A theoretical support for the discovery of the $\bar{K}NN$ nucleus at J-PARC and its perspective/implication in heavy ion collision

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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. 26 (2019) 023009.

[3] T. S. , E. Oset, and A. Ramos, under discussion.

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1. Introduction

2. Reaction calculation for the $\bar{K}NN$ nucleus production in the J-PARC E15 experiment: $K^- \, {}^3He \to \Lambda \, p \, n$

3. Perspective/implication in heavy ion collisions

4. Summary

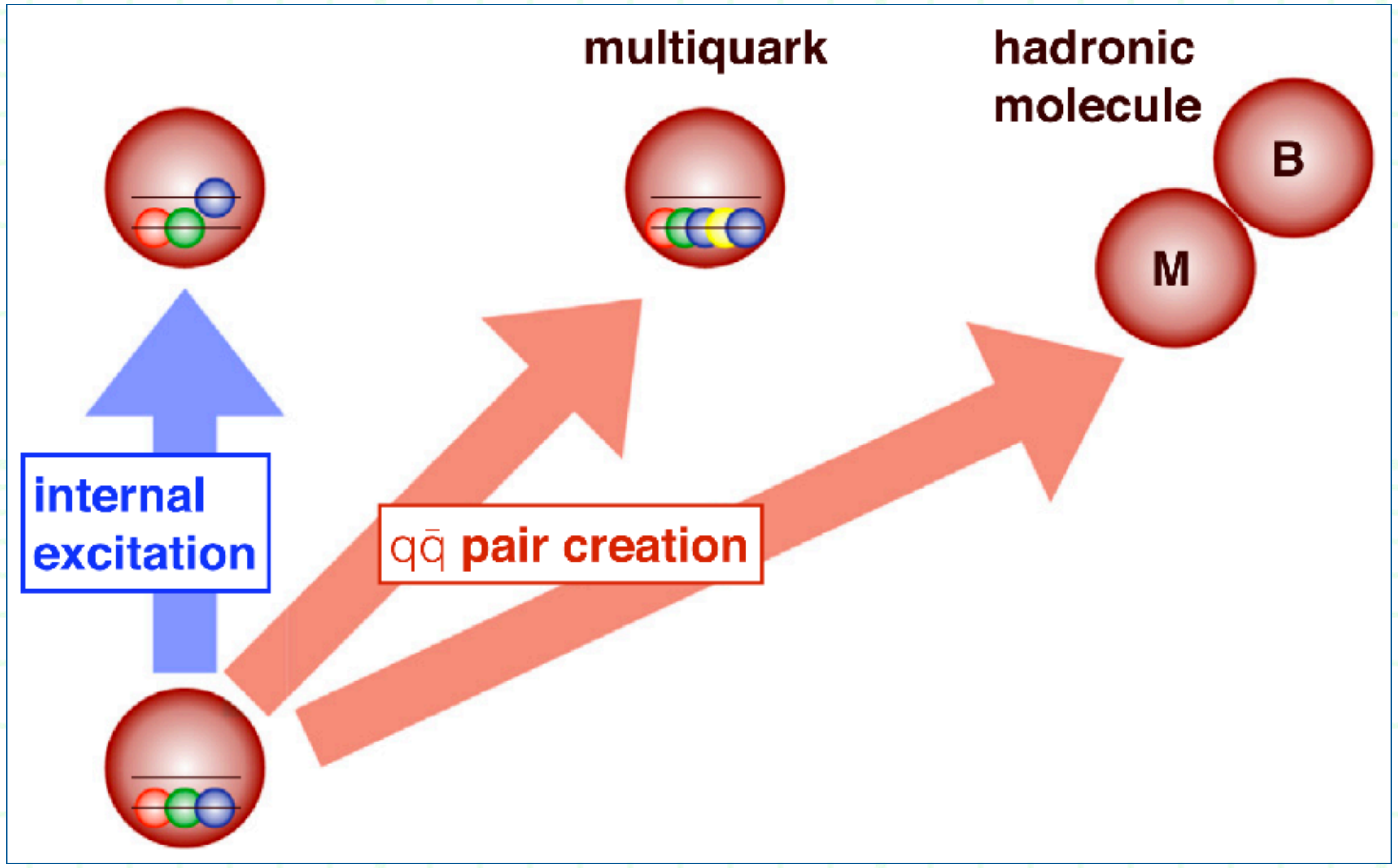
1. Introduction

1. Introduction

++ Exotic states in the hadron spectrum ++

- Hadrons = Particles composed of quarks, interact via strong interactions.

– Underlying theory for strong interactions: Quantum Chromodynamics (QCD).



Cho et al., Prog. Part. Nucl. Phys. 95 (2017) 279.

- Ground-state hadrons are described well by quark models.

– qqq for baryons, $q\bar{q}$ for mesons.

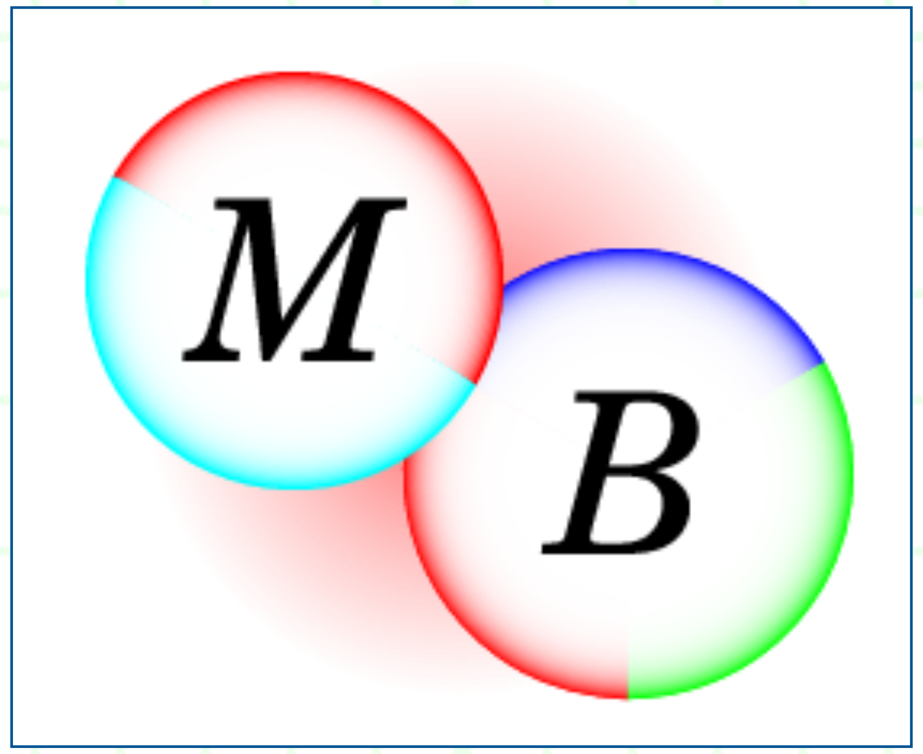
- Then, how about excited states ... ?

1. Introduction

++ Exotic states in the hadron spectrum ++

■ We focus on the hadronic molecules.

– Meson-baryon, baryon-baryon, meson-meson, ….



Hadronic molecules composed of meson and baryon.

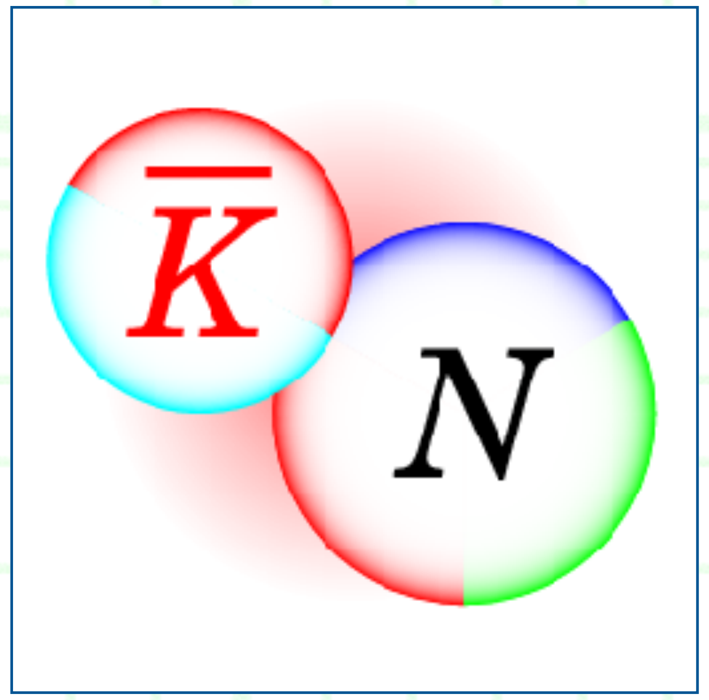
■ In particular, meson decree of freedom is interesting, because meson number does not conserve.

–> We can expect that exotic states in which meson degree of freedom is significant may be "embedded" in the hadron spectrum.

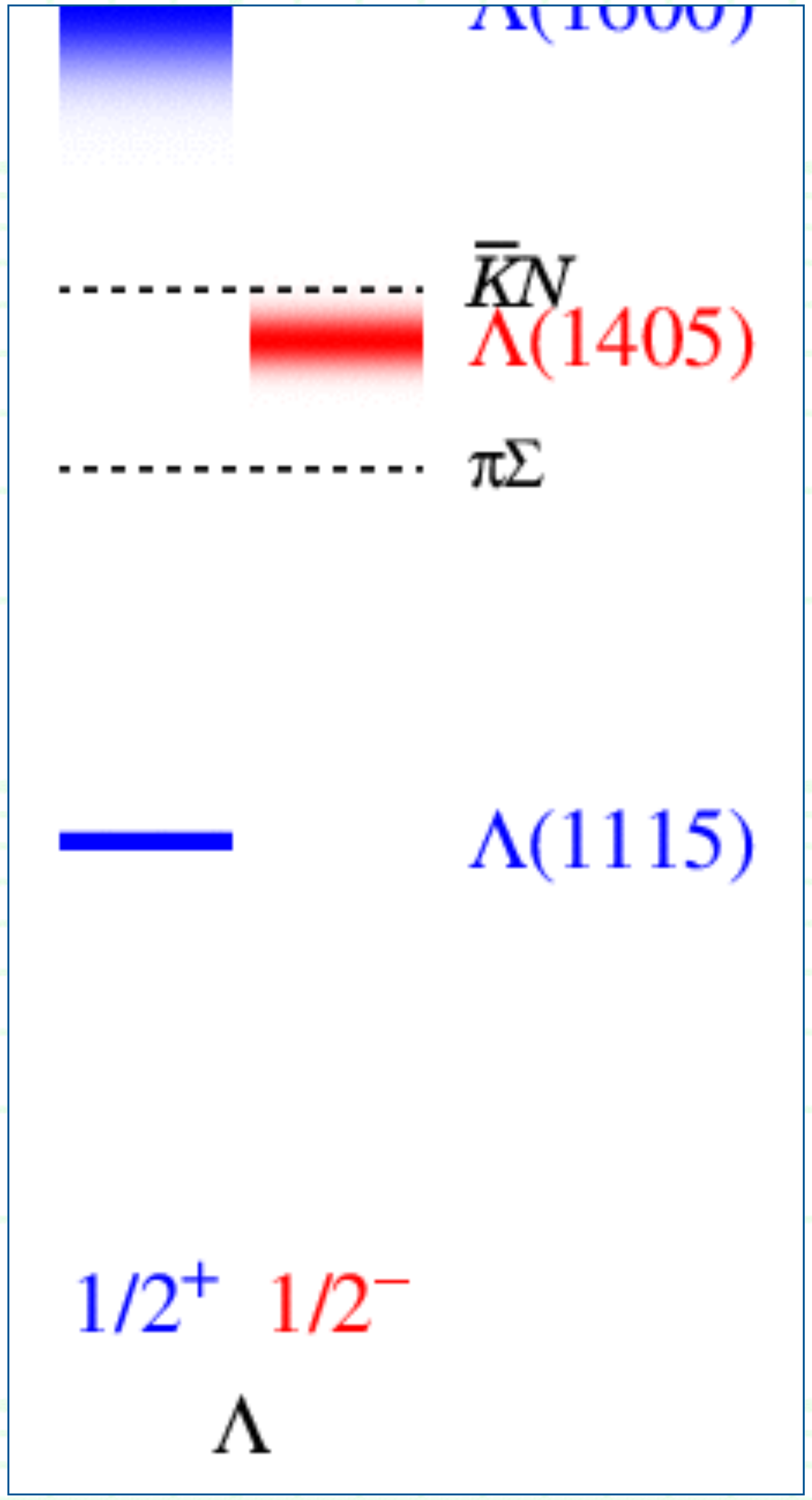
1. Introduction

++ The $\Lambda(1405)$ as a classic ++

- The most famous candidate of the hadronic molecules is the $\Lambda(1405)$ resonance.
  - ☐ The spontaneous breaking of chiral symmetry.
  - ☐ The $\bar{\mathrm{K}}\mathrm{N}$ interaction in chiral dynamics is attractive enough to generate a bound state as $\Lambda(1405)$.



Bound state as $\Lambda(1405)$!



- Theoretical studies support the $\bar{\mathrm{K}}\mathrm{N}$ molecular nature of the $\Lambda(1405)$ resonance.
  - ☐ Compositeness = the norm of the two-body wave function.

    T. S. , Hyodo and Jido, PTEP 2015 063D04; Kamiya and Hyodo, PTEP 2017 023D02; ….
  - ☐ Dominant $\bar{\mathrm{K}}\mathrm{N}$ component in lattice QCD simulations.

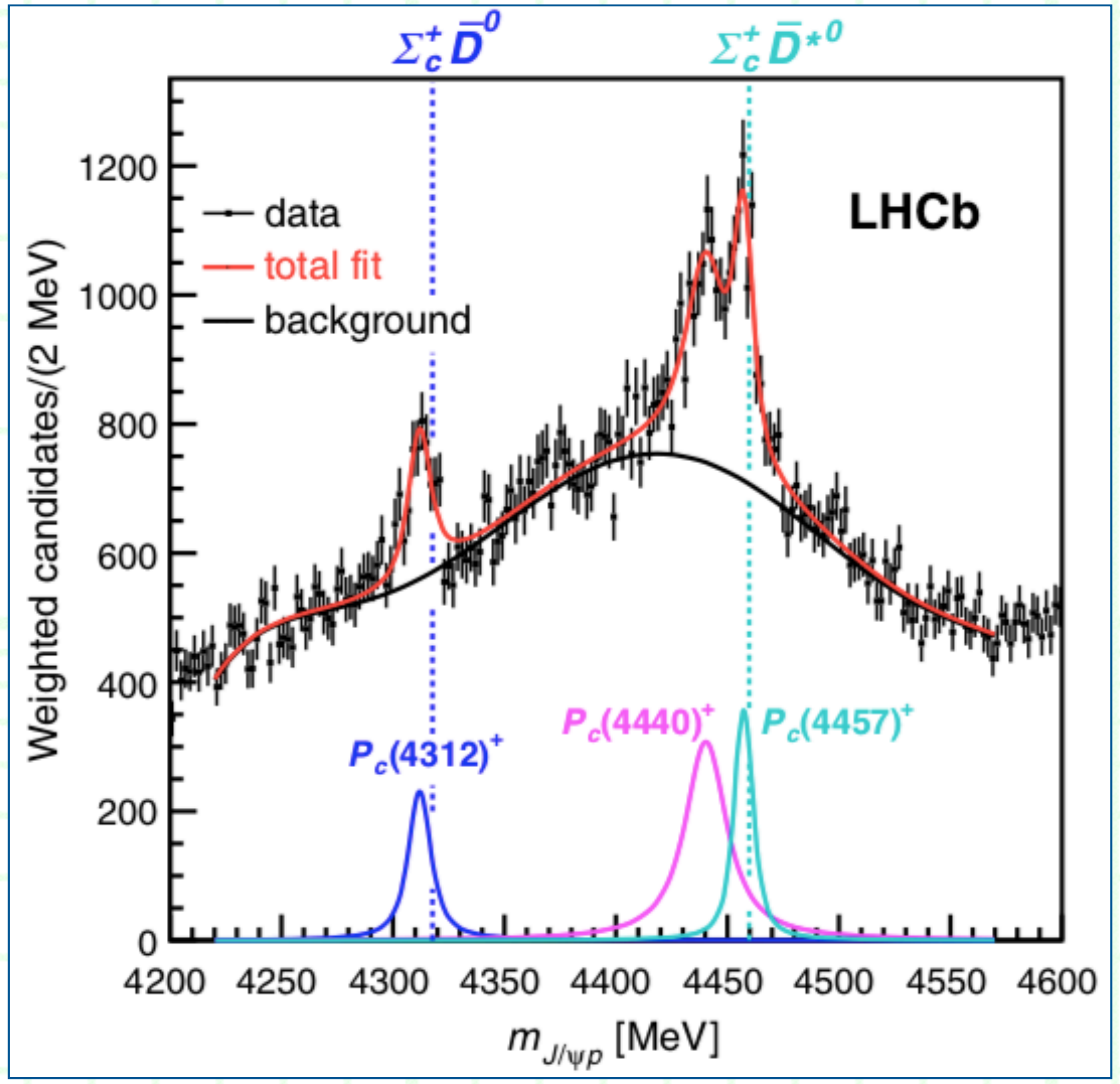
    Hall et al., Phys. Rev. Lett. 114 (2015) 132002.

1. Introduction

++ Further hadrons at thresholds ++

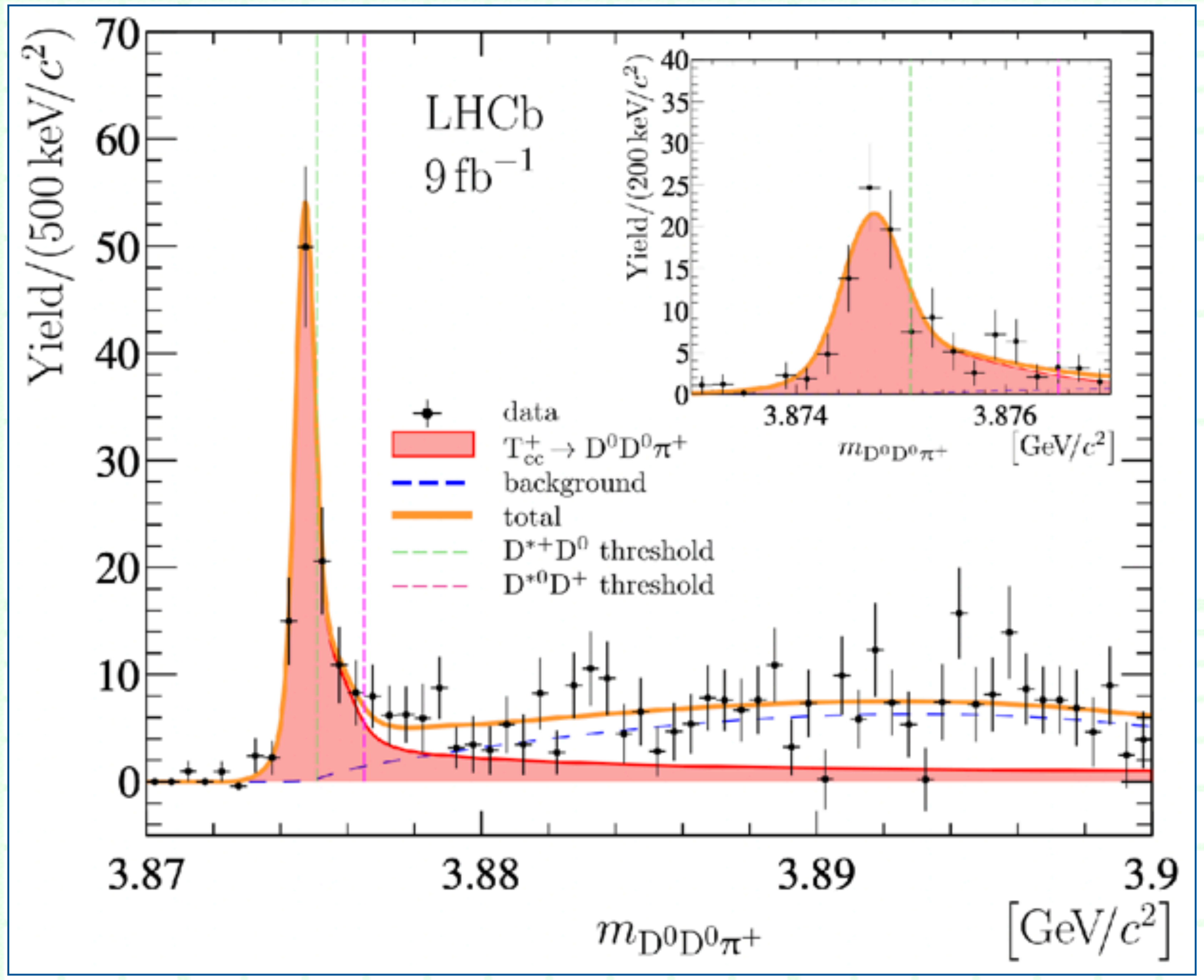
■ Hadronic molecule candidates have also been found in the heavy-quark sector.

☐ The charmonium-pentaquark P_c s.



LHCb, Phys. Rev. Lett. 122 (2019) 222001.

☐ The doubly charmed tetraquark T_{cc} .



LHCb, Nature Commun. 13 (2022) 3351.

