Investigation of fundamental properties of the $\bar{K}NN$ state

32nd J-PARC PAC meeting
(14-16, July, 2021)

Takumi Yamaga (RIKEN)

Short summary

– For stage-1 approval –

Beam-time request

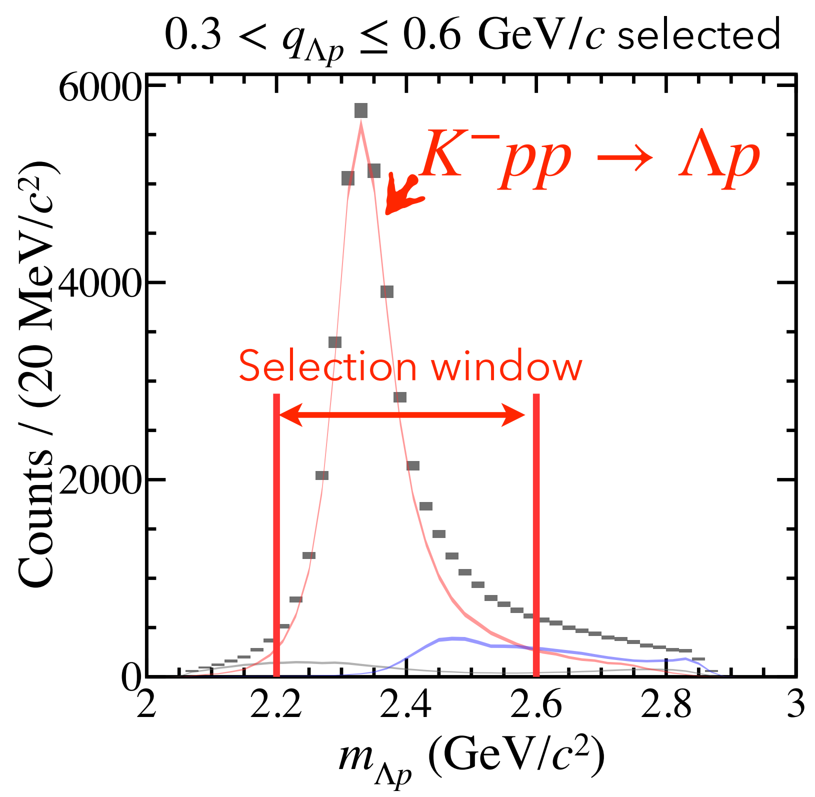
8 weeks ⊗ 90 kW @ K1.8BR

(648 kW·week @ 90% up-time)

Expected results

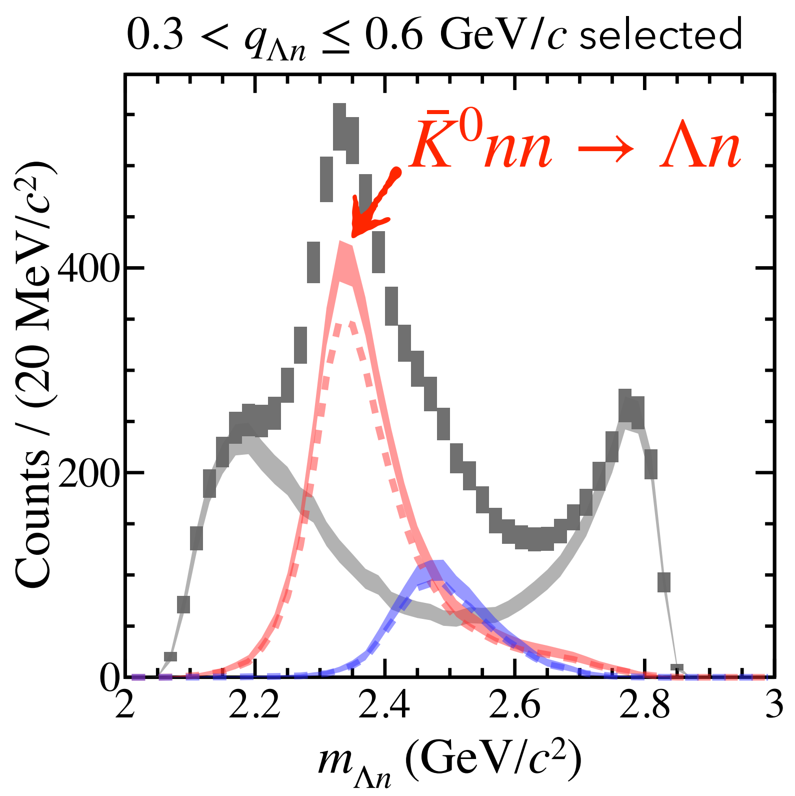
To confirm $I = 1/2\ \bar{K}NN$ doublet

Measurement for Λp pair



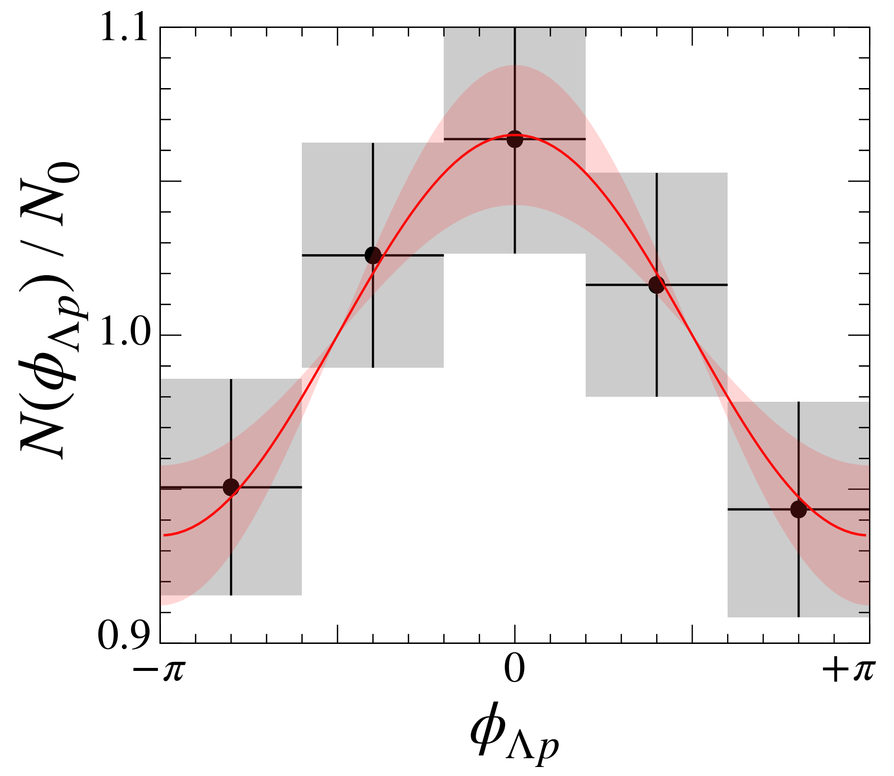
Measurement for Λn pair

*Assuming $J^P = 0^-$ (strict case)

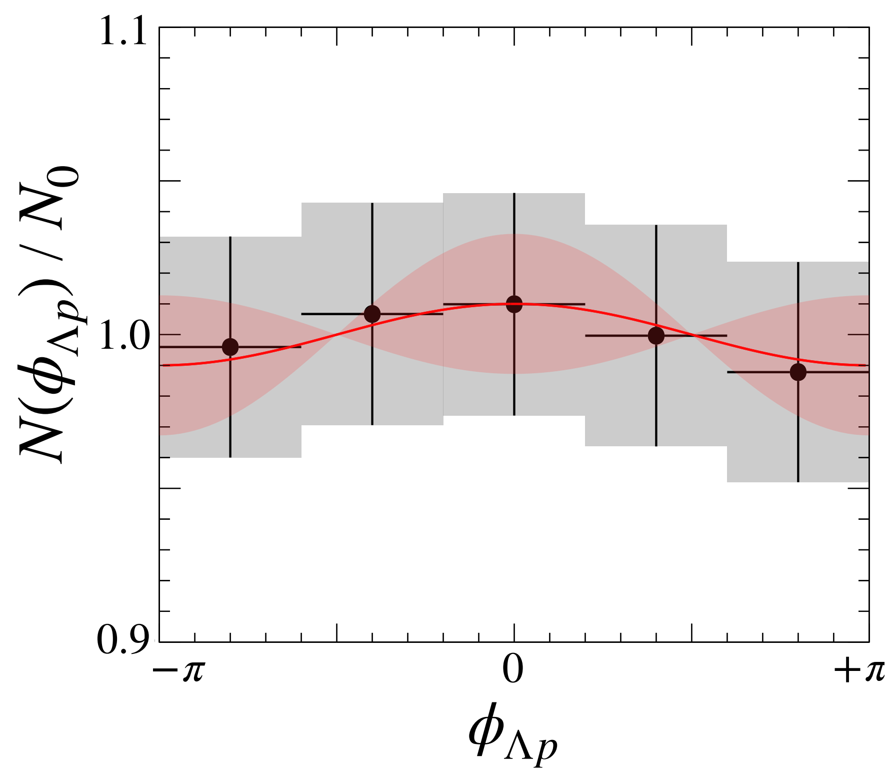


To determine J^P of $\bar{K}NN$

$J^P = 0^-$



$J^P = 1^-$

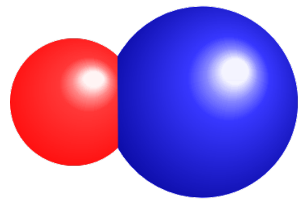


New programs for kaonic nuclei

– Further investigation of $\bar{K}NN$ & Searching for lighter & heavier systems –

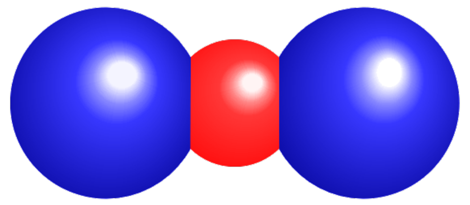
– This experiment –

Lighter system



$\Lambda(1405) = K^{-}p$

$\bar{K}NN$ system



Most fundamental / Internal structure

J^P determination

Study for $\bar{K}^0nn$

Relation to Λ^*

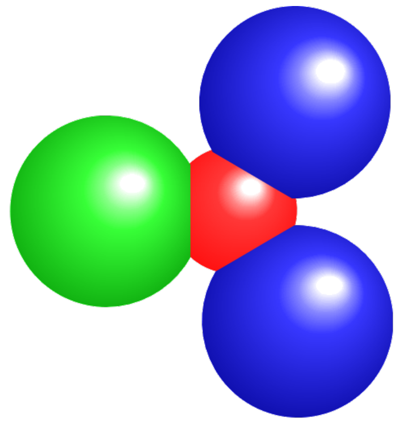
Decay branch

Large Γ

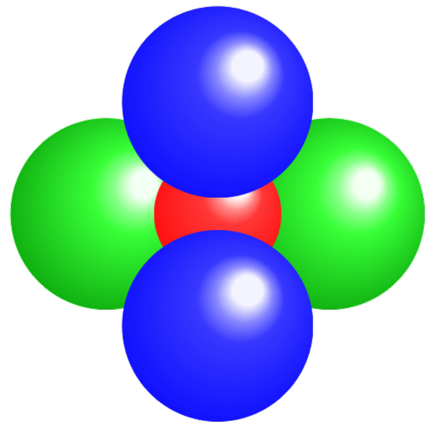
Heavier system

E80 $\bar{K}NNN$ system

Spokesperson : F. Sakuma



$\bar{K}NNNN$ system



$\bar{K}\alpha\alpha$ system

The simplest kaonic nucleus system, $\bar{K}NN$

– Exotic bound state resulting strong attractive $\bar{K}N$ interaction –

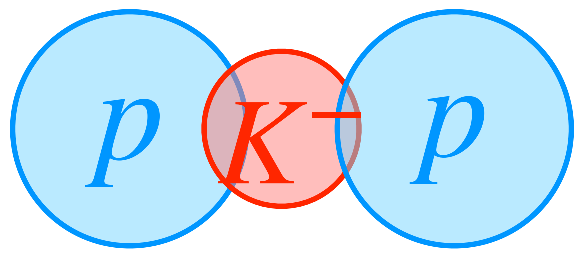
$\bar{K}NN$ bound state

Bound system of anti-kaon and two nucleons

$$\left[\bar{K}_{I=\frac{1}{2}}(NN)_{I=1}\right]_{I=\frac{1}{2}} \quad (J^P = 0^-)$$

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

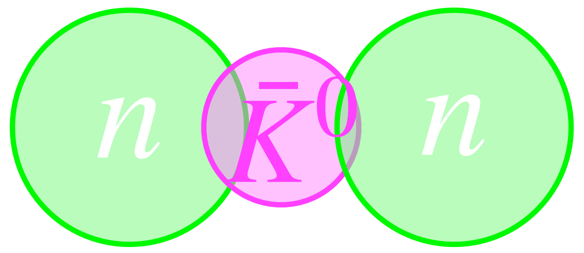
$(K^-pp$ - $\bar{K}^0pn)$



"K^-pp"

