Experimental studies on the K^{bar}N interaction

- Recent Topics from J-PARC -

F. Sakuma, RIKEN

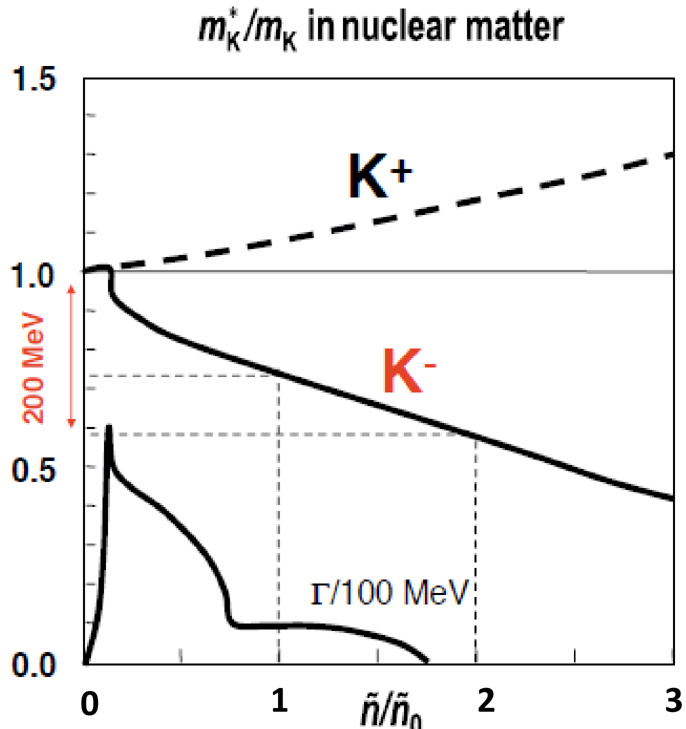
on behalf of the J-PARC E15/E31/E57/E62 collaboration

SNP2017, Mar. 12-14, 2017, Osaka

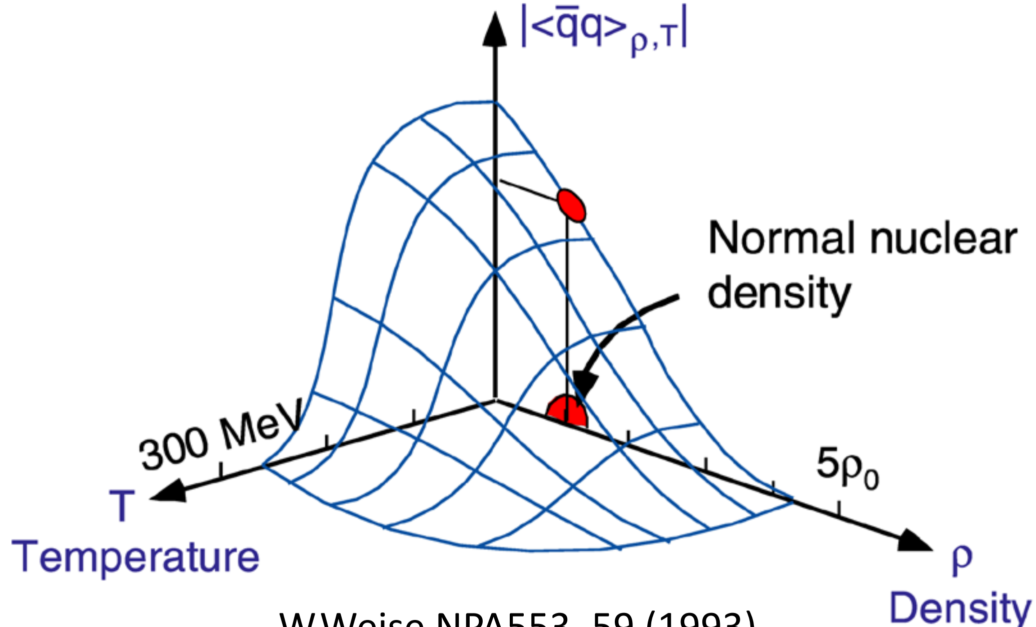
Physics Motivation

- **Meson properties change in nuclear media?**
- **$K^{bar}N$ interaction : attractive in I=0**

→ A good probe for low energy QCD



T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

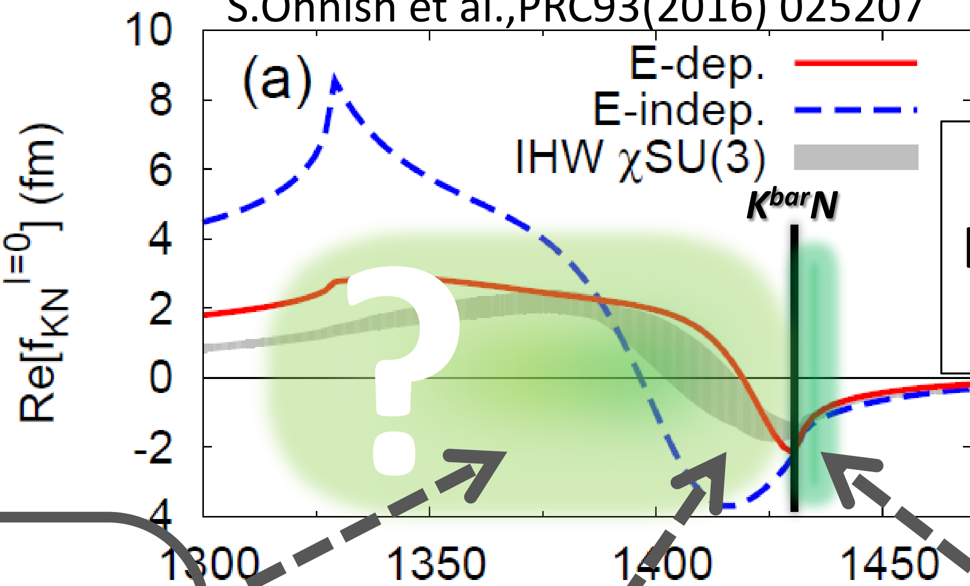


W.Weise NPA553, 59 (1993).

provide new insight on M-B interaction in media

Investigation of K^bar N int. @ J-PARC

S.Ohnish et al.,PRC93(2016) 025207



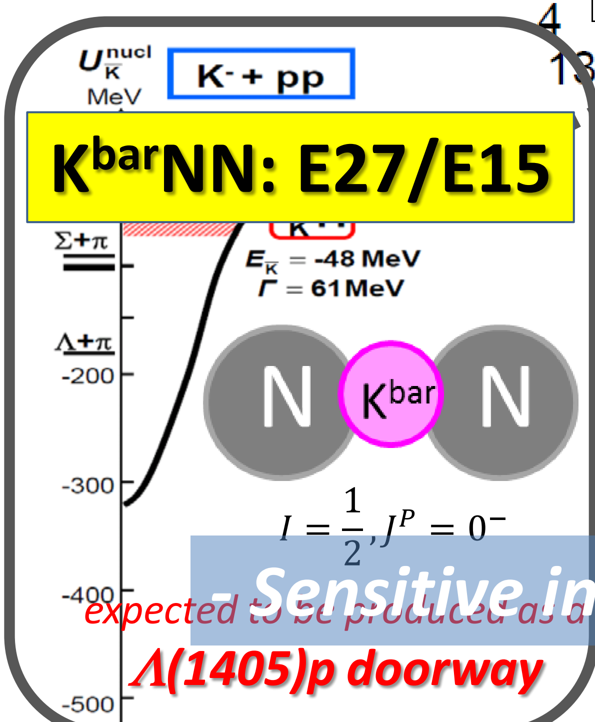
Calculation on K^bar N amplitude in I = 0

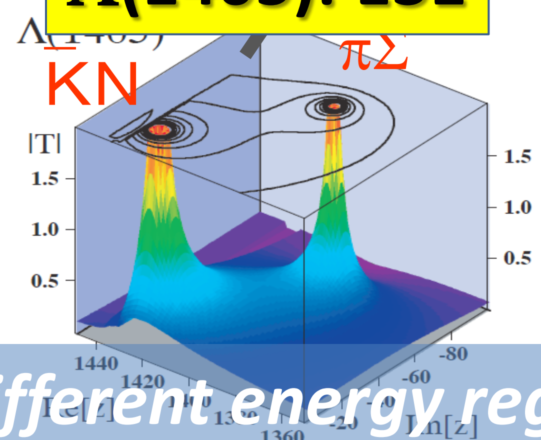
M. Bazzi et al., (SIDDHARTA Coll.), Phys. Lett. B704(2011)113

K^bar NN: E27/E15

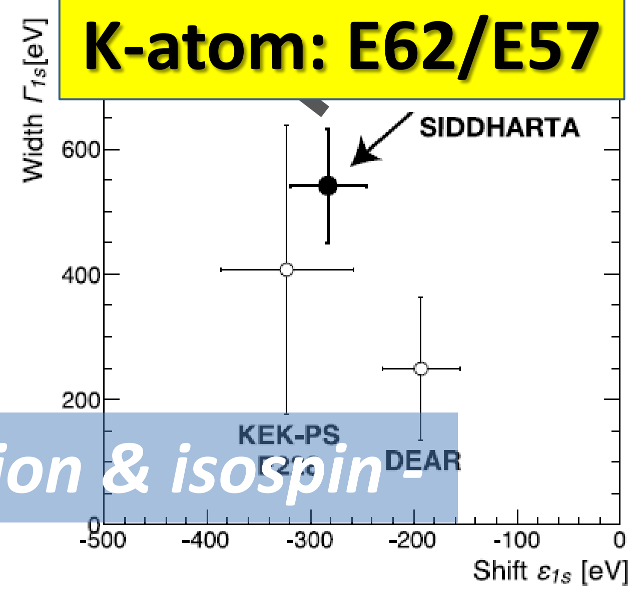
Λ(1405): E31

K-atom: E62/E57





ChU model, T. Hyodo



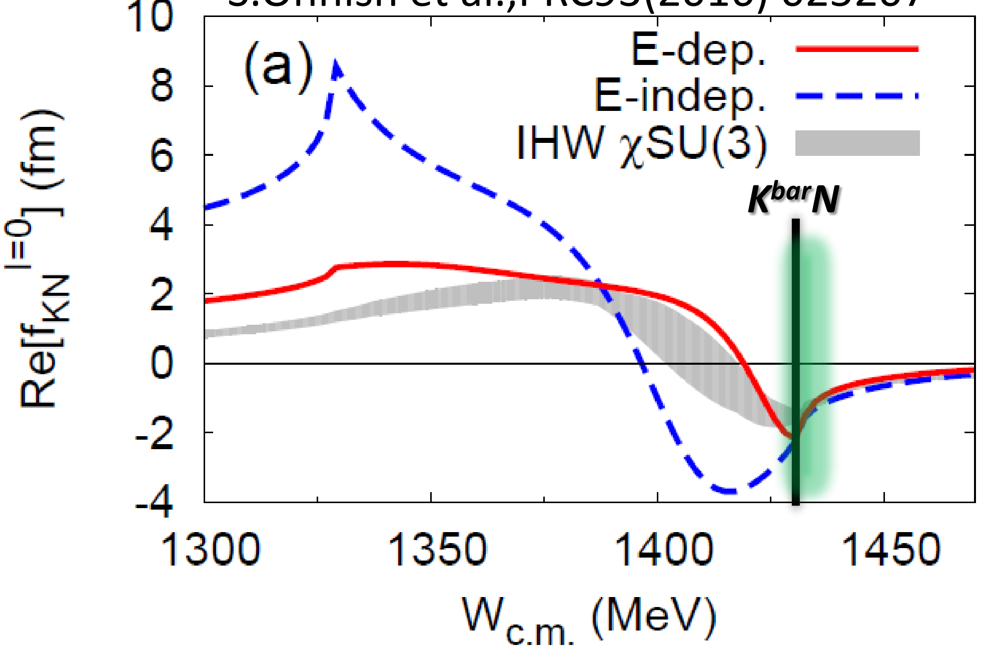
- Sensitive in different energy region & isospin -

① Kaonic-Atom Measurements

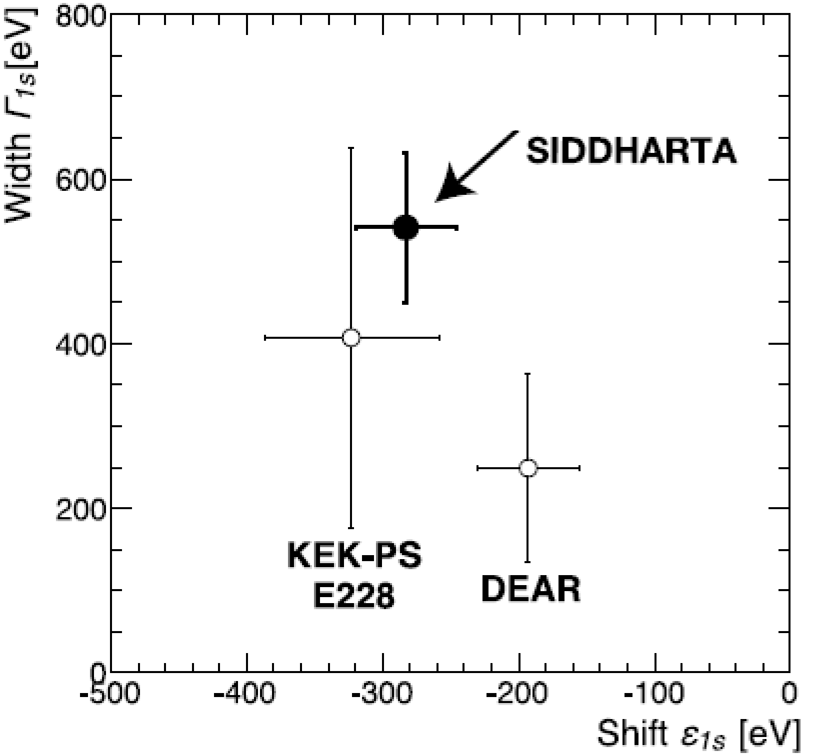
$K^{bar}N$ Interaction at the threshold

- ✓ Low-energy K-p scattering
- ✓ Kaonic hydrogen X-ray

S.Ohnish et al.,PRC93(2016) 025207



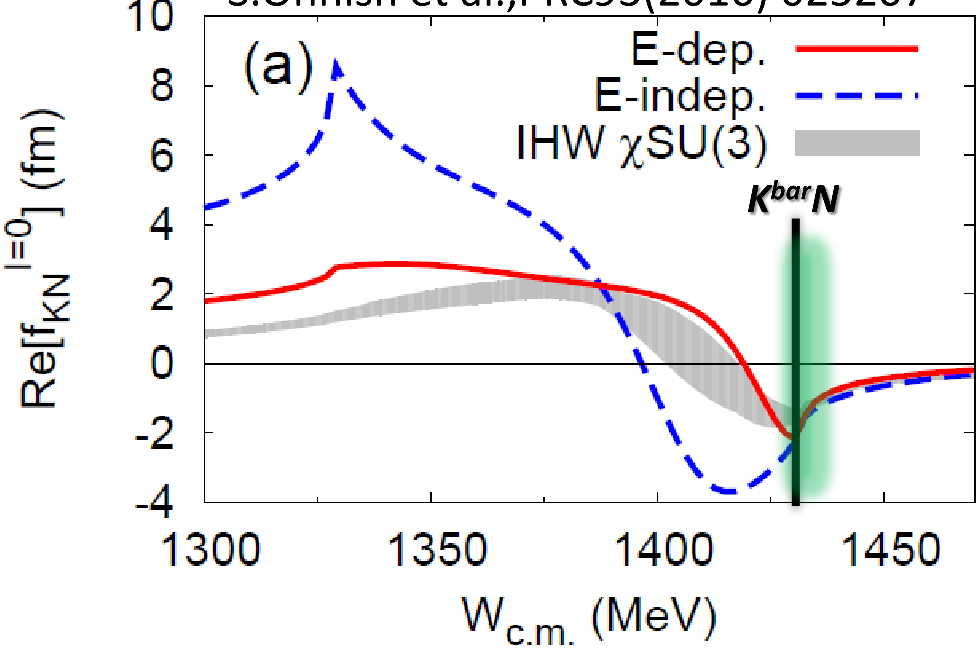
M. Bazzi et al.,(SIDDHARTA Coll.), Phys. Lett. B704(2011)113

