Experimental study of $\bar{K}NN$ and future experiments for kaonic nuclei

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for the J-PARC E15 collaboration

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$\bar{K}N$ 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 state with $I_{\bar{K}N} = 0$

$\Lambda(1405)$

$\bar{K}$-nuclei

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

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

Ground state

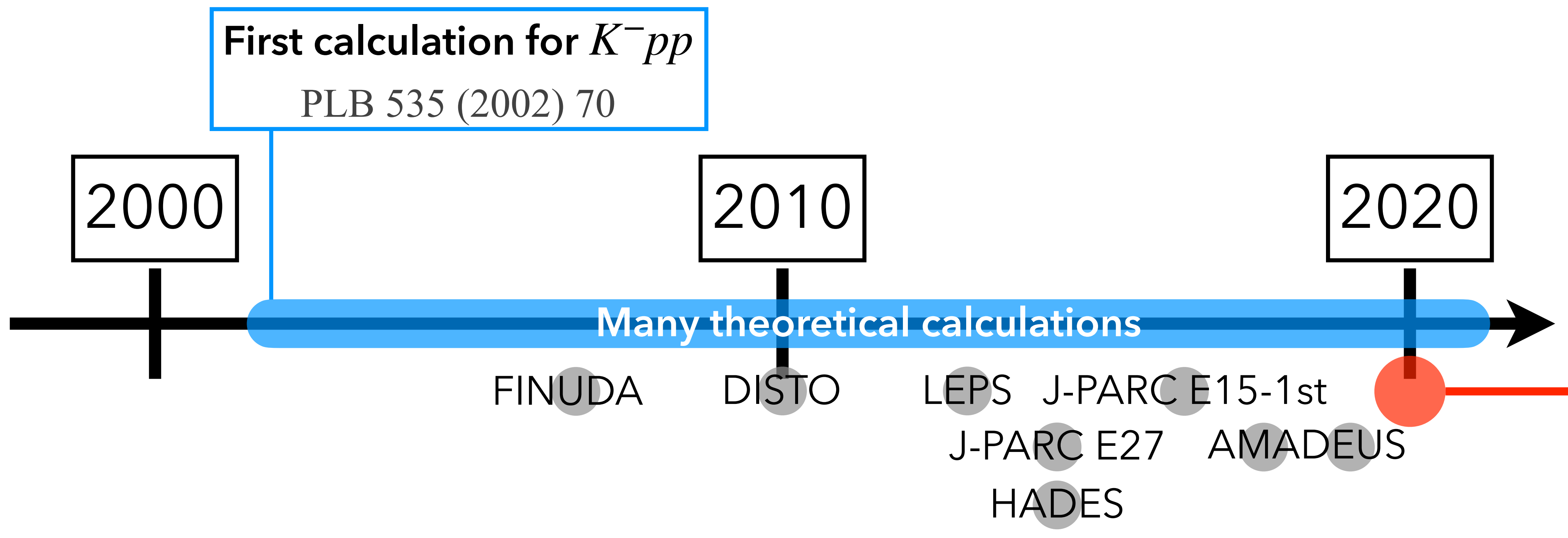
No theoretical study doubts the existence of $\bar{K}NN$,

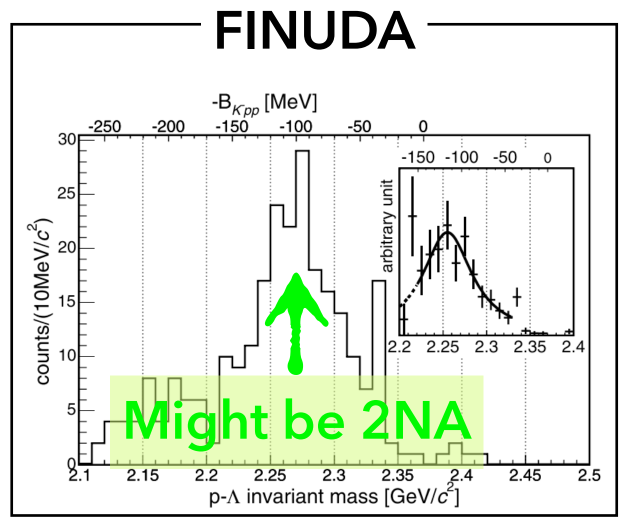
but predicted BE & Γ highly depend on model.

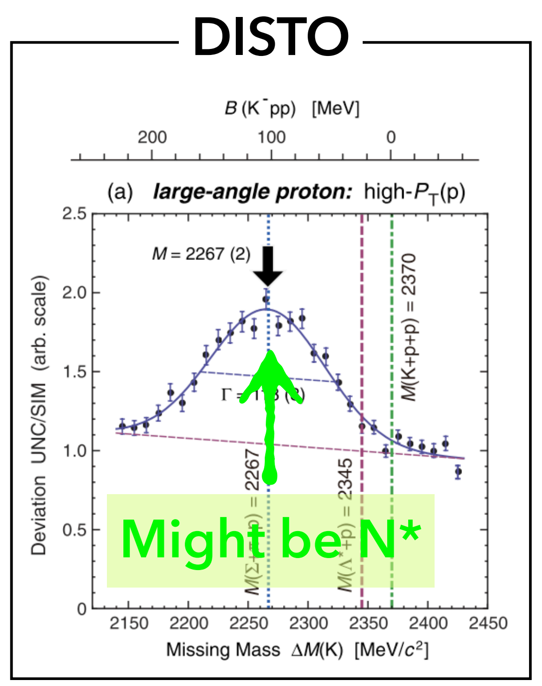
BE = 9 – 95 MeV $\quad$ Γ = 16 – 110 MeV

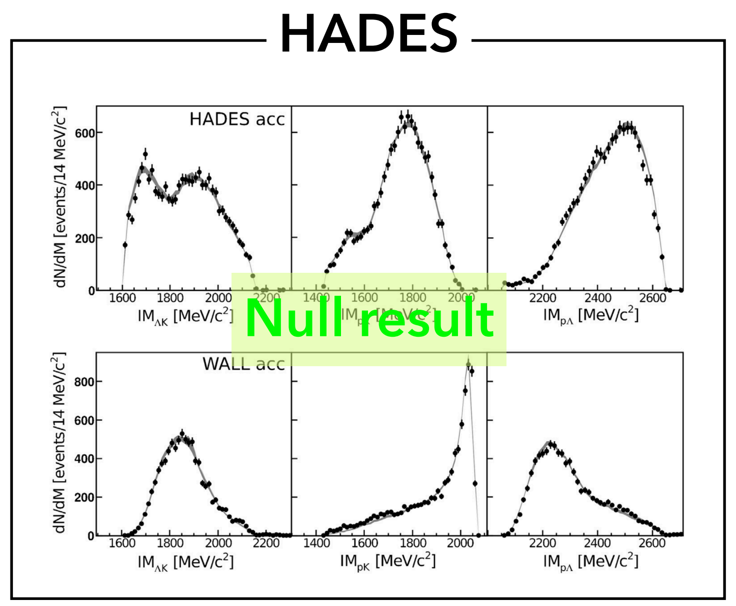
Prog.Part.Nucl.Phys. 112 (2020) 103770

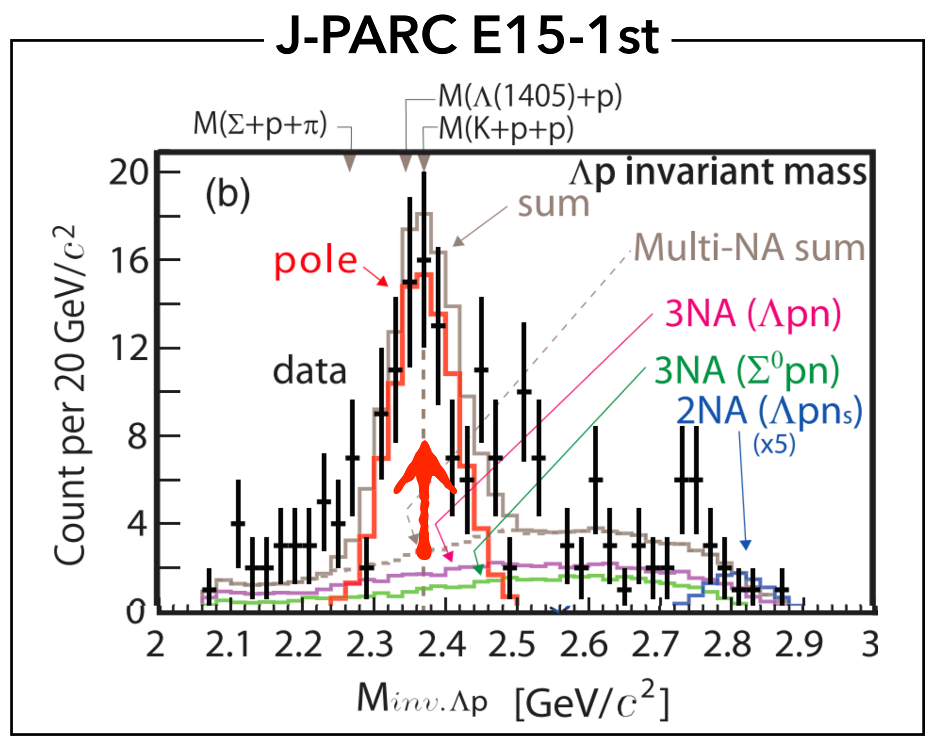
Studies for $\bar{K}NN$ so far

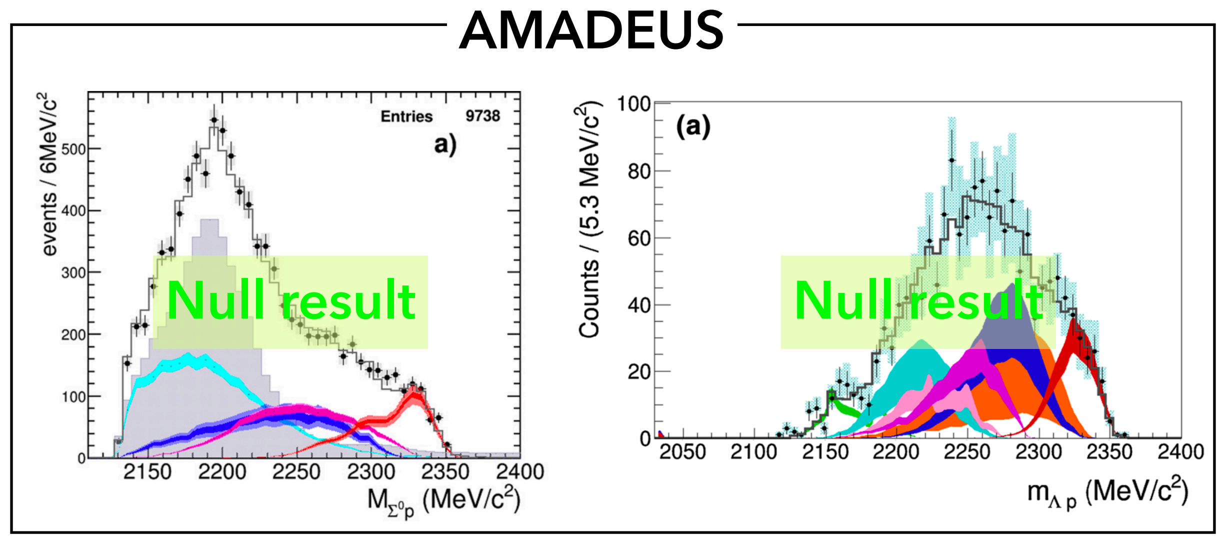


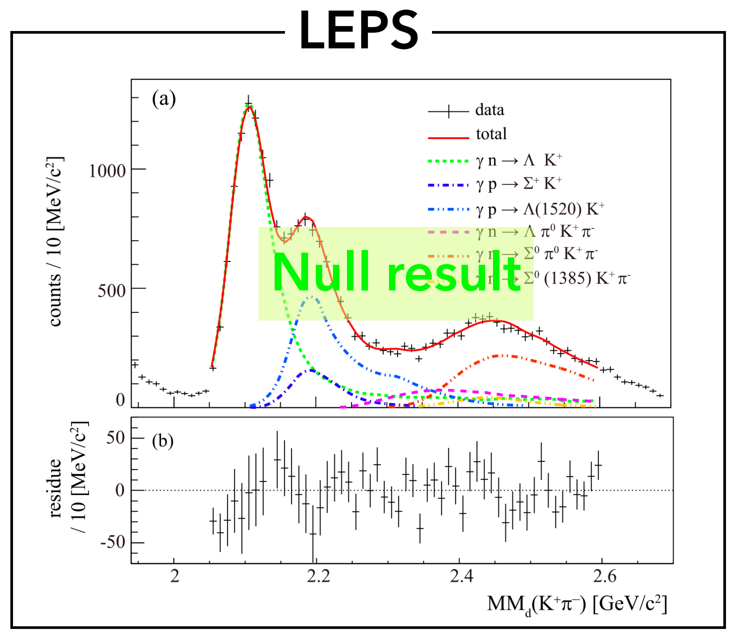


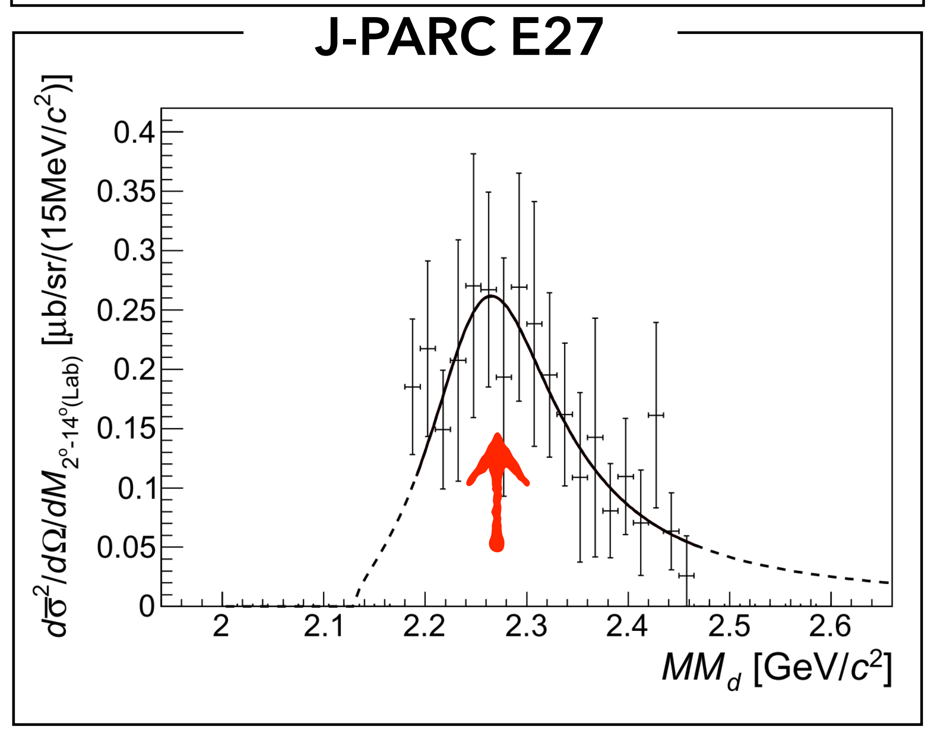












PHYSICAL REVIEW C **102**, 044002 (2020)

