Experimental Investigations of the $K^{bar}N$ Interaction at J-PARC K1.8BR

F. Sakuma, RIKEN

for the J-PARC E15/E31/E57/E62 collaboration

Reimei workshop, JAEA, Jan.18-20, 2016

$K^{bar}N$ Interaction

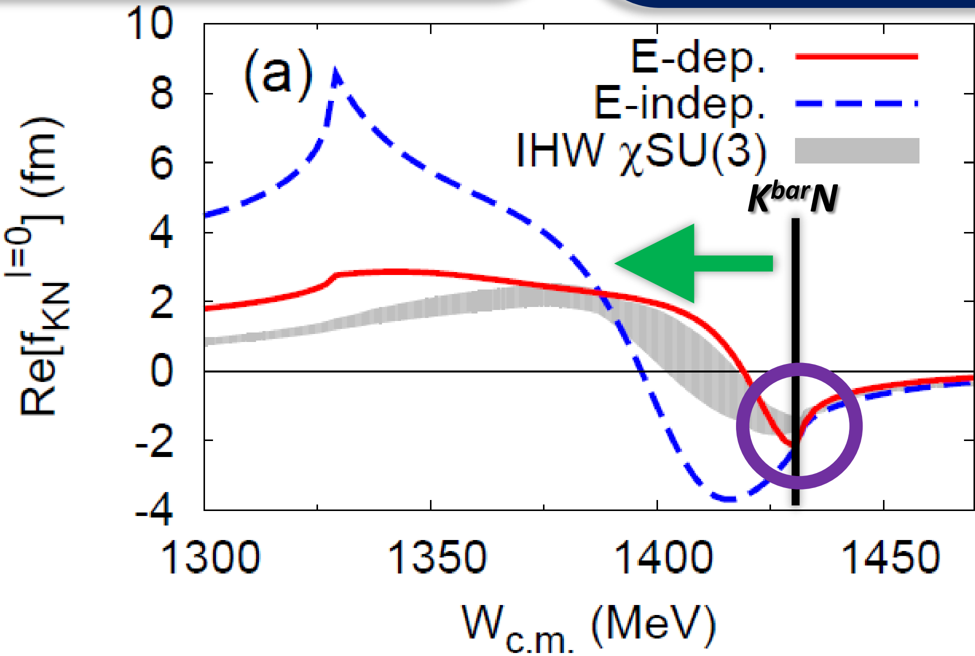
A good prove for low energy QCD

Below the $K^{bar}N$ threshold:

- ? **structure of the $\Lambda(1405)$?**
- ? **existence of the bound kaonic-nuclear states?**

At the $K^{bar}N$ threshold:

- ✓ precise K-p atom / K-p scattering experiments data
- ? **isospin dependent $K^{bar}N$ interaction?**



S.Ohnish et al., arXiv:1512.00123

Experiments at J-PARC K1.8BR

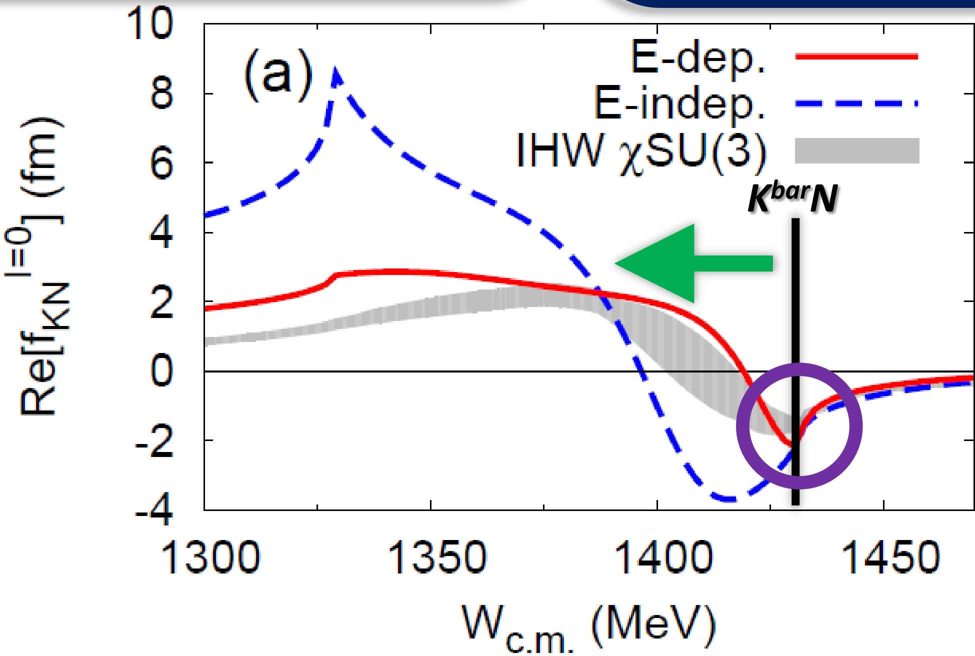
Sensitive in different energy region & isospin

Below the $K^{bar}N$ threshold:

- ? **Λ(1405) → E31**
- ? **$K^{bar}NN$ → E15**

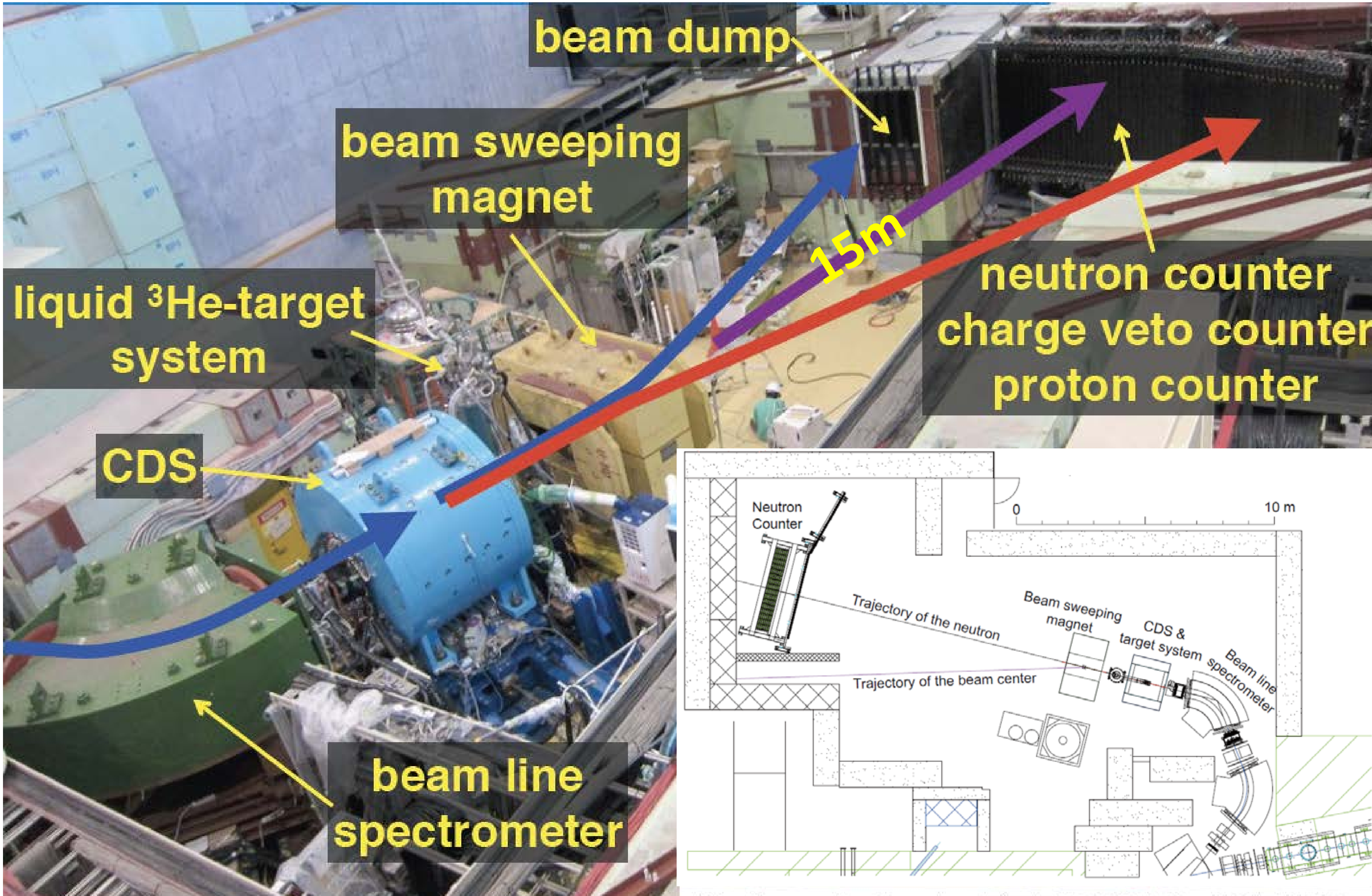
At the $K^{bar}N$ threshold:

- ✓ precise K-p atom / K-p scattering experiments data
- ? **K^{bar}-atom → E17/E57**



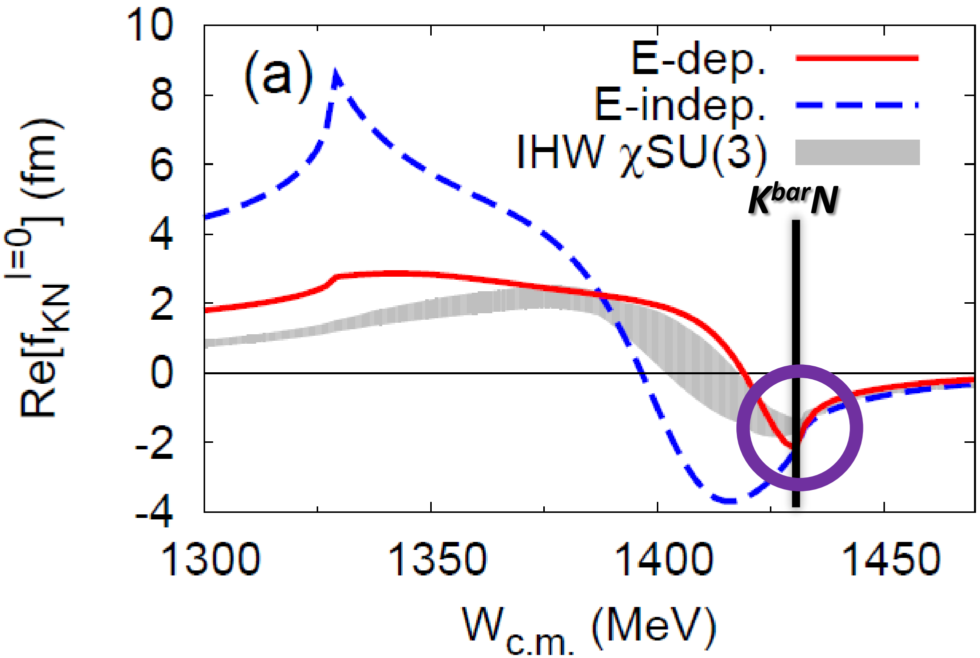
S.Ohnish et al.,arXiv:1512.00123

J-PARC K1.8BR Spectrometer



K. Agari et. al., PTEP 2012, 02B011

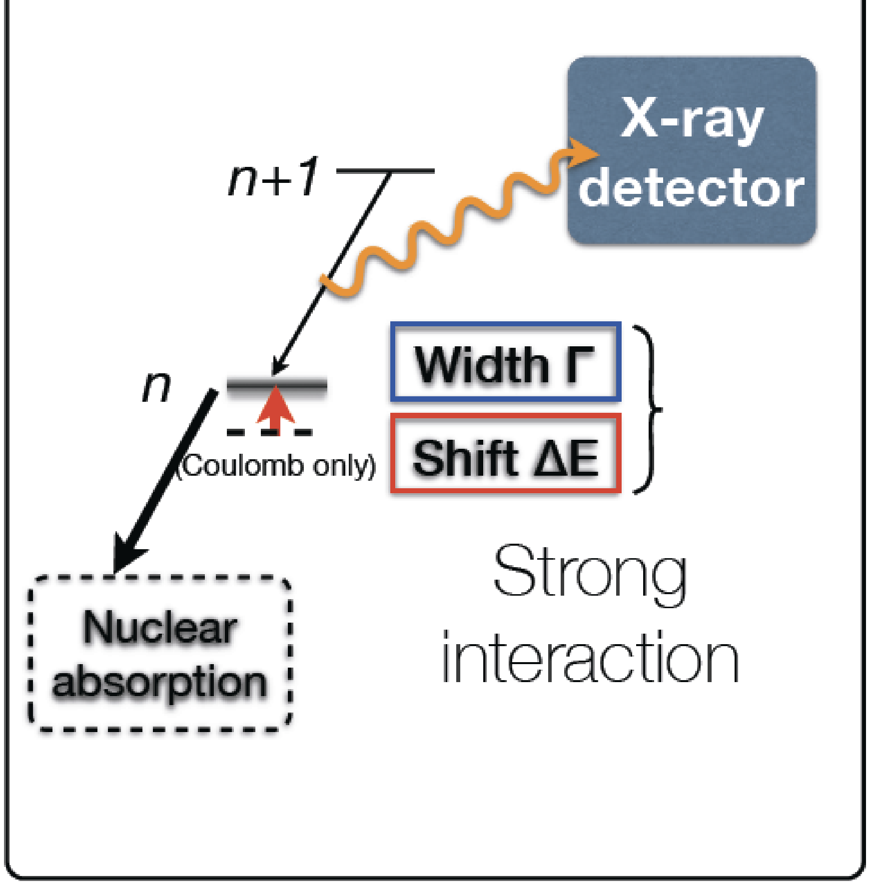
Kaonic-atom:
E17(→E62)/E57



S.Ohnish et al.,arXiv:1512.00123

$K^{bar}N$ Interaction via Kaonic-atoms

Kaonic atom
X-ray spectroscopy



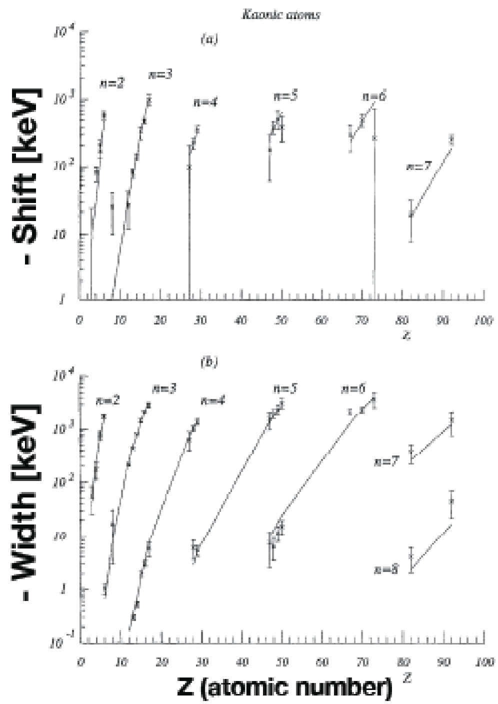
	E62	E57
Kaonic X-ray	**K-He** *3d-2p*	**K-d** *2p-1s*
Energy	~ 6 keV	~ 8 keV
Width	~ 2 eV	~ 1000 eV
Yield per stop-K	~ 7 % (Liquid He)	~ 0.1 % (0.05% of liq. D2 density)
X-ray detector	**TES**	**SDD**
FWHM resolution	~ 5 eV	~ 150 eV
Effective area	~ 0.2 cm^2	~ 200 cm^2
Physics	**K-nucleus potential** — K-N in nuclei —	**KN** (to disantangle I=0,1components) - KN in free space -

