EXOTIC ATOMS: STUDY OF STRONG INTERACTION WITH STRANGENESS FROM DAΦNE TO J-PARC

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SIDDHARTA and E57 collaboration
SMI, Vienna, Austria

MESON IN NUCLEUS - MIN16
Yukawa Institute, Kyoto Aug. 2, 2016

OUTLINE

- Motivation
- Measuring principle
- Kaonic hydrogen at DAΦNE - results
- Kaonic deuterium at J-PARC - plans
- Summary

WHY STRANGE QUARKS

Strange quarks are neither "light" nor "heavy"

- interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD

Testing ground: high-precision antikaon-nucleon threshold physics

- attractive low-energy KN interaction

Nature and structure of $\Lambda(1405)$ B=1; S=-1, $J^P = 1/2^-$

- three-quark valence structure, or "molecular" meson-baryon state
- quest for quasi-bound antikaon-NN systems

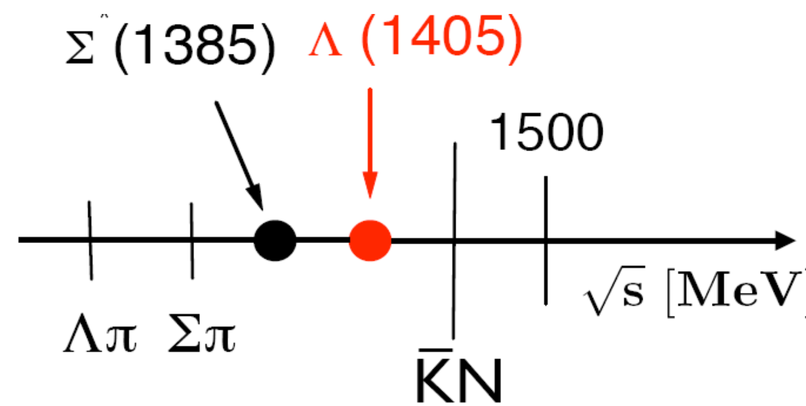
Role of strangeness in dense baryonic matter

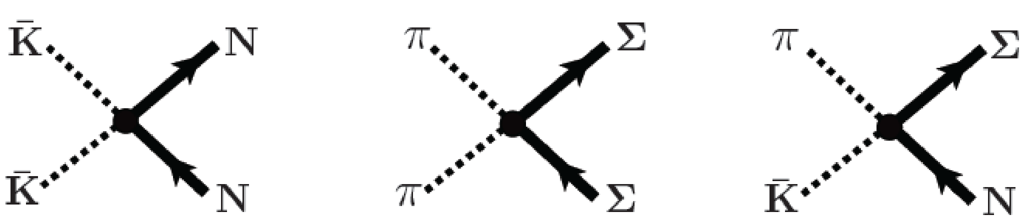
- kaon condensation, strange quark matter, hyperons in neutron stars

LOW-ENERGY $\bar{K}N$ INTERACTION

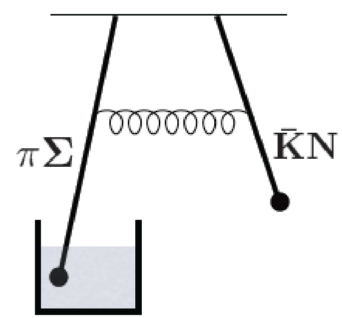
Chiral perturbation theory developed for πp, ππ **not** applicable for $\bar{K}N$ systems

non-perturbative coupled channels approach based on **chiral SU(3) dynamics**





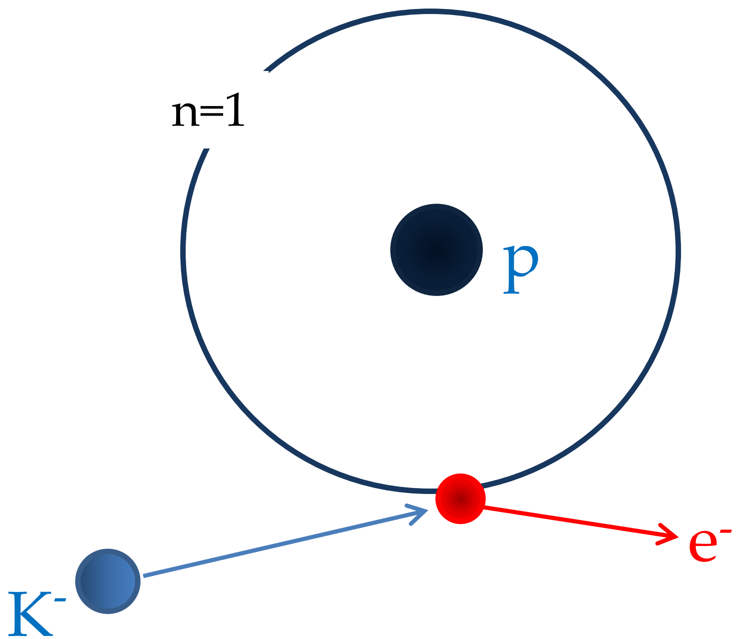
channel coupling



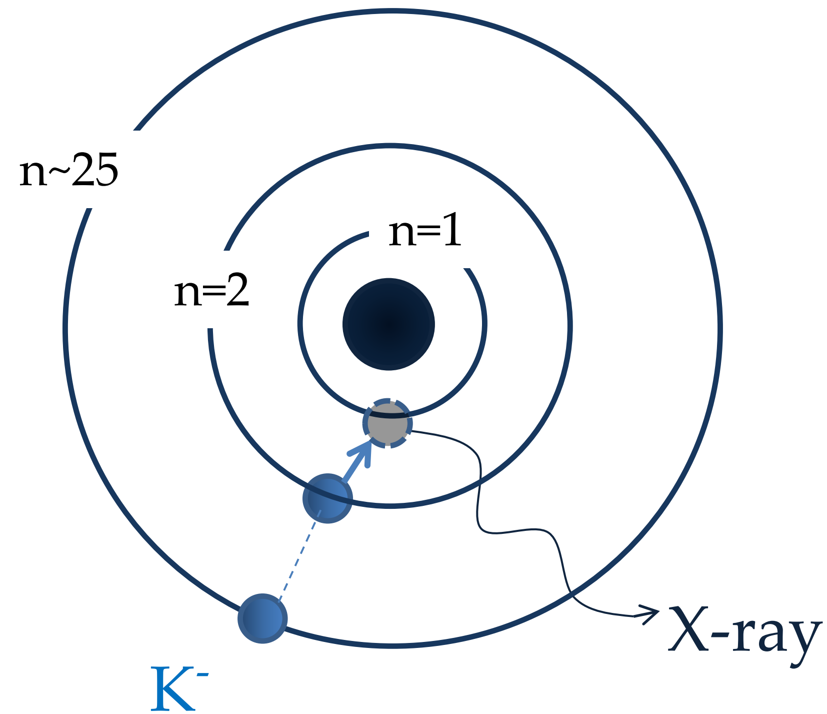
Review:
T. Hyodo, D. Jido
Prog. Part. Nucl. Phys. 67 (2012) 55