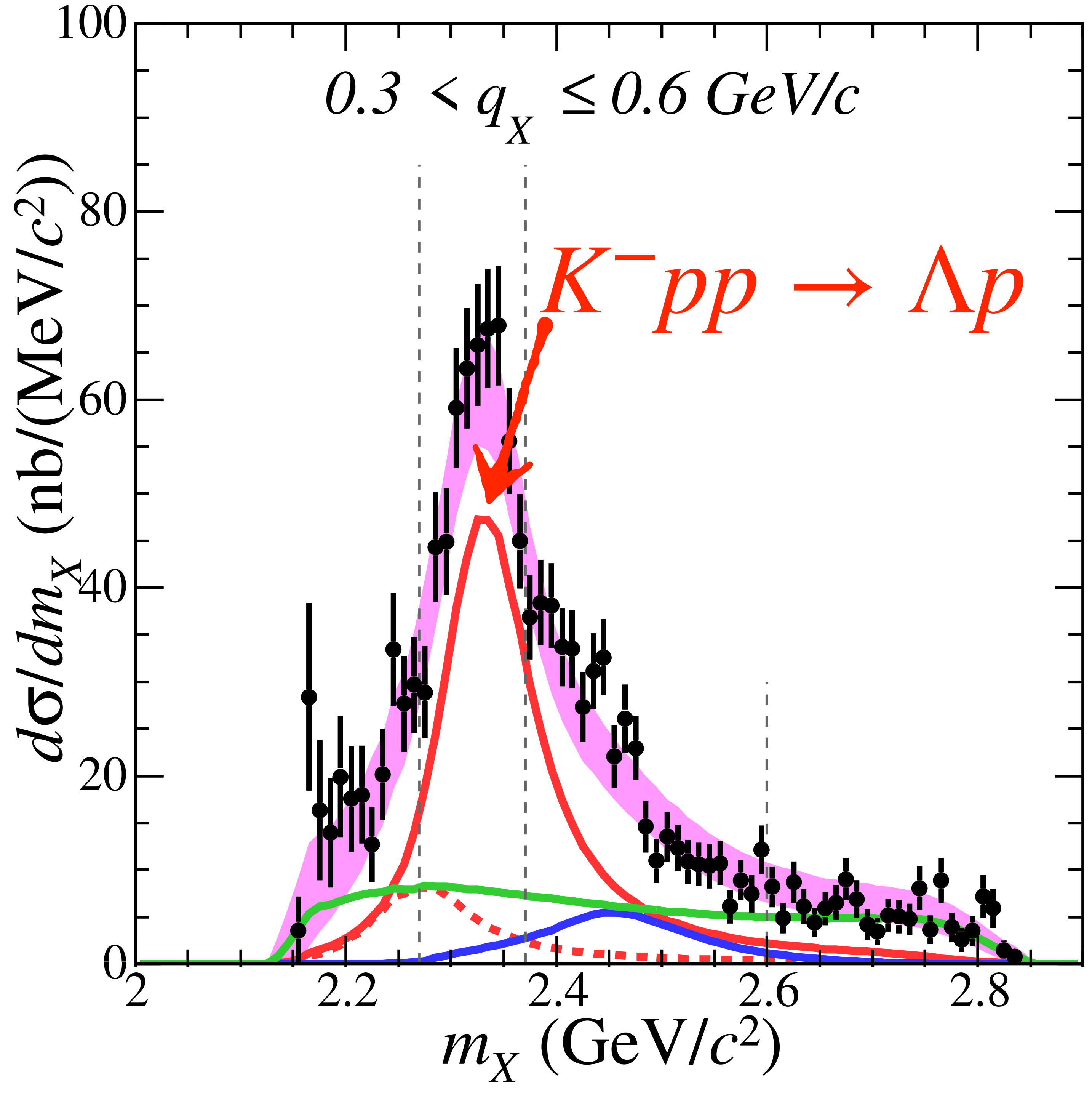
$I^{(z)}_{\bar{K}NN} = -1/2$

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



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

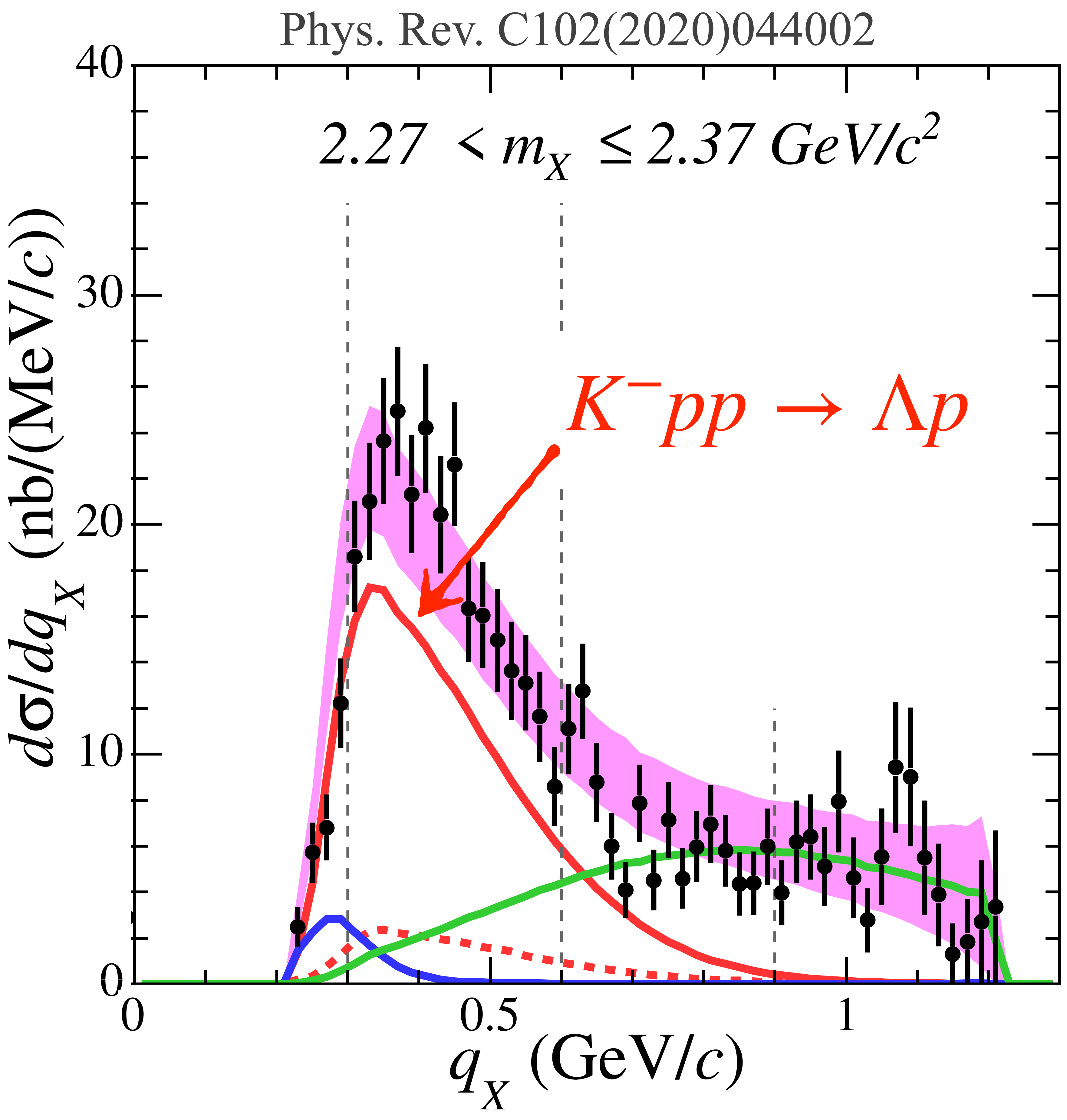
Phys. Rev. C102(2020)044002



A clear formation signal of K^-pp was observed.

The simplest kaonic nucleus system, $\bar{K}NN$

– Momentum transfer dependence & spacial size of the $\bar{K}NN$ –



q_X -dependence based on PWIA

$$\frac{d\sigma}{dq_X} \propto \exp\left(-\frac{q^2}{Q^2}\right)$$

$Q \sim 400$ MeV/c : S-wave Gaussian form factor

The result suggests that the spacial size would be surprisingly small ($r \sim 0.6$ fm).

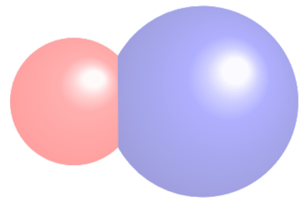
We need more precise measurement & analysis to conclude the spacial size of the $\bar{K}NN$

New programs for kaonic nuclei

– Further investigation of $\bar{K}NN$ & Searching for lighter & heavier systems –

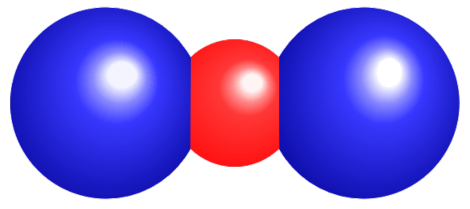
– This experiment –

Lighter system



$\Lambda(1405) = K^{-}p$

$\bar{K}NN$ system



Most fundamental / Internal structure

J^P determination

Study for $\bar{K}^0 nn$

Relation to Λ^*

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Heavier system

E80 $\bar{K}NNN$ system

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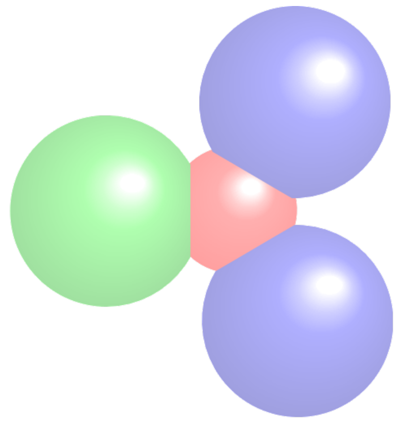
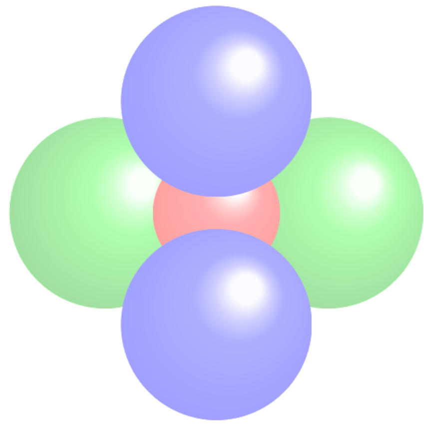


$\bar{K}NNNN$ system



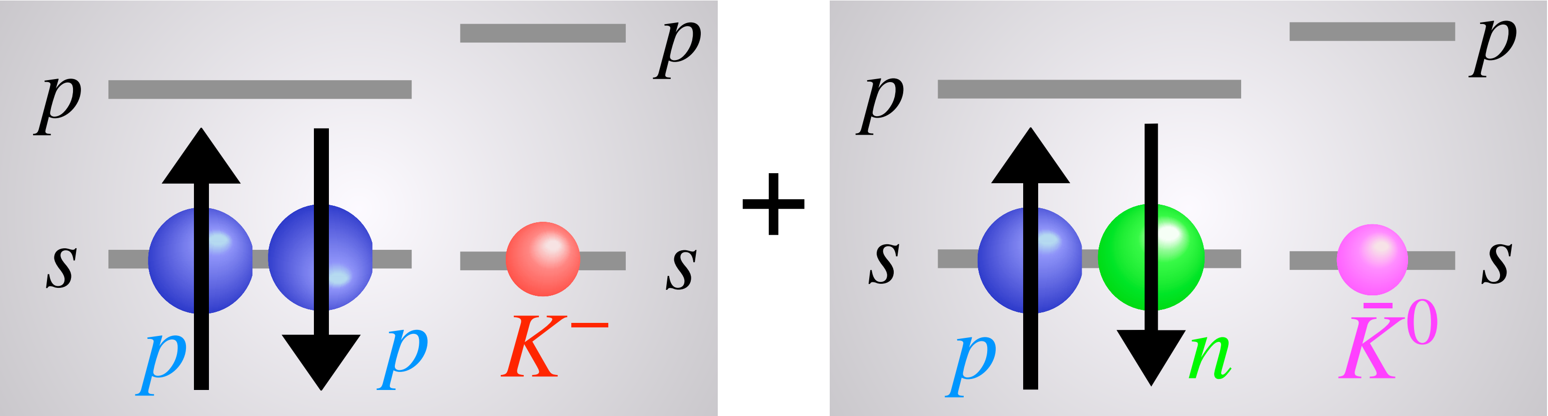
$\bar{K}\alpha\alpha$ system

Internal structure & spin-parity

There are two possible J^P as for the $\bar{K}NN$ ground state.

$$\text{“} (NN)_{(I.sym \times S.asym)} \otimes \bar{K} \text{”}$$

$$J^P = 0^-$$

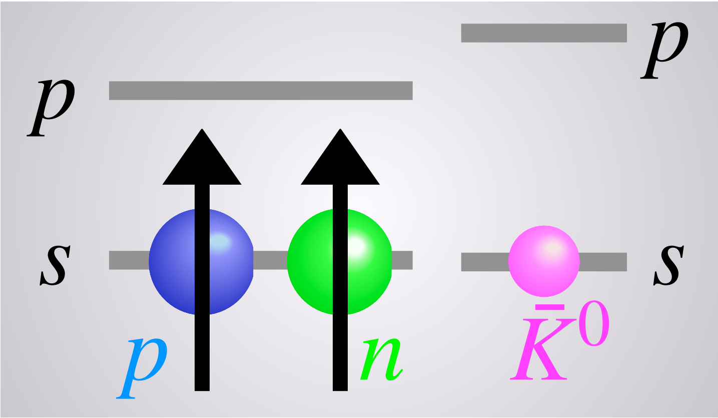


$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{3}{1}$$

Deeper bound expected

$$\text{“} (NN)_{(I.asym \times S.sym)} \otimes \bar{K} \text{”}$$

$$J^P = 1^-$$



$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{1}{3}$$

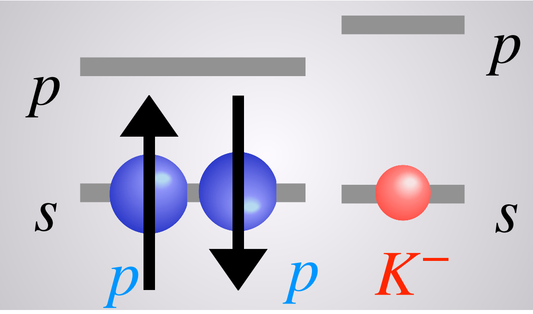
Shallower bound expected

* *Positive parity state should be higher excited state if exist.*

How to determine J^P

– Λp spin-spin correlation ($\alpha_{\Lambda p}$) in $K^- pp \to \Lambda p$ decay –

$J^P = 0^-$



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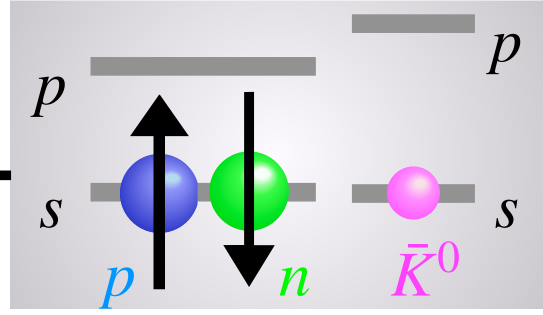


To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 0$

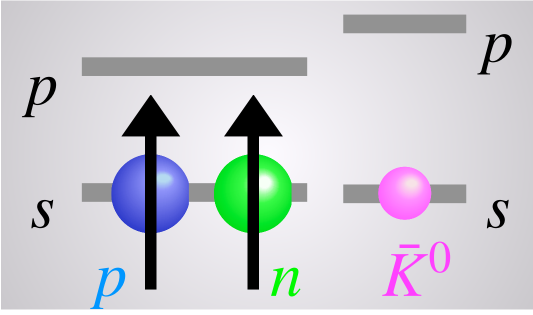
$S_{\Lambda p} = 1$

⬇

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

Spin parallel

$J^P = 1^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 1$

$BR = 1/3$ $S_{\Lambda p} = 0$ + $S_{\Lambda p} = 1$ $BR = 2/3$

⬇ ⬇

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

Spin anti-parallel *Spin parallel*

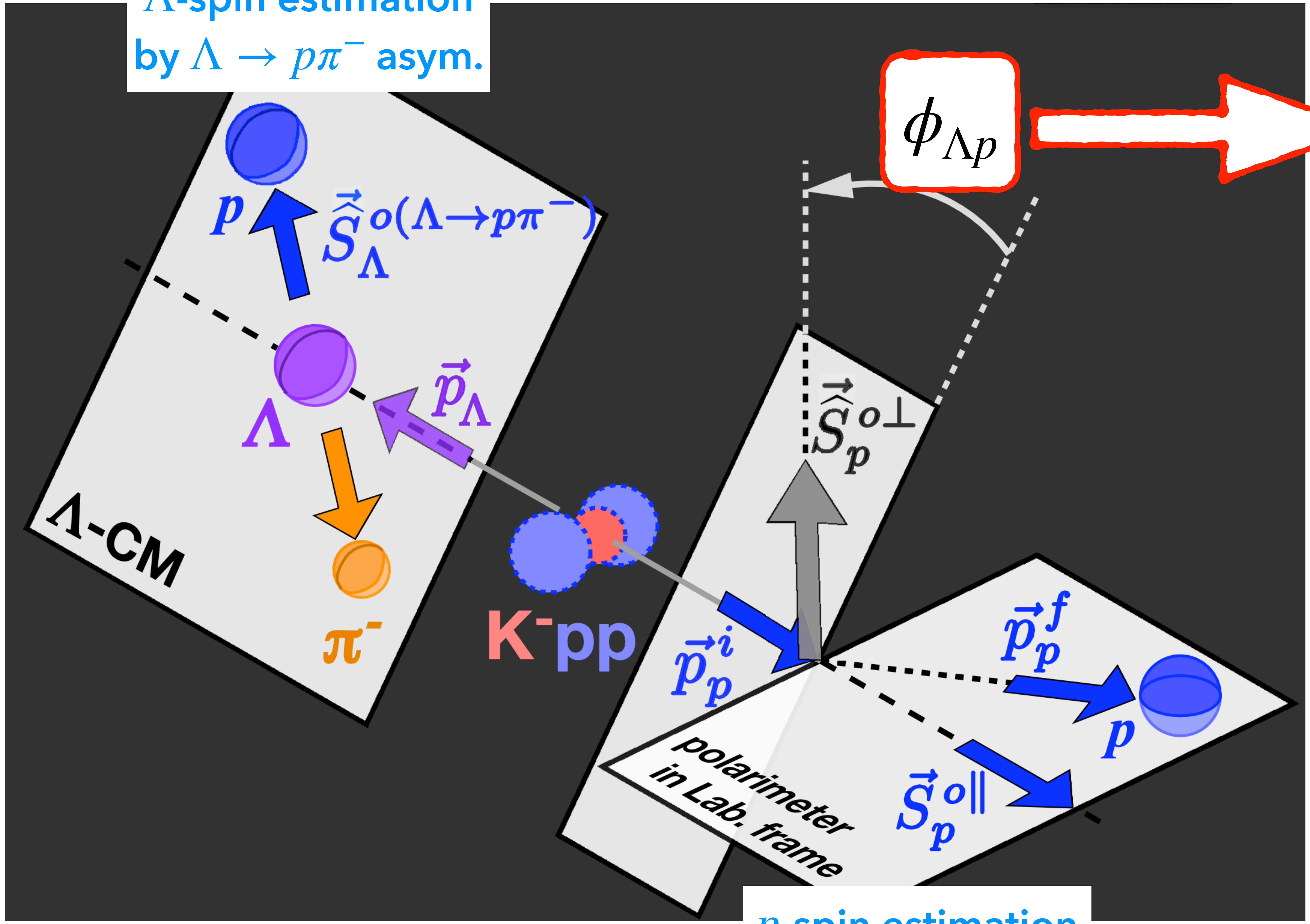
We can deduce J^P from $\alpha_{\Lambda p}$ measurement.

Experimental method

How to measure spin-spin correlation

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

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



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

Spin-spin correlation on ϕ-asymmetry

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

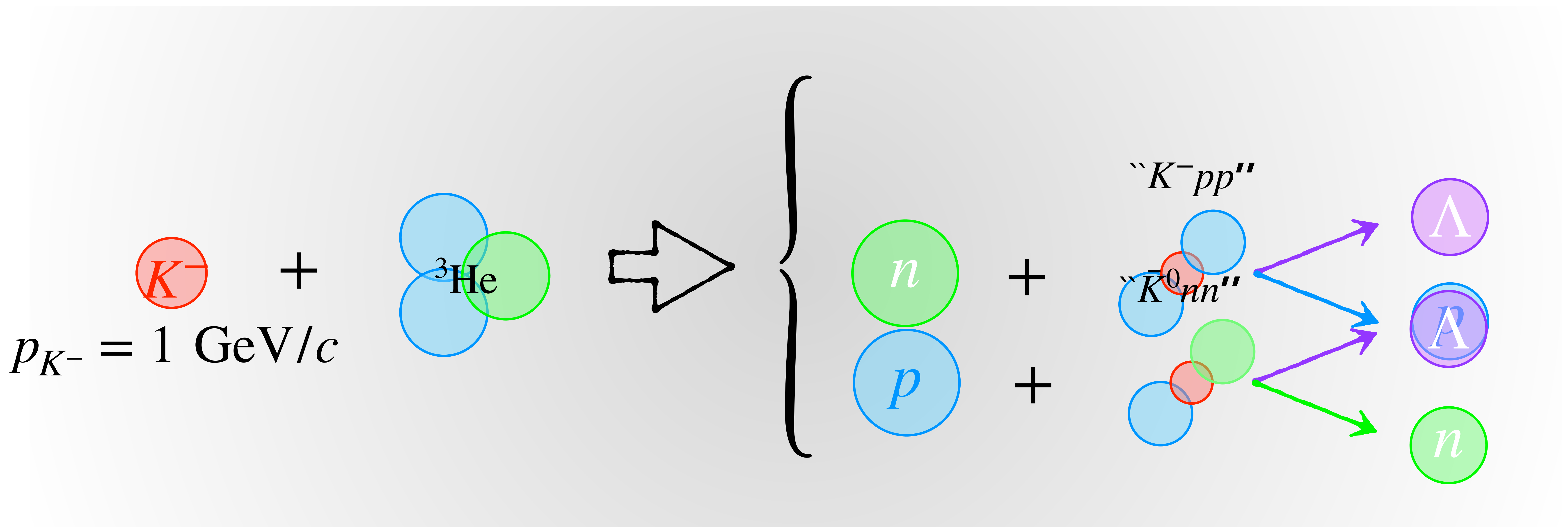
$r^{(J^P)}$: asymmetry reduction factor defined by;

- 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

We can observe $\alpha_{\Lambda p}$ from $\phi_{\Lambda p}$-distribution.

