Systematic investigation of kaonic nuclei at J-PARC

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Hadron Experimental Facility extension (HEF-ex) workshop
(2022.02.16 – 18)

Skip introduction

Studies of $\bar{K}$-nuclei @ J-PARC so far

Search for $K^{-}pp$

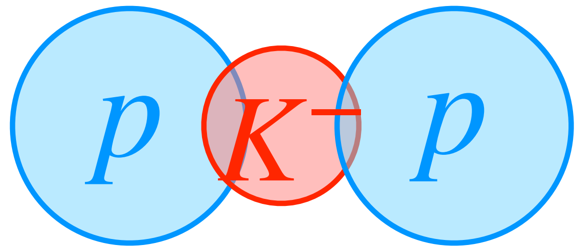
$\bar{K}NN$ bound state

Bound system of anti-kaon and two nucleons

$$\left[\bar{K}_{I=\frac{1}{2}}(NN)_{I=1}\right]_{I=\frac{1}{2}} \quad (J^P = 0^-)$$

$I^{(z)}_{\bar{K}NN} = +1/2$

$(K^{-}pp$ - $\bar{K}^{0}pn)$

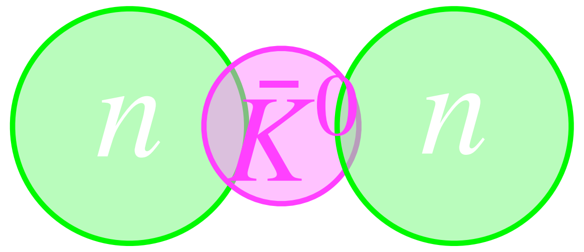


"$K^{-}pp$"

⇒ $\Lambda p/\Sigma^{0}p$

$I^{(z)}_{\bar{K}NN} = -1/2$

$(\bar{K}^{0}nn$ - $K^{-}pn)$

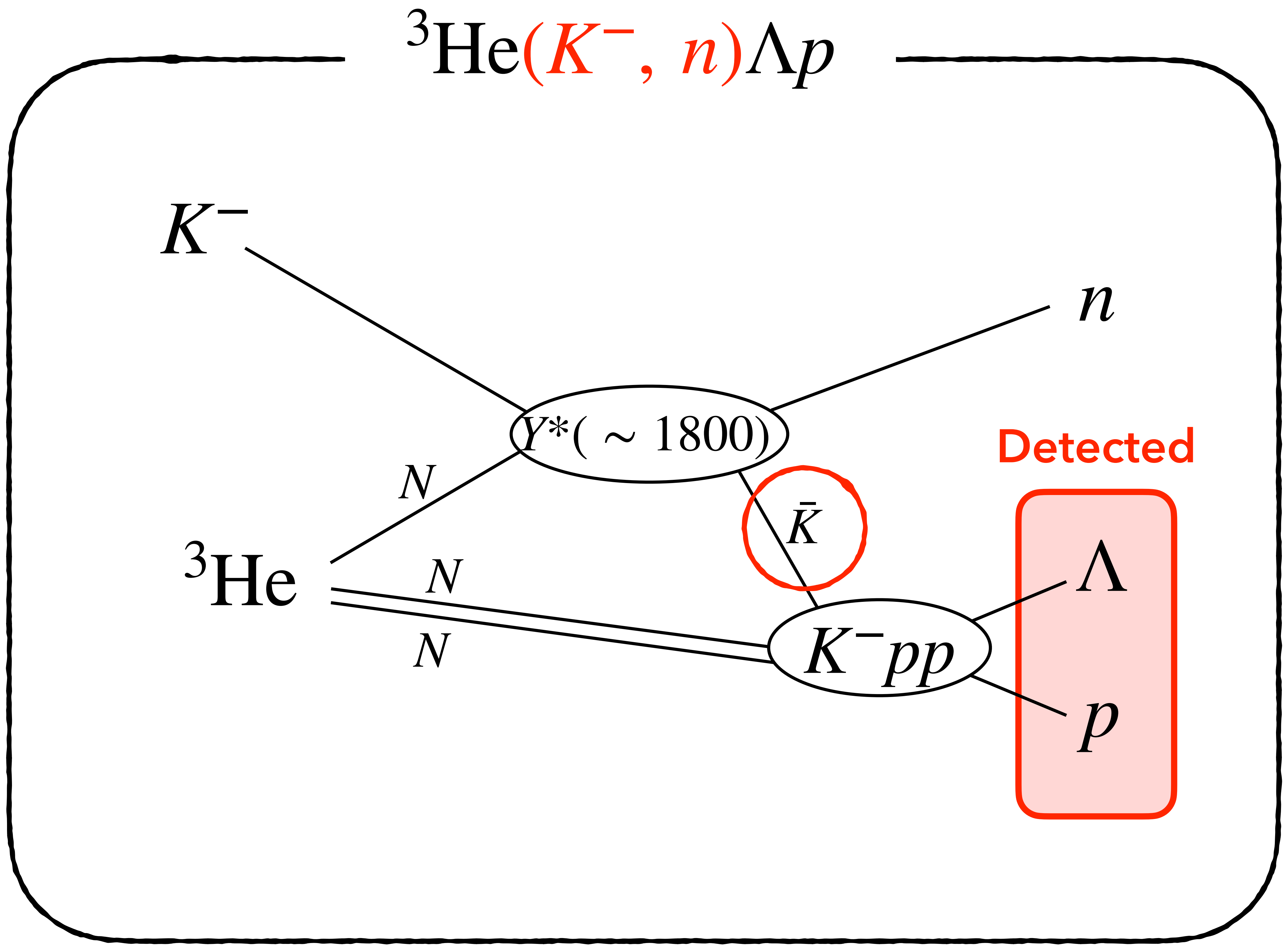


"$\bar{K}^{0}nn$"

$K^{-}pp$ is the simplest to detect experimentally.

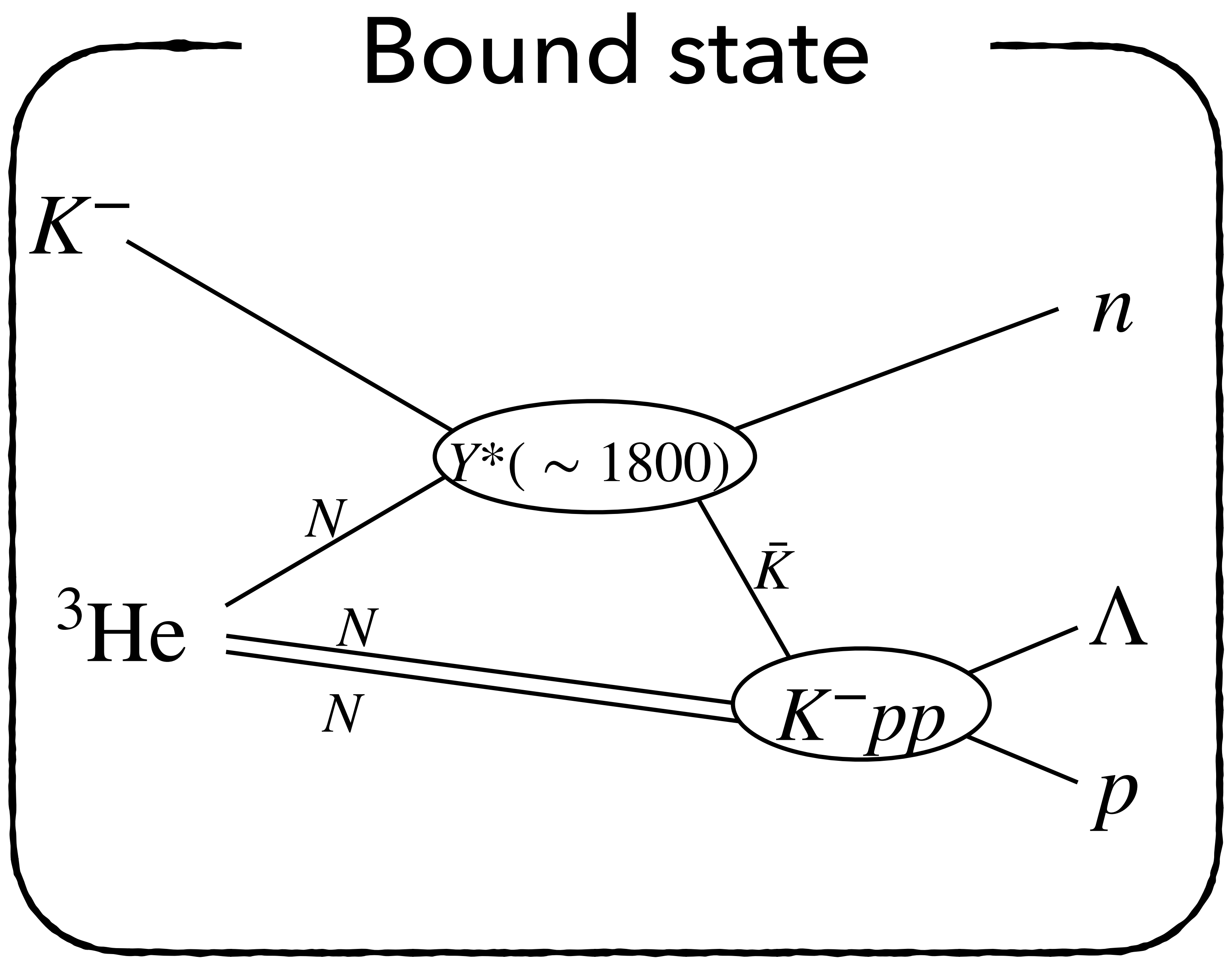
What we measured

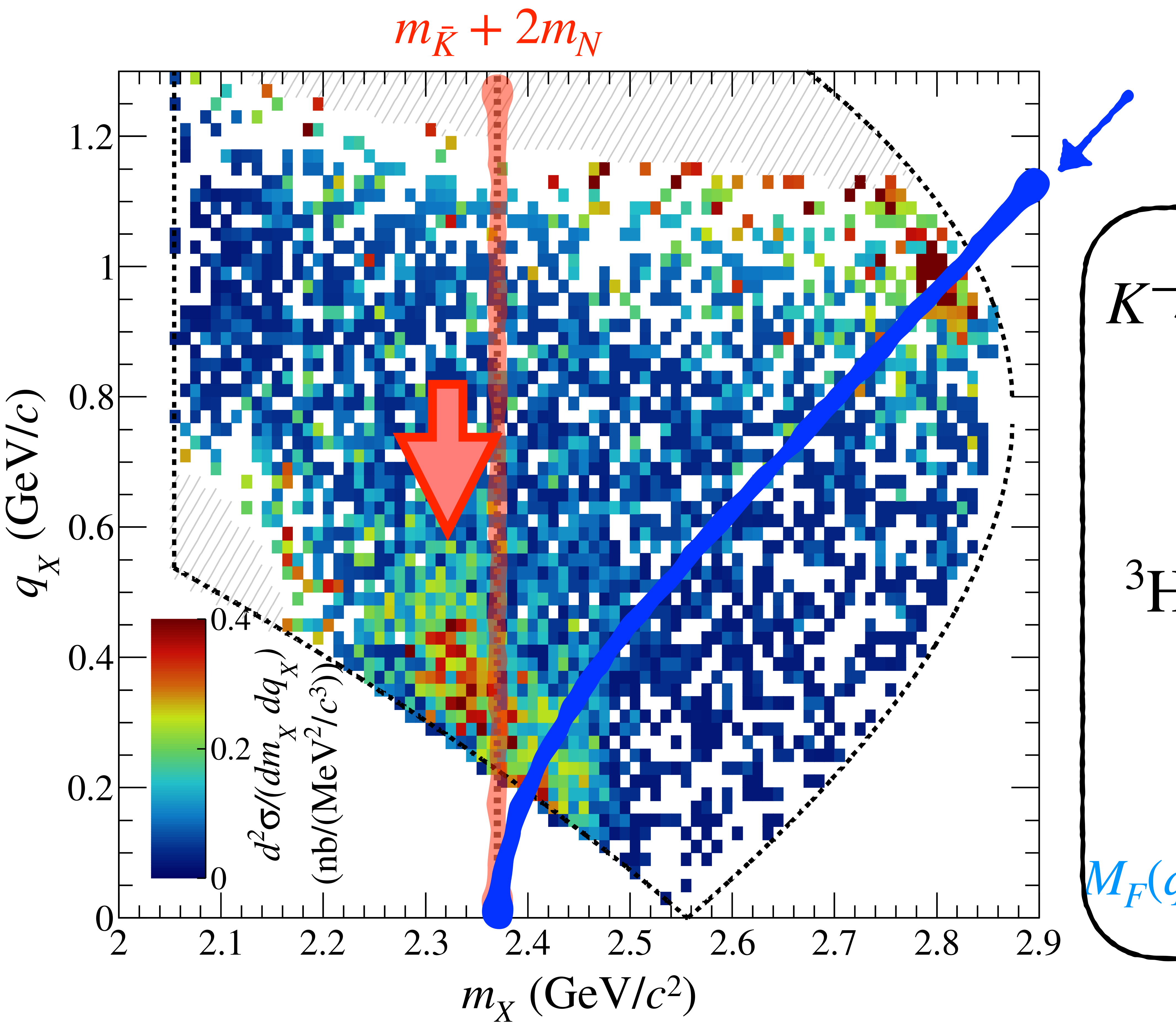
in E15 experiment

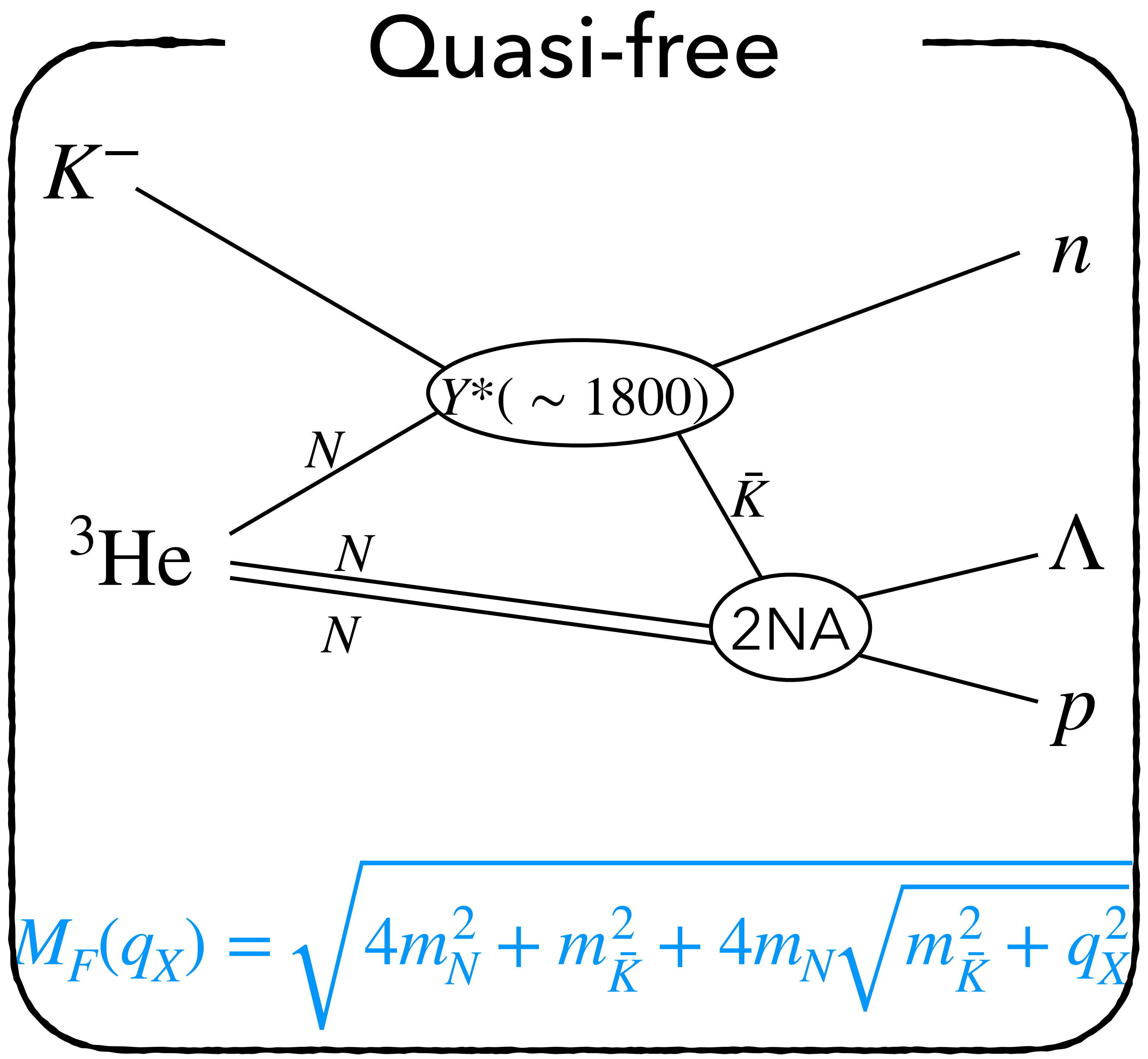


K^-pp production is occurred by intermediate $\bar{K}$.

