Experimental study toward spin-parity assignment of the first Kaonic nuclear bound state, K^-pp

— One of the most fundamental quantity to be defined experimentally —

M. Iwasaki

RIKEN

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K-pp was observed very clearly in exclusive non-mesonic reaction channel $K^- + {}^3\mathrm{He} \rightarrow (\Lambda + p) + n$

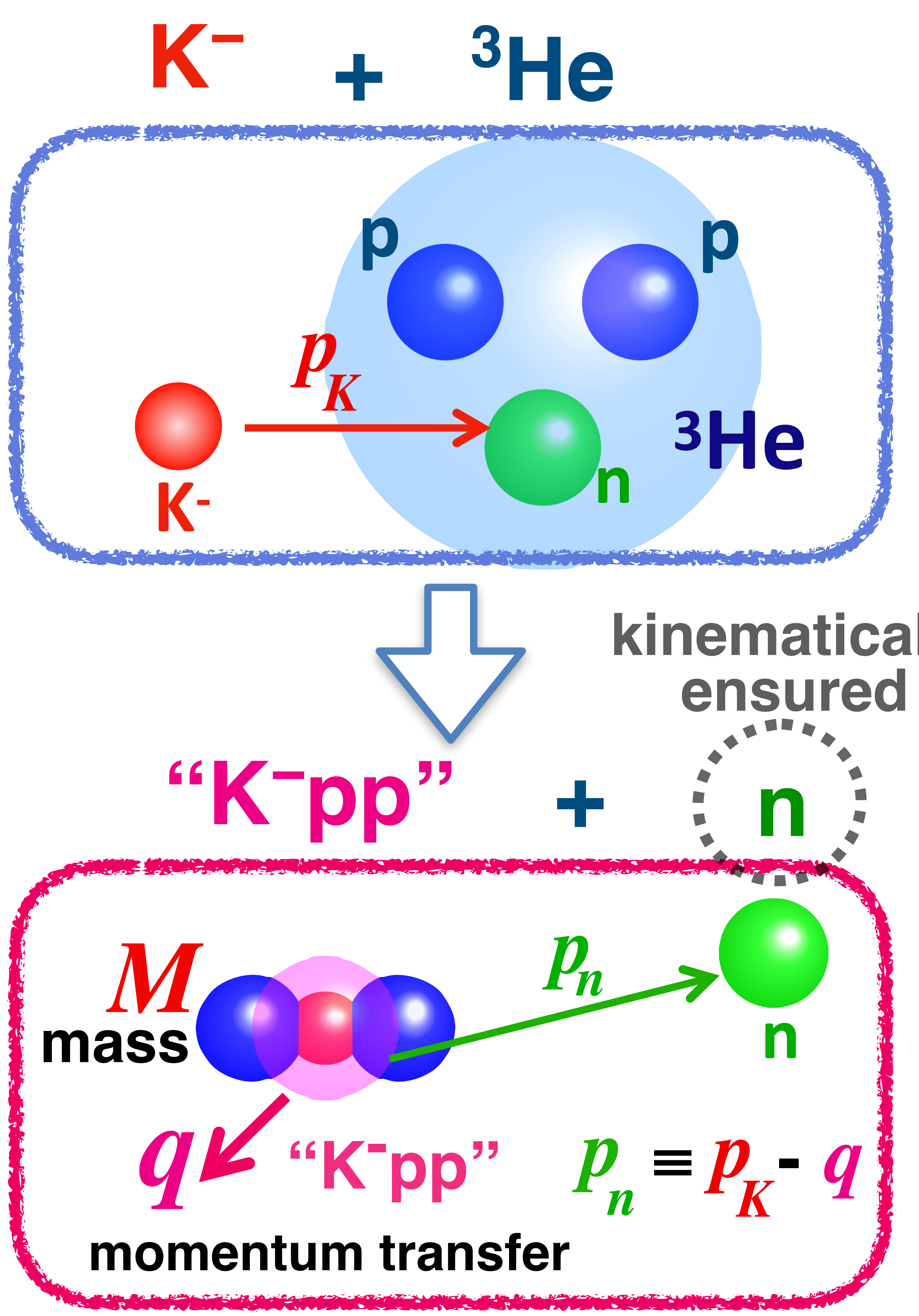
specified to be simplest final state

less ambiguity in interpretation

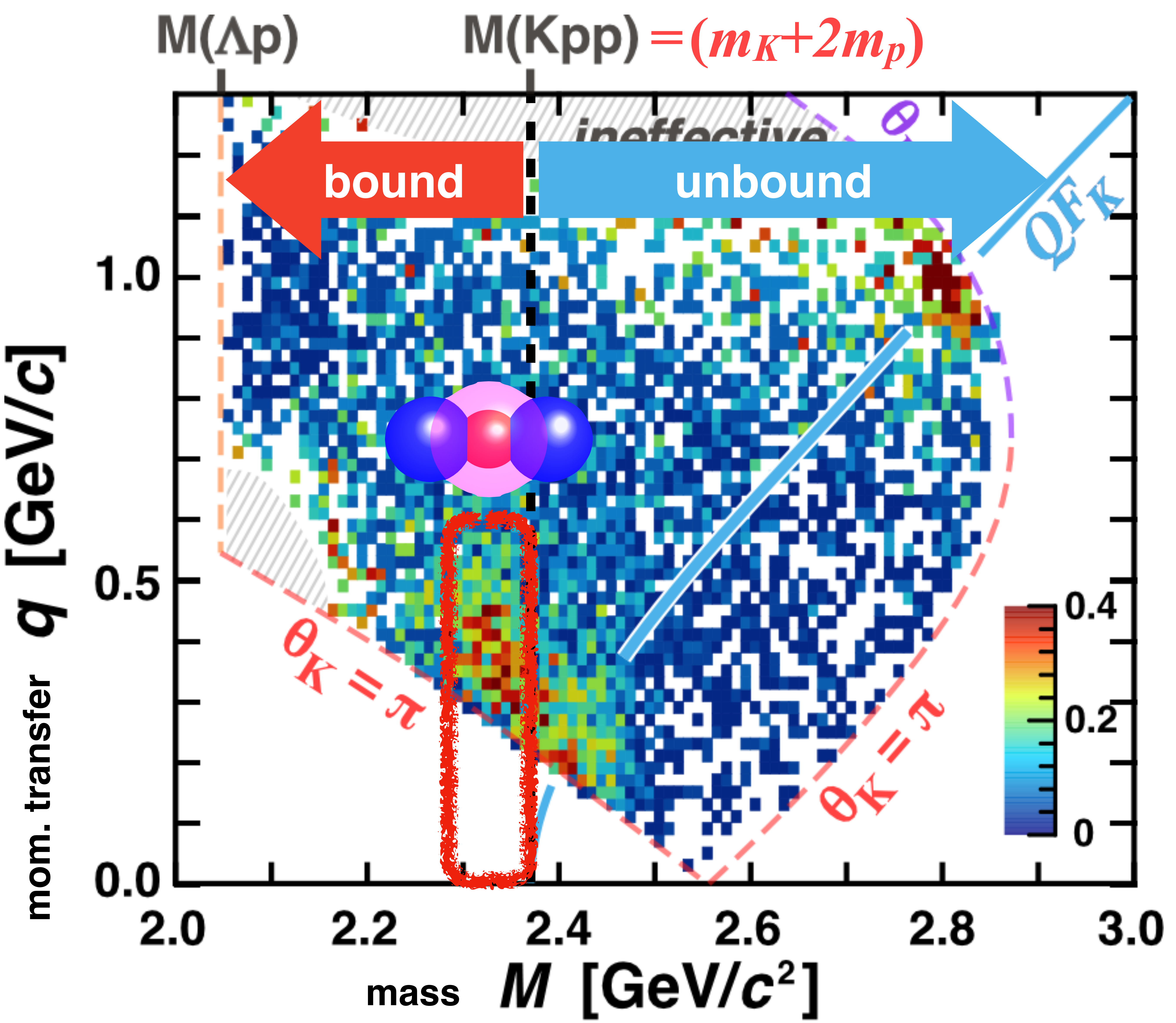
$(M_{\Lambda p}, q_{\Lambda p})$; $E_{\Lambda p}^2 = M_{\Lambda p}^2 + q_{\Lambda p}^2$

detail → Appendix:9

2D analysis on (*M*, *q*)



kinematics defined by
(*M*, *q*)



$$M = m_K + 2m_p - B_K$$

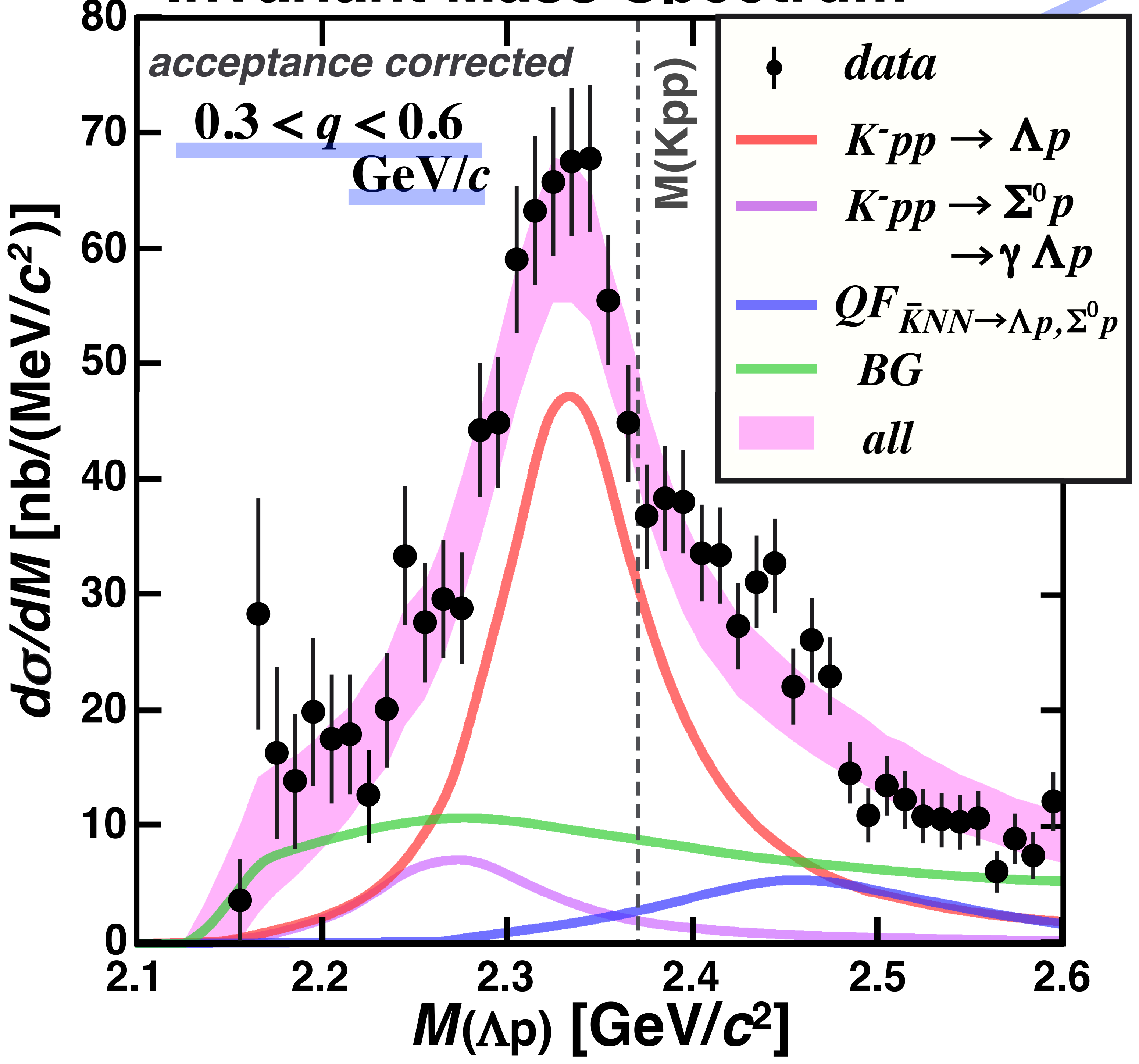
PWIA based interpretation

(plane wave impulse approximation)

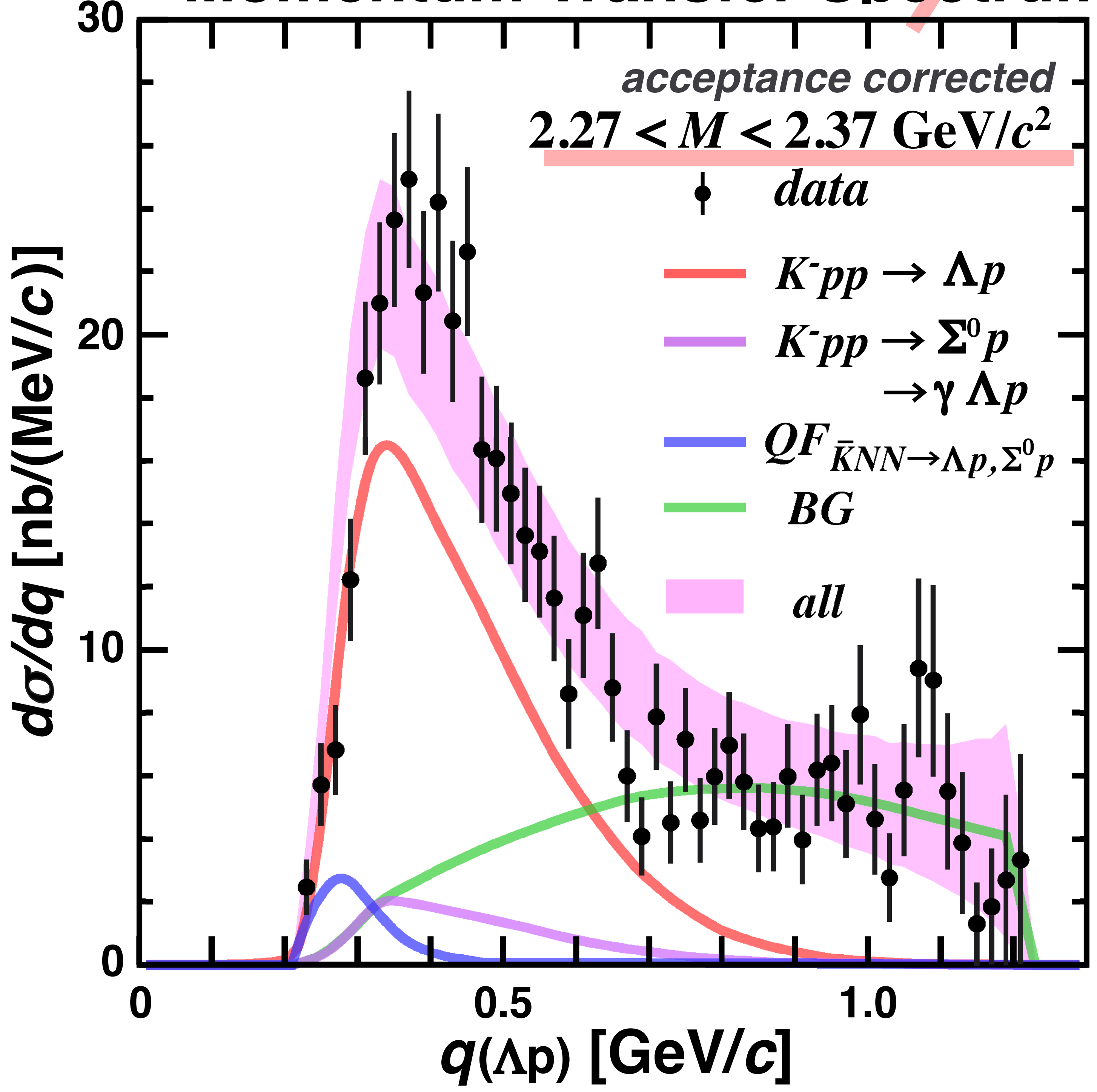
$$\sigma(M, q) \propto \rho_{3B}(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

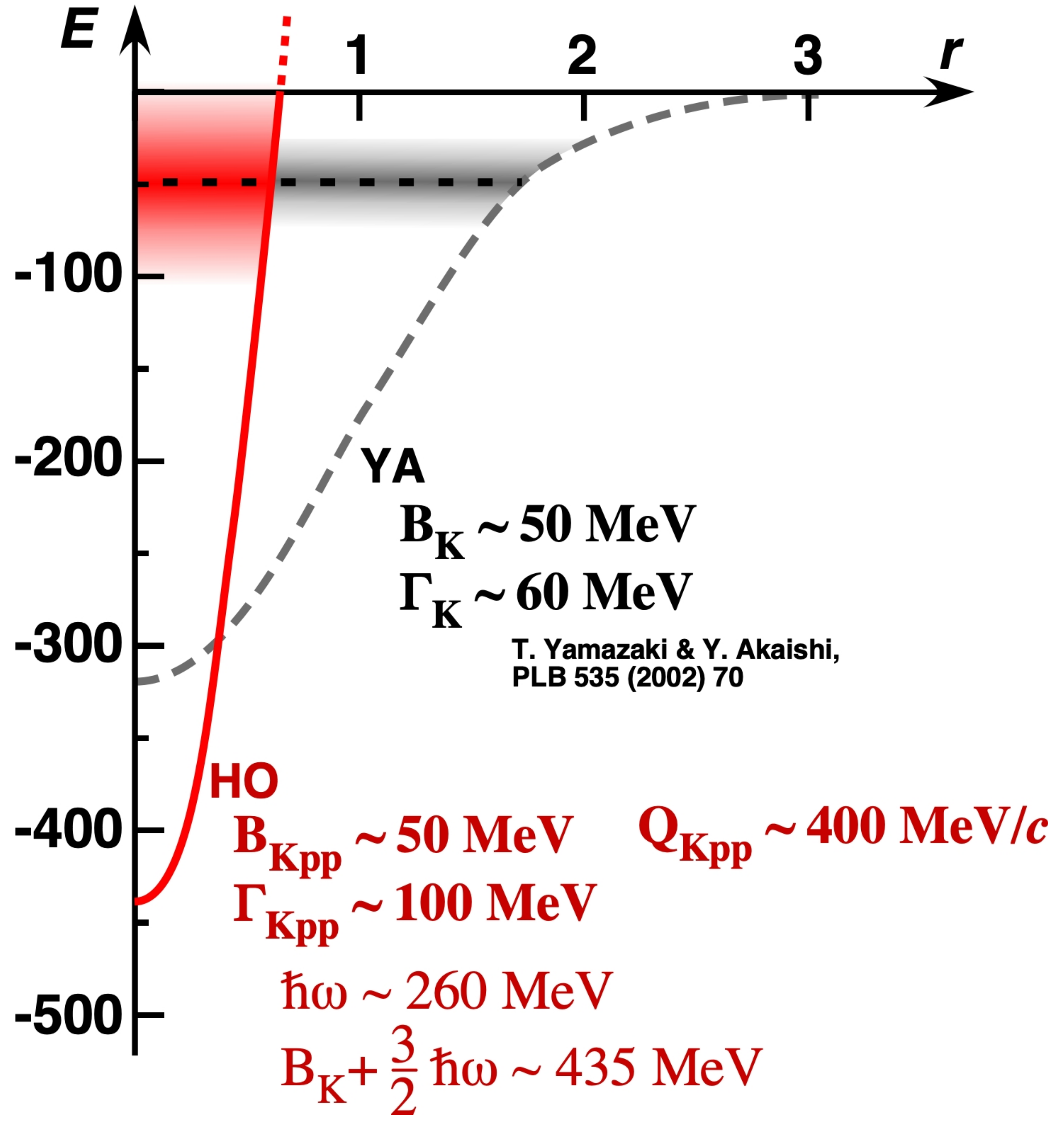
Differential cross section — Lorentz invariant phase space (Λpn) — B.W. / Lorentzian — form factor / structure factor

Invariant Mass Spectrum



Momentum Transfer Spectrum





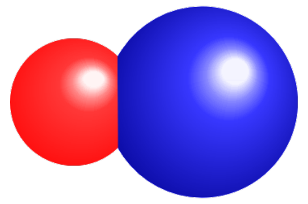
strong binding ($\bar{K}N$ attraction) — wide momentum width — quite compact?

$B_{Kpp} \sim 40$ MeV, $\Gamma_{Kpp} \sim 90$ MeV — $Q_{Kpp} \sim 400$ MeV/c ($R_{Kpp} \sim 0.6$ fm (H.O.))