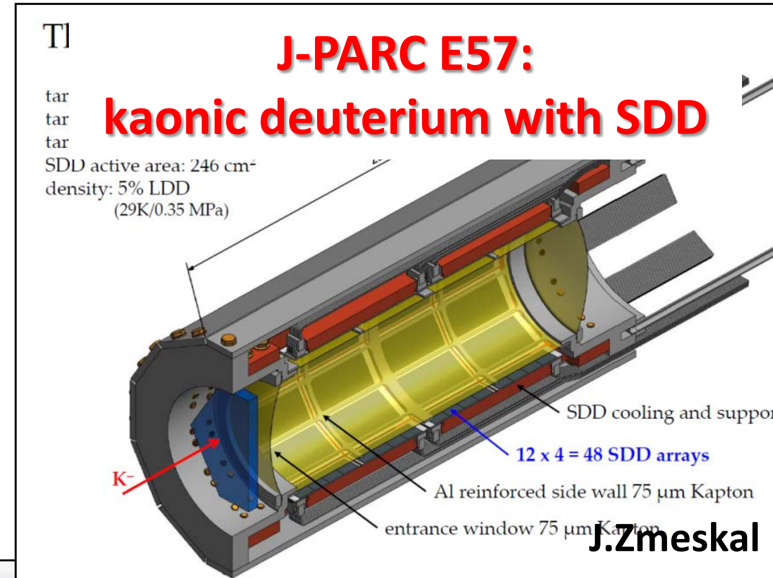


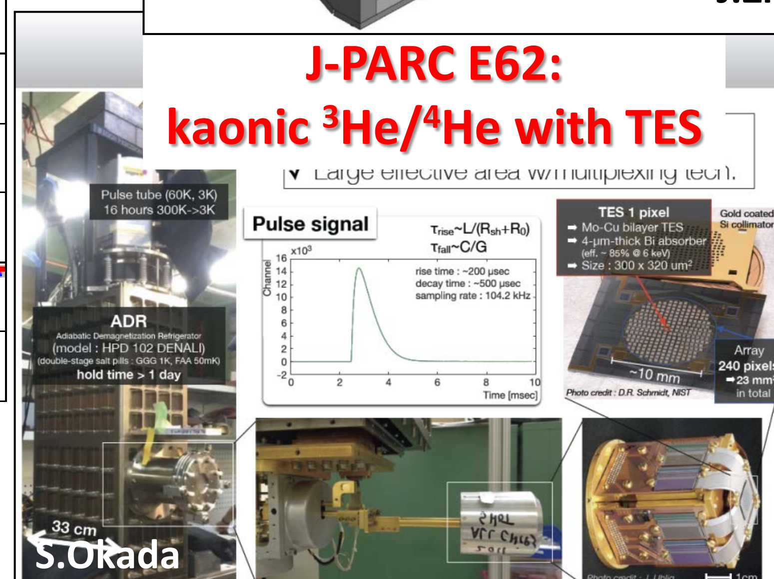
K^barN Interaction at the threshold

- ✓ Low-energy K-p scattering
- ✓ Kaonic hydrogen X-ray
- ? **isospin dependent K^barN**

S.Ohnish et al.,PRC93(2016) 025207

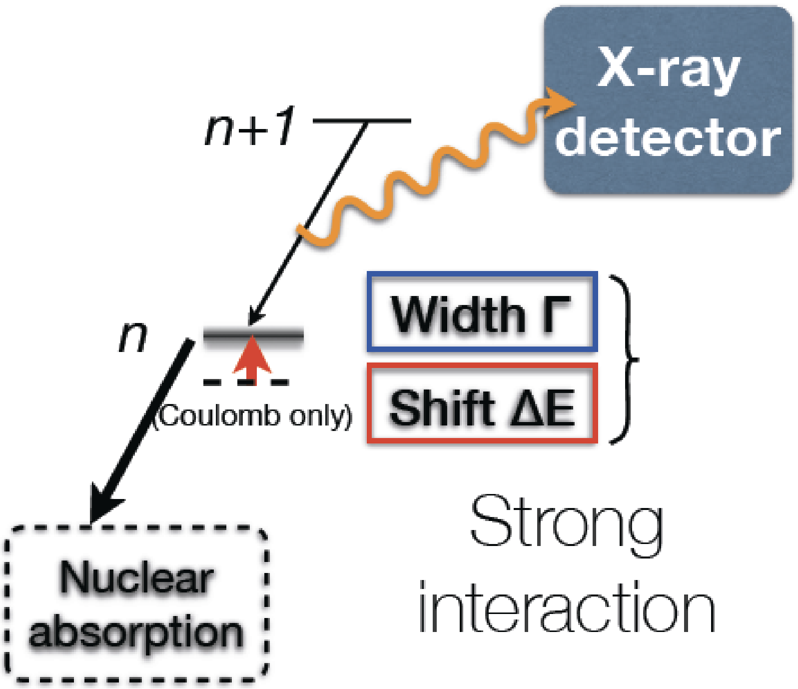






$K^{bar}N$ Interaction via Kaonic-atoms

Kaonic atom X-ray spectroscopy



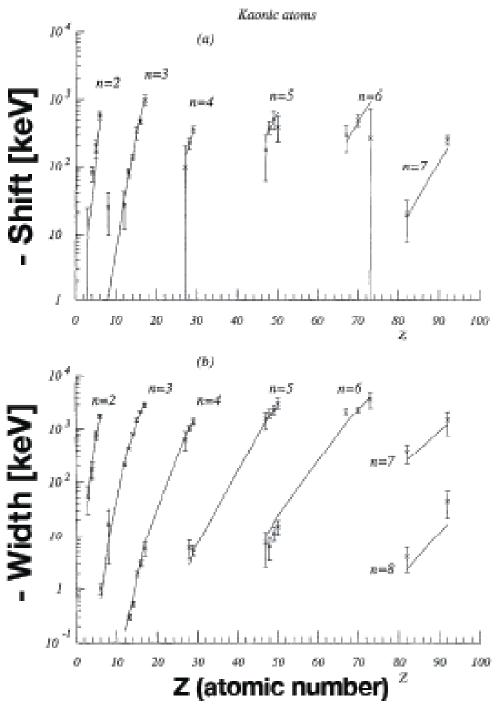
	E62	E57
Kaonic X-ray	**K-He** *3d-2p*	**K-d** *2p-1s*
Energy	~ 6 keV	~ 8 keV
Width	~ 2 eV	~ 1000 eV
Yield per stop-K	~ 7 % (Liquid He)	~ 0.1 % (0.05% of liq. D2 density)
X-ray detector	**TES**	**SDD**
FWHM resolution	~ 5 eV	~ 150 eV
Effective area	~ 0.2 cm^2	~ 200 cm^2
Physics	**K-nucleus potential**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

S.Okada, 21th J-PARC PAC

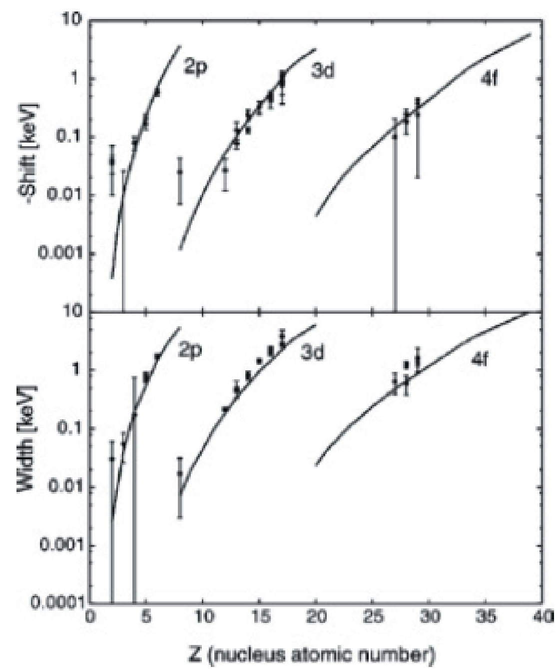
E62: K-nucleus Potential

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

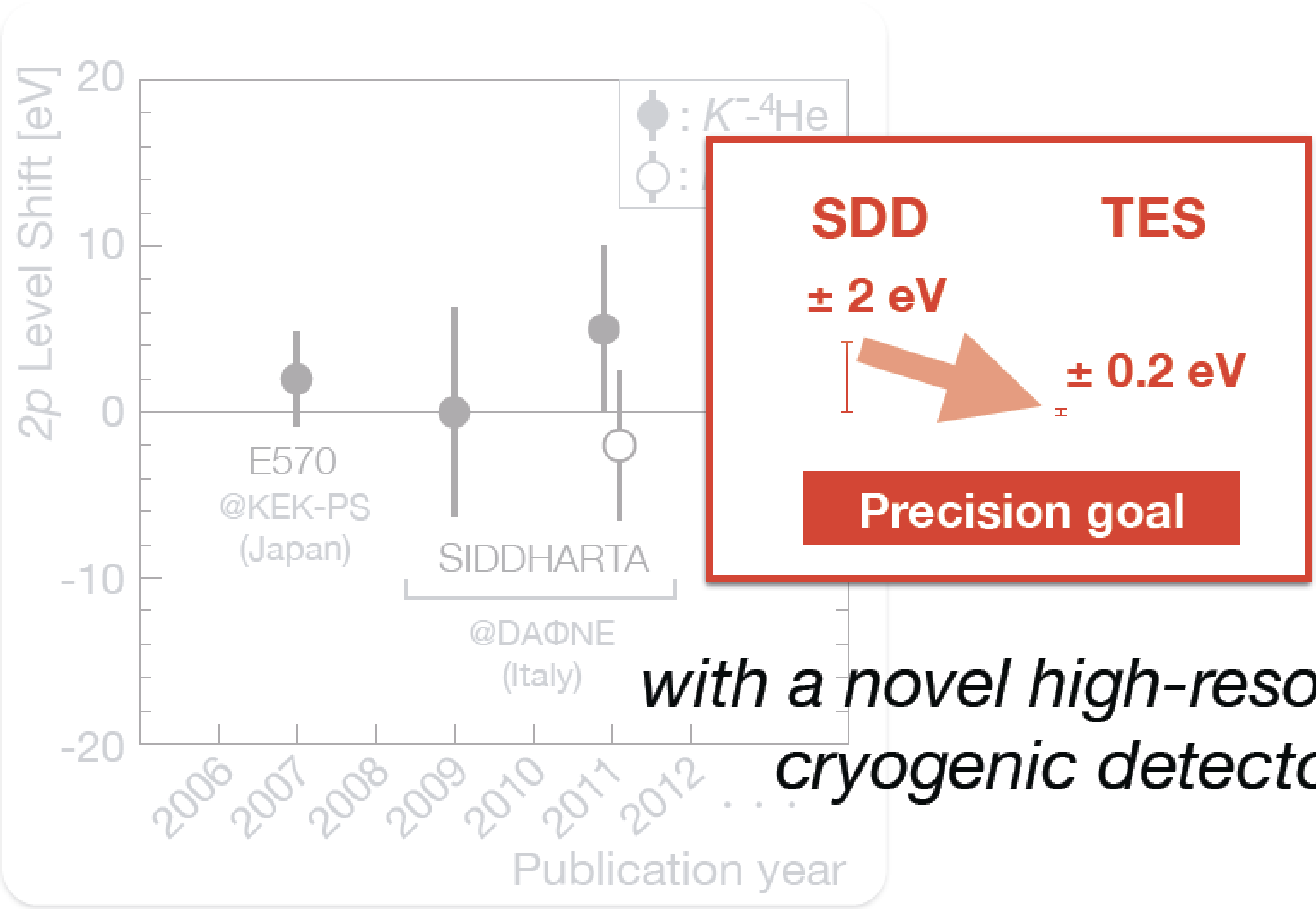
E62: $K^{3/4}$HeX with TES

S.Okada, 21th J-PARC PAC

Theo.

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

Expt.



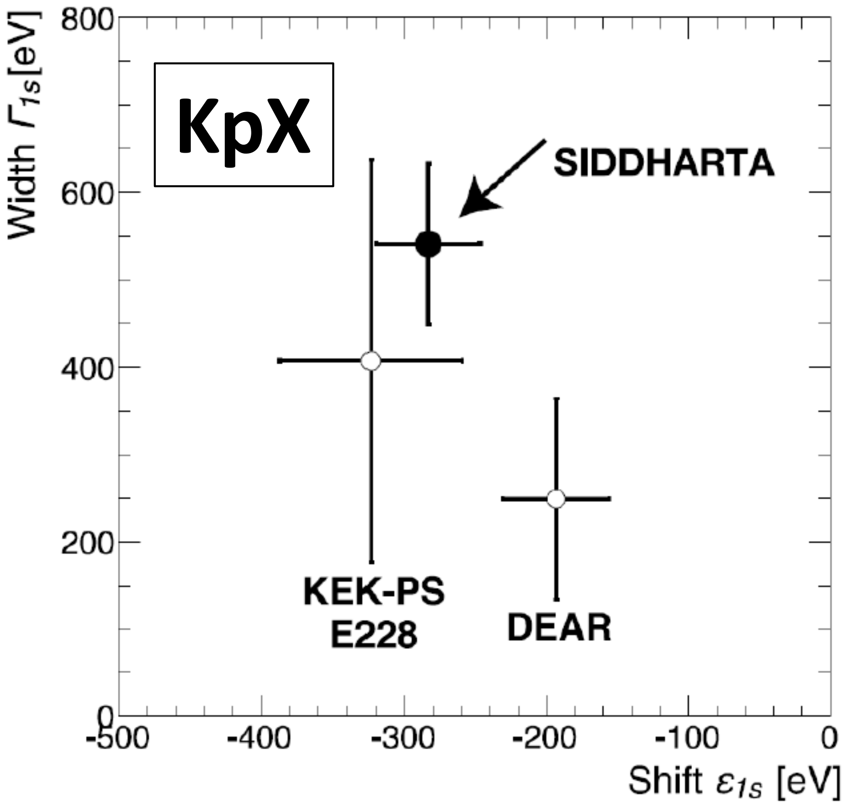
with a novel high-resolution cryogenic detector

E57: KdX Measurement

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}

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

(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

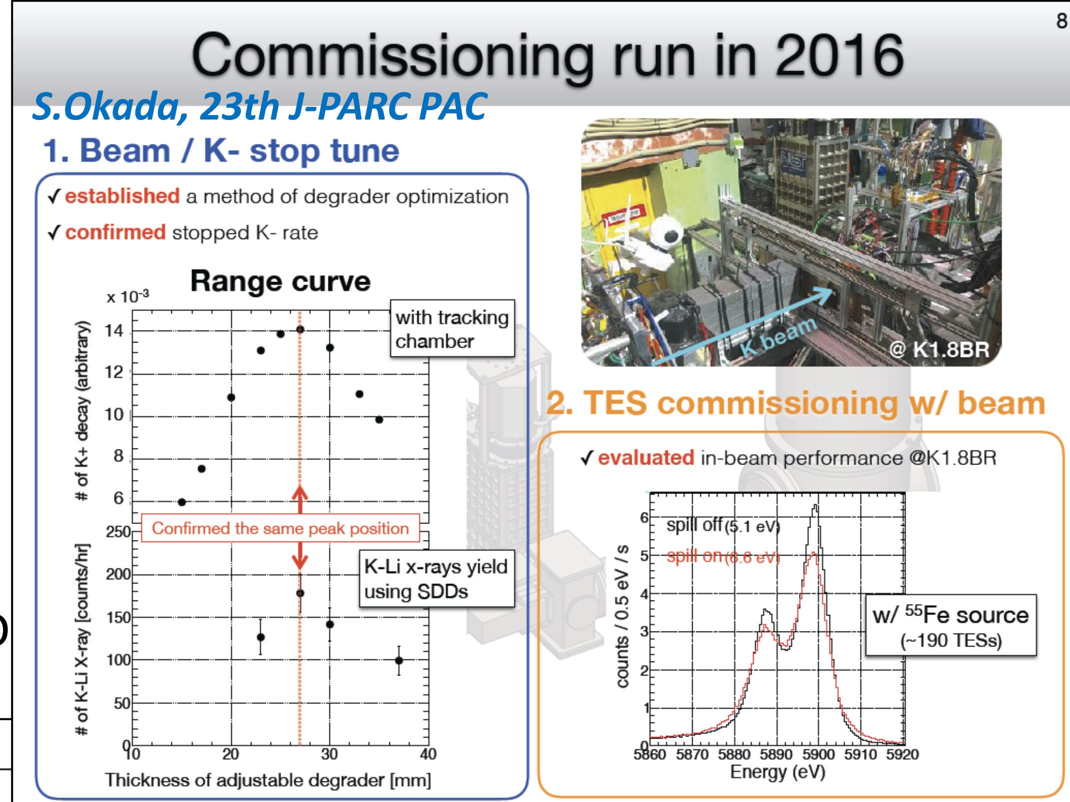
$$a_{K^-p} = \frac{1}{2}[a_0 + a_1]$$

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

$\leftarrow$ a_{K^-d}

Commissioning Runs

- **Successfully performed in 2016**
  - E62: TES under beam-condition
  - E57: K-Li Lα with prototype SDD



Kaonic Lithium 3→2

J.Zmeskal, 23th J-PARC PAC

Sum of all K^- runs, extracted

$K^-Li_{L\alpha}$ transition:

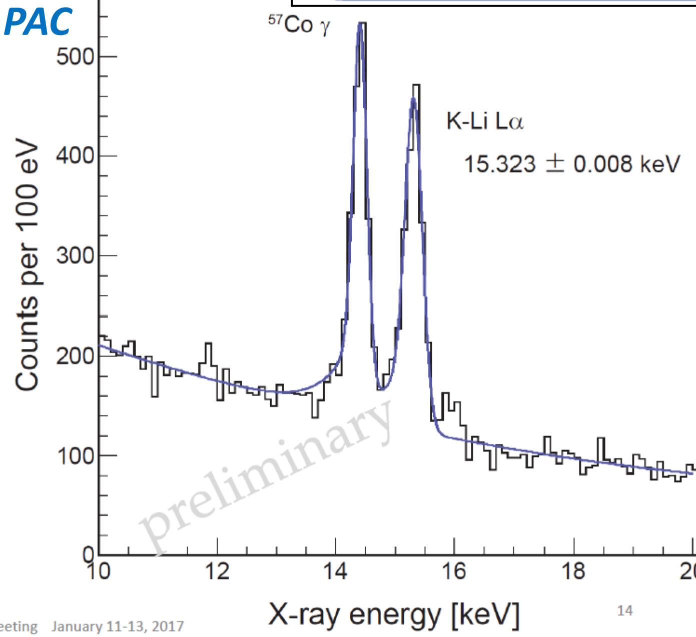
> ➢ 15.323 ± 0.008 keV
> ~ 1200 counts
> resolution 160 eV (sigma)

Theory:

15.330 keV (pure QED)
J.P.Santos et al.
Phys. Rev. A 71 (2005) 032501

Experiment:

15.321 ± 0.024 keV
C.J.Batty et al.
Nuclear Physics A282 (1977) 487



J-PARC 23rd PAC Meeting January 11-13, 2017

- **Scheduled in 2018**
  - E62: production
  - E57: start from K-p before K-d

② Λ(1405) Measurement

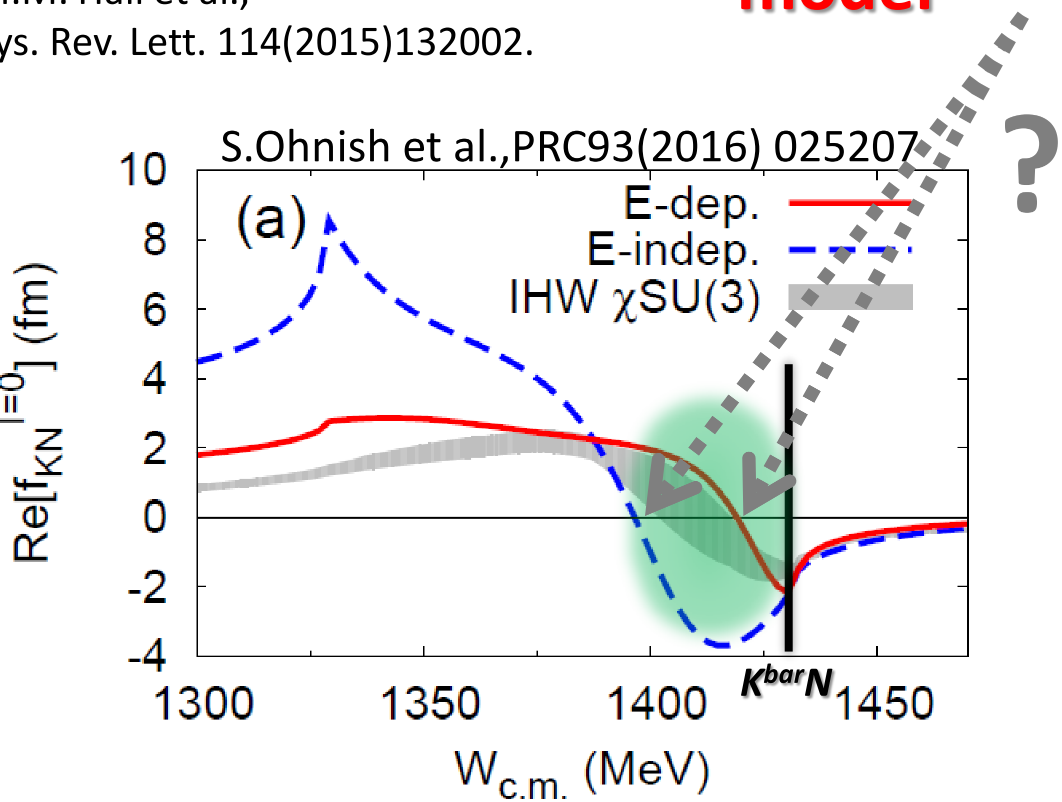
$K^{bar}N$ Interaction below the threshold

- ✓ $K^{bar}N$ int. plays an important role for $\Lambda(1405)$
- ● $J^P = \frac{1}{2}^-$ Moriya et al., (CLAS Coll.), Phys. Rev. Lett. 112(2014)082004
- ● $K^{bar}N$ molecular from LQCD
  J.M.M. Hall et al., Phys. Rev. Lett. 114(2015)132002.

? $\Lambda(1405)$ or $\Lambda(1420)$

➢ **Depending on $K^{bar}N$ int. model**

S.Ohnish et al.,PRC93(2016) 025207

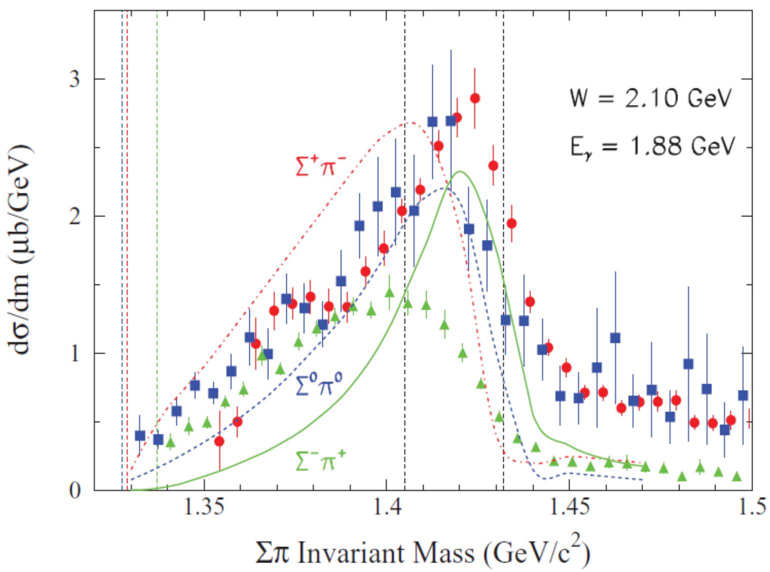


Spectral Shape of $\Lambda(1405)$?

✓ γ/p-induced experiments

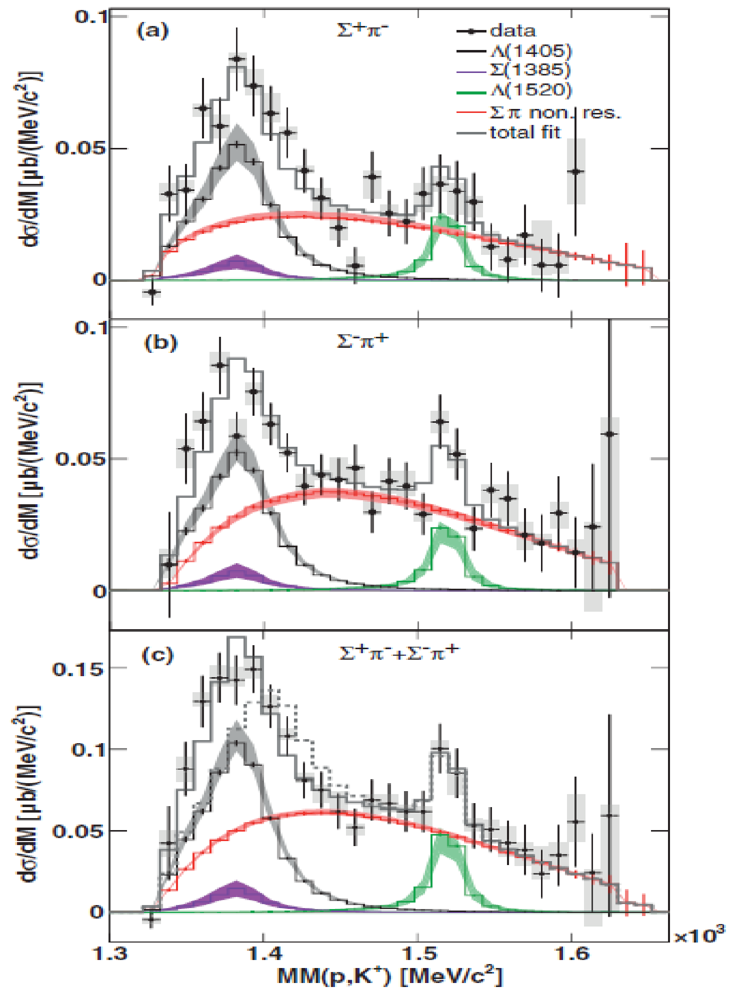
- **Spectral shape is still controversial**

$\gamma p \rightarrow K^+\pi^-\Sigma^+, K^+\pi^0\Sigma^0, K^+\pi^+\Sigma^-$



CLAS collaboration: PRC87, 035206

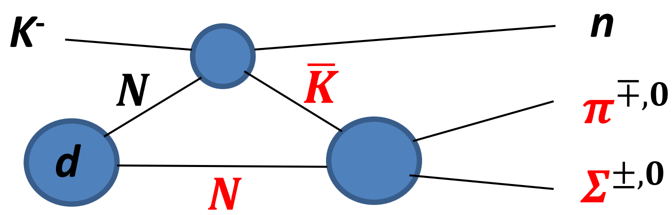
$pp \rightarrow K^+p\pi^-\Sigma^+, K^+p\pi^+\Sigma^-$



HADES collaboration: PRC87, 025201

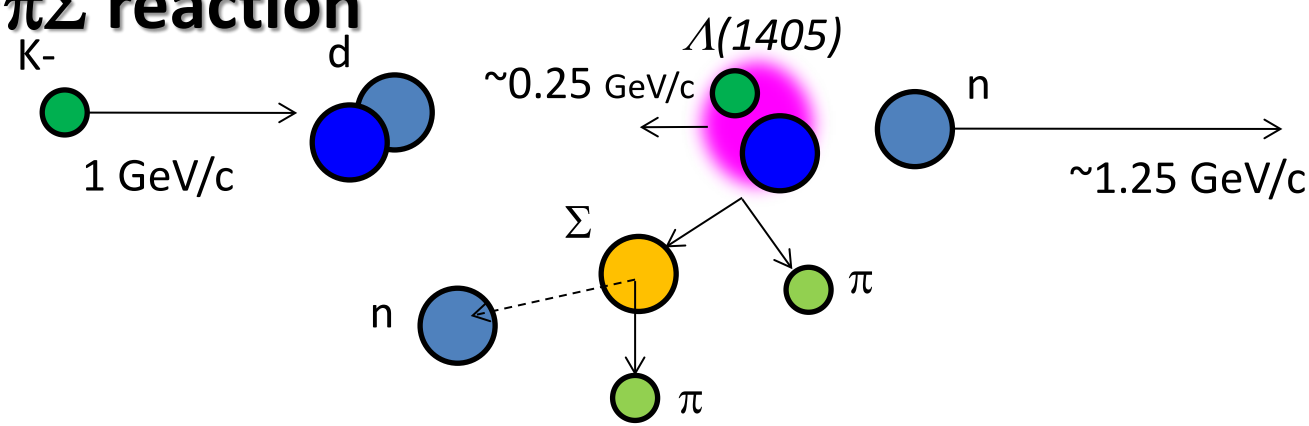
J-PARC E31 Experiment

Measurement of Λ(1405) line shape via K^{bar}N→πΣ



Inoue

- d(K$^-$,n)πΣ reactions at θ_n~0 degree to enhance **S-wave K^{bar}N→πΣ reaction**

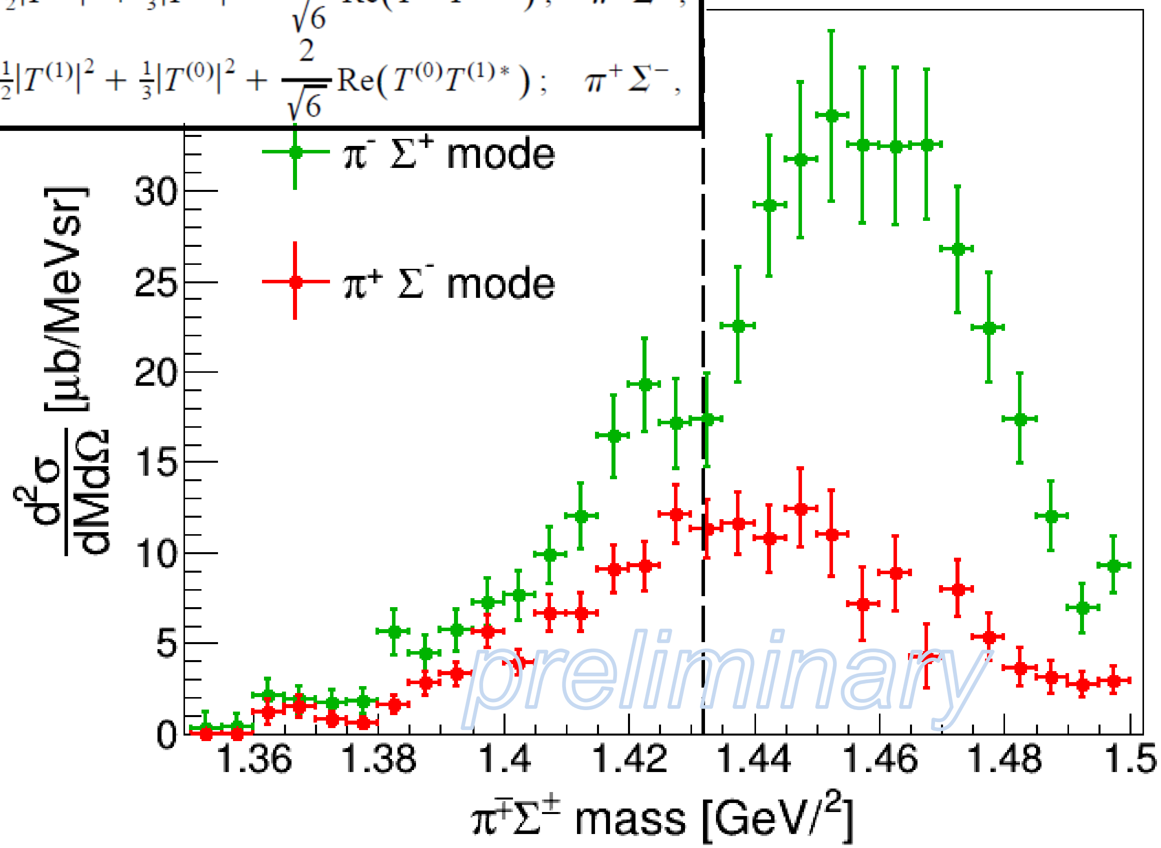


- Decomposition of I=0 and 1 amplitudes by identifying final state

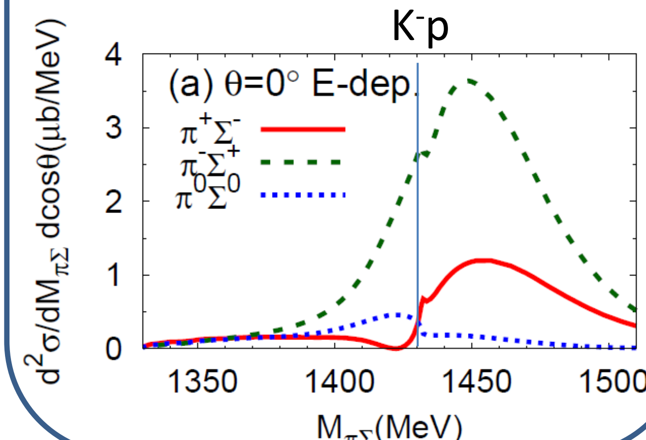
Λ(1405)	**I = 0**	**S wave**	$\pi^{\pm}\Sigma^{\mp}, \pi^{0}\Sigma^{0}$
Σ(1385)	I = 1	P wave	$\pi^{\pm}\Sigma^{\mp}, \pi^{0}\Lambda$
Non-resonant	I = 0,1	S,P,D,…	

I = 0, 1 Mode ($\pi^{\pm}\Sigma^{\mp}$)

$$\frac{1}{2}|T^{(1)}|^2 + \frac{1}{3}|T^{(0)}|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*}); \quad \pi^-\Sigma^+,$$
$$\frac{1}{2}|T^{(1)}|^2 + \frac{1}{3}|T^{(0)}|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*}); \quad \pi^+\Sigma^-,$$

