On the structure observed in the in-flight $^{3}\mathrm{He}(K^{-}, \Lambda p)n$ reaction at J-PARC

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in collaboration with

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and **Angels RAMOS** (Barcelona Univ.)

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1. Introduction
2. Scenario I: Uncorrelated $\Lambda(1405)$ p
3. Scenario II: $\bar{K}NN$ bound state
4. Summary

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[1] T. S., E. Oset and A. Ramos, arXiv:1607.02058 [hep-ph].

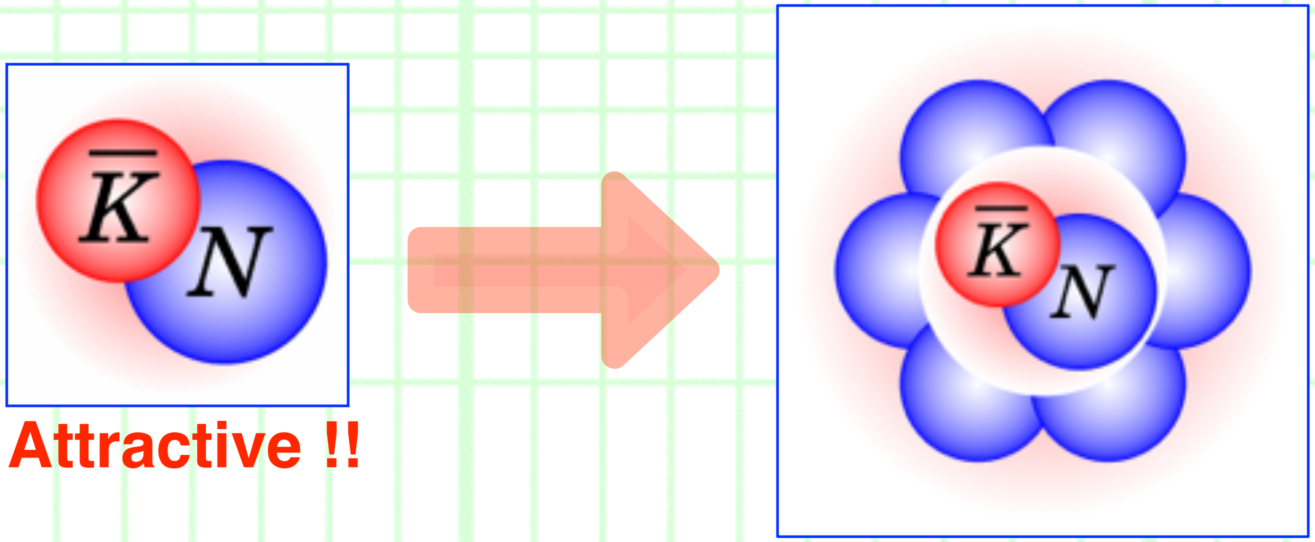
1. Introduction

++ Kaonic nuclei ++

- We expect that kaonic nuclei should exist, which are bound states of $\bar{K}$ and nuclei via strong interaction between them.
  - ☐ $\bar{K}$-nucleon (N) interaction is strongly attractive.

--- So strong that the $\bar{K}N$ system can be bound to be $\Lambda(1405)$.

Kaiser-Siegel-Weise ('95);
Oset-Ramos ('98); ...



Attractive !!

There should exist !!

  - ☐ Unfortunately, kaonic nuclei will be unstable with respect to strong interaction: pionic & non-pionic decay modes.

- There are motivations to study kaonic nuclei.
  - ☐ Exotic state of many-body systems in strong interaction.
  - ☐ Kaons in finite nuclear density.

1. Introduction

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

by Jido-san

- **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**:

    Akaishi and Yamazaki, *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**.

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K^bar^NN
by Jido-san

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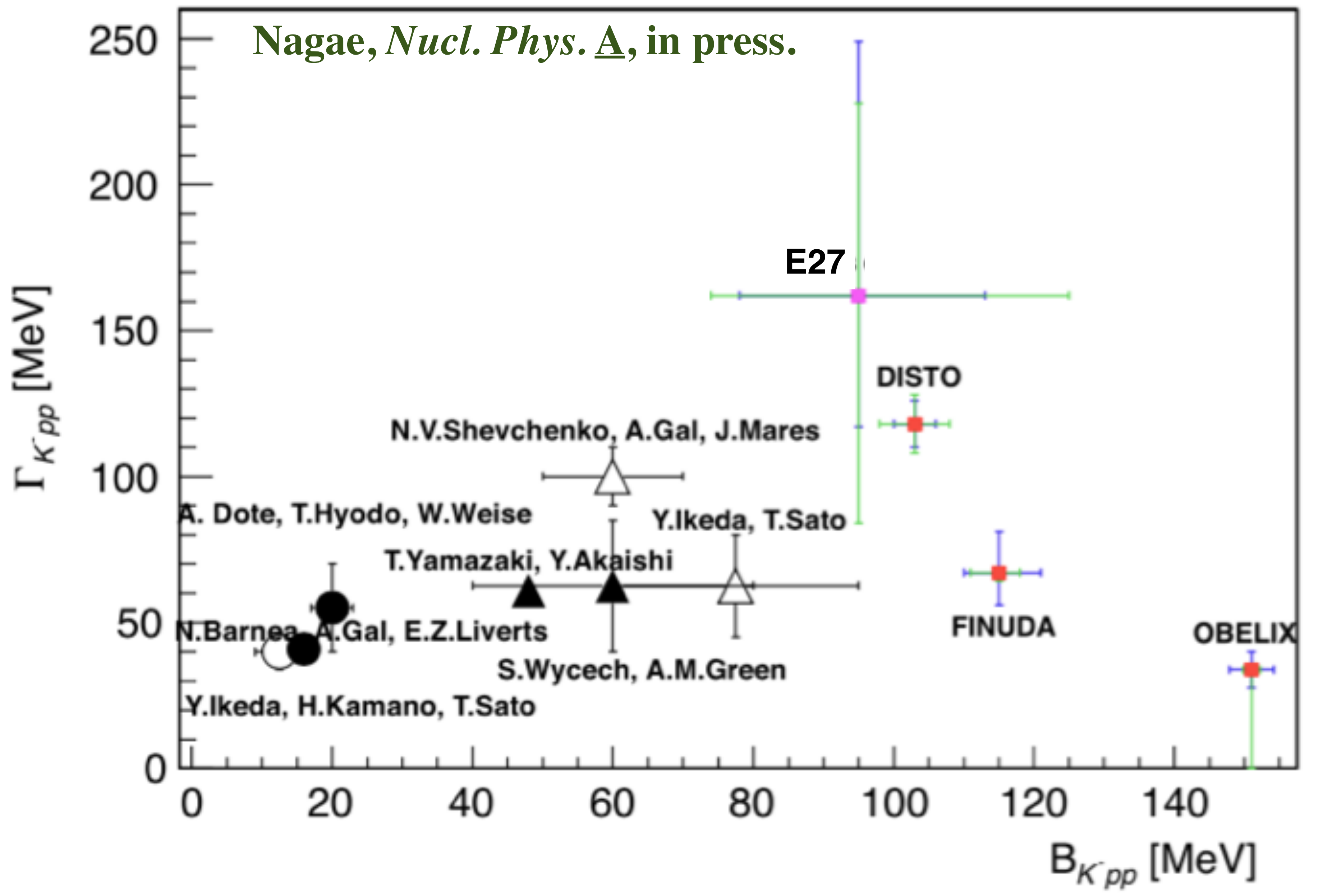
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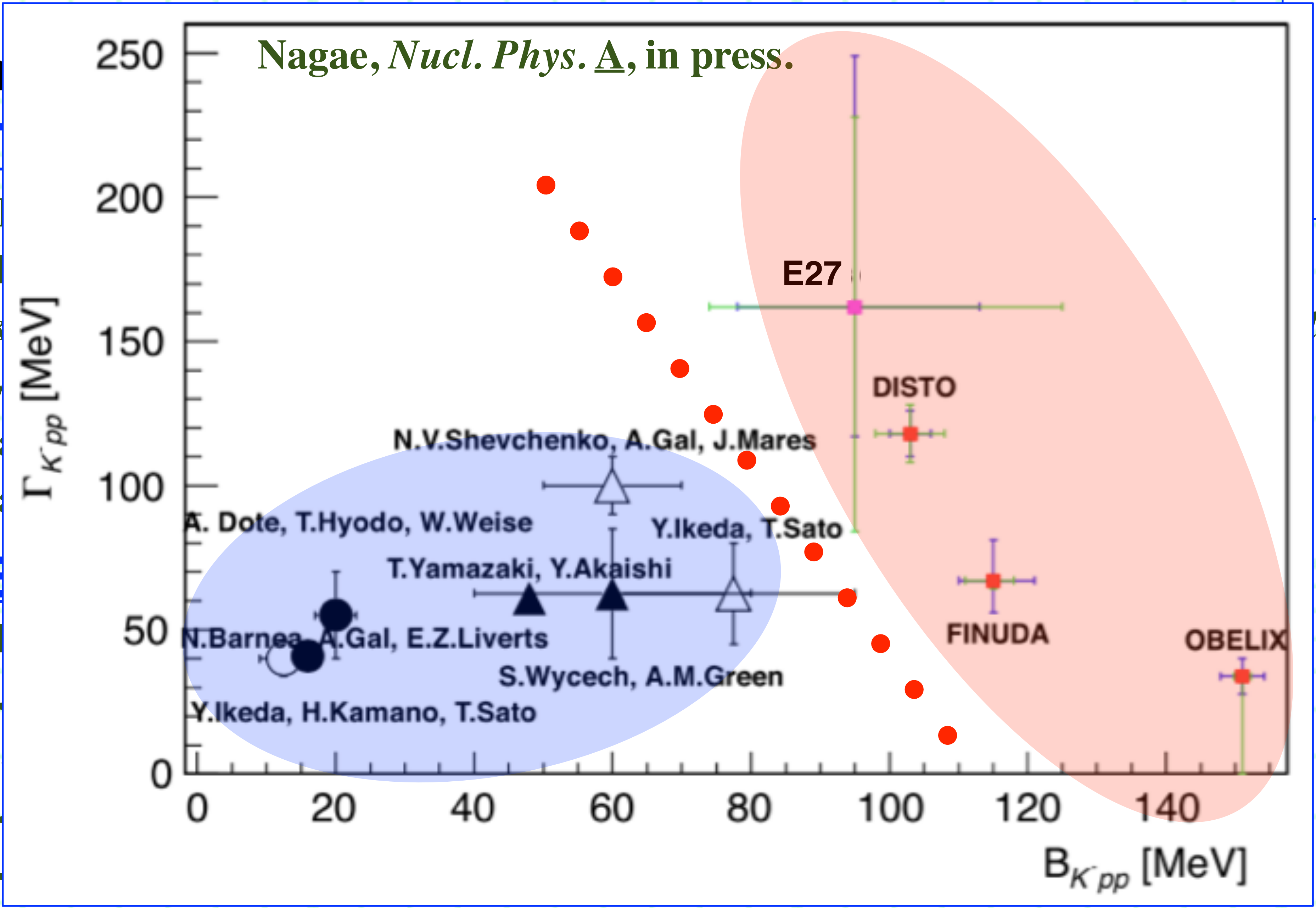
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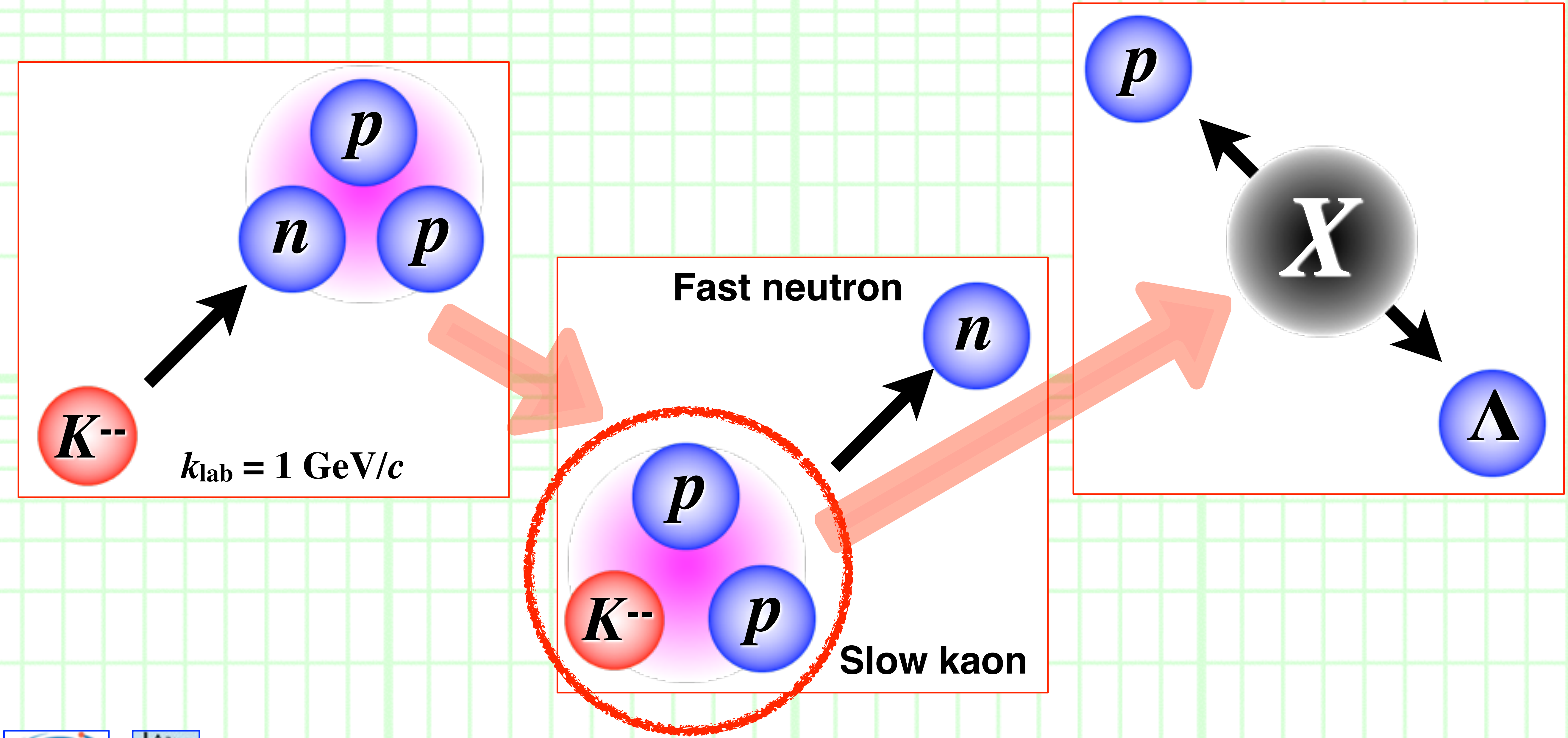
1. Introduction

++ J-PARC E15 data ++

- Recently, the J-PARC E15 collaboration has observed **a structure near the $\bar{K}NN$ threshold** in the in-flight ^{3}He $(K^-, \Lambda p)\ n$ reaction.

