Stefan Meyer Institute

Kaonic Atoms - from DAΦNE to J-PARC

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Progress on J-PARC hadron physics in 2014
November 30 - December 2, 2014

Outline

- Motivation
- Measuring principle
- SIDDHARTA setup at DAΦNE
- Results of kaonic helium and hydrogen
- Kaonic deuterium at J-PARC
- Summary

Motivation

Exotic (kaonic) atoms – probes for strong interaction

- hadronic shift ε_{1s} and width Γ_{1s} directly observable
- experimental study of low energy QCD
- testing chiral symmetry breaking in systems with strangeness

Kaonic hydrogen

- <u>scattering lengths</u>, no extrapolation to zero energy
- precise experimental data:

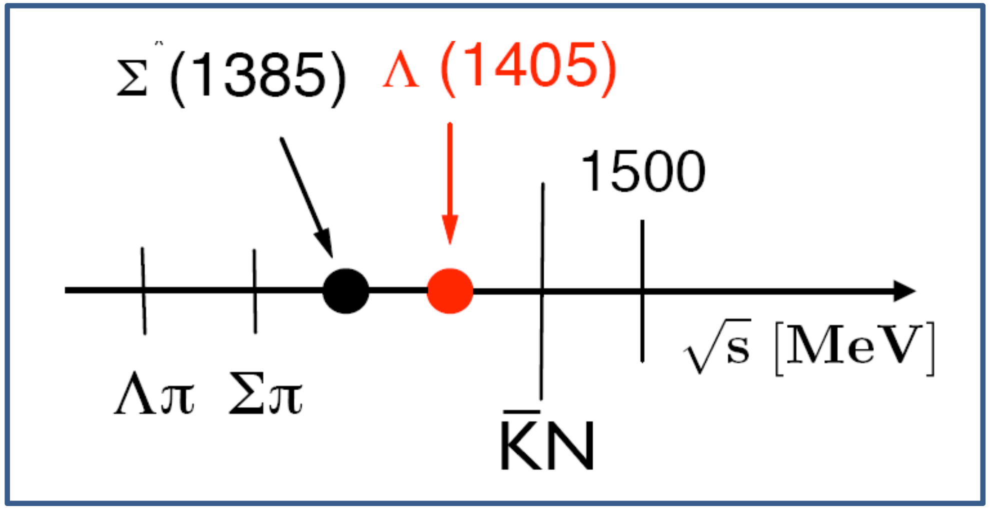
K^-p (K^-He) $\rightarrow$ SIDDHARTA

K^-d measurement is urgently needed

- **determination of the isospin dependent $\overline{K}N$ scattering lengths**

Low-energy $\bar{K}$-N systems

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



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

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

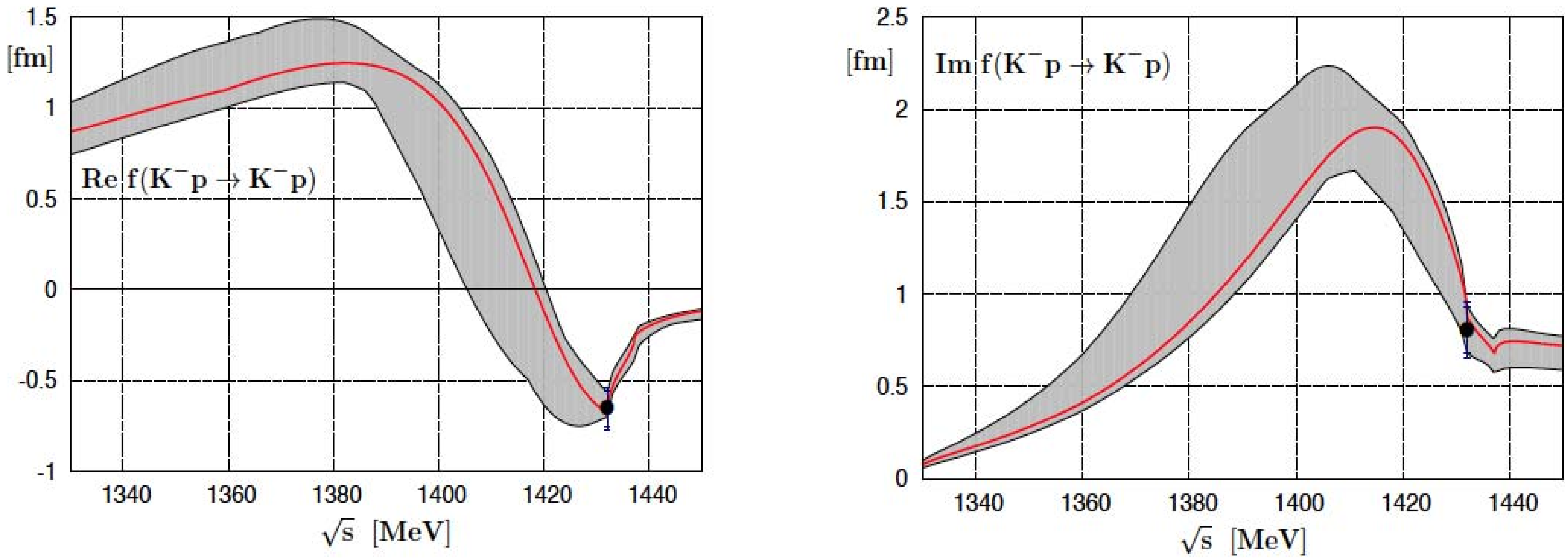


Fig. 3. Real part (left) and imaginary part (right) of the $K^-p \to K^-p$ forward scattering amplitude extrapolated to the subthreshold region. The empirical real and imaginary parts of the K^-p scattering length deduced from the recent kaonic hydrogen measurement (SIDDHARTA [7]) are indicated by the dots including statistical and systematic errors. The shaded uncertainty bands are explained in the text.

Scattering lengths

Deser-type relation[1)] connect the observables shift ε_{1s} and width Γ_{1s} of the 1s state with the real and imaginary part of the scattering length $a_{K\text{-}p}$ (μ_C reduced mass of the K^-p system, α fine-structure constant)

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

1) U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

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

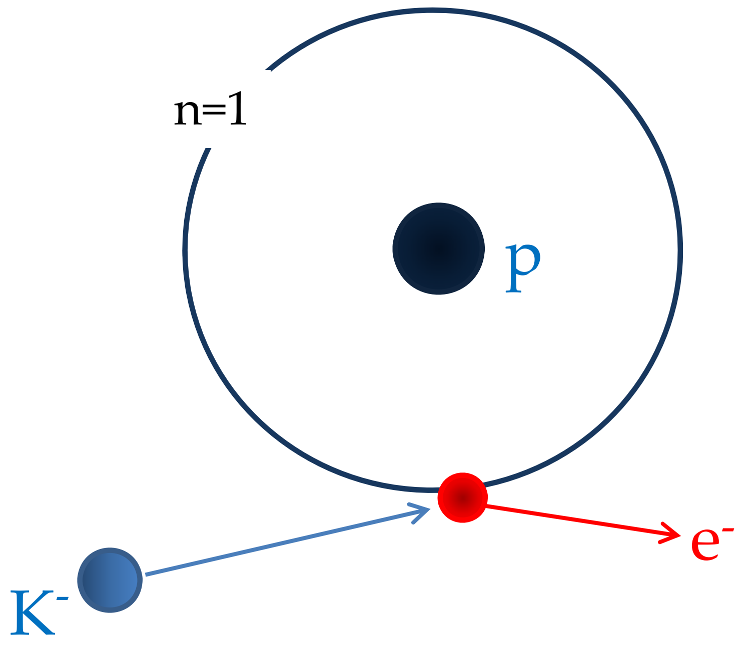
$$a_{K^-n} = a_1$$

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

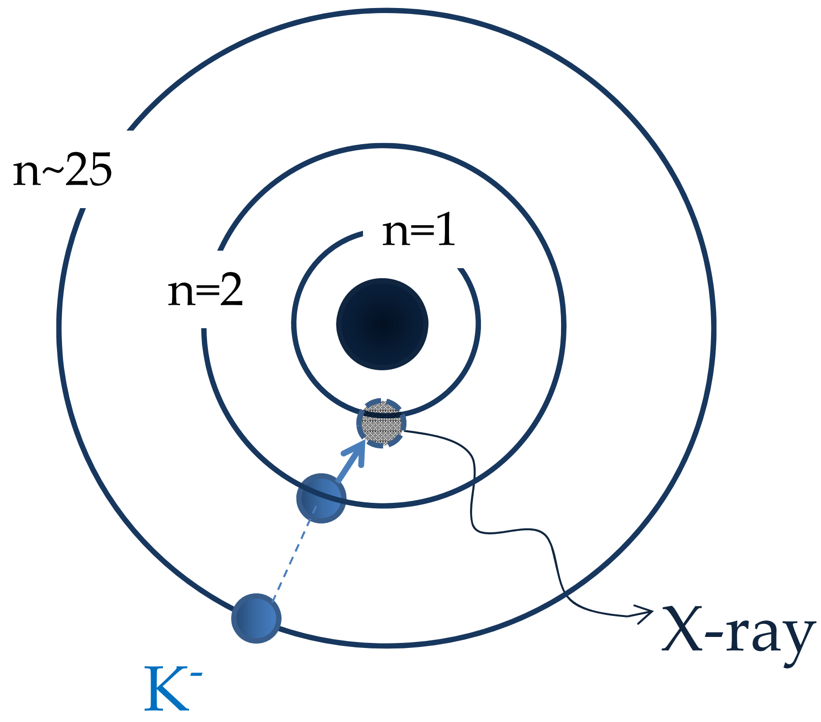
$$k = \frac{4\left[m_n + m_K\right]}{\left[2m_n + m_K\right]}$$

