What can we learn about the “$\bar{K}NN$” from the J-PARC E15 peak ?

– Relation between the Λp invariant mass spectrum and “$\bar{K}NN$” –

Takayasu SEKIHARA *
(Research Center for Nuclear Physics, Osaka Univ.)

in collaboration with

Eulogio OSET (Valencia Univ.)
and **Angels RAMOS** (Barcelona Univ.)

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* Freelance science writer

[1] T. S. , E. Oset and A. Ramos, *PTEP* 2016 123D03.

[2] T. S. , E. Oset and A. Ramos, *JPS Conf. Proc.* (2019), in press [arXiv:1903.10773].

[3] T. S. , E. Oset and A. Ramos, in preparation.

The 14th Hadron Spectroscopy Cafe “$\bar{K}NN$ at J-PARC” @ Tokyo Inst. Tech. (May 27, 2019)

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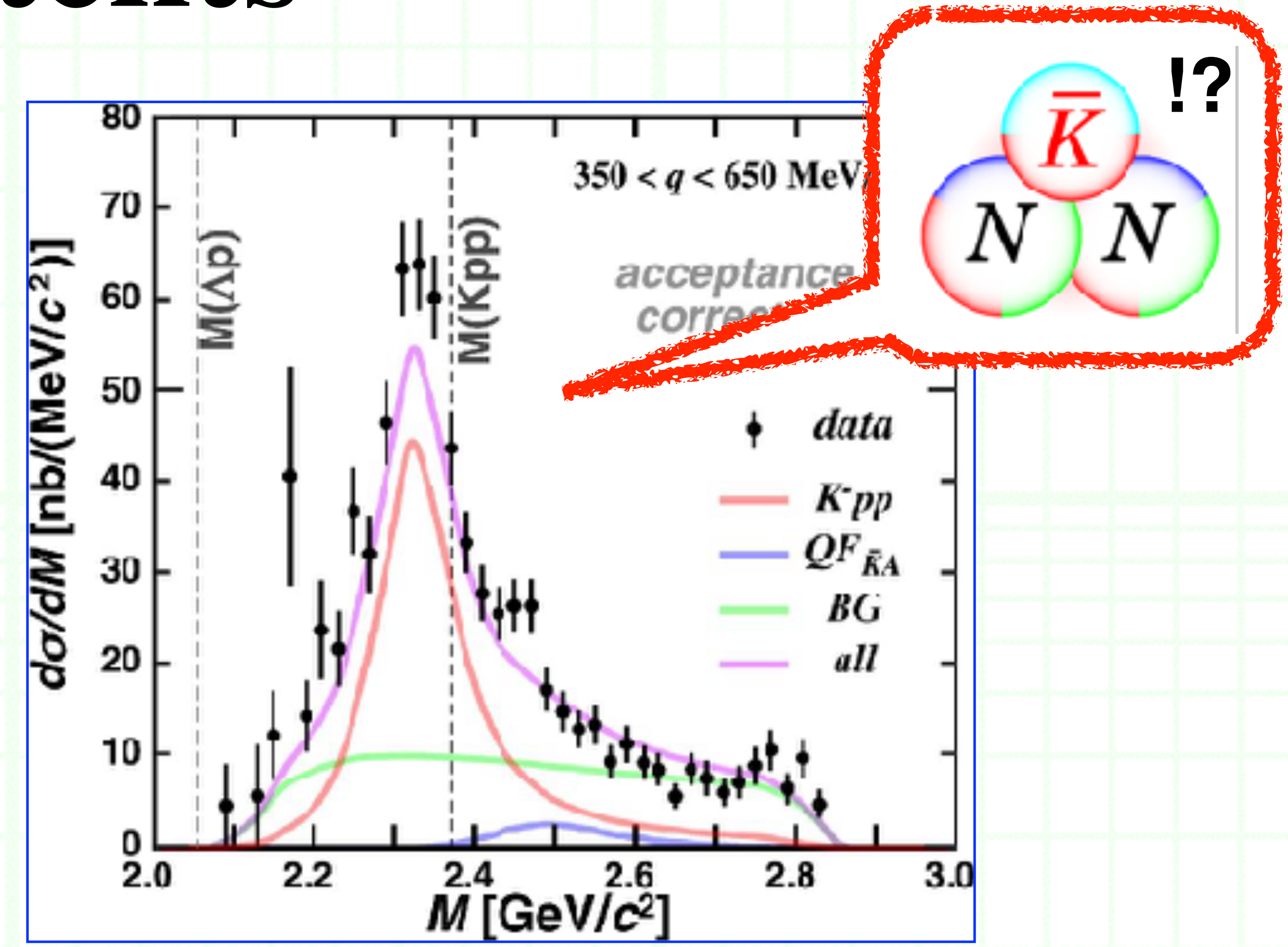
J-PARC chan
by HIGGSTAN.



J-PARC E15 Exp. [2nd run data]

2. **Building block:**
   The $\bar{K}N$ bound state / Λ(1405)

3. **Physics on the $\bar{K}NN$ bound state**

4. **Summary**

1. Introduction

1. Introduction

++ Strangeness nuclear physics ++

- **Strangeness nuclear physics / strange quark is interesting !**

□ **In the transition region from chiral to heavy symmetry.**

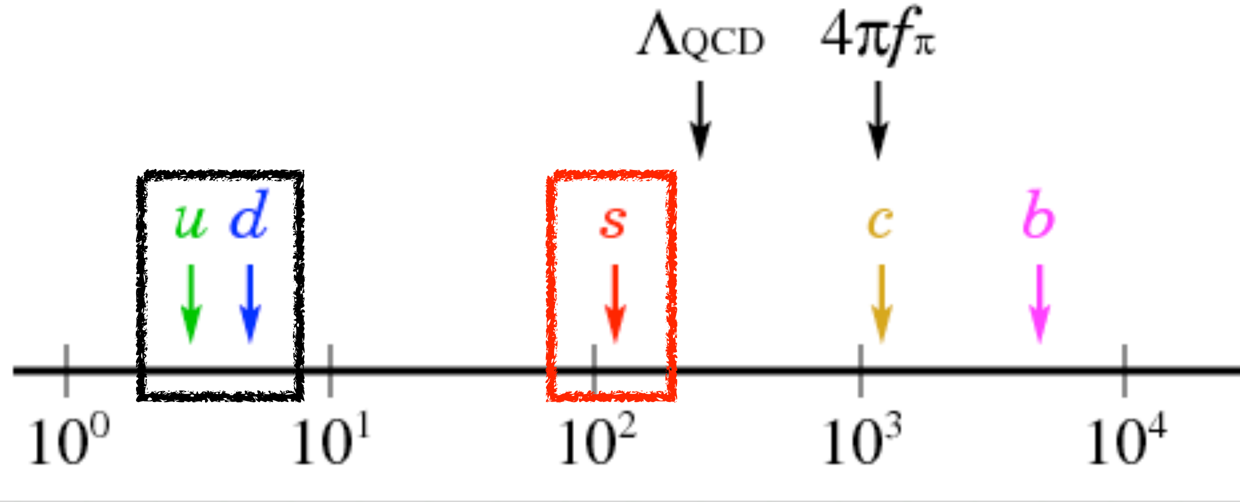
--- **Different viewpoint** compared to usual nuclear physics (*u* & *d*).

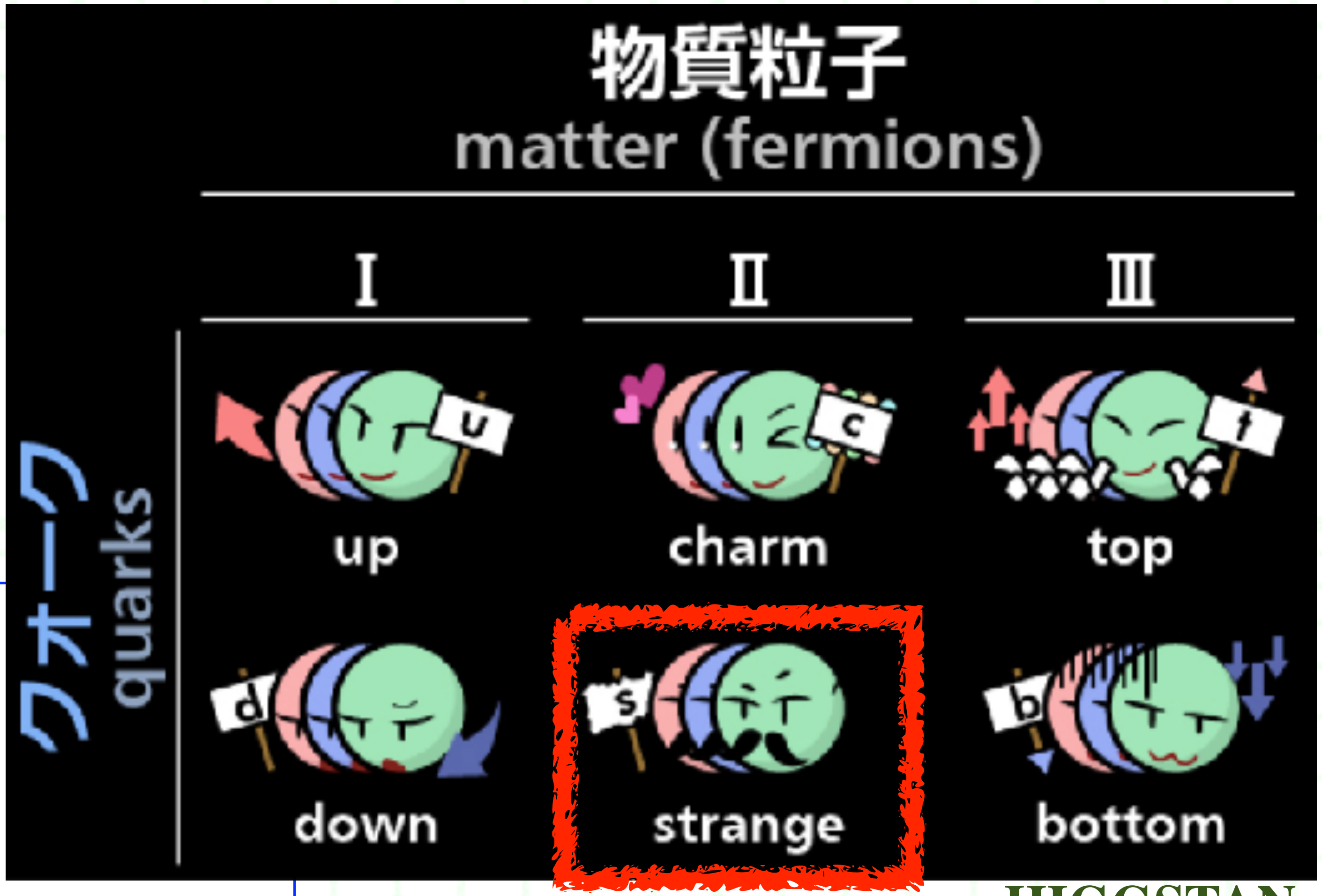
--- **Dynamical part of constituent strange quark** will still play an important role in the hadron spectroscopy.

□ **It exists in “Nature”.**

--- Possibly in neutron stars.

□ **Easier to produce in Exps.**





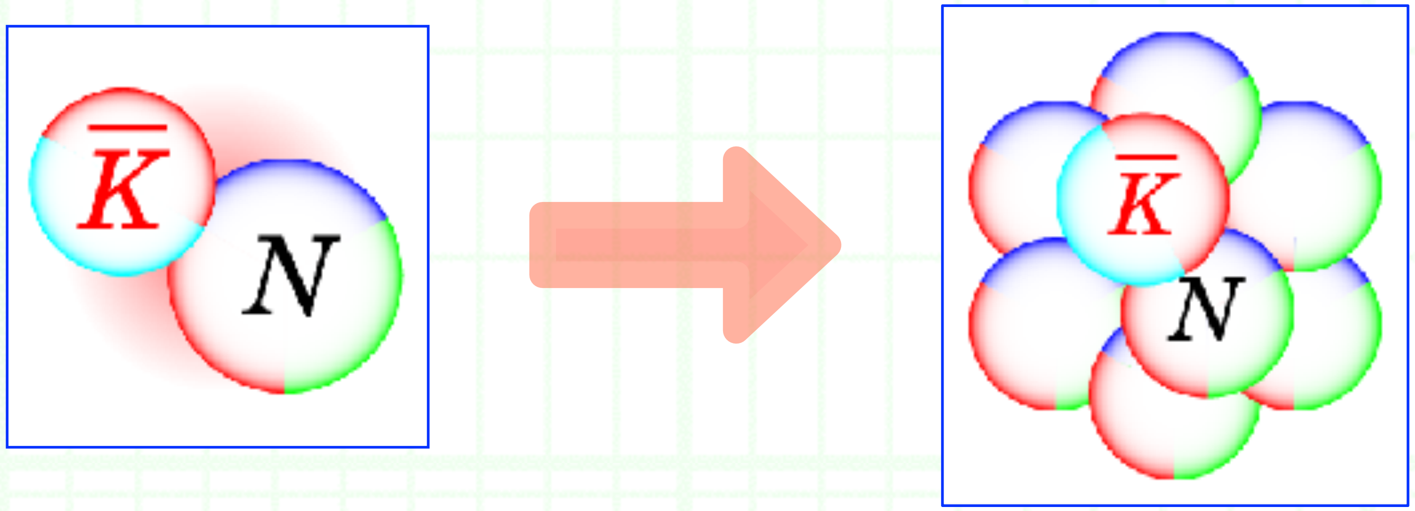
HIGGSTAN.

1. Introduction

++ Kaonic nuclei ++

- Antikaon ($\bar{K}$) -nuclear systems are “attractive” !
  - The $\bar{K}N$ interaction is strong enough to make a bound state as Λ(1405).
  - There should exist kaonic nuclei, which are bound states of $\bar{K}$ and nuclei via strong interaction between them.

Bound state
as Λ(1405) !



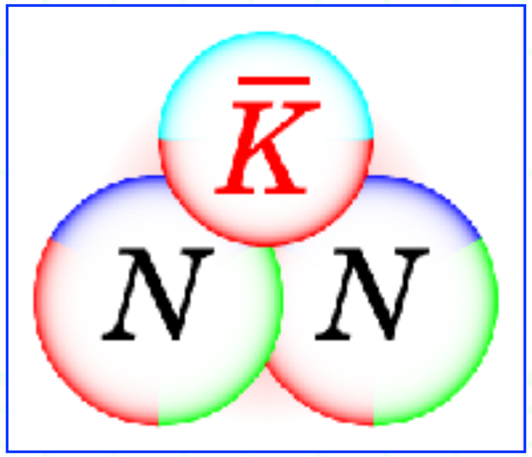
Kaonic nuclei
should exist !!

- There are several motivations to study kaonic nuclei themselves:

1. Exotic states of many-body systems in strong interaction.
2. Feedback to the $\bar{K}N$ interaction.
3. Kaons / strangeness in finite nuclear density.

1. Introduction

++ The “$K^- pp$” state ++



- The $\bar{K}NN$ (I=1/2) state --- so-called “$K^- pp$” state --- is the simplest state of the kaonic nuclei.

- There have been many studies on this state.
  - ☐ Theoretical studies:

    Yamazaki and Akaishi, *Phys. Lett.* B535 (2002) 70; *Phys. Rev.* C65 (2002) 044005;
    Shevchenko, Gal and Mares, *Phys. Rev. Lett.* 98 (2007) 082301;
    Ikeda and Sato, *Phys. Rev.* C76 (2007) 035203; Dote, Hyodo and Weise, *Nucl. Phys.* A804 (2008) 197;
    Wycech and Green, *Phys. Rev.* C79 (2009) 014001;
    Bayar, Yamagata-Sekihara and Oset, *Phys. Rev.* C84 (2011) 015209;
    Barnea, Gal and Liverts, *Phys. Lett.* B712 (2012) 132; ...

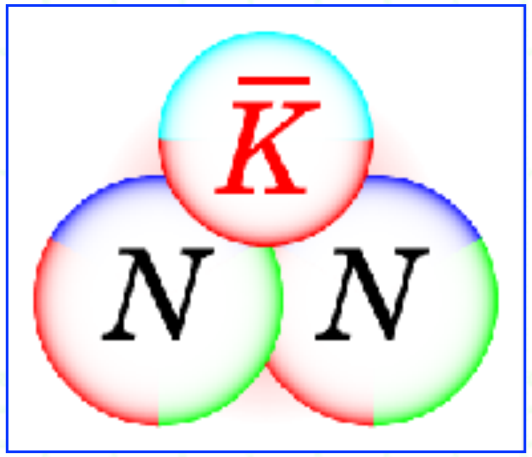
  - ☐ Experimental studies:

    M. Agnello *et al.* [FINUDA], *Phys. Rev. Lett.* 94 (2005) 212303;
    T. Yamazaki *et al.* [DISTO], *Phys. Rev. Lett.* 104 (2010) 132502;
    A. O. Tokiyasu *et al.* [LEPS], *Phys. Lett.* B728 (2014) 616;
    Y. Ichikawa *et al.* [J-PARC E27], *PTEP* 2015 021D01; 061D01;
    T. Hashimoto *et al.* [J-PARC E15], *PTEP* 2015 061D01; ...

--- However, this state is still controversial.

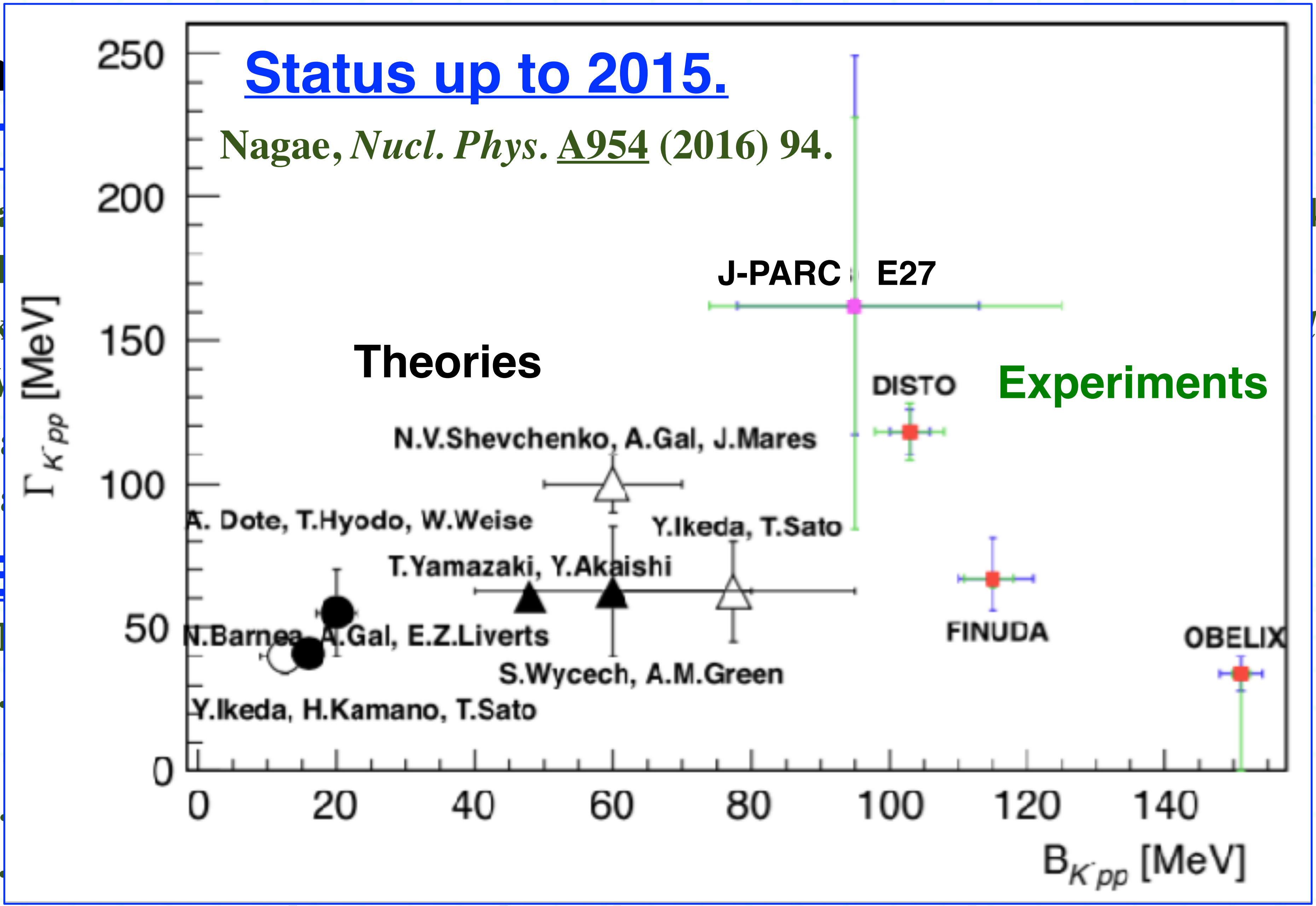
1. Introduction

++ The "K^-pp" state ++



- **The $\bar{K}NN$ (I=1/2) state** --- so-called **"K^-pp"** state --- is **the simplest state** of the kaonic nuclei.

- Th
  - ☐ **T**
    Y 005;
    Sl
    Ik . *Phys.* A804 (2008) 197;
    W
    B
    B
  - ☐ **E**
    M
    T.
    A
    Y.
    T.



Status up to 2015.

Nagae, *Nucl. Phys.* A954 (2016) 94.

--- However, this state is **still controversial**.

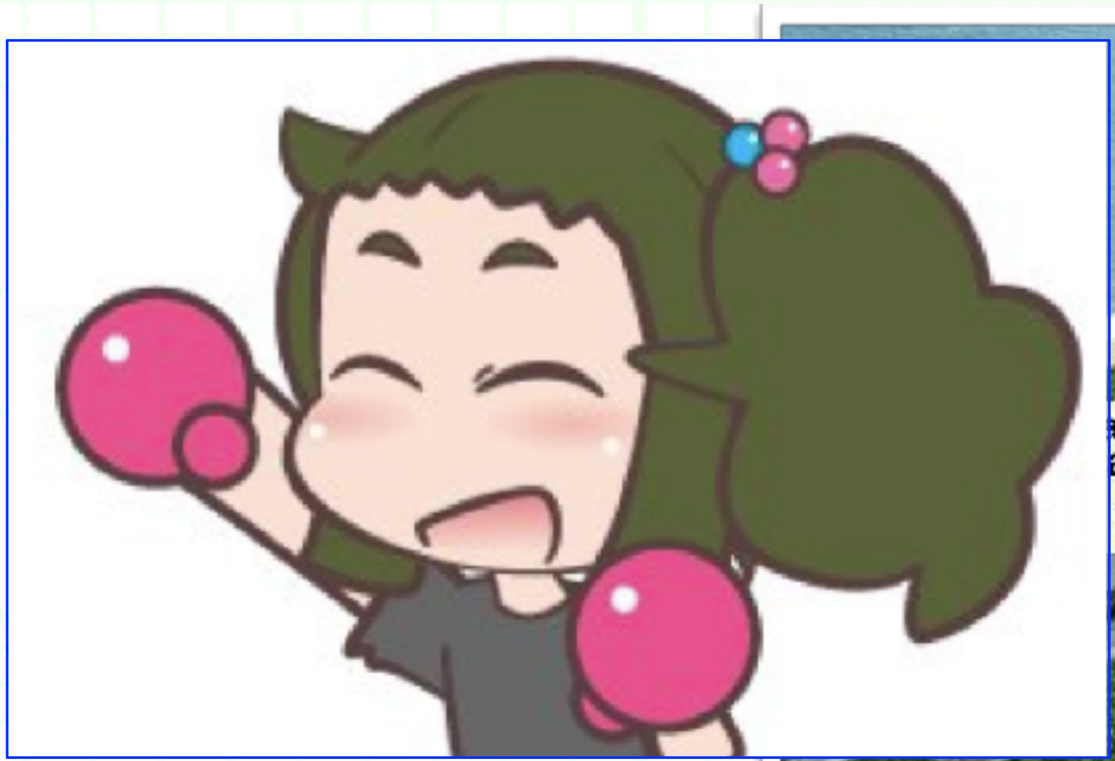
1. Introduction

++ J-PARC ++

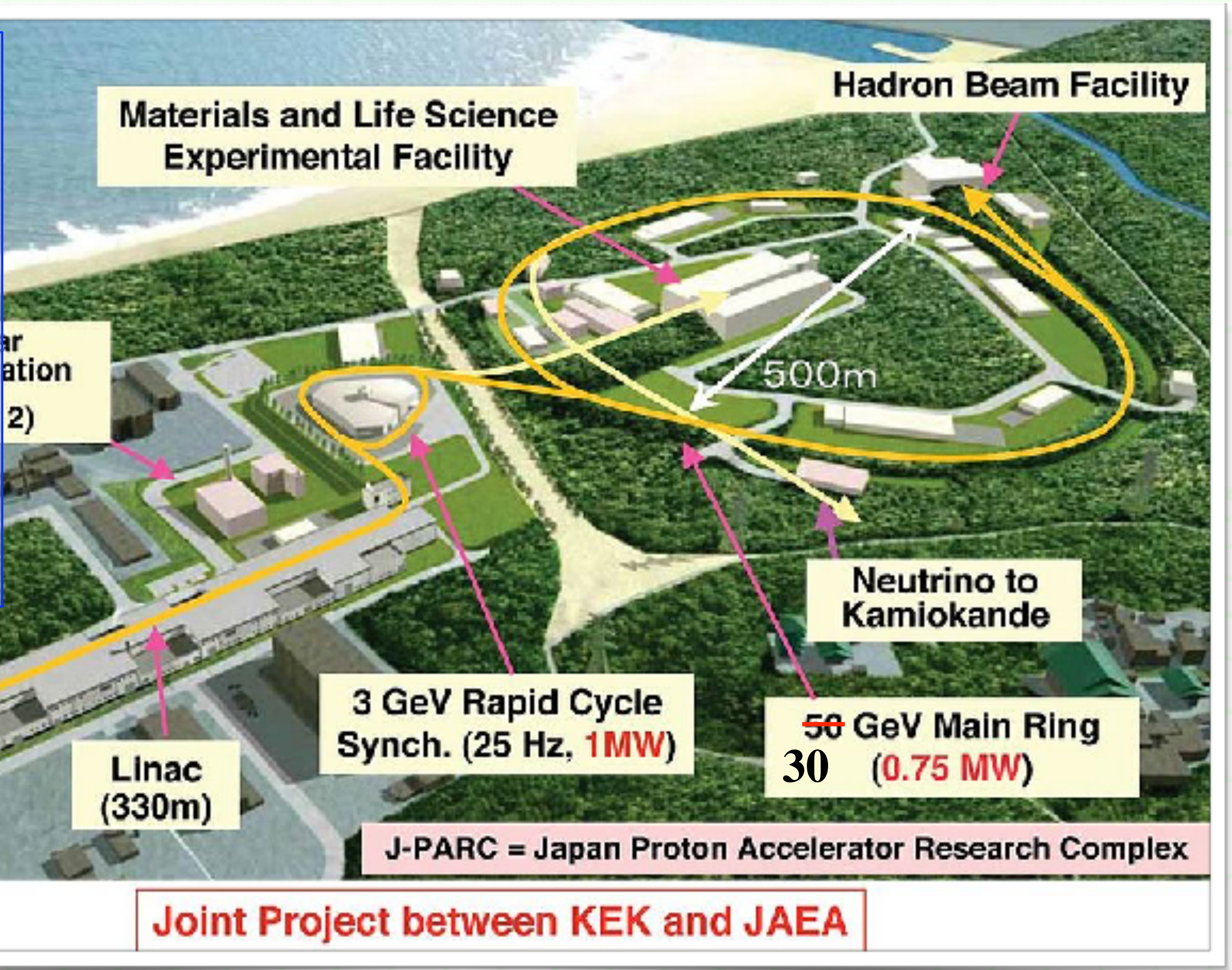
- **Recently, the J-PARC E15 Exp. was performed to search for the $\bar{K}NN$ bond state with the in-flight K^- ^{3}He –> Λ p n reaction.**

Y. Sada *et al.*, *PTEP* 2016 051D01; Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

- ☐ **J-PARC --- Japan Proton Accelerator Research Complex.**



J-PARC chan
by HIGGSTAN.