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

☐ Reaction mechanism:



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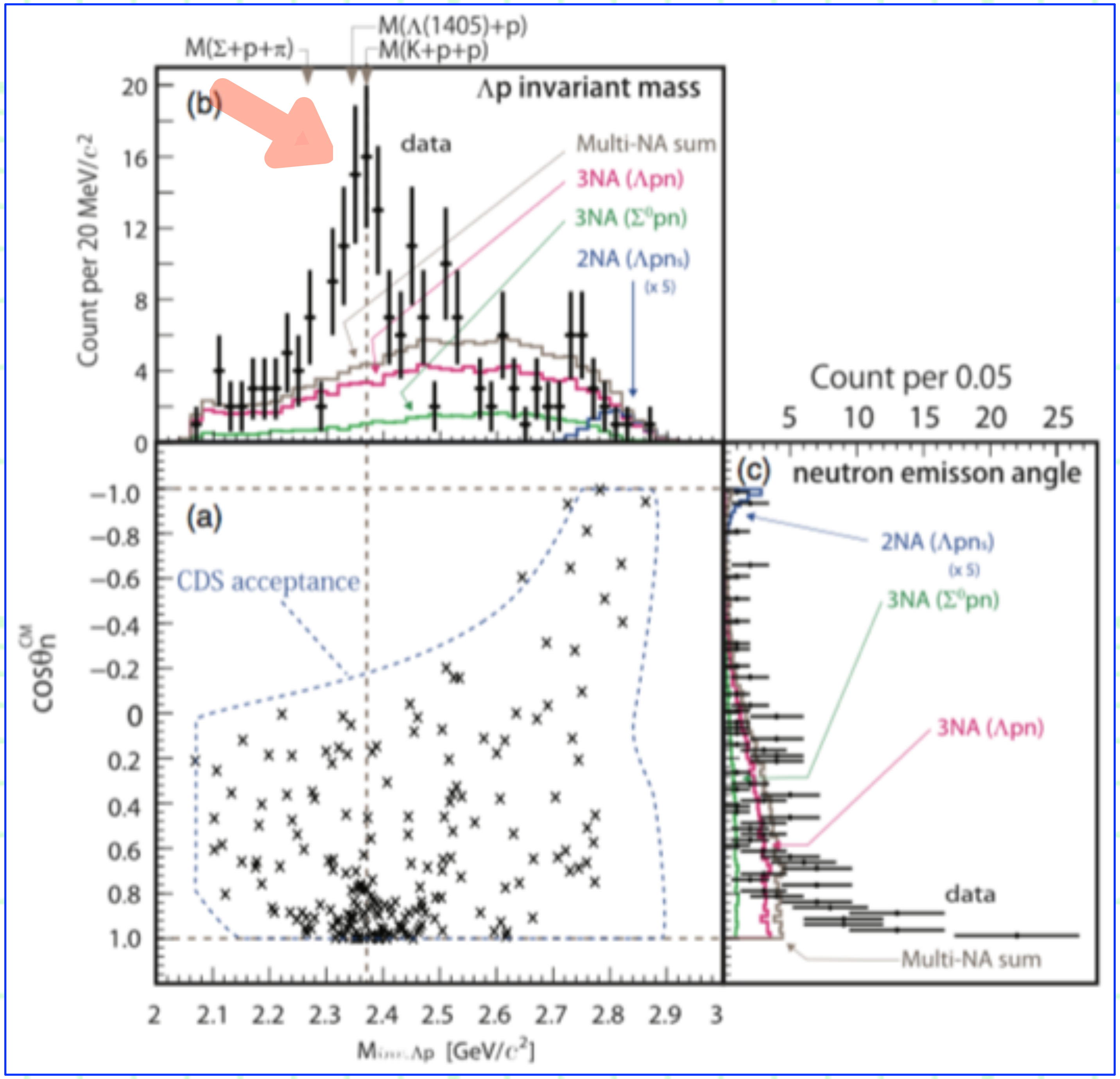

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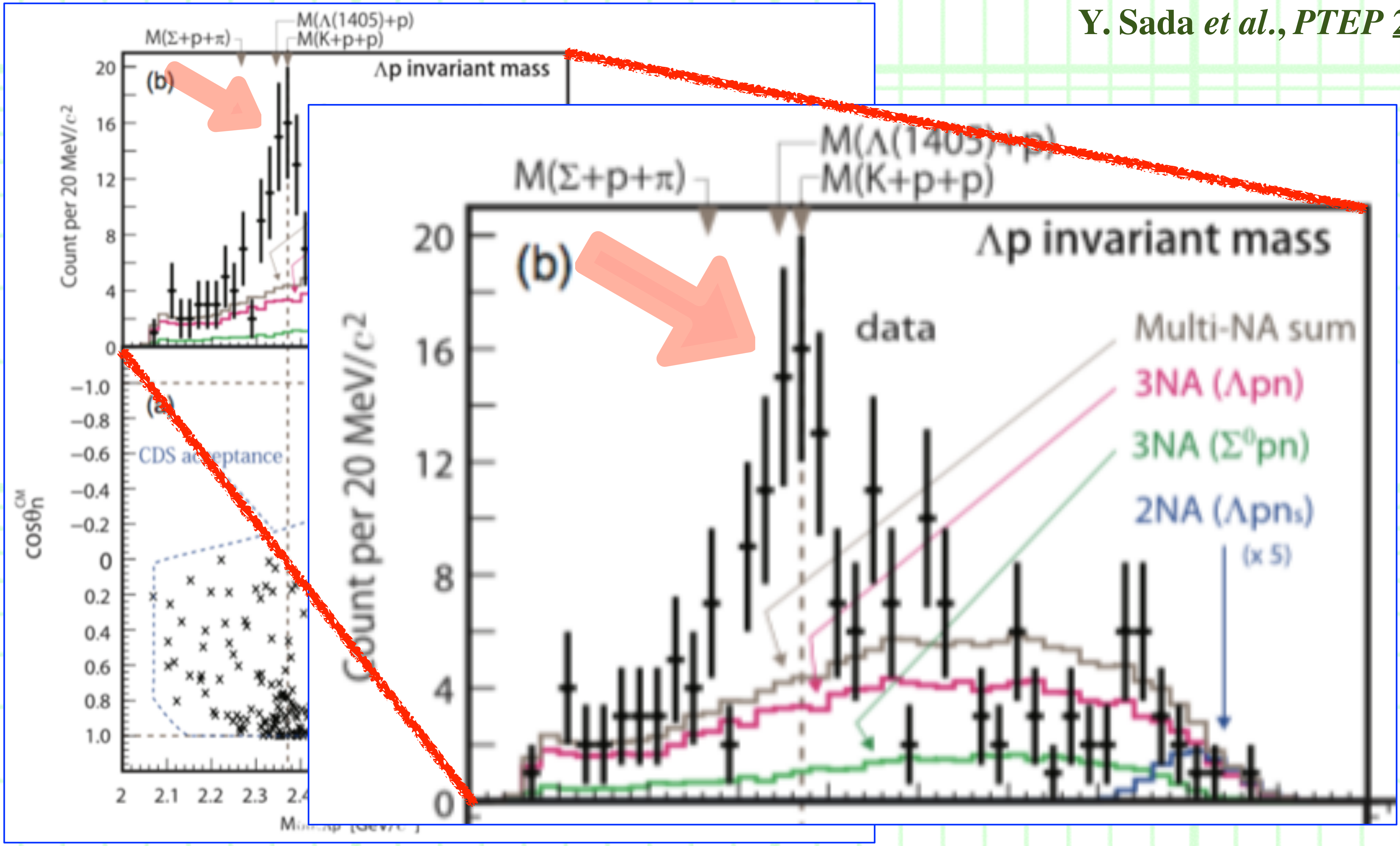

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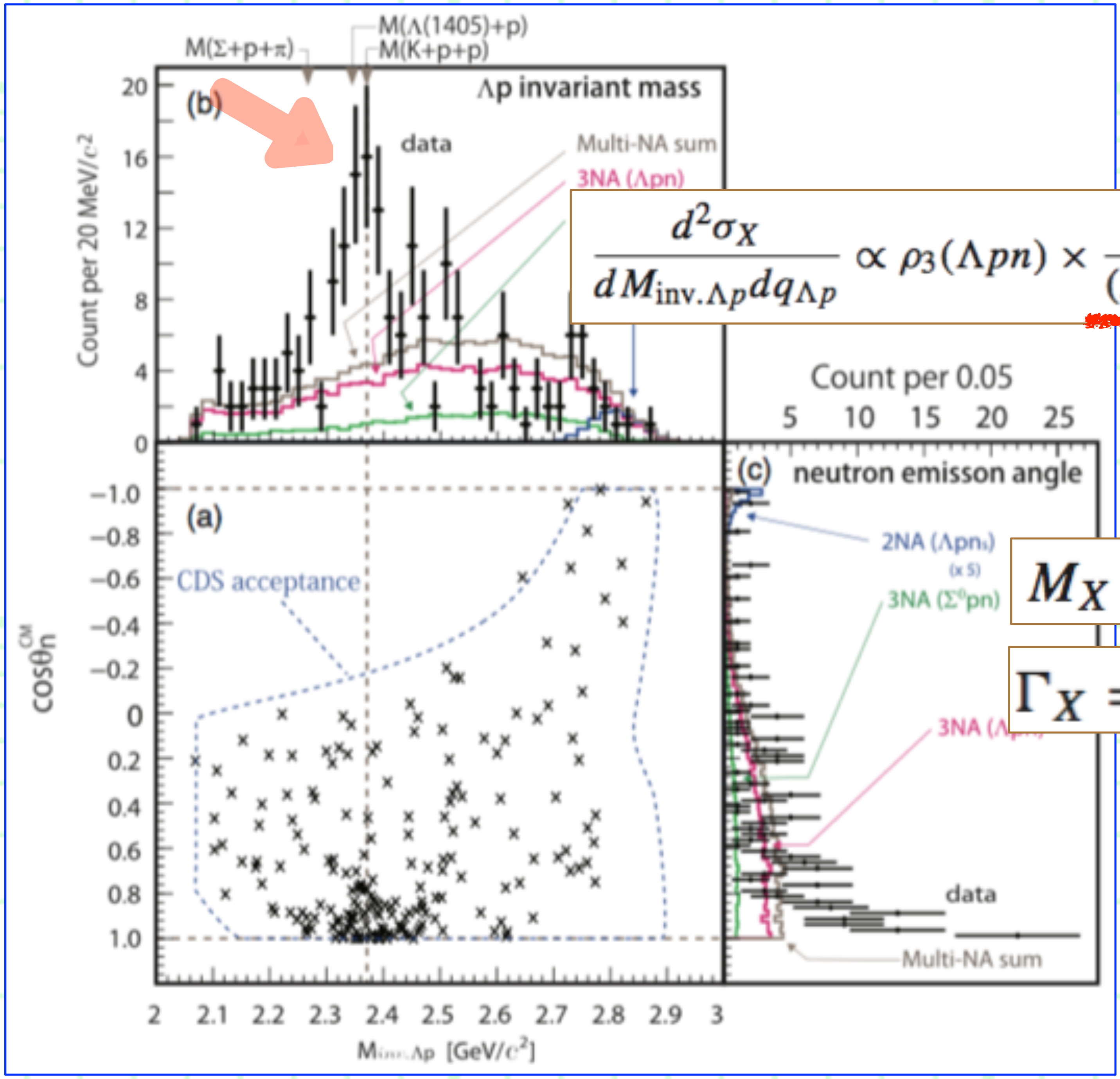

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□ **Fitted by Breit-Wigner form:**

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

--- Λp invariant mass $M_{\Lambda p}$ and momentum transfer $q_{\Lambda p}$.

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

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

□ **What is this peak ???**

--- Is this a signal of the $\bar{K}NN$ bound state ???

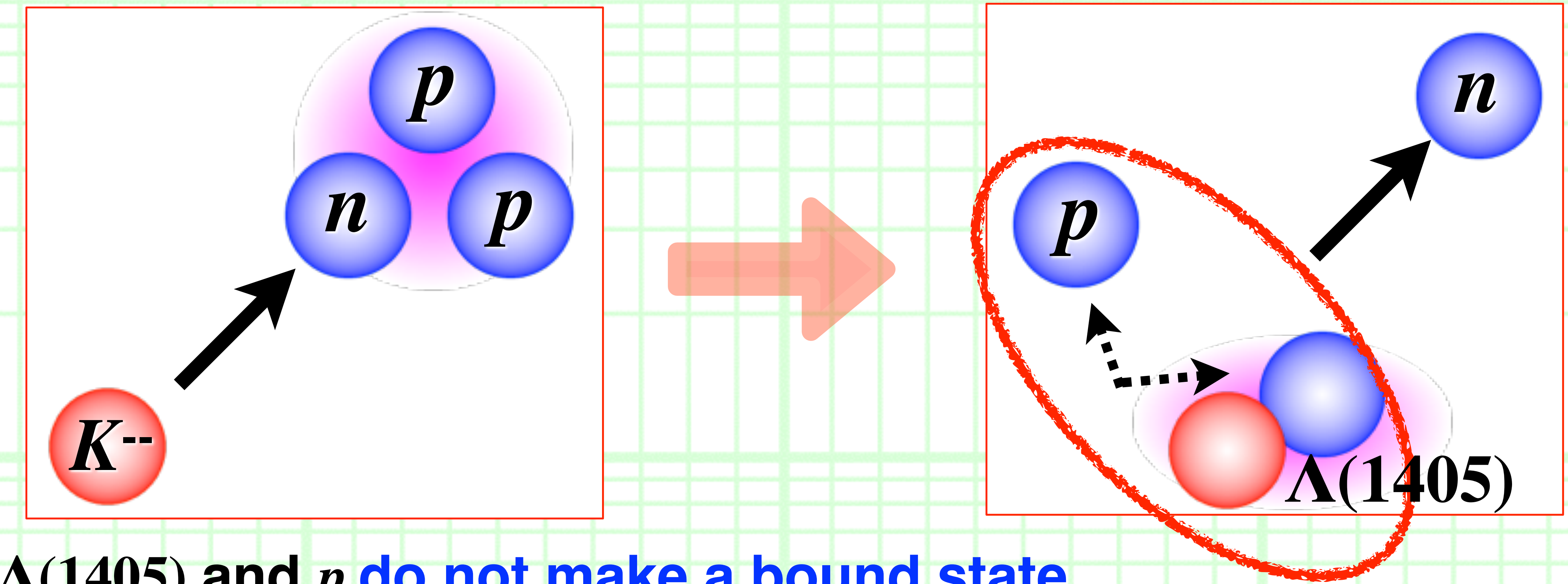
1. Introduction

++ Purpose of this study ++

- We want to know what is the origin of this peak.

--> Examine 2 scenarios in which peak will appear around $\bar{K}NN$ Thr.

□ Scenario I: Uncorrelated Λ(1405)*p*.



--- Λ(1405) and *p* do not make a bound state.

--- The Λ(1405)*p* system makes conversion to Λ*p*.

□ Because Λ(1405) exists below the $\bar{K}N$ threshold, the uncorrelated Λ(1405)*p* system may create a peak even they do not bound.

1. Introduction

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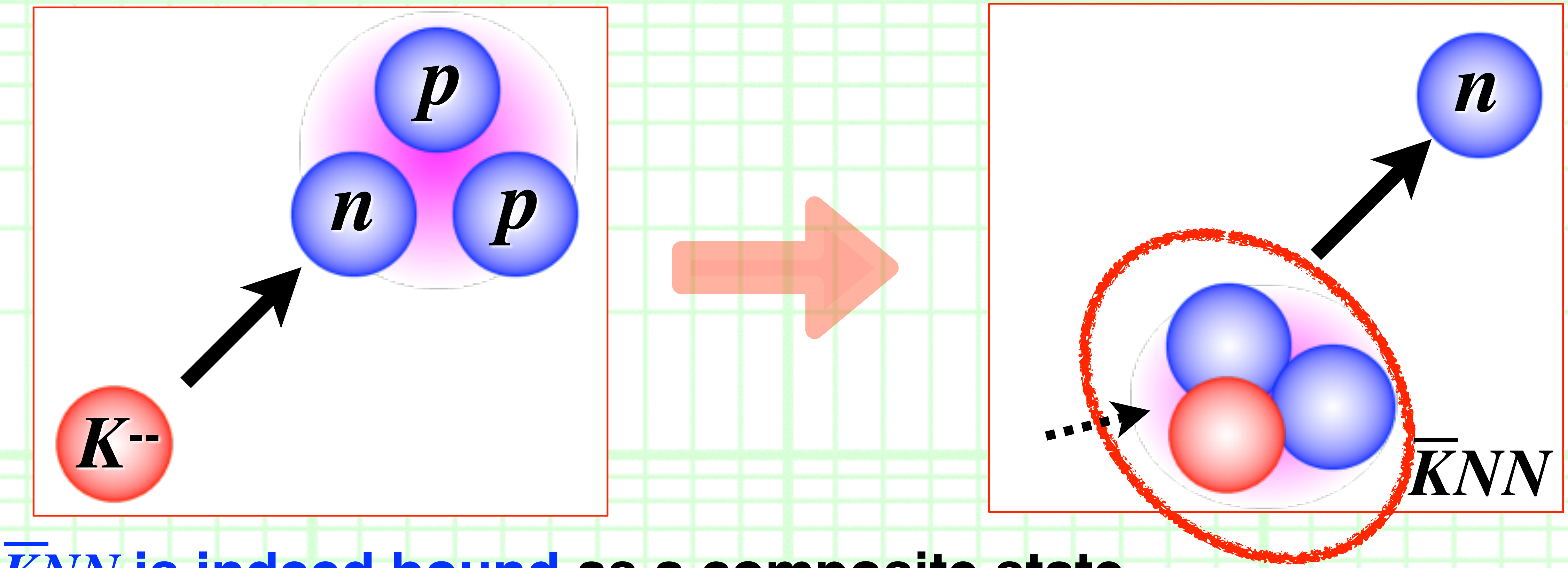
--> Examine 2 scenarios in which peak will appear around $\bar{K}NN$ Thr.