Observation of a $\overline{K}NN$ bound state in the $^3He(K^-, \Lambda p)n$ reaction

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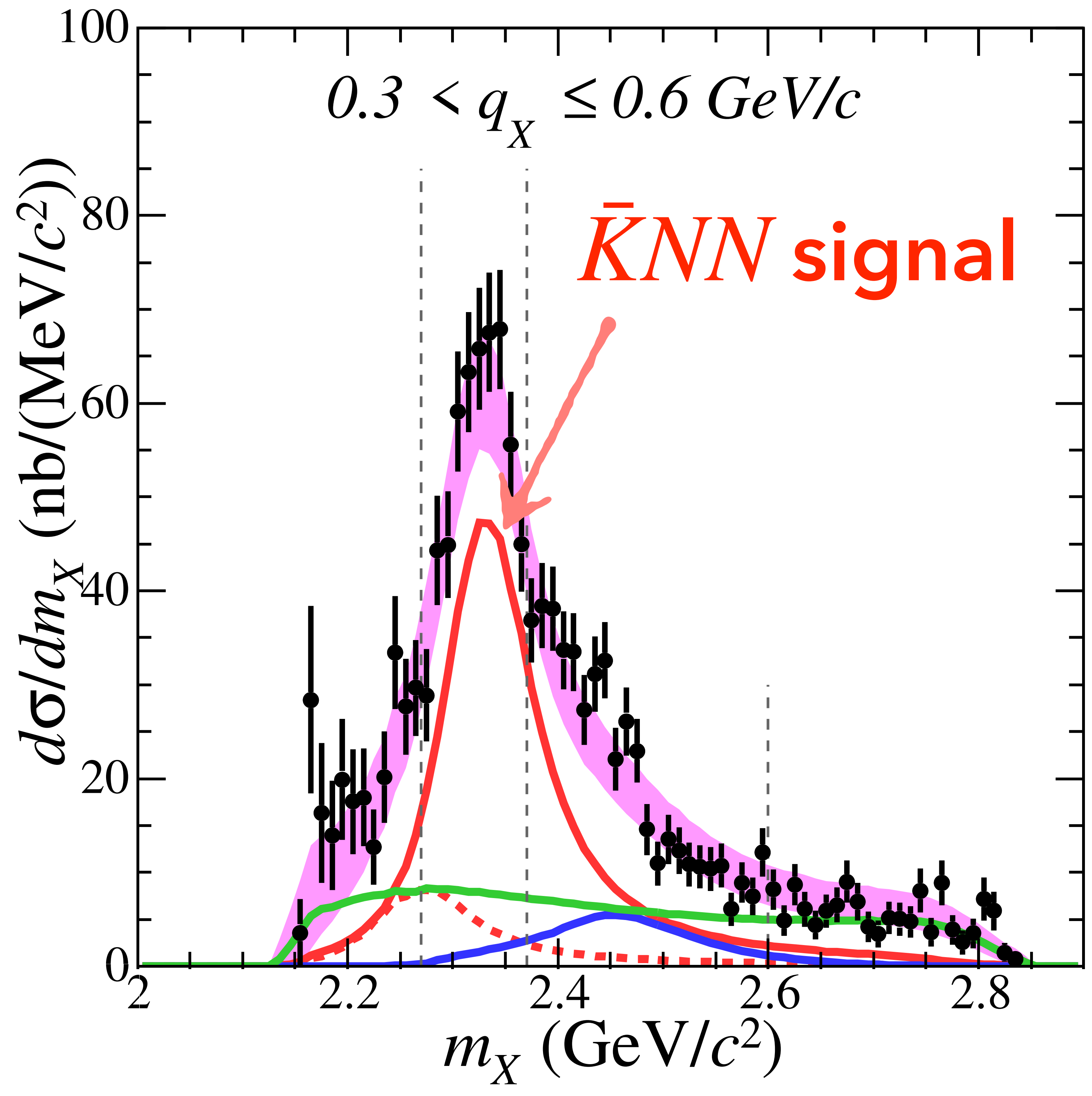
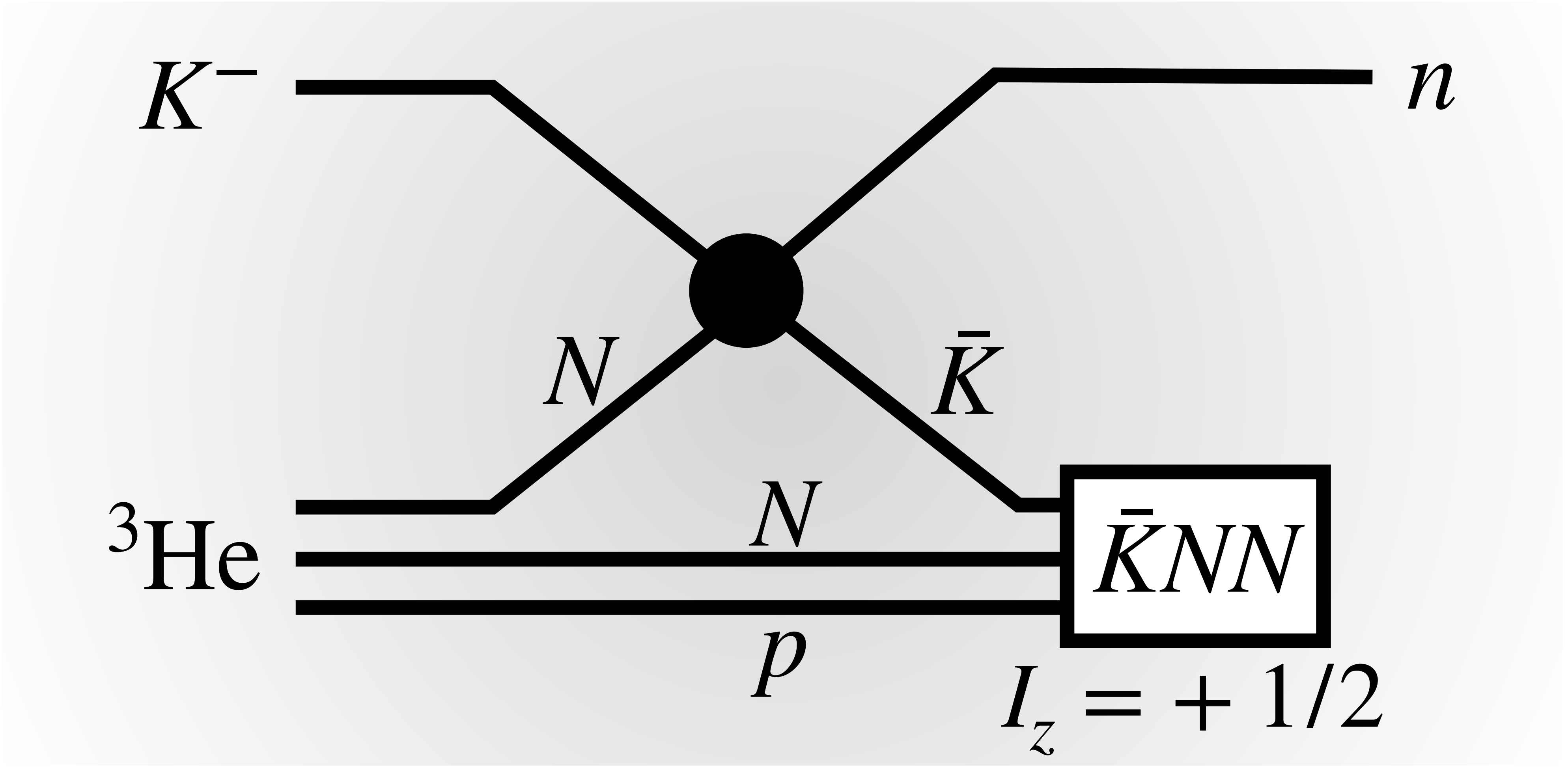
(J-PARC E15 Collaboration)



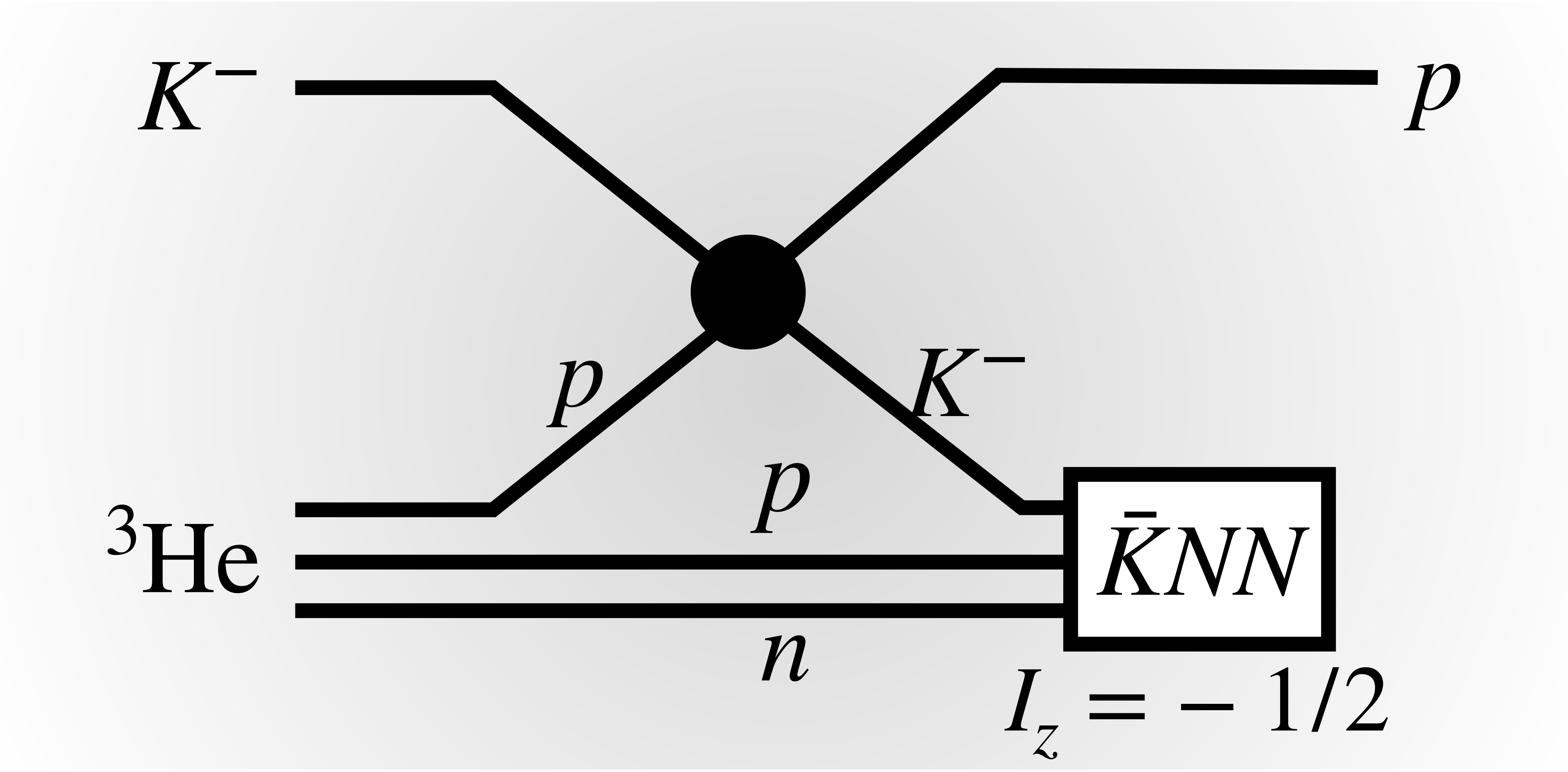
$\bar{K}NN$ production by $^3\mathrm{He}(K^-, N)$ reaction