Forming “exotic” atoms

“normal” hydrogen



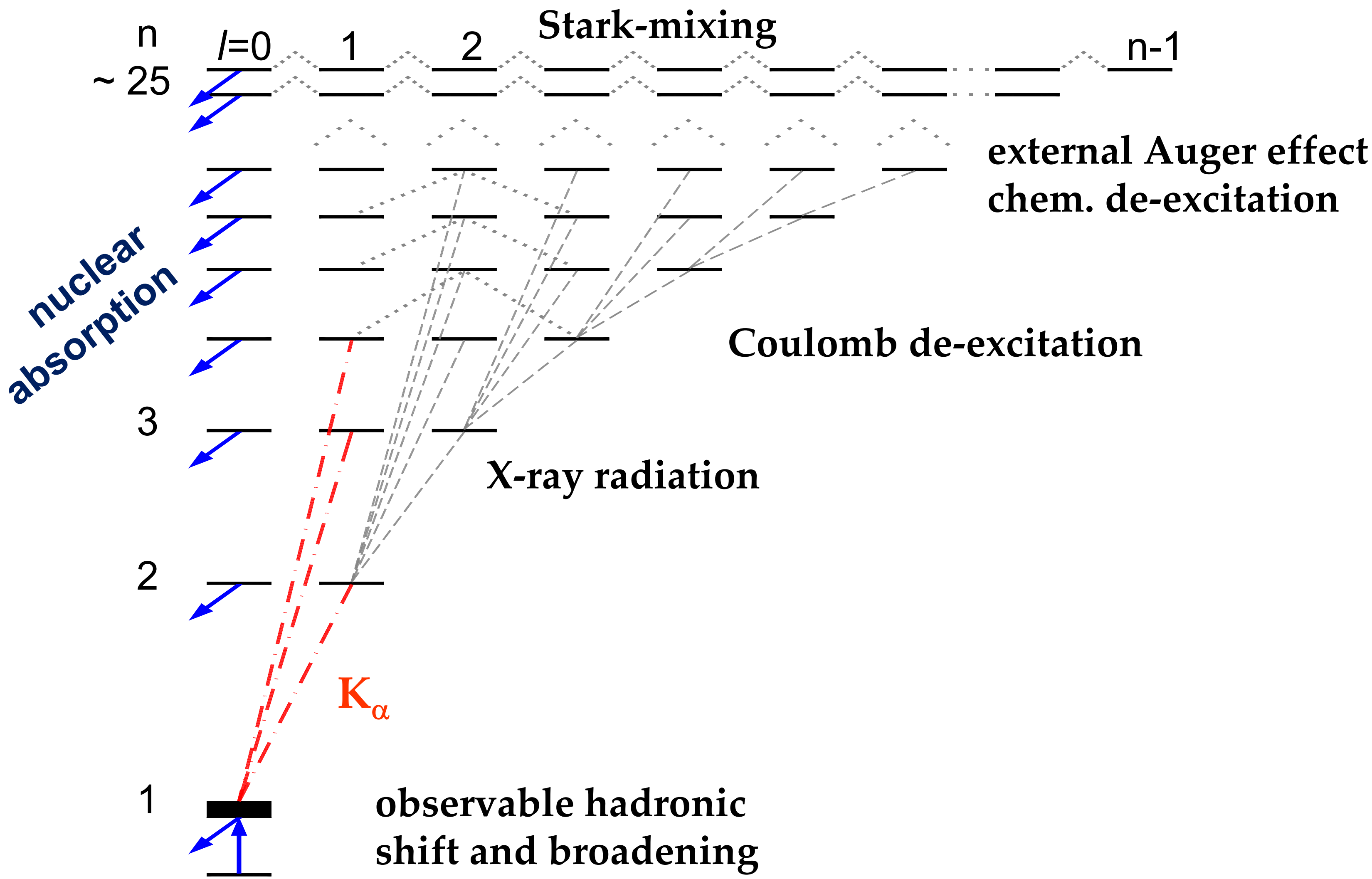
“exotic” (kaonic) hydrogen



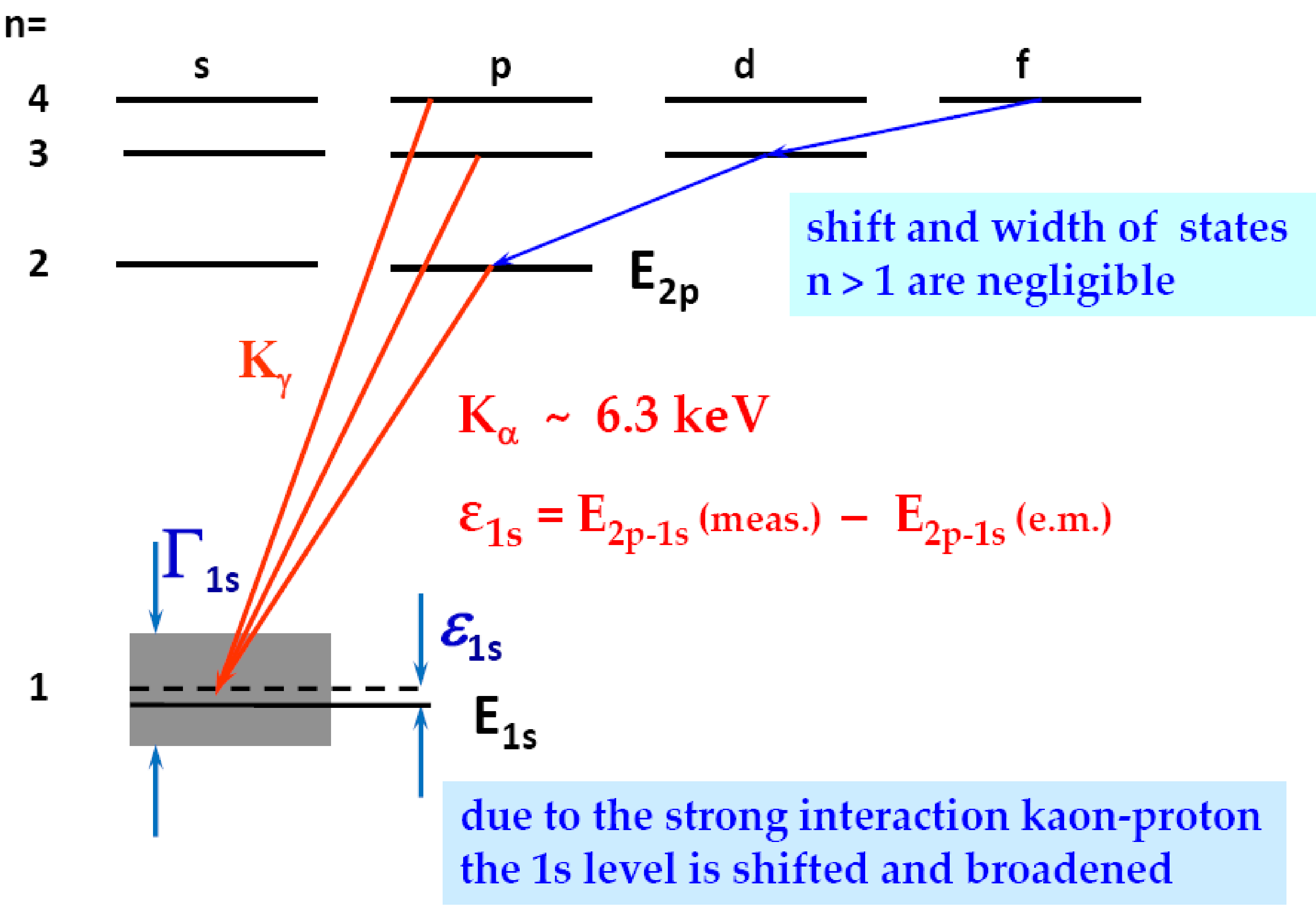
$$n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e$$

2p → 1s
K_α transition

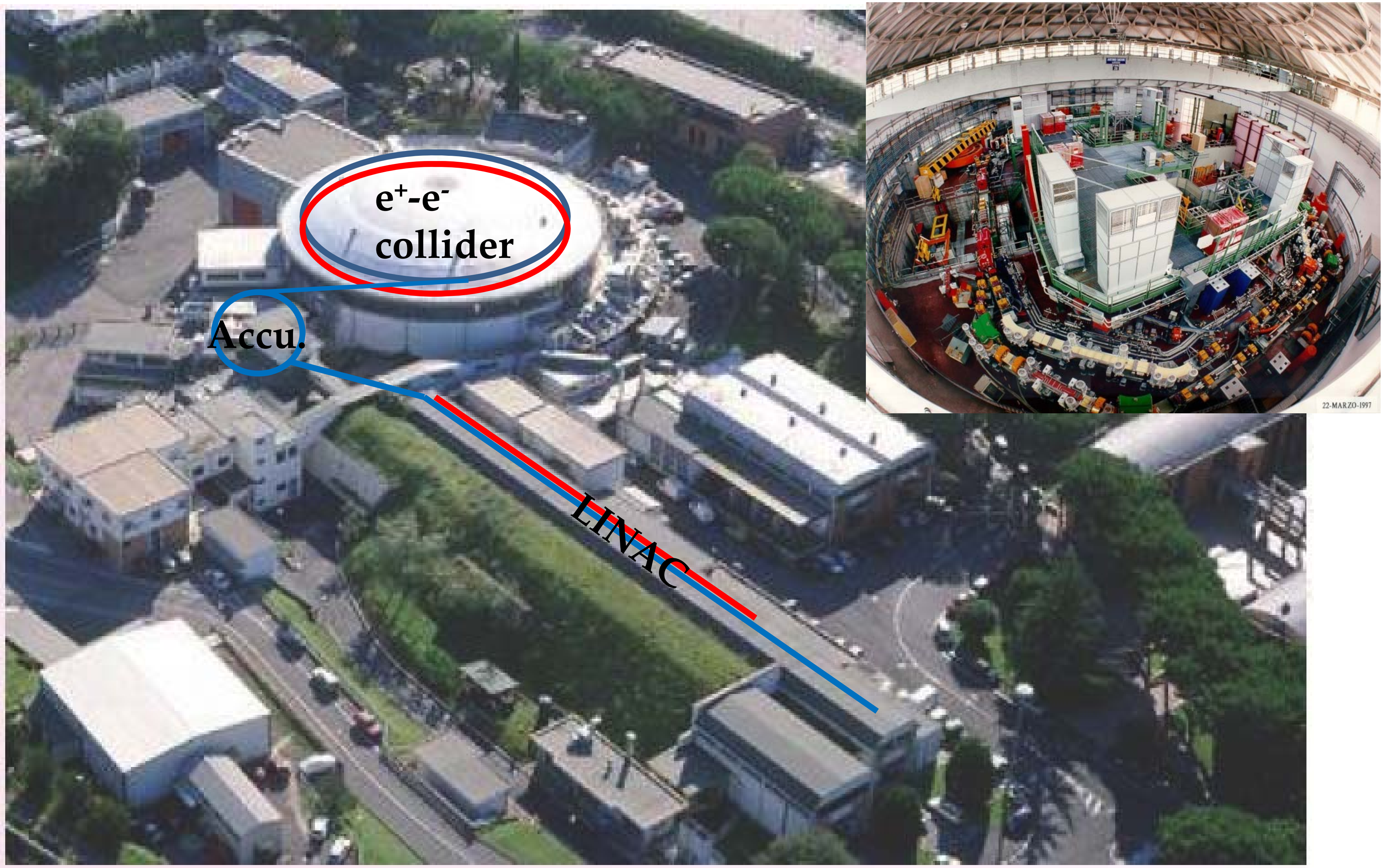
Cascade processes



X-ray transitions to the 1s state

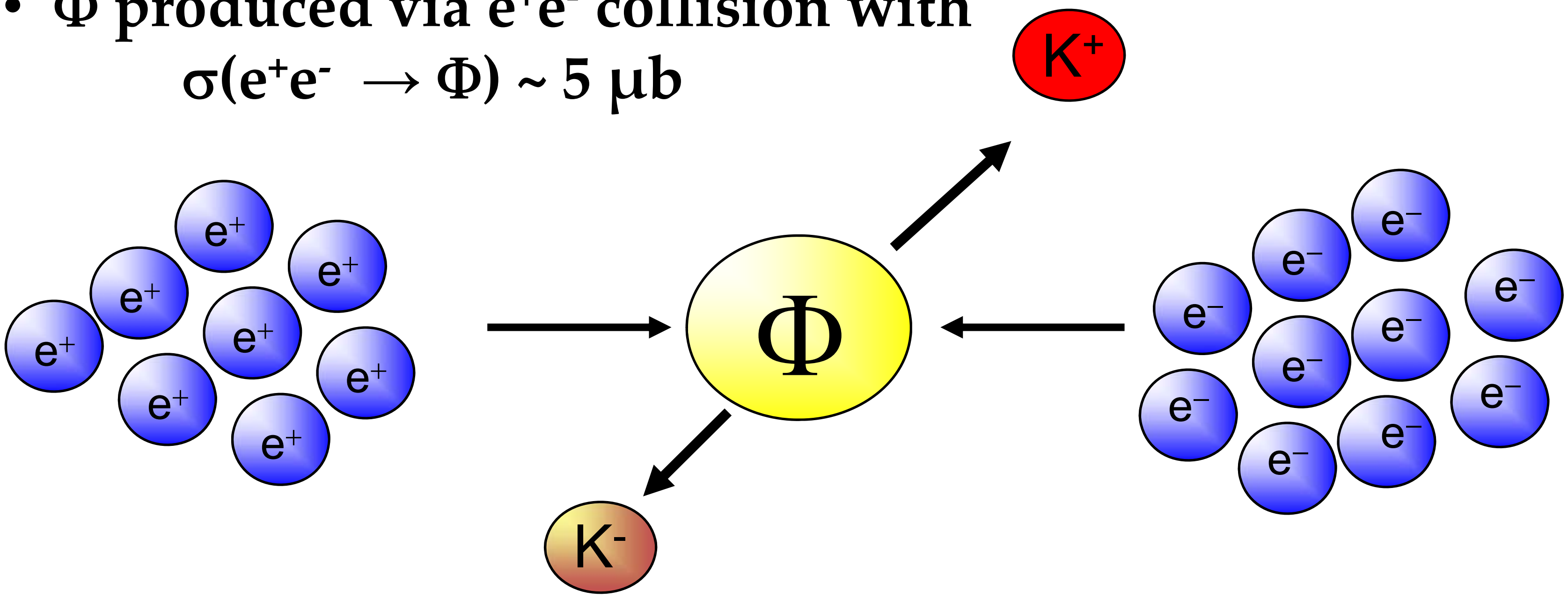


Kaonic hydrogen atoms at DAΦNE



DAΦNE principle

- operates at the centre-of-mass energy of the Φ meson
  mass $m = 1019.413 \pm .008$ MeV
  width $\Gamma = 4.43 \pm .06$ MeV
- Φ produced via e^+e^- collision with
  $\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$



→ Φ production rate $2.5 \times 10^3\ s^{-1}$

→ monochromatic kaon beam (127 MeV/c)

Detectors for $K^{-}p$ experiments

	KpX	DEAR	SIDDHARTA
	@ KEK	@ DAΦNE	
Detector	Si(Li)	CCD	SDD
Energy resolution	350 eV	180 eV	150 eV
Time resolution	μs	30 s	μs
Thickness	mm	30 μm	400 μm
Efficiency at 6 keV	~ 100%	~ 60%	~ 100%
Active area	120 cm²	116 cm²	114 cm²

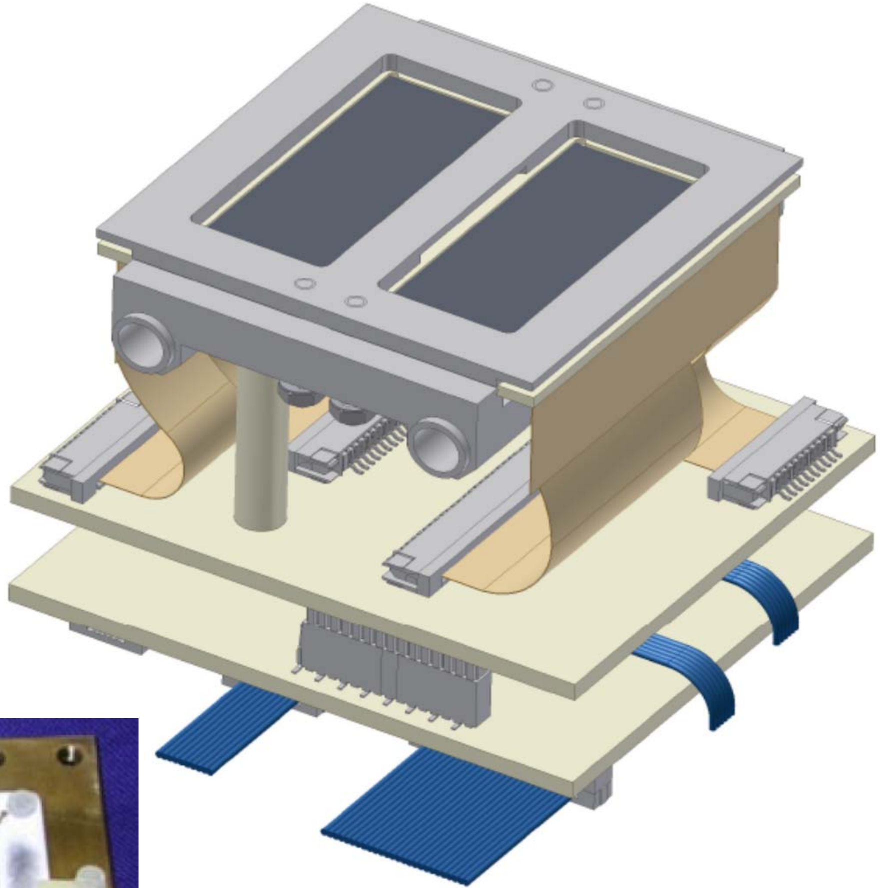
Development of large area SDDs

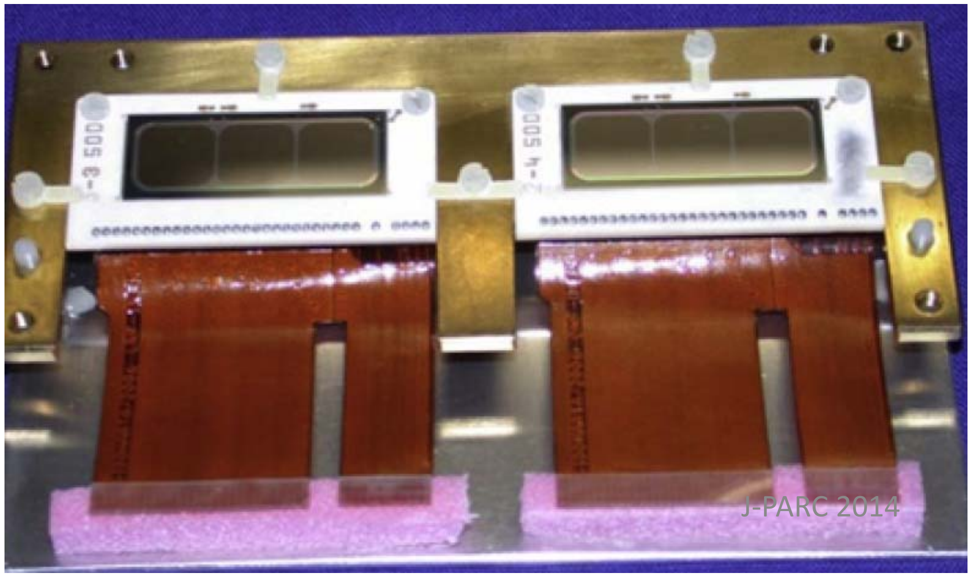
SDD window frame
(pure Al 99.999%)

