On the structure observed in the in-flight ^{3}He(K^{-} , Λp)n reaction at J-PARC

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(Japan Atomic Energy Agency)

in collaboration with

Eulogio OSET (Valencia Univ.)
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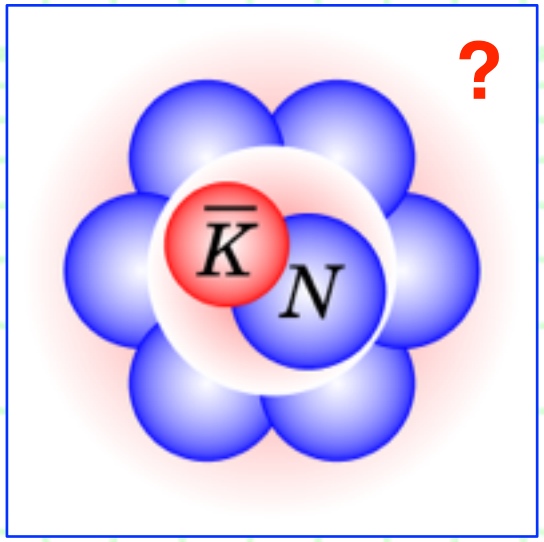
[1] T. S. , E. Oset and A. Ramos, *PTEP* 2016 123D03; *JPS Conf. Proc.* 13 (2017) 020002.

1. Introduction

++ Hadron-nucleus bound states ++

- Some hadrons rather than nucleon are expected to be bound with usual nucleus by strong interaction between them.
  - □ Λ hyper nuclei. --- Existence is established.
  - □ How about other possibilities ? (*e.g.* Mesic nuclei)
  - □ Kaonic nuclei ??? <-- Really exist or not ?

- Motivations of studying the hadron-nucleus bound states.
  1. Exotic state of many-body systems in strong interaction.
  --- Inter-hadron interaction, many-body theory, ...
  2. Probe physics of the strong interaction in finite nuclear density.



Kaonic nuclei

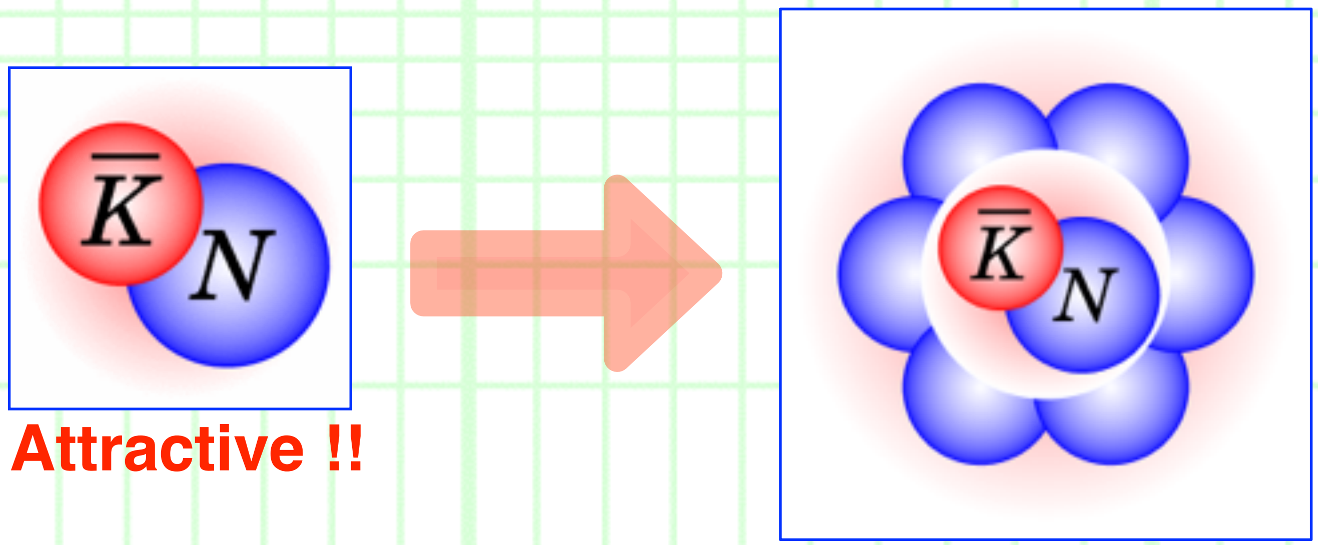
1. Introduction

++ Kaonic nuclei ++

- We expect that **kaonic nuclei should exist**, which are bound states of $\bar{K}$ and nuclei via strong interaction between them.
  - □ Because $\bar{K}$-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.

1. Exotic state of many-body systems in strong interaction.
2. Kaons 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:

    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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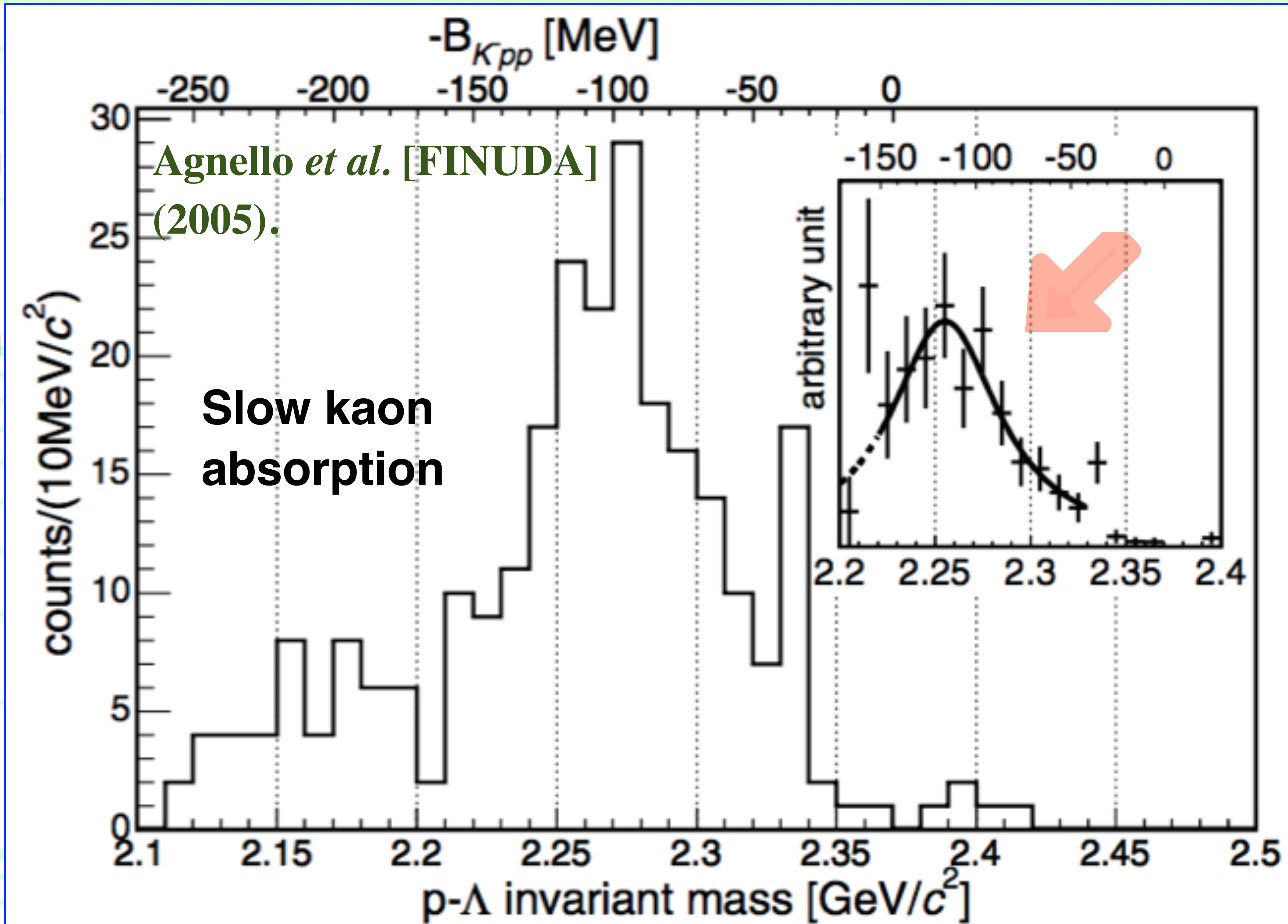

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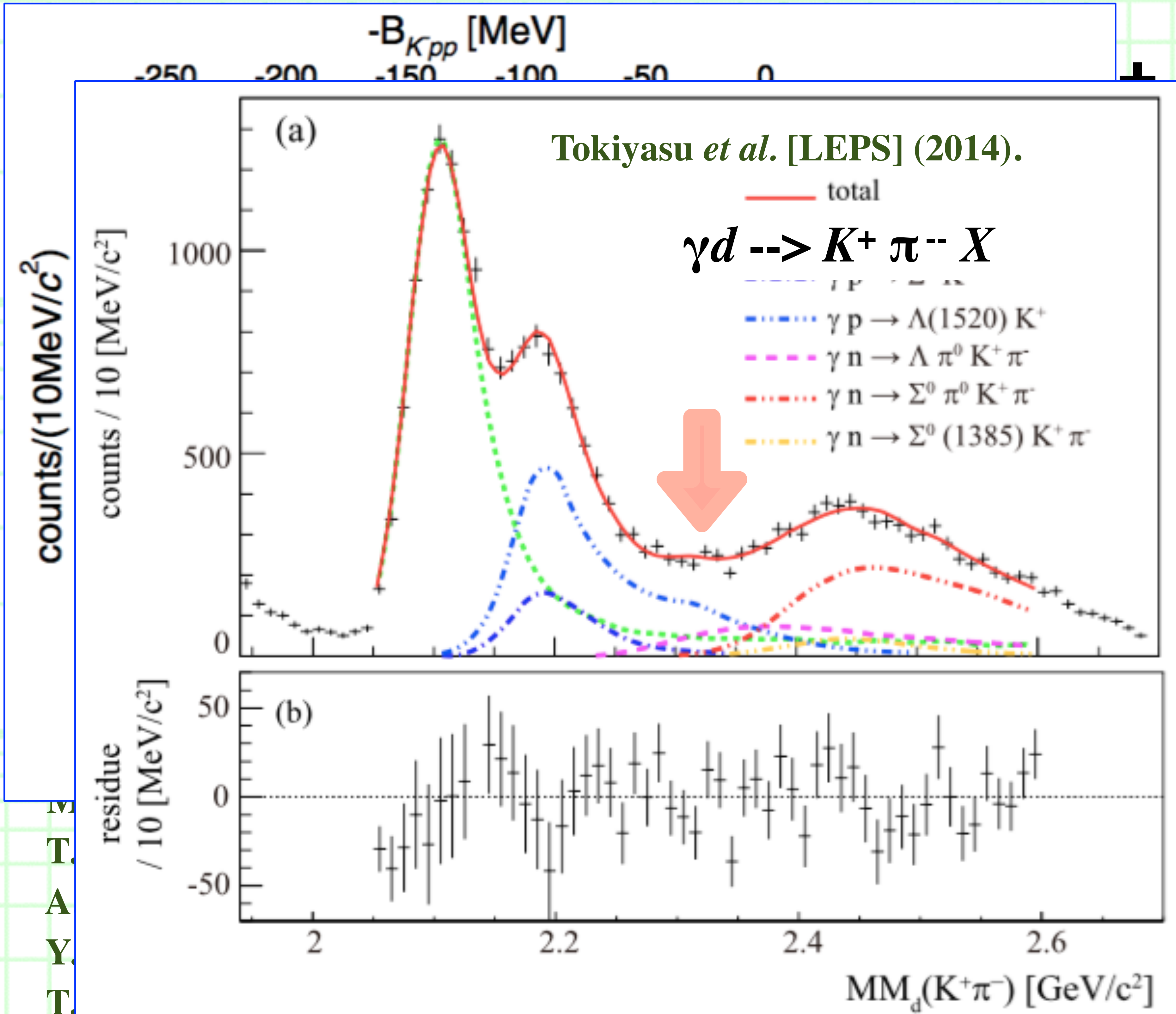

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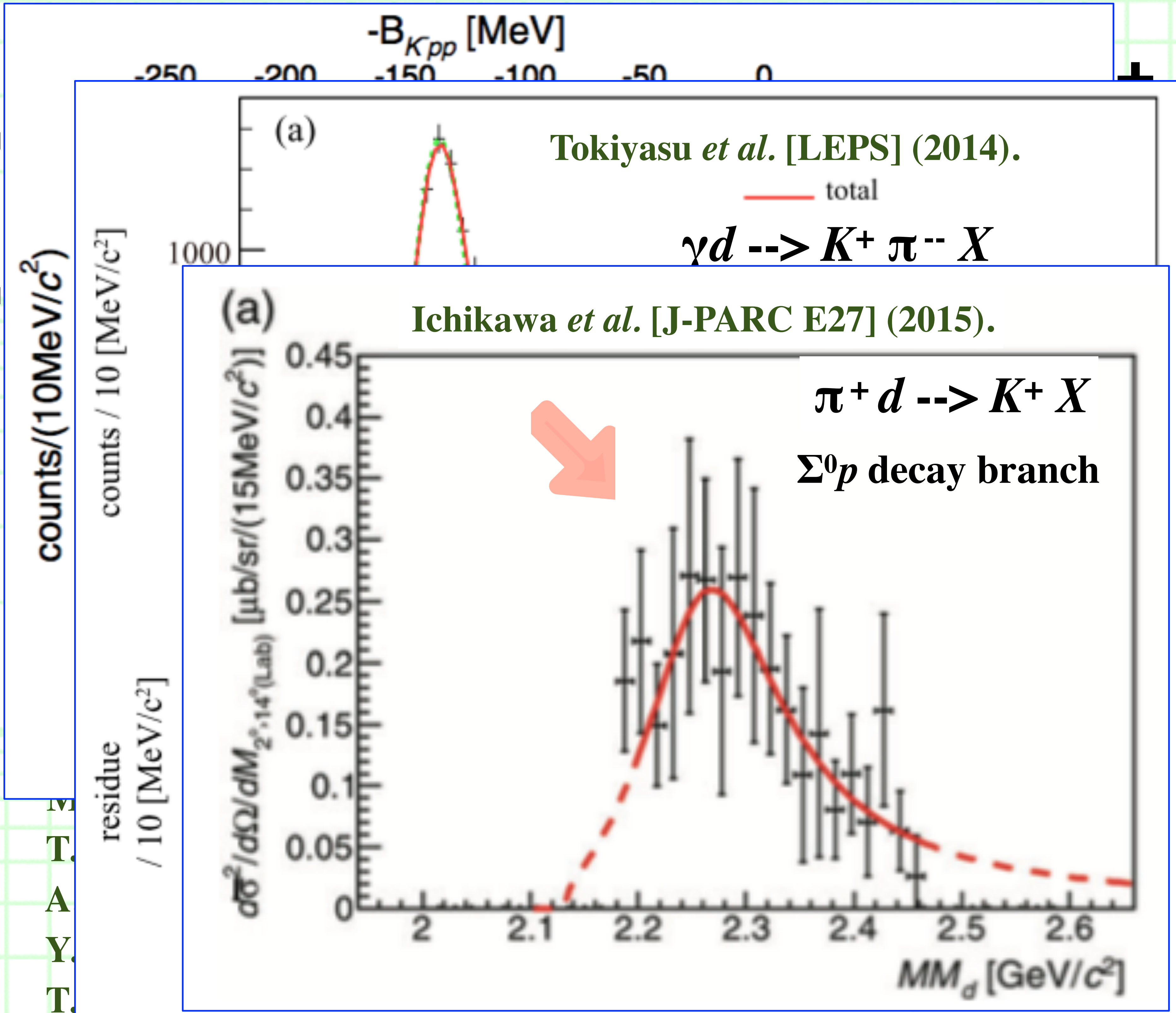

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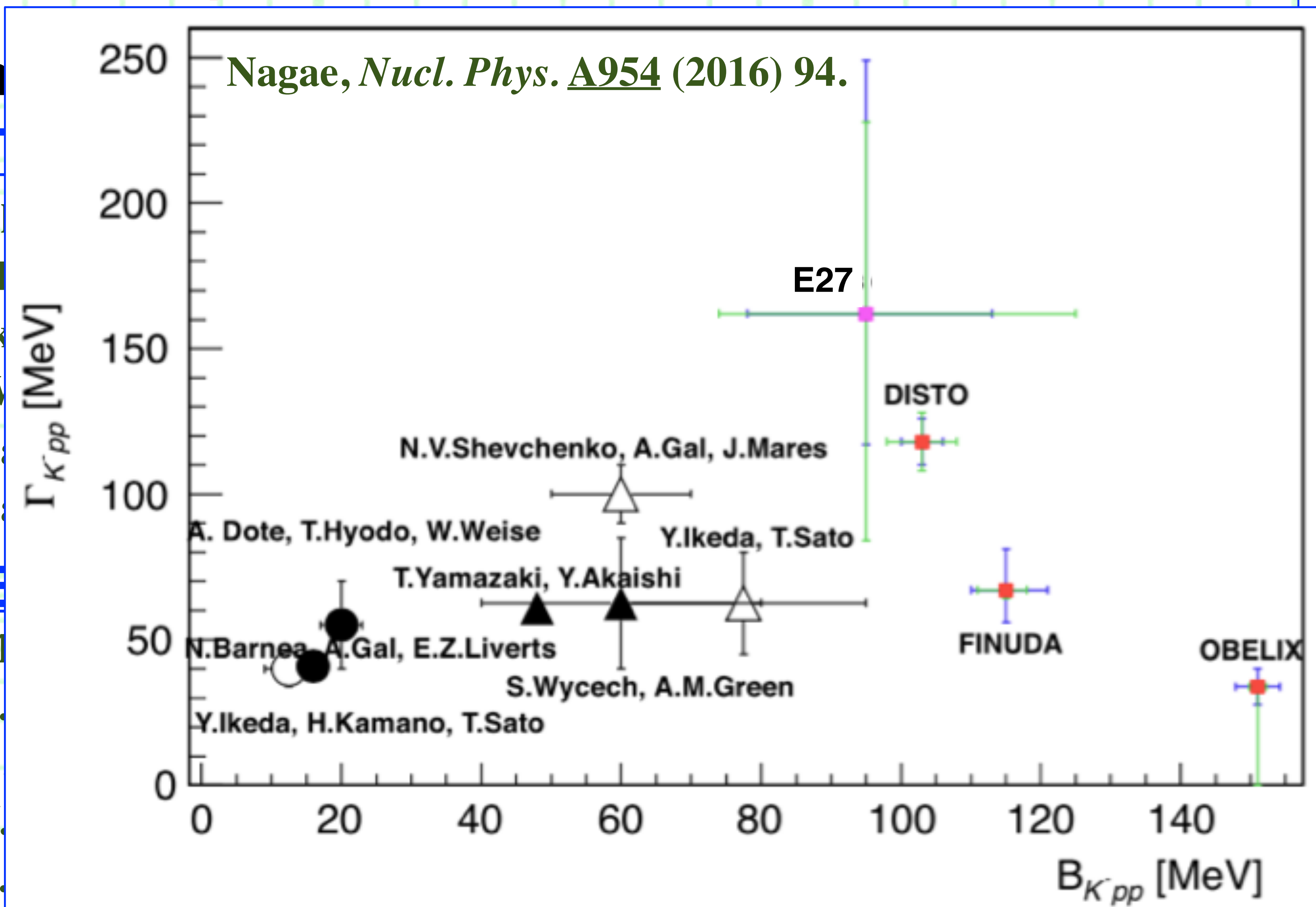

