Result of $\bar{K}NN$ search at J-PARC and future projects

Takumi Yamaga (RIKEN)

ECT* workshop
2022.10.17 – 21

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\bar{K}[NN]^{I=0})^{I=1/2}$
$J^\pi = 0^-$	$J^\pi = 1^-$
$\boxed{\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N} + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$	$\boxed{-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N} + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$

ground state

shallow bound?

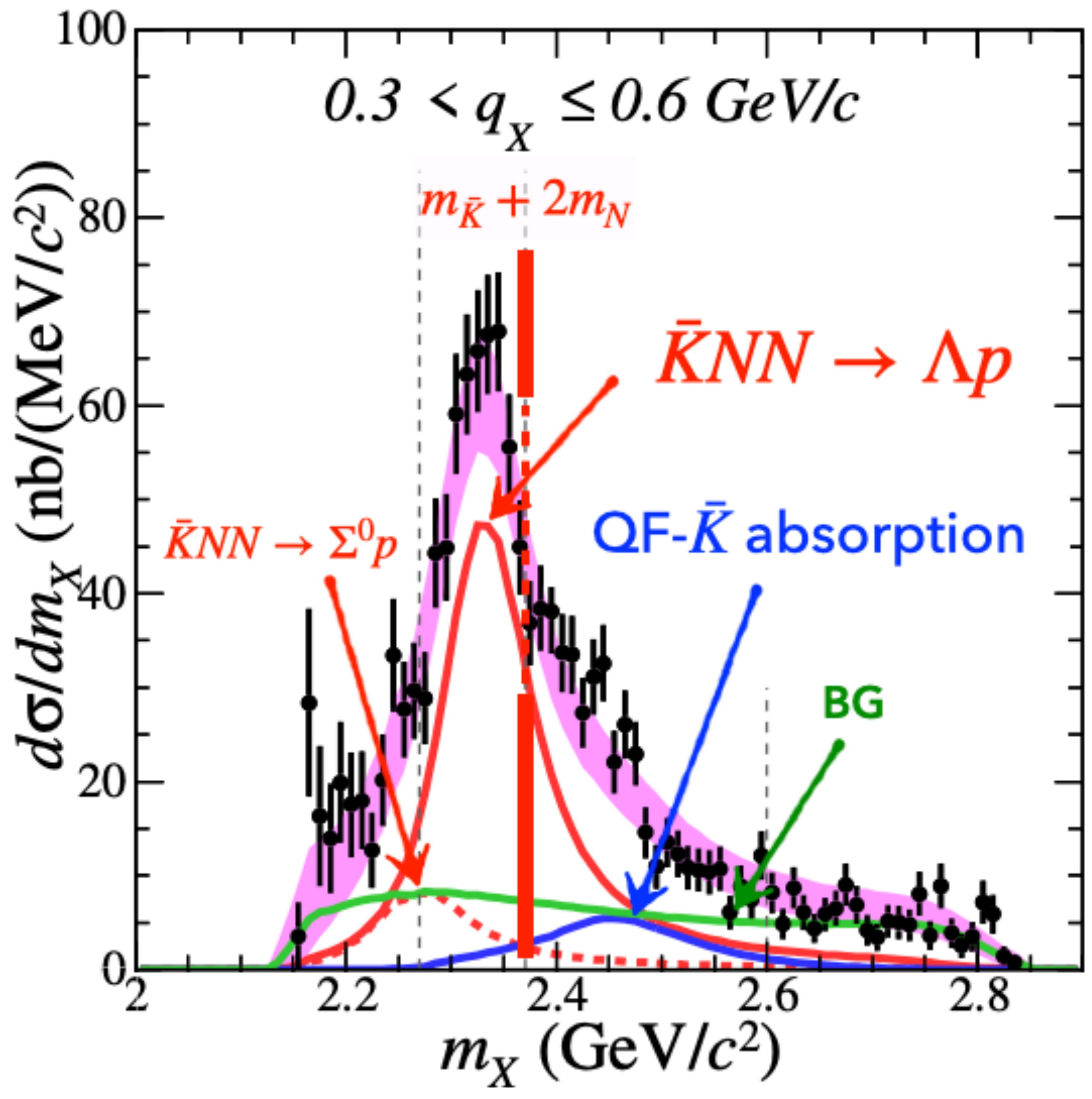
N. Shevchenko, Few-Body syst. **61** (2020) 27

$I_z = +1/2$ K^-pp - $\bar{K}^0pn$ → We observed signal in J-PARC E15

$I_z = -1/2$ K^-pn - $\bar{K}^0nn$

So far,

J-PARC E15



We observed a signal of
$\bar{K}NN^{(I_z=+1/2)} \rightarrow \Lambda p$

Future,

J-PARC P89

new CDS @ modified K.18BR
(8 weeks ⊗ 90 kW)

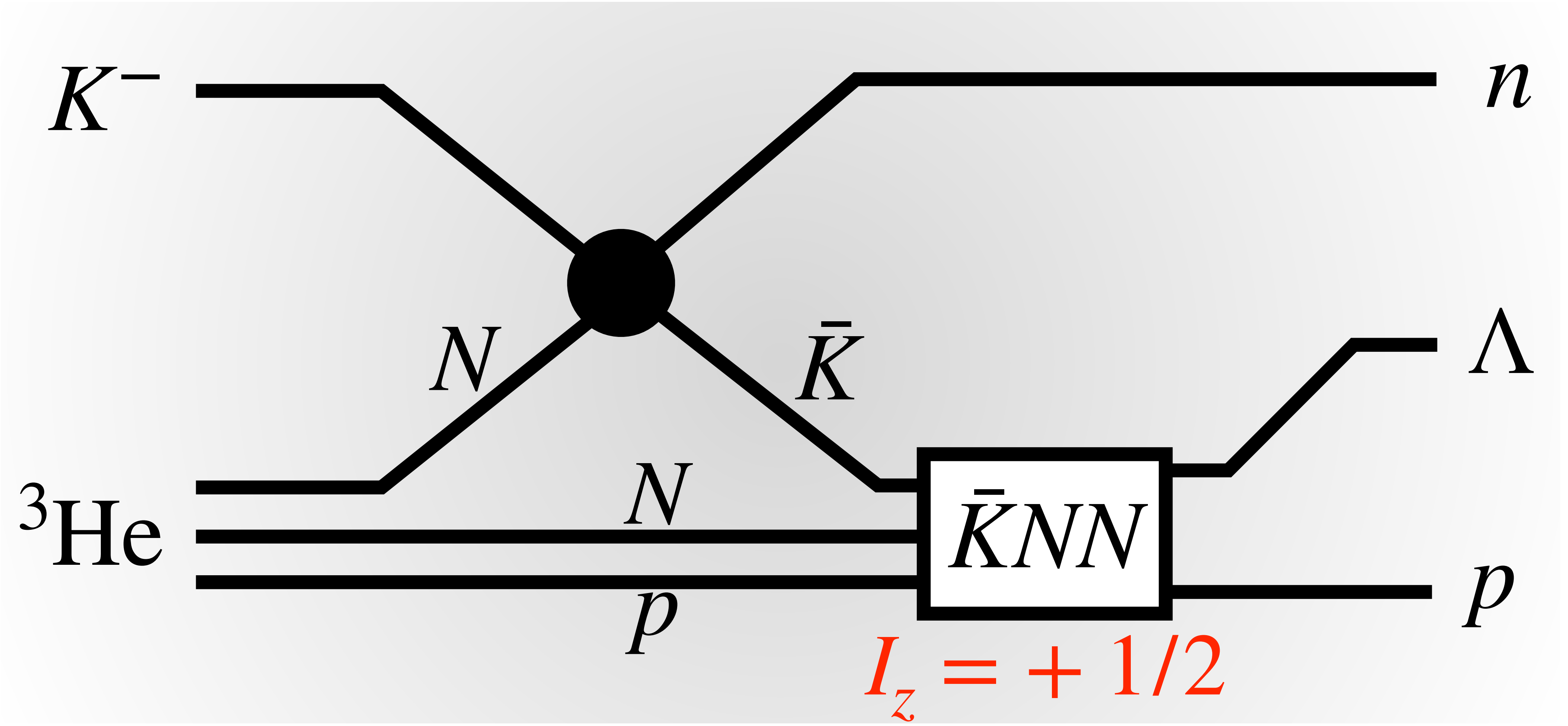
We will measure,

Spin-spin correlation of Λp
to determine J^π

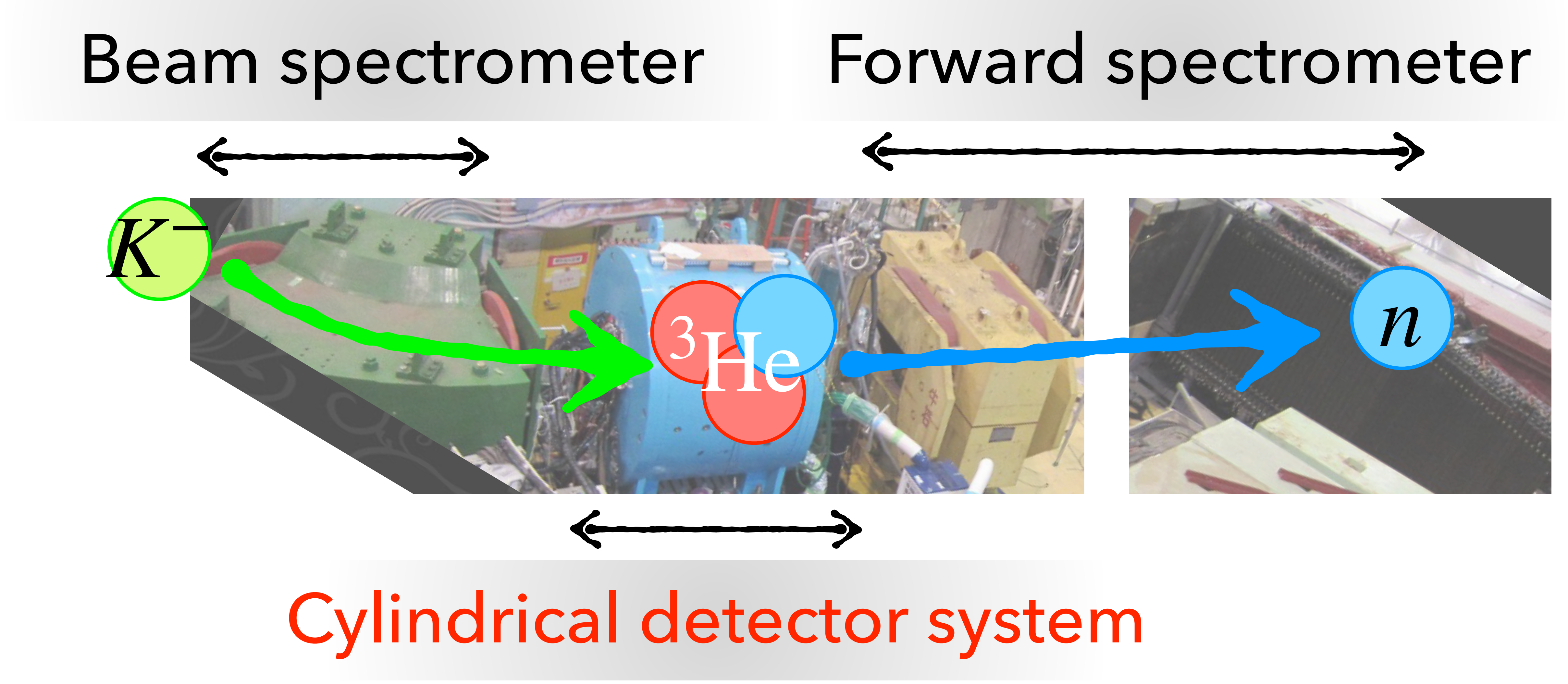
(m, q) distribution of Λn & $\Sigma^- p$ pairs
to search for $\bar{K}NN^{(I_z=-1/2)}$

J-PARC E15

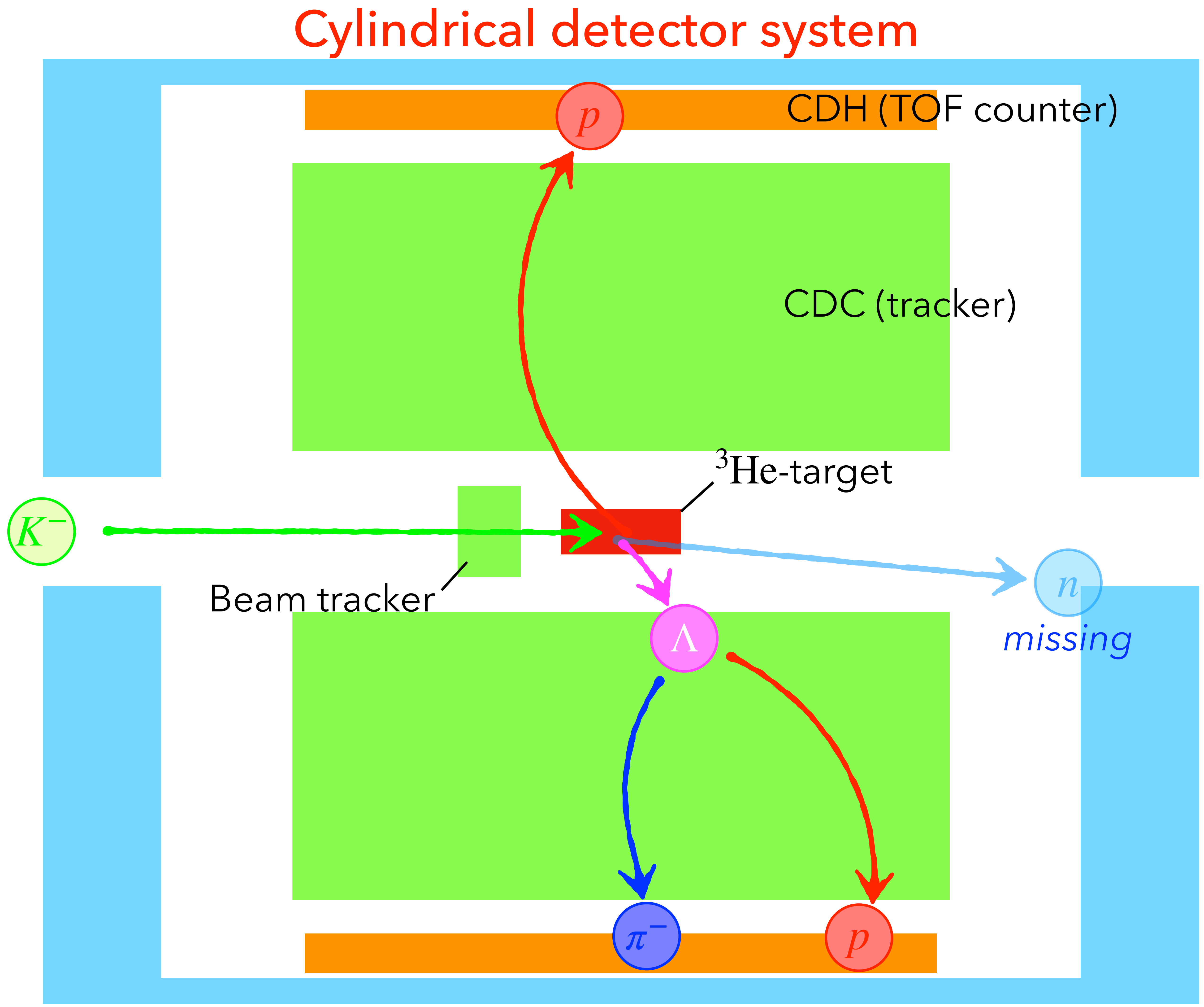
Production reaction



Detector system



J-PARC E15



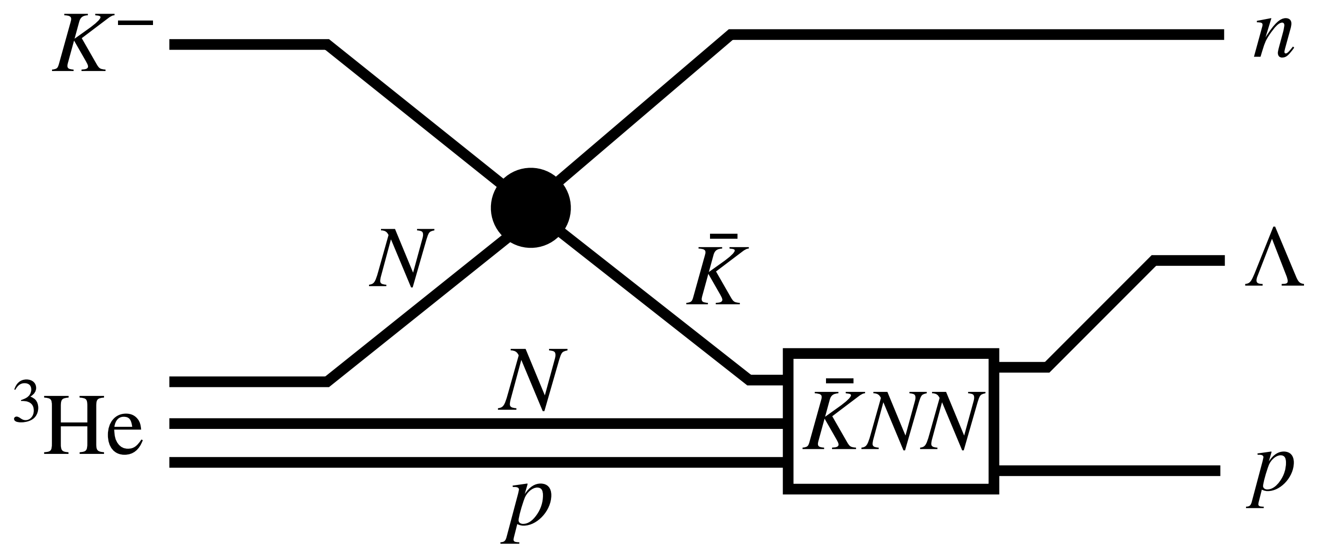
- Selecting $\Lambda p + n_{\mathrm{miss}}$ final state