□ Scenario II: $\bar{K}NN$ bound state.



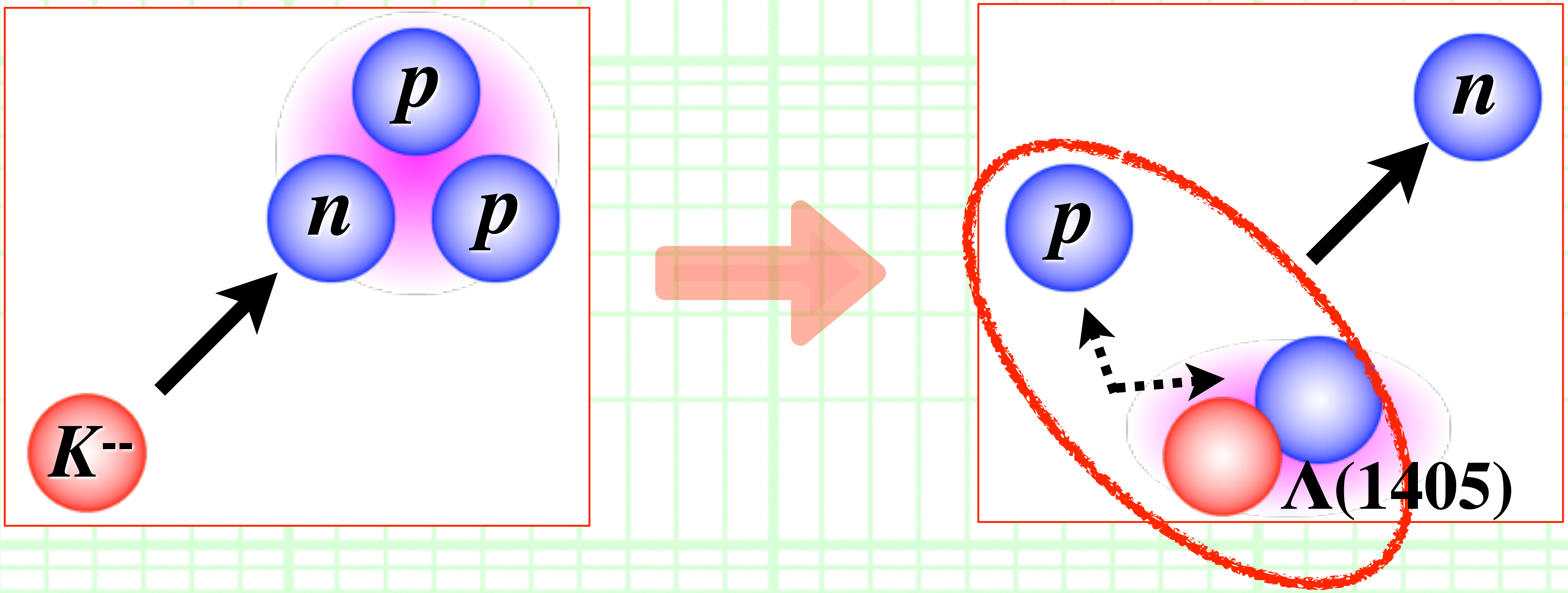
--- $\bar{K}NN$ is indeed bound as a composite state after the fast neutron emission.

□ If the $\bar{K}NN$ signal is strong enough, we will see a peak in the Λp invariant mass spectrum.

2. Uncorrelated $\Lambda(1405)\,p$

++ Reaction mechanism ++

- Scenario I: Uncorrelated $\Lambda(1405)p$.
  This system may create a peak in the Λp mass spectrum.

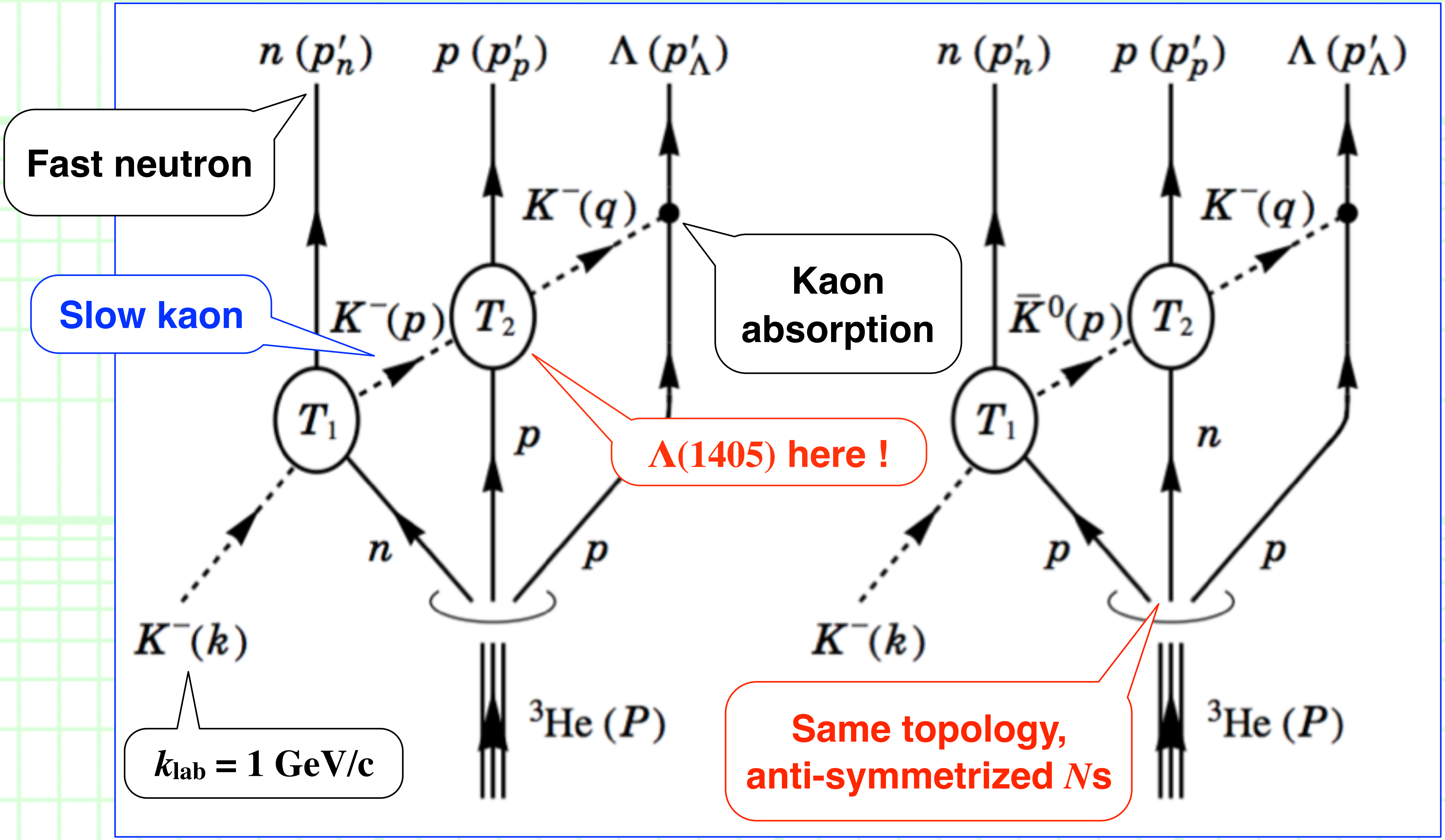


☐ Because $\Lambda(1405)$ exists below the $\bar{K}N$ threshold, the uncorrelated $\Lambda(1405)p$ system may create a peak even they do not bound.

2. Uncorrelated Λ(1405) *p*

++ Scattering amplitude ++

- For this process, we use the following diagrams:



Fast neutron

Slow kaon

Kaon absorption

Λ(1405) here !

k_{lab} = 1 GeV/c

Same topology, anti-symmetrized *N*s

2. Uncorrelated Λ(1405) *p*

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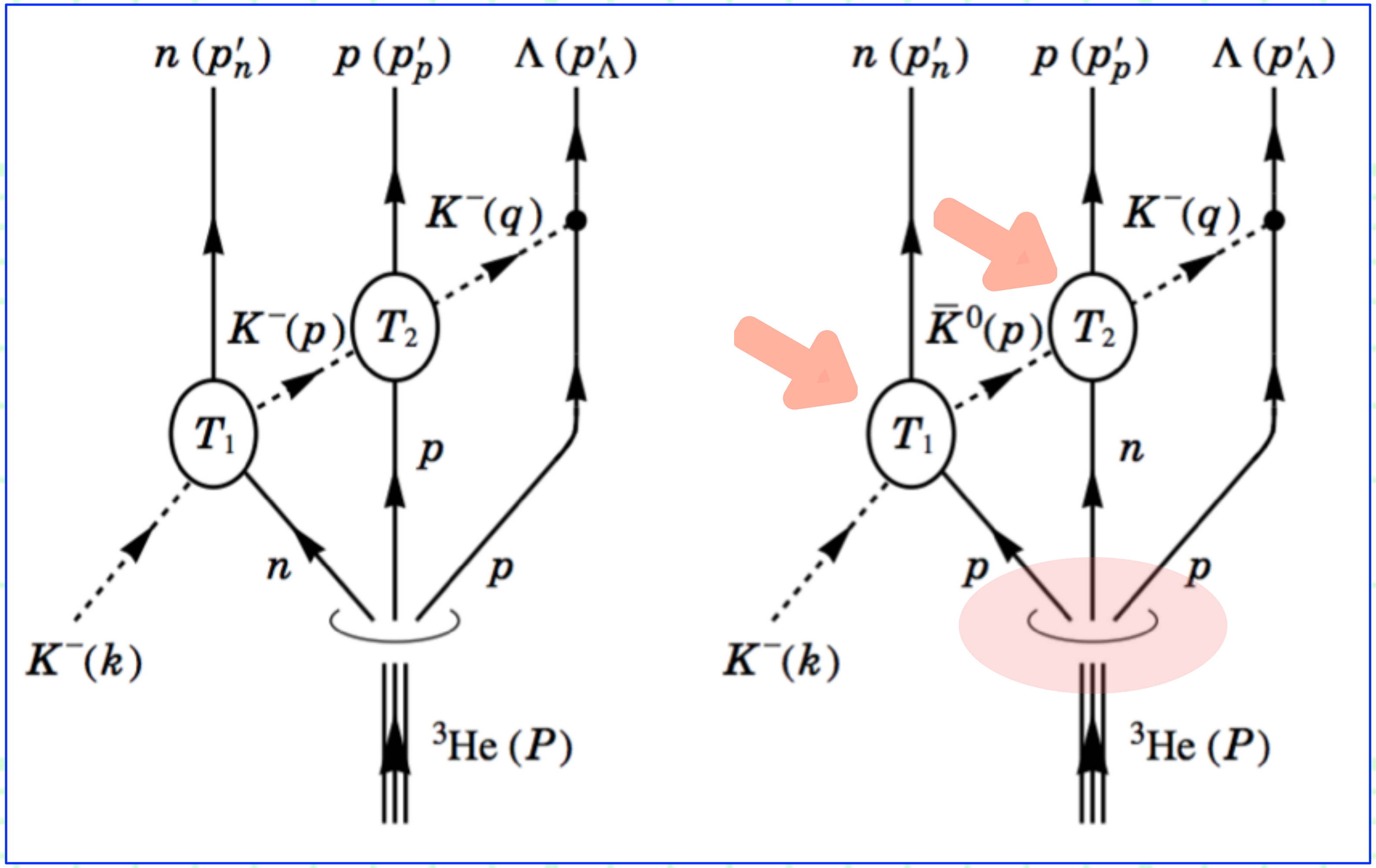


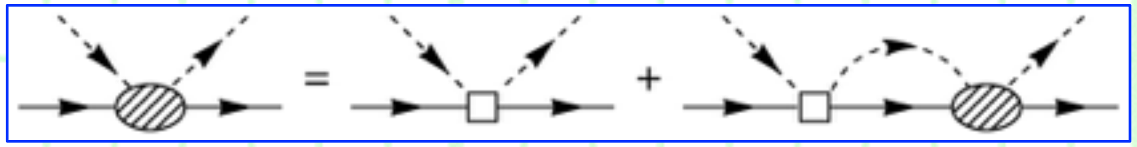
□ **The ^{3}He wave function is obtained as the anti-symmetrized 3 nucleons in the harmonic oscillator potential.**

□ **Amplitude T_1 (k=1 GeV/c):**

$$\begin{cases} K^- n \to K^- n_{\text{escape}} \\ K^- p \to \bar{K}^0 n_{\text{escape}} \end{cases}$$

--- Taken from Exp. dσ/dΩ.

□ **Amplitude T_2:** $\begin{cases} K^- p \to K^- p \\ \bar{K}^0 n \to K^- p \end{cases}$ **around $\bar{K}N$ threshold.**



--- Calculate in chiral unitary approach with kaon absorption width (ε --> Γ_K = 15 MeV in kaon prop.).

2. Uncorrelated $\Lambda(1405)\,p$

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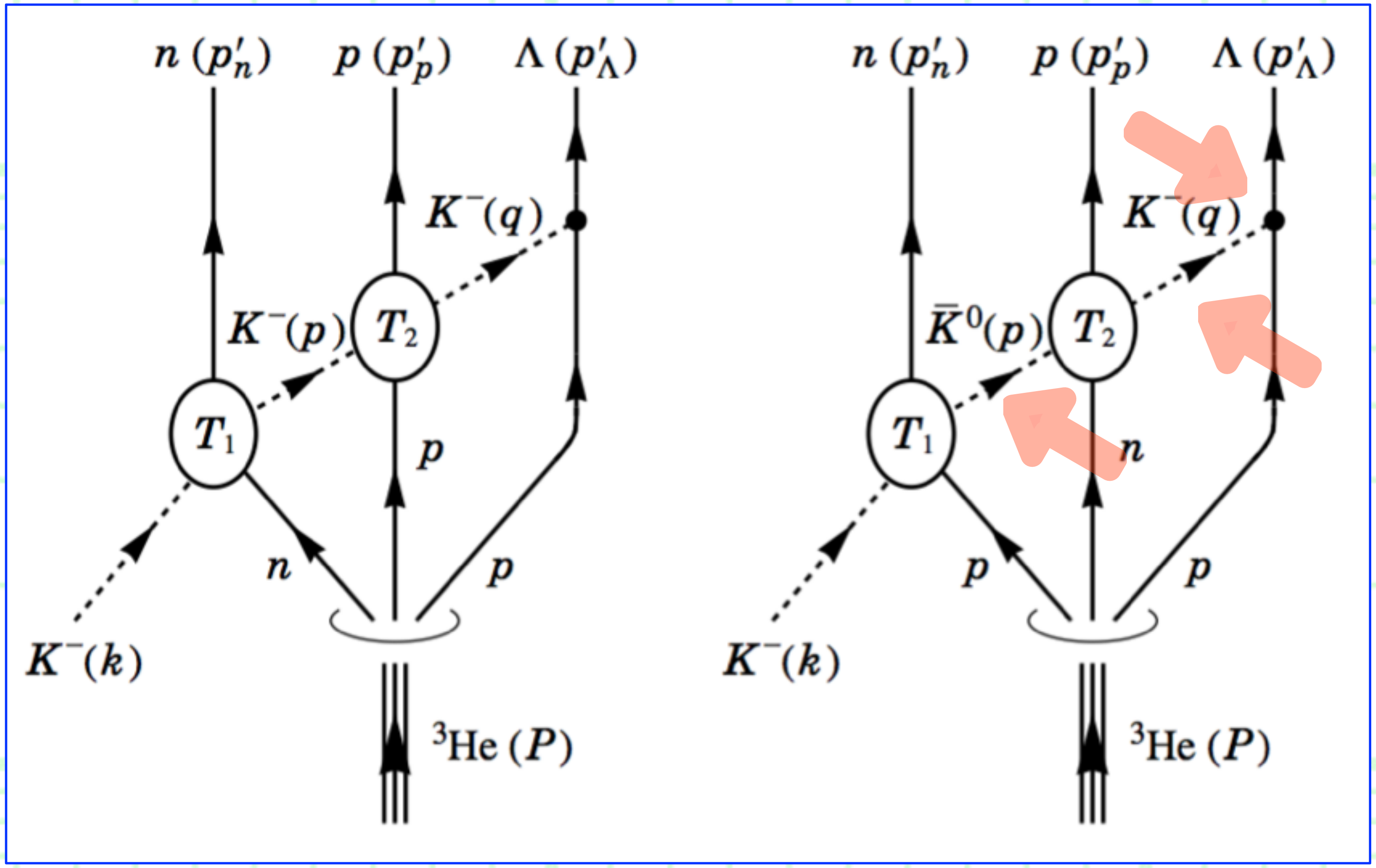