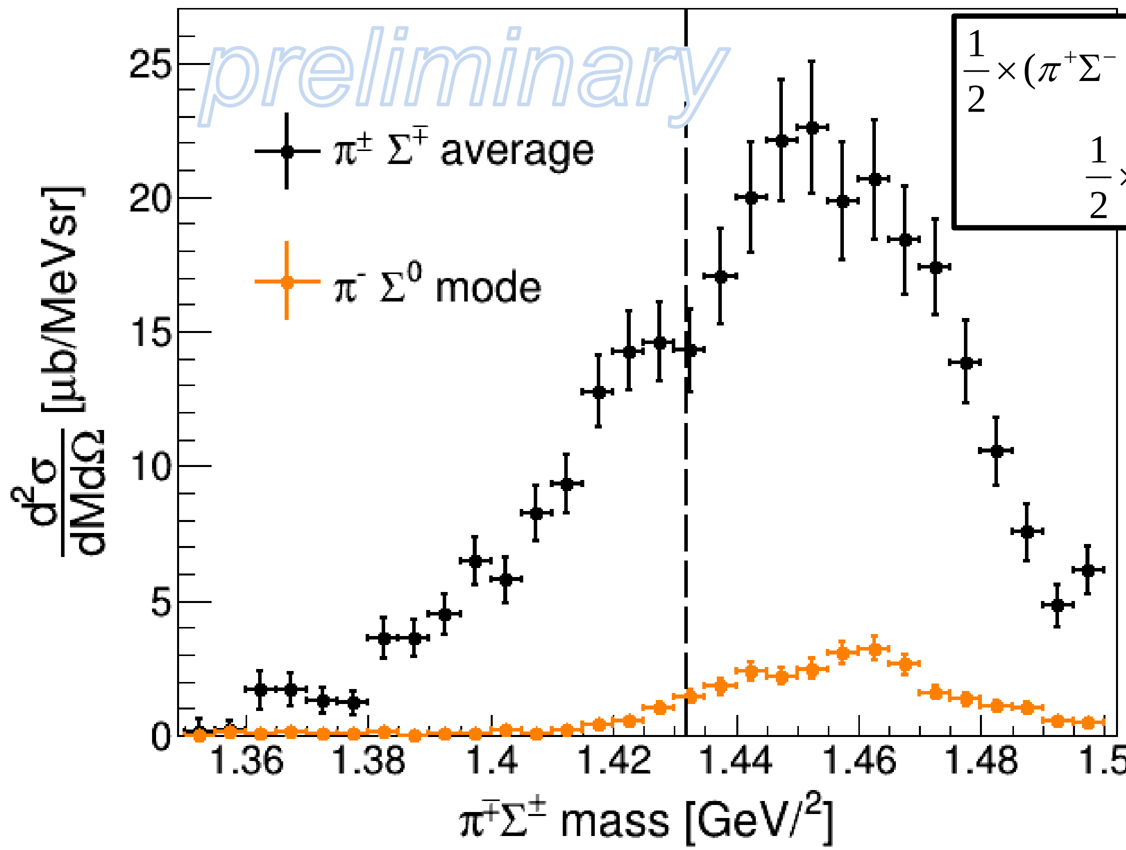


c.f.
Faddeev calc. (AGS)
S.Ohnishi et al., PRC93(2016)025207
w/ angular dependence



- interference between the I = 0 and 1 terms of the $\pi\Sigma$ scattering amplitudes is observed

Comparison between I = 0, 1 ($\pi^{\pm}\Sigma^{\mp}$) & I = 1 ($\pi^{-}\Sigma^{0}$)

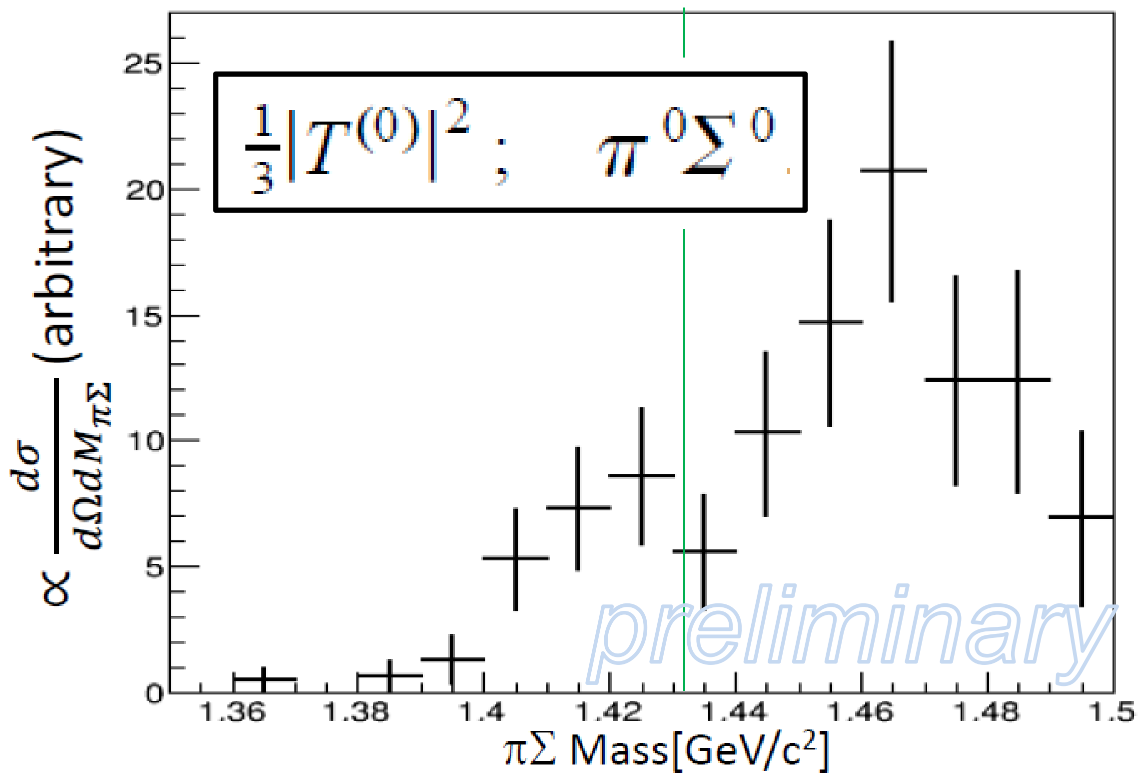


$$\frac{1}{2}\times(\pi^{+}\Sigma^{-}+\pi^{-}\Sigma^{+})=\frac{1}{2}\left|T^{(1)}\right|^{2}+\frac{1}{3}\left|T^{(0)}\right|^{2}$$

$$\frac{1}{2}\times(\pi^{-}\Sigma^{0})=\frac{1}{2}\left|T^{(1)}\right|^{2}$$

- I = 0 dominant below the threshold
  - $|T^{(0)}|^2/|T^{(1)}|^2 \sim 100$

I = 0 Mode ($\pi^0\Sigma^0$)

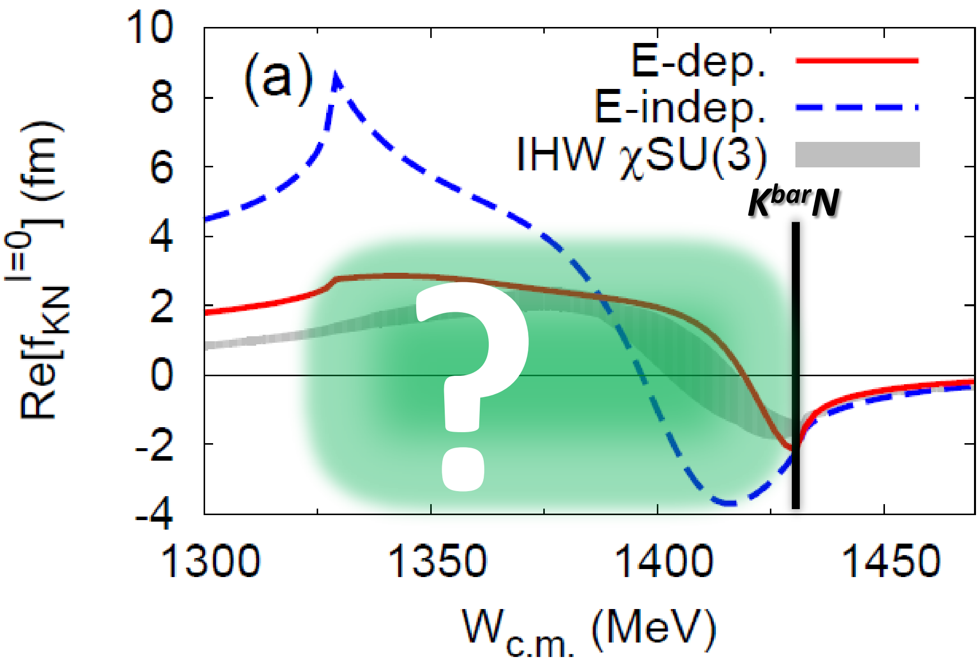


- The pure I = 0 channel is observed
- For further statistics:
  - **E31-2nd will be performed in May-Jun. 2017**

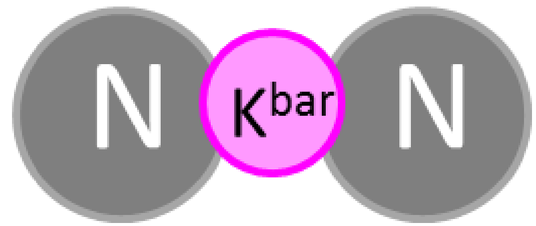
③ Kaonic-Nuclei Searches

Kaonic Nuclei

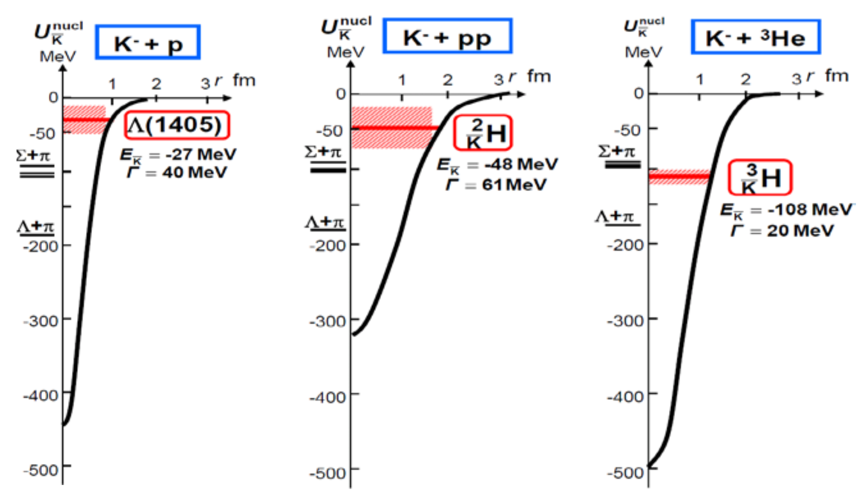
- **Bound states of nucleus and anti-kaon**
- Predicted as a consequence of **attractive $K^{bar}N$ interaction in I=0**



the simplest kaonic nuclei:



$$I = \frac{1}{2}, J^P = 0^-$$



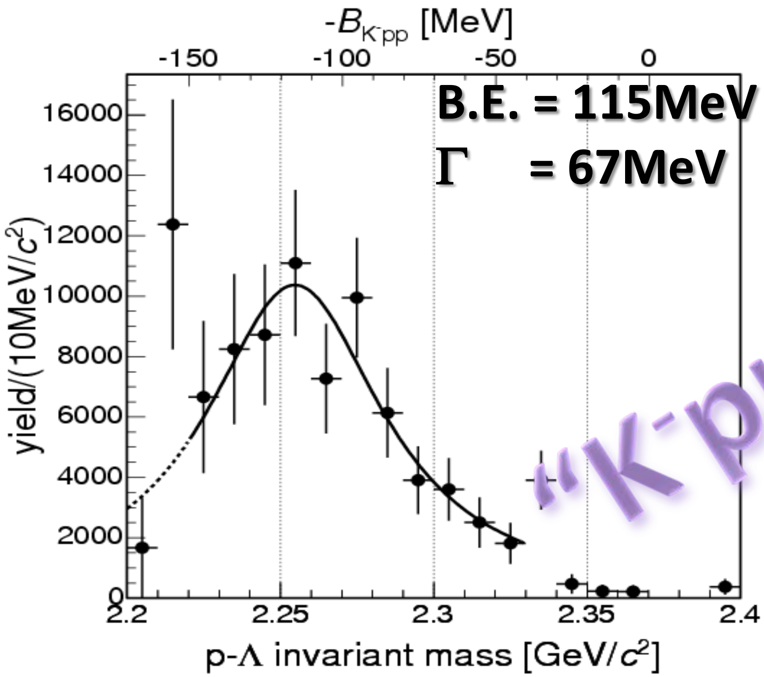
Y.Akaishi & T.Yamazaki, PLB535, 70(2002).

Theoretical Calculations on $K^{bar}NN$

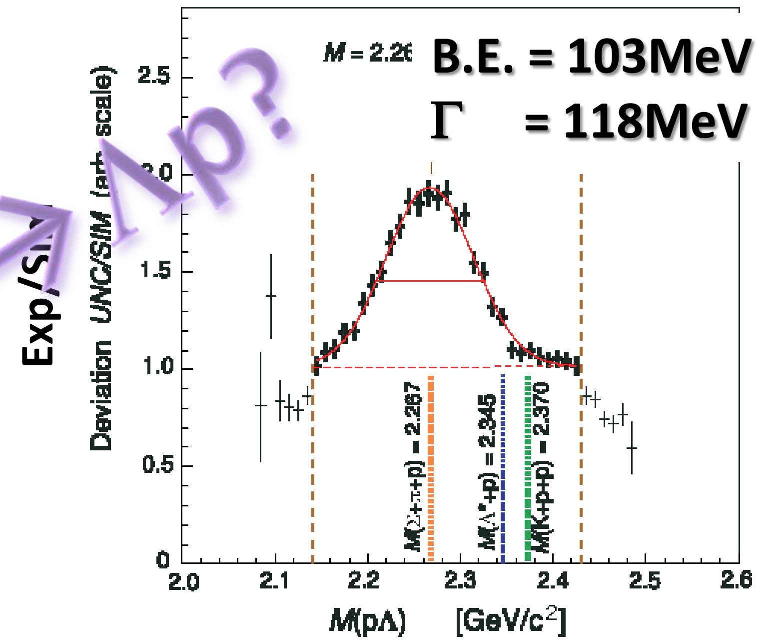
$K^{bar}N$ int.	Chiral SU(3) (energy dependent)			Phenomenological (energy independent)			
Method	Variational		Faddeev	Variational		Faddeev	
	Barnea, Gal, Liverts	Dote, Hyodo, Weise	Ikeda, Kamano, Sato	Yamazaki, Akaishi	Wyceck, Green	Shevchenko, Gal, Mares	Ikeda, Sato
B (MeV)	**16**	**17-23**	**9-16**	**48**	**40-80**	**50-70**	**60-95**
Γ (MeV)	**41**	**40-70**	**34-46**	**61**	**40-85**	**90-110**	**45-80**

- **$K^{bar}N$ interaction model:**
  - Chiral SU(3) [energy dependent] → **B.E. ~ 20 MeV**
  - Phenomenological [energy independent] → **B.E. ~ 40-70 MeV**
- **Calculation method:**
  - Almost the same results = *depending on $K^{bar}N$ interaction*

Pioneering Experiments on K^{bar}NN



"K$^-$pp" → Λp?



FINUDA@DAΦNE

PRL**94**(2005)212303

^{6}Li+^{7}Li+^{12}C(*stopped* K$^-$, Λp)

2NA followed by FSI?

PRC74(2006)025206

PRC82(2010)034608 etc.

