AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

KAONIC ATOMS AS PROBE FOR LOW-ENERGY QCD

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SIDDHARTA and E57 collaboration
SMI, Vienna, Austria

INPC
Adelaide, AUSTRALIA
11 – 16 September 2016

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OUTLINE

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

WHY STRANGE QUARKS

Strange quarks are neither “light” nor “heavy”

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

High-precision antikaon-nucleon physics at threshold

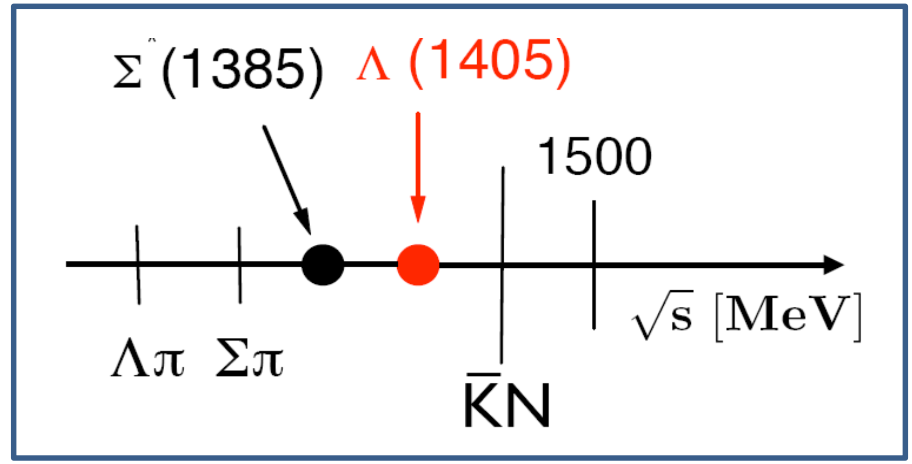
- ➢ nature and structure of $\Lambda(1405)$ B=1; S=-1, $J^P = 1/2^-$
  - three-quark valence structure, or “molecular” meson-baryon state
- ➢ quest for quasi-bound antikaon-NN systems

talks given by: J.Marton - AMADEUS at DAFNE (Friday)
T.Yamaga - E15 at J-PARC
H.Tamura - Hypernuclear Physi

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

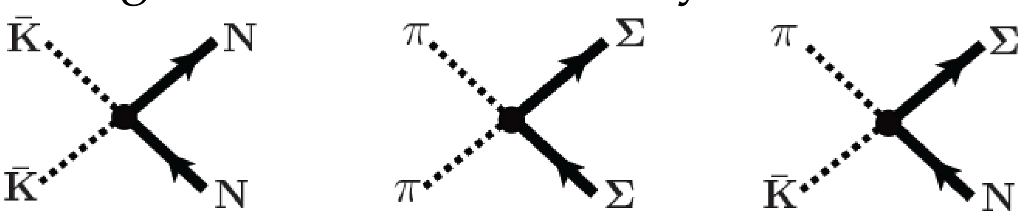
studied in the framework of Chiral SU(3) effective field theory

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

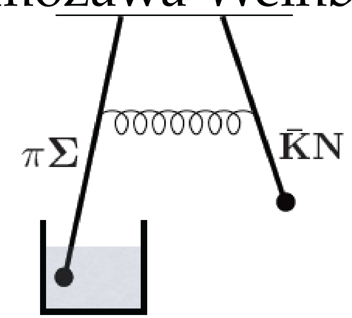


non-perturbative coupled channels approach based on **chiral SU(3) dynamics**

leading s-wave I=0 meson-baryon interactions (Tomozawa-Weinberg)



