Experimental investigation of $\bar{K}NN$ state using $K^- +^3$ He reaction at J-PARC

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for the J-PARC E15 collaboration

EMMI workshop “Meson and hyperon interactions with nuclei”
(2022.9.14-16)

$\bar{K}N$ 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

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

$(\bar{K}[NN]^{I=0})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=3/2}$
$J^\pi = 1^-$	$J^\pi = 0^-$	$J^\pi = 0^-$
$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$	$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$	$[\bar{K}N]^{I=1}N$
weakly *bound?*	*ground state*	*not bound*

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

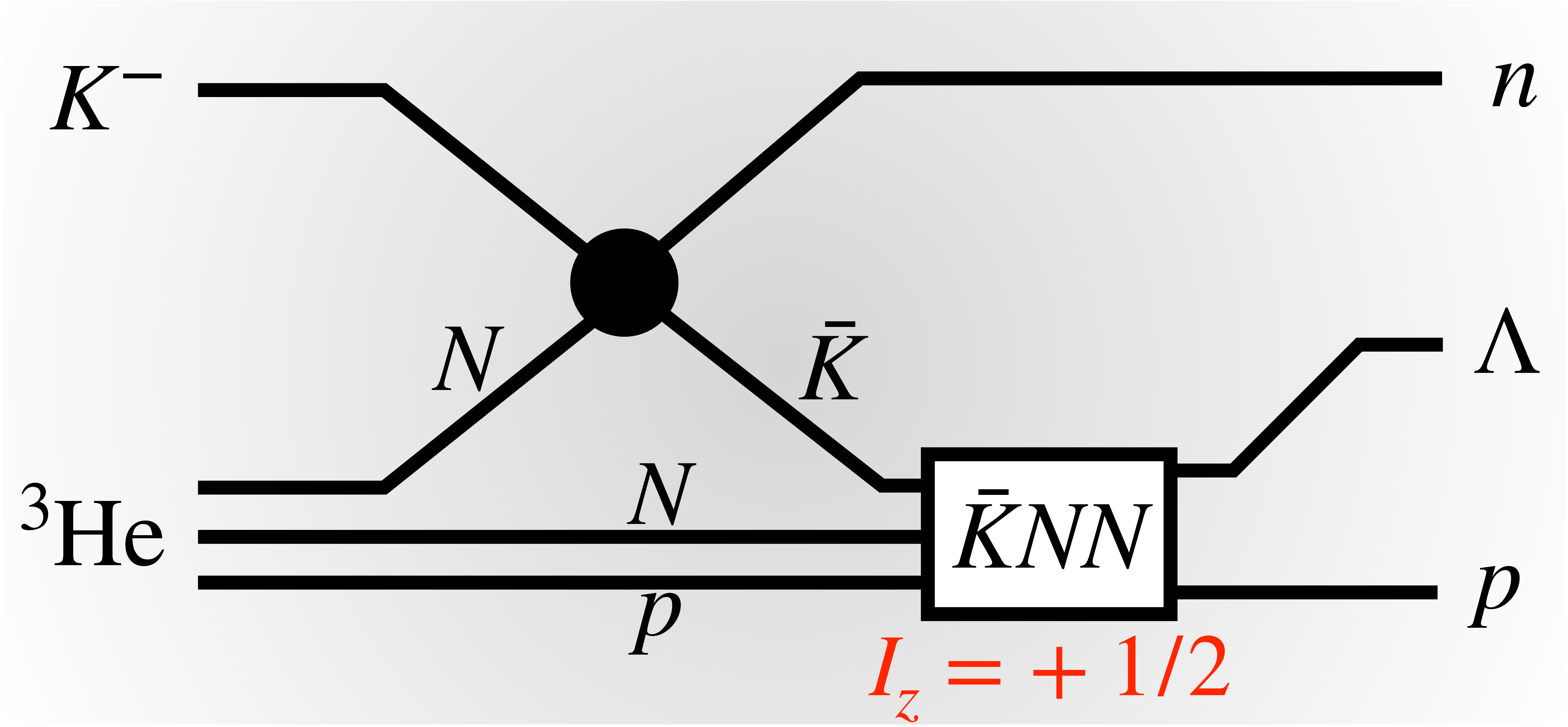
$(\bar{K}[NN]^{I=0})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=3/2}$
$J^\pi = 1^-$	$J^\pi = 0^-$	$J^\pi = 0^-$
$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$	$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$	$[\bar{K}N]^{I=1}N$
weakly *bound?*	*ground state*	*not bound*