  → n_{miss} ID by missing mass technique

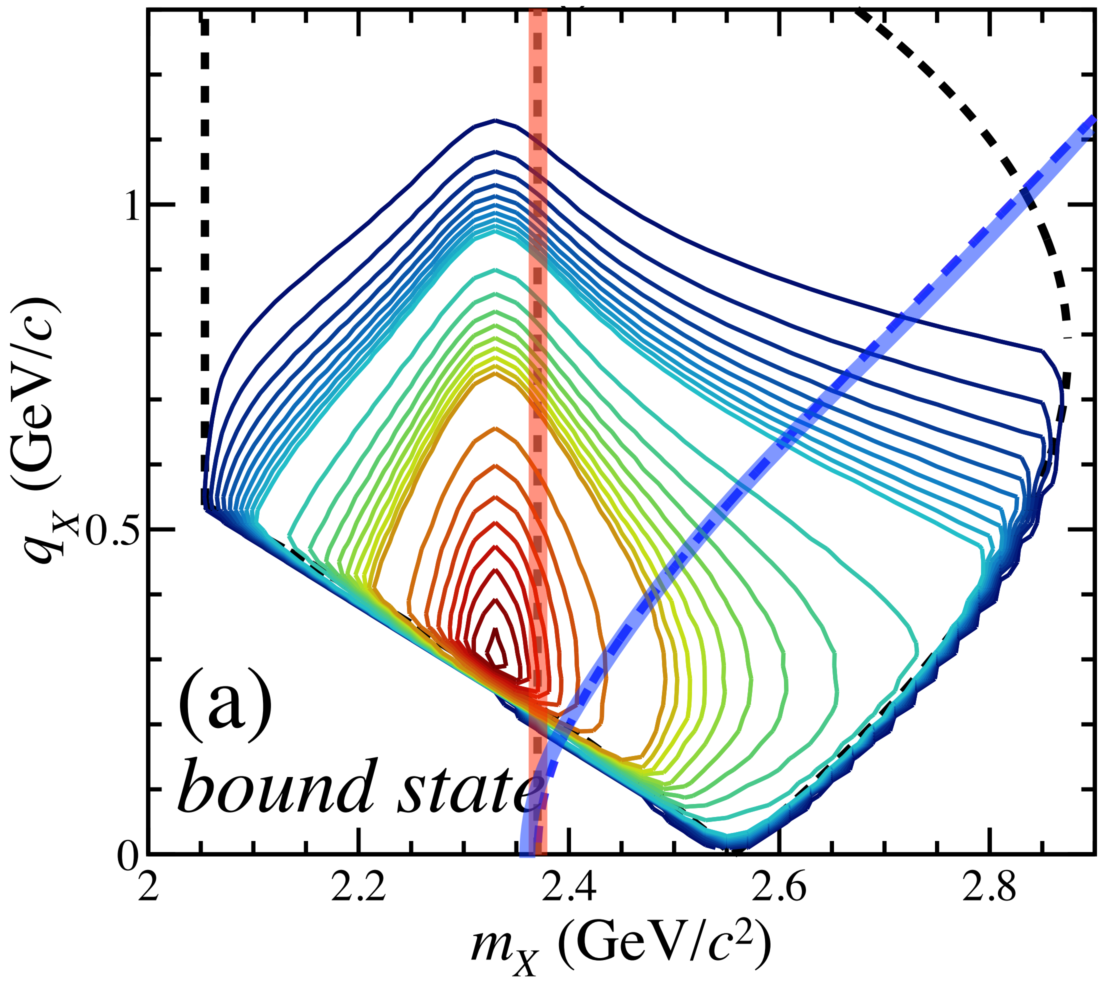
- Measuring Λp invariant-mass

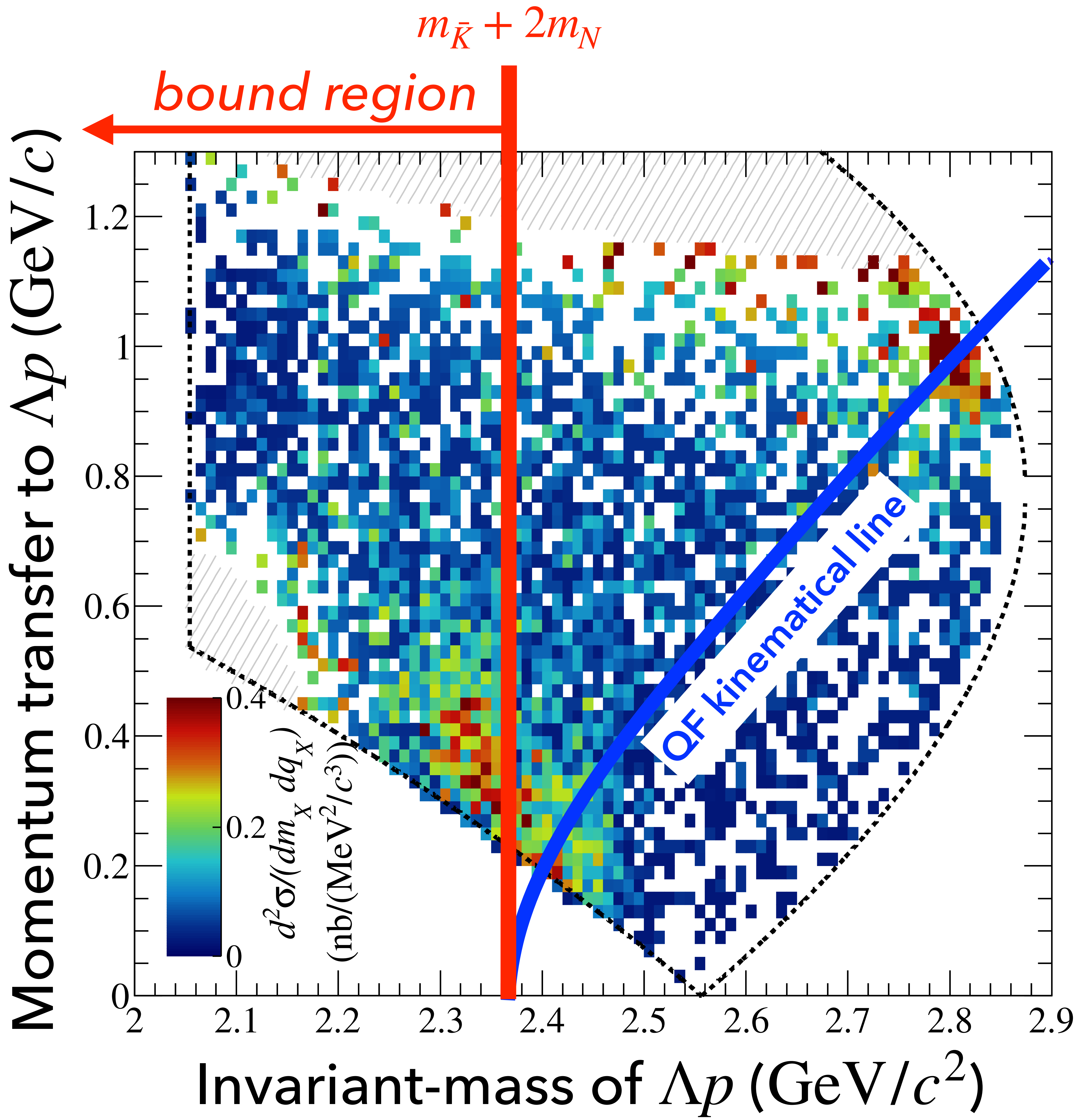
  & momentum transfer

$\bar{K}NN$ production

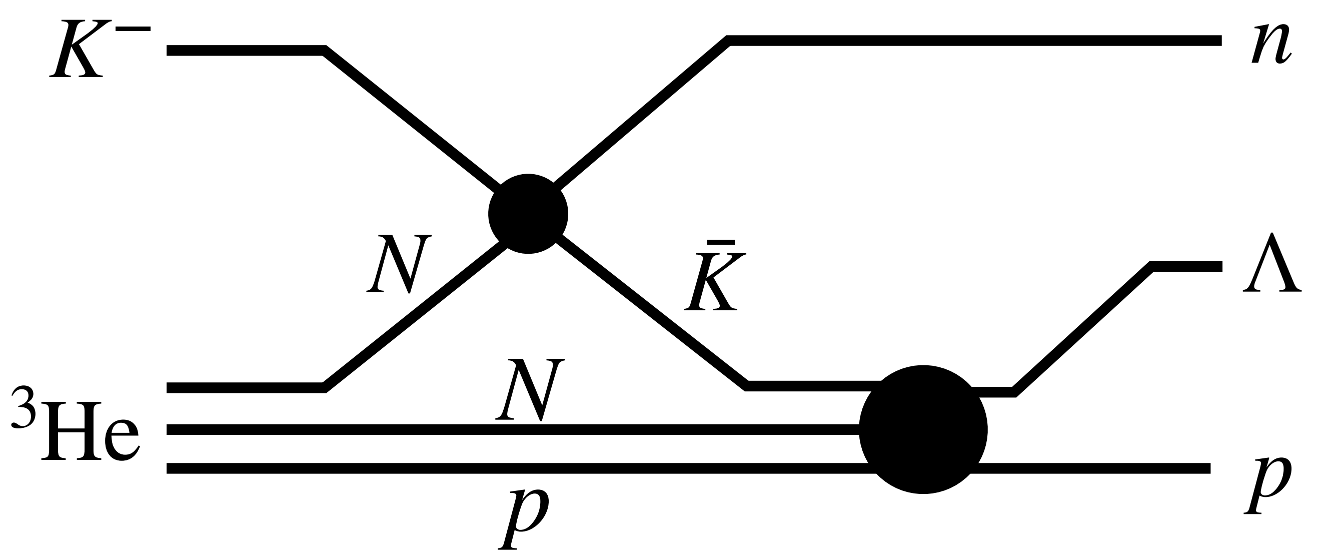


$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$

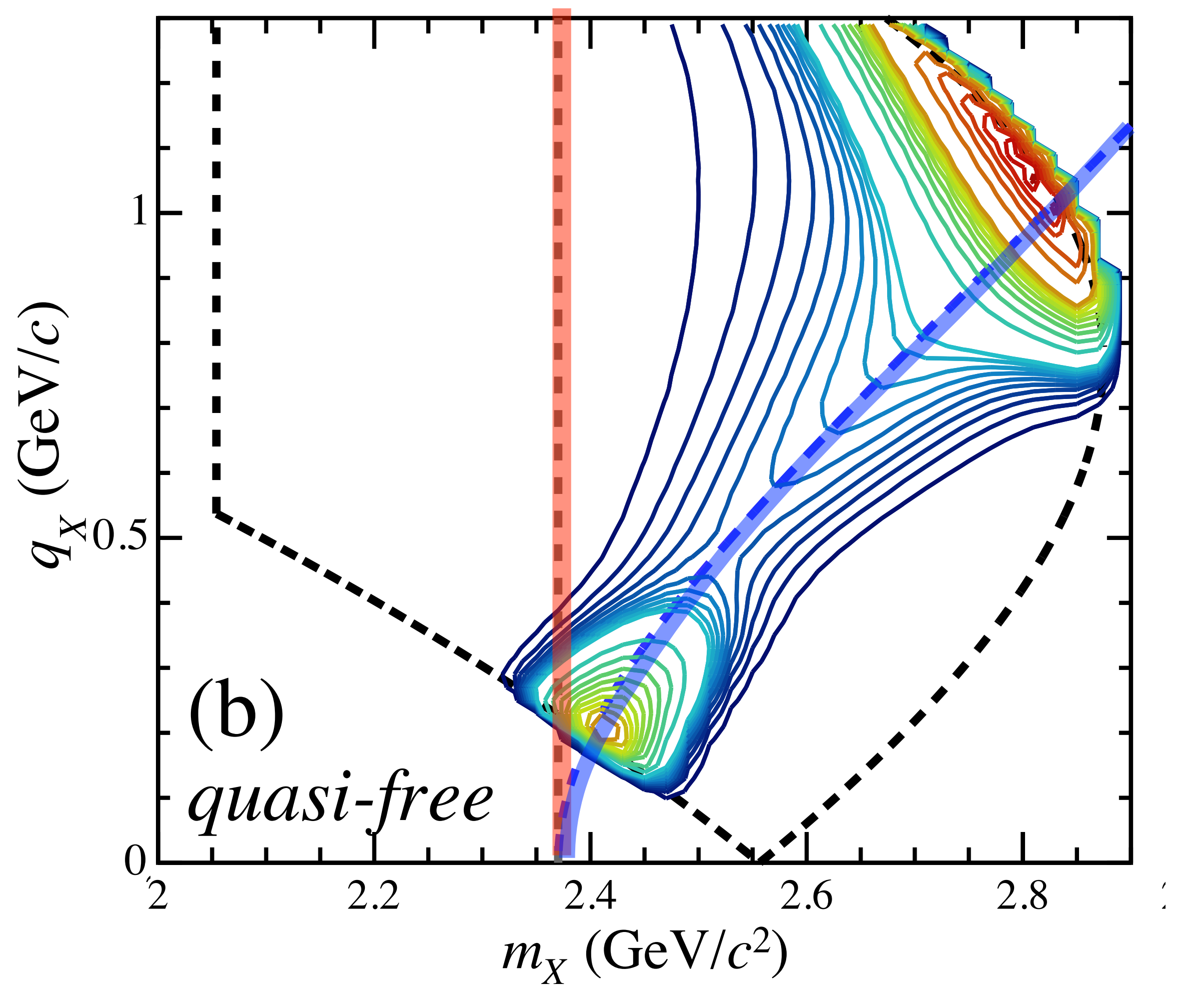




Quasi-free process with (K^-, n)

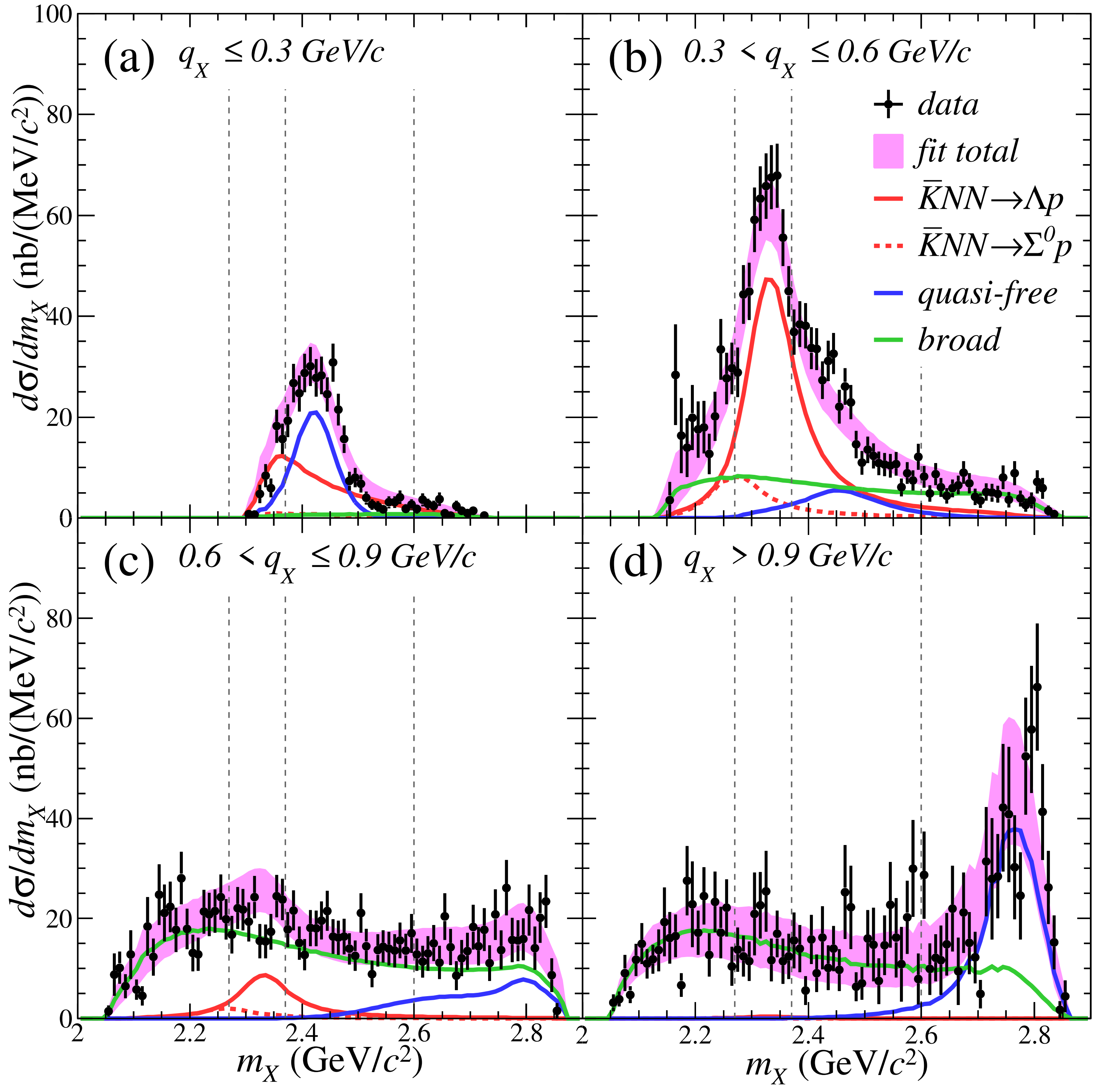


$$f_{\mathrm{QF}}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{\mathrm{QF}}(q_X)$$

