Experimental studies of the kaon-nucleus interaction at low energy with x-ray spectroscopy of kaonic atoms

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Laboratori Nazionali di Frascati, INFN

14th, Sep. 2016
KAON 2016,
Birmingham Univ.

Topics of KAON series

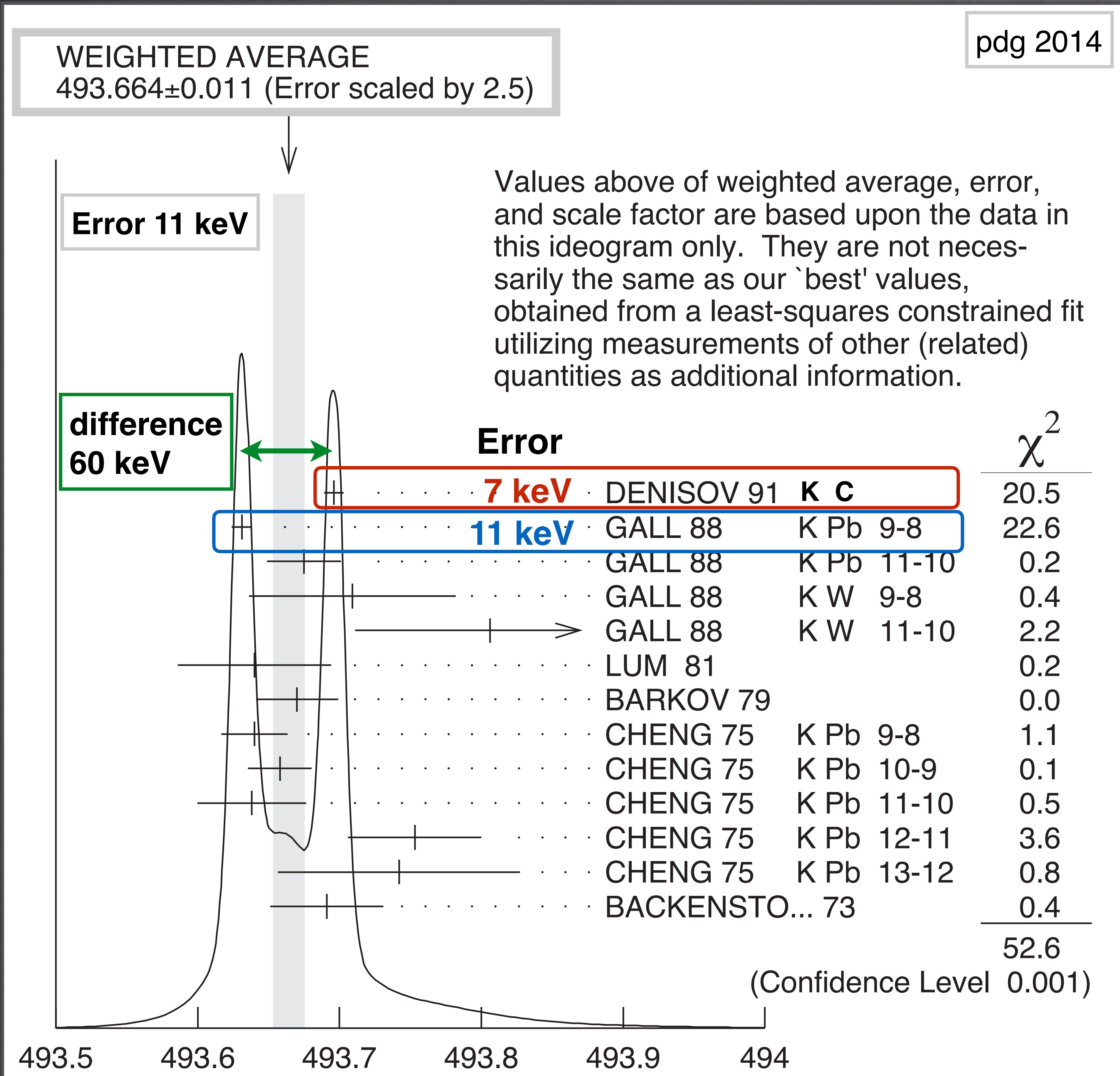
- CP and T violation
- CKM matrix and Flavor Mixing
- Rare decays
- Precision SM tests
- CPT and Quantum Mechanics
- Lepton universality and flavor violation
- Lattice gauge theory
- Chiral perturbation theory
- Physics beyond the Standard Model
- Future opportunities in Kaon Physics

this talk

Kaonic atoms

fundamental topics/questions of kaon
from a nuclear/hadronic physics point of view

Intro - the K^- mass puzzle



fundamental quantity the mass of K^- :

PDG 2014 value
493.664 ± 0.011 MeV

most recent two precise results have more than <u>*5 σ*</u> discrepancy

experimental method:
kaonic atom x-rays

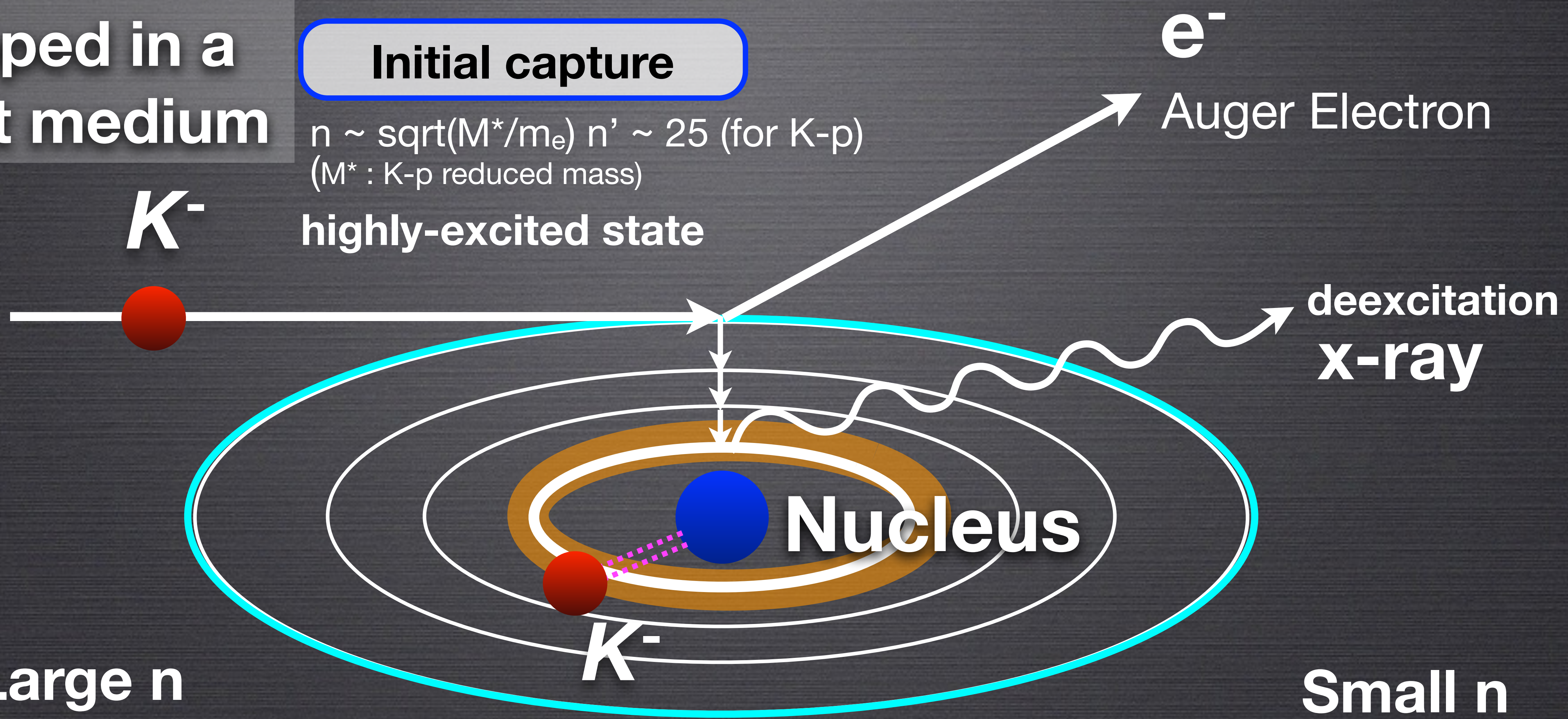
Kaonic atom

stopped in a target medium

Initial capture

n ~ sqrt(M*/mₑ) n' ~ 25 (for K-p)
(M* : K-p reduced mass)