FORMING "EXOTIC" ATOMS

"normal" hydrogen



"exotic" (kaonic) hydrogen

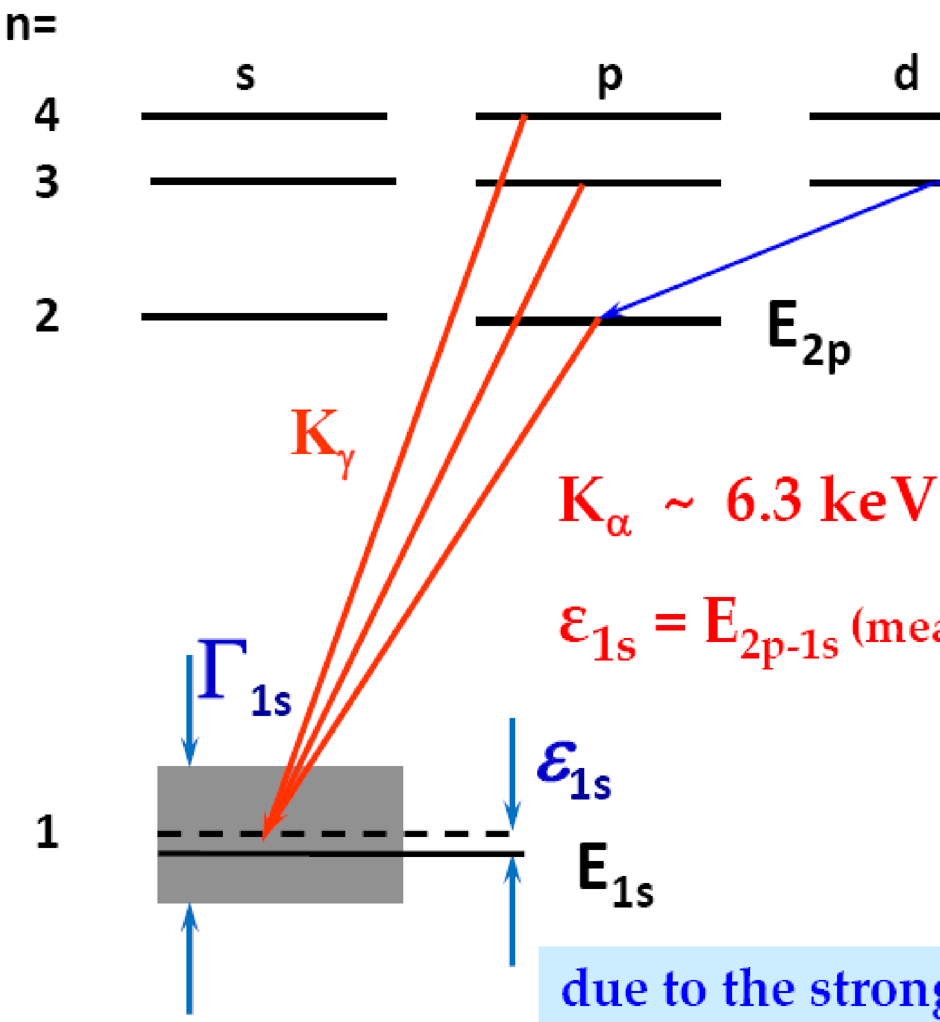


$$n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e$$

2p → 1s

K_α transition

X-RAY TRANSITIONS TO THE 1s STATE



shift and width of states n > 1 are negligible

K_α ~ 6.3 keV

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

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 $a_{\text{K-p}}$

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

(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

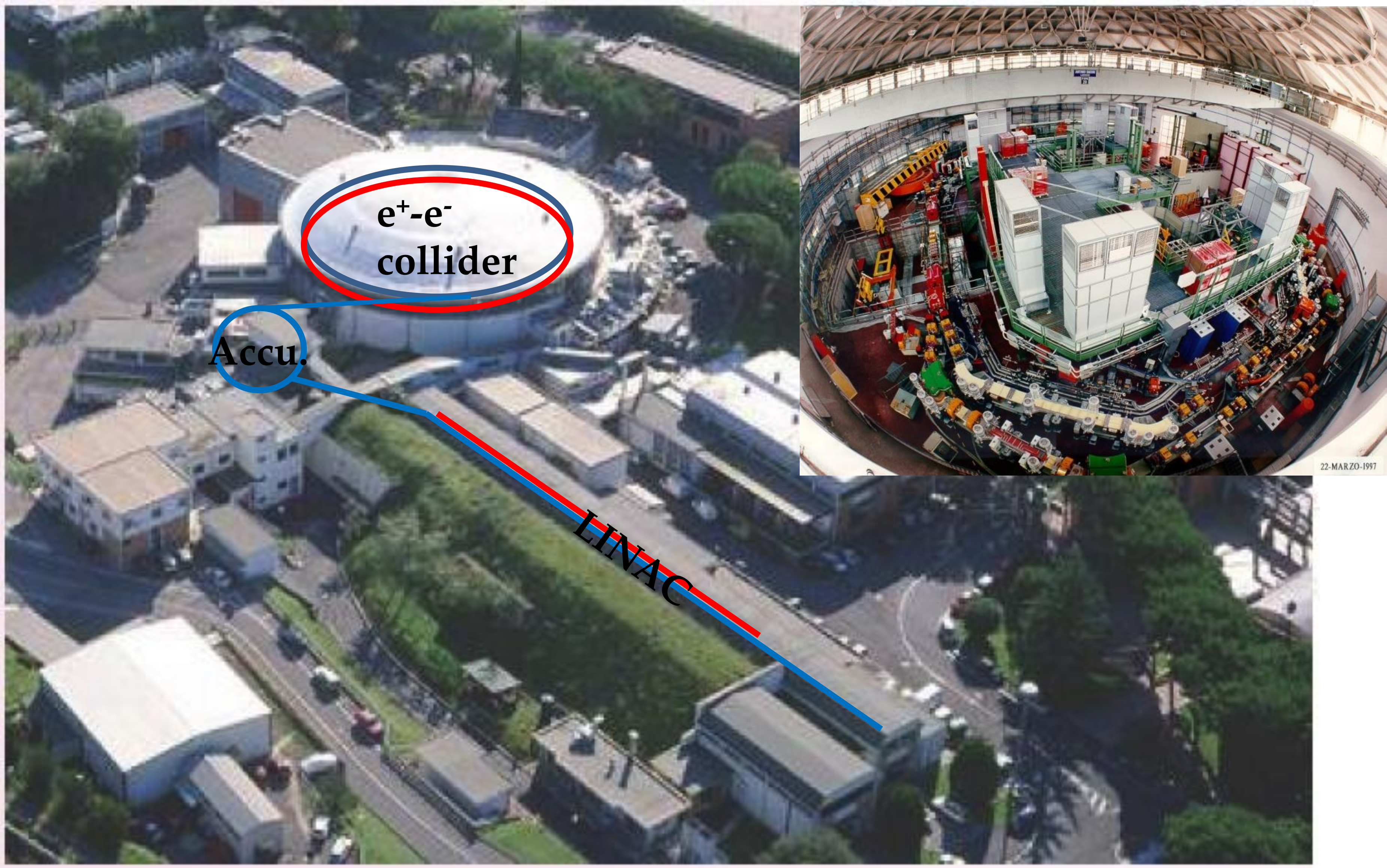
$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$

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

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

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

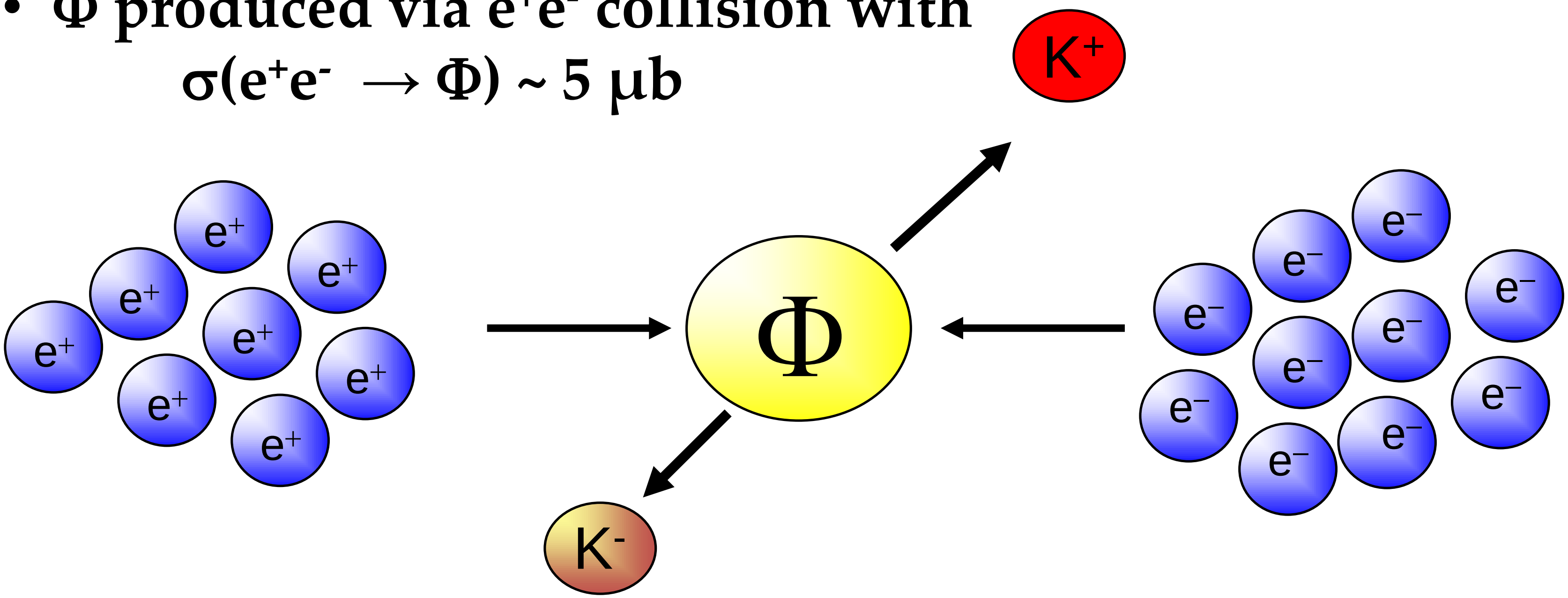
KAONIC HYDROGEN ATOMS AT DAΦNE



DAΦNE PRINCIPLE

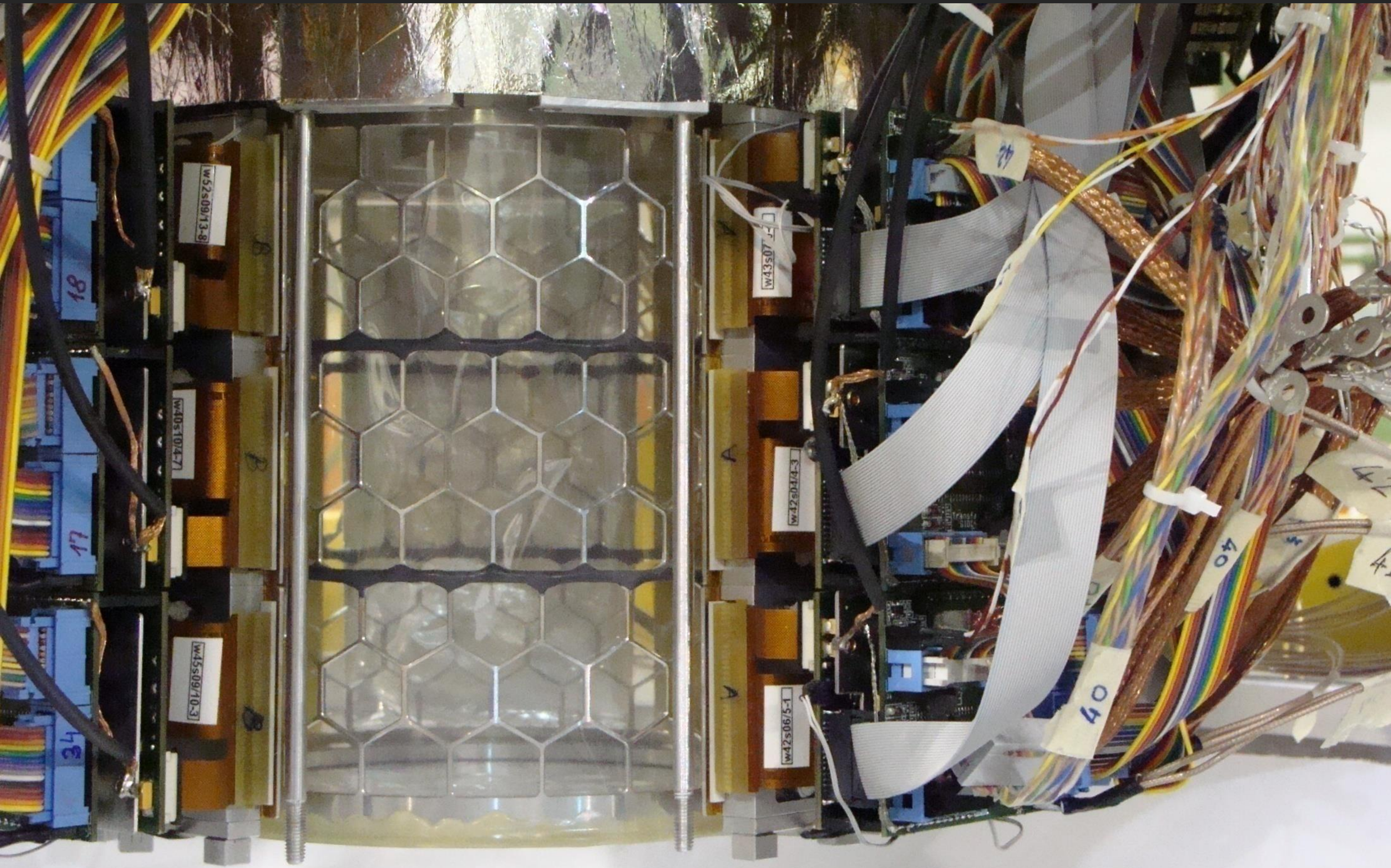
- **operates at the centre-of-mass energy of the Φ meson**
  mass m = 1019.413 ± .008 MeV
  width Γ = 4.43 ± .06 MeV

- **Φ produced via e^+e^- collision with**
  $\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$



→ monochromatic kaon beam (127 MeV/c)

