Theoretical investigation of the reaction mechanisms for the $\bar{K}N$ and $\bar{K}NN$ systems with K^- beam at J-PARC

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(Kyoto Prefectural Univ.)

[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] J. Yamagata-Sekihara, T. S. , and D. Jido, under discussion.
[4] T. S. , E. Oset, and A. Ramos, under discussion.

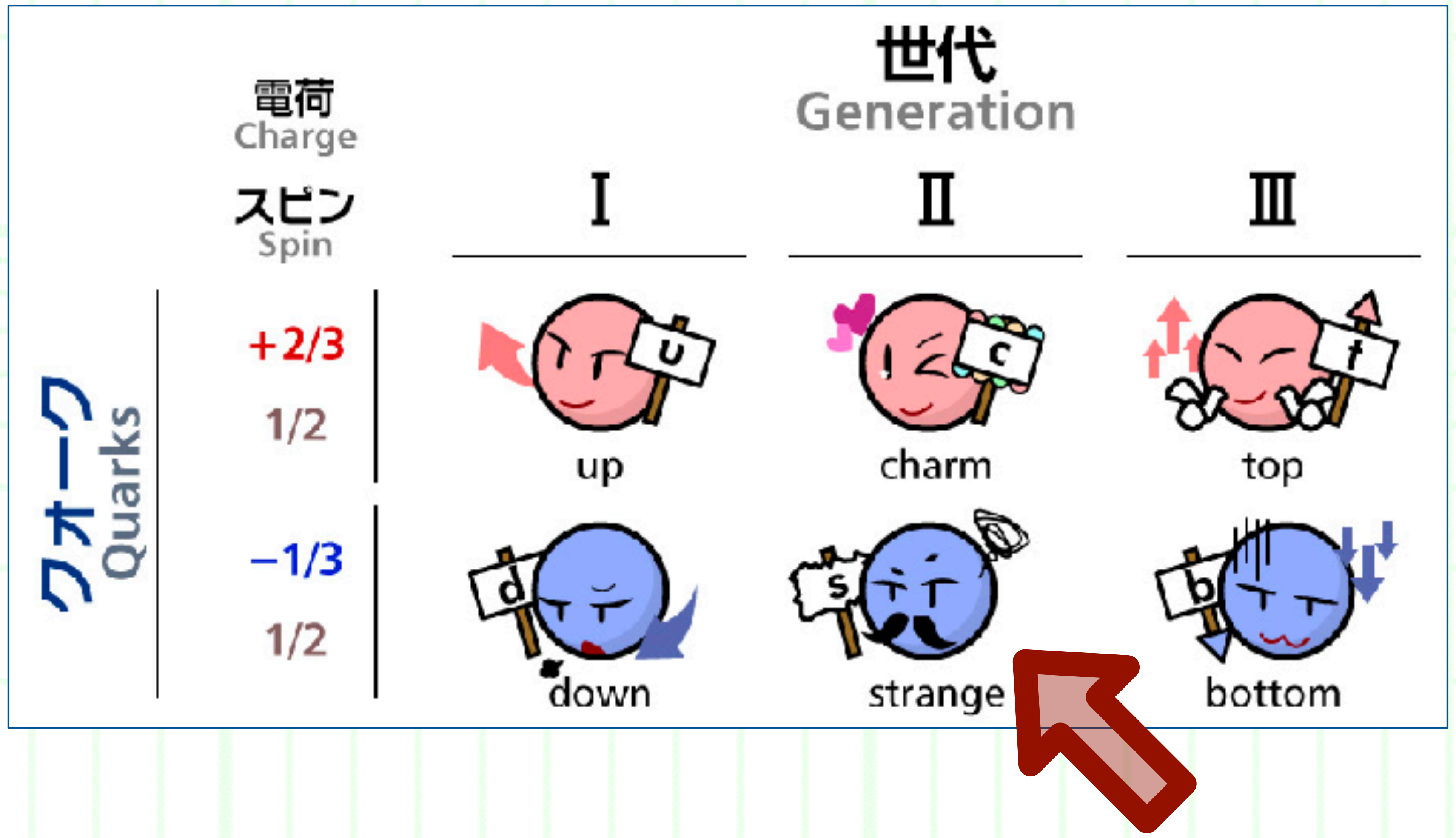
Contents

1. Introduction

1. Introduction

++ Strange hadrons as a precision tool ++

HIGGSTAN.

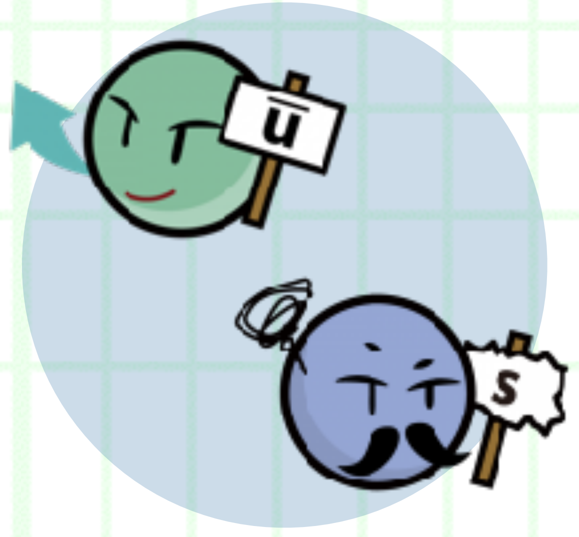


- **Hadrons = Particles composed of quarks, interact via strong interactions.**
  - Underlying theory for strong interactions: Quantum Chromodynamics (QCD).

$$\mathcal{L}_{\rm QCD} = \sum_{f={\rm flavor}} \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4} G^a{}_{\mu\nu} G^{a\,\mu\nu}$$

  - We want to understand strong interactions from QCD.

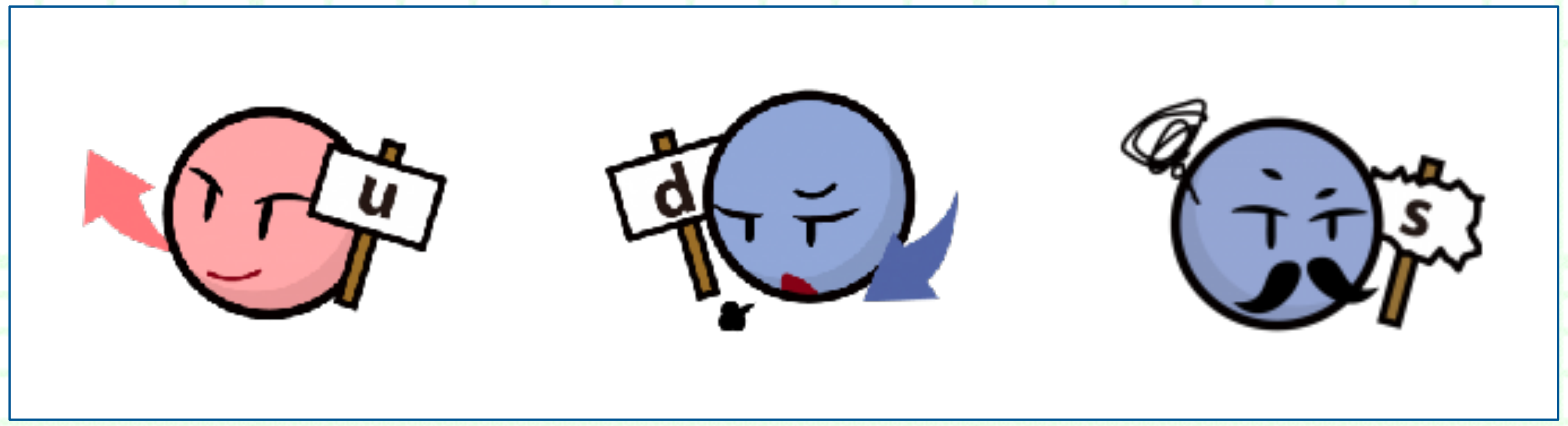
- **Recently, much attention has paid to the hadronic systems with strange quarks = non-zero strangeness.**
  - The experiments and numerical simulations are now available !
  - A different perspective on hadron physics.



K^- meson.

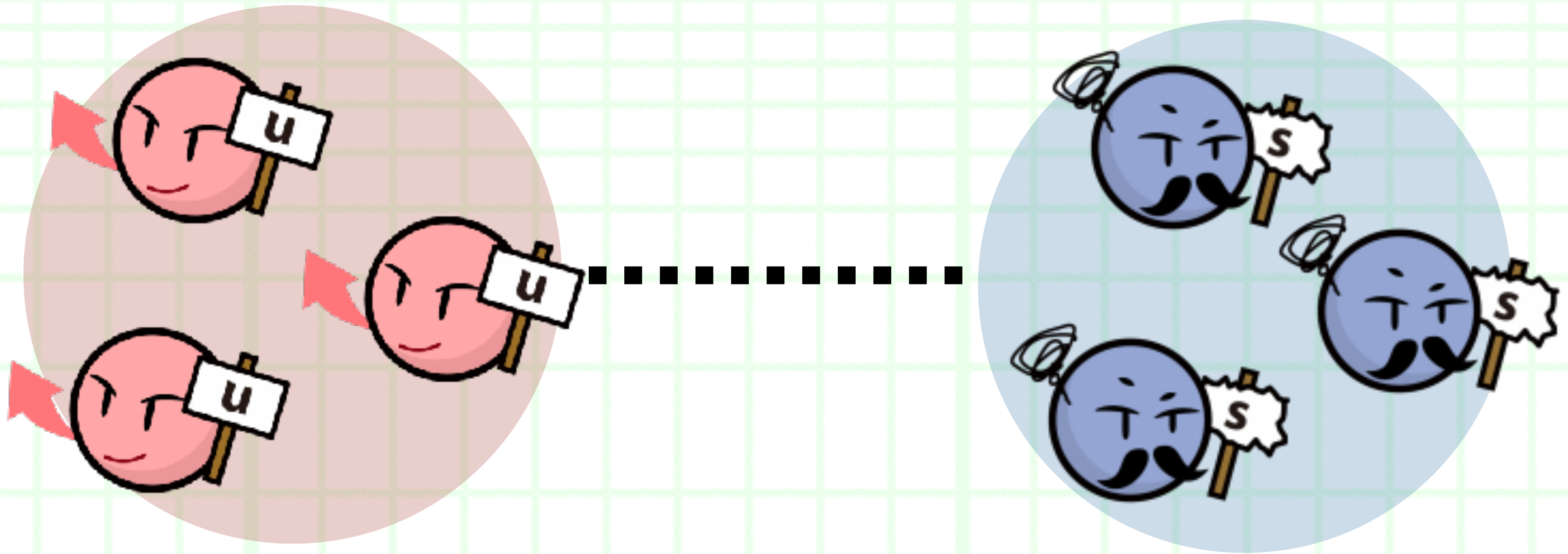
1. Introduction

++ An example: Baryon-baryon interaction ++



■ An example: Baryon-baryon interaction.

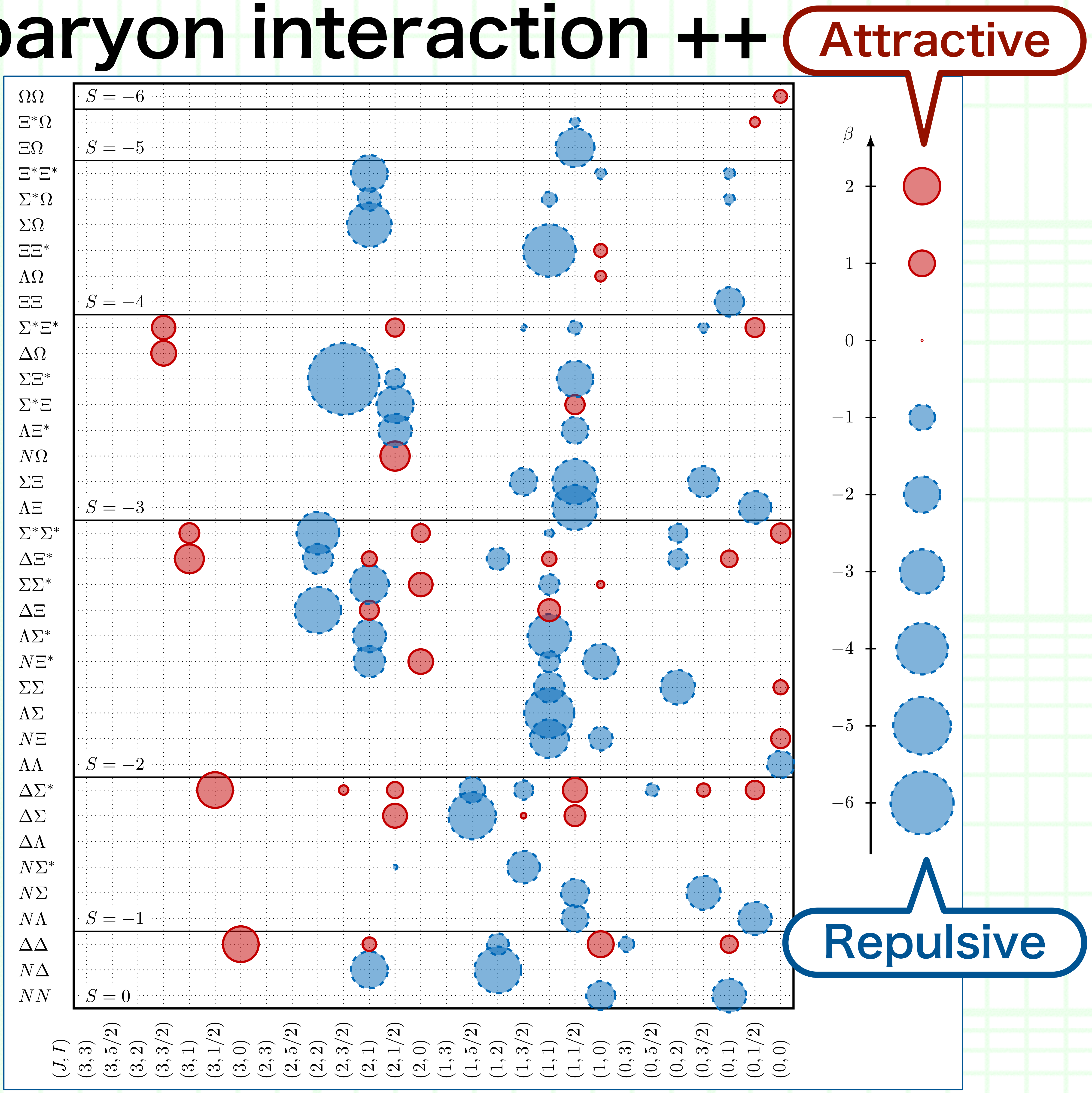
□ Do the properties of the nuclear force persist even in the baryon-baryon interactions with strangeness ?



Δ^{++} Ω

□ Baryon-baryon Int. in a quark model.

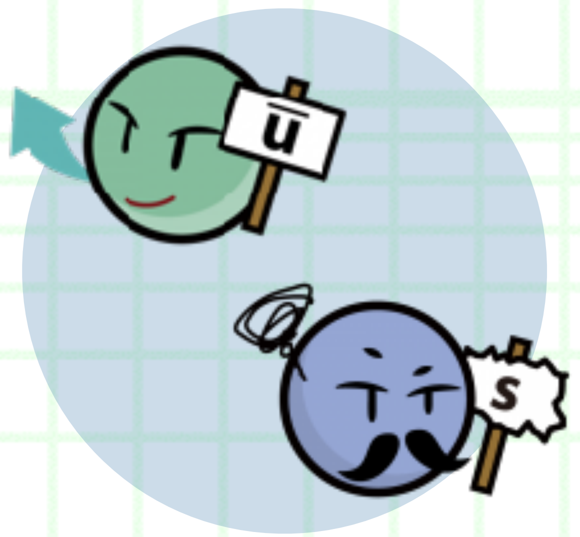
T. S. and T. Hashiguchi, Phys. Rev. C108 (2023) 065202.

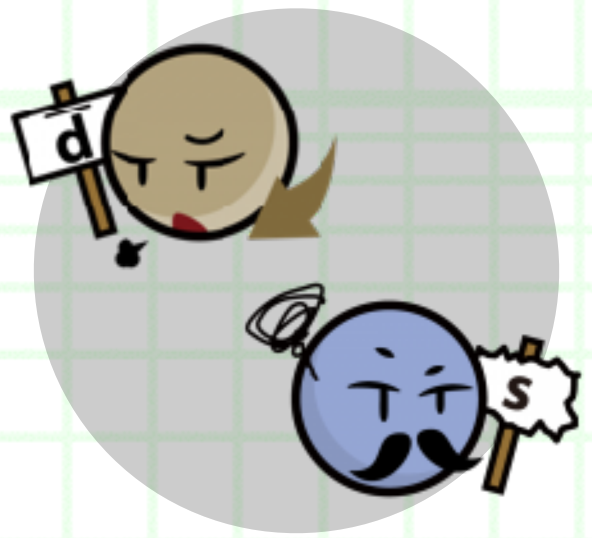


1. Introduction

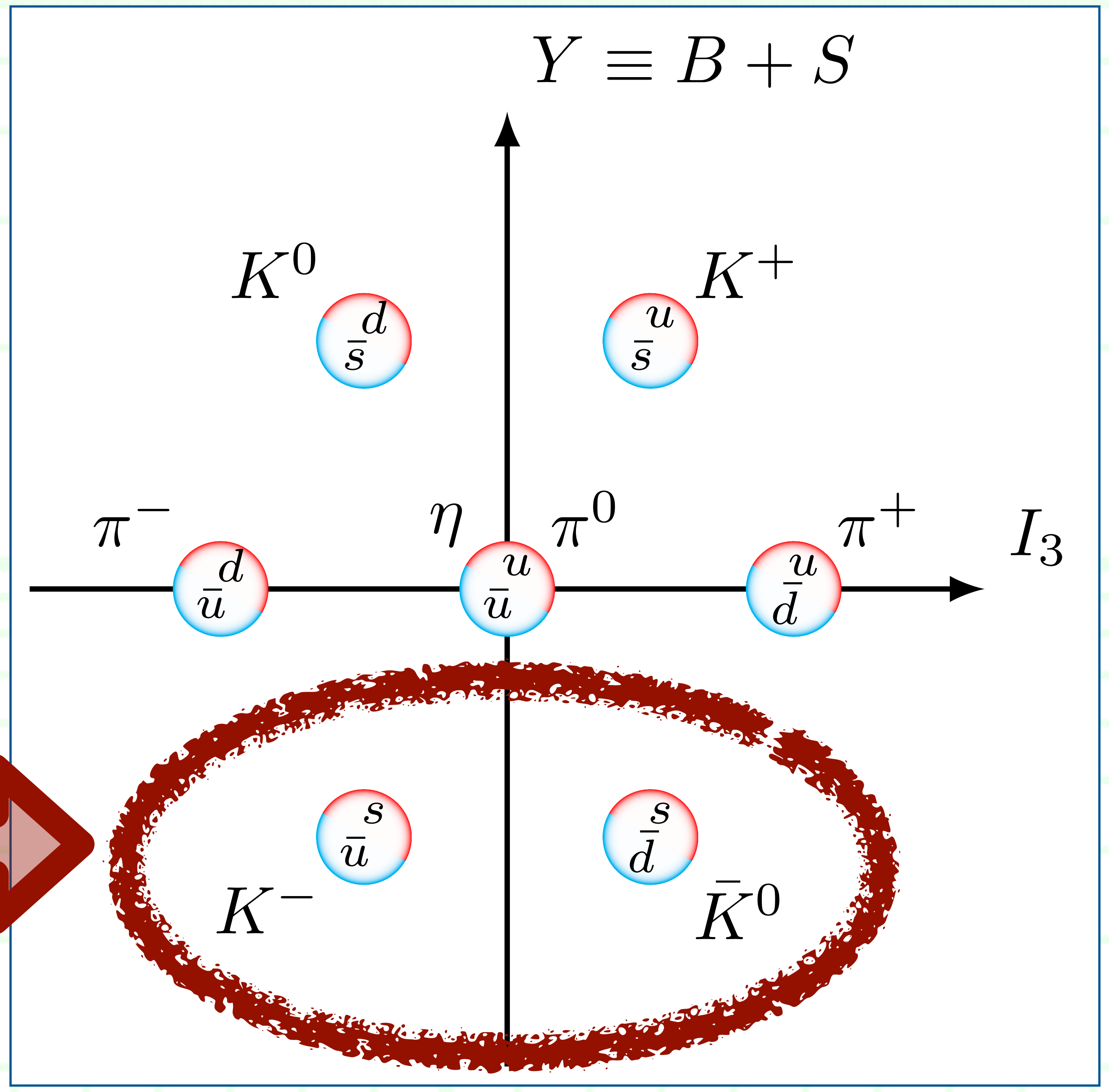
++ Anti-kaon $\bar{K}$ ++

■ We focus on the anti-kaon $\bar{K} = (K^-, \bar{K}^0)$.

K−




$\bar{K}^0$



Octet mesons

□ $\bar{K}$ is lighter as a Nambu-Goldstone boson.
–> The dynamics is constrained by
the spontaneous breaking of chiral symmetry.

$$\mathcal{L}_{\mathrm{QCD}} \to \mathcal{L}_{\mathrm{ChPT}} = \sum_n \mathcal{L}_n$$

– Chiral perturbation theory (ChPT).

□ $\bar{K}$ is heavier than the pion $\pi = (\pi^+, \pi^0, \pi^-)$.
–> Easier to make a bound state, when the interaction is attractive enough.

1. Introduction

++ The $\bar{K}N$ and $\bar{K}NN$ systems ++

■ Indeed, the $\bar{K}N$ interaction in chiral dynamics is attractive enough to generate a bound state as $\Lambda(1405)$.

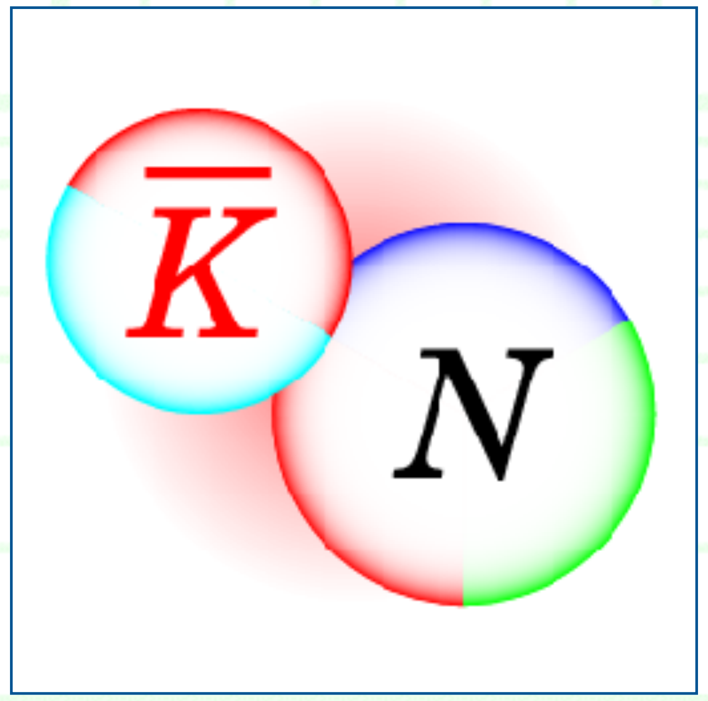
□ Theoretical studies support the $\bar{K}N$ molecular nature of the $\Lambda(1405)$ resonance.

- Compositeness = the norm of the two-body wave function.

  T. S. , Hyodo and Jido, PTEP 2015 063D04; Kamiya and Hyodo, PTEP 2017 023D02; ⋯.

- Dominant $\bar{K}N$ component in lattice QCD simulations.

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



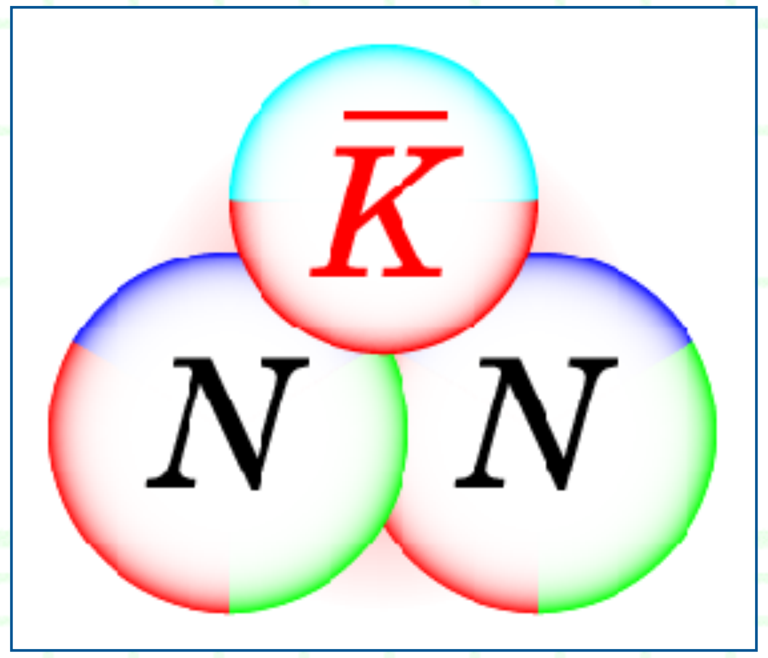
Bound state as $\Lambda(1405)$!

