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

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in collaboration with

Eulogio OSET (Valencia Univ.)

and Angels RAMOS (Barcelona Univ.)

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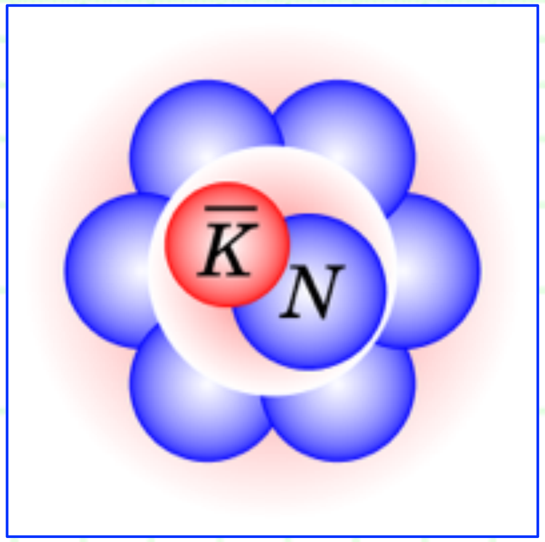
[1] __T. S.__ , E. Oset and A. Ramos, *PTEP* __2016__ 123D03
[2] __T. S.__ , E. Oset and A. Ramos, *JPS Conf. Proc.* __13__ (2017) 020002.
[3] __T. S.__ , E. Oset and A. Ramos, *Acta Phys. Polon.* __B__ (201x) xxx [arXiv:1709.08487 [nucl-th]].

Contents



Kaonic nuclei

1. Introduction

2. What makes the peak structure in the J-PARC E15 experiment ?

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

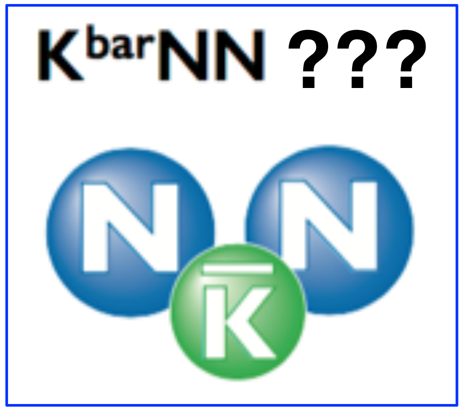
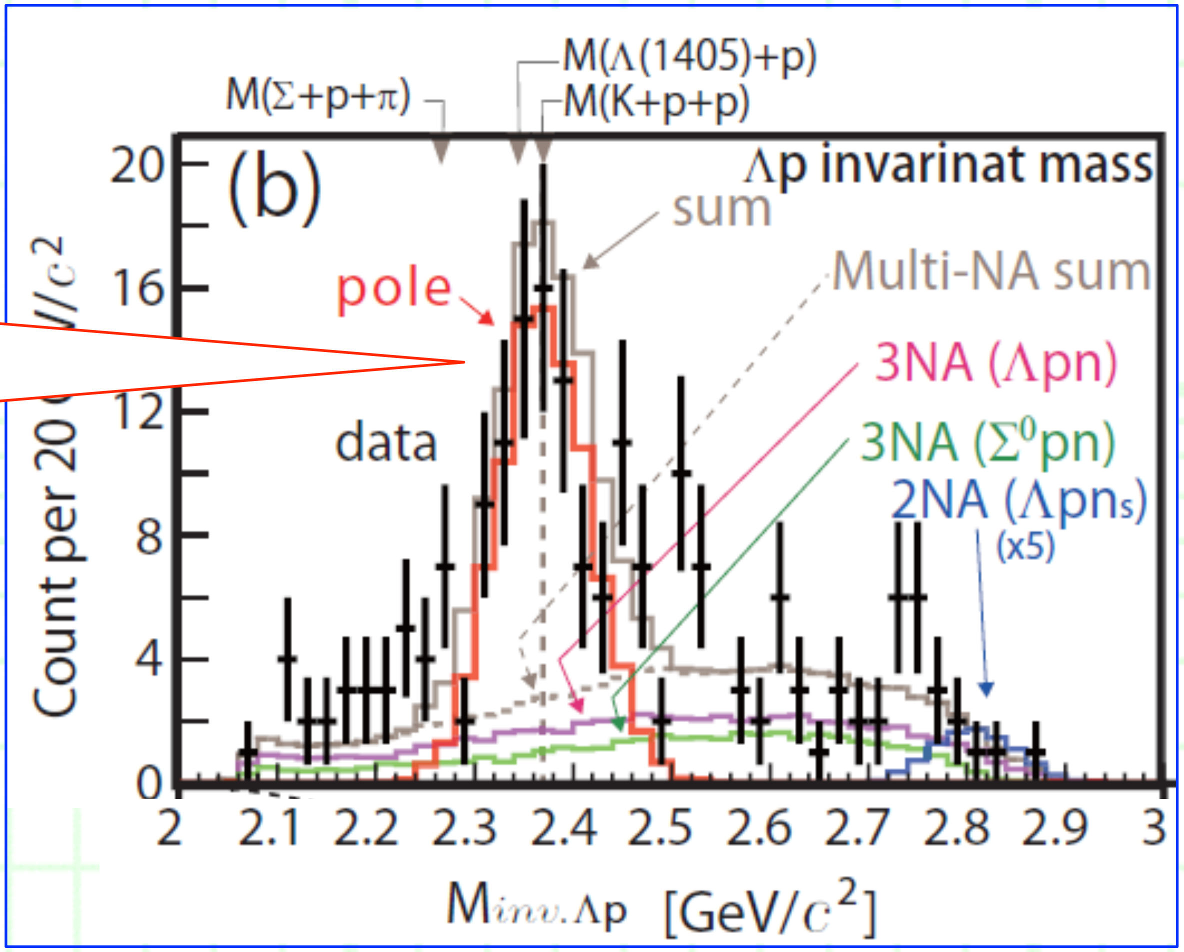


Figure by Jido-san.



J-PARC E15 Exp. [1st run data]

3. Summary

1. Introduction

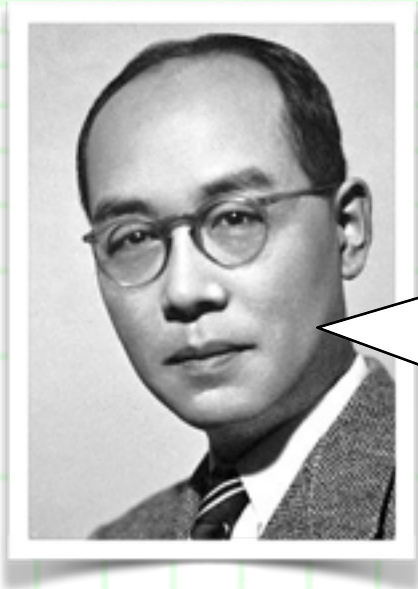
1. Introduction

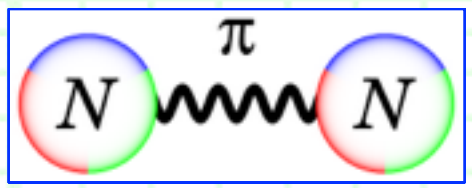
++ From *NN* to hadron-hadron interaction ++

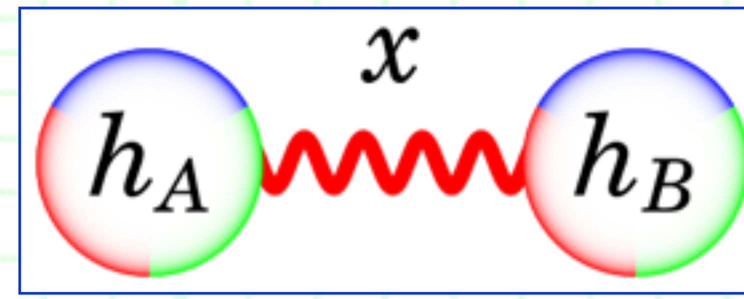
- **Our ultimate goal:** **To understand completely the strong interaction between various combinations of hadrons.**

--- *cf.* π meson exchange for the *NN* interaction.

???





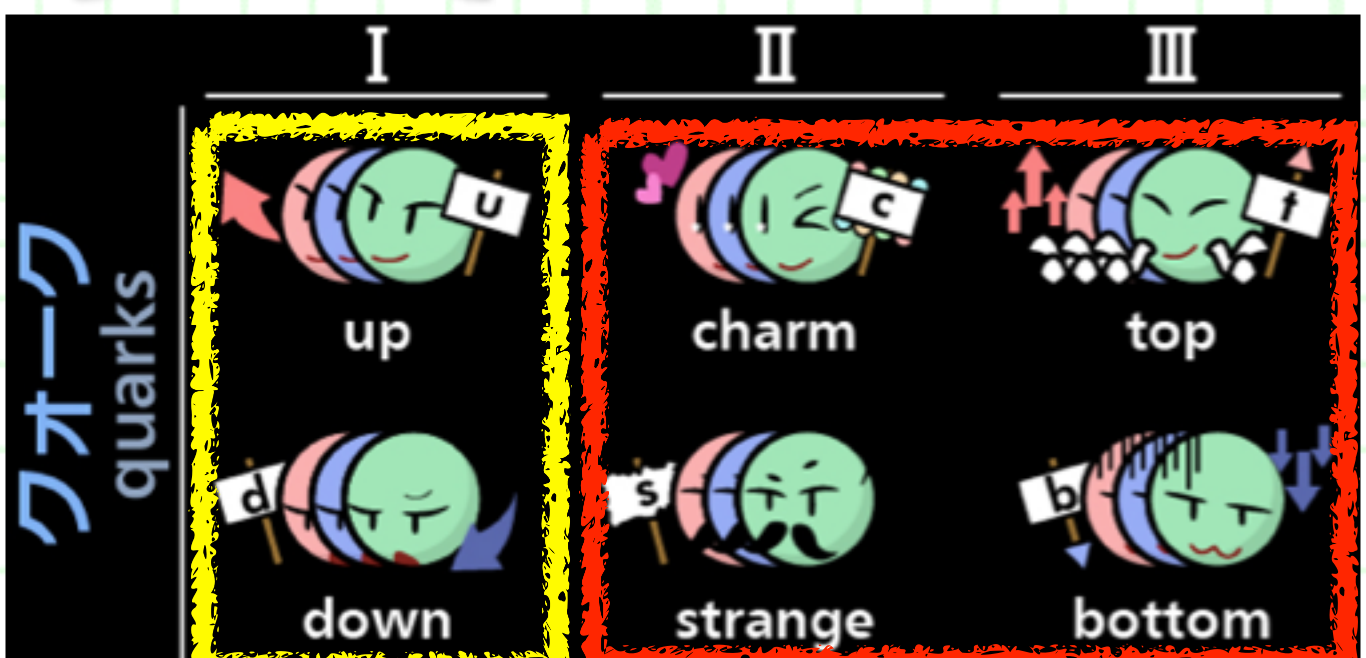


Let's exchange mesons !

Yukawa (1935)

- **Extend our understanding of strong interaction** from the *NN* interaction to interactions of various hadron pairs.

--- Various combinations of hadrons with various flavors.



1. Introduction

++ Hadron interaction with strangeness ++

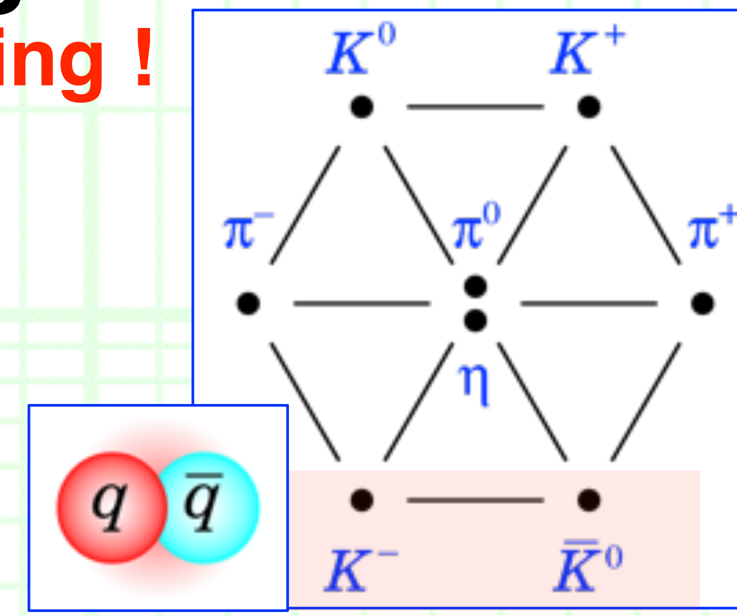
- **Antikaon ($\bar{K}$) -nucleon (N) interaction is interesting !**

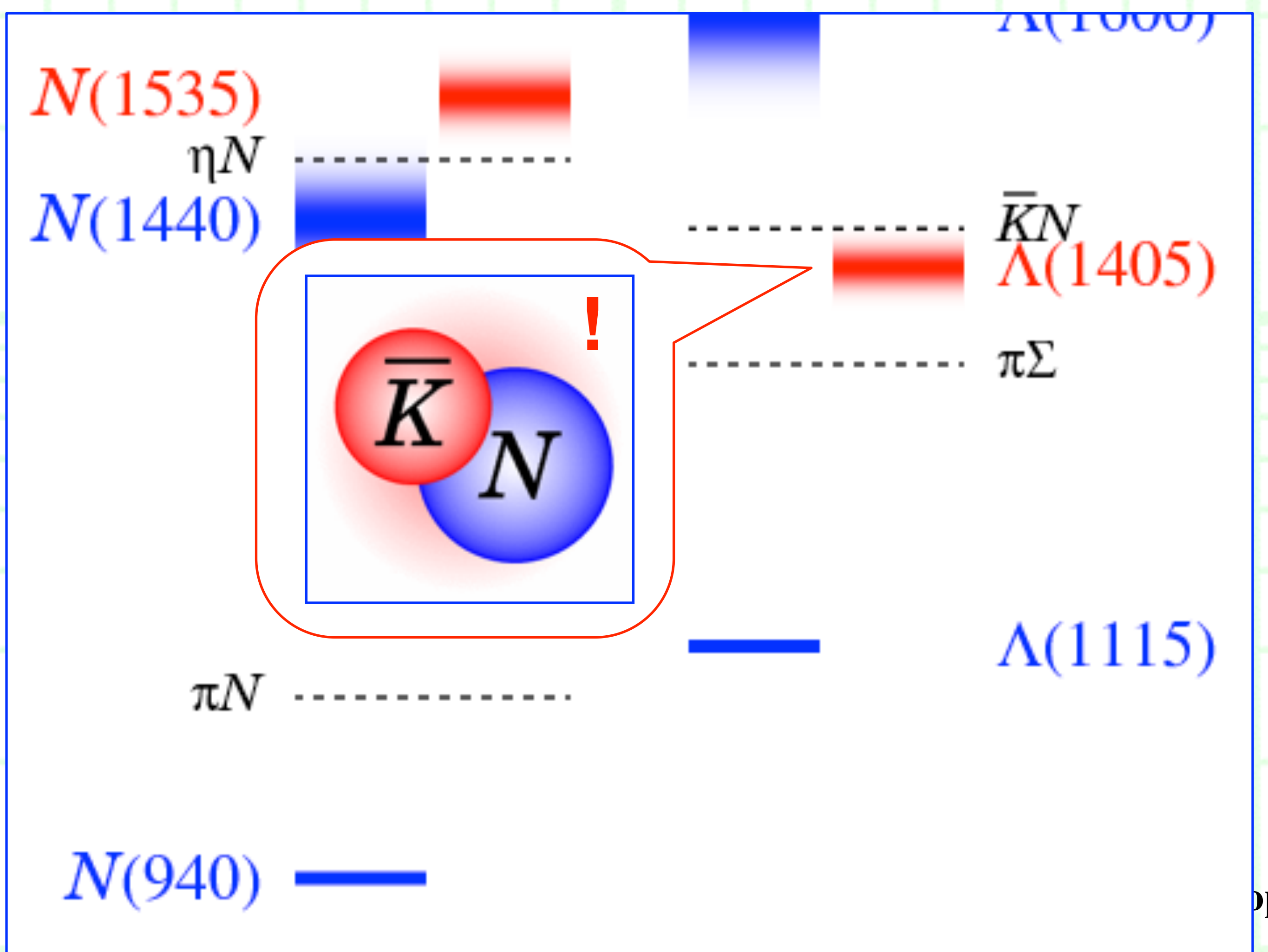
--- **Two aspects of kaons:**

- □ **A Nambu-Goldstone boson of spontaneous chiral symmetry breaking of QCD.**

$$SU(3)_{\mathrm{L}} \otimes SU(3)_{\mathrm{R}} \to SU(3)_{\mathrm{flavor}}$$

- □ **Massive by strange quark:** $m_K \sim 495$ MeV.





