J-PARC K1.8BRにおける K^-ビームを用いた$K^{bar}N$相互作用の研究

Tadashi Hashimoto (RIKEN)

for the J-PARC E15/E62 collaboration

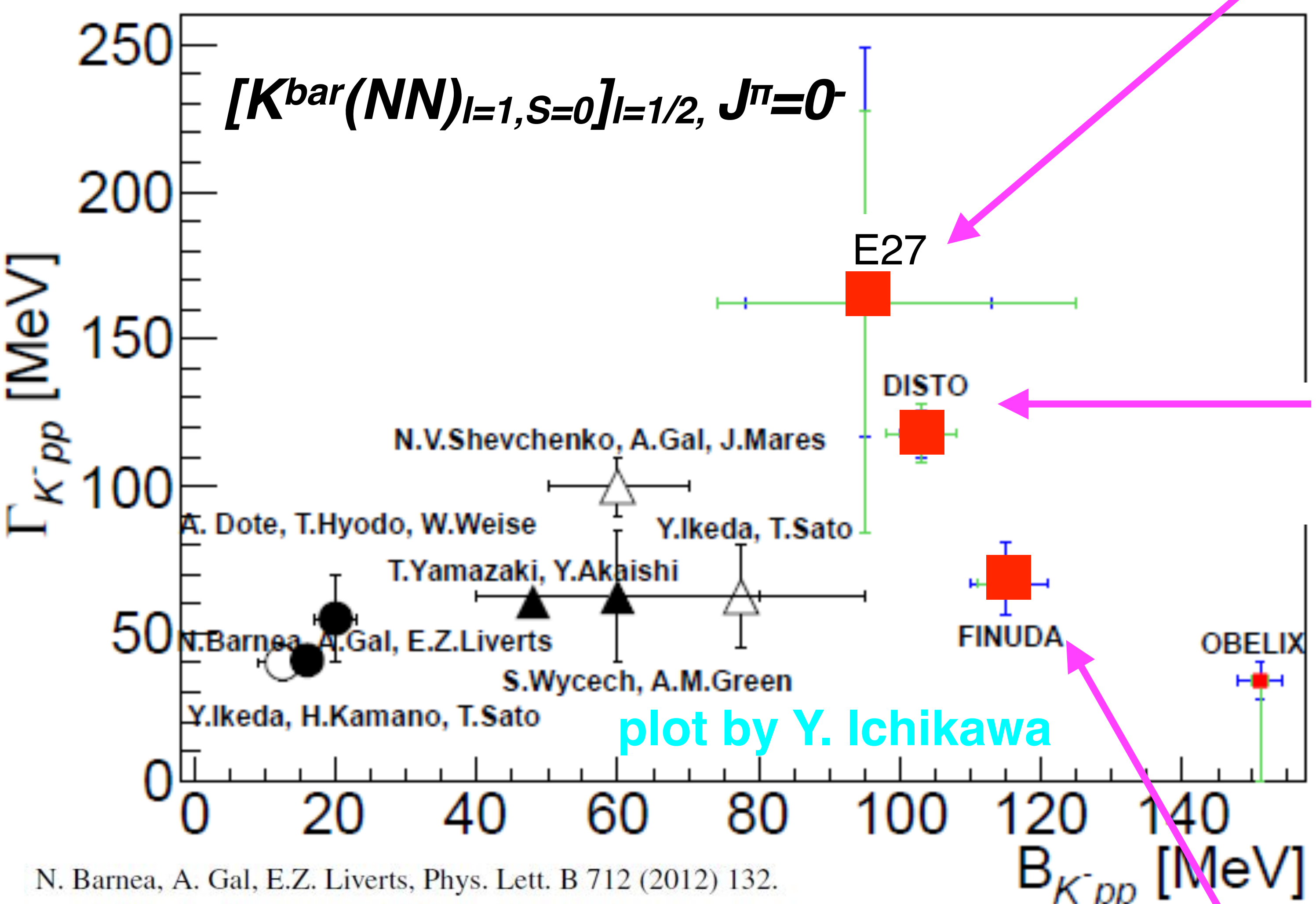
Antikaon in nuclear medium

- **K^{bar}N interaction**
  - **Strongly attractive in I=0** (weekly attractive in I=1)
  - Good data above the threshold
    - kaonic hydrogen x-rays, low-energy scattering data
  - Poor sub-threshold information

- **What will happen if K^- is embedded in a nucleus?**
  - kaonic nuclear states might exist.
    - dense matter? neutron star? mass reduction? partial restoration of CSB?
  - Attractive K^{bar}-nucleus interaction is supported qualitatively.
    - kaonic atom x-rays
    - (K,N) spectrum shape, K^-/K^+ ratio in pA collision, …

still not understood quantitatively…

Status of the "K⁻pp" study



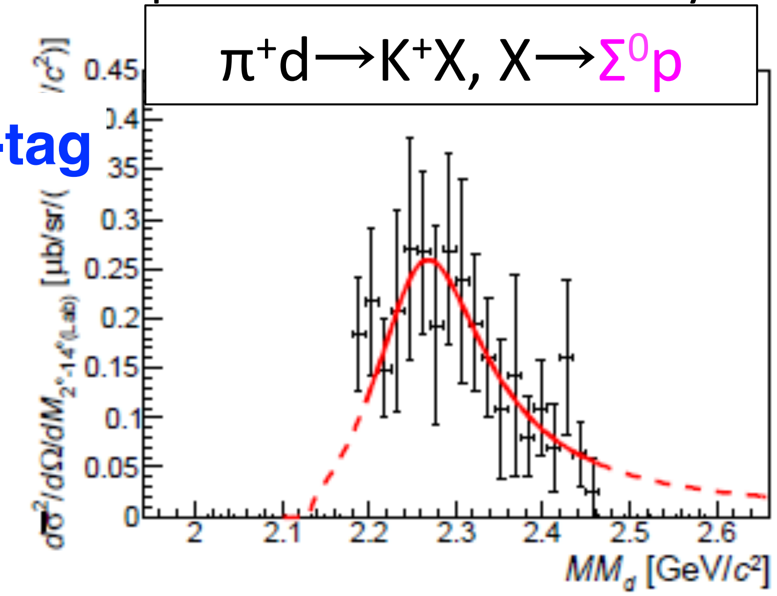
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712 (2012) 132.
A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804 (2008) 197;
A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79 (2009) 014003.
Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124 (2010) 533.
T. Yamazaki, Y. Akaishi, Phys. Lett. B 535 (2002) 70.
N.V. Shevchenko, A. Gal, J. Mareš, Phys. Rev. Lett. 98 (2007) 082301;
N.V. Shevchenko, A. Gal, J. Mareš, J. Revai, Phys. Rev. C 76 (2007) 044004.
Y. Ikeda, T. Sato, Phys. Rev. C 76 (2007) 035203;
Y. Ikeda, T. Sato, Phys. Rev. C 79 (2009) 035201.
S. Wycech, A.M. Green, Phys. Rev. C 79 (2009) 014001.

<2proton coincidence analysis>

J-PARC E27

$d(\pi^+,K^+)X$, Σ^0p-tag

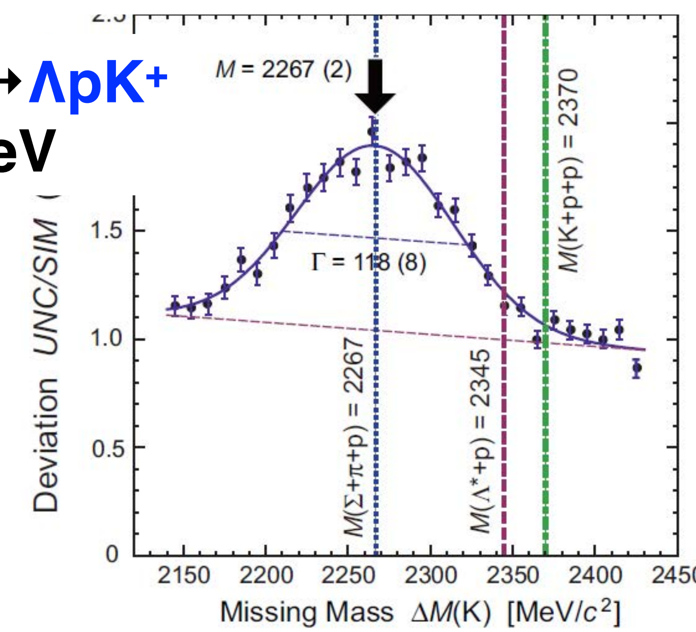
PTEP2015,021D01



DISTO

$pp \rightarrow$ ("K⁻pp"K^+) $\rightarrow \Lambda p K^+$
@T_p=2.85 GeV

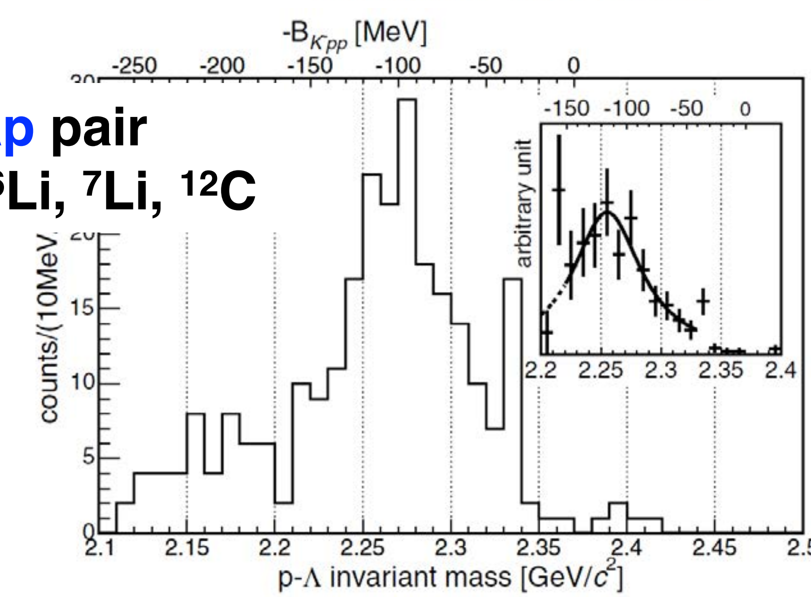
PRL**104**, 132502 (2010).
EPJ*A* **48**, 183 (2012).



FINUDA

back-to-back Λp pair
stopped K^- on ^{6}Li, ^{7}Li, ^{12}C

PRL**94**, 212303 (2005).

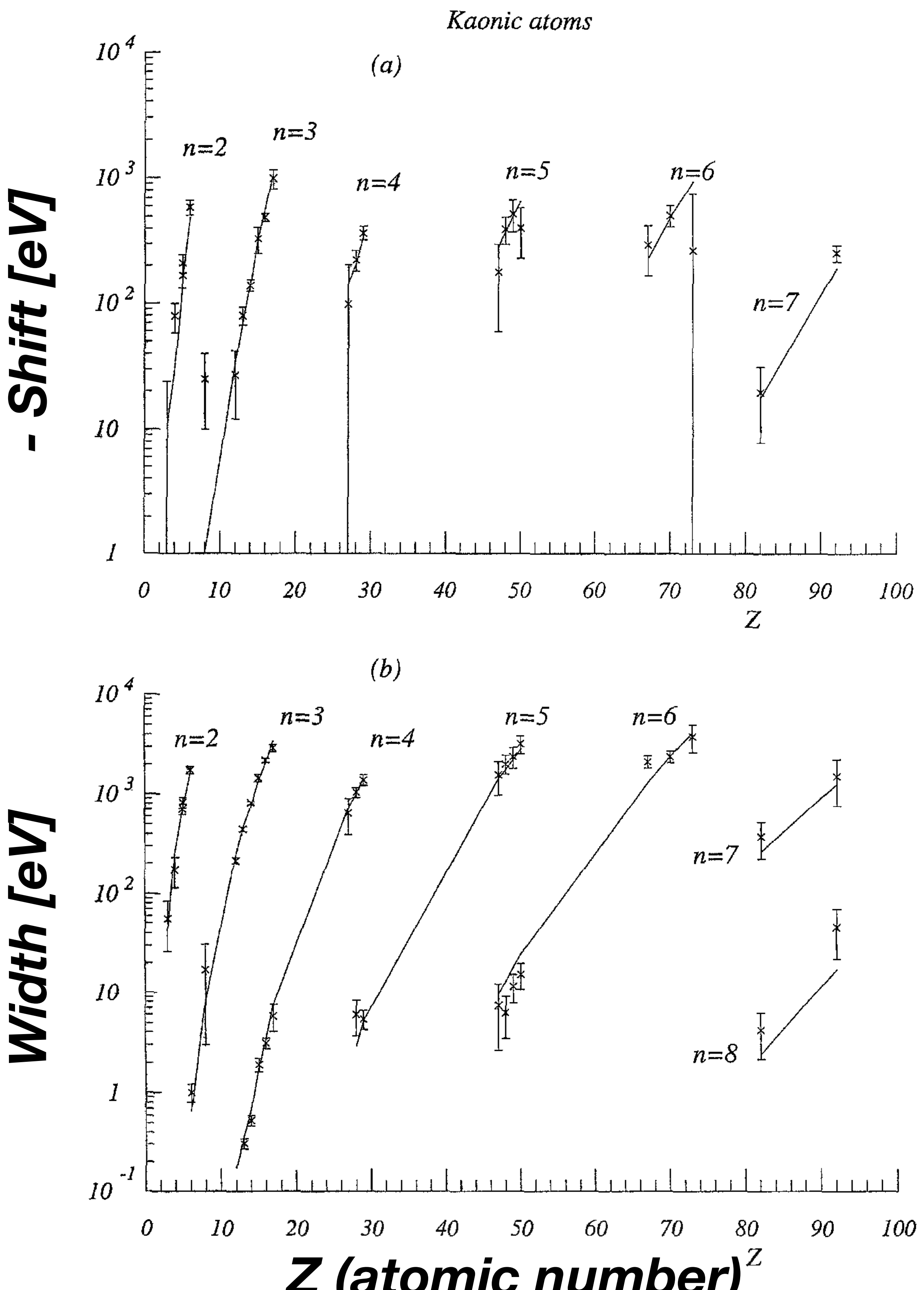


- All theoretical studies predict existence of "K⁻pp"
- Experimental observation cannot be explained

Further experimental information with different reaction channels is important

K^{bar}-nucleus interaction from Kaonic atom data

C. J. Batty, E. Friedman, and A. Gal, Phys. Rep., 287 (1997) 385.



- **Data points exist across the periodic table**
  - K-p: SIDDHARTA
  - K-d: no Data
  - Z = 2(He) ~ 92(U)
    - measurements in 1970's & 80's not so good quality…

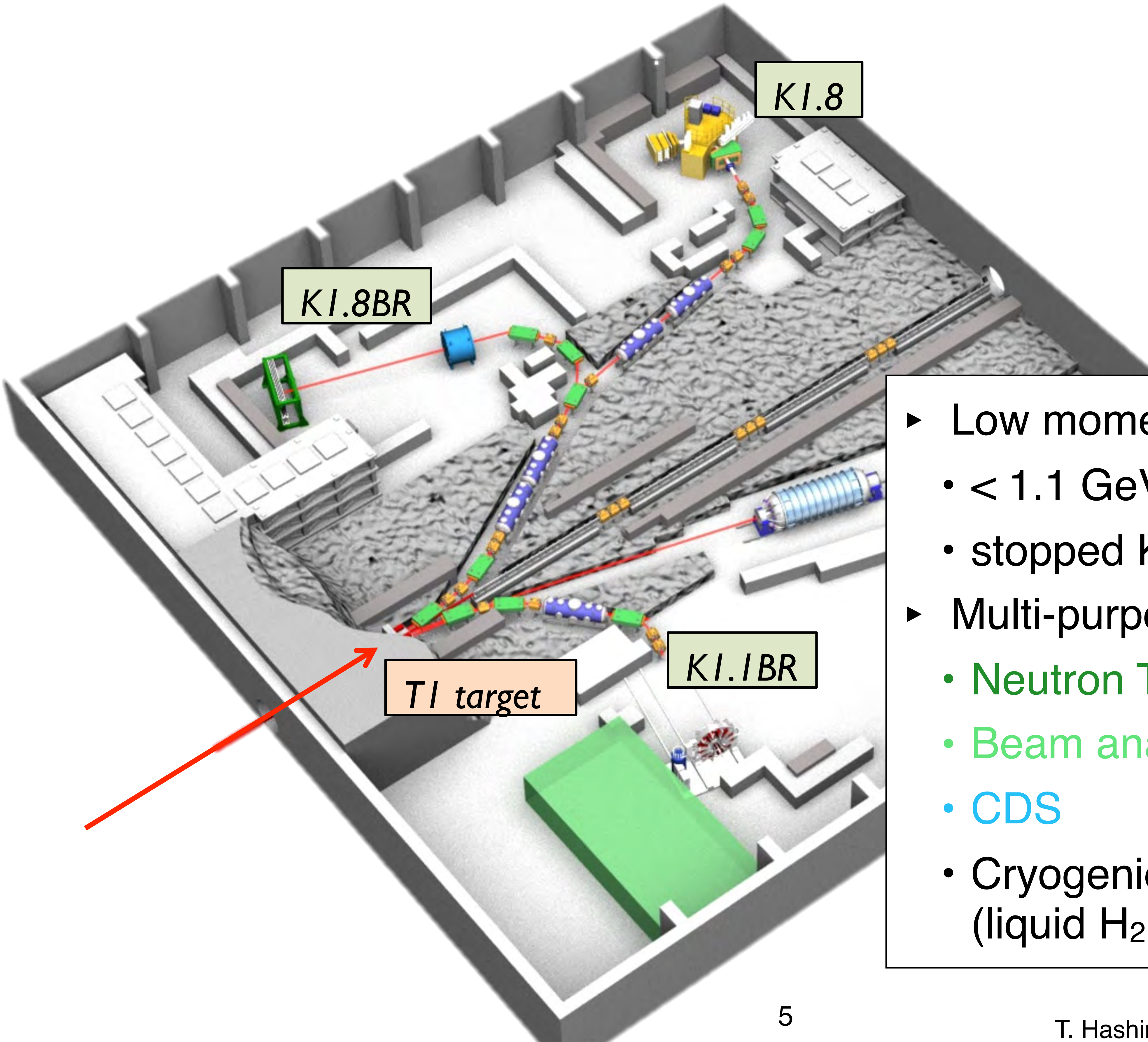
- **Global analysis prefer a deep potential?**

  - Re V ~ 150~200 MeV

  - Phenomenological density dependent optical potential
    Phys. Rep., 287 (1997) 385.
  - Chiral potential (~50 MeV) *Ramos, Oset, NPA671(00)481*
    + phen. multi nucleon terms.
    E. Friedman and A. Gal, NPA 899(2013) 60.

New systematic measurements with improved precision are important

J-PARC hadron hall



Features of K1.8BR

- Low momentum kaon beam
  - < 1.1 GeV/c
  - stopped K
- Multi-purpose detector system
  - Neutron TOF counter
  - Beam analyzer
  - CDS
  - Cryogenic target (liquid H_2 / D_2 / $^{3/4}He$)

Experiments at K1.8BR

- **All approved experiments investigate the $\bar{K}N$ interaction**
  - ***with different channels & processes***
  - ***sensitive in different energy region & isospin***

1.
- E15: Search for K^-pp via $^3He(K^-, n)$
  1st physics data in 2013. x10 times data coming soon.

- E31: Spectroscopic study of Λ(1405) via $d(K^-,n)$
  small data-set as an E15 calibration. requesting beam time.

- E57: K^-p, K^-d X-rays
  1st-stage approval. start with K-p to confirm S/N.

2.
- E62$_{(\leftarrow E17)}$: Kaonic $^3He/^4He$ atom X-rays
  Update with TES confirmed as 2nd-stage.

E15: "K^-pp" search via $^3He(K^-,n)$

Results of the 1st physics run

1. Semi-inclusive $^3He(K^-,$**n**$)$
2. Exclusive 3He(K-,**Λp**)n

J-PARC E15 collaboration

S. Ajimura[a], G. Beer[b], H. Bhang[c], M. Bragadireanu[e], P. Buehler[f], L. Busso[g,h], M. Cargnelli[f], S. Choi[c], C. Curceanu[d], S. Enomoto[i], D. Faso[g,h], H. Fujioka[j], Y. Fujiwara[k], T. Fukuda[l], C. Guaraldo[d], T. Hashimoto[k], R. S. Hayano[k], T. Hiraiwa[a], M. Iio[o], M. Iliescu[d], K. Inoue[i], Y. Ishiguro[j], T. Ishikawa[k], S. Ishimoto[o], T. Ishiwatari[f], K. Itahashi[n], M. Iwai[o], M. Iwasaki[m,n*], Y. Kato[n], S. Kawasaki[i], P. Kienle[p], H. Kou[m], Y. Ma[n], J. Marton[f], Y. Matsuda[q], Y. Mizoi[l], O. Morra[g], T. Nagae[j$], H. Noumi[a], H. Ohnishi[n], S. Okada[n], H. Outa[n], K. Piscicchia[d], M. Poli Lener[d], A. Romero Vidal[d], Y. Sada[j], A. Sakaguchi[i], F. Sakuma[n], M. Sato[n], A. Scordo[d], M. Sekimoto[o], H. Shi[k], D. Sirghi[d,e], F. Sirghi[d,e], K. Suzuki[f], S. Suzuki[o], T. Suzuki[k], K. Tanida[c], H. Tatsuno[d], M. Tokuda[m], D. Tomono[n], A. Toyoda[o], K. Tsukada[r], O. Vazquez Doce[d,s], E. Widmann[f], B. K. Weunschek[f], T. Yamaga[i], T. Yamazaki[k,n], H. Yim[t], Q. Zhang[n], and J. Zmeskal[f]

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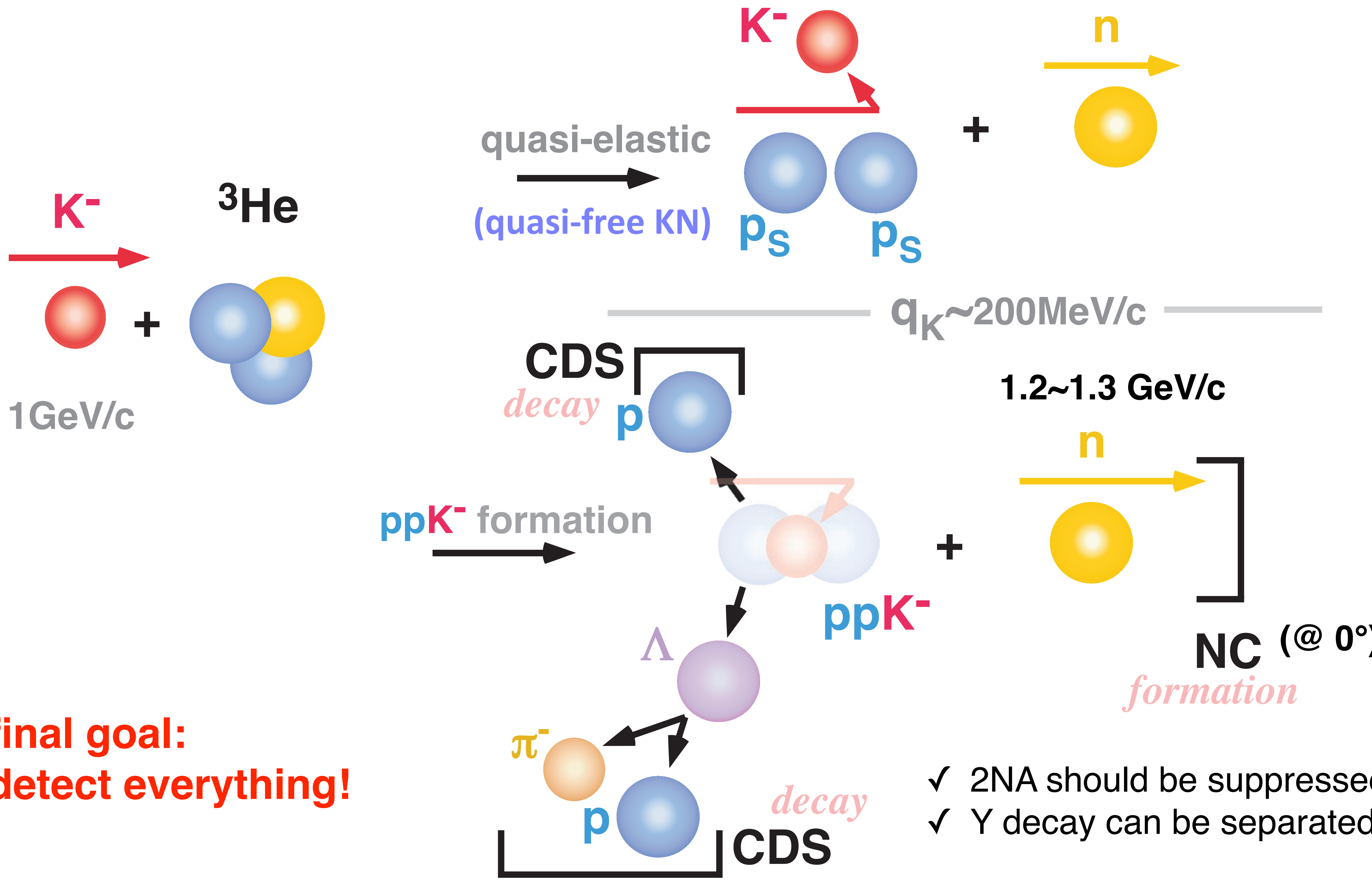
(*) Spokesperson
($) Co-Spokesperson