- ☐ The $K^-p\Lambda$ vertex is taken from chiral Lagrangian x phenomenological FF.
- ☐ The intermediate kaon energy is fixed as:

$$q^0 = p_\Lambda^{\prime 0} - \left(m_N - \frac{B_{^3\mathrm{He}}}{3} \right)$$

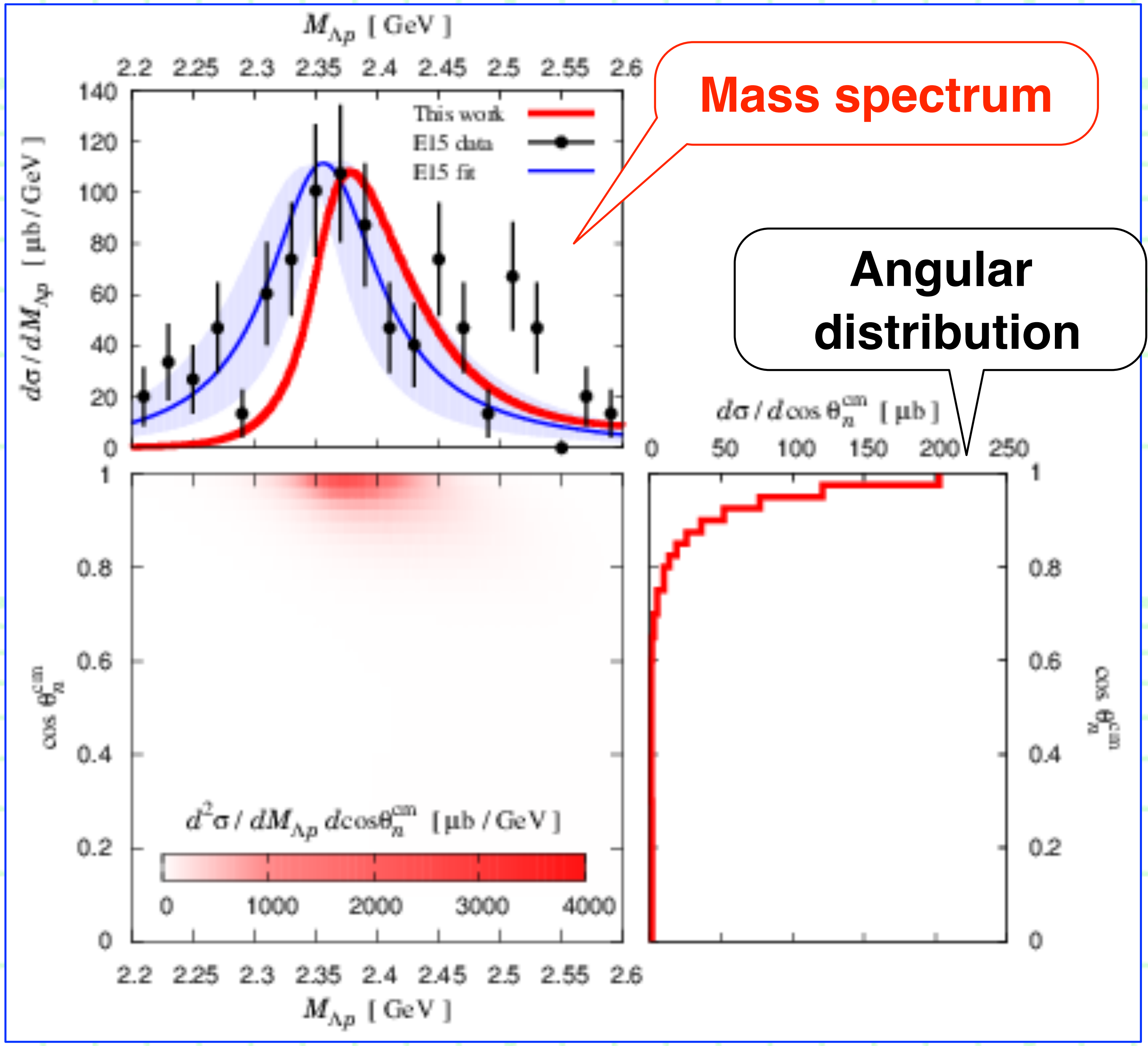
$$p^0 = p_\Lambda^{\prime 0} + p_p^{\prime 0} - 2 \left(m_N - \frac{B_{^3\mathrm{He}}}{3} \right)$$

K. M. Watson, *Phys. Rev.* 89 (1953) 575;
D. Jido, E. Oset and T. S. , *Eur. Phys. J.* A49 (2013) 95.

2. Uncorrelated Λ(1405) *p*

++ Numerical results ++

- Now we calculate the cross section and Λ*p* mass spectrum of the ^{3}He (K^- , Λ*p*) *n* reaction in the uncorrelated Λ(1405)*p* scenario.



Mass spectrum

Angular distribution

- ☐ Our mass spectrum is compared with that from Exp. analysis: Y. Sada *et al.* (2016).

$$\frac{d\sigma}{dM_{\Lambda p}} \propto p'_n p^*_\Lambda \frac{\Gamma_X^2}{(M_{\Lambda p}-M_X)^2+\Gamma_X^2/4}$$

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

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<-- Shown in blue line / band, but in arbitrary units.

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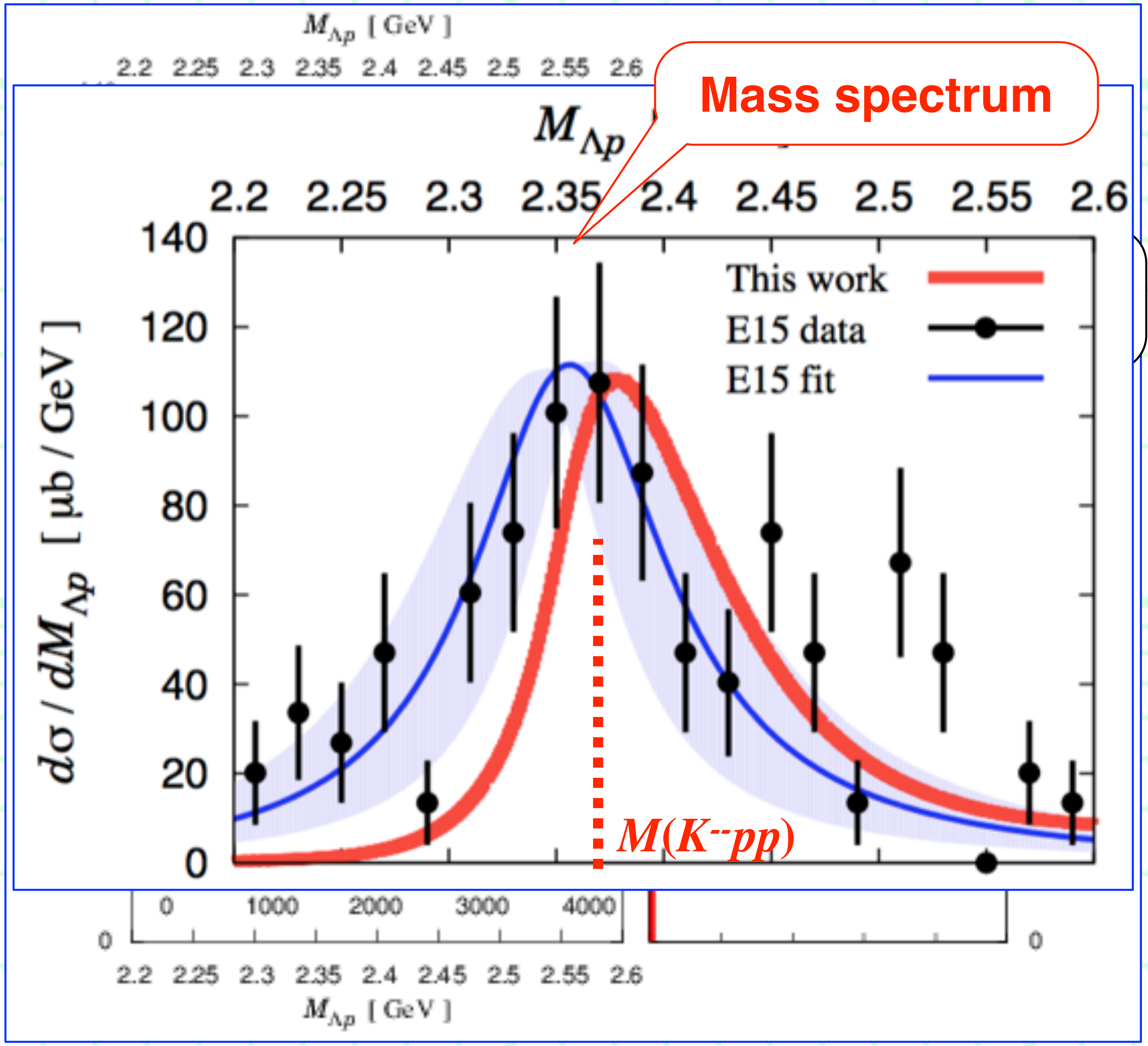

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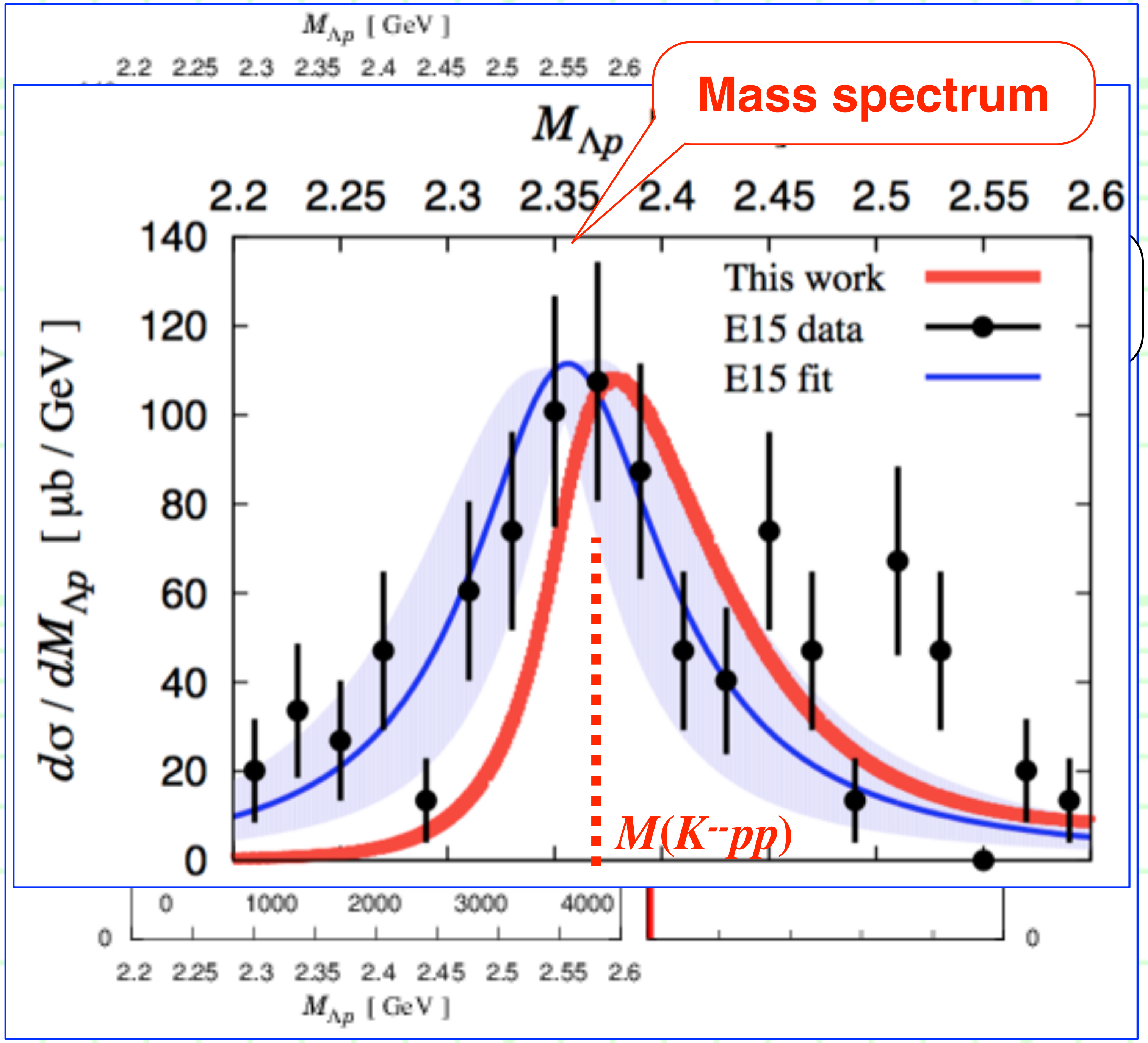


Mass spectrum

☐ The peak position is inconsistent with the Exp.

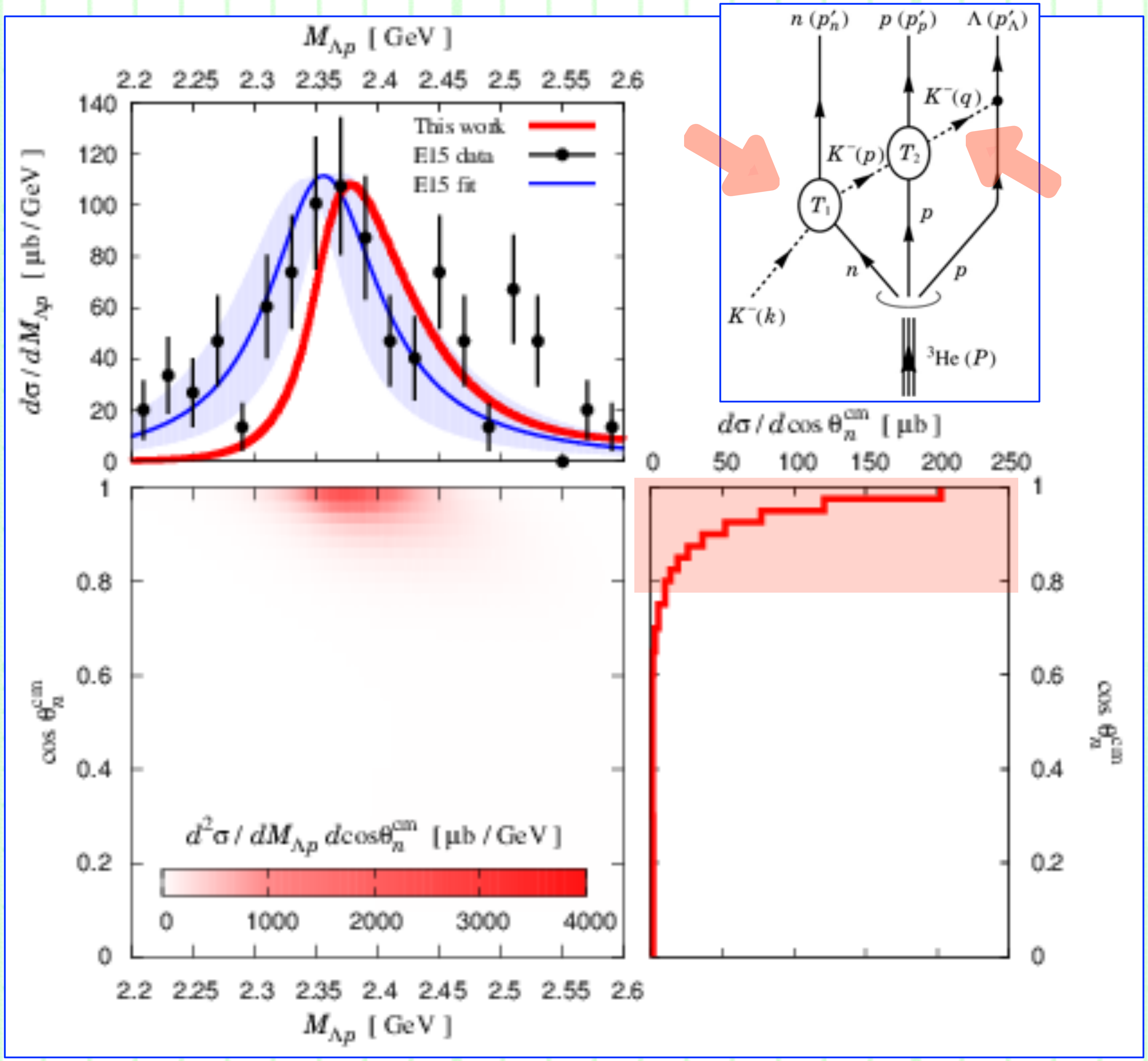
--- Peak at 2355 MeV (Exp.) vs. 2370 MeV (this work).

