

Kaonic atoms – status, results and plans

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SIDDHARTA, E57 and E62

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and Strange Particle Physics
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Content

- Motivation
- Charged kaon production
- Status kaonic hydrogen
- Towards kaonic deuterium: SIDDHARTA-2
- Status kaonic helium
- Possible future experiments at DAΦNE

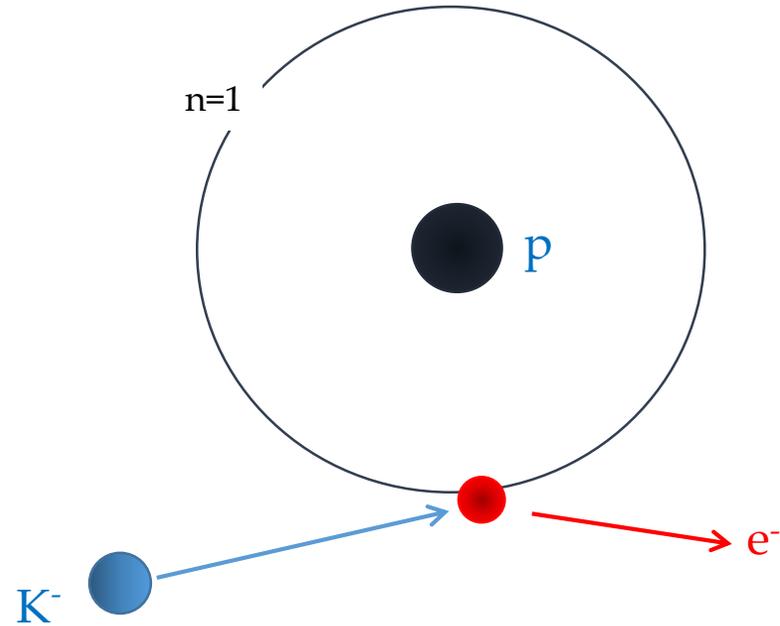
The modern era of light kaonic atom experiments
Rev. Mod. Phys. 91, 025006

Motivation to study hadronic atoms

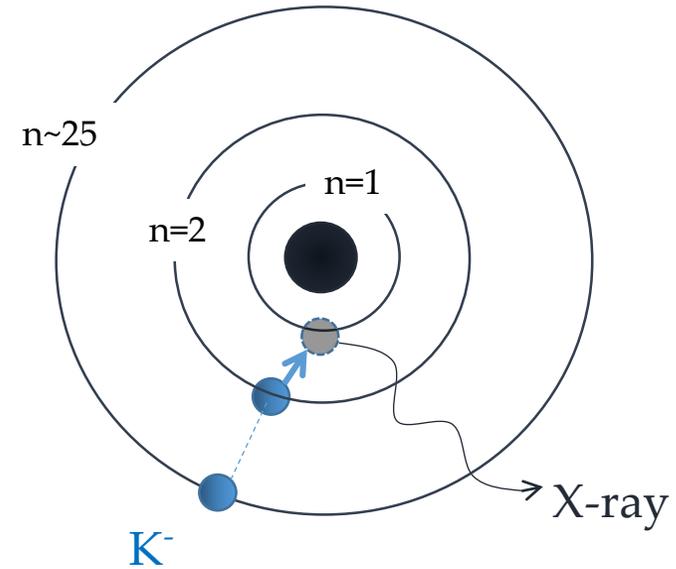
- exotic hadronic atoms are bound by Coulomb force - QED
- e.g. $\pi^+\pi^-$, π^-p , π^-d , K^-p , K^-d , ...
 - observable effects of QCD
 - energy shift from pure Coulomb value
 - decay width
 - access to scattering at zero energy
- these scattering lengths are sensitive to chiral and isospin symmetry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

Forming “exotic” atoms

“normal” hydrogen



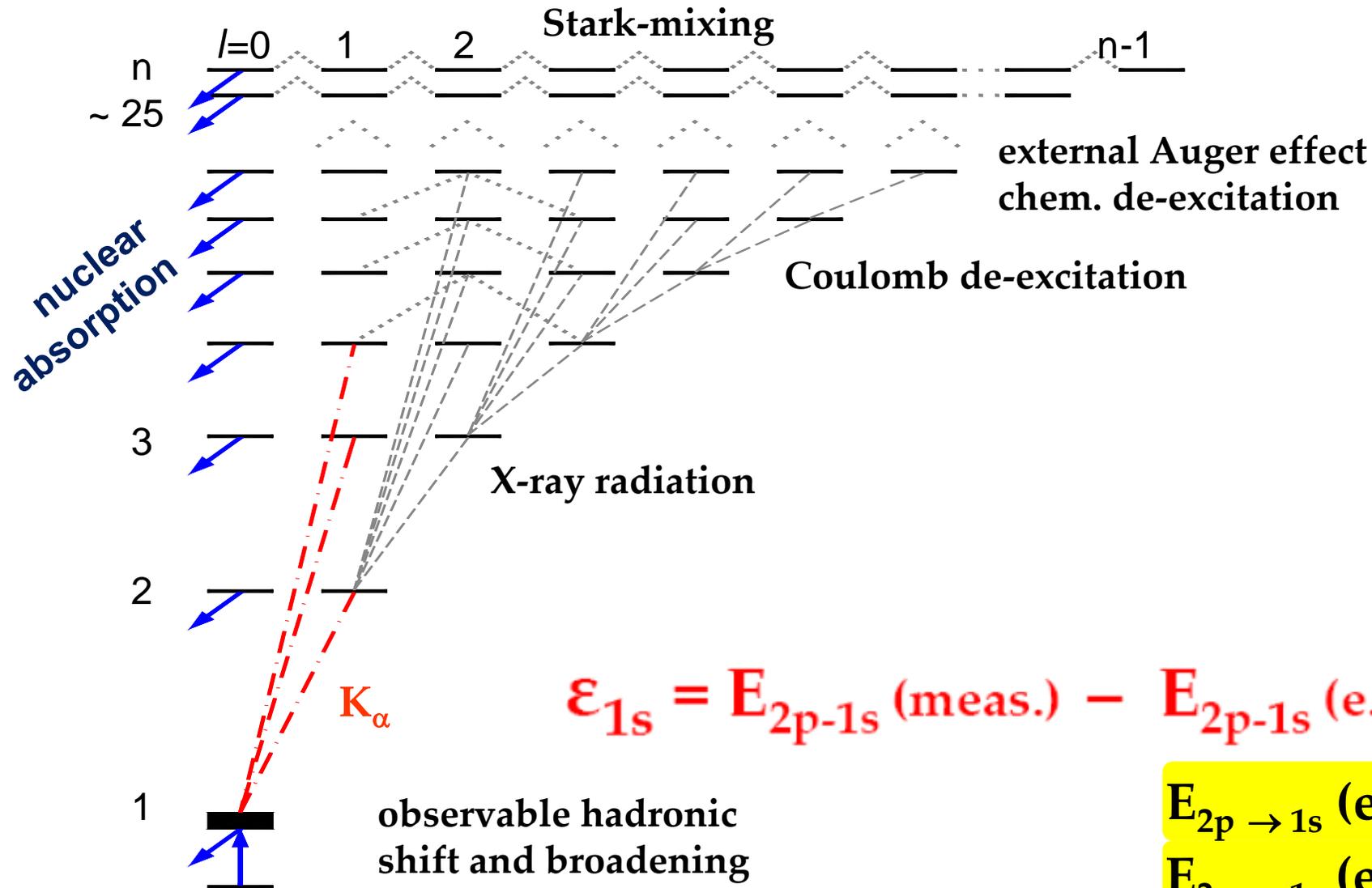
“exotic” (kaonic) hydrogen



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

2p → 1s
K_α transition

Cascade process – kaonic hydrogen atom



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

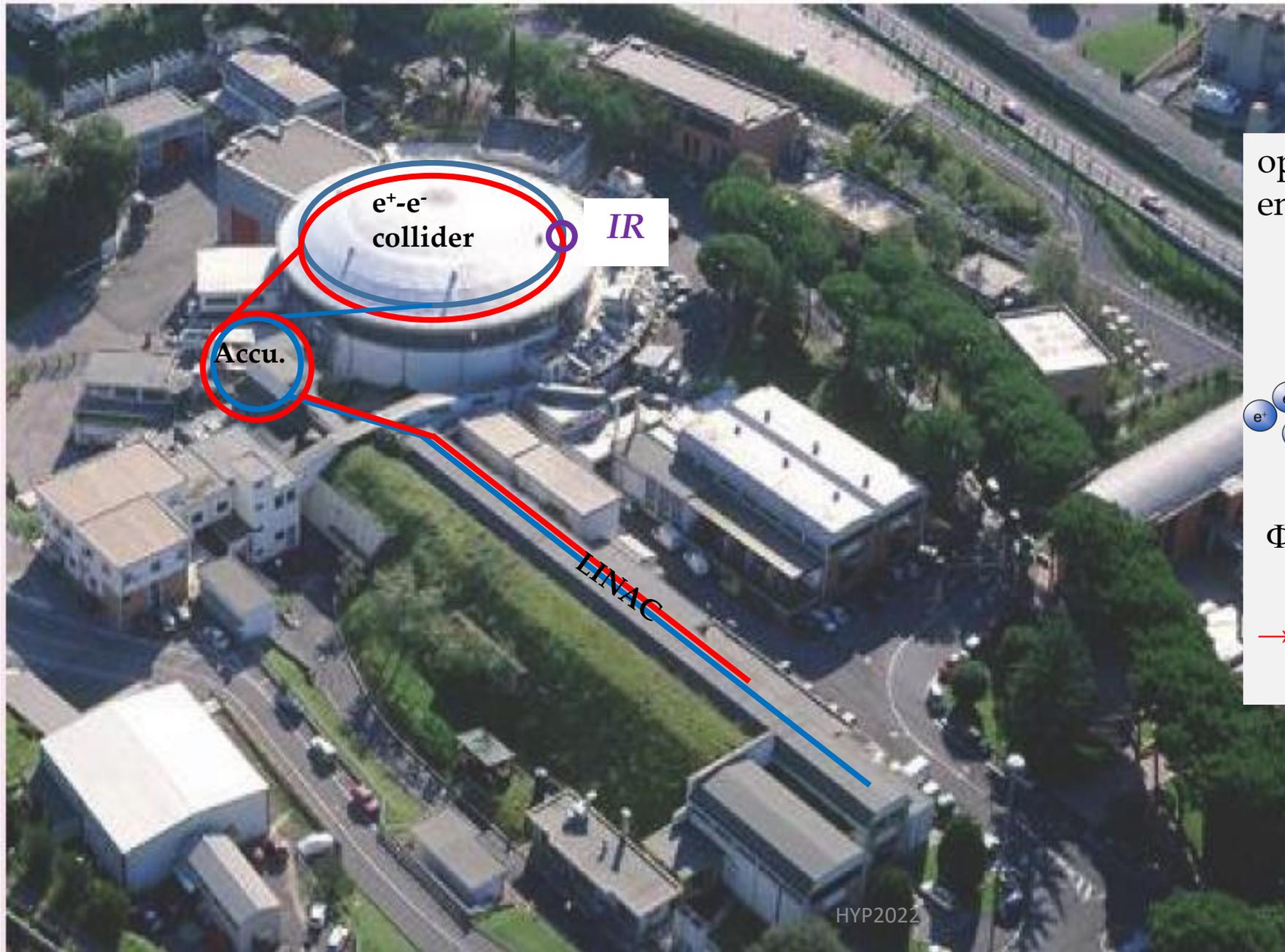
$$E_{2p \rightarrow 1s} (\text{e.m.}) (\text{K-p}) = 6480 \pm 1 \text{ eV}$$

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

Charged kaon production

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

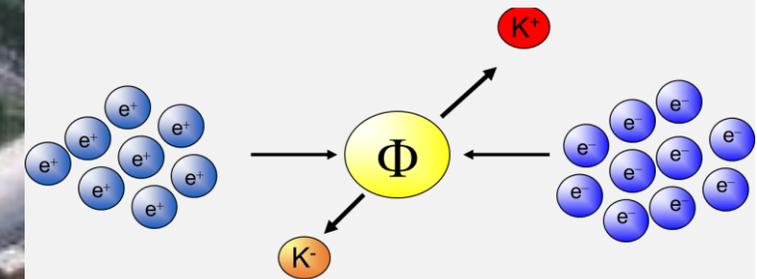
DAΦNE at LNF



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

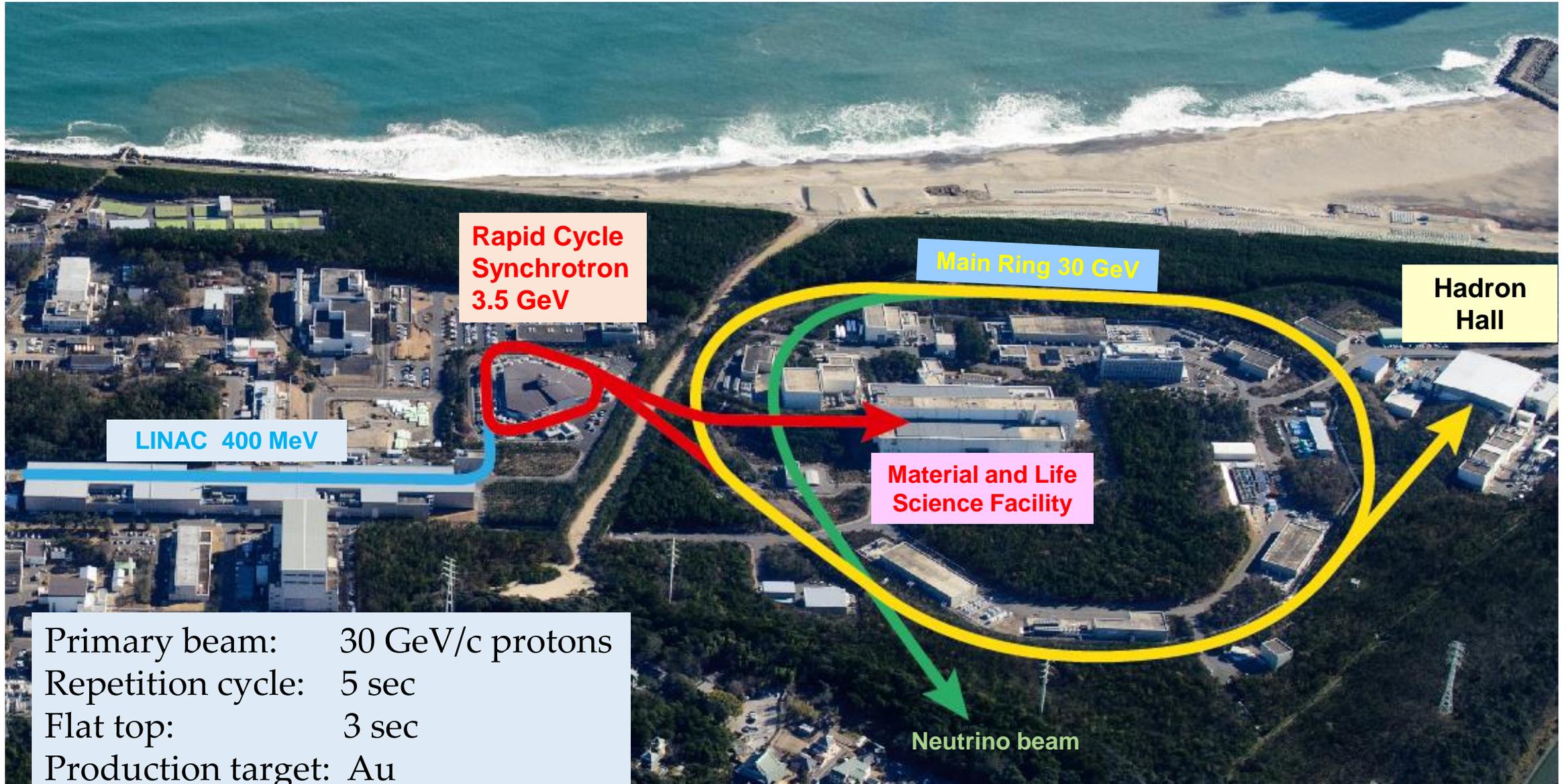


Φ produced via e^+e^- collision

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

→ **monochromatic kaon beam**
(127 MeV/c)