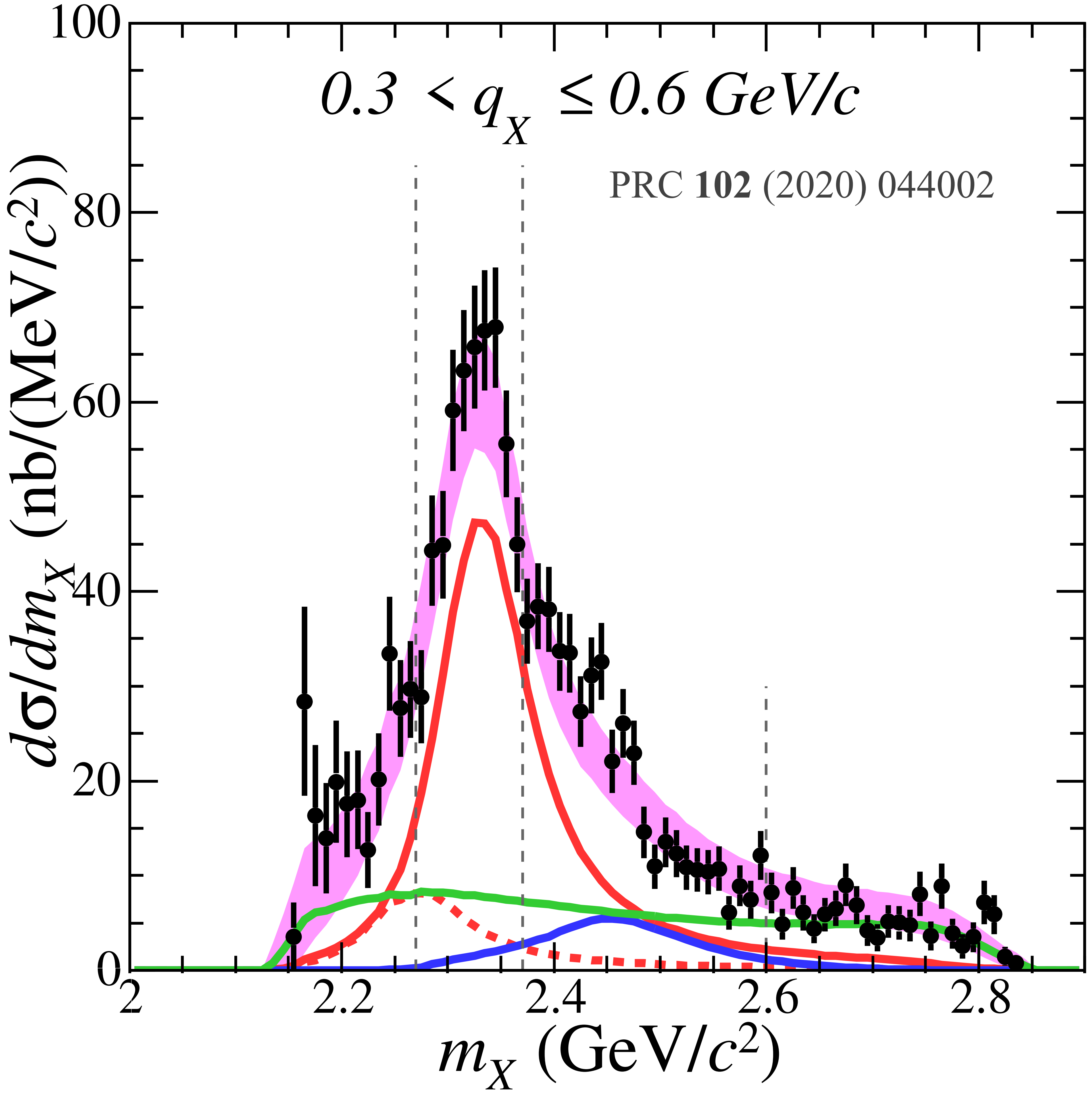
Result of E15



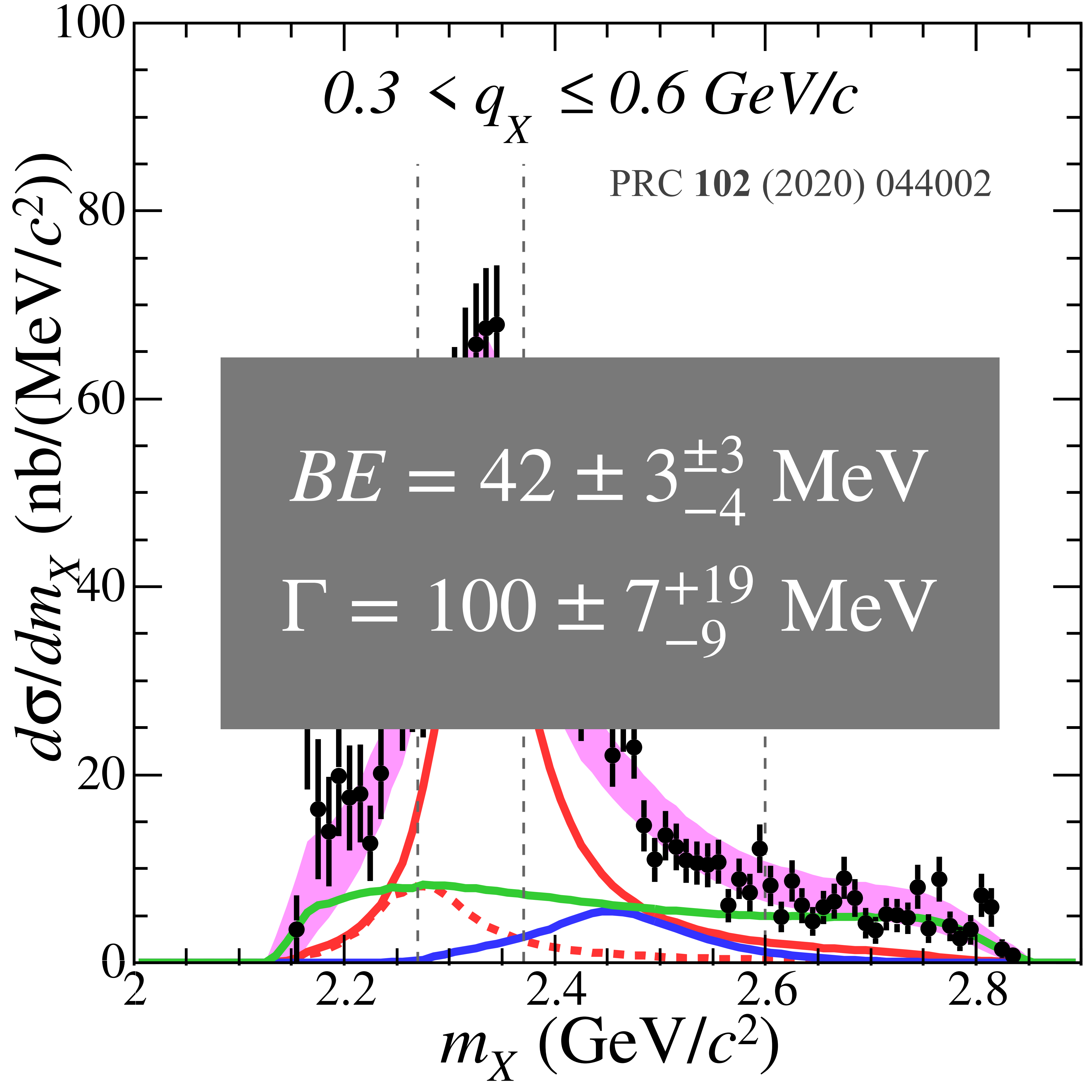


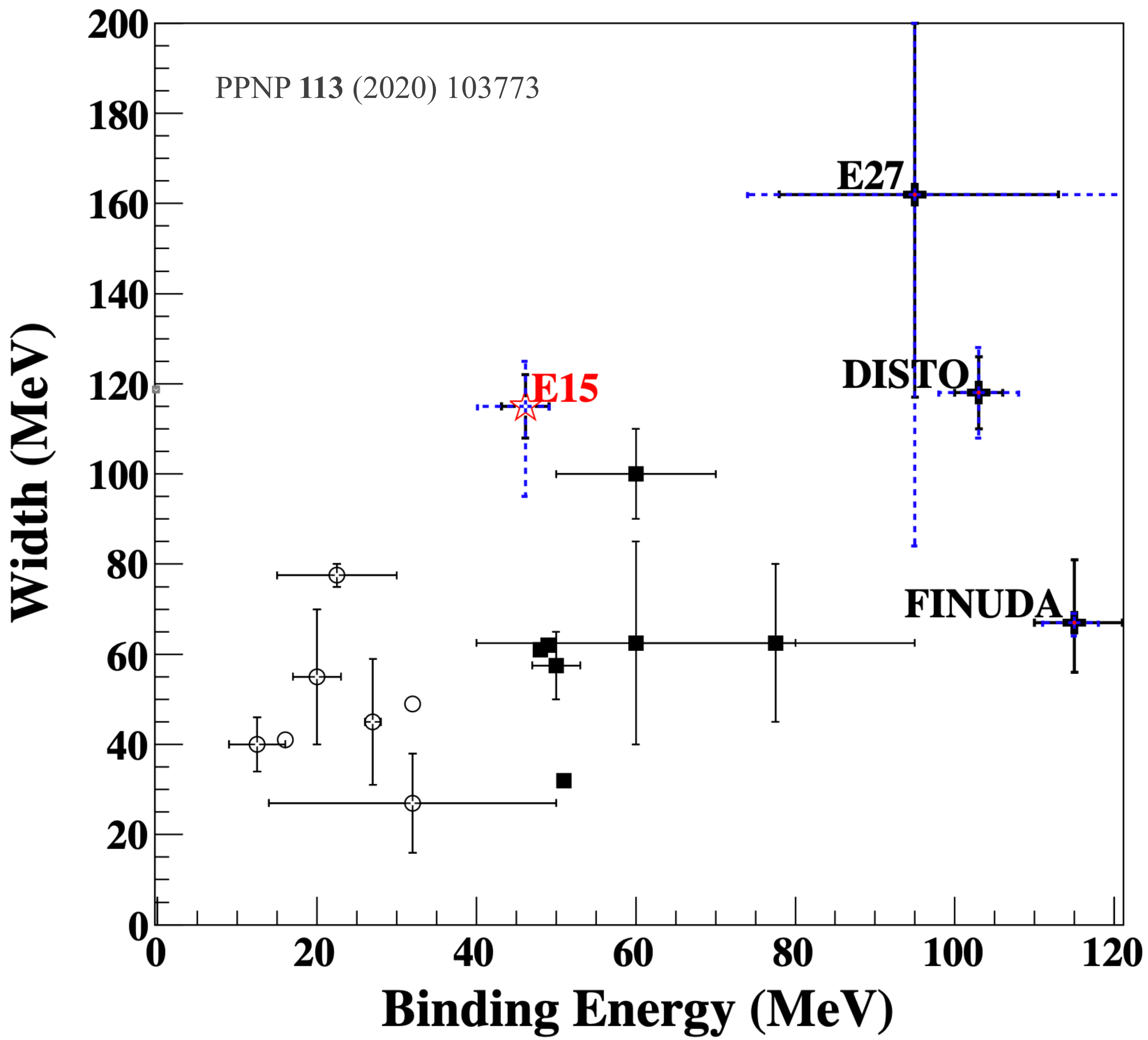


Result of E15

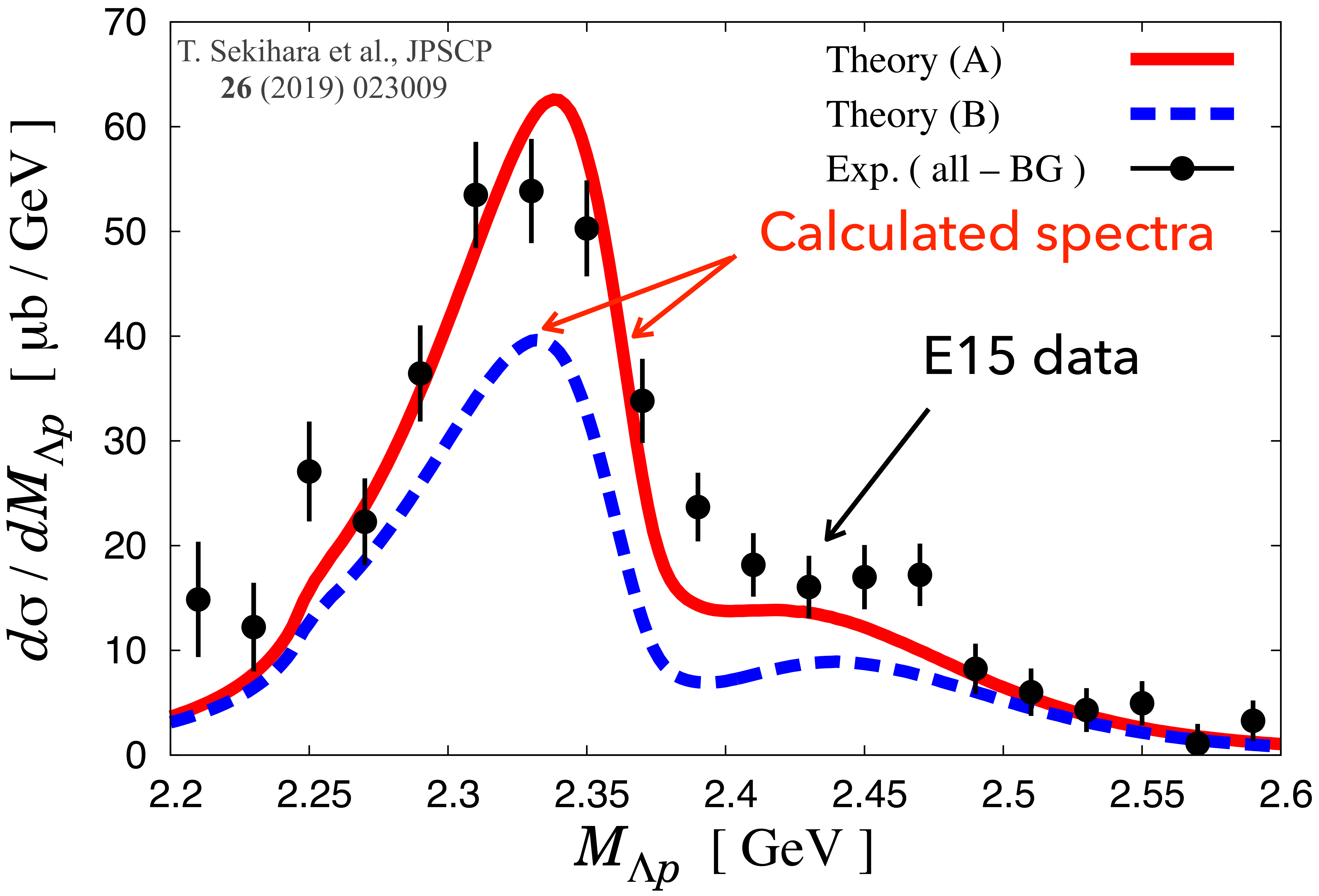


Result of E15





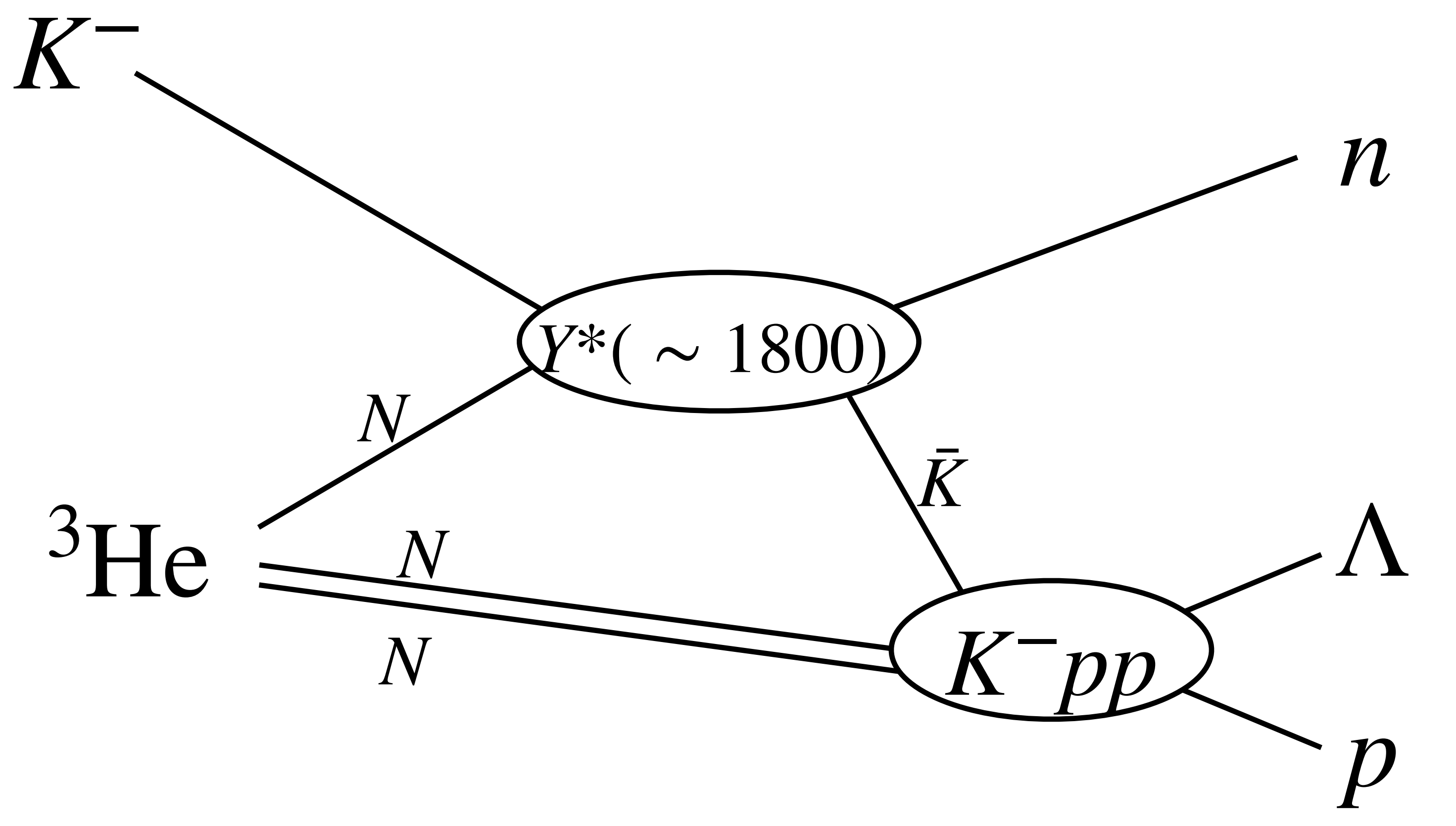
E15 result & Theor. calc. are consistent.
The most natural interpretation is that the peak is a signal of $K^{-}pp$.



E15 result & Theor. calc. are consistent.
The most natural interpretation is that the peak is a signal of $K^{-}pp$.

