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.)

and Angels RAMOS (Barcelona Univ.)

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

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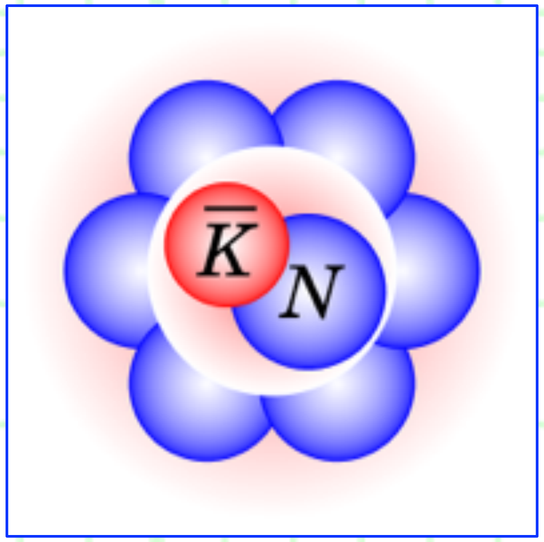


Kaonic nuclei

1. Introduction

2. Kaonic nuclei: up to now

3. On the peak of the J-PARC E15 experiment:

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

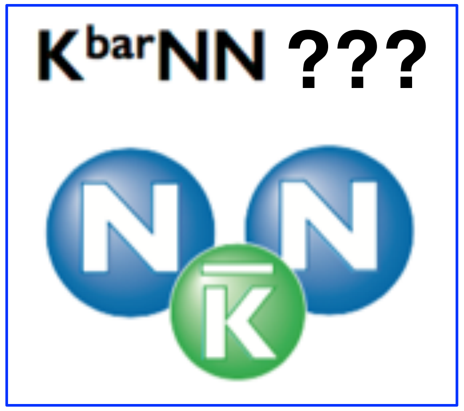
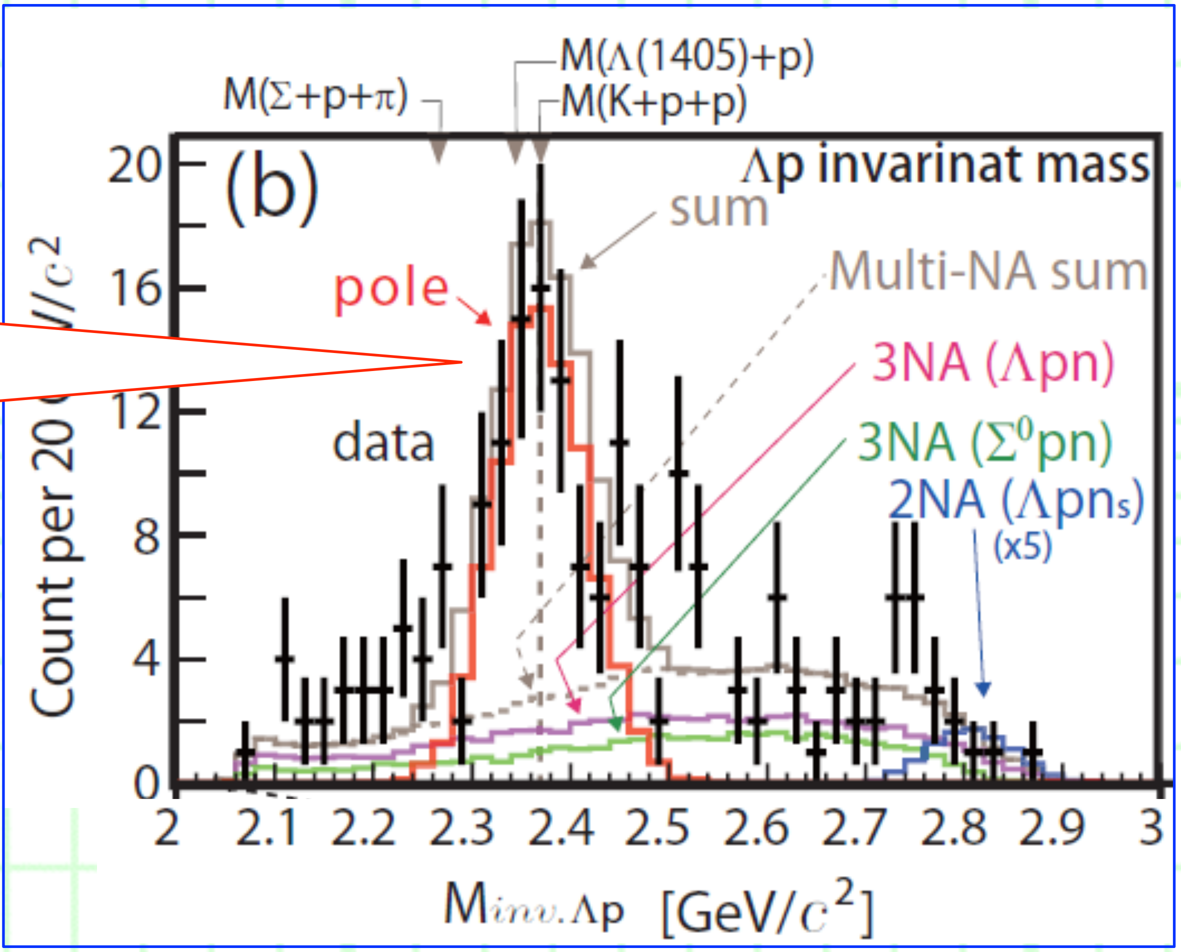


Figure by Jido-san.



J-PARC E15 Exp.

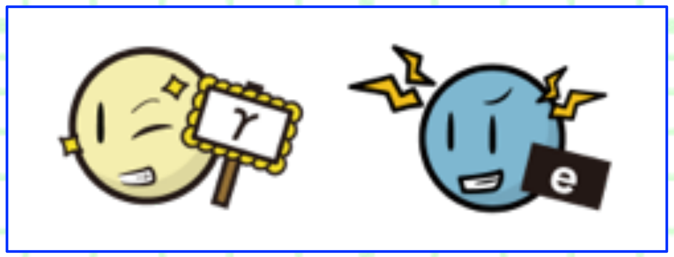
4. Summary

1. Introduction

1. Introduction

++ 4 fundamental interactions in Nature ++

- **What forces make our universe as it is ???**
  - ☐ Electromagnetic interaction.
    --- Ex.) *s*, *p*, ... orbits for electrons in atoms.



Cute figures by HIGGSTAN.

  - ☐ Weak interaction.
    --- Ex.) Decay of neutron: $n \rightarrow p\, e^{-}\, \nu_e$.

Unified as the electro-weak interaction.

Weinberg, Salam, Glashow, Higgs, ...

  - ☐ Strong interaction.
    --- Ex.) Origin of nuclear force.

Standard model.

  - ☐ Gravitation.
    --- Classical theory is established by Einstein. How about quantum theory ???

1. Introduction

++ 4 fundamental interactions in Nature ++

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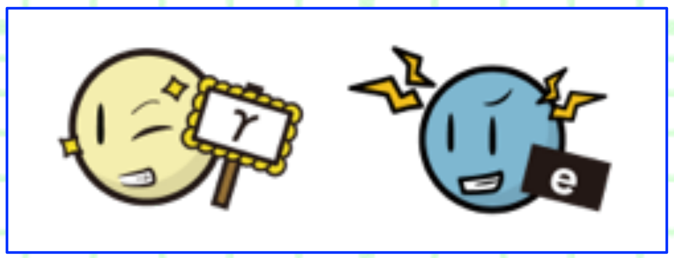

Cute figures by HIGGSTAN.

□ Weak interaction.

--- Ex.) Decay of neutron: $n \to p\, e^- \nu_e$.

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□ Strong interaction.

--- Ex.) Origin of nuclear force.

Our interest !

Standard model.

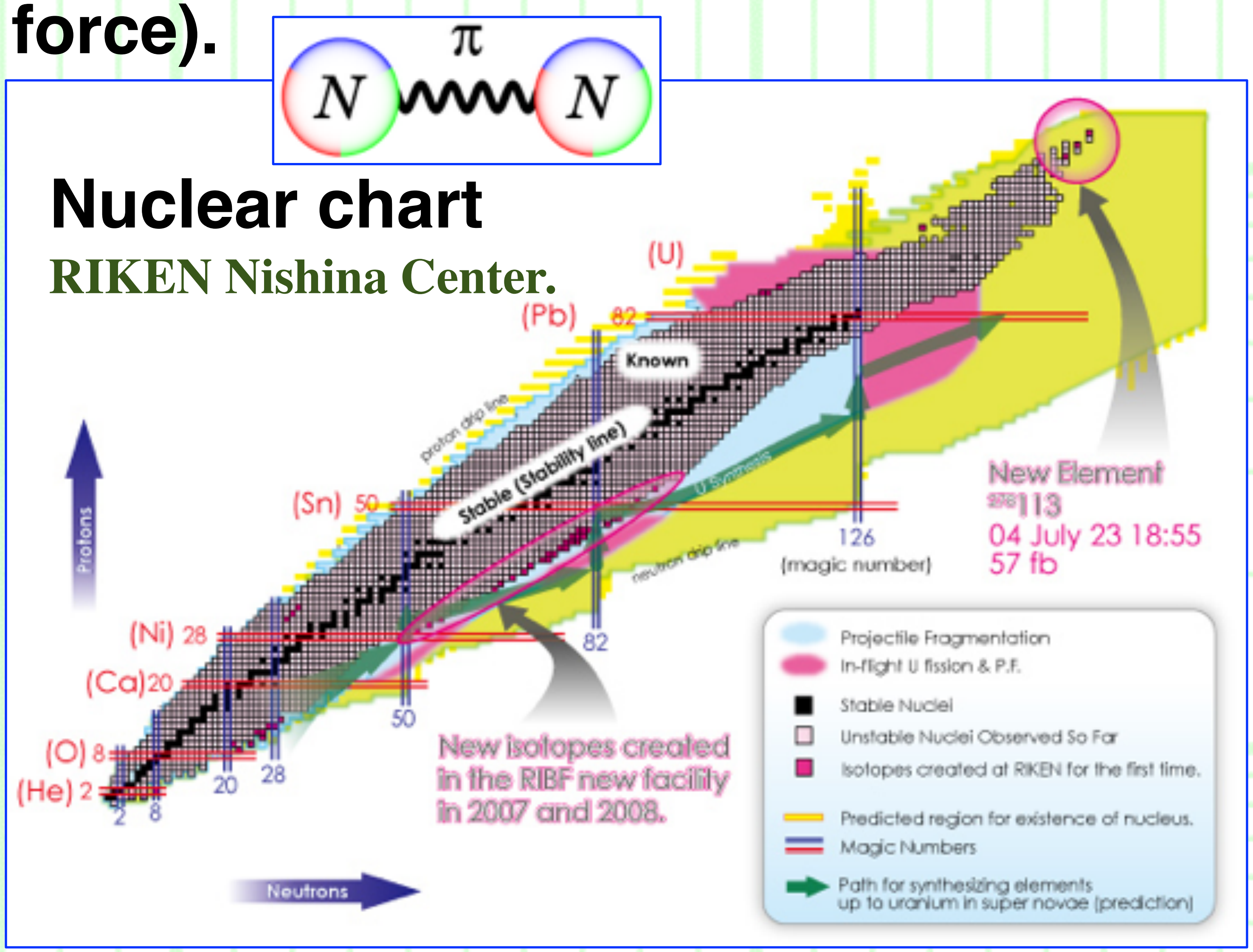
□ Gravitation.

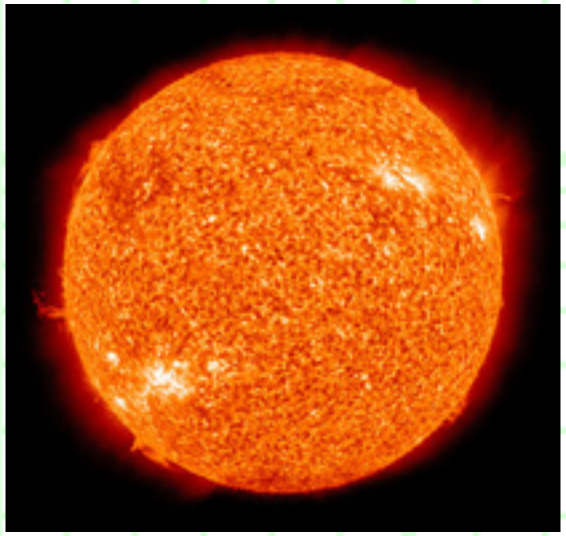
--- Classical theory is established by Einstein. How about quantum theory ???

1. Introduction

++ Physics of strong interaction ++

- Strong interaction causes many things near ourselves:
  - *NN* interaction (= nuclear force).
  - Binding atomic nuclei by nuclear force.
  - Atomic energies from nuclear fission / fusion.
  - Shining (usual) stars.





  - Neutron stars as "huge nuclei".
  - ...

- Our final goal: Understand all phenomena of strong interaction.

<--> Many things about strong interaction are not understood.

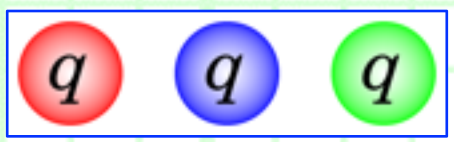
1. Introduction

++ Origin of strong interaction ++

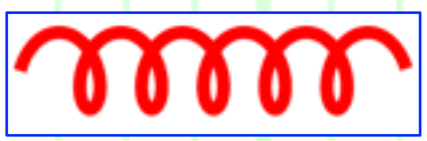
- The fundamental theory of strong interaction is established.
  - □ QCD (Quantum ChromoDynamics), an $SU(3)_{\mathrm{color}}$ gauge theory:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(i\not{D} - m)q - \frac{1}{4}G^{a}_{\mu\nu}G^{a\,\mu\nu}$$

  - □ Matter field: Quarks q.



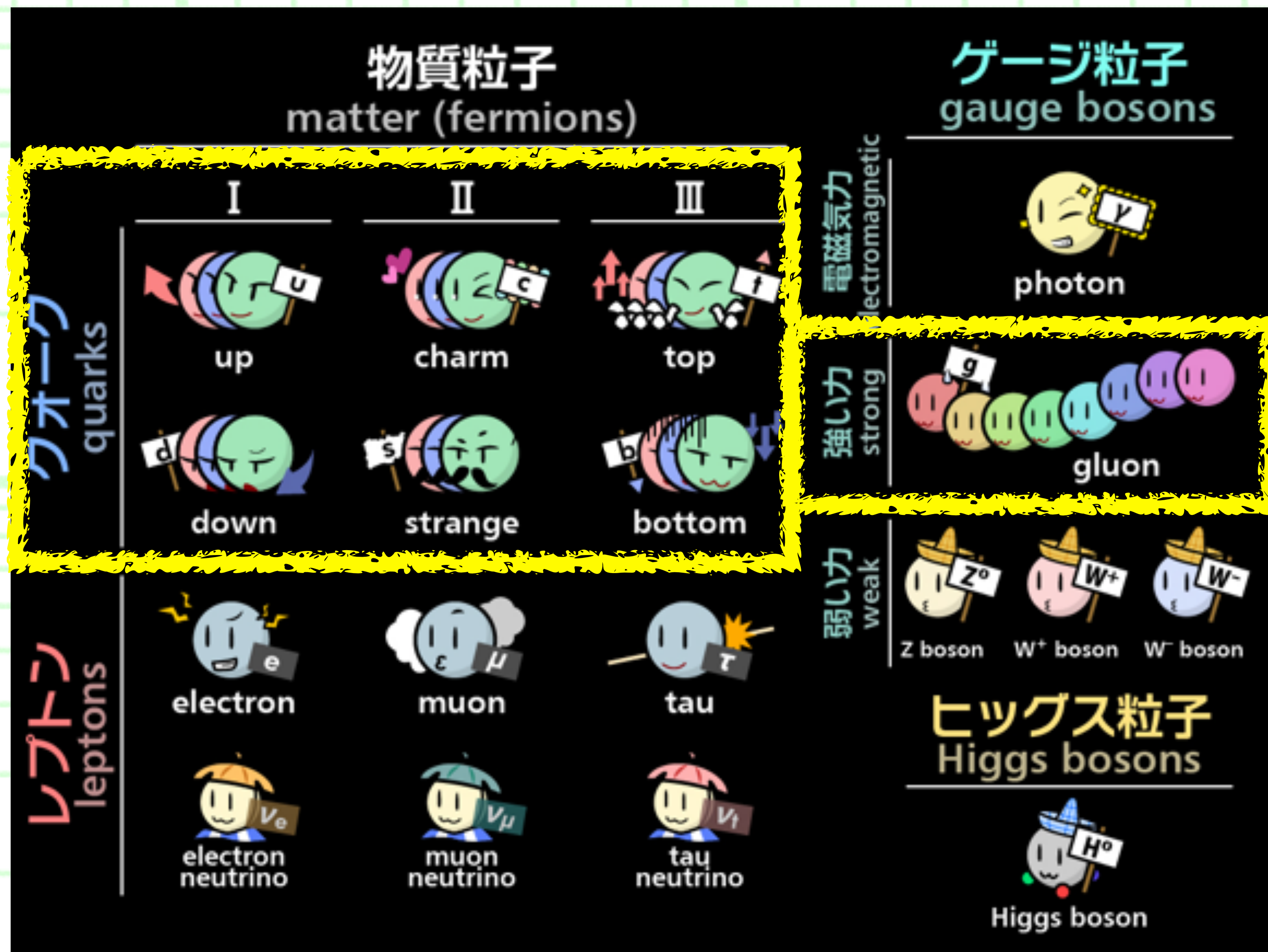
  - □ Gauge field: Gluons A^{a}_{μ}.



x 8

  - □ A huge range of physics from QCD Lagrangian written in only 1 line !

HIGGSTAN.

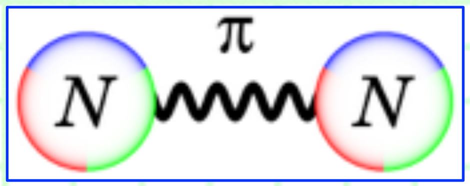


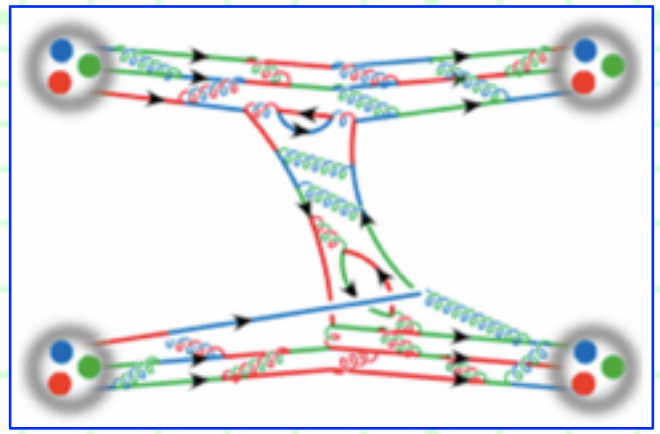
1. Introduction

++ Approach to strong interaction ++

- However, due to very large non-perturbative effects of QCD, we cannot calculate various quantities directly from QCD.

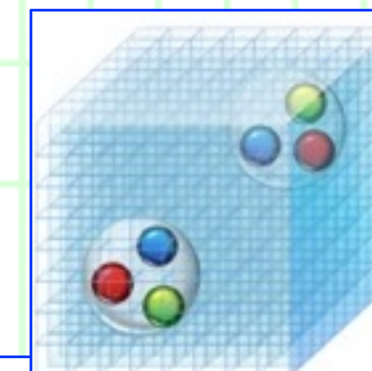
--- Ex.) The *NN* interaction (= nuclear force) in terms of QCD.





HAL QCD Collab.

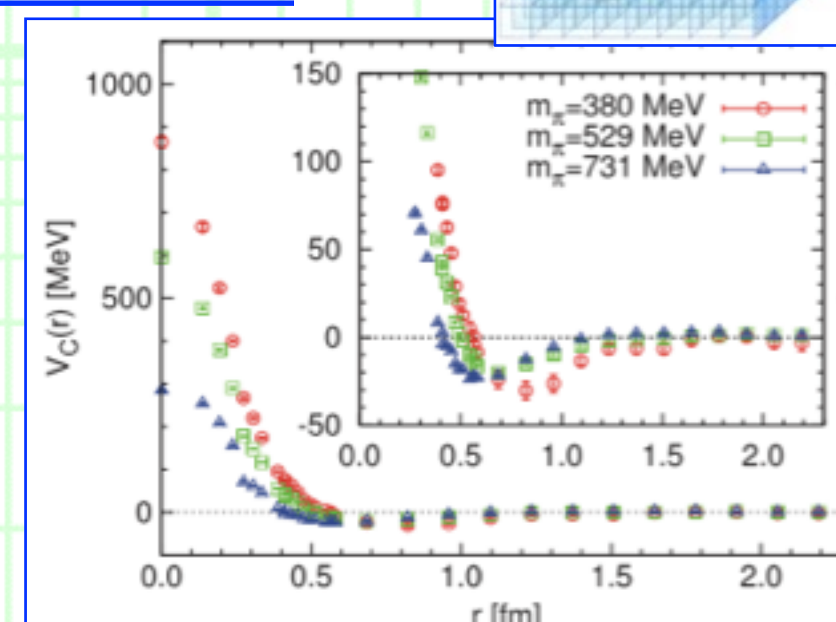
<-- Very difficult to calculate in QCD !



□ Only the recent progress of super computers allows us to simulate the *NN* interaction in QCD with a lattice.

K computer
at Kobe, JAPAN.

Aoki, Hatsuda, and Ishii (2010).



1. Introduction

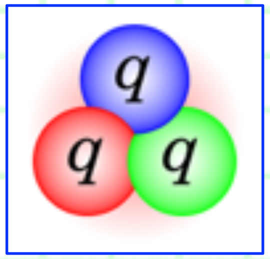
++ Approach to strong interaction ++

- Instead of "expensive" lattice QCD simulations, one can take phenomenological approaches.

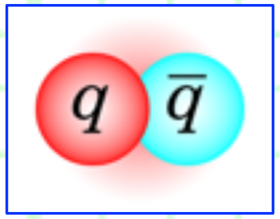
□ QCD inspired models.

--- *cf.* Constituent quark models.

Quarks ! (1964)



Baryons:
proton, neutron, Λ, ...