Japan Proton Accelerator Research Complex - J-PARC



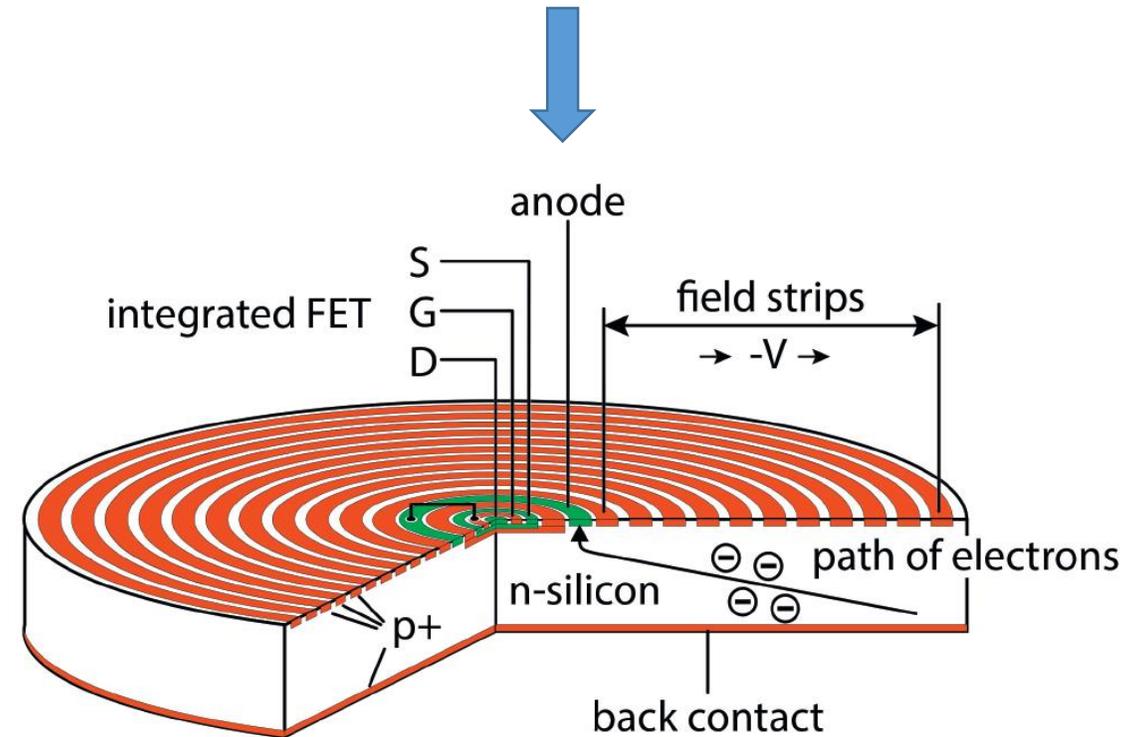
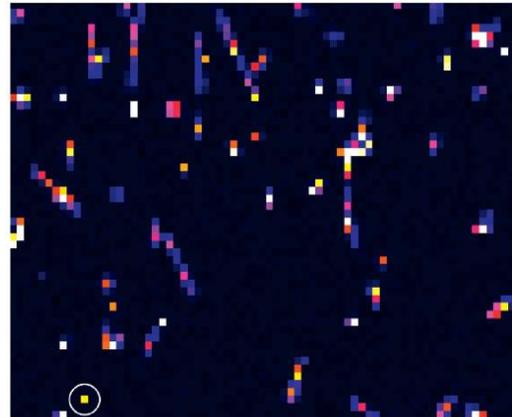
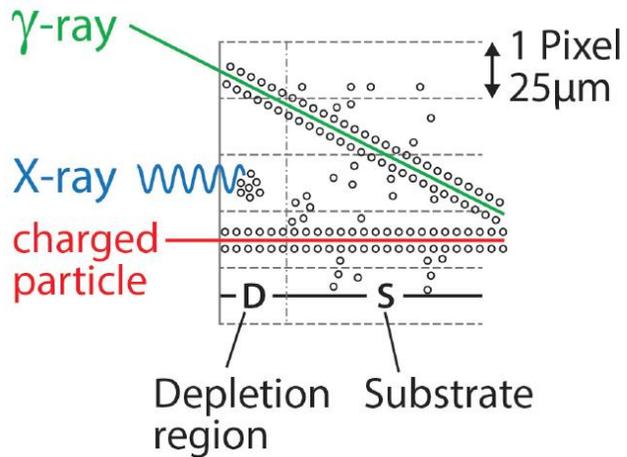
Primary beam: 30 GeV/c protons
Repetition cycle: 5 sec
Flat top: 3 sec
Production target: Au
Kaon momentum: 1.2 GeV/c (max.)

Status kaonic hydrogen

- KpX at KEK
- DEAR at DAΦNE
- SIDDHARTA at DAΦNE

Detector development

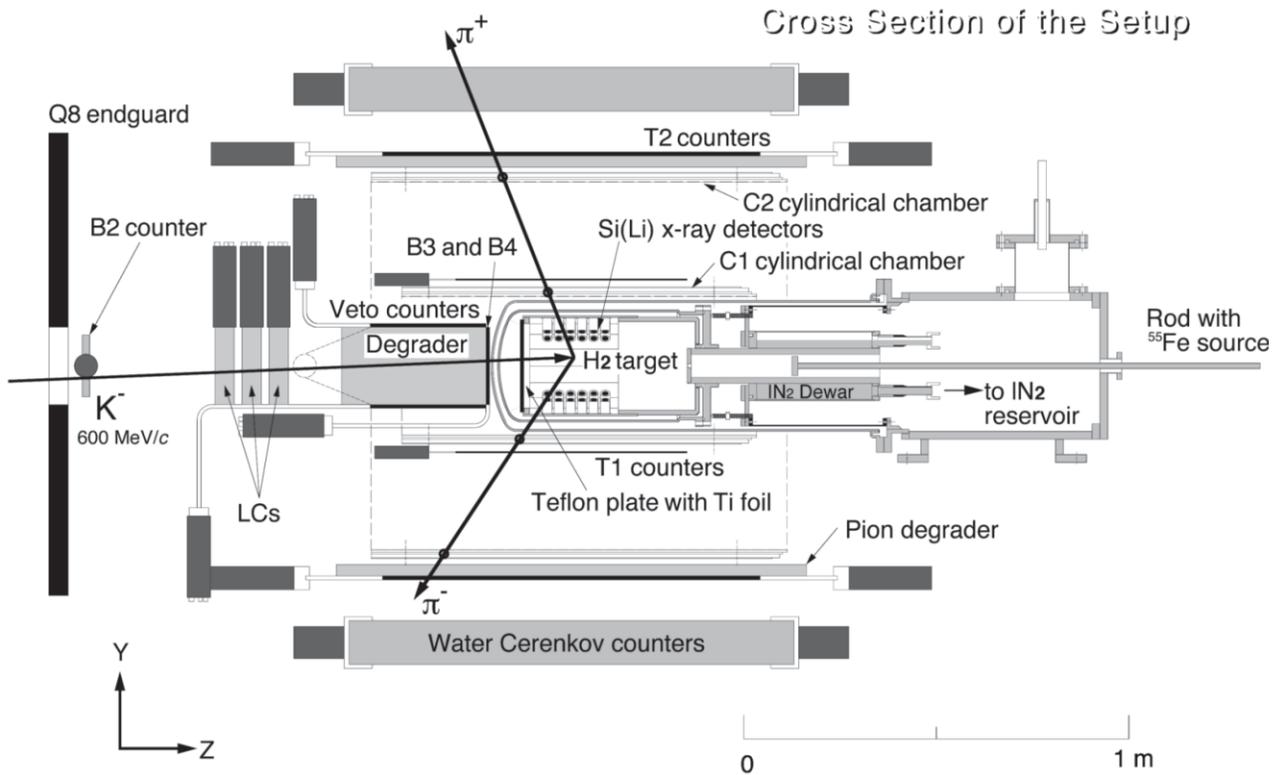
Detector	Si(Li)	CCD	SDD-KETEK	SDD-JFET	SDD-CUBE
Effective area (mm ²)	200	724	1 × 100	3 × 100	8 × 64
Thickness [mm]	5	0.03	0.26	0.45	0.45
Energy resolution [eV] at 6 keV	410	150	190	160	140
Drift time [ns]	290	-	375	800	300
Experiment	KpX	DEAR	E570	SIDDHARTA	E57, SIDDHARTA-2
Reference	(Iwasaki, 1997)	(Ishiwatari, 2006)	(Okada, 2007)	(Bazzi, 2011a)	(Quaglia, 2015)



E228 KpX at KEK

Negatively charged kaons of 600 MeV/c from KEK 12 GeV-PS

Detector: Si(Li)

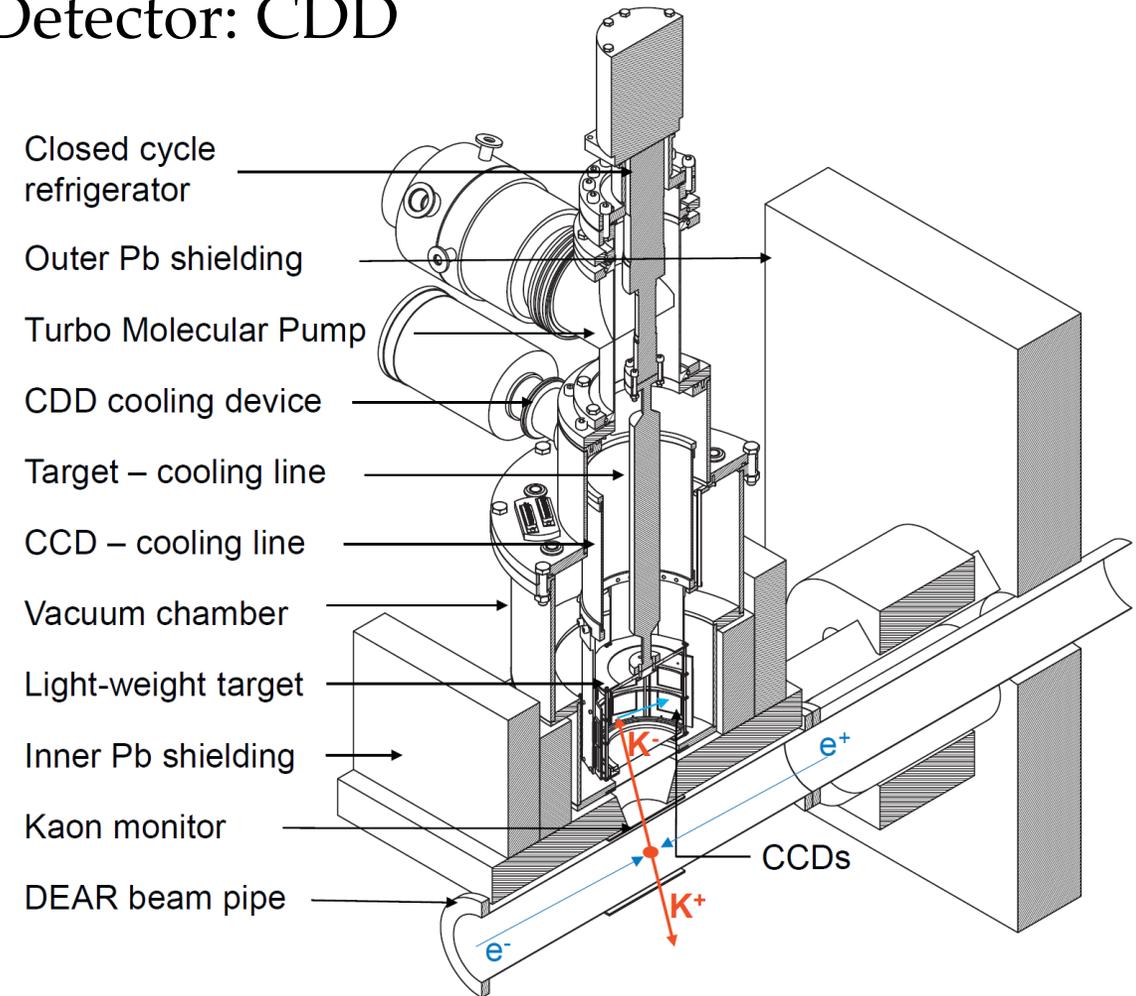


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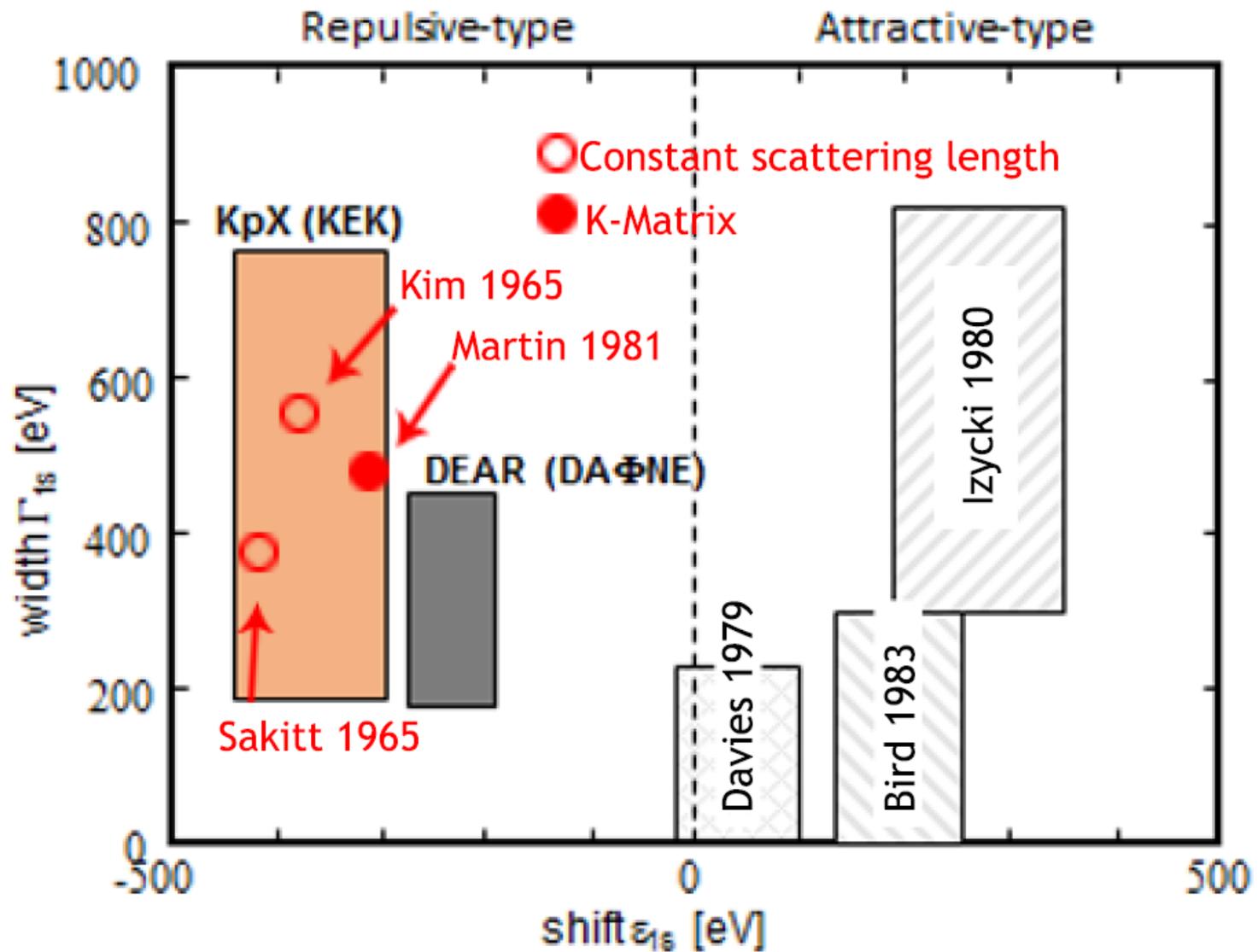
DEAR at DAΦNE