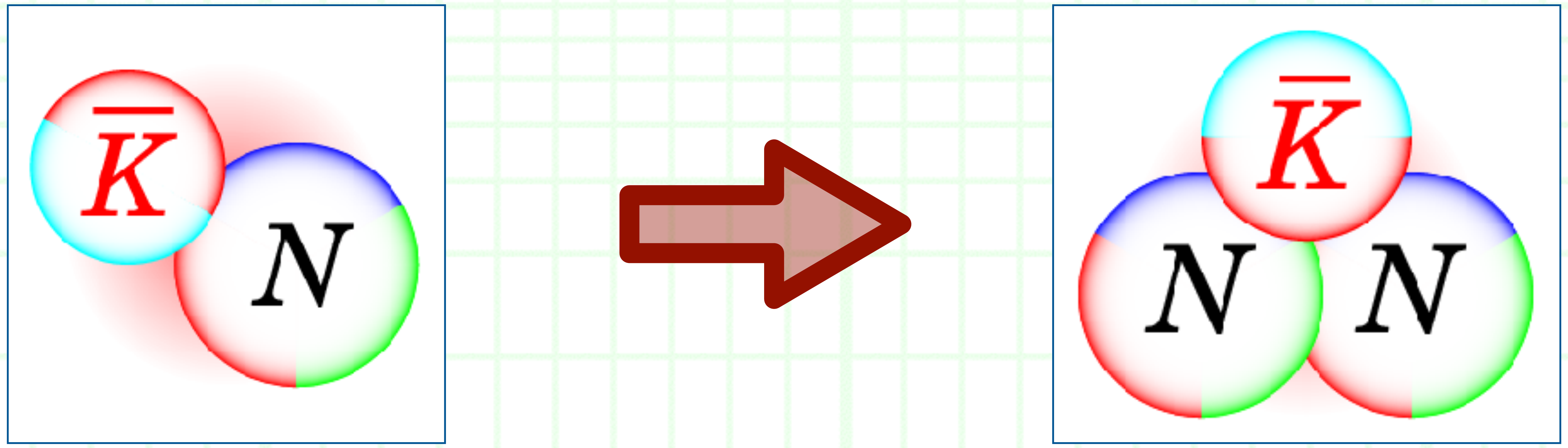
■ They exist just below the meson-baryon and meson-meson thresholds.

– Someone said: “Interesting things happen at thresholds.”

1. Introduction

++ The “K^-pp” state ++

- We can extend the discussion from the $\bar{K}N$ to the $\bar{K}NN$ bound state (nucleus) – so-called “K^-pp” state – as the simplest kaonic nuclei.



Bound !

Expect to be bound !
$\bar{K}N$ Int.: attractive
NN Int.: attractive

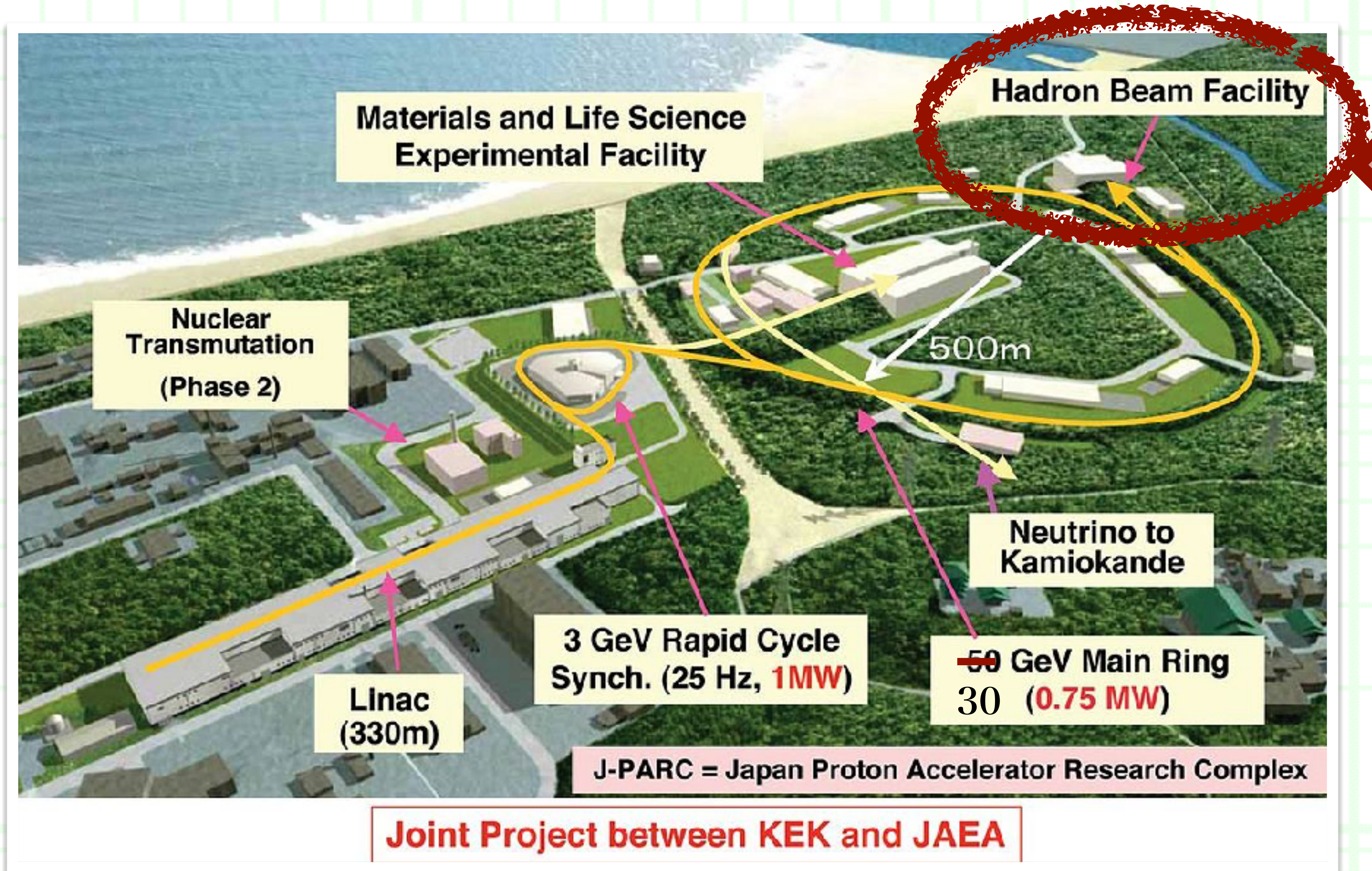
- There have been many studies on the $\bar{K}NN$ bound state, both in the theoretical and experimental sides.
  - Theoretically, the strongly attractive $\bar{K}N$ interaction indicates that the $\bar{K}NN$ system is bound.
  - Experimentally, the J-PARC E15 Exp. observed a signal of the $\bar{K}NN$ bound state.

1. Introduction

++ J-PARC E15 Exp., a breakthrough ++

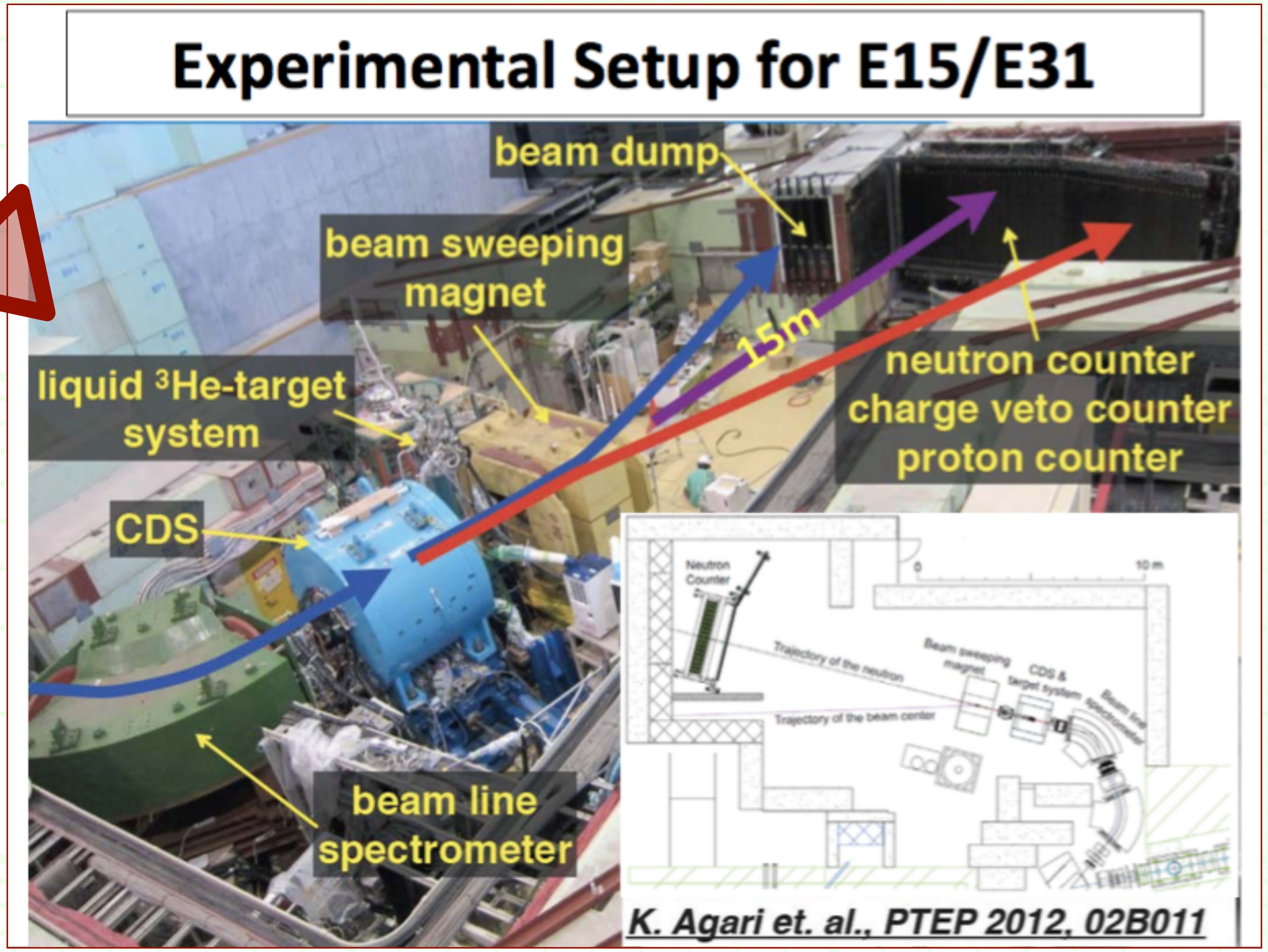
- ■ Today the world's highest-intensity kaon beam is available at J-PARC !
  - ☐ The J-PARC E15 Exp. was performed to search for the $\bar{K}NN$ bound state in the K^- ^{3}He –> Λ p n reaction with forward n.

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



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA



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

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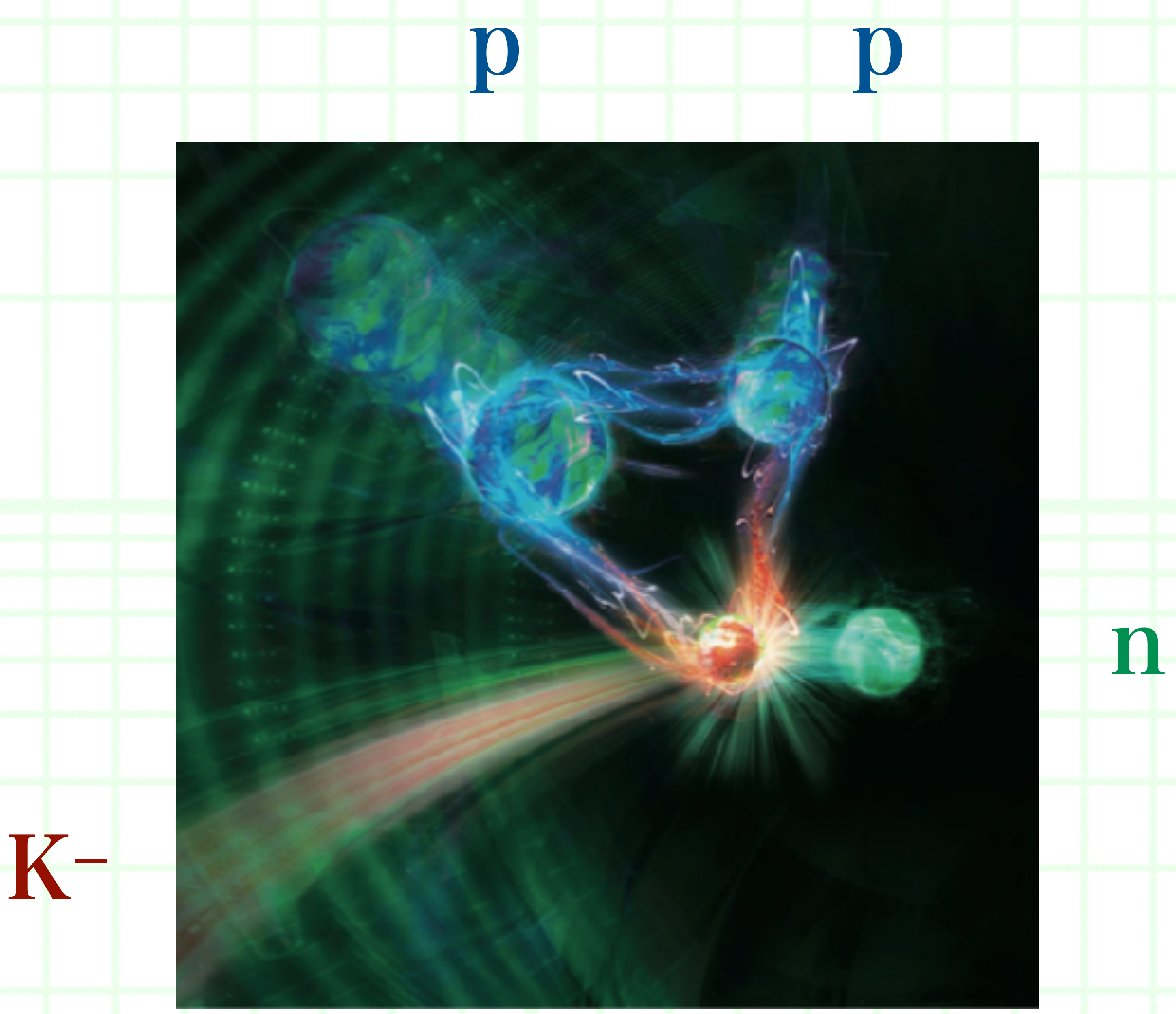
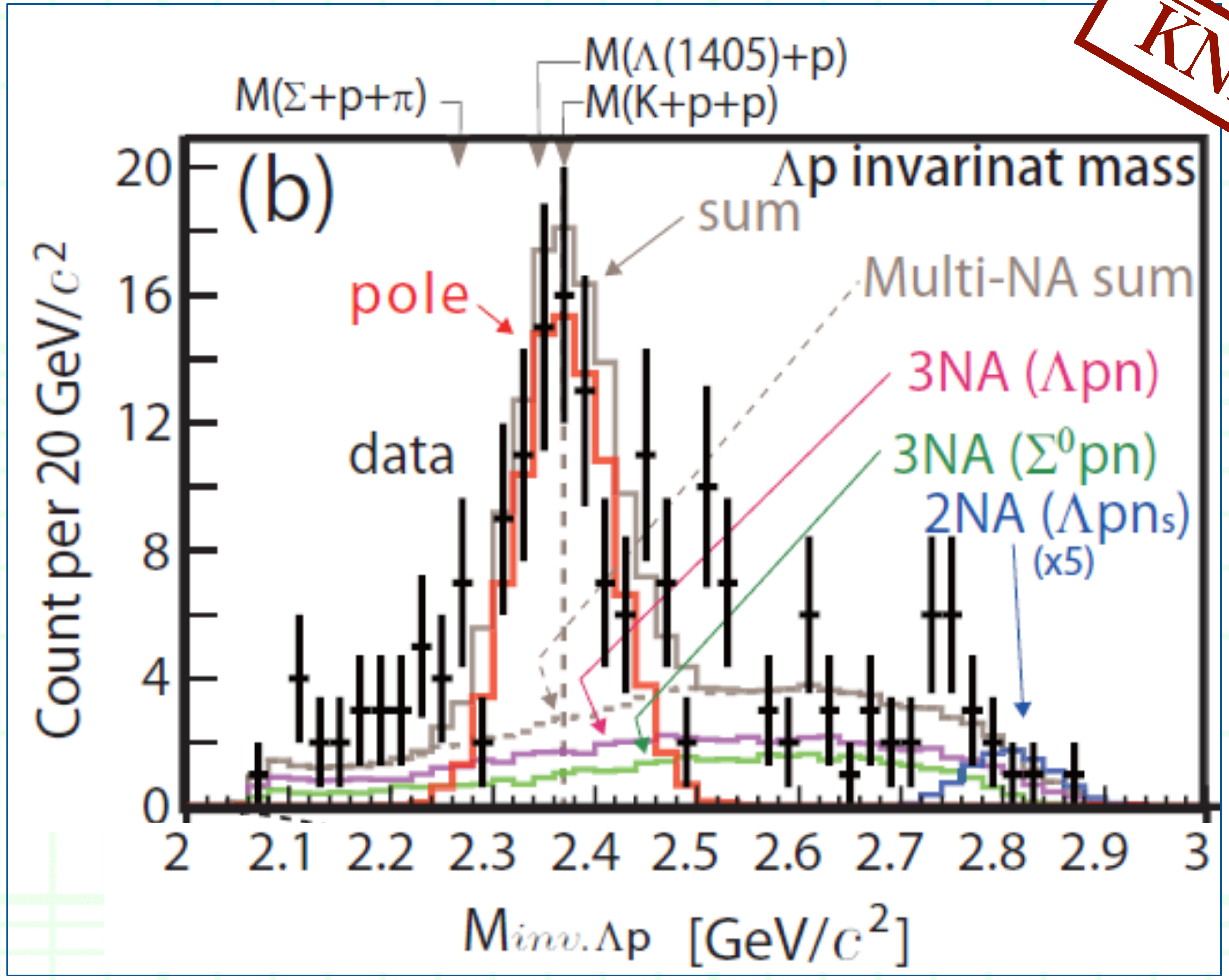


The Austrian Academy of Sciences, Harald Ritsch.

1st run (2013) data

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

$\bar{K}NN$ (?) -> Λ p



1. Introduction

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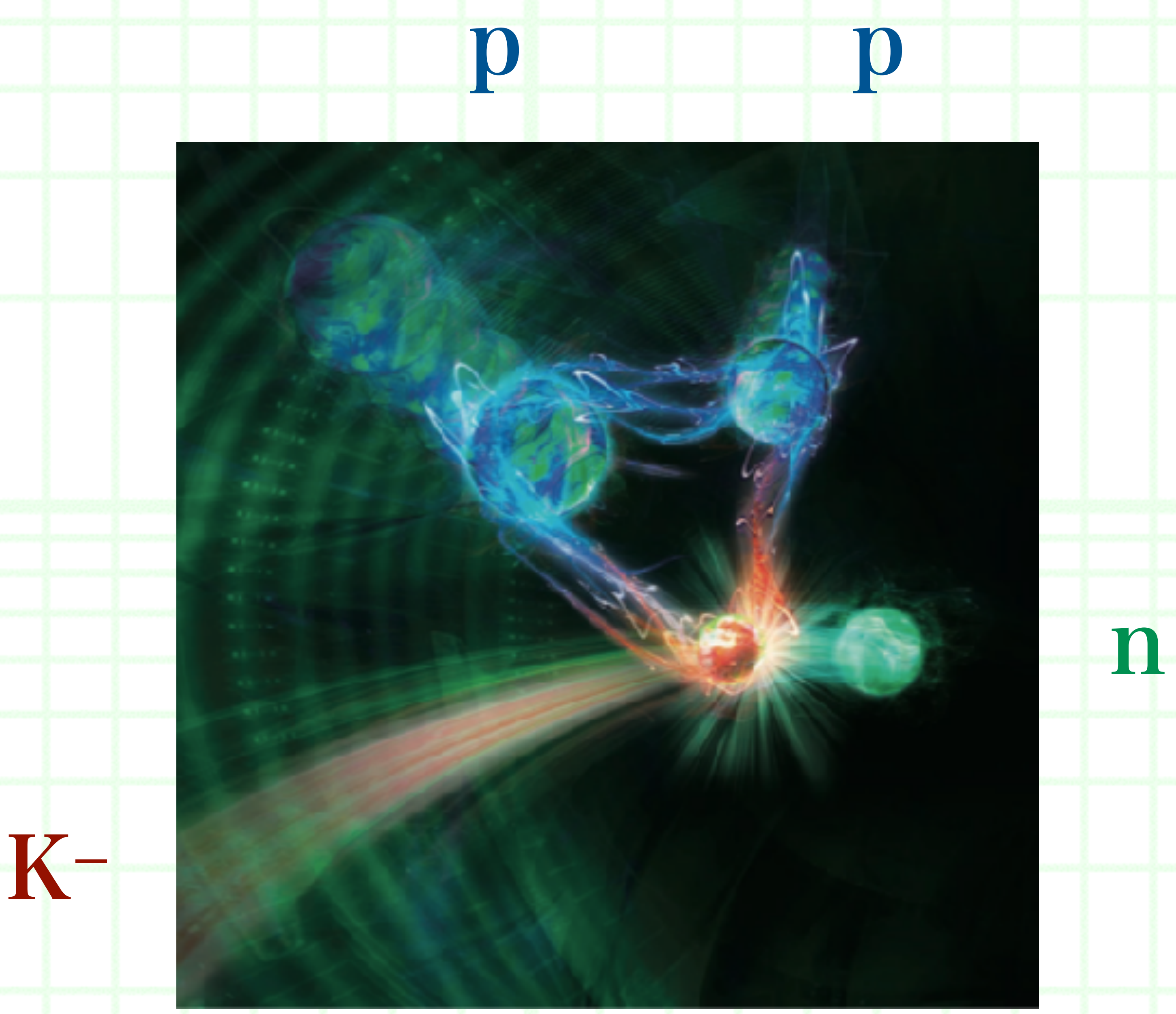
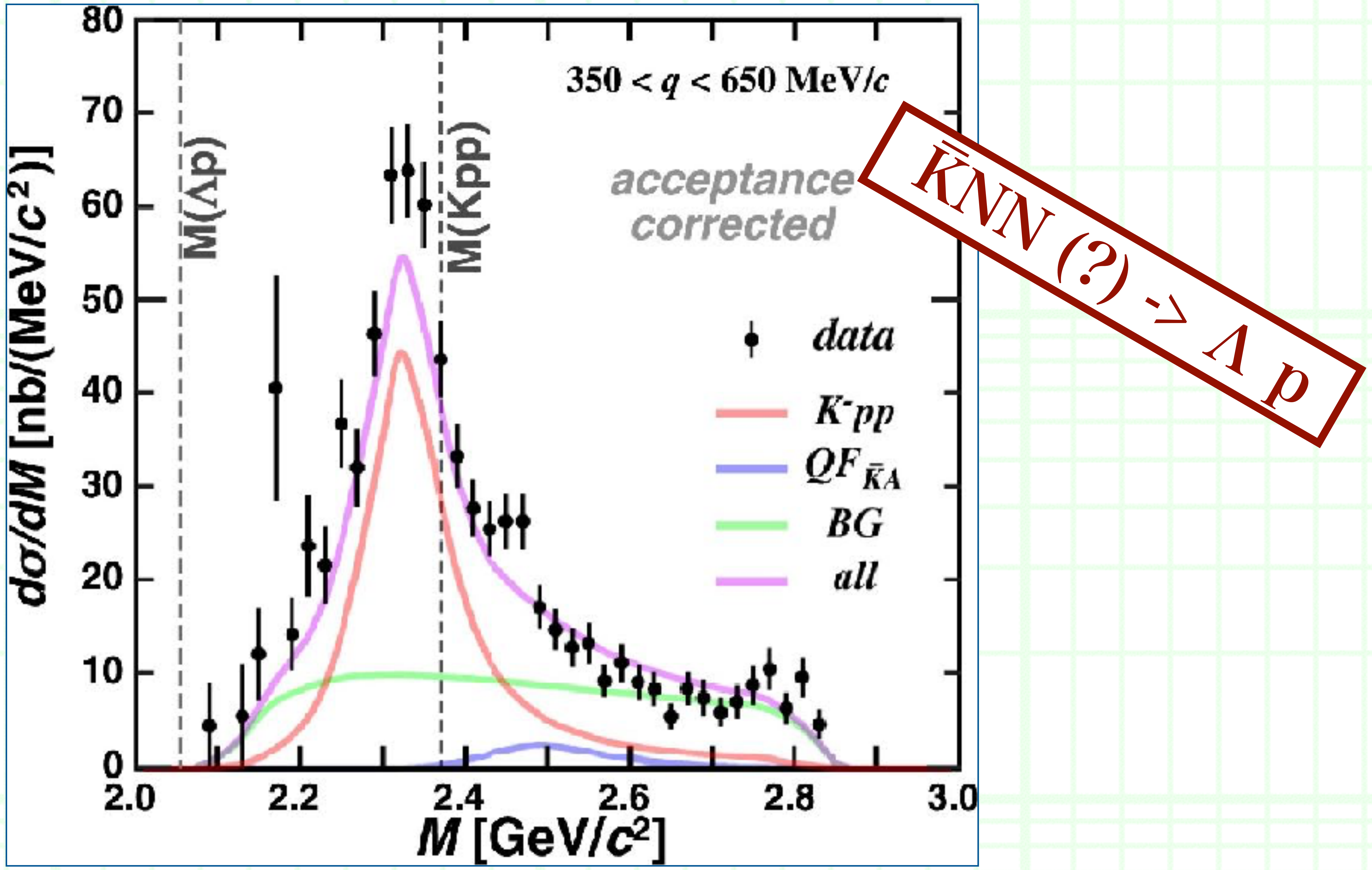


The Austrian Academy of Sciences, Harald Ritsch.