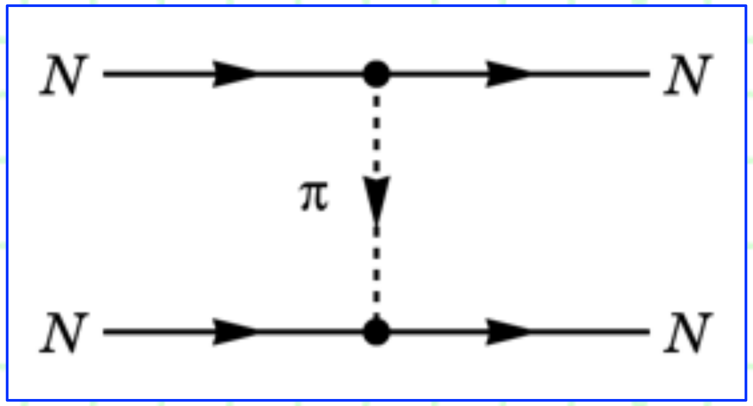


Mesons:
π, ϱ, J/ψ, ...

Gell-Mann.

□ More phenomenological models constructed with observable states = mesons & baryons.

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



Let's exchange mesons ! (1935)

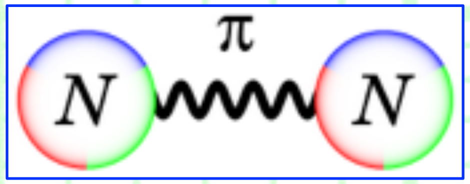
--- Coupling constants are fixed with experimental data.

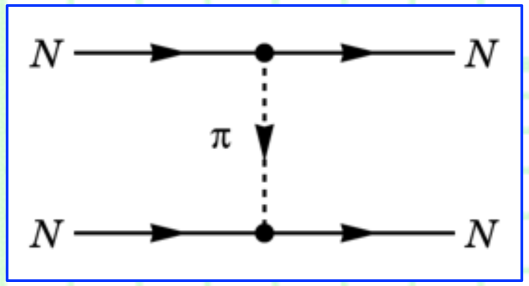
Yukawa.

1. Introduction

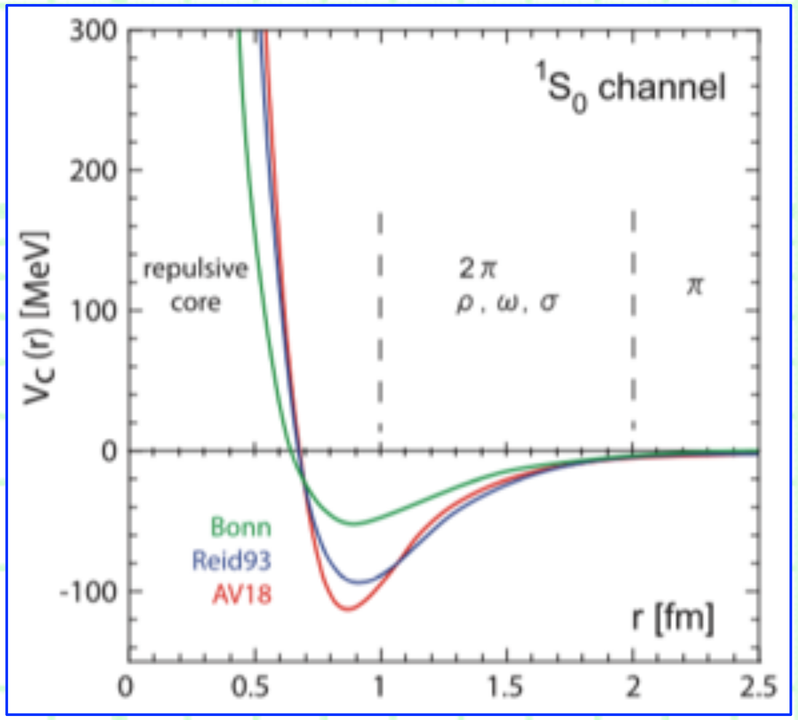
++ My approach ++

- My approach is essentially "more phenomenological models" constructed in the hadron degrees of freedom.





Aoki, Hatsuda, and Ishii (2010).



□ The *NN* interaction has been studied well with the meson exchange models, *etc*.

□ What happens if *N* is replaced with other hadrons ?

--- There are more than 300 hadrons in our universe.

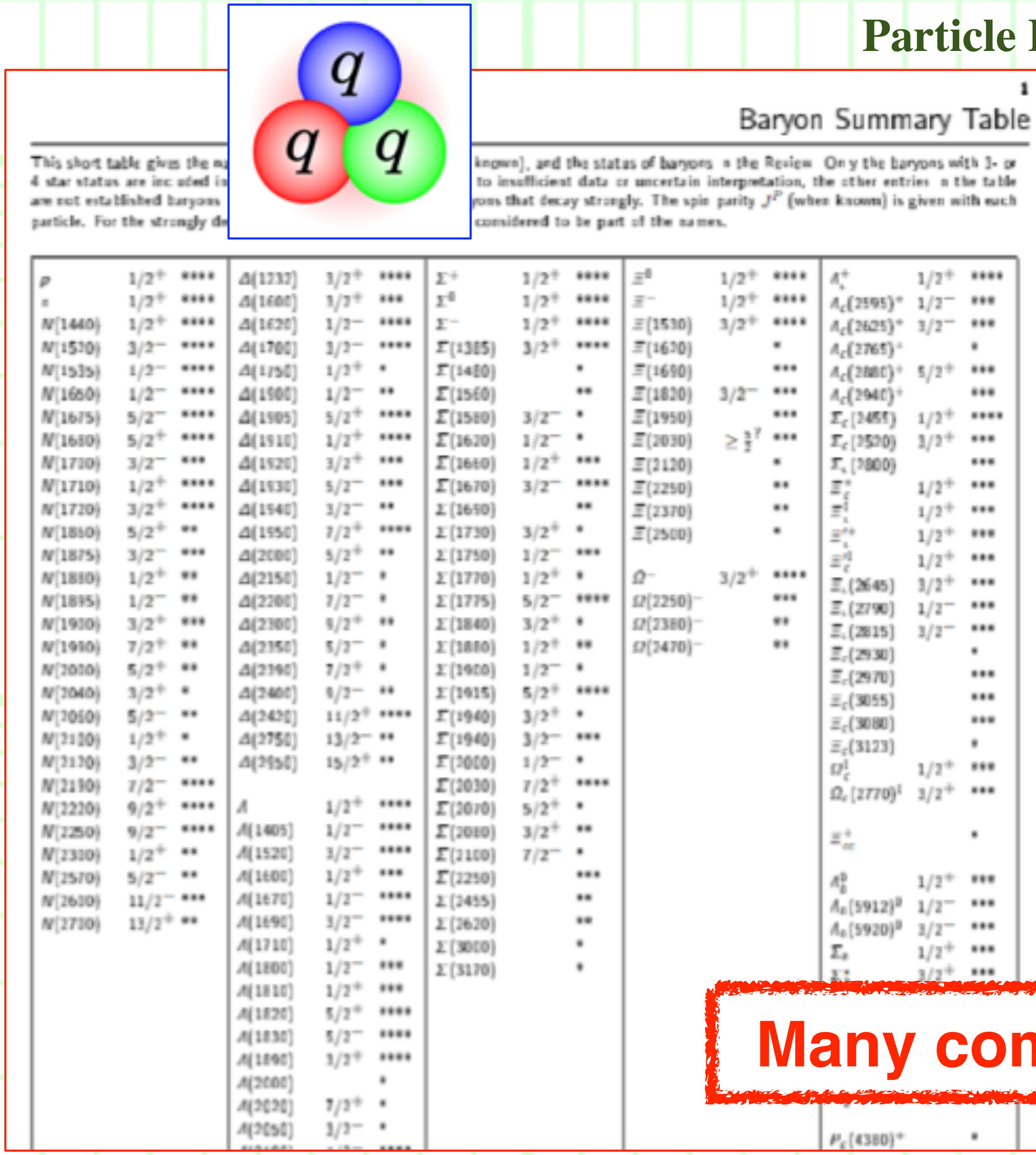
--- In particular, more flavors are available in recent experiments. (only up & down quarks in *NN*, but strange, charm, and bottom quarks are now available with enough statistics).

1. Introduction

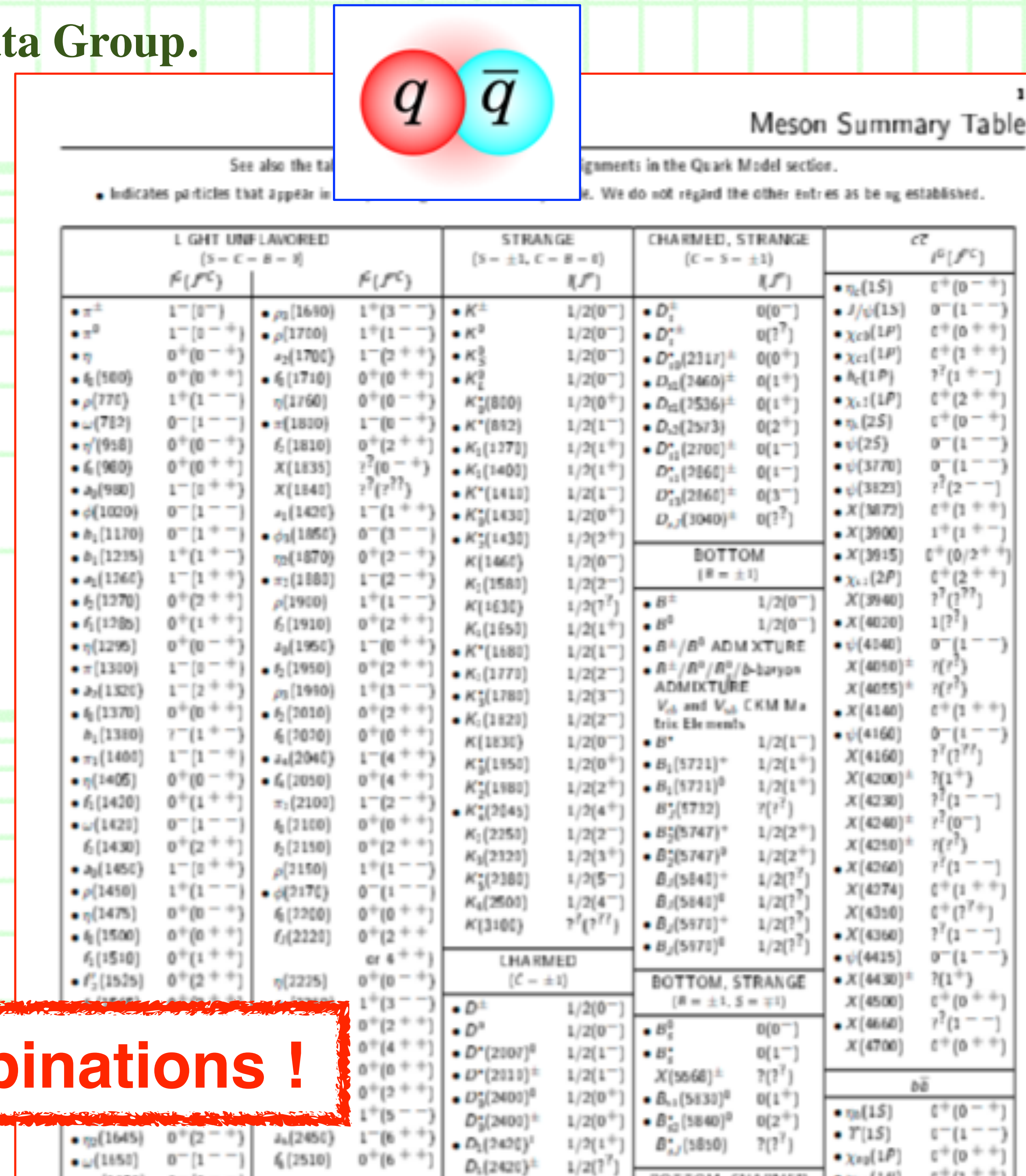
++ More than 300 hadrons ++

Particle Data Group.

- **Baryons**



- **Mesons**



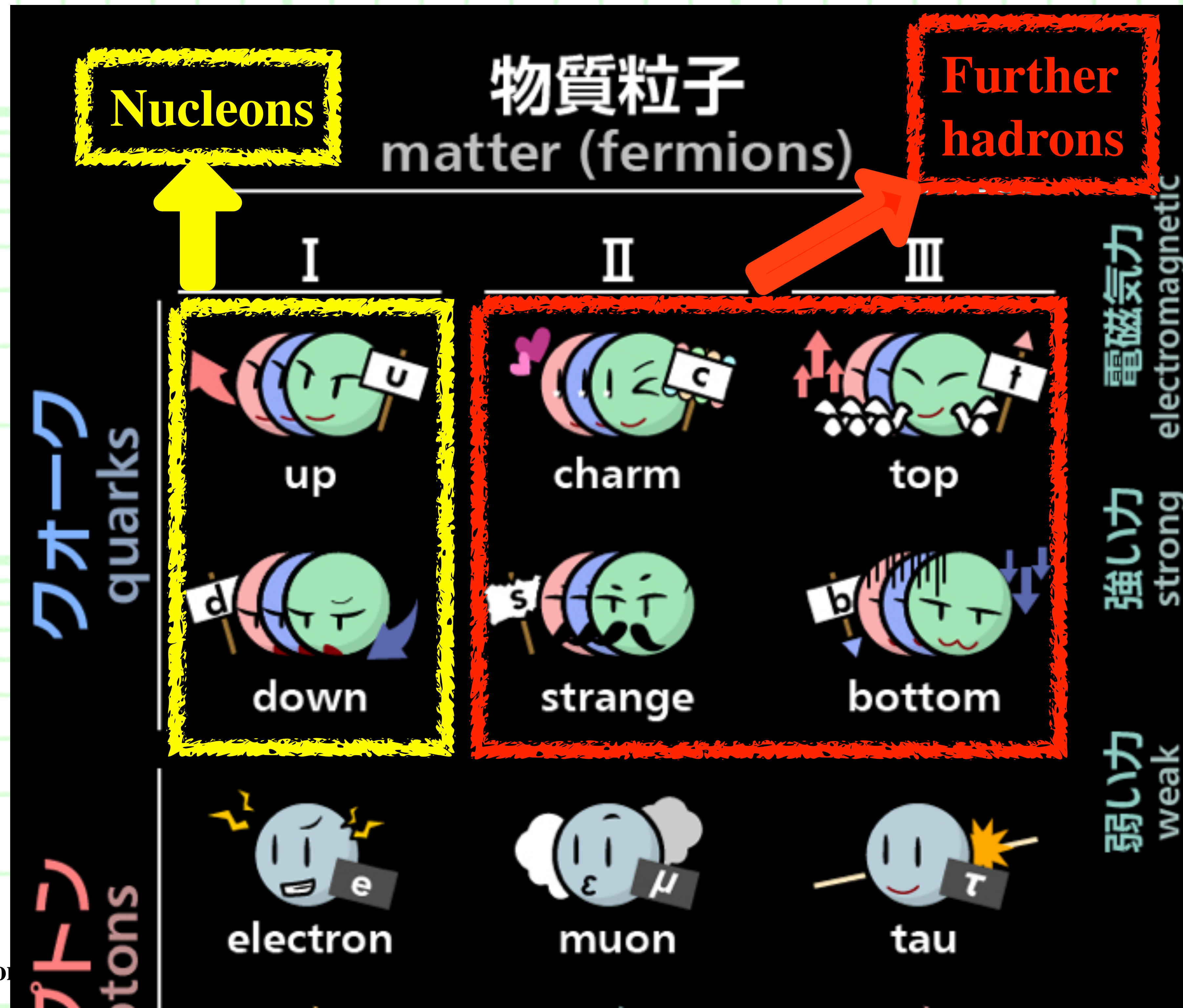
Many combinations !

1. Introduction

++ More flavors ++

- In our universe, **only up and down quarks can be stable**.

--- Proton: *uud*,
Neutron: *udd*.



- If we explore strong interactions with more flavors (strange, charm, and bottom), then we can **extend our understanding of strong interaction**.

--- From 2 dimensions to 3, 4, 5 Dims.

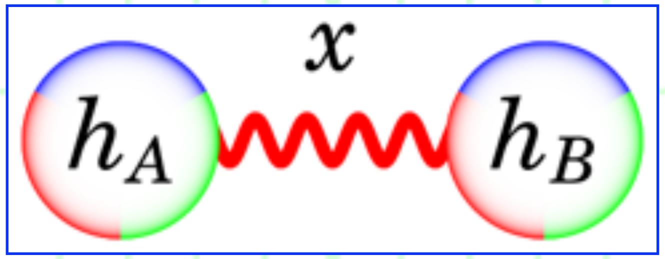
1. Introduction

++ Our study and motivation ++

- We **theoretically study various hadron-hadron interactions** by **using experimental findings**.

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

--- **Various combinations of hadrons** with **various flavors**.

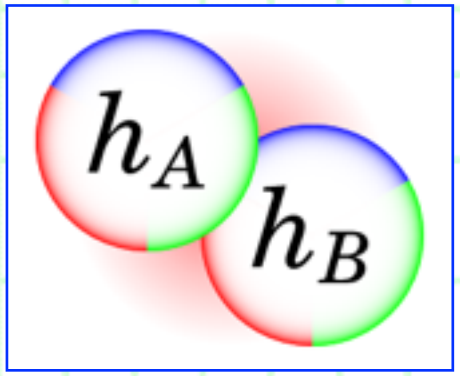


  - In addition, in some combinations **hadrons interact strongly attractive enough to make an exotic bound state**.

--- **Exotic nuclear many-body system !**

cf. Deuteron as a *NN* bound state.

Bound state !



2. Kaonic nuclei: up to now

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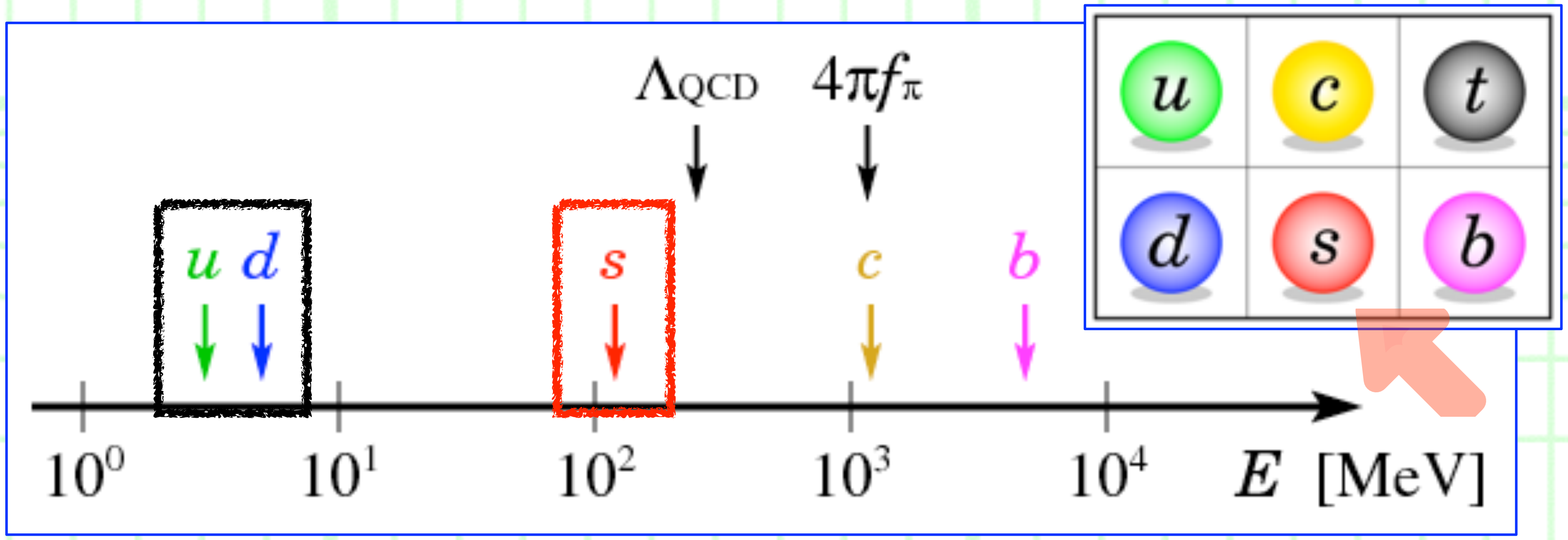
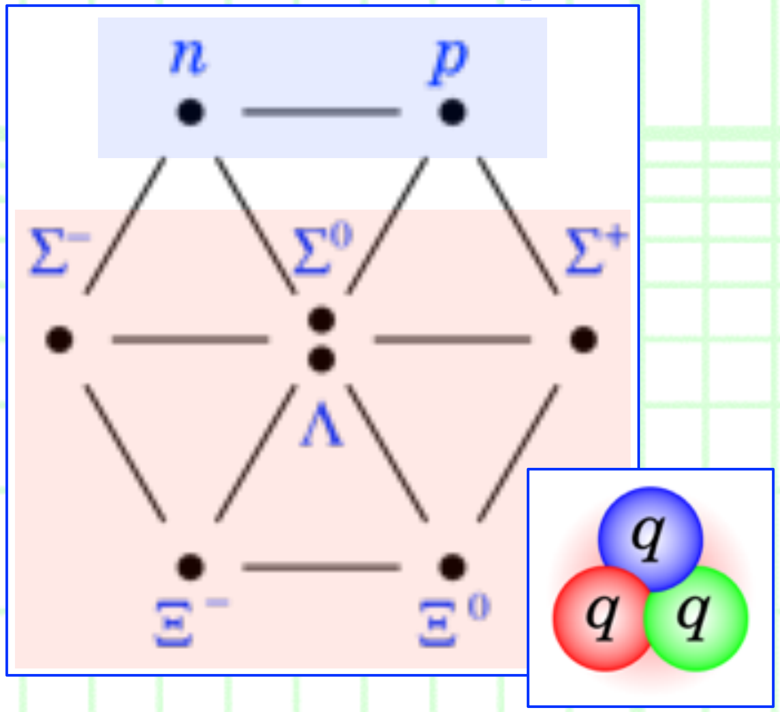
++ Strange quark into nuclei ++

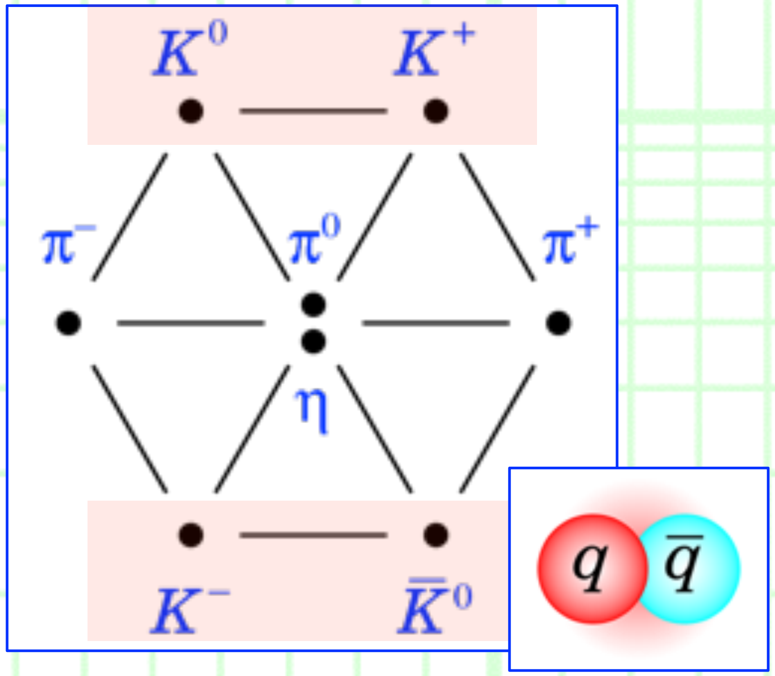
- **Let us put strange quark(s) into nuclei.**

--- Strange quark is the lightest quark among unstable quarks in our universe.