S.Okada, 21th J-PARC PAC

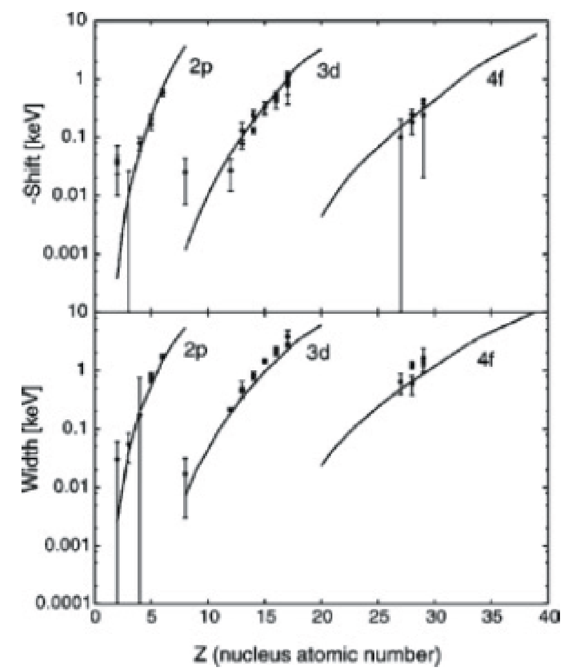
E17(→E62): KHeX with TES

Two theoretical approaches

Phenomenological Model
— **deep potential** —
typically 180 MeV deep



Chiral Unitary Model
— **shallow potential** —
typically 50 MeV deep



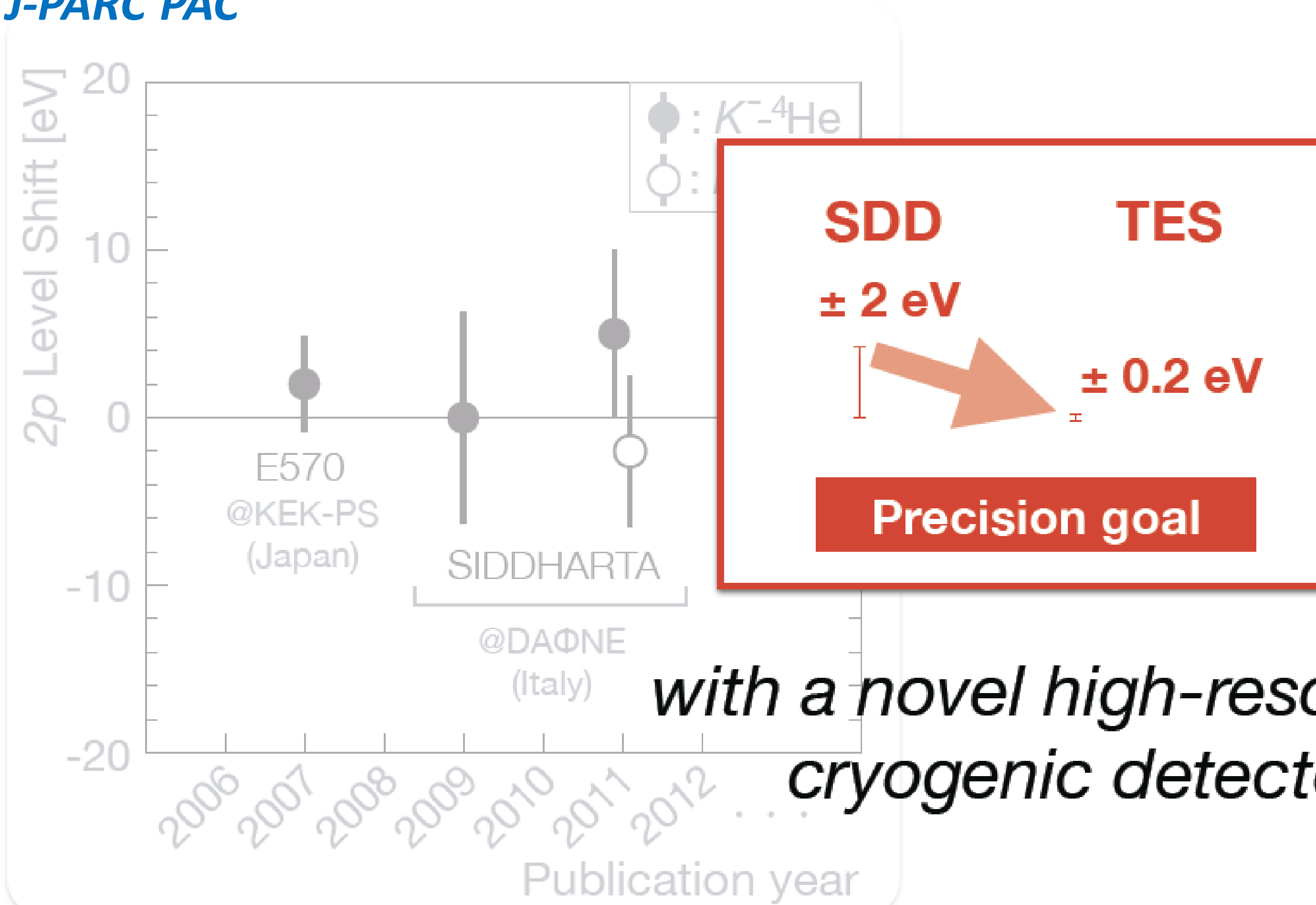
→ Closely related to **K^- nuclear cluster** study
→ **Current data quality is not good enough**
to determine K-nucl. potential strength

S.Okada, 21th J-PARC PAC

E17(→E62): KHeX with TES

S.Okada, 21th J-PARC PAC

Expt.



with a novel high-resolution cryogenic detector

Theo.

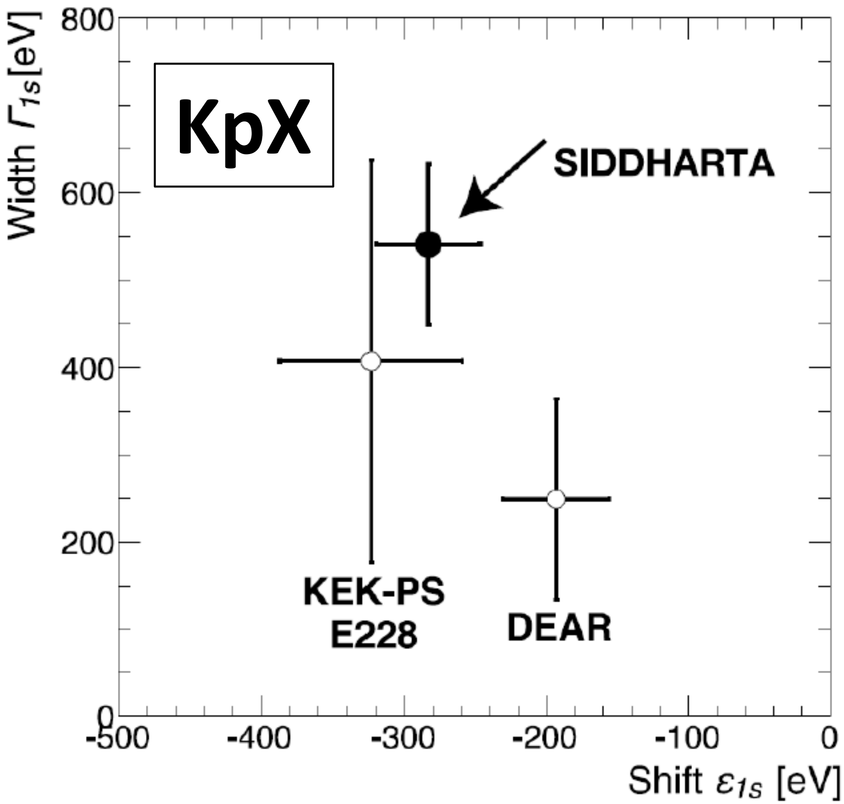
Many of theoretical calculations predict **finite values** of $|\Delta E_{2p}| < 1$ eV (e.g., **~0.2 eV**)

E57: KdX with SDD

K-p scattering length

Precise measurement @ SIDDHARTA

- ✓ the strong-int. shift and width of the kaonic hydrogen 1s



K-d scattering length

NO experimental results

- ✓ due to the difficulty of the X-ray measurement
- ✓ missing information in the low-energy $K^{bar}N$ int.

Scattering lengths *J.Zmeskal, 20th J-PARC PAC*

Deser-type relation[1)] connect the observables shift ε_{1s} and width Γ_{1s} of the 1s state of K^-d to the real and imaginary part of the scattering length a_{K^-d}

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

(μ_c reduced mass of the K⁻p system, α fine-structure constant)

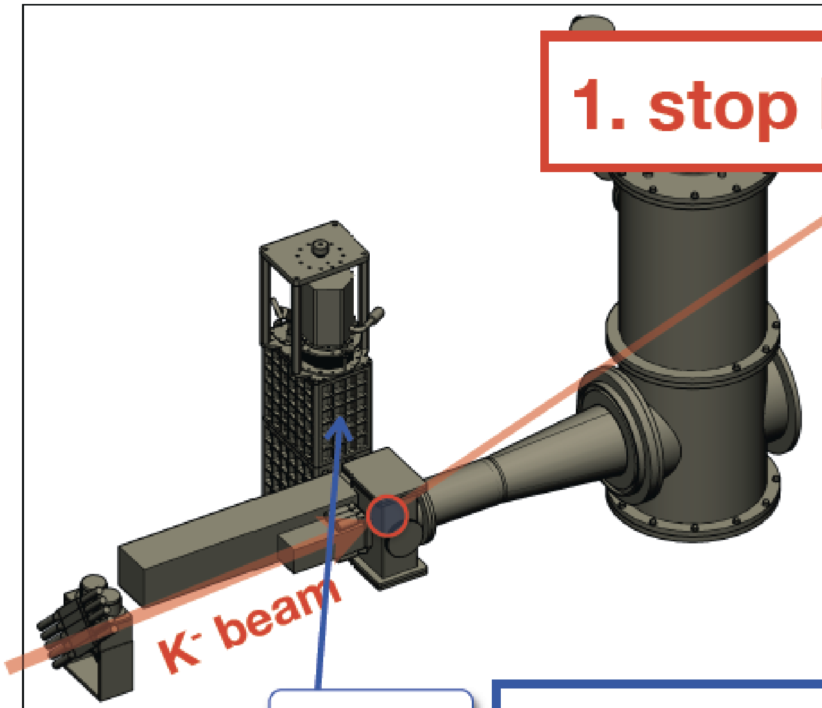
1) U.-G. Meißner, U.Raha, A.Rusetsky, Eur. Phys. J. C35 (2004) 349 next-to-leading order, including isospin breaking corrections

$$\boxed{\begin{aligned} a_{K^-p} &= \frac{1}{2}[a_0 + a_1] \\ a_{K^-n} &= a_1 \end{aligned}} \Leftarrow \boxed{a_{K^-d}}$$