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



2nd run (2015) data

1. Introduction

++ J-PARC E15 Exp., a breakthrough ++

- ■ Today the world's highest-intensity kaon beam is available at J-PARC !
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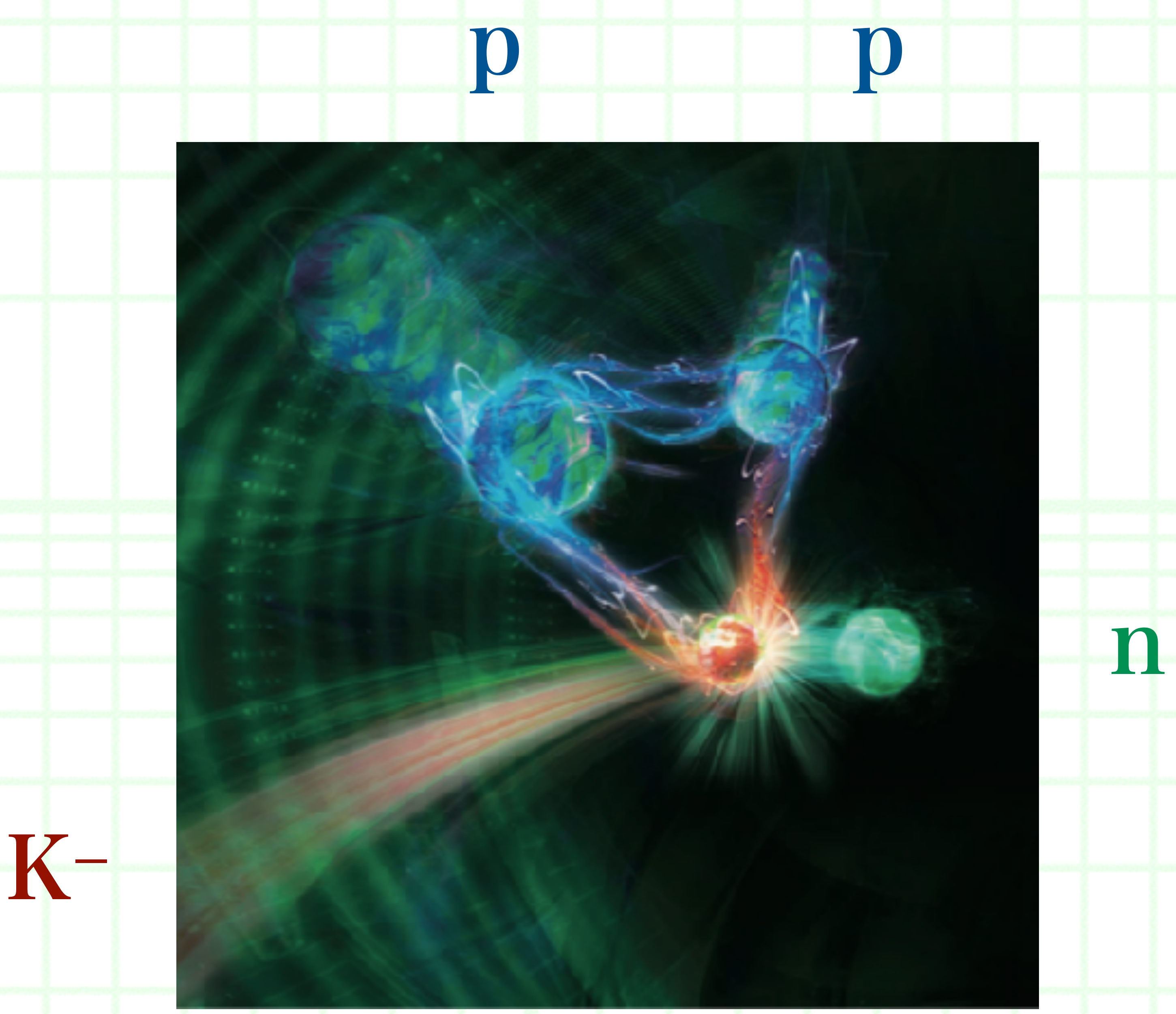
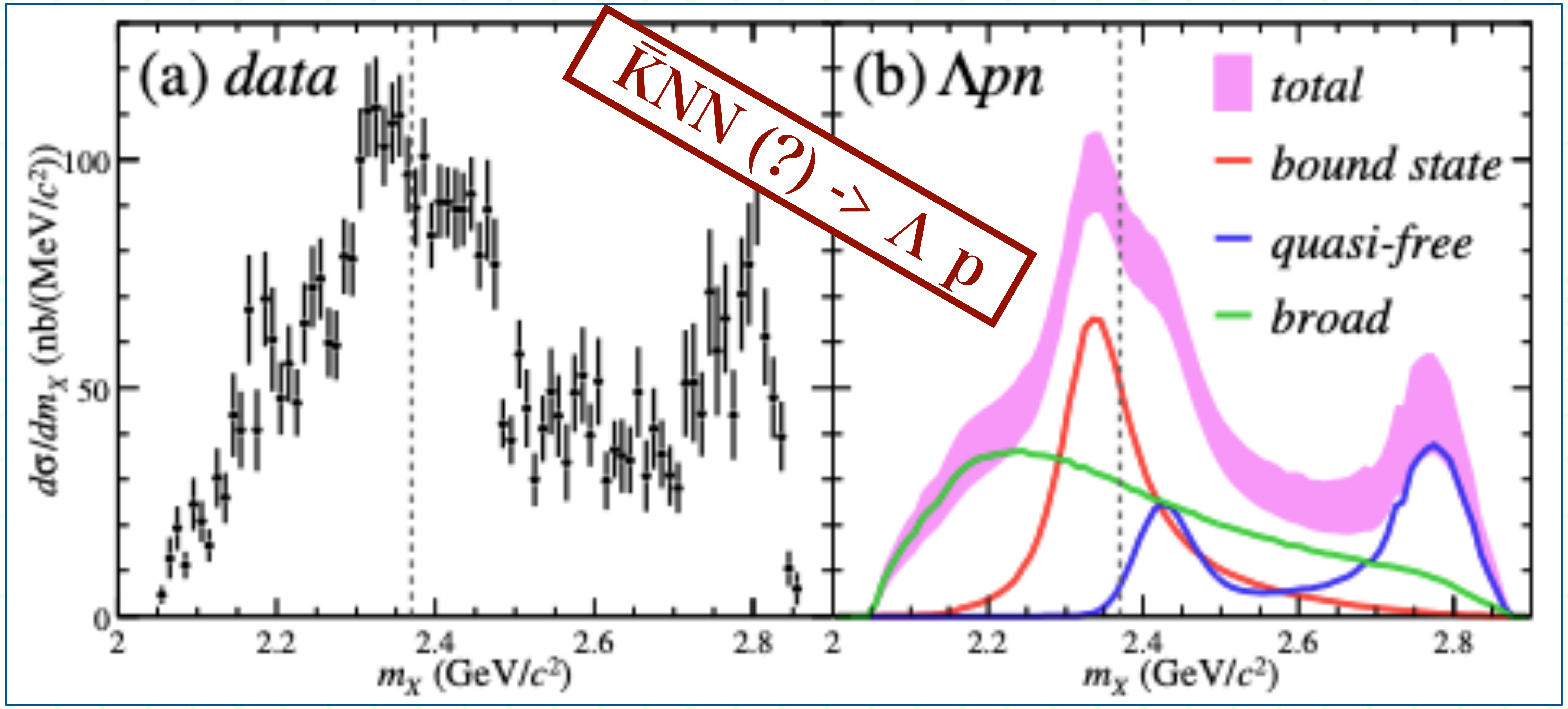


The Austrian Academy of Sciences, Harald Ritsch.

Yamaga et al., Phys. Rev. C102 (2020) 044002.



$\bar{K}NN$ (?) -> Λ p

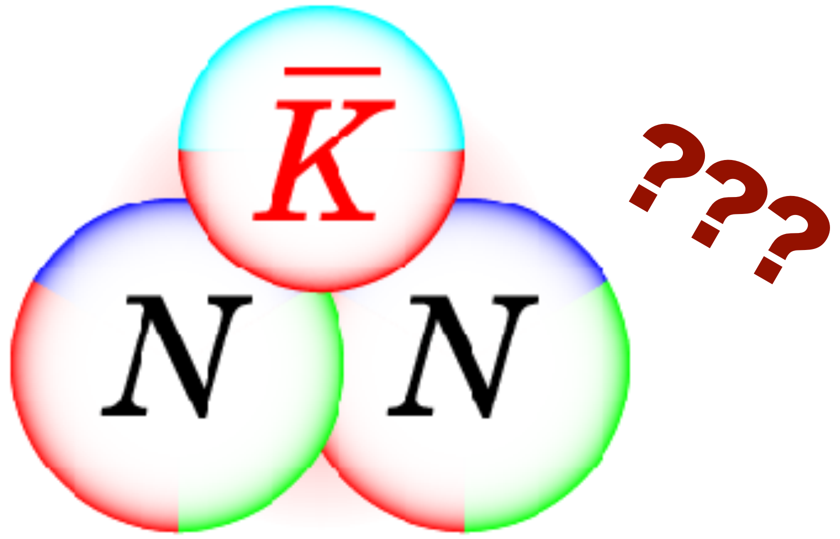
Analysis in the latest version

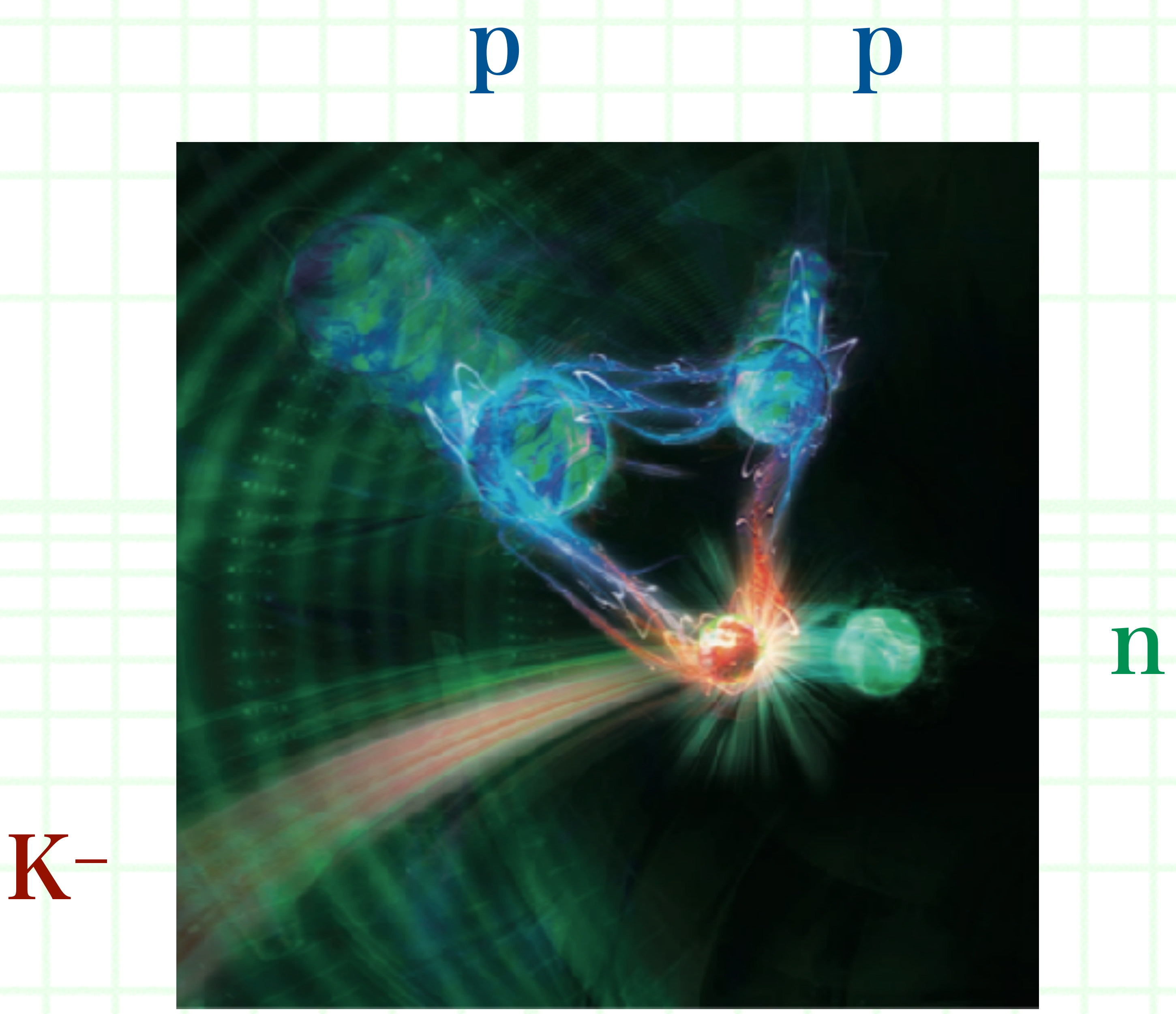
1. Introduction

++ J-PARC E15 Exp., a breakthr

- Today the world's highest-intensity kaon beam is availa
  - ☐ The J-PARC E15 Exp. was performed to search for the
    in the $K^- {}^3He \to \Lambda\, p\, n$ reaction with forward n.

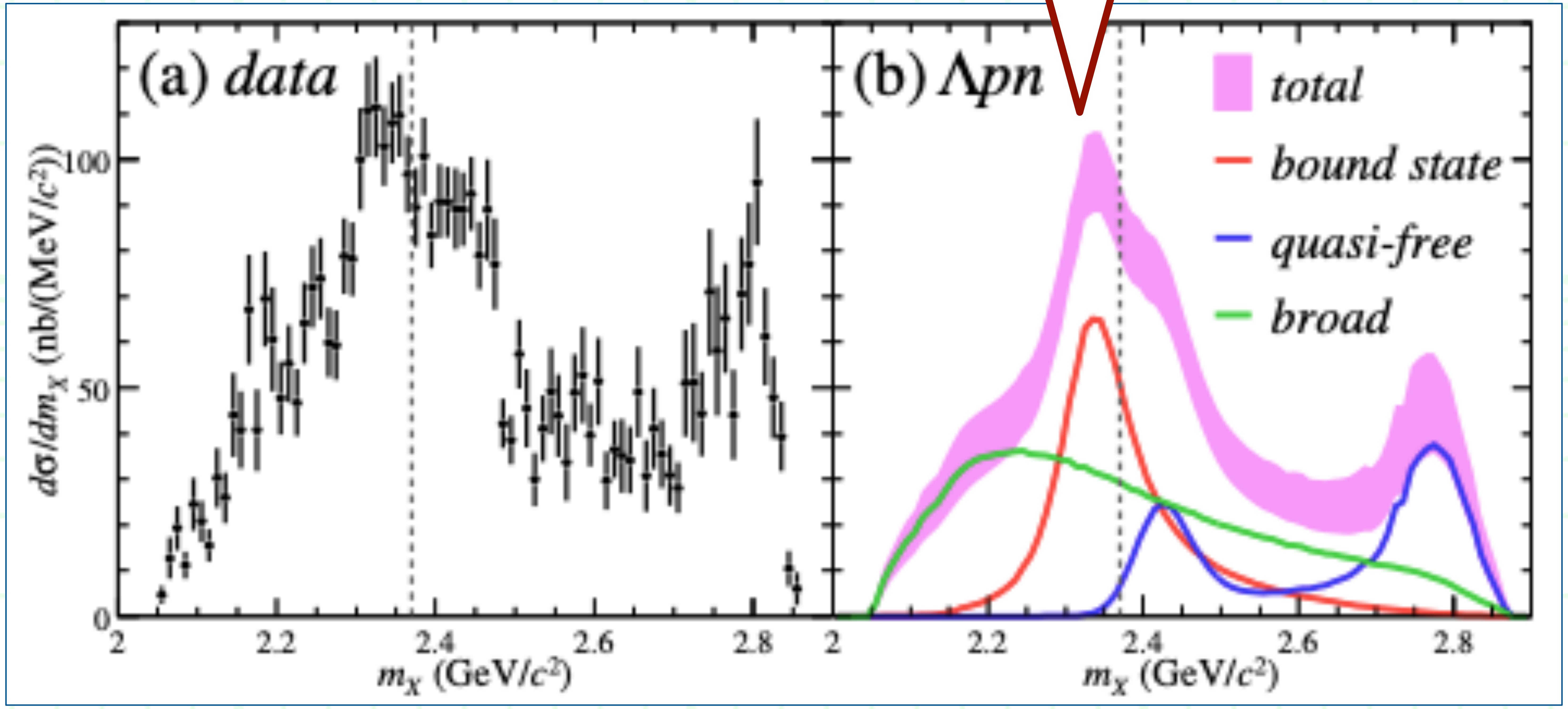
Really the $\bar{K}NN$
bound state signal ???





The Austrian Academy of Sciences, Harald Ritsch.

Yamaga et al., Phys. R



Analysis in the latest version

2. Reaction calculation for the $\bar{K}NN$ nucleus production in the J-PARC E15 experiment: $K^- \, {}^3He \to \Lambda \, p \, n$

2. Reaction calculation: $K^- \, {}^3He \rightarrow \Lambda \, p \, n$

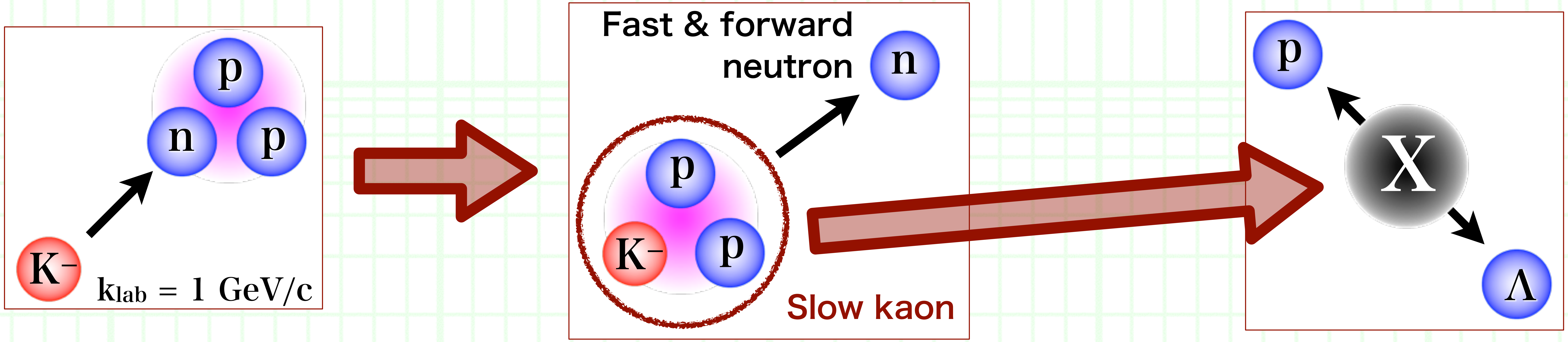
++ Expected reaction mechanism ++

- The expected mechanism of the reaction: $K^- \, {}^3He \rightarrow \Lambda \, p \, n$.

1. K^- kicks out a neutron. –> Fast neutron ejected forward.

2. $\bar{K}$ becomes slow and generates a bound state together with two nucleons.

3. The $\bar{K}NN$ bound state (or something X) decays into $\Lambda \, p$.



2. Reaction calculation: $K^- \, {}^3\mathrm{He} \to \Lambda \, p \, n$

++ Expected reaction mechanism ++

- Therefore, to confirm this reaction mechanism, we perform the reaction calculation of the $K^- \, {}^3\mathrm{He} \to \Lambda \, p \, n$.

