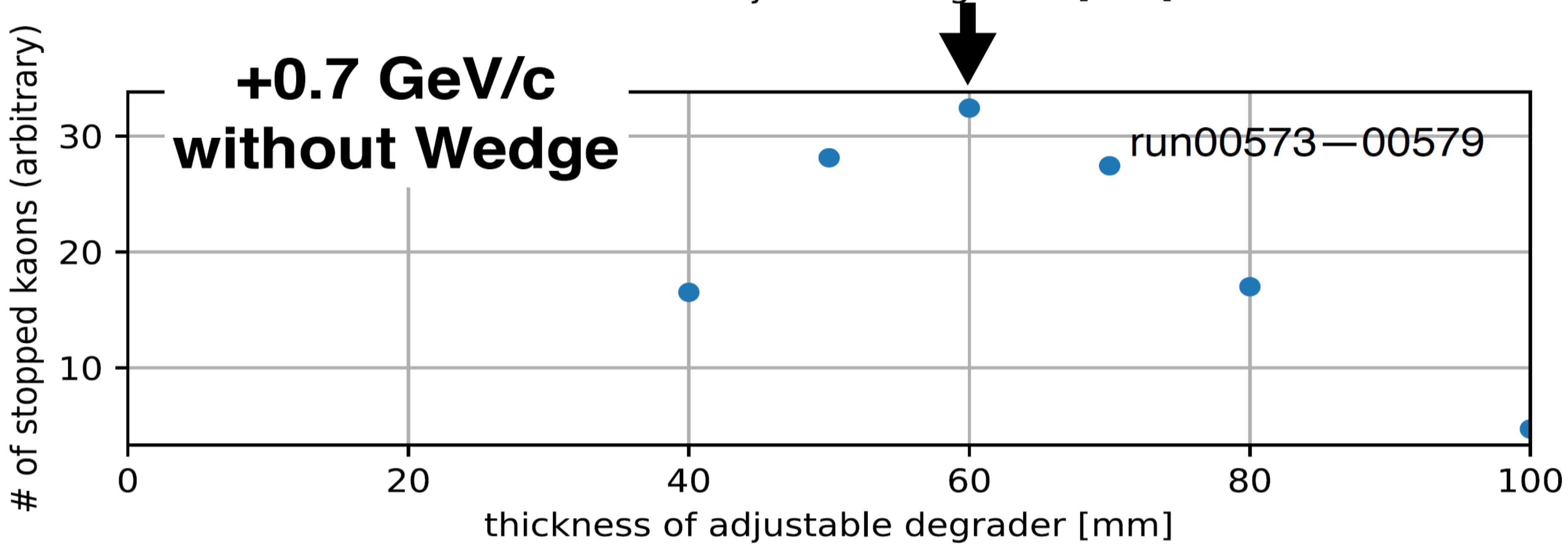
XY

T. Hashimoto@20190515

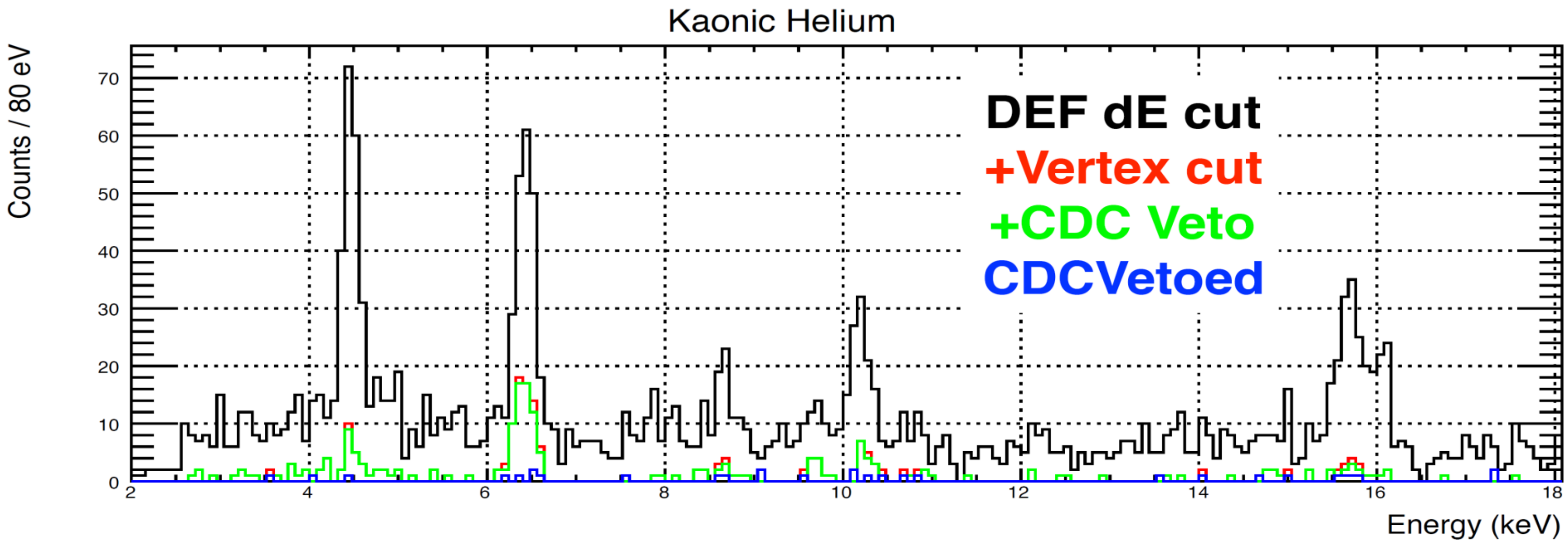
K+ run: Range curve