New programs open to kaonic nuclei

Lighter system

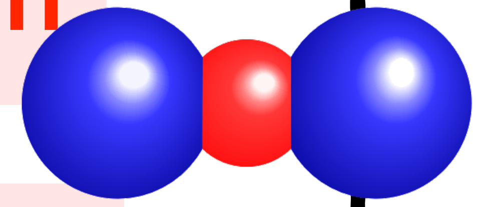
$\Lambda(1405)$
$= K^- p$



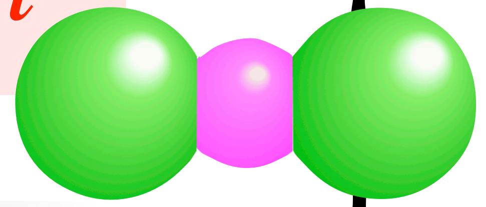
$I(J^P) = 0\left(\frac{1}{2}^-\right)$

$\bar{K}NN$ system

J^P determination



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

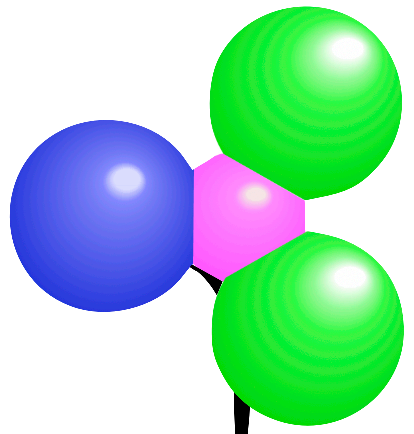


Relation to Λ^*

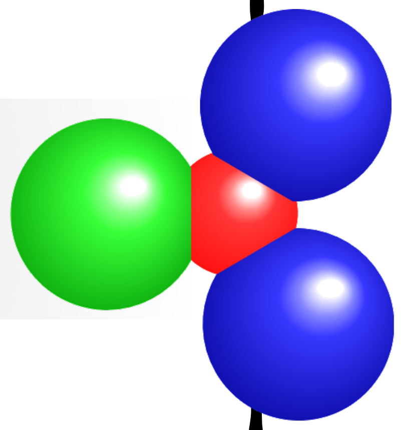
Decay branch

Large Γ

Heavier system

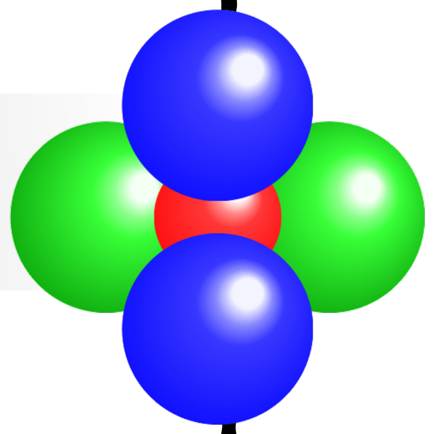


E80 $\bar{K}NNN$ system



Spokesperson F. Sakuma

$\bar{K}NNNN$ system

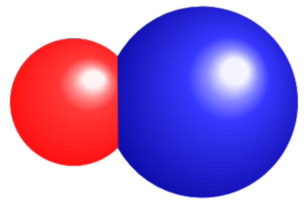


$\bar{K}\alpha\alpha$ system

New programs open to kaonic nuclei

Lighter system

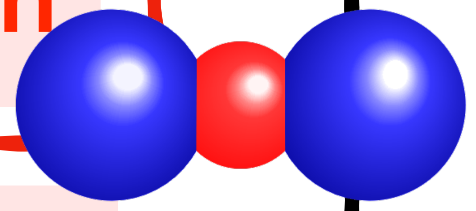
$\Lambda(1405)$
$= \quad K^{-}p$



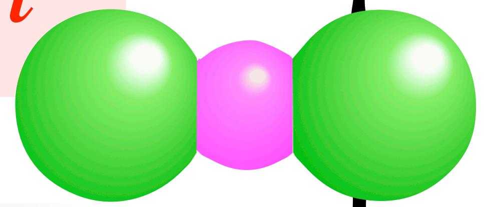
$I(J^P) = 0\left(\frac{1}{2}^{-}\right)$

$\bar{K}NN$ system

J^P determination



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

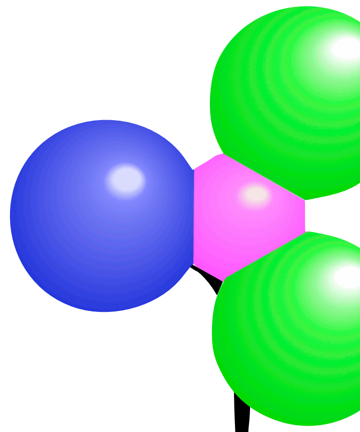


Relation to Λ^*

Decay branch

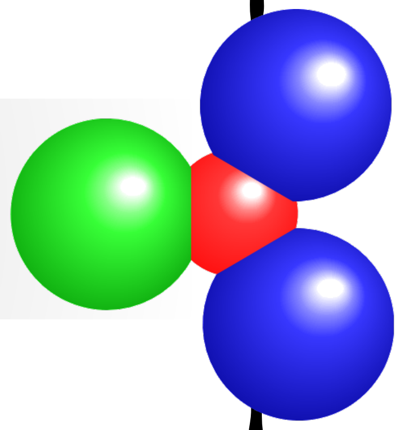
Large Γ

Heavier system

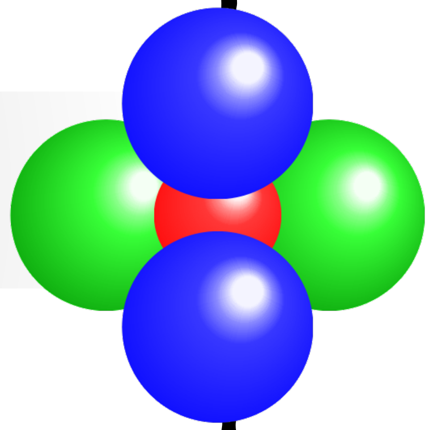


E80 $\bar{K}NNN$ system

Spokesperson F. Sakuma



$\bar{K}NNNN$ system



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

Spin-parity (J^P) is the most fundamental quantum number need to be examined experimentally

J^P defines internal structure of $\bar{K}NN$

Internal structure of K^-pp

There are two candidates as for the $\bar{K}NN$ ground state, in which NN symmetry and $N\bar{K}$ couplings are different

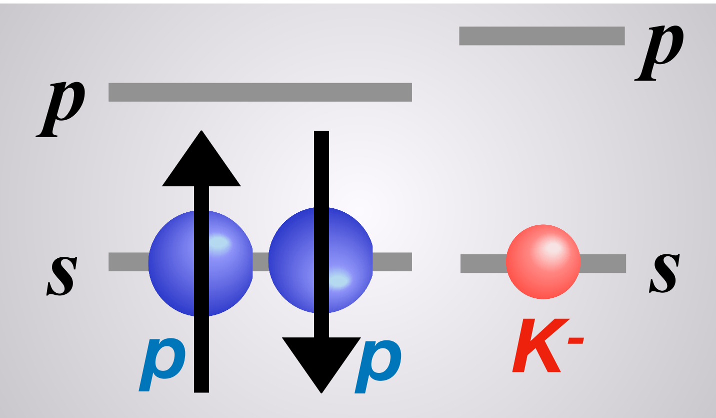
$J^P = 0^-$

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

$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{3}{1}$$

expected to be deep

strong interaction in S-wave



symbolical representation as “K^-pp”

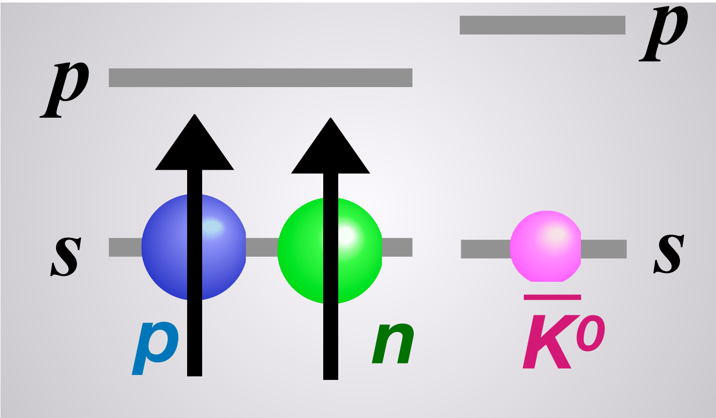
$J^P = 1^-$

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

$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{1}{3}$$

expected to be shallow

strong interaction in S-wave

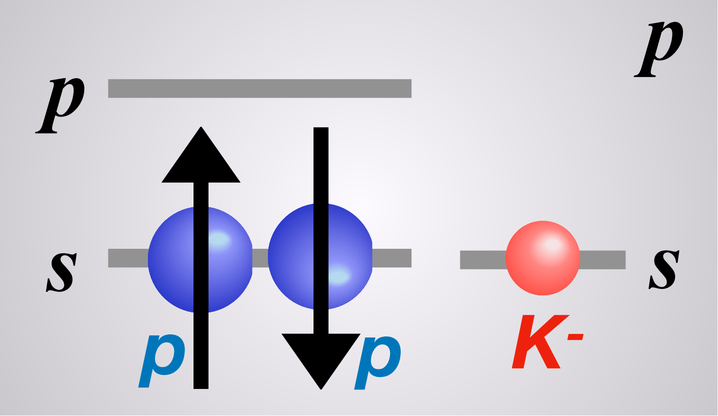


Naturally, $J^P = 0^-$ is expected to be the ground state, because $I_{\bar{K}N} = 0$ channel is strongly attractive, while $I_{\bar{K}N} = 1$ channel is weak

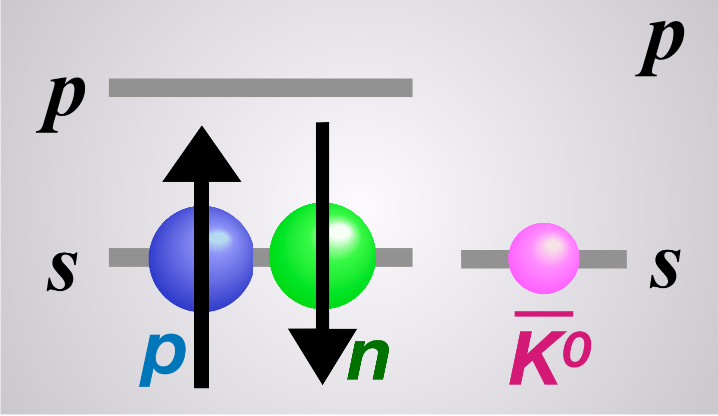
Specific representation of $\bar{K}NN$

"$(NN)_{(I.sym\times S.Asym)} \otimes \bar{K}$"

$J^P = 0^-$



+



expected to be deep

$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{3}{1}$$

$\bar{K}NN$: I = 1/2: I_{NN} = 1, S_{NN} = 0, $L_{\bar{K}}$ = 0

$$\frac{N(N\otimes\bar{K})_{I=0} + (N\otimes\bar{K})_{I=0}N}{N(N\otimes\bar{K})_{I=1} + (N\otimes\bar{K})_{I=1}N} = \frac{\sqrt{3}}{1}$$

most likely

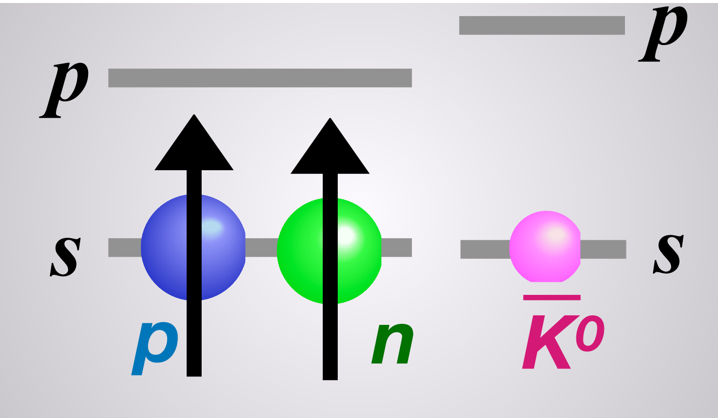
"K^-pp"… I_z = +1/2 $\sqrt{\frac{1}{3}}\left(\sqrt{2}ppK^- - \frac{pn+np}{\sqrt{2}}\bar{K}^0\right)\otimes\left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)$

should exist

"$\bar{K}^0nn$"… I_z = -1/2 $\sqrt{\frac{1}{3}}\left(\frac{pn+np}{\sqrt{2}}K^- - \sqrt{2}nn\bar{K}^0\right)\otimes\left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)$

"$(NN)_{(I.Asym\times S.sym)} \otimes \bar{K}$"

$J^P = 1^-$



expected to be shallow

$$\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2} = \frac{1}{3}$$

KNN : I = 1/2: I_{NN} = 0, S_{NN} = 1, $L_{\bar{K}}$ = 0

$$\frac{N(N\otimes\bar{K})_{I=0} - (N\otimes\bar{K})_{I=0}N}{N(N\otimes\bar{K})_{I=1} - (N\otimes\bar{K})_{I=1}N} = \frac{1}{\sqrt{3}}$$

can it be possible?

I_z = +1/2 $\frac{(np-pn)}{\sqrt{2}}\bar{K}^0 \otimes \left(\uparrow\uparrow, \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}, \downarrow\downarrow\right)$ … "$\bar{K}^0pn$"

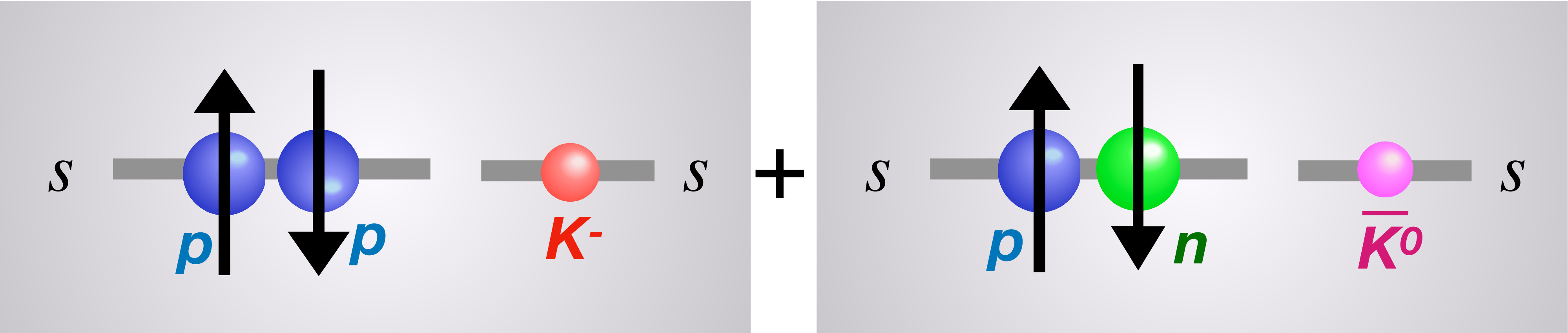
I_z = -1/2 $\frac{(np-pn)}{\sqrt{2}}K^- \otimes \left(\uparrow\uparrow, \frac{\uparrow\downarrow + \downarrow\uparrow}{\sqrt{2}}, \downarrow\downarrow\right)$ … "K^-pn"

detail → Appendix:1

How to access J^P by the $K^-pp \to \Lambda p$ decay

J = 0 means no angular correlation?

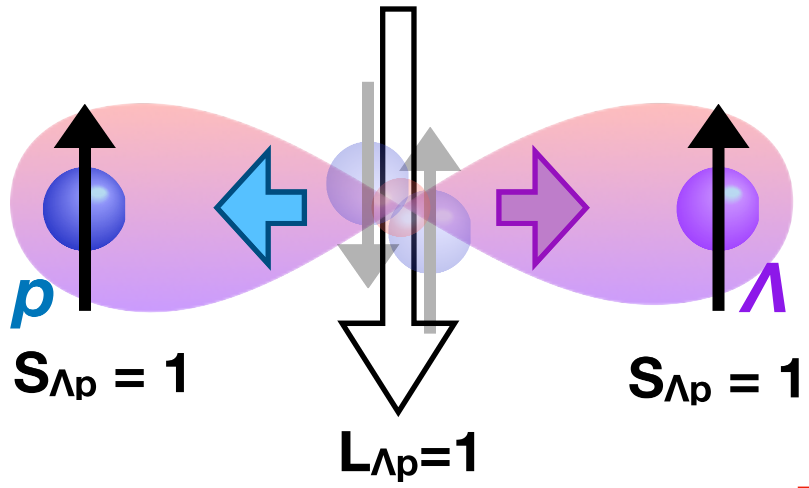
$$J^P_{\bar{K}NN} = 0^-$$



To be negative parity as $J^P = \left(\frac{1}{2}\right)^+_\Lambda \times \left(\frac{1}{2}\right)^+_p$

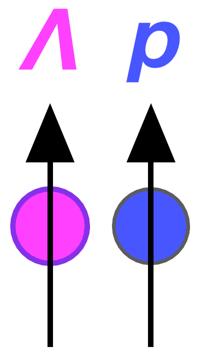
$L_{\Lambda p} = 1$ $\quad P = (-1)^{L_{\Lambda p}}$

To be $J_{\Lambda p} = L_{\Lambda p} + S_{\Lambda p} = 0,\ S_{\Lambda p} = S_\Lambda + S_p$

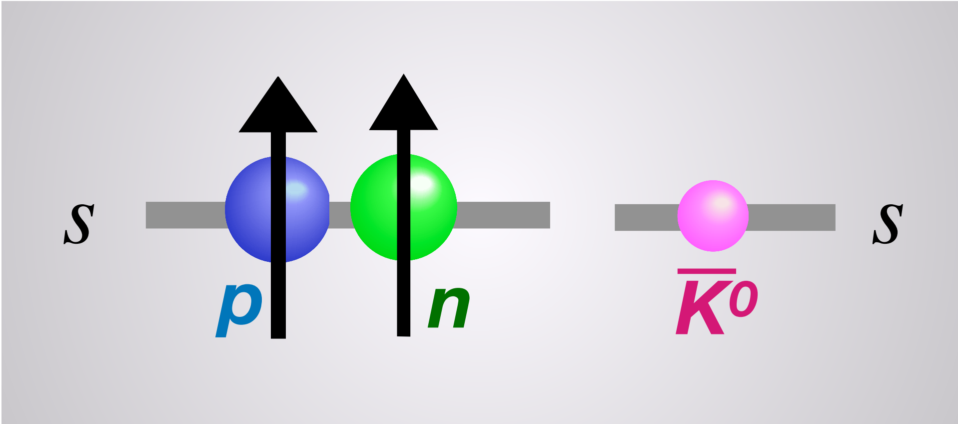


$S_{\Lambda p} = 1$

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



$$J^P_{\bar{K}NN} = 1^-$$



To be negative parity as $J^P = \left(\frac{1}{2}\right)^+_\Lambda \times \left(\frac{1}{2}\right)^+_p$

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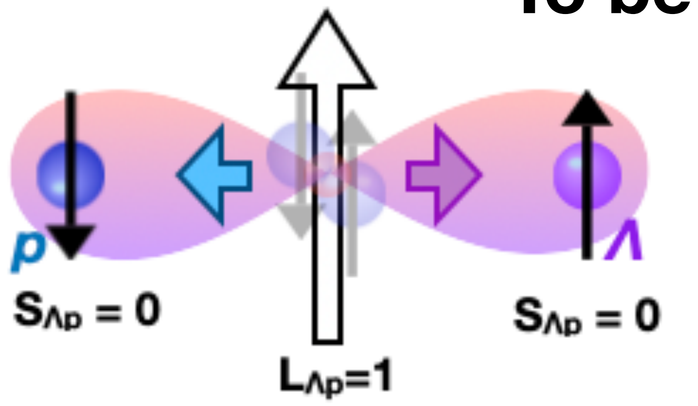
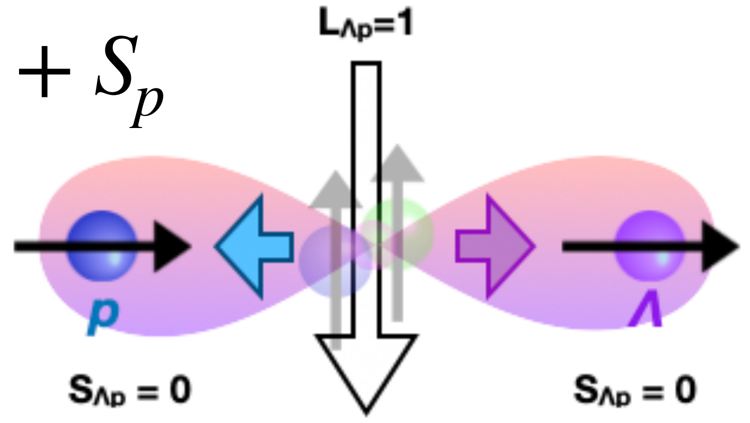
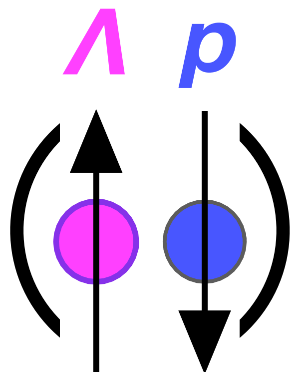
To be $J_{\Lambda p} = L_{\Lambda p} + S_{\Lambda p} = 1,\ S_{\Lambda p} = S_\Lambda + S_p$