■ We can extend the discussion from the $\bar{K}N$ to the $\bar{K}NN$ bound state.

— The simplest kaonic nucleus.

□ Theoretically, the attractive $\bar{K}N$ interaction indicates that the $\bar{K}NN$ system is bound.

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



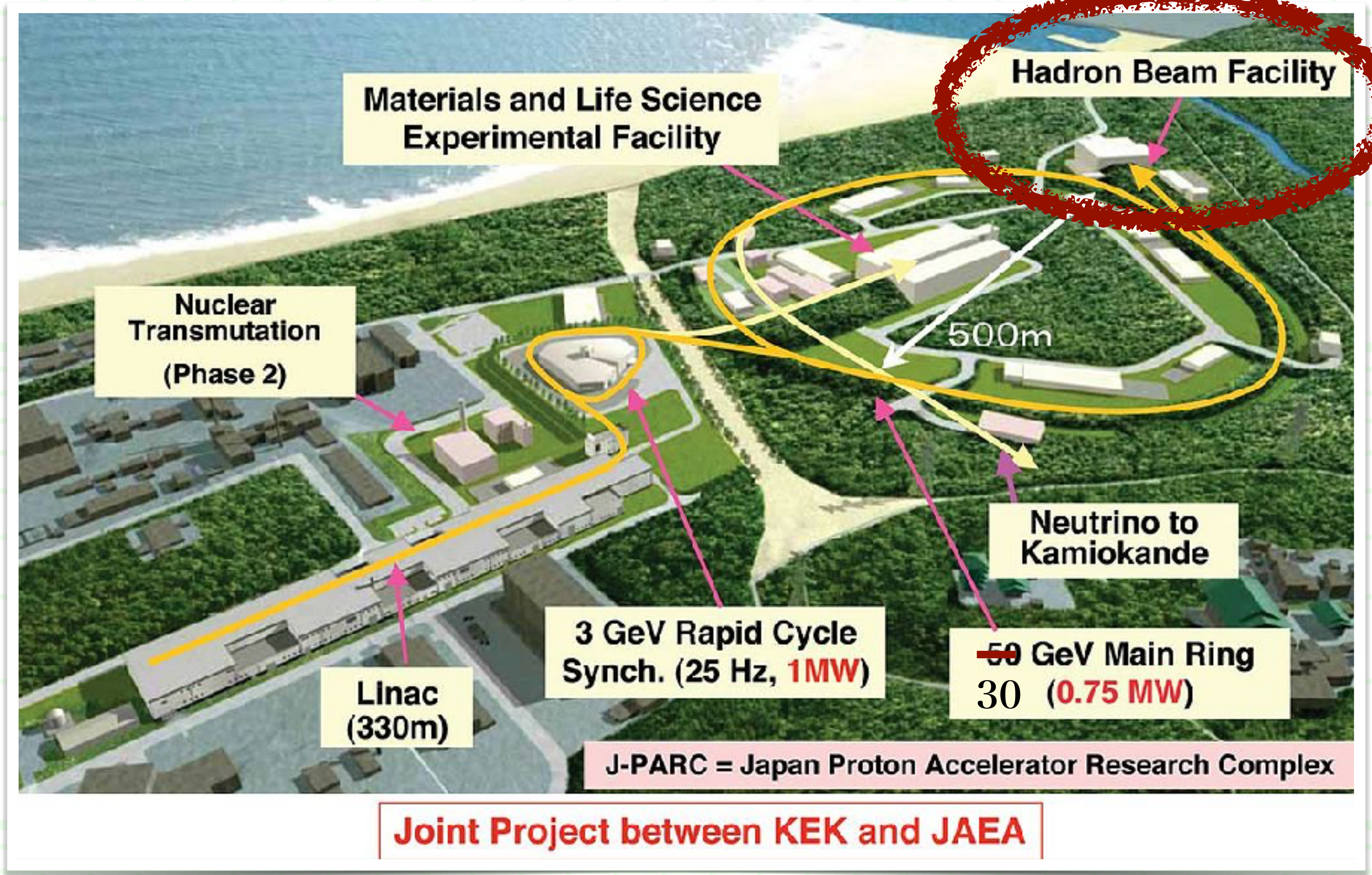
1. Introduction

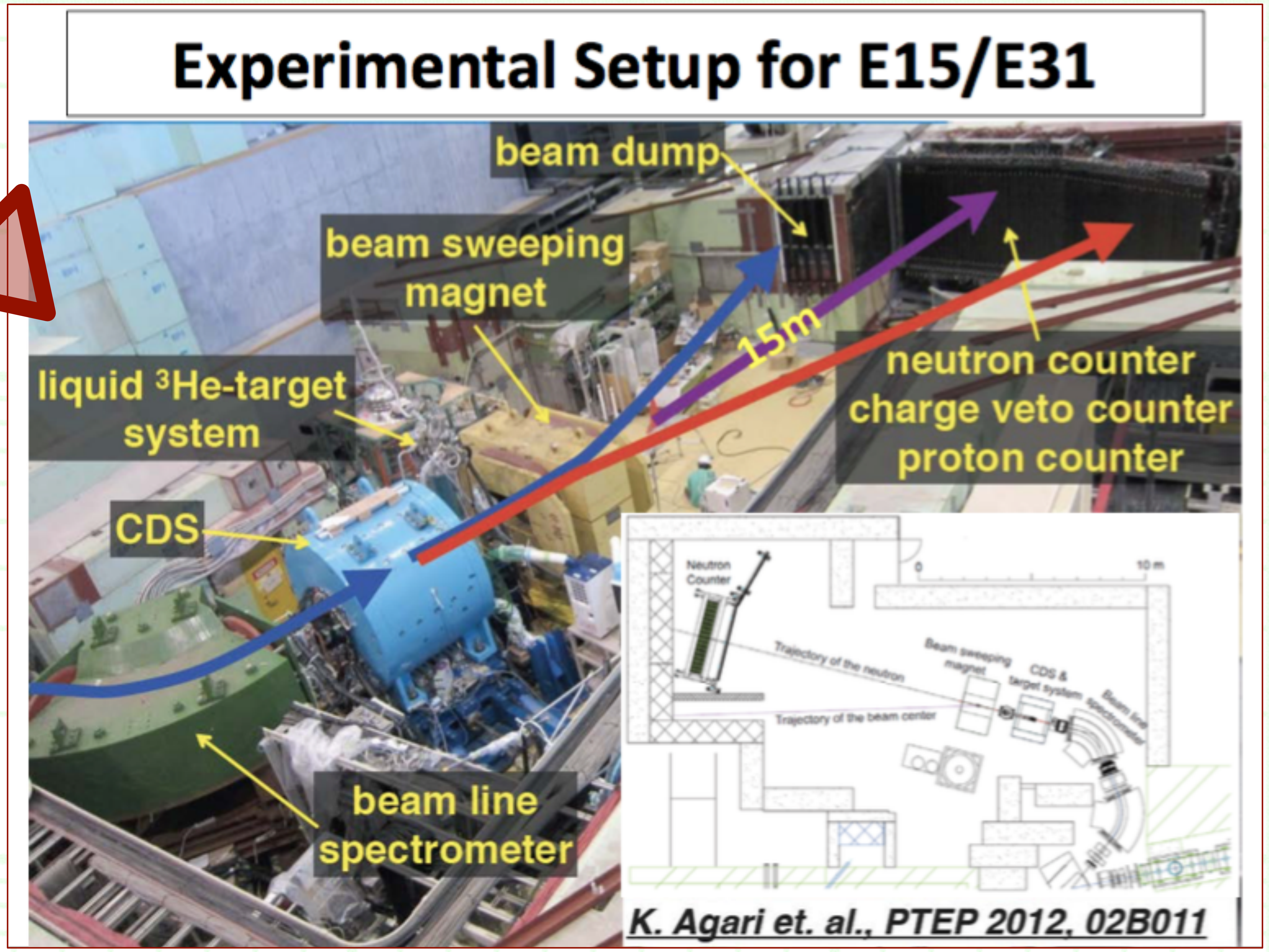
++ $\bar{K}$ experiments at J-PARC ++

■ Such $\bar{K}N$ and $\bar{K}NN$ systems can be studied at J-PARC.

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

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



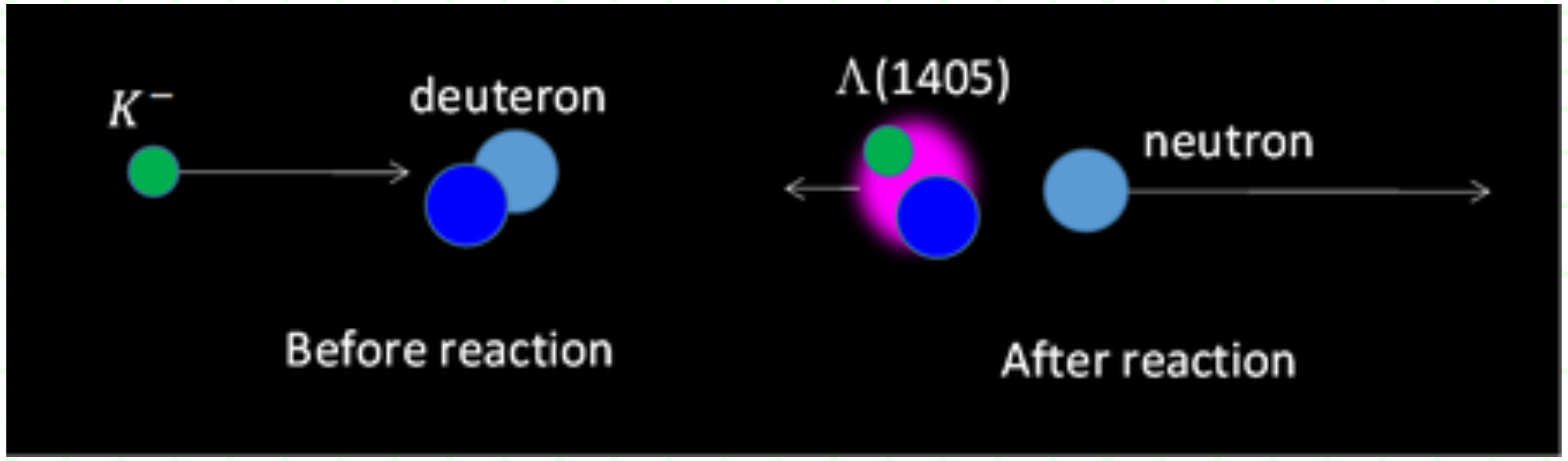


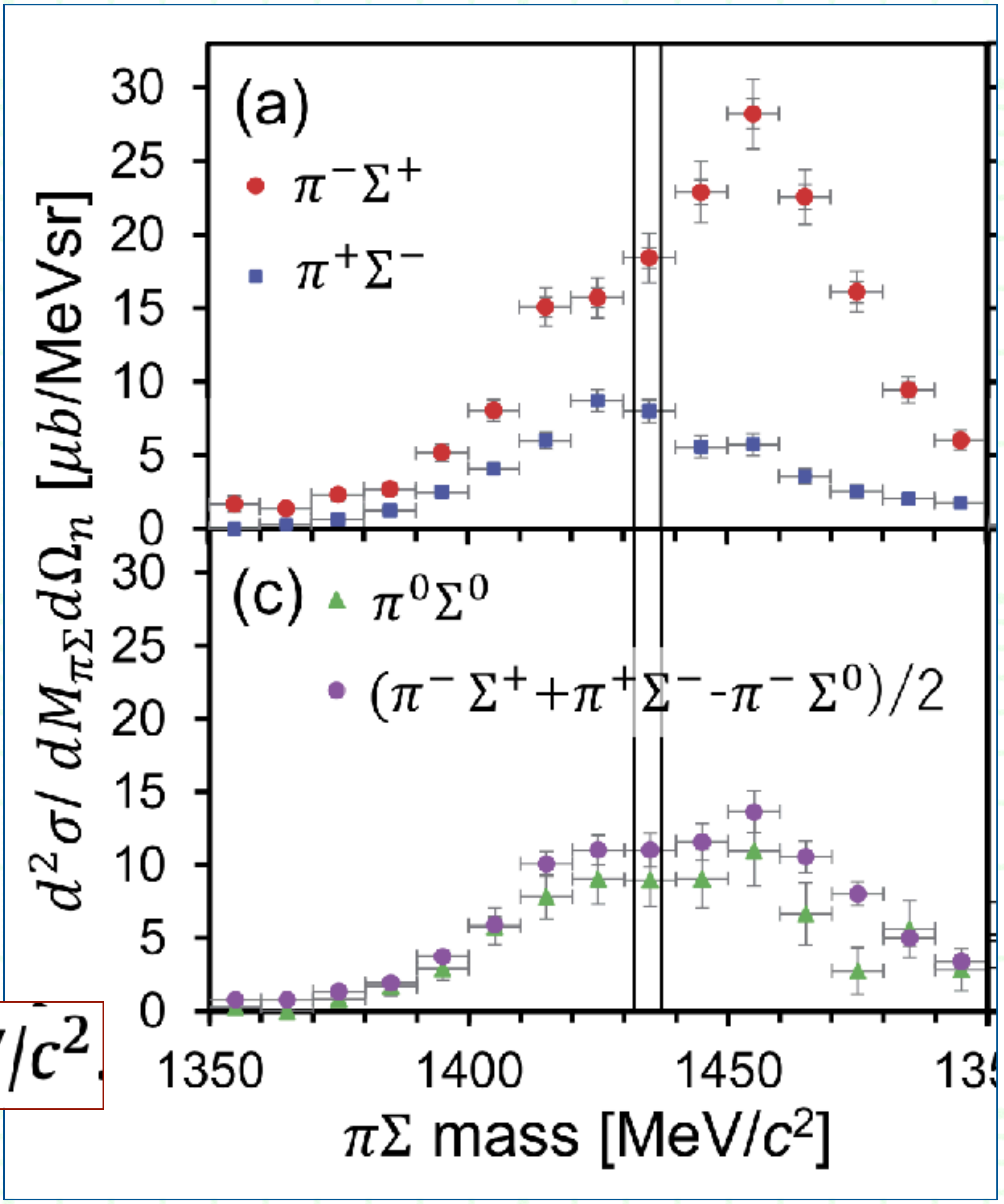
1. Introduction

++ J-PARC E31 Exp. for the $\bar{K}N$ system ++

■ The J-PARC E31 Exp. was performed to produce the $\Lambda(1405)$ resonance from the $\bar{K}N$ channel in the $K^- d \rightarrow \pi \Sigma n$ reaction.

J-PARC press release.





□ If the $\Lambda(1405)$ is indeed a $\bar{K}N$ bound state, peak position and pole position would provide good information on the binding energy.

□ J-PARC E31 Exp. analysis suggests:

$$1417.7^{+6.0}_{-7.4}(\mathrm{fit})^{+1.1}_{-1.0}(\mathrm{syst.}) + [-26.1^{+6.0}_{-7.9}(\mathrm{fit})^{+1.7}_{-2.0}(\mathrm{syst.})]i \ \mathrm{MeV}/c^2$$

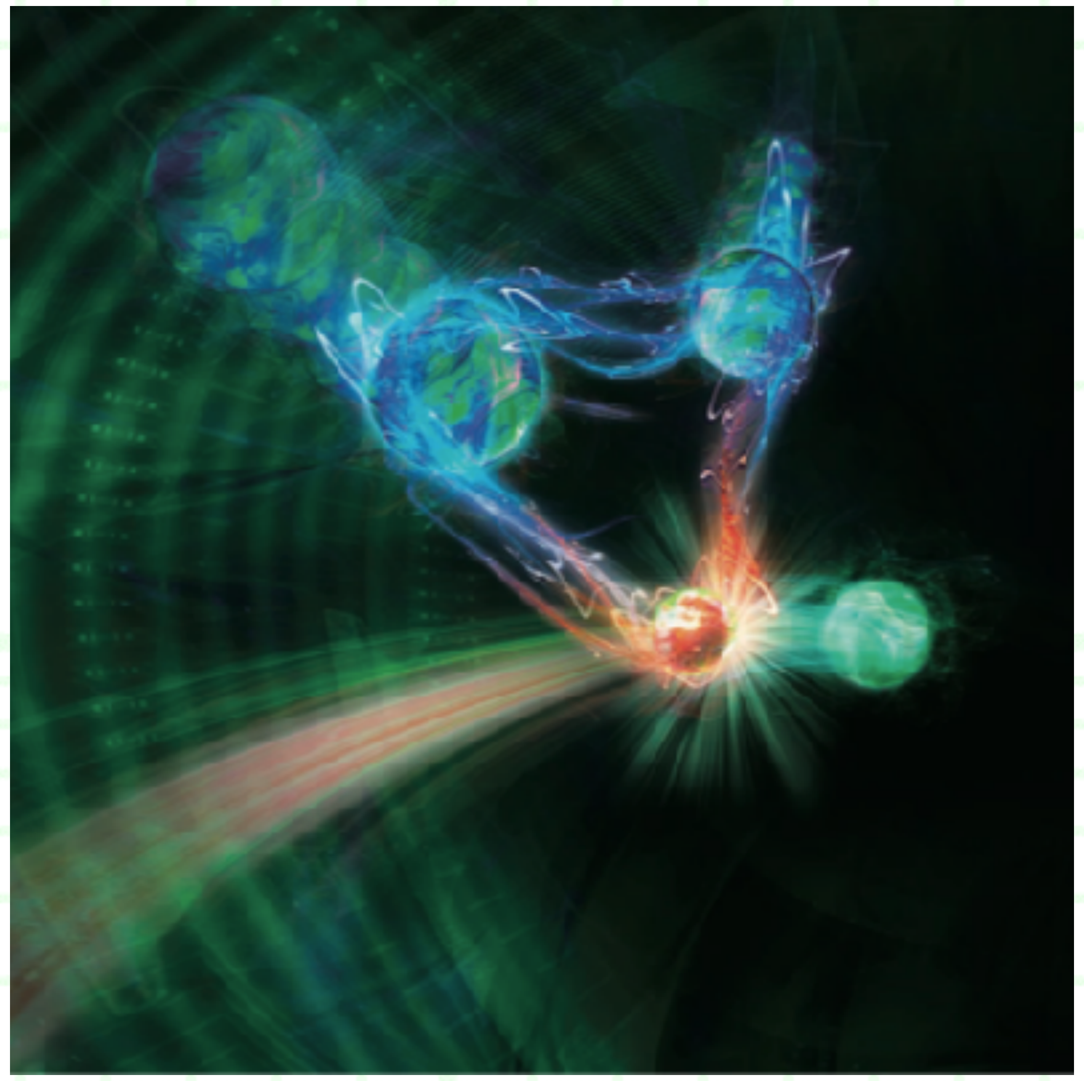
J-PARC E31 Collab., Phys. Lett. B837 (2023) 137637.

1. Introduction

++ J-PARC E15 Exp. for the $\bar{K}NN$ system ++

■ The J-PARC E15 Exp. was performed to search for the $\bar{K}NN$ bound state in the $K^- \, {}^3He \to \Lambda pn$ reaction.

p p

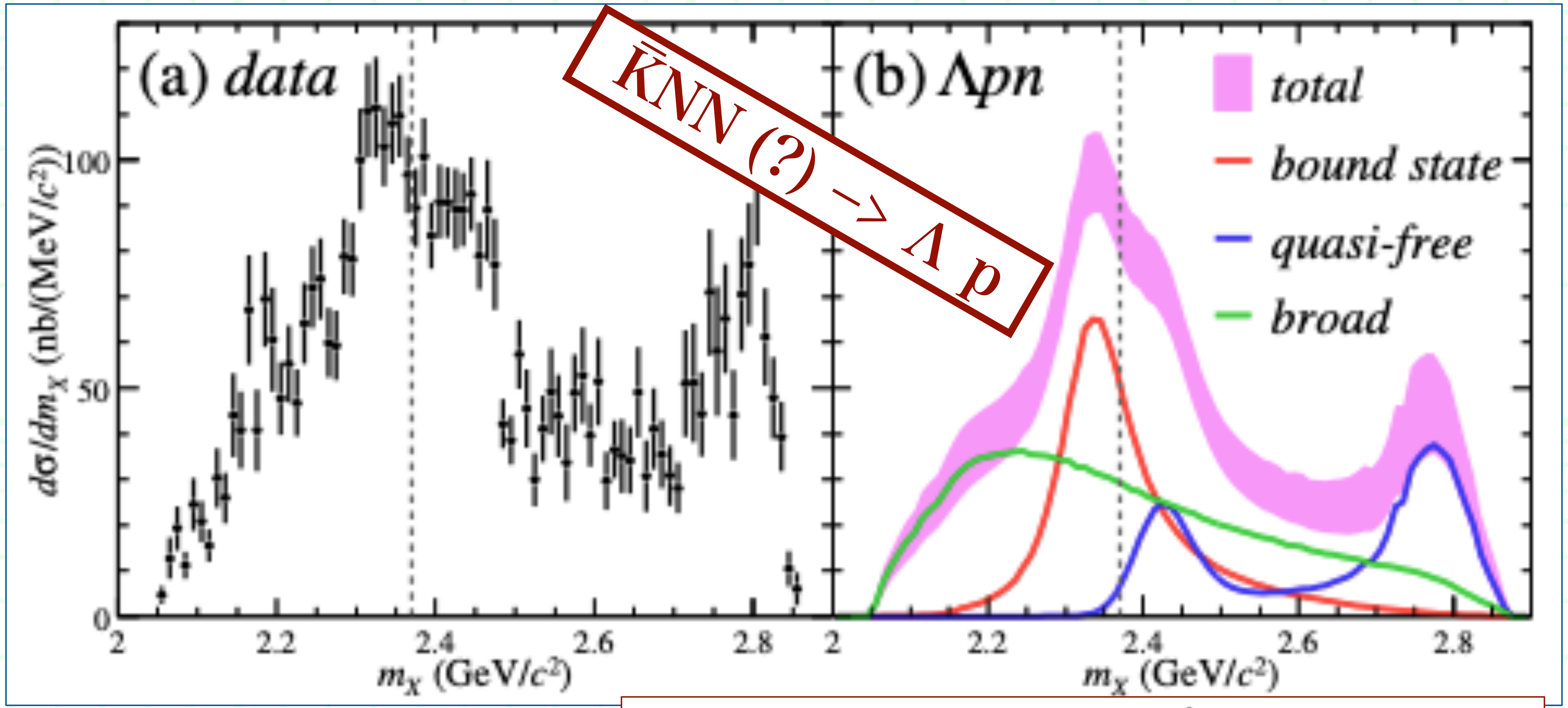


n

K^-

The Austrian Academy of Sciences, Harald Ritsch.

Yamaga et al. [J-PARC E15], Phys. Rev. C102 (2020) 044002.