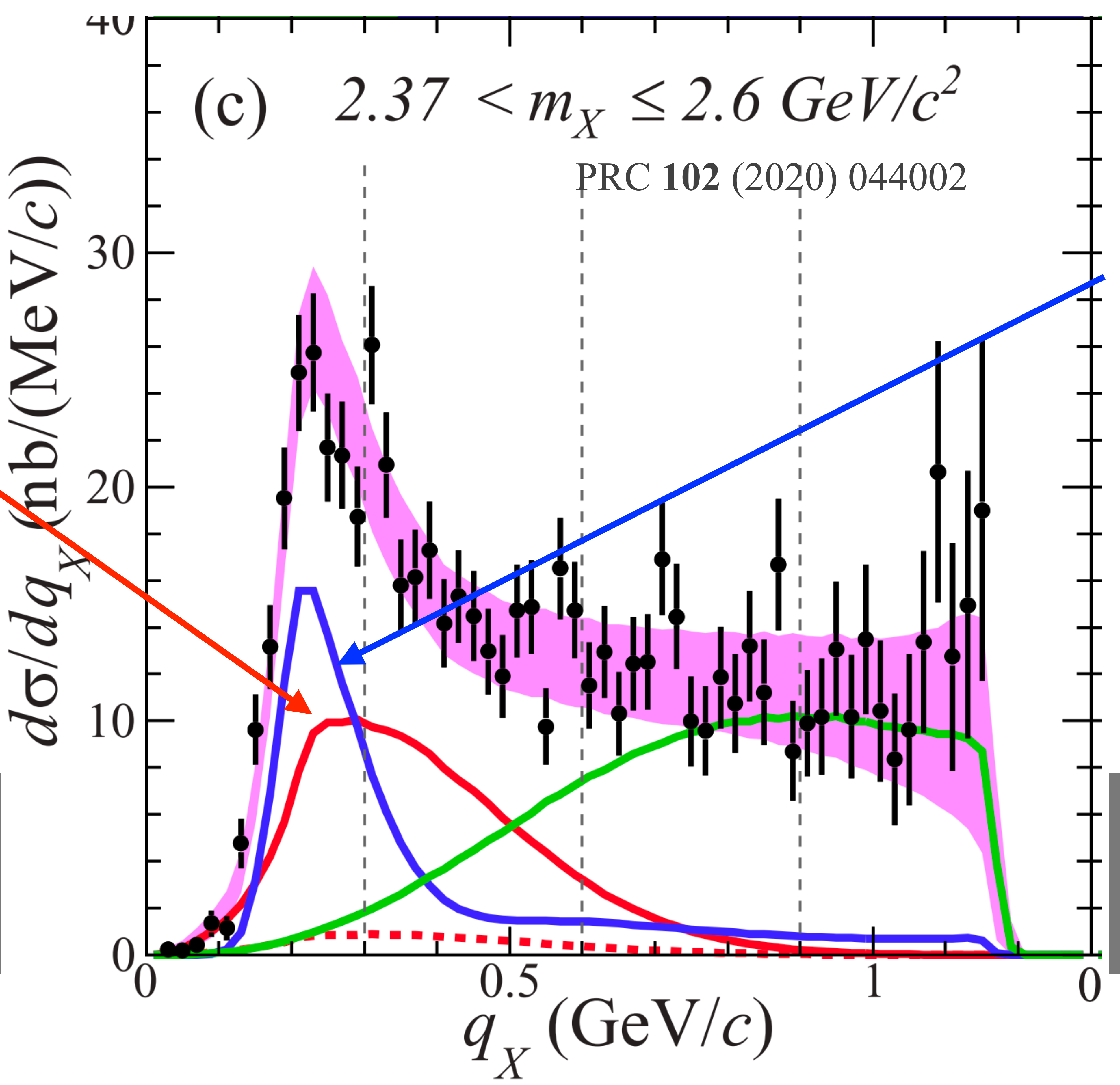
Internal structure of $K^{-}pp$

Bound state

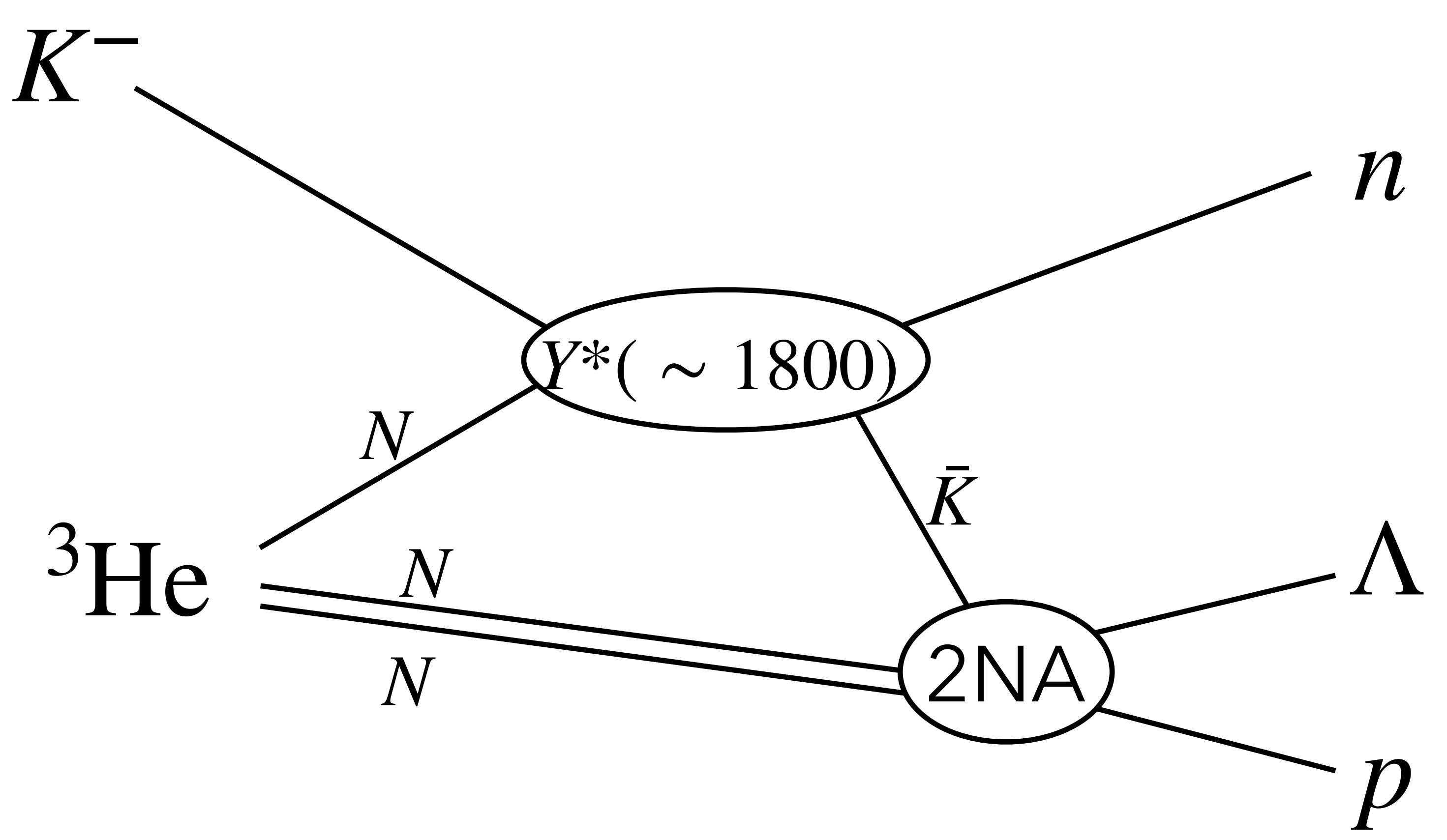


$Q_{K^-pp} = 383 \pm 11^{+4}_{-1}$ MeV/c

Very compact??



Quasi-free



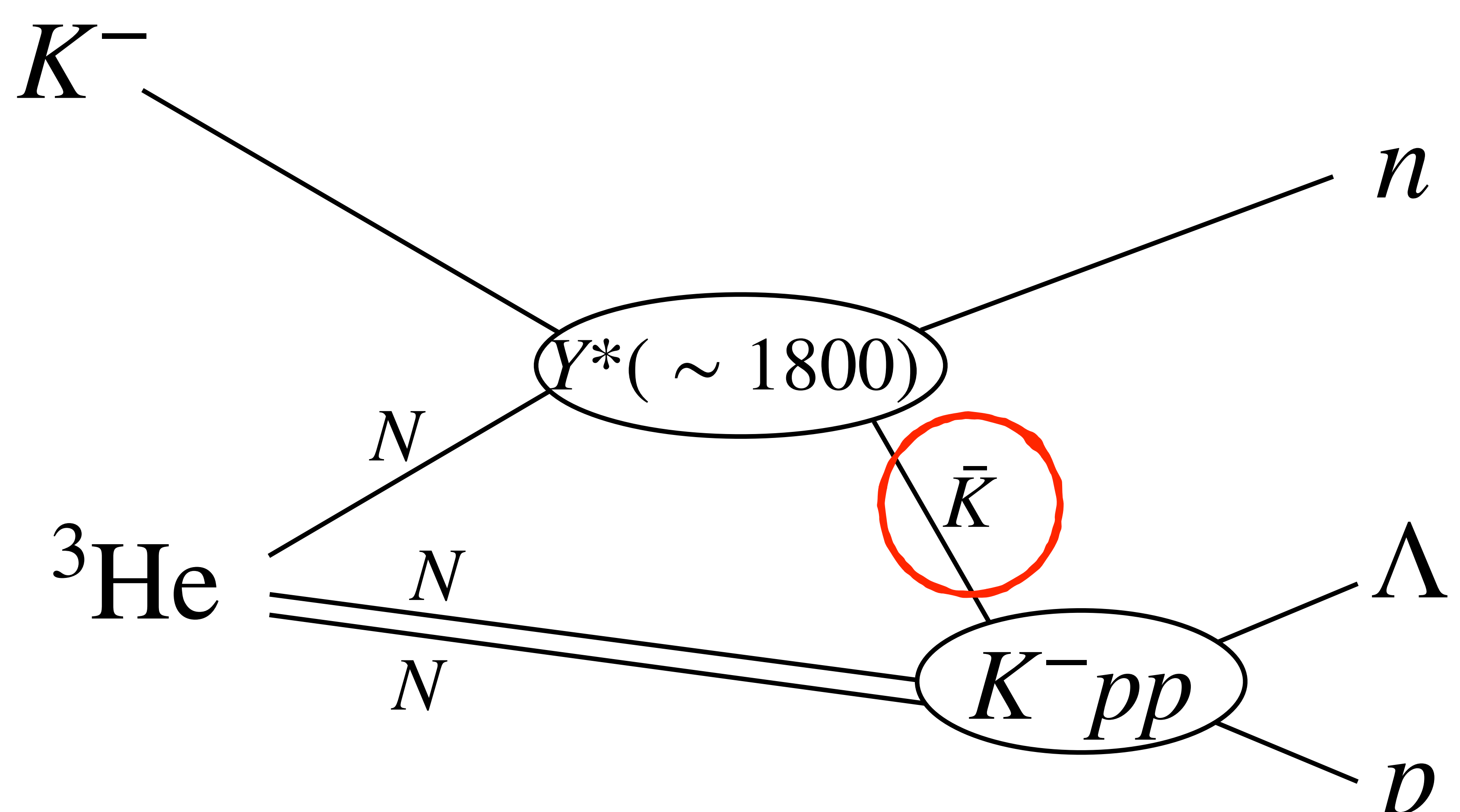
$Q_{QF} = 172 \pm 9^{+3}_{-5}$ MeV/c

Understanding of the larger Q_{K^-pp} will provide information of system size.

Comparison between E15 & E27

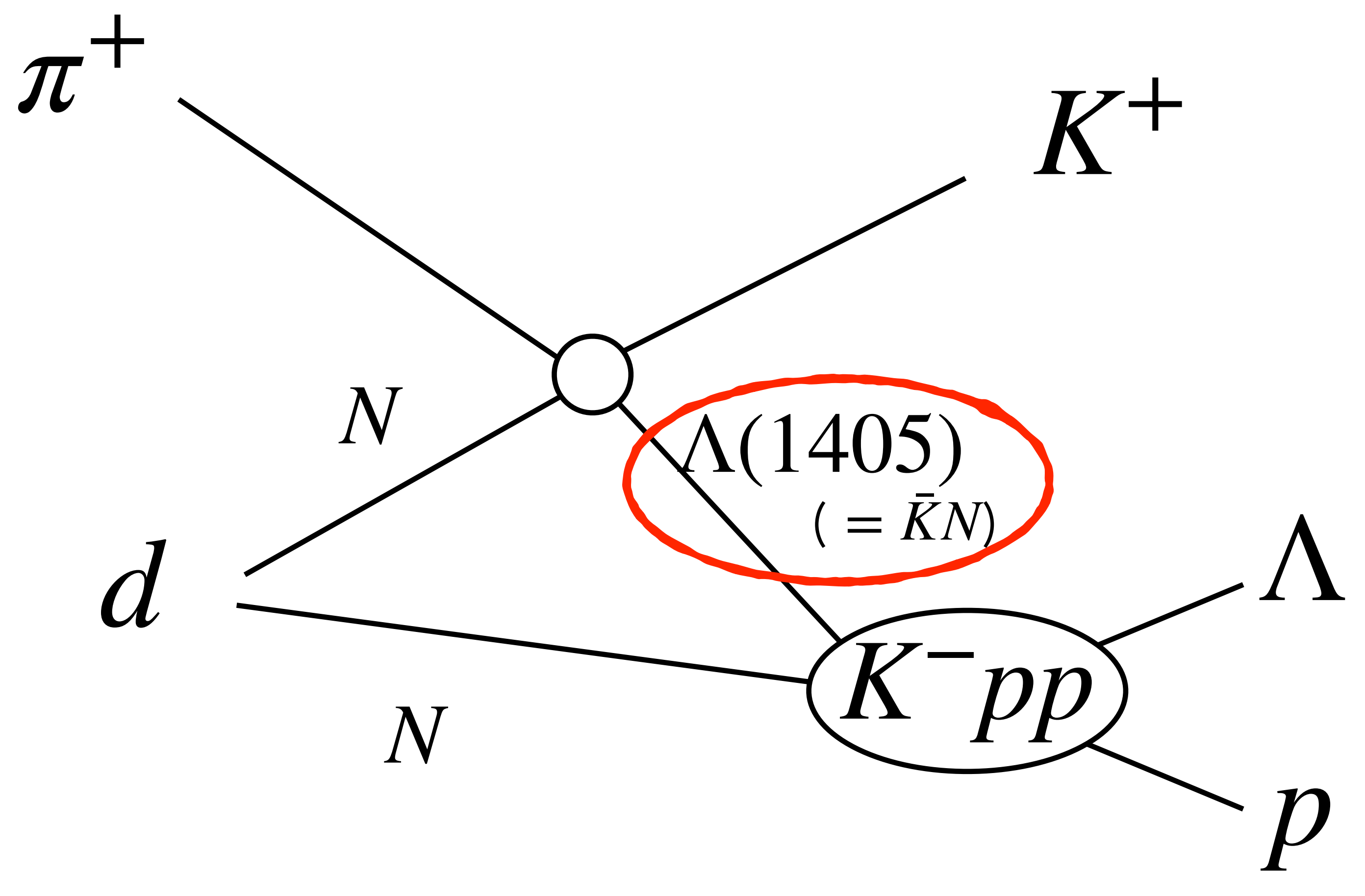
J-PARC E15

$^3\mathrm{He}(K^-, n)\Lambda p$



J-PARC E27

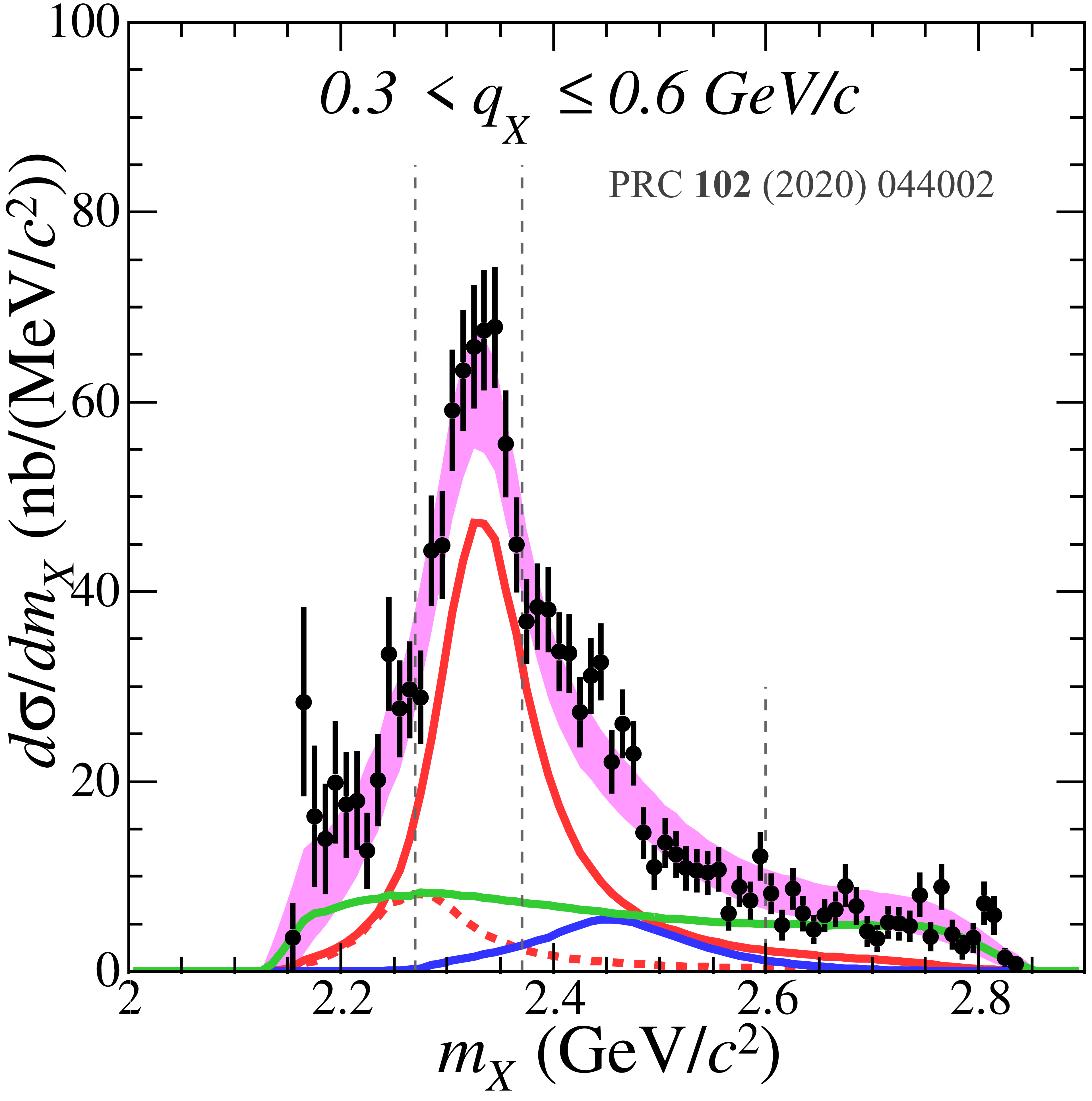
$d(\pi^+, K^+)\Lambda p/\Sigma^0 p$



Production of K^-pp is essentially the same.
Occurred by intermediate $\bar{K}$ or $\bar{K}N$