Low-momentum (127 MeV/c) kaon-pairs from DAΦNE

Detector: CDD

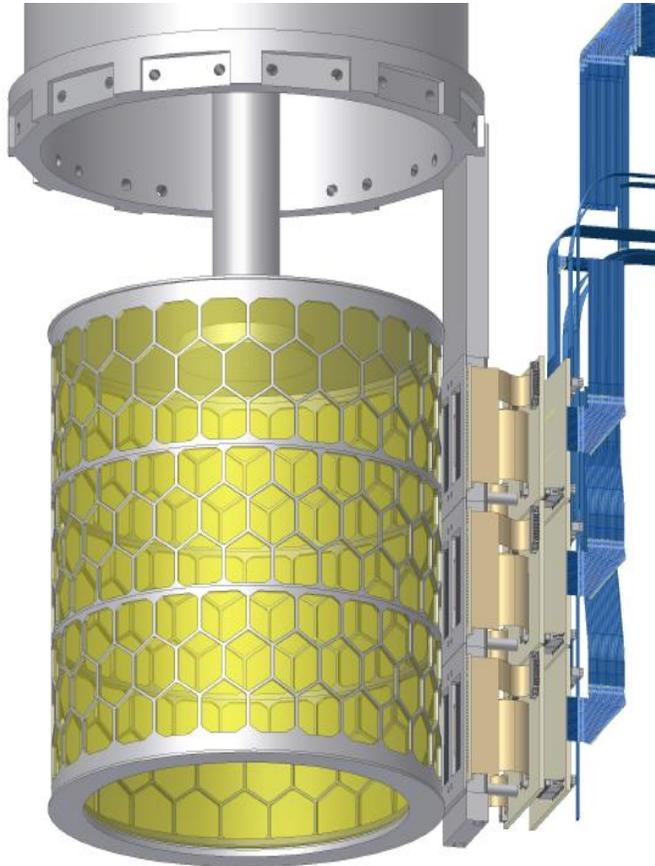


Kaonic hydrogen “puzzle”

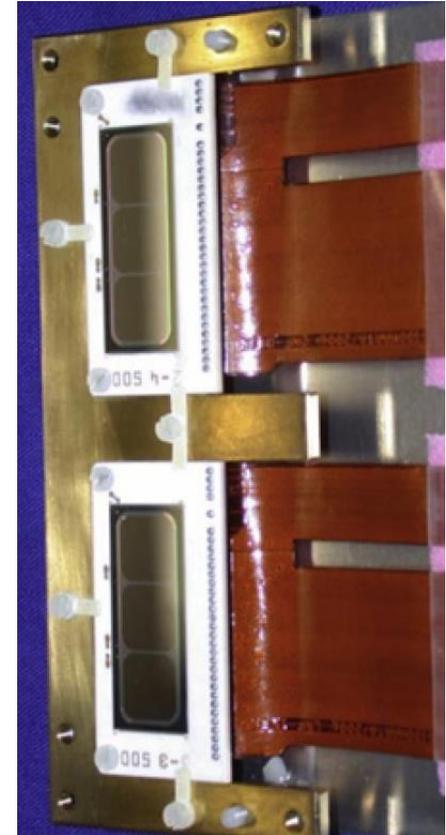
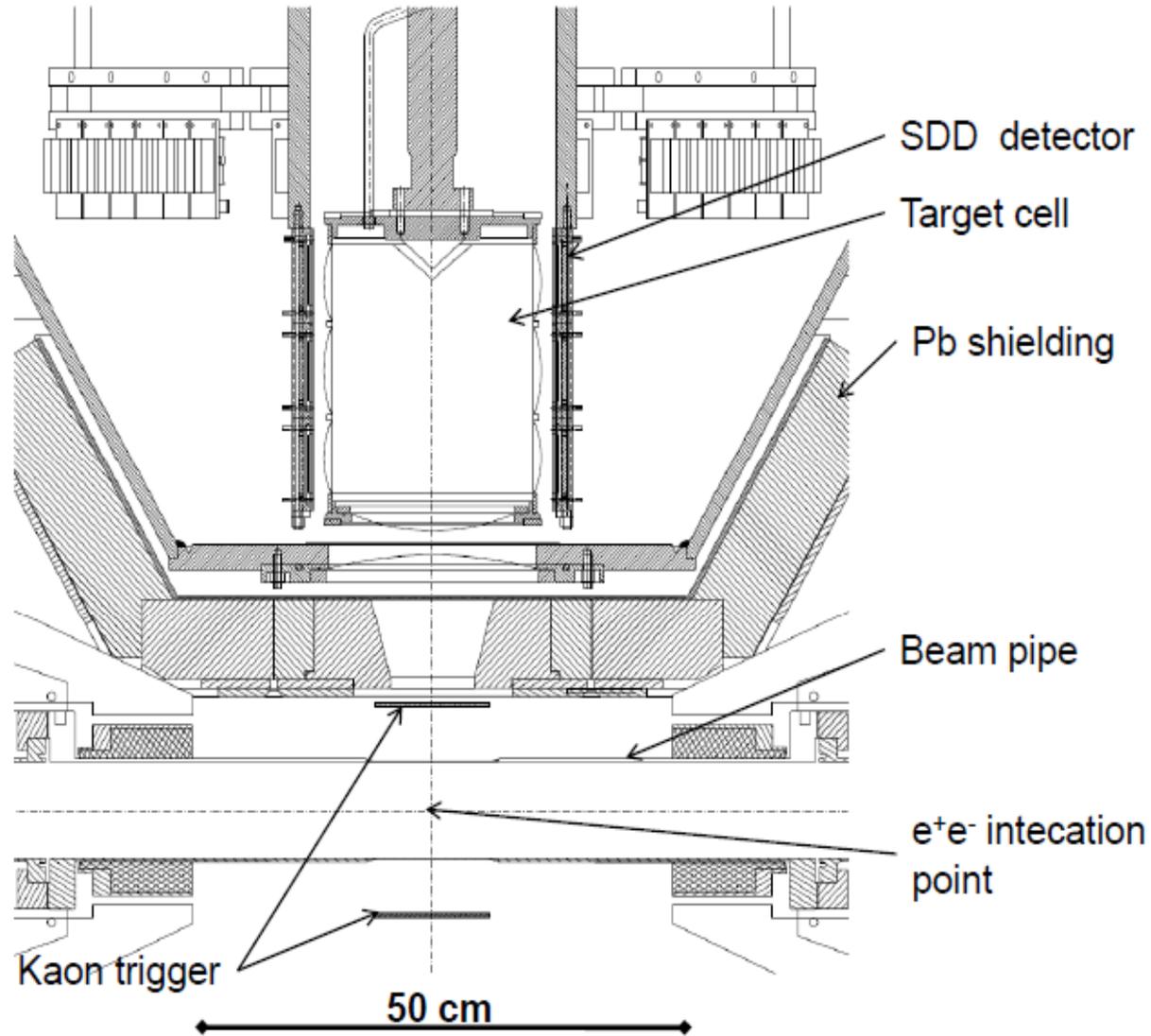


SIDDHARTA setup

working $T = 25\text{ K}$
working $P = 1.5\text{ bar}$



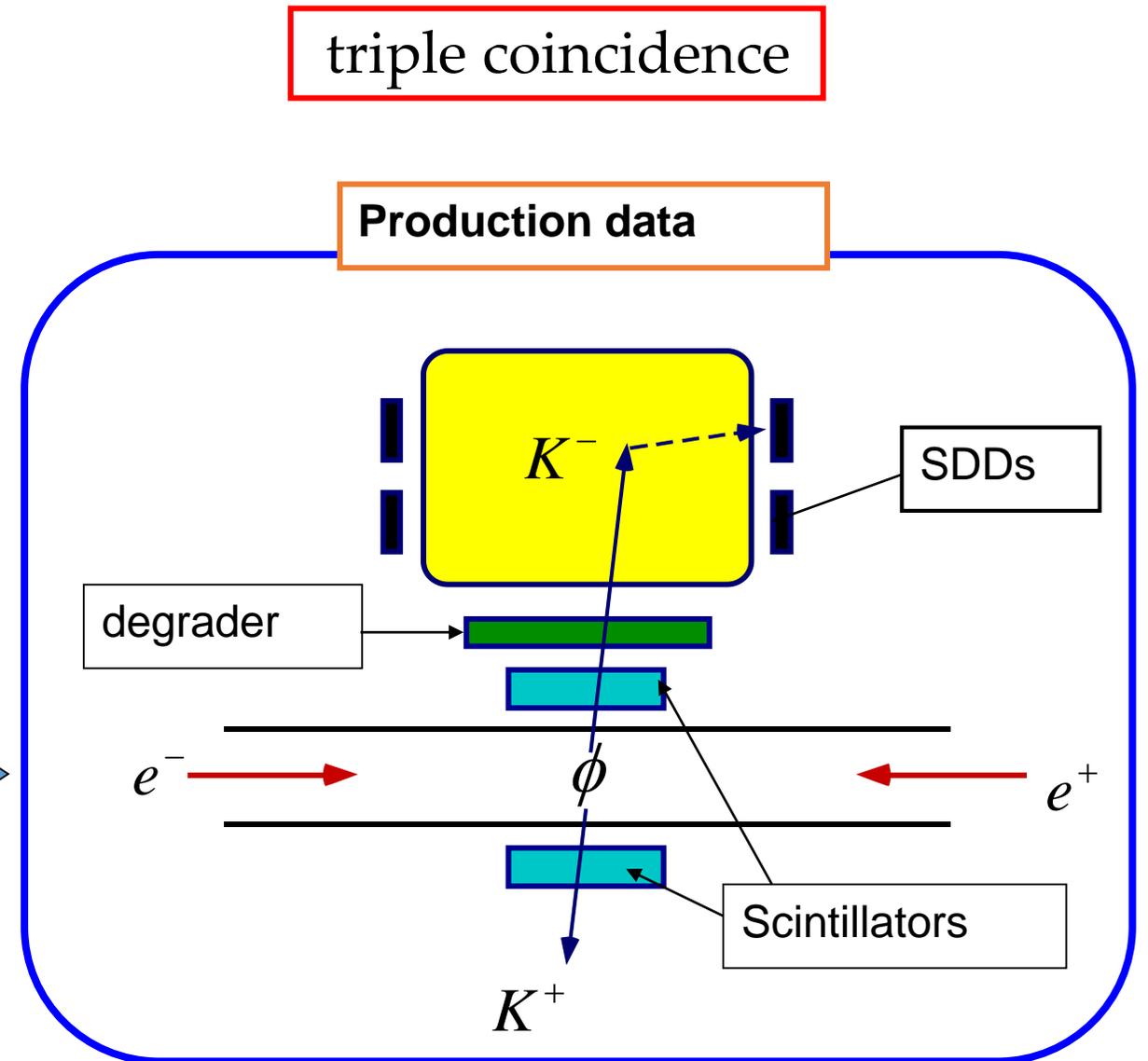
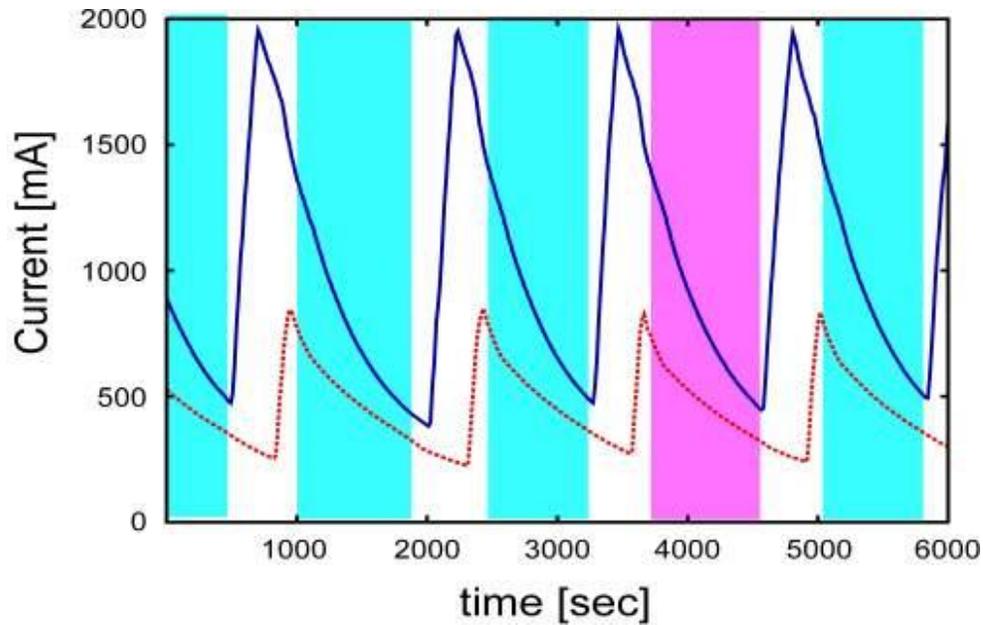
side wall: $50\ \mu\text{m}$
entrance window: $75\ \mu\text{m}$



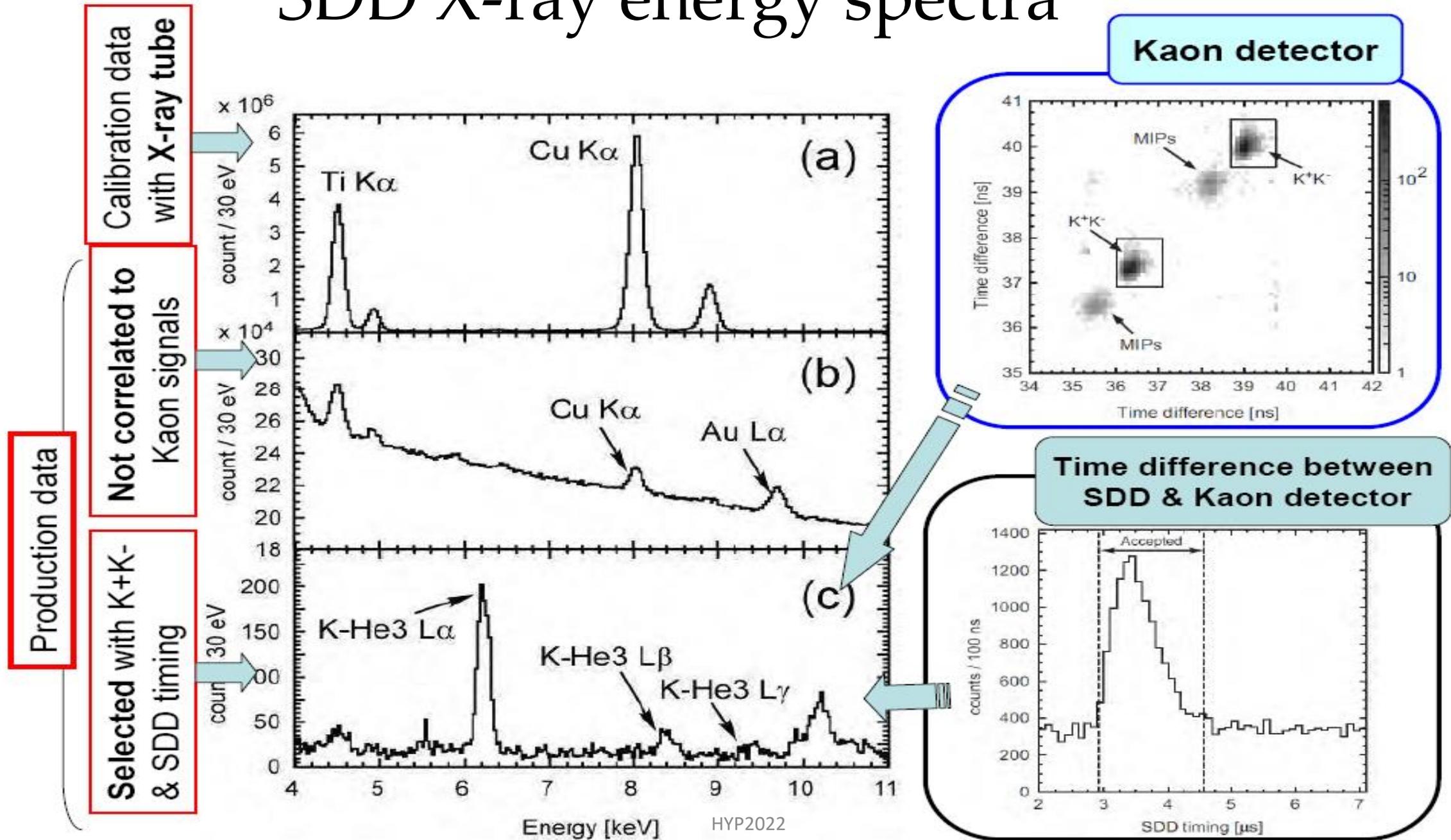
energy resolution:
 $160\ \text{eV}$
drift time:
 $\sim 800\ \text{ns}$