- First step to extend the *NN* interaction (up & down sector).
- Easier to produce in experiments.

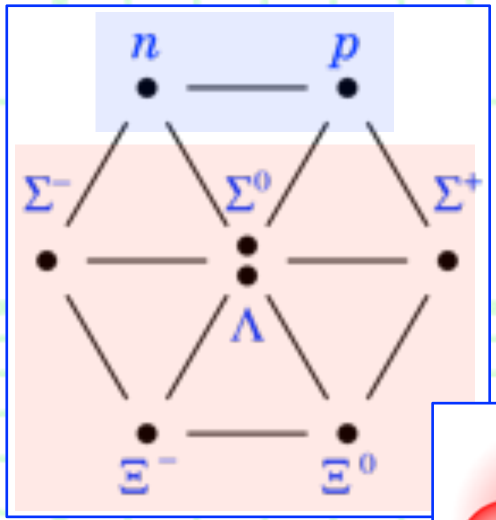


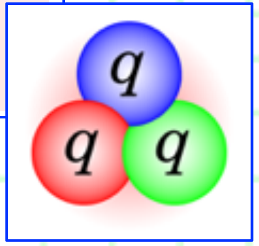


- In a high dense matter, such as in a neutron star, hadrons with strange quark are expected to exist in addition to *N*s.

2. Kaonic nuclei: up to now

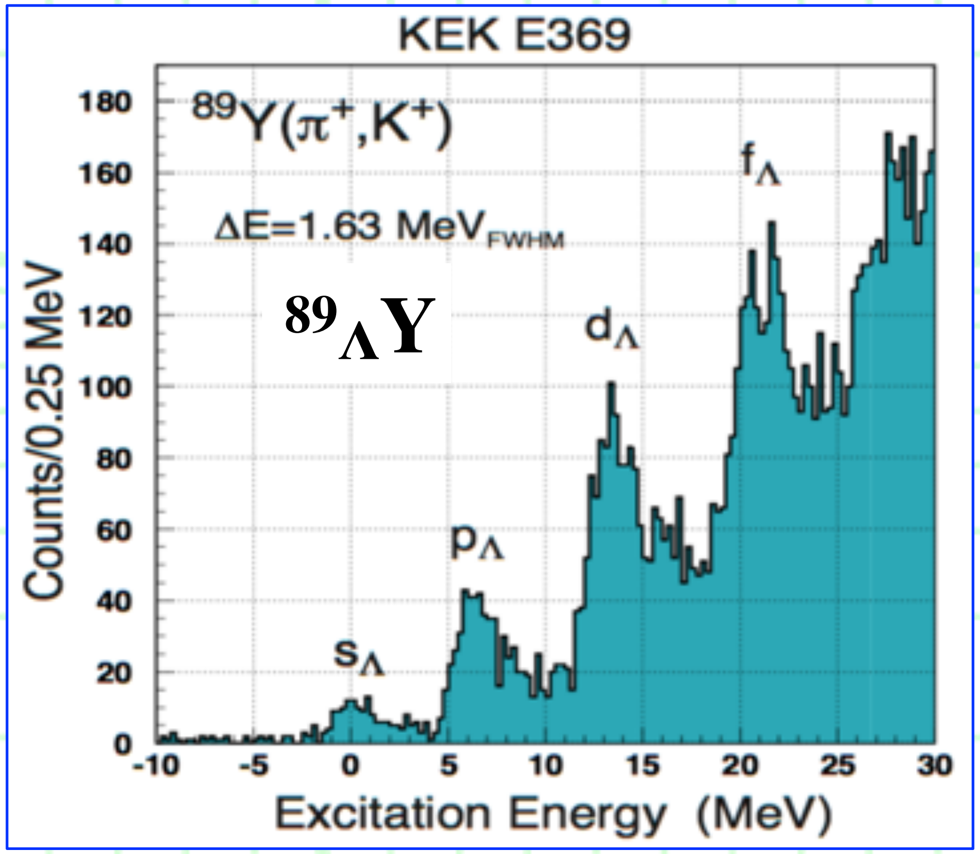
++ Strange quark into nuclei ++





- $\Lambda(uds)$ - nuclear interaction.
  - ◻ It is established that Λ - nuclear interaction is attractive and generates Λ - nuclear bound states (Λ hyper-nuclei).
  - ◻ From the Λ - nuclear bound states, we can extract the ΛN interaction !

H. Hotch *et al.*, *Phys. Rev.* C64 (2001) 044302.



- $\Sigma(uus, uds, dds)$ - nuclear interaction.
  - ◻ Exp. data imply repulsive Σ - nuclear interaction ??
- $\Xi(uss, dss)$ - nuclear interaction.
  - ◻ Small attraction ?
  - ◻ Searching for Ξ - nuclear bound states (Ξ hyper-nuclei).

2. Kaonic nuclei: up to now

++ Strange quark into nuclei ++

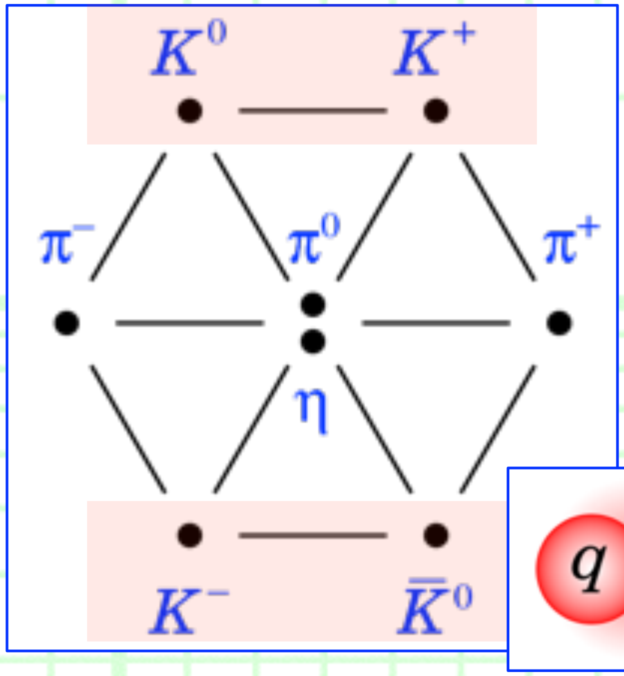
- How about the kaon-nuclear interaction ?

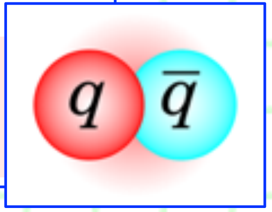
--- Two aspects of kaons:

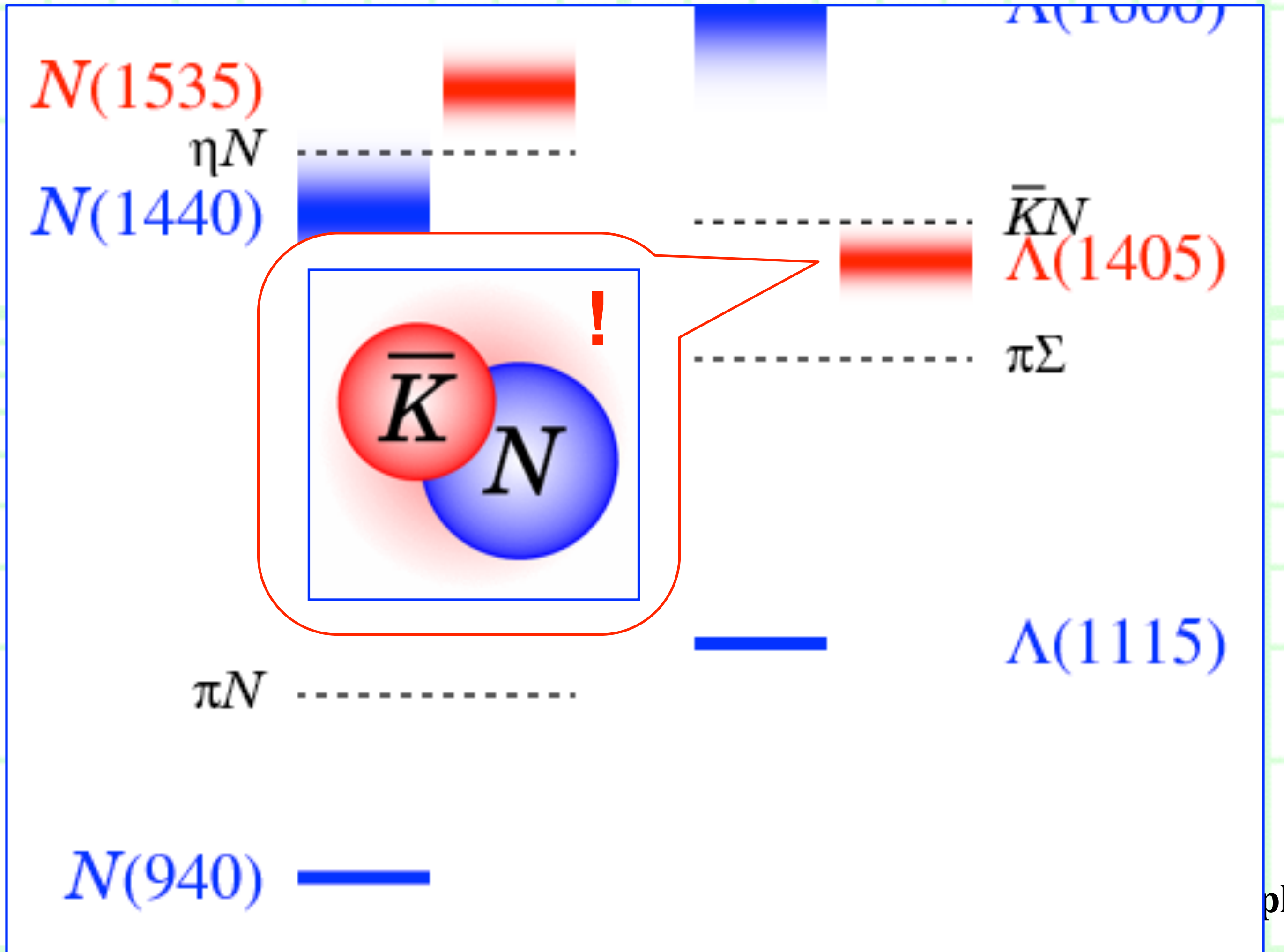
- A Nambu-Goldstone boson of spontaneous chiral symmetry breaking of QCD.

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

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







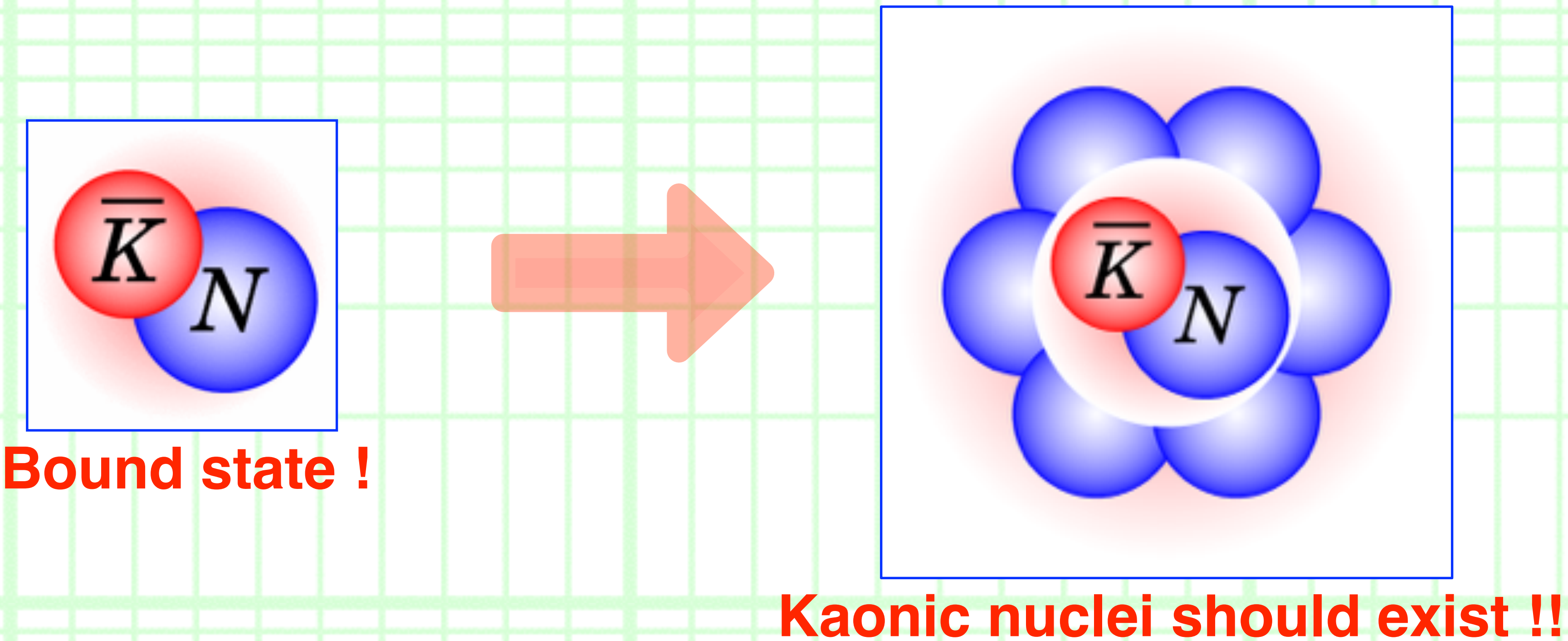
- Spontaneous chiral symmetry breaking predicts a strongly attractive $\bar{K}(s\bar{u}, s\bar{d})\ N$ interaction. [$K(u\bar{s}, d\bar{s})\ N$ Int. is repulsive].

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

2. Kaonic nuclei: up to now

++ 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.



- 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.

2. Kaonic nuclei: up to now

++ 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;

    ...

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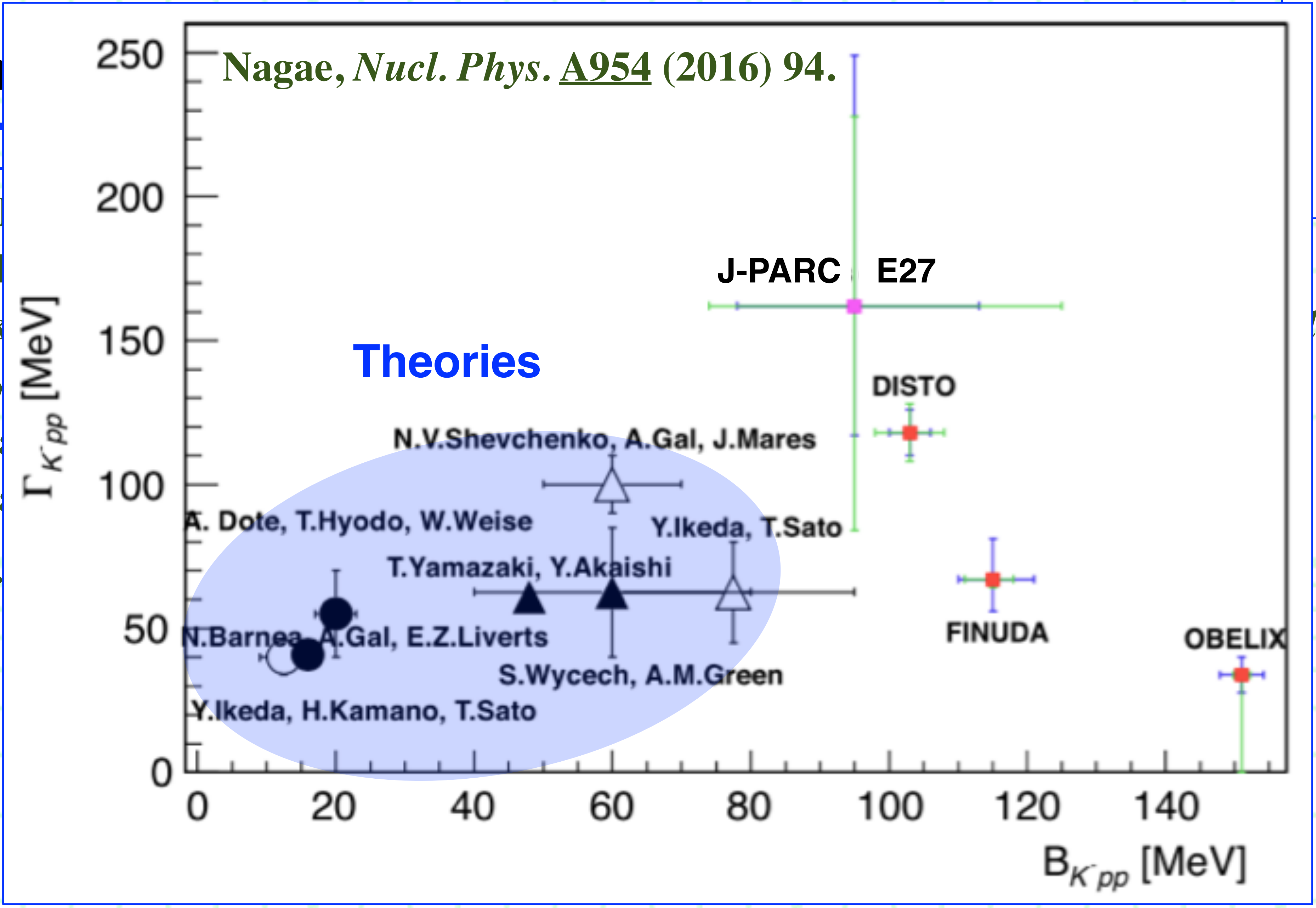

--- The difference mainly comes from the $\bar{K}N$ interaction (<-- model).

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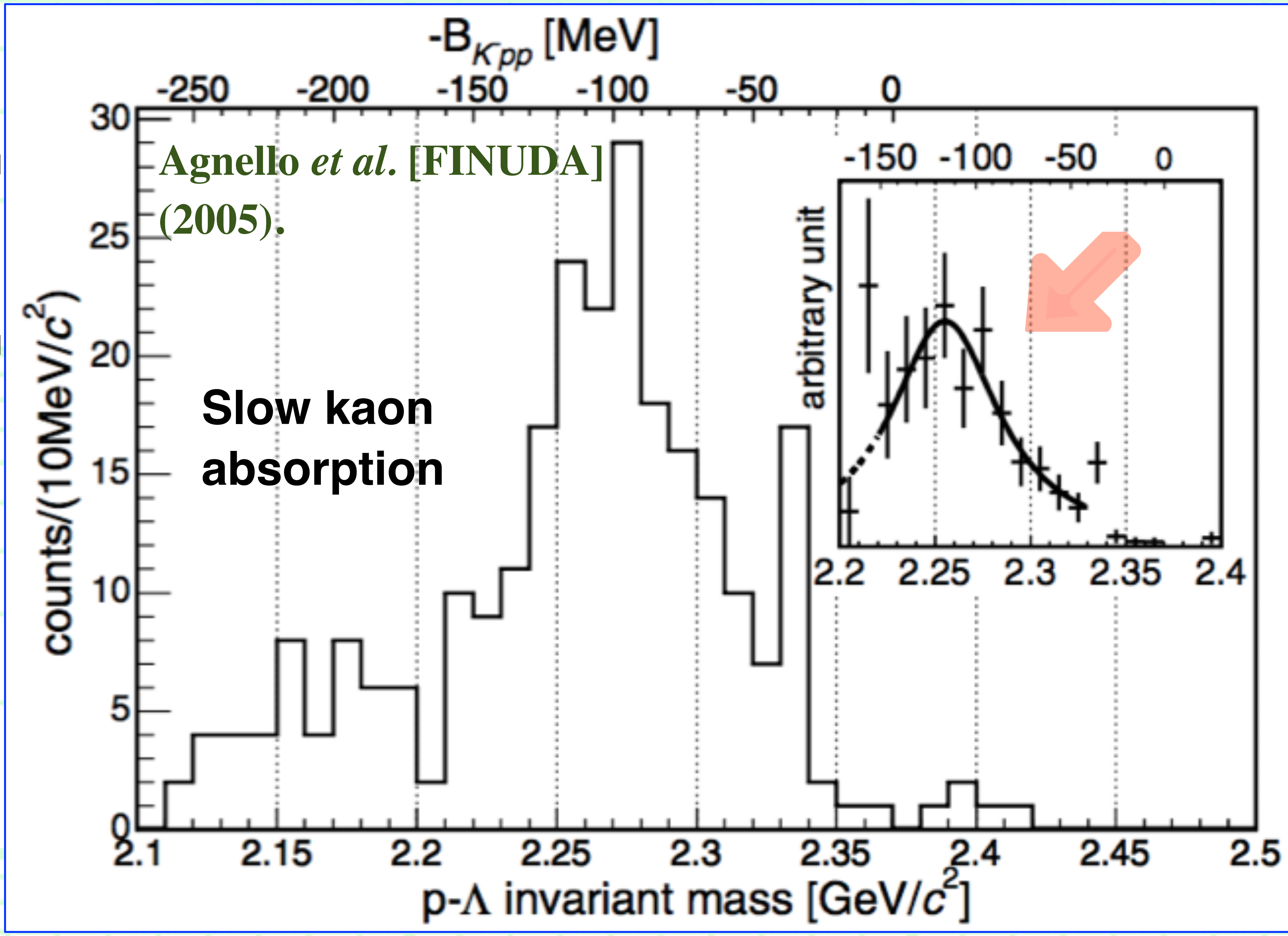
  - **Experimental studies:**

    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;
    ...