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

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

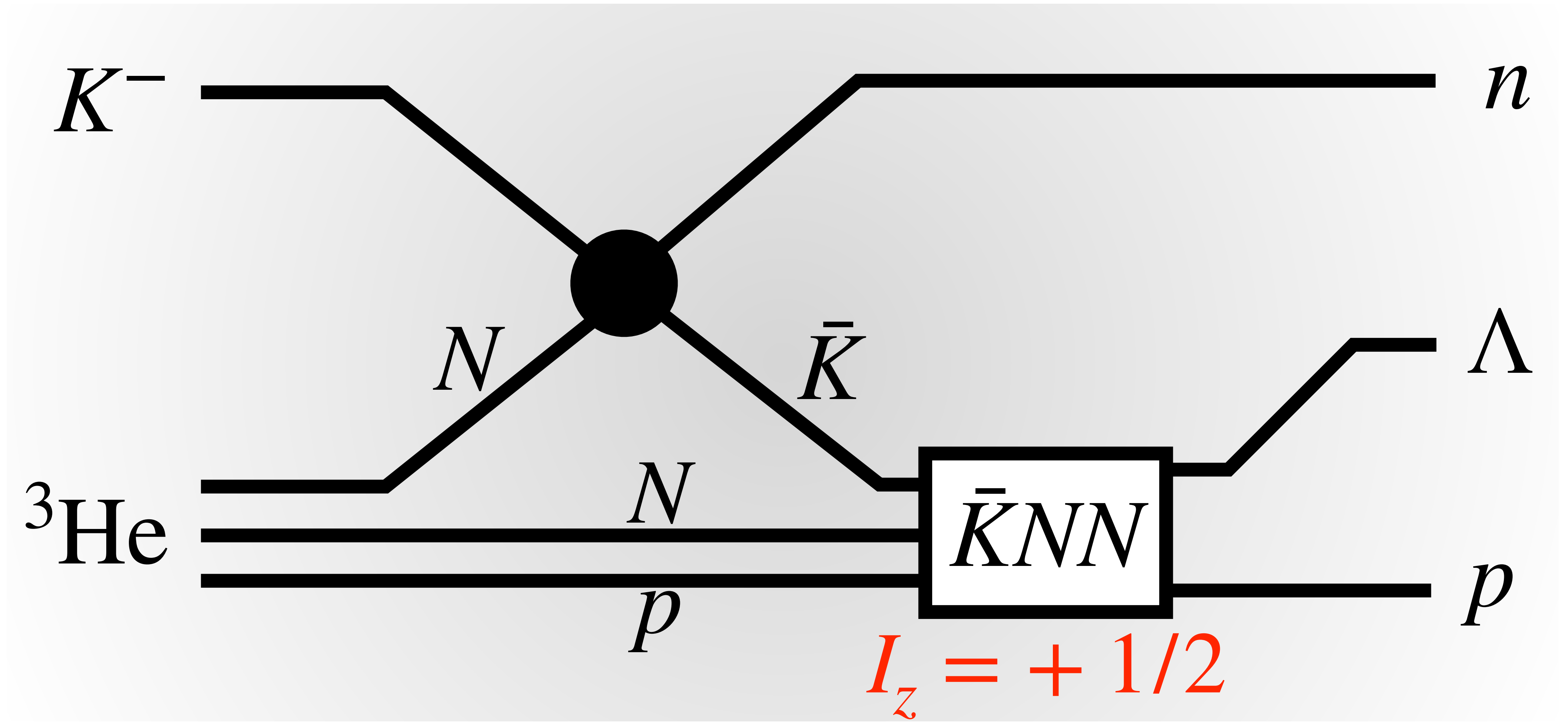
J-PARC E15

Production reaction

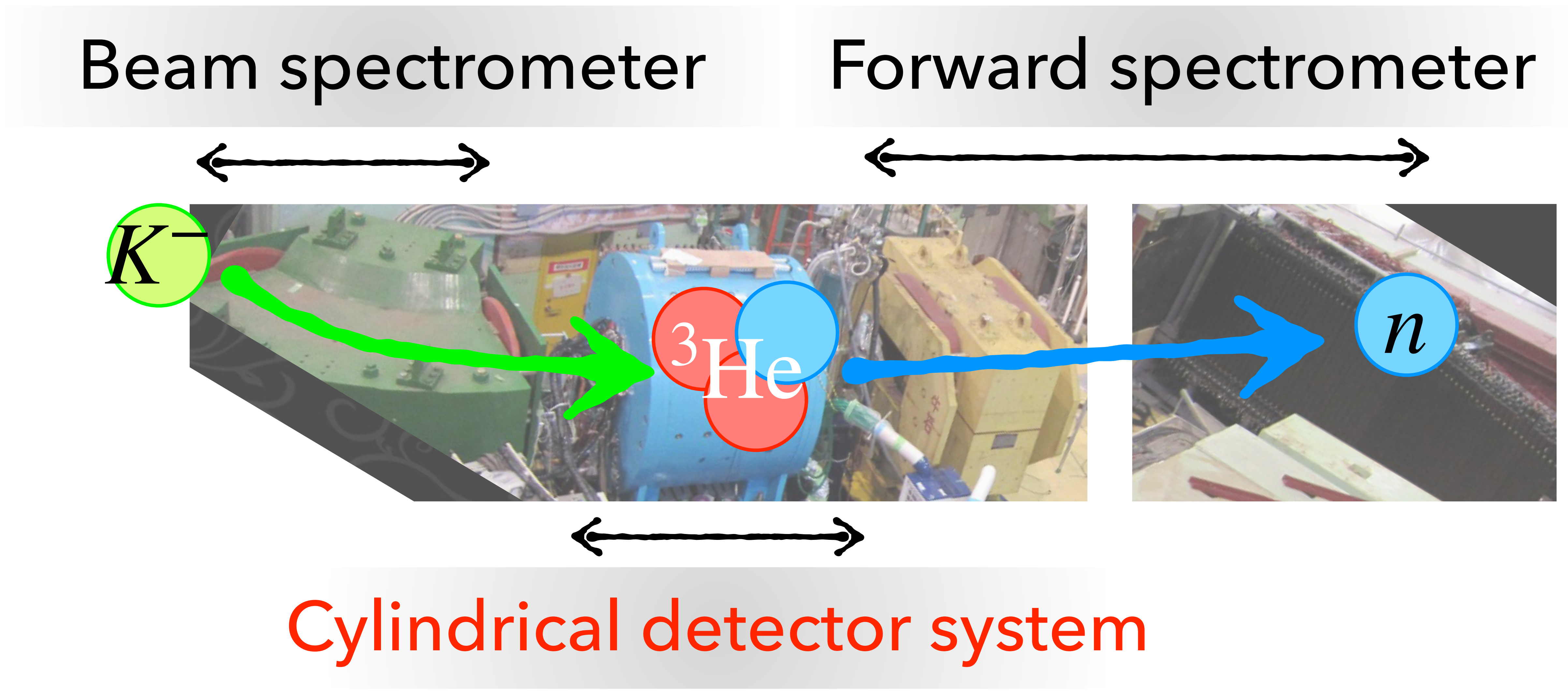


J-PARC E15

Production reaction

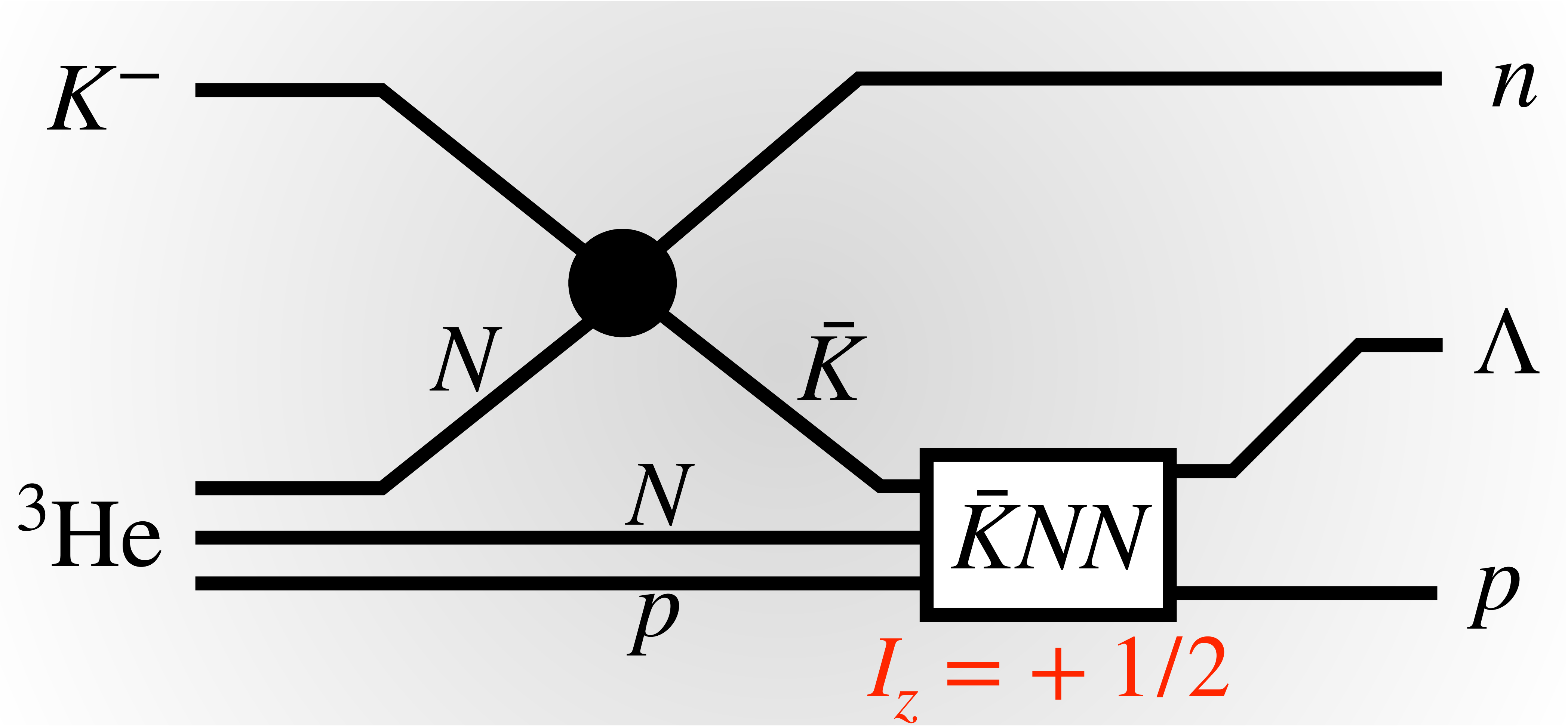


Detector system

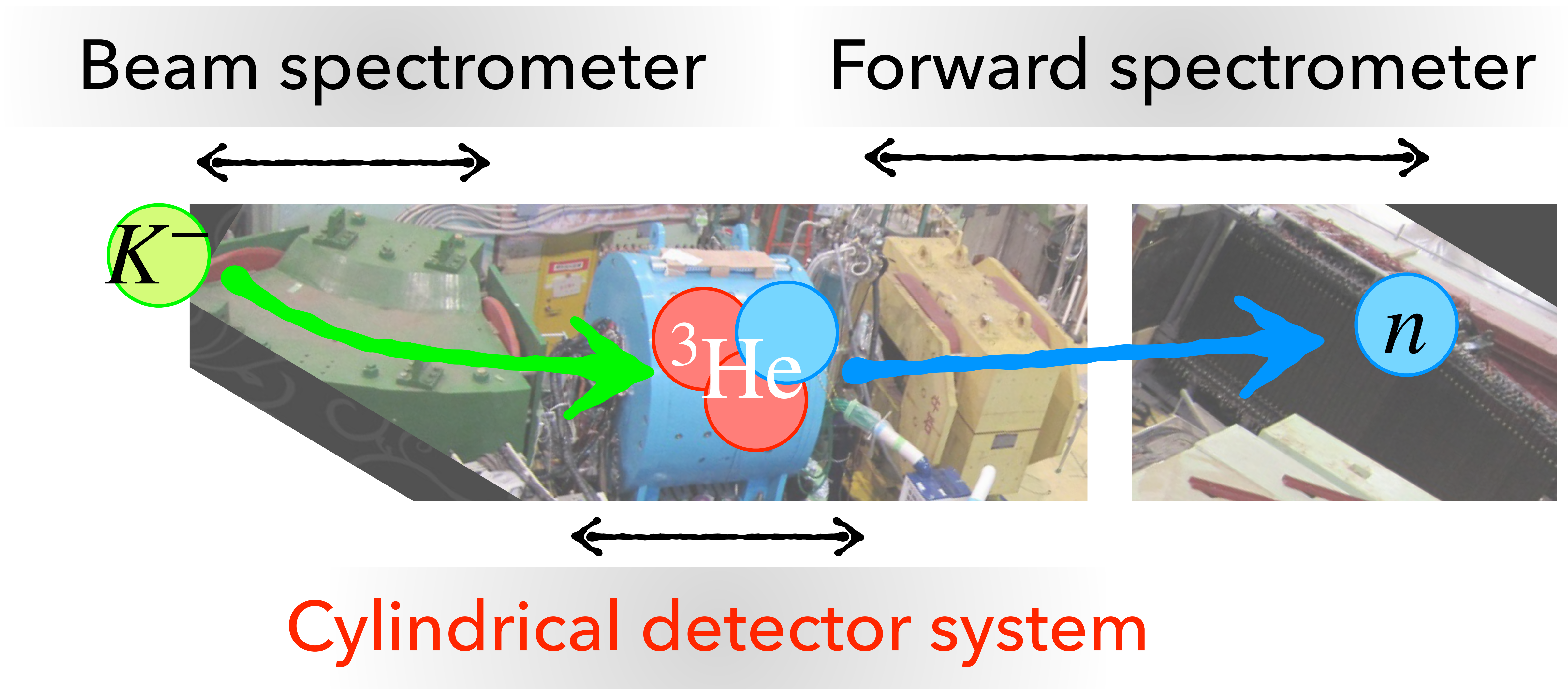


J-PARC E15

Production reaction



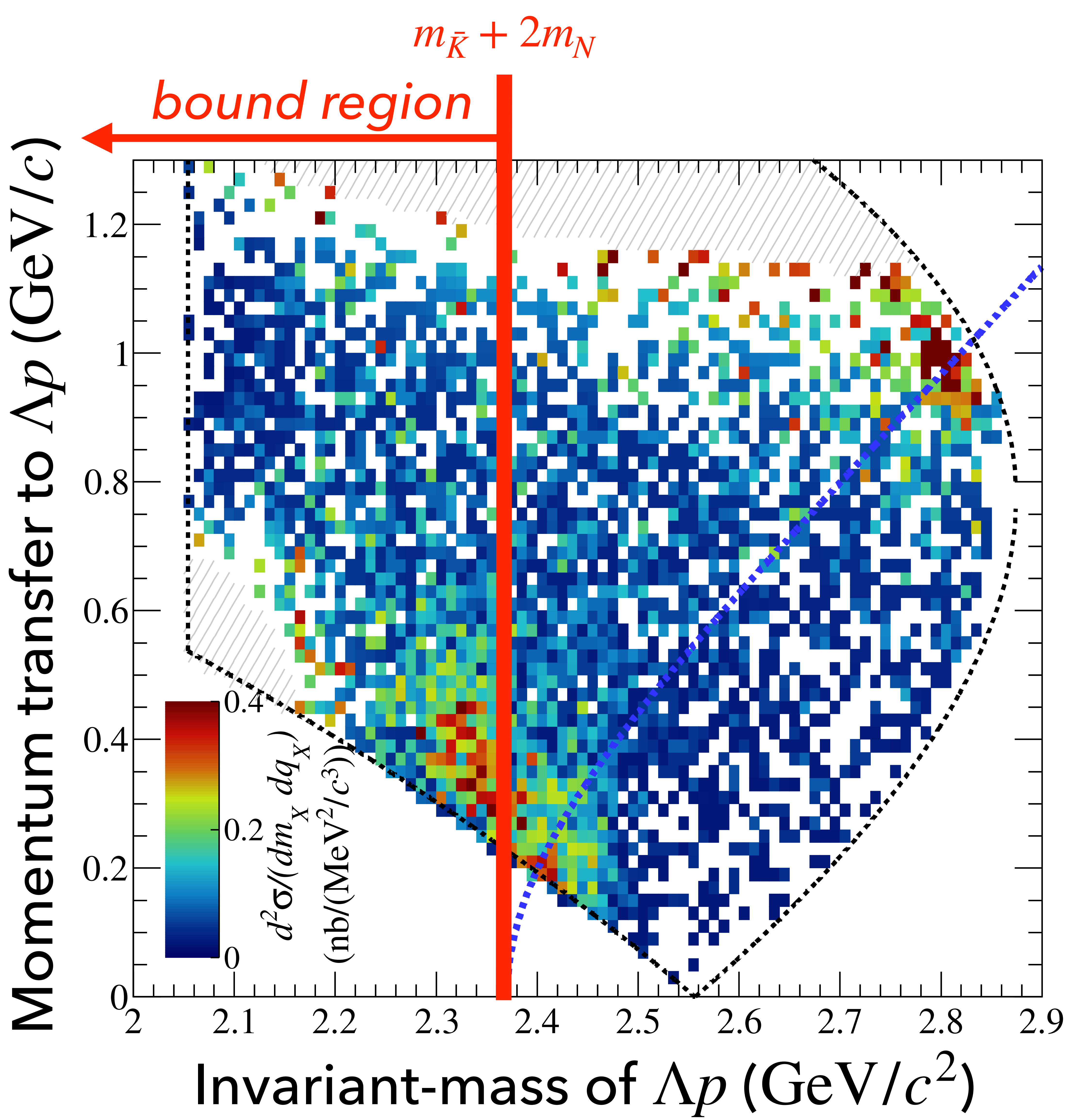
Detector system

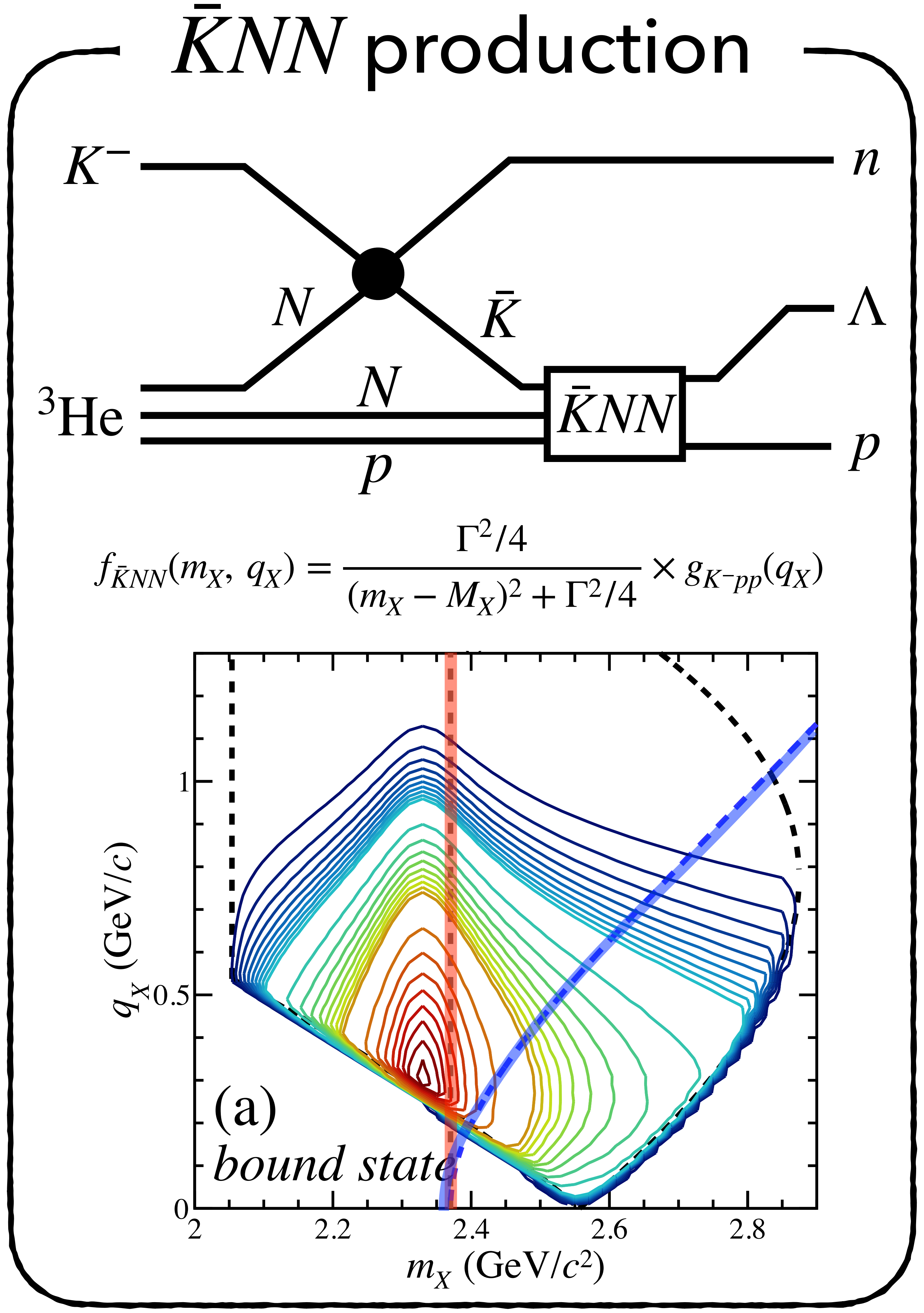


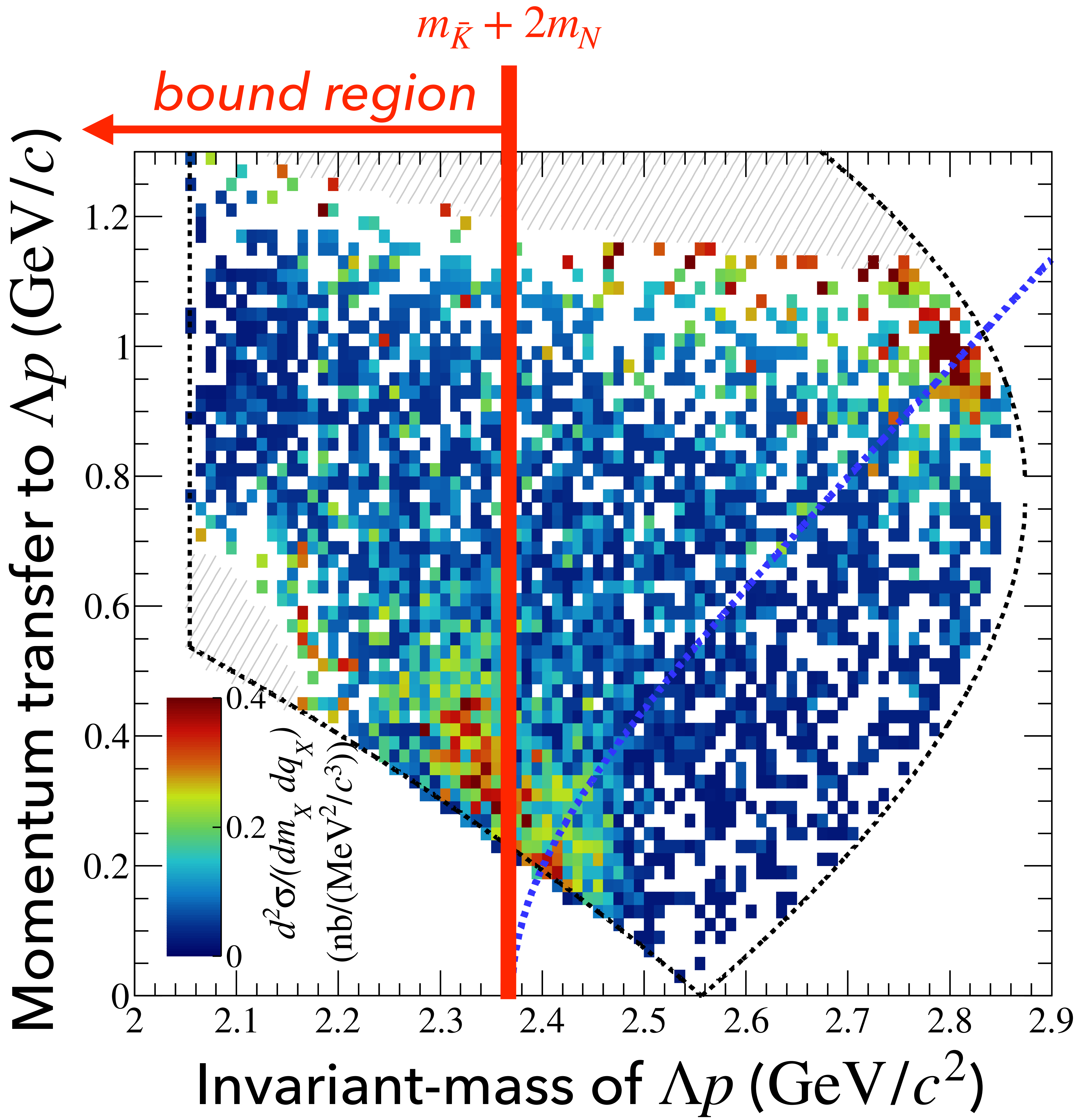
Exclusive invariant-mass spectroscopy

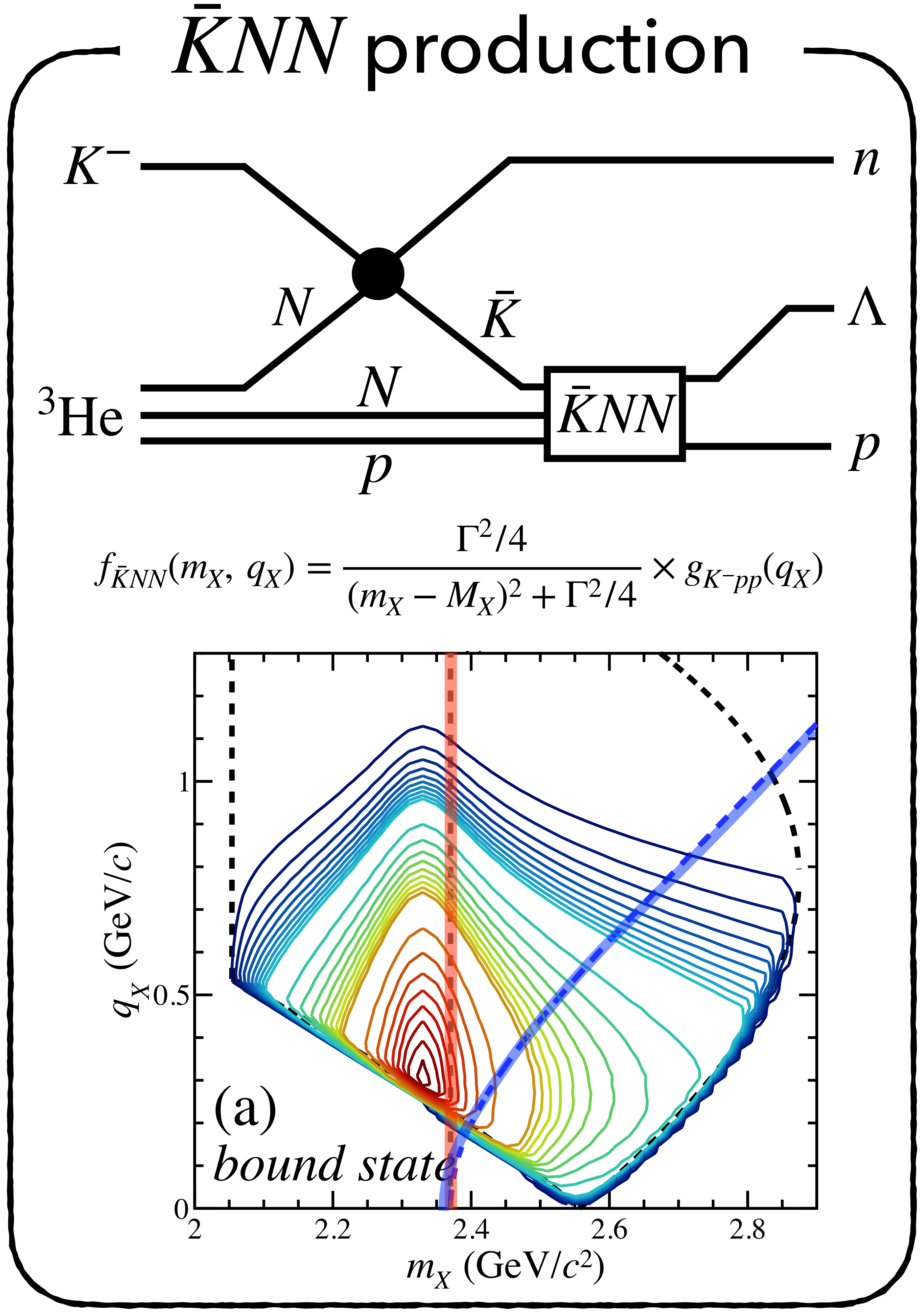
To select Λpn final state

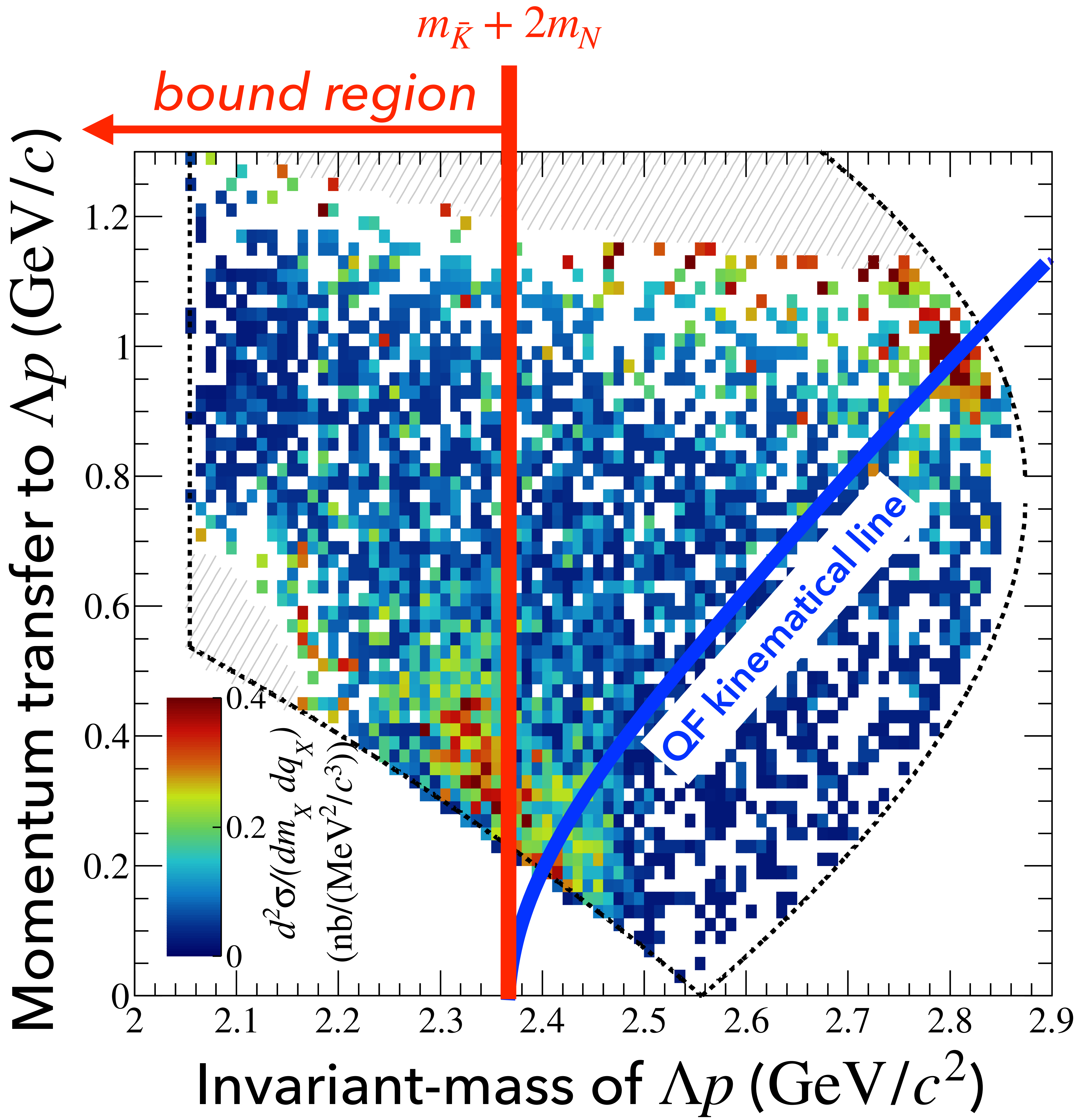
To measure Λp invariant-mass & momentum transfer

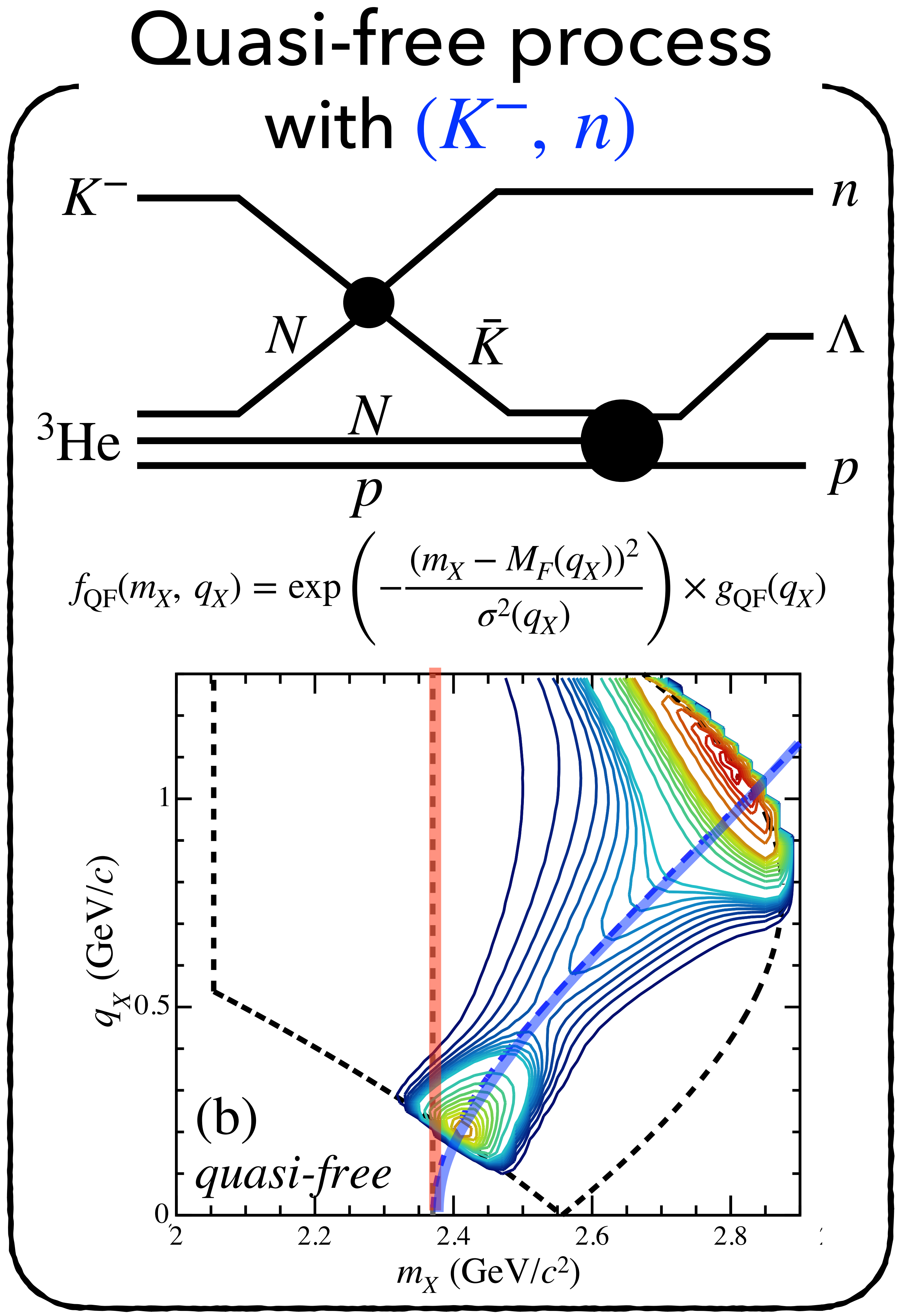

$m_{\bar{K}} + 2m_N$
bound region
Momentum transfer to Λp (GeV/c)
Invariant-mass of Λp (GeV/c^2)
$d^2\sigma/(dm_X\,dq_X)$
(nb/(MeV^2/c^3))
0.4
0.2
0
1.2
1
0.8
0.6
0.4
0.2
0
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9


$\bar{K}NN$ production
K^-
n
N
$\bar{K}$
Λ
^{3}He
N
$\bar{K}NN$
p
p
$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K\text{-}pp}(q_X)$
(a)
bound state
q_X (GeV/c)
m_X (GeV/c^2)


$m_{\bar{K}} + 2m_N$
bound region
Momentum transfer to Λp (GeV/c)
Invariant-mass of Λp (GeV/c^2)
$d^2\sigma/(dm_X\, dq_X)$
(nb/(MeV^2/c^3))

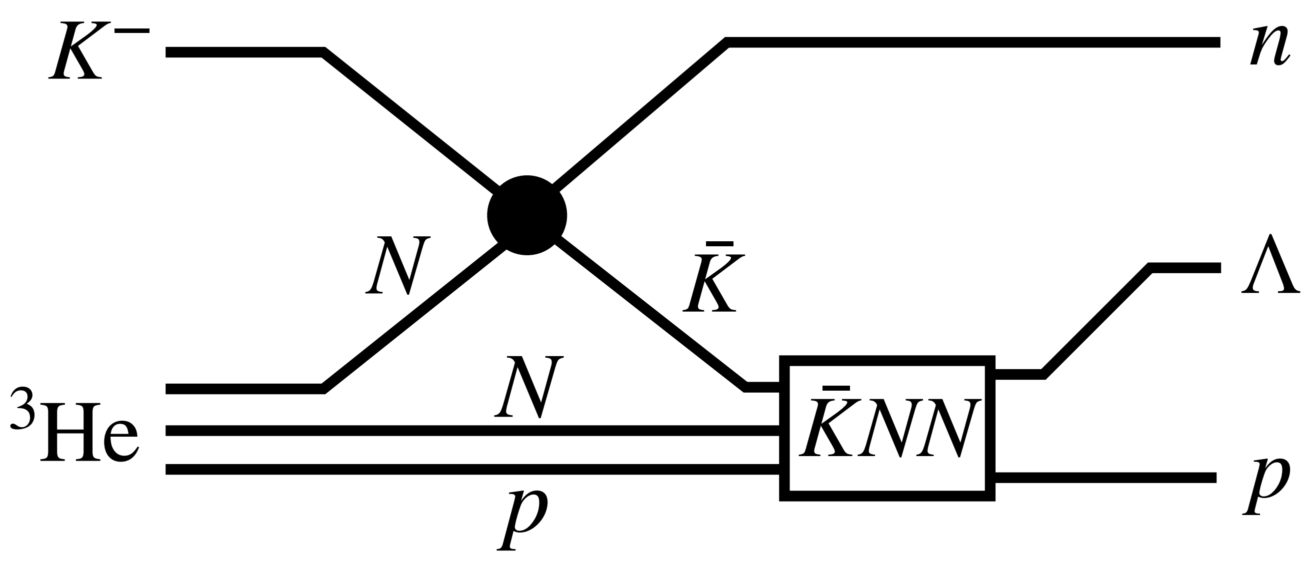

$\bar{K}NN$ production
K^-
n
N
$\bar{K}$
Λ
^{3}He
N
$\bar{K}NN$
p
p
$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$
(a)
bound state
q_X (GeV/c)
m_X (GeV/c^2)


$m_{\bar{K}} + 2m_N$
bound region
Momentum transfer to Λp (GeV/c)
QF kinematical line
$d^2\sigma/(dm_X\, dq_X)$ (nb/(MeV^2/c^3))
Invariant-mass of Λp (GeV/c^2)