☐ In particular, we cannot reproduce the behavior of the lower tail ~ 2.3 GeV.

☐ Therefore, the E15 signal in the $^3\mathrm{He}\,(K^-, \Lambda p)\,n$ reaction is NOT the uncorrelated $\Lambda(1405)p$ state.

2. Uncorrelated Λ(1405) *p*

++ Numerical results ++



- ☐ **Diff. cross section $d\sigma/d\cos\theta_n$ indicates forward neutron emission is favored.**

--- Cross section of the first step,

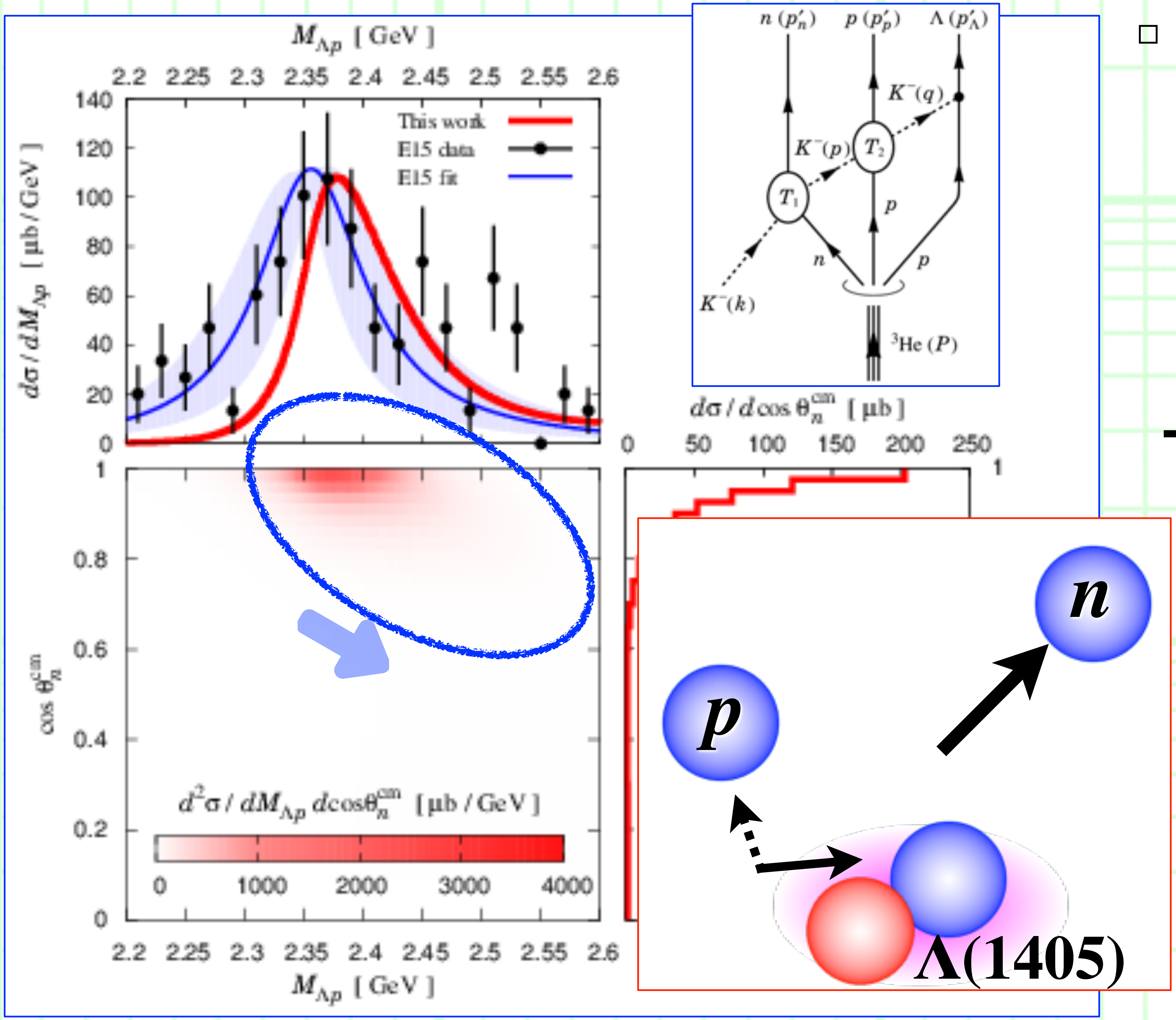
$$\begin{cases} K^- n \to K^- n_{\rm escape} \\ K^- p \to \bar{K}^0 n_{\rm escape} \end{cases}$$

has a local maximum at $\theta_n = 0^{\rm o}$.

--- Higher momentum in kaon propagator suppresses $d\sigma/d\cos\theta_n$ (higher p_K for larger θ_n in the Lab. frame).

2. Uncorrelated Λ(1405) *p*

++ Numerical results ++



- ☐ There is a "band" of the uncorrelated Λ(1405)*p* contribution in $d^2\sigma/dM_{\Lambda p}d\cos\theta_n$, although its strength is weak for $\cos\theta \lesssim 0.9$.

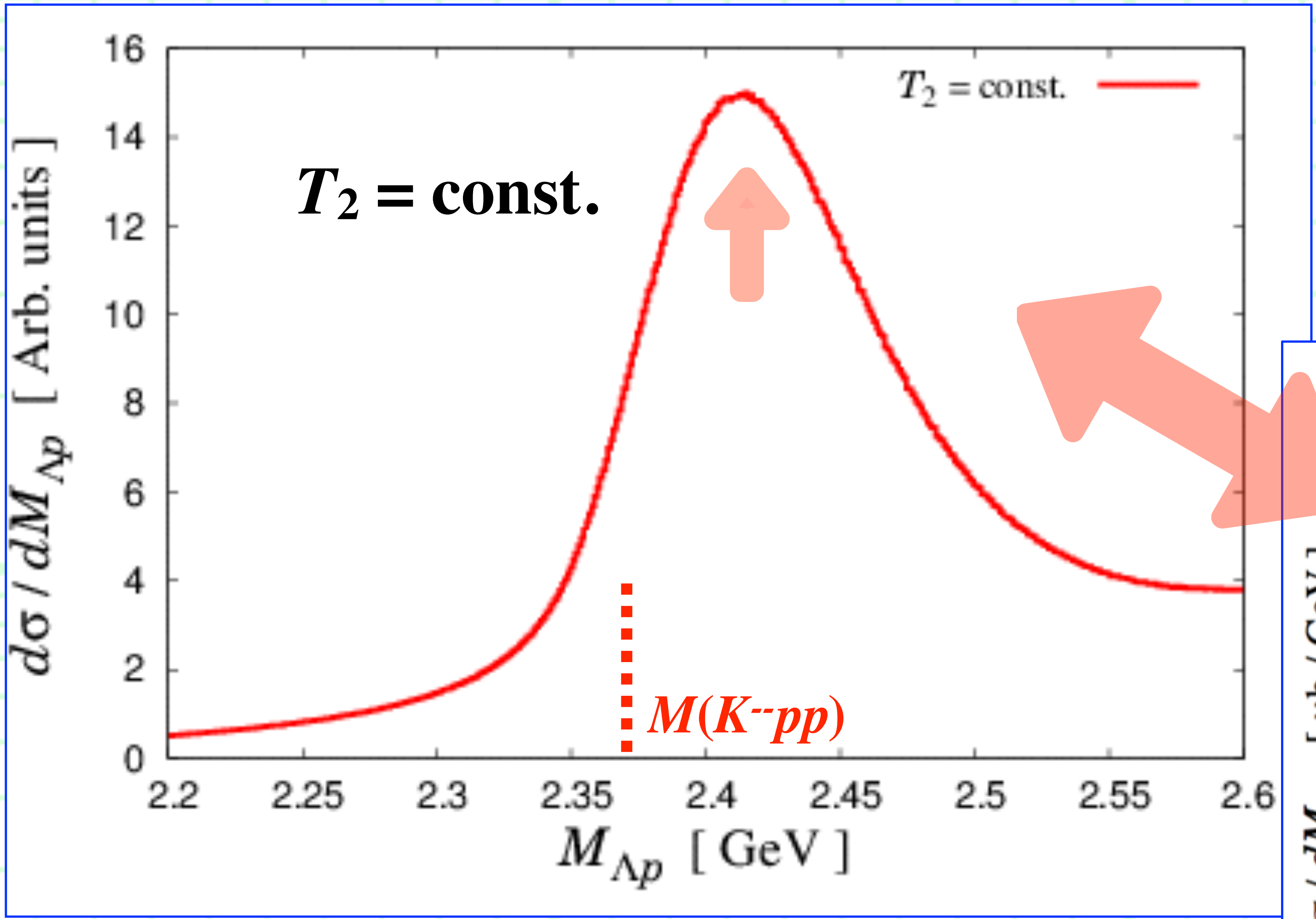
--- Λ(1405) gets more momentum from the kaon after the first scattering.

2. Uncorrelated $\Lambda(1405)\,p$

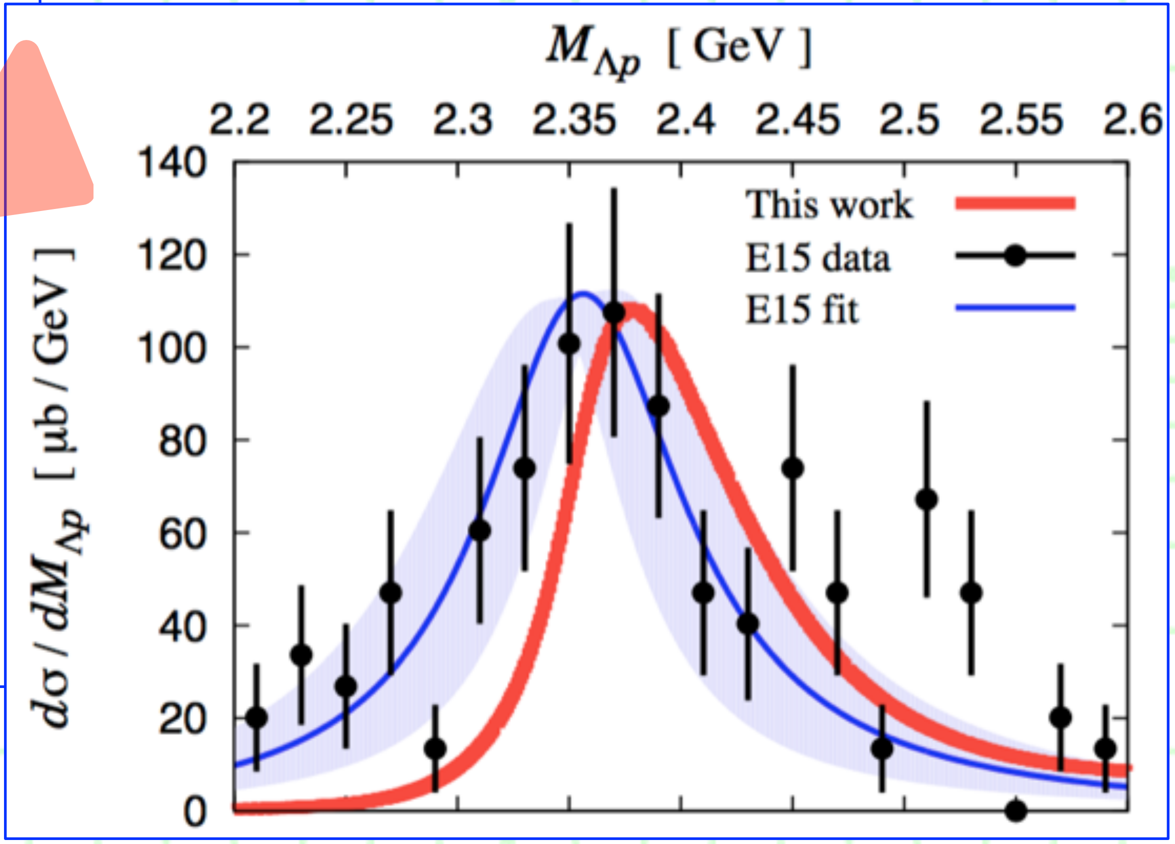
++ Underlying kinematic feature ++

- **We find that there is an underlying kinematic feature rather than by the $\Lambda(1405)p$ system.**

--- This can be seen by taking $T_2 = \text{const.}$ <=> Ignoring $\Lambda(1405)$.



- ☐ **Indicates underlying kinematic features rather than by the $\Lambda(1405)p$.**



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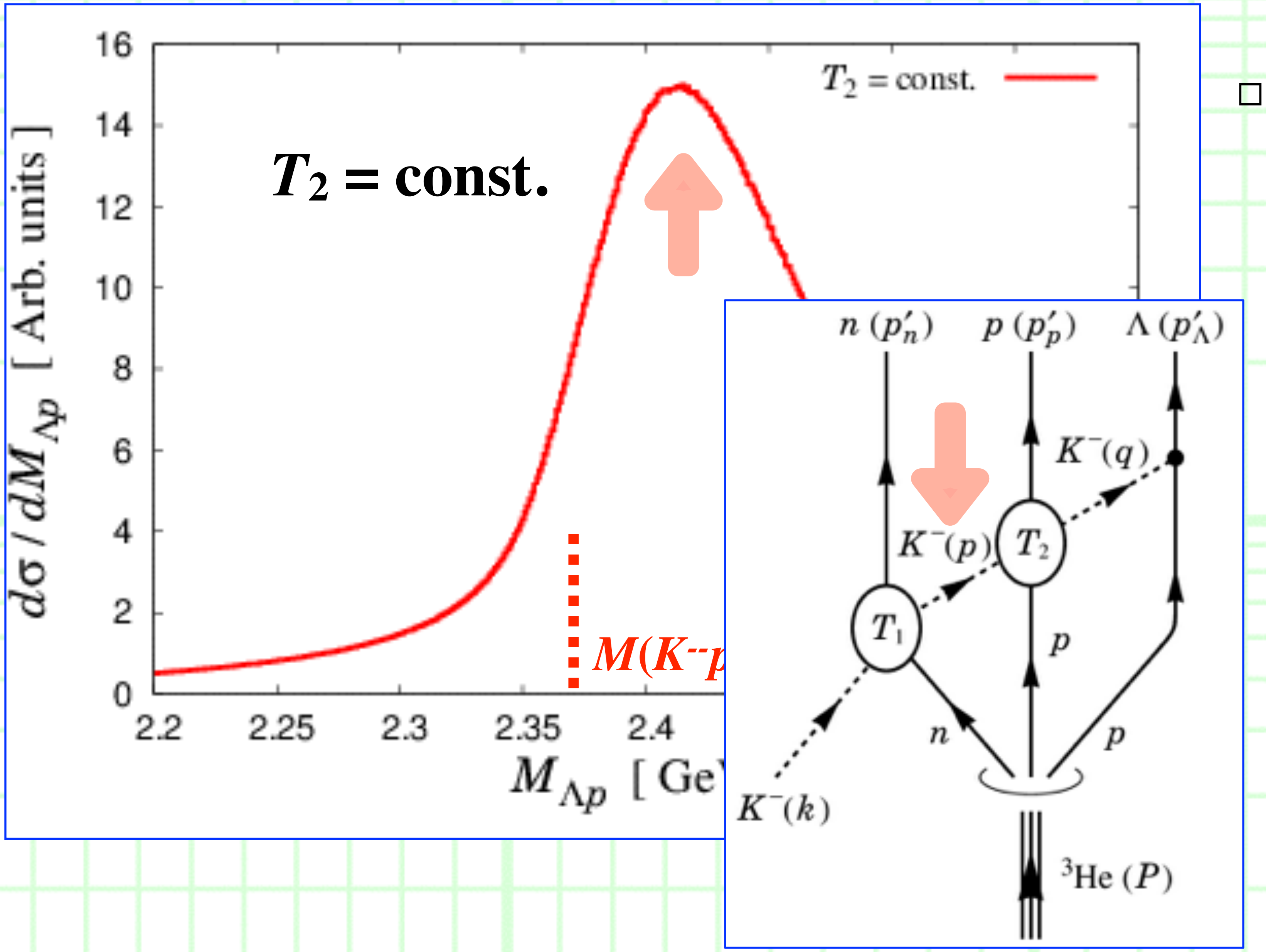


- **Actually, this is due to the quasi-elastic kaon scattering in the first step.**

  --- The intermediate kaon after the fast neutron emission goes almost to its on mass shell.