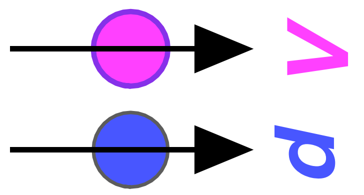
$S_{\Lambda p} = 0$ + $S_{\Lambda p} = 1$

BR=1/3 *BR=2/3*





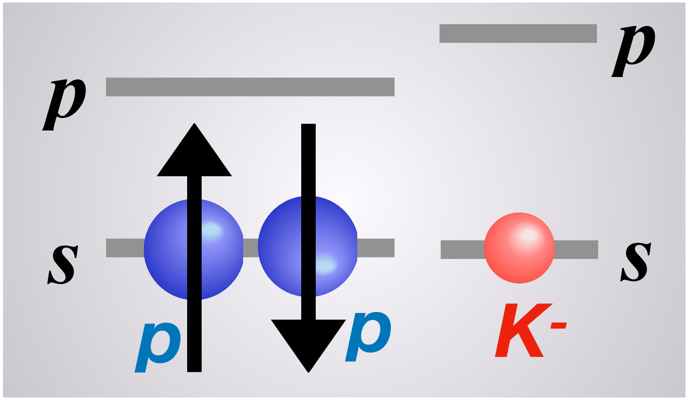
$\alpha_{\Lambda p} = -1$ + $\alpha_{\Lambda p} = +1$



Distribution of spin- and decay-axis ($\bar{K}NN$ for $J^P = 0^-$ & 1^-)

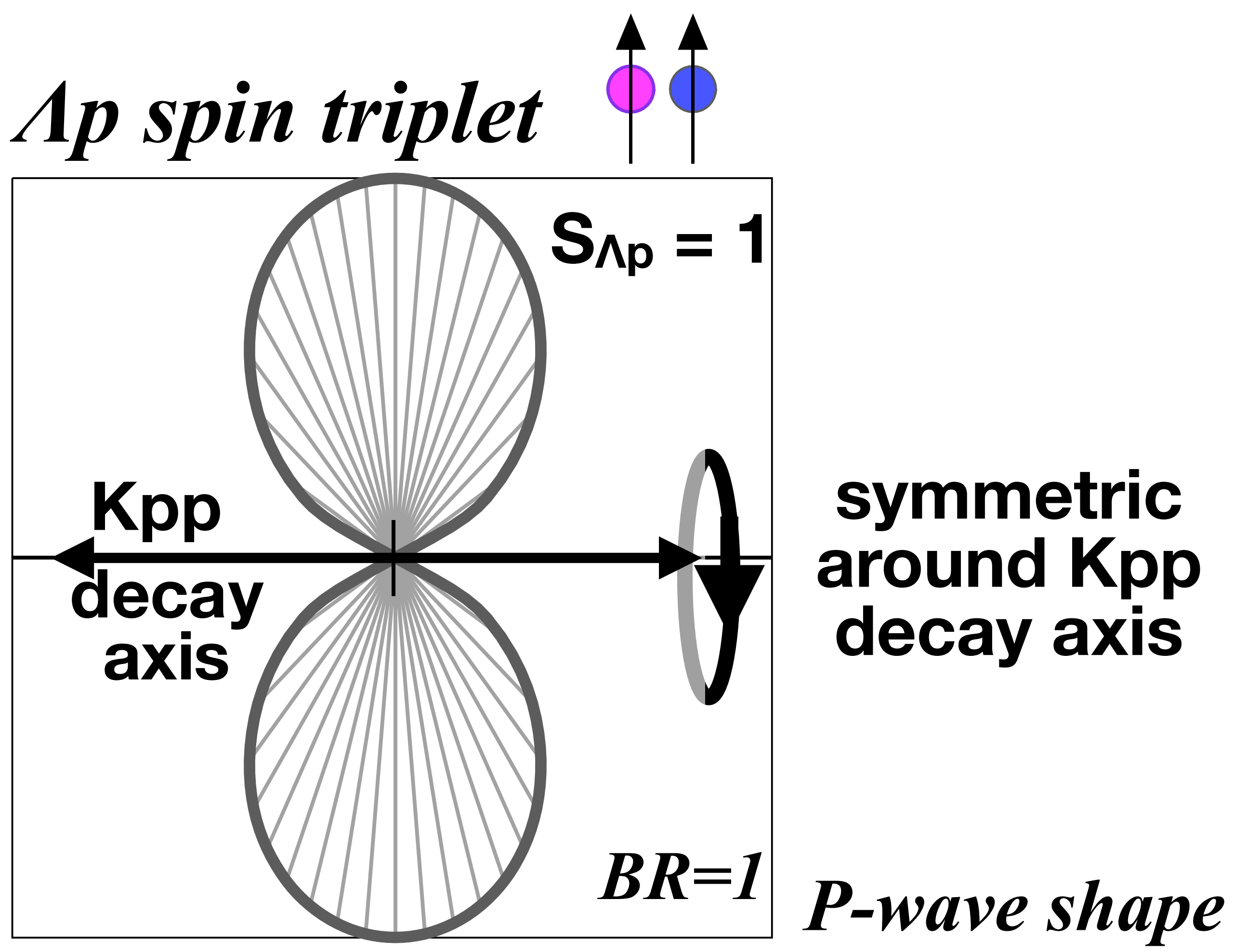
$(J^P = 0^-)$ " $(NN)_{(I.sym \times S.Asym)} \otimes \bar{K}$ "

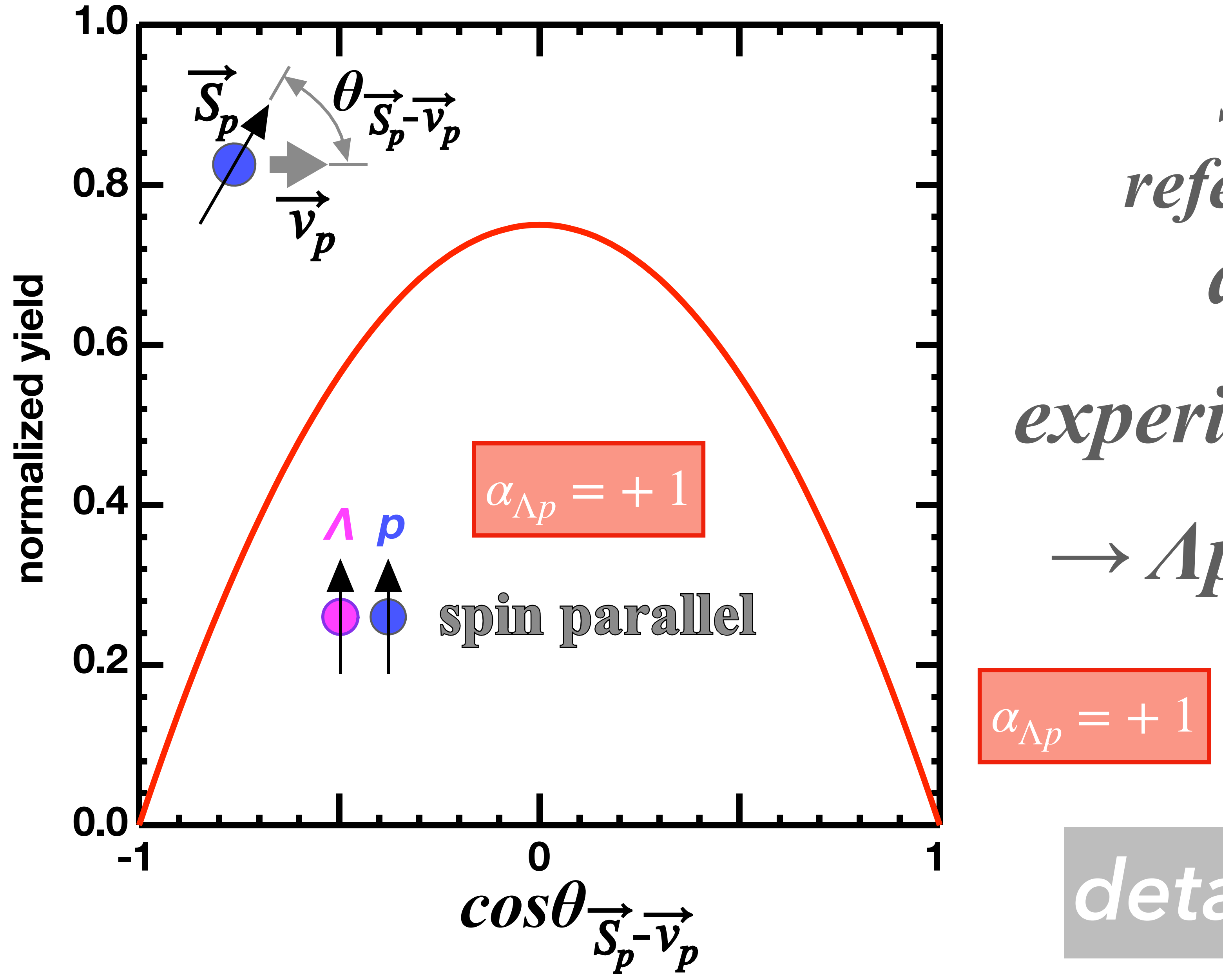
deeper



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

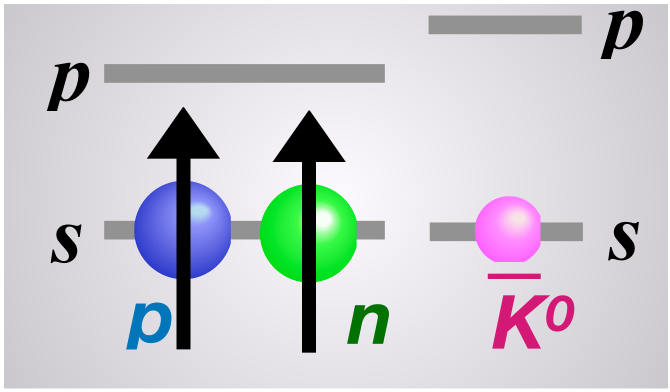
$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{3}{1}$$





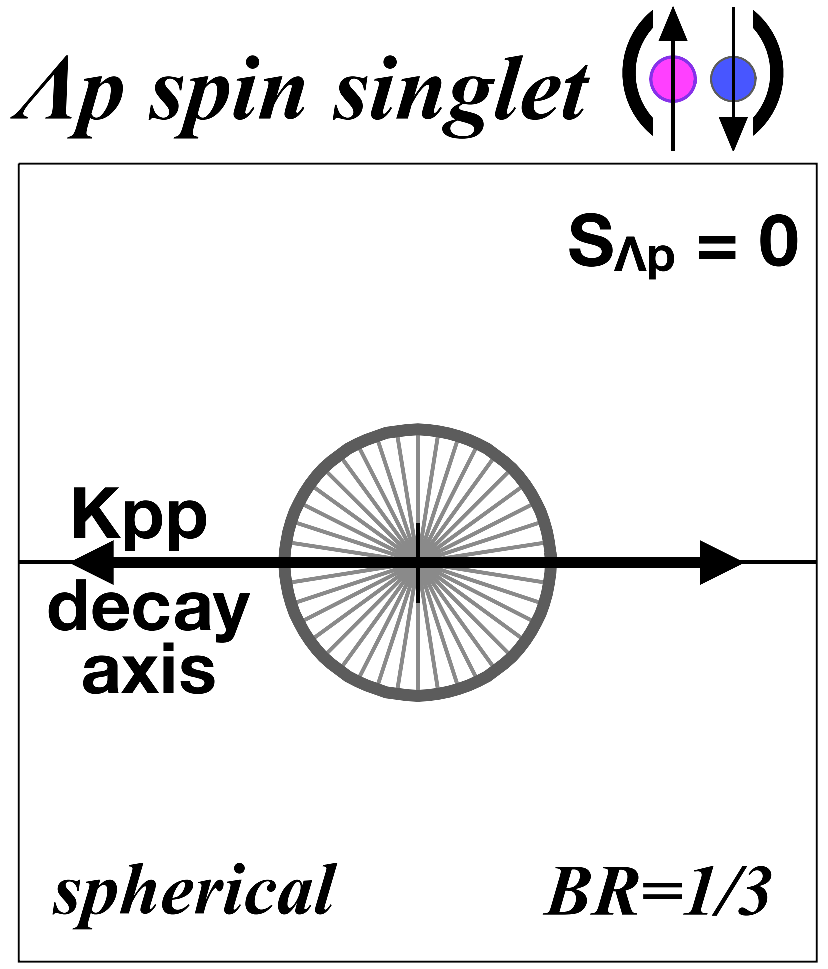
$(J^P = 1^-)$ " $(NN)_{(I.Asym \times S.sym)} \otimes \bar{K}$ "