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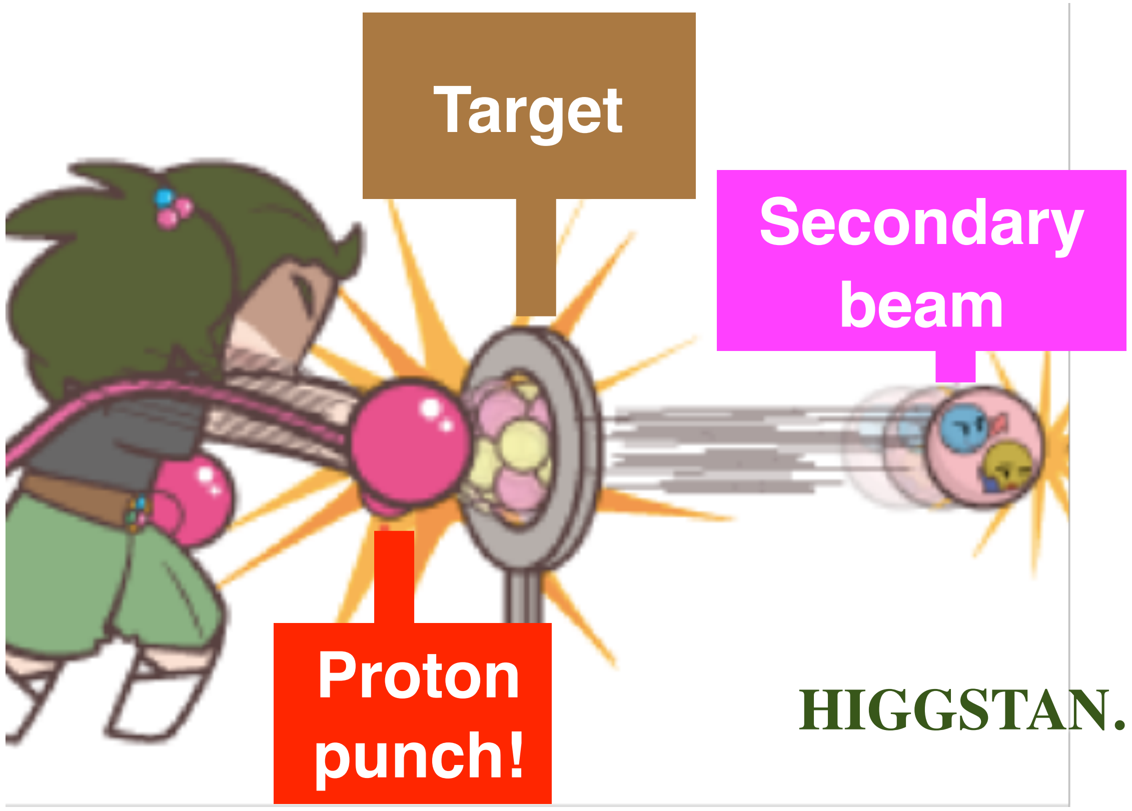
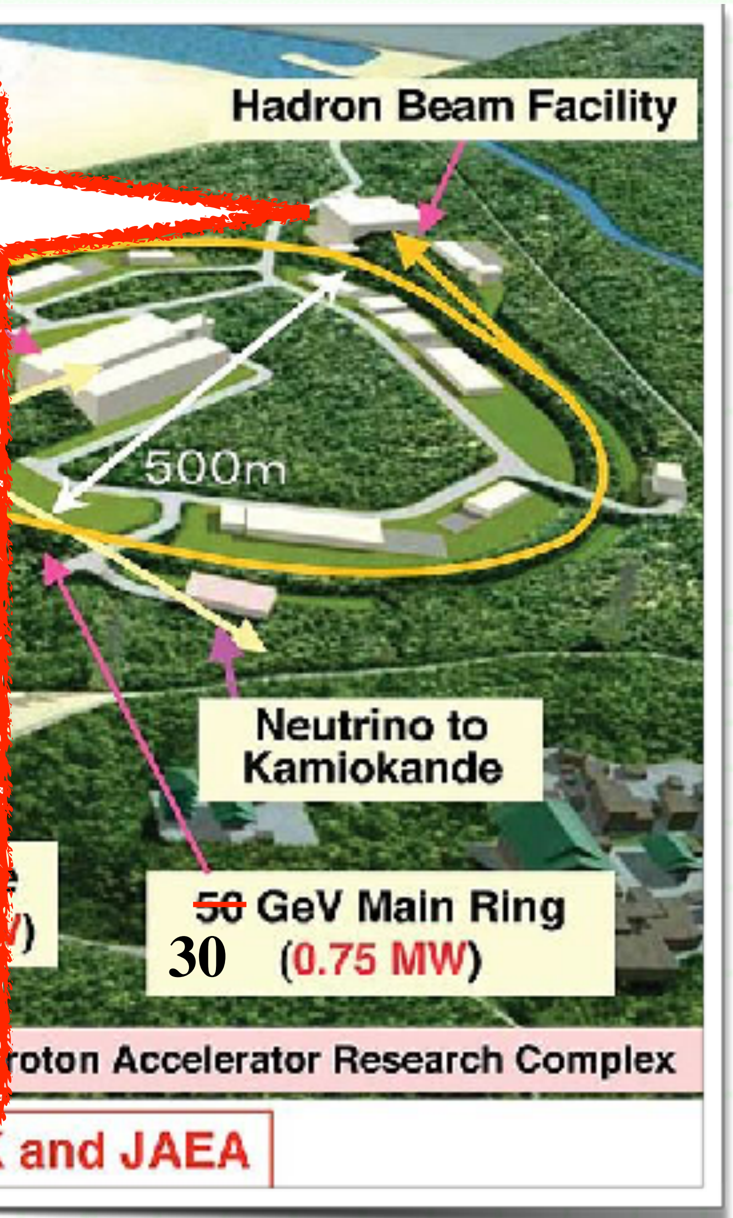
☐ **J-PARC --- Japan Proton Accelerator Research Complex.**

J-PARC chan
by HIGGSTAN.

☐ **Primary proton beam: ~ 10^{12} / s.**



☐ **Secondary K^- beam: ~ 10^4 / s.**



1. Introduction

++ J-PARC E15 ++

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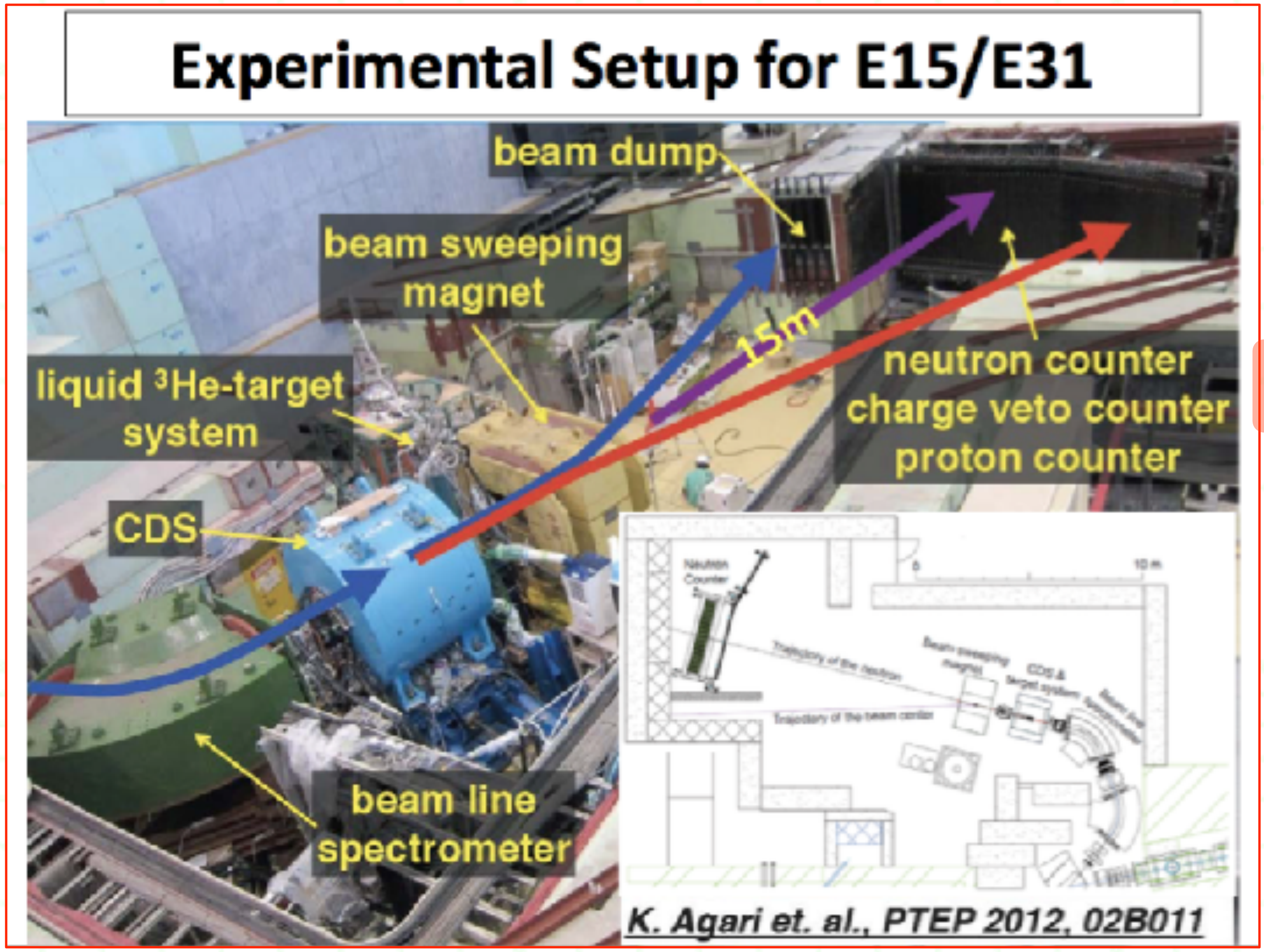
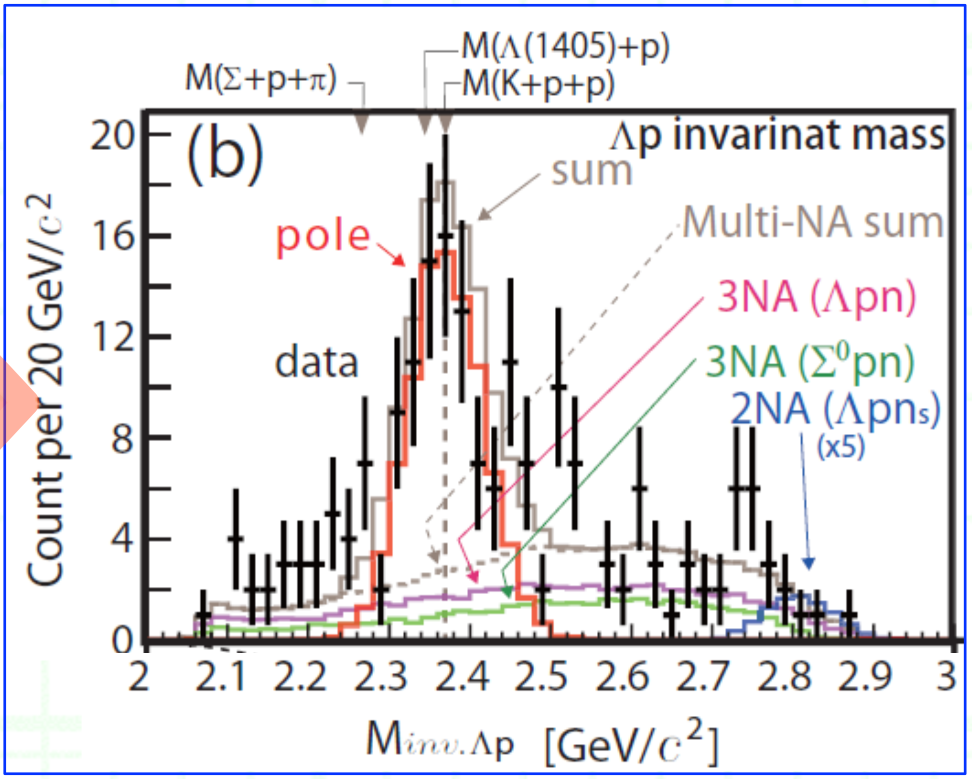
Y. Sada *et al.*, *PTEP* 2016 051D01.


Experimental Setup for E15/E31

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

Sakuma-san, talk at ECT* (2017).



- ☐ **Big advantage: we can directly put kaon into the nucleus.**

1. Introduction

++ J-PARC E15 ++

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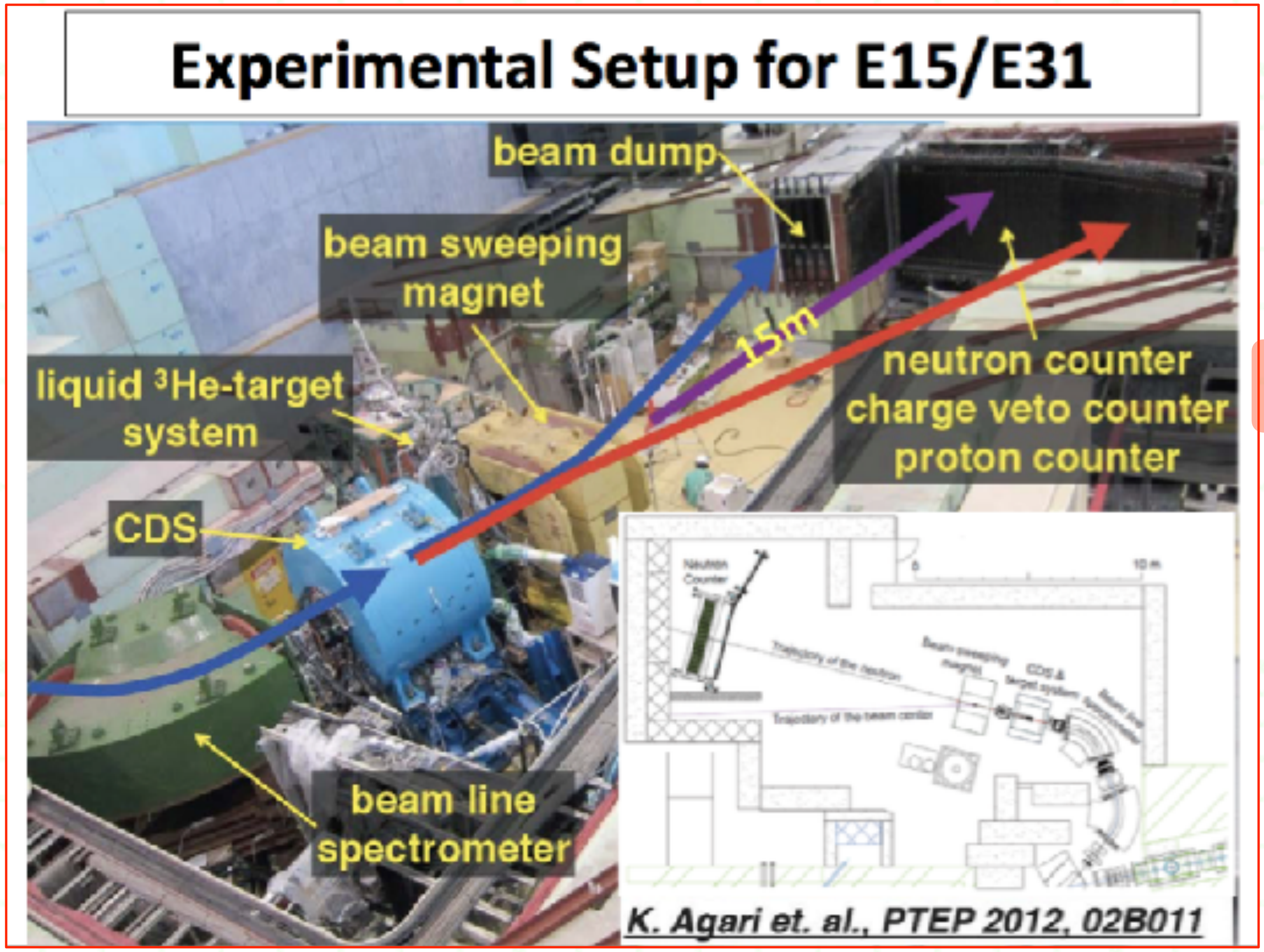
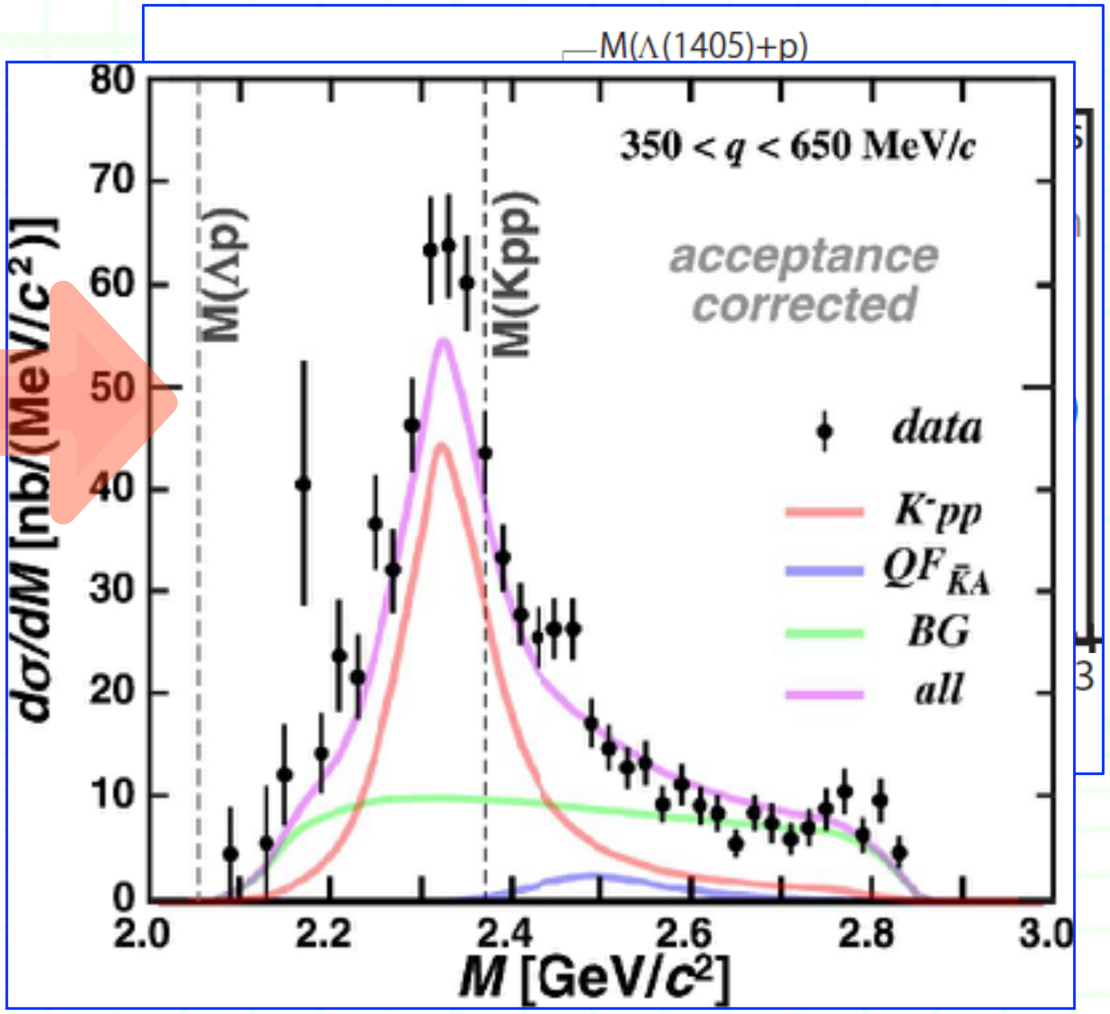
Y. Sada *et al.*, *PTEP* 2016 051D01.



Sakuma-san, talk at ECT* (2017).



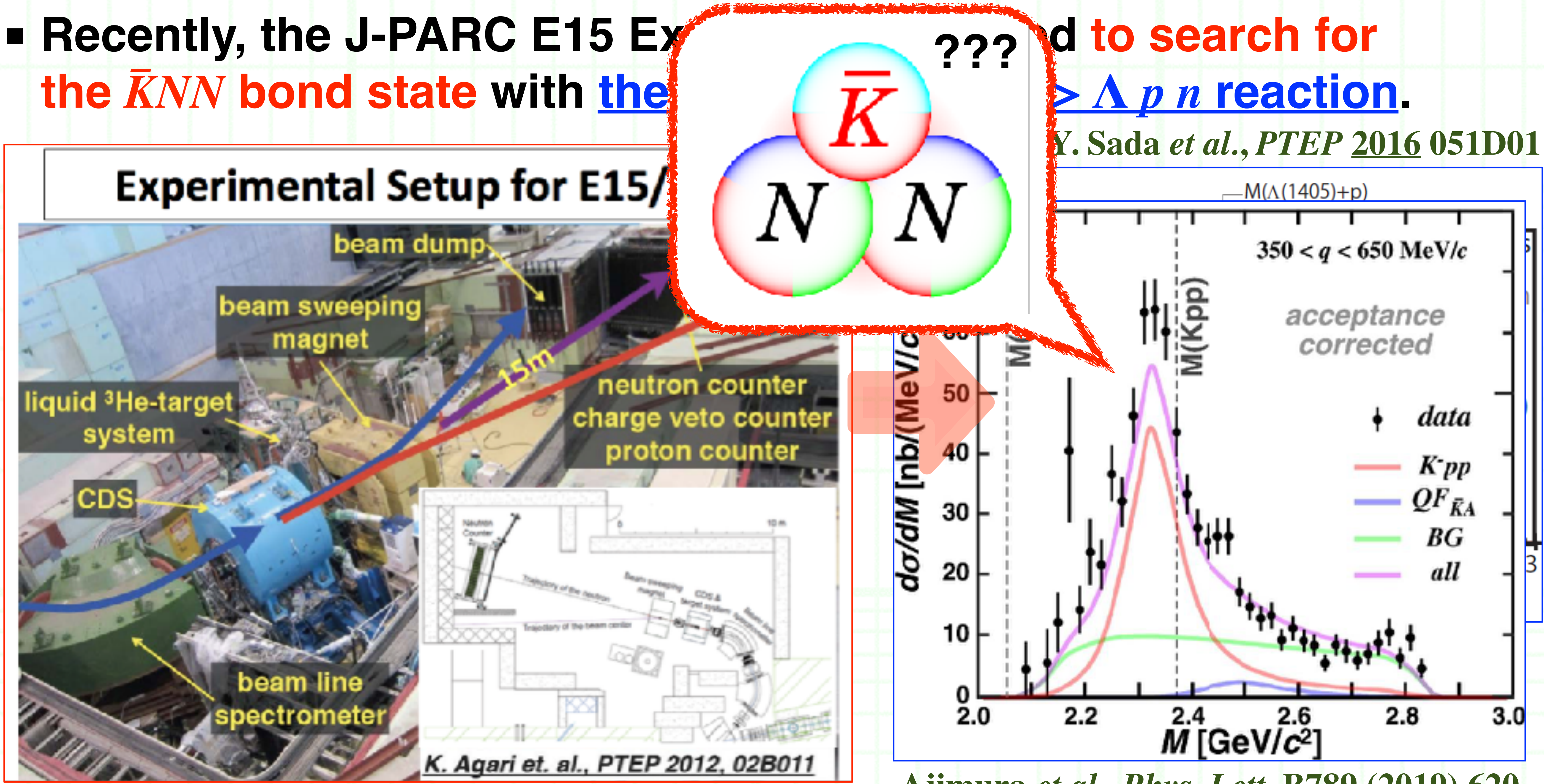
Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

- □ Big advantage: we can directly put kaon into the nucleus.

1. Introduction

++ J-PARC E15 ++

- **Recently, the J-PARC E15 Ex** ??? **d to search for the $\bar{K}NN$ bond state with the** **> $\Lambda\ p\ n$ reaction.**



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

Sakuma-san, talk at ECT* (2017).

Y. Sada *et al.*, *PTEP* 2016 051D01.

Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

- Big advantage: we can directly put kaon into the nucleus.

1. Introduction

++ Questions about $\bar{K}NN$ ++

- From the J-PARC E15 data, what can we learn about the $\bar{K}NN$?
  - □ Does the $\bar{K}NN$ bound state really exist ?
  - □ Spin / parity ?
  - □ Relation between the Exp. peak and the resonance pole ?
  - □ Pole position ?
  - □ How does the $\bar{K}$-nucleus interaction realize ?
  - □ …

- The same questions can arise for the $\bar{K}N$ bound state.

--> We discuss how the same questions have been attacked in the $\bar{K}N$ bound-state case (as a building block of the $\bar{K}NN$), and then extend it to the $\bar{K}NN$ bound-state case.

2. Building block:
The $\bar{K}N$ bound state / $\Lambda(1405)$

2. Building block: $\bar{K}N$ / Λ(1405)

++ About the $\bar{K}N$ bound state ++

	Λ(1405) as $\bar{K}N$ bound state
Prediction	
Discovery	
Spin / parity	
Interaction	
Component	
Peak position	
Pole position	

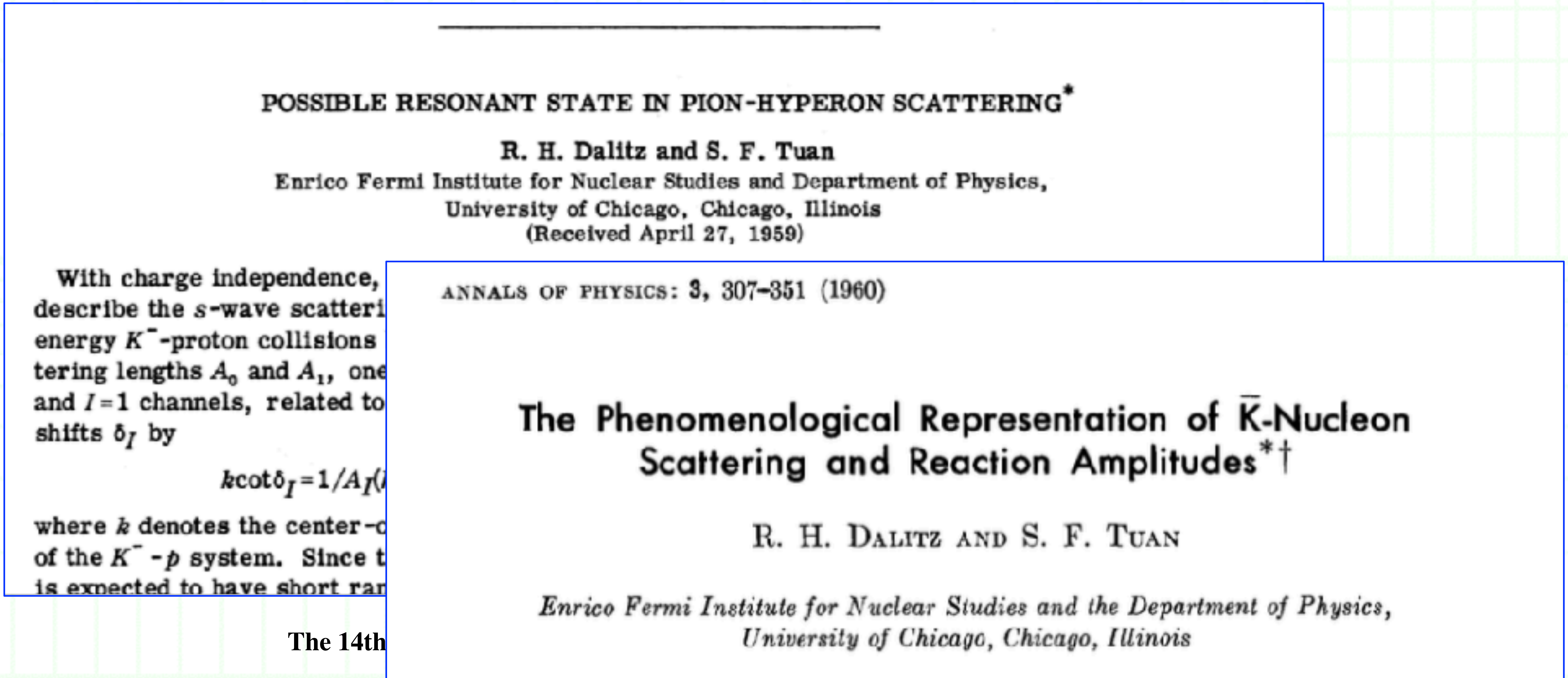
2. Building block: $\bar{K}N$ / Λ(1405)

++ Prediction ++

- [Theory] A resonance state [= Λ(1405)] was predicted in 1959.