highly-excited state



Large n

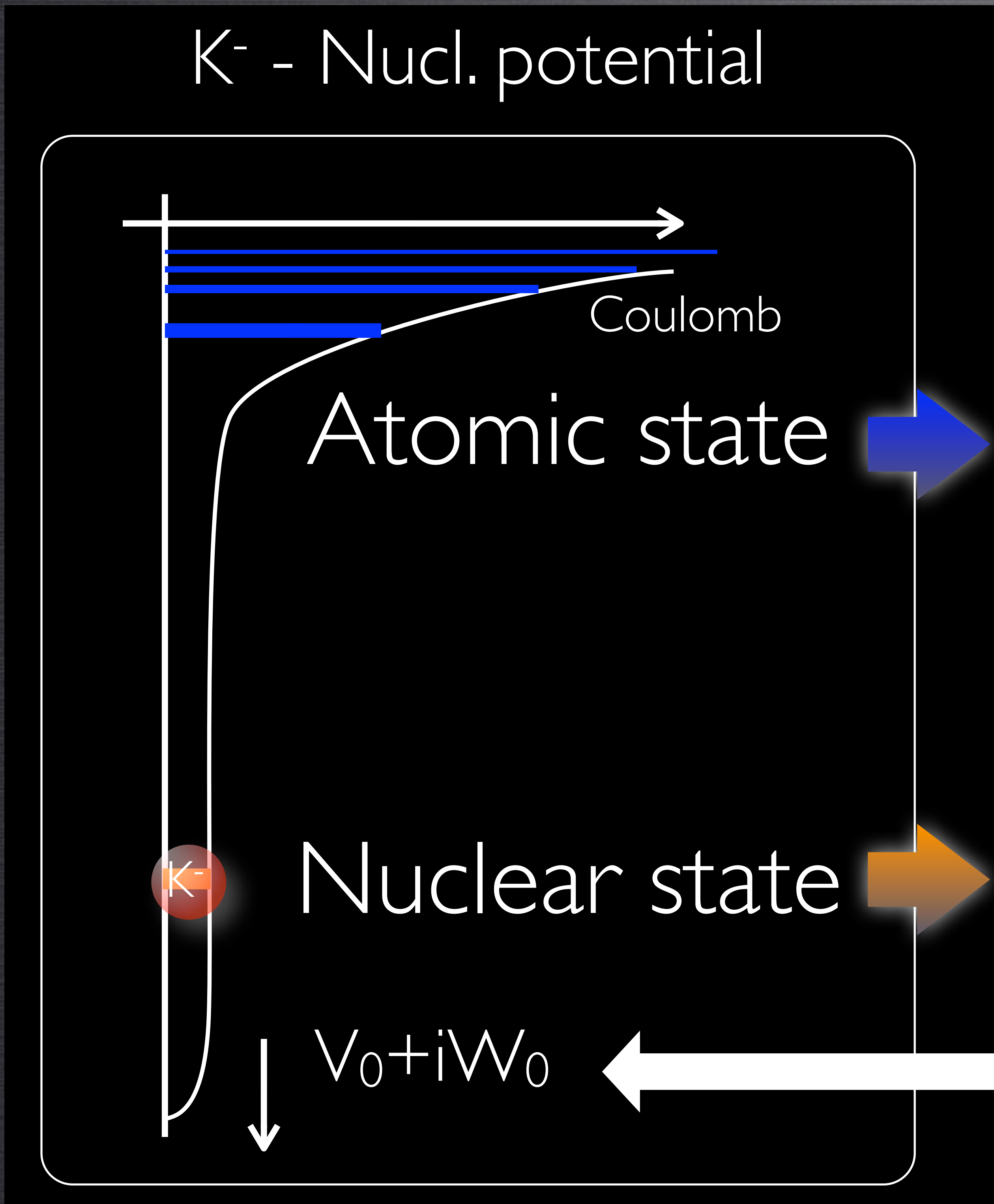
Kaon mass from reduced mass

only the EM force

Small n

Strong-interaction effect

Kaon-nucleus interaction



Experimental approaches

Precision x-ray measurement

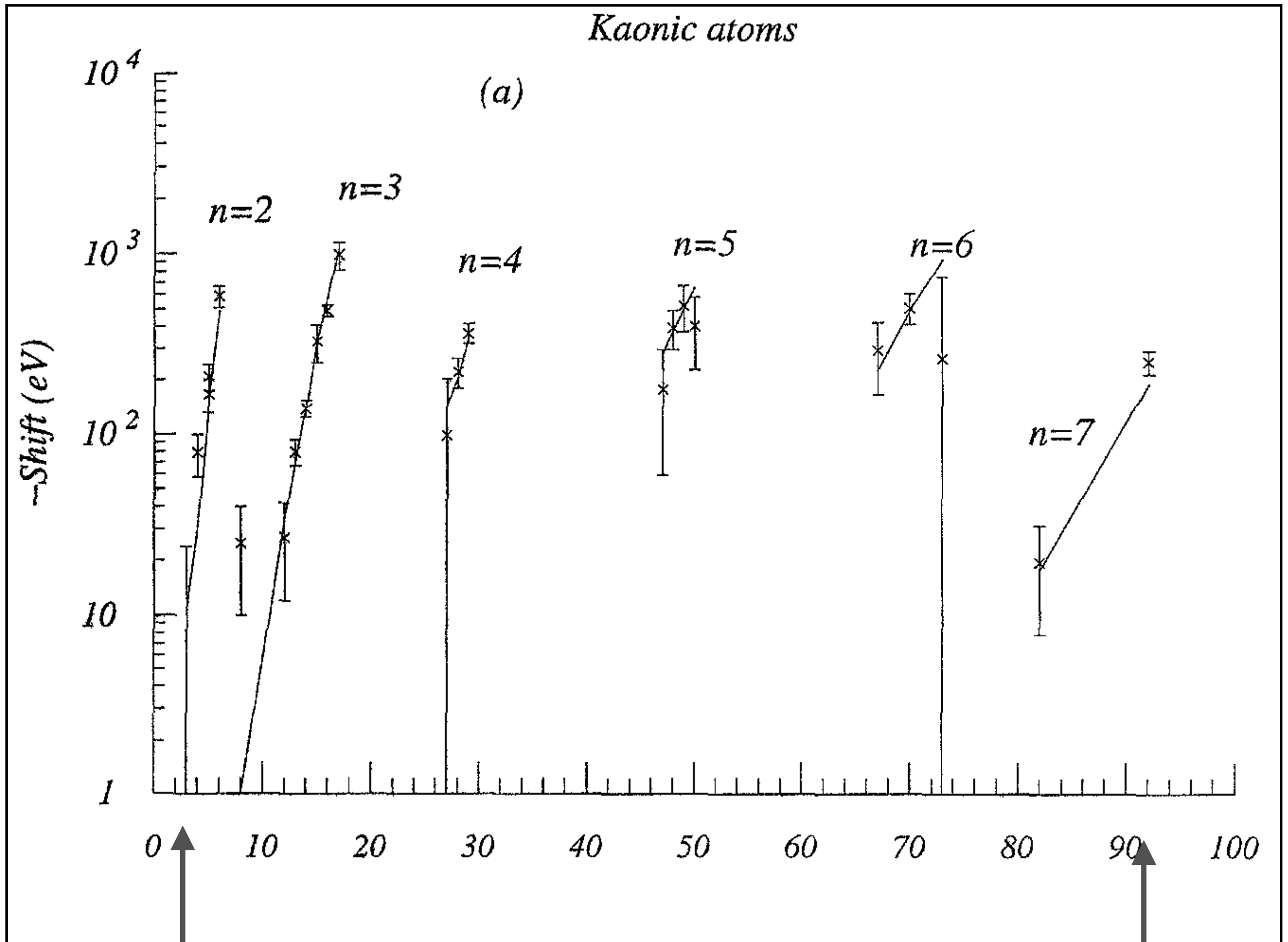
strong-interaction at threshold

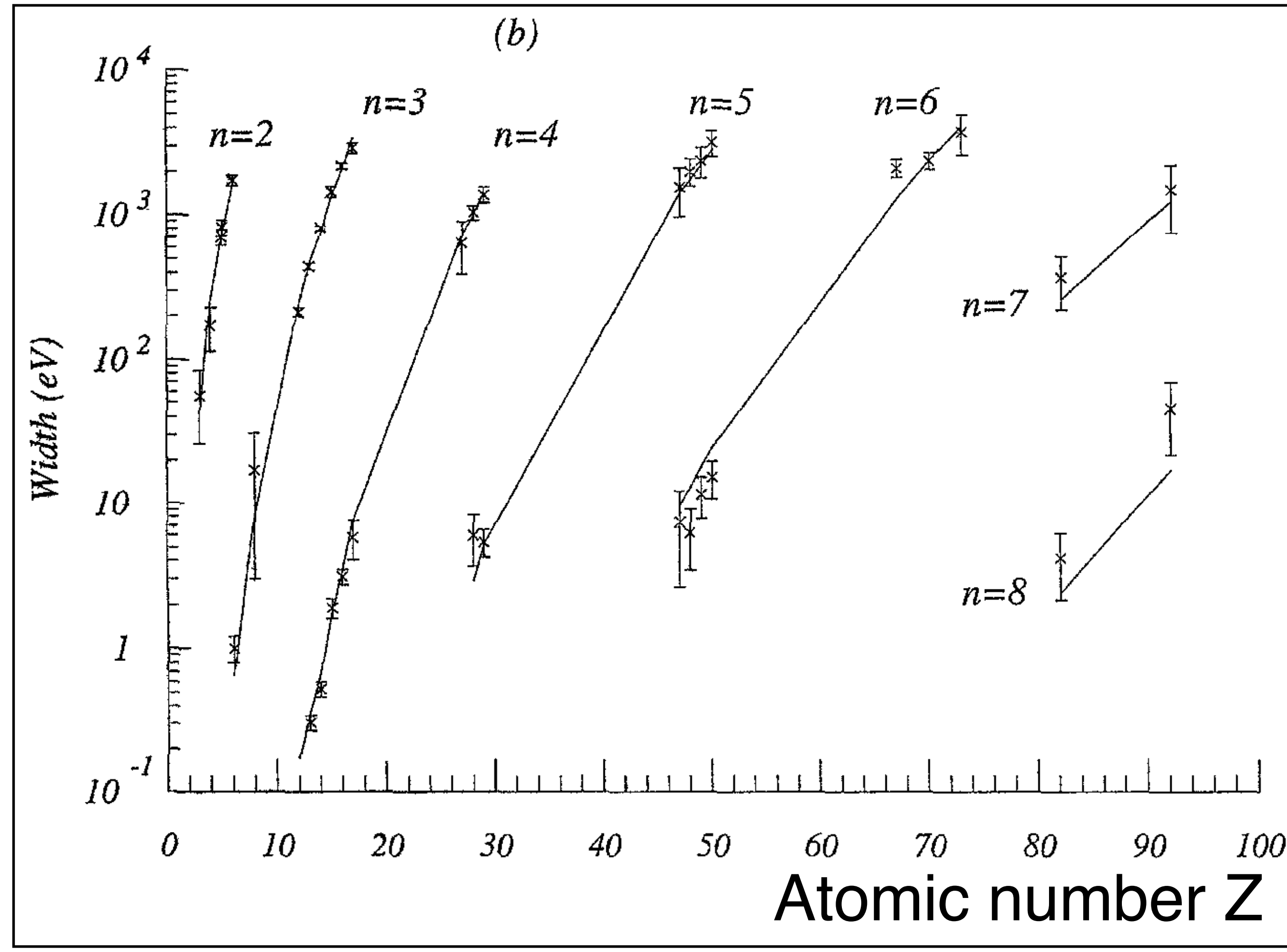
Reaction formation

deeply bound *K*⁻ - nuclei search

Kaonic atom data and optical potential

Shift [eV] **Width [eV]**





Z = 3 (Li)

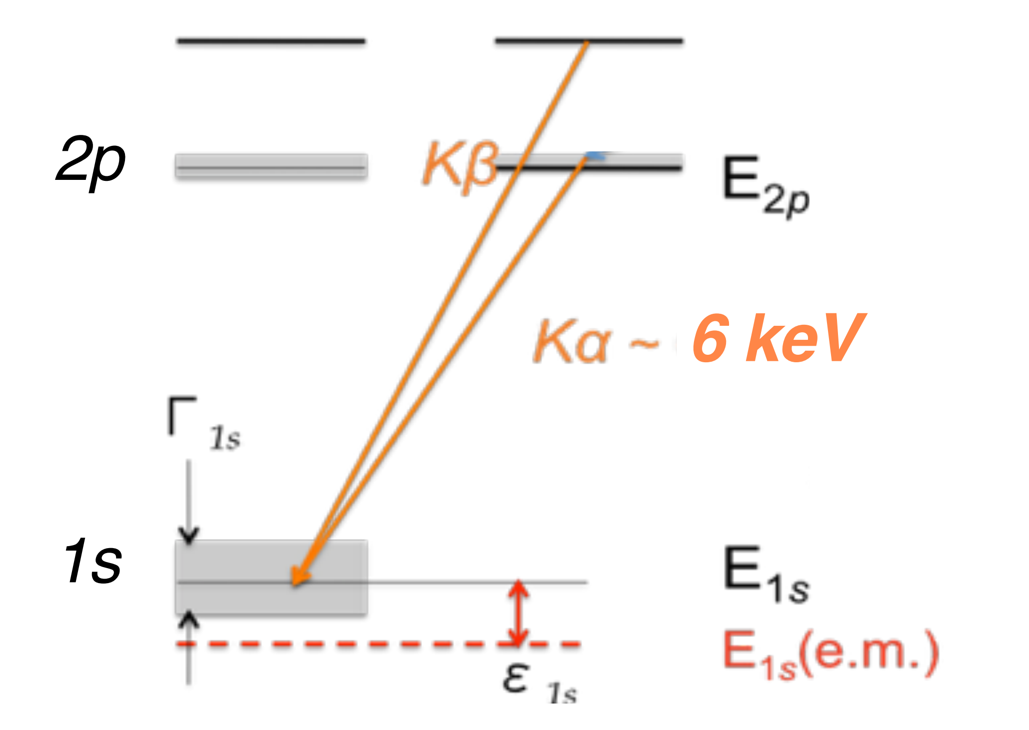
Z = 92 (U)

C.J. Batty, E. Friedman, A. Gal, Physics Reports 287 (1997) 385 - 445

Global fit with optical potential fro Z > 2

- imaginary part (absorption) : W_0 ~ 70 MeV
- real part (depth of potential) : model - dependent, open problem
  "shallow" : - 40 ~ 50 MeV; "deep" : ~ - 200 MeV.

Kaonic hydrogen



Kaonic hydrogen case

Deser-Truman formula

$$\epsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3 \mu_c^2 a_{K^-p}$$

Kaonic hydrogen shift and width

s-wave scattering length using isospin I=0 and I=1 components a_0, a_1 :

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

μ_c : reduced mass of *K*-p

S. Deser. K. Baumann, W. Thirring, Phys. Rev. 96 (3) (1954) 774–776.

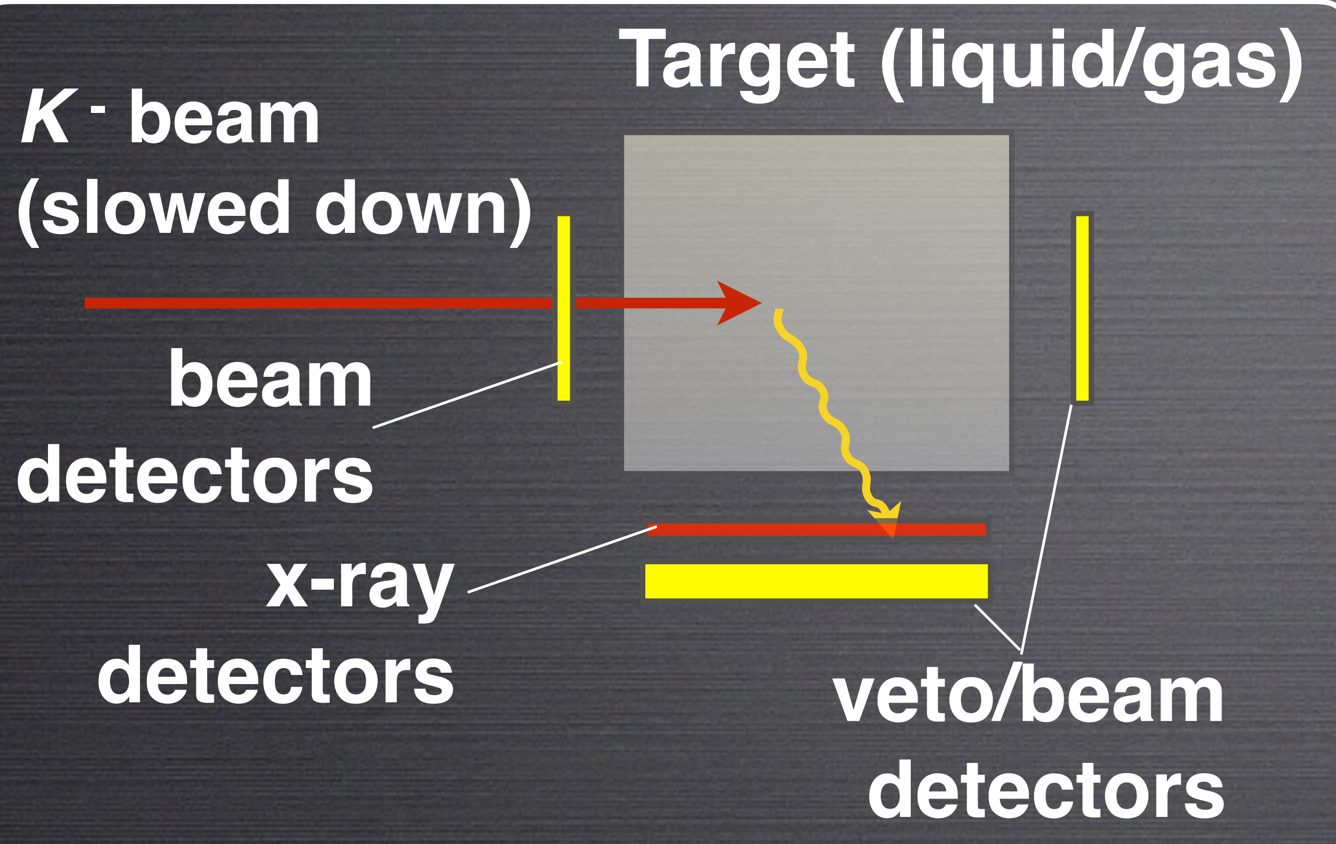
U.-G. Meißner, U. Raha, A. Rusetsky, Eur. Phys. J. C 35 (2004) 349

to determine separately a_0 and a_1 :

kaonic deuterium x-ray measurement

a major challenge of the field

Experimental method



Key factors for the experiment

- **low absolute x-ray yield**
  target type / detector acceptance
- **background rejection**
  event selection by timing/fiducial cut
- **energy resolution**
  resolution / stability / calibration