SIDDHARTA at DAΦNE

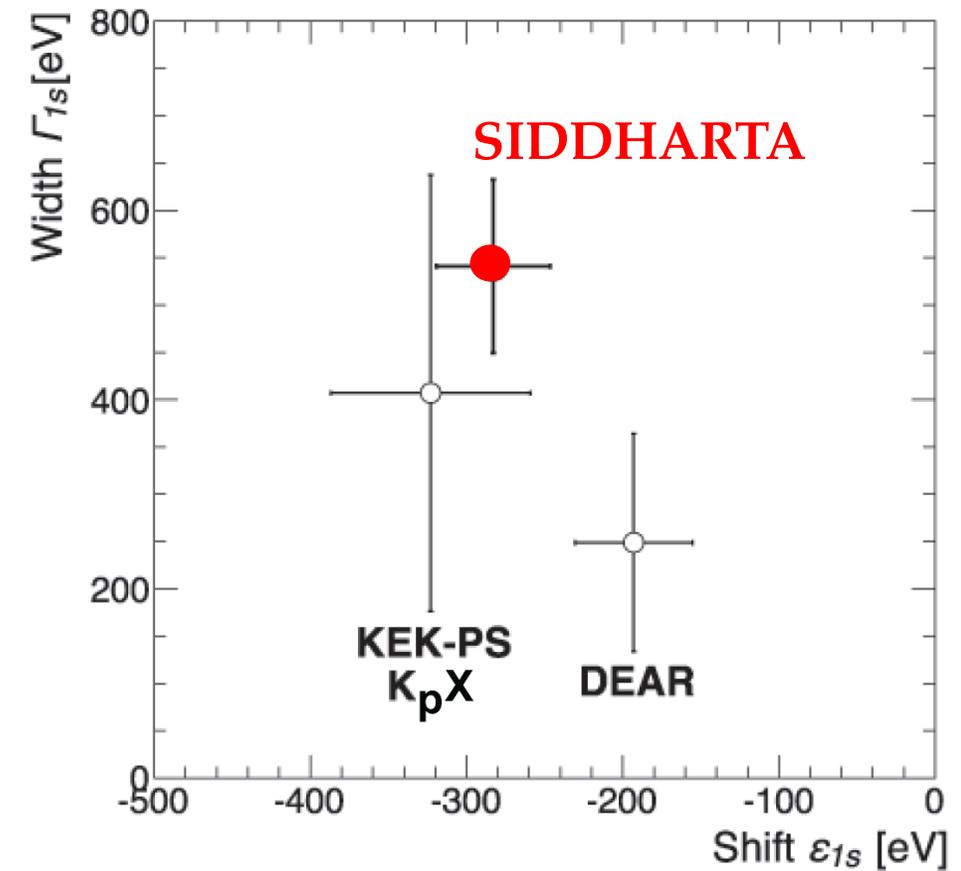
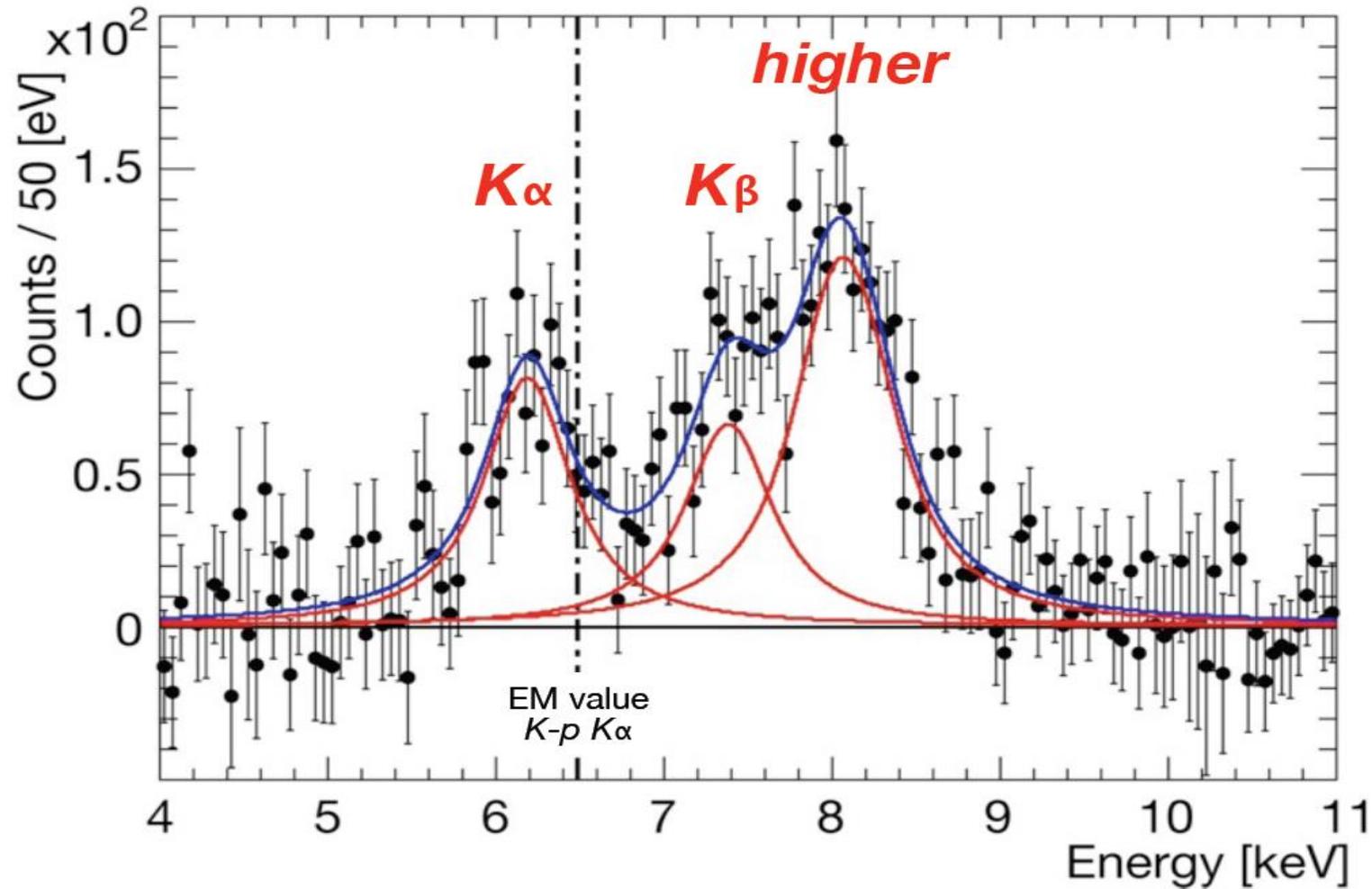
**K^+K^- pairs produced
at DAΦNE**



SDD X-ray energy spectra



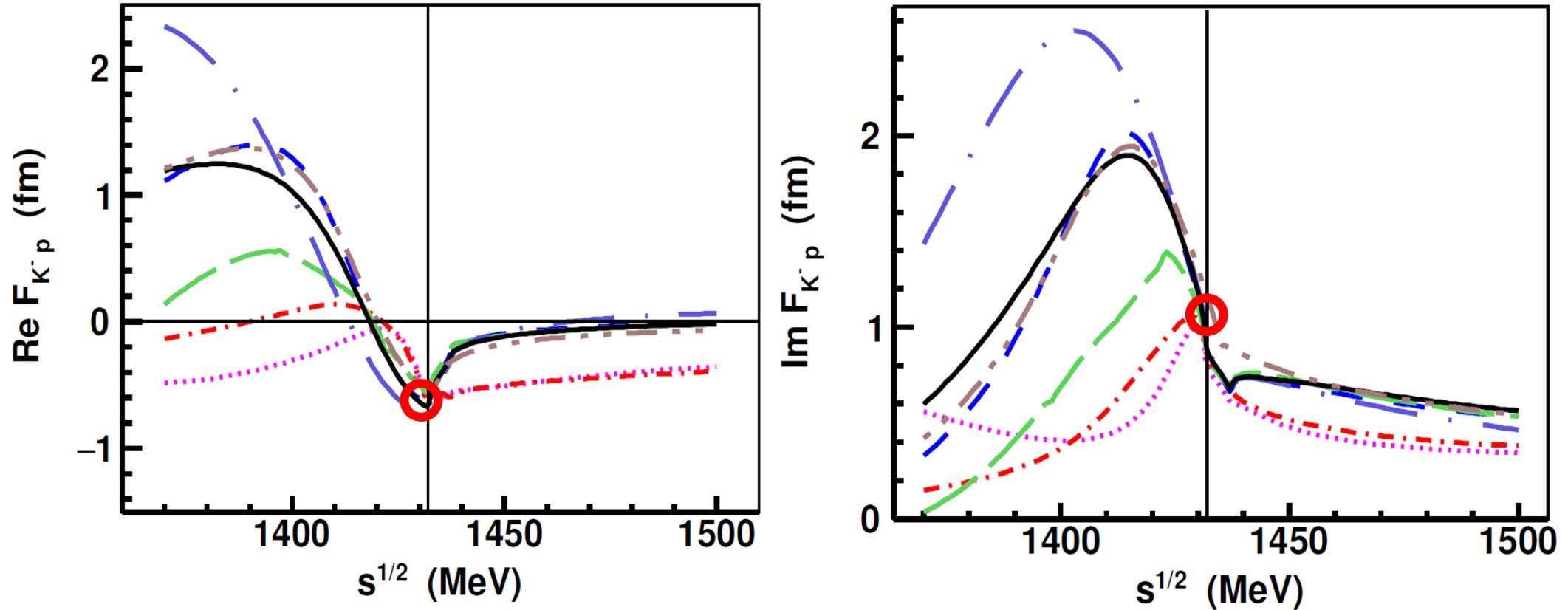
K^-p spectrum, BG subtracted



$$\varepsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst}) \text{ eV}$$
$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst}) \text{ eV}$$

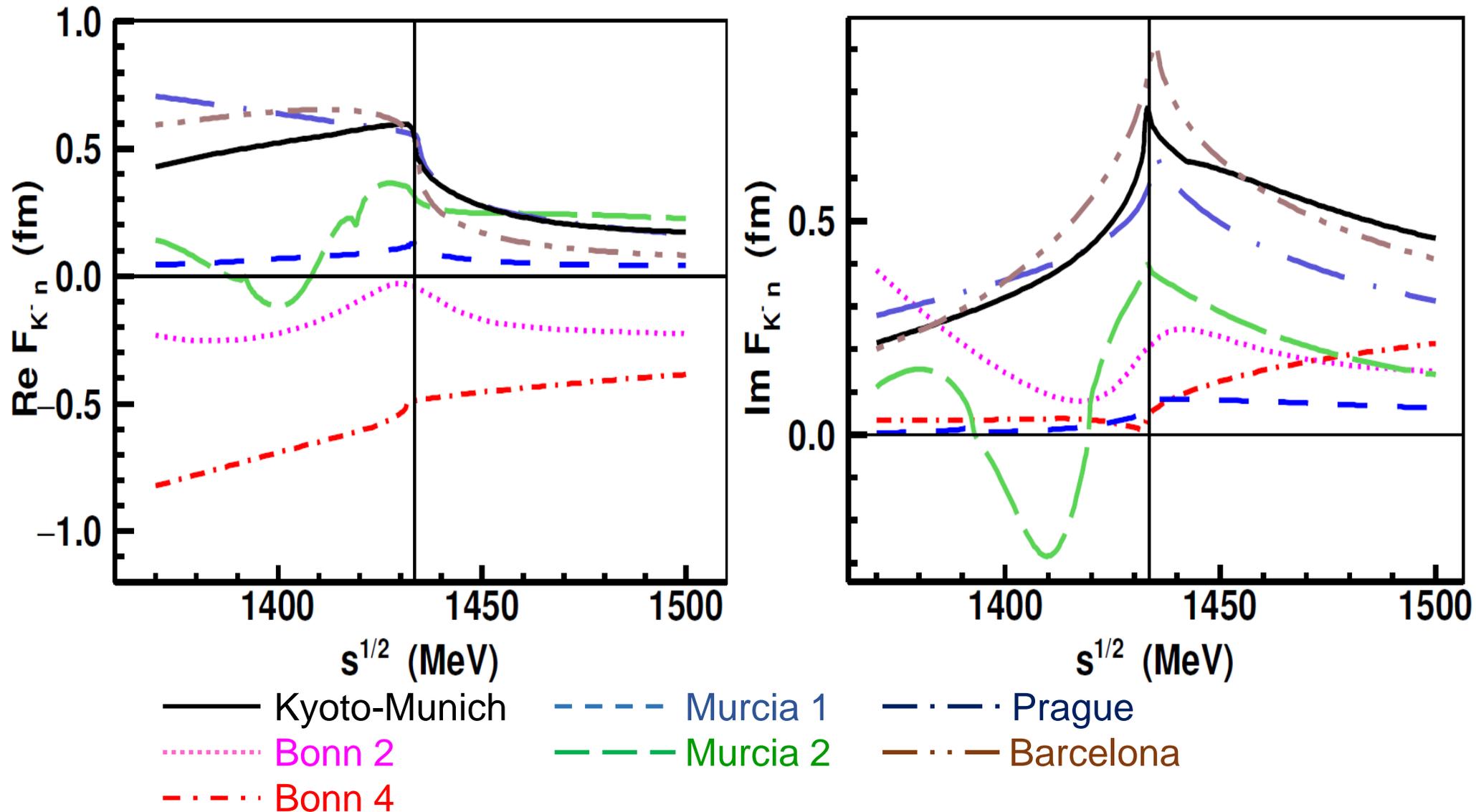
$K^-p \rightarrow K^-p$ forward scattering amplitude

