Measurement of spin-spin correlation in $K^{-}pp$ decay

– To determine spin-parity of $\bar{K}NN$–

2021 2/23-24 「日本のスピン物理学の展望」

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$\bar{K}N$ interaction & $\bar{K}NN$ bound state

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

$\bar{K}N$ interaction

Strong attractive in $I = 0$

I=0 pairs

p	Iz = +1/2	$\bar{K}^0$	p K^-
n	Iz = -1/2	K^-	n $\bar{K}^0$

$\Lambda(1405)$ state

Considered to be $\bar{K}N$-molecule

Λ^* I=0, J^P = 1/2$^-$ = p K^-

$\bar{K}NN$ bound state

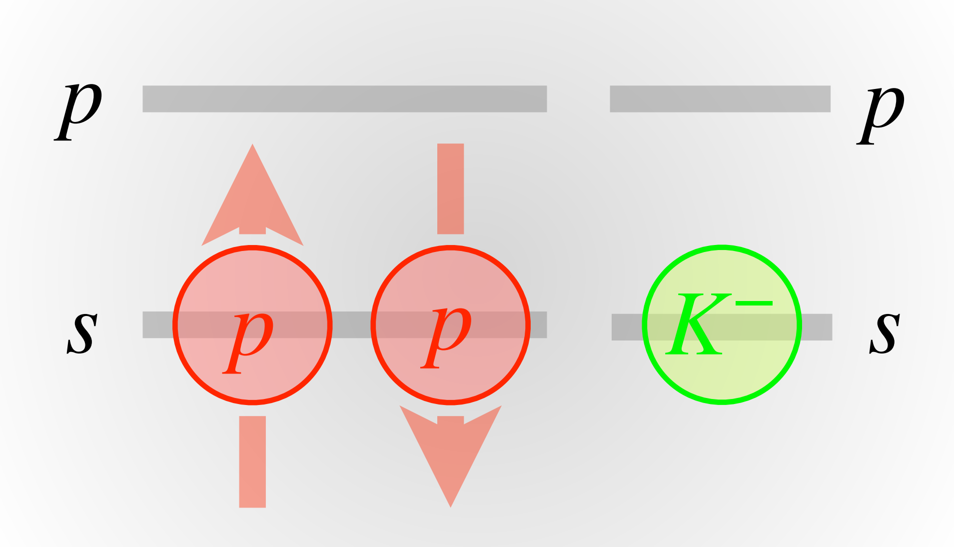
The simplest kaonic nucleus system

Bound system of anti-kaon and two nucleons

$$\left[\bar{K}_{I=\frac{1}{2}}(NN)_{I=1}\right]_{I=\frac{1}{2}}$$

K^-pp	p K^- p	**Iz = +1/2** (K^-pp - $\bar{K}^0pn$)
$\bar{K}^0nn$	n $\bar{K}^0$ n	**Iz = -1/2** (K^-pn - $\bar{K}^0nn$)

Considered to be J^P = 0$^-$



$I_{NN} = 1,\ S_{NN} = 0,\ L_{\bar{K}} = 0$

Overview of J-PARC E15 experiment

– Observation of $K^{-}pp$ bound state –

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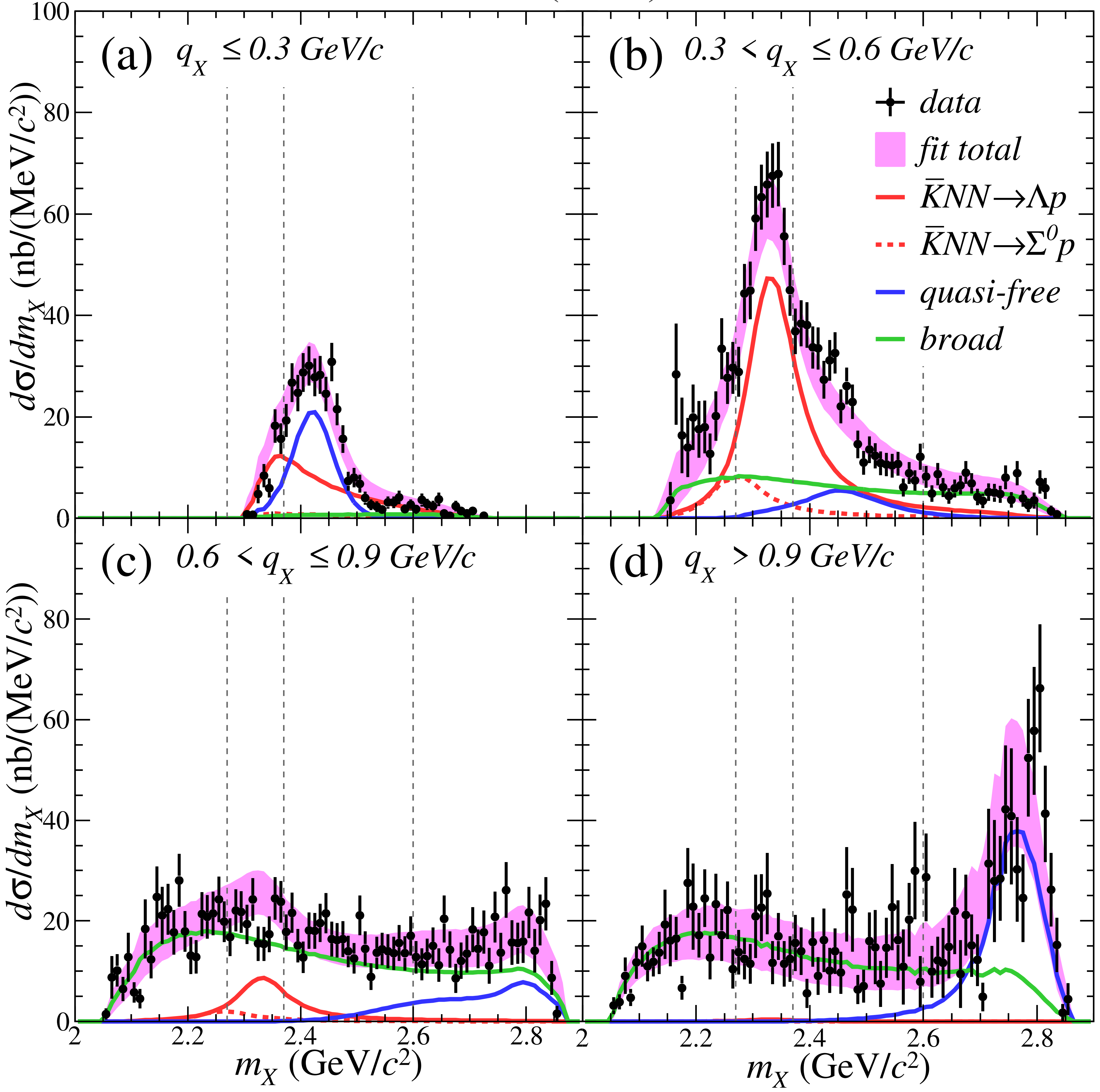


- $K^{-}pp$ production by $K^{-} + {}^{3}\mathrm{He} \to \Lambda p + n$ reaction @ J-PARC
  - Λp invariant-mass (m_X) & momentum transfer (q_X) were measured.
  - Clear signal of $K^{-}pp$ was observed.
- Basic parameters of $K^{-}pp$ were determined.
  - Binding energy
  - Decay width etc.
    - S-wave Gaussian form factor implies that the system would be very small (r~0.6 fm).

New experiment for Kaonic nuclei

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

$\bar{K}NN$ system

J^P determination

To confirm the existence more robustly

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

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

Isospin-partner of K^-pp

$\bar{K}^0nn \to \Lambda n$ decay

Relation to Λ^*

Production mechanism of $\bar{K}N$ & $\bar{K}NN$

Large Γ

Large branch to non-mesonic or substructure

Decay branch

Non-mesonic

Λp, $\Sigma^0 p$, $\Sigma^+ n$

Mesonic

$\pi\Lambda N$, $\pi\Sigma N$

Heavier system

$\bar{K}NNN$ system

Door to heavier system

$^4\mathrm{He}(K^-, N)$ reaction

K^-ppn (I=0) $K^-ppp/\bar{K}^0nnn$ (I=1)

$\bar{K}NNNN$ system

Expected large B.E. & high density

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

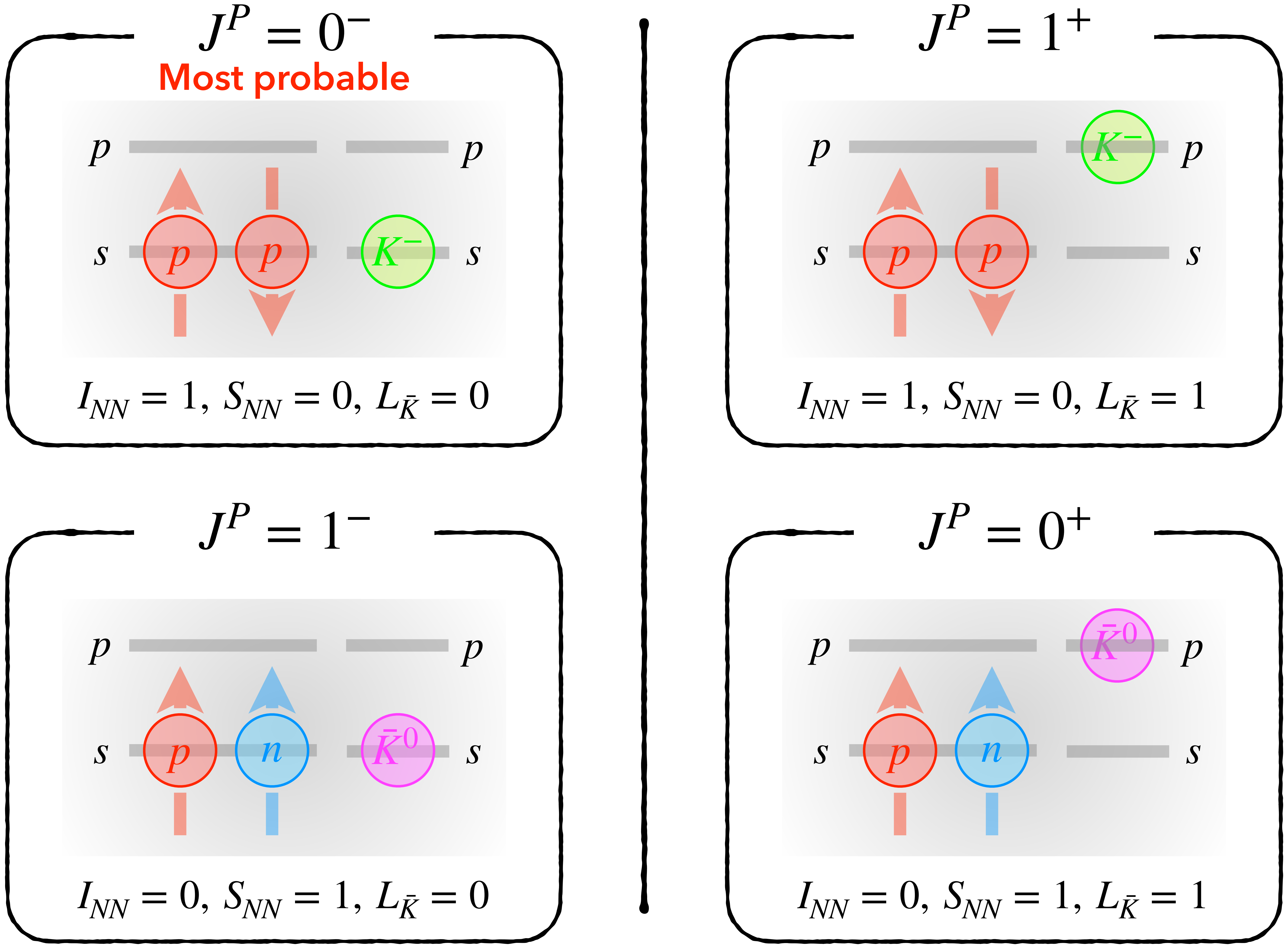
K^--α $\bar{K}^0$-α

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

$^9\mathrm{Be}(K^-, N)$ reaction

Possible J^P states

– Schematic drawing of internal configuration of K^-pp –



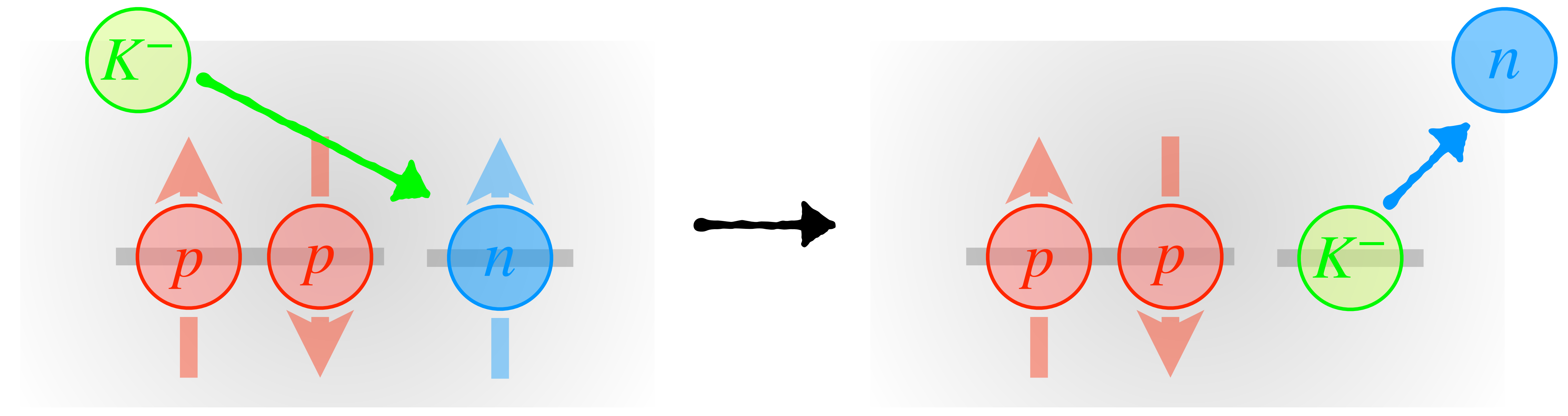
- Assuming NN in S-wave
- If $\bar{K}$-meson is in **S-wave**:
  - $J^P = 0^-$ with spin-singlet NN
    - Most probable one
  - $J^P = 1^-$ with spin-triplet NN
    - Recently predicted the existence, but expected to be shallow binding (a few MeV)
- If $\bar{K}$-meson is in **P-wave**:
  - $J^P = 1^+$ with spin-singlet NN
  - $J^P = 0^+$ with spin-triplet NN