flexible Kapton
boards

pre-amplifier
board

HV+LV distribution
board





FP-6 EU programme:
HadronPhysics

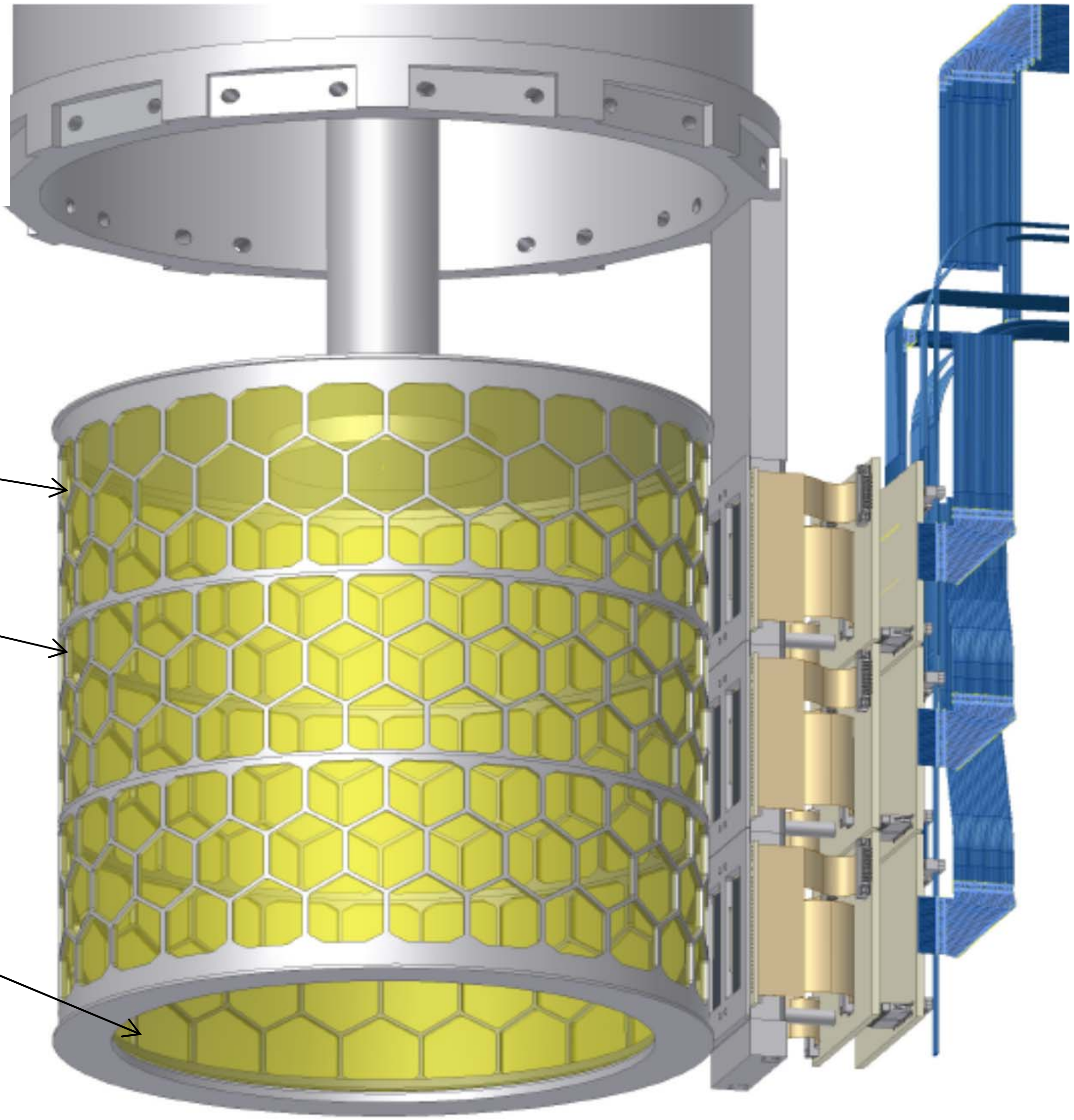
Lightweight cryogenic target cell

working T 22 K
working P 1.5 bar

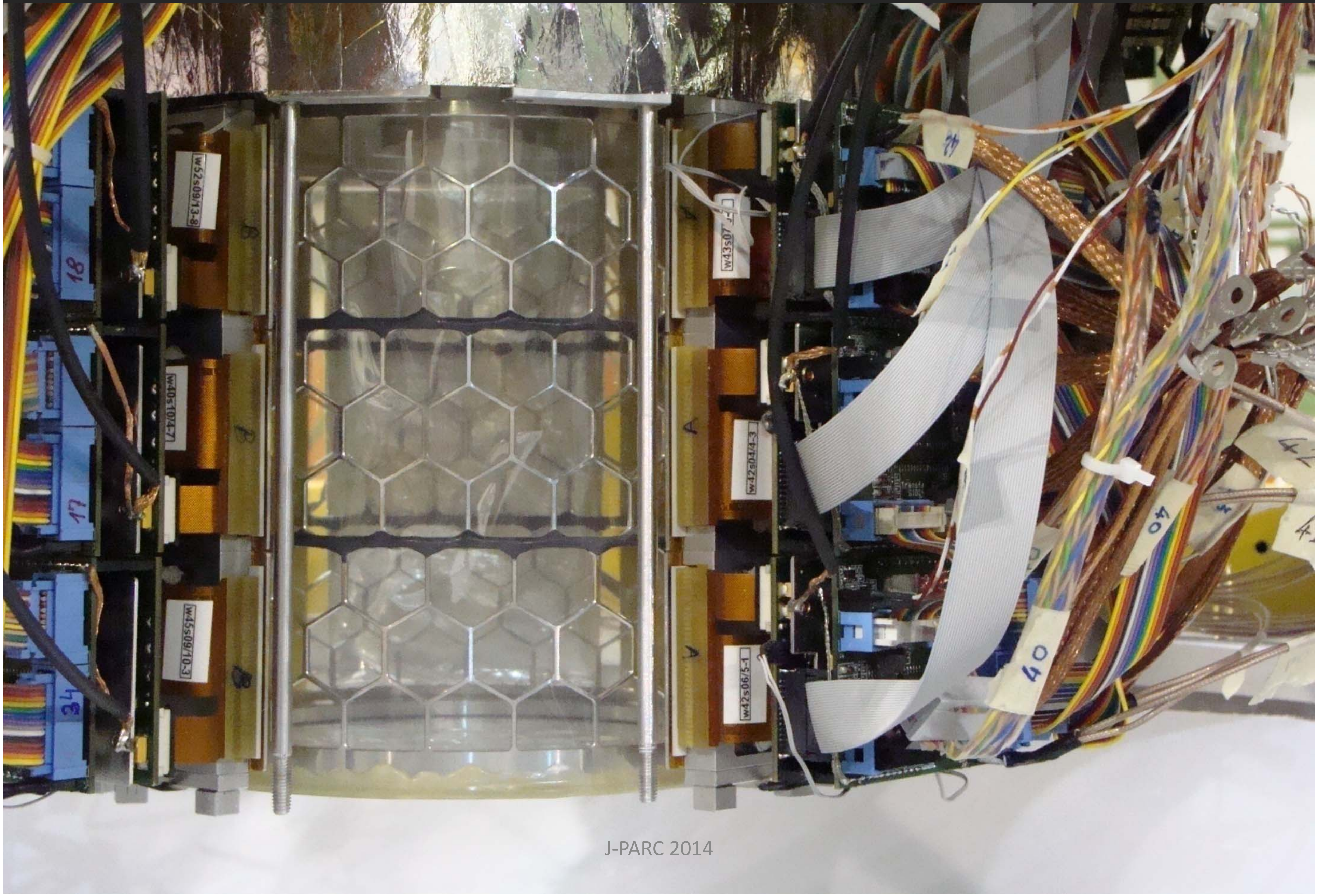
Alu-grid

Side wall:
Kapton 50 μm

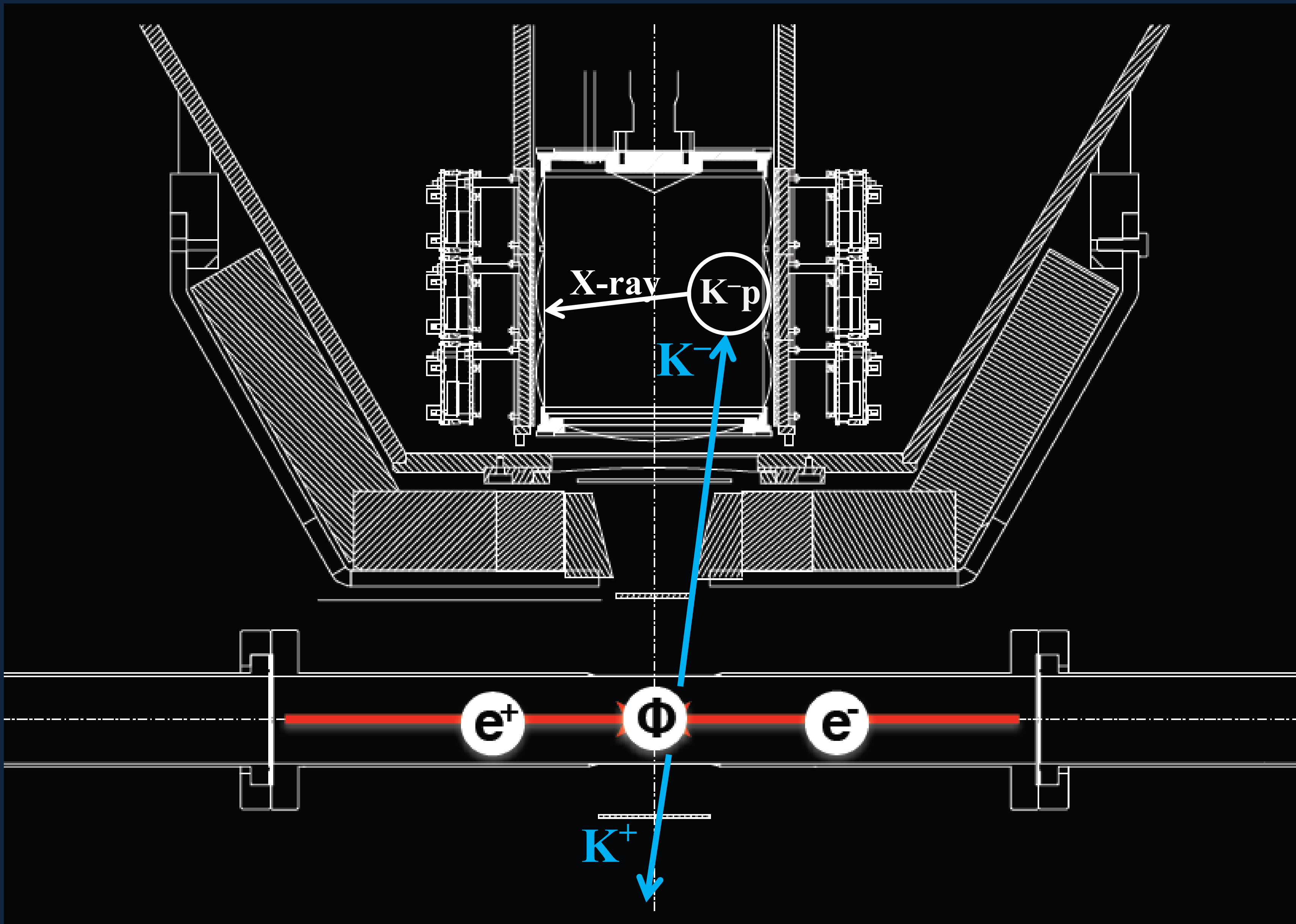
Kaon entrance
Window:
Kapton 75 μm



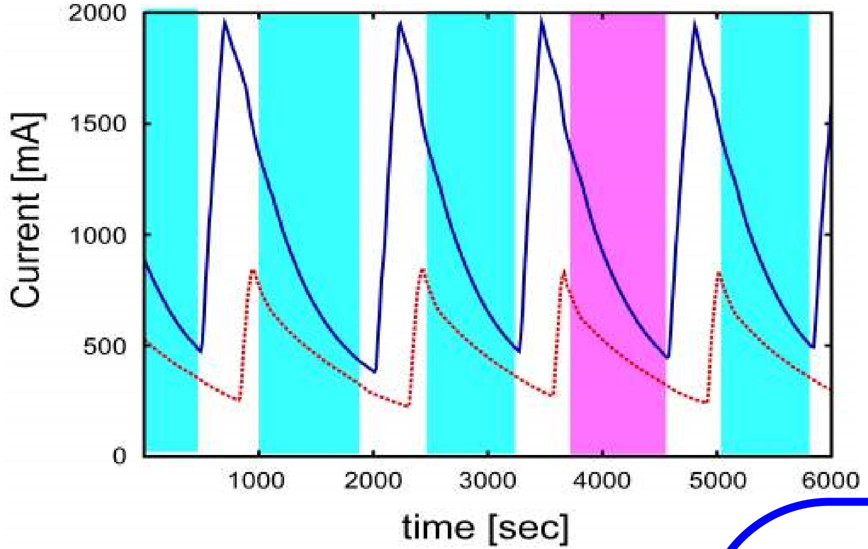
SIDDHARTA target - detector



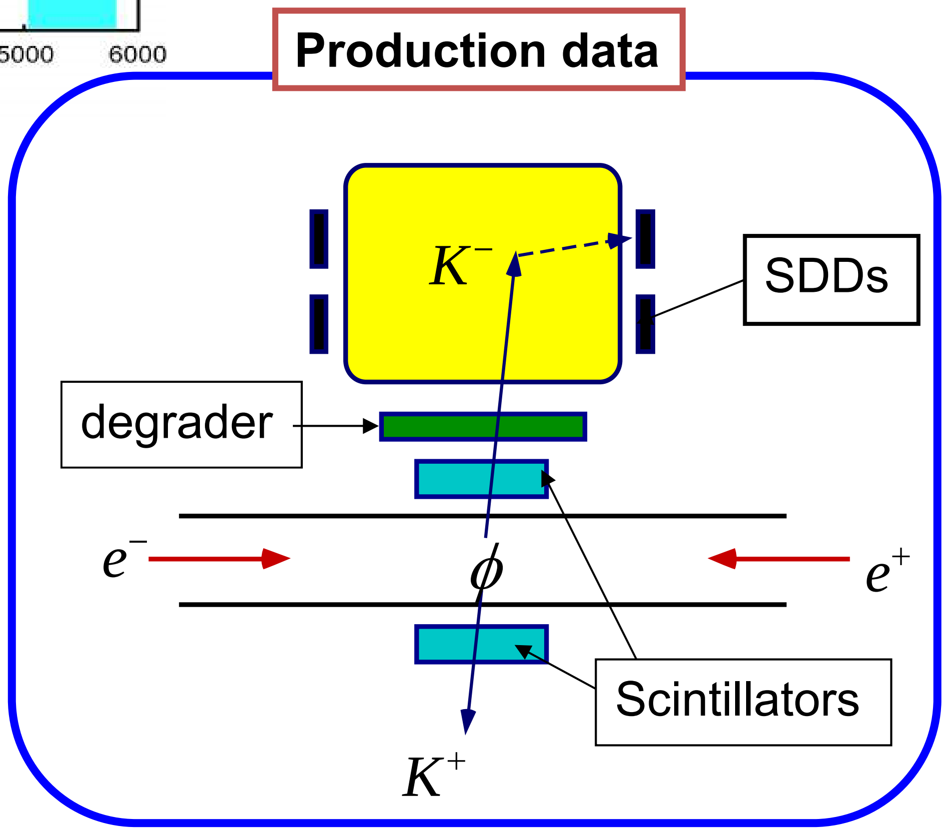
“triple” coincidence method



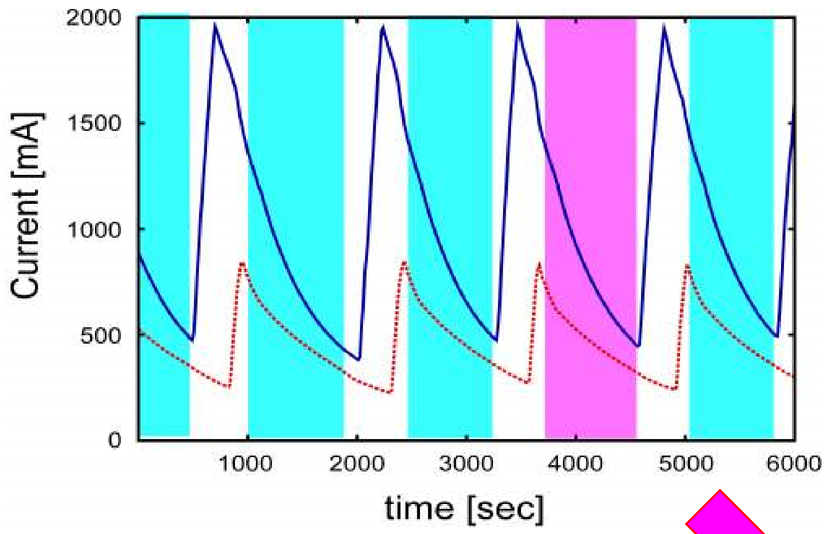
Data taking scheme at DAΦNE



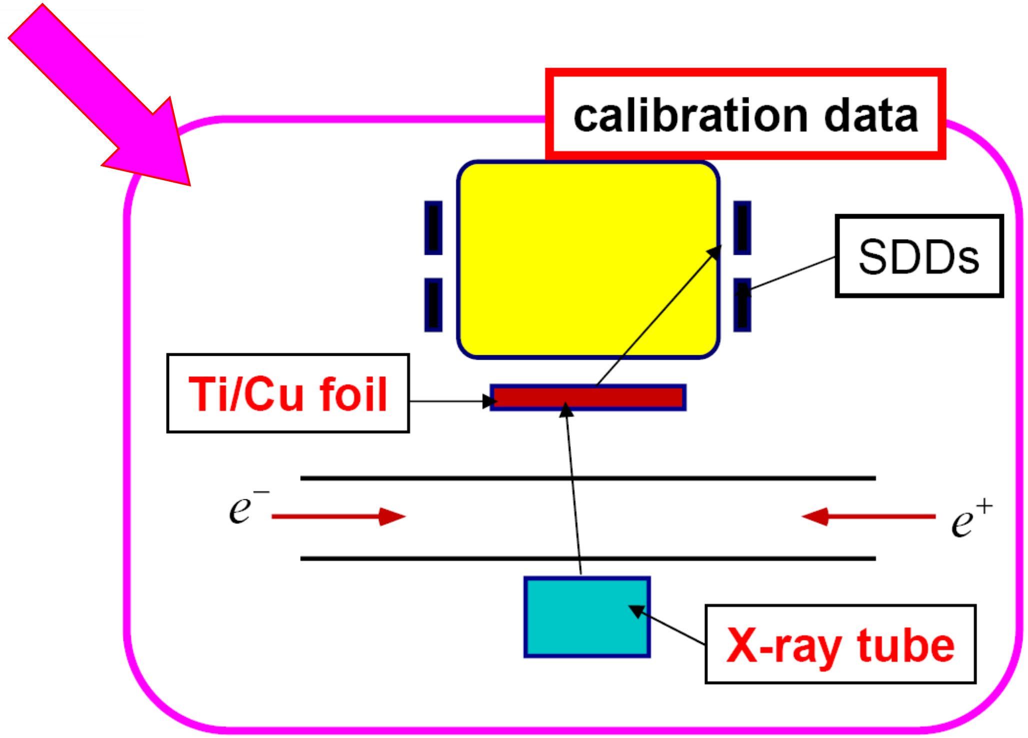
K^+K^- pairs produced at DAΦNE



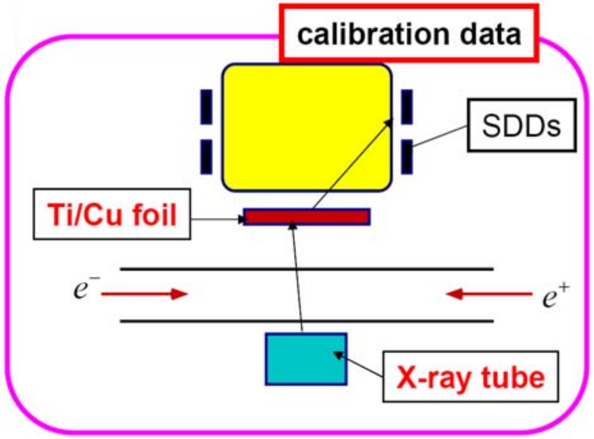
Data taking scheme at DAΦNE



“X-ray tube” data
taken with “beam” ON

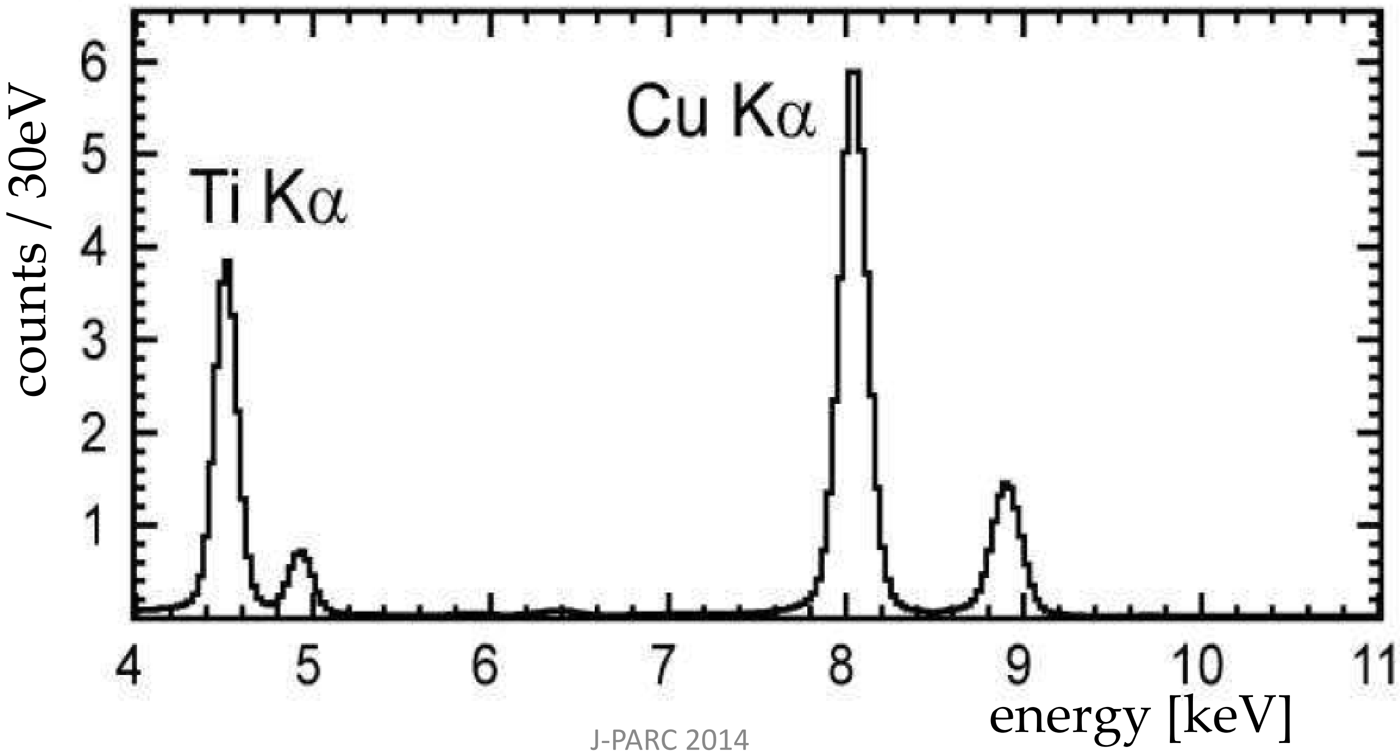


SDD X-ray energy spectra

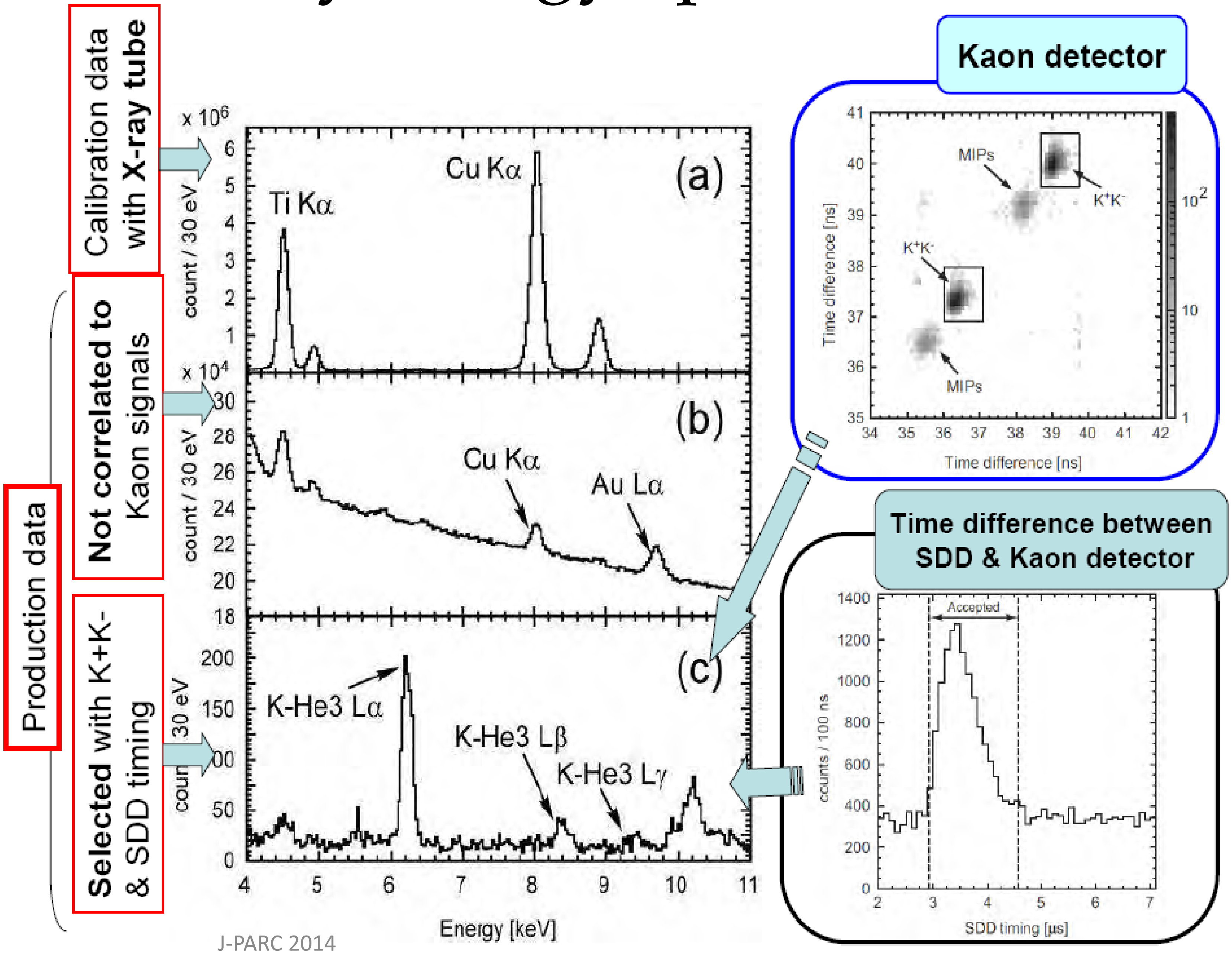