☐ The reaction diagram is composed of:

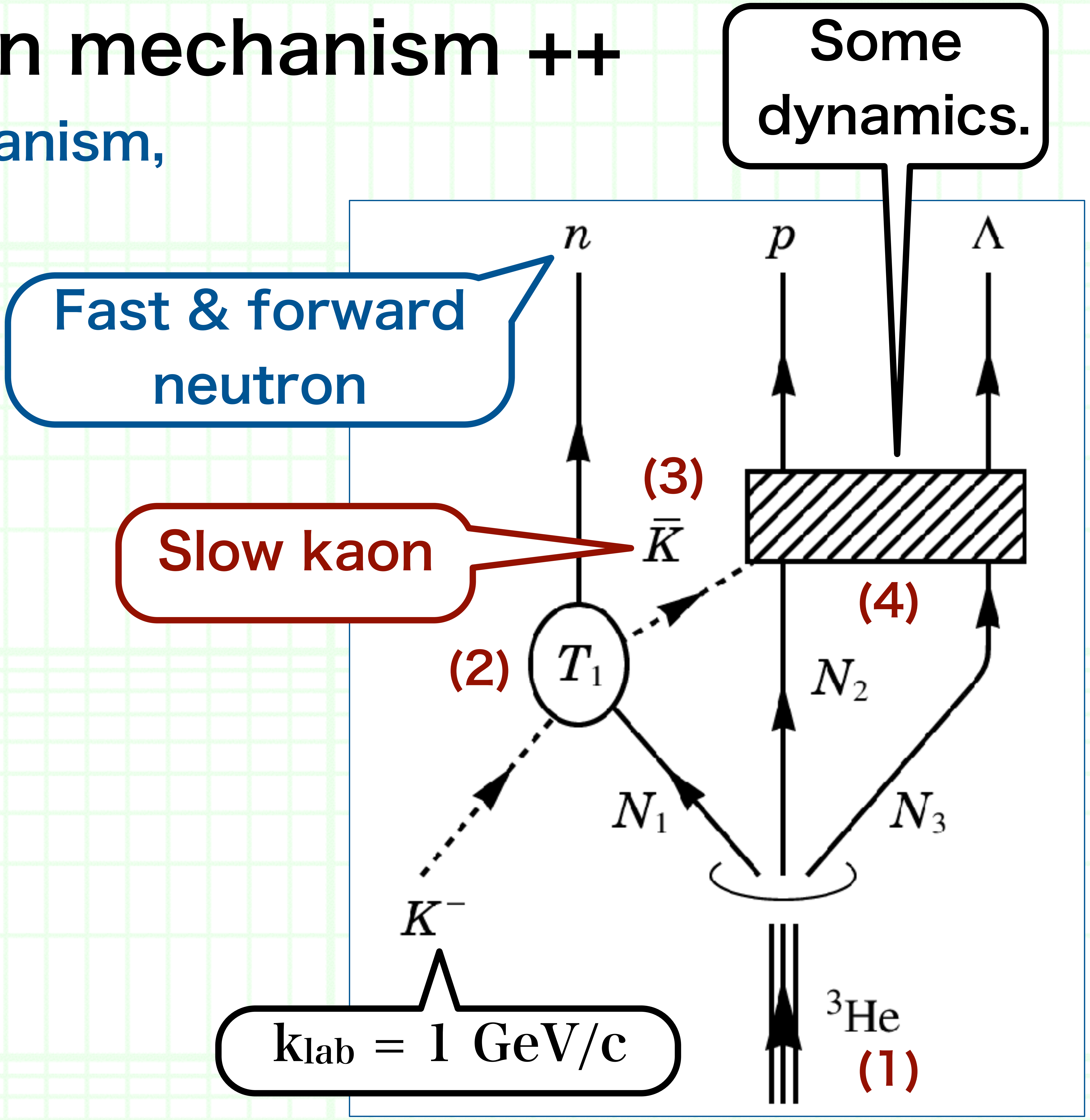
(1) ${}^3\mathrm{He}$ wave function.

(2) Amplitude T_1 ($k_{lab} = 1$ GeV/c).

(3) Propagator for the slow $\bar{K}$.

(4) $\bar{K}NN \to \bar{K}NN$ three-body amplitude
× $\bar{K}NN \to \Lambda p$ transition amplitude.

– Below we focus on (4), in which the $\bar{K}NN$ bound state is generated.



2. Reaction calculation: K^- ^{3}He –> Λ p n

++ Three-body amplitude ++

- Calculate the spectrum by assuming that the $\bar{K}$NN bound state is generated.

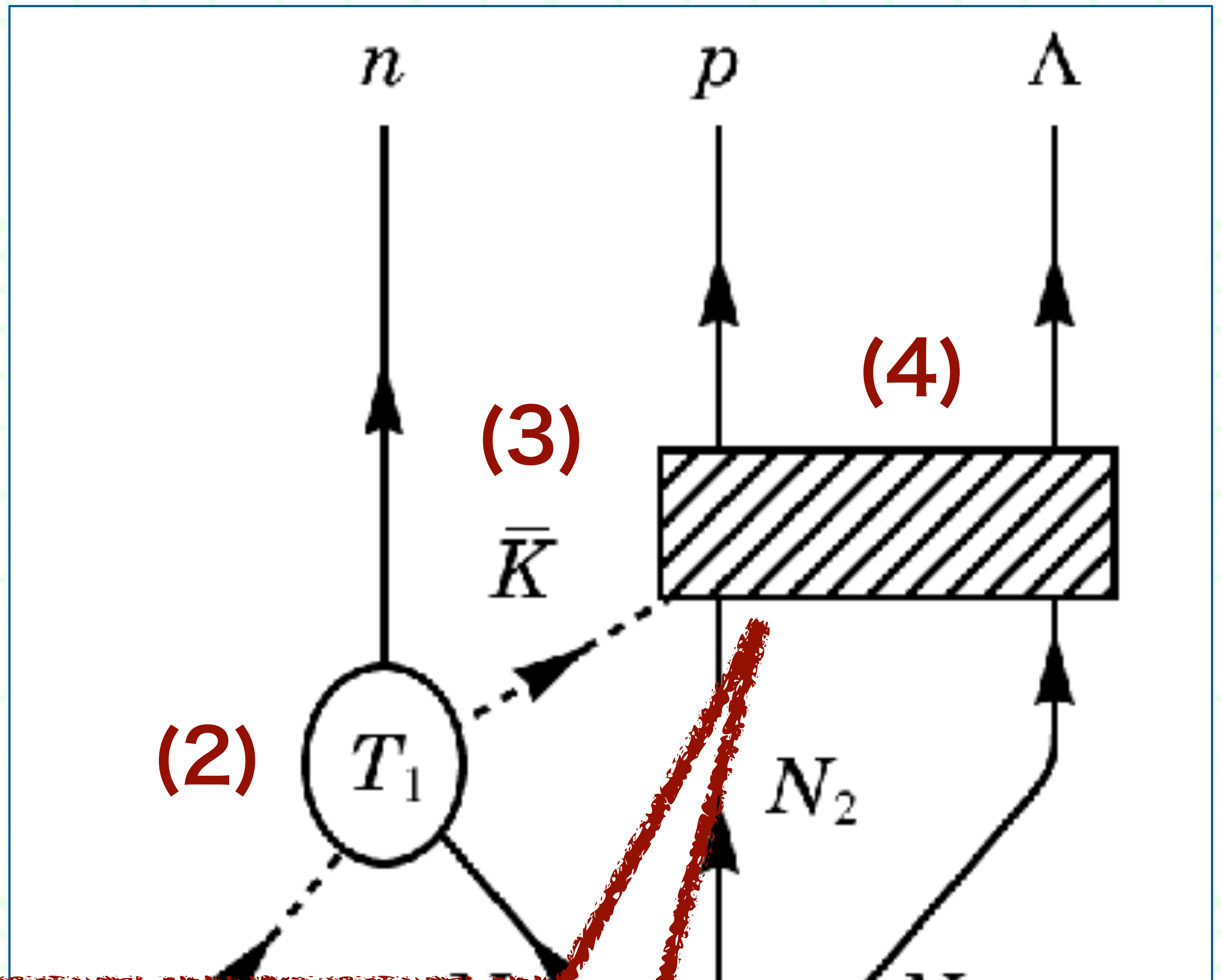
(4) $\bar{K}$NN –> $\bar{K}$NN three-body amplitude

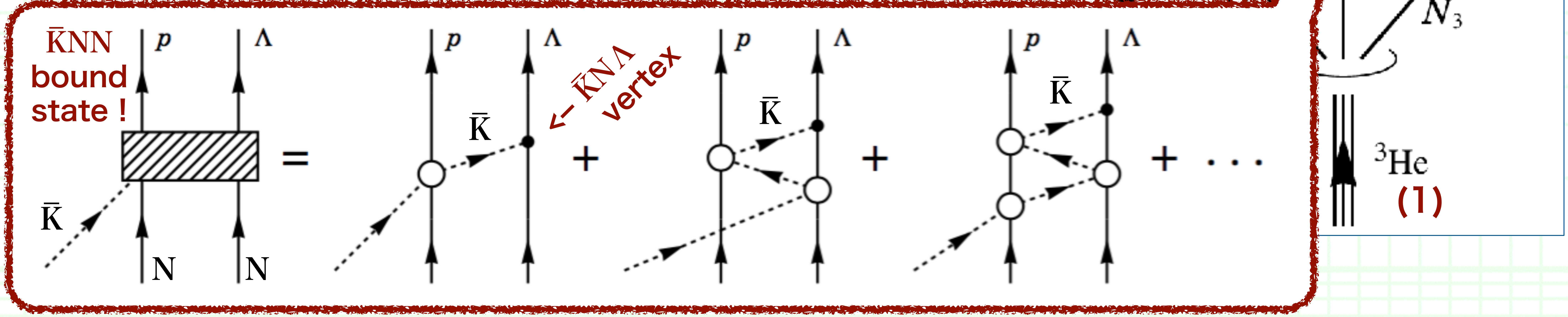
× $\bar{K}$NN –> Λp transition amplitude.

–> Solve the $\bar{K}$NN Faddeev Eq.

by so-called fixed-center Approx.

– Two nucleons are treated in a kind of adiabatic Approx.



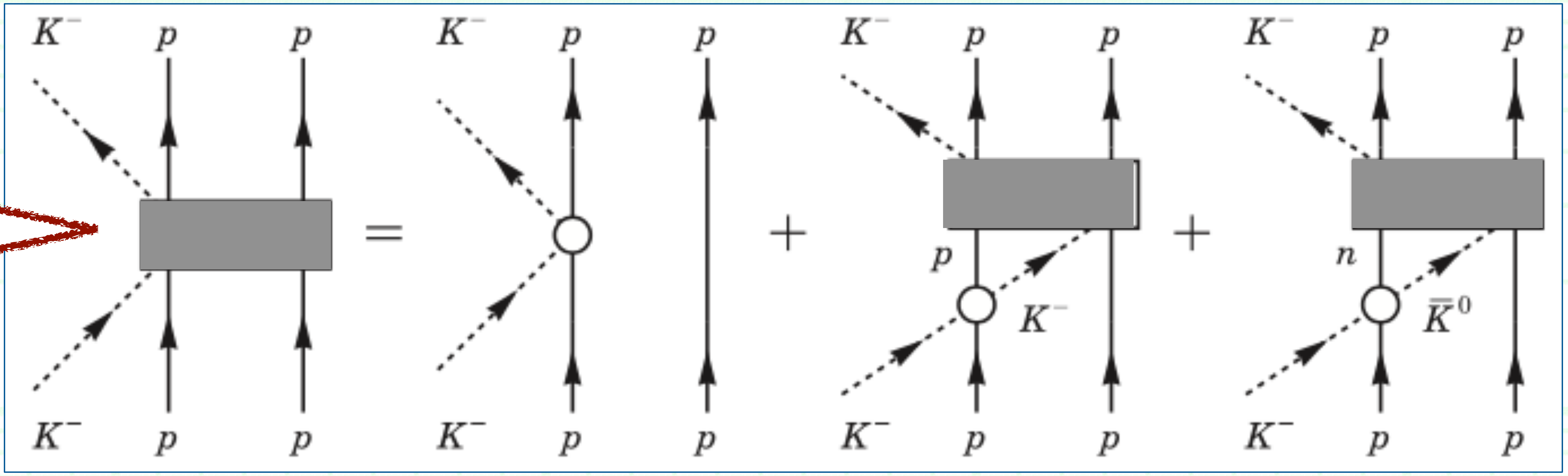


2. Reaction calculation: K^{-} ^{3}He –> Λ p n

++ Fixed-center approximation ++

■ To solve the $\bar{K}$NN Faddeev Eq., we employ the so-called fixed-center Approx.
– A kind of adiabatic Approx.

Bound state pole at
E_{pole} = 2354 – 36 i MeV.
–> B_E ~ 15 MeV,
Γ ~ 70 MeV.



☐ Only the $\bar{K}$N amplitude is explicitly taken into account.
– We employ the chiral dynamics for the $\bar{K}$N amplitude.

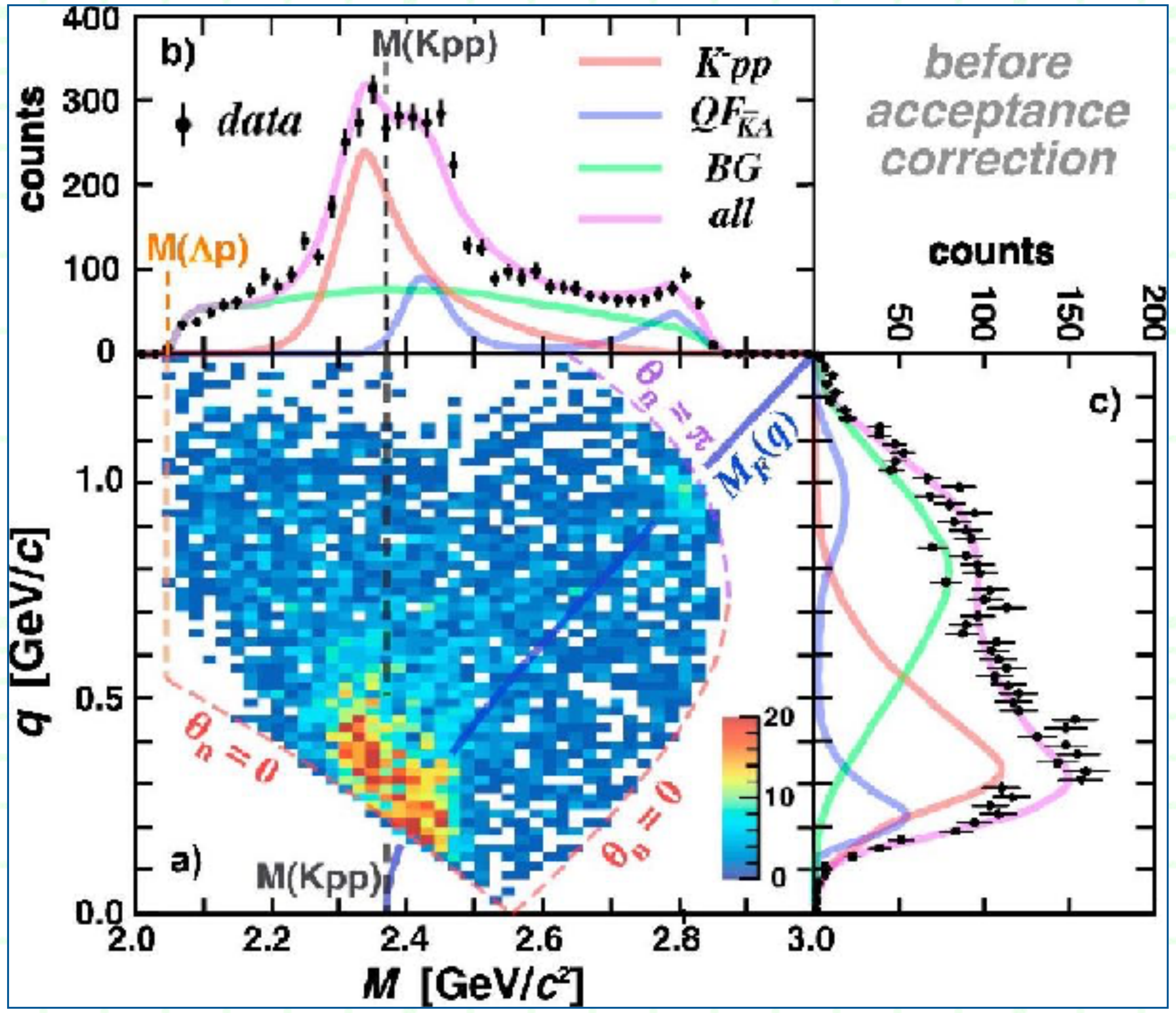
☐ The distance between two nucleons are the model parameter.
–> Fixed to be the distance in the ^{3}He nucleus.

2. Reaction calculation: K^{-} ^{3}He –> Λ p n

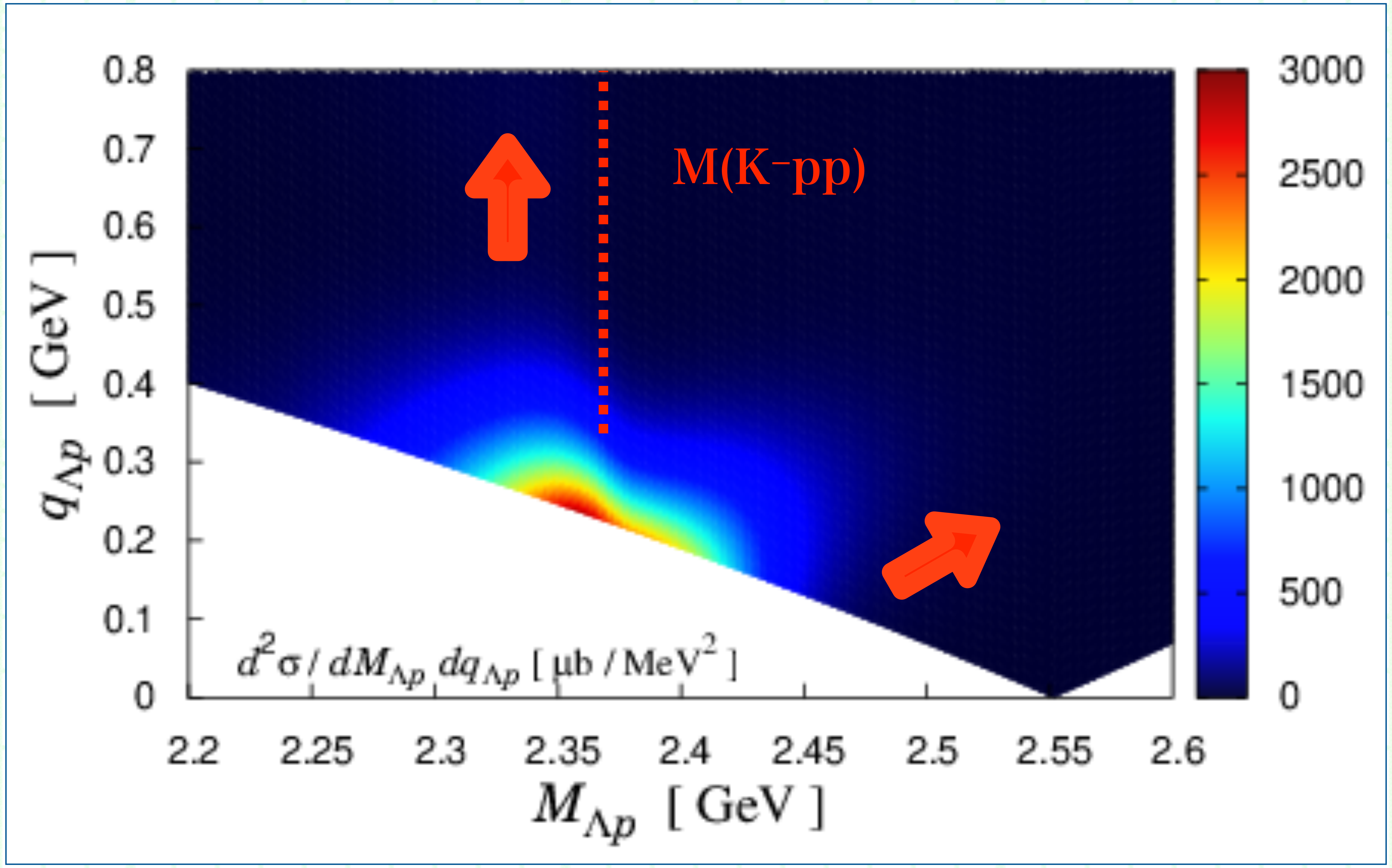
++ Production calculation ++

■ Calculate the spectrum by assuming that the $\bar{K}NN$ bound state is generated.

T.S., Oset and Ramos, JPS Conf. Proc. 26 (2019) 023009.