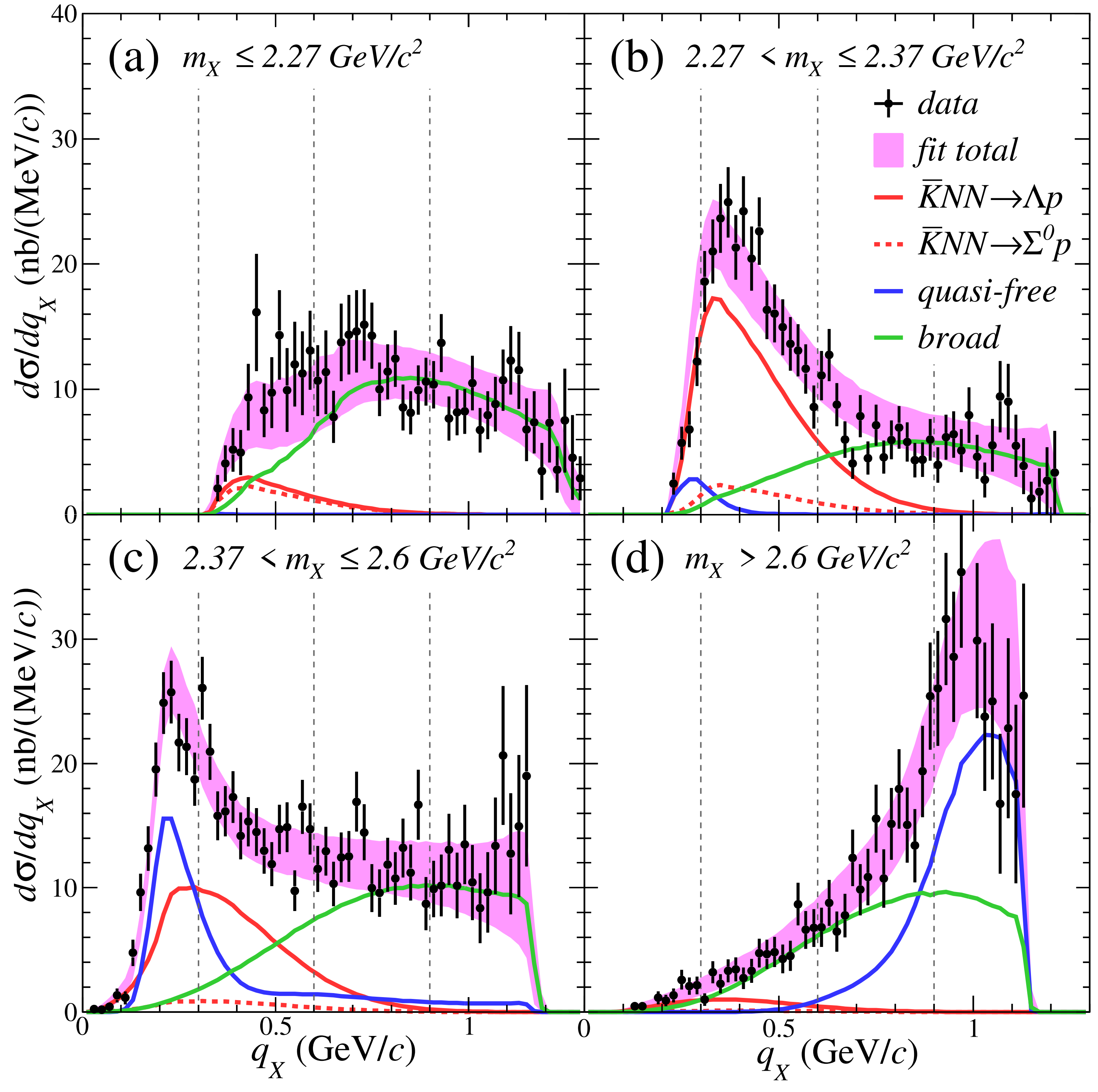


Fit result

Λp invariant-mass

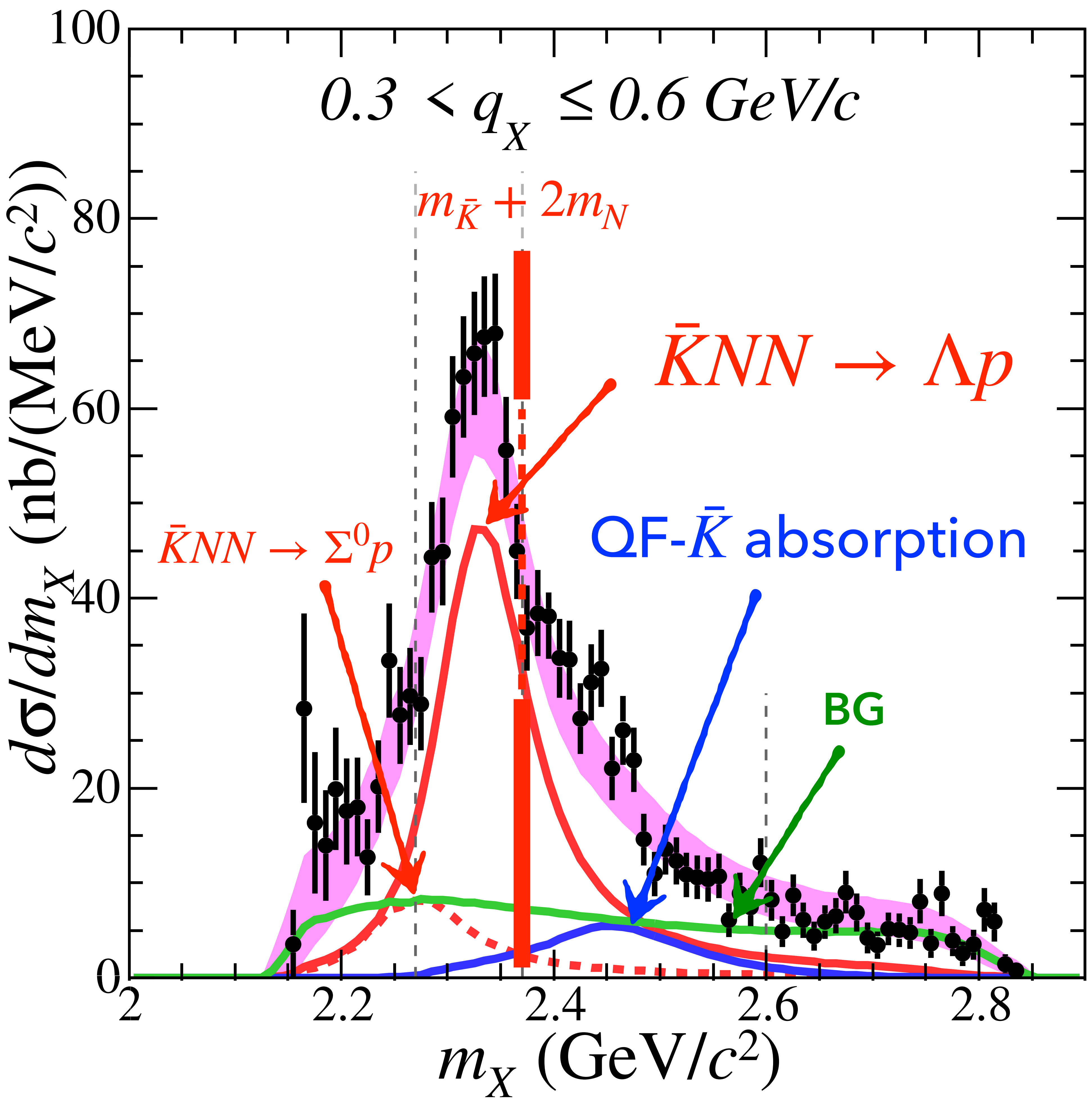


Momentum transfer to Λp



→ The whole 2D distribution is well reproduced.

What we observed



The peak position does not depend on q.

➔ *It should be resonance.*

QF-$\bar{K}$ absorption process is clearly observed.

➔ *Intermediate-$\bar{K}$ exist during the reaction.*

The peak position is below the $M_{\bar{K}NN}$.

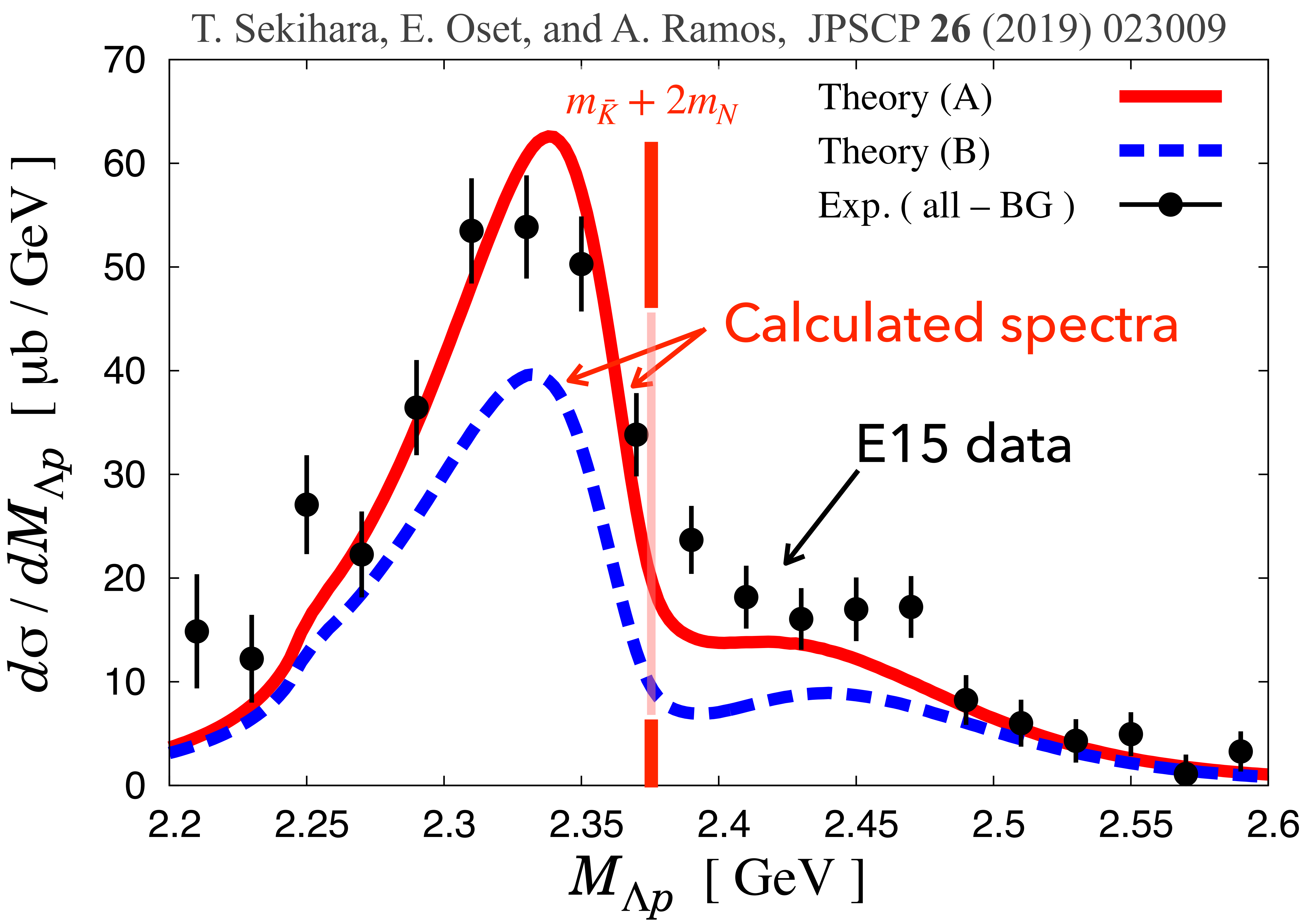
➔ *We interpreted it as $\bar{K}NN$ signal.*

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

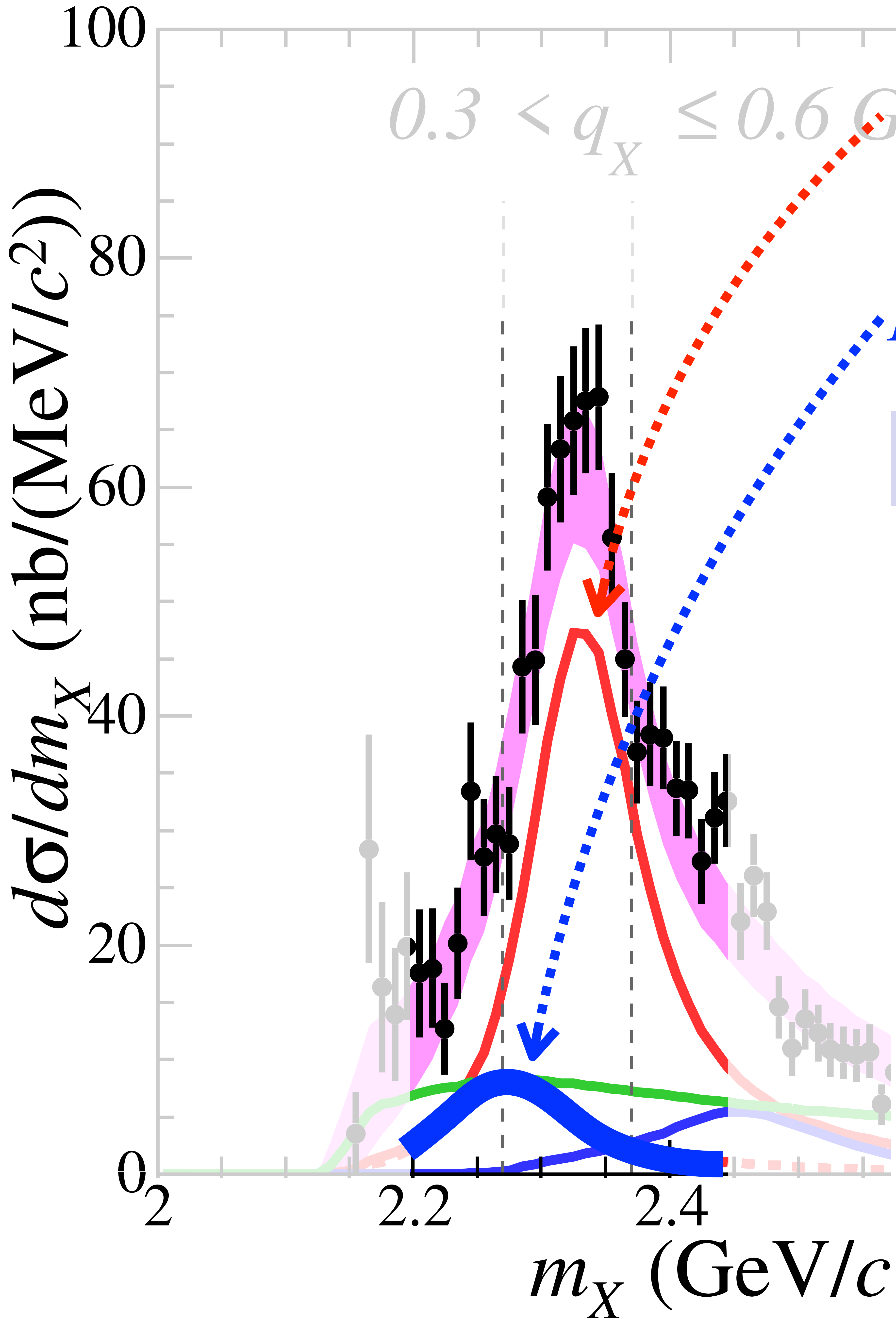
$$\Gamma = 100 \pm 7 \text{ (stat.) } {}^{+19}_{-9} \text{ (syst.) MeV}$$

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

Compare to theoretical calculation



→ Theoretical calculation supports that the observed peak is $\bar{K}NN$ signal.