➤ subthreshold amplitudes not yet well determined



A. Cieplý

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



Towards kaonic deuterium

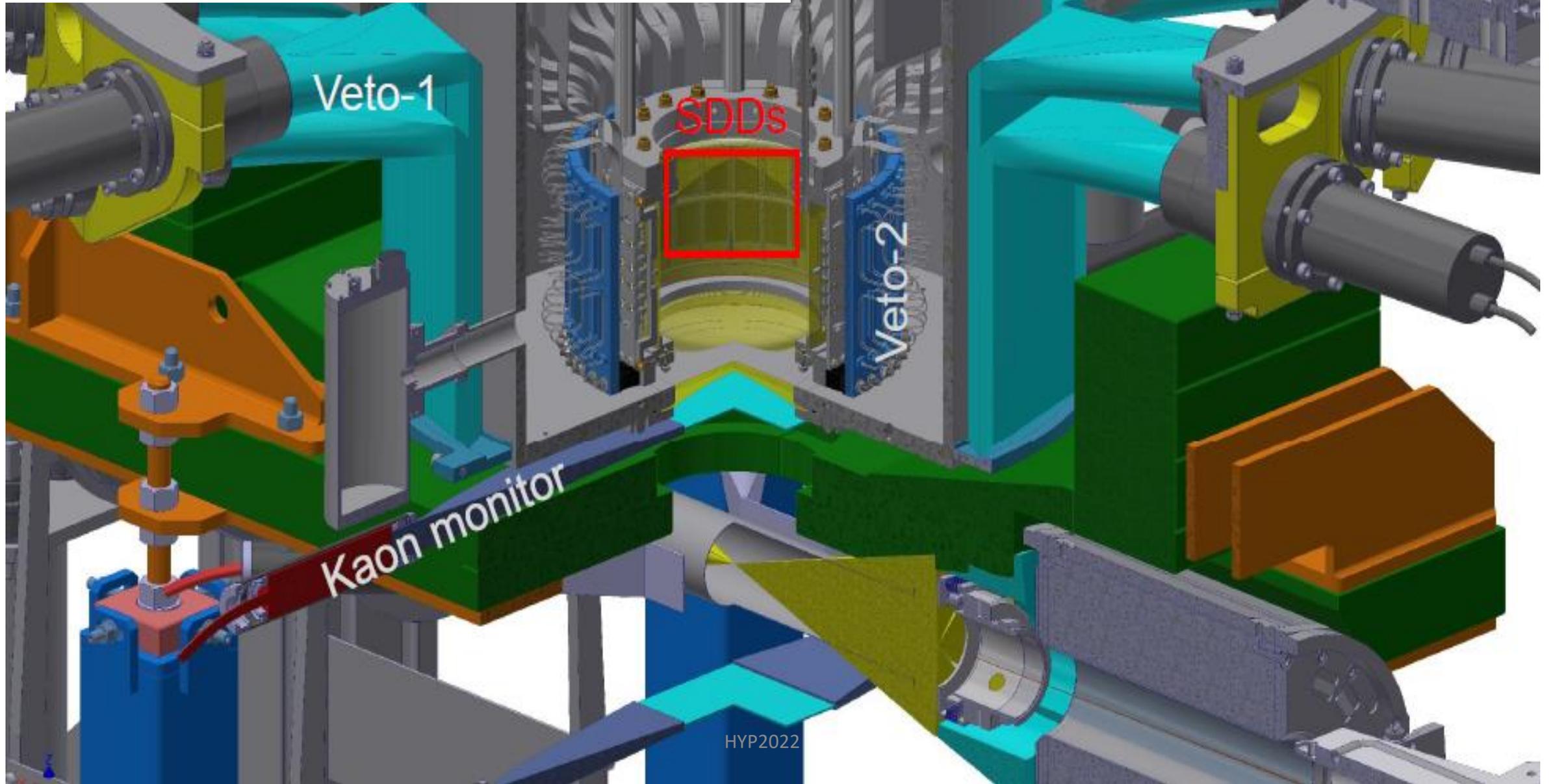
- SIDDHARTA-2 at DAΦNE
- E57 at J-PARC
 - Kaonic hydrogen pilot run

Experimental challenges towards K^-d

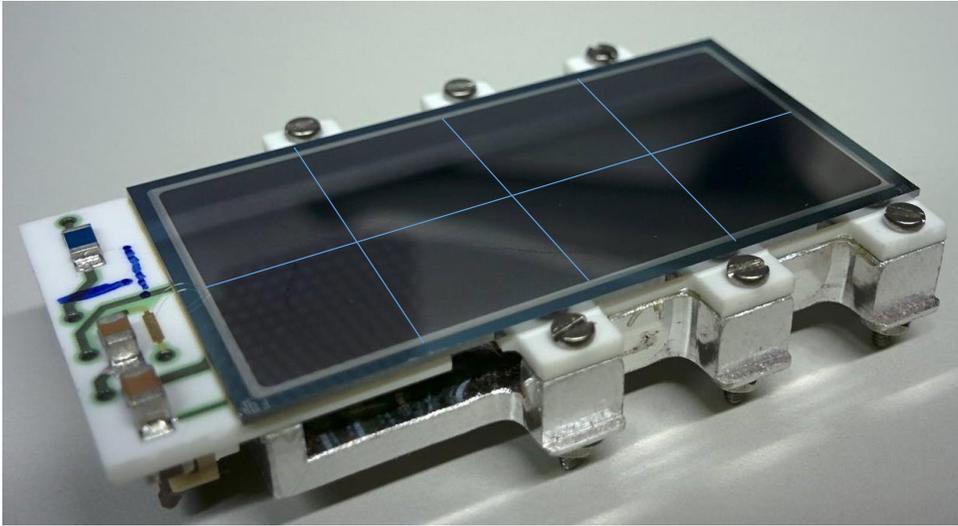
- X-ray yield: $K^-p \sim 1\%$
 $K^-d \sim 0.1\%$
- 1s state width: $K^-p \sim 540\text{ eV}$
 $K^-d \sim 800 - 1000\text{ eV}$

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

SIDDHARTA-2 setup for K^0 installed at DAΦNE

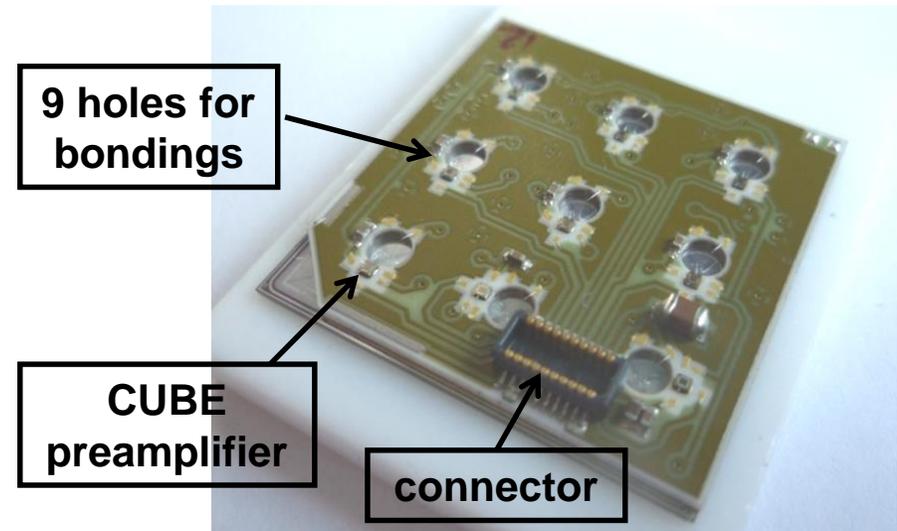
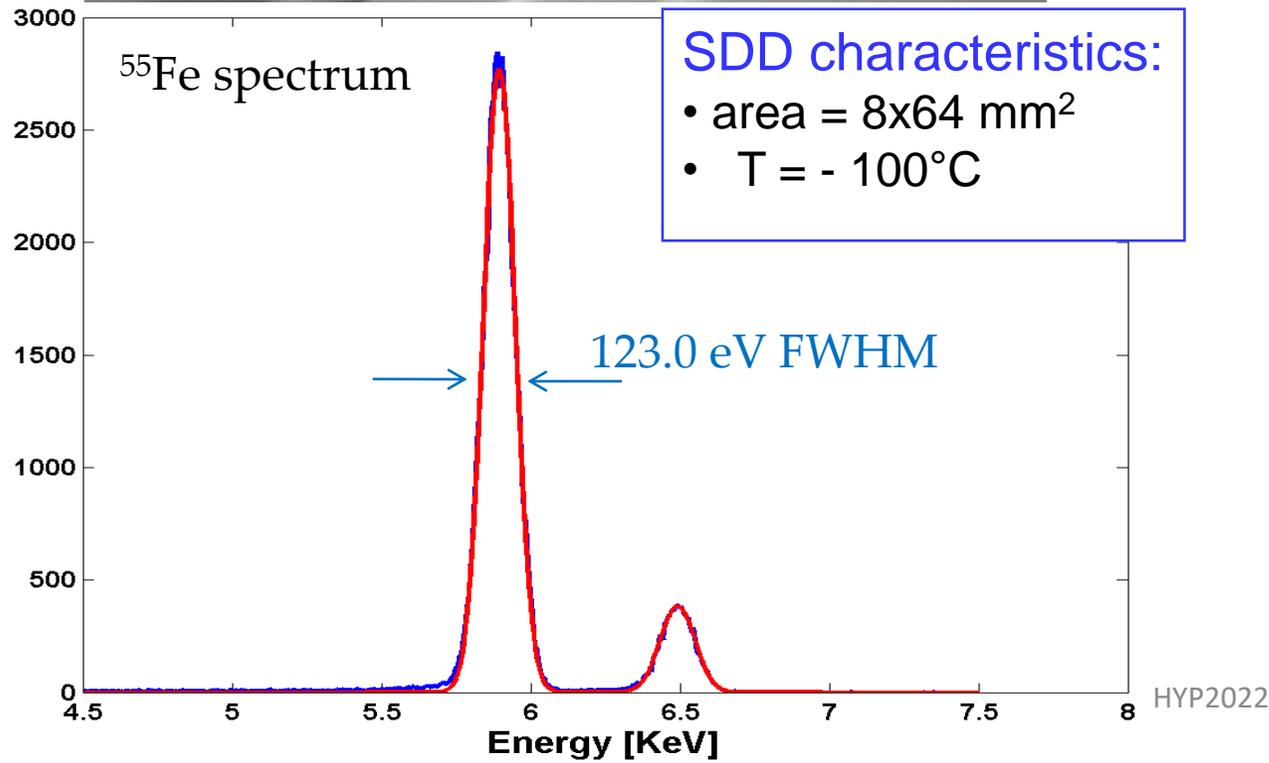


New SDD technology with CUBE preamplifier for K⁻d



SDD-chip back side with bonding pads

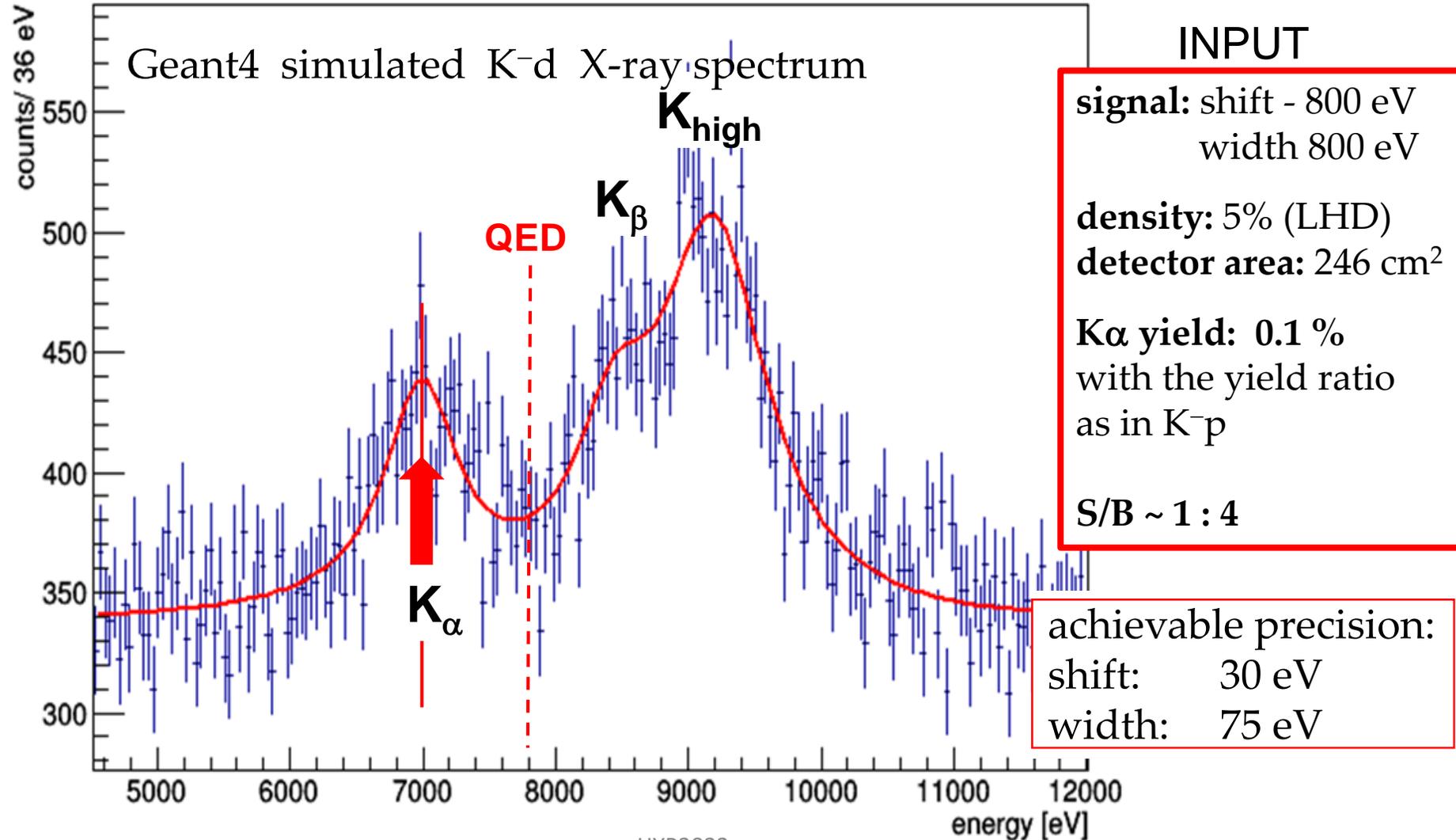
SDD-chip glued to ceramic board, bonded to CUBE preamplifier