2. Kaonic nuclei: up to now



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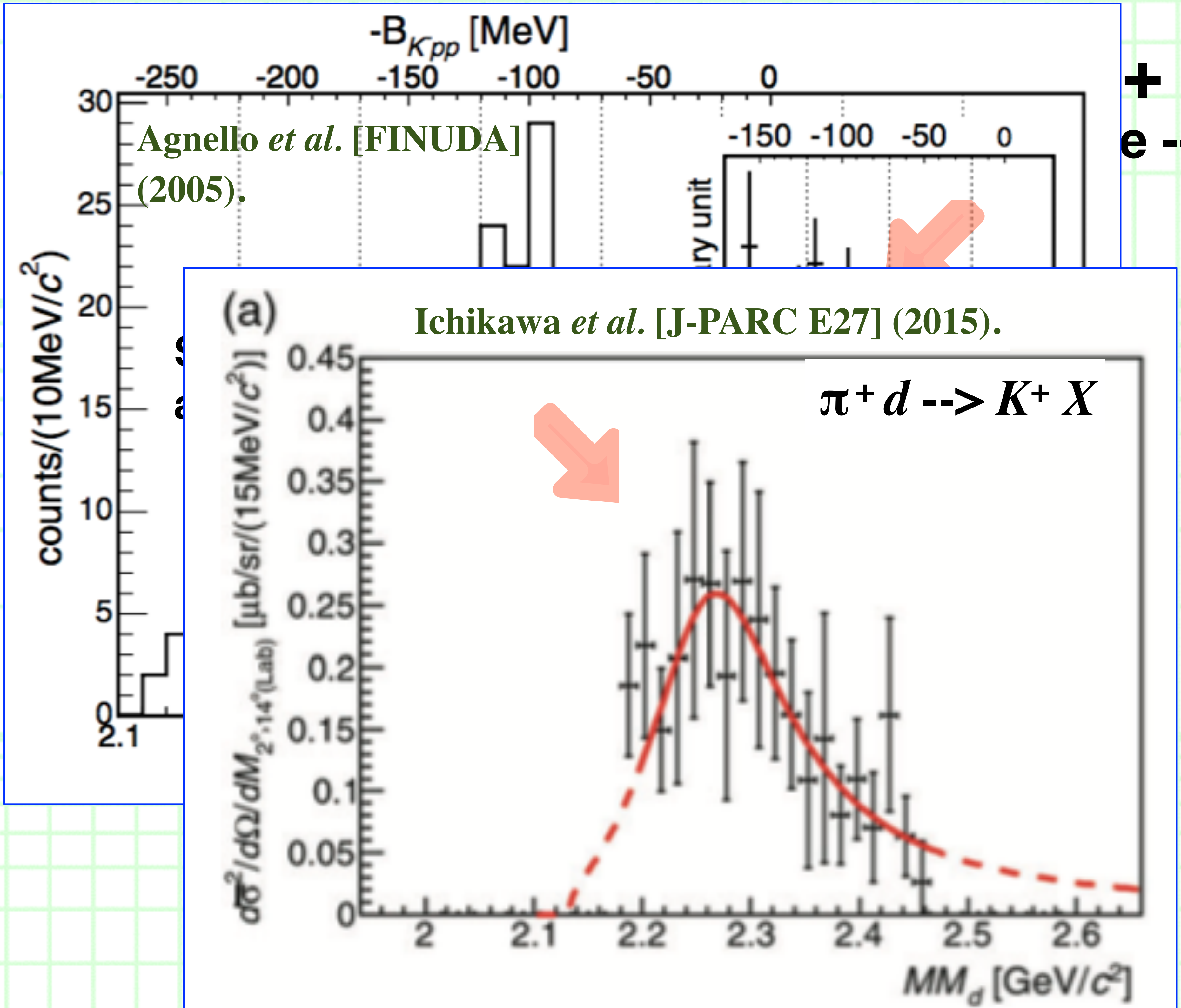
e ---

2. Kaonic nuclei: up to now



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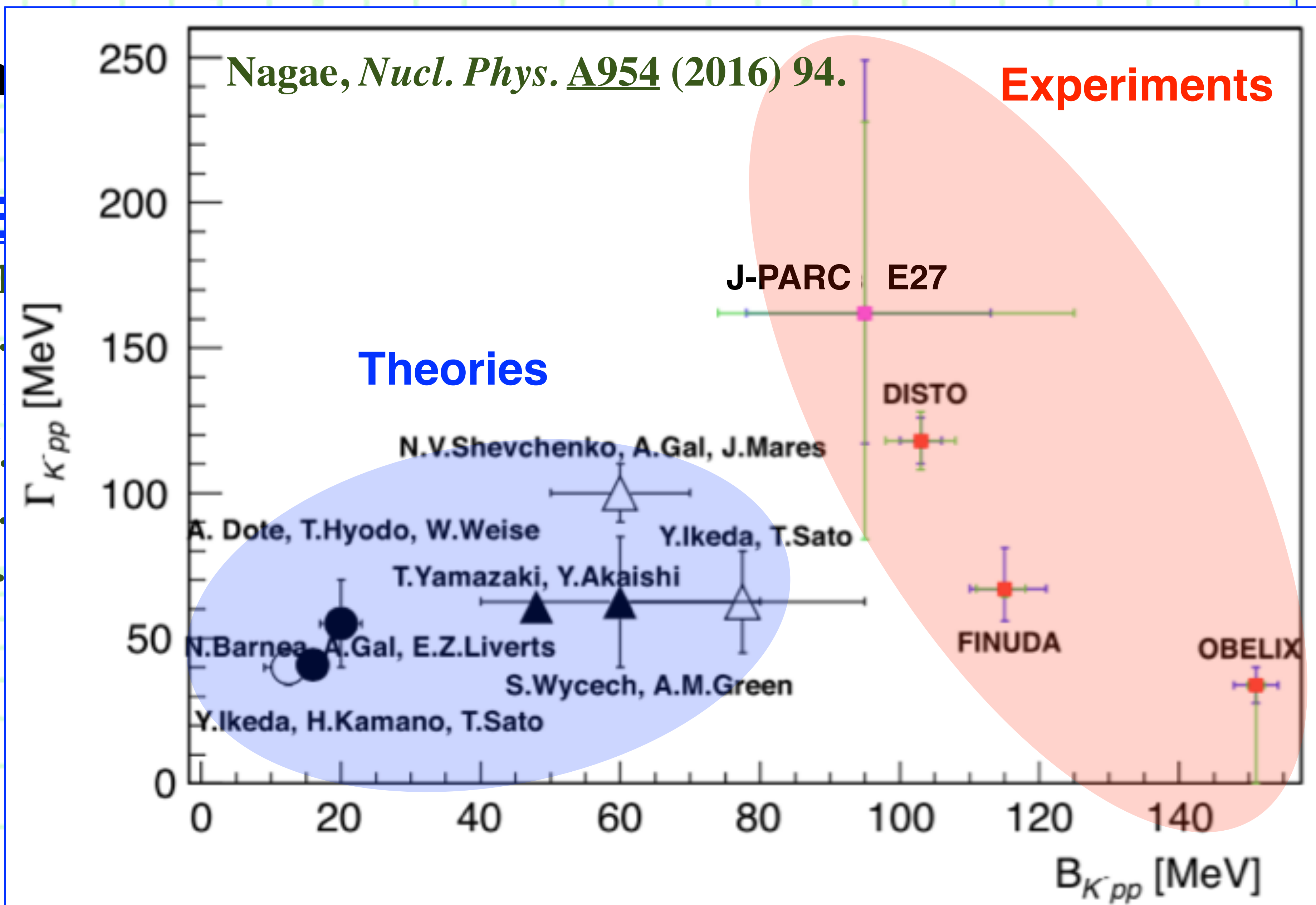

--- However, this state is still controversial.

2. Kaonic nuclei: up to now

++ 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.

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

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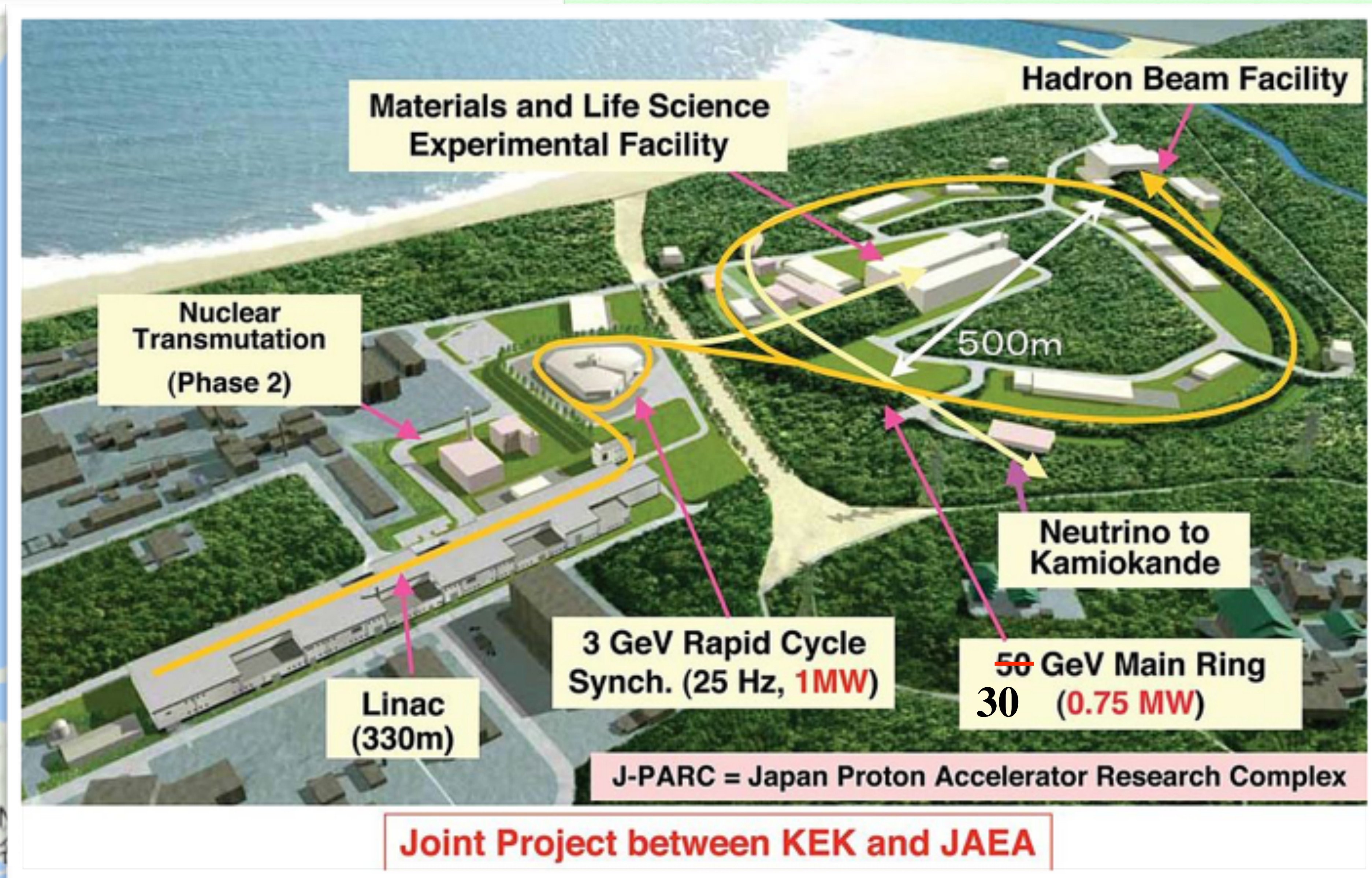

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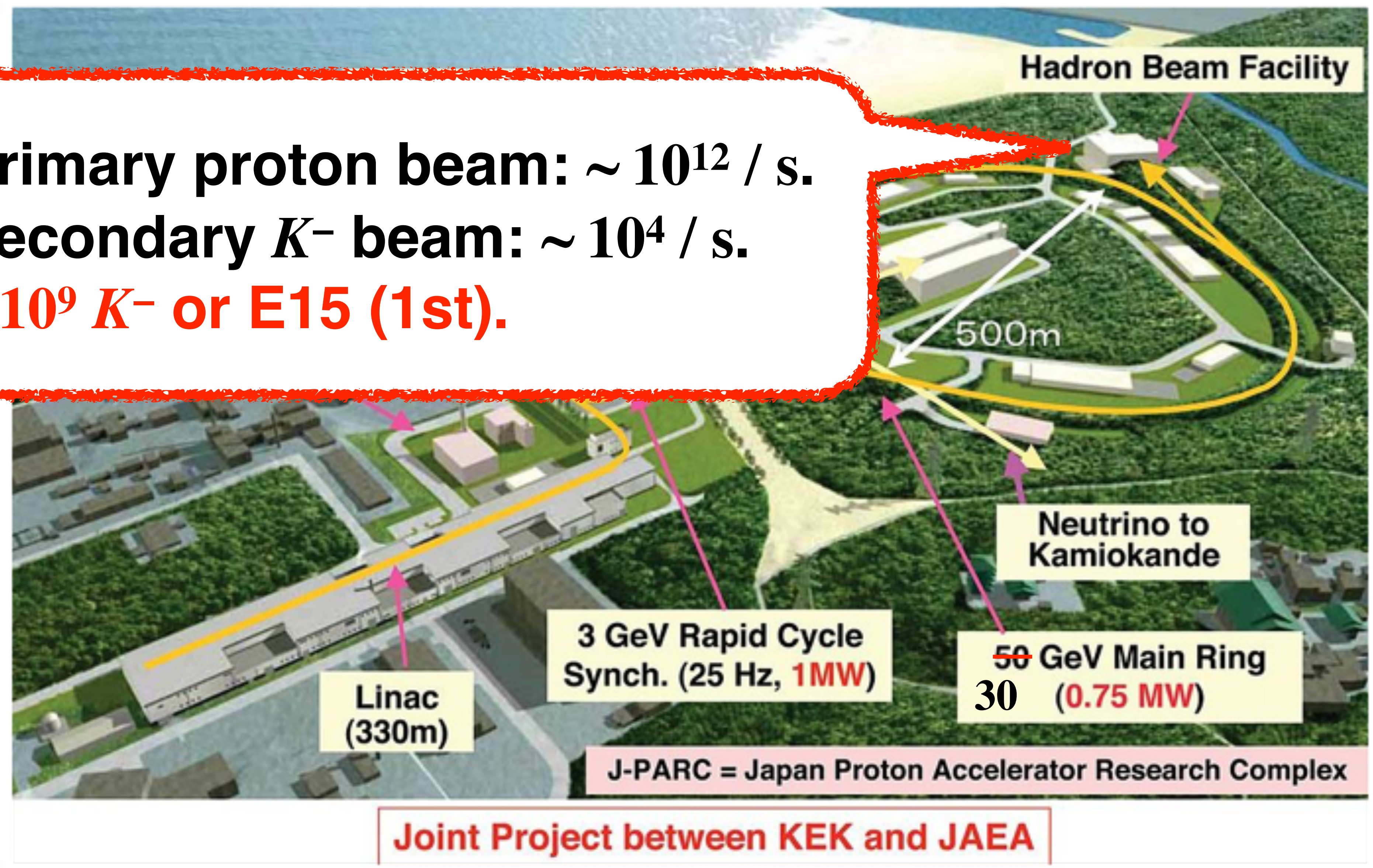
- □ J-PARC --- Japan Proton Accelerator Research Complex.

- □ Primary proton beam: ~ 10^{12} / s.
- □ Secondary K^- beam: ~ 10^4 / s.

--> 10^9 K^- or E15 (1st).



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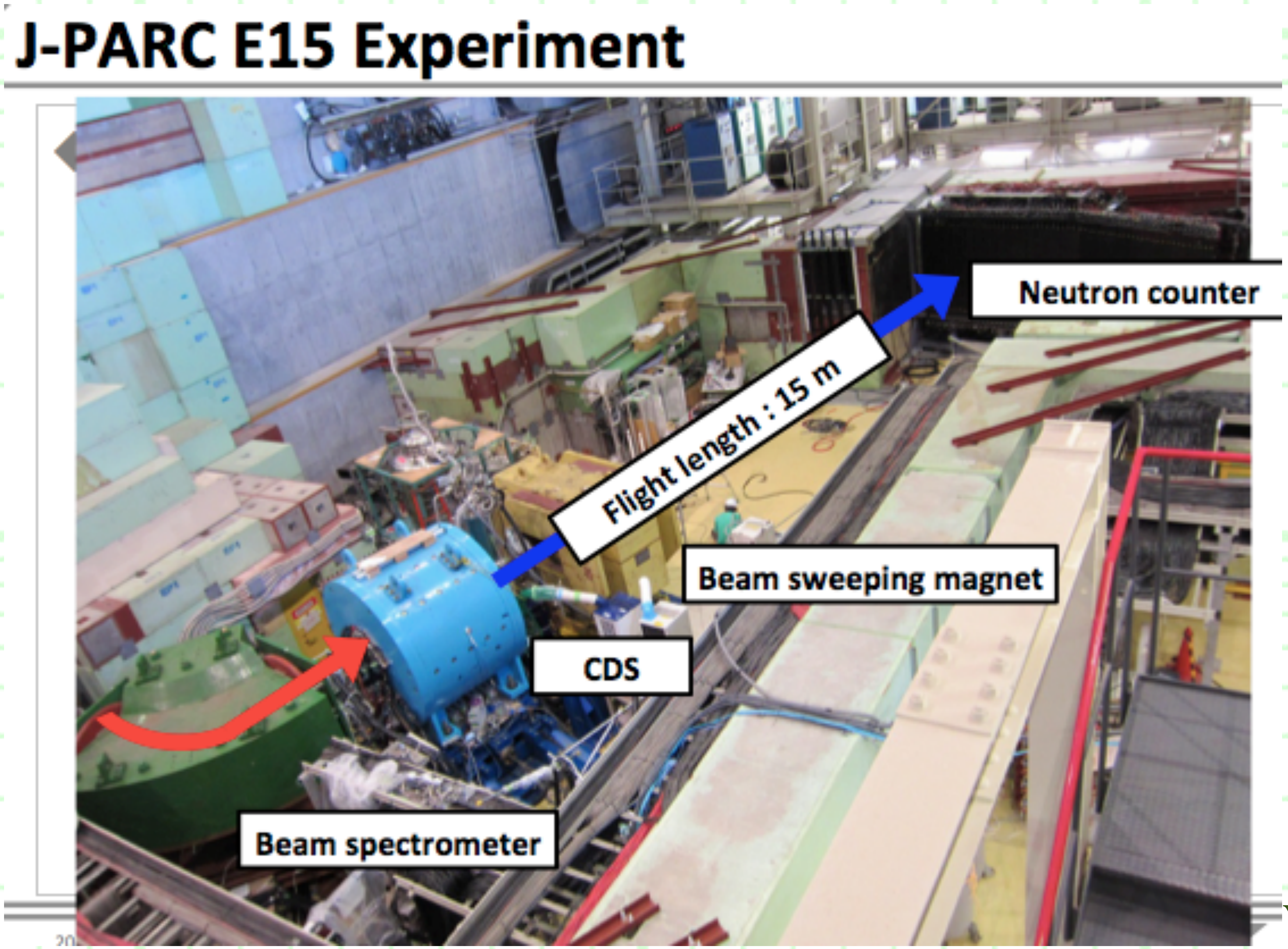

Yamaha.

2. Kaonic nuclei: up to now

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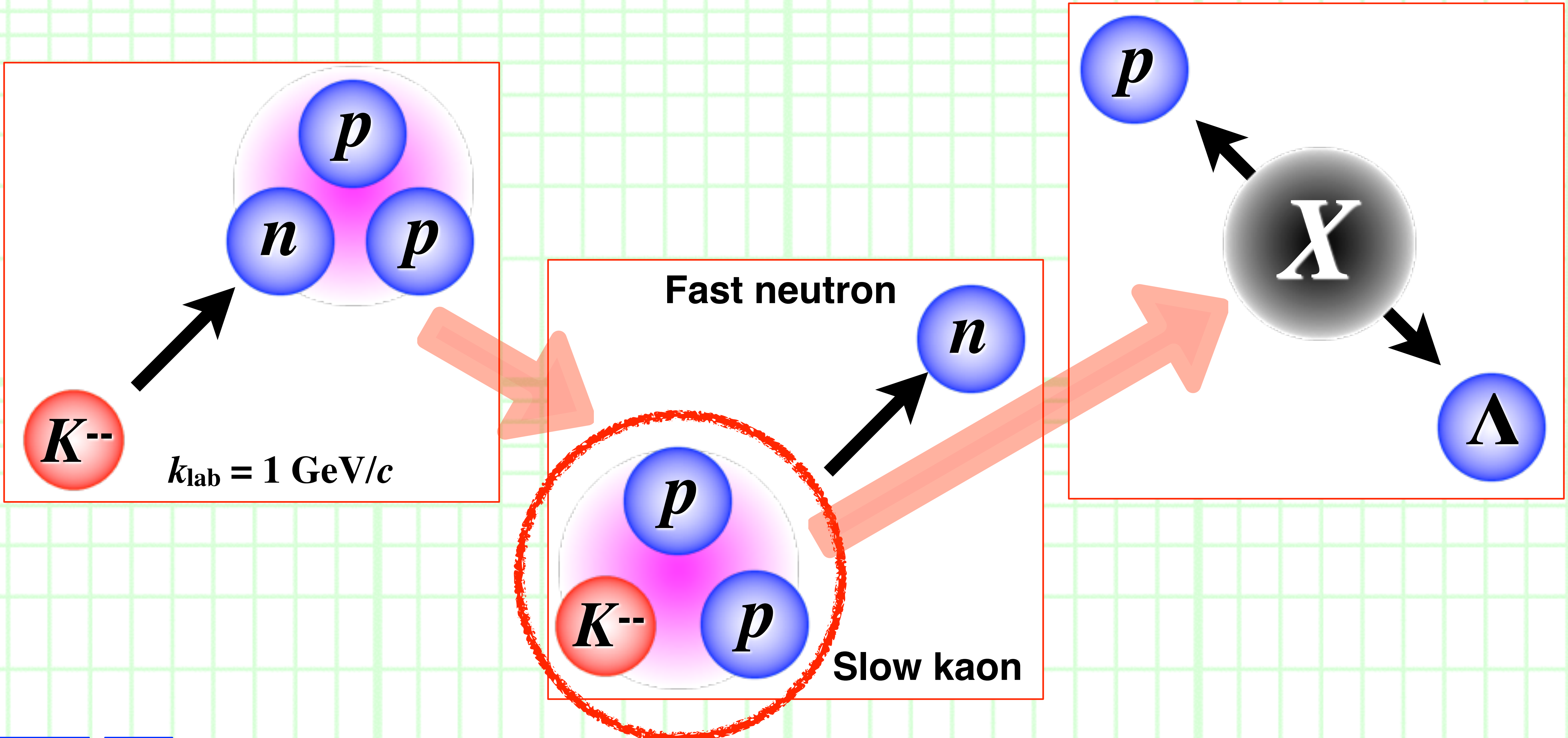
  - Reaction mechanism:



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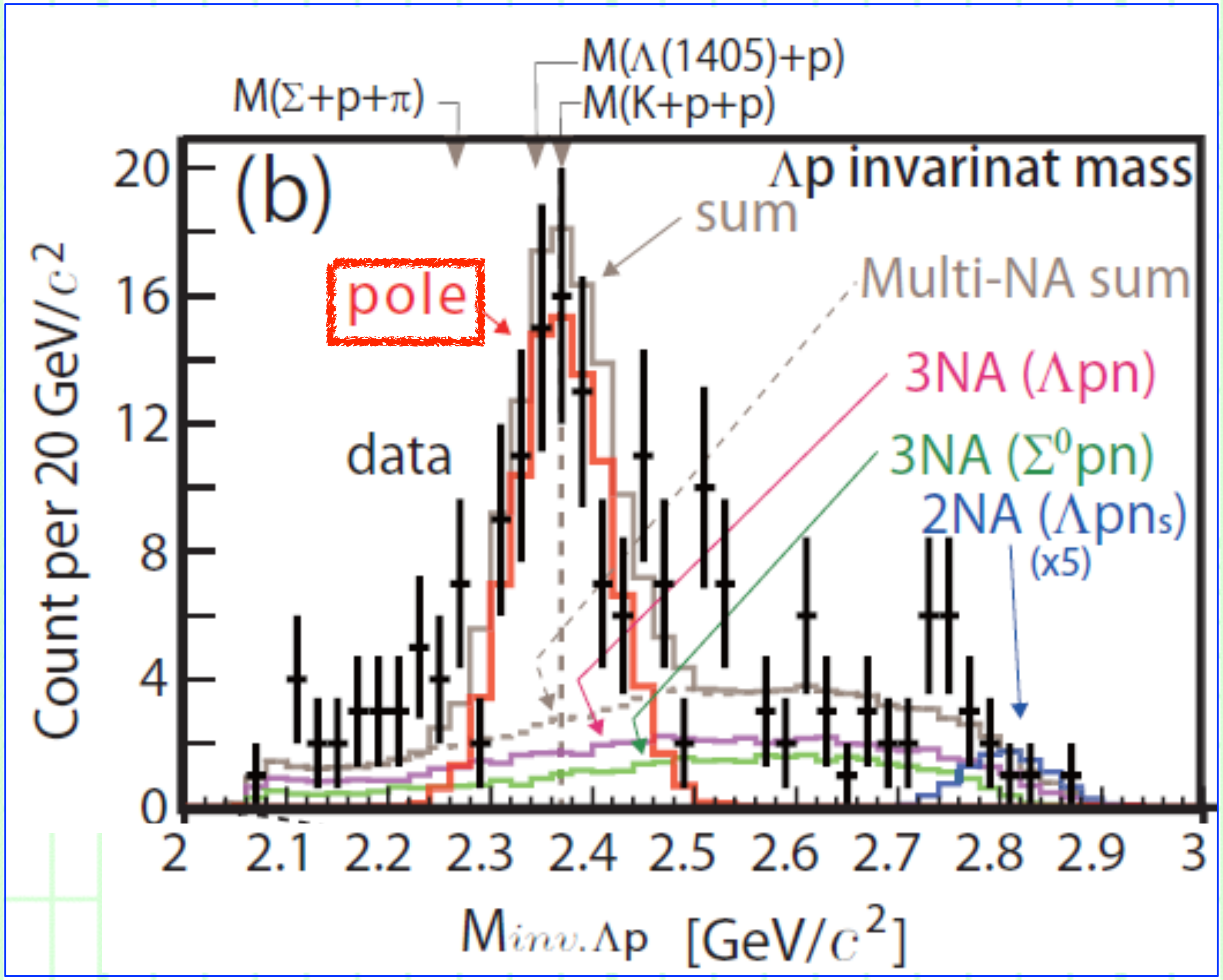
- Recently, the J-PARC E15 collaboration has observed **a structure near the $\bar{K}NN$ threshold** in **the in-flight ^{3}He $(K^-, \Lambda p)\, n$ reaction**.

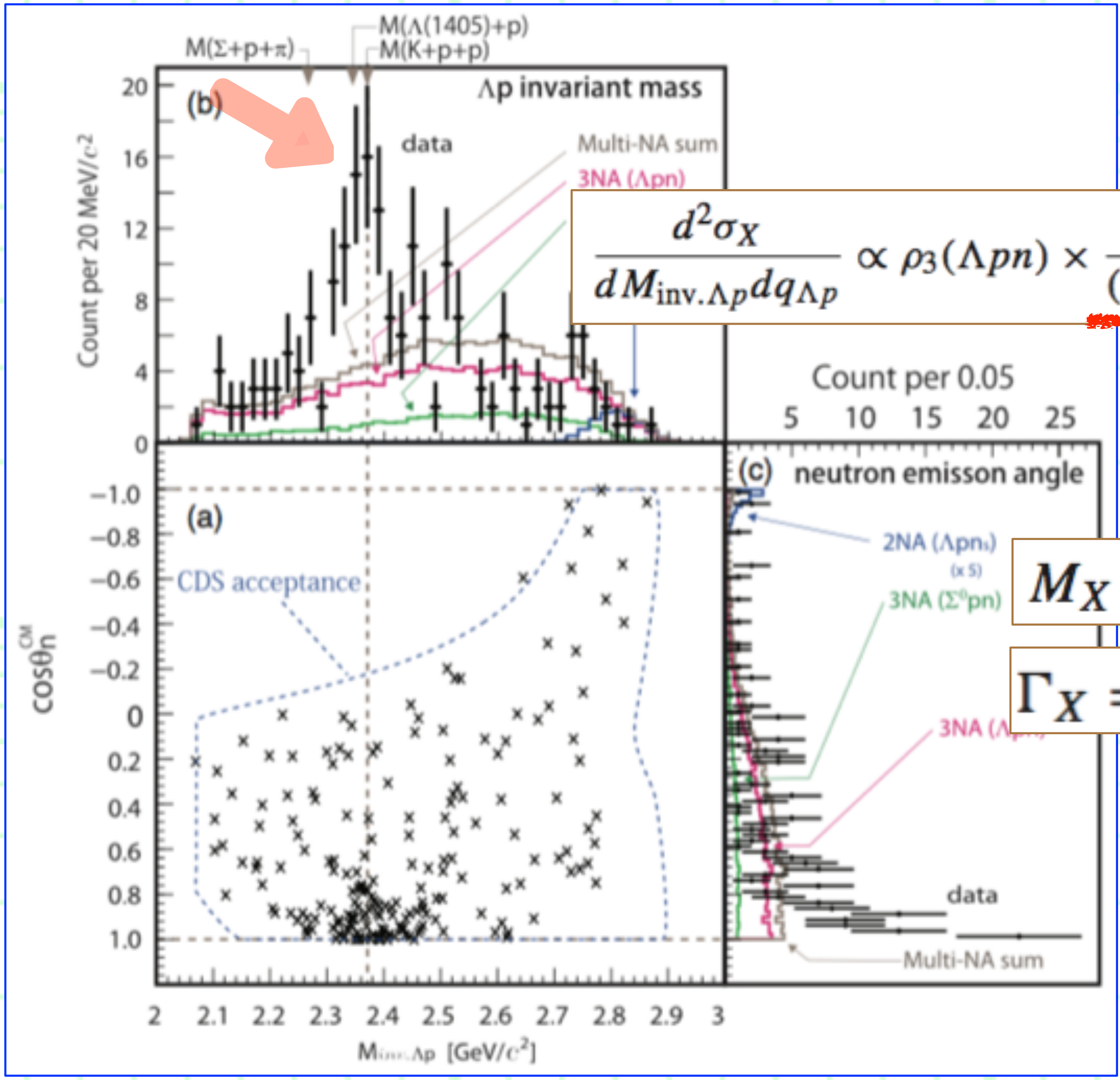
Y. Sada *et al.*, *PTEP* 2016 051D01.



2. Kaonic nuclei: up to now

++ 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.

- 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** ???

3. On the peak of the J-PARC E15 experiment:

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

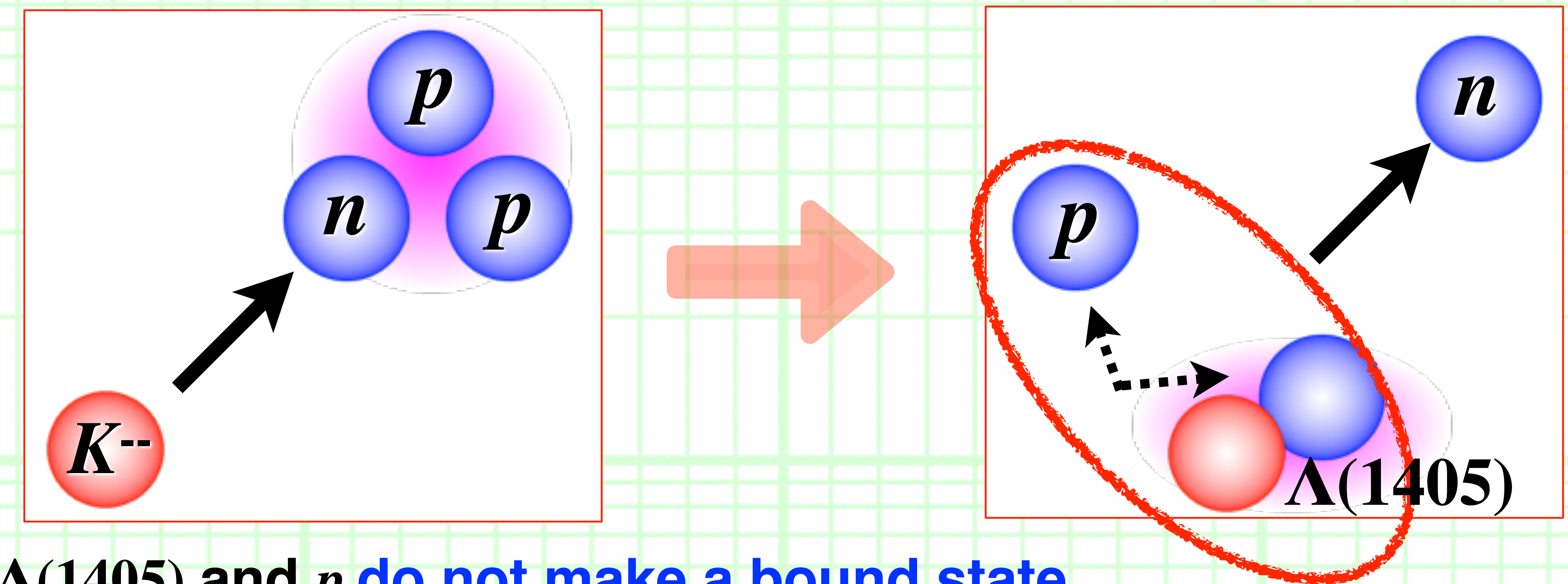
3. Is this really a signal of $\bar{K}NN$?

++ Purpose of this study: Scenario I ++

- **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.

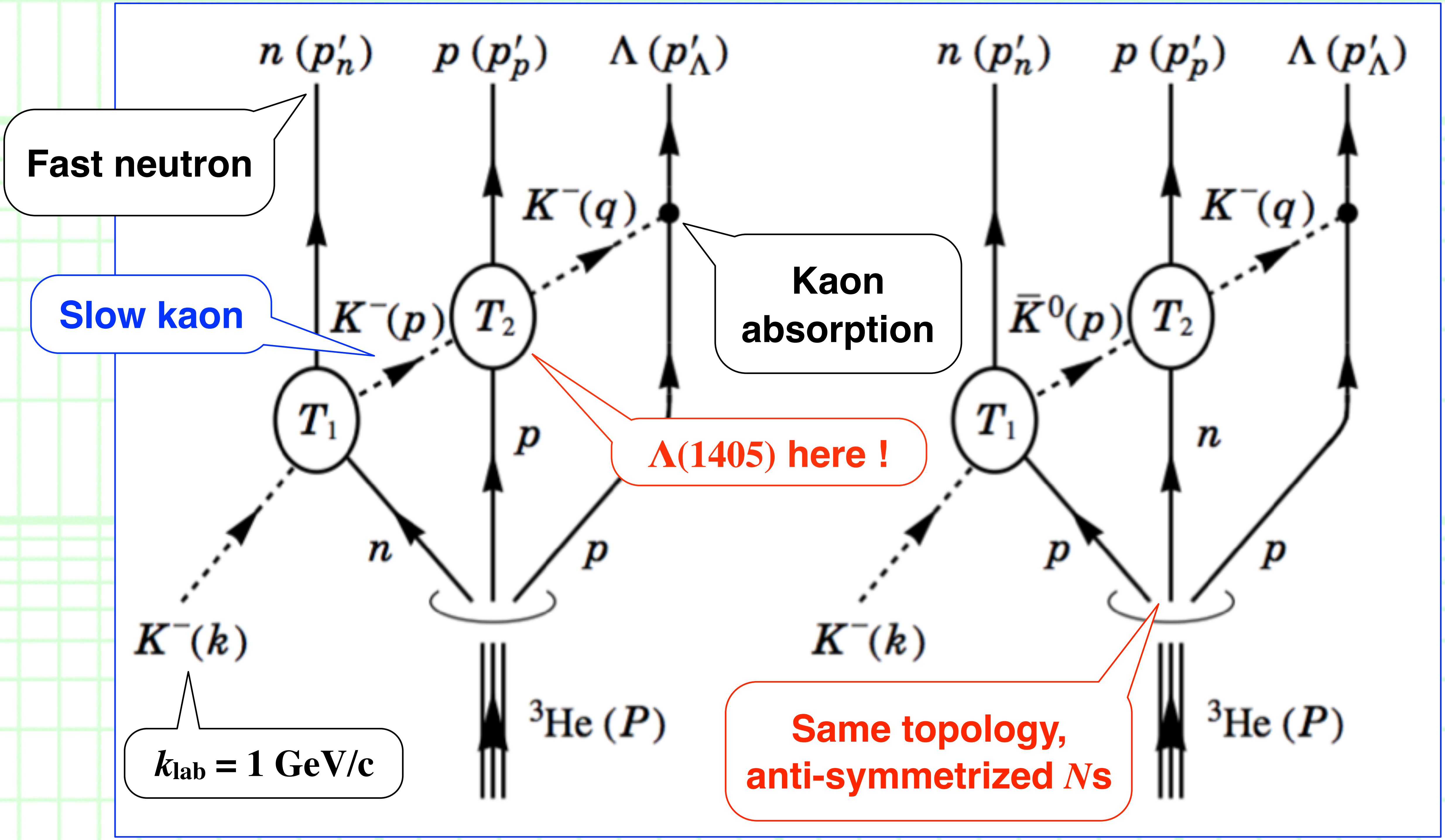
--- The Λ(1405)p system makes conversion to Λp.

□ **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.**

3. Is this really a signal of $\bar{K}NN$?

++ Uncorrelated Λ(1405)p: Scattering amplitude ++

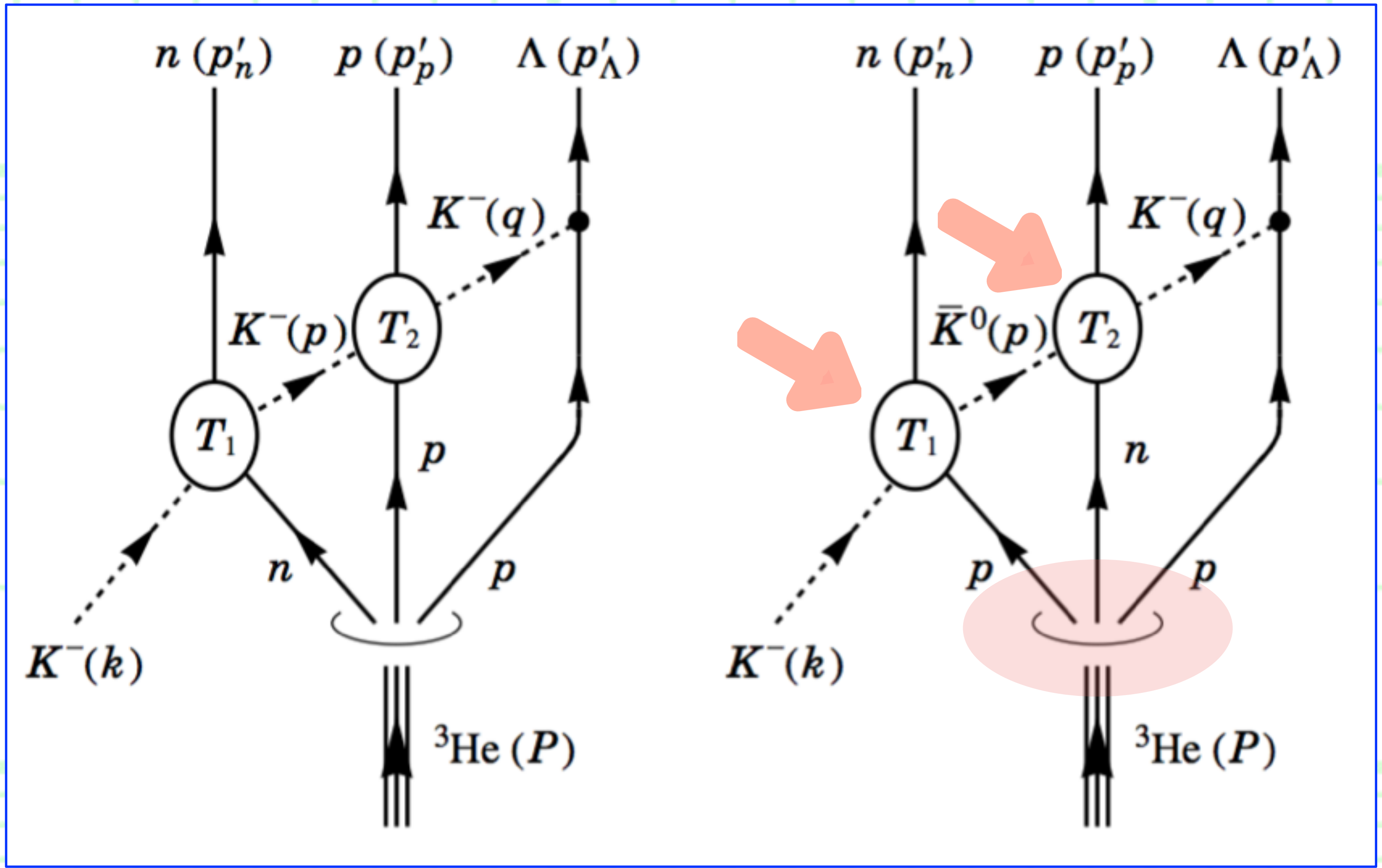
- For this process, we use the following diagrams:



3. Is this really a signal of $\bar{K}NN$?

++ Uncorrelated $\Lambda(1405)p$: Scattering amplitude ++

- For this process, we use the following diagrams:



- The ³He wave function is obtained as the anti-symmetrized 3 nucleons in the harmonic oscillator potential.

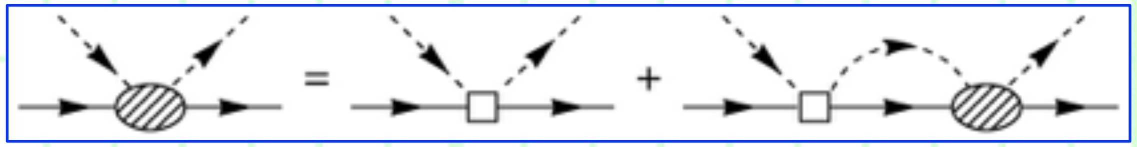
- Amplitude T_1 (k=1 GeV/c):

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

--- 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

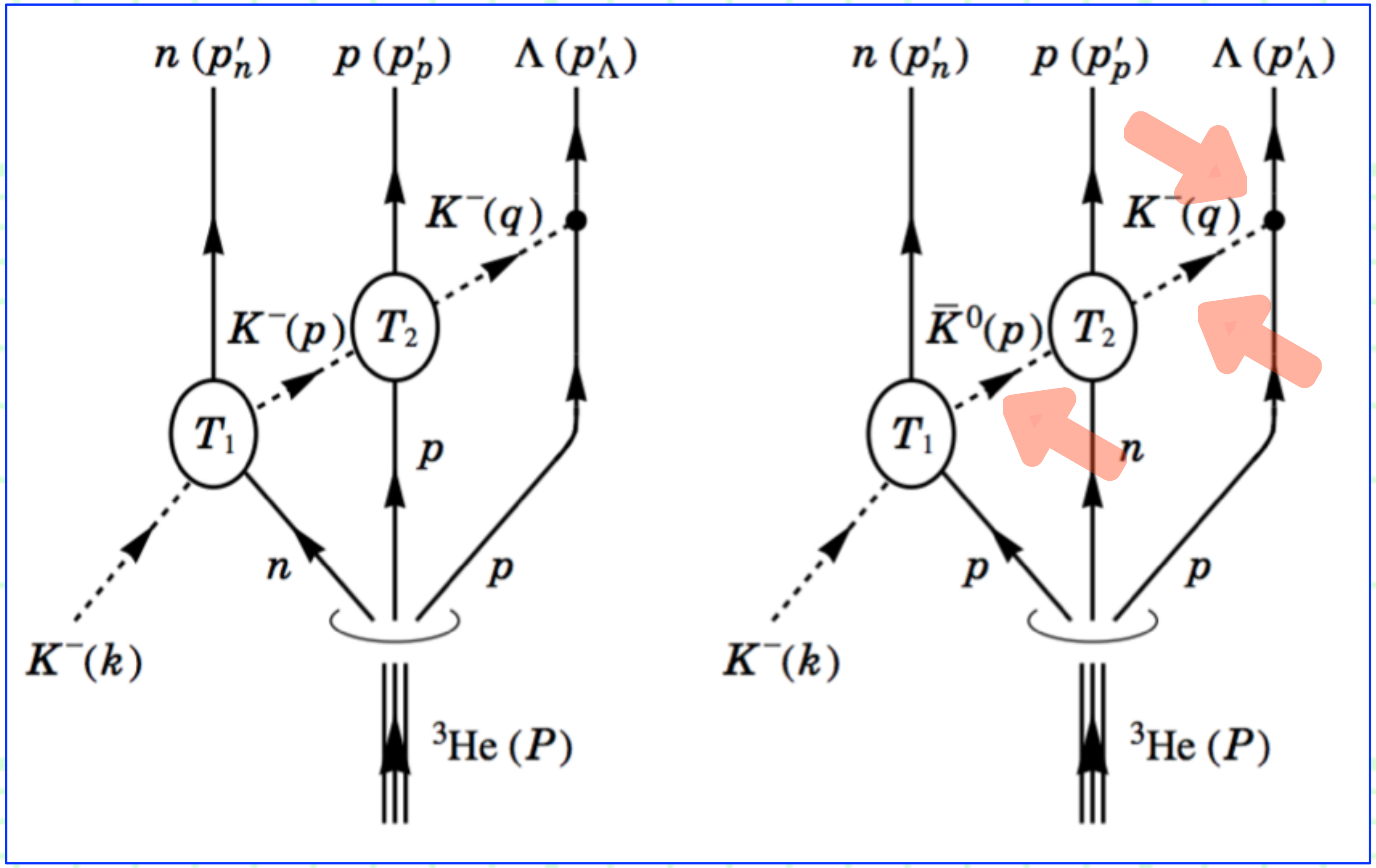


with kaon absorption width (ε --> Γ_K = 15 MeV in kaon prop.).