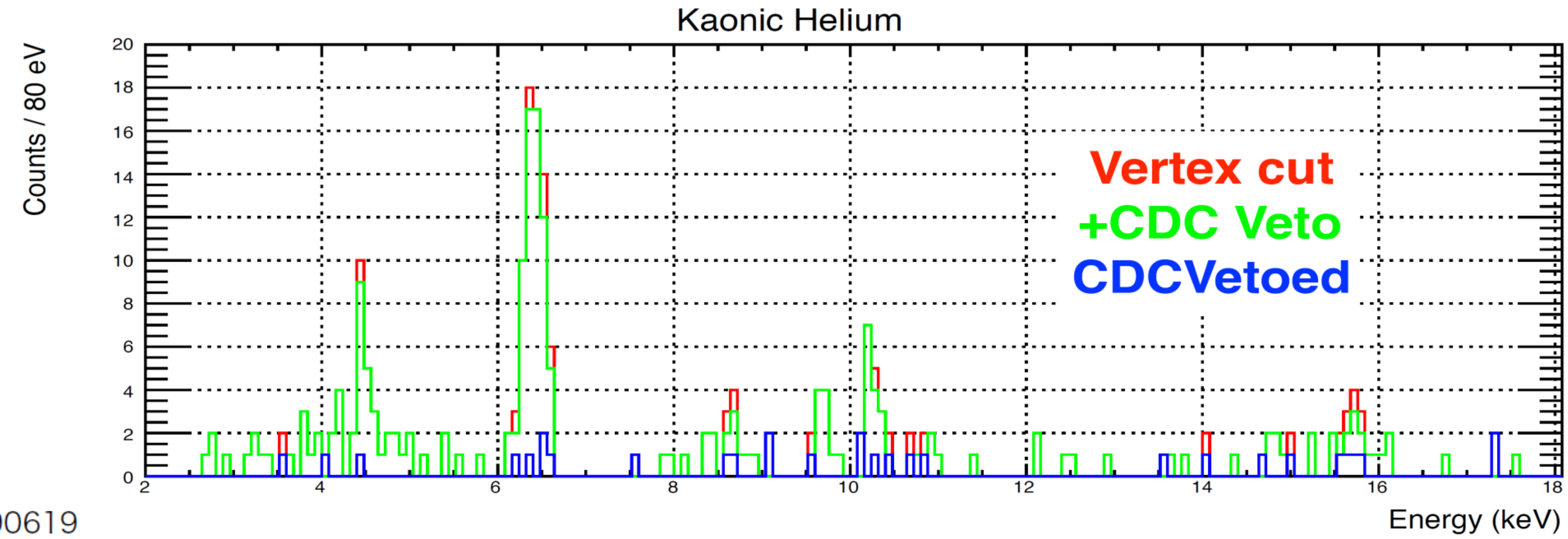
Carbon Degrader
Fixed: 500mm
Adjust.: Carbon equiv.
Normalized by TM