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



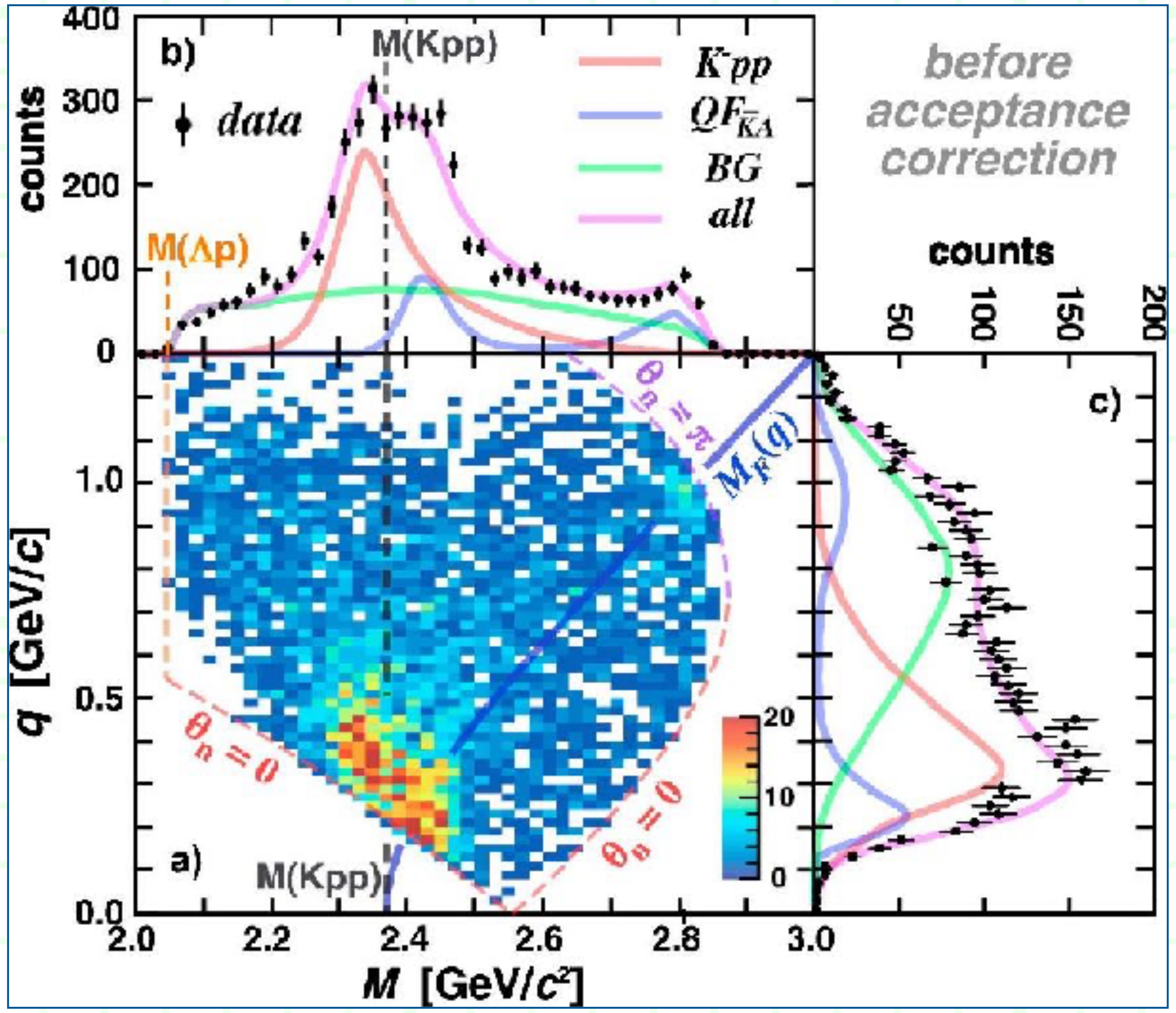
☐ The same behavior for the differential cross section.

2. Reaction calculation: K$^-$ ^{3}He –>

++ Production calculation ++

- Calculate the spectrum by assuming that the $\bar{K}NN$ bound state is

T.S., Oset and Ramos, JPS Conf. Proc. 2



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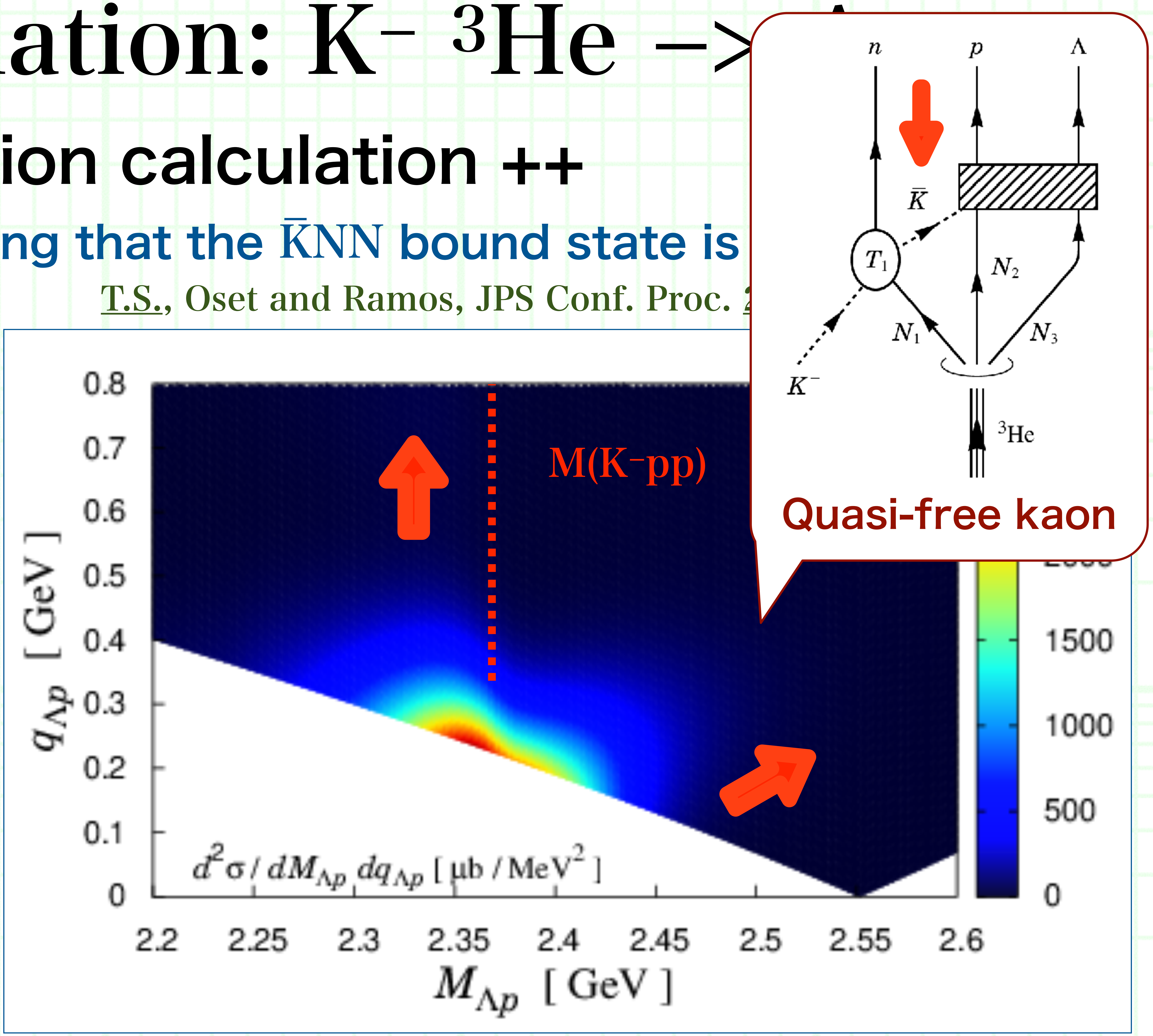


Quasi-free kaon

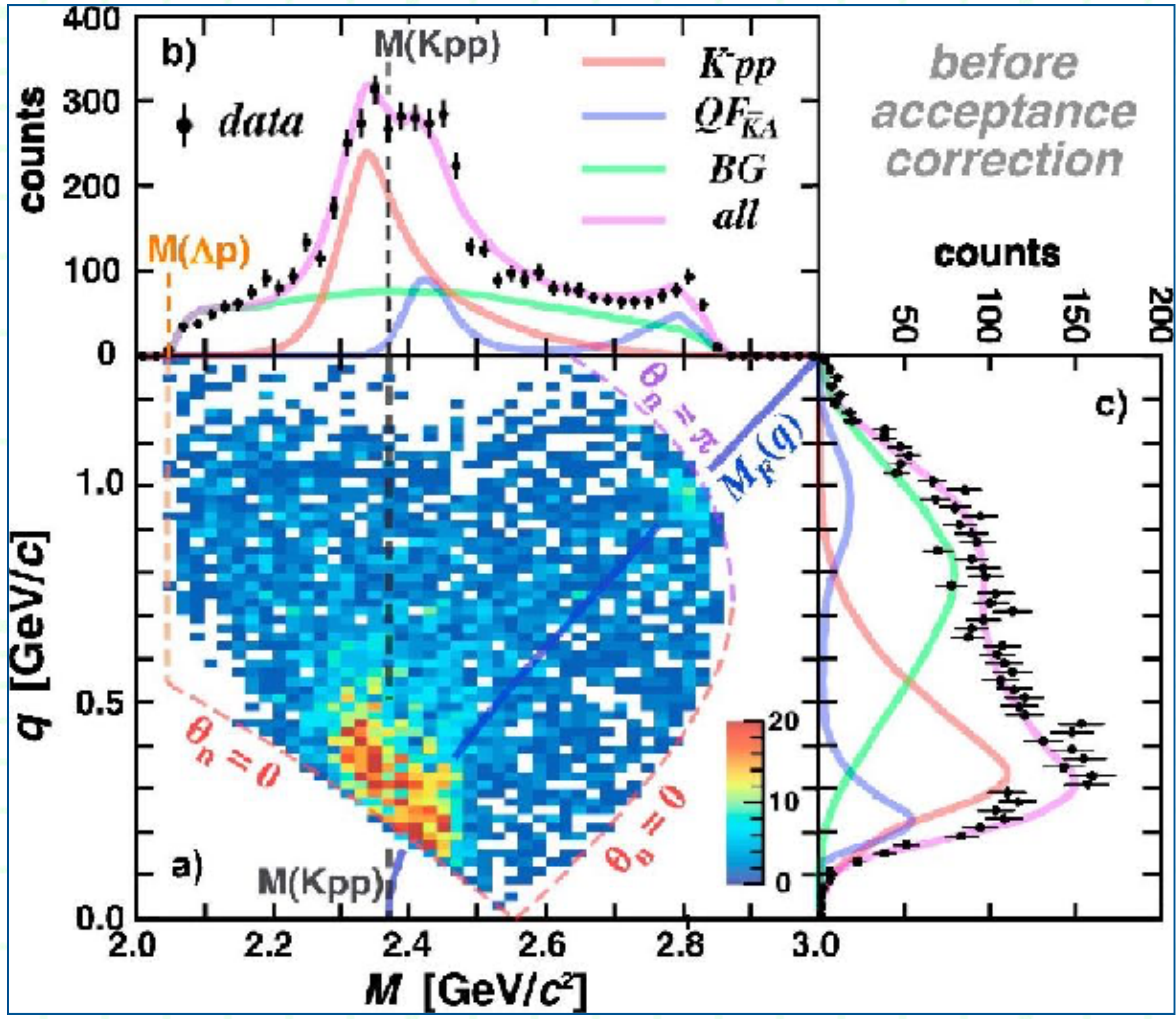
☐ **The same behavior** for the differential cross section.

2. Reaction calculation: K^{-} ^{3}He –> Λ p n

++ Pro culation +

■ Calculate the spectrum by a e K̄NN bound

et and Ramos, JPS C



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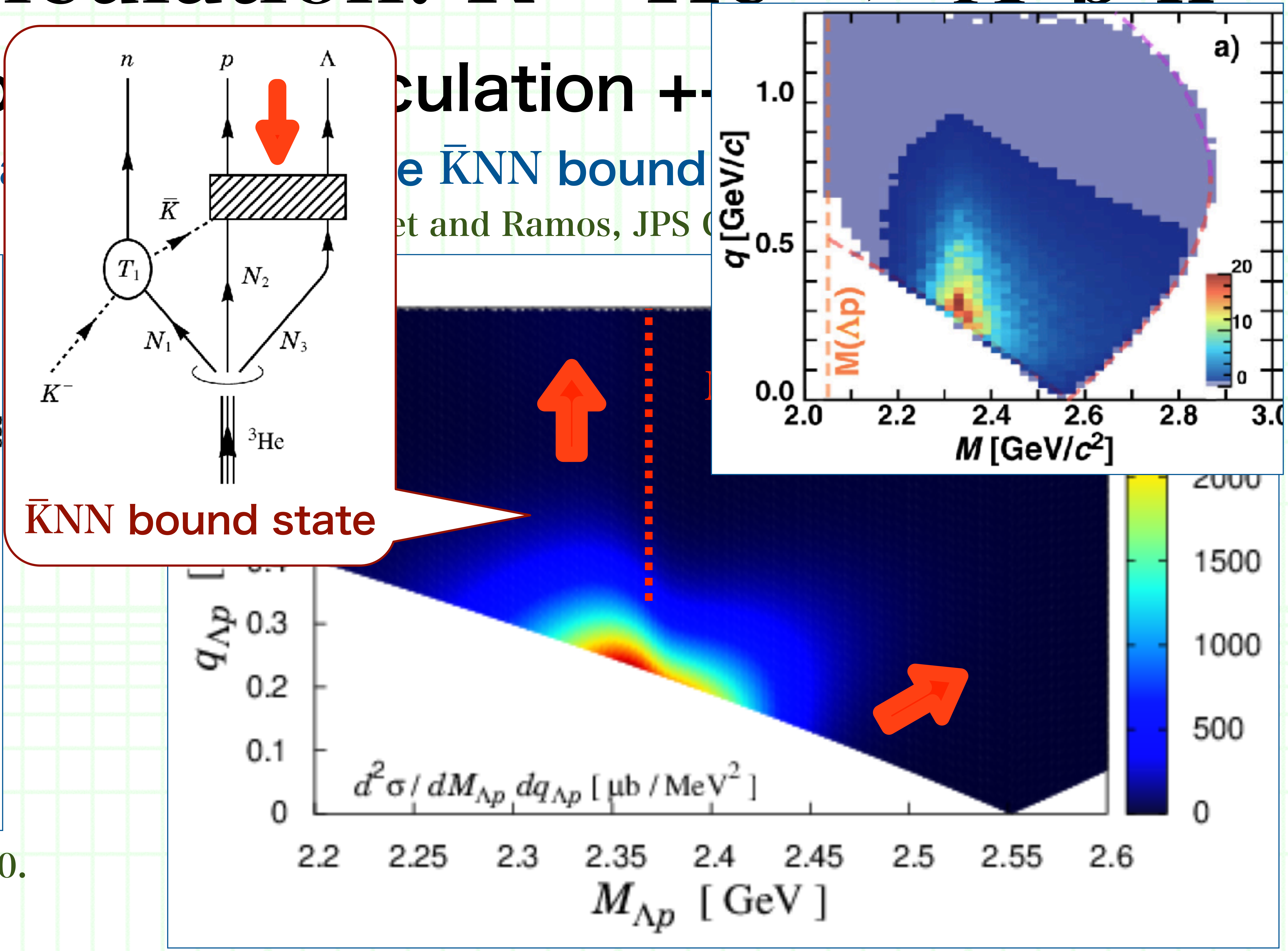


K̄NN bound state

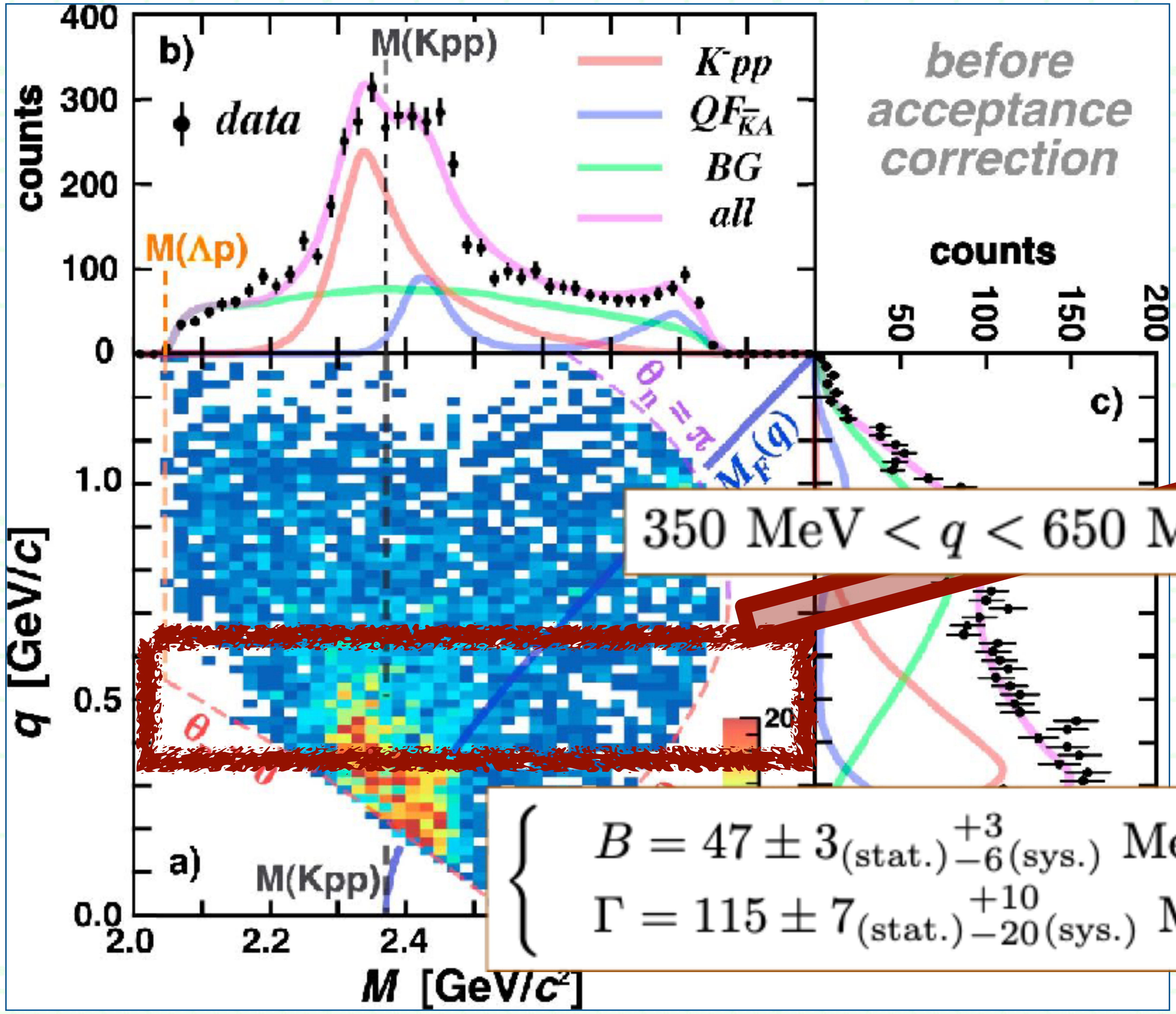
☐ The same behavior for the differential cross section.

2. Reaction calculation: K^{-} ^{3}He –> Λ p n

++ Momentum transfer cut ++

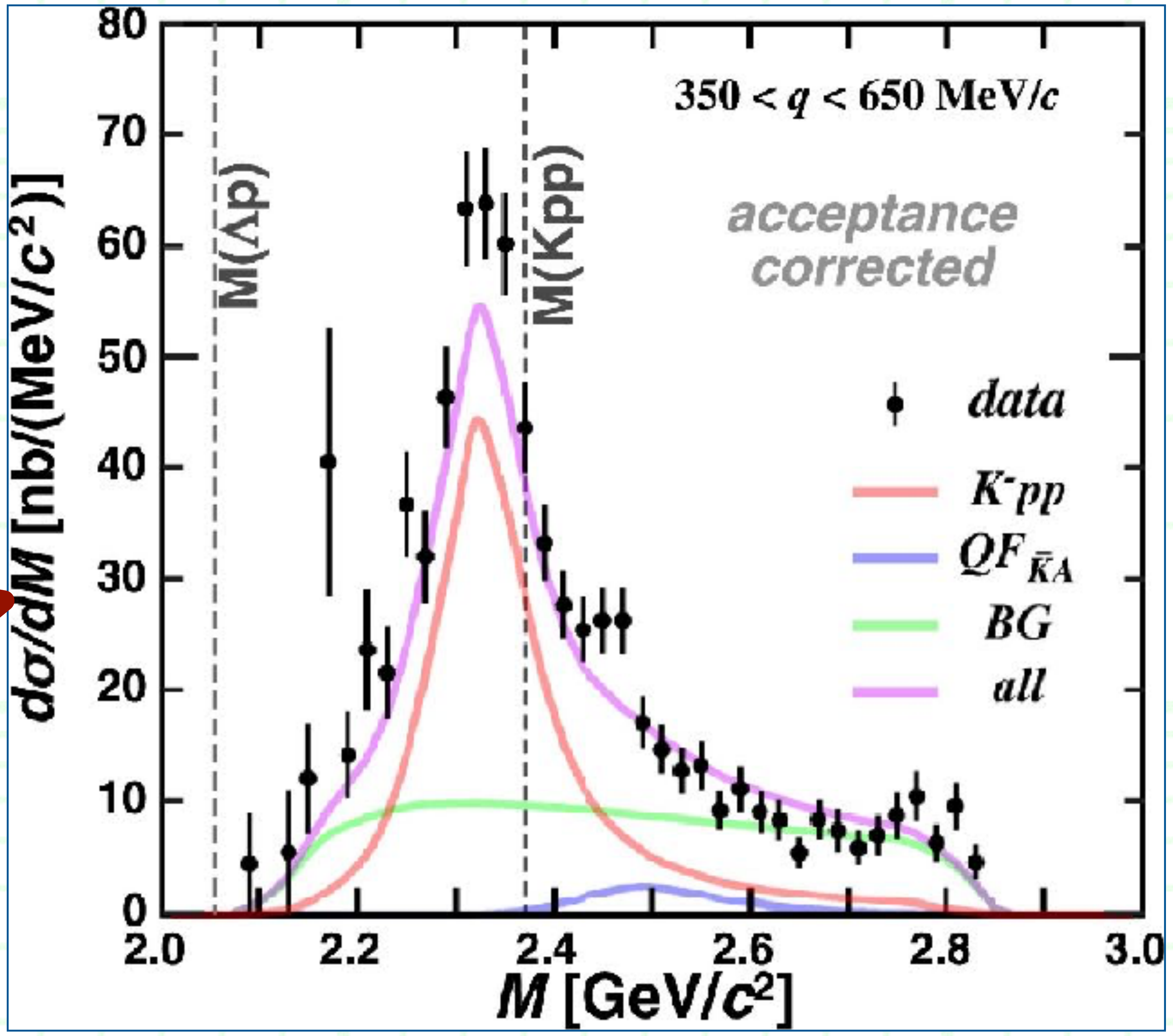
■ Cut of the momentum transfer in Exp. analysis.