Active facilities

DAΦNE e^-e^+ collider, Italy

- $\phi \to K^+ K^-$ (49.1%)
- Slow, monochromatic K^-
- Low hadronic background

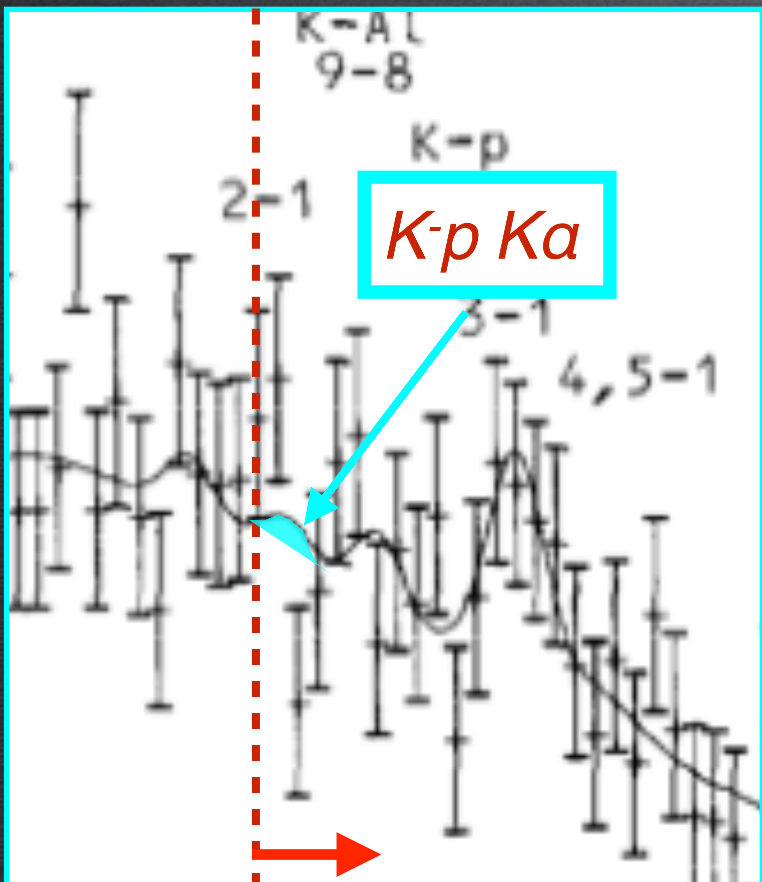
J-PARC (KEK-PS)
proton synchrotron, Japan

- Secondary kaon beam
- High intensity beam
- Beam spectrometer system

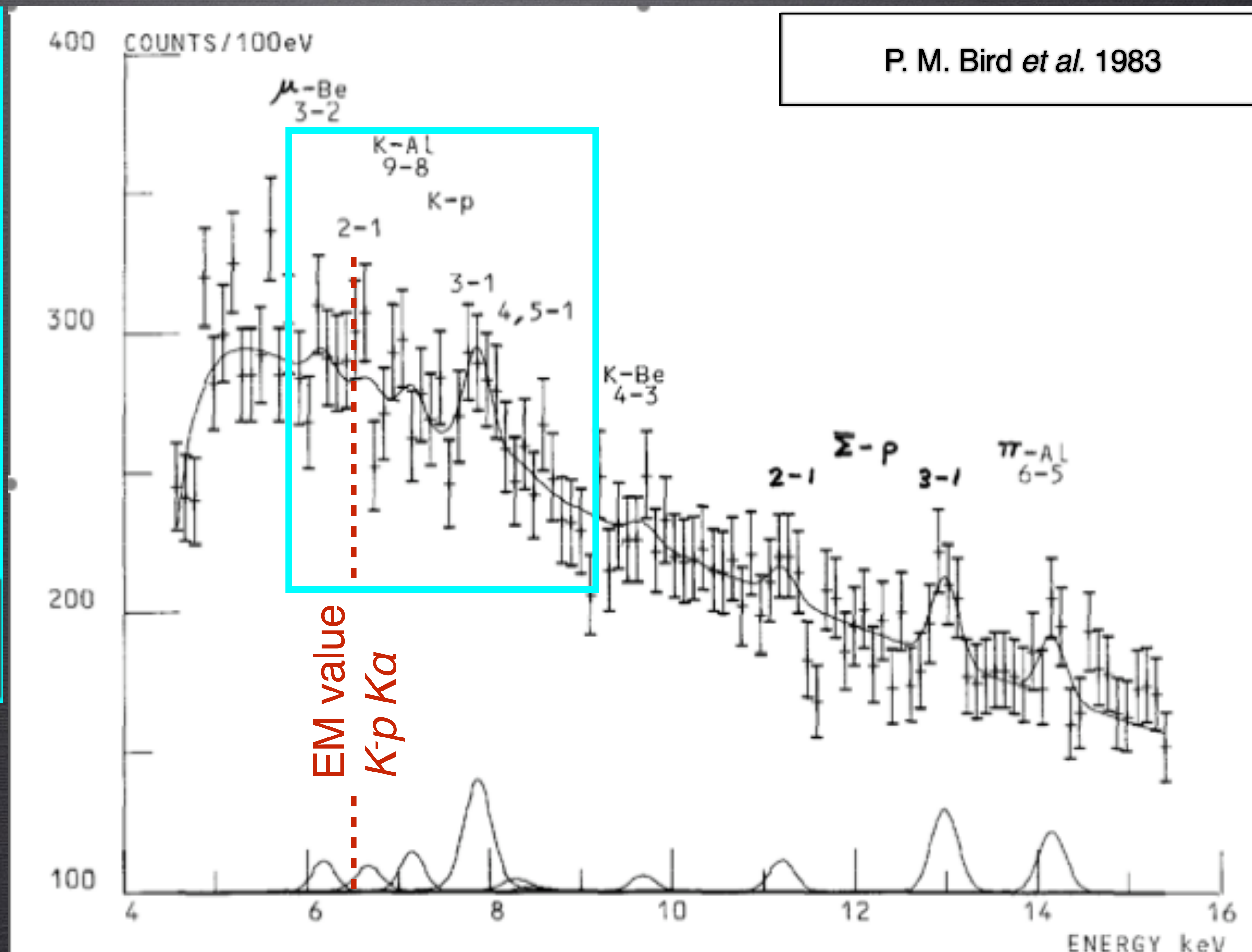
Past experiments - 1

J. D. Davies et al., Phys. Lett. 83B, 55 (1979)
M. Izycki et al., Z. Phys. A 297, 11 (1980)
P. M. Bird et al., Nucl. Phys. A404, 482 (1983)

three experiments 1970s - 1980s
liquid targets

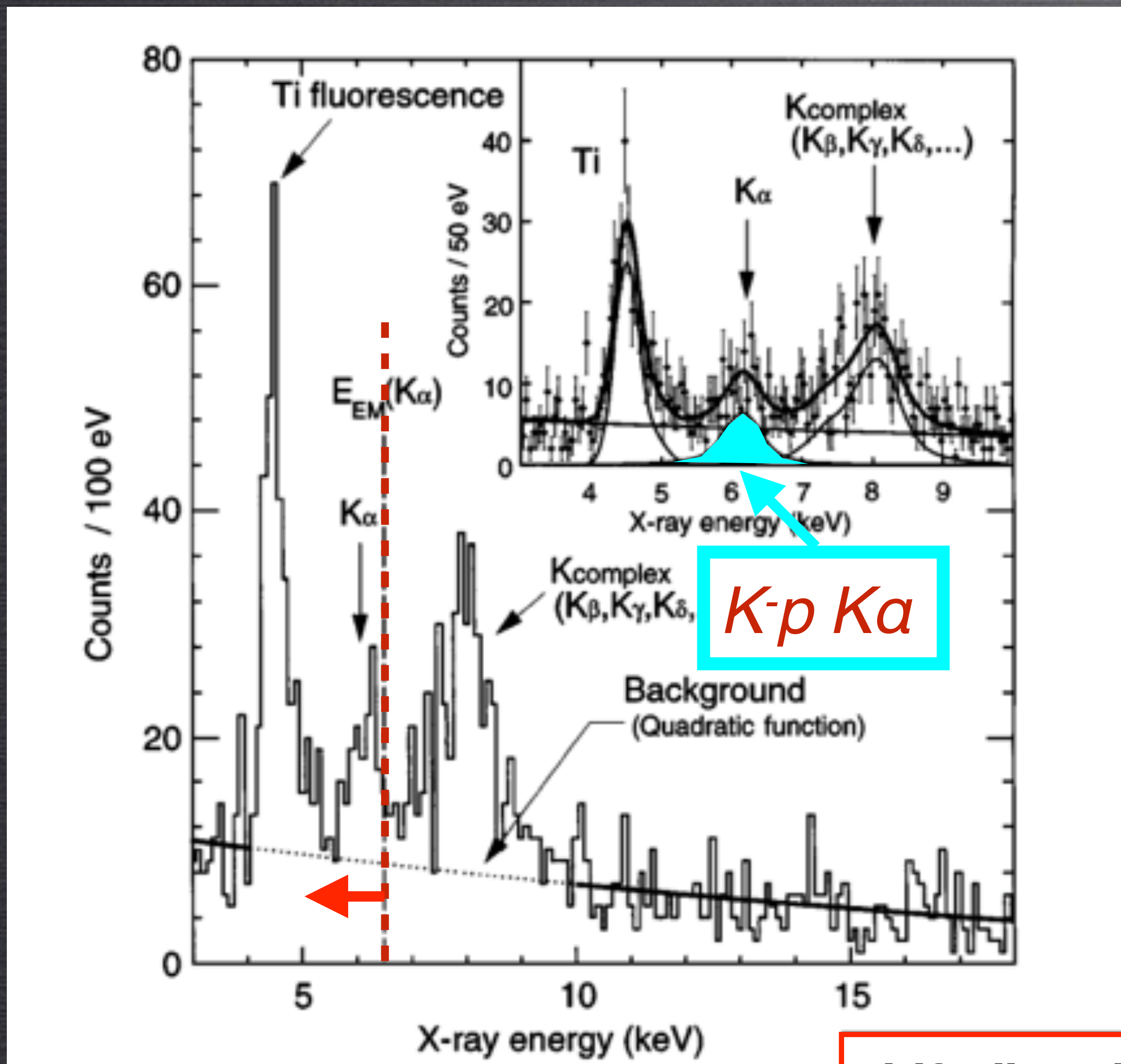


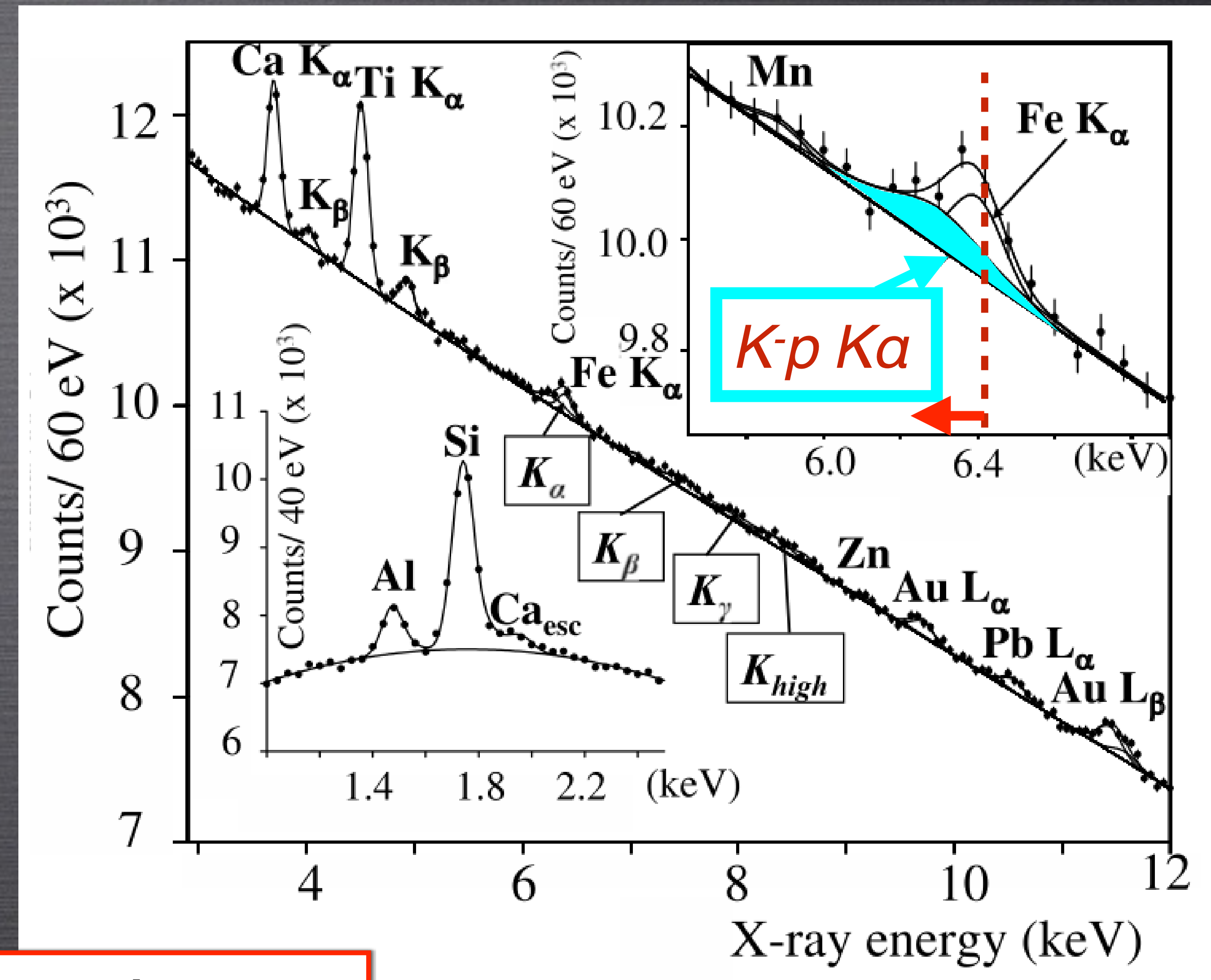
shift direction against theory & scattering data