Dalitz and Tuan, *Phys. Rev. Lett.* 2 (1959) 425; *Ann. Phys.* 10 (1960) 307.

- ▫ Spin / parity $J^P = 1/2^-$, isospin $I = 0$, strangeness $S = -1$, below the $\bar{K}N$ threshold and decays into the πΣ channel.
- ▫ Based on analysis of the Exp. data of the $\bar{K}N$ scattering length.



POSSIBLE RESONANT STATE IN PION-HYPERON SCATTERING*

R. H. Dalitz and S. F. Tuan
Enrico Fermi Institute for Nuclear Studies and Department of Physics,
University of Chicago, Chicago, Illinois
(Received April 27, 1959)

With charge independence,
describe the s-wave scatteri
energy K^--proton collisions
tering lengths A_0 and A_1, one
and $I=1$ channels, related to
shifts δ_I by

$$k\cot\delta_I=1/A_I($$

where k denotes the center-c
of the K^--p system. Since t
is expected to have short rar

ANNALS OF PHYSICS: 3, 307–351 (1960)

The Phenomenological Representation of $\bar{\text{K}}$-Nucleon Scattering and Reaction Amplitudes*†

R. H. Dalitz and S. F. Tuan

Enrico Fermi Institute for Nuclear Studies and the Department of Physics,
University of Chicago, Chicago, Illinois

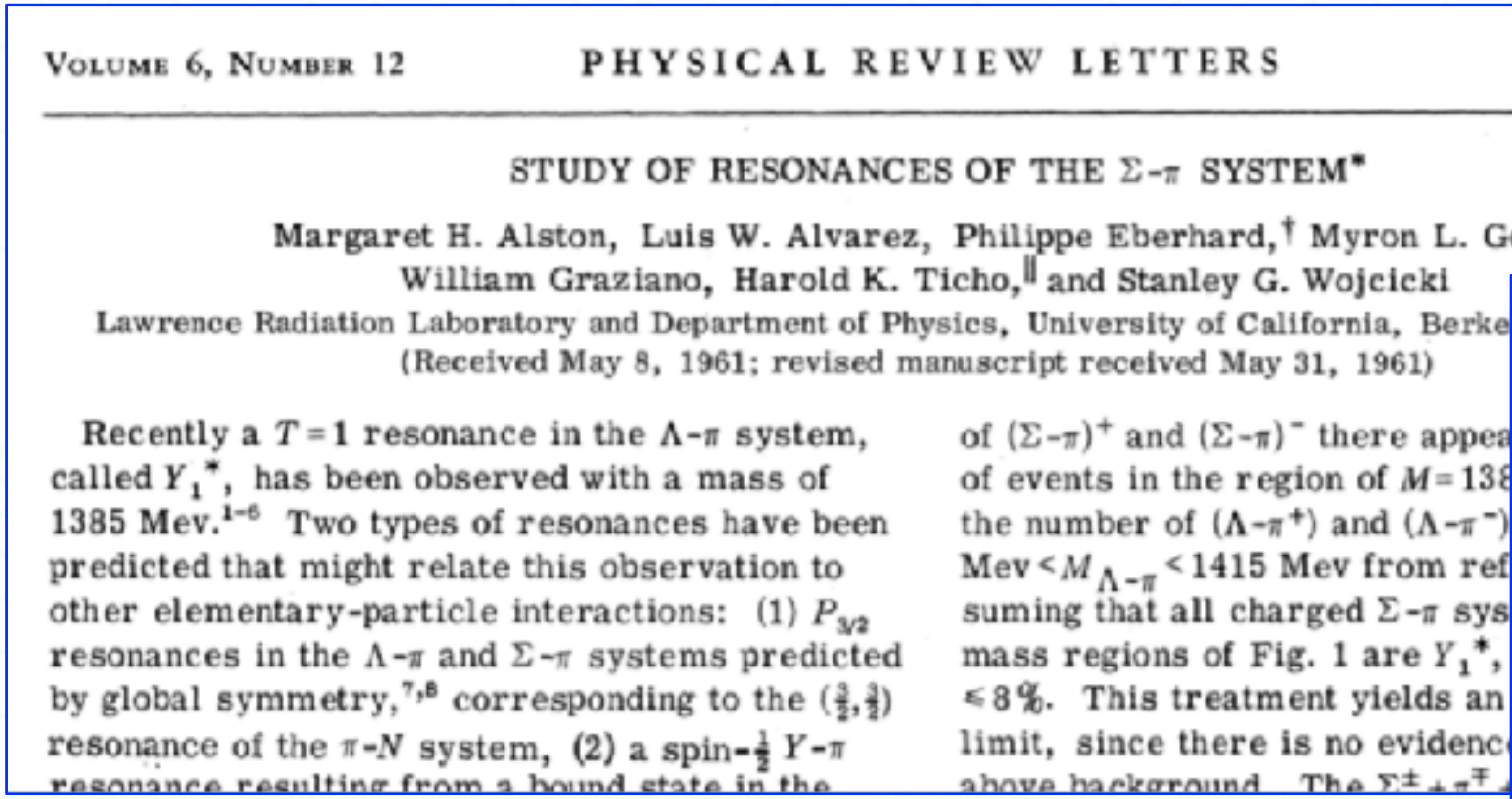
2. Building block: $\bar{K}N$ / Λ(1405)

++ Discovery of Λ(1405) ++

- [Exp.] The Λ(1405) resonance was discovered in 1961.

Alston *et al.*, *Phys. Rev. Lett.* 6 (1961) 698.

- ▫ Then, what is the structure of Λ(1405) ?
- ▫ Λ(1405) can be naturally explained as a $\bar{K}N$ bound state.
  But how can we “proof" that ? <-- Long-standing problem !



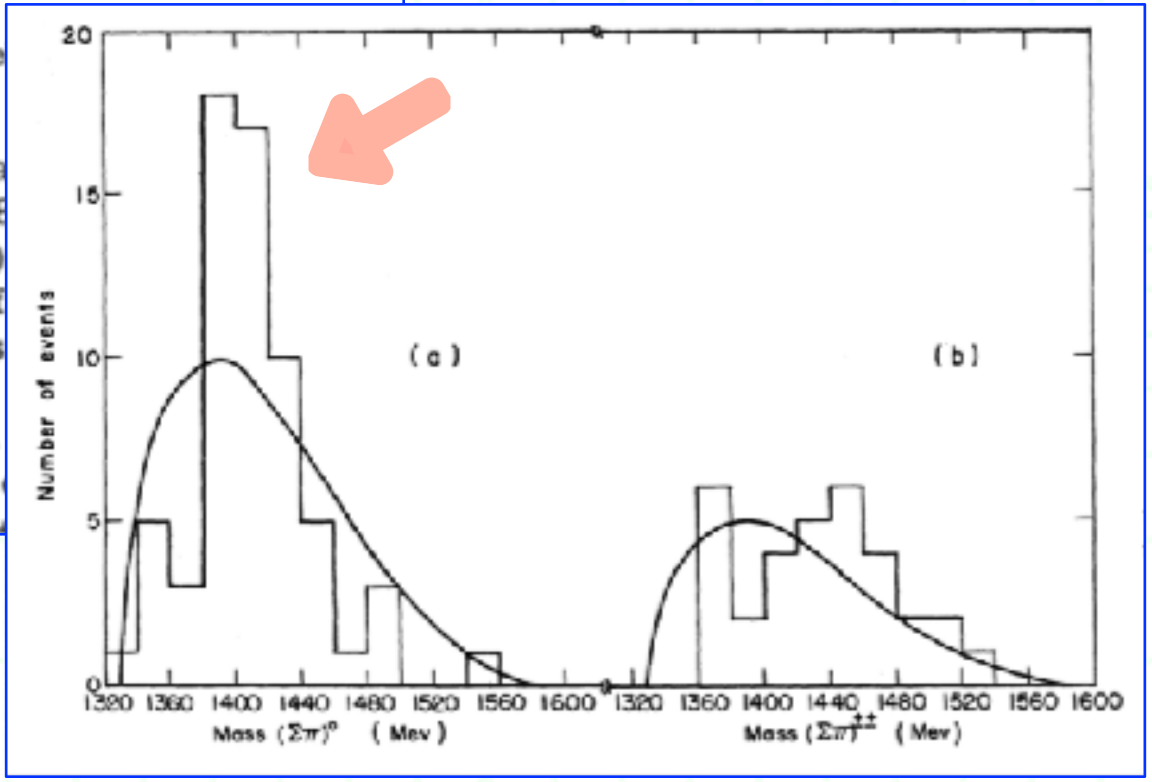
VOLUME 6, NUMBER 12 PHYSICAL REVIEW LETTERS JUNE 15, 1961

STUDY OF RESONANCES OF THE Σ-π SYSTEM*

Margaret H. Alston, Luis W. Alvarez, Philippe Eberhard,† Myron L. Good,‡
William Graziano, Harold K. Ticho,‖ and Stanley G. Wojcicki
Lawrence Radiation Laboratory and Department of Physics, University of California, Berke
(Received May 8, 1961; revised manuscript received May 31, 1961)

Recently a $T=1$ resonance in the Λ-π system, called Y_1^*, has been observed with a mass of 1385 Mev.[1-6] Two types of resonances have been predicted that might relate this observation to other elementary-particle interactions: (1) $P_{3/2}$ resonances in the Λ-π and Σ-π systems predicted by global symmetry,[7,8] corresponding to the $(\frac{3}{2},\frac{3}{2})$ resonance of the π-N system, (2) a spin-$\frac{1}{2}$ Y-π resonance resulting from a bound state in the

of $(\Sigma\text{-}\pi)^+$ and $(\Sigma\text{-}\pi)^-$ there appea
of events in the region of $M=138$
the number of $(\Lambda\text{-}\pi^+)$ and $(\Lambda\text{-}\pi^-)$
Mev $< M_{\Lambda\text{-}\pi} < 1415$ Mev from ref
suming that all charged Σ-π sys
mass regions of Fig. 1 are Y_1^*,
$\leq 8\%$. This treatment yields an
limit, since there is no evidenc
above background. The $\Sigma^\pm + \pi^\mp$



2. Building block: $\bar{K}N$ / Λ(1405)

++ Λ(1405) in chiral dynamics ++

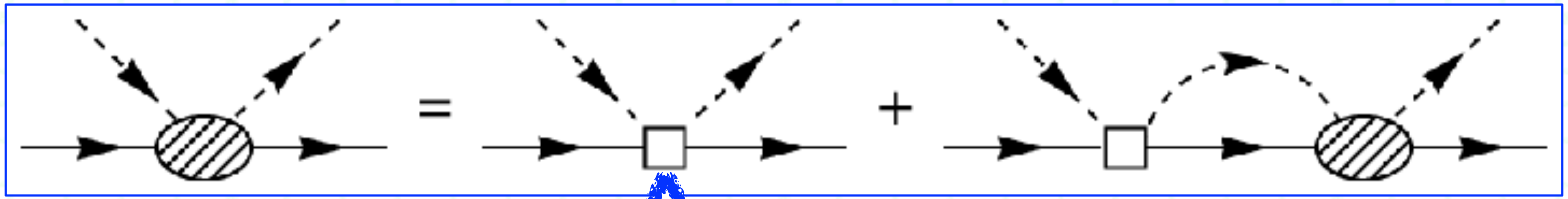
- [Theory] Λ(1405) is well described in chiral dynamics.

Kaiser, Siegel and Weise (1995); Oset and Ramos (1998); ...

- ☐ $\bar{K}$ is a Nambu-Goldstone boson of spontaneous chiral symmetry breaking in QCD. $\boxed{SU(3)_{\mathrm{L}} \otimes SU(3)_{\mathrm{R}} \to SU(3)_{\mathrm{flavor}}}$
- ☐ $\bar{K}$ is massive by strange quark: $m_K \sim 495$ MeV.

--> Interaction from chiral perturbation theory & its unitarization can dynamically generate Λ(1405) in $\bar{K}N$ coupled channels.

--- Chiral dynamics !

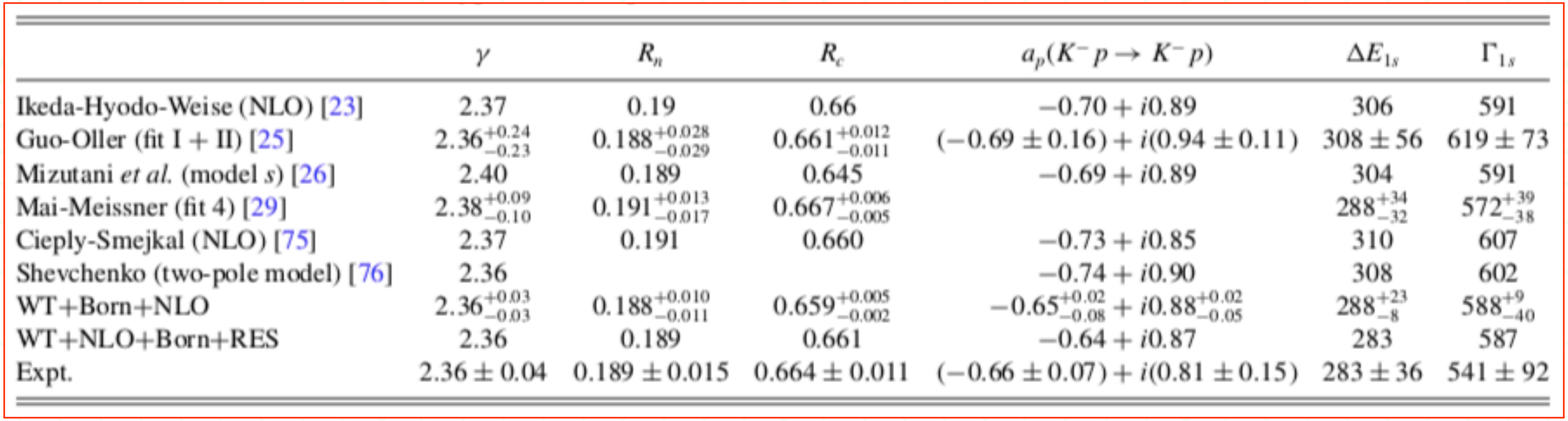


chiral perturbation theory

2. Building block: $\bar{K}N$ / Λ(1405)

++ Λ(1405) in chiral dynamics ++

- [Theory] Λ(1405) is well described in chiral dynamics.
  - Observables at the K^-p threshold.



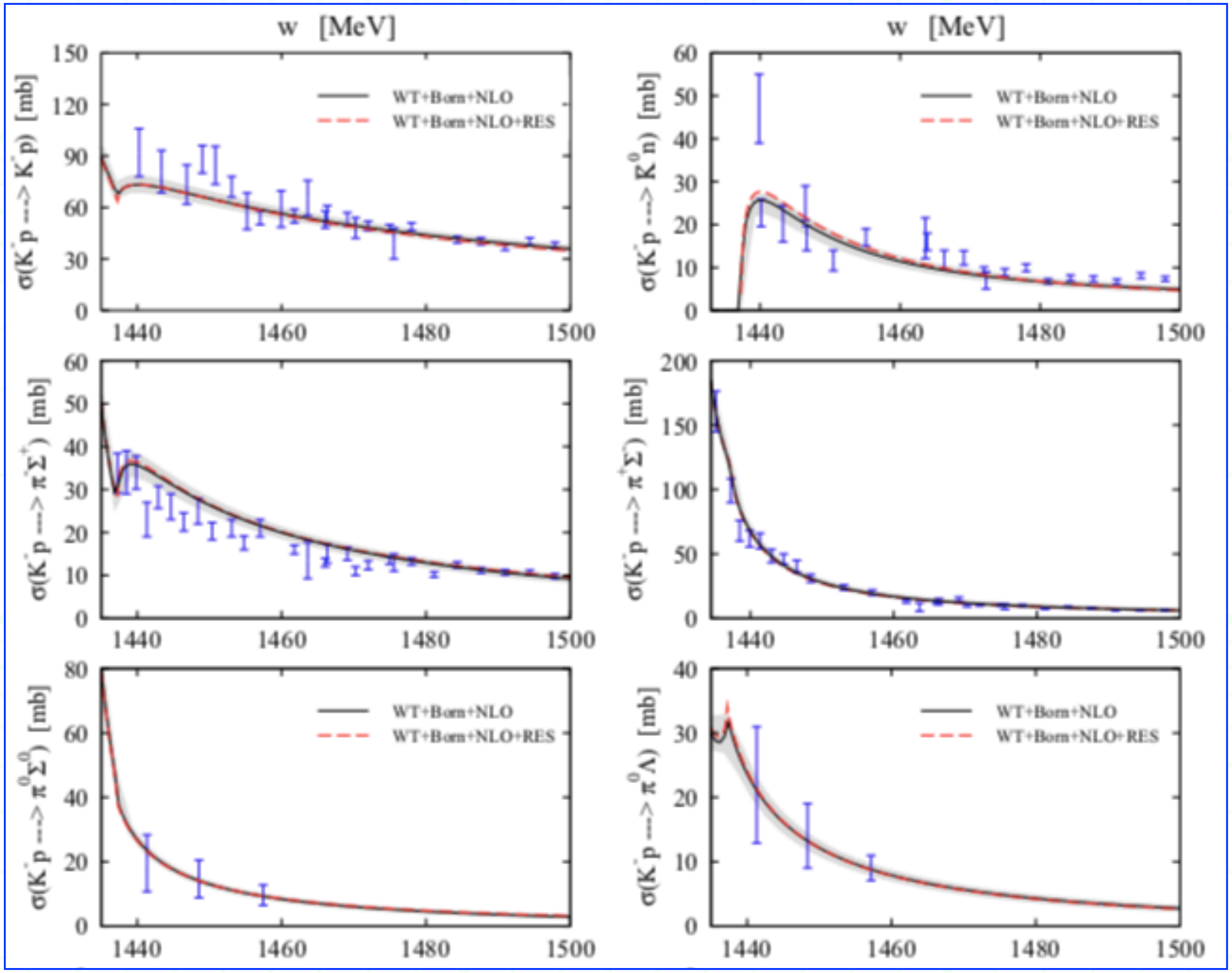
	γ	R_n	R_c	$a_p(K^-p \to K^-p)$	ΔE_{1s}	Γ_{1s}
Ikeda-Hyodo-Weise (NLO) [23]	2.37	0.19	0.66	$-0.70 + i0.89$	306	591
Guo-Oller (fit I + II) [25]	$2.36^{+0.24}_{-0.23}$	$0.188^{+0.028}_{-0.029}$	$0.661^{+0.012}_{-0.011}$	$(-0.69 \pm 0.16) + i(0.94 \pm 0.11)$	308 ± 56	619 ± 73
Mizutani *et al.* (model *s*) [26]	2.40	0.189	0.645	$-0.69 + i0.89$	304	591
Mai-Meissner (fit 4) [29]	$2.38^{+0.09}_{-0.10}$	$0.191^{+0.013}_{-0.017}$	$0.667^{+0.006}_{-0.005}$		288^{+34}_{-32}	572^{+39}_{-38}
Cieply-Smejkal (NLO) [75]	2.37	0.191	0.660	$-0.73 + i0.85$	310	607
Shevchenko (two-pole model) [76]	2.36			$-0.74 + i0.90$	308	602
WT+Born+NLO	$2.36^{+0.03}_{-0.03}$	$0.188^{+0.010}_{-0.011}$	$0.659^{+0.005}_{-0.002}$	$-0.65^{+0.02}_{-0.08} + i0.88^{+0.02}_{-0.05}$	288^{+23}_{-8}	588^{+9}_{-40}
WT+NLO+Born+RES	2.36	0.189	0.661	$-0.64 + i0.87$	283	587
Expt.	2.36 ± 0.04	0.189 ± 0.015	0.664 ± 0.011	$(-0.66 \pm 0.07) + i(0.81 \pm 0.15)$	283 ± 36	541 ± 92

Feijoo, Magas and Ramos, *Phys. Rev.* C99 (2019) 035211.

2. Building block: $\bar{K}N$ / Λ(1405)

++ Λ(1405) in chiral dynamics ++

- [Theory] **Λ(1405) is well described in chiral dynamics.**



☐ **Cross sections.**

Feijoo, Magas and Ramos, *Phys. Rev.* C99 (2019) 035211.

2. Building block: $\bar{K}N$ / Λ(1405)

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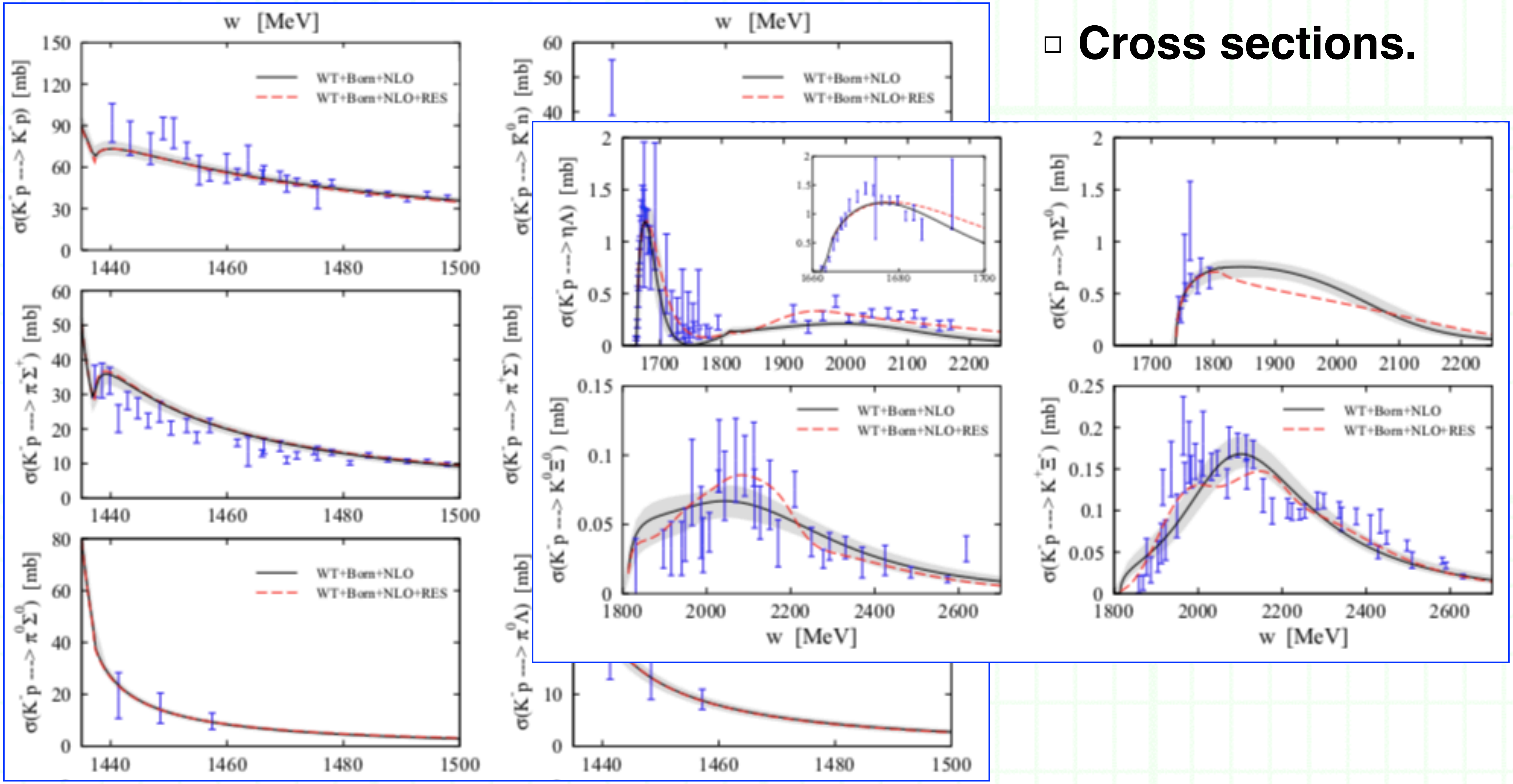
□ **Cross sections.**



Feijoo, Magas and Ramos, *Phys. Rev.* C99 (2019) 035211.

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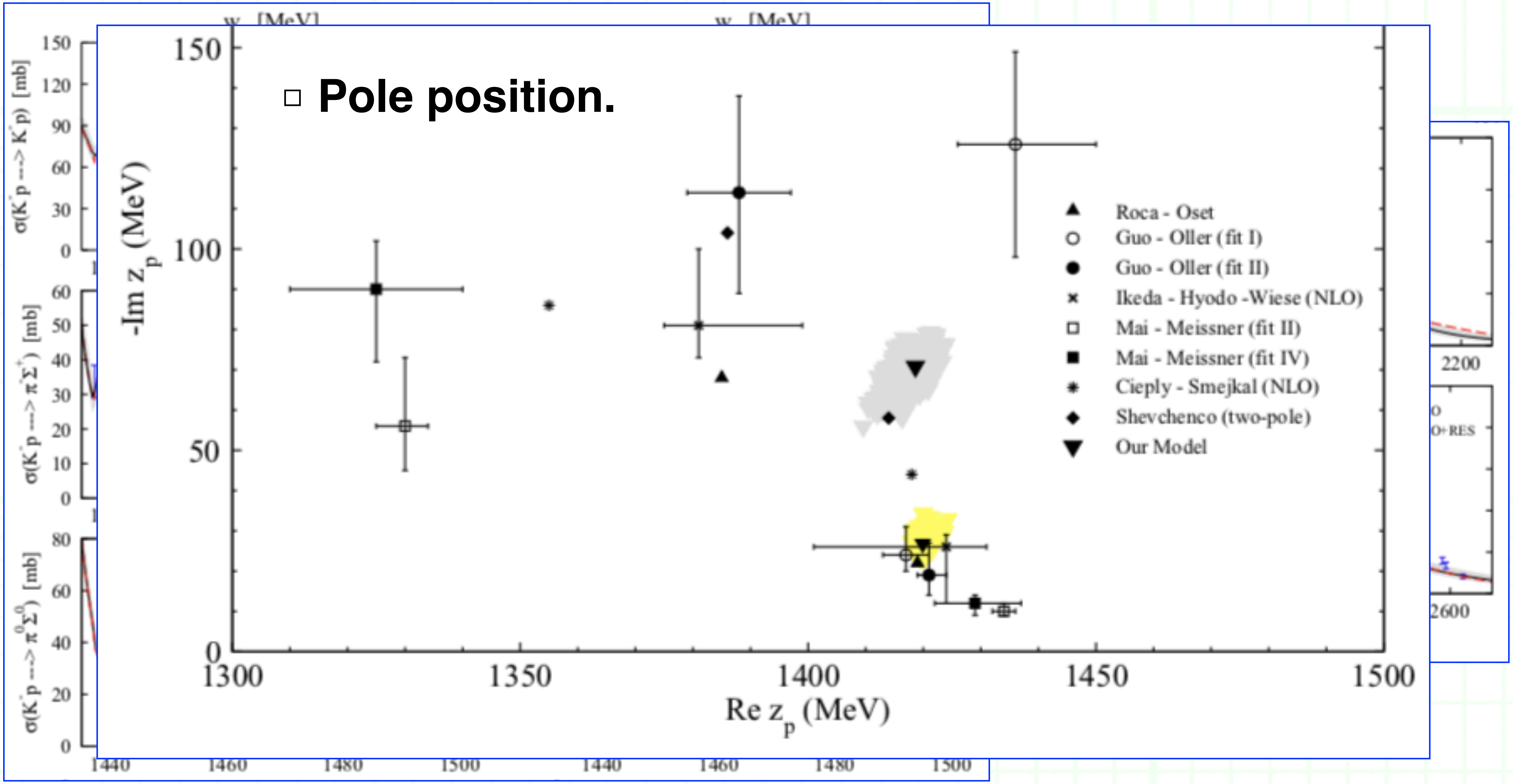

□ **Pole position.**

Feijoo, Magas and Ramos, *Phys. Rev.* C99 (2019) 035211.