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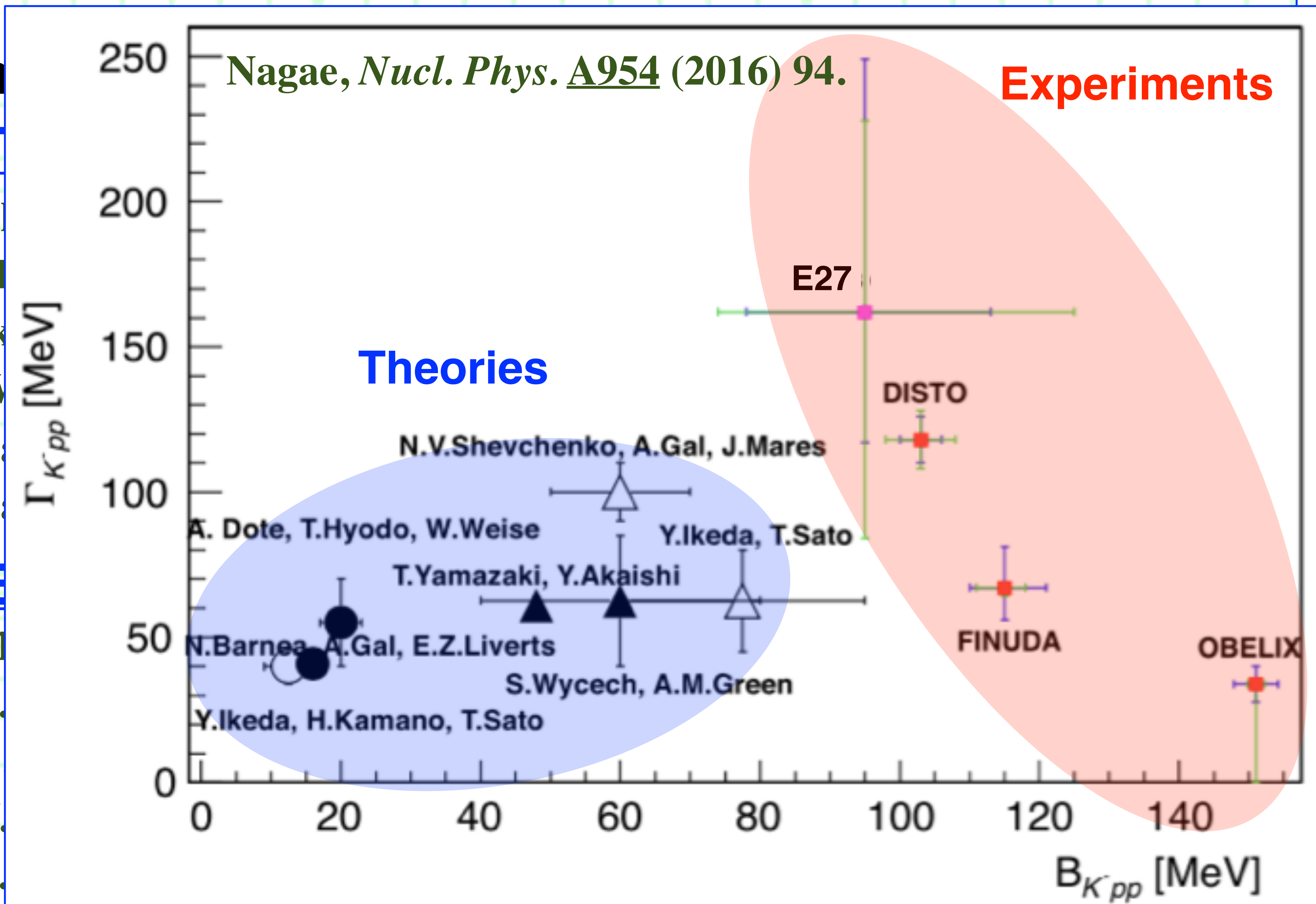

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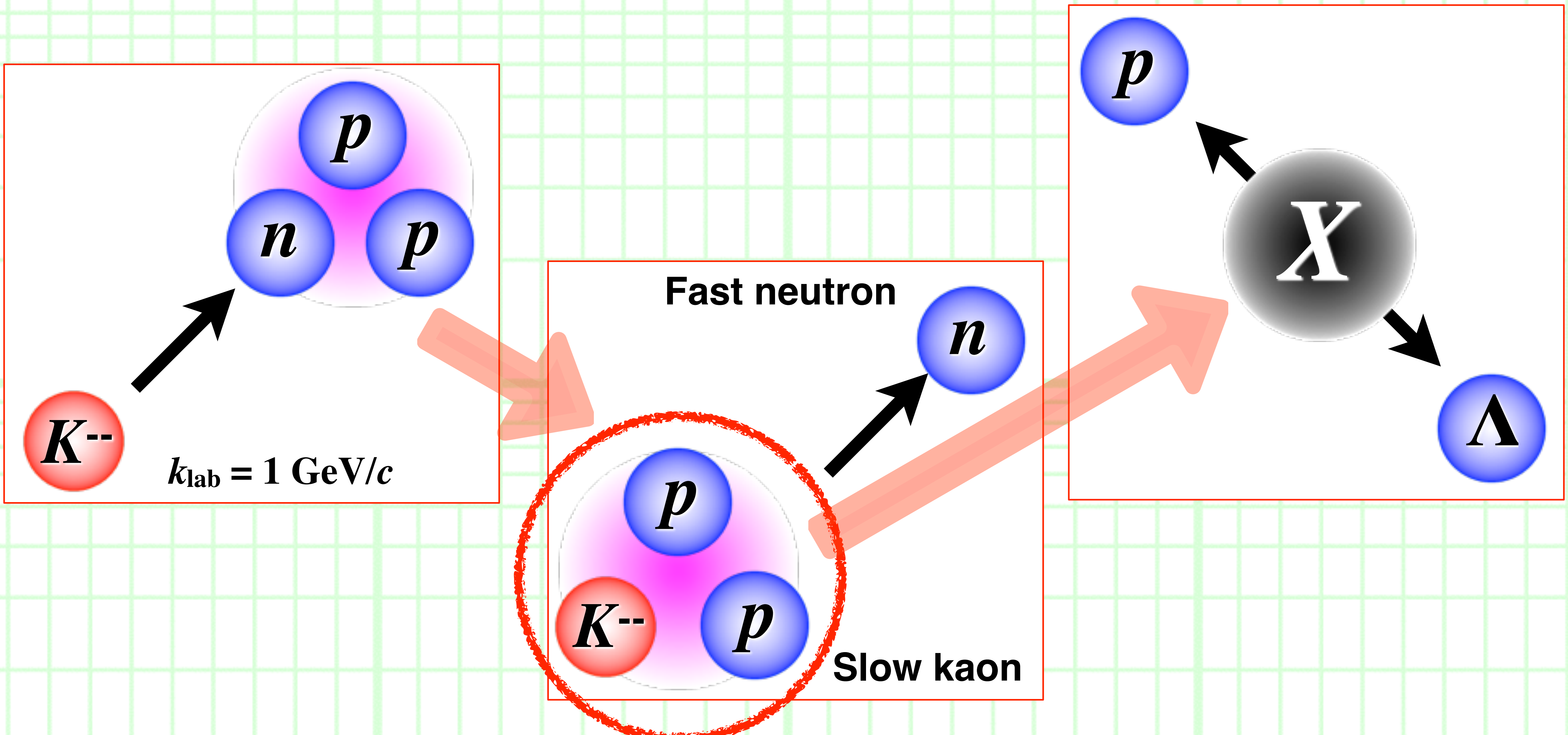
1. Introduction

++ 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^- , Λp) n reaction.**

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

- **Reaction mechanism:**



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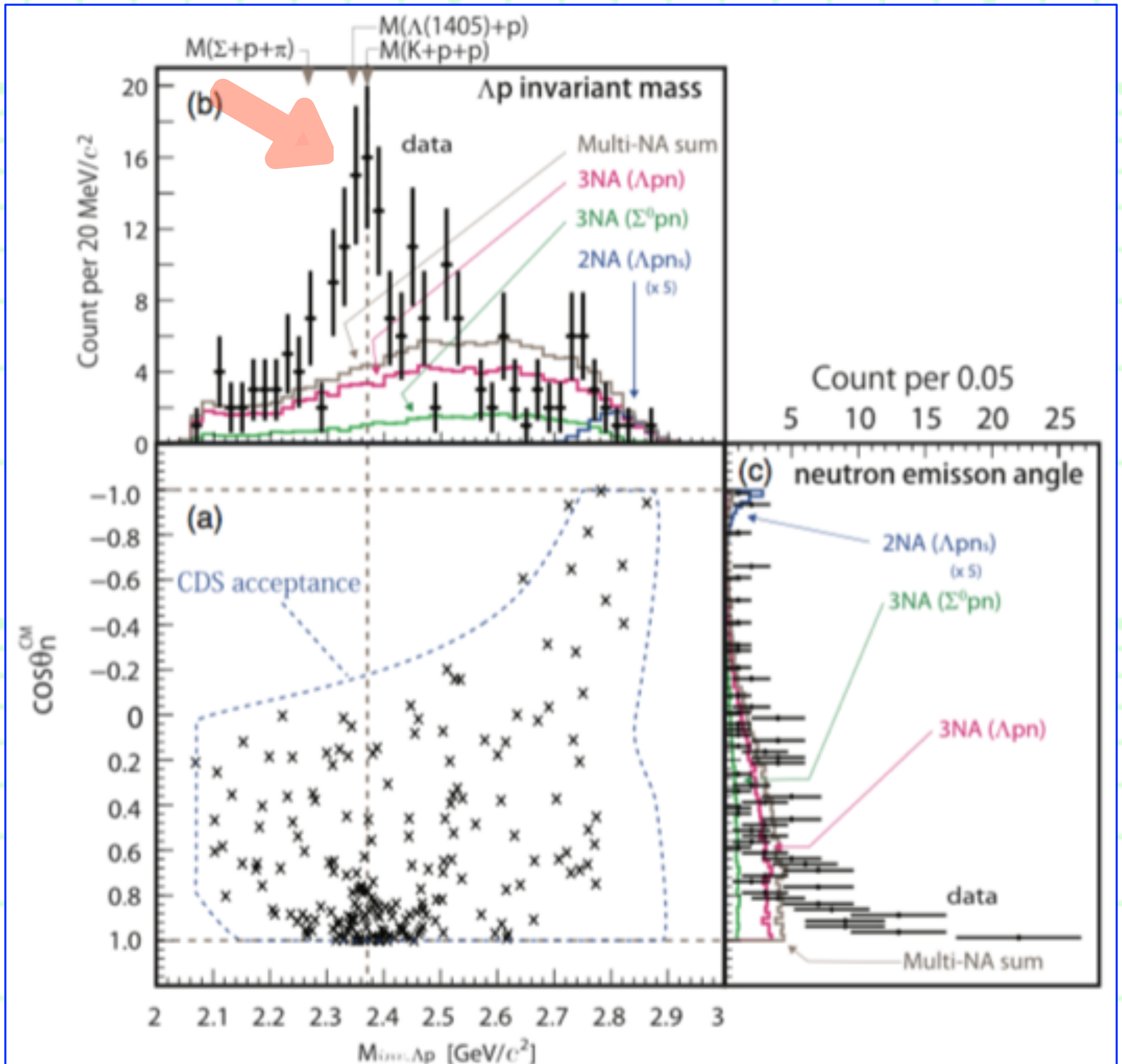

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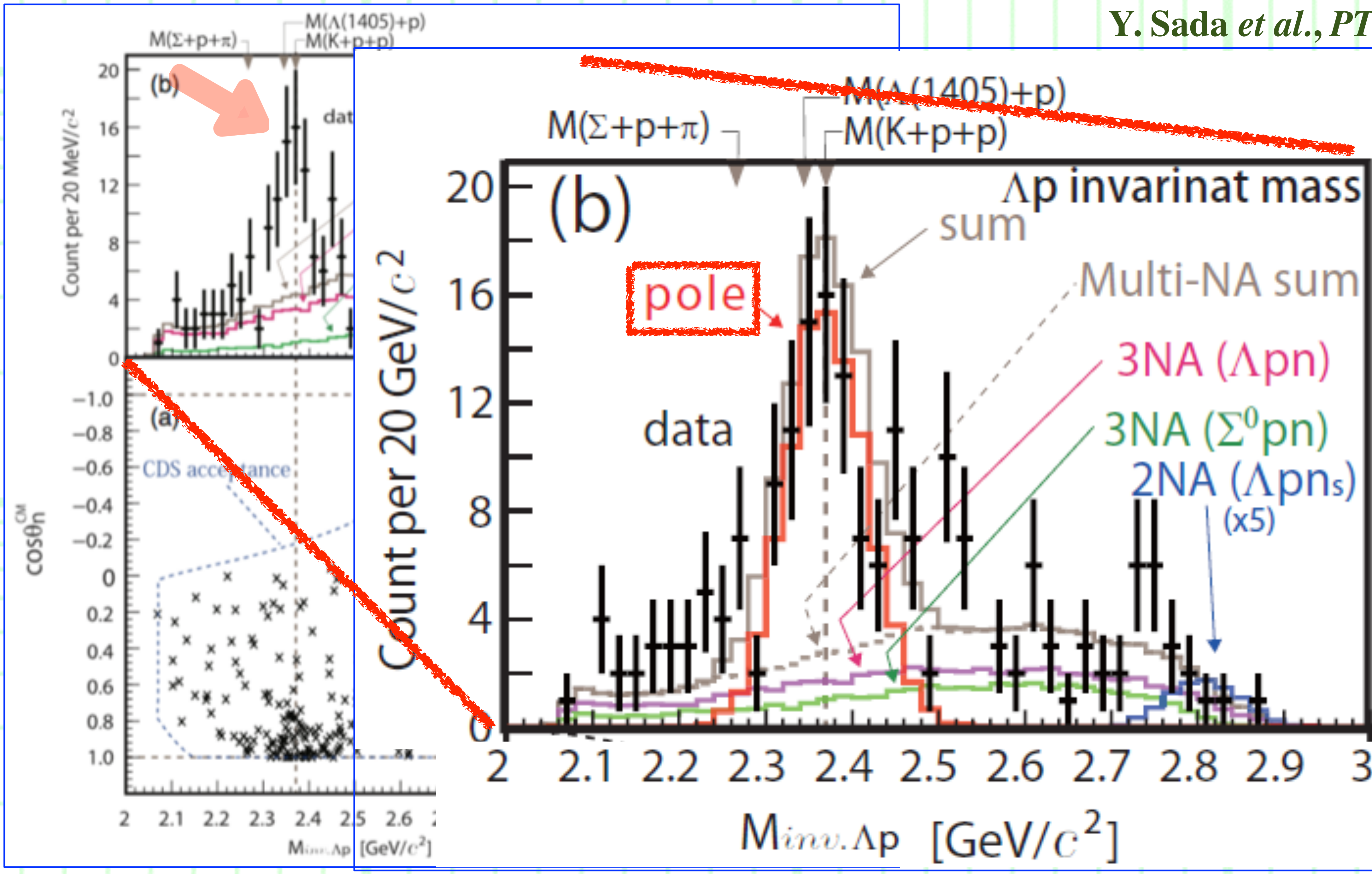

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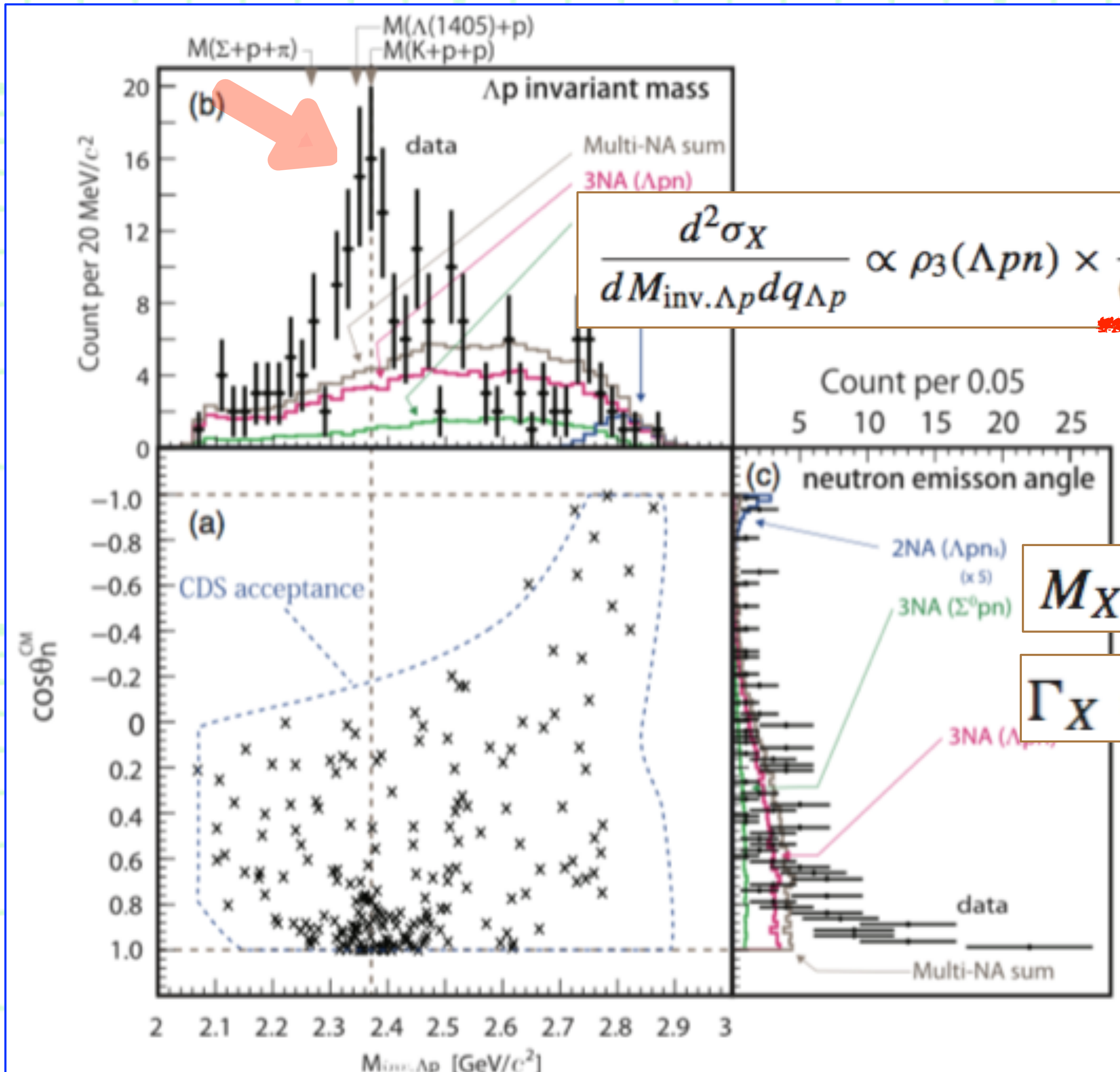


□ Fitted by Breit-Wigner form:

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

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

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

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

□ What is this peak ???