"kaonic hydrogen puzzle"

Past experiments-2





shift direction consistent with theory & scattering data

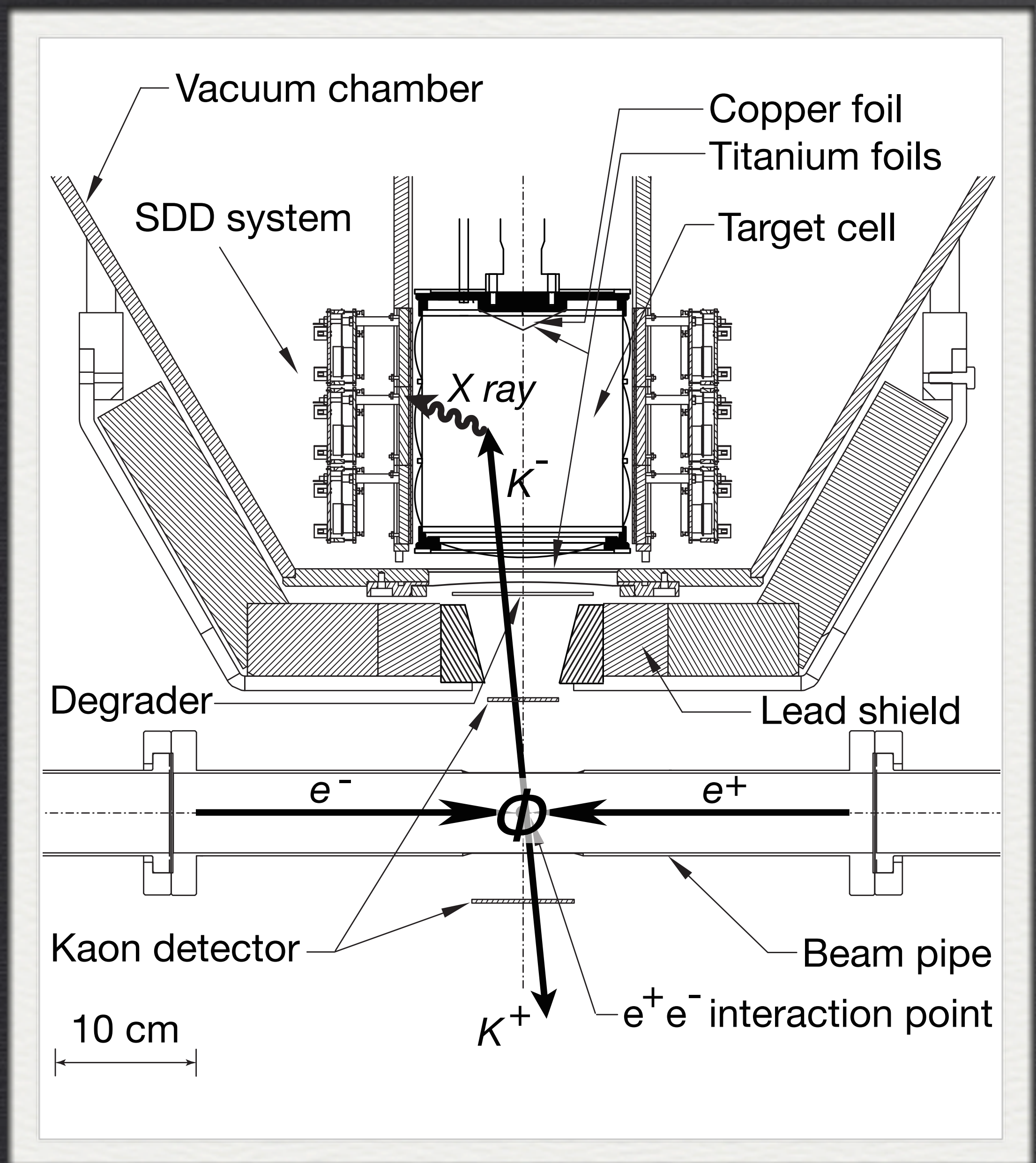
KEK-PS E228 (KpX) 1997

- 120 cm² Si(Li) x-ray detector
- 340 eV FWHM @ 6 keV
- fiducial volume cut for bg rejection

DEAR DAFNE 2005

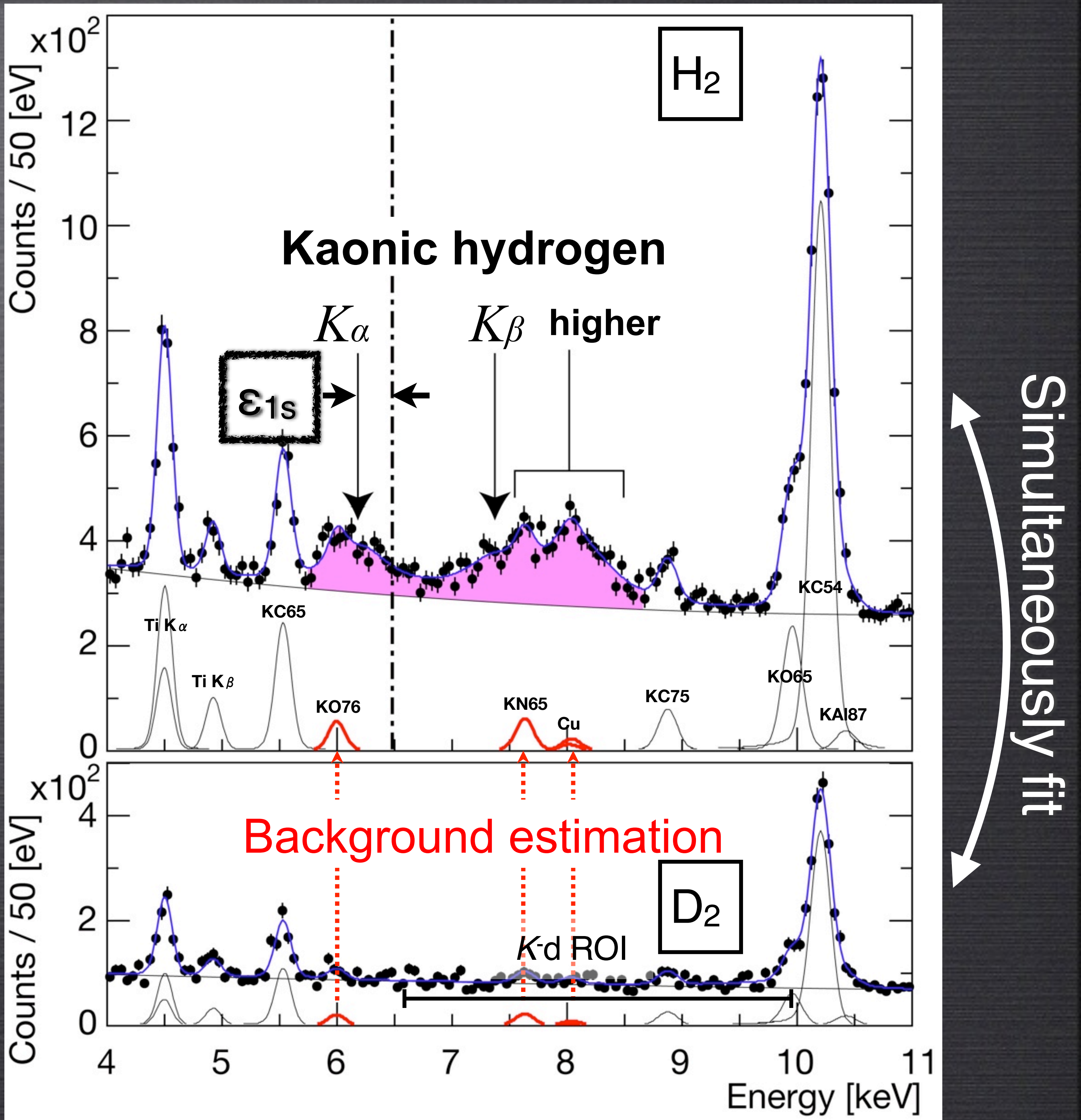
- 116 cm² CCD x-ray detector
- 180 eV FWHM @ 6 keV
- no bg rejection

SIDDHARTA experiment at DAΦNE



M. Bazzi, et al., Phys. Lett. B 704 (2011) 113-117

- **gaseous target**
- ***K*⁻ origin X-ray by SDD timing**
- **144 cm² SDDs : 10 % solid angle**
- **150 eV FWHM @ 6 keV**

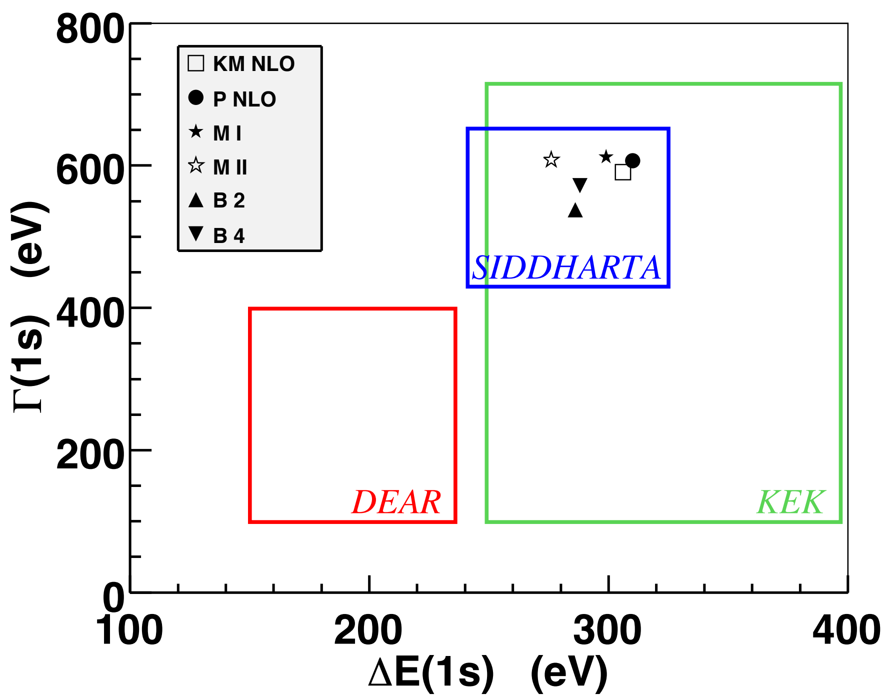


- **best precision of K^-p 1s shift & width**
- **exploratory measurement of K^-d**