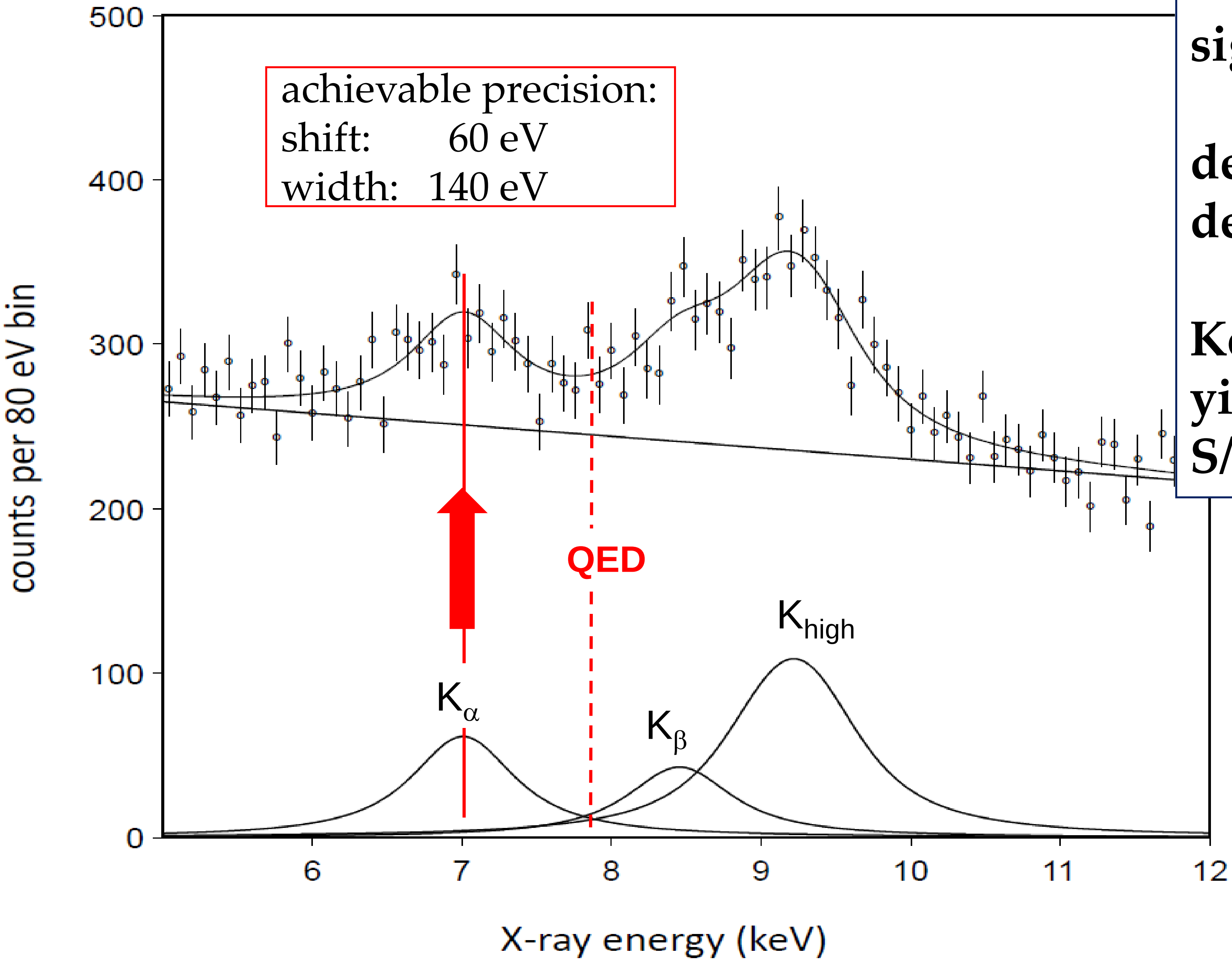


Event selection by CDC analysis





Geant4 simulated $K^- d$ X-ray spectrum



signal: shift - 800 eV
width 800 eV
density: 5% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
yield ratio as in $K^- p$
S/B ~ 1 : 4