- **Spontaneous chiral symmetry breaking predicts a strongly attractive $\bar{K}N$ interaction.**

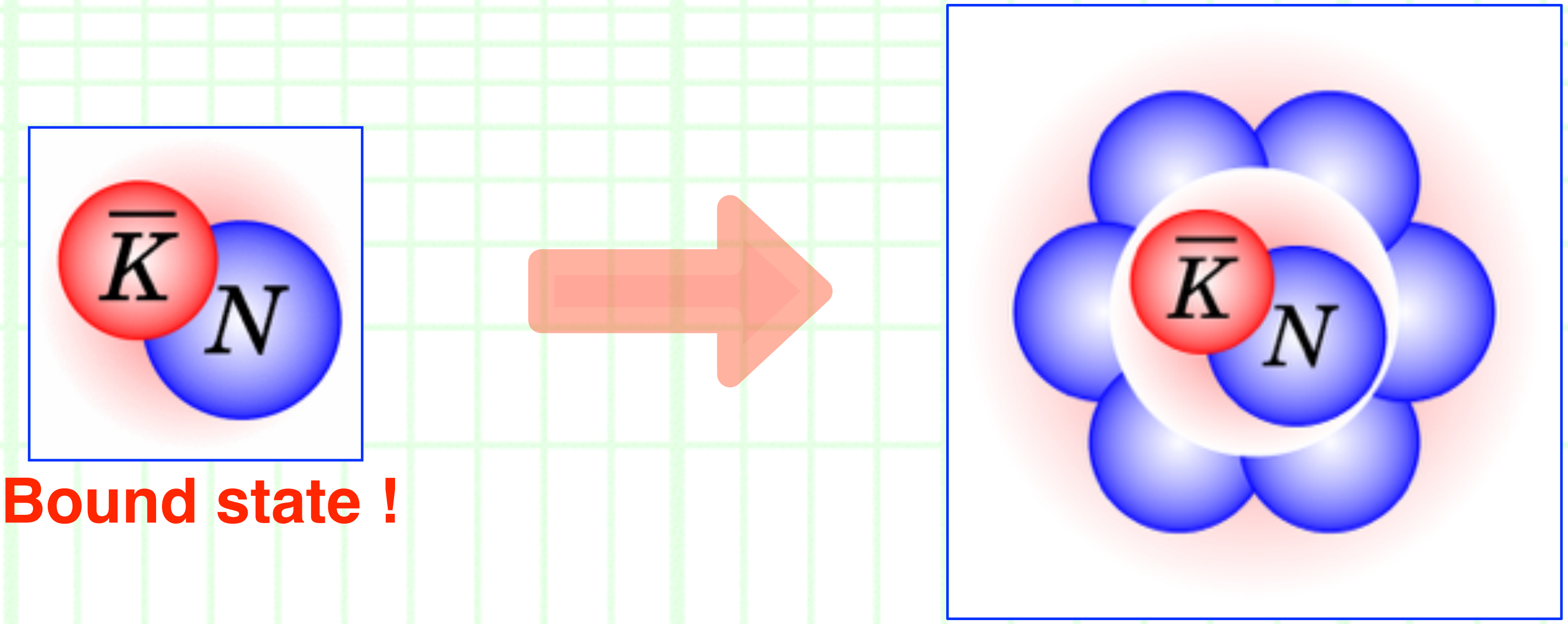
Kaiser-Siegel-Weise ('95);
Oset-Ramos ('98); ...

- **$\bar{K}N$ interaction is attractive enough to generate a $\bar{K}N$ bound state as $\Lambda(1405)$!**

1. Introduction

++ Kaonic nuclei ++

- Because $\bar{K}N$ interaction is strong enough to make a bound state, there should exist kaonic nuclei, which are bound states of $\bar{K}$ and nuclei via strong interaction between them.



Bound state !

Kaonic nuclei should exist !!

- There are several motivations to study kaonic nuclei:
  1. Exotic states of many-body systems in strong interaction.
  2. Feedback to the $\bar{K}N$ interaction.
  3. 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:

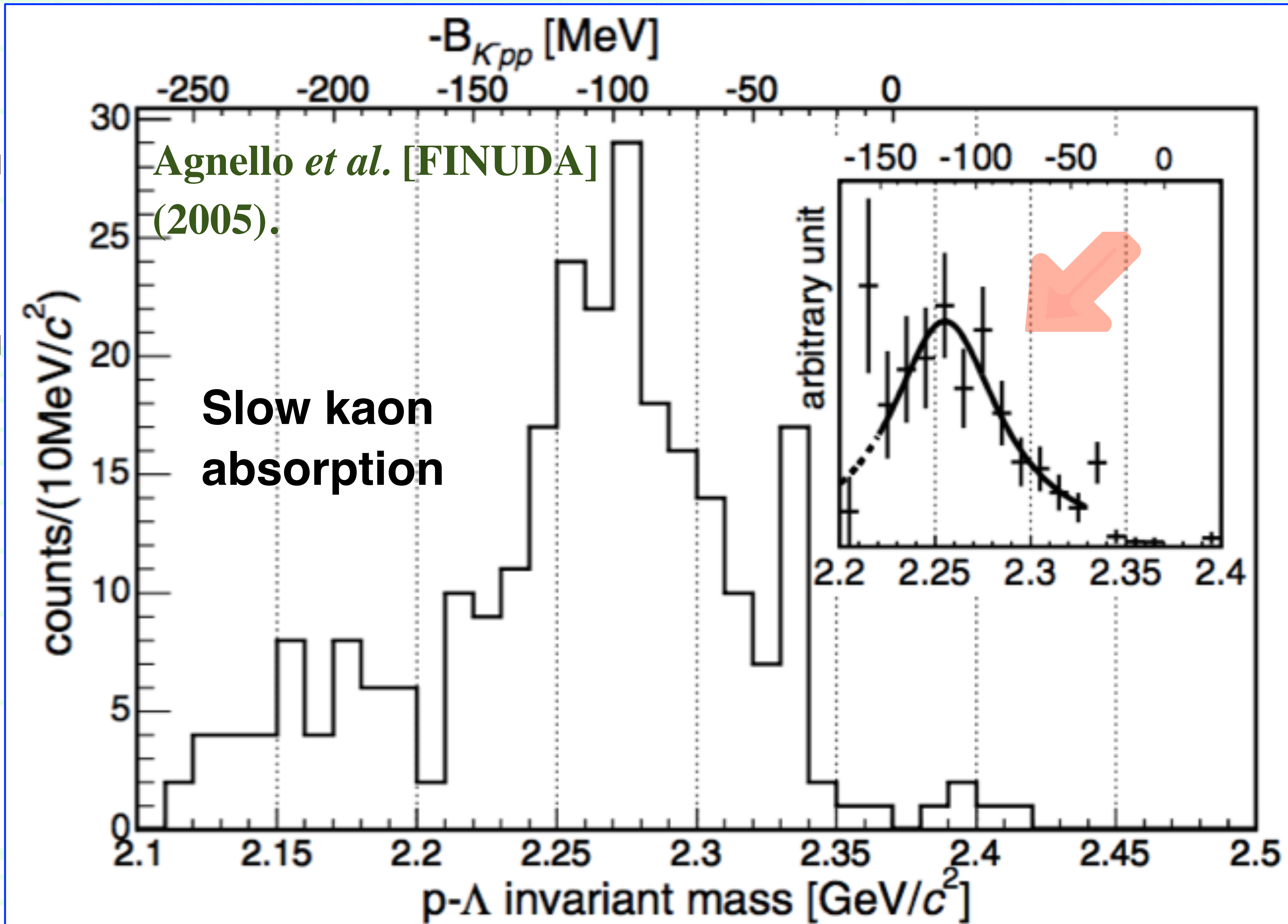
    Akaishi and Yamazaki, *Phys. Rev.* C65 (2002) 044005;
    Shevchenko, Gal and Mares, *Phys. Rev. Lett.* 98 (2007) 082301;
    Ikeda and Sato, *Phys. Rev.* C76 (2007) 035203; Dote, Hyodo and Weise, *Nucl. Phys.* A804 (2008) 197;
    Wycech and Green, *Phys. Rev.* C79 (2009) 014001;
    Bayar, Yamagata-Sekihara 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.

1. Introduction



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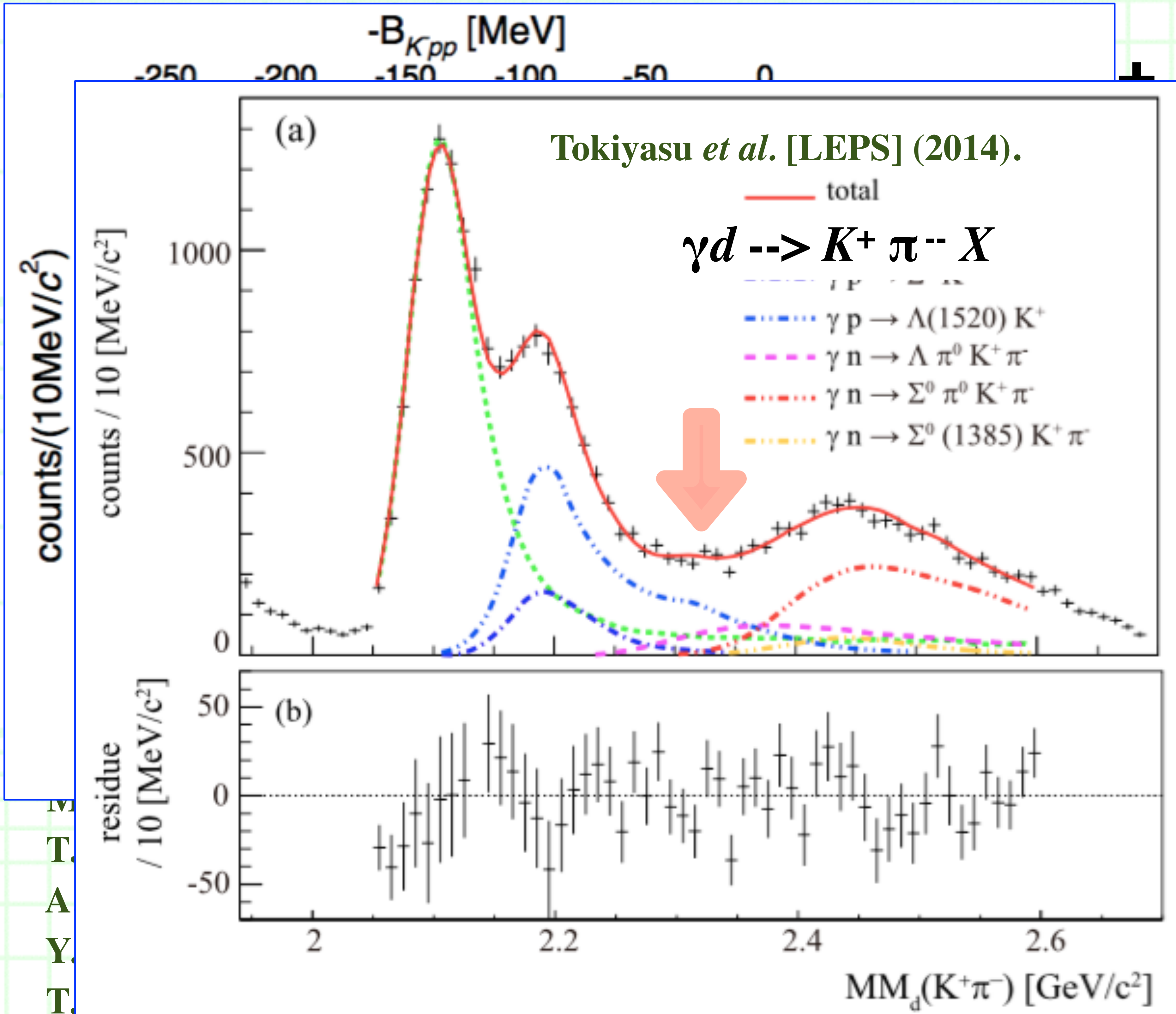