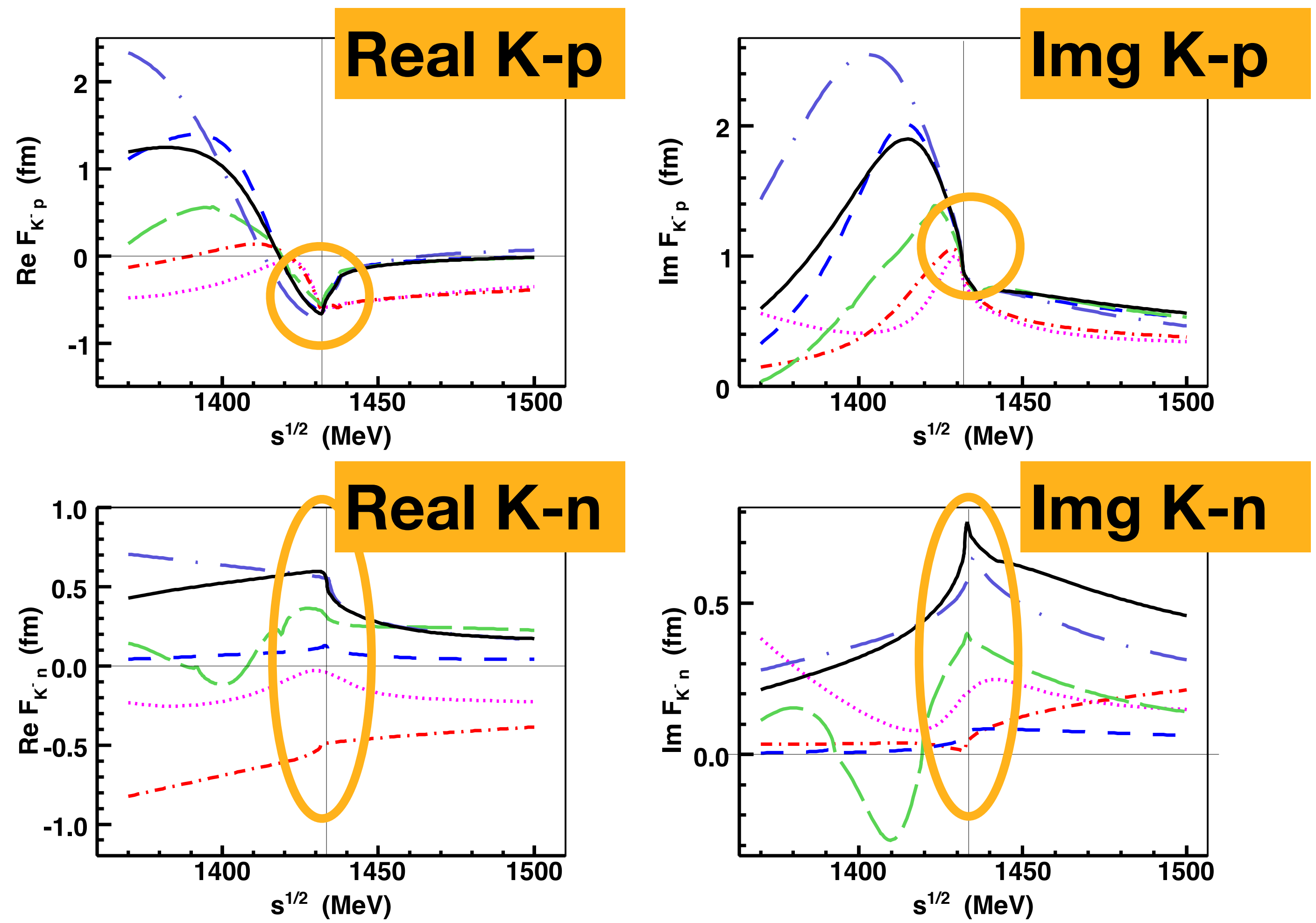
x-ray yield 10^{-1} less than K^-p

Kaonic hydrogen exp. and theory

Parallel session C6 by A. CIEPLY



A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2



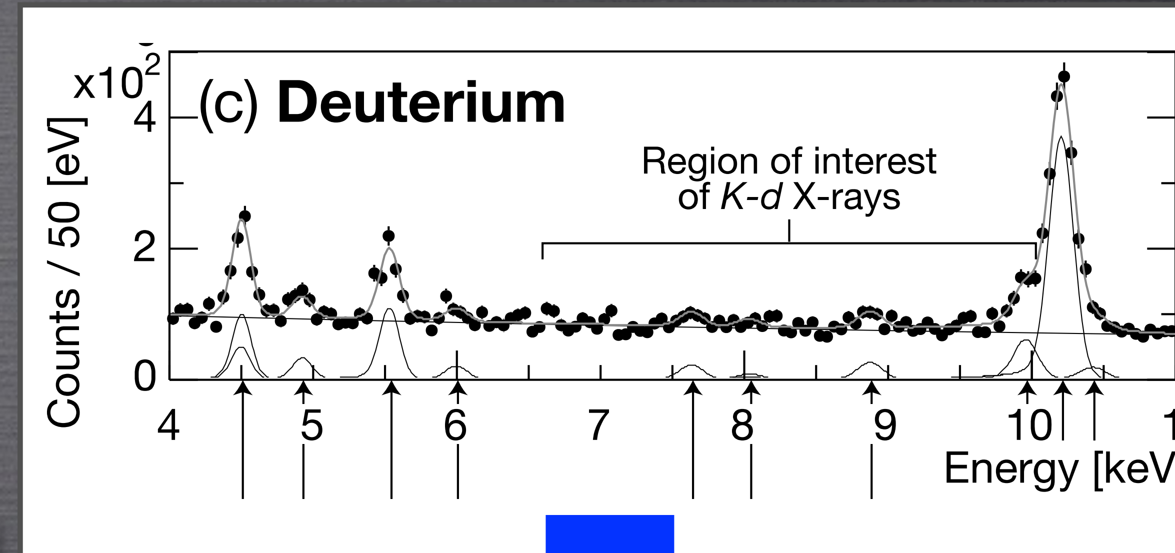
- theory reproduces the K^-p results at threshold
- various predictions for K^-n scattering length (pure isospin 1)
- K^- d result is awaited to determine the isospin dependence

H. Tatsuno (Lund U.)
MESON 2016

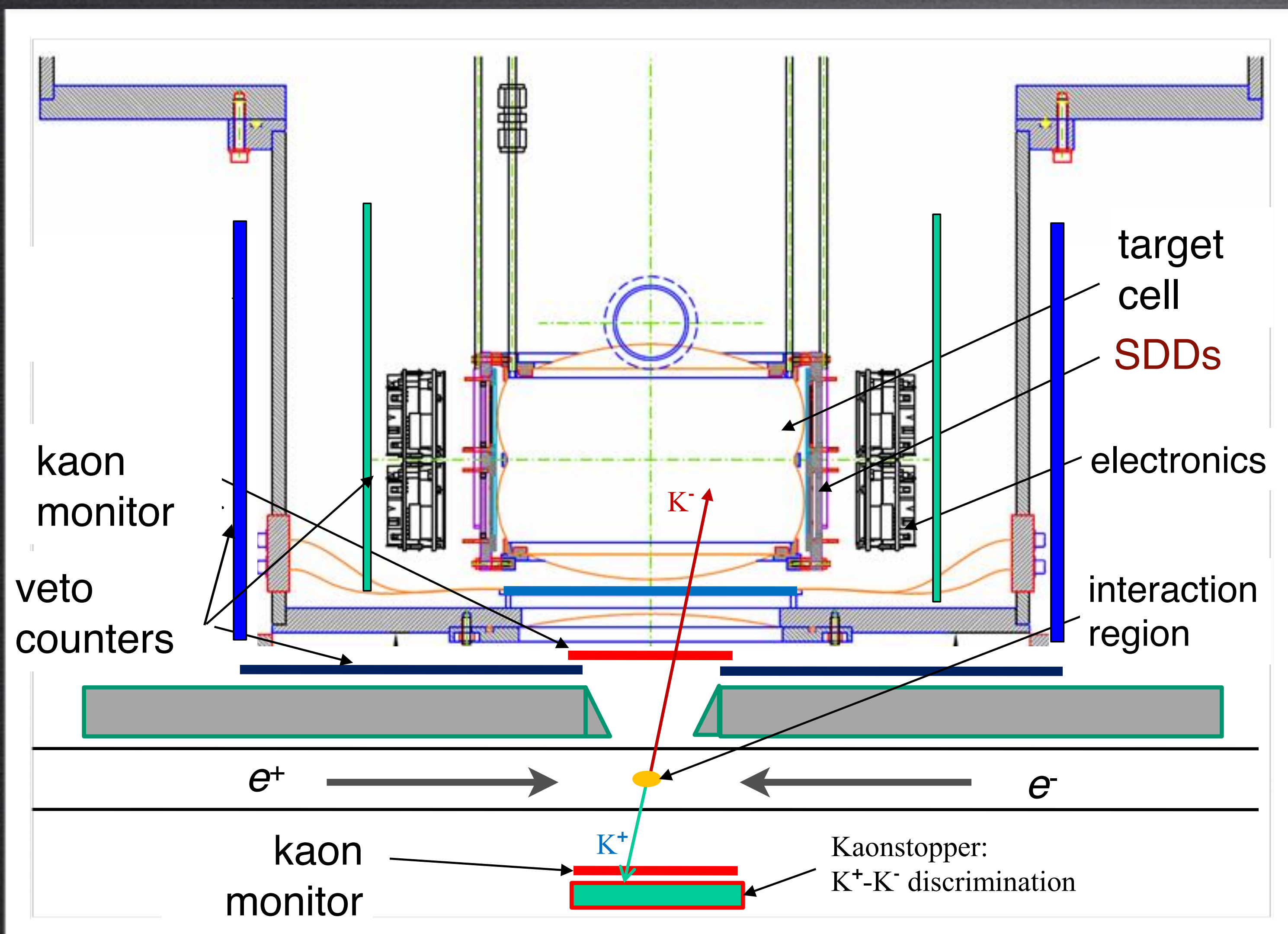
Kaonic deuterium at DAΦNE

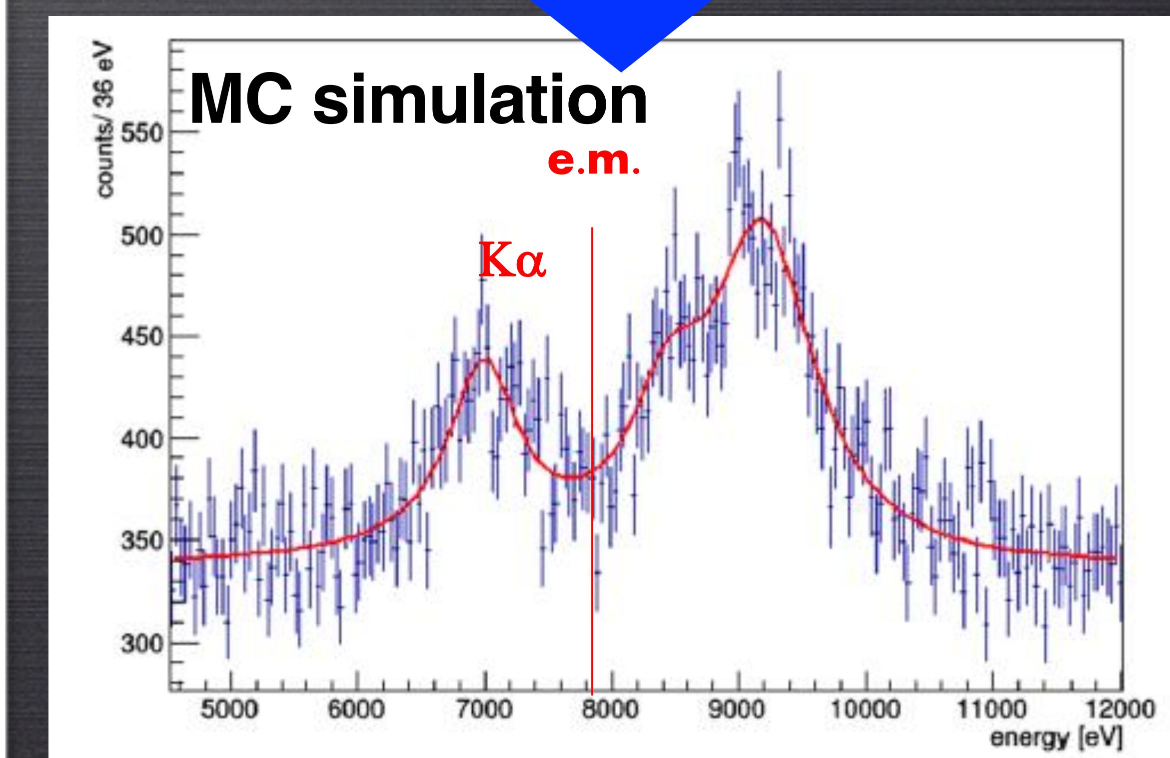
SIDDHARTA-2 @ DAΦNE

- **300 cm² SDD x-ray detector**
- **400 ns timing resolution**
- **efficient *K*⁻ origin x-ray selection with veto counters**
- **reduction of beam background**



> 10 times improvement in S/B ratio





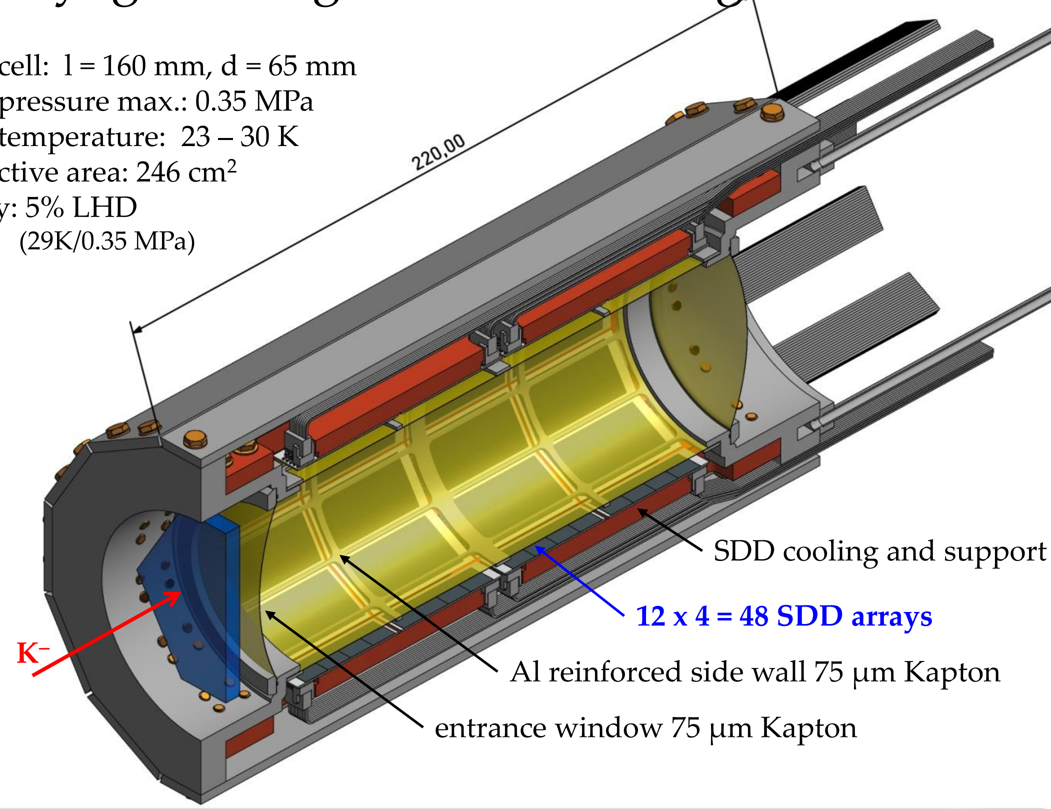
Kaonic deuterium at J-PARC

J-PARC E 57 @ K1.8 BR beam line

- 200 cm^2 SDD x-ray detector
- 400 ns timing resolution
- fiducial volume cut for K^- stopping position