How to produce $\bar{K}NN$

$\bar{K}NN$ production in $K^- + {}^3\mathrm{He} \to \Lambda pn$ reaction



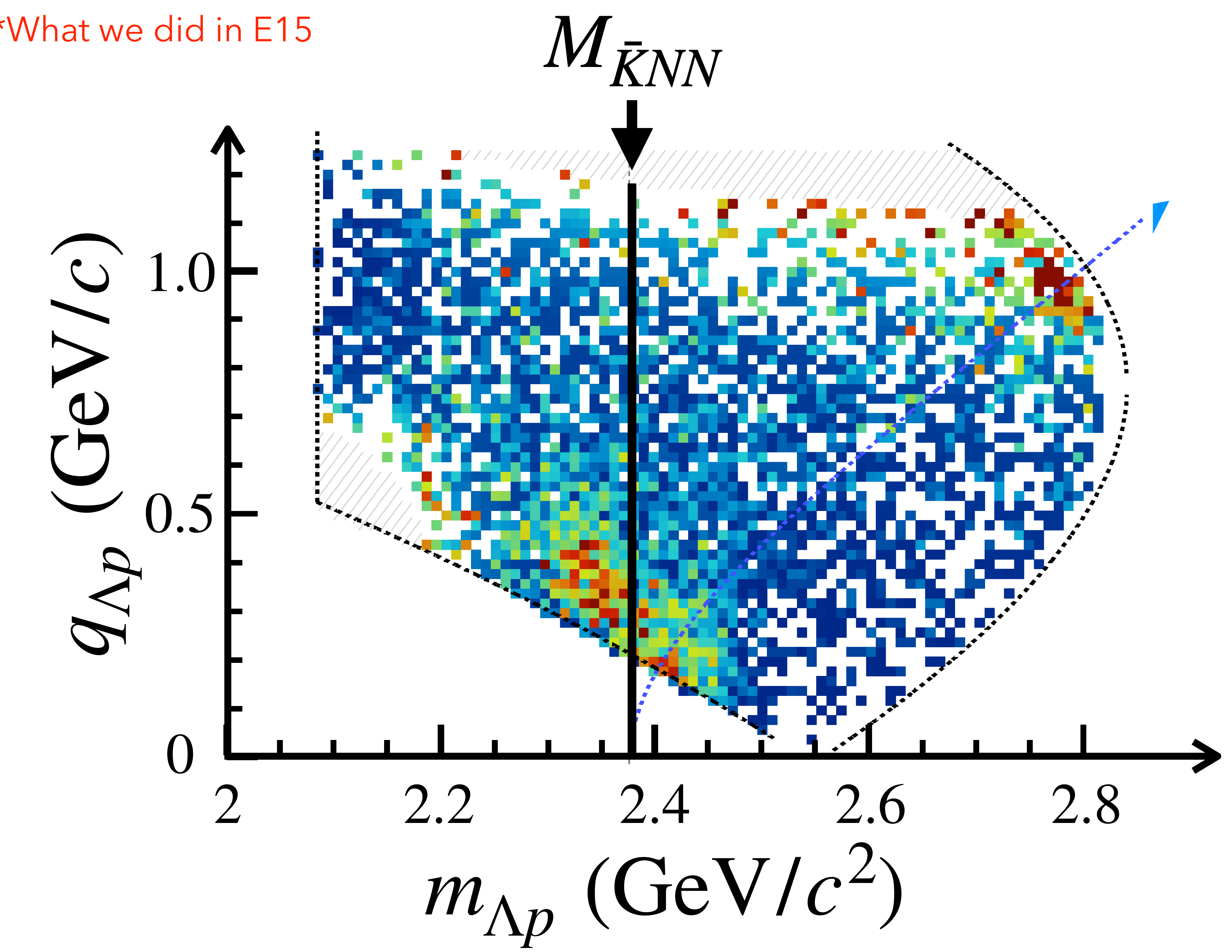
Both K^-pp & $\bar{K}^0nn$ are produced in $K^- + {}^3\mathrm{He}$ reaction.

How to measure $\bar{K}NN$

– 2D analysis for invariant-mass & momentum transfer of ΛN systems –

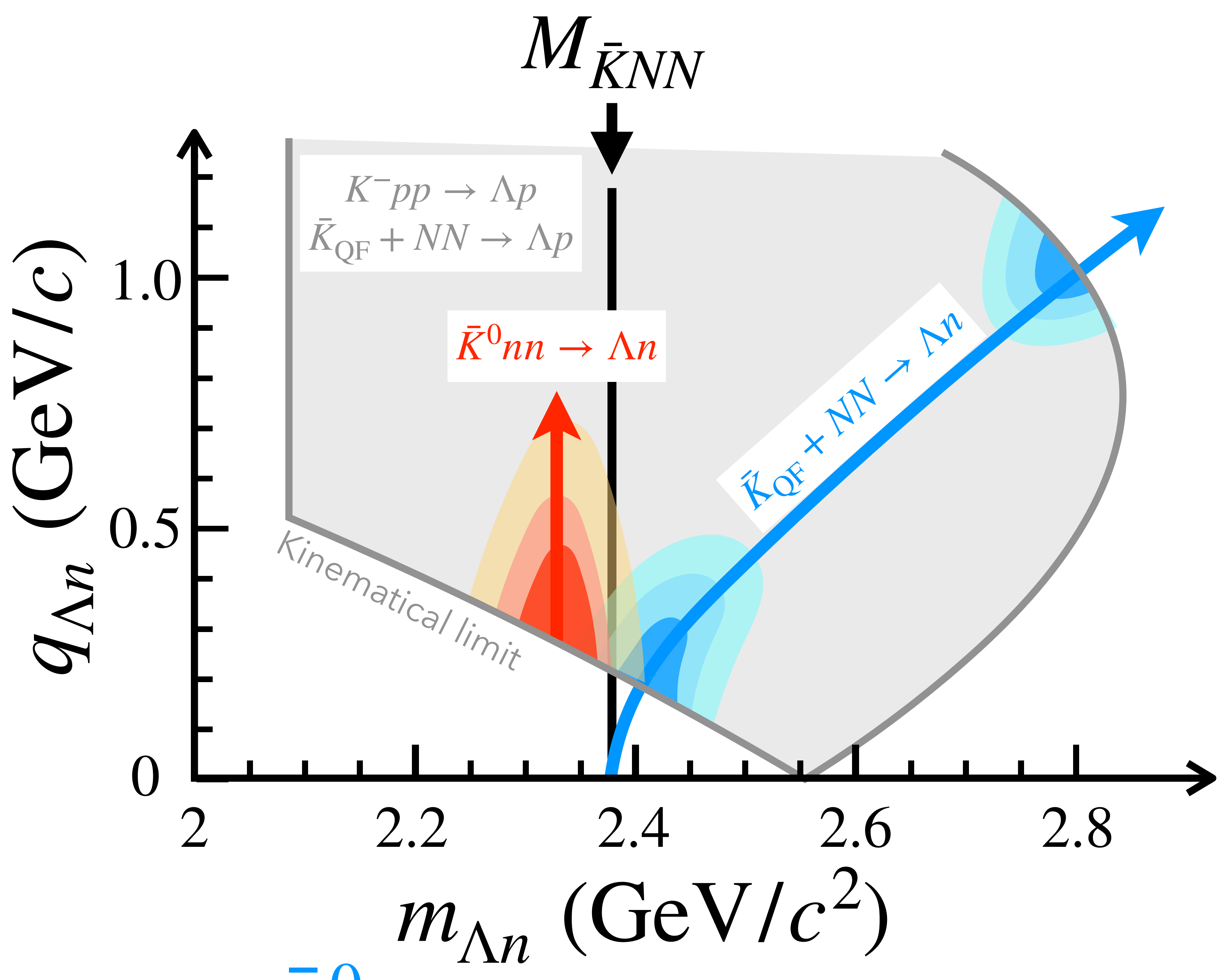
Measurement for Λp pair

*What we did in E15



K^-pp **can be seen.**

Measurement for Λn pair

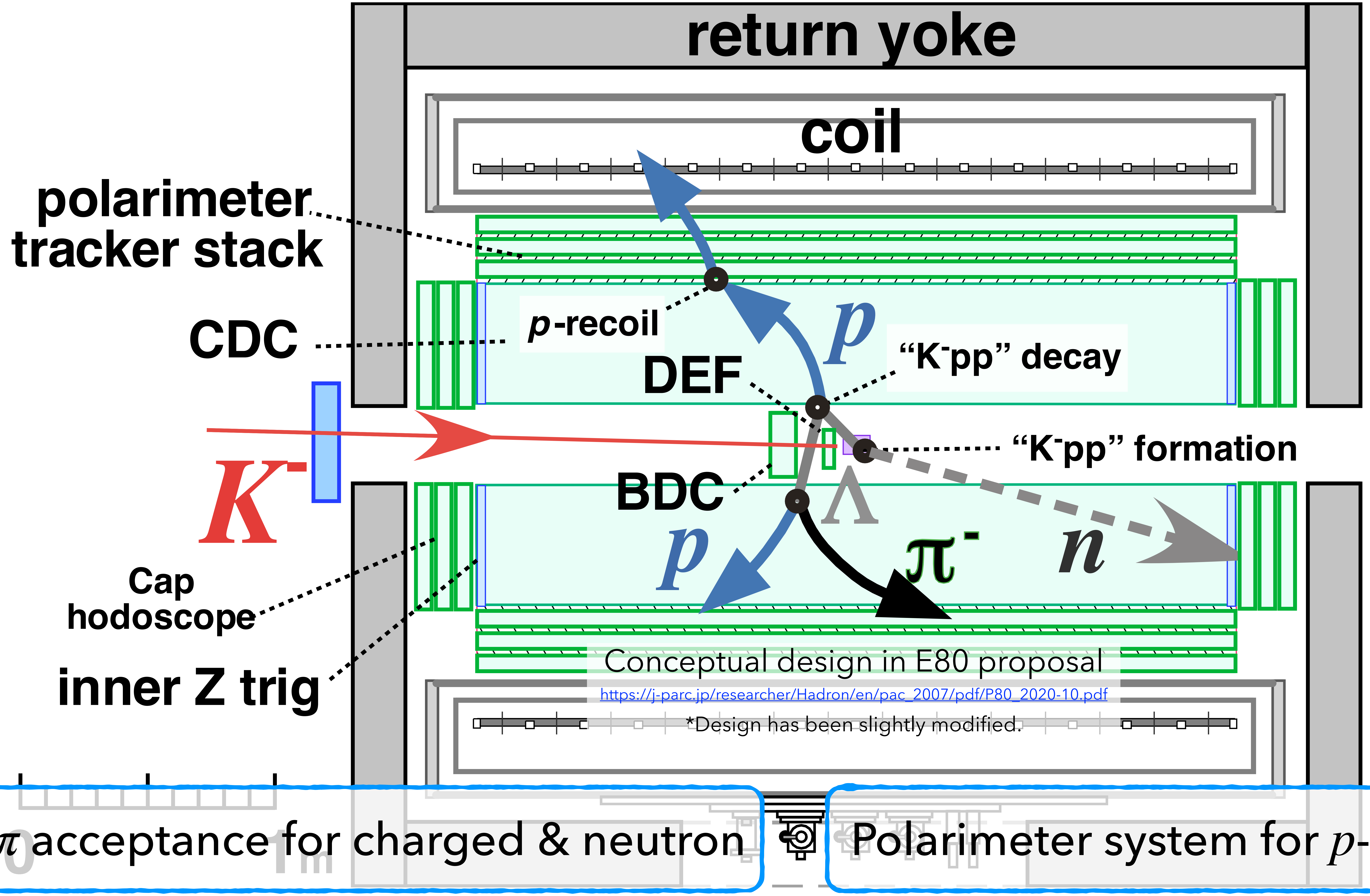


$\bar{K}^0nn$ **can be seen.**

K^-pp & $\bar{K}^0nn$ make event concentration in Λp & Λn pair

Experimental setup

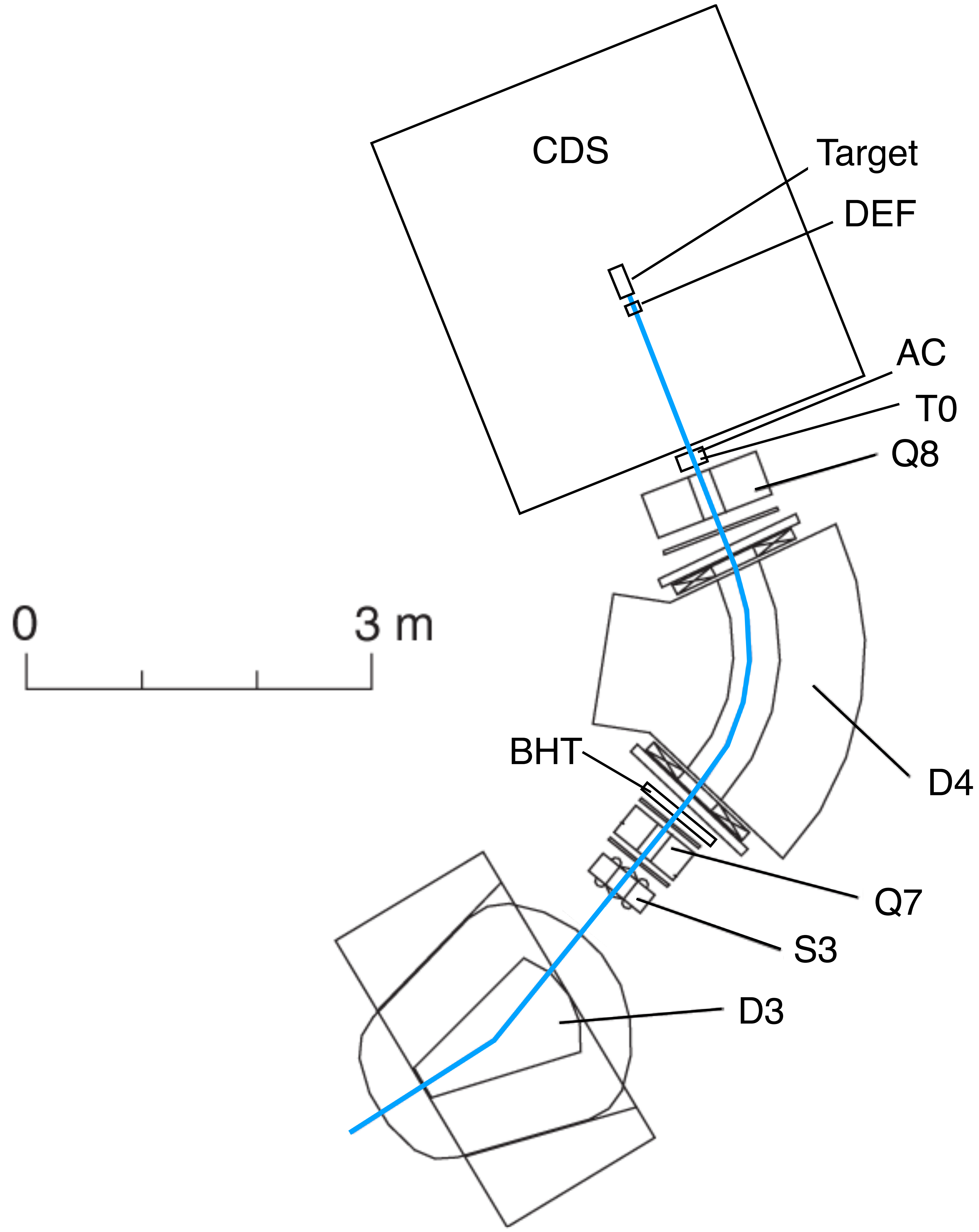
Cylindrical detector system



$\sim 4\pi$ acceptance for charged & neutron

Polarimeter system for p-spin measurement

K1.8BR beam-line



Conceptual design in E80 proposal

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

Expected K^--beam intensity (1 GeV/c)

$\sim$ 320 k /spill on target (@ 90kW)