Kaonic-atom Experiments @ K1.8BR

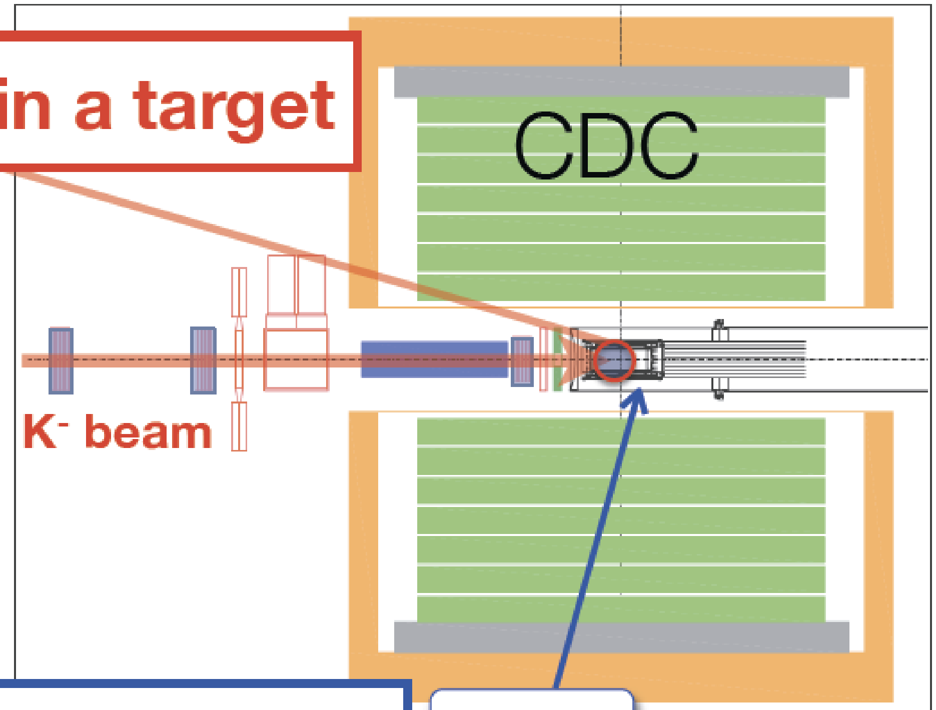
E62

Kaonic helium 3d-2p



E57

Kaonic deuterium 2p-1s



1. stop K⁻ in a target

2. Detect Kaonic x-rays

S.Okada, 21th J-PARC PAC

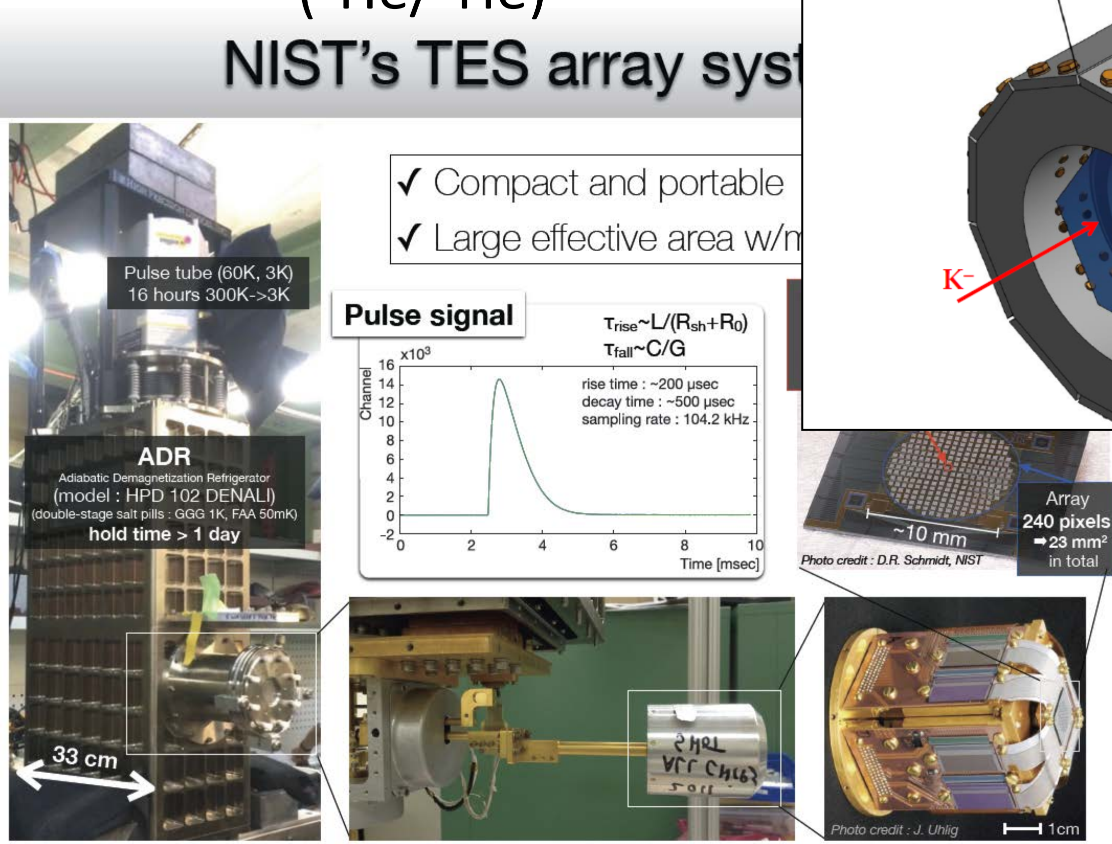
Experimental Apparatus

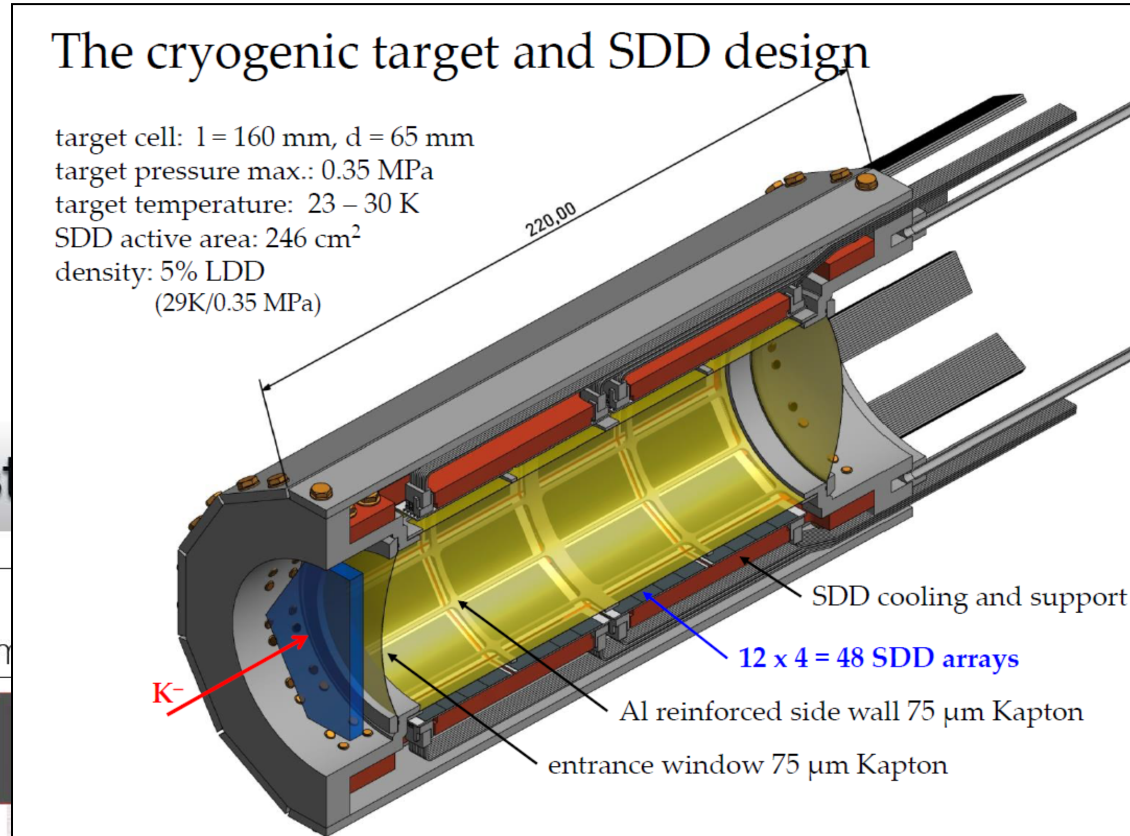
E62 - TES

S.Okada, 20th J-PARC PAC

will be performed in 2017

(^{3}He/^{4}He)





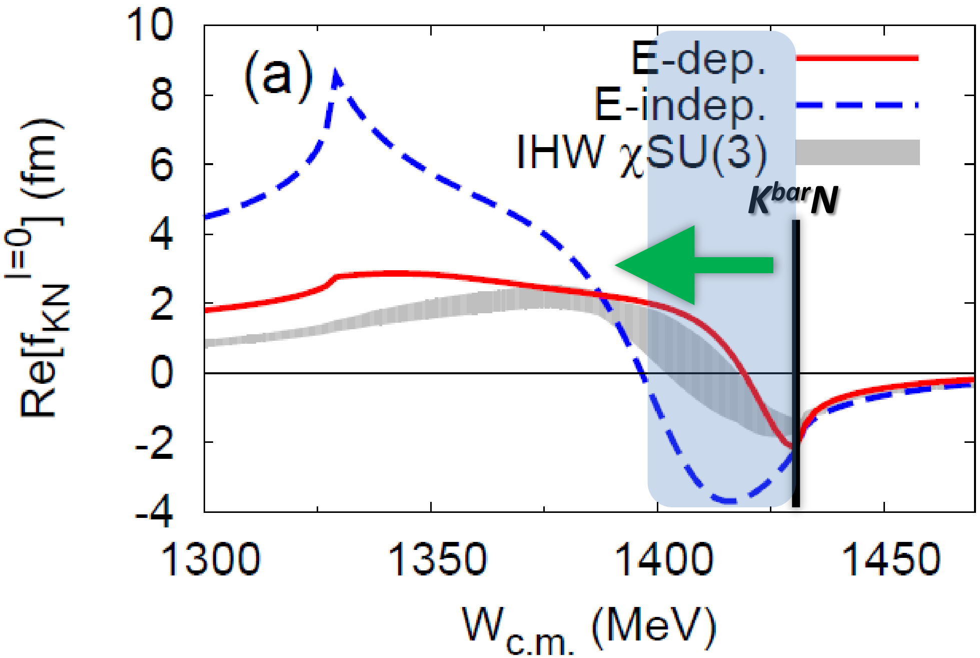
E57 - SDD

J.Zmeskal, 20th J-PARC PAC

will be started from H_2

in 2017 (E57^{1st})

Λ(1405) via d(K^-,n): E31



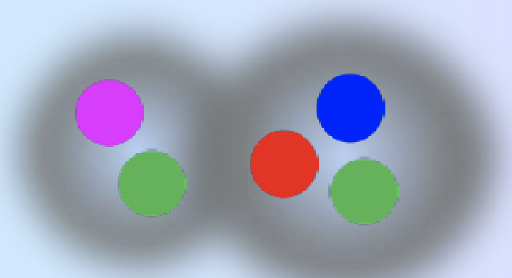
S.Ohnish et al.,arXiv:1512.00123

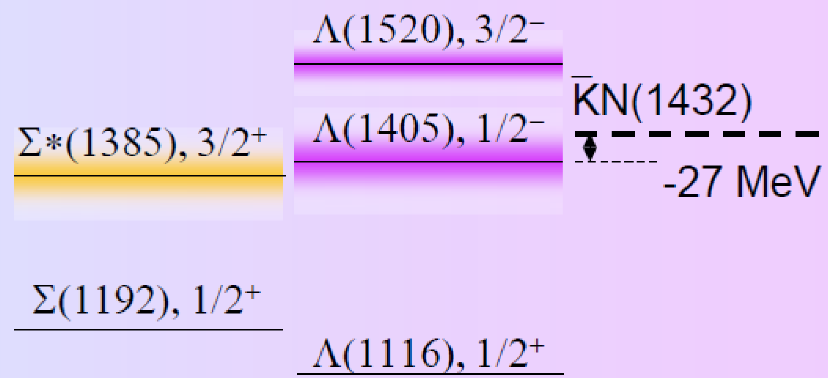
Open Problem of Λ(1405)

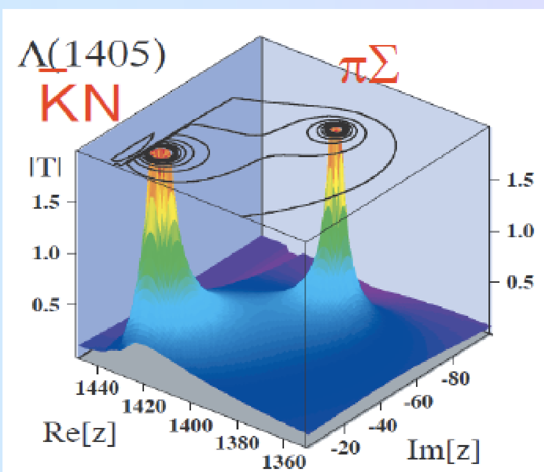
Λ(1405) : Double pole?

H.Noumi, 21th J-PARC PAC

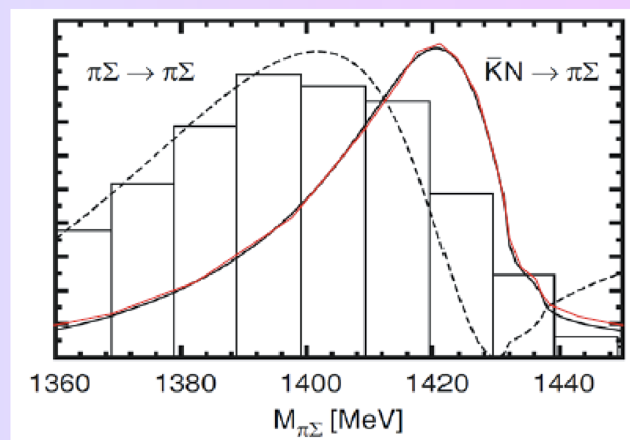
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{K\mathrm{bar}N}$, lightest in neg. parity baryons







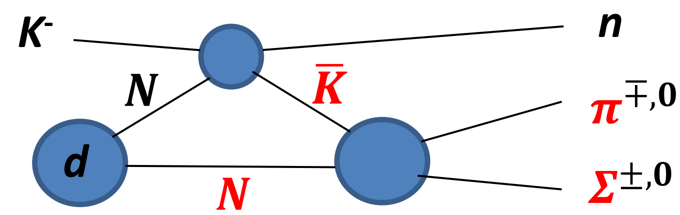
ChU model, T. Hyodo



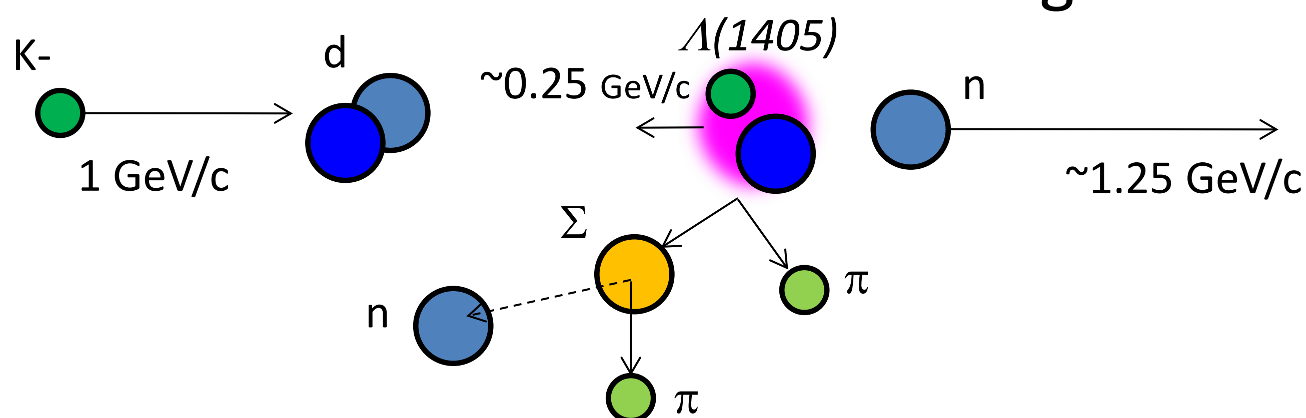
Chiral Unitary Model:
D. Jido et al., NPA725(03)181

J-PARC E31 Experiment

aim to reveal line shape of $\Lambda(1405)$ via $K^{bar}N \rightarrow \pi\Sigma$



- employ $d(K^-,n)\pi\Sigma$ reactions at θ_n~0 deg., which is expected to enhance an S-wave $K^{bar}N \rightarrow \pi\Sigma$ scattering

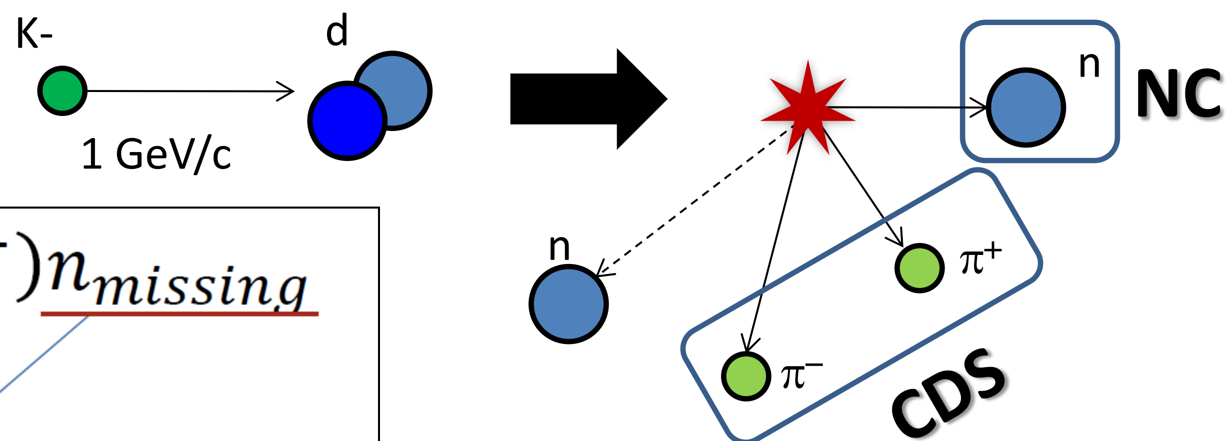


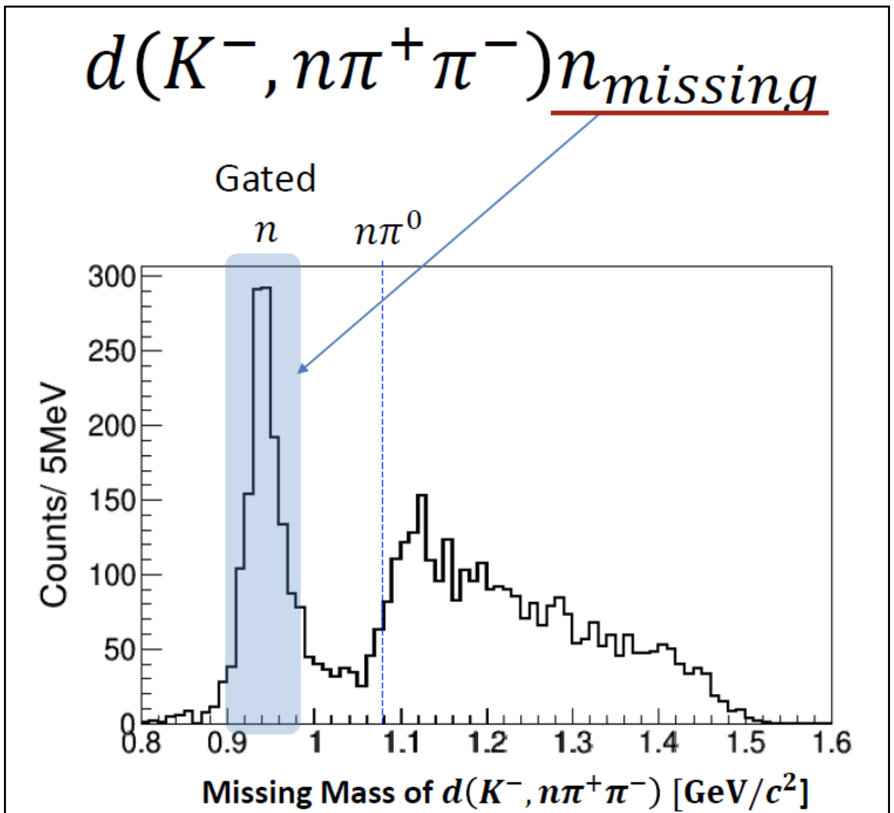
- identify all the final states to decompose the I=0 and I=1 amplitudes.