- **The actual mass spect. is essentially the product with | T_2 |^2.**

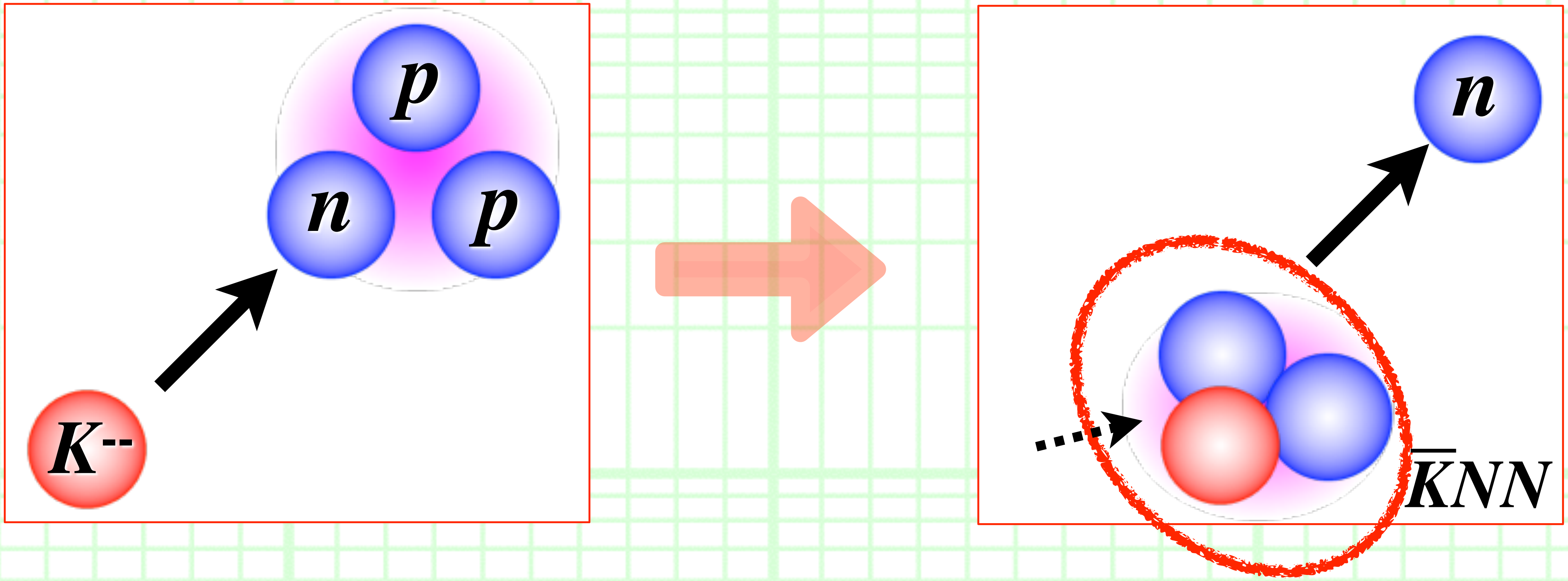
  --> They merge to be a single peak.

3. $\bar{K}NN$ bound state

++ Reaction mechanism ++

- **Scenario II**: $\bar{K}NN$ bound state.

--- $\bar{K}NN$ is indeed bound as a composite state after the fast neutron emission.

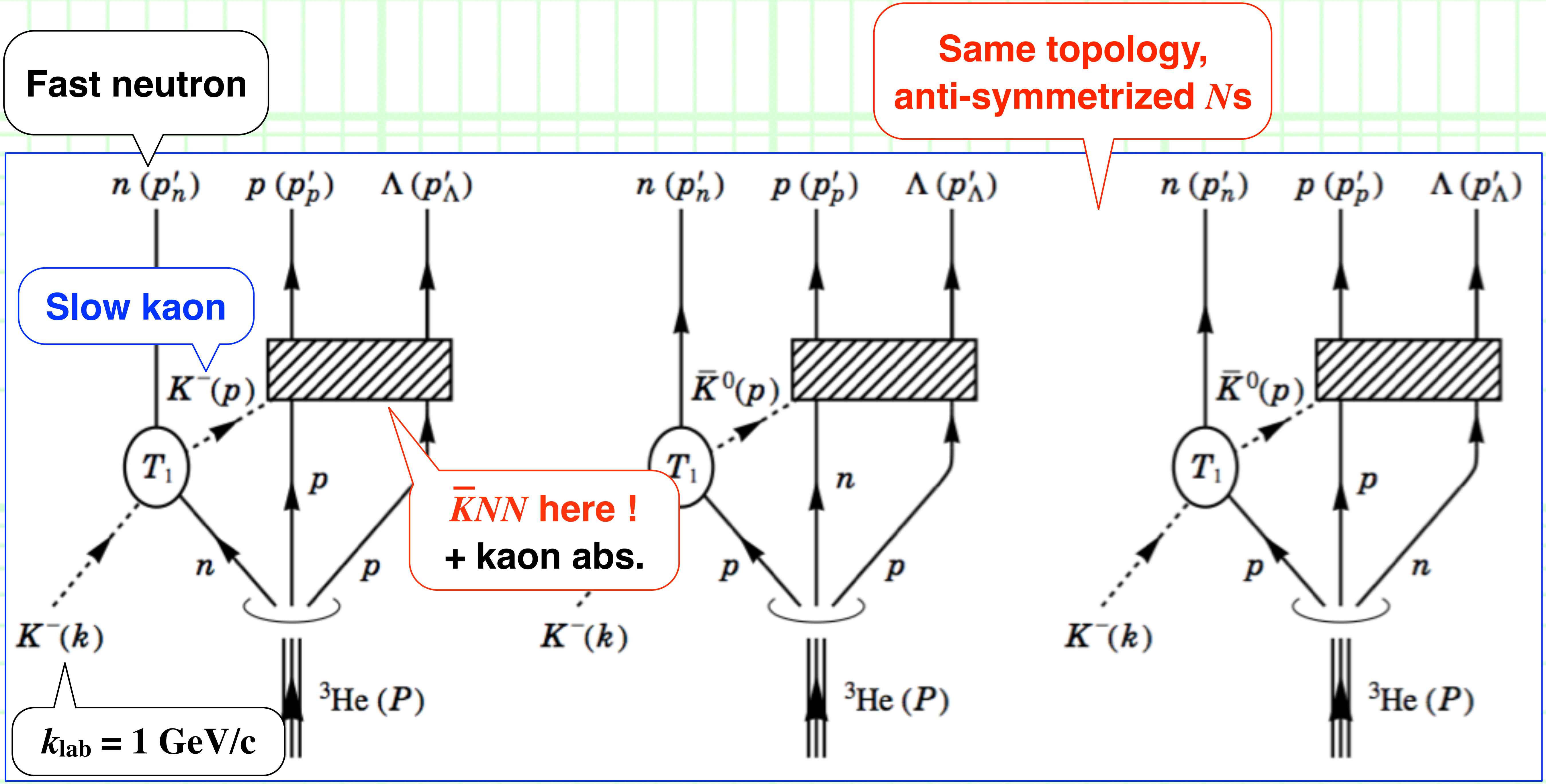


☐ If the $\bar{K}NN$ signal is strong enough, we will see a peak in the Λp invariant mass spectrum.

3. $\bar{K}NN$ bound state

++ Scattering amplitude ++

- For this process, we use the following diagrams:



Fast neutron

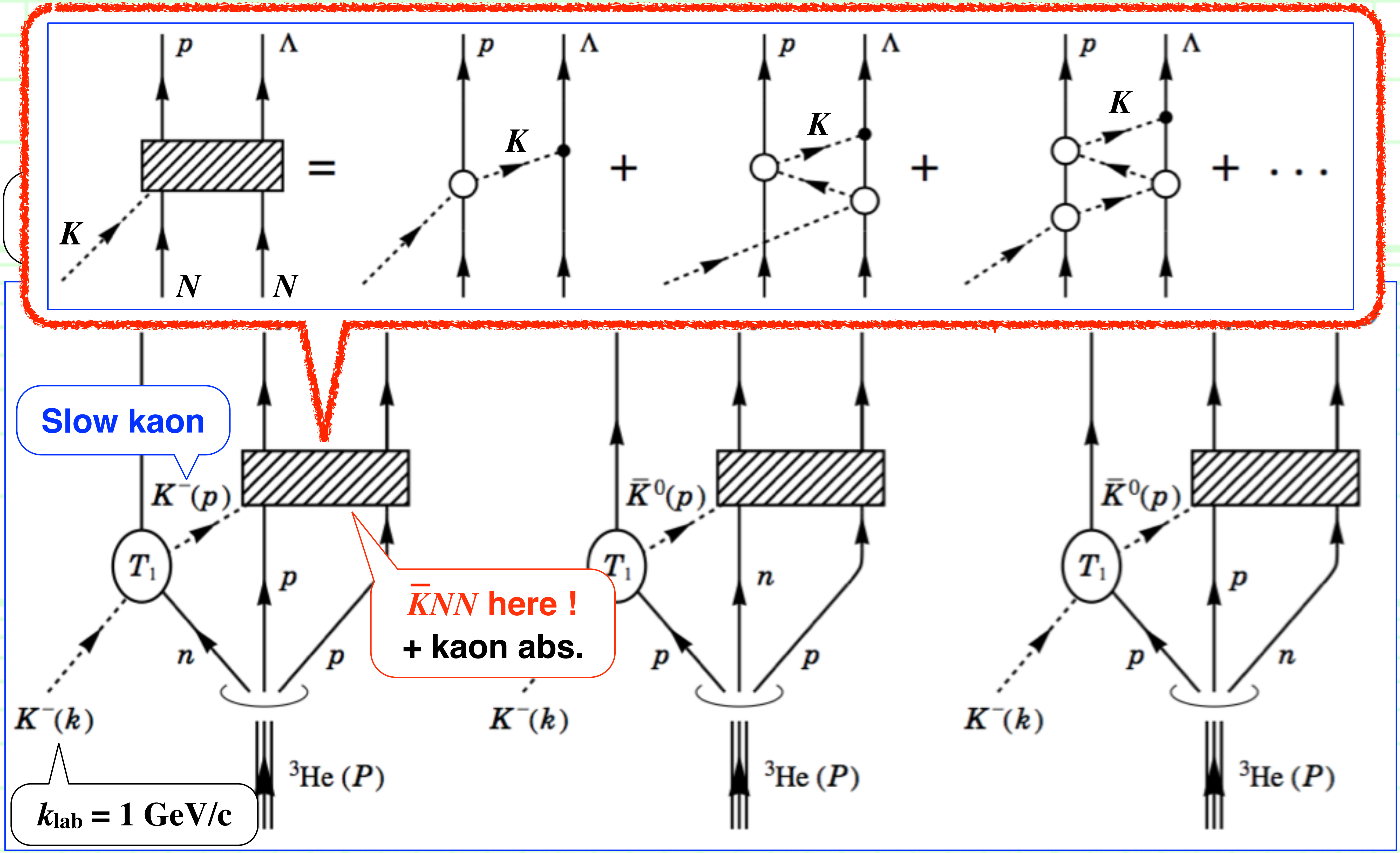
Same topology, anti-symmetrized Ns

Slow kaon

$\bar{K}NN$ here !
+ kaon abs.

$k_{\text{lab}} = 1$ GeV/c

3. $\bar{K}NN$ bound state



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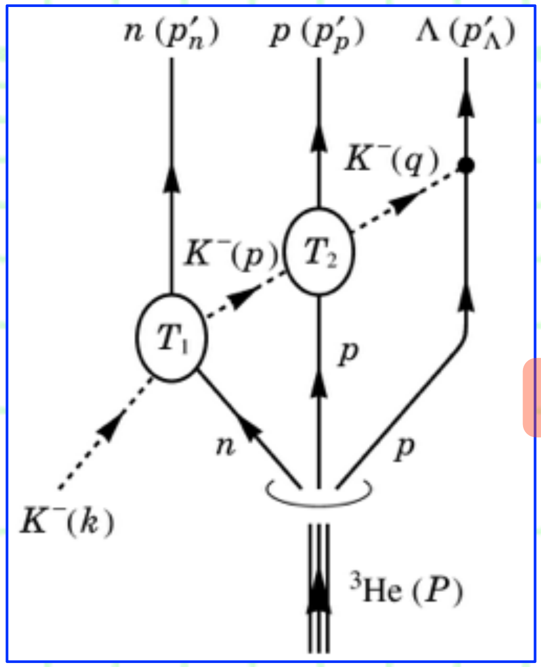
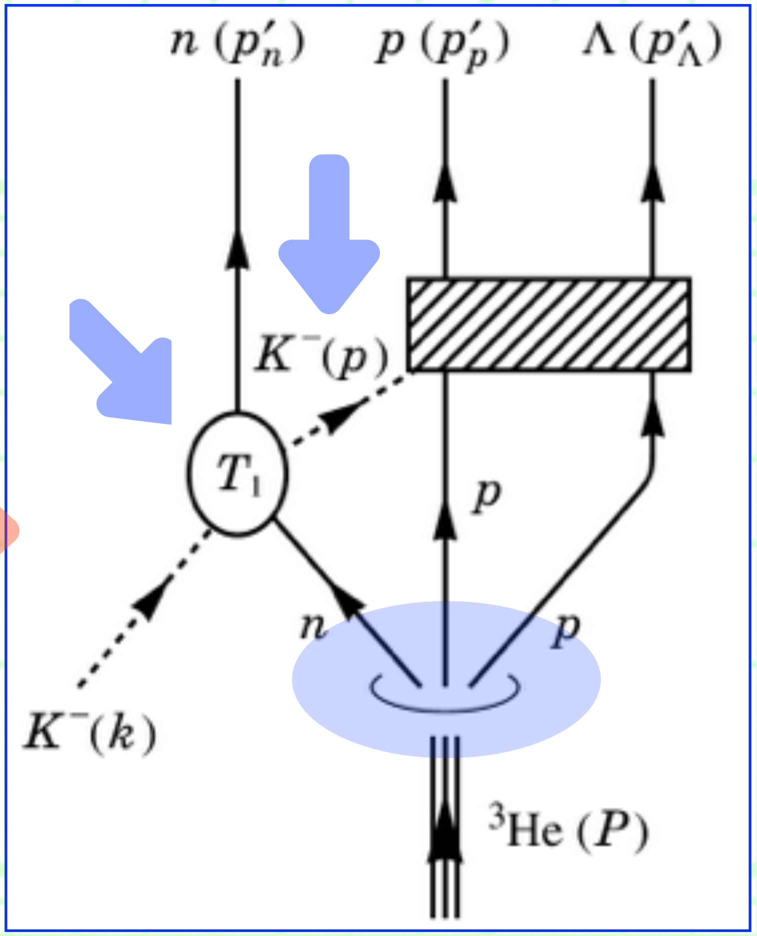




--- We can use **same form**:

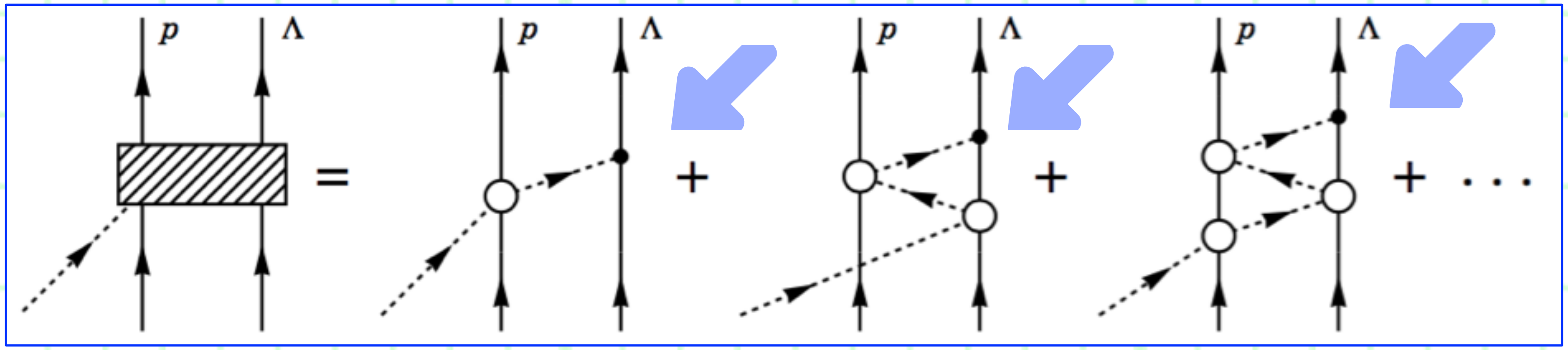
☐ **The ^{3}He wave function**.