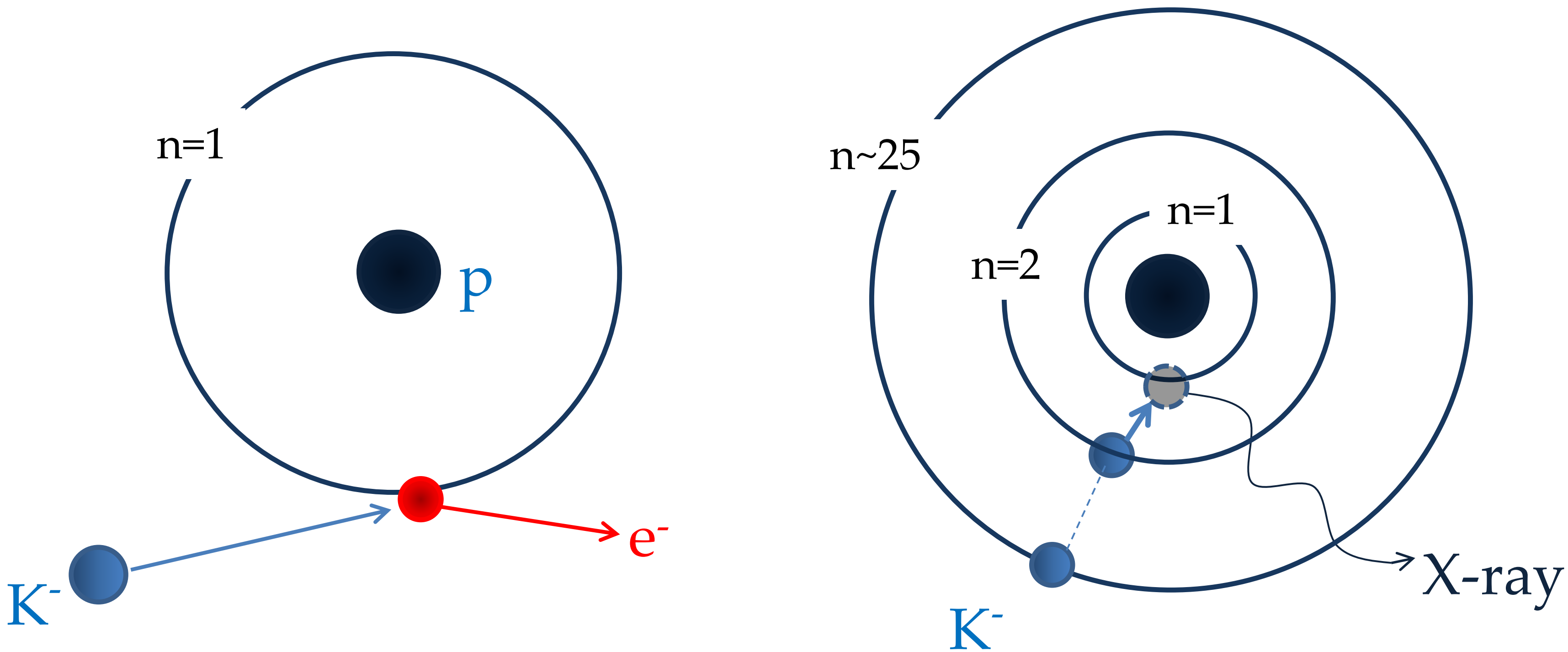
channel coupling



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

FORMING "EXOTIC" ATOMS

"normal" hydrogen | "exotic" (kaonic) hydrogen

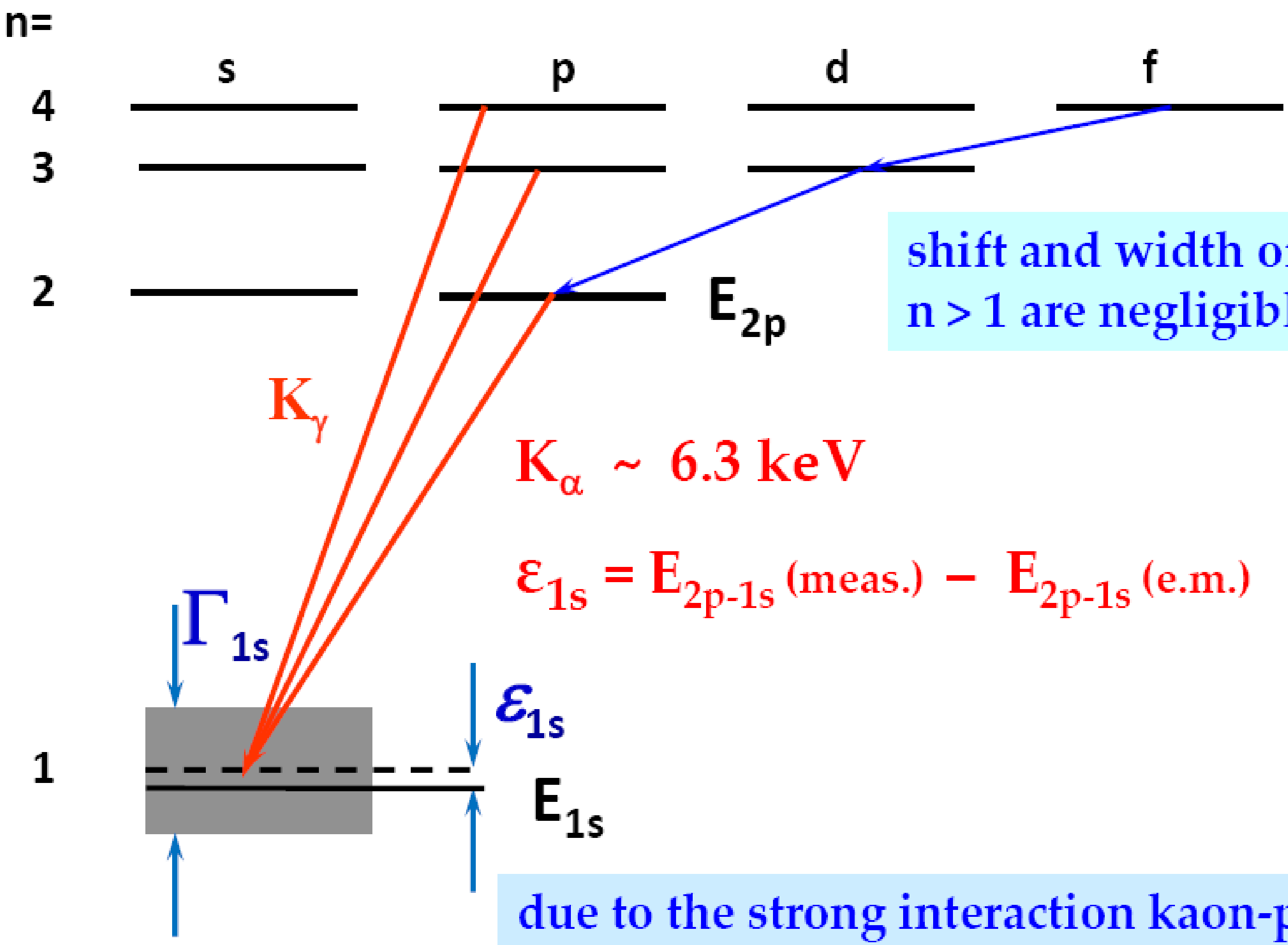


$$n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e$$

$2p \rightarrow 1s$

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

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

(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

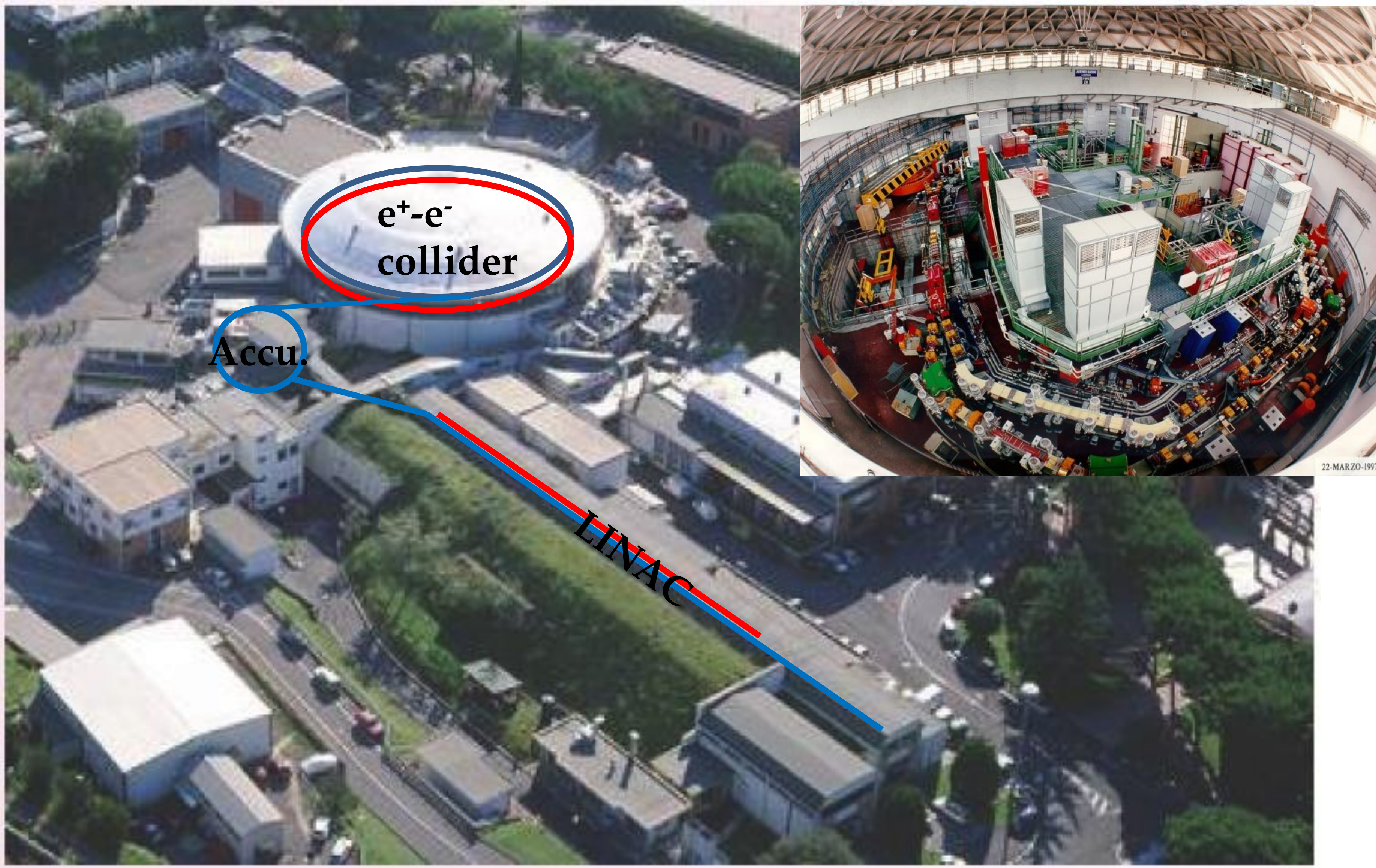
$$a_{K^-p} = \frac{1}{2}\left[a_0 + a_1\right]$$