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

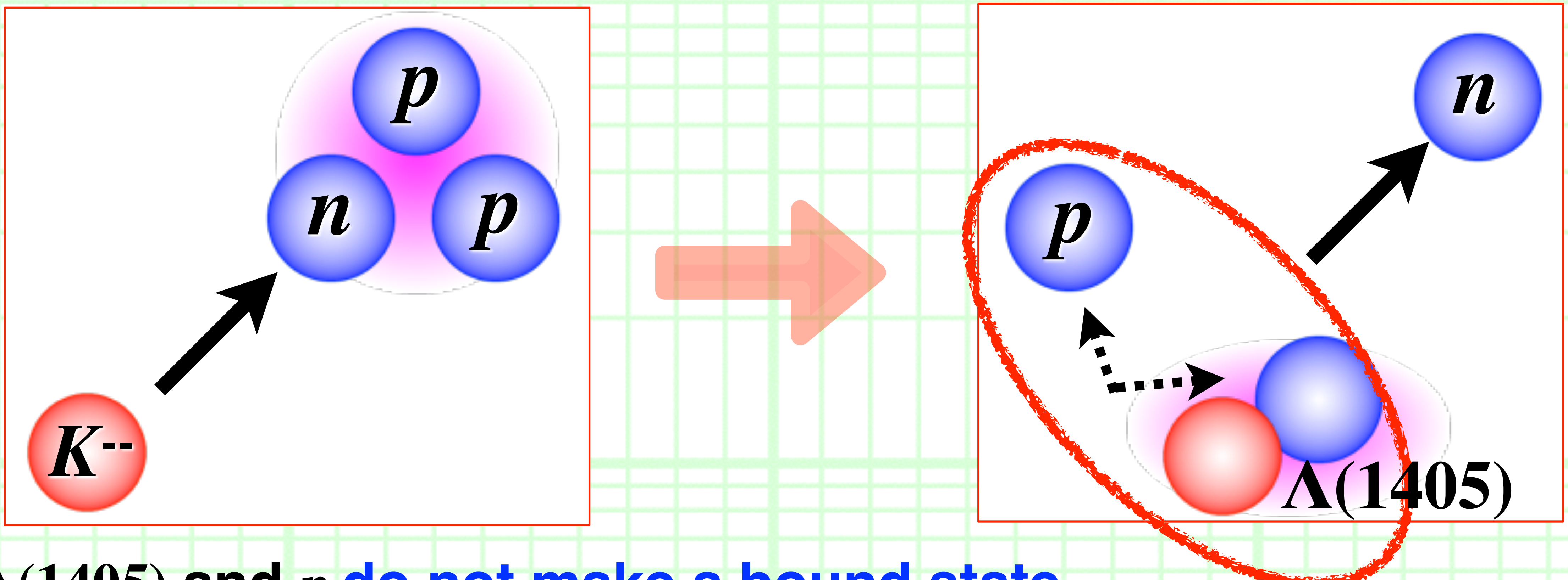
1. Introduction

++ 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 $\Lambda(1405)p$.



--- $\Lambda(1405)$ and p do not make a bound state.

--- The $\Lambda(1405)p$ system makes conversion to Λp.

- 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.

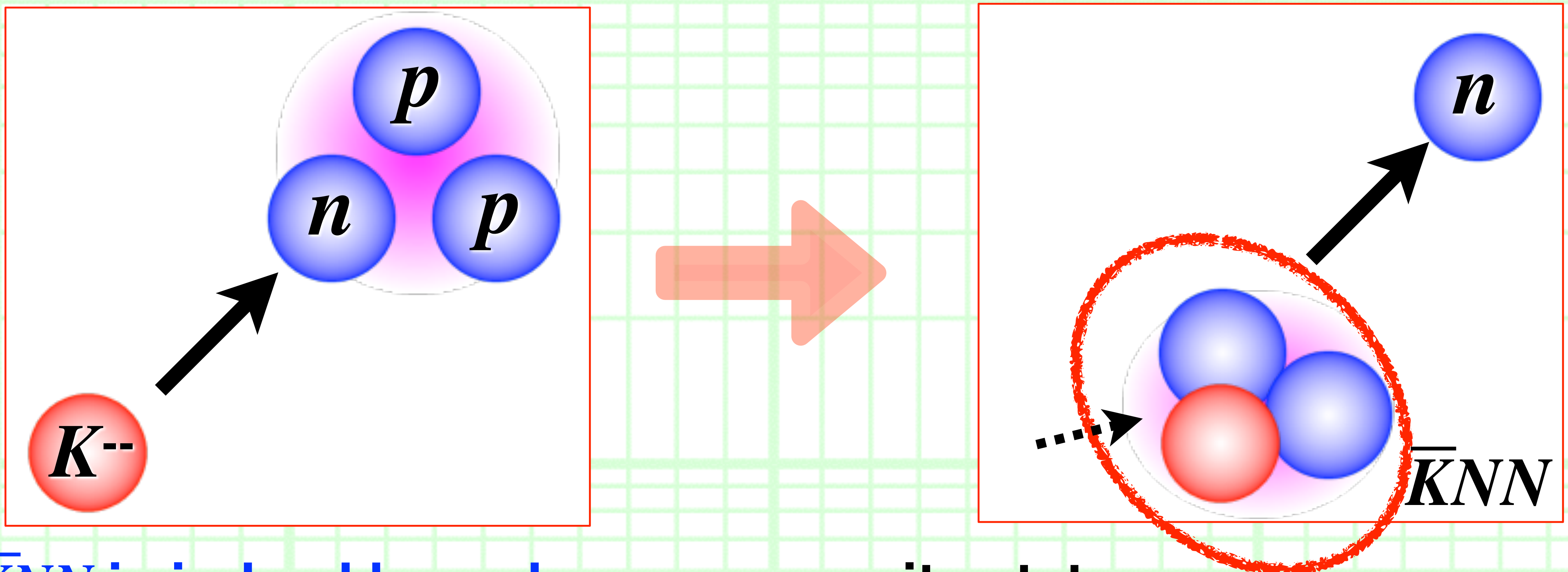
1. Introduction

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



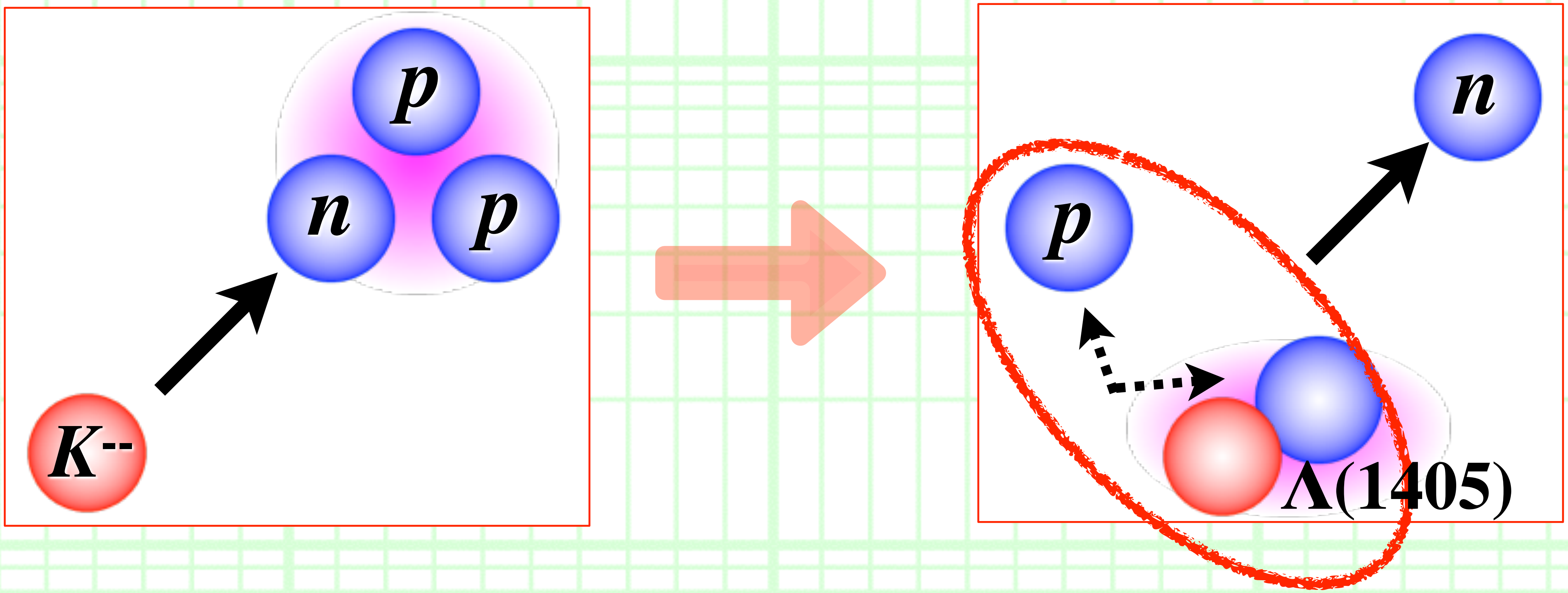
--- $\bar{K}NN$ is indeed bound as a composite state after the fast neutron emission.

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

2. Uncorrelated Λ(1405) *p*

++ Reaction mechanism ++

- Scenario I: Uncorrelated Λ(1405)*p*.
  This system may create a peak in the Λ*p* mass spectrum.

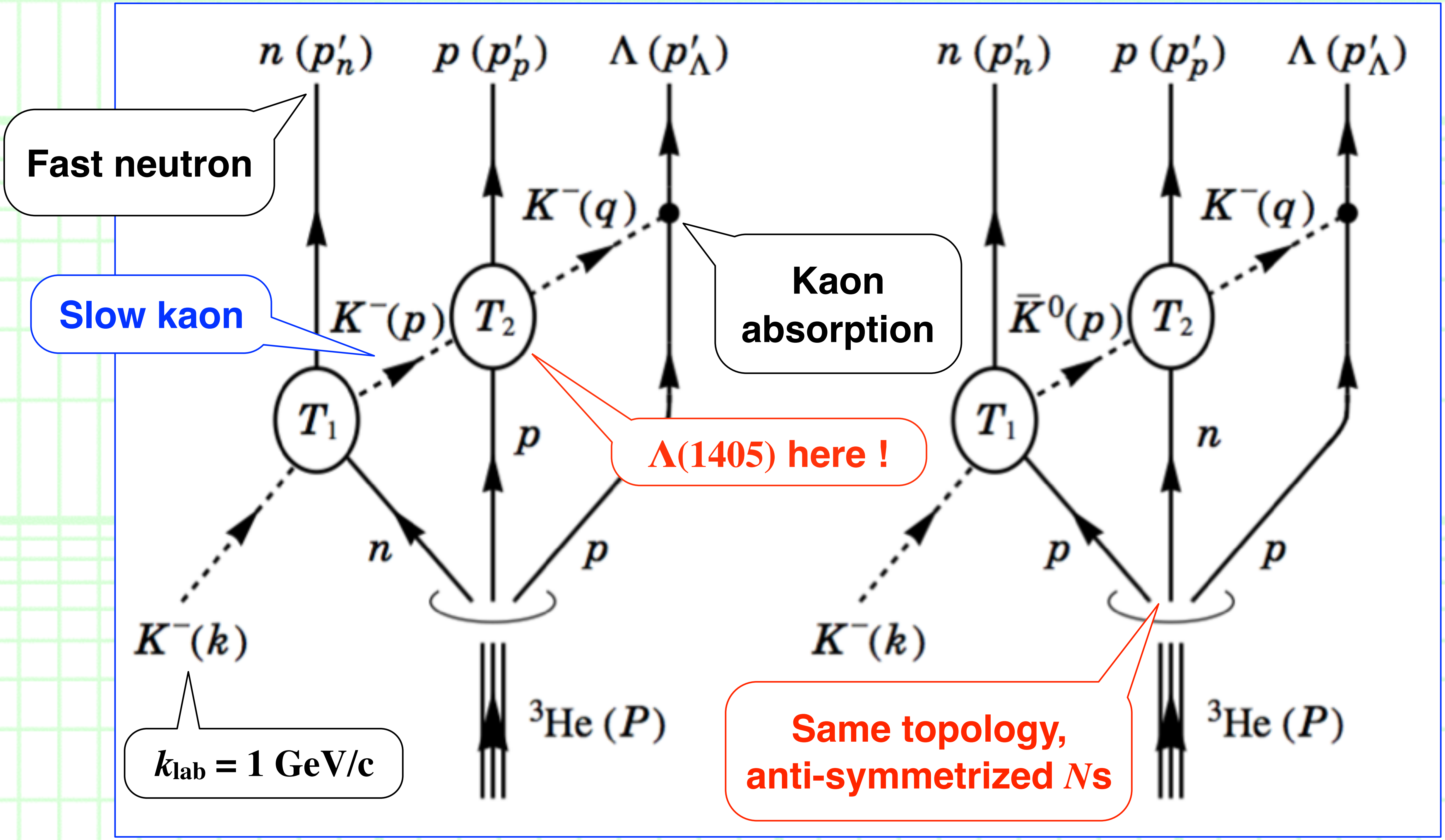


- Because Λ(1405) exists below the $\bar{K}N$ threshold, the uncorrelated Λ(1405)*p* system may create a peak even they do not bound.

2. Uncorrelated Λ(1405) *p*

++ Scattering amplitude ++

- For this process, we use the following diagrams:



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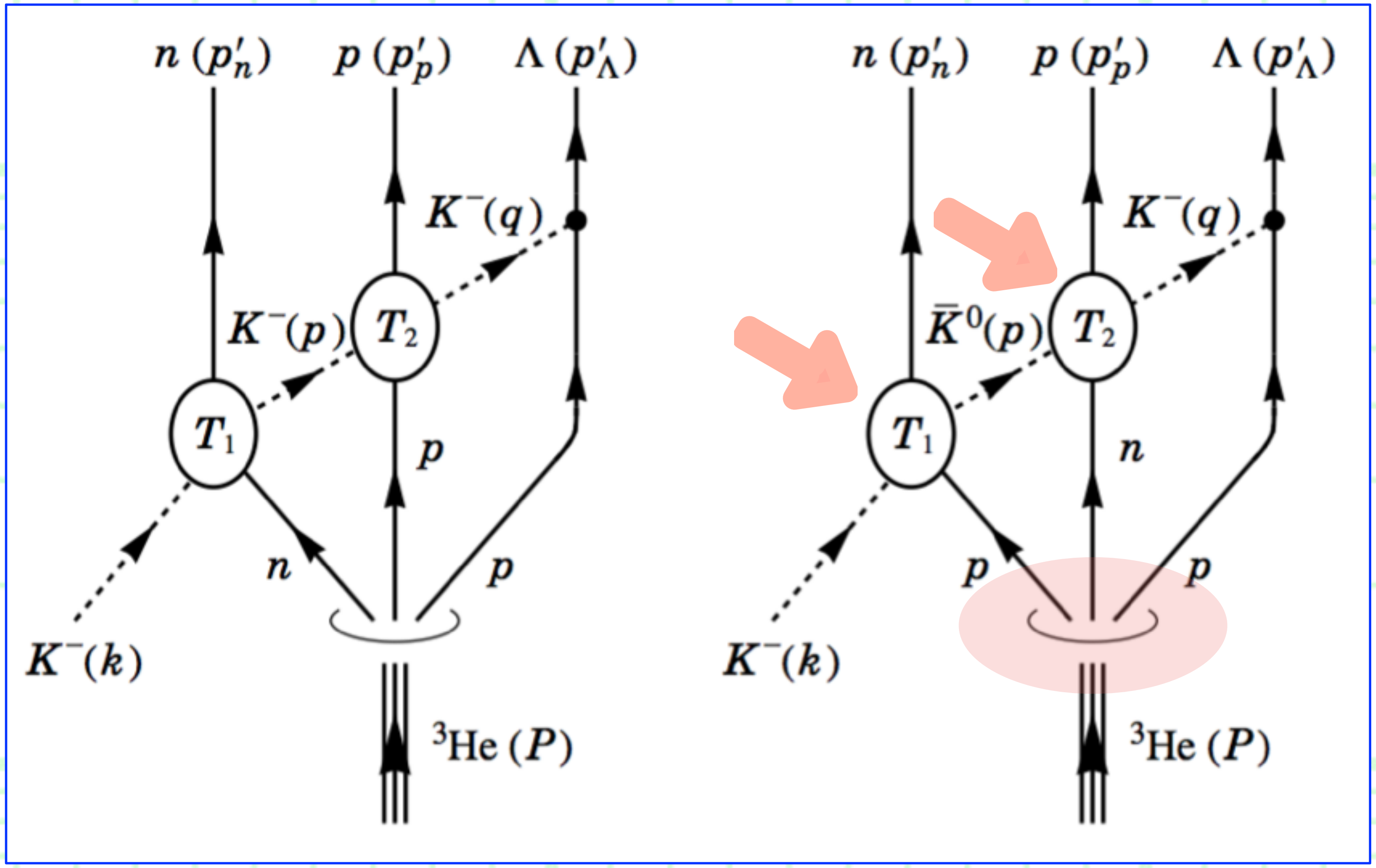


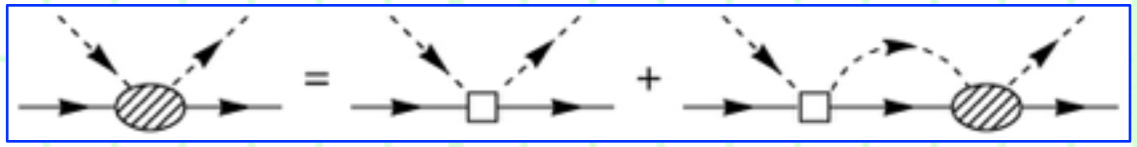
- The ^{3}He wave function is obtained as the anti-symmetrized 3 nucleons in the harmonic oscillator potential.
- Amplitude T_1 (k=1 GeV/c):

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

--- 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 Λ(1405) p

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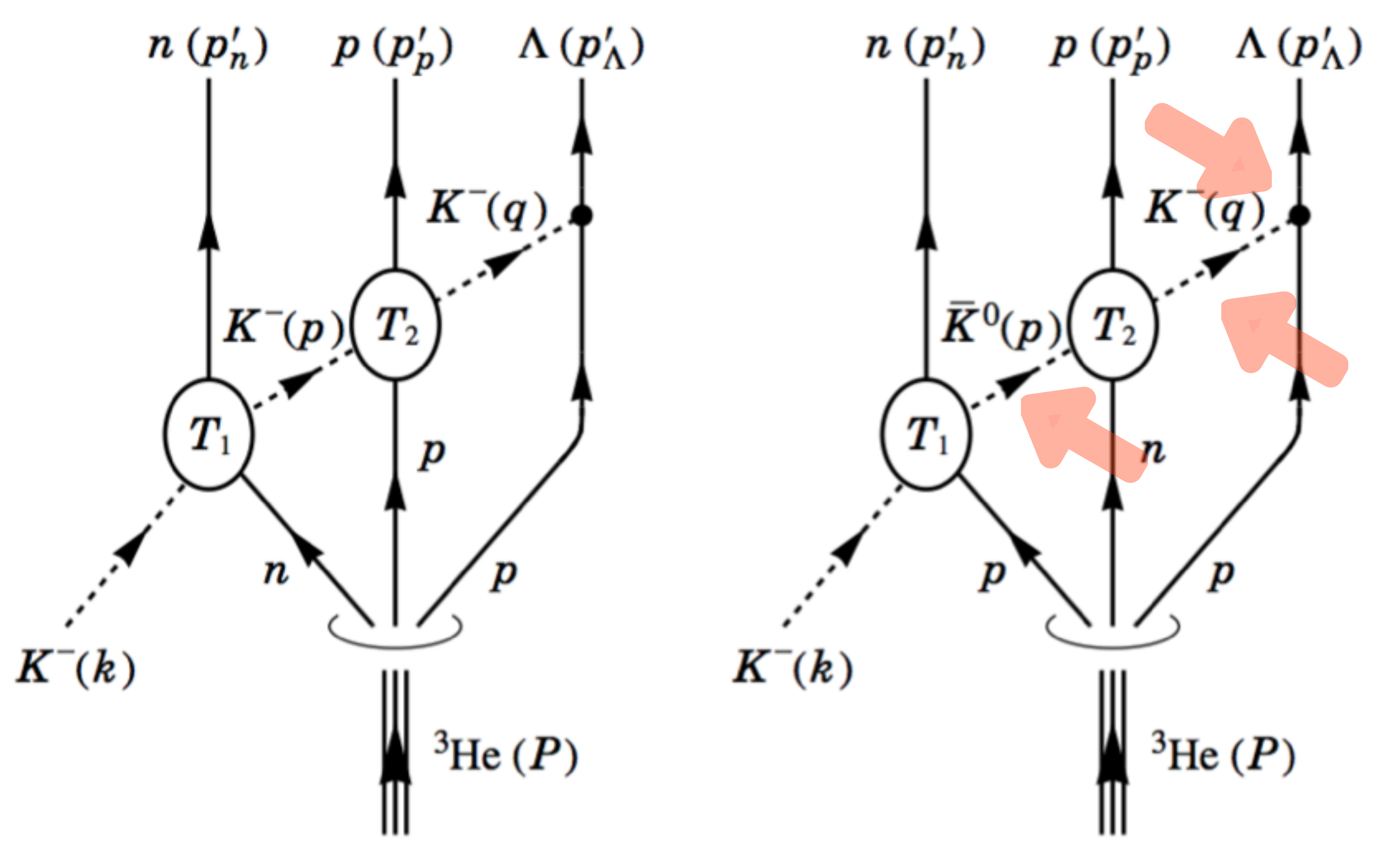