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

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

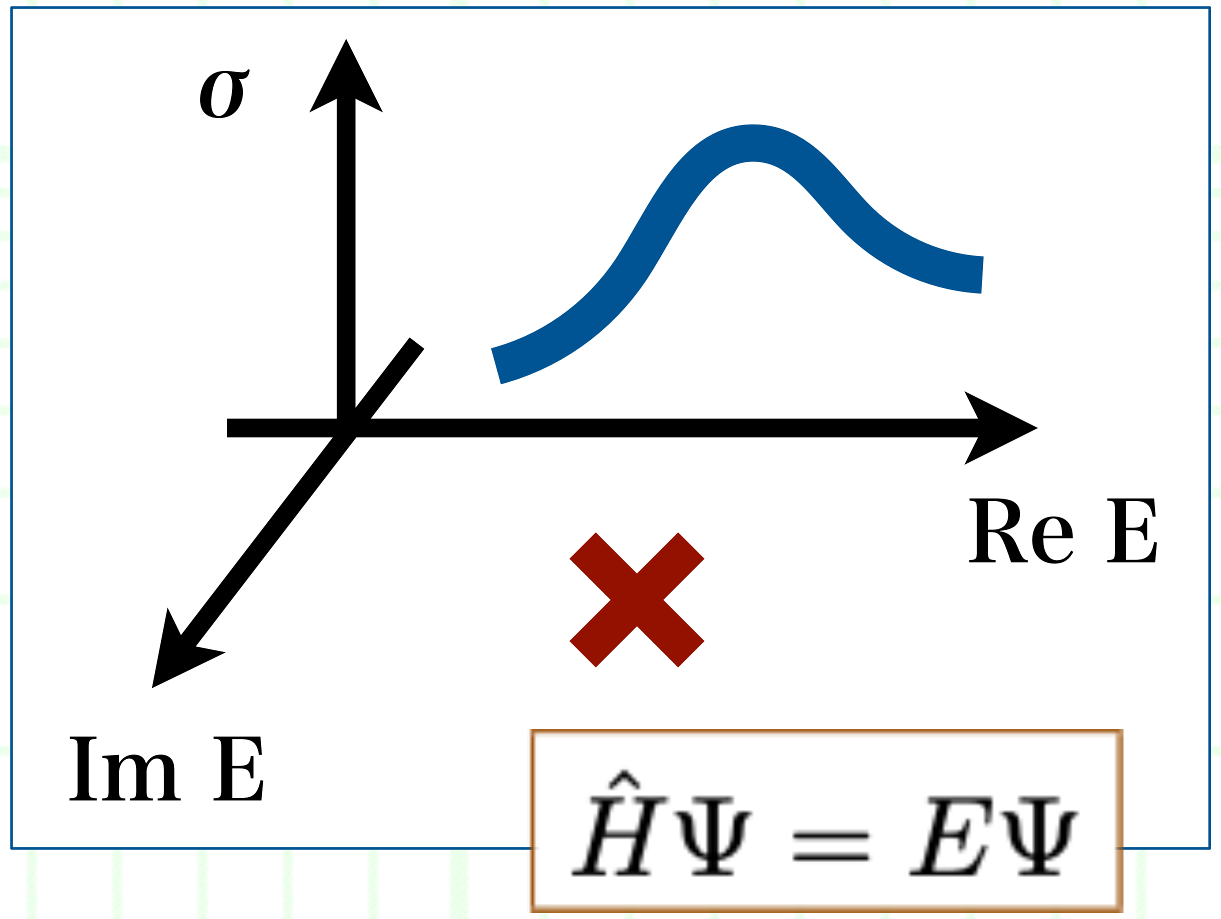
□ Is this really the signal of the $\bar{K}NN$ bound state ?

1. Introduction

++ Motivation ++

■ Are these peaks really the signals of the $\bar{\mathrm{K}}\mathrm{N}$ and $\bar{\mathrm{K}}\mathrm{NN}$ systems ?

— Does the $\bar{\mathrm{K}}$ survive the reaction ?



■ Resonance poles vs. Exp. peaks.

□ Resonance poles correspond to the eigenstates of the Schrödinger Eq.

□ Exp. peak position, which is on the real energy axis, may differ from the real part of the pole position due to interference between the pole and background.

■ We aim to connect the resonance pole and Exp. observables by reaction calculations.

— Determine the analytic form of the scattering Amp. on the complex energy plane.

2. The $\bar{K}N$ system in the $K^{-} d \to \pi \Sigma n$ reaction: J-PARC E31

2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

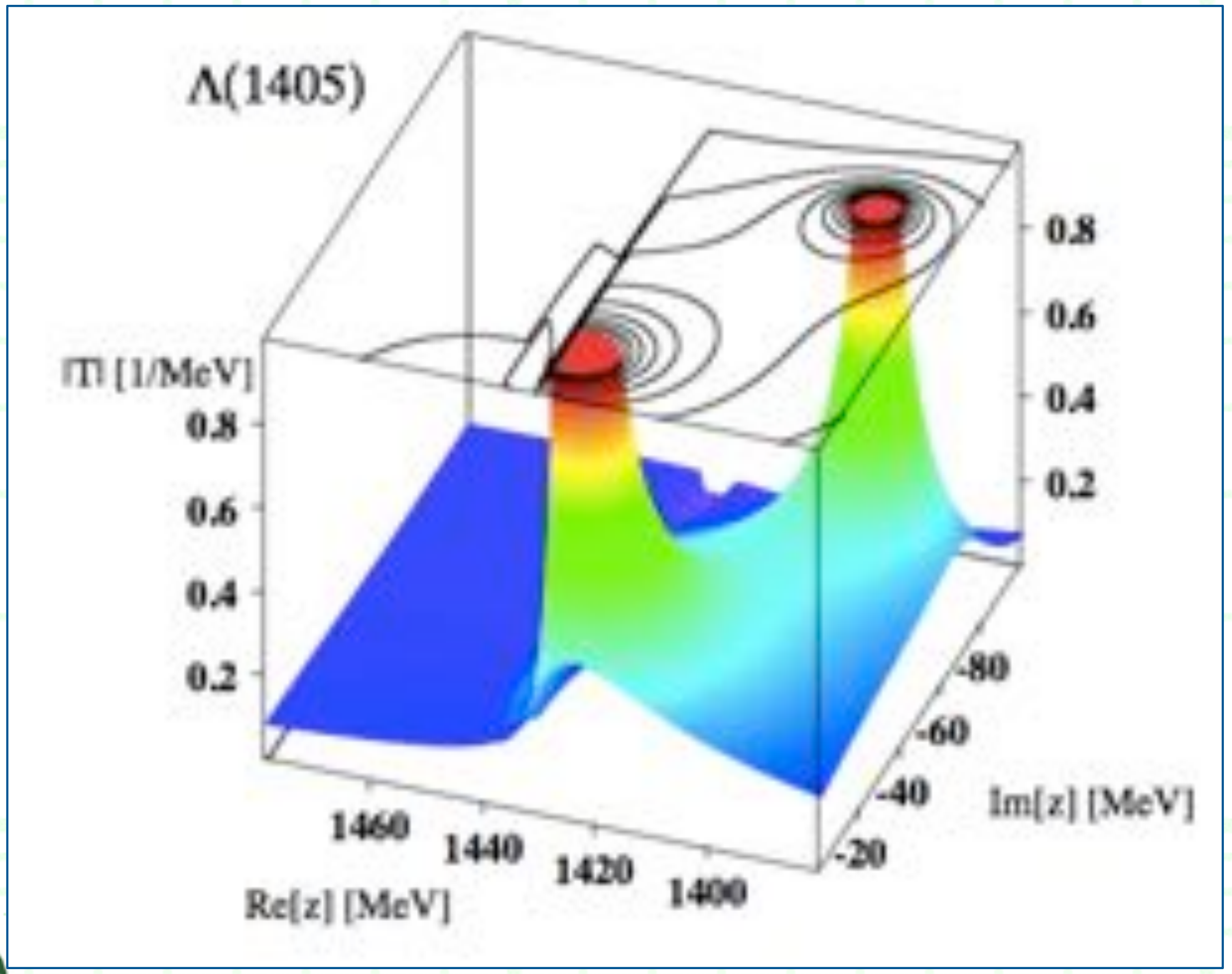
++ Resonance pole(s) of the $\Lambda(1405)$ ++

■ The pole structure of the $\Lambda(1405)$ resonance has been a hot topic in the $\bar{K}$ physics.

☐ Two poles ?

☐ The higher pole strongly couples to $\bar{K}N$?

☐ Where is the lower pole ?



Hyodo and Jido, Prog. Part. Nucl. Phys. 67 (2012) 55.

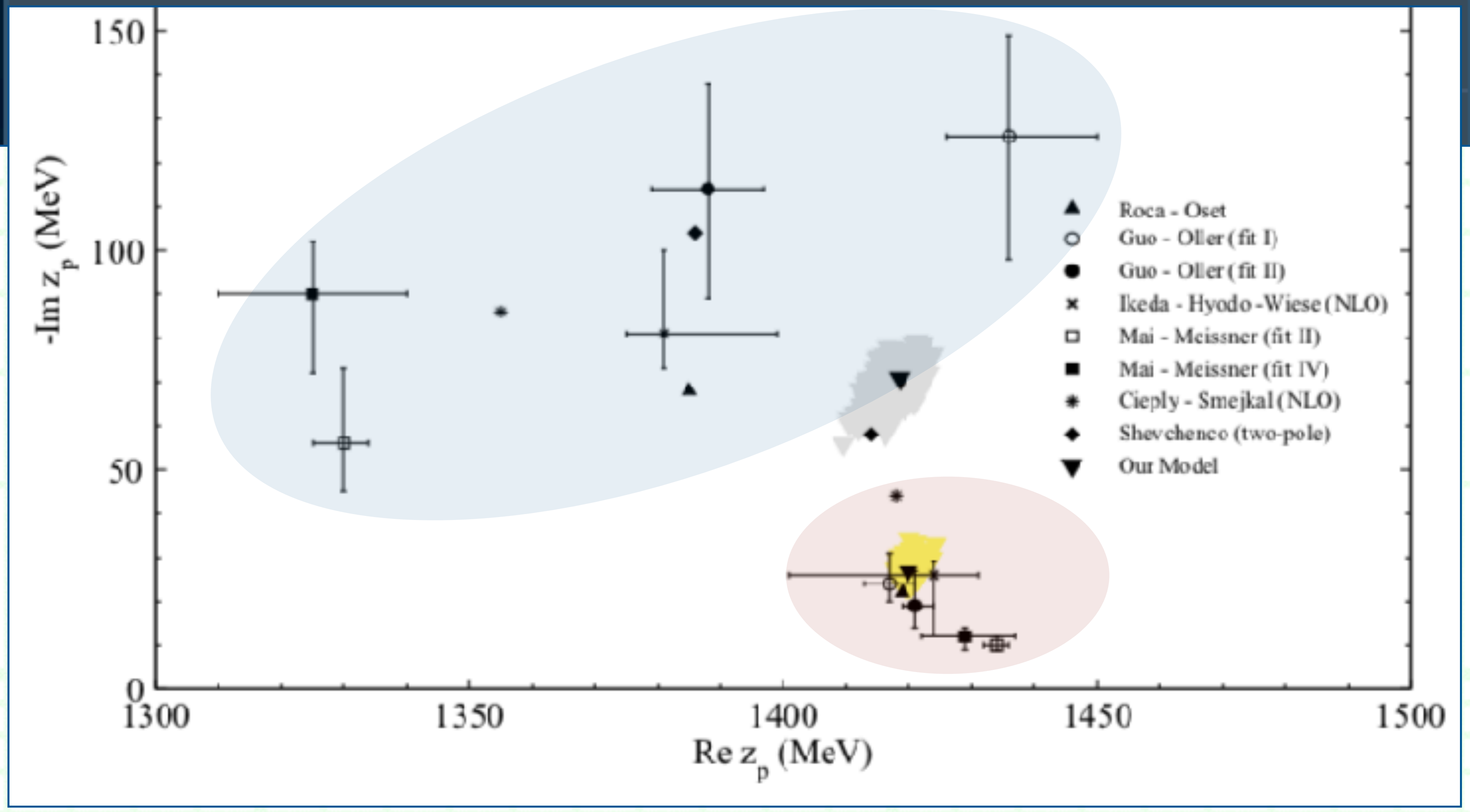
Resonance pole in the scattering Amp.

PDG Live.

Λ BARYONS ($S = -1$, $I = 0$)

$\Lambda^0 = u\,d\,s$

Λ and Σ Resonances			PDF
Pole Structure of the Λ(1405) Region			PDF
Λ	$1/2^+$	****	
Λ(1380)	$1/2^-$	**	
Λ(1405)	$1/2^-$	****	



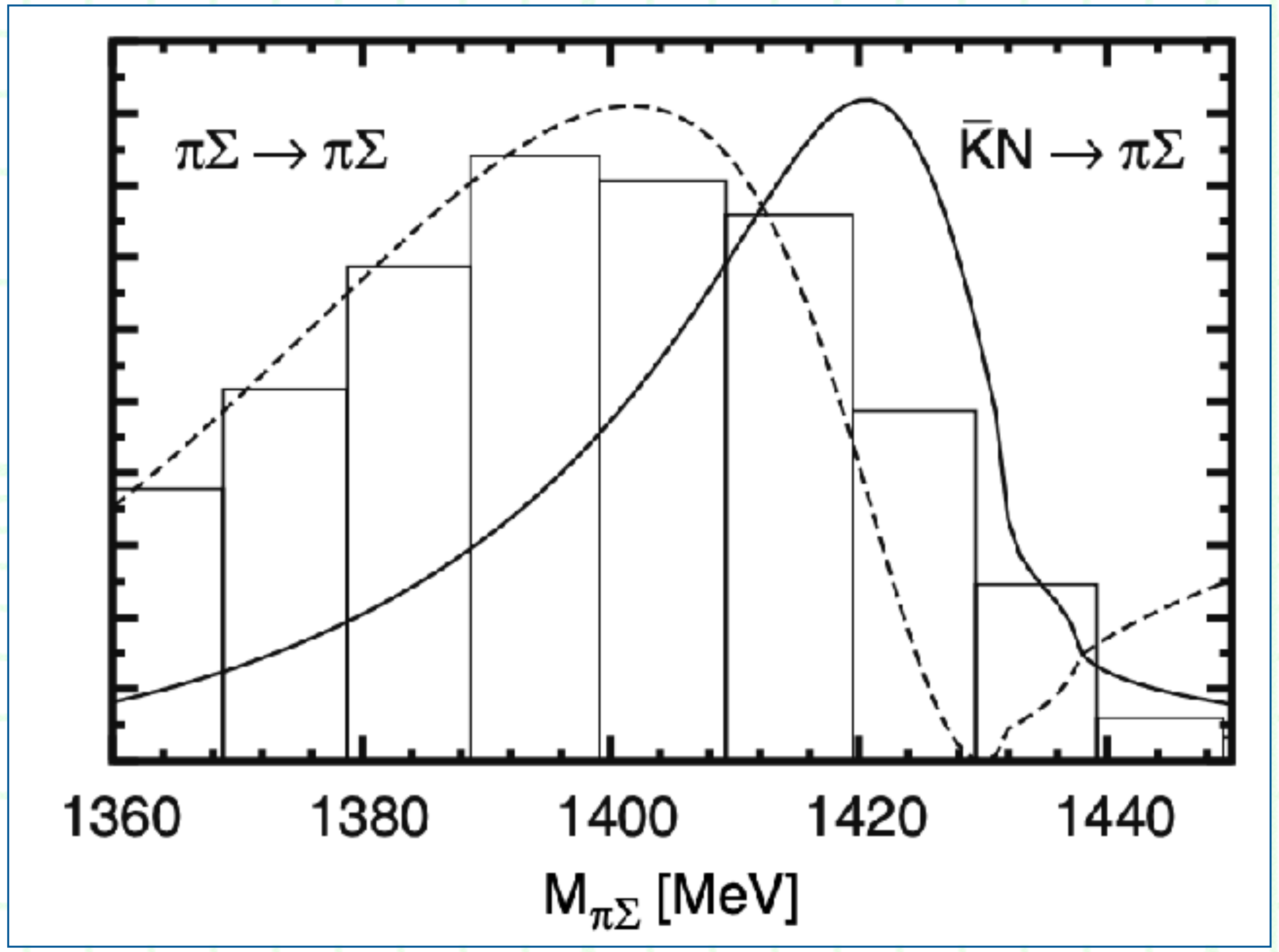
Feijoo, Magas and Ramos, Phys. Rev. C99 (2019) 035211.

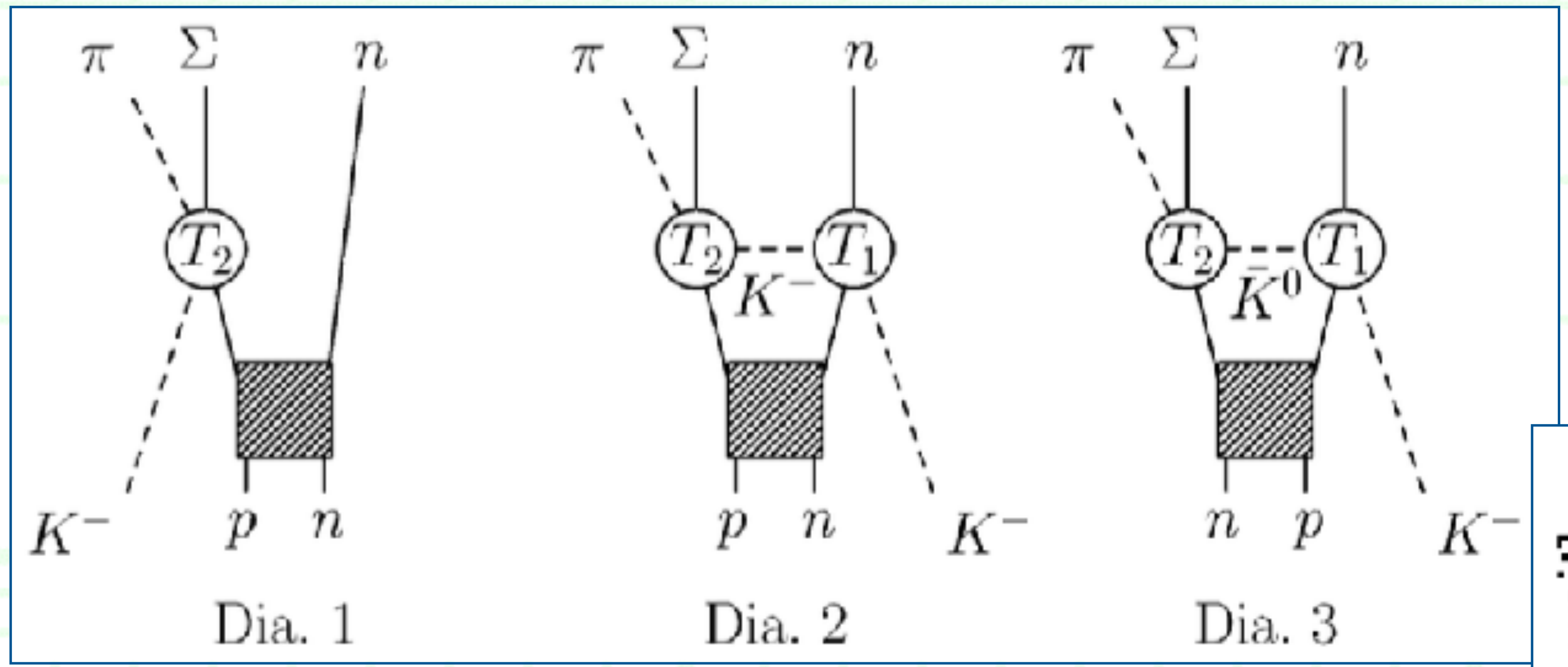
2. The $\bar{K}N$ system in $K^- d \to \pi\Sigma n$

++ Resonance pole(s) of the $\Lambda(1405)$ ++

- To elucidate the $\Lambda(1405)$ pole structure, the $\Lambda(1405)$ production directly from the $\bar{K}N$ channel was proposed.

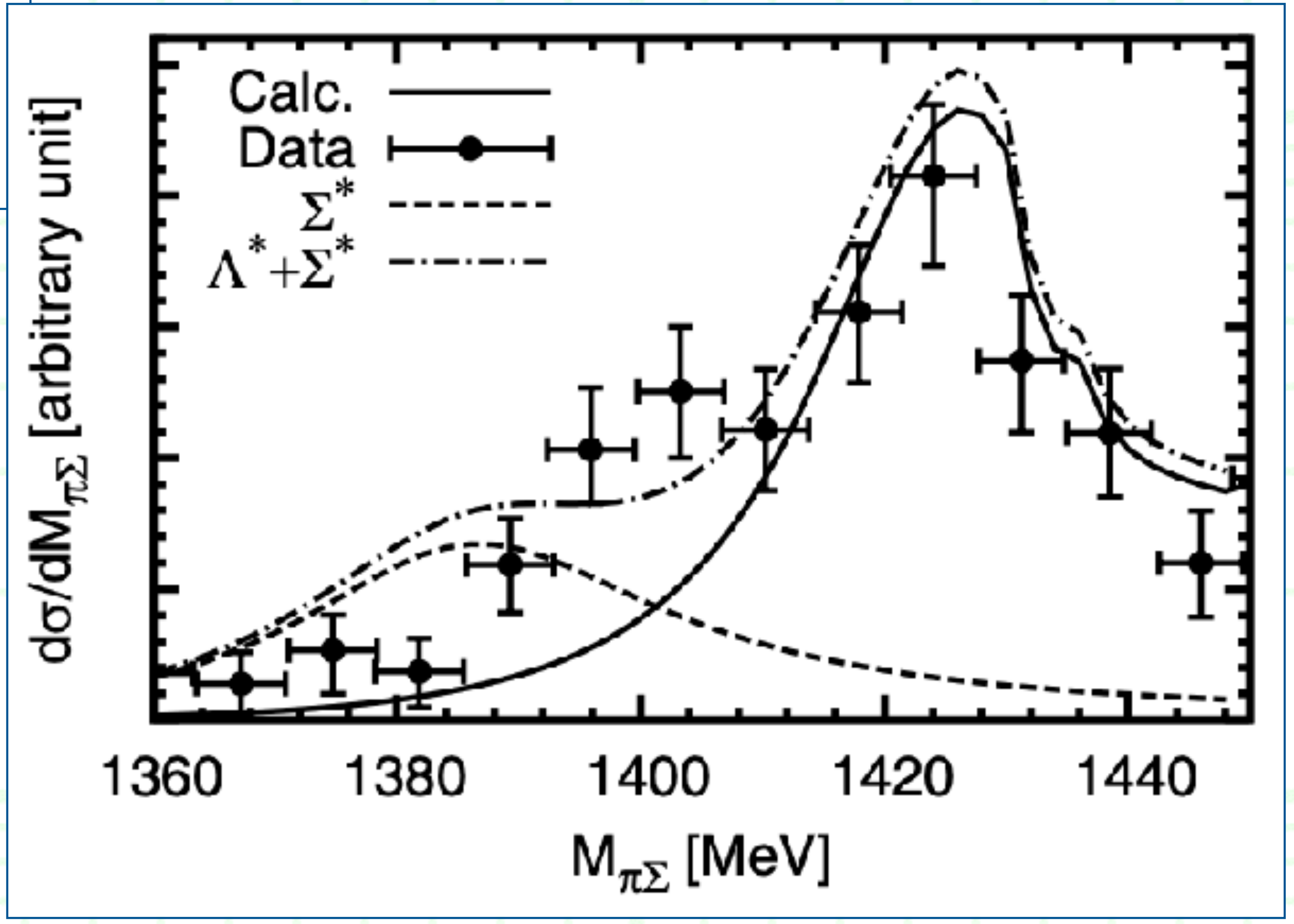
–> The $K^- d \to \pi\Sigma n$ reaction is the best way. D. Jido, E. Oset, and T. S. , Eur. Phys. J. A42 (2009) 257.





$p_K = 800\,\mathrm{MeV}/c$

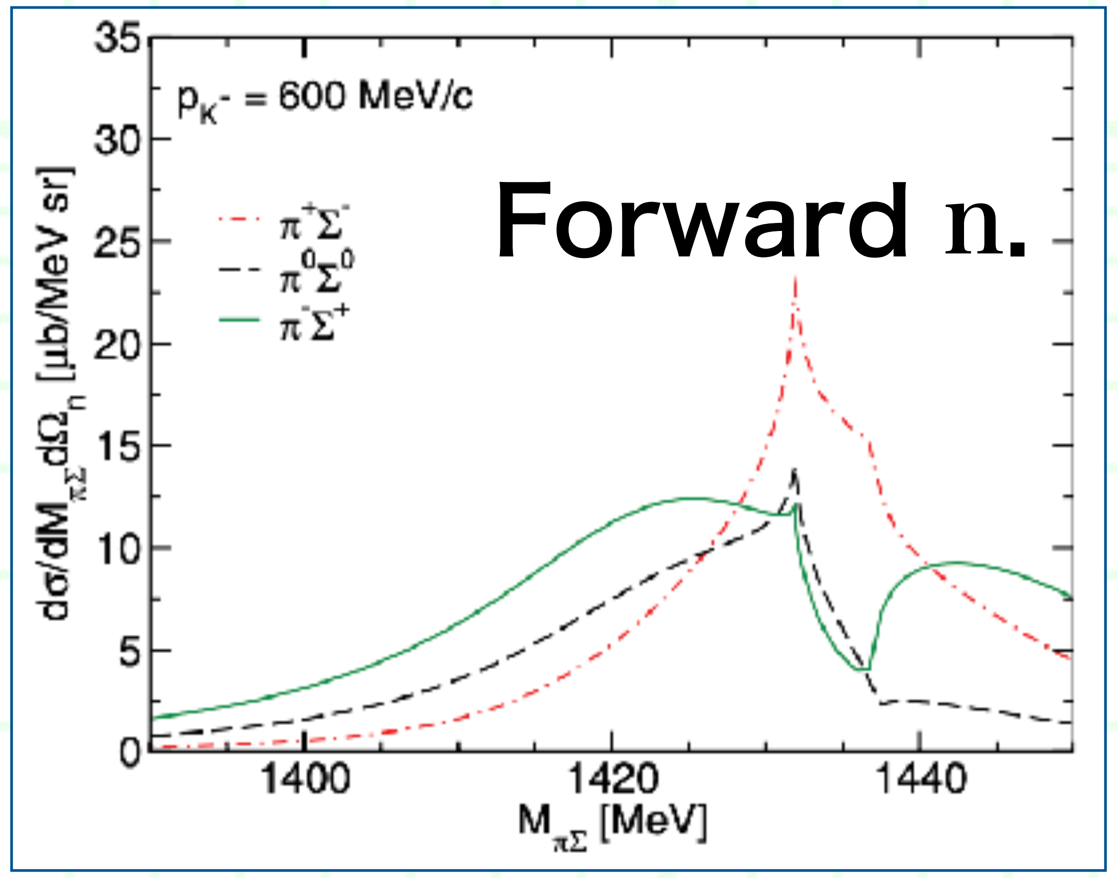
Whole angles.