Purity

$K/\pi \sim 1/2$

Expected trigger rate

$\sim$ 4000 /spill

Rate capability of existing DAQ

>90% efficiency up to $\sim$ 10000/spill

Expected $\bar{K}NN$ yield (reconstructed)

$K^-pp \to \Lambda p$ (9.3 μb)	$\bar{K}^0 nn \to \Lambda n$ (1.2 μb)
$\sim$ 6000 /week	$\sim$ 250 /week

# of K^-pp reconstructed in E15

$\sim$ 1700 /(4 weeks)

Sensitivity estimation

Sensitivity for $\phi_{\Lambda p}$-asymmetry

– Formalism of asymmetry reduction factor –

Spin-spin correlation on ϕ-asymmetry

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

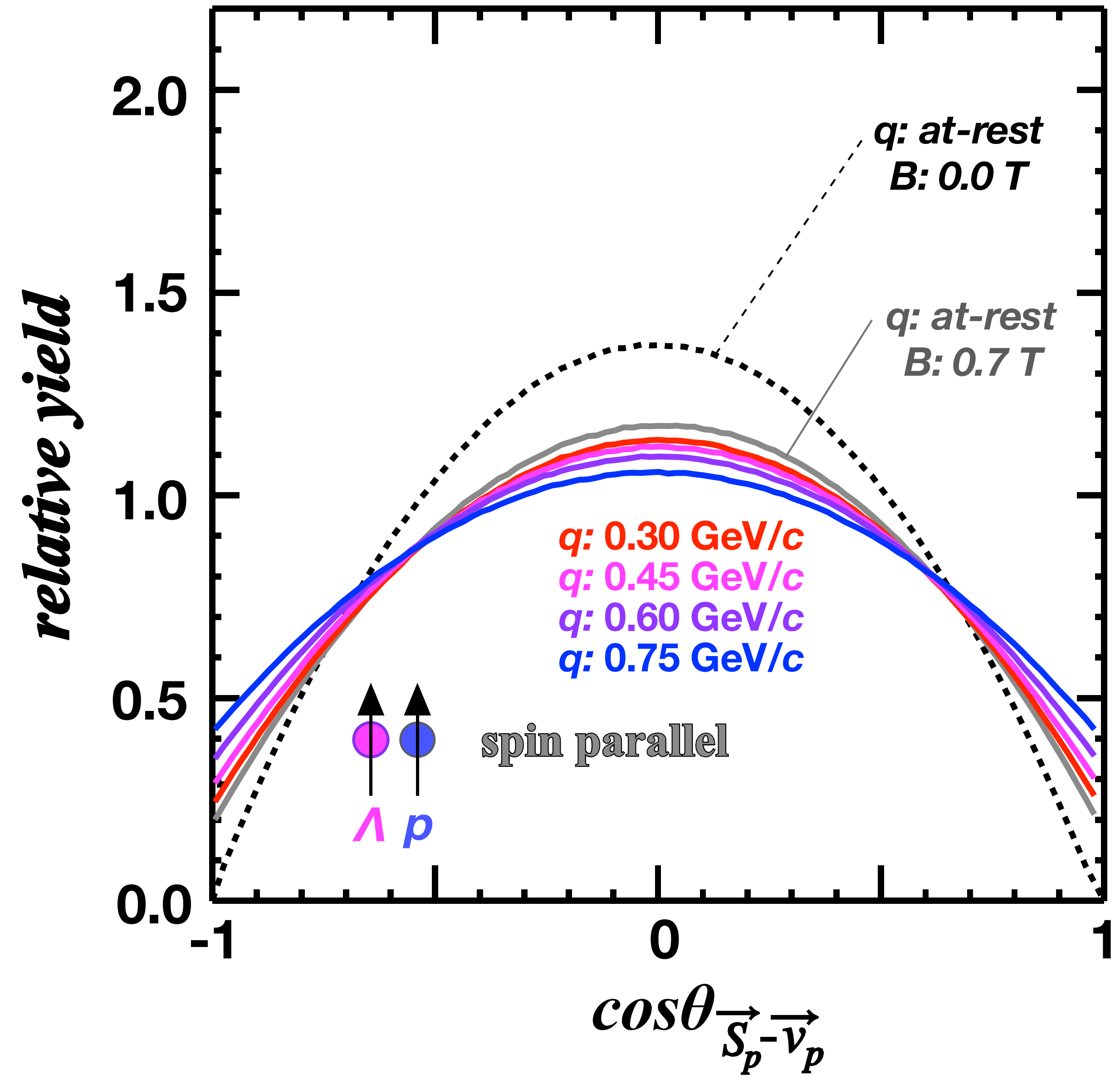
$$r^{(J^P)} = \frac{\pi}{4} \alpha_- A_{pC} \int d\Omega f_{\vec{S}_\Lambda} \sin^2 \theta_\Lambda$$

$\alpha_- = 0.72$: Λ asymmetry parameter

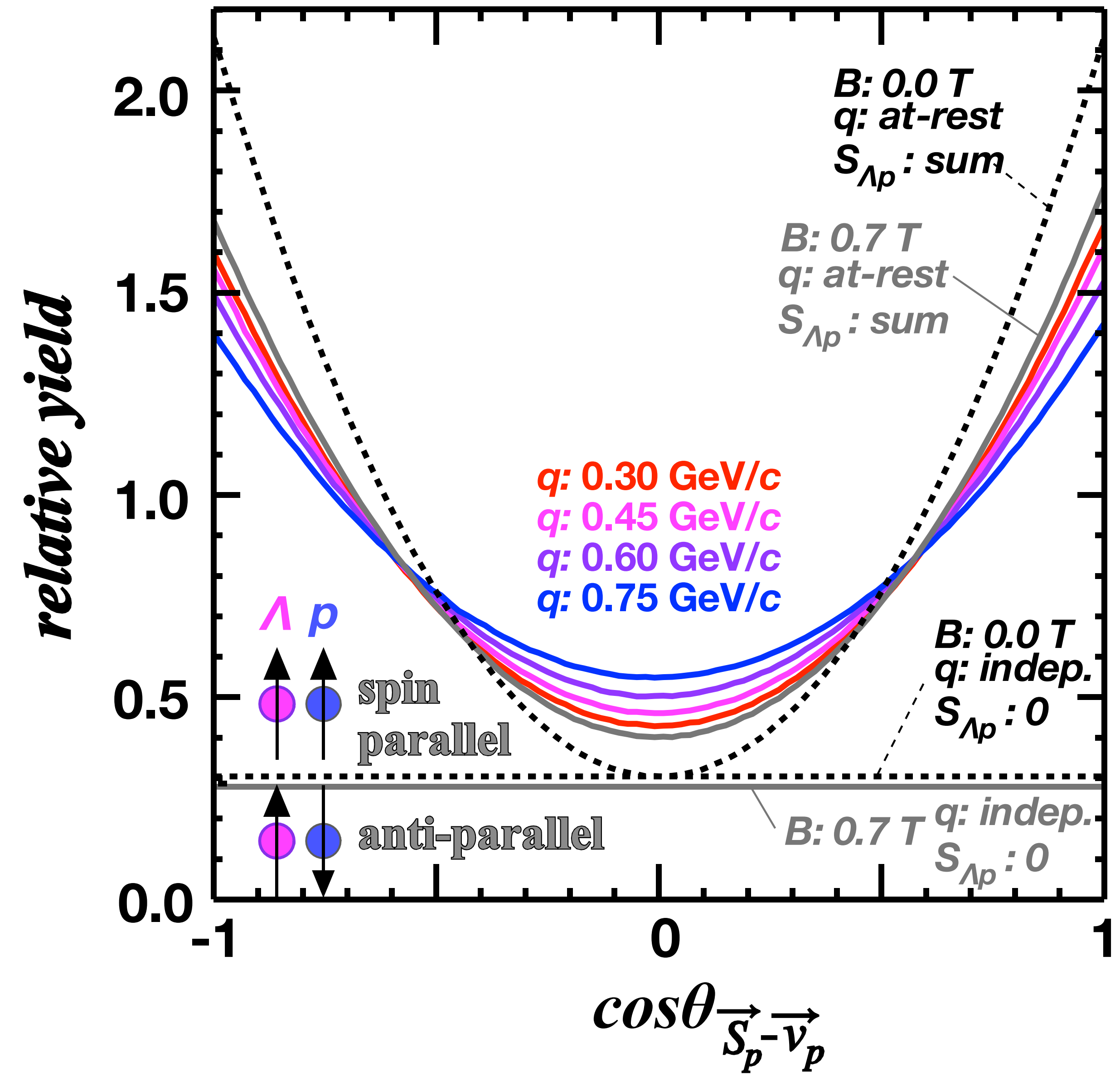
$< A_{pC} > \sim 0.3$: Analyzing power

Spin distribution $f_{\vec{S}_\Lambda}$

$J^P = 0^-$



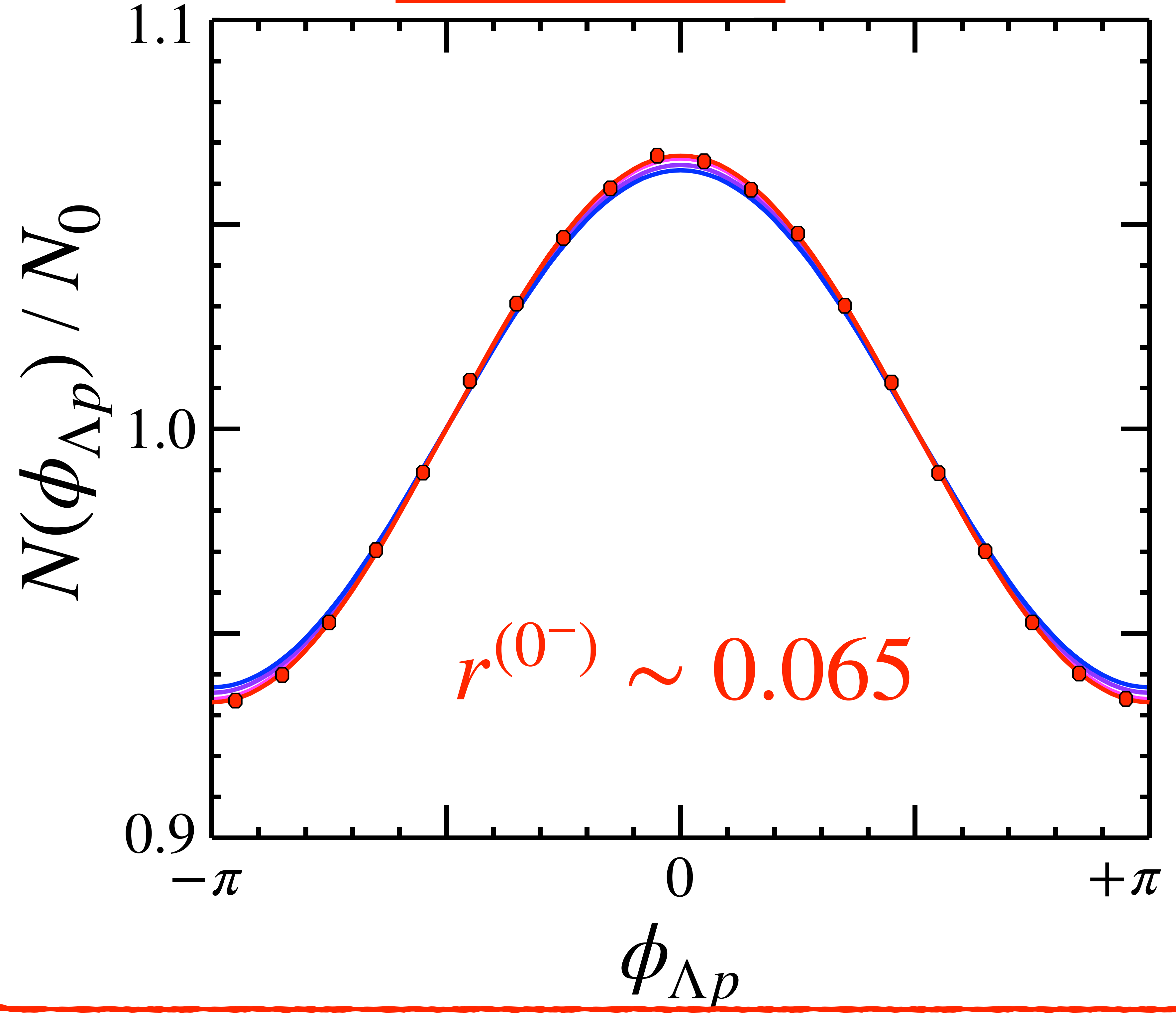
$J^P = 1^-$



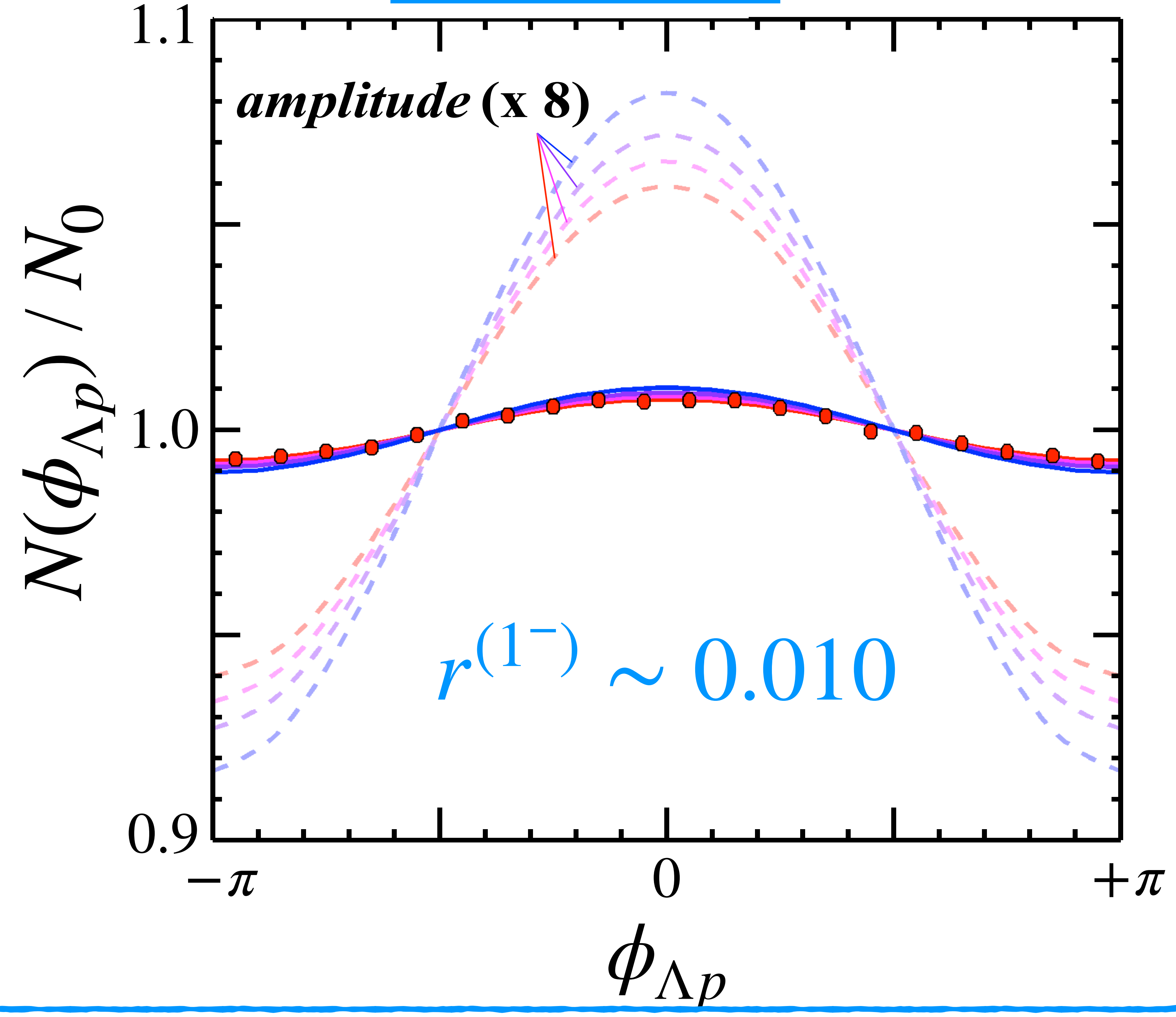
Sensitivity for $\phi_{\Lambda p}$-asymmetry

