Kaonic nuclei experiments at J-PARC

Takumi Yamaga (RIKEN)
for the J-PARC E15/E80/P89 collaboration

3rd HEF-ex workshop @ J-PARC
2023.3.14–16

$\bar{K}N$ interaction

$I_{\bar{K}N} = 0$	$\frac{1}{\sqrt{2}}\left(-K^- p + \bar{K}^0 n\right)$	Strong attractive
$I_{\bar{K}N} = 1$	$\bar{K}^0 p$ $\frac{1}{\sqrt{2}}\left(K^- p + \bar{K}^0 n\right)$ $K^- n$	attractive

Possible to make quasi-bound states with $I_{\bar{K}N} = 0$

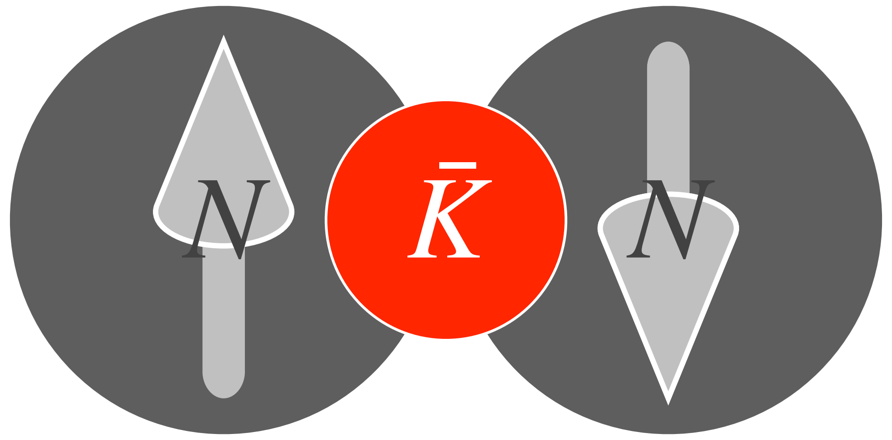
$\Lambda(1405)$

$\bar{K}$-nuclei

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

The lightest $\bar{K}$-nucleus

$J^\pi = 0^-$



$$(\bar{K}[NN]^{I=1})^{I=1/2}$$

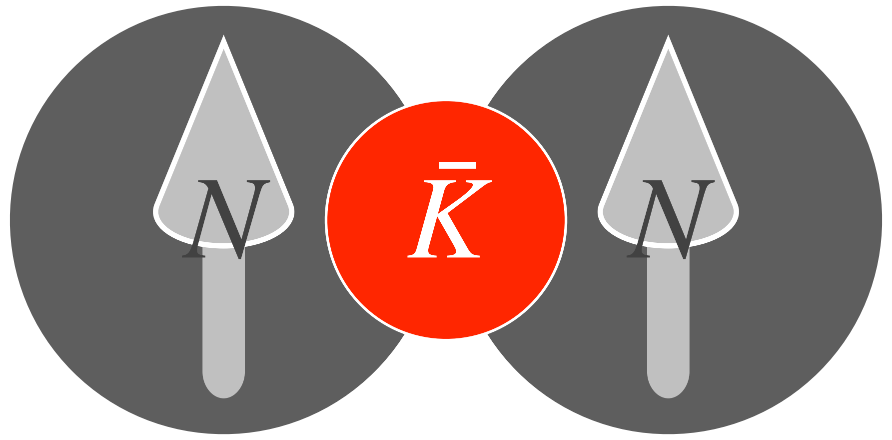
$$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$$

Deeper

$$BE = 25 - 28 \text{ MeV}$$
$$\Gamma = 30 - 60 \text{ MeV}$$

S. Ohnishi et al., PRC **95** (2017) 065202

$J^\pi = 1^-$



$$(\bar{K}[NN]^{I=0})^{I=1/2}$$

$$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$$

Shallower

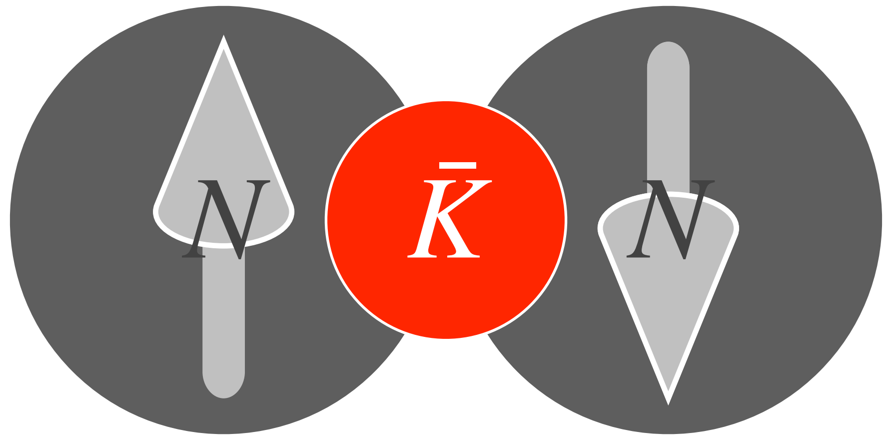
$$BE = 1 - 2 \text{ MeV}$$
$$\Gamma = 40 - 60 \text{ MeV}$$

N. V. Shevchenko, Few Body Syst. **61** (2020) 27

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

The lightest $\bar{K}$-nucleus

$J^\pi = 0^-$



$(\bar{K}[NN]^{I=1})^{I=1/2}$

$I_z = +1/2$ state

"$K^- pp$"

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

$BE = 26 - 28$ MeV
$\Gamma = 31 - 59$ MeV

S. Ohnishi et al., PRC **95** (2017) 065202

$I_z = -1/2$ state

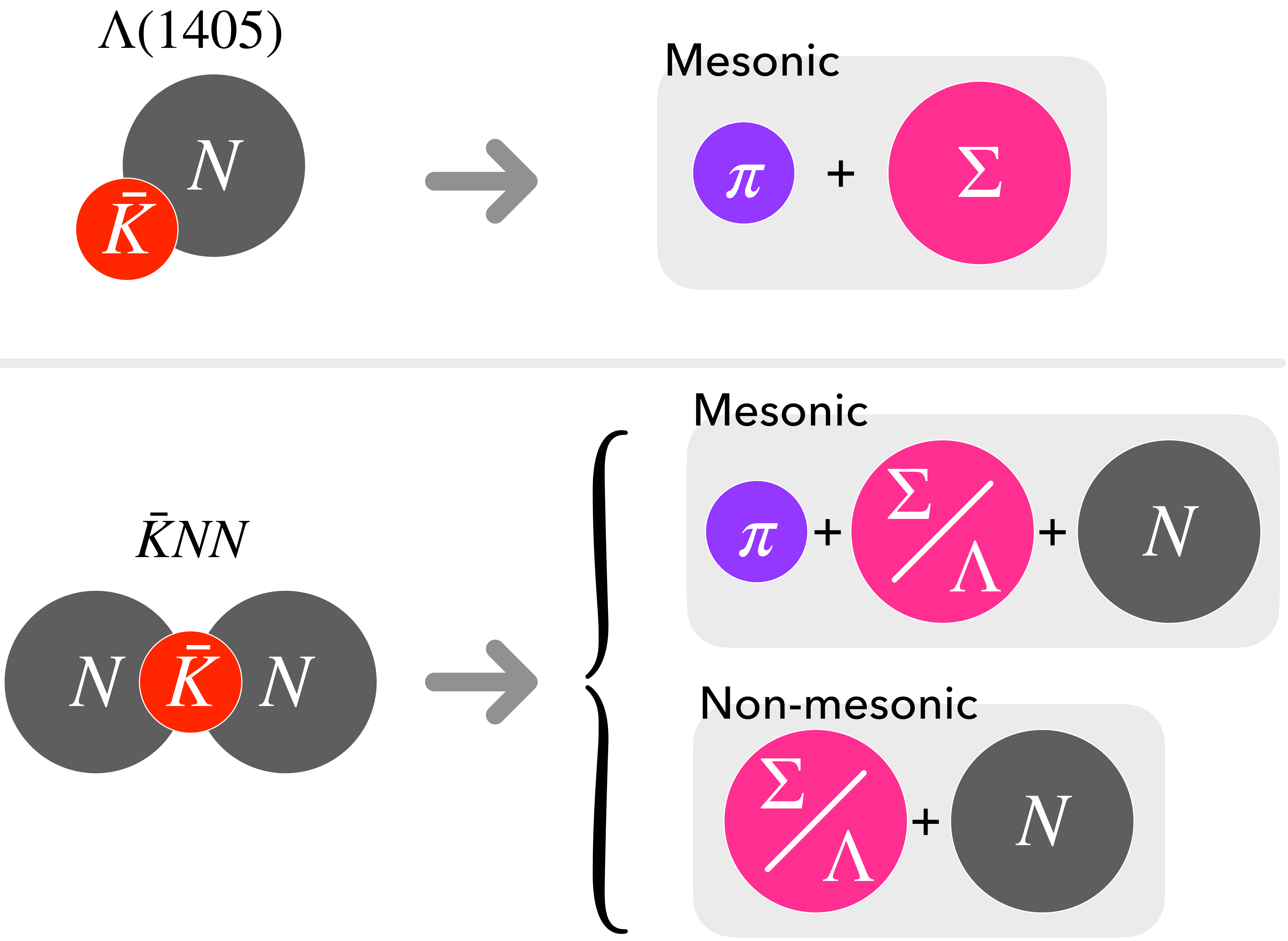
"$\bar{K}^0 nn$"

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

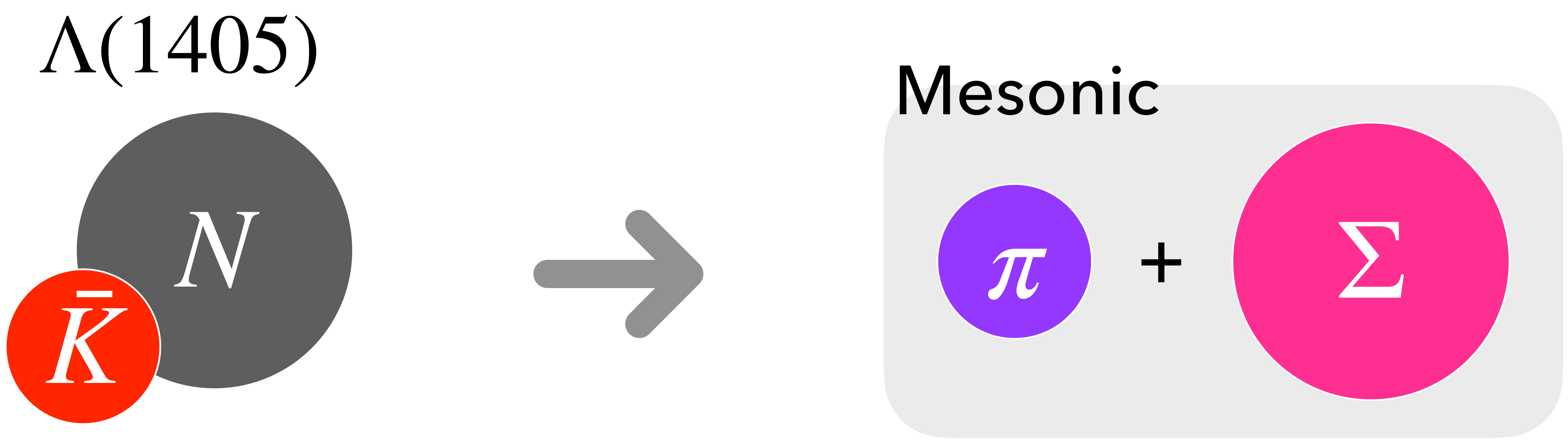
$BE = 25 - 28$ MeV
$\Gamma = 31 - 59$ MeV

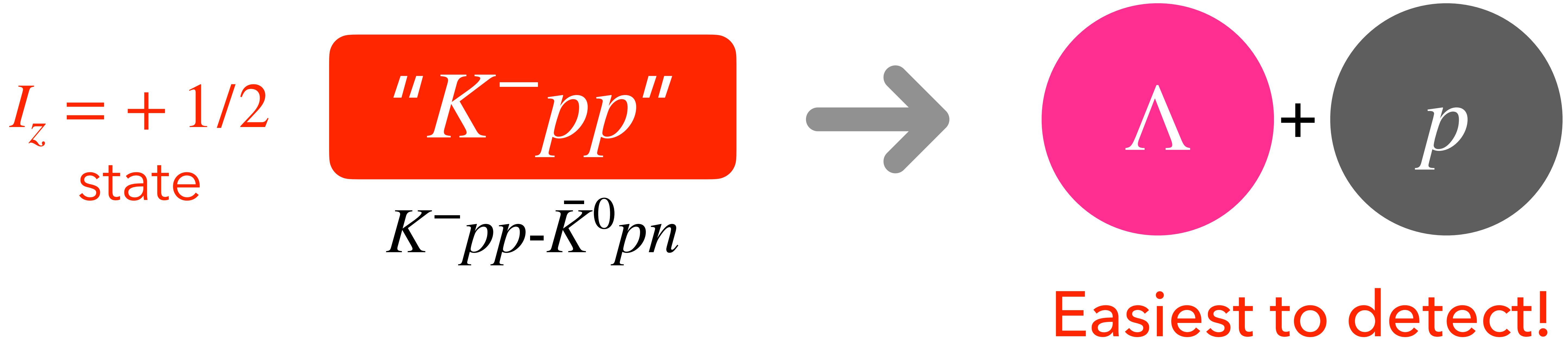
S. Ohnishi et al., PRC **95** (2017) 065202

Decay



Decay


Λ(1405)
N
K̄
Mesonic
π
+
Σ

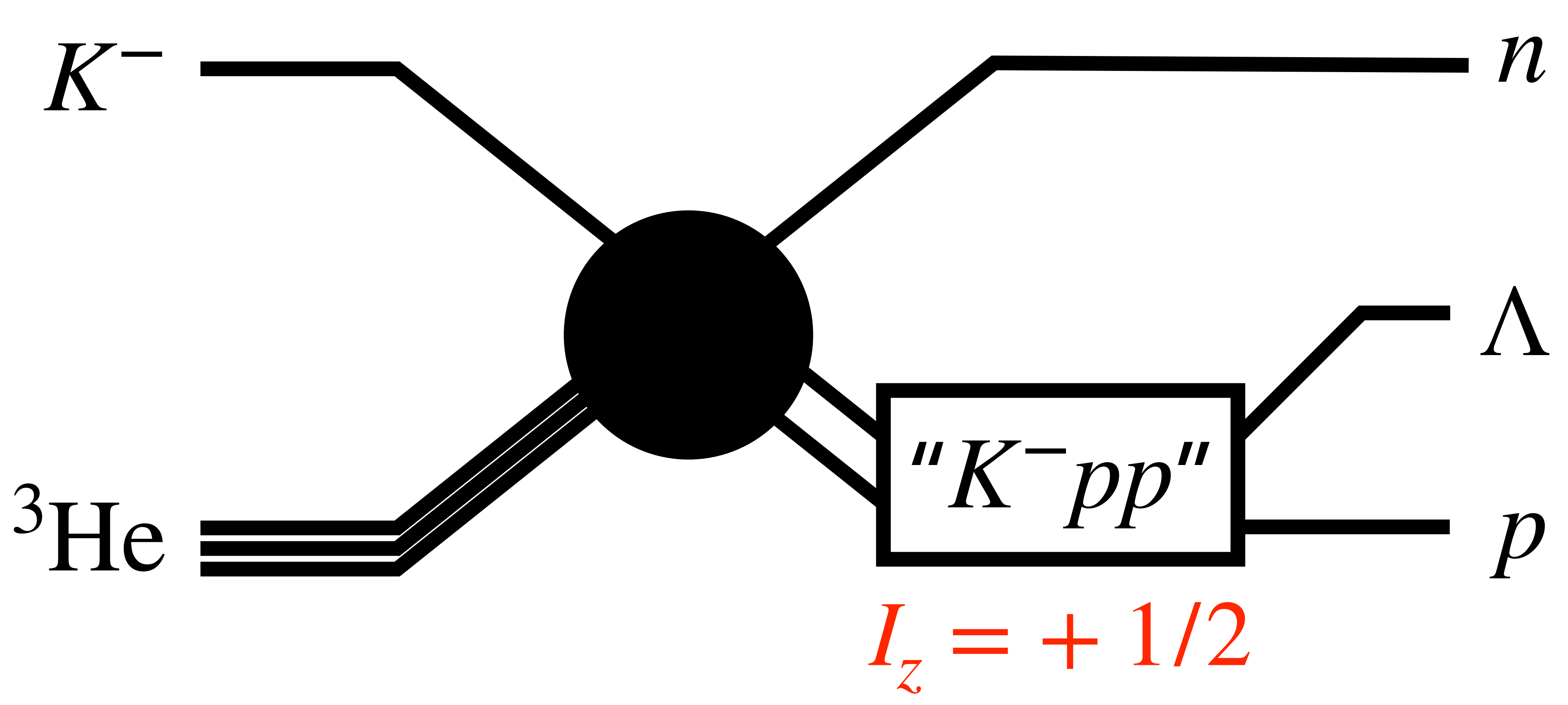

$I_z = +1/2$
state
"$K^- pp$"
K^-pp-$\bar{K}^0pn$
Λ
+
p
Easiest to detect!

The J-PARC E15 experiment

Searching for "K^-pp"

Production reaction

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

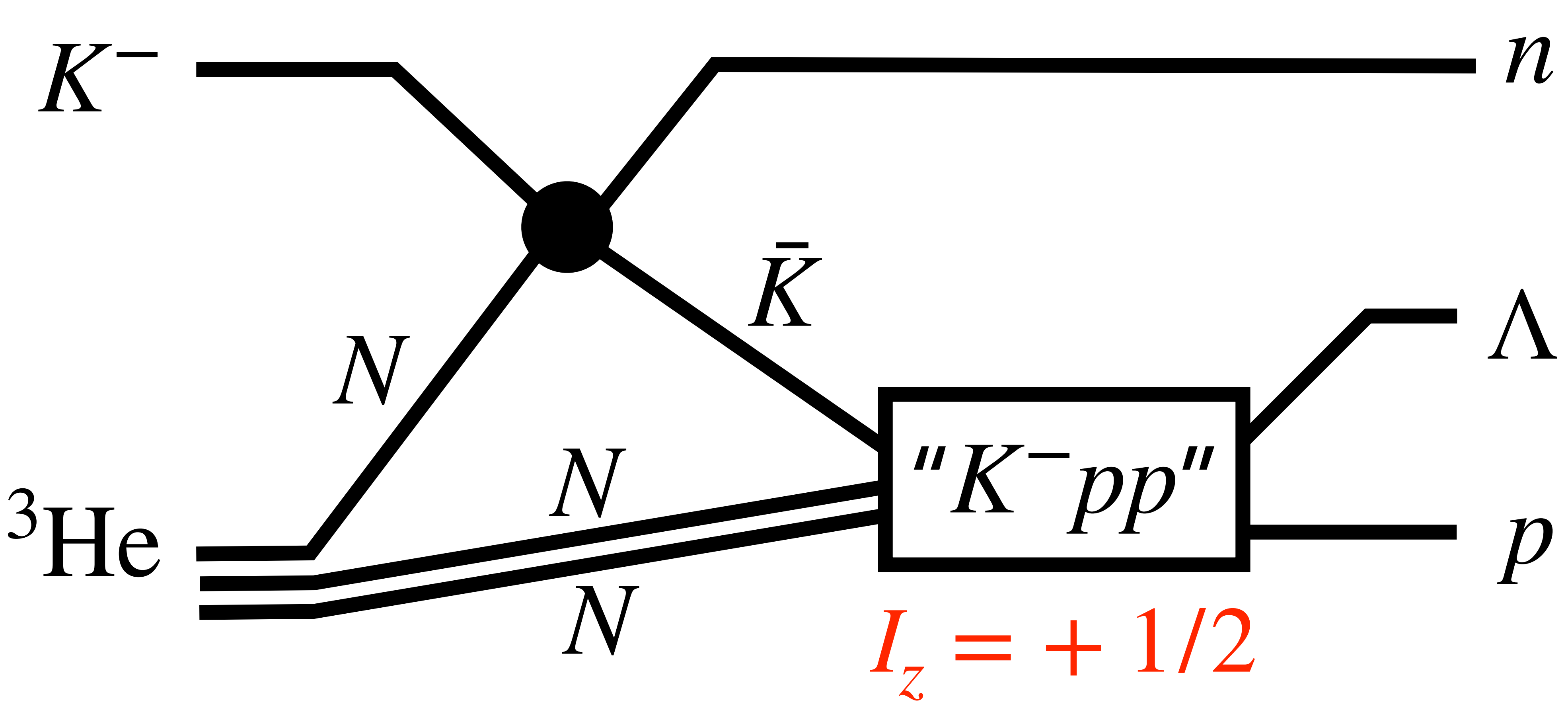


The J-PARC E15 experiment

Searching for "K^-pp"

Production reaction

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



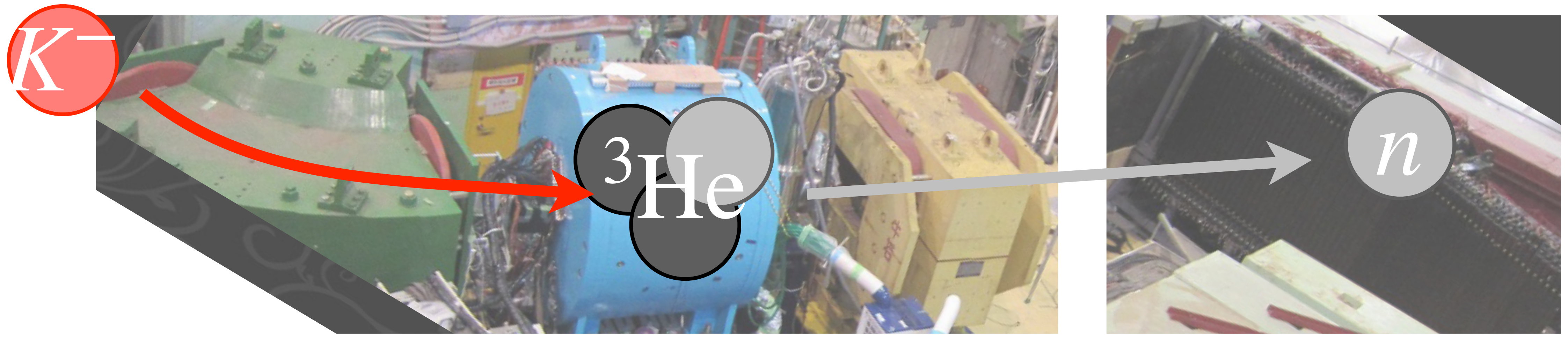
The J-PARC E15 experiment

Searching for "$K^- pp$"