$\bar{K}NN \to \Lambda p$

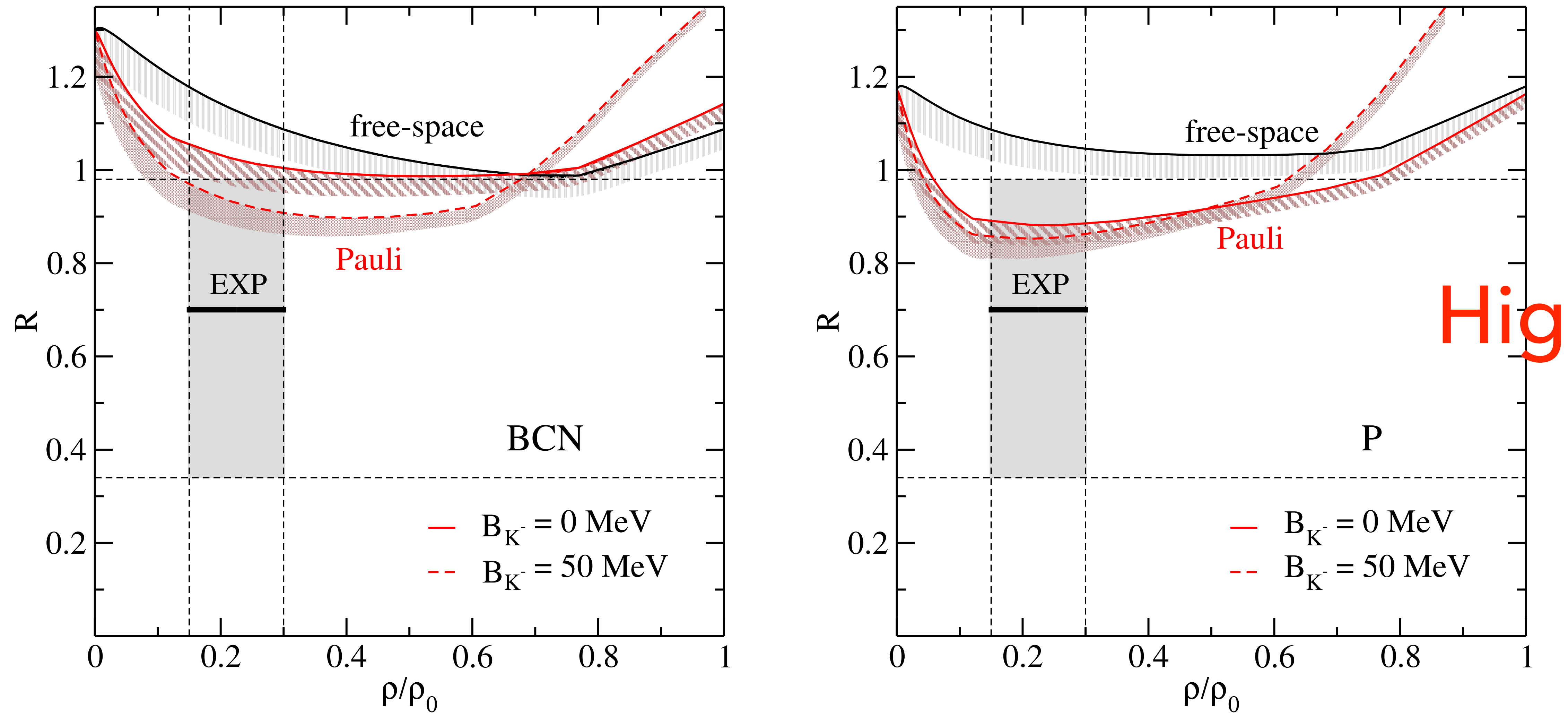
$\bar{K}NN \to \Sigma^0 p$

$$\frac{\Gamma(\bar{K}NN \to \Lambda p)}{\Gamma(\bar{K}NN \to \Sigma^0 p)} \sim 1.7$$

AMADEUS: Ratio for 2N absorption J. Obertova's talk in ECT*

Recently measured ratio *R. Del Grande et al., EPJ C79 (2019) 190*

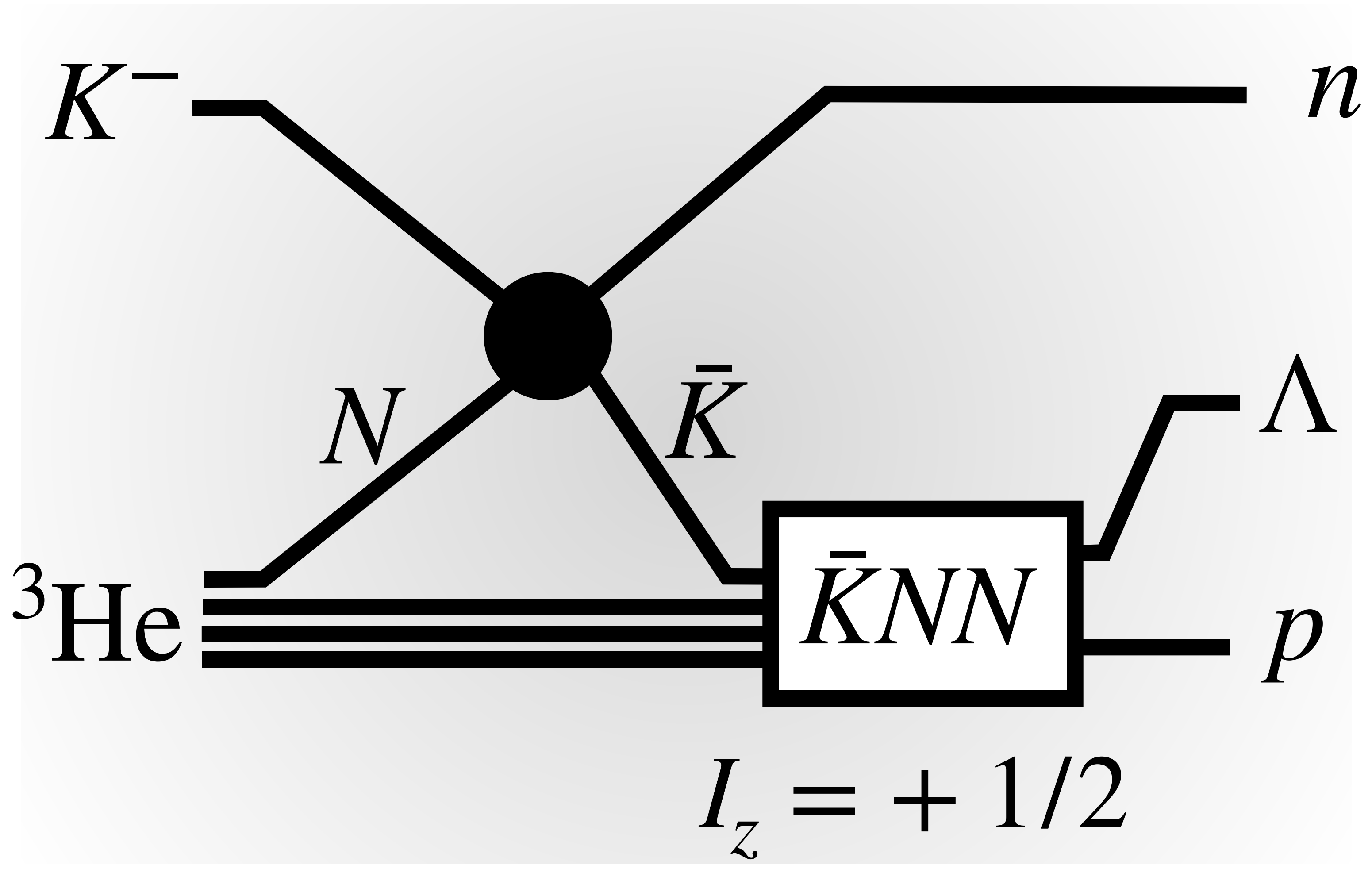
$$R = \frac{\mathrm{BR}(K^- pp \to \Lambda p)}{\mathrm{BR}(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2(\mathrm{stat.})^{+0.2}_{-0.3}(\mathrm{syst.})$$



Higher density?

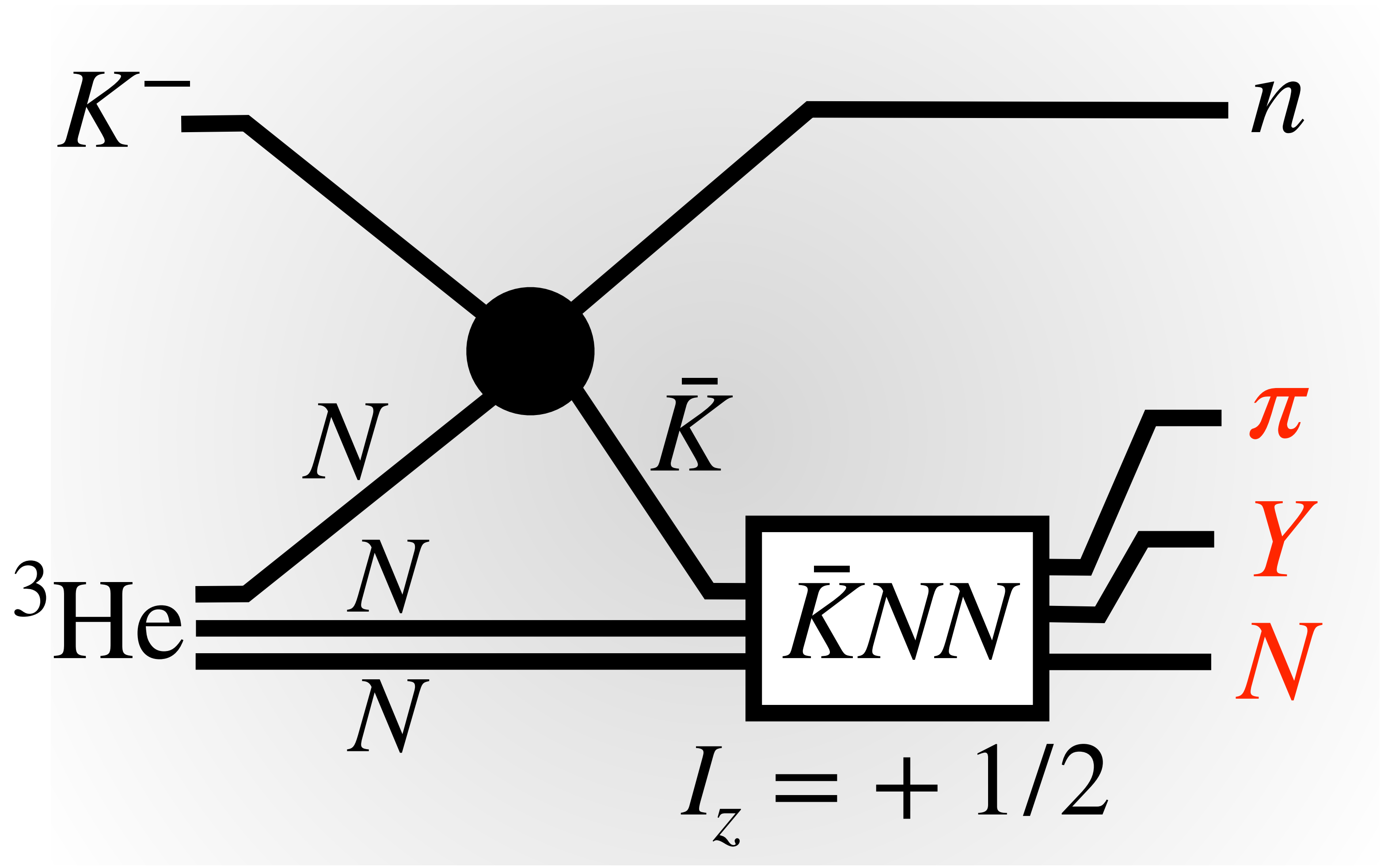
Fig.4: The ratio R as a function of relative density, calculated using the free-space and Pauli blocked amplitudes for $B_{K^-} = 0$ MeV and $B_{K^-} = 50$ MeV. Color bands denote the uncertainty due to different cut-off values $\Lambda_c =$ 800 − 1200 MeV.

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



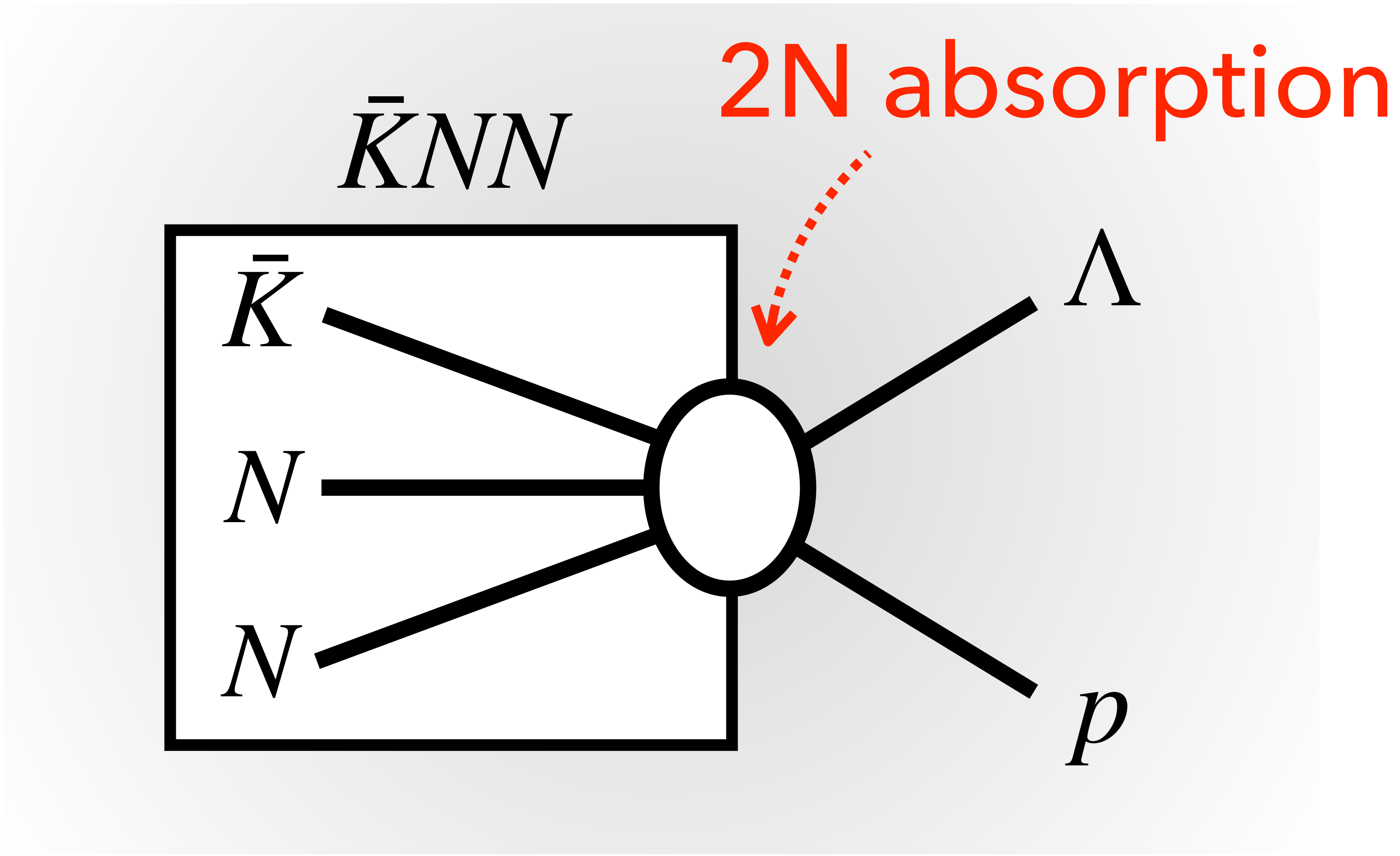
Non-mesonic decay of $\bar{K}NN$

$K^{-}+{}^{3}\mathrm{He}\rightarrow\pi YN+n$



Mesonic decay of $\bar{K}NN$

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



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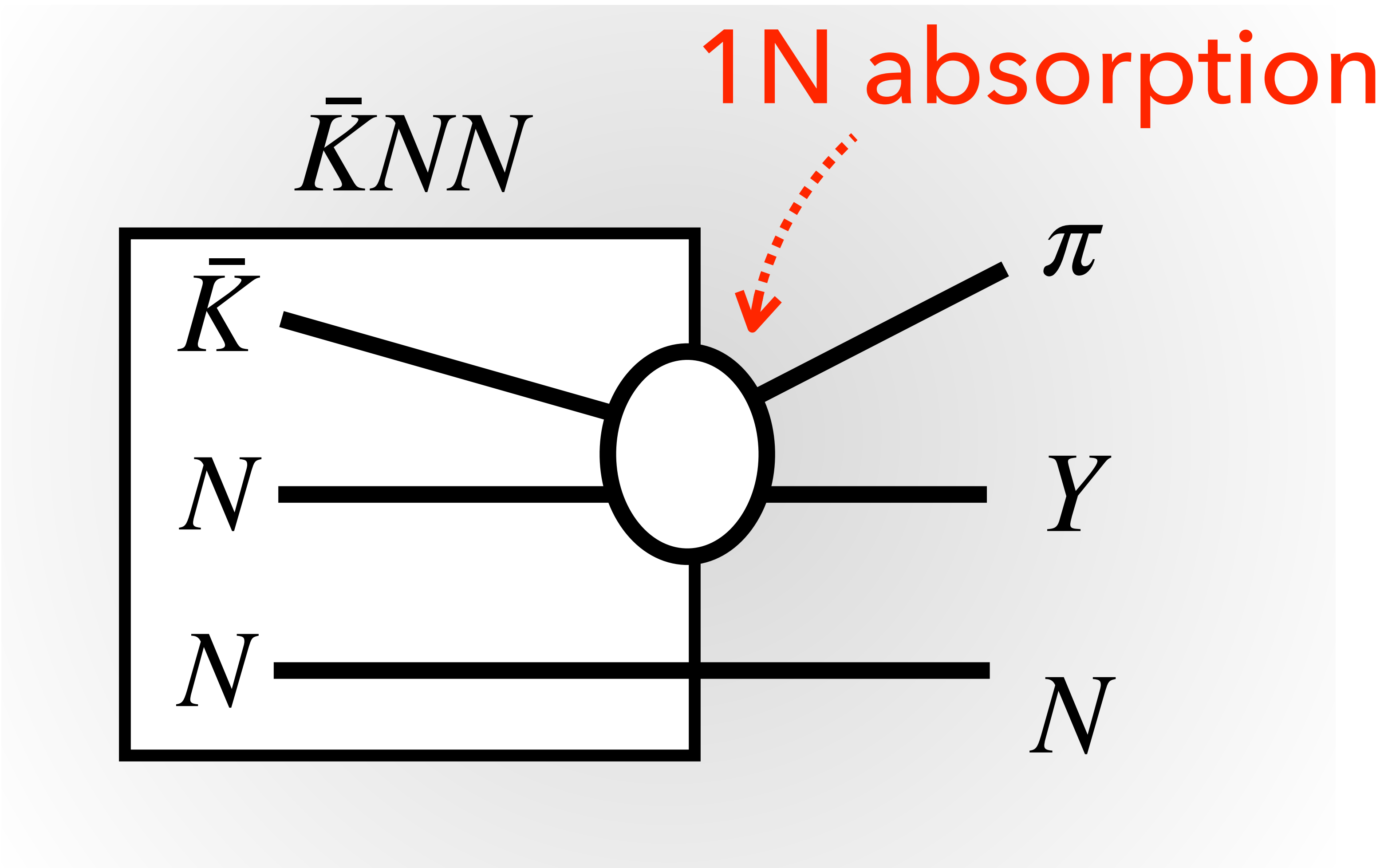