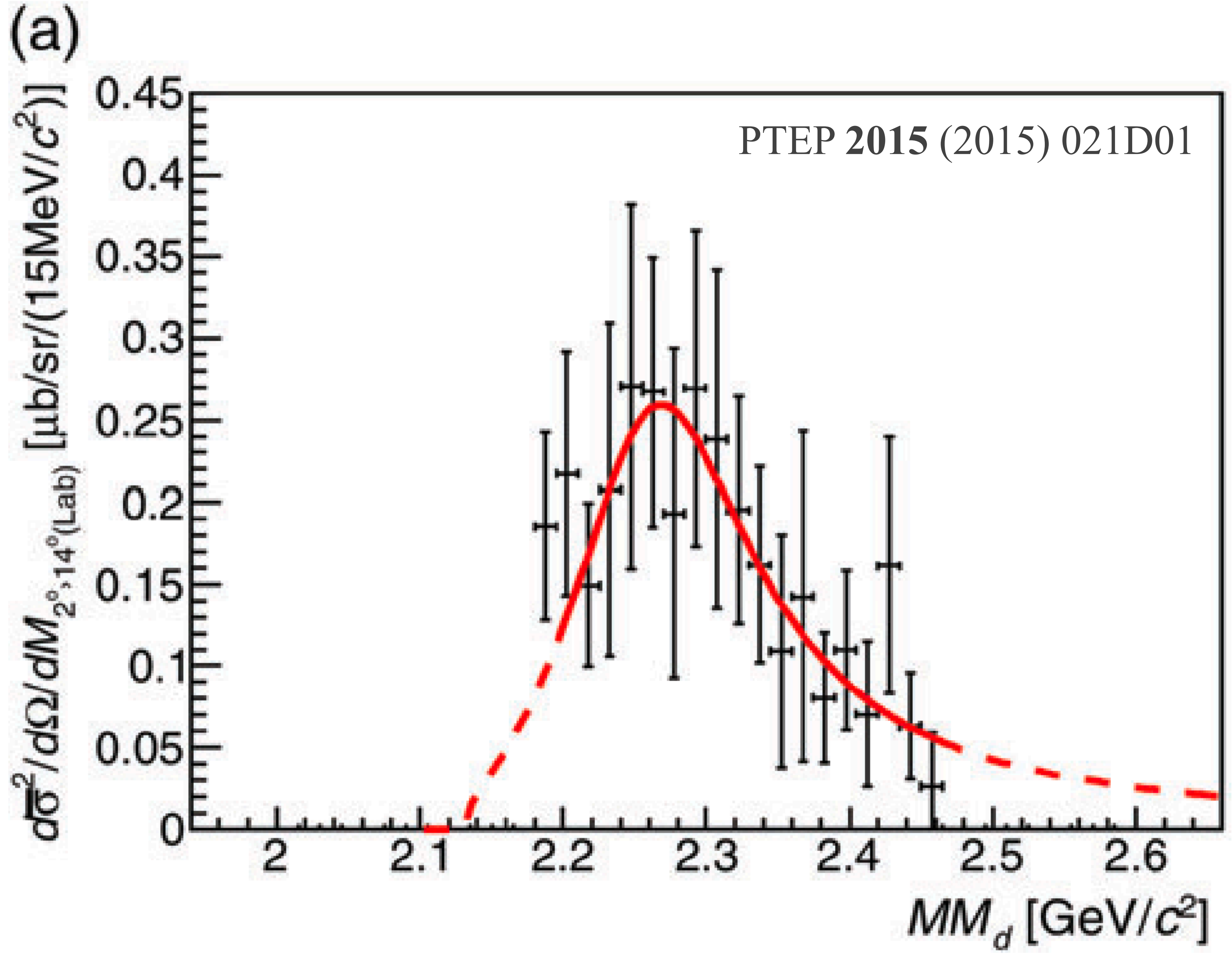
J-PARC E15

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



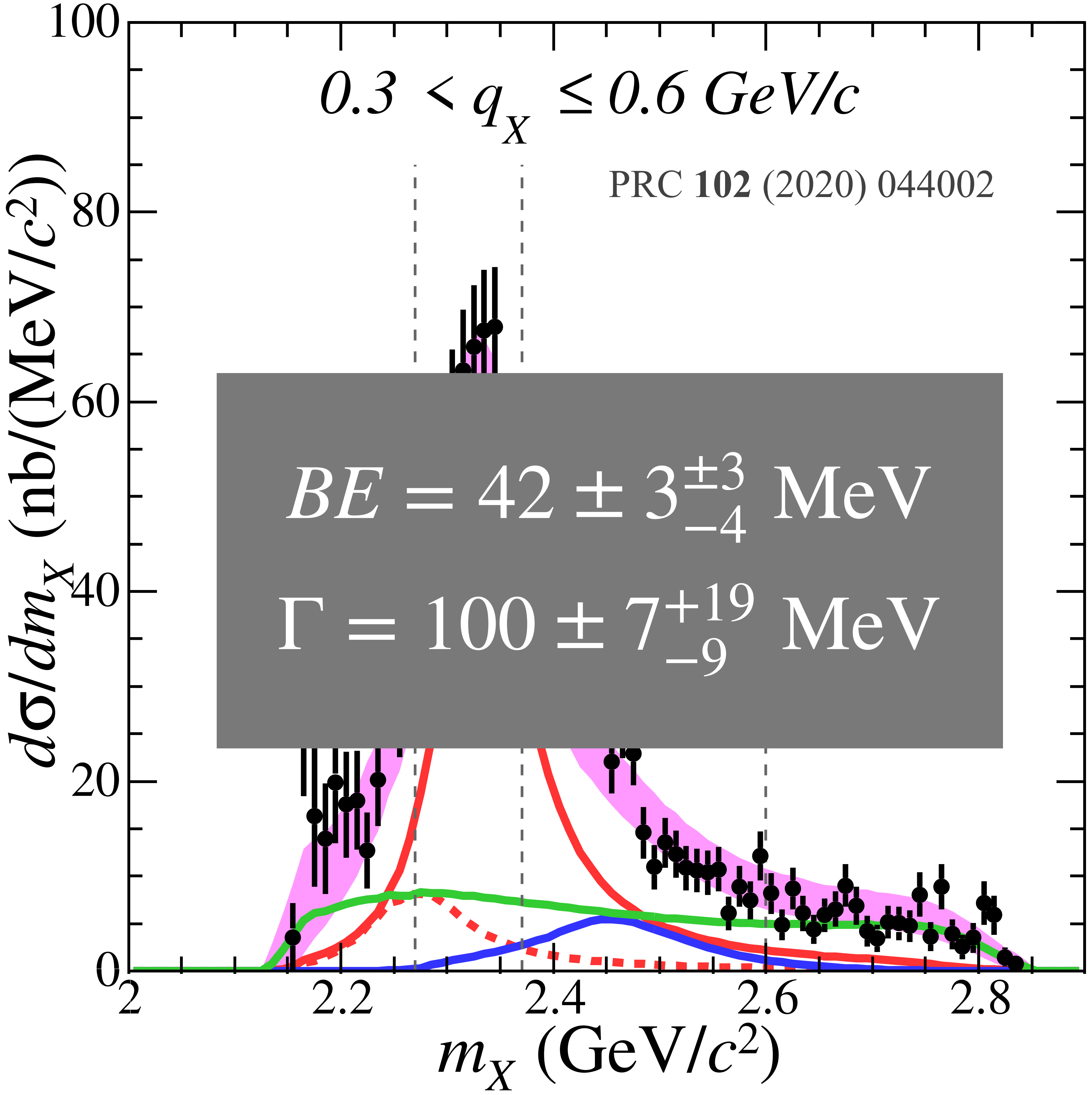
J-PARC E27

$d(\pi^+, K^+)\Lambda p/\Sigma^0 p$



J-PARC E15

$^{3}\mathrm{He}(K^{-}, n)\Lambda p$

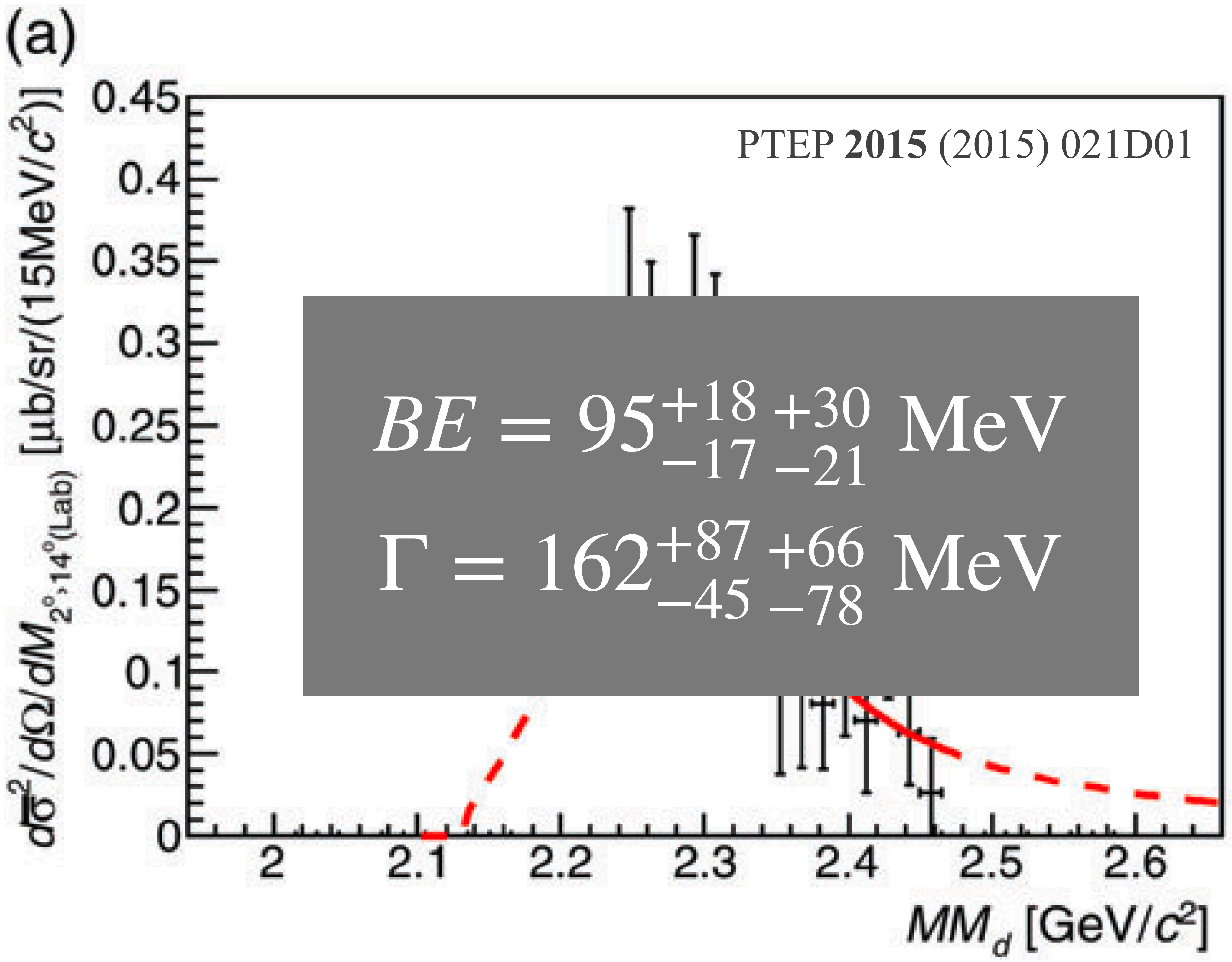


$BE = 42 \pm 3^{+3}_{-4}$ MeV

$\Gamma = 100 \pm 7^{+19}_{-9}$ MeV

J-PARC E27

$d(\pi^{+}, K^{+})\Lambda p/\Sigma^{0}p$

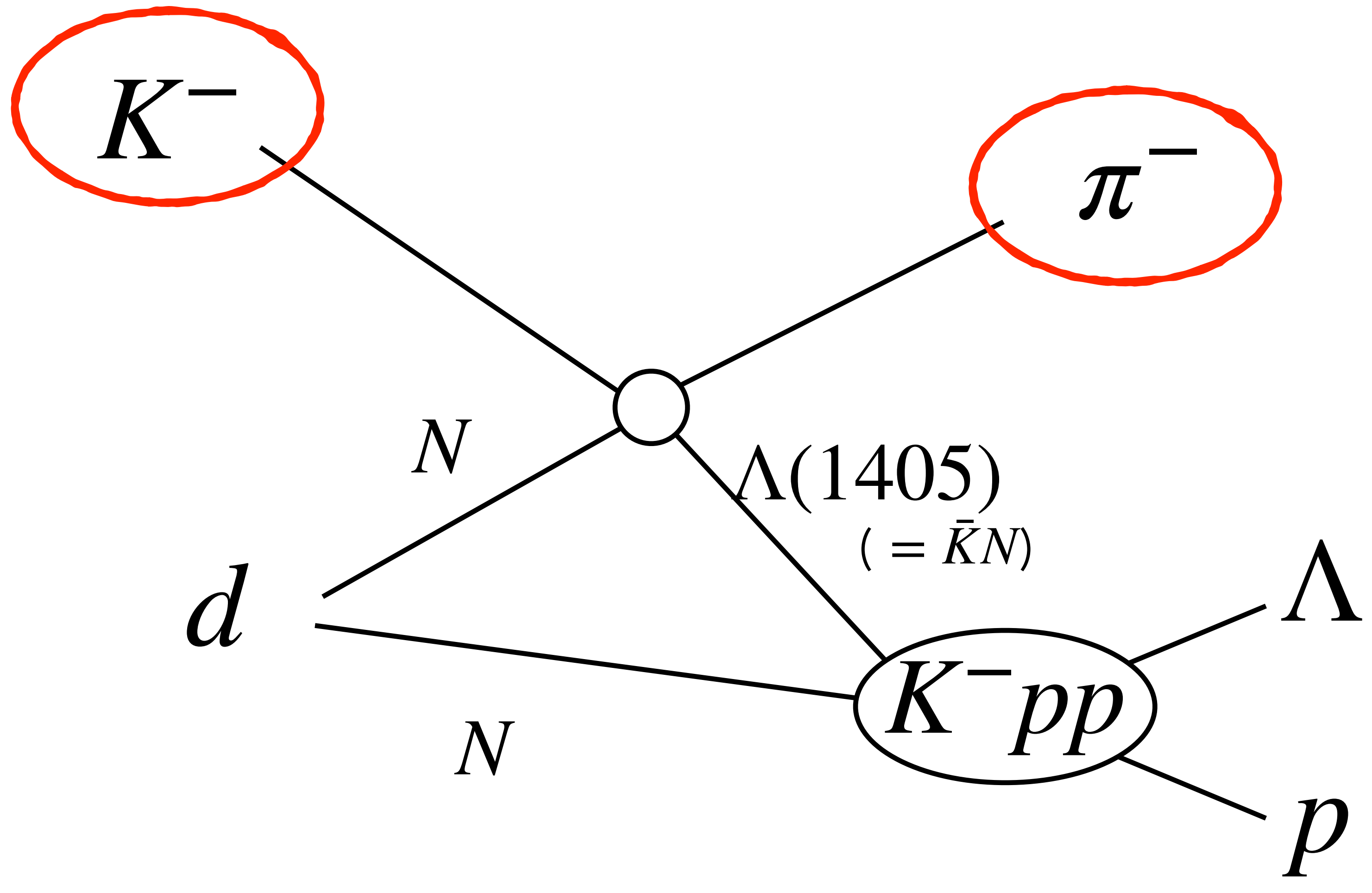


$BE = 95^{+18}_{-17}{}^{+30}_{-21}$ MeV

$\Gamma = 162^{+87}_{-45}{}^{+66}_{-78}$ MeV

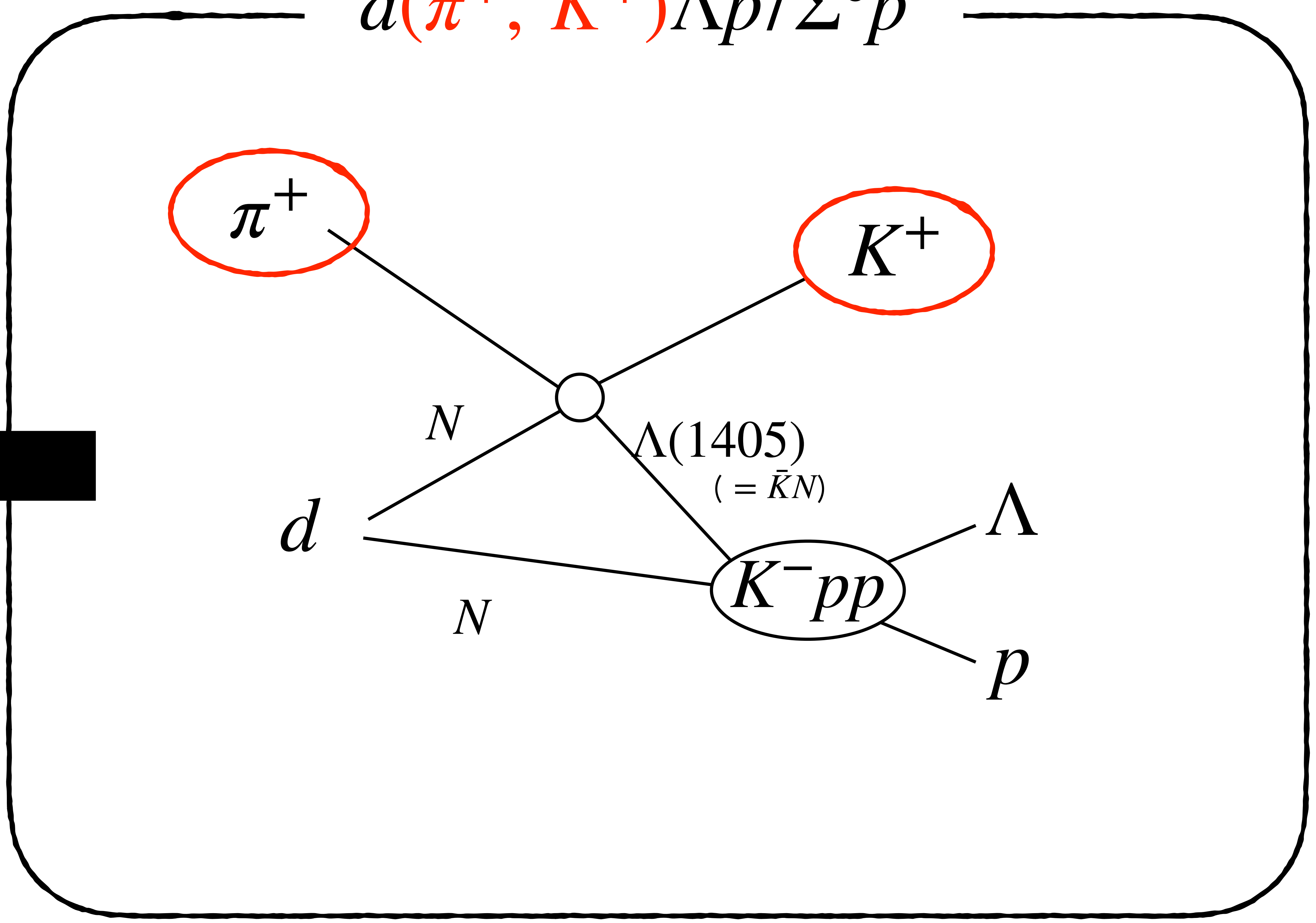
Different state? Need more precision

The (K^-, π^-) reaction can be similarly used.



