Experimental study of $\bar{K}NN$ and future $\bar{K}$-nuclei experiments at J-PARC

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

$\Lambda(1405)$

$\bar{K}$-nuclei

$\bar{K}NN$

The lightest $\bar{K}$-nucleus

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

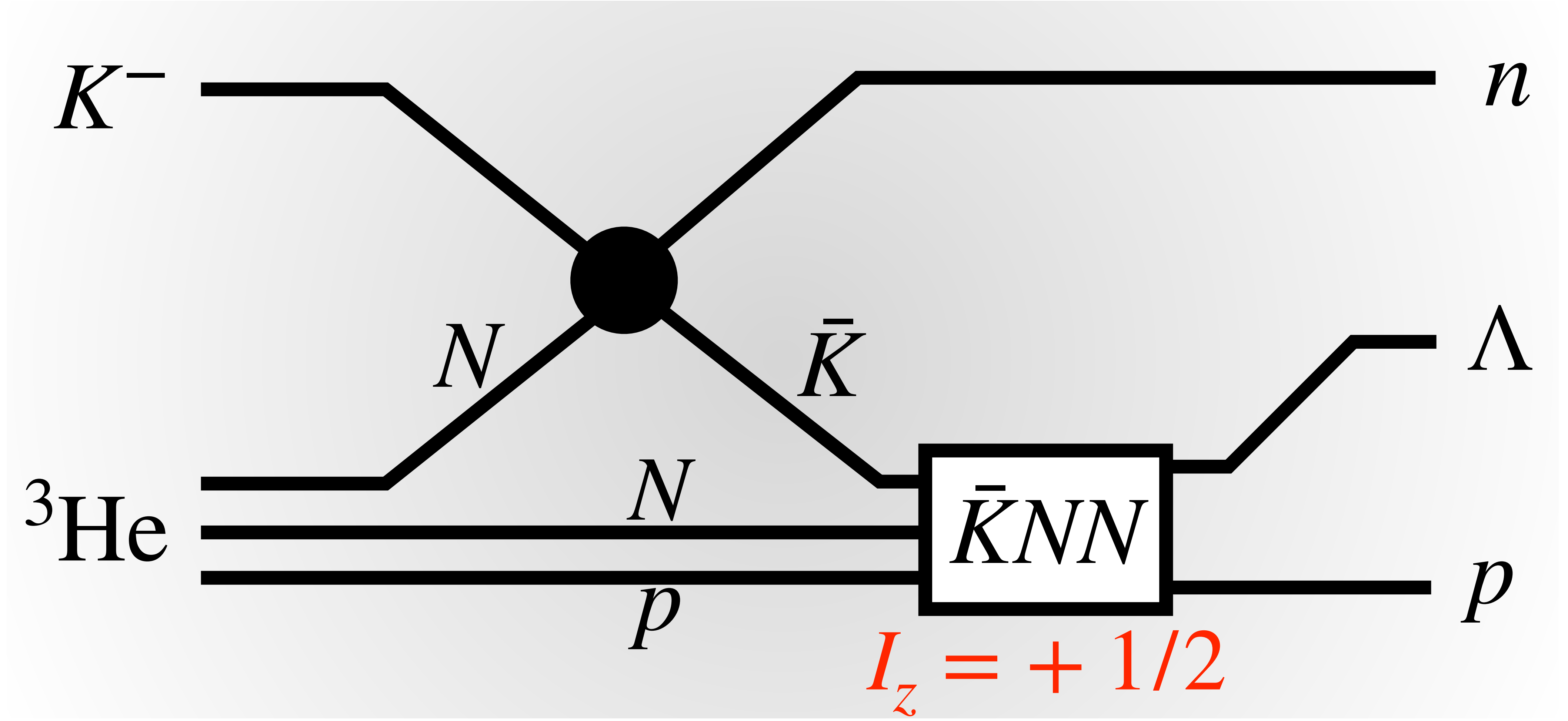
Should be the ground state

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

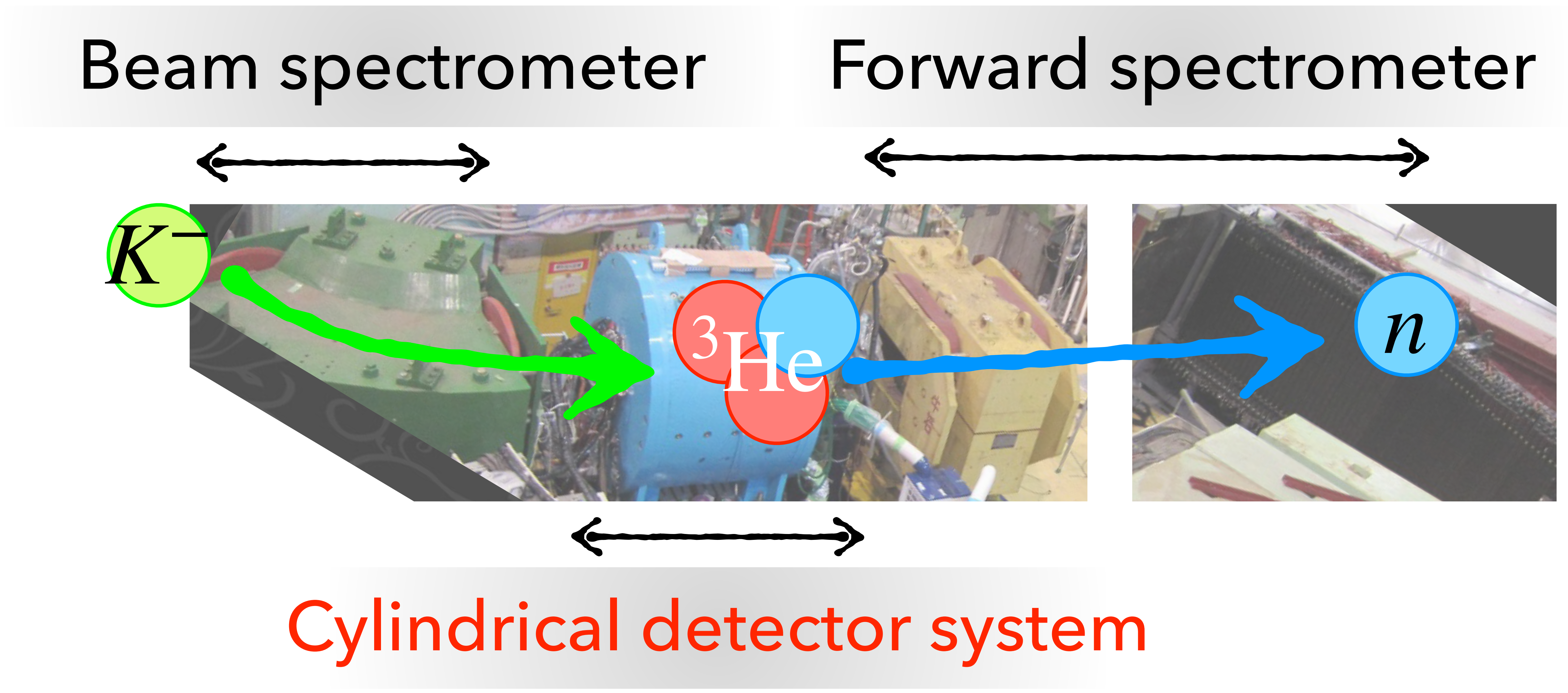
$I_z = -1/2$ $K^{-}pn$ - $\bar{K}^{0}nn$