with (K^-, n) *reaction*



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

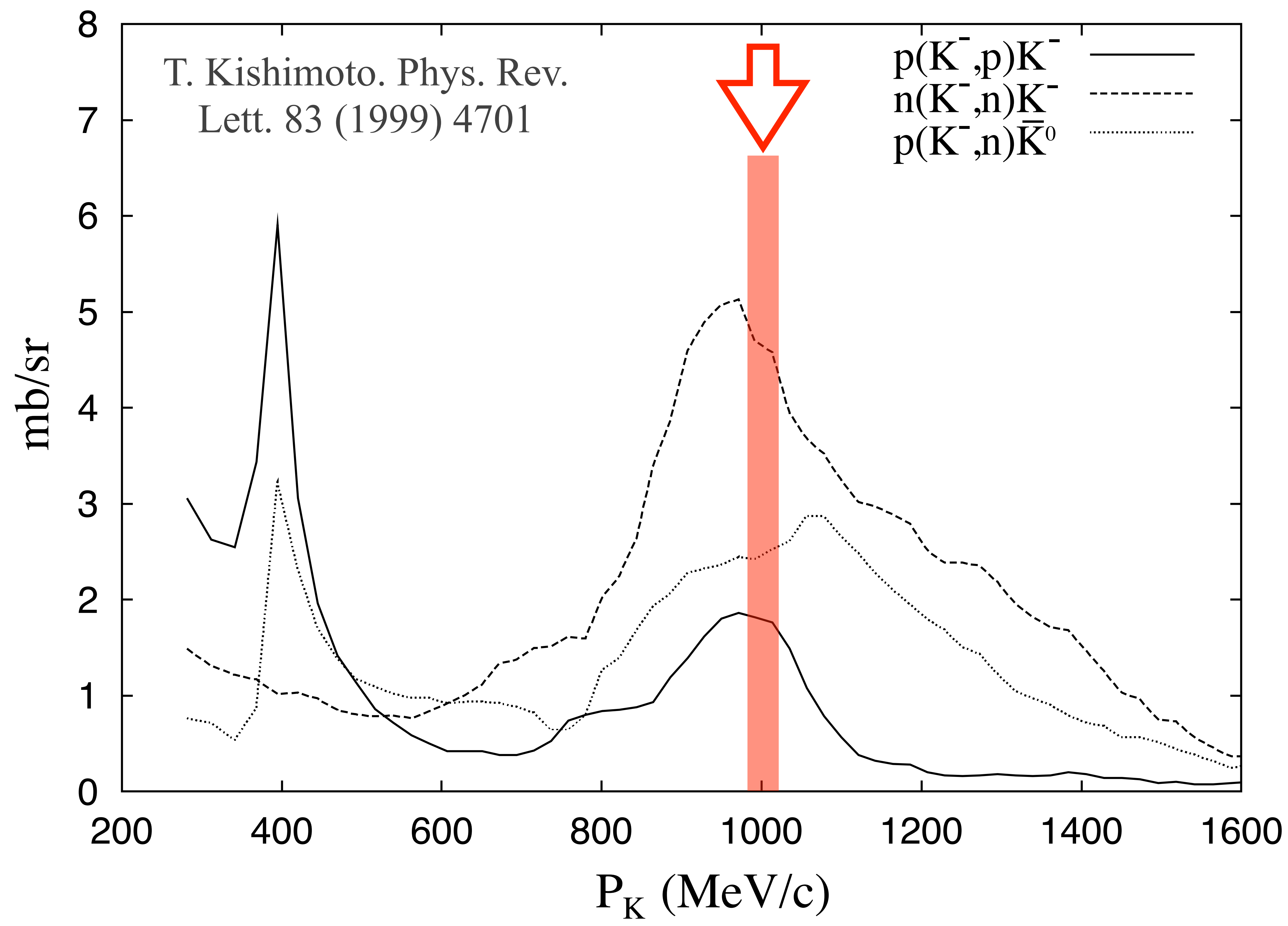
with (K^-, p) *reaction*



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

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

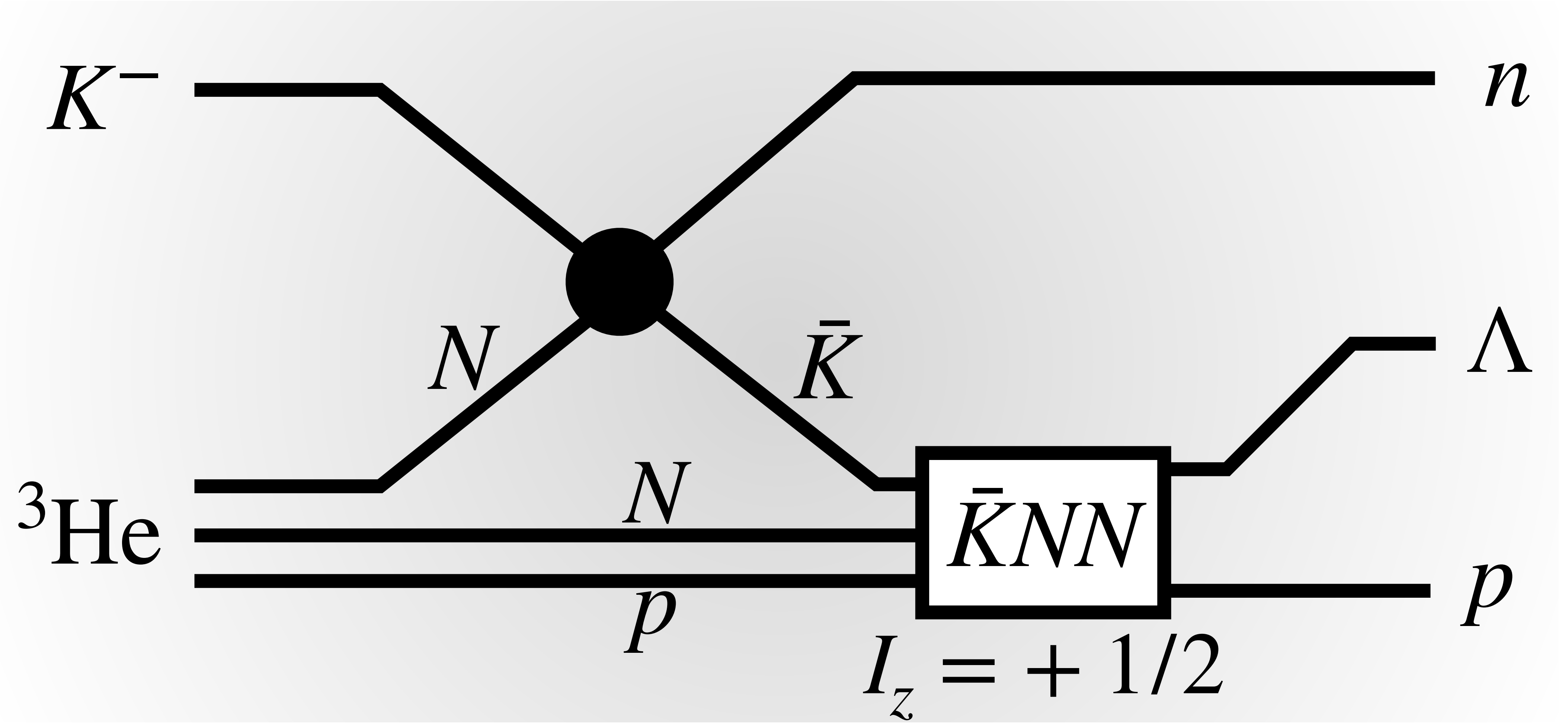
(K^{-}, N) elementary cross sections @ $\theta_N = 0^\circ$



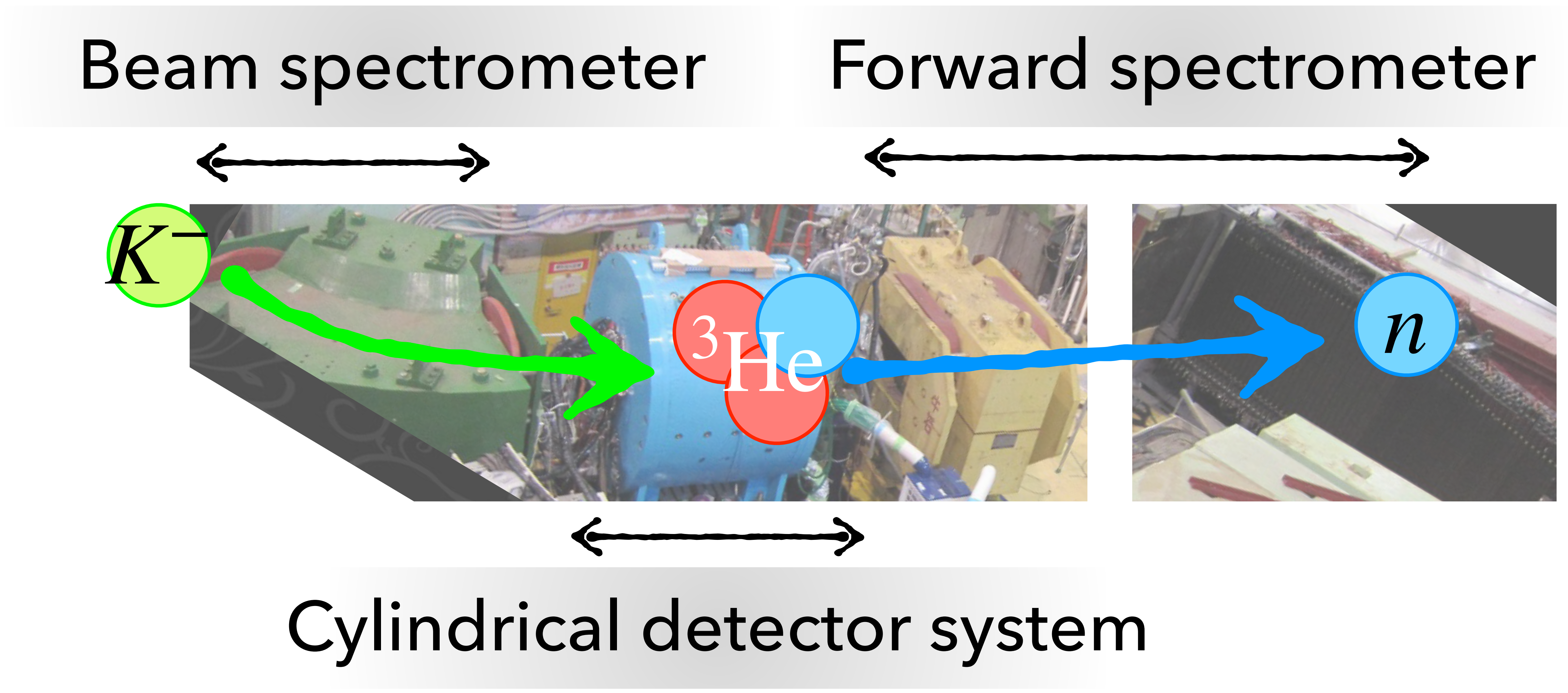
$p_{K^-} = 1\ \mathrm{GeV}/c$ is chosen to maximize CS of (K^{-}, N)