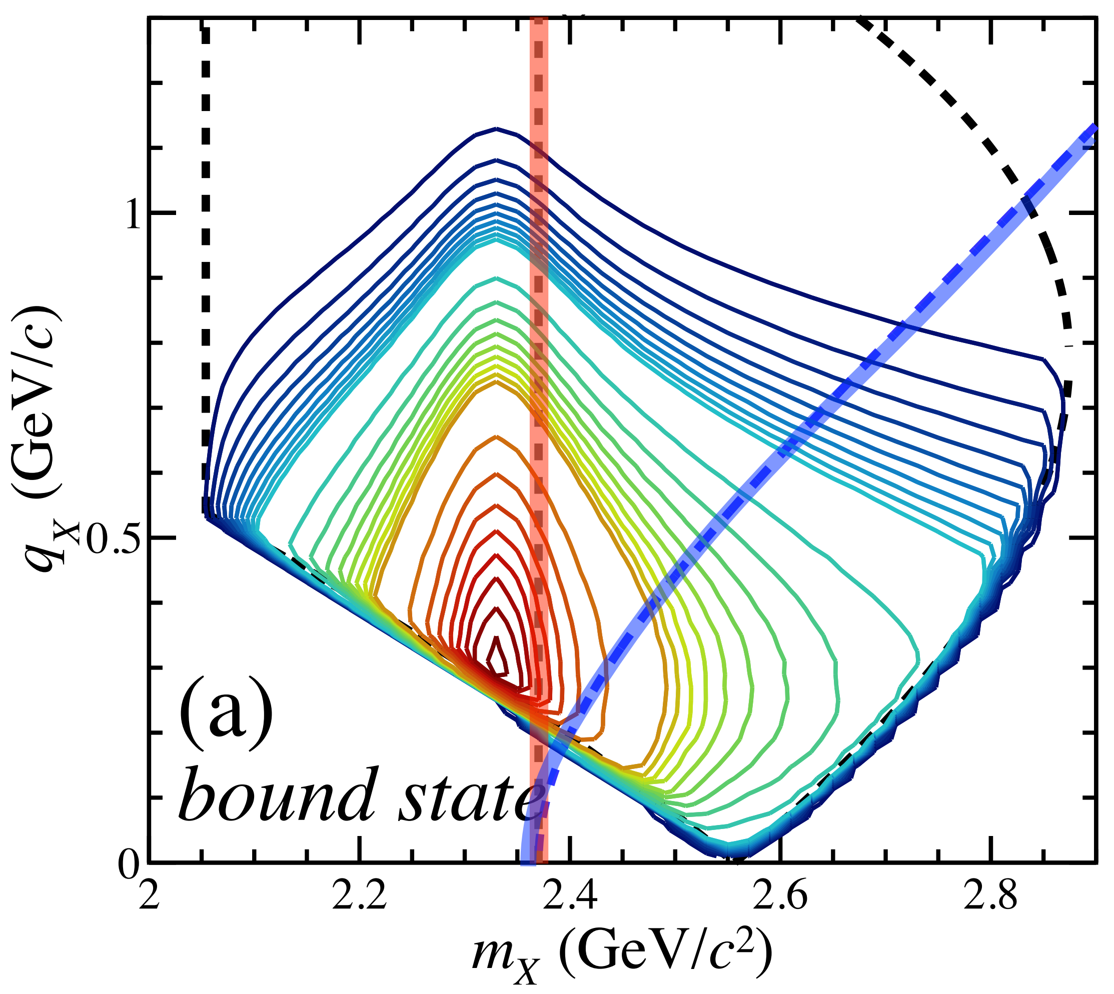

Quasi-free process with (K^-, n)
K^-
n
N
$\bar{K}$
Λ
^{3}He
N
p
p
$f_{QF}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{QF}(q_X)$
(b)
quasi-free
q_X (GeV/c)
m_X (GeV/c^2)

Model functions for fitting

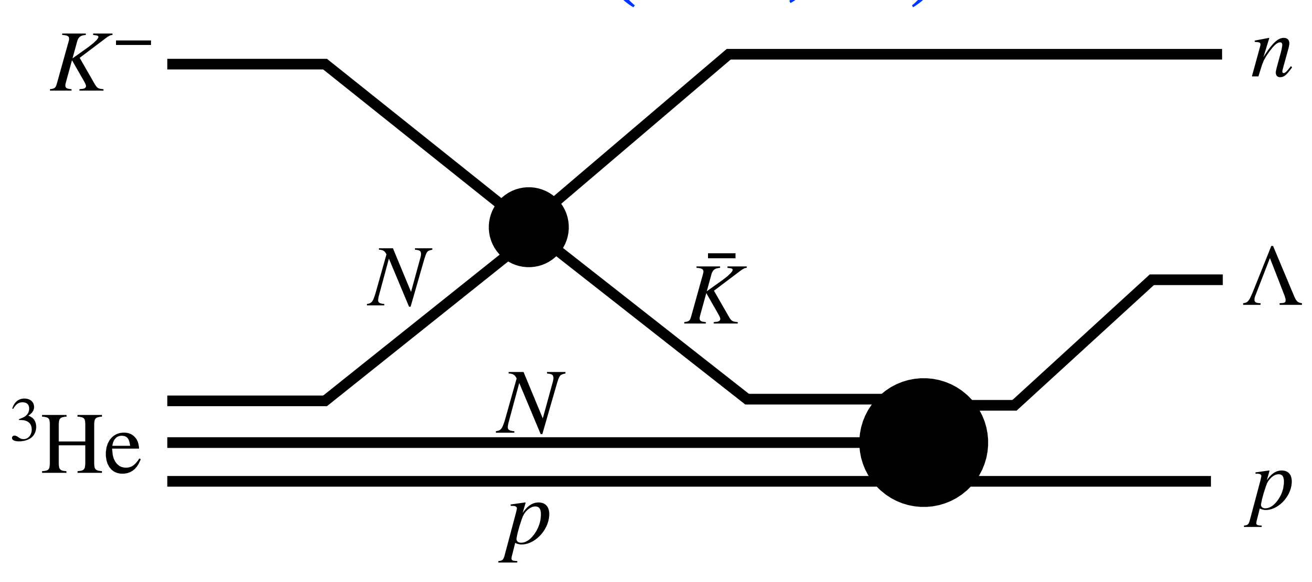
$\bar{K}NN$ production



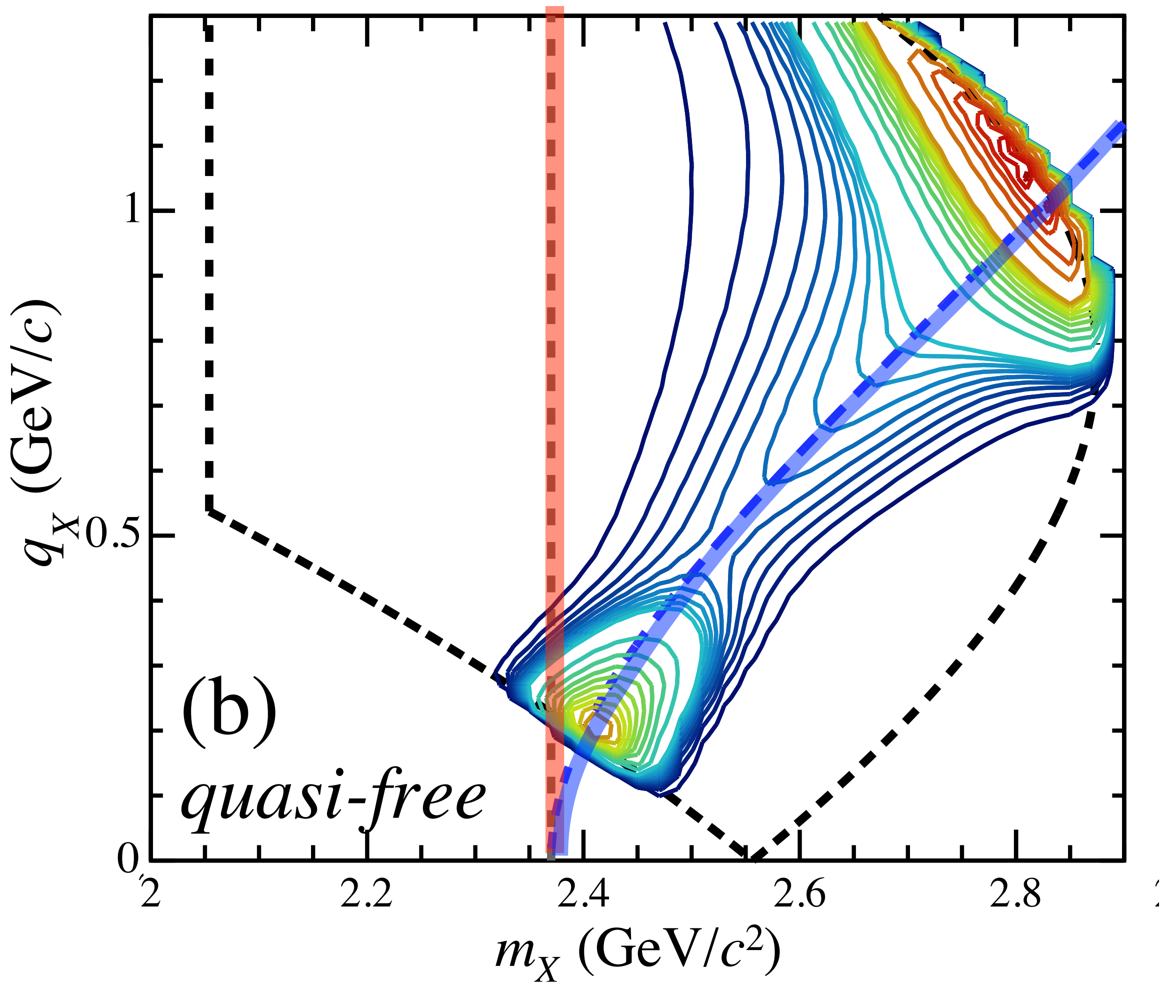
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



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

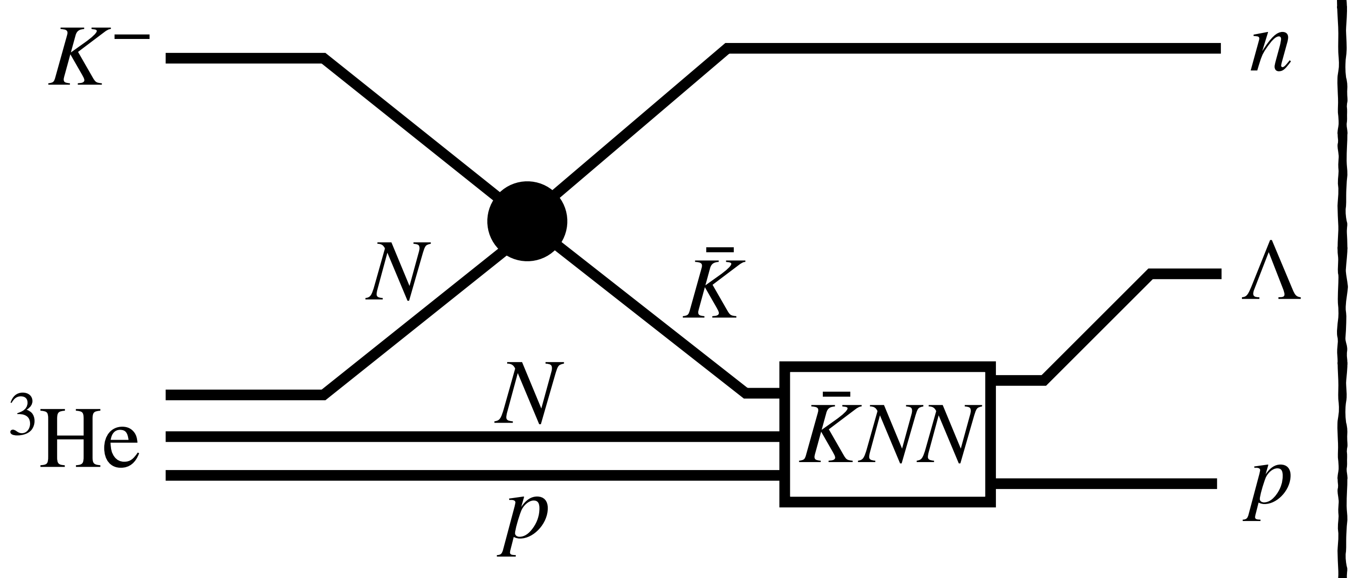


$$f_{\mathrm{QF}}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{\mathrm{QF}}(q_X)$$



Model functions for fitting

$\bar{K}NN$ production



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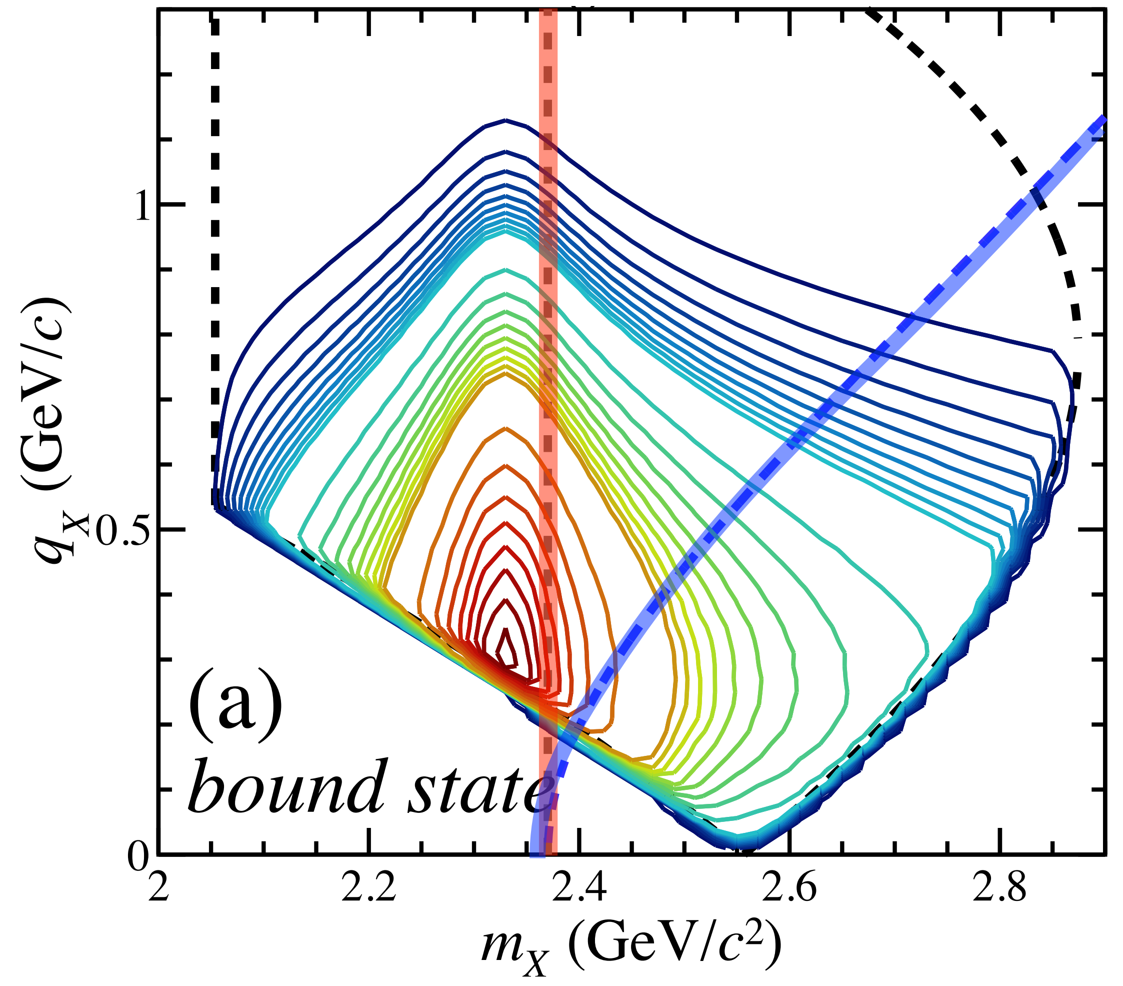
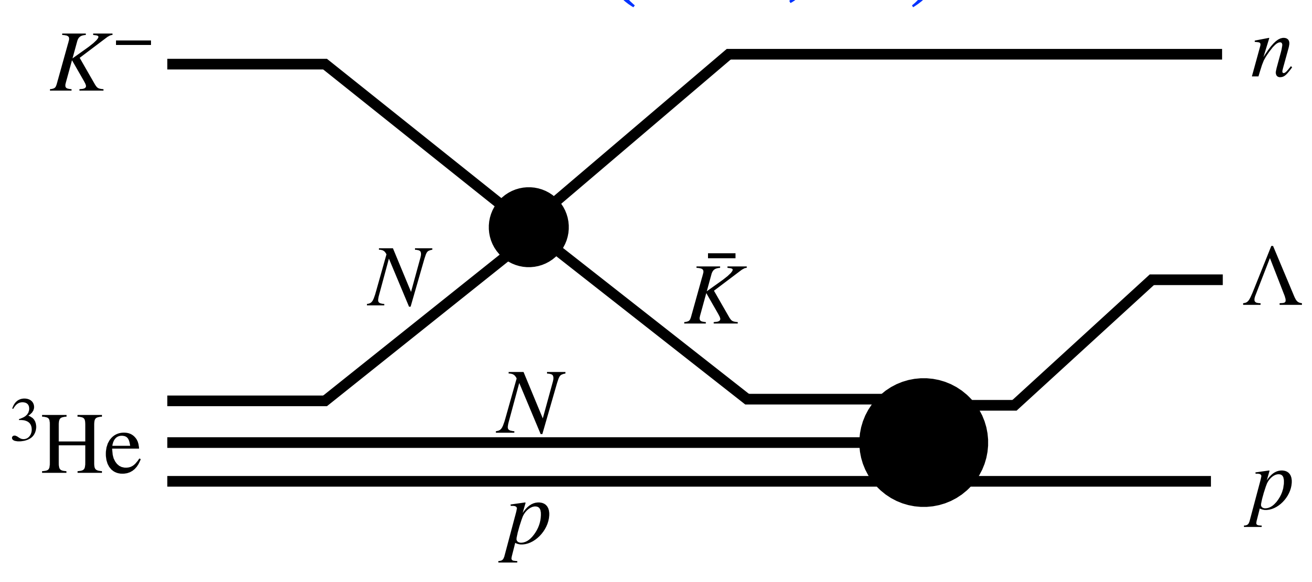


Quasi-free process with (K^-, n)



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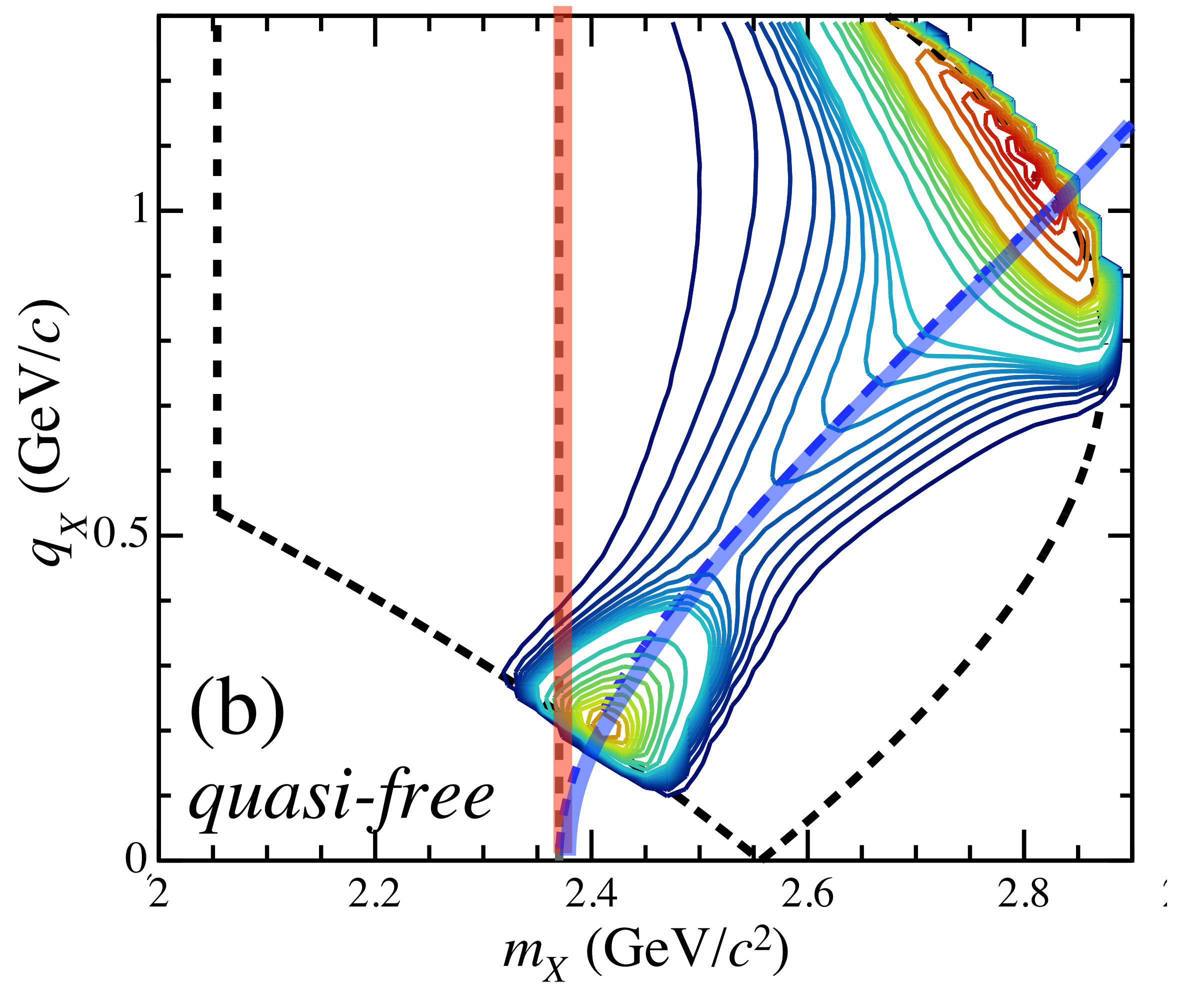
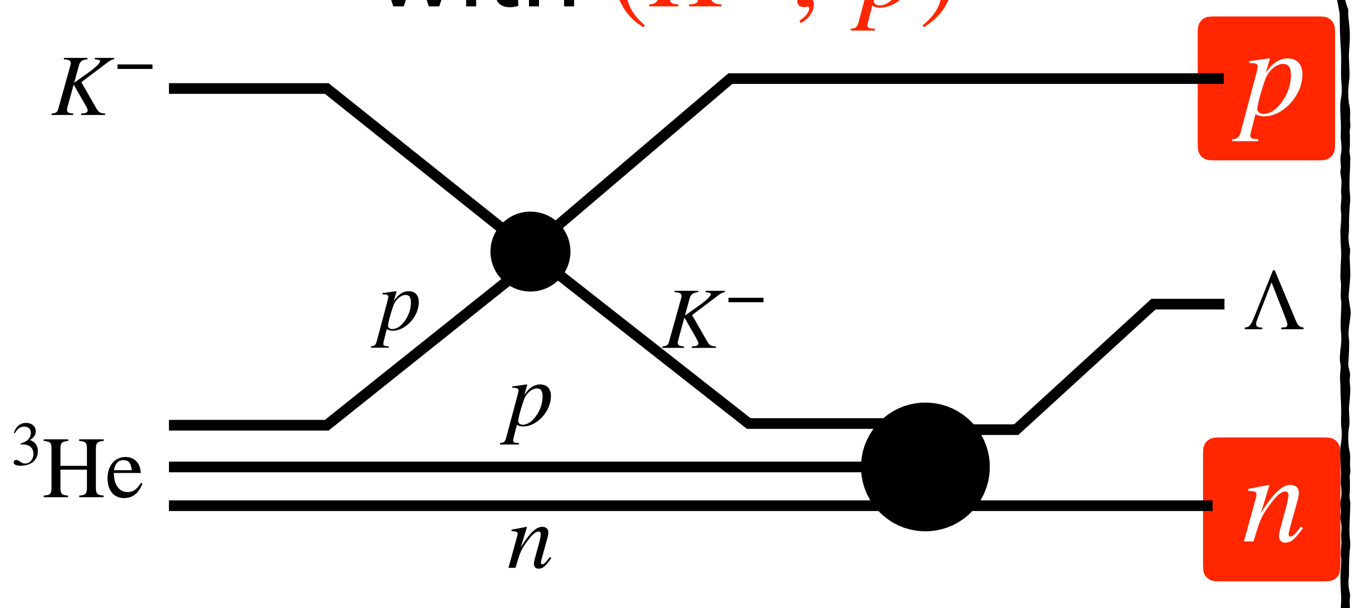
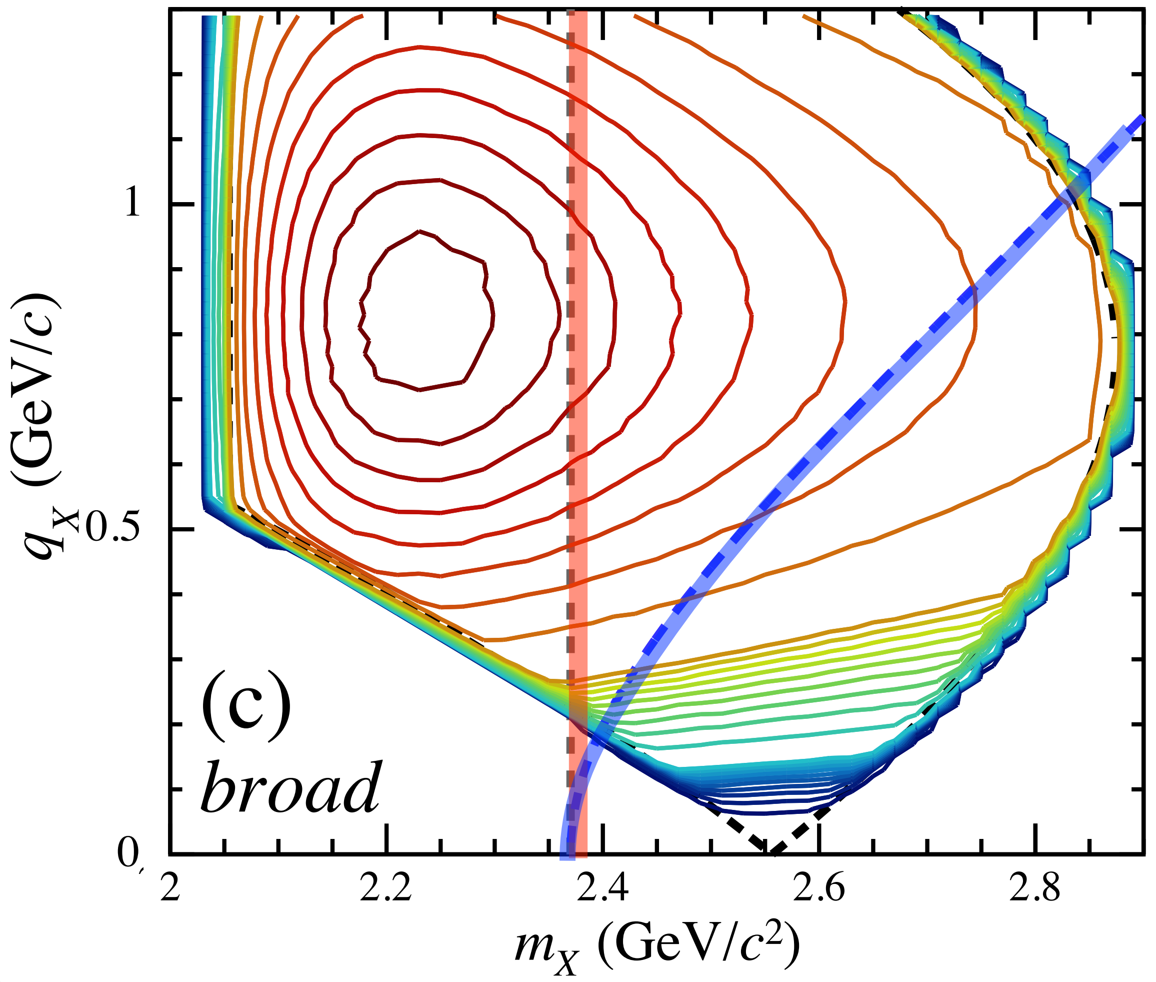