2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ The $K^- d \to \pi \Sigma n$ reaction ++

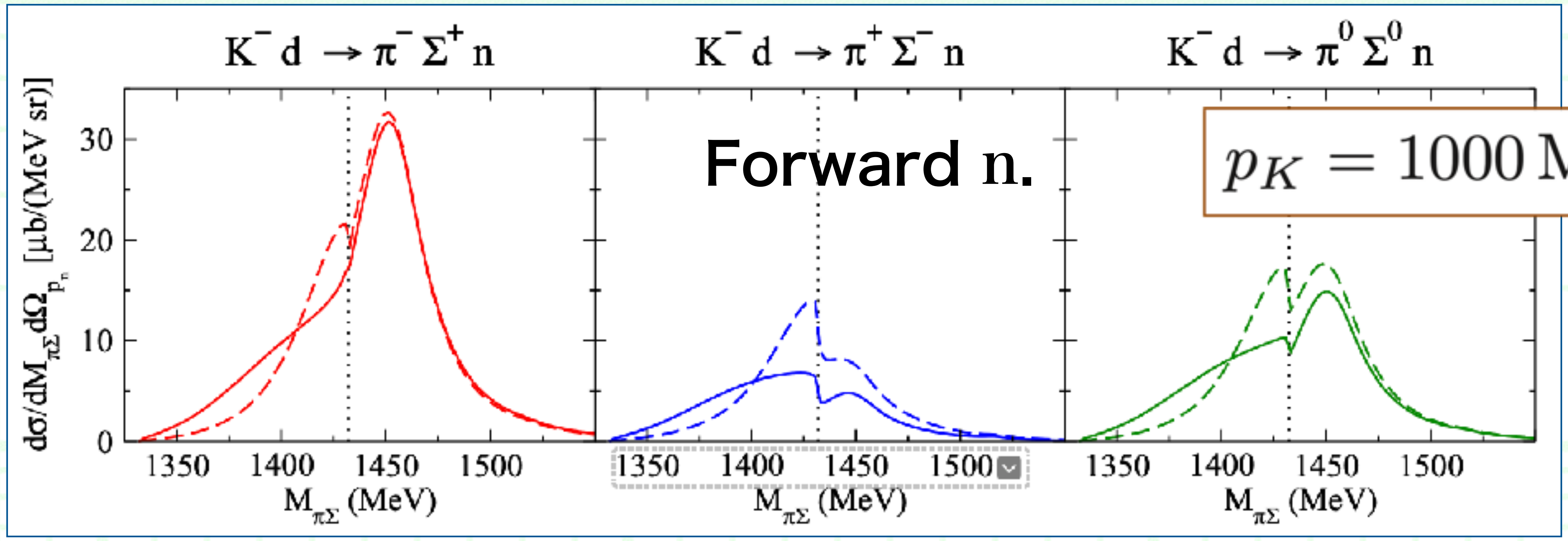
■ Preceding theoretical studies on the $K^- d \to \pi \Sigma n$ reaction.



Forward n.

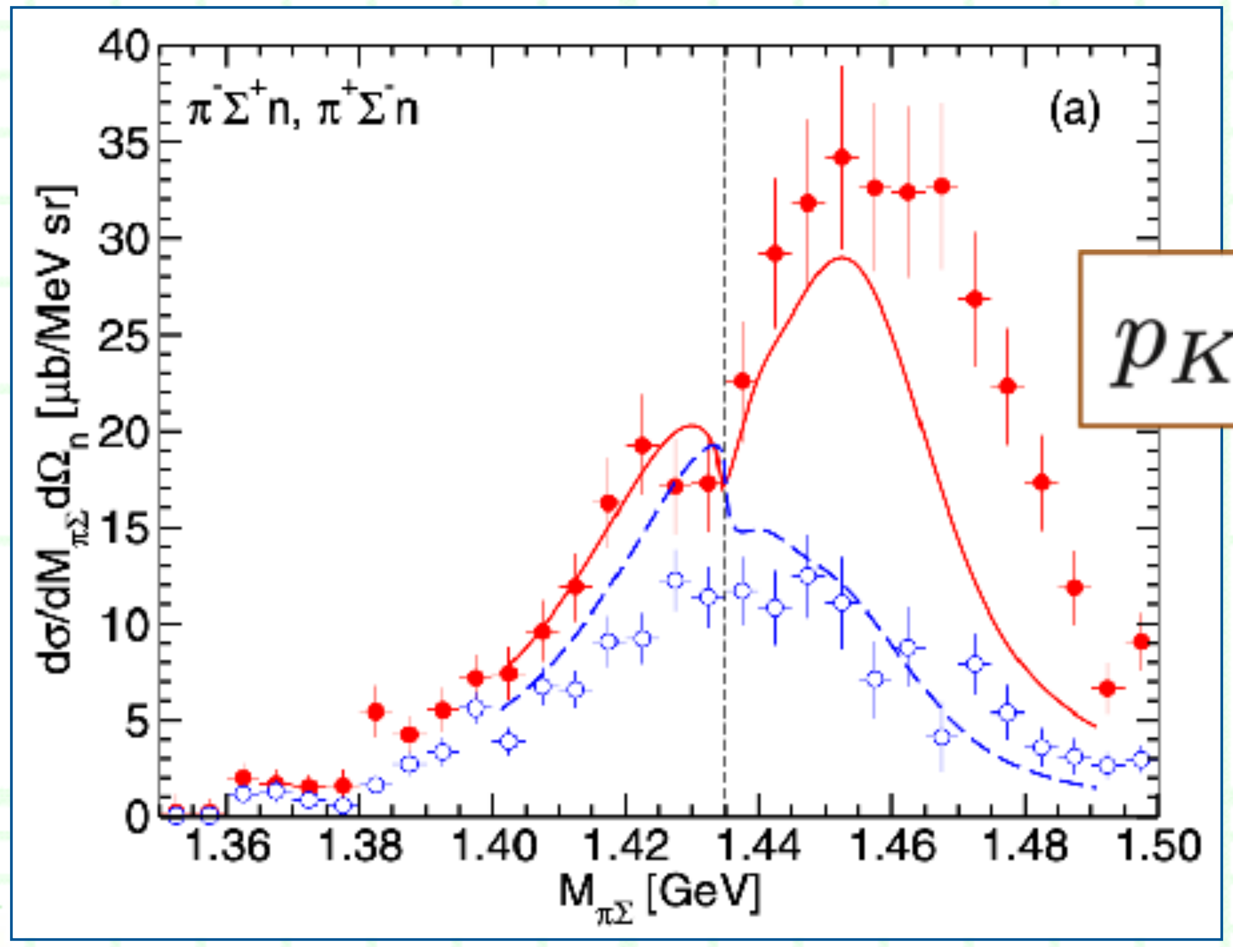
Miyagawa and Haidenbauer (2012).

Kamano and Lee (2016).



Forward n.

$p_K = 1000\,\mathrm{MeV}/c$

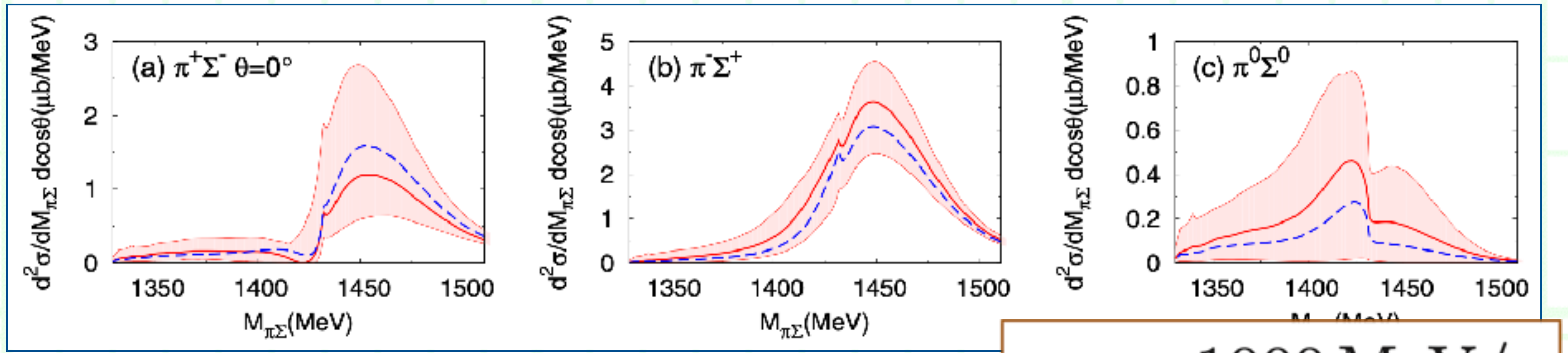


$p_K = 1000\,\mathrm{MeV}/c$

Forward n.

Miyagawa, Haidenbauer, and Kamada (2018).

Ohnishi, Ikeda, Hyodo, and Weise (2016).



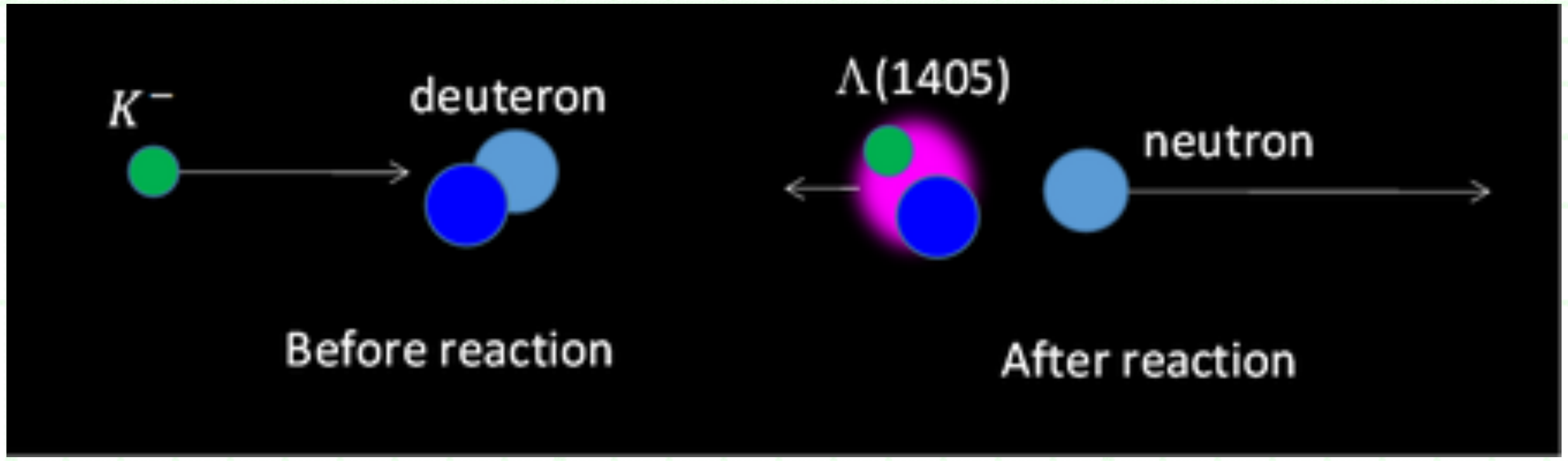
$p_K = 1000\,\mathrm{MeV}/c$

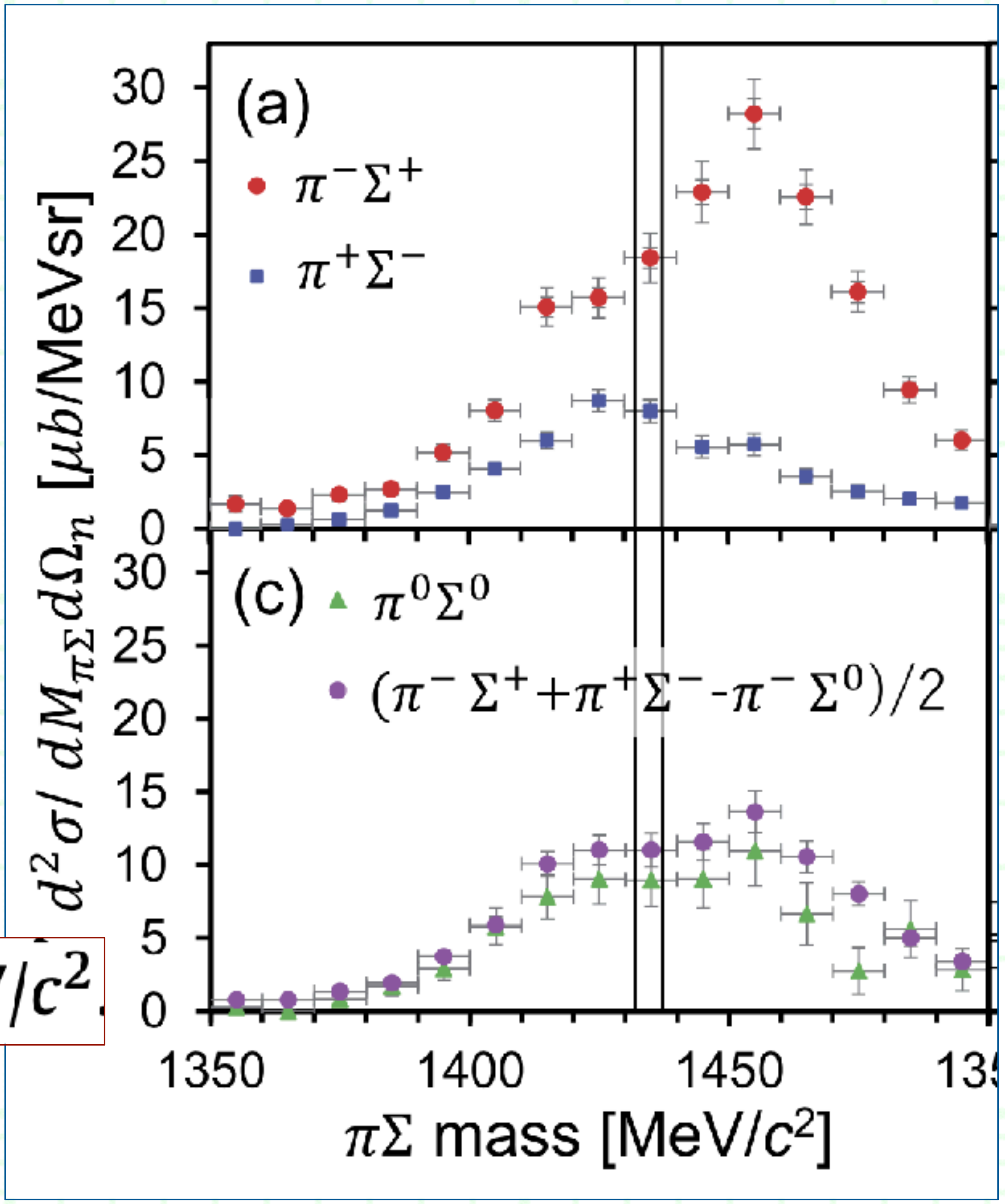
2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ J-PARC E31 Exp. for the $\bar{K}N$ system ++

■ The J-PARC E31 Exp. was performed to produce the $\Lambda(1405)$ resonance from the $\bar{K}N$ channel in the $K^- d \to \pi \Sigma n$ reaction.

J-PARC
press release.





□ J-PARC E31 Exp. analysis suggests:

$$1417.7^{+6.0}_{-7.4}(\text{fit})^{+1.1}_{-1.0}(\text{syst.}) + [-26.1^{+6.0}_{-7.9}(\text{fit})^{+1.7}_{-2.0}(\text{syst.})]i \ \text{MeV}/c^2$$

J-PARC E31 Collab., Phys. Lett. B837 (2023) 137637.

2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ Our calculation ++

■ We calculate the cross section of the $K^- d \to \pi \Sigma n$ reaction.

J. Yamagata-Sekihara, T. S. , and D. Jido, under discussion.

☐ Angular (= momentum transfer q_{trans}) dependence ?

$\mathbf{q}_{\rm trans} = \mathbf{p}_K - \mathbf{p}_n$ at Lab. frame

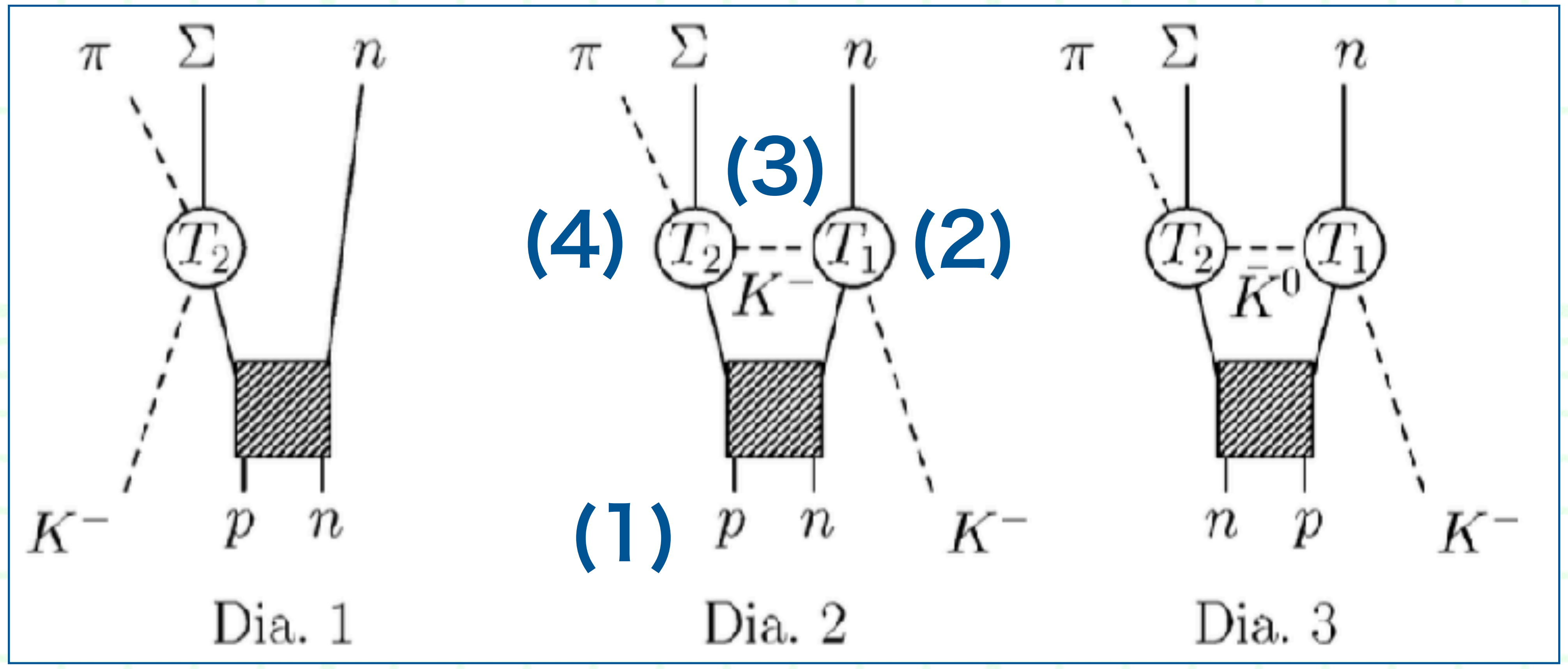
☐ Contribution from each component of the reaction diagram ?

(1) Deuteron wave function.

(2) 1st step T_1 ($\bar{K}N \to \bar{K}N$, P_K = 1 GeV/c).

(3) $\bar{K}$ propagator.

(4) 2nd step T_2 ($\bar{K}N \to \pi \Sigma$).



–> We aim to construct a precise model to determine the pole position of the $\Lambda(1405)$ in the complex energy plane.

2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ Deuteron wave function & $\bar{K}$ propagator ++

■ Deuteron wave function.

☐ Taken from the CD-Bonn potential (s wave only, ∼ 95 %): Small uncertainty.

Machleidt, Phys. Rev. C63 (2011) 024001.

■ Together with the $\bar{K}$ propagator, the scattering Amp. becomes:

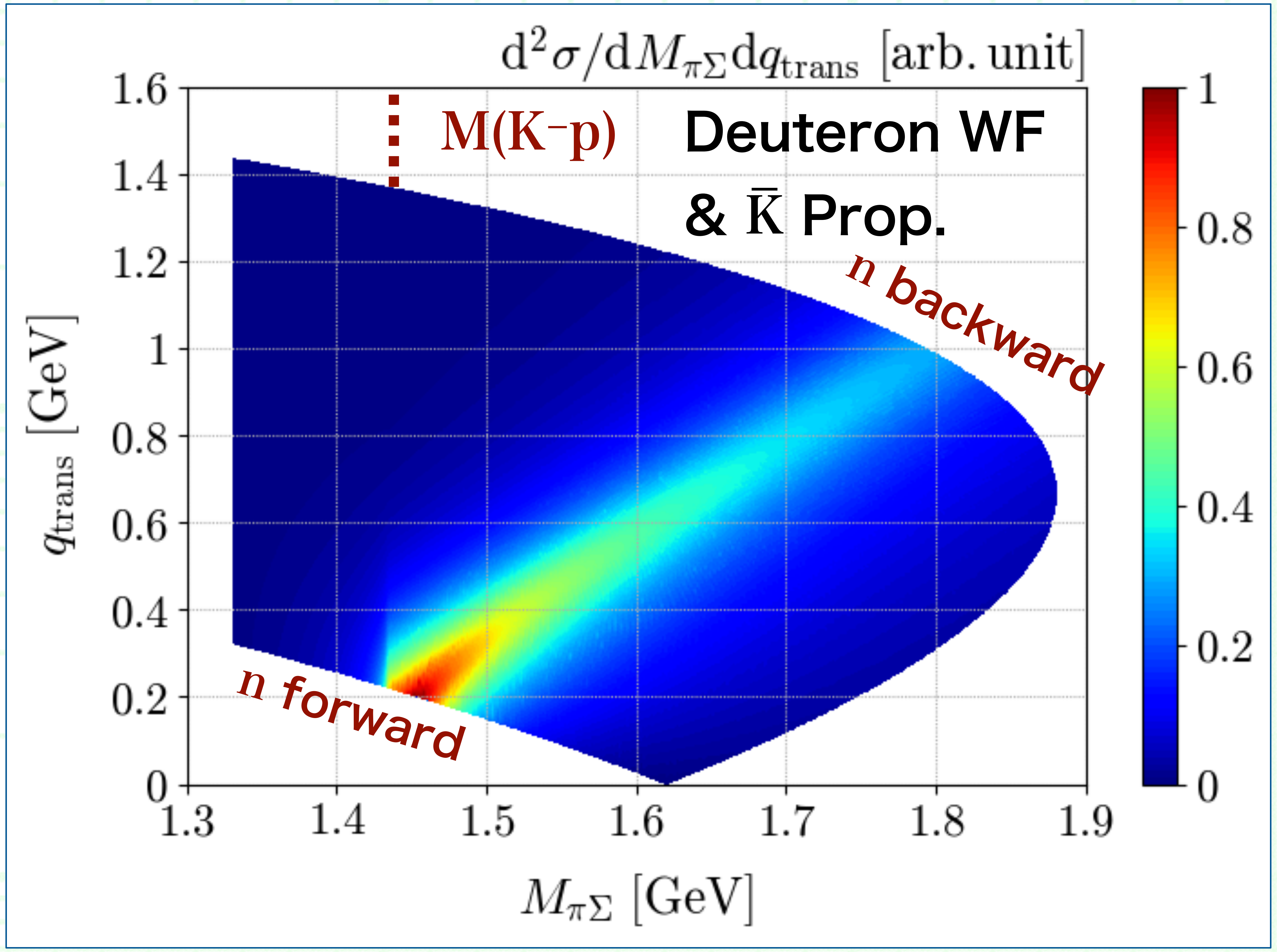
$$\mathrm{Amp.} = \int \frac{d^3 q_{\mathrm{ex}}}{(2\pi)^3} \frac{\varphi_{\mathrm{deut}}(|\mathbf{q}_{\mathrm{ex}} - \mathbf{q}_{\mathrm{trans}}|)}{{q_{\mathrm{ex}}}^2 - {m_K}^2 + i0}$$

$$\mathbf{q}_{\mathrm{trans}} = \mathbf{p}_K - \mathbf{p}_n$$

☐ Band width owing to the deuteron WF.