J-PARC E15

Production reaction



Detector system

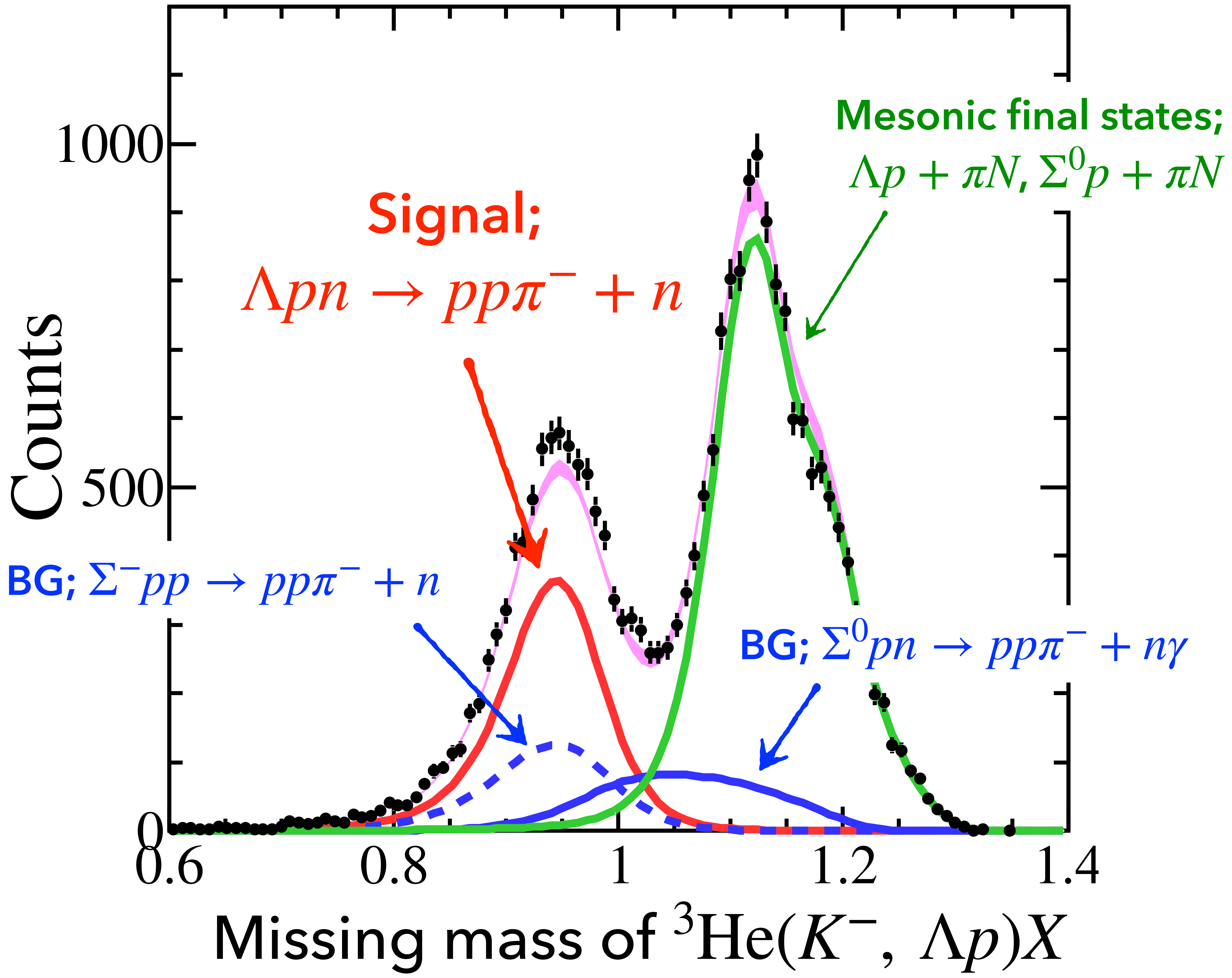


exclusive Invariant-mass spectroscopy

To select Λpn final state

To measure Λp invariant-mass & momentum transfer

Event selection for Λpn final state



signal

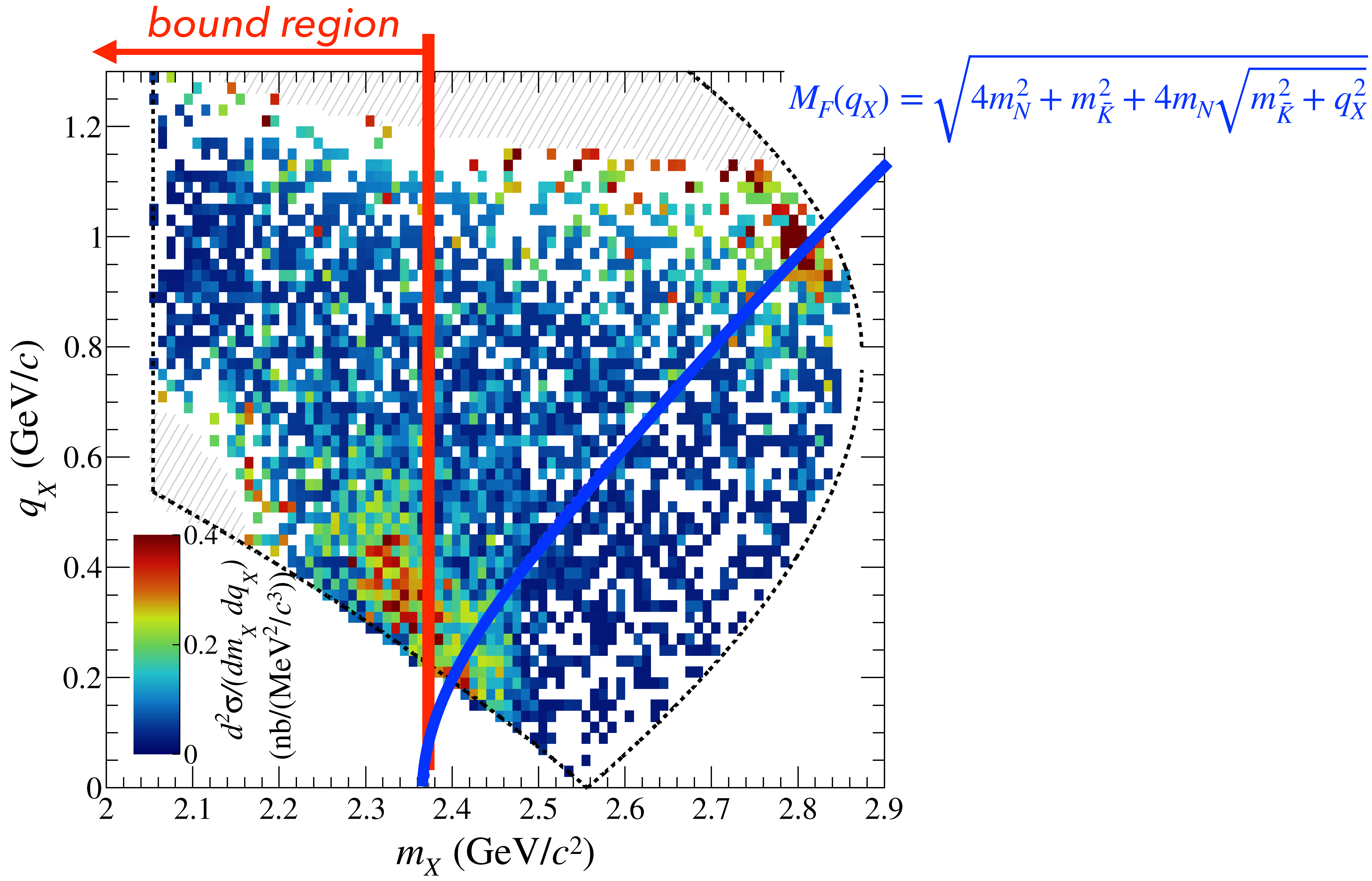
$\Lambda pn; \sim 80\,\%$

background

$\Sigma^0 pn \to \gamma\Lambda pn; \sim 12\,\%$

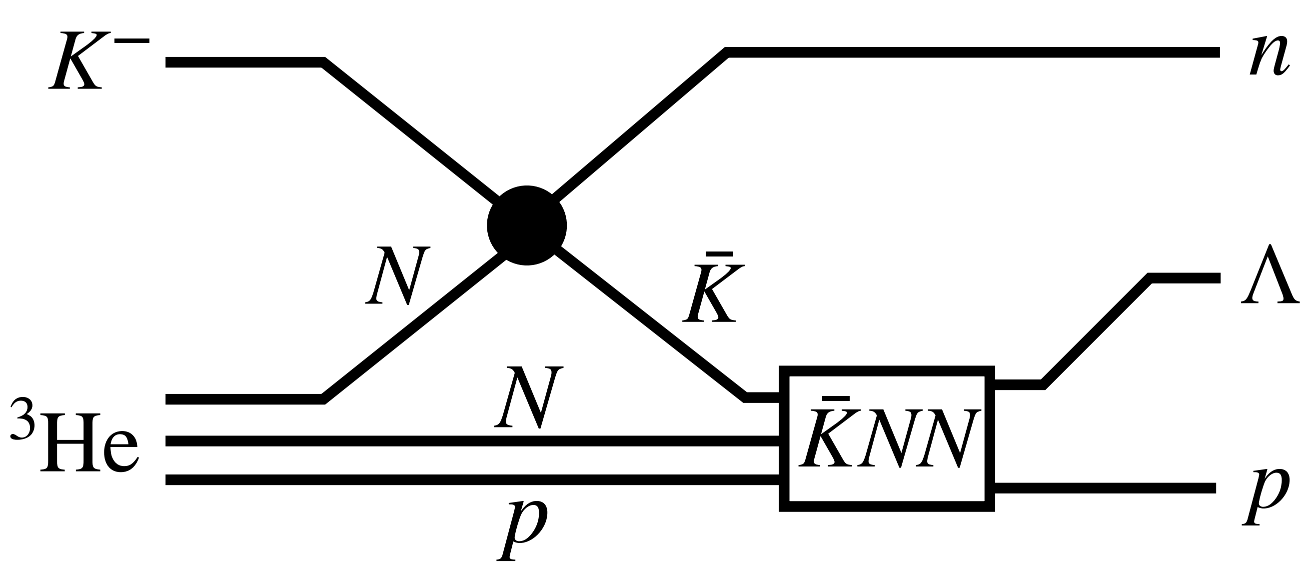
$\Sigma^- pp \to \pi^- ppn; \sim 7\,\%$

Obtained spectrum

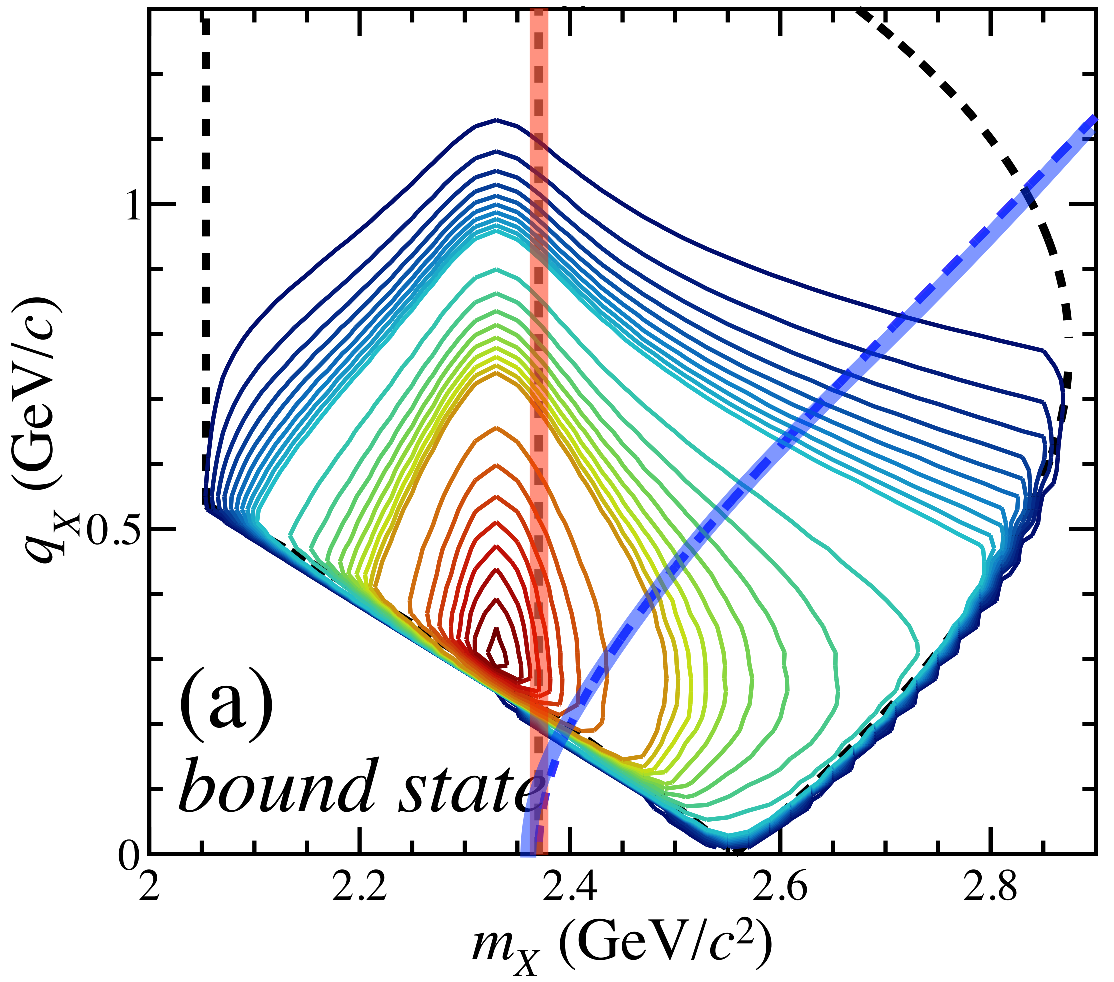


Model functions

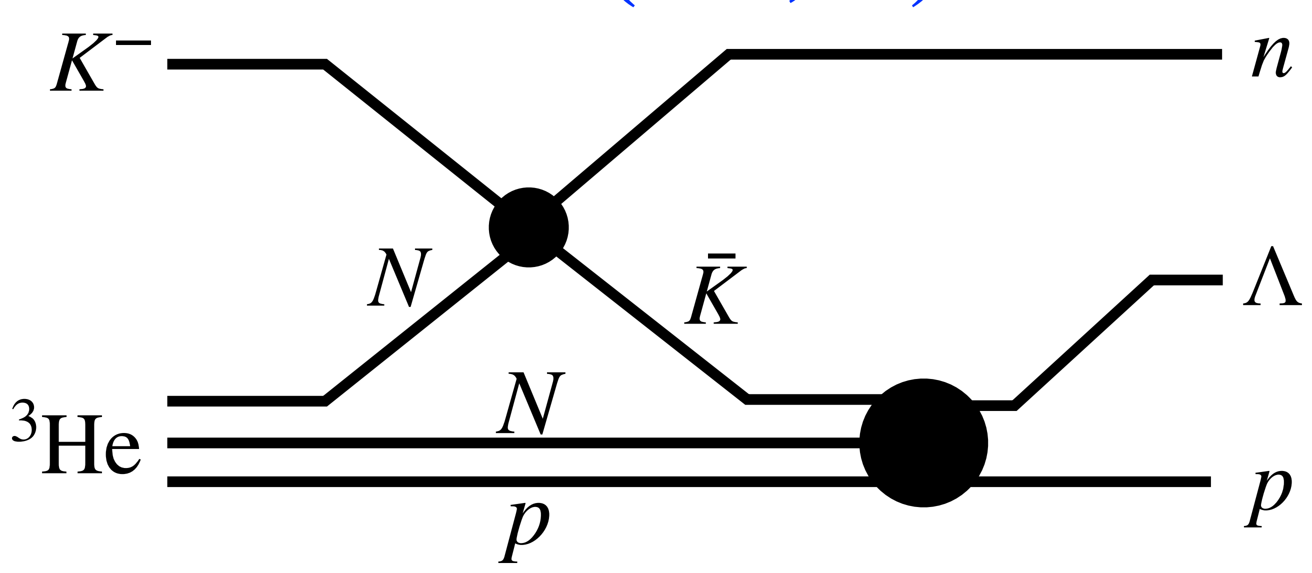
$\bar{K}NN$ production



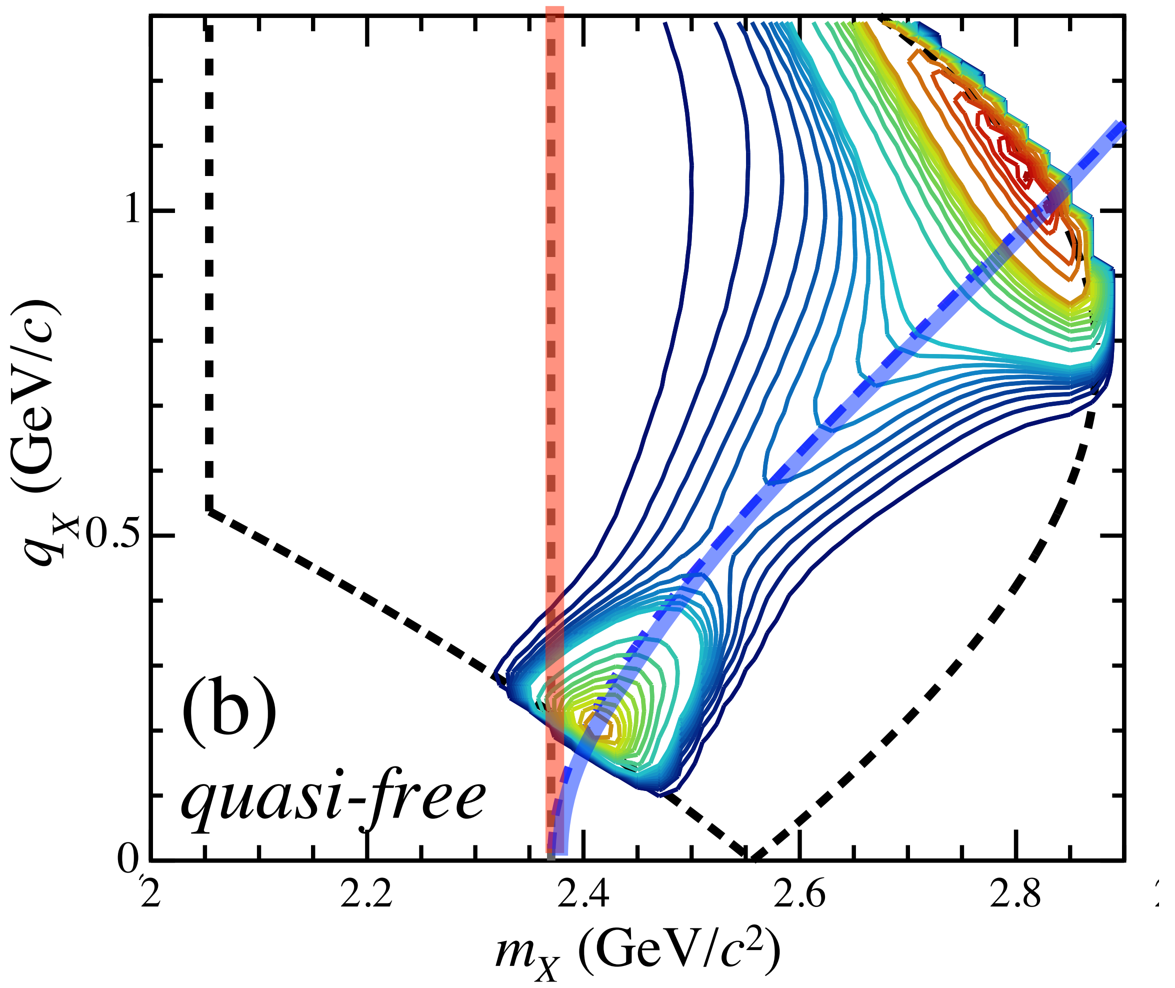
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



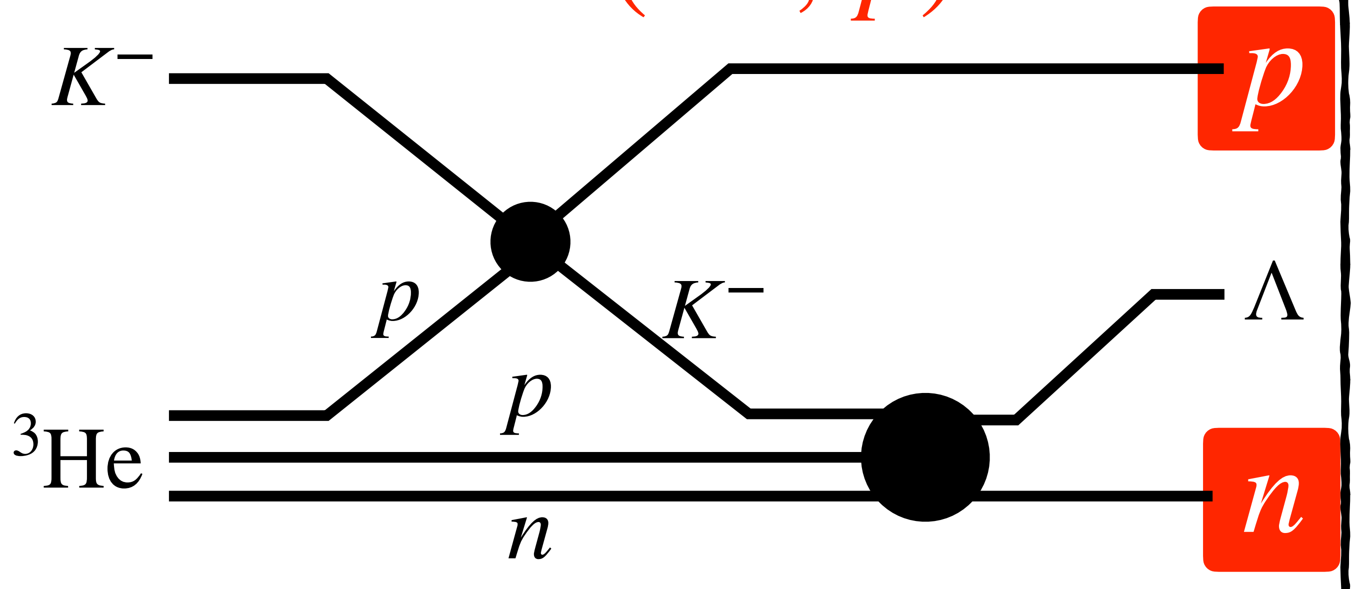
Quasi-free process with (K^-, n)