Mesonic decay of $\bar{K}NN$

T. Sekihara *et al.*, Phys. Rev. C **86** (2012) 065205

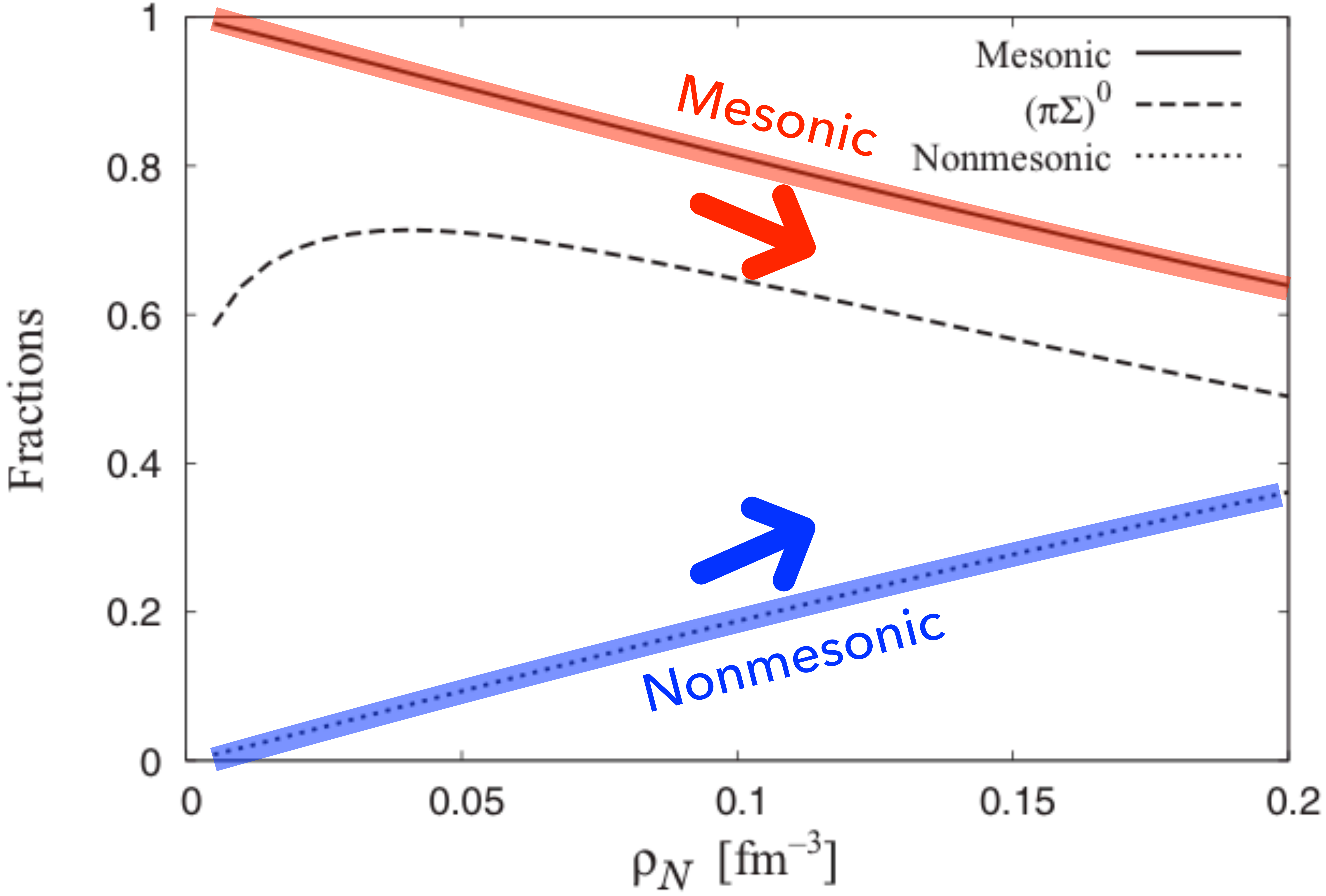
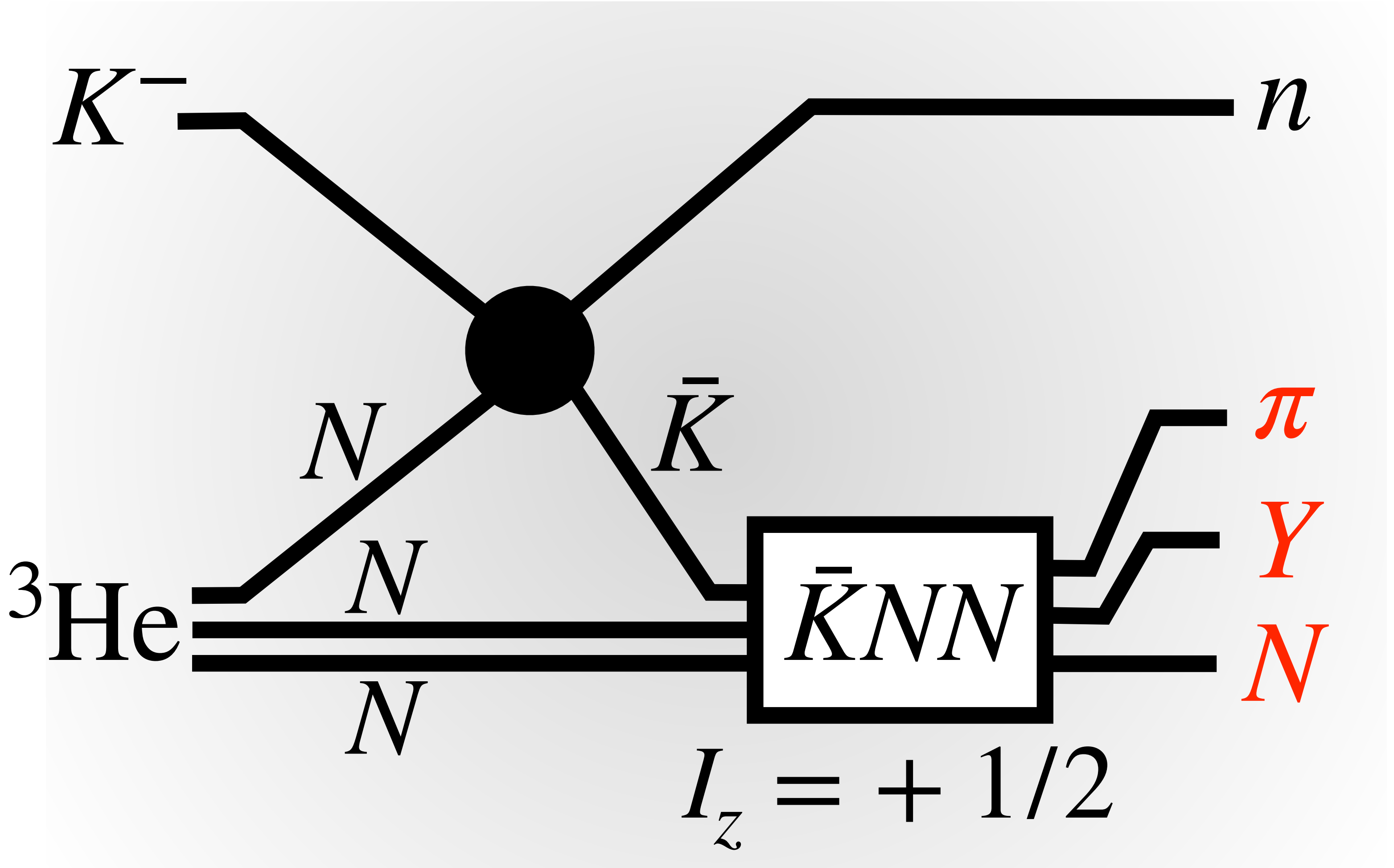


FIG. 13. Fractions of mesonic, sum of $(\pi\Sigma)^0$, and nonmesonic absorption to total absorption.