$\Lambda(1405)$	I=0	S wave	$\pi^{\pm}\Sigma^{\mp}, \pi^0\Sigma^0$
$\Sigma(1385)$	I=1	P wave	$\pi^{\pm}\Sigma^{\mp}, \pi^0\Lambda$
Non-resonant	I=0,1	S,P,D,...	

$\pi^{\pm}\pi^{\mp}$n“n” Final States in E15 Calibration

Apr-May, 2015 (Run#62)	calibration D_2	26.5 kW (33 Tppp, 6s)	130 k/spill	53 h	2.8 x 10^9

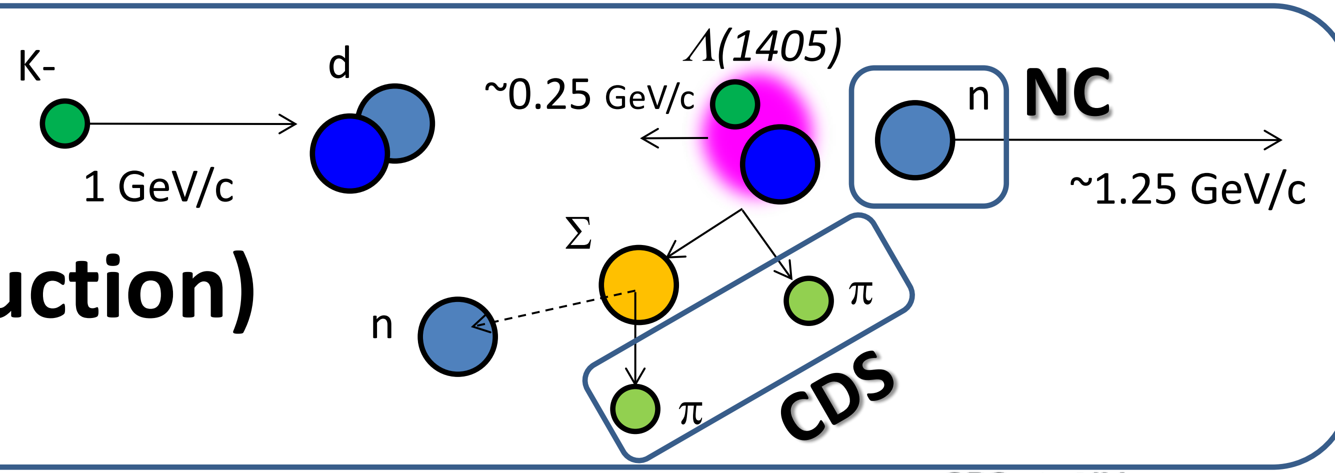




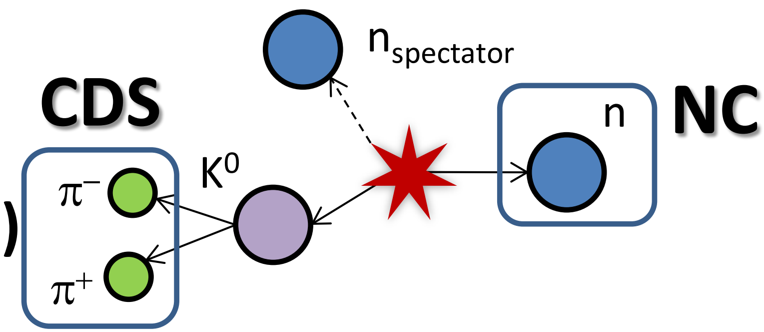
$\pi^{\pm}\pi^{\mp}$n“n” final states can be identified clearly

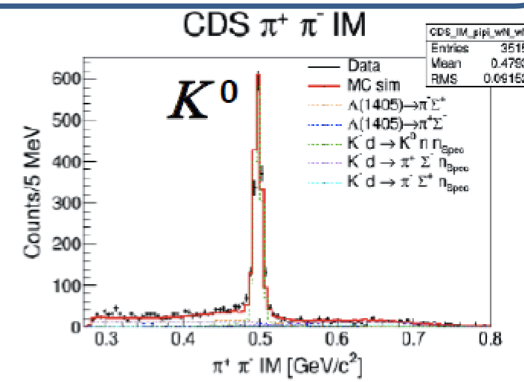
Signal & Background in $\pi^{\pm}\pi^{\mp}n$“n”

Signal (Λ^* production)

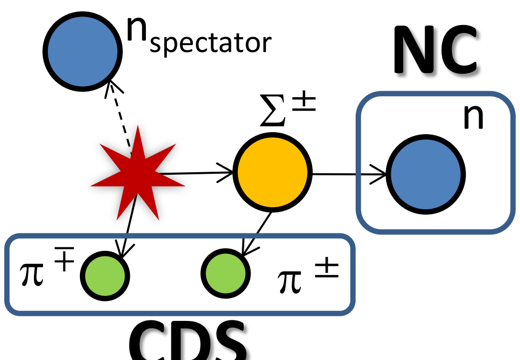


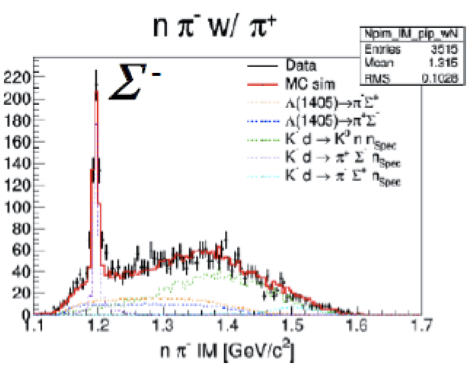
Background (K^0 production)

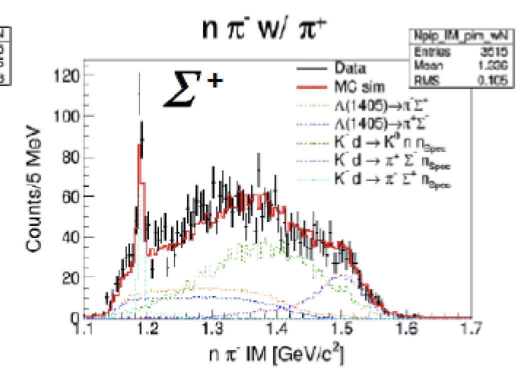




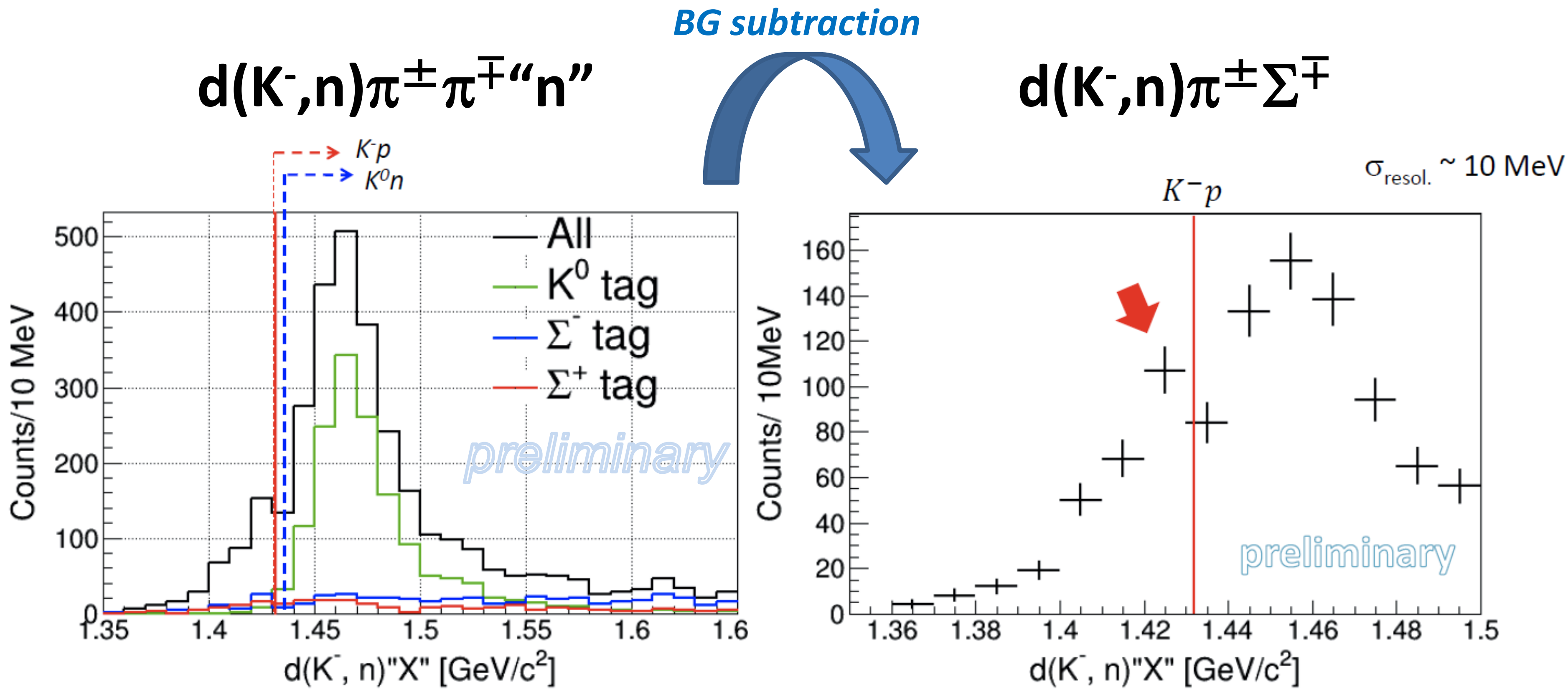
Background (Σ production)







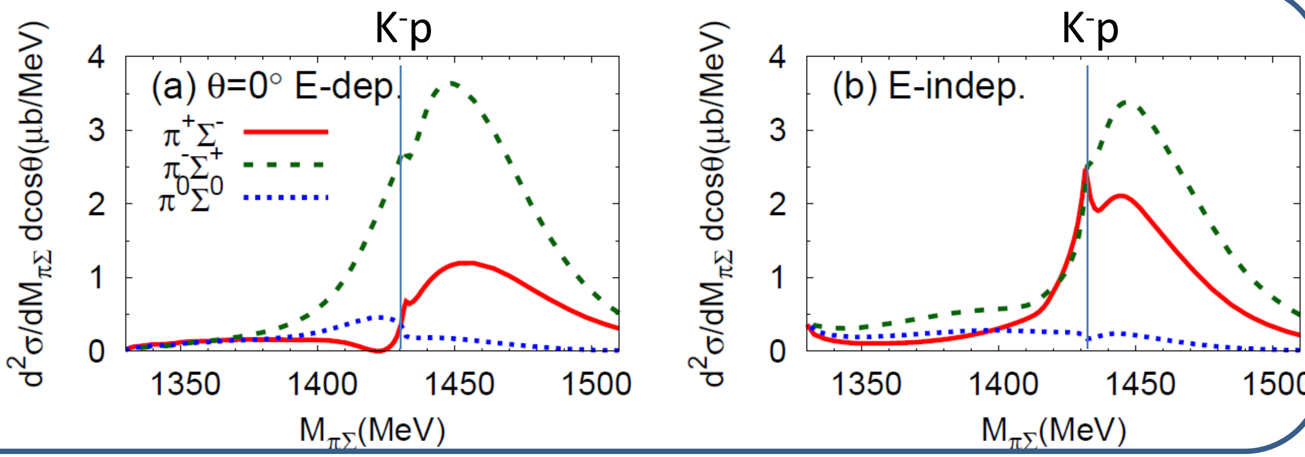
$d(K^-,n)\pi^{\pm}\pi^{\mp}$"n" Spectrum



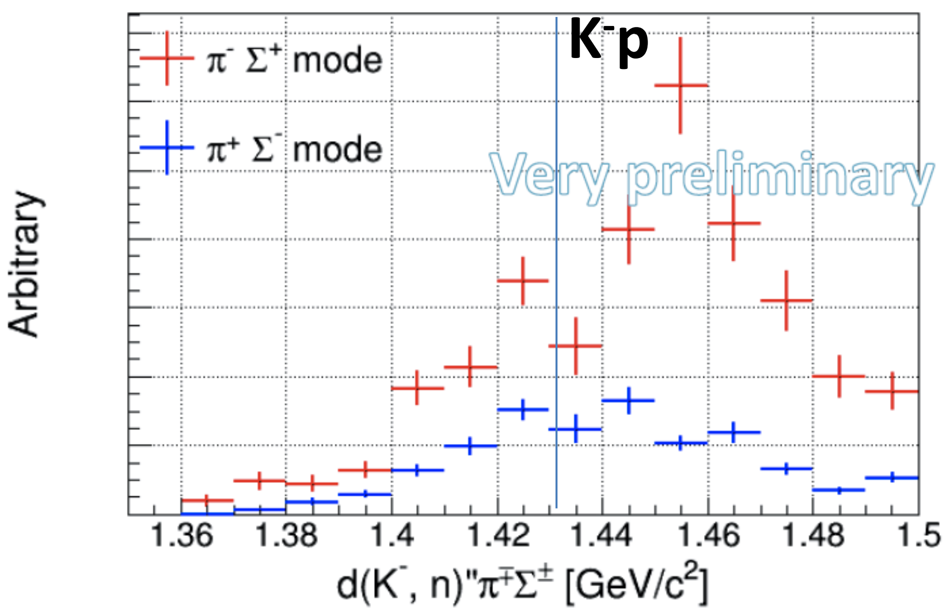
- A bump structure around 1420 MeV/c^2
  - ✓ a $K^{bar}N$ pole ?
- A "QF" like structure above the K^-p mass threshold
  - ✓ as predicted by Faddeev calculation (AGS)

$\pi^{\pm}\Sigma^{\mp}$ Mode Separation

c.f.
Faddeev calc. (AGS)
S.Ohnishi et al.,
Nucl-th: **arXiv:1512.00123**
w/ angular dependence

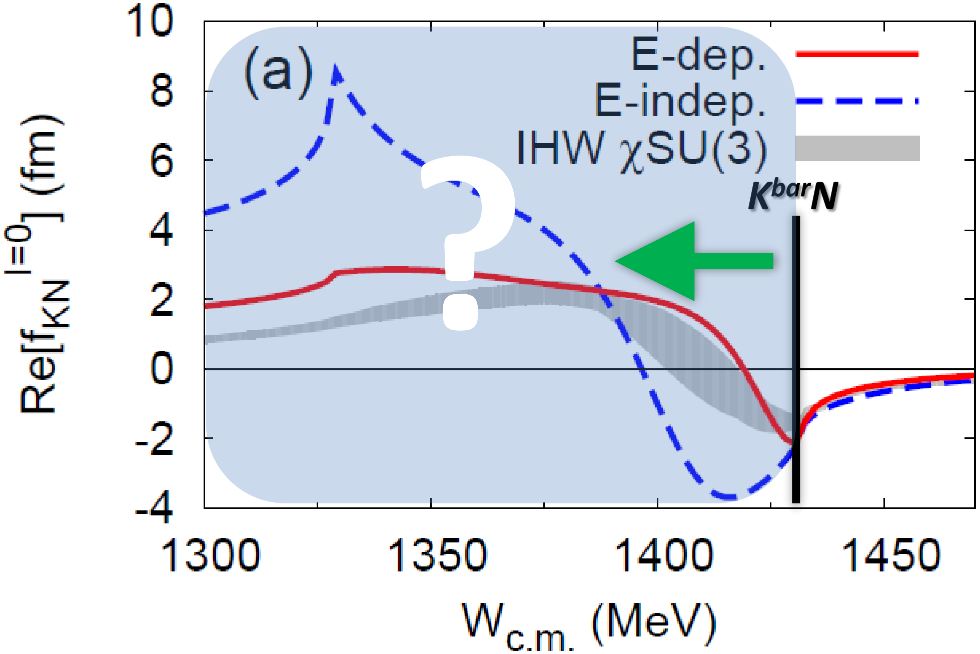


Applying acceptance correction & cocktail fitting



- both I=0 & I=1 channels are contained
- **$\pi^0\Sigma^0$ mode is essential**
  → More data is needed
- **E31 will start in May 2016**