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



350 MeV $< q <$ 650 MeV

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

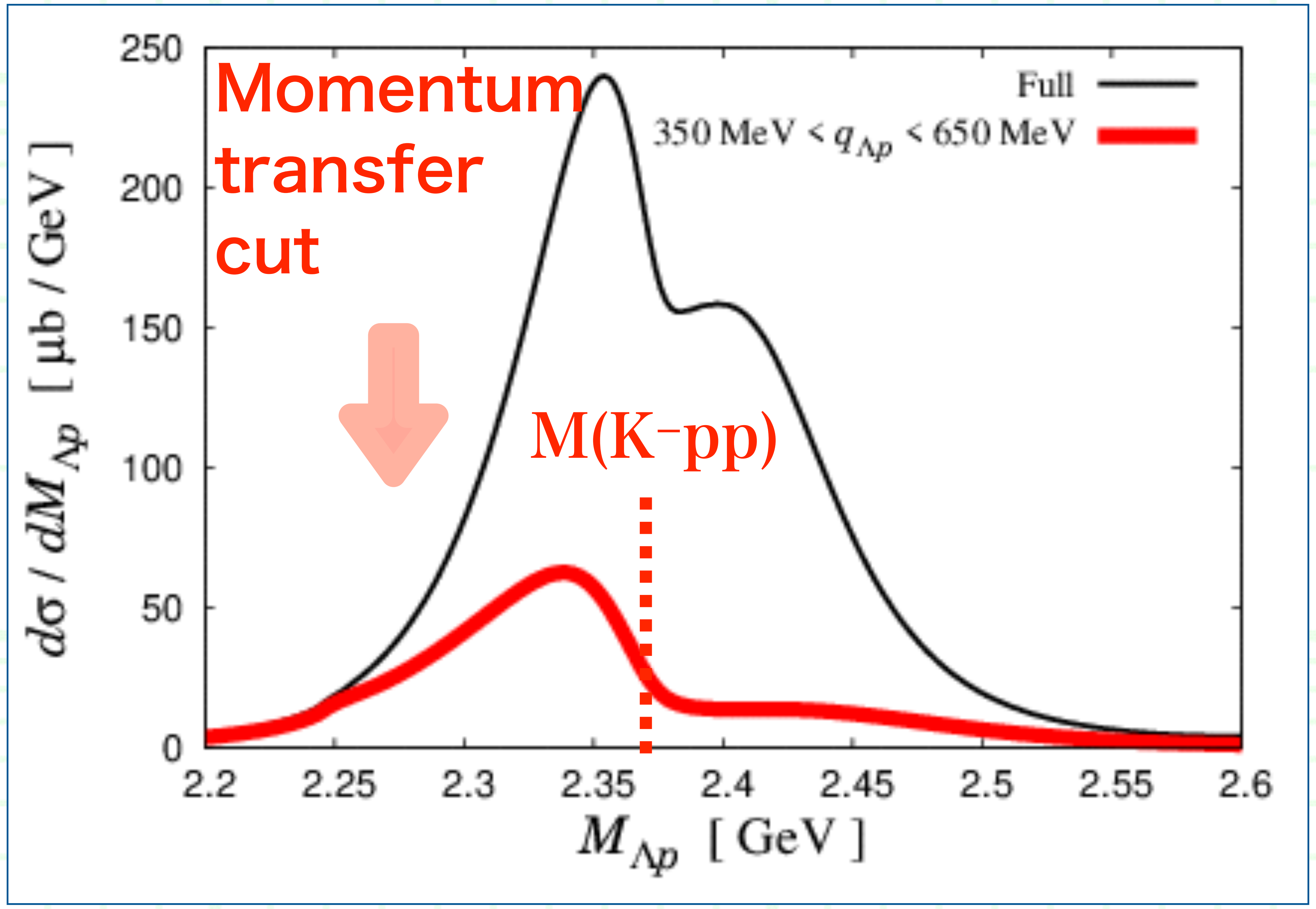


☐ Cutting the quasi-free kaon part, they observed a clear peak !

2. Reaction calculation: $K^- \, {}^3\mathrm{He} \to \Lambda \, p \, n$

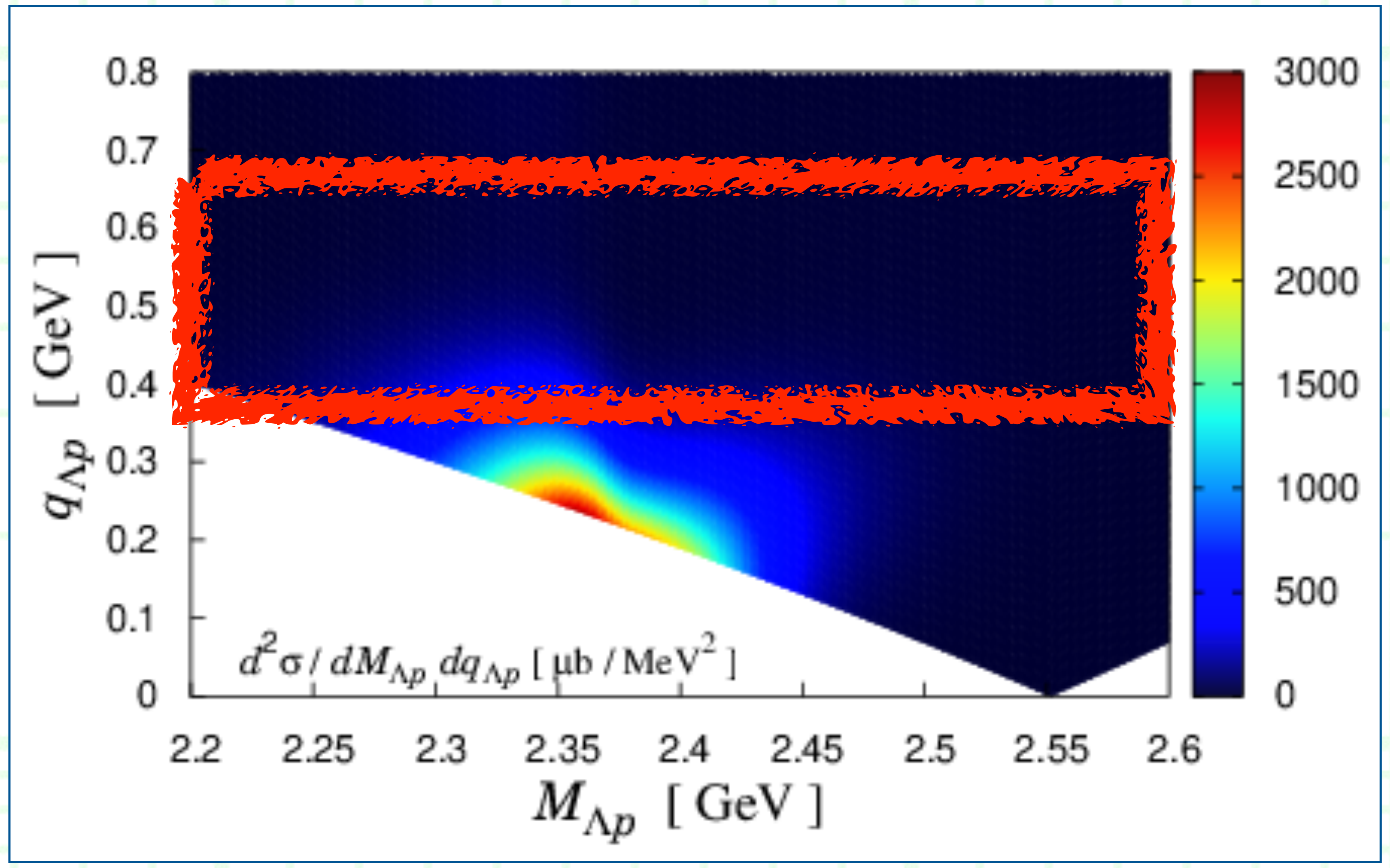
++ Momentum transfer cut ++

- Perform the same cut for the momentum transfer as the Exp. analysis.



Momentum transfer cut

$M(K^-pp)$



– 350 MeV < $q_{\Lambda p}$ < 650 MeV.

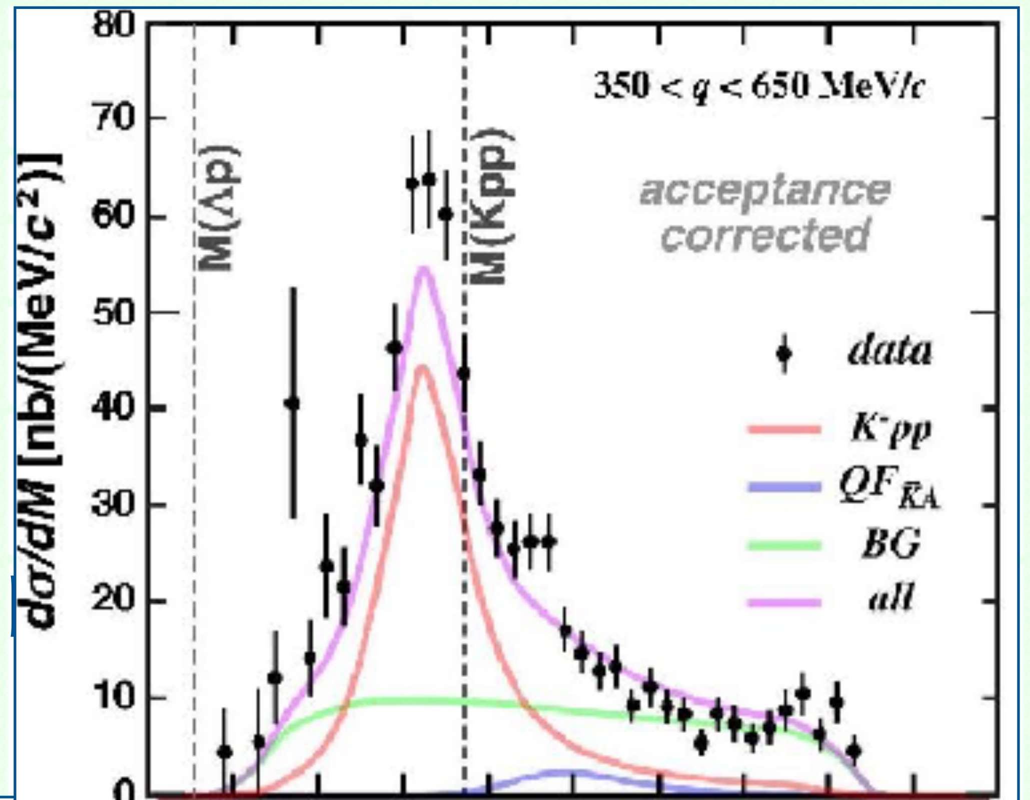
☐ Only the bound-state peak survives after the cut.

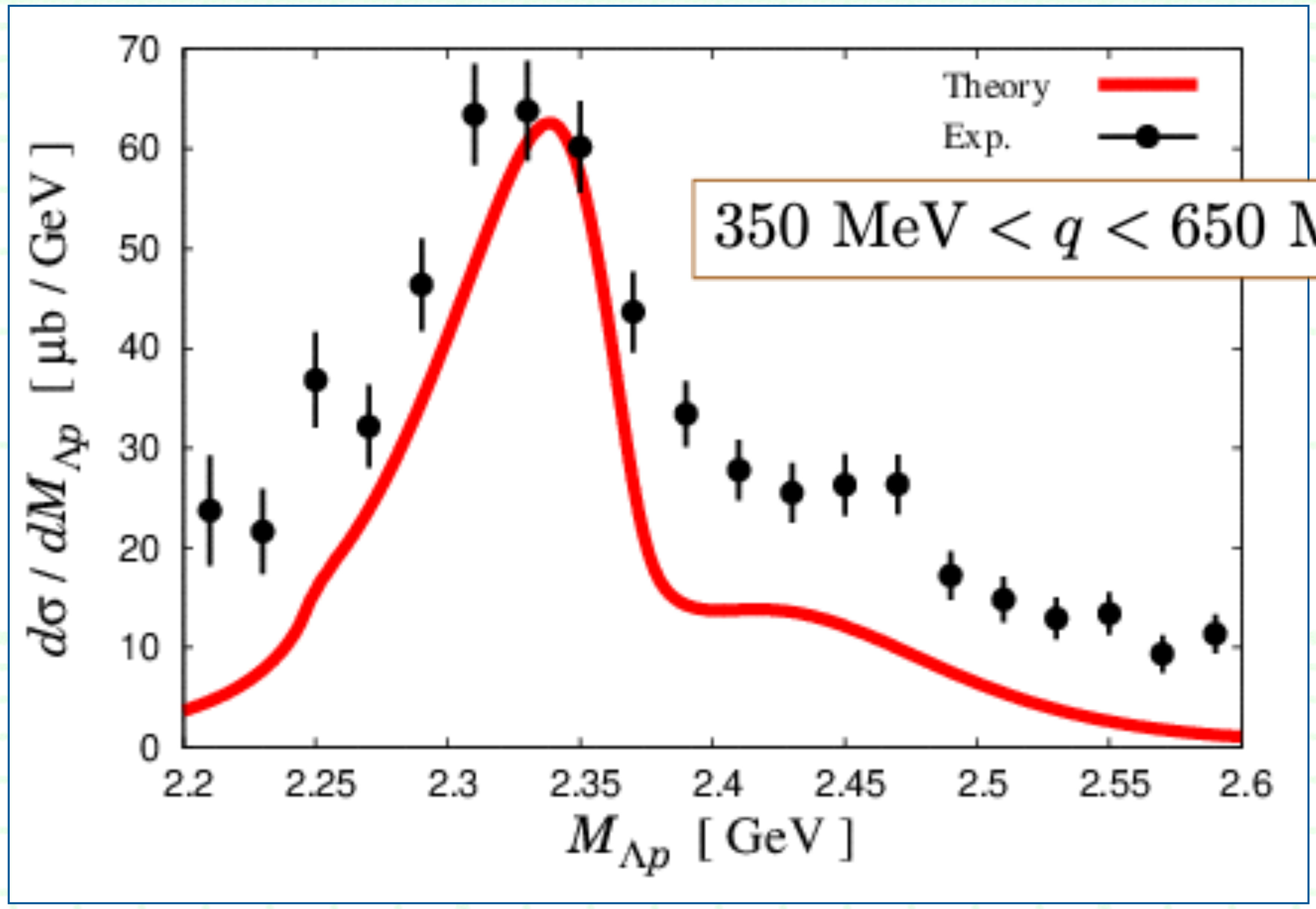
– Supports the validity of the Exp. cut.

2. Reaction calculation: K⁻ ³He –

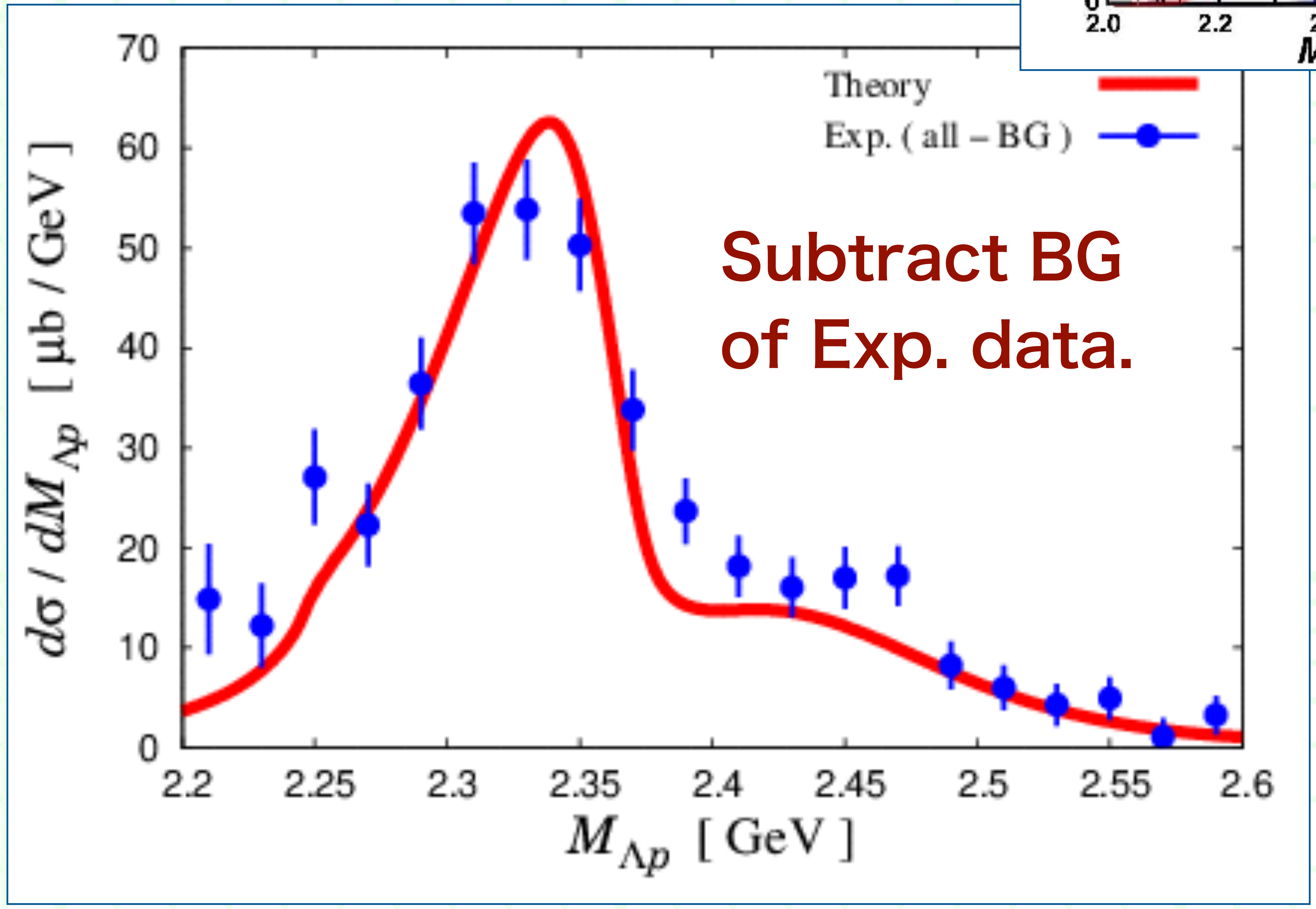
++ Momentum transfer cut ++

- Perform the same cut for the momentum transfer as the Exp. a





350 MeV < q < 650 MeV



Subtract BG
of Exp. data.

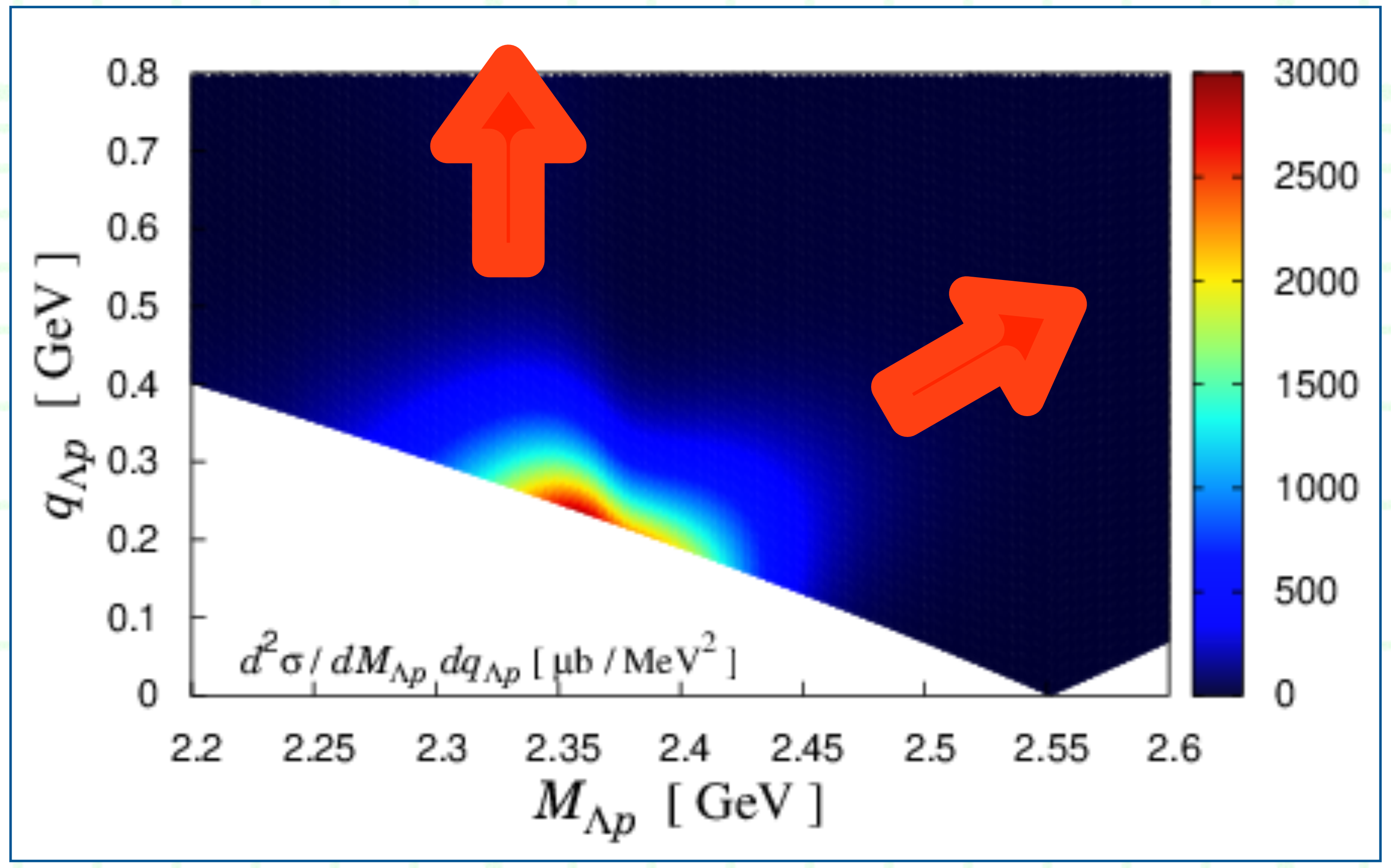
☐ The calculation reproduces well the peak structure.