2. Building block: $\bar{K}N$ / Λ(1405)

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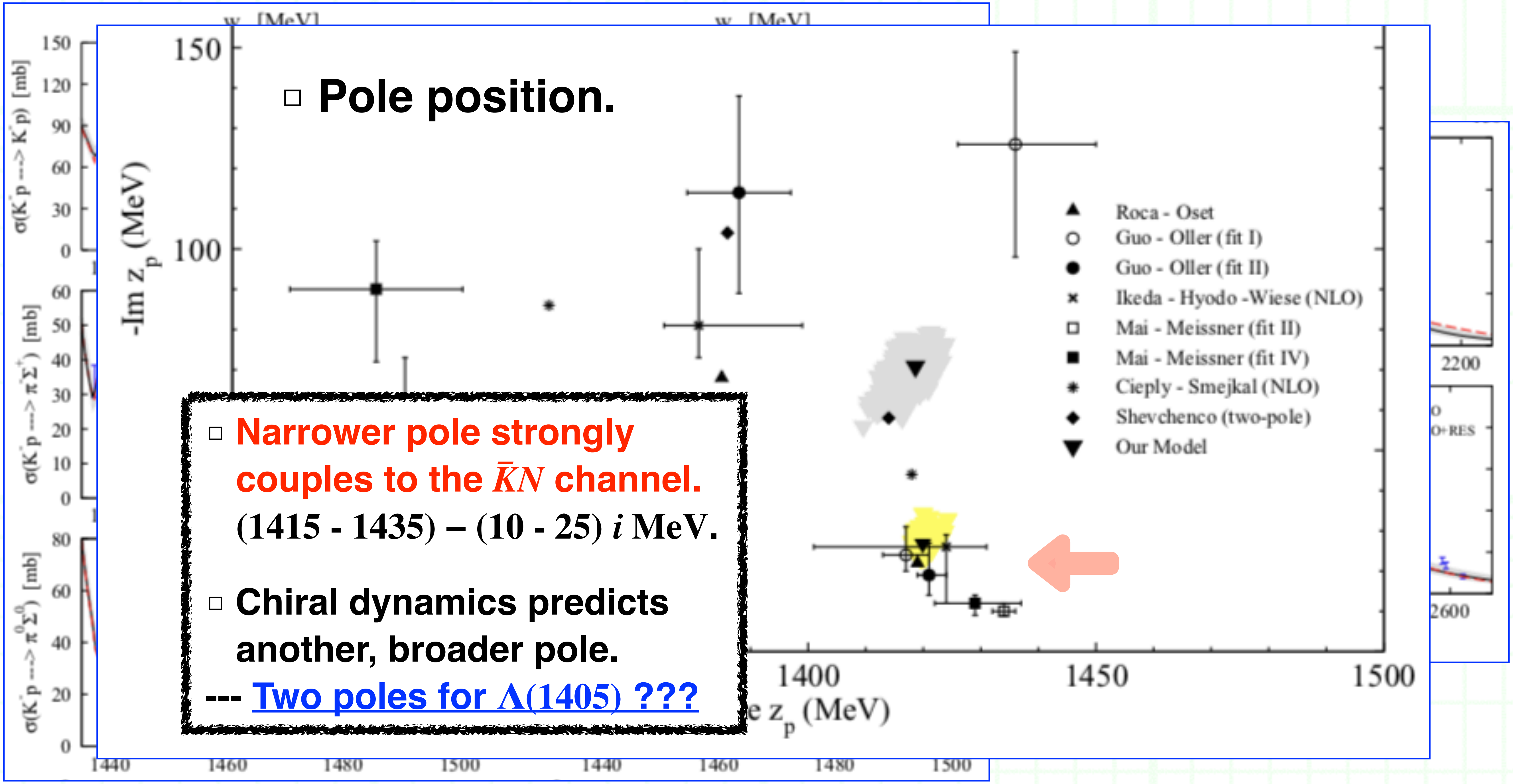


□ Pole position.

□ Narrower pole strongly couples to the $\bar{K}N$ channel.
(1415 - 1435) – (10 - 25) i MeV.

□ Chiral dynamics predicts another, broader pole.
--- Two poles for Λ(1405) ???

Feijoo, Magas and Ramos, *Phys. Rev.* C99 (2019) 035211.

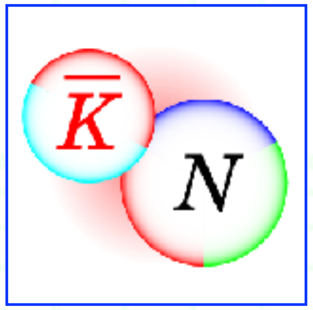
2. Building block: $\bar{K}N$ / Λ(1405)

++ Structure of Λ(1405) ++

- [Theory] What is the structure of Λ(1405) ?

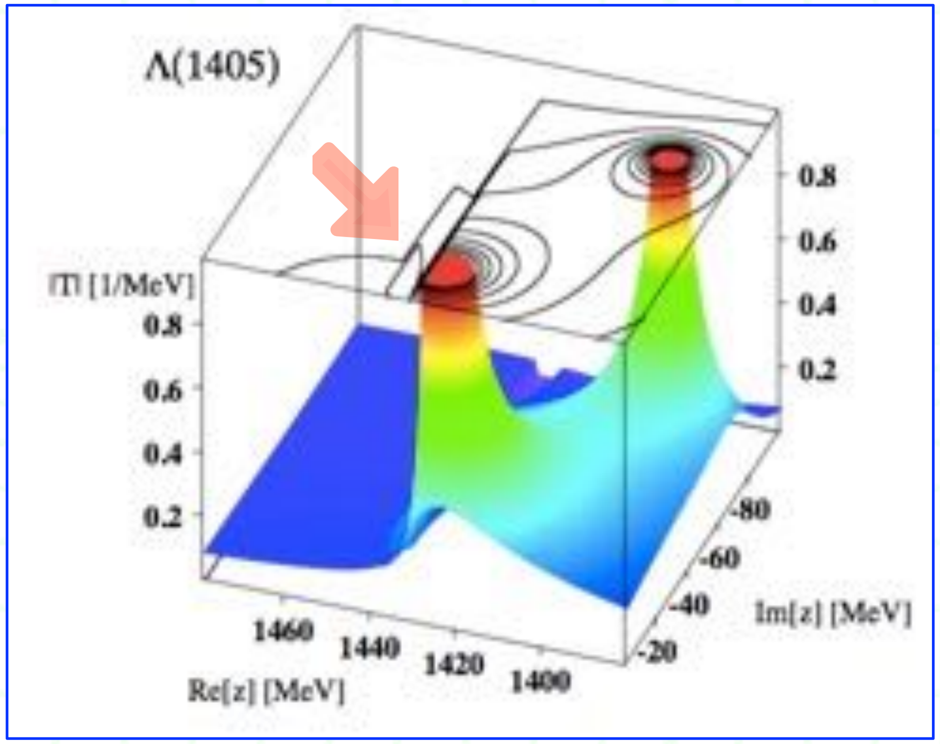
--> To check how much Λ(1405) contains the $\bar{K}N$ component, the compositeness was calculated in chiral dynamics.

- ◻ Compositeness = Norm of the two-body wave function for each resonance pole.



How much ?

- ◻ Uniquely determined once model space and parameters are fixed.



Hyodo and Jido ('12).

T. S. , Hyodo and Jido, *PTEP* 2015, 063D04.

	Λ(1405), higher pole	Λ(1405), lower pole
$\sqrt{s_{\text{pole}}}$	$1424 - 26i$ MeV	$1381 - 81i$ MeV
$X_{\bar{K}N}$	$1.14 + 0.01i$	$-0.39 - 0.07i$
$X_{\pi\Sigma}$	$-0.19 - 0.22i$	$0.66 + 0.52i$
$X_{\eta\Lambda}$	$0.13 + 0.02i$	$-0.04 + 0.01i$
$X_{K\Xi}$	$0.00 + 0.00i$	$-0.00 + 0.00i$
Z	$-0.08 + 0.19i$	$0.77 - 0.46i$

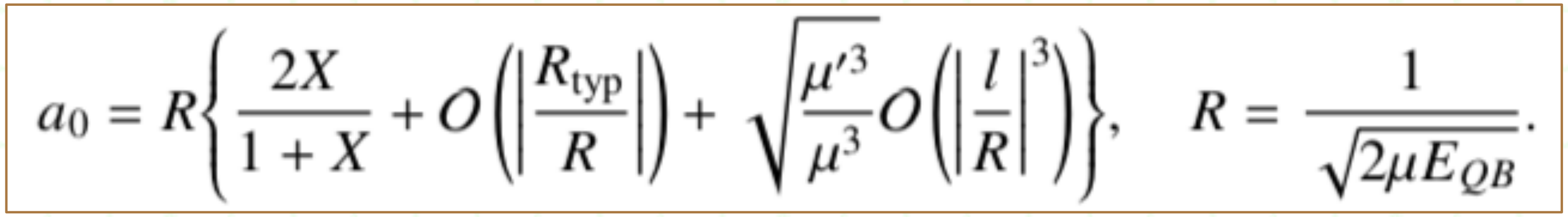
2. Building block: $\bar{K}N$ / Λ(1405)

++ Structure of Λ(1405) ++

- [Theory] What is the structure of Λ(1405) ?

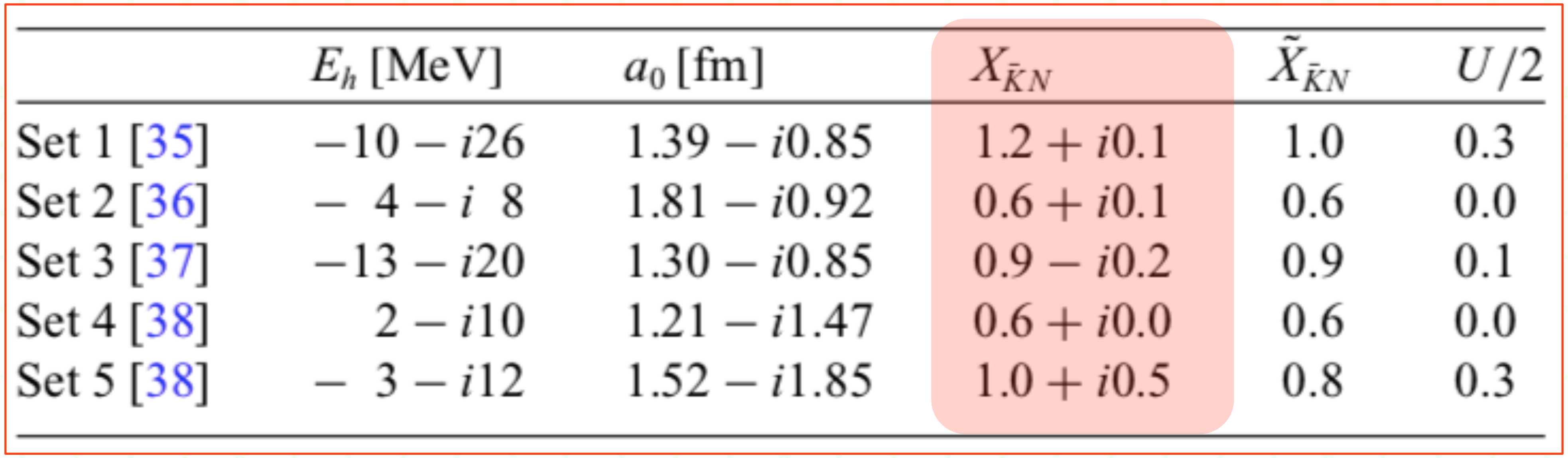
--> To check how much Λ(1405) contains the $\bar{K}N$ component, the compositeness was calculated in chiral dynamics.

- One may evaluate the compositeness only from “observables" in model independent manner --- Pole position and Scatt. length.



$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\mathrm{typ}}}{R}\right|\right) + \sqrt{\frac{\mu'^3}{\mu^3}}\,\mathcal{O}\left(\left|\frac{l}{R}\right|^3\right)\right\}, \quad R = \frac{1}{\sqrt{2\mu E_{QB}}}.$$

Kamiya and Hyodo, *PTEP* 2017 023D02.



	E_h [MeV]	a_0 [fm]	$X_{\bar{K}N}$	$\tilde{X}_{\bar{K}N}$	$U/2$
Set 1 [35]	$-10 - i26$	$1.39 - i0.85$	$1.2 + i0.1$	1.0	0.3
Set 2 [36]	$-4 - i8$	$1.81 - i0.92$	$0.6 + i0.1$	0.6	0.0
Set 3 [37]	$-13 - i20$	$1.30 - i0.85$	$0.9 - i0.2$	0.9	0.1
Set 4 [38]	$2 - i10$	$1.21 - i1.47$	$0.6 + i0.0$	0.6	0.0
Set 5 [38]	$-3 - i12$	$1.52 - i1.85$	$1.0 + i0.5$	0.8	0.3

2. Building block: $\bar{K}N$ / Λ(1405)

++ Structure of Λ(1405) ++

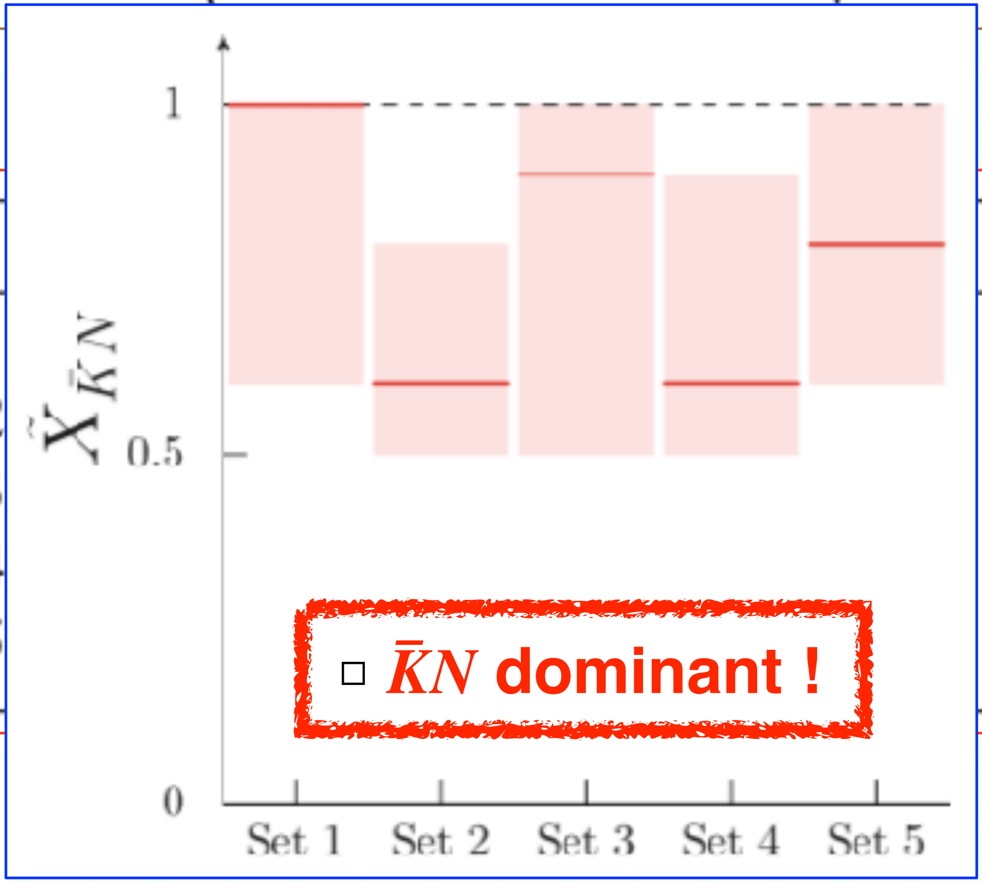
- [Theory] What is the structure of Λ(1405) ?

--> To check how much Λ(1405) contains the $\bar{K}N$ component, the compositeness was calculated in chiral dynamics.

□ One may evaluate the compositeness only from "observables" in model independent manner --- Pole position and Scatt. length.

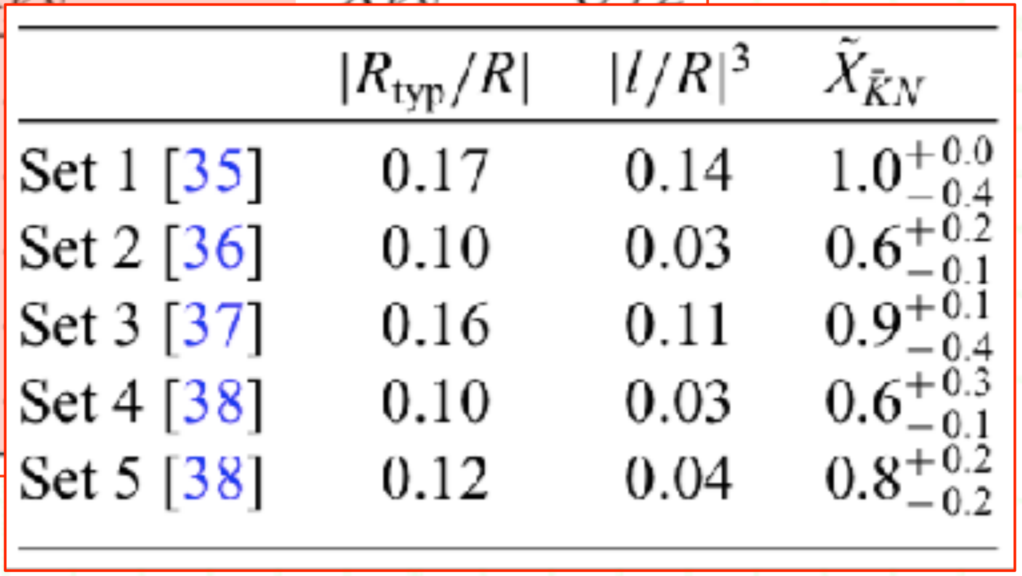
$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\rm typ}}{R}\right|\right) + \sqrt{\frac{\mu'^3}{\mu^3}}\,\mathcal{O}\left(\left|\frac{l}{R}\right|^3\right)\right\}, \quad R = \frac{1}{\sqrt{2\mu E_{QB}}}.$$

Kamiya and Hyodo, *PTEP* 2017 023D02.



□ $\bar{K}N$ dominant !

	$X_{\bar{K}N}$	$\tilde{X}_{\bar{K}N}$	$U/2$
Set 1	1		
Set 2	0		
Set 3	0		
Set 4	0		
Set 5	1		



	$\lvert R_{\rm typ}/R\rvert$	$\lvert l/R\rvert^3$	$\tilde{X}_{\bar{K}N}$
Set 1 [35]	0.17	0.14	$1.0^{+0.0}_{-0.4}$
Set 2 [36]	0.10	0.03	$0.6^{+0.2}_{-0.1}$
Set 3 [37]	0.16	0.11	$0.9^{+0.1}_{-0.4}$
Set 4 [38]	0.10	0.03	$0.6^{+0.3}_{-0.1}$
Set 5 [38]	0.12	0.04	$0.8^{+0.2}_{-0.2}$

2. Building block: $\bar{K}N$ / Λ(1405)

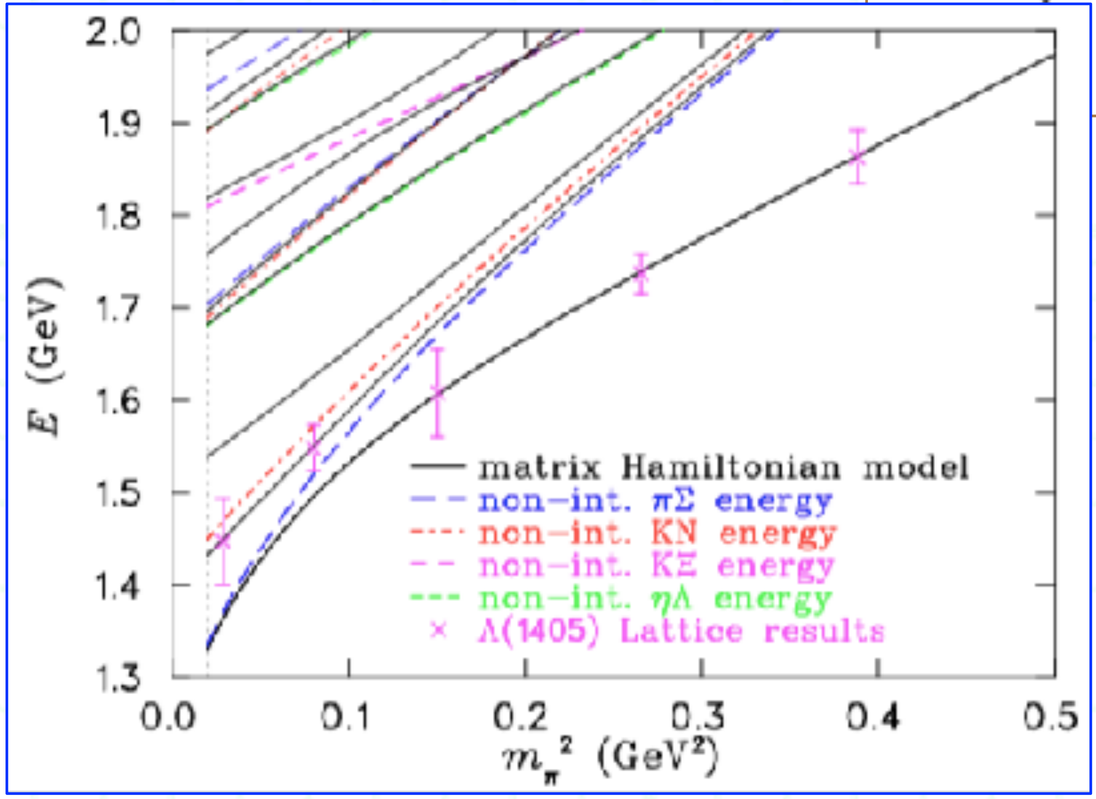
++ Structure of Λ(1405) ++

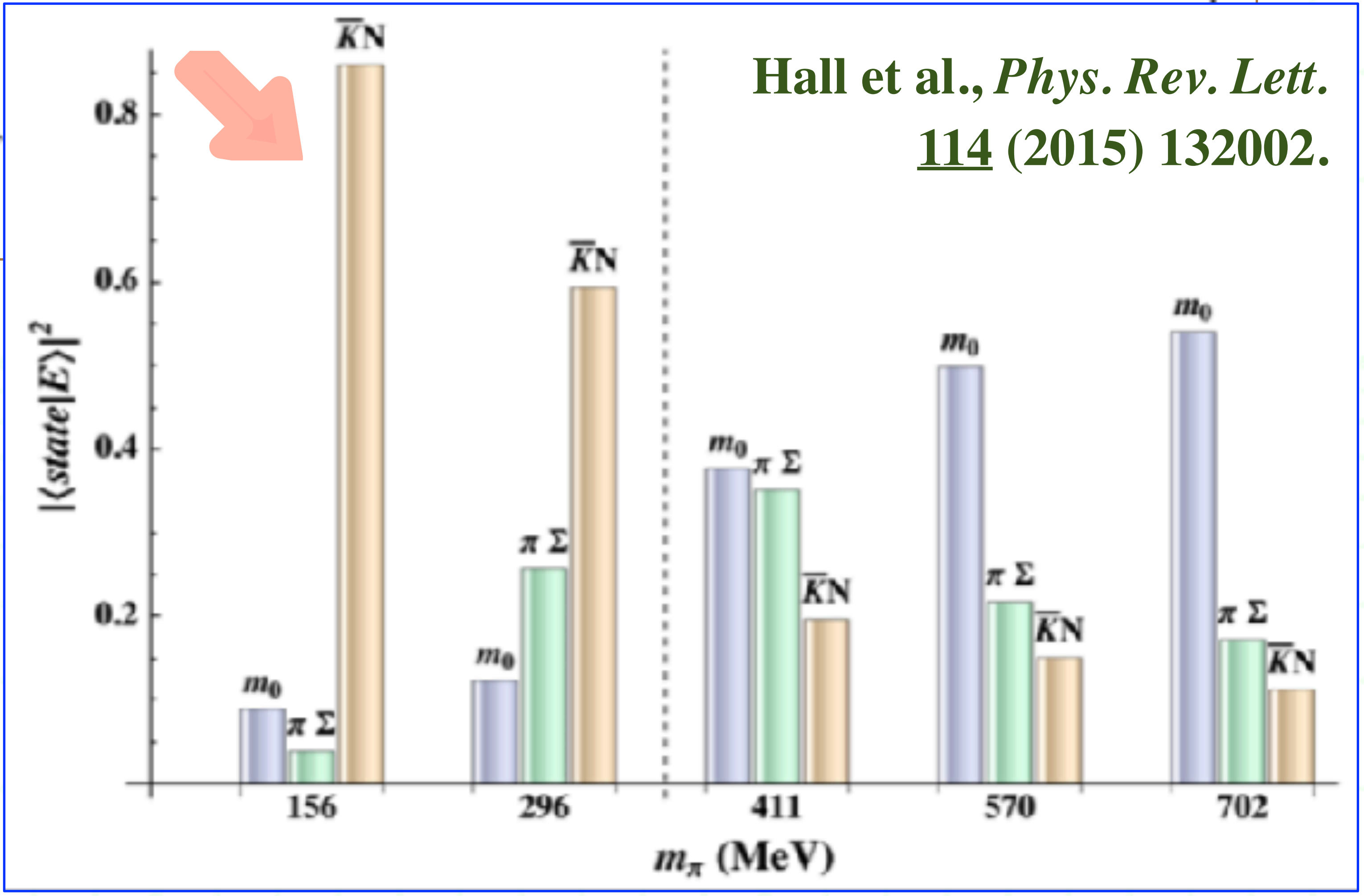
- [Theory] What is the structure of Λ(1405) ?
  - ☐ Lattice QCD energy levels together with a Hamiltonian effective-field-theory model suggested dominant $\bar{K}N$ component.

$$H^I = H_0^I + H_{\rm int}^I,$$

$$H_0^I = \sum_{B_0} |B_0\rangle m_B^0 \langle B_0| + \sum_{\alpha} \int d^3\vec{k} \times |\alpha(\vec{k})\rangle [\omega_{\alpha_M}(k) + \omega_{\alpha_B}(k)] \langle \alpha(\vec{k})|,$$

$$\mathcal{H}^0_{\rm int} = \begin{pmatrix} 0 & \mathcal{G}^0_{\pi\Sigma,B_0}(k_0) & \mathcal{G}^0_{\bar{K}N,B_0}(k_0) & \cdots & \mathcal{G}^0_{\pi\Sigma,B_0}(k_1) & \cdots \\ \mathcal{G}^0_{\pi\Sigma,B_0}(k_0) & \mathcal{V}^0_{\pi\Sigma,\pi\Sigma}(k_0,k_0) & \mathcal{V}^0_{\pi\Sigma,\bar{K}N}(k_0,k_0) & \cdots & \mathcal{V}^0_{\pi\Sigma,\pi\Sigma}(k_0,k_1) & \cdots \\ \mathcal{G}^0_{\bar{K}N,B_0}(k_0) & \mathcal{V}^0_{\bar{K}N,\pi\Sigma}(k_0,k_0) & \mathcal{V}^0_{\bar{K}N,\bar{K}N}(k_0,k_0) & \cdots & \mathcal{V}^0_{\bar{K}N,\pi\Sigma}(k_0,k_1) & \cdots \\ \mathcal{G}^0_{\pi\Sigma,} & & & & & \end{pmatrix}$$





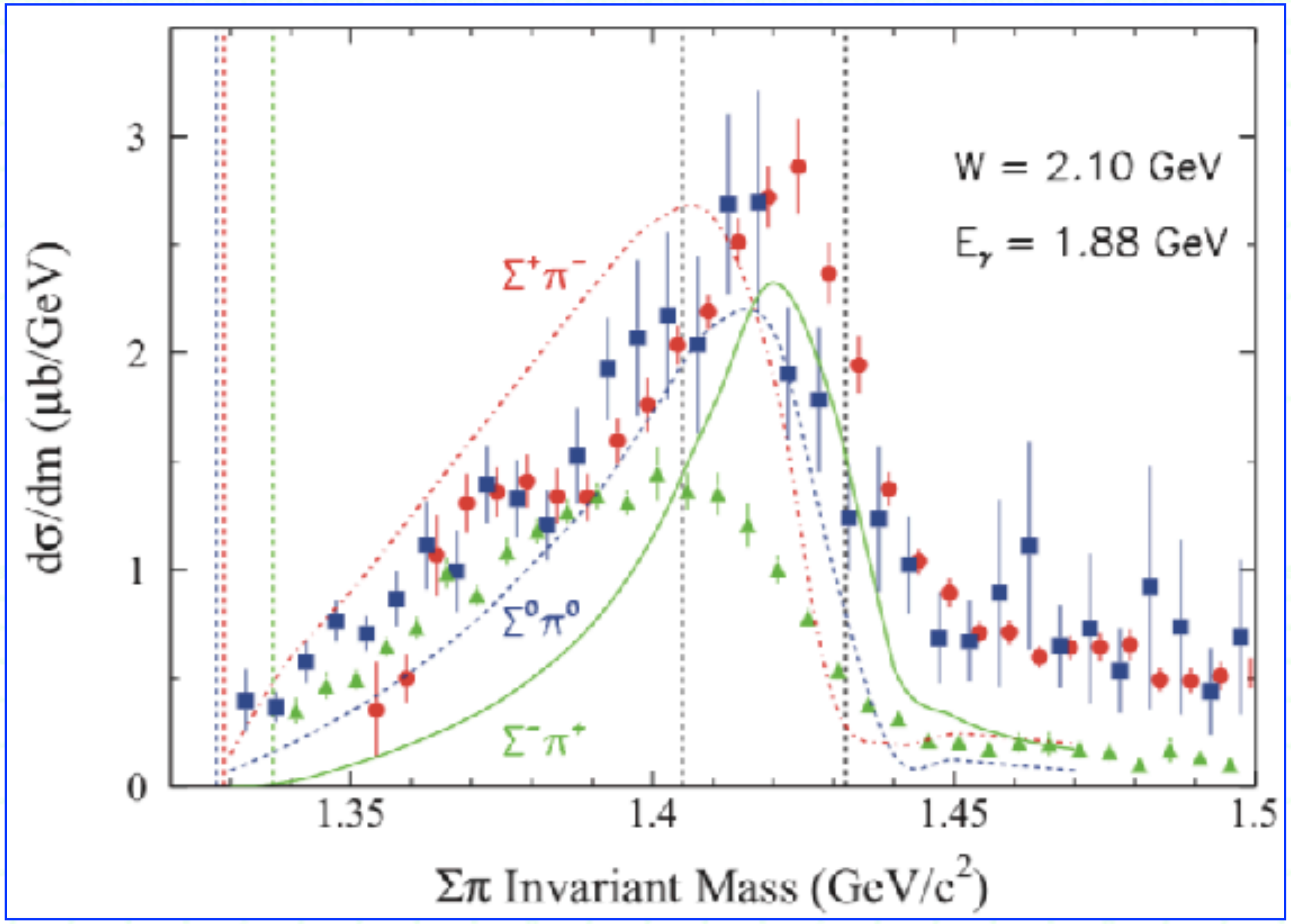
Hall et al., *Phys. Rev. Lett.* 114 (2015) 132002.