$K^{bar}NN$ via $^3He(K^-,n)$: E15



S.Ohnish et al.,arXiv:1512.00123

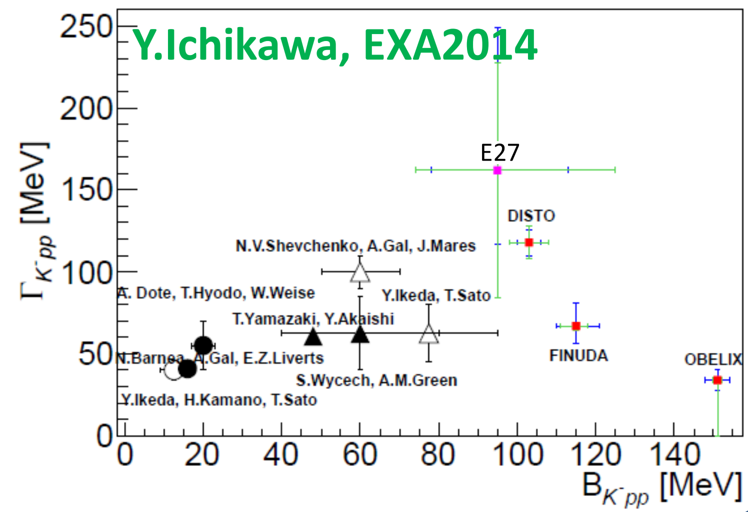
$K^{bar}NN$ Bound State

$K^{bar}NN$: the simplest K^{bar}-nuclear state

Calculated K^-pp binding energies B and widths Γ (in MeV). **A.Gal, NPA914(2013)270**

	Chiral, energy dependent			Non-chiral, static calculations			
	var. [7]	var. [8]	Fad. [9]	var. [10]	Fad [11]	Fad [12]	var. [13]
B	16	17–23	9–16	48	50–70	60–95	40–80
Γ	41	40–70	34–46	61	90–110	45–80	40–85

[7] N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712 (2012) 132.
[8] A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804 (2008) 197;
A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79 (2009) 014003.
[9] Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124 (2010) 533.
[10] T. Yamazaki, Y. Akaishi, Phys. Lett. B 535 (2002) 70.
[11] 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.
[12] Y. Ikeda, T. Sato, Phys. Rev. C 76 (2007) 035203;
Y. Ikeda, T. Sato, Phys. Rev. C 79 (2009) 035201.
[13] S. Wycech, A.M. Green, Phys. Rev. C 79 (2009) 014001.

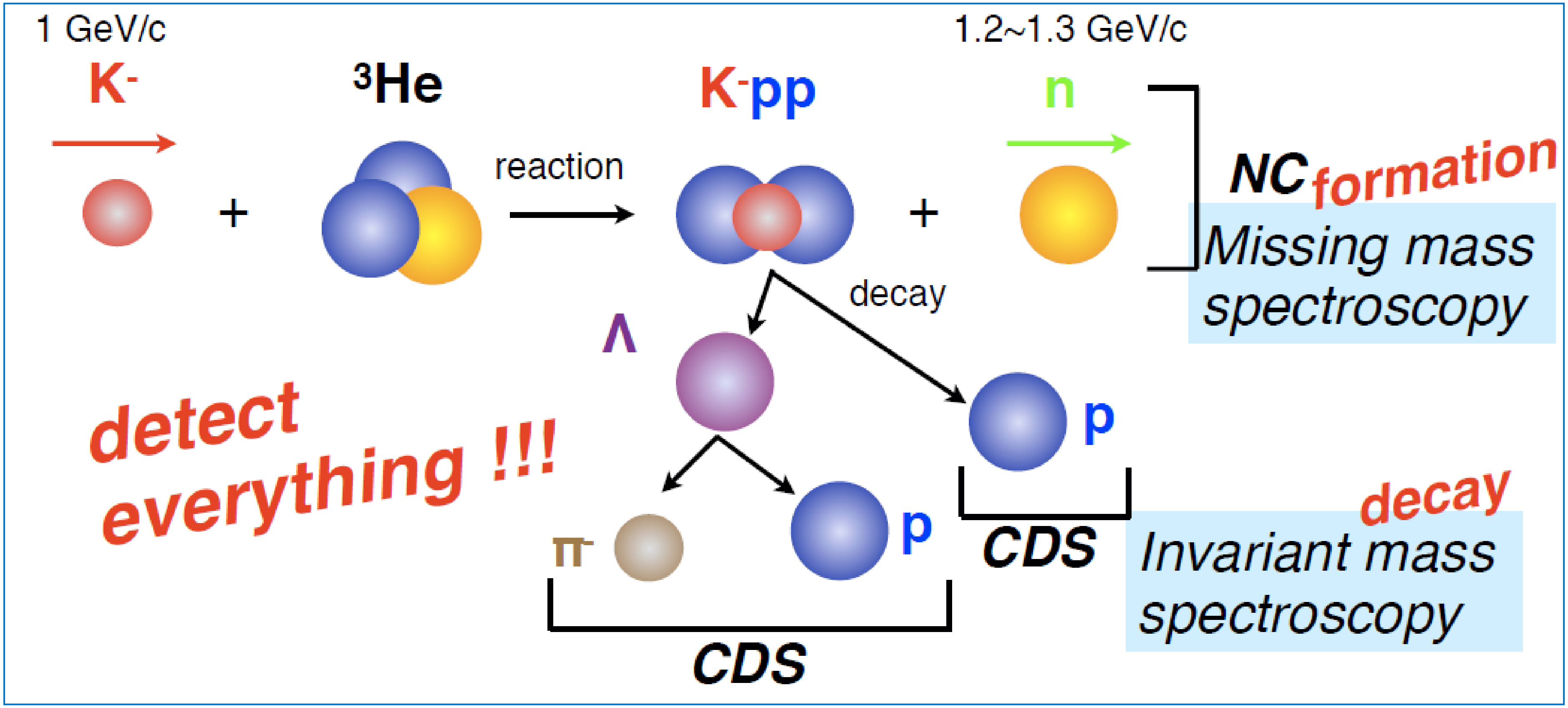


All theoretical studies predict existence of the $K^{bar}NN$

→ However, the situation is still controversial!

J-PARC E15 Experiment

A search for the simplest kaonic nucleus, $K^{bar}NN$, using ^{3}He(*in-flight* K^-,n) reaction



- two-nucleon absorption
- hyperon decays

CAN be discriminated kinematically

Status of the E15 Experiment

- ***~10% of the approved proposal*** was successfully carried out in 2013/2015.

	Exp. Target	Primary-beam intensity	Secondary-kaon intensity	Duration	Kaons on target (w/ tgt selection)
May, 2013 (Run#49c)	E15[1st] ^{3}He	24 kW (30 Tppp, 6s)	140 k/spill	88 h	5.3×10^9
Apr-May, 2015 (Run#62)	calibration H_2	26.5 kW (33 Tppp, 6s)	130 k/spill	73 h	3.7×10^9
Apr-May, 2015 (Run#62)	calibration D_2	26.5 kW (33 Tppp, 6s)	130 k/spill	53 h	2.8×10^9
Nov-Dec, 2015 (Run#65)	E15[2nd] **^{3}He**	**42 kW (48 Tppp, 5.52s)**	**190k/spill**	**520h**	**43×10^9**

** production target: Au 50% loss, spill length: 2s, spill duty factor: 35~45%, K/pi ratio: ~1/2*

** ~70% of beam kaons hit the fiducial volume of ^{3}He target*

Results of E15-1st Experiment

--- only 4days data-taking ---

	Exp. Target	Primary-beam intensity	Secondary-kaon intensity	Duration	Kaons on target (w/ tgt selection)
May, 2013 (Run#49c)	E15 1st ^{3}He	24 kW (30 Tppp, 6s)	140 k/spill	88 h	5.3×10^9
Apr-May, 2015 (Run#62)	calibration H_2	26.5 kW (33 Tppp, 6s)	130 k/spill	73 h	3.7×10^9
Apr-May, 2015 (Run#62)	calibration D_2	26.5 kW (33 Tppp, 6s)	130 k/spill	53 h	2.8×10^9
Nov-Dec, 2015 (Run#65)	E15 2nd ^{3}He	42 kW (48 Tppp, 5.52s)	190k/spill	520h	43×10^9

Formation Channel, Semi-Inclusive ^{3}He(K$^-$,n)X

T.Hashimoto et al., PTEP(2015)061D01.

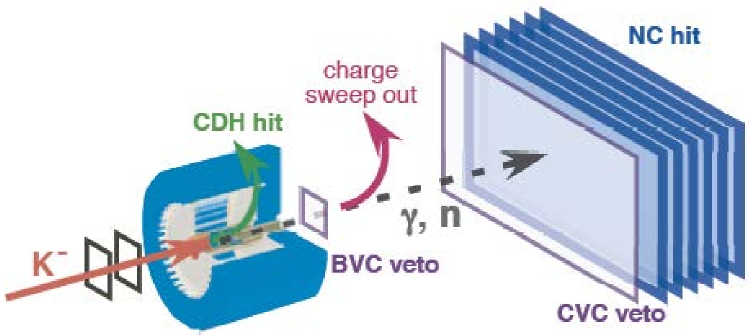
PTEP

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

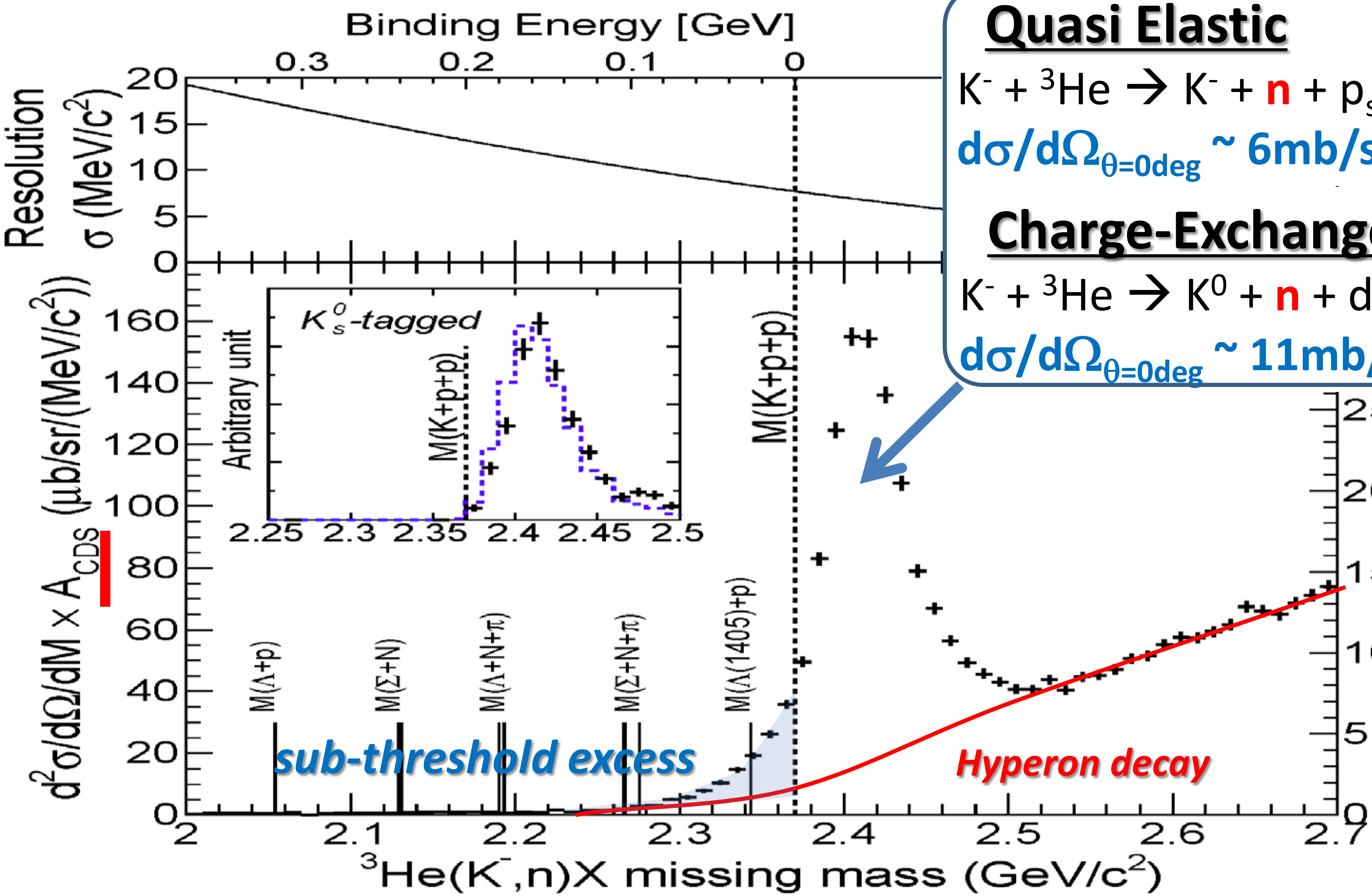
Letter

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],



Semi-Inclusive Spectrum of $^3He(K^-,n)X$



Quasi Elastic

$K^- + {}^3He \rightarrow K^- + \mathbf{n} + p_s + p_s$

$d\sigma/d\Omega_{\theta=0deg} \sim 6mb/sr$

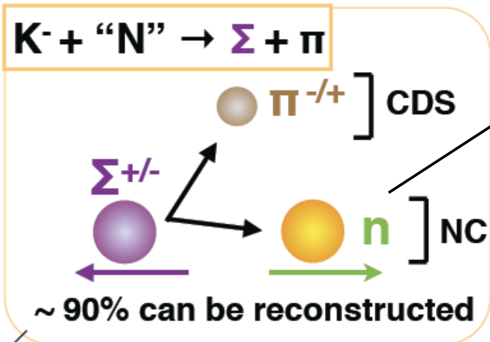
Charge-Exchange

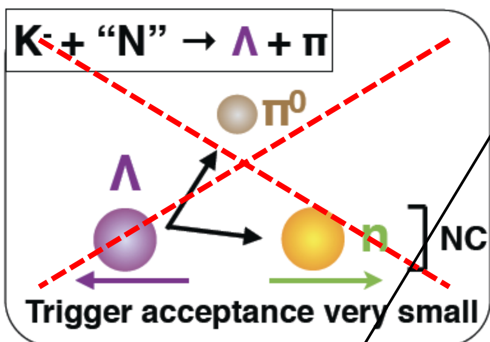
$K^- + {}^3He \rightarrow K^0 + \mathbf{n} + d_s$