Quasi-free process with (K^-, p)

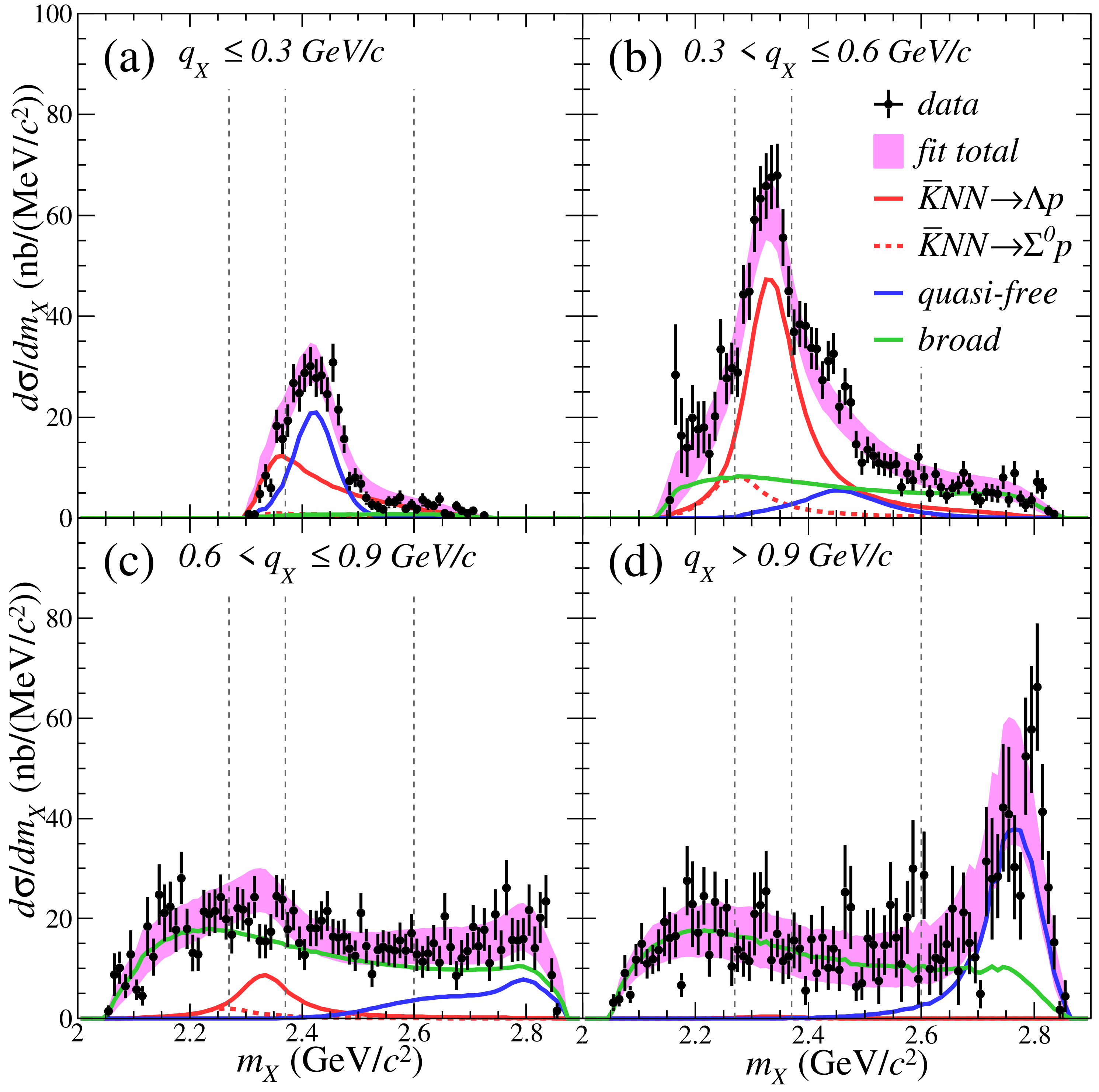


widely distributing

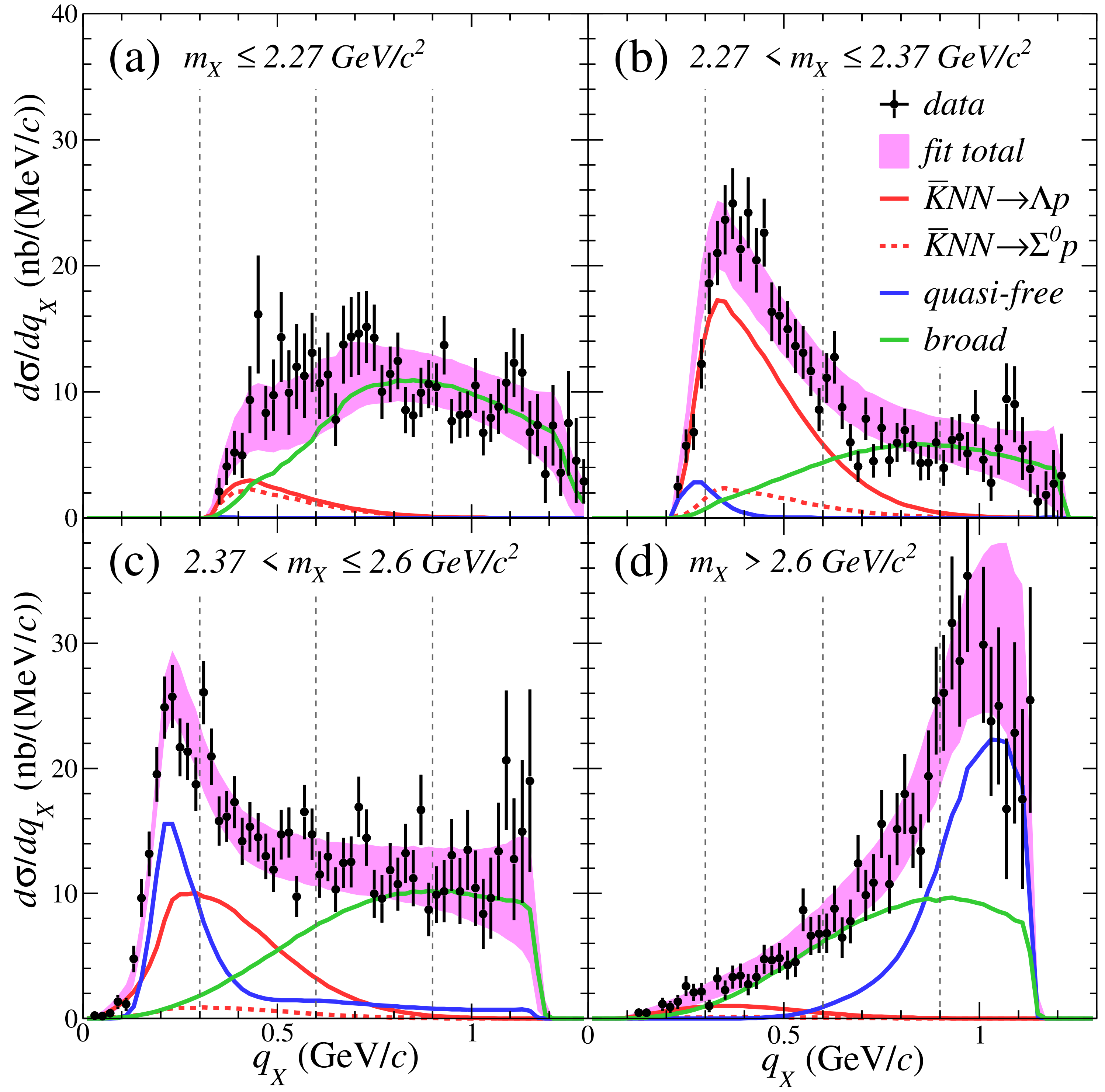


Fit result

Λp invariant-mass

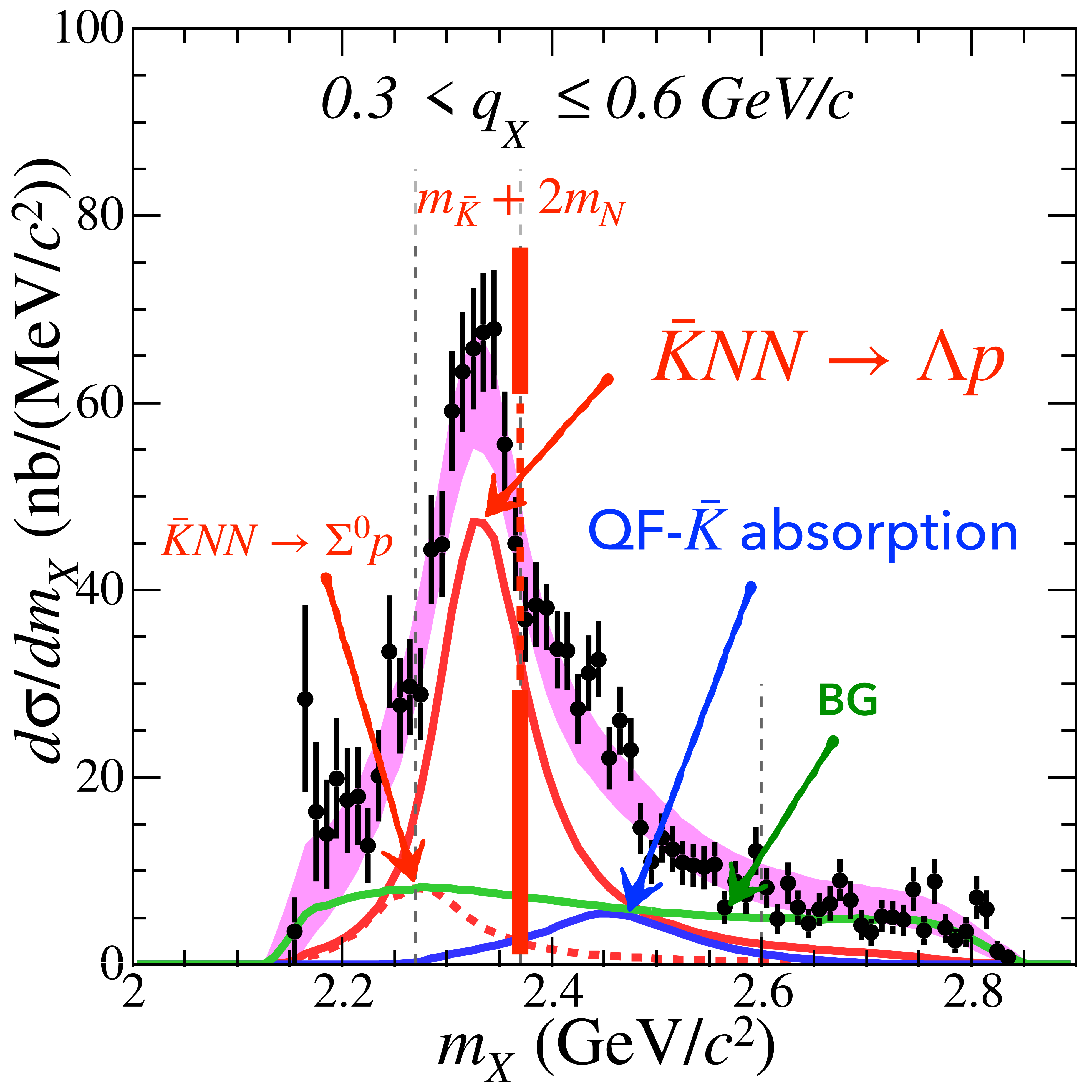


Momentum transfer to Λp

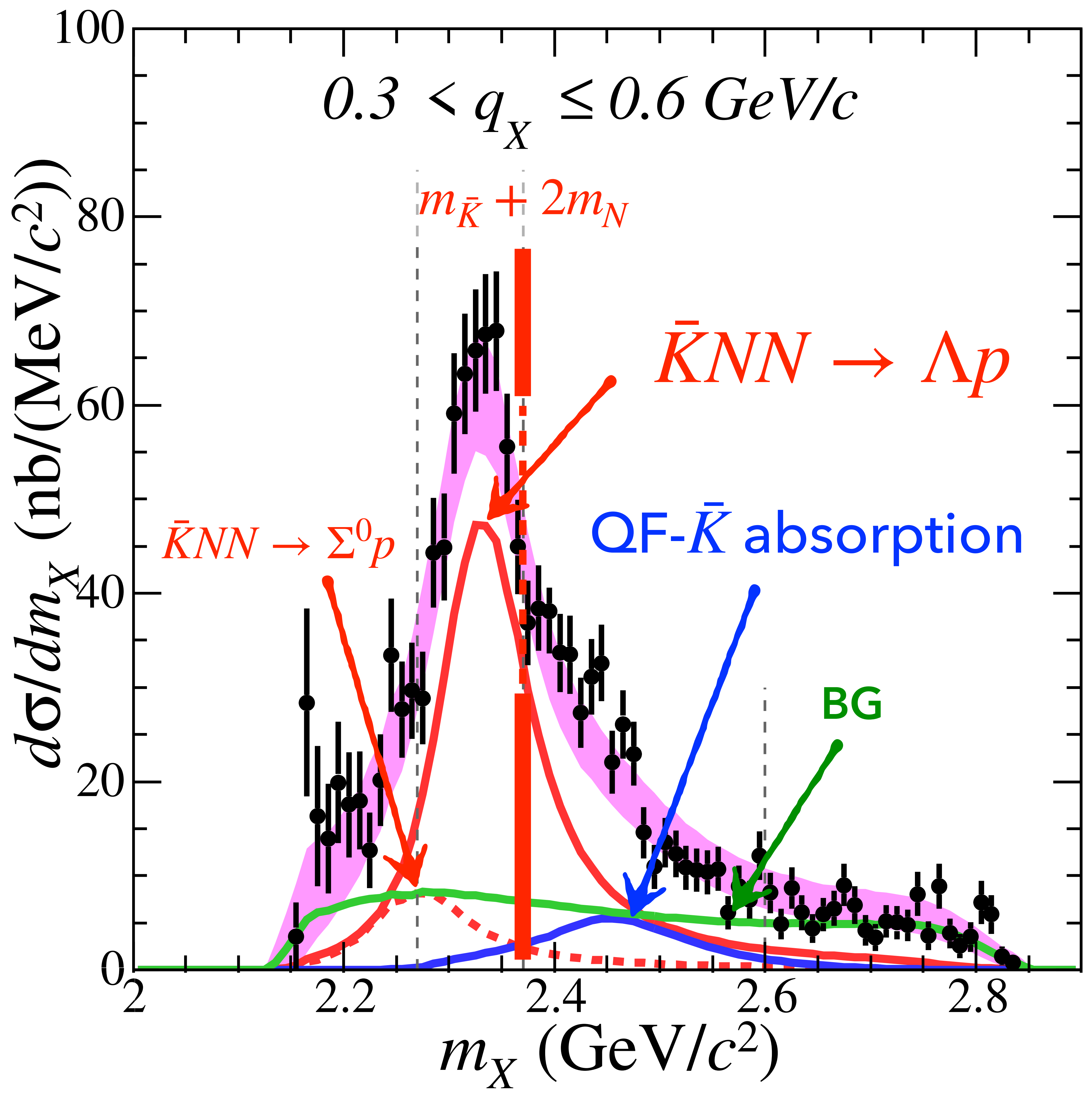


→ **The whole 2D distribution is well reproduced.**

What we observed



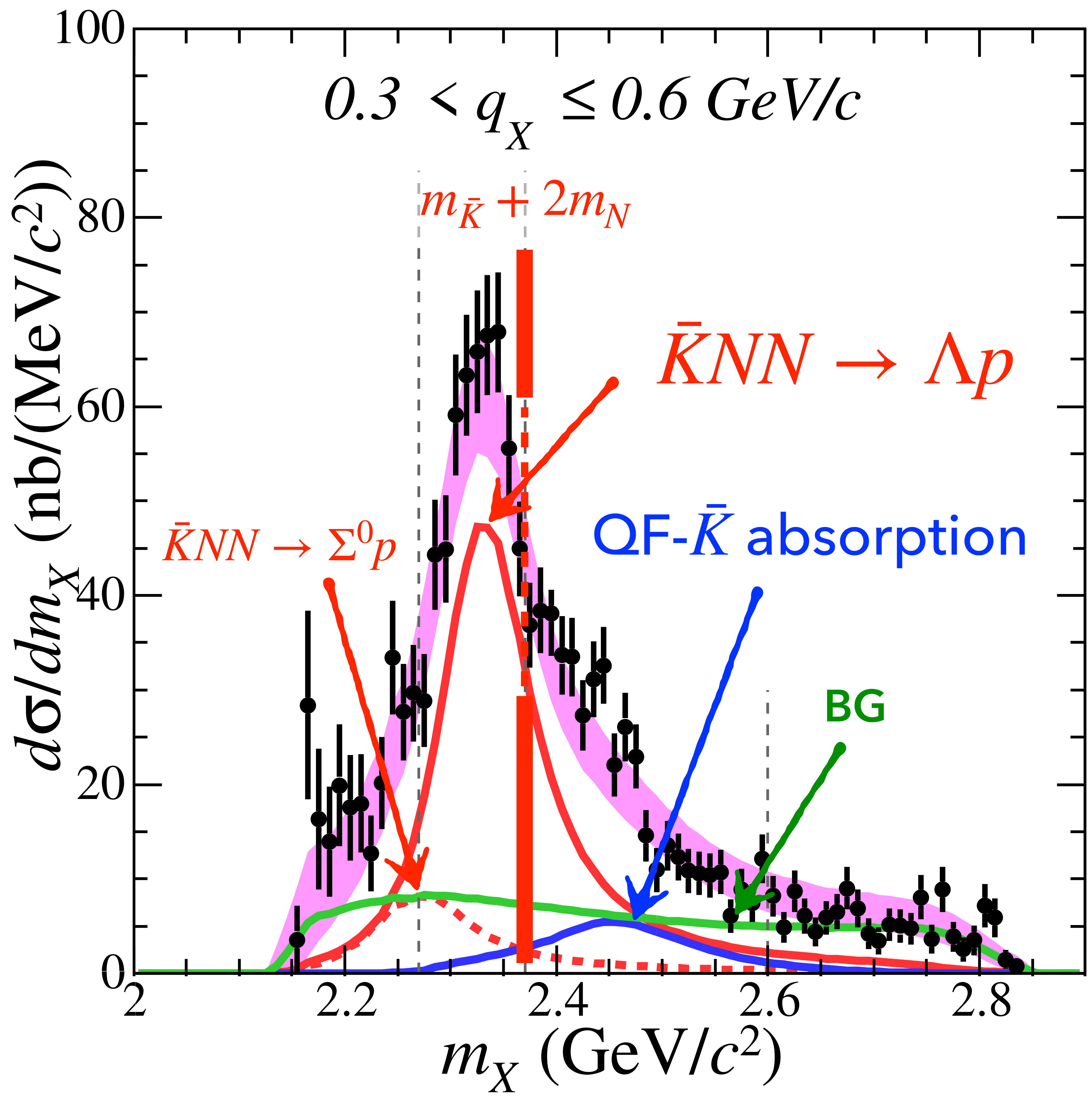
What we observed



The peak position does not depend on q.