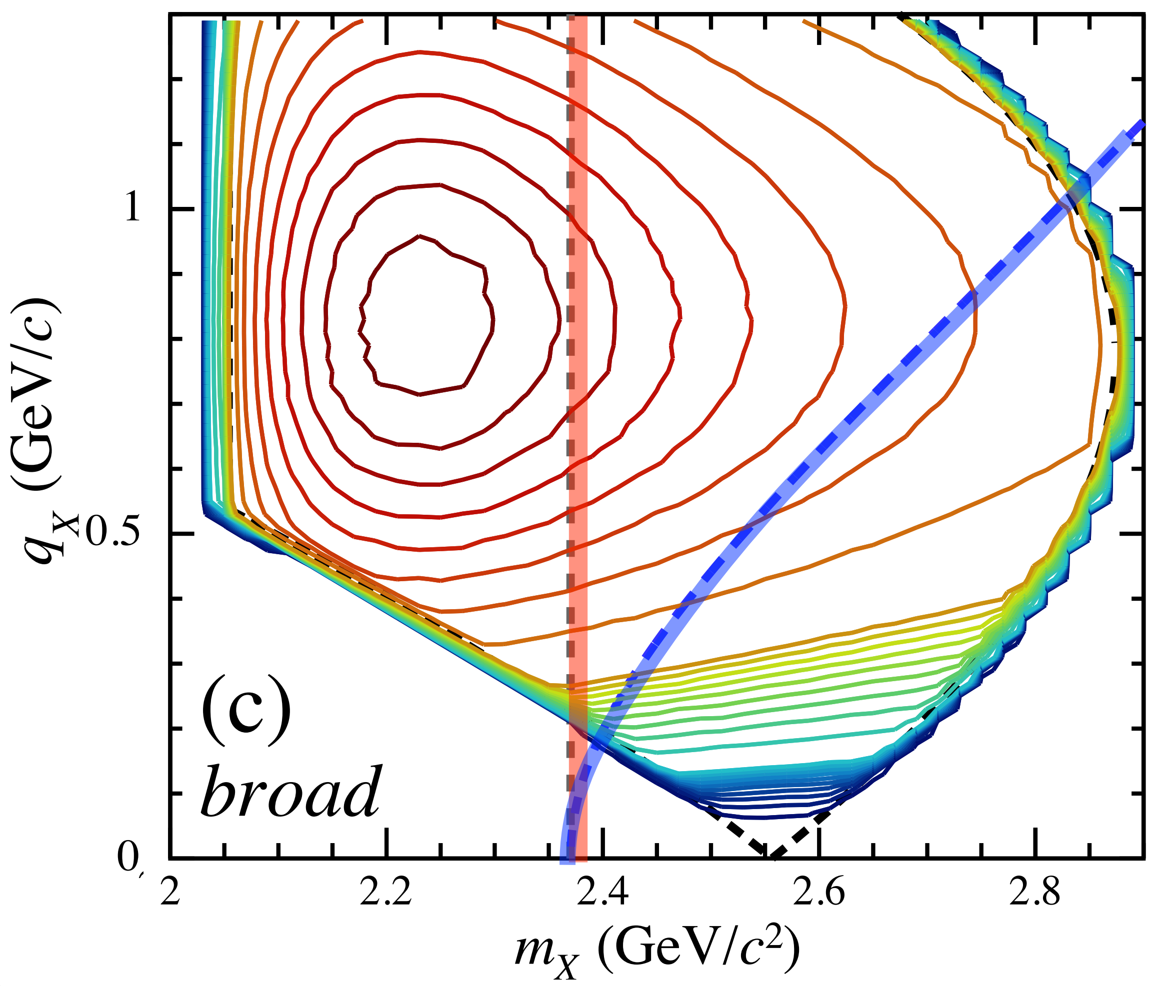
$$f_{\mathrm{QF}}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{\mathrm{QF}}(q_X)$$



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

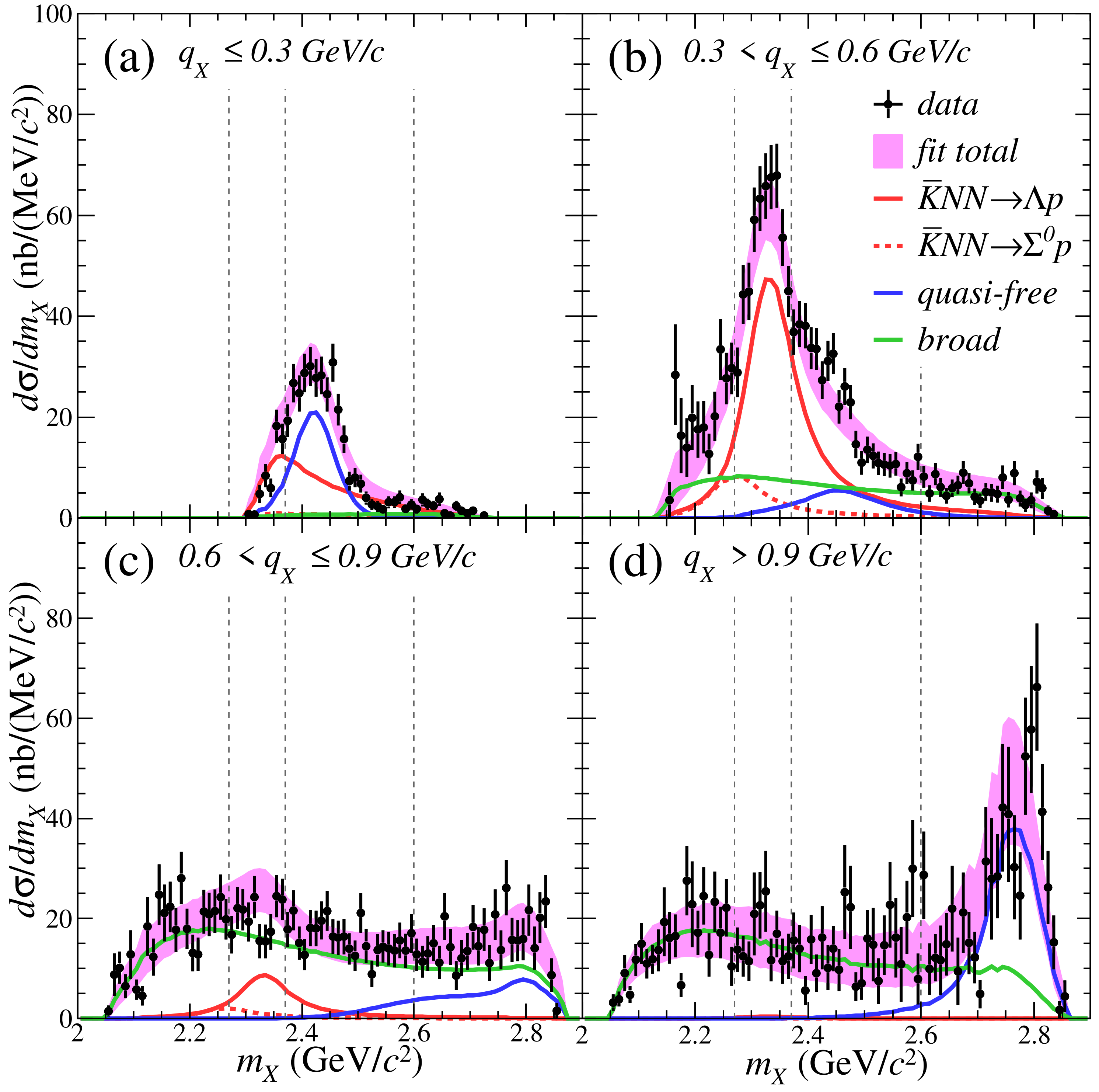


widely distributing

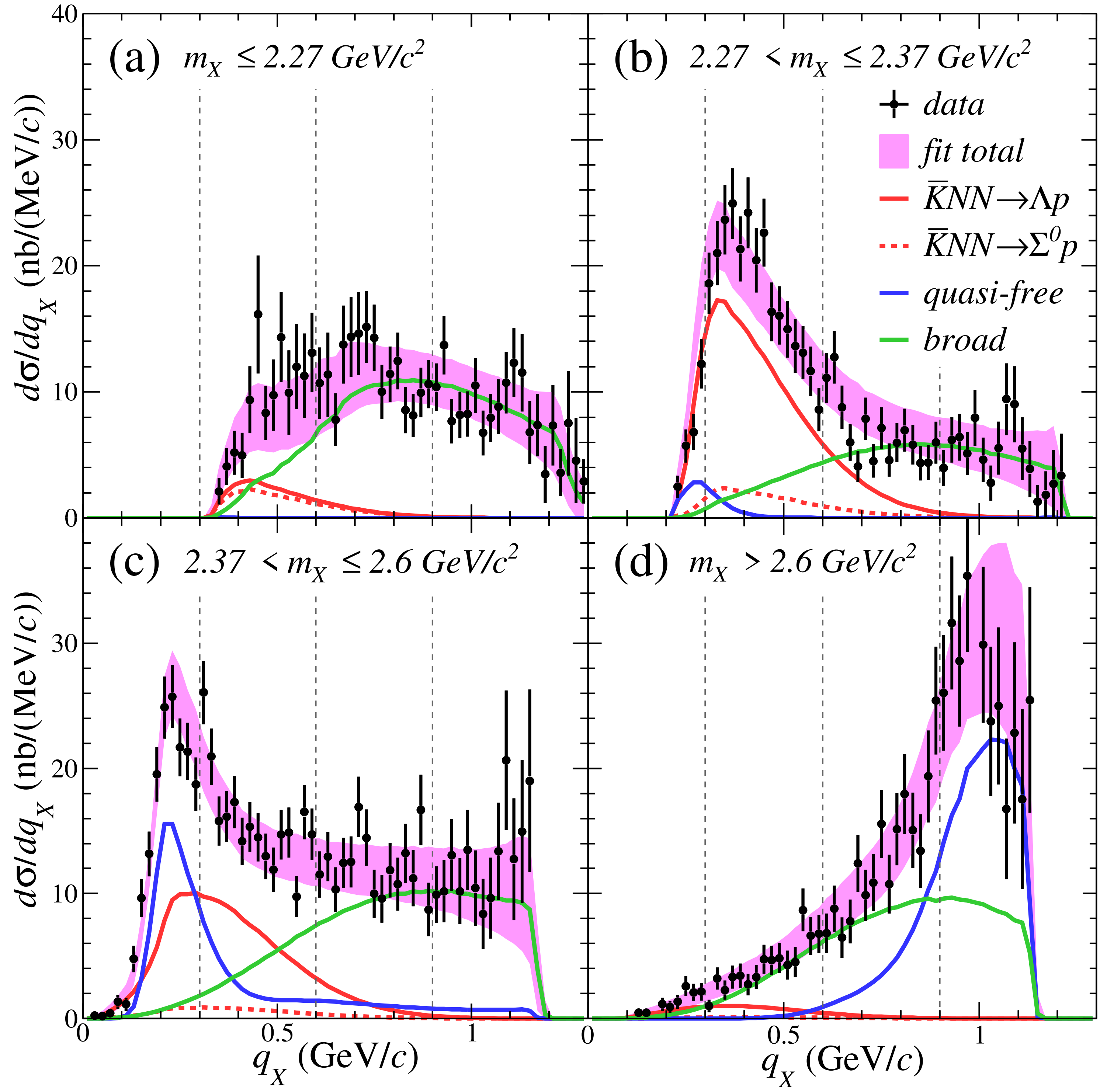


Fit result

Λp invariant-mass

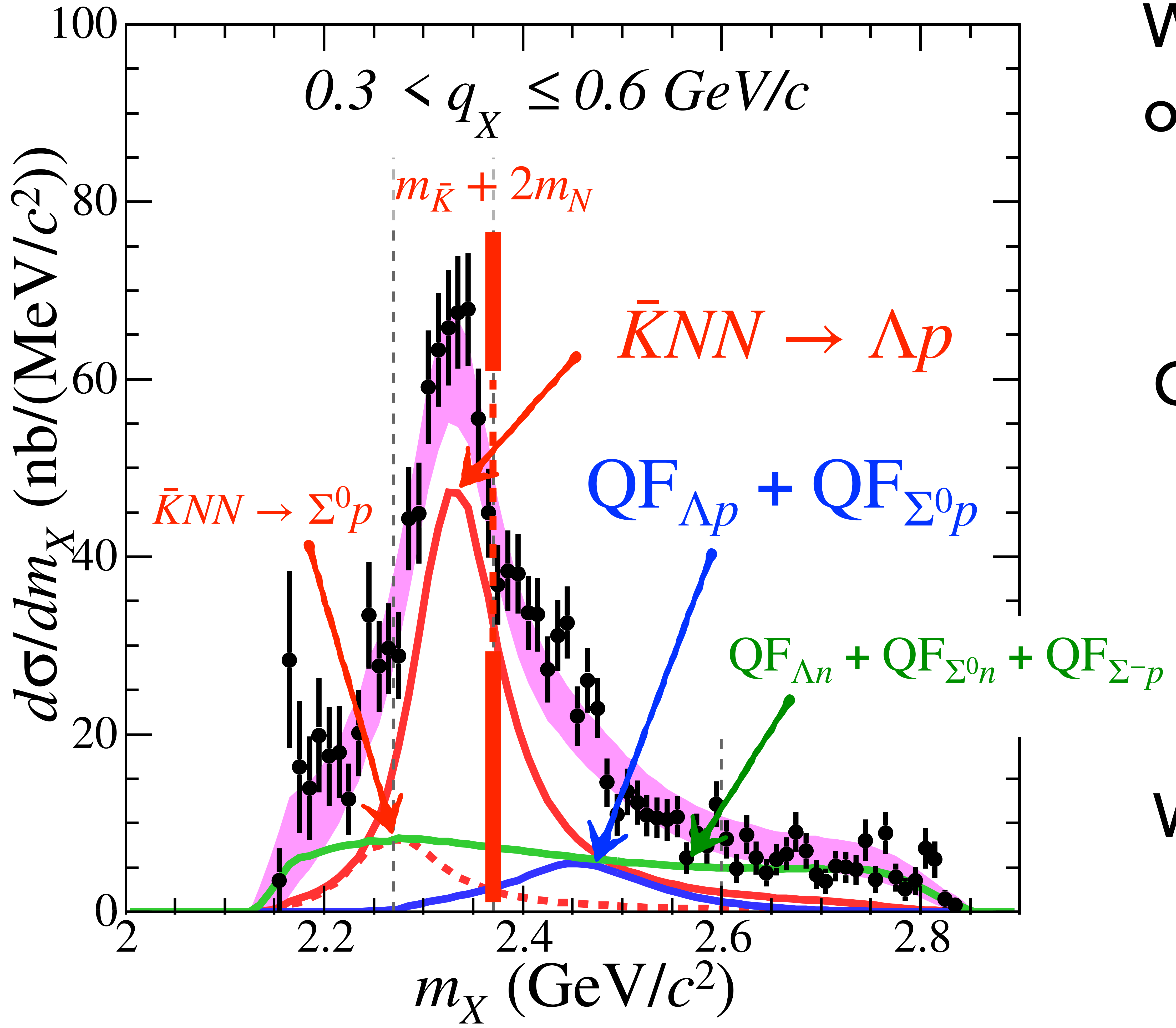


Momentum transfer to Λp



Whole distributions are well reproduced.