J-PARC E15

Production reaction



Detector system



Exclusive invariant-mass spectroscopy

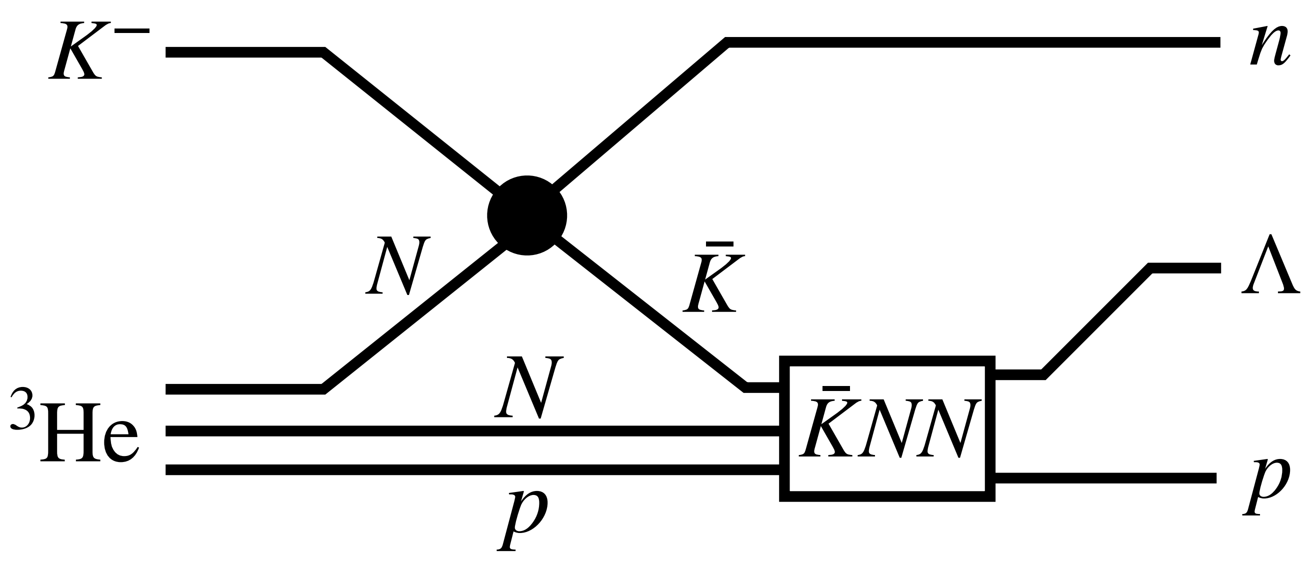
To select Λpn final state

To measure Λp invariant-mass & momentum transfer

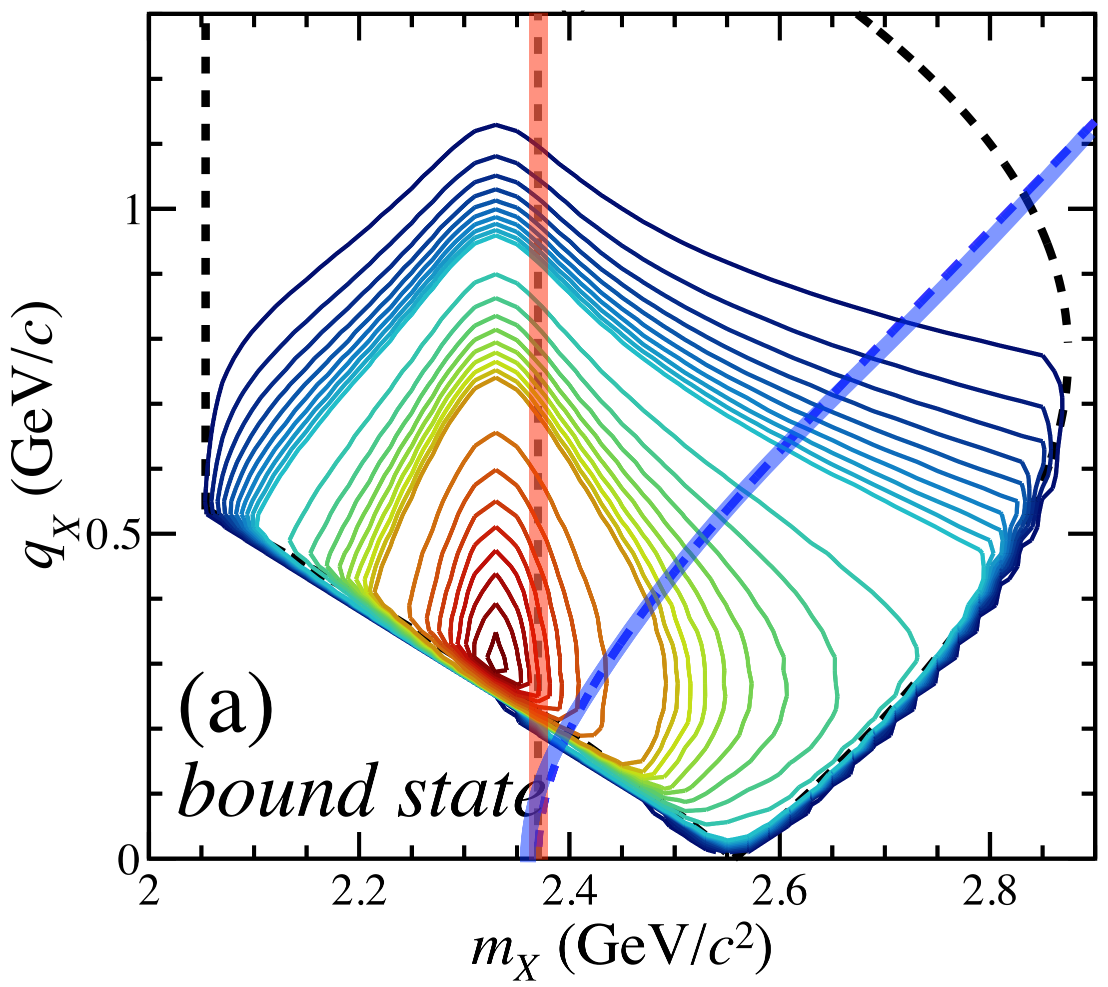
Obtained 2D distribution

Model functions

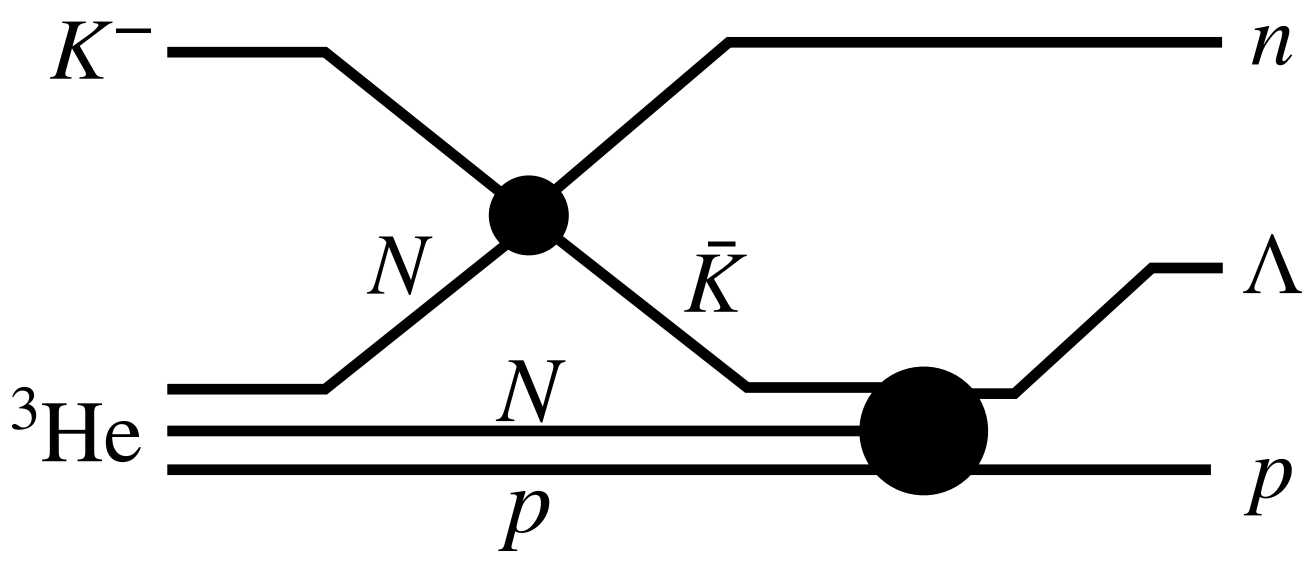
$\bar{K}NN$ production