Detector system

Beam spectrometer

Forward spectrometer



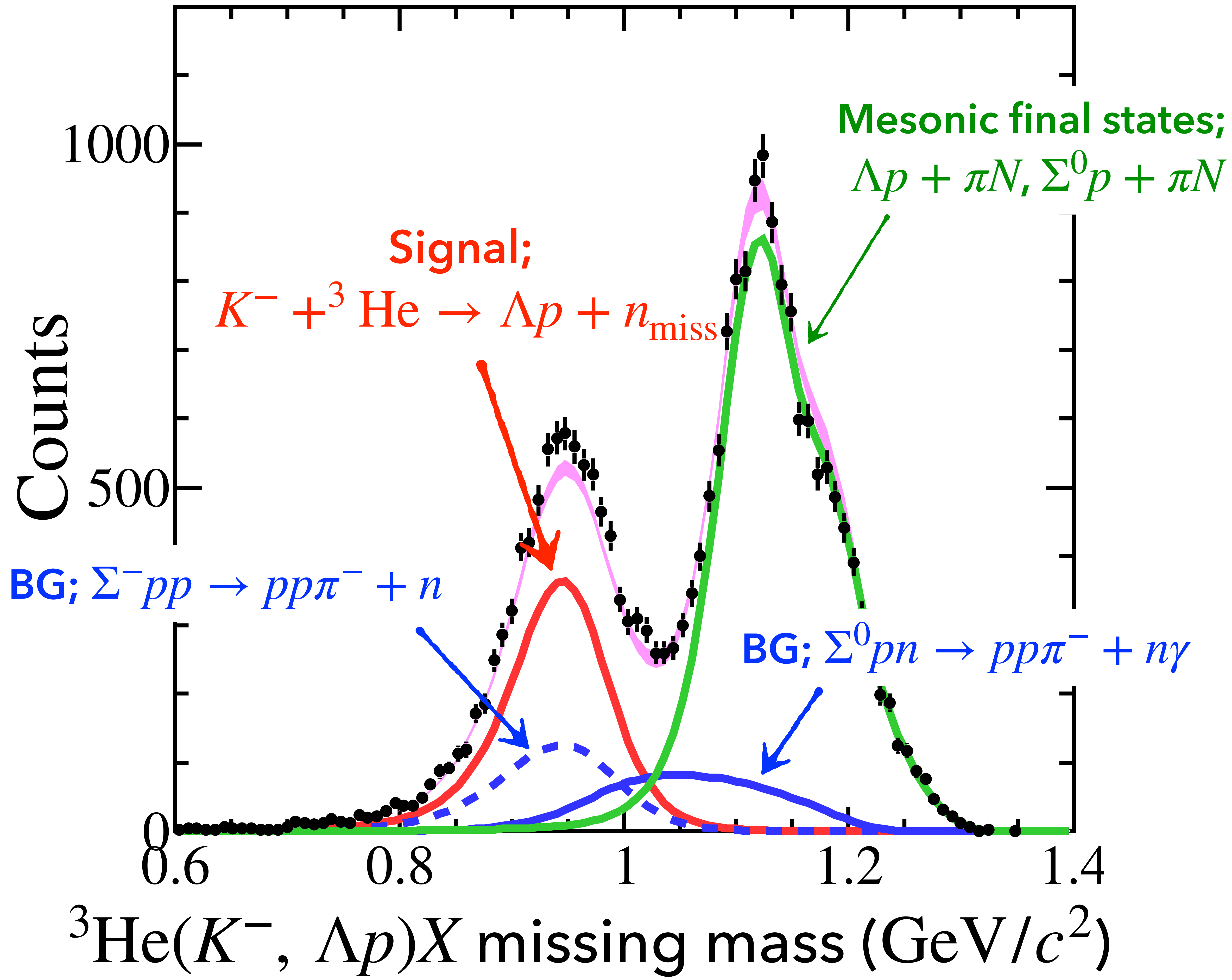
Cylindrical detector system

To detect "$K^- pp$" $\rightarrow \Lambda p \rightarrow (p\pi^-)p$

Selection of the Λpn final state events

signal:

$\Lambda pn \sim 80\,\%$



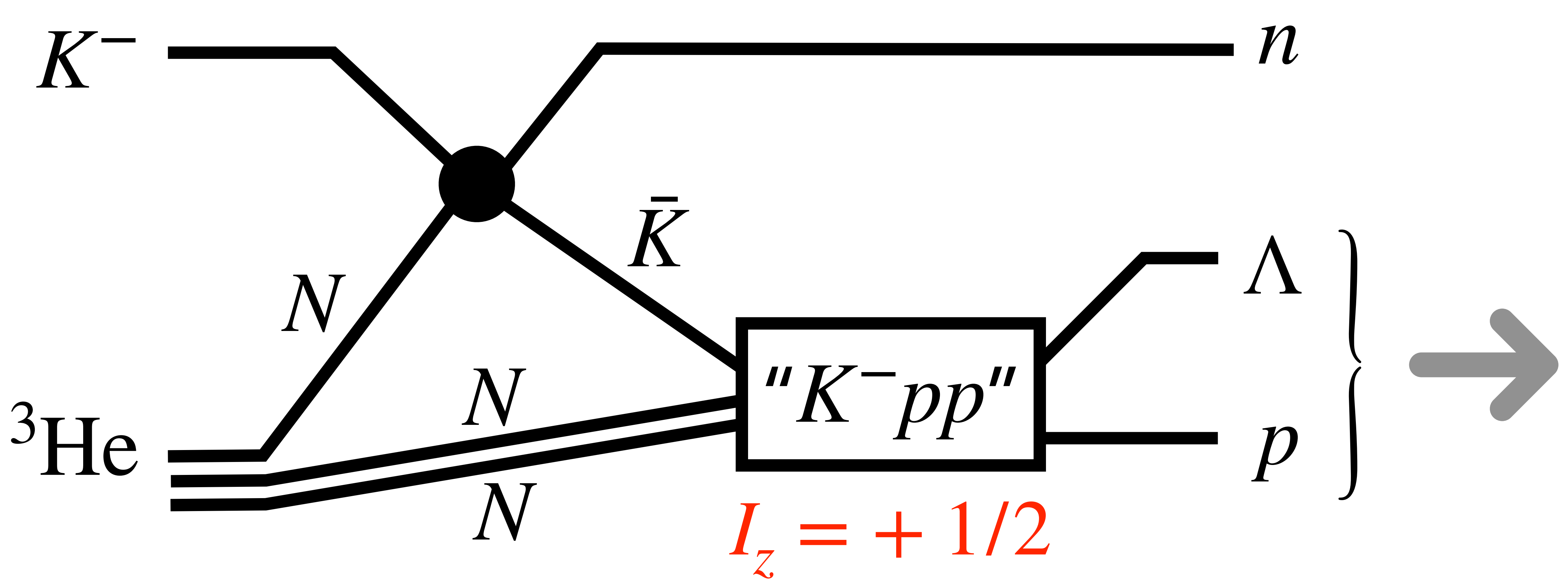
BG:

$\Sigma^0 pn \sim 12\,\%$

$\Sigma^- pp \sim 7\,\%$

$\pi YNN \sim 2\,\%$

Measurement

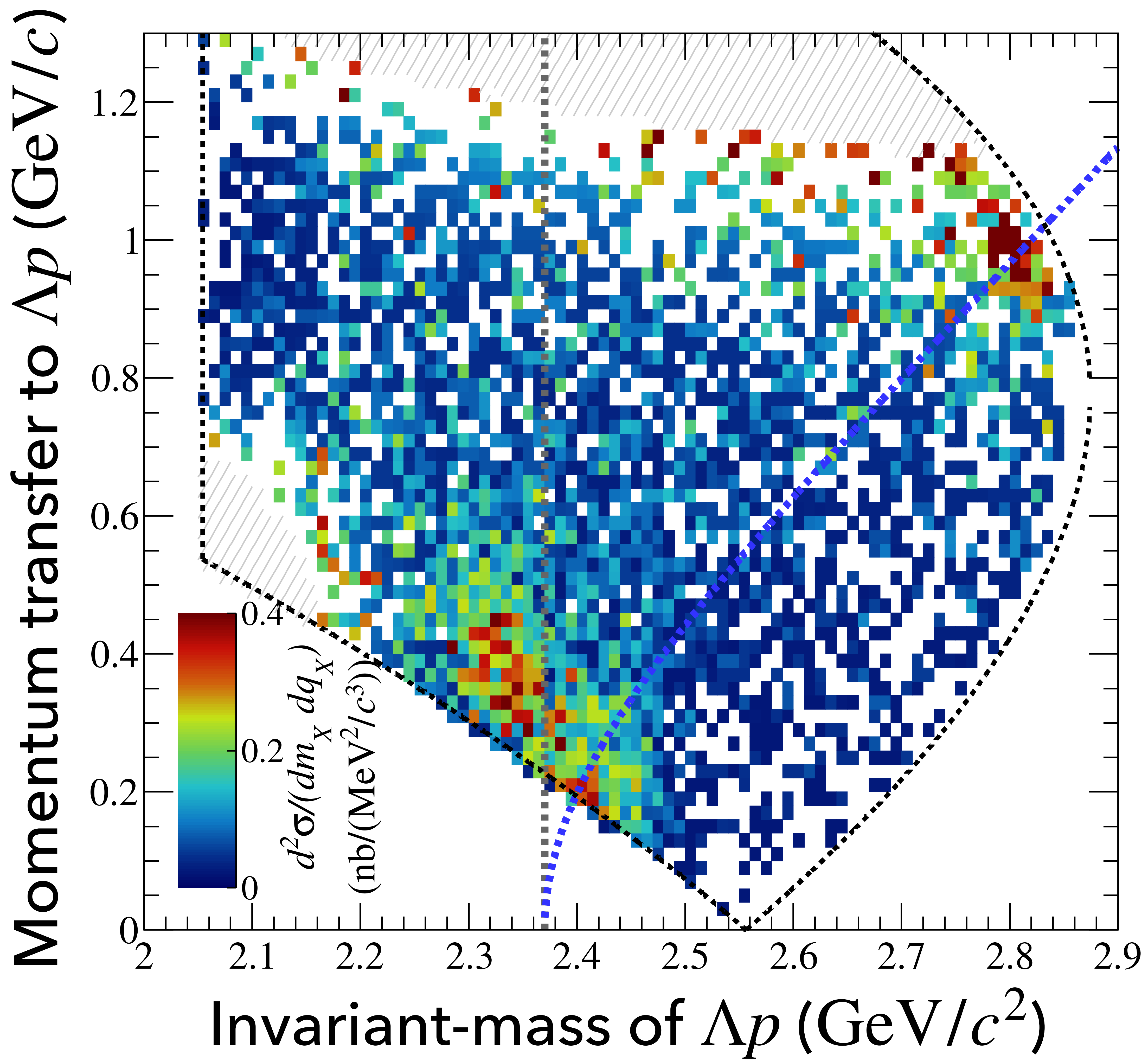


Invariant-mass, m_X

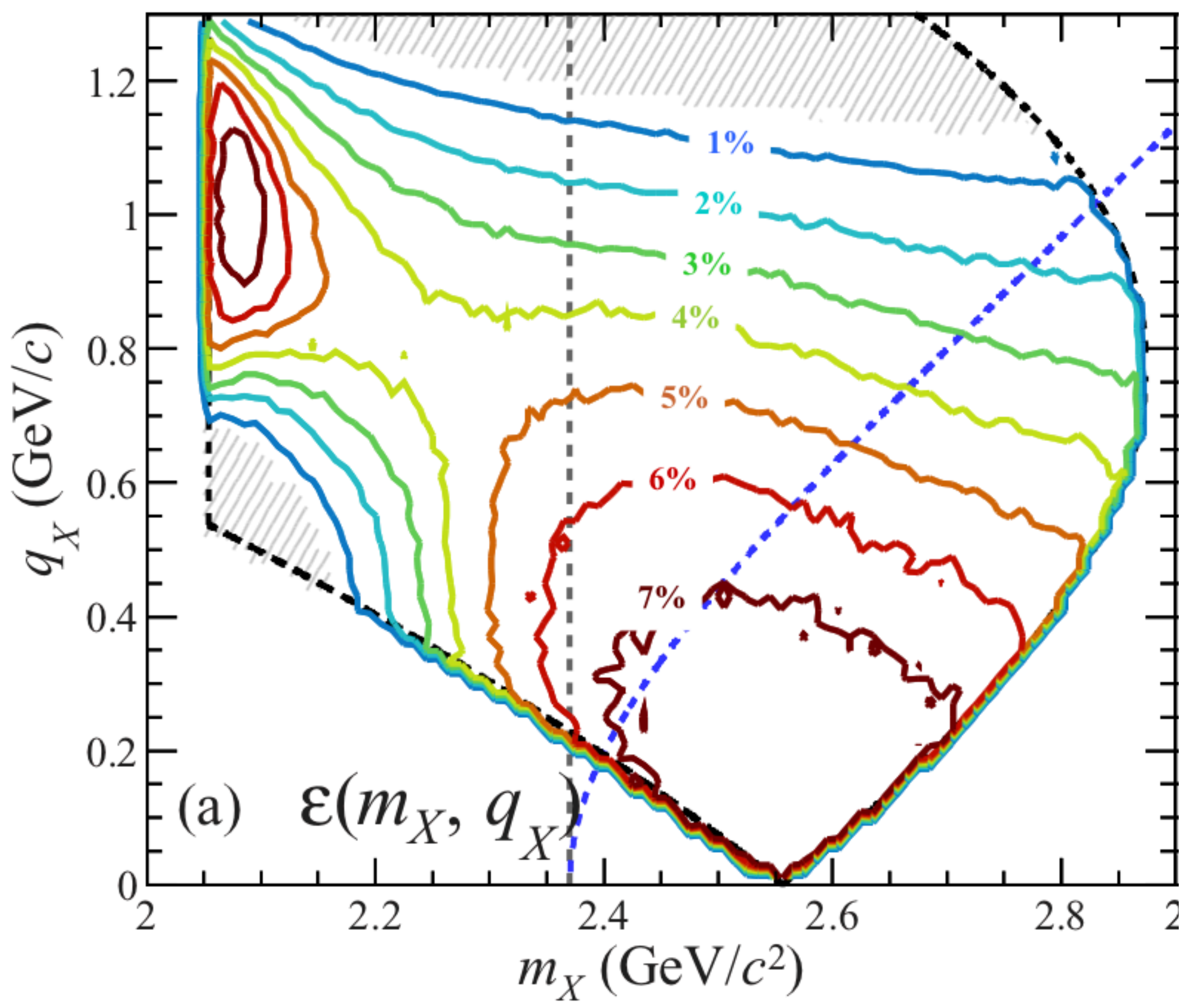
&

Momentum transfer, q_X

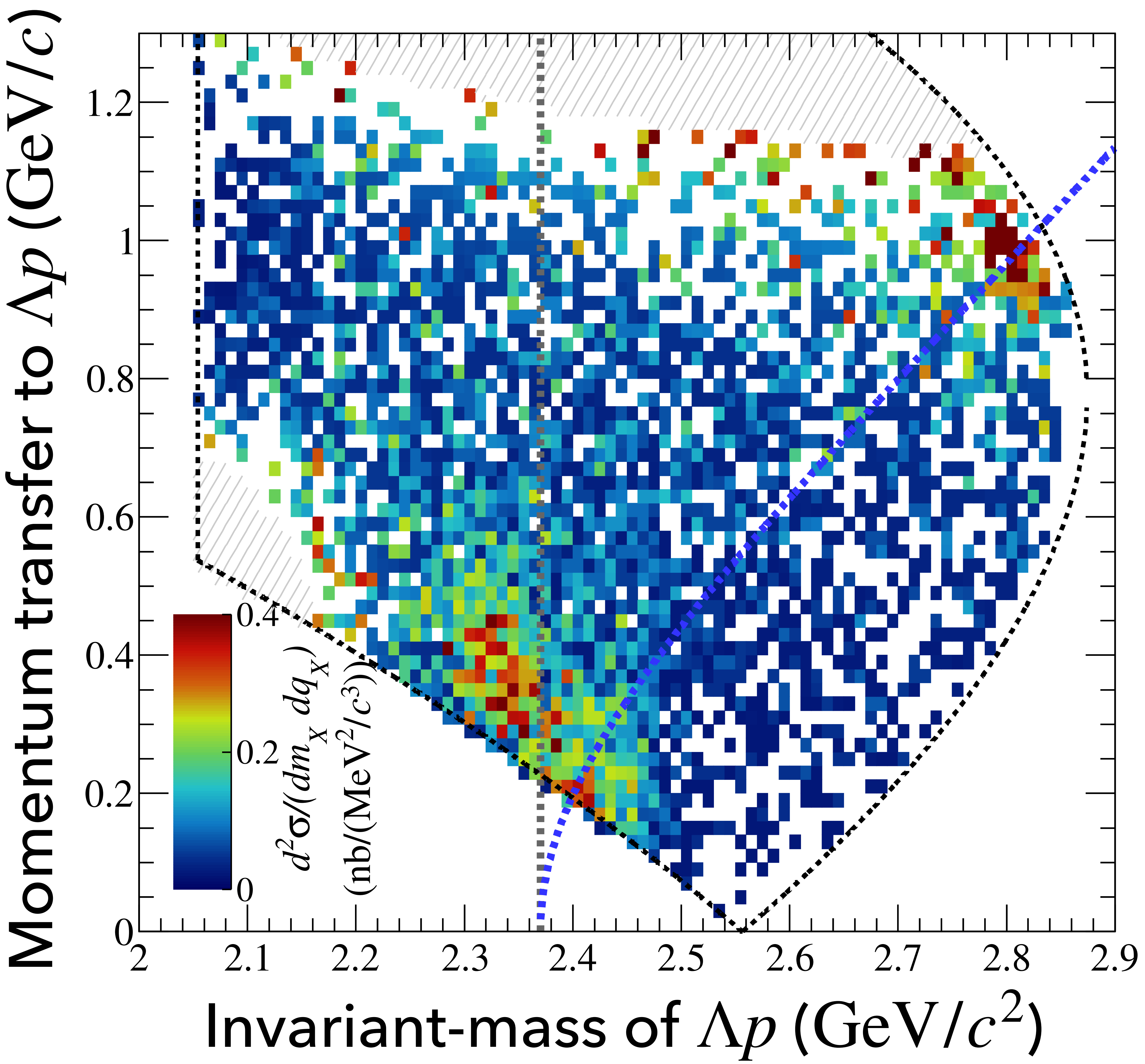
Result



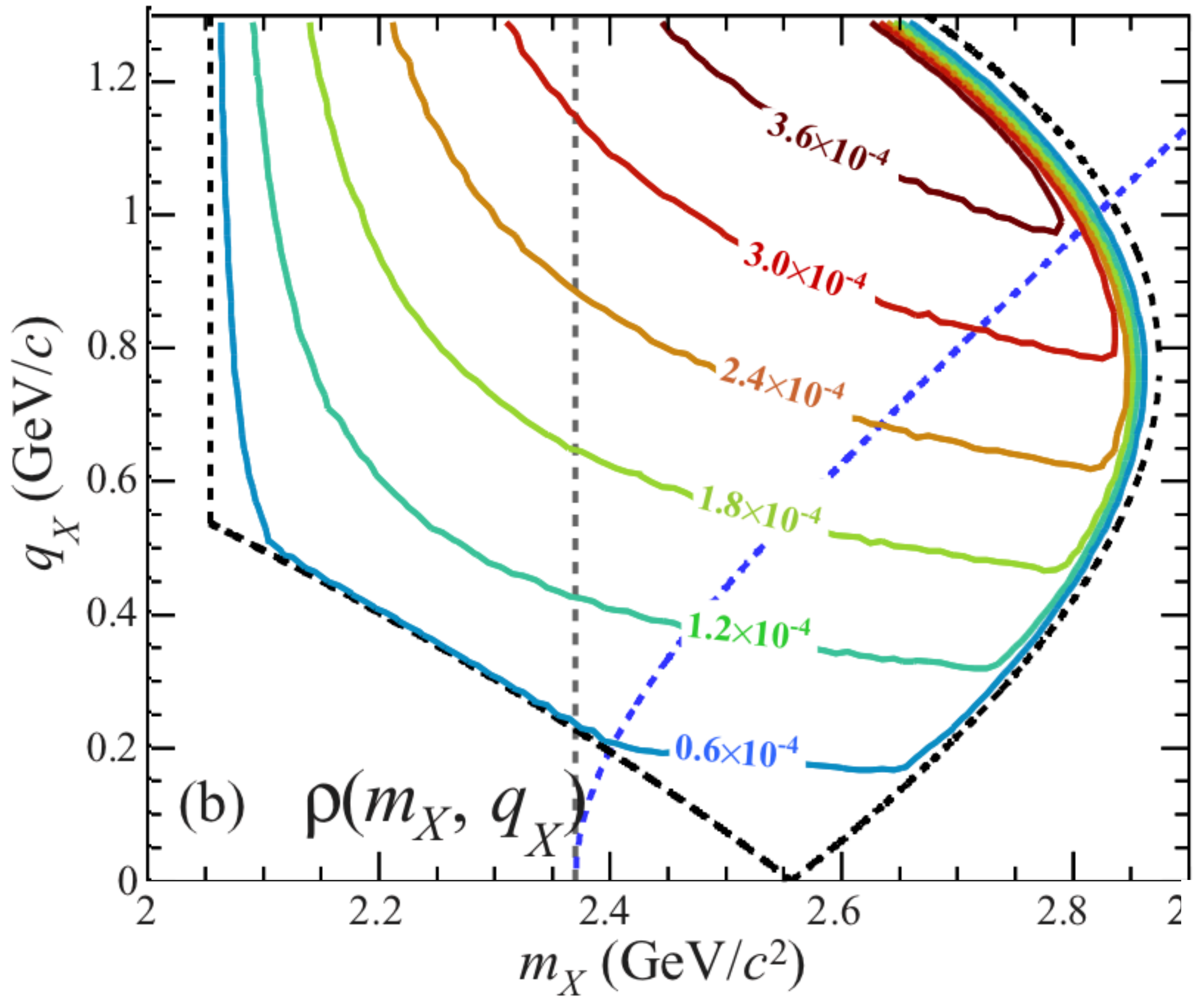
Acceptance map



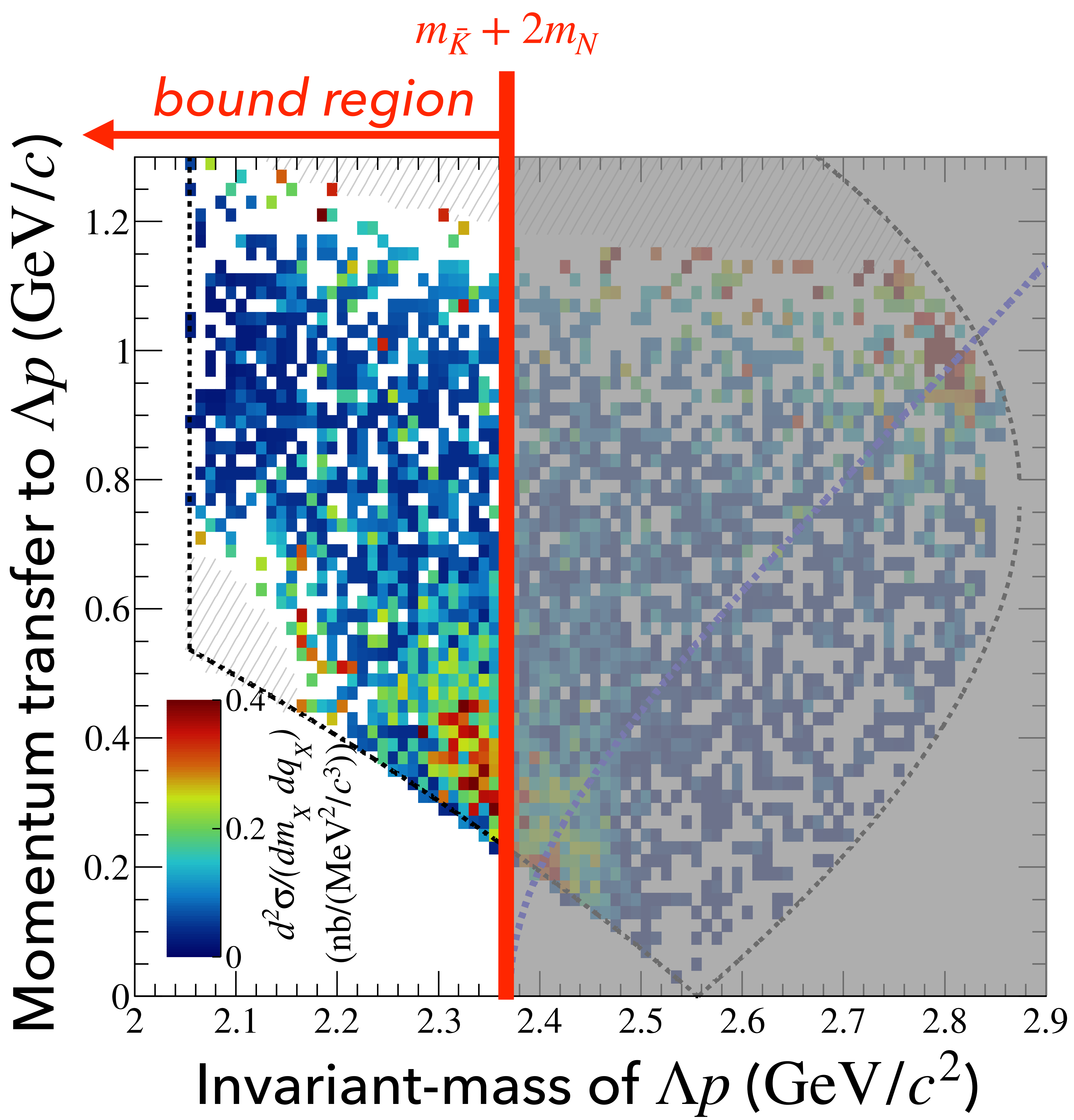
Result



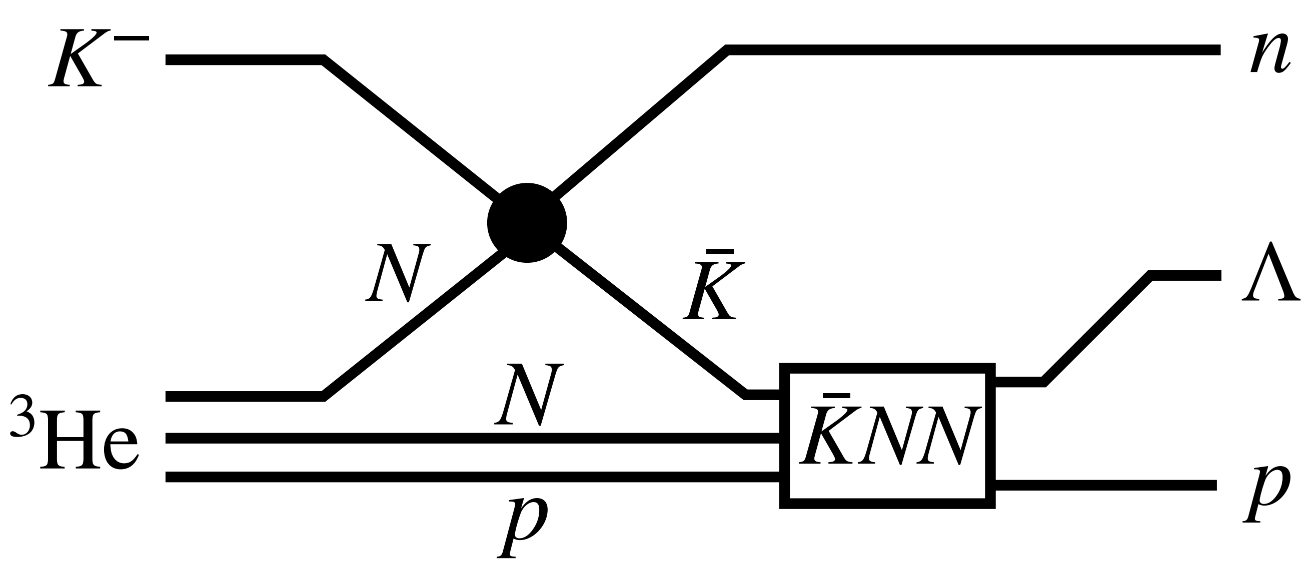
Phase-space distribution



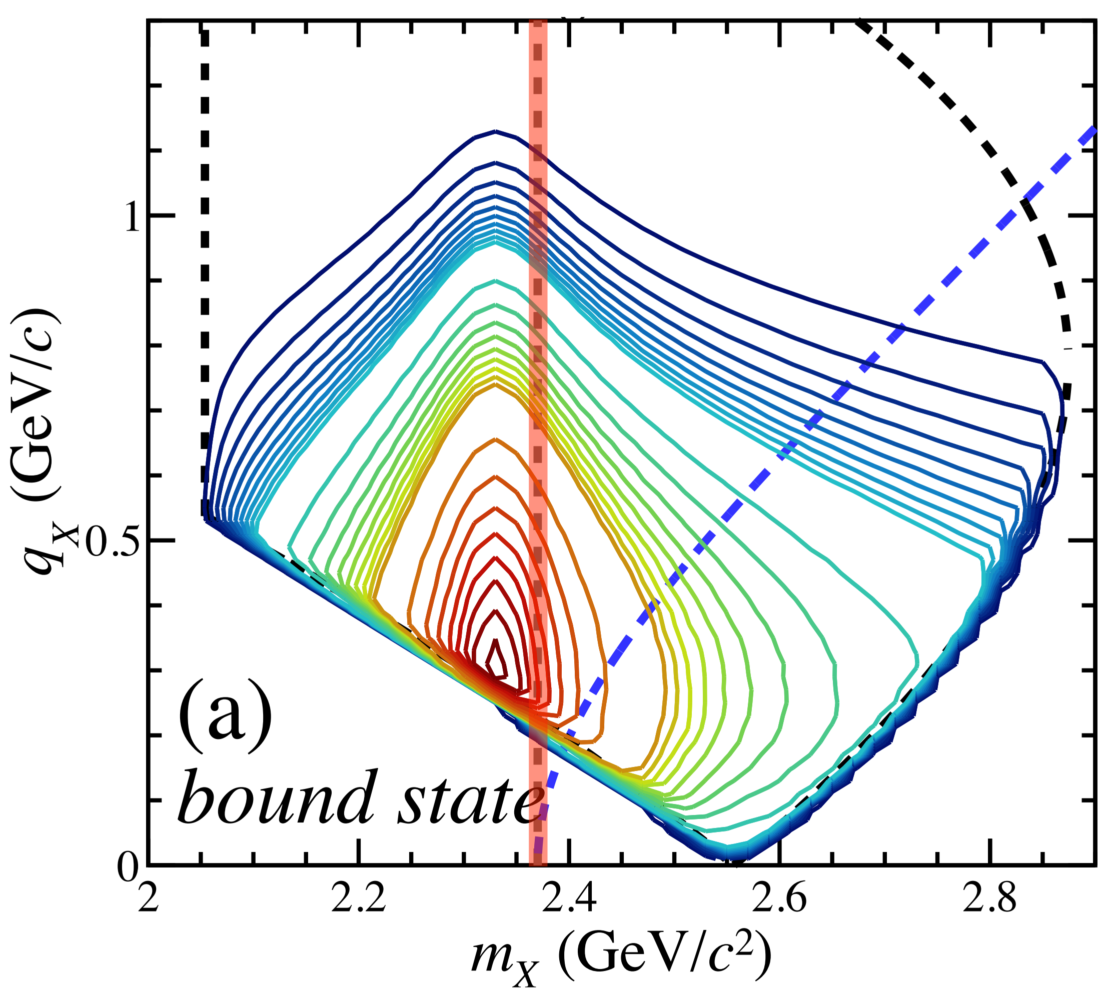
Result



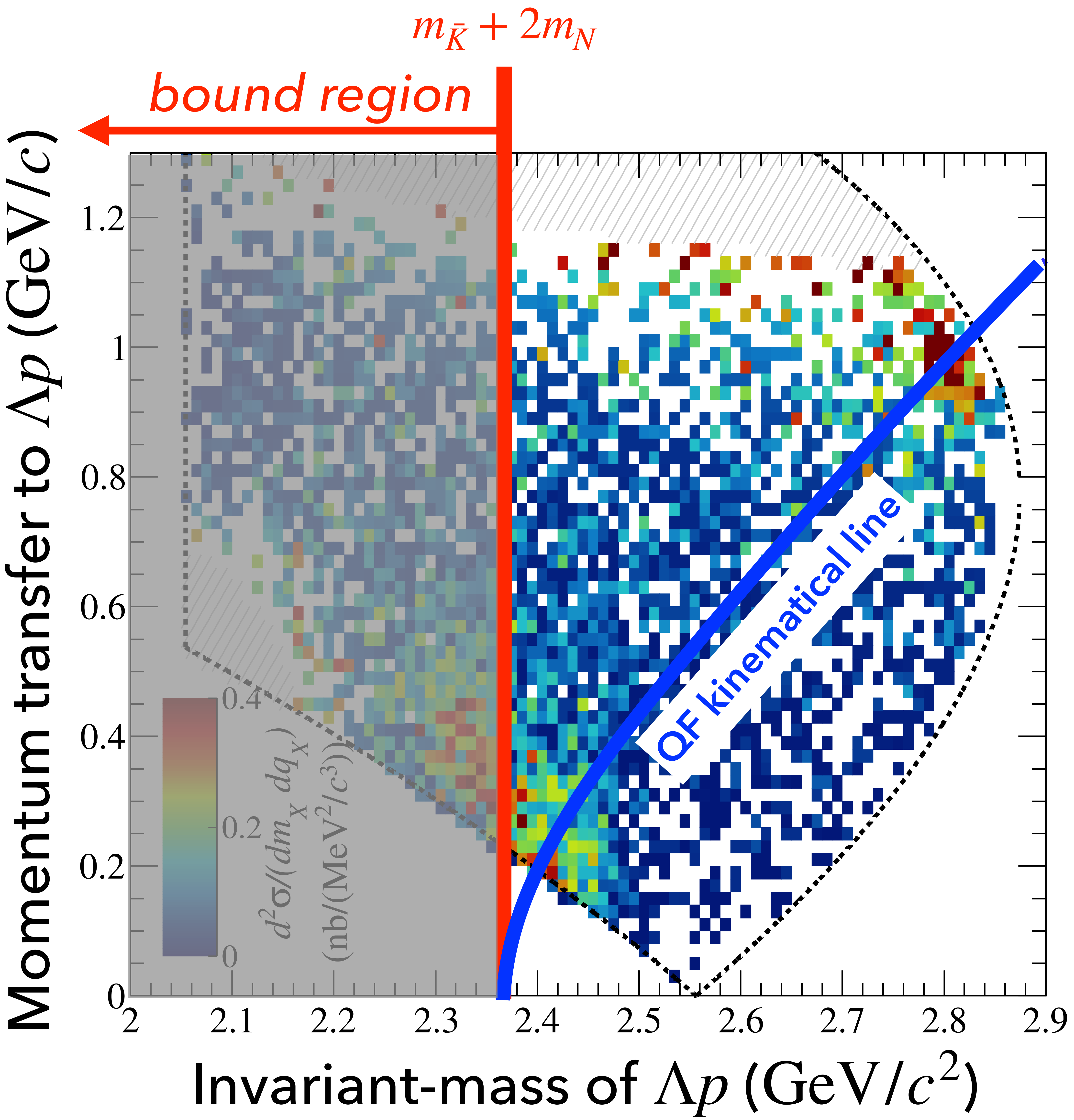
$\bar{K}NN$ production



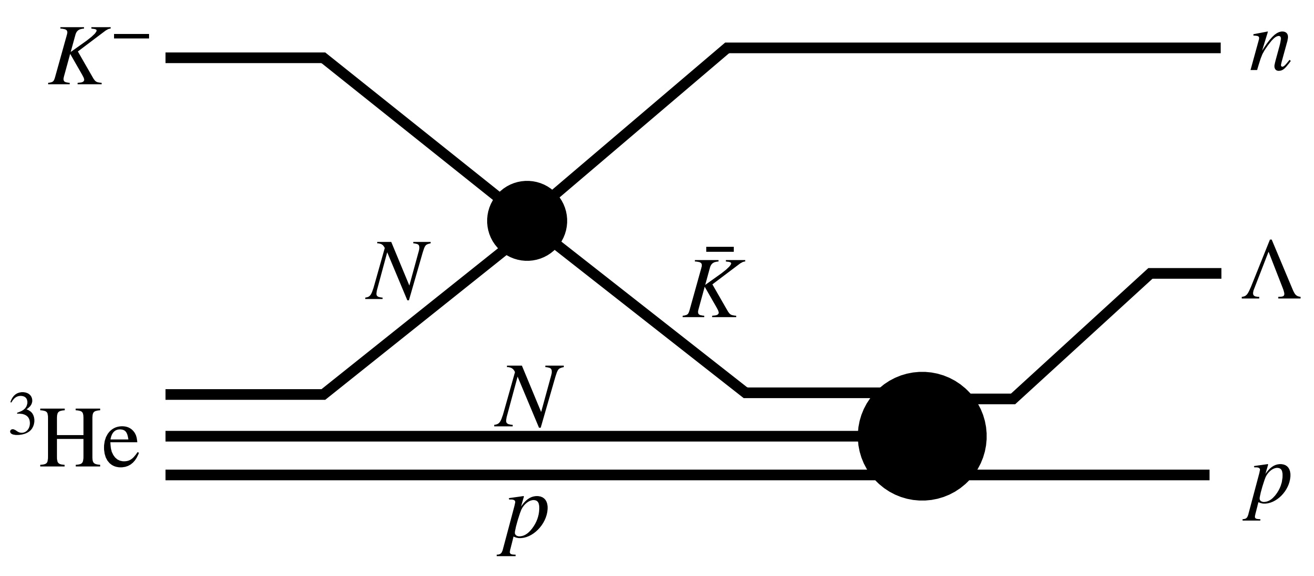
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



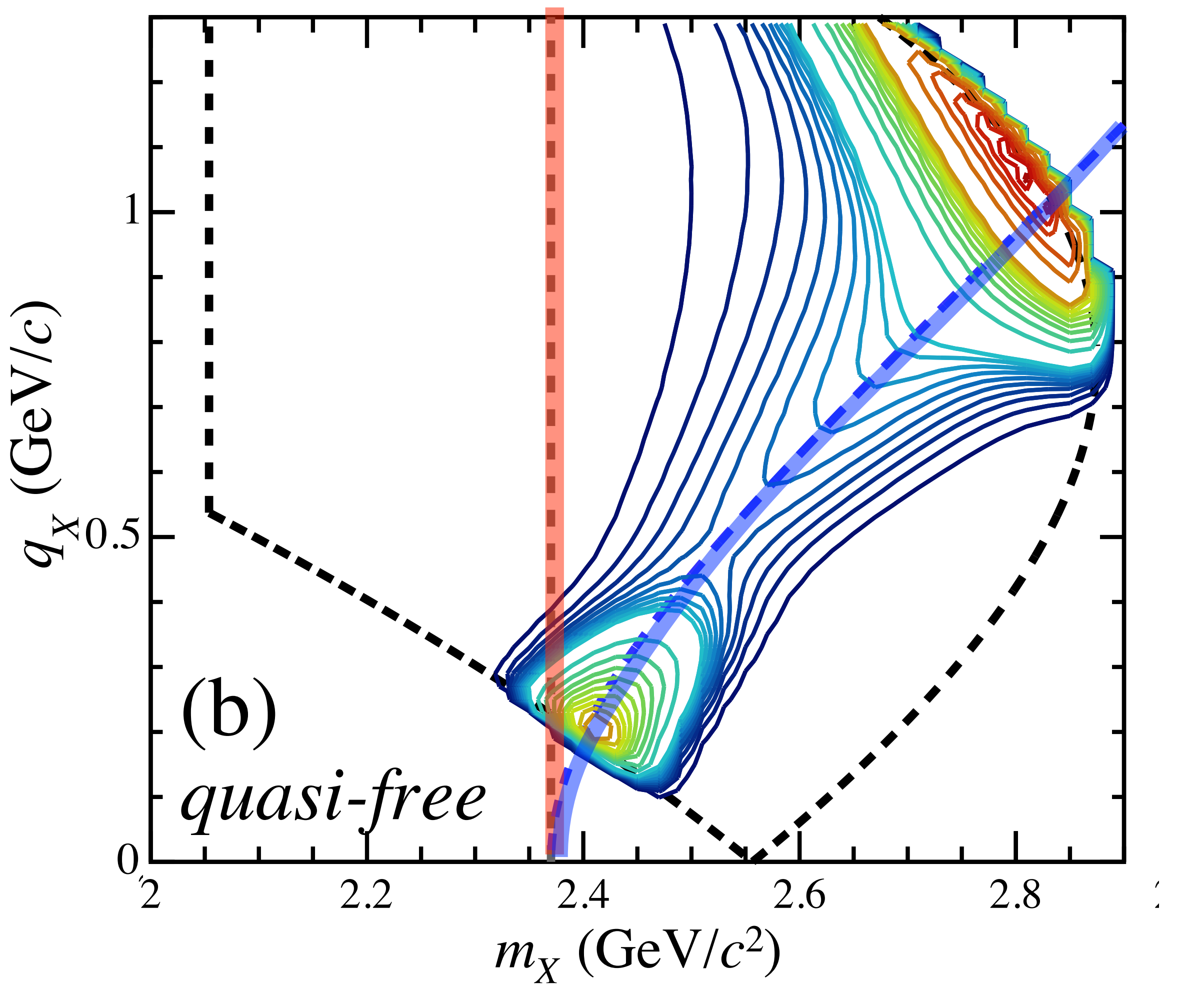
Result



Quasi-free process

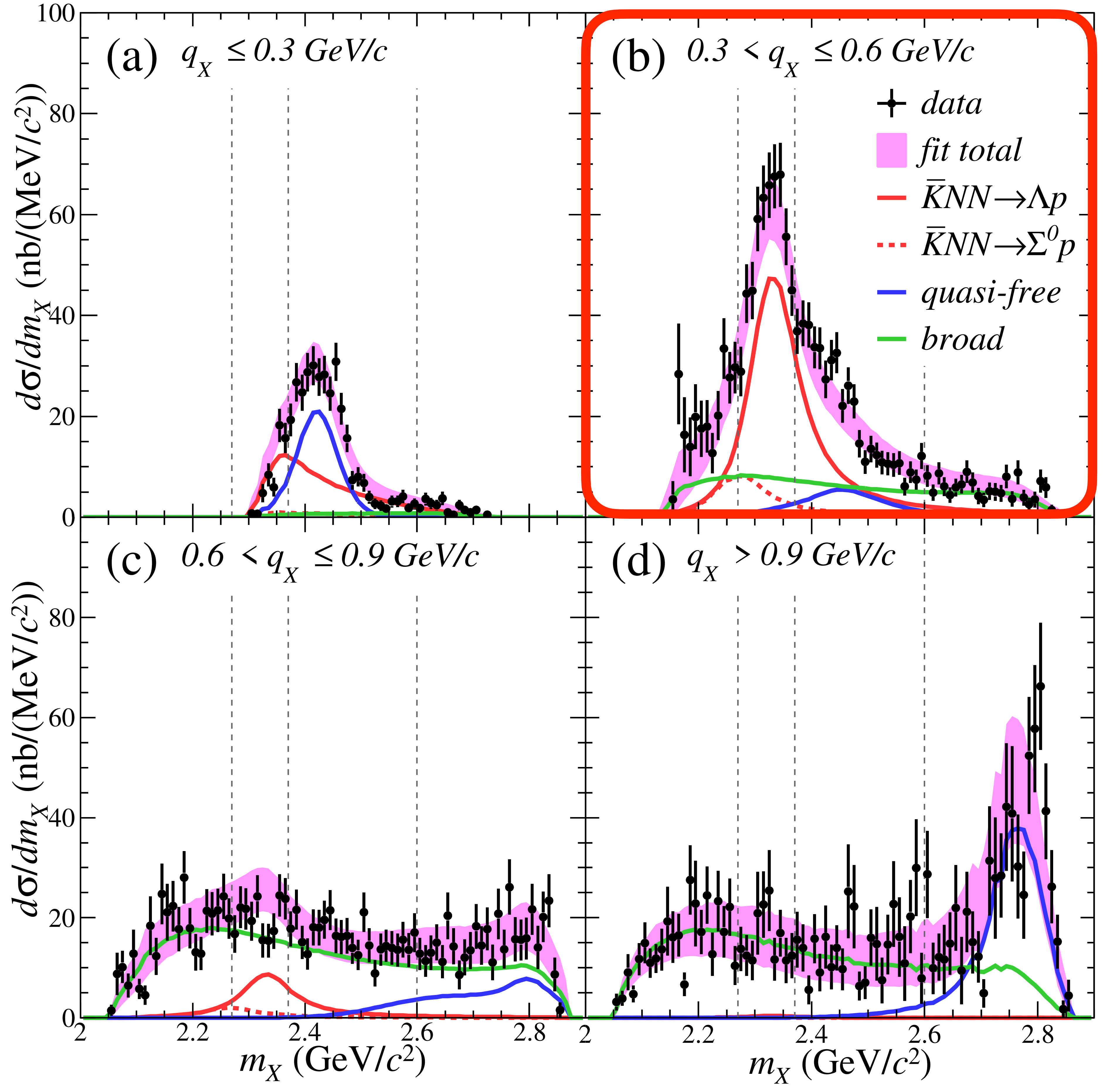


$$f_{\mathrm{QF}}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{\mathrm{QF}}(q_X)$$