2. Building block: $\bar{K}N$ / Λ(1405)

++ Observed peak(s) of Λ(1405) ++

- [Exp.] **How Λ(1405) emerges in spectra ?**
  - □ $\gamma\, p \to K^+ (\pi\Sigma)^0$ reaction.

    Moriya *et al.* [CLAS], *Phys. Rev.* C87 (2013) 035206.



□ **Peak position depends on the charge of the πΣ state**: $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, and $\pi^0\Sigma^0$.

--- **Interference with $I = 1$** in the spectra.

Schumacher and Moriya, *Nucl. Phys.* A914 (2013) 51.

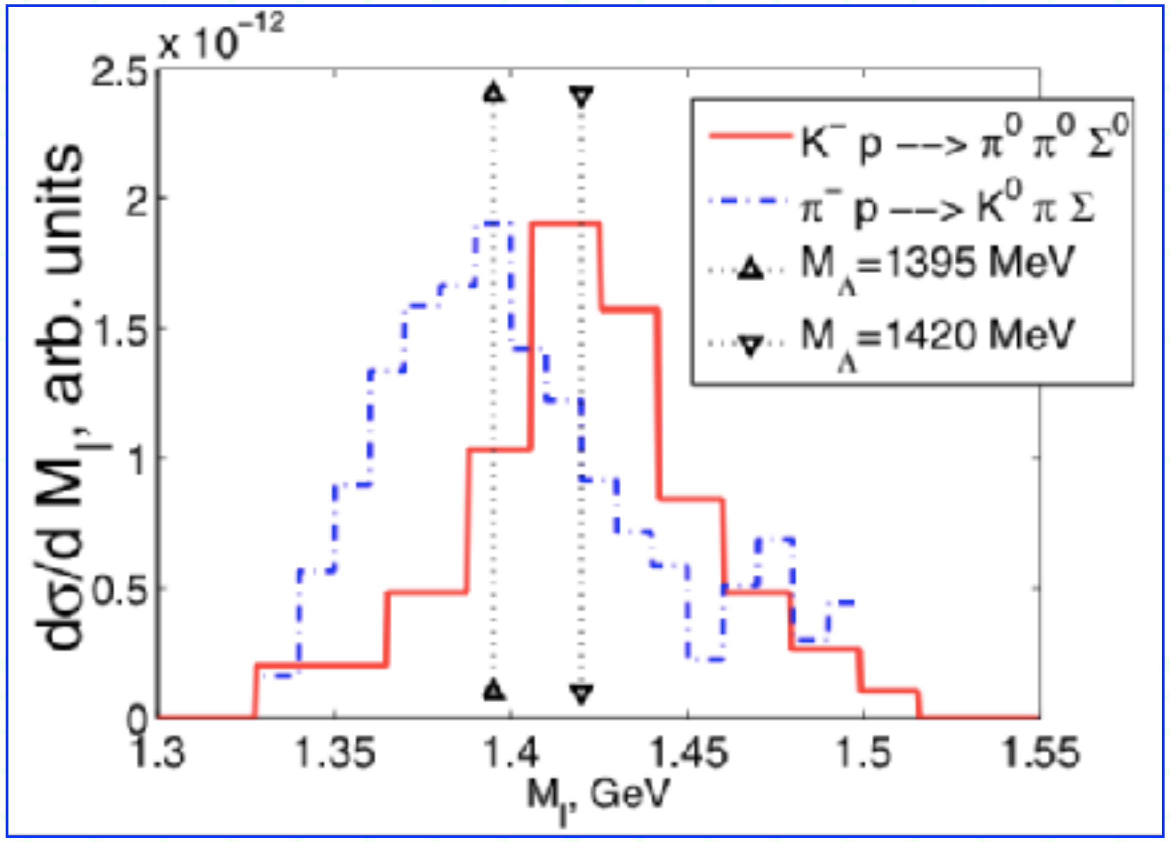
□ Therefore, **one cannot directly conclude the pole position** from the peak position.

--- **Need detailed analysis of production process.**

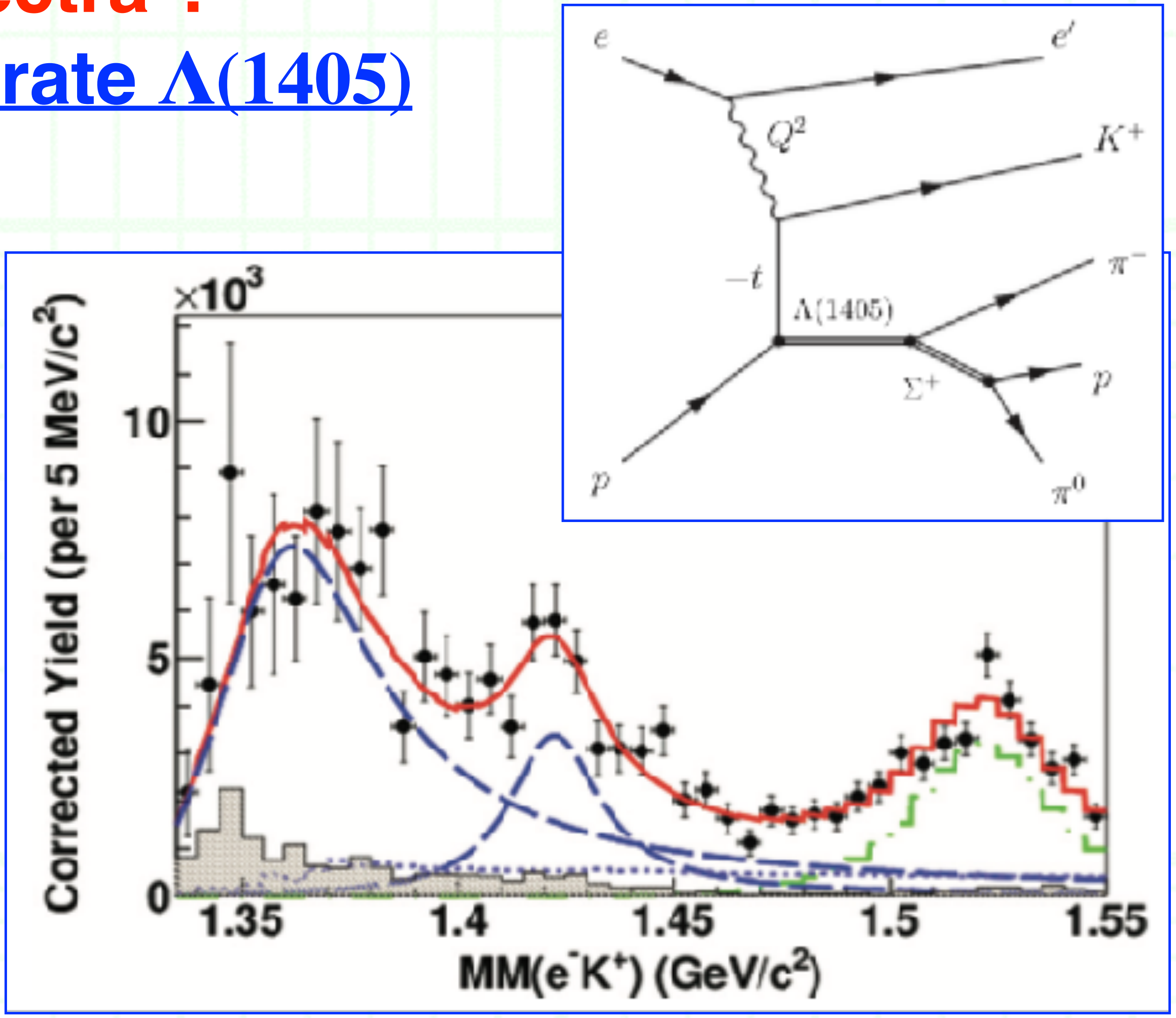
2. Building block: $\bar{K}N$ / Λ(1405)

++ Observed peak(s) of Λ(1405) ++

- [Exp.] How Λ(1405) emerges in spectra ?
  - ☐ In addition, some reactions generate Λ(1405) with much lower peak position.



Magas, Oset and Ramos, *Phys. Rev. Lett.* 95 (2005) 052301;
Prakhov *et al.* [Crystall Ball], *Phys. Rev.* C70 (2004) 034605;
Thomas *et al.*, *Nucl. Phys.* B56 (1973) 15.



☐ $e\, p \rightarrow e\, K^+\, \pi^- \Sigma^+$.

Lu *et al.* [CLAS],
Phys. Rev. C88 (2013) 045202.

--- Effect of the two-pole nature for the Λ(1405) ???

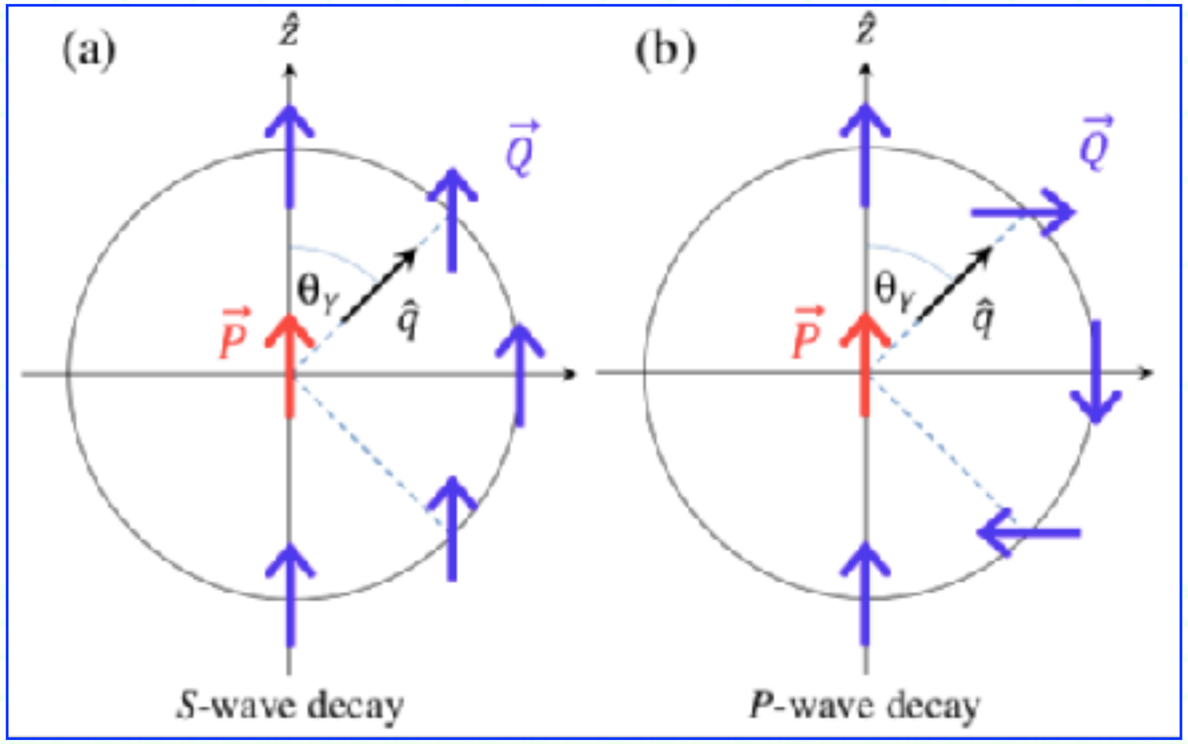
2. Building block: $\bar{K}N$ / Λ(1405)

++ Spin / parity of Λ(1405) ++

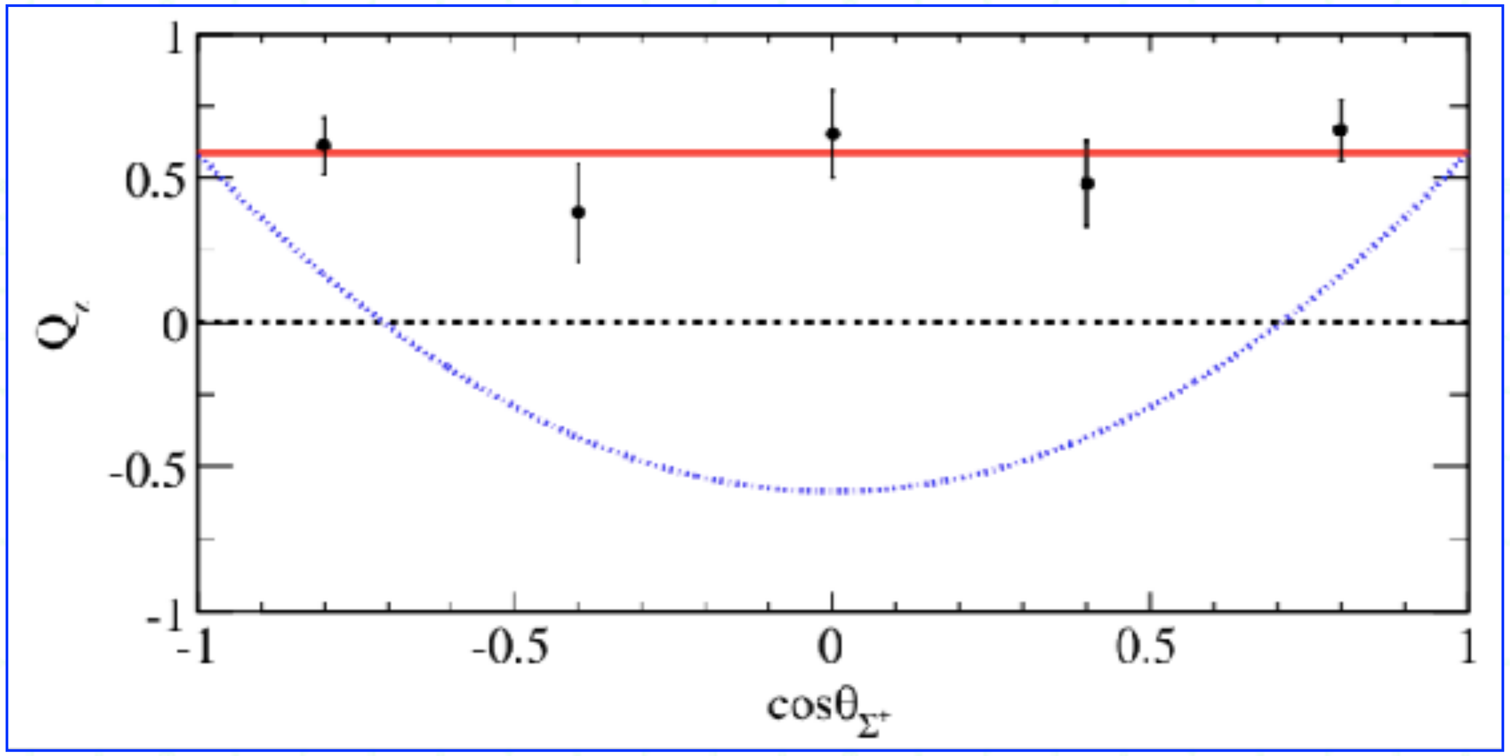
- [Exp.] What is the spin / parity of Λ(1405) ?

Moriya *et al.* [CLAS], *Phys. Rev. Lett.* 112 (2014) 082004.

□ Complete Exp. confirmation of the spin & parity of Λ(1405) was done very recently.



□ γ *p* –> K^+ Λ(1405) reaction.



□ Consistent with $J^P = 1/2^-$!

2. Building block: $\bar{K}N$ / $\Lambda(1405)$

++ Summary of the $\bar{K}N$ bound state ++

	$\Lambda(1405)$ as $\bar{K}N$ bound state
Prediction	1959
Discovery	1961
Spin / parity	$1/2^-$ (2014)
Interaction	Chiral dynamics
Component	$\bar{K}N$ dominant in chiral D (2015 ~)
Peak position	Depends on reaction
Pole position	$(1415 - 1435) - (10 - 25)\,i$ MeV*

* Assuming chiral dynamics.

3. Physics on the $\bar{K}NN$ bound state

3. Physics on the $\bar{K}NN$ bound state

++ Extension to the $\bar{K}NN$ bound state ++

	$\Lambda(1405)$ as $\bar{K}N$ bound state	$\bar{K}NN$ bound state
Prediction	**1959**	
Discovery	**1961**	
Spin / parity	$1/2^-$ **(2014)**	
Interaction	**Chiral dynamics**	
Component	$\bar{K}N$ **dominant in chiral D**	
Peak position	**Depends on reaction**	
Pole position	$(1415 - 1435) - (10 - 25)\, i$ MeV*	

*** Assuming chiral dynamics.**

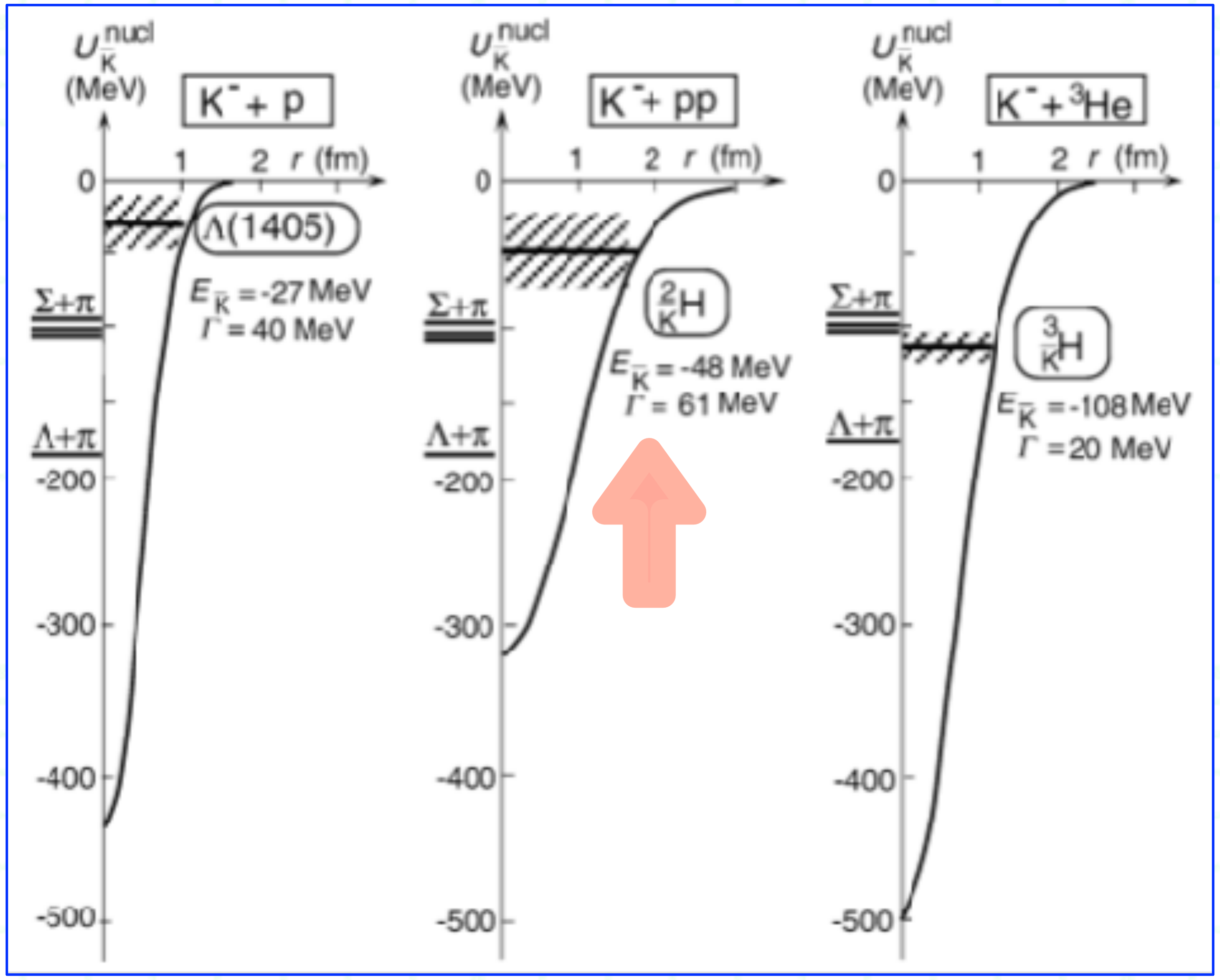
3. Physics on the $\bar{K}NN$ bound state

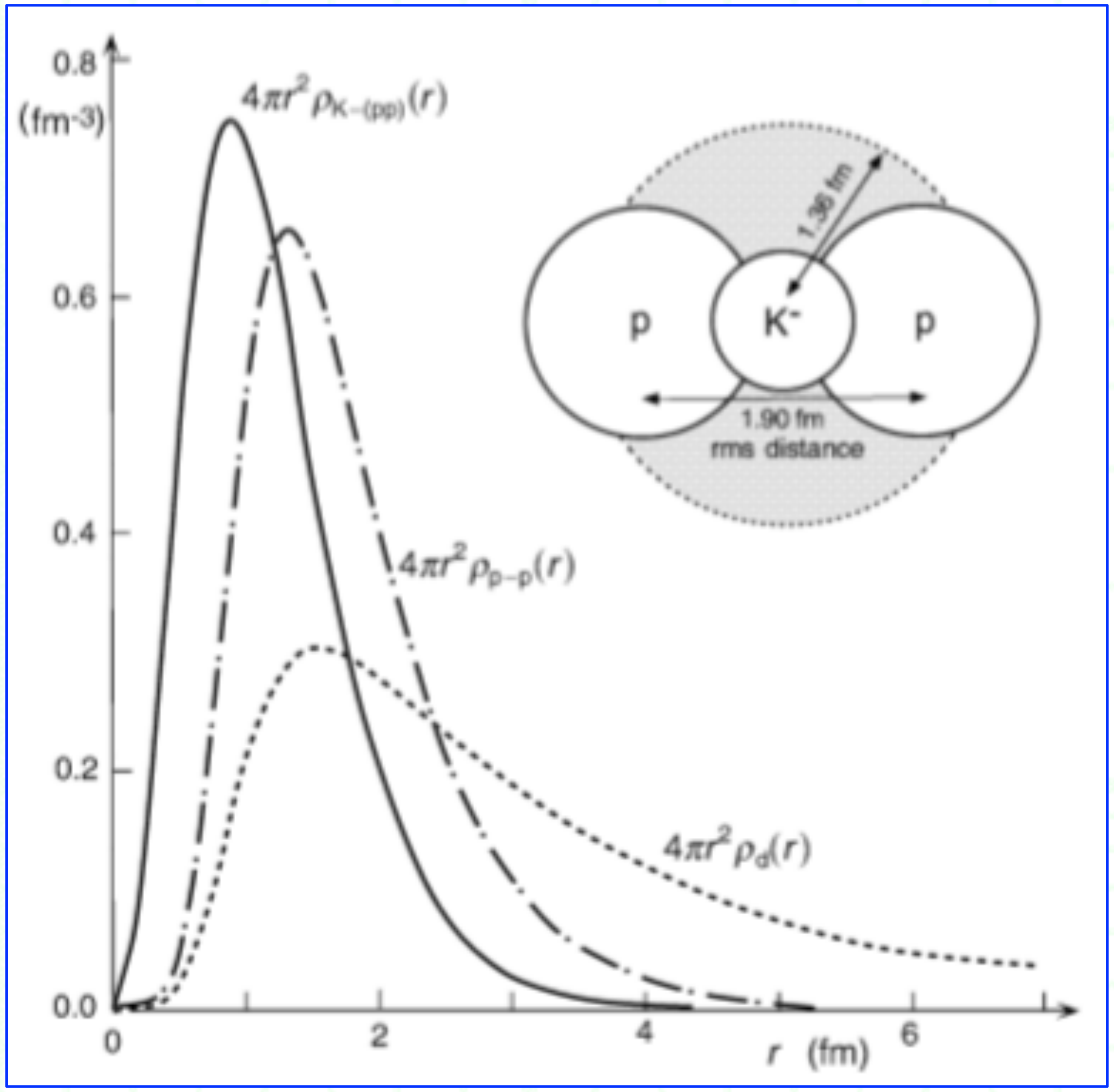
++ Prediction ++

- [Theory] **The $\bar{K}NN$ bound state was predicted in 2002.**

Yamazaki and Akaishi, *Phys. Lett.* B535 (2002) 70; ...

- □ Spin / parity $J^P = 0^-$.