$d\sigma/d\Omega_{\theta=0deg} \sim 11mb/sr$

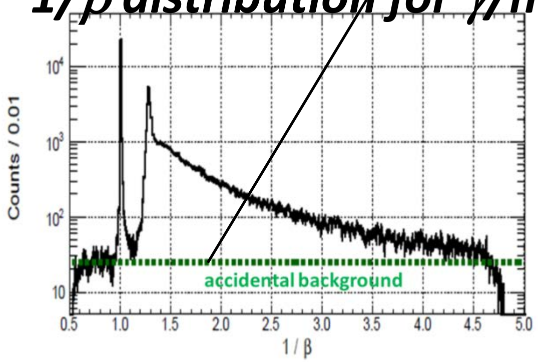
Comparison of ^{3}He(K^{-},n)X

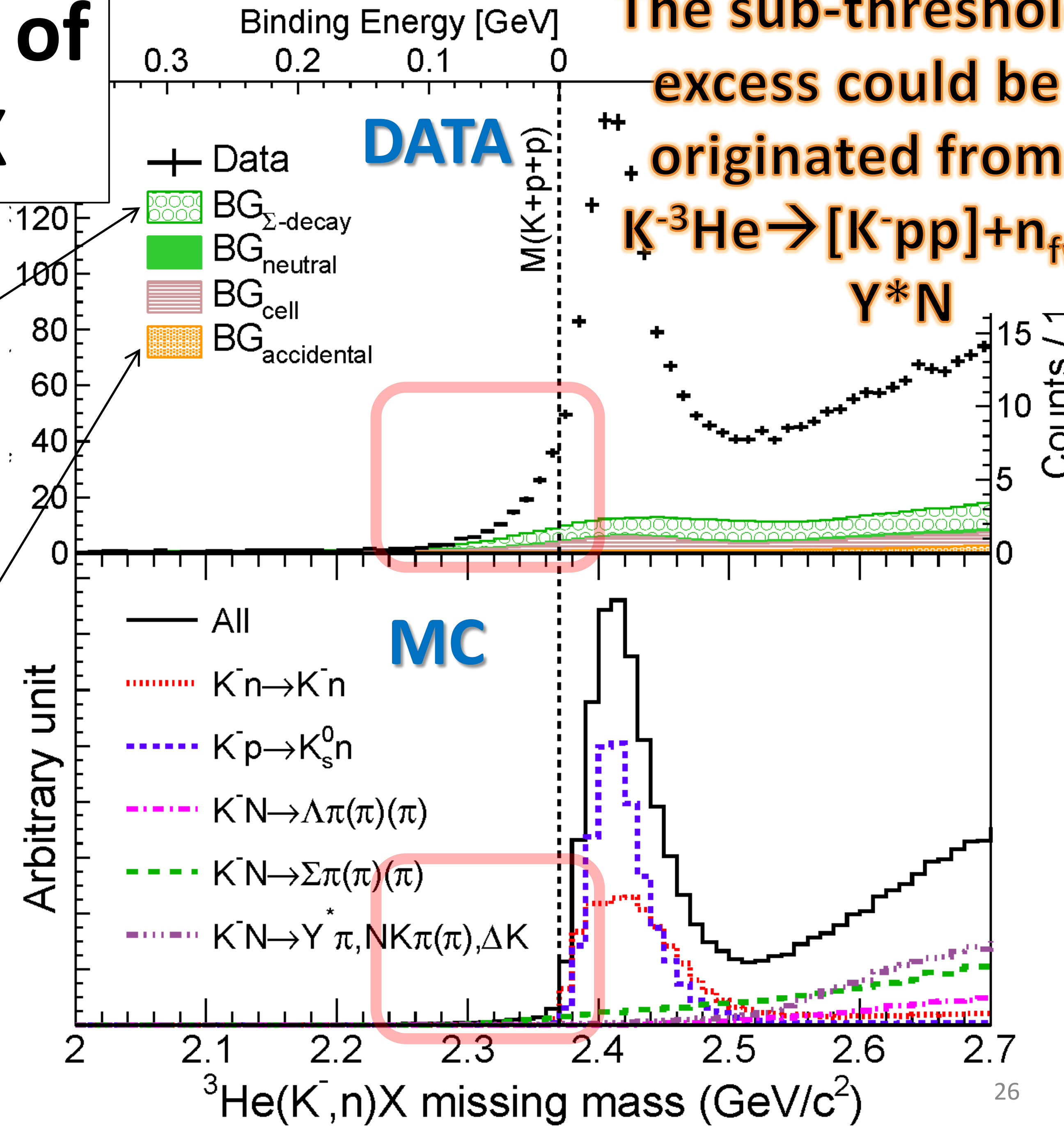
The sub-threshold excess could be originated from $K^{-3}He \rightarrow [K^{-}pp]+n_{fw}$ Y*N



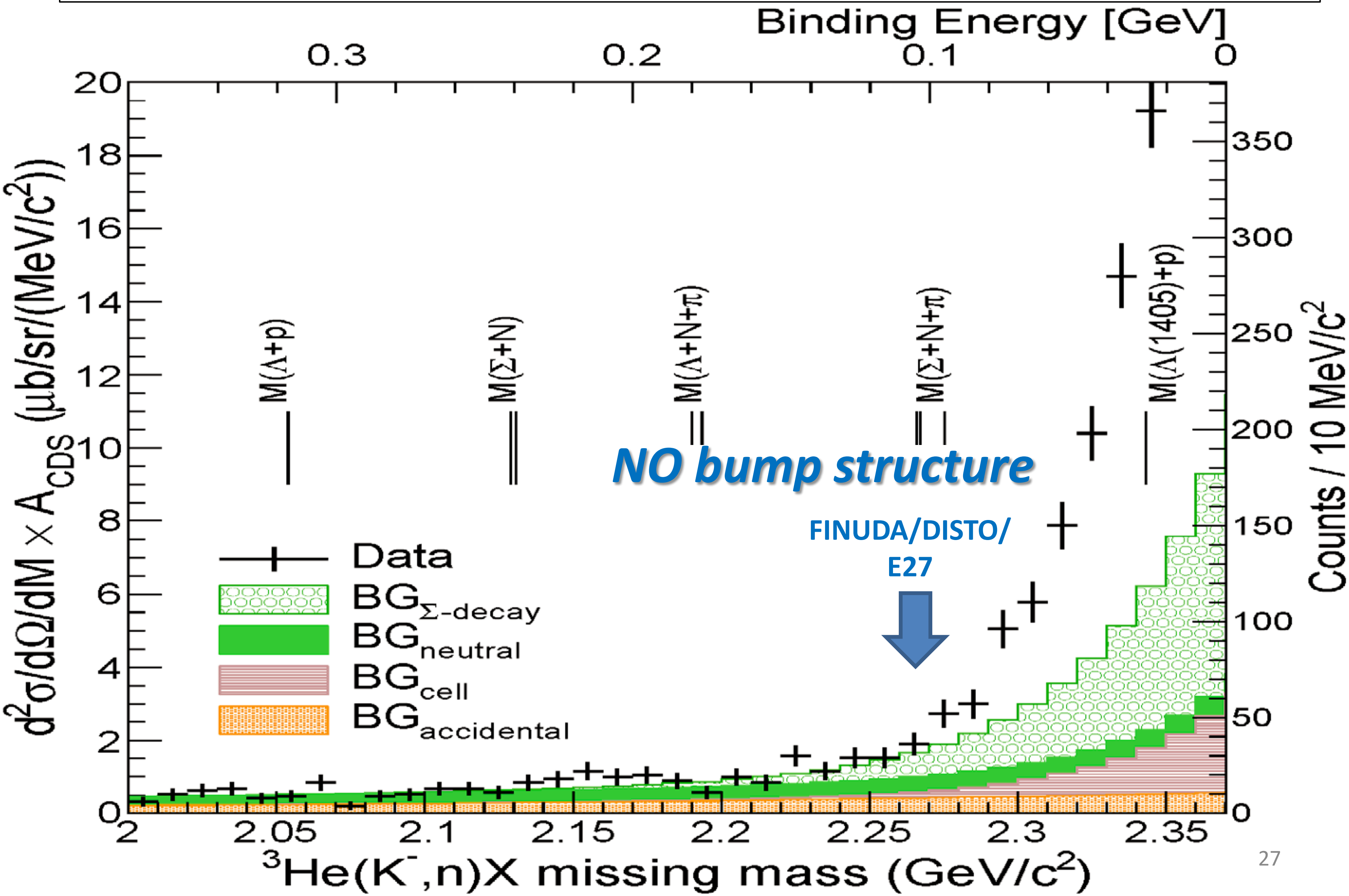


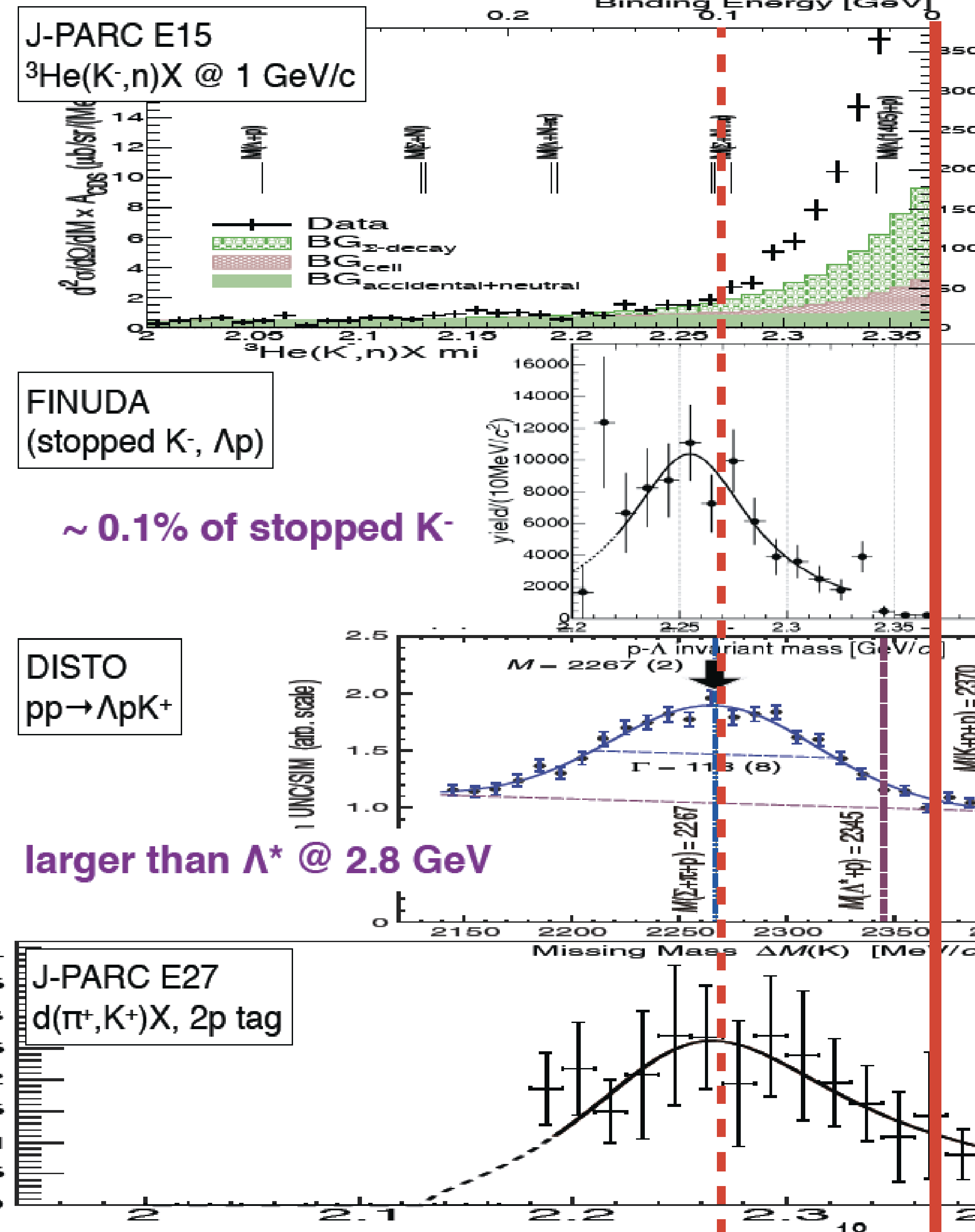
1/β distribution for γ/n





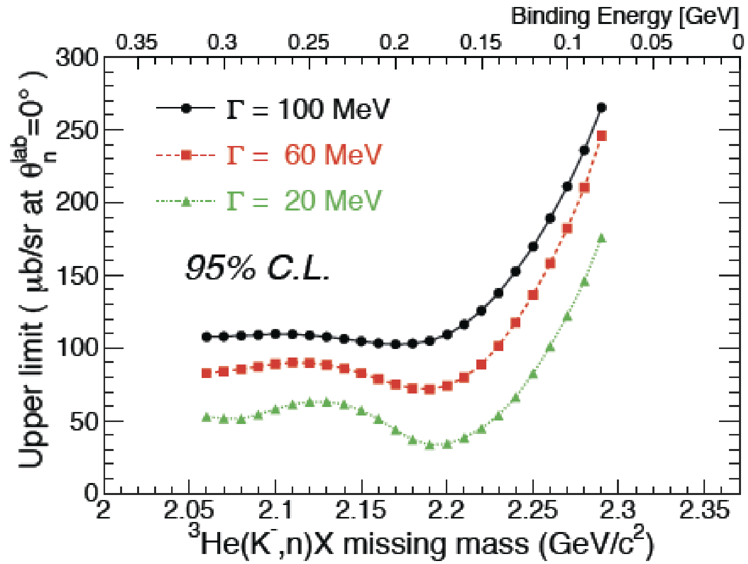
the Deeply-Bound Region





~ 0.1% of stopped K$^-$

larger than Λ* @ 2.8 GeV



Assumptions

Intrinsic peak shape:	Breit-Wigner
Decay mode:	**K$^-$pp→Λp 100%** (isotropic decay)

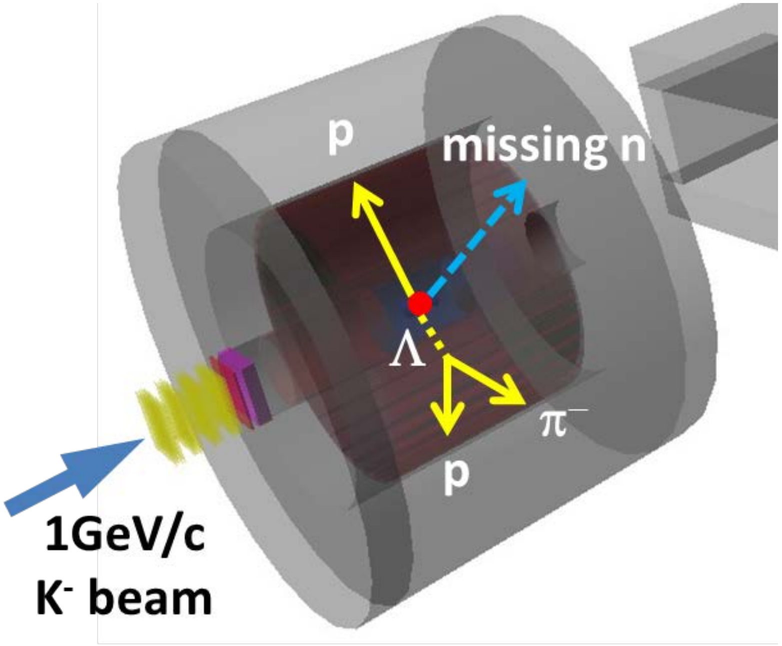
- **J-PARC E15 (U.L.)**
  30 ~ 300 μb/sr @ 0 deg.
  0.5 - 5% of quasi-elastic
  smaller than usual hypernucleus sticking