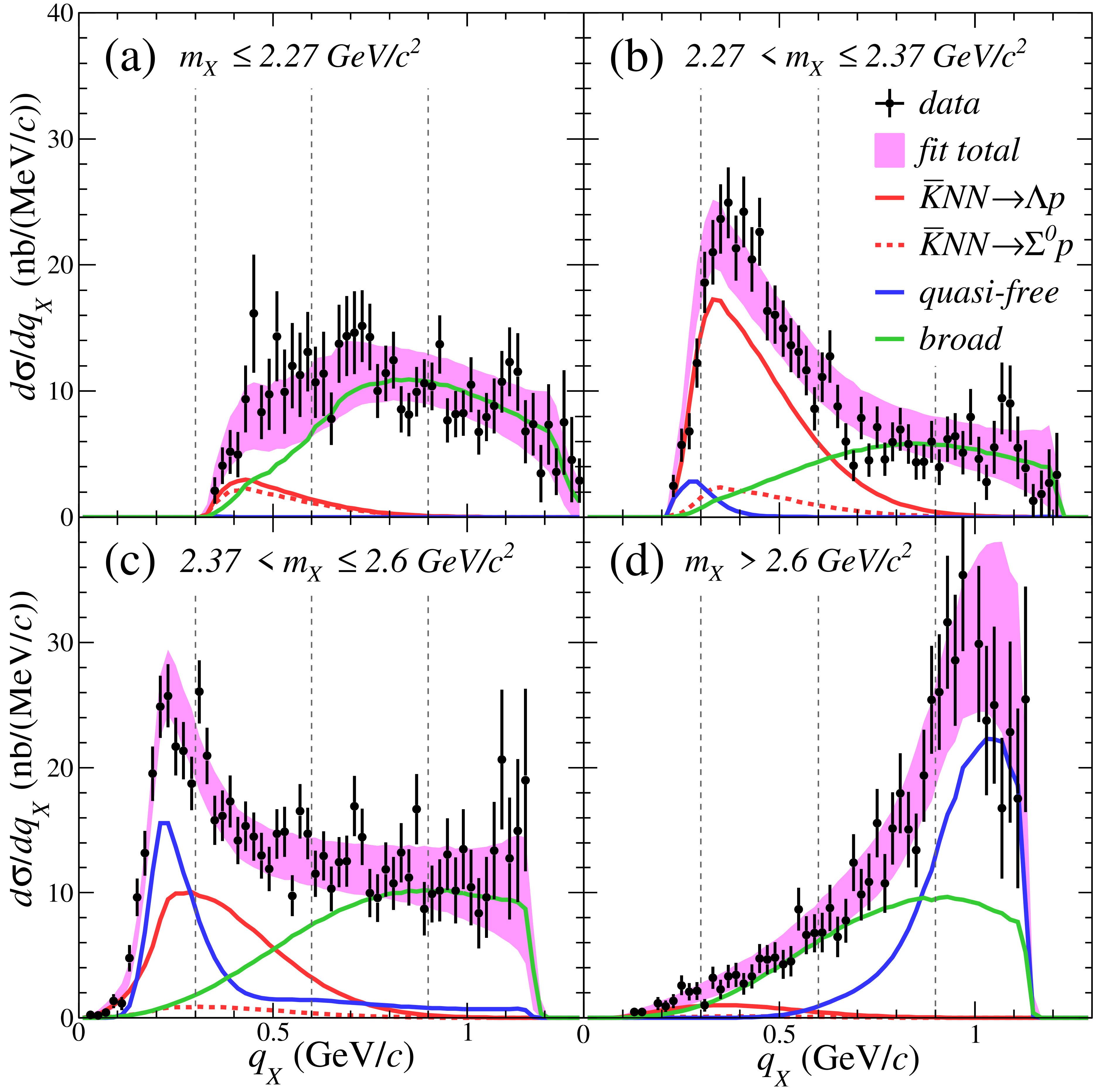


Fit result

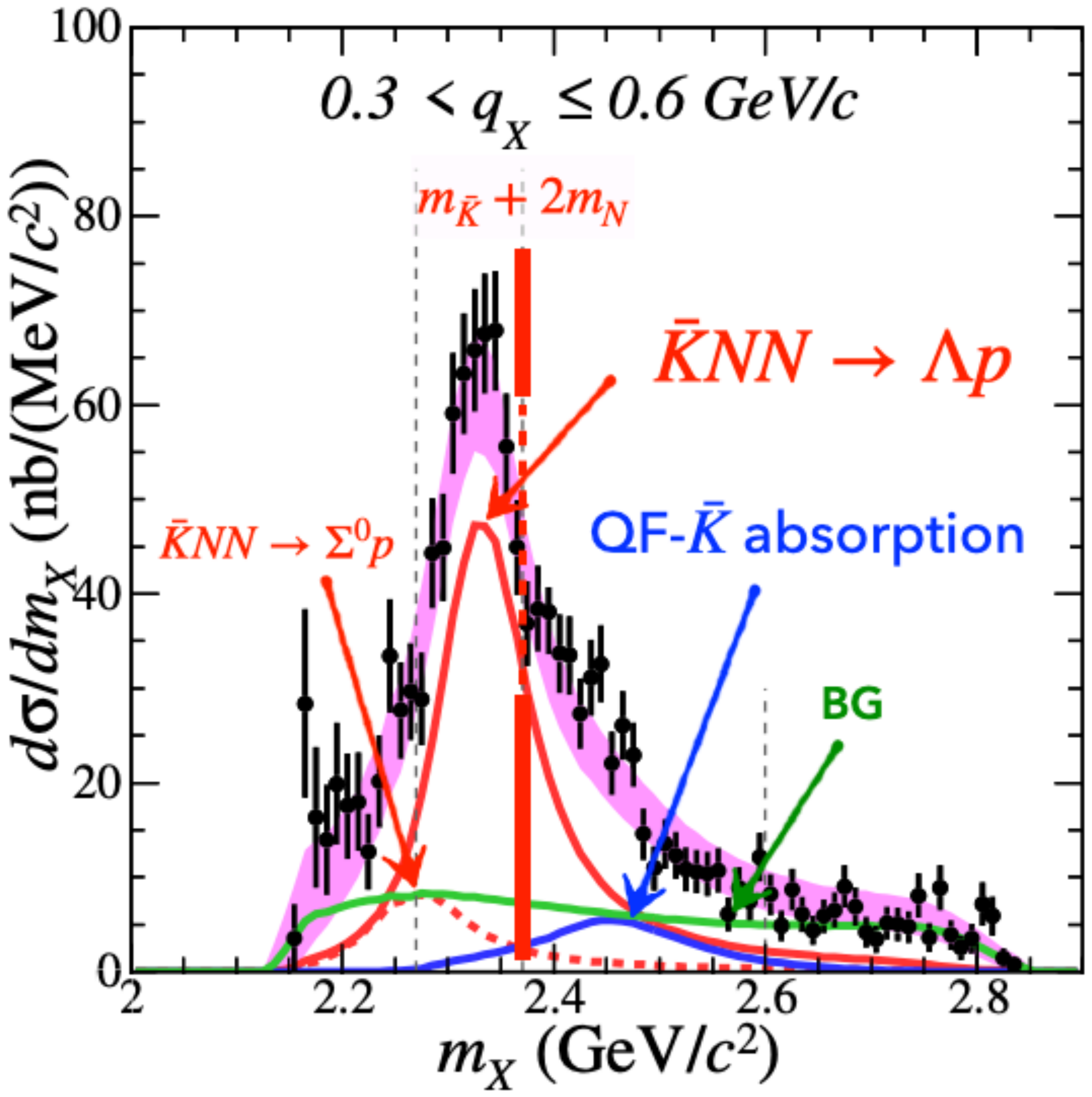
Λp invariant-mass



Momentum transfer to Λp

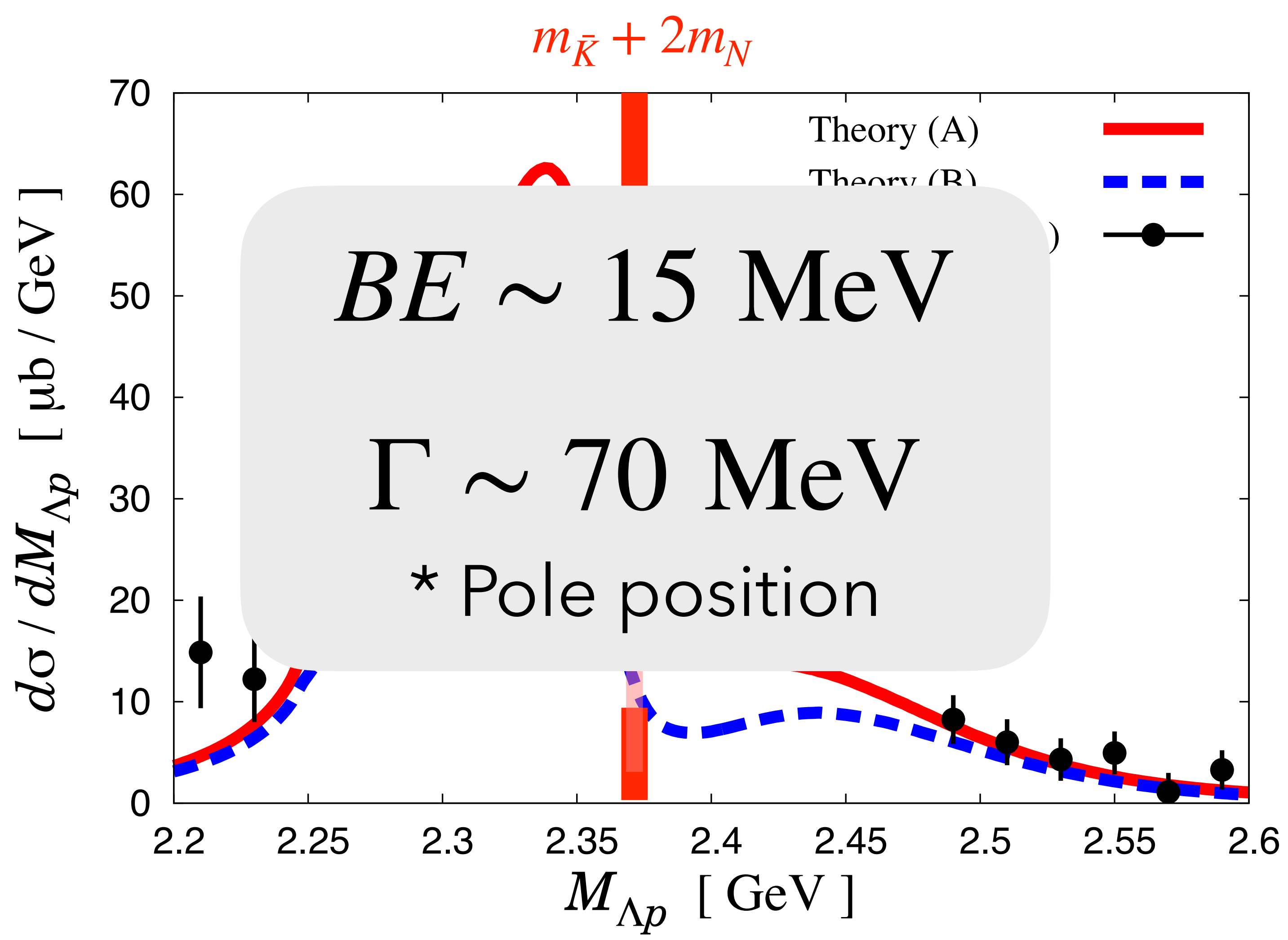


Fit result



Theor. calc.

T. Sekihara, et al.,, JPSCP **26** (2019) 023009



$BE \sim 15$ MeV

$\Gamma \sim 70$ MeV

* Pole position

We observed the first clear signal of $\bar{K}NN$.

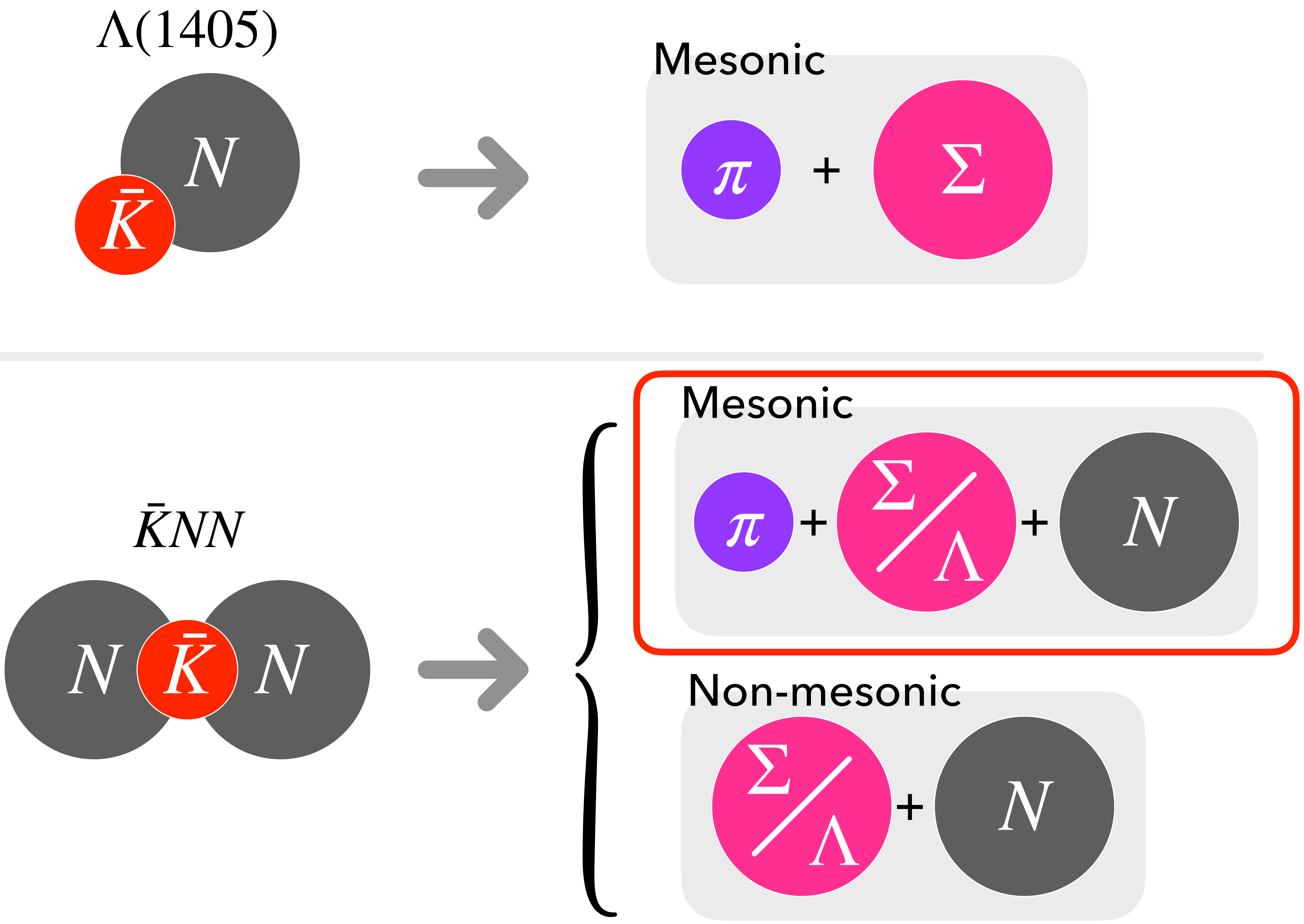
$$\begin{cases} BE = 42 \pm 3 \text{ (stat.) } {}^{+3}_{-4} \text{ (syst.) MeV} \\ \Gamma = 100 \pm 7 \text{ (stat.) } {}^{+19}_{-9} \text{ (syst.) MeV} \end{cases}$$

* obtained as peak position & width of simple Breit-Wigner

Ongoing analysis

Other decay channel of $\bar{K}NN$

Decay

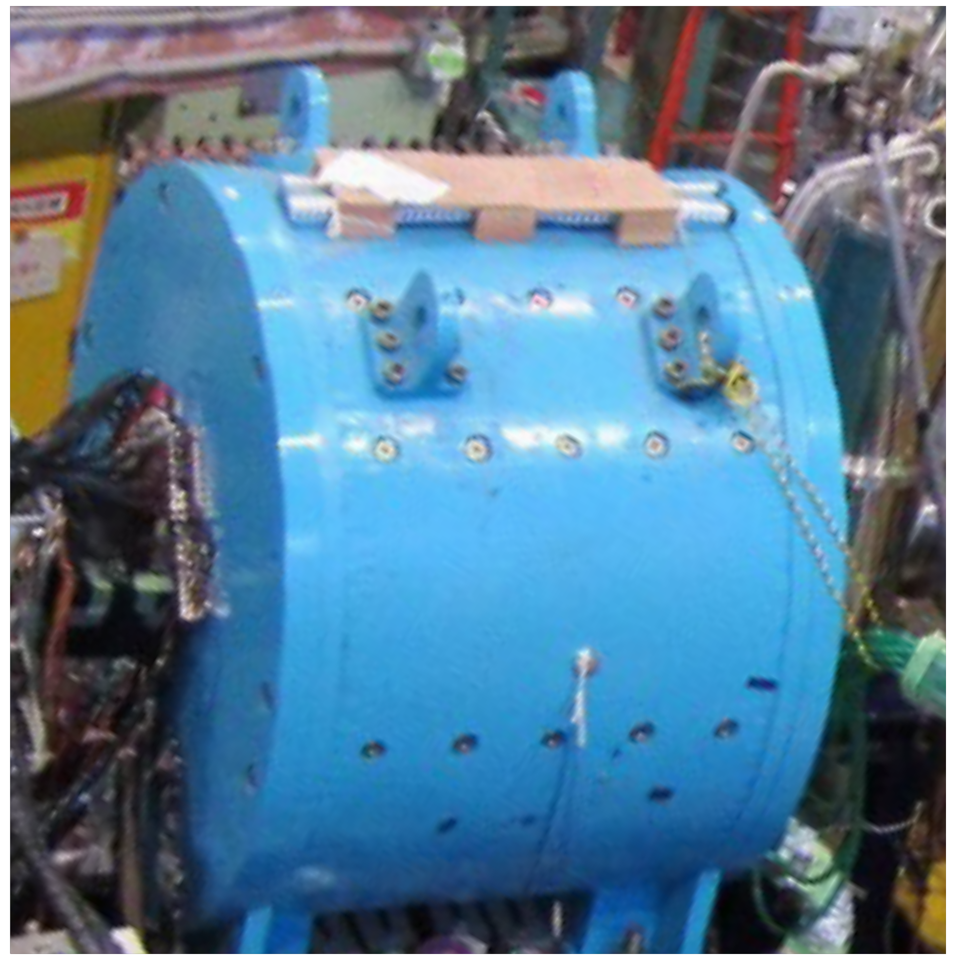


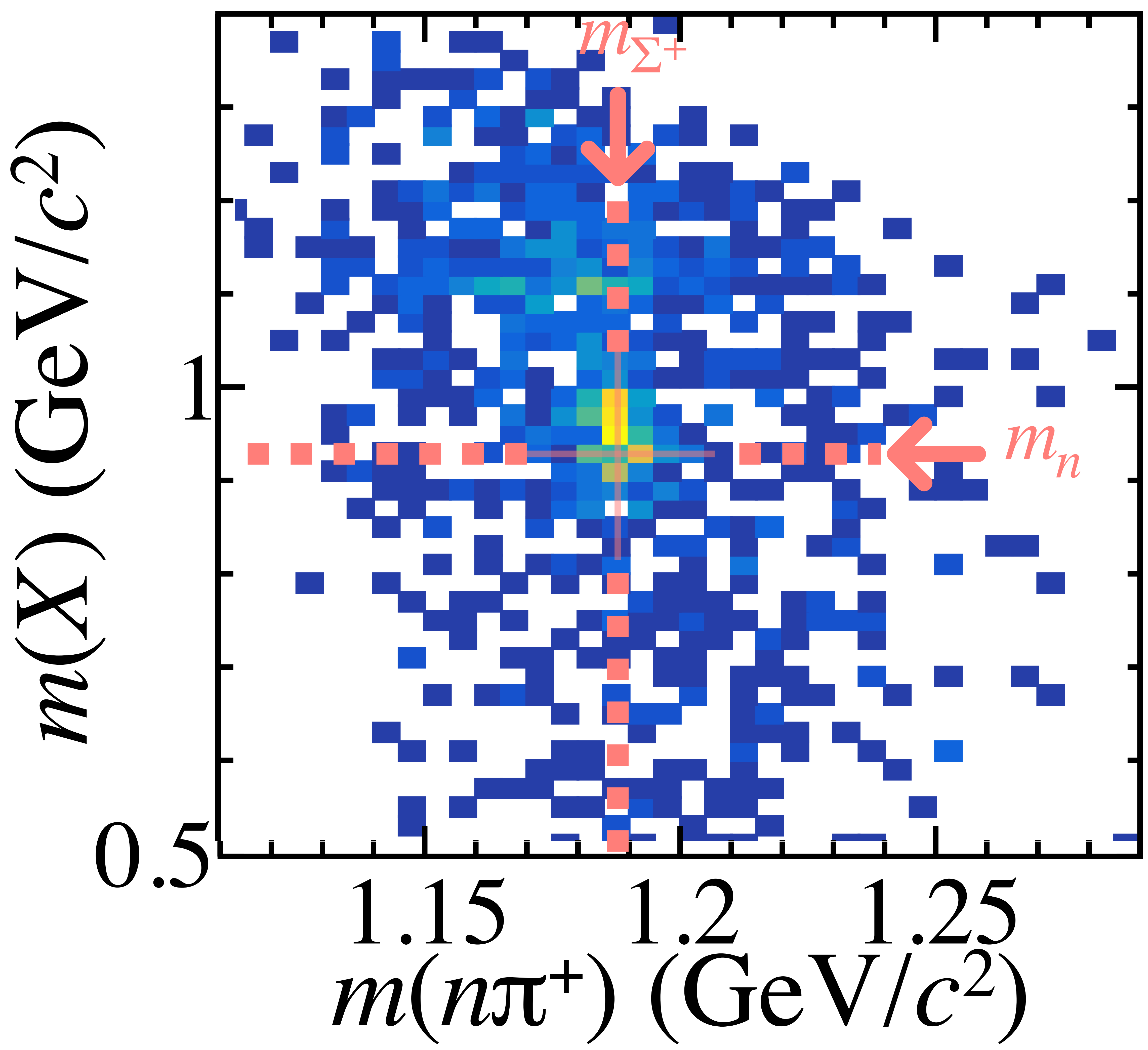
Selection of the $\pi^-\Sigma^+pn$ final state events