3. Is this really a signal of $\bar{K}NN$?

++ Uncorrelated $\Lambda(1405)p$: Scattering amplitude ++

- For this process, we use the following diagrams:



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

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

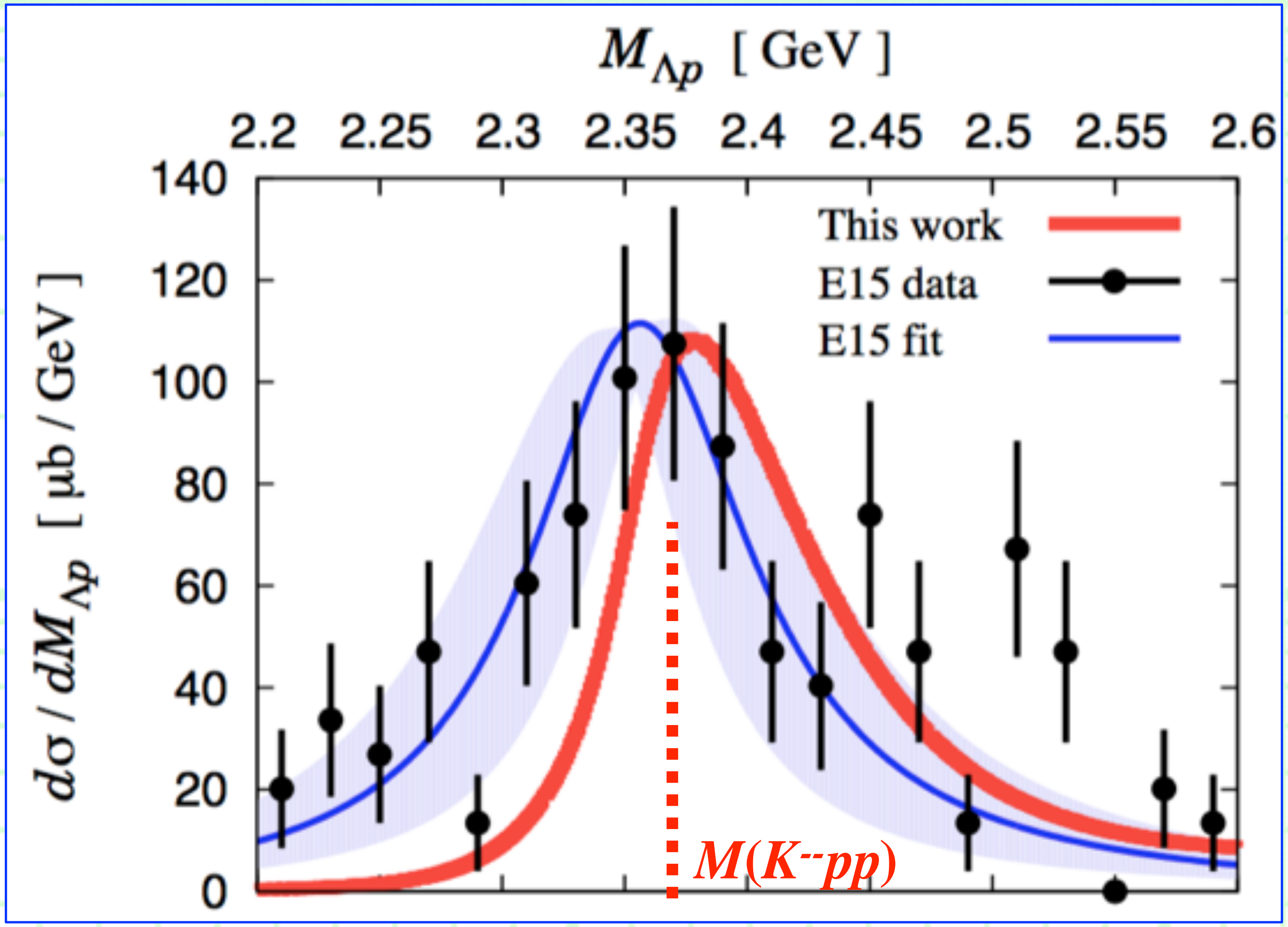
$$p^0 = p'^0_\Lambda + p'^0_p - 2\left(m_N - \frac{B_{^3\mathrm{He}}}{3} \right)$$

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

3. Is this really a signal of $\bar{K}NN$?

++ 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**.

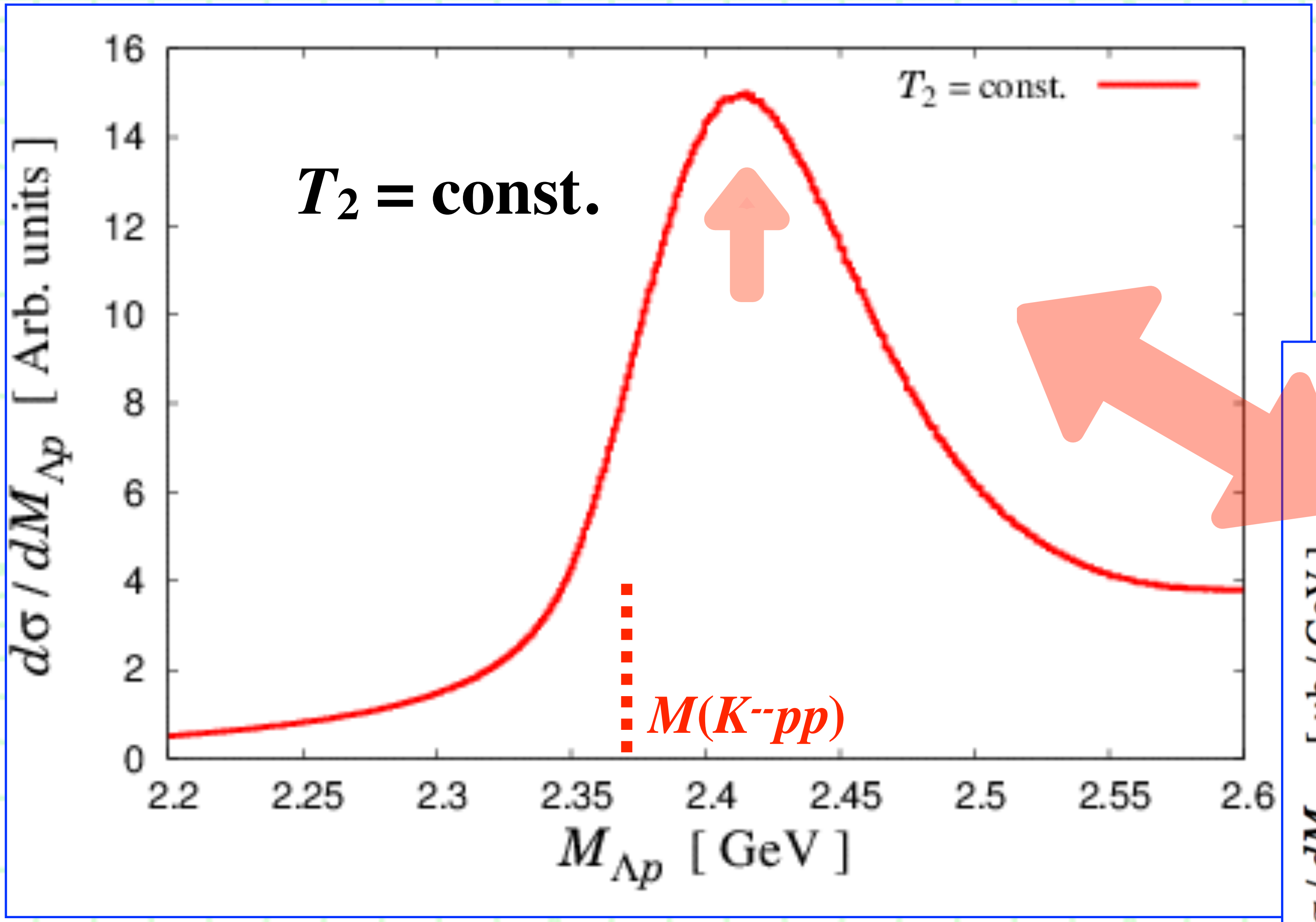
□ Therefore, the E15 signal in the ^{3}He (K^-, Λp) n reaction is **NOT the uncorrelated $\Lambda(1405)p$ state**.

3. Is this really a signal of $\bar{K}NN$?

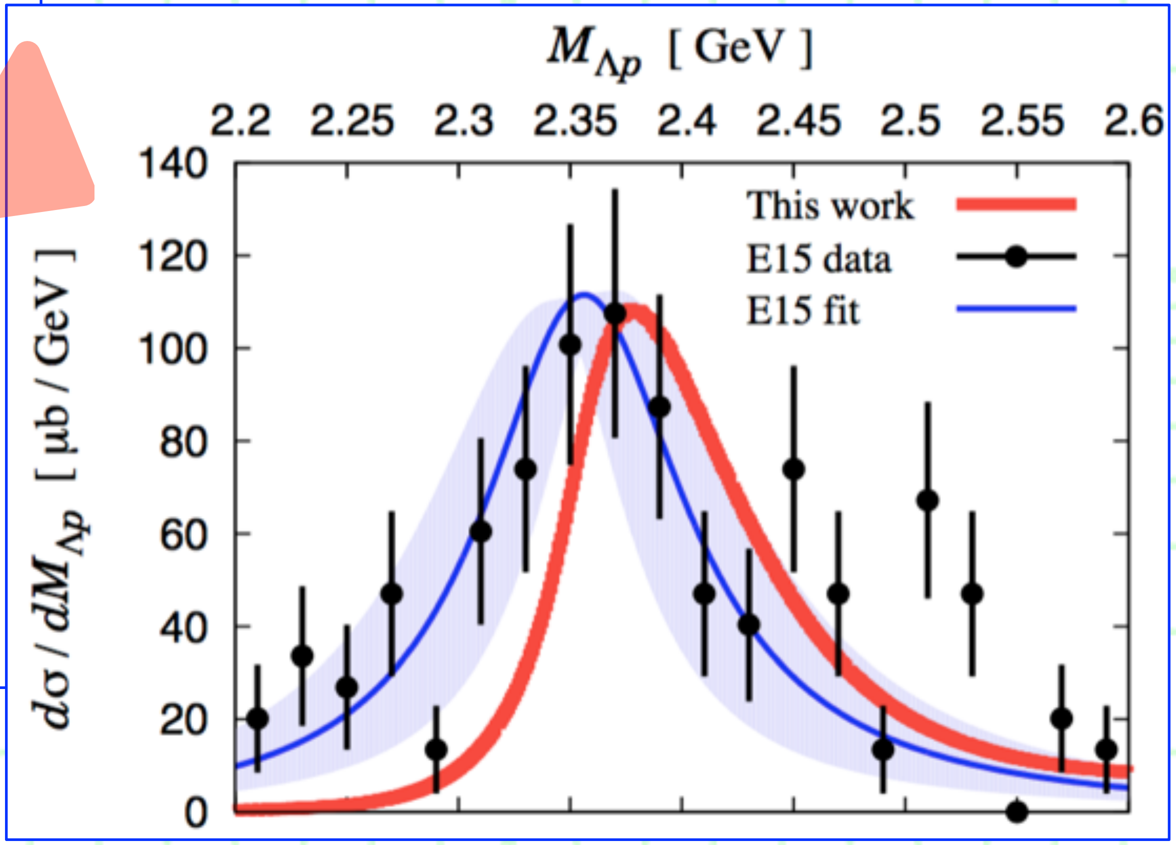
++ Underlying kinematic feature ++

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

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



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



3. Is this really a signal of $\bar{K}NN$?

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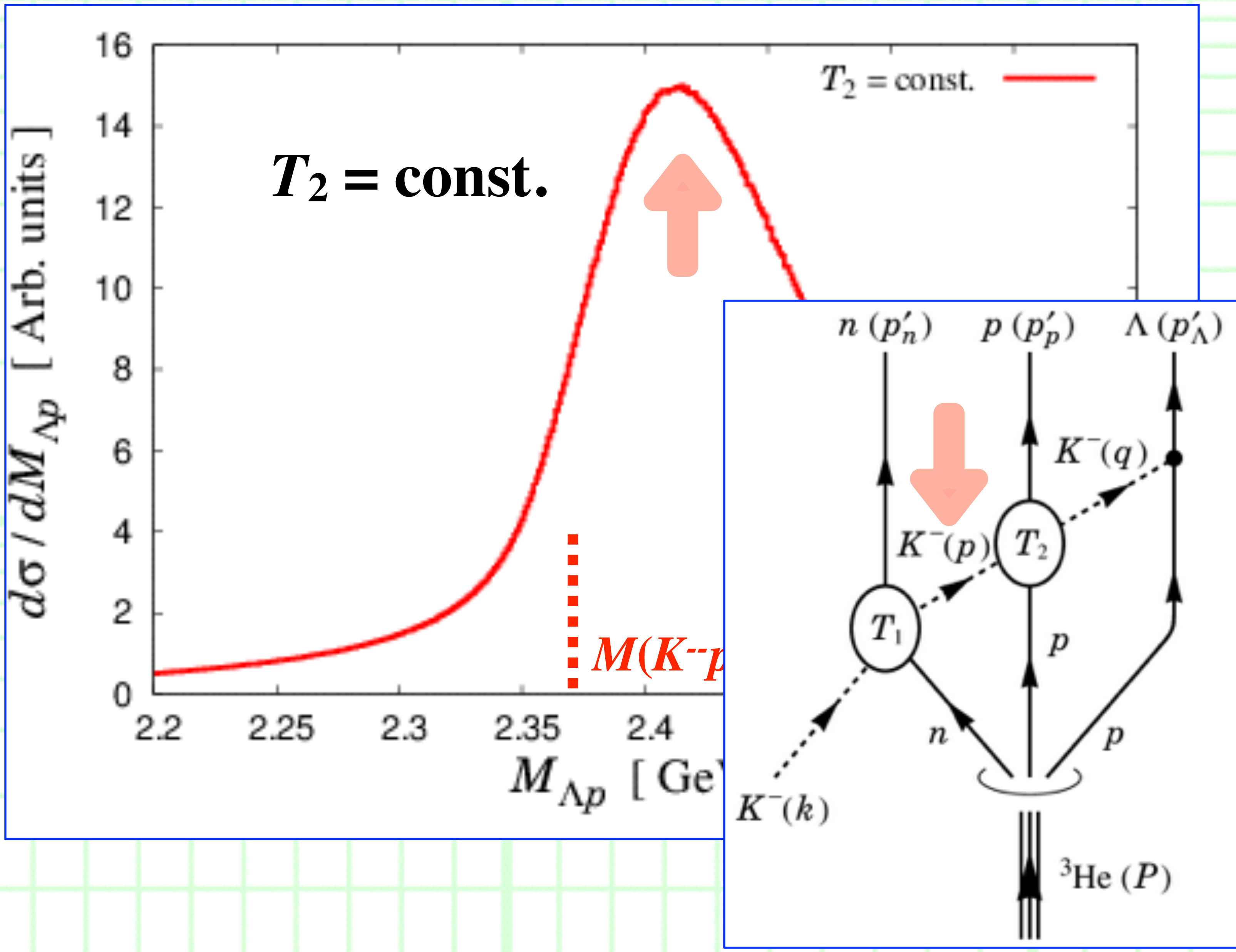


- Actually, this is due to **the quasi-elastic kaon scattering in the first step**.
  - --- The intermediate kaon after the fast neutron emission goes almost to its on mass shell.
- The actual mass spect. is essentially the product with $|T_2|^2$.
  - --> **They merge to be a single peak**.

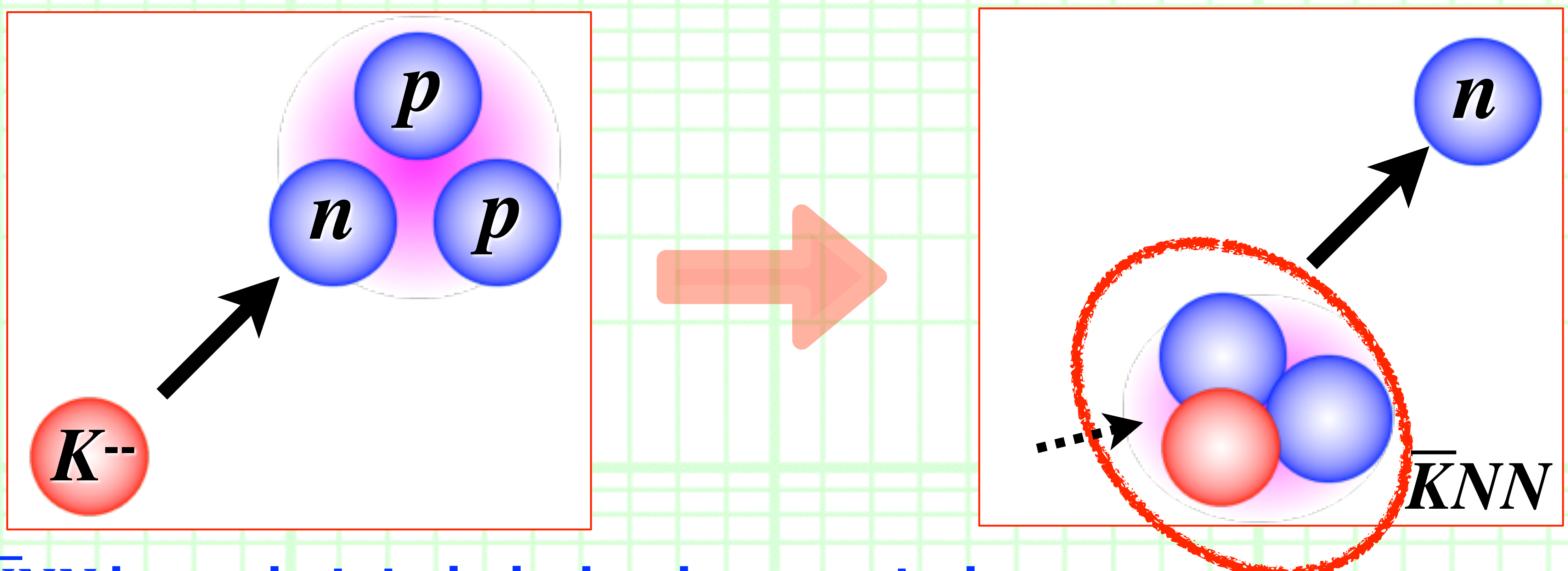
3. Is this really a signal of $\bar{K}NN$?

++ Purpose of this study: Scenario II ++

- 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.



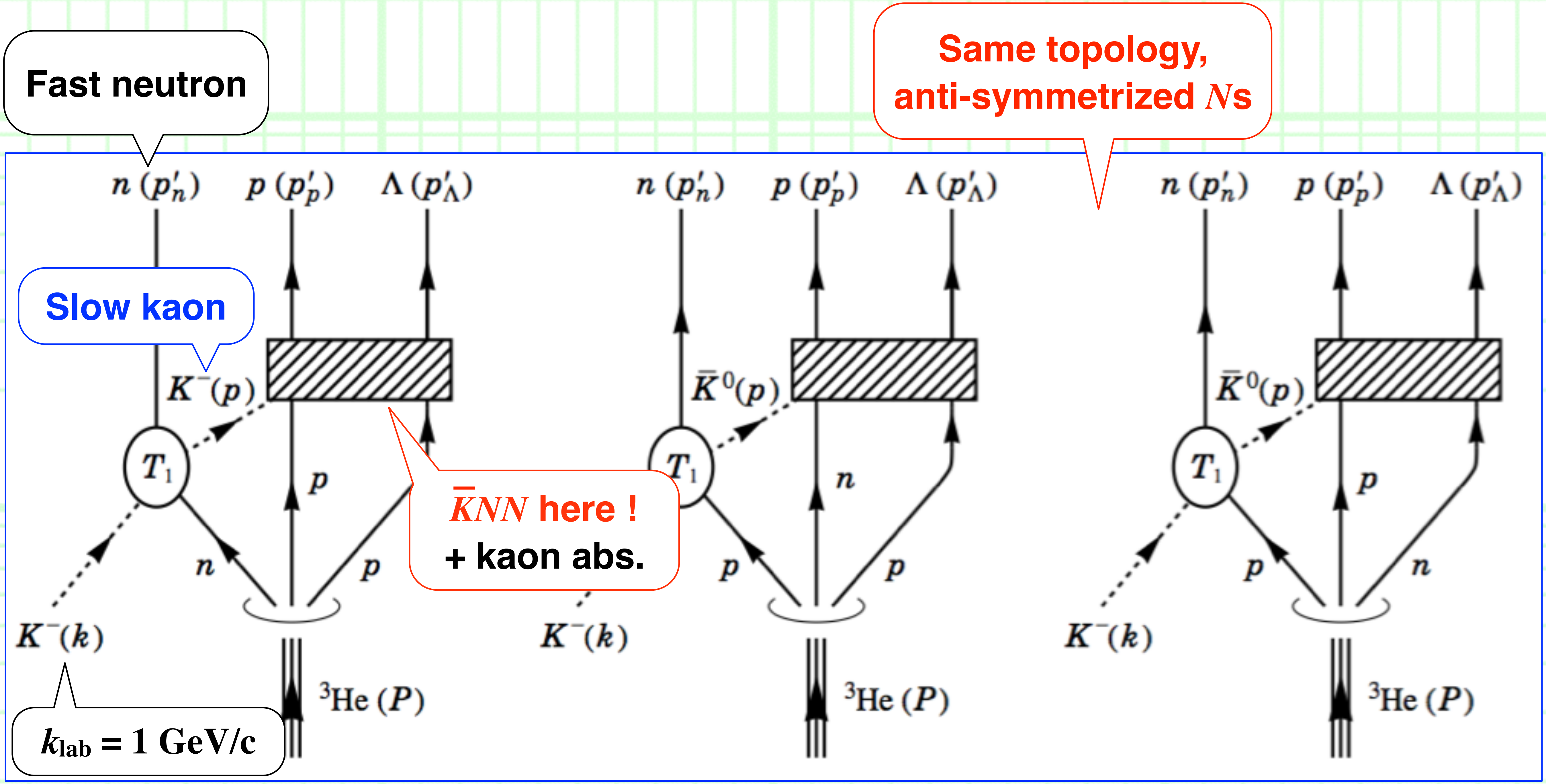
--- $\bar{K}NN$ bound state is indeed generated after the fast neutron emission.