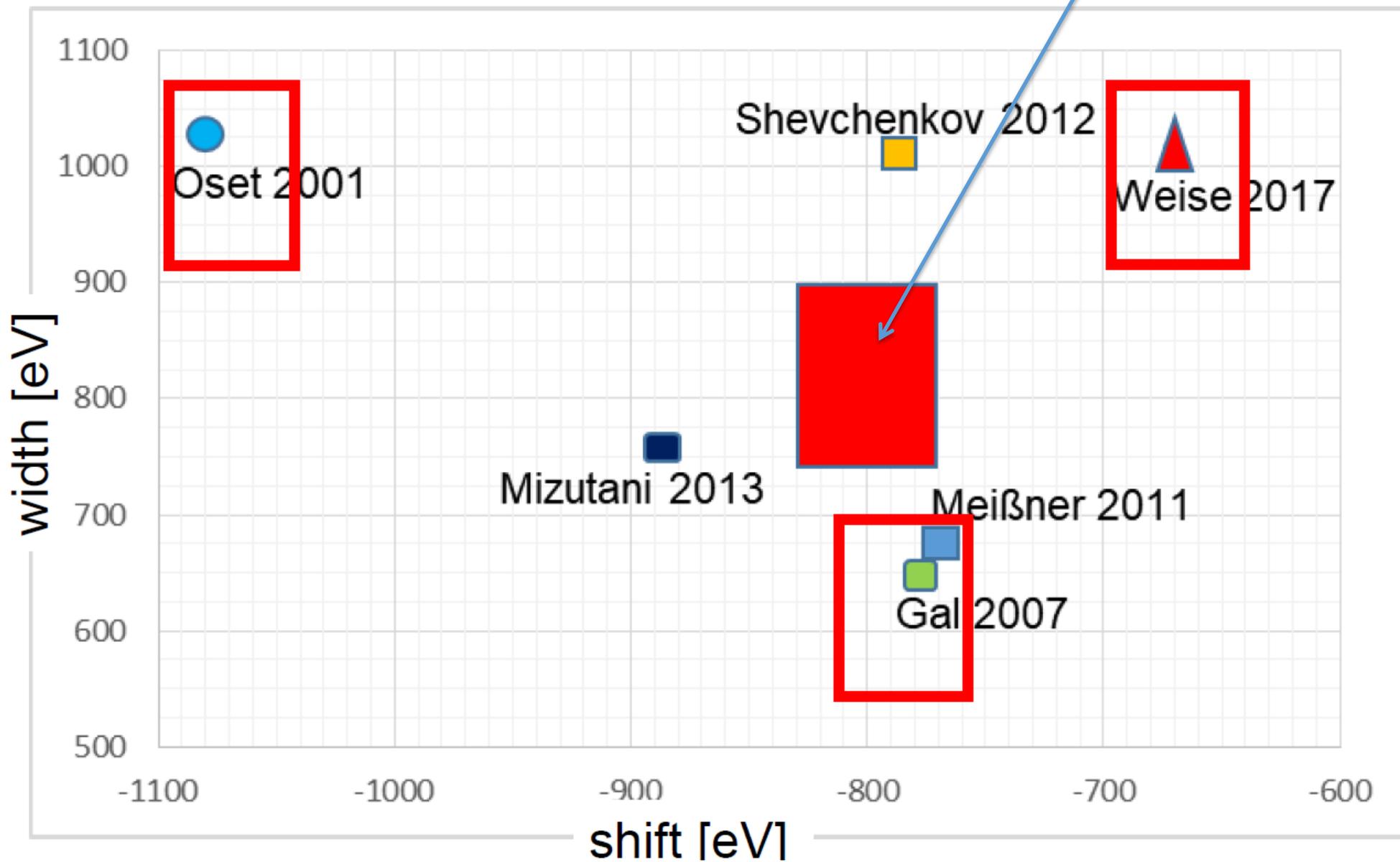
The scientific goal of SIDDHARTA-2 and E57

➤ **a first measurement of kaonic deuterium**

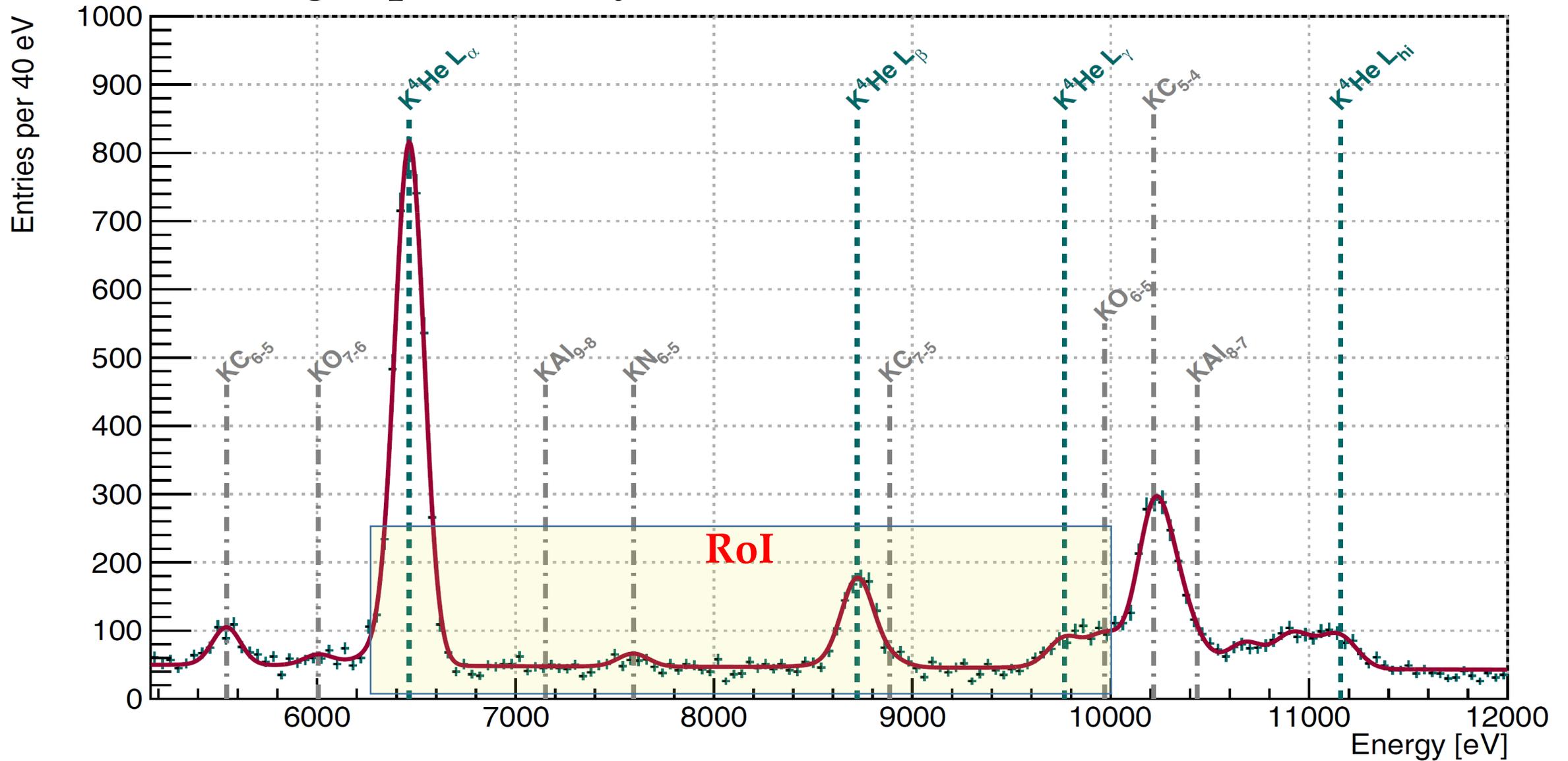
to extract the $\bar{K}N$ isospin dependent scattering lengths



E57 / SIDDHARTA-2 targeted precision



Beam tuning April – May 2022, He measurement

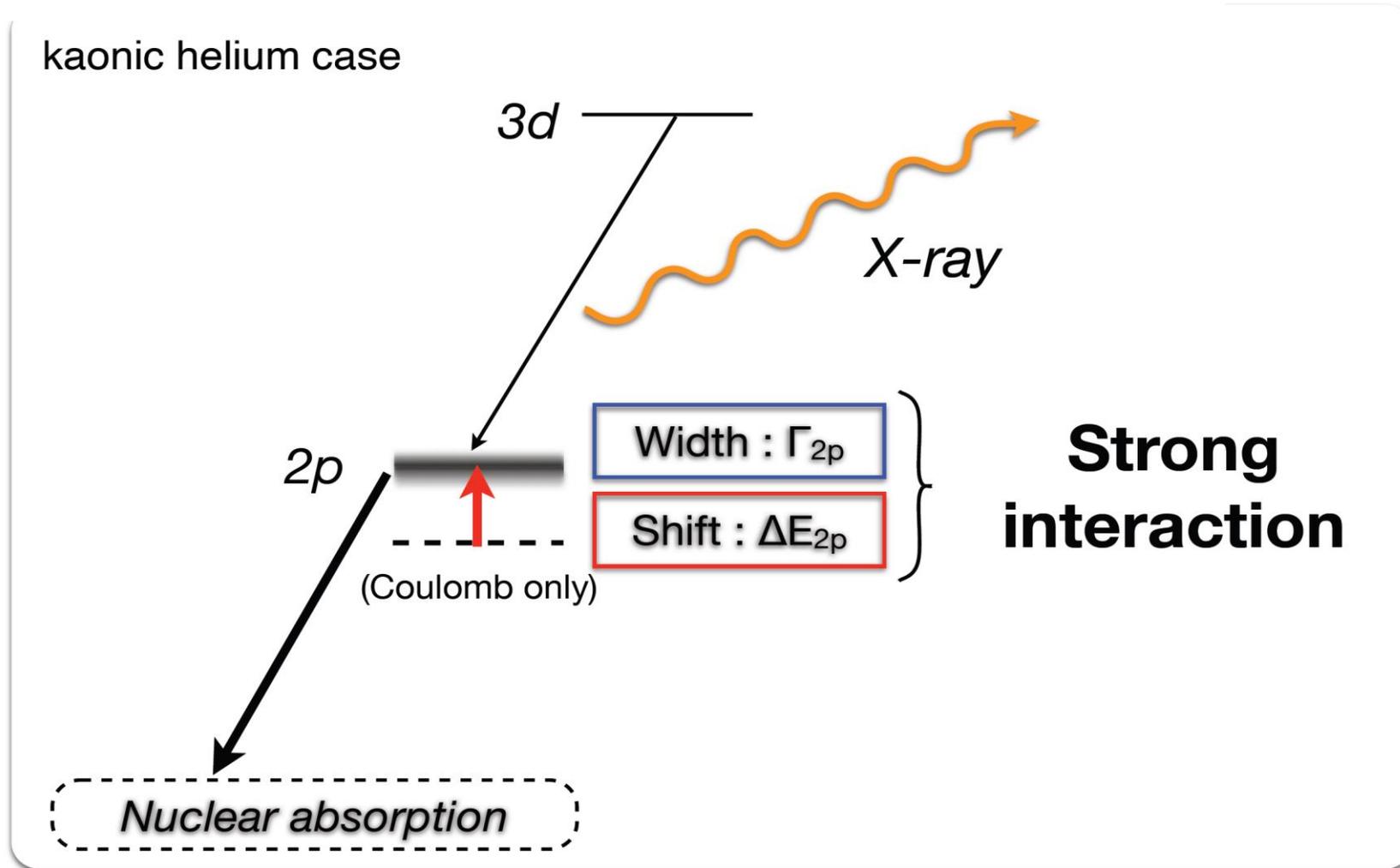


➤ *Deuterium measurement started begin of June 2022 at DAΦNE*

Status kaonic helium

- KEK
- SIDDHARTA at DAΦNE
- E62 at J-PARC

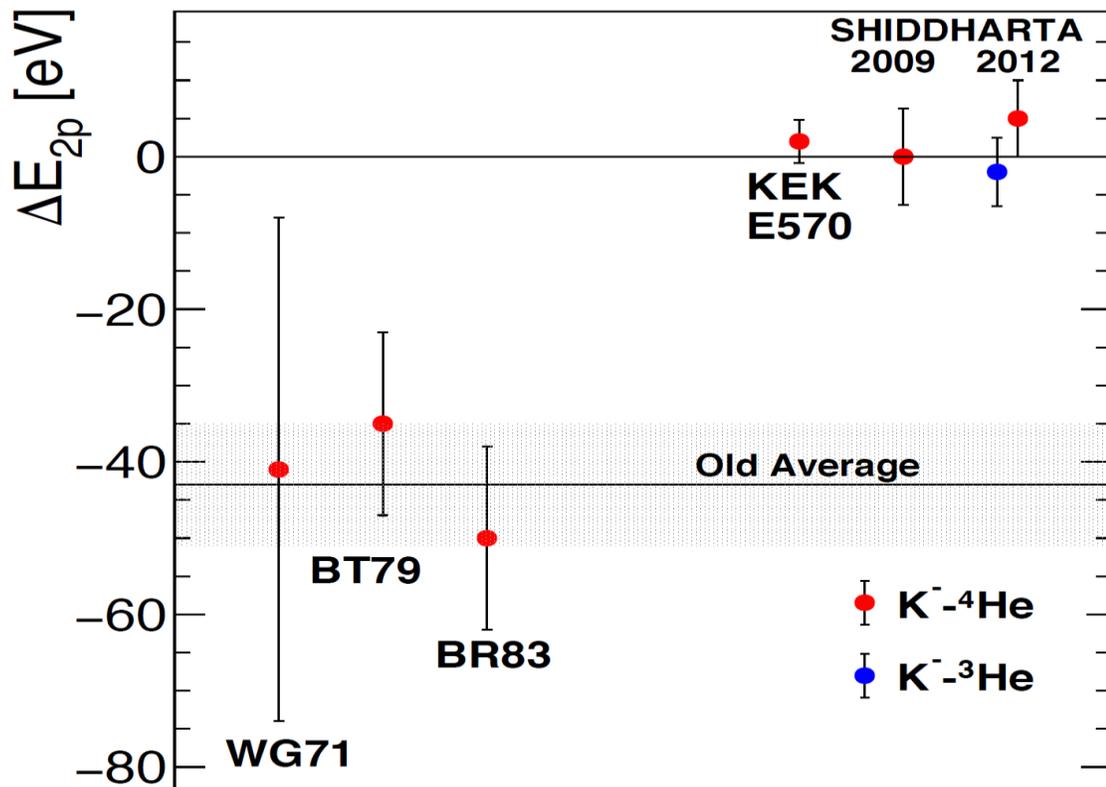
Kaonic helium X-rays



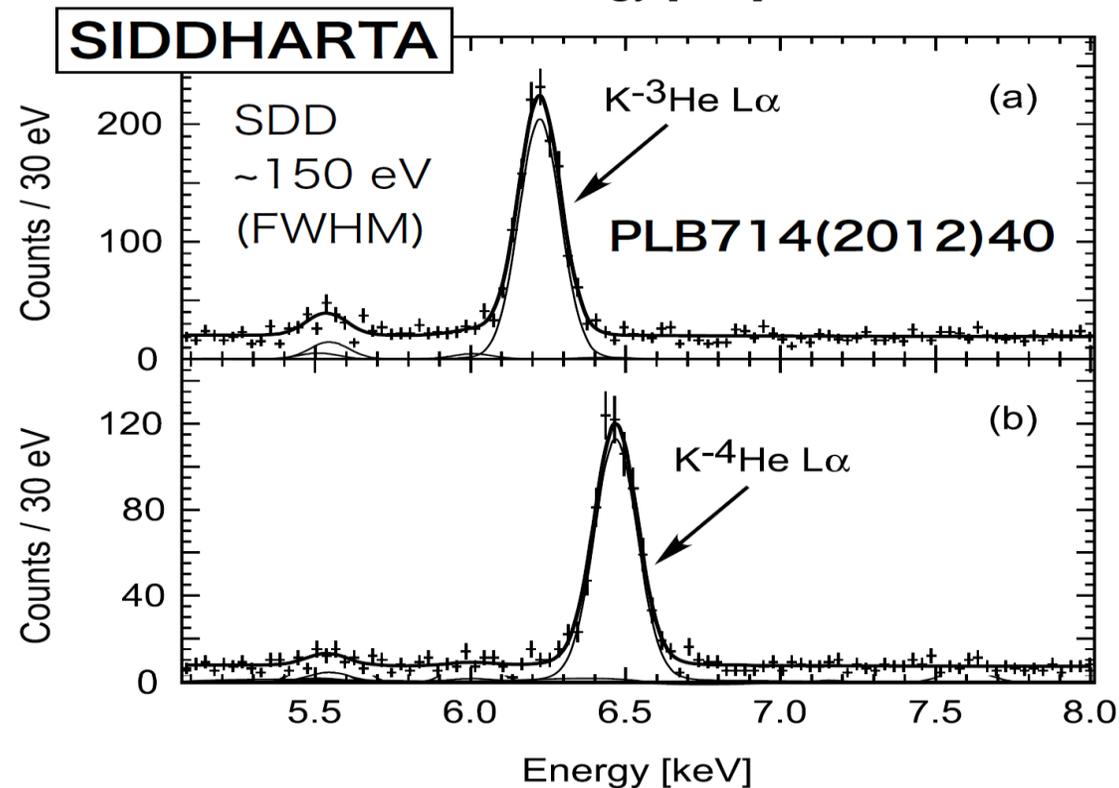
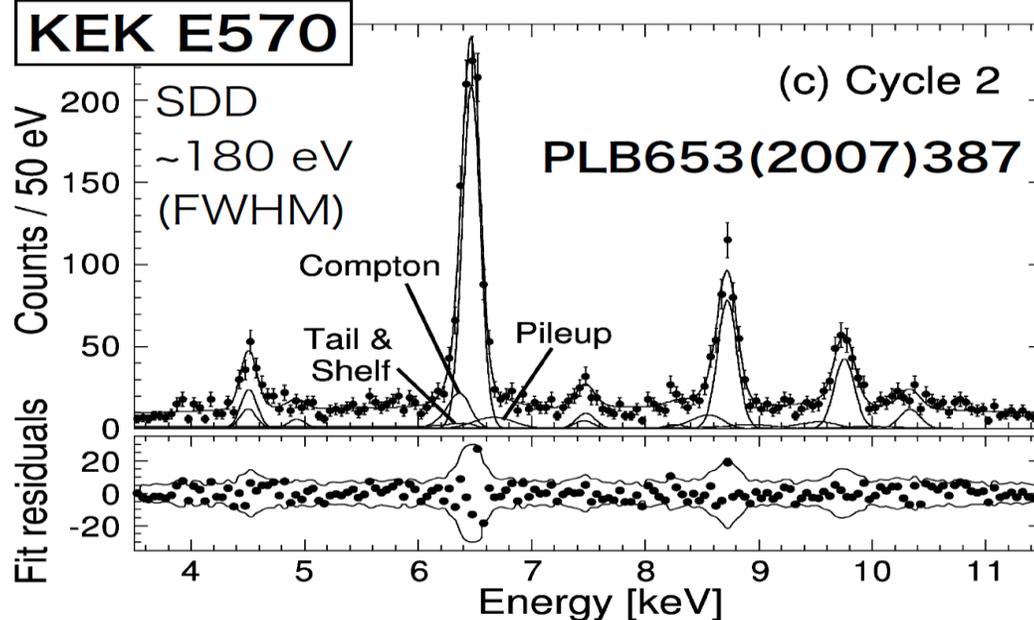
Unique probe of the K^{bar} -nucleus strong interaction at the threshold energy