➜ *It should be resonance.*

What we observed



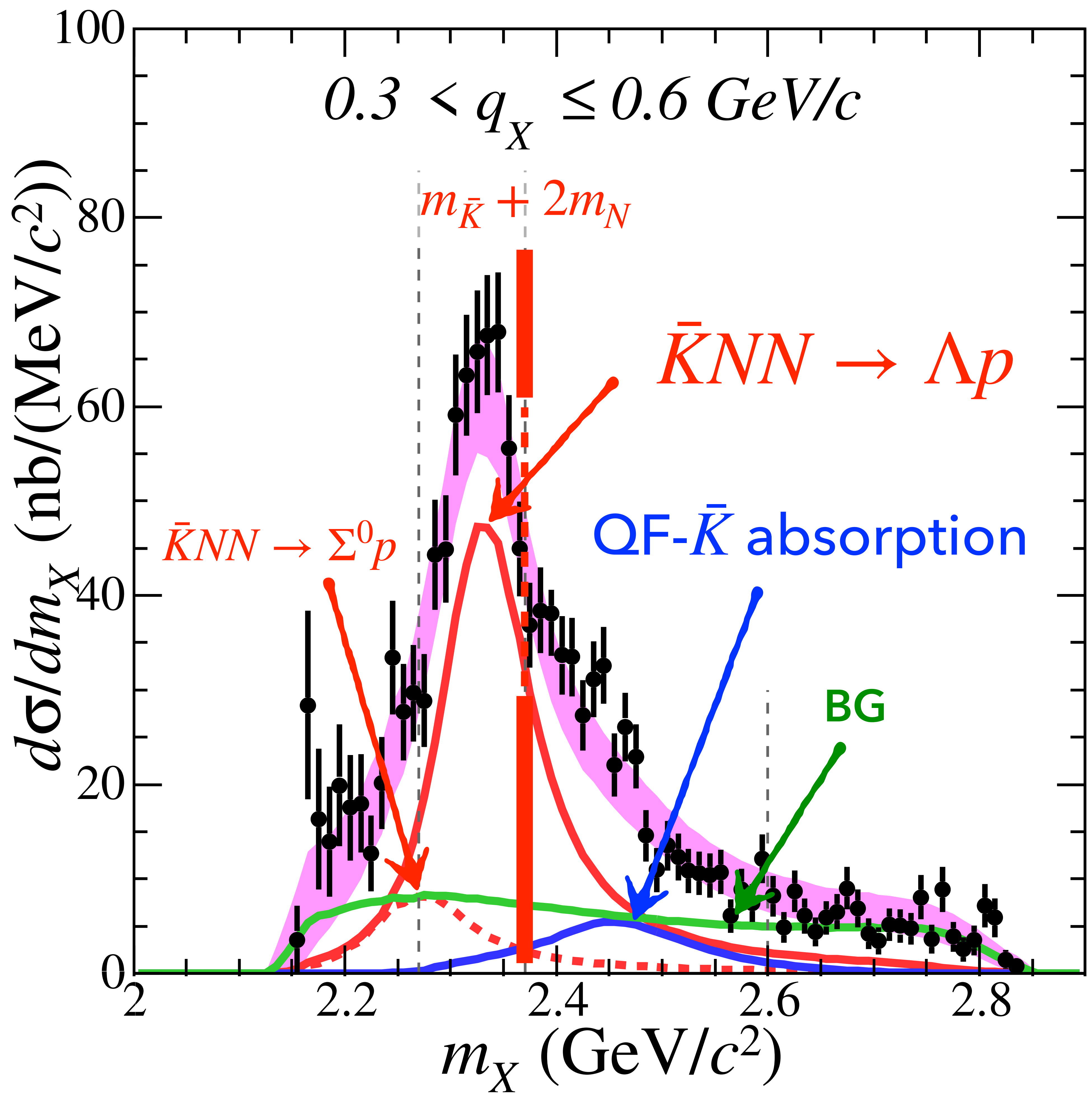
The peak position does not depend on q.

➔ *It should be resonance.*

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

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

What we observed



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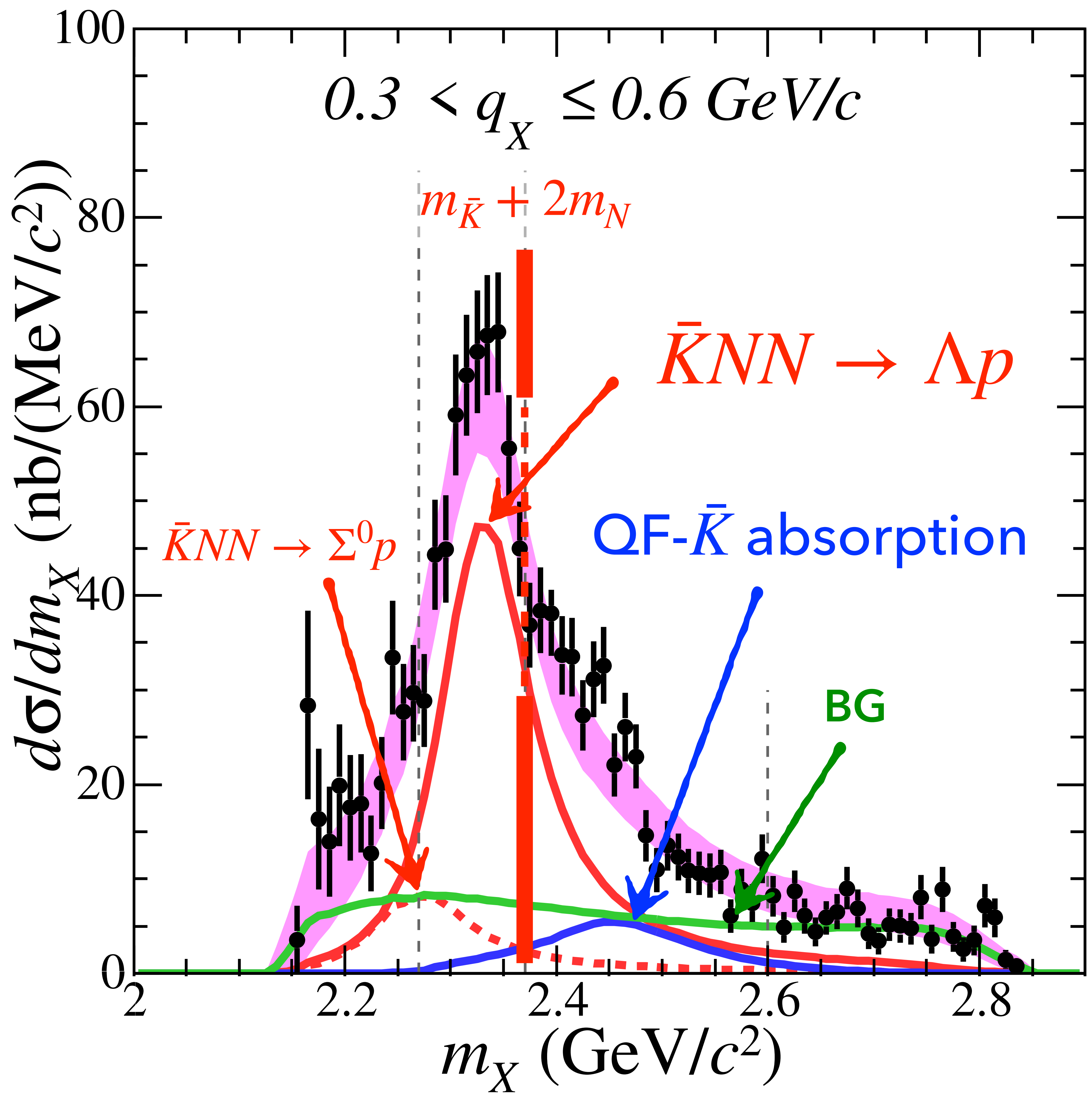
The peak position is below the $M_{\bar{K}NN}$.

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

What we observed



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

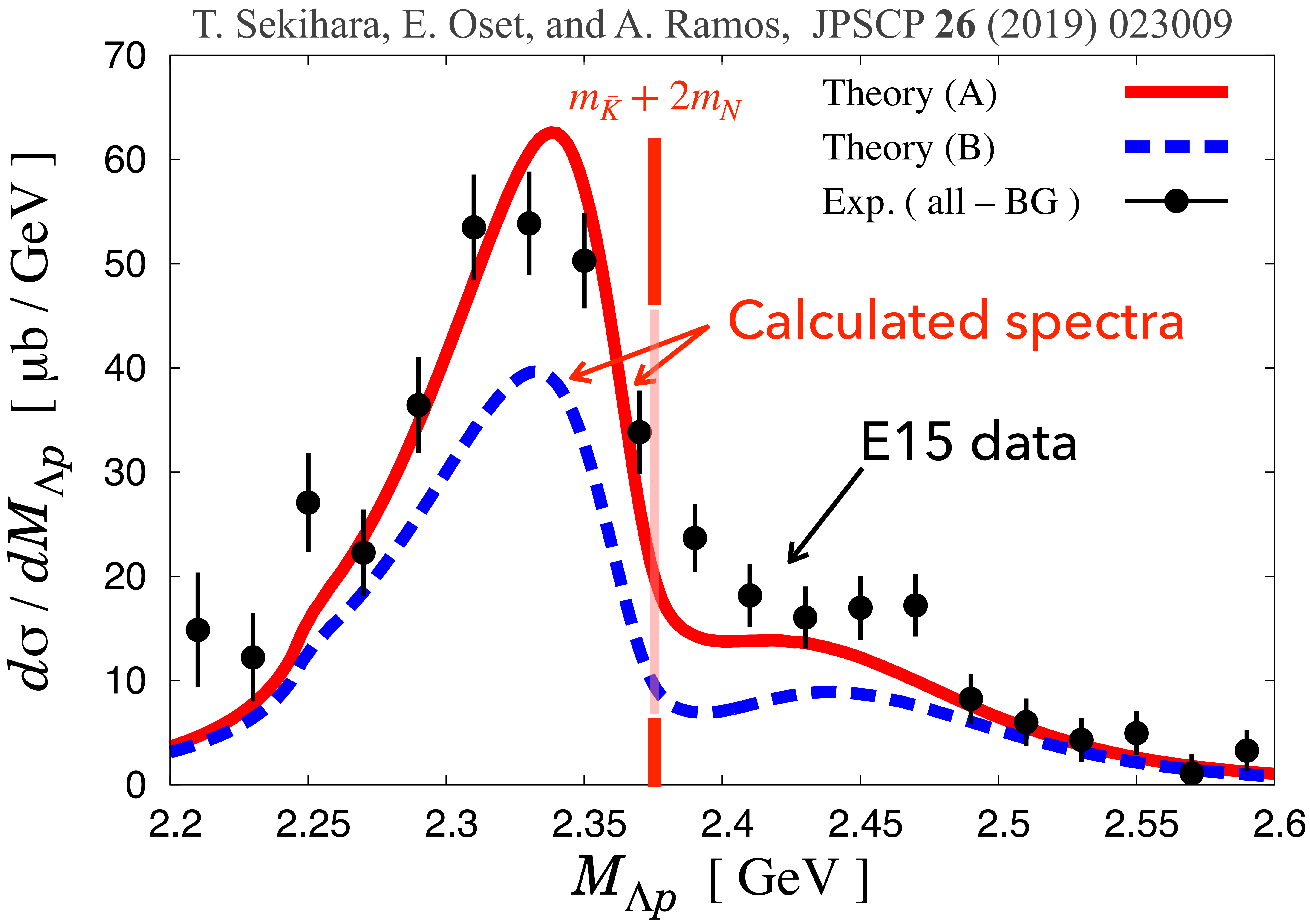
➔ *We interpreted it as $\bar{K}NN$ signal.*