$K^- + {}^3\mathrm{He} \rightarrow \pi Y N + n$



Mesonic decay of $\bar{K}NN$

Mesonic channels

$I_z = +1/2$

$\boxed{\pi^+ \Lambda n} + n_{\mathrm{miss}}$

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

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

Non-mesonic

$I_z = +1/2$

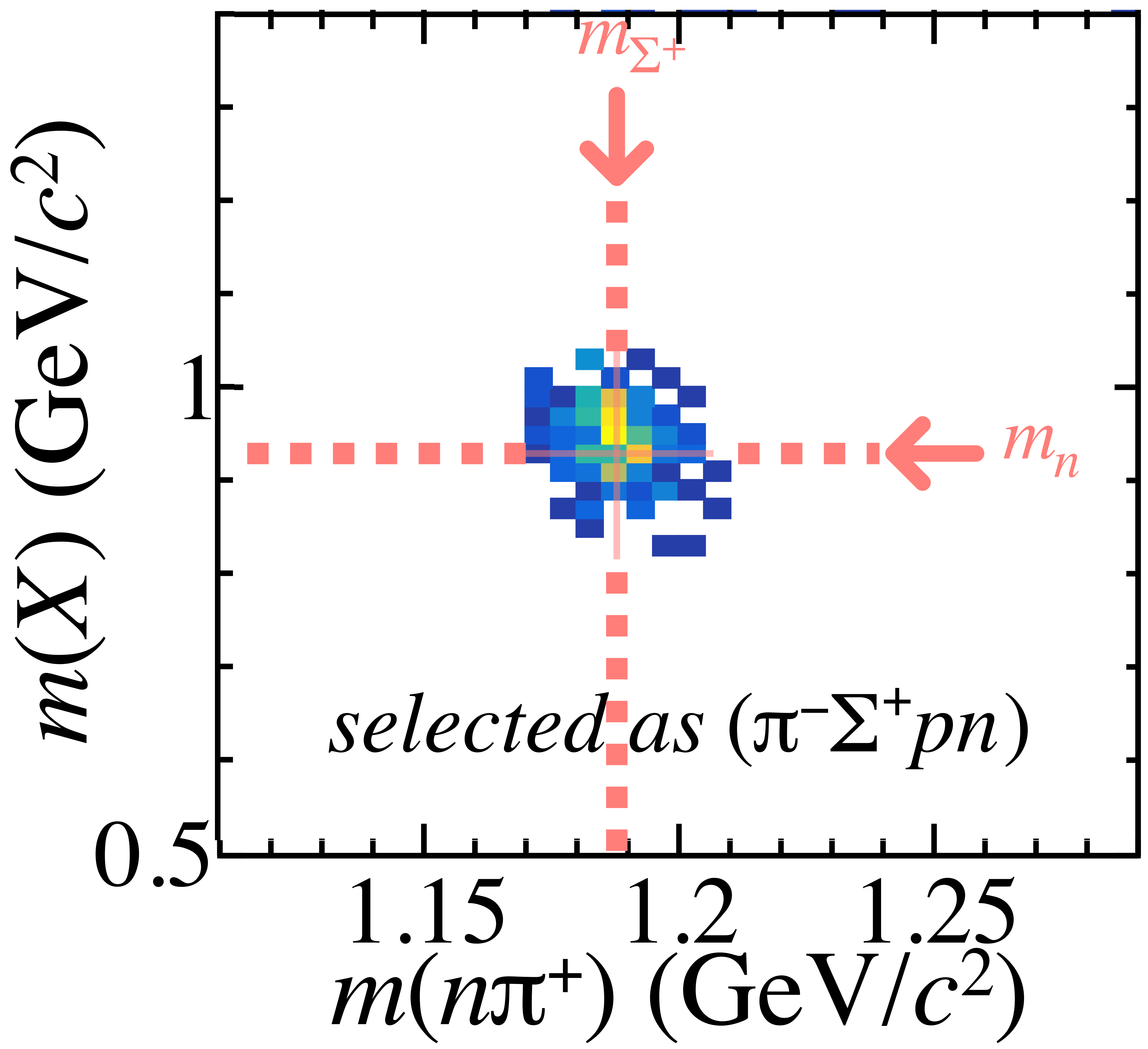
$\boxed{\Lambda p} + n_{\mathrm{miss}}$

Event selection for mesonic decay

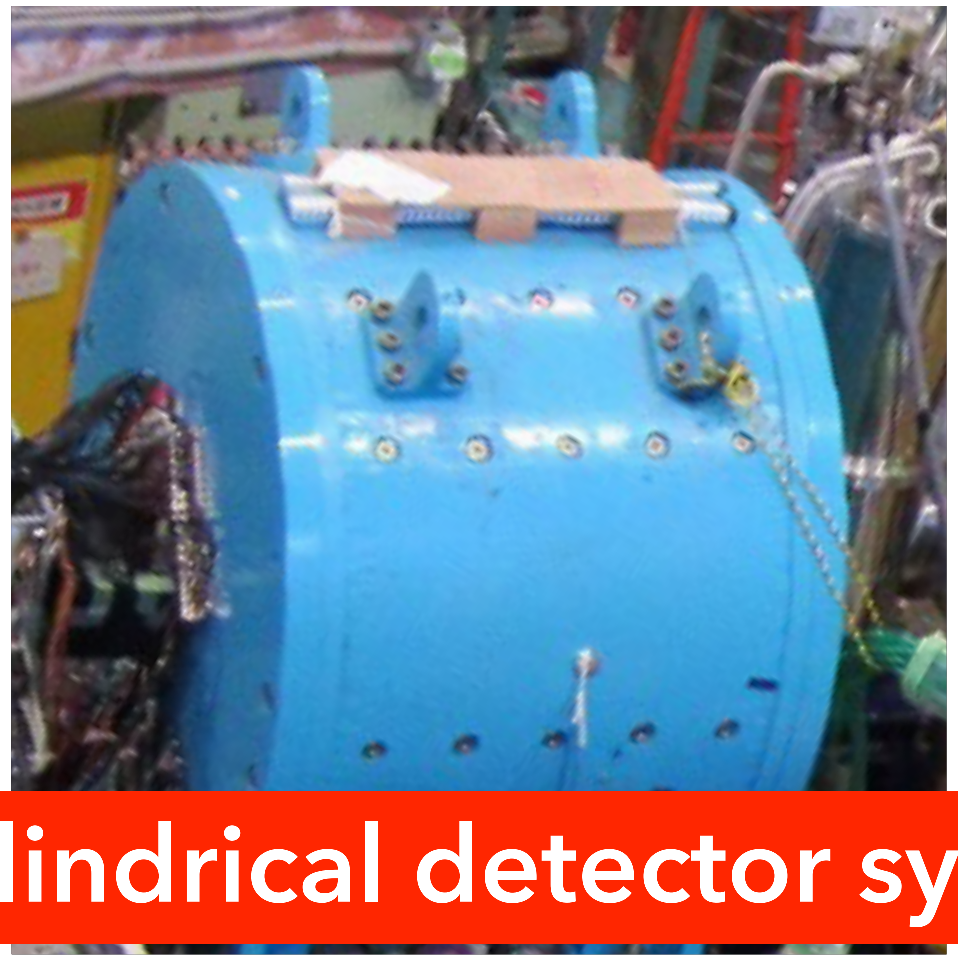
In the case of

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

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



Event selection for mesonic decay

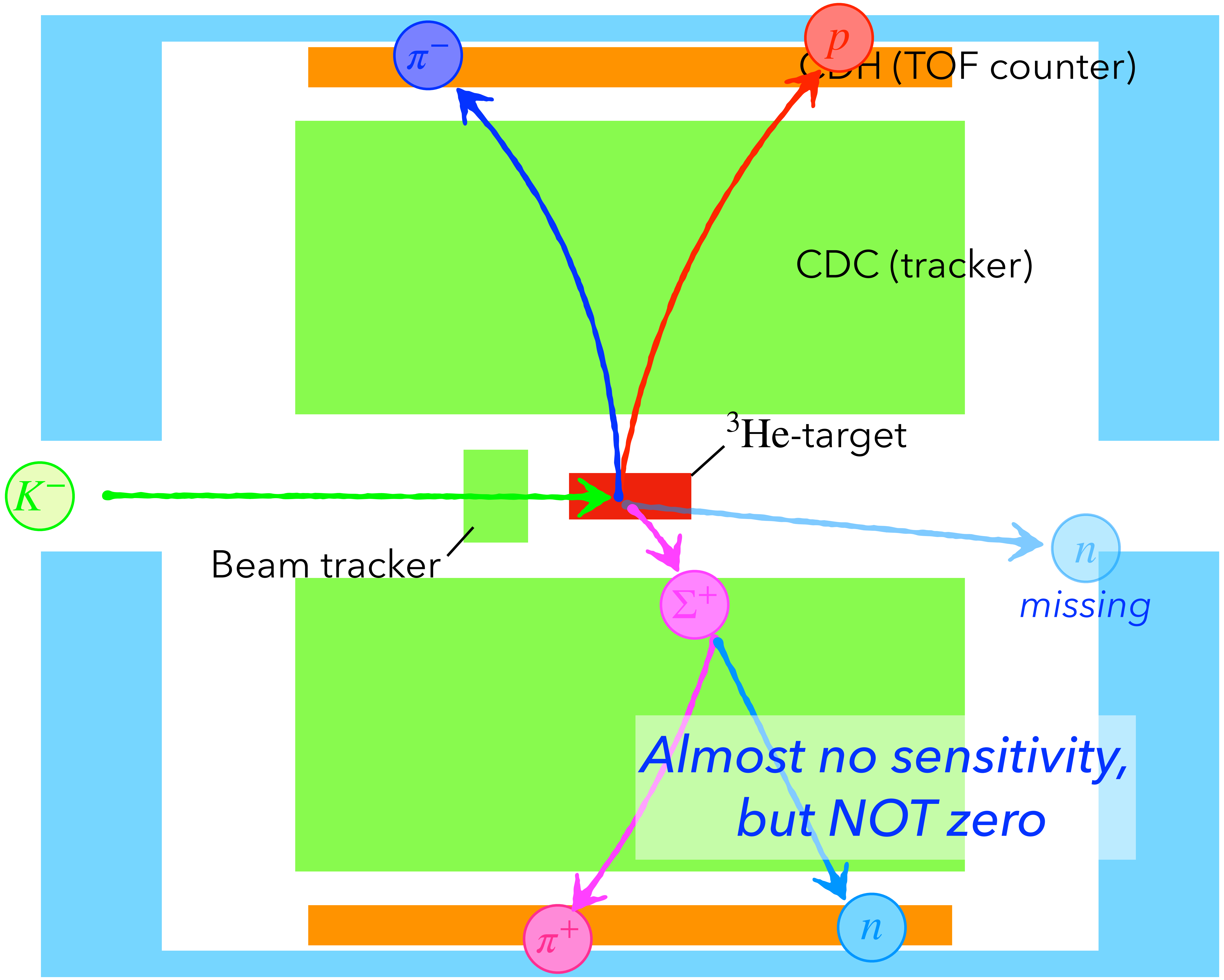


Cylindrical detector system

In the case of

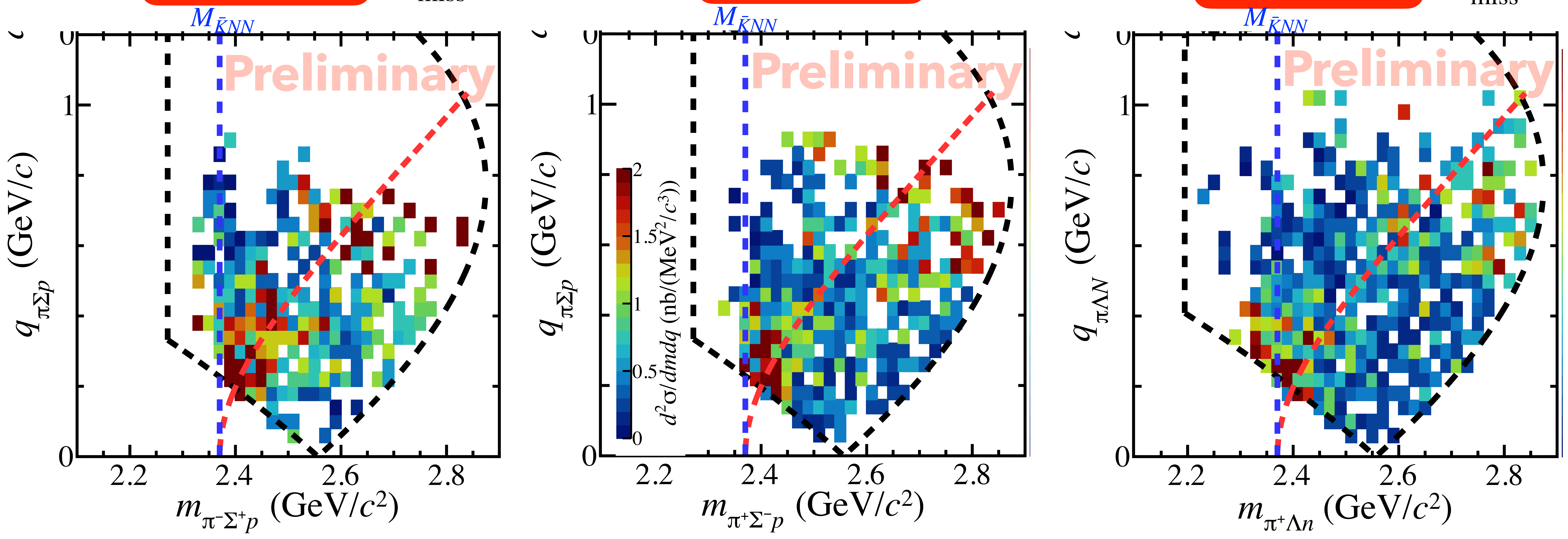
$$\boxed{\pi^-\Sigma^+ p} + n_{\mathrm{miss}}$$

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




$\pi^-\Sigma^+p$ $+n_{miss}$
$\pi^+\Sigma^-p$ $+n_{miss}$
$\pi^+\Lambda n$ $+n_{miss}$
$M_{\bar{K}N}$
(c) $(\pi^-\Sigma^+)$ system
in $(\pi^-\Sigma^+pn)$
(d) $(\pi^+\Sigma^-)$ system
in $(\pi^+\Sigma^-pn)$
(b) $(\pi^+\Lambda)$ system
in $(\pi^+\Lambda nn)$
Preliminary
$m_\pi + m_\Sigma$
$m_\pi + m_\Lambda$
$d\sigma/dm$ (μb/(MeV/c^2))
$m_{\pi Y}$ (GeV/c^2)
$\Lambda(1405)$ + Phase space
$\Sigma(1385)^+$ + Phase space

$\pi^-\Sigma^+p_{+n_{\mathrm{miss}}}$ $\pi^+\Sigma^-p_{+n_{\mathrm{miss}}}$ $\pi^+\Lambda n_{+n_{\mathrm{miss}}}$



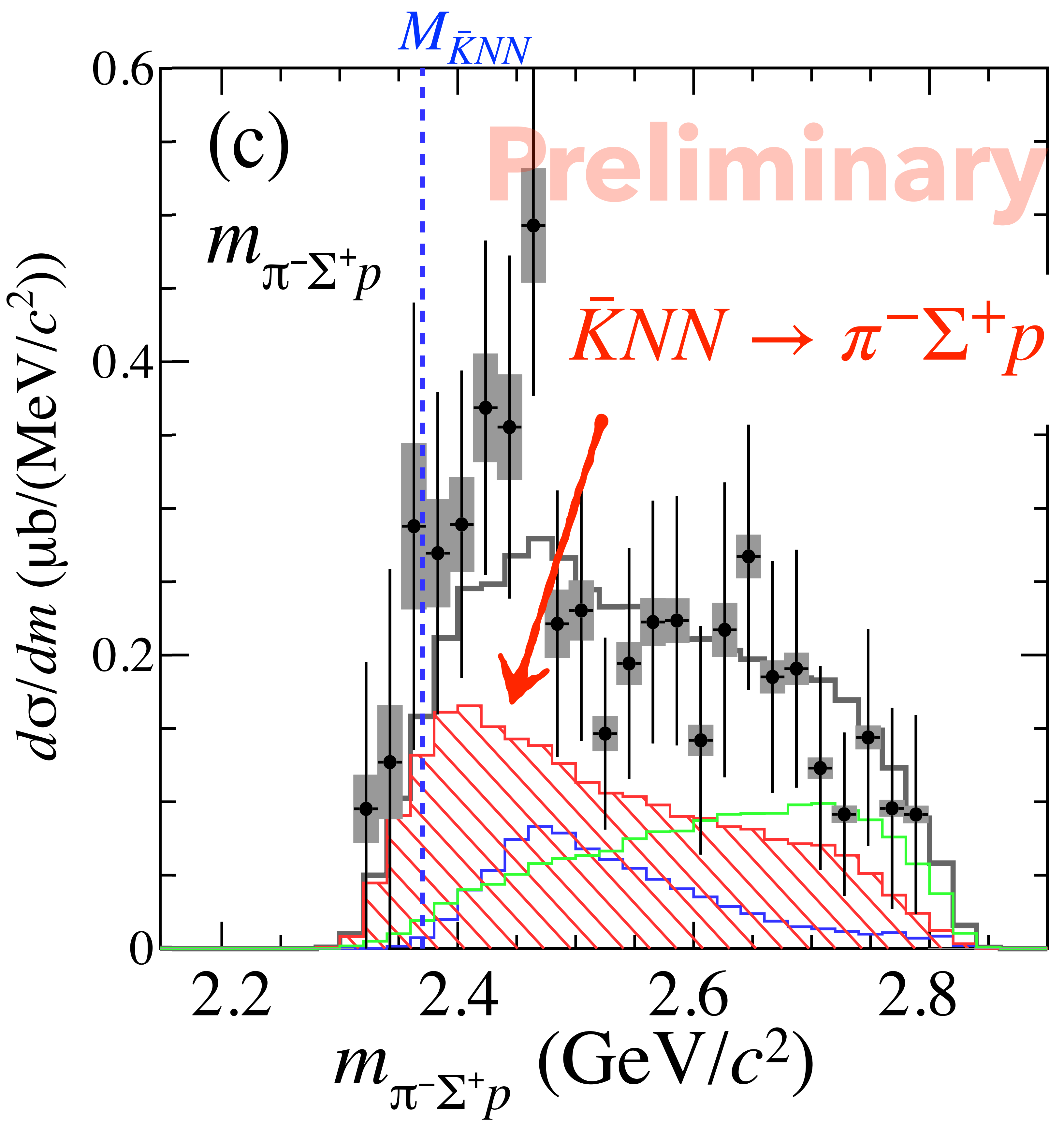
Similar to $\Lambda p_{+n_{\mathrm{miss}}}$

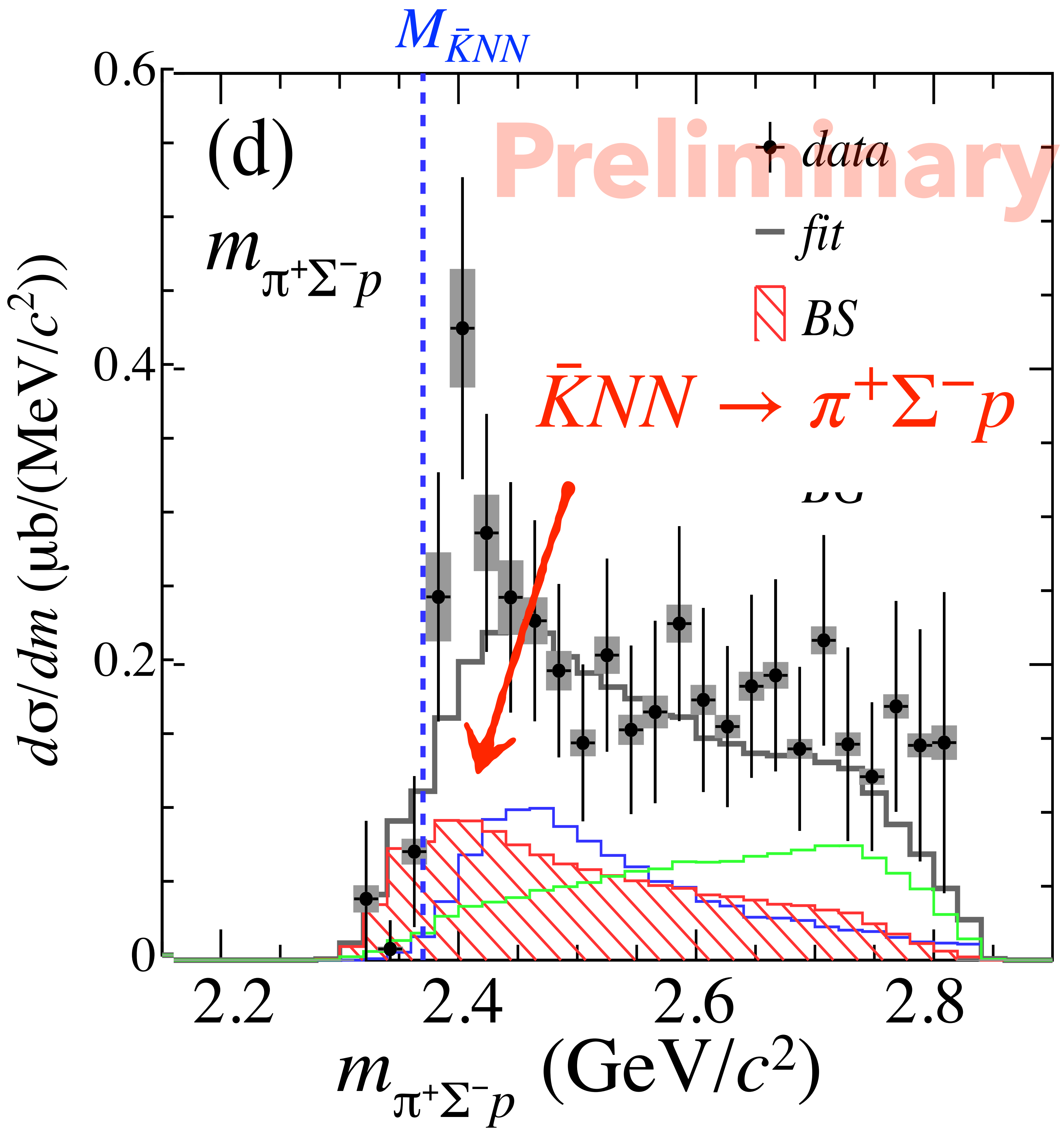
➜ The reaction could be understood as $\bar{K}NN$ production & quasi-free process

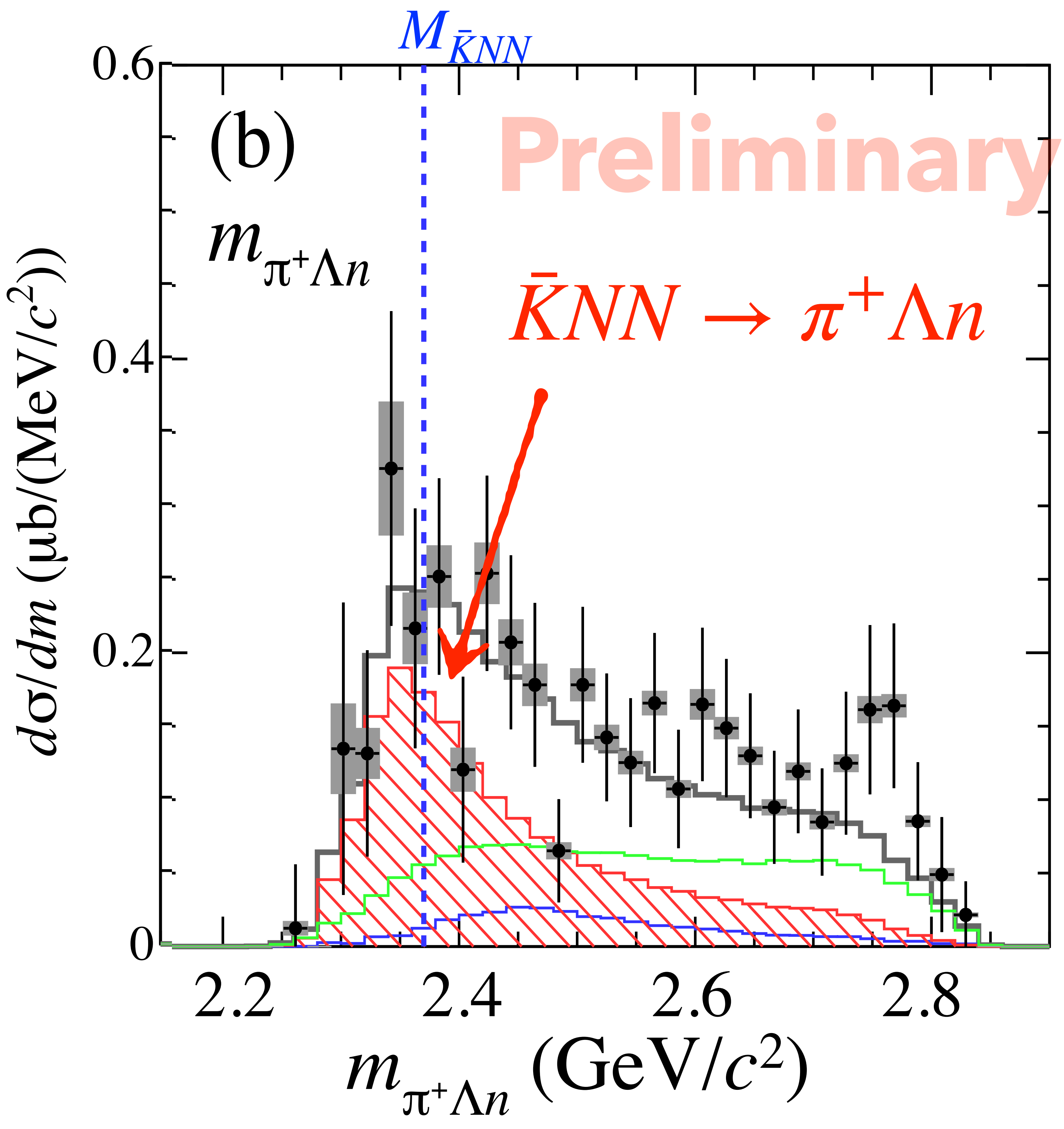
$\pi^-\Sigma^+p$ $+n_{\mathrm{miss}}$

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

$\pi^+\Lambda\, n$ $+n_{\mathrm{miss}}$







Fit result

Cross section of $\bar{K}NN$

※Statistical error only

$\pi^-\Sigma^+p$ $+n_{\mathrm{miss}}$	Preliminary $85.4 \pm 21.2\ \mu\mathrm{b}$
$\pi^+\Sigma^-p$ $+n_{\mathrm{miss}}$	Preliminary $43.8 \pm 9.6\ \mu\mathrm{b}$
$\pi^+\Lambda n$ $+n_{\mathrm{miss}}$	Preliminary $83.6 \pm 12.0\ \mu\mathrm{b}$
c.f. Λp $+n_{\mathrm{miss}}$	$9.3 \pm 0.8^{+1.4}_{-1.0}\ \mu\mathrm{b}$

$$\Gamma_{\mathrm{non-mesonic}} \ll \Gamma_{\mathrm{mesonic}}$$

$\Gamma_{\mathrm{mesonic}}$ would be $\mathcal{O}(10)$ times larger than $\Gamma_{\mathrm{non-mesonic}}$.