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

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

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

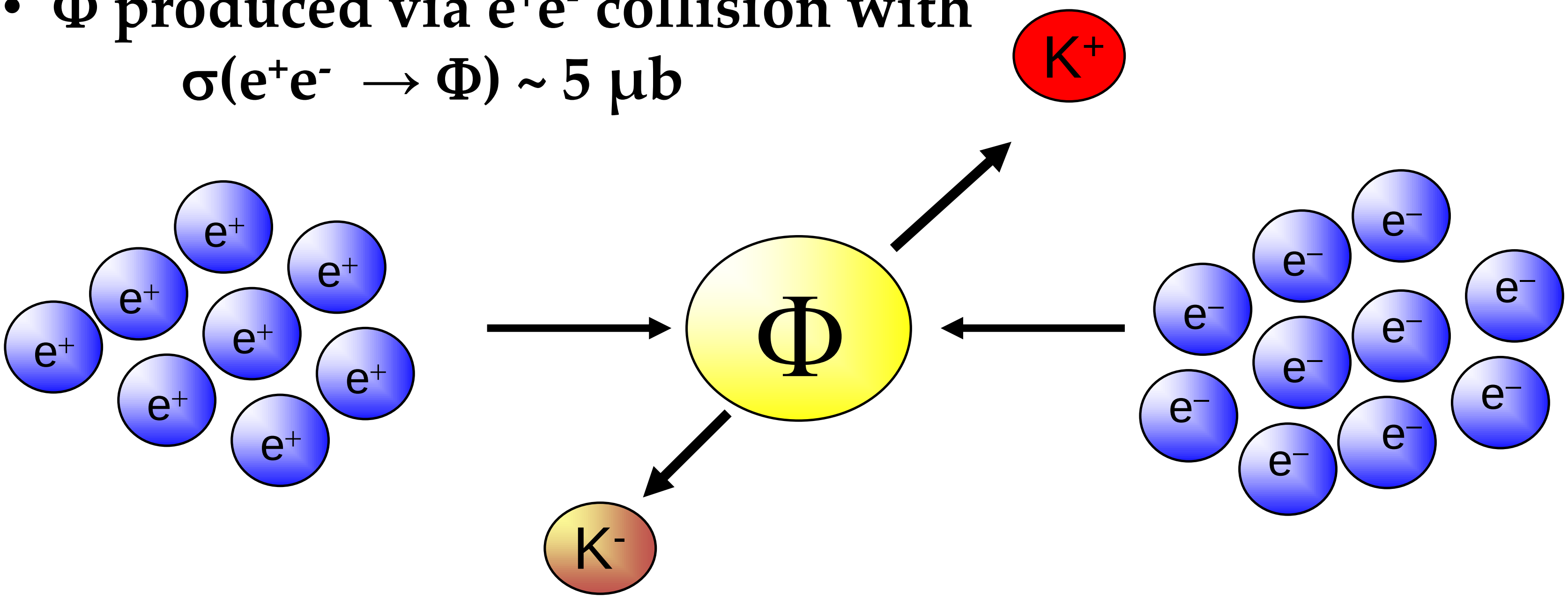
KAONIC HYDROGEN ATOMS AT DAΦNE



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

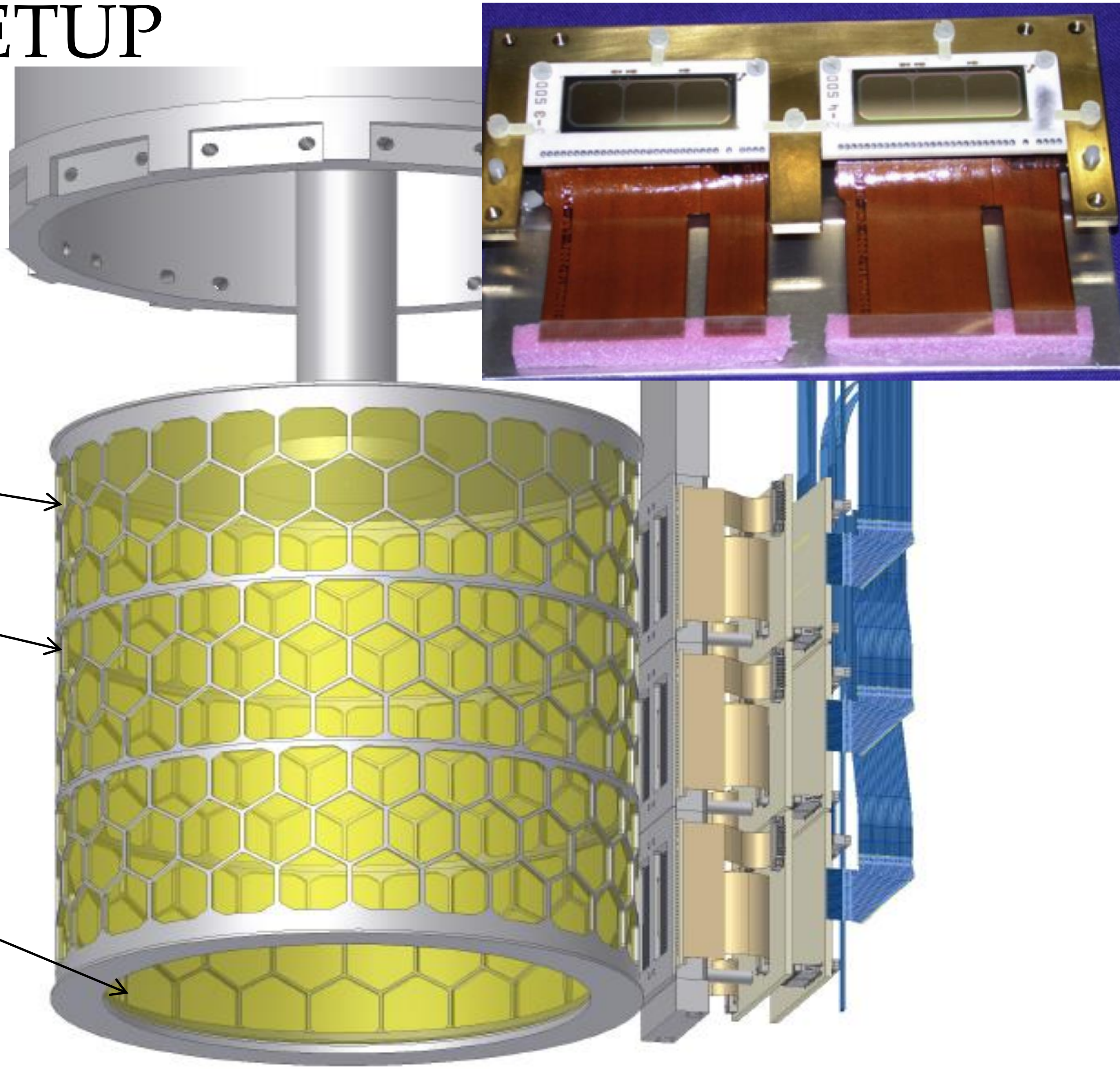
- **Φ produced via e^+e^- collision with**
  $\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$



→ monochromatic kaon beam (127 MeV/c)