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

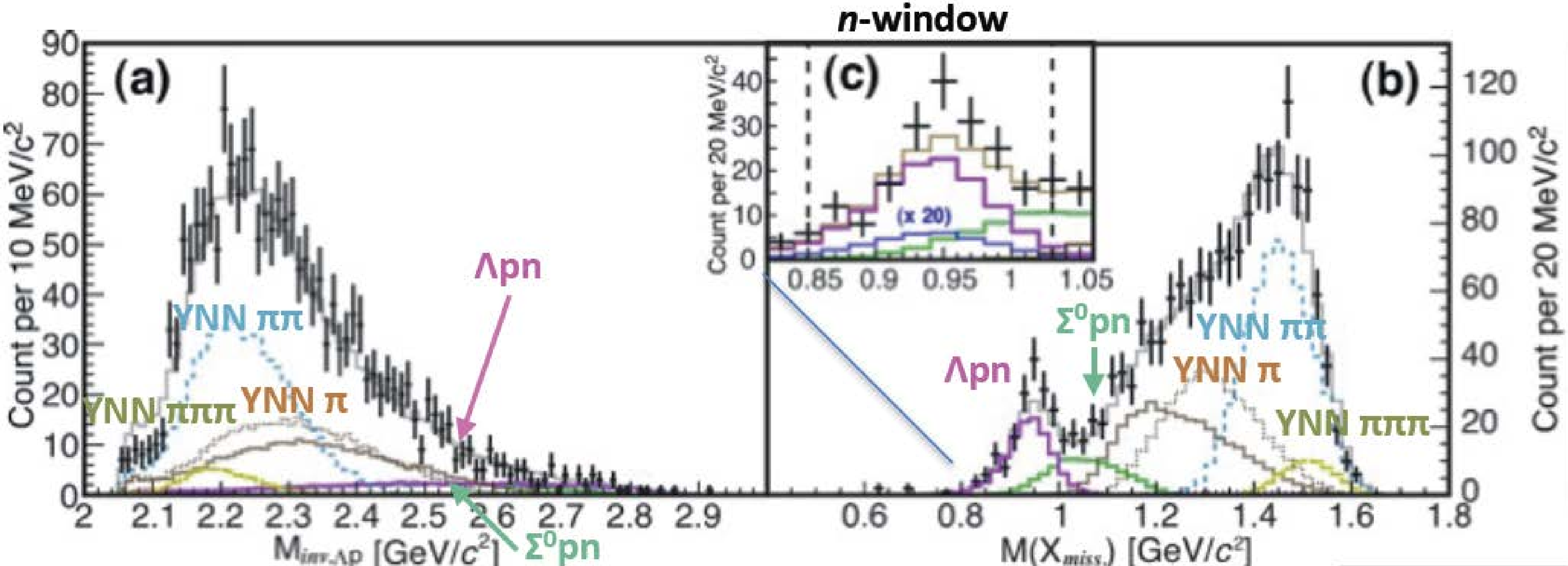
- **HADES (pp @ 3.5 GeV)**
  0.7-4.2 μb (Λ* ~ 10 μb)

Decay Channel,
Exclusive $^3He(K^-, \Lambda p)n$

Y.Sada et al., paper in preparation



Inclusive ^{3}He(K$^-$,Λp)X



Identify neutron by kinematics

$K^- + {}^3He \rightarrow \Lambda + p + n_{mis.}$

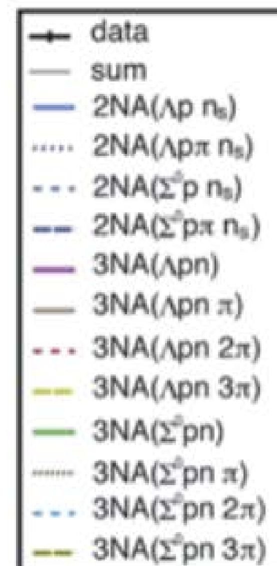
– *# of Λpn events: ~200*

To know components in *n*-window, we conducted

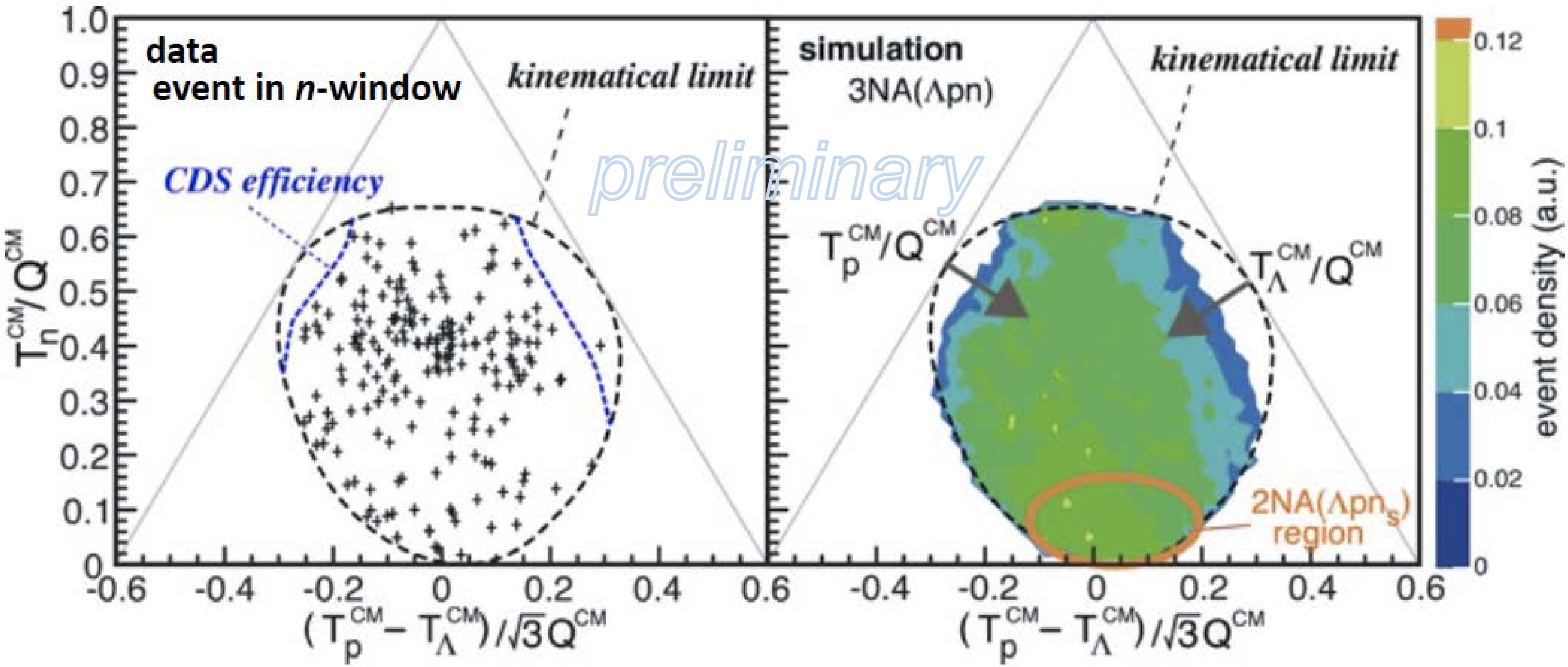
global fit both Λp invariant-mass & missing mass

***cf.* 3NA(Λpn) :** $\dfrac{d^2\sigma_{3NA(\Lambda pn)}}{dT_n^{CM}\, d\cos\theta_n^{CM}} \propto \rho_3(\Lambda pn)$

– *Σ⁰pn contamination: ~20%*

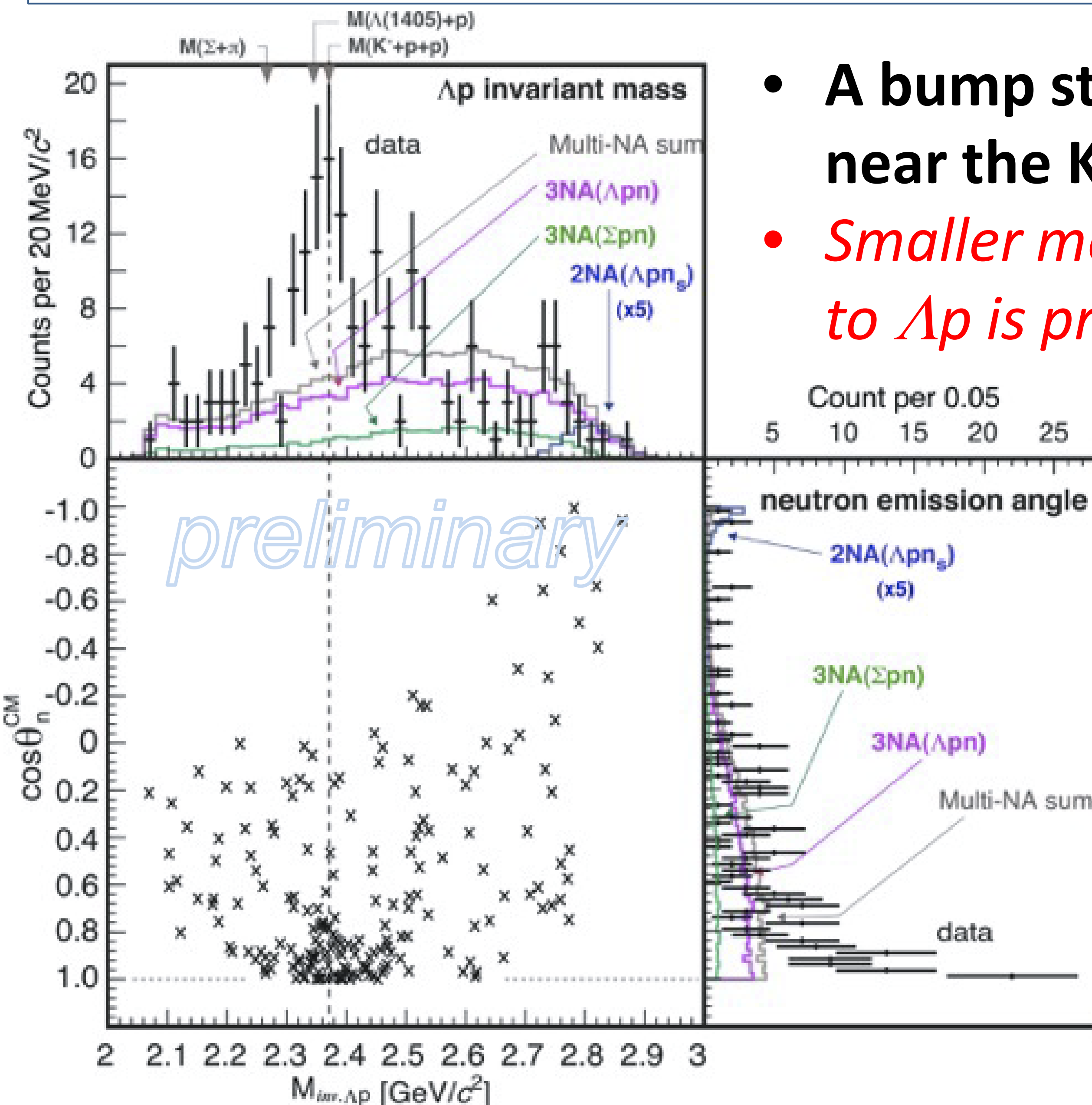


Exclusive $^{3}He(K^{-},\Lambda p)n$



- The events widely distribute in the phase space
  - Contribution from 2NA processes seem to be very small
- Event concentration is seen at T^{CM}_{n}/Q^{CM}~0.4

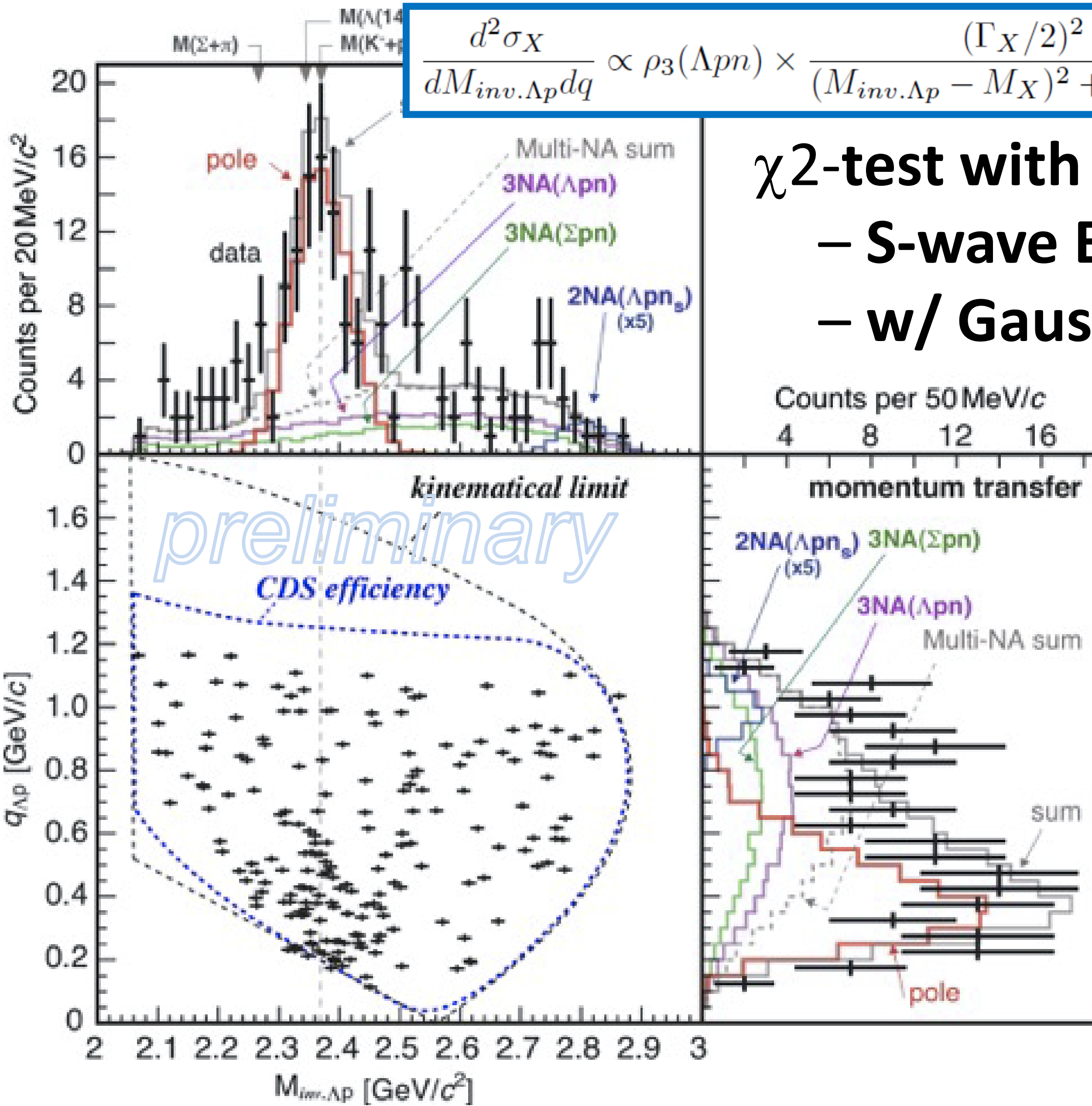
A Global-fit Result for ^{3}He(K$^-$,Λp)n



- **A bump structure exists near the K-pp threshold**
- *Smaller momentum transfer to Λp is preferred* (0.8<cosθ^{CM}_n)

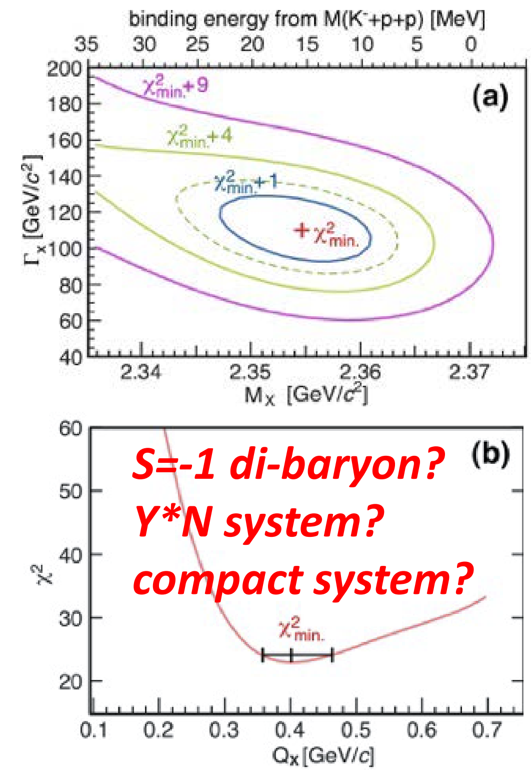
Assuming a Breit-Wigner

$$\frac{d^2\sigma_X}{dM_{inv.\Lambda p}dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{inv.\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times |\exp(-q^2/2Q_X^2)|^2,$$



$\chi 2$-test with pole & 3NA(Ypn)

- S-wave Breit-Wigner pole
- w/ Gaussian form-factor



S=-1 di-baryon?
*Y*N system?*
compact system?