In the case of

$$\boxed{\pi^-\Sigma^+p} + n_{\mathrm{miss}}$$

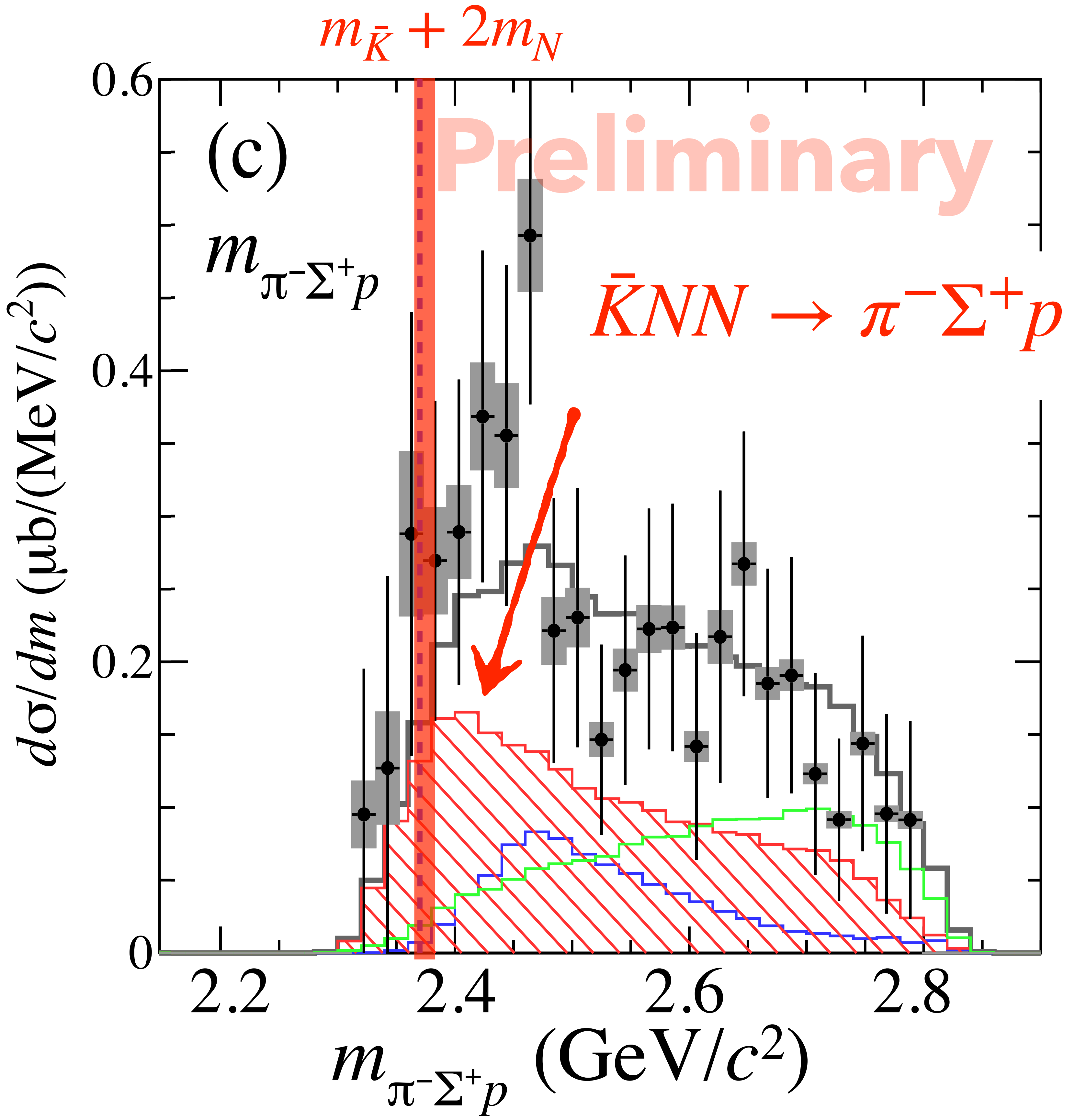
$$\to \underbrace{\pi^-(\pi^+n)p}_{\text{Detected with CDS}}$$





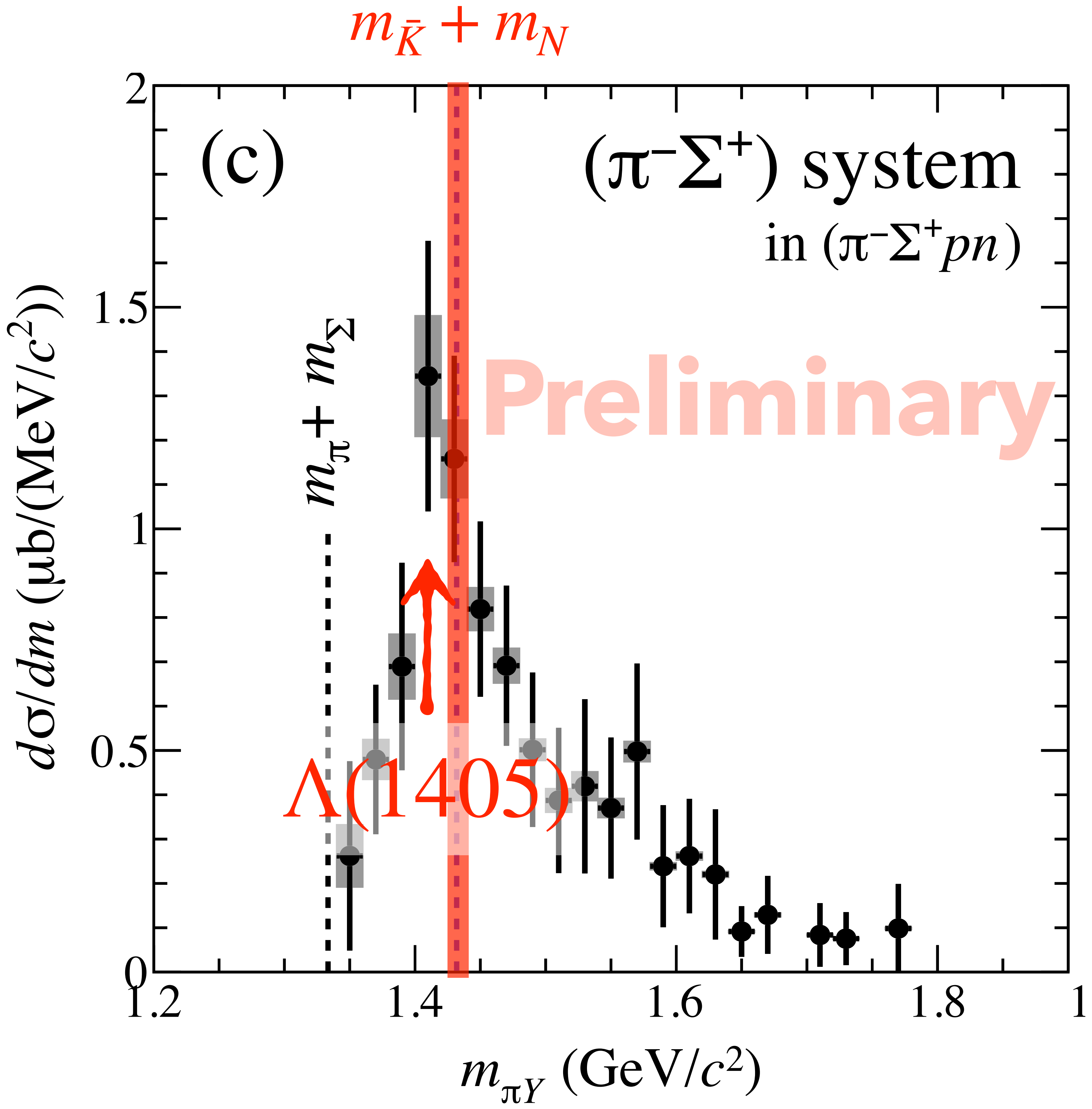
Preliminary result

$m_{\pi^-\Sigma^+p}$ vs. $q_{\pi^-\Sigma^+p}$



$\Gamma_{\pi YN} \gg \Gamma_{YN}$

$m_{\pi^-\Sigma^+}$



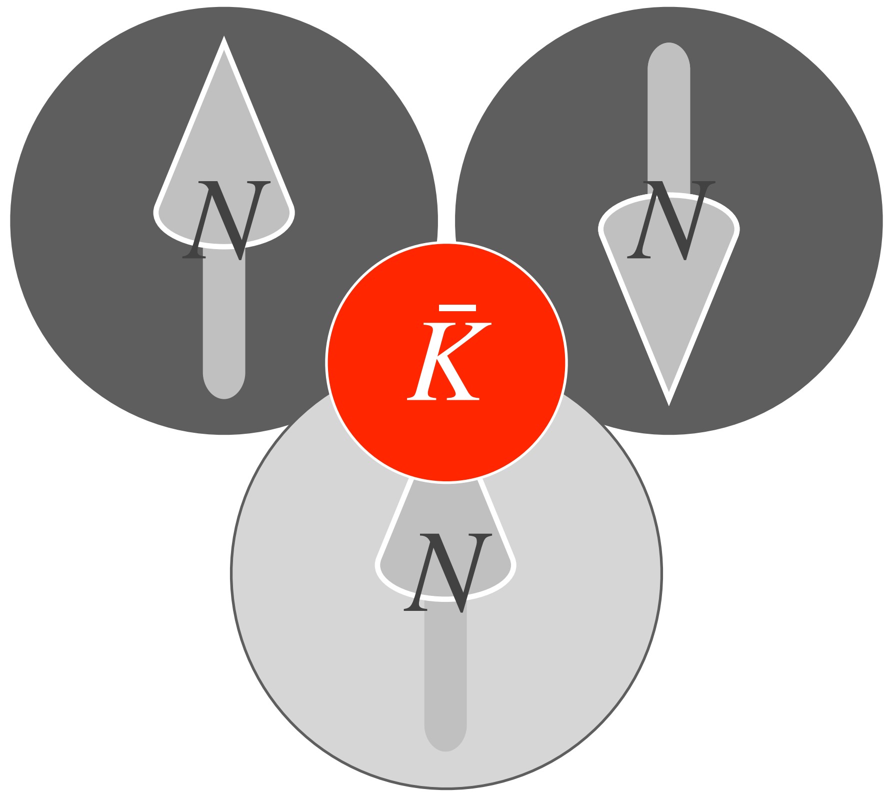
Clear peak of $\Lambda(1405)$

$\bar{K}NNN$

$(\bar{K}NNN)^{I=0}$

The second lightest $\bar{K}$-nucleus

$J^{\pi} = 1/2^{-}$



$K^{-}ppn$-$\bar{K}^{0}pnn$

$BE = 45 - 50$ MeV
$\Gamma = 26 - 69$ MeV

S. Ohnishi et al., PRC **95** (2017) 065202

c.f., $\bar{K}NN$:

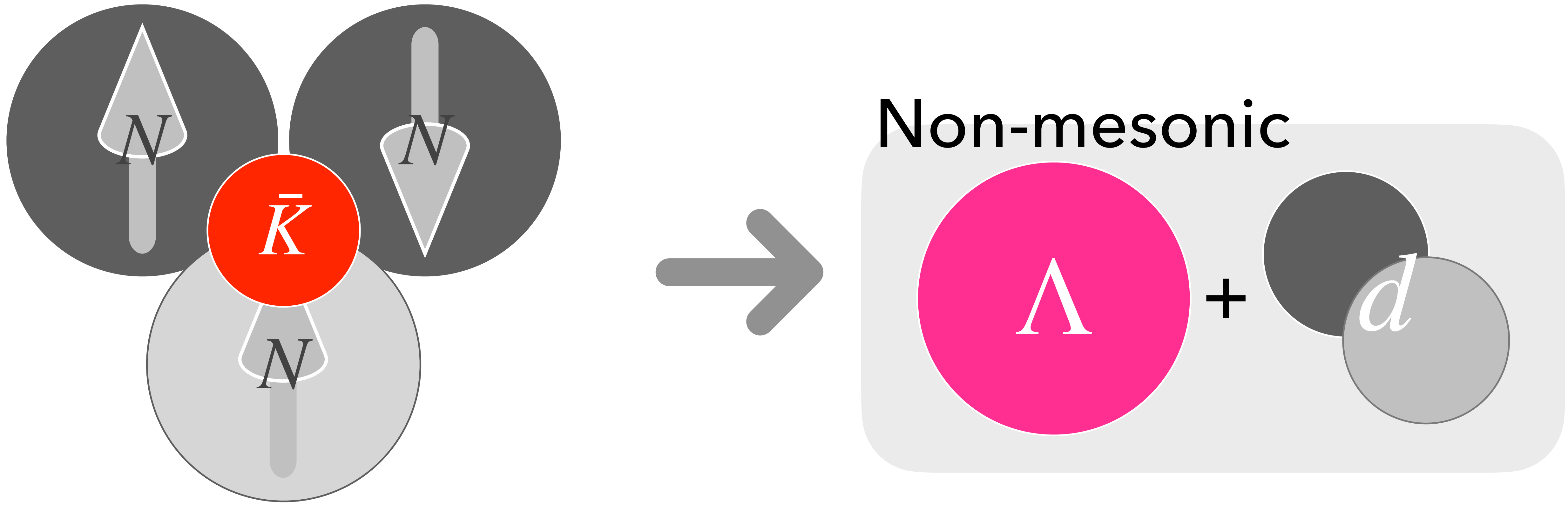
$BE = 25 - 28$ MeV
$\Gamma = 30 - 60$ MeV