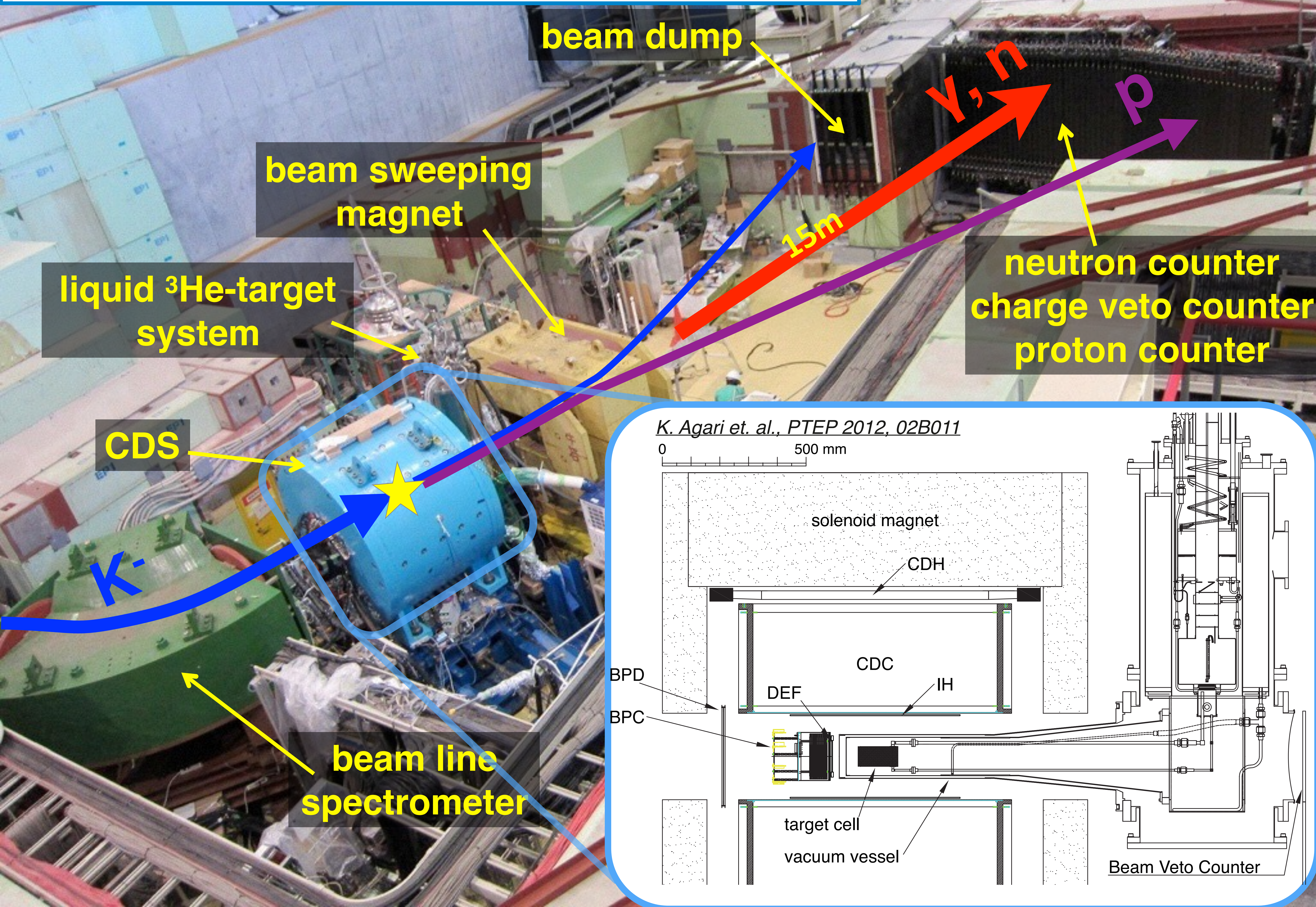
In-flight K^- reaction on ^3He



final goal:
detect everything!

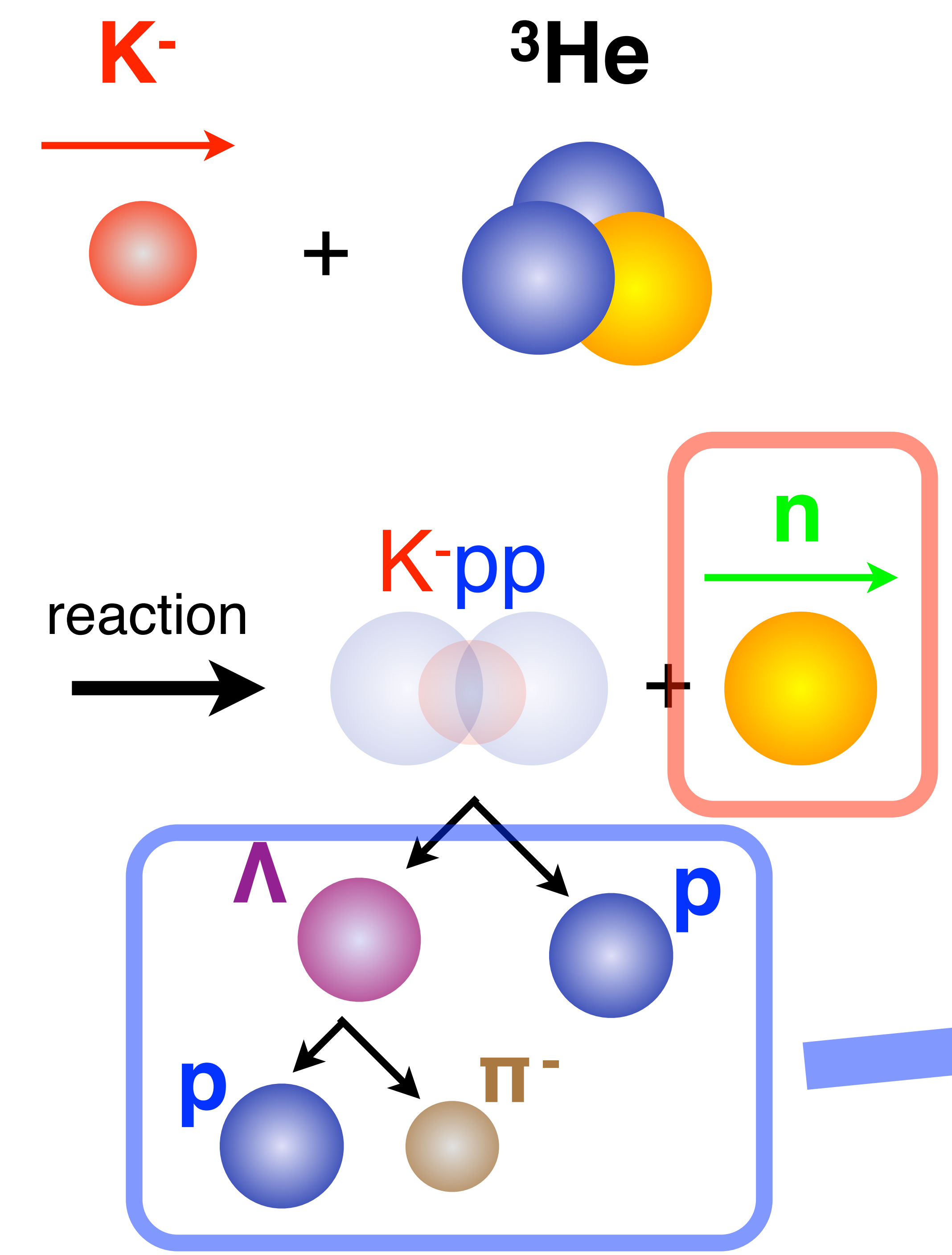
- ✓ 2NA should be suppressed
- ✓ Y decay can be separated

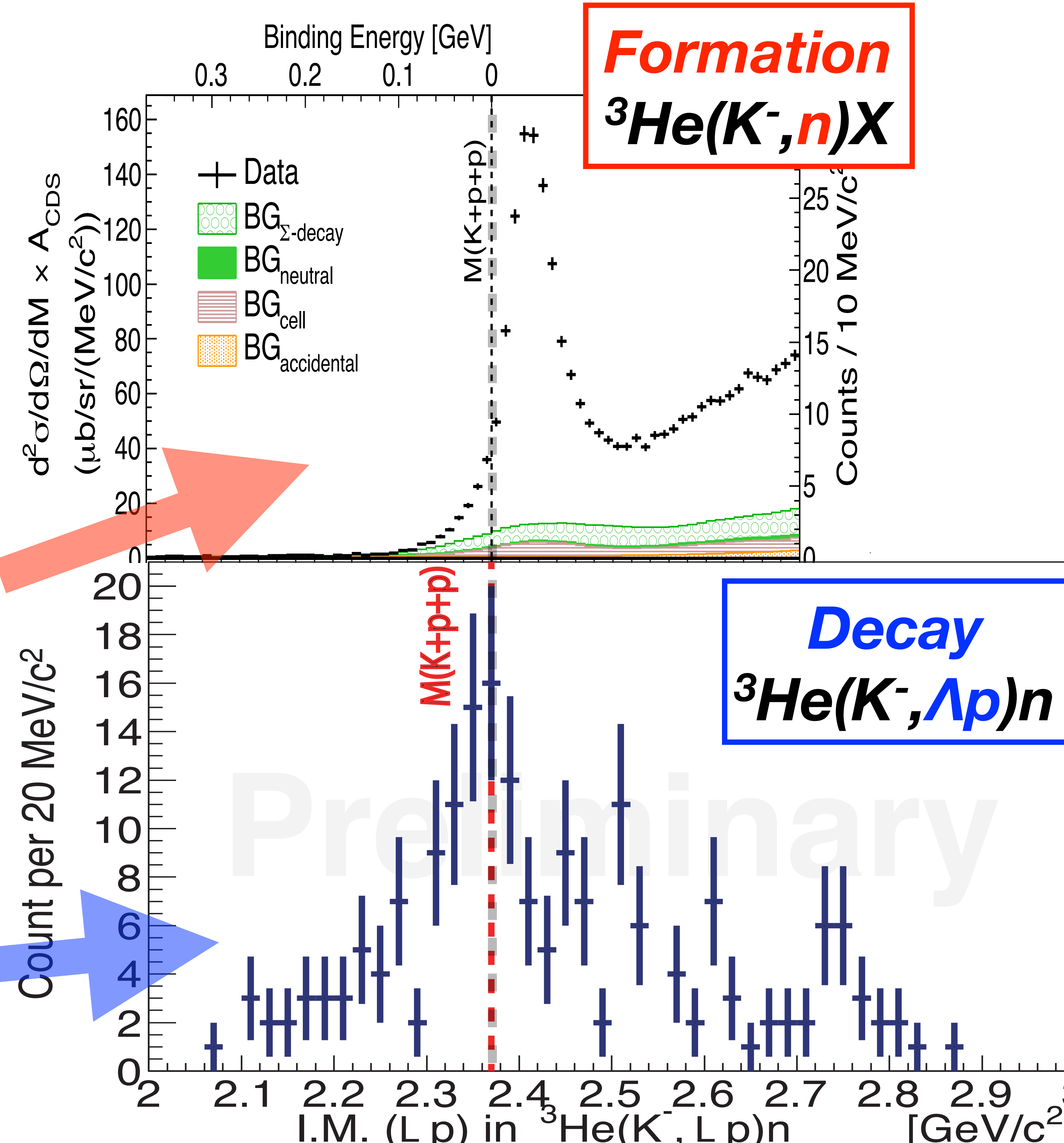
J-PARC K1.8BR spectrometer



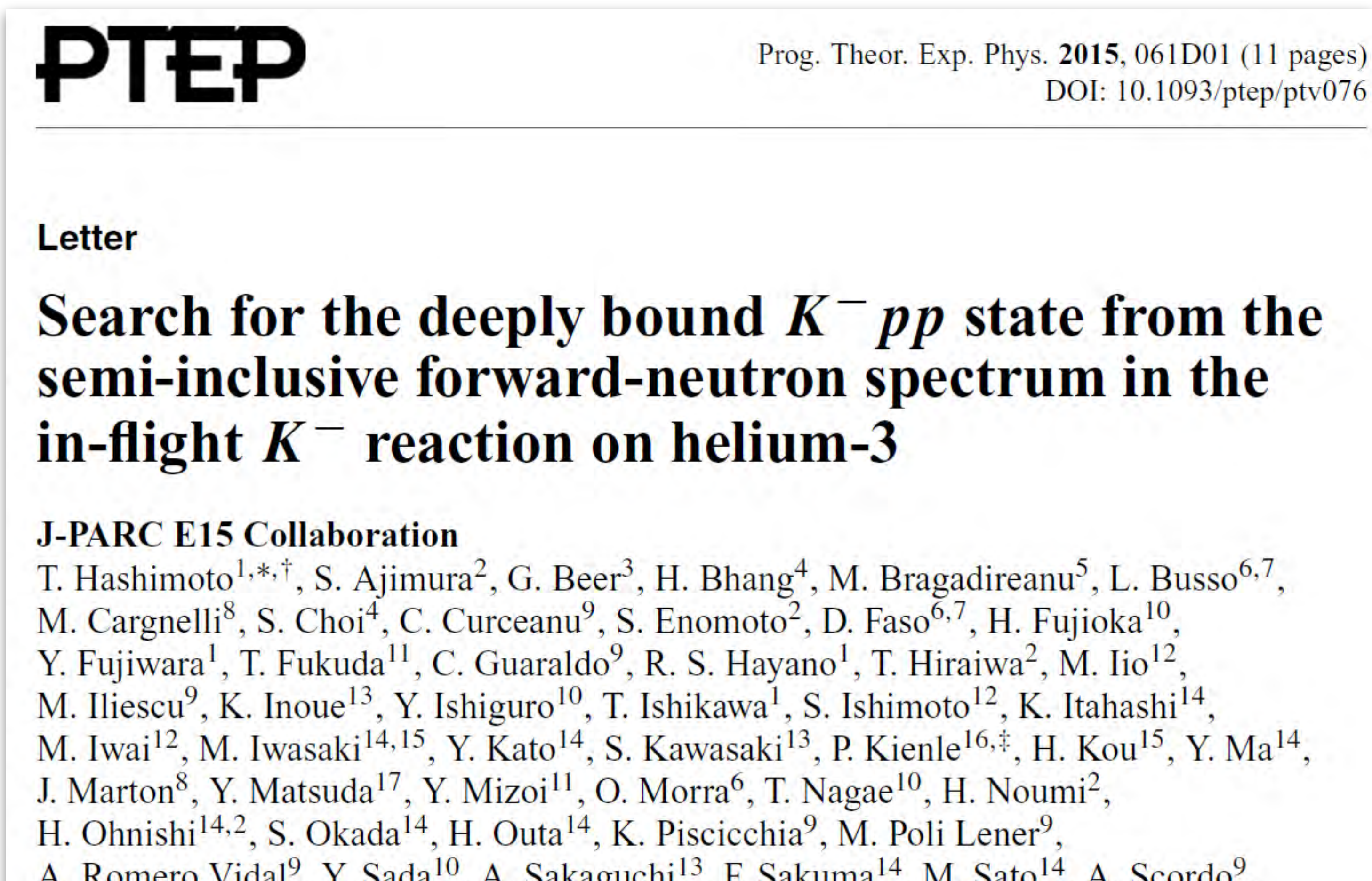
J-PARC E15 1st stage experiment

5×10^9 kaons
(~ 1% of full proposal)





Formation channel
Semi-inclusive $^{3}He(K^{-}, n)$



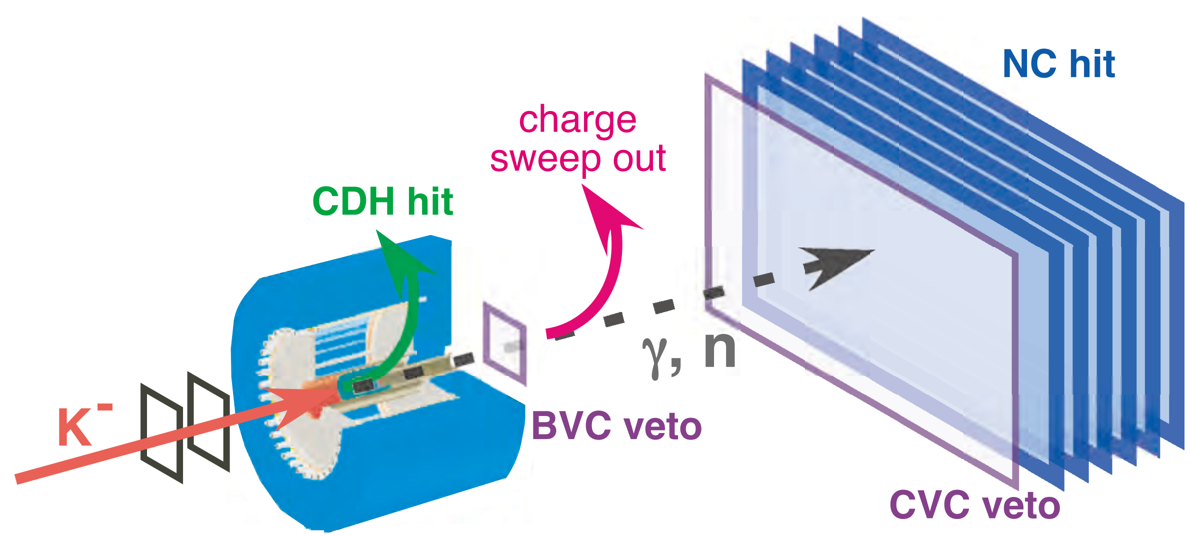
PTEP

Prog. Theor. Exp. Phys. **2015**, 061D01 (11 pages)
DOI: 10.1093/ptep/ptv076

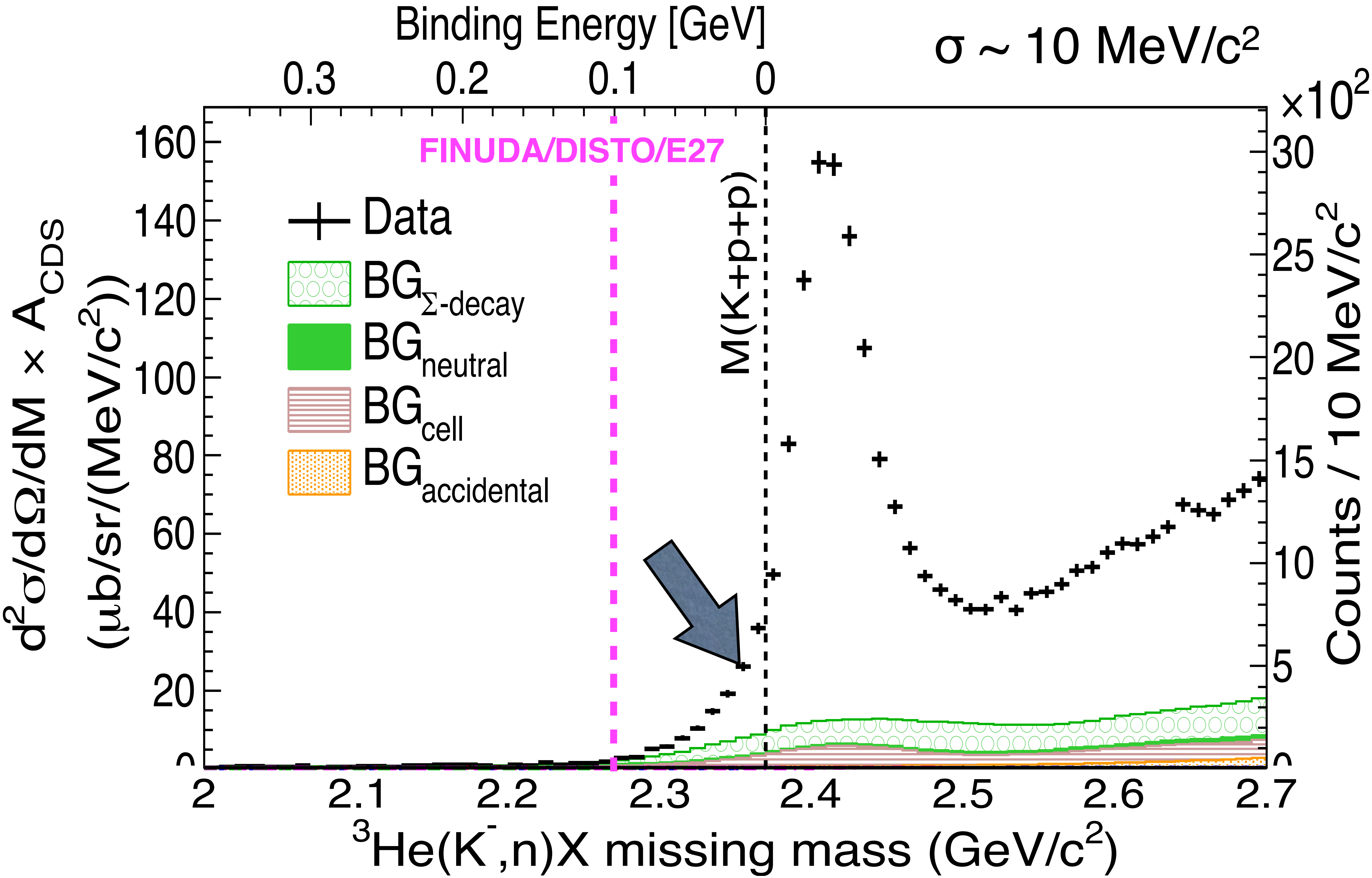
Letter

Search for the deeply bound $K^{-}pp$ state from the semi-inclusive forward-neutron spectrum in the in-flight K^{-} reaction on helium-3