J-PARC E27

$d(\pi^+, K^+)\Lambda p/\Sigma^0 p$



E31 : $p_K = 1$ GeV/c

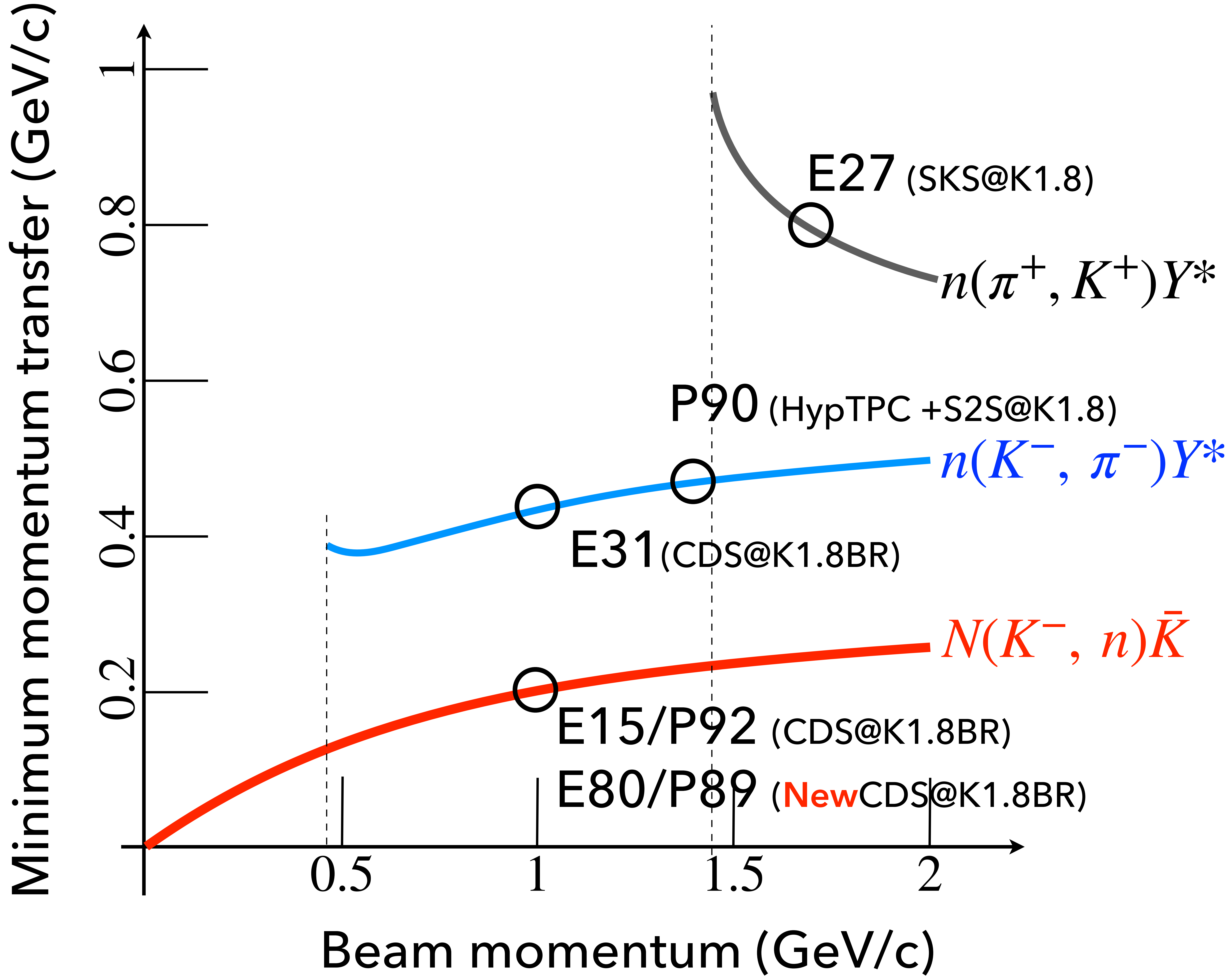
(Study for $\Lambda(1405)$ by the (K^-, n) reaction)

P90 : $p_K = 1.4$ GeV/c

(Study for ΣN cusp by the (K^-, π^-) reaction)

Results with the (K^-, π^-) reaction will come in the future.

Momentum transfer in each reaction

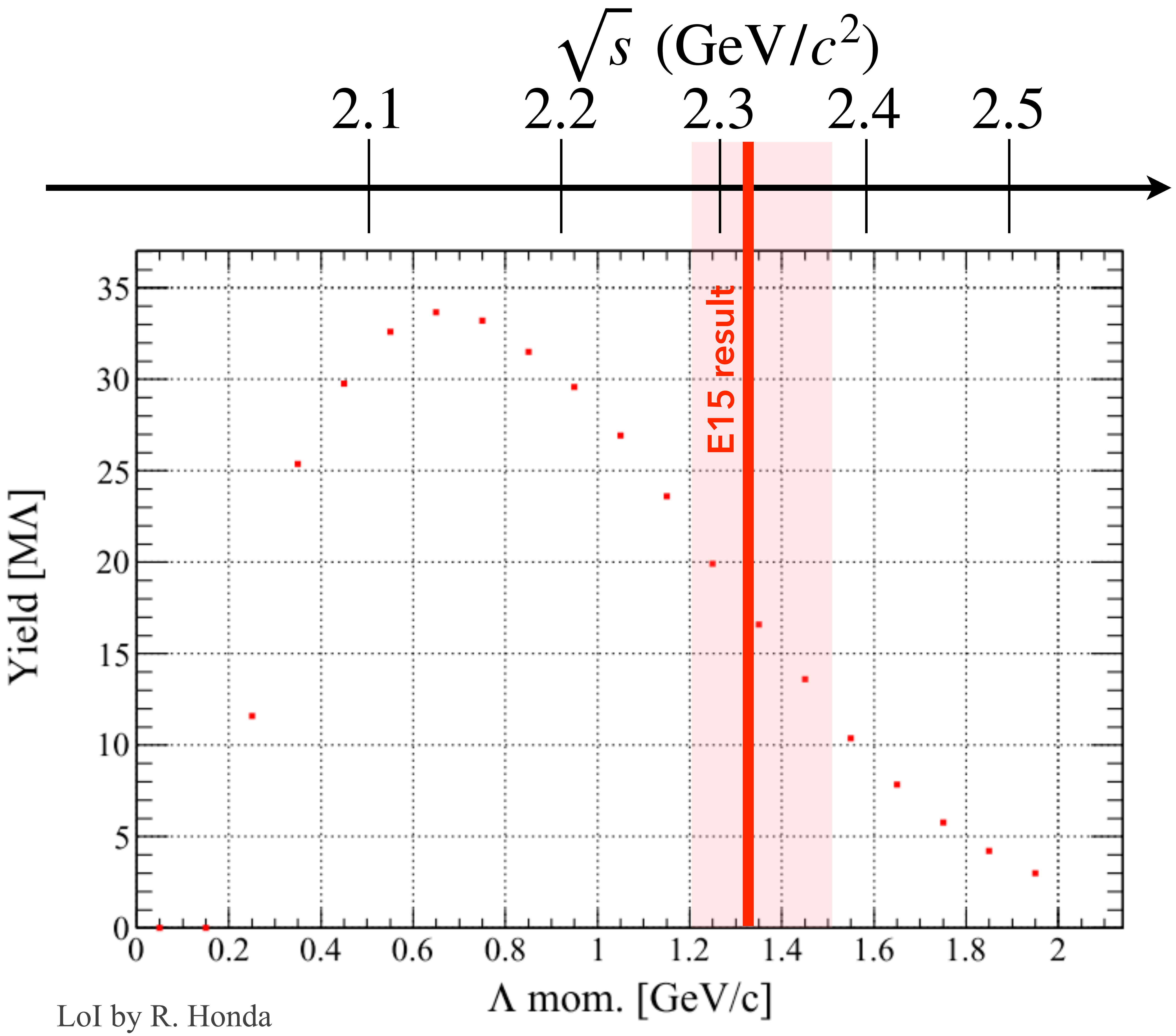


Wide q-region is covered.

Measurement is done with different detector systems.

J-PARC HEF is suitable & unique facility to study for kaonic nuclei.

Another possibility to study $K^{-}pp$



LoI by R. Honda
https://j-parc.jp/researcher/Hadron/en/pac_2007/pdf/LoI_2020-08.pdf

Λp scattering @ High-p beam-line

p_{Λ} : 1.2 – 1.5 GeV/c is region of interest.

➡ Enough yield is expected.

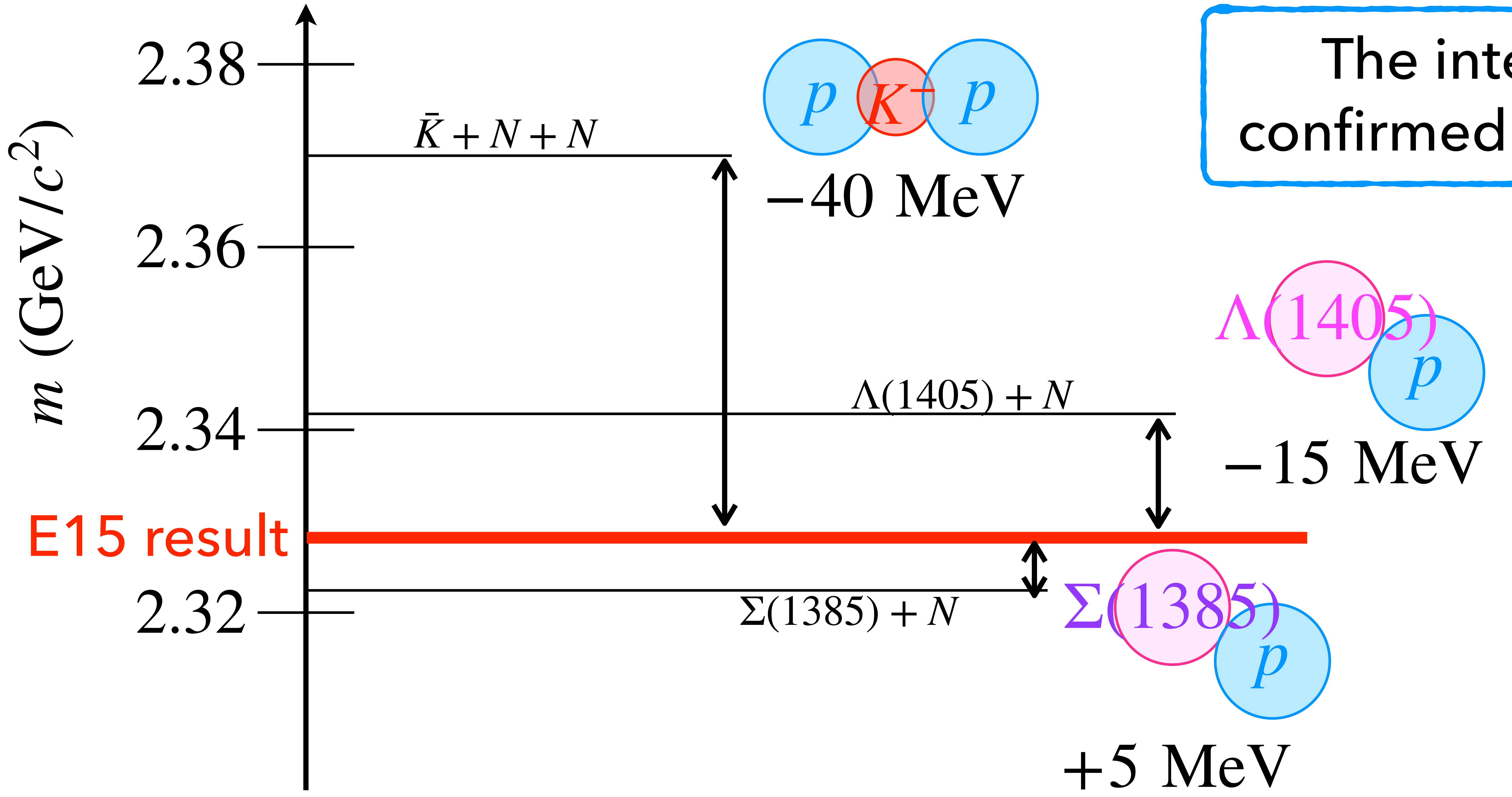
Moreover,

Parity might be determine by angular dist.

Internal structure of $K^- pp$

Although the most natural interpretation is $K^- pp$,

$N_B = 2$ & $S = -1$ possibilities are $K^- pp$ & $Y^* N$



The internal structure of $K^- pp$ will confirmed with systematic investigation.