SIDDHARTA TARGET - DETECTOR



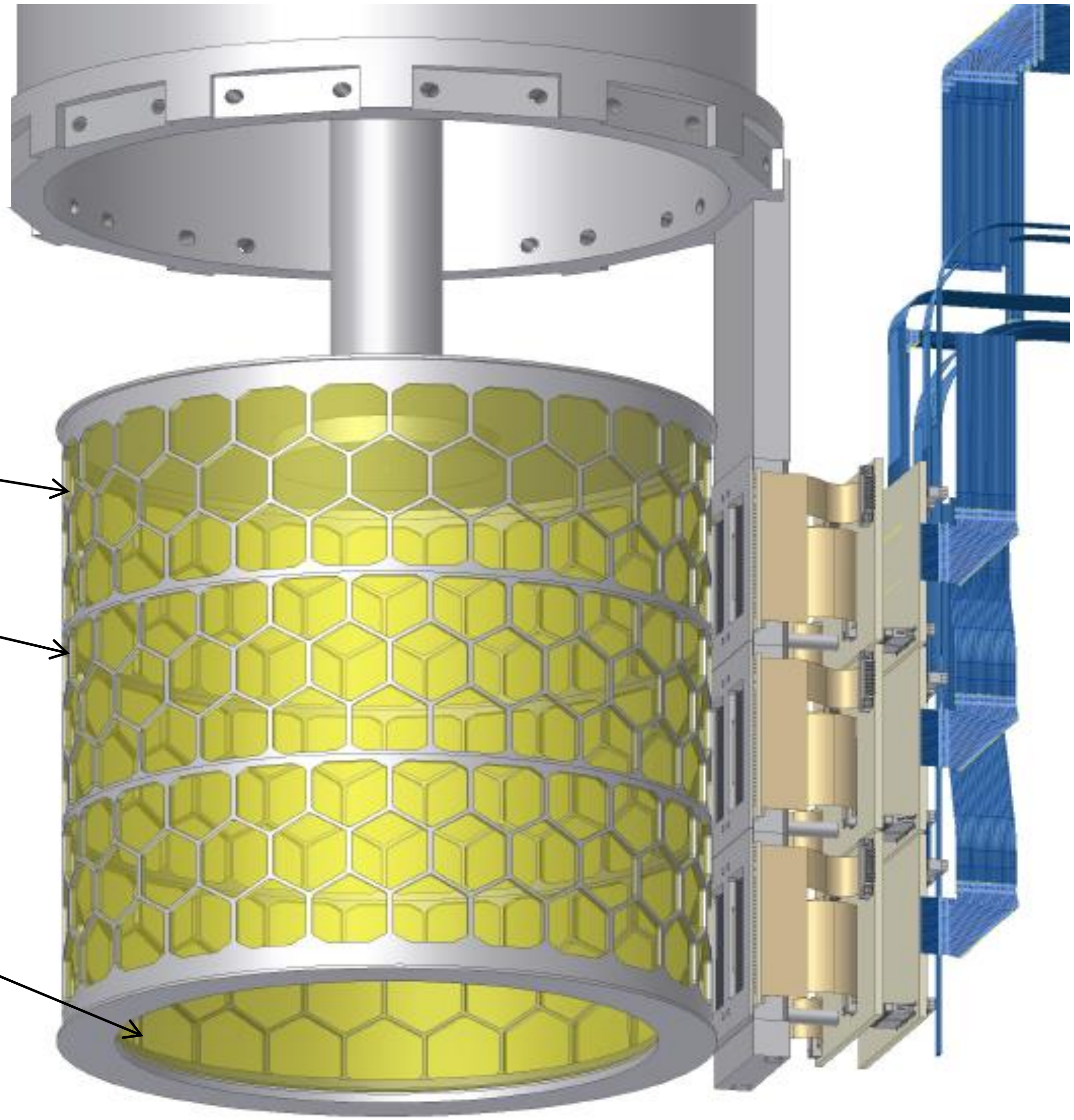
LIGHTWEIGHT CRYOGENIC TARGET

working T 25 K
working P 1.5 bar

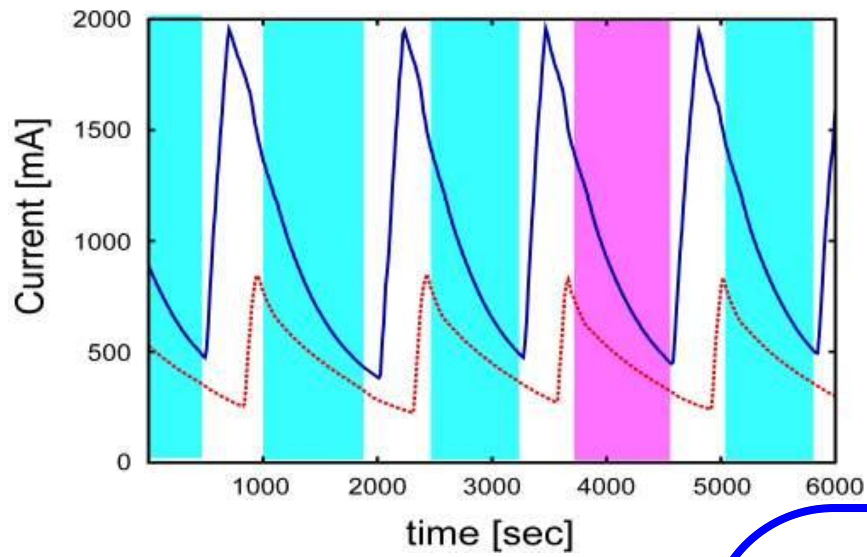
Alu-grid

Side wall:
Kapton 50 μm

Kaon entrance
Window:
Kapton 75 μm

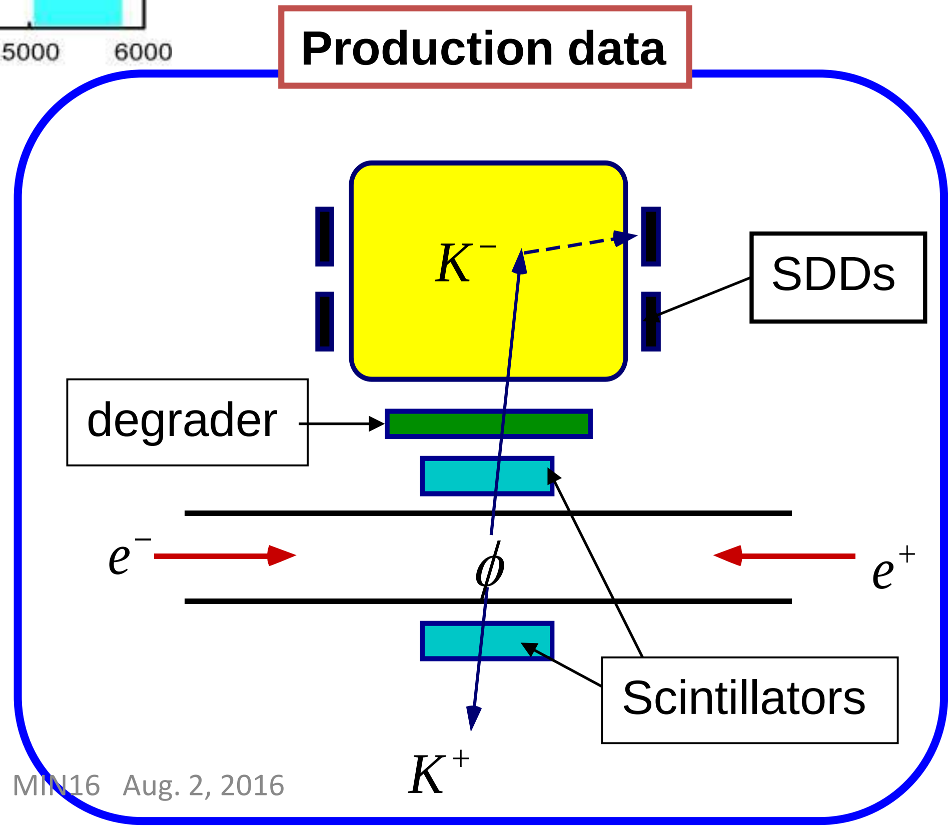


DATA TAKING SCHEME

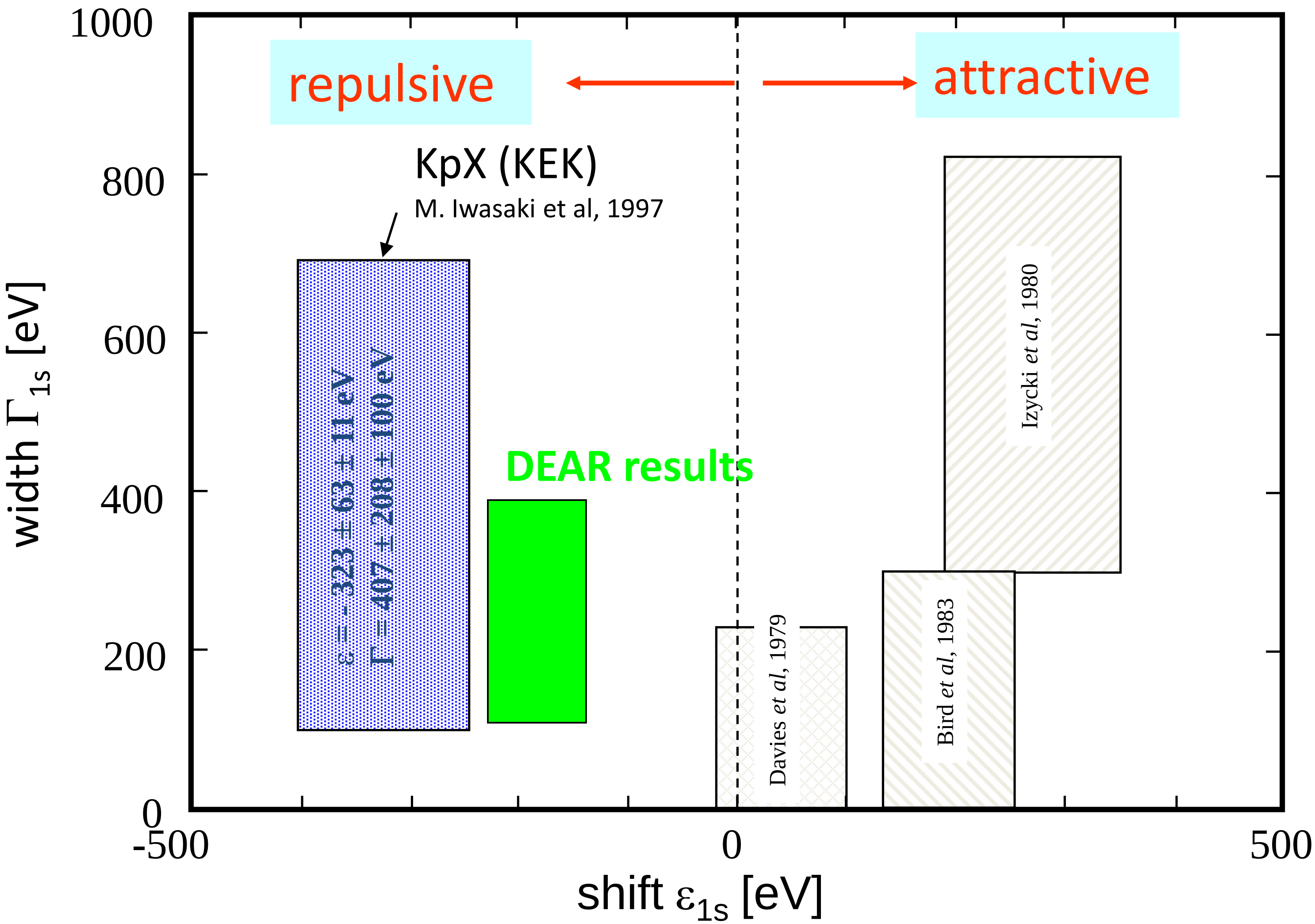


K^+K^- pairs produced at DAΦNE

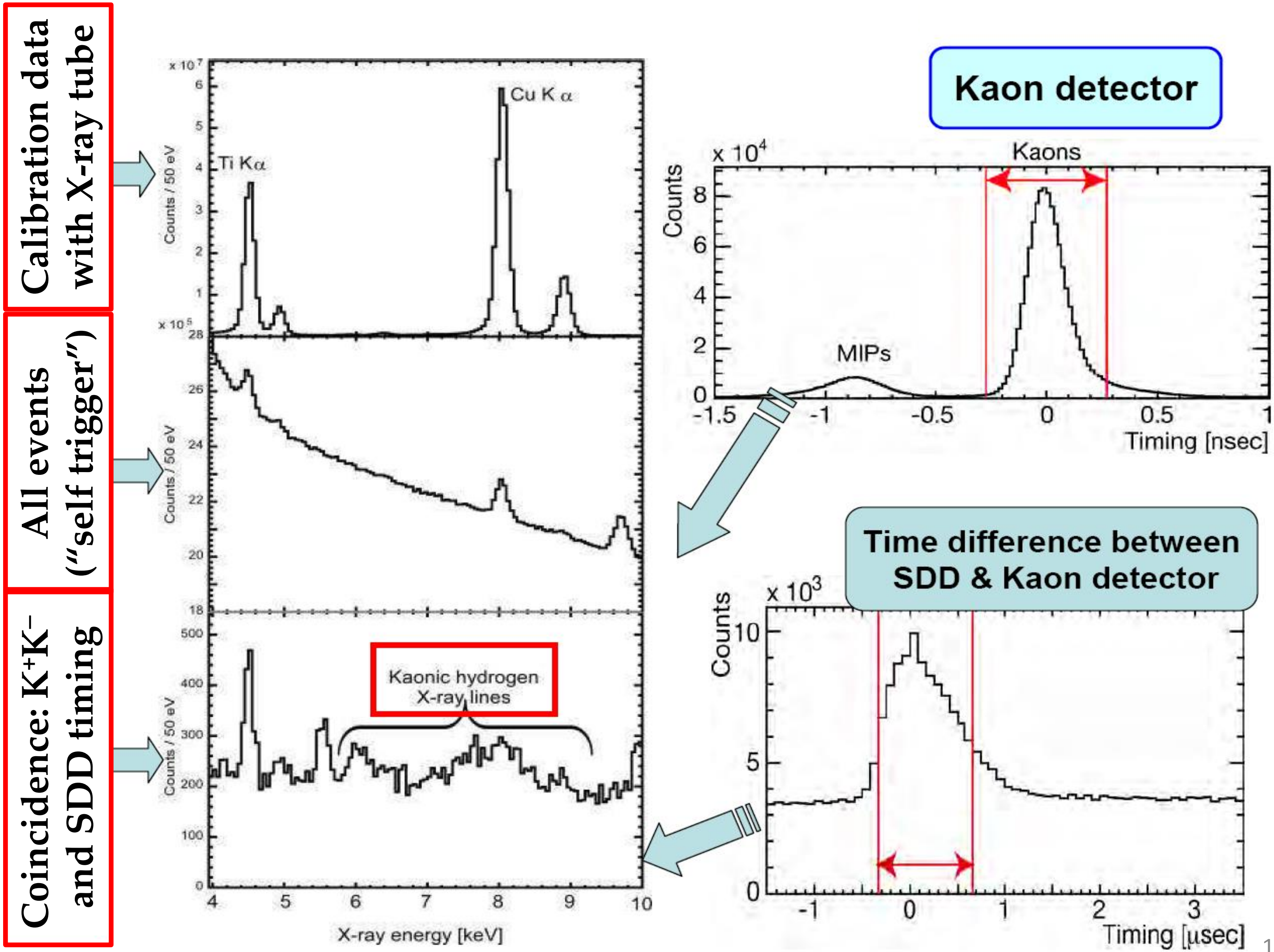
triple coincidence



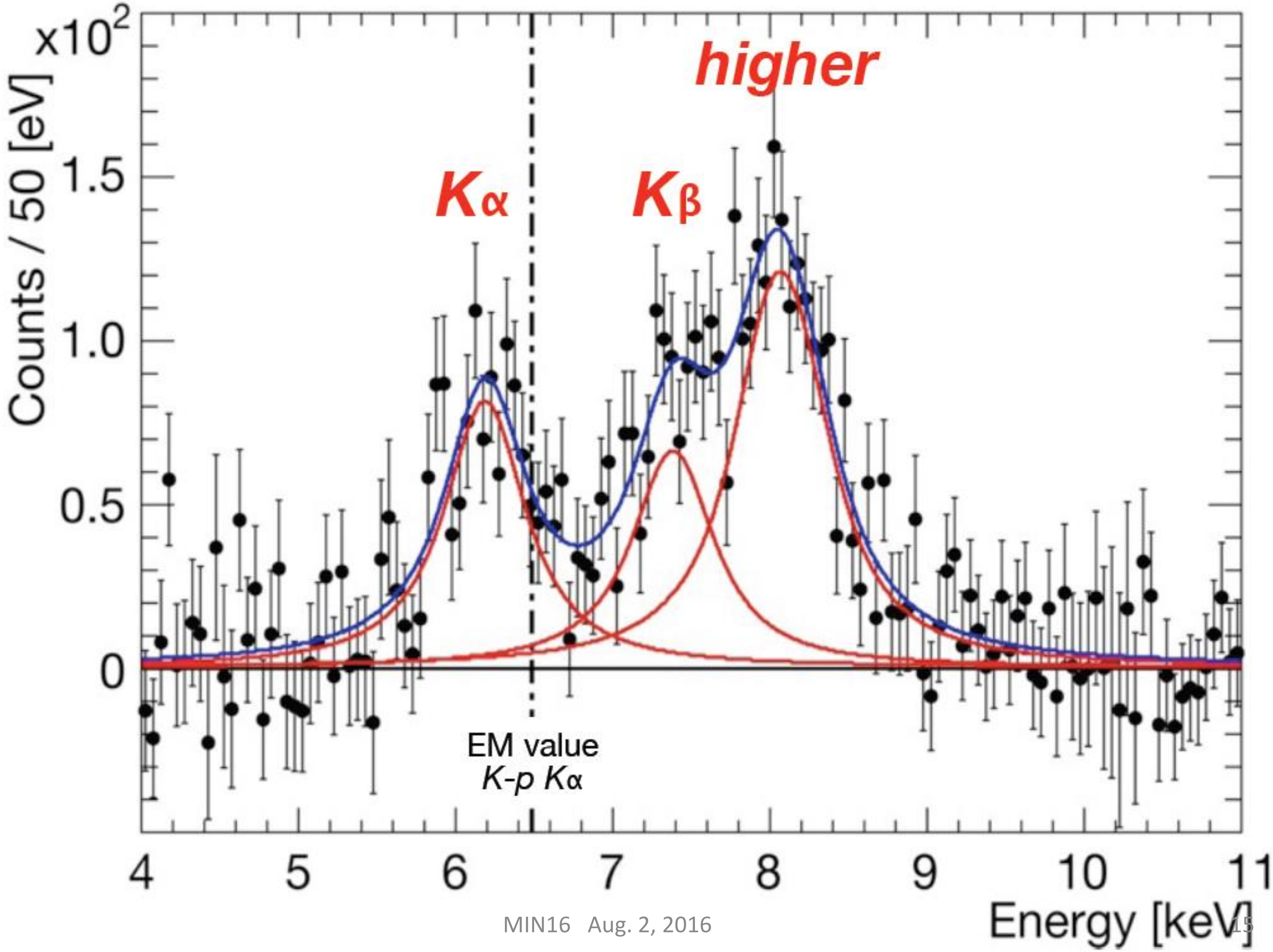
KAONIC HYDROGEN: KpX and DEAR results



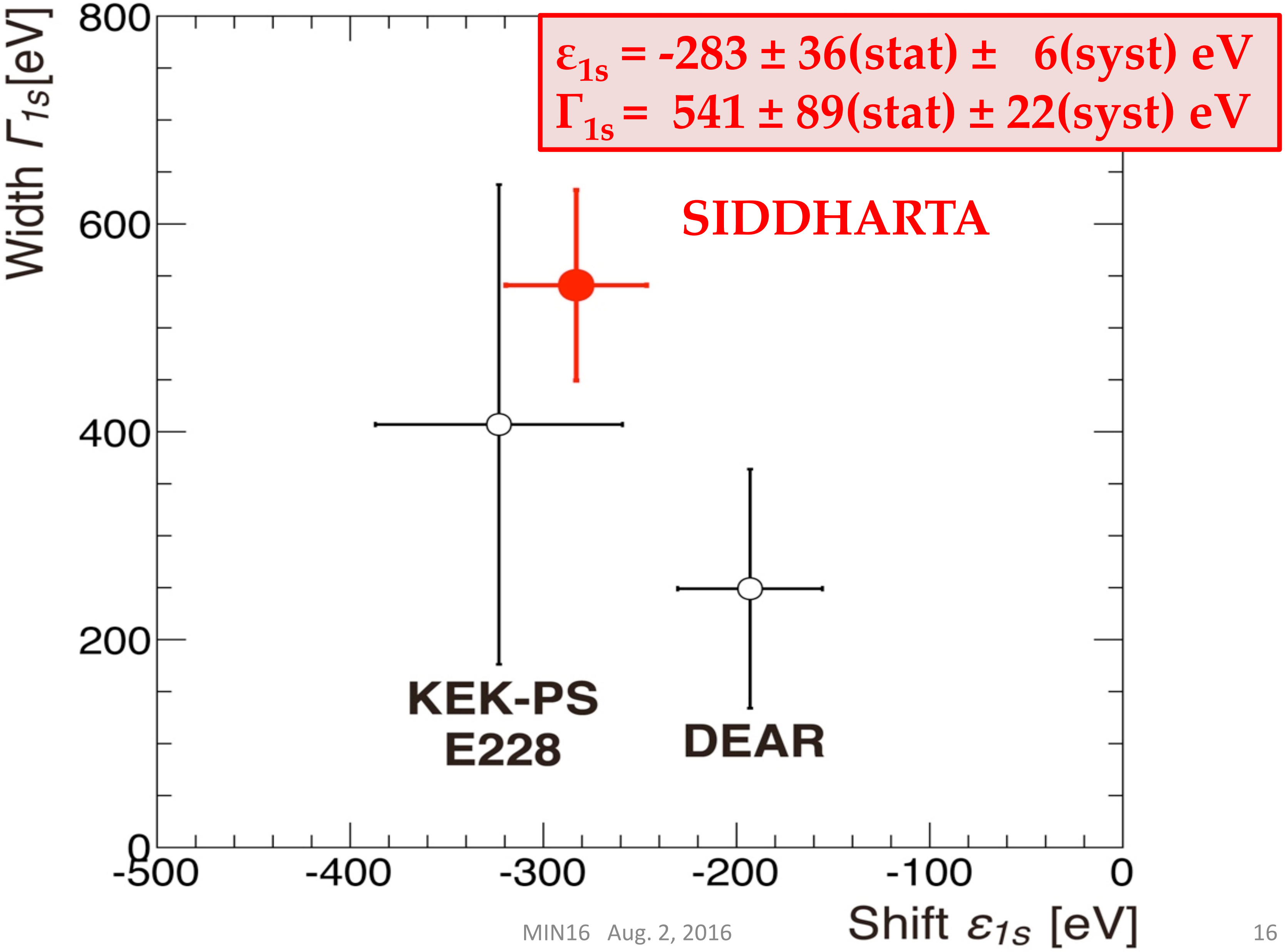
KAONIC HYDROGEN



K⁻p SPECTRUM, BG SUBTRACTED



KAONIC HYDROGEN



ANALYSIS OF THE **K^-p** THRESHOLD PHYSICS

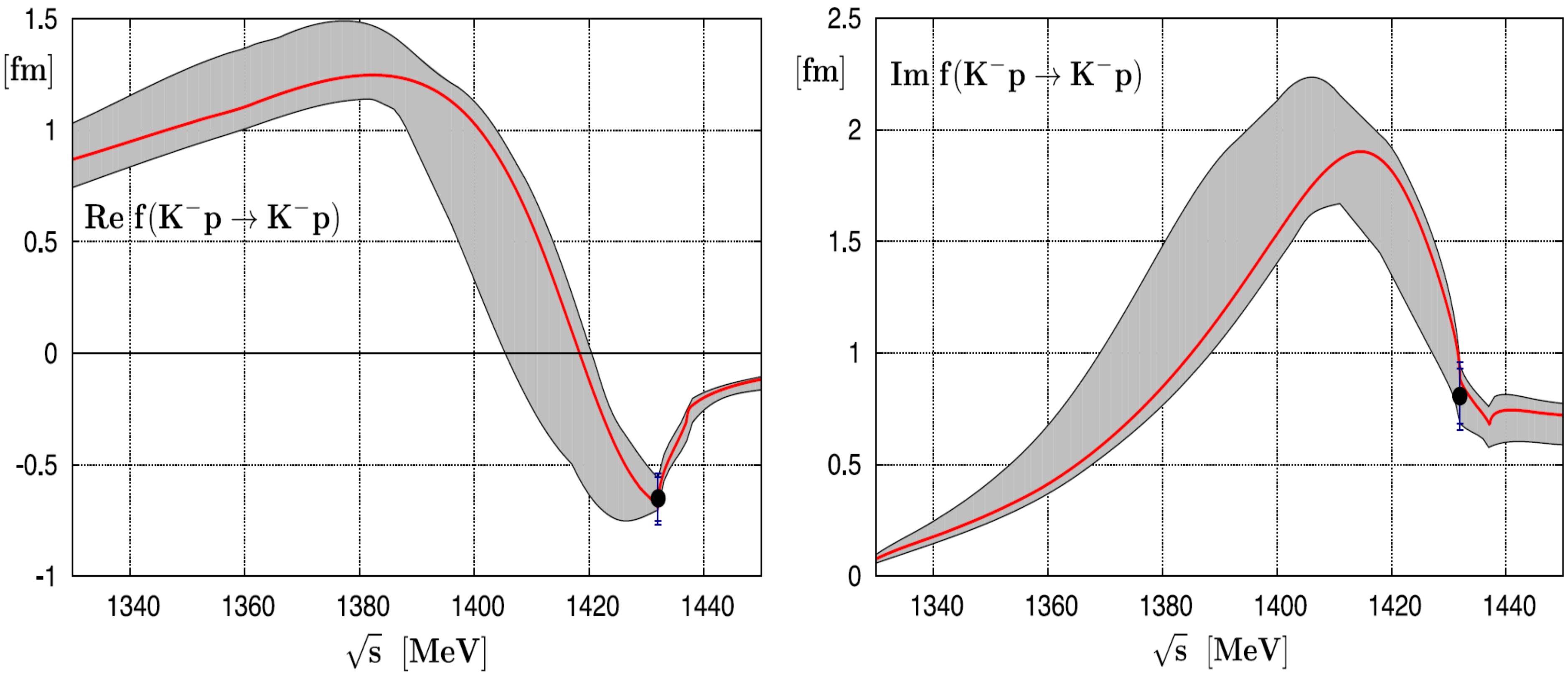
Chiral SU(3) coupled-channels dynamics