- □ The $K^-p\Lambda$ vertex is taken from chiral Lagrangian x phenomenological FF.
- □ The intermediate kaon energy is fixed as:

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

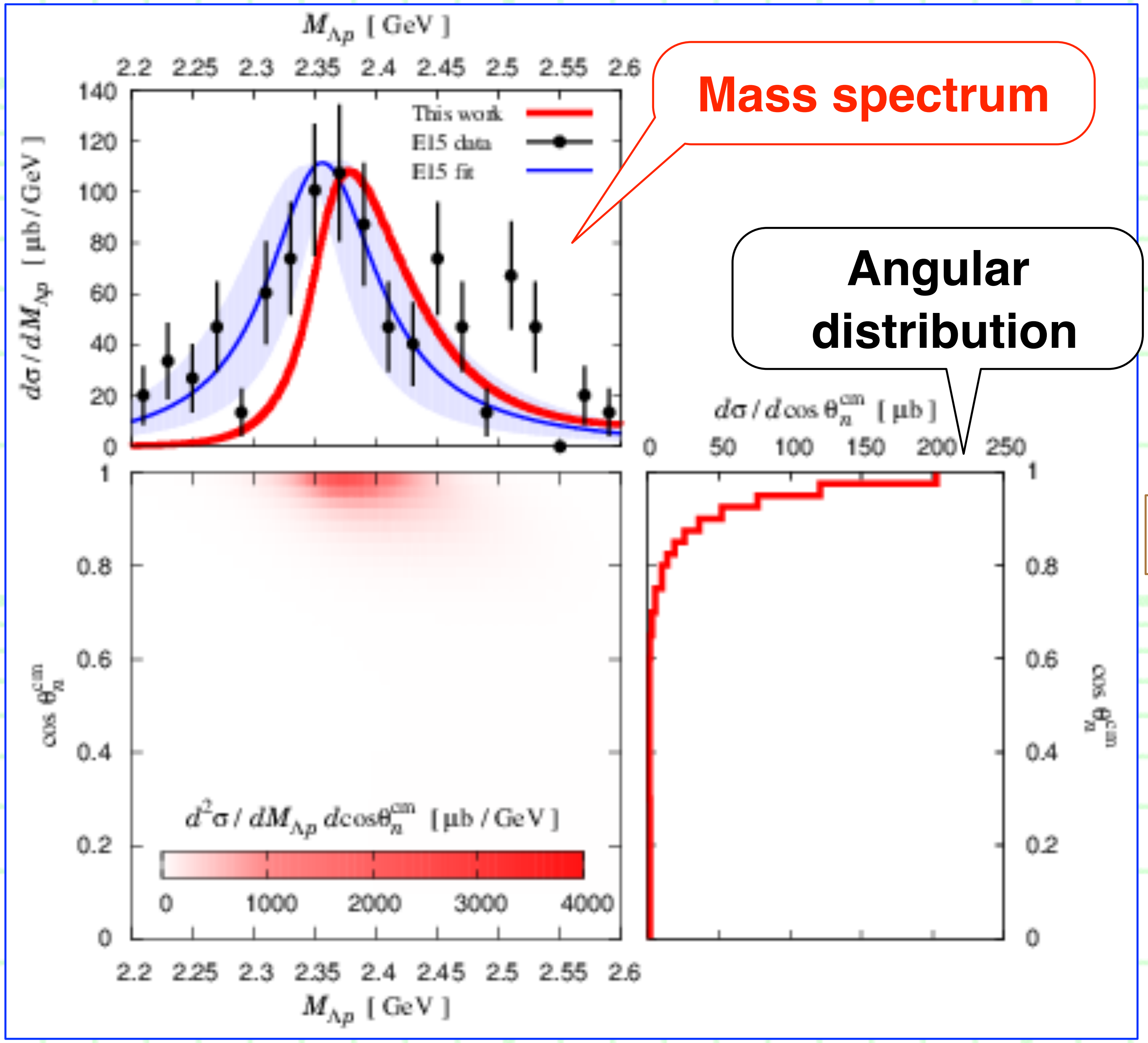
$$p^0 = p'^0_\Lambda + p'^0_p - 2\left(m_N - \frac{B_{^3\mathrm{He}}}{3} \right)$$

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.



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

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

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

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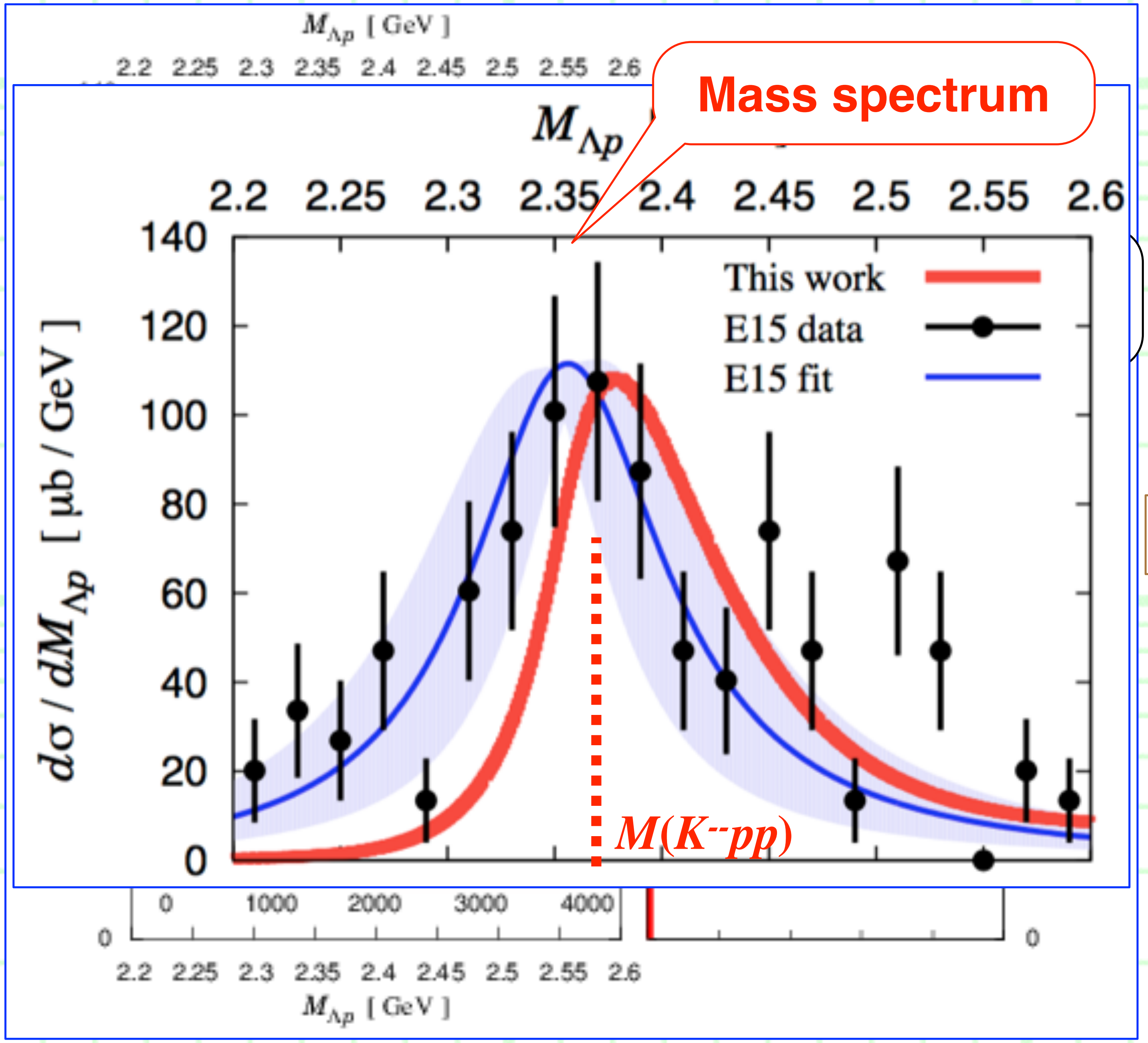
<-- Shown in blue line / band, but in arbitrary units.

2. Uncorrelated Λ(1405) p

++ Numerical results ++

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



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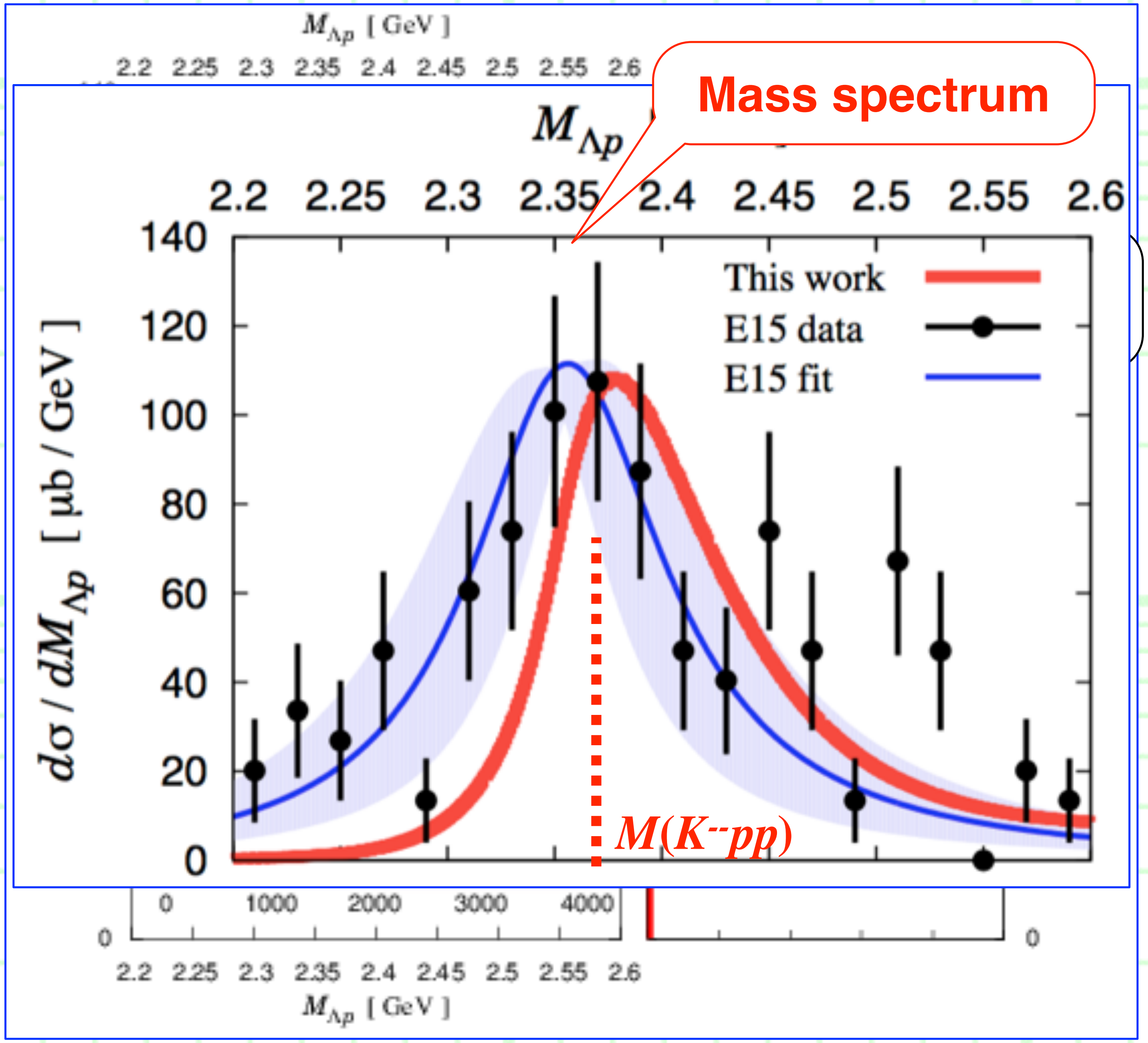
2. Uncorrelated Λ(1405) *p*

++ Numerical results ++

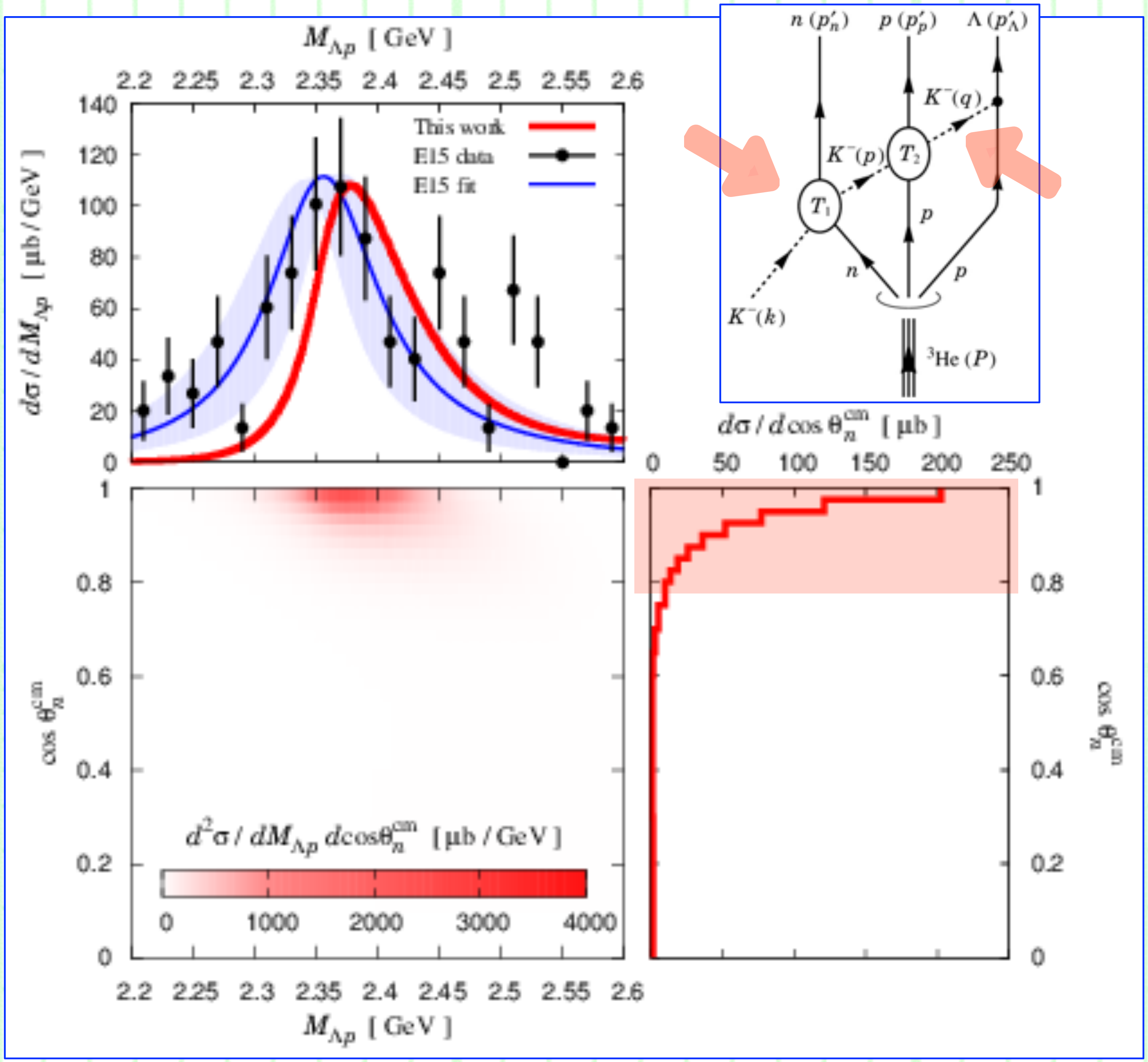
- Now we calculate **the cross section and Λ*p* mass spectrum of the ^{3}He (K^-, Λ*p*) *n* reaction** in **the uncorrelated Λ(1405)*p* scenario**.



- 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}He (K^-, Λ*p*) *n* reaction is **NOT the uncorrelated Λ(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,

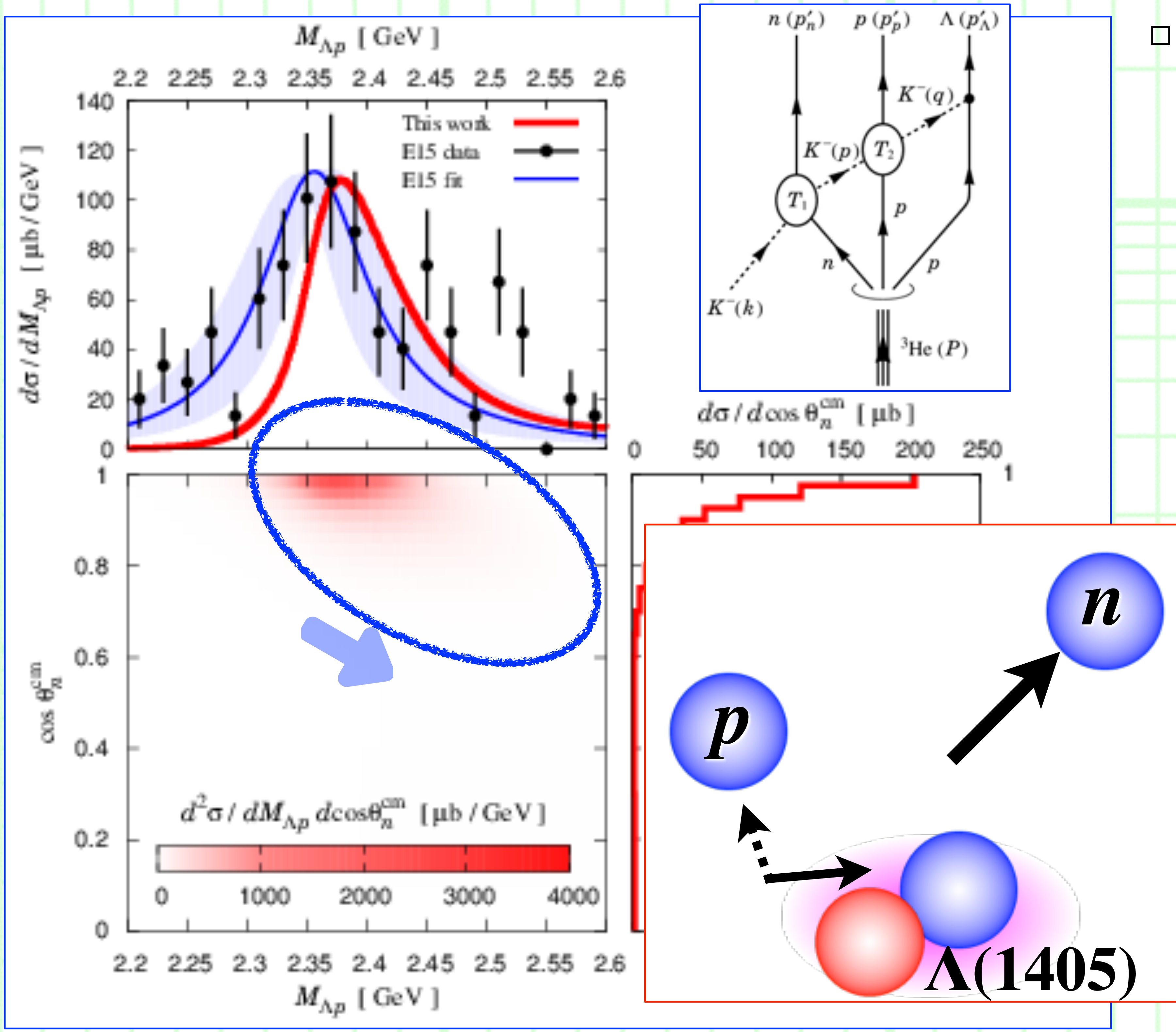
$$\begin{cases} K^- n \to K^- n_{\rm escape} \\ K^- p \to \bar{K}^0 n_{\rm escape} \end{cases}$$

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

--- 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 $\cos\theta \lesssim 0.9$.