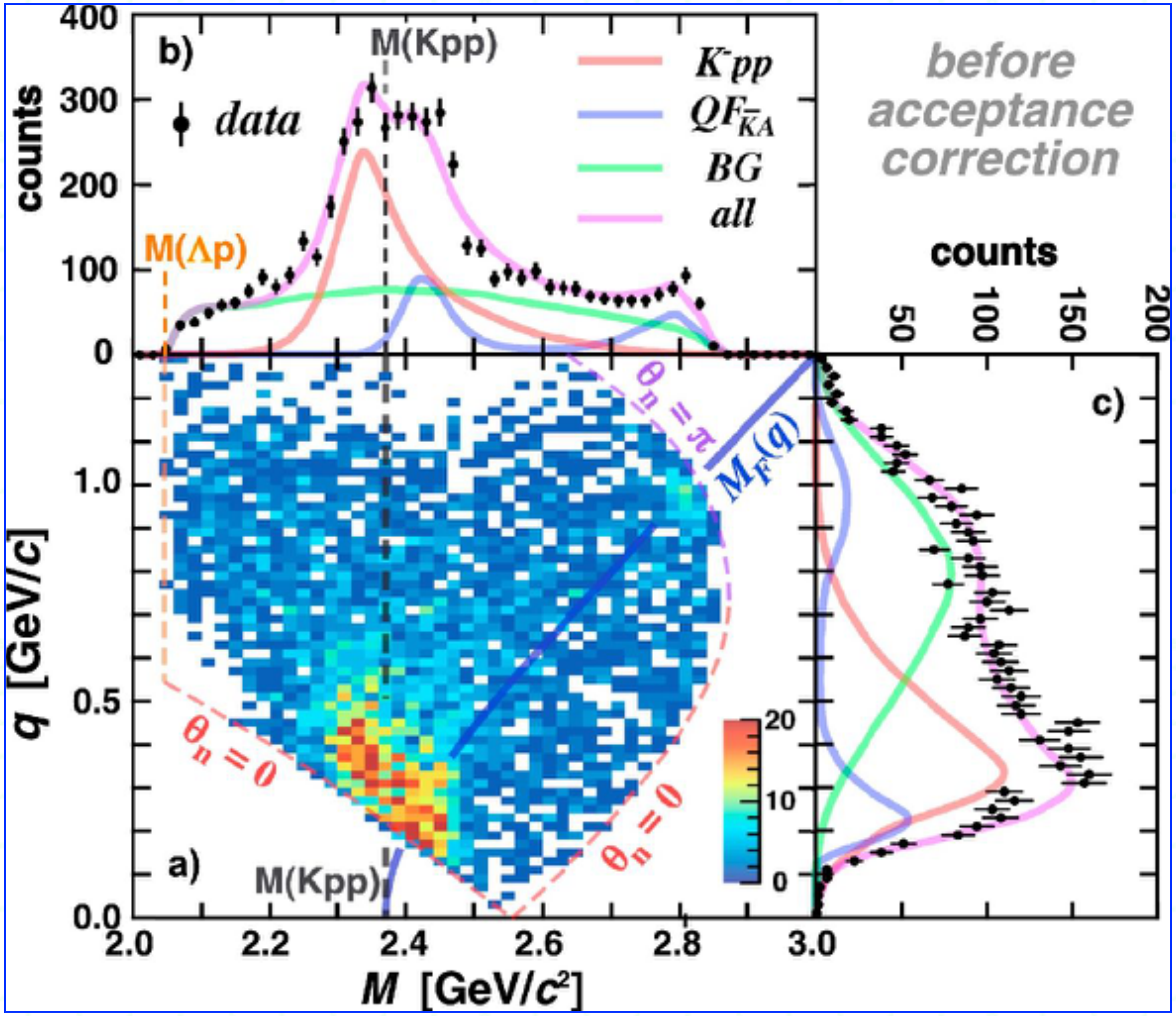
- □ Sophisticated models followed, and it was found that
$\bar{K}NN$ system is bound as long as the $\bar{K}N$ Int. is strongly attractive.

3. Physics on the $\bar{K}NN$ bound state

++ Discovery ??? ++

- [Exp.] **Beautiful data from the J-PARC E15 Exp.** !

Ajimura *et al.*, *Phys. Lett.* B789,(2019) 620.



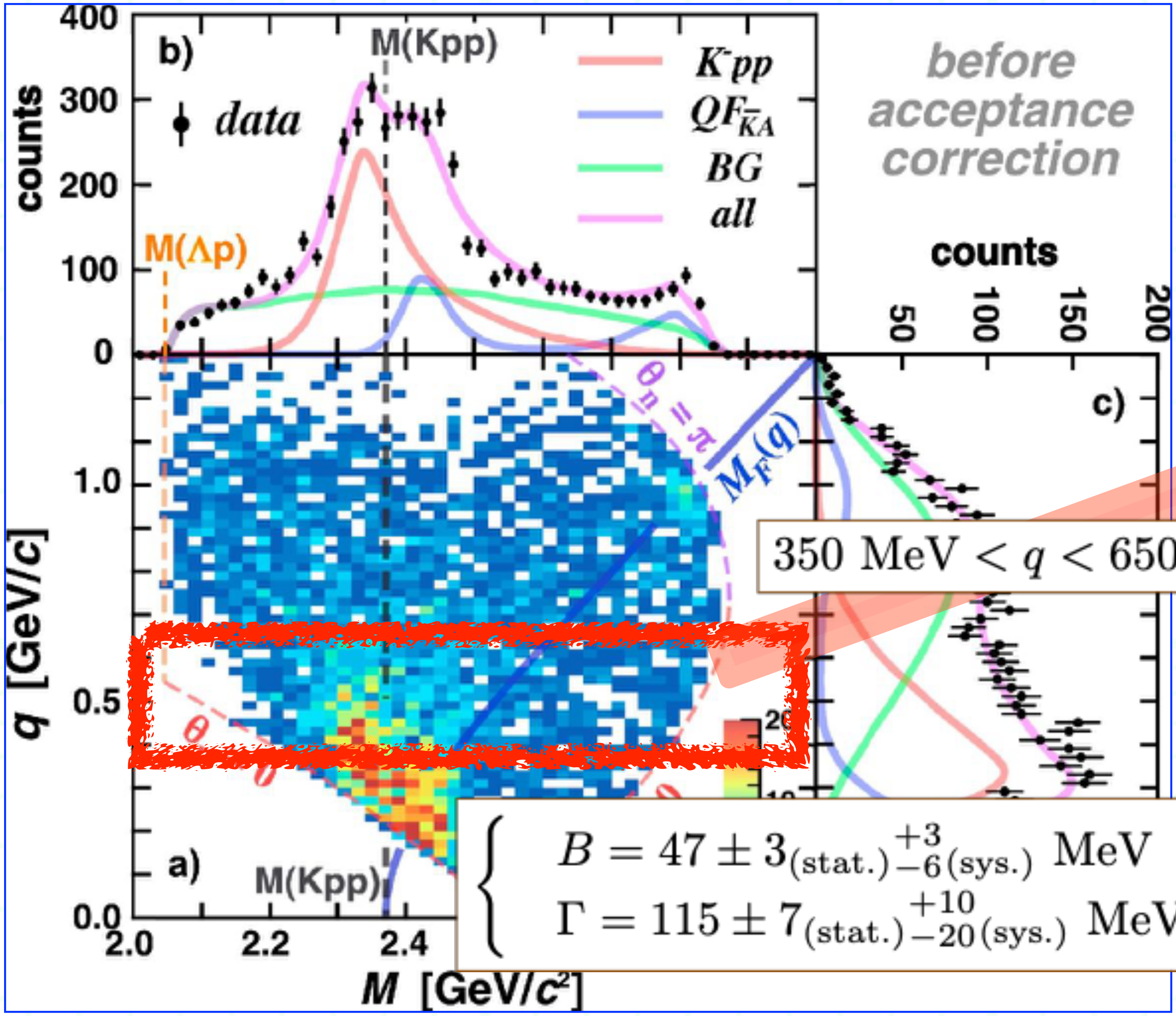
- □ **The reaction:**
  in-flight ^{3}He $(K^-, \Lambda p)$ n
  with $k_{lab} = 1$ GeV/c.

3. Physics on the $\bar{K}NN$ bound state

++ Discovery ??? ++

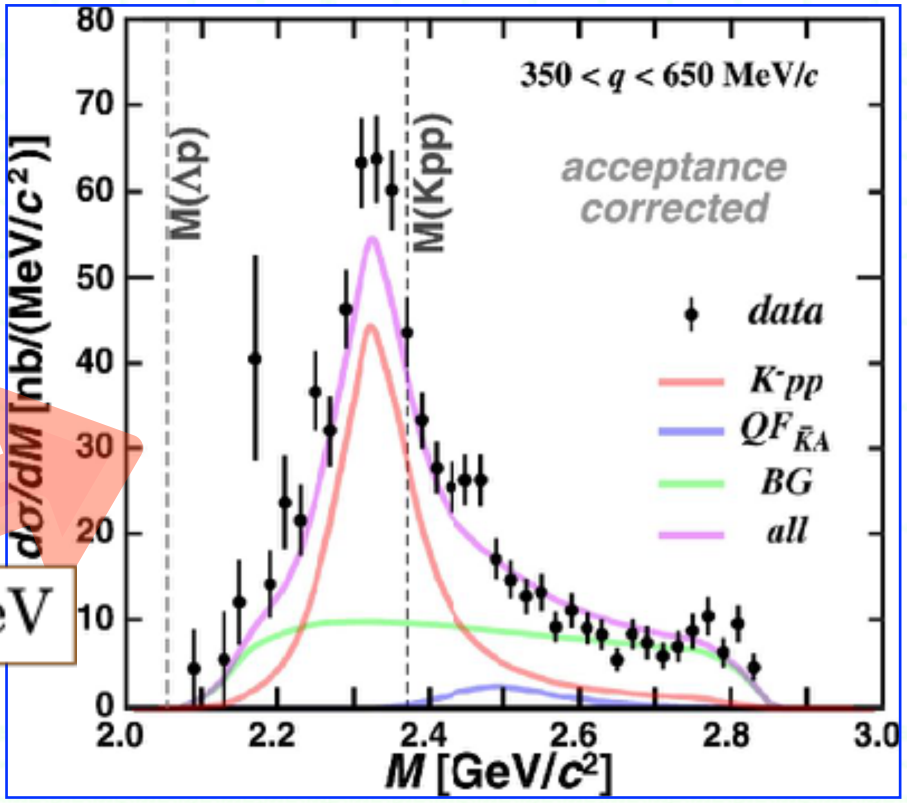
- [Exp.] **Beautiful data from the J-PARC E15 Exp.** !

Ajimura *et al.*, *Phys. Lett.* B789,(2019) 620.



350 MeV < q < 650 MeV

$$\begin{cases} B = 47 \pm 3_{(\text{stat.})}{}^{+3}_{-6}{}_{(\text{sys.})}\ \text{MeV} \\ \Gamma = 115 \pm 7_{(\text{stat.})}{}^{+10}_{-20}{}_{(\text{sys.})}\ \text{MeV} \end{cases}$$

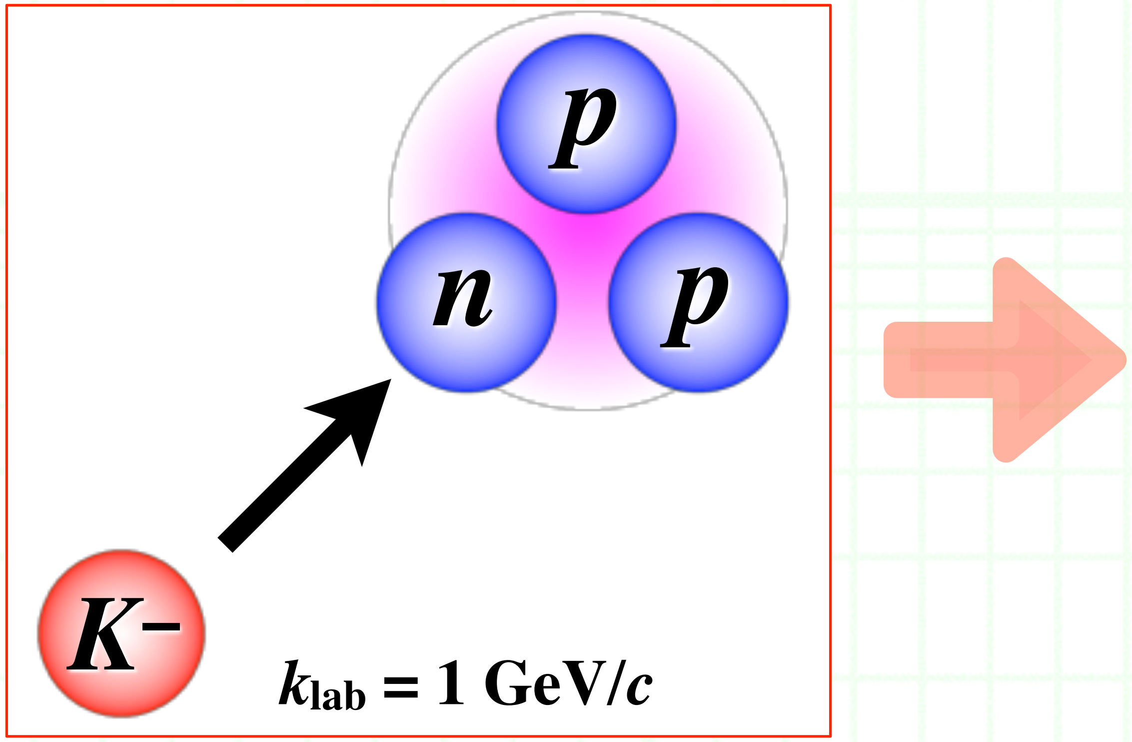


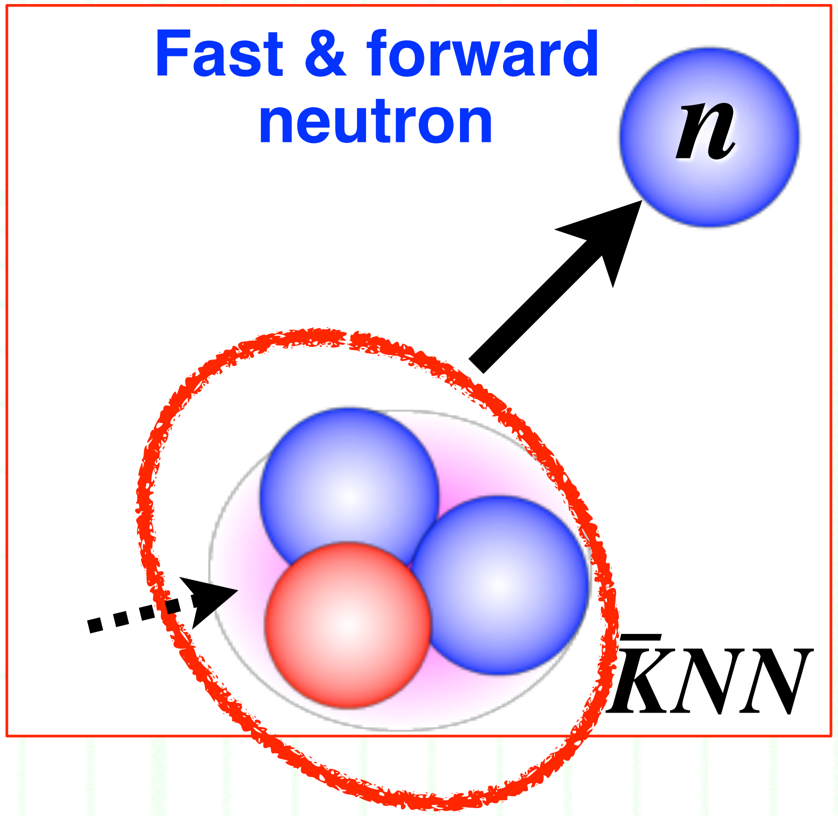
□ After **the cut to separate the bound-state signal** and **quasi-free kaon scattering**, they found **a single peak structure** !

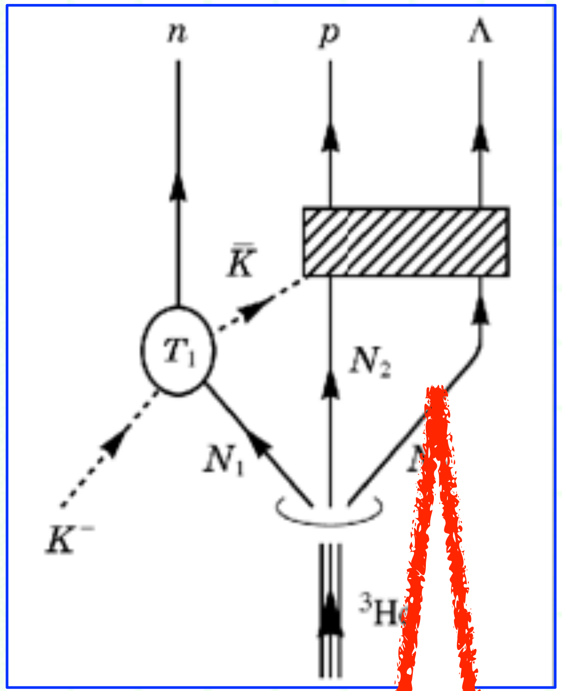
3. Physics on the $\bar{K}NN$ bound state

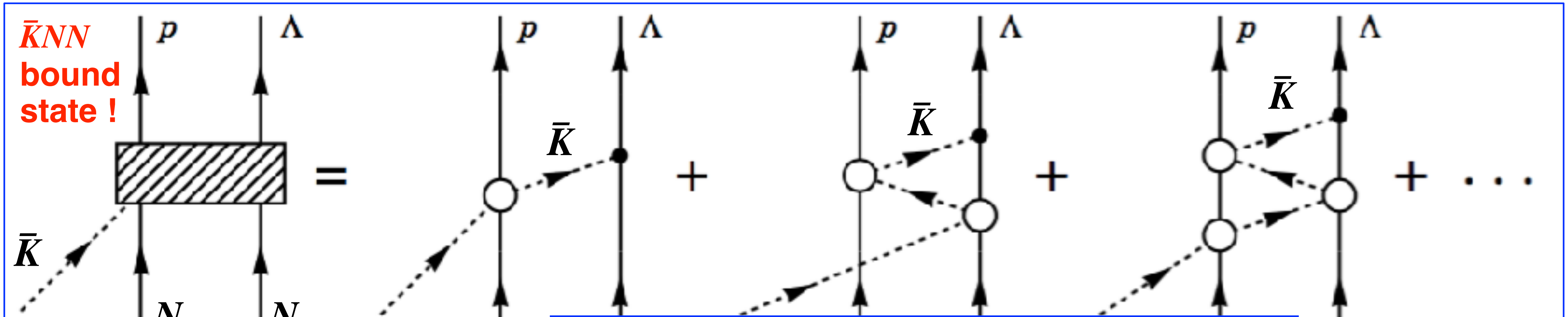
++ Discovery ??? ++

- [Theory.] Calculate the spectrum in the $\bar{K}NN$ bound state scenario.







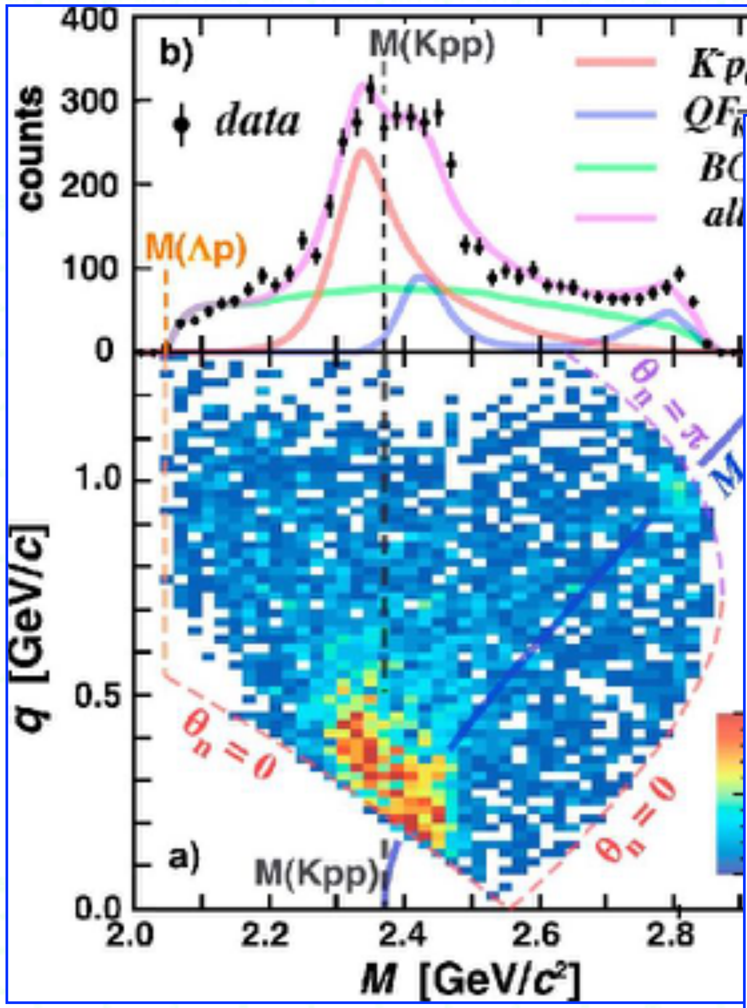


Phenomenological two-nucleon absorption was introduced in the $\bar{K}$ propagators.

3. Physics on the $\bar{K}NN$ bound state

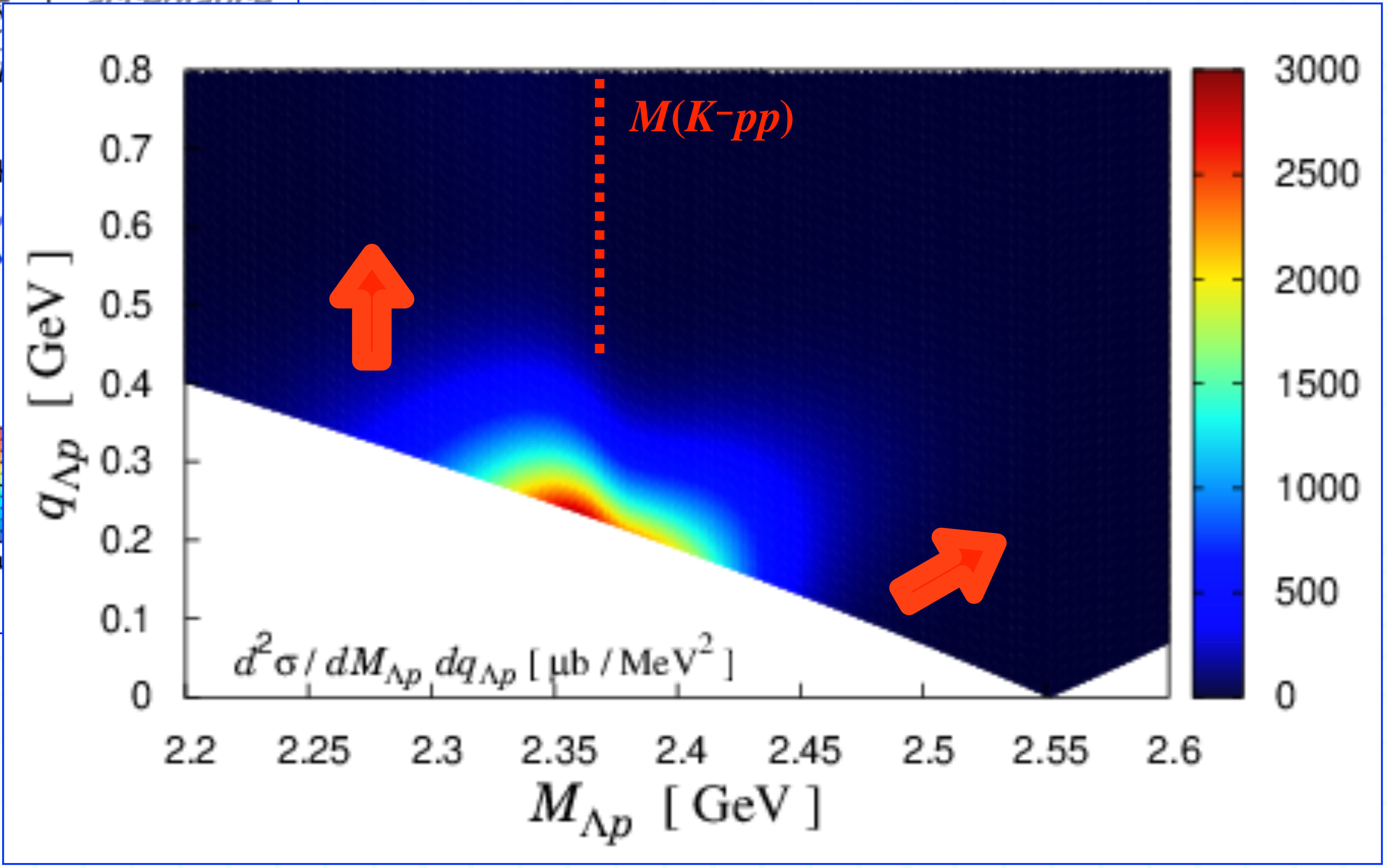
++ Discovery ??? ++

- [Theory.] Calculate the spectrum in the $\bar{K}NN$ bound state scenario.



Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

T.S., Oset and Ramos, arXiv:1903.10773.

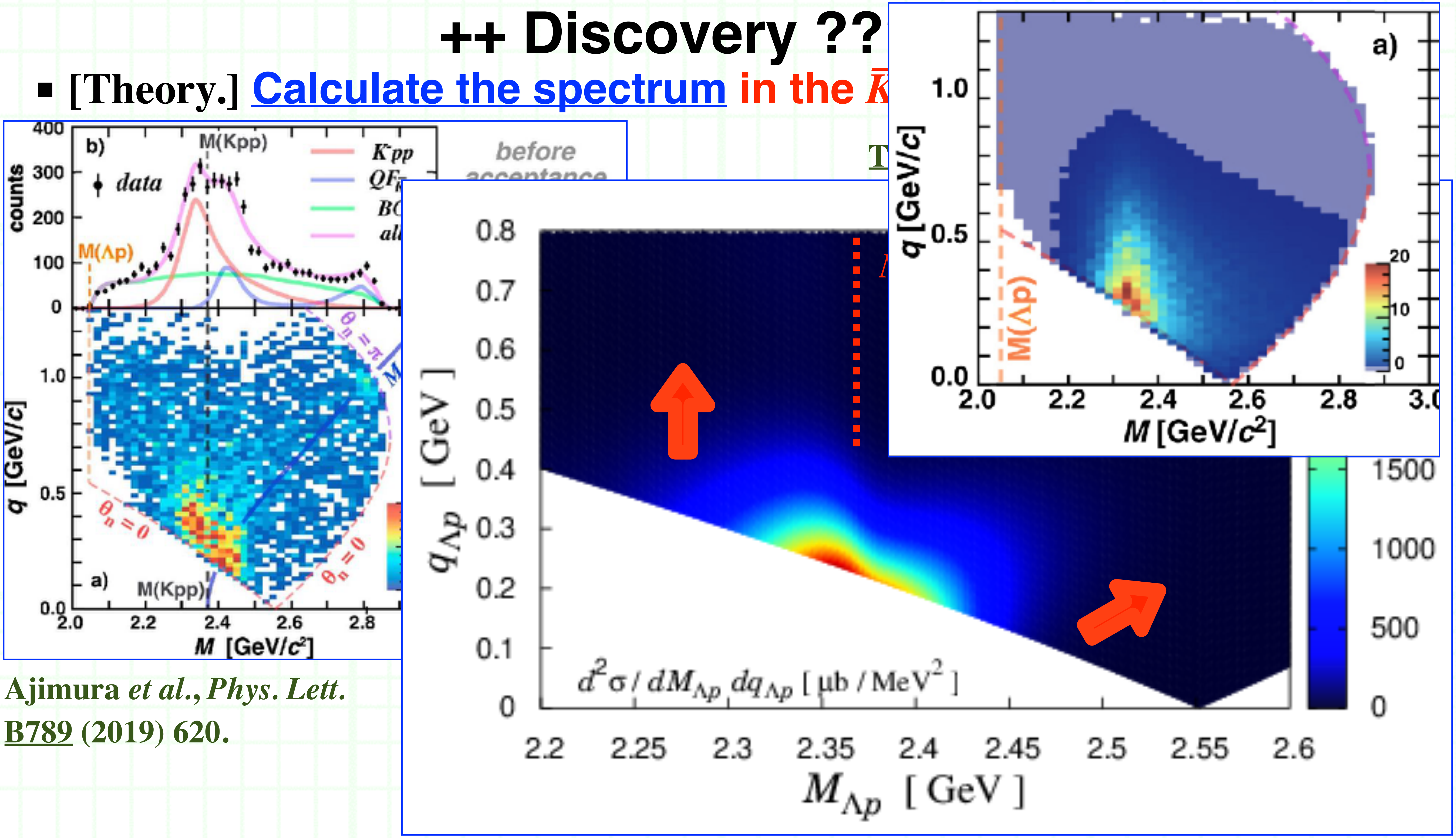


- ☐ The same behavior for the differential cross section.

3. Physics on the $\bar{K}NN$ bound state

++ Discovery ??