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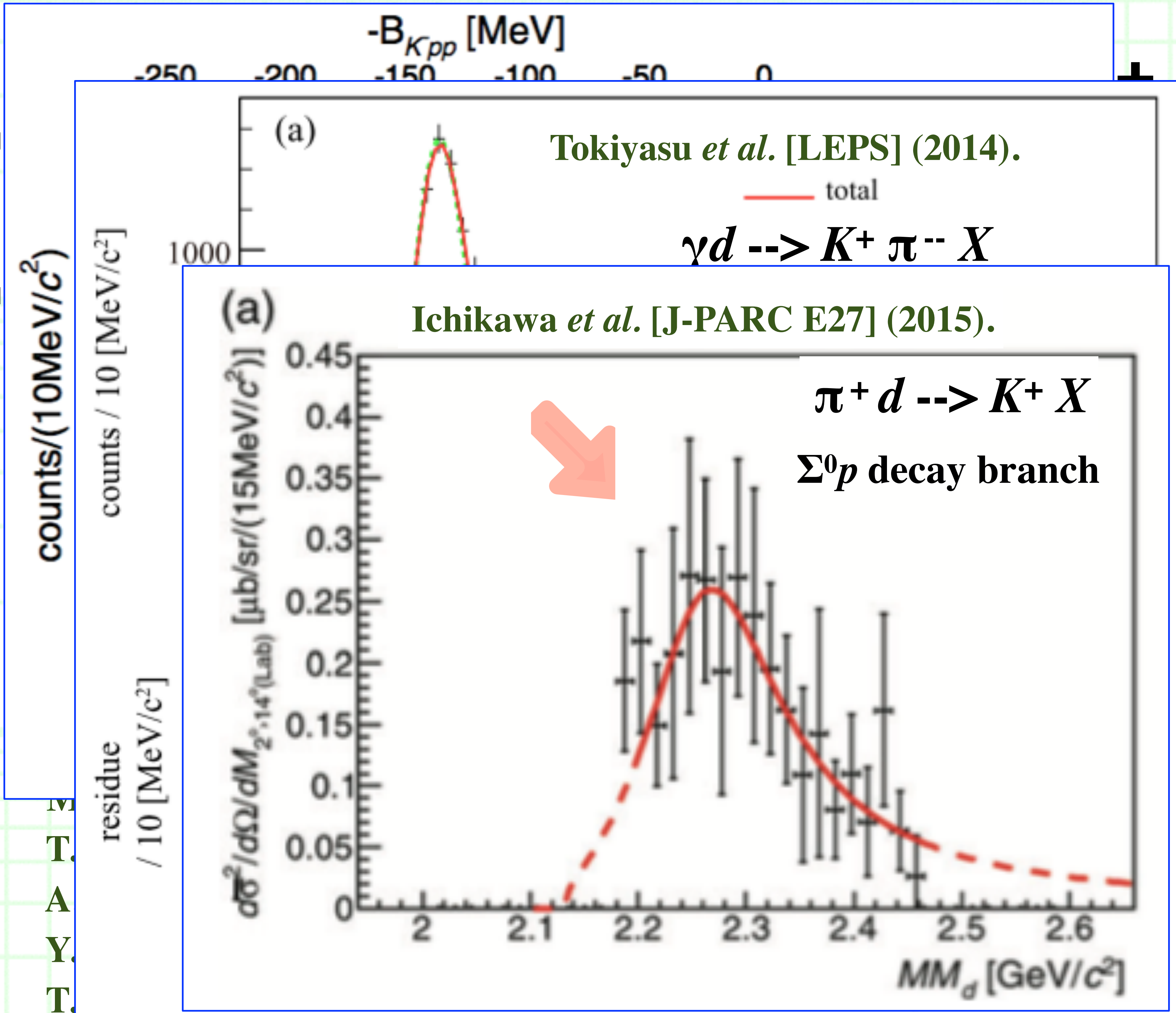

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KbarNN
by Jido-san

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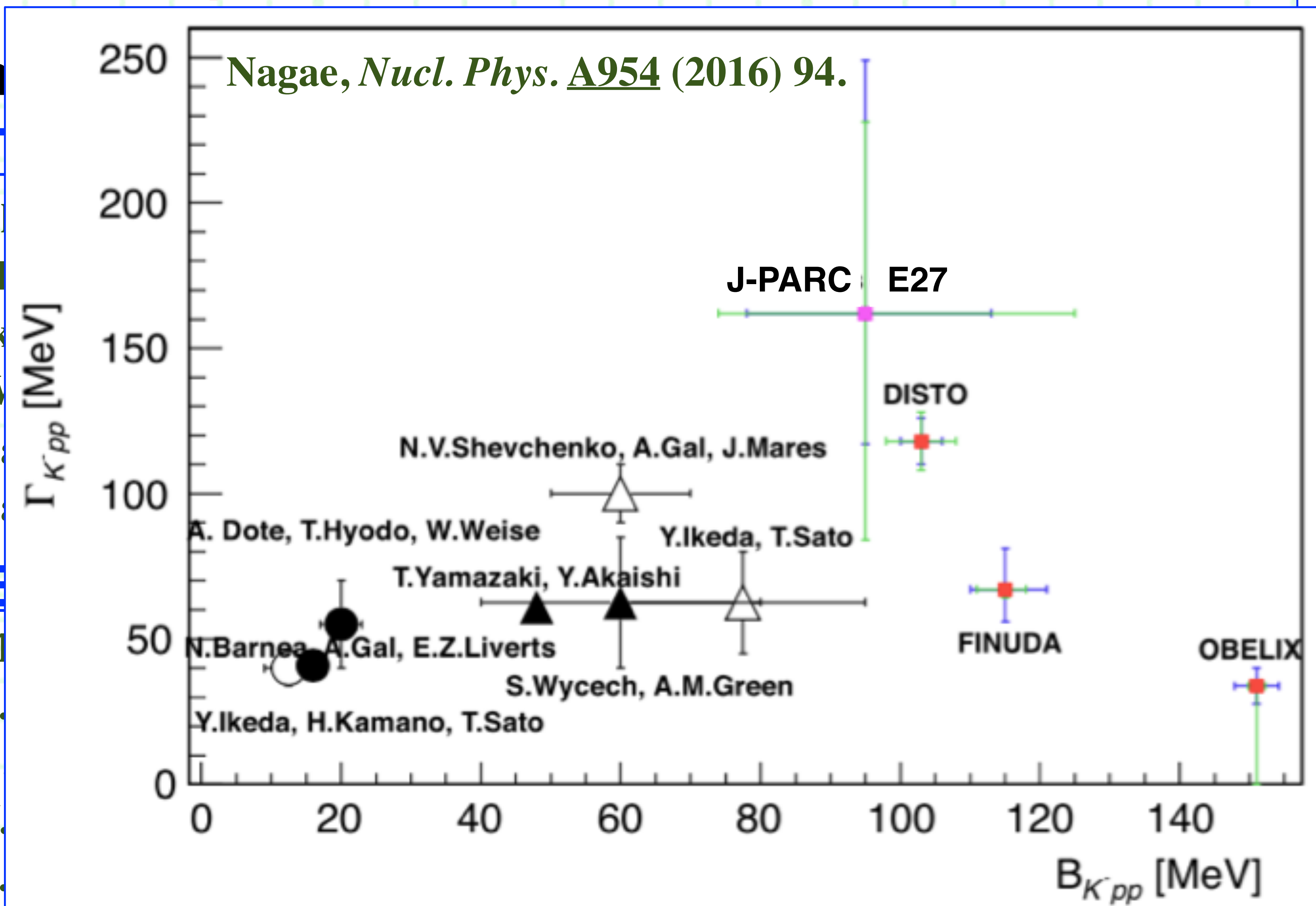

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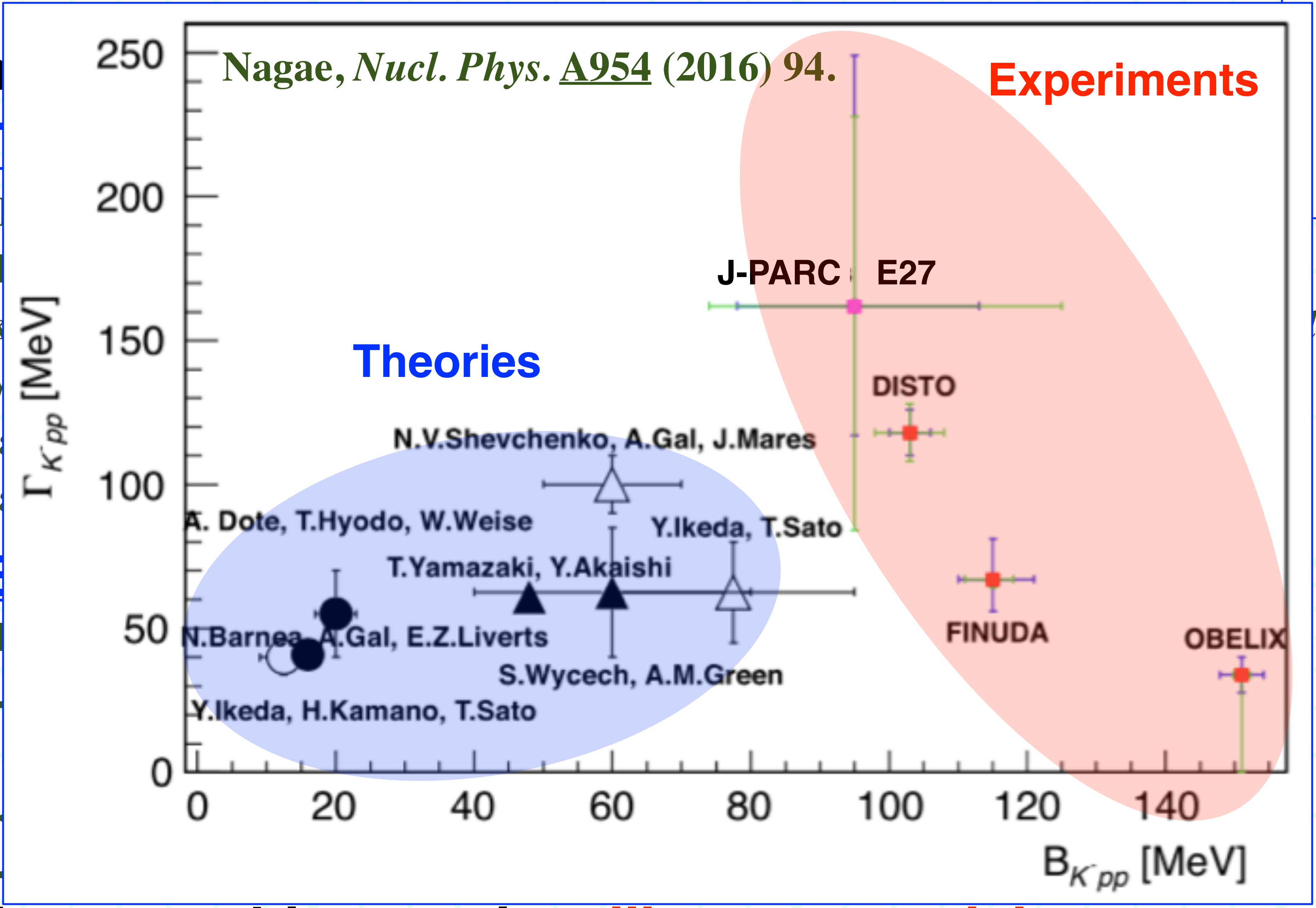

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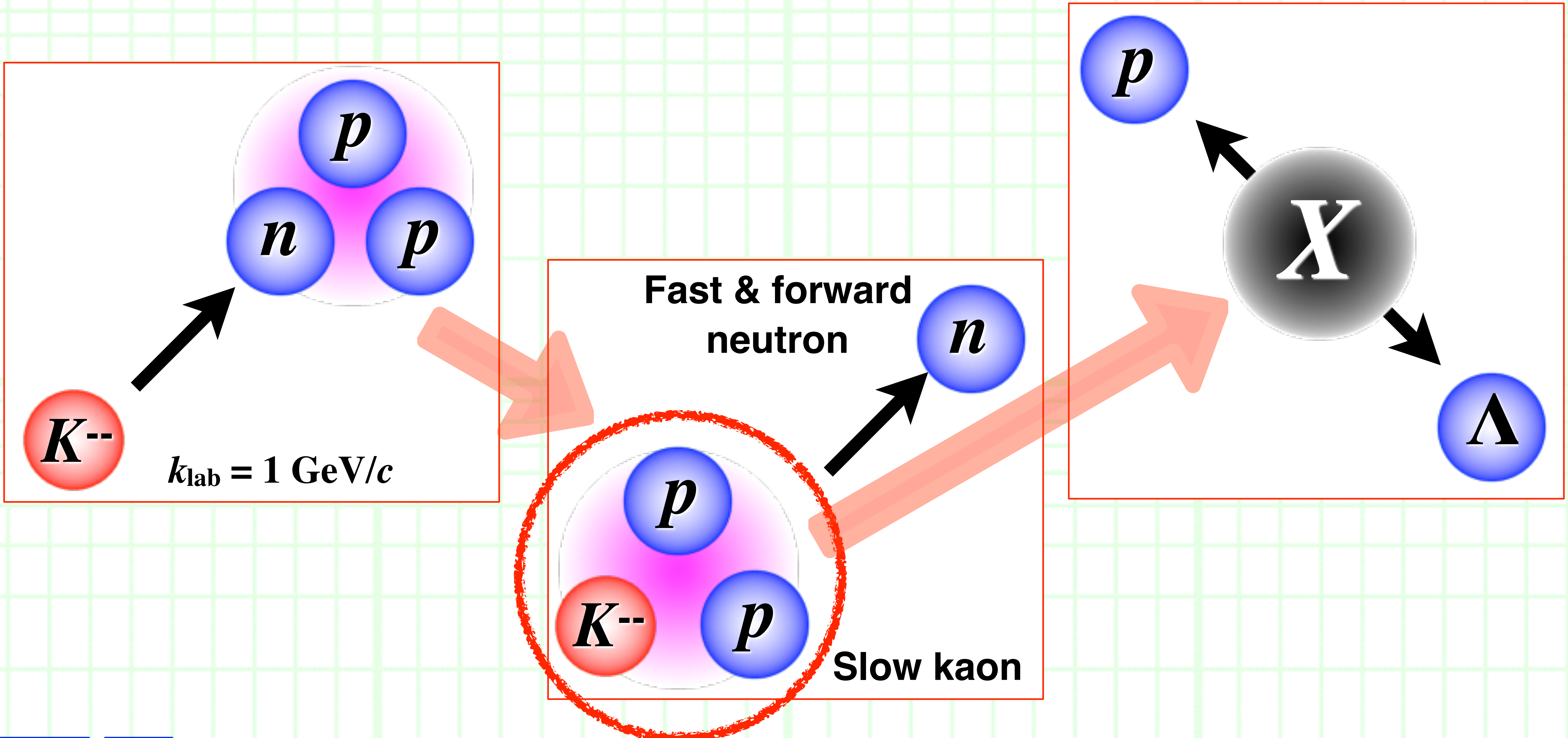
1. Introduction