"X-ray tube" data taken

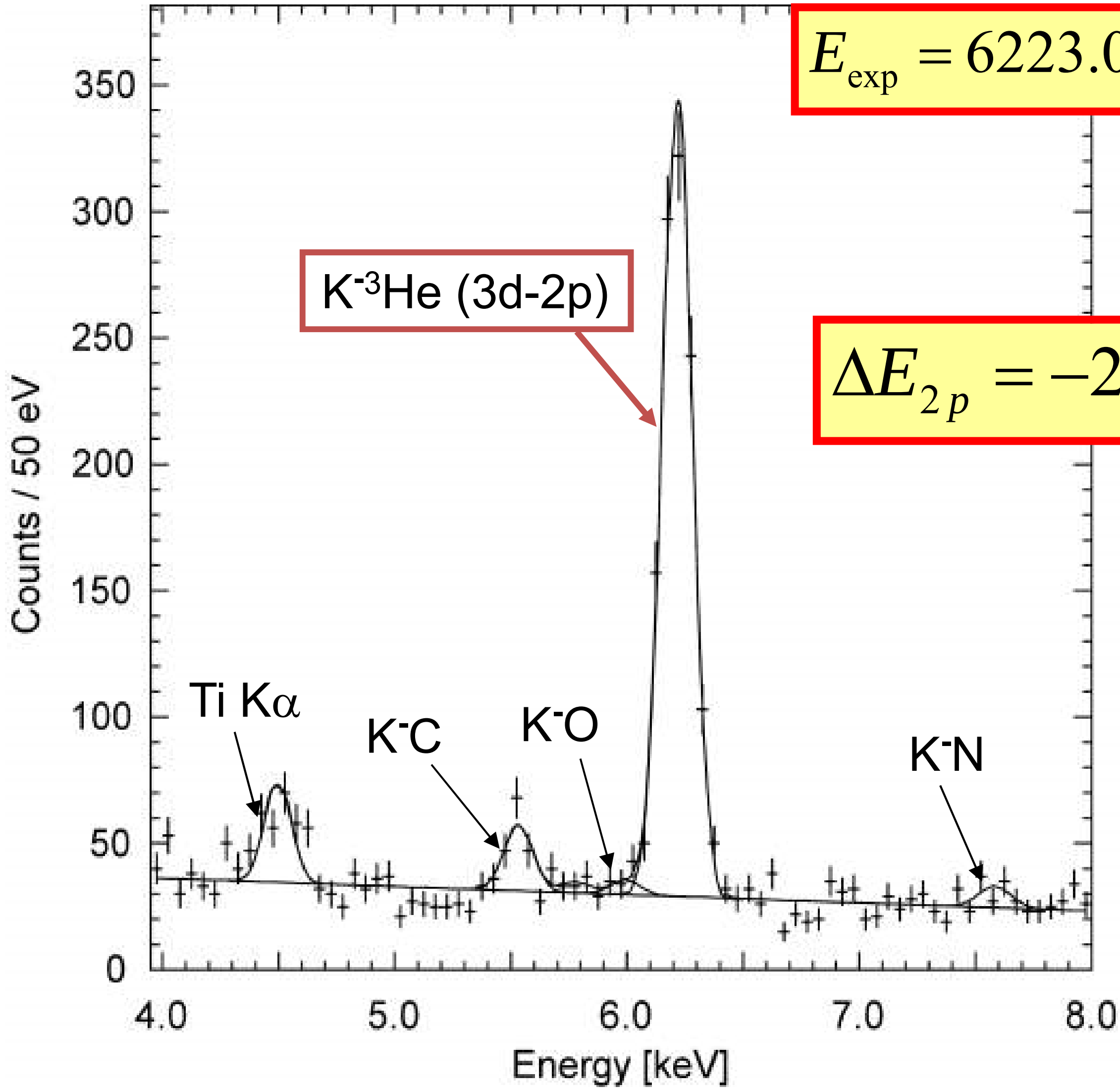
estimated systematic error ~ 3-4 eV



SDD X-ray energy spectra



Kaonic helium-3 measurement



$$E_{exp} = 6223.0 \pm 2.4(sta) \pm 3.5(sys)\ \text{eV}$$

QED value: E_{em}= 6224.6 eV

$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

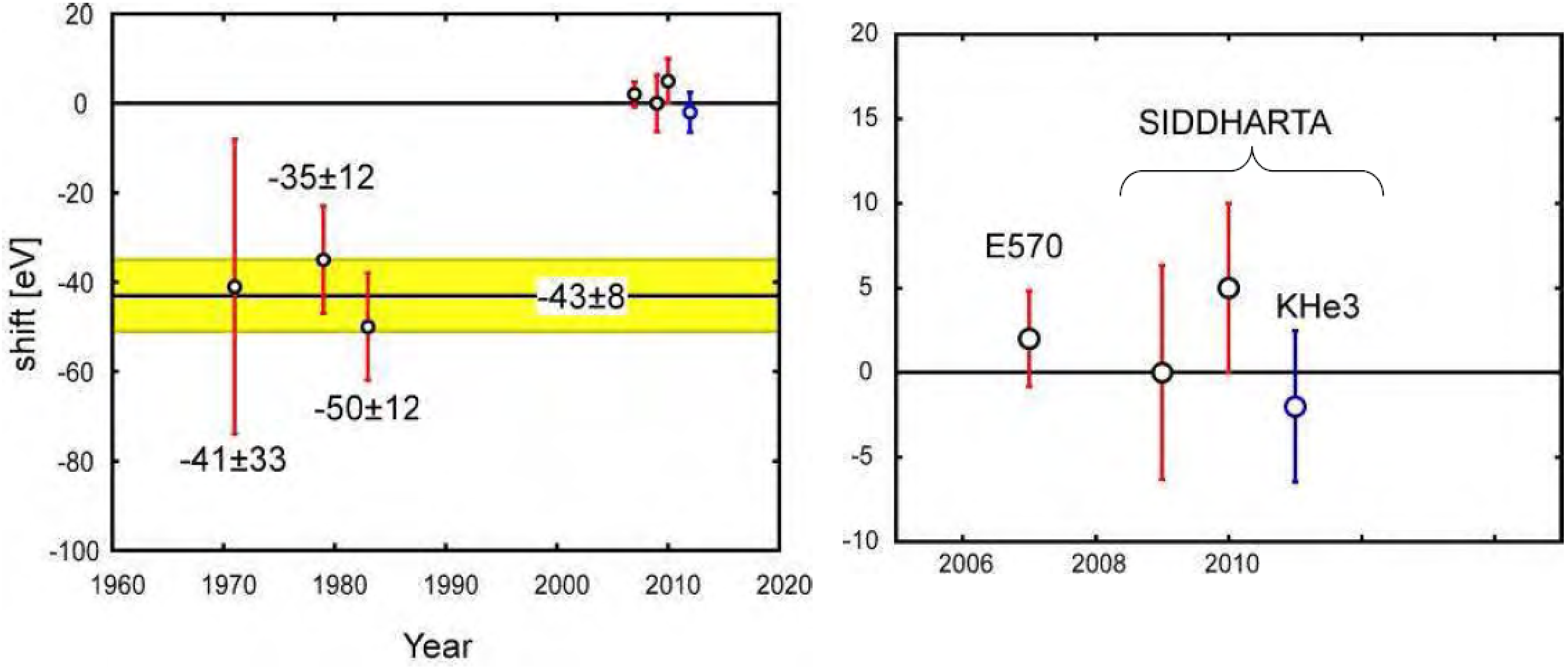
$$\Delta E_{2p} = E_{exp} - E_{e.m.}$$

First observation of K-^3He X-rays

PLB 697(2011)199

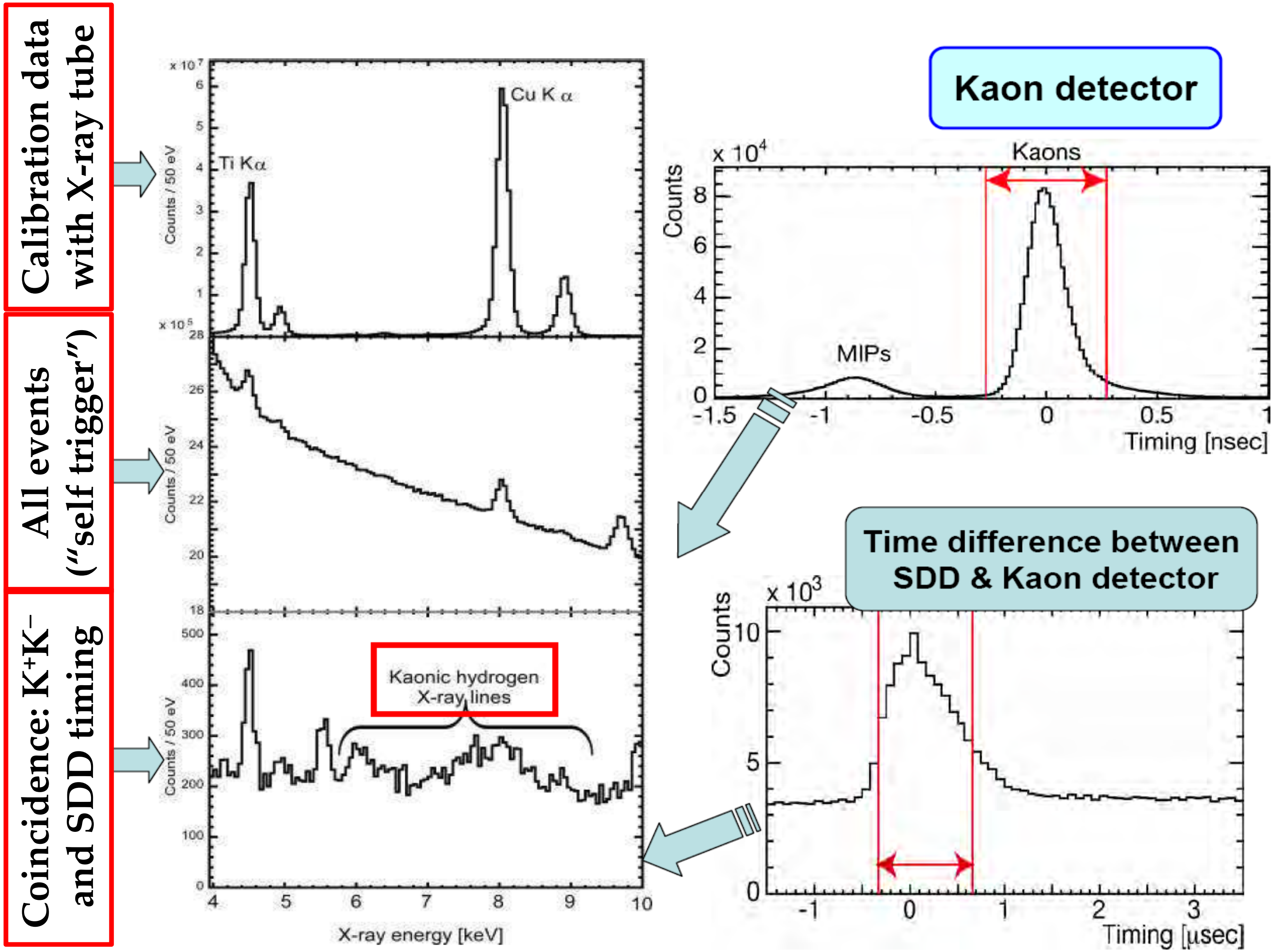
Kaonic helium results

	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	

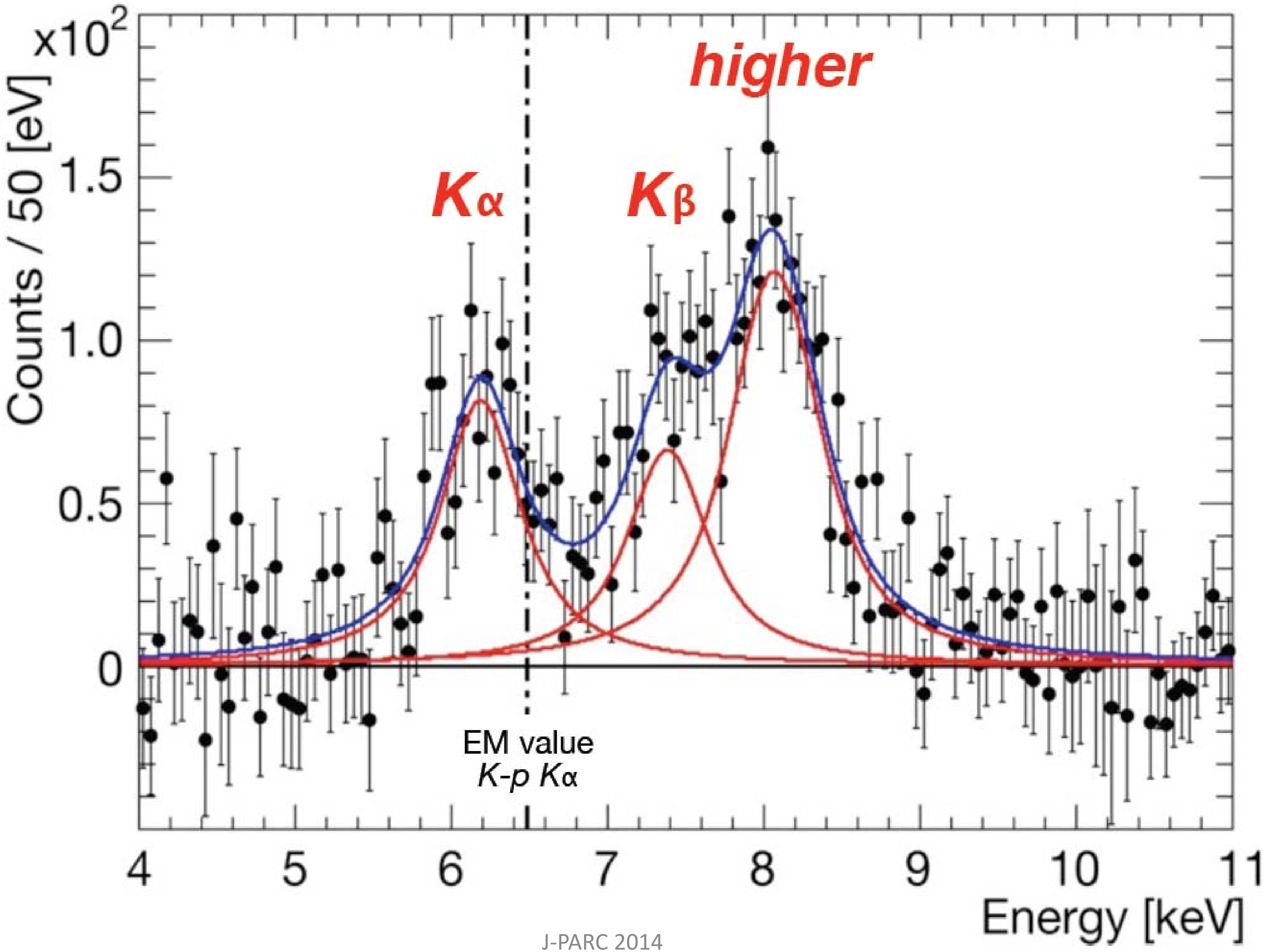


➢ **calibration under control within several eV**

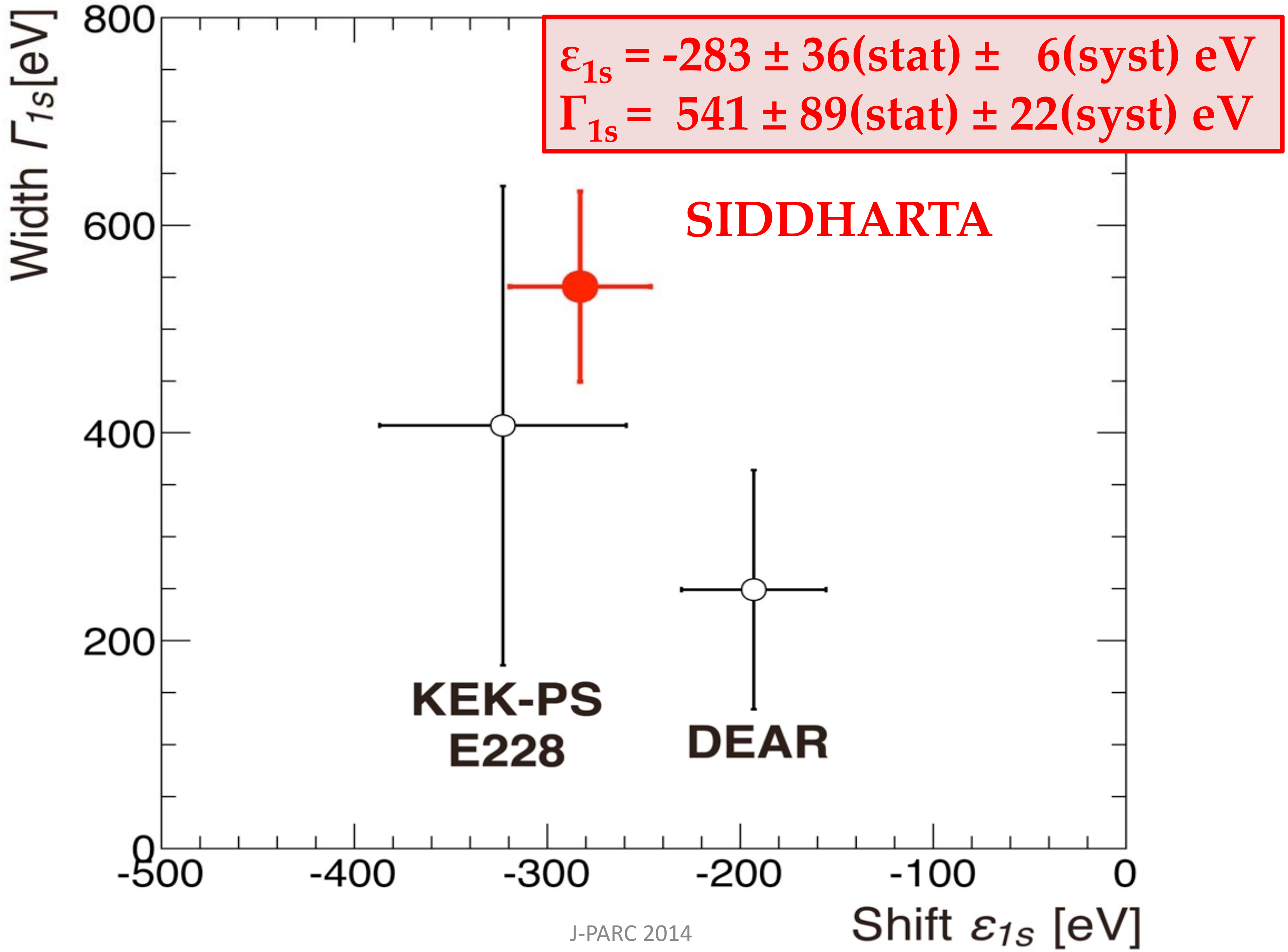
Kaonic hydrogen



K^-p spectrum after BG subtraction



State of the art: Kaonic hydrogen



UPDATED ANALYSIS of K^-p THRESHOLD PHYSICS

Y. Ikeda, T. Hyodo, W.W. (2011)