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

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

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

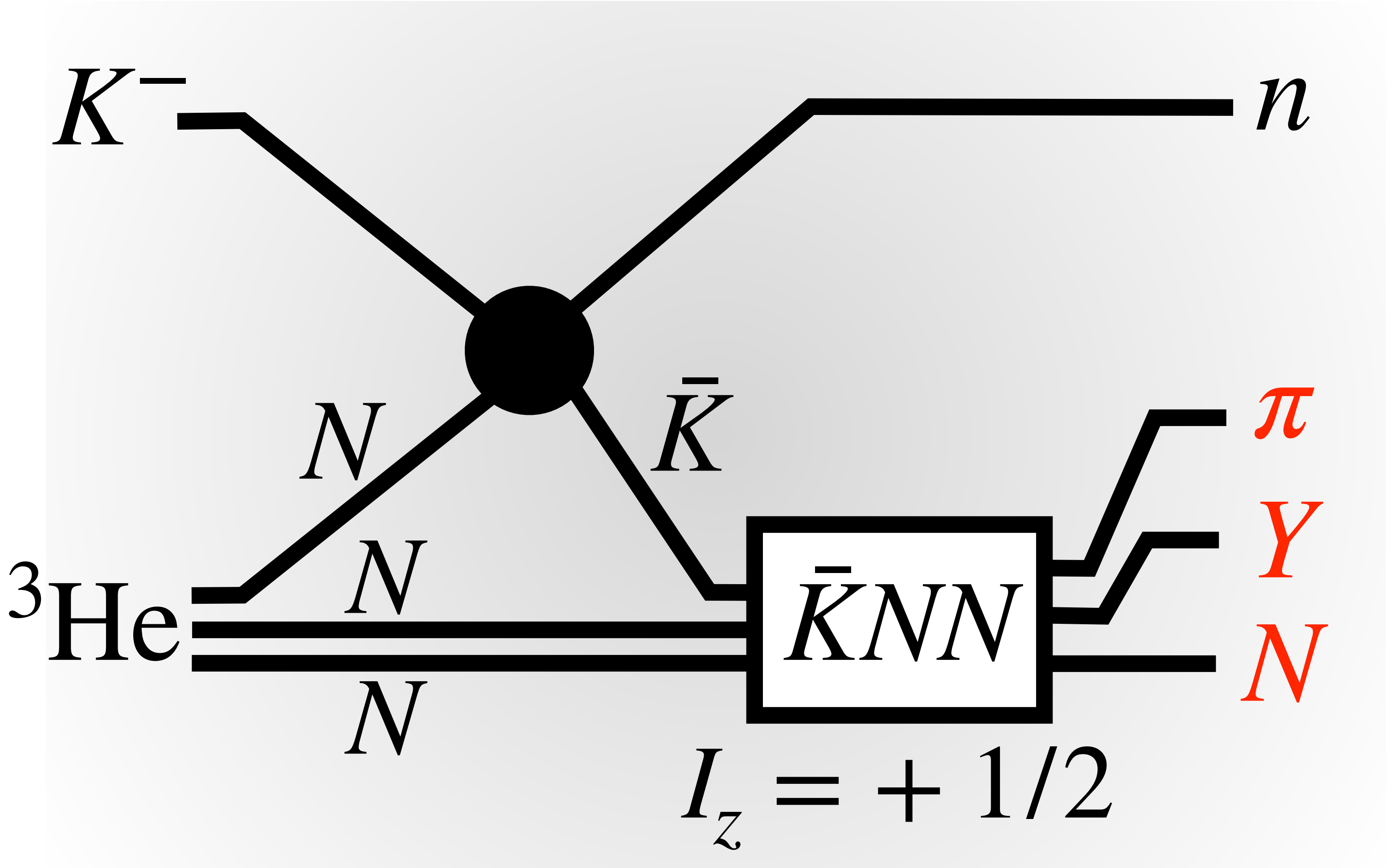
Compare to theoretical calculation



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

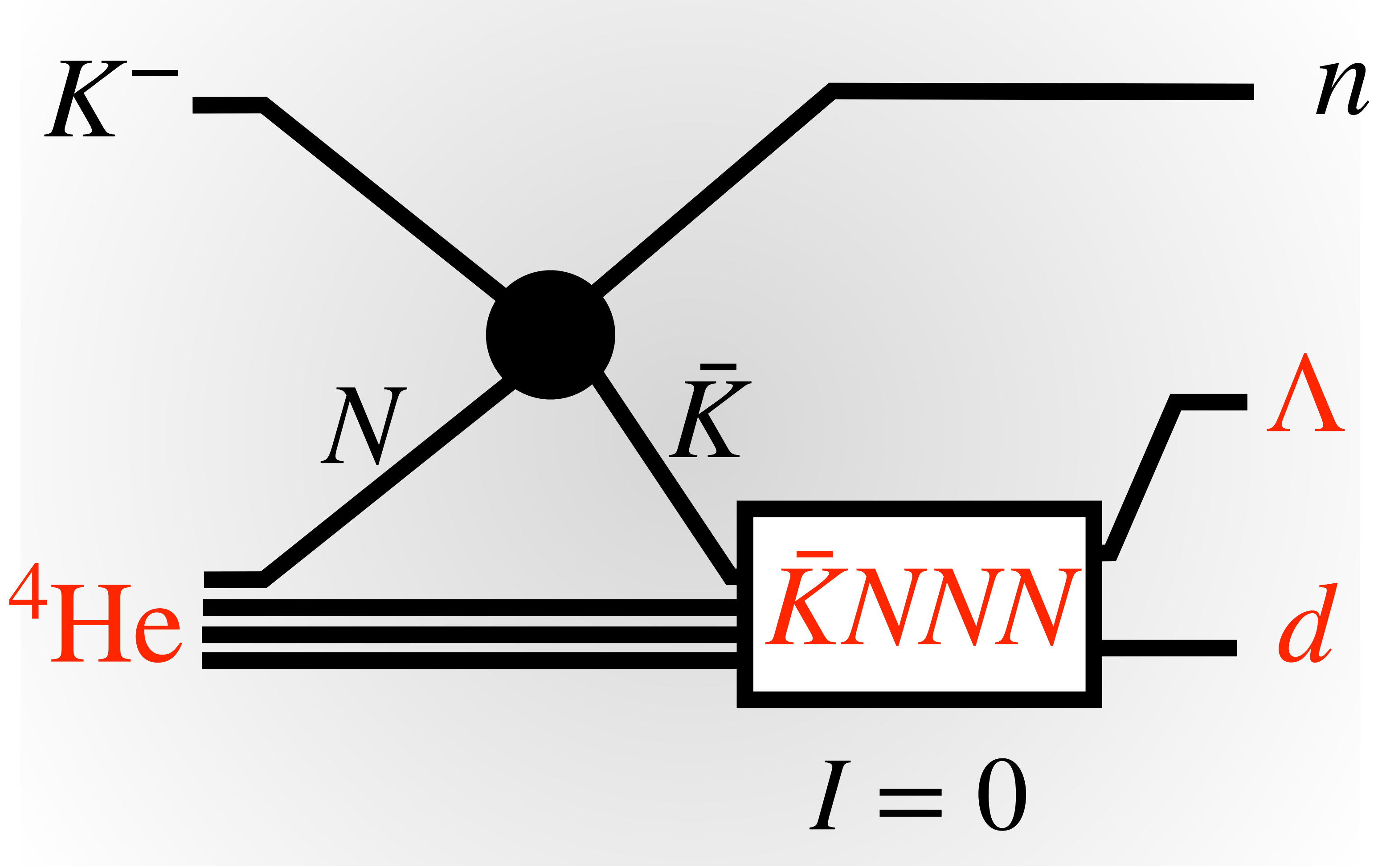
Ongoing analysis for $\bar{K}$-nuclei

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



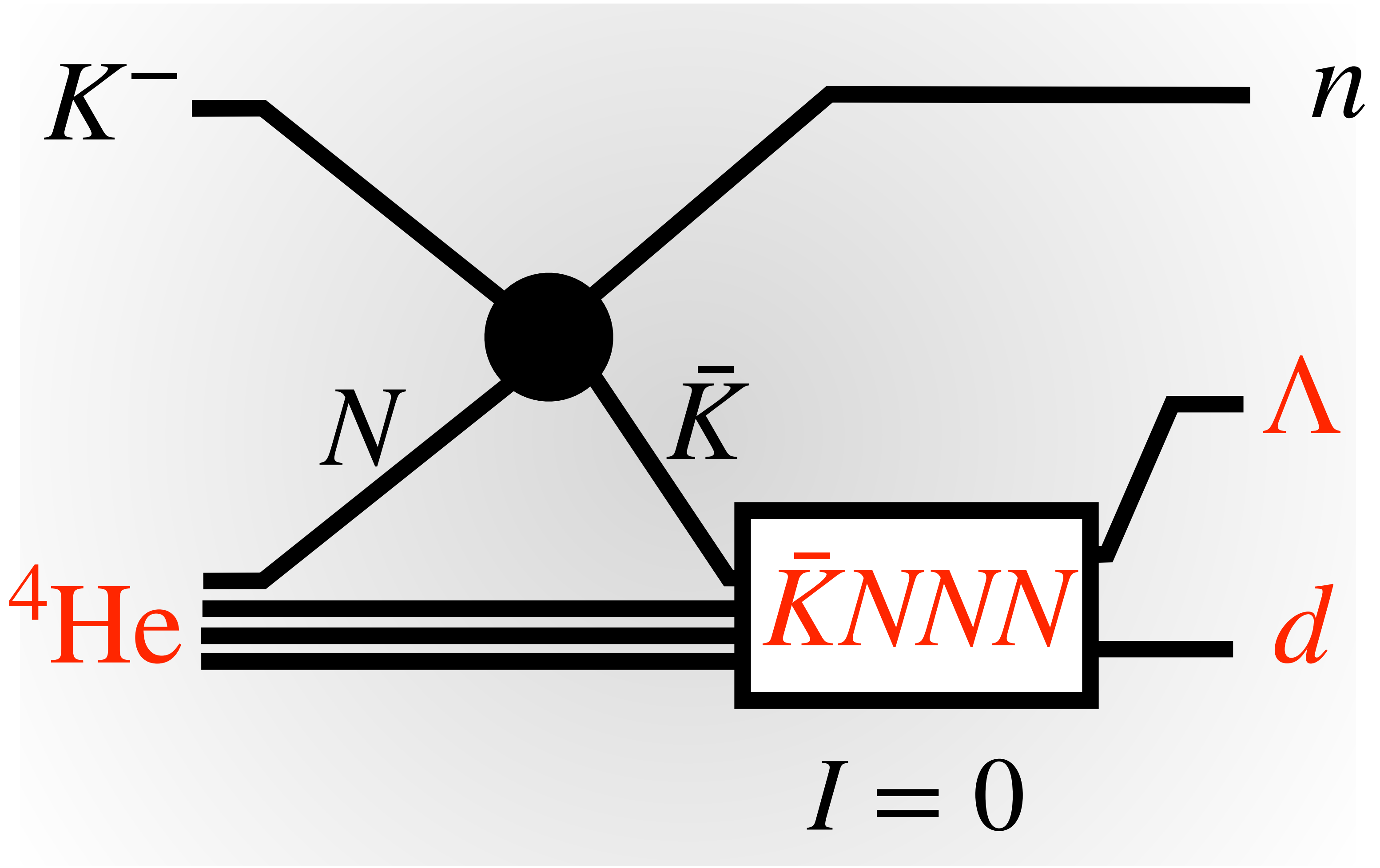
Mesonic decay of $\bar{K}NN$

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



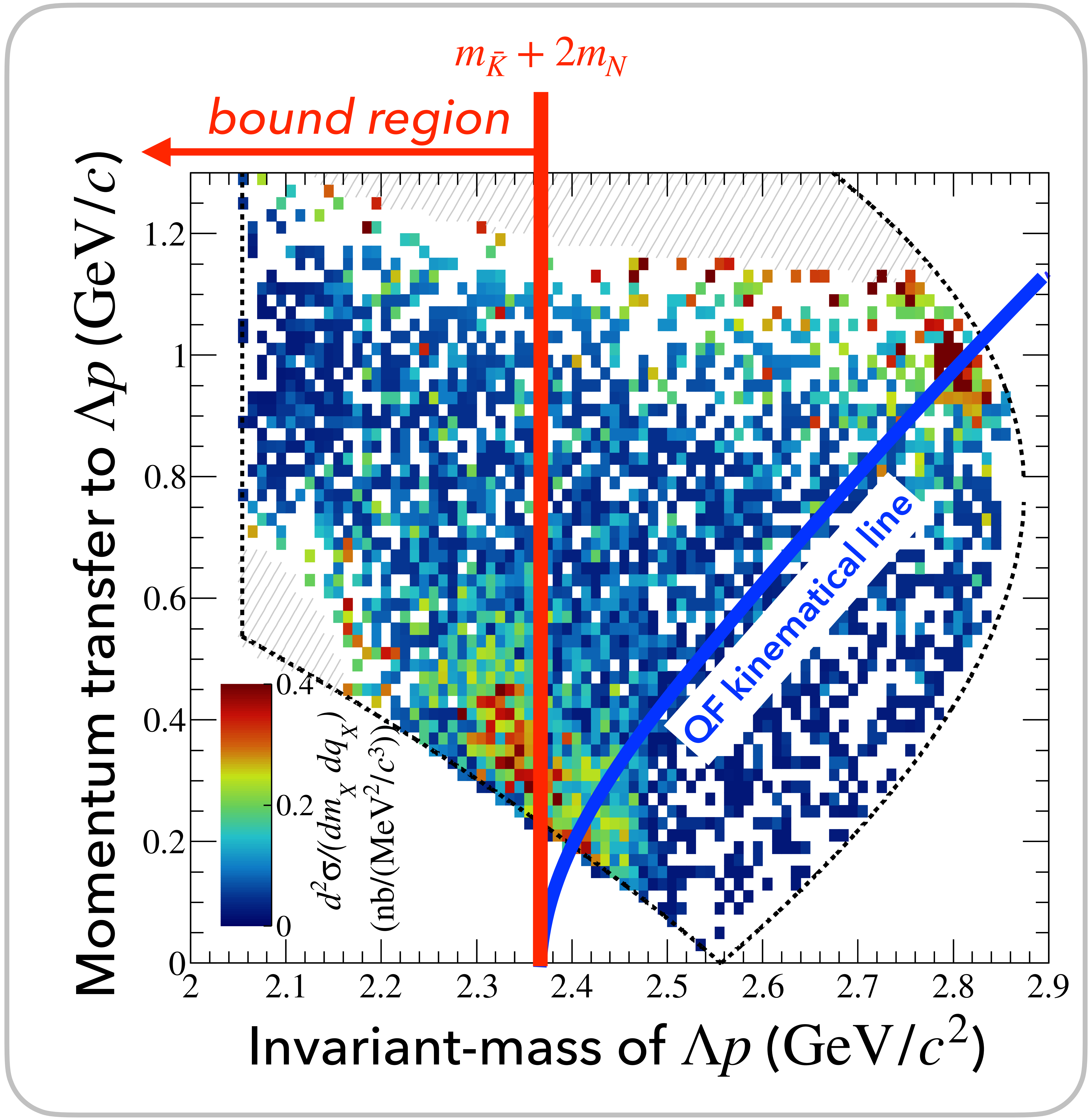
$\bar{K}NNN$ production

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

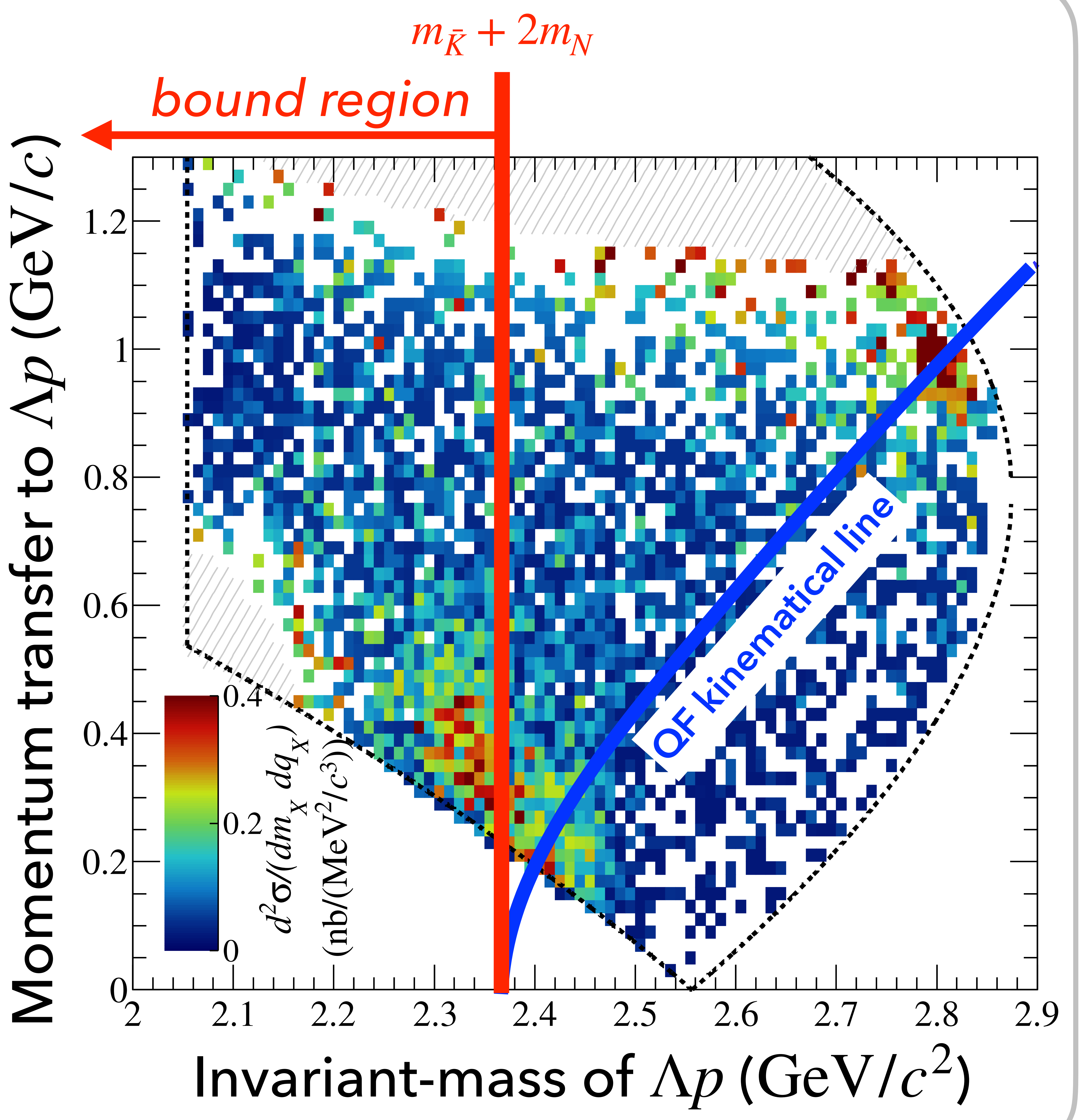


$\bar{K}NNN$ production

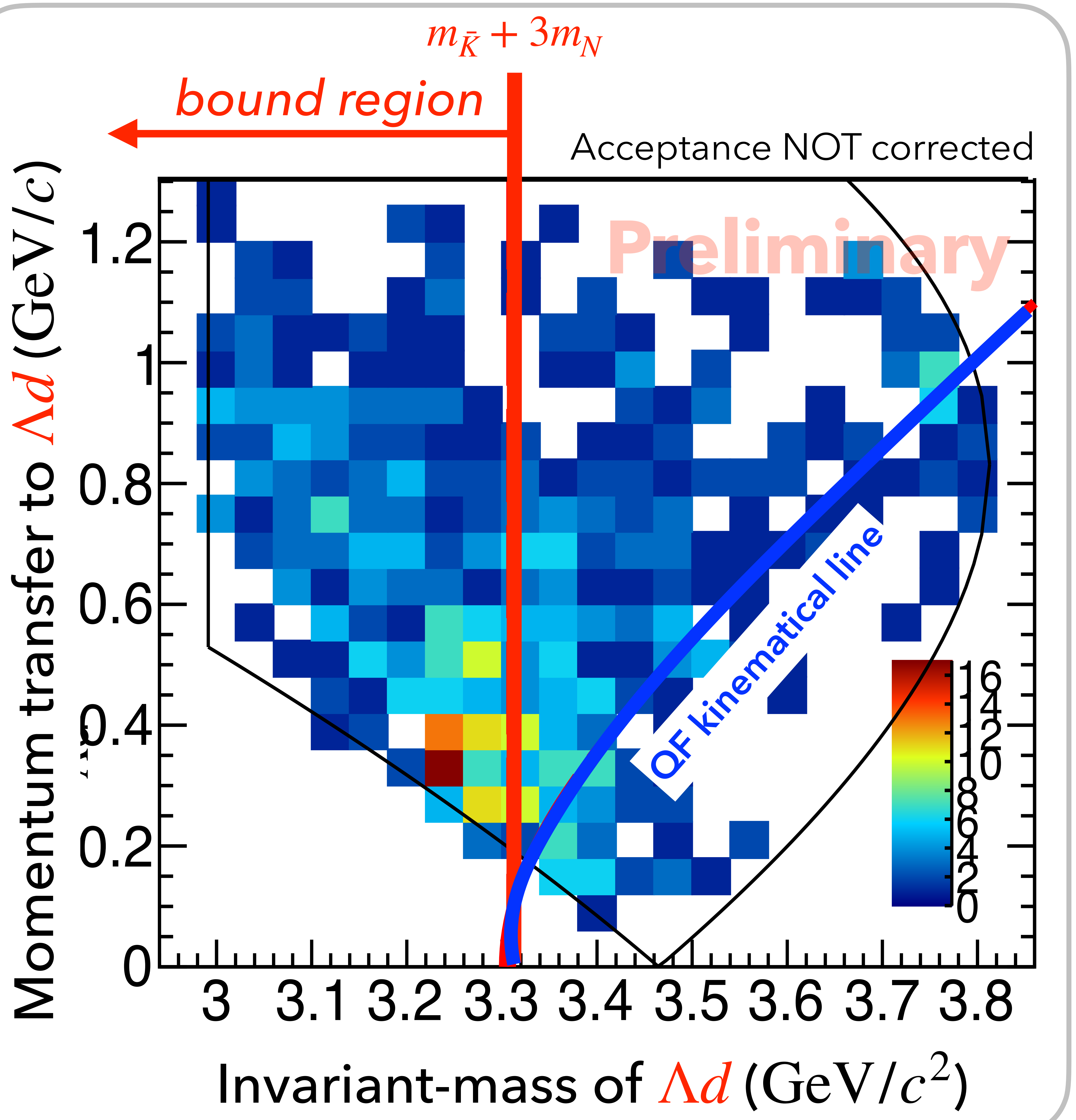
$K^{-}+{}^{3}\mathrm{He}\rightarrow\Lambda p+n$



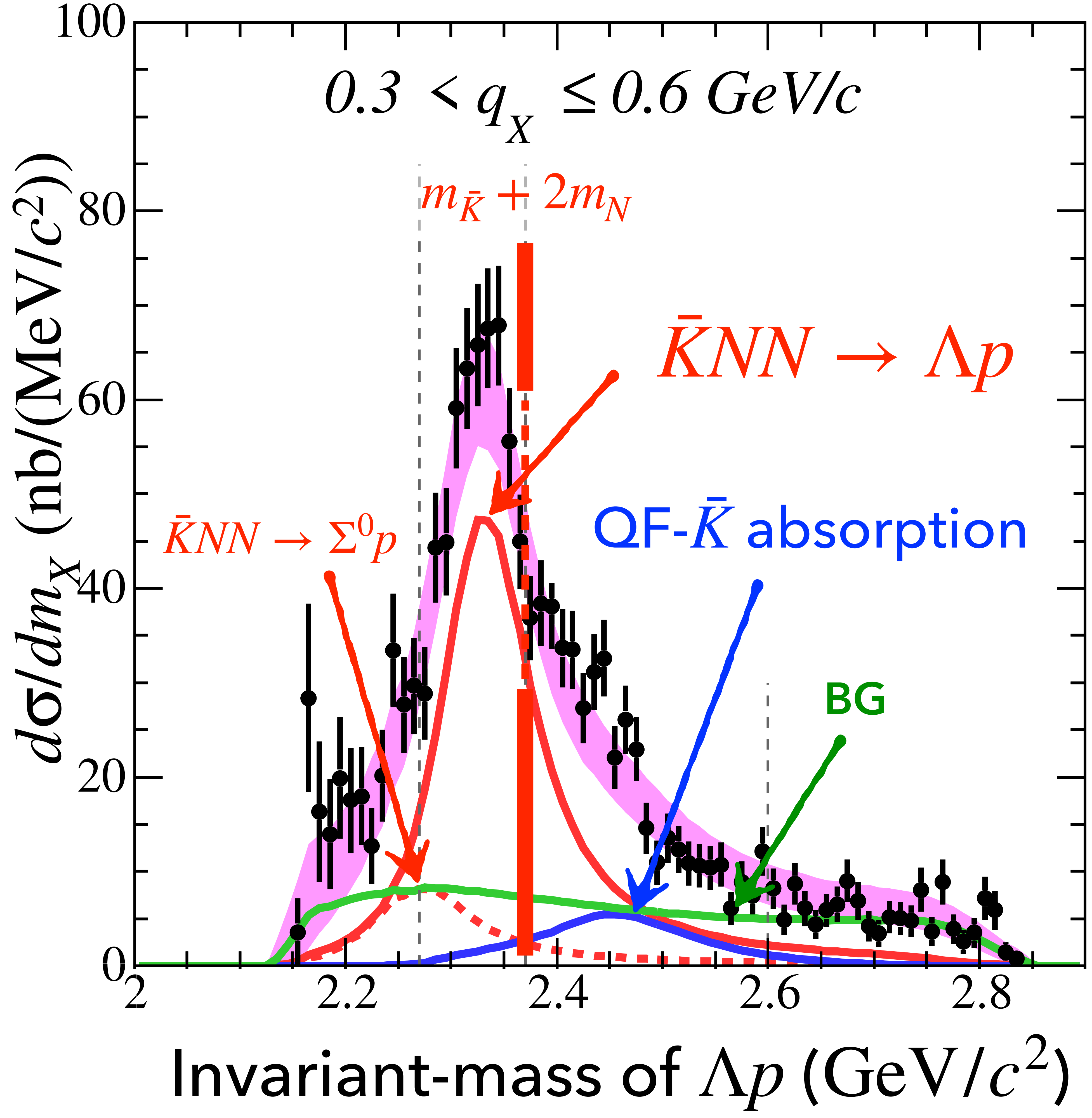
$K^- + {}^3\mathrm{He} \rightarrow \Lambda p + n$



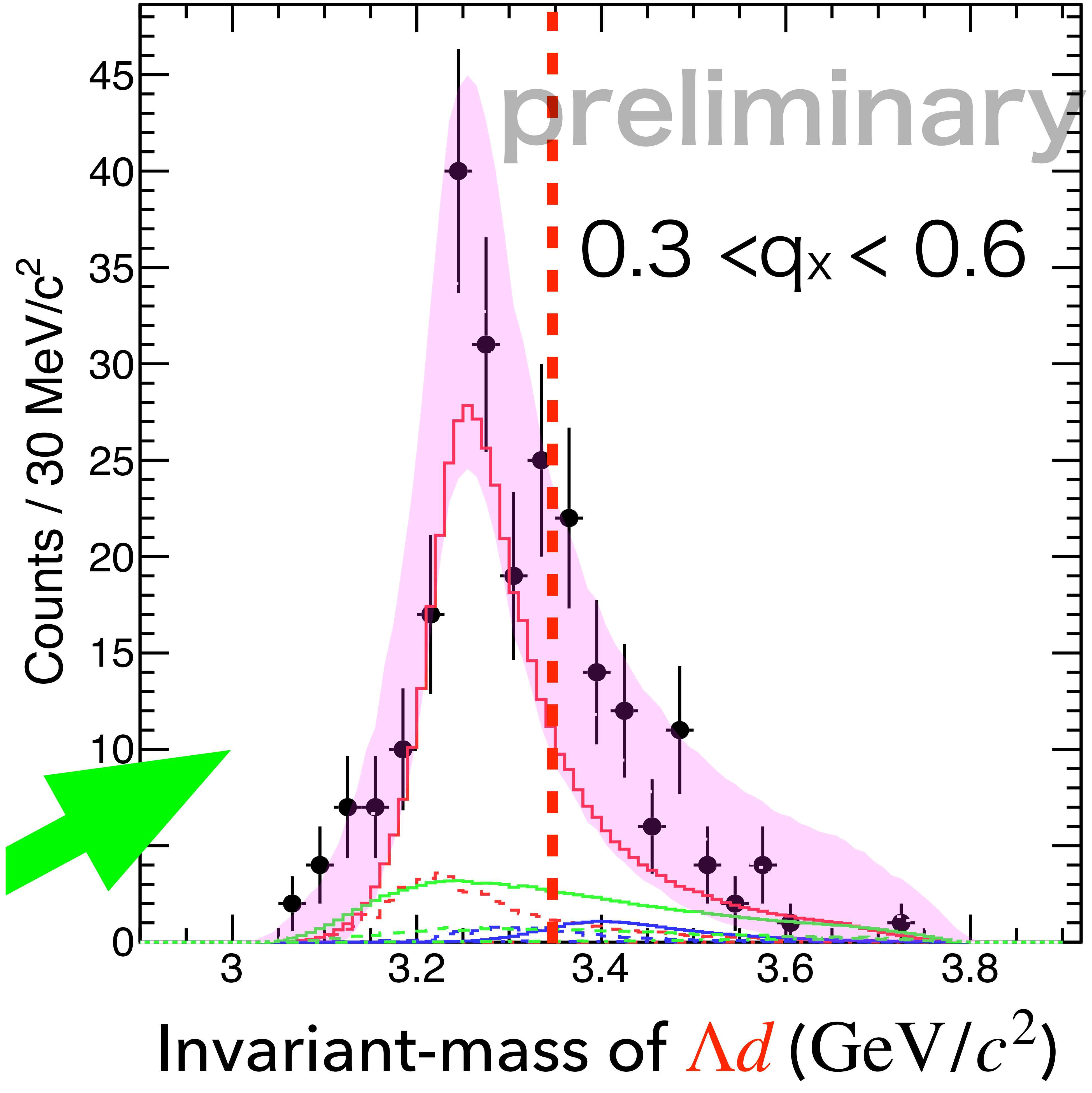
$K^- + {}^4\mathrm{He} \rightarrow \Lambda d + n$