++ J-PARC E15 data ++

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

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

- **Reaction mechanism:**



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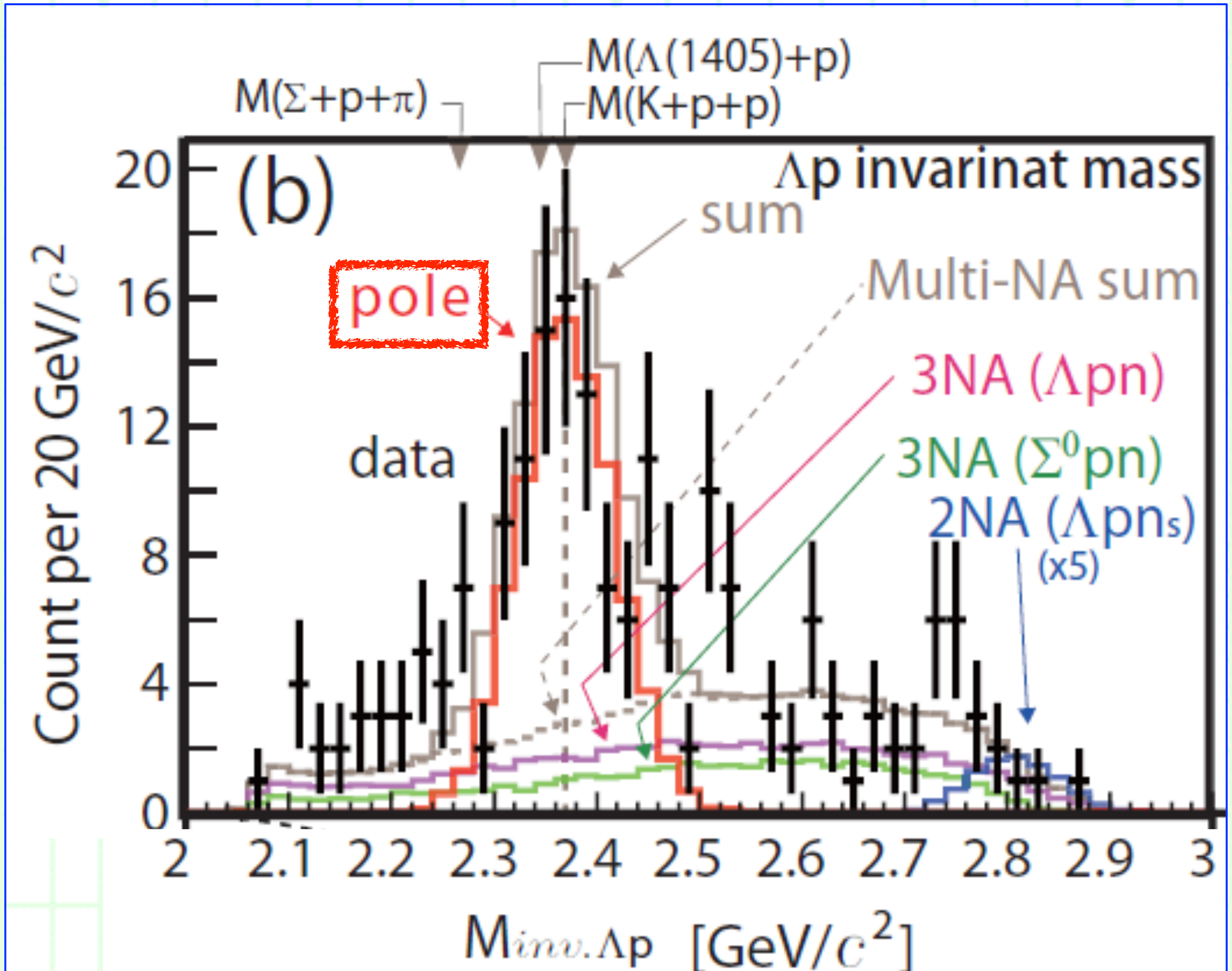

1. Introduction

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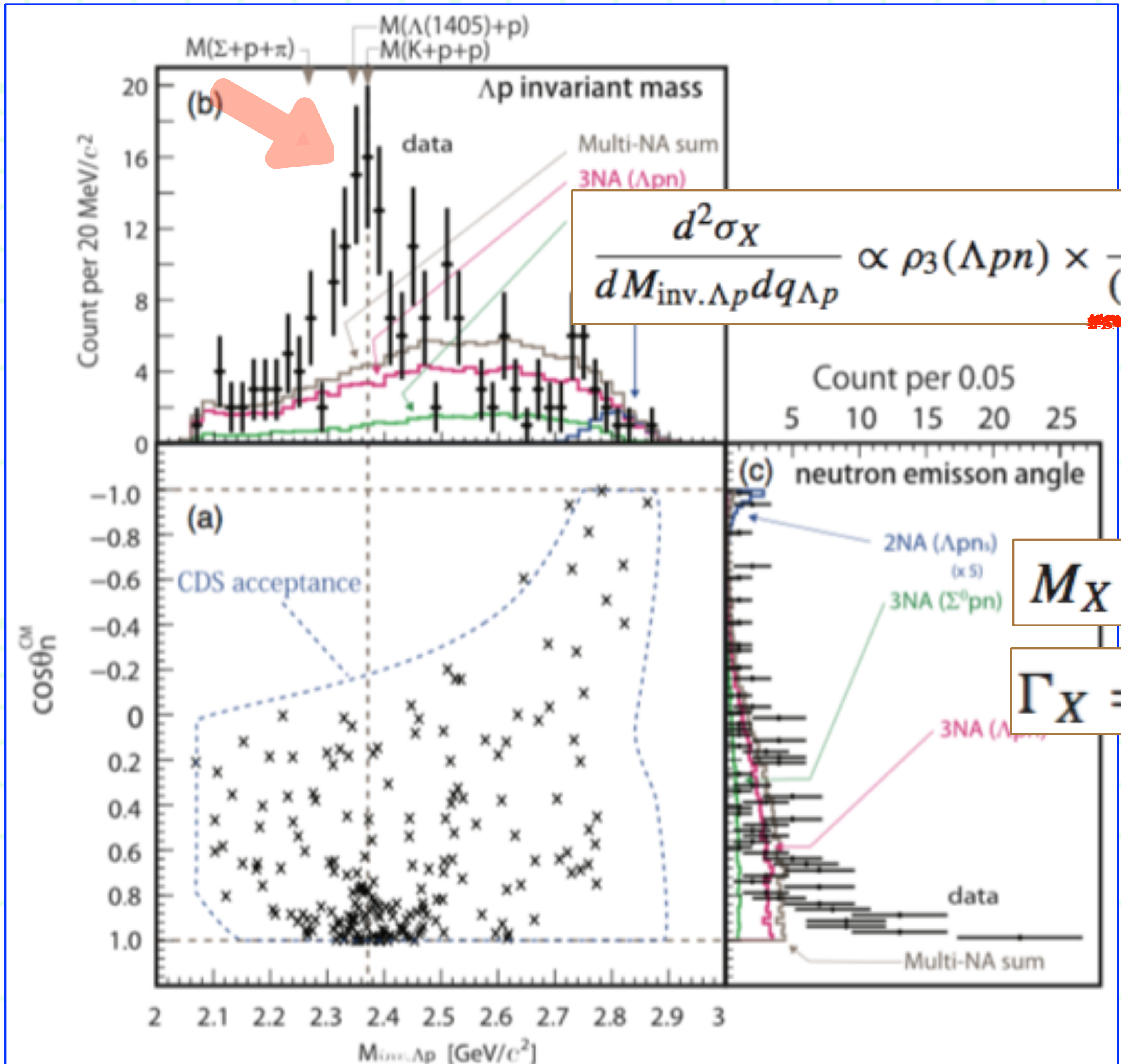


Y. Sada *et al.*, *PTEP* 2016 051D01.

- **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 ???**

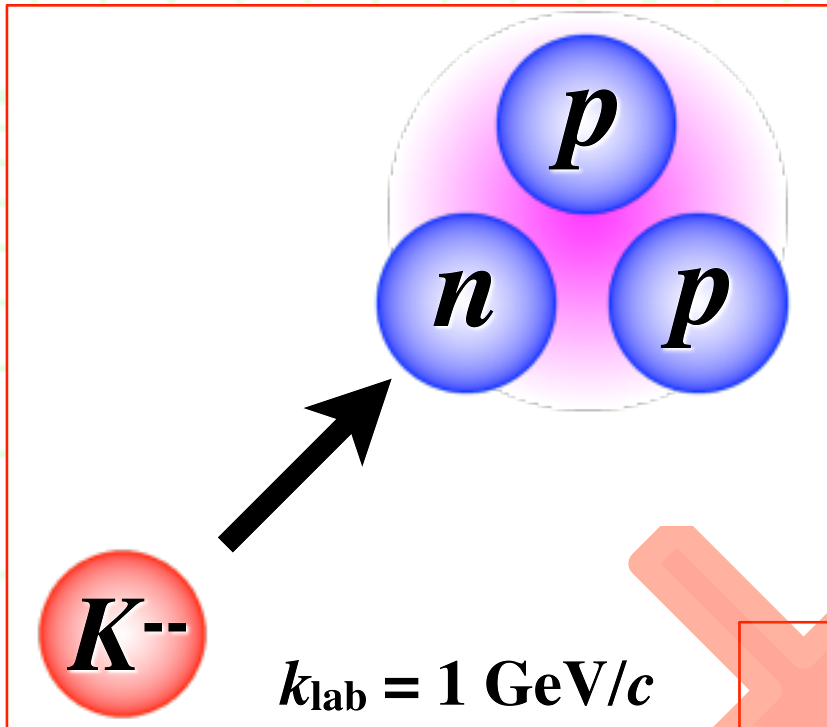
2. What makes the peak structure in the J-PARC E15 experiment ?

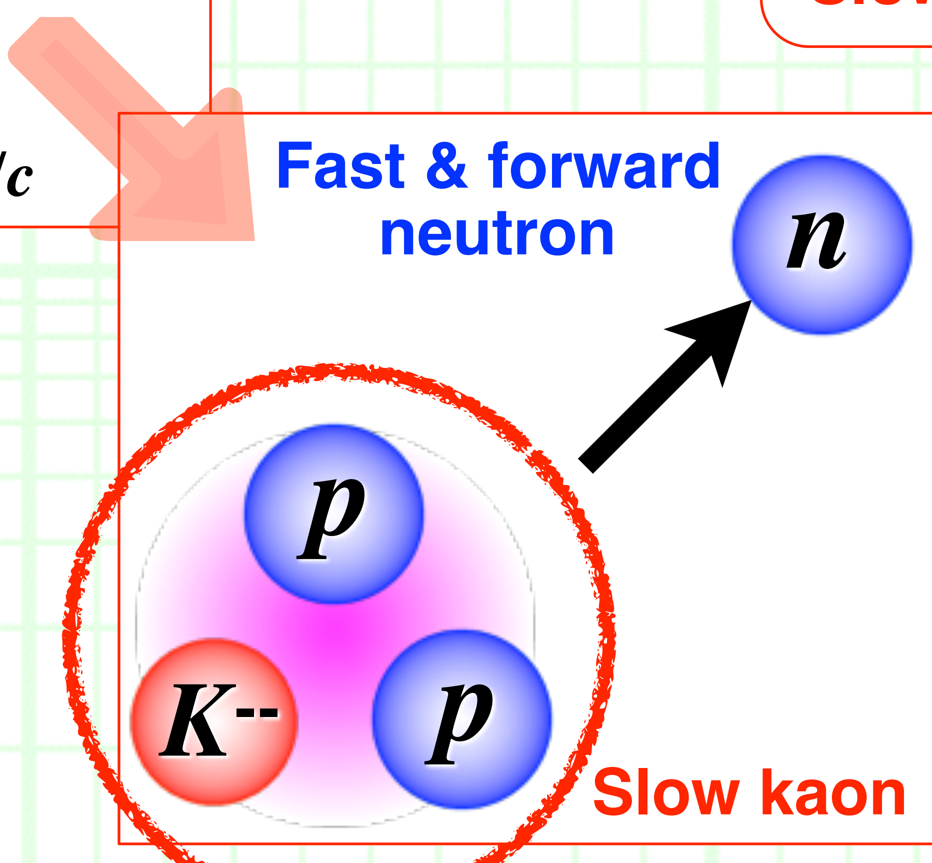
2. What makes the peak structure ?

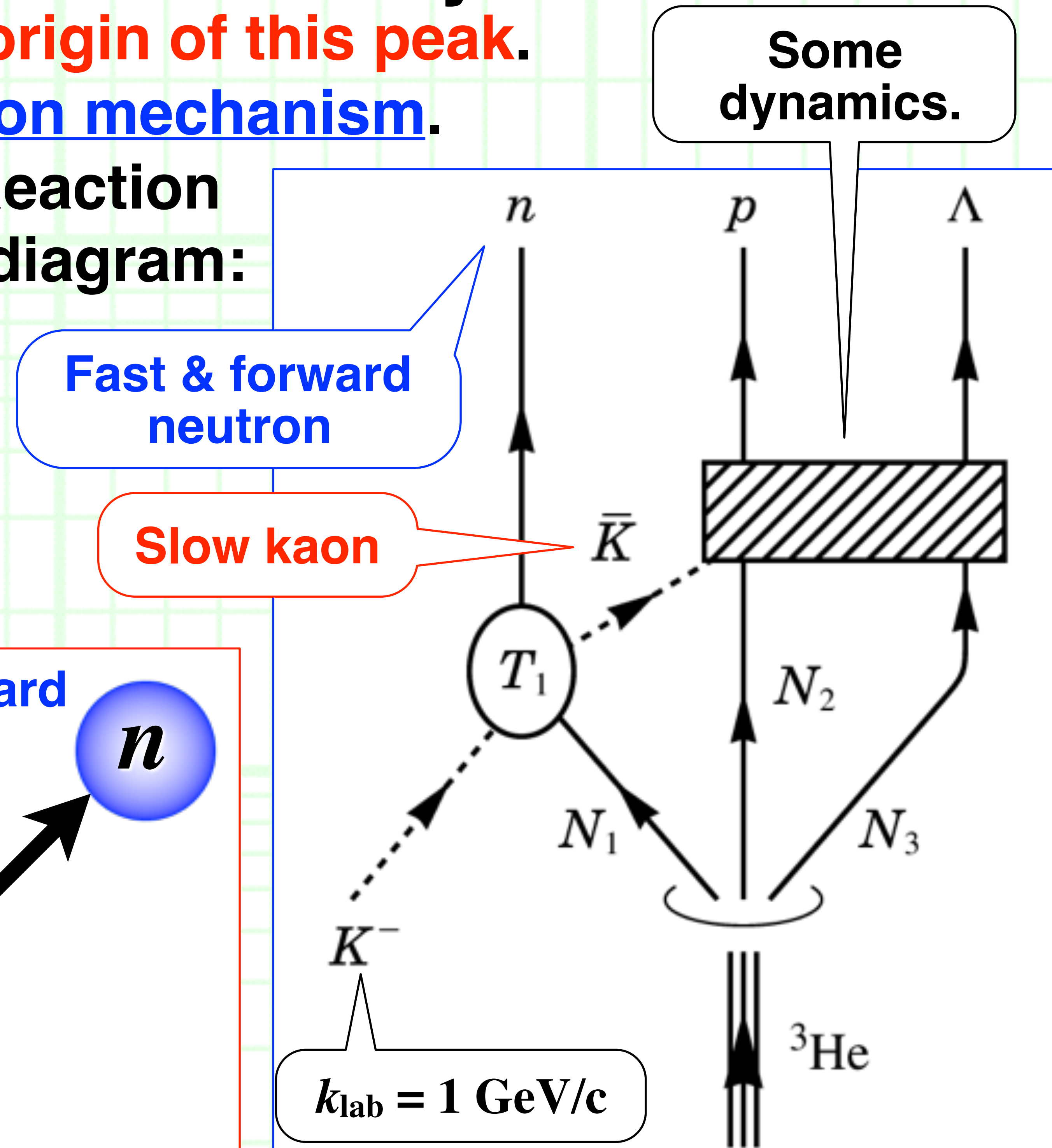
++ Purpose of this study ++

- We want to **know what is the origin of this peak.**
  - First, we **pin down the reaction mechanism.**