S. Ohnishi et al., PRC **95** (2017) 065202

$(\bar{K}NNN)^{I=0}$

The second lightest $\bar{K}$-nucleus

$J^\pi = 1/2^-$

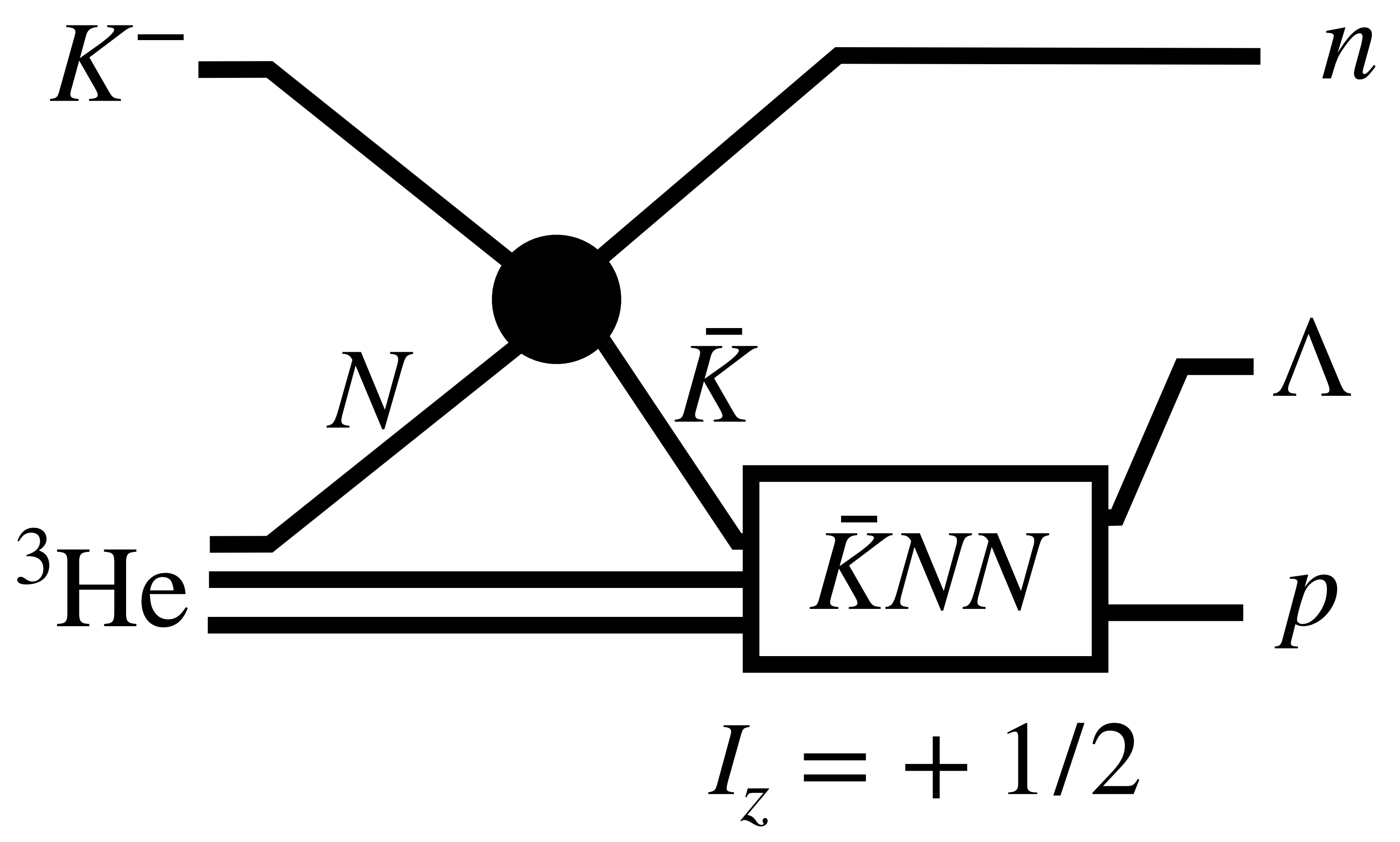


$K^- ppn$-$\bar{K}^0 pnn$

Production reactions

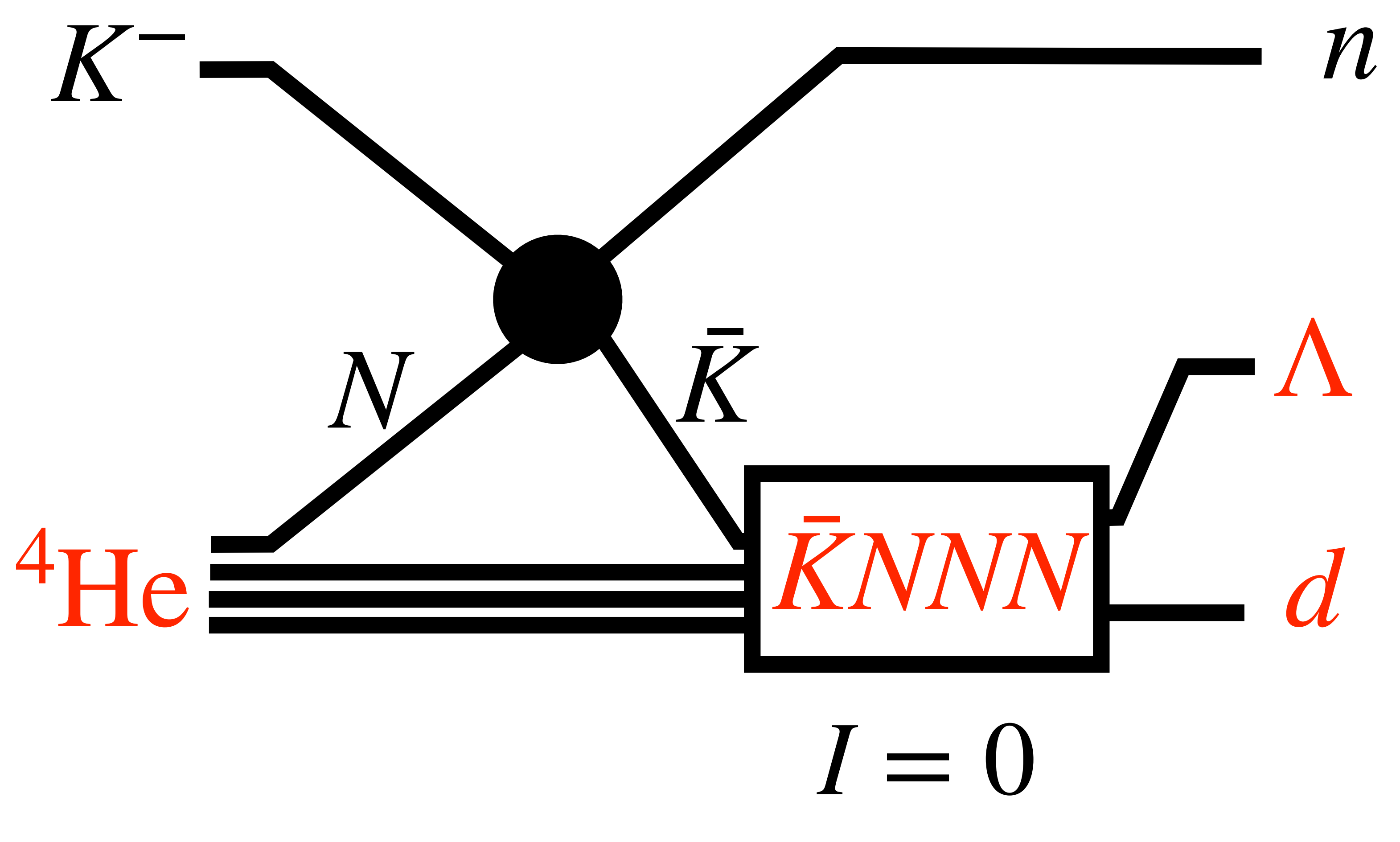
$\bar{K}NN$ production

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

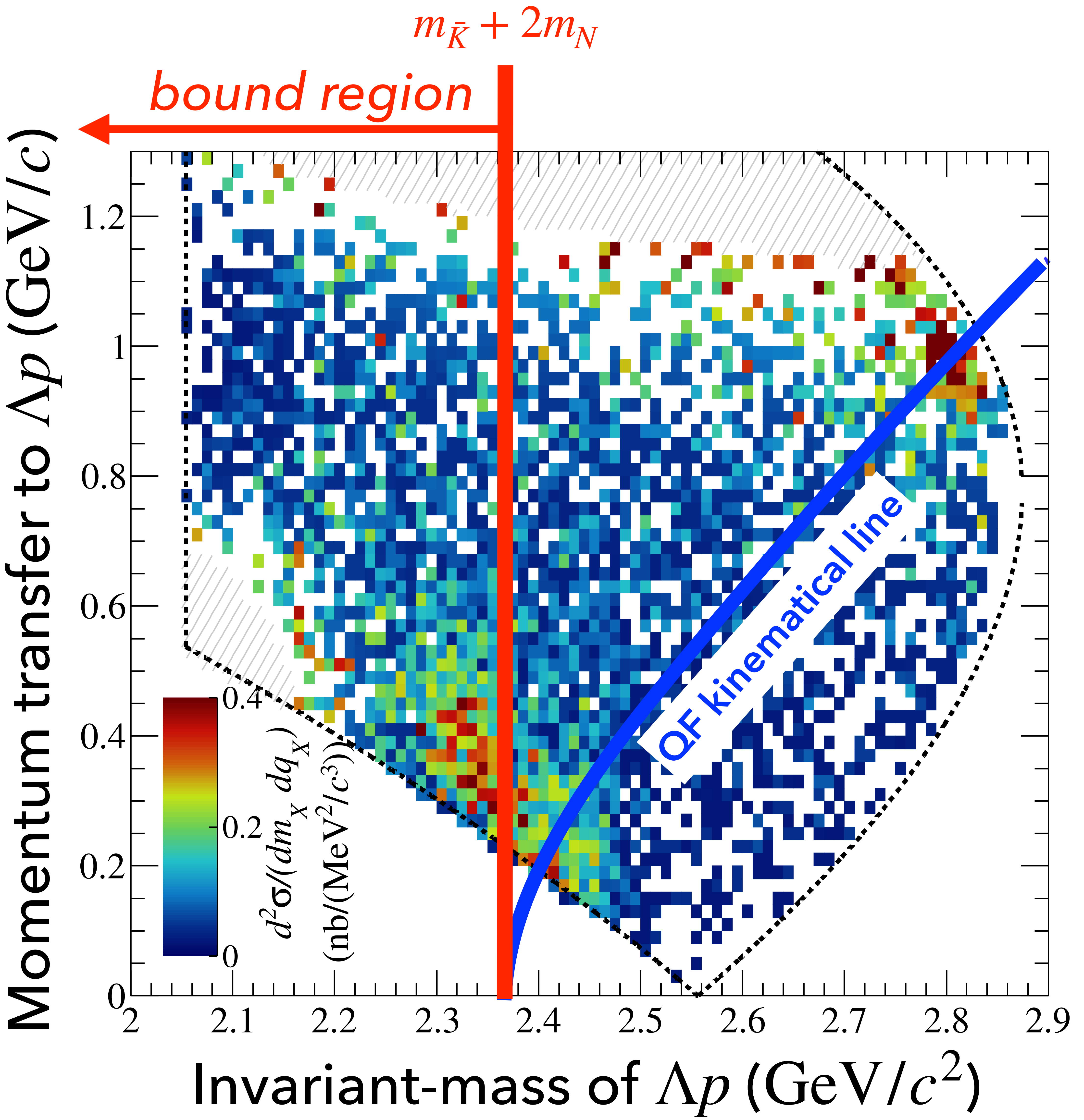


$\bar{K}NNN$ production

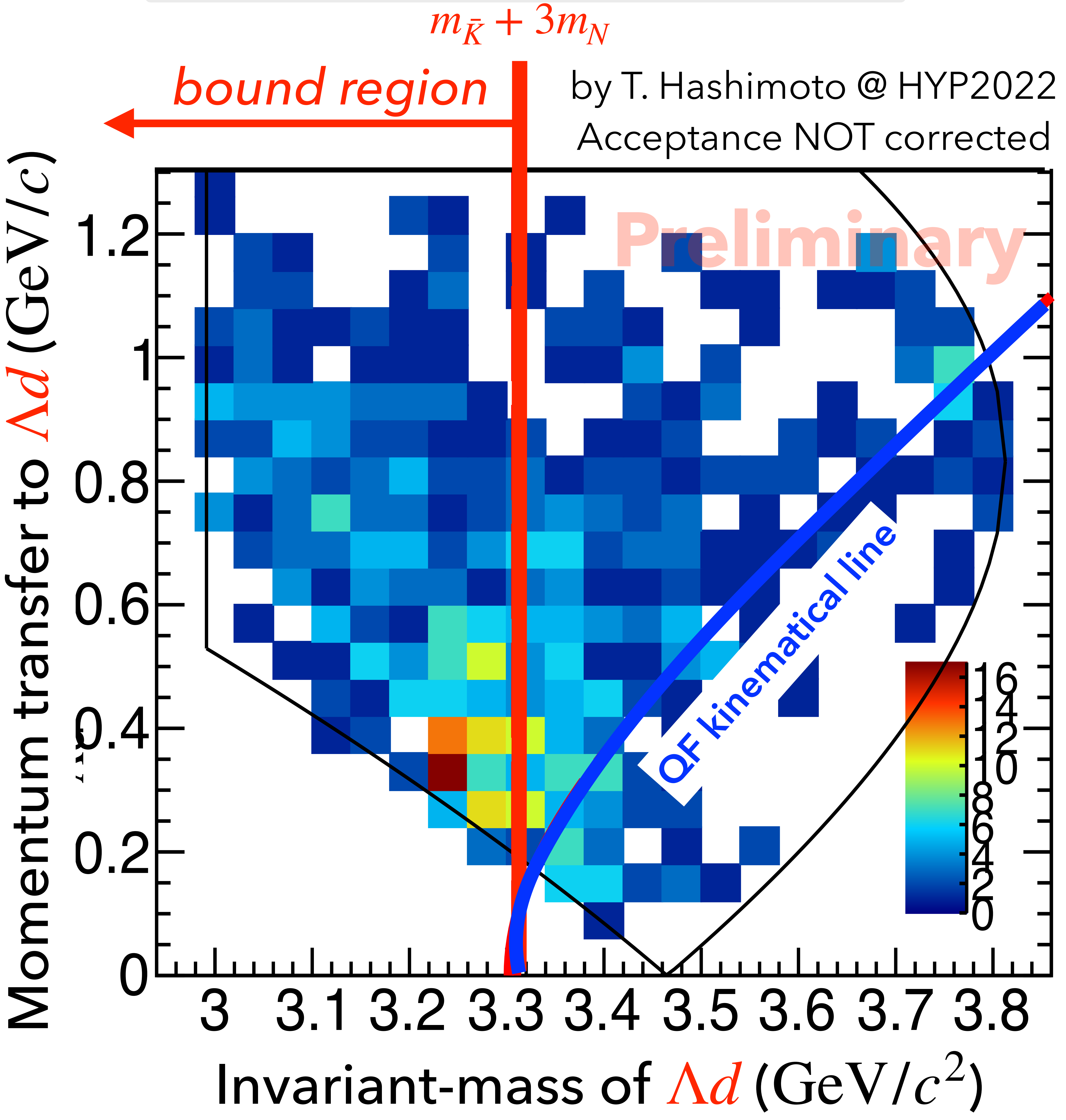
$^{4}\text{He}(K^{-}, n)$



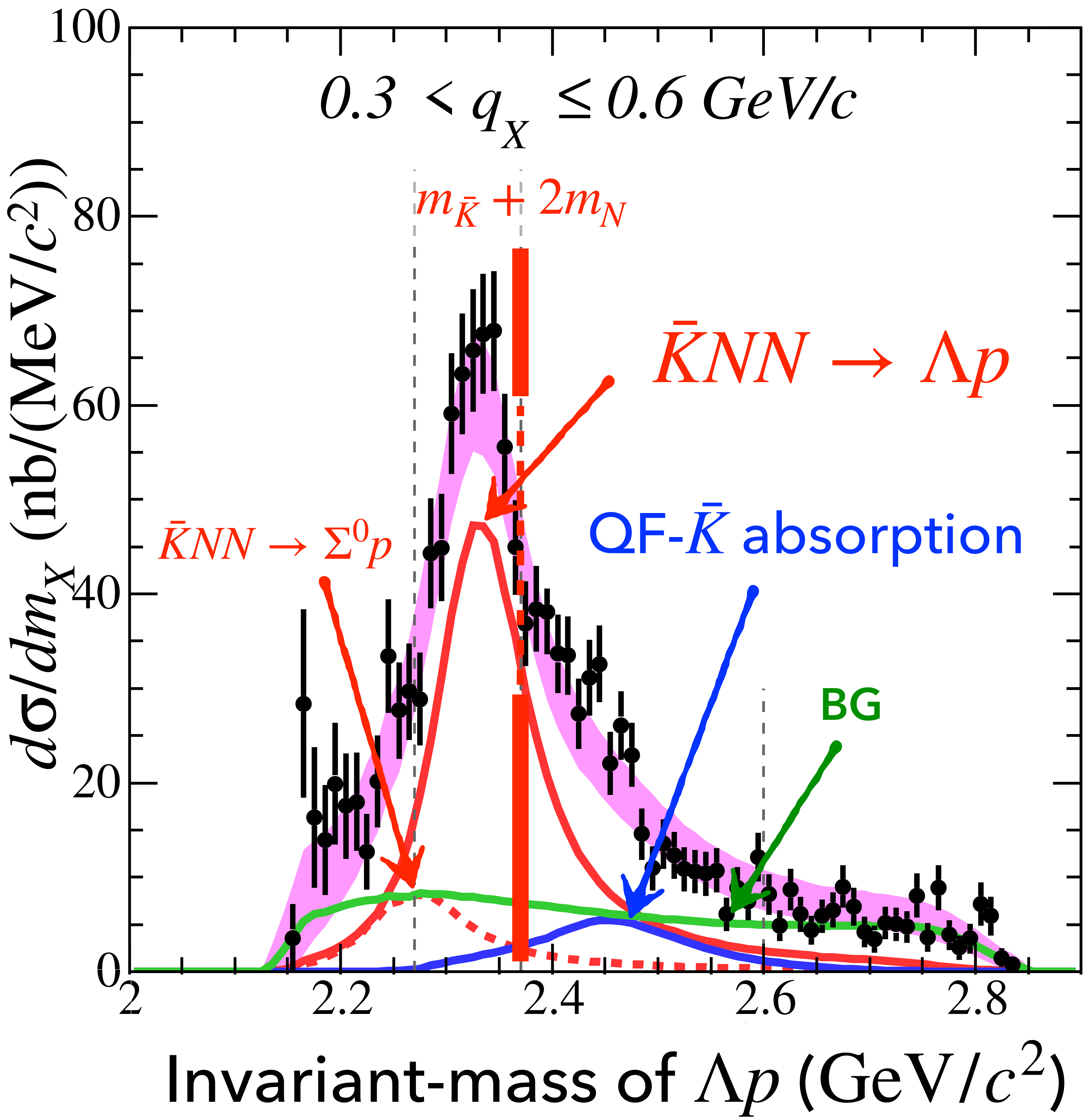
$K^- + {}^3\mathrm{He} \to \Lambda p + n$



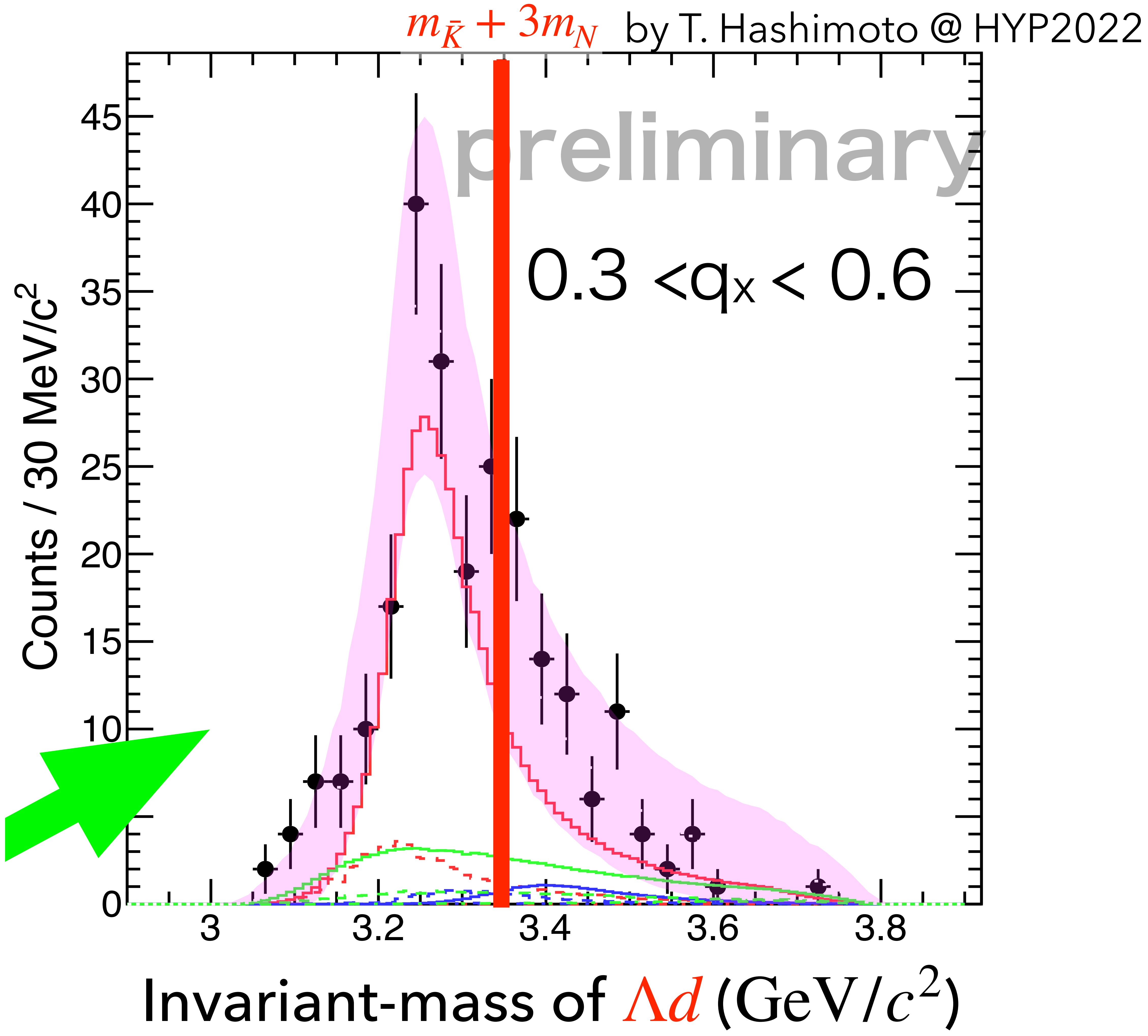
$K^- + {}^4\mathrm{He} \to \Lambda d + n$



$K^- + {}^3\mathrm{He} \rightarrow \Lambda p + n$

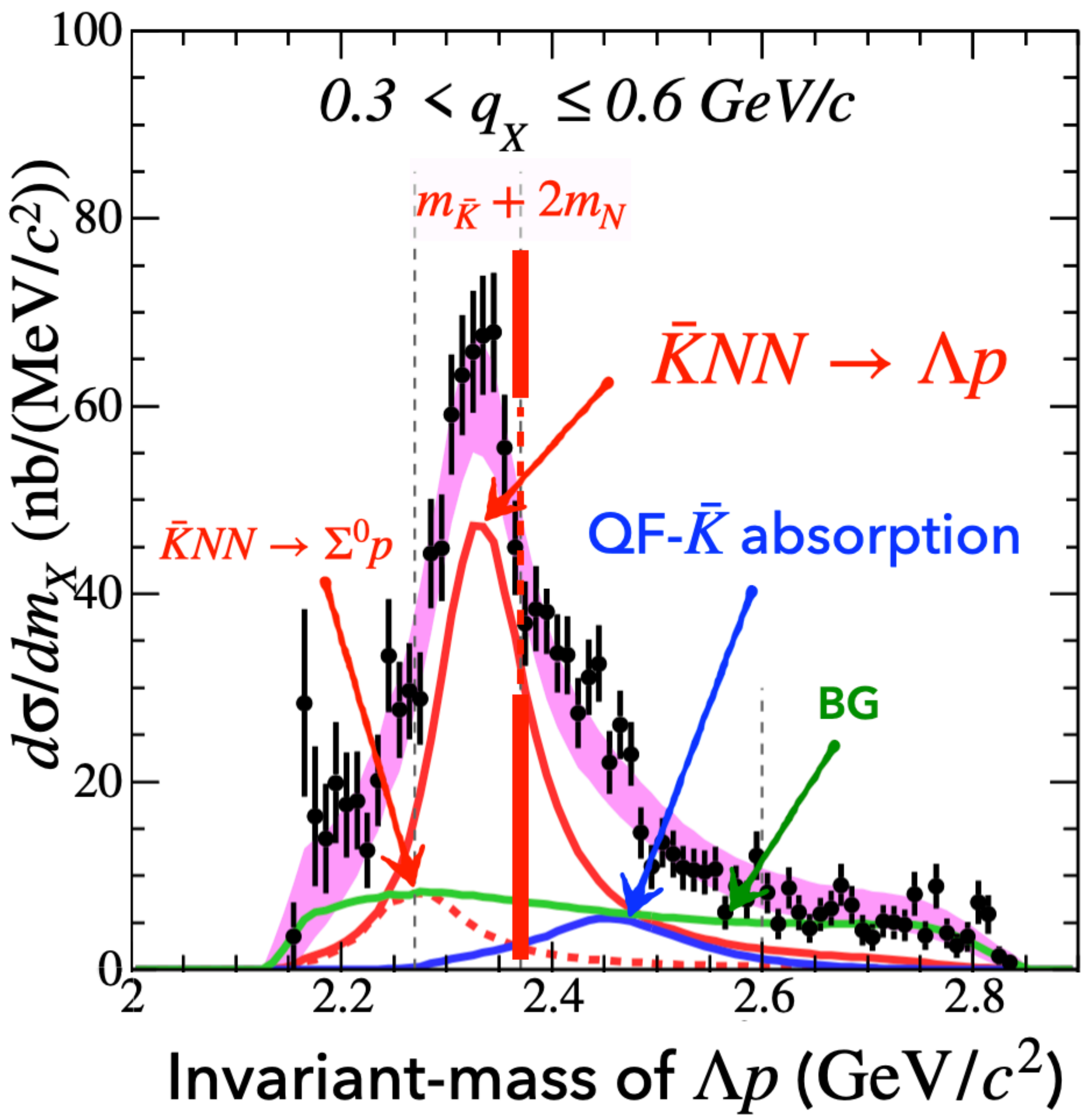
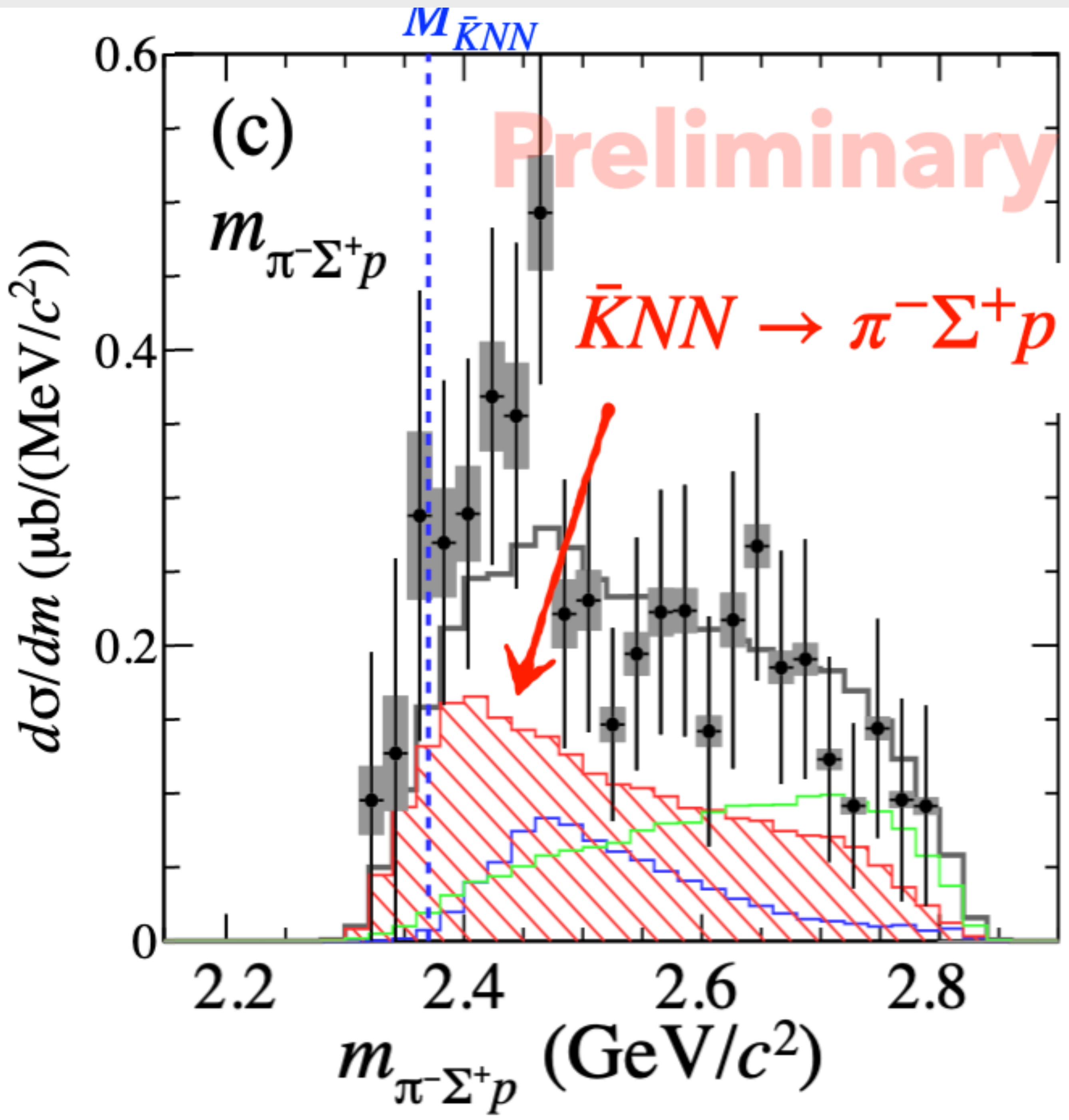
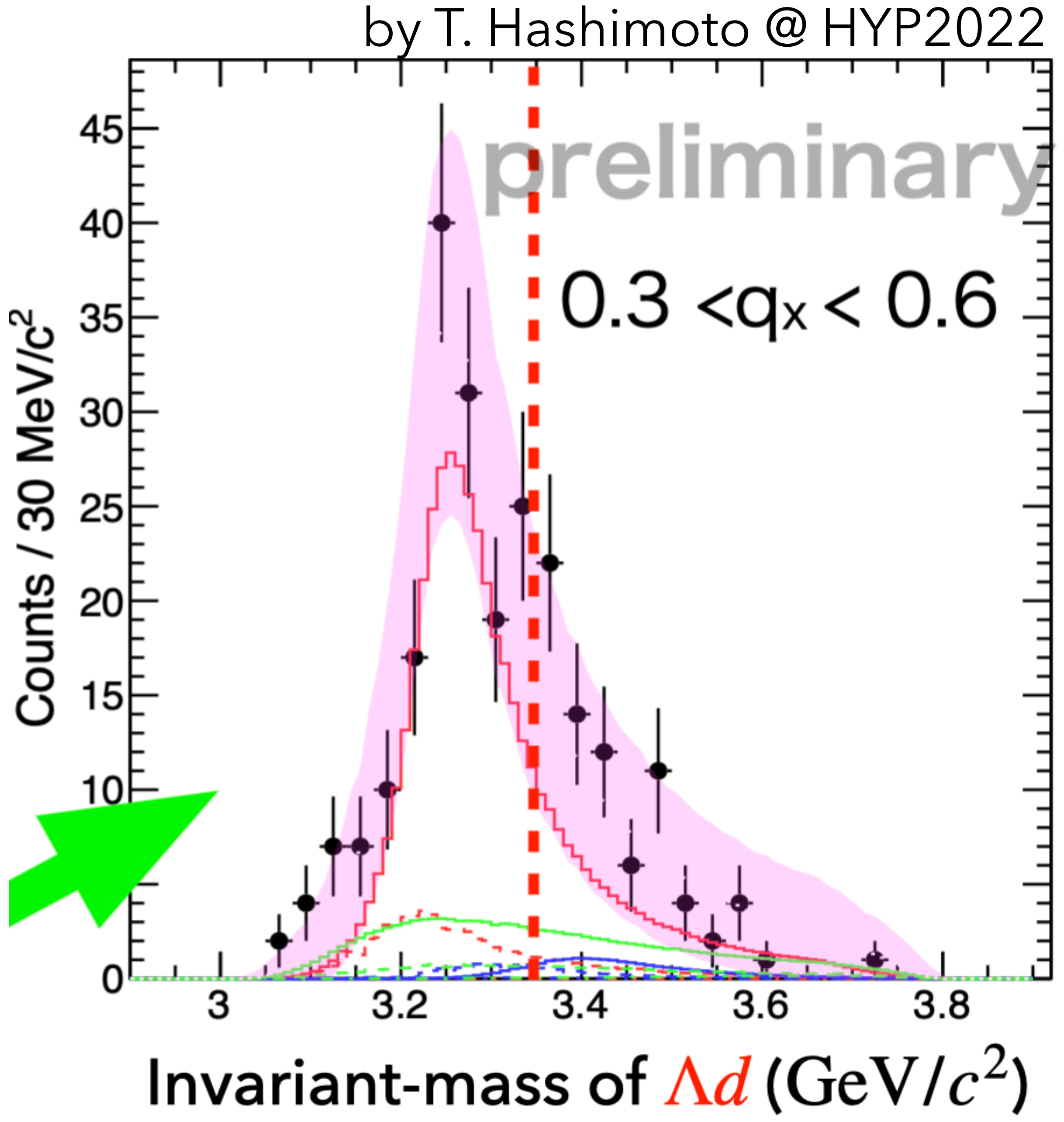