— Off-shell N inside the deuteron.

☐ On this band, we may treat the propagating $\bar{K}$ as (almost) on-shell particle.



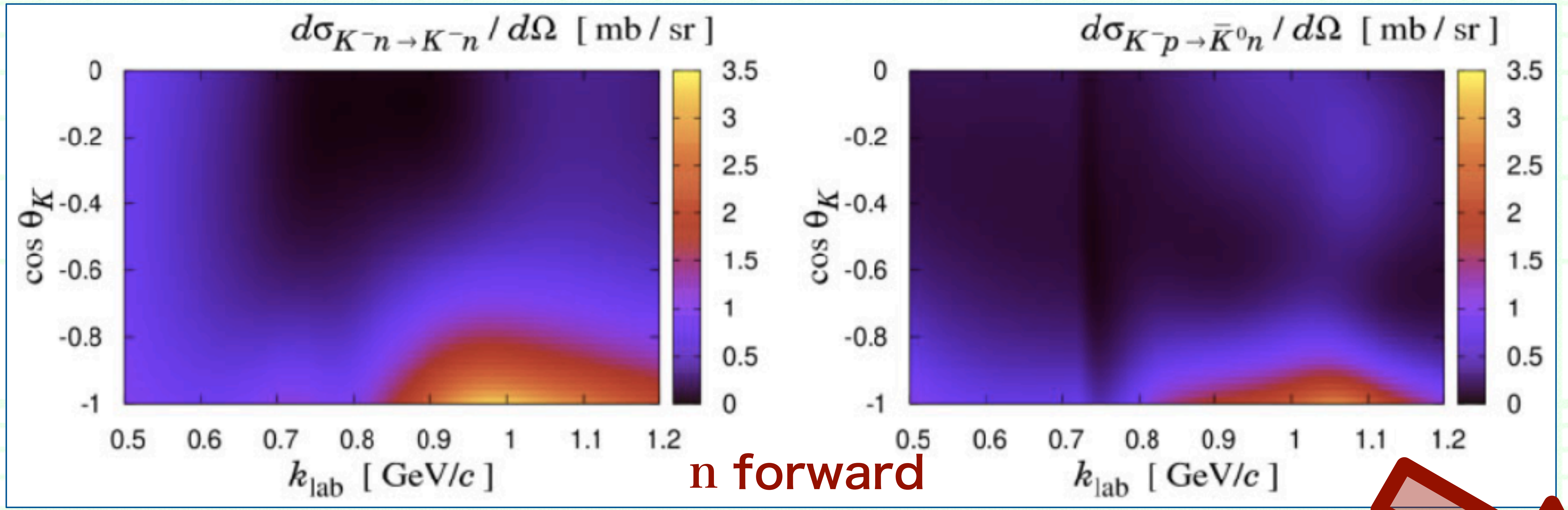
2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ & the 1st step $\bar{K}N \to \bar{K}N$ ++

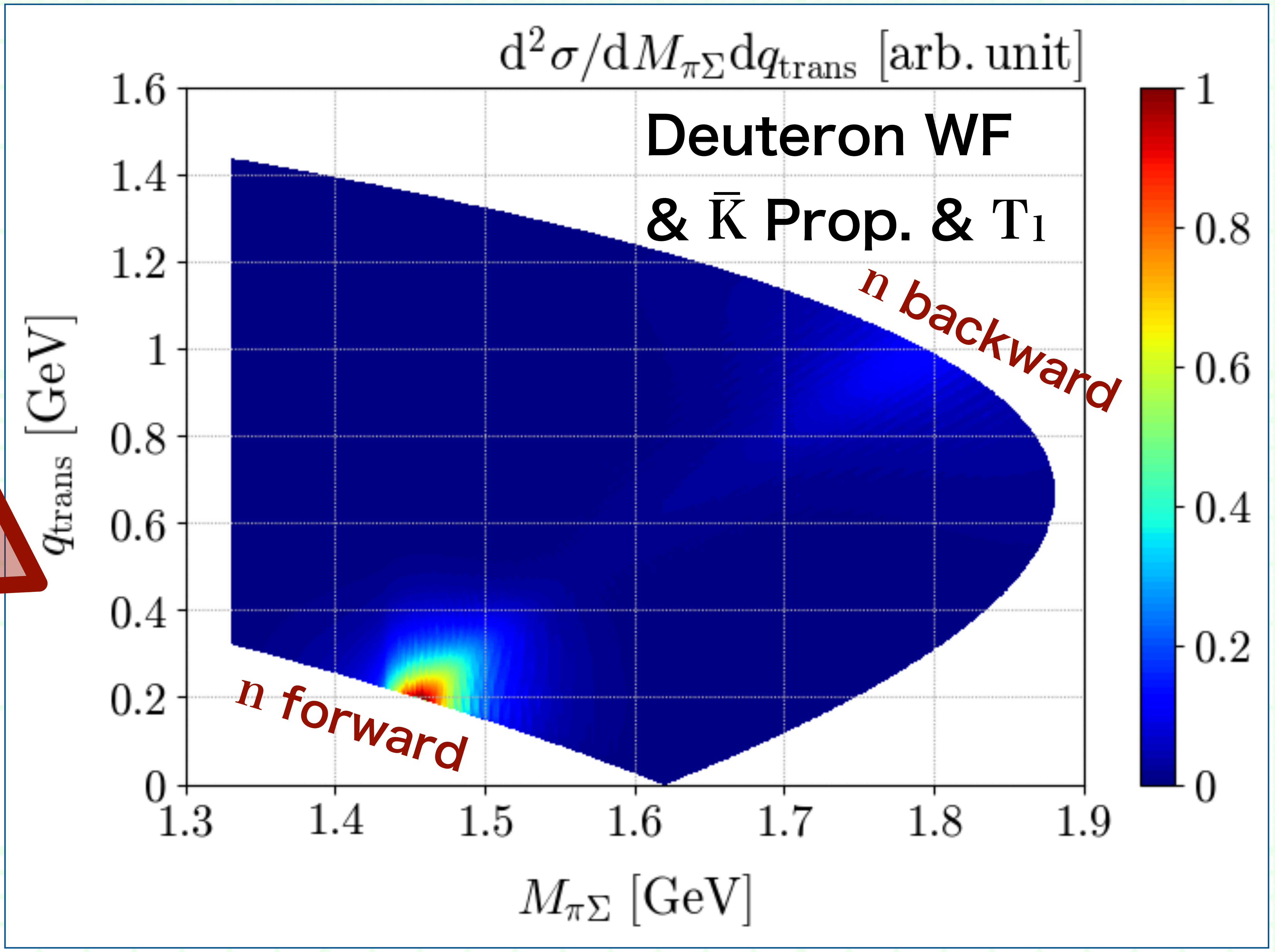
■ Inclusion of the 1st step T_1 ($\bar{K}N \to \bar{K}N$, P_K = 1 GeV/c).

–> Employ the Kamano et al. on-shell amplitude.

Kamano, Nakamura, Lee, and Sato, Phys. Rev. C90 (2014) 065204.



$$\mathrm{Amp.} = \int \frac{d^3 q_{\rm ex}}{(2\pi)^3} \frac{\varphi_{\rm deut}(|\mathbf{q}_{\rm ex} - \mathbf{q}_{\rm trans}|)}{{q_{\rm ex}}^2 - {m_K}^2 + i0} T_1^{(\mathrm{Kamano})}$$



□ Dominated by the small momentum transfer region $q_{\rm trans} < 0.4$ GeV.

2. The $\bar{K}N$ system in K^- d –> $\pi\,\Sigma\,$n

++ & the 2nd step $\bar{K}N$ –> $\pi\,\Sigma$ ++

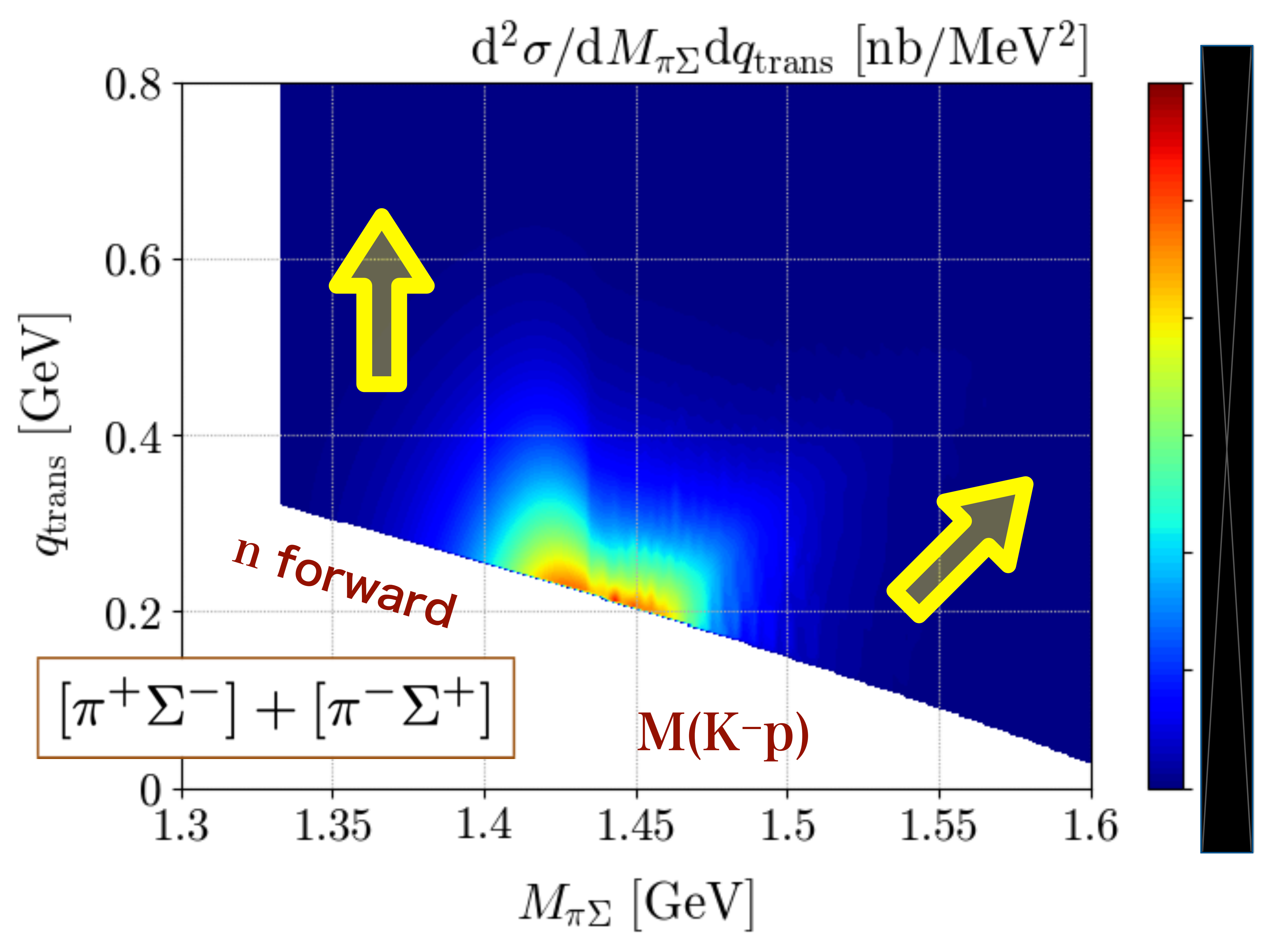
■ **Inclusion of the 2nd step T_2 ($\bar{K}N$ –> $\pi\,\Sigma$).**

–> Employ the Ikeda-Hyodo-Weise amplitude, which contains the $\Lambda(1405)$.

Ikeda, Hyodo, and Weise, Nucl. Phys. A881 (2012) 98.

$$\mathrm{Amp.} = \int \frac{d^3 q_{\mathrm{ex}}}{(2\pi)^3} \frac{\varphi_{\mathrm{deut}}(|\mathbf{q}_{\mathrm{ex}} - \mathbf{q}_{\mathrm{trans}}|)}{{q_{\mathrm{ex}}}^2 - {m_K}^2 + i0} T_1^{(\mathrm{Kamano})} T_2^{(\mathrm{IHW})}$$

–> Full calculation.



□ We have two trends.

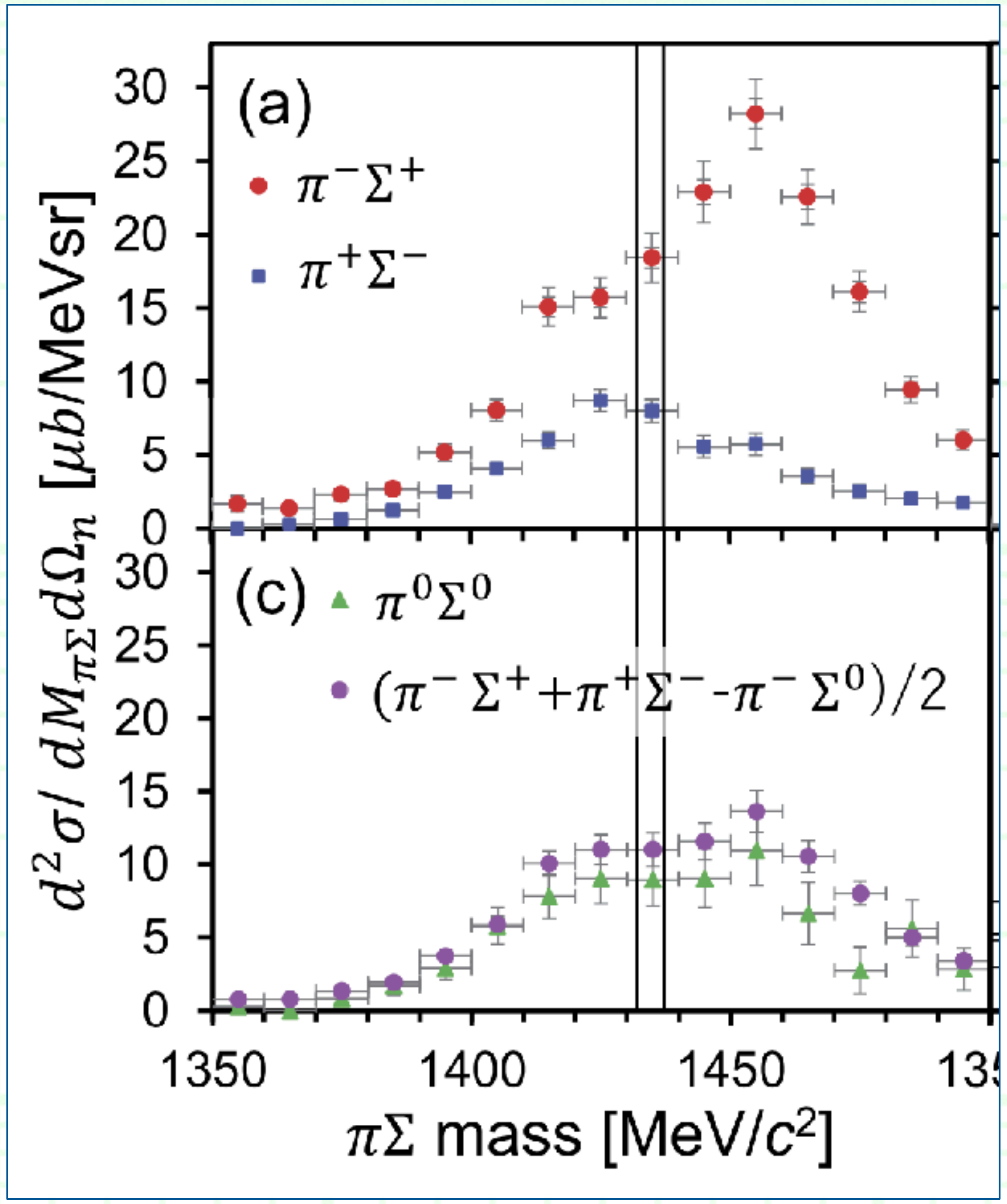
- Below the $\bar{K}N$ threshold:
  The $\Lambda(1405)$ signal.
- Above the $\bar{K}N$ threshold:
  The quasi-free $\bar{K}$ propagation.

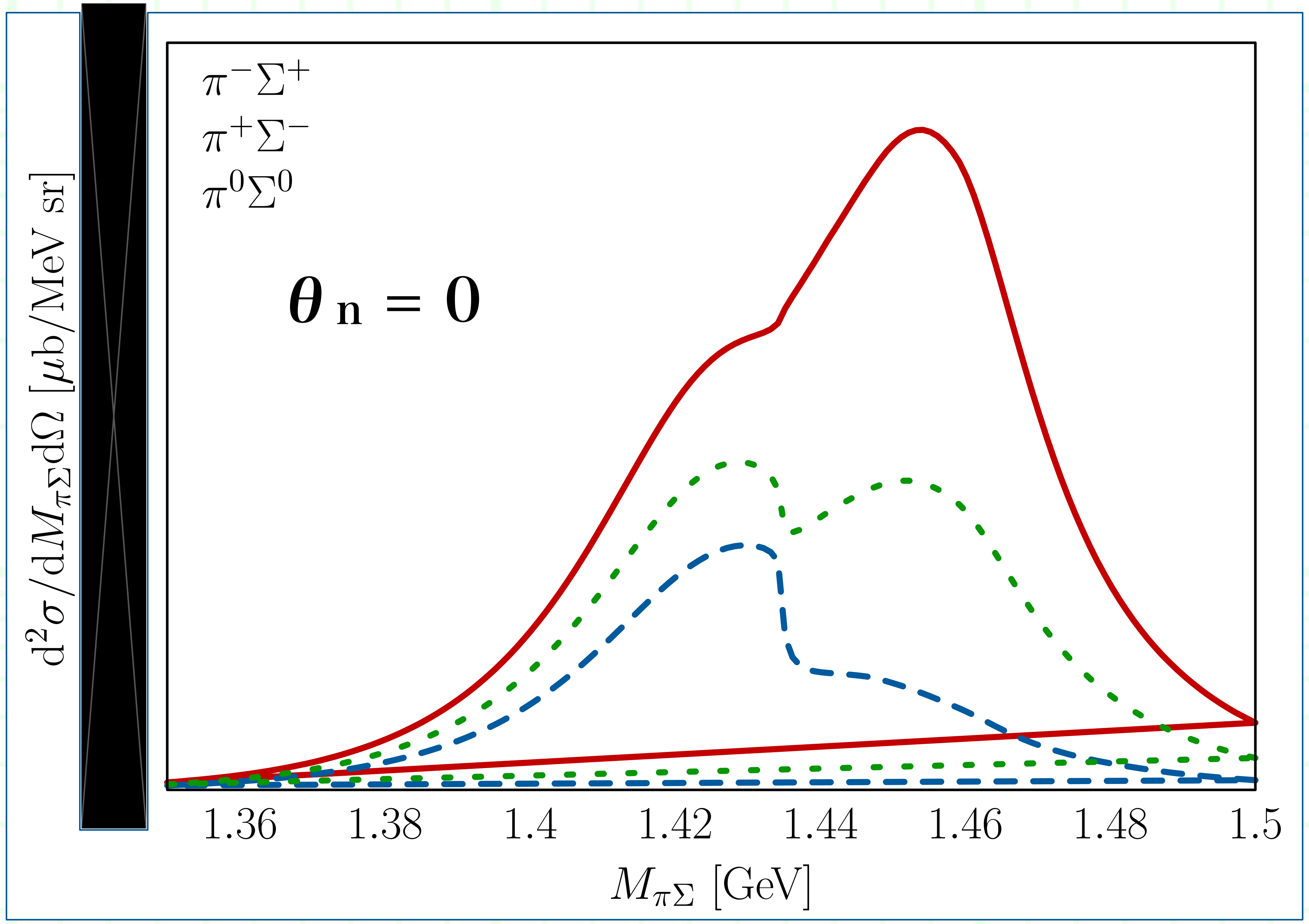
2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ Spectrum at the forward n ++

- We can compare the $\pi\Sigma$ spectrum at the forward n condition with the Exp. data.

J-PARC E31 Collab., Phys. Lett. B837 (2023) 137637.





- Quite similar shapes, although the peak heights are quantitatively different.

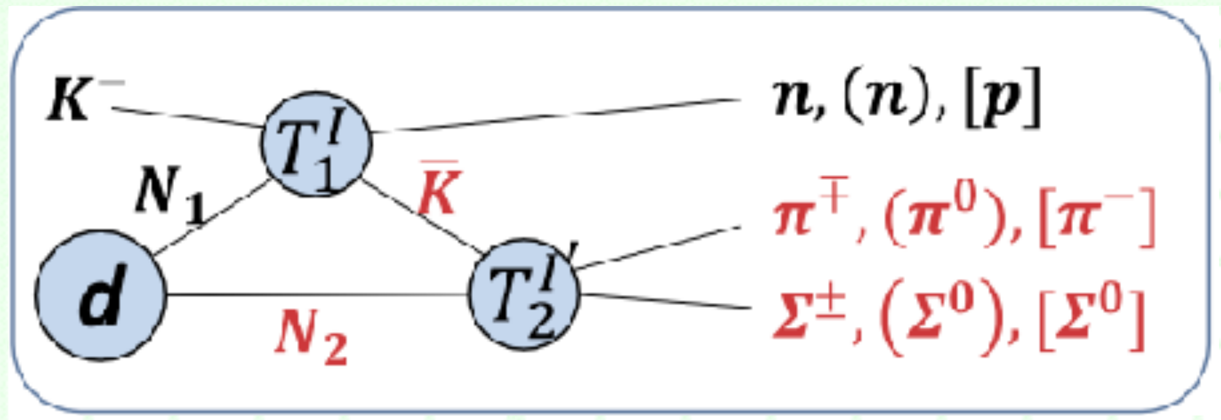
2. The $\bar{K}N$ system in $K^- d \to \pi \Sigma n$

++ Summary and outlook ++

■ After all, what makes the structure in the $K^- d \to \pi \Sigma n$ reaction ?

☐ Deuteron wave function: Robust.

J-PARC E31 Collab., Phys. Lett. B837 (2023) 137637.

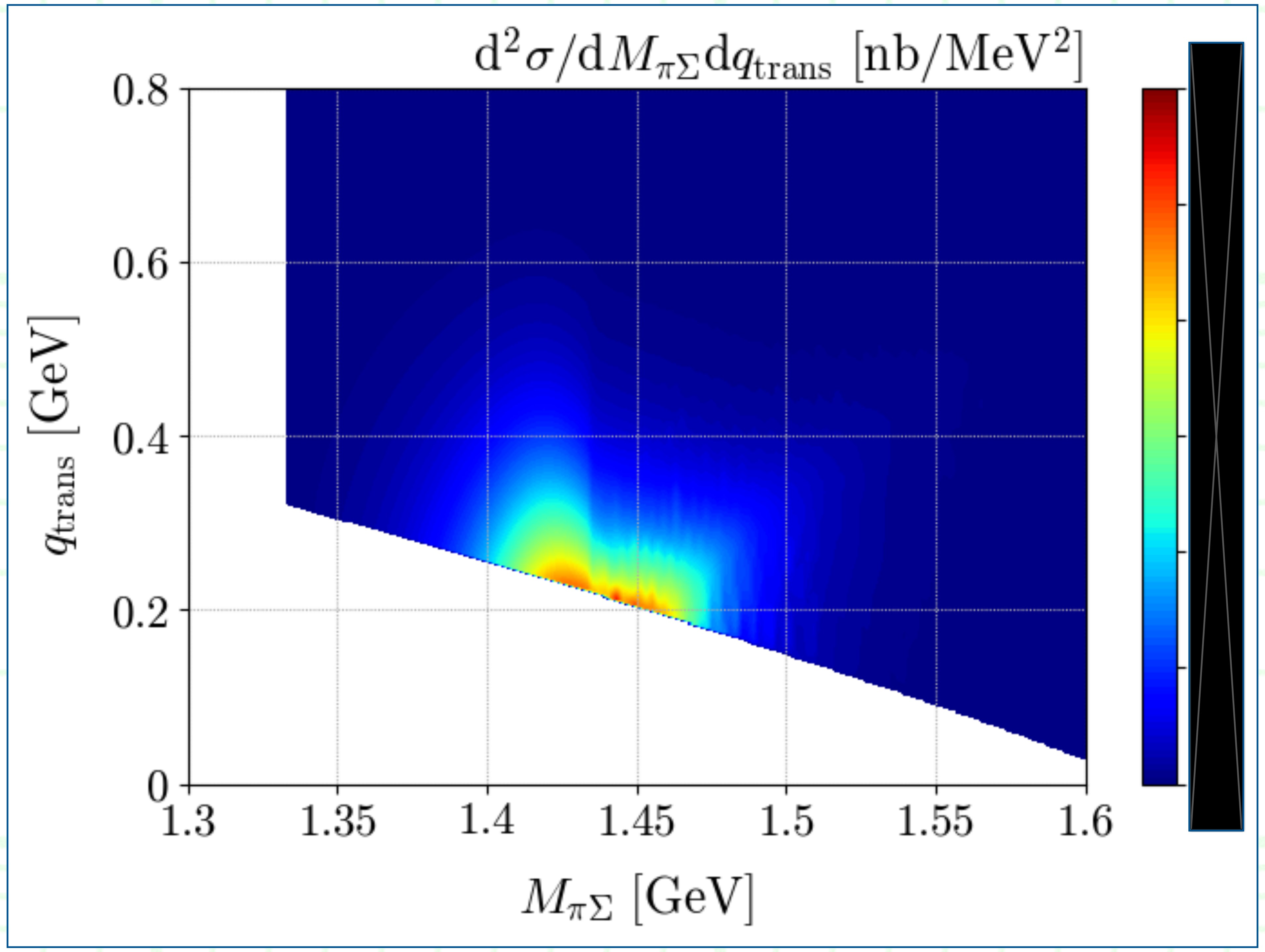


☐ $\bar{K}$ propagator × 1st step $T_1^{(\mathrm{Kamano})}$ (on-shell) : Fairly robust.