– Estimation of observable $\phi_{\Lambda p}$-asymmetry –

$J^P = 0^-$



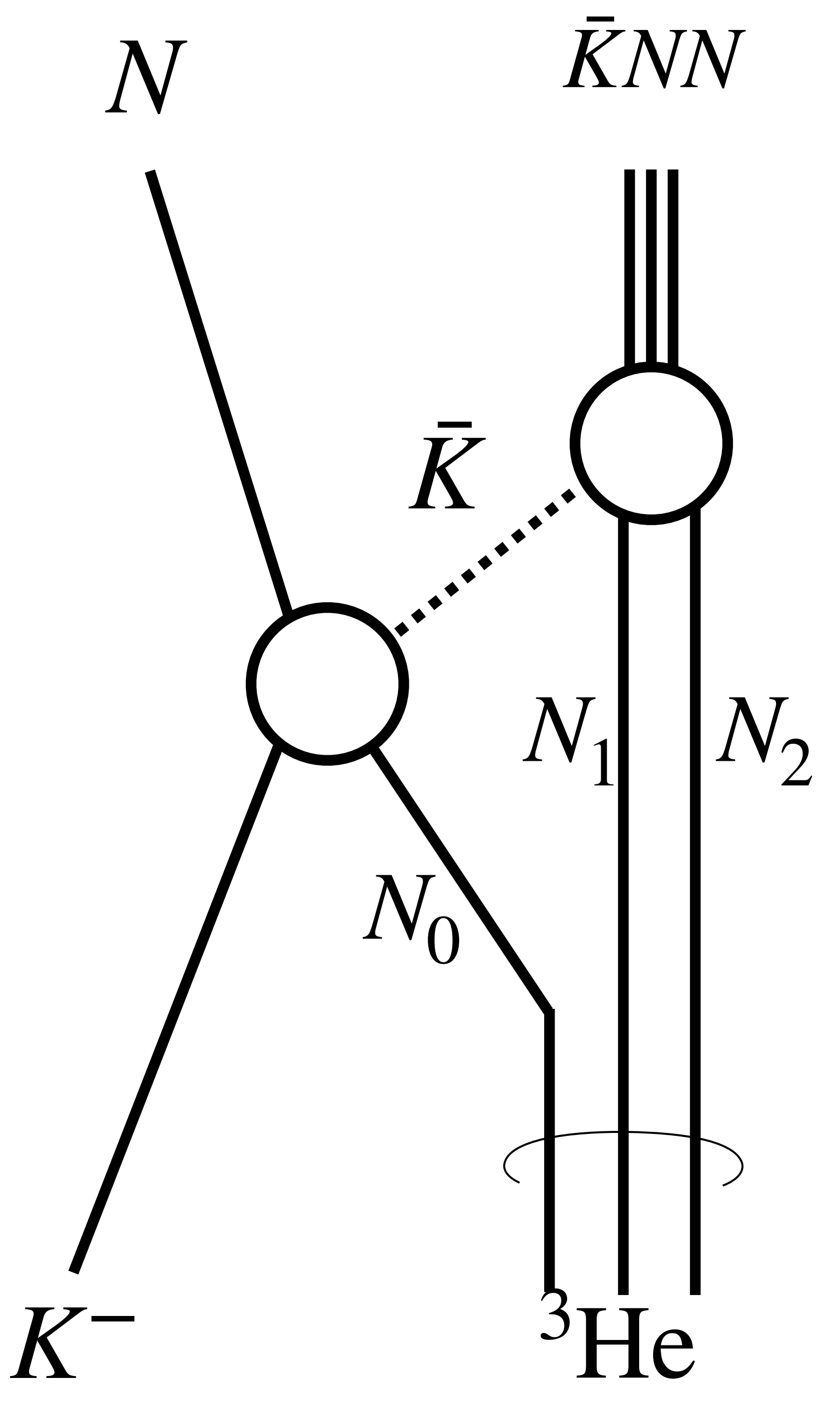
$J^P = 1^-$



$r^{(J^P)}$ is large enough to deduce J^P.

Sensitivity for $\bar{K}^0 nn$ search

– Expected formalism of production cross section of $\bar{K}NN$ –



$$\sigma^{J^P}_{I^{(z)}_{\bar{K}NN}} = R_{\bar{K}NN} \times \sum_{\bar{K}N} \left(\sigma_{\bar{K}N} \times C^2_{I_{NN}} \times C^2_{I^{(z)}_{\bar{K}NN}} \times \mathscr{A}_N \right)$$

Formation probability
– *Common* –

Effective nucleon number

neutron	1
proton	$2^{2/3} \sim 2$

Elementary CSs @ $\theta_N = 0^\circ$

$I^{(z)}_{\bar{K}NN} = +1/2$	$\sigma_{K^-n} = 4.7$ (mb/sr) or $\sigma_{\bar{K}^0 n} = 2.4$ (mb/sr)
$I^{(z)}_{\bar{K}NN} = -1/2$	$\sigma_{K^-p} = 1.8$ (mb/sr)

Isospin coupling of $I_{N_1} \otimes I_{N_2}$

	$J^P = 0^-$	$J^P = 1^-$
$I^{(z)}_{\bar{K}NN} = +1/2$	1/2 or 1	1/2 or 0
$I^{(z)}_{\bar{K}NN} = -1/2$	1/2	1/2

Isospin coupling of $I_{\bar{K}} \otimes I_{NN}$

	$J^P = 0^-$	$J^P = 1^-$
$I^{(z)}_{\bar{K}NN} = +1/2$	1/3 or 2/3	1
$I^{(z)}_{\bar{K}NN} = -1/2$	1/3	1

Sensitivity for $\bar{K}^0 nn$ search

– Estimated $\bar{K}^0 nn$ production cross section–

$\sigma_{K^-pp} \cdot Br_{\Lambda p}$

$9.3\ \mu b$

Measured in E15

$\sigma_{\bar{K}^0 nn} \cdot Br_{\Lambda n}$

*Assuming $\mathscr{A}_p = 2^{2/3}$, $Br_{\Lambda n} = Br_{\Lambda p}$

$J^P = 0^-$

$1.2\ \mu b$

$J^P = 1^-$

$7.0\ \mu b$

$\sigma_{\bar{K}^0 nn}$ is large enough to see a signal.

$\sigma_{\bar{K}^0 nn}/\sigma_{K^-pp}$ is also a good indicator for J^P.

Beam-time request

8 weeks $\otimes$ 90 kW

(648 kW·week @ 90% up-time)

Ready to start in 2025

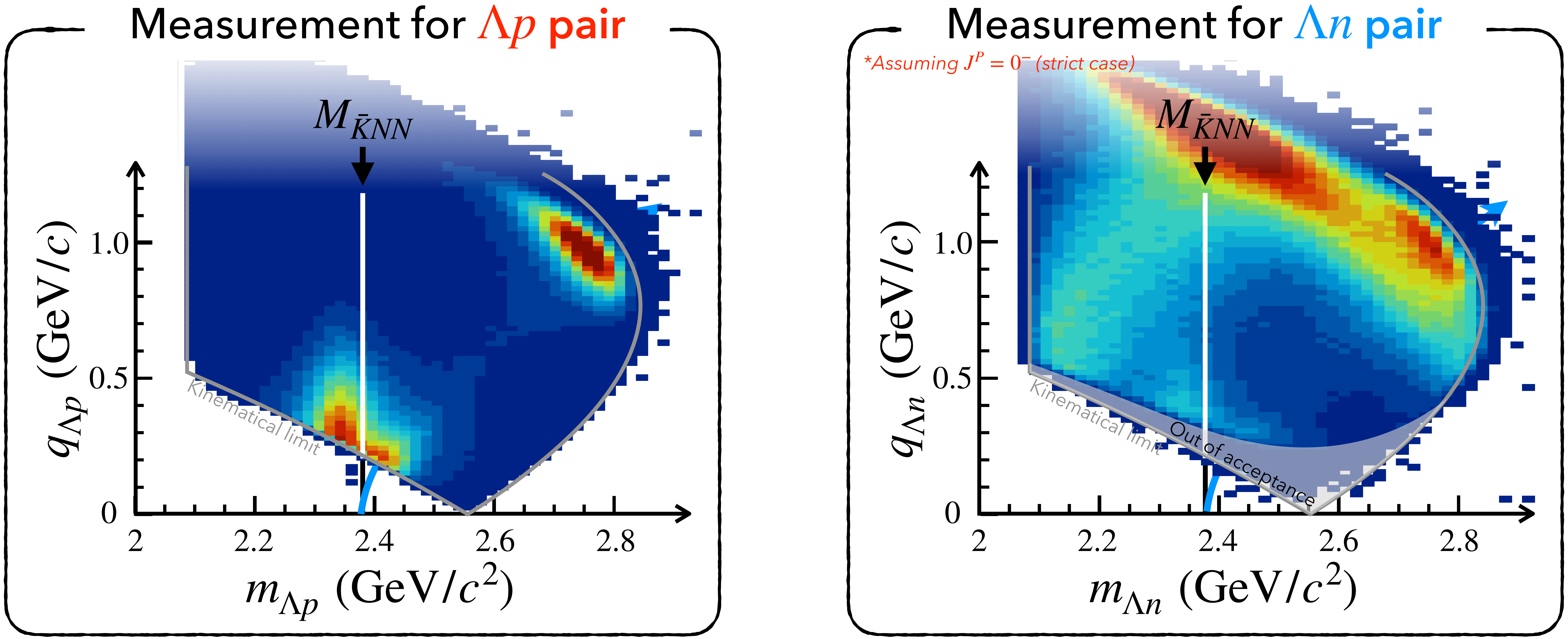
Additional tasks from E80

To construct polarimeter system

To purchase additional 300L gaseous ^3He

Expected spectra

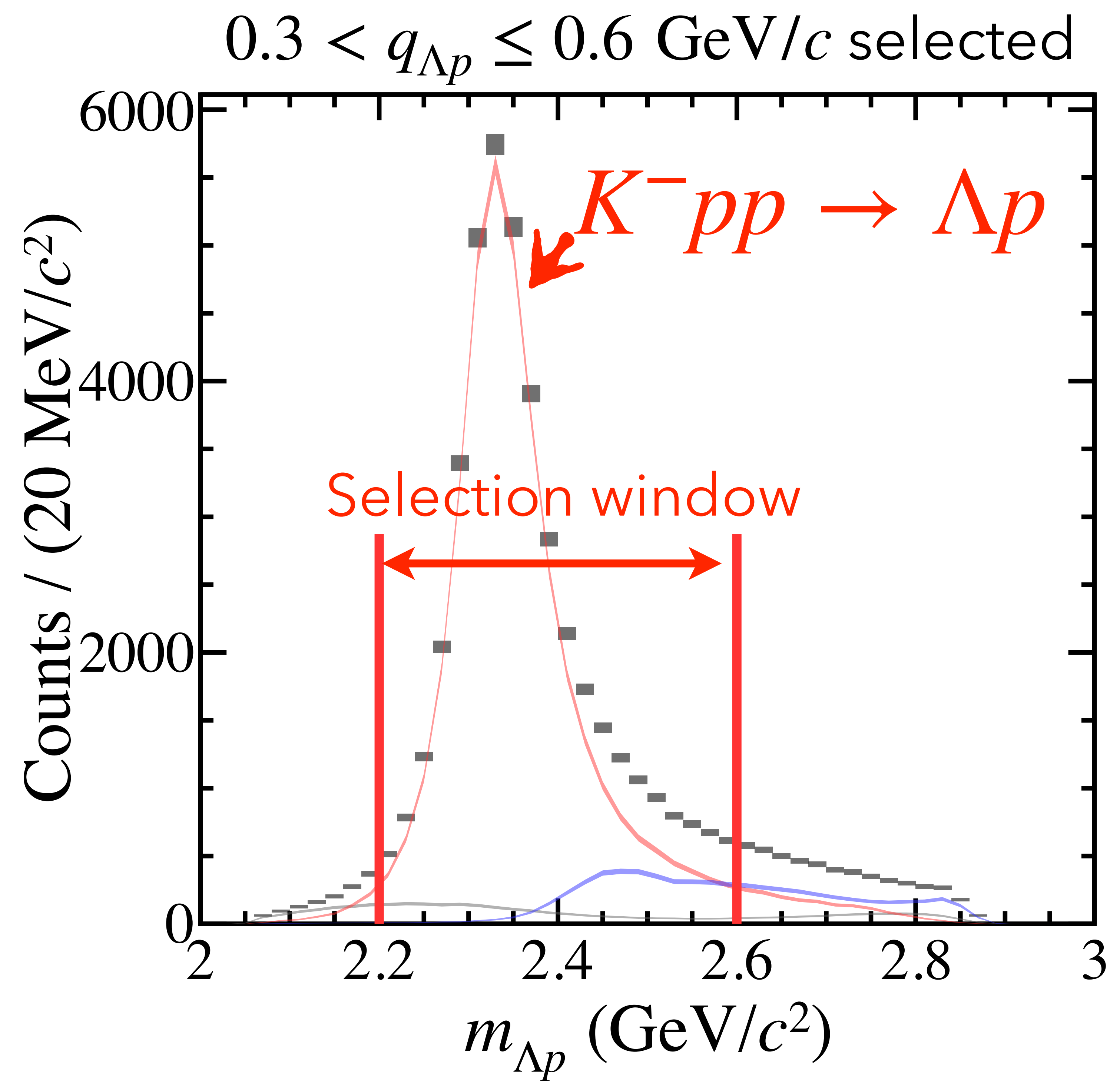
– To detect K^-pp & $\bar{K}^0nn$–



Expected spectra

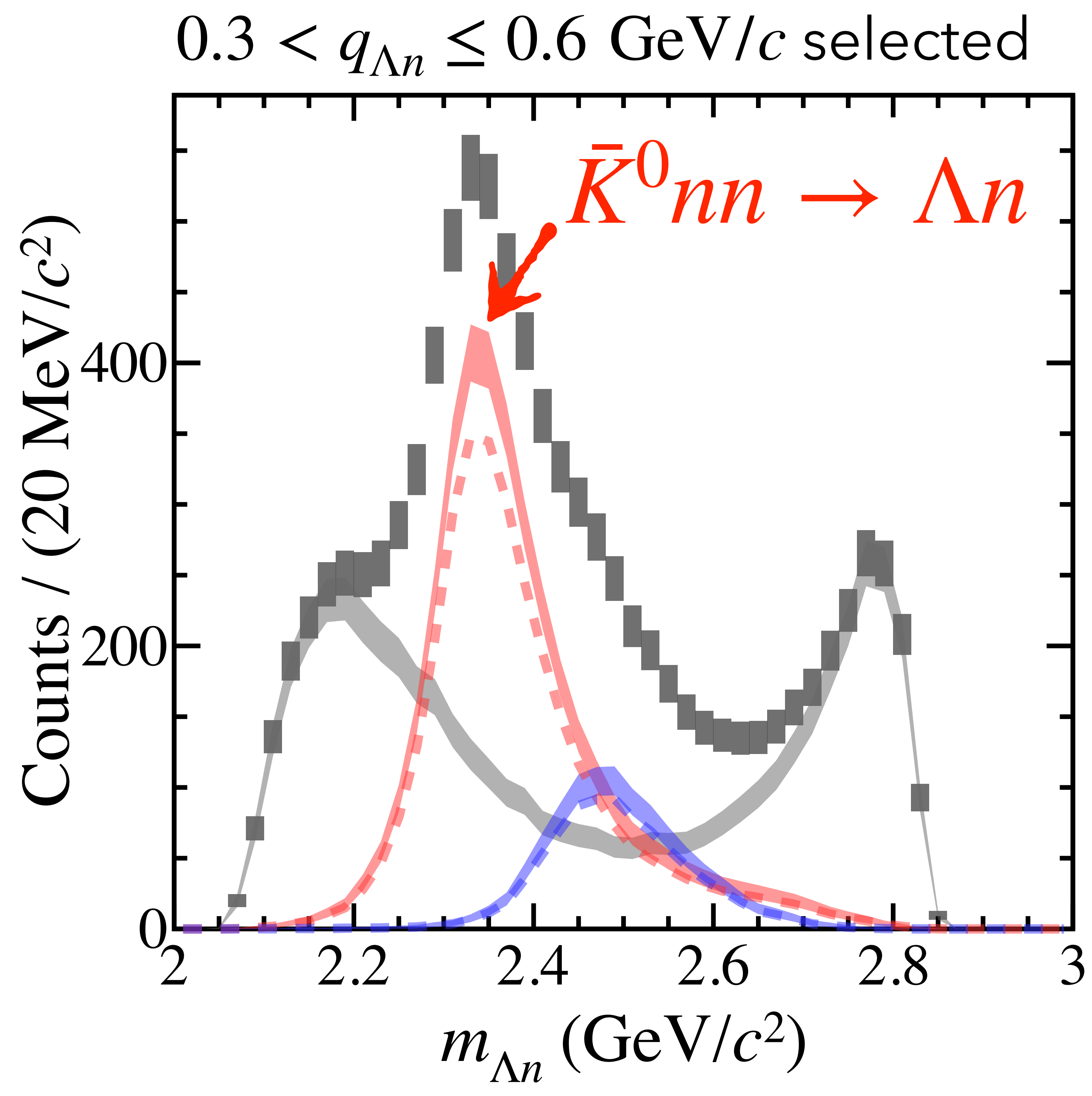
– To detect $K^{-}pp$ & $\bar{K}^{0}nn$–

Measurement for Λp pair



Measurement for Λn pair

*Assuming $J^P = 0^-$ (strict case)