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

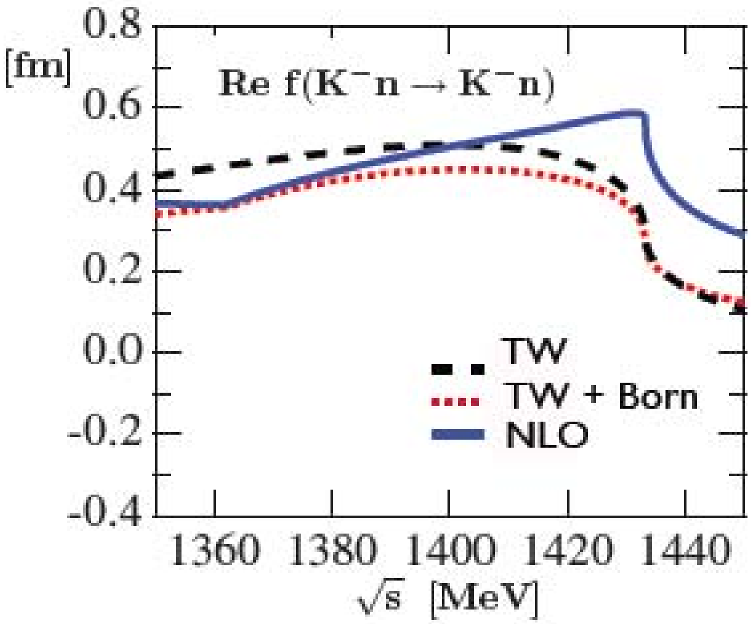
kaonic hydrogen shift & width	theory (NLO)	exp.
ΔE (eV)	306	$283 \pm 36 \pm 6$
Γ (eV)	591	$541 \pm 89 \pm 22$
threshold branching ratios		
$\frac{\Gamma(K^-p \to \pi^+\Sigma^-)}{\Gamma(K^-p \to \pi^-\Sigma^+)}$	2.36	2.36 ± 0.04
$\frac{\Gamma(K^-p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \to \text{all inelastic channels})}$	0.66	0.66 ± 0.01
$\frac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \text{neutral states})}$	0.19	0.19 ± 0.02
scattering length (fm)	$\text{Re}\, a(K^-p) = -0.65 \pm 0.10$	$\text{Im}\, a(K^-p) = 0.81 \pm 0.12$

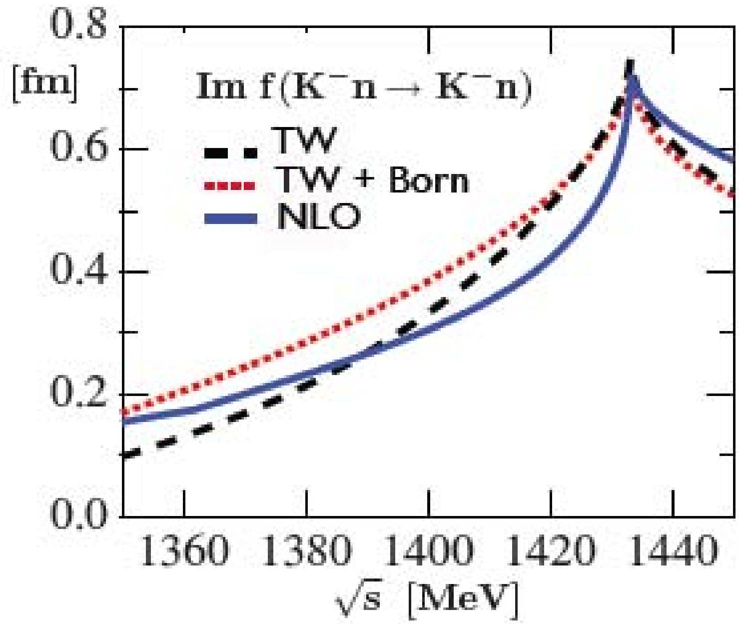
fit achieved with $\chi^2/d.o.f \simeq 1.0$

$\mathrm{K^-n}$ 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

➢ $K^{-}d$ at J-PARC

- development of a new X-ray detector
- use of the K1.8BR spectrometer
- proposal submitted to J-PARC PAC