Weinberg-Tomozawa + Born terms +NLO

kaonic hydrogen ε_{1s} and Γ_{1s}	theory (NLO)	experiment
$\Delta\varepsilon$ [eV]	306	$283 \pm 36 \pm 6$
$\Delta\Gamma$ [eV]	591	$541 \pm 89 \pm 22$

threshold branching ratios		
$\frac{\Gamma(K^- p \rightarrow \pi^+ \Sigma^-)}{\Gamma(K^- p \rightarrow \pi^- \Sigma^+)}$	2.36	2.36 ± 0.04
$\frac{\Gamma(K^- p \rightarrow \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \rightarrow all\ inelastic\ channels)}$	0.66	0.66 ± 0.01
$\frac{\Gamma(K^- p \rightarrow \pi^0 \Lambda)}{\Gamma(K^- p \rightarrow neutral\ states)}$	0.19	0.19 ± 0.02

- **Re $a(K^-p) = (-0.65 \pm 0.10)$ fm   Im $a(K^-p) = (0.81 \pm 0.12)$ fm**

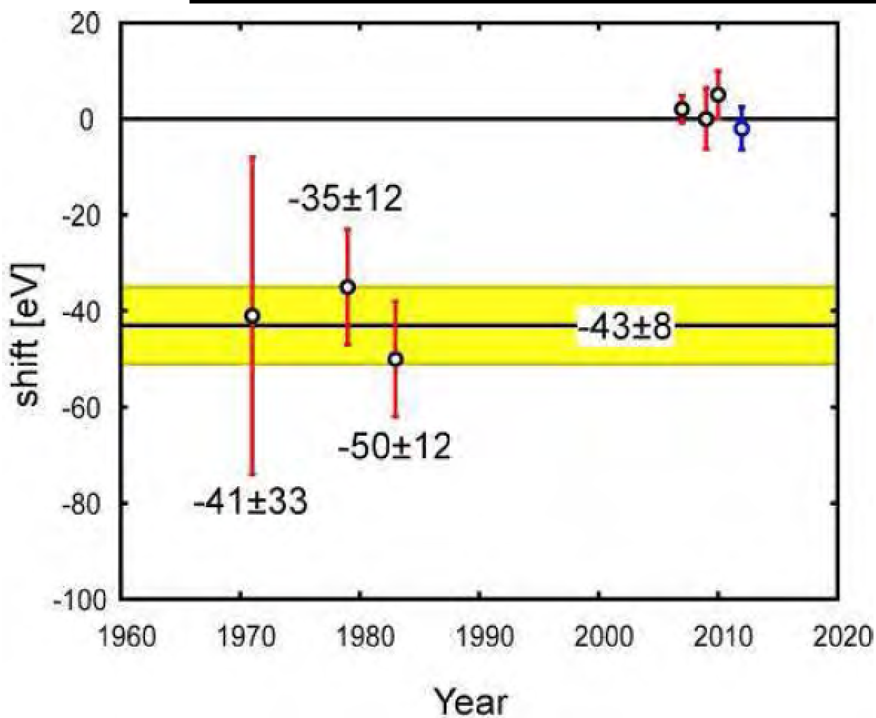
Improved constraints on chiral SU(3) dynamics from kaonic hydrogen:
Y. Ikeda, T. Hyodo and W. Weise, PLB 706 (2011) 63