Discussion



We observed clear peak below $m_{\bar{K}NN}$ threshold of which peak position does not depends on q_X.

⇨ Signal of resonance

Quasi-free $\bar{K}$ absorption process is clearly seen.

⇨ Clear evidence of the existence of Intermediate-$\bar{K}$ during the reaction

⇩

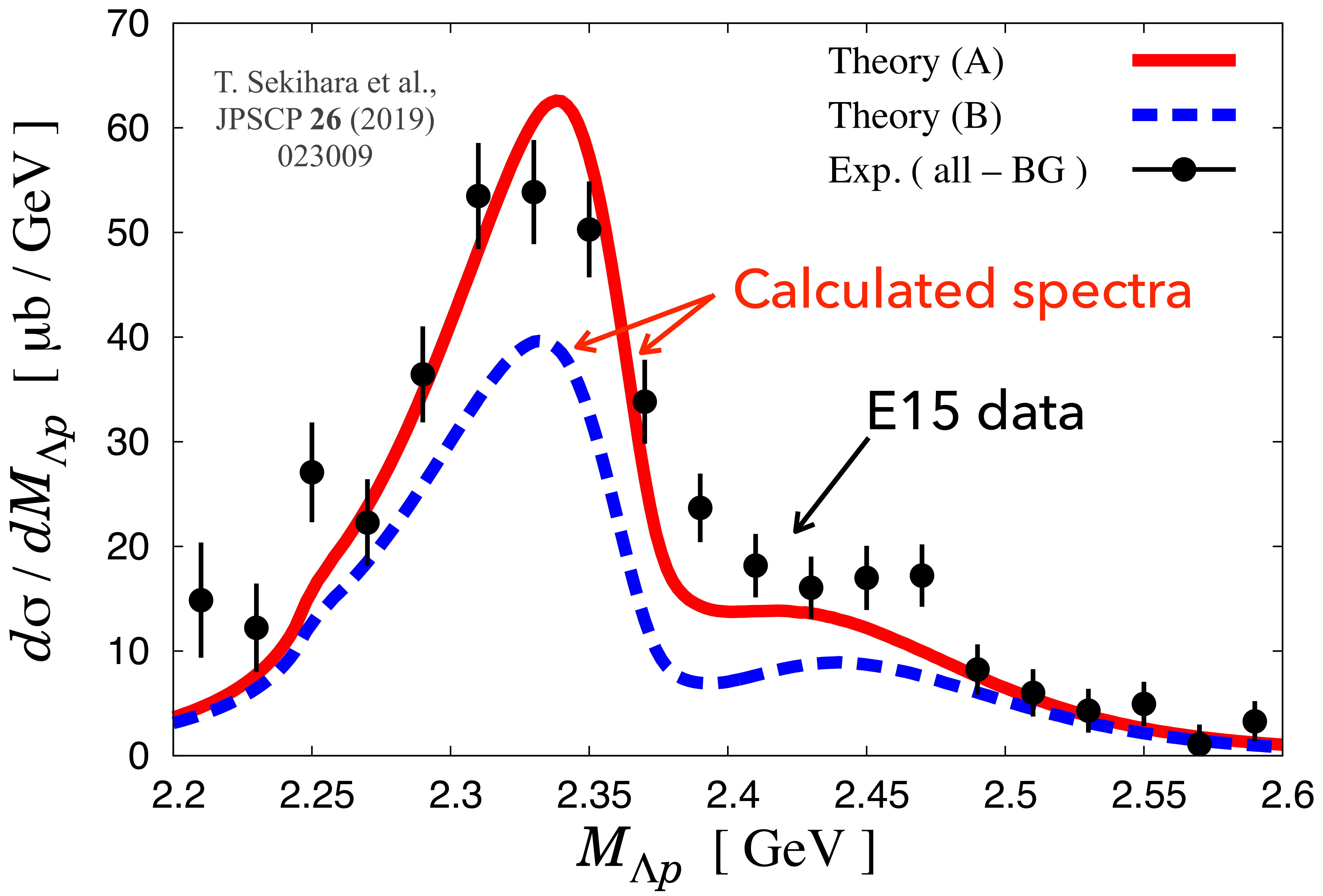
We interpreted that it is signal of $\bar{K}NN \to \Lambda p$.

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

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

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

Theoretical calculation



Theoretically calculated spectral shape based on Chi-SU(3) well reproduce data.

Questions

Is the observed resonance really what we expected?

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

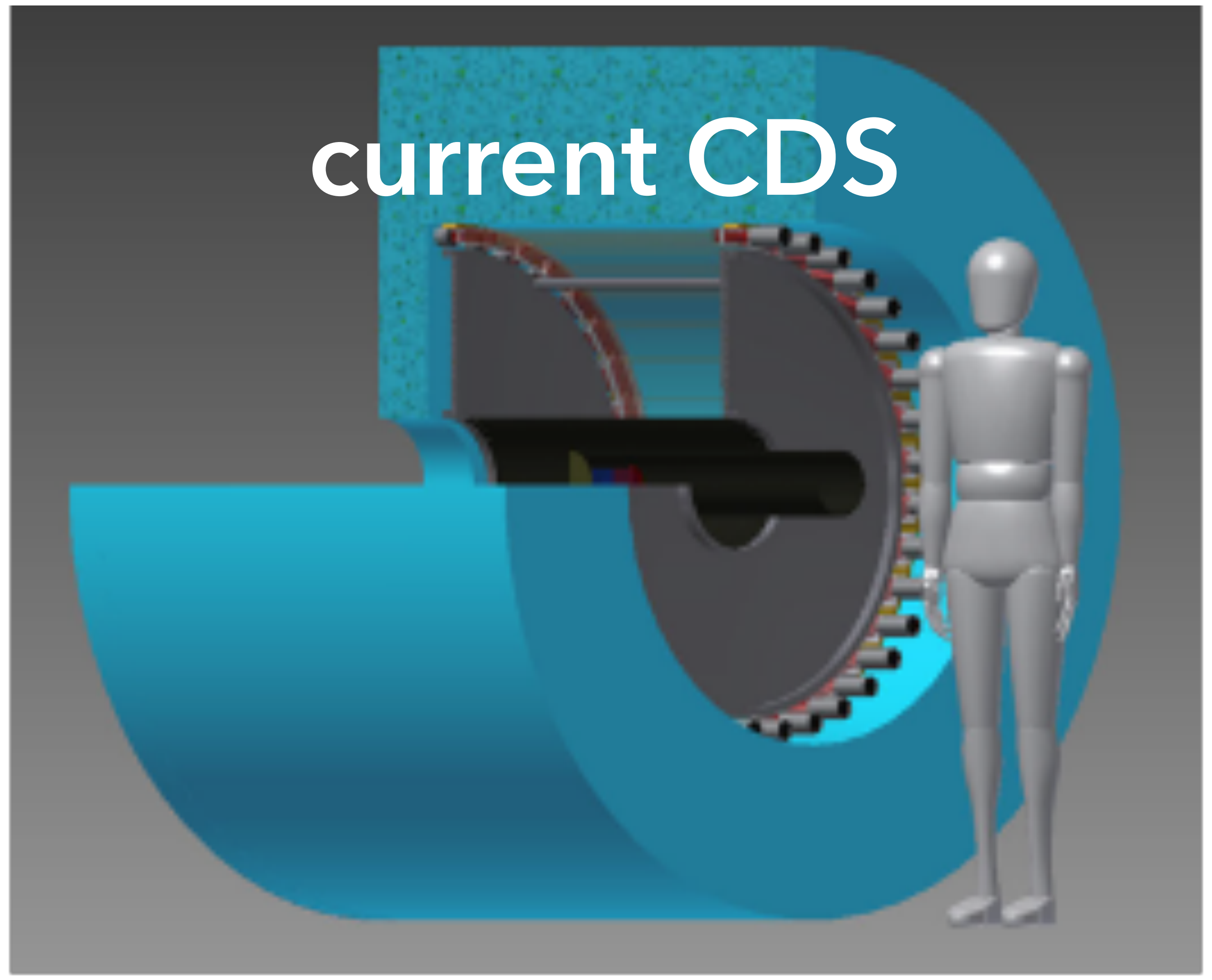
Does $\bar{K}$ really keep it particle identity?