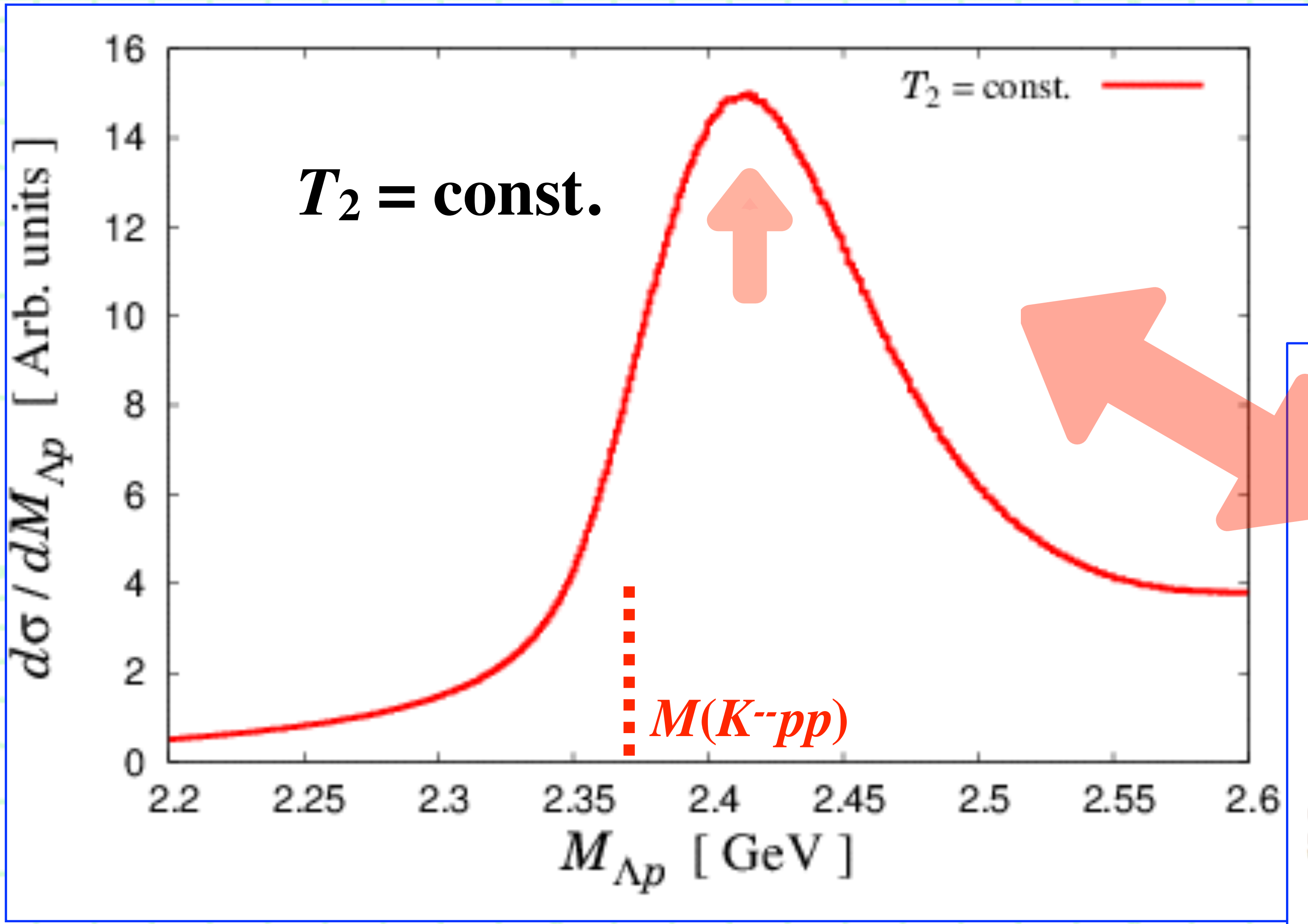
  --- **Λ(1405) gets more momentum** from the kaon after the first scattering.

2. Uncorrelated Λ(1405) *p*

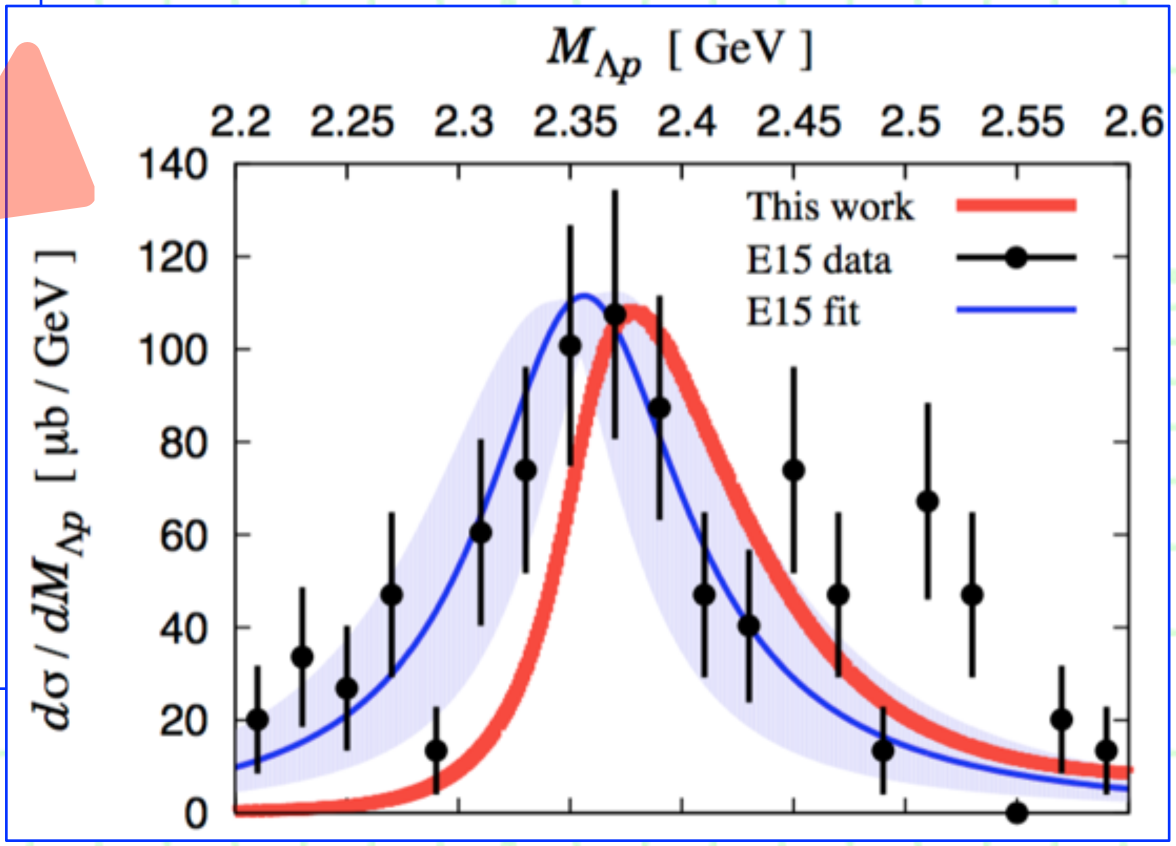
++ Underlying kinematic feature ++

- We find that there is **an underlying kinematic feature** rather than by the Λ(1405)*p* system, **in addition to the "Λ(1405)*p*" contribution.**

--- This can be seen by taking T_2 = const. <=> Ignoring Λ(1405).



- Indicates **underlying kinematic features** rather than by the Λ(1405)*p*.



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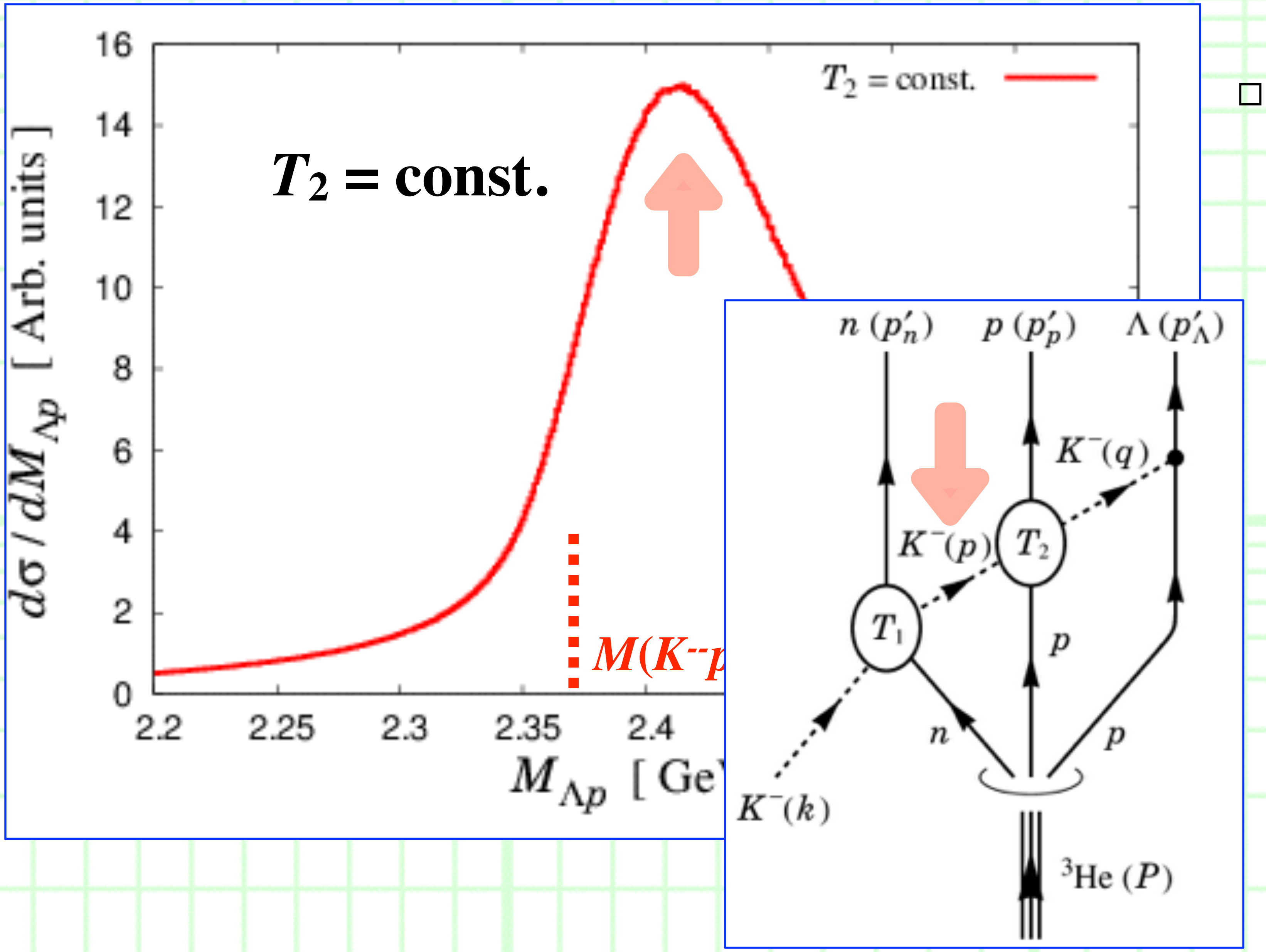


- Actually, this is due to the quasi-elastic kaon scattering in the first step.
  --- The intermediate kaon after the fast neutron emission goes almost to its on mass shell.

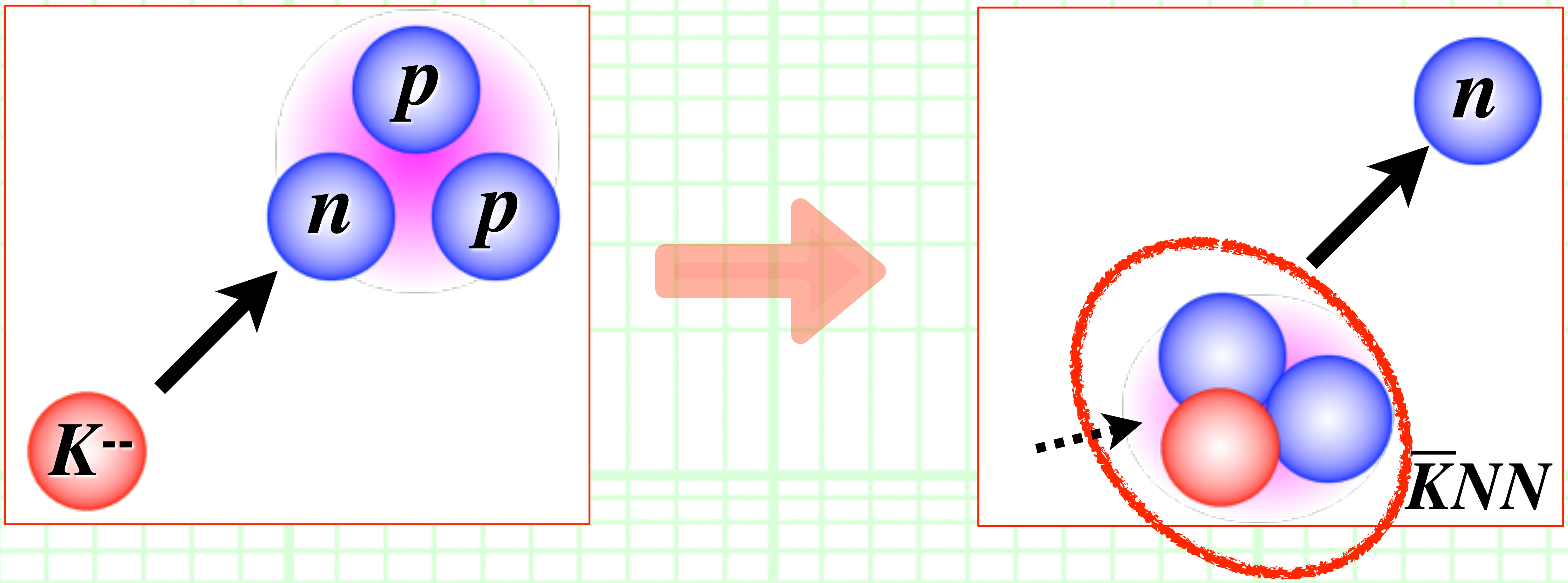
- The actual mass spect. is essentially the product with | T_2 |^2.
  --> They merge to be a single peak.

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.**

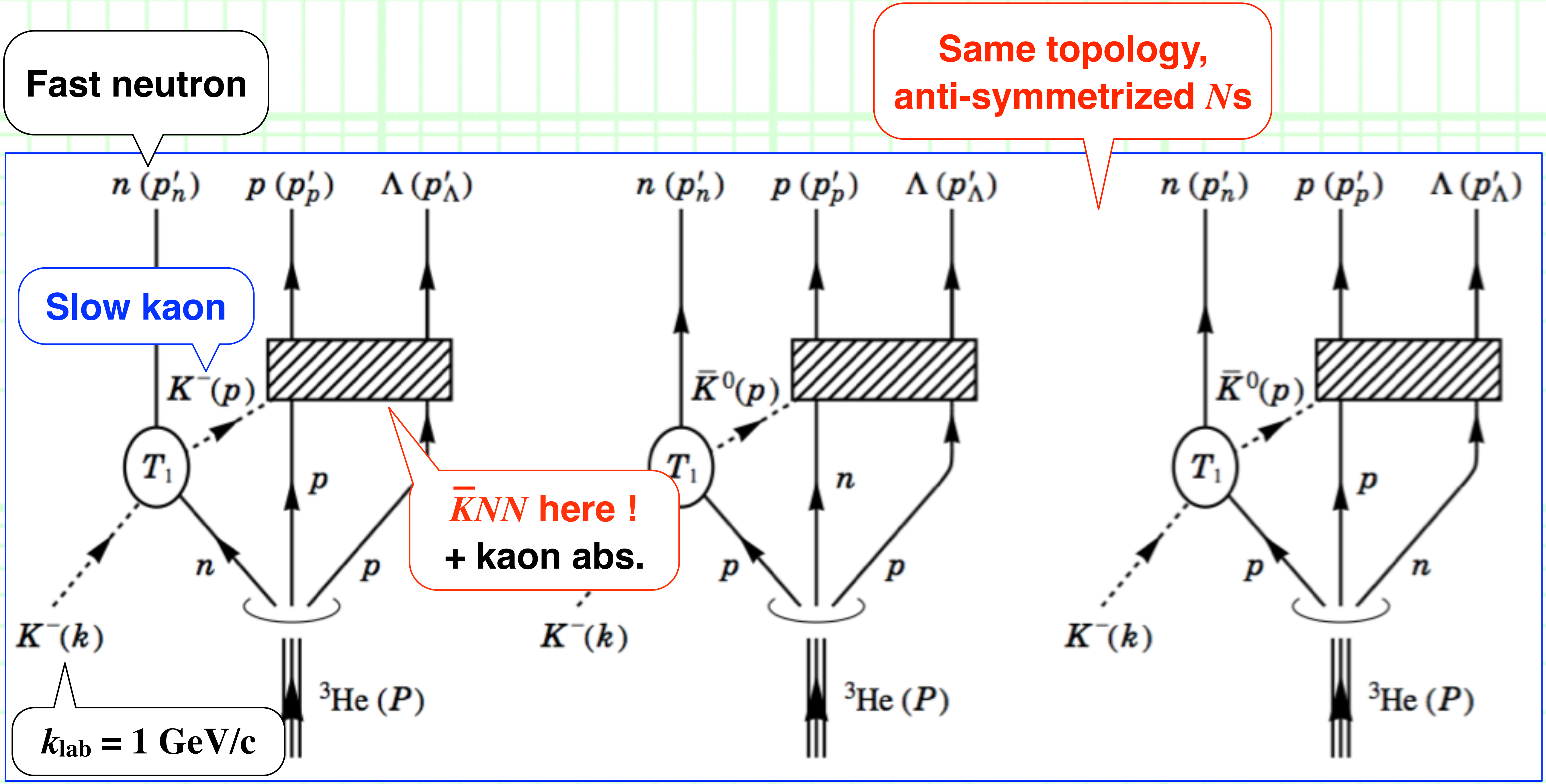


□ **If the $\bar{K}NN$ signal is strong enough, we will see a peak in the Λp invariant mass spectrum.**