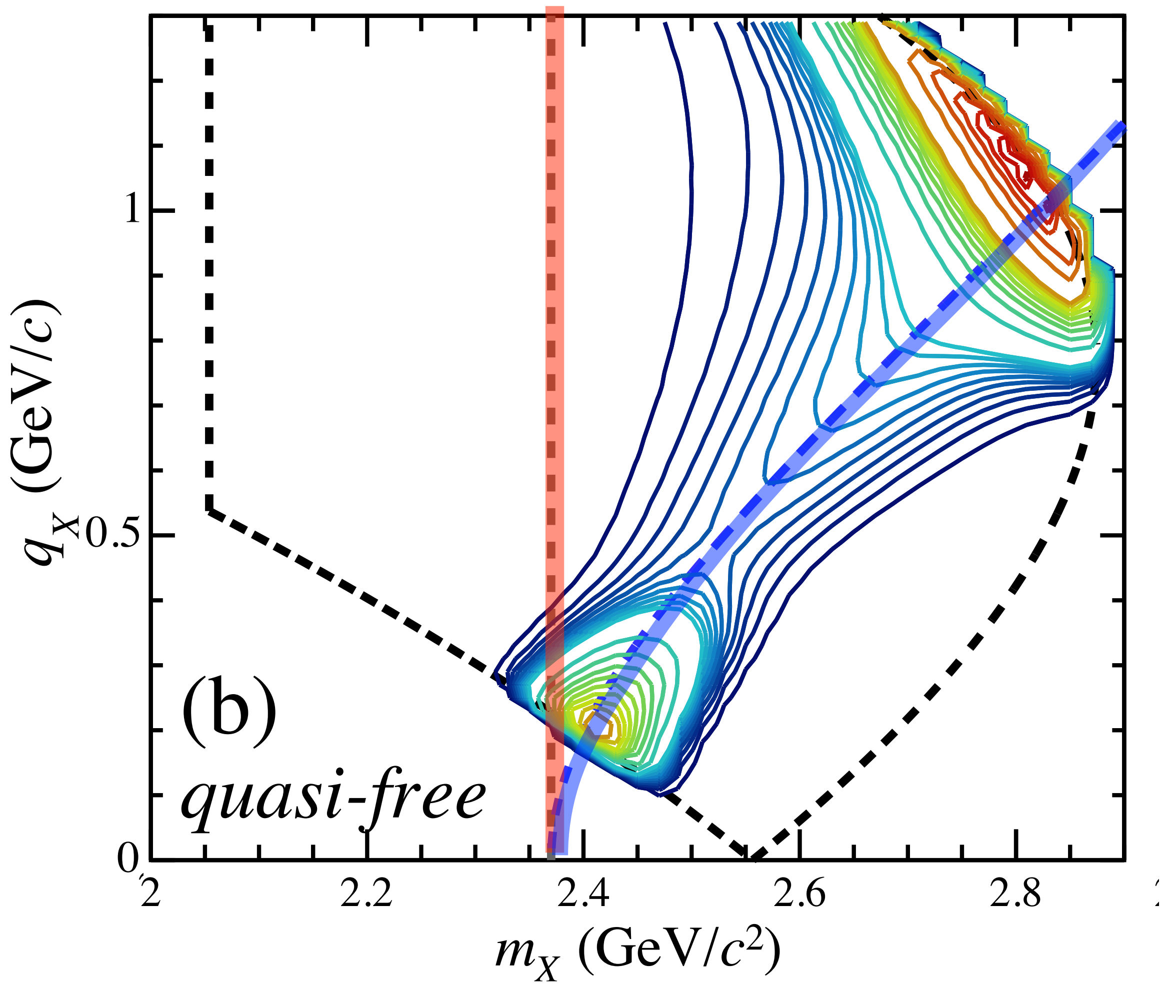
$$f_{\bar{K}NN}(m_X, q_X) = \frac{\Gamma^2/4}{(m_X - M_X)^2 + \Gamma^2/4} \times g_{K^-pp}(q_X)$$



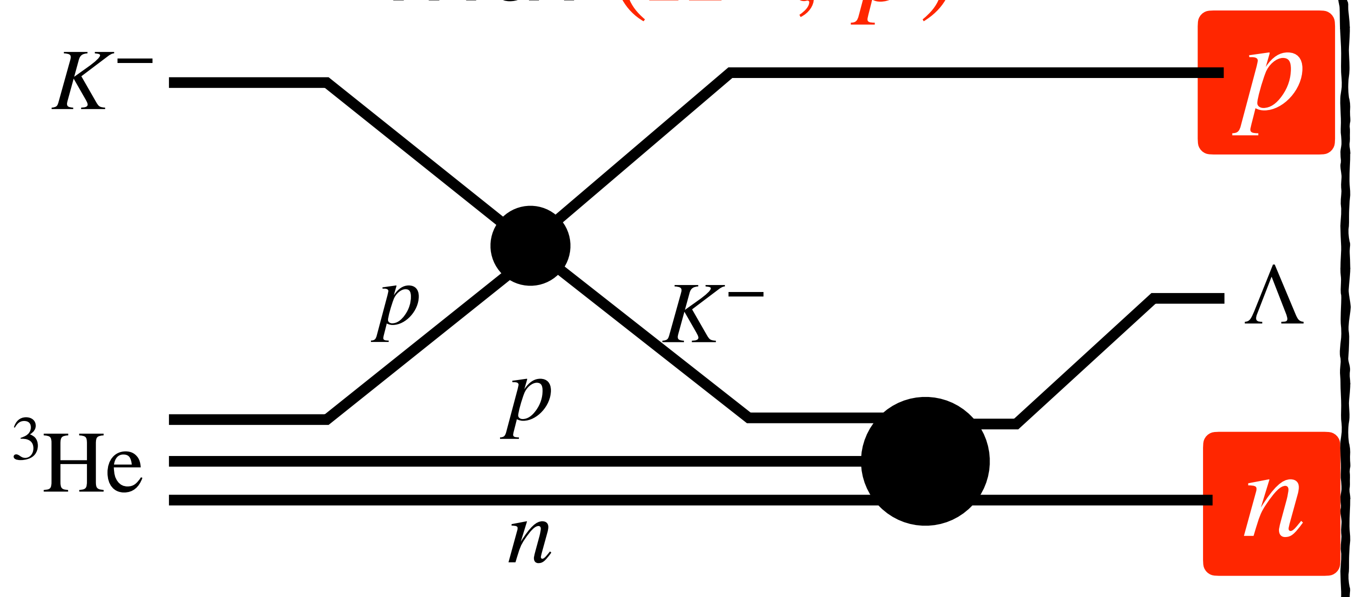
Quasi-free process with (K^-, n)



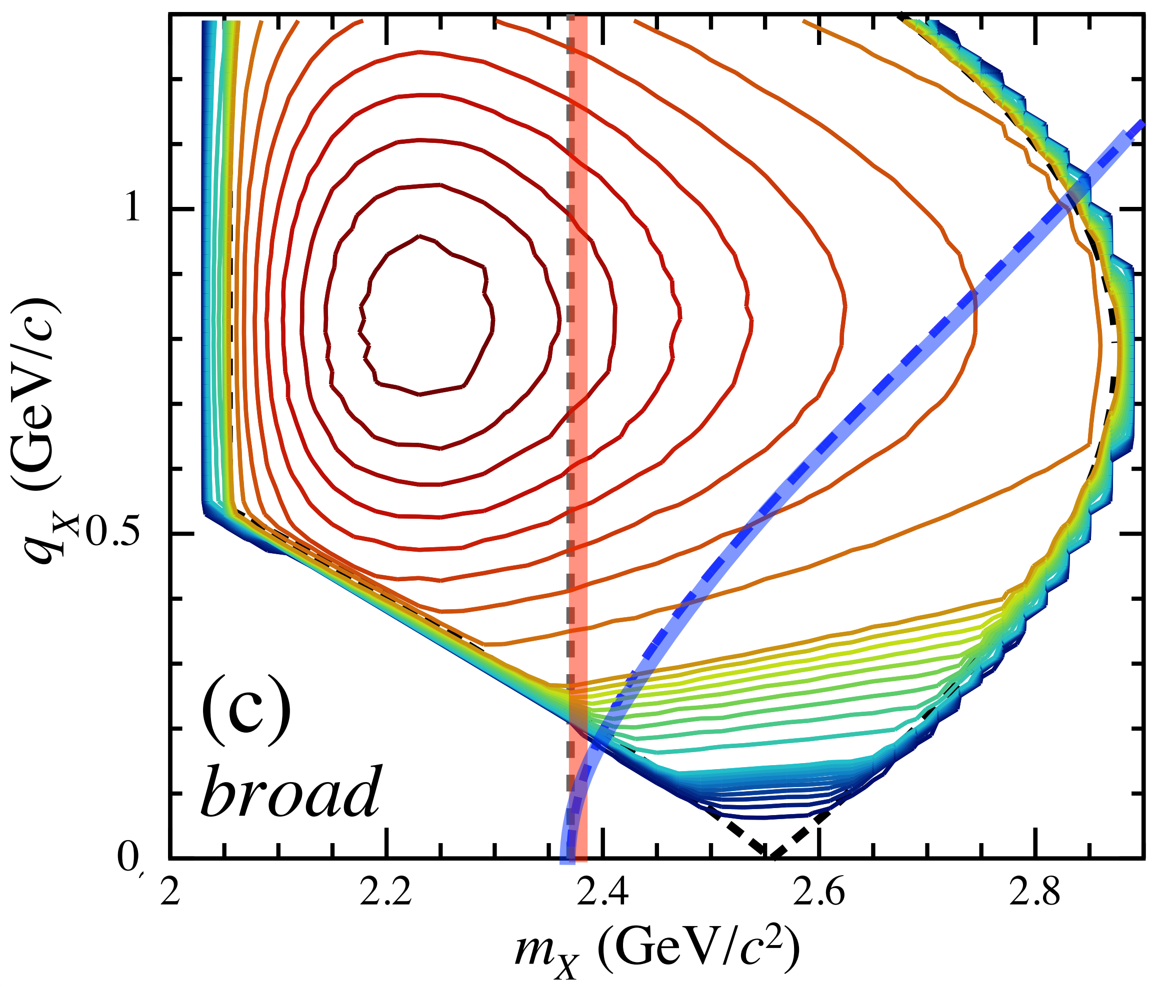
$$f_{QF}(m_X, q_X) = \exp\left(-\frac{(m_X - M_F(q_X))^2}{\sigma^2(q_X)}\right) \times g_{QF}(q_X)$$