Summary of E15^{1st}

● Deeply-bound region

The bump-structure, which was reported by FINUDA/DISTO/E27, has NOT been observed

● Around the threshold

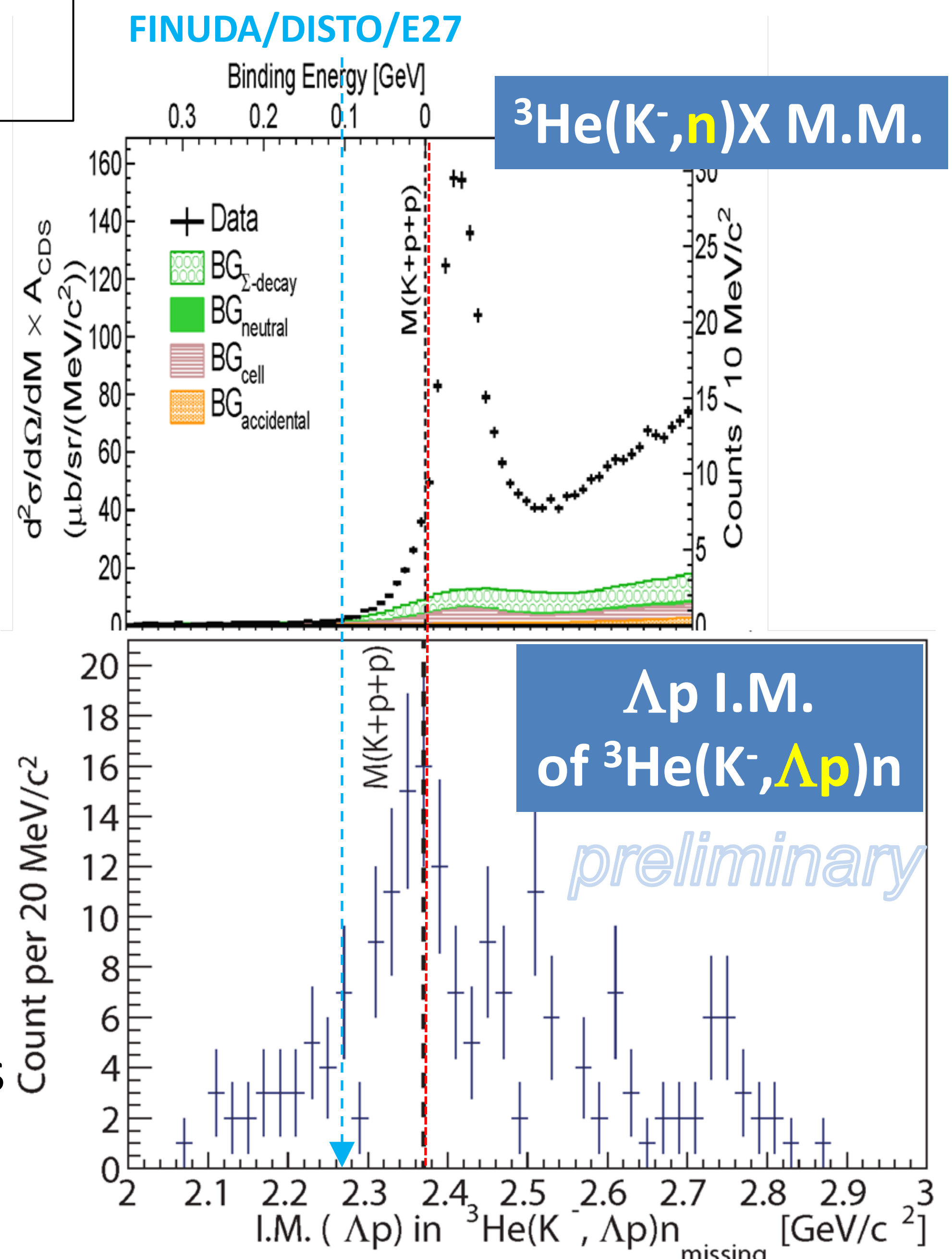
Structure has been seen both in formation- and decay-channel

- Contribution of Y*?
- Hint of S=-1 di-baryon state?

☐ Reaction dependence?

$K^{bar}NN$ formation strongly depends on reaction channel?

- ➢ γ/π/K/p induced reaction?
- ➢ momentum transfer?



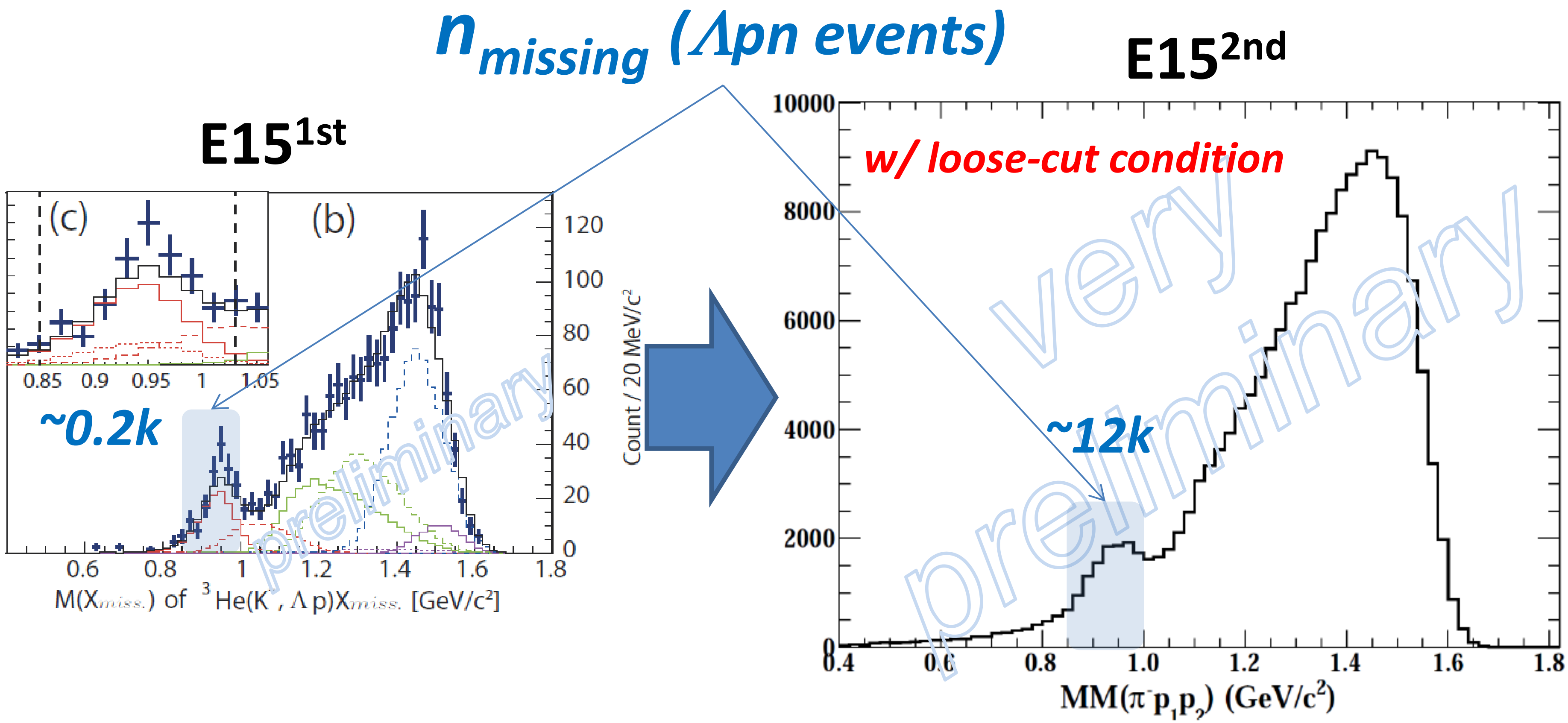
Status of E15-2nd Experiment
--- *just completed in Dec. 2015* ---

calibration is ongoing by T.Yamaga et al.

	Exp. Target	Primary-beam intensity	Secondary-kaon intensity	Duration	Kaons on target (w/ tgt selection)
May, 2013 (Run#49c)	E15 1st ^3He	24 kW (30 Tppp, 6s)	140 k/spill	88 h	5.3×10^9
Apr-May, 2015 (Run#62)	calibration H_2	26.5 kW (33 Tppp, 6s)	130 k/spill	73 h	3.7 [illegible] 10^9
Apr-May, 2015 (Run#62)	calibration D_2	26.5 kW (33 Tppp, 6s)	130 k/spill	53 h	2.8 [illegible] 10^9
Nov-Dec, 2015 (Run#65)	**E15 2nd ^3He**	**42 kW (48 Tppp, 5.52s)**	**190k/spill**	**520h**	**43×10^9**

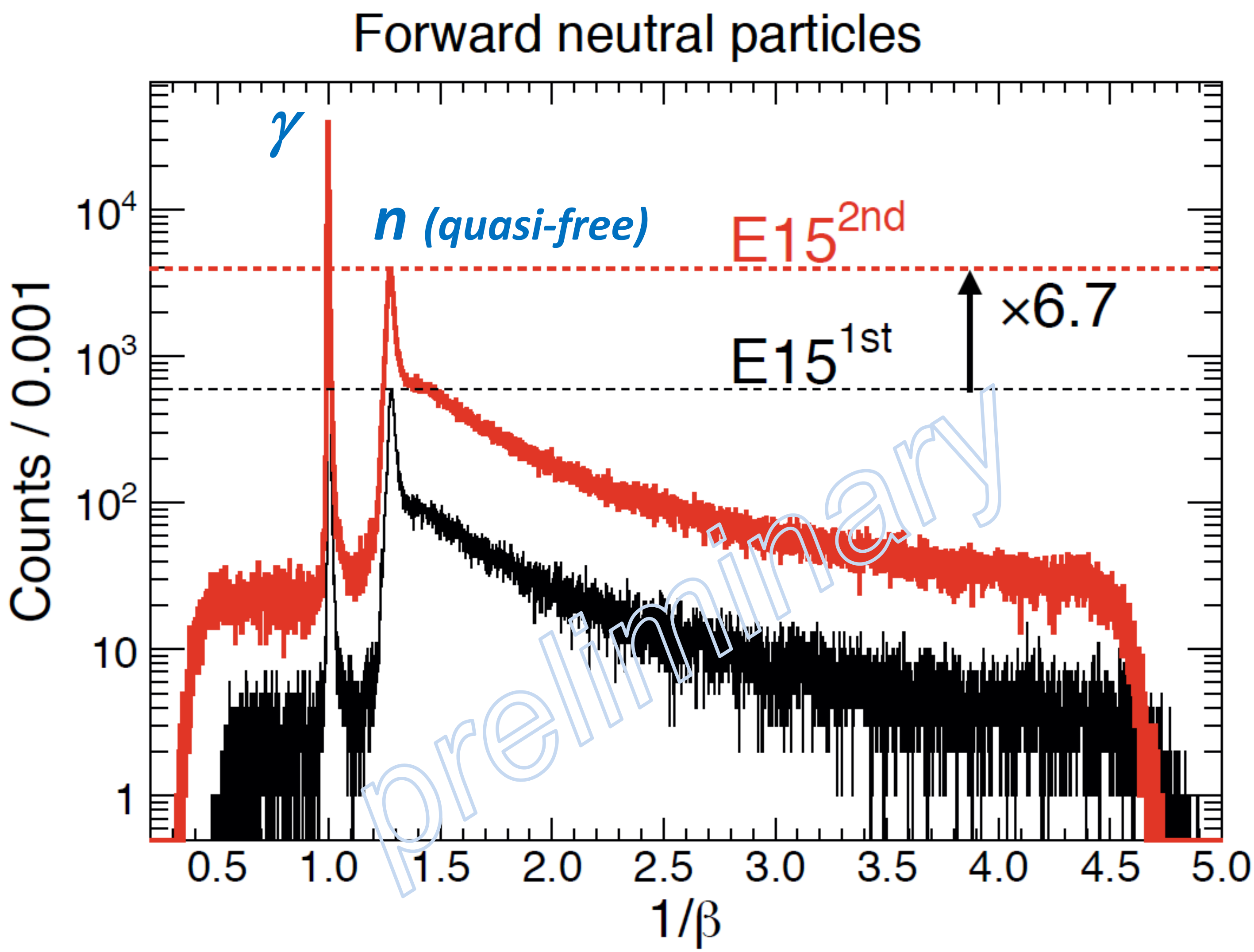
~x8

$^{3}He(K^{-},\Lambda p)$ events in $E15^{2nd}$



- **Dedicated trigger (CDH3) was introduced for $^{3}He(K-,\Lambda p)n$**
- $^{3}He(K-,\Lambda p)$ events increase by ~50 times compared with $E15^{1st}$ data as expected

$^3He(K^-,n)$ events in E15^{2nd}



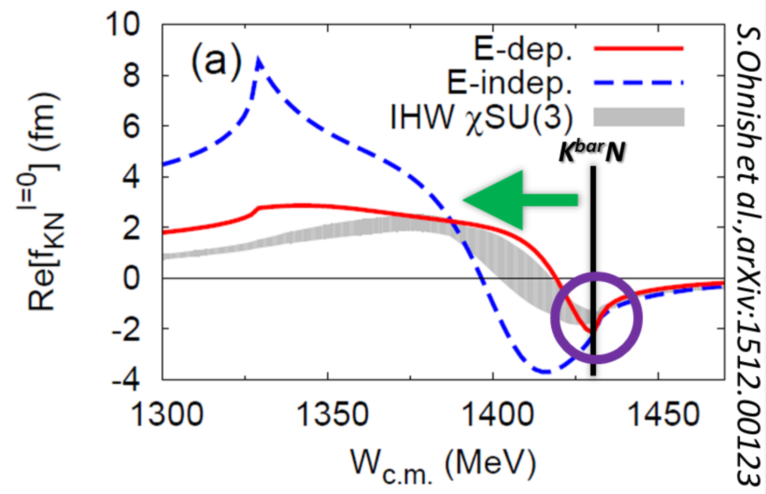
- $^3He(K-,n)$ events increase by ~7 times compared with E15^{1st} data as expected

Summary

To investigate the $K^{bar}N$ interaction, various experiments are proposed/conducting at K1.8BR

- Sensitive in different energy region & isospin -

- **Kaonic-atom: E62/E57**
  - will start in 2017
- **Λ(1405): E31**
  - pre-analysis will be finalized
  - will start in 2016
- **$K^{bar}NN$: E15**
  - fruitful results have been obtained in $E15^{1st}$
  - $E15^{2nd}$ has been just completed
  - $E15^{3rd}$ be discussed after analyzing new data



The Collaborations

J-PARC E15/E31 collaboration

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J-PARC E57 collaboration (K-d)

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