J-PARC E15 Collaboration
T. Hashimoto[1,*,†], S. Ajimura[2], G. Beer[3], H. Bhang[4], M. Bragadireanu[5], L. Busso[6,7], M. Cargnelli[8], S. Choi[4], C. Curceanu[9], S. Enomoto[2], D. Faso[6,7], H. Fujioka[10], Y. Fujiwara[1], T. Fukuda[11], C. Guaraldo[9], R. S. Hayano[1], T. Hiraiwa[2], M. Iio[12], M. Iliescu[9], K. Inoue[13], Y. Ishiguro[10], T. Ishikawa[1], S. Ishimoto[12], K. Itahashi[14], M. Iwai[12], M. Iwasaki[14,15], Y. Kato[14], S. Kawasaki[13], P. Kienle[16,‡], H. Kou[15], Y. Ma[14], J. Marton[8], Y. Matsuda[17], Y. Mizoi[11], O. Morra[6], T. Nagae[10], H. Noumi[2], H. Ohnishi[14,2], S. Okada[14], H. Outa[14], K. Piscicchia[9], M. Poli Lener[9], A. Romero Vidal[9], Y. Sada[10], A. Sakaguchi[13], F. Sakuma[14], M. Sato[14], A. Scordo[9],

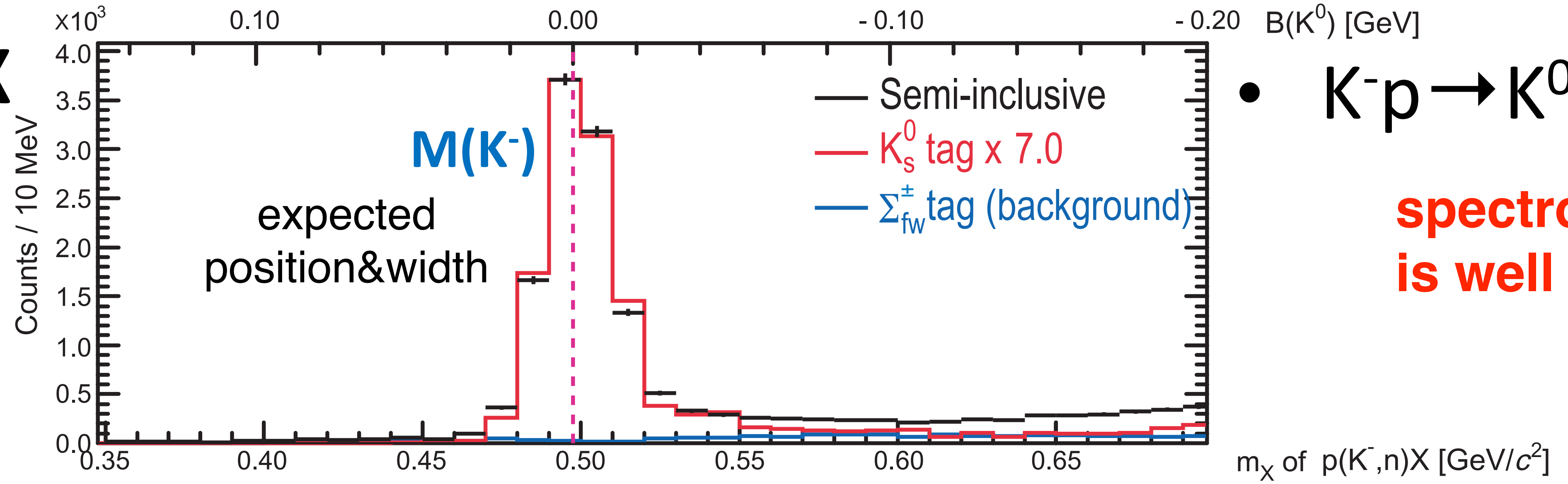


Semi-inclusive $^3He(K^-,n)$ at $\theta_n = 0$



Forward neutron specta on p/d/^{3}He

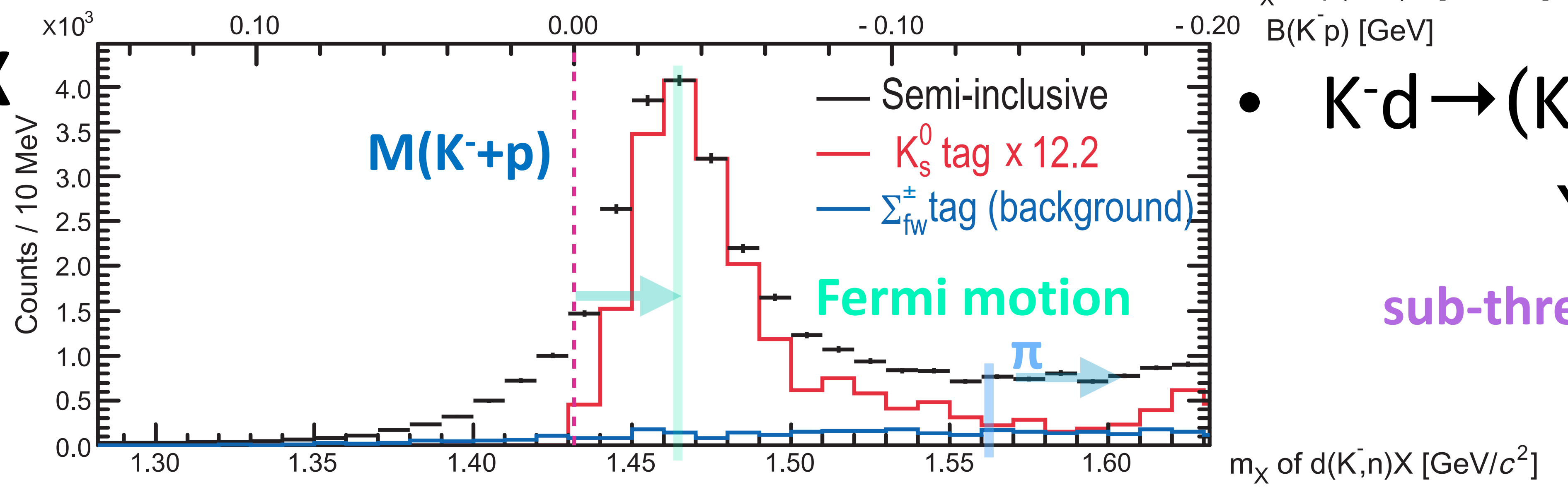
p(K$^-$,n)X



- $K^-p \rightarrow K^0 + n_{fw}$

spectrometer is well understood!!

d(K$^-$,n)X



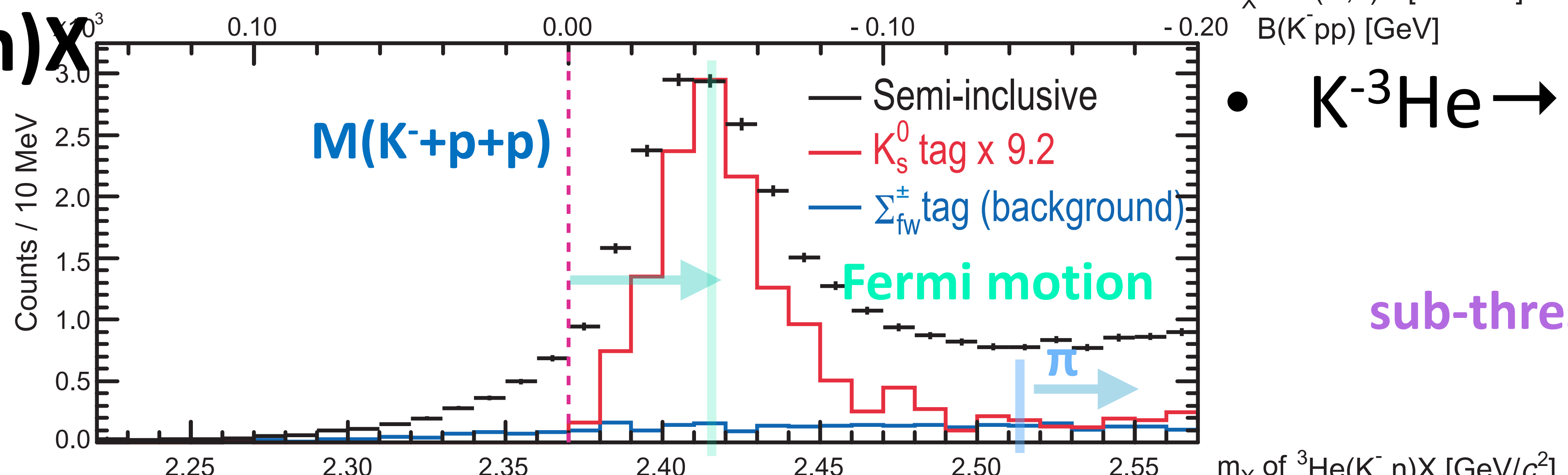
- $K^-d \rightarrow (K^-p) + n_{fw}$

  Y*

sub-threshold excess!

cf. E31

^{3}He(K$^-$,n)X



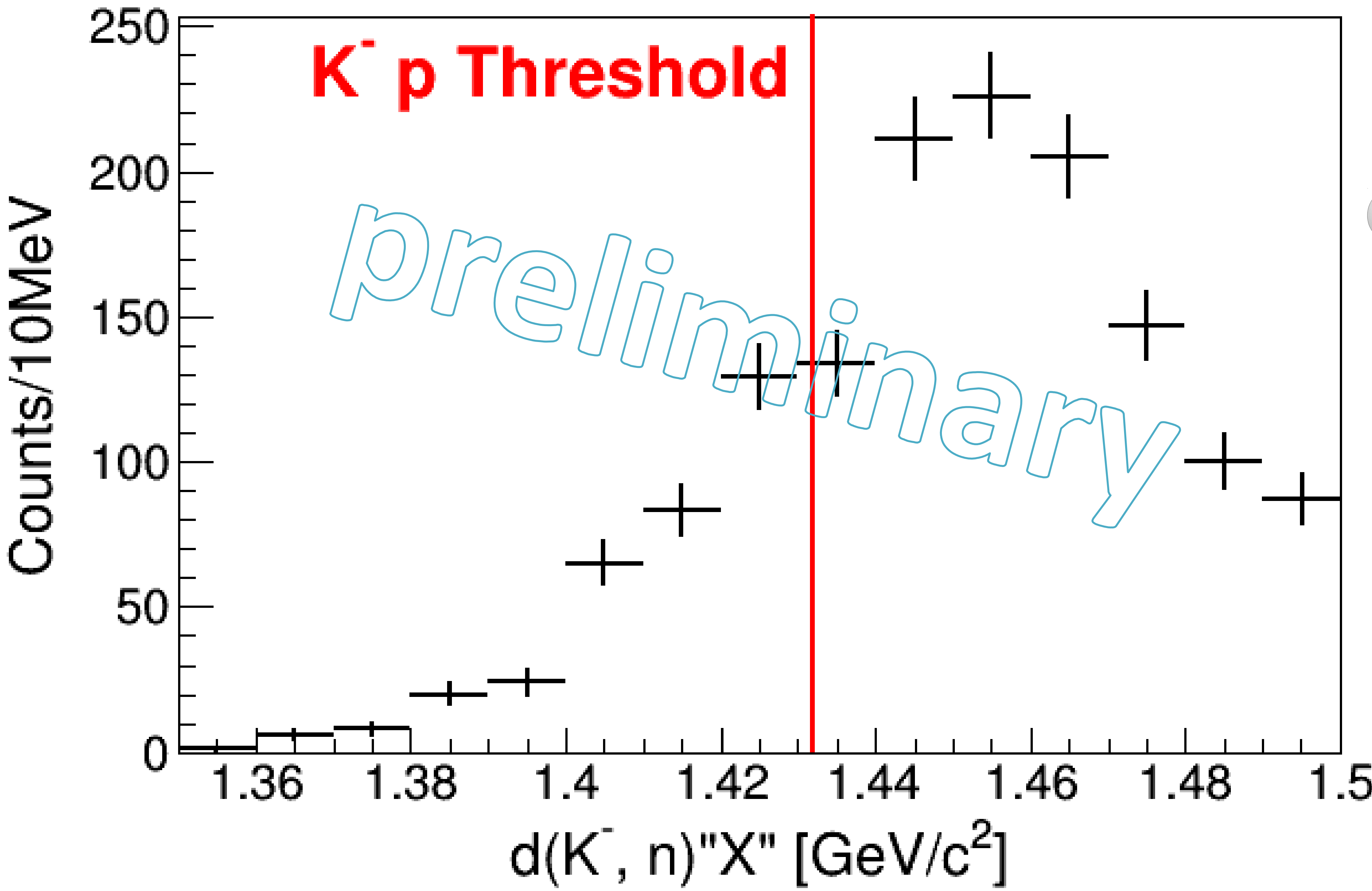
- $K^-{}^3He \rightarrow (K^-pp) + n_{fw}$

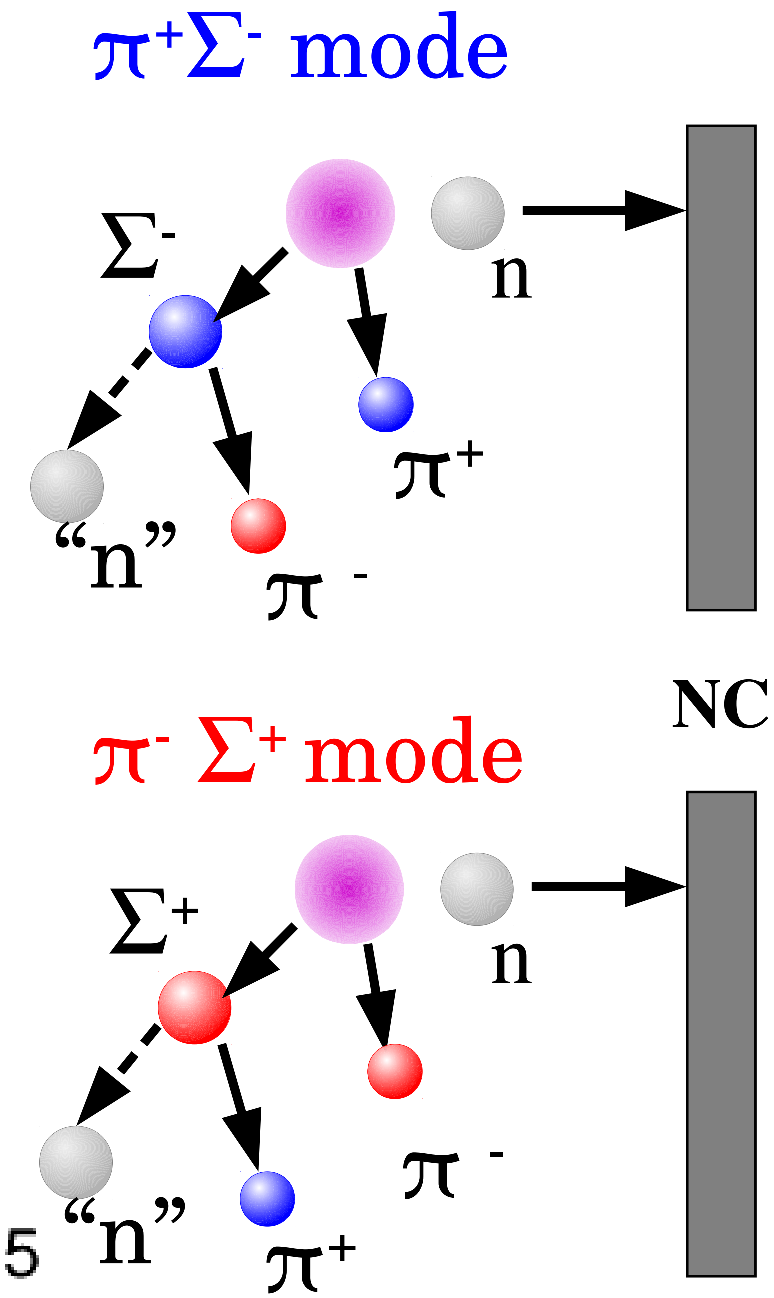
  Y*N

sub-threshold excess!

d(K$^-$, n)"X$_{\pi^\mp\Sigma^\pm}$" Spectrum

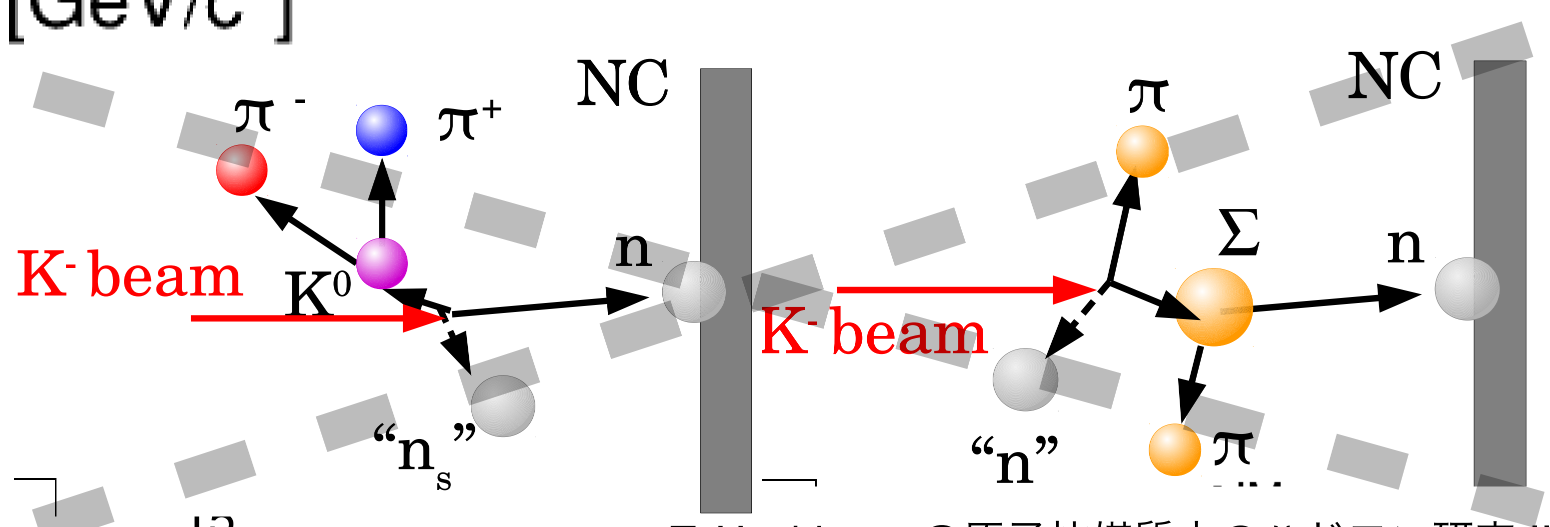
K. Inoue@HYP2015





No separation btw. 2 charged modes
No acceptance correction

K^0 & forward-going Σ contributions are rejected



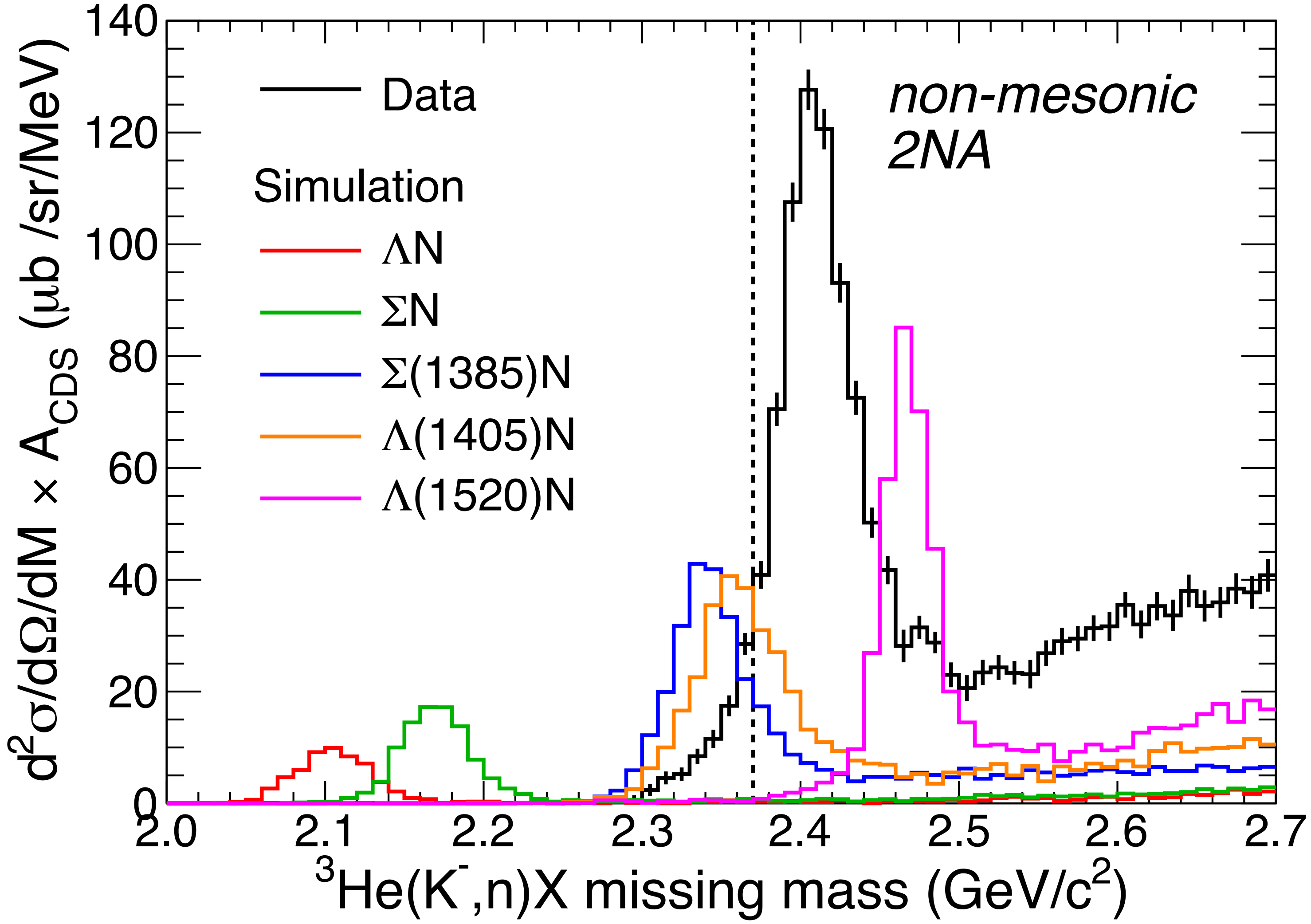
What is the origin of the excess?

naively understood by attractive & absorptive potential

other possibilities are…

1. non-mesonic two-nucleon absorption: Λ(1405)n branch

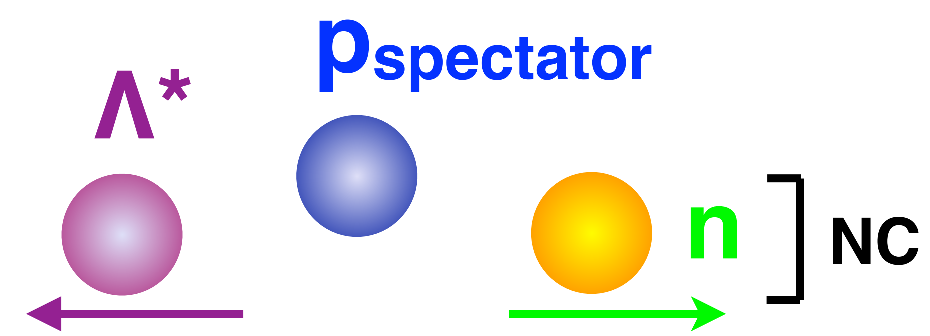
- rather large cross-section ~ 5 mb/sr
- U.L. of deeply bound states: 1 ~ 10% of Λ*n branch?