DISTO@SATURNE

PRL**104**(2010)132502

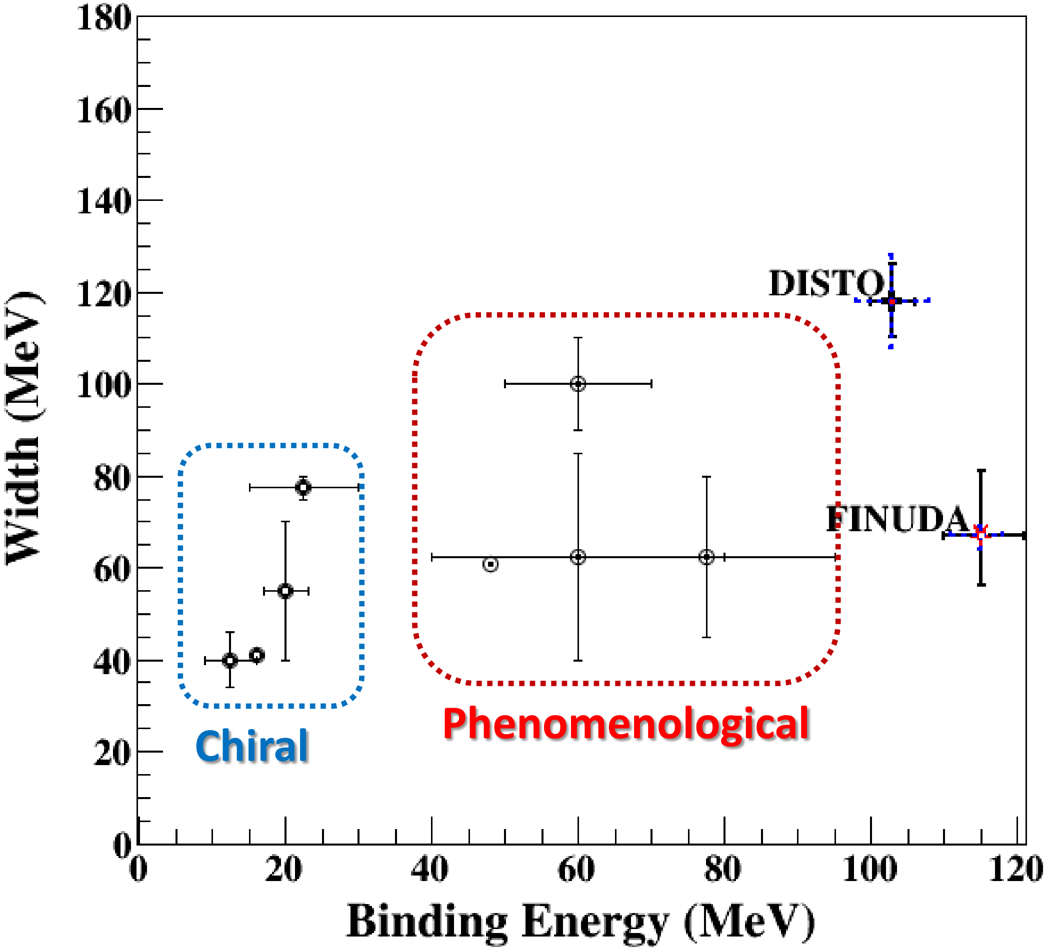
p + p → (Λ + p) + K$^+$ @ 2.85GeV

pp→p(N*)→p(ΛK$^+$)?

PRC92(2015)044002

vs. **K.Suzuki, HYP2015 talk**

Comparison between Calcs. and Exps.



- **Binding energy**
  - Chiral:
    B.E. ~ 20MeV
  - Phenomenological:
    B.E. ~ 40-80MeV
  - FINUDA/DISTO *(if $K^{bar}NN$)*:
    B.E. ~ 100MeV
- **Width**
  - almost agreement in Γ~40-100MeV
    - Theor.: mesonic decay
    - Exp.: non-mesonic decay

Upper limits were also obtained:

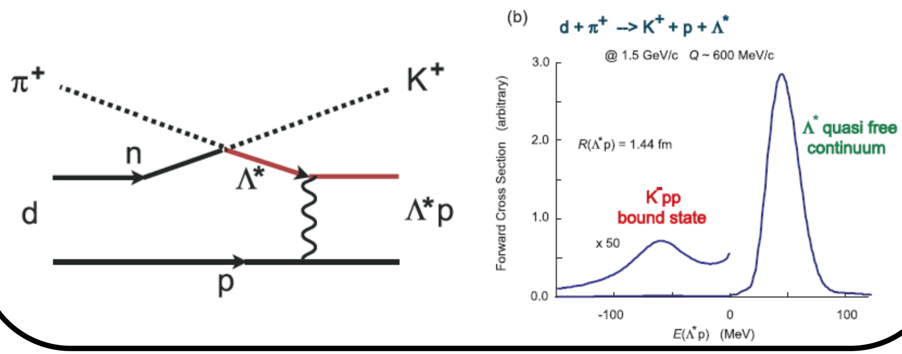
- **LEPS@SPring8 [Inclusive $d(\gamma, K^+\pi^-)X$]**
- **HADES@GSI [Exclusive $pp \rightarrow p\Lambda K^+$]**

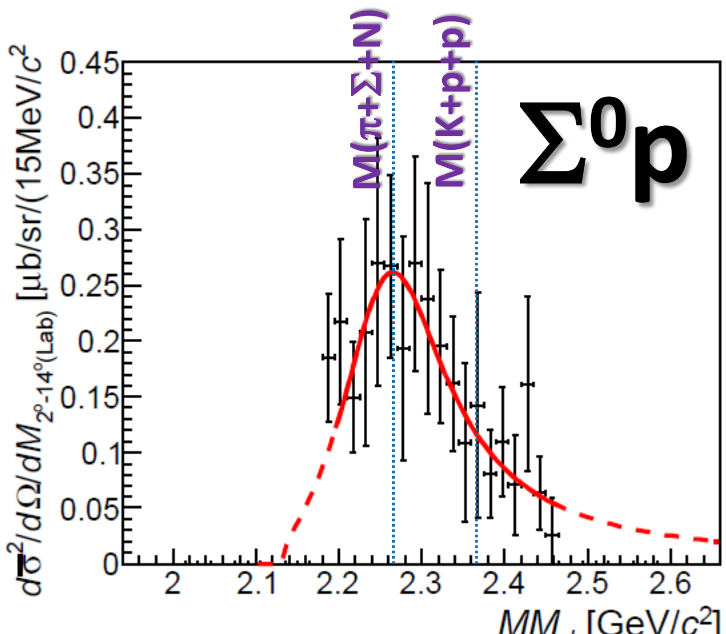
Recent Measurement at J-PARC E27

π^+ + "n" --> "Λ^*" + K^+

"Λ^*" + "p" --> bound K^-pp *minor*

--> quasi-free Λ^* *dominant*





Y. Ichikawa et al., PTEP (2015) 021D01.

- **Exclusive** $\pi^+ d \rightarrow K^+ Y p$
  - $p_{\pi+}$ = 1.69 GeV/c
  - $\Delta p/p \sim 2\times10^{-3}$
  - $\Delta\Omega \sim 100$ msr
  - **final-state is identified by MM[d(π^+,K^+pp)X]**
- **Bump structure in $\Sigma^0 p$ decay mode:**
  - Mass

$$2275 \,^{+17}_{-18}\,(\mathrm{stat.})\,^{+21}_{-30}\,(\mathrm{syst.})\ \mathrm{MeV}/c^2$$

  - Binding energy

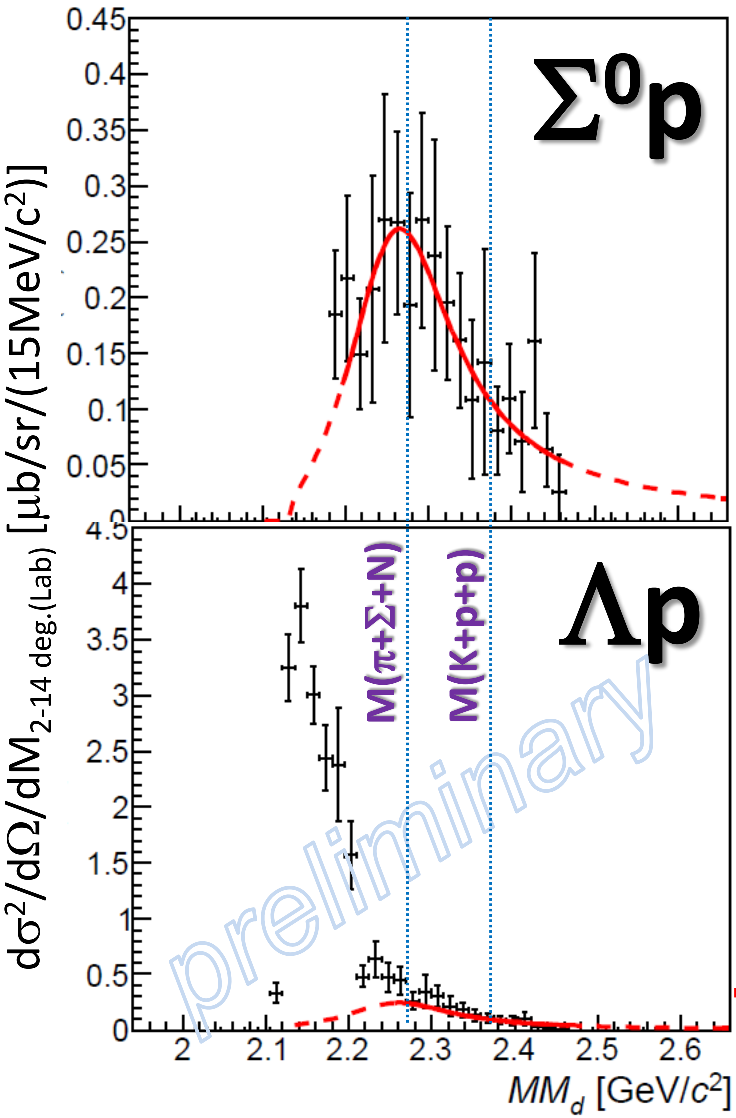
$$95 \,^{+18}_{-17}\,(\mathrm{stat.})\,^{+30}_{-21}\,(\mathrm{syst.})\ \mathrm{MeV}$$

  - Width

$$162 \,^{+87}_{-45}\,(\mathrm{stat.})\,^{+66}_{-78}\,(\mathrm{syst.})\ \mathrm{MeV}$$

Recent Measurement at J-PARC E27

Y. Ichikawa et al., PTEP (2015) 021D01.



- Decay branch:

$$\Gamma_{\Lambda p}/\Gamma_{\Sigma^0 p} = 0.92\ ^{+0.16}_{-0.14}\ (\mathrm{stat.})\ ^{+0.60}_{-0.42}\ (\mathrm{syst.}).$$

Theor. Cal. on Y*N→YN : $\Gamma_{\Lambda p}/\Gamma_{\Sigma 0p}$ = 1.2

Sekihara, Jido, Kanda-En'yo PRC79(2009)062201(R).

- $d\sigma/d\Omega_{\text{“K-pp”}\to\Sigma 0p}$:

$$3.0 \pm 0.3\ (\mathrm{stat.})\ ^{+0.7}_{-1.1}\ (\mathrm{syst.})\ \mu b/sr$$

Y.Ichikawa, PhD-thesis. Kyoto-U (2015)

$p(\pi^-,K^0)\Lambda(1405)$ @ 1.69GeV/c:
$d\sigma/d\Omega_{\Lambda(1405)}$=36.9μb/sr
BNL, NPB56(1973)15

= $(d\sigma/d\Omega_{\text{“K-pp”}\to Yp}) / (d\sigma/d\Omega_{\Lambda(1405)})$ ~ 7-8%

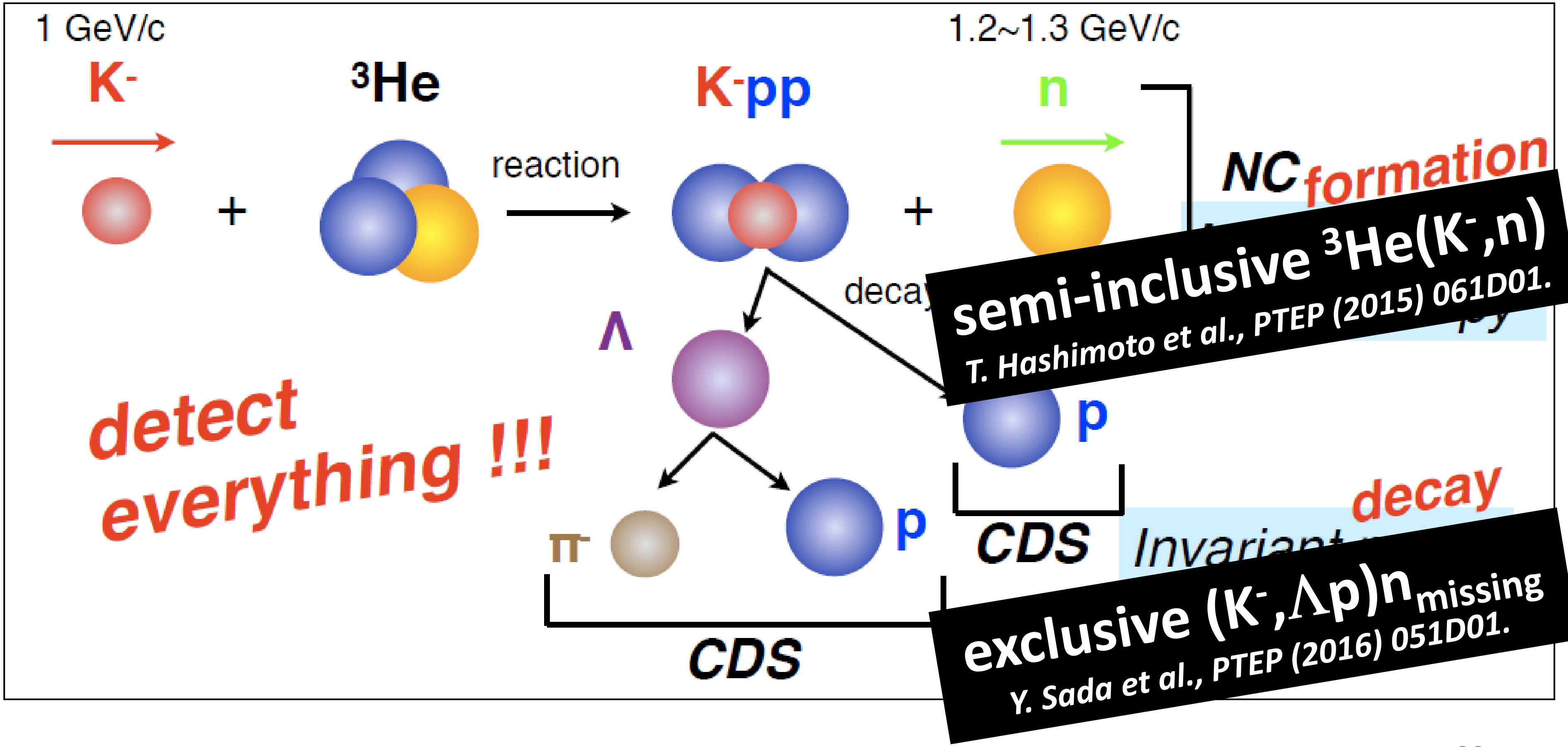
→ large prob. of Λ(1405)p→“K^-pp”

c.f., large prob. in DISTO, but < 50% in HADES

T.Nagae

J-PARC E15 Experiment

- ^{3}He(*in-flight* K^-,n) reaction @ 1.0 GeV/c
  - 2NA processes and Y decays can be discriminated kinematically



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

--- result of E15-1st in 2013 ---

Y.Sada et al., PTEP (2016) 051D01.

PTEP

Prog. Theor. Exp. Phys. **2016**, 051D01 (11 pages)
DOI: 10.1093/ptep/ptw040

Letter

Structure near the $K^- + p + p$ threshold in the in-flight $^3He(K^-, \Lambda p)n$ reaction