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

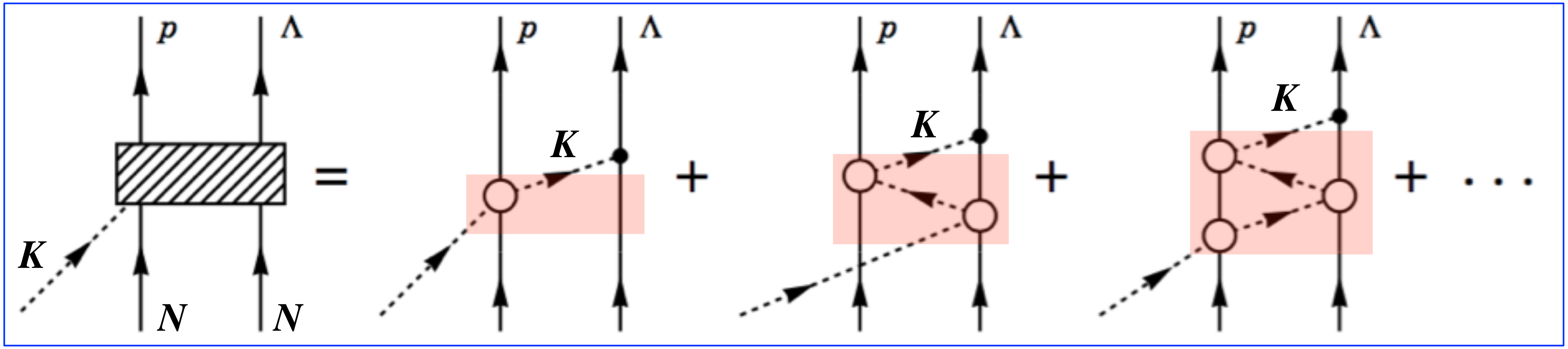
3. Is this really a signal of $\bar{K}NN$?

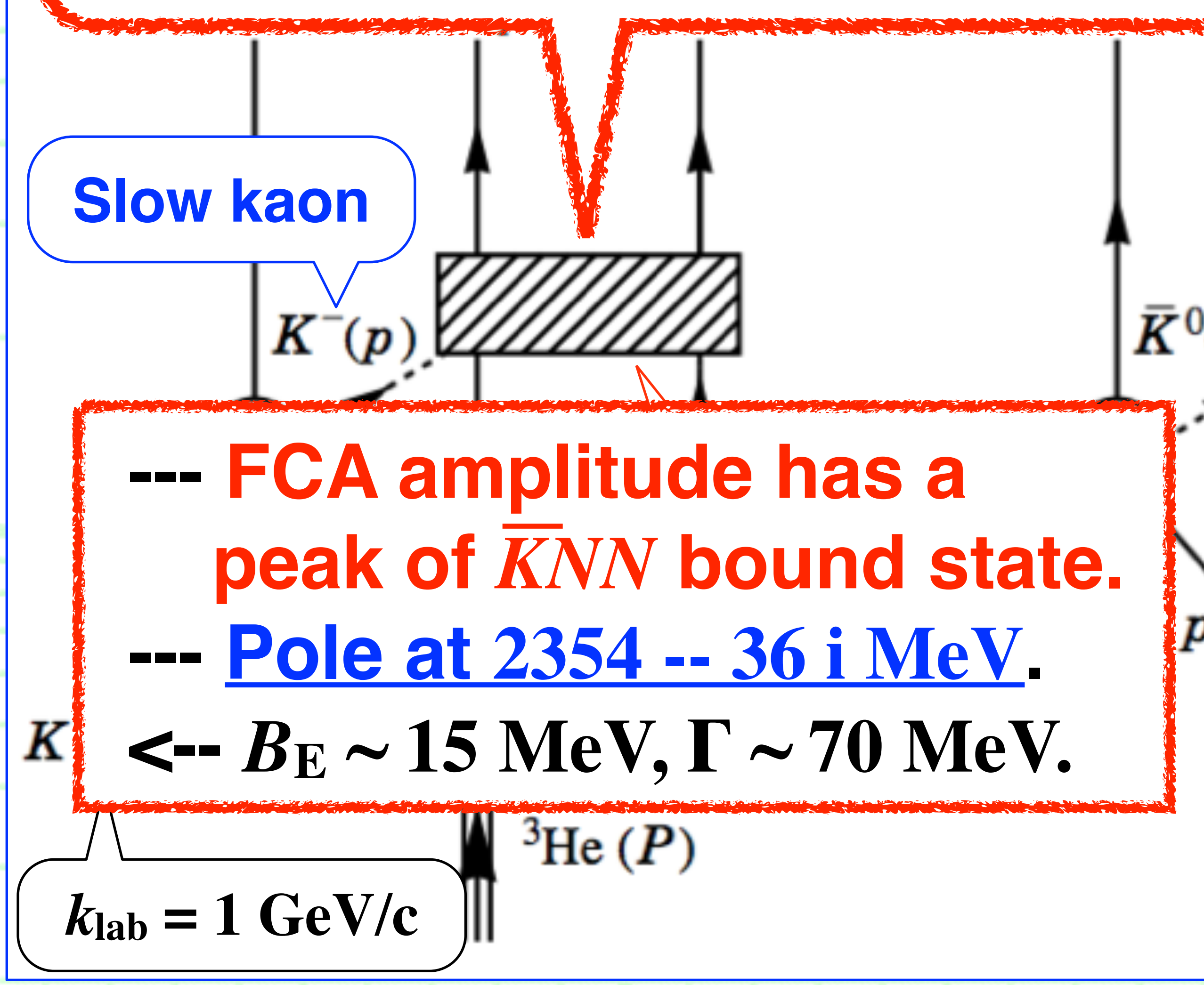
++ $\bar{K}NN$ bound state: Scattering amplitude ++

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



3. Is this really a signal of $\bar{K}NN$?

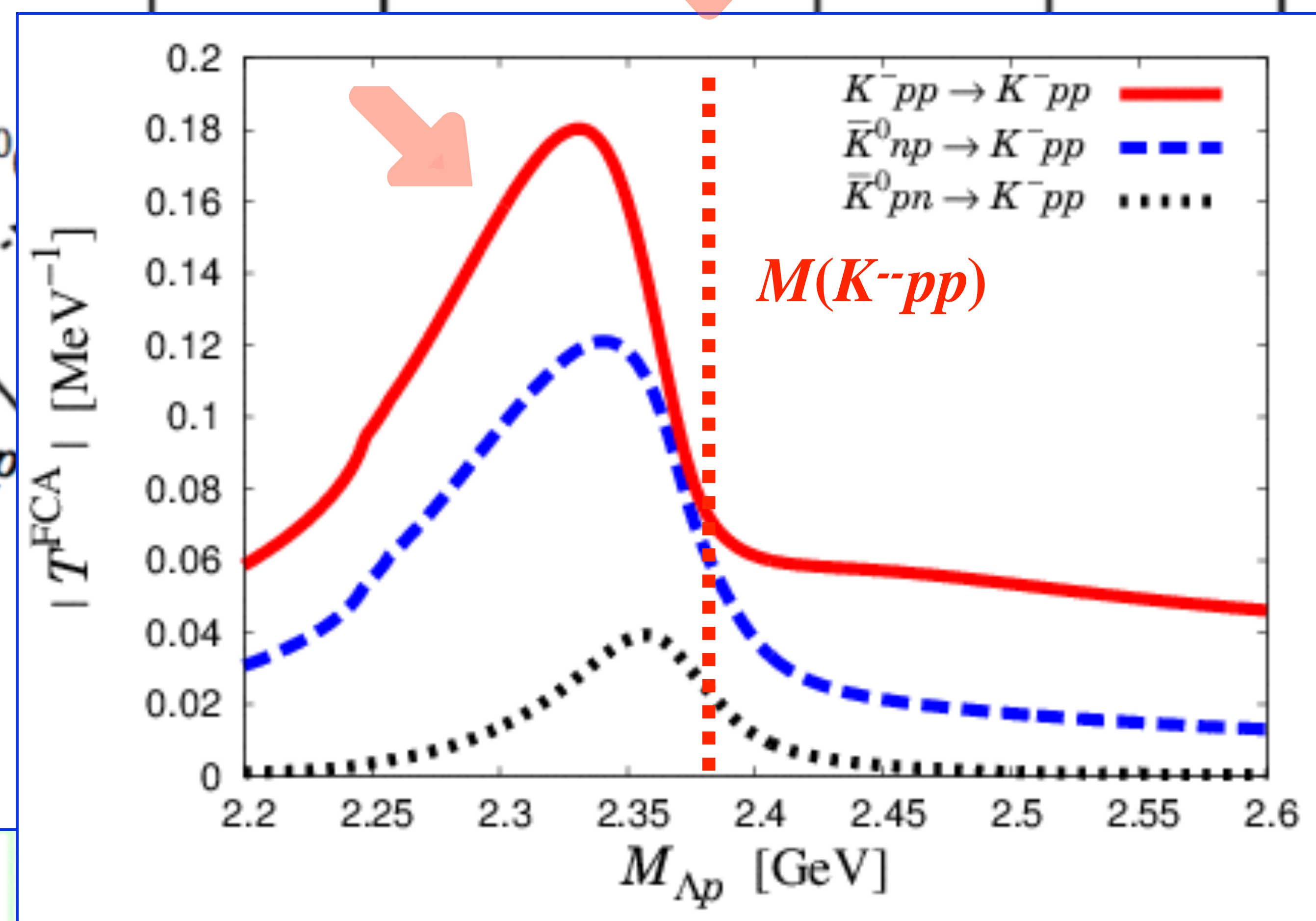




--- FCA amplitude has a peak of $\bar{K}NN$ bound state.

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

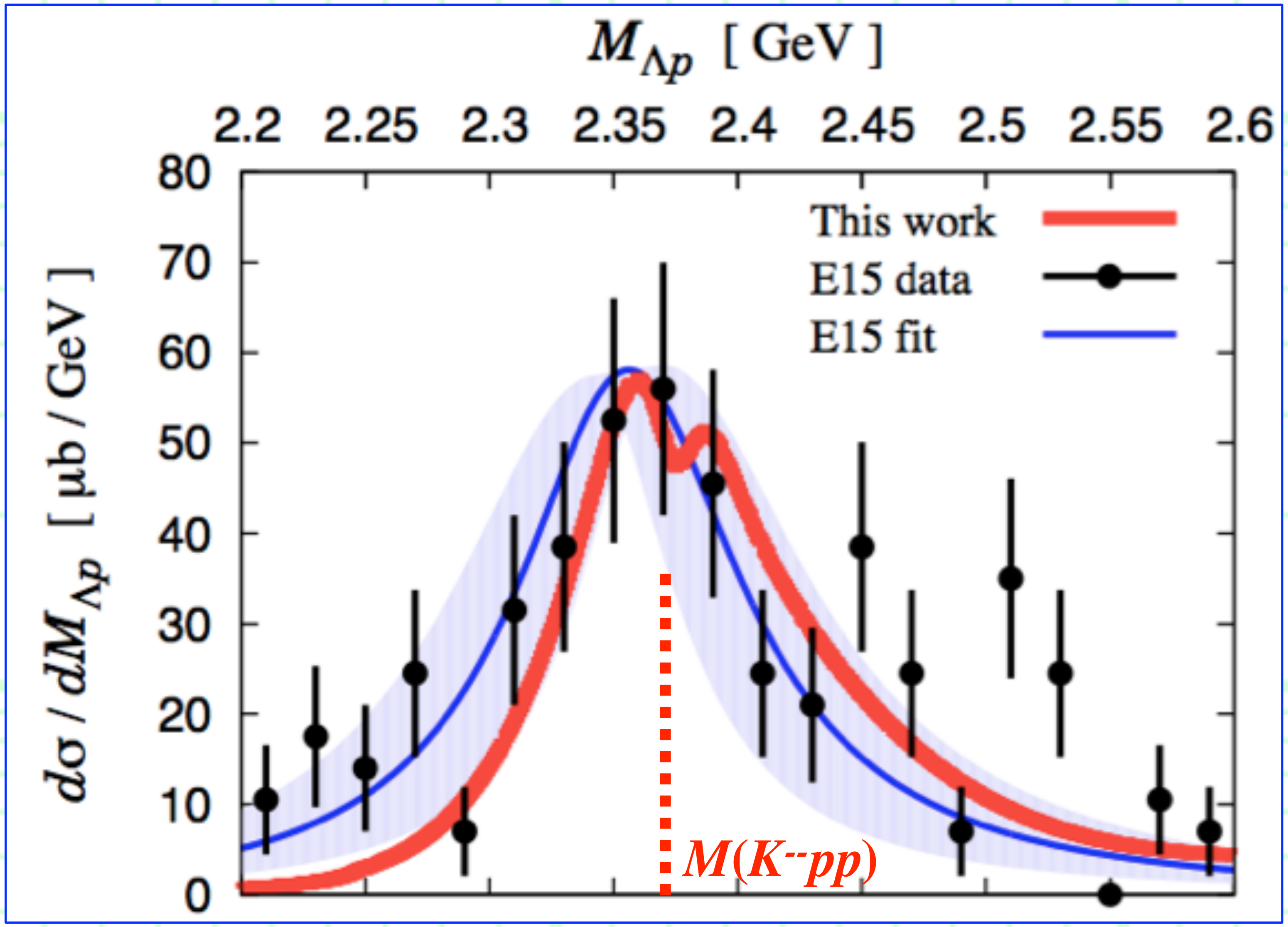
<-- $B_E \sim 15$ MeV, $\Gamma \sim 70$ MeV.



3. Is this really a signal of $\bar{K}NN$?

++ $\bar{K}NN$ 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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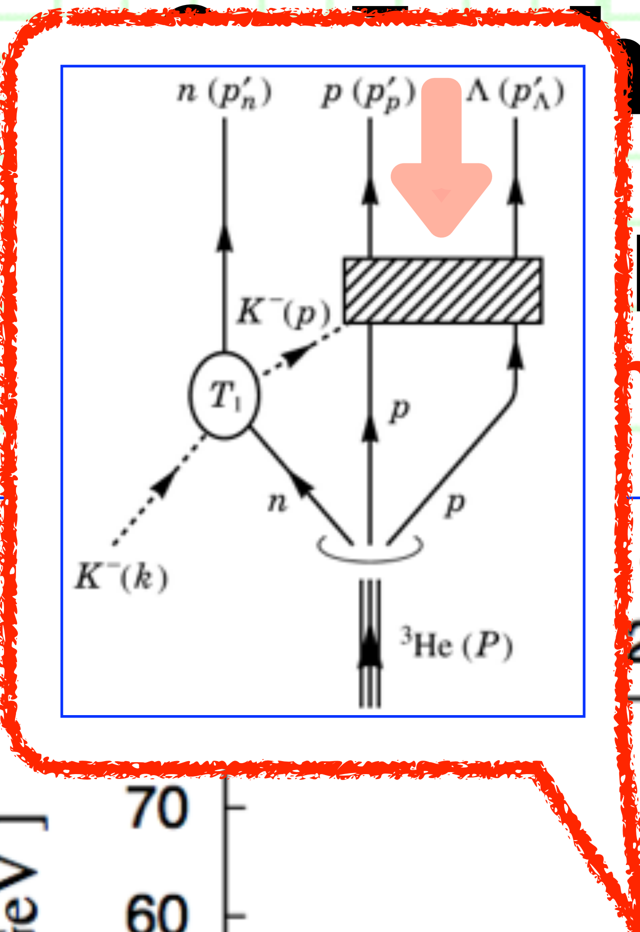
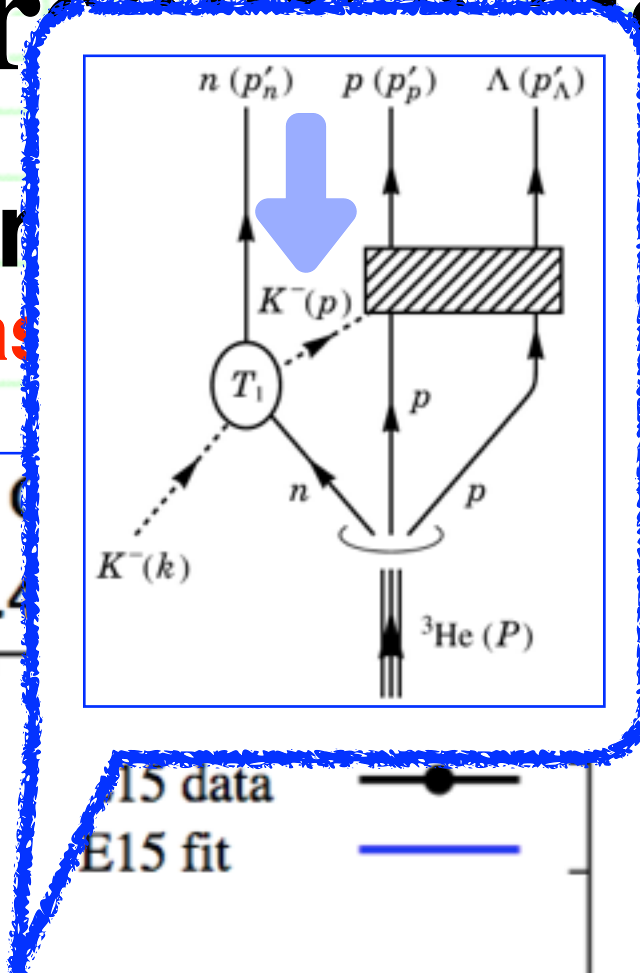
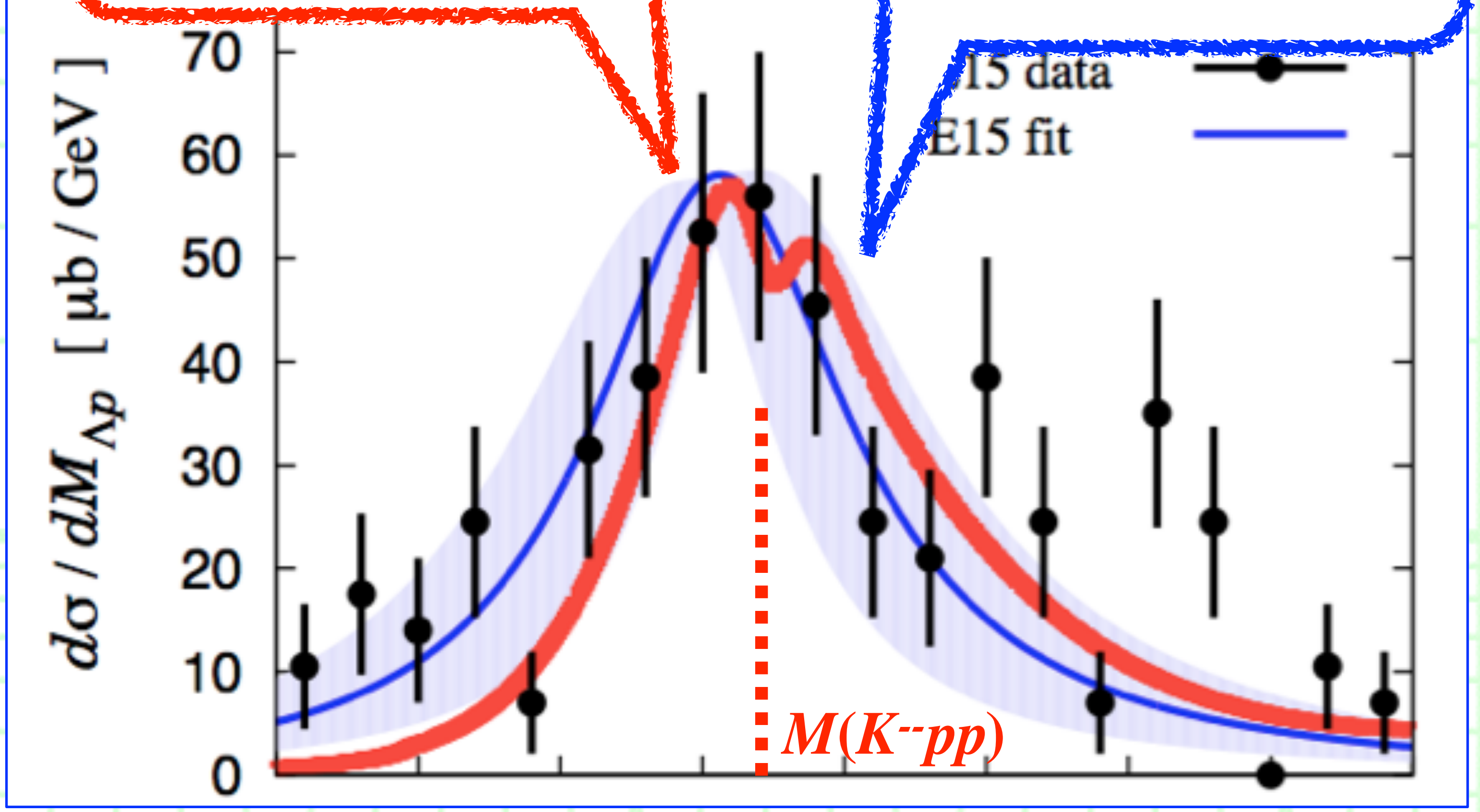






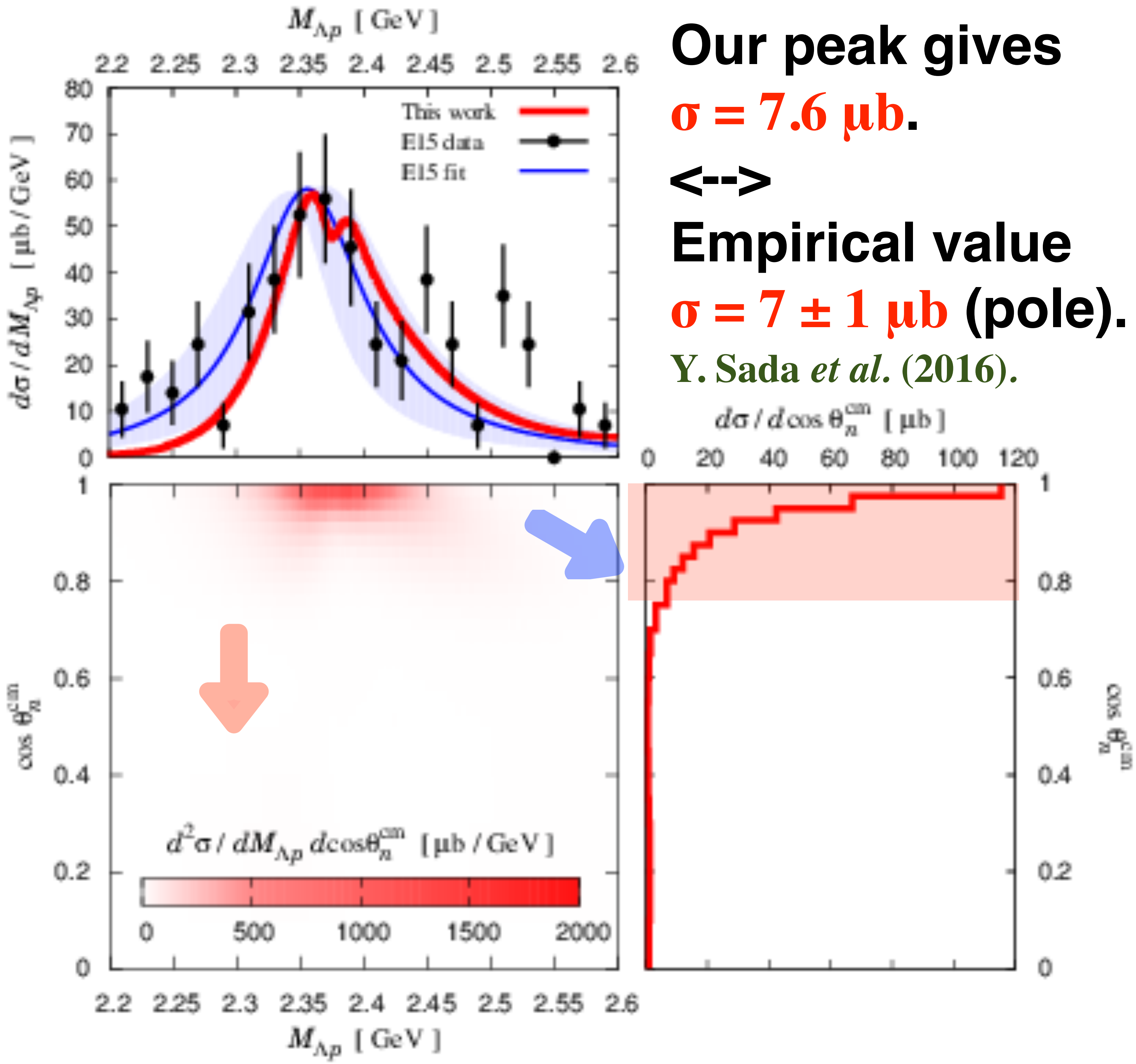
□ One more thing:
Our spectrum has
a "double peak" structure
around the $\bar{K}NN$ threshold.