☐ 2nd step $T_2^{(\mathrm{IHW})}$ (contains $\Lambda(1405)$) : Fairly robust.

–> Double-step process makes the structure !

$\bar{K}$ survives the reaction.



■ Then, we can upgrade the reaction calculation.

☐ Final-state interaction ?

☐ Difference from the $\Sigma(1385)$ / $\Lambda(1520)$?

–> More precise properties of the $\Lambda(1405)$.

3. The $\bar{K}NN$ system in the $K^- \, {}^3He \to \Lambda \, p \, n$ reaction: J-PARC E15

3. The $\bar{K}NN$ system in $K^- \, {}^3He \to \Lambda pn$

++ J-PARC E15 Exp. for the $\bar{K}NN$ system ++

■ The J-PARC E15 Exp. was performed to search for the $\bar{K}NN$ bound state in the $K^- \, {}^3He \to \Lambda pn$ reaction.

Yamaga et al. [J-PARC E15], Phys. Rev. C102 (2020) 044002.

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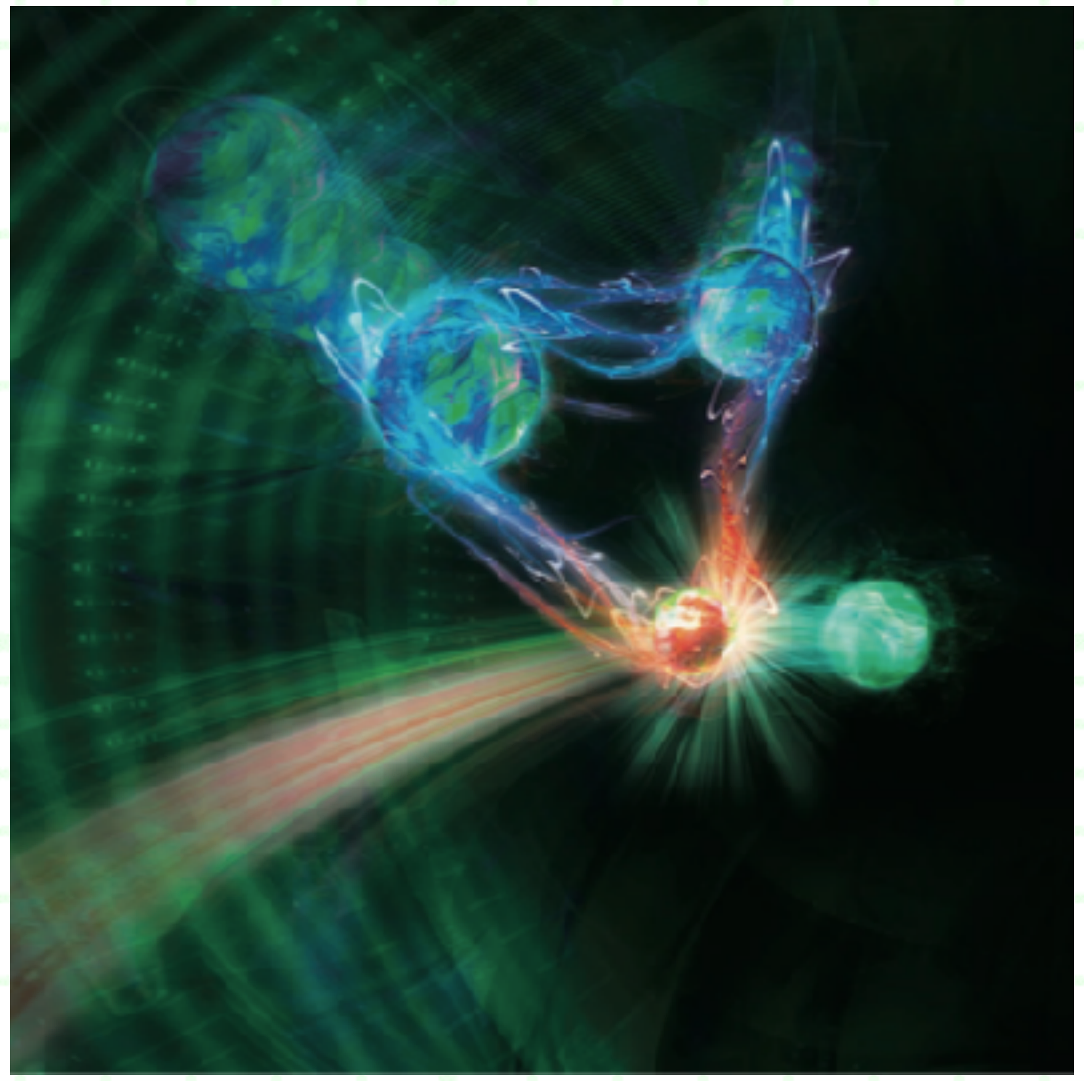
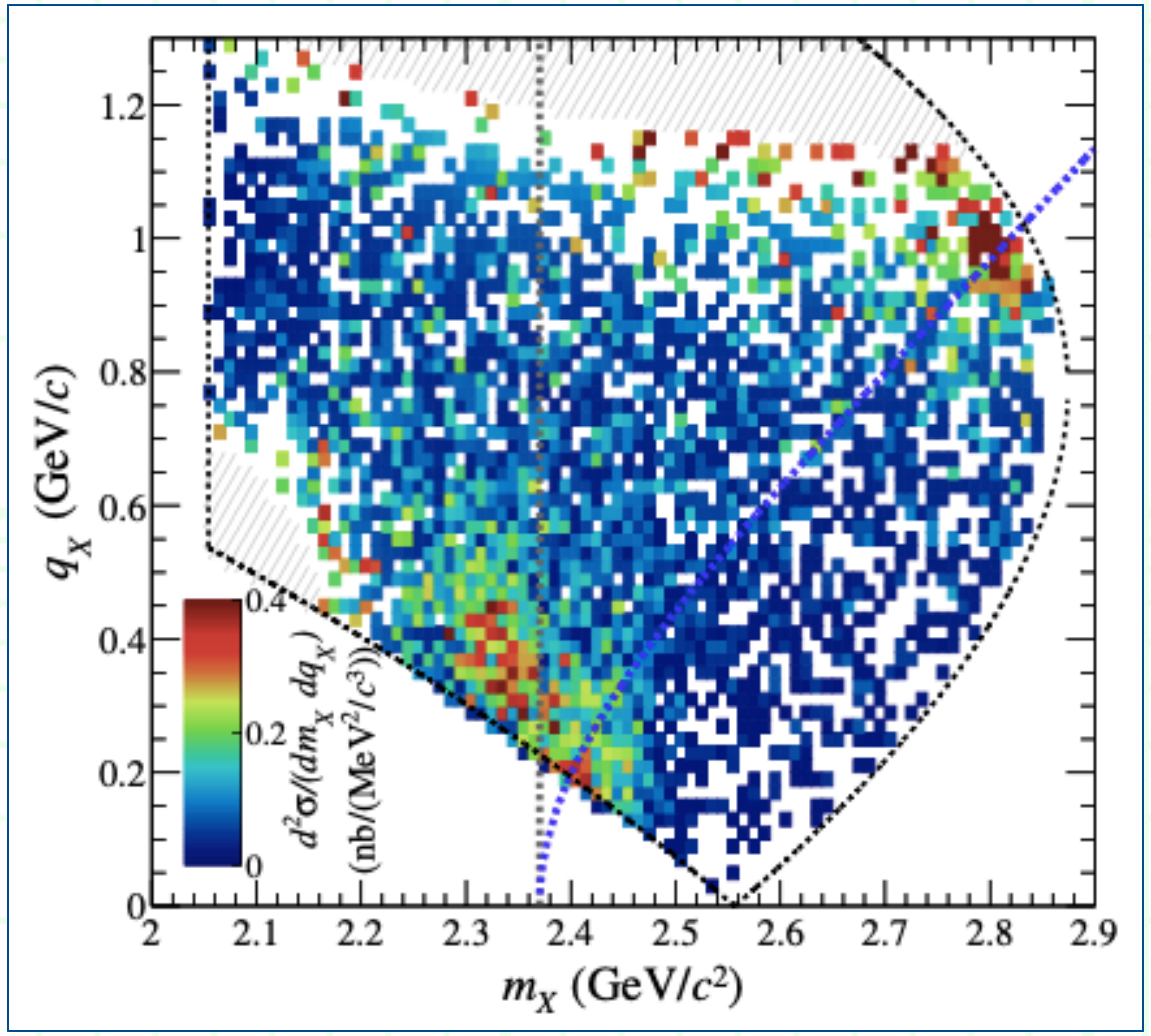
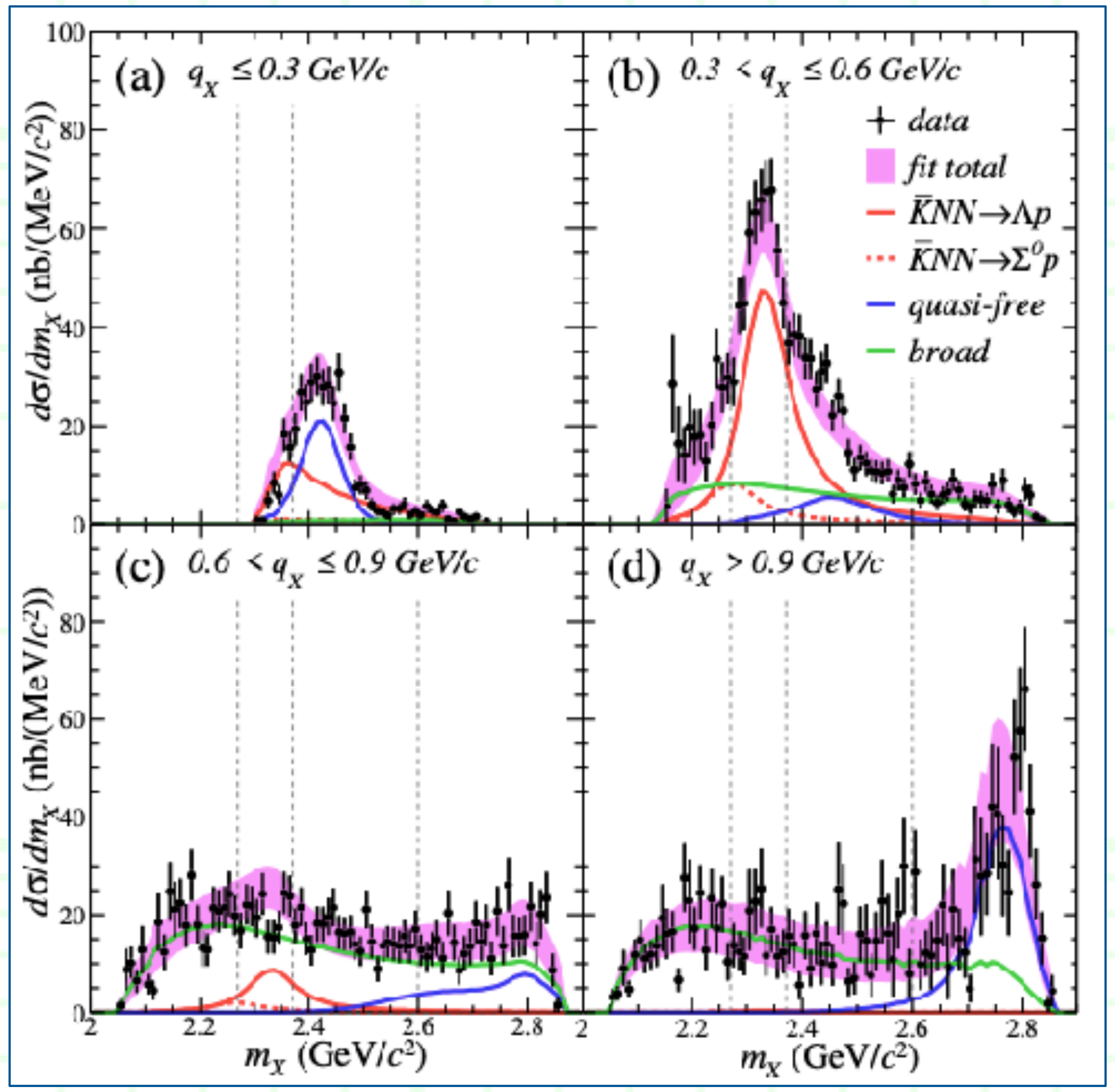


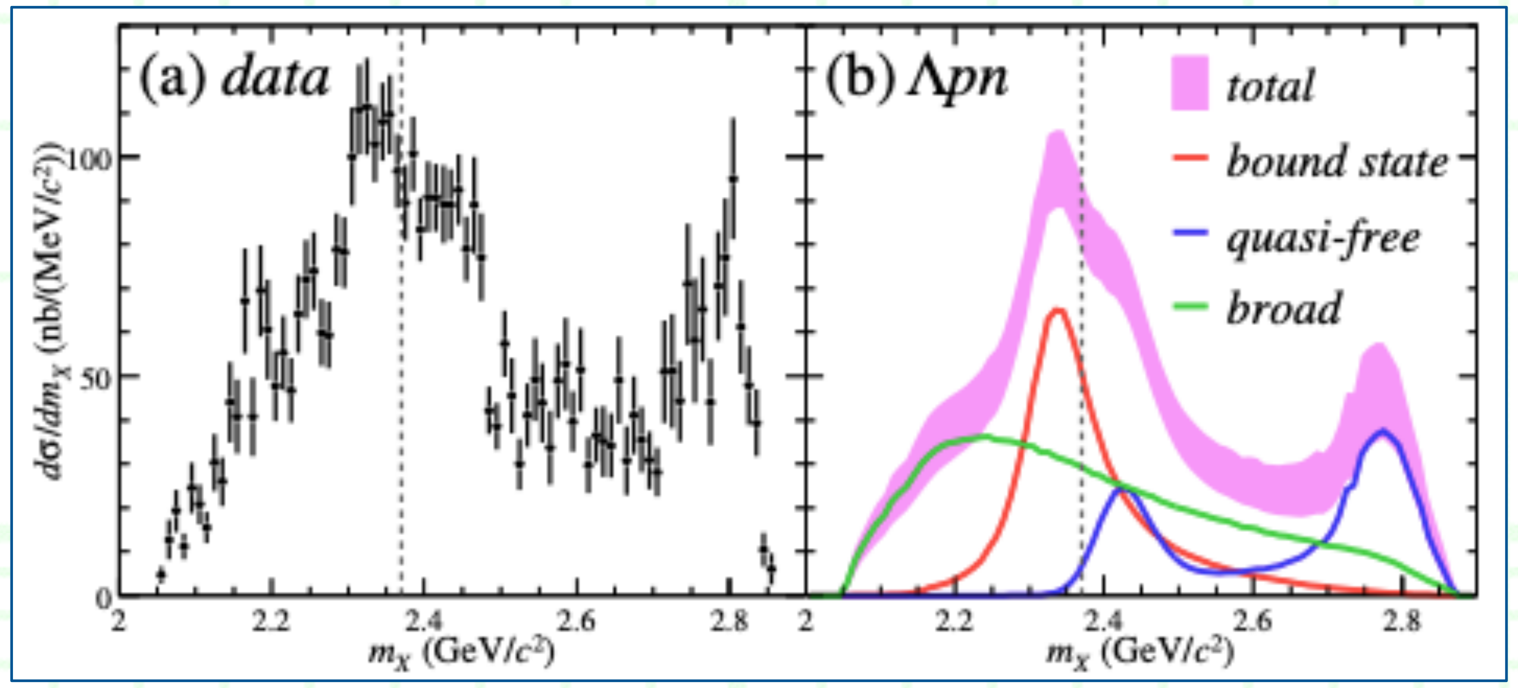
n

K^-

The Austrian Academy of Sciences, Harald Ritsch.







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

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

3. The $\bar{K}NN$ system in $K^- \, {}^3He \to \Lambda pn$

++ Our calculation ++

■ We calculate the cross section of the $K^- \, {}^3He \to \Lambda pn$ reaction.

T. S. , E. Oset, and A. Ramos, PTEP 2016 123D03; under discussion.

☐ Momentum transfer q_{trans} dependence ?

$$\mathbf{q}_{trans} = \mathbf{p}_K - \mathbf{p}_n \text{ at Lab. frame}$$

☐ Contribution from each component of the reaction diagram ?

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

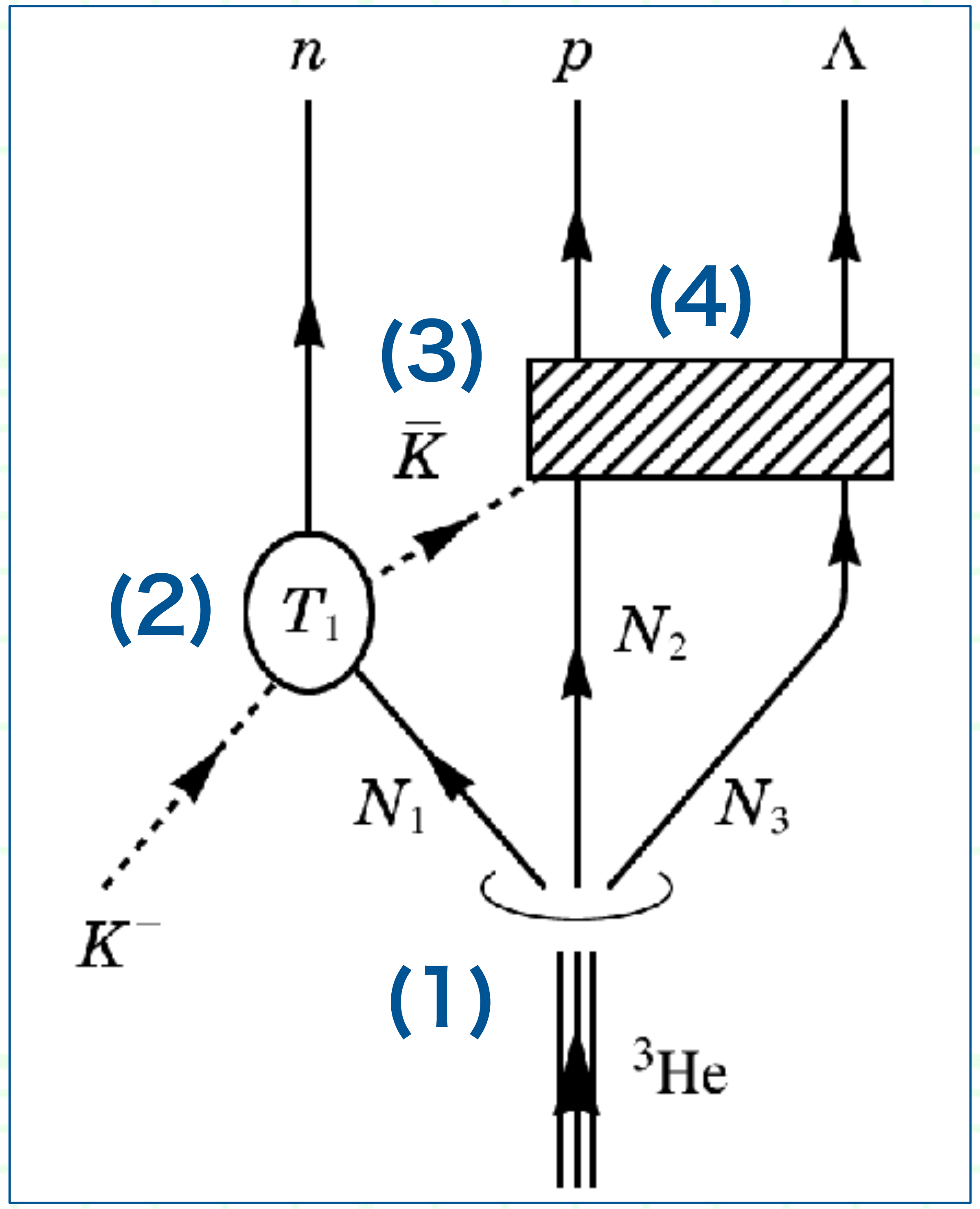
(2) 1st step T_1 ($\bar{K}N \to \bar{K}N$, P_K = 1 GeV/c).

(3) $\bar{K}$ propagator.

(4) Faddeev & $\bar{K}$ absorption $T(\bar{K}NN \to \Lambda p)$.

–> We aim to construct a precise model

to search for the $\bar{K}NN$ pole in the complex energy plane.

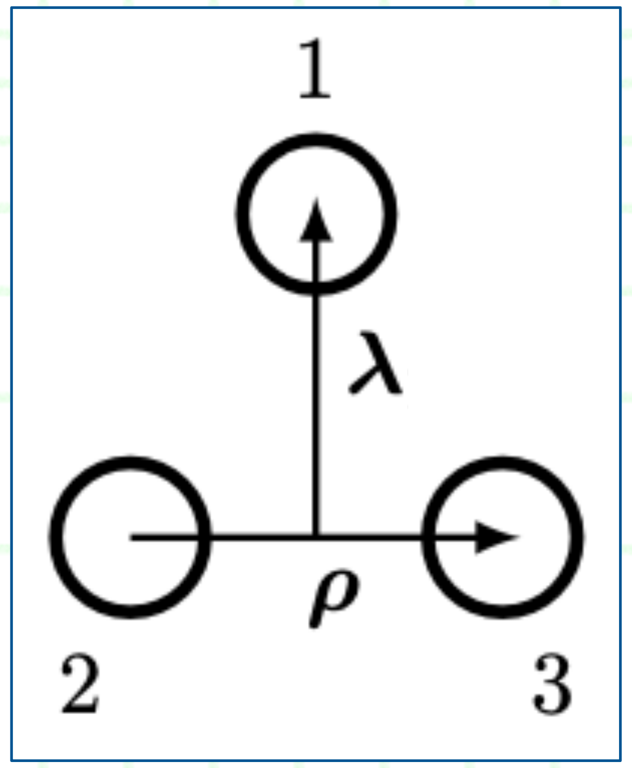


3. The $\bar{K}$NN system in K⁻ ³He –> Λpn

++ ³He wave function ++

- ³He wave function.
  - ☐ A separable parameterization fit for the NNN wave function with the CD-Bonn potential (s wave only, ~ 90 %).