$K^- + {}^4\mathrm{He} \rightarrow \Lambda d + n$



Can be explained by the same manner

Short summary so far

$K^{-}+{}^{3}\mathrm{He}\to\Lambda p+n$	$K^{-}+{}^{3}\mathrm{He}\to\pi YN+n$	$K^{-}+{}^{4}\mathrm{He}\to\Lambda d+n$
		
Signal of $\bar{K}NN$	$\Gamma_{\pi YN} \gg \Gamma_{YN}$	Signal of $\bar{K}NNN$

Let's move to the next stage!

Future project

== Systematic measurement for kaonic nuclei ==

Programs for $\bar{K}$-nuclei

Lighter system

$\Lambda(1405)$

with wider q-region

$d(K^-, n)$ reaction

$\pi^{\pm}\Sigma^{\mp}$ decay

&

$\pi^0\Sigma^0$ decay as well

$\bar{K}NN$ system

J^π determination

To confirm the existence more robustly

Measuring $d\sigma/dq$ & $\alpha_{\Lambda p}$

Search for $(\bar{K}NN)^{I_z=-1/2}$

Isospin partner of observed $\bar{K}NN$

$\bar{K}NN \rightarrow \Lambda n$ decay

Decay branch

Non-mesonic	Mesonic
Λp, $\Sigma^0 p$, $\Sigma^+ n$	$\pi\Lambda N$, $\pi\Sigma N$

J-PARC P89

Heavier system

J-PARC E80

$\bar{K}NNN$ system

Door to heavier system

$^4\mathrm{He}(K^-, N)$ reaction

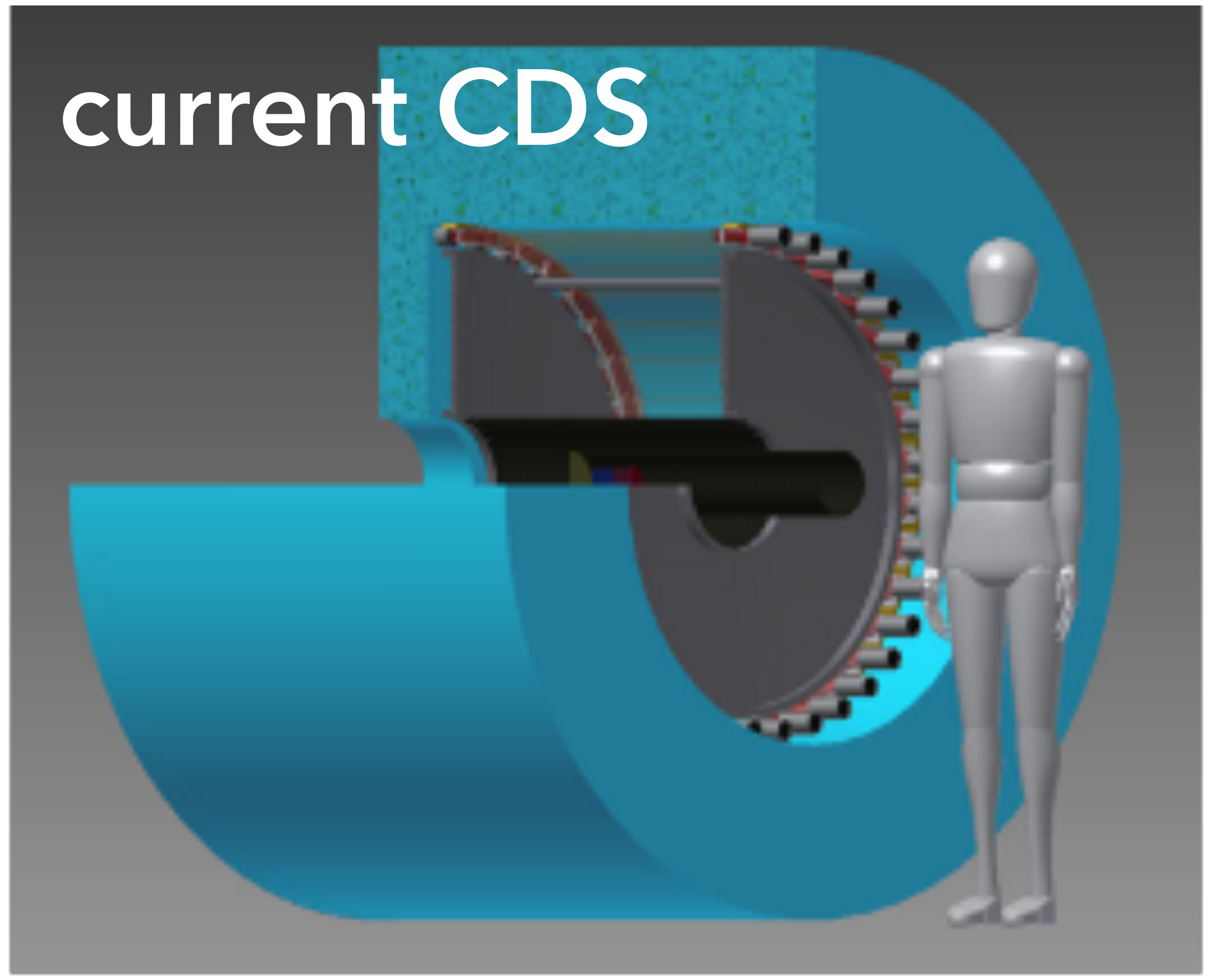
$K^-ppn - \bar{K}^0pnn$ (I=0)

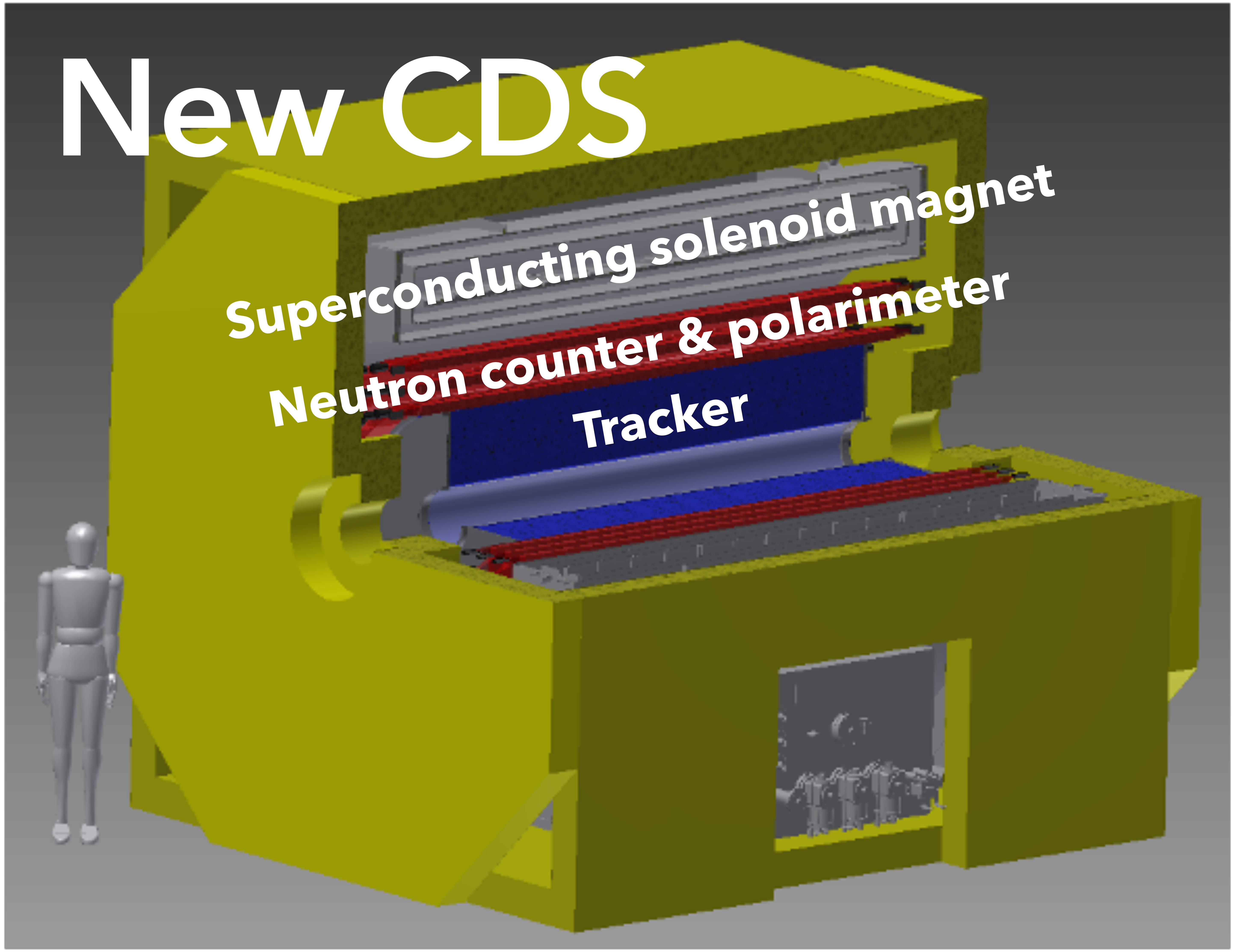
$\bar{K}NNNN$ system

Expected large B.E. & high density

$^6\mathrm{Li}(K^-, d)$ reaction

K^--α $\quad$ $\bar{K}^0$-α

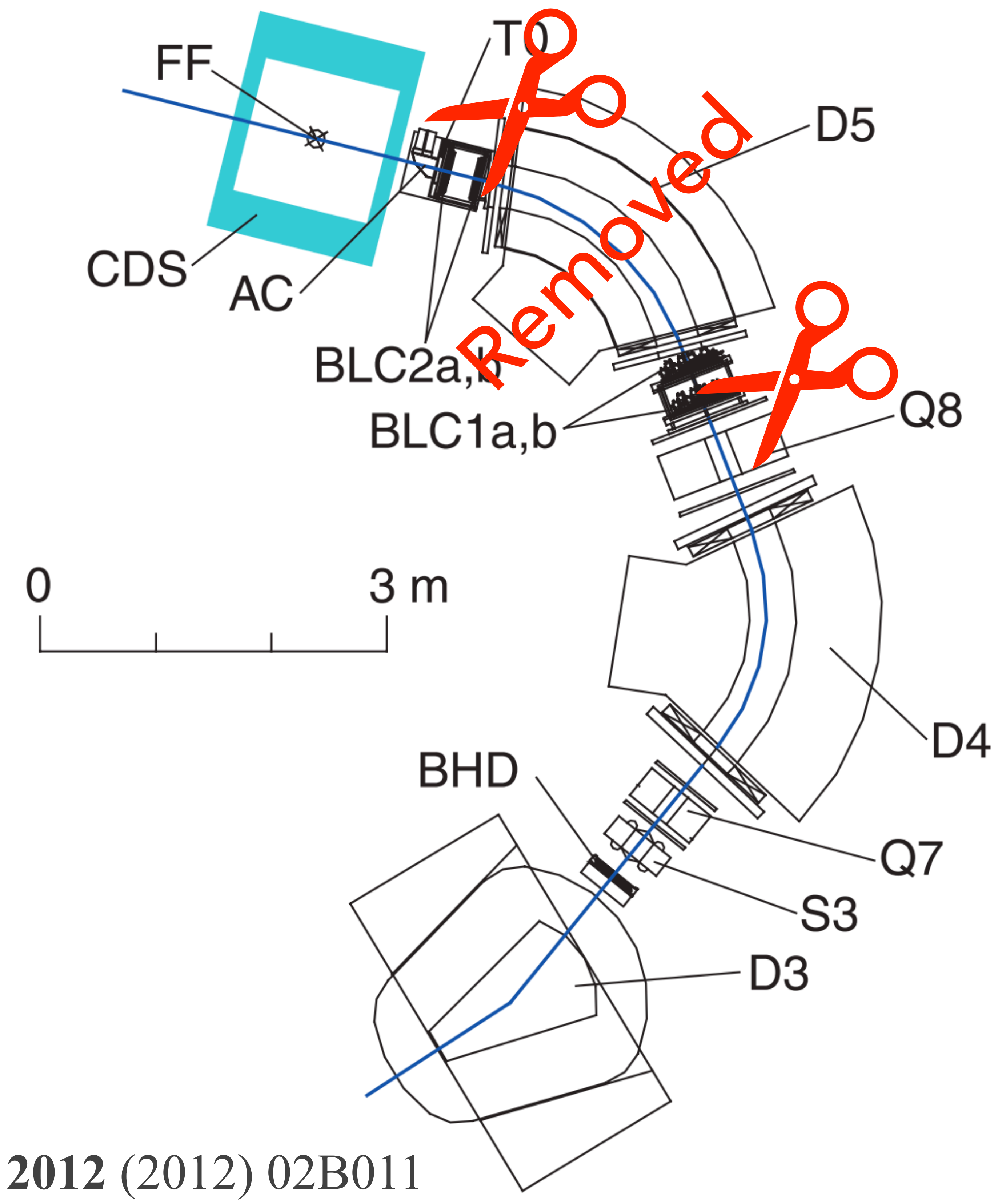




Construction has been started
(Completed in 2025)