SIDDHARTA CRYOGENIC TARGET – DETECTOR SETUP

working T 25 K
working P 1.5 bar

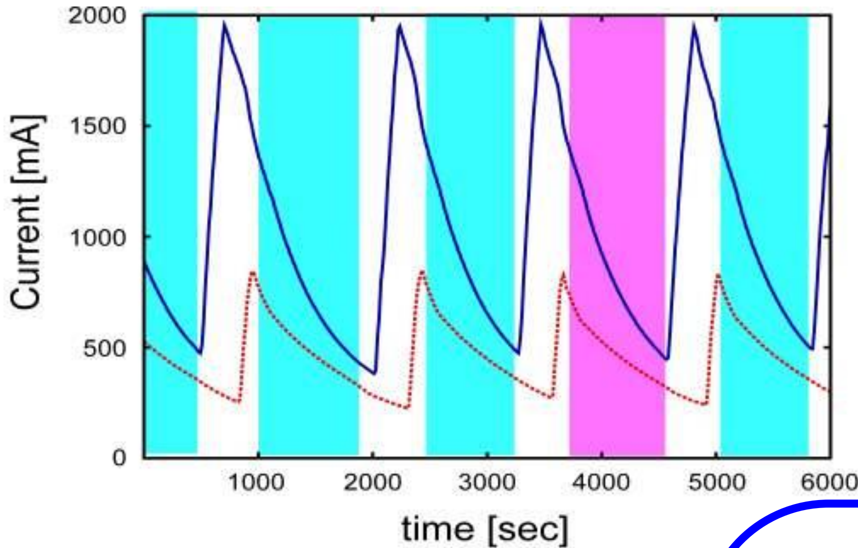


Alu-grid

Side wall: Kapton 50 μm

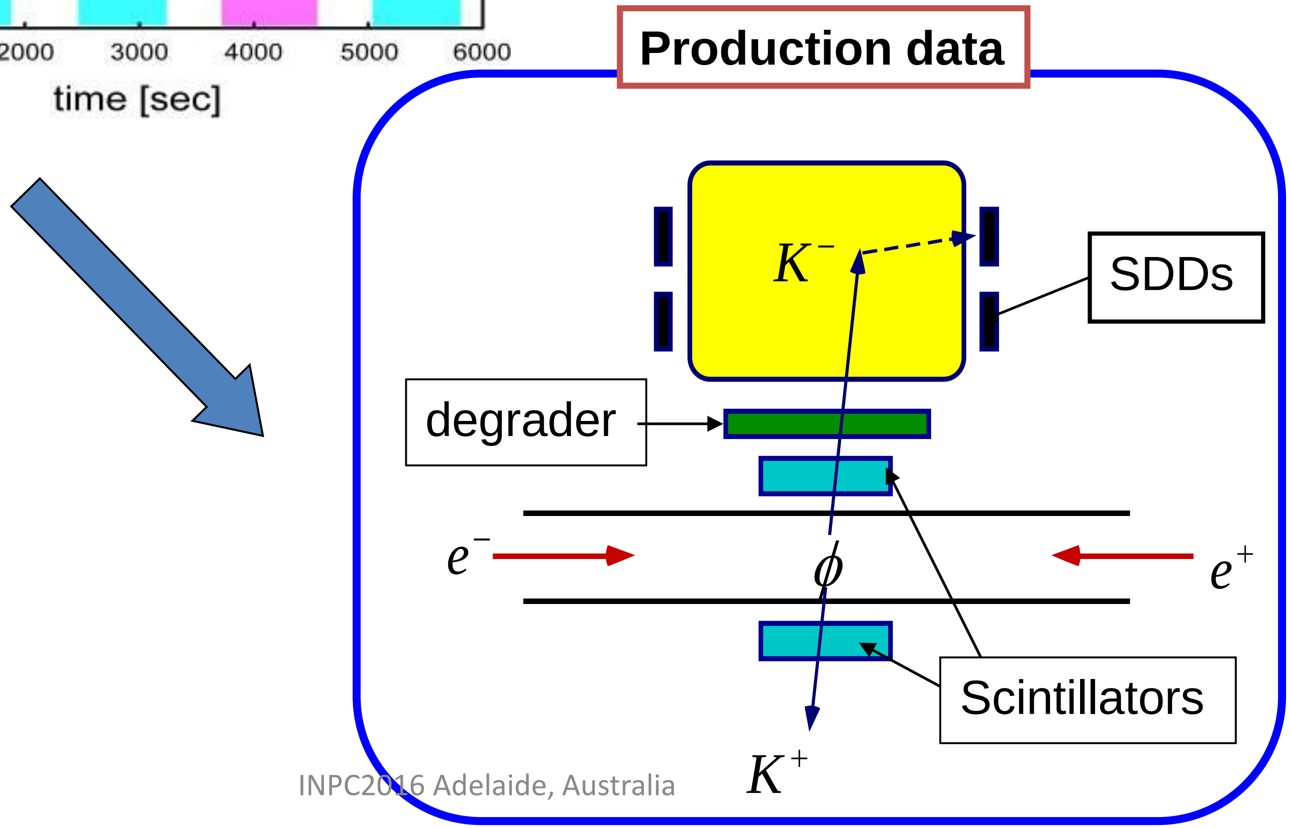
Kaon entrance Window: Kapton 75 μm

DATA TAKING SCHEME

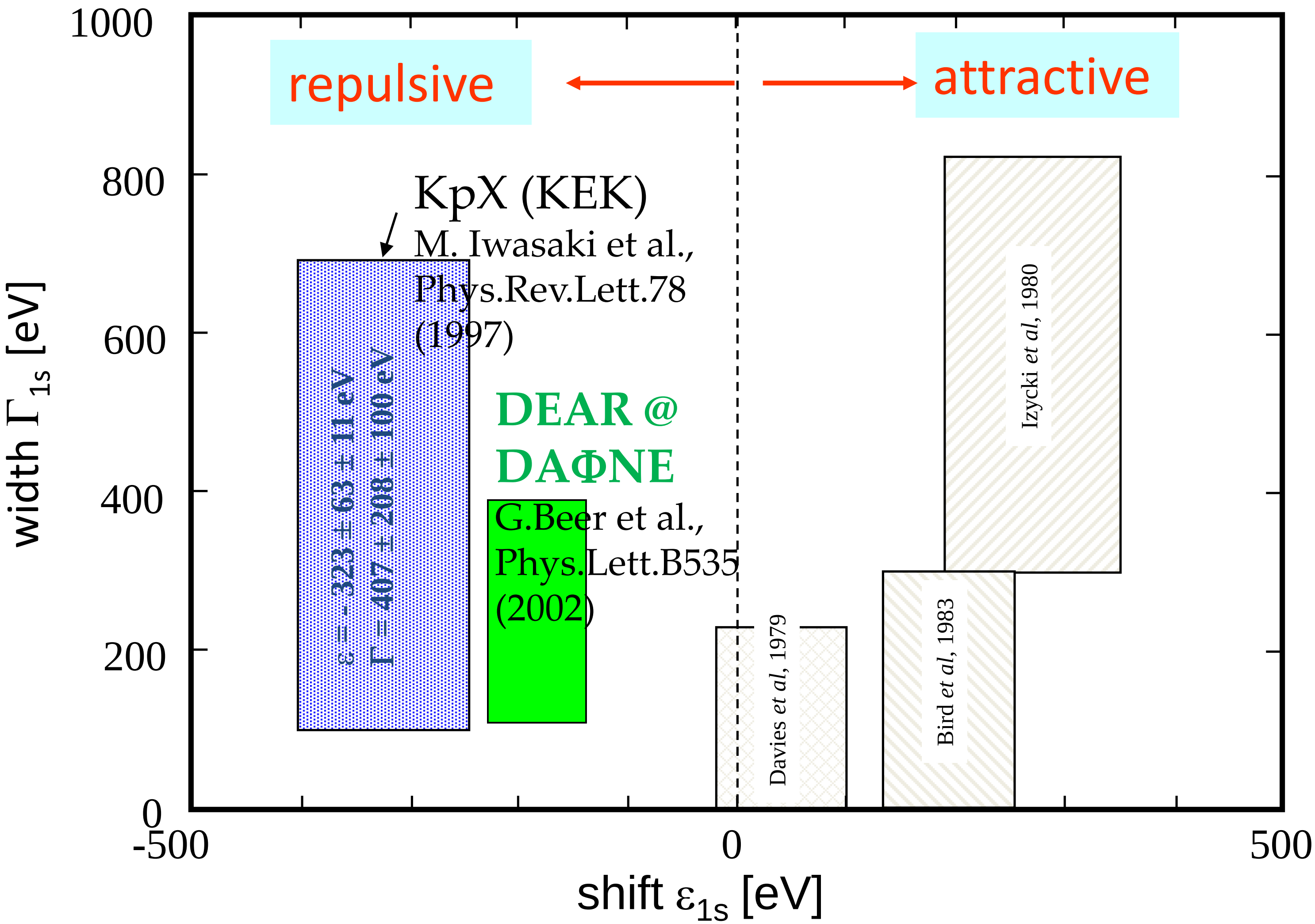


K⁺K⁻ pairs produced at DAΦNE

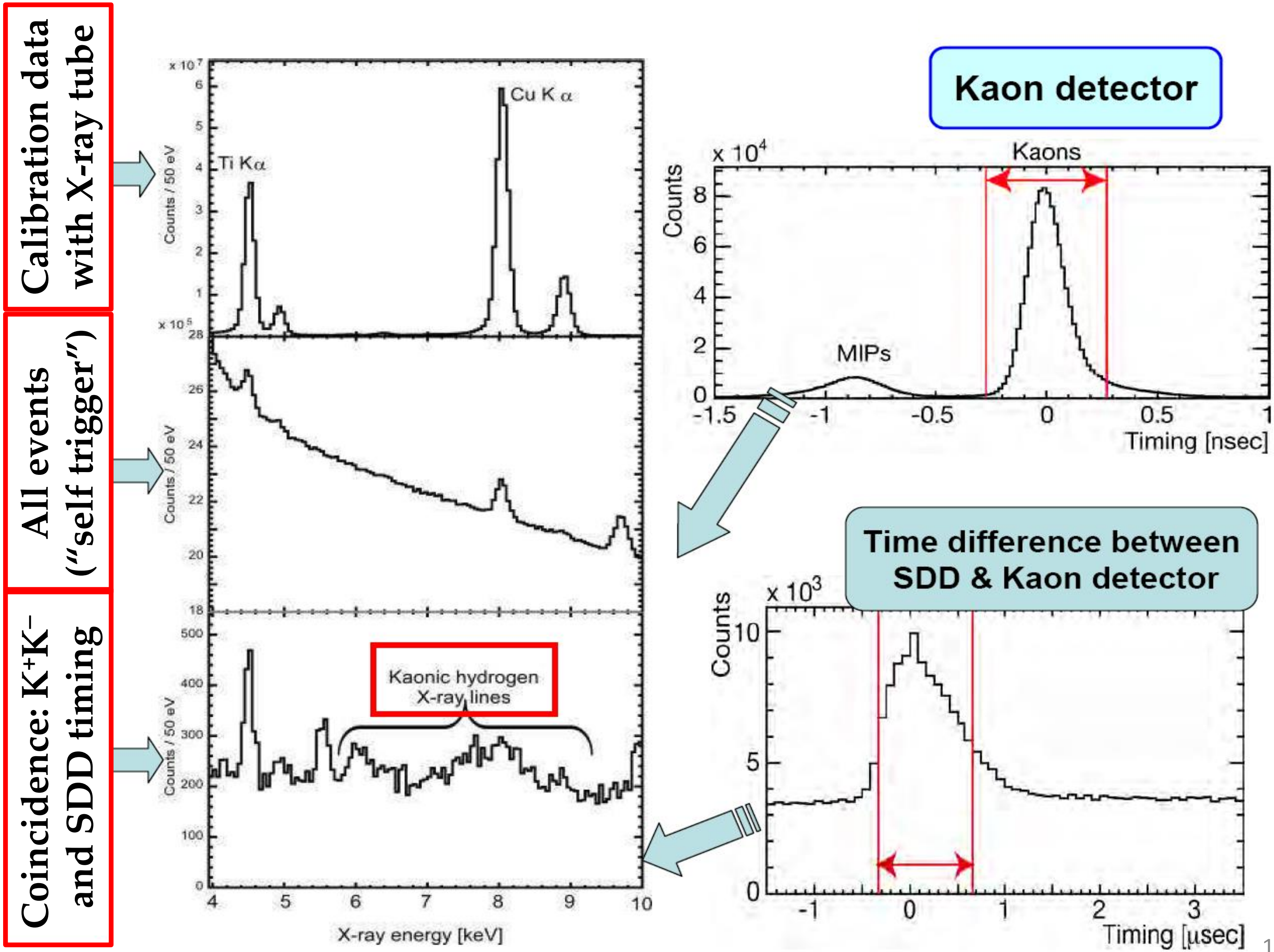
triple coincidence