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

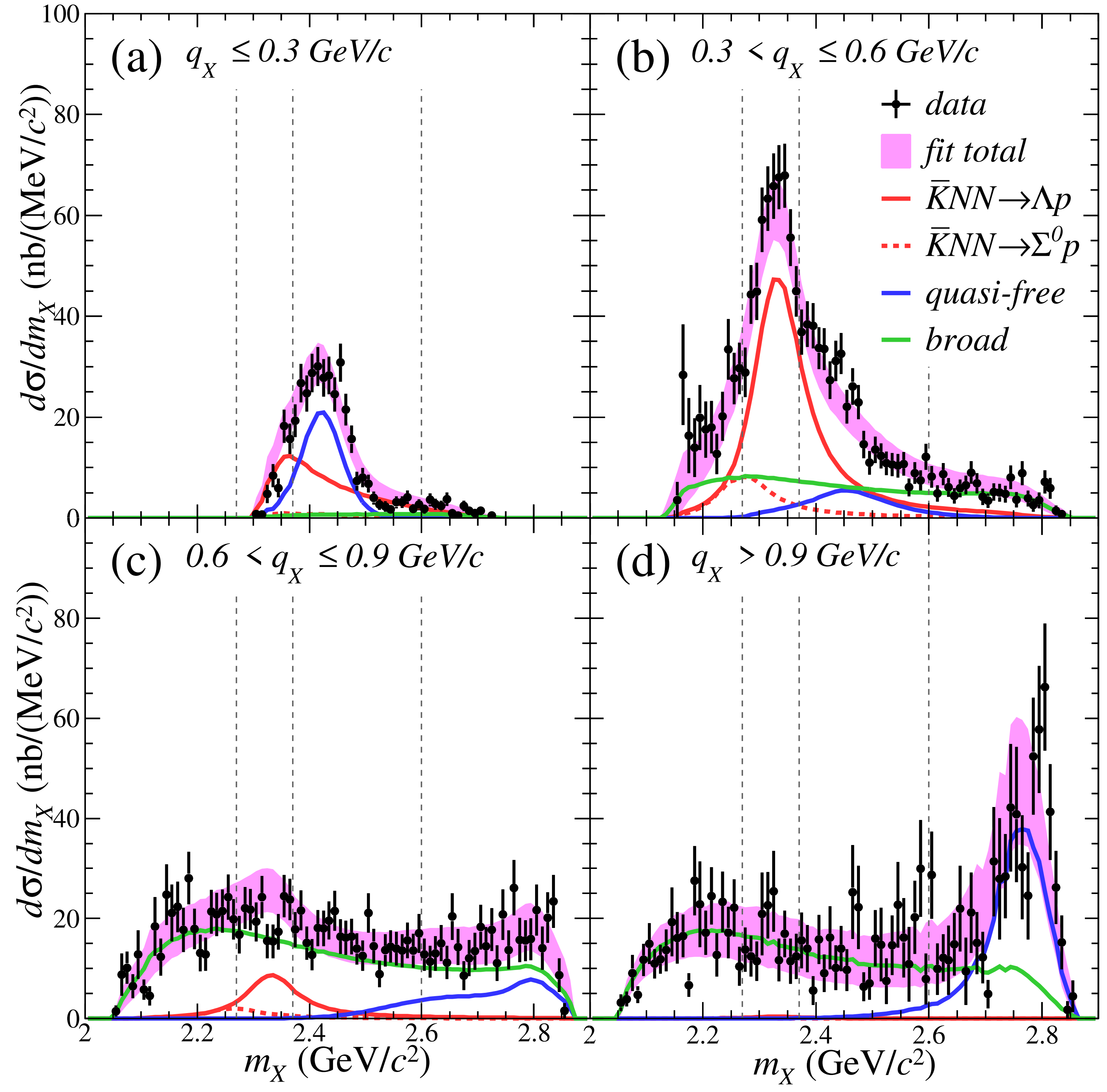


widely distributing

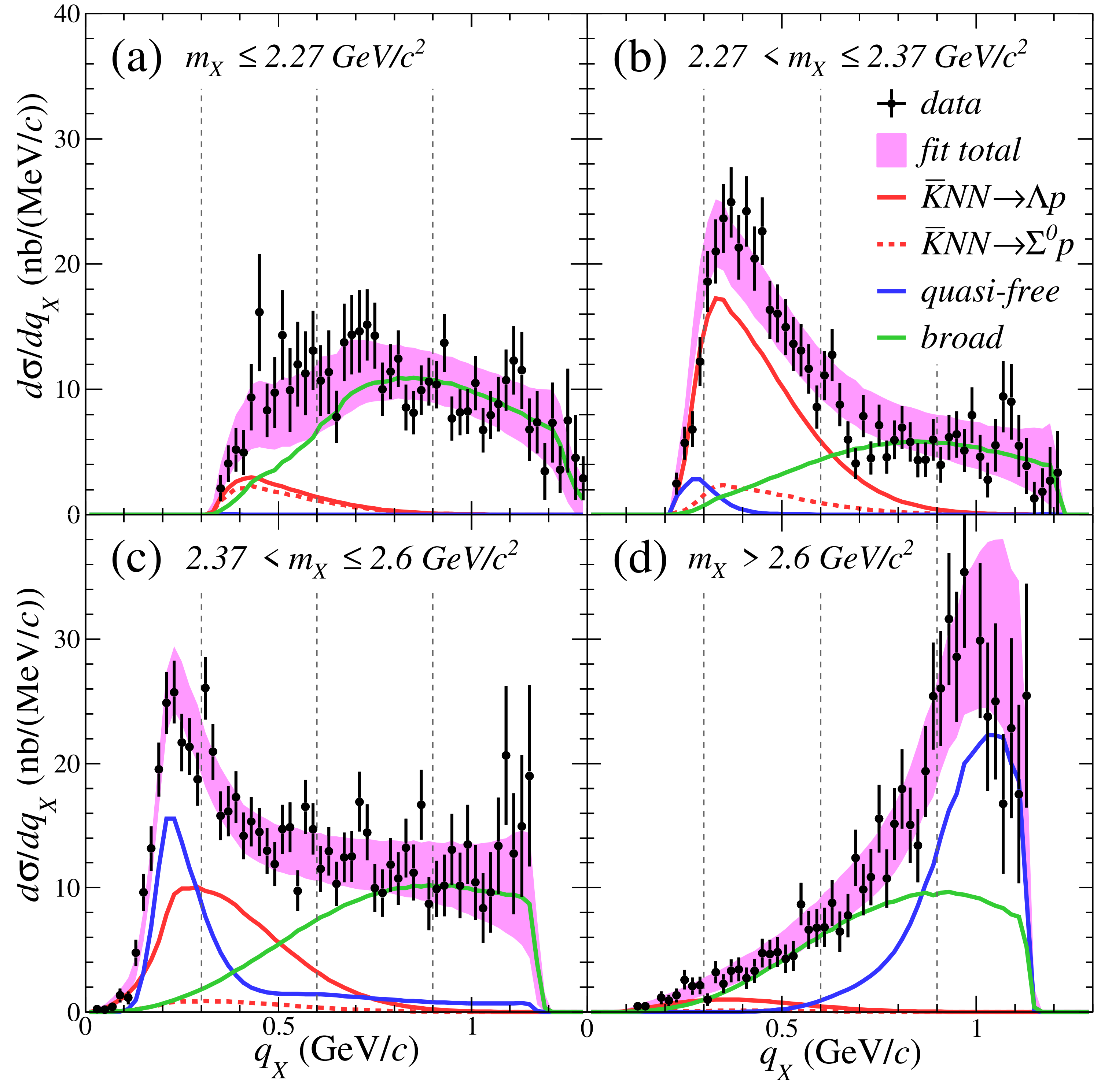


Fit result

Λp invariant-mass

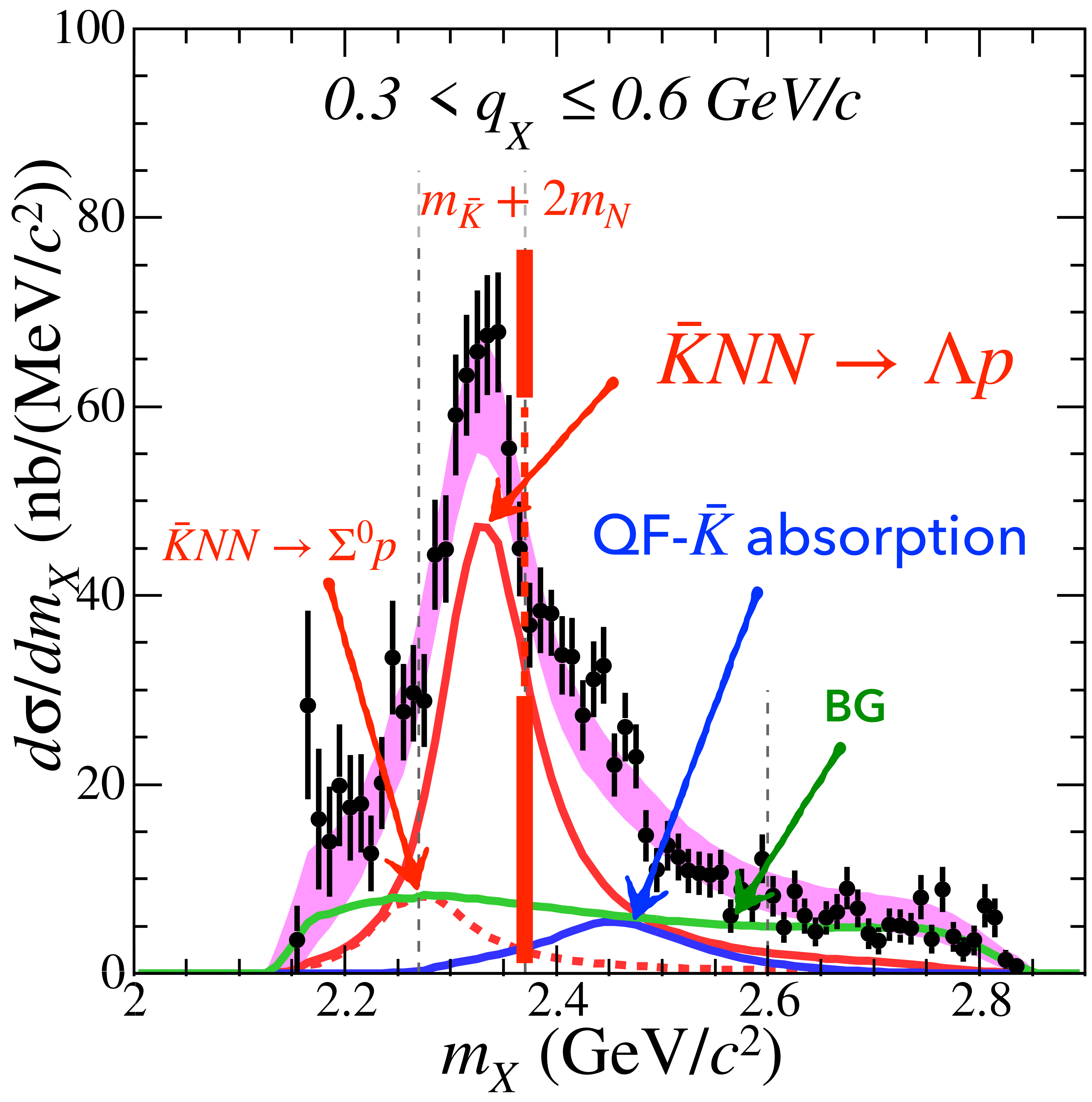


Momentum transfer to Λp



Whole distributions are 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 $M_{\bar{K}NN}$.