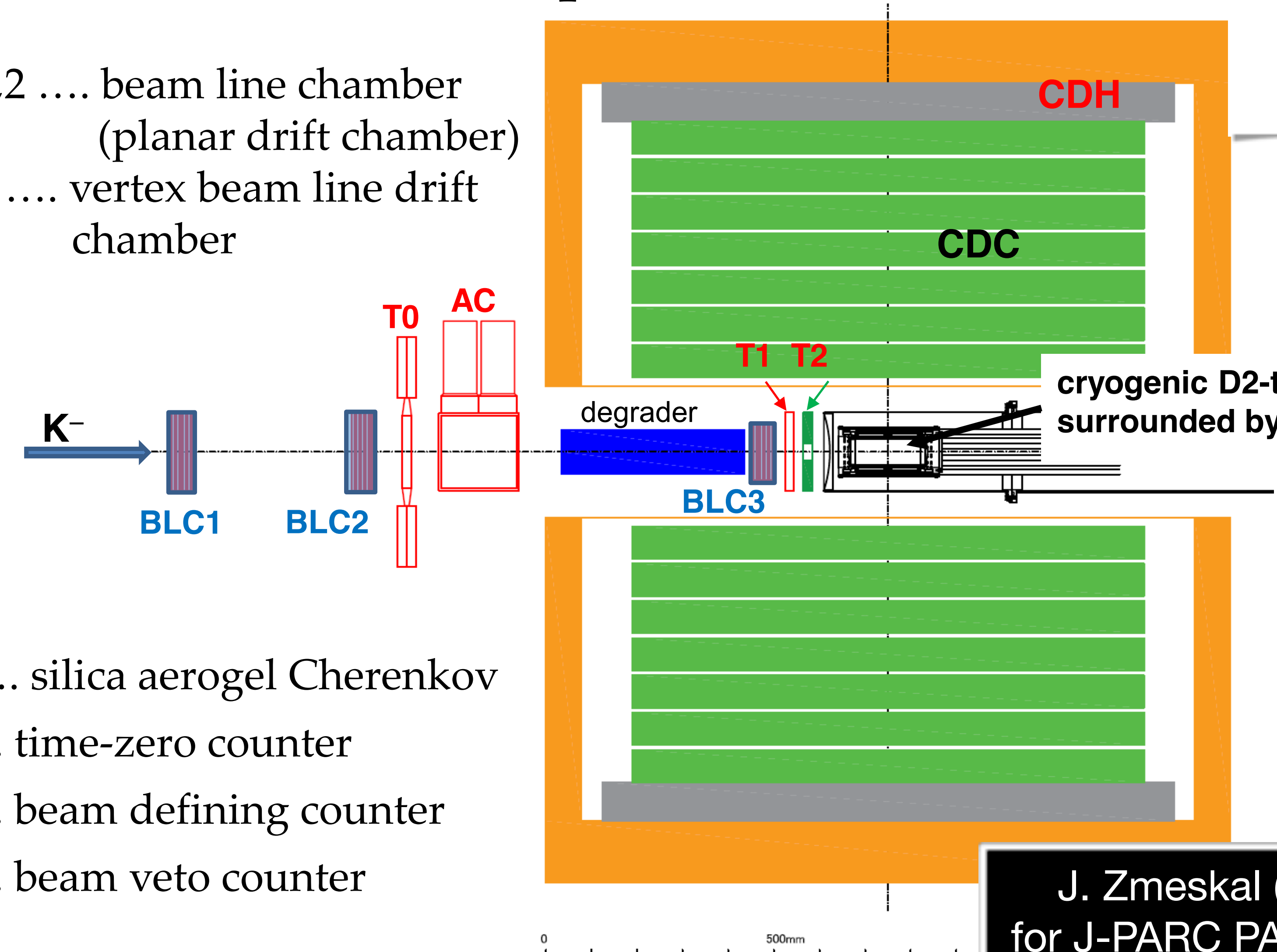
The cryogenic target and SDD design

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)



Sketch of the K⁻d setup

BLC1,2 …. beam line chamber (planar drift chamber)
BLC3 …. vertex beam line drift chamber



AC …. silica aerogel Cherenkov
T0 …. time-zero counter
T1 …. beam defining counter
T2 …. beam veto counter

precision for K-d shift and width will be compatible as SIDDHARTA-2

J. Zmeskal (SMI)
for J-PARC PAC 2015

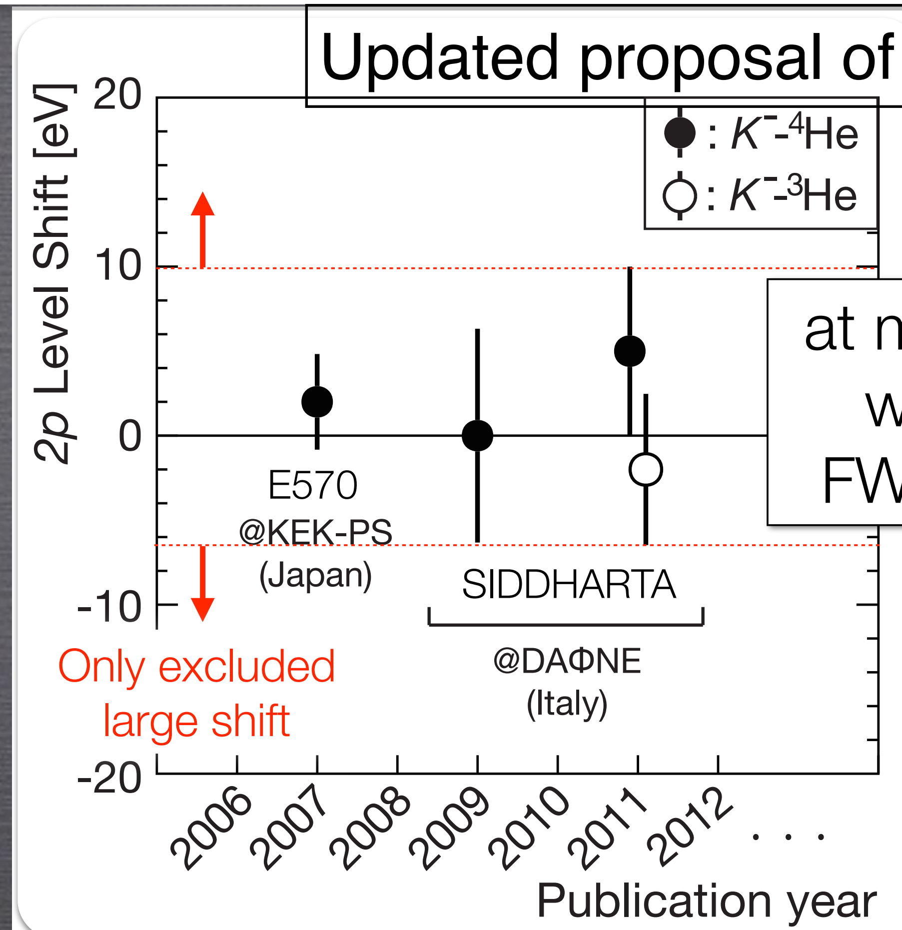
Kaonic helium

nuclear potential effect on 2p level small, shift < 10 eV. (with SDDs)

S. Okada et al., Phys. Lett. B 653, 387 (2007)
M. Bazzi et al., Phys. Lett. B 681, 310 (2009)
M. Bazzi et al., Phys. Lett. B 697, 199 (2011)

With ultra-high resolution hints for :
- kaon-nucleus potential;
- search for deeply-bound kaon states.

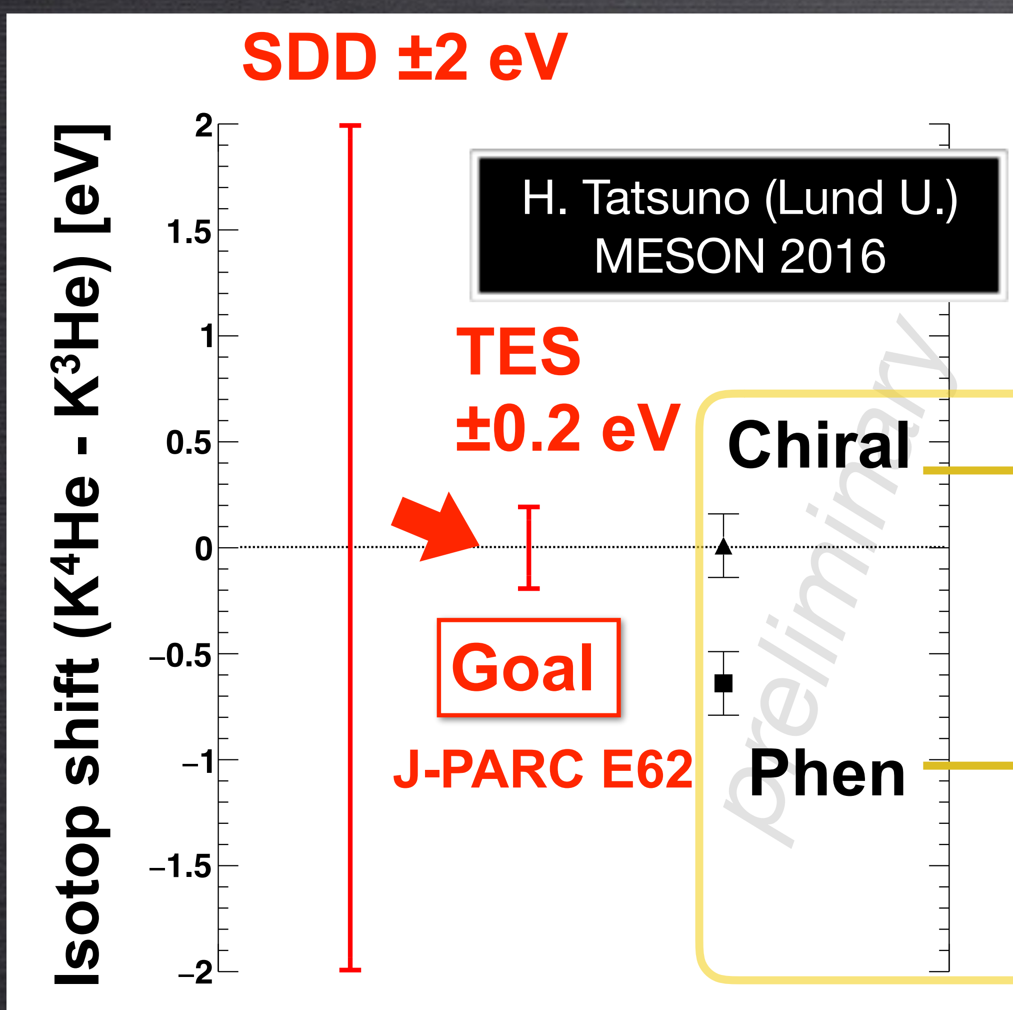
Updated proposal of E17 (E62) experiment



at most **± 2 eV** accuracy with SDD resolution, FWHM 150 eV @ 6 keV

need breakthrough in detector resolution

Many of theoretical calculations predict **finite values** of $|\Delta E_{2p}| < 1$ eV (e.g., **~0.2 eV**)



Chiral SU(3) model — Ramos, Oset, NPA67 (00) 481

$V_{opt}(r=0) \sim -($ ***40*** $+ 55i)$ MeV

reproduces the *K⁻p 1s* shift & width of SIDDHARTA

phenomenological model — Mares, Freidman, Gal, NPA 770 (06) 84

$V_{opt}(r=0) \sim -($ ***180*** $+ 73i)$ MeV

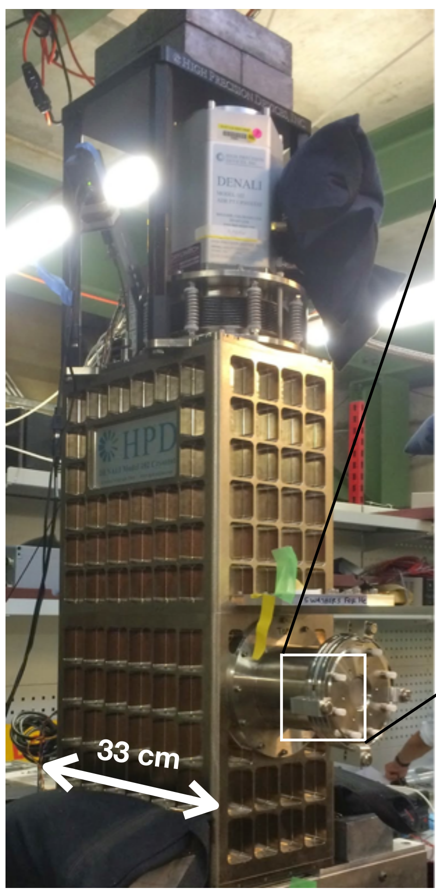
best fit for the early kaonic atoms data

HEATES (J-PARC E62) experiment

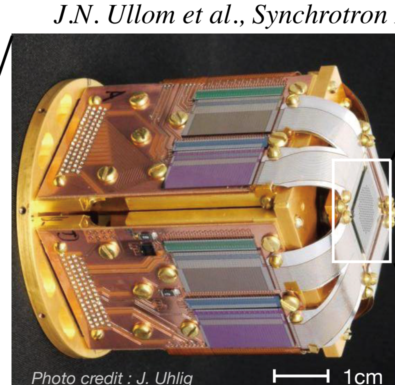
E62 @ J-PARC

- *K*⁻ He 3d-*2p* shift with 0.2 eV precision
- Transition Edge Sensor detector - micro-calorimeter for photons
- ~ μs timing resolution
- ~ 5 eV FWHM @ 6 keV