20 mb/sr @ θ=0

***Breit-Wigner** with PDG mass&width*

$$K^- + {}^3\text{He} \rightarrow Y^{(*)} + \boxed{N} + N_s.$$



ΛN/ΣN branches are negligibly small

Λ(1520)n branch < 2 mb/sr

What is the origin of the excess?

naively understood by attractive & absorptive potential

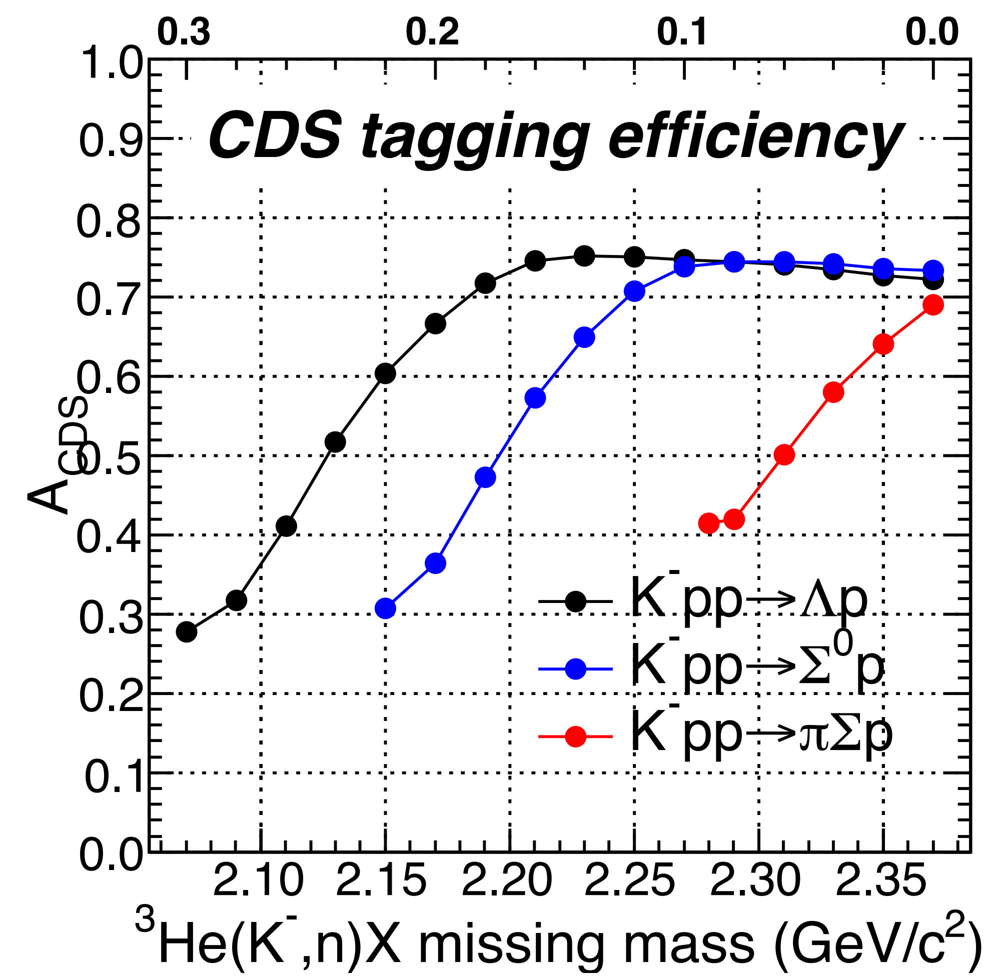
other possibilities are…

1. non-mesonic two-nucleon absorption: Λ(1405)n branch

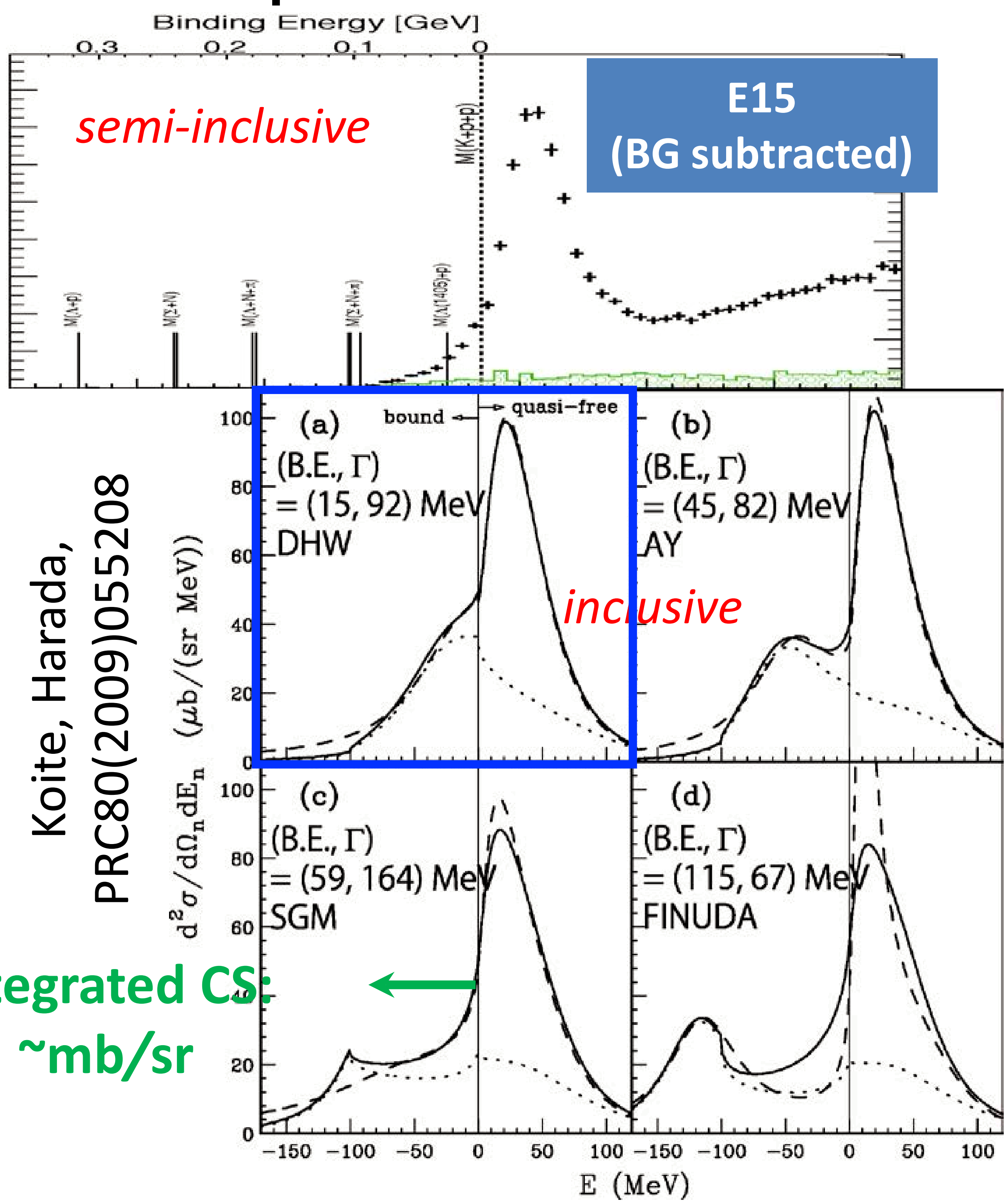
- rather large cross-section ~ 5 mb/sr
- U.L. of deeply bound states: 1 ~ 10% of Λ*n branch?

2. Loosely-bound "*K⁻pp*" state

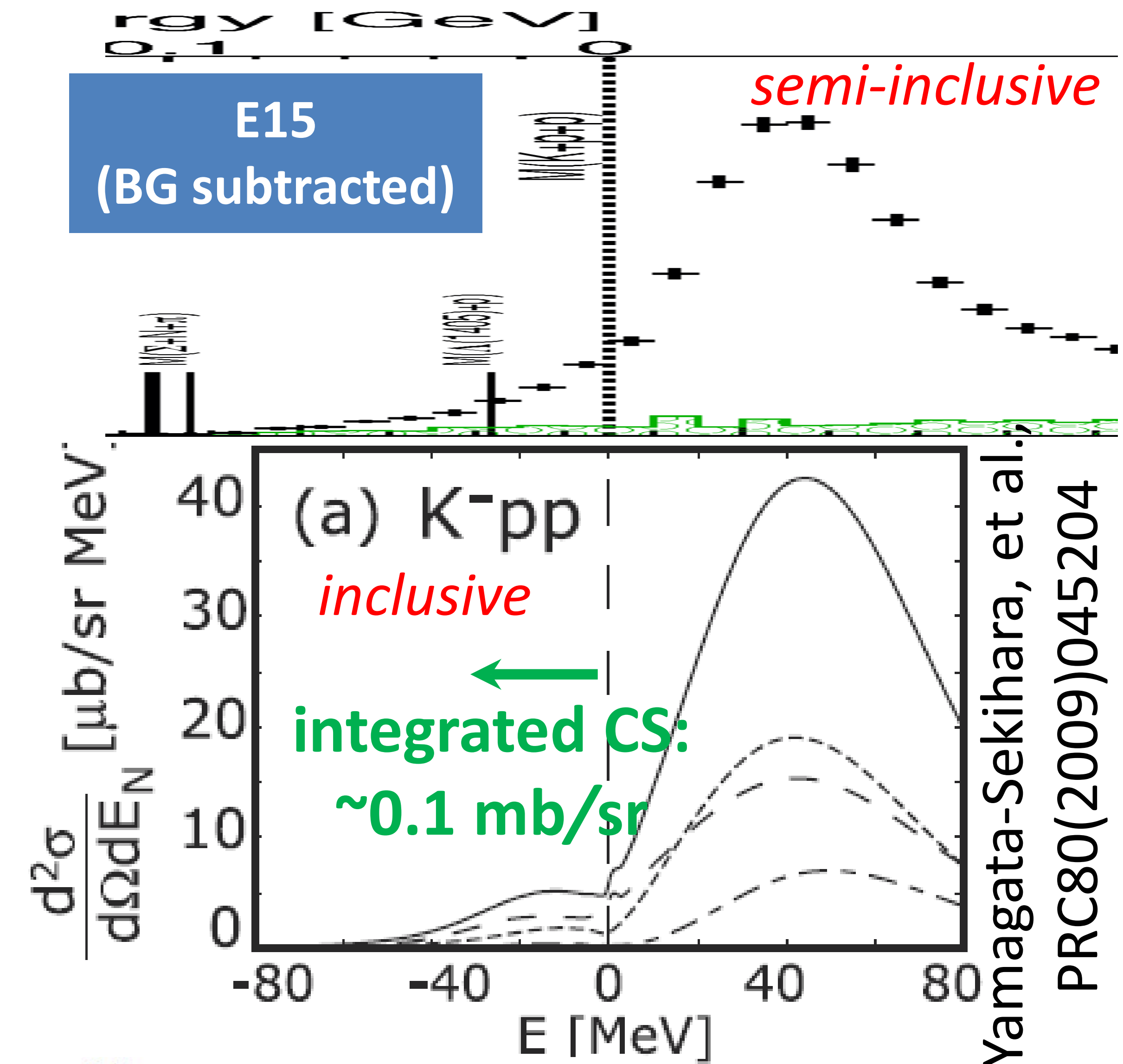
- The excess corresponds to 1~2 mb/sr
  - ~ 10% of quasi-elastic peak
- Assumptions
  - Fully attributed to the K⁻pp state
  - isotropic decay K⁻pp→Λp/Σp/πΣp



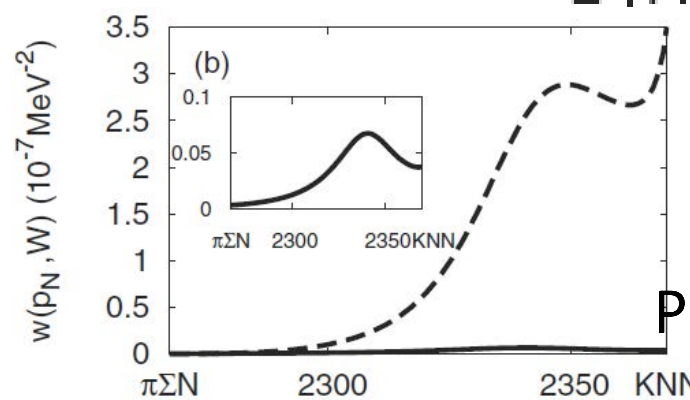
Comparison with theoretical spectral functions



Koite, Harada, PRC80(2009)055208

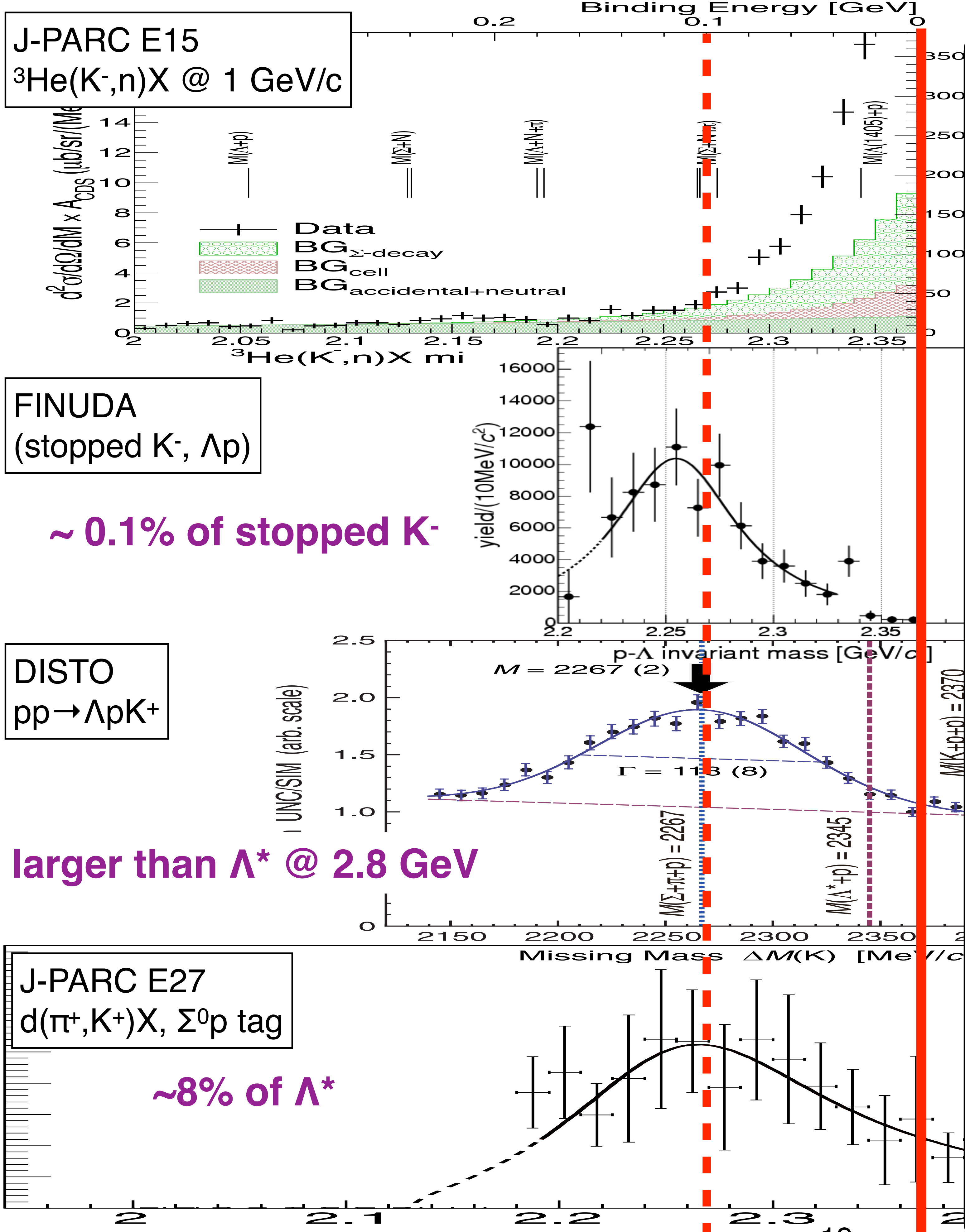


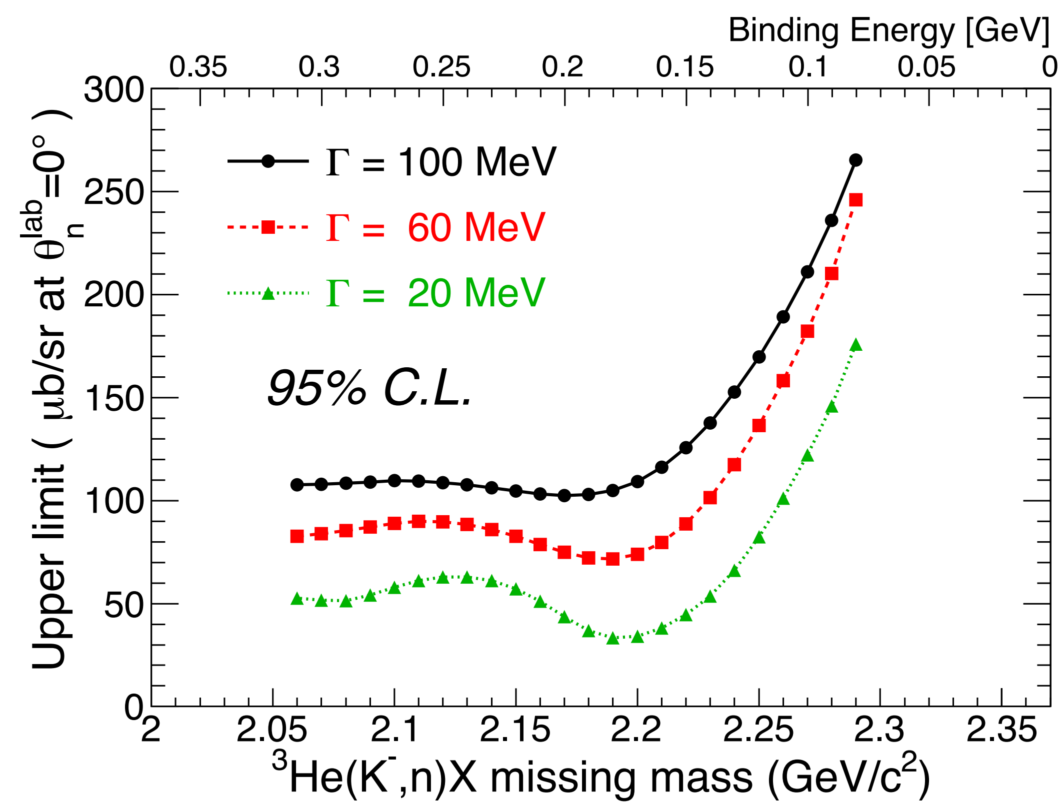
Yamagata-Sekihara, et al., PRC80(2009)045204



S.Ohnishi, et al., PRC88(2013)025204

Experimental spectrum is similar to theoretical predictions with a loosely-bound state.
(Λ(1405) production is not considered)





Assumptions

Intrinsic peak shape: Breit-Wigner

Decay mode: **K$^-$pp→Λp 100%** (isotropic decay)

- **J-PARC E15 (U.L.)**
  30 ~ 300 μb/sr @ 0 deg.
  0.5 - 5% of quasi-elastic
  smaller than usual hypernucleus sticking

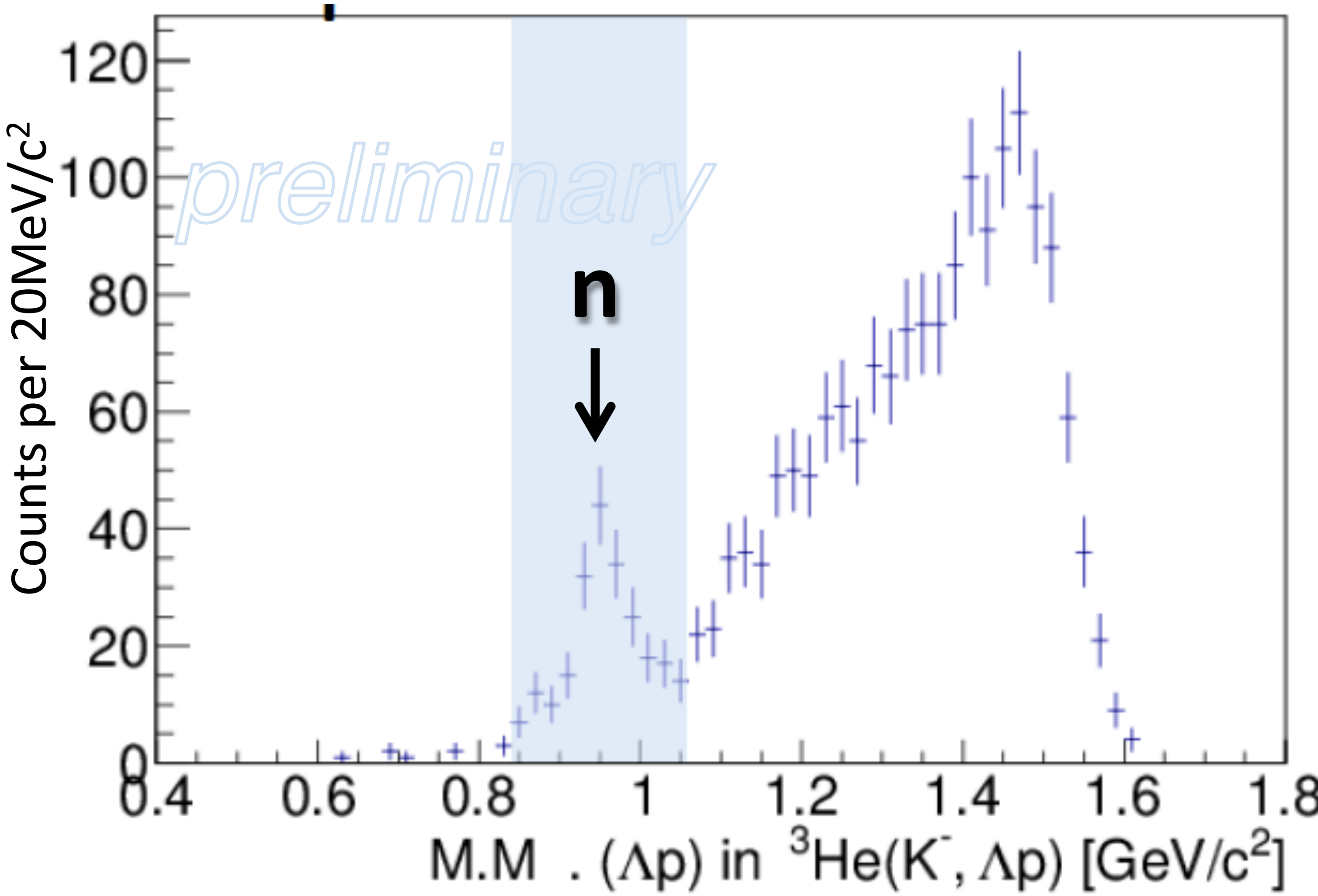
- **LEPS (γ+d) (U.L.)**
  1.5-26% of γN→K$^+$π$^-$Y