- [Theory.] Calculate the spectrum in the $\bar{K}$



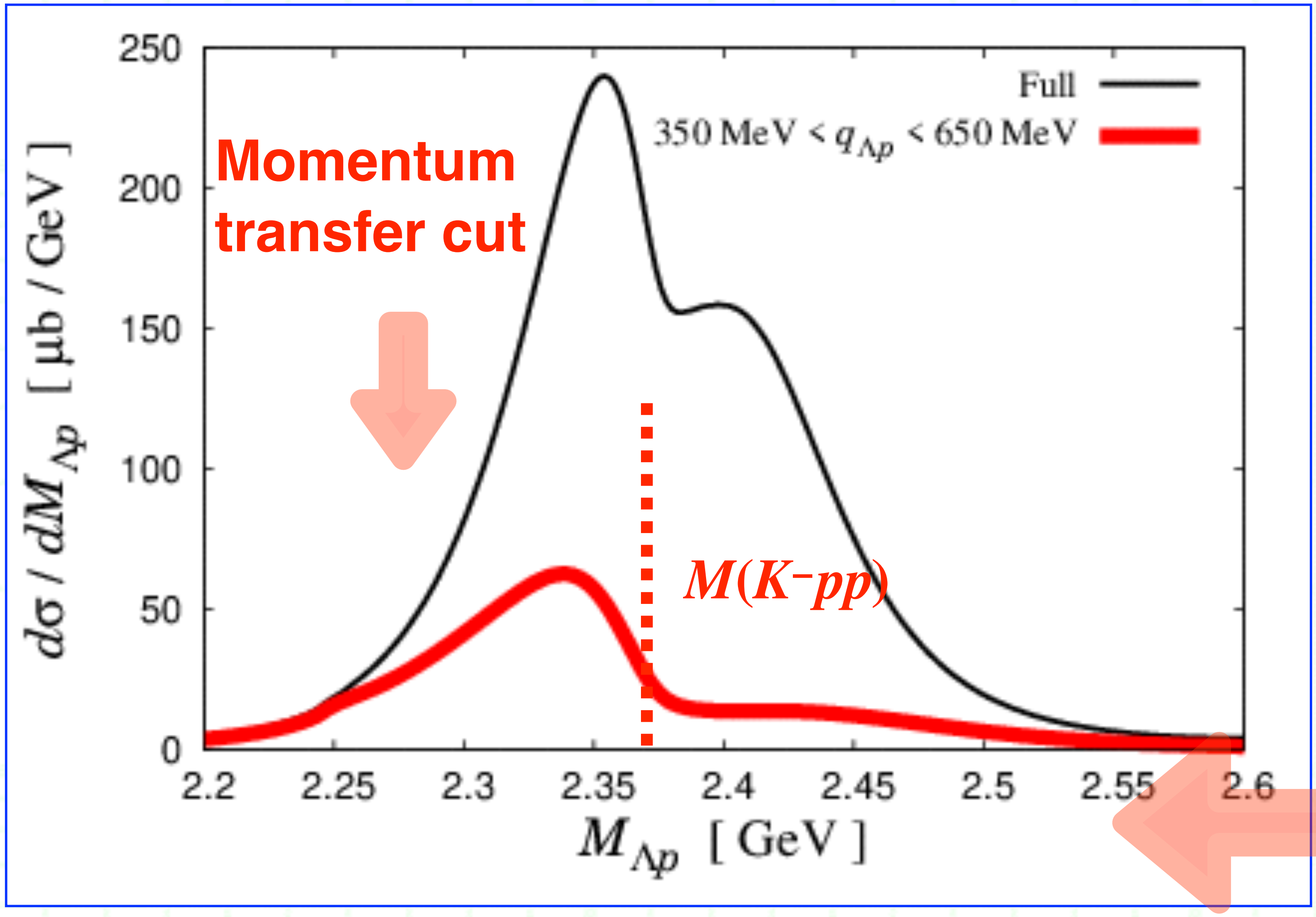
Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

□ The same behavior for the differential cross section.

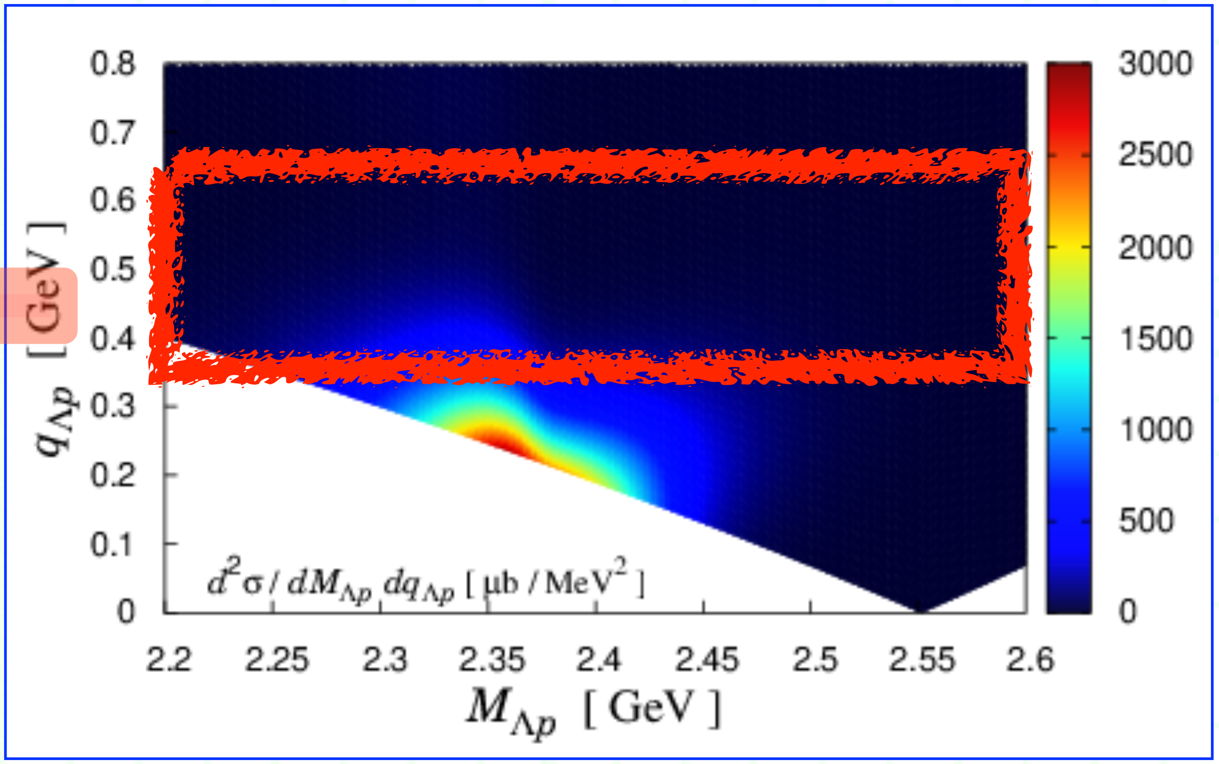
3. Physics on the $\bar{K}NN$ bound state

++ Discovery ??? ++

- [Theory.] Calculate the spectrum in the $\bar{K}NN$ bound state scenario.



☐ Perform the same cut for the momentum transfer as the Exp. data: $350\ \mathrm{MeV} < q_{\Lambda p} < 650\ \mathrm{MeV}$.



☐ Only the peak of the bound-state signal survives after the cut.

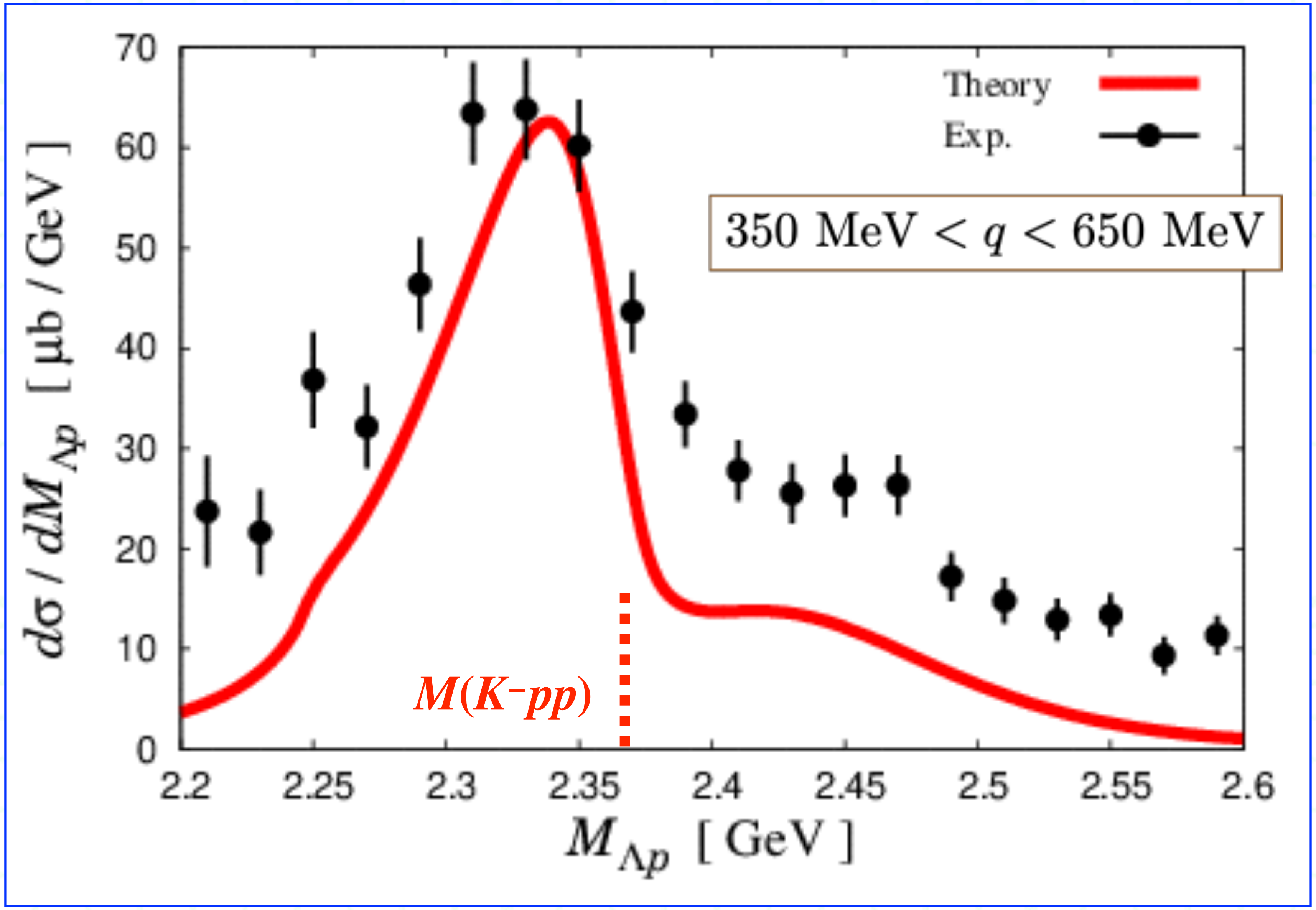
--- This result supports the validity of the Exp. cut.

3. Physics on the $\bar{K}NN$ bound state

++ Discovery ??? ++

- [Theory.] Calculate the spectrum in the $\bar{K}NN$ bound state scenario.

T.S., Oset and Ramos, arXiv:1903.10773.



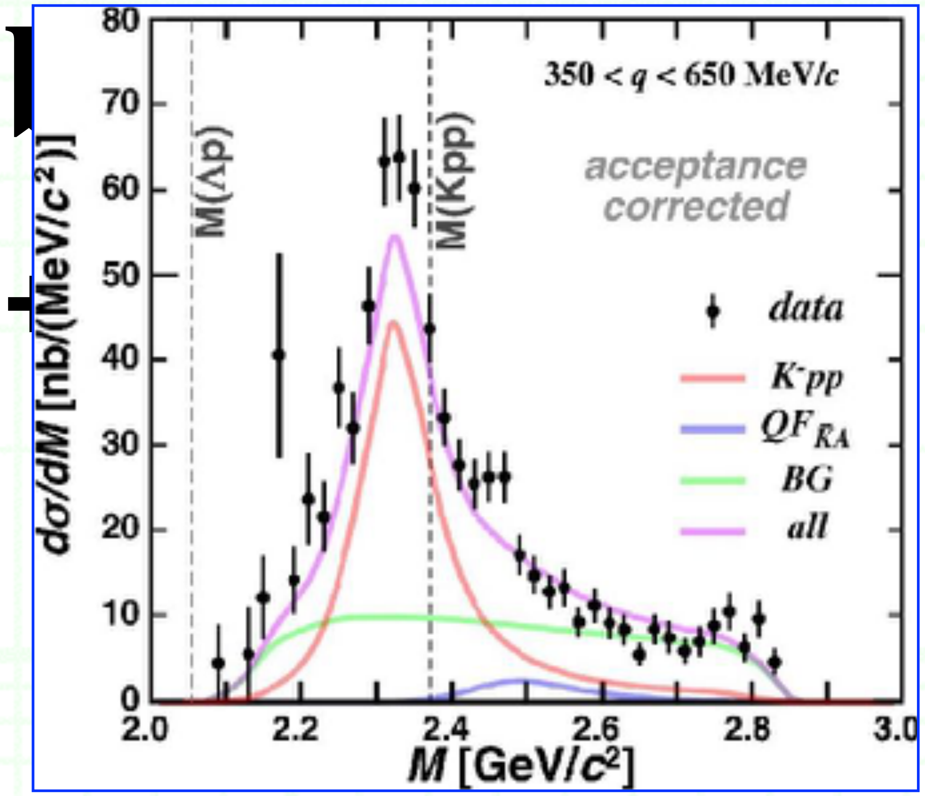
□ With the cut 350 MeV < $q_{\Lambda p}$ < 650 MeV, peak structures are similar to each other.

--> This supports the production of the $\bar{K}NN$ bound state.

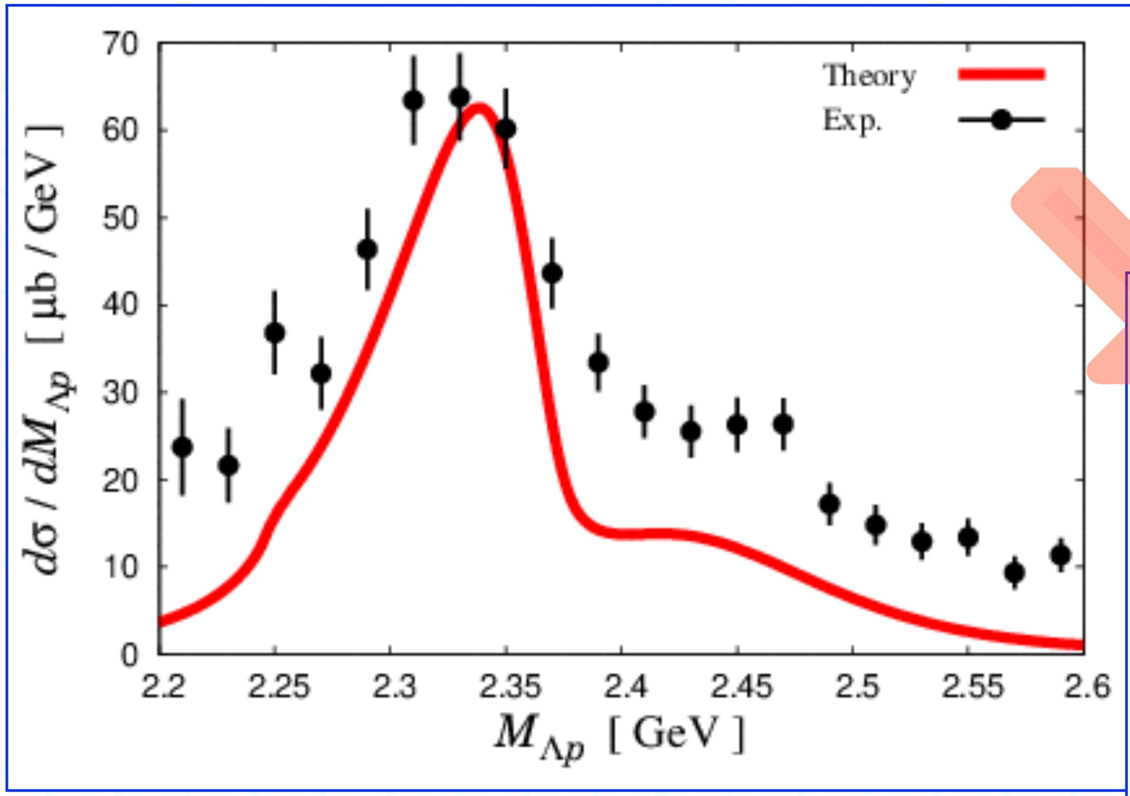
□ Note: Exp. data contain background. <-- Absent in our model.

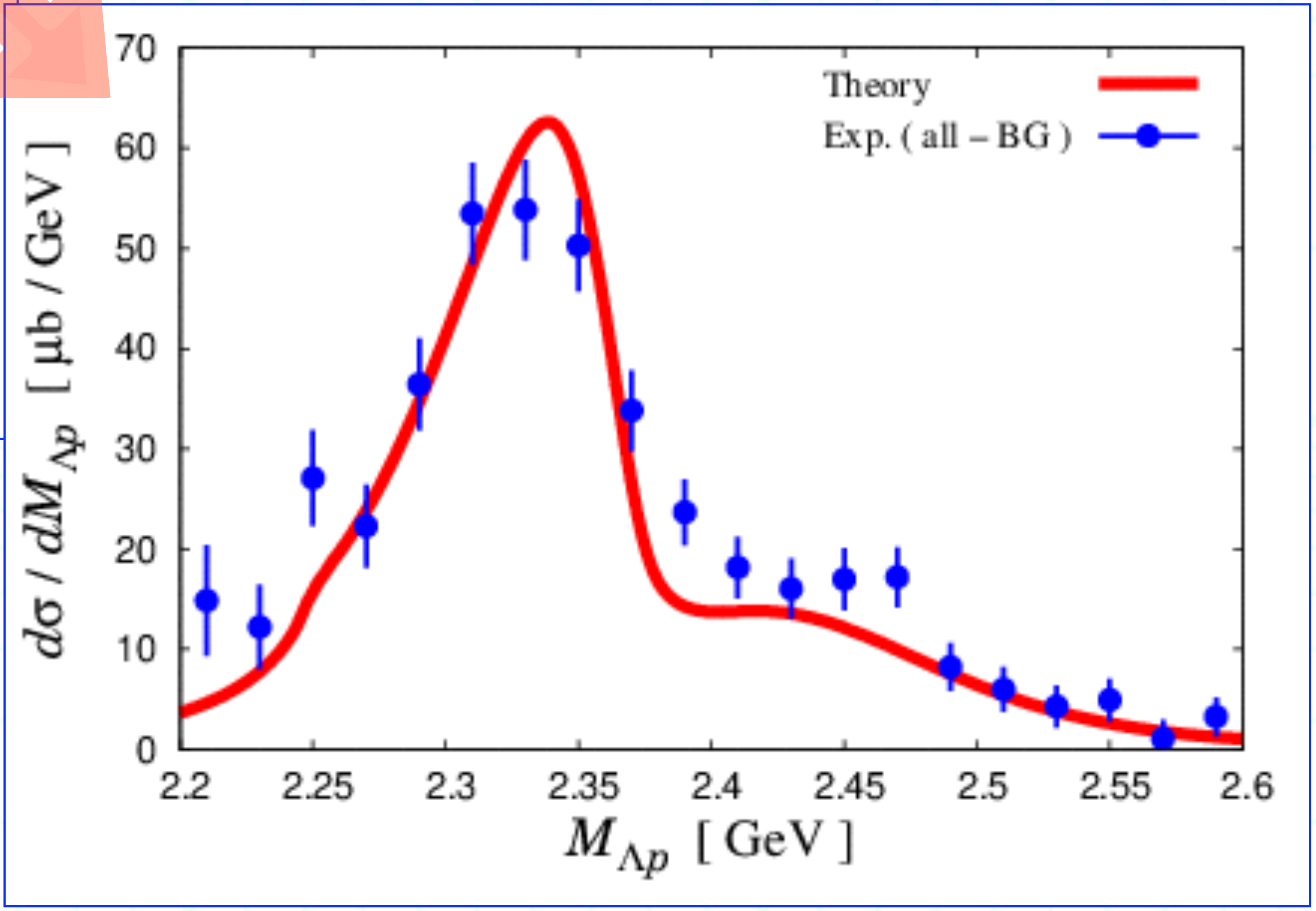
3. Physics on the $\bar{K}NN$ b

++ Discovery ??? +



- [Theory.] Subtract the "background" contribution from the E15 2nd data.





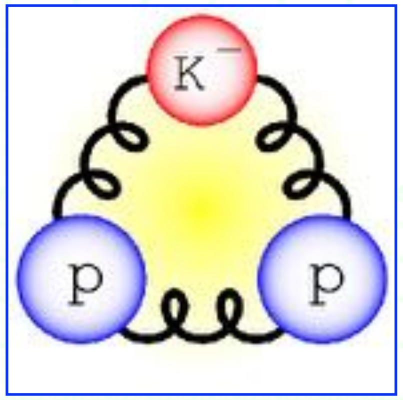
- I want to say that **this is the discovery of the $\bar{K}NN$ bound state !!!**

T.S., Oset and Ramos, arXiv:1903.10773.

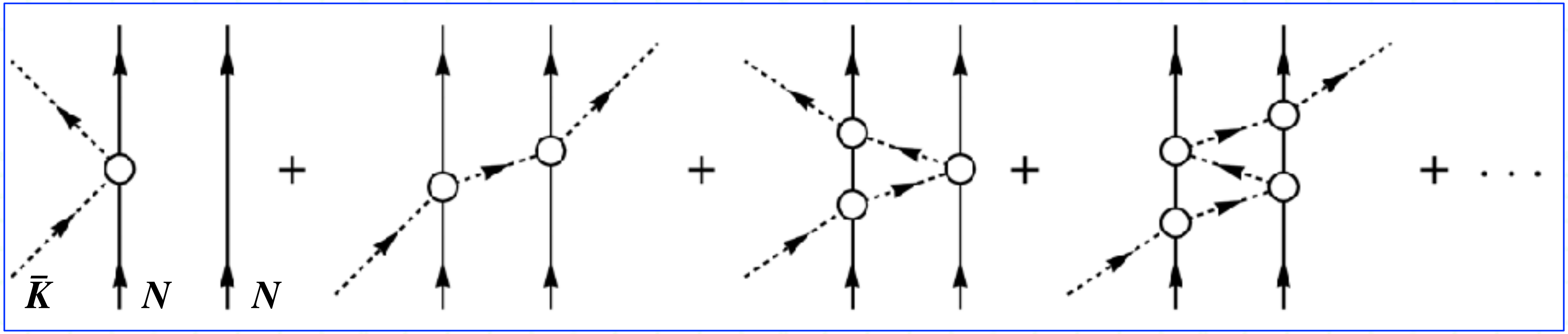
3. Physics on the $\bar{K}NN$ bound state

++ Interactions in the $\bar{K}NN$ bound state ++

- [Theory] The attraction to form the $\bar{K}NN$ bound state comes from the two-body $\bar{K}N$ and NN interactions.
  - ☐ Usually, theoretical calculations are done with the two-body $\bar{K}N$ and NN interactions.
  - ☐ In terms of the fixed-center approximation to the Faddeev Eq., the $\bar{K}NN$ three-body calculation with the two-body $\bar{K}N$ Int. can be done:



JAEA press release.



Bayar, Yamagata-Sekihara and Oset, *Phys. Rev.* C84 (2011) 015209;
T.S., Oset and Ramos, *PTEP* 2016 123D03.

--- NN interaction has been taken into account to form “NN center”.

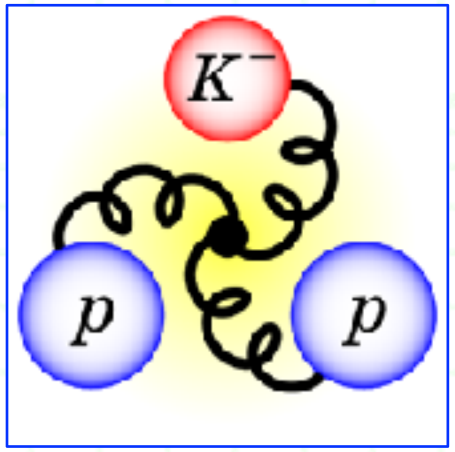
3. Physics on the $\bar{K}NN$ bound state

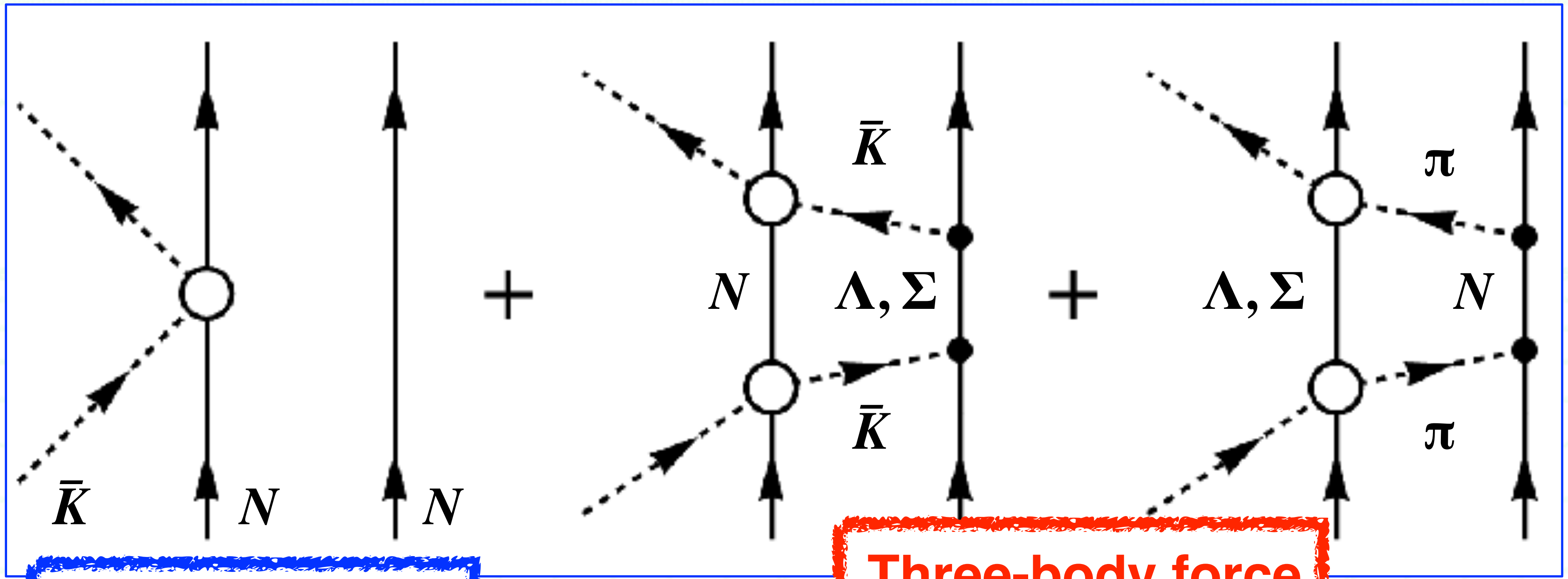
++ Interactions in the $\bar{K}NN$ bound state ++

- [Theory] However, there should exist $\bar{K}NN$ three-body force !
  - □ The $\bar{K}NN$ three-body interaction reflects non-conservation of the meson number.

    --- New type of three-body force.

  - □ The $\bar{K}NN$ three-body interaction in this way is added to the two-body $\bar{K}N$ interaction as:





Two-body force

Three-body force

Bayar and Oset, *Phys. Rev.* C88 (2013) 044003;
T.S., Oset and Ramos, in preparation.