K–d collaboration

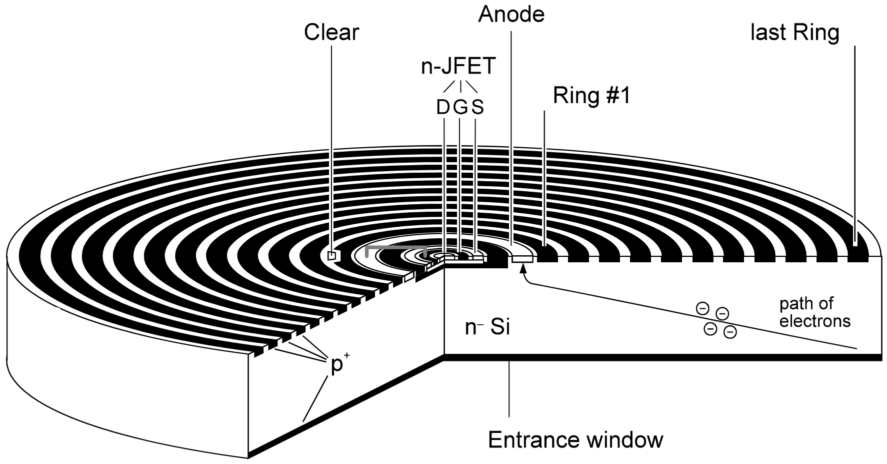
LNF- INFN, Frascati, Italy
SMI- ÖAW, Vienna, Austria
IFIN – HH, Bucharest, Romania
Politecnico, Milano, Italy
RIKEN, Japan
Tokyo Univ., Japan
Victoria Univ., Canada
KEK, Tsukuba, Japan
RCNP, Osaka, Japan
Seoul Univ., South Korea
Zagreb Univ., Croatia
INFN, Torino, Italy
Osaka Univ., Japan
TUM, Garching,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

Development of new SDD-chips

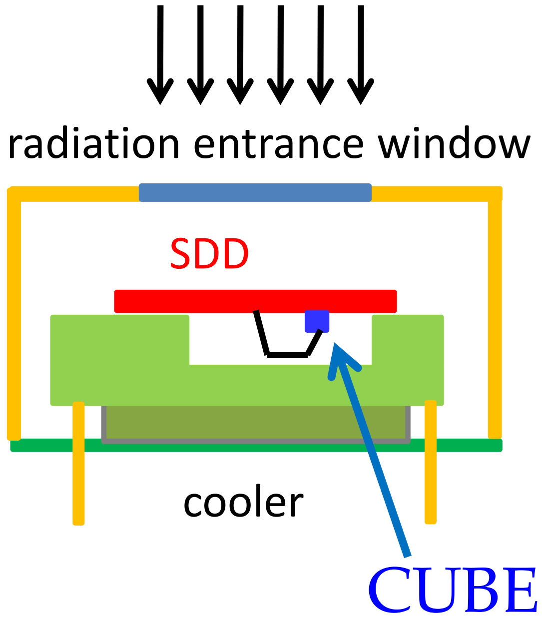
➢ **SIDDHARTA**

- JFET integrated on SDD
- lowest total anode capacitance
- limited JFET performance
- sophisticated SDD+JFET technology

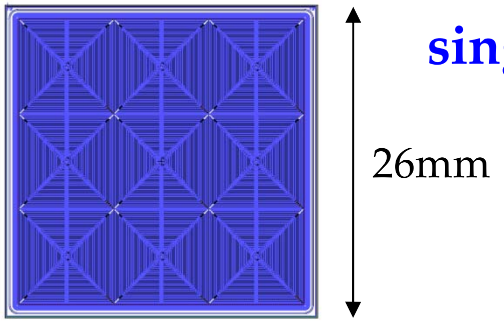


➢ **K⁻d @ J-PARC**

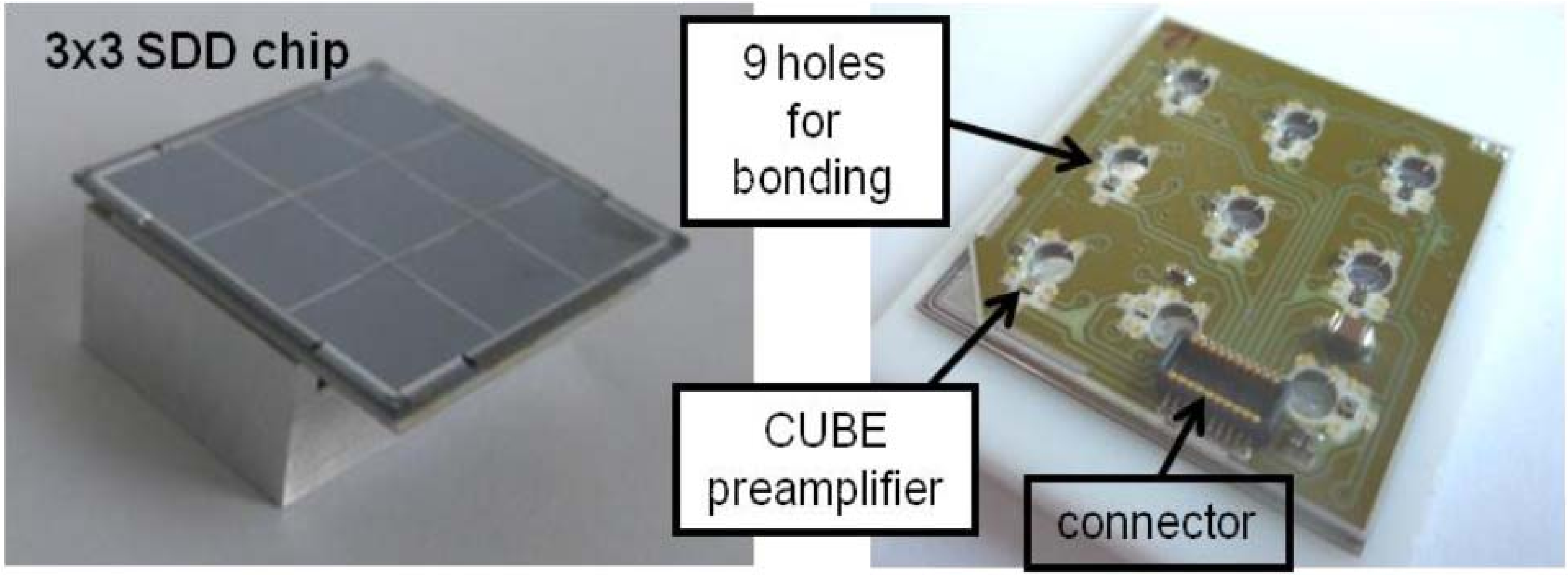
- external CUBE preamplifier (MOSFET input transistor)
- larger total anode capacitance
- better FET performances
- standard SDD technology