K-He experiments

$$\Delta E = E_{exp.} - E_{EM}$$

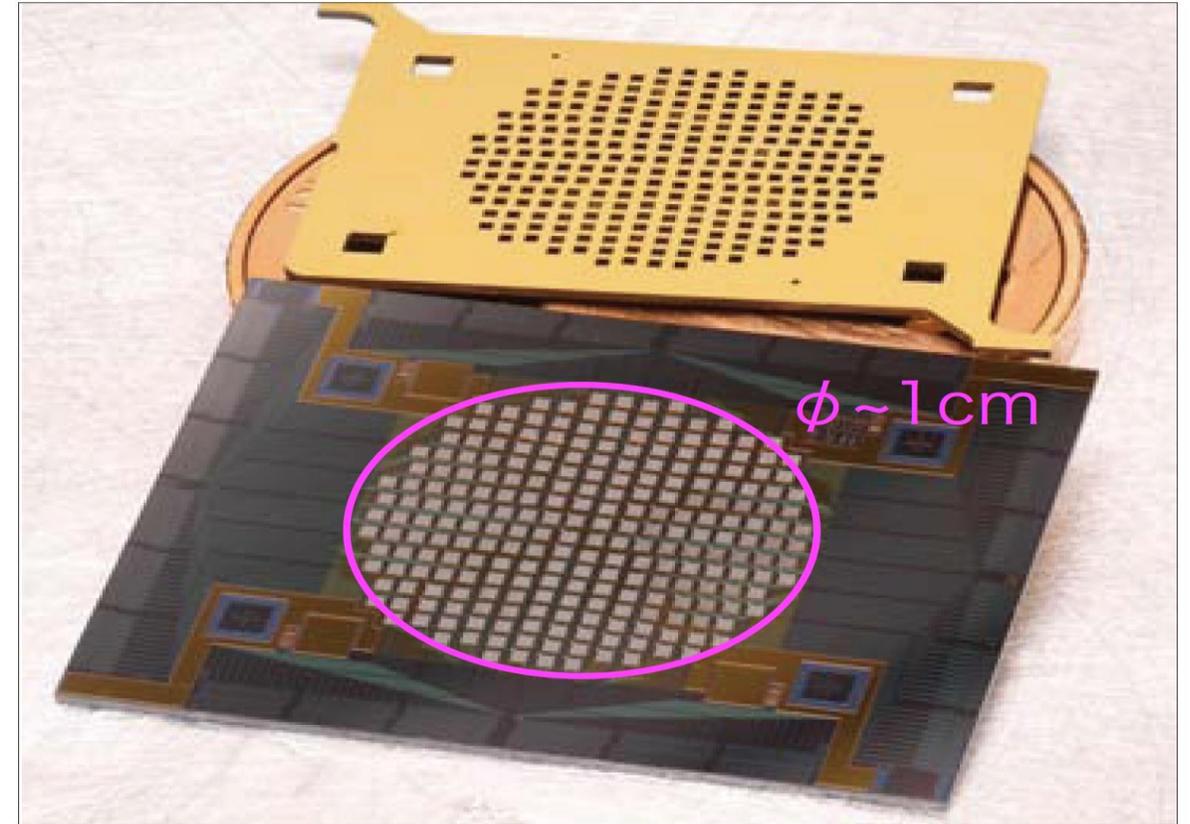
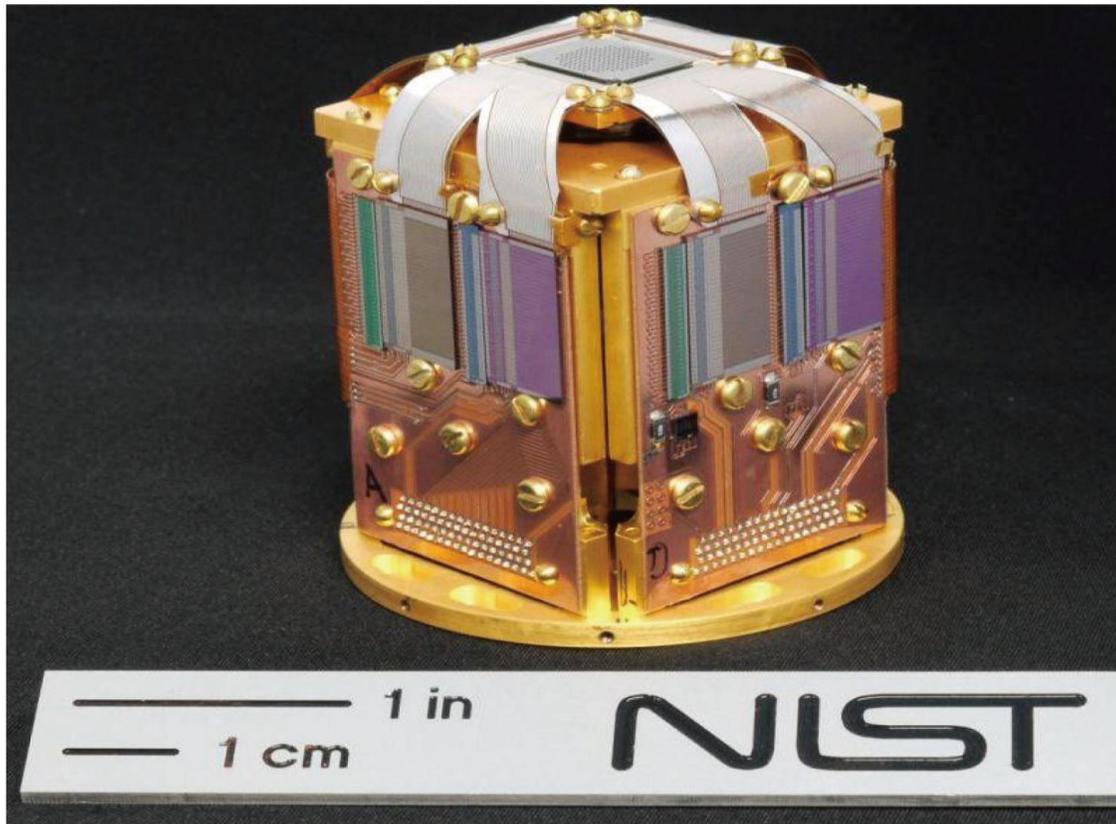


- Old “puzzle” has been solved
- Shift < 5 eV, Width < 20 eV
- Precision ~ 2 eV << Resolution 150 eV



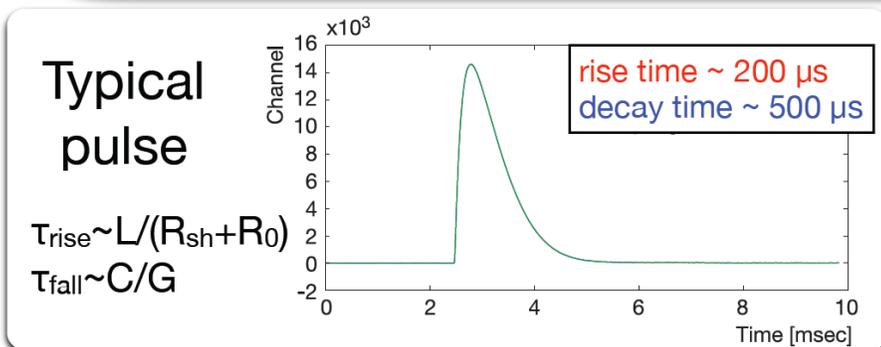
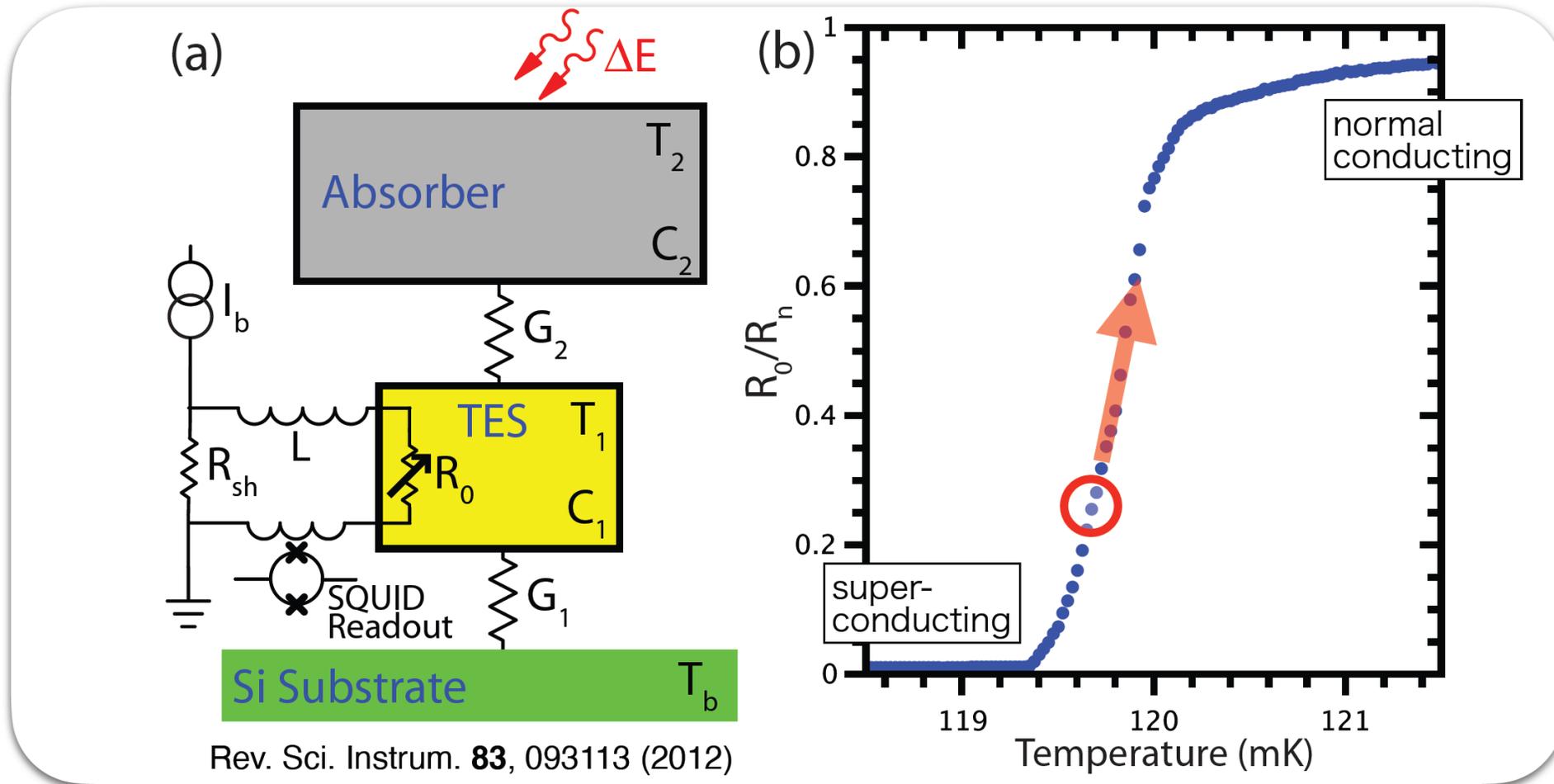
NIST(US) TES spectrometer for E62

Review of Scientific Instruments **88**, 053108 (2017)