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

++ Scattering amplitude ++

- For this process, we use **the following diagrams**:



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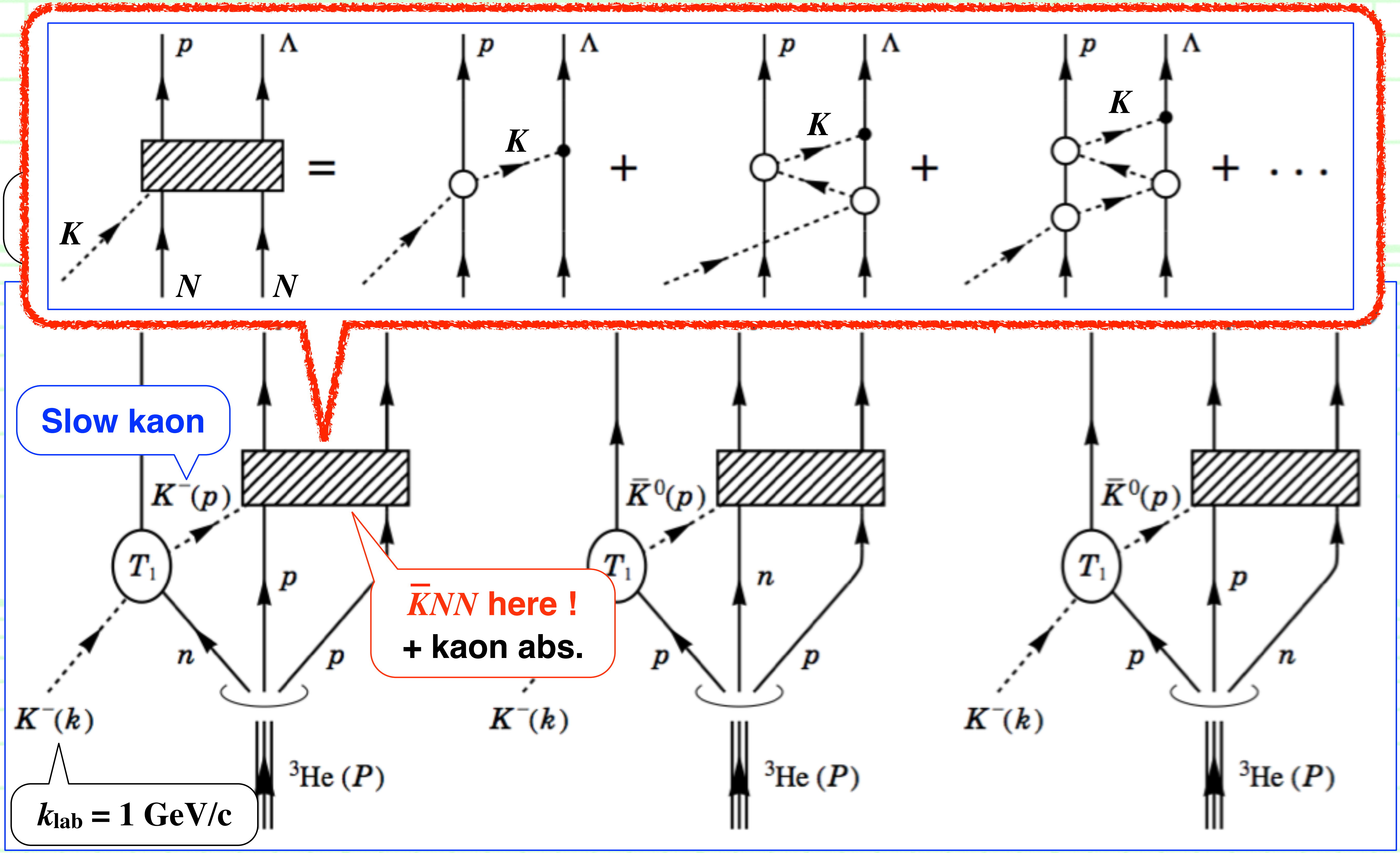

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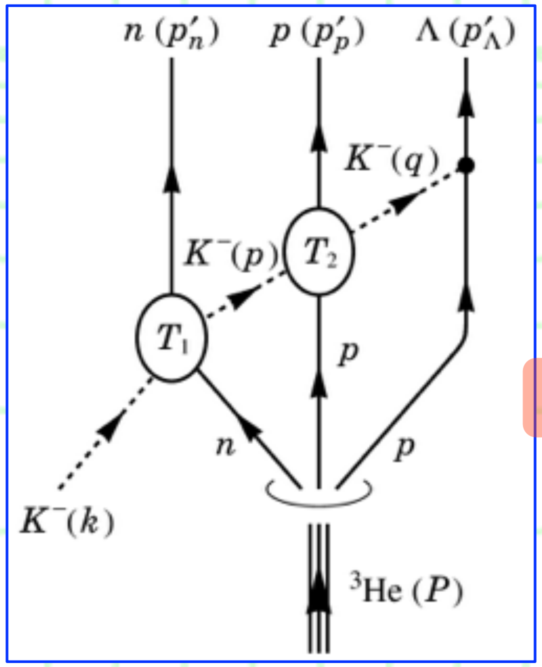
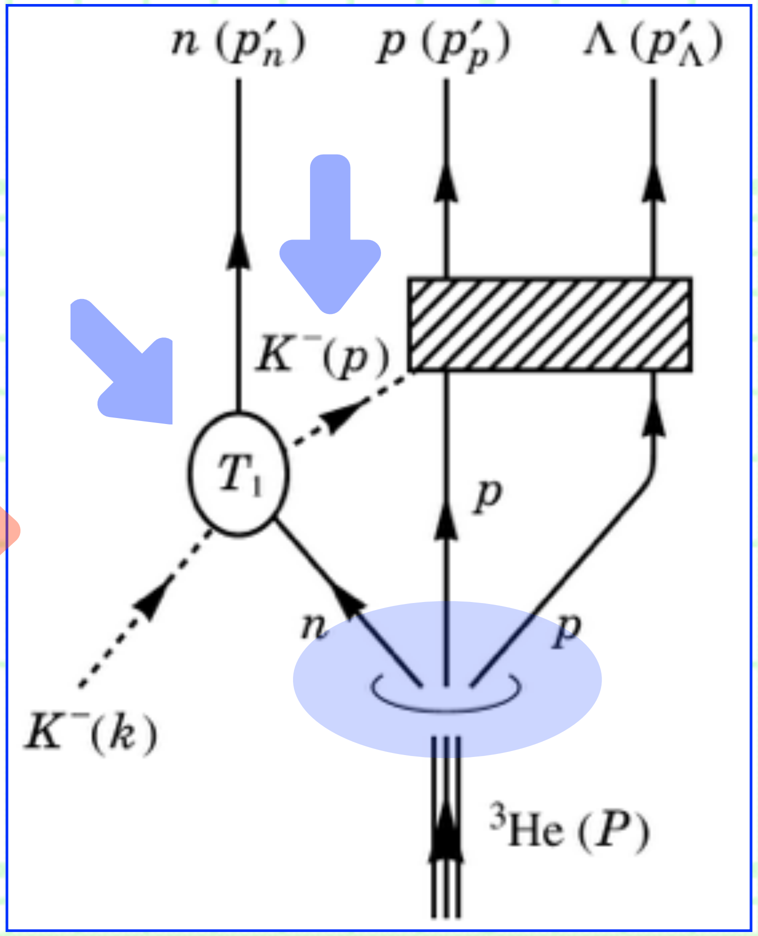


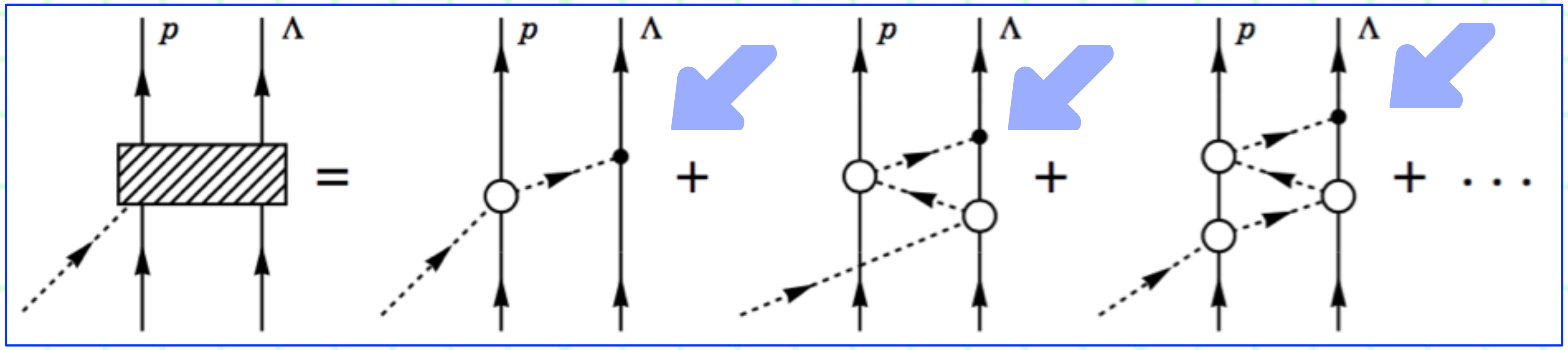


--- We can use same form:

- □ The ^{3}He wave function.
- □ Amplitude T_1 (k=1 GeV/c):

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

- □ The $\bar{K}N\Lambda$ vertex.
- □ The intermediate kaon energy.



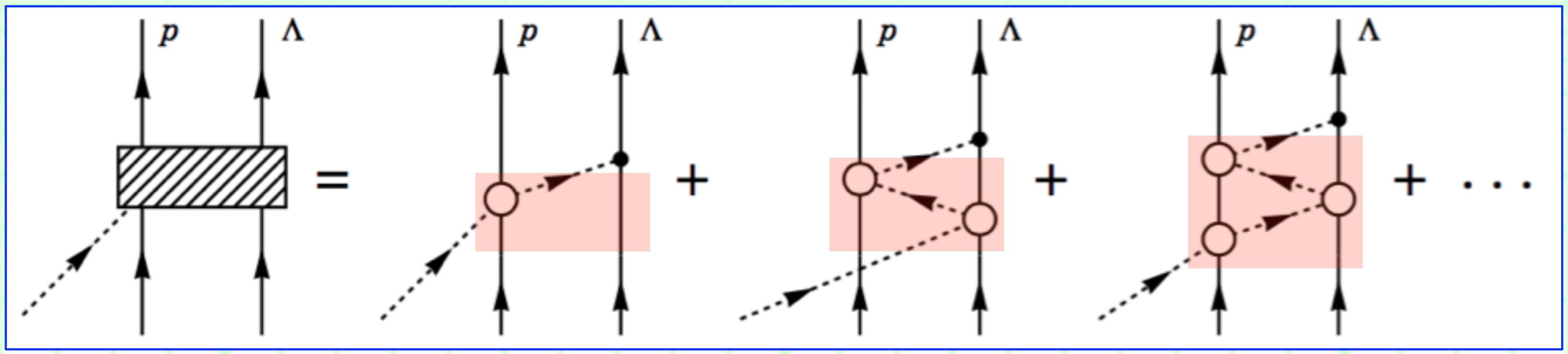
- □ We can use the same formula for them as in the uncorr. $\Lambda(1405)p$.

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

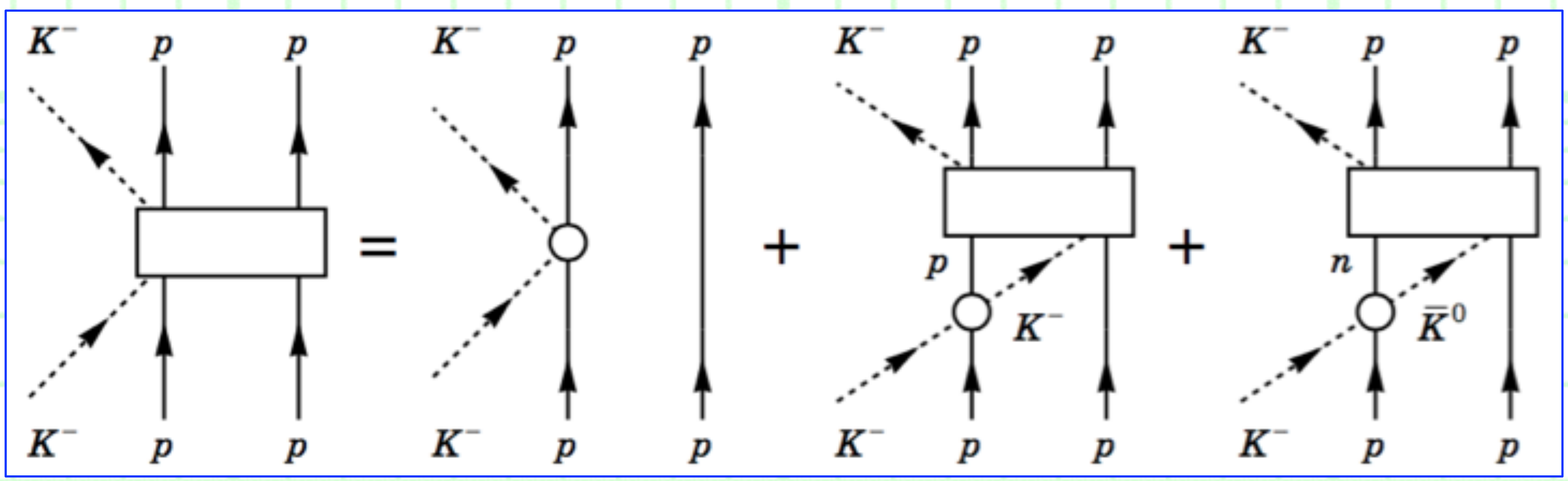
++ Scattering amplitude ++

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

--> 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.

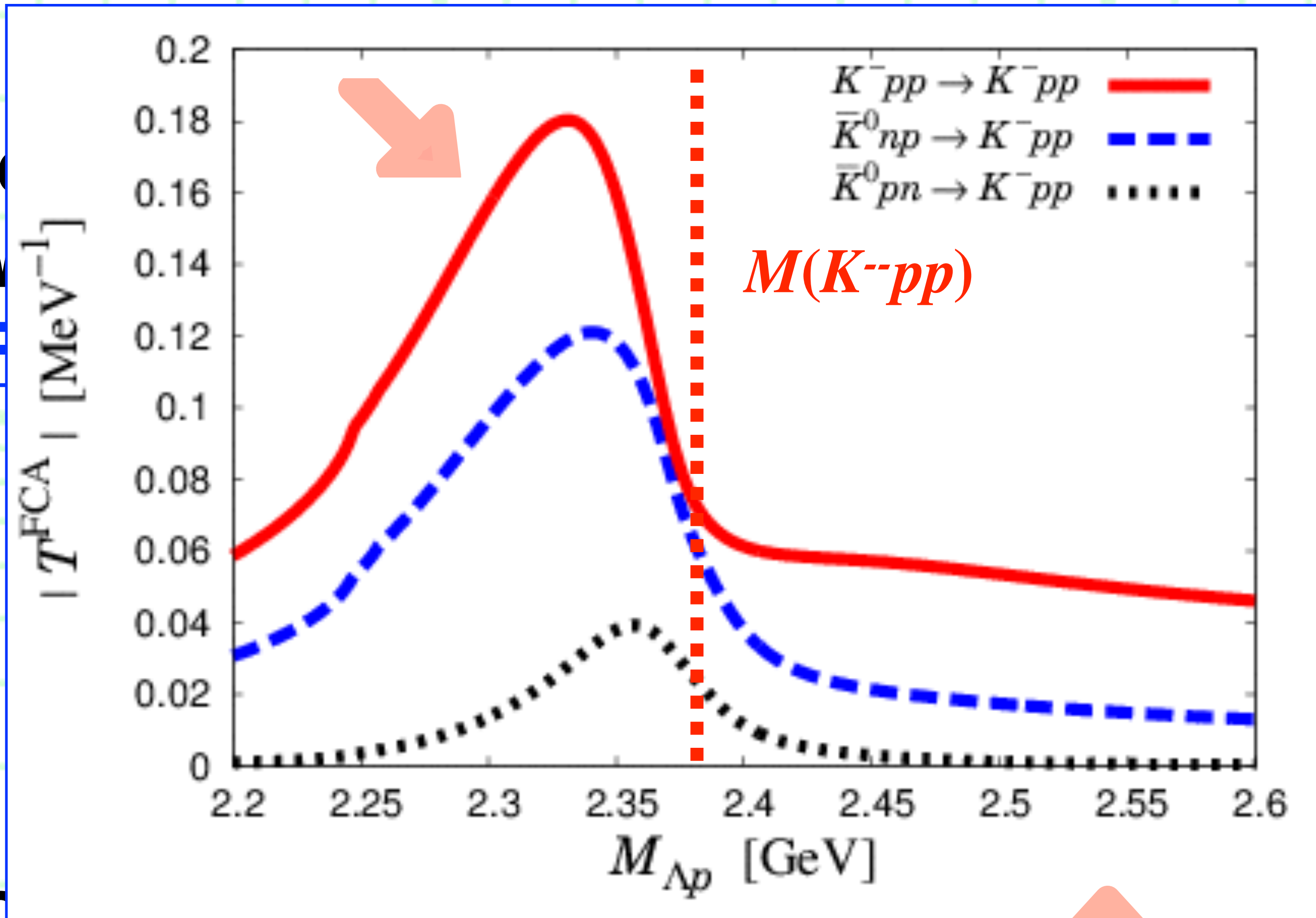
3. $\bar{K}NN$ bound state

++ ...plitude ++

■ W... n scattering with two Ns.

--> V... r approximation to the

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

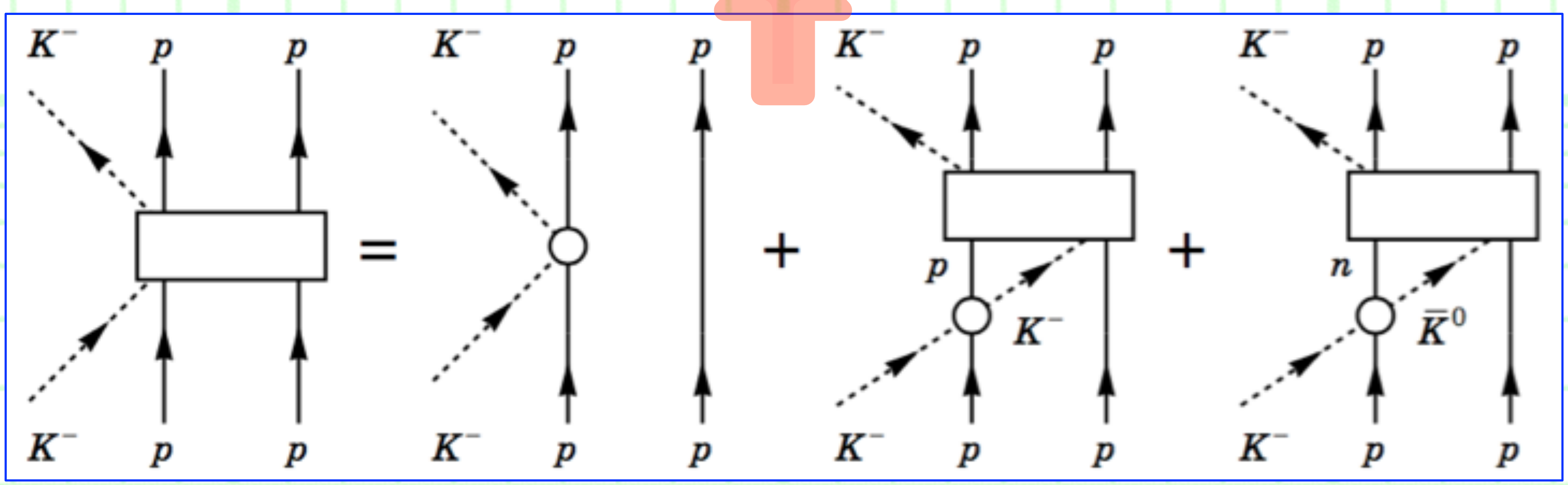


--- FCA amplitude has a peak of $\bar{K}NN$ bound state.