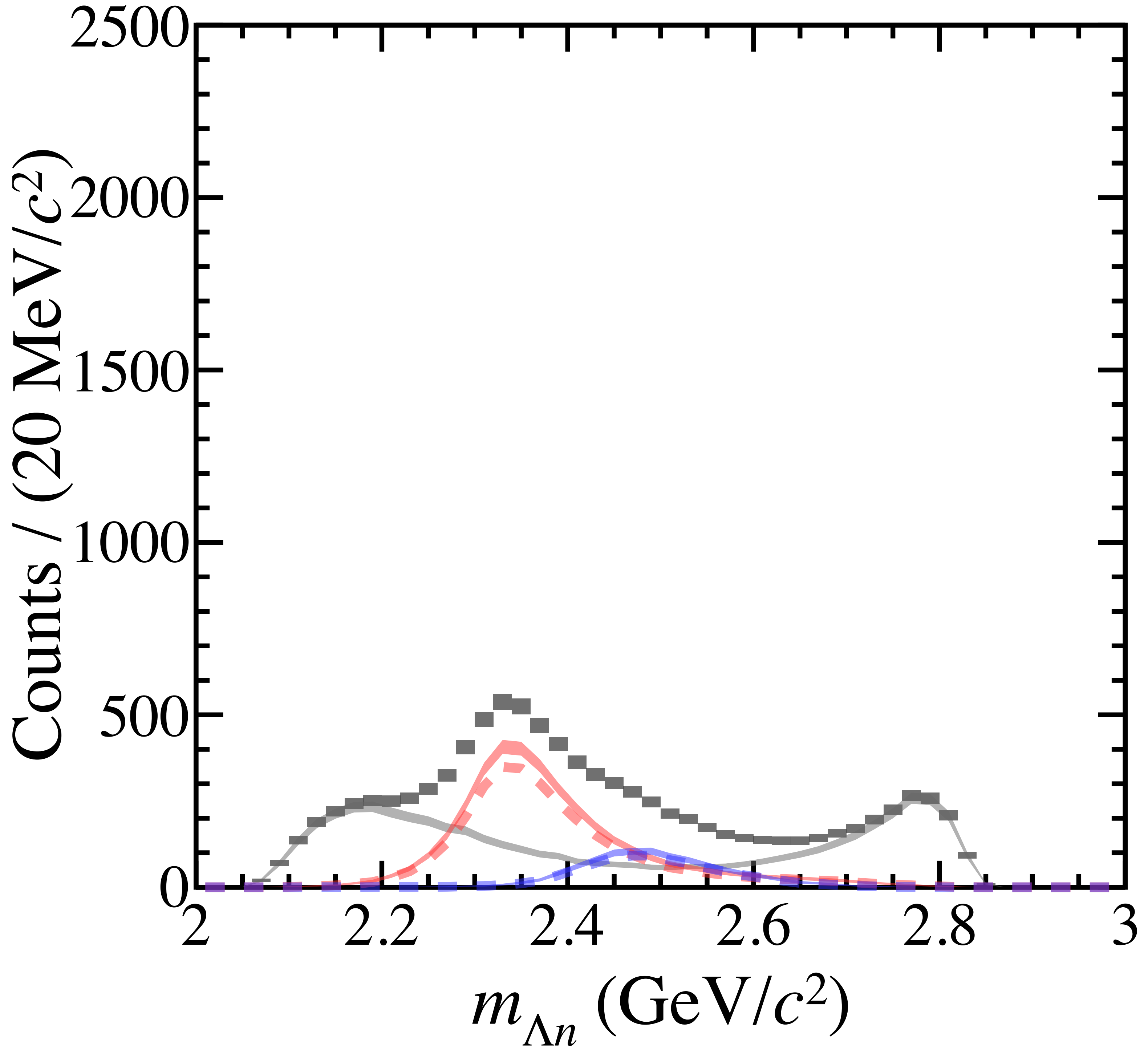


We would observe distinct peaks of both $K^{-}pp$ & $\bar{K}^{0}nn$

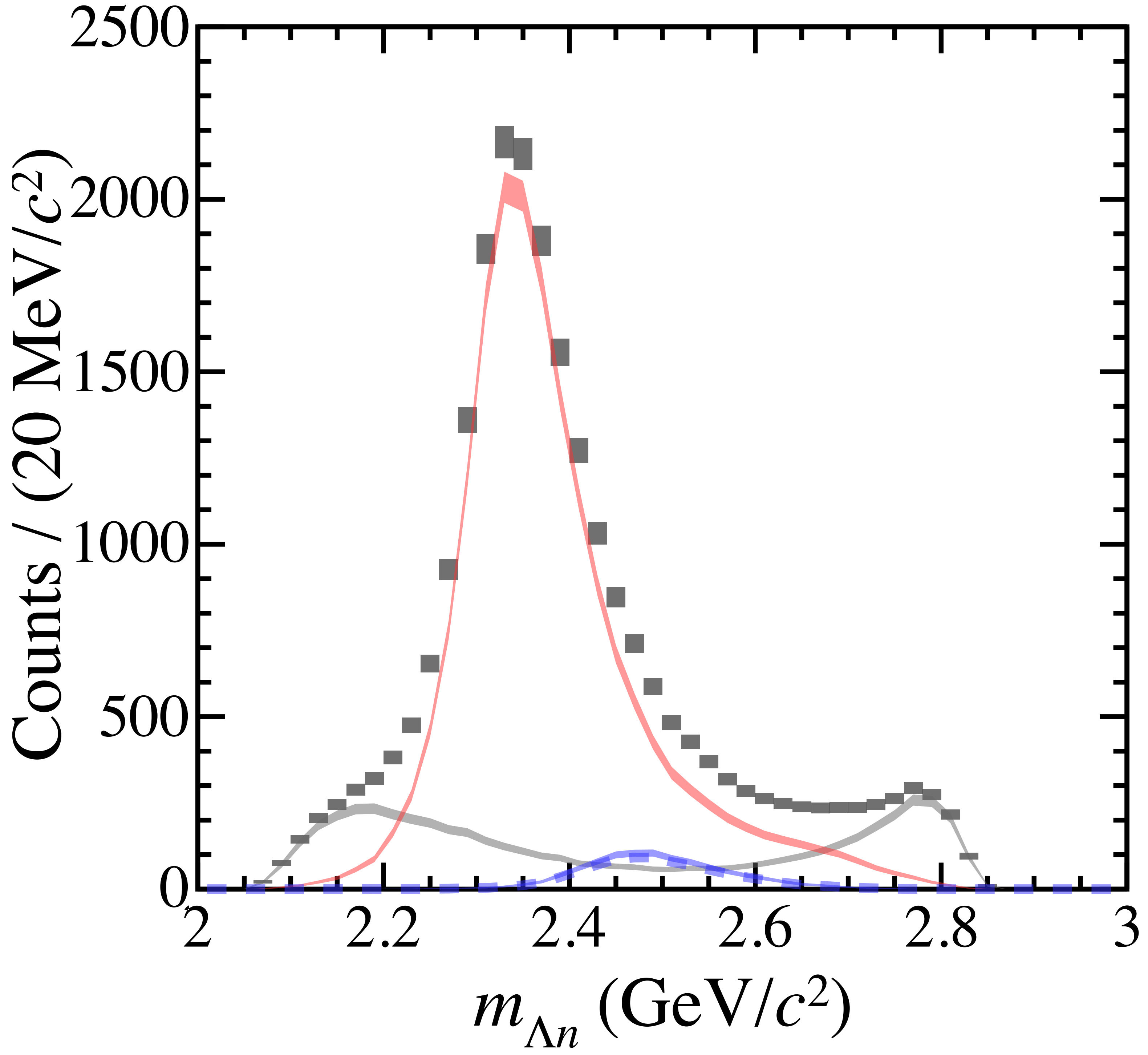
Expected spectra

– To measure $\sigma_{\bar{K}^0 nn}$ for J^P determination–

$J^P = 0^-$



$J^P = 1^-$

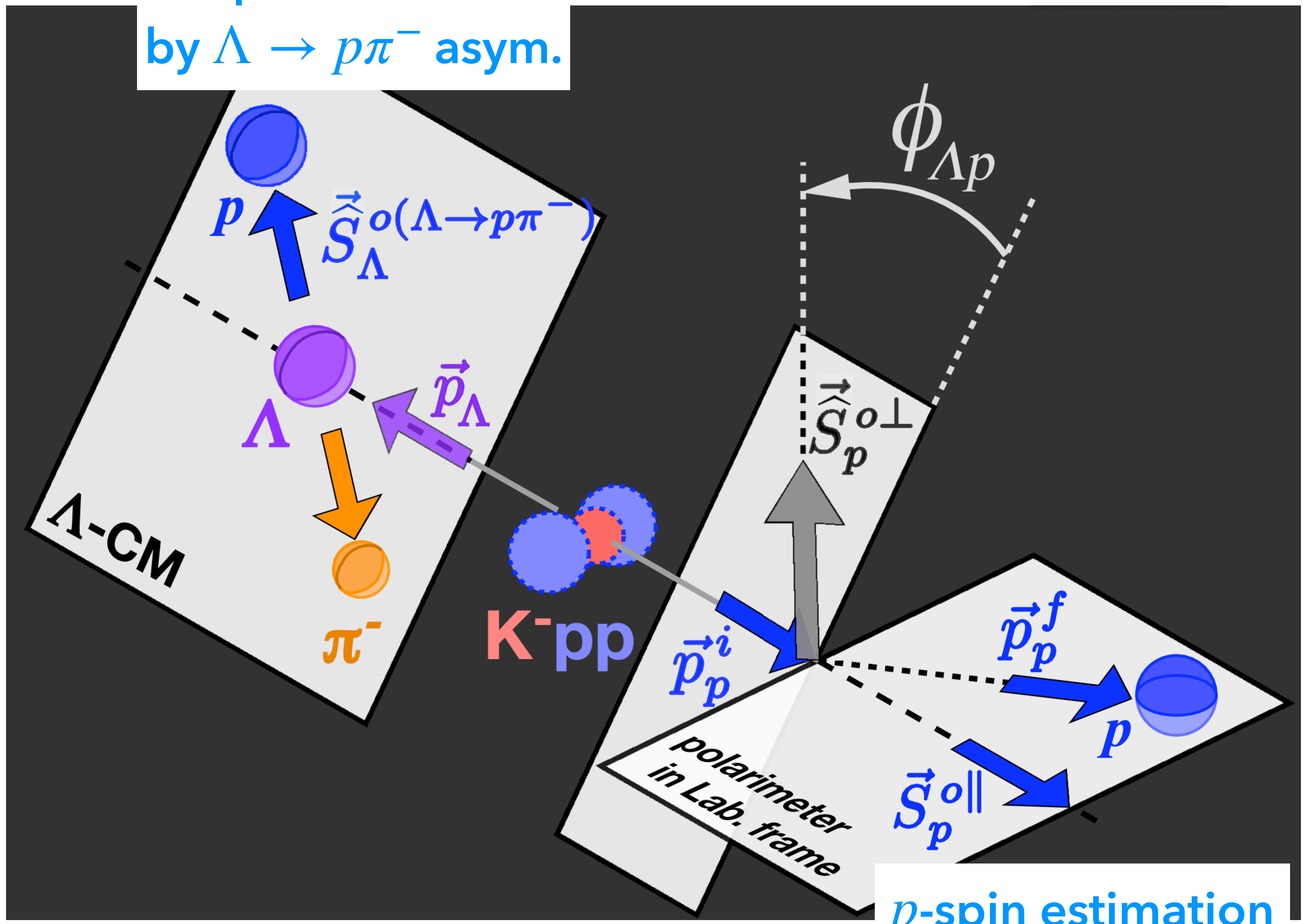


To measure $\sigma_{\bar{K}^0 nn}$ will help us to deduce J^P precisely.

Expected spectra

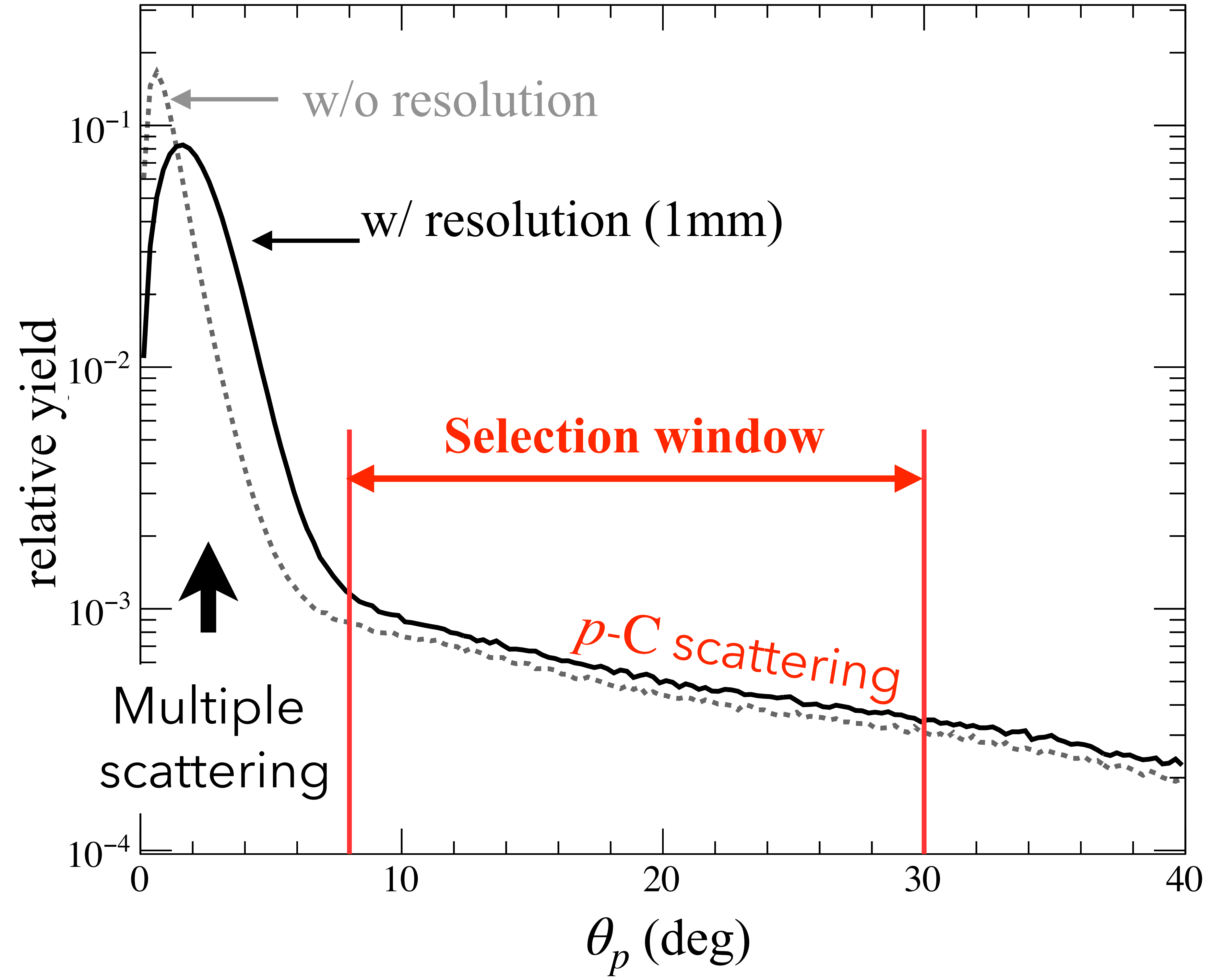
– To measure $\phi_{\Lambda p}$-asymmetry for J^P determination –