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

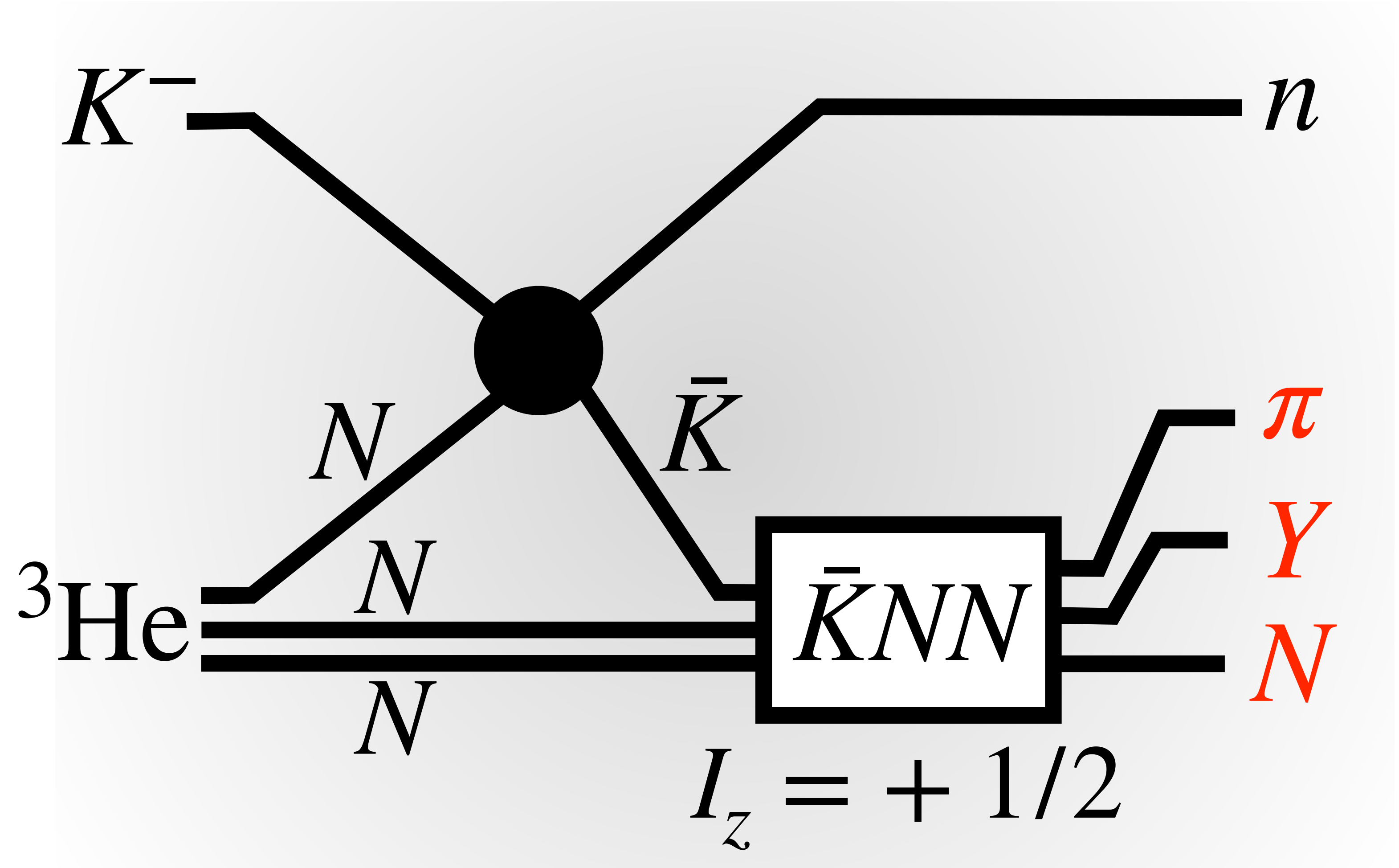


$K^- + {}^4\mathrm{He} \rightarrow \Lambda d + n$



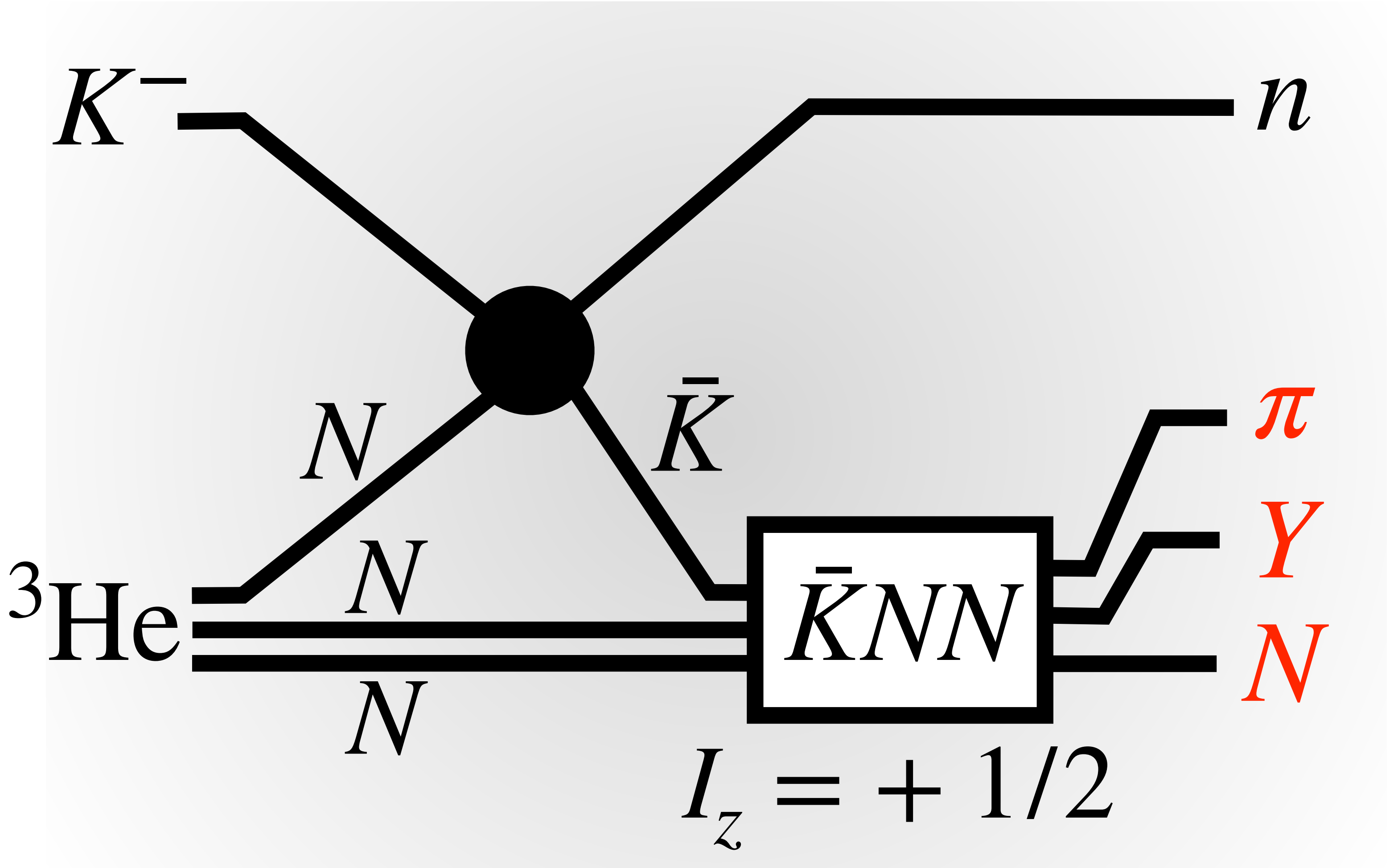
→ Peak observed in Λd invariant-mass could be signal of $\bar{K}NNN$.

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



Mesonic decay of $\bar{K}NN$

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



Mesonic decay of $\bar{K}NN$

Mesonic channels

$I_z = +1/2$

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

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

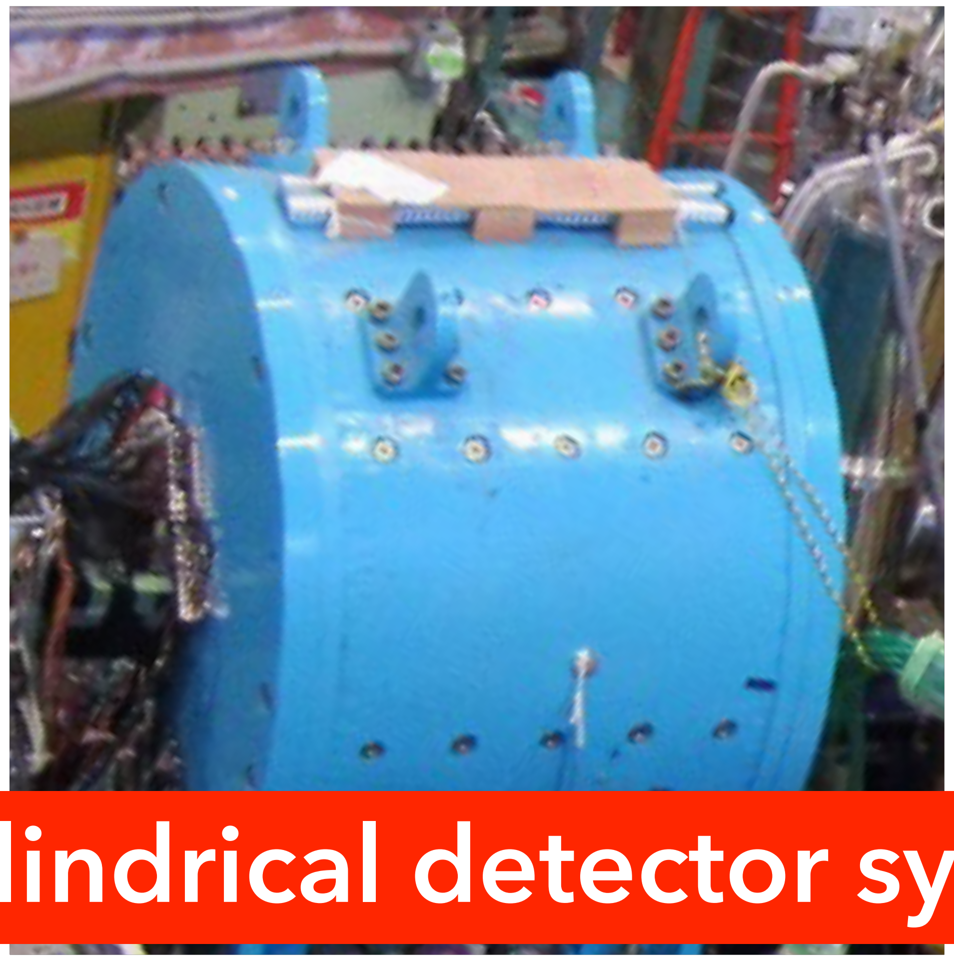
$\pi^{+}\Sigma^{-}p + n_{\mathrm{miss}}$

Non-mesonic

$I_z = +1/2$

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

Event selection for mesonic decay



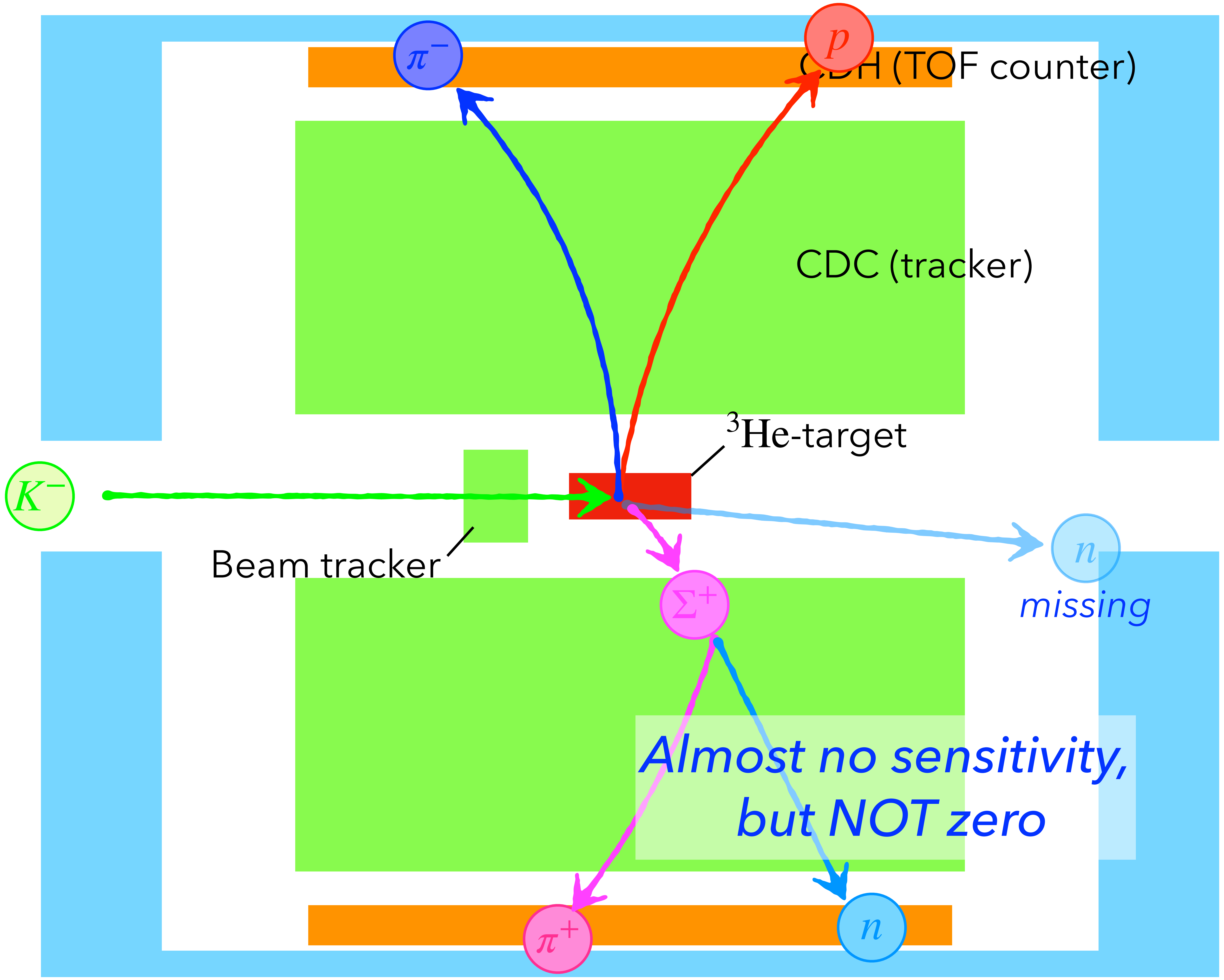
Cylindrical detector system

In the case of

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

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

Detected with CDS



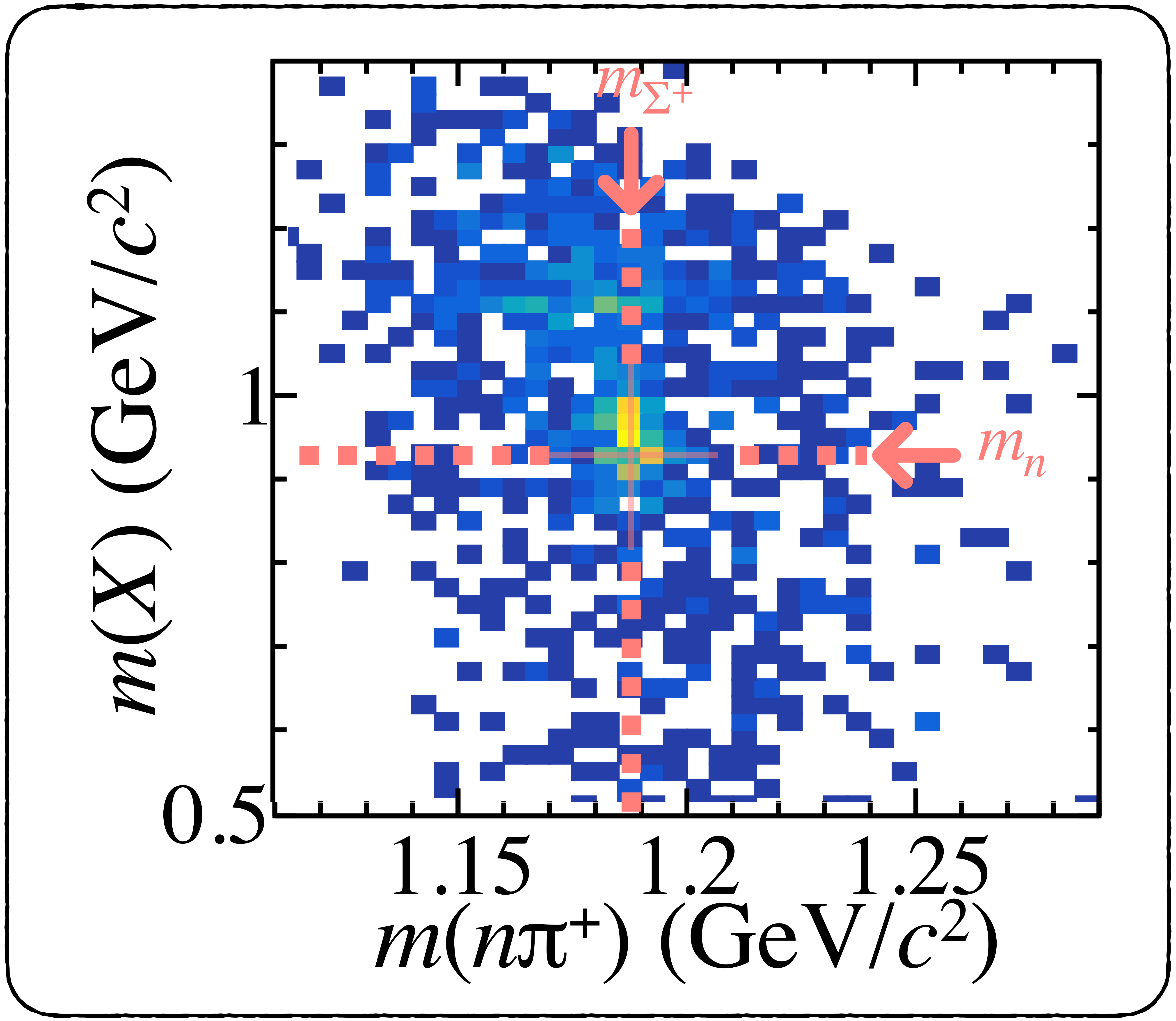
Event selection for mesonic decay

In the case of

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

$$\rightarrow \underbrace{\pi^-(\pi^+n)p}$$

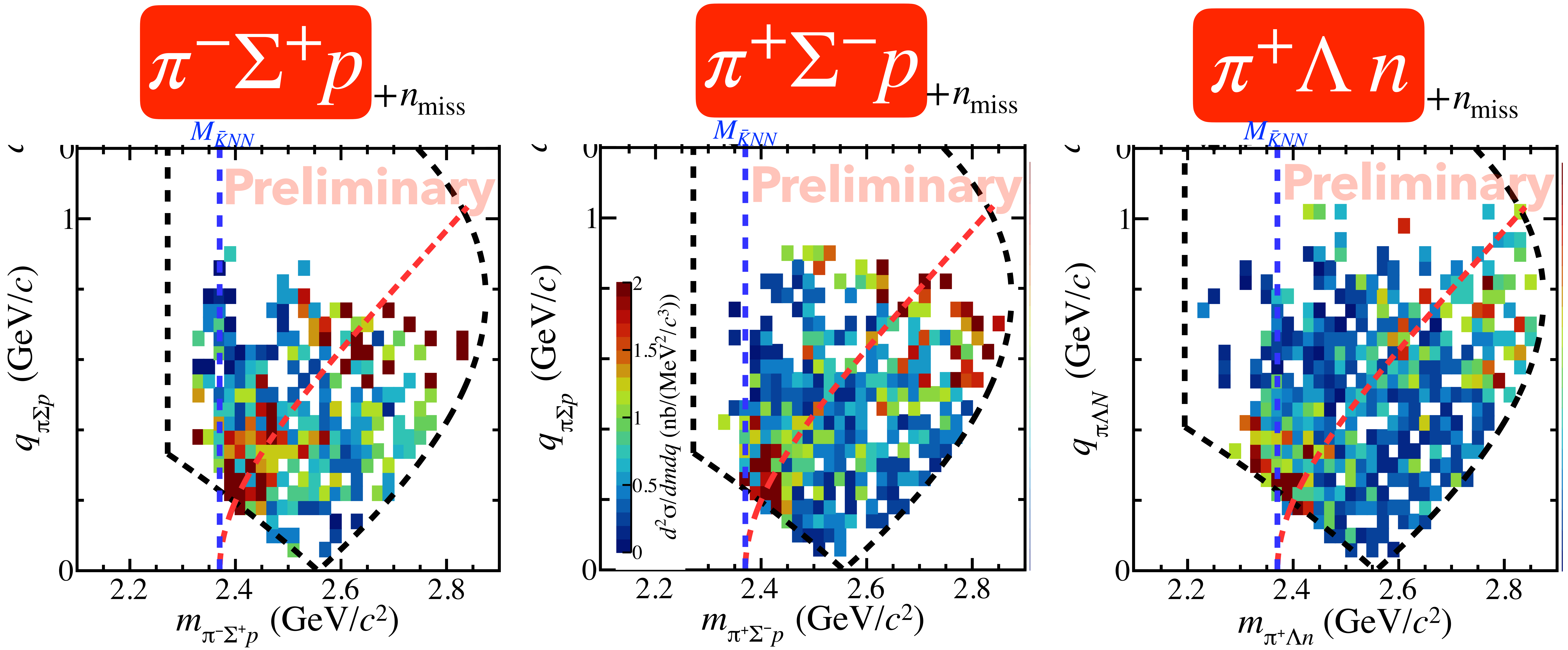
Detected with CDS



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

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

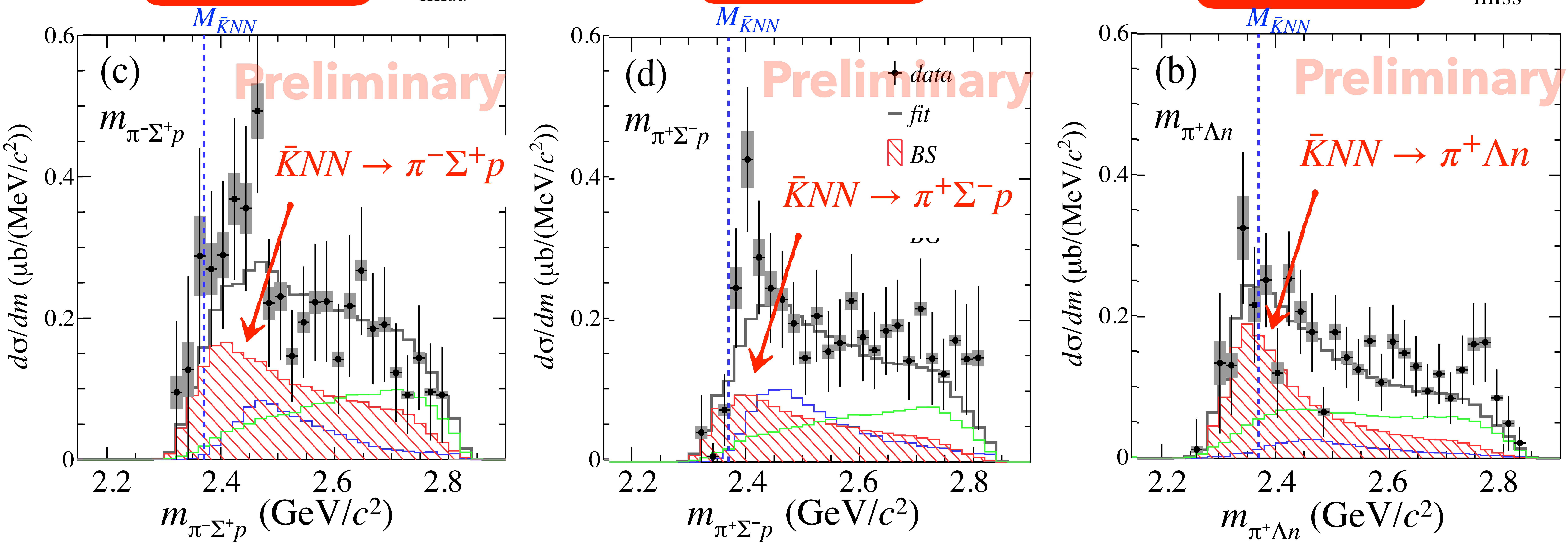
$\pi^+\Lambda\, n$ $+n_{\text{miss}}$



Similar to Λp $+n_{miss}$

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

$\pi^-\Sigma^+p + n_{miss}$ | $\pi^+\Sigma^-p + n_{miss}$ | $\pi^+\Lambda n + n_{miss}$



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

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

Remaining questions

Is the observed resonance really what we expected?

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

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

Remaining questions

Is the observed resonance really what we expected?