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

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

■ Solve the following scattering equation with a "fixed center".

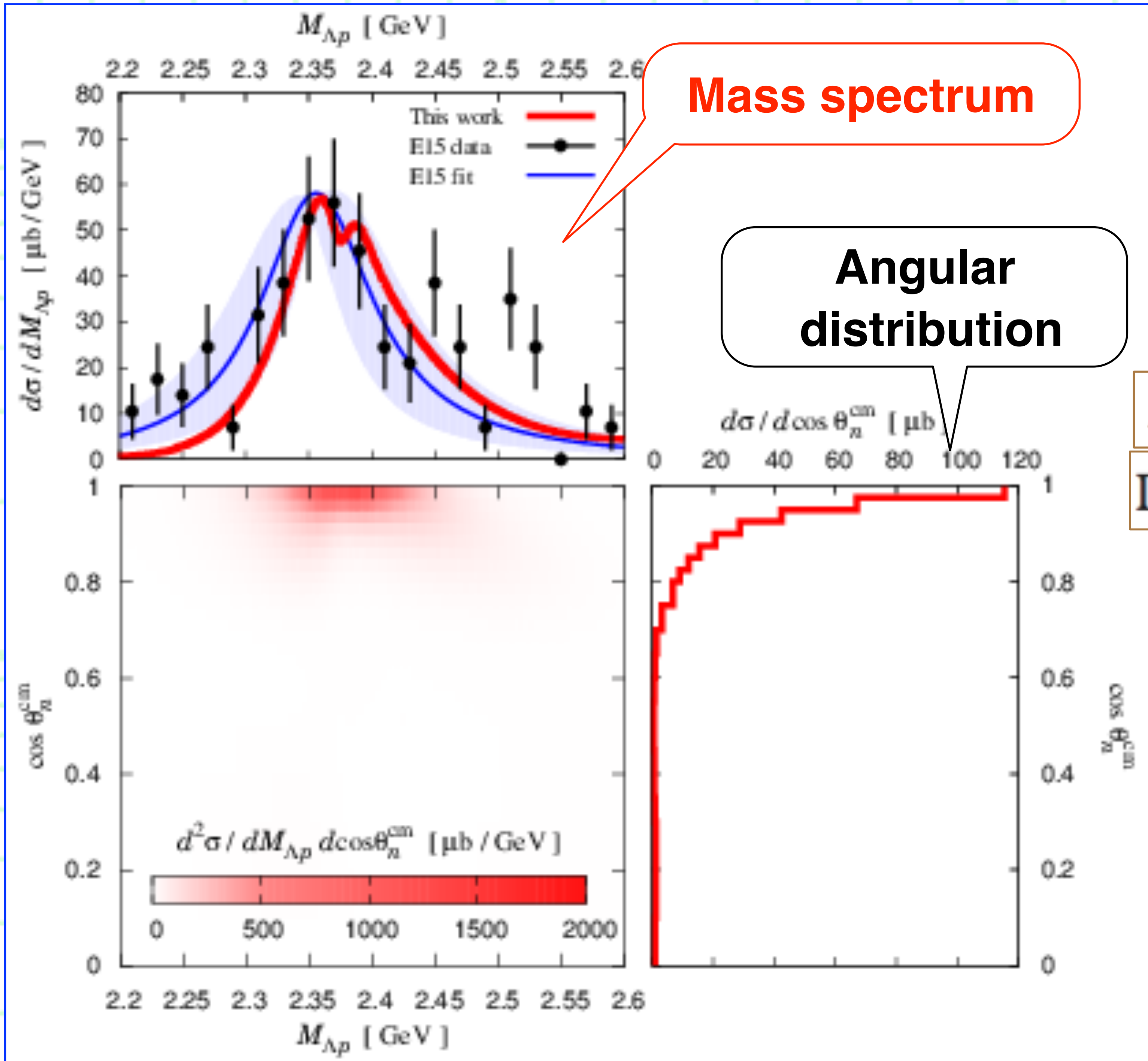


--- Open circle: $\bar{K}N$ --> $\bar{K}N$ amplitude in chiral unitary approach.

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

++ Numerical results ++

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



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

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

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

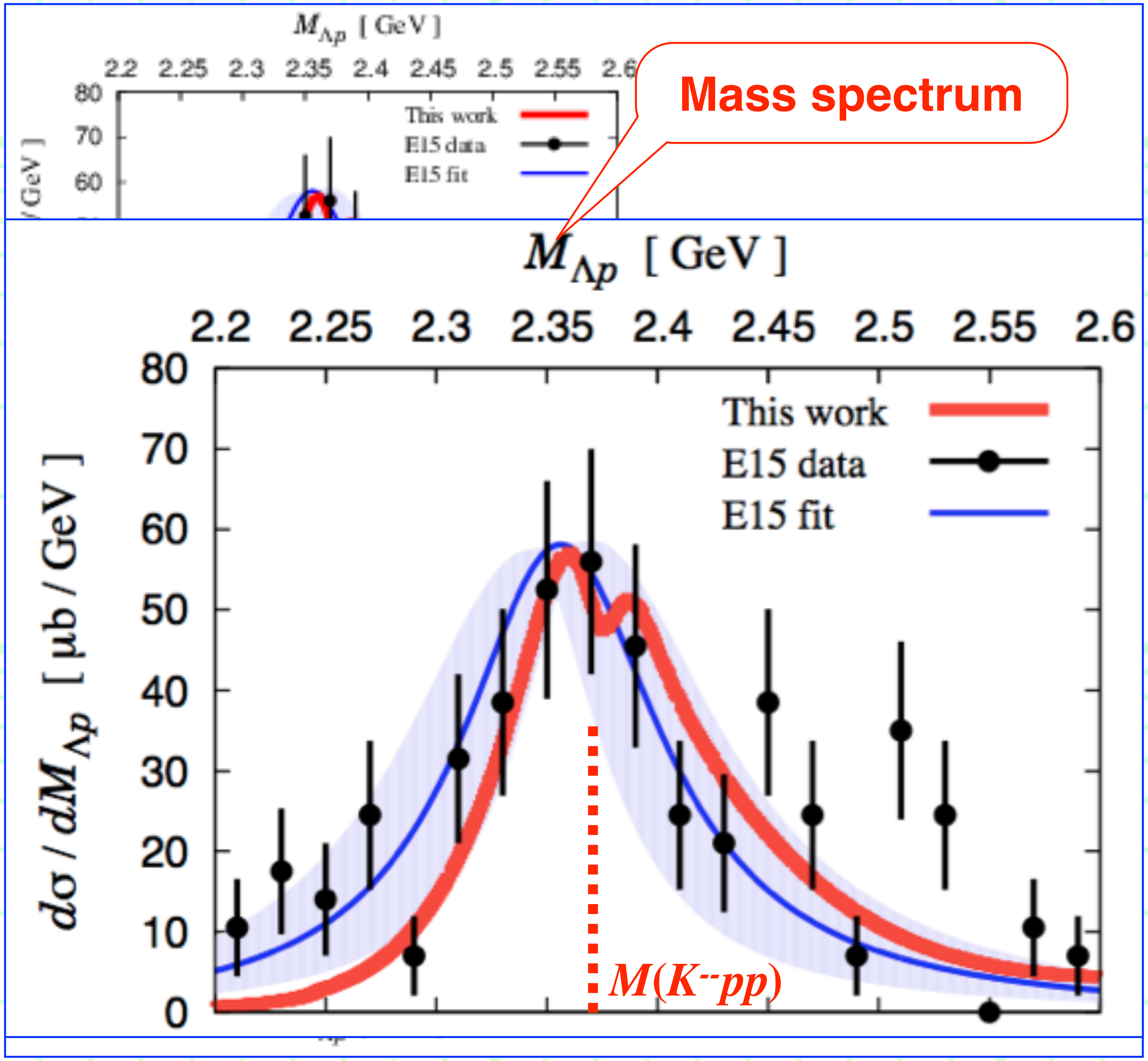
$$\Gamma_X = 110^{+19}_{-17}\ (\text{stat.}) \pm 27\ (\text{syst.})\ \text{MeV}/c^2,$$

<-- 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.



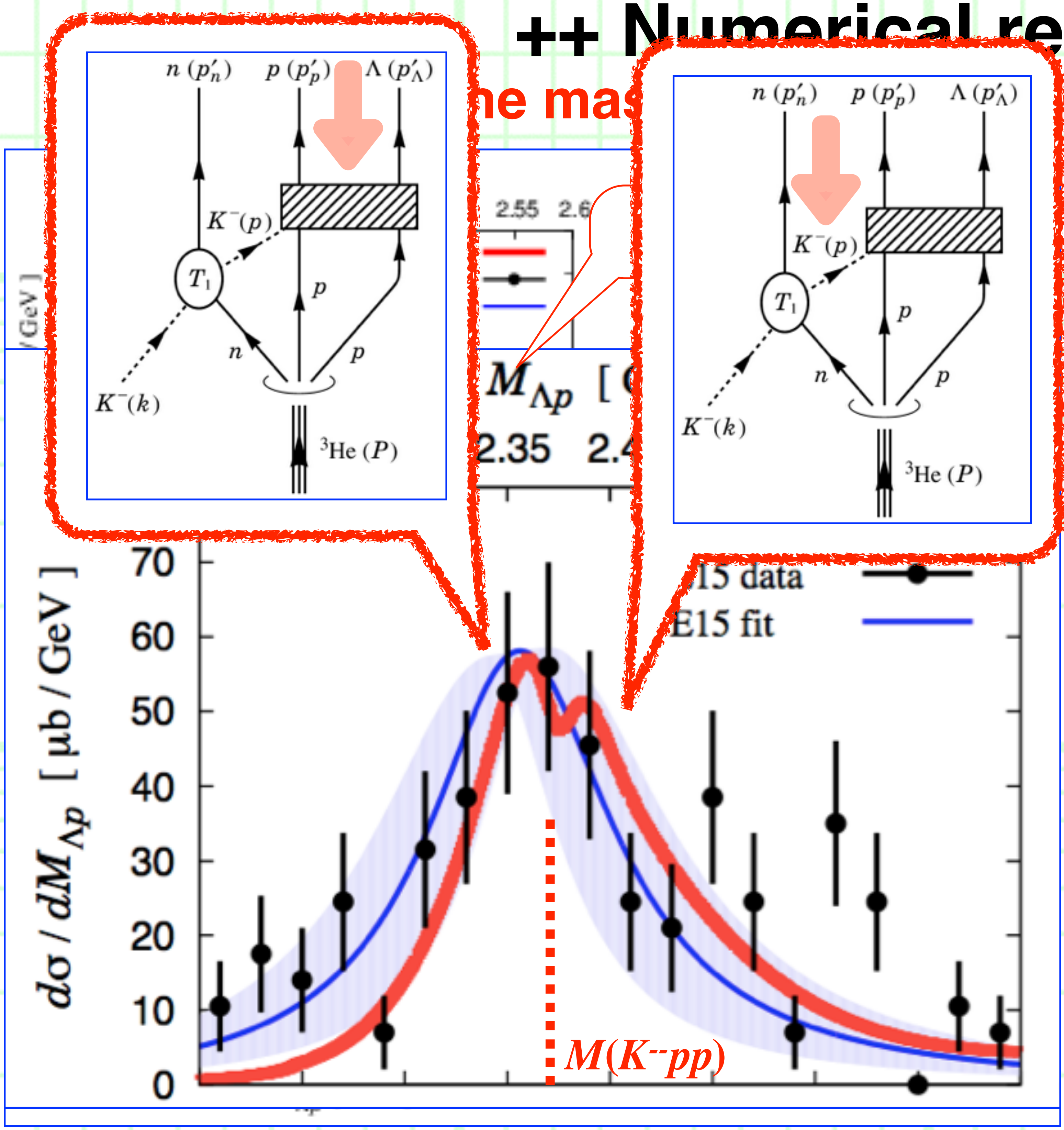
- Our mass spectrum is consistent with the Exp. within the present errors.
  --- Reproduce the tail at lower energy ~ 2.3 GeV.

- Therefore, our spectrum supports the explanation that the E15 signal in the ^{3}He (K^-, Λp) 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.



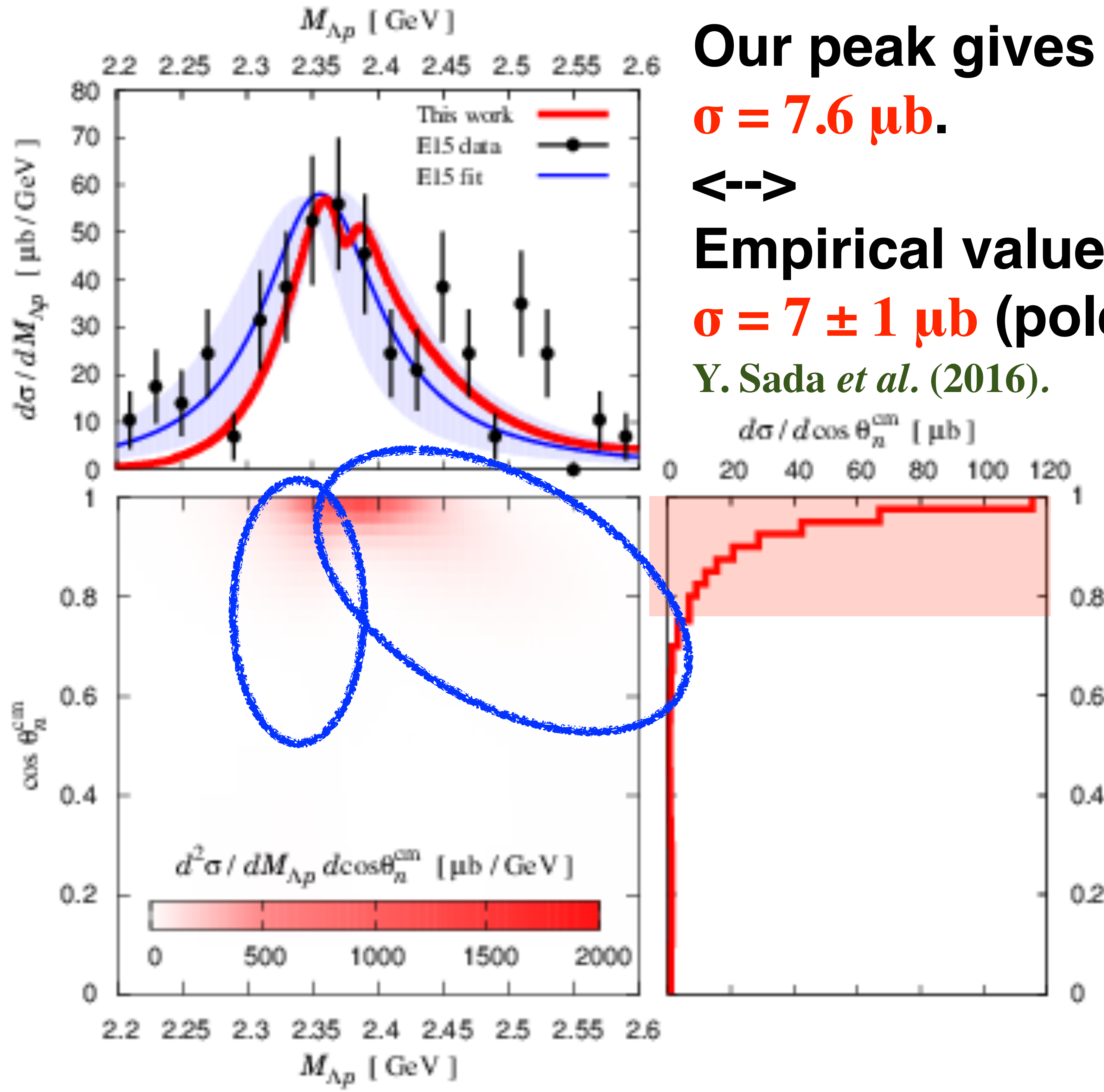
- One more thing:
  Our spectrum has
  a "double peak" structure
  around the $\bar{K}NN$ threshold.

--- 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 ++

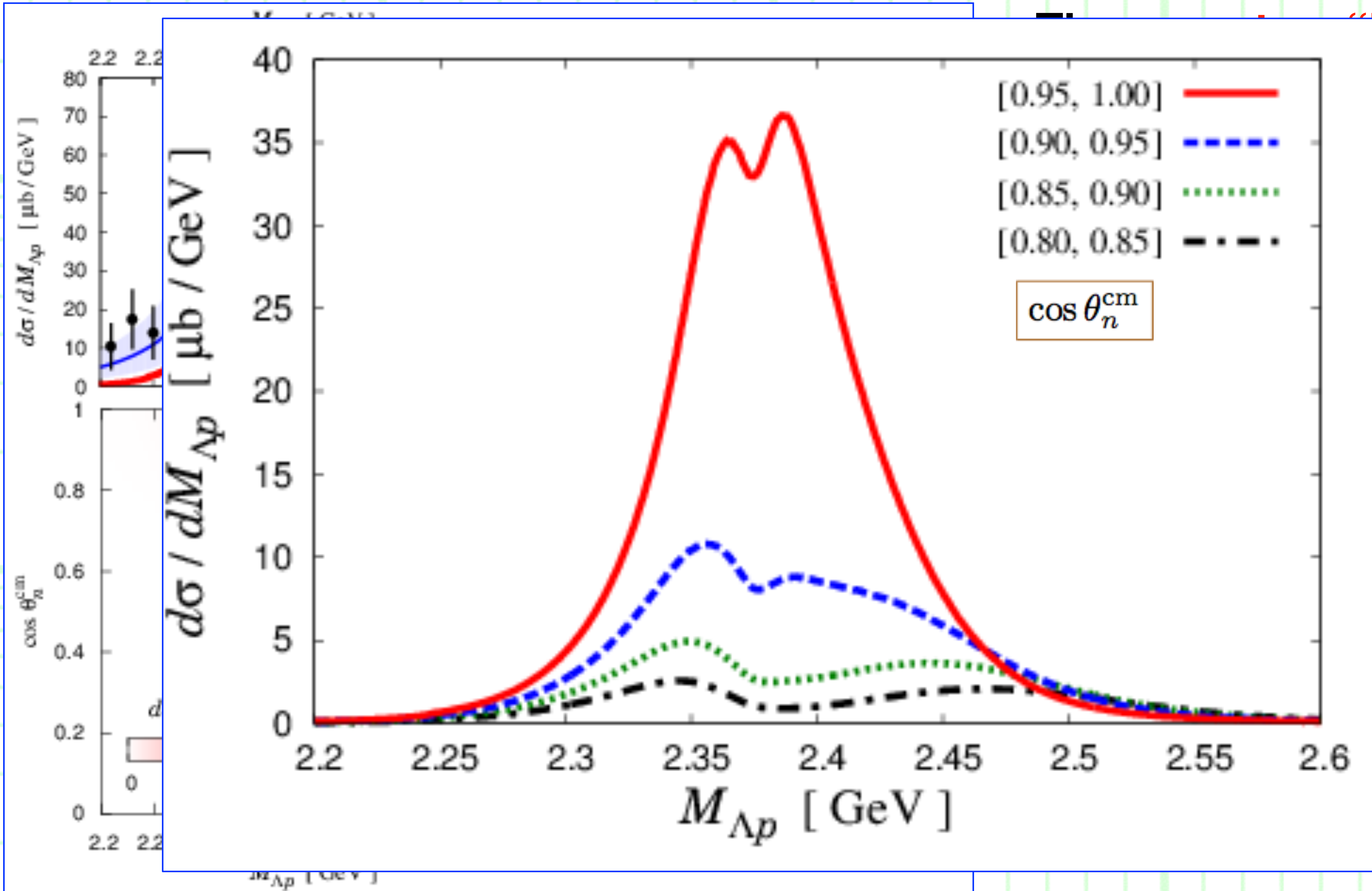


Our peak gives
σ = 7.6 μb.
<-->
Empirical value
σ = 7 ± 1 μb (pole).
Y. Sada *et al.* (2016).