Production of K^-pp

– $K^- + {}^3\mathrm{He}$ reaction involved by elementary $K^-N \to \bar{K}n$ –

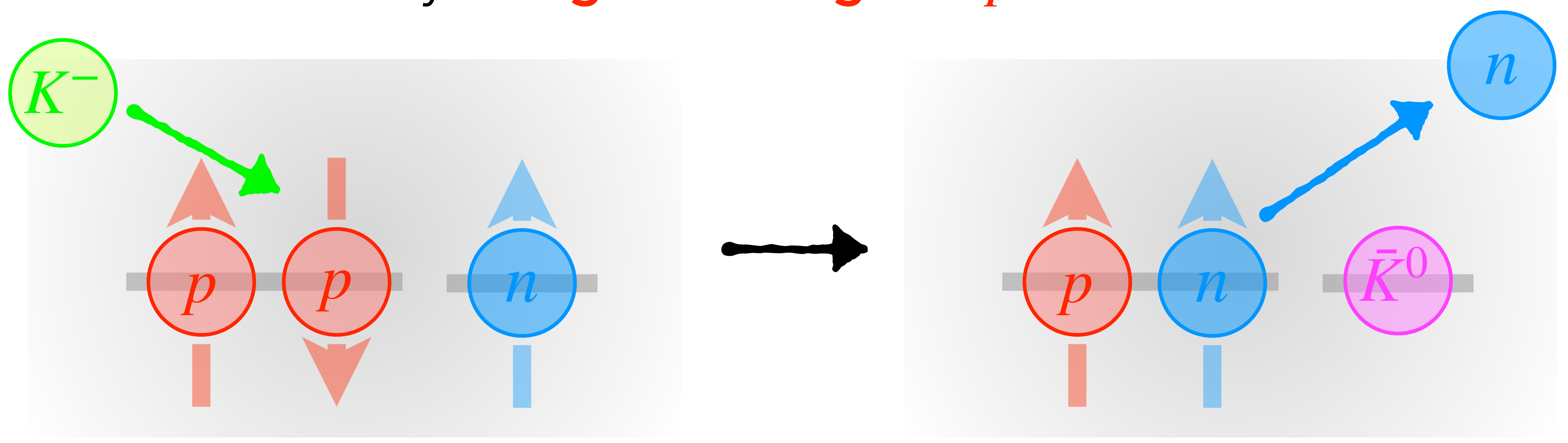
Production of $J^P = 0^-$

Involved by **elastic $K^-n \to K^-n$** reaction



Production of $J^P = 1^-$

Involved by **charge-exchange $K^-p \to \bar{K}^0 n$** reaction

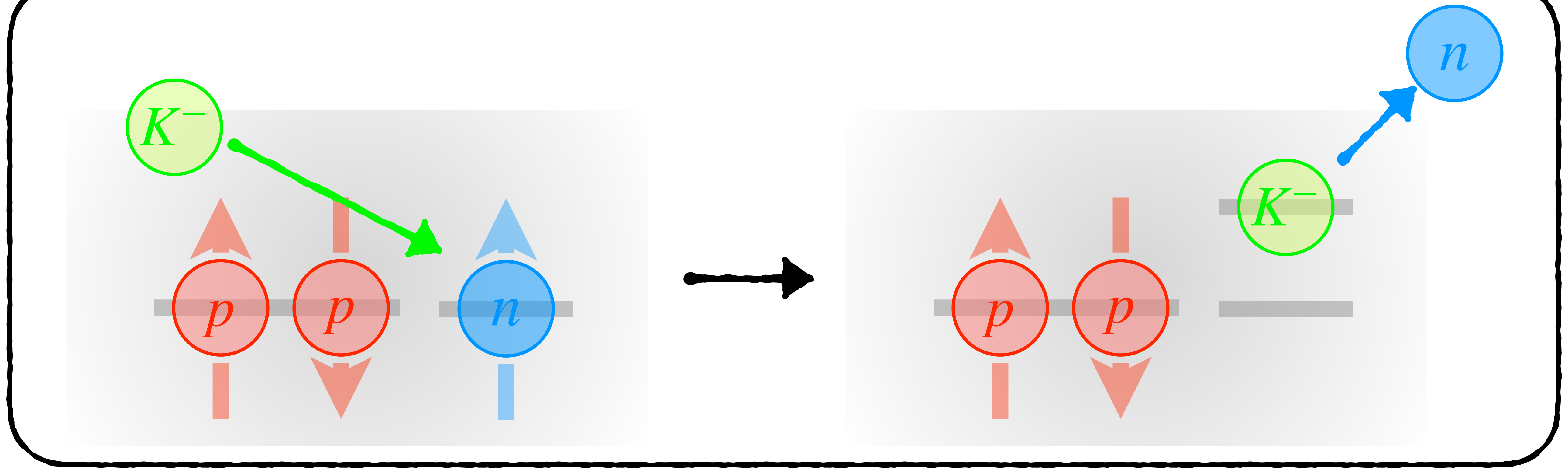


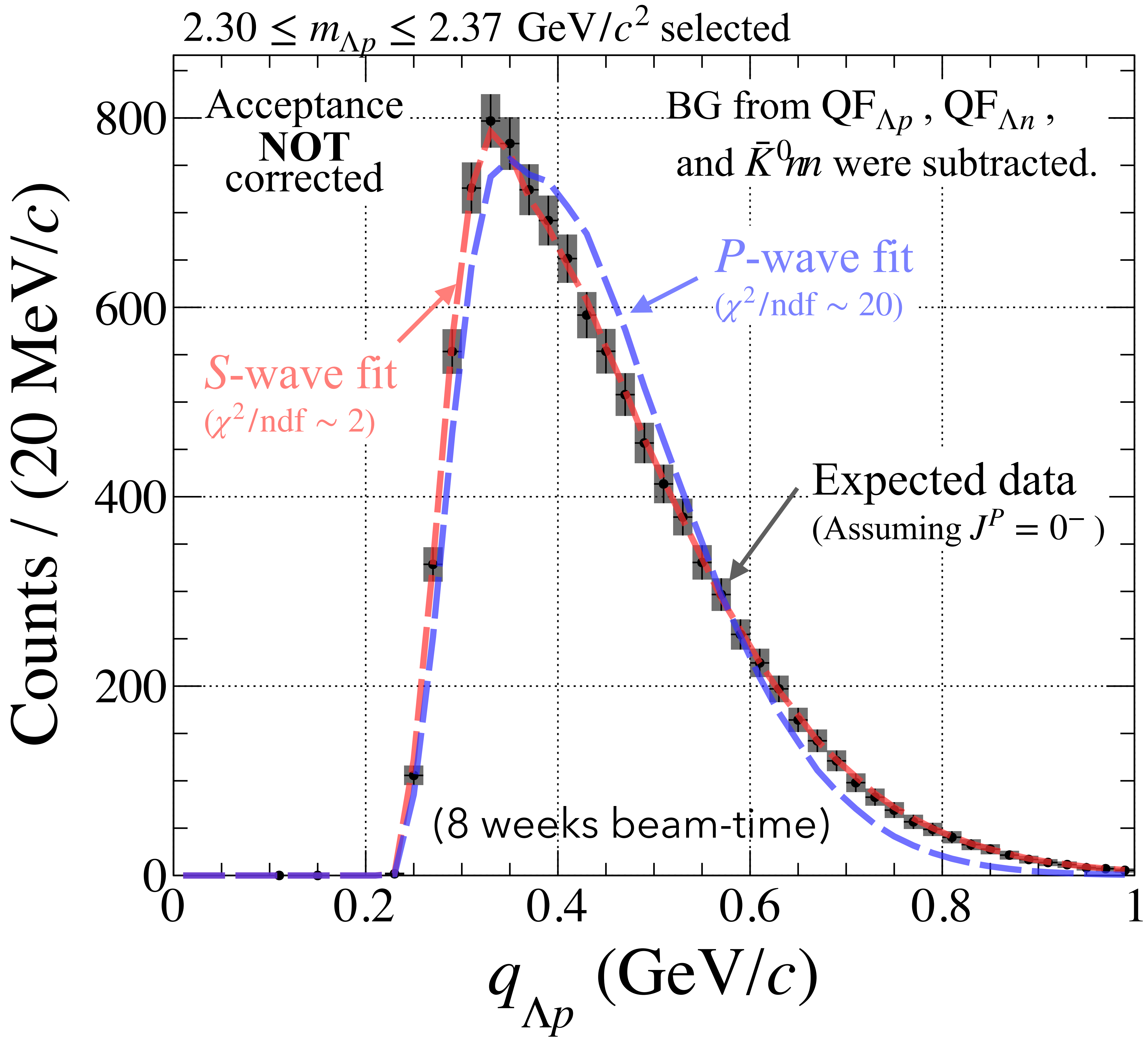
- K^-pp production involved by elementary $K^-N \to \bar{K}n$ reaction
  - By **elastic $K^-n \to K^-n$**
    - $J^P = 0^-$ **&** 1^+ are produced.
    - $\sigma \sim 5$ mb $(\theta_n = 0^\circ)$
  - By **charge-exchange $K^-p \to \bar{K}^0 n$**
    - $J^P = 1^-$ **&** 0^+ are produced.
    - $\sigma \sim 2.5$ mb $(\theta_n = 0^\circ)$
- $J^P = 0^-$ **&** 1^+ production would be favored in $K^- + {}^3\mathrm{He}$ reaction.

Production of $K^- pp$

– Momentum transfer dependence of S & P -wave states –

Production of $J^P = 1^+$





- Differential cross section should be different:
  - $\propto \exp\left(-\frac{q^2}{Q^2}\right)$ for **S-wave** state
  - $\propto \frac{q^2}{Q^2} \exp\left(-\frac{q^2}{Q^2}\right)$ for **P-wave** state

What we measure

– Spin observable in $K^- pp \to \Lambda p$ decay –

- Spin-spin correlation between Λ & proton ($\vec{S}_\Lambda \cdot \vec{S}_p \equiv \alpha_{\Lambda p}$);
  - Λ-spin ($\vec{S}_\Lambda$) is measured by $\Lambda \to p\pi^-$ **decay asymmetry**.
  - Proton spin ($\vec{S}_p$) is measured by **p-C scattering asymmetry**.

$I_{K^-} = \frac{1}{2}, J^P_{K^-} = 0^-$

$I_{pp} = 1, J^P_{pp} = 0^+$

$$K^- pp$$

$$I_{K^- pp} = \frac{1}{2}, J^P_{K^- pp} = 0^-$$

Strong decay →

I **&** J^P **conserved**

$S_{\Lambda p}$ **should be one.**

$$\Lambda p$$

$$I_{\Lambda p} = \frac{1}{2}, J^P_{\Lambda p} = 0^-$$

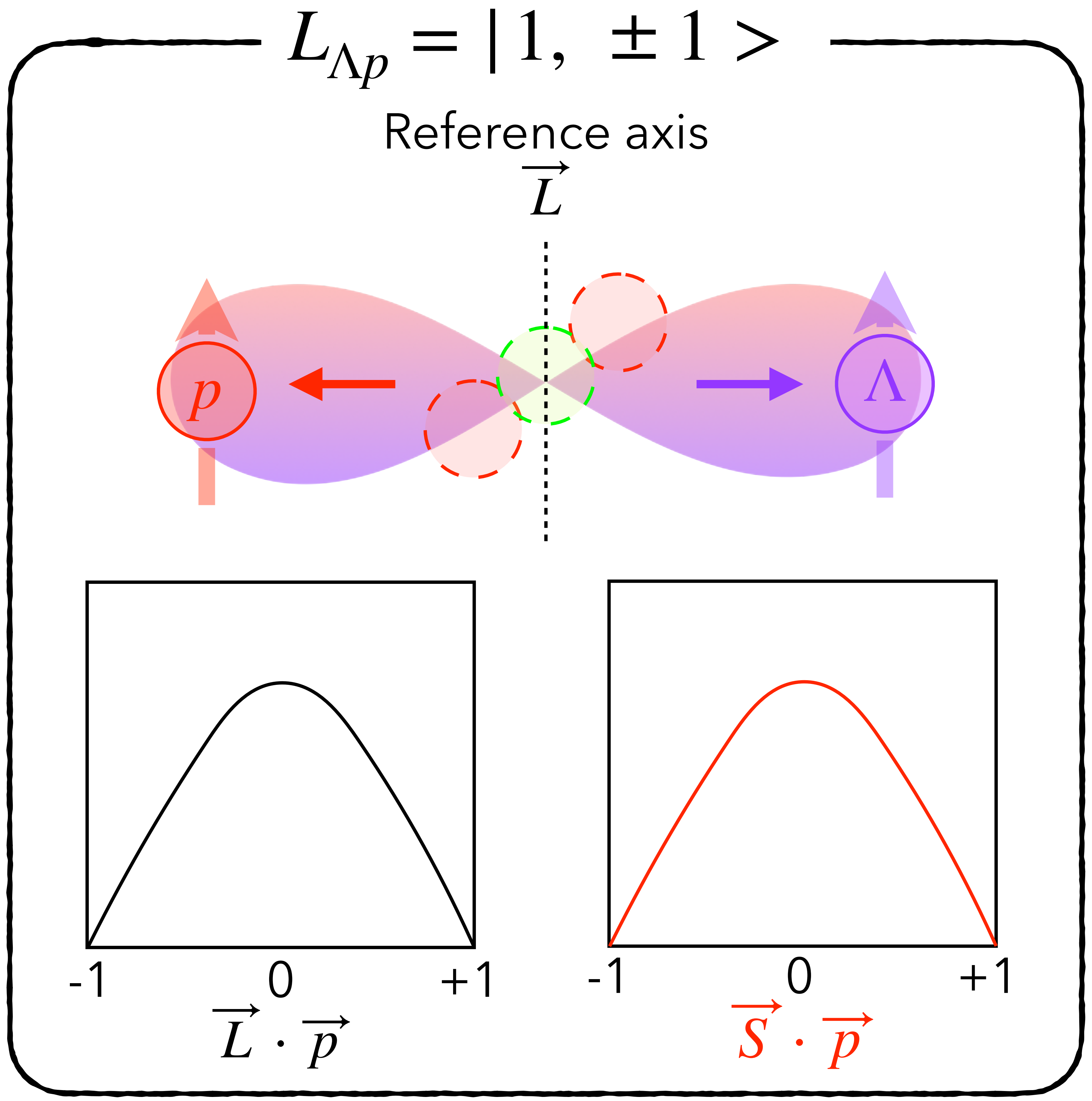
$I_\Lambda = 0, J^P_\Lambda = \frac{1}{2}^+$