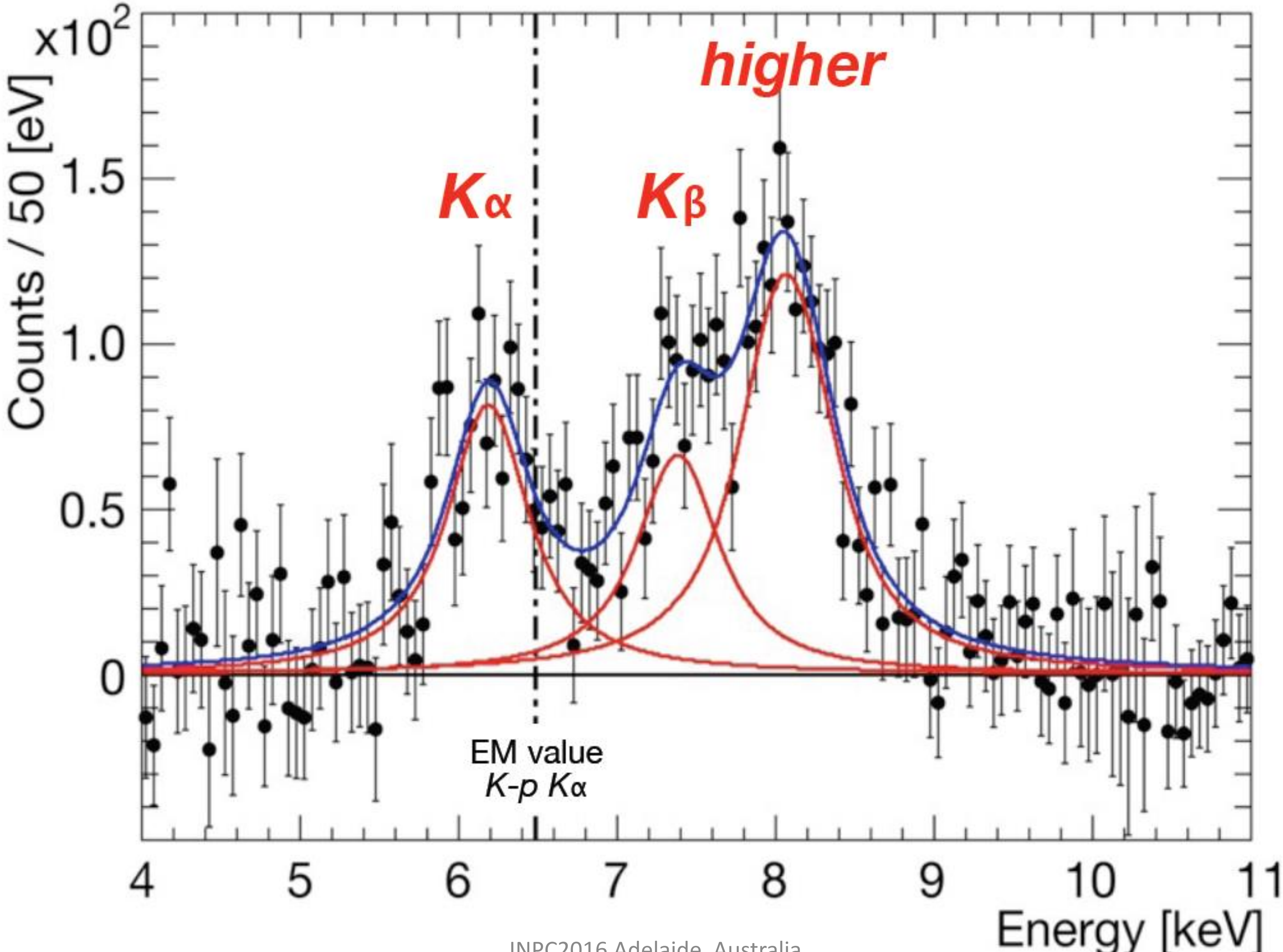
KpX AND DEAR RESULTS



KAONIC HYDROGEN – DATA ANALYSIS



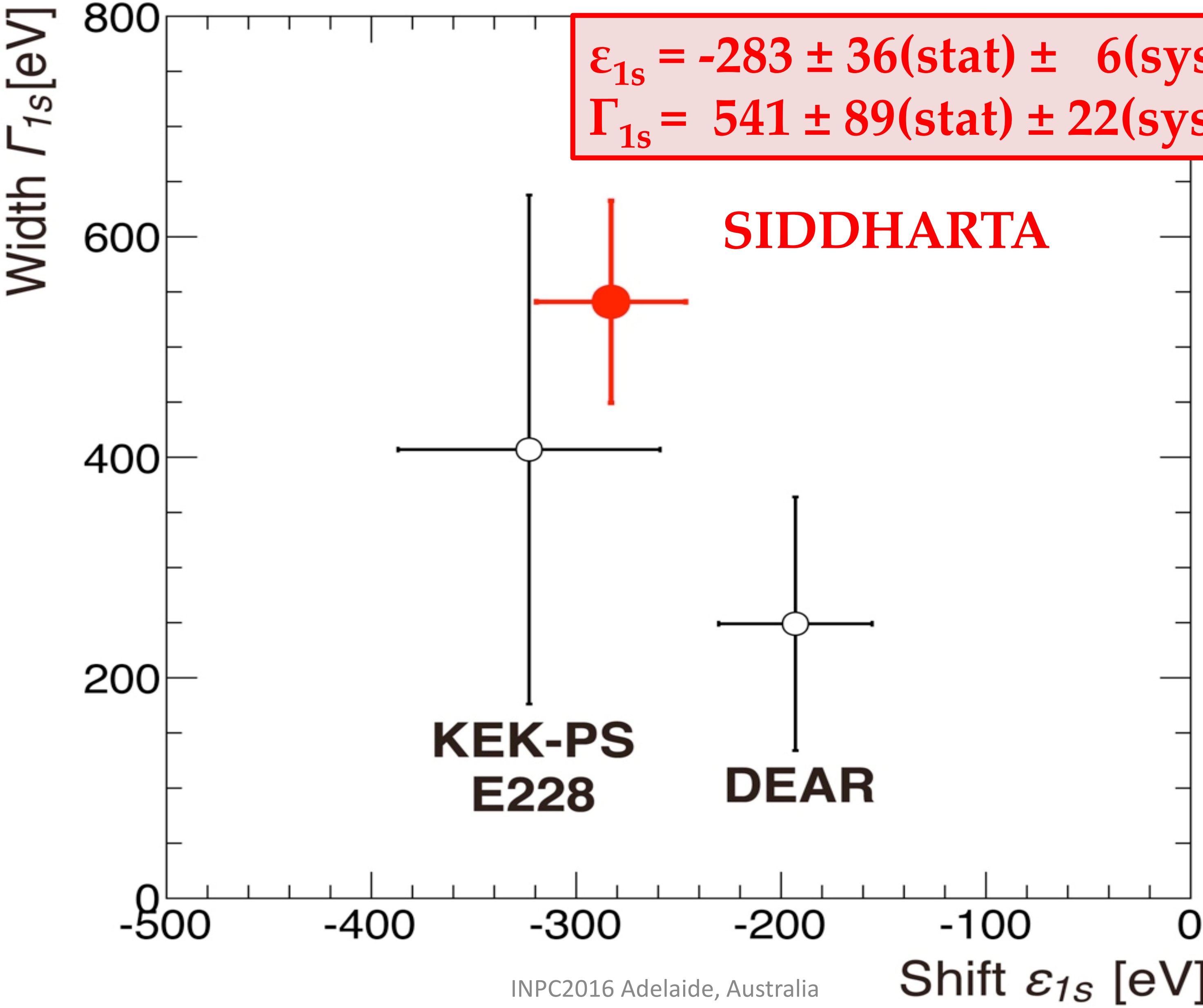
SIDDHARTA KAONIC HYDROGEN RESULT



KAONIC HYDROGEN

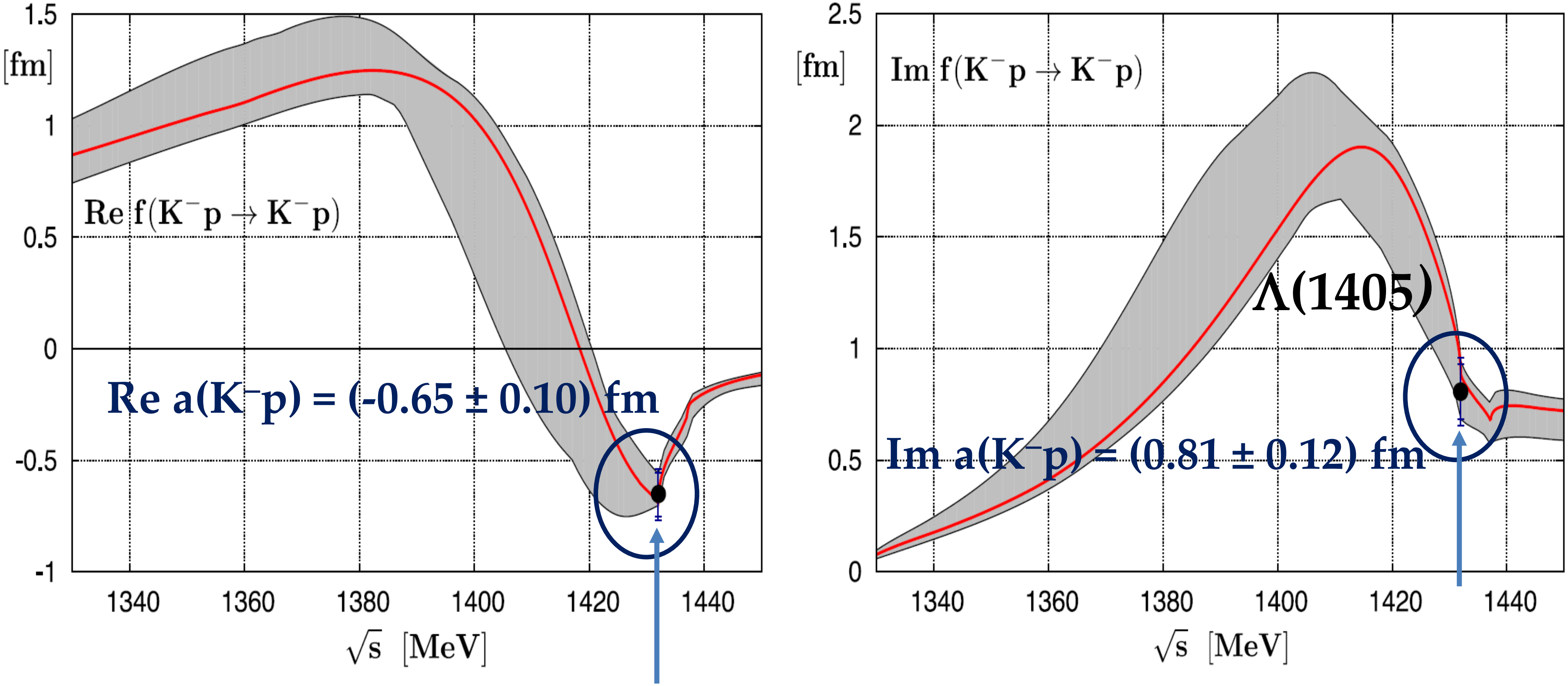
ε_{1s} = -283 ± 36(stat) ± 6(syst) eV

Γ_{1s} = 541 ± 89(stat) ± 22(syst) eV



Improved constraints on chiral SU(3) coupled channels dynamics from SIDDHARTA kaonic hydrogen:

Y. Ikeda, T. Hyodo and W. Weise, PLB 706 (2011) 63, NPA881 (2012) 98



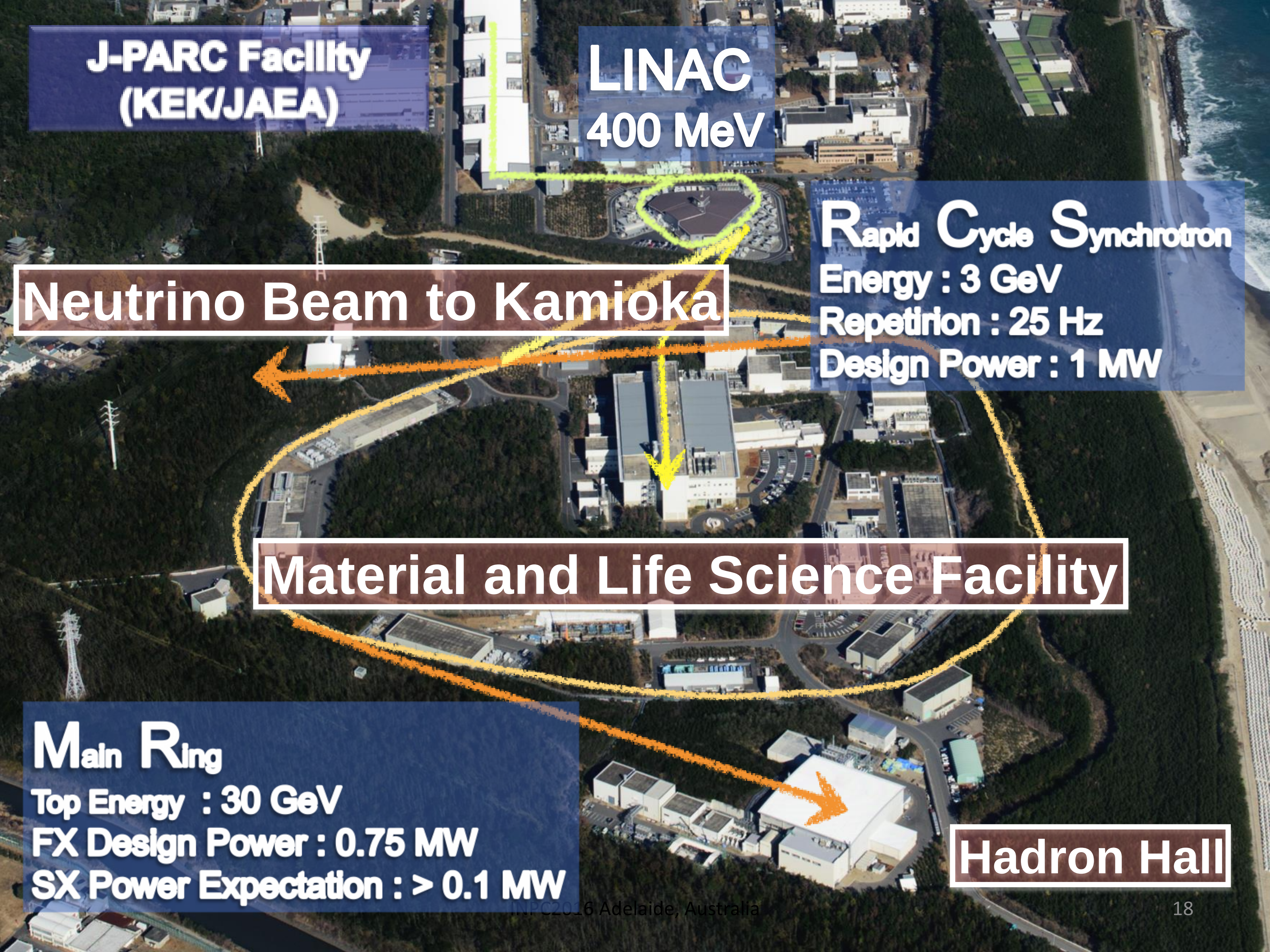
Real part (left) and imaginary part (right) of the $K^-p \to K^-p$ forward scattering amplitude extrapolated to the subthreshold region, deduced from the SIDDHARTA kaonic hydrogen measurement.

K-d at J-PARC

K–d collaboration

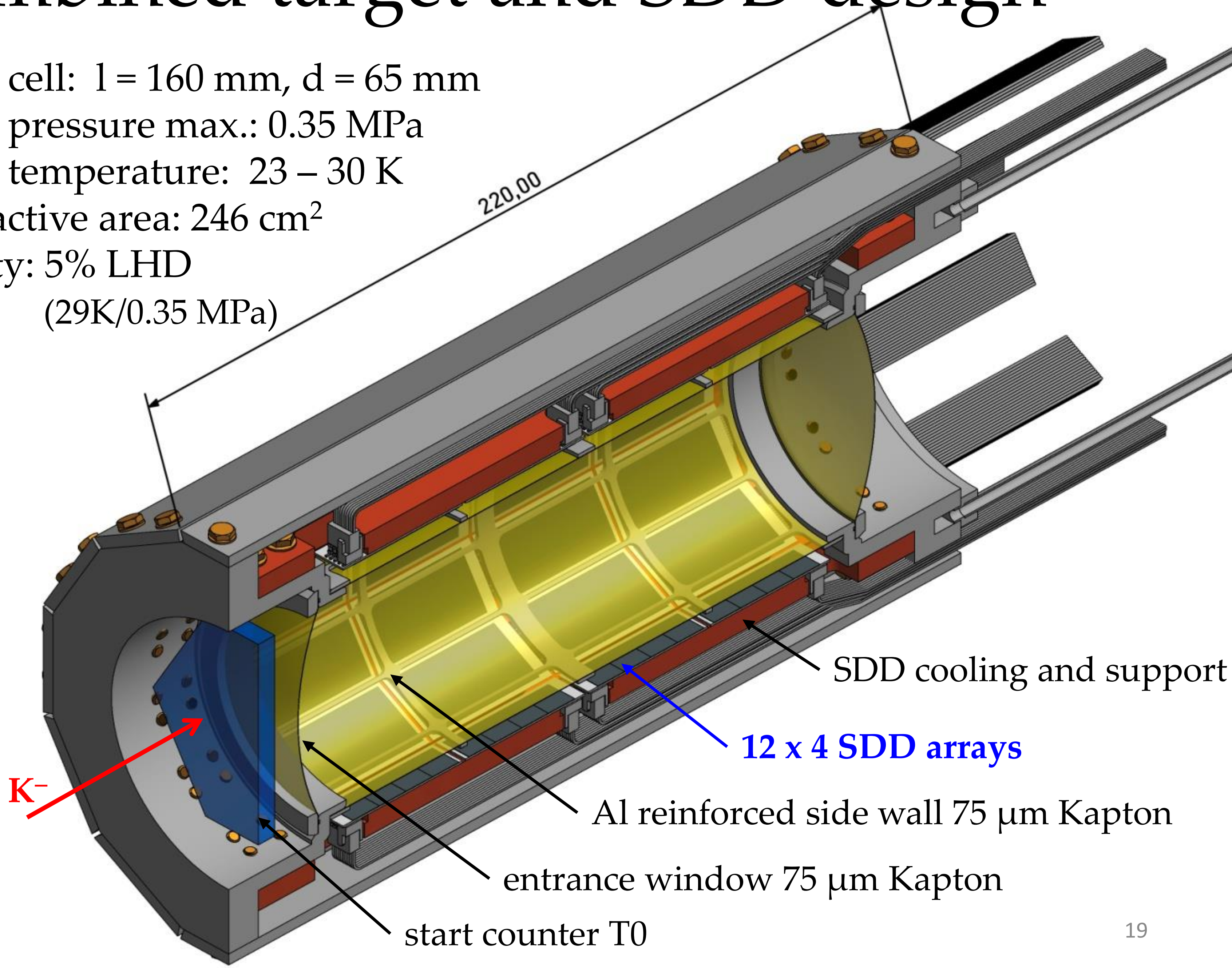
LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
IFIN – HH, Bucharest, Romania
Politecnico, Milano, Italy
RIKEN, Japan
Tokyo Univ., Japan
Victoria Univ., Canada
KEK, Tsukuba, Japan
RCNP, Osaka, Japan
Seoul Univ., South Korea
Zagreb Univ., Croatia
INFN, Torino, Italy
Osaka Univ., Japan
TUM, Garching, 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

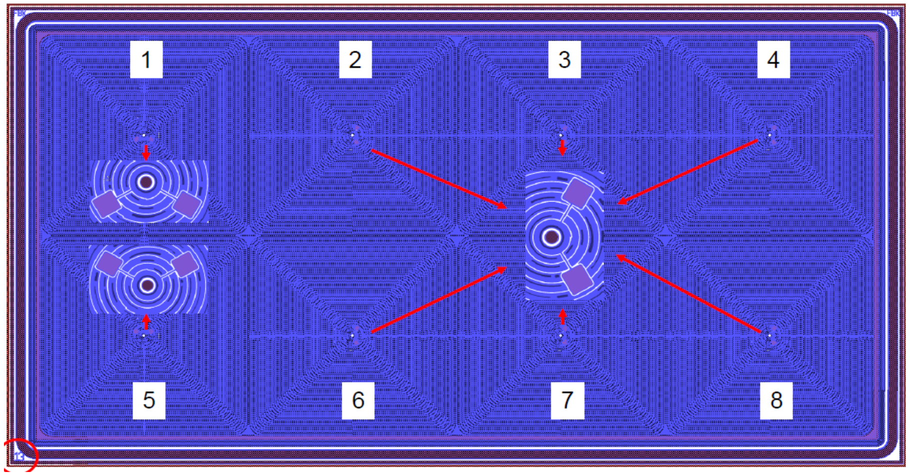

J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetirion : 25 Hz
Design Power : 1 MW
Neutrino Beam to Kamioka
Material and Life Science Facility
Main Ring
Top Energy : 30 GeV
FX Design Power : 0.75 MW
SX Power Expectation : > 0.1 MW
Hadron Hall

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)