--> Reaction diagram:





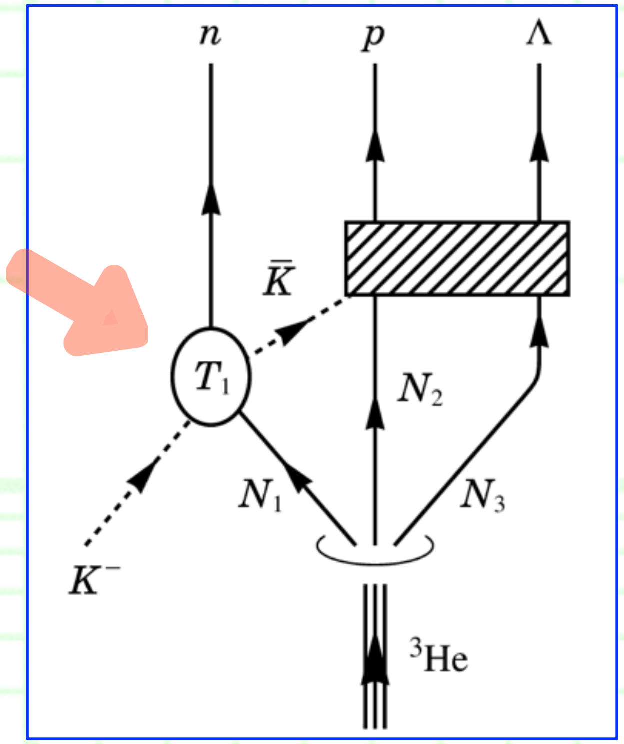


2. What makes the peak structure ?

++ First collision ++

- **Amplitude T_1 (k_{lab} = 1 GeV/c):**

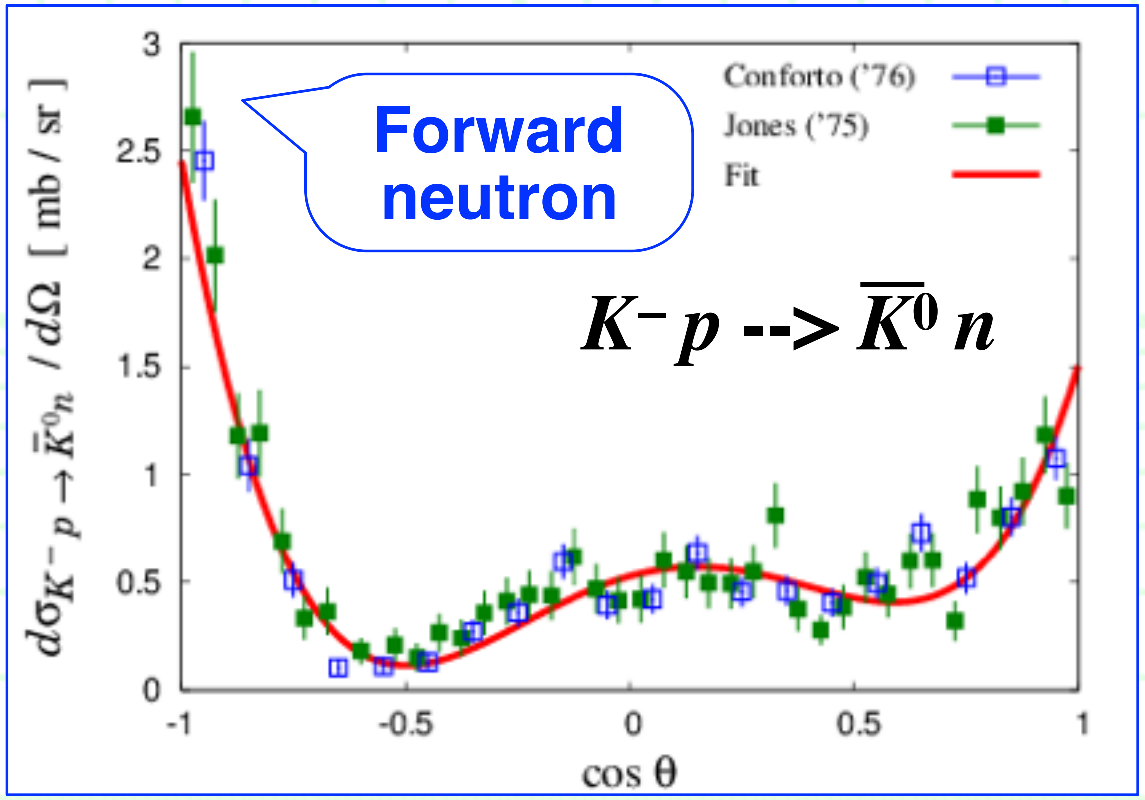
$$\begin{cases} K^- n \to K^- n_{\text{escape}} \\ K^- p \to \bar{K}^0 n_{\text{escape}} \end{cases}$$

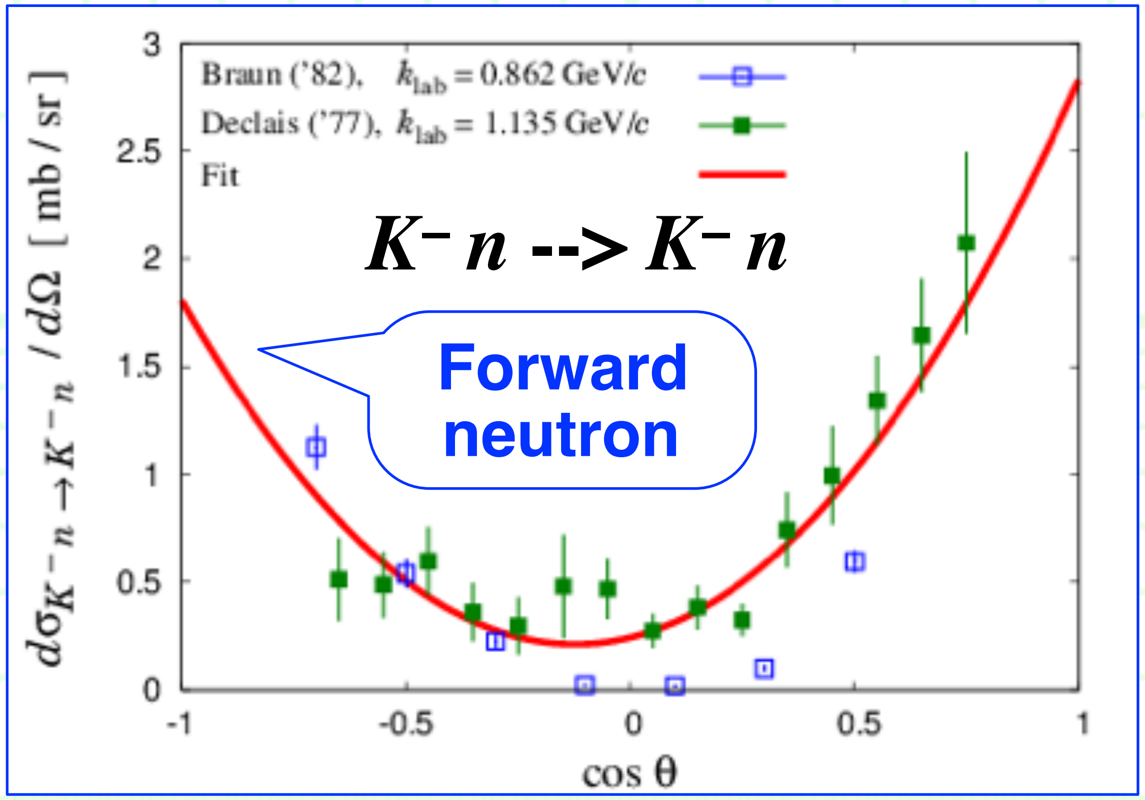


--- Fitted so as to reproduce the Exp. dσ/dΩ.

$$T_{\bar{K}N\to\bar{K}N}(\cos\theta) = \frac{4\pi w}{m_N}\left(\frac{d\sigma_{\bar{K}N\to\bar{K}N}}{d\Omega}\right)^{1/2}$$

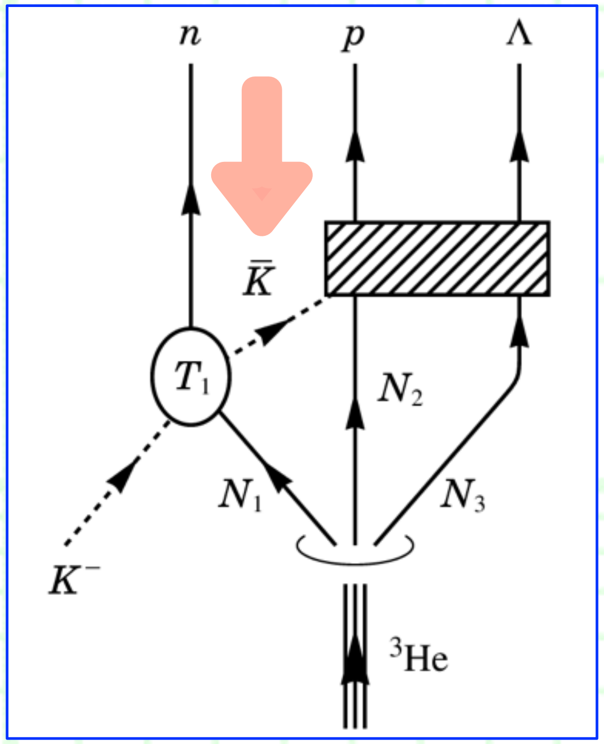
- **dσ$_{KN \to KN}$/dΩ favors forward neutron emission in ^{3}He (K^-, Λp) n !**





--- Note: Form factor for the $\bar{K}$ absorption also favors forward n.

2. What makes the peak structure ?



++ Propagating kaon ++

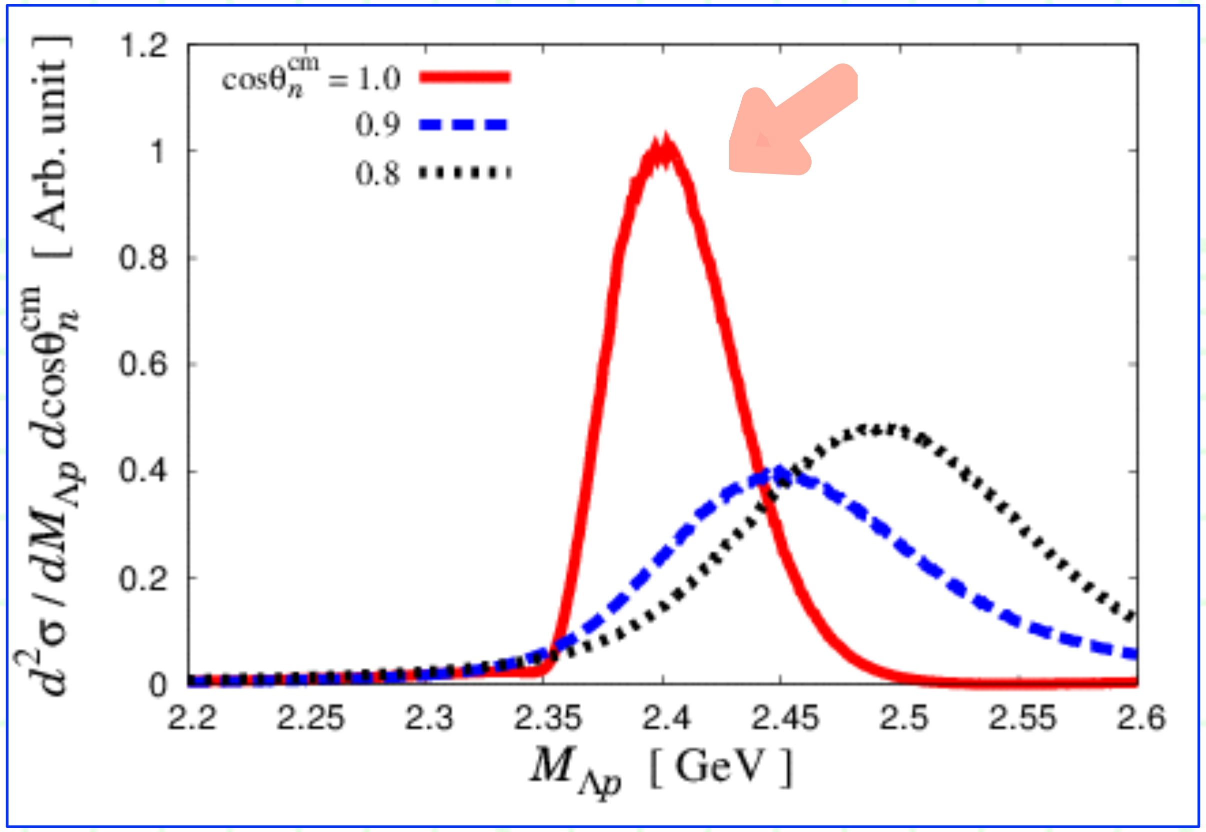
- **The slow kaon after the first collision propagates and is absorbed into two nucleons.**
  - **The expression of the propagator:**

$$= \frac{1}{(p^{\mu}_{\rm prop})^2 - m_K^2 + i m_K \Gamma_K}$$

--- **Two-nucleon Abs. width Γ_K = 15 MeV.**

--> This can create a "kinematic peak", because the propagating kaon can go almost on its mass shell.