J-PARC E15 Collaboration

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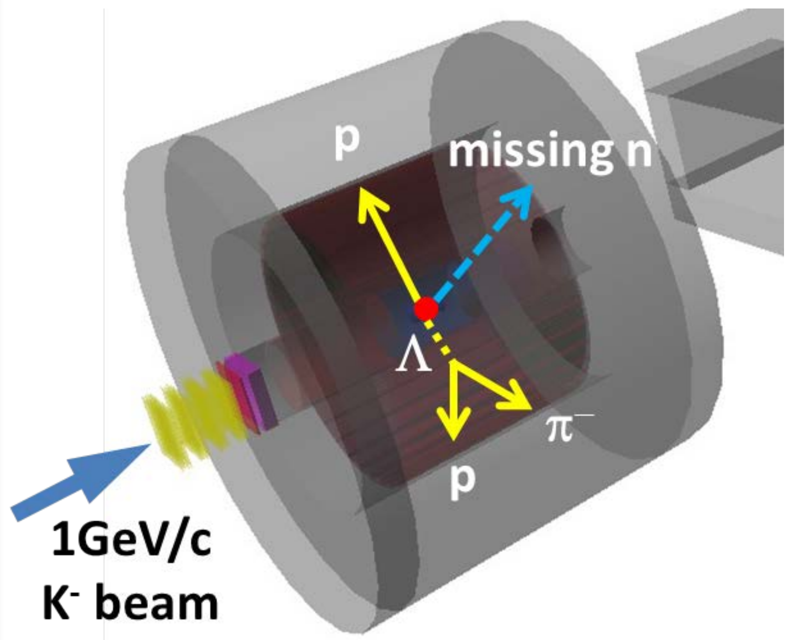
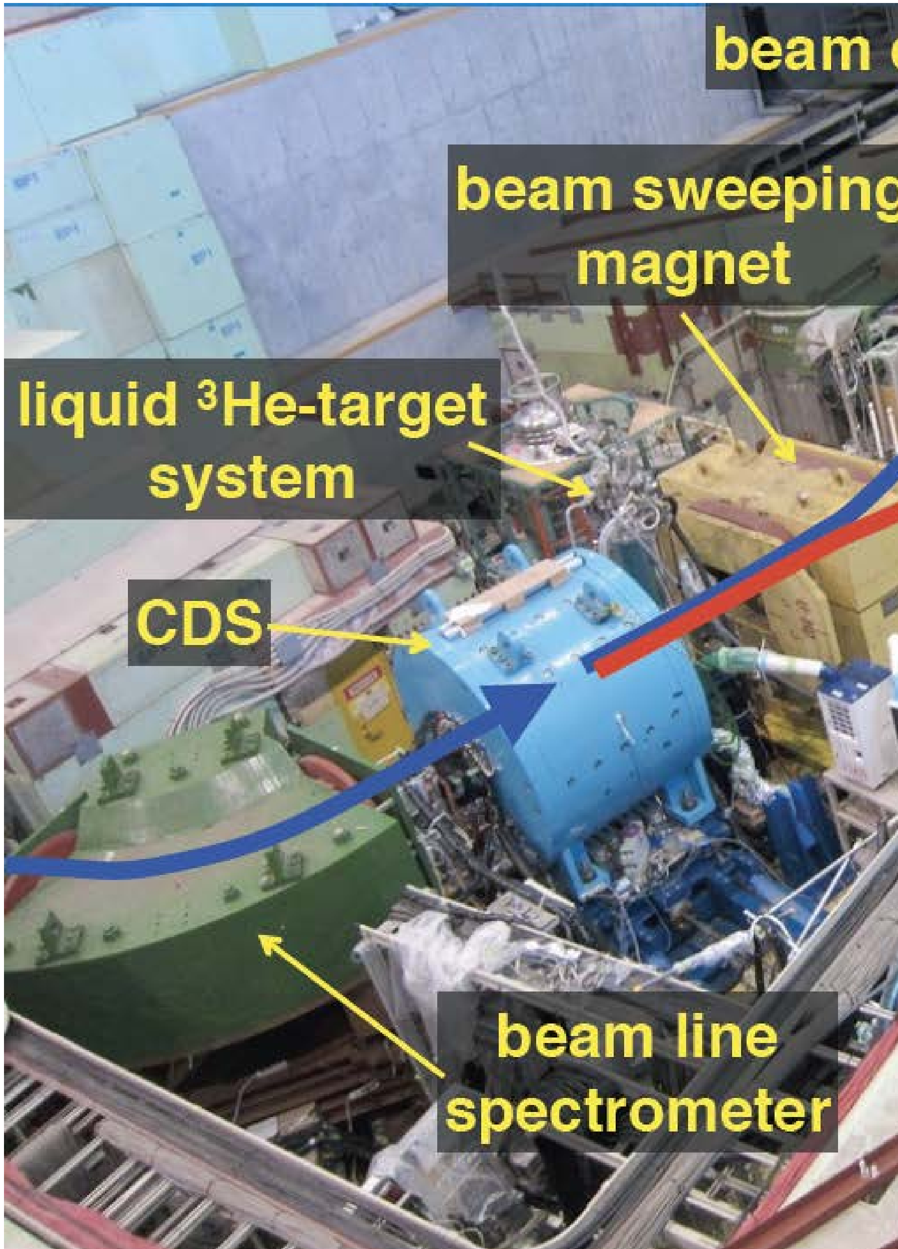
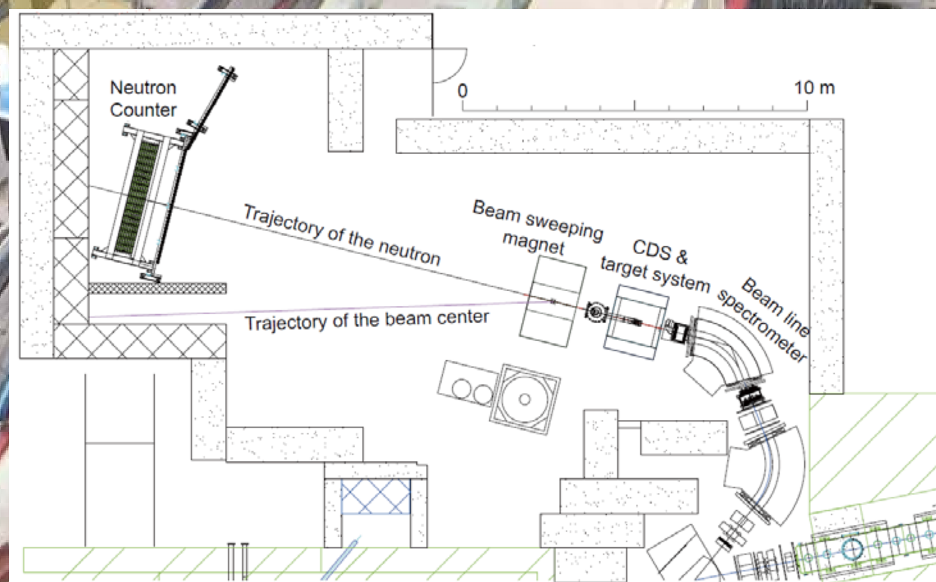


Experimental Setup

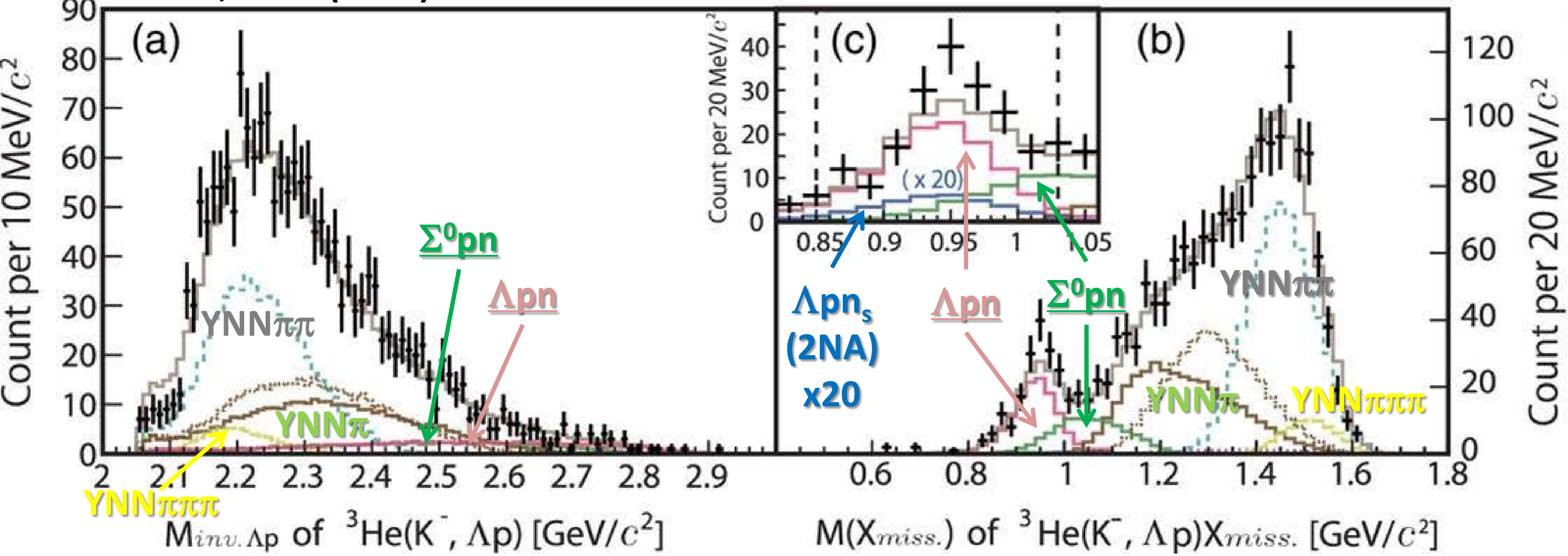




K. Agari et. al., PTEP 2012, 02B011

n-ID from Inclusive ^{3}He(K$^-$,Λp)X

Y. Sada et al., PTEP (2016) 051D01.



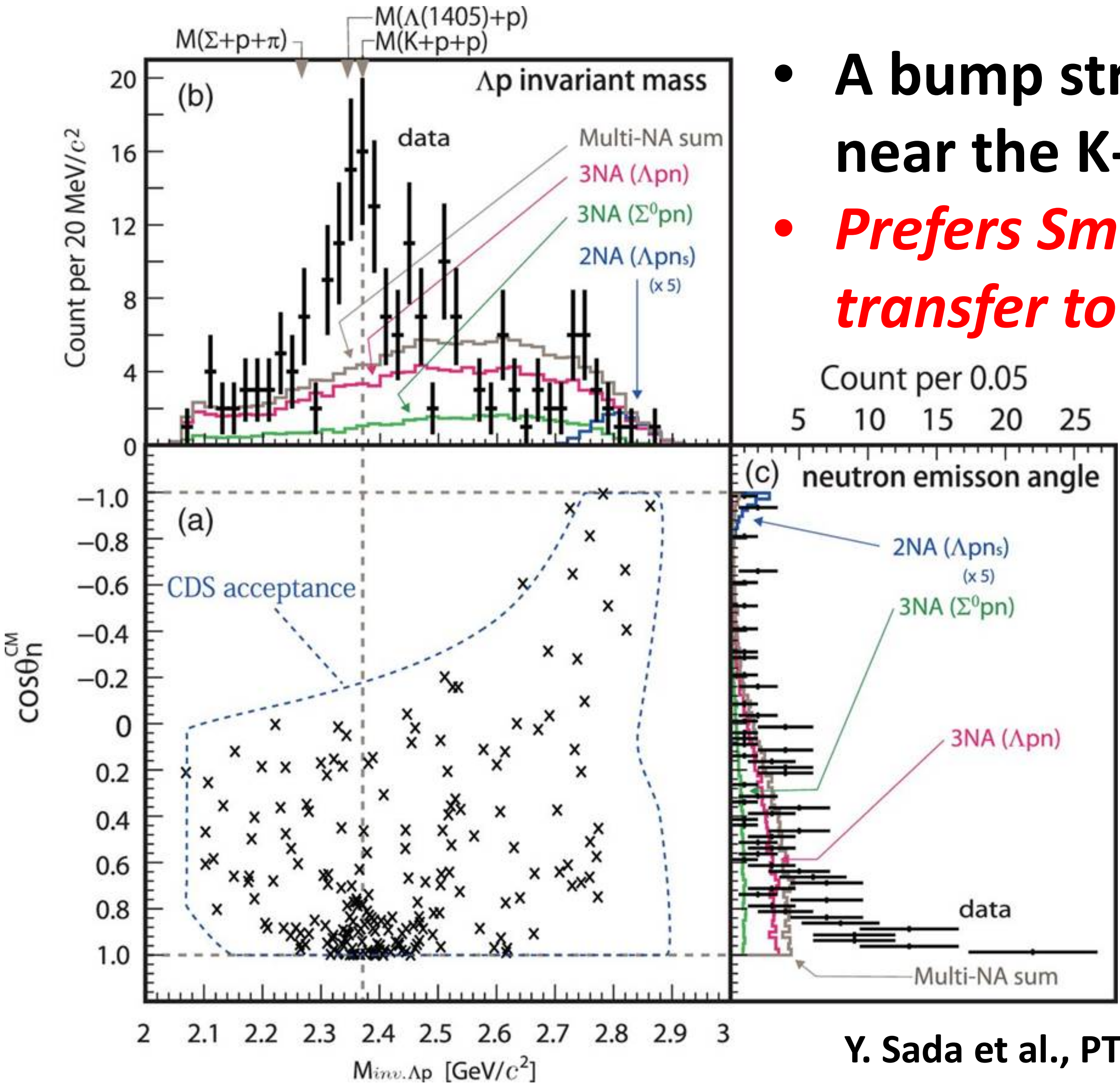
- Global fit both in Λp invariant- and missing-mass
  - σ ~ 10 MeV/c^2
  - w/ simulated spectra of 2NA/3NA

$$\text{3NA}(\Lambda\text{pn}): \frac{d^2\sigma_{3NA(\Lambda pn)}}{dT_n^{CM} d\cos\theta_n^{CM}} \propto \rho_3(\Lambda pn)$$

- **Neutron was identified by kinematics**
  - **^{3}He(K$^-$, Λp)n$_{missing}$**

- *# of Λpn events: ~200*
- *Σ^{0}pn contamination: ~20%*

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



- **A bump structure exists near the K-pp threshold**
- ***Prefers Smaller momentum transfer to Λp*** ***(0.8<cosθ^{CM}_n)***
- **S=-1 dibaryon?**
  - **Λ*N?**
  - **$K^{bar}NN$?**
  - **…**

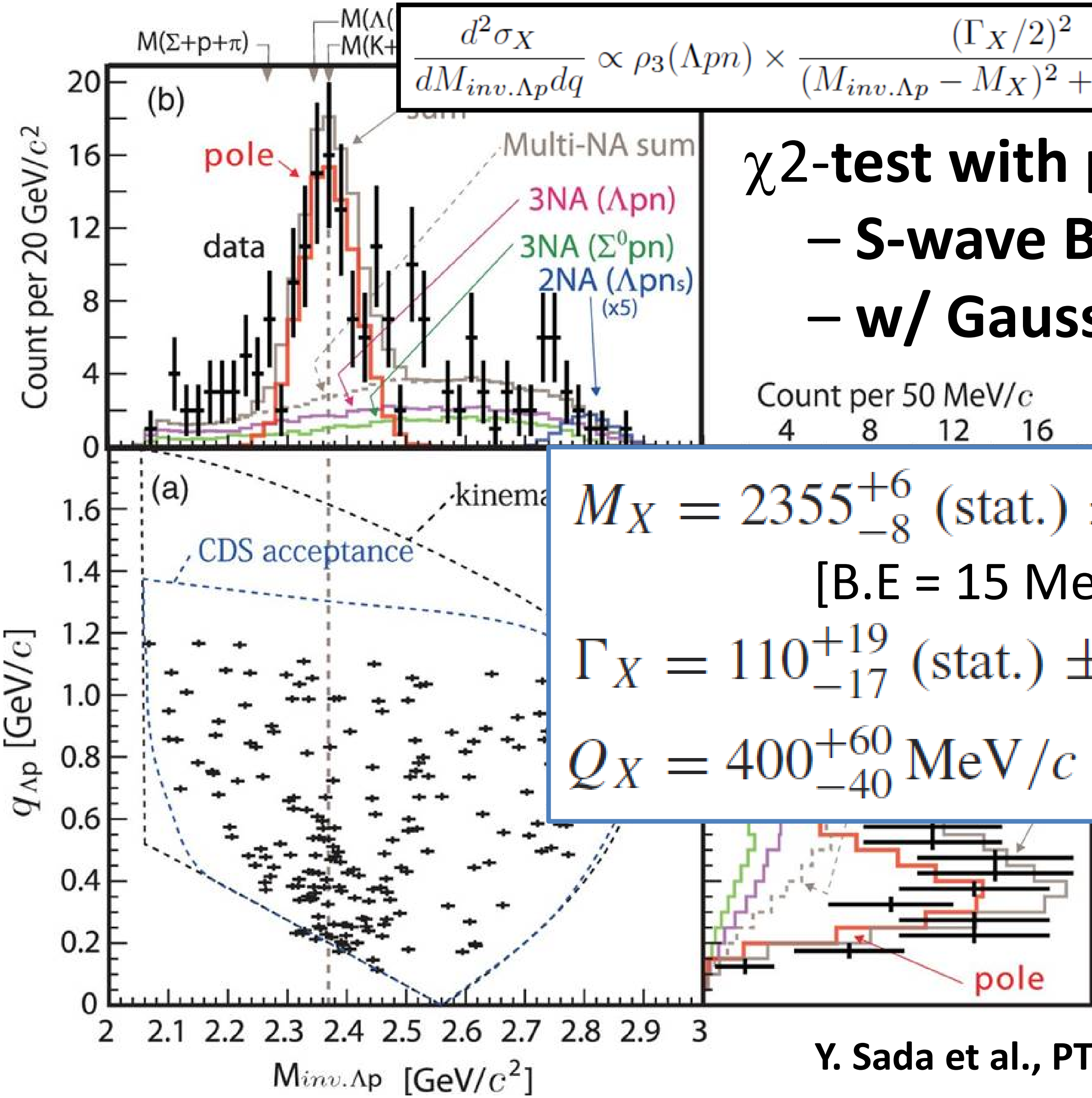
Y. Sada et al., PTEP (2016) 051D01.

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**



$$M_X = 2355^{+6}_{-8}\ (\mathrm{stat.}) \pm 12\ (\mathrm{syst.})\ \mathrm{MeV}/c^2$$

[B.E = 15 MeV/c^2]

$$\Gamma_X = 110^{+19}_{-17}\ (\mathrm{stat.}) \pm 27\ (\mathrm{syst.})\ \mathrm{MeV}/c^2$$

$$Q_X = 400^{+60}_{-40}\ \mathrm{MeV}/c$$

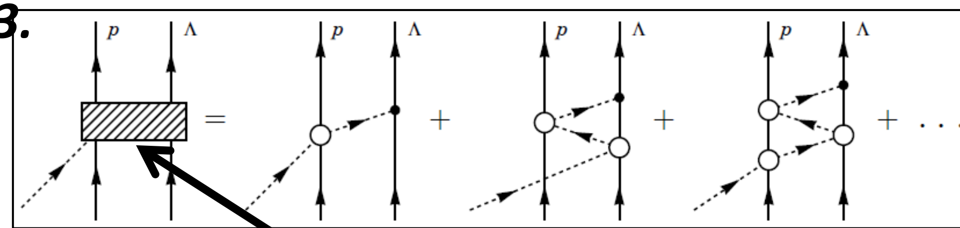
Y. Sada et al., PTEP (2016) 051D01.