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



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

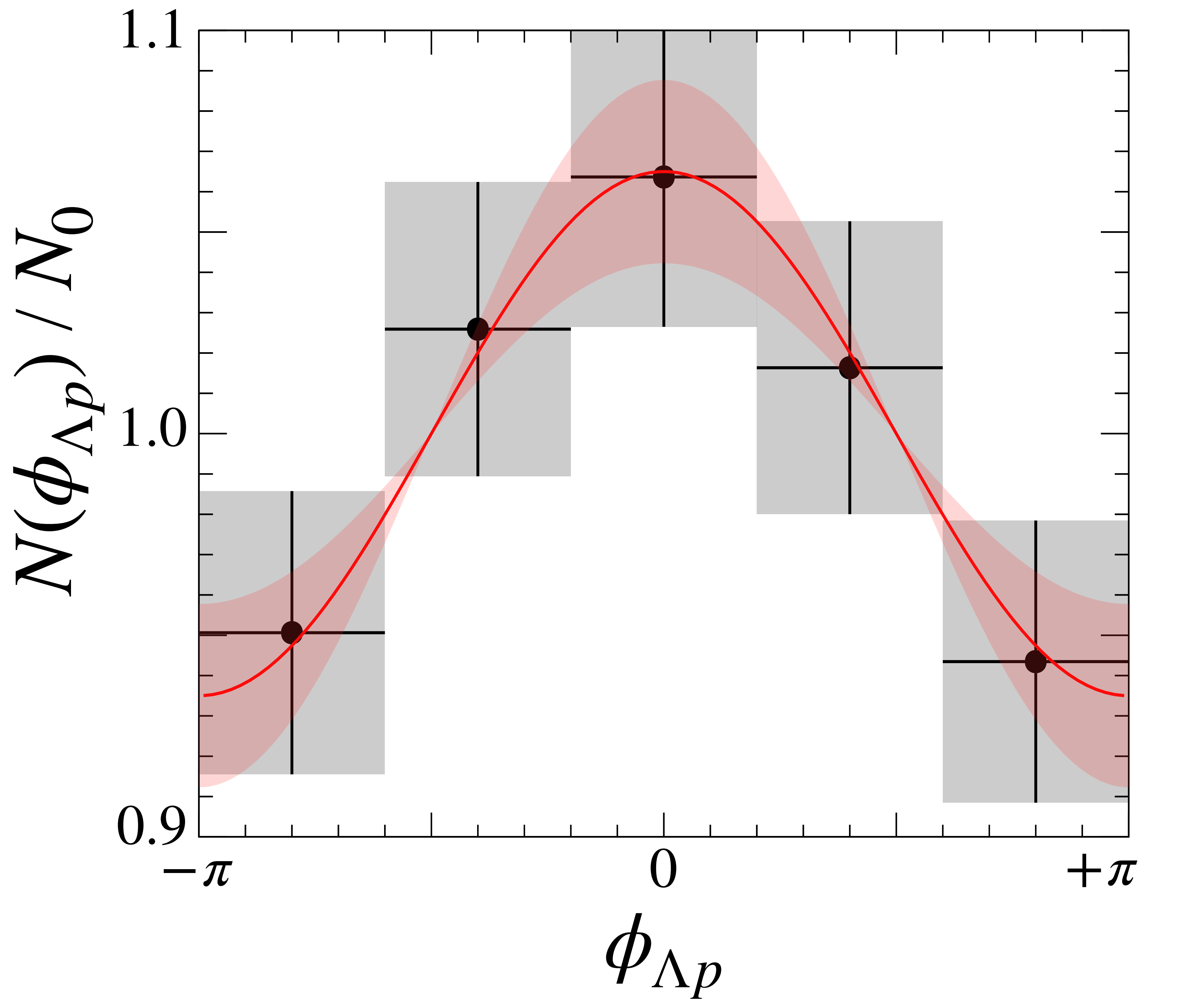
Event selection for p-C scattering



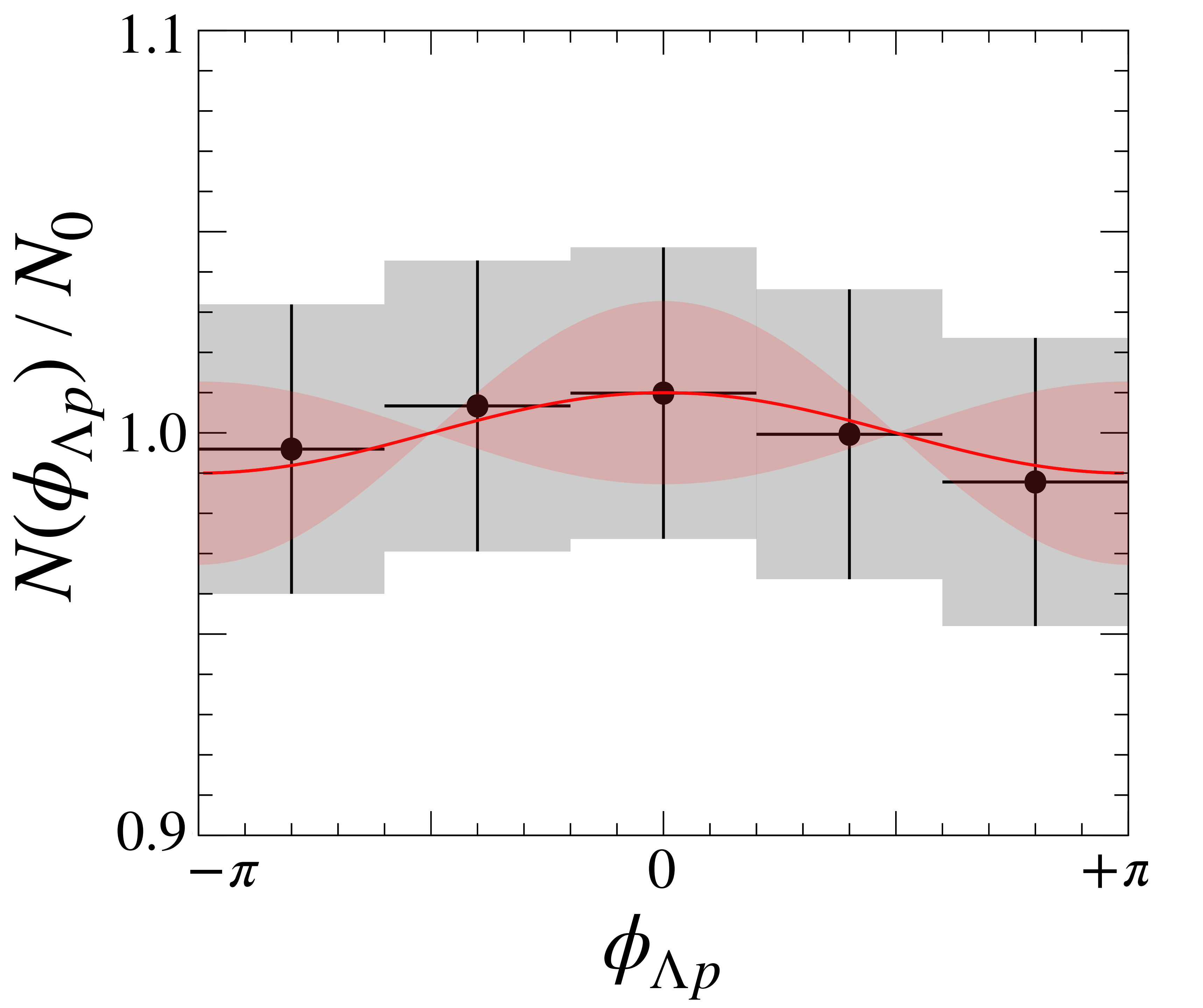
Expected spectra

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

$J^P = 0^-$



$J^P = 1^-$



We would exclude $J^P = 1^-$ with **95%** confidence level from **only $\phi_{\Lambda p}$-asym**.

Collaboration

Experimentalists

RIKEN: H. Asano, K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma, T. Yamaga

JAEA: T. Hashimoto, K. Tanida

TOHOKU: H. Ohnishi, Y. Sada, C. Yoshida

OSAKA UNIVERSITY: T. Akaishi

T. Nagae

RCNP: K. Inoue, S. Kawasaki, H. Noumi, K. Shirotori

INFN Istituto Nazionale di Fisica Nucleare: M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, M. Miliucci, A. Scordo, D. Sirghi, F. Sirghi

Tokyo Tech: H. Fujioka

KEK: M. Iio, S. Ishimoto, K. Ozawa, S. Suzuki

J. Marton, H. Shi, M. Tuechler, E. Widmann, J. Zmeskal

Theorists

Tokyo Tech: D. Jido

T. Sekihara

We investigate $\bar{K}NN$ both experimentally & theoretically.
Especially, to deduce the spacial size from q-dependence

Summary

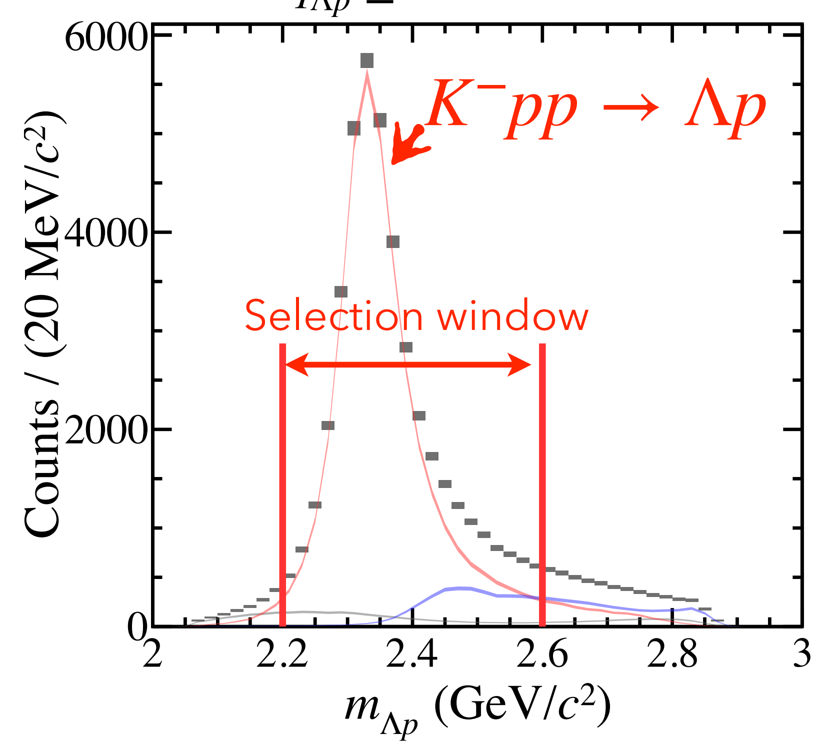
– For stage-1 approval –

Expected results

8 weeks ⊗ 90 kW @ K1.8BR

To confirm $I = 1/2\ \bar{K}NN$ doublet

Measurement for Λp pair



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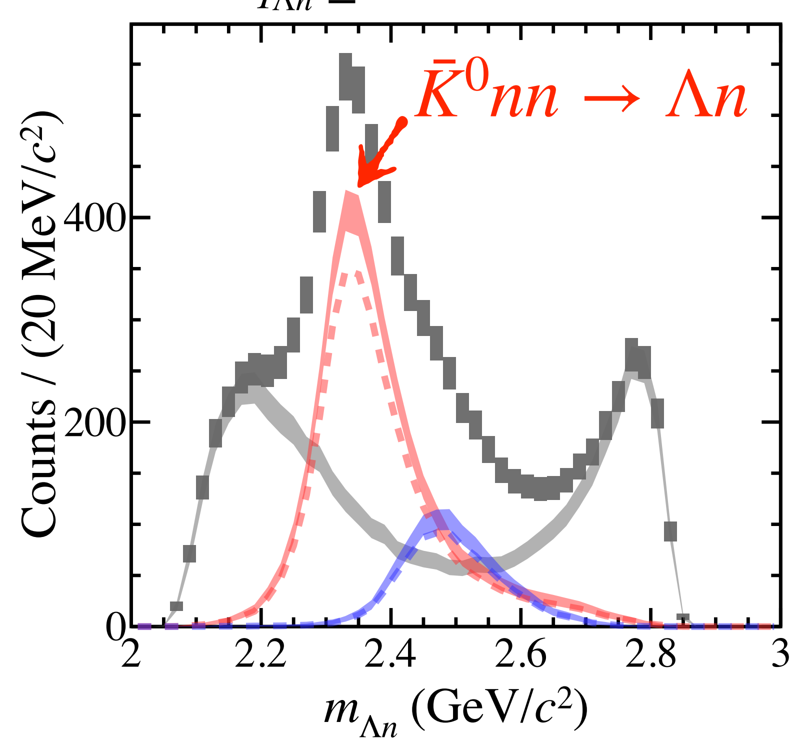
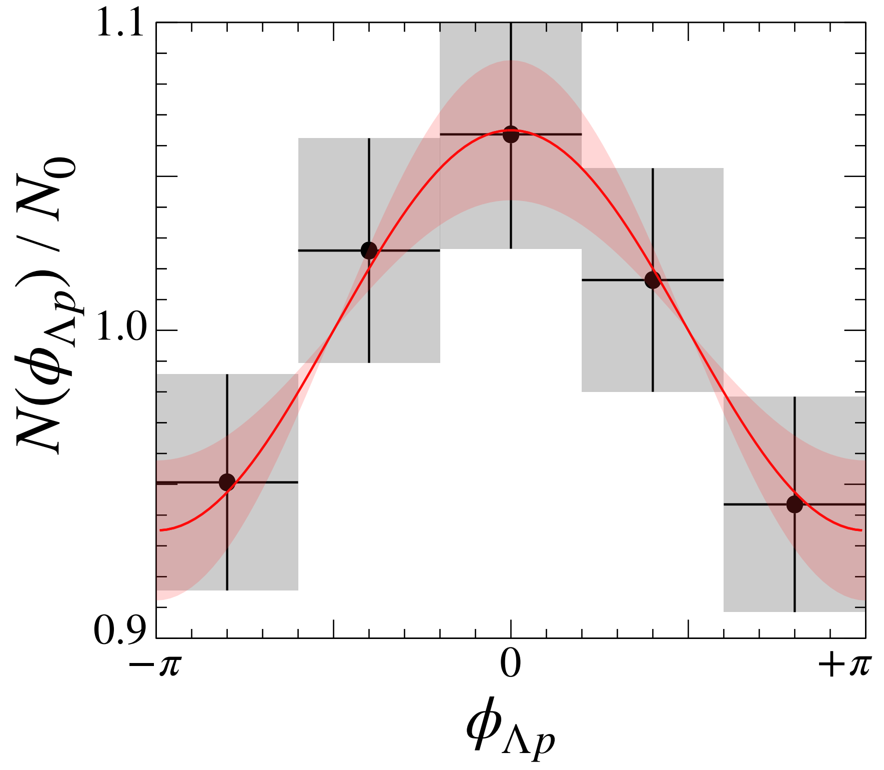
*Assuming $J^P = 0^-$ (strict case)