(1 / prop ~ 0)



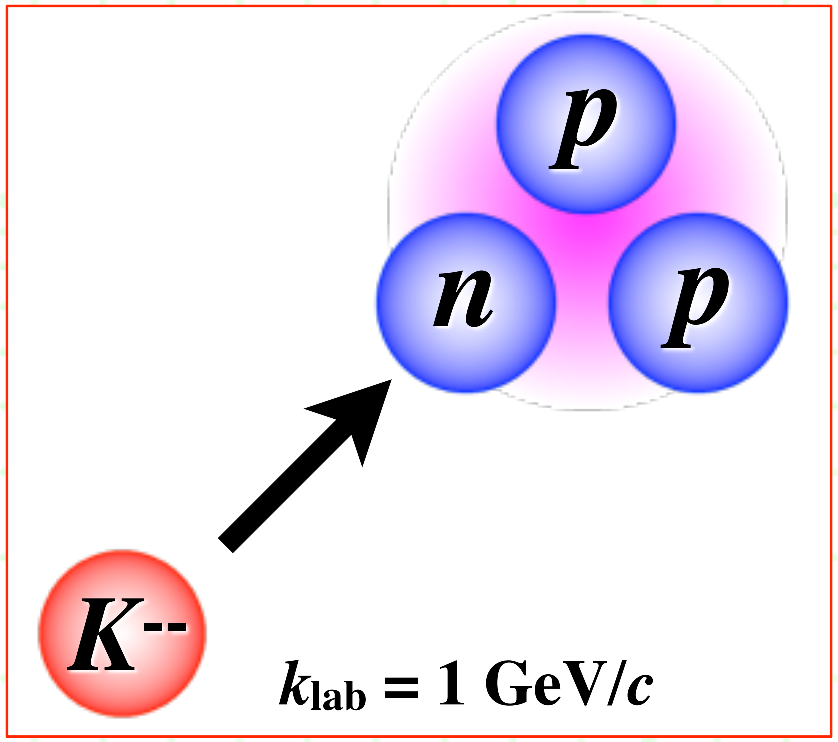
- **Taking the shaded box = 1.**
  (w/o dynamics of $\bar{K}NN$ system)

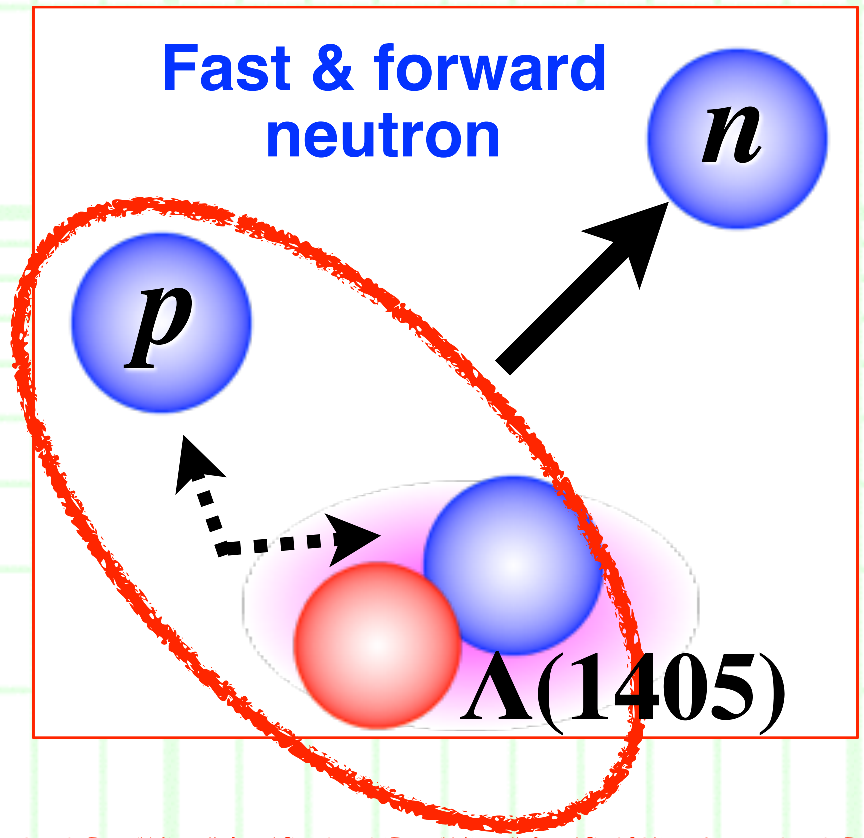
--> The quasi-elastic kaon scattering in the first step.

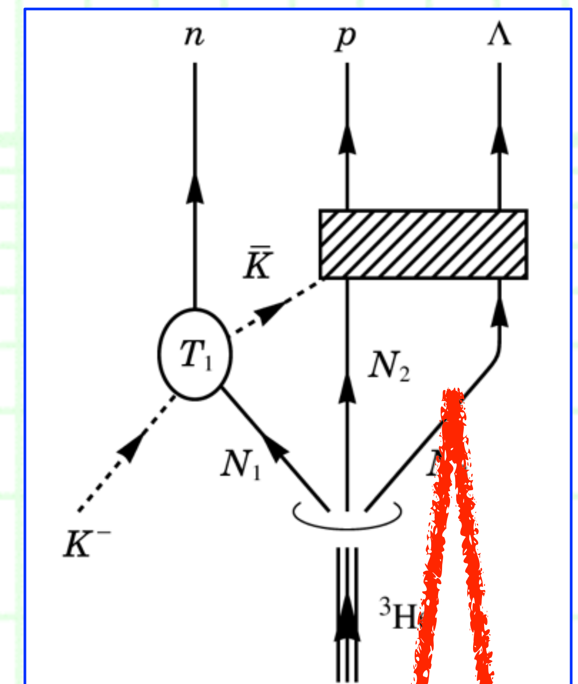
2. What makes the peak structure ?

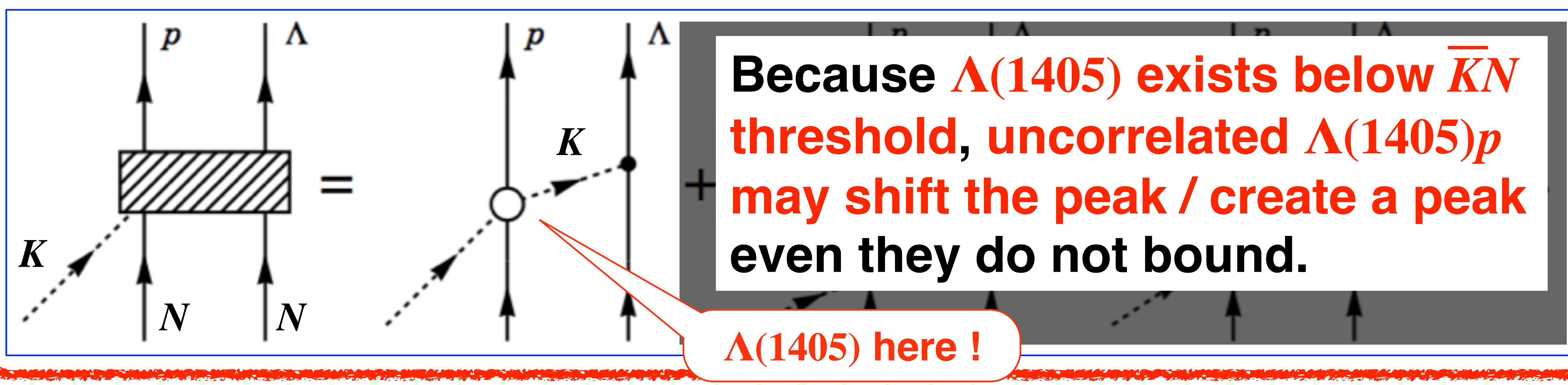
++ Scenario I: Uncorrelated $\Lambda(1405)p$ ++

- We now consider scenario I: Uncorrelated $\Lambda(1405)p$.







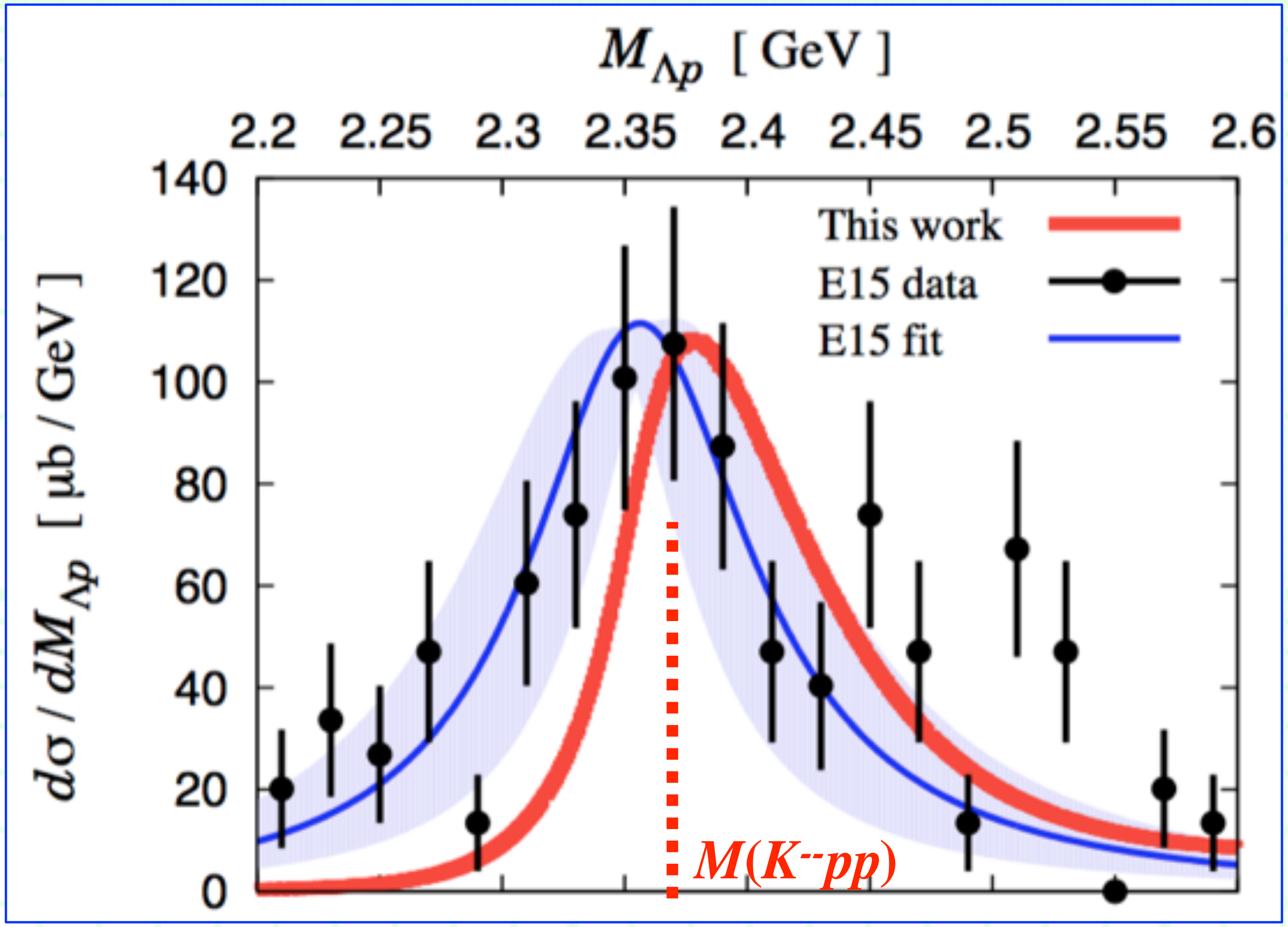


Because $\Lambda(1405)$ exists below $\bar{K}N$ threshold, uncorrelated $\Lambda(1405)p$ may shift the peak / create a peak even they do not bound.

2. What makes the peak structure ?

++ Uncorrelated $\Lambda(1405)p$: Numerical results ++

- Now we calculate the Λp mass spectrum of the ^{3}He (K^- , Λp) n reaction in the uncorrelated $\Lambda(1405)p$ scenario.



- The peak position is inconsistent with the Exp.

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

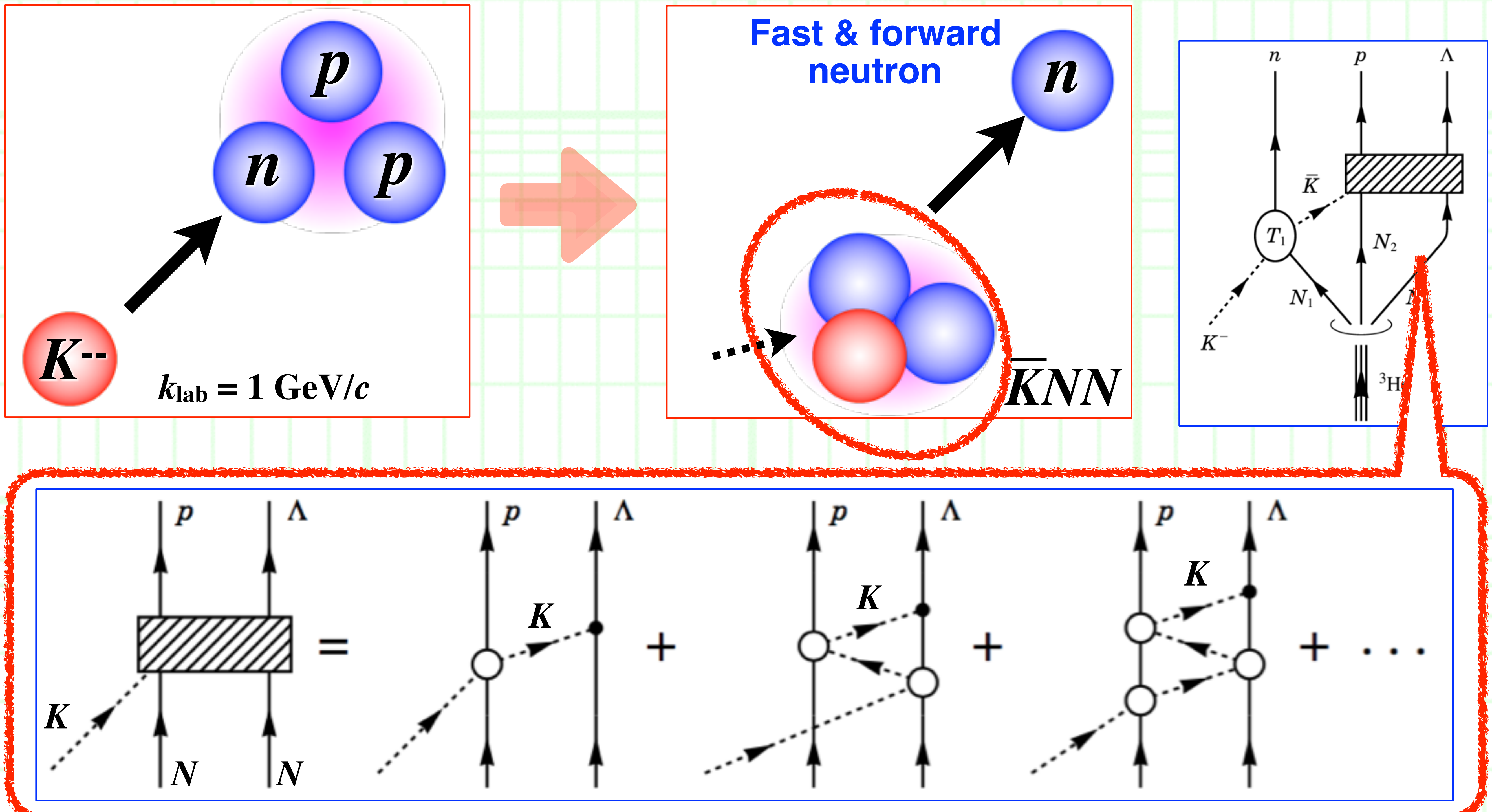
- In particular, we cannot reproduce the behavior of the lower tail ~ 2.3 GeV.

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

2. What makes the peak structure ?

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

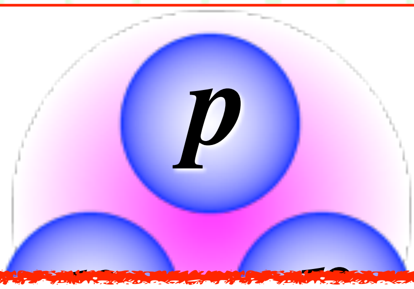
- We next consider <u>scenario II</u>: $\bar{K}NN$ **bound state**. Signal is strong ?