☐ **Amplitude T_1** (k=1 GeV/c):

$$\begin{cases} K^- n \to K^- n_{\text{escape}} \\ K^- p \to \bar{K}^0 n_{\text{escape}} \end{cases}$$

☐ **The $\bar{K}N\Lambda$ vertex**.

☐ **The intermediate kaon energy**.



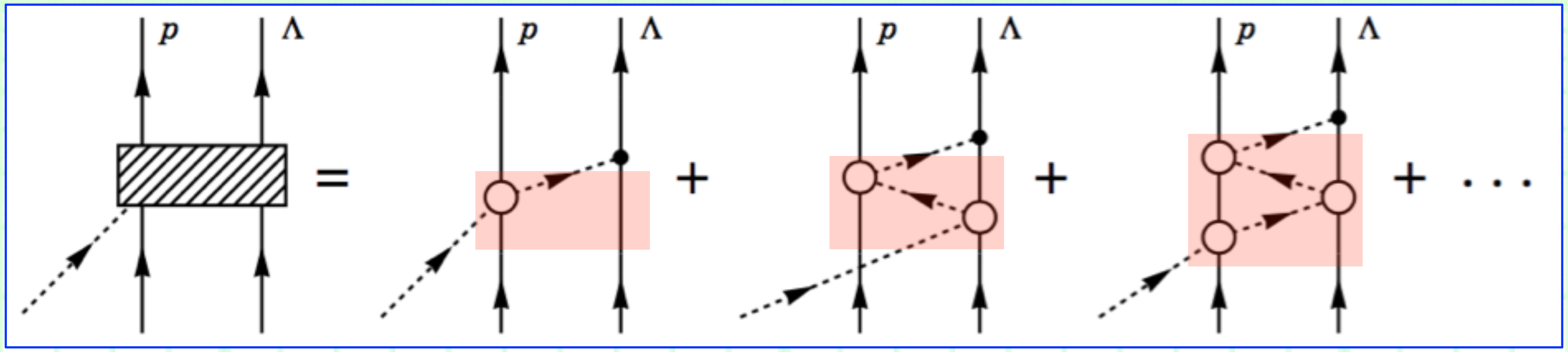
☐ We can use **the same formula** for them as in the uncorr. $\Lambda(1405)p$.

3. $\bar{K}NN$ bound state

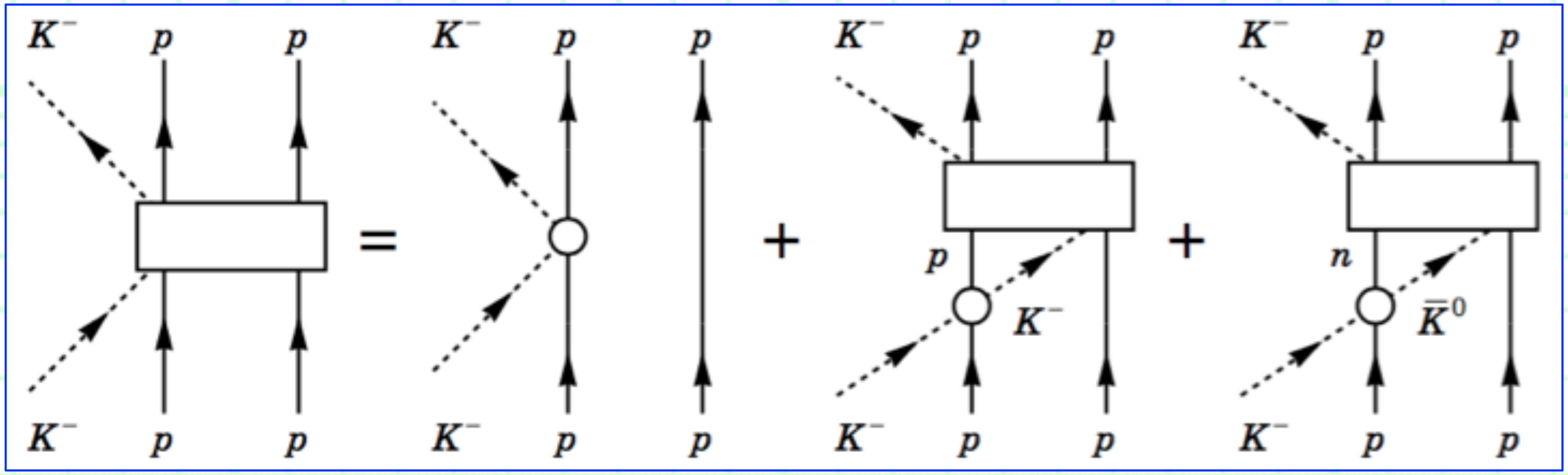
++ Scattering amplitude ++

- We have to calculate **the multiple kaon scattering with two *N*s**.

--> We employ the so-called fixed center approximation to the Faddeev equation. Bayar, Yamagata-Sekihara and Oset, *Phys. Rev.* C84 (2011) 015209.

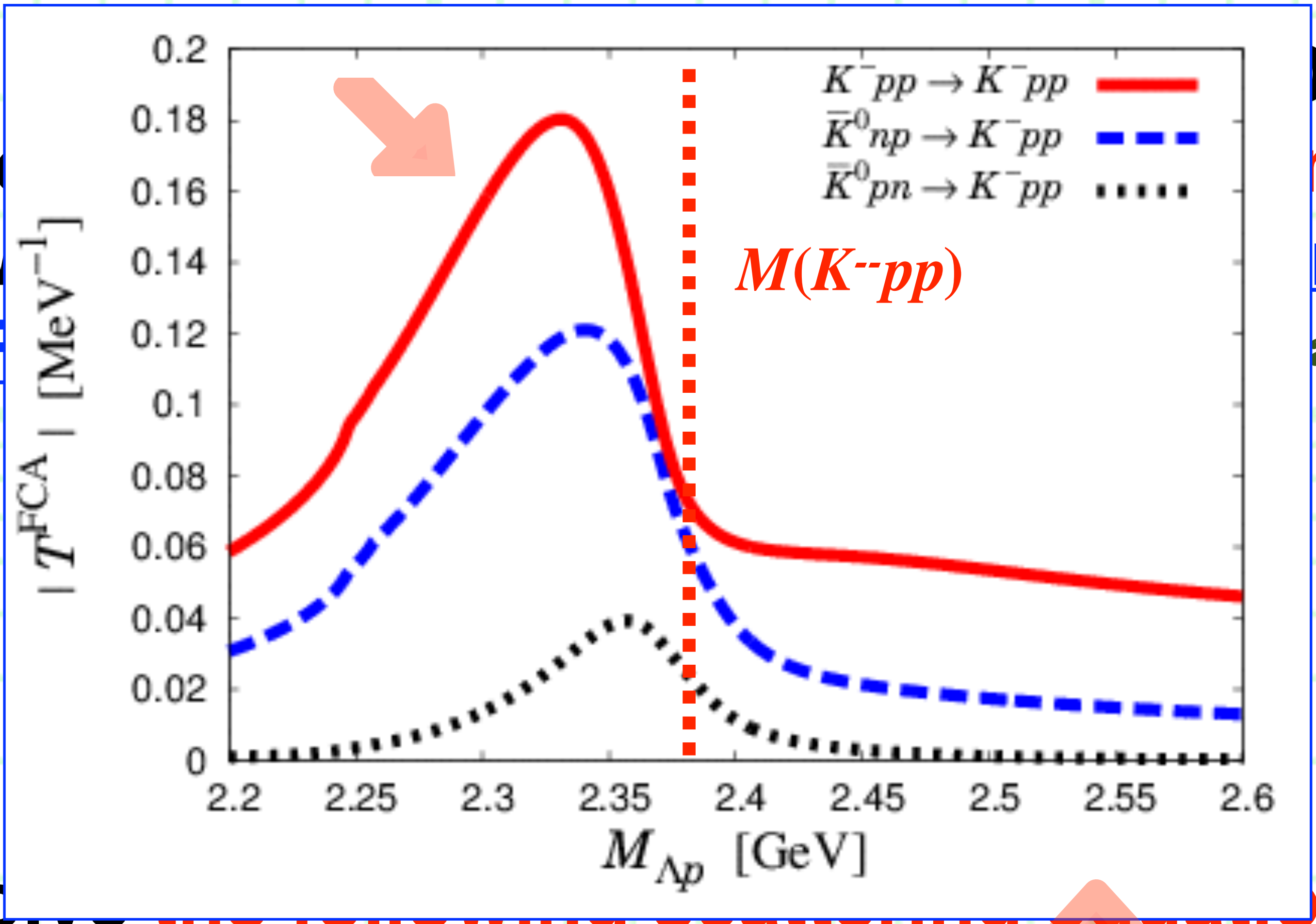


- Solve **the following scattering equation** with a "fixed center".



--- Open circle: $\bar{K}N$ --> $\bar{K}N$ amplitude in chiral unitary approach.

3. $\bar{K}NN$ bound state



litude ++

- W n scattering with two Ns.

--> V r approximation to the

F

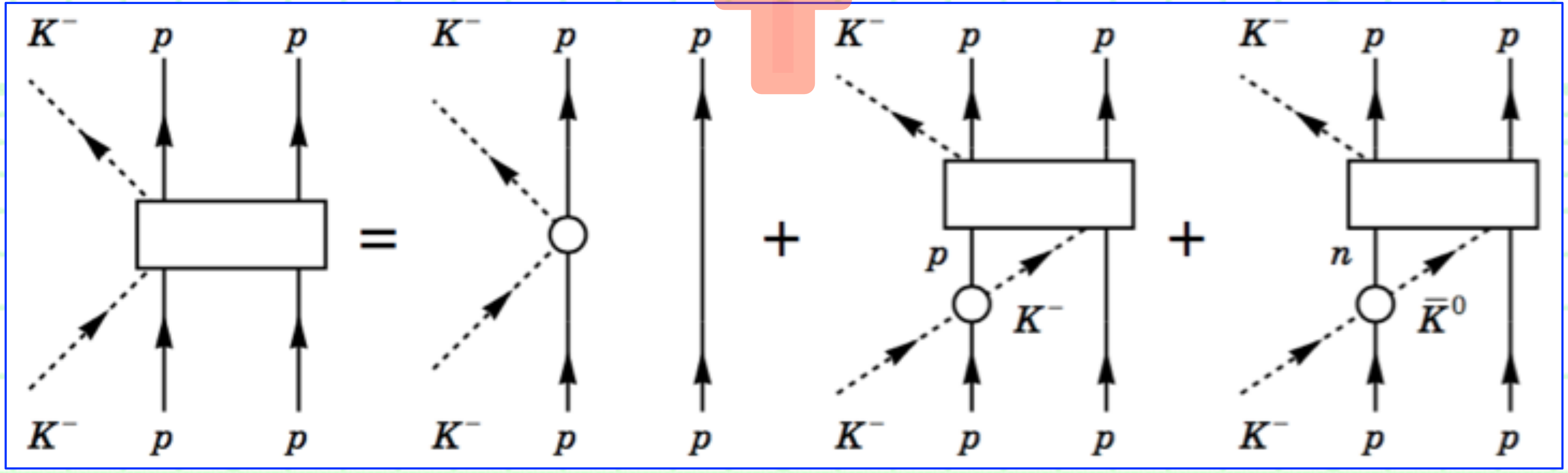
ara and Oset, *Phys. Rev.* C84 (2011) 015209.

--- FCA amplitude has a peak of $\bar{K}NN$ bound state.

--- Pole at 2354 -- 36 i MeV.

<-- $B_E \sim 15$ MeV, $\Gamma \sim 70$ MeV.

- Solve the following scattering equation with a “fixed center”.

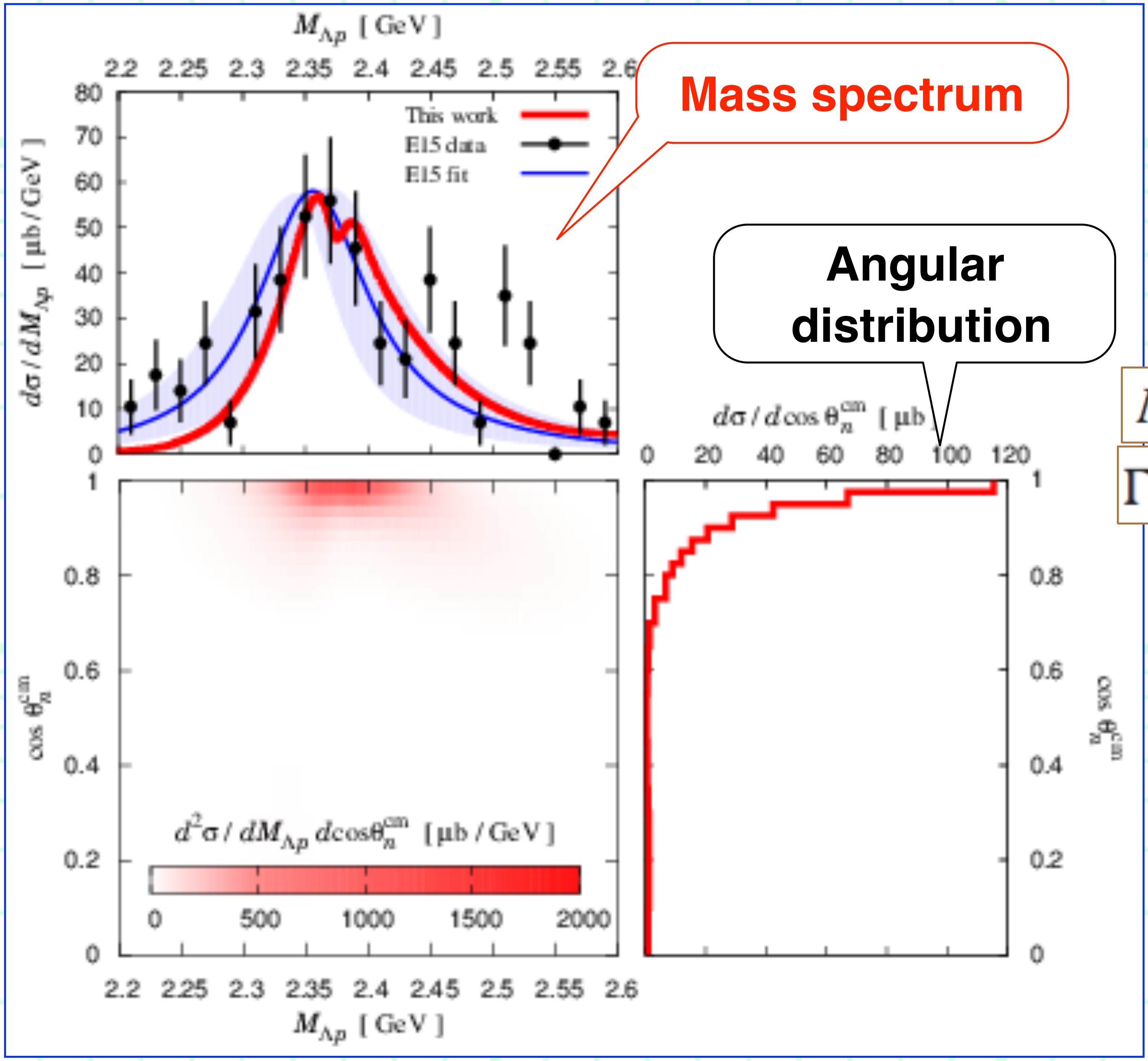


--- Open circle: $\bar{K}N \to \bar{K}N$ amplitude in chiral unitary approach.