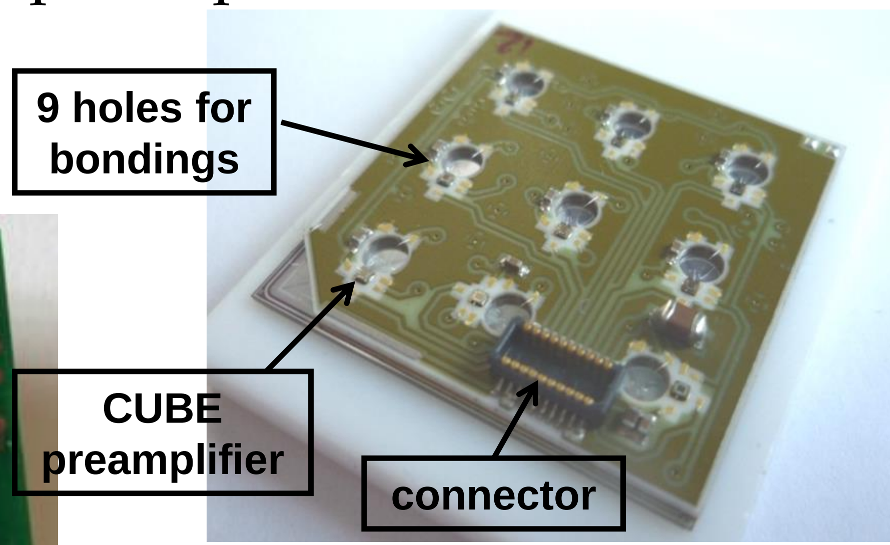


The new 4x2 SDD array for K⁻d

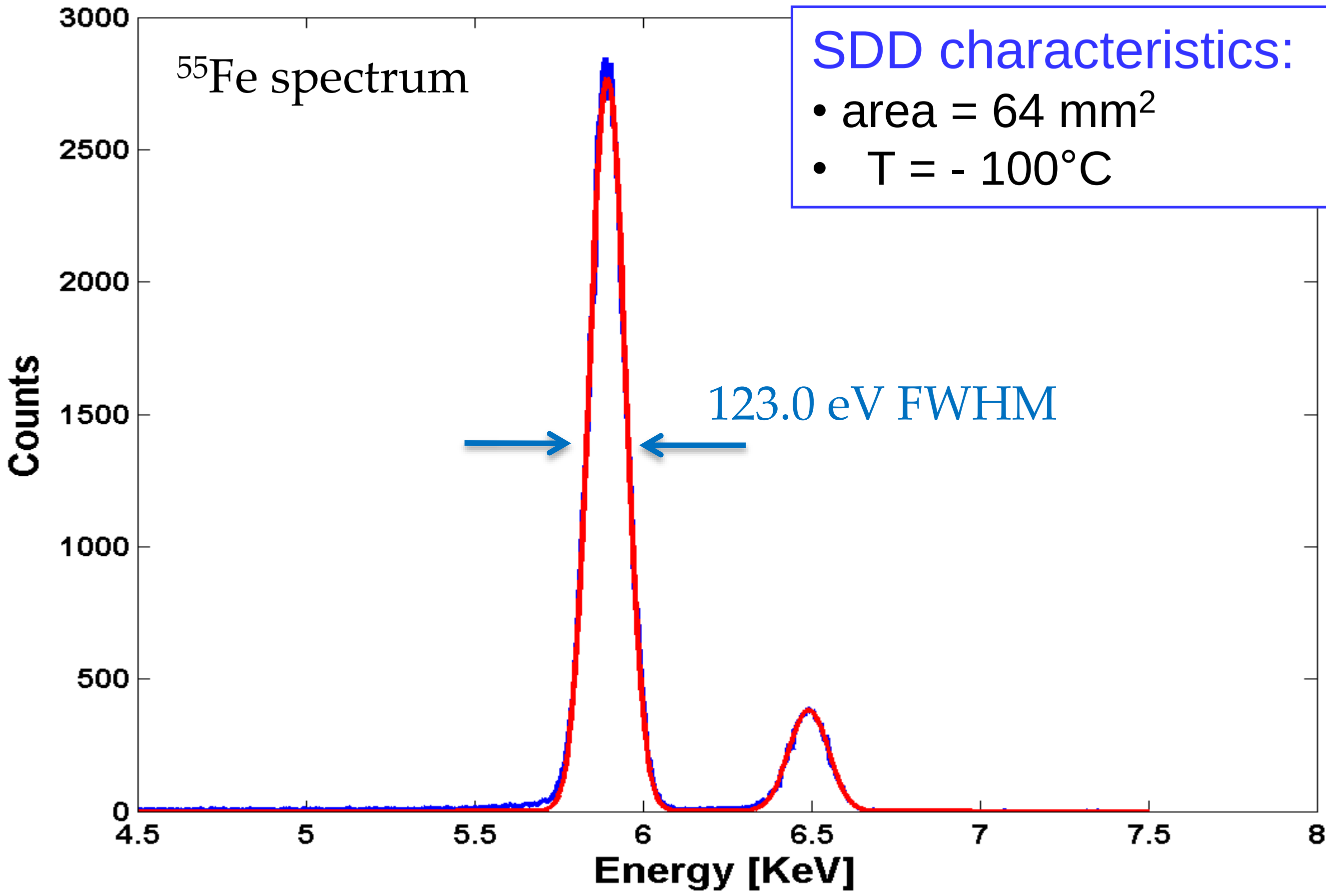


SDD-chip back side with bonding pads

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

→ new SDD-chips available

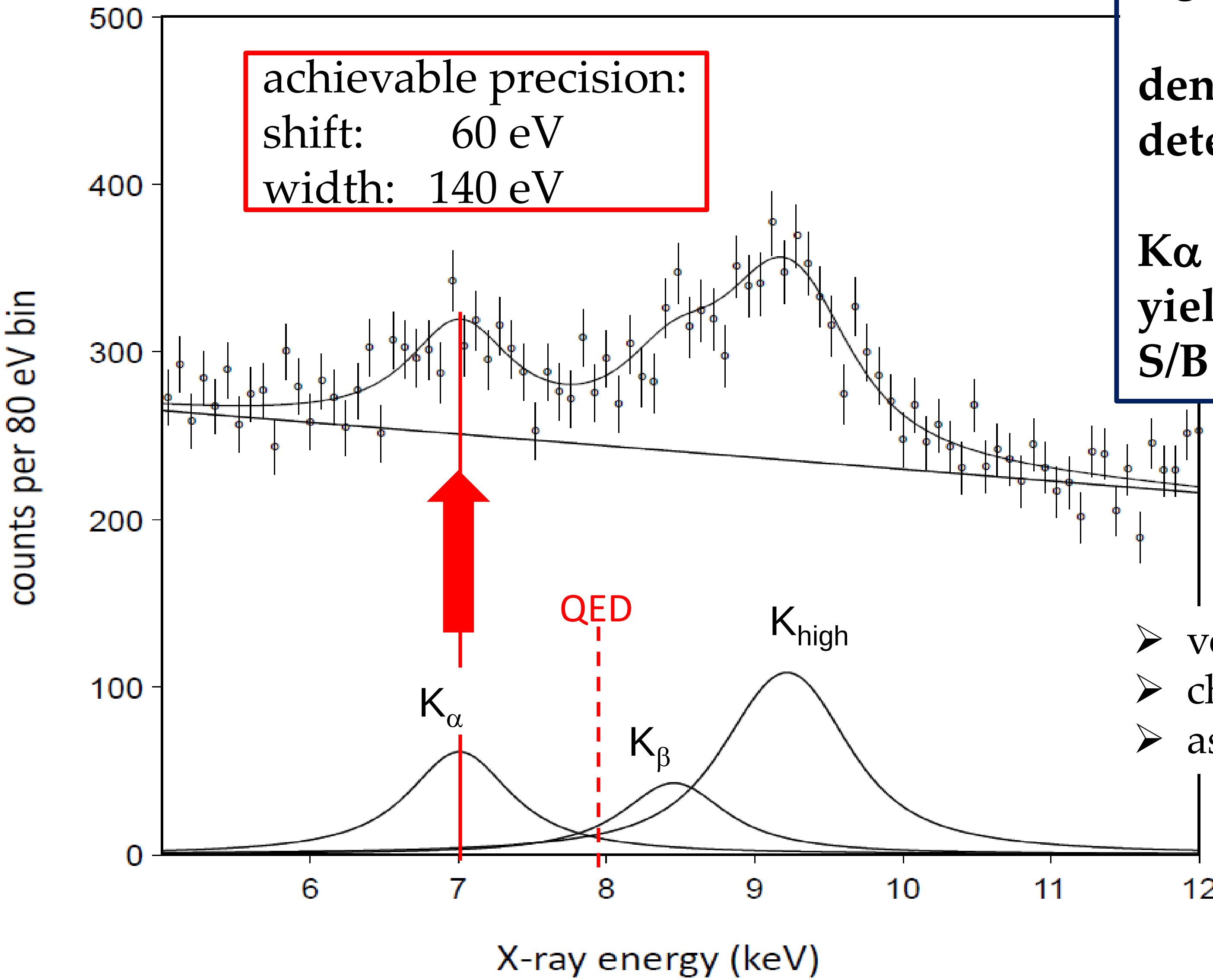
K^-d scattering lengths - theory

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

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

SUMMARY - OUTLOOK

SIDDHARTA @ DAΦNE

K^-p data set → important input for chiral SU(3) effective field theory

- **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)

➢ **still missing: K^-d data set to determine the K^-n scattering length**

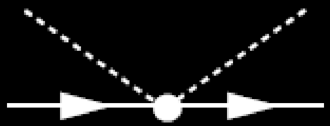
⇒ **Experiment at J-PARC (E57)**
– new SDDs with cryogenic gas target
– K1.8 BR spectrometer

Coupled-channels chiral SU(3) dynamics

Interaction kernels : chiral EFT up to next-to-leading order

Leading order (Tomozawa-Weinberg) term : O(p)