2. What makes the peak structure ?

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

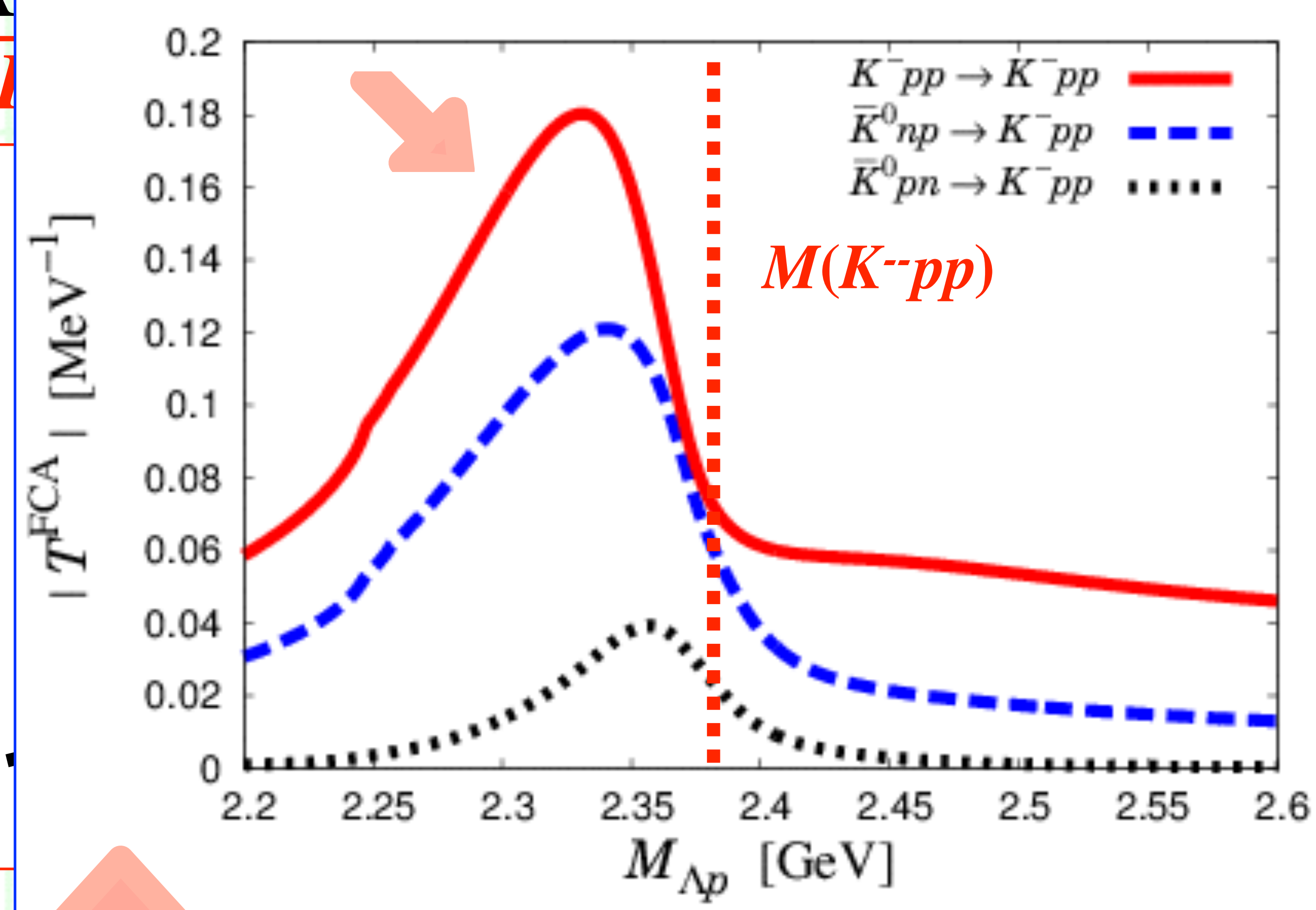
- We next consider scenario II: ...

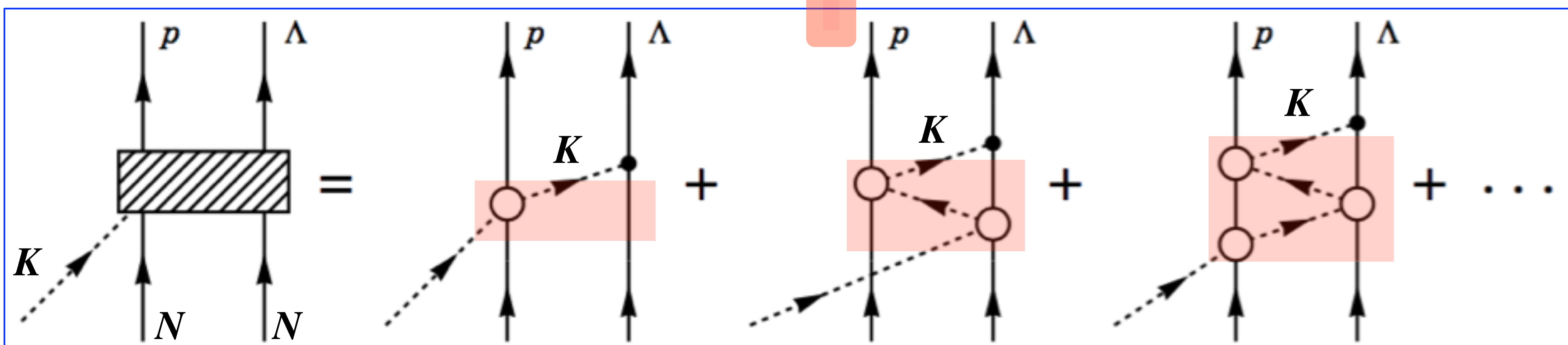


--- Fixed center Approx. (FCA) amplitude has a peak of KNN bound state.

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

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

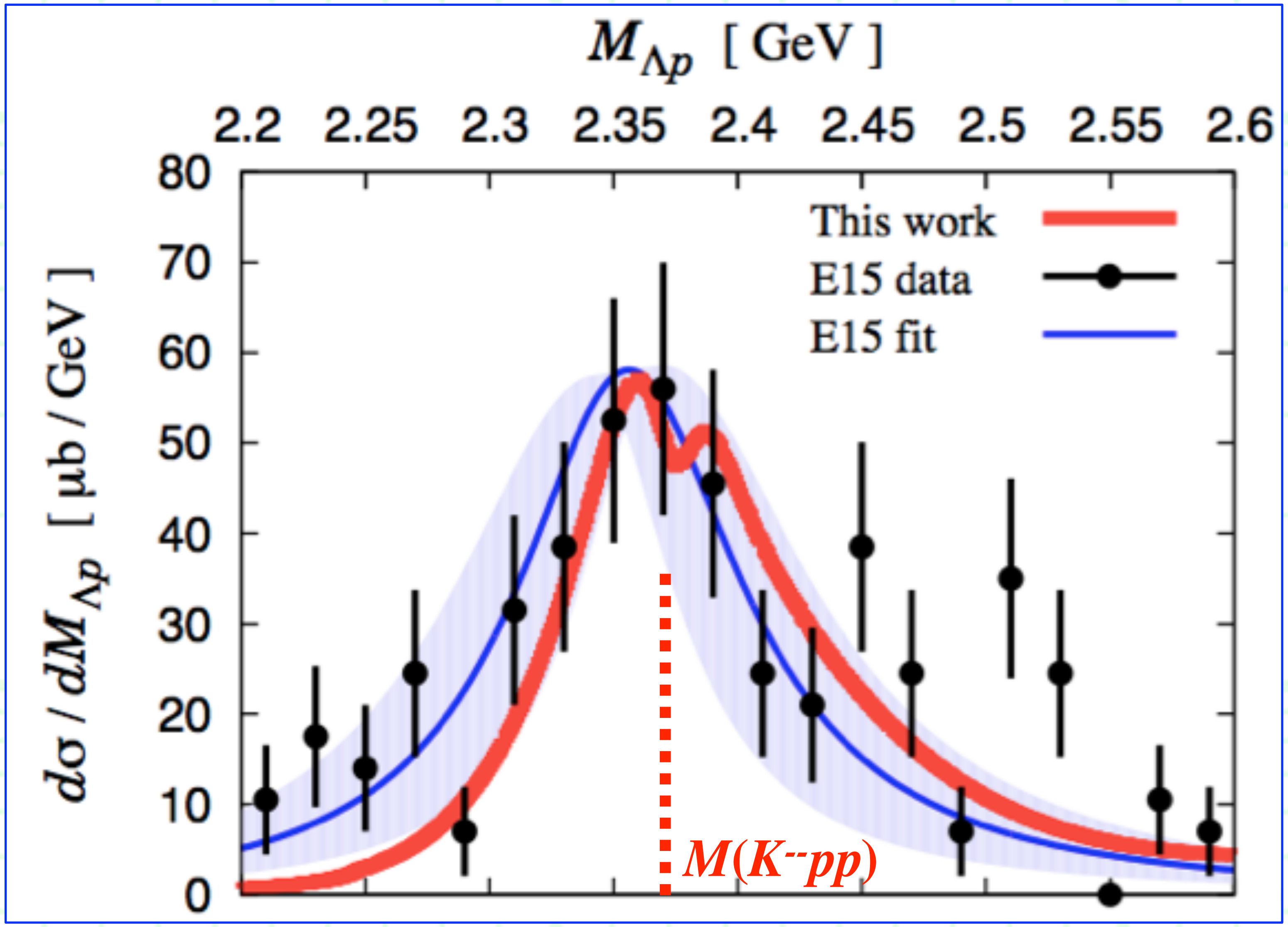




2. What makes the peak structure ?

++ $\bar{K}NN$ bound state: Numerical results ++

- We calculate the mass spectrum 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.

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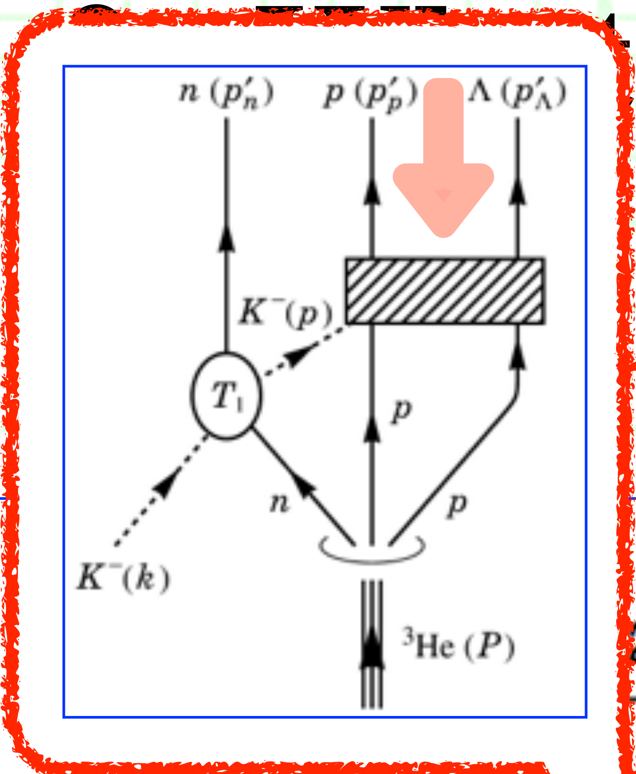
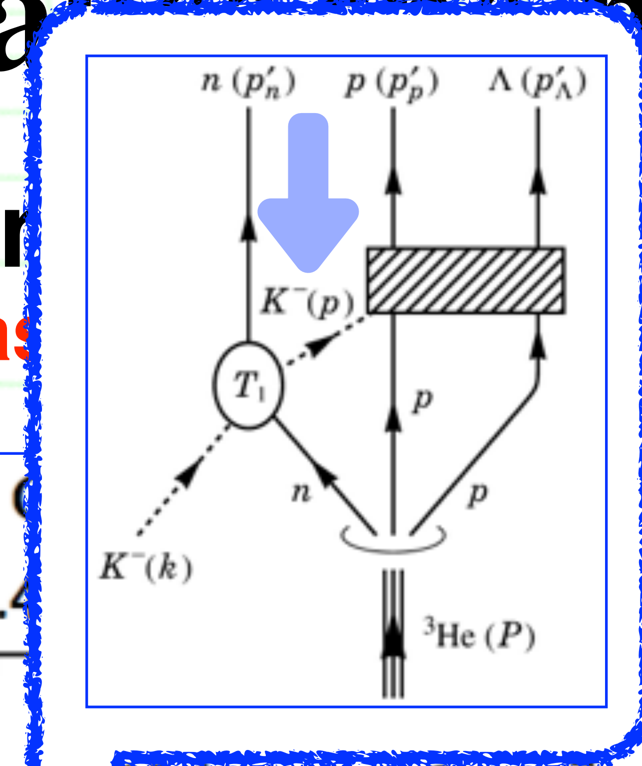
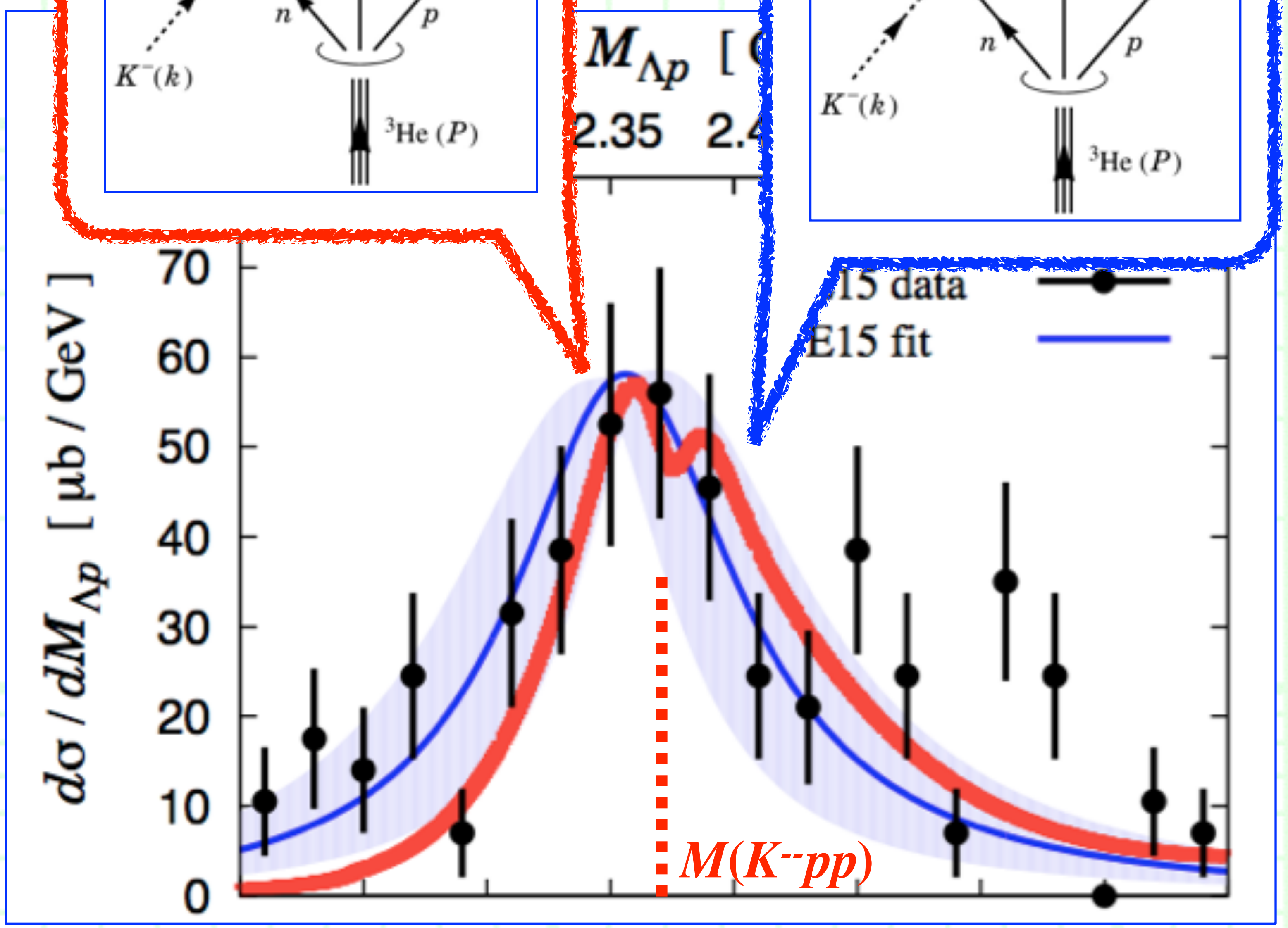