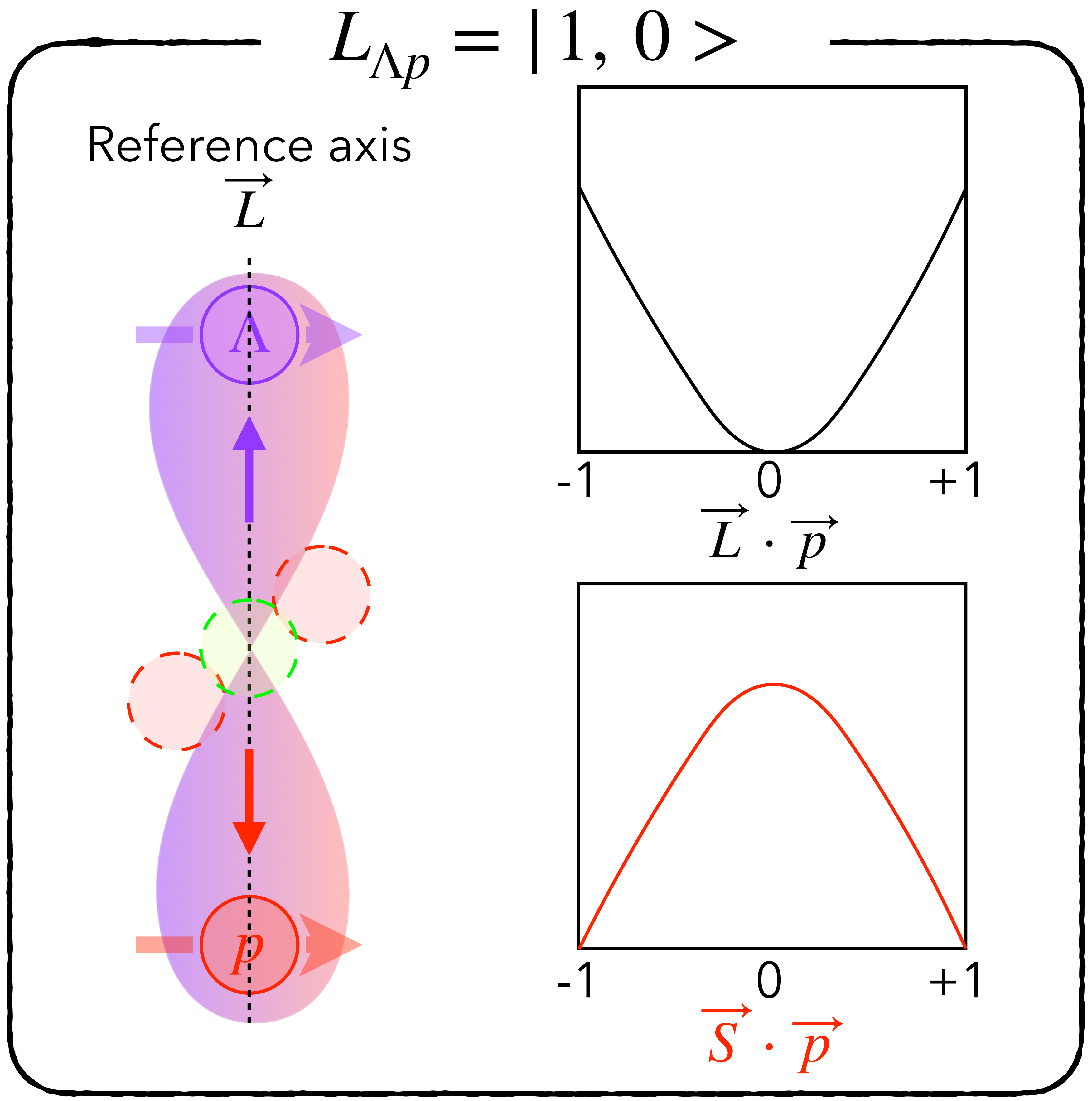
$I_p = \frac{1}{2}, J^P_p = \frac{1}{2}^+$

Λ & proton are **not polarized**,
but their spins are **correlated**.

Decay of $J^P = 0^-$ state

– P-wave decay ($L_{\Lambda p} = 1$) with parallel spin of Λ & proton ($S_{\Lambda p} = 1$) –

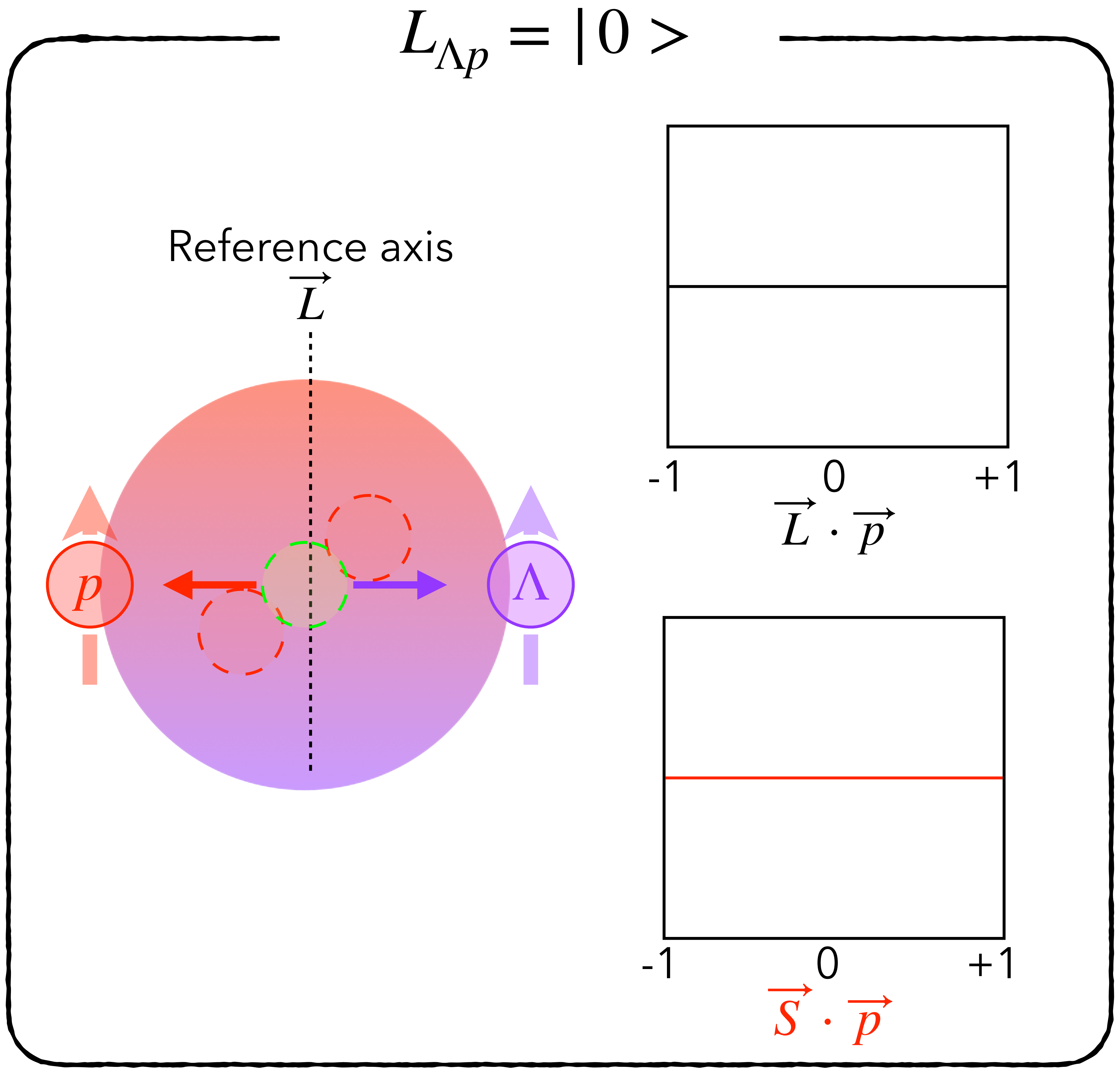




- $L_{\Lambda p} = 1$ to make negative parity
- $S_{\Lambda p} = 1$ to make $J = 0$
  - So that, $\alpha_{\Lambda p} = +1$ is expected.
- $\vec{S} \cdot \vec{p} = 0$ is favored.
  - It cannot be measured, but it would makes measured $\alpha_{\Lambda p}$ different from S-wave decay.

Decay of $J^P = 1^+$ state

– S-wave decay ($L_{\Lambda p} = 0$) with parallel spin of Λ & proton ($S_{\Lambda p} = 1$) –

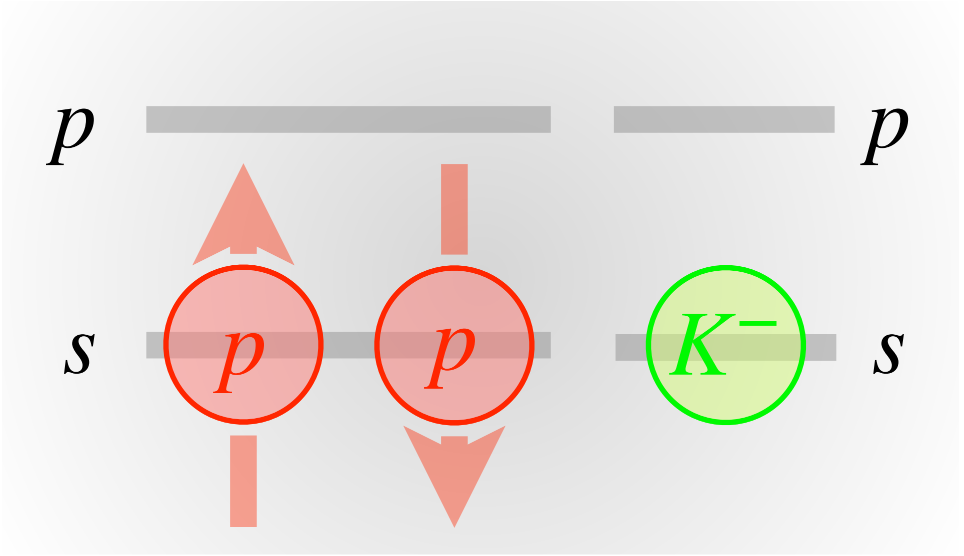


- $L_{\Lambda p} = 0$ to make positive parity
- $S_{\Lambda p} = 1$ to make $J = 1$
  - So that, $\alpha_{\Lambda p} = +1$ is expected.

- $\vec{S} \cdot \vec{p}$ is flat.