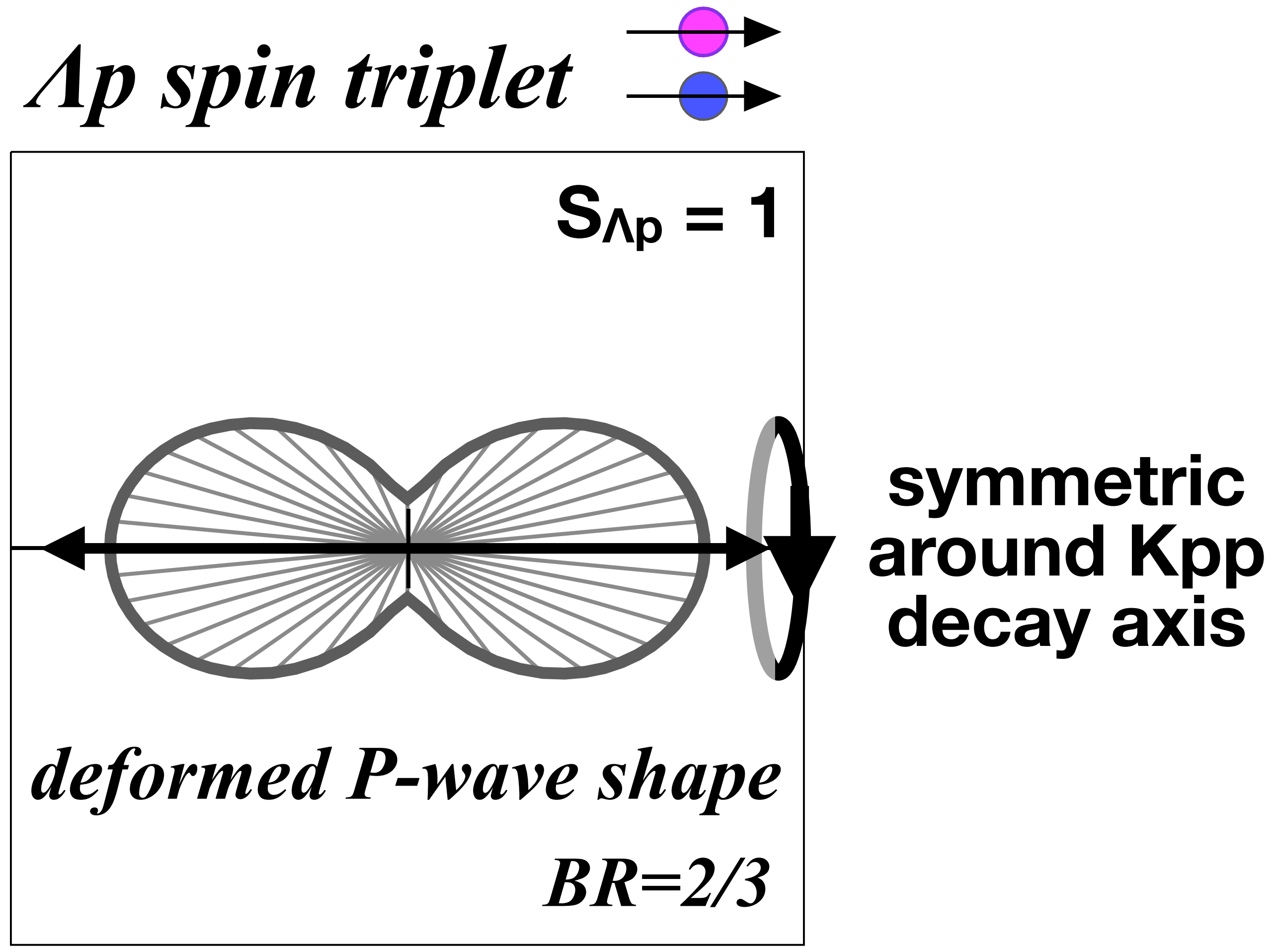
shallower



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

$$\frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{1}{3}$$

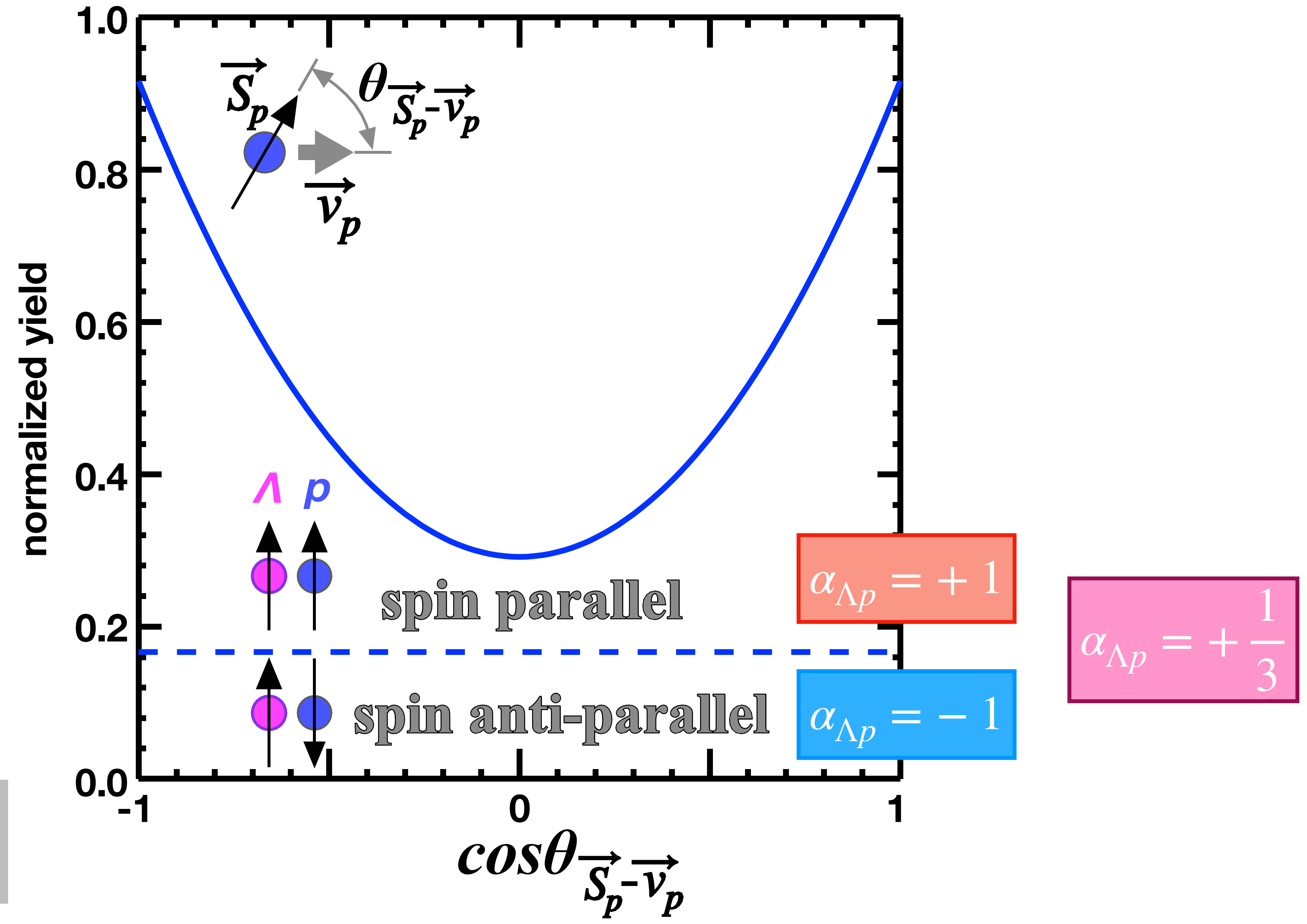




spin distributions referring to the decay axis are quite different

experimentally not accessible

→ Λp spin-spin correlation

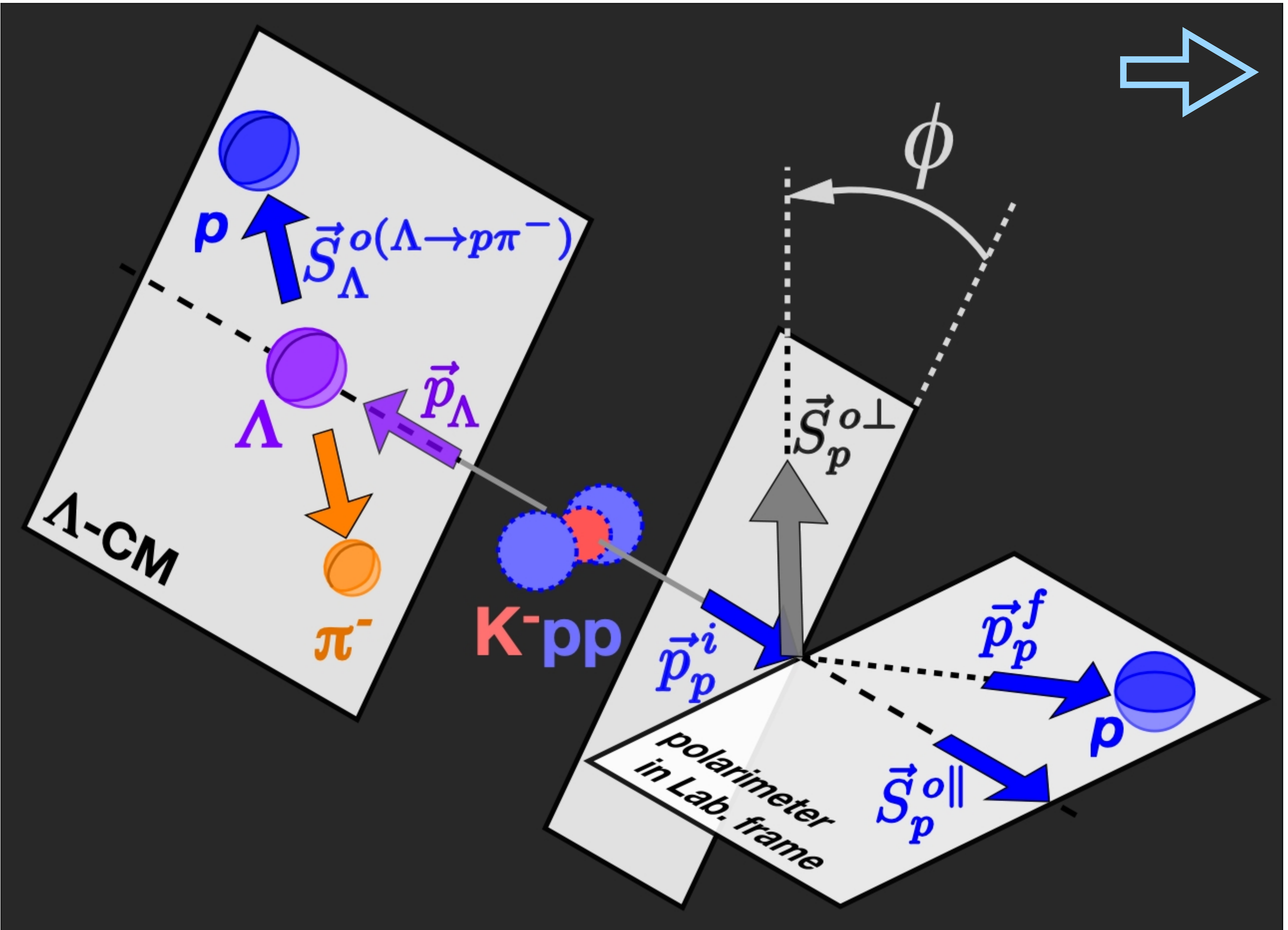


detail → Appendix: 2, 3, 4

How to measure spin-spin correlation

– spin asymmetry measurement using $\Lambda \to p\pi^-$ & p-C scattering–

$\overrightarrow{S}_{\Lambda}^{o(\Lambda\to p\pi^-)} \approx \overrightarrow{v}_{p}^{(\Lambda\to p\pi^-)}(in\ \Lambda\text{–}CM)$



$$N(\phi)\,d\phi \propto (1 + r \cdot \alpha_{\Lambda p} \cos\phi)\,d\phi$$

r : scaling factor defined by
A_{Λ}, A_{pC}, $f(\vec{s})$, B, q, and B_K

A_{Λ} : Λ asymmetry parameter

A_{pC} : proton spin-analyzing-power on carbon

$f(\vec{s})$: spin angular distribution referring to motional axis

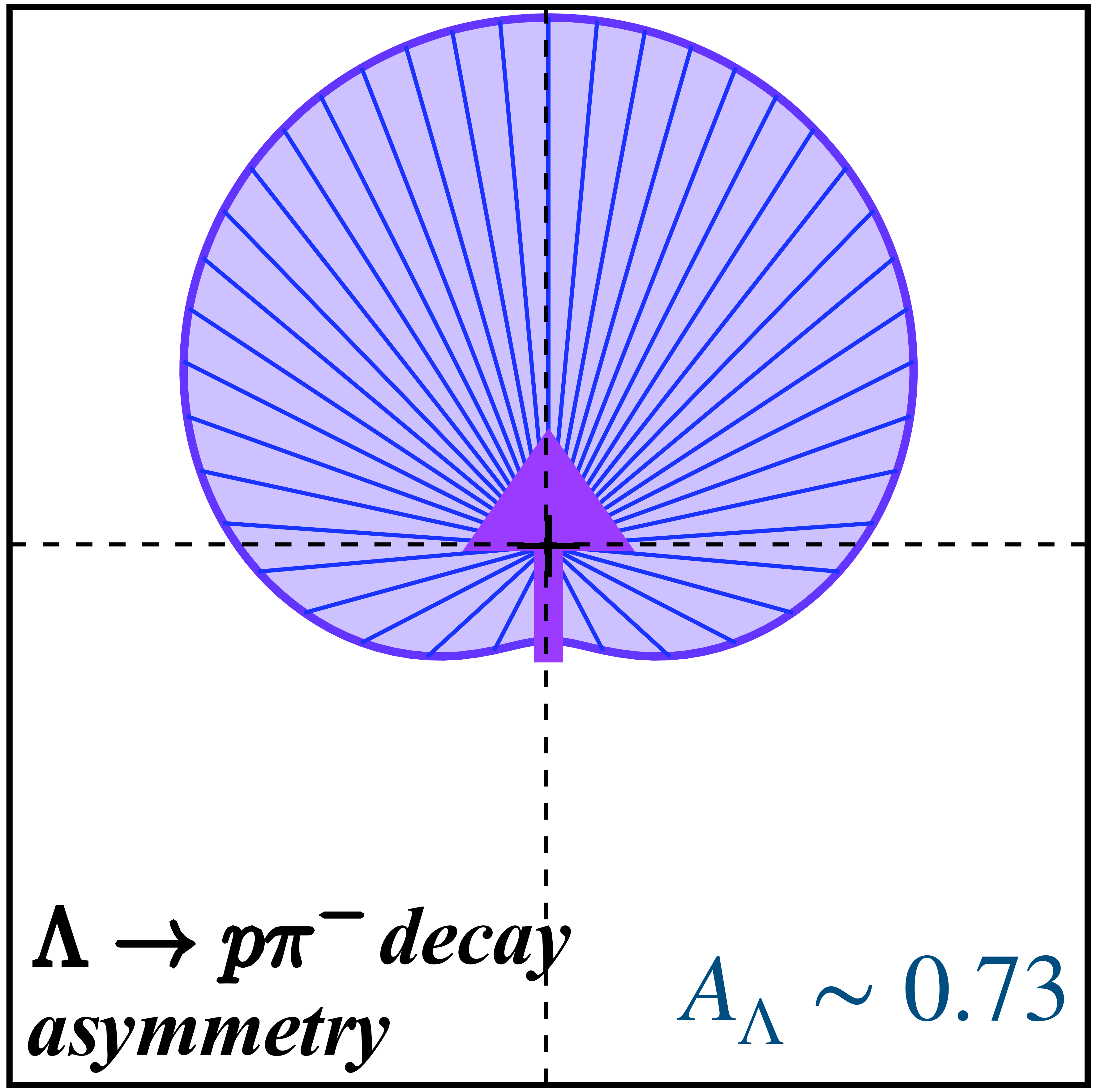
B: magnetic field

B_K: K binding energy, q: momentum transfer

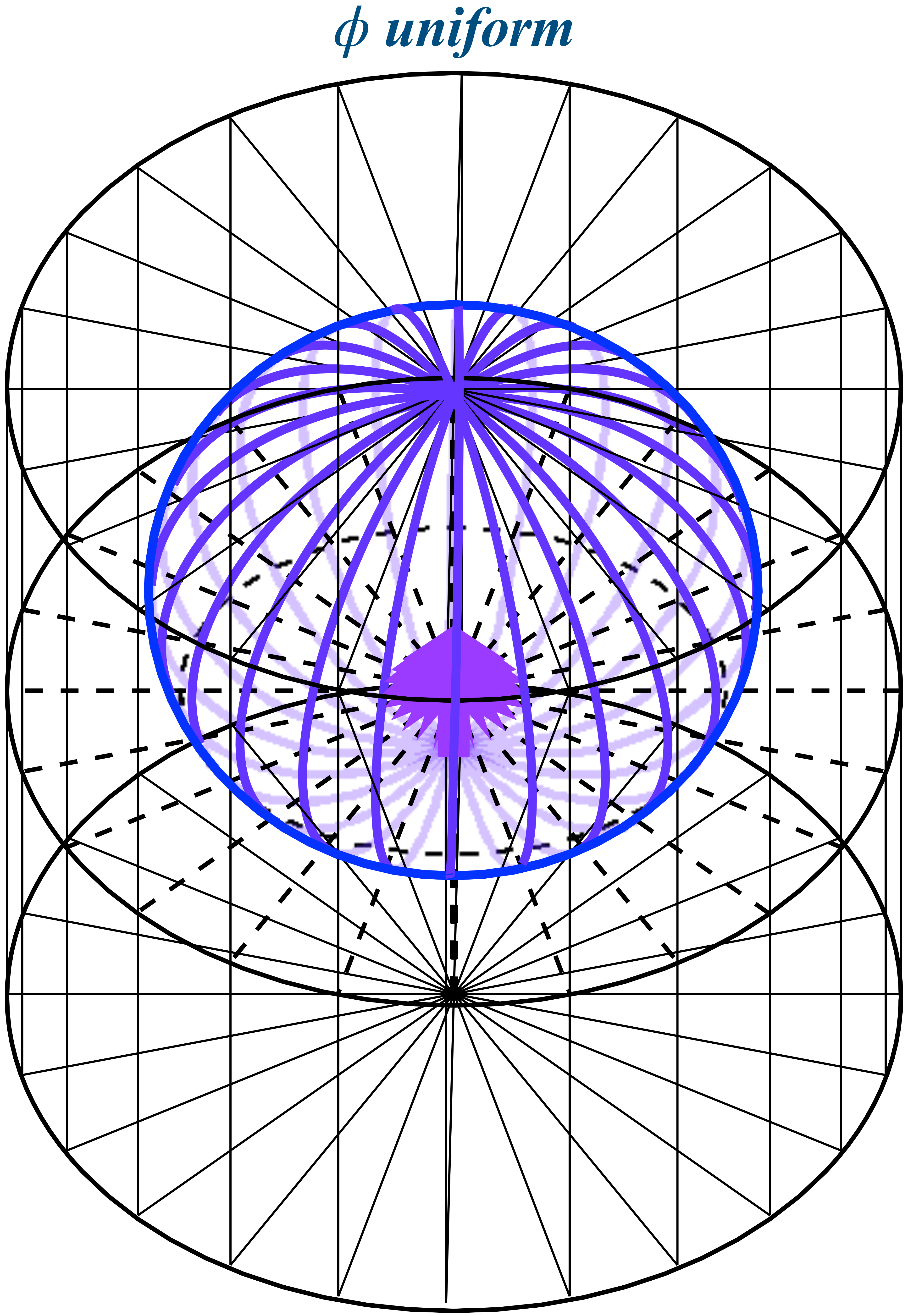
How to measure Λ spin

weak decay asymmetry

$$N(\theta)\, d\Omega \propto (1 + A_\Lambda \cos\theta)\, d\Omega$$



spherical asymmetry : (θ, ϕ)

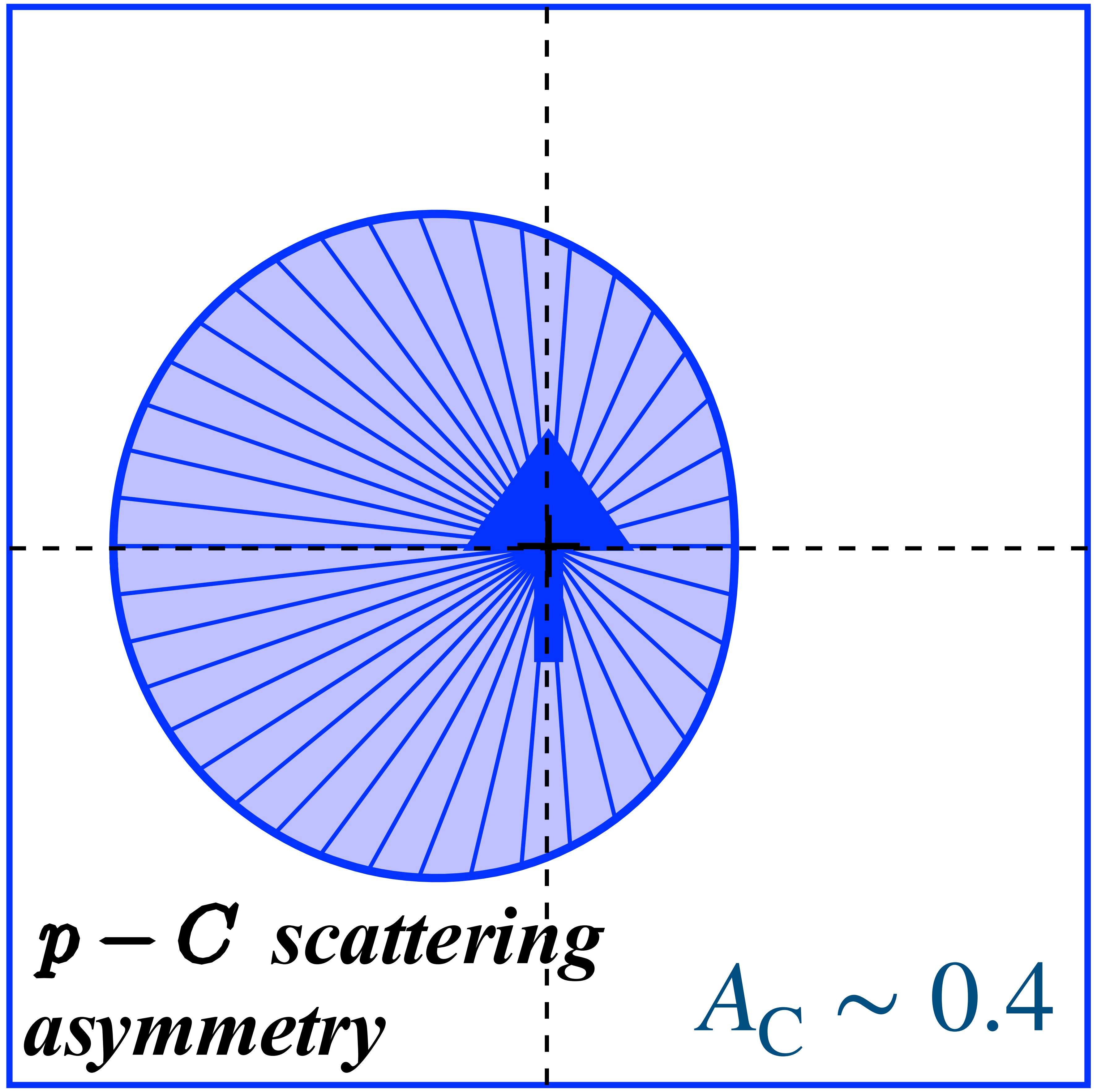


How to measure *p* spin

pC nuclear scattering asymmetry

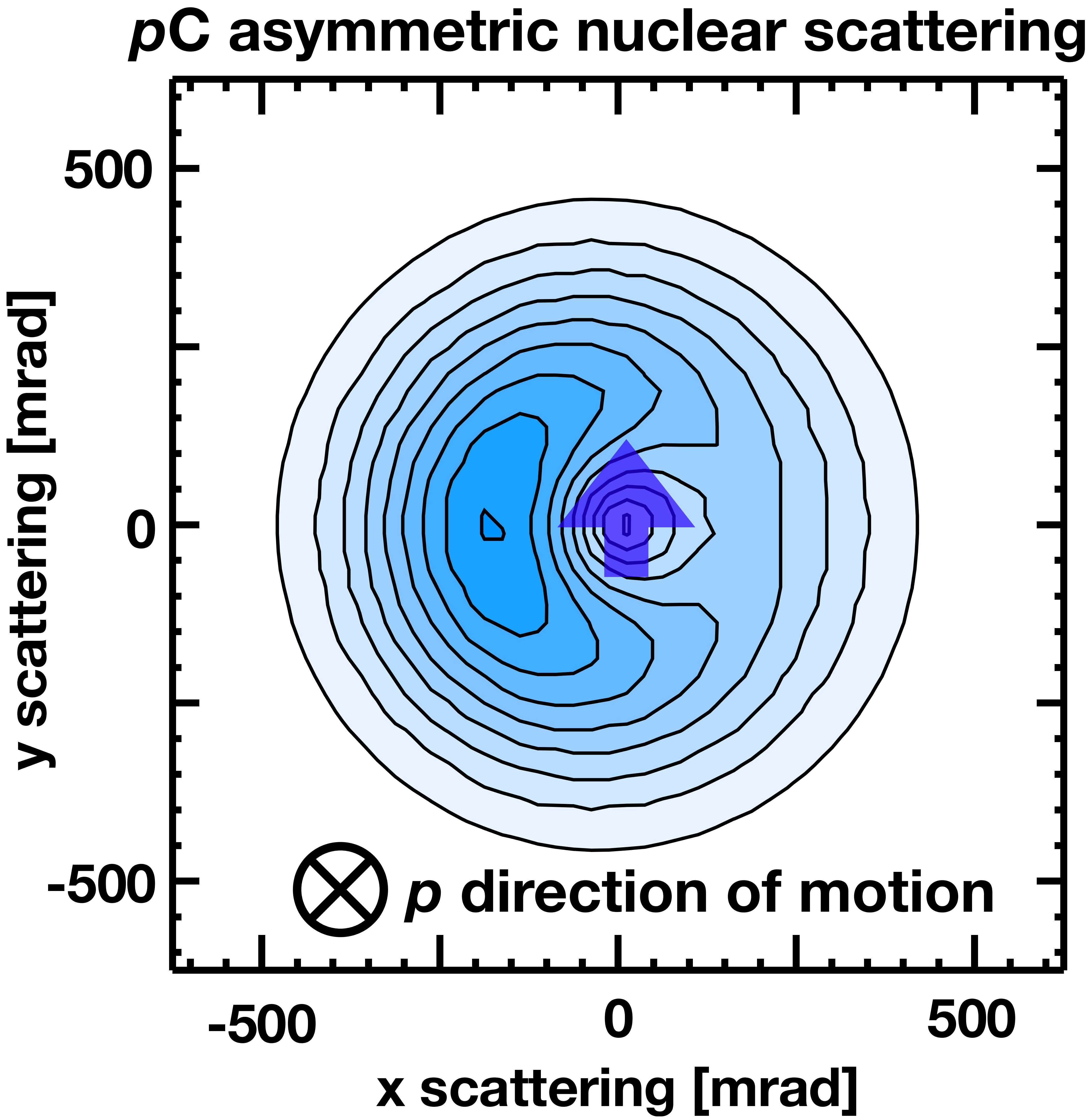
$$N(\phi)\,d\phi \propto (1 + A\cos\phi)\,d\phi$$