A Theoretical Interpretation

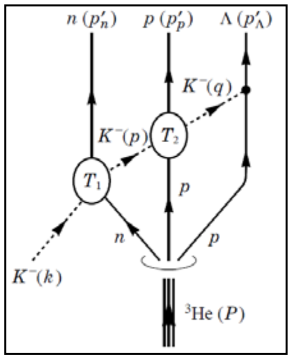
Sekihara, Oset, Ramos, PTEP(2016)123D03.

Chiral unitary approach

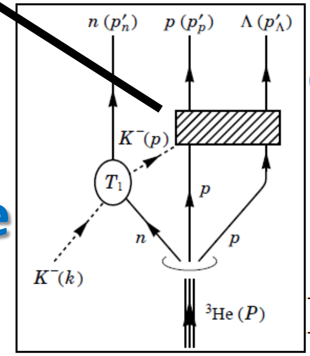
Sekihara



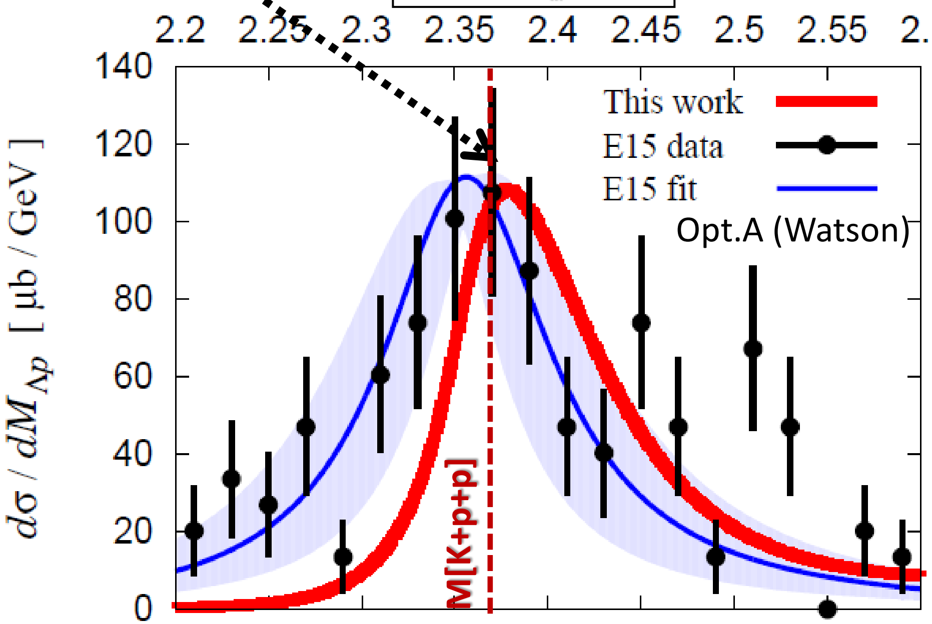
Uncorrelated Λ(1405)p state

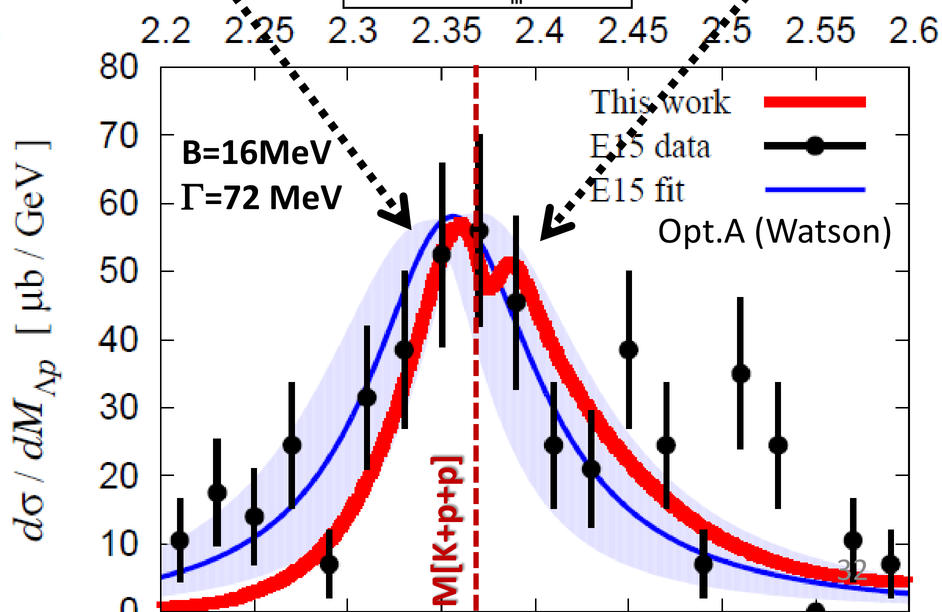


K^{bar}NN bound-state



quasi-elastic kaon scattering





What is the structure observed in E15^{1st} data?

E15-2nd Experiment

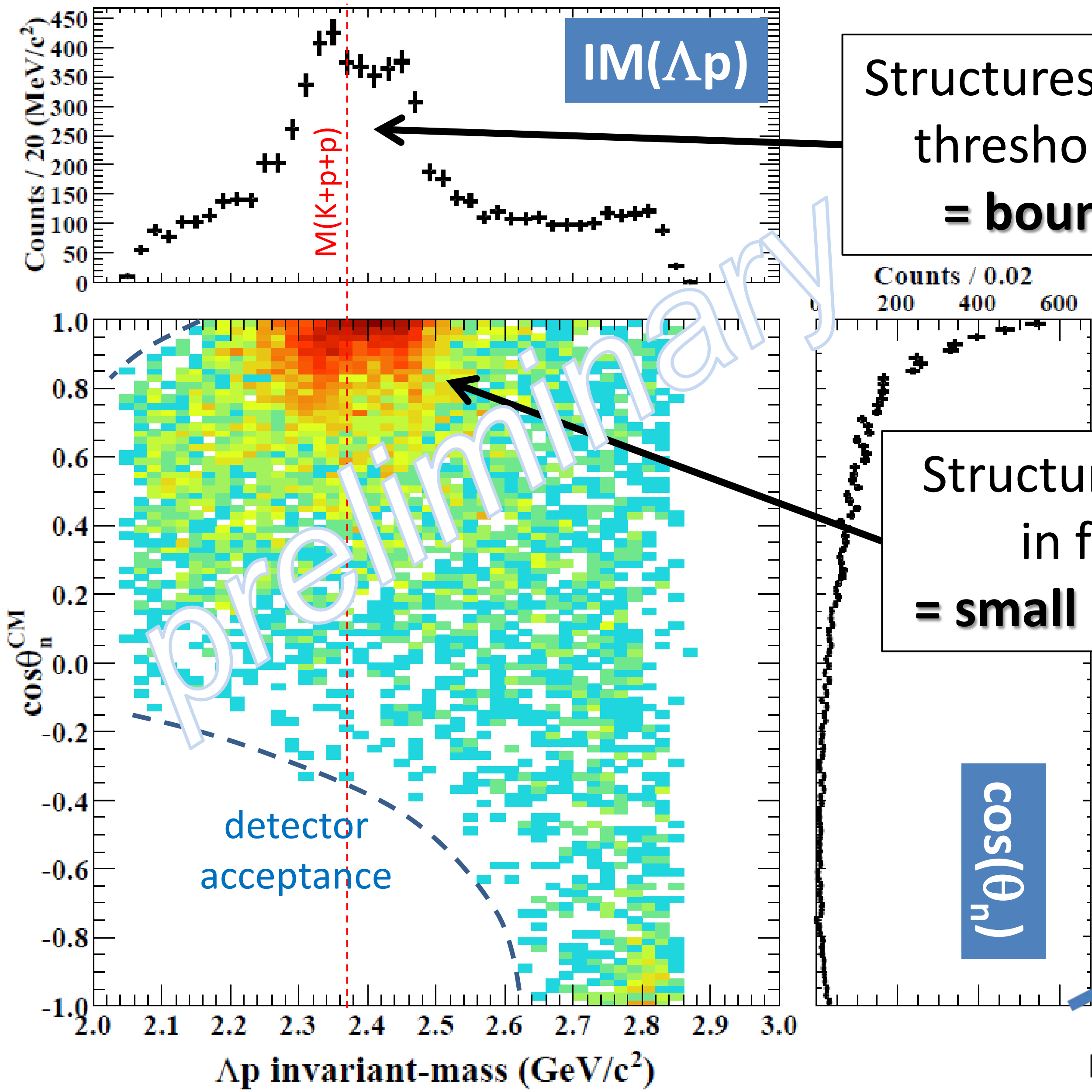
--- completed in Dec. 2015 ---

	E15-1st in 2013	E15-2nd in 2015
data-taking	4 days	3 weeks
(K^-,n)	~7 times more data	
(K^-,Λp)	~30 times more data*	

* dedicated trigger was introduced for (K-,Λp)

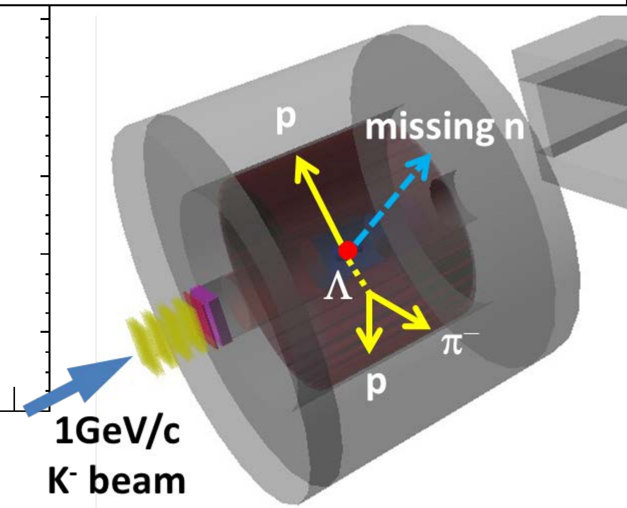
Will be published as "T.Yamaga et al., XXX (2017) XXX."

Results of $^{3}He(K^{-},\Lambda p)n$ [E15-2nd]

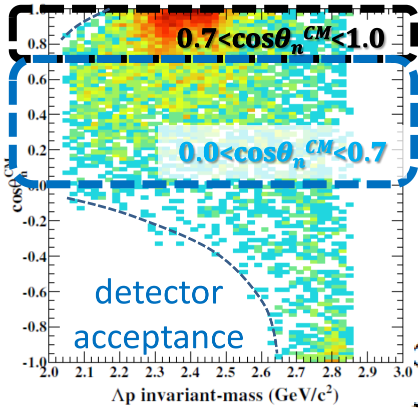


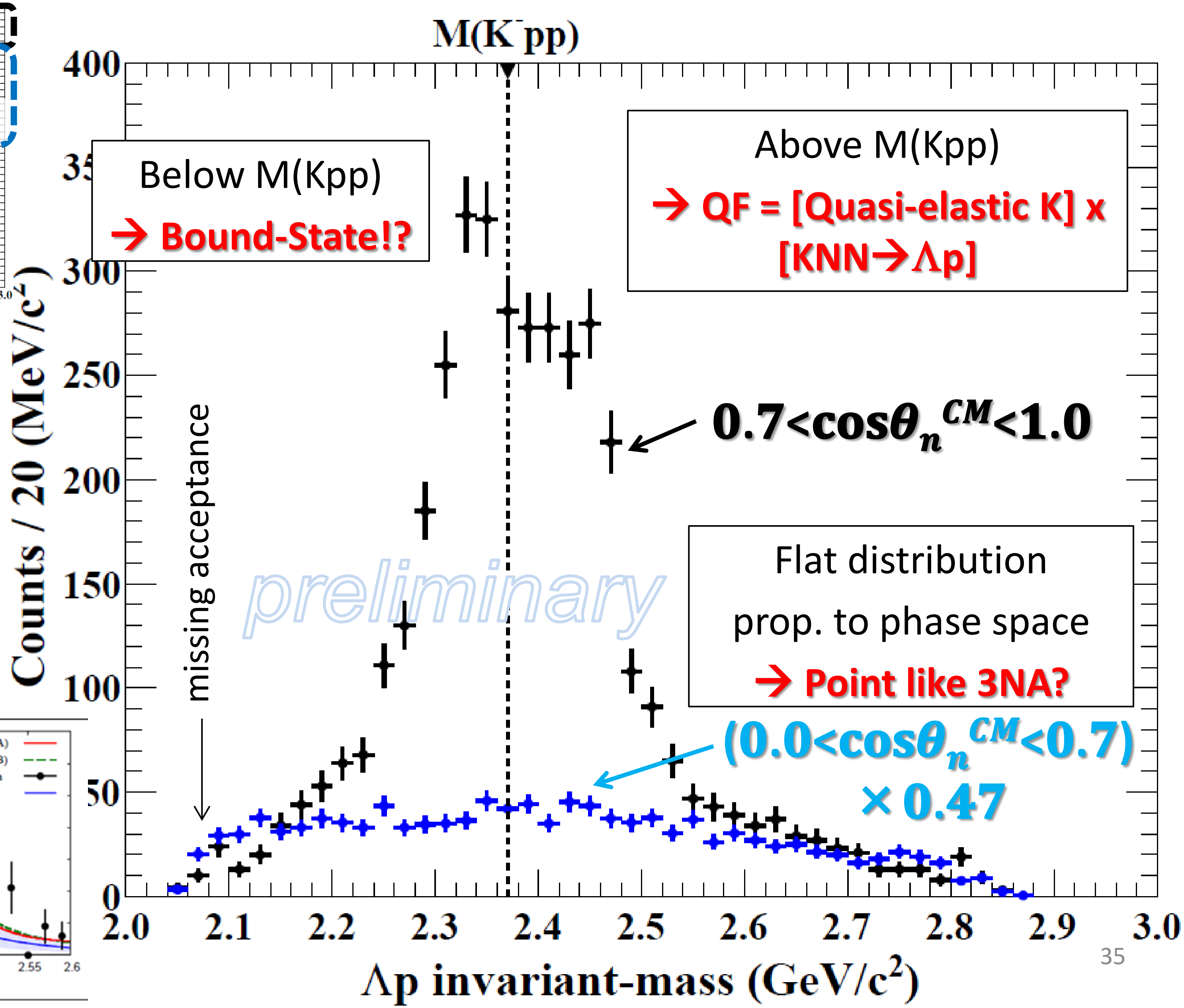
Structures around the Kpp threshold can be seen
= bound-state + QF

Structures are concentrated in forward-n region
= small momentum-transfer



Results of $^3He(K^-,\Lambda p)n$ [E15-2nd]

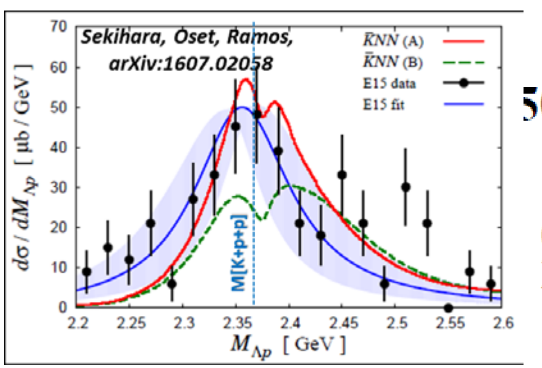




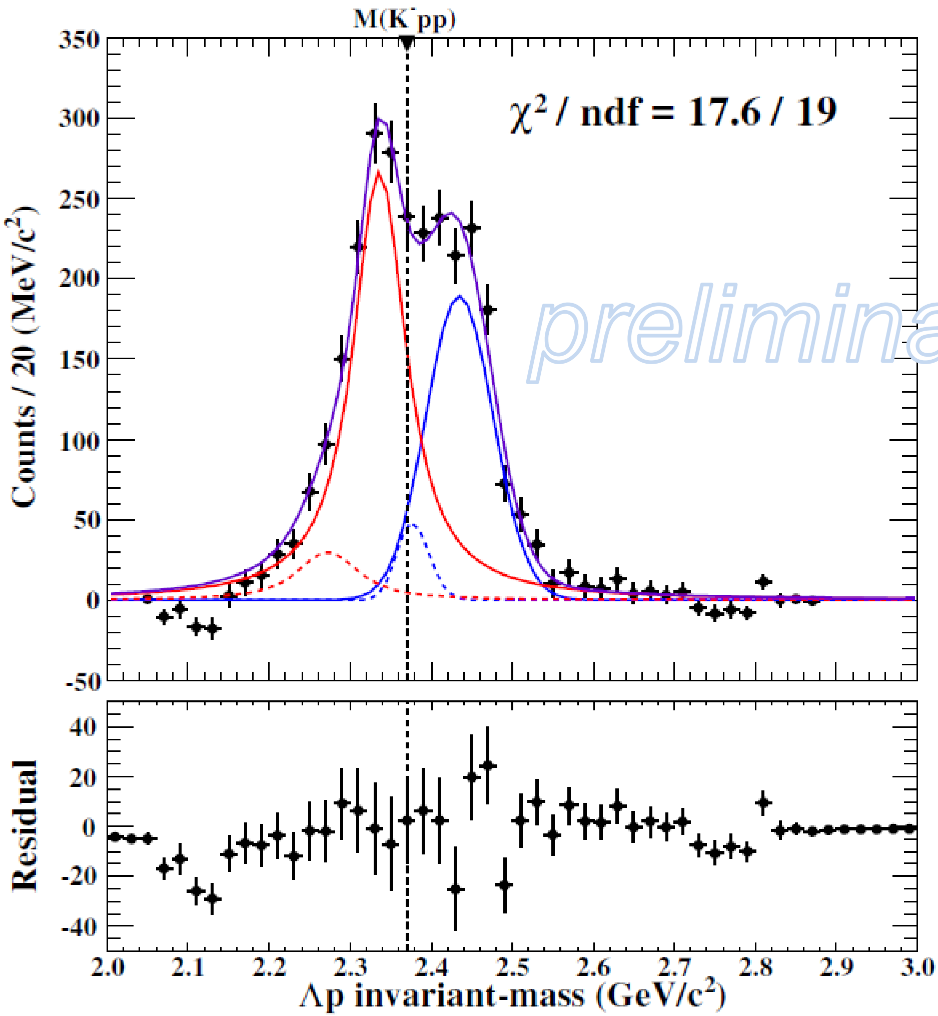
Below M(Kpp)
→ Bound-State!?