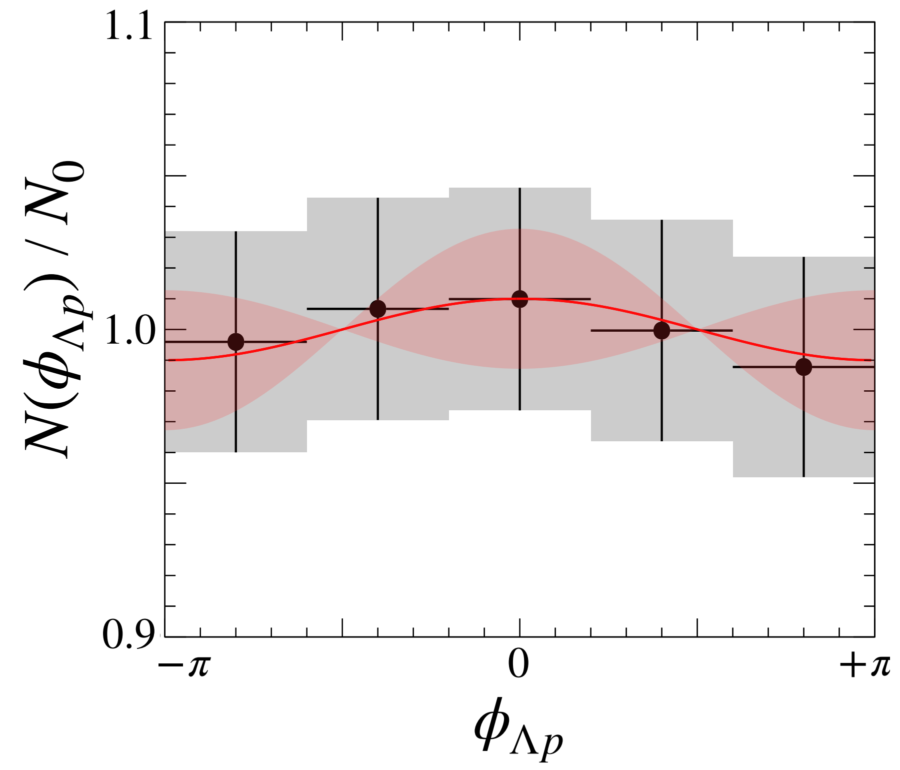


To determine J^P of $\bar{K}NN$

$J^P = 0^-$



$J^P = 1^-$

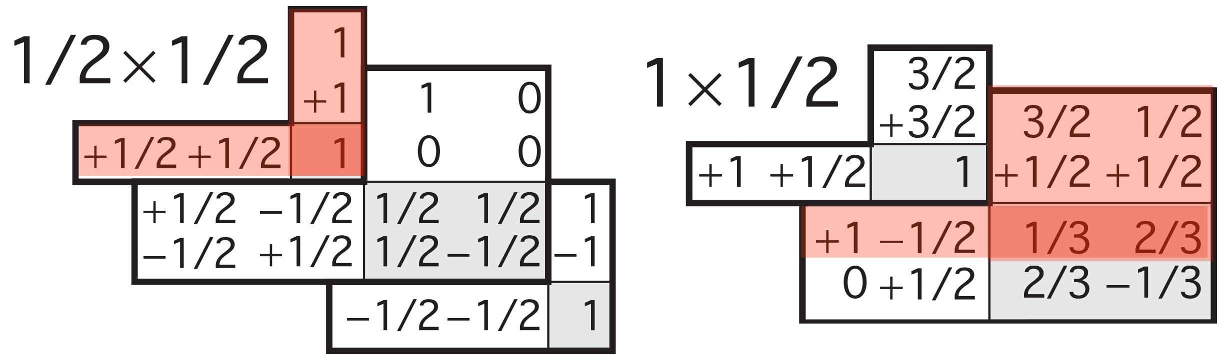


We wish to open a new doorway to access high-density matter

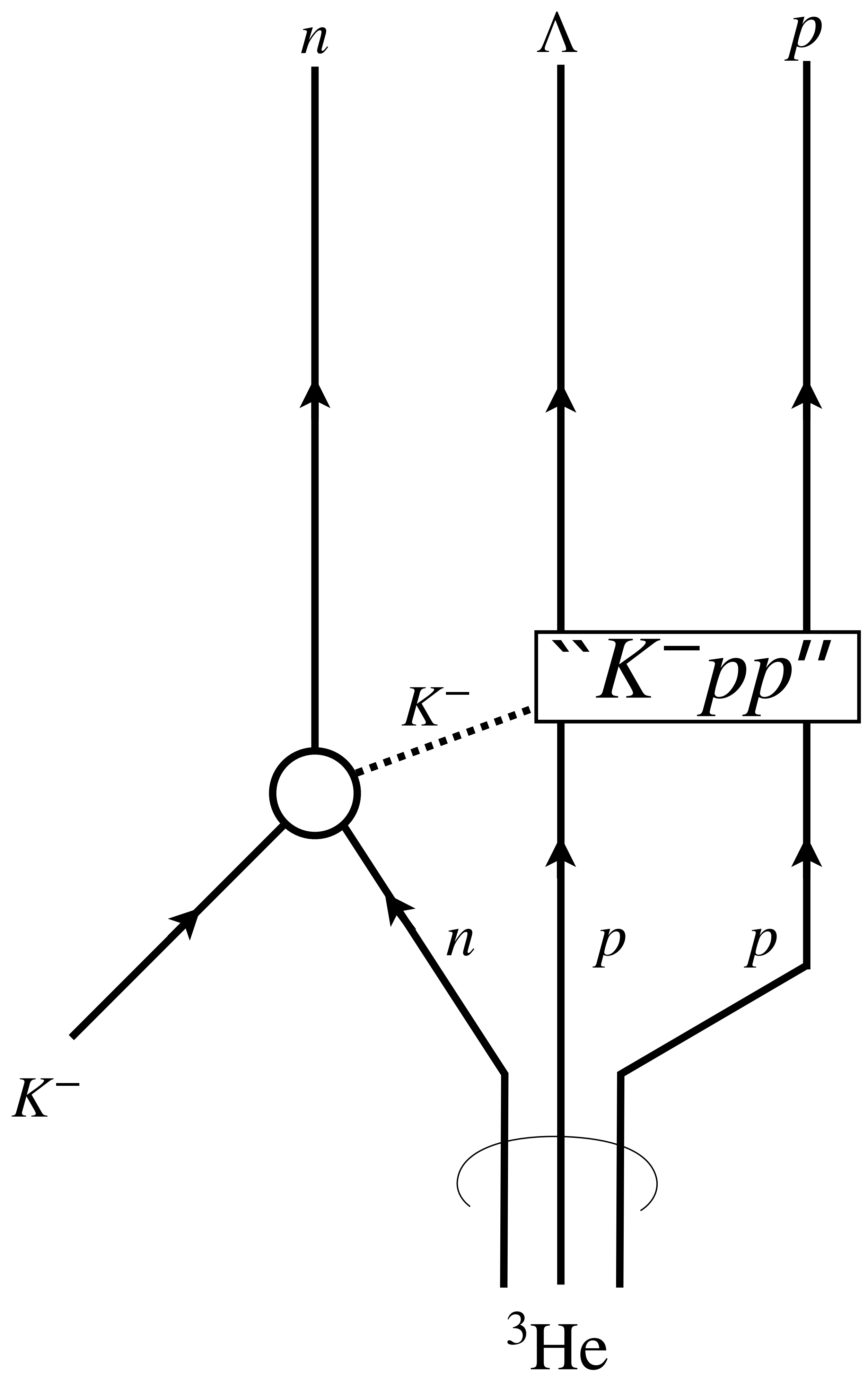
Thank you for your attention!

Backup

Production of "$K^- pp$"



$K^- n \to K^- n,$
$K^- + (pp) \to$ "$K^- pp$"



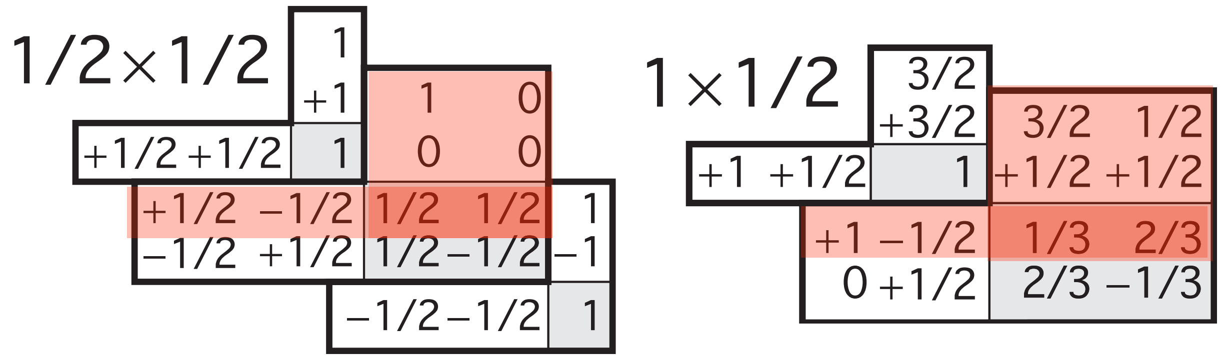
$$I_{NN} = \underbrace{|1/2, +1/2>}_{p} \otimes \underbrace{|1/2, +1/2>}_{p} = |1, +1>$$

; Only $J^P = 0^-$ can be produced.

$$I_{\bar{K}NN} = |1, +1> \otimes \underbrace{|1/2, -1/2>}_{K^-}$$

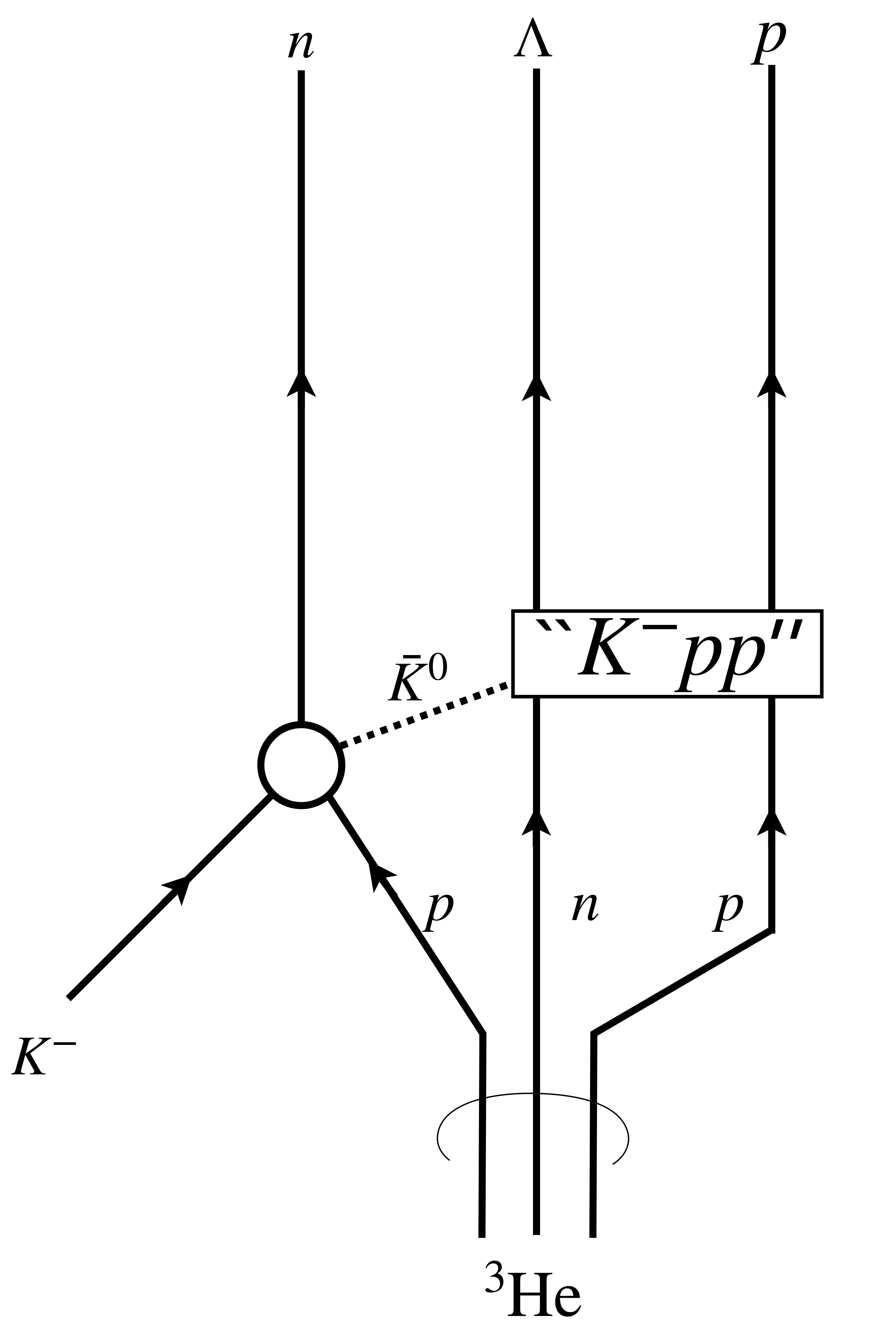
$$= \sqrt{\frac{1}{3}} |3/2, +1/2>_{I_{NN}=1} + \underbrace{\boxed{\sqrt{\frac{2}{3}} |1/2, +1/2>_{I_{NN}=1}}}_{J^P = 0^-}$$

$J^P = 0^-$	$J^P = 1^-$
$1 \times \frac{2}{3}$	0



Production of "$K^- pp$"

$$K^- p \to \bar{K}^0 n,$$
$$\bar{K}^0 + (pn) \to \text{“}K^- pp\text{''}$$



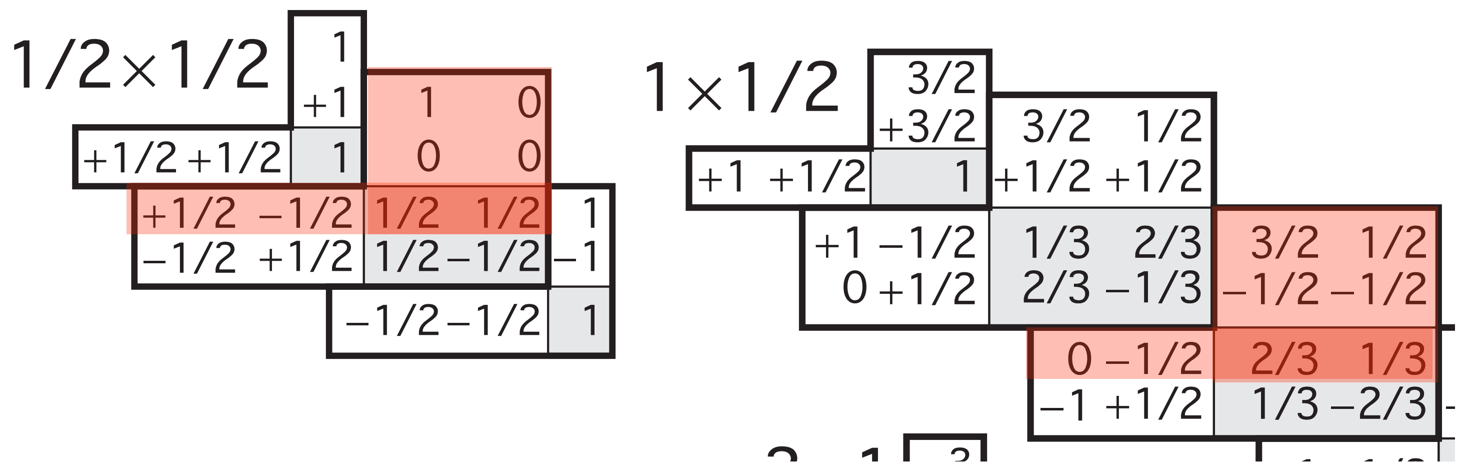
$$I_{NN} = \underbrace{|1/2, +1/2>}_{p} \otimes \underbrace{|1/2, -1/2>}_{n} = \sqrt{\frac{1}{2}}\left(|1,0> + |0,0>\right)$$

$$I_{\bar{K}NN} = \sqrt{\frac{1}{2}}\left(|1,0> + |0,0>\right) \otimes \underbrace{|1/2, +1/2>}_{\bar{K}^0}$$

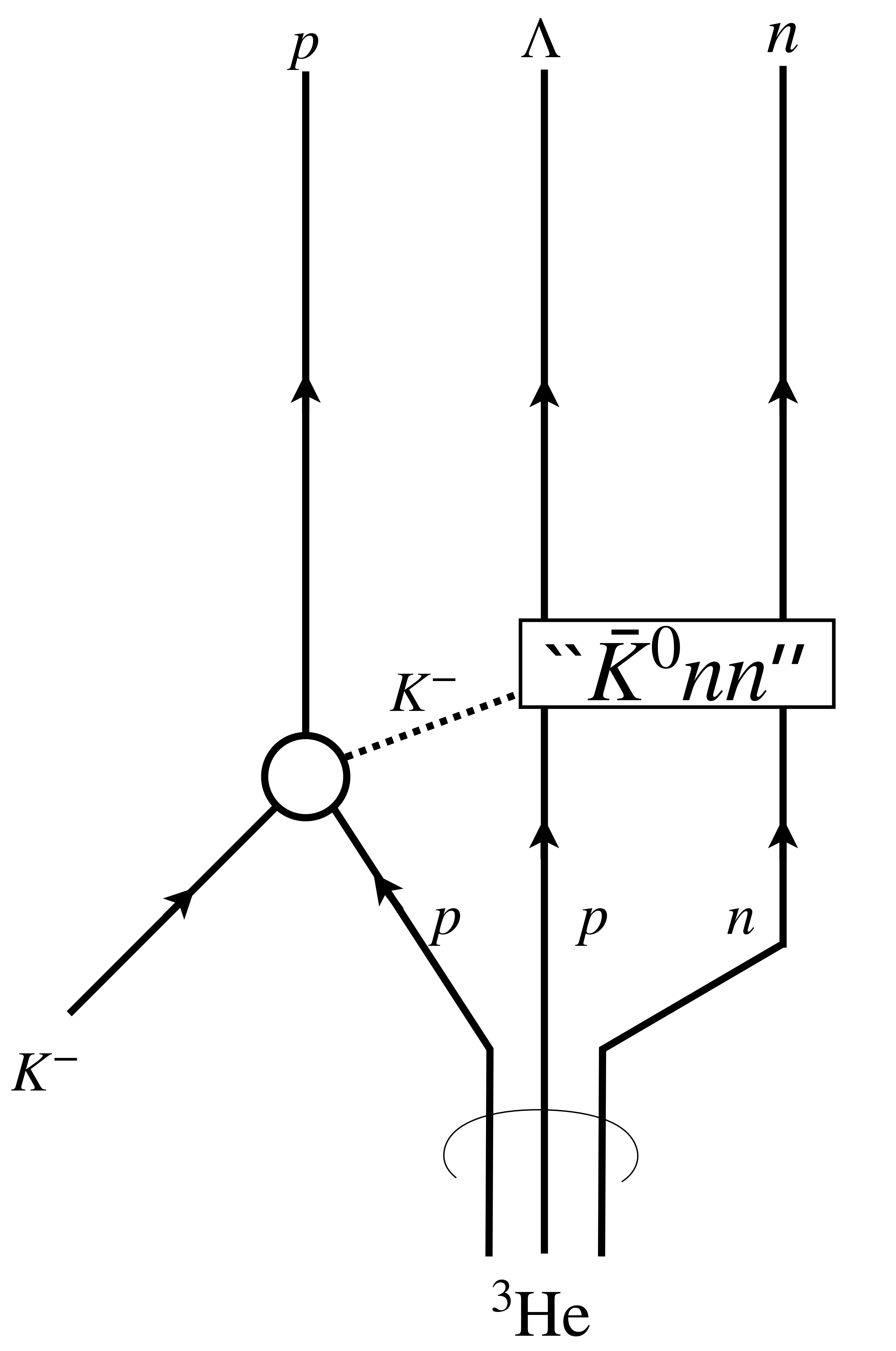
$$= \sqrt{\frac{1}{2}}\left(\sqrt{\frac{2}{3}}|3/2, +1/2>_{I_{NN}=1} - \underbrace{\boxed{\sqrt{\frac{1}{3}}|1/2, +1/2>_{I_{NN}=1}}}_{J^P = 0^-}\right)$$
$$+ \underbrace{\boxed{\sqrt{\frac{1}{2}}|1/2, +1/2>_{I_{NN}=0}}}_{J^P = 1^-}$$

$J^P = 0^-$	$J^P = 1^-$
$\frac{1}{2} \times \frac{1}{3}$	$\frac{1}{2}$

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



$$K^- p \to K^- p,$$
$$K^- + (pn) \to \text{``}\bar{K}^0 nn\text{''}$$



$$I_{NN} = \underbrace{|1/2, +1/2>}_{p} \otimes \underbrace{|1/2, -1/2>}_{n} = \sqrt{\frac{1}{2}}\left(|1{,}0> + |0{,}0>\right)$$

$$I_{\bar{K}NN} = \sqrt{\frac{1}{2}}\left(|1{,}0> + |0{,}0>\right) \otimes \underbrace{|1/2, -1/2>}_{K^-}$$

$$= \sqrt{\frac{1}{2}}\left(\sqrt{\frac{2}{3}}|3/2, -1/2>_{I_{NN}=1} + \underbrace{\boxed{\sqrt{\frac{1}{3}}|1/2, -1/2>_{I_{NN}=1}}}_{J^P = 0^-}\right)$$

$$+ \underbrace{\boxed{\sqrt{\frac{1}{2}}|1/2, -1/2>_{I_{NN}=0}}}_{J^P = 1^-}$$

$J^P = 0^-$	$J^P = 1^-$
$\frac{1}{2} \times \frac{1}{3}$	$\frac{1}{2}$

Expected spectra

– To detect $\bar{K}^0 nn$ & study isospin symmetry for $\bar{K}NN$ –