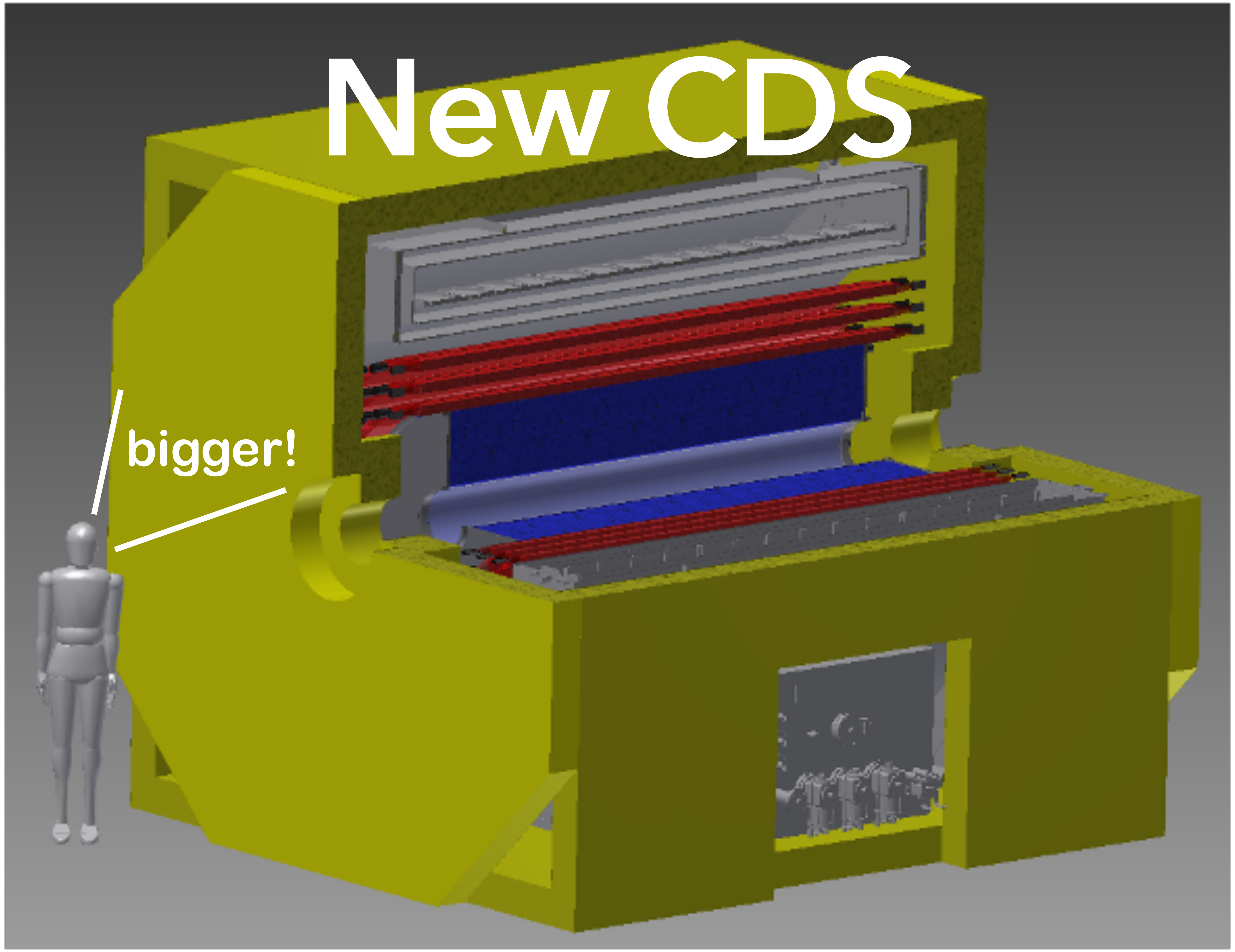
⇩

Key issues for $\bar{K}NN$

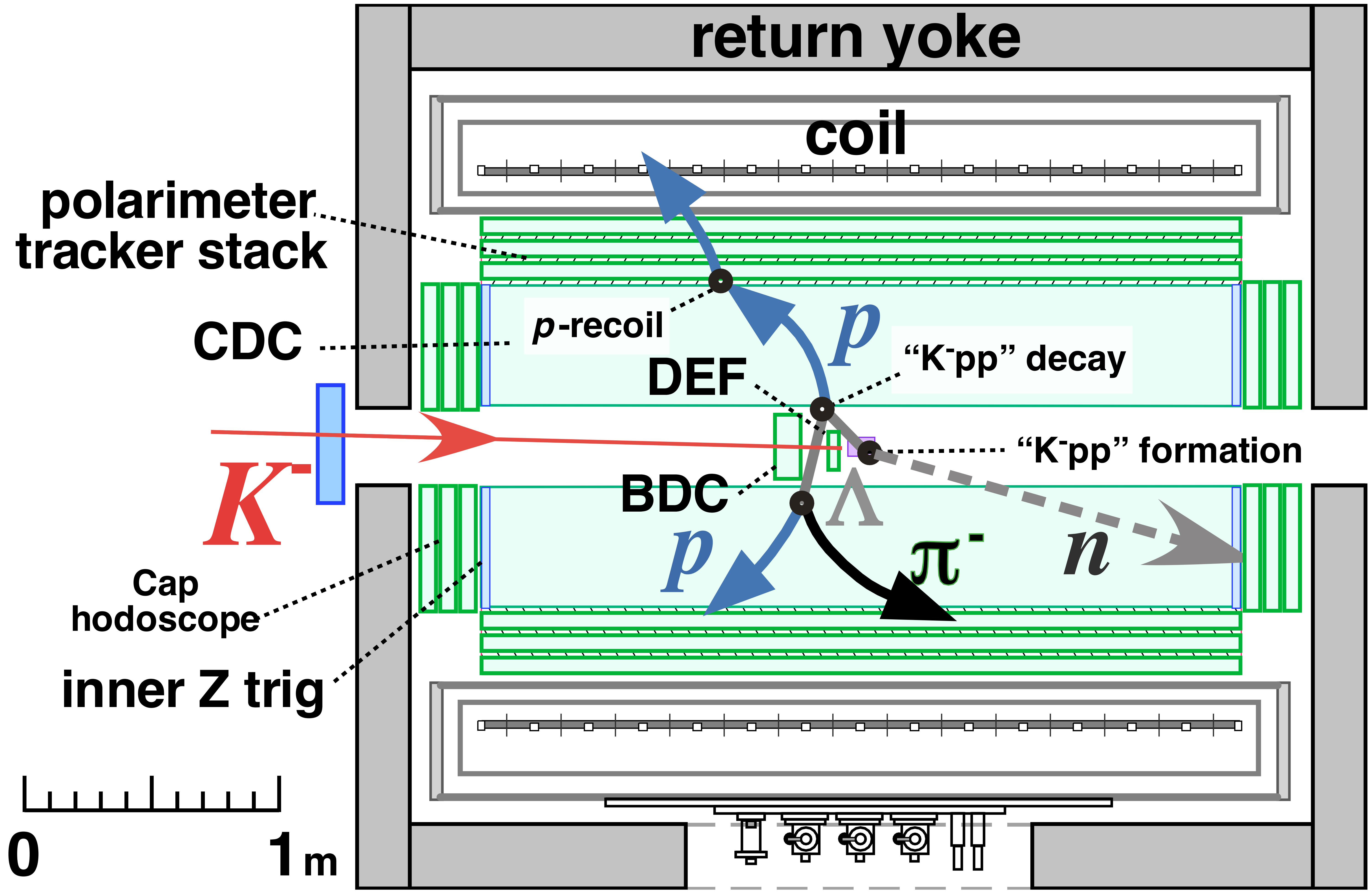
J^π & $(\bar{K}NN)^{I_z=-1/2}$

Future plan





New CDS



>90% solid angle coverage

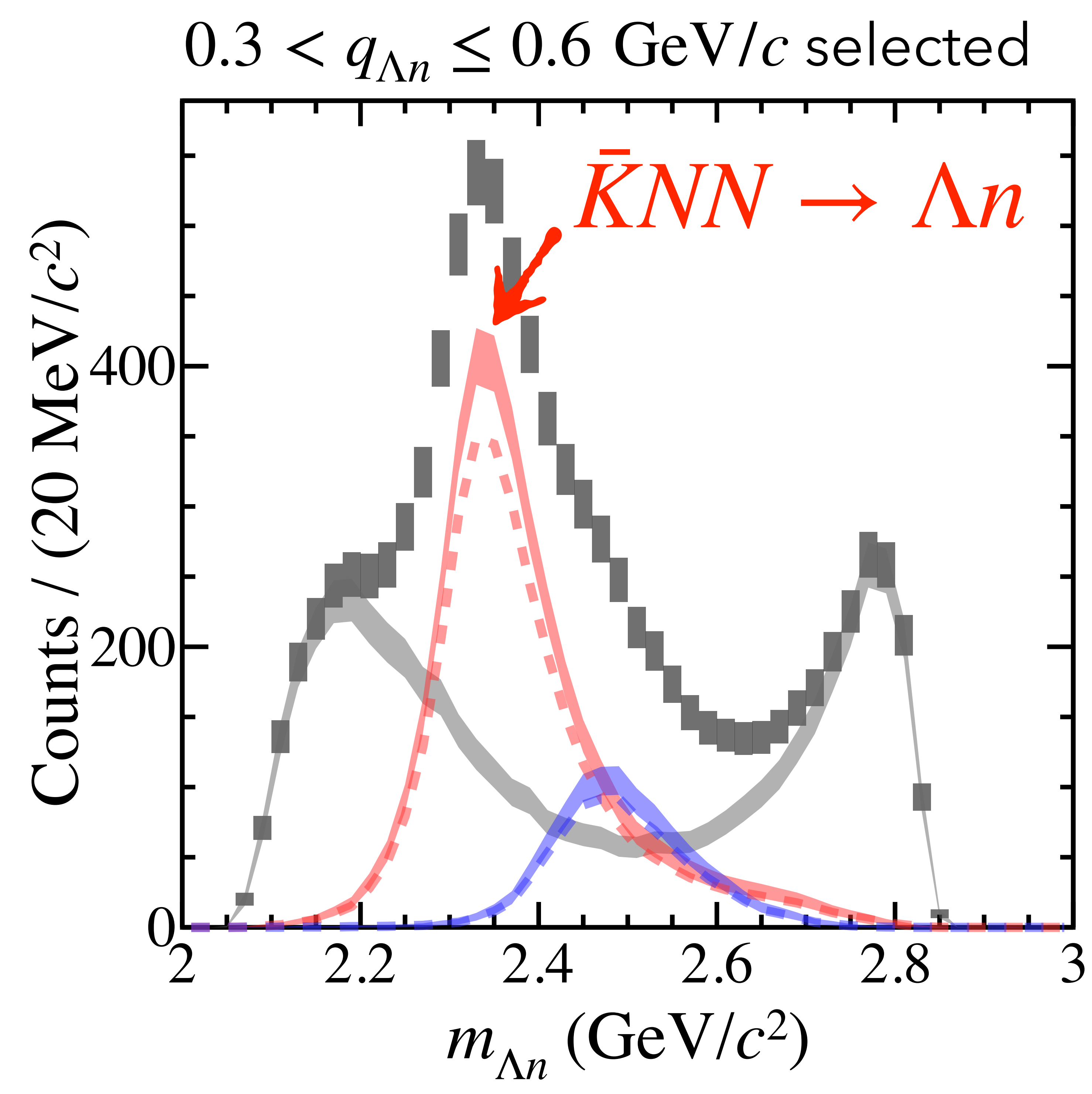
Neutron detection capability

Sensitivity for proton polarization

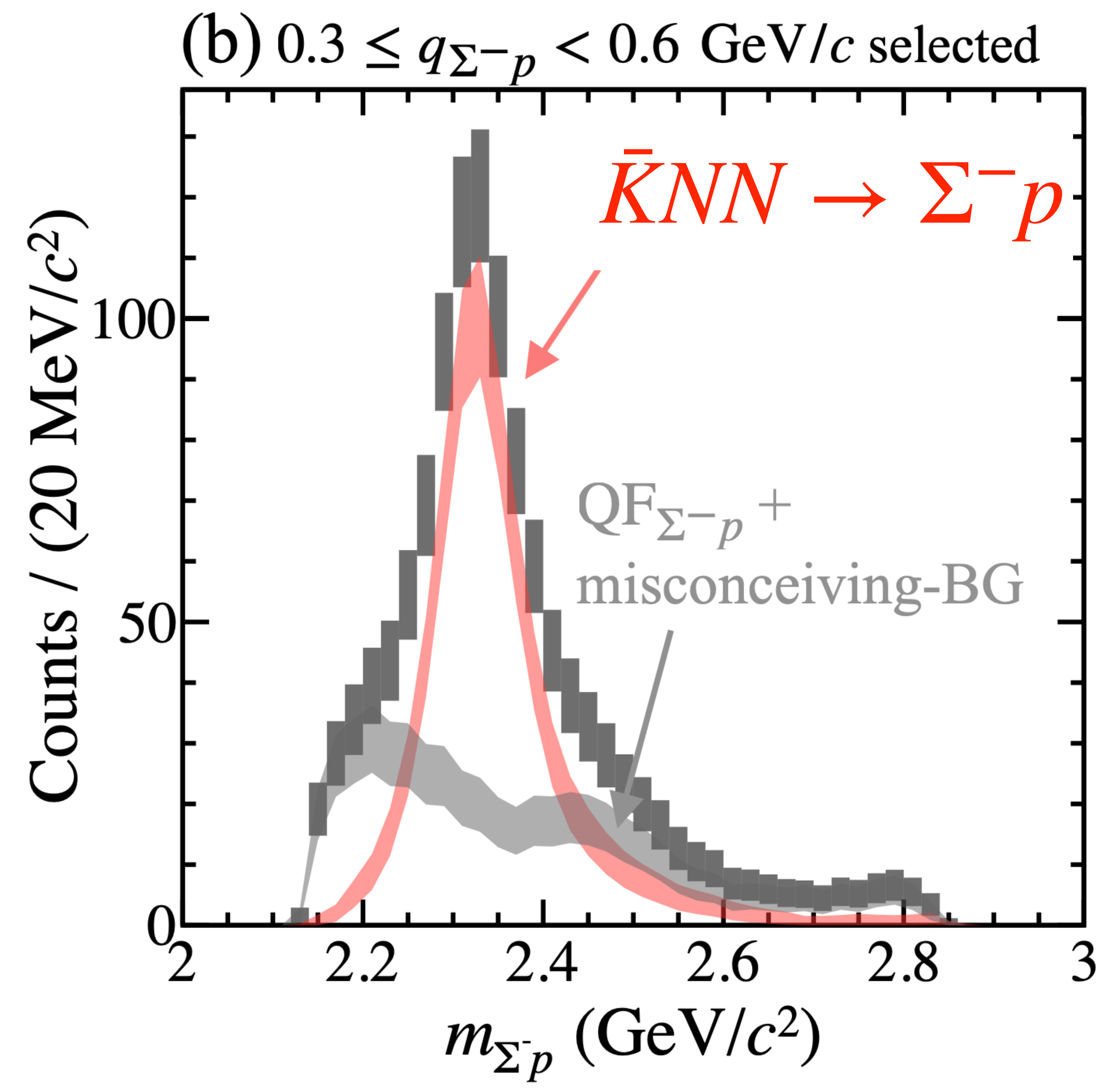
Construction has been started (Completed in 2025)

Expected spectra of $(\bar{K}NN)^{1/2,-1/2}$

By Λn decay



By $\Sigma^- p$ decay



We expect to observe distinct peak of $(\bar{K}NN)^{I_z=-1/2}$

Let's consider $\bar{K}NN \to \Lambda p$ decay

$$J^\pi = (S_{\Lambda p} \otimes L_{\Lambda p})^{-1^{(L_{\Lambda p})}}$$

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

$J^\pi = 1^-$

$[L_{\Lambda p} = 1]$

$\otimes$

$\frac{2}{3}[S_{\Lambda p} = 1] + \frac{1}{3}[S_{\Lambda p} = 0]$

⇩

$\alpha_{\Lambda p} = +1/3$

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

$J^\pi = 0^-$

$[L_{\Lambda p} = 1]$

$\otimes$

$[S_{\Lambda p} = 1]$

⇩

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

$(\Sigma^* N)^{I_z=1/2}$

$J^\pi = 2^+$

$[L_{\Lambda p} = 2]$

$\otimes$

$\frac{1}{2}[S_{\Lambda p} = 1] + \frac{1}{2}[S_{\Lambda p} = 0]$

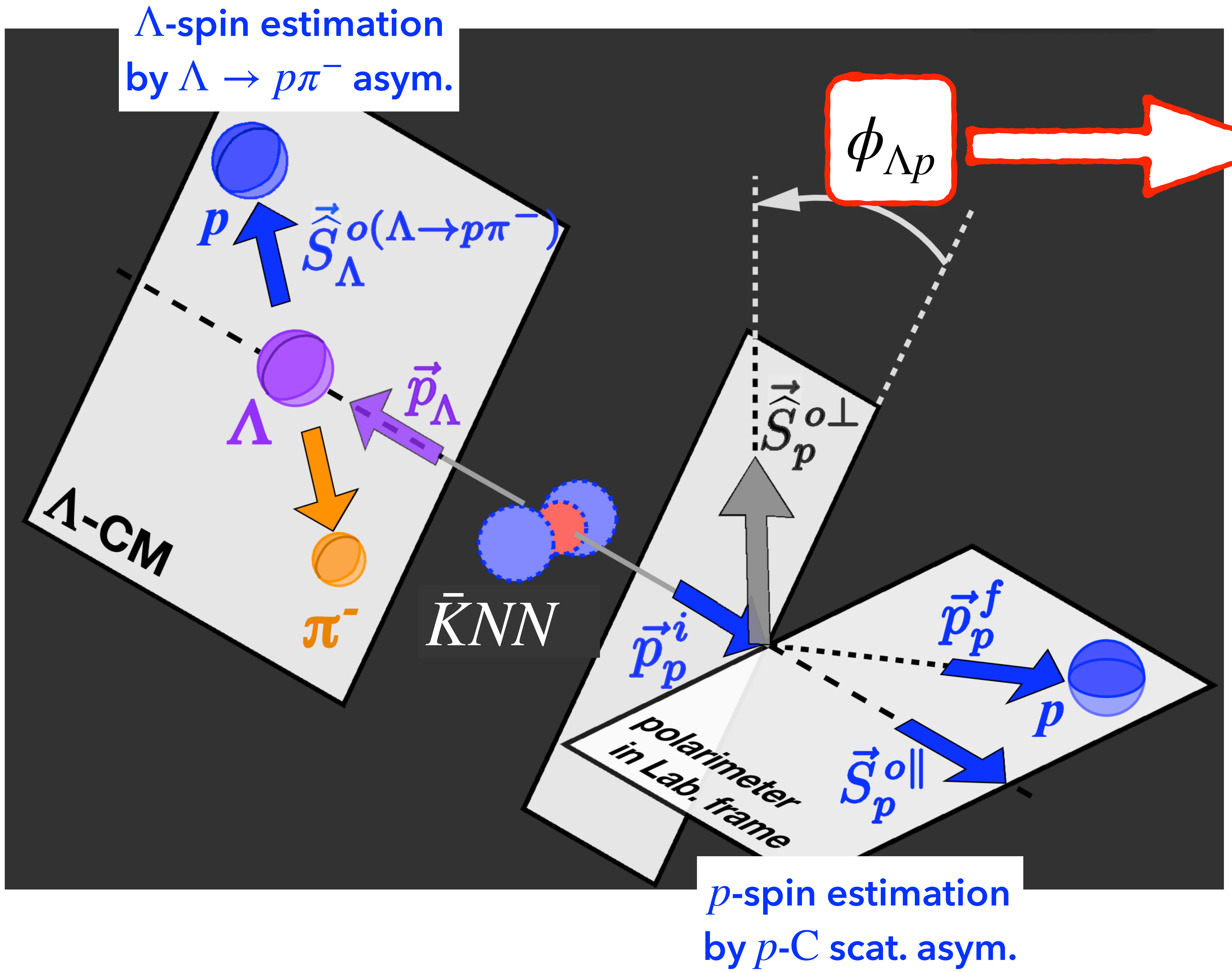
⇩

$\alpha_{\Lambda p} = \pm 0$

Three different internal configurations can be distinguished with $\alpha_{\Lambda p}$.