Above M(Kpp)
→ QF = [Quasi-elastic K] x [KNN→Λp]

Flat distribution
prop. to phase space
→ Point like 3NA?



Results of $^3He(K^-,\Lambda p)n$ [E15-2nd]

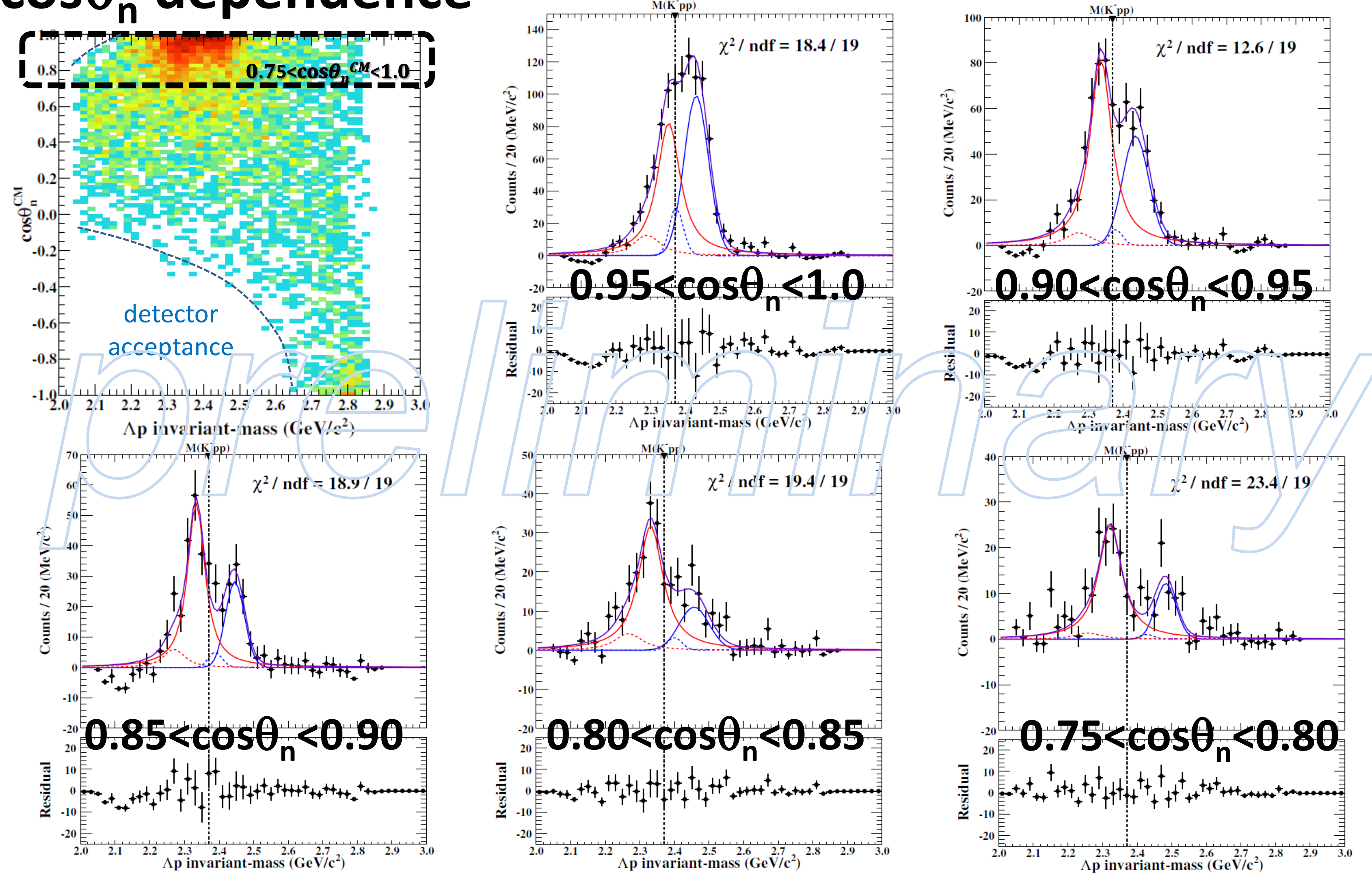


- Simple fitting w/o 3NA
  - **B.S.: Breit-Wigner**
  - QF: Gaussian ← Fermi-mom. Eff.
  - w/ Σ^0p contamination ← from MM(^{3}He(K^-,Λp)X)
- Well reproduce the spectrum
  - B.E ~ 34 MeV/c^2
  - Γ ~ 75 MeV/c^2

preliminary

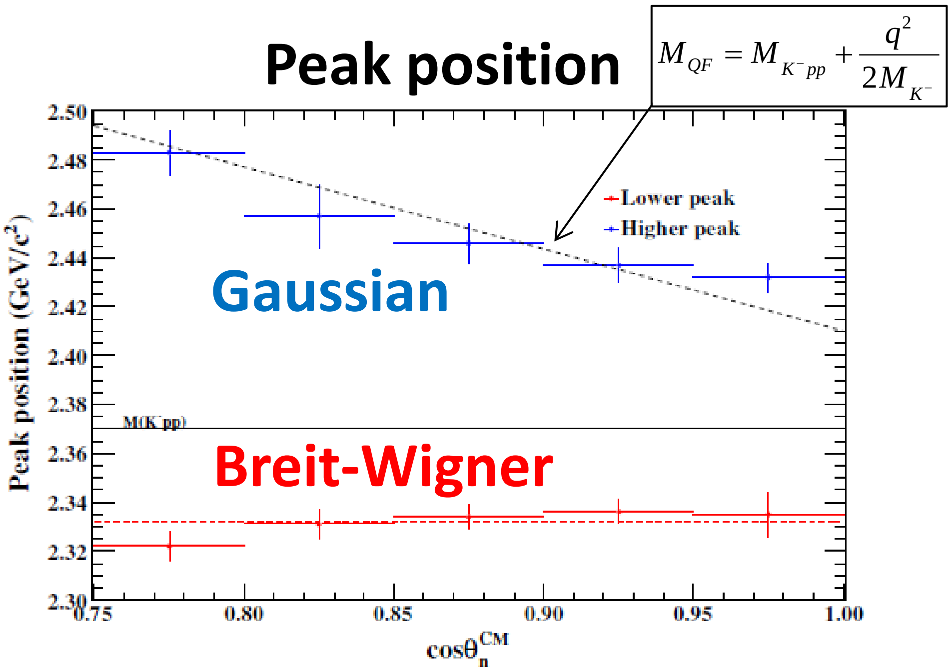
Results of ^{3}He(K$^-$,Λp)n [E15-2nd]

cosθ$_n$ dependence

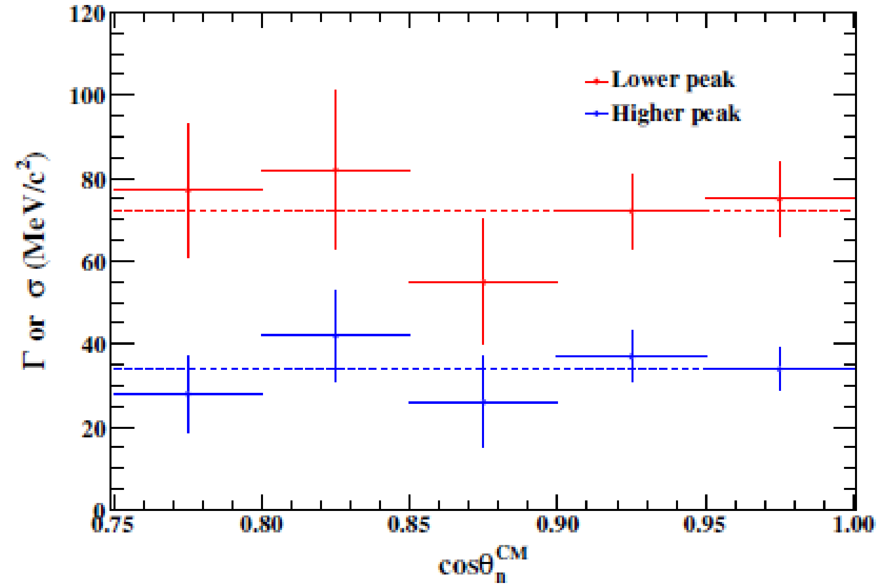


Results of $^3He(K^-,\Lambda p)n$ [E15-2nd]

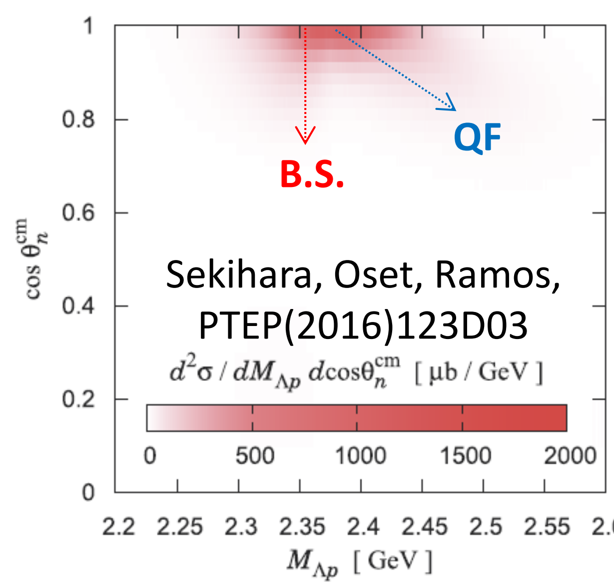
Peak position



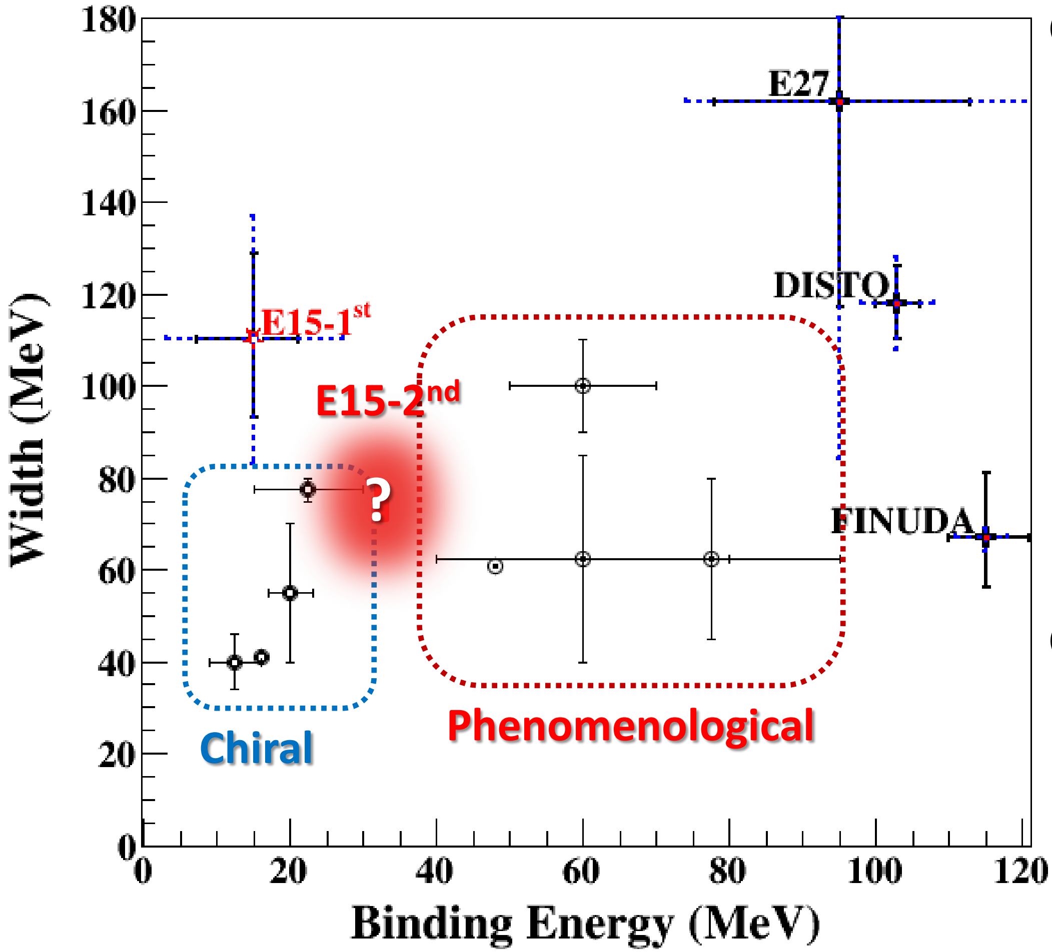
Width



- **Above M(K-pp):**
  - **peak shift by recoil kaon energy**
- **Below M(K-pp):**
  - **peak is independent to cosθ_n (~ momentum transfer)**
- **Similar tendency as a theoretical calc.**



Present Status of K^{bar}NN



- **Exp. CANDIDATES**
  - *Upper limit*
    - LEPS/HADES
  - *B.E ~ 10-40 MeV*
    - E15
  - *B.E. ~ 100 MeV*
    - FINUDA/DISTO/E27
- **Theor. calculations.**
  - Difficult to reproduce deeply bound state using normal K^{bar}N int.

For further understanding:

✓ Λ(1405) production → Λ*N doorway

✓ πΣN decay channel → new info. of K^{bar}NN

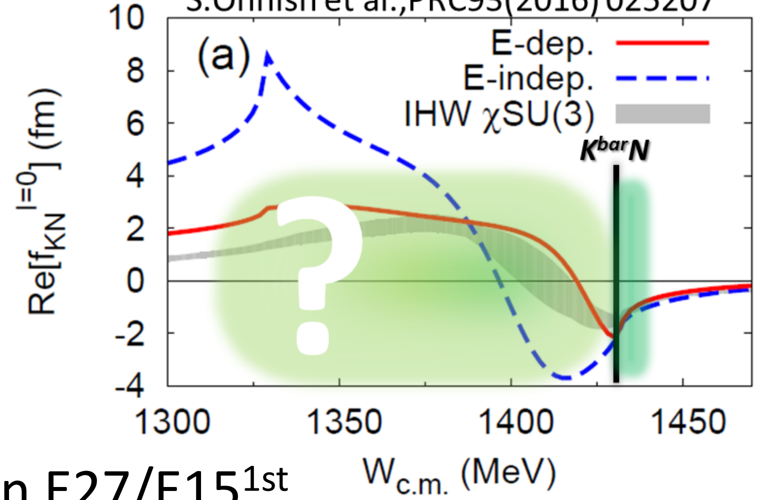
Summary

To investigate the $K^{bar}N$ interaction, various experiments are proposed/conducting at J-PARC

- Sensitive in different energy region & isospin -

- **Kaonic-atom: E62/E57**
  - will start in 2018/2019
- **Λ(1405): E31**
  - 1st: analysis will be finalized
  - 2nd: will start in 2017
- **$K^{bar}NN$: E27/E15**
  - fruitful results were obtained in E27/E15 1st
  - analysis of E15 2nd data is going on
  - E15 3rd be discussed after analyzing new data

S.Ohnish et al.,PRC93(2016) 025207



The Collaborations @ J-PARC K1.8BR

J-PARC E15/E31 collaboration

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J-PARC E57 collaboration (K-d)

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