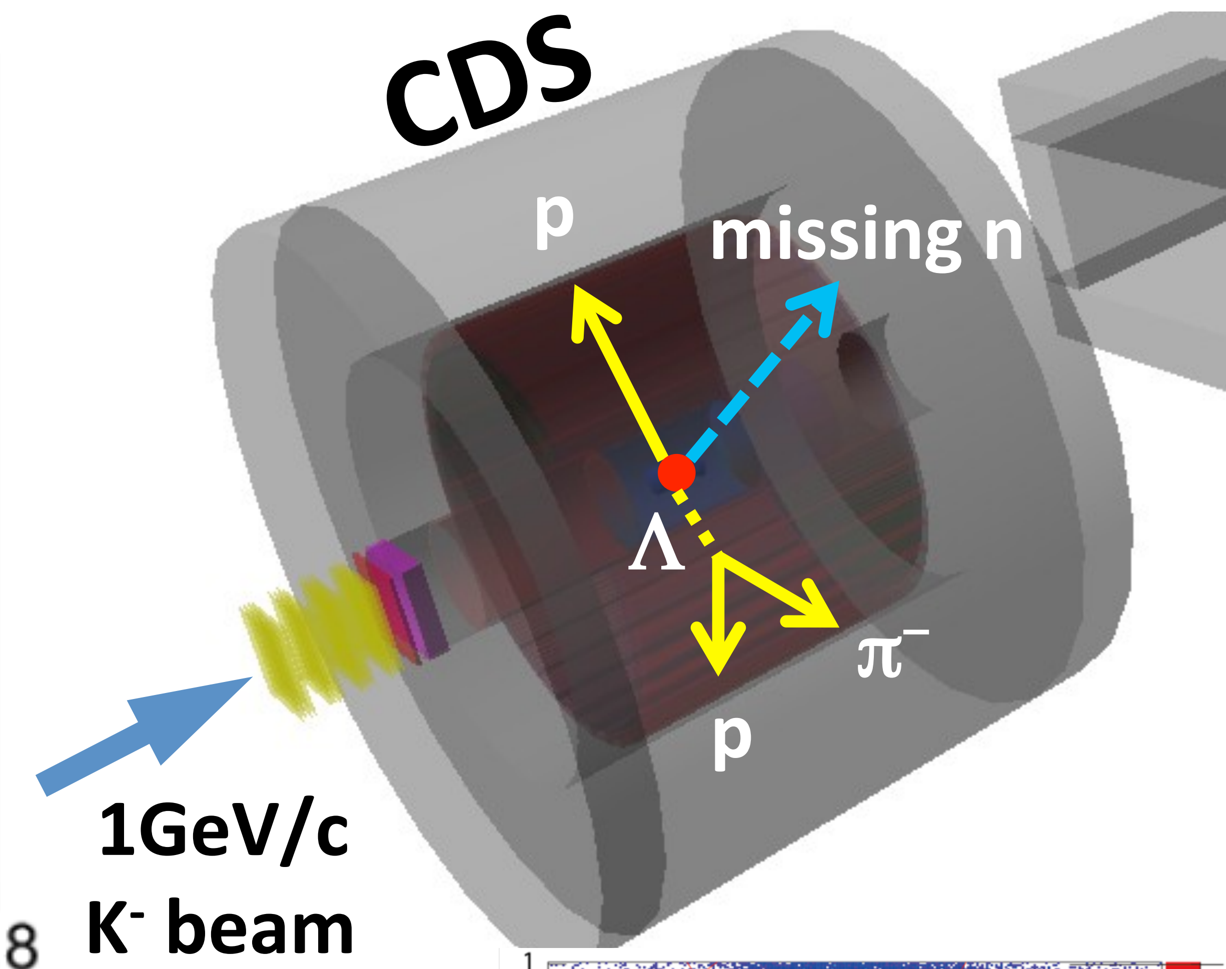
- **HADES (pp @ 3.5 GeV) (U.L.)**
  0.7-4.2 μb (Λ* ~ 10 μb)

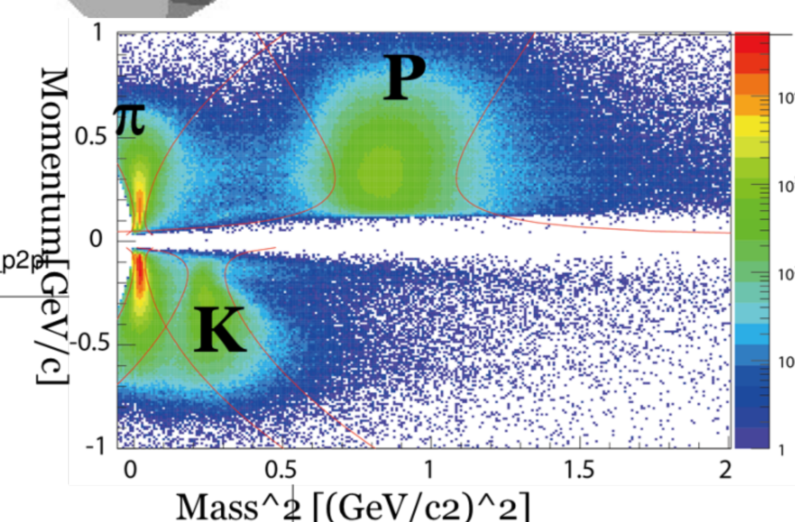
Decay channel
Exclusive ^{3}He(K^{-}, Λp)n

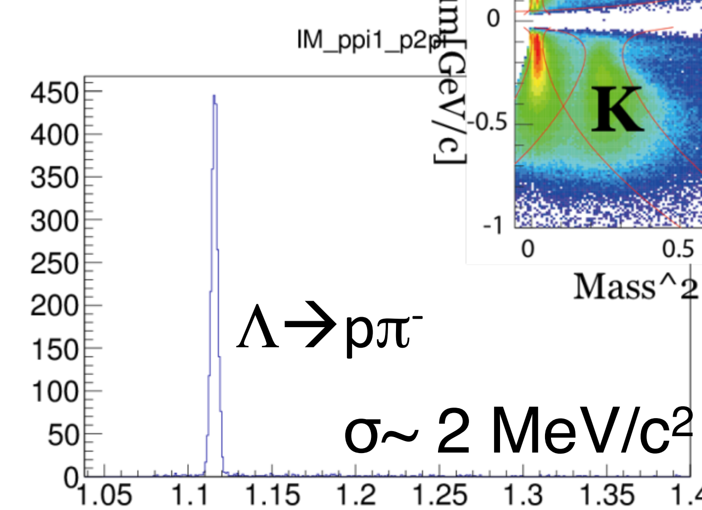
to be submitted soon…

Λpn identification



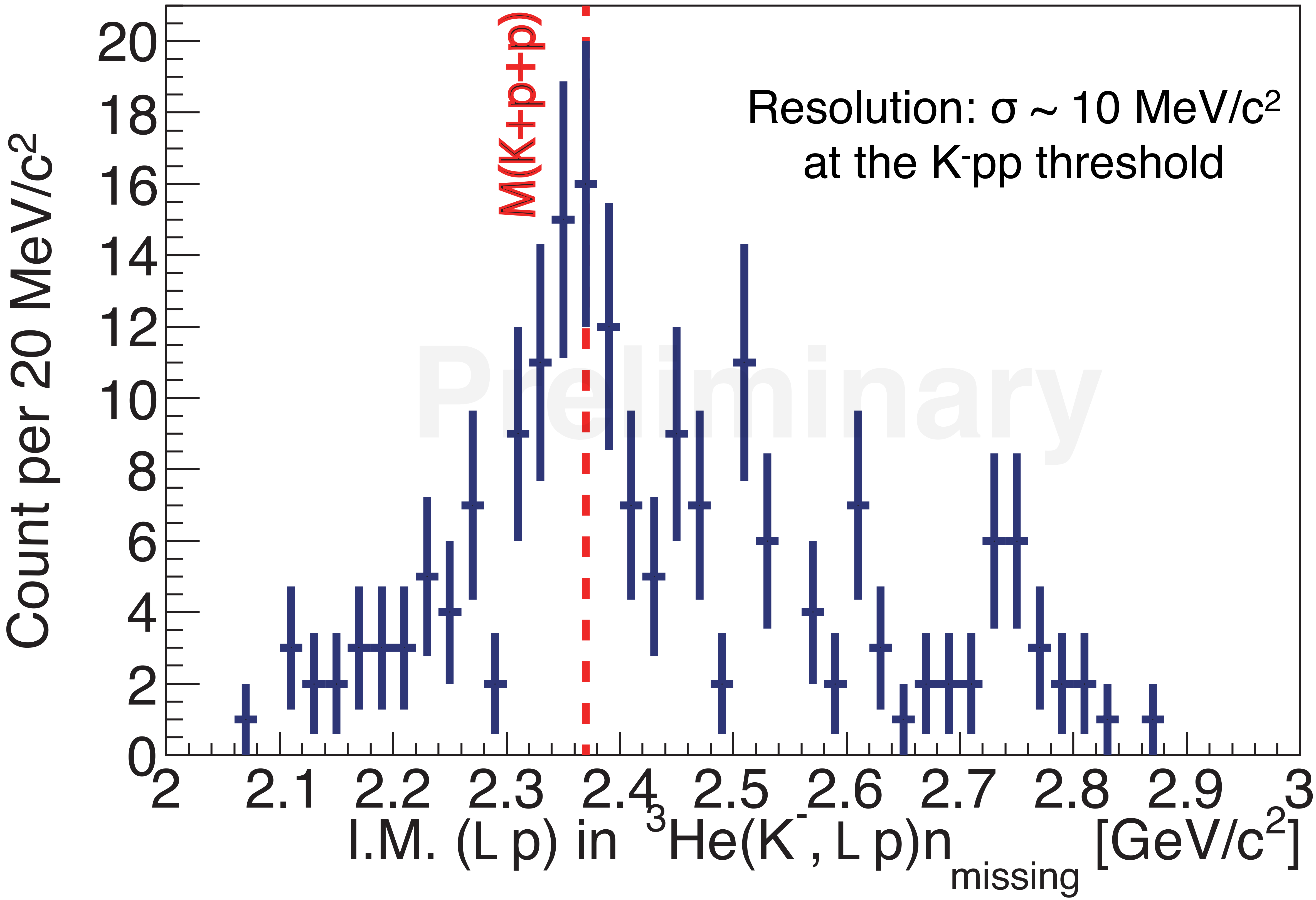




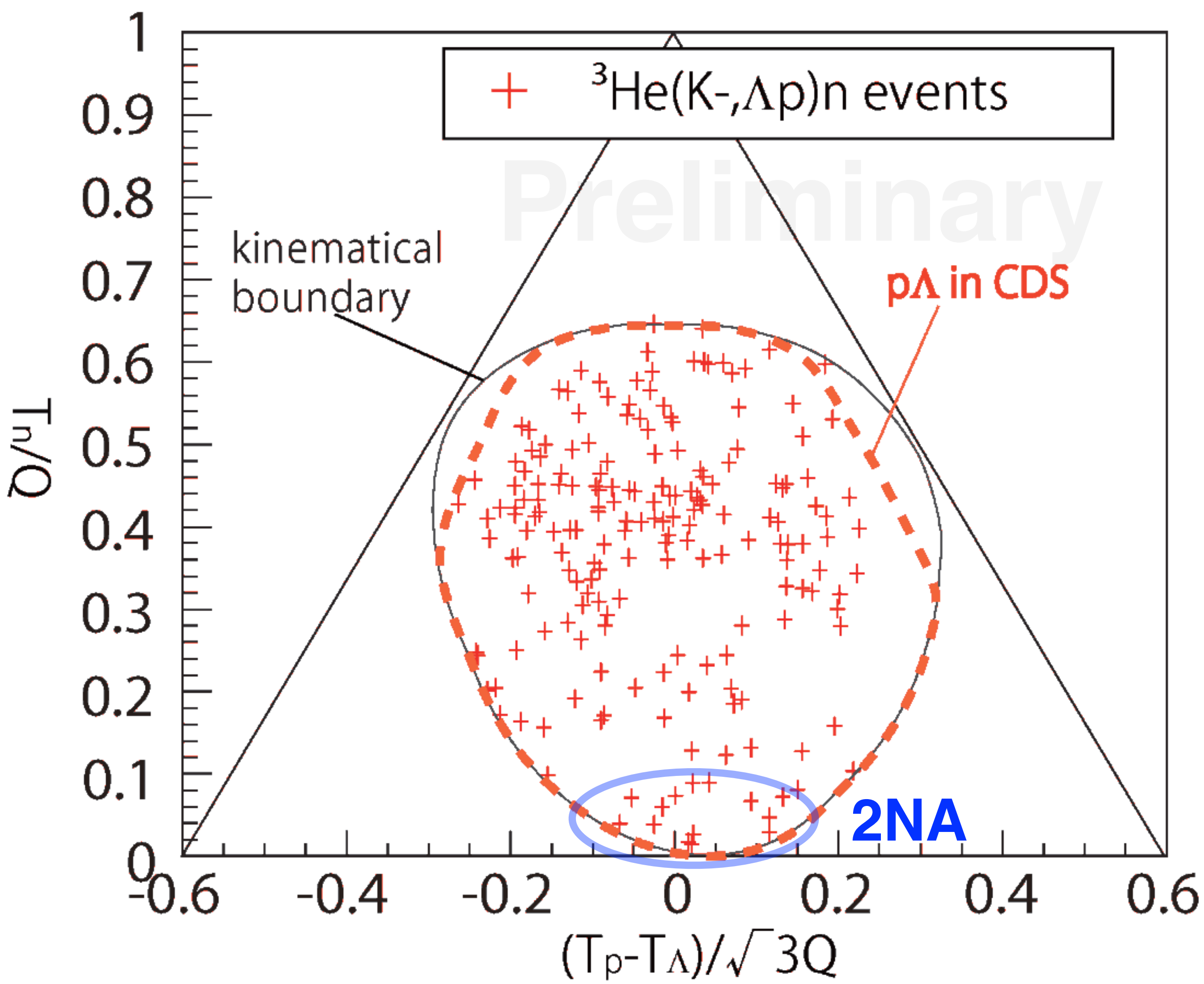


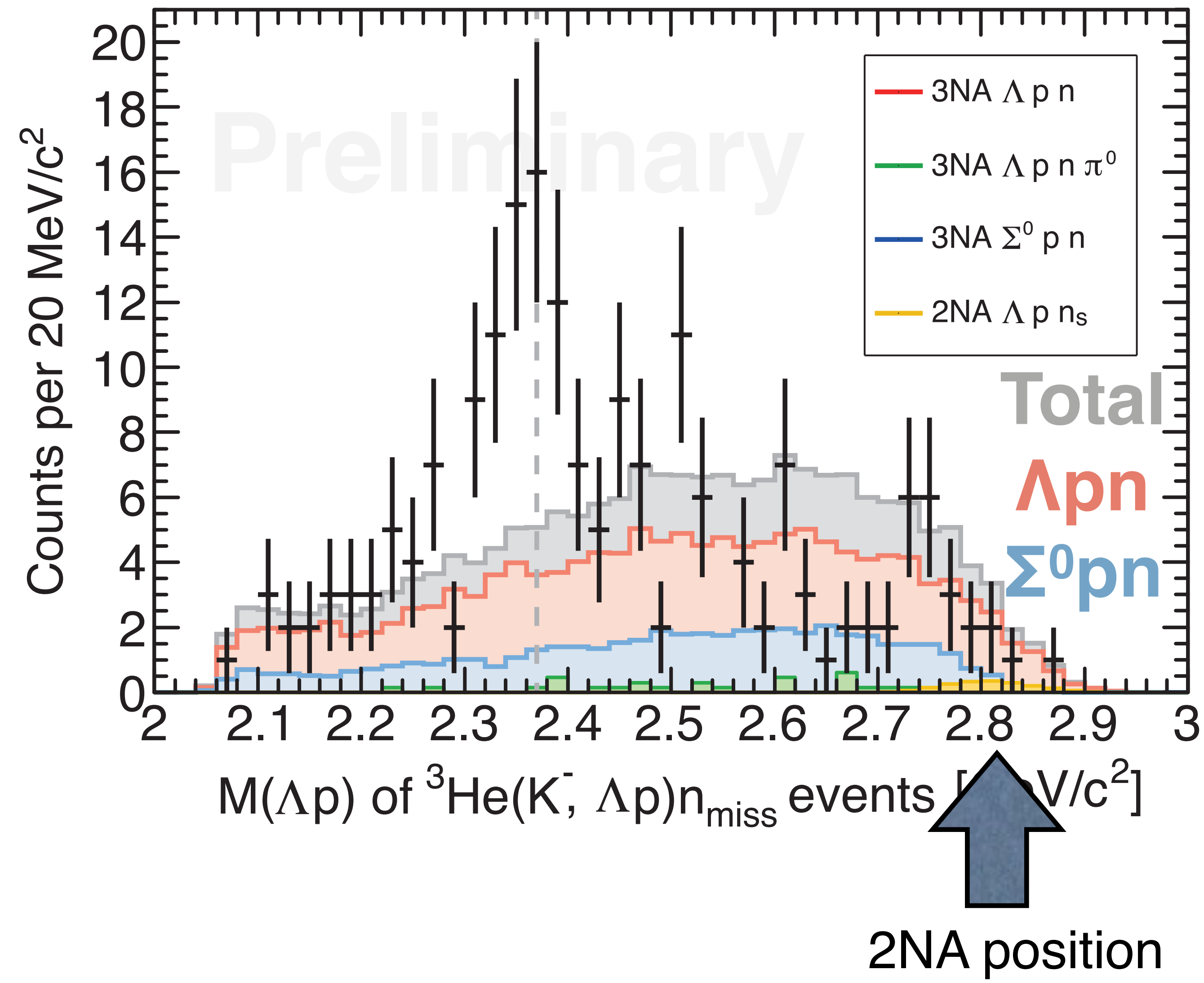
- Λpn final state can be identified exclusively: ~ 200 events
- Σ^0pn contamination ~ 20%

Λpn exclusive spectrum



Comparison with Phase space

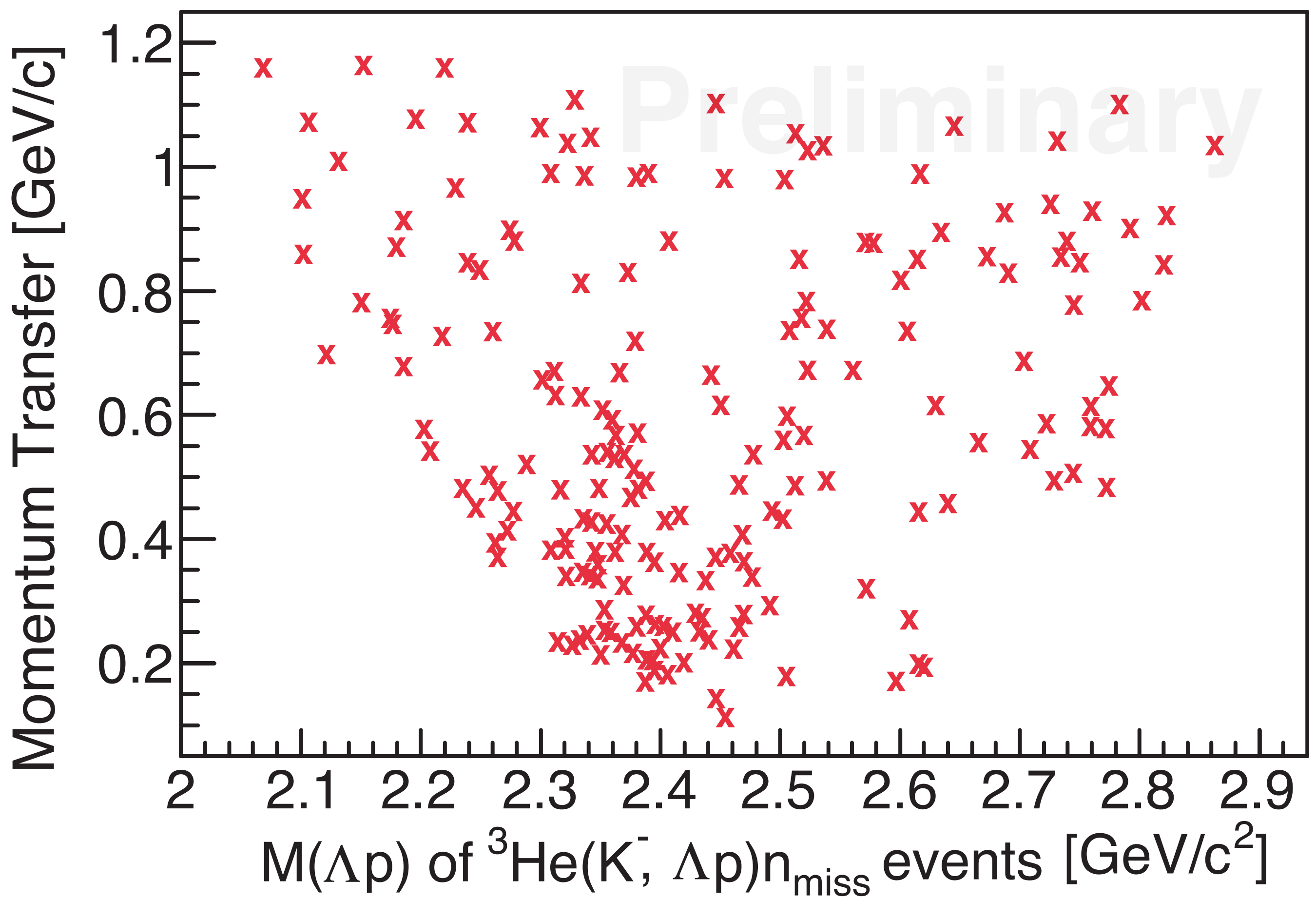




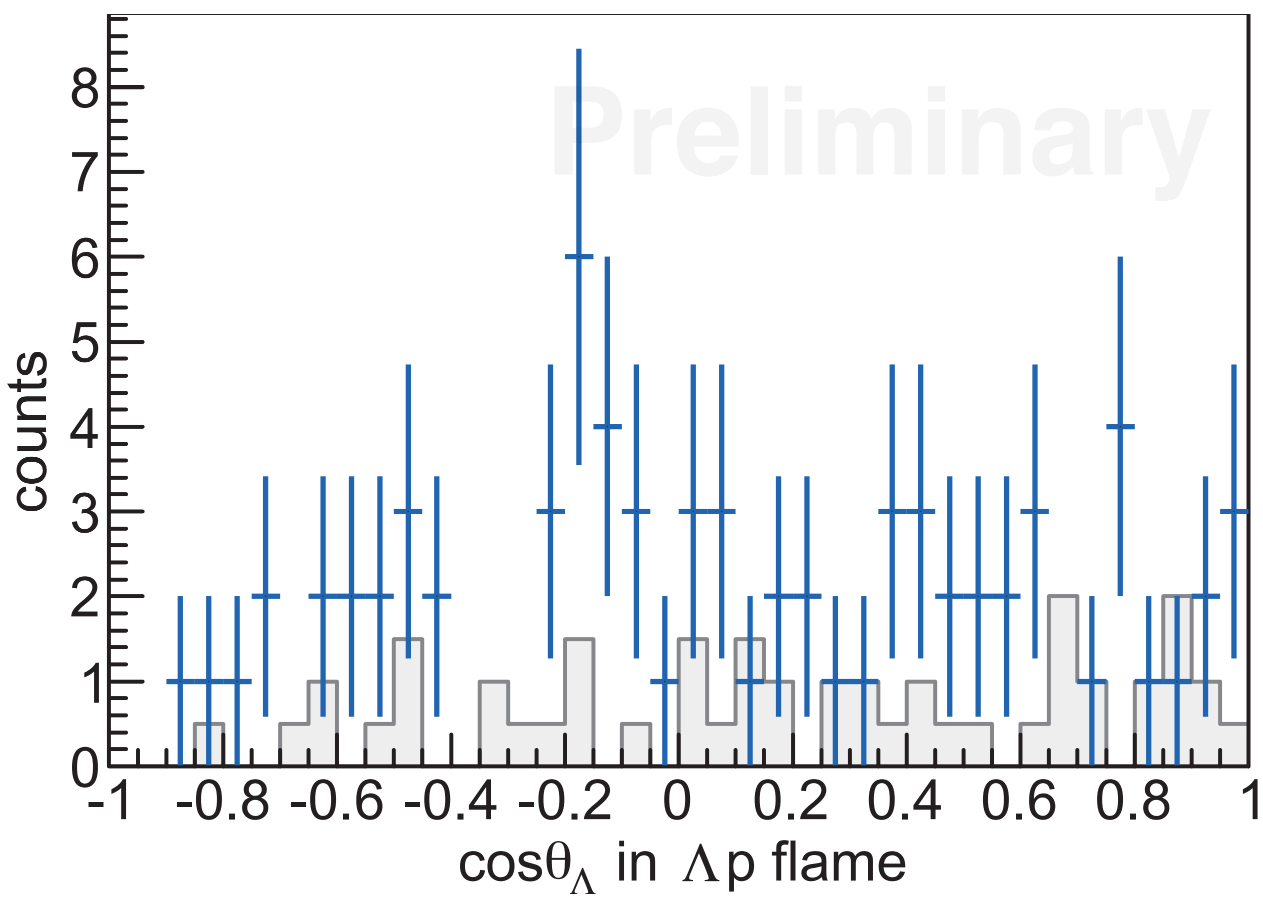
- 2NA reaction $K^- + {}^3He \rightarrow \Lambda + p + n_s$ seem to be very weak
- 3NA reaction $K^- + {}^3He \rightarrow \Lambda + p + n$ seem to exist
- Enhancement around the K^-pp threshold