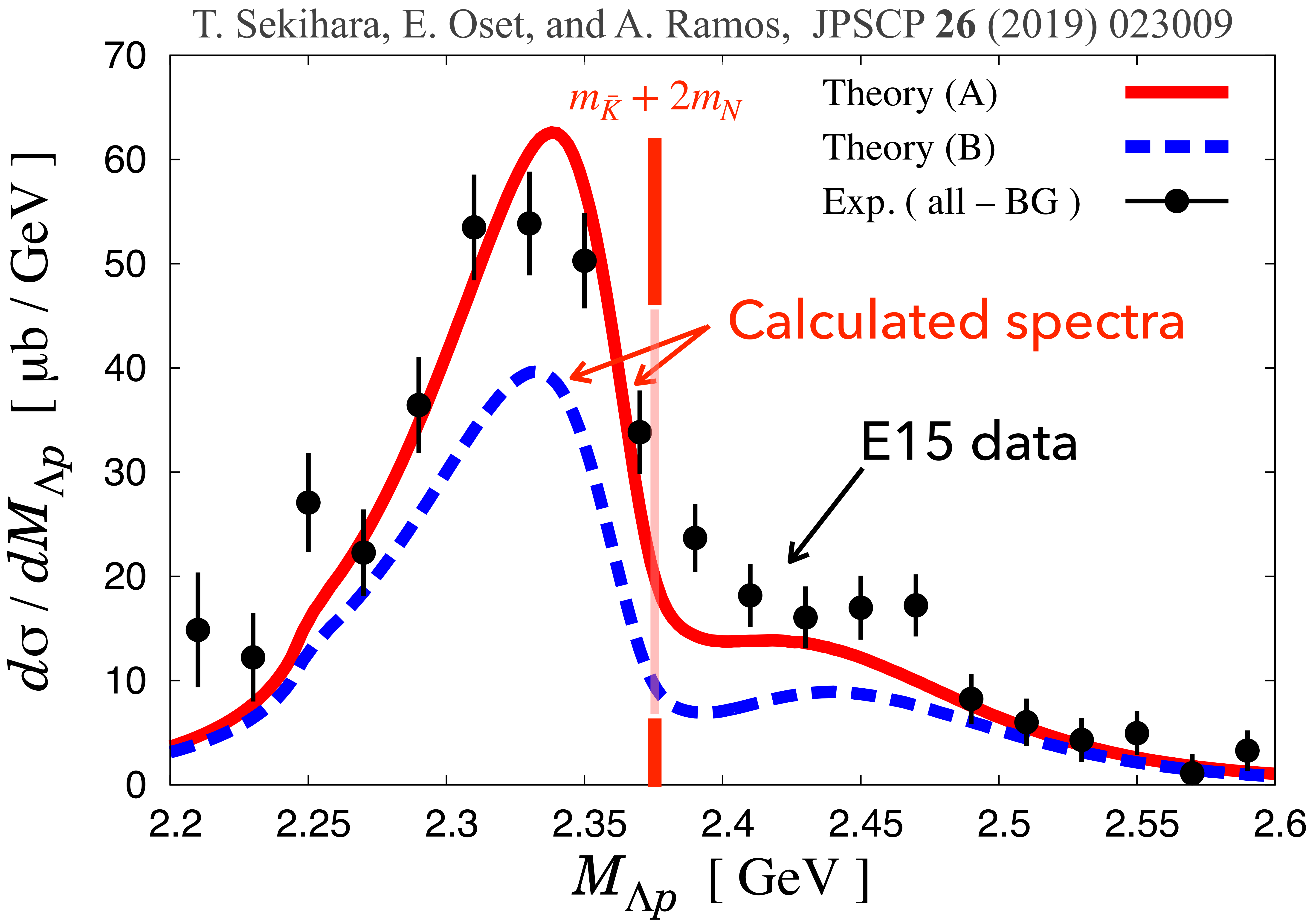
➔ *We interpreted it as $\bar{K}NN$ signal.*

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

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

* 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.

Remaining questions

Is the observed resonance really what we expected?