Expected spin-spin correlation

$J^P = 0^-$

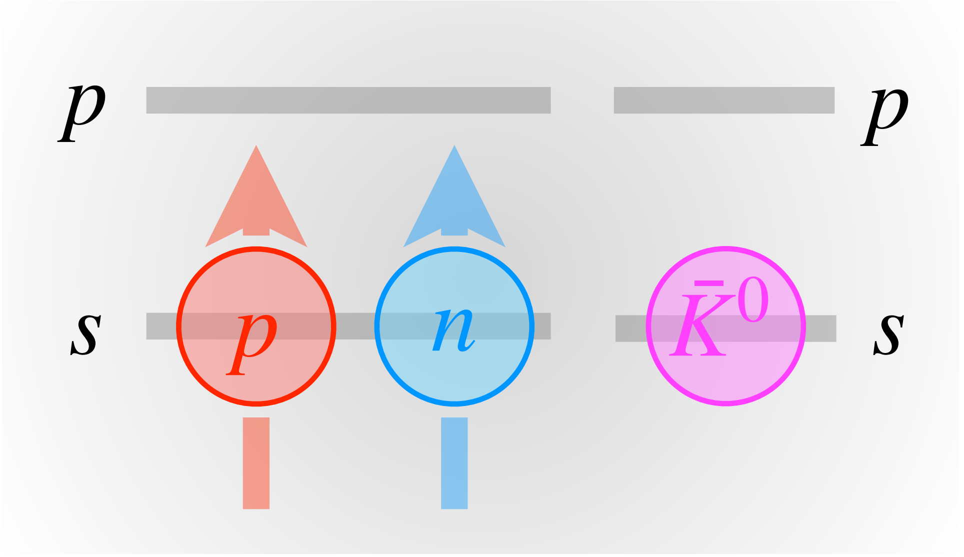


P-wave decay

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

$I_{NN} = 1,\ S_{NN} = 0,\ L_{\bar{K}} = 0$

$J^P = 1^-$



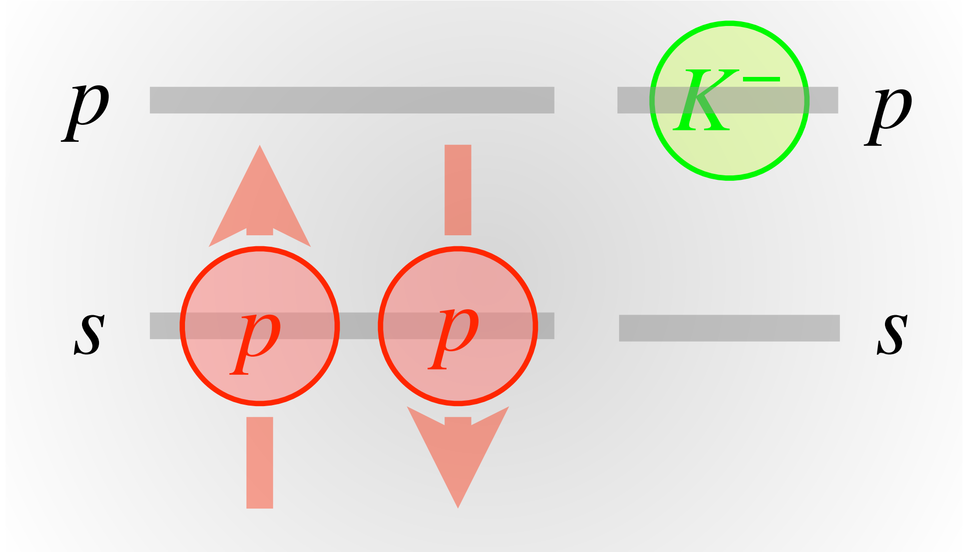
P-wave decay

$\alpha_{\Lambda p} = ?$

To be discussed in next

$I_{NN} = 0,\ S_{NN} = 1,\ L_{\bar{K}} = 0$

$J^P = 1^+$

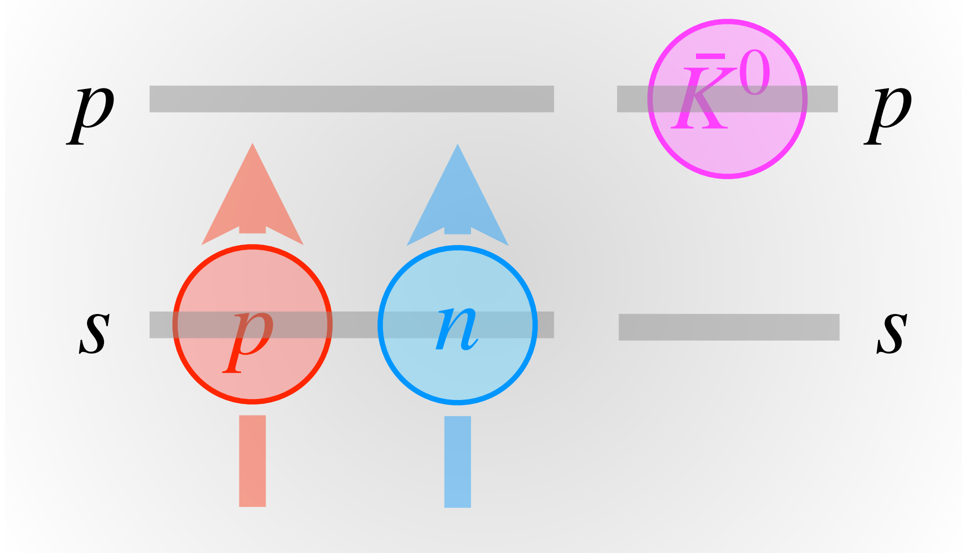


S-wave decay

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

$I_{NN} = 1,\ S_{NN} = 0,\ L_{\bar{K}} = 1$

$J^P = 0^+$



S-wave decay

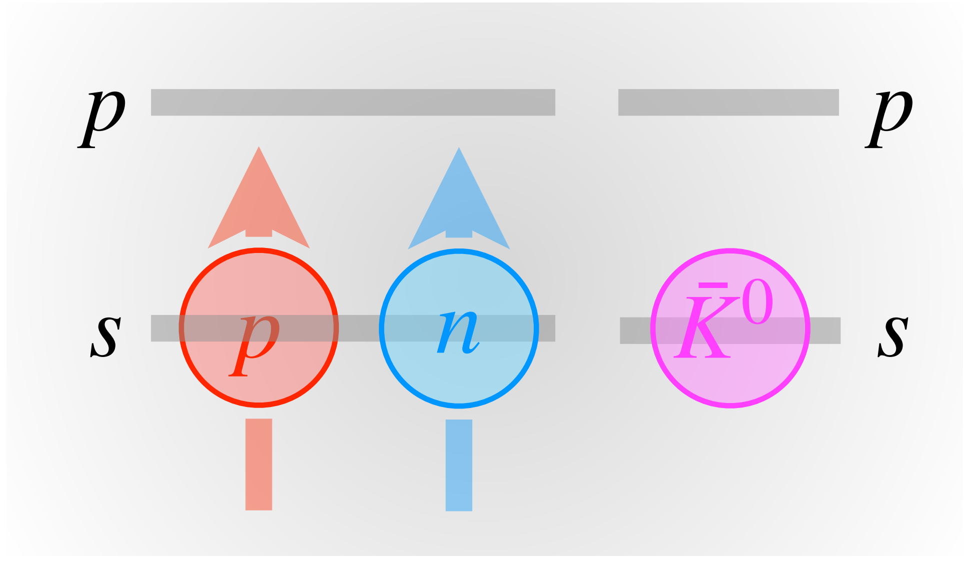
$\alpha_{\Lambda p} = -1$

$I_{NN} = 0,\ S_{NN} = 1,\ L_{\bar{K}} = 1$

Decay of $J^P = 1^-$ state

– P-wave decay ($L_{\Lambda p} = 1$) with both $S_{\Lambda p} = 0$ & 1 –

$J^P = 1^-$



$I_{NN} = 0,\ S_{NN} = 1,\ L_{\bar{K}} = 0$

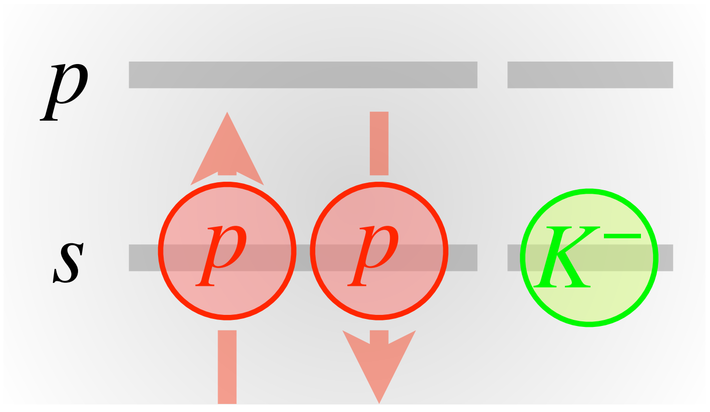
P-wave decay

$\alpha_{\Lambda p} = ?$

$\alpha_{\Lambda p} = -1$ (Spin flip)

$\alpha_{\Lambda p} = +1$ (Spin non-flip)

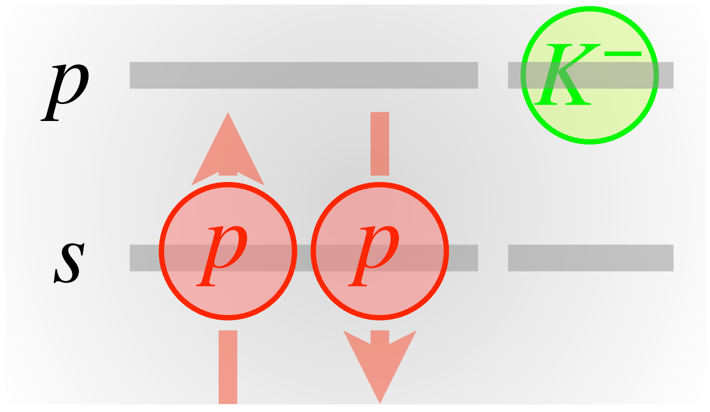
$J^P = 0^-$



$S_{NN} = 0 \rightarrow S_{\Lambda p} = 1$

Spin flip

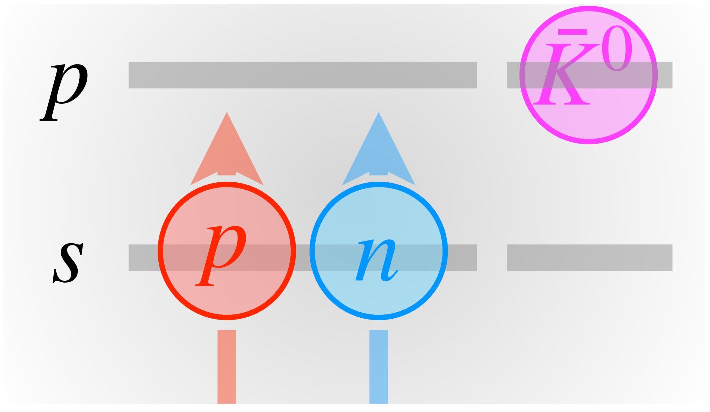
$J^P = 1^+$



$S_{NN} = 0 \rightarrow S_{\Lambda p} = 1$

Spin flip

$J^P = 1^+$



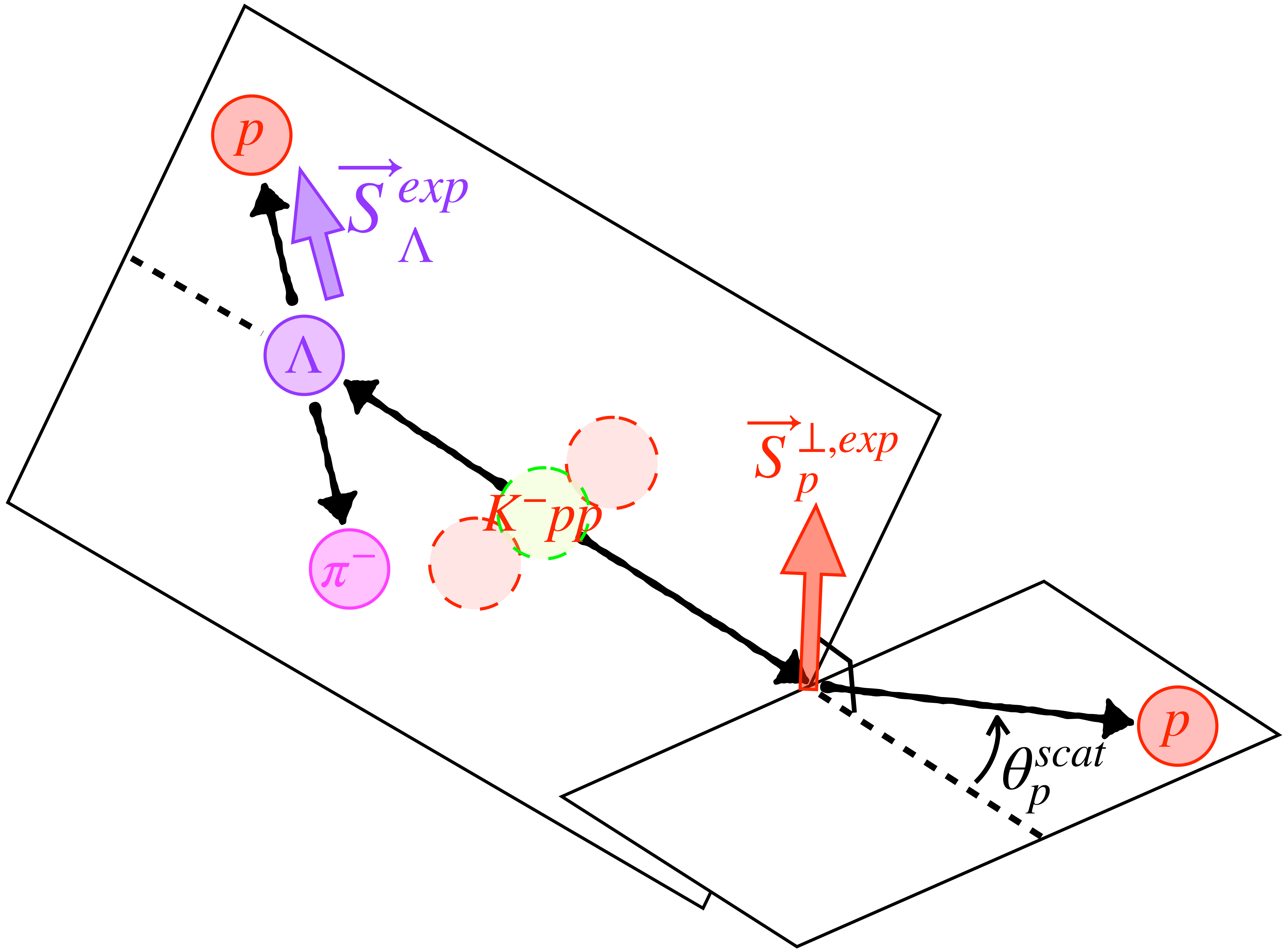
$S_{NN} = 1 \rightarrow S_{\Lambda p} = 0$

Spin flip

- Both $S_{\Lambda p} = 0$ & 1 possible
  - $S_{\Lambda p} = 0$: spin flip
  - $S_{\Lambda p} = 1$: spin non-flip
- If spin flip is dominant: $\alpha_{\Lambda p} \rightarrow -1$
- If spin non-flip is dominant: $\alpha_{\Lambda p} \rightarrow +1$
  - In other J^P states, always spin flip
- If spin flip & spin non-flip are comparable,
  - $\alpha_{\Lambda p} \rightarrow \pm 0$ (we assume this.)
    - Discussion with theoreticians is ongoing.