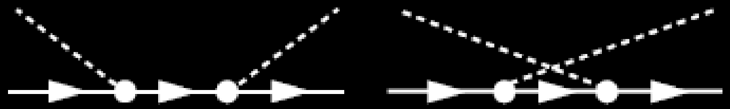
$$\mathcal{L}^{\mathrm{TW}} = \frac{i}{8f^2}\mathrm{tr}[\bar{B}\gamma^\mu[v_\mu, B]]$$



input : meson decay constant

Direct and crossed Born terms : O(p)

$$\mathcal{L}^{\mathrm{Born}} = \mathrm{tr}\left(\frac{D}{2}(\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}) + \frac{F}{2}(\bar{B}\gamma^\mu\gamma_5[u_\mu, B])\right)$$

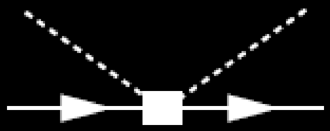


input : axial-vector constants from hyperon beta decays

D=0.80, F=0.46 --> g_A=D+F=1.26

Next-to-leading order (NLO) terms : O(p^2)

$$\begin{aligned}\mathcal{L}^{\mathrm{NLO}} = & b_D\mathrm{tr}(\bar{B}\{\chi_+, B\}) + b_F\mathrm{tr}(\bar{B}[\chi_+, B]) + b_0\mathrm{tr}(\bar{B}B)\mathrm{tr}(\chi_+) \\ & + d_1\mathrm{tr}(\bar{B}\{u^\mu, [u_\mu, B]\}) + d_2\mathrm{tr}(\bar{B}[u^\mu, [u_\mu, B]]) \\ & + d_3\mathrm{tr}(\bar{B}u^\mu)\mathrm{tr}(u_\mu B) + d_4\mathrm{tr}(\bar{B}B)\mathrm{tr}(u^\mu u_\mu)\end{aligned}$$



input : 7 low energy constants

(b_D, b_F, b_0, d_1, d_2, d_3, d_4)

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	$541 \pm 89 \pm 22$

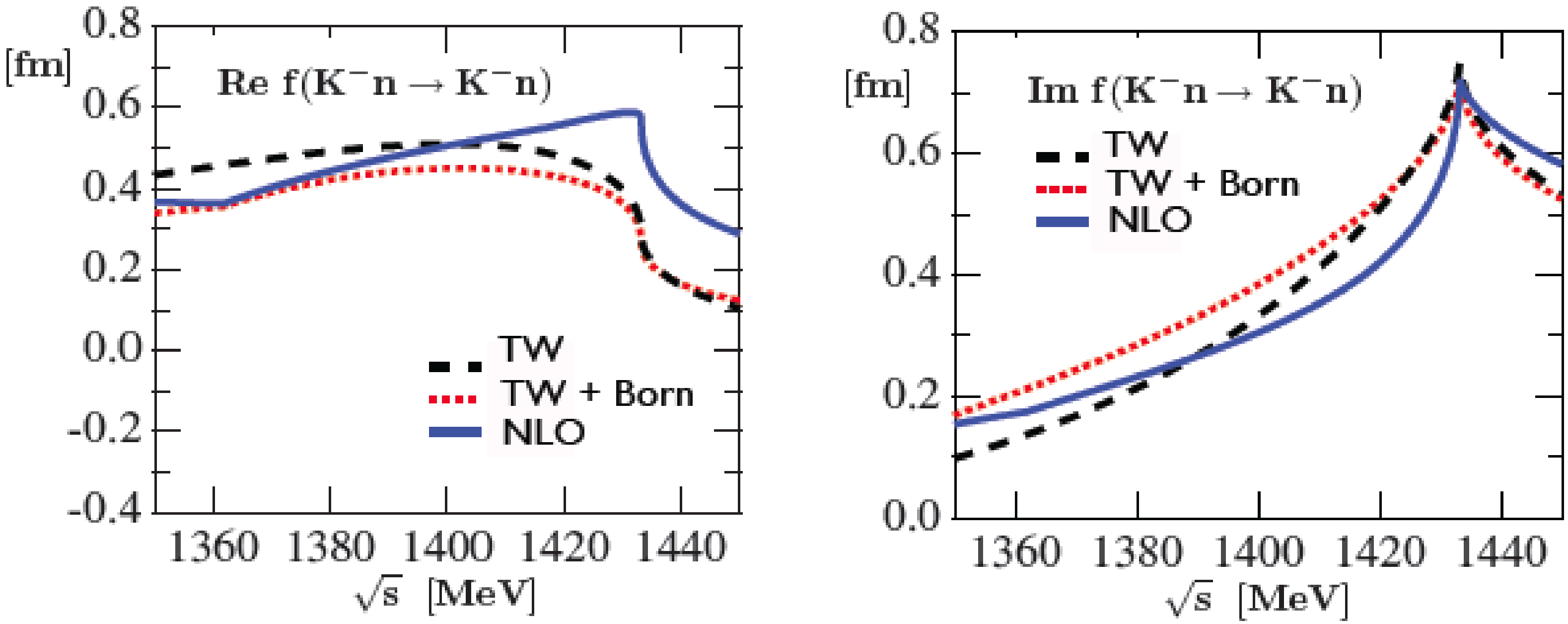
threshold branching ratios		
$\frac{\Gamma(K^- p \to \pi^+ \Sigma^-)}{\Gamma(K^- p \to \pi^- \Sigma^+)}$	2.36	2.36 ± 0.04
$\frac{\Gamma(K^- p \to \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \to all\ inelastic\ channels)}$	0.66	0.66 ± 0.01
$\frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to neutral\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

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

$K^- n$ SCATTERING AMPLITUDE

$$f(K^- n) = f_{\bar{K}N}(I = 1)$$

- threshold region and subthreshold extrapolation



- complex scattering length

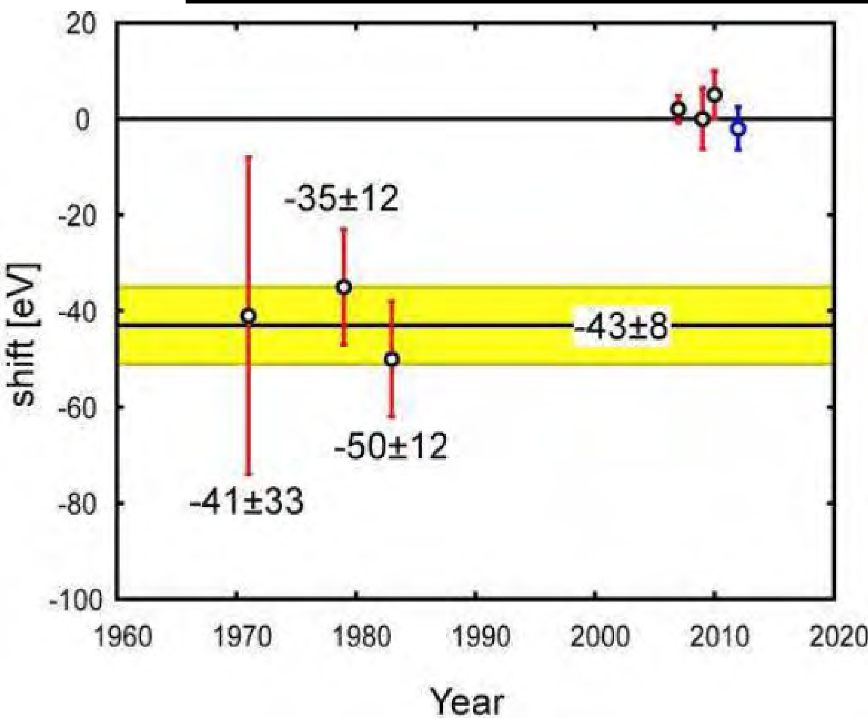
$$\mathrm{Re}\ a(K^- n) = 0.57^{+0.1}_{-0.2}\ \mathrm{fm}$$

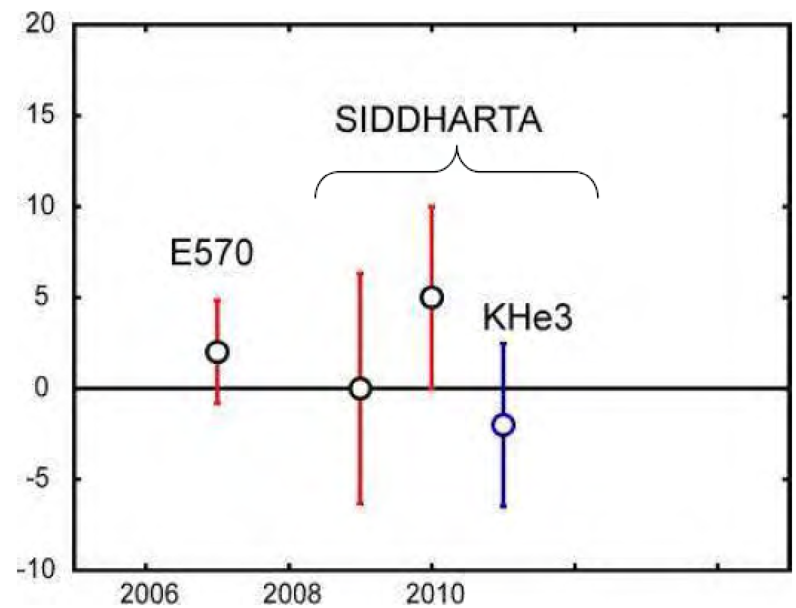
$$\mathrm{Im}\ a(K^- n) = 0.72^{+0.3}_{-0.4}\ \mathrm{fm}$$

Y. Ikeda, T. Hyodo, W.W.: Nucl. Phys. A (2012), in print

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	





J-PARC K1.8BR spectrometer