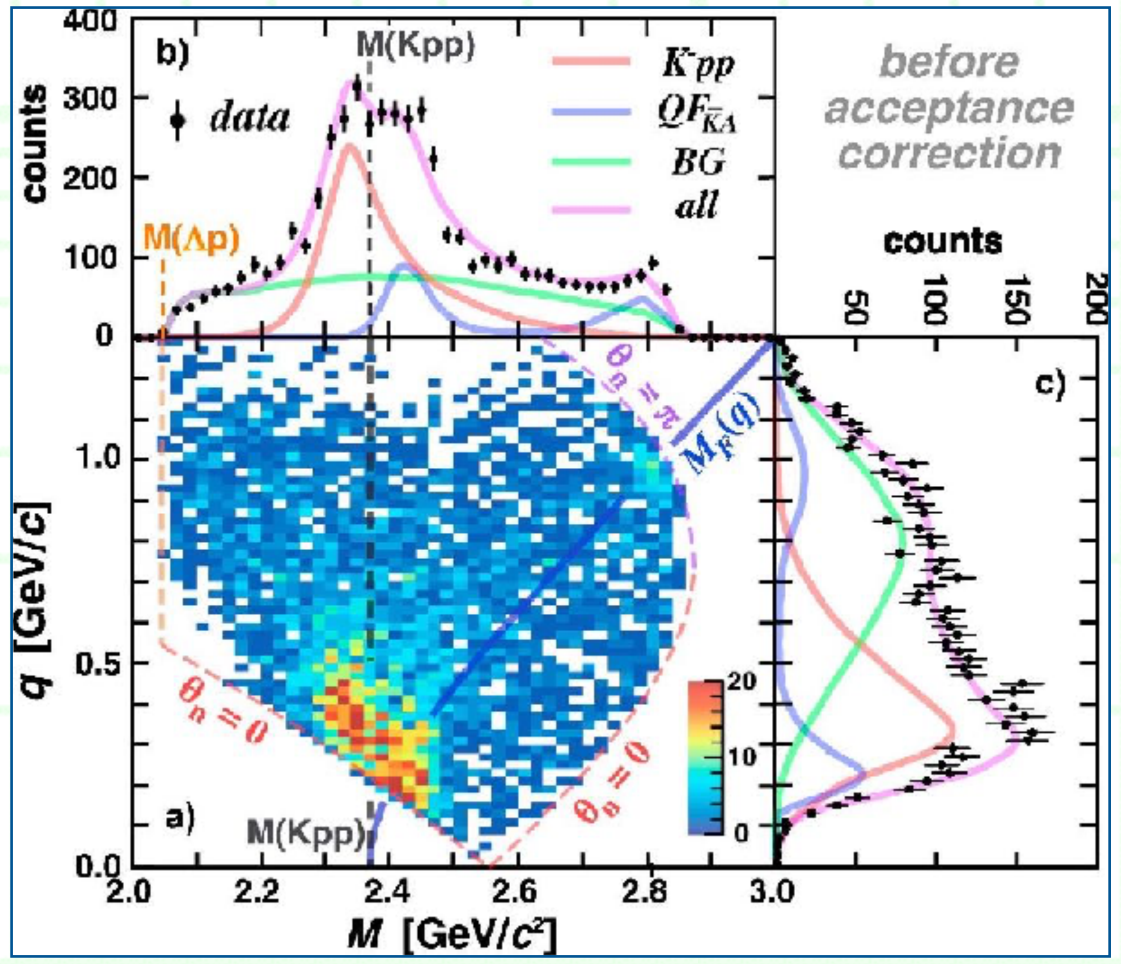
–> Supports the production of the $\bar{K}NN$ bound state.

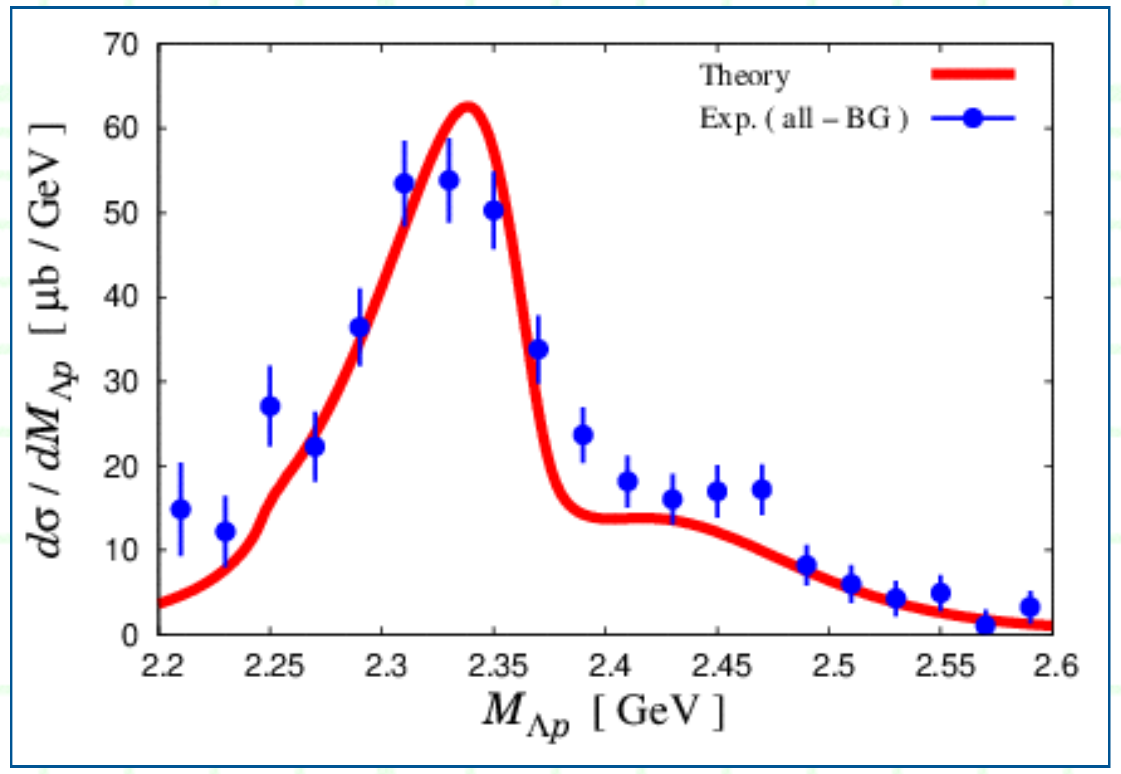
2. Reaction calculation: $K^- \, {}^3\mathrm{He}$ -> Λ p n

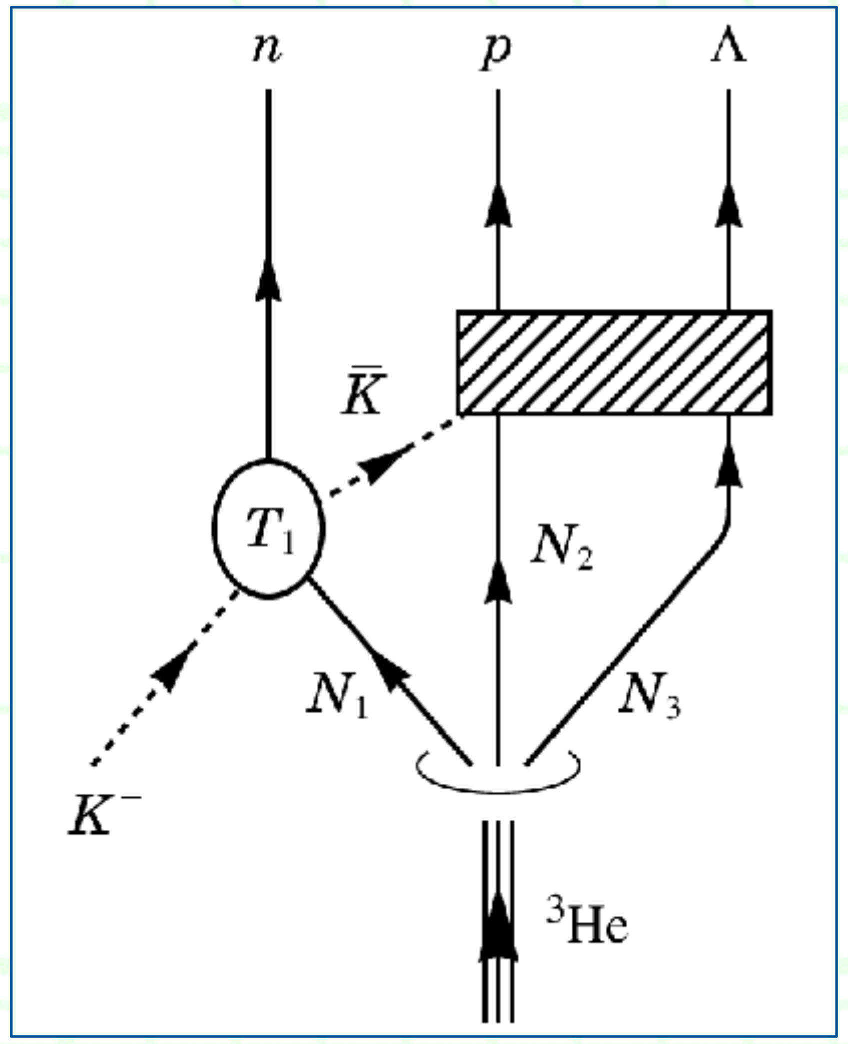
++ Theoretical support ++

- Calculate the spectrum by assuming that the $\bar{K}NN$ bound state is generated.









1. Appearance of the quasi-free kaon line.

-> $\bar{K}$ is indeed mediated.

2. The q independent signal is almost same as the theoretical calculation.

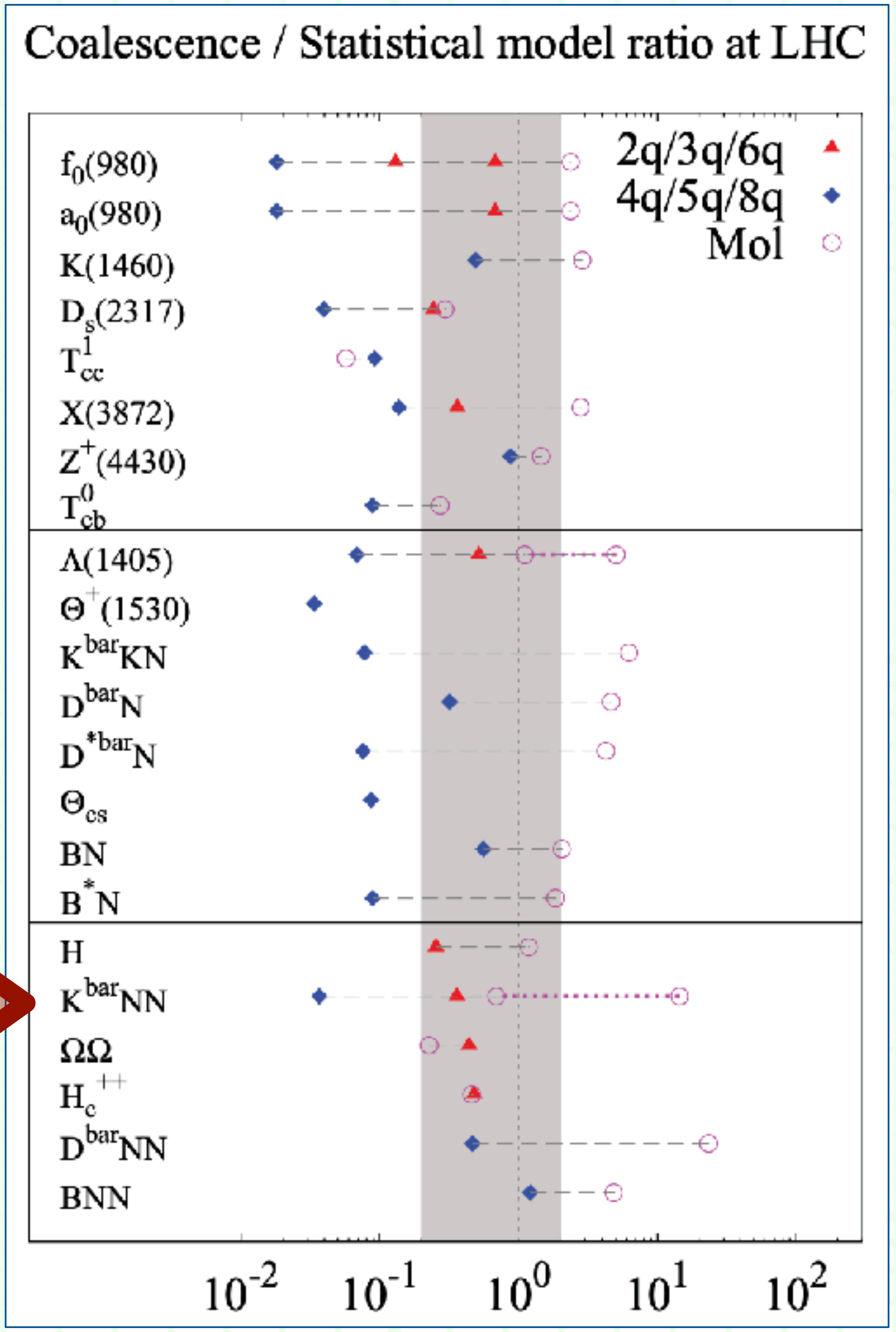
-> Strongly support the existence of the $\bar{K}NN$ bound state.

3. Perspective/implication in heavy ion collisions

3. Perspective/implication in HIC

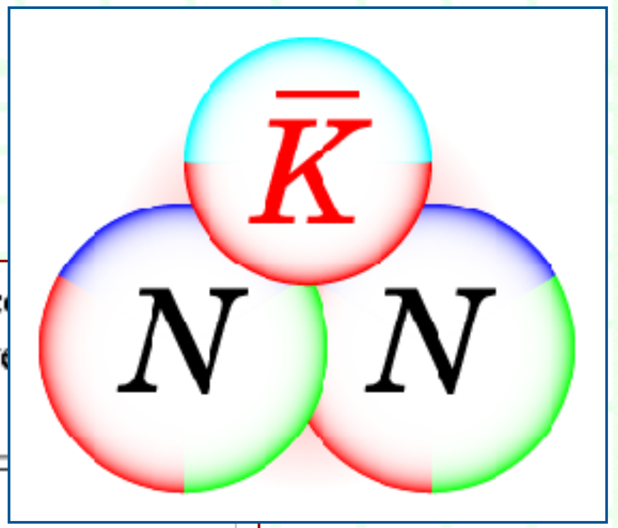
++ Exotic hadrons in heavy ion collisions ++

■ The ExHIC collaboration predicted production yields of exotic hadron candidates.



Cho et al., Phys. Rev. C84 (2011) 064910.

☐ The $\bar{\mathrm{K}}$NN bound state was in the list.



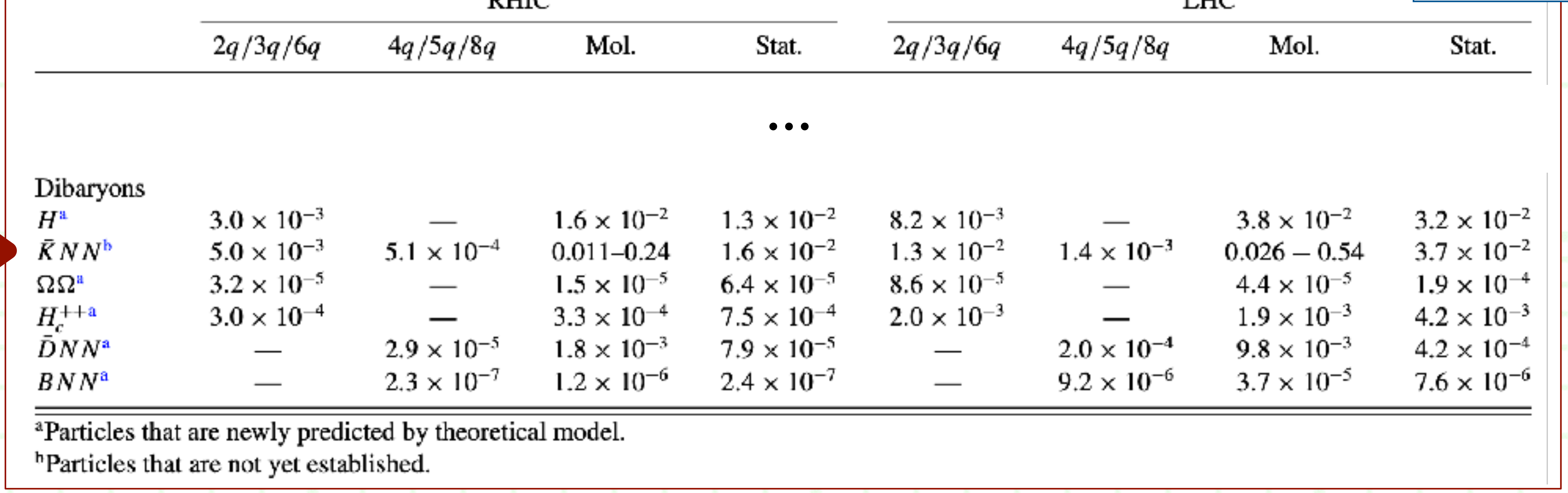


TABLE V. Exotic hadron yields in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC and in central Pb + Pb c $\sqrt{s_{NN}} = 5.5$ TeV at LHC from the quark coalescence (2q/3q/6q and 4q/5q/8q) and the hadron coalescence (Mol.), as we the statistical model (Stat.)

	RHIC				LHC			
	2q/3q/6q	4q/5q/8q	Mol.	Stat.	2q/3q/6q	4q/5q/8q	Mol.	Stat.
…								
Dibaryons								
H^{a}	3.0×10^{-3}	—	1.6×10^{-2}	1.3×10^{-2}	8.2×10^{-3}	—	3.8×10^{-2}	3.2×10^{-2}
$\bar{K}NN^{b}$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026 – 0.54	3.7×10^{-2}
$\Omega\Omega^{a}$	3.2×10^{-5}	—	1.5×10^{-5}	6.4×10^{-5}	8.6×10^{-5}	—	4.4×10^{-5}	1.9×10^{-4}
H_c^{++a}	3.0×10^{-4}	—	3.3×10^{-4}	7.5×10^{-4}	2.0×10^{-3}	—	1.9×10^{-3}	4.2×10^{-3}
$\bar{D}NN^{a}$	—	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	—	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}
BNN^{a}	—	2.3×10^{-7}	1.2×10^{-6}	2.4×10^{-7}	—	9.2×10^{-6}	3.7×10^{-5}	7.6×10^{-6}

[a] Particles that are newly predicted by theoretical model.

[b] Particles that are not yet established.

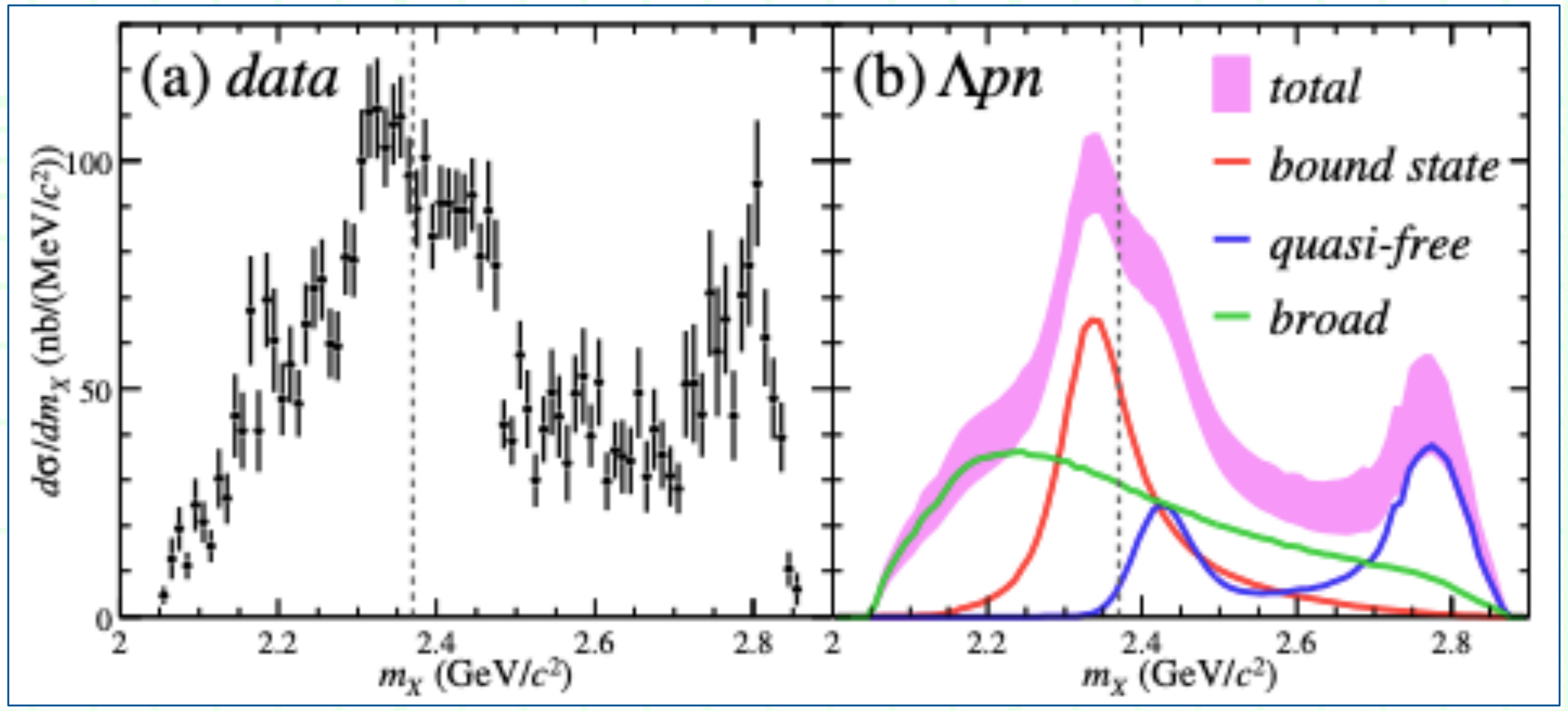
– However, at that time the $\bar{\mathrm{K}}$NN was not yet established.

☐ Now that the existence of the $\bar{\mathrm{K}}$NN bound state is strongly supported, we can say something about it.

3. Perspective/implication in HIC

++ Properties of the $\bar{\mathrm{K}}$NN nucleus ++

■ From the experimental data, the experimentalists concluded:



$$M_K = 2.328 \pm 0.003(\mathrm{stat.})^{+0.004}_{-0.003}(\mathrm{syst.})\ \mathrm{GeV}/c^2$$

$$(B_K = 42 \pm 3(\mathrm{stat.})^{+3}_{-4}(\mathrm{syst.})\ \mathrm{MeV}),$$

$$\Gamma_K = 100 \pm 7(\mathrm{stat.})^{+19}_{-9}(\mathrm{syst.})\ \mathrm{MeV},$$

– Fit with the Breit-Wigner (-like) formula.

Yamaga et al., Phys. Rev. C102 (2020) 044002.