scattering plane orthogonal to proton motion

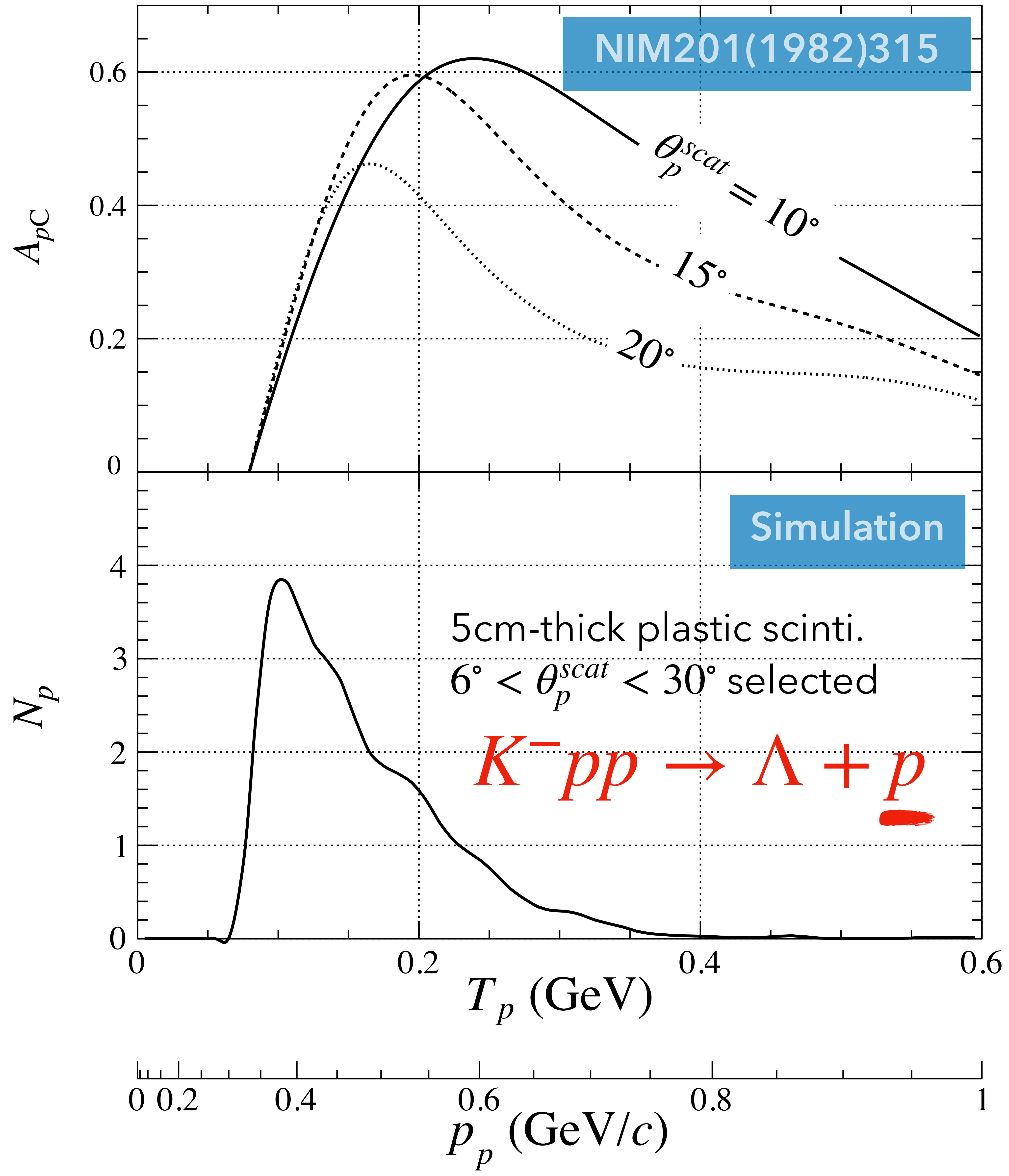


axial asymmetry: ϕ

one can measure proton spin component orthogonal to the motion

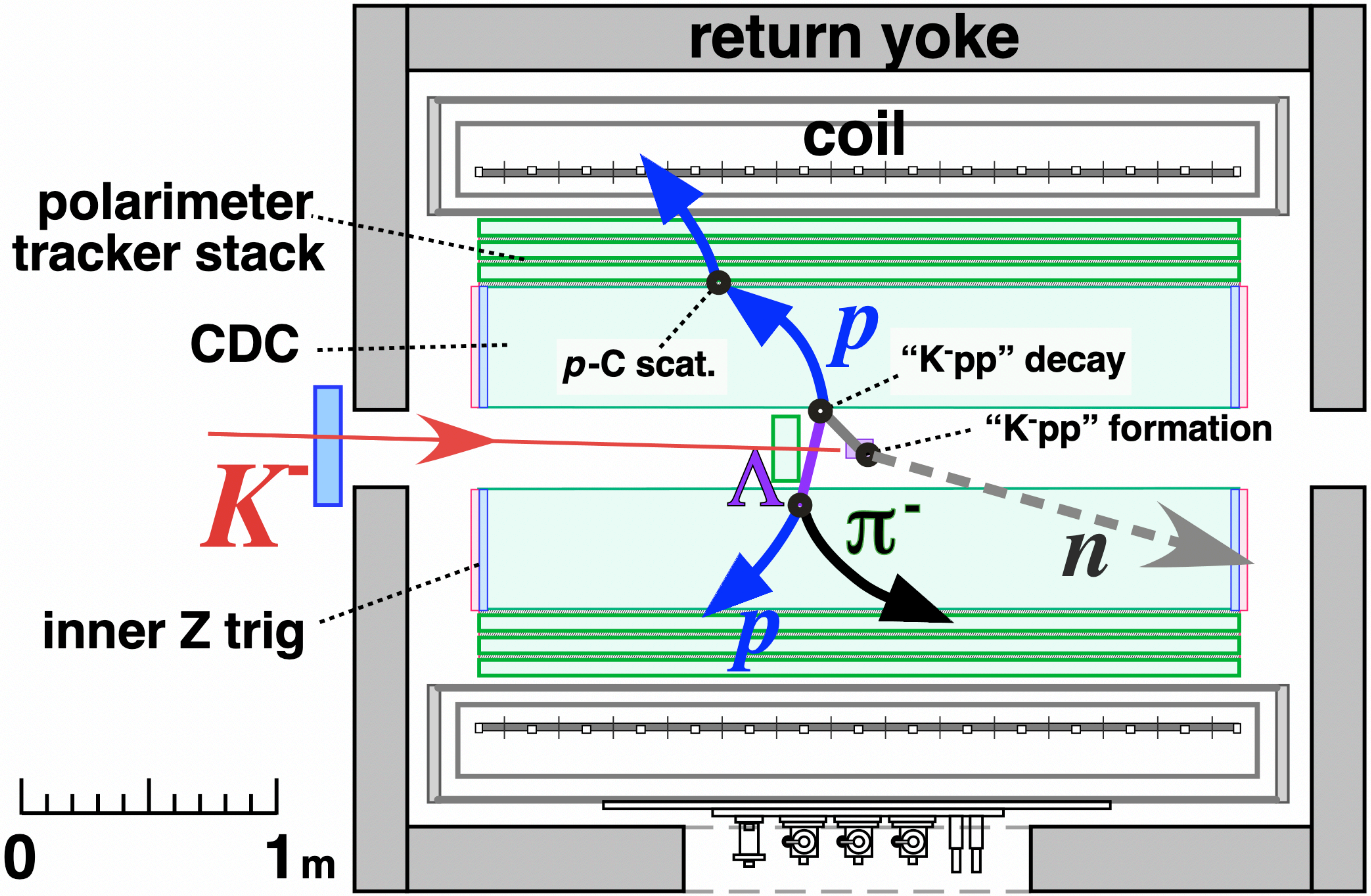


Analyzing power of proton spin



- Analyzing power of carbon taken from Ref. NIM 201 (1982) 315
  - Asymmetry max. around $T_P = 0.2$ GeV
- Proton $(K^- pp \to \Lambda + p)$ momentum in spin sensitive range
  - Slightly lower than max. asymmetry
  - Simulated by MC with 5cm thick carbon
    - $6° < \theta_p^{scat} < 30°$ selected
- Average asymmetry : $< A_{pC} > \sim 0.4$
  - … GIANT is not good at in handling spins …

Experimental setup for spin-spin correlation



dedicated setup needed

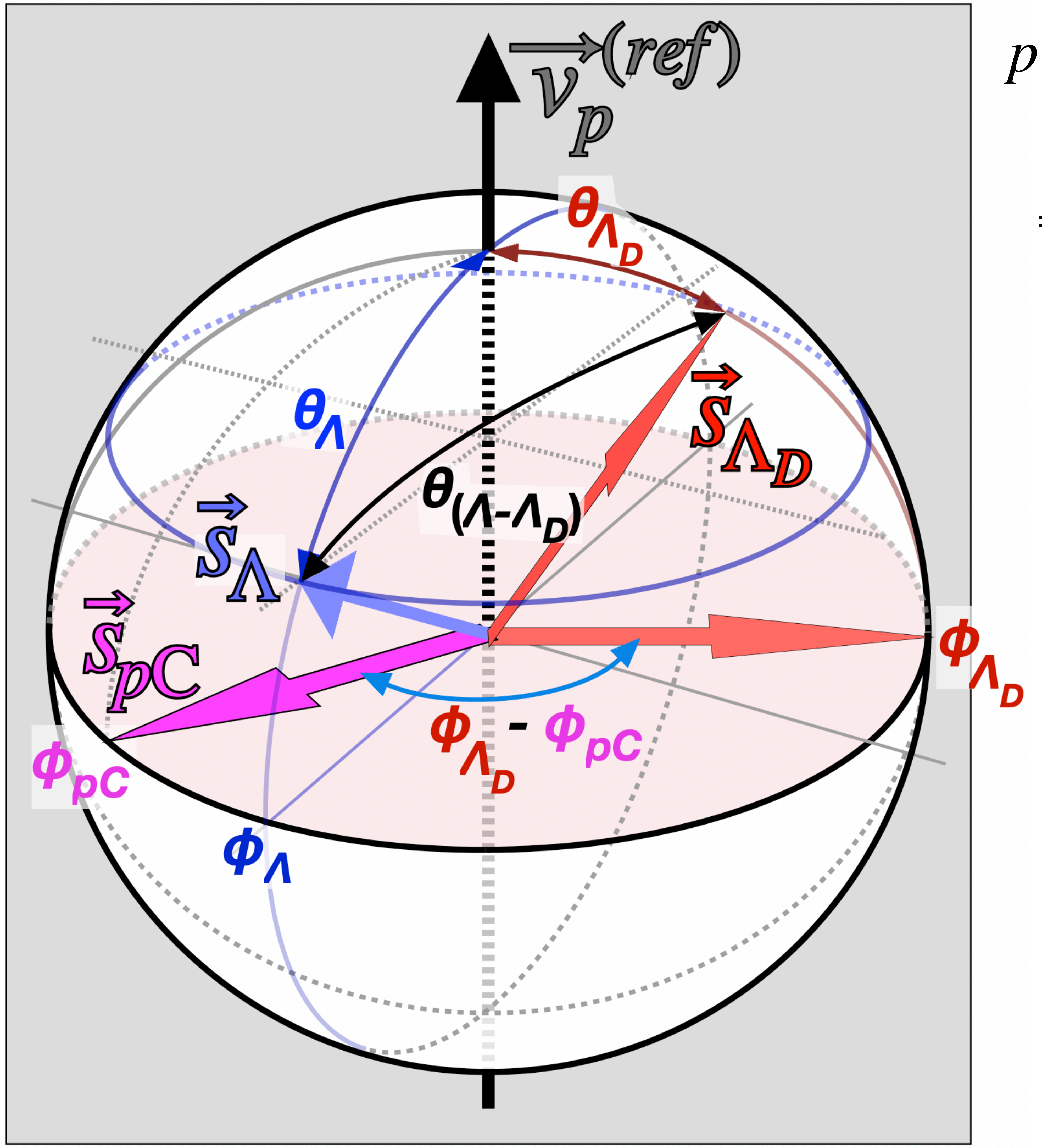
large acceptance

- **large CDS**
- **w/ inner charge trigger counter**
- **barrel polarimeters & tacking chamber layers**

detail → Appendix: 5

Describe $r \cdot \alpha_{\Lambda p}$ as a function of ϕ

proton motion vector
(*proton spin reference vector*)



spin observation probability

detail → Appendix: 7

$$p = \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda \cos\theta_{(\Lambda-\Lambda_D)}\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

$$= \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda(\cos\theta_\Lambda\cos\theta_{\Lambda_D} + \sin\theta_\Lambda\sin\theta_{\Lambda_D}\cos(\phi_\Lambda - \phi_{\Lambda_D}))\right)\left(1 + A_{pC}\,\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

Describe $r \cdot \alpha_{\Lambda p}$ as a function of ϕ

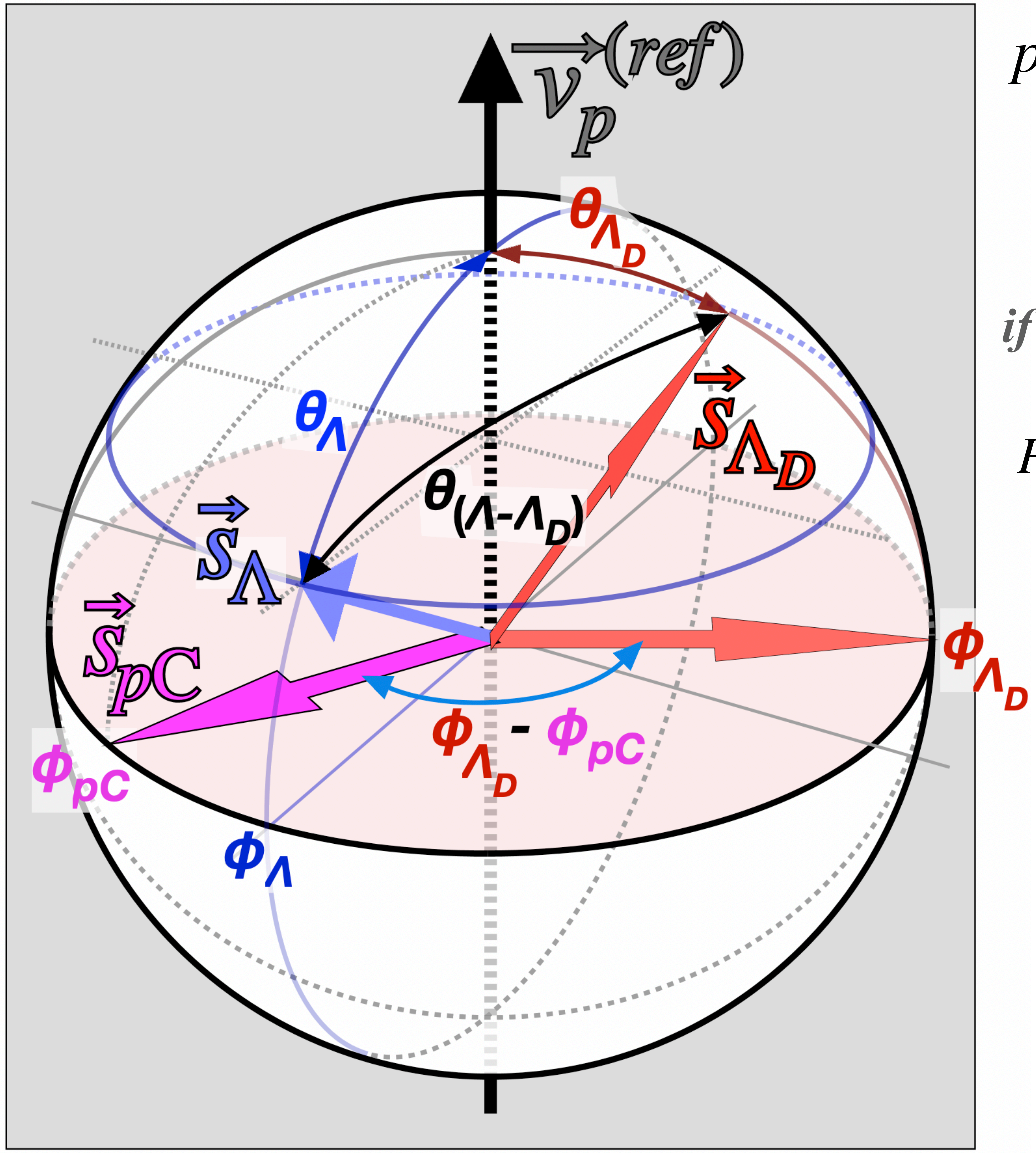
simple convolution for B=0, q=0 and $\vec{s}$ uniform

(more specifically, if $\int f(\vec{s}) e^{i(2\phi_\Lambda + \delta)} d\phi_\Lambda = 0$)

detail → Appendix: 7

proton motion vector

(proton spin reference vector)



spin observation probability

$$p = \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda \cos\theta_{(\Lambda-\Lambda_D)}\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

$$= \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda(\cos\theta_\Lambda\cos\theta_{\Lambda_D} + \sin\theta_\Lambda\sin\theta_{\Lambda_D}\cos(\phi_\Lambda - \phi_{\Lambda_D}))\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

if spin direction $\vec{s}_\Lambda$ is uniform in ϕ_Λ direction,

$$P(\phi_{\Lambda_D} - \phi_{pC}) = \int d(\cos\theta_{\Lambda_D}) \int d\vec{s}_\Lambda \left\{p(\theta_{\Lambda_D}, \vec{s}_\Lambda)\right\}$$

$$= \frac{1}{4\pi}\int d(\cos\theta_\Lambda) f_{\vec{s}}(\theta_\Lambda)\left(1 + \frac{\pi}{4}A_\Lambda A_{pC}\sin^2\theta_\Lambda\cos(\phi_{\Lambda_D} - \phi_{pC})\right)$$

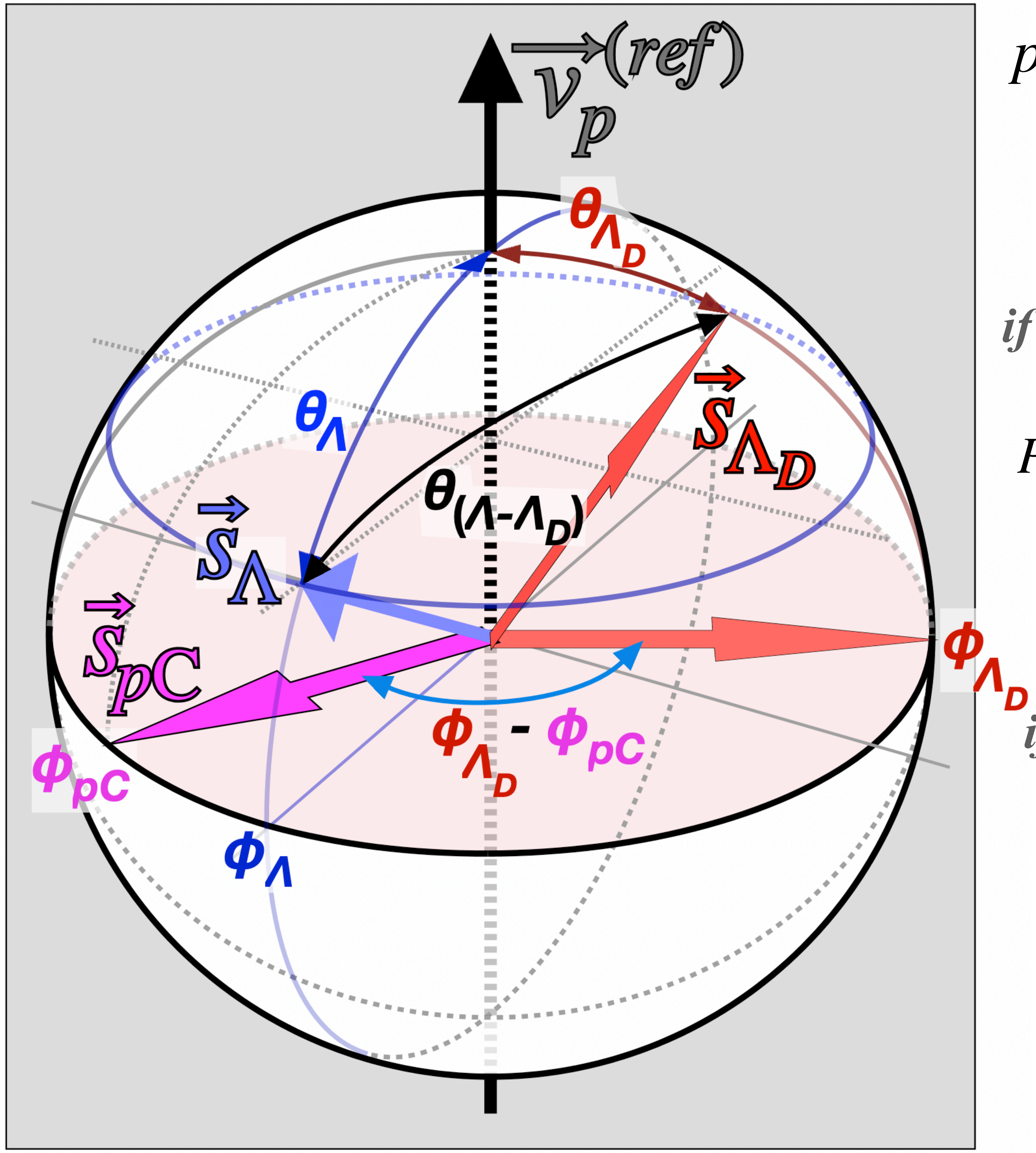
Describe $r \cdot \alpha_{\Lambda p}$ as a function of ϕ

simple convolution for B=0, q=0 and $\vec{s}$ uniform

(more specifically, if $\int f(\vec{s}) e^{i(2\phi_\Lambda+\delta)} d\phi_\Lambda = 0$)

proton motion vector

(proton spin reference vector)



detail → Appendix: 7

spin observation probability

$$p = \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda \cos\theta_{(\Lambda-\Lambda_D)}\right)\left(1 + A_{pC}\sin\theta_\Lambda \cos(\phi_\Lambda - \phi_{pC})\right)$$

$$= \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda(\cos\theta_\Lambda\cos\theta_{\Lambda_D} + \sin\theta_\Lambda\sin\theta_{\Lambda_D}\cos(\phi_\Lambda - \phi_{\Lambda_D}))\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

if spin direction $\vec{s}_\Lambda$ is uniform in ϕ_Λ direction,

$$P(\phi_{\Lambda_D} - \phi_{pC}) = \int d(\cos\theta_{\Lambda_D}) \int d\vec{s}_\Lambda \left\{p(\theta_{\Lambda_D}, \vec{s}_\Lambda)\right\}$$

$$= \frac{1}{4\pi}\int d(\cos\theta_\Lambda) f_{\vec{s}}(\theta_\Lambda)\left(1 + \frac{\pi}{4}A_\Lambda A_{pC}\sin^2\theta_\Lambda\cos(\phi_{\Lambda_D} - \phi_{pC})\right)$$

if $\vec{s}_\Lambda$ is also uniform in θ_Λ direction (experimentally this is NOT),

$$P(\phi) = \frac{1}{2\pi}\left(1 + \frac{\pi}{12}A_\Lambda A_{pC}\cos\phi\right) \qquad (\phi = \phi_{\Lambda_D} - \phi_{pC})$$