To confirm existence of $\bar{K}$-nuclei more robustly

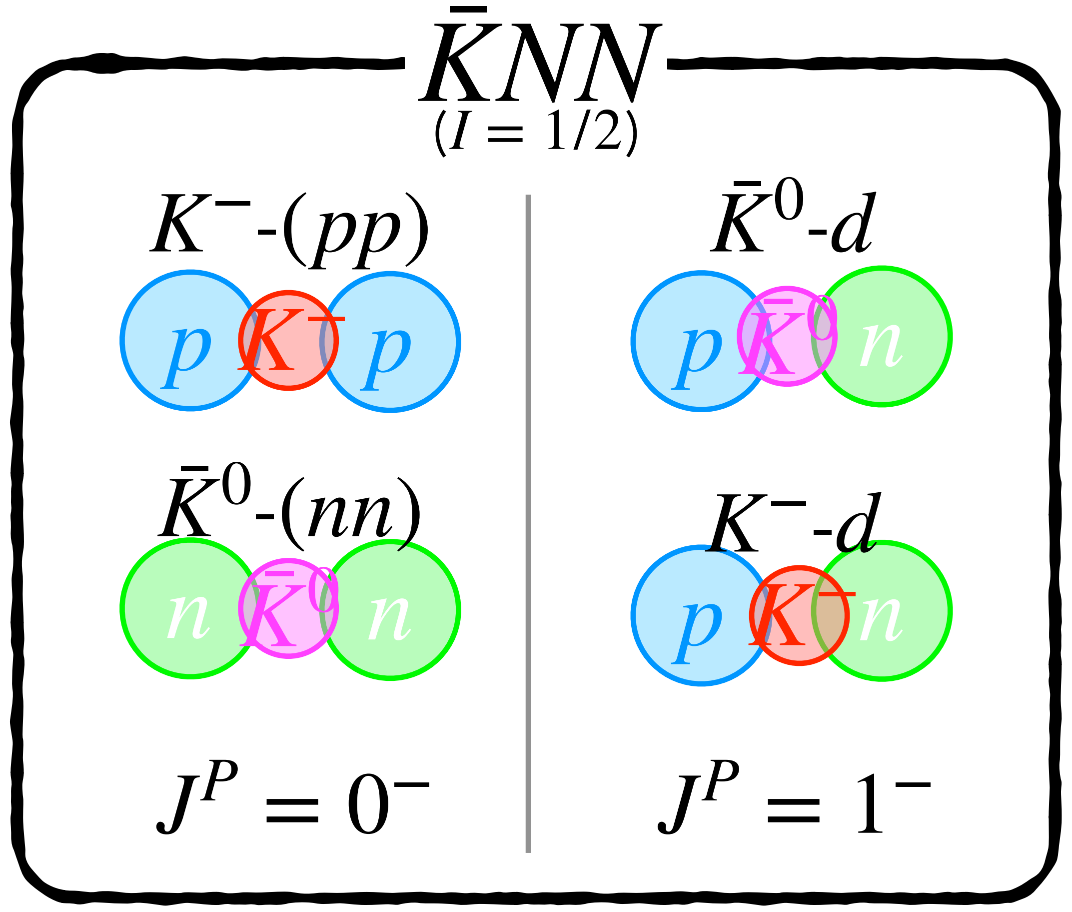
Systematic study for $\bar{K}$-nuclei

To confirm internal structure of $\bar{K}$-nuclei

More careful study for K^-pp

(our) Future plan of systematic investigation

What we need to investigate

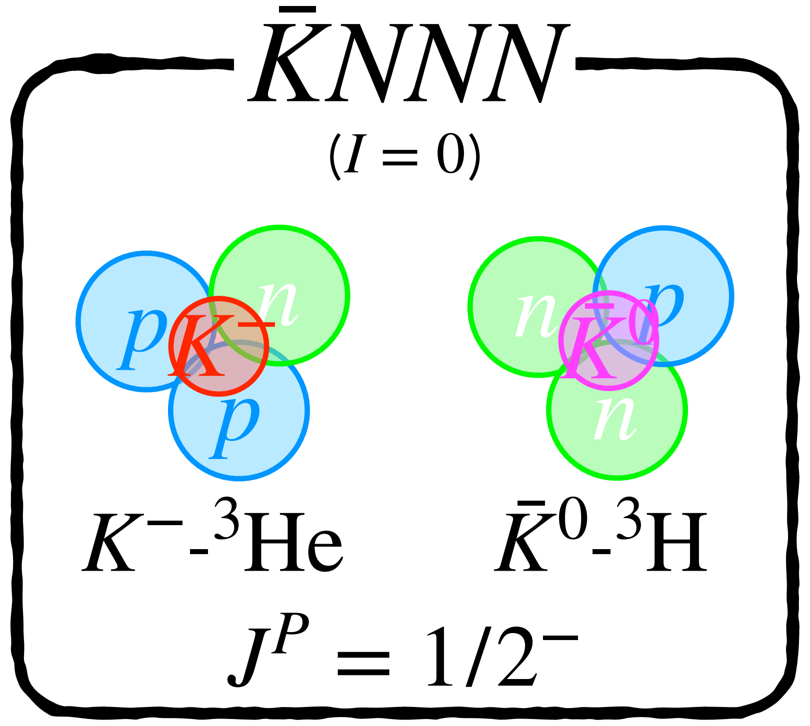


Existence of isospin partner of observed $K^- pp$

$\bar{K}^0 nn$

Existence of heavier kaonic nuclei

The next lightest system, $K^- ppn$



Internal structure of $\bar{K}$-nuclei

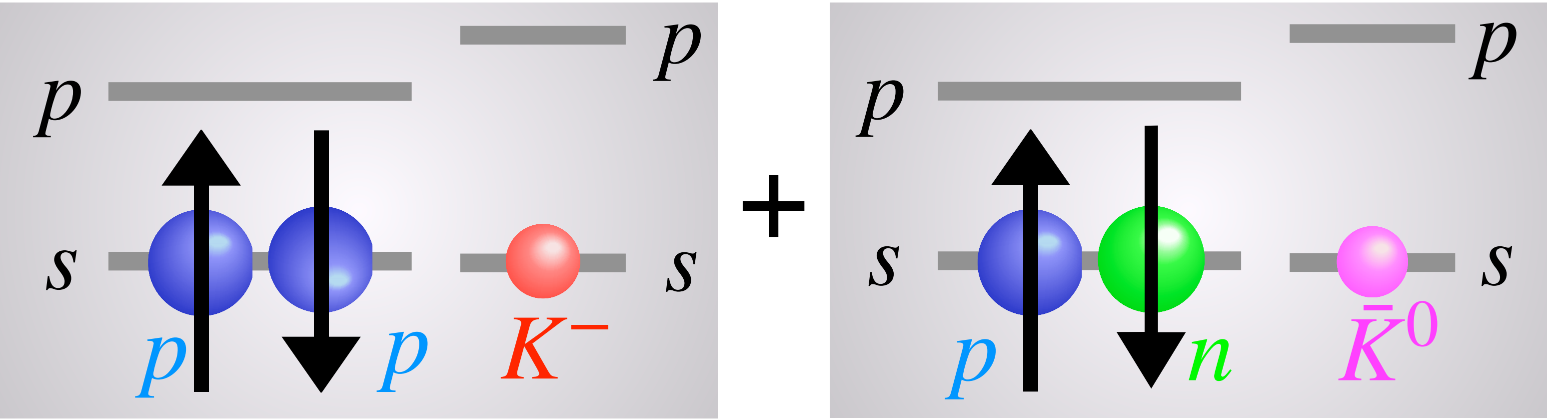
Spin and parity (next page)

Internal structure & spin-parity

There are two possible J^P as for the $\bar{K}NN$ ground state.

$$\text{" }(NN)_{(I.sym \times S.asym)} \otimes \bar{K}\text{ "}$$

$$J^P = 0^-$$

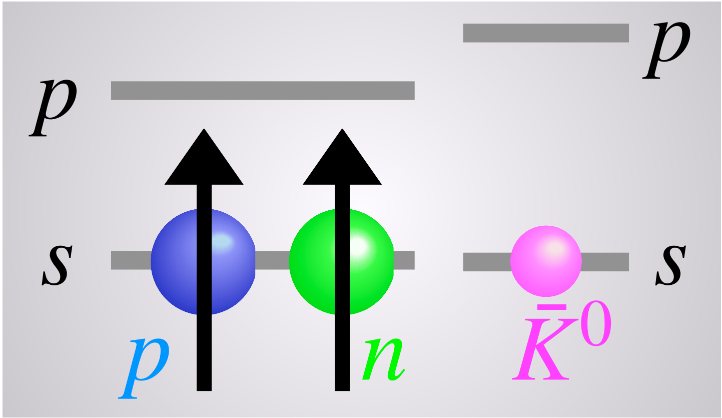


$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{3}{1}$$

Deeper bound expected

$$\text{" }(NN)_{(I.asym \times S.sym)} \otimes \bar{K}\text{ "}$$

$$J^P = 1^-$$



$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{1}{3}$$

Shallower bound expected

* *Positive parity state should be higher excited state if exist.*

Proposed experiments

with CurrentCDS

P92

Search for $K^- ppn \to \Lambda d$

Dedicated to observe $K^- ppn$ from its two-body decay

$(K^- ppn \to \Lambda d \to p\pi^- d)$

with NewCDS (next page)

P89

Spin and parity

Decay branch

Search for $\bar{K}^0 nn \to \Lambda n / \Sigma^- p$

E80

Search for $K^- ppn \to \Lambda d / \Lambda pn$

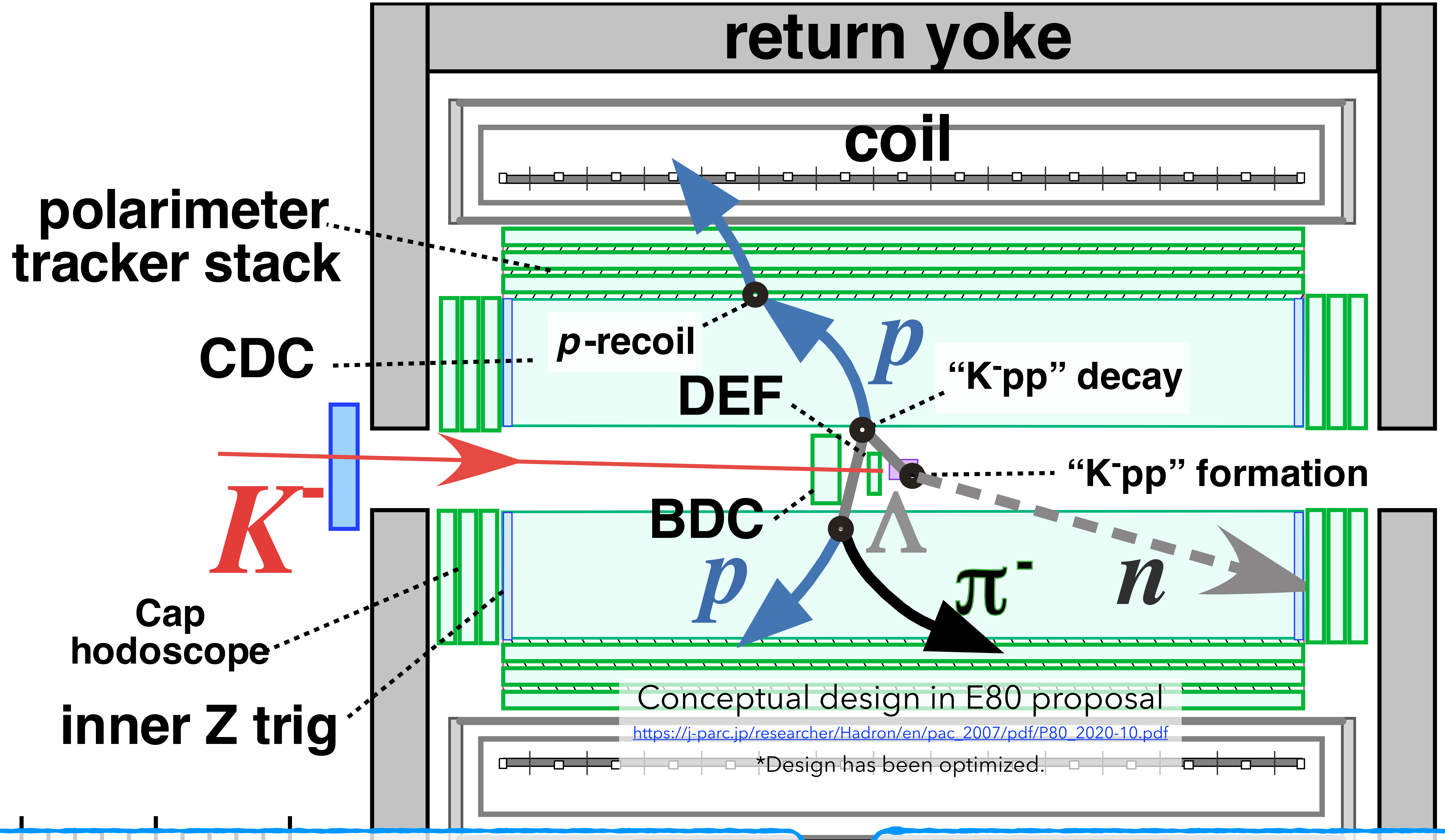
Decay branch

$(J^P?)$

$K^- pp$ production by (K^-, d)

Reaction mechanism can be confirmed with $\sim 4\pi$ spectrometer

NewCDS

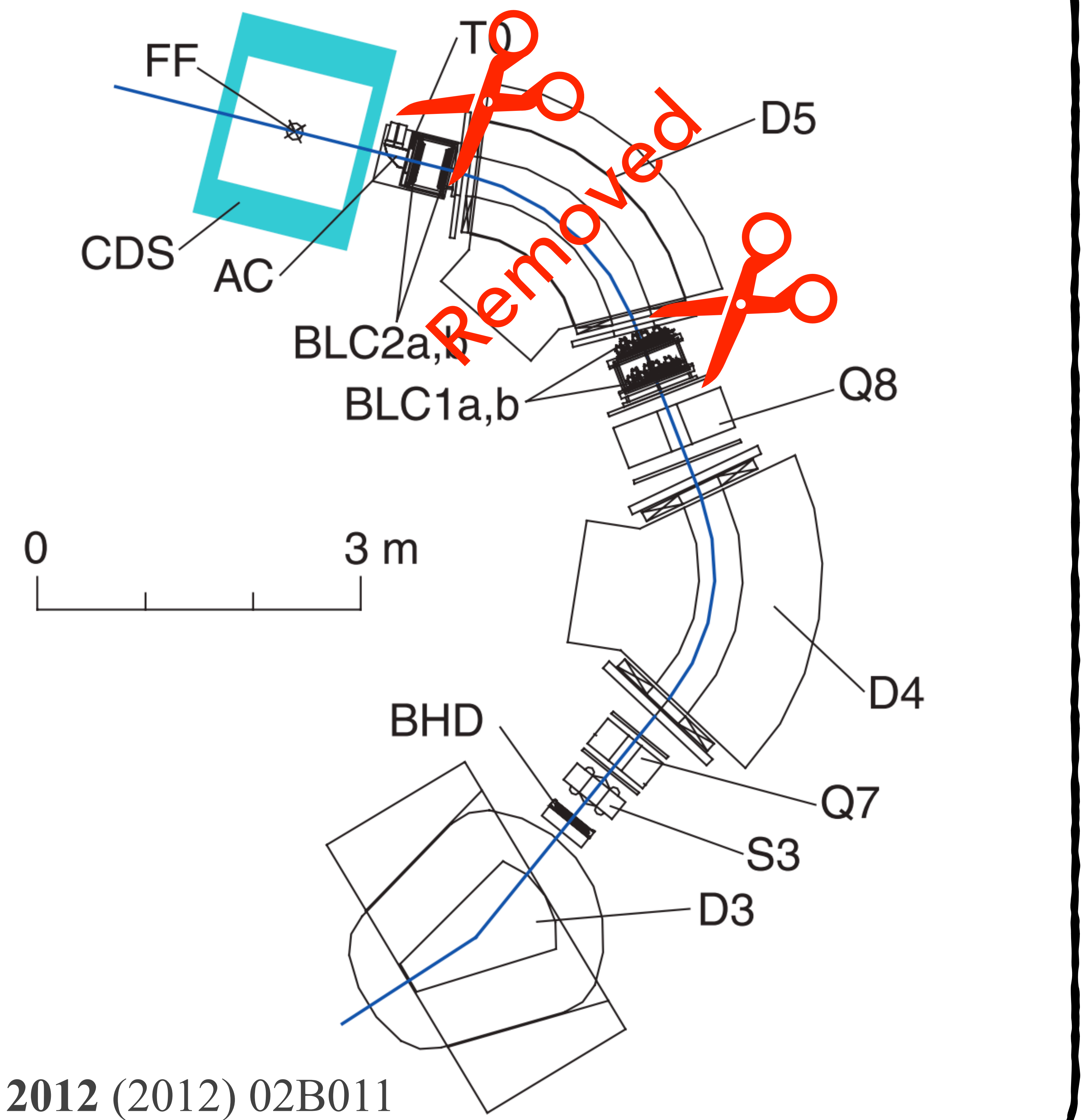


$\sim 4\pi$ acceptance for charged & neutron

Polarimeter system for p-spin measurement

K1.8BR beam-line modification plan

Current K1.8BR

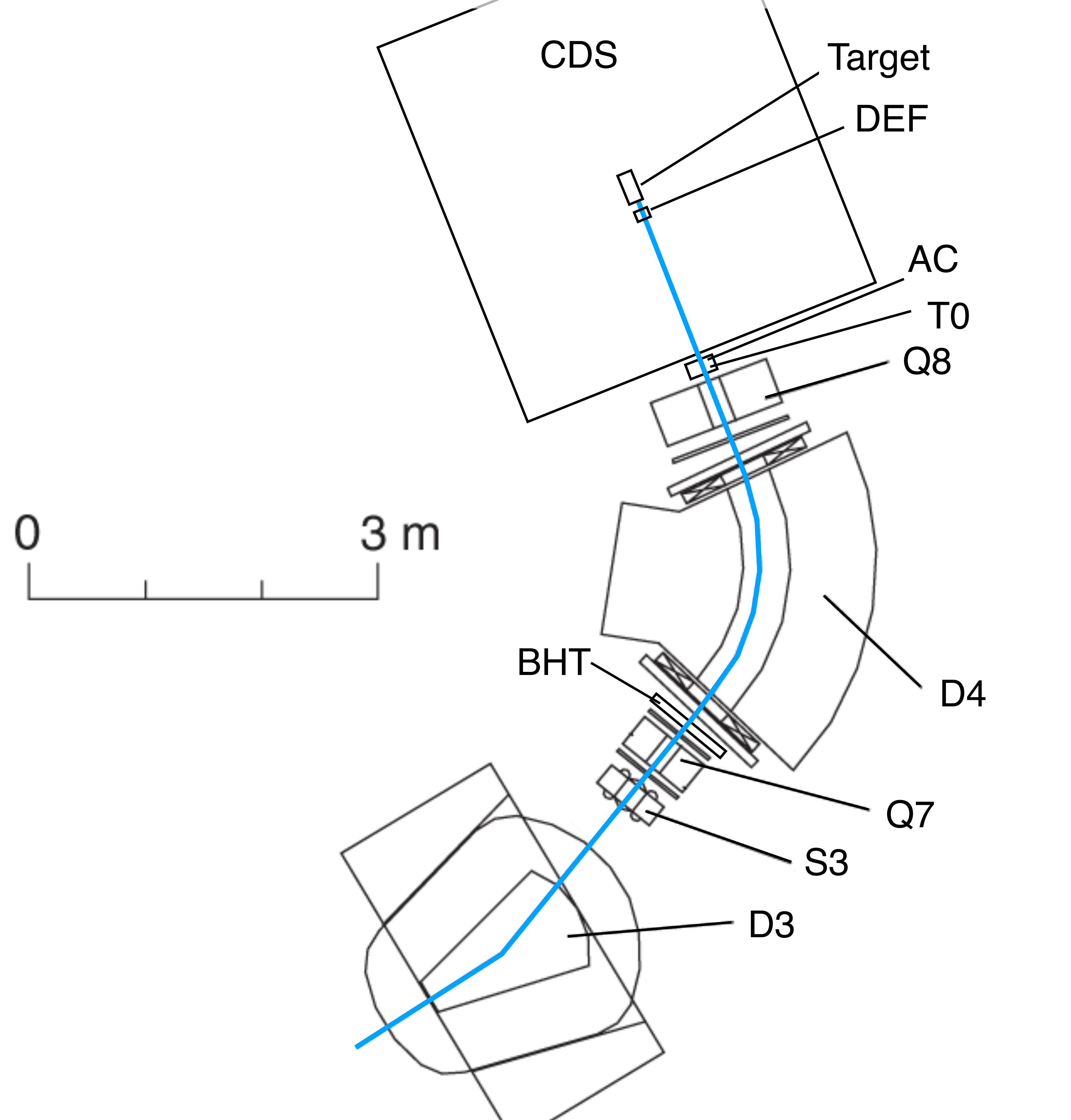


PTEP **2012** (2012) 02B011

Planned modification

Conceptual design in E80 proposal

https://j-parc.jp/researcher/Hadron/en/pac_2007/pdf/P80_2020-10.pdf

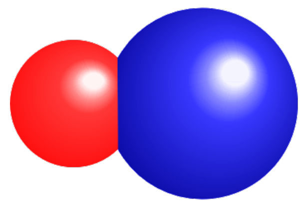


$\sim$ 1.4times K^--beam intensity @ $p_K = 1$ GeV/c with keeping beam focusing.