Monolithic array of 3x3 SDDs



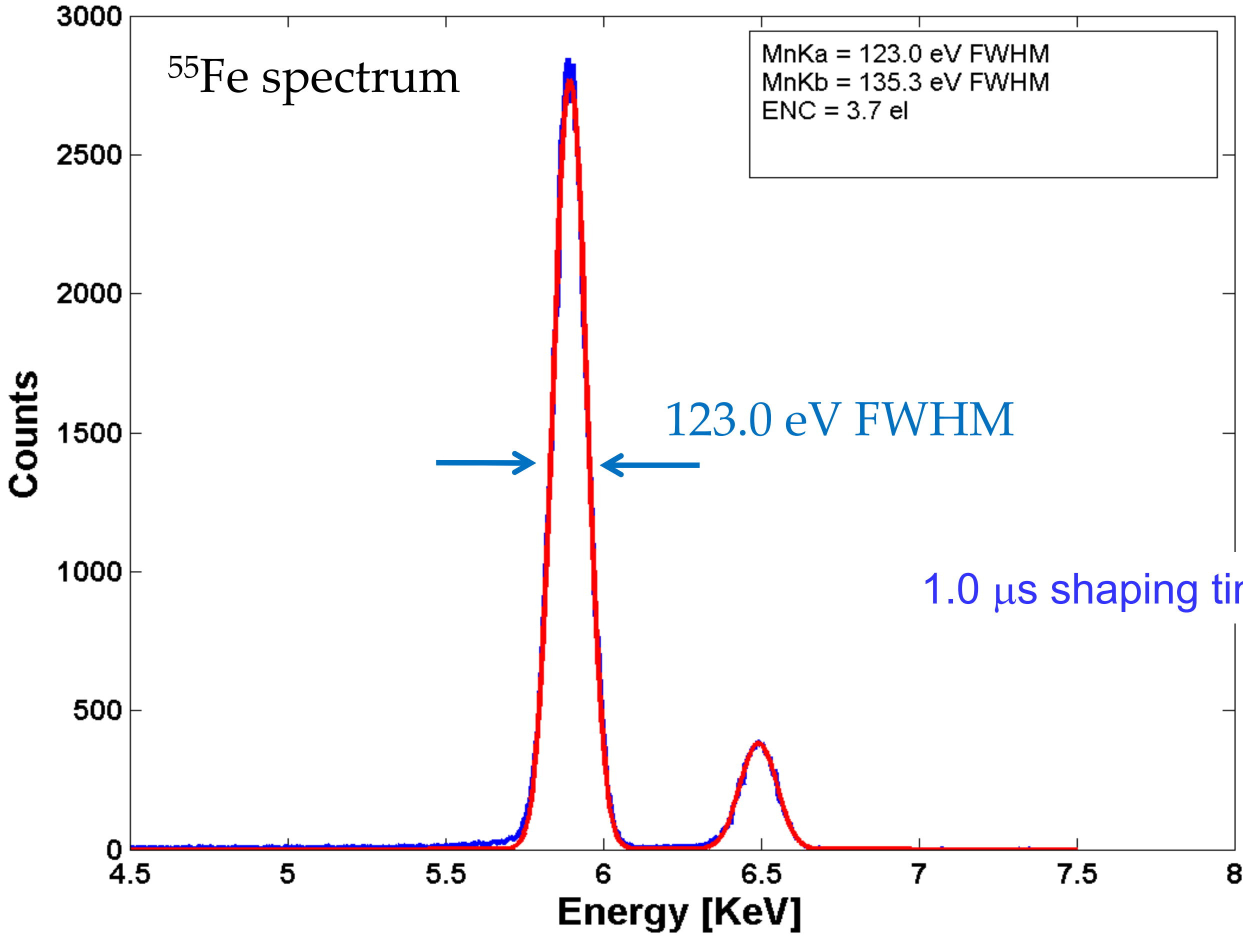
single cell size 8 x 8 mm^2



1mm dead space on each side:
80% active area

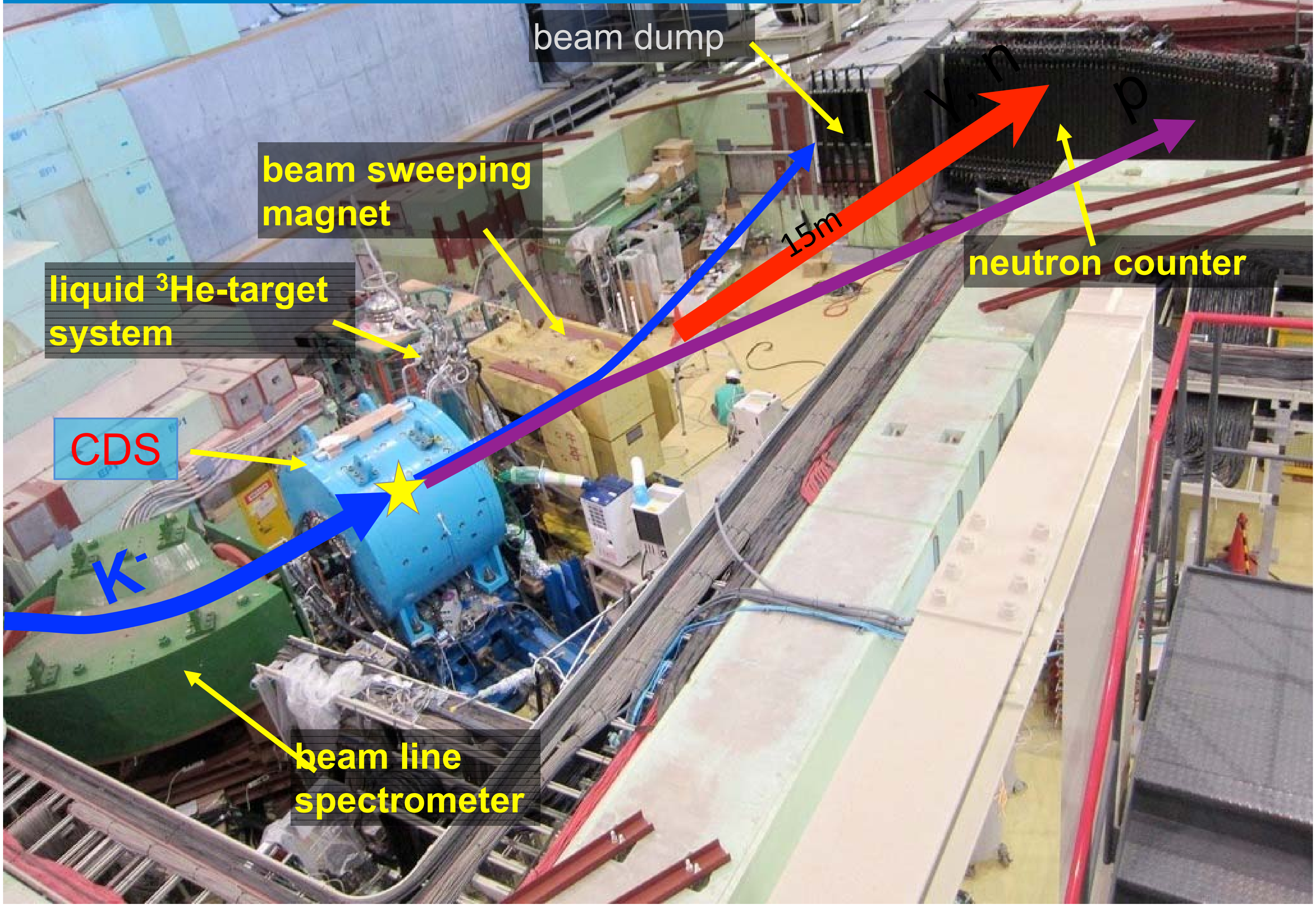
Best performances of new SDD technology and CUBE preamplifier

SDD characteristics:
- Area = 10 mm^2
- T = -40° C



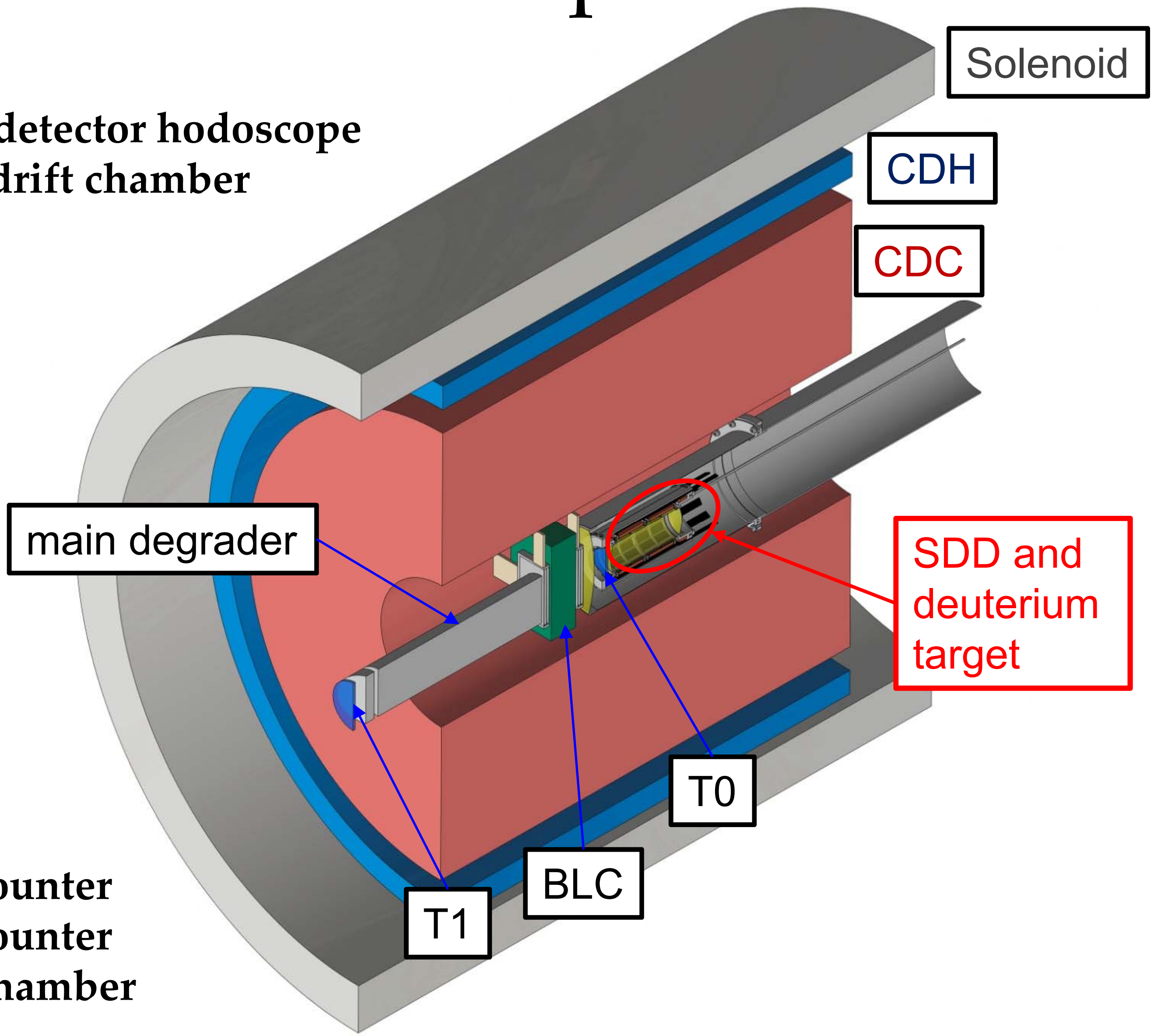
1.0 μs shaping time (optimum)

J-PARC K1.8BR spectrometer



K^-d within the K1.8BR spectrometer

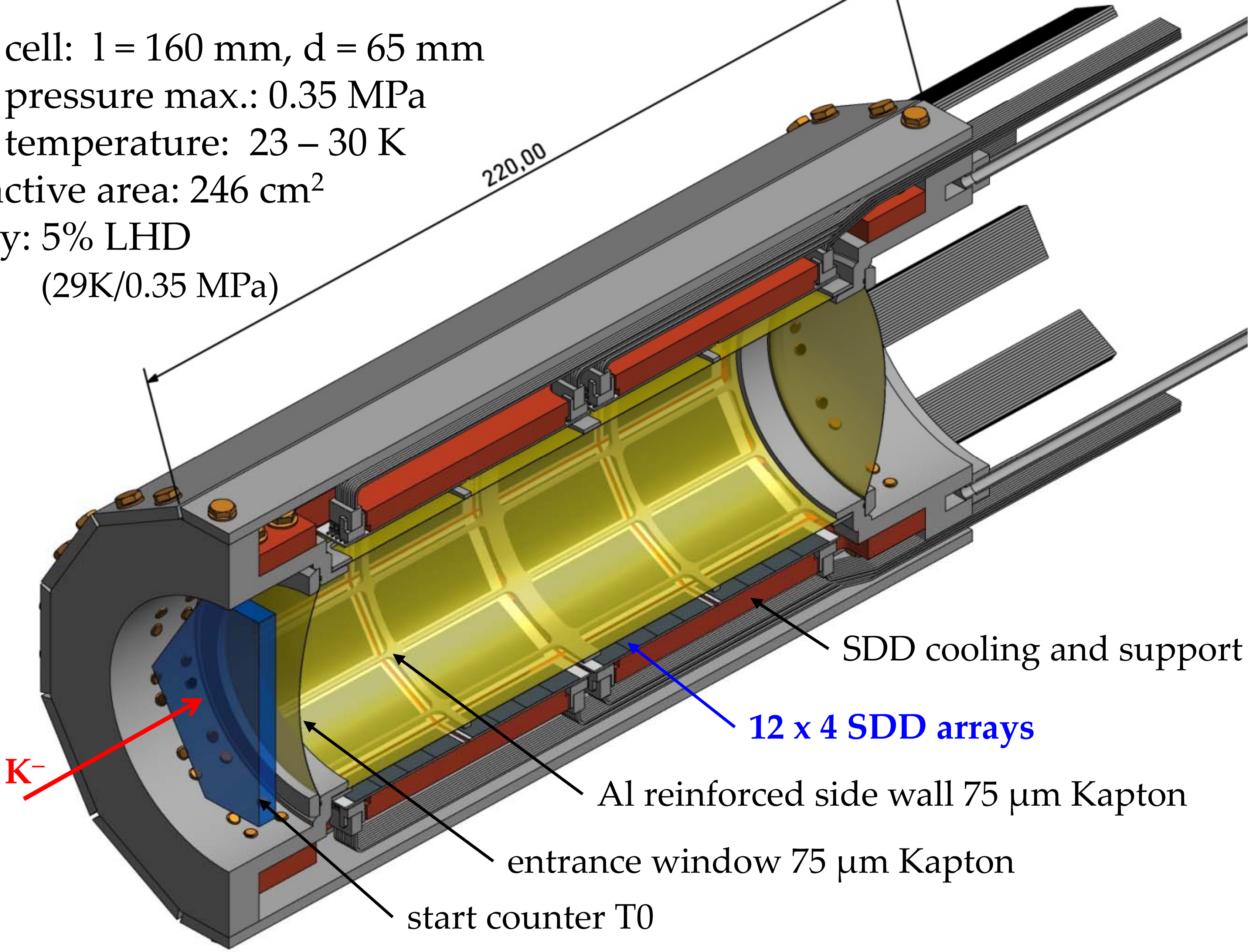
CDH...cylindrical detector hodoscope
CDC...cylindrical drift chamber