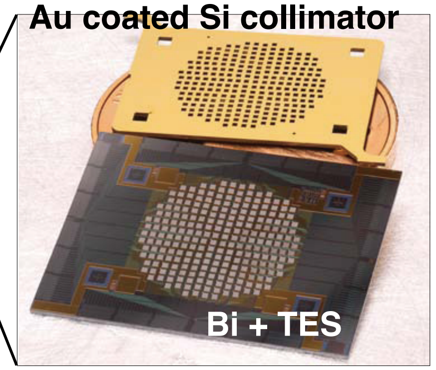
TES Spectrometer



J.N. Ullom et al., Synchrotron Radiation News, Vol. 27, 24 (2014)



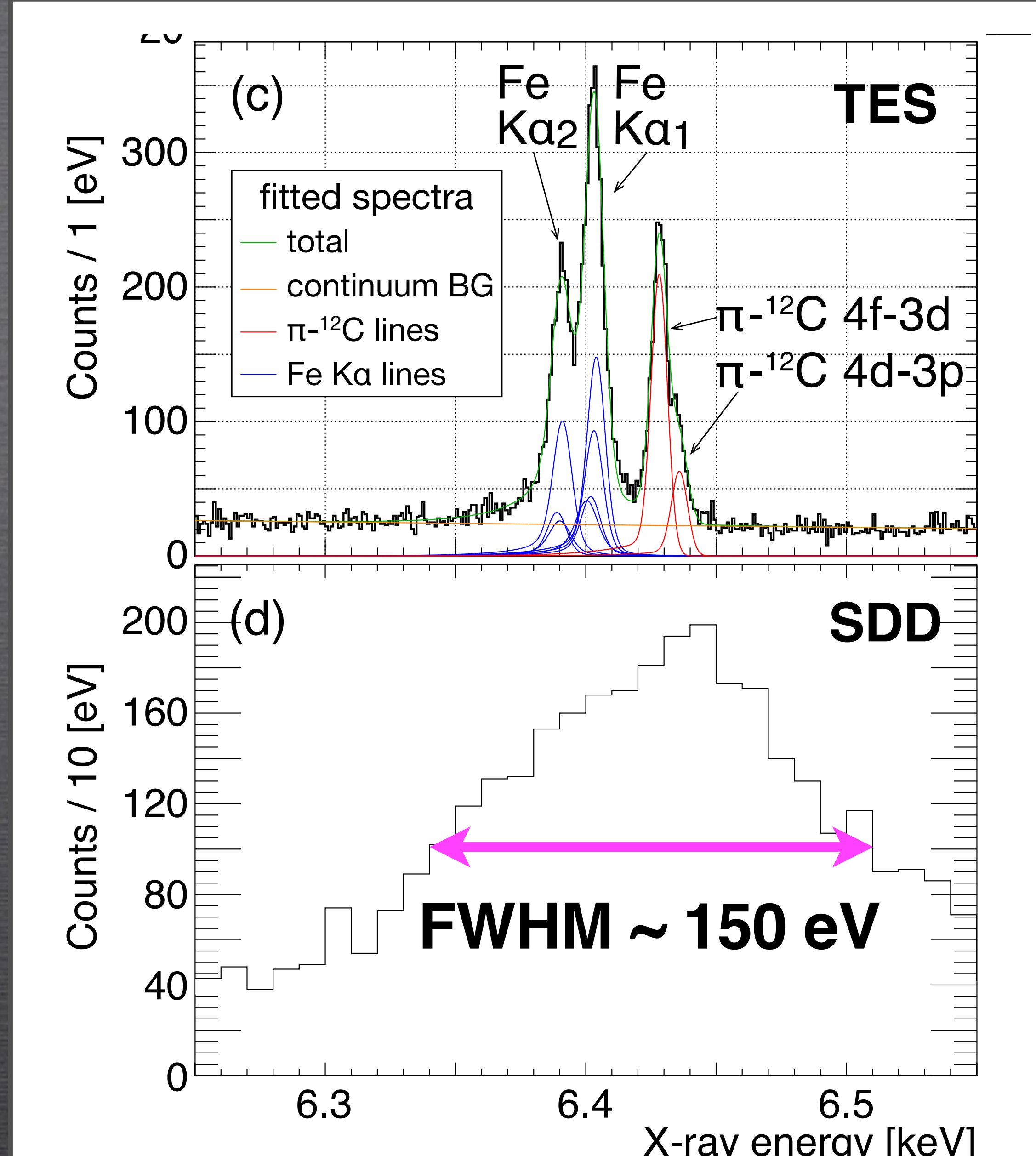
Au coated Si collimator



Cryostat
- Pulse tube (50K, 3K) + ADR (1K, 50mK)
- Temperature regulation hold time 36 hours
- Manufactured by HPD, designed at NIST

TES array
- 240 pixel Mo-Cu bilayer TES
- pixel area: 305 μm x 320 μm → total 23mm^2
- 4-μm thick Bi absorber → 85% efficiency at 6 keV

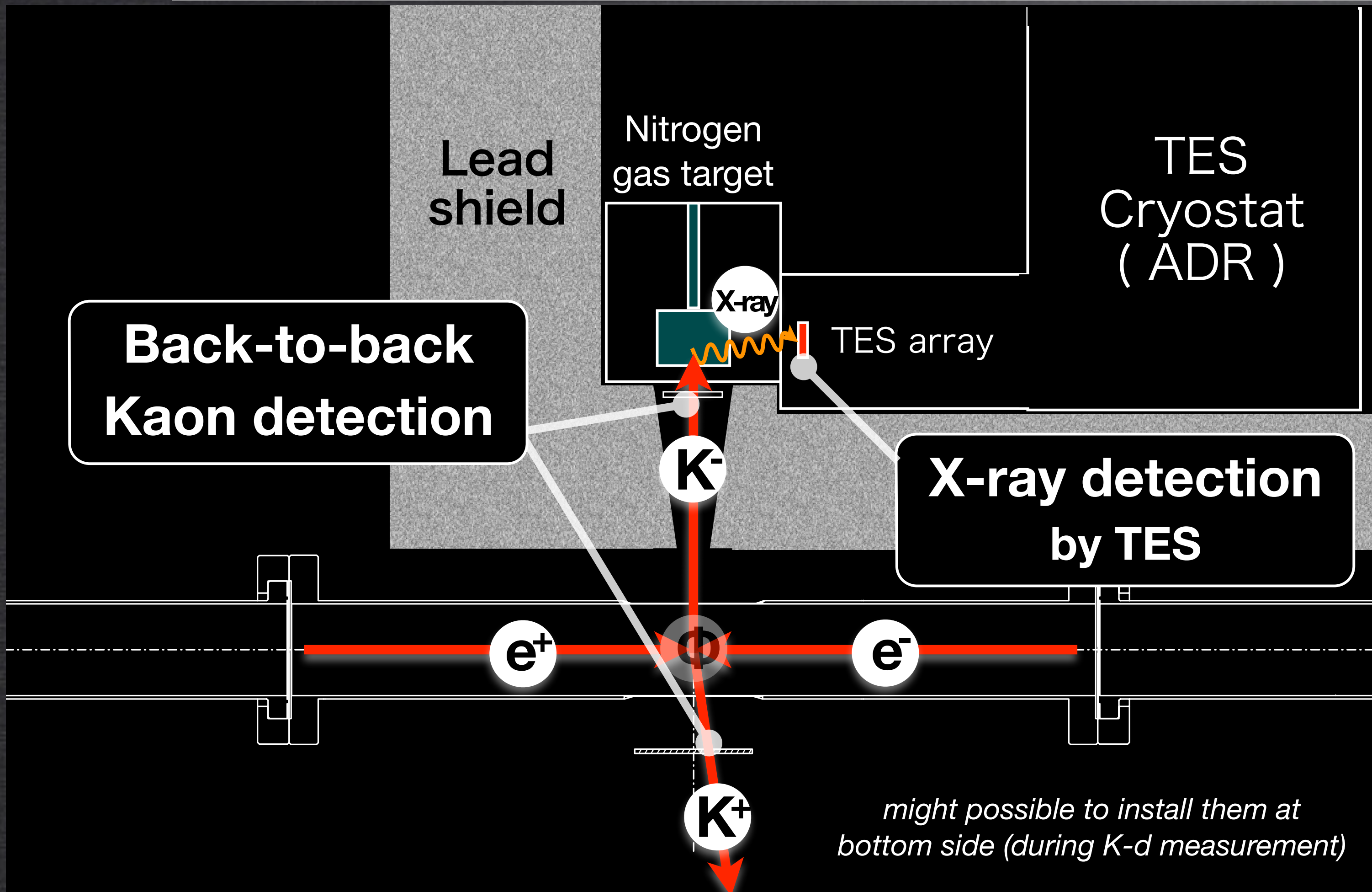
8 H.Tatsuno@Hadron2015



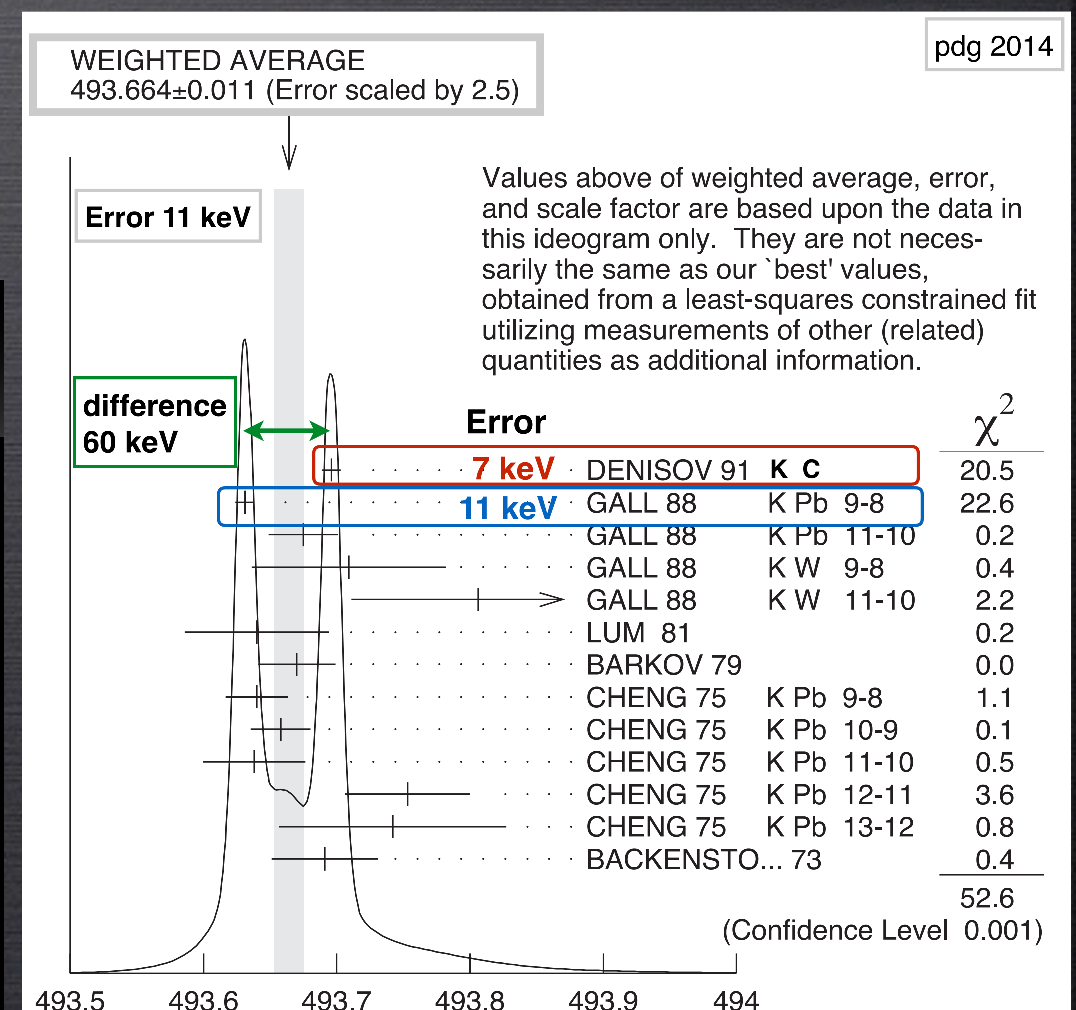
Accepted by Prog. Theor. Exp. Phys. 2016

first kaon beam measurement at J-PARC K1.8BR done in June 2016. Li target, kaonic-Li *3d-2p* x-ray successfully measured

Kaon mass measurement



A possible setup at DAΦNE



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Estimated stat. precision of K^- mass

assuming :
- K-N 6-5 x-ray ~ **1500 events / month** (135 pb^{-1})
- Energy resolution **~ 6.5 eV (FWHM)**
- No background

⇩

Stat. accuracy : ΔE (x-ray energy) ~ ± 0.07 eV

Δm (K-mass) = ΔE / E x m ~ ± 4.6 keV

S. Okada (RIKEN)
@ MESON 2015

Summary

❖ Light kaonic atom provides unique information of the kaon-nucleus interaction near the threshold

- Kaonic hydrogen : $K^{-}p$ scattering length at threshold determined with high precision;
- Kaonic deuterium : precision measurement in preparation; will disentangle isospin dependent $K^{-}p$ scattering length;
- K-^{3}He and K-^{4}He : sub-electron volt precision measurement will be key for kaon-nucleus potential and deeply-bound kaon state search;
- New detector technology applicable to determine kaon mass.