New programs for kaonic nuclei

– Further investigation of $\bar{K}NN$ & Searching for lighter & heavier systems –

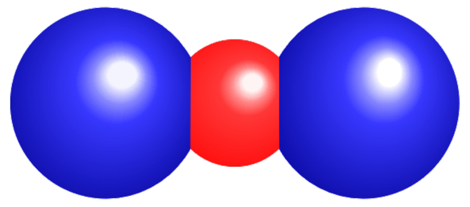
Lighter system



$\Lambda(1405) = K^{-}p$

$\bar{K}NN$ system

P89



J^P determination

Study for $\bar{K}^0 nn$

Relation to Λ^*

Decay branch

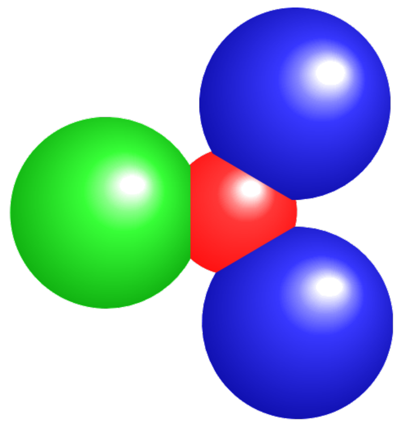
Large Γ

Heavier system

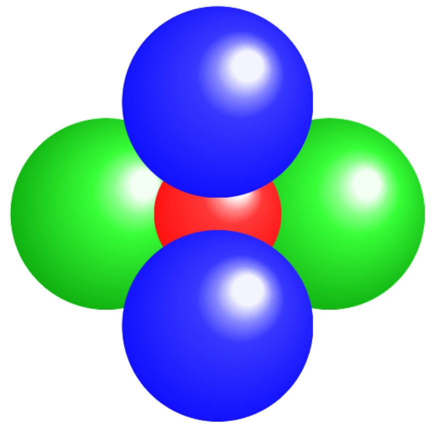
E80

P92

$\bar{K}NNN$ system



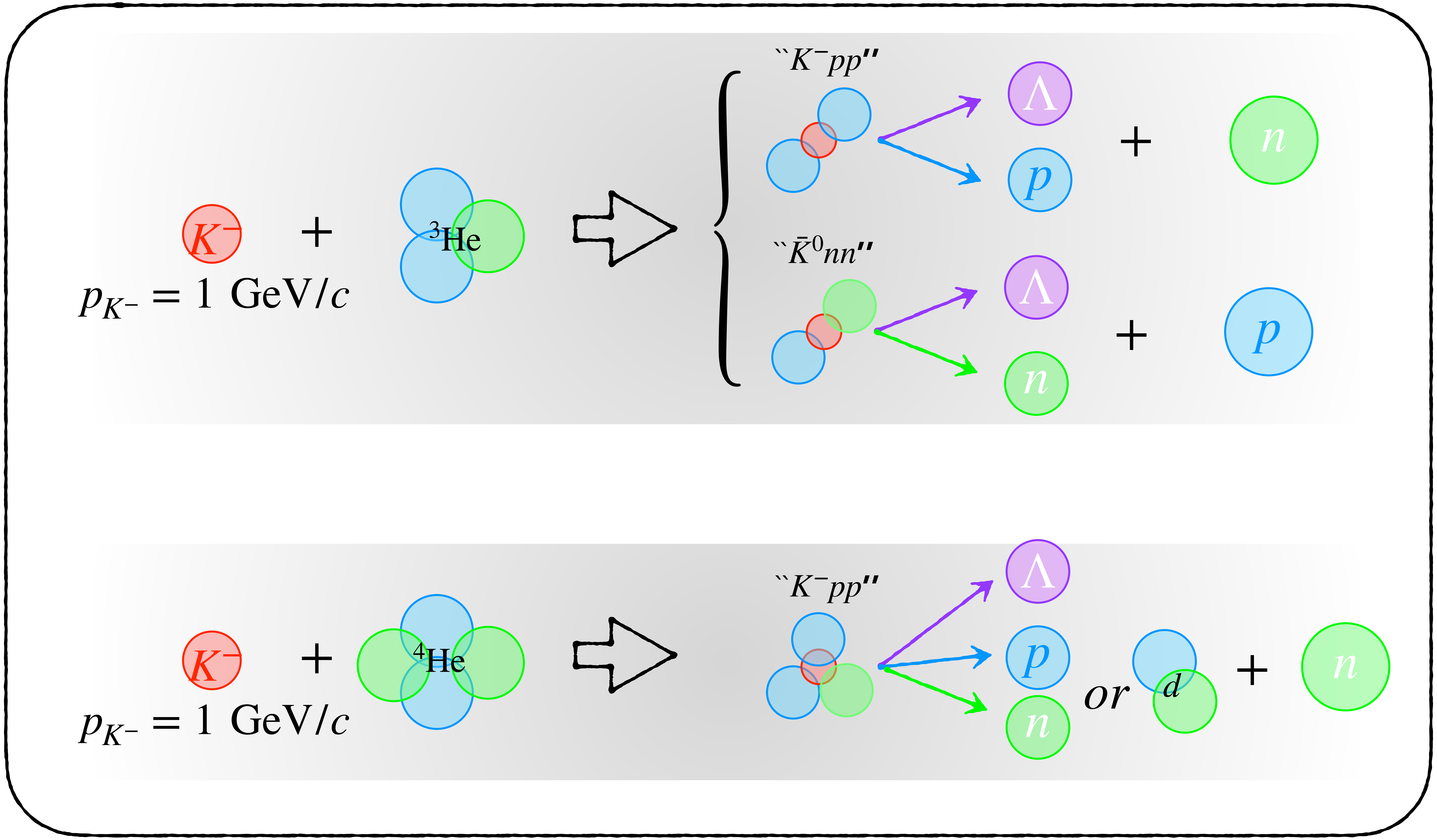
$\bar{K}NNNN$ system



$\bar{K}\alpha\alpha$ system

How to measure $\bar{K}^0nn$ / K^-ppn

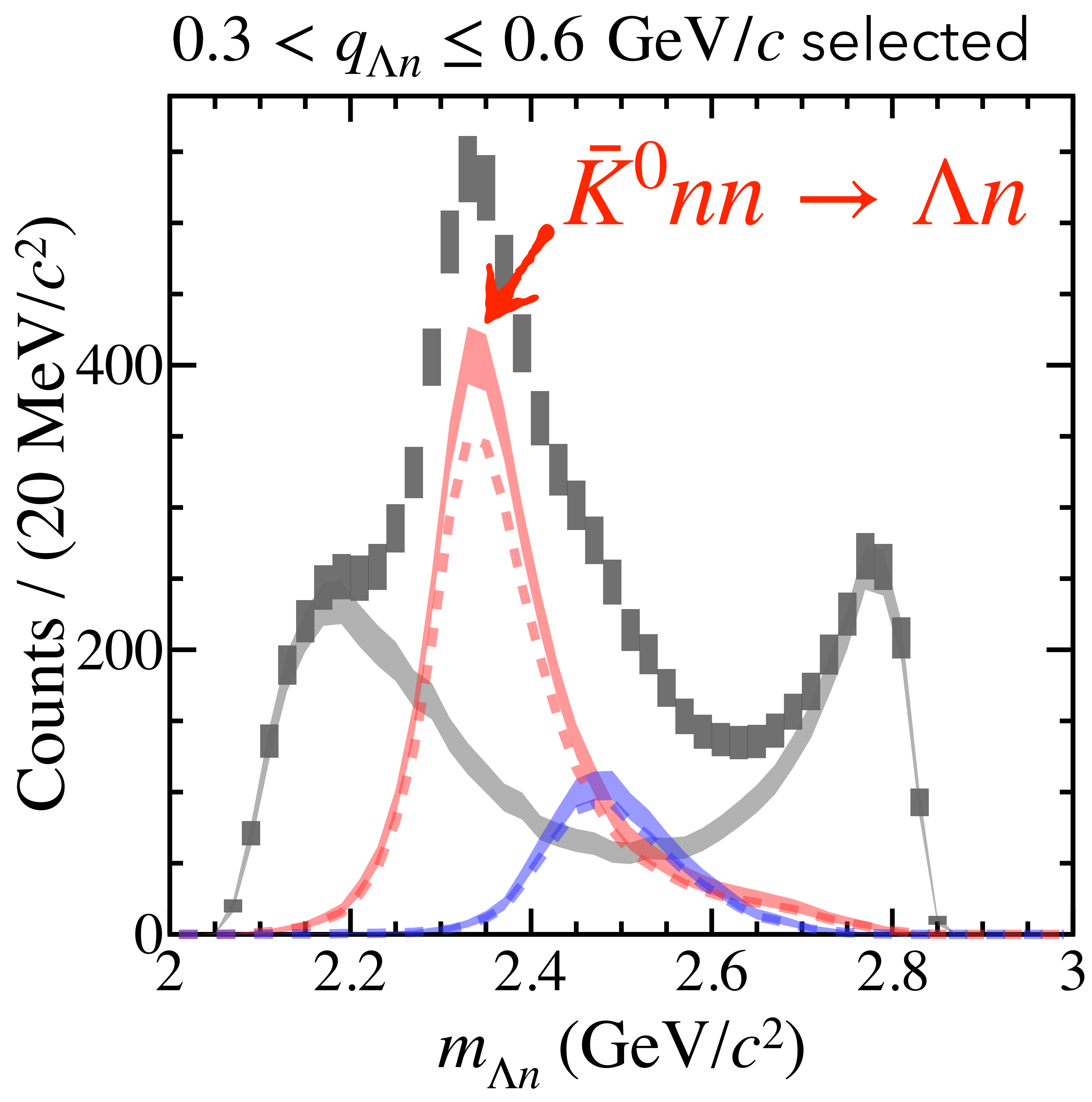
How to produce/detect K^-pp / $\bar{K}^0nn$ / K^-ppn



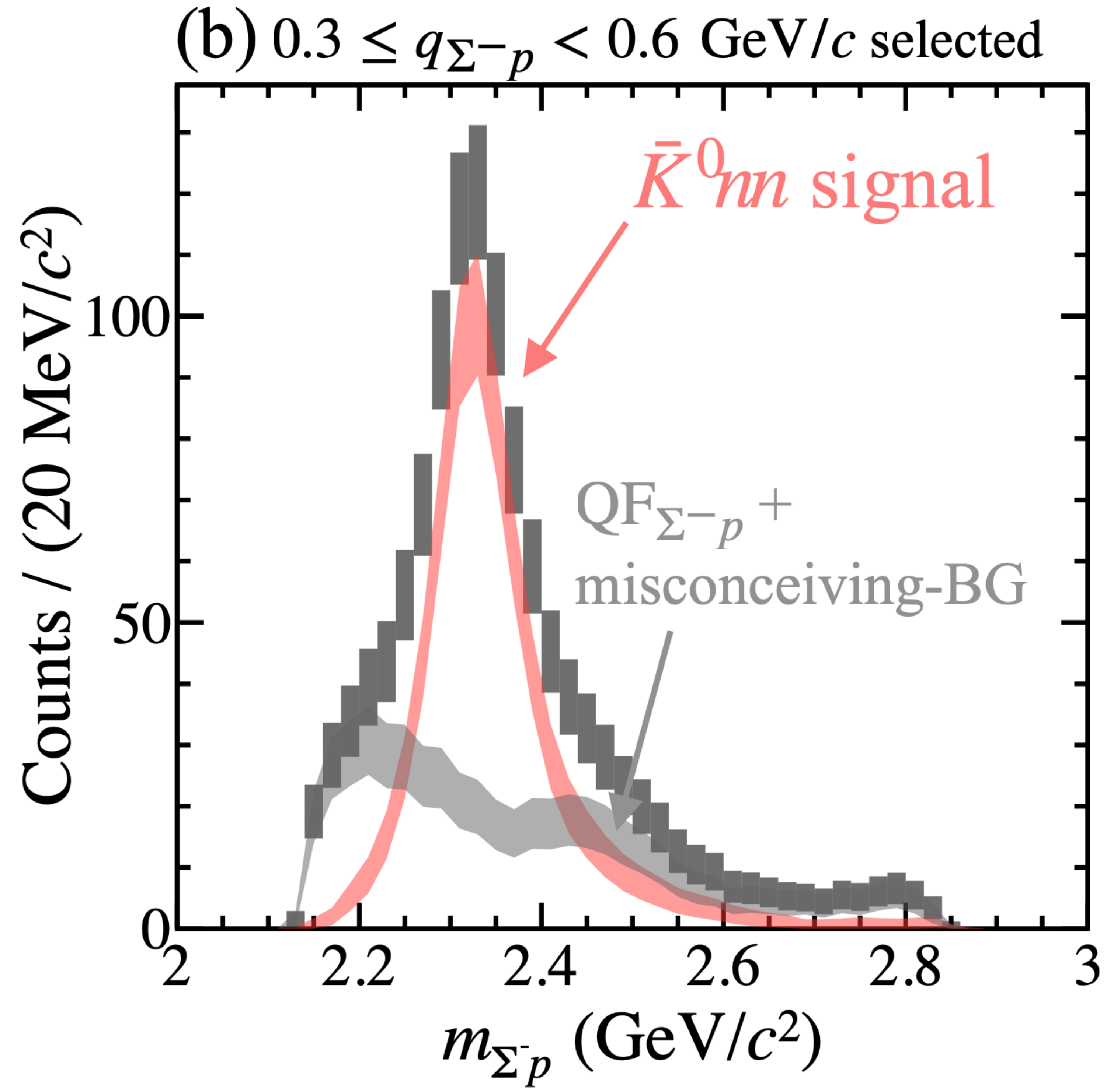
Expected spectra of $\bar{K}^0 nn$

By Λn decay

*Assuming $J^P = 0^-$ (strict case)



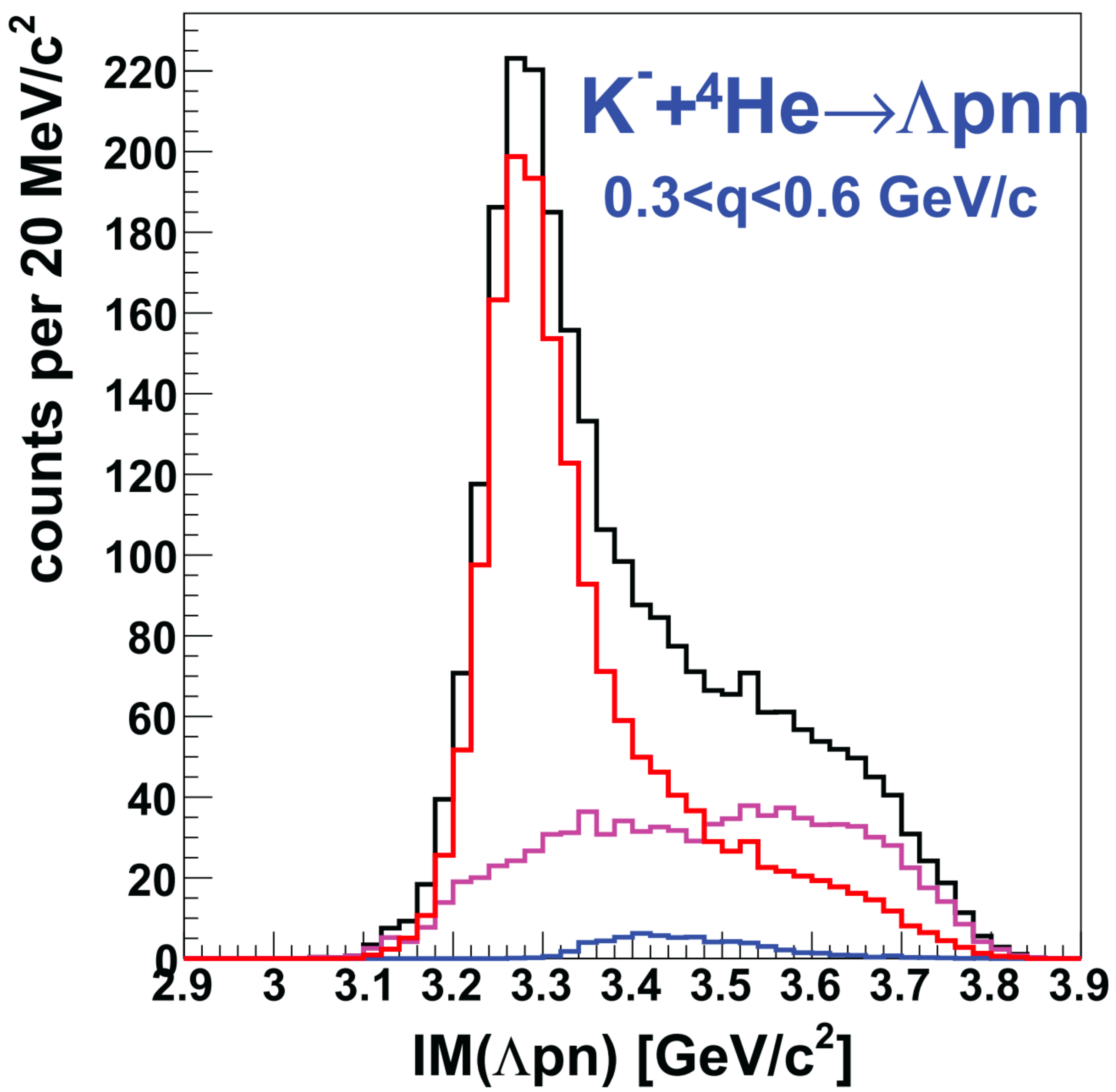
By $\Sigma^- p$ decay



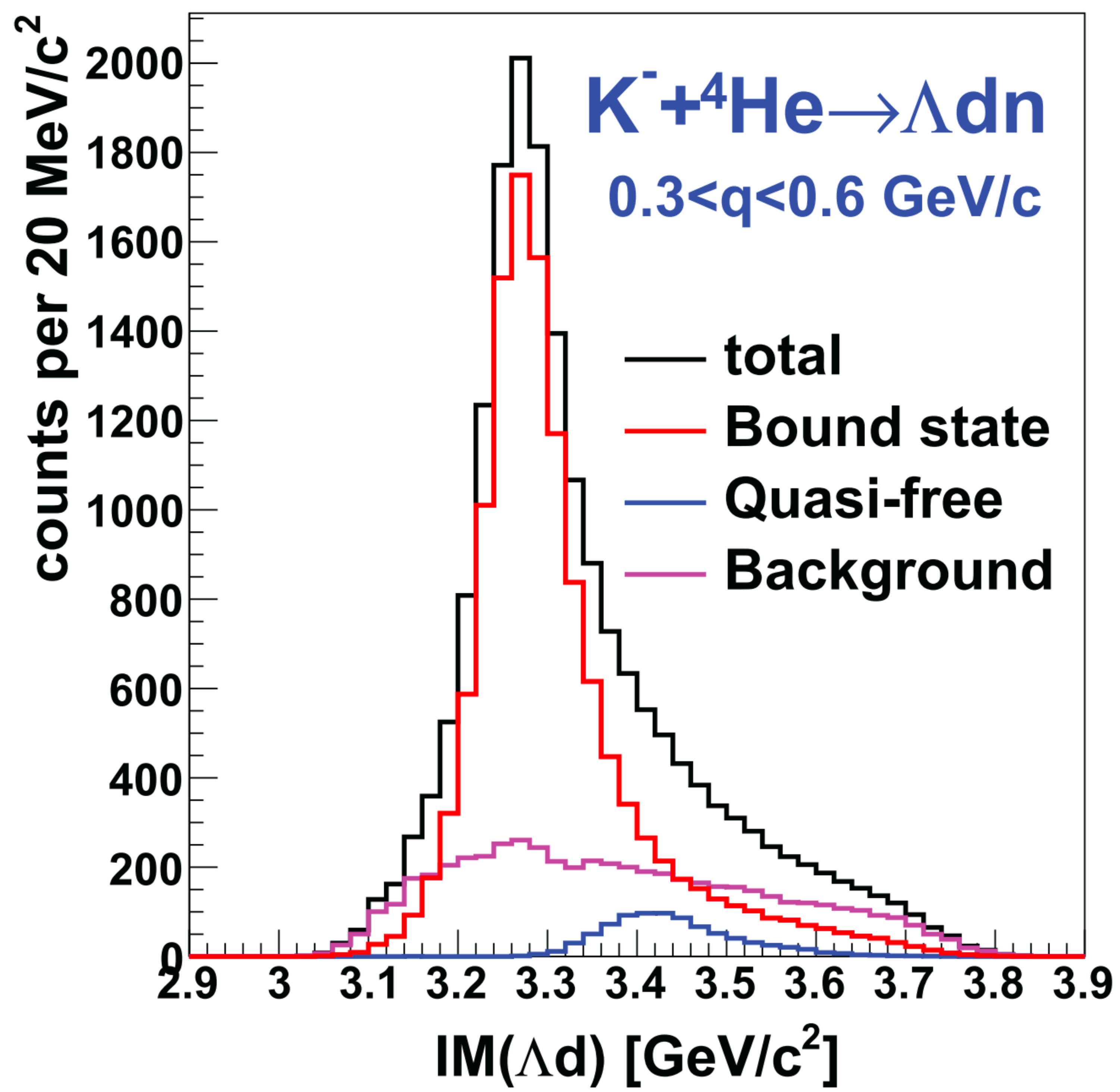
We would observe distinct peaks of $\bar{K}^0 nn \rightarrow \Lambda n / \Sigma^- p$

Expected spectra of $K^{-}ppn$

By Λpn decay



By Λd decay



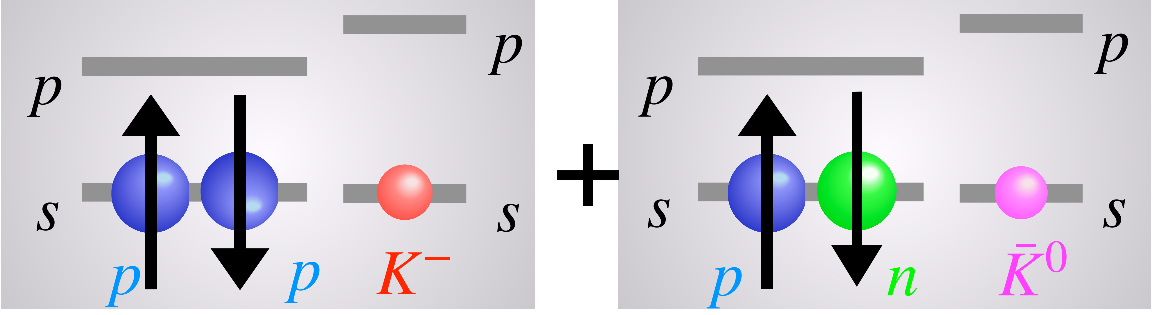
$K^{-}ppn$ can be reconstructed by both Λpn / Λd decay modes.

How to determine J^P of K^-pp

How to determine J^P

– Λp spin-spin correlation ($\alpha_{\Lambda p}$) in $K^- pp \to \Lambda p$ decay –

$J^P = 0^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

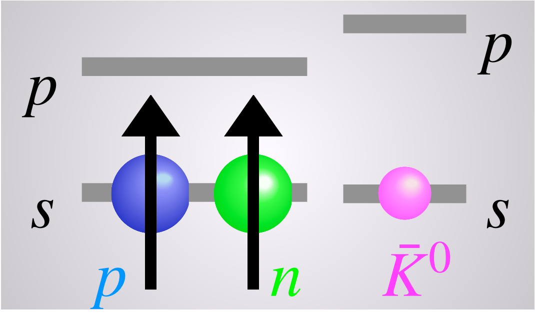
To be $J = 0$

$S_{\Lambda p} = 1$

$\alpha_{\Lambda p} = +1$

Spin parallel

$J^P = 1^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 1$

$BR = 1/3$ $S_{\Lambda p} = 0$ + $S_{\Lambda p} = 1$ $BR = 2/3$

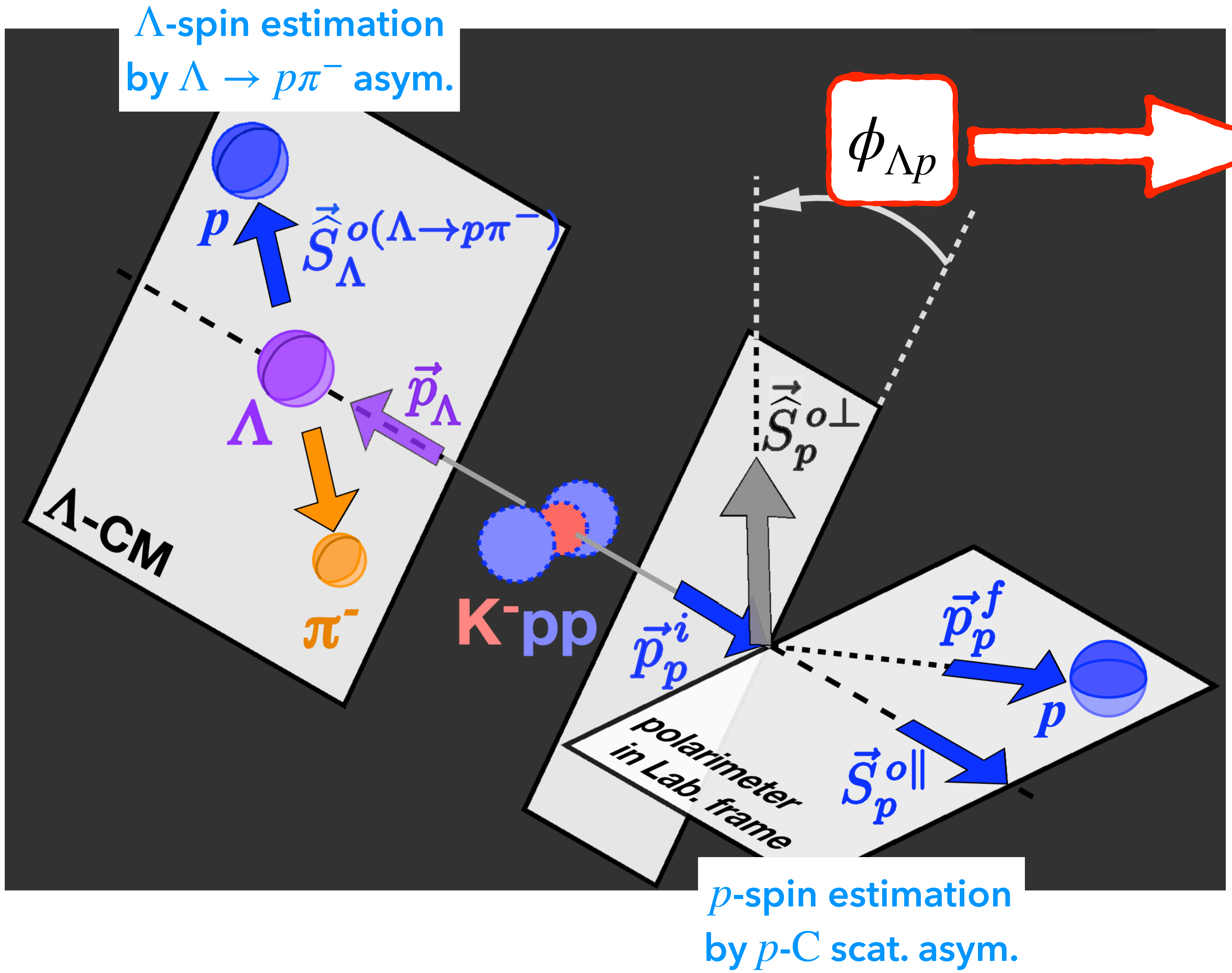
$\alpha_{\Lambda p} = -1$ + $\alpha_{\Lambda p} = +1$

Spin anti-parallel *Spin parallel*

We can deduce J^P from $\alpha_{\Lambda p}$ measurement.

How to measure spin-spin correlation

– Spin alignment measurement by $\Lambda \to p\pi^-$ & p-C scattering –



Spin-spin correlation on ϕ-asymmetry

$$N(\phi_{\Lambda p}) = N_0 \cdot (1 + r^{(J^P)} \cdot \alpha_{\Lambda p} \cos \phi_{\Lambda p})$$

$r^{(J^P)}$: asymmetry reduction factor defined by;

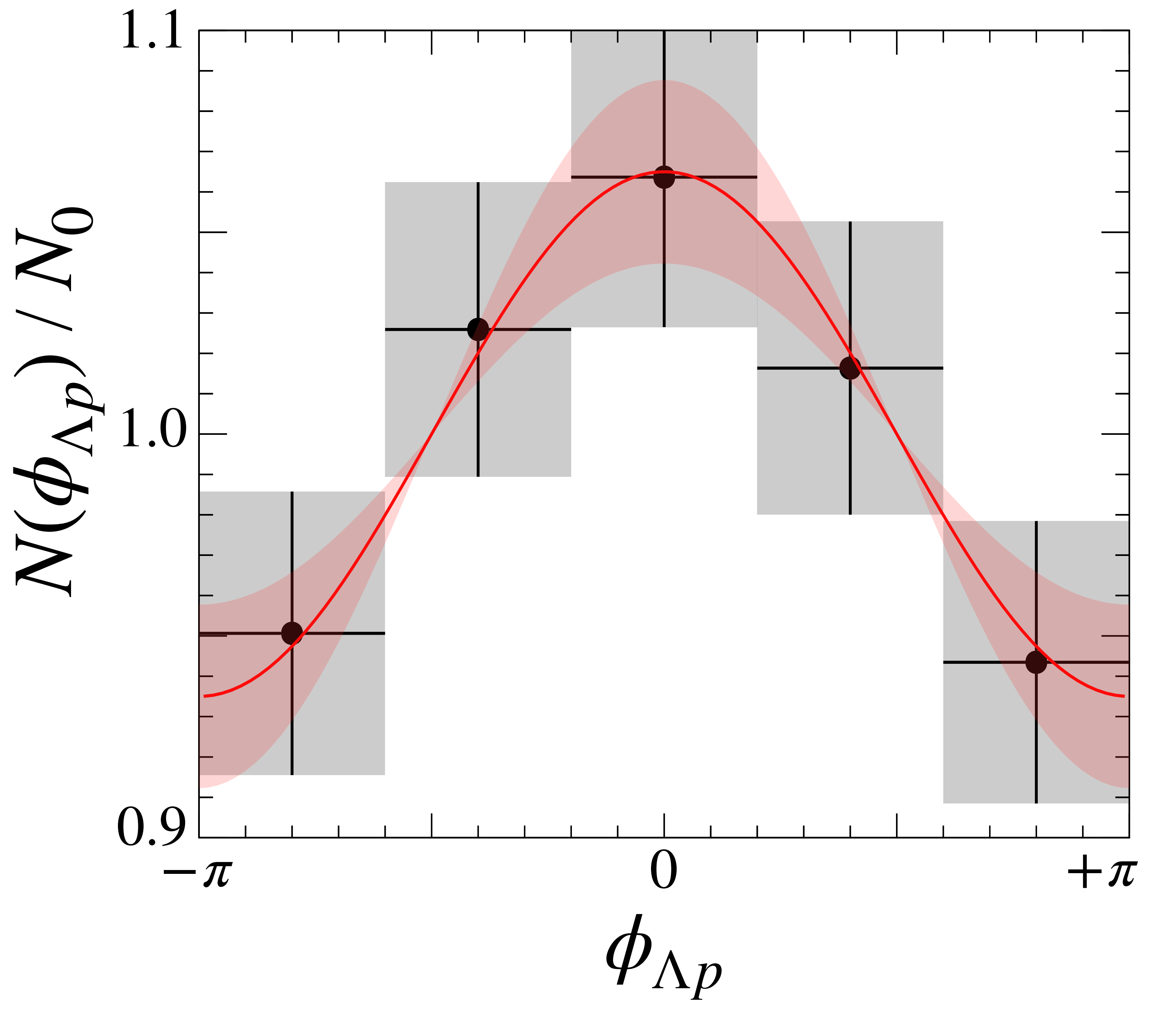
- α_- : Λ asym. parameter
- A_{pC} : Analyzing power
- $f_{\vec{S}_\Lambda}$: Spin distribution
- B : Magnetic field
- $B_{\bar{K}}$: Binding energy
- q : Momentum transfer

We can observe $\alpha_{\Lambda p}$ from $\phi_{\Lambda p}$-distribution.

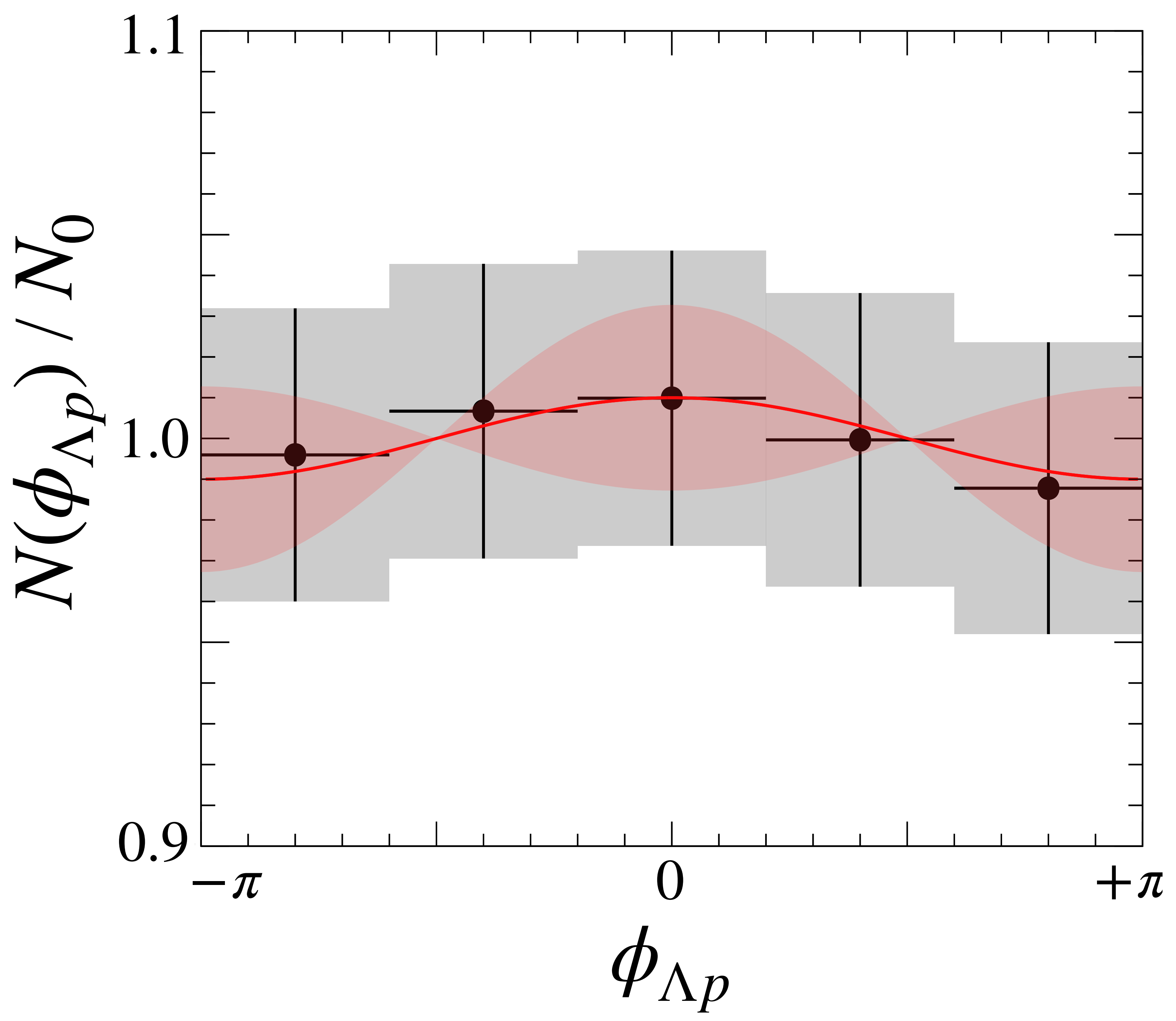
Expected spectra

– To measure $\phi_{\Lambda p}$-asymmetry for J^P determination –

$J^P = 0^-$



$J^P = 1^-$



We would exclude $J^P = 1^-$ with **95%** confidence level from **only $\phi_{\Lambda p}$-asym**.

Summary

J-PARC HEF is suitable & unique facility
to study for kaonic nuclei.

Proposed experiments

with CurrentCDS

P92 — Search for $K^- ppn \to \Lambda d$

Dedicated to observe $K^- ppn$ from its two-body decay

$(K^- ppn \to \Lambda d \to p\pi^- d)$

with NewCDS (next page)

P89 — Spin and parity; Decay branch; Search for $\bar{K}^0 nn \to \Lambda n / \Sigma^- p$

E80 — Search for $K^- ppn \to \Lambda d / \Lambda pn$; Decay branch; $(J^P?)$; $K^- pp$ production by (K^-, d)

Reaction mechanism can be confirmed with $\sim 4\pi$ spectrometer

Thank you for your attention!

= Collaboration =

Experimentalists

RIKEN: H. Asano, K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma, T. Yamaga

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