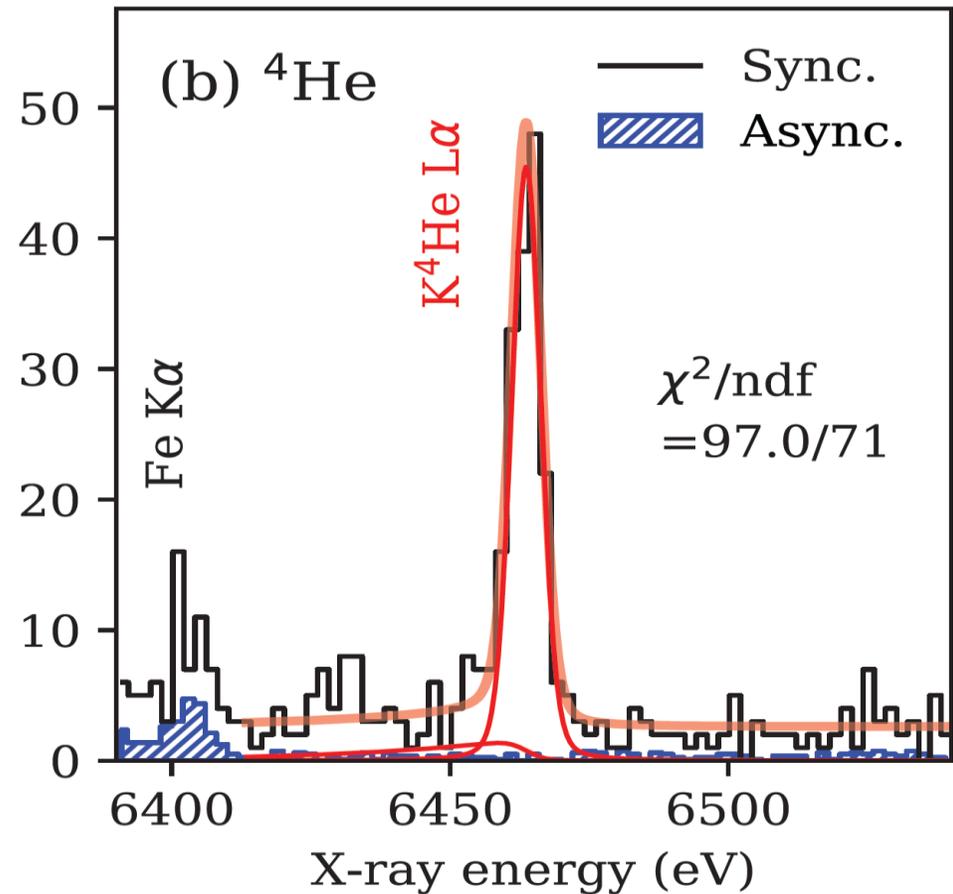
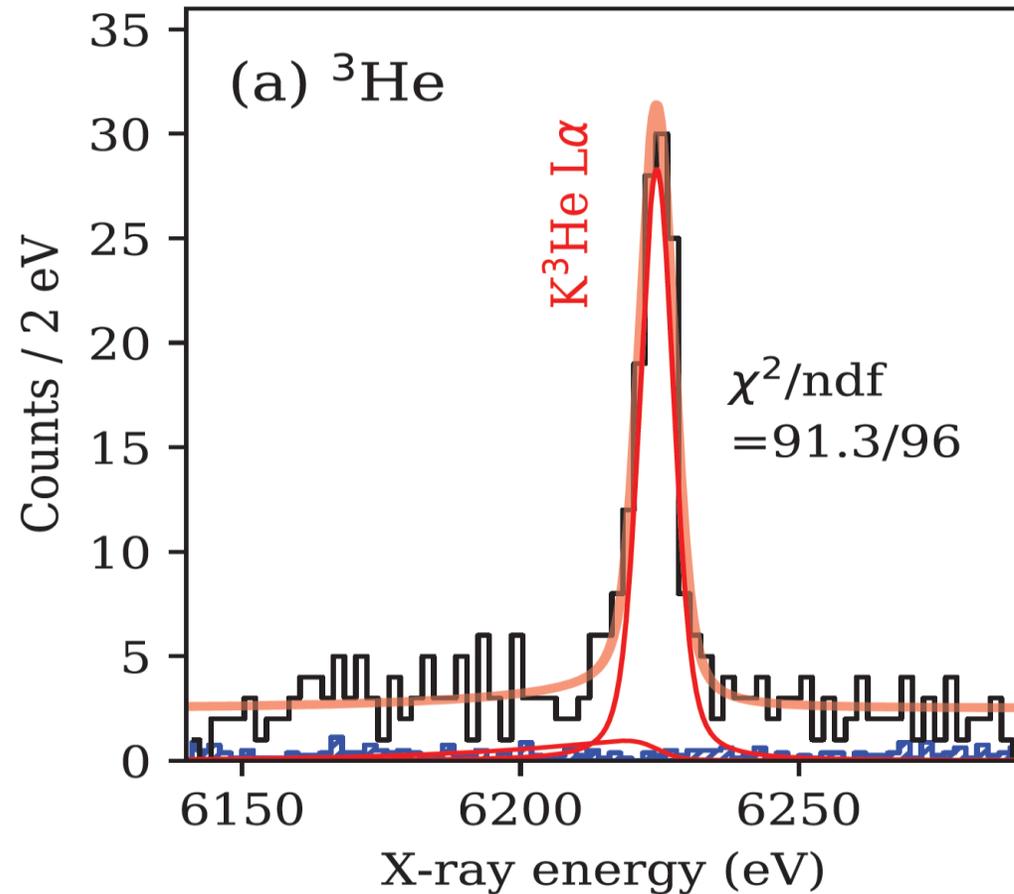
- Cooled down to 70 mK with ADR & pulse tube.
- 240 pixel: 8 columns x 30 rows time-division multiplexing (TDM) readout
- $\sim 23 \text{ mm}^2$, Mo/Cu + Bi 4 μm (85% eff.@6 keV)
- First case to operate in a hadron beam environment.

Transition-Edge-Sensor microcalorimeters



Resolution: $\sim 5 \text{ eV FWHM @ } 6 \text{ keV}$
Dynamic range: 4-15 keV

Result of E62 at J-PARC



$$E_{3d \rightarrow 2p}^{K^{-3}\text{He}} = 6224.5 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.}) \text{ eV,}$$

$$E_{3d \rightarrow 2p}^{K^{-4}\text{He}} = 6463.7 \pm 0.3(\text{stat.}) \pm 0.1(\text{syst.}) \text{ eV,}$$

$$\Gamma_{2p}^{K^{-3}\text{He}} = 2.6 \pm 1.0(\text{stat.}) \pm 0.4(\text{syst.}) \text{ eV,}$$

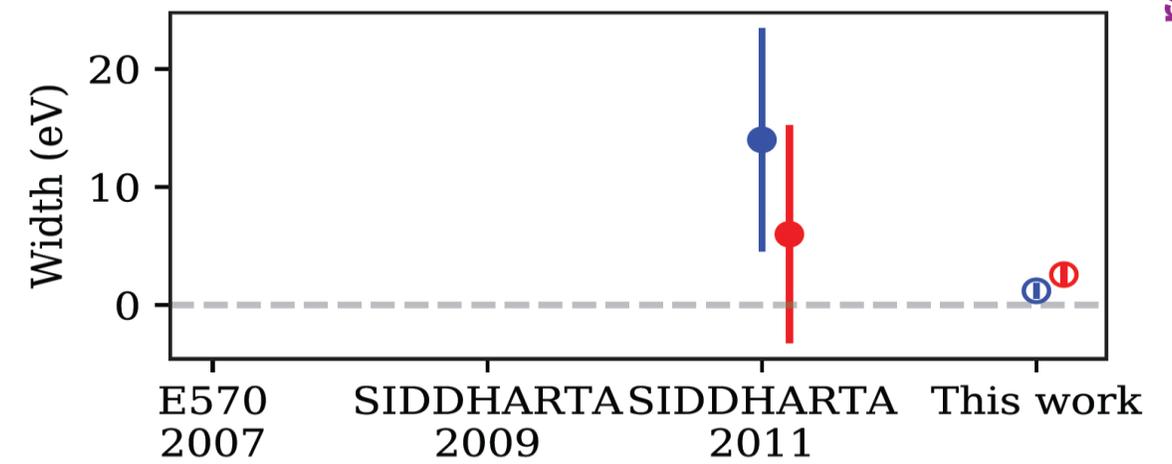
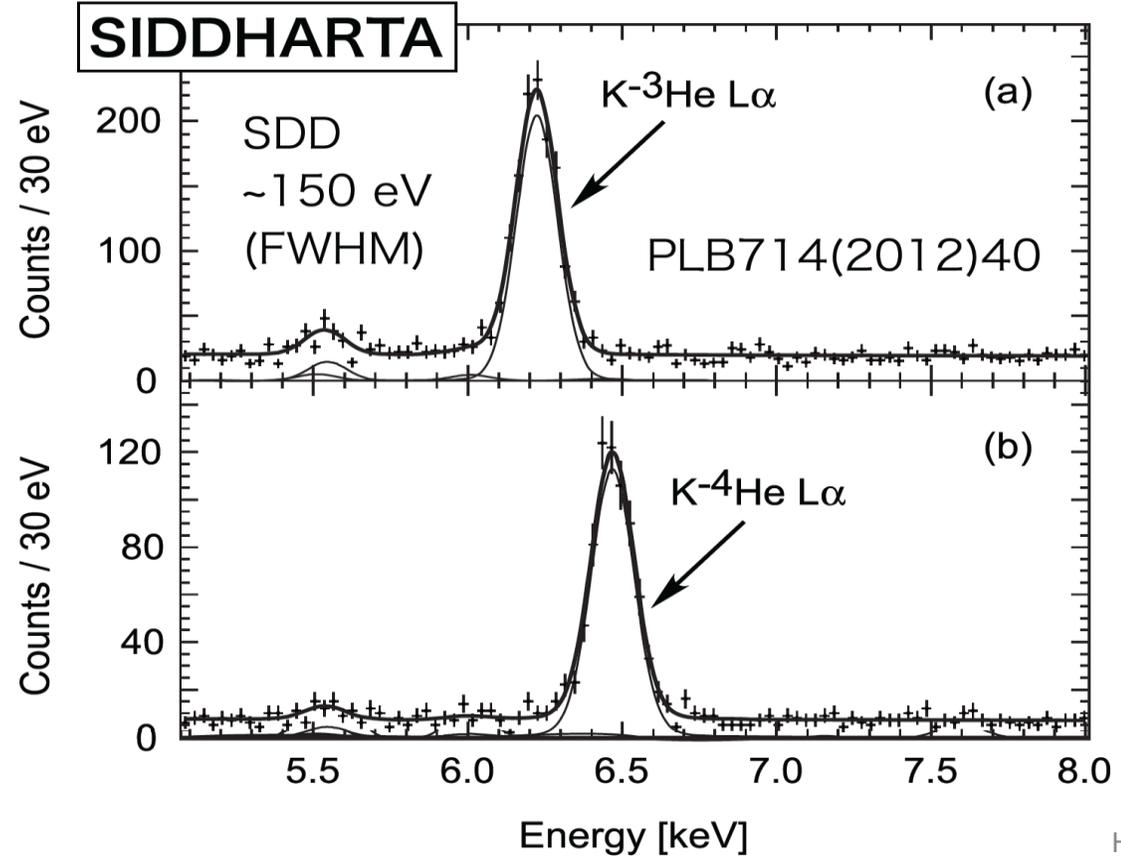
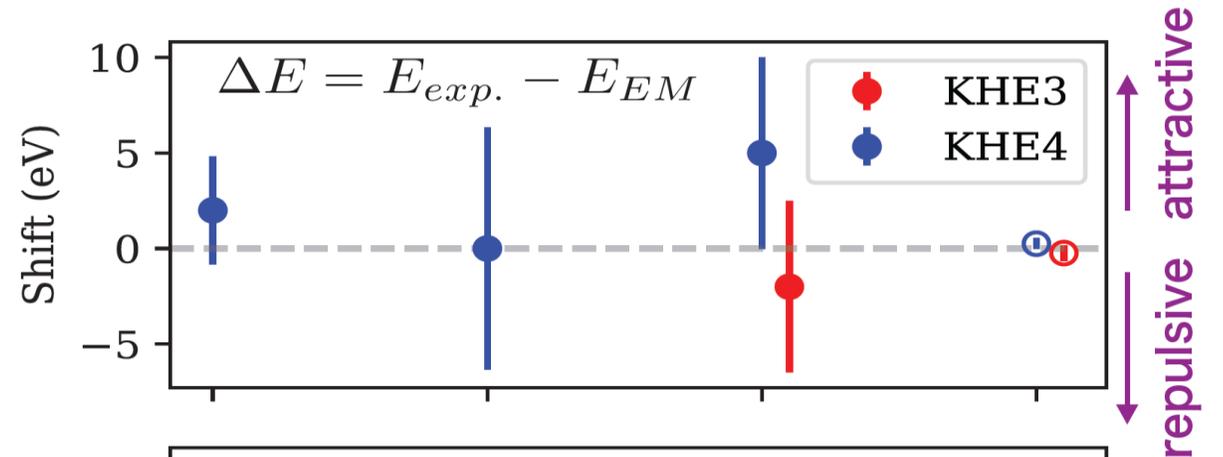
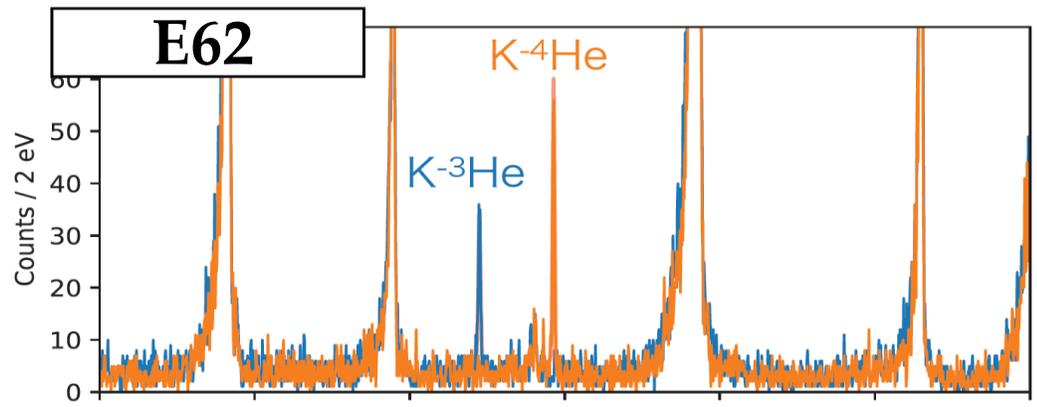
$$\Gamma_{2p}^{K^{-4}\text{He}} = 1.2 \pm 0.6(\text{stat.}) \pm 0.3(\text{syst.}) \text{ eV.}$$

HYP2022

$$\Delta E_{2p}^{K^{-3}\text{He}} = -0.2 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.}) \text{ eV,}$$

$$\Delta E_{2p}^{K^{-4}\text{He}} = 0.1 \pm 0.3(\text{stat.}) \pm 0.2(\text{syst.}) \text{ eV.}$$

$$\Delta E_{2p}^{\text{isotope}} = -0.4 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.}) \text{ eV.}$$



Error bar
quadratic sum of stat. & sys.

Outlook

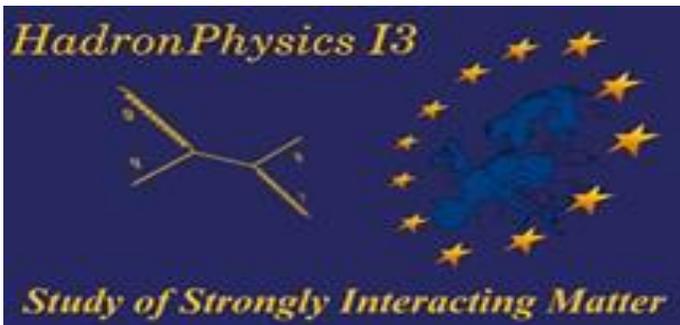
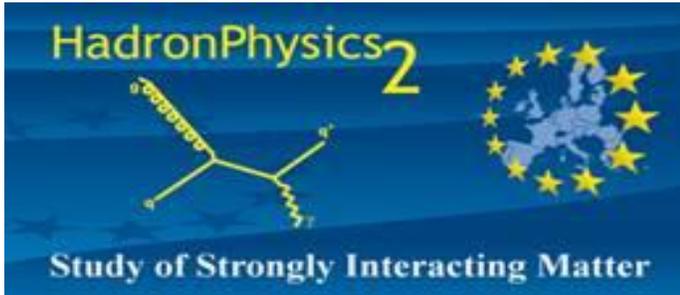
- Kaonic deuterium at J-PARC
- Kaonic atoms at DAΦNE

Strangeness precision frontier – experiments at DAΦNE

presented at the LNF-workshop in Feb. 2021

- **Improvement on kaonic hydrogen** with SIDDHARTA-2 apparatus
 - ☐ for 100 pb⁻¹
- **Determination of the charged kaon mass (K⁻) using VOXES / TES**
parallel measurement of kaonic atoms (with selected solid targets) using HPGe
 - ☐ for 200 pb⁻¹ in 2021
- **Low energy charged kaon scattering studies on H and D**
development of an “**active TPC**” within EU-programme STRONG2020
 - ☐ for 200 pb⁻¹ in 2022
- **Determination of the 1s state of kaonic helium**
in parallel kaon scattering on helium
development of **CdZnTe detectors** within EU-programme STRONG2020
 - ☐ for 400 pb⁻¹ in 2023

Supported by:



Farnesina

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e della Cooperazione Internazionale

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[650962/0001 VI/2/2009]

FWF Der Wissenschaftsfonds.

Austrian Science Fund
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JSPS

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< KAKENHI >

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