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

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

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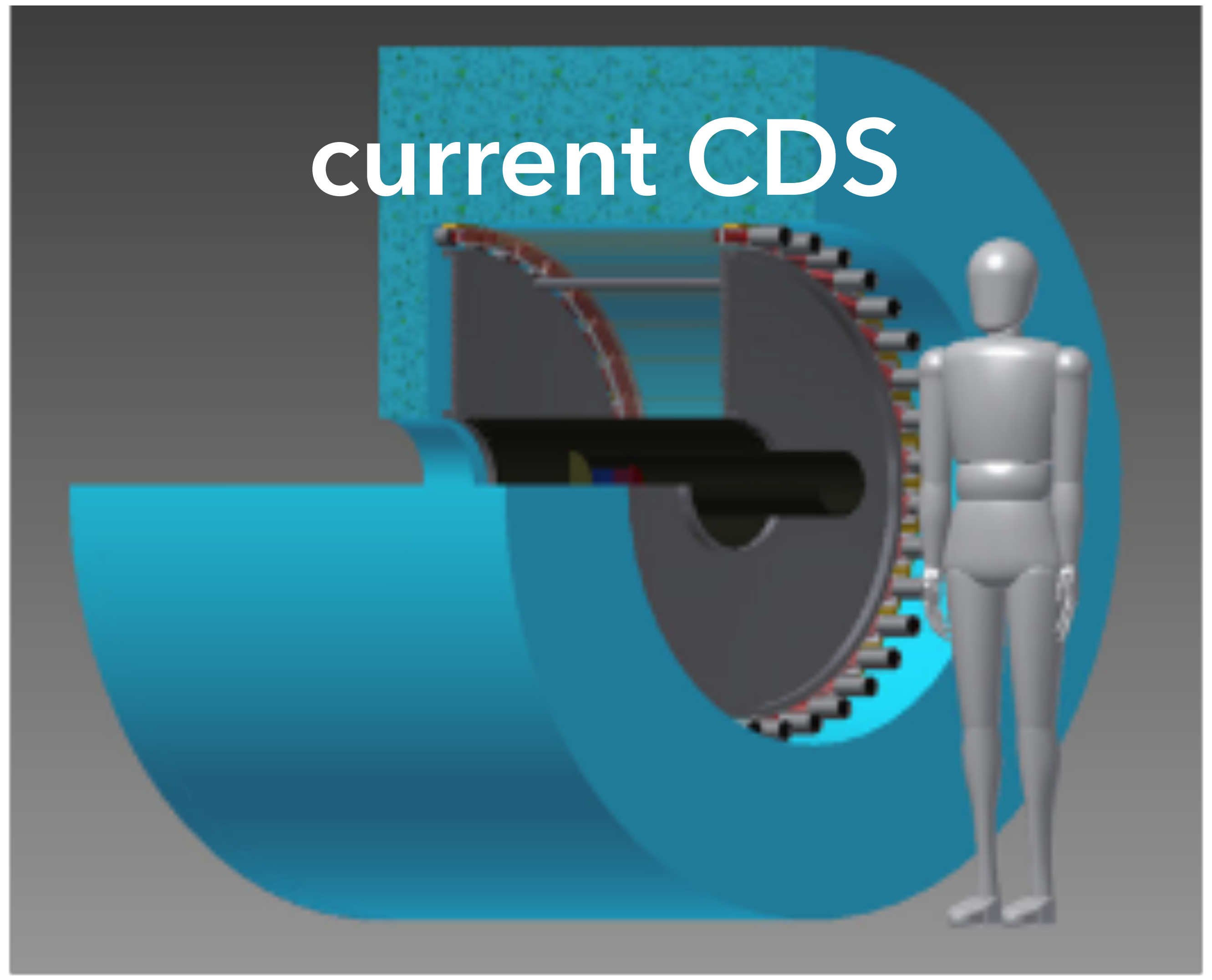
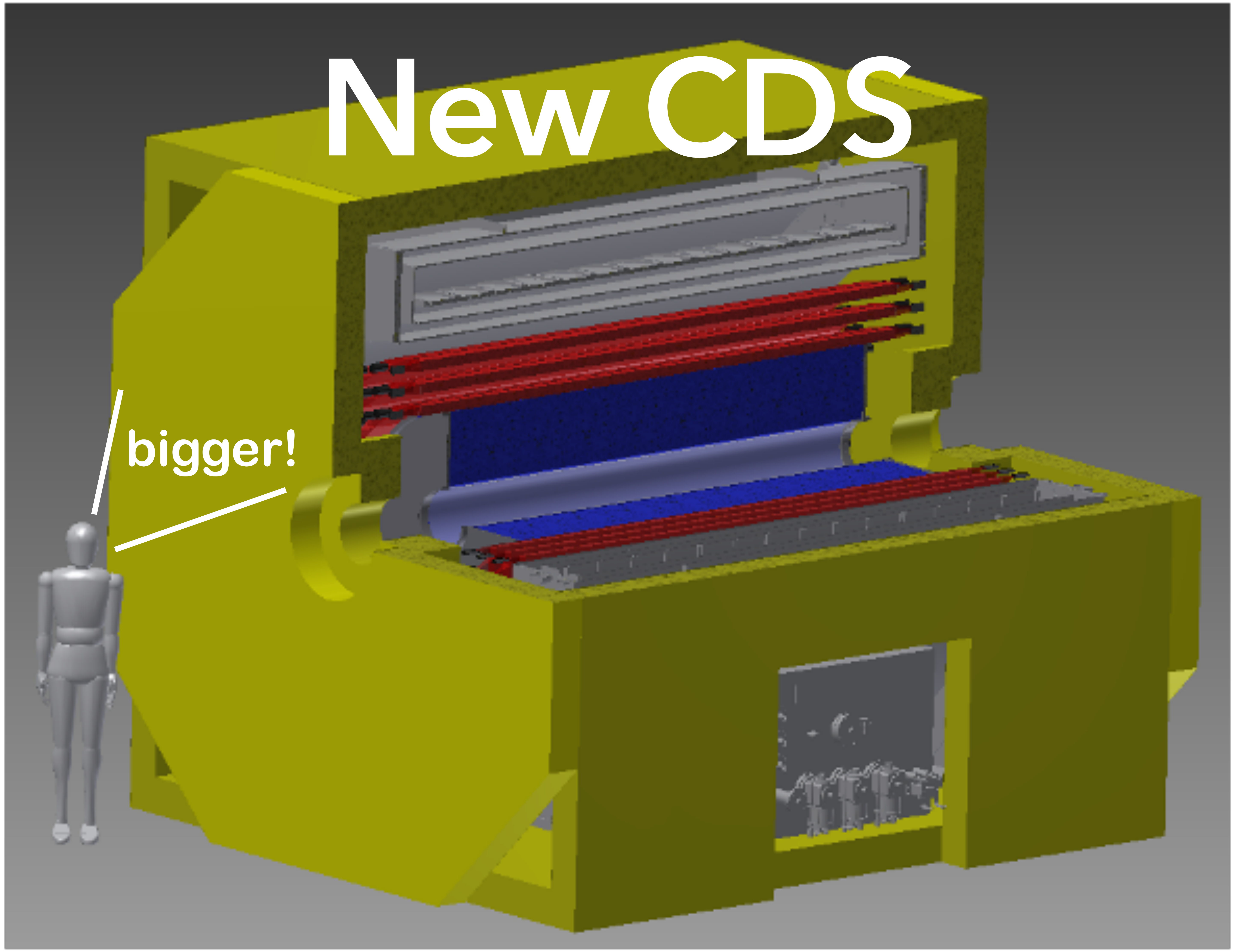
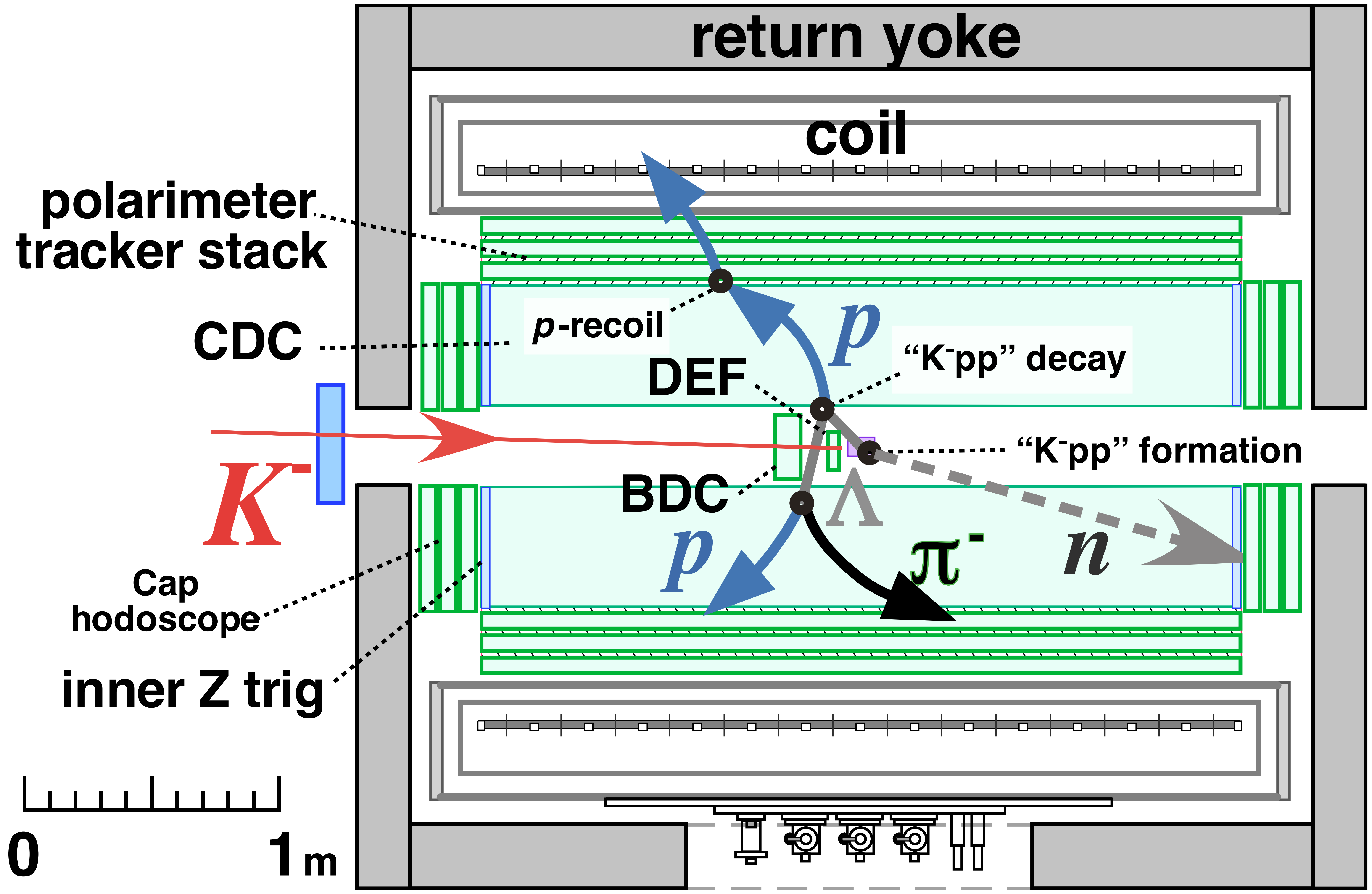
We need further systematic measurements
to answer the questions & to robustly confirm $\bar{K}$-nuclei.