How to measure spin-spin correlation

– Measuring spin directions using asymmetries of $\Lambda \to p\pi^-$ decay & p-C scattering –

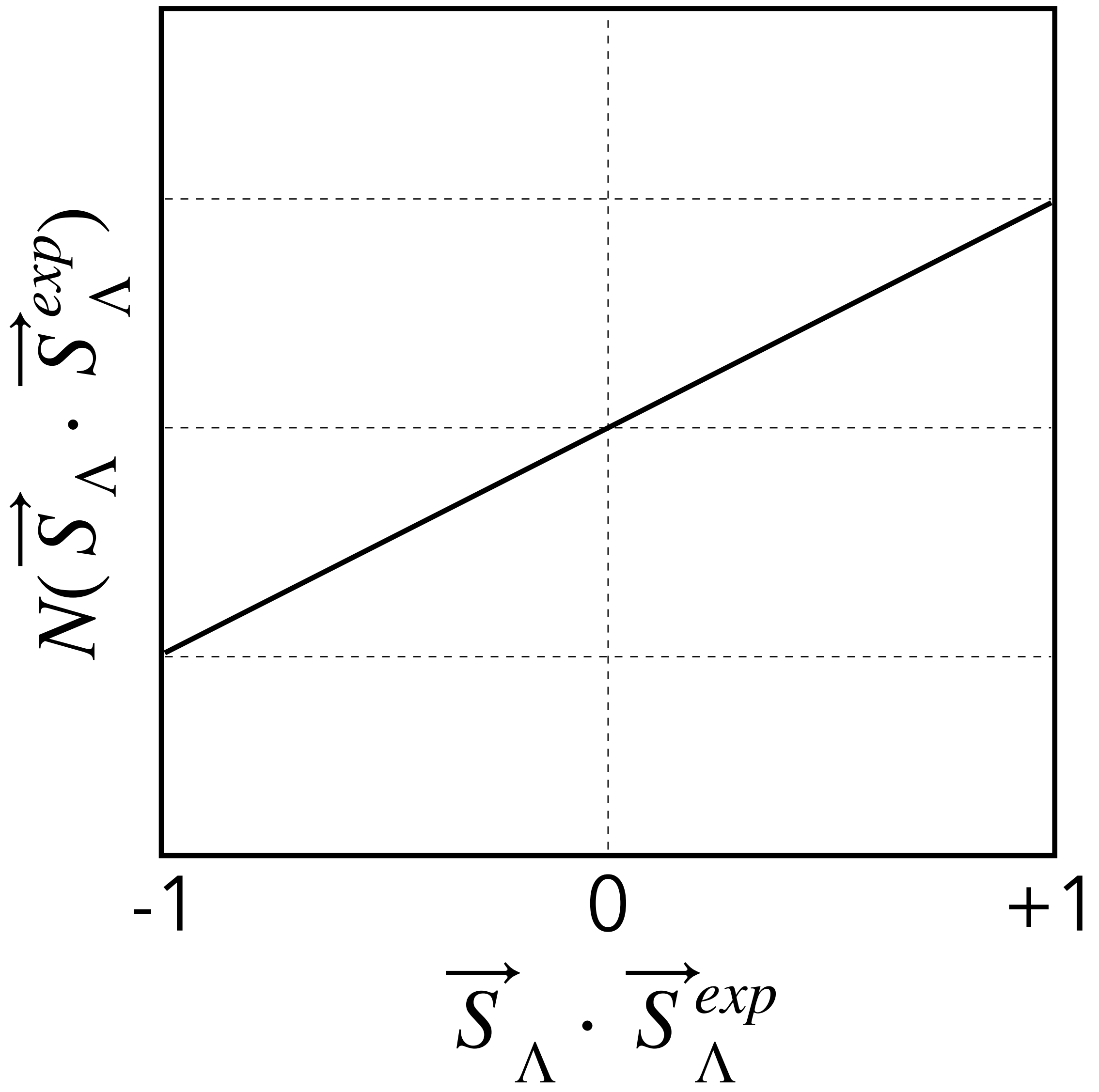


Λ-spin

Asymmetry of $\Lambda \to p\pi^-$ decay

$$\vec{S}_\Lambda^{exp} = \frac{\vec{p}_{p\ \text{from}\ \Lambda}}{|\vec{p}_{p\ \text{from}\ \Lambda}|}$$

Slope : α_- **(Decay param. of** Λ**)**

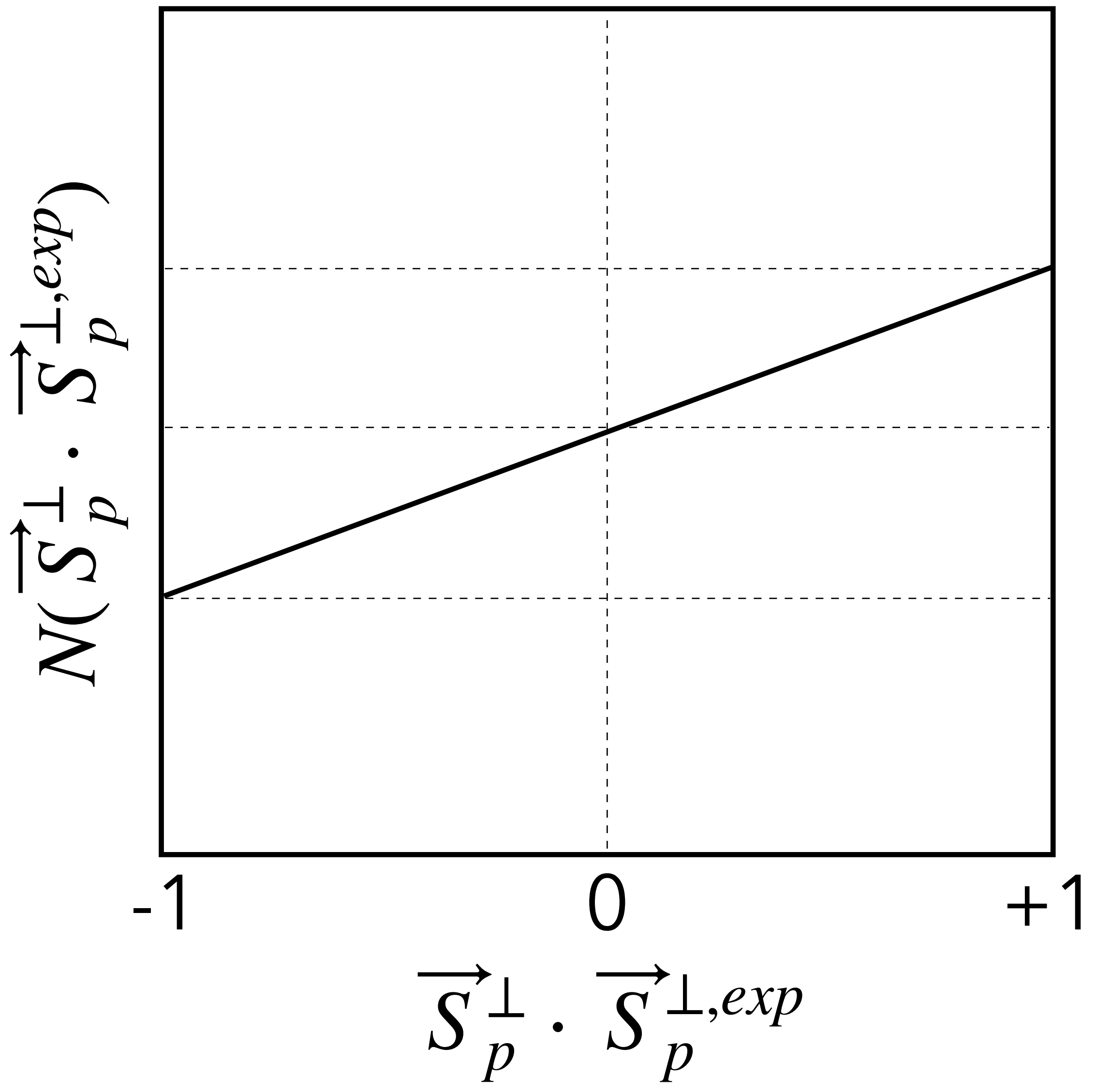


Proton spin

Asymmetry of p-C scattering

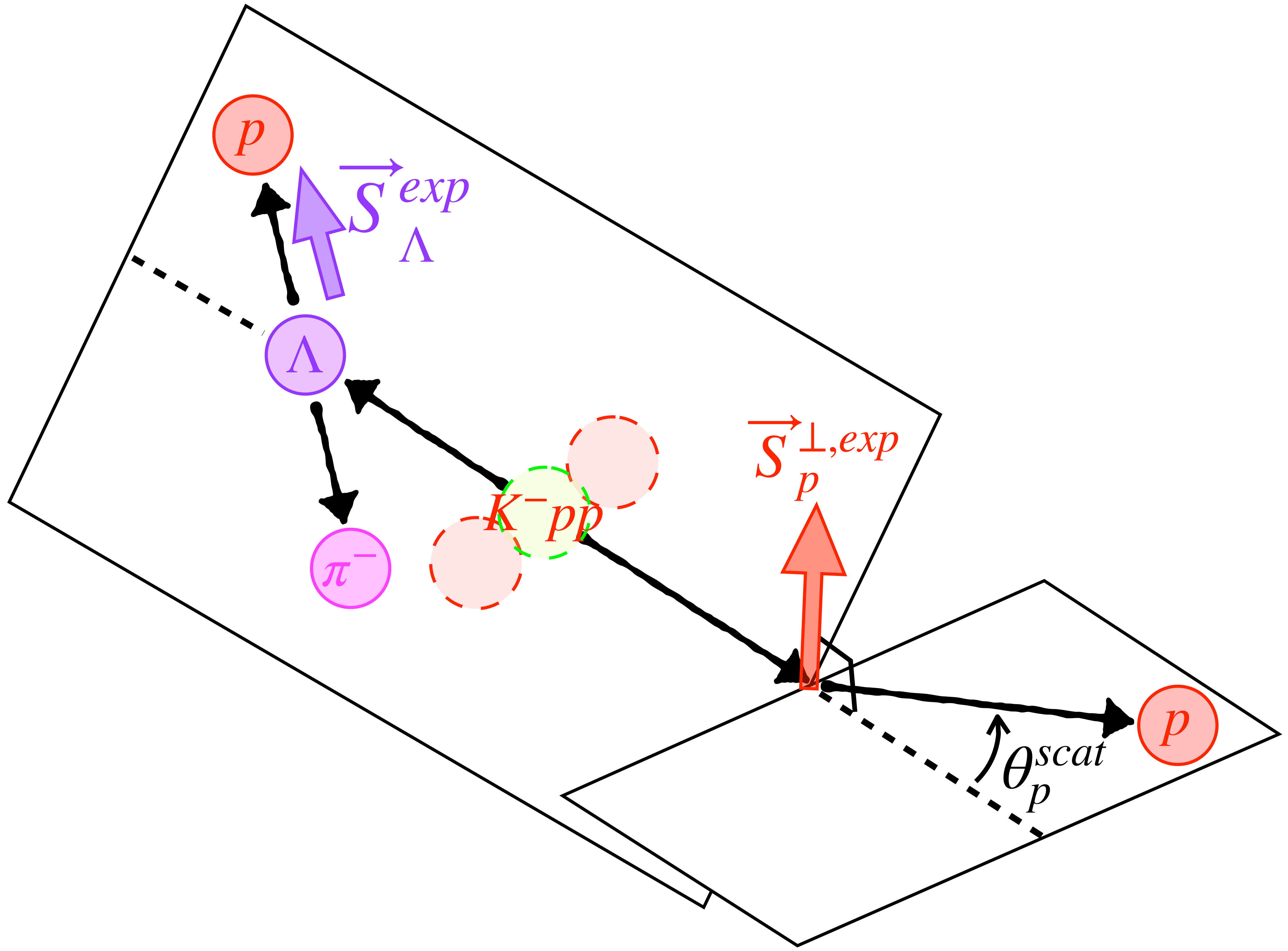
$$\vec{S}_p^{\perp,exp} = \frac{\vec{p}_p \times \vec{p}_{p'}}{|\vec{p}_p \times \vec{p}_{p'}|}$$