3. $\bar{K}NN$ bound state

++ Numerical results ++

- We calculate the mass spectrum and cross section in scenario II.



Mass spectrum

Angular distribution

☐ Our mass spectrum is compared with that from Exp. analysis: Y. Sada *et al.* (2016).

$$\frac{d\sigma}{dM_{\Lambda p}} \propto p_n' p_\Lambda^* \frac{\Gamma_X^2}{(M_{\Lambda p} - M_X)^2 + \Gamma_X^2/4}$$

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

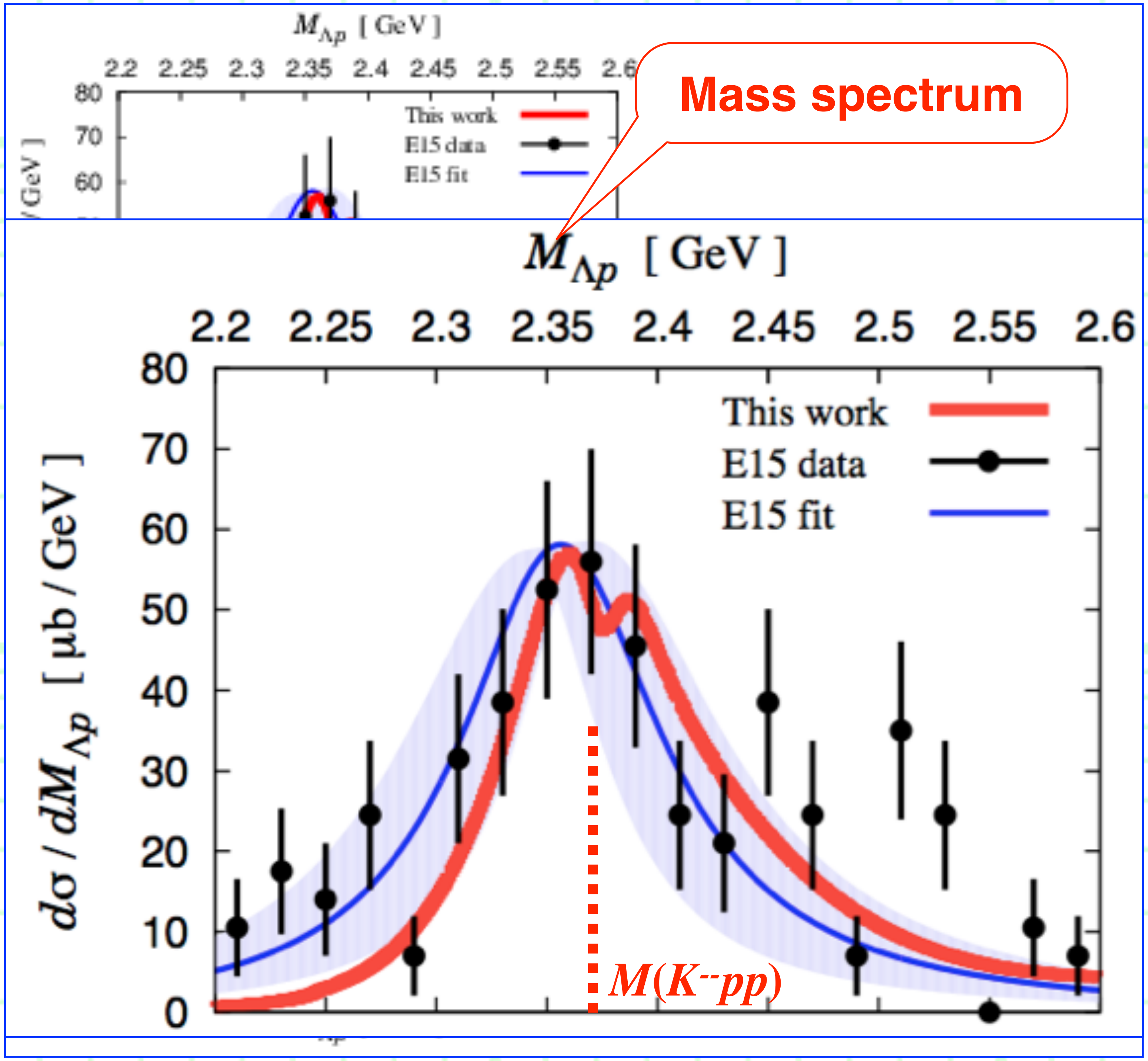
$$\Gamma_X = 110^{+19}_{-17}\ (\text{stat.}) \pm 27\ (\text{syst.})\ \text{MeV}/c^2,$$

<-- Shown in blue line / band, but in arbitrary units.

3. $\bar{K}NN$ bound state

++ Numerical results ++

- **We calculate the mass spectrum and cross section in scenario II.**



Mass spectrum

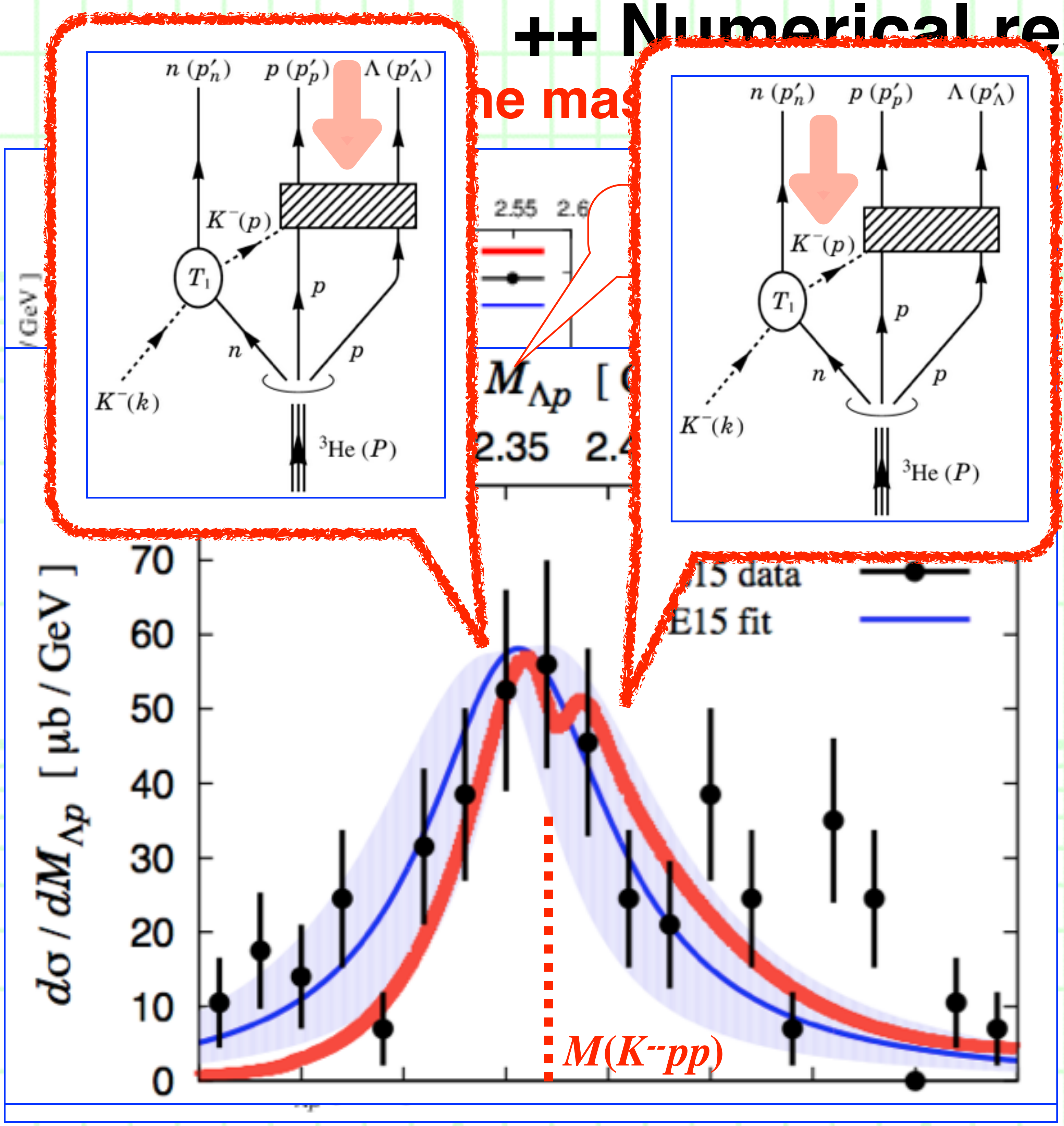
☐ **Our mass spectrum is consistent with the Exp. within the present errors.**
--- Reproduce the tail at lower energy ~ 2.3 GeV.

☐ **Therefore, our spectrum supports the explanation that the E15 signal in the ^{3}He $(K^-, \Lambda p)\, n$ reaction is indeed a signal of the $\bar{K}NN$ bound state.**

3. $\bar{K}NN$ bound state

++ Numerical results ++

he mas cross section in scenario II.



☐ One more thing:
Our spectrum has
a "double peak" structure
around the $\bar{K}NN$ threshold.

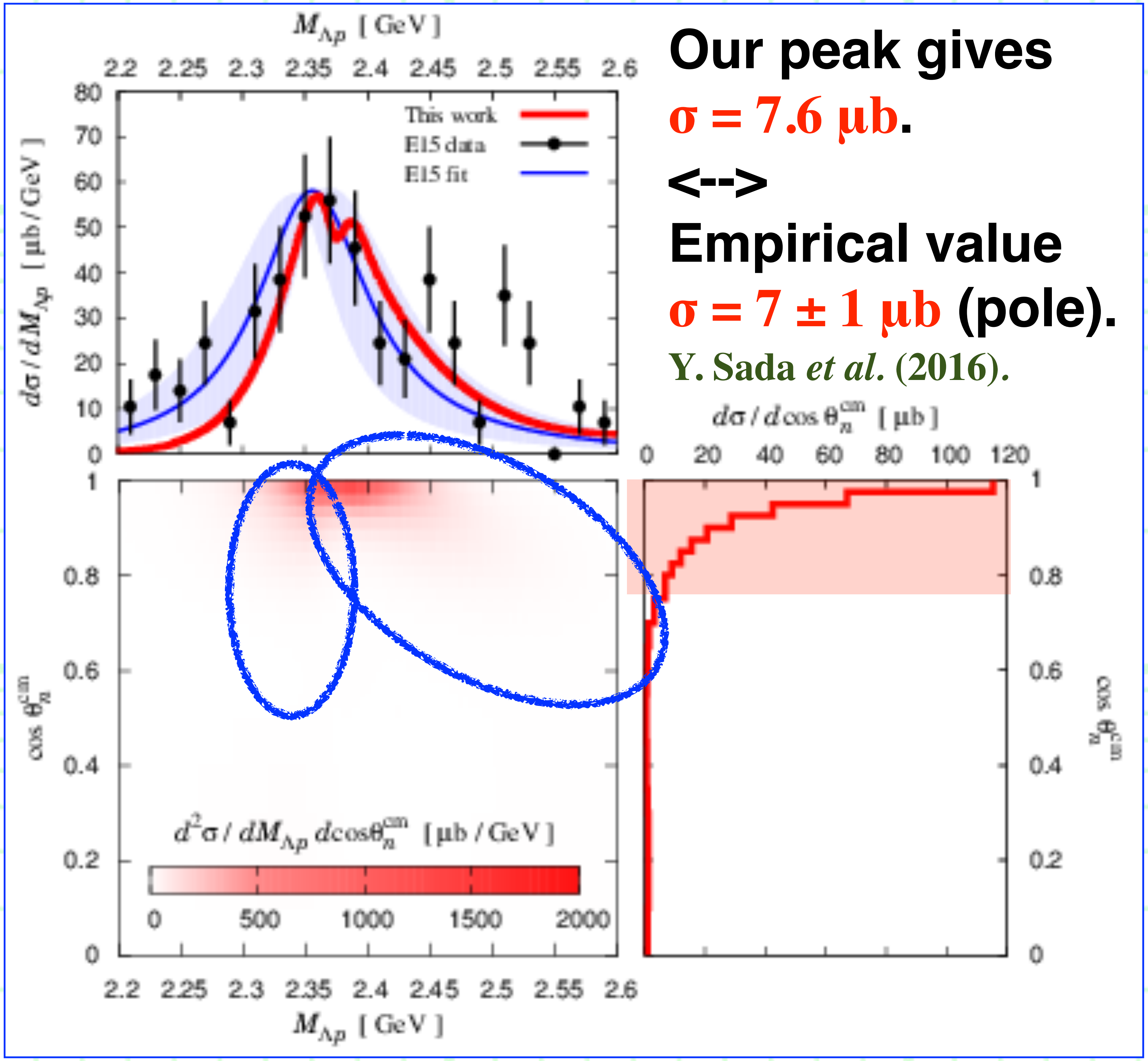
--- The lower peak is the signal of the $\bar{K}NN$ bound state.

--- The higher peak comes from the quasi-elastic kaon scattering in the first step.

<-- Almost on-shell kaon.

3. $\bar{K}NN$ bound state

++ Numerical results ++



Our peak gives
$\sigma = 7.6$ μb.
<-->
Empirical value
$\sigma = 7 \pm 1$ μb (pole).
Y. Sada *et al.* (2016).

- □ **There are two "bands" in $d^2\sigma/dM_{\Lambda p}d\cos\theta_n$.**

--- One is the signal of the $\bar{K}NN$ bound state.

--- The other comes from the quasi-elastic kaon scattering in the first step.

- □ **Diff. cross section $d\sigma/d\cos\theta_n$ again indicates forward neutron emission is favored.**

4. Summary

- We have investigated the origin of the peak structure near the $\bar{K}NN$ threshold in the ^{3}He $(K^-, \Lambda p)$ n reaction observed by J-PARC E15.

--- We have considered 2 scenarios to create the peak.

- ☐ Uncorrelated $\Lambda(1405)p$, which does not make a bound state.
- ☐ $\bar{K}NN$ bound state.

- As a result, we have found that the experimental signal is qualitatively well reproduced by the assumption that a $\bar{K}NN$ bound state is generated in the reaction, while we have discarded the interpretation in terms of an uncorrelated $\Lambda(1405)p$ state.

- Outlook: we must "prove" the E15 peak is indeed the $\bar{K}NN$ signal.

--- We need to check consistency between experiments and theories for various quantities.

- ☐ High statistics data from Exp. & More precise calc. from theory.
- ☐ Angular dependence of the peak structure.
- ☐ Branching ratio Λp / $\Sigma^0 p$.
- ☐ ...

Thank you very much for your kind attention !