- vertex cut
- charged particle veto
- asynchronous BG

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Accepted Paper

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

Thank you for your attention!

ABSTRACT

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

Rev. Mod. Phys. 91, 025006 – Published 20 June 2019

K^-d scattering lengths - theory

ε_{1s} [eV]	Γ_{1s} [eV]	Reference
- 670	1016	Weise 2017 [2]
- 887	757	Mizutani 2013 [4]
- 736	826	Shevchenko 2015 [5]
- 779	650	Meißner 2011 [1]
- 769	674	Gal 2007 [6]
- 884	665	Meißner 2006 [7]
- 1080	1024	Oset 2001 [3]

[1] M. Döring, U.-G. Meißner, Phys. Lett. B 704 (2011) 663
[2] T. Hoshino et al., Physical Review C96 (2017) 045204
[3] S.S. Kamakov, E. Oset, A. Ramos, Nucl. Phys. A 690 (2001) 494
[4] T. Mizutani, C. Fayard, B. Saghai, K. Tsushima, Phys. Rev. C 87, 035201 (2013), arXiv:1211.5824[hep-ph]
[5] N.V. Shevchenko, Phys. Lett. B 744 (2015) 105
[6] A. Gal, Int. J. Mod. Phys. A22 (2007) 226
[7] U.-G. Meißner, U. Raha, A. Rusetsky, Eur. phys. J. C47 (2006) 473

Scattering lengths

Deser formula connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of $\boldsymbol{a}_{\text{K-p}}$