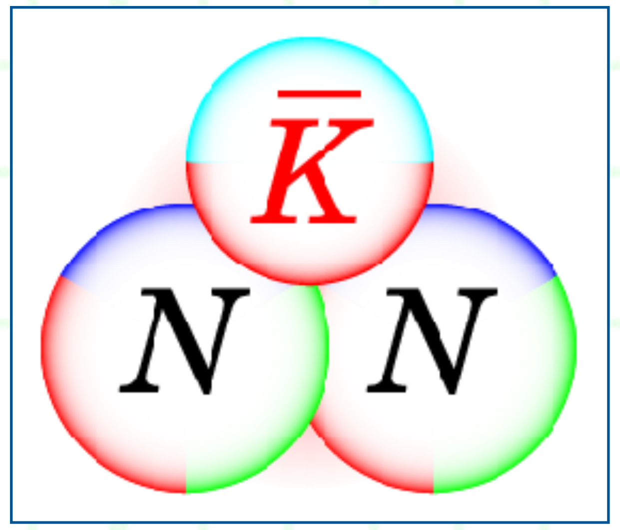
☐ Just below the K^-pp threshold (2370 MeV).

– Note: Peak position ≠ Real part of the pole position.

☐ Large width ~ 100 MeV.

– Mesonic $\bar{\mathrm{K}}$NN –> $\pi\,\Lambda$N, $\pi\,\Sigma$N

& Non-mesonic $\bar{\mathrm{K}}$NN –> ΛN, ΣN (two-nucleon absorption, 2NA).



3. Perspective/implication in HIC

++ Two-nucleon absorption (2NA) in $\bar{\mathrm{K}}\mathrm{NN}$ ++

■ Three-body is different.

☐ There exists 2NA in the $\bar{\mathrm{K}}\mathrm{NN}$ system owing to the non-conservation of the meson number.

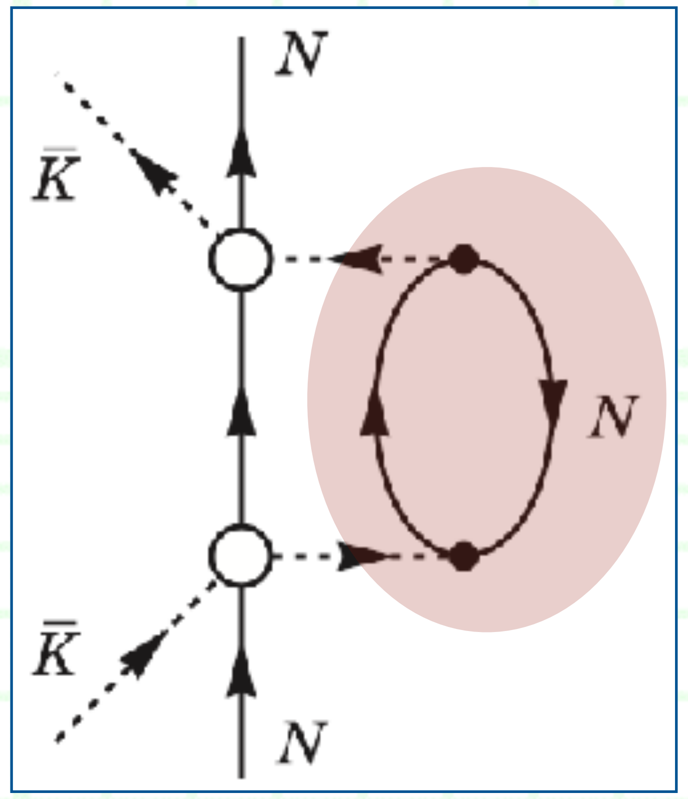
$$\bar{K}NN \to \left\{ \begin{array}{c} \Lambda N \\ \Sigma N \end{array} \right\} \to \bar{K}NN$$

– No analogue in NNN.

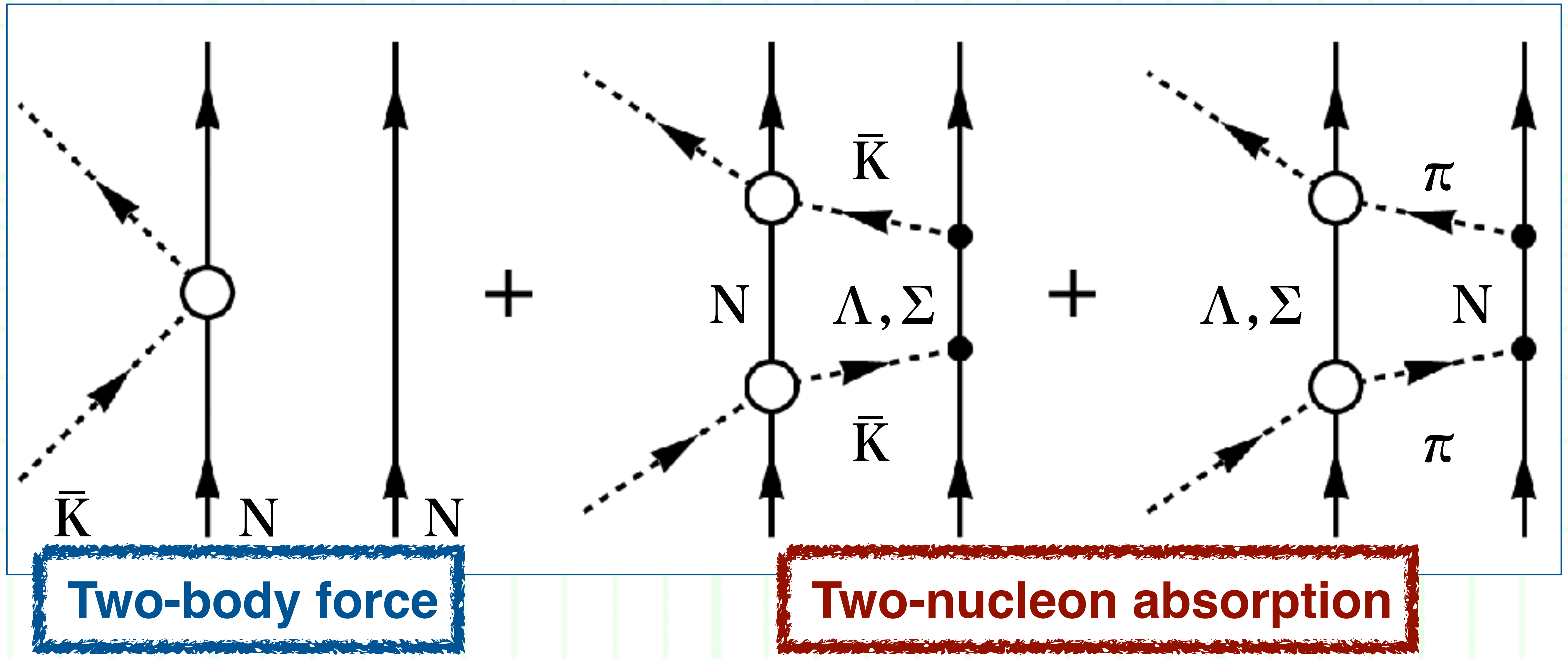
☐ The 2NA can be explicitly added to the two-body $\bar{\mathrm{K}}\mathrm{N}$ interaction as:

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

Reaction calculation in Sec. 2 has been done with:



$$\frac{1}{(p^{\mu}_{\mathrm{ex}})^2 - m_K^2 \underline{+ i m_K \Gamma_K}}$$

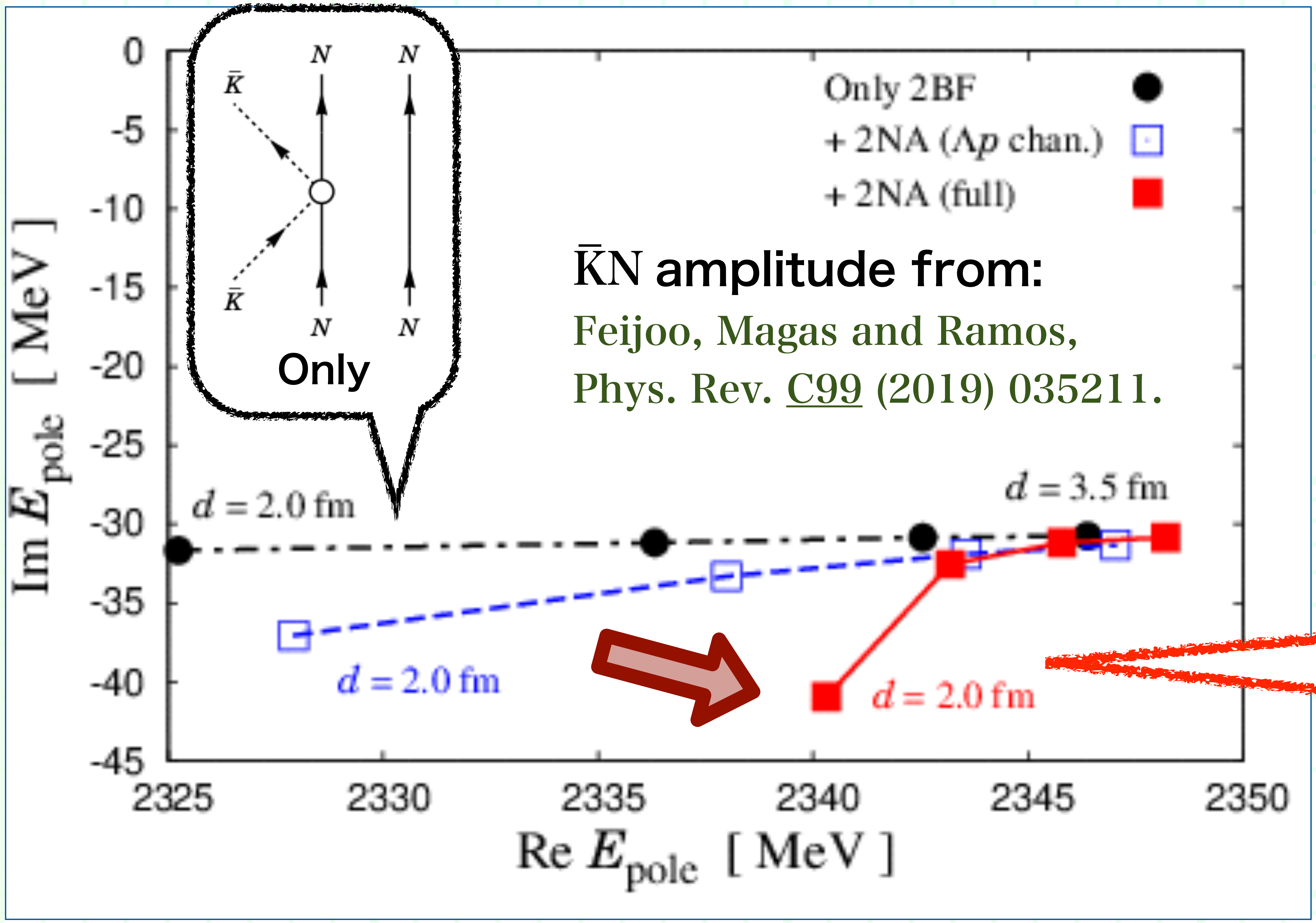


– The 2NA has real part as well as imaginary part.

3. Perspective/implication in HIC

++ Pole position ++

■ We obtain the pole of the $\bar{K}NN$ bound state in the scattering amplitude.

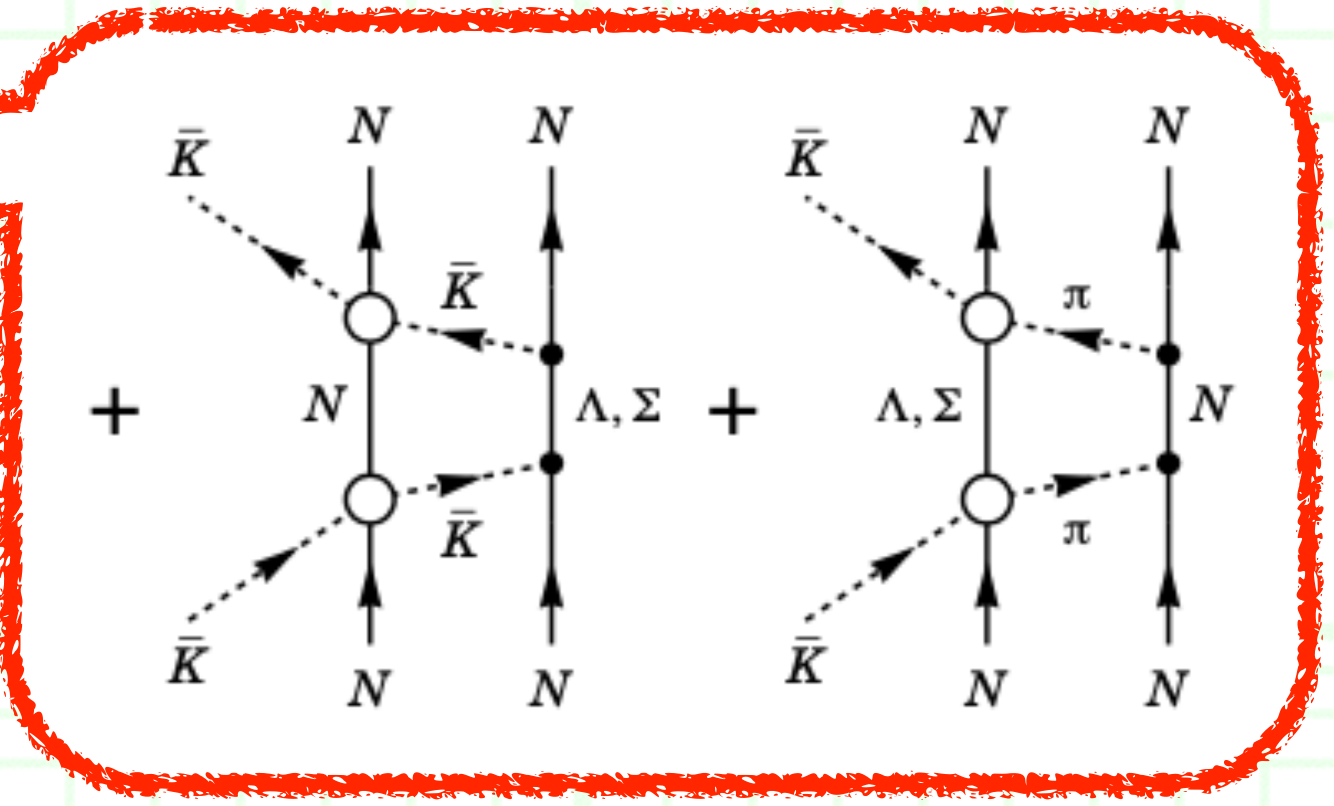


$\bar{K}N$ amplitude from:
Feijoo, Magas and Ramos,
Phys. Rev. C99 (2019) 035211.

☐ Parameter: NN distance d.

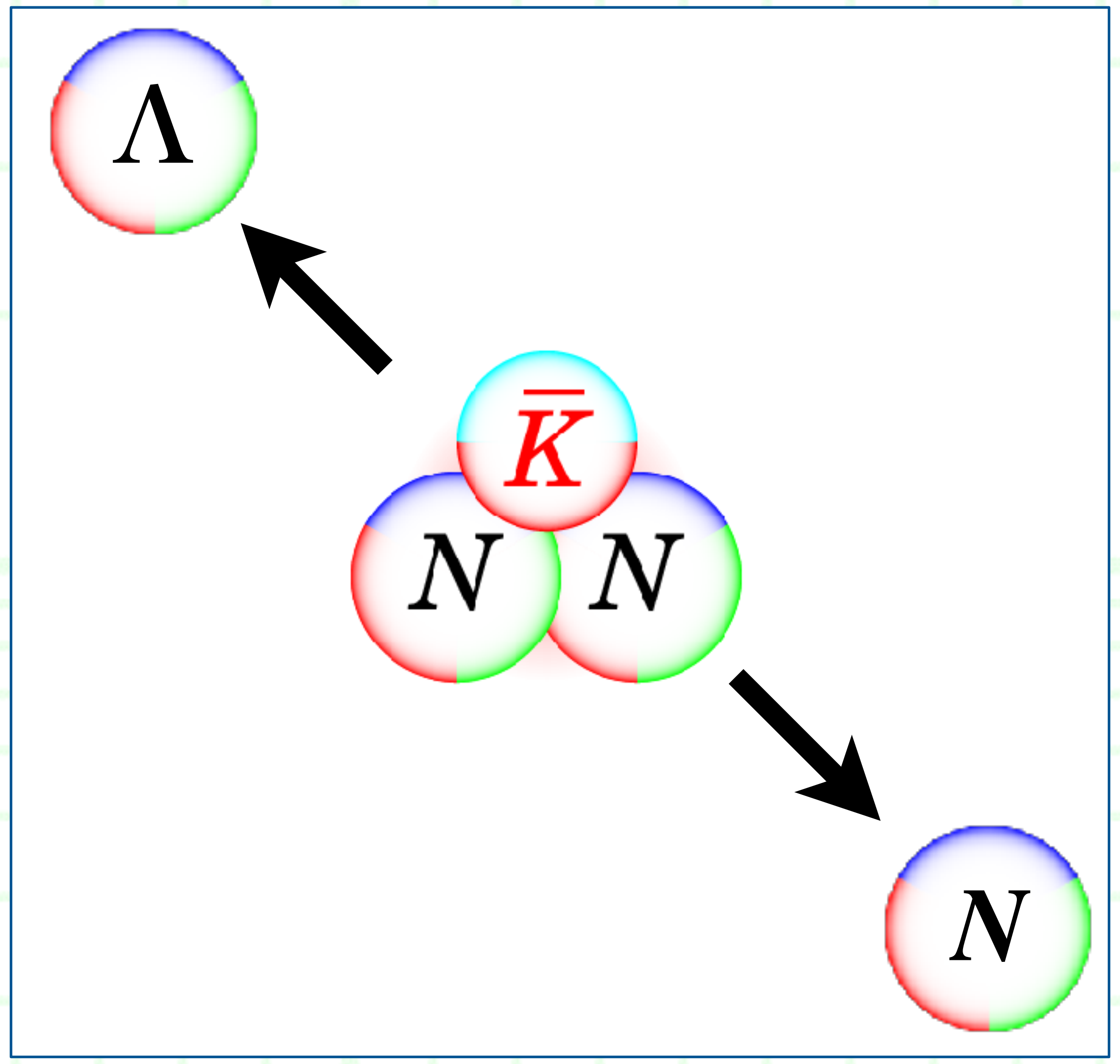
☐ The 2NA gives repulsion (real part) and absorption (imaginary part).

☐ At d = 2 fm, the pole shift via the 2NA is $\Delta E_{\rm pole} = +15 - 9\,i$ MeV ($E_{\rm pole} = 2340 - 41\,i$ MeV).



3. Perspective/implication in HIC

++ Perspective ++



■ The $\bar{\mathrm{K}}\mathrm{NN}$ bound state has large decay width $\sim$ 100 MeV.

– Mesonic $\bar{\mathrm{K}}\mathrm{NN} \to \pi\Lambda\mathrm{N},\ \pi\Sigma\mathrm{N}$ & Non-mesonic $\bar{\mathrm{K}}\mathrm{NN} \to \Lambda\mathrm{N},\ \Sigma\mathrm{N}$.

□ The $\Lambda\mathrm{p}$ and $\Sigma\mathrm{p}$ channels will be important when we want to observe the signal of the $\bar{\mathrm{K}}\mathrm{NN}$ in the heavy ion collision.

□ However, the signal may be “buried” in the spectrum owing to the large width.

■ Similar things may happen to other exotic candidates.

□ Large decay width.

– Fortunately, some of the exotic candidates have small decay widths.

□ Meson absorption owing to the non-conservation of the meson number.

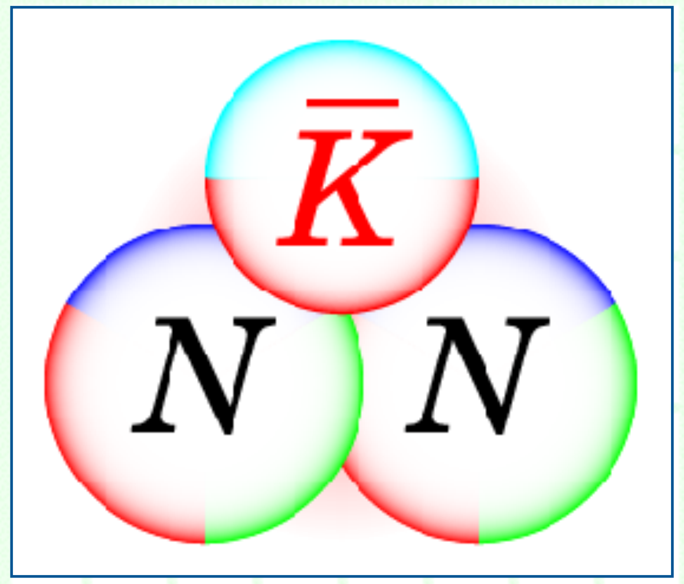
– In such a case, inclusion of three-body effects might be important.

cf. Du et al., Phys. Rev. D105 (2022) 014024; Meng et al., arXiv:2204.08716.

4. Summary

4. Summary

++ Summary ++



■ There should exist the $\bar{\mathrm{K}}\mathrm{NN}$ bound state, which is generated by the strongly attractive interaction between $\bar{\mathrm{K}}$ and nucleons.

☐ Results in the J-PARC E15 Exp. with the $\mathrm{K}^{-}\,{}^{3}\mathrm{He} \to \Lambda\ \mathrm{p}\ \mathrm{n}$ reaction give us key clues to understand the $\bar{\mathrm{K}}\mathrm{NN}$ bound state.

☐ We have performed a reaction calculation to support that the observed peak in the J-PARC E15 Exp. is indeed the signal of the $\bar{\mathrm{K}}\mathrm{NN}$ bound state.

■ The $\bar{\mathrm{K}}\mathrm{NN}$ bound state has large decay width $\sim 100\ \mathrm{MeV}$.

– Mesonic $\bar{\mathrm{K}}\mathrm{NN} \to \pi\Lambda\mathrm{N},\ \pi\Sigma\mathrm{N}$ & Non-mesonic $\bar{\mathrm{K}}\mathrm{NN} \to \Lambda\mathrm{N},\ \Sigma\mathrm{N}$.

☐ Can we observe the signal of the $\bar{\mathrm{K}}\mathrm{NN}$ bound state in heavy ion collisions ?

☐ Large decay width / meson absorption may happen to other exotic candidates.

Thank you very much
for your kind attention !