How to measure spin-spin correlation

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



Spin-spin correlation on ϕ-asymmetry

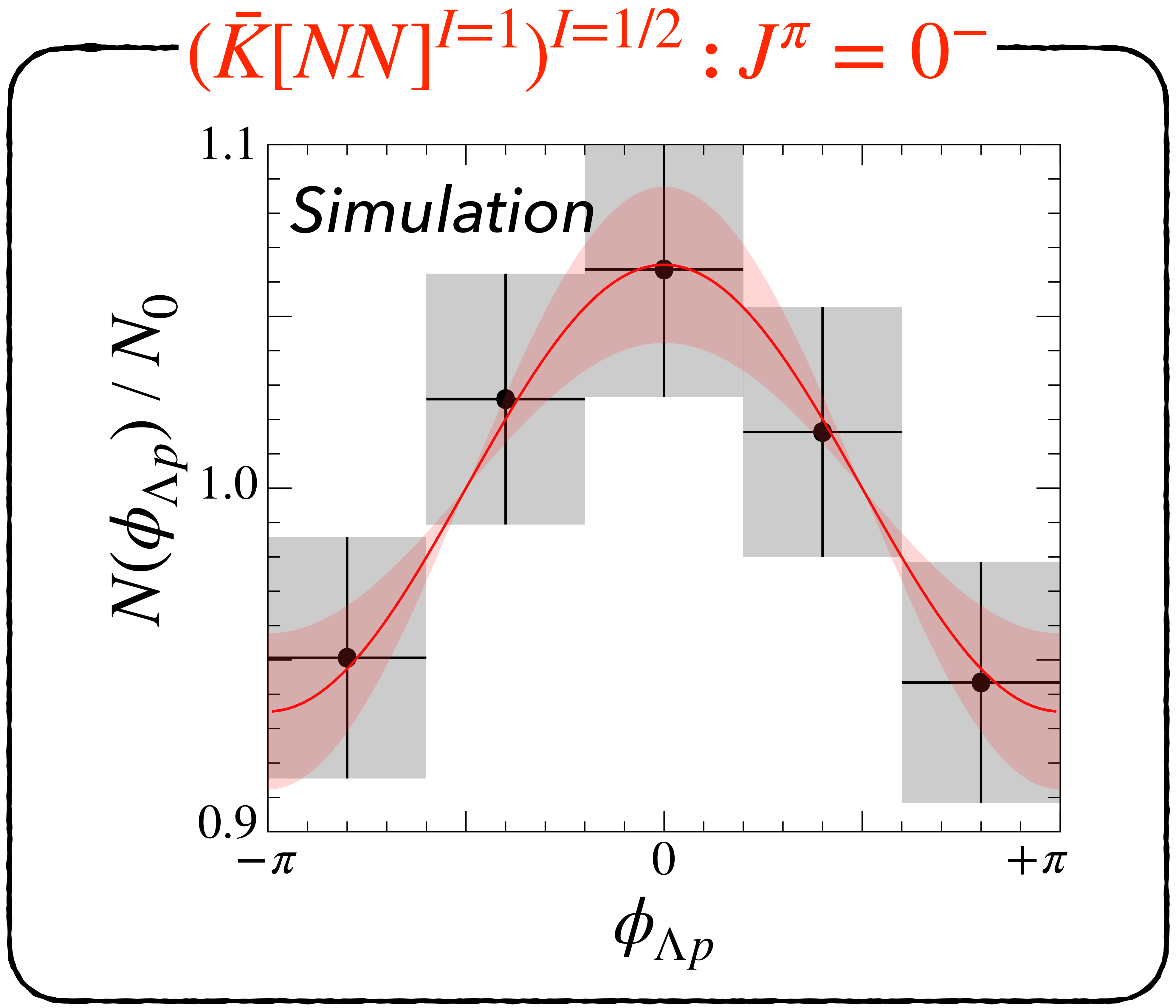
$$N(\phi_{\Lambda p}) = N_0 \cdot (1 + r^{(J^P)} \cdot \alpha_{\Lambda p} \cos \phi_{\Lambda p})$$

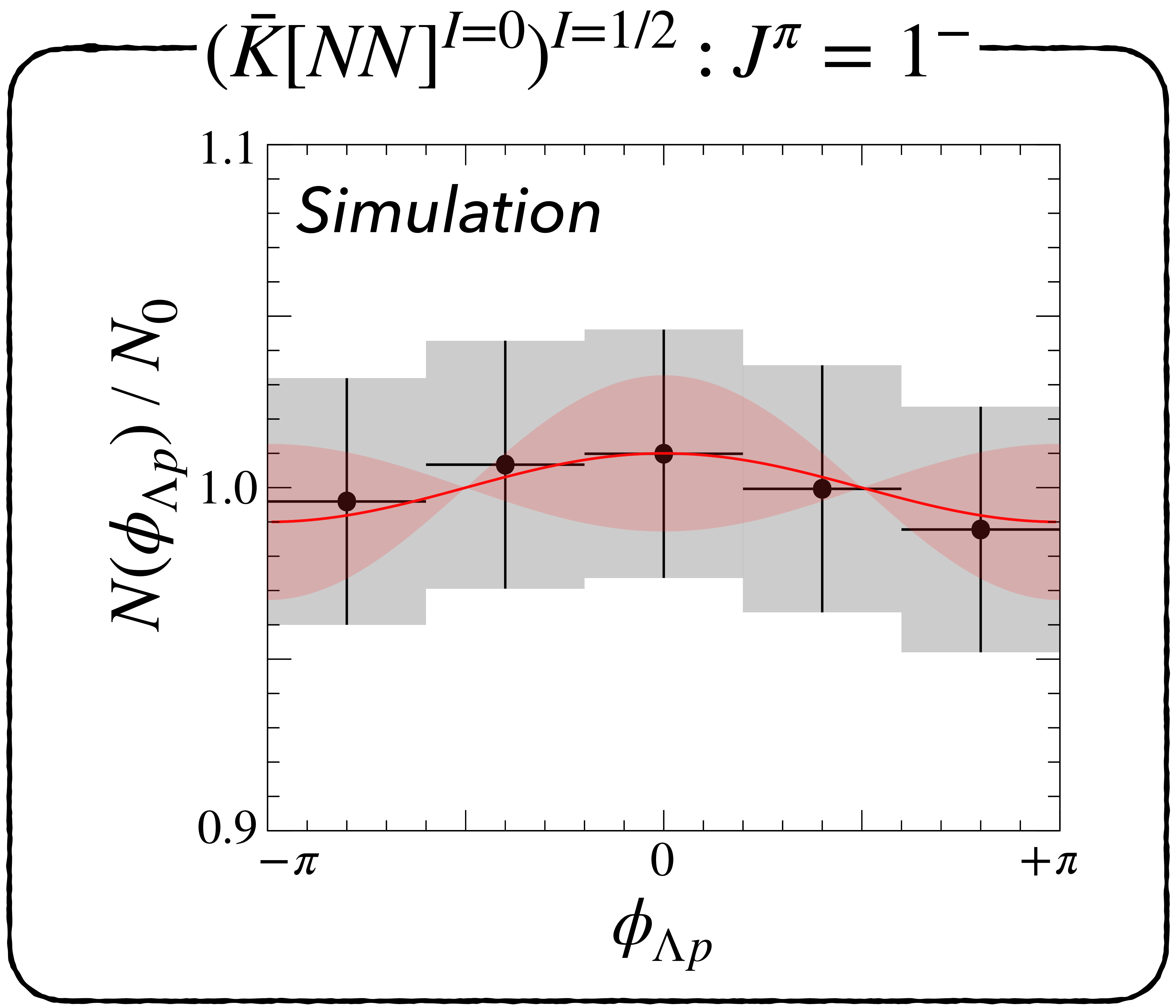
$r^{(J^P)}$: asymmetry reduction factor defined by;

- 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

Expected $\phi_{\Lambda p}$ distributions

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





Additionally, we can use production cross section ratio between $I_z = \pm 1/2$ states

New programs for kaonic 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^P determination

To confirm the existence more robustly

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

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

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)

T. Hashimoto's talk (Mon-IV)

$\bar{K}NNNN$ system

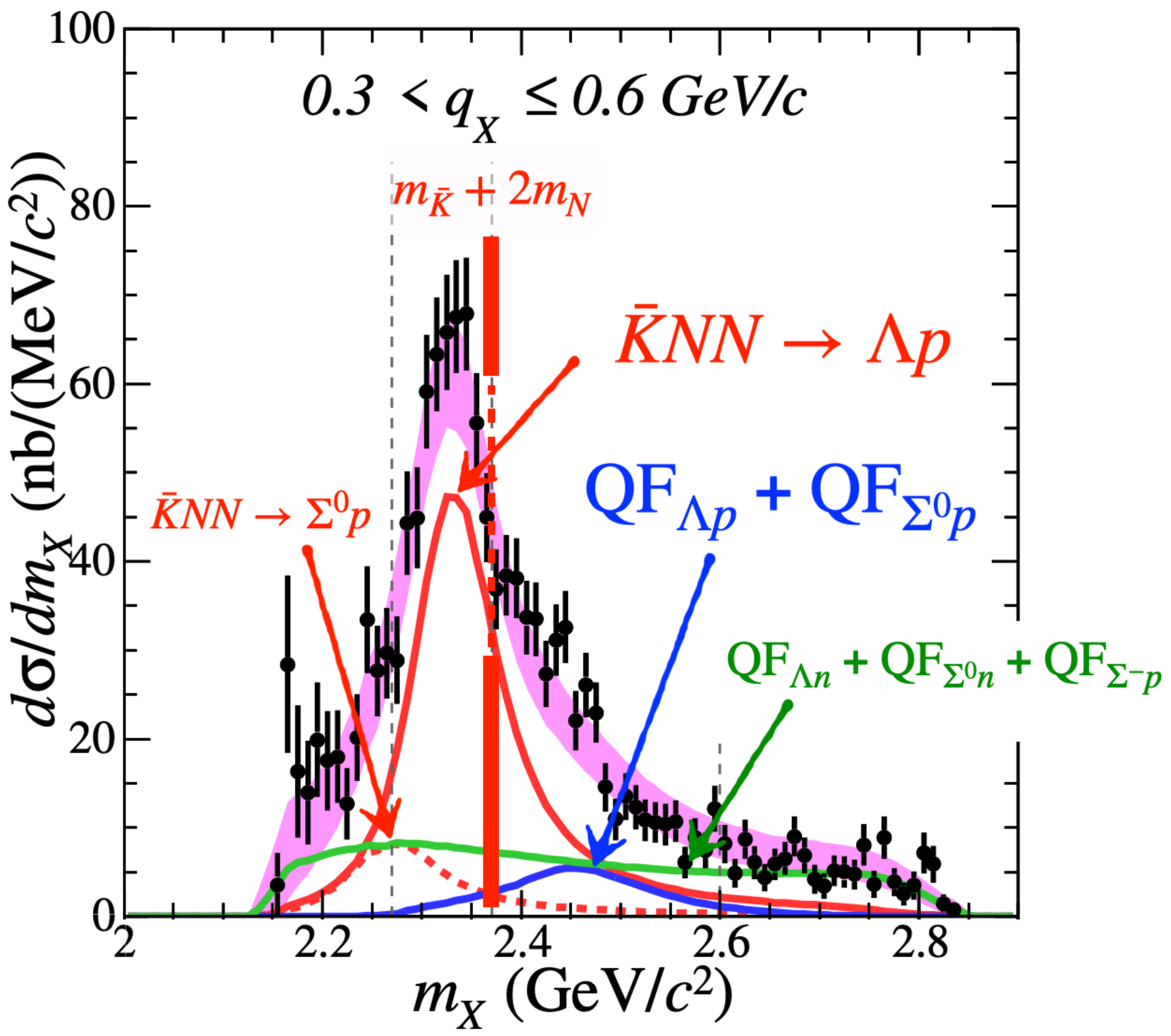
Expected large B.E. & high density

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

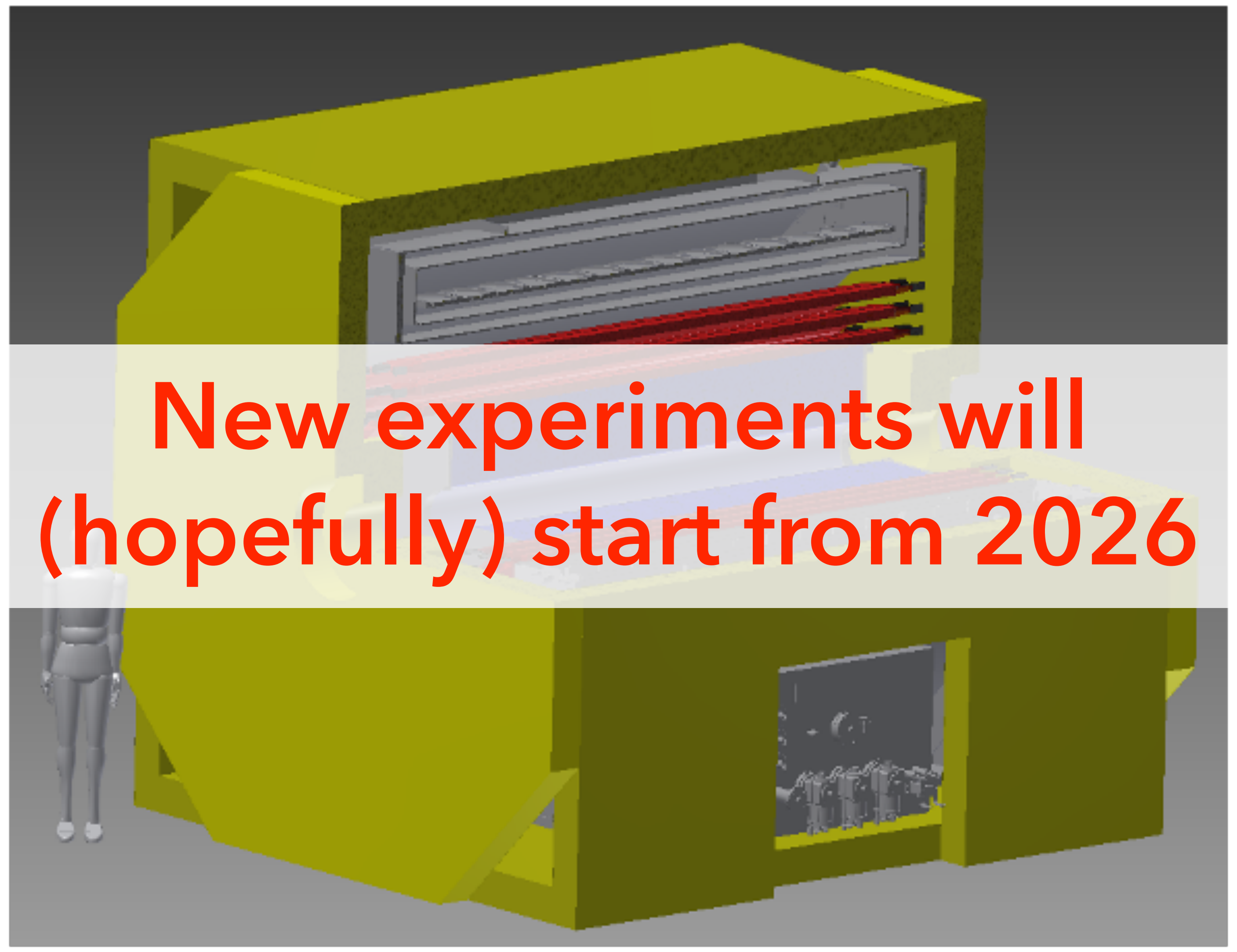
K^--α $\bar{K}^0$-α

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



Are you interested in? Join us!

Thank you for your attention!

= Collaboration =

Experimentalists

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