Future experiments





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^P 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}He(K^-, N) reaction

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

$\bar{K}NNNN$ system

Expected large B.E. & high density

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

K^--α $\quad$ $\bar{K}^0$-α

Determination of J^P for $\bar{K}NN$

Internal configuration & J^P

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

Possible internal configurations have different J^P.

How to determine J^P

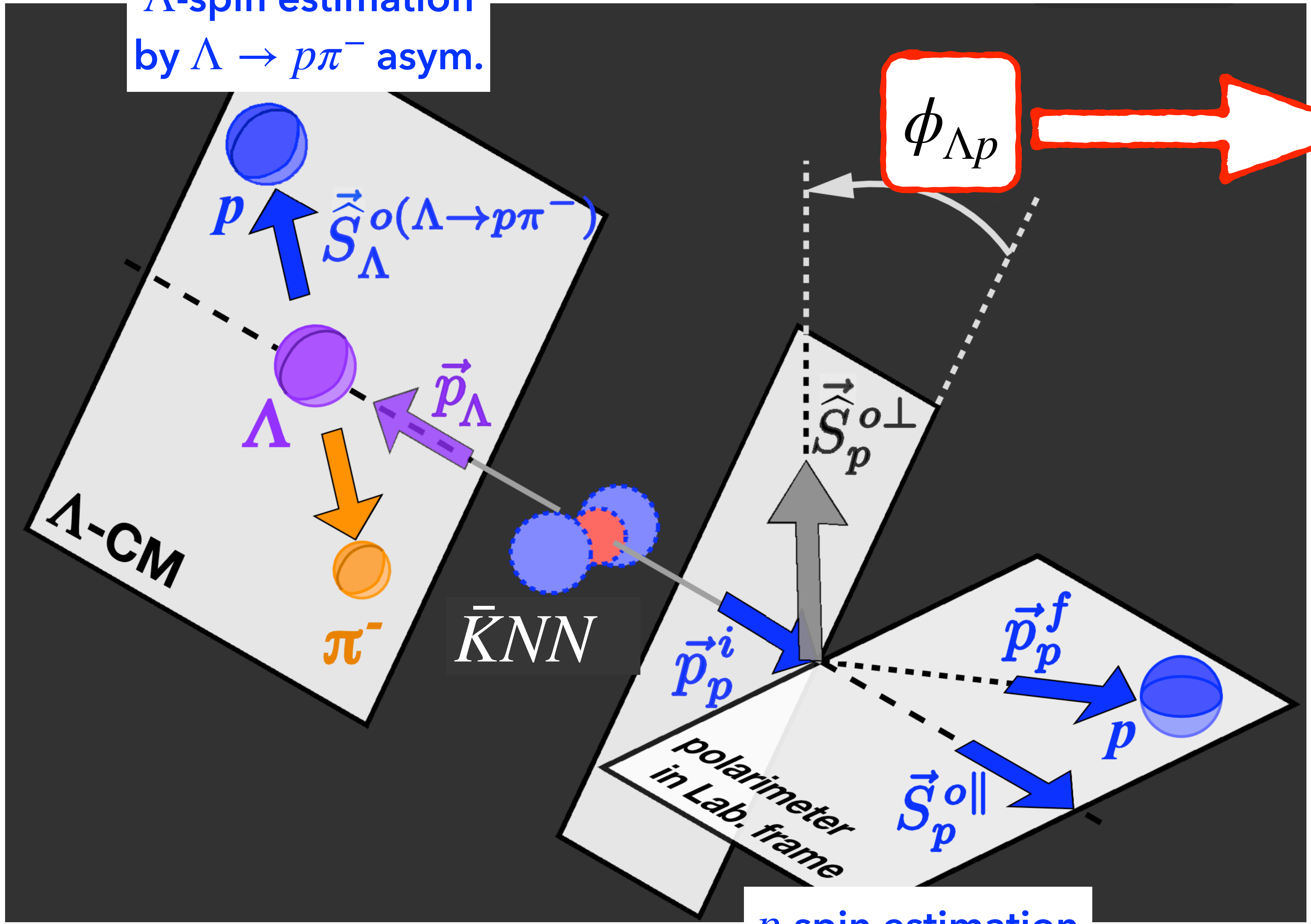
$(\bar{K}[NN]^{I=0})^{I=1/2}$	$(\bar{K}[NN]^{I=1})^{I=1/2}$	$(\Sigma^* N)^{I=1/2}$
$J^\pi = 1^-$	$J^\pi = 0^-$	$J^\pi = 2^+$
$[L_{\Lambda p} = 1]$	$[L_{\Lambda p} = 1]$	$[L_{\Lambda p} = 2]$
$\otimes$	$\otimes$	$\otimes$
$\frac{2}{3}[S_{\Lambda p} = 1] + \frac{1}{3}[S_{\Lambda p} = 0]$	$[S_{\Lambda p} = 1]$	$\frac{1}{2}[S_{\Lambda p} = 1] + \frac{1}{2}[S_{\Lambda p} = 0]$
⇩	Spin alignment $\alpha_{\Lambda p}$ ⇩	⇩
$\alpha_{\Lambda p} = +1/3$	$\alpha_{\Lambda p} = +1$	$\alpha_{\Lambda p} = \pm 0$

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

Measurement of $\alpha_{\Lambda p}$

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

Λ-spin estimation by $\Lambda \rightarrow p\pi^-$ asym.



p-spin estimation by p-C scat. asym.

Spin-spin correlation on ϕ-asymmetry

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

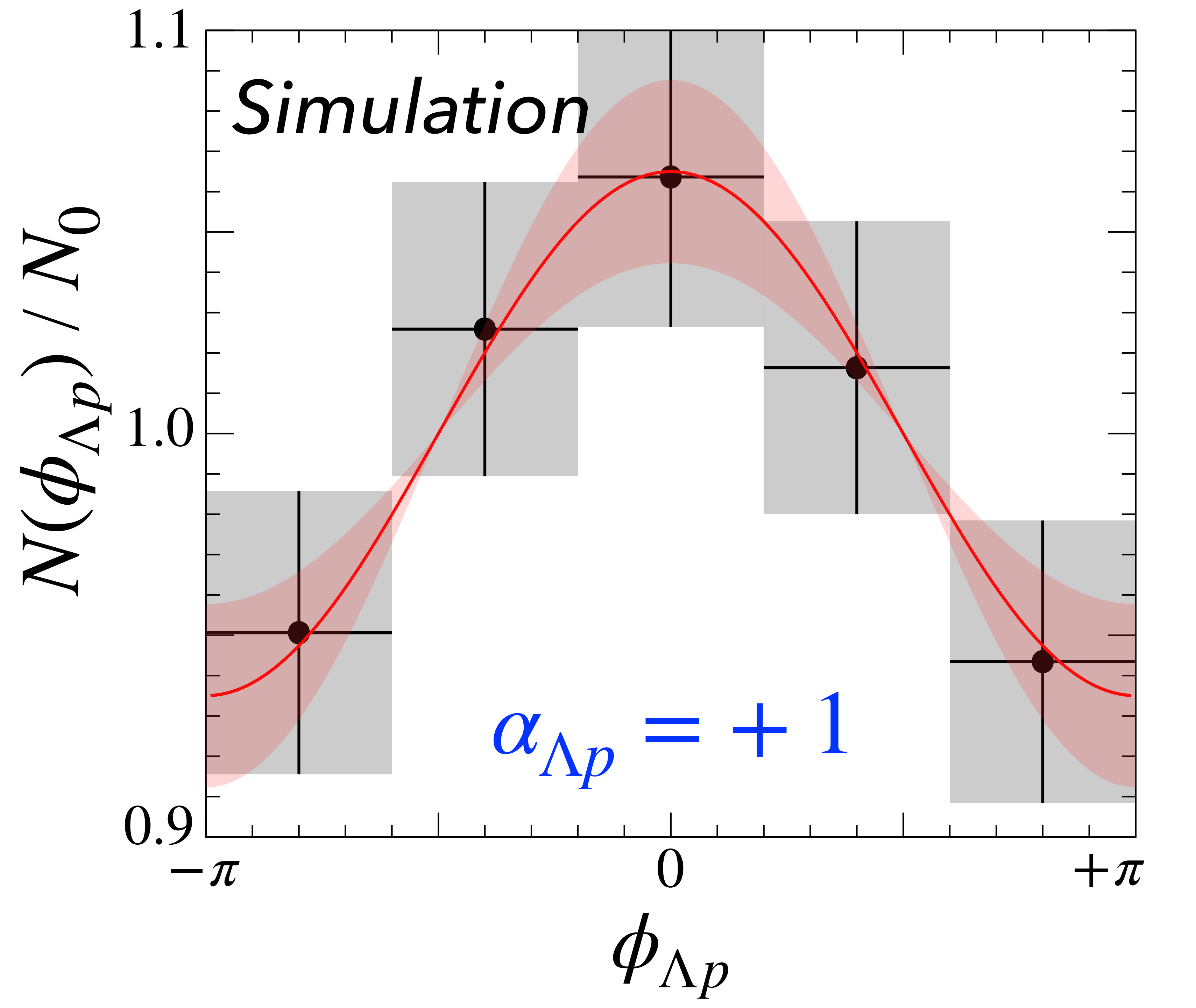
$r^{(J^P)}$: asymmetry reduction factor defined by;