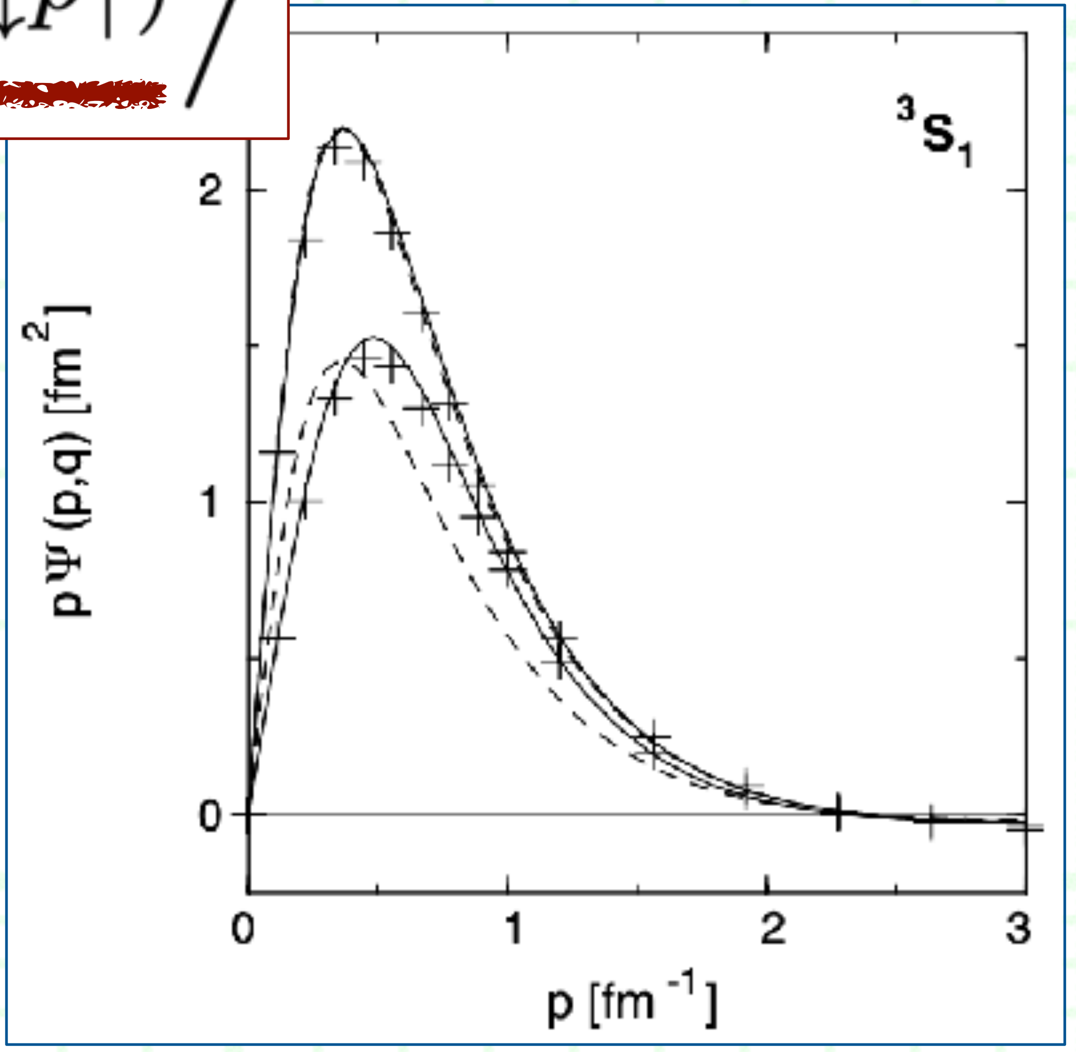
Baru, Haidenbauer, Hanhart, and Niskanen, Eur. Phys. J. A16 (2003) 437.



$^1S_0$ $\quad$ $^1S_0$

$$|^3\mathrm{He}_\uparrow\rangle = v_{^1S_0}(p_\rho)w_{^1S_0}(p_\lambda)\left|-\frac{1}{\sqrt{3}}n_\uparrow(p_\uparrow p_\downarrow - p_\downarrow p_\uparrow) + \frac{1}{2\sqrt{3}}p_\uparrow(p_\uparrow n_\downarrow + n_\uparrow p_\downarrow - p_\downarrow n_\uparrow - n_\downarrow p_\uparrow)\right\rangle$$
$$+v_{^3S_1}(p_\rho)w_{^3S_1}(p_\lambda)\left|-\frac{1}{\sqrt{3}}p_\downarrow(p_\uparrow n_\uparrow - n_\uparrow p_\uparrow) + \frac{1}{2\sqrt{3}}p_\uparrow(p_\uparrow n_\downarrow - n_\uparrow p_\downarrow + p_\downarrow n_\uparrow - n_\downarrow p_\uparrow)\right\rangle$$

$^3S_1$ $\quad$ $^3S_1$



– Functions v and w are given by a five-term expansion:

$$v_\nu(p) = \sum_{n=1}^{5}\frac{a_n^\nu}{p^2+(m_n^\nu)^2}, \quad w_\nu(p) = \sum_{n=1}^{5}\frac{b_n^\nu}{p^2+(M_n^\nu)^2} \quad (\nu = {}^1S_0, {}^3S_1)$$

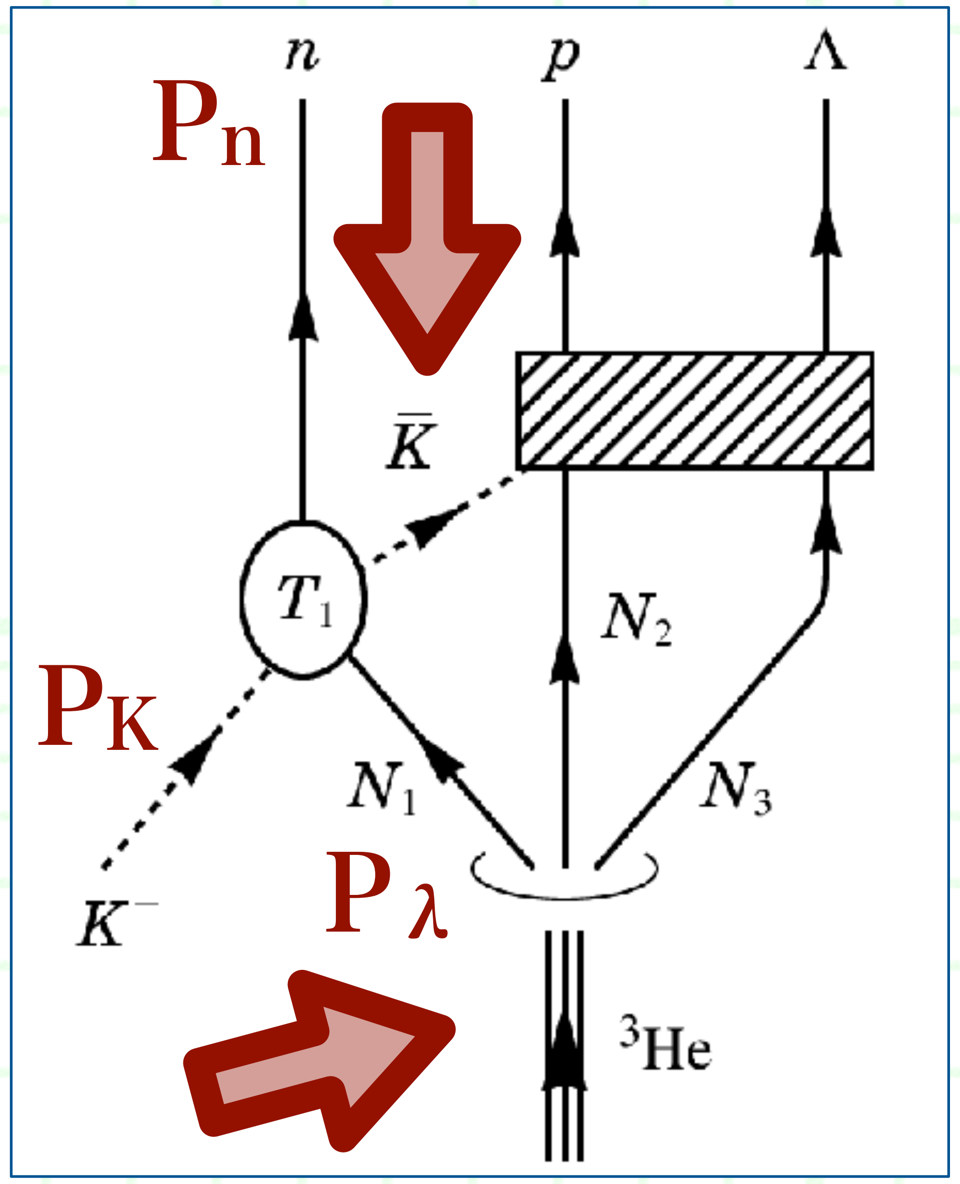
3. The $\bar{K}NN$ system in $K^- \, {}^3He \to \Lambda pn$

++ & $\bar{K}$ propagator ++

■ Together with the $\bar{K}$ propagator, the scattering Amp. becomes:

$$\mathrm{Amp.} = \int \frac{d^3p_\lambda}{(2\pi)^3} \frac{w_\nu(p_\lambda)}{({q_{\rm ex}}^0)^2 - |\mathbf{p}_\lambda + \mathbf{p}_K - \mathbf{p}_n|^2 - {m_K}^2 + i0}$$

$$\mathbf{q}_{\rm trans} = \mathbf{p}_K - \mathbf{p}_n$$

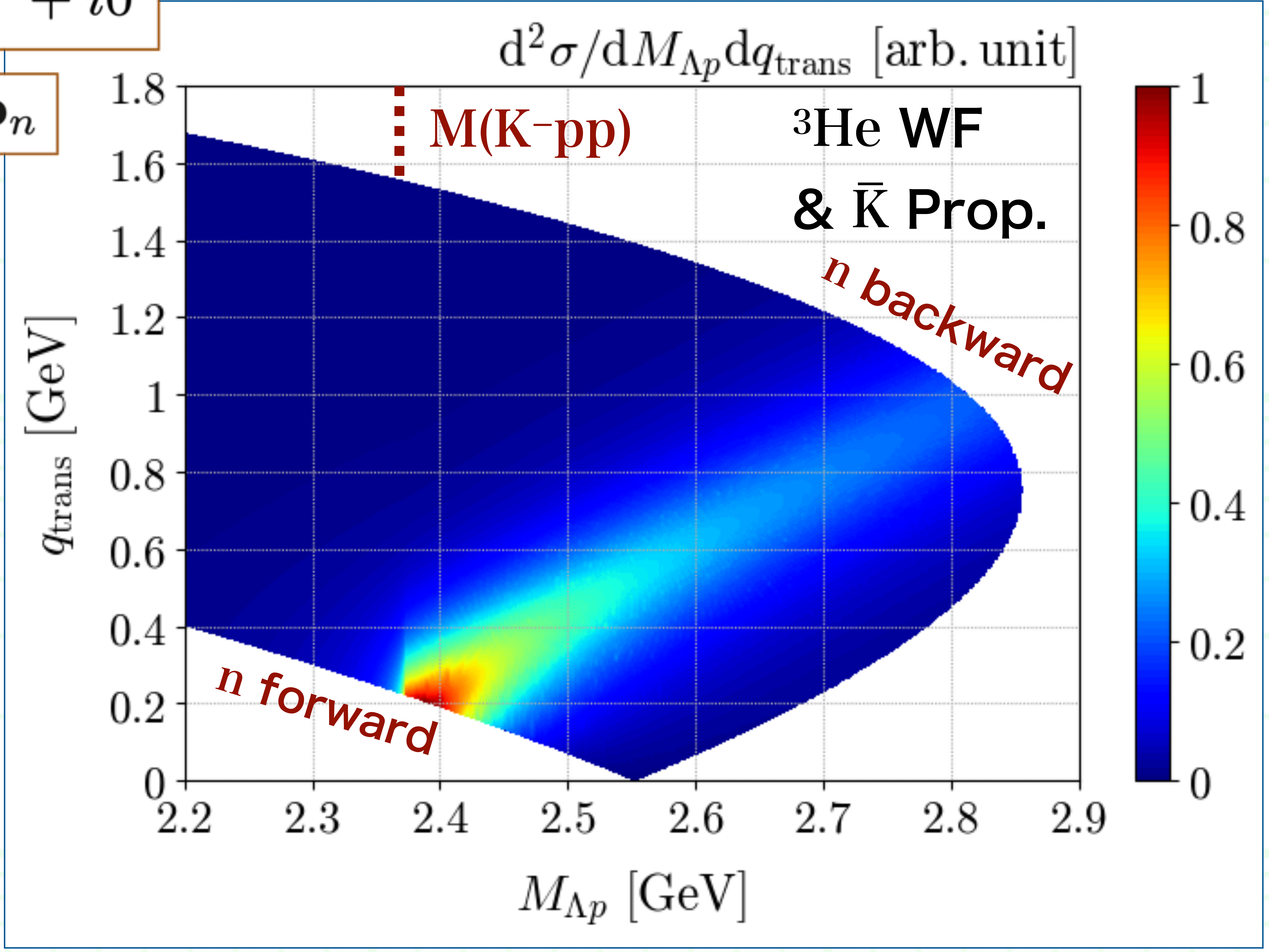


□ Again we have a band structure.

□ Band width owing to the ^{3}He WF.

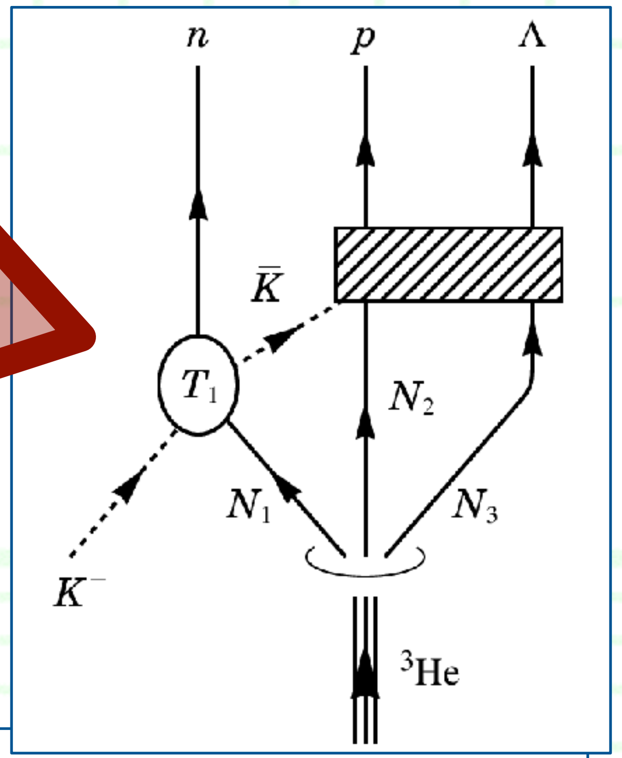
— Off-shell N inside ^{3}He.

□ On this band, we may treat the propagating $\bar{K}$ as (almost) on-shell particle.



3. The $\bar{K}NN$ system in $K^{-}\,{}^{3}He \to \Lambda pn$

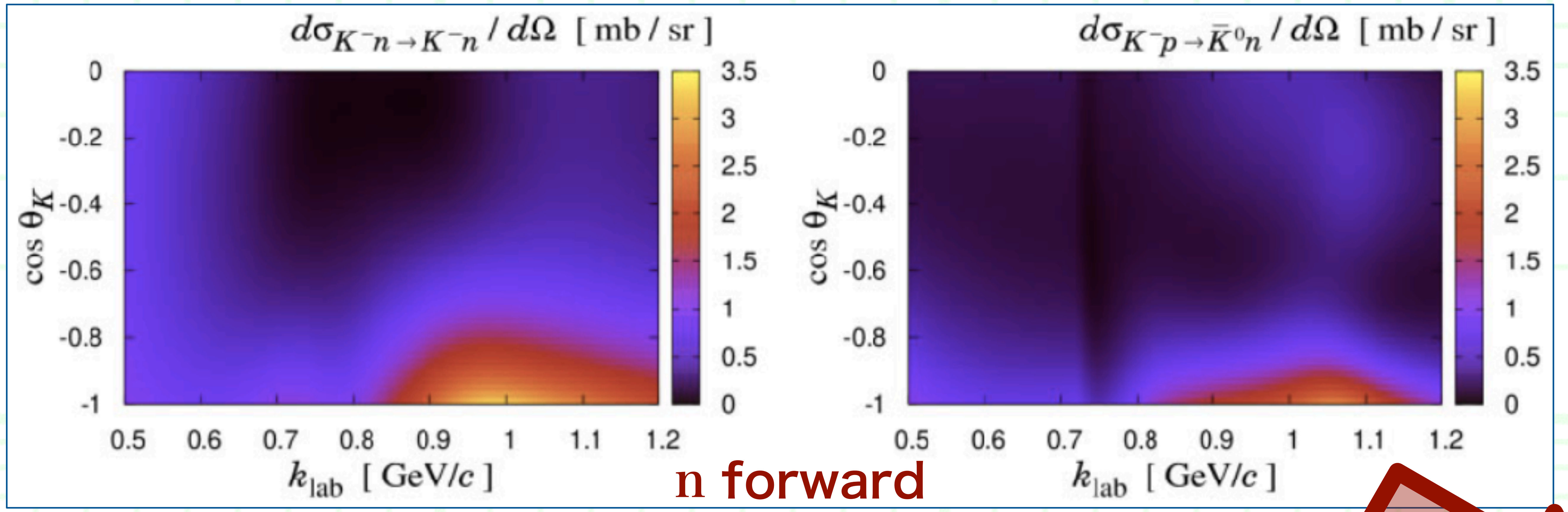
++ & the 1st step $\bar{K}N \to \bar{K}N$ ++



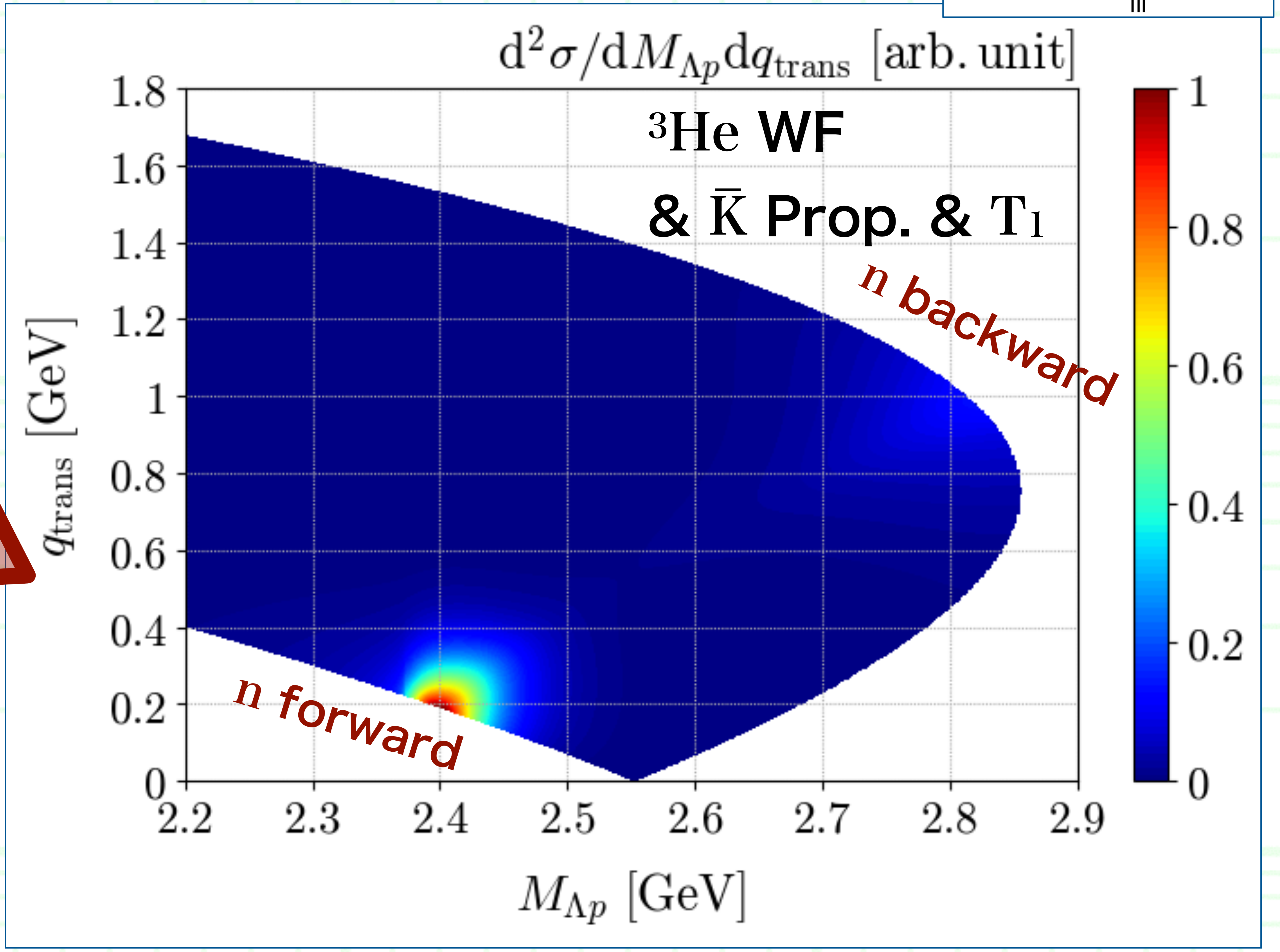
■ Inclusion of the 1st step T_1 ($\bar{K}N \to \bar{K}N$, P_K = 1 GeV/c).

–> Again employ **Kamano et al. on-shell amplitude**.

Kamano, Nakamura, Lee, and Sato, Phys. Rev. C90 (2014) 065204.



$$\text{Amp.} = \int \frac{d^3p_\lambda}{(2\pi)^3} \frac{w_\nu(p_\lambda)T_1^{(\text{Kamano})}}{(q_{\text{ex}}{}^0)^2 - |\mathbf{p}_\lambda + \mathbf{p}_K - \mathbf{p}_n|^2 - m_K{}^2 + i0}$$

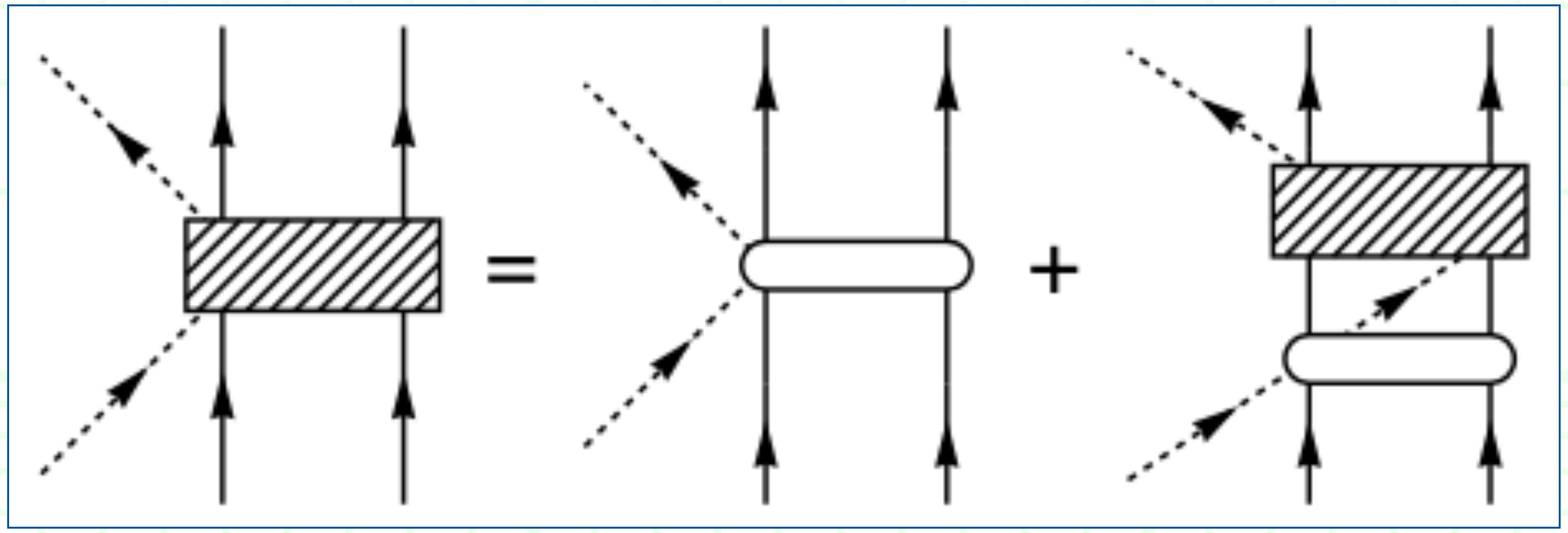


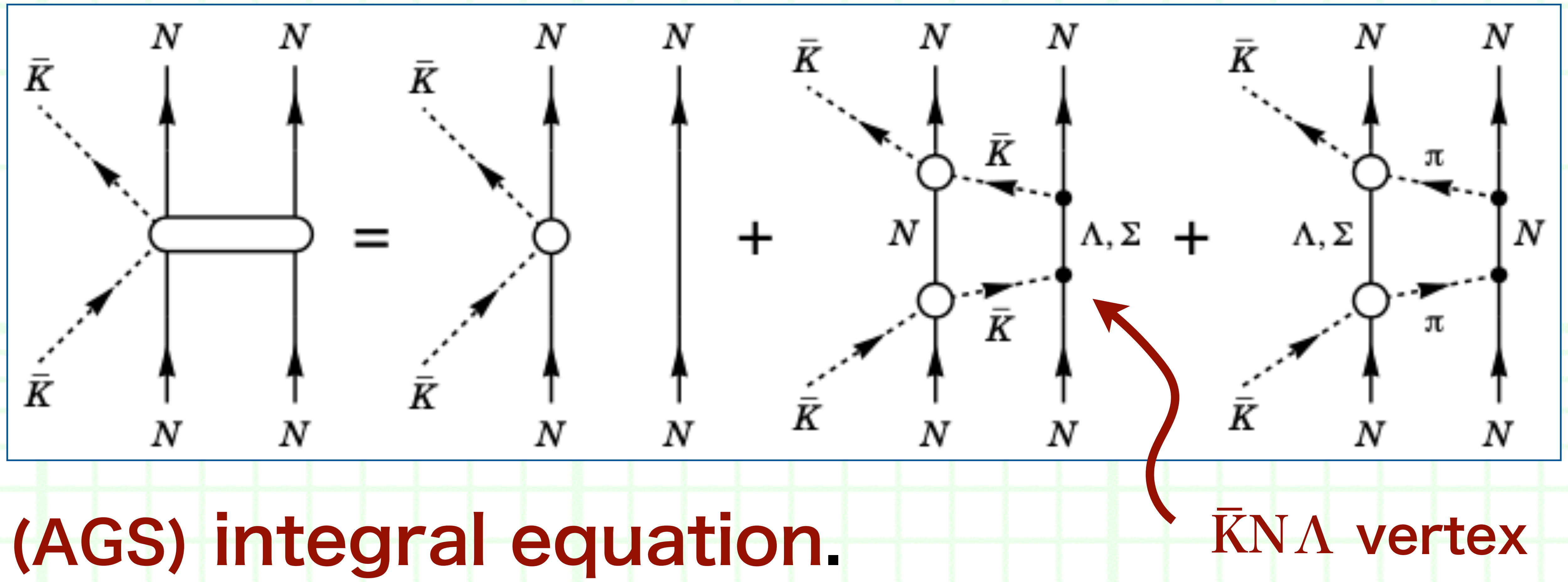
☐ Dominated by the **small momentum transfer region** $q_{\text{trans}} < 0.4$ GeV, again.