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

--- The higher peak comes
from kinetic reason:
The quasi-elastic kaon scattering in the 1st step.
<-- Almost on-shell kaon.

3. Is this really a signal of $\bar{K}NN$?

++ $\bar{K}NN$ 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.**

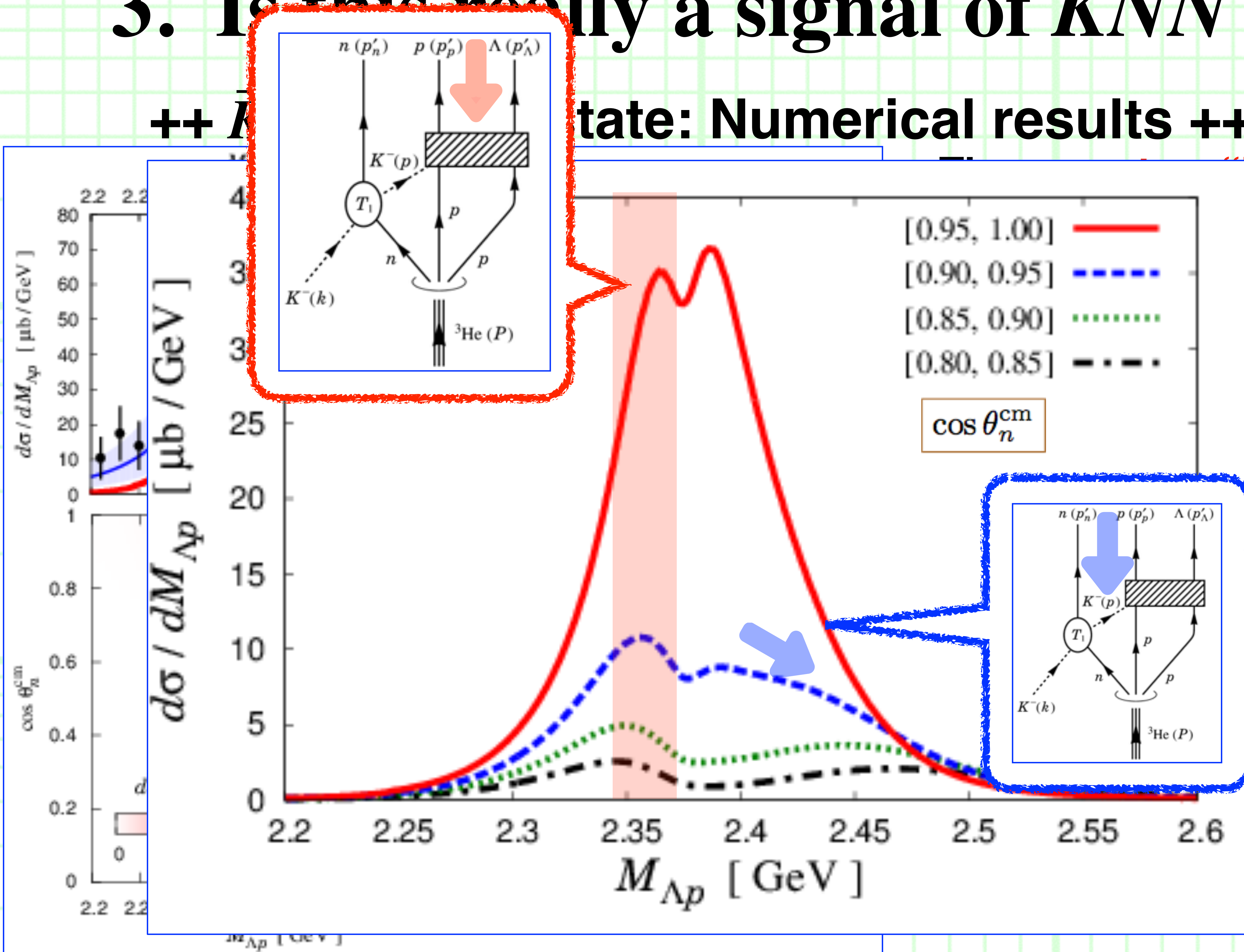
- □ **Diff. cross section $d\sigma/d\cos\theta_n$ indicates forward neutron emission is favored.**

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

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

3. Is this really a signal of $\bar{K}NN$?

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



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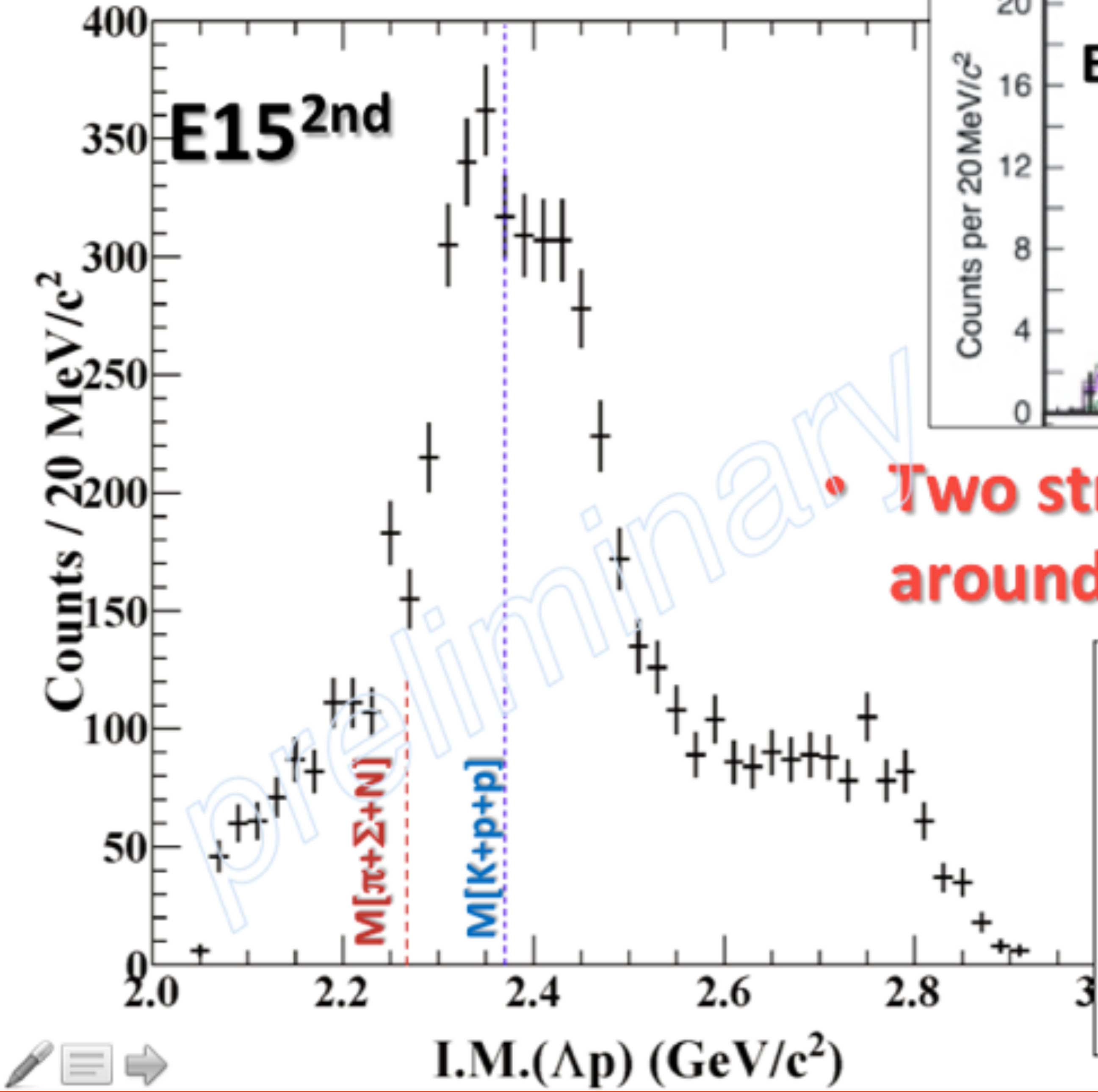
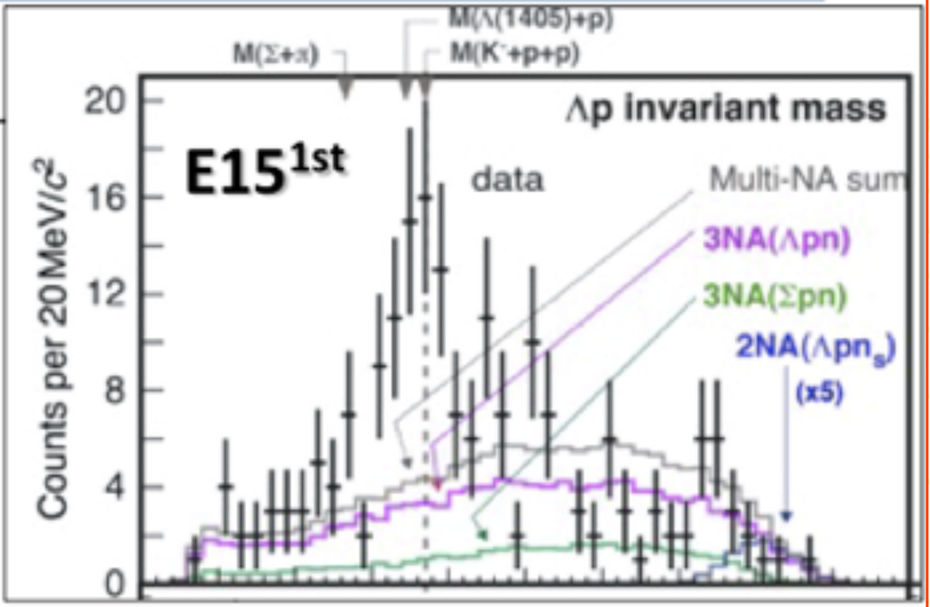
3. Is this really a signal of $\bar{K}NN$?

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

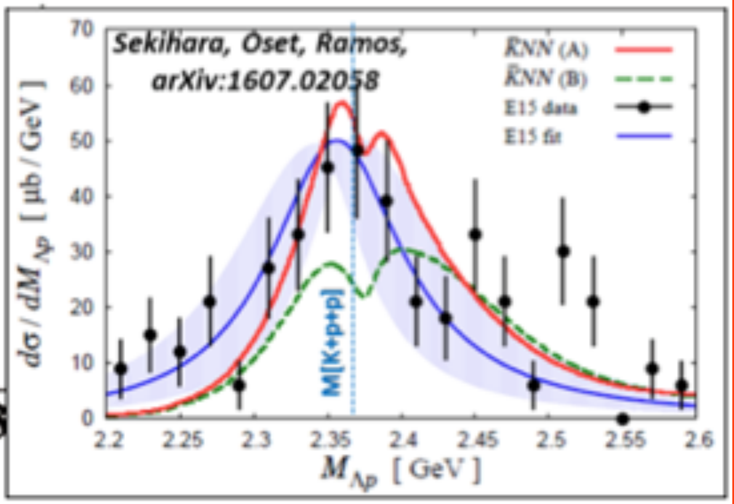
Exclusive ^{3}He(K$^-$,Λp)n

Sakuma-sun at MENU 2016.



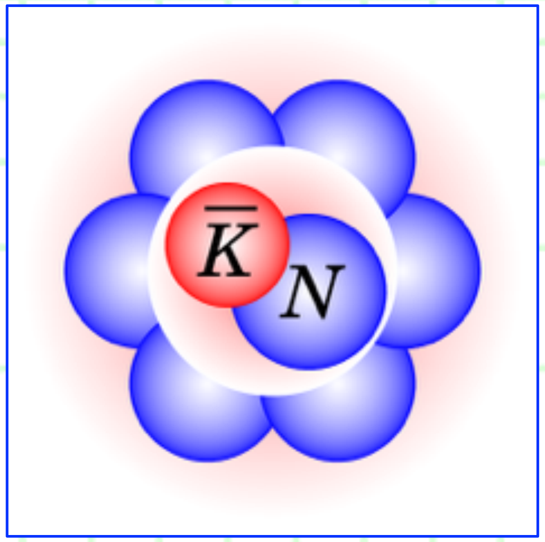


- Two structures are seen around M[K+p+p]!?



4. Summary

4. Summary



++ Summary ++

- There should be **many-body bound states of hadrons** generated by the strong interaction.

--- Kaonic nuclei are candidates.

- 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.** □ **...**

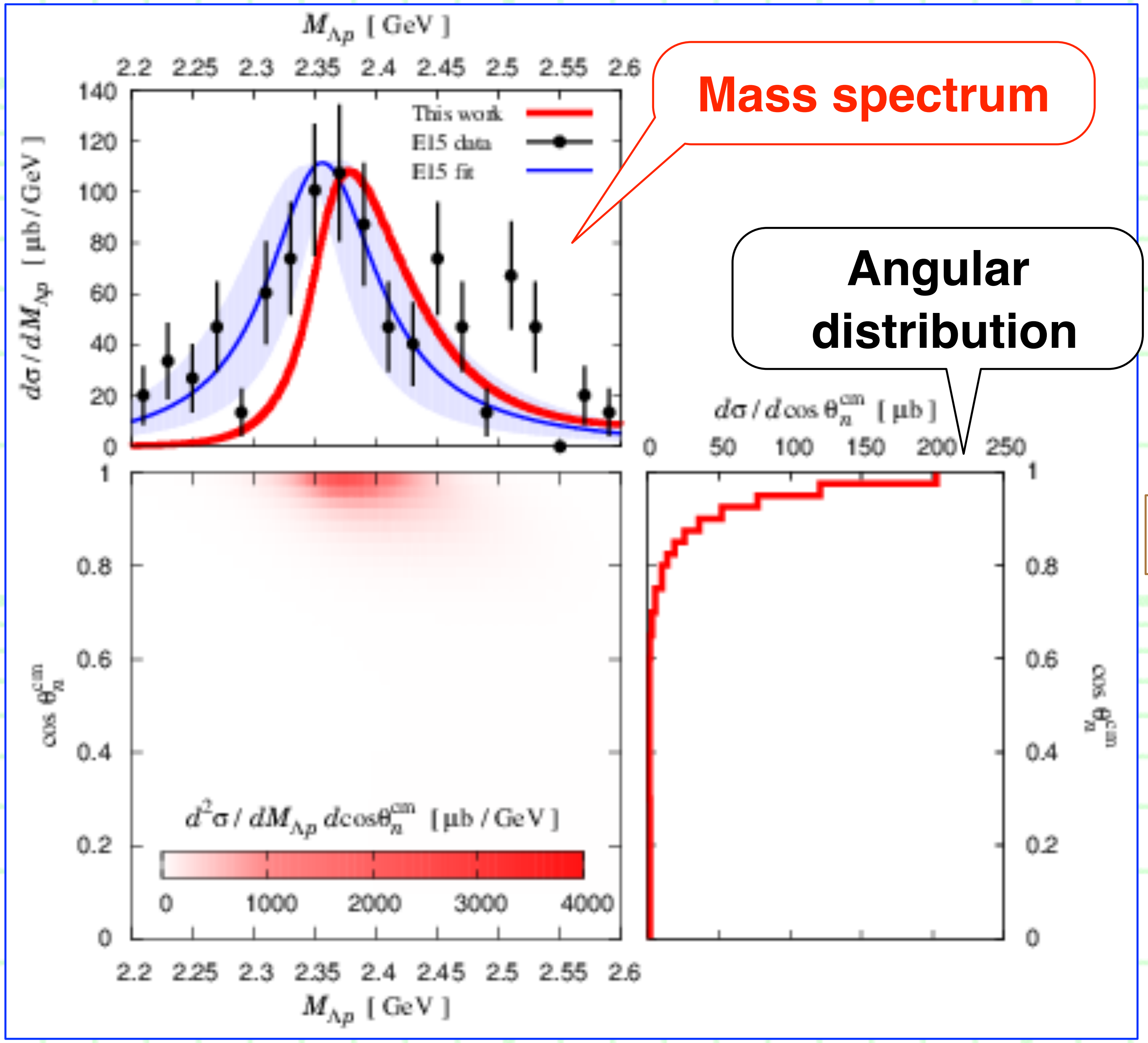
Thank you very much for your kind attention !

Appendix

Appendix

++ Scenario I: Numerical results ++

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



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

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

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

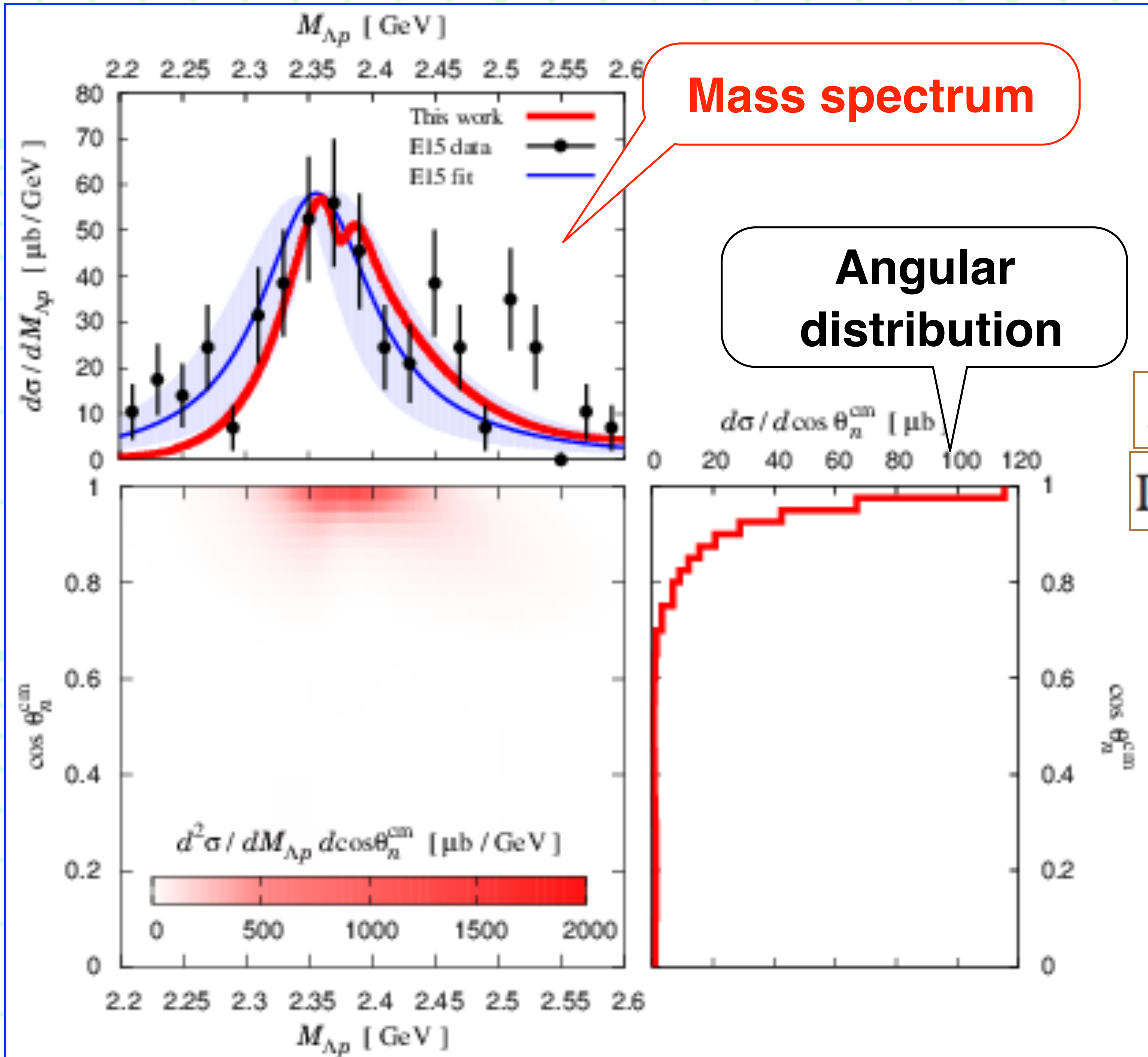
$$\Gamma_X = 110^{+19}_{-17}\ \text{(stat.)} \pm 27\ \text{(syst.)}\ \text{MeV}/c^2,$$

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

Appendix

++ Scenario II: Numerical results ++

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



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