SIDDHARTA Collaboration

M. Bazzi [A], G. Beer [B], L. Bombelli [C], A.M. Bragadireanu [A,D],
M. Cargnelli [E], G. Corradi [A], C. Curceanu (Petrascu) [A],
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C. Guaraldo [A], R. S. Hayano [G], M. Iliescu [A,D], T. Ishiwatari [E],
M. Iwasaki [H], P. Kienle [E,I], P. Levi Sandri [A], A. Longoni [C],
V. Lucherini [A], J. Marton [E], S. Okada [A], D. Pietreanu [A], T. Ponta [D],
A. Rizzo [A], A.Romero [A], A. Scordo [A], H. Shi [G], D.L. Sirghi [A,D],
F. Sirghi [A,D], H. Tatsuno [A], A. Tudorache [D], V. Tudorache [D],
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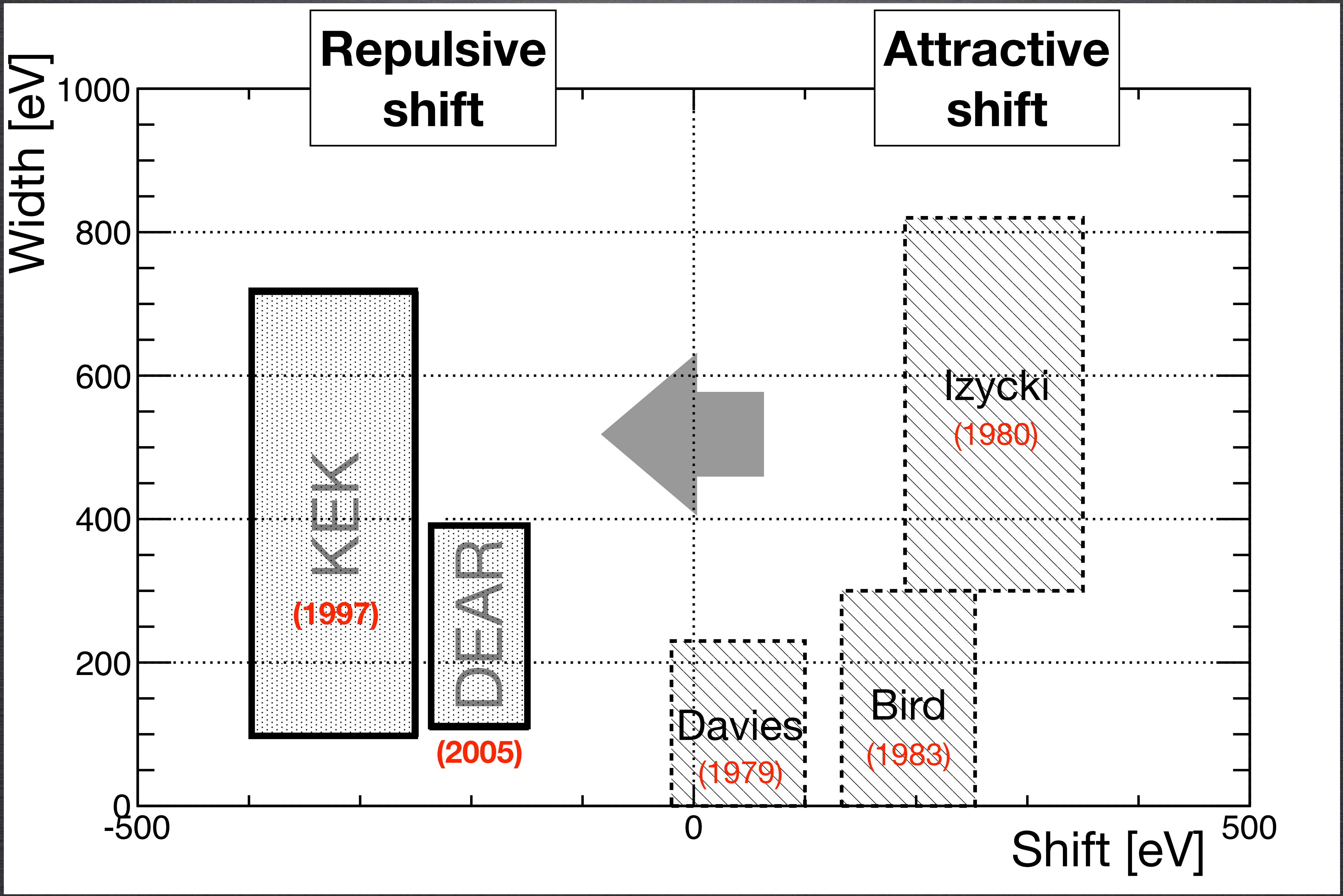
Politecnico Milano [C], *IFIN-HH* [D], *SMI* [E],
INFN Sezione di Roma I and Istituto Superiore di Sanita' [F],
Univ. Tokyo [G], *RIKEN* [H], *TUM* [I]

Appendix

Past experiments-1

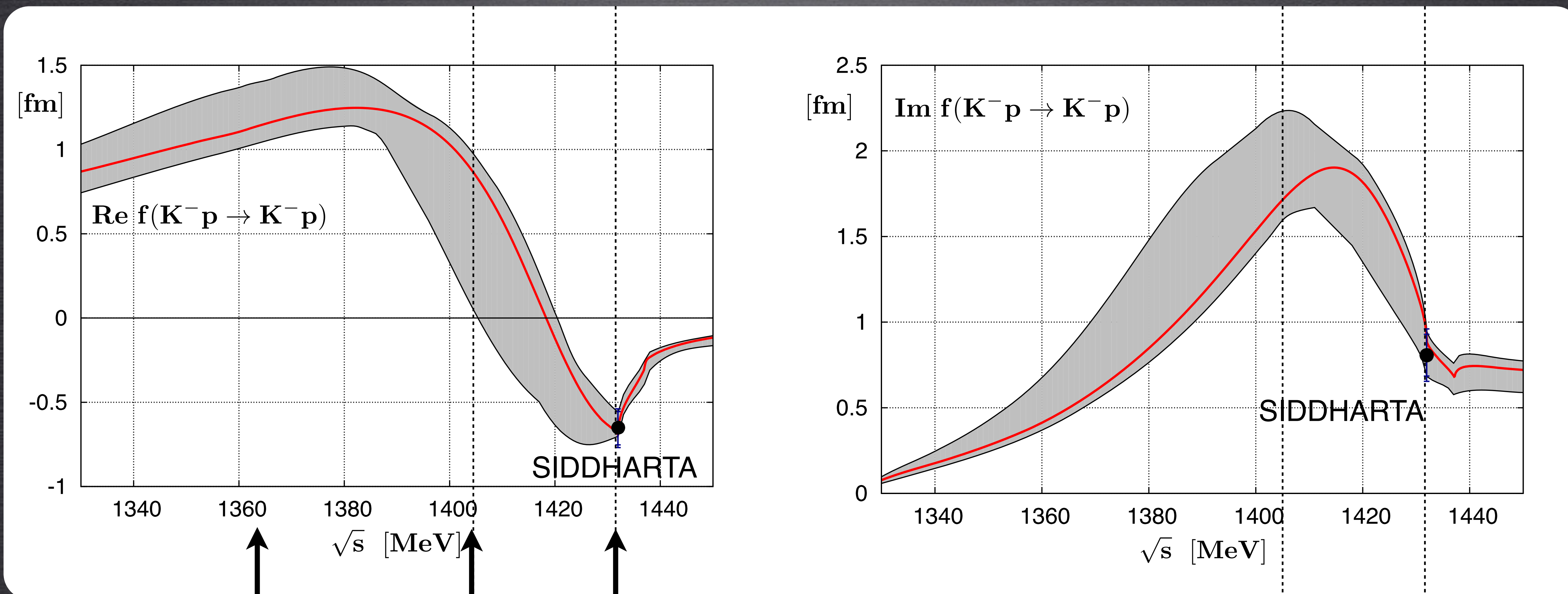


J. D. Davies et al., Phys. Lett. 83B, 55 (1979)
M. Izycki et al., Z. Phys. A 297, 11 (1980)
P. M. Bird et al., Nucl. Phys. A404, 482 (19

QCD predictions near *K-p* threshold

π-p system : successfully described by the chiral perturbation theory

-> but NOT with **K-p system**
due to the presence of Λ(1405) resonance only 25 MeV below threshold



Σπ **Λ(1405)** **K-p threshold**

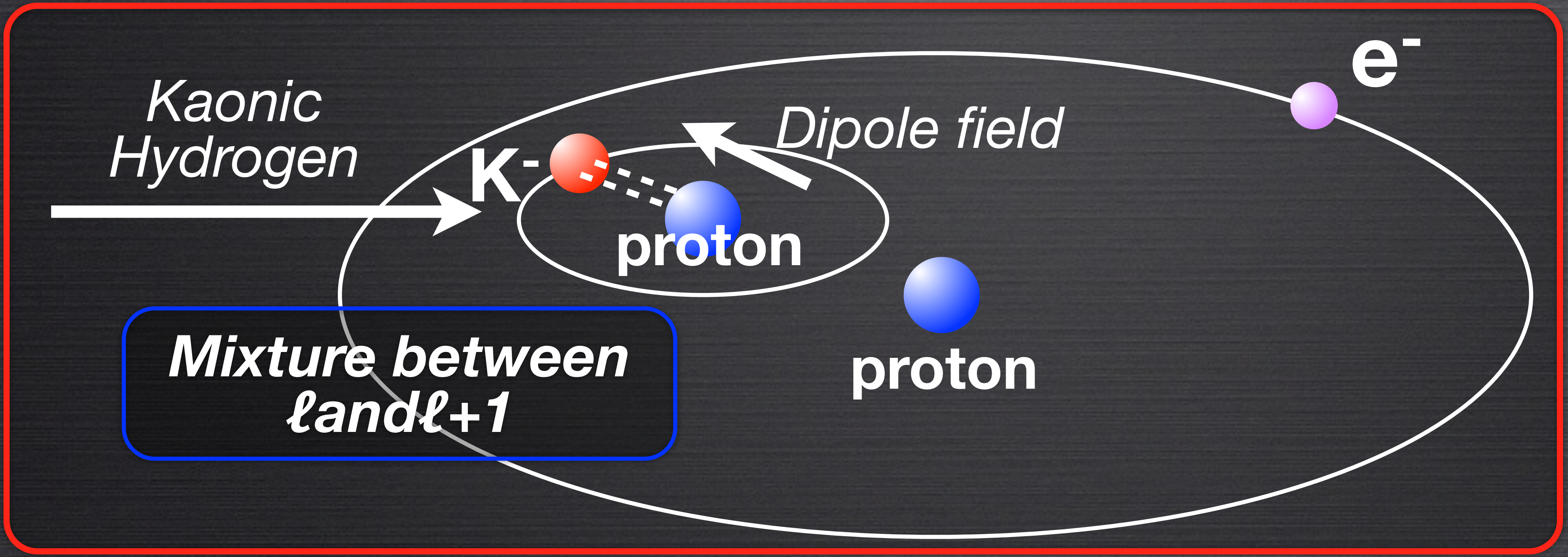
Kaon-nucleus deeply-bound state ?
-> Kaon condensation in dense matter.

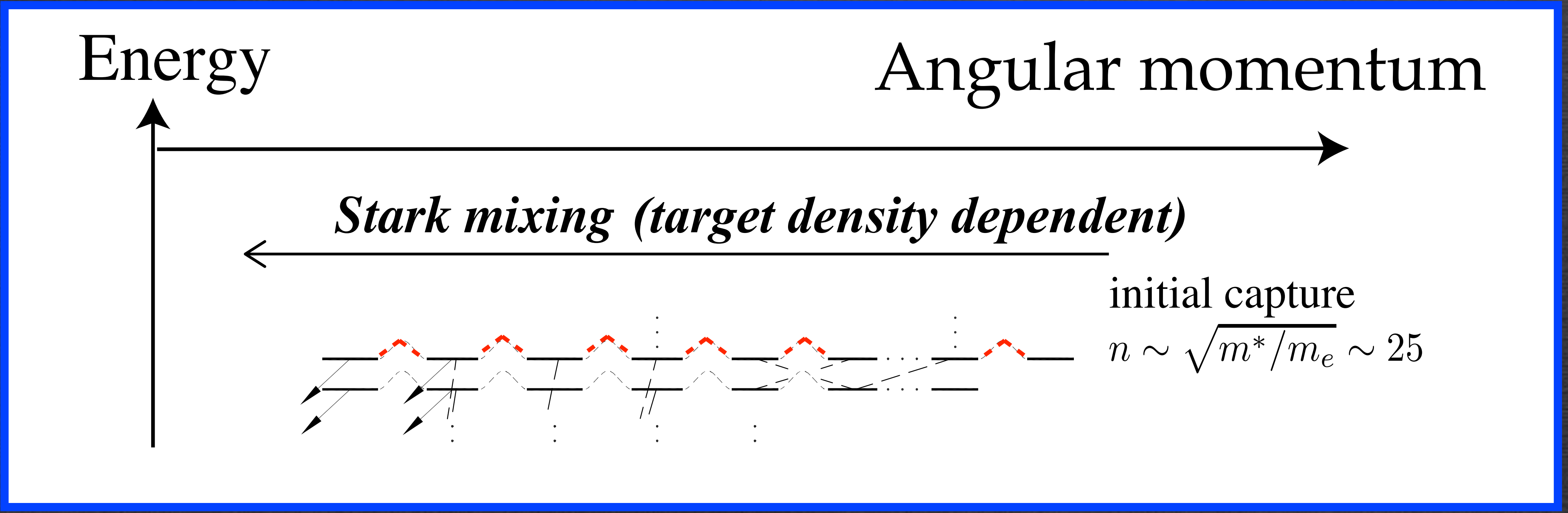
Y. Ikeda et.al., PLB 706(2011)63-67

Chiral SU(3) effective theory with a relativistic coupled-channels approach:
Kp→Kp forward scattering amplitude obtained from the NLO calculation extrapolated to the sub-threshold region

Difficulty of Kp and Kd X-ray measurment

Density-dependent yield due to **Stark mixing**





❖Low density gaseous target

❖ Low energy Kaon with small energy spread