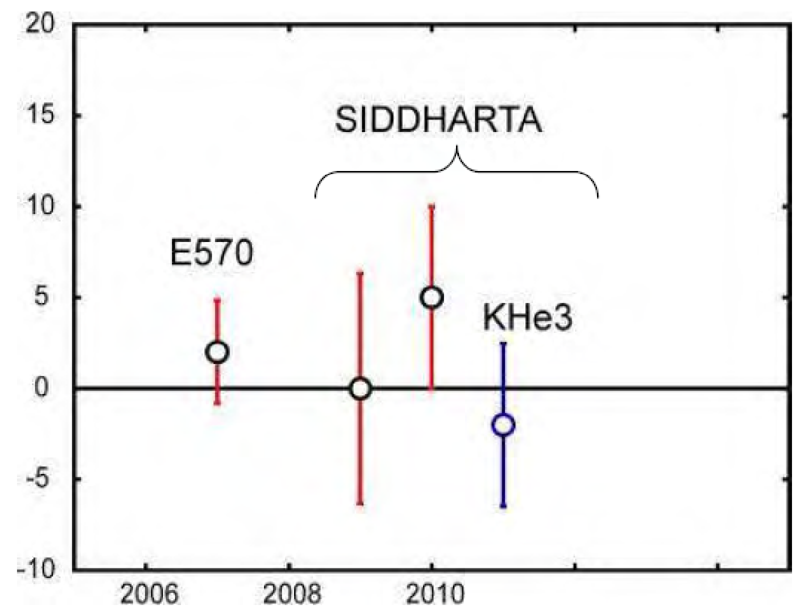


Real part (left) and imaginary part (right) of the $K^-p \rightarrow K^-p$ forward scattering amplitude extrapolated to the subthreshold region, deduced from the SIDDHARTA kaonic hydrogen measurement.

KAONIC HELIUM RESULTS

	Shift [eV]	Reference
KEK E570	+2±2±2	PLB653(2007)387
SIDDHARTA (He4 with 55Fe)	+0±6±2	PLB681(2009)310
SIDDHARTA (He4)	+5±3±4	arXiv:1010.4631, PLB697(2011)199
SIDDHARTA (He3)	-2±2±4	





- **Shinji Okada, next talk**

K-d at 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

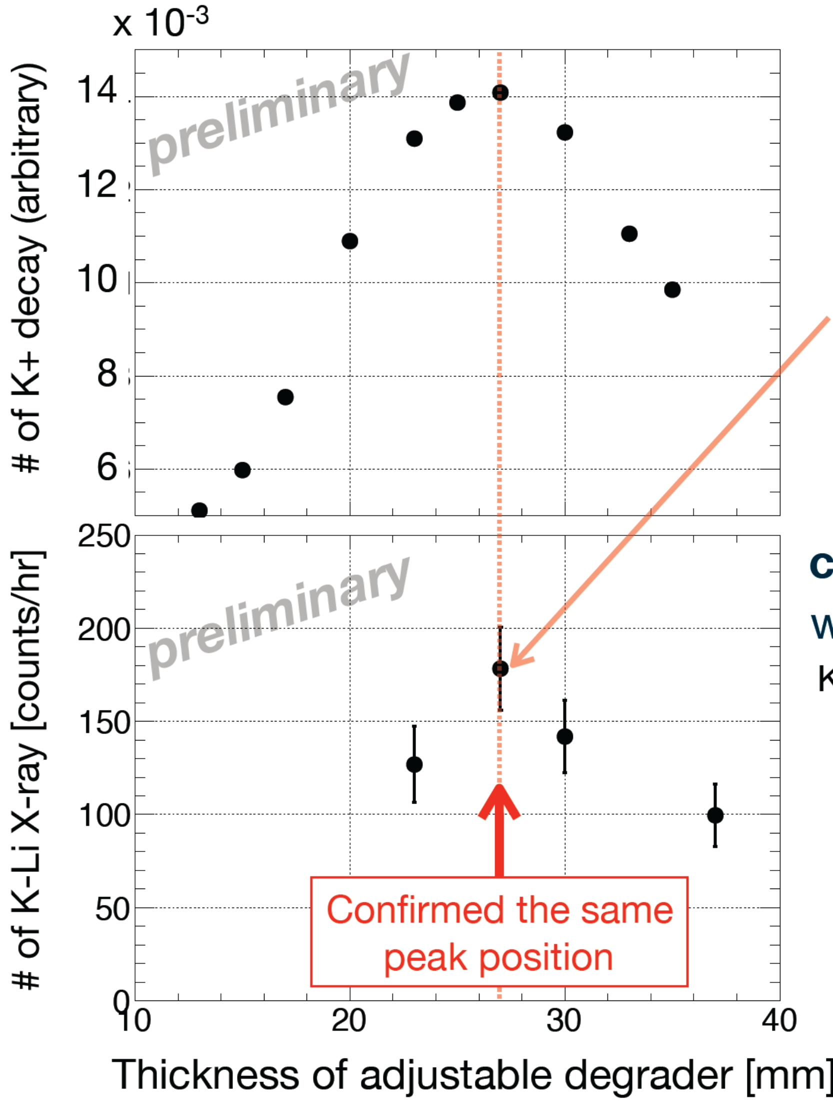
20 Institutes / 10 Countries

$\mathbf{K^-d}$ AT J-PARC

- X-ray detection: large active area
- charge particle tracking
- lightweight cryogenic target
- stopped K^-