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

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)



Prediction for kaonic deuterium

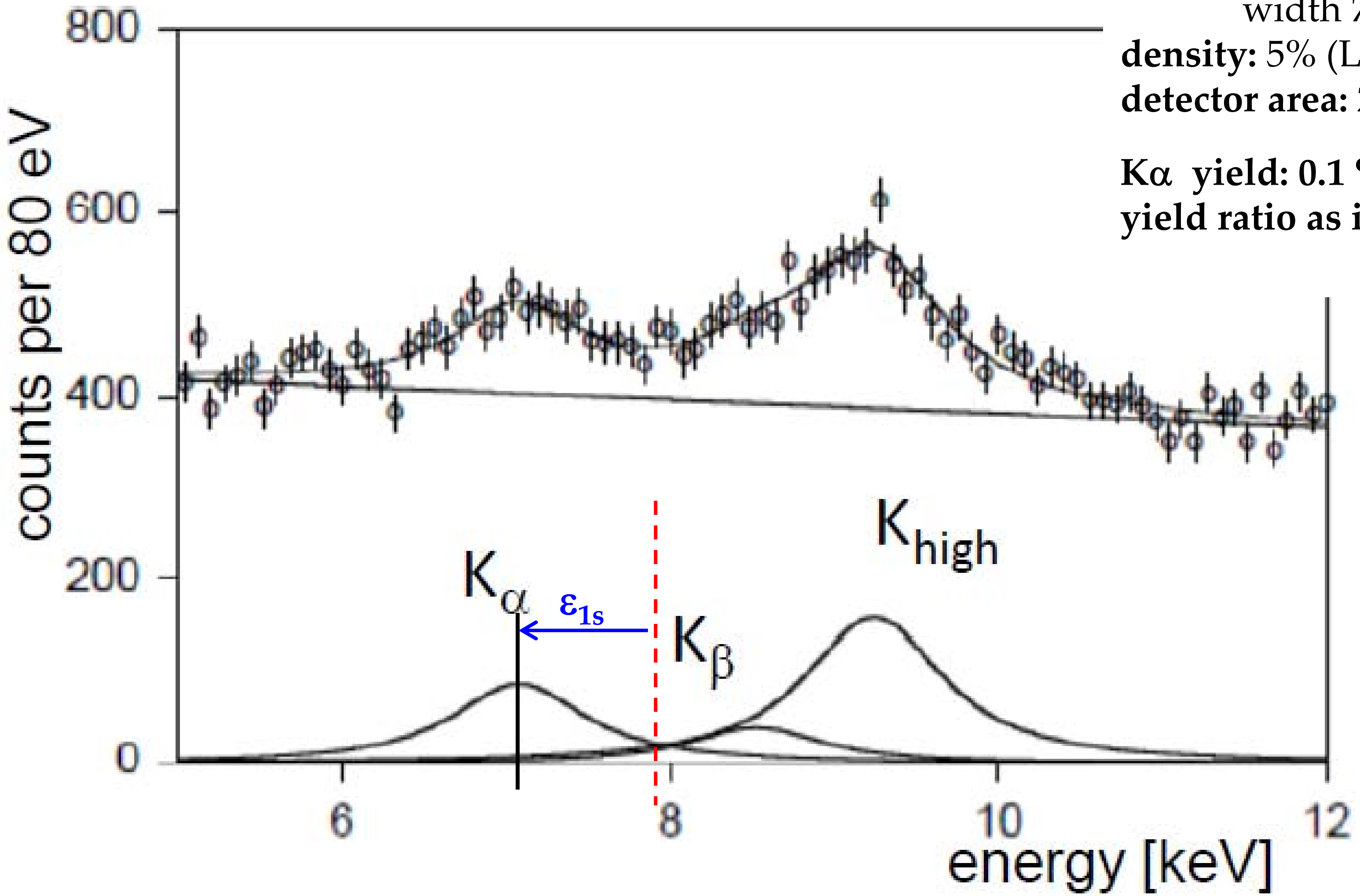
Compilation of predicted K^-d scattering lengths a_{K^-d}
and corresponding experimental quantities ε_{1s} and Γ_{1s}

a_{K^-d} [fm]	ϵ_{1s} [eV]	Γ_{1s} [eV]	ref.
-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] M. Döring, U.-G. Meißner, Phys. Lett. B 704 (2011) 663.
[2] Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706 (2011) 63.
[3] U.-G. Meißner, U. Raha, A. Rusetsky, Eur. Phys. J. C 35 (2004) 349.
[4] T. Mizutani, C. Fayard, B. Saghai, K. Tsushima, arXiv:1211.5824 [hep-ph], 2013.
[5] N.V. Shevchenko, Nucl. Phys. A 890–891 (2012) 50–61.
[6] A. Gal, Int. J. Mod. Phys. A 22 (2007) 226.
[7] U.-G. Meißner, U. Raha, A. Rusetsky, Eur. Phys. J C 47 (2006) 473.

Kaonic deuterium @ J-PARC

30 kW beam power, 100 shifts
signal to background ~ 1:4
precision: shift ~56 eV, width ~139 eV



Assumptions
signal: shift - 800 eV
width 750 eV
density: 5% (LHD)
detector area: 246 cm^2

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

Summary

Kaonic 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)
- **$K^-\,^3He$:** first-time measurement (PLB 697 (2011) 199)
- **$K^-\,^4He$:** measured in gaseous target (PLB 681 (2009) 310)

➢ **Proposal to measure K^-d at J-PARC (P57)**

– new SDDs

– K1.8 BR spectrometer

Supported by

HadronPhysics I3 FP6 European Community program: Contract No. RII3-CT-2004-506078

European Community Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (HadronPhysics2, Grant Agreement No. 227431) under the Seventh Framework Programme of EU

Thank you

Austrian Federal Ministry of Science and Research BMBWK [650962/0001 VI/2/2009]

Romanian National Authority for Scientific Research [2-CeX 06-11-11/2006]

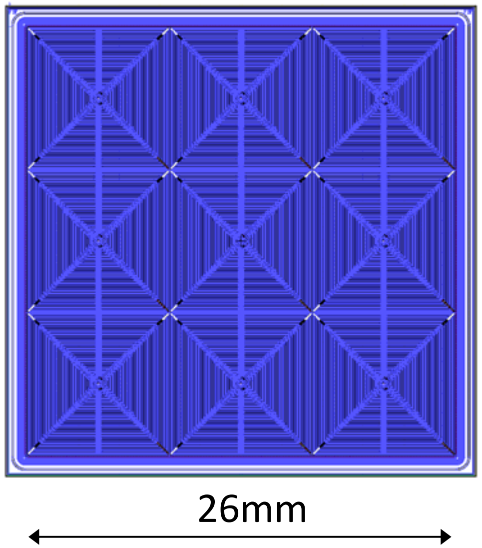
Grant-in-Aid for Specially Promoted Research (20002003), MEXT, Japan

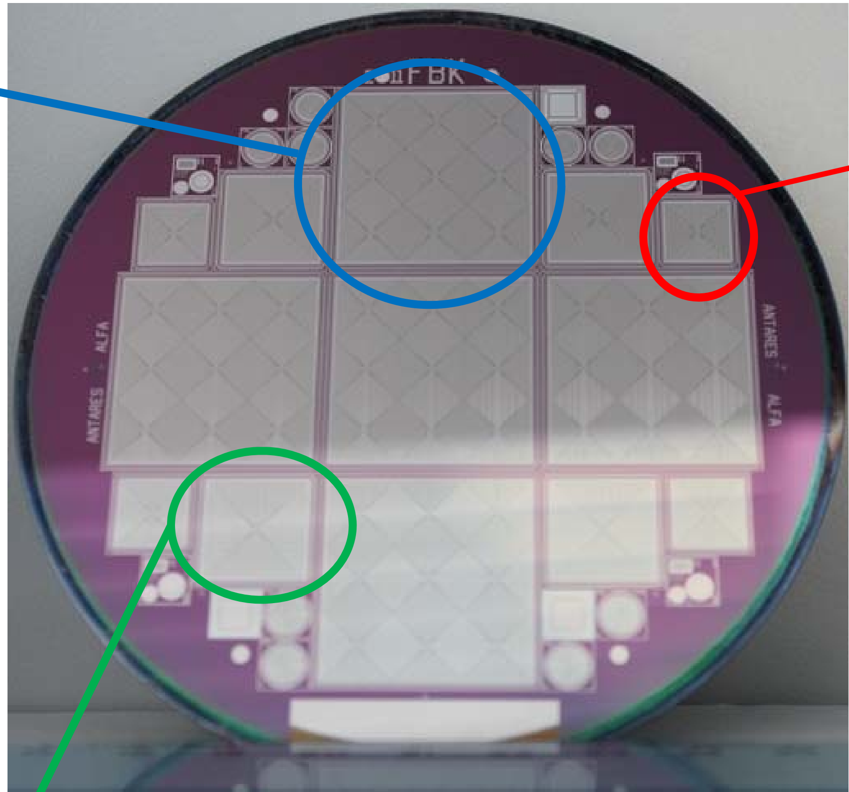
Austrian Science Fund (FWF): [P2(P24756-N20

New SDDs - present layouts

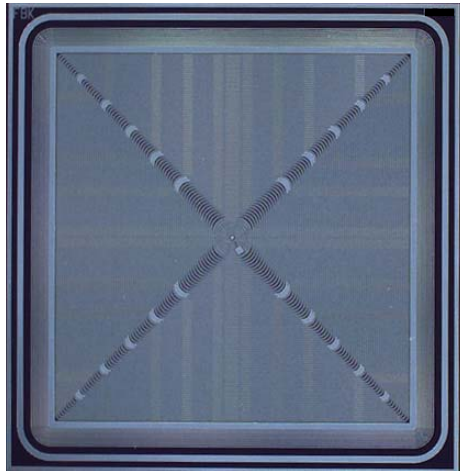
developed by Politech Milano and FBK-Trento, Italy

Array: 9 SDDs (8×8 mm^2 each)





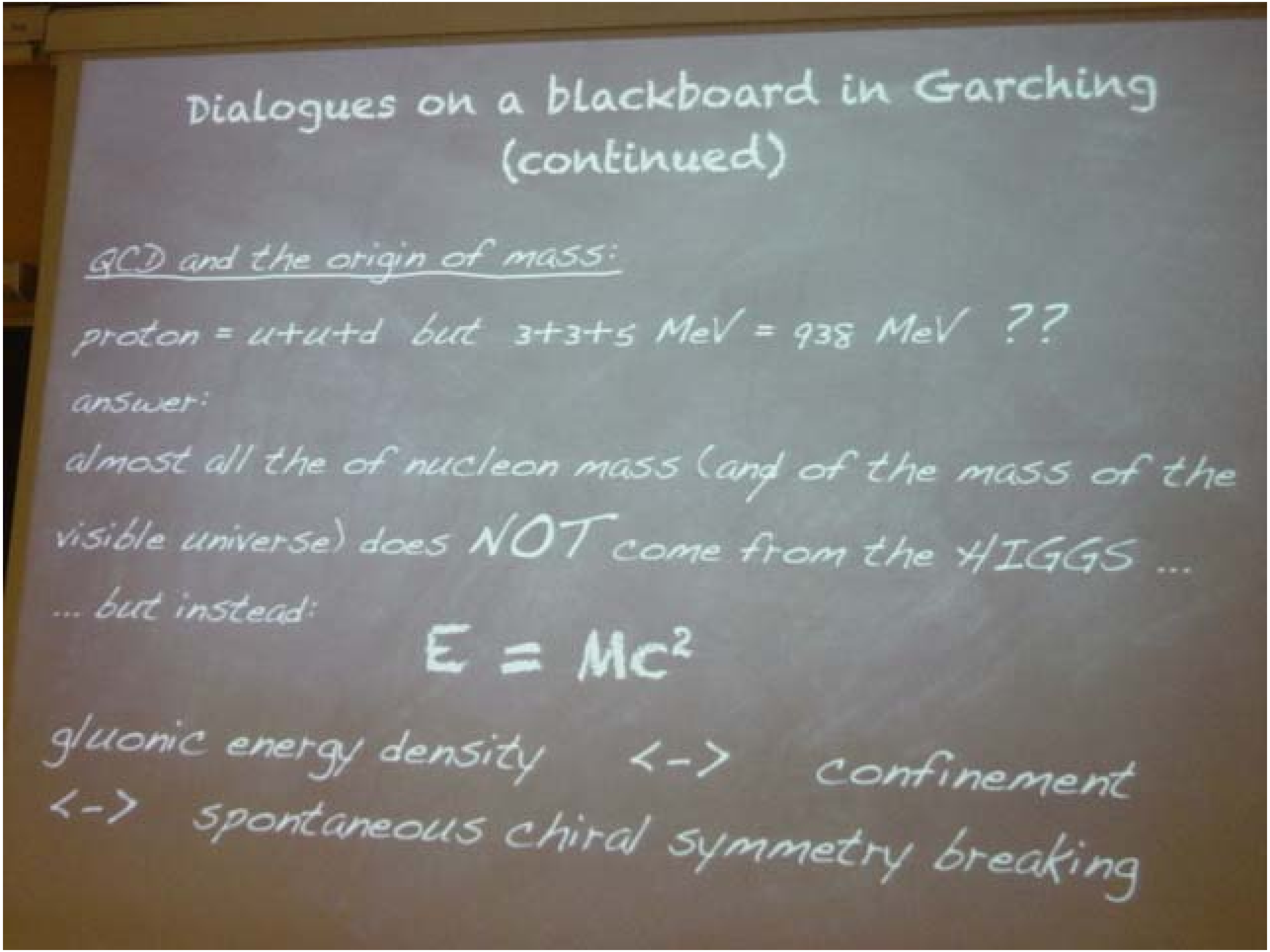
8 x 8 mm^2 single SDD



12 x 12 mm single SDD

FBK production:

- 4'' wafer
- 6'' wafer upgrade just finished


Dialogues on a blackboard in Garching
(continued)
QCD and the origin of mass:
proton = u+u+d but 3+3+5 MeV = 938 MeV ??
answer:
almost all the of nucleon mass (and of the mass of the
visible universe) does NOT come from the HIGGS ...
... but instead:
E = Mc²
gluonic energy density <-> confinement
<-> spontaneous chiral symmetry breaking