Kinematics of the structure

Mom. Trans vs. IM(Λp)



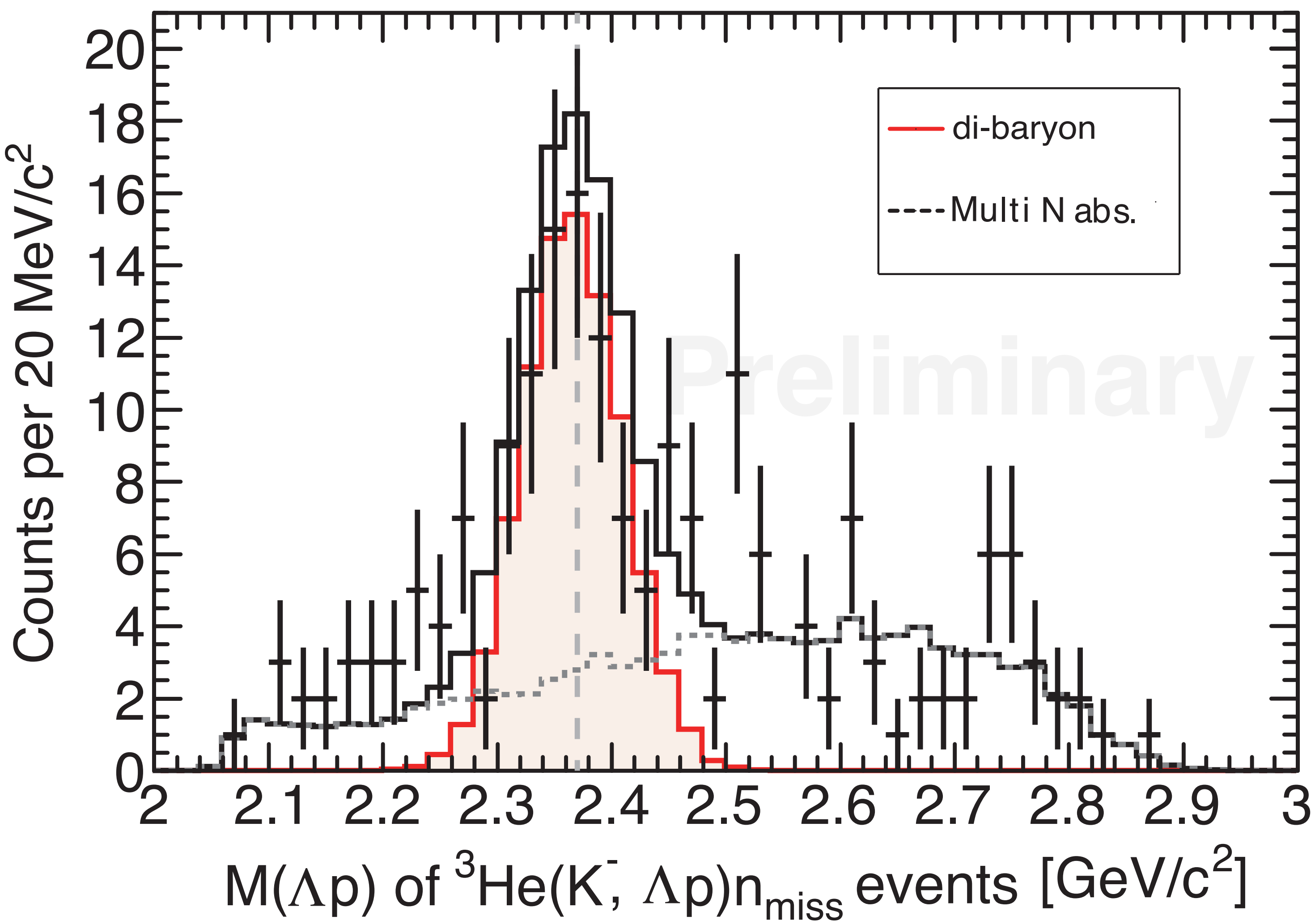
Λp decay-angle in CM

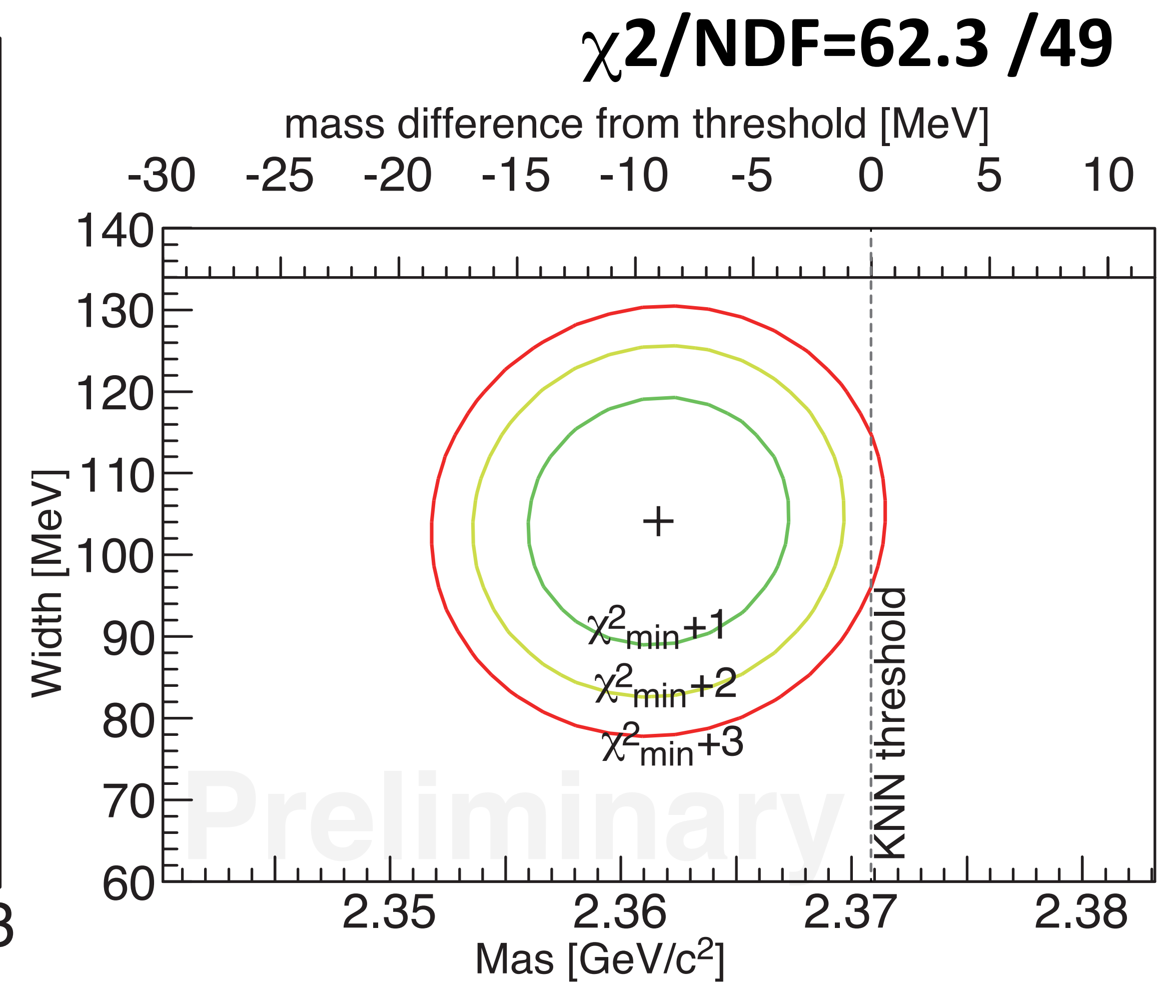


$\cos\theta_\Lambda = 1$ relative to the Λp frame

- low-momentum transfer(=forward neutron) is enhanced
- isotropic decay?

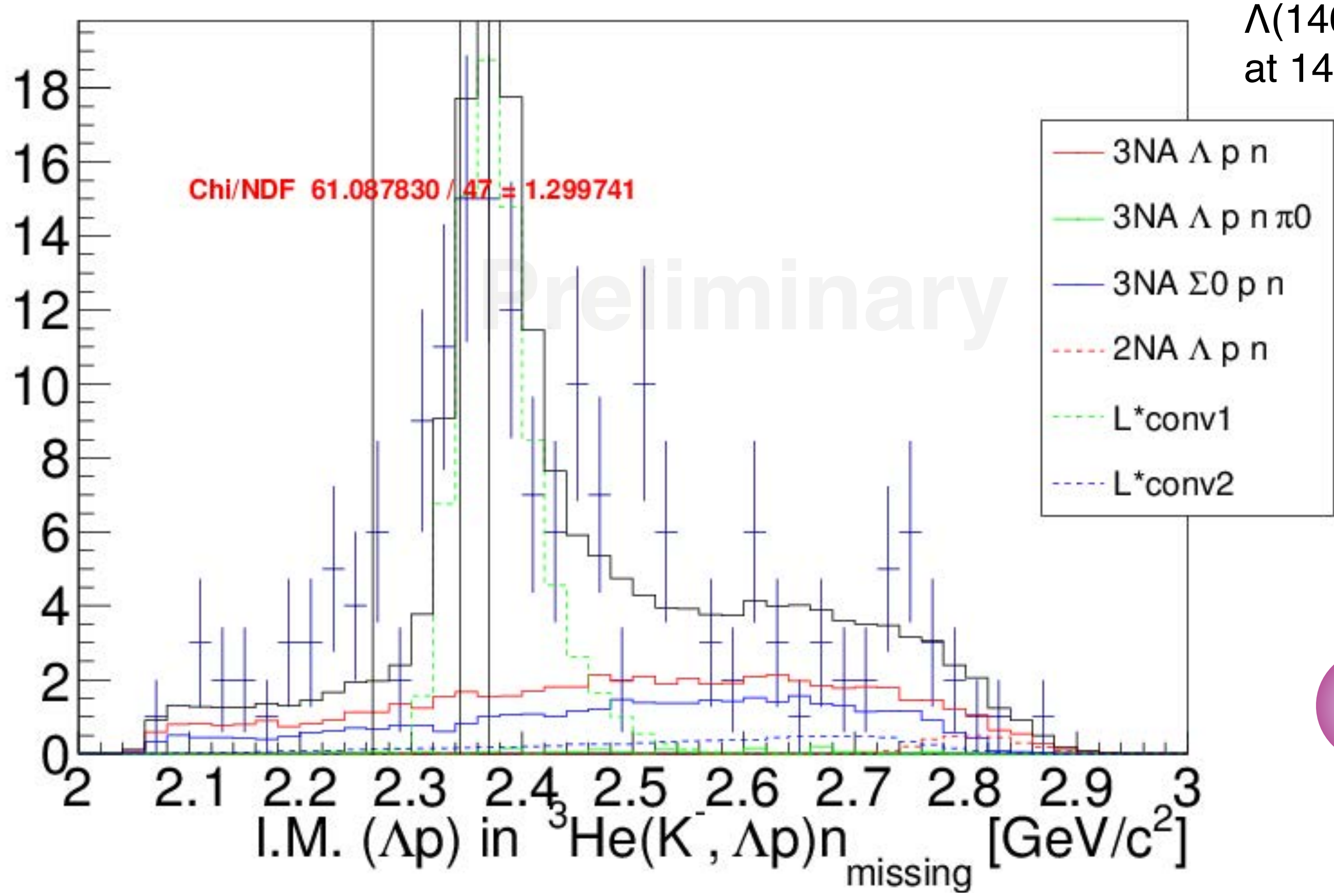
Assuming Breit-Wigner



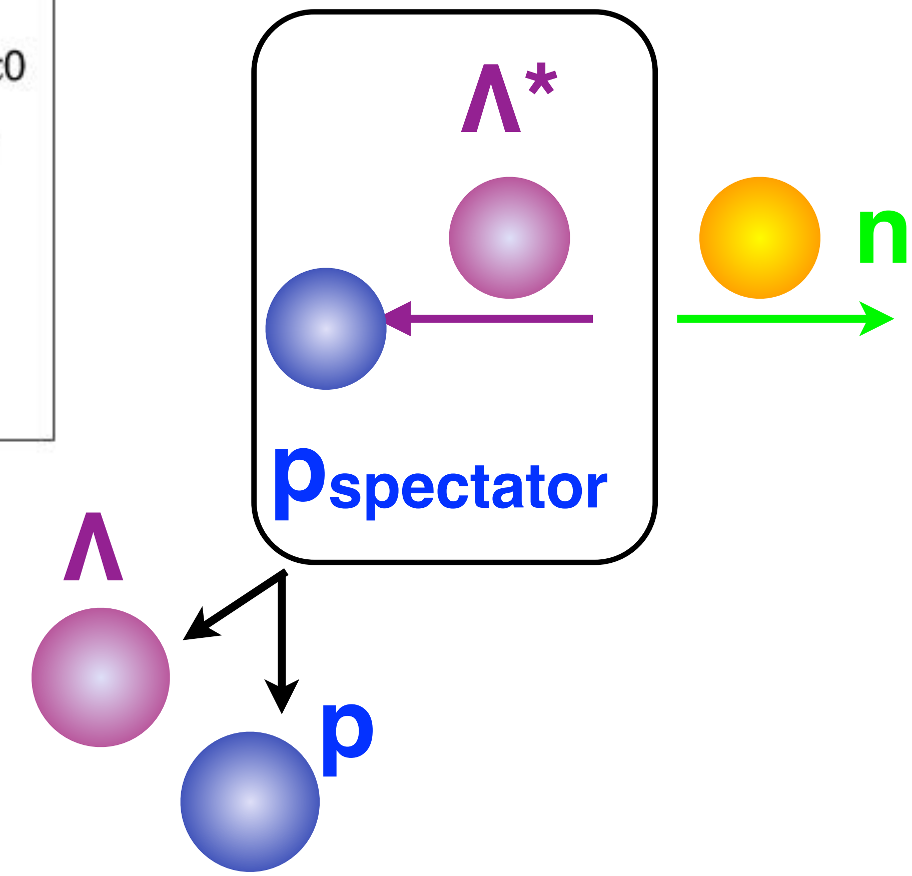


- **~ 15 μb, a few μb/sr at θ_n=0**
  - not contradict with the forward neutron analysis
    - < 1~2 mb/sr excess in semi-inclusive neutron spectrum
    - theories suggest K-pp→Λp << K-pp→πΣp

Λ(1405)p_s→Λp conversion



Λ(1405): Breit-Wigner
at 1405 MeV/c^2, Γ=50 MeV (PDG)



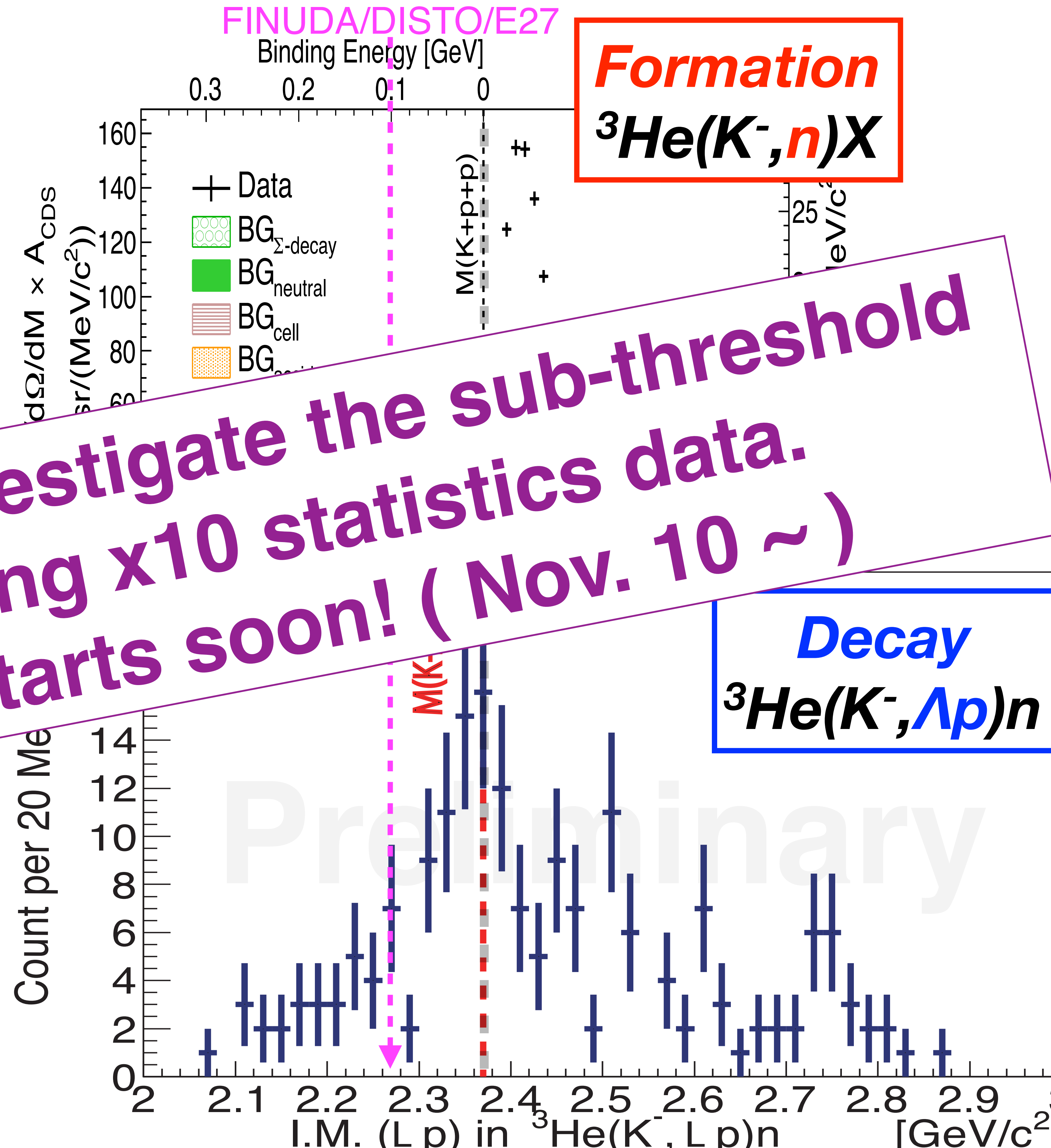
- **Difficult to distinguish from the "K-pp" experimentally.**
- **Should be compared with quasi-free Λ*N**
  - < 5 mb/sr from forward neutron analysis
  - ~ 0.5 mb/sr from theoretical calc. on K-d.
  - a few percent conversion probability?

further studies are ongoing…

Summary of E15 1st

- **Around the threshold**
  - Some excess of the events both in formation- and decay-channel
  - Hint of S=-1 di-baryon state?
  - ex...
  - ...DISTO/E27, has **NOT** been observed with the current statistics.
  - cross section strongly depend on the reaction?

We will further investigate the sub-threshold structure using x10 statistics data. Data taking starts soon! (Nov. 10 ~)



E17→E62: Kaonic helium atom X rays

1. Introduction
2. Detector: **T**ransition-**E**dge-**S**ensor microcalorimeters
3. Feasibility test at PSI
4. Simulation study for the J-PARC experiment

HEATES collaboration (J-PARC E62)

- High-resolution Exotic Atom x-ray spectroscopy with TES microcalorimeter -

M. Bazzi[a], D.A. Bennett[b], C. Berucci[c], D. Bosnar[d], C. Curceanu[a], W.B. Doriese[b], J.W. Fowler[b], H. Fujioka[e], C. Guaraldo[a], F. Parnefjord Gustafsson[f], T. Hashimoto[g], R.S. Hayano[h*], J.P. Hays-Wehle[b], G.C. Hilton[b], T. Hiraiwa[i], M. Iio[j], M. Iliescu[a], S. Ishimoto[j], K. Itahashi[g], M. Iwasaki[g,l], Y. Ma[g], H. Noumi[i], G.C. O'Neil[b], H. Ohnishi[g], S. Okada[g†], H. Outa[g‡], K. Piscicchia[a], C.D. Reintsema[b], Y. Sada[i], F. Sakuma[g], M. Sato[g], D.R. Schmidt[b], A. Scordo[a], M. Sekimoto[j], H. Shi[a], D. Sirghi[a], F. Sirghi[a], K. Suzuki[c], D.S. Swetz[b], K. Tanida[k], H. Tatsuno[b,i], M. Tokuda[l], J. Uhlig[f], J.N. Ullom[b,m], S. Yamada[n], T. Yamazaki[h], and J. Zmeskal[c]

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1. Introduction

Kaonic atom X-rays

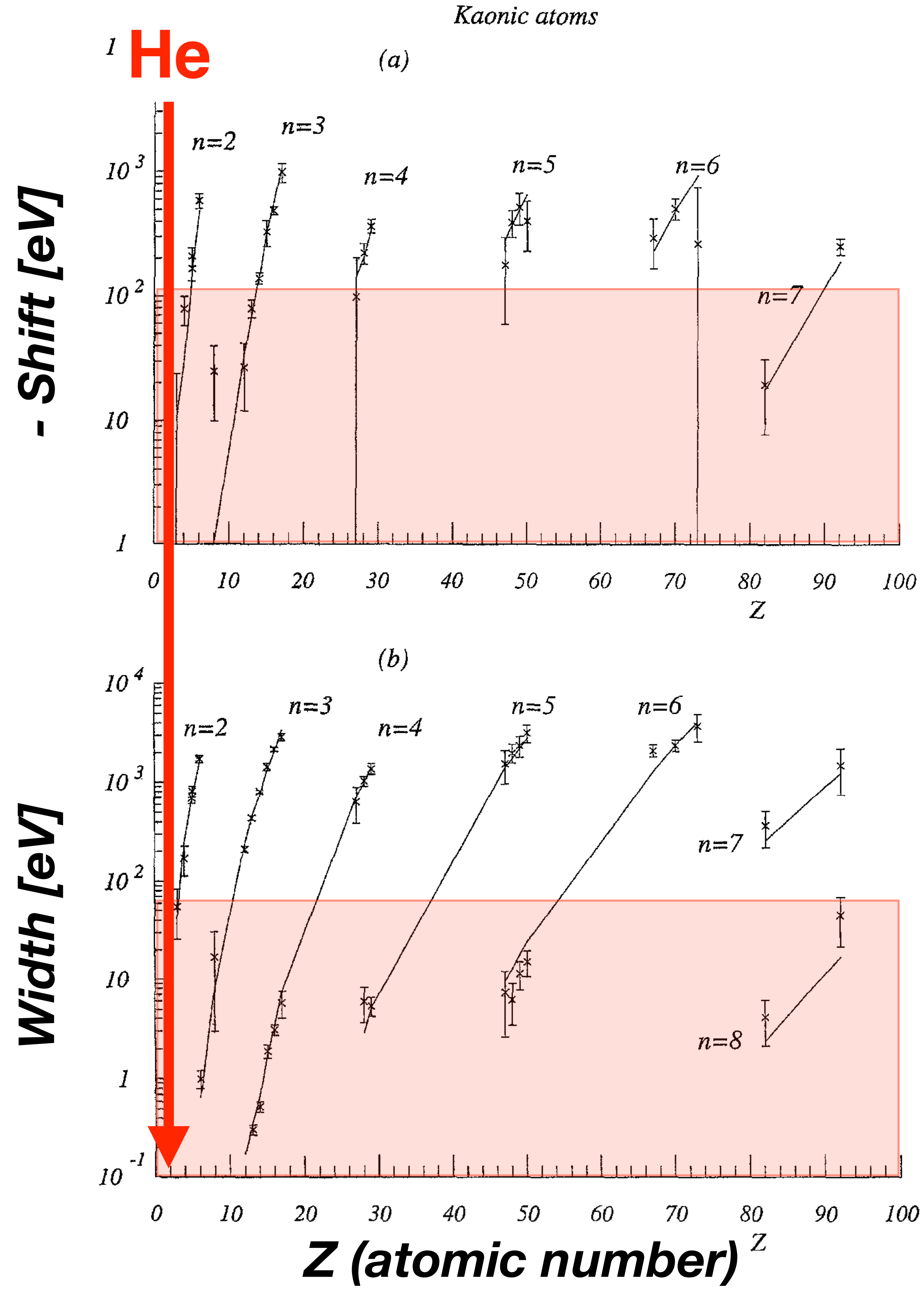
kaonic helium case

Nuclear absorption

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

Kbar-nucleus interaction from Kaonic atom data

C. J. Batty, E. Friedman, and A. Gal, Phys. Rep., 287 (1997) 385.



with improved energy resolution…

1. **Precision measurements for energy levels with small shift and narrow width**