- 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

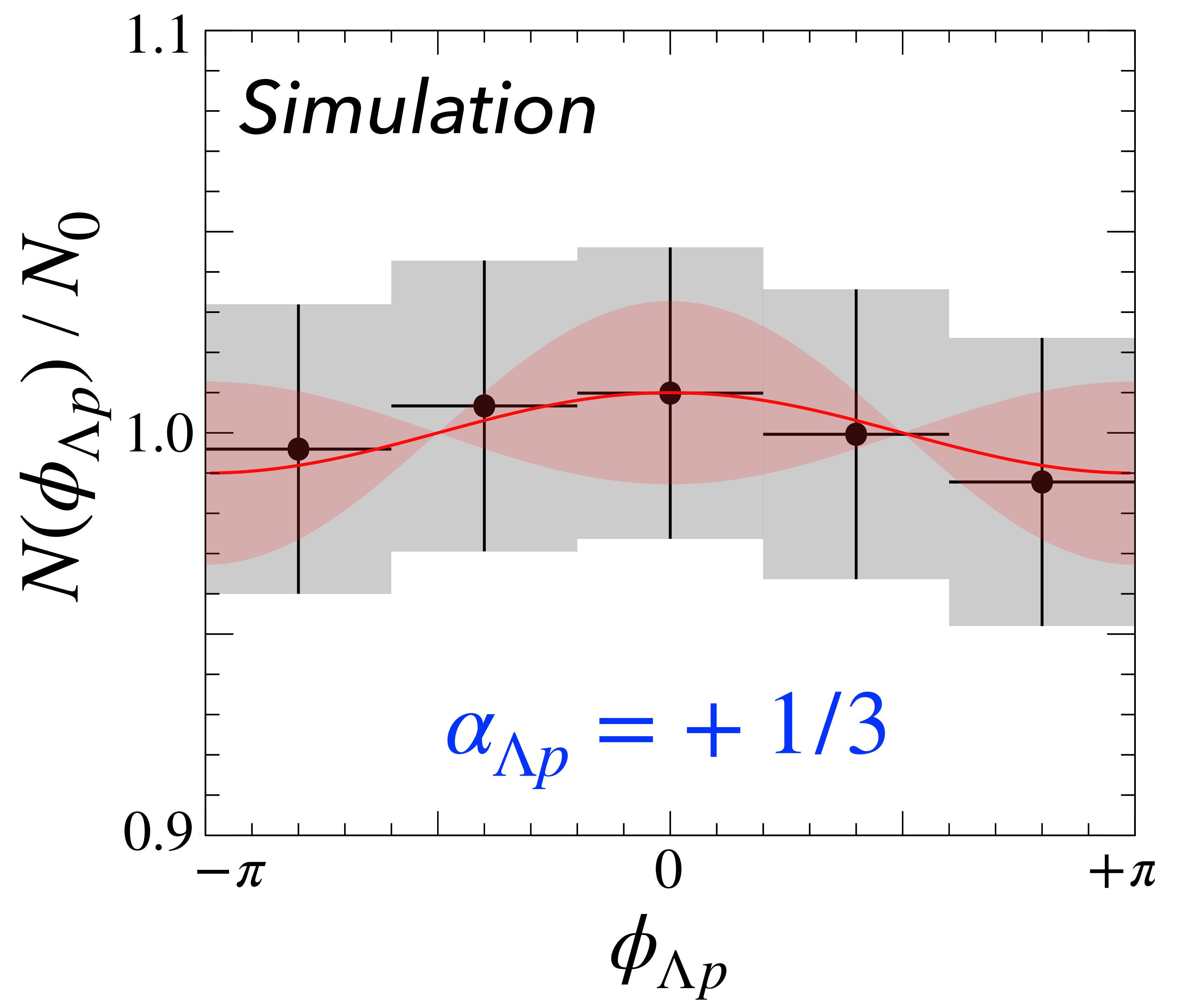
Expected $\phi_{\Lambda p}$ distributions

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

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



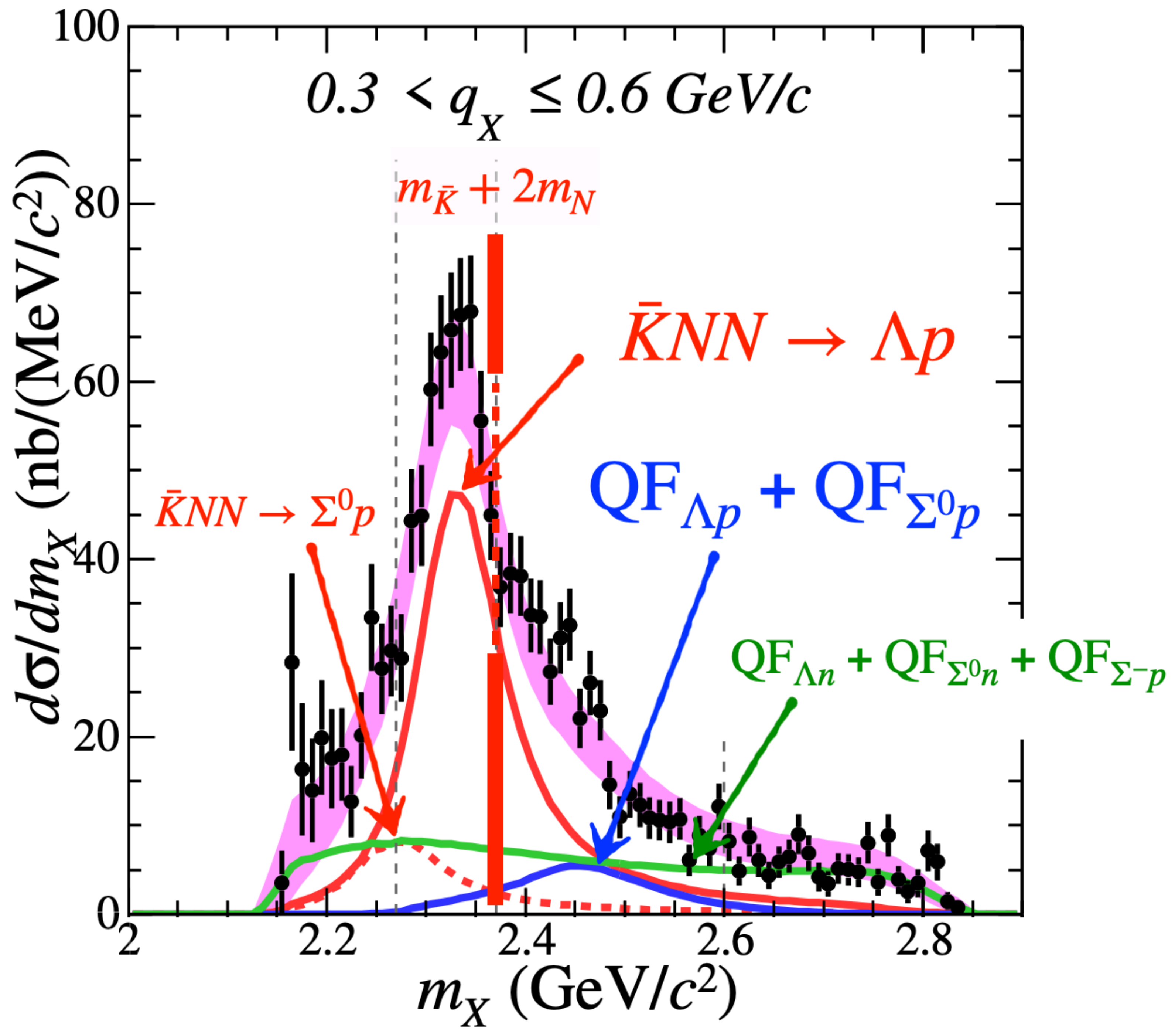
$(\bar{K}[NN]^{I=0})^{I=1/2} : J^\pi = 1^-$



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

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 =

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