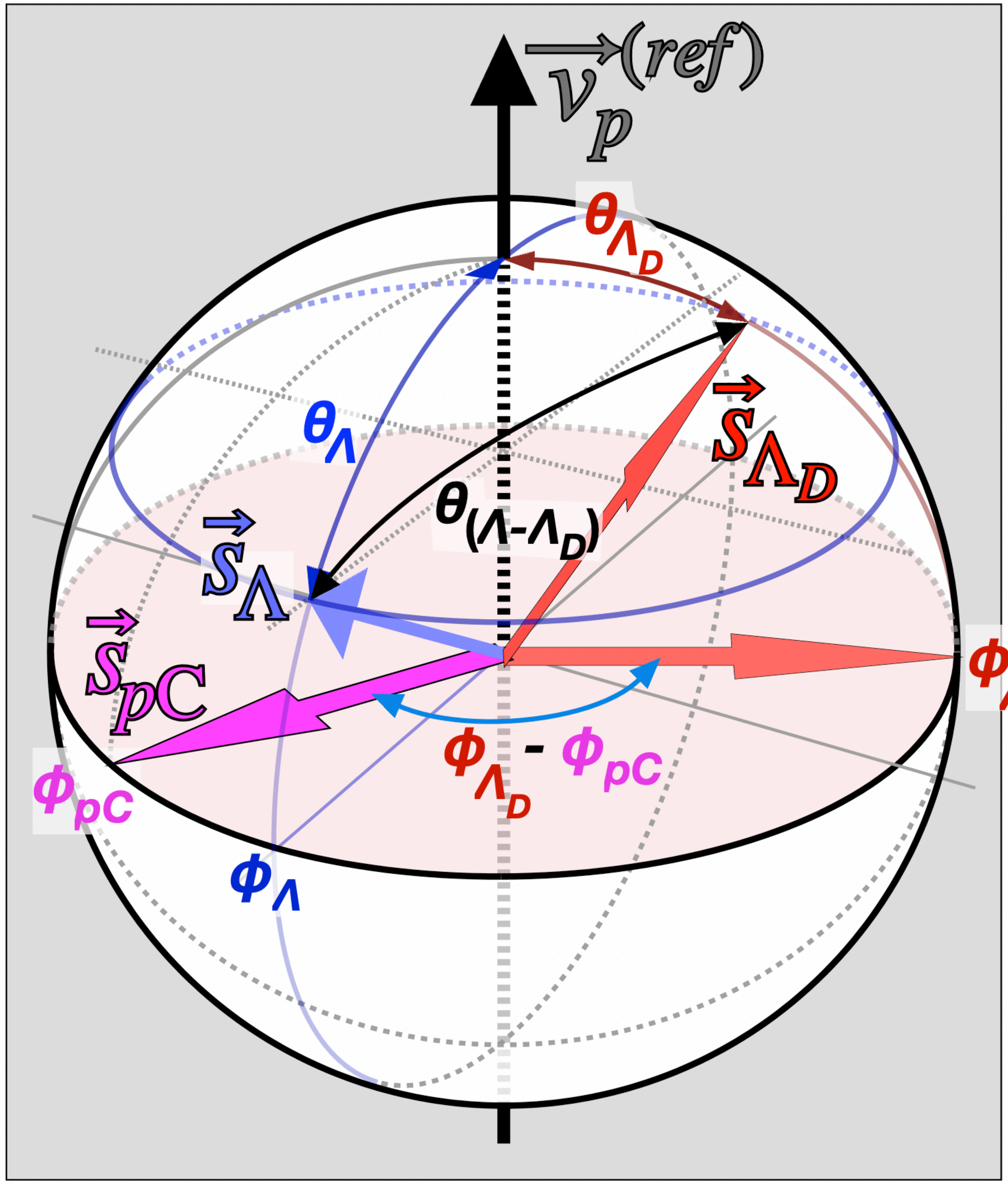
$$A_{uni.S} = \frac{\pi}{12}A_\Lambda A_{pC}\cos\phi \sim 0.076 \qquad \textit{if } \vec{s}_\Lambda \textit{ is uniform}$$

small, but sufficient for dedicated setup

Describe $r \cdot \alpha_{\Lambda p}$ as a function of ϕ

proton motion vector

(proton spin reference vector)



simple convolution for B=0, q=0 and $\vec{s}$ uniform

(more specifically, if $\int f(\vec{s}) e^{i(2\phi_\Lambda+\delta)} d\phi_\Lambda = 0$)

detail → Appendix: 7

spin observation probability

$$p = \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda \cos\theta_{(\Lambda-\Lambda_D)}\right)\left(1 + A_{pC}\sin\theta_\Lambda \cos(\phi_\Lambda - \phi_{pC})\right)$$

$$= \frac{f(\vec{s}_\Lambda)}{(4\pi)^2}\left(1 + A_\Lambda(\cos\theta_\Lambda \cos\theta_{\Lambda_D} + \sin\theta_\Lambda \sin\theta_{\Lambda_D}\cos(\phi_\Lambda - \phi_{\Lambda_D}))\right)\left(1 + A_{pC}\sin\theta_\Lambda \cos(\phi_\Lambda - \phi_{pC})\right)$$

if spin direction $\vec{s}_\Lambda$ is uniform in ϕ_Λ direction,

$$P(\phi_{\Lambda_D} - \phi_{pC}) = \int d(\cos\theta_{\Lambda_D}) \int d\vec{s}_\Lambda \left\{ p(\theta_{\Lambda_D}, \vec{s}_\Lambda)\right\}$$

$$= \frac{1}{4\pi}\int d(\cos\theta_\Lambda) f_{\vec{s}}(\theta_\Lambda)\left(1 + \frac{\pi}{4}A_\Lambda A_{pC}\sin^2\theta_\Lambda \cos(\phi_{\Lambda_D} - \phi_{pC})\right)$$

effective asymmetry $\propto \sin^2\theta_\Lambda$

*if $\vec{s}_\Lambda$ is also uniform in θ_Λ direction (**experimentally this is NOT**),*

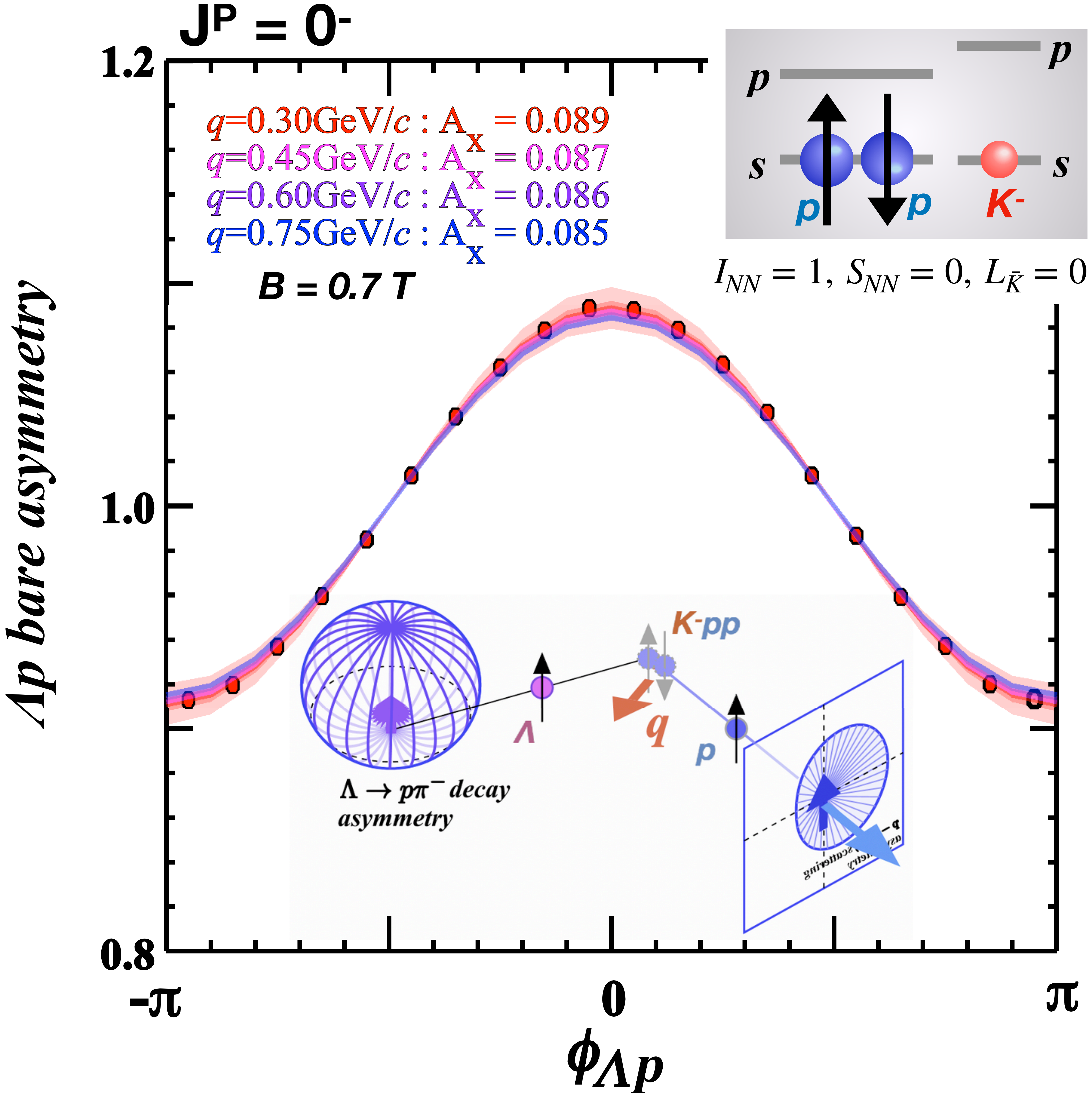
$$P(\phi) = \frac{1}{2\pi}\left(1 + \frac{\pi}{12}A_\Lambda A_{pC}\cos\phi\right) \qquad (\phi = \phi_{\Lambda_D} - \phi_{pC})$$

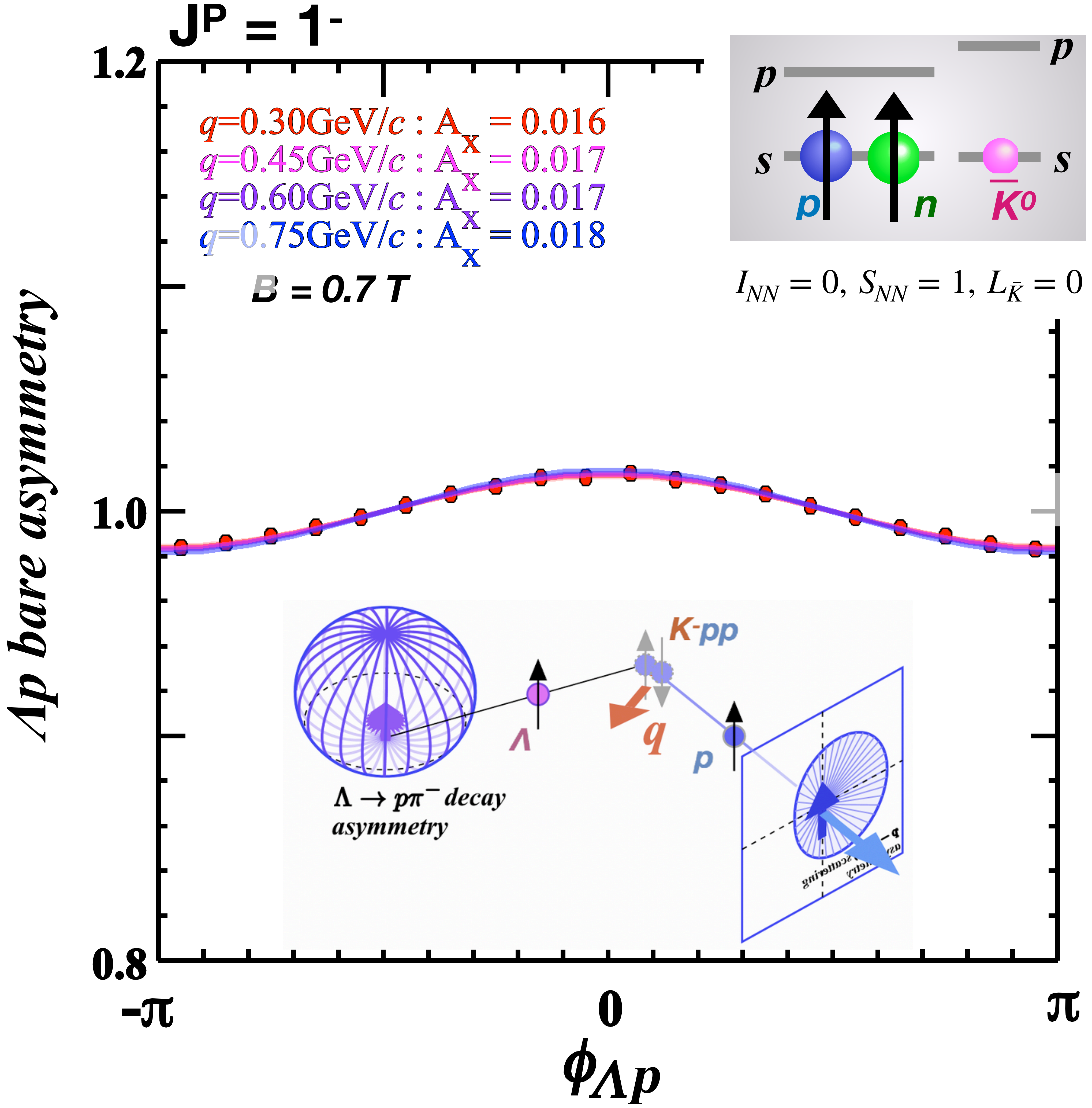
$$A_{uni.S} = \frac{\pi}{12}A_\Lambda A_{pC}\cos\phi \sim 0.076$$ *if $\vec{s}_\Lambda$ is uniform*

small, but sufficient for dedicated setup

Λ-p bare asymmetry

$$= \frac{N_{\phi_j}(\phi_{\Lambda p})}{\sum_{\phi_j} N_{\phi_j}(\phi_{\Lambda p})/N_{bin}} = 1 + A_{all}\cos(\phi_{\Lambda p}) \quad \dots \quad (\phi_j = \phi_{\Lambda p})$$





A_x ~ 0.9 (> $A_{uni.S}$) for $J^P=0^-$

A_x < 0.2 (< $A_{uni.S}/3$) for $J^P=1^-$

Why $J^P=0^-$ & 1^- asymmetries are so much different?

It helps to discriminate $J^P=0^-$ & 1^-, though

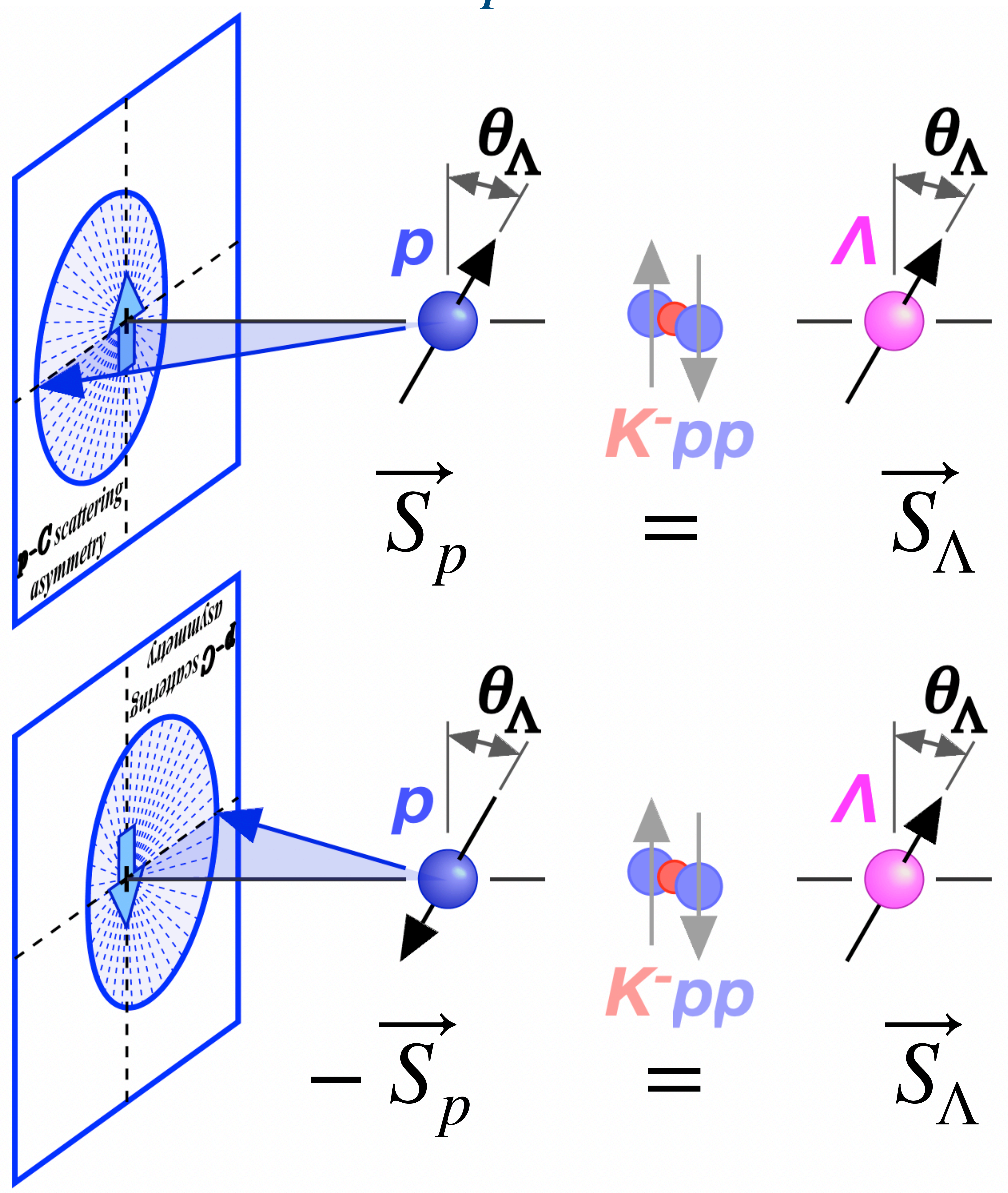
Because 1) asymmetry cancelling happens on polarimeter (NOT at K⁻pp decay where $\alpha_{\Lambda p}$ is defined), and 2) effective asymmetry $\propto \sin^2\theta_\Lambda$