2. Direct measurements of 'upper' level widths
   - Determined by x-ray yield ratio so far
   - One-nucleon absorption could be separated from multi nucleon processes

E.Friedman, A.Gal, NPA899(2013)60

3. Charged kaon mass
   - Higher levels where strong-interaction effect is negligible

4. Other hadronic atoms (Σ^-,Ξ^-)

K-He atom 2p level shift

a recent theoretical calculation

J. Yamagata-Sekihara, S. Hirenzaki :
— Strong-intaction Shift & Width calc.
E. Hiyama : (Gauss expansion method)
— Charge-density dist calc. for ^{4}He&^{3}He

Choosing the following two typical models : *[Pheno.] Mares, Friedman, Gal, NPA770(06)84* *[Chiral] Ramos, Oset, NPA671(00)481*	**deep** **Phenomenological** $V_{opt}(r=0) \sim -(180 + 73i)$ MeV	**shallow** **Chiral** $V_{opt}(r=0) \sim -(40 + 55i)$ MeV
K-^{4}He	-0.41 eV	-0.09 eV
K-^{3}He	0.23 eV	-0.10 eV
Isotope shift (K-^{4}He - K-^{3}He)	**-0.64 eV** ⟷	**0.01 eV**

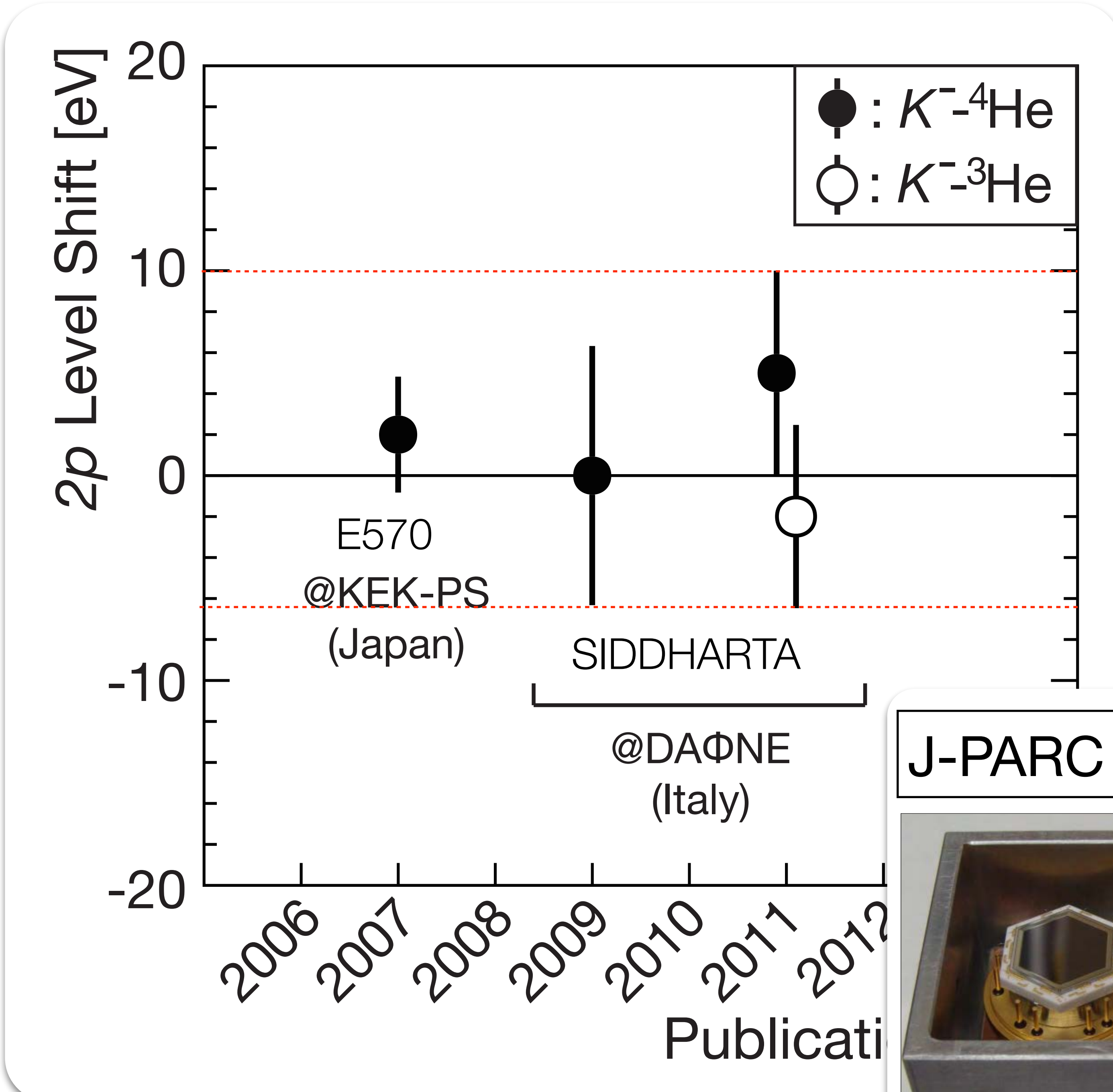
preliminary

Dominant systematic error (~0.15 eV)
due to kaon-mass uncertainty will be cancelled.

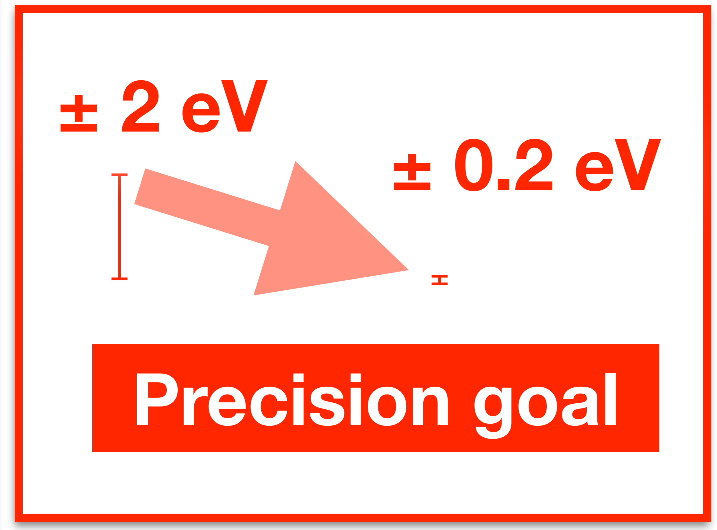
Width : 2 ~ 4 eV

Present status

3d → 2p transition ~ 6 keV x-rays

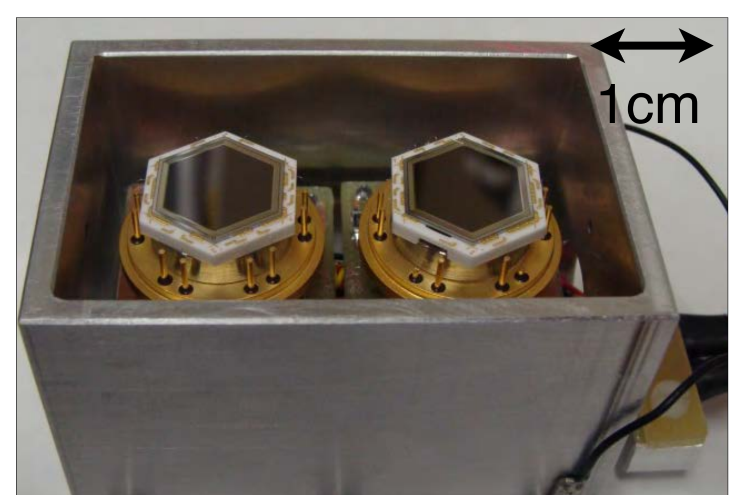


Theoretical calculations predict
$|\Delta E_{2p}| < 1$ eV, $\Gamma \sim 2$ eV

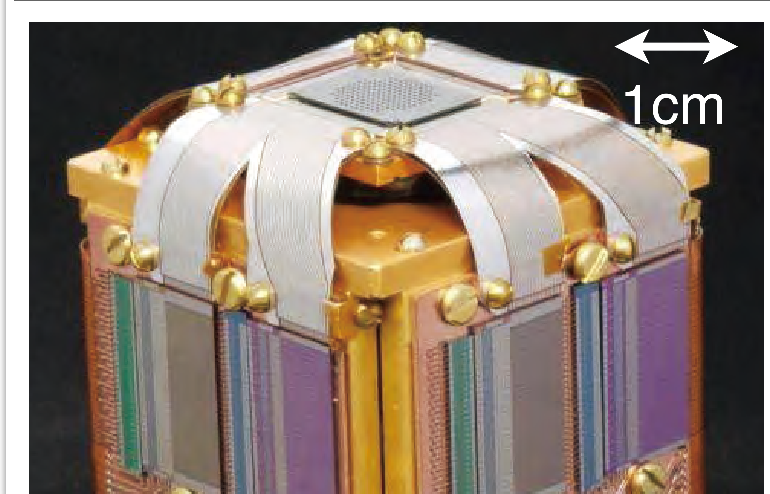


Width: sensitive to
$\Gamma >$ ~2 eV

J-PARC E17 with SDD

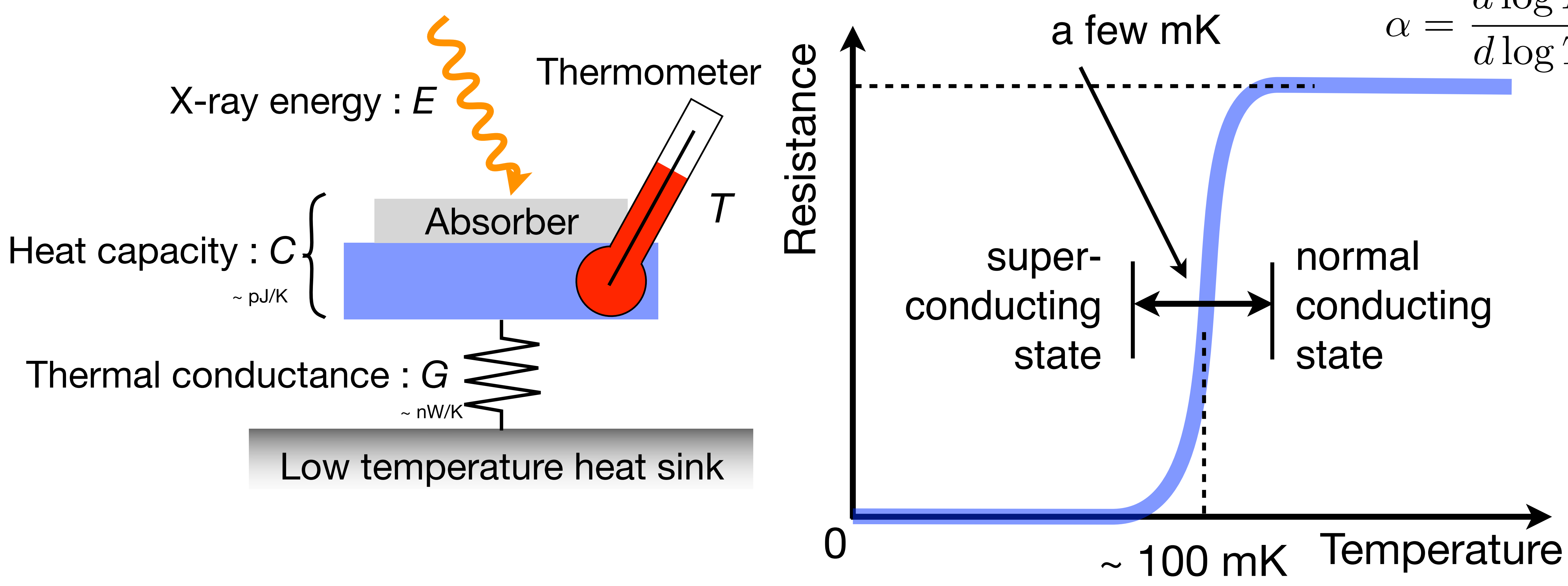


J-PARC E62 with TES



2. Detector

Transition-Edge-Sensor microcalorimeters



$$\alpha = \frac{d \log R}{d \log T}$$

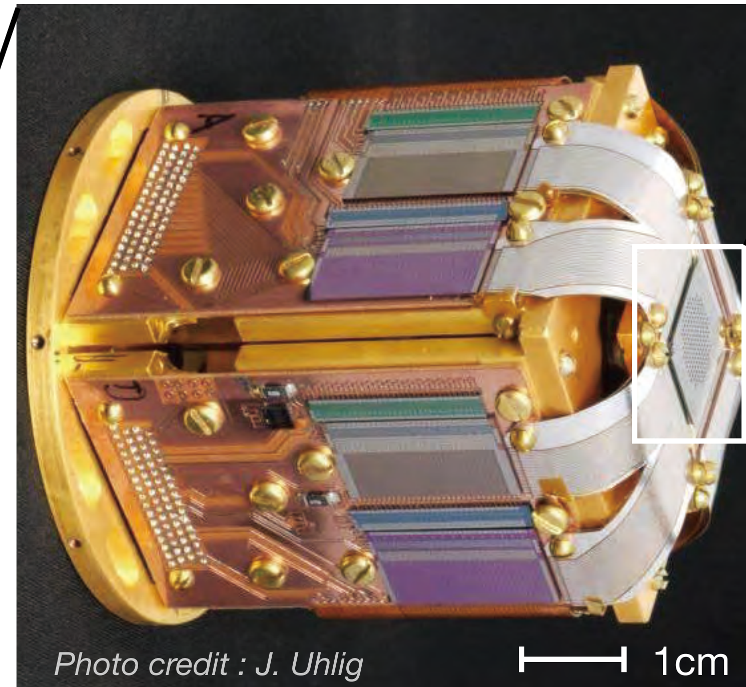
- ✓ Excellent energy resolution ~2 eV FWHM@ 6 keV
- ✓ Wide dynamic range
- ✓ Large effective area with multiplexing technique
- ✓ Portable & compact system

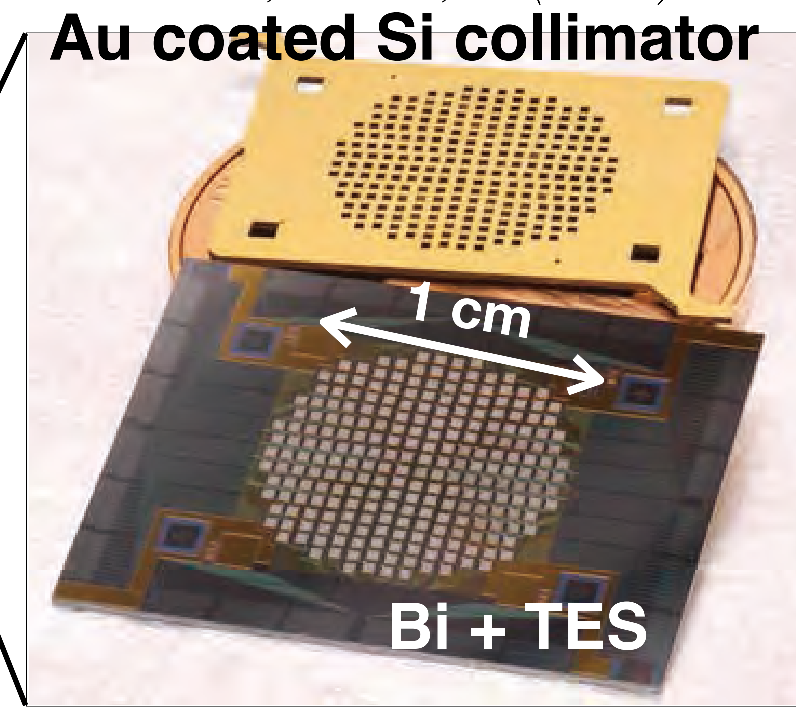
$$\Delta E = 2.355 \sqrt{\frac{k_B T^2 C}{\alpha}}$$

$$E_{max} \propto \frac{C}{\alpha}$$

NIST TES system

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





- **NIST designed cryostat**
  - Pulse tube (60K, 3K) + ADR (1K, 50mK)
  - ADR hold time: > 1 day
  - Manufactured by High Precision Devices, Inc.

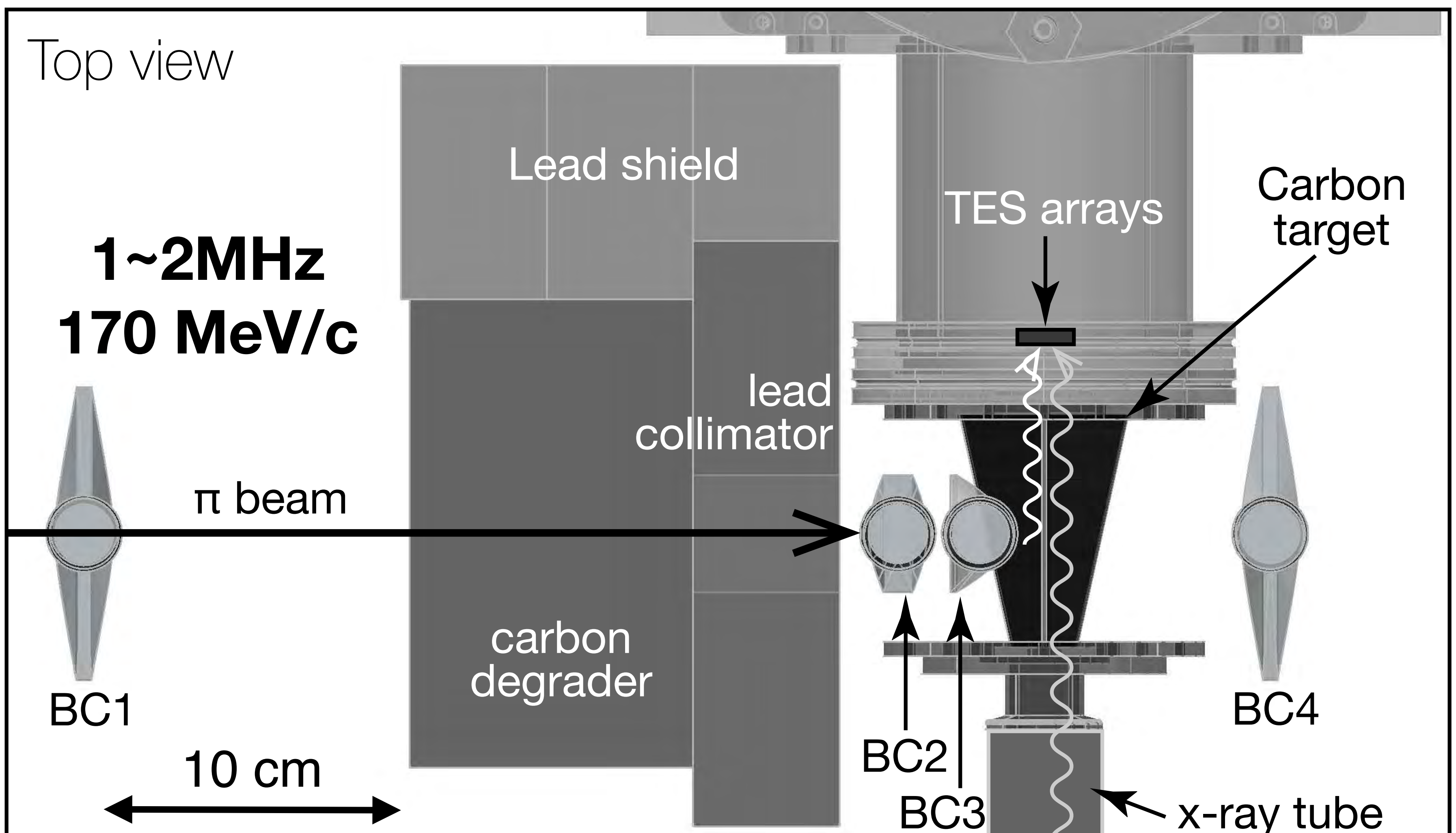
- **Detector snout**
  - 240 pixel Mo-Cu bilayer TES
    30 ch TDM(time division multiplexing) readout
  - 1 pixel : 300 x 320 um^2 → total ~ 23 mm^2
  - 4 um Bi absorber → efficiency ~0.85@6 keV