STOPPED KAONS

RANGE CURVE MEASURED @ J-PARC – June 2016



with tracking chamber system for **0.9 GeV/c K⁺**

with SDDs for **0.9 GeV/c K⁻**

K-Li x-ray yield :
~180 counts / hr
(with 24 good SDDs)

consistent with G4 sim

within error of ref. value:

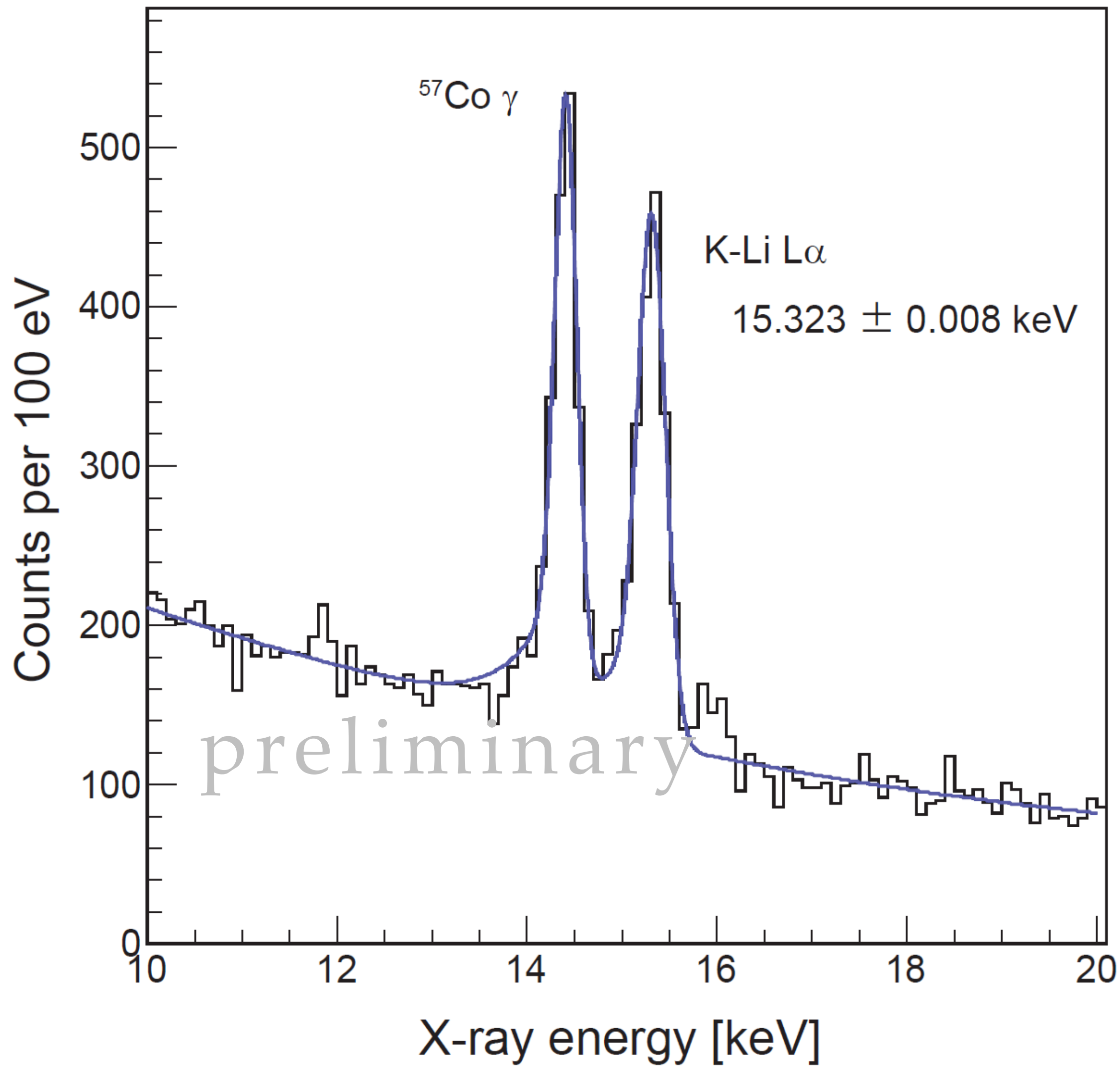
K-Li yield = 15 ± 3 % / stop K
[PRA 9 (1974) 2282]

Note that the simulation was performed again with obtained beam profile & actual geometrical inputs.

KAONIC LITHIUM 3→2

- ✓ Sum of K^- runs (0.7 and 0.9 GeV/c)
- ✓ 15.323 ± 0.008 keV
  ~ 1200 counts
  resolution 160 eV

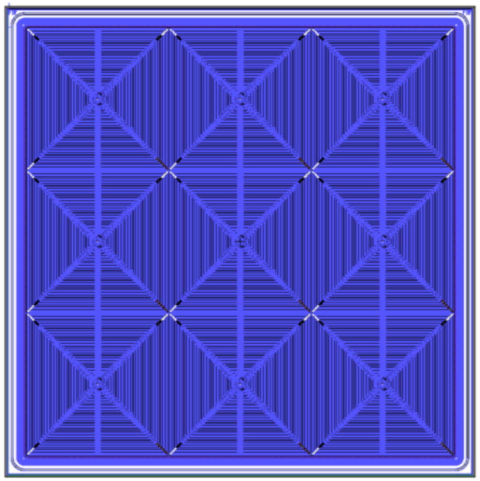
$K^-Li_{L\alpha}$ transition:
15.330 keV (pure QED9)
J.P.Santos et al.
Phys. Rev. A 71 (2005) 032501



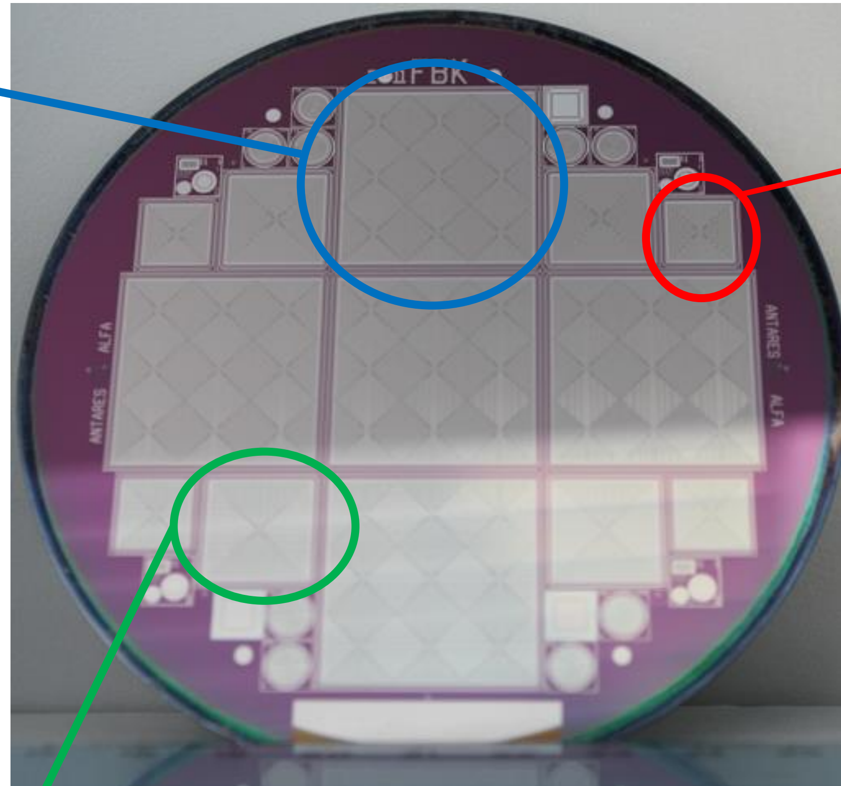
Large area Silicon Drift Detector

developed by Politech Milano and FBK-Trento, Italy

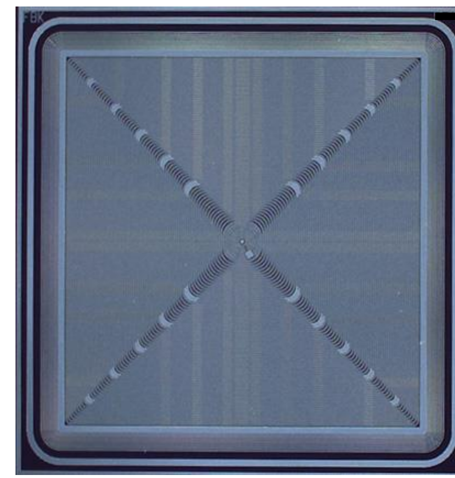
Array: 9 SDDs
(8 x 8 mm^2
each)



26mm



8 x 8 mm^2
single SDD

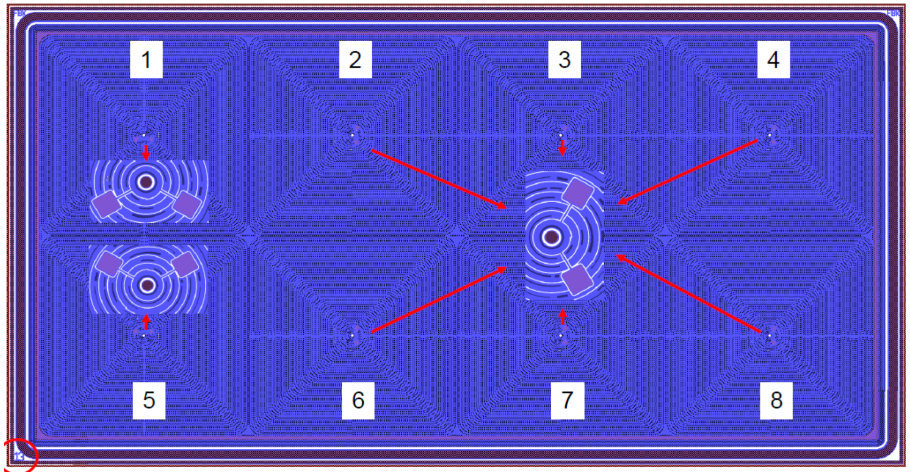


12 x 12 mm
single SDD

FBK production:

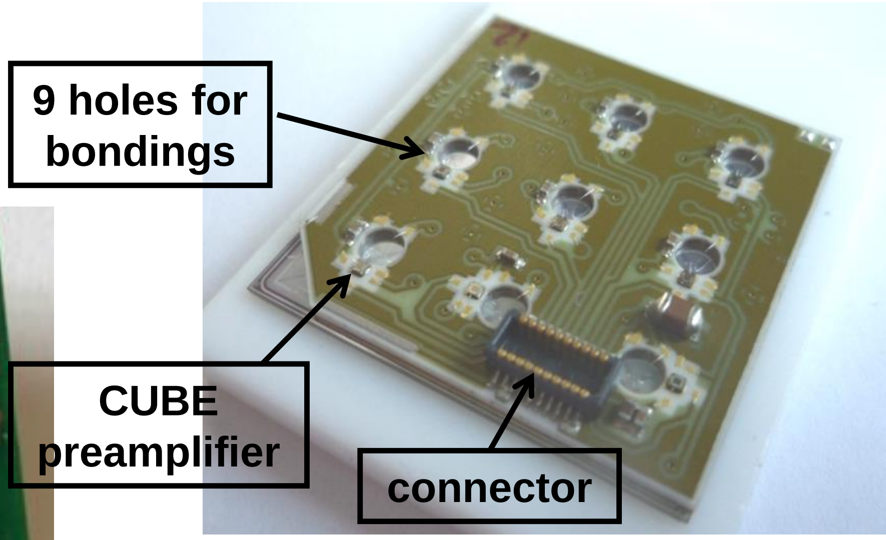
- 4” wafer
- 6” wafer upgrade just finished

The new 4x2 SDD array for K$^-$d

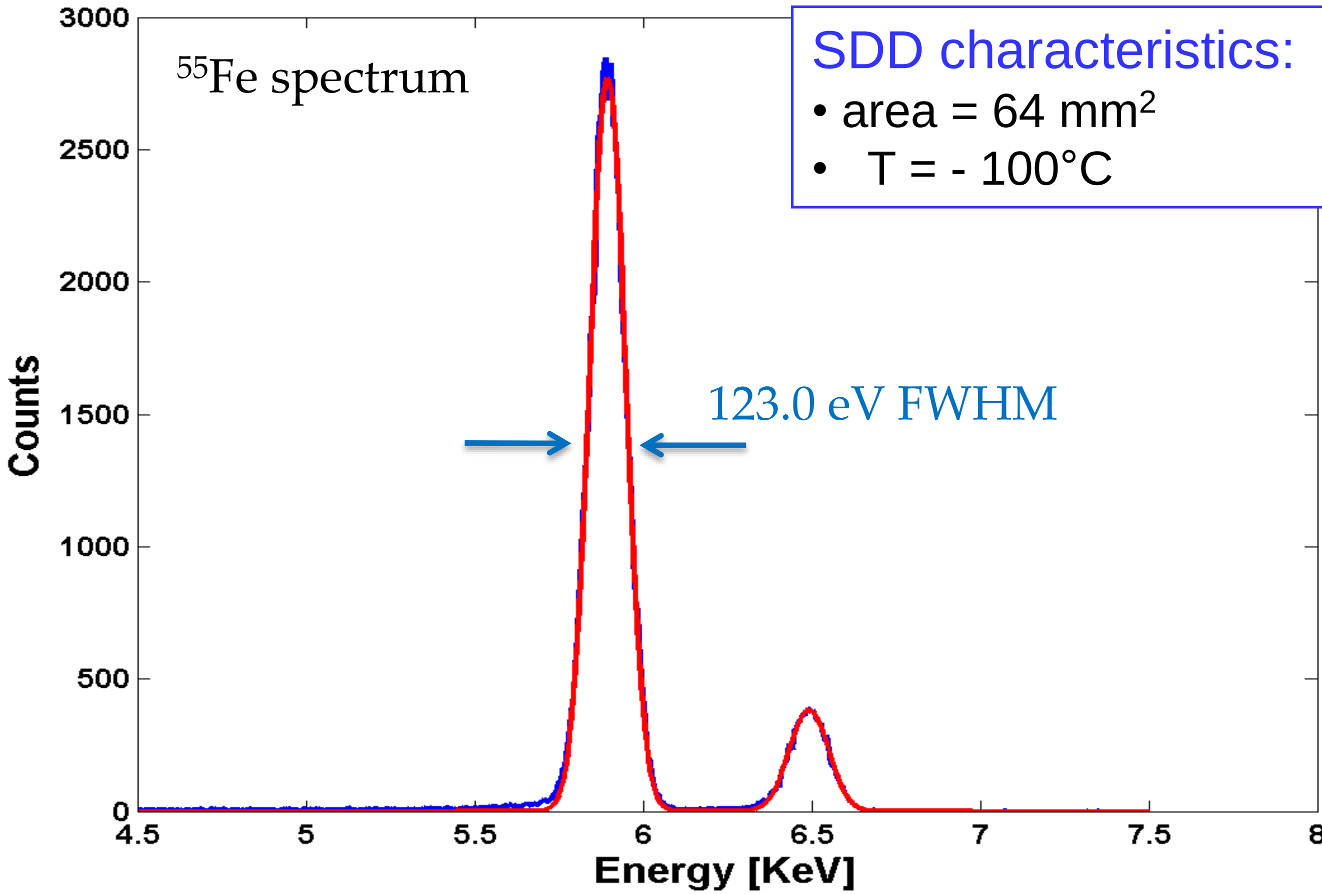


SDD-chip back side with bonding pads

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



New SDD technology with CUBE preamplifier



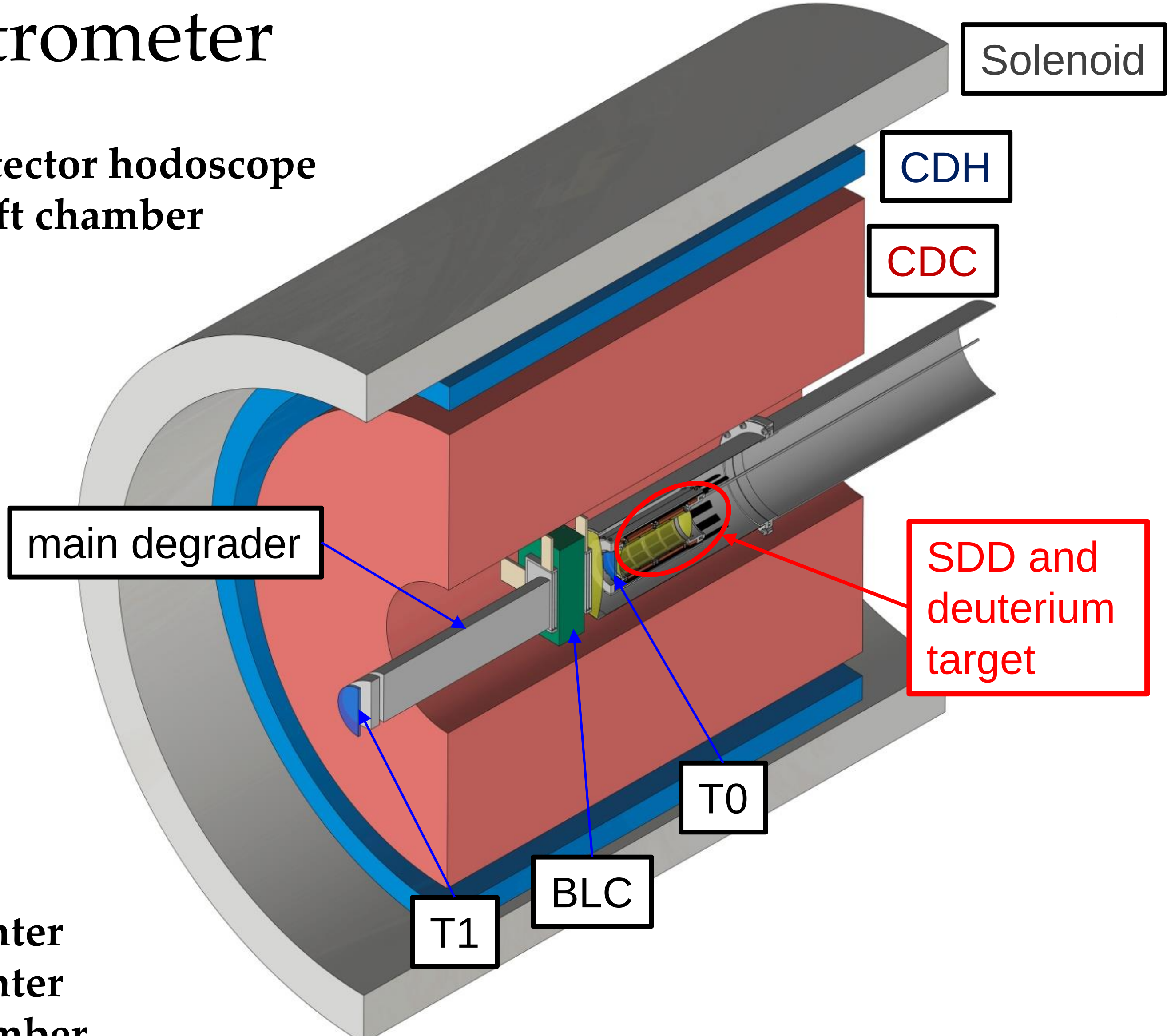
SDD characteristics:

- area = 64 mm^2
- T = - 100°C

first series of new SDD-chips available

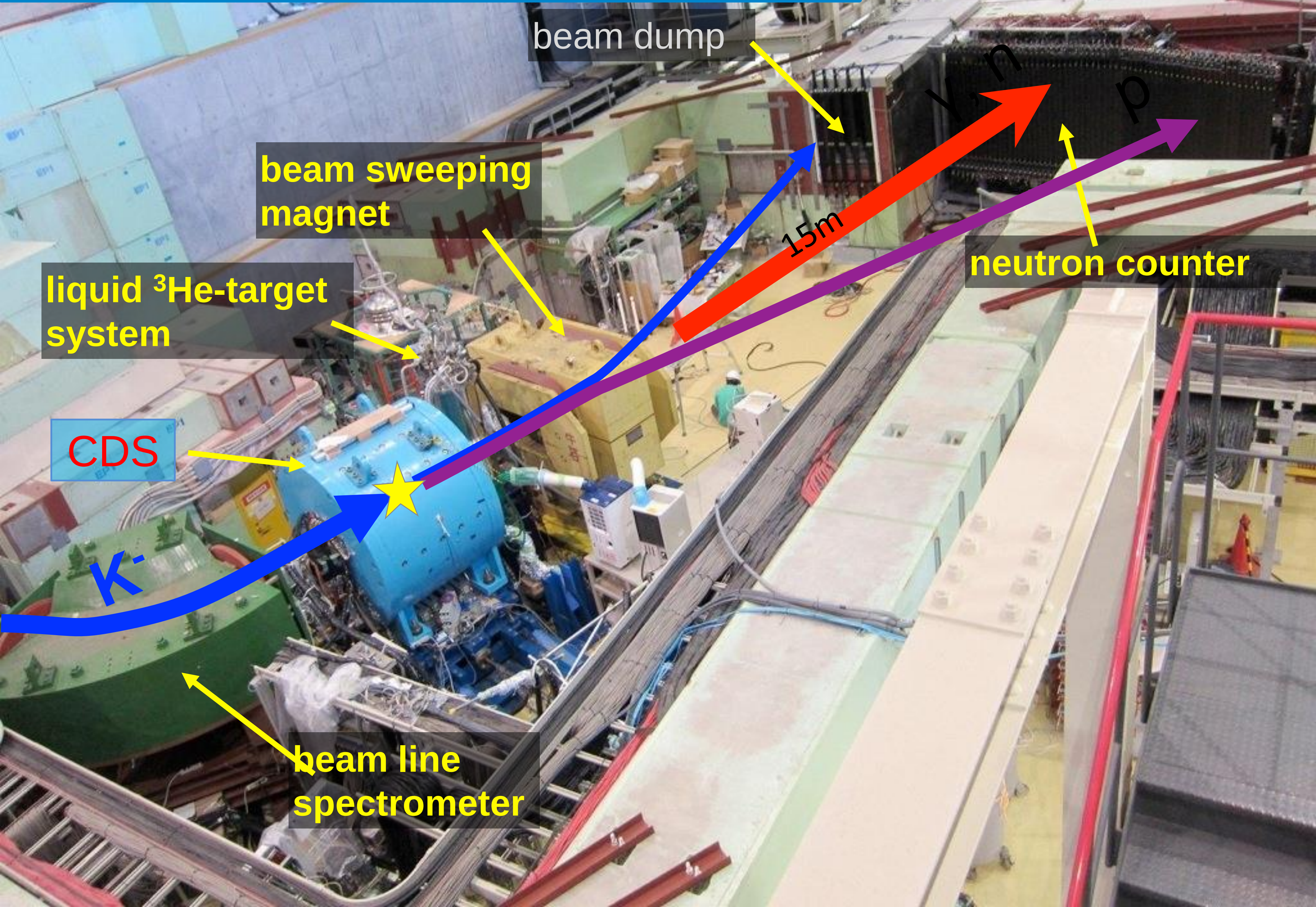
Charged particle tracking with the K1.8BR spectrometer