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

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

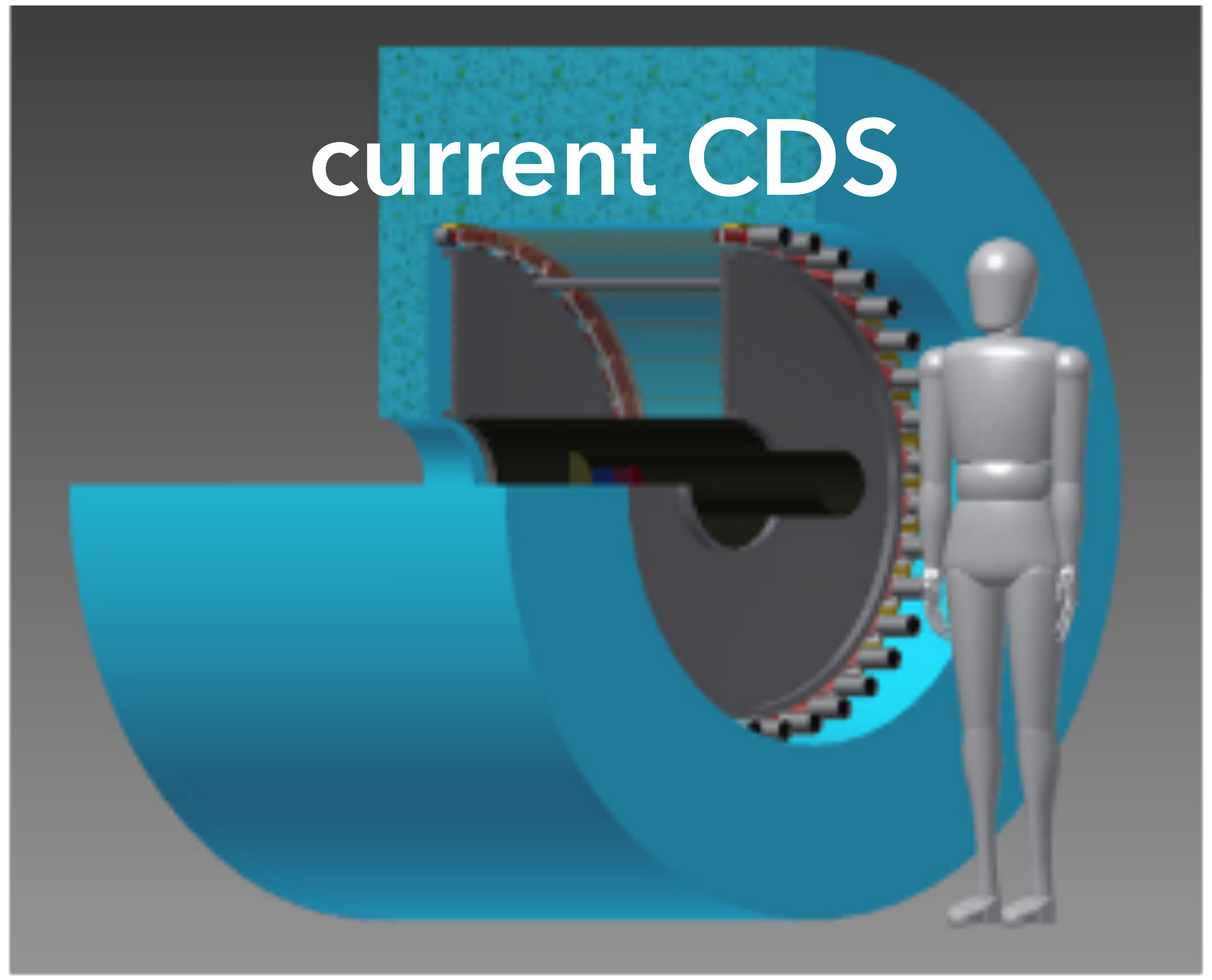
↓

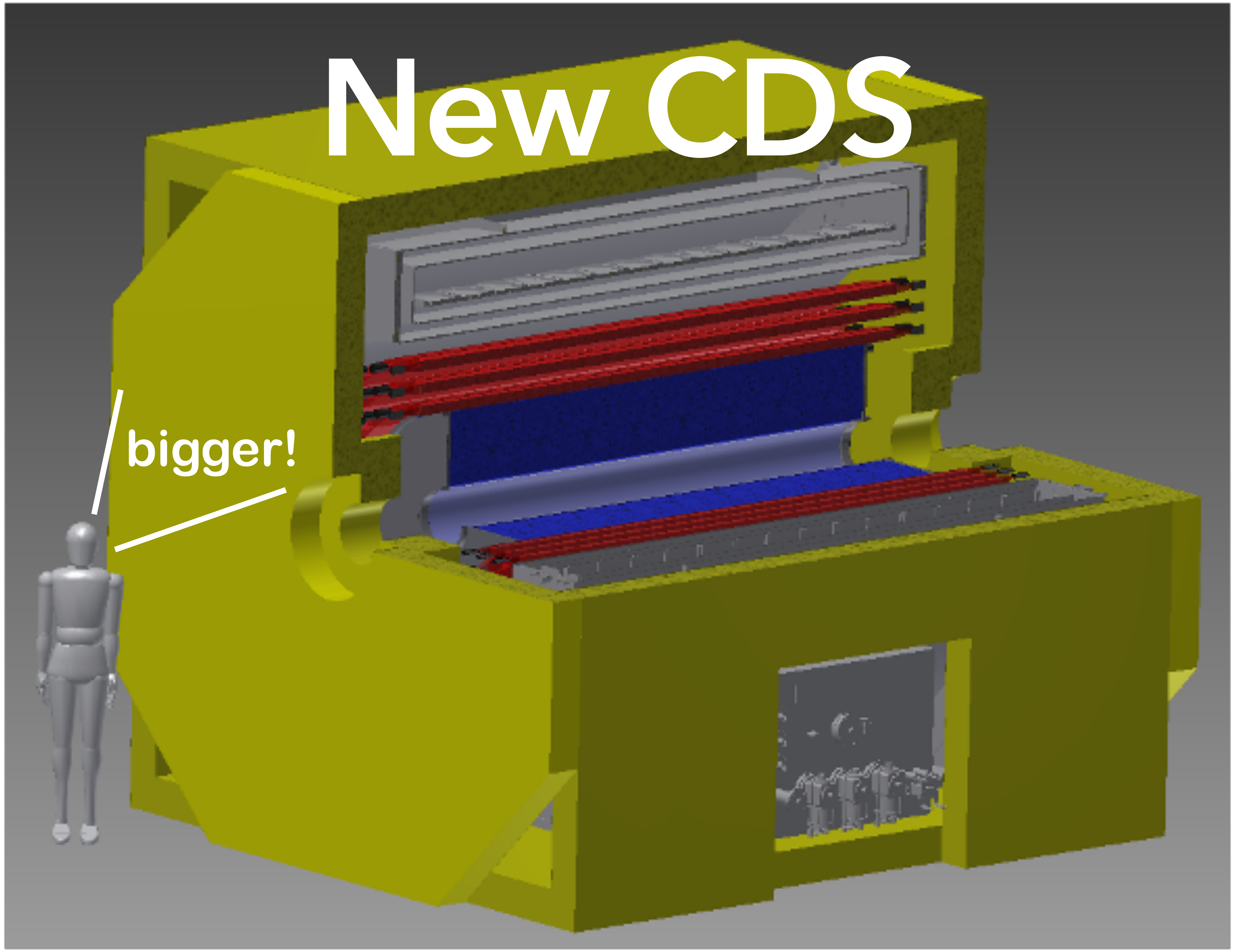
We need further systematic measurements
to answer the questions & to robustly confirm $\bar{K}$-nuclei.

Precise study for $\bar{K}NN$

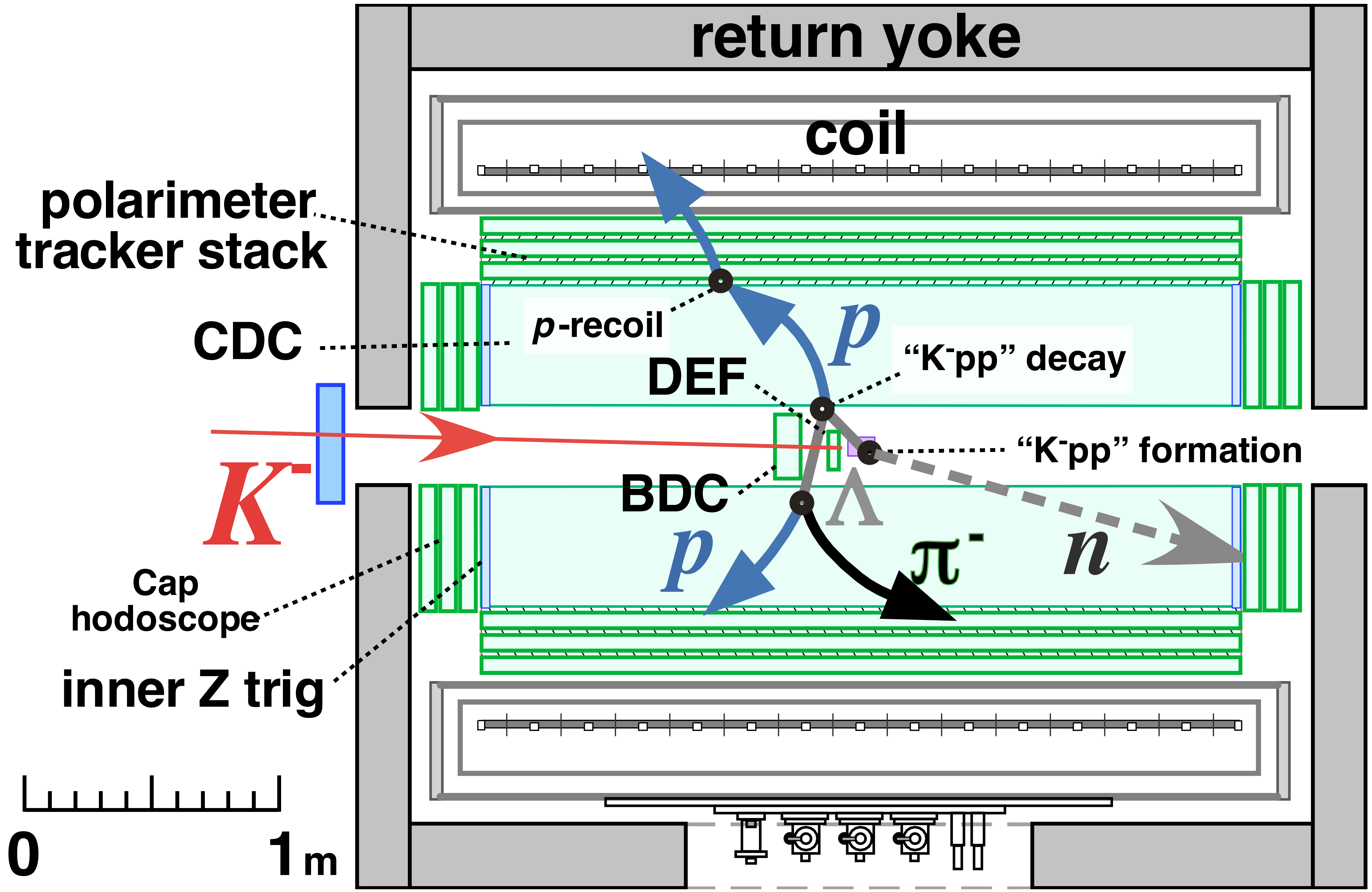
Search for heavier $\bar{K}$-nuclei

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 $\bar{K}NN$

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

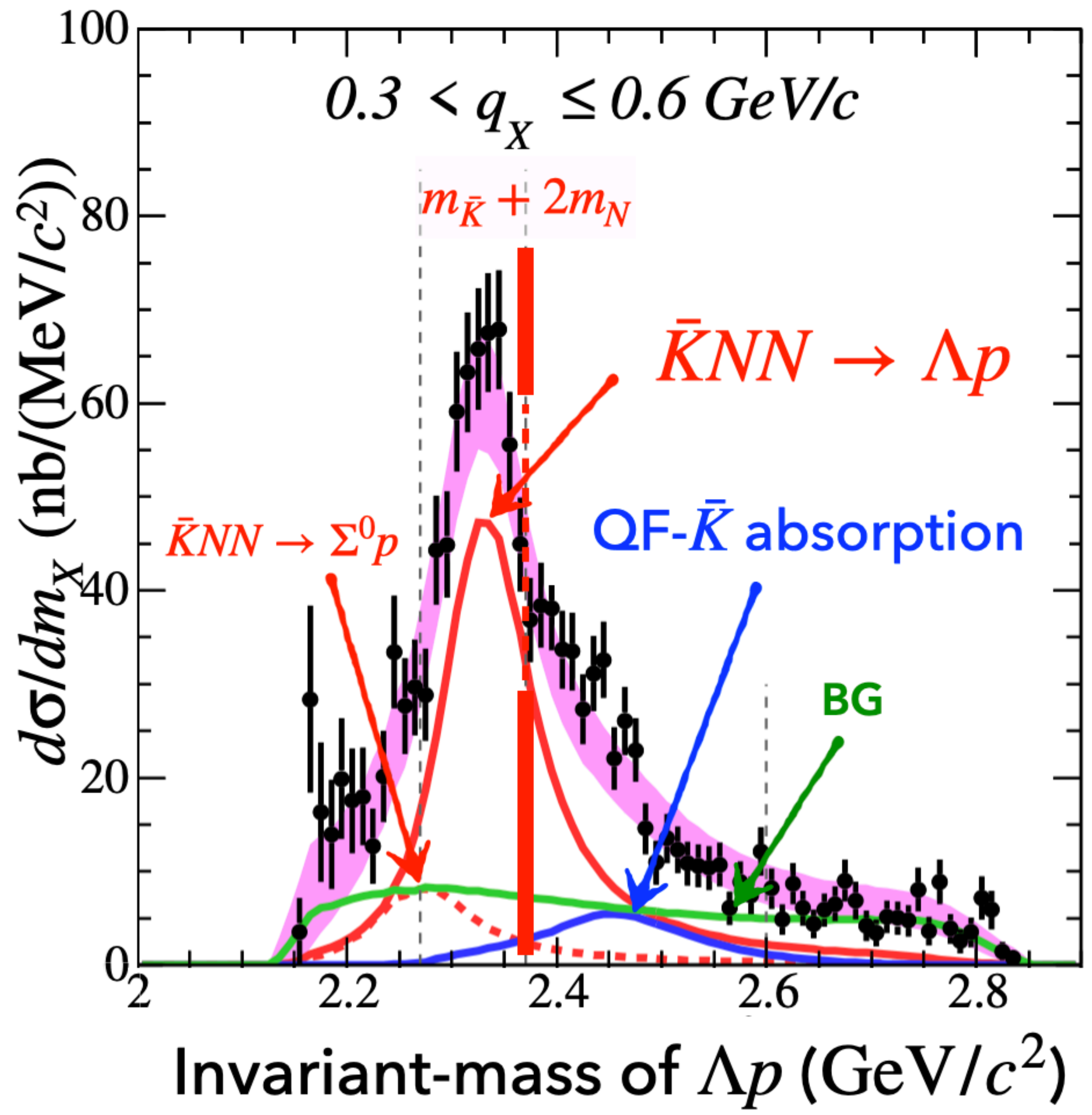
Expected large B.E. & high density

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

K^--α $\bar{K}^0$-α

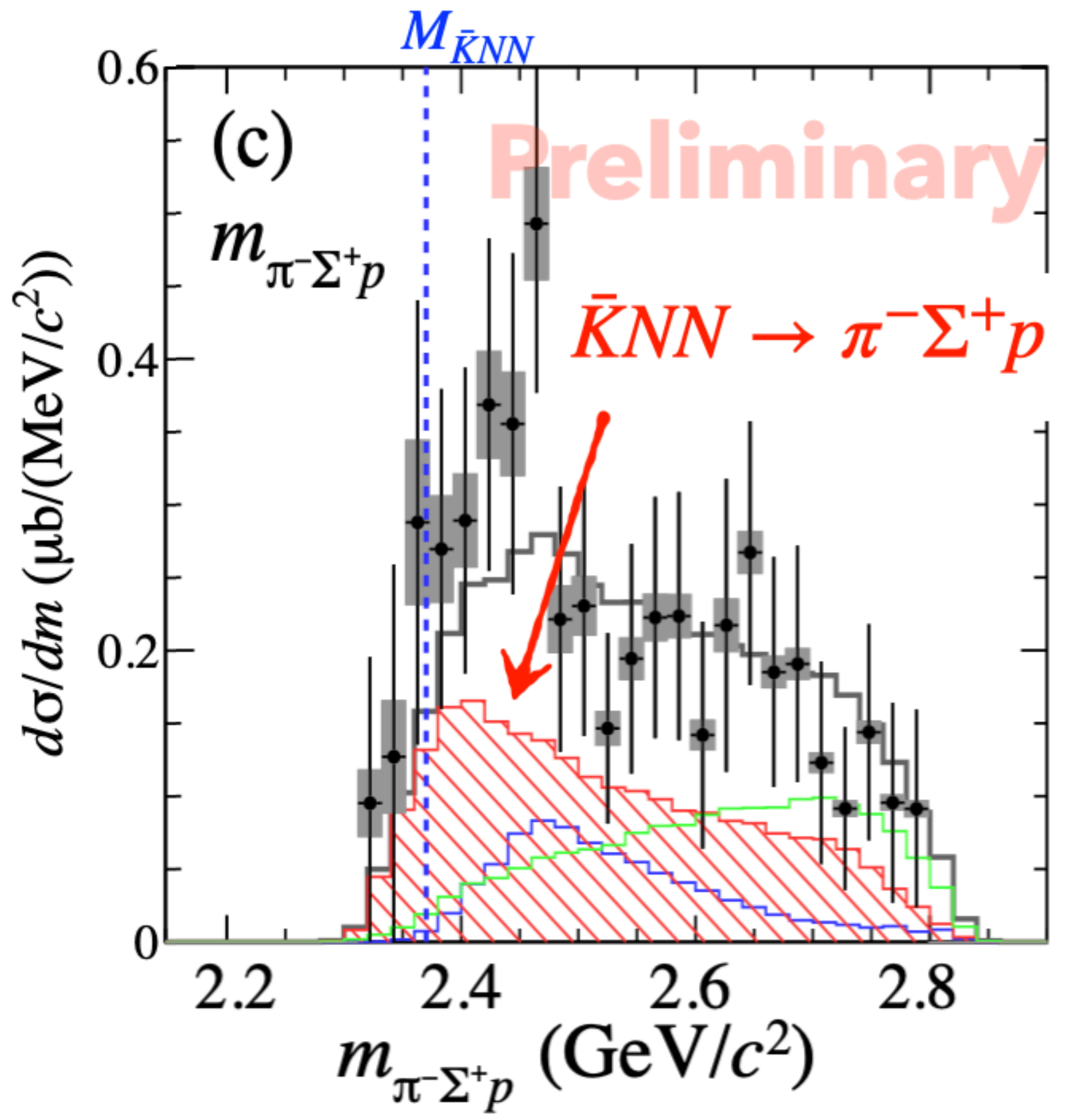
Summary

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



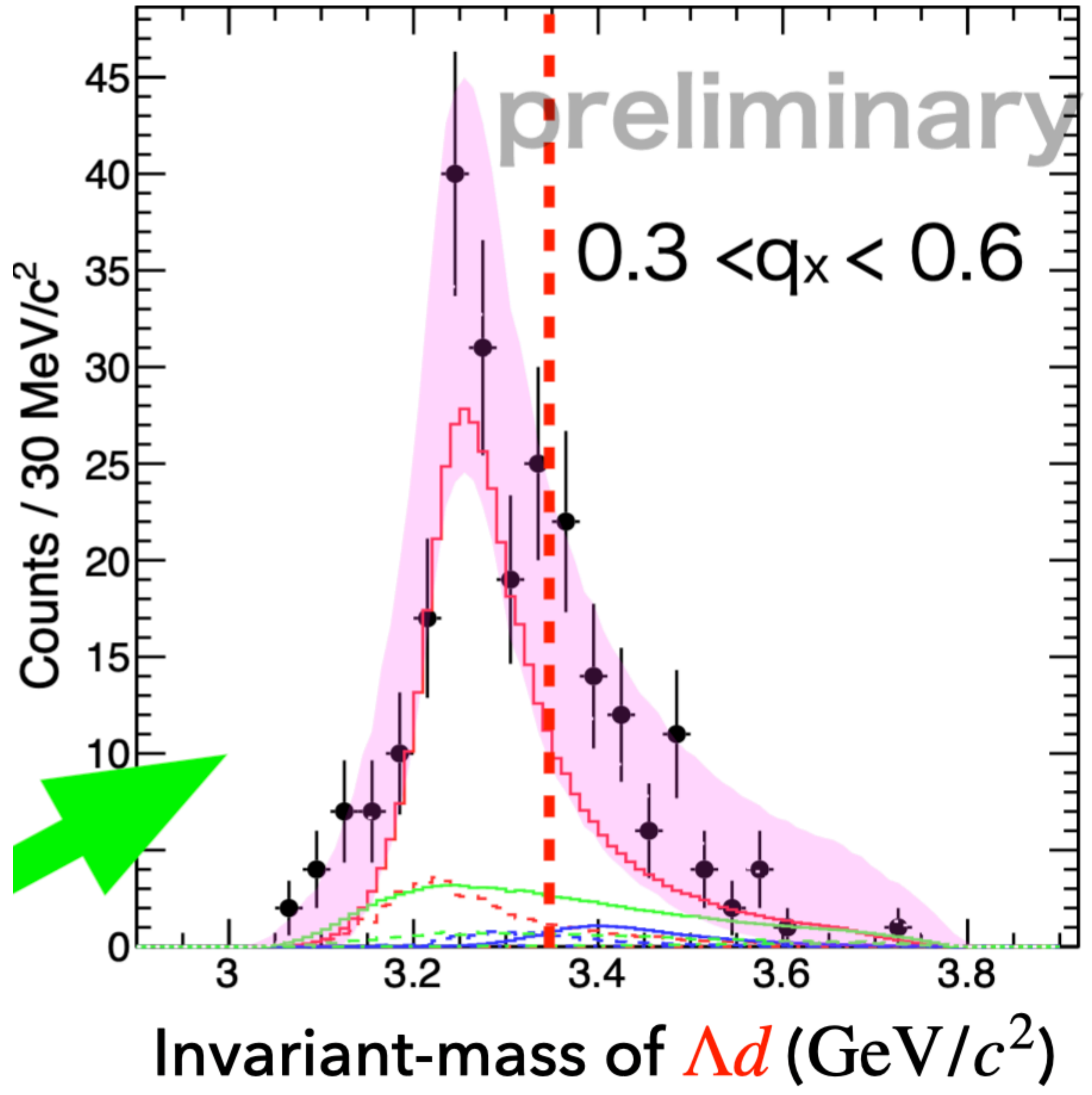
Signal of $\bar{K}NN$

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



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

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



Signal of $\bar{K}NNN$

New experiments will (hopefully) start in 2026.

Thank you for your attention!

= Collaboration =

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