But, other mesonic channels should be measured to conclude the exact ratio.

Theoretical works

T. Sekihara et. al., PRC **86**, 065205 (2012).

$\Gamma_{\mathrm{non-mesonic}} \sim \Gamma_{\mathrm{mesonic}}/2$ @ nuclear dens.

(depending on density)

→ *To be compared in more detailed*

Remaining questions

Is the observed resonance really what we expected?

Other possibilities such as $\Sigma^* N$?

Does $\bar{K}$ really keep it particle identity?

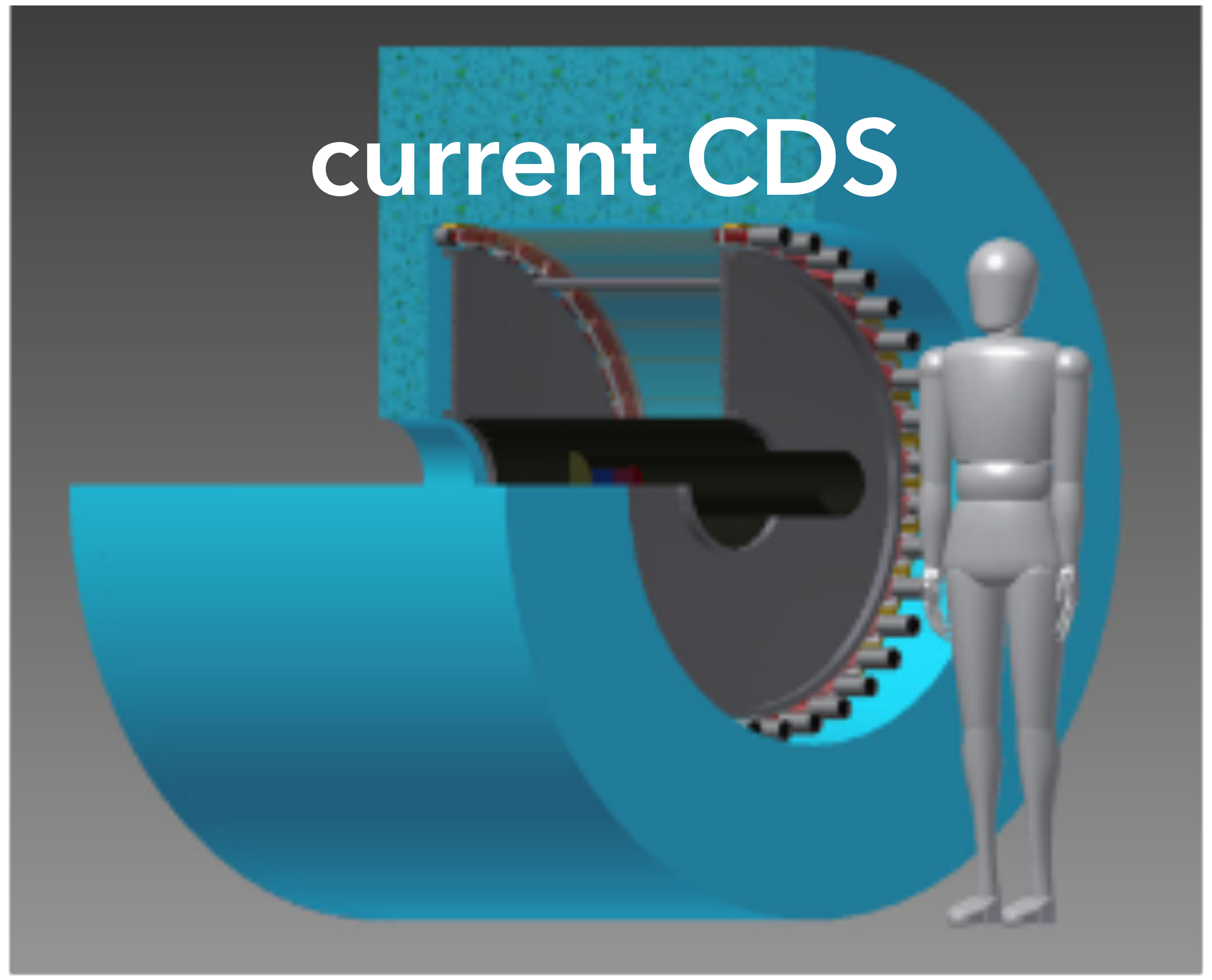
↓

We need further systematic measurements
to answer the questions & to robustly confirm $\bar{K}$-nuclei.

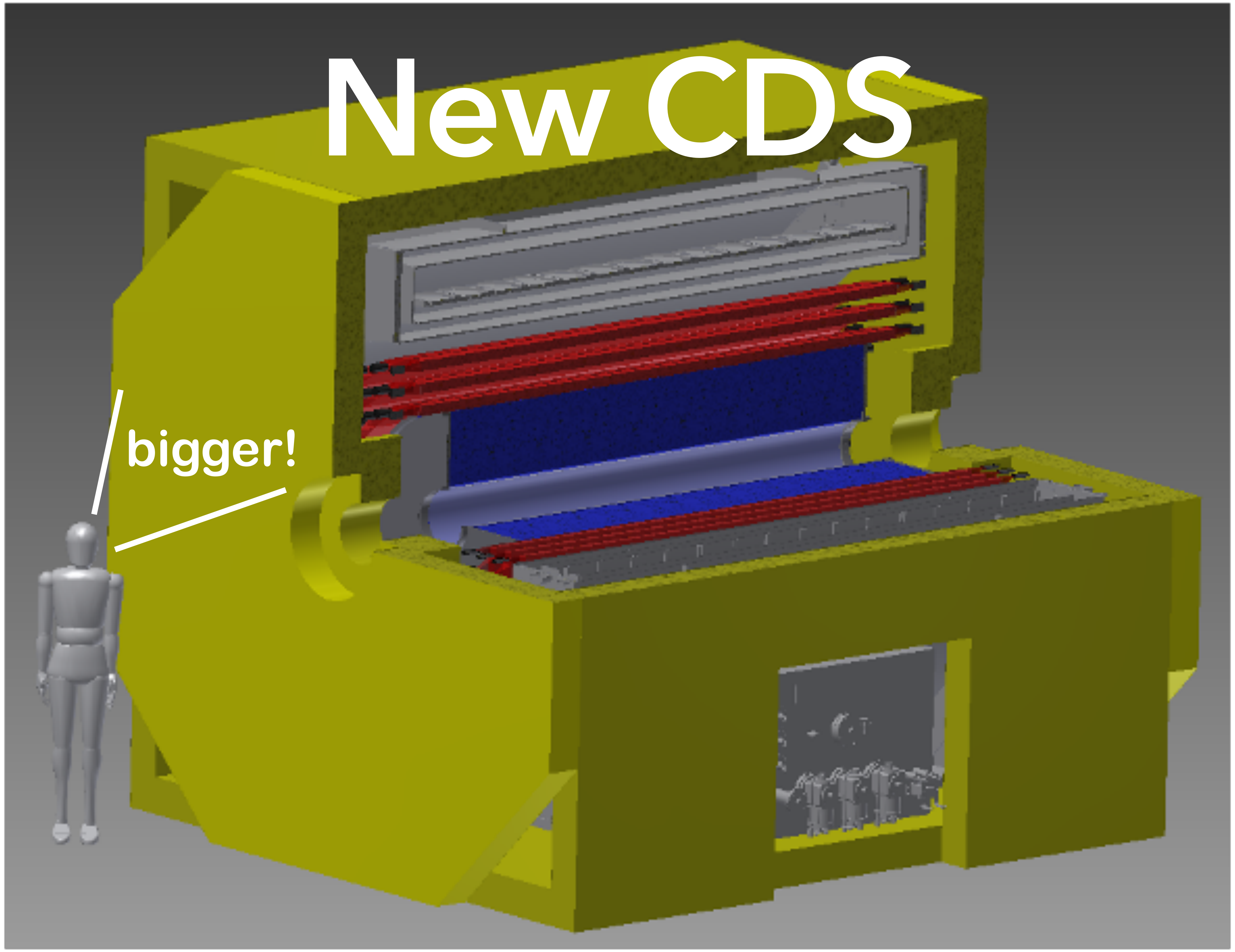
Precise study for $\bar{K}NN$

Search for heavier $\bar{K}$-nuclei

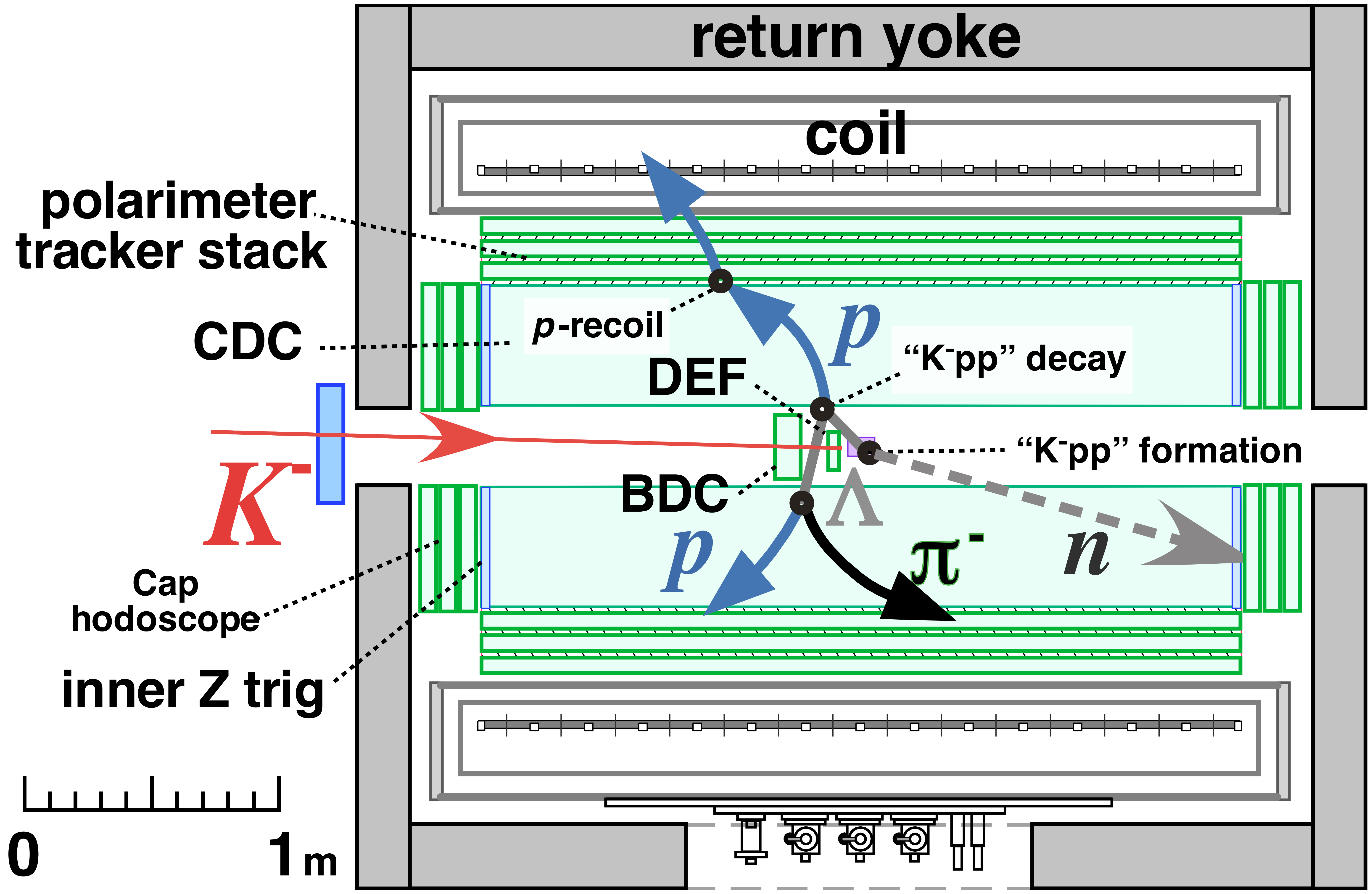
Future projects



→



Conceptual design of new CDS



>90% solid angle coverage

Neutron detection capability

Sensitivity for proton polarization

Construction has been started
(Completed in 2025)

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, $\Sigma^0 p$, $\Sigma^+ n$	$\pi\Lambda N$, $\pi\Sigma N$