- 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**.

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

++ Numerical results ++



Th... "bands"

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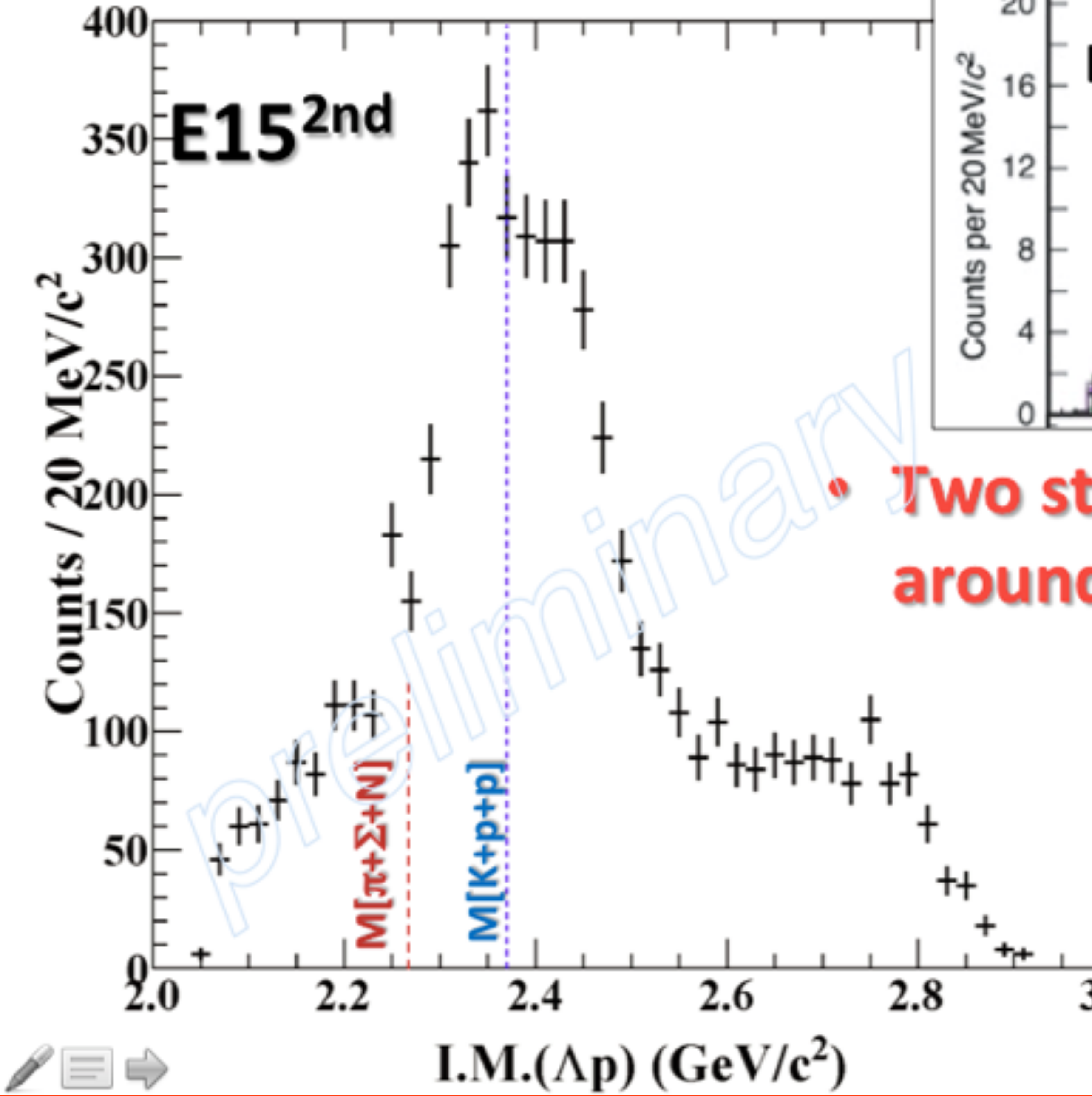
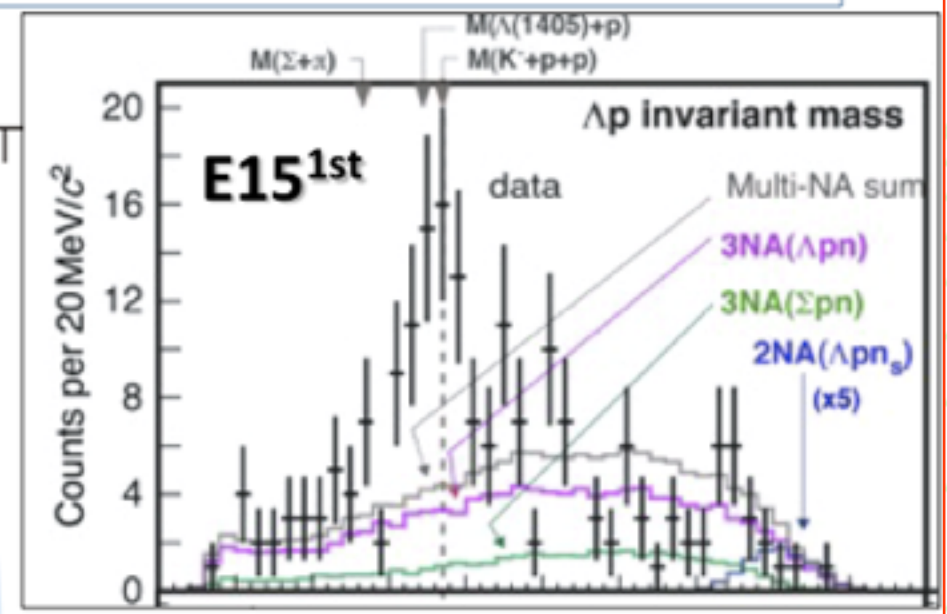
3. $\bar{K}NN$ bound state

++ Data in 2nd run of J-PARC E15 ... ++

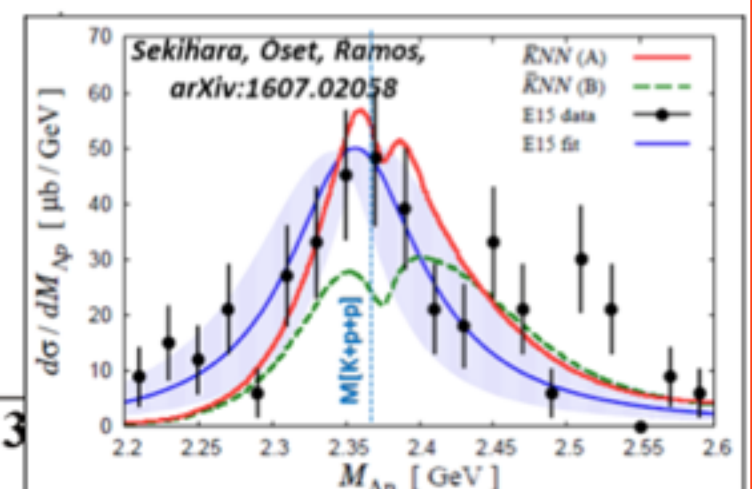
Exclusive $^3He(K^-,\Lambda p)n$

Sakuma-sun at MENU 2016.





- Two structures are seen around M[K+p+p]!?



4. Summary

++ 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.

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

4. Summary

++ 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 / $\Sigma^0 p$.
- □ Spin / parity of the system for the peak.
- □ ...

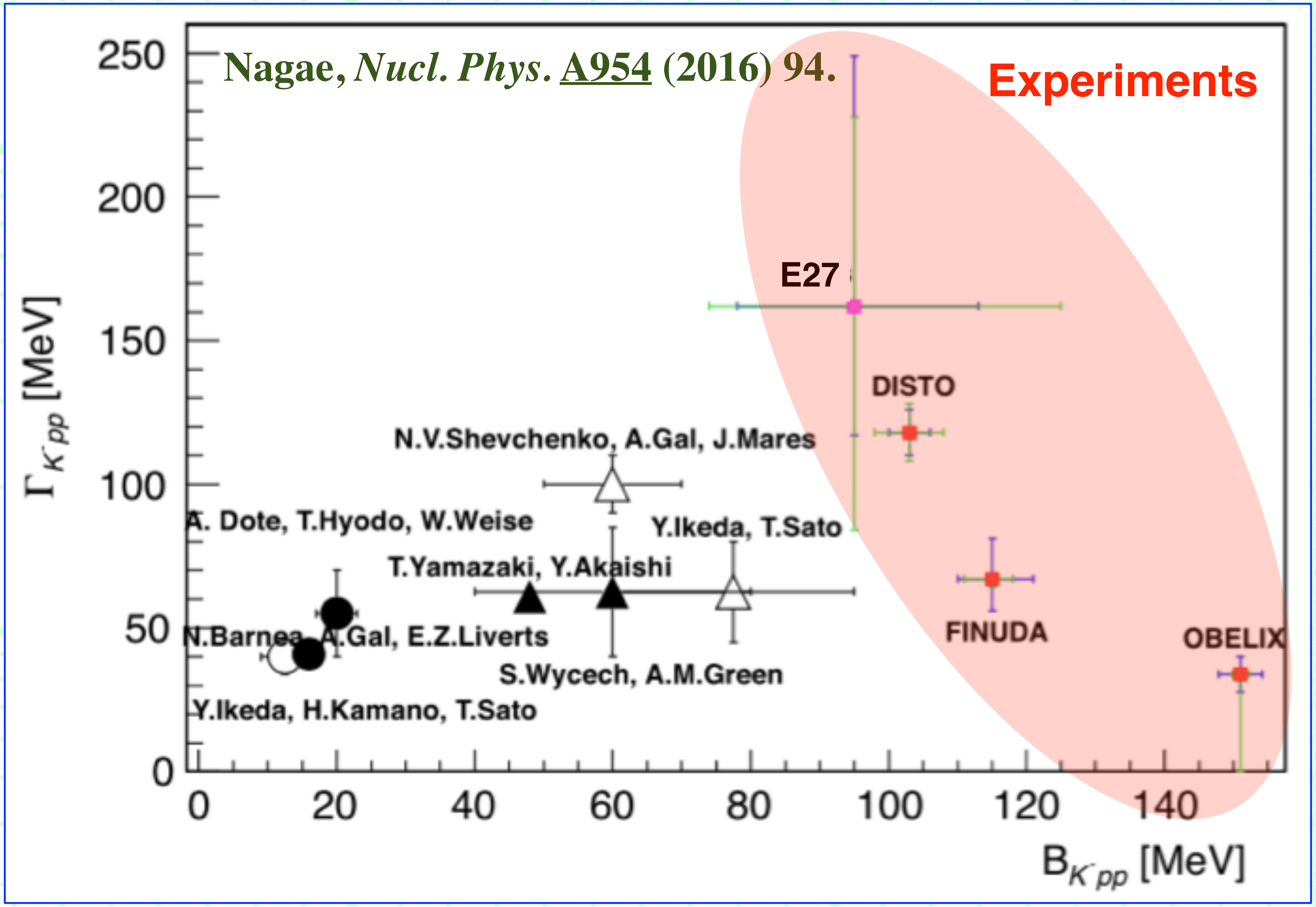
Thank you very much for your kind attention !

Appendix

Appendix

++ Outlook ++

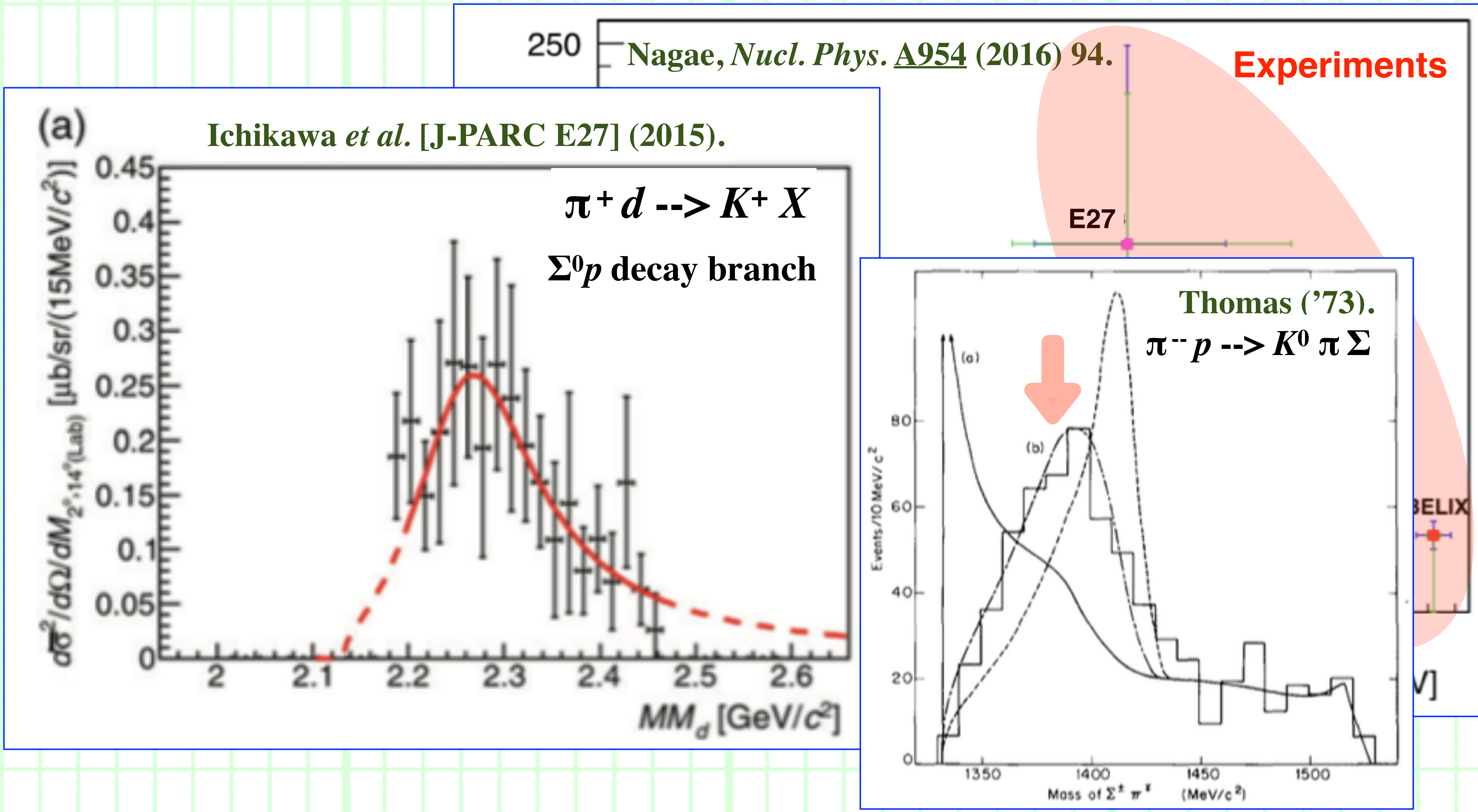
- **How about the difference between E15 and others ?**



Appendix

++ Outlook ++

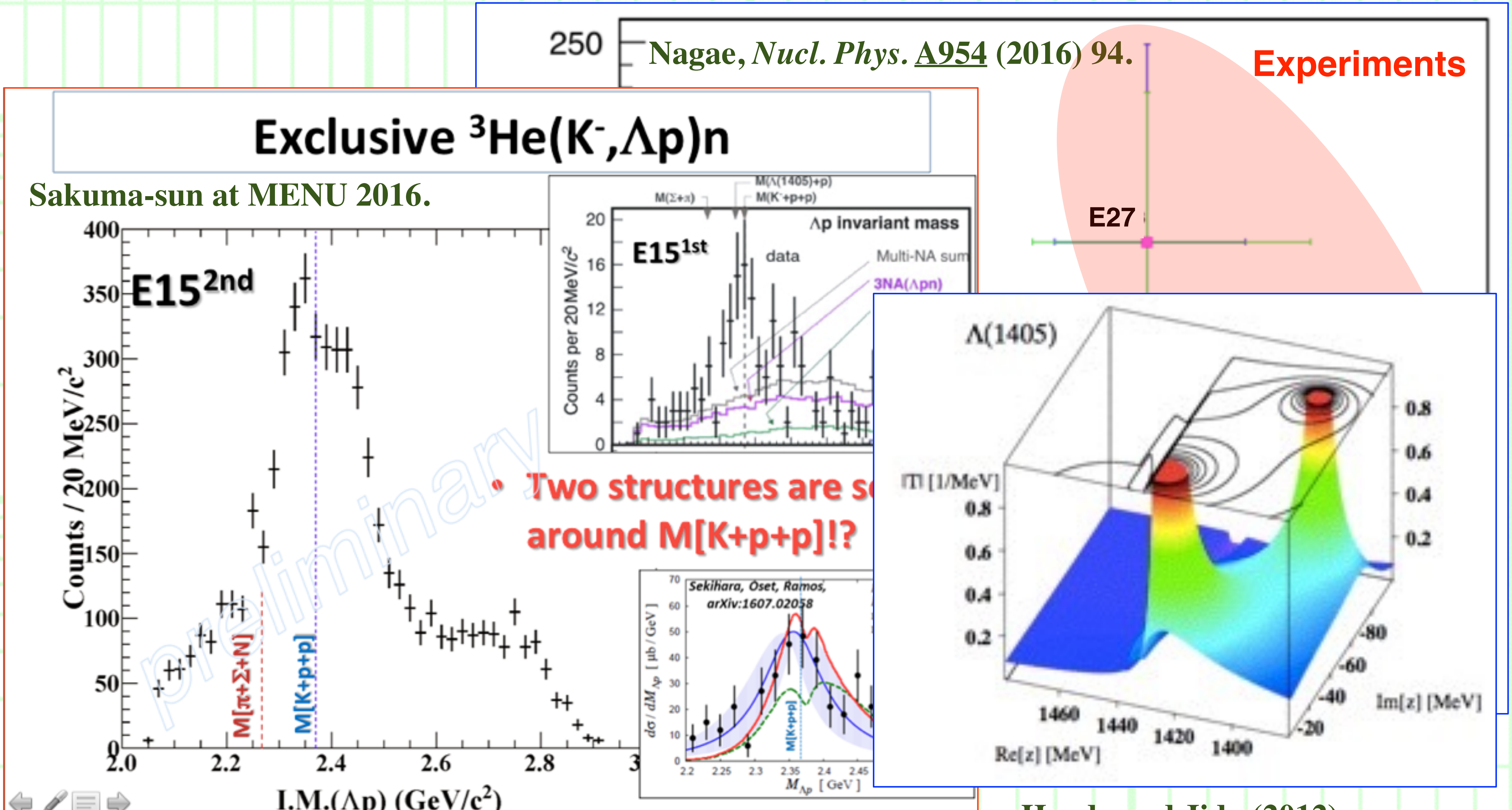
- How about **the difference between E15 and others** ?



Appendix

++ Outlook ++

- How about **the difference between E15 and others** ?



Hyodo and Jido (2012).