3. The $\bar{K}NN$ system in $K^{-}\,{}^{3}He \to \Lambda pn$

++ The AGS equation and $\bar{K}NN \to \Lambda p$ ++

- Solve the Faddeev Eq. with the explicit NN interaction as well as $\bar{K}N$.
  - ☐ NN interaction: Separable form which reproduces the NN($^1S_0$, $^3S_1$) phase shift.
  - ☐ $\bar{K}N$ interaction: $\bar{K}N \to \bar{K}N$ in chiral dynamics & Two-nucleon absorption.





–> Solve the Alt-Grassberger-Sandhas (AGS) integral equation.

$$X_{i,j}(E,p_i,p_j) = Z_{i,j}(E,p_i,p_j) + \sum_n \int_0^\infty \frac{dk}{2\pi^2} k^2 Z_{i,n}(E,p_i,k) T_n(E,k) X_{n,j}(E,k,p_j)$$

— $\bar{K}NN$ bound state is generated !

3. The $\bar{K}$NN system in K⁻ ³He –> Λpn

++ Reaction cross section ++

■ Inclusion of the $\bar{K}$NN –> Λp part. –> Full calculation.

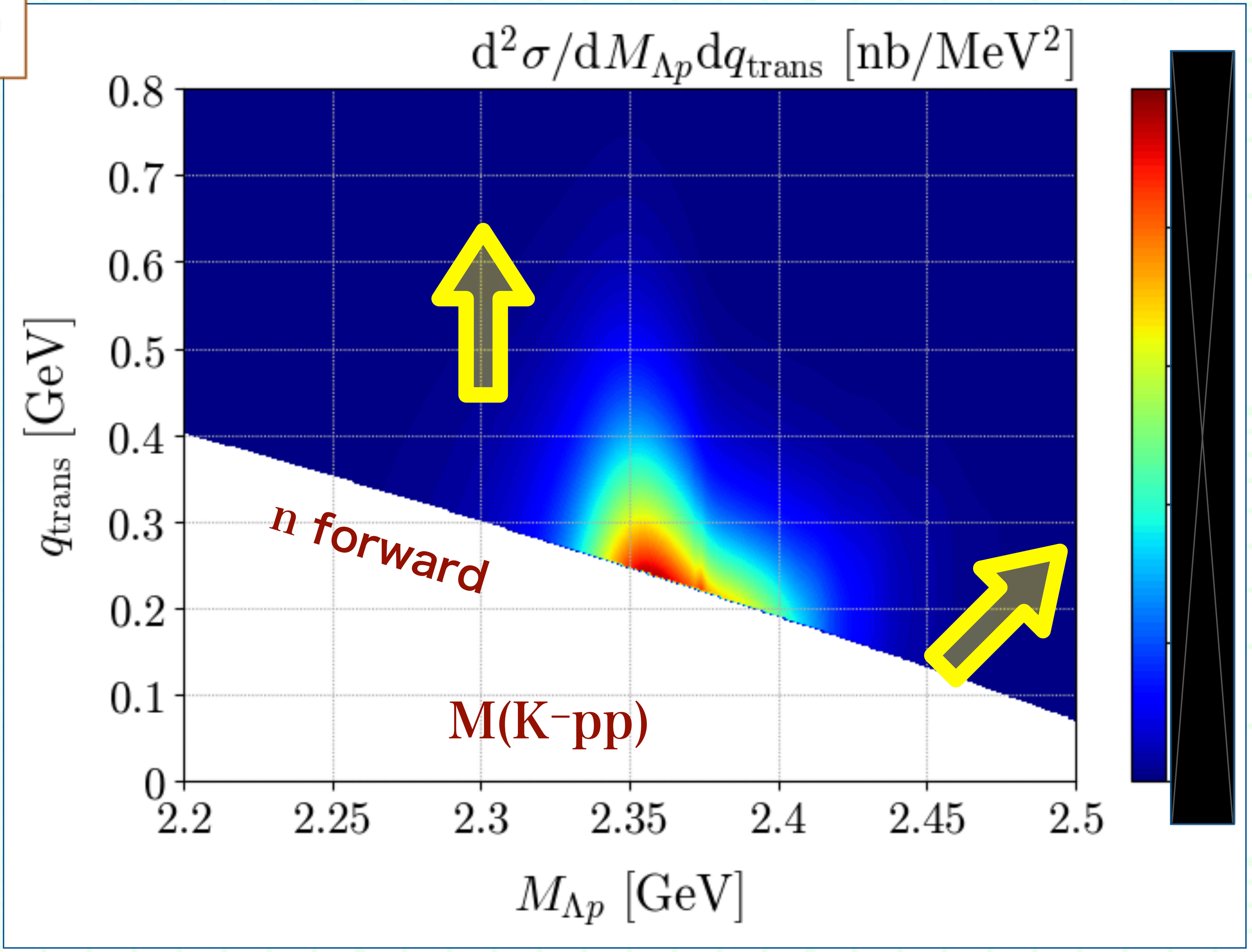
$$\text{Amp.} = \int \frac{d^3p_\lambda}{(2\pi)^3} \frac{w_\nu(p_\lambda) T_1^{(\text{Kamano})} T_{\bar{K}NN\to\Lambda p}}{({q_\text{ex}}^0)^2 - |\mathbf{p}_\lambda + \mathbf{p}_K - \mathbf{p}_n|^2 - {m_K}^2 + i0}$$

$$T_{\bar{K}NN\to\Lambda p} = \int \frac{d^3p_\rho}{(2\pi)^3} \frac{v_\nu(p_\rho) V_{\bar{K}N\Lambda} X_\text{AGS}}{(q'_\text{ex})^2 - {m_K}^2 + i0}$$

□ We have two trends.

- Below the $\bar{K}$NN threshold:
  The $\bar{K}$NN bound state signal.
- Above the $\bar{K}$NN threshold:
  The quasi-free $\bar{K}$ propagation.

□ These two trends are consistent with the Exp. data.



3. The $\bar{K}NN$ system in $K^- {}^3He \to \Lambda pn$

++ Summary and outlook ++

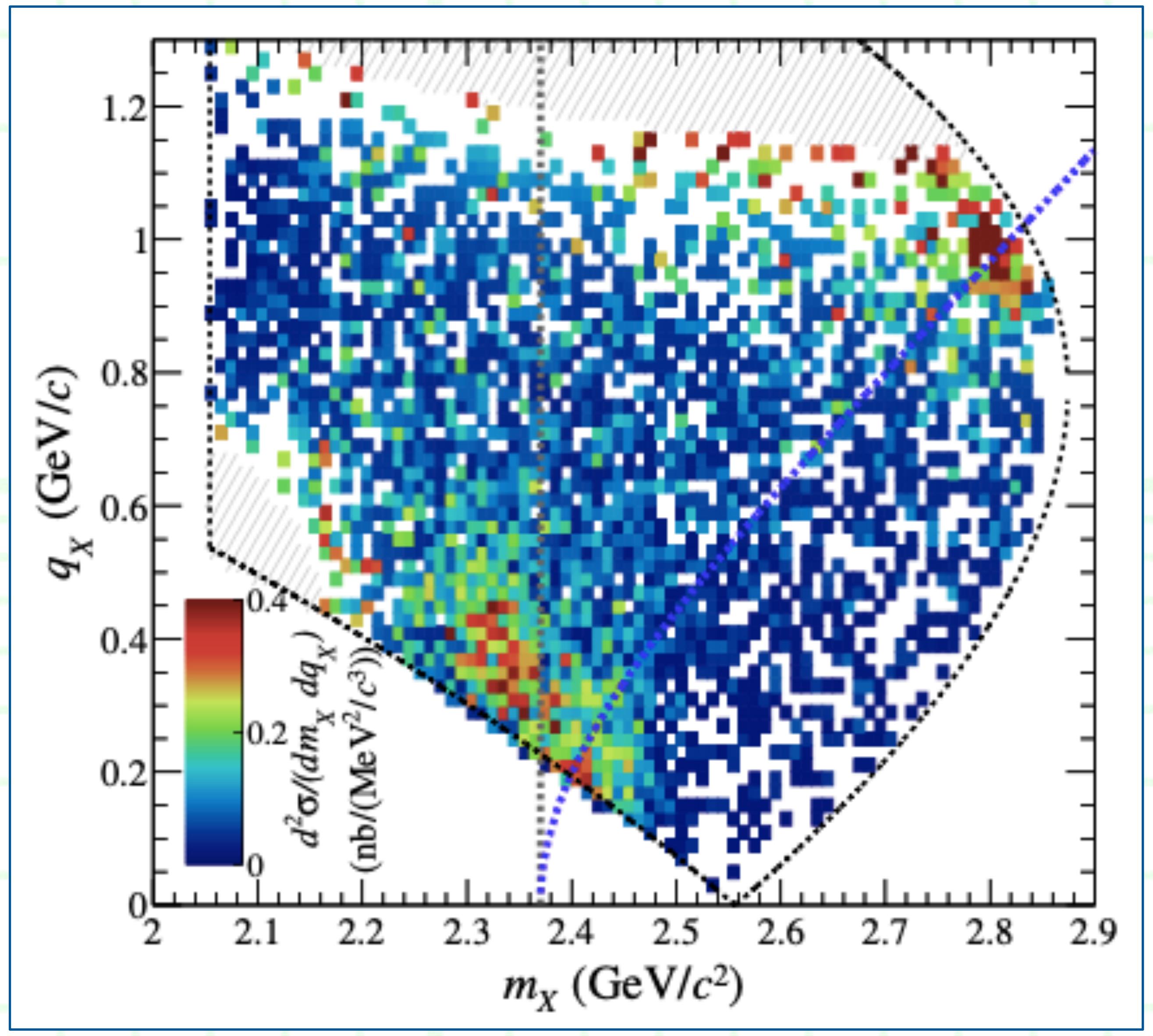
■ Consistency of the $K^- {}^3He \to \Lambda pn$ reaction cross section.

1. Appearance of the quasi-free kaon line.

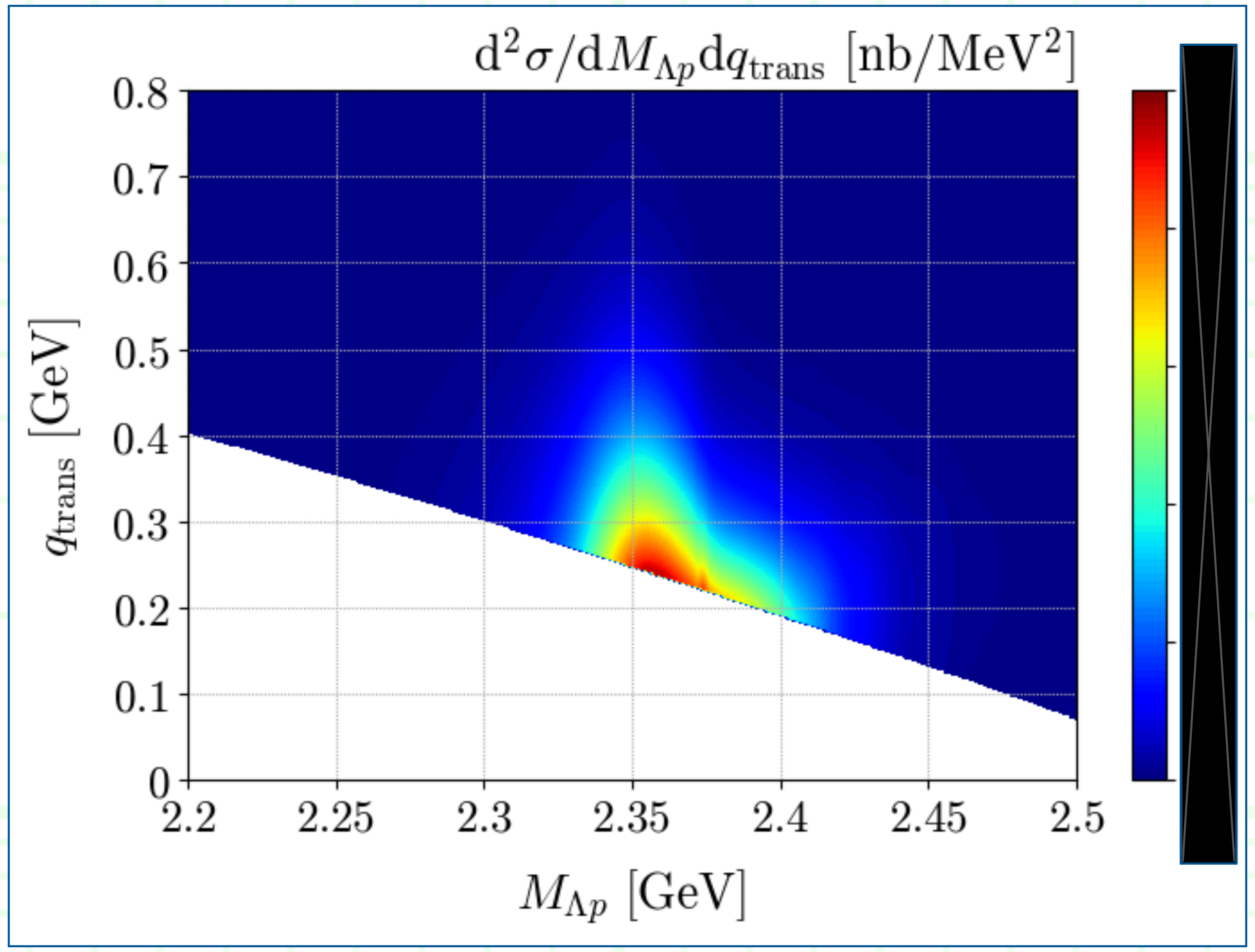
–> $\bar{K}$ is indeed mediated.

2. The q independent signal below the $\bar{K}NN$ threshold.

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



Yamaga et al. [J-PARC E15], Phys. Rev. C102 (2020) 044002.



■ Then, we can investigate the scattering amplitude.

☐ Pole position of the $\bar{K}NN$ bound state ?

☐ Spin/parity of the bound state ?

☐ ….

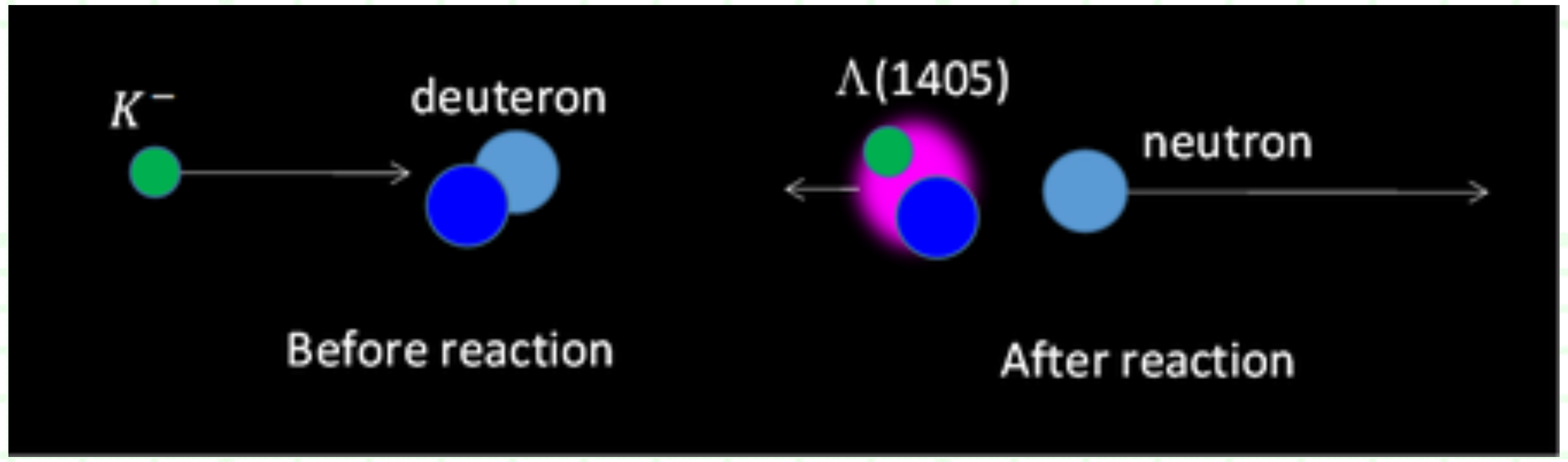
4. Summary

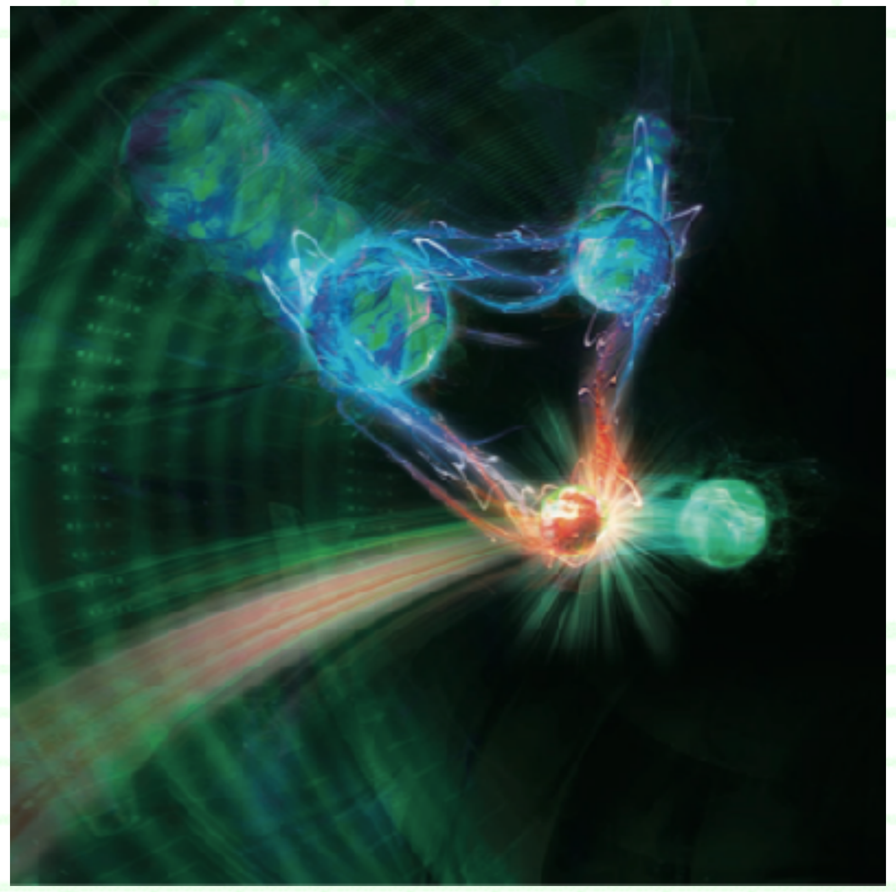
4. Summary

■ Are the peaks of the J-PARC Exps. the signals of the $\bar{\mathrm{K}}$N and $\bar{\mathrm{K}}$NN systems ?

— Yes. $\bar{\mathrm{K}}$ is indeed mediated !

The peak structure is consistent with our calculations.

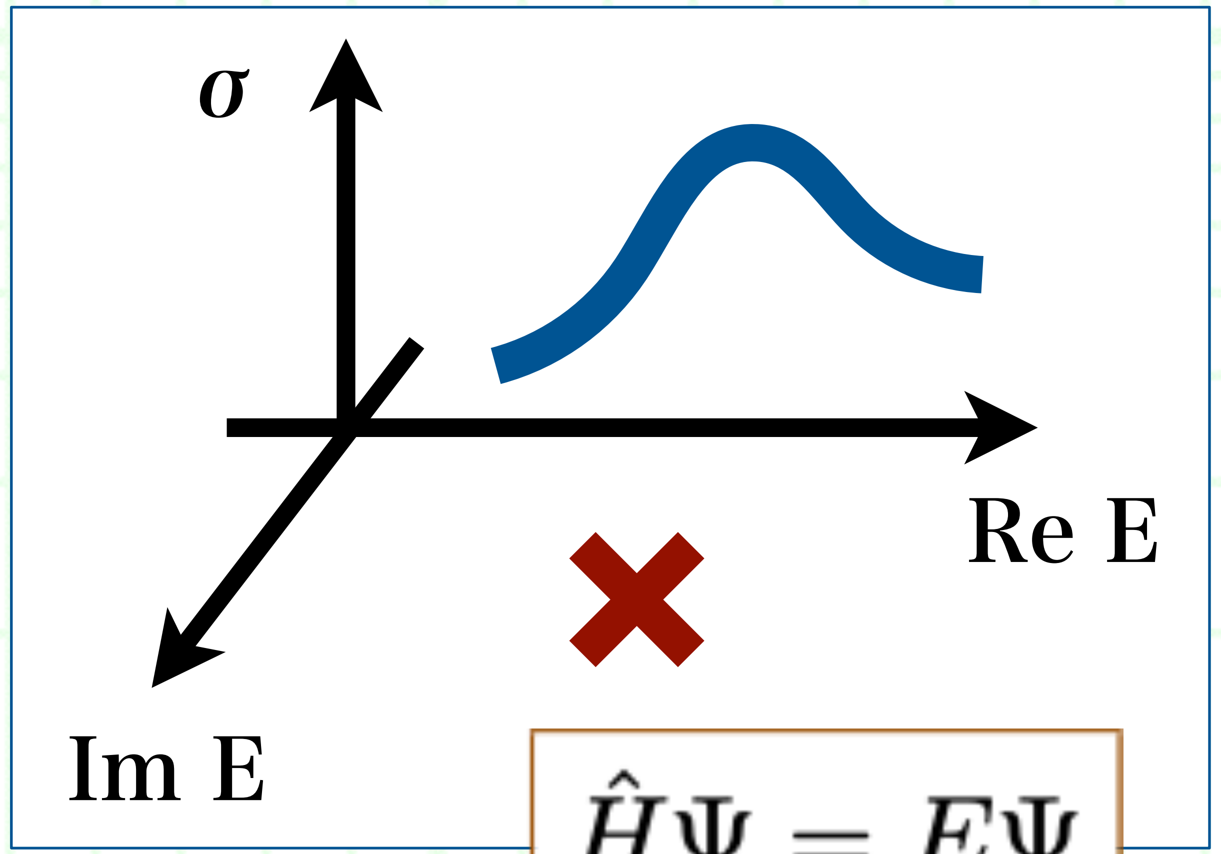




■ We have constructed scattering amplitudes of the reaction $K^- d \to \pi \Sigma n$ and $K^- {}^3He \to \Lambda\, p\, n$ to connect the resonance pole and Exp. observables.

□ We want to extract the information on the resonance pole.

The research is on going ….



$$\hat{H}\Psi = E\Psi$$

Thank you very much for your kind attention !