CDH...cylindrical detector hodoscope
CDC...cylindrical drift chamber



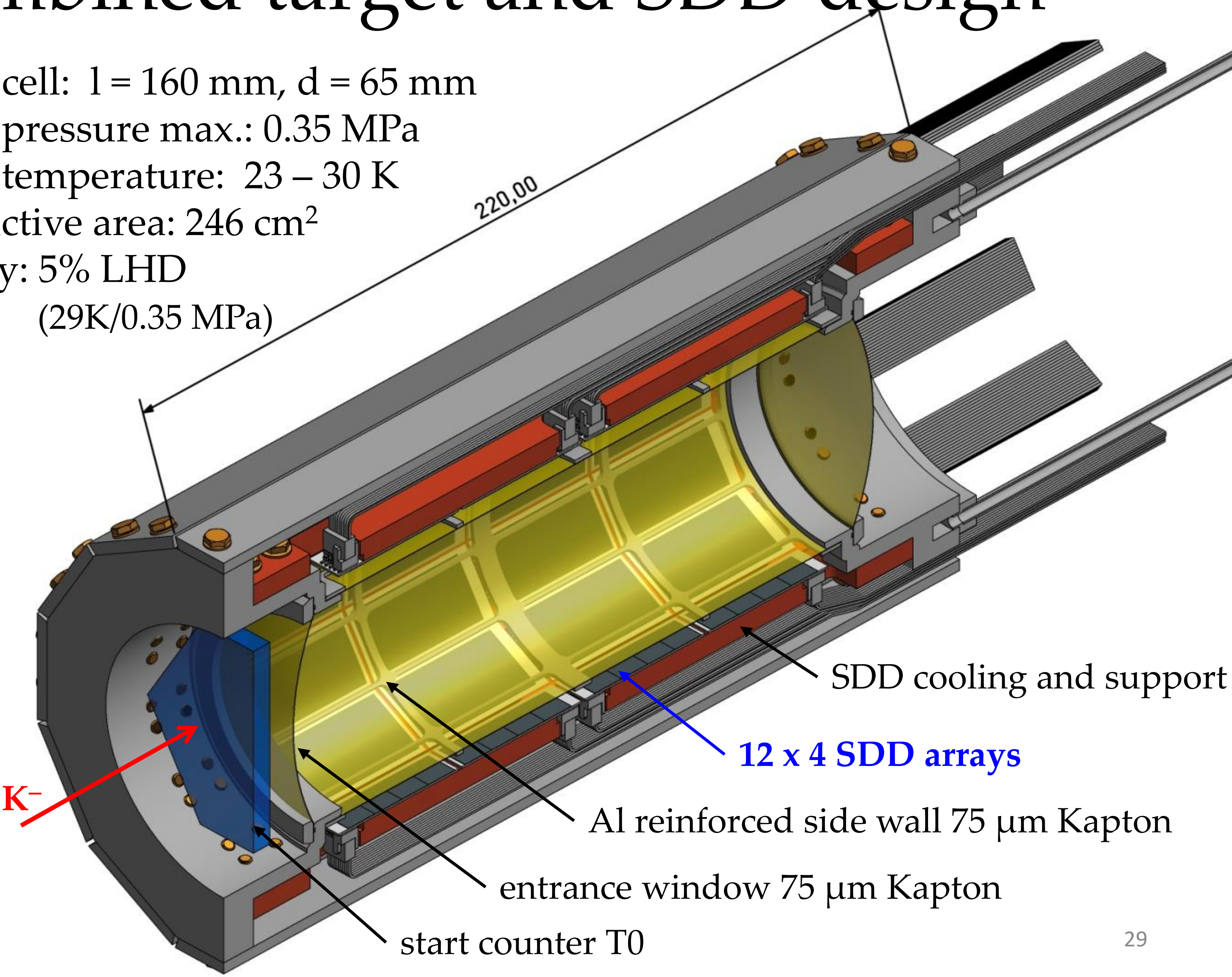
T0.......beam line counter
T1.......beam line counter
BLC....beam line chamber

J-PARC K1.8BR spectrometer

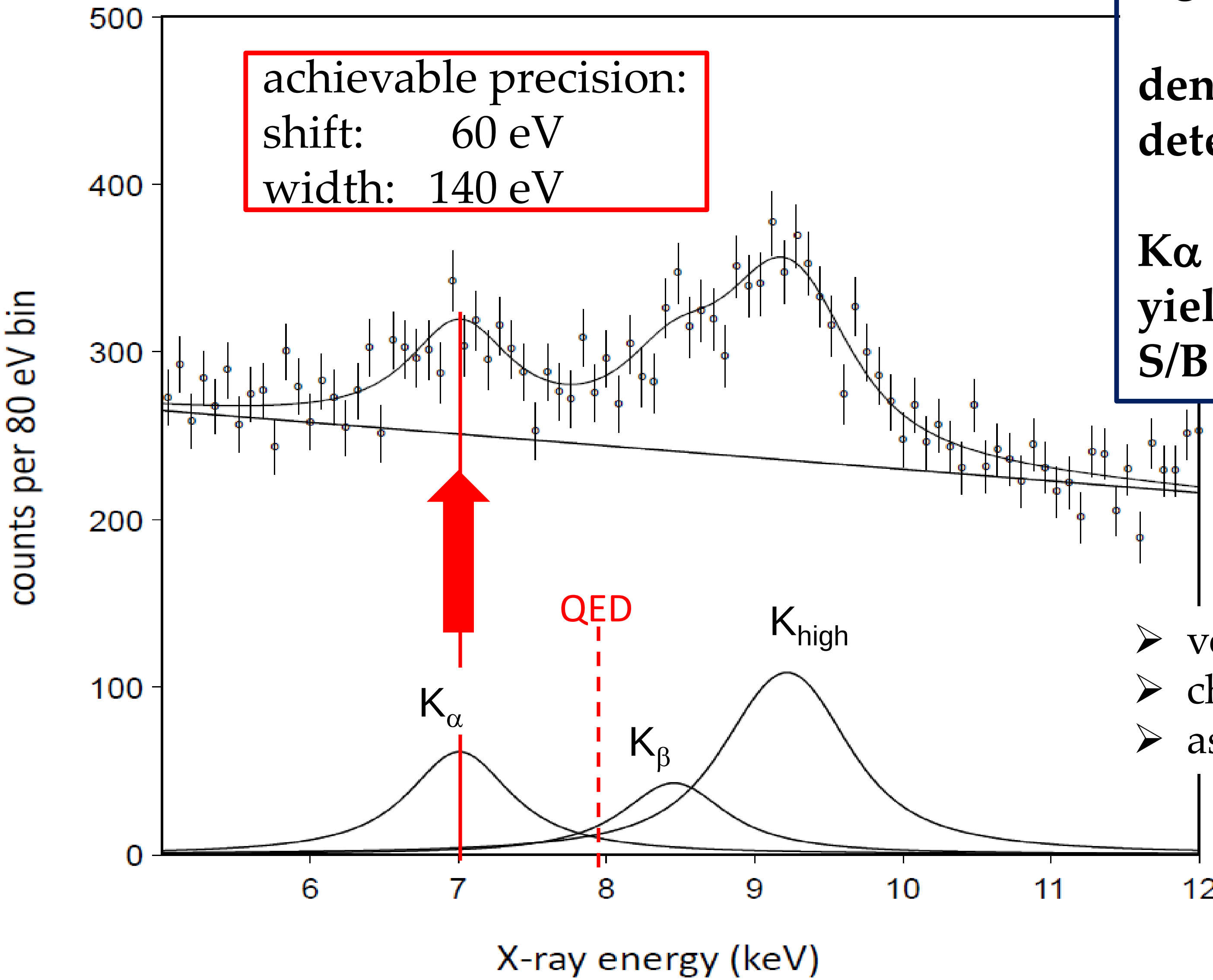


Combined target and SDD design

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)



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

$K^{-}d$ scattering lengths - theory

a_{Kd} [fm]	ε_{1s} [eV]	Γ_{1s} [eV]	Reference
-1.55 + *i* 1.66	- 969	938	Weise 2015 [2]
-1.58 + *i* 1.37	- 887	757	Mizutani 2013 [4]
-1.48 + *i* 1.22	- 787	1011	Shevchenko 2012 [5]
-1.46 + *i* 1.08	- 779	650	Meißner 2011 [1]
-1.42 + *i* 1.09	- 769	674	Gal 2007 [6]
-1.66 + *i* 1.28	- 884	665	Meißner 2006 [7]
-1.62 + *i* 1.91	- 1080	1024	Oset 2001 [3]

for simulation:
shift = - 800 eV
width = 800 eV

[1] M. Döring, U.-G. Meißner, Phys. Lett. B 704 (2011) 663
[2] W. Weise, arXiv:1412.7838[nucl-theo]2015
[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, Nucl. Phys. A 890-891 (2012) 50-61
[6] A. Gal, Int. J. Mod. Phys. A22 (2007) 226
[7] U.-G. Meißner, U. Raha, A. Rusetsky, Eur. phys. J. C47 (2006) 473

SUMMARY

SIDDHARTA@ DAΦNE

X-ray spectra measured with several targets:

- **$K^{-}p$:** provided the most precise values (PLB 704 (2011) 113)
- **$K^{-}d$:** first exploratory measurement (Nuclear Physics A 907 (2013) 69)
- **$K^{-}\,^{3}He$:** first-time measurement (PLB 697 (2011) 199)
- **$K^{-}\,^{4}He$:** measured in gaseous target (PLB 681 (2009) 310)

$K^{-}d$ at J-PARC (E57)

- **stage 1 approval**
  – new SDDs with cryogenic gas target
  – K1.8 BR spectrometer