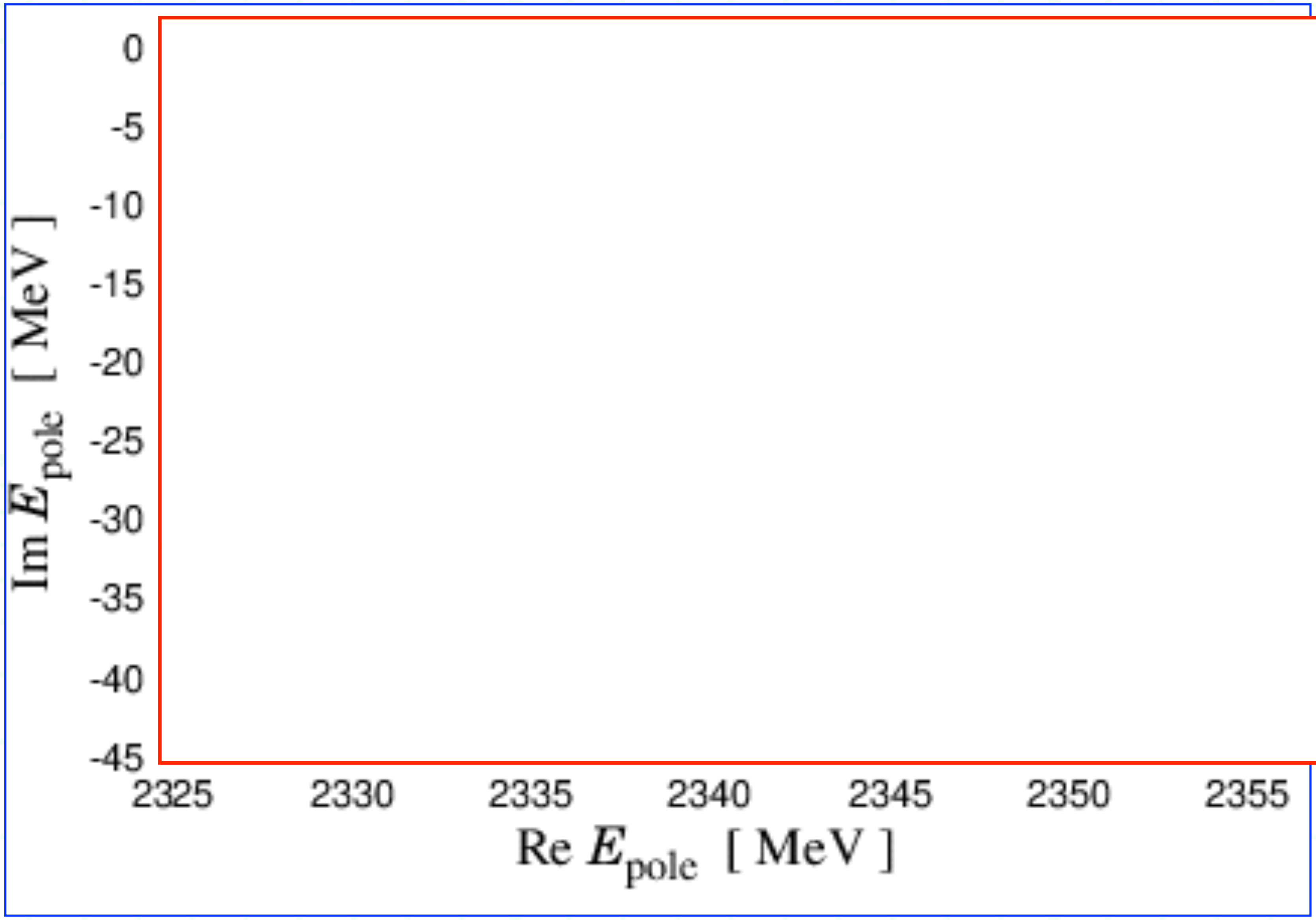
3. Physics on the $\bar{K}NN$ bound state

++ Interactions in the $\bar{K}NN$ bound state ++

- [Theory] Only two-body force vs. including three-body force.
  - ☐ Pole position of the $\bar{K}NN$ bound state in the fixed-center Approx.

--- Parameter in the fixed-center approximation

d: distance between *NN* as a “center”.



($\boxed{E_{\mathrm{pole}} = 2339 - 41i \text{ MeV}}$)

T.S., Oset and Ramos, in preparation.

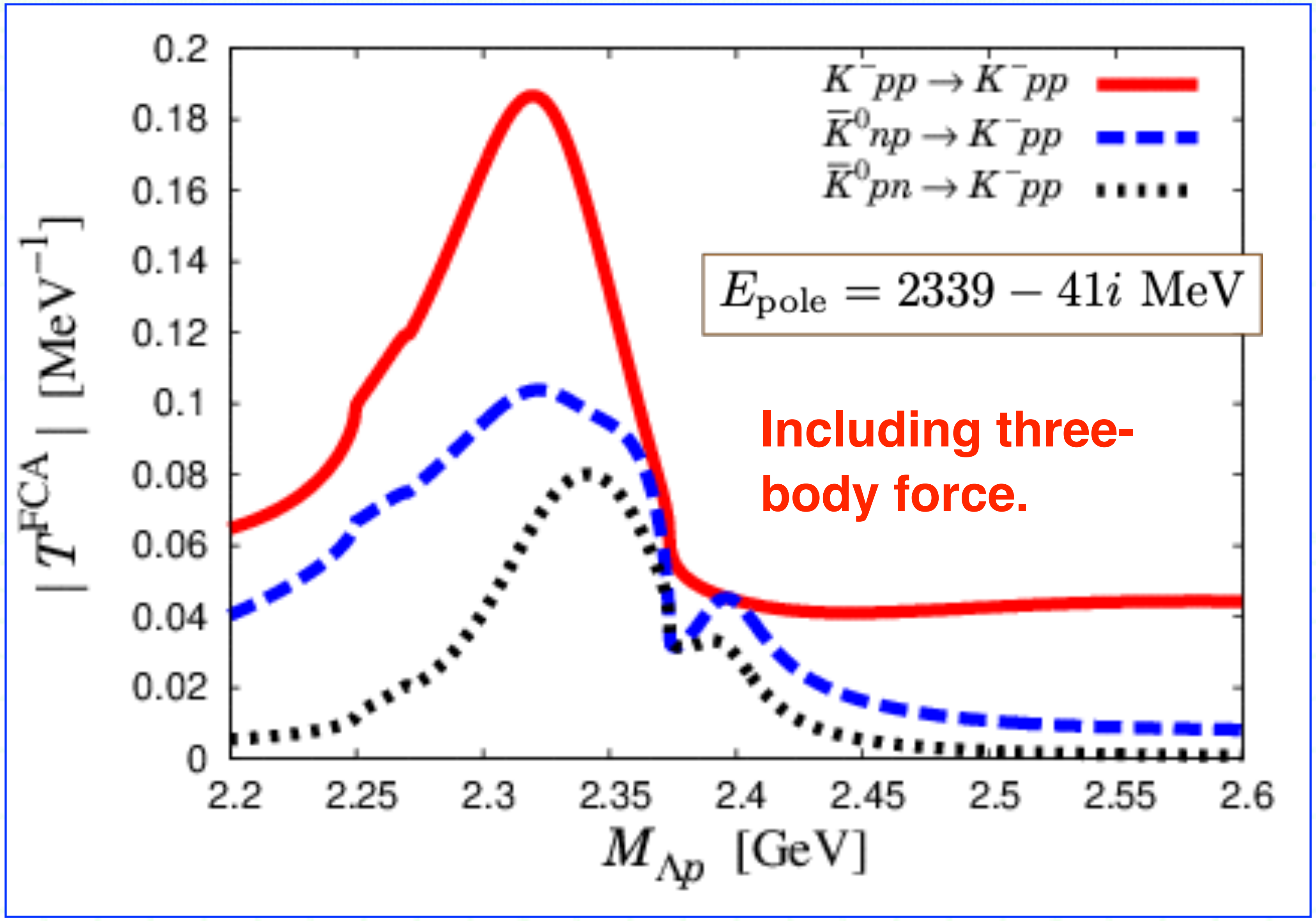
3. Physics on the $\bar{K}NN$ bound state

++ Observed peak(s) ++

- [Theory / Exp.] How the $\bar{K}NN$ bound state emerges in spectra ?
  - □ $\bar{K}NN$ –> $\bar{K}NN$ amplitude in the particle basis.

--- $K^{-}pp$, $\bar{K}^{0}np$, and $\bar{K}^{0}pn$ –> $\bar{K}NN$.

T.S., Oset and Ramos, in preparation.



□ Peak position depends on the charge of the $\bar{K}NN$ state: $K^{-}pp$, $\bar{K}^{0}np$, and $\bar{K}^{0}pn$

--- Interference with $I = 1$ in the spectra.

□ Therefore, one cannot directly conclude the pole position from the peak position.

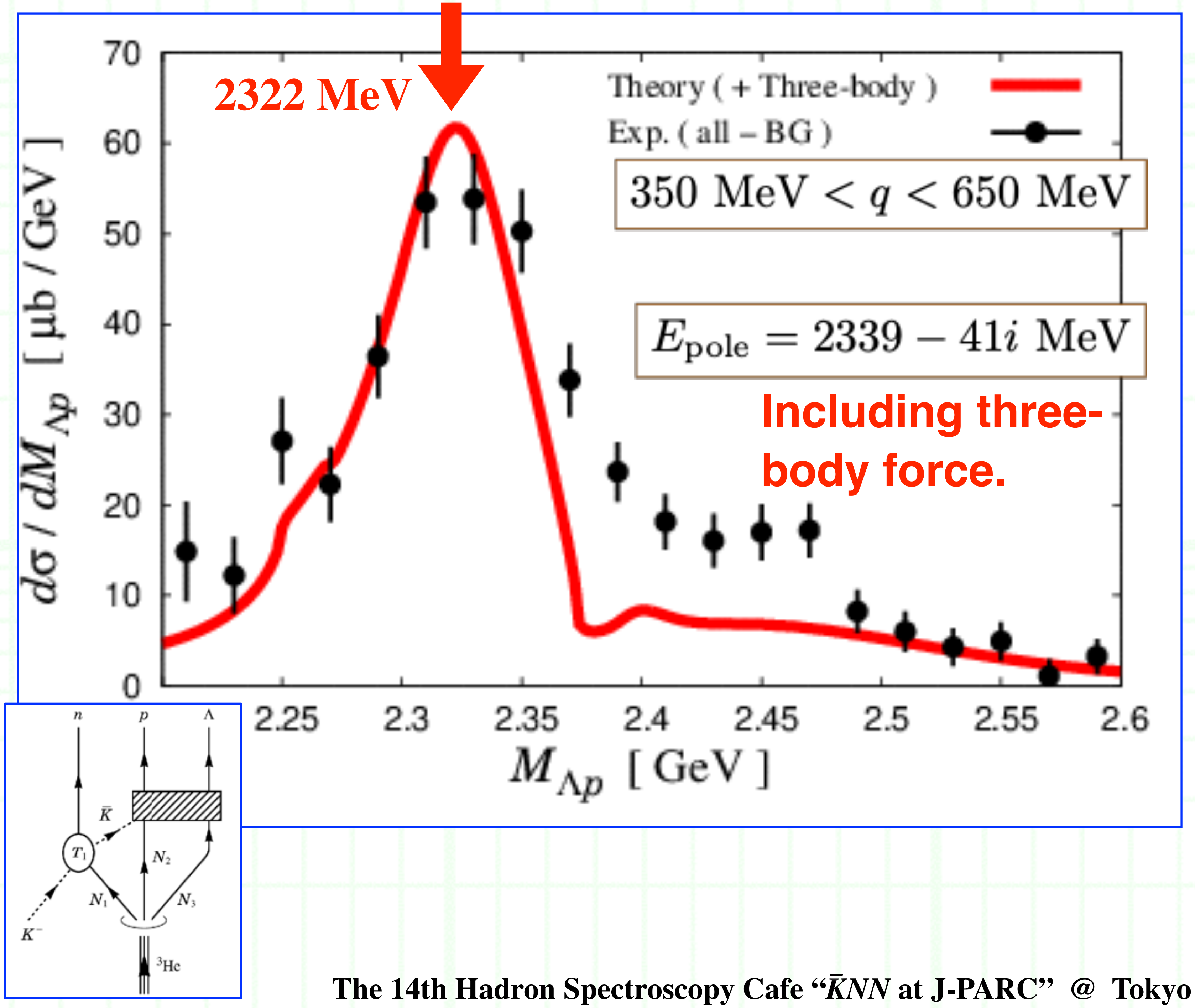
--- Need detailed analysis of production process.

3. Physics on the $\bar{K}NN$ bound state

++ Observed peak(s) ++

- [Theory / Exp.] **How the $\bar{K}NN$ bound state emerges in spectra ?**
  - ☐ **Calculate the Λp invariant mass spectrum of $K^- \, {}^3\mathrm{He} \to \Lambda\, p\, n$.**

T.S., Oset and Ramos, in preparation.



$350 \text{ MeV} < q < 650 \text{ MeV}$

$E_{\text{pole}} = 2339 - 41i \text{ MeV}$

Including three-body force.

☐ **Clearly, we see that the peak position $2322 \text{ MeV} < \mathrm{Re}(E_{\text{pole}})$.**

--- **About –17 MeV shift.**

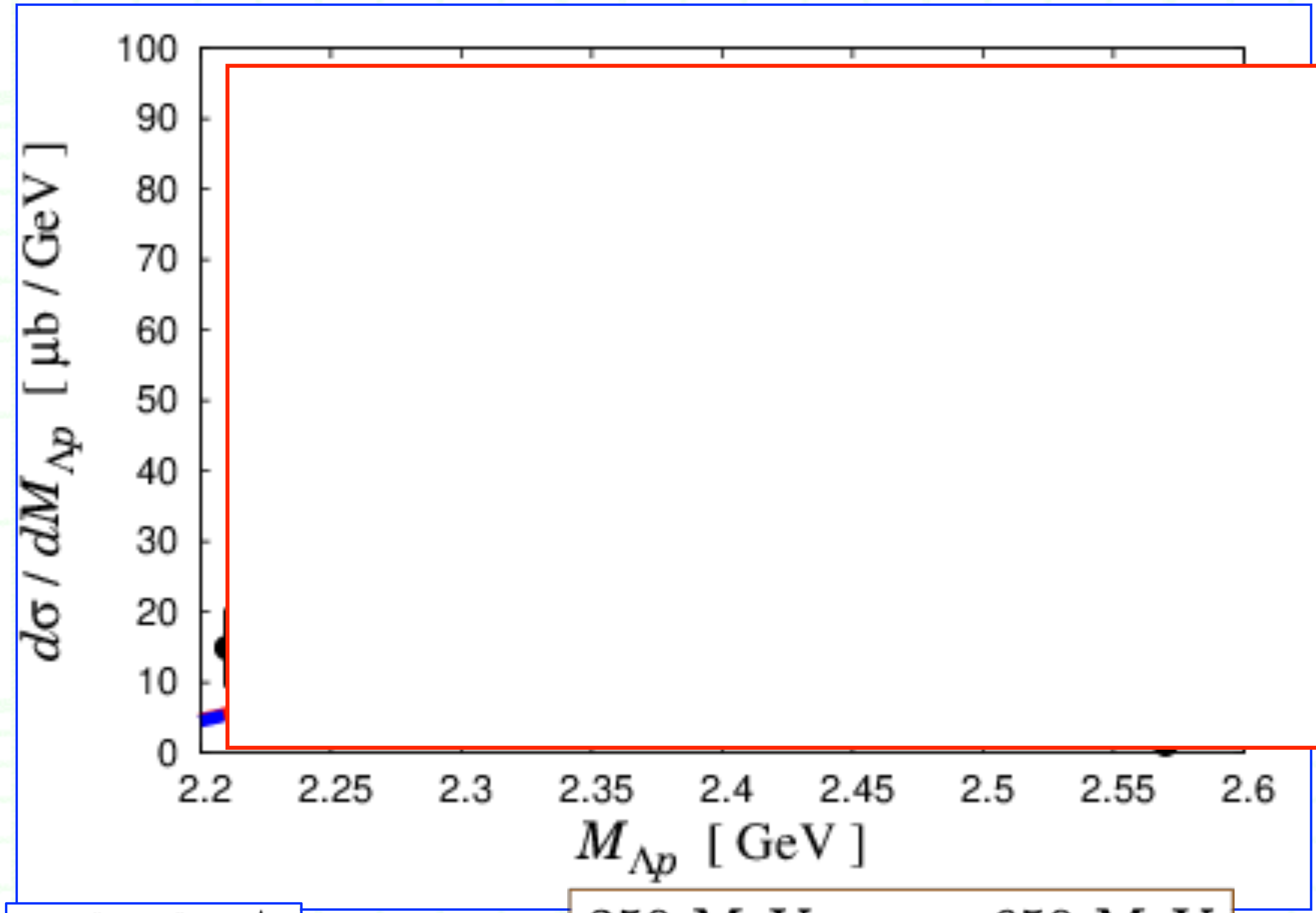
☐ **Therefore, the Breit-Wigner parameters do not coincide with the pole position.**

3. Physics on the $\bar{K}NN$ bound state

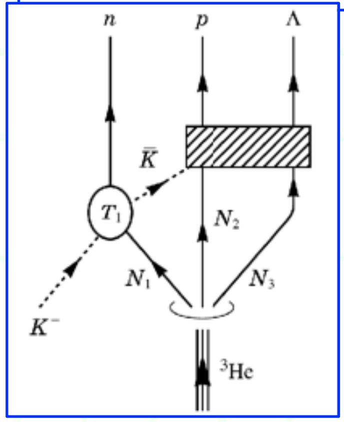
++ Observed peak(s) ++

- [Theory / Exp.] How the $\bar{K}NN$ bound state emerges in spectra ?
  - ☐ Calculate the Λp invariant mass spectrum of $K^{-}\,{}^{3}\mathrm{He} \to \Lambda\, p\, n$.

T.S., Oset and Ramos, in preparation.



$350\ \mathrm{MeV} < q < 650\ \mathrm{MeV}$

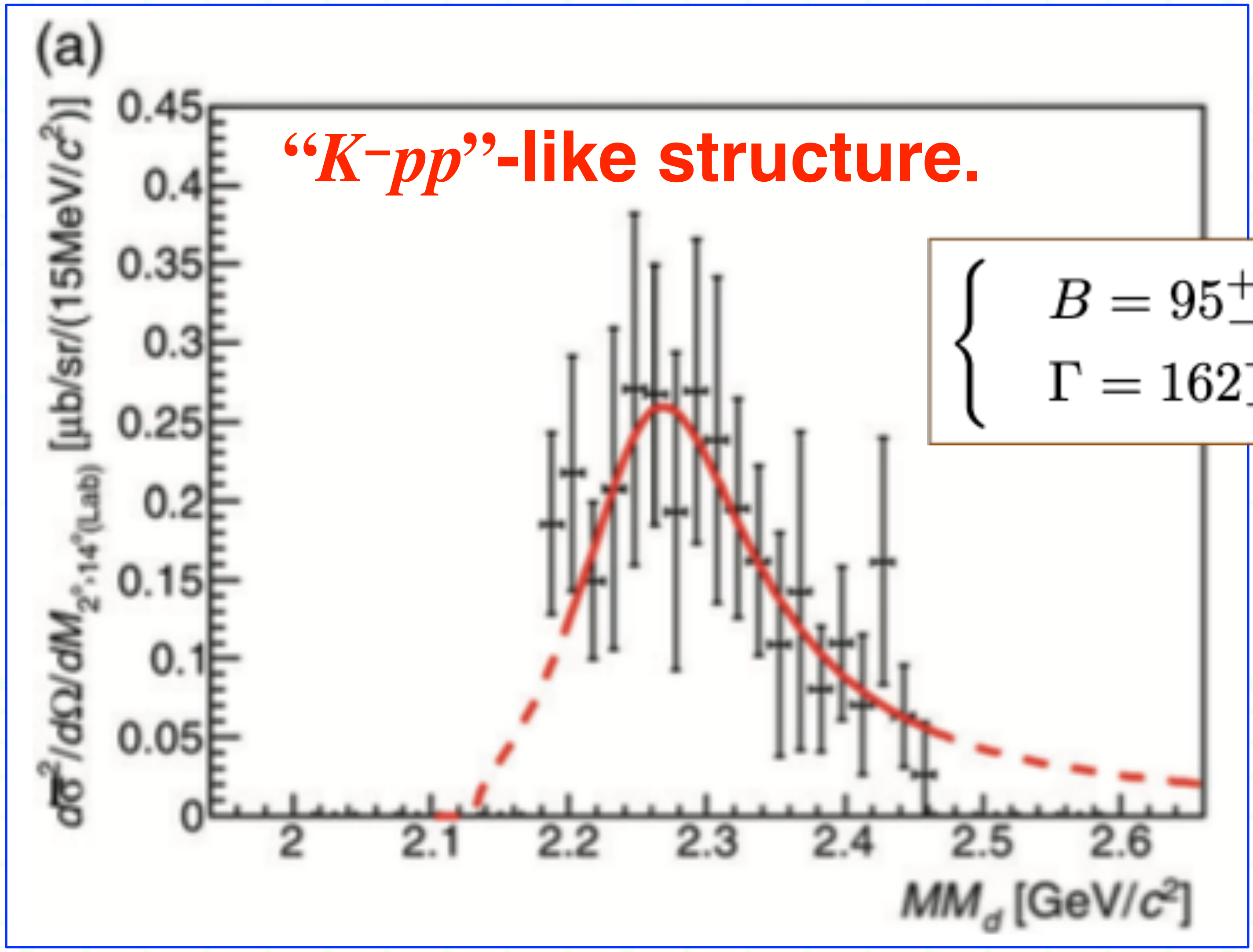


☐ According to the Exp. width, the absorption part of the three-body force seems to be significant !

3. Physics on the $\bar{K}NN$ bound state

++ Observed peak(s) ++

- [Exp.] How about the peak in the J-PARC E27 data ?
  - ☐ The $\pi^+ d \to K^+ \Sigma^0 p$ reaction.



"K^-pp"-like structure.

$$\begin{cases} B = 95^{+18}_{-17}(\text{stat.})^{+30}_{-21}(\text{sys.}) \ \text{MeV} \\ \Gamma = 162^{+87}_{-45}(\text{stat.})^{+66}_{-78}(\text{sys.}) \ \text{MeV} \end{cases}$$

Ichikawa *et al*. [J-PARC E27], *PTEP* 2015 021D01.

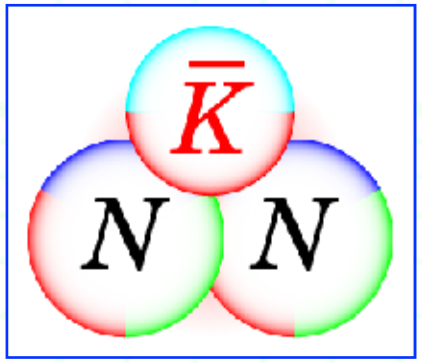
--- Two-pole nature for the $\bar{K}NN$ bound state, as Λ(1405) ???

3. Physics on the $\bar{K}NN$ bound state

++ Structure ++

- [Theory / Exp.] What is the “structure” of the $\bar{K}NN$ bound state ?

--- How much the resonance state discovered in J-PARC E15 contains the $\bar{K}NN$ fraction ?



How much ?

☐ For the moment, we can only say that there exist a resonance in the Λp spectrum of $K^{-}\,{}^{3}\mathrm{He} \to \Lambda\, p\, n$.

☐ Because the resonance is generated by the $\bar{K}$ beam and decays into Λp, the resonance contains certain fractions of $\bar{K}NN$ and Λp.

--- The resonance couples to the $\bar{K}NN$ and Λp channels.

☐ We have to define three-body compositeness for the $\bar{K}NN$ bound state and establish how to evaluate it in theoretical models / from Exp. data.

3. Physics on the $\bar{K}NN$ bound state

++ Spin / parity ++

- [Exp.] What is the spin / parity of the $\bar{K}NN$ bound state ?
  - The Exp. signal of the $\bar{K}NN$ bound state can be explained by single Breit-Wigner form as:

$$f_{\{Kpp\}} = \frac{C_{Kpp}\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \exp\left(-\left(\frac{q}{Q_{Kpp}}\right)^2\right)$$

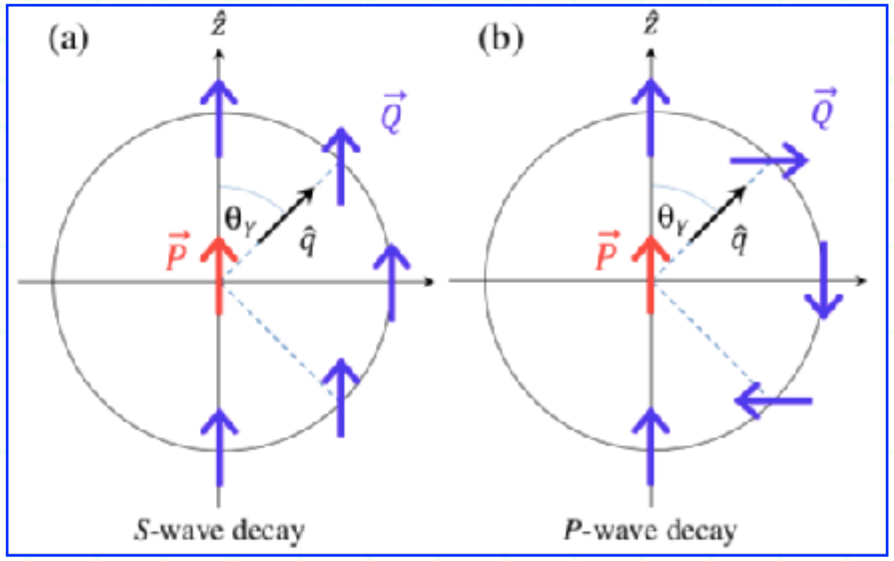
--- Angular dependence of the Exp. data is consistent with the $\bar{K}NN$ state in S wave. --> Consistent with $J^P = 0^-$.

Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

  - To fix the spin / parity in Exp. in a model independent manner, we have to measure decay angle and polarizations of Λ and p.

--- *cf.* $\gamma\, p \to K^+\, \Lambda(1405)$ reaction.

Moriya *et al.* [CLAS], *Phys. Rev. Lett.* 112 (2014) 082004.



3. Physics on the $\bar{K}NN$ bound state

++ Spatial size ++

- [Exp.] **From the analysis of Exp. data, they commented on the “spatial size” of the $\bar{K}NN$ bound state.**

$$f_{\{Kpp\}} = \frac{C_{Kpp}\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \exp\left(-\left(\frac{q}{Q_{Kpp}}\right)^2\right)$$

Ajimura *et al.*, *Phys. Lett.* B789 (2019) 620.

--- With $Q_{Kpp} = 381 \pm 14\,(stat.)\,^{+57}_{-0}\,(sys.)\ \mathrm{MeV}/c$ **, which is very large value, a very compact system was formed (~ 0.5 fm).**

- [Theory] **However, there are several factors which generates q dependence of the cross section.**
  - ☐ **Spatial size of the $\bar{K}NN$ bound state.**
  - ☐ **Angular dependence of the K^-n –> K^-n and K^-p –> $\bar{K}^0n$ amplitudes at the first collision. They should be off-shell !**

--> Therefore, we cannot directly conclude the spatial size of the formed $\bar{K}NN$ bound state.

3. Physics on the $\bar{K}NN$ bound state

++ Summary of the $\bar{K}NN$ bound state ++

	$\bar{K}NN$ bound state
Prediction	2002 ~
Discovery	2019 ?
Spin / parity	$J^P = 0^-$???
Interaction	Two-body $\bar{K}N$ *and* NN + Three-body $\bar{K}NN$?
Component	$\bar{K}NN$ dominant ???
Peak position	Depends on reaction
Pole position	???

4. Summary

4. Summary

++ Summary ++

	$\Lambda(1405)$ as $\bar{K}N$ bound state	$\bar{K}NN$ bound state
Prediction	1959	2002 ~
Discovery	1961	2019 ?
Spin / parity	$1/2^-$ (2014)	$J^P = 0^-$???
Interaction	Chiral dynamics	Two-body $\bar{K}N$ *and* NN + Three-body $\bar{K}NN$?
Component	$\bar{K}N$ dominant in chiral D (2015 ~)	$\bar{K}NN$ dominant ???
Peak position	Depends on reaction	Depends on reaction
Pole position	(1415 - 1435) – (10 - 25) i MeV*	???

* Assuming chiral dynamics.

- [My guess] Without any excellent ideas, we need one-half century to pin down properties of the $\bar{K}NN$ bound state in Exps.

Thank you very much for your kind attention !