Heavier system

$\bar{K}NNN$ 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

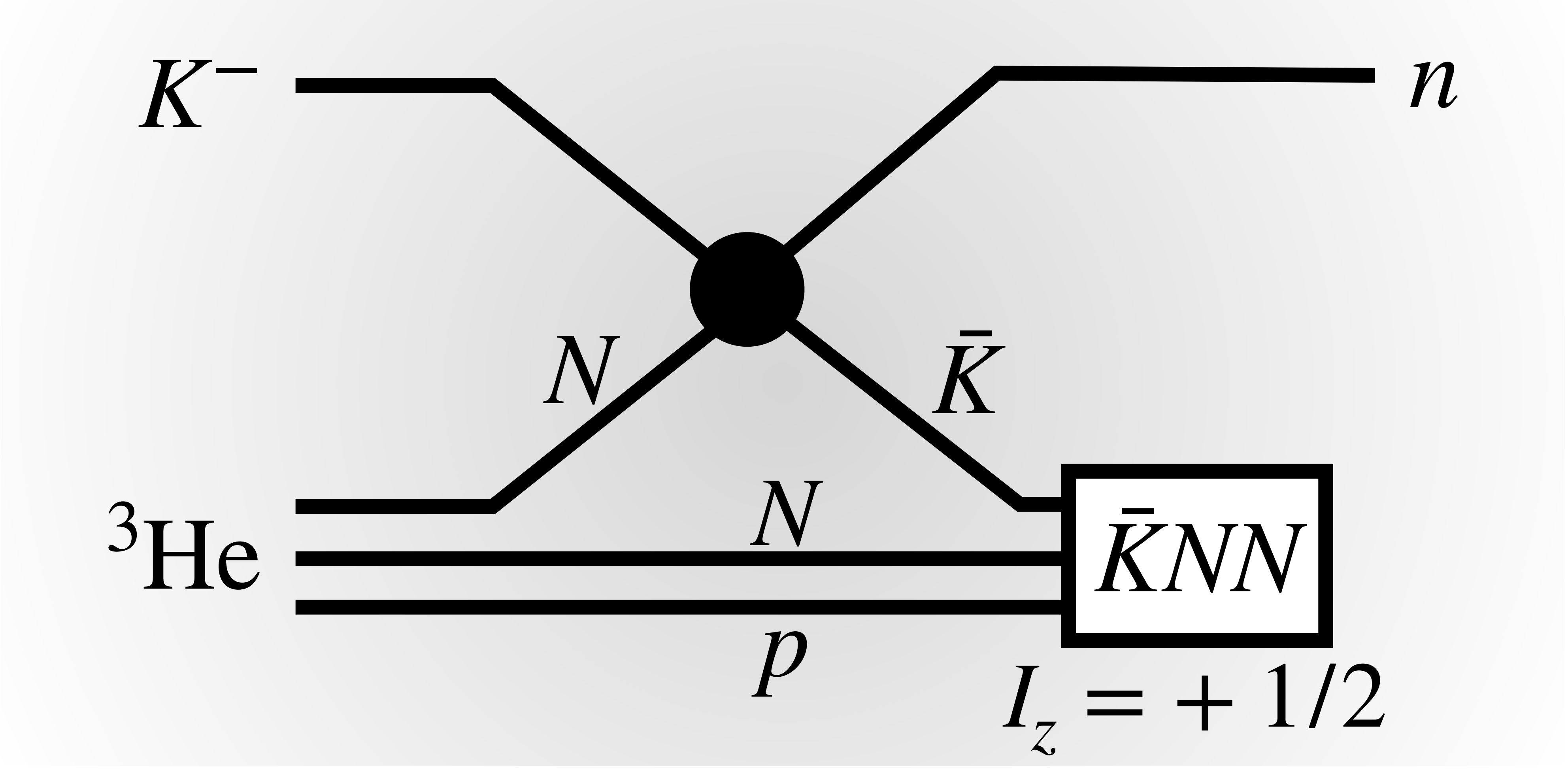
K^--α $\bar{K}^0$-α

→ J-PARC P89

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

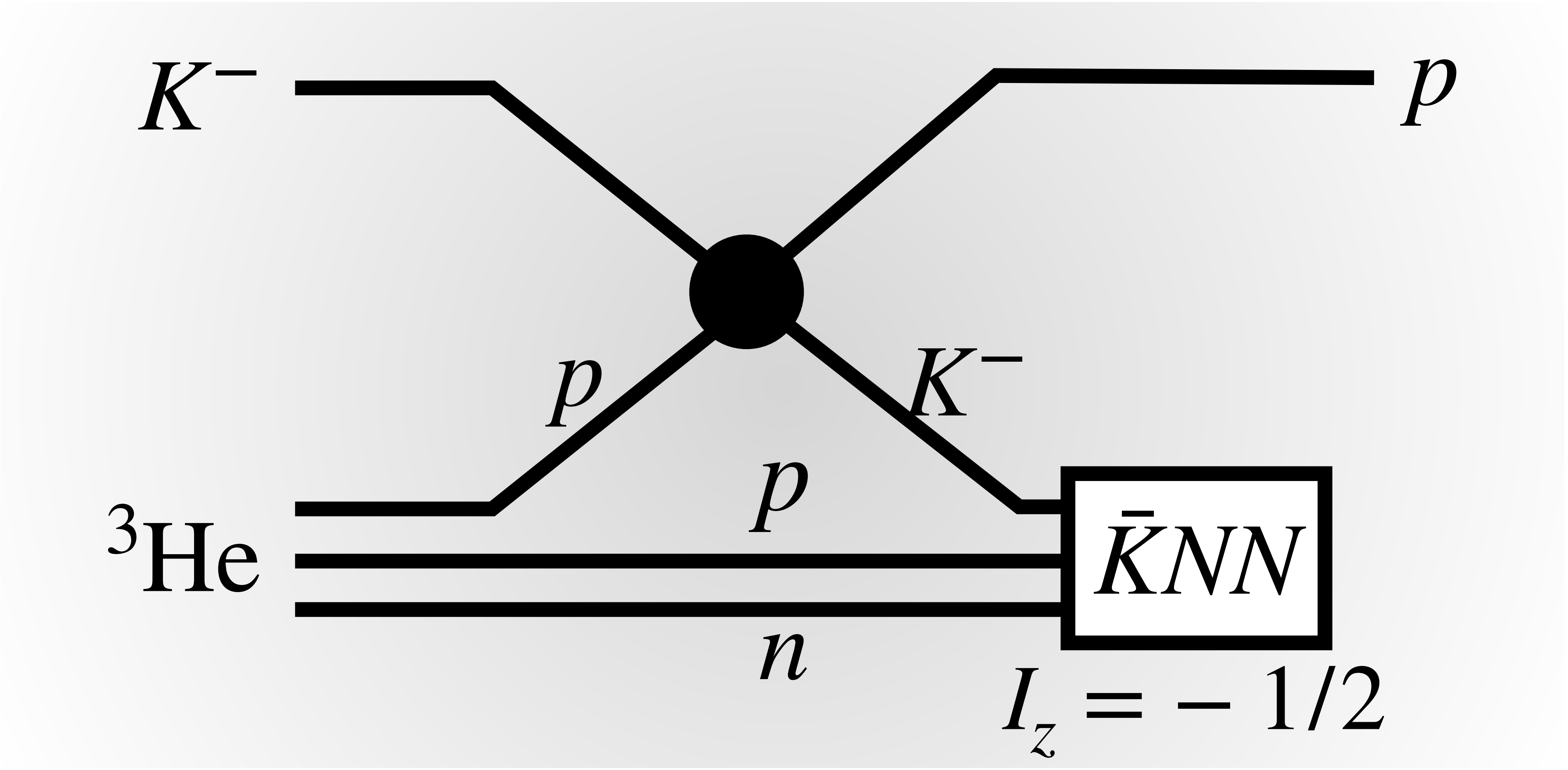
$\bar{K}NN$ production by $^3\mathrm{He}(K^-, N)$ reaction

with (K^-, n) reaction



$(\bar{K}NN)^{I_z=+1/2}$ is produced.

with (K^-, p) reaction



$(\bar{K}NN)^{I_z=-1/2}$ is produced.

$K^-n \rightarrow K^-n$ & $K^-p \rightarrow \bar{K}^0 n$

4.7 mb/sr 2.4 mb/sr

$K^-p \rightarrow K^-p$

1.8 mb/sr

Production cross sections

$\sigma_{\bar{K}NN(I_z=+1/2)} \cdot Br_{\Lambda p}$

$9.3\ \mu b$

Measured in E15

$\sigma_{\bar{K}NN(I_z=-1/2)} \cdot Br_{\Lambda n}$

$J^P = 0^-$

$0.5\ \mu b$

$J^P = 1^-$

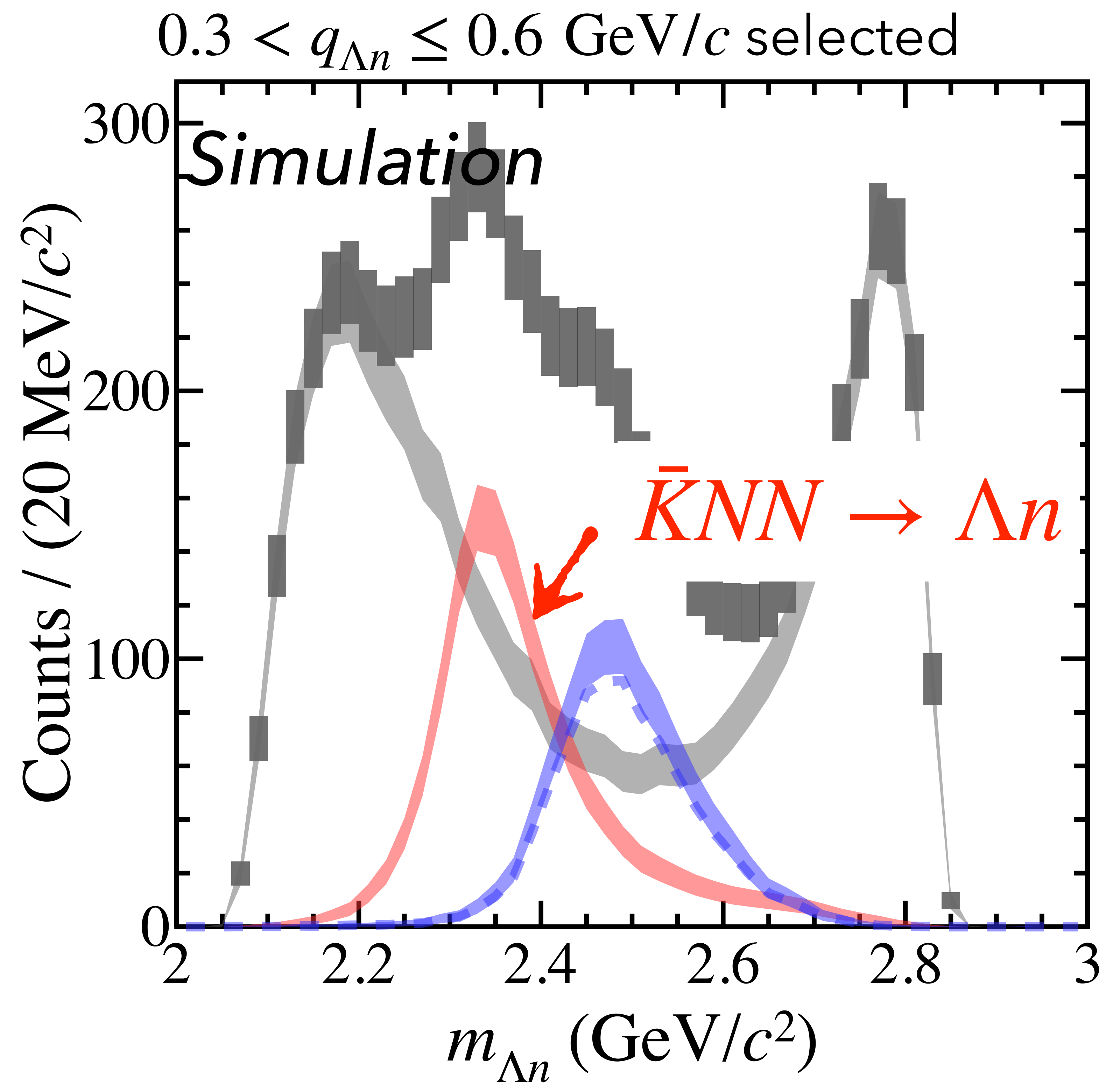
$7.0\ \mu b$

The relative yield of $I_z = \pm 1/2$ states is also a good indicator for J^π

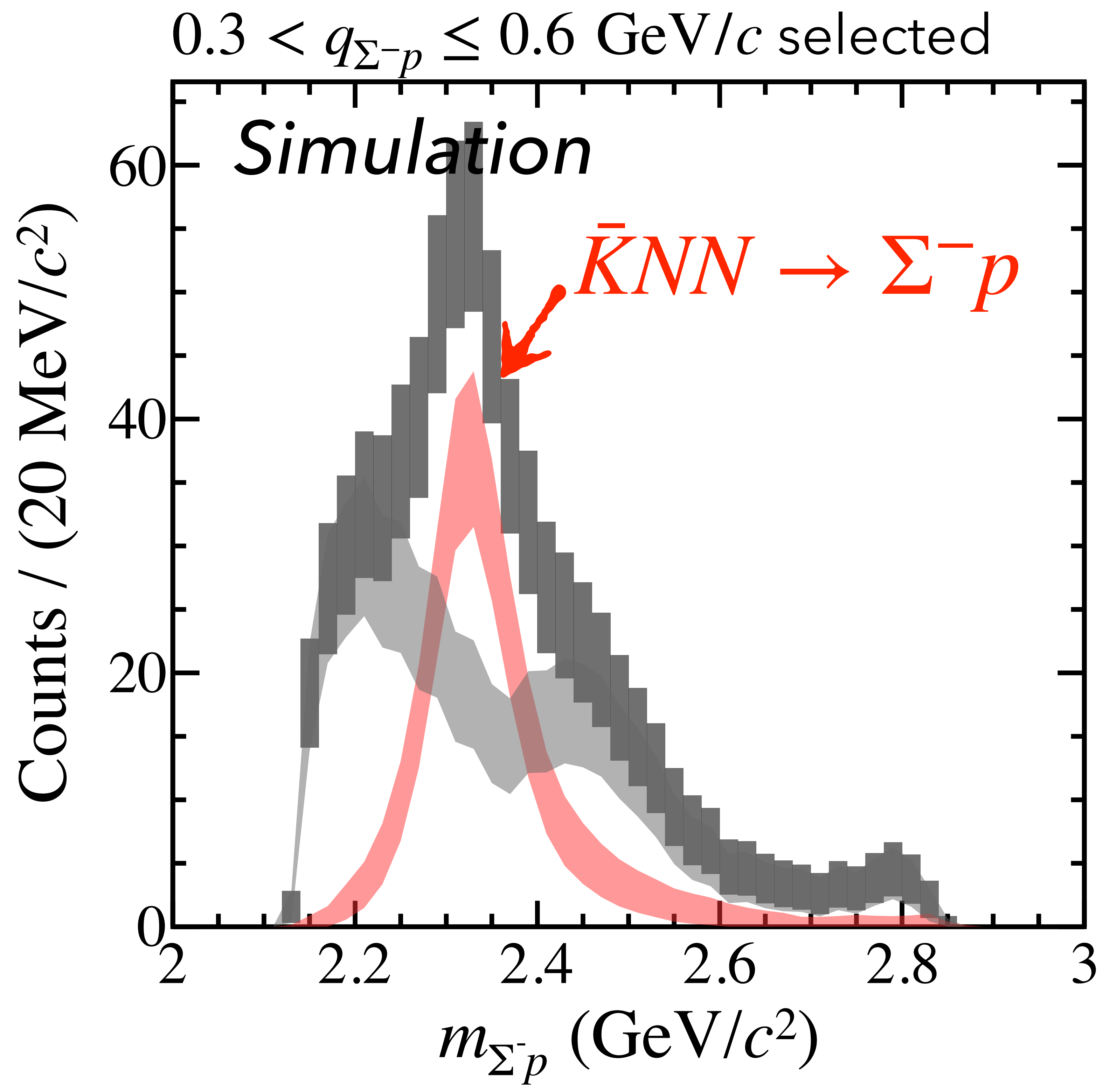
Expected spectra of $(\bar{K}NN)^{I_z=-1/2}$ $(J^\pi = 0^-)$

8 weeks ⊗ 90 kW

By Λn decay



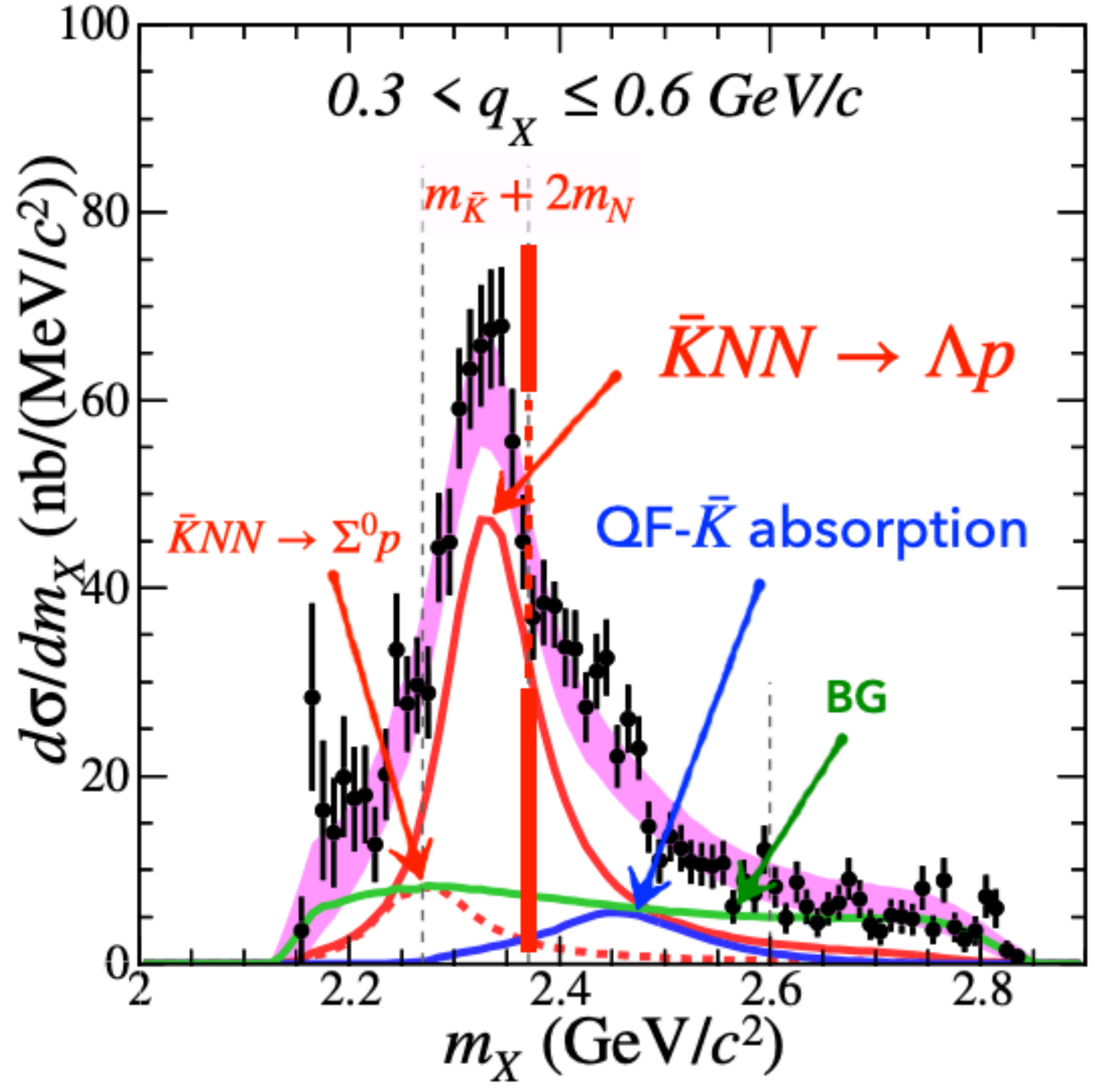
By $\Sigma^- p$ decay



Summary

So far,

J-PARC E15



We observed a signal of
$\bar{K}NN^{(I_z=+1/2)} \to \Lambda p$

Future

J-PARC P89

new CDS @ modified K.18BR
(8 weeks ⊗ 90 kW)

We will measure,

Spin-spin correlation of Λp
to determine J^π

$(m,\, q)$ distributions of Λn & $\Sigma^- p$ pairs
to search for $\bar{K}NN^{(I_z=-1/2)}$

Thank you for your attention!

= J-PARC E15 collaboration =

S. Ajimura[1], H. Asano[2], G. Beer[3], C. Berucci[4], H. Bhang[5], M. Bragadireanu[6], P. Buehler[4], L. Busso[7,8], M. Cargnelli[4], S. Choi[5], C. Curceanu[9], S. Enomoto[10], H. Fujioka[11], Y. Fujiwara[12], T. Fukuda[13], C. Guaraldo[9], T. Hashimoto[14], R. S. Hayano[12], T. Hiraiwa[1], M. Iio[10], M. Iliescu[9], K. Inoue[1], Y. Ishiguro[15], T. Ishikawa[12], S. Ishimoto[10], K. Itahashi[2], M. Iwasaki[2,11,*] K. Kanno[12], K. Kato[15], Y. Kato[2], S. Kawasaki[1], P. Kienle[16,†] H. Kou[11], Y. Ma[2], J. Marton[4], Y. Matsuda[12], Y. Mizoi[13], O. Morra[7], T. Nagae[15], H. Noumi[1], H. Ohnishi[17,2], S. Okada[2], H. Outa[2], K. Piscicchia[9], Y. Sada[1], A. Sakaguchi[1], F. Sakuma[2,‡] M. Sato[10], A. Scordo[9], M. Sekimoto[10], H. Shi[9], K. Shirotori[1], D. Sirghi[9,6], F. Sirghi[9,6], K. Suzuki[4], S. Suzuki[10], T. Suzuki[12], K. Tanida[14], H. Tatsuno[18], M. Tokuda[11], D. Tomono[1], A. Toyoda[10], K. Tsukada[17], O. Vazquez Doce[9,16], E. Widmann[4], T. Yamaga[2,1,§] T. Yamazaki[12,2], Q. Zhang[2], and J. Zmeskal[4]

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Thank you for your attention!

= Collaboration =

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