3. Feasibility study at PSI

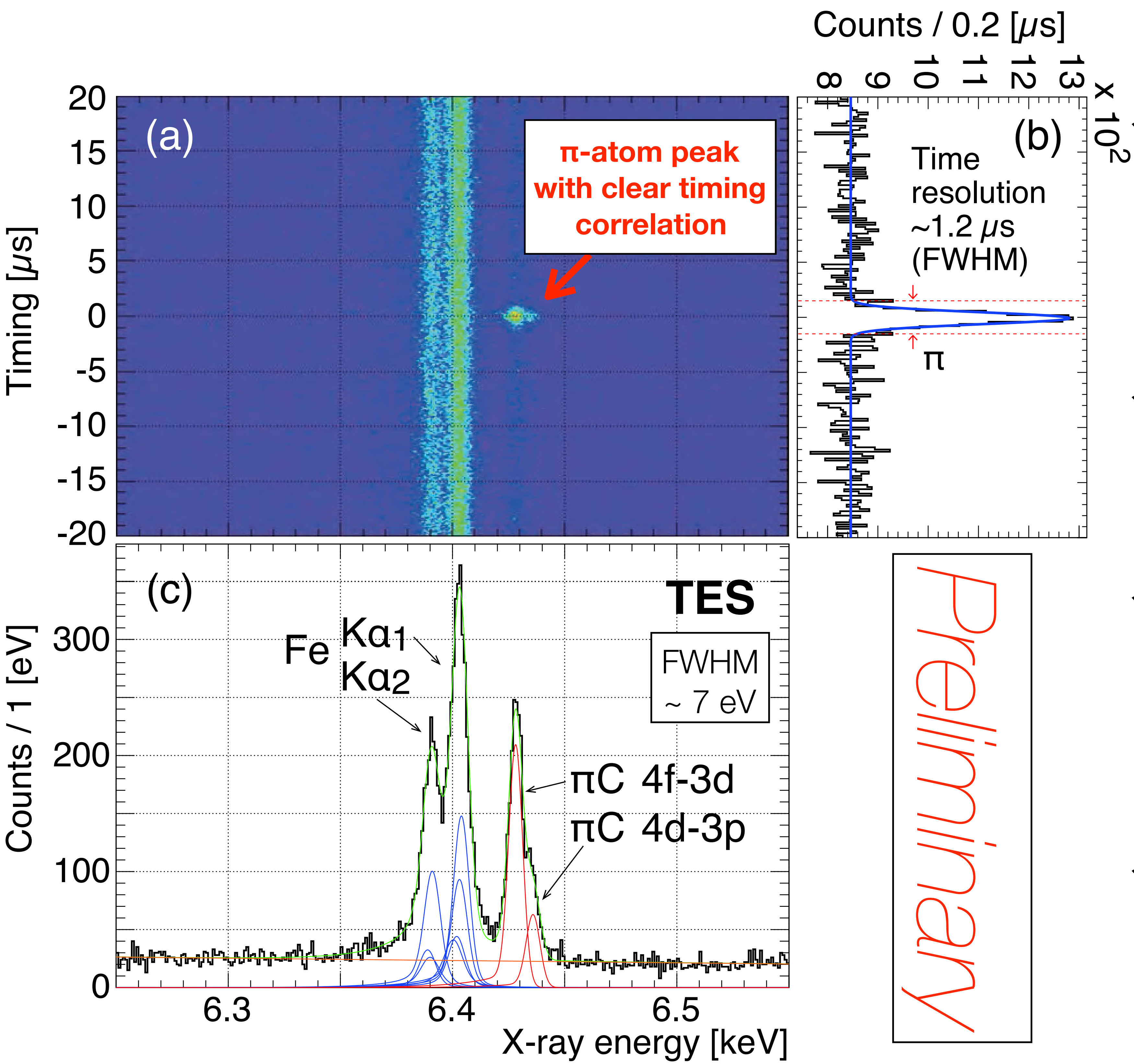
Feasibility test : πC x-ray measurement

- Aim : studying in-beam performance of TES
- Site : Paul Scherrer Institute (PSI) at PiM1 beamline
- Measured x-rays: πC 4f→3d transition ~ 6.4 keV

(strong-interaction effect is small)



πC 4-3 X rays



✓ Excellent energy resolution even in the hadron beam

5 eV (beam off)→7 eV (beam on) [FWHM@ 6.4 keV]

✓ Good timing resolution comparable with SDDs

✓ Accurate energy calibration using Cr&Co lines

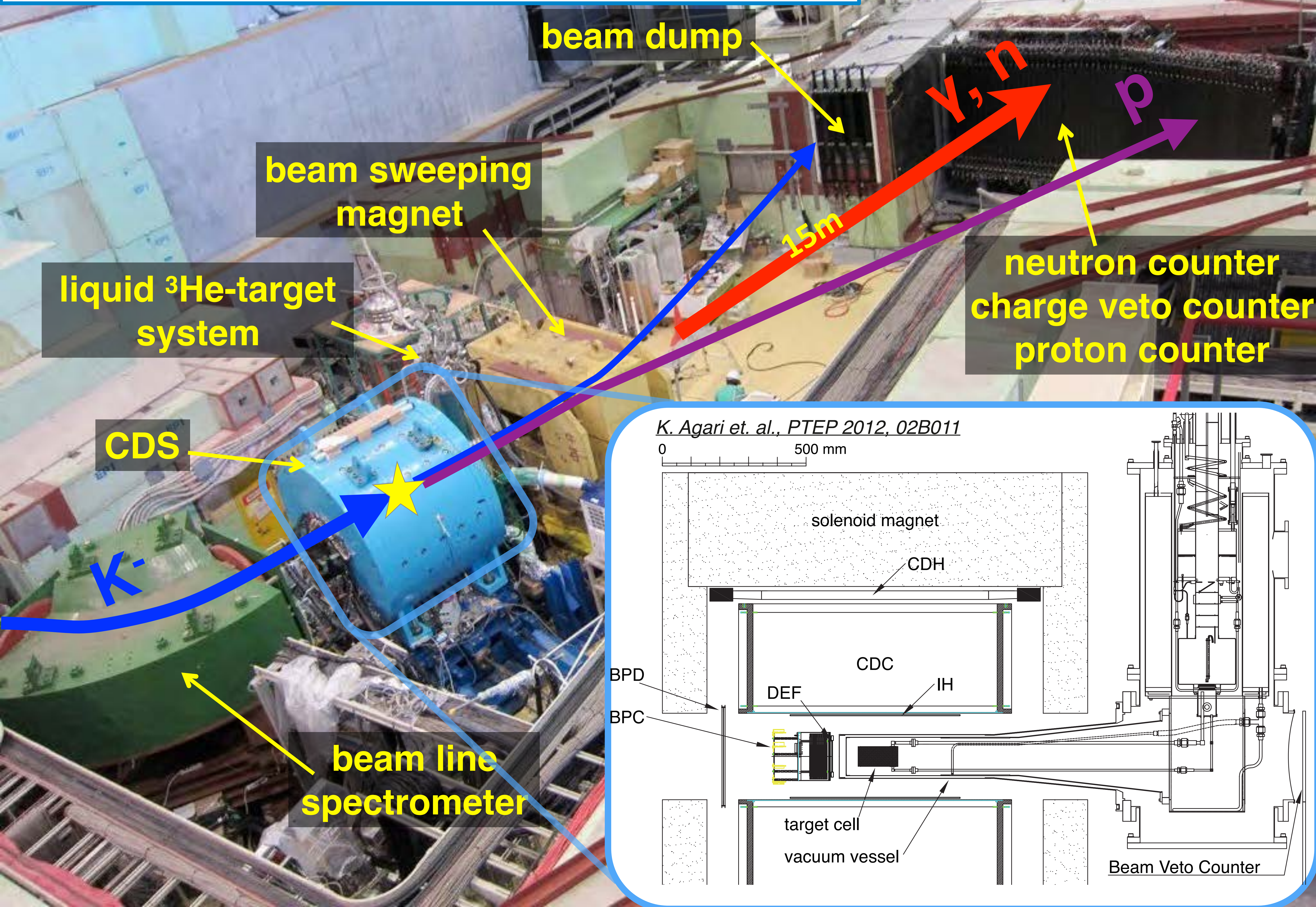
< 0.1 eV accuracy @ FeKα

✓ piC x-ray energies agree with EM calc.

Experimental uncertainty ±0.13(stat.)±0.09(syst.) eV

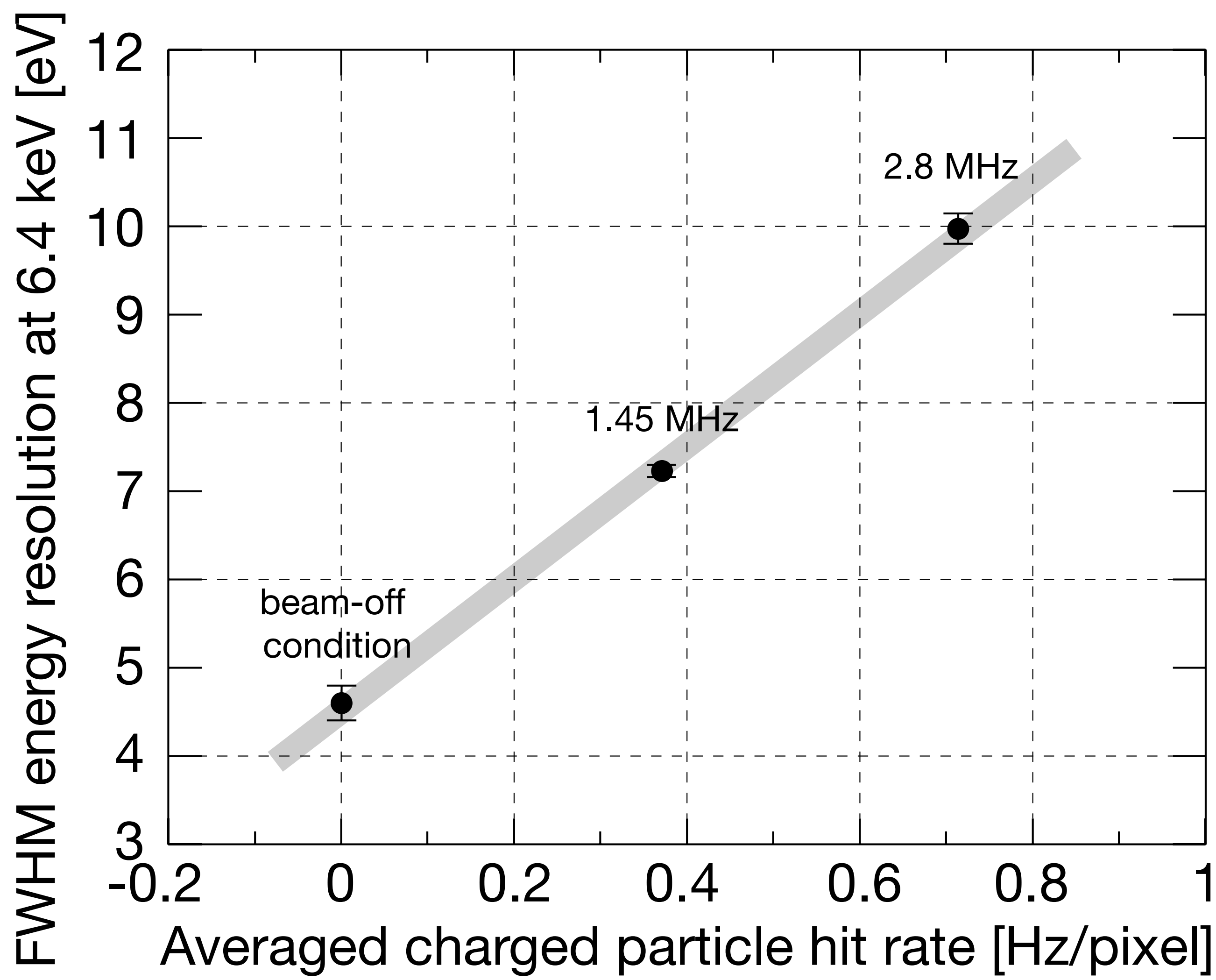
4. J-PARC experiment

J-PARC K1.8BR spectrometer



Experimental setup at J-PARC K1.8BR

Can we operate TES in the kaon beam at J-PARC?



Energy deterioration observed at higher beam intensities

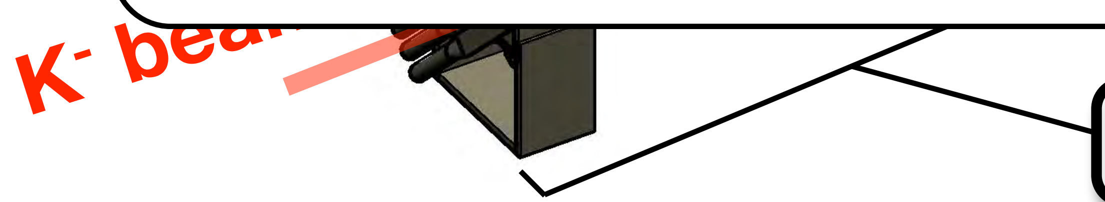
↓

Due to thermal crosstalks induced by charged particle hits
(details in H. Tatsuno's talk)

↓

Simulation study
with realistic kaon beam condition

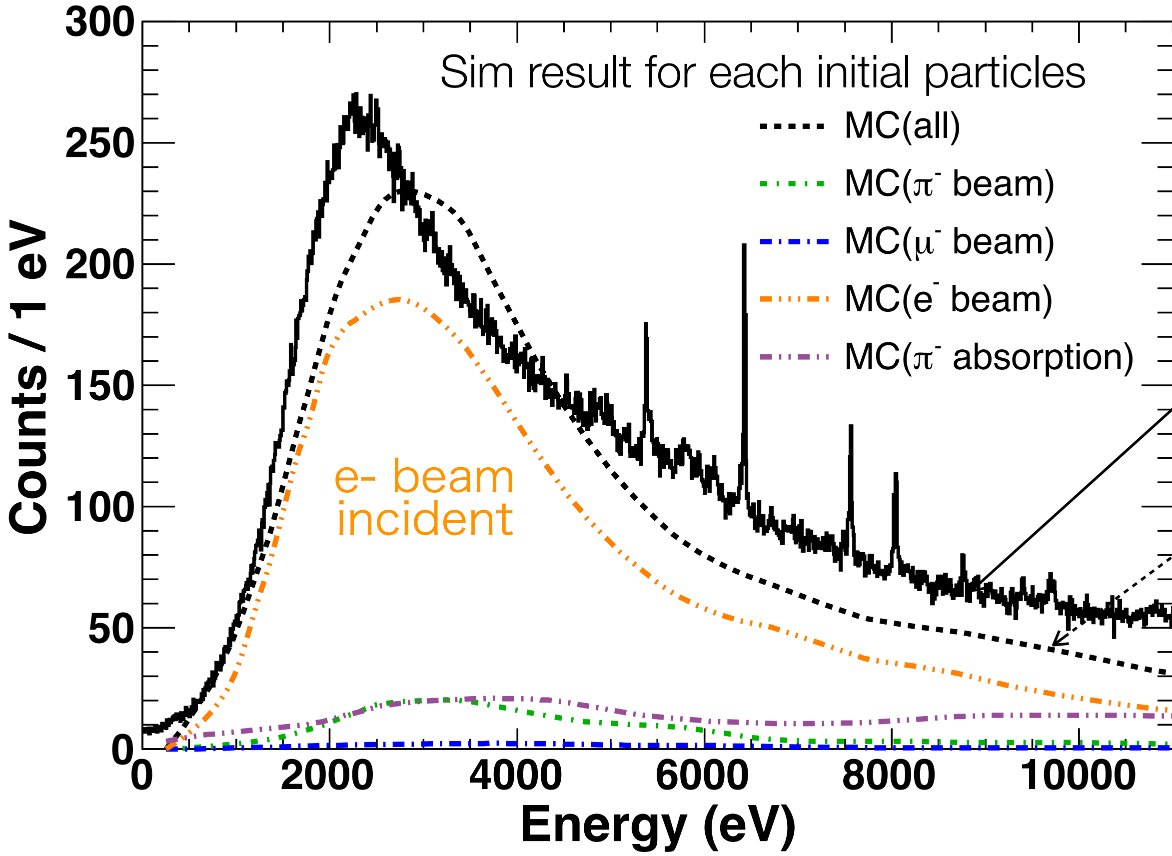
em
4
xpt.)



Kaon beam detectors

Simulation study for the J-PARC kaon beam

Comparison of PSI data with the simulation



	TES trigger rate /pixel
Measured	**0.71 ± 0.11 /sec**
Simulation	**0.64 / sec**

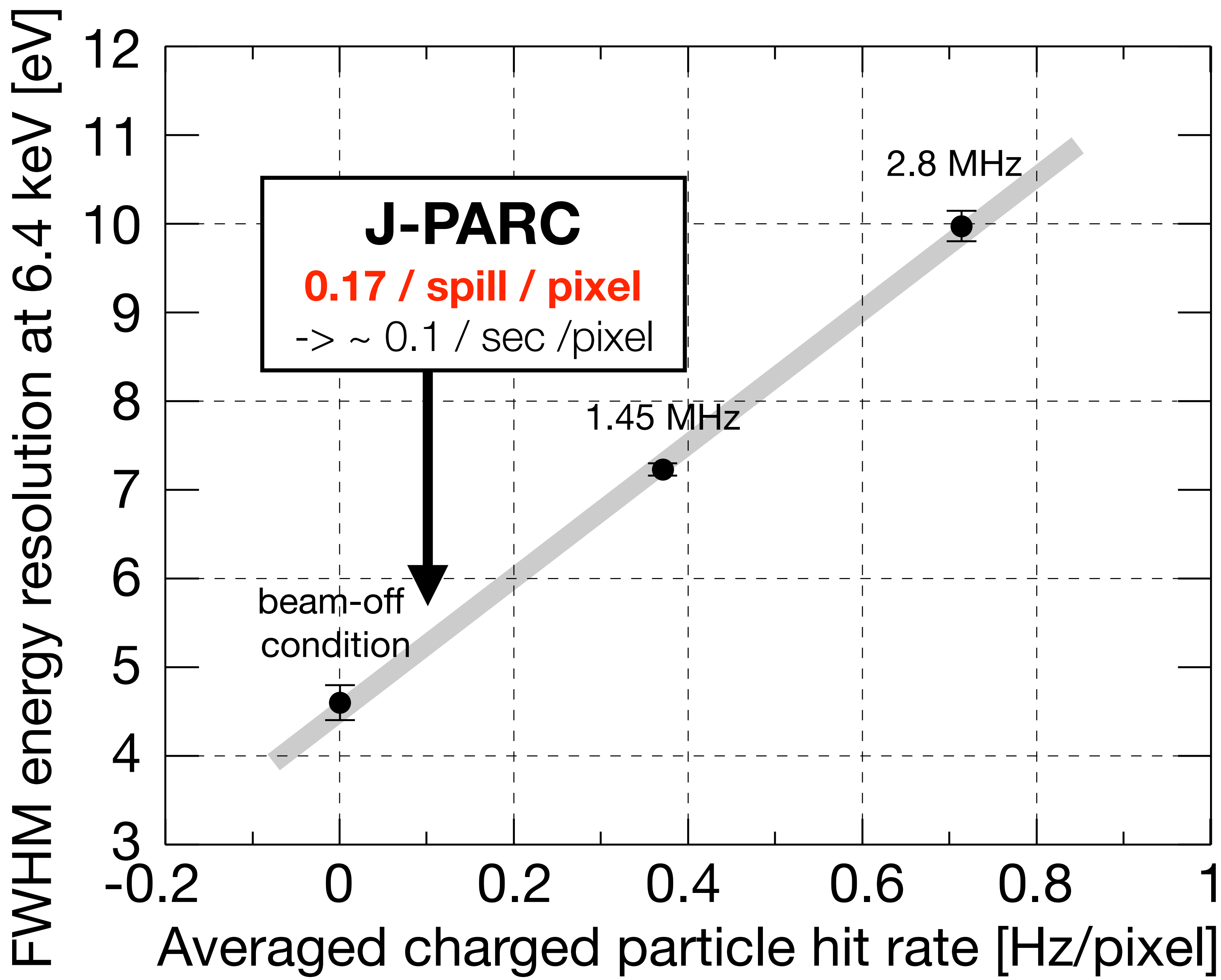
(normalized by # of incident beam)

Good reproducibility of hit rate & spectral shape

	πM1 at PSI	K1.8BR at J-PARC
Beam momentum	173 MeV/c	900 MeV/c
Total beam intensity	2.8×10^6 /sec	8.0×10^5 / spill (@ 50 kW)
$K^-/\pi^-/\mu^-/e^-$ ratio	—/ 40% / 5% / 55%	20% / 60% / 10% / 10%
TES trigger rate / pixel	0.64/sec	0.17 /spill
Energy deposit on Si	152 MeV/sec	46 MeV/spill

J-PARC will be less severe compared with PSI

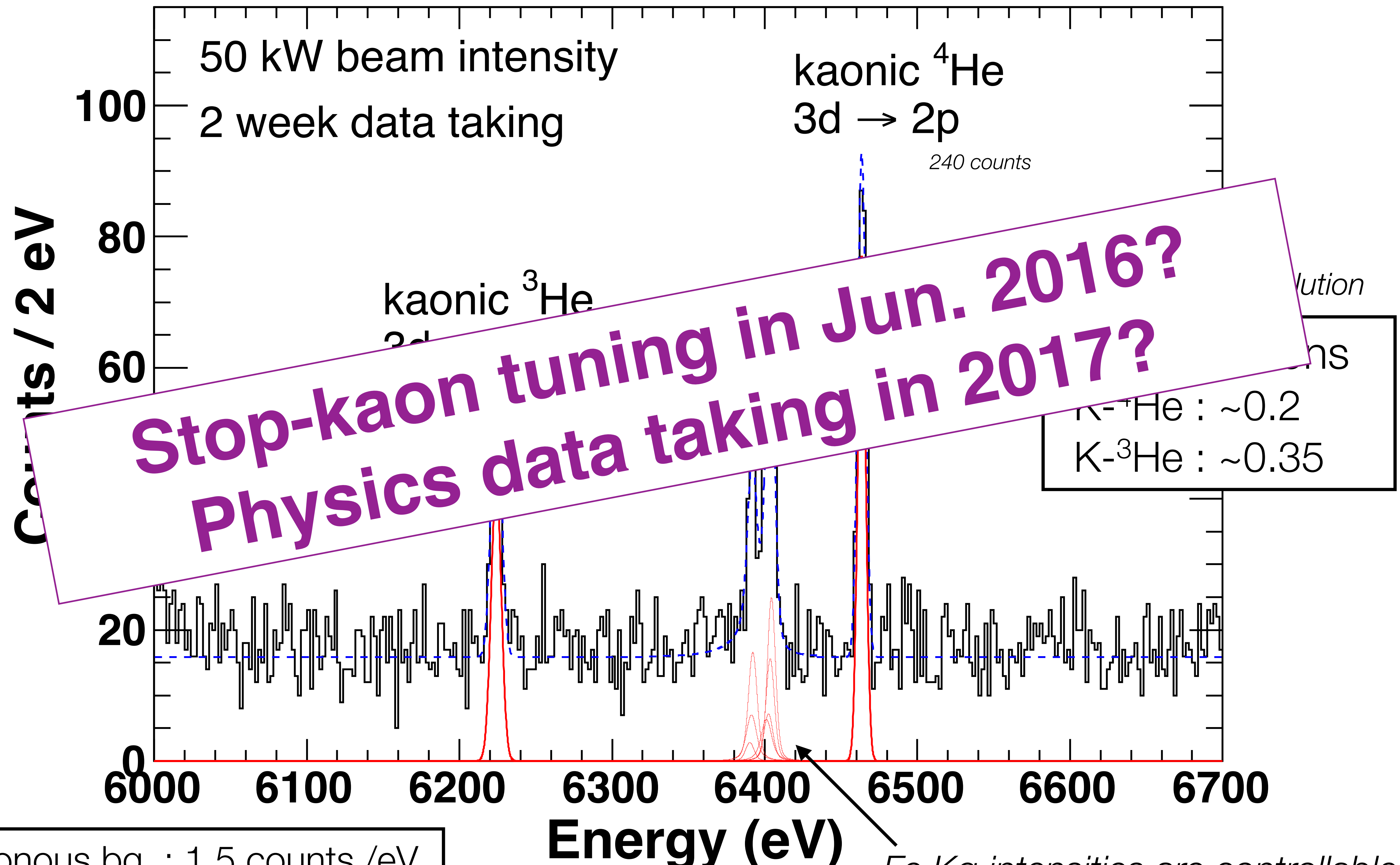
TES operation in the J-PARC kaon beam



TES should work well in the J-PARC kaon beam !!

Energy resolution : 5 ~ 6 eV FWHM

Expected spectrum in J-PARC E62



Stop-kaon tuning in Jun. 2016?
Physics data taking in 2017?

Asynchronous bg. : 1.5 counts /eV
Synchronous bg. : 6 counts /eV

Fe Kα intensities are controllable with applied voltage of x-ray tube

Summary

- **We investigate the $K^{bar}N$ interaction using K^- beam at J-PARC K1.8BR**

- **We have started data taking !**
  - **E15 1st physics run has been successfully performed**
    - some structure found around the threshold
    - no significant structure in deeply bound region
  - H2/D2 target data as calibration
    - d(K-,n)πΣ

- **More data will come soon.**
  - E15: 2nd physics run with x10 statistics **from the middle of Nov.**
  - E31: Λ(1405) via d(K^-,n)
  - E57: K-p x-rays followed by K-d x-rays.
  - E62: KHe x-rays with TES.