Slope : $< A_C > \cdot < |\vec{S}_p \times \vec{p}_p| >$



How to measure spin-spin correlation

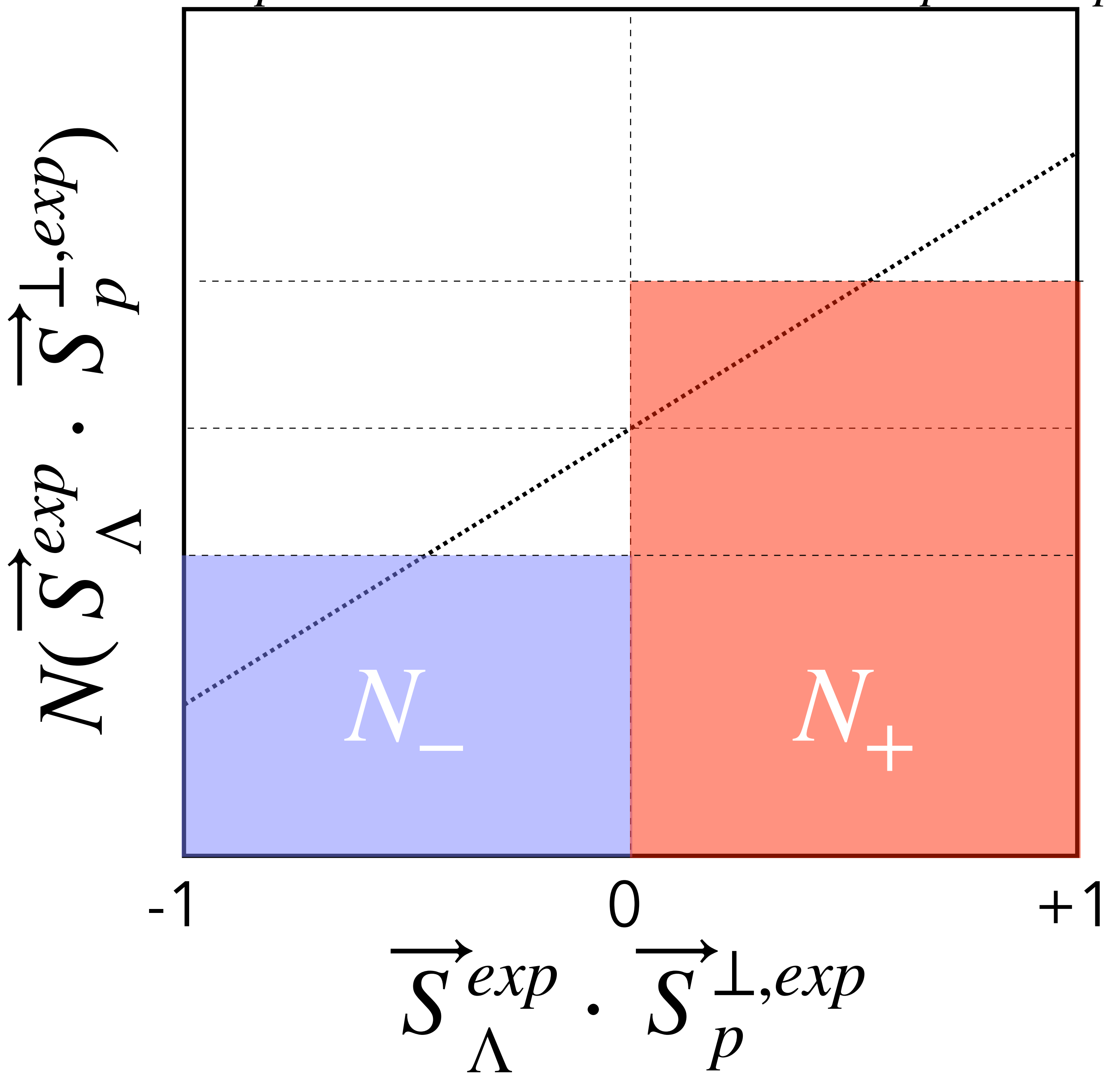
– Measuring spin-spin correlation from two spin directions–



Spin-spin correlation; $\alpha_{\Lambda p}$

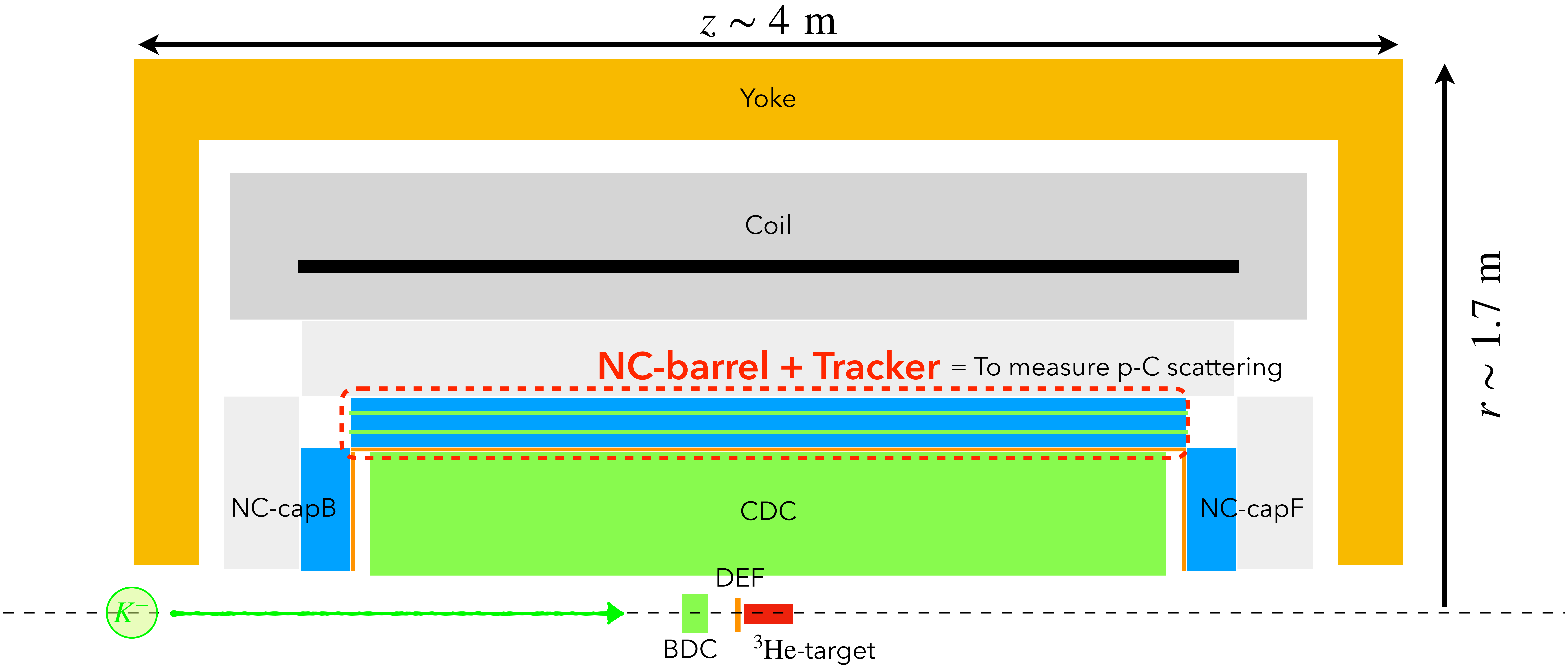
$$\alpha_{\Lambda p} = \frac{N_+ - N_-}{N_+ + N_-} \cdot \frac{2}{r} \qquad r \equiv \alpha_- \cdot < A_C > \cdot < |\vec{S}_p \times \vec{p}_p| >$$

Slope : $\alpha_{\Lambda p} \cdot \alpha_- \cdot < A_C > \cdot < |\vec{S}_p \times \vec{p}_p| >$



Detector system for new experiment

– Large acceptance cylindrical detector system –



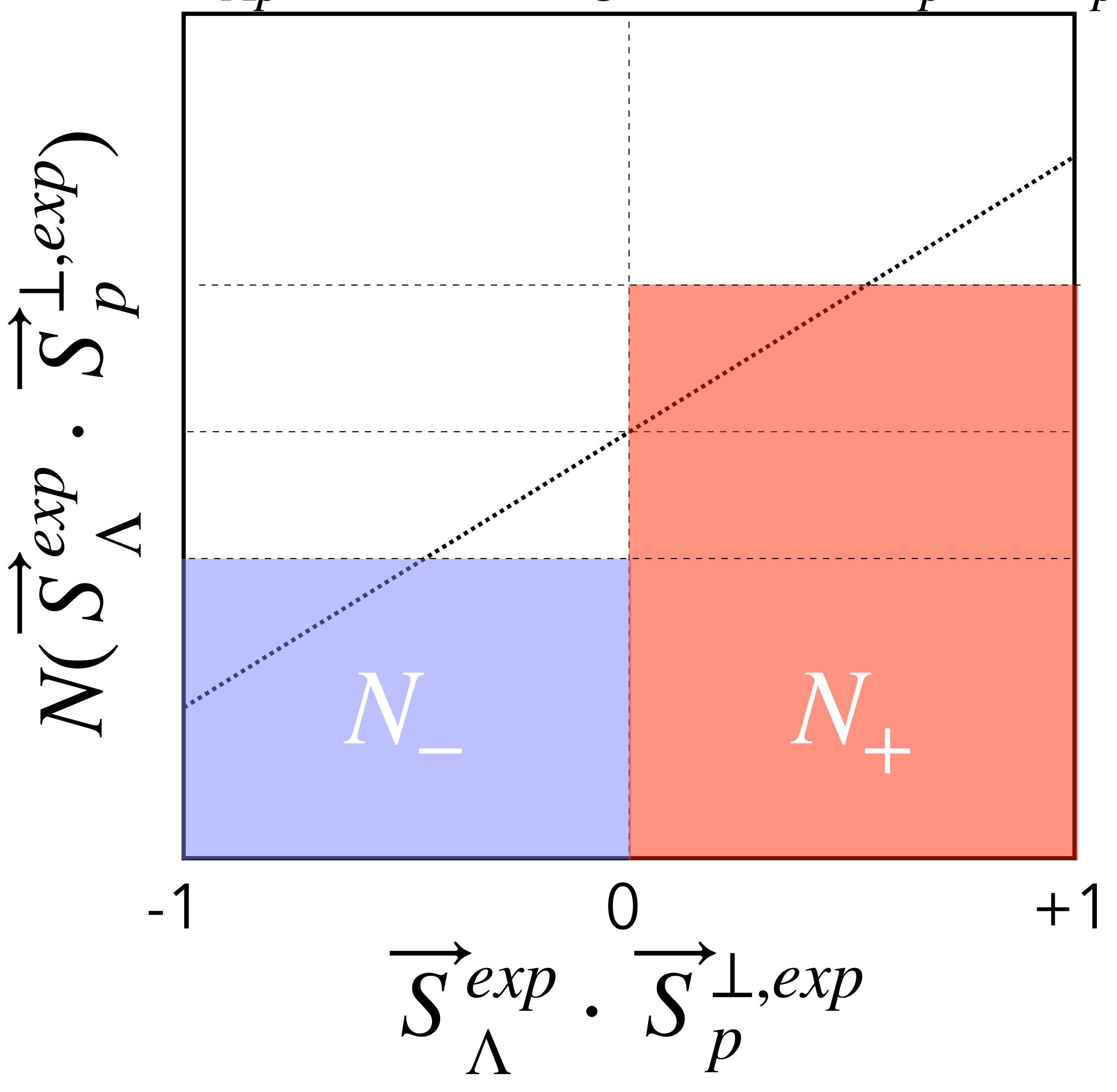
Estimation of the accuracy

– Overview –

Spin-spin correlation; $\alpha_{\Lambda p}$

$$\alpha_{\Lambda p} = \frac{N_+ - N_-}{N_+ + N_-} \cdot \frac{2}{r} \qquad r \equiv \alpha_- \cdot < A_C > \cdot < | \vec{S}_p \times \vec{p}_p | >$$

Slope : $\alpha_{\Lambda p} \cdot \alpha_- \cdot < A_C > \cdot < | \vec{S}_p \times \vec{p}_p | >$



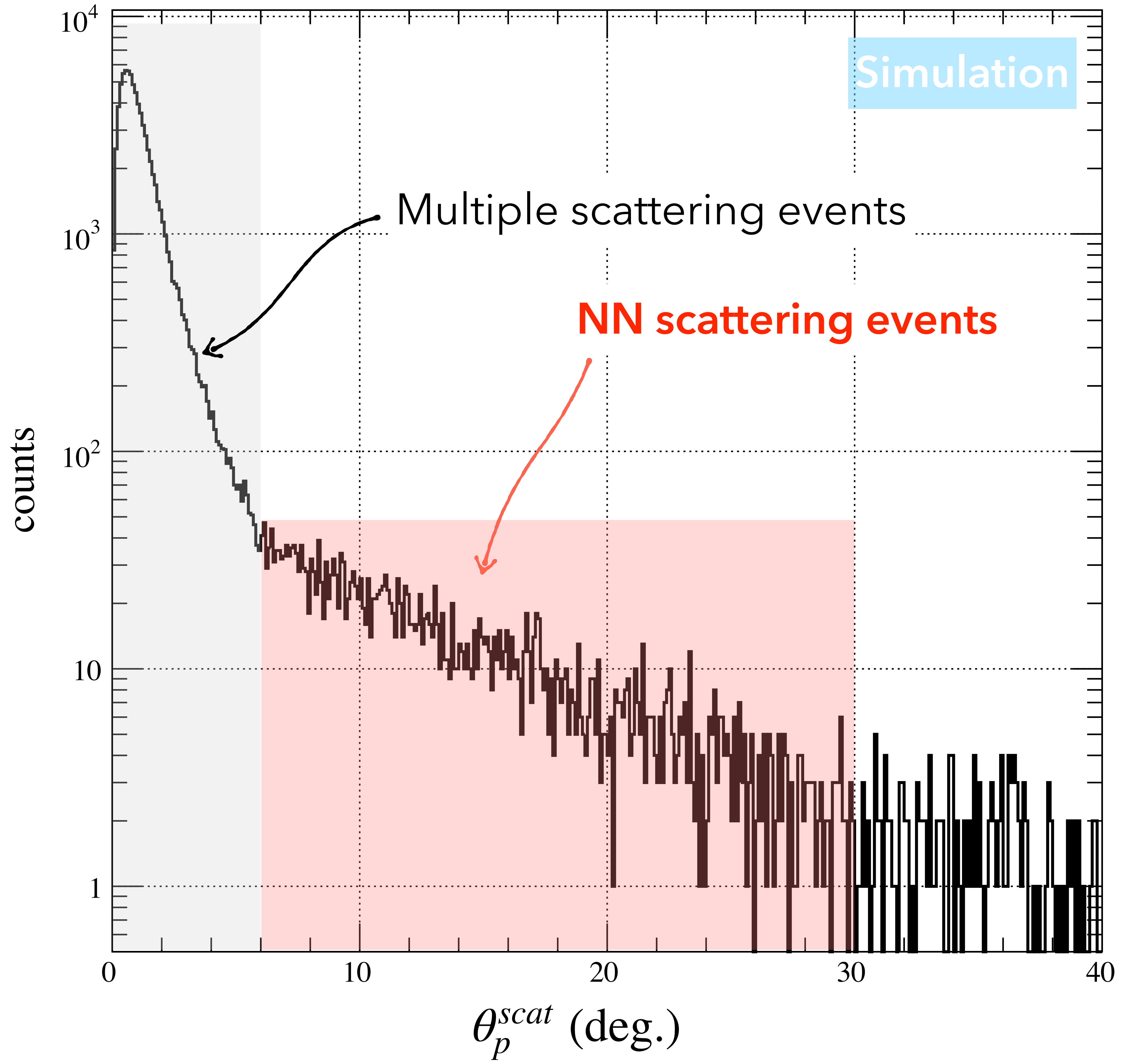
- Statistical error;

$$\Delta\alpha_{\Lambda p} = \frac{2}{\alpha_- \cdot < A_C > \cdot < | \vec{S}_p \times \vec{p}_p | >} \cdot \frac{1}{\sqrt{N_+ + N_-}}$$

  - $\alpha_- \sim 0.7$ (well known)
  - $< A_C >$, $< | \vec{S}_p \times \vec{p}_p | >$, and number of scattering events should be studied.
- Systematic error;
  - Good reference to evaluate systematic
    - Proton polarization in $\Lambda \rightarrow p\pi^-$ decay
    - To be discussed later

Estimation of the accuracy

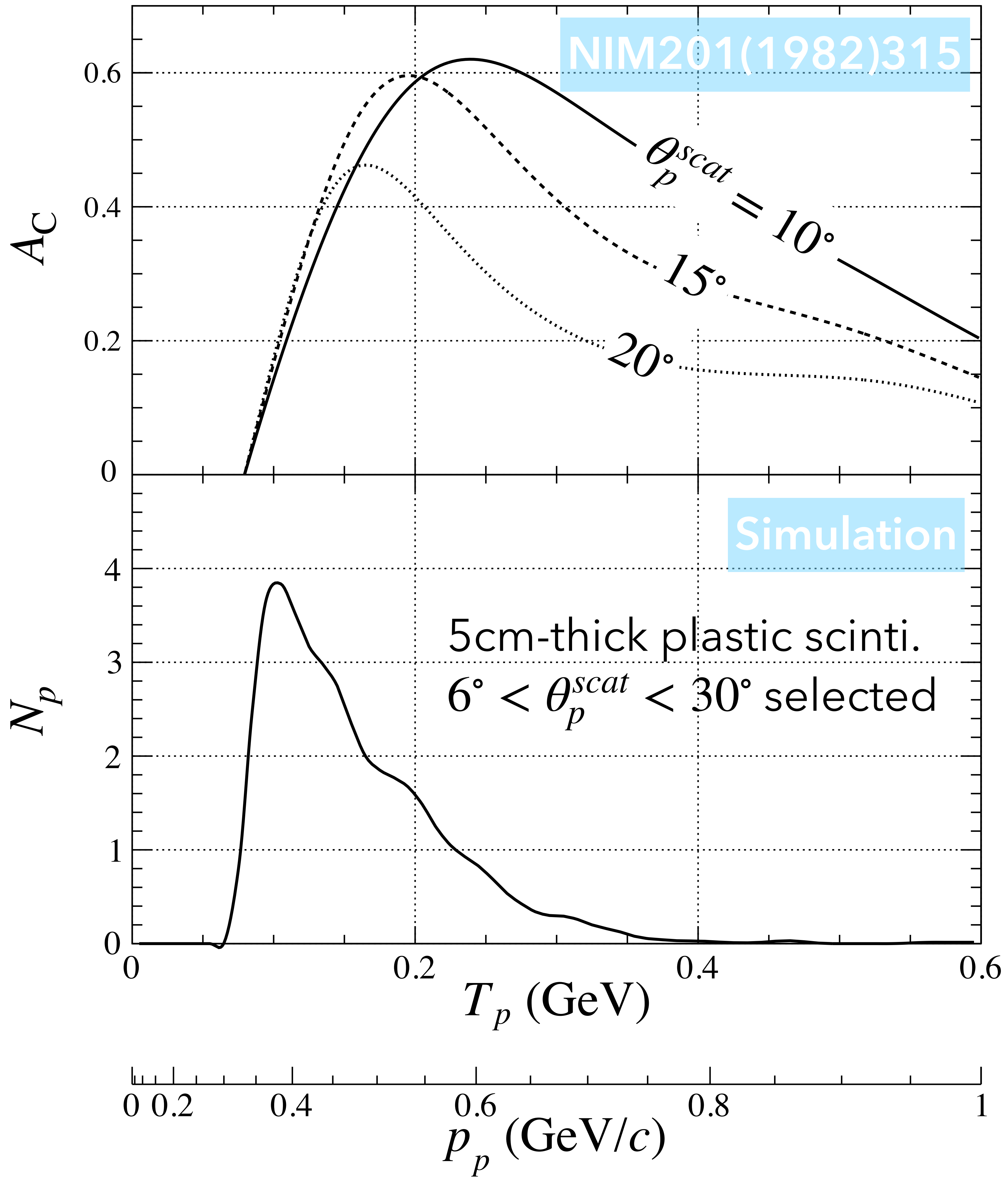
– Numbers of $K^{-}pp \to \Lambda p$ & p-C scattering –



- Number of $K^{-}pp \to \Lambda p$ to be detected
  - $N^{det}_{K^{-}pp} \sim 3000/\text{week}$
    - Cross section of $K^{-}pp$: $\sigma_{K^{-}pp} \cdot \mathrm{BR}_{\Lambda p} = 9.3\ \mu\mathrm{b}$ (measured value)
    - Expected luminosity : $\mathscr{L}_{week} = 2.8\ \mathrm{nb}^{-1}/\mathrm{week}$ (estimation with 90kW beam-power)
    - Acceptance including analysis efficiency : $\sim 15\,\%$ (proton detected by barrel-part of new CDS)
- **Number of p-C scattering**
  - $N_{total} = N_{+} + N_{-} \sim 300$ events/week
    - 5 cm x 3 layers plastic-scintillators used as "scattering target"
    - Reaction rate : $\sim 3\,\%$ of all incident proton per one 5cm-plastic-scintillator (Estimated by Geant4 based MC simulation)

Estimation of the accuracy

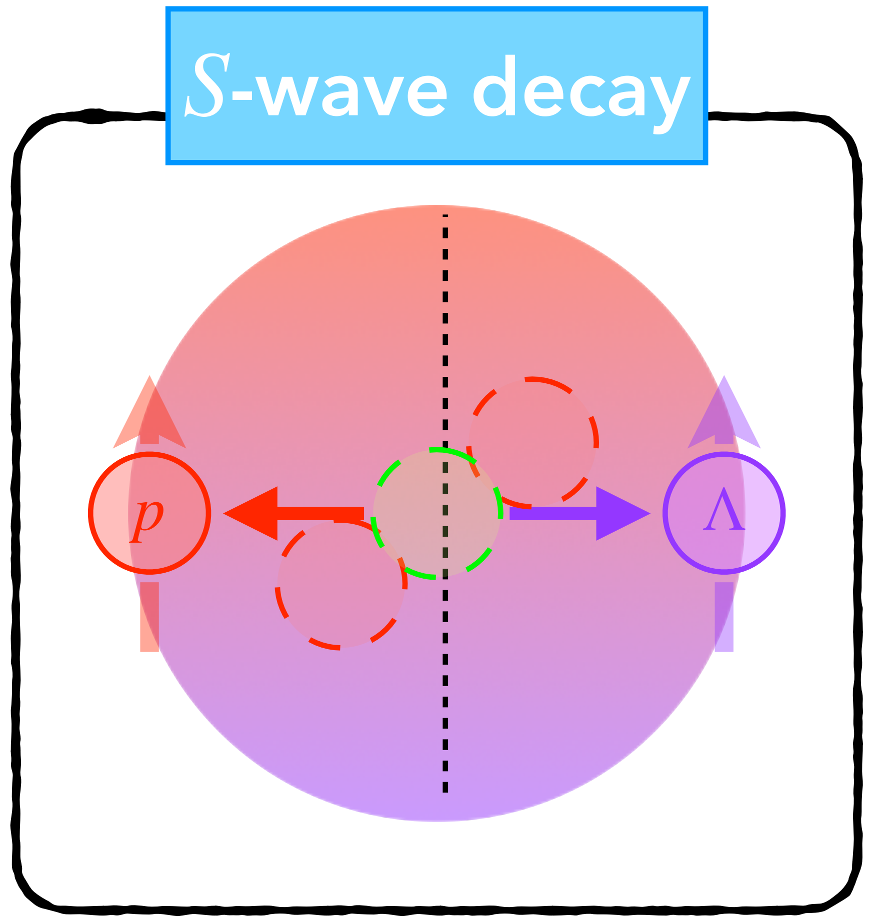
– Analyzing power –

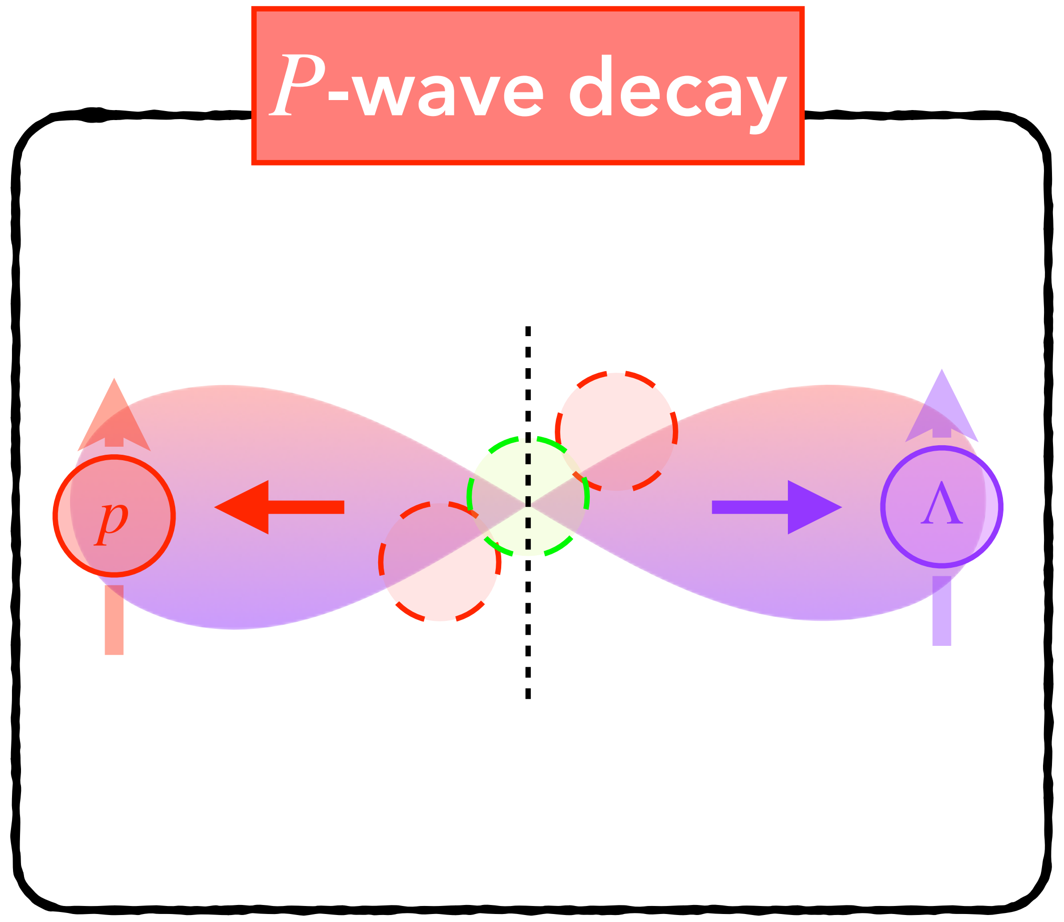


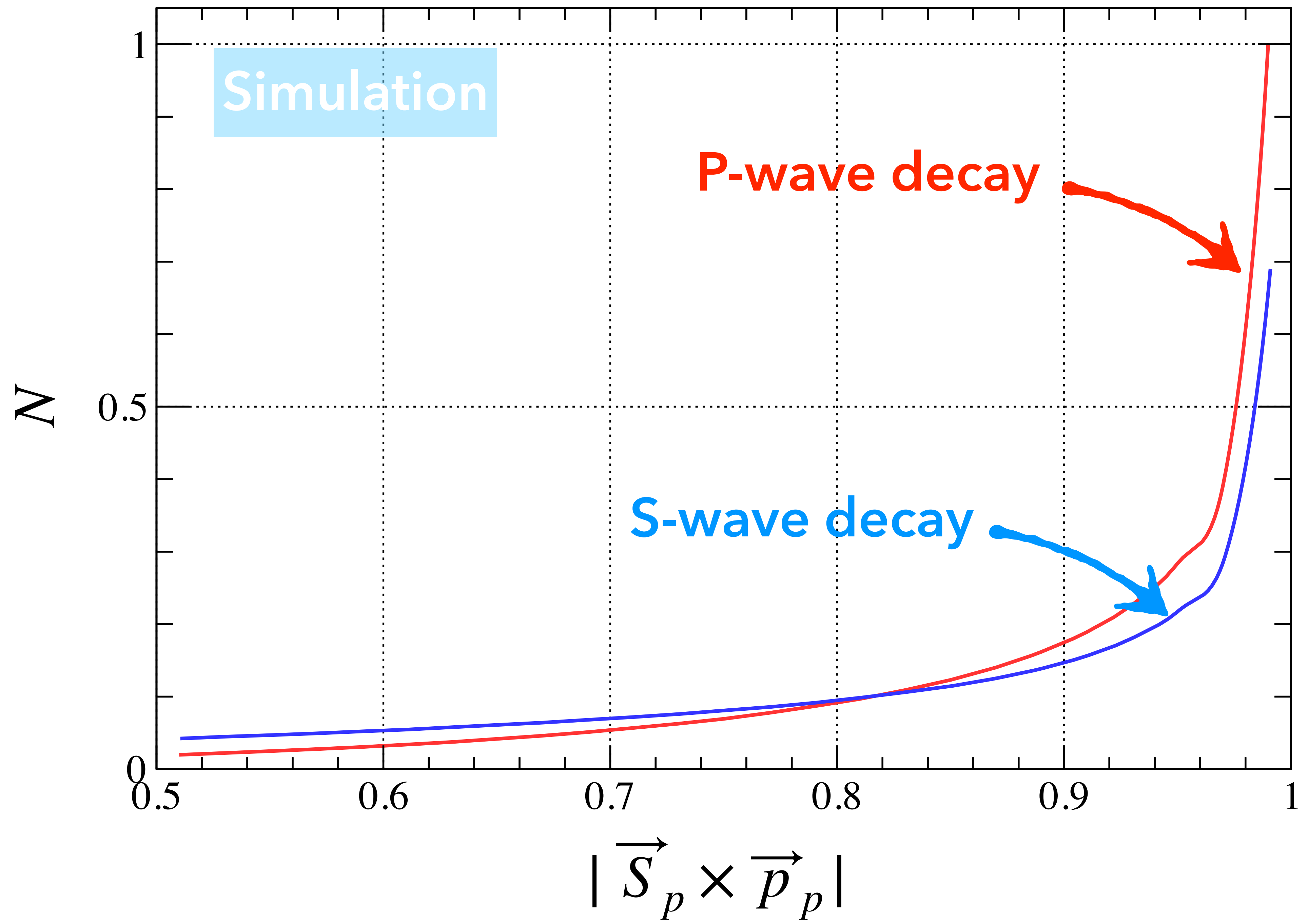
- Analyzing power of carbon taken from Ref.
  - Peak around $T_P = 0.2$ GeV
- Momentum distribution of proton
  - Simulated by MC
    - with 5cm thickness plastic scintillator
    - $6° < \theta_p^{scat} < 30°$ selected
  - Similar to A_C shape
- **Average :** $< A_C > \sim 0.4$

Estimation of the accuracy

– Transverse component of proton spin –



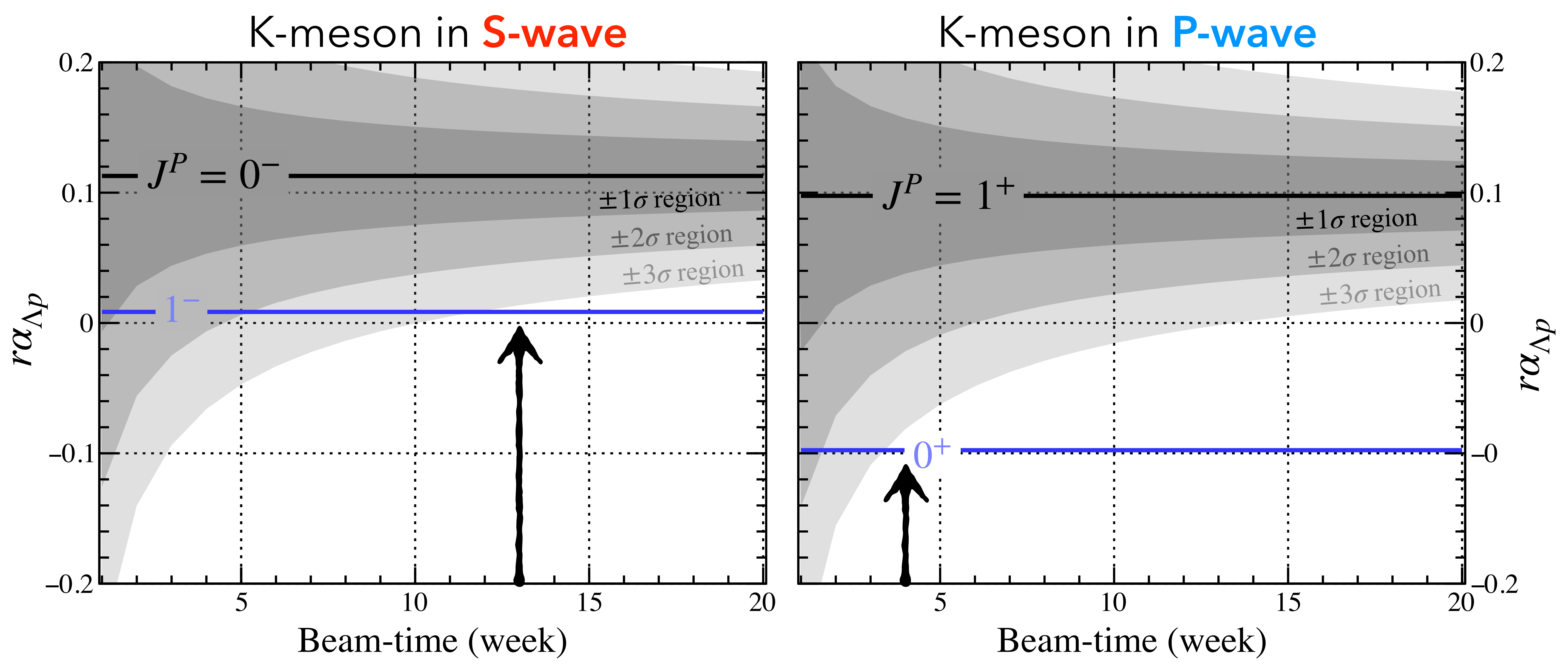




- Large transverse component is expected.
  - better to measure
- Small difference between S & P wave decay
  - $<|\vec{S}_p \times \vec{p}_p|> \sim 0.8$ (S-wave decay)
  - $<|\vec{S}_p \times \vec{p}_p|> \sim 0.9$ (P-wave decay)

Estimation of the accuracy

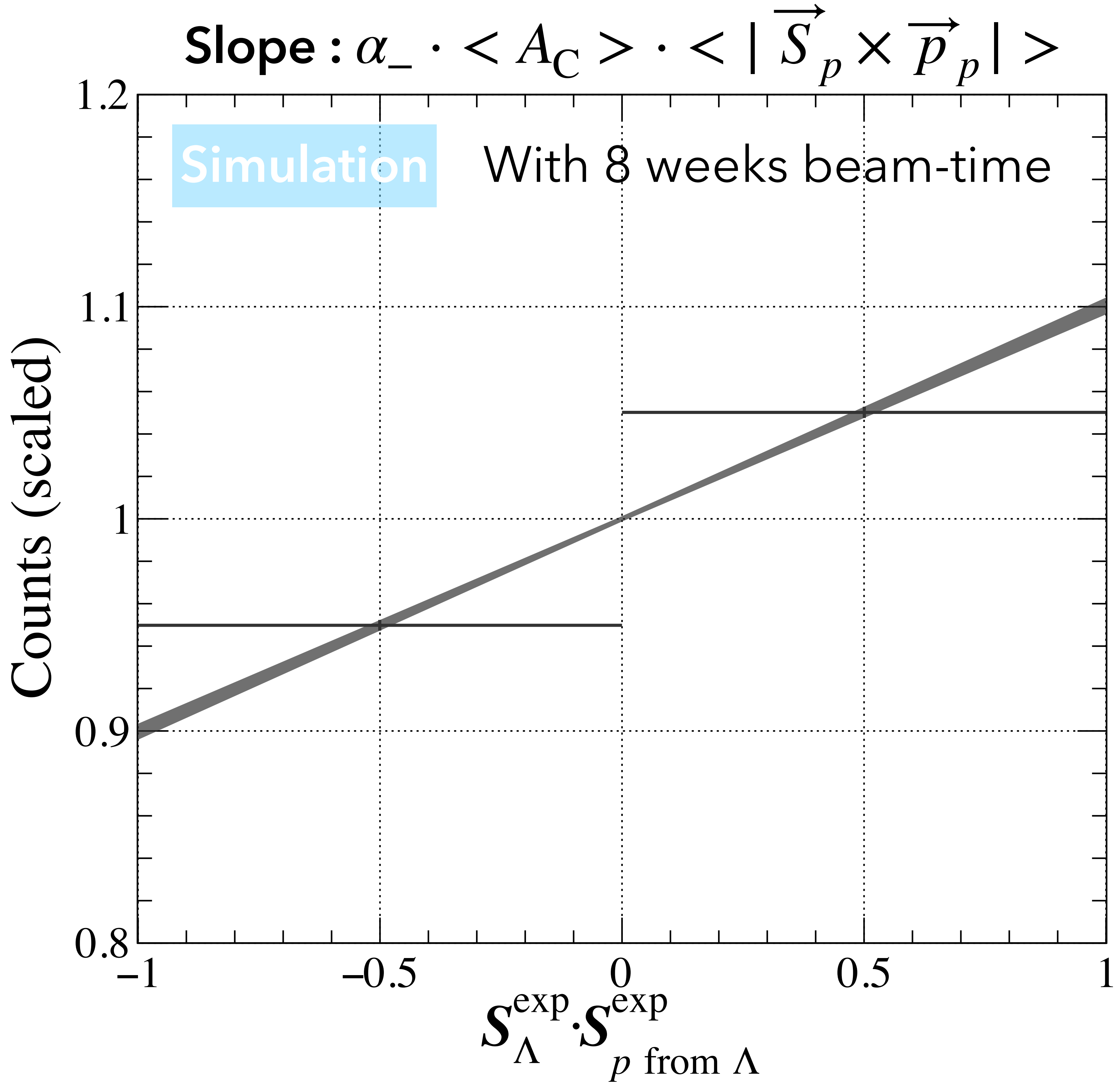
– The accuracy & Necessary beam-time to determine J^P –

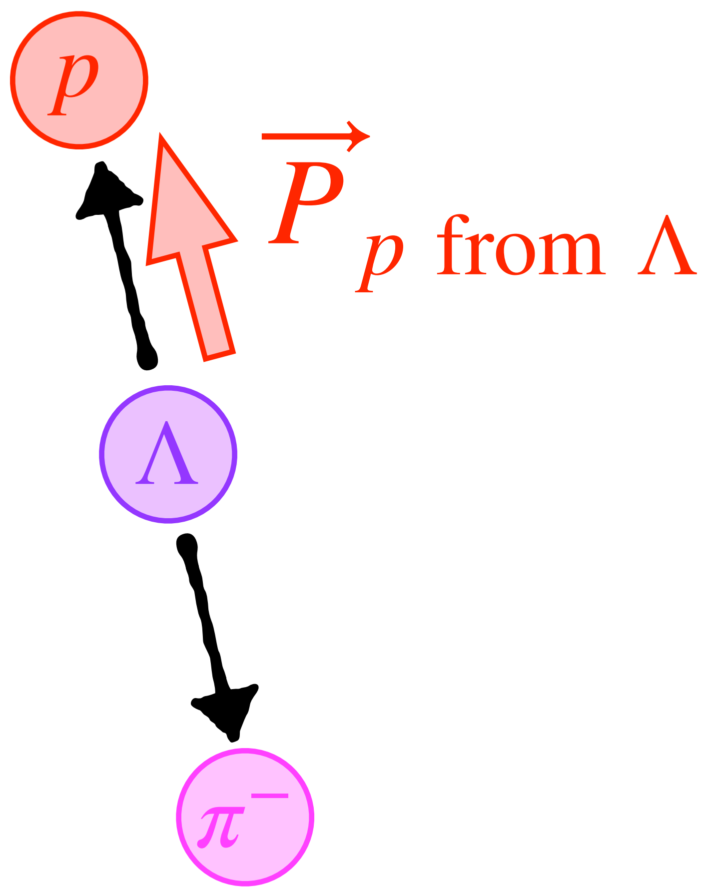


- J^P would be determined with reasonable beam-time.
  - K-meson in **S-wave** : **~13 weeks**
  - K-meson in **P-wave** : **~4 weeks**
    - Assuming $\alpha_{\Lambda p} = \pm 0$ for 1^- state
    - Proton detected by barrel part of the new CDS
    - With 90kW beam power & 5 cm x 3 layers plastic scintillator

Feasibility study for $\alpha_{\Lambda p}$ measurement

– Measurement of proton polarization in $\Lambda \to p\pi^-$ decay –





- Proton polarization in Λ-decay;
  $\vec{P}_{p\ \mathrm{from}\ \Lambda} = \alpha_- \cdot \vec{p}_{p\ \mathrm{from}\ \Lambda}$
- Measuring similar scalar product to $\alpha_{\Lambda p}$ measurement;

  $$N\left(\vec{S}_\Lambda^{exp} \cdot \vec{S}_{p\ \mathrm{from}\ \Lambda}^{exp}\right) \propto 1 + r$$

  - $r \equiv \alpha_- \cdot < A_C > \cdot < | \vec{S}_p \times \vec{p}_p | >$
- Huge number of Λ can be easily obtained.
  - r & systematic uncertainty would be evaluated precisely.

Summary

– Measurement of spin-spin correlation in $K^{-}pp$ decay –

- We have plan to propose a new experiment to determine J^P of $K^{-}pp$.
  - High statistics momentum transfer dependence would separate $0^{-}/1^{-}$ & $1^{+}/0^{+}$ states.
  - Additional measurement of spin-spin correlation between Λ & proton would determine J^P.

- The accuracy of spin-spin correlation measurement was estimated.
  - J^P of $K^{-}pp$ would be determined with reasonable beam-time at J-PARC.
  - Polarization of proton from Λ-decay is useful to study a feasibility of the measurement as well as systematic uncertainty.

Thank you for your attention!