- One more thing: Our spectrum has **a "double peak" structure around the $\bar{K}NN$ threshold.**

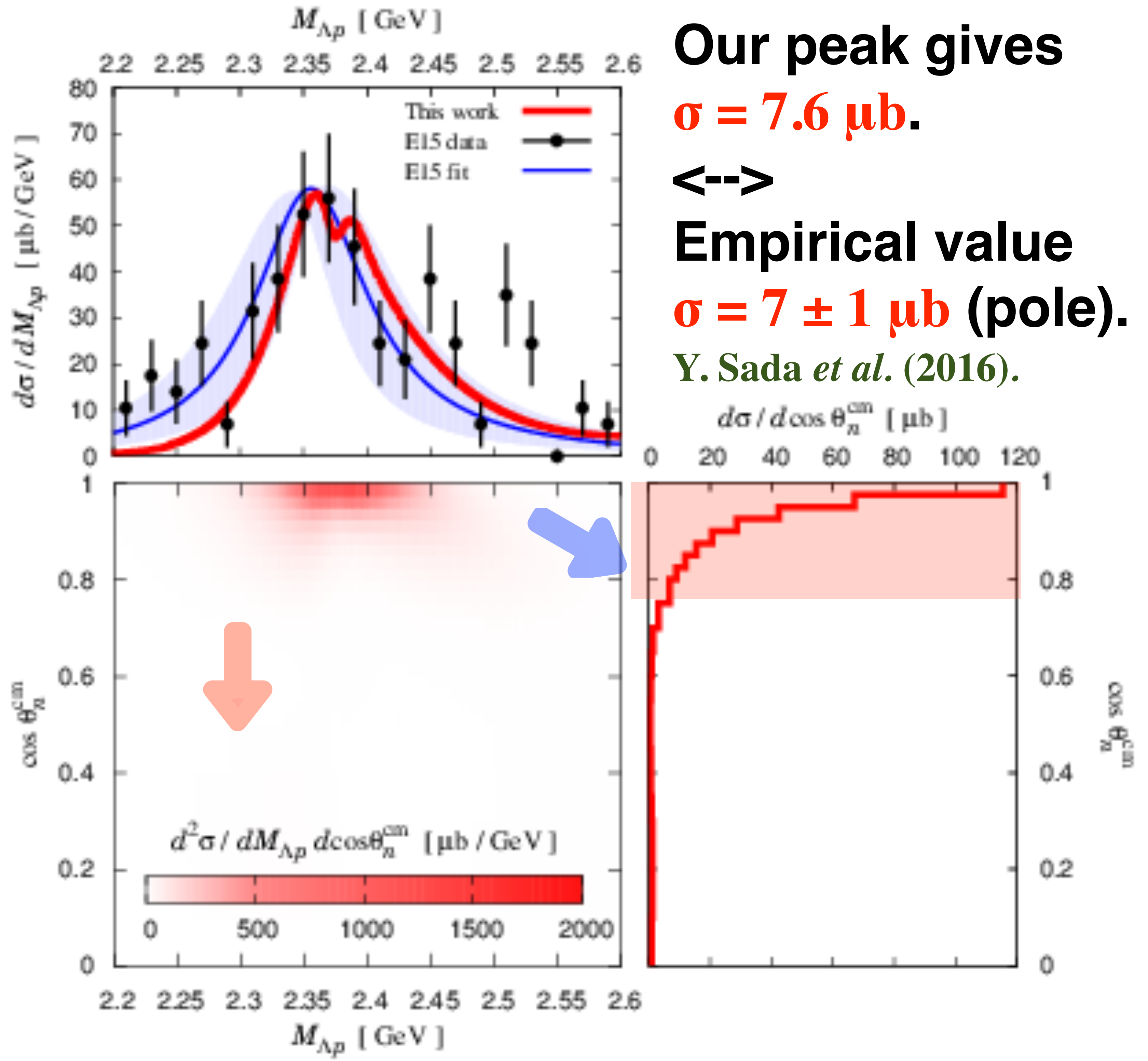
--- The lower peak is the signal of the $\bar{K}NN$ bound state.

--- The higher peak comes from kinematic reason: The quasi-elastic kaon scattering in the 1st step.

<-- **Almost on-shell kaon.**

2. What makes the peak structure ?

++ $\bar{K}NN$ 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.

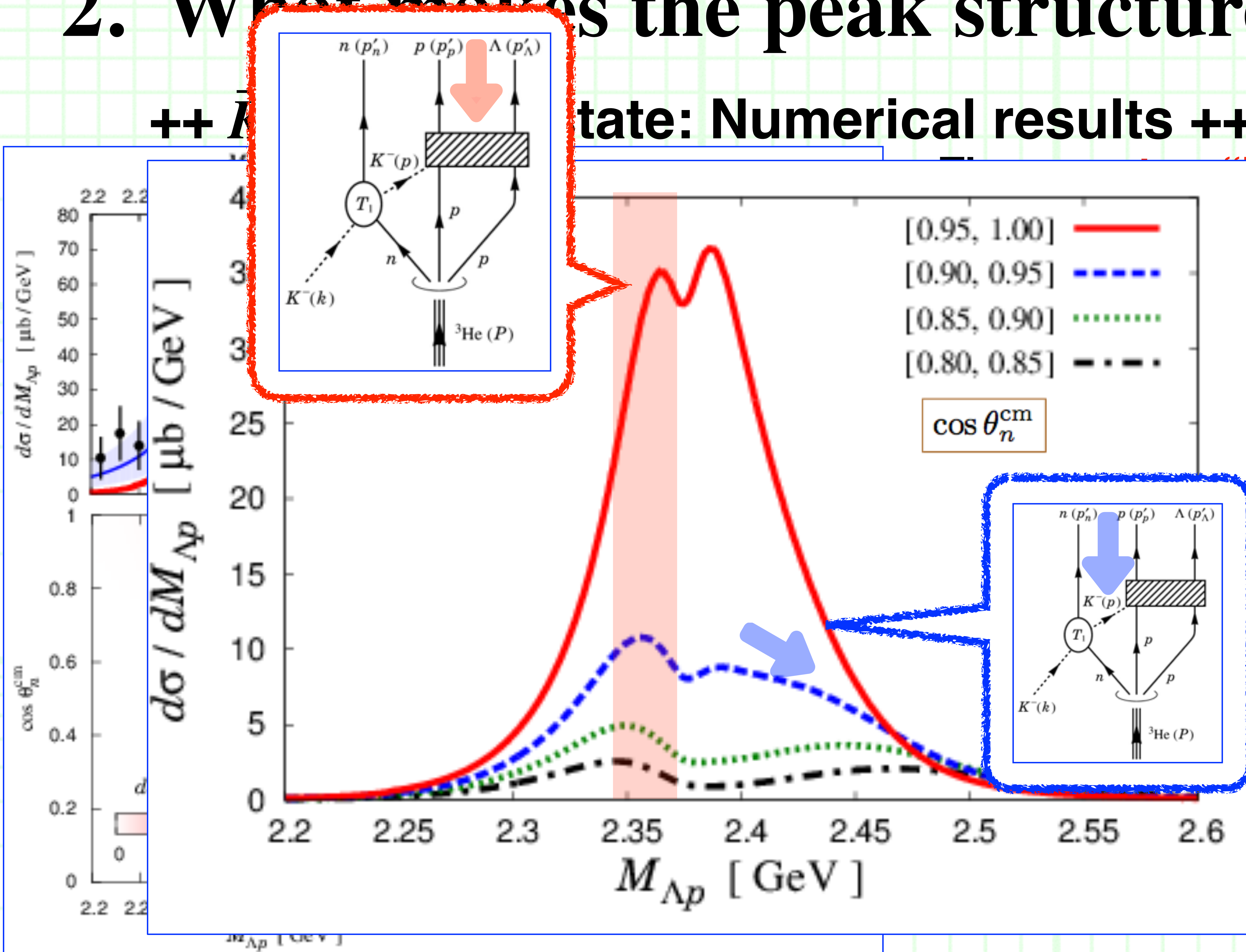
- Diff. cross section $d\sigma/d\cos\theta_n$ indicates forward neutron emission is favored.

--- FF and $d\sigma/d\Omega$ of:

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

2. What makes the peak structure ?

++ $\bar{K}$ ... state: Numerical results ++



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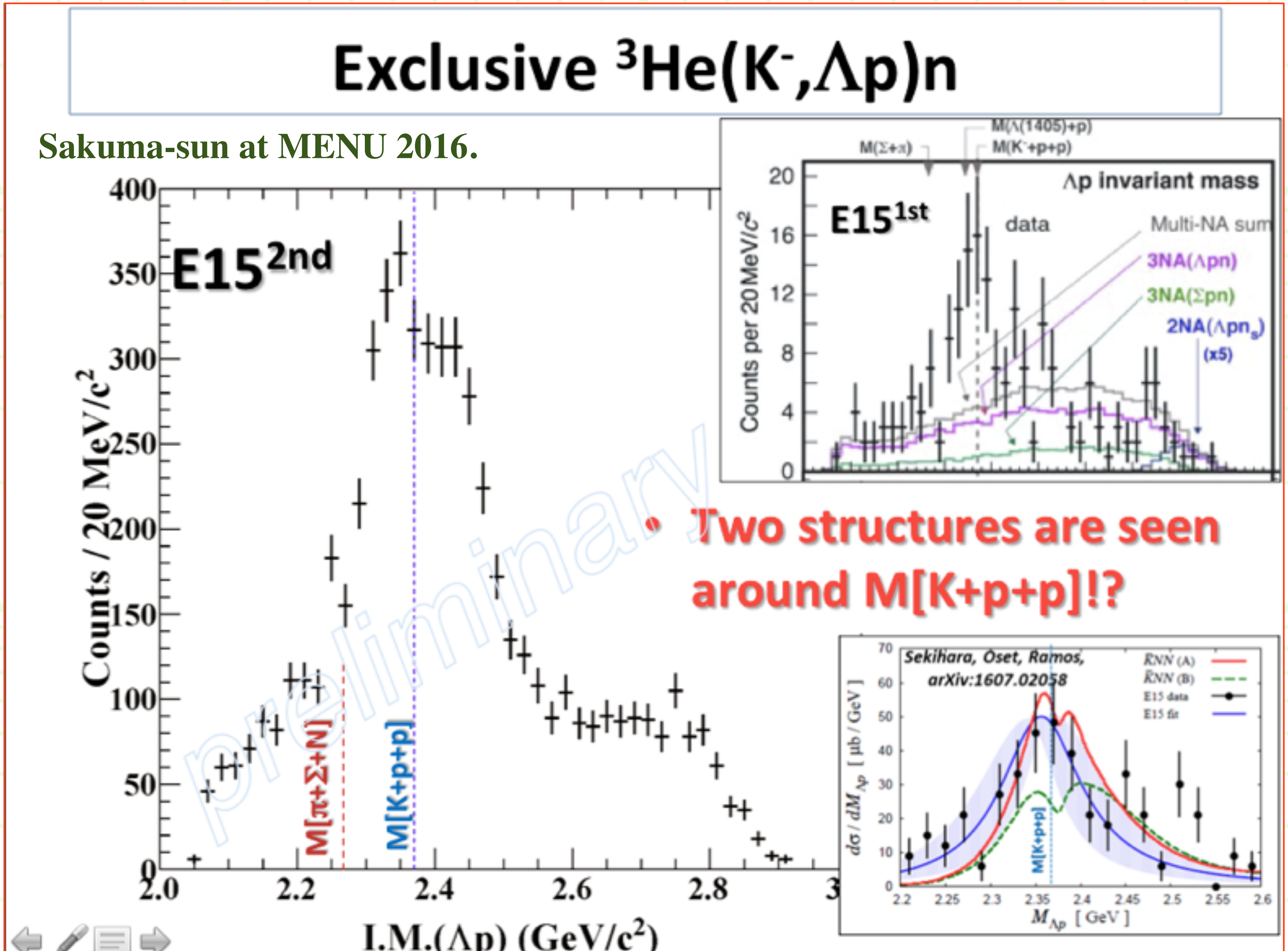
2. What makes the peak structure ?

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



3. Summary

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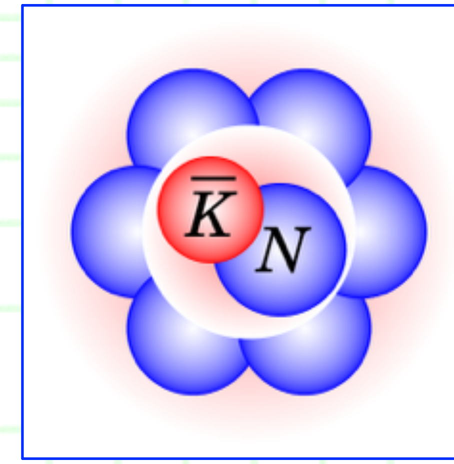

- There should exist **kaonic nuclei**, generated by the strong interaction between antikaon and nuclei.

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

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

1. <u>Uncorrelated $\Lambda(1405)p$</u>, which does not make a bound state.
   --> Inconsistent with the Exp. data.

2. <u>$\bar{K}NN$ bound state</u>.
   --> <u>Qualitatively well reproduce</u> the Exp. data.

* * *

- <u>We must "prove" the E15 peak is indeed the $\bar{K}NN$ signal.</u>

--- Need to check <u>consistency between experiments and theories</u>.

- □ <u>High statistics data</u> from Exp. & <u>More precise calc.</u> from theory.
- □ <u>Angular dependence</u> of the peak structure.
- □ <u>Branching ratio $\Lambda p / \Sigma^0 p$.</u>   □ <u>Spin / parity of the structure.</u>   □ ...

Thank you very much for your kind attention !