$J^P = 0^-$
$S_{\Lambda p} = 1$

or

$J^P = 1^-$
$S_{\Lambda p} = 1$

$J^P = 1^-$
$S_{\Lambda p} = 0$



$J^P = 0^-$

$\alpha_{cancel}(B, M, q) = 1$

no anti-parallel component in $J^P=0^-$

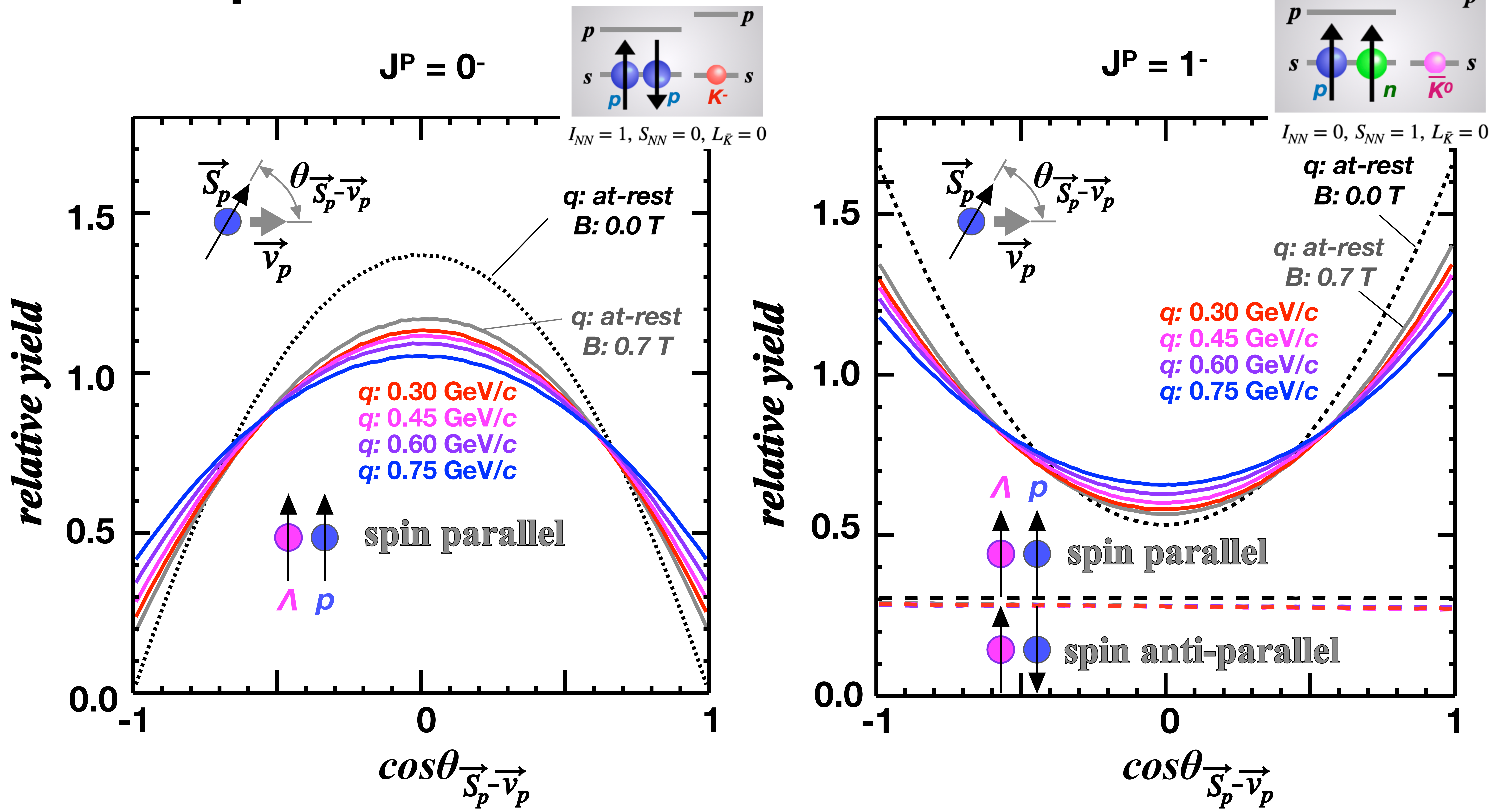
effective asymmetry $\propto \sin^2\theta_\Lambda$

$J^P = 1^-$

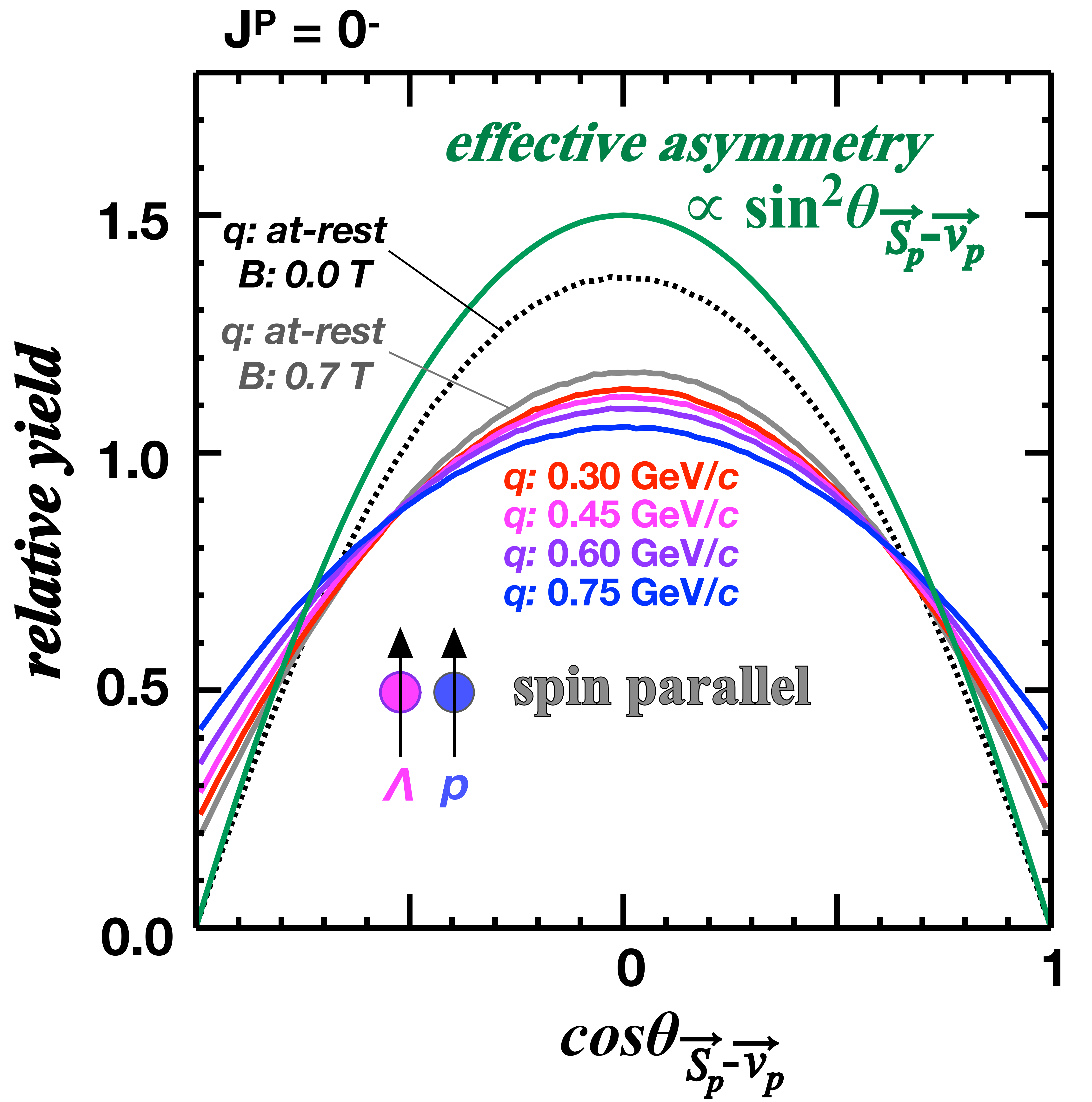
$$\alpha_{cancel}(B, M, q) = \frac{\left(2\alpha_{\Lambda p}^{(S_{\Lambda p}=1)} + \alpha_{\Lambda p}^{(S_{\Lambda p}=0)}\right)}{(2+1)} \left\{ \frac{\int \left(f(\theta_p) + g(\theta_p)\right) \sin^2\theta_p \, d\Omega_p}{\int \left(f(\theta_p) - g(\theta_p)\right) \sin^2\theta_p \, d\Omega_p} \right\}_{@pC}$$

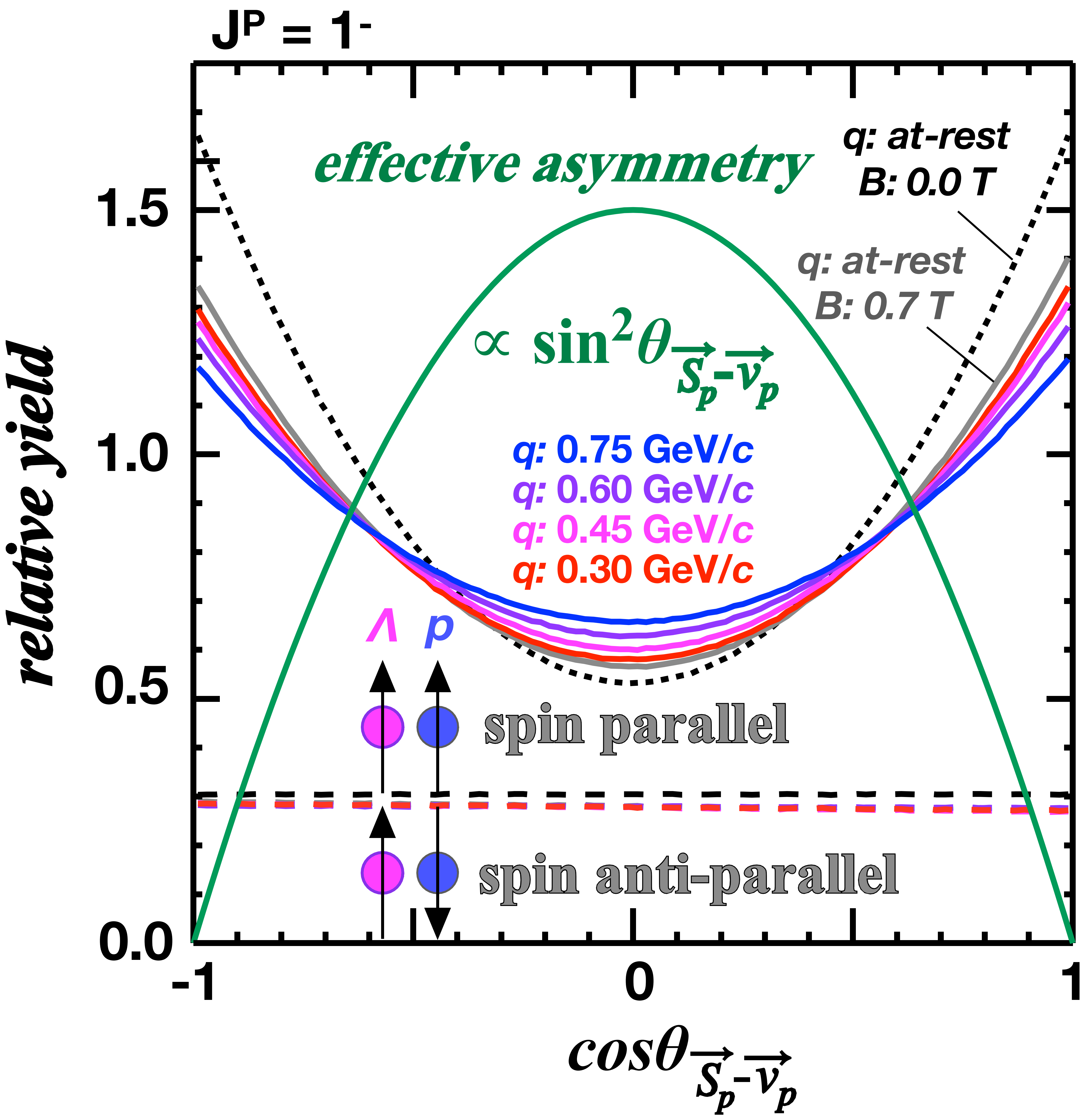
only for $J^P=1^-$

Proton Spin distribution to the direction of motion

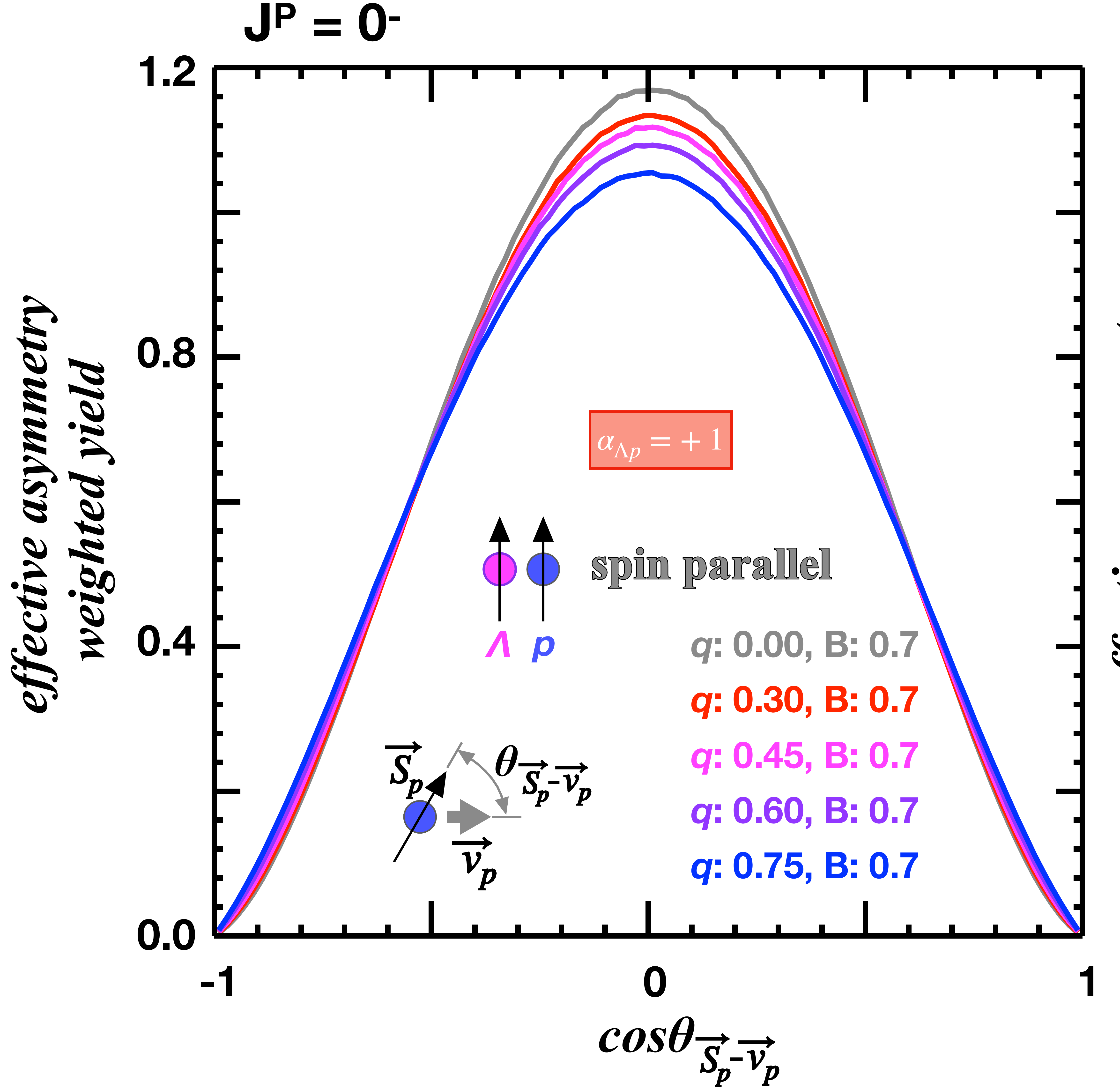


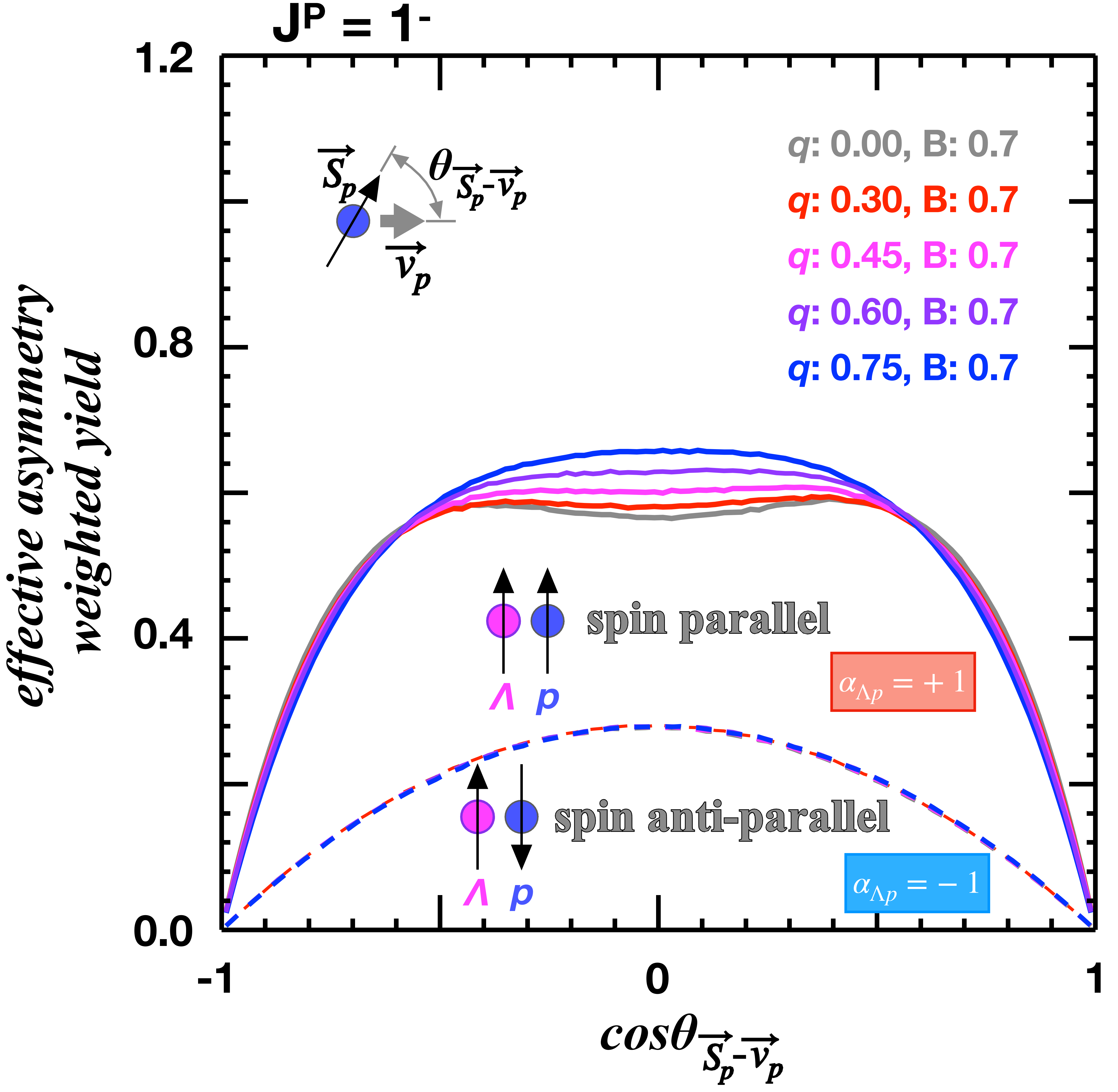
Effective-asymmetry weighted spin distribution





Effective-asymmetry weighted spin distribution

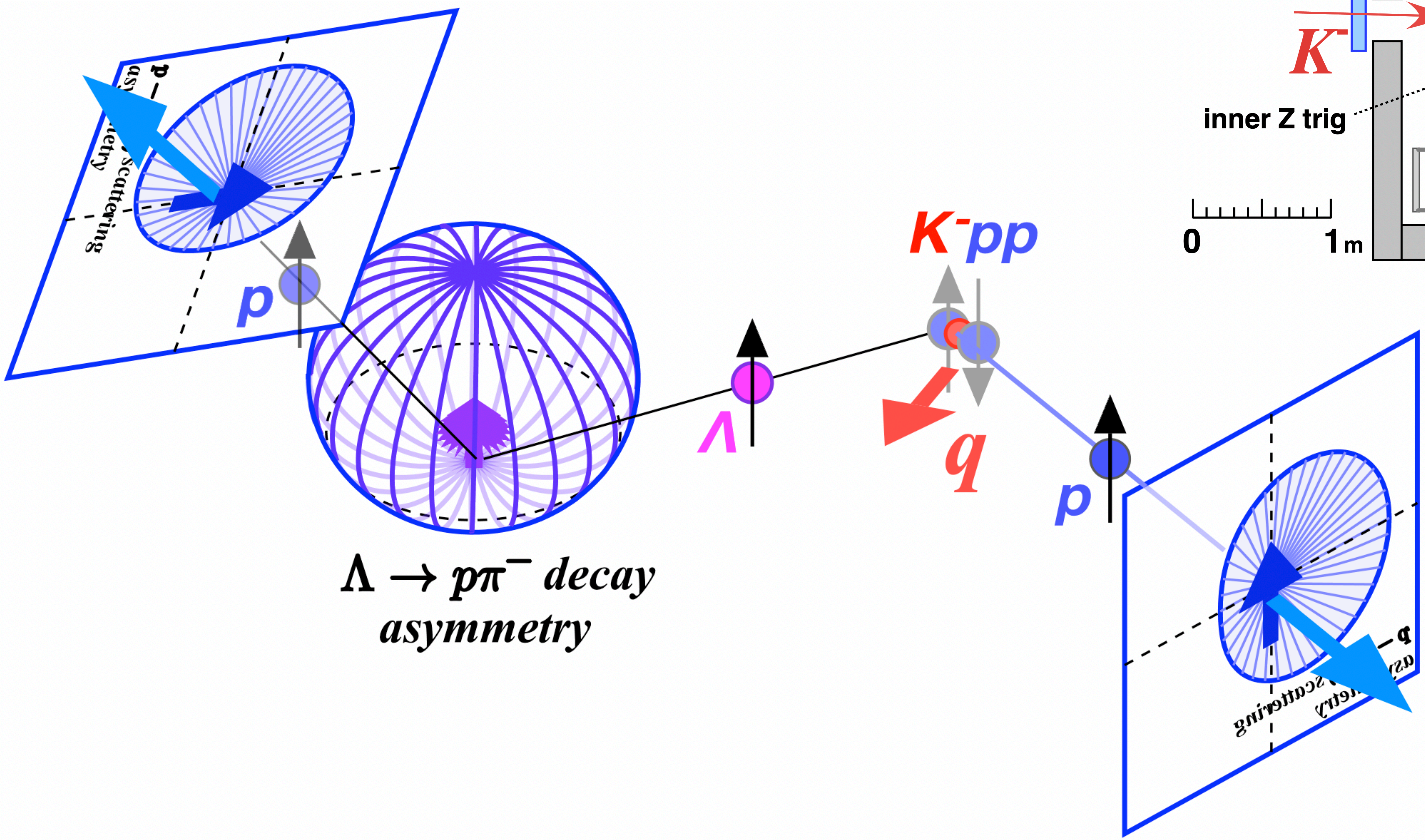


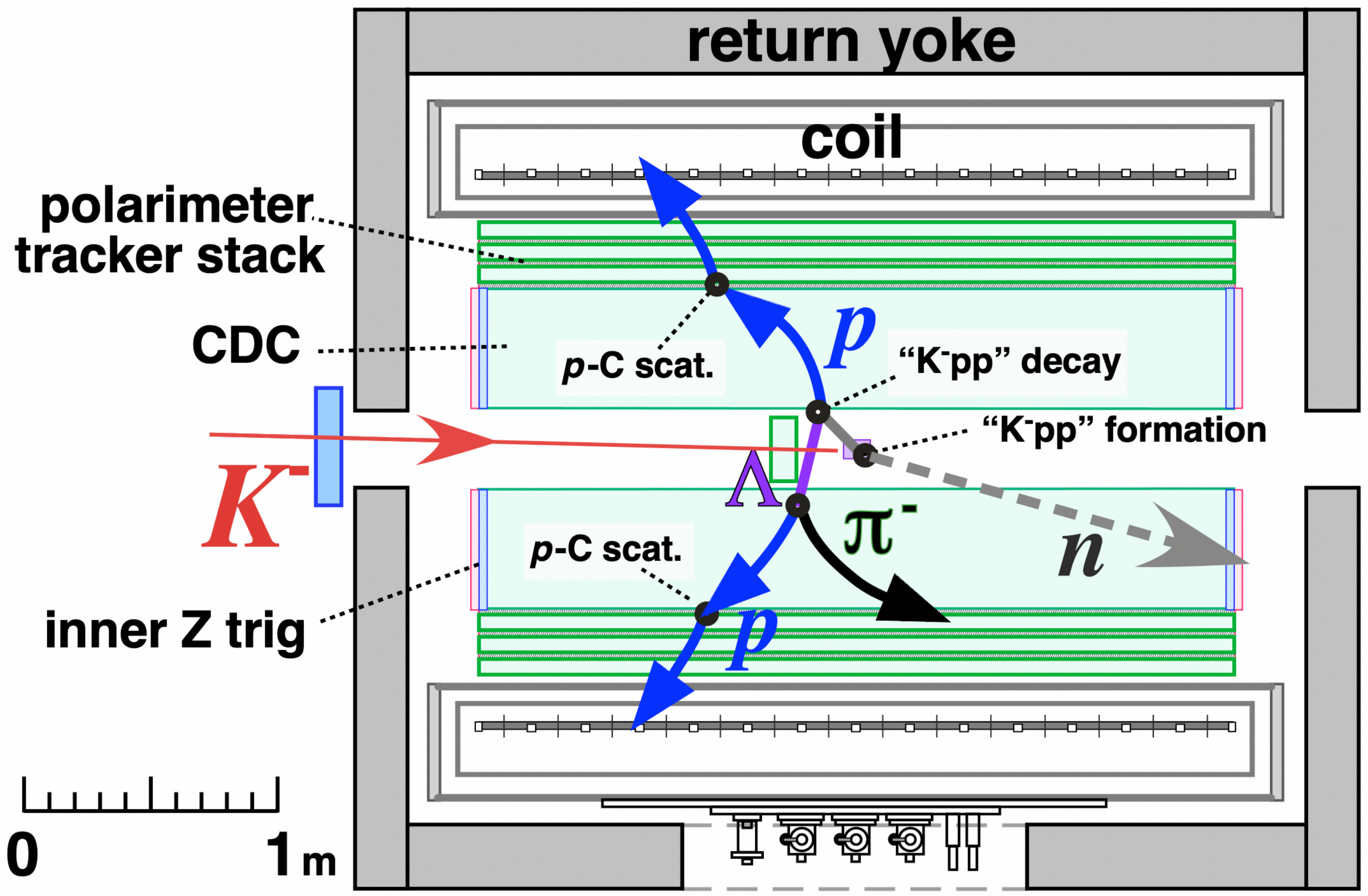


How to derive $\alpha_{\Lambda p}$ from observed asymmetry?

How to remove r from spin-spin asymmetry $r \cdot \alpha_{\Lambda p}$,
in the experimental condition (at finite B & q)?

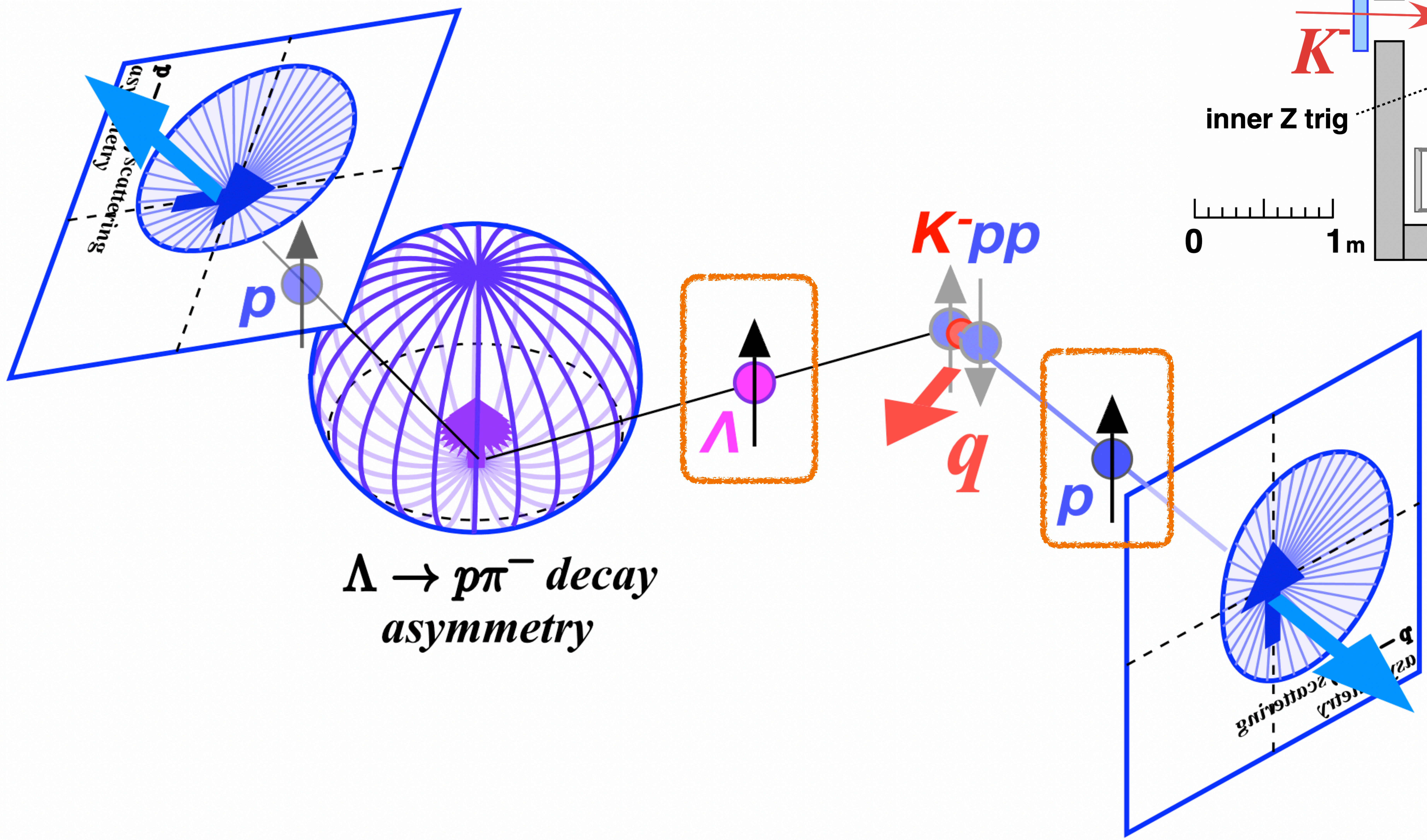
A typical event topology in which
particle motions and momentum kicks are exaggerated

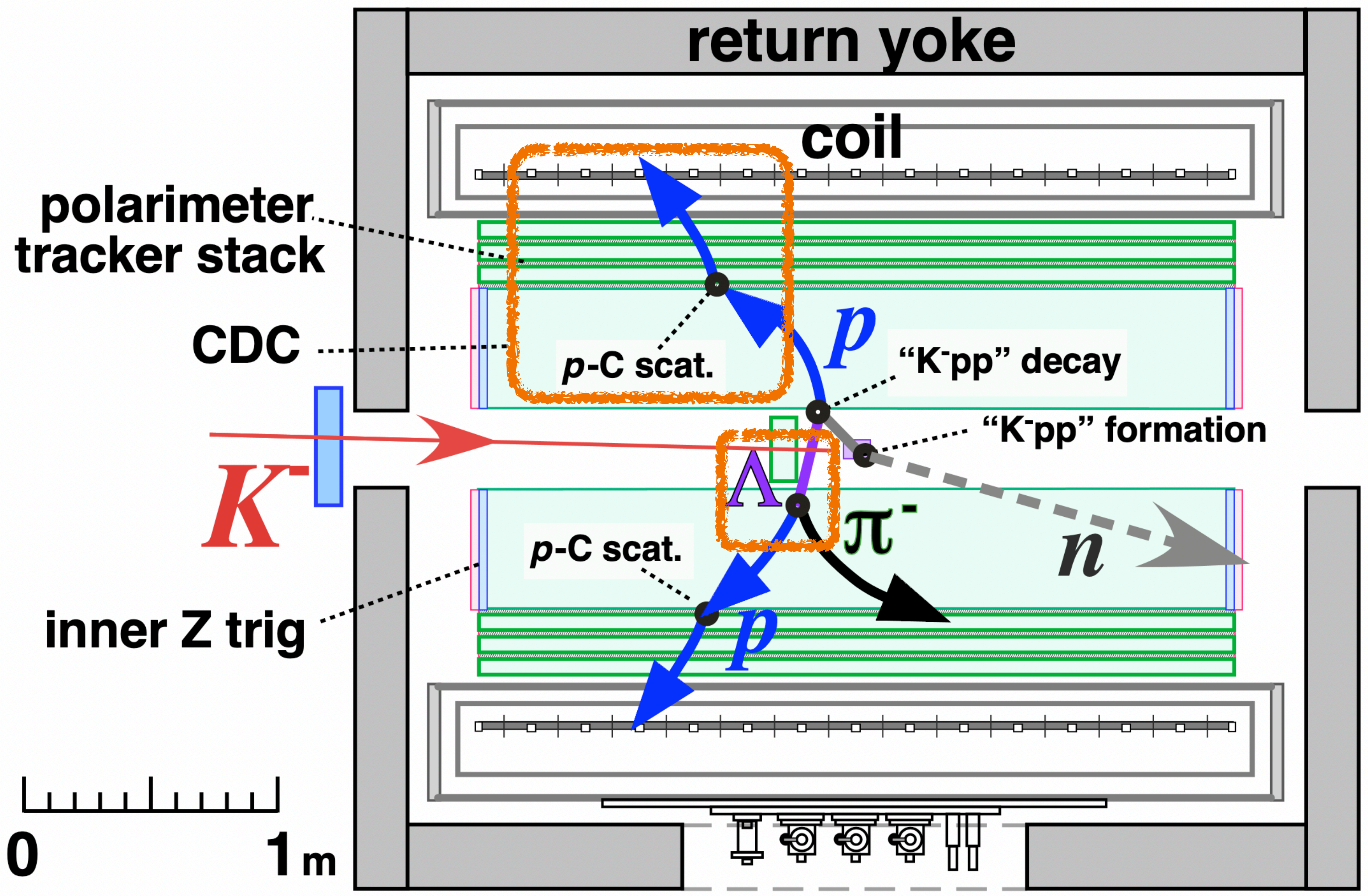




effect of
particle motions and
momentum kicks
can be simulated

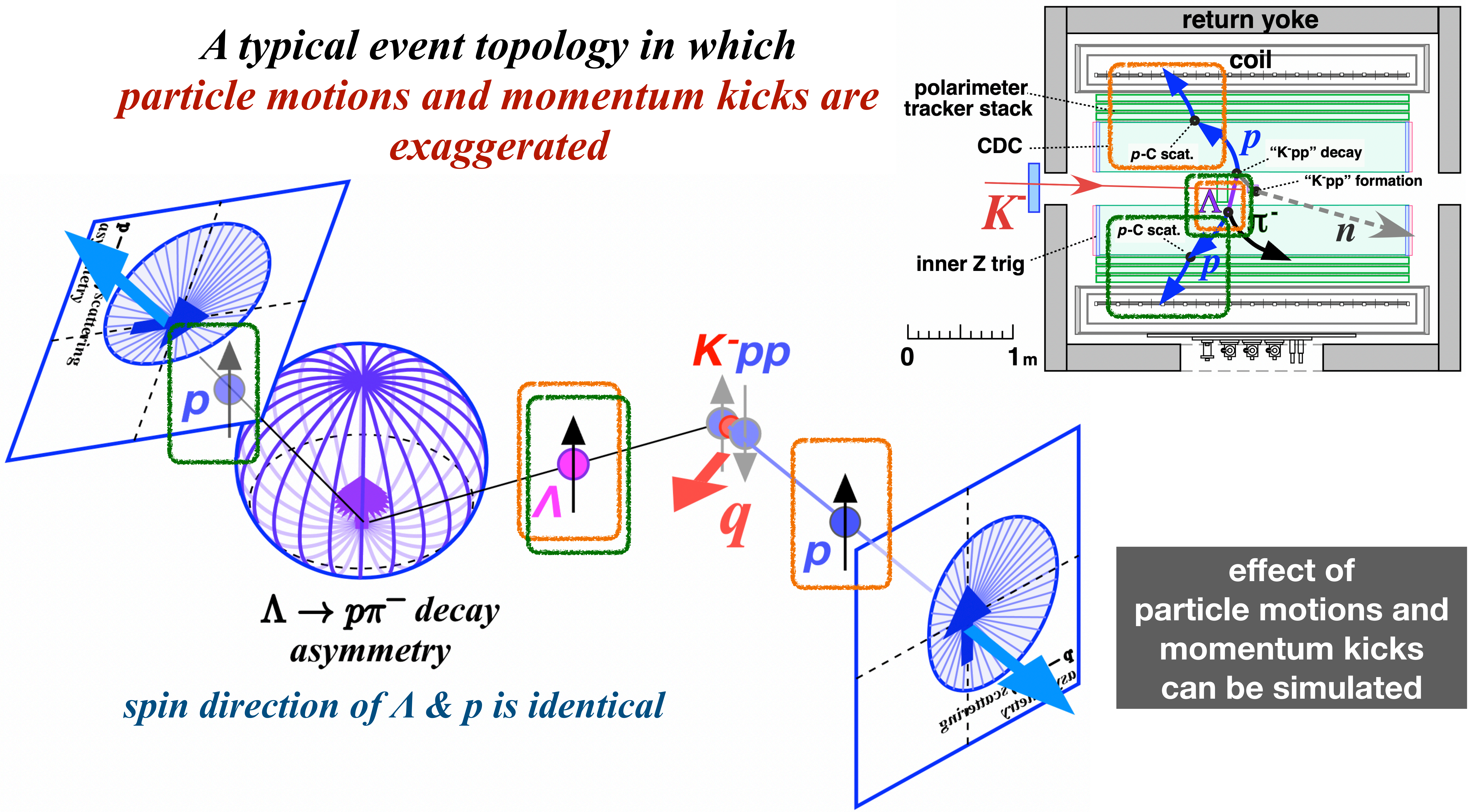
A typical event topology in which particle motions and momentum kicks are exaggerated





effect of particle motions and momentum kicks can be simulated

A typical event topology in which *particle motions and momentum kicks are exaggerated*



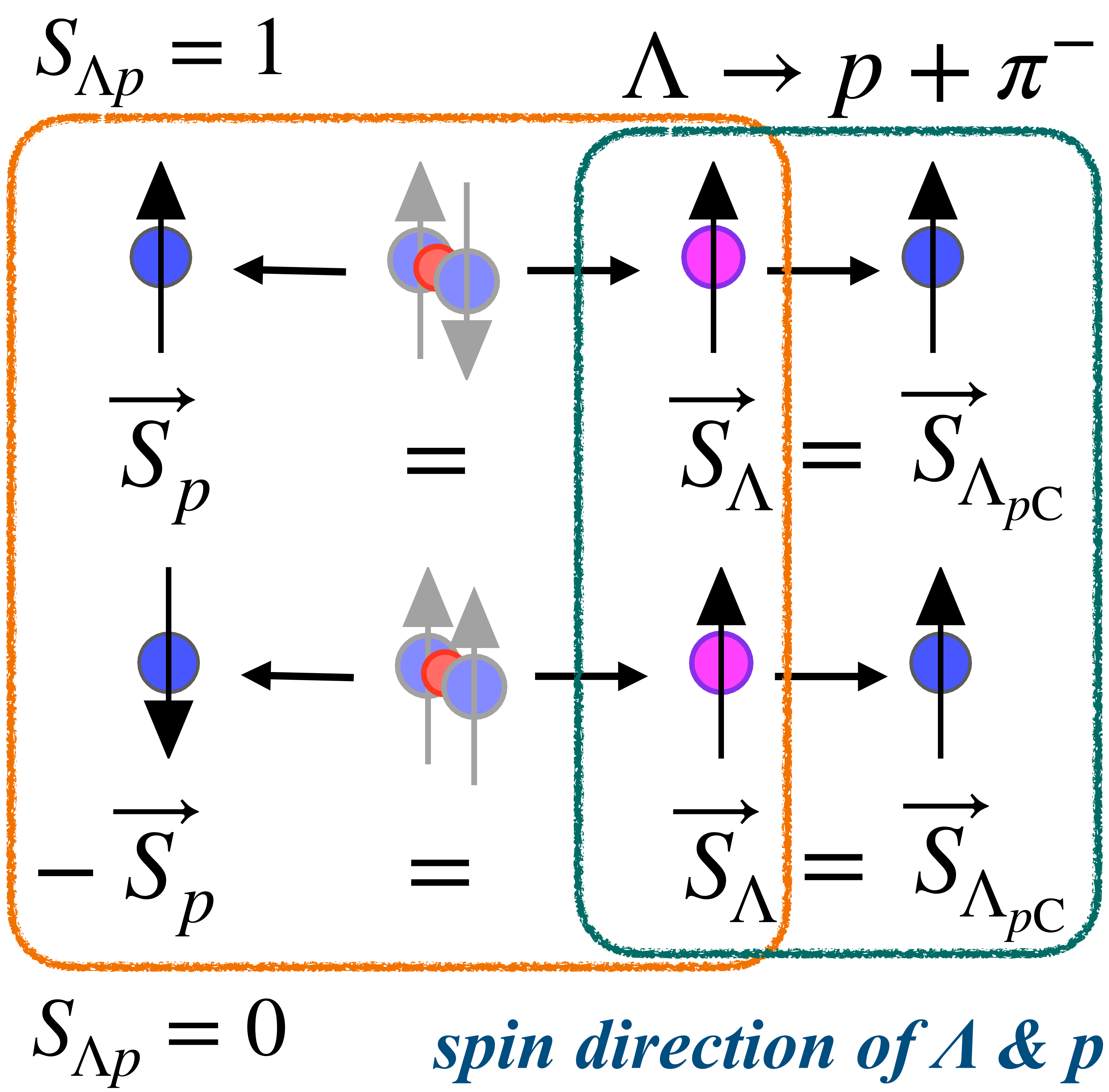
spin direction of Λ & p is identical

effect of particle motions and momentum kicks can be simulated

How to calibrate the absolute value of $\alpha_{\Lambda p}$?

self-calibration factor $\mathscr{A}_{