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

μ…reduced mass of the K^-p system
α…fine-structure constant

Improved Deser formula with isospin corrections

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

V. Baru, E. Epelbaum, and A. Rusetsky, Eur. Phys. J. A 42 (2009) 111

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

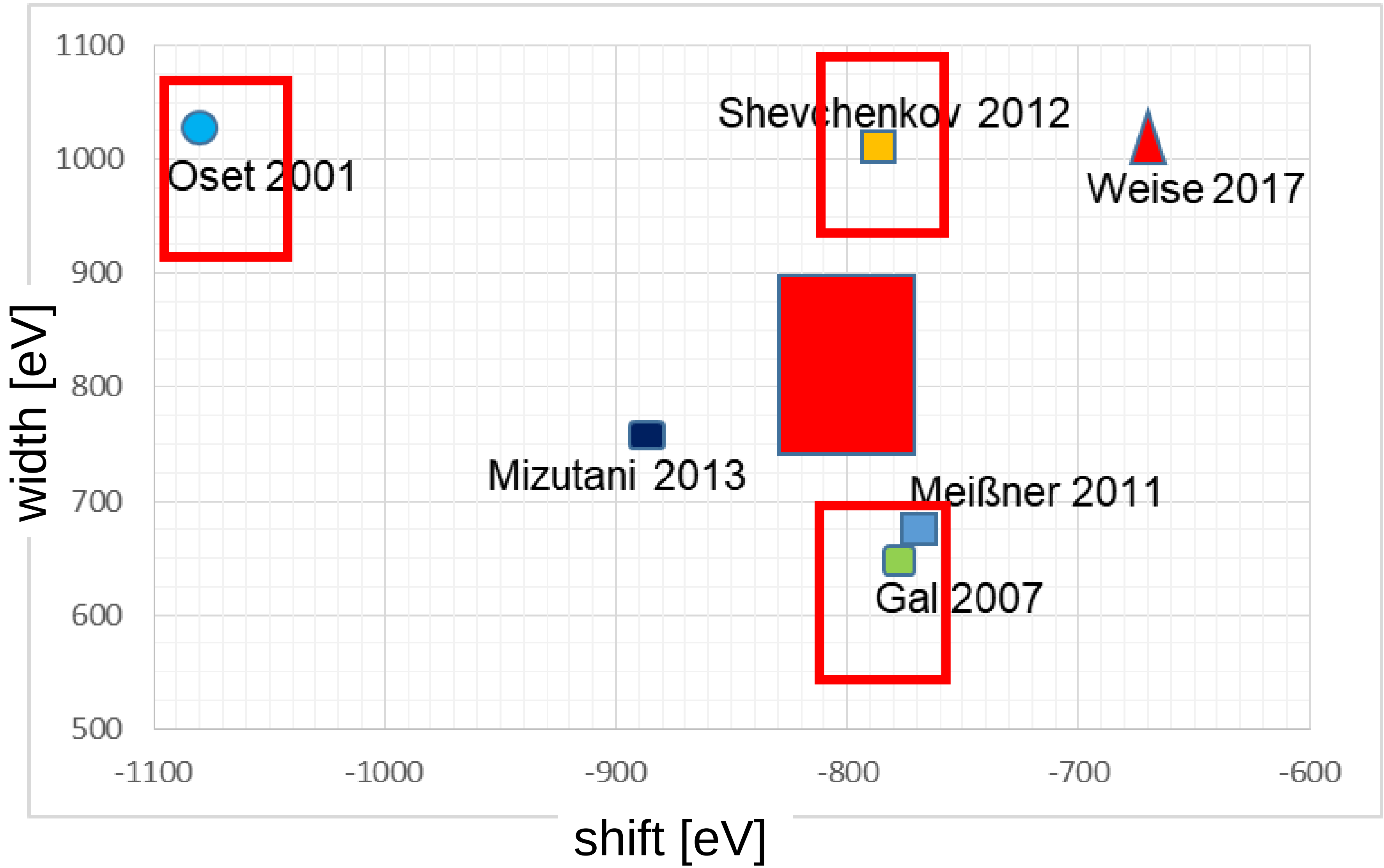
$$k = \frac{4\left[m_n + m_K\right]}{\left[2m_n + m_K\right]}$$

C includes all higher-order contributions, all other physics associated with the K-d three-body interaction.

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

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

Theory – K^-d precision SIDDHARTA-2 and E57



Physical Review C96 (2017) 045204

arXiv:1705.06857v1 [nucl-th] 19 May 2017

Constraining the $\bar{K}N$ interaction from the $1S$ level shift of kaonic deuterium

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[3] *Physik-Department, Technische Universität München, 85748 Garching, Germany*

Motivated by the precise measurement of the $1S$ level shift of kaonic hydrogen, we perform accurate three-body calculations for the spectrum of kaonic deuterium using a realistic antikaon-nucleon ($\bar{K}N$) interaction. In order to describe both short- and long-range behavior of the kaonic atomic states, we solve the three-body Schrödinger equation with a superposition of a large number of correlated Gaussian basis functions covering distances up to several hundreds of fm. Transition energies between $1S$, $2P$ and $2S$ states are determined with high precision. The complex energy shift of the $1S$ level of kaonic deuterium is found to be $\Delta E - i\Gamma/2 = (670 - i\,508)$ eV. The sensitivity of this level shift with respect to the isospin $I = 1$ component of the $\bar{K}N$ interaction is examined. It is pointed out that an experimental determination of the kaonic deuterium level shift within an uncertainty of 25 % will provide a constraint for the $I = 1$ component of the $\bar{K}N$ interaction significantly stronger than that from kaonic hydrogen.

Physics Letters B 744 (2015) 105–108

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Three-body calculation of the 1*s* level shift in kaonic deuterium

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A B S T R A C T

The first exact calculation of a three-body hadronic atom was performed. Kaonic deuterium 1*s* level shift and width were evaluated using Faddeev-type equations with Coulomb interaction. The obtained exact results were compared with commonly used approximate approaches.