Modification of K1.8BR beam line

Current K1.8BR

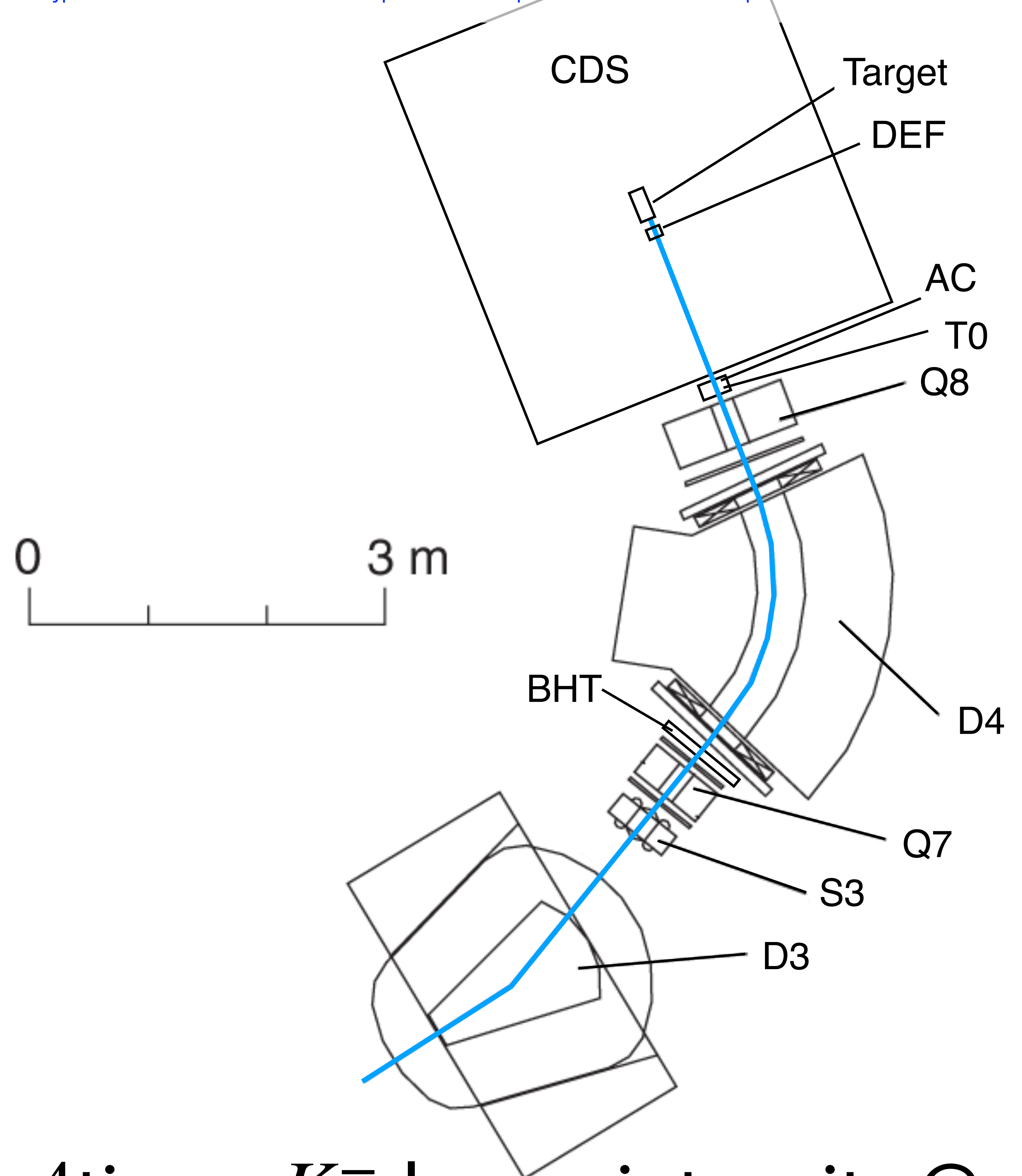


PTEP **2012** (2012) 02B011

Planned modification

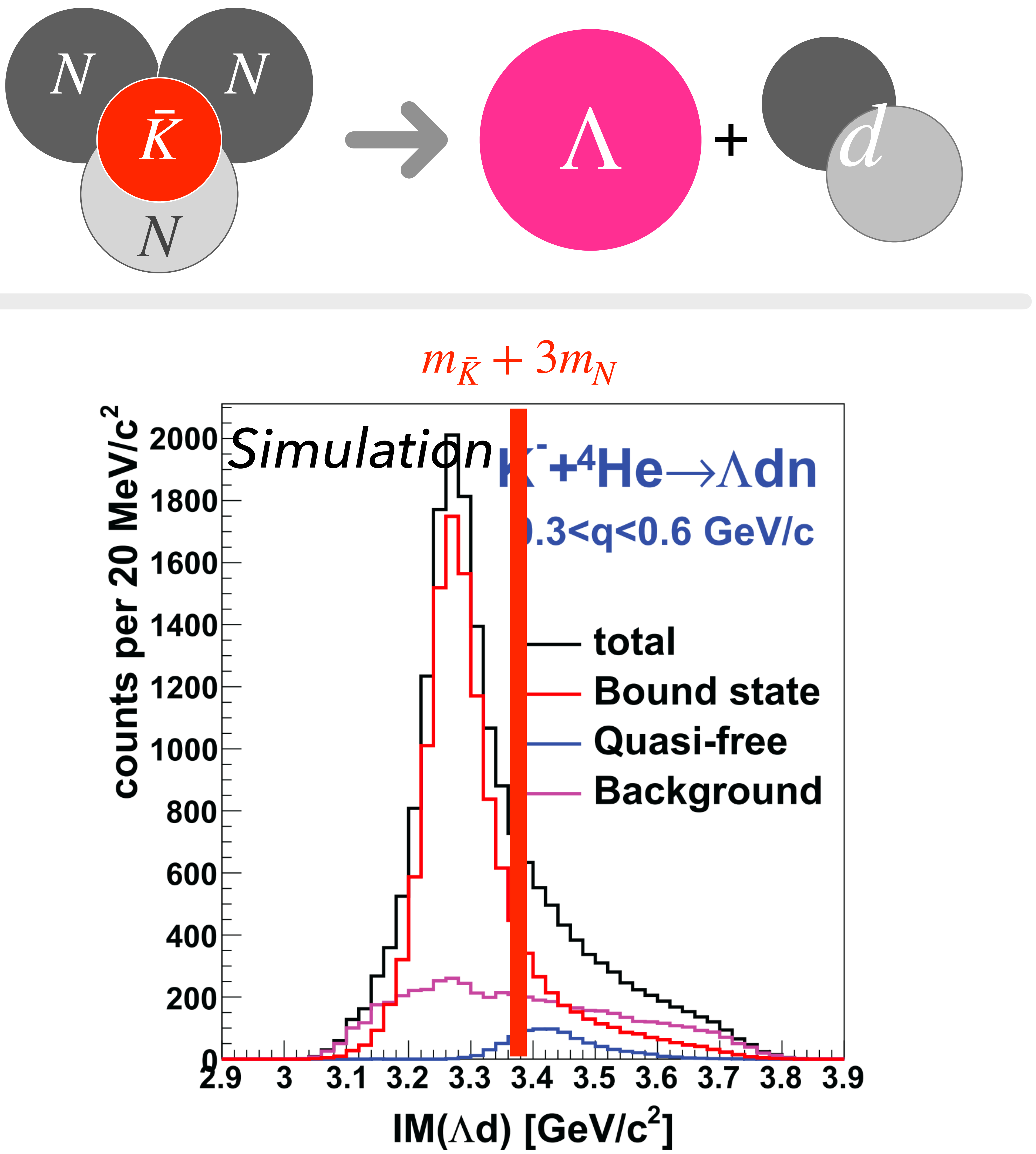
Conceptual design in E80 proposal

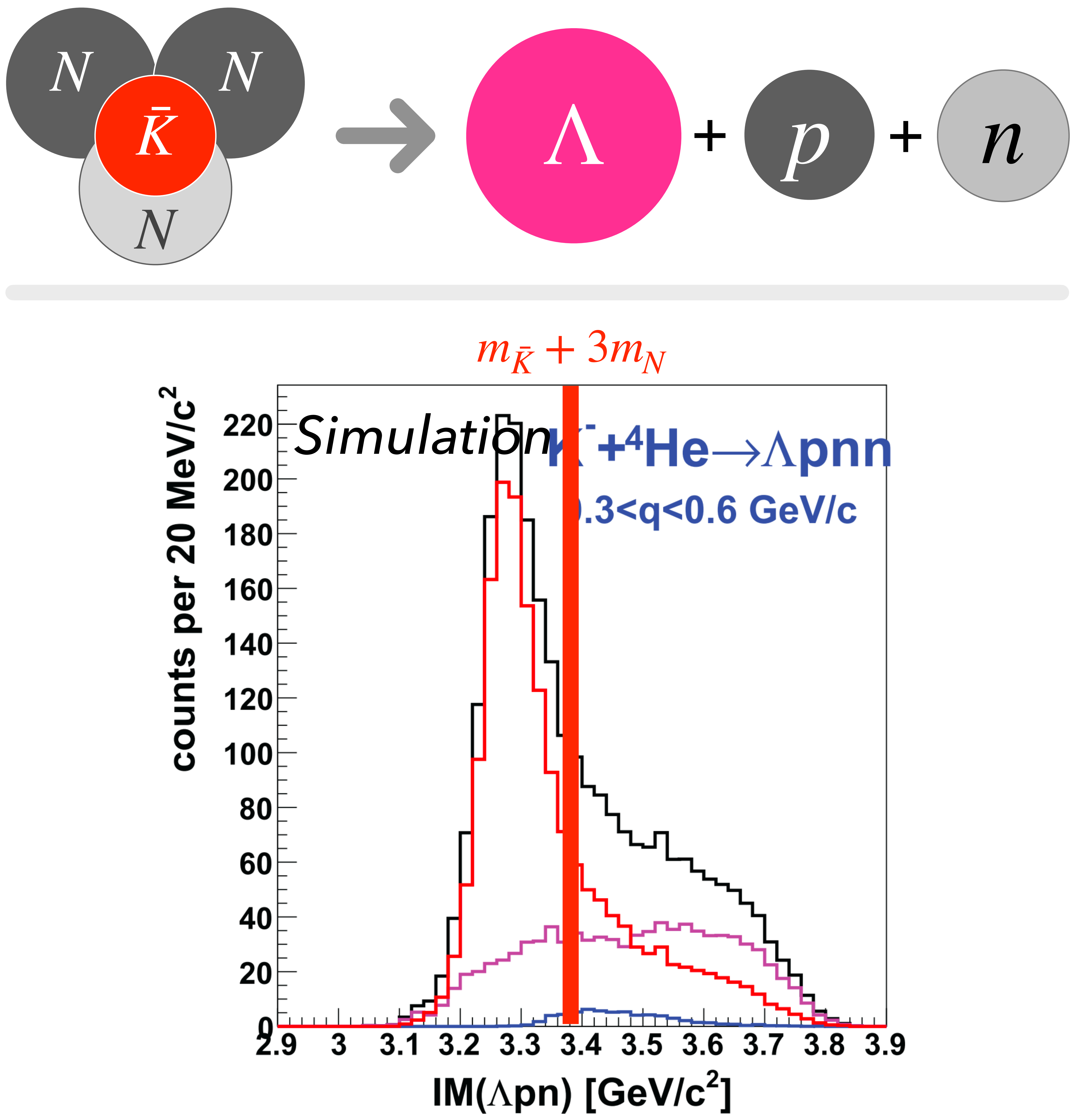
https://j-parc.jp/researcher/Hadron/en/pac_2007/pdf/P80_2020-10.pdf



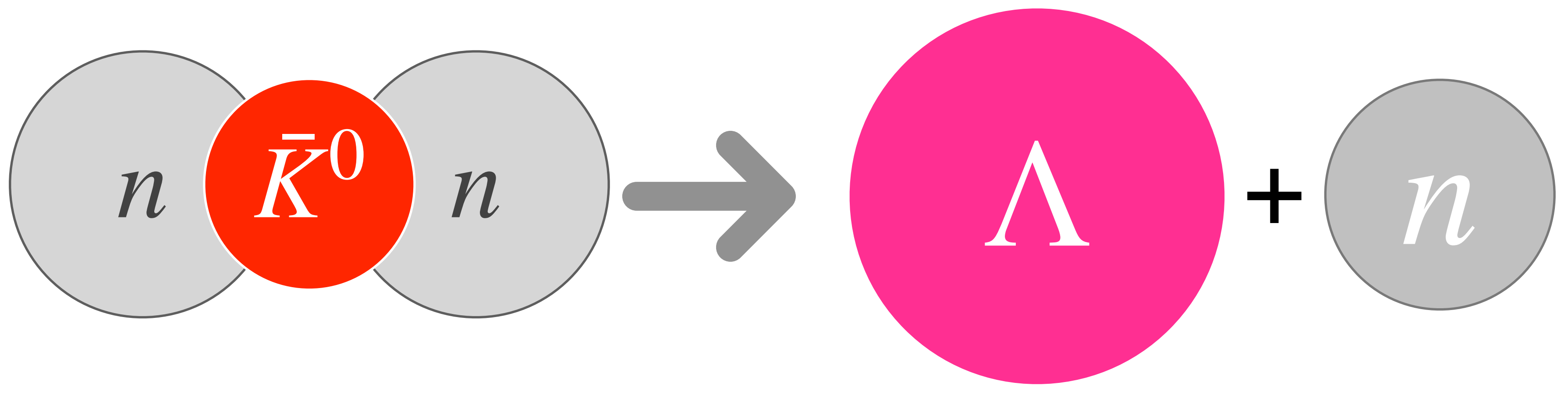
$\sim$ 1.4times K^{-}-beam intensity @ $p_K = 1$ GeV/c with keeping beam focusing.

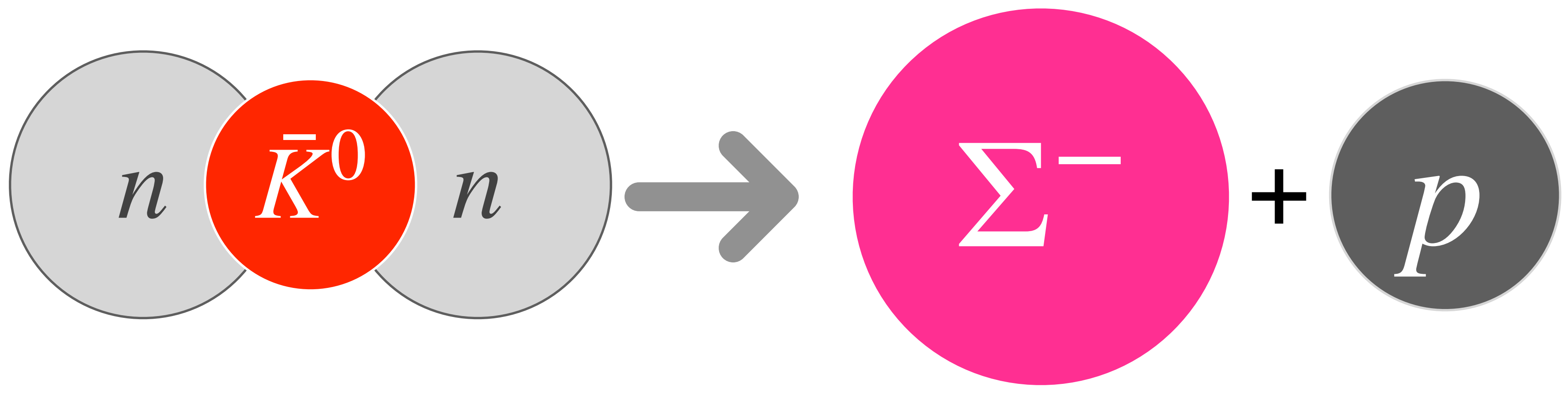
Expected results

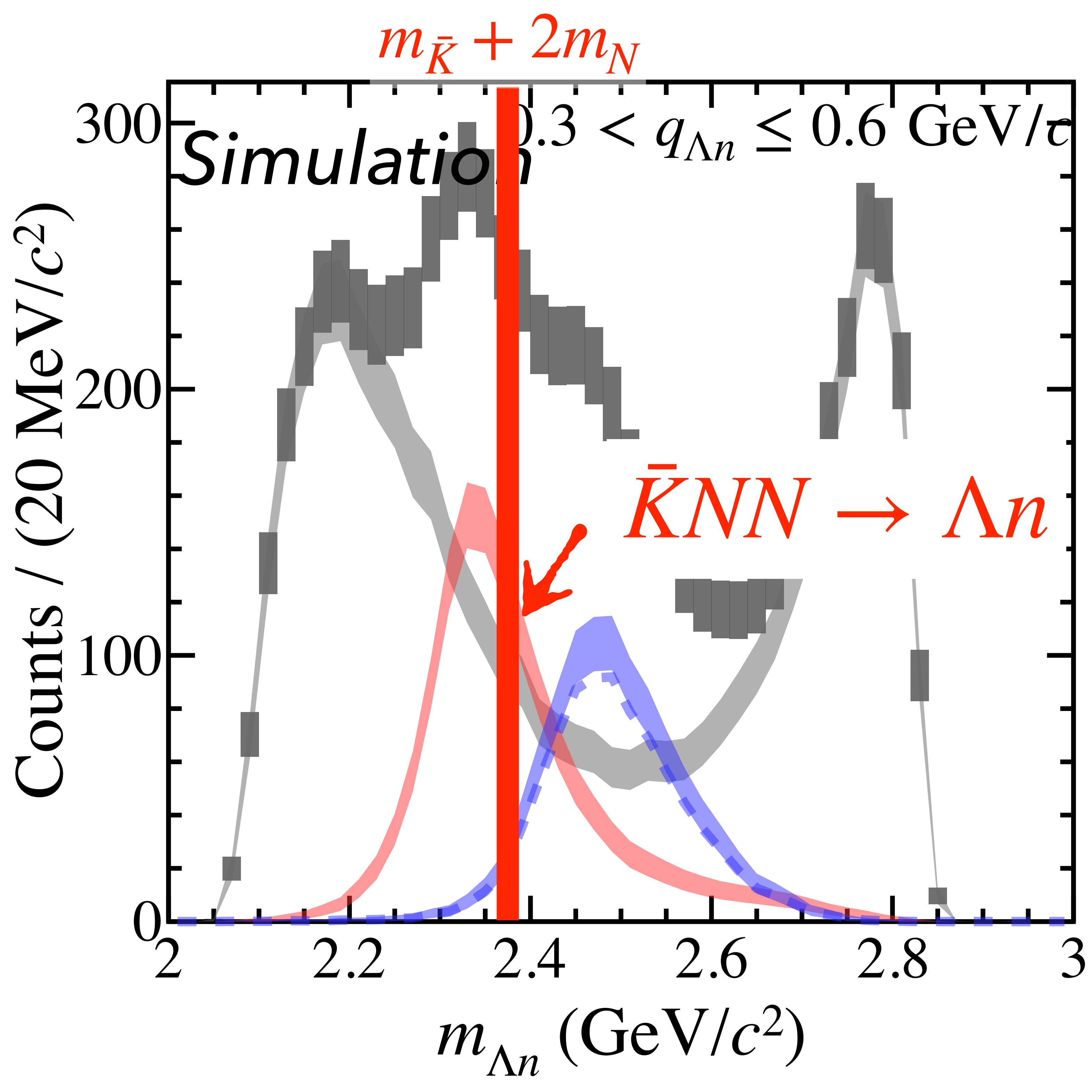


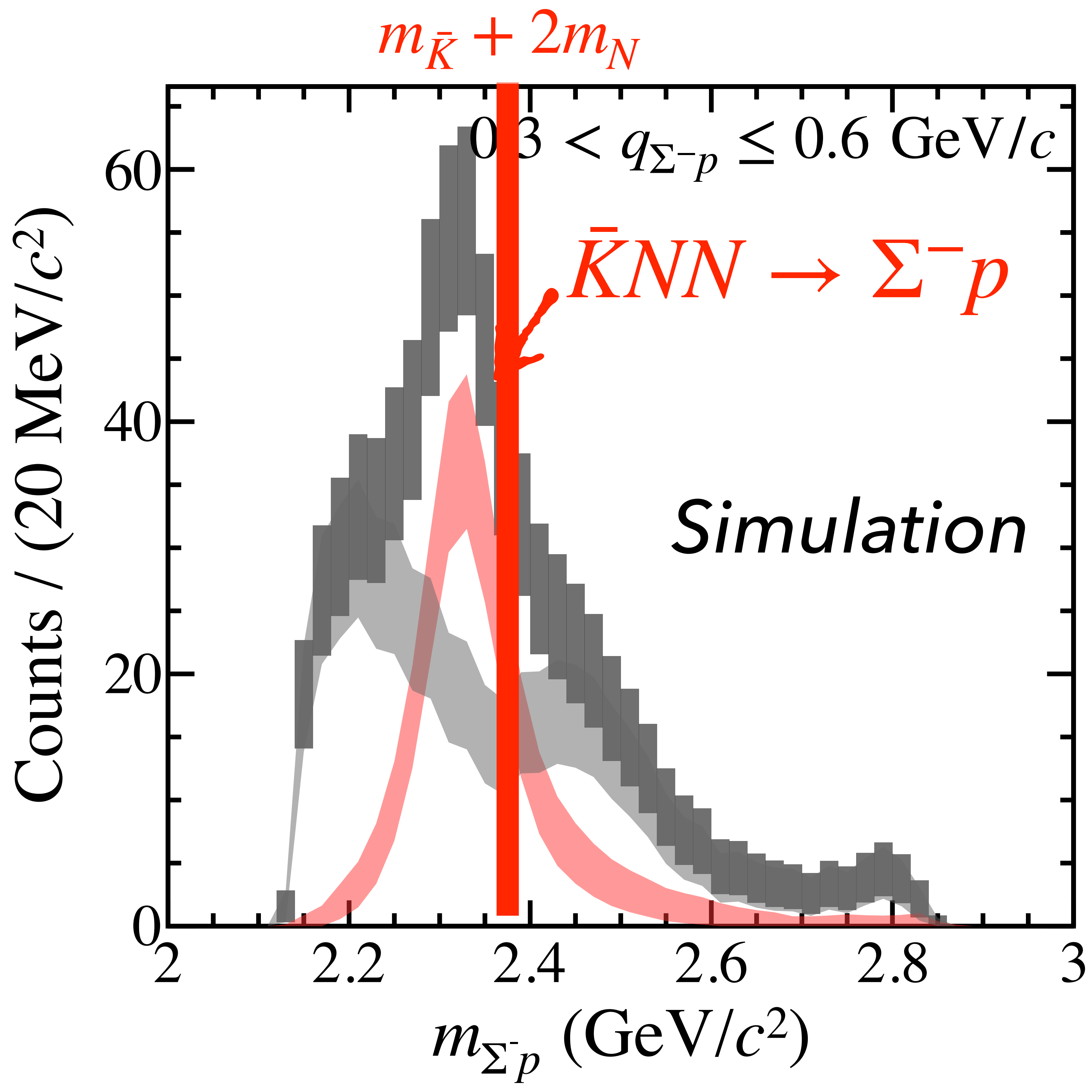


Expected results



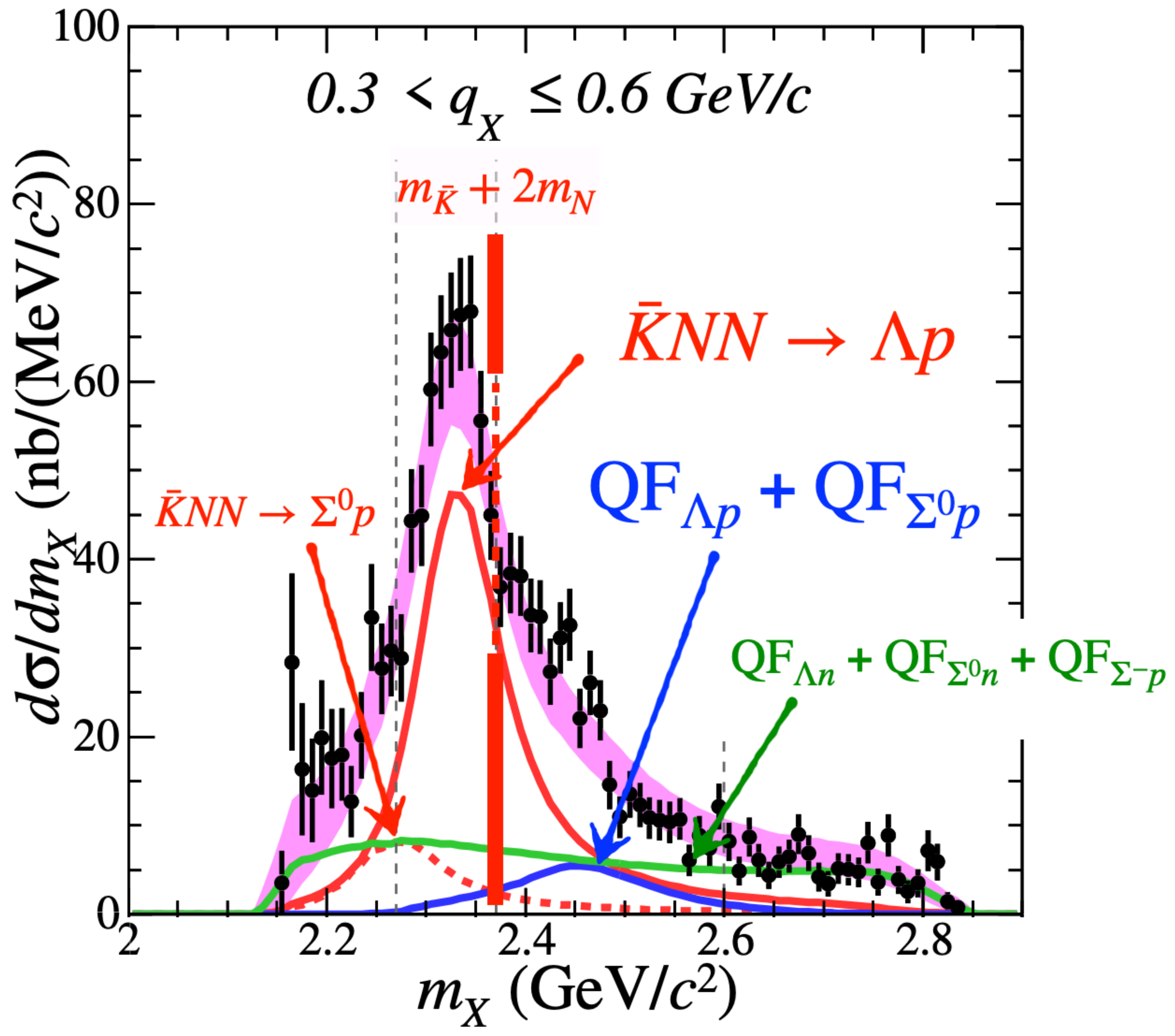






Summary

We observed the first clear signal of $\bar{K}NN$ in J-PARC E15



We would like to robustly confirm the existence of $\bar{K}$-nuclei

&

clarify their internal structure

Thank you for your attention!

= The J-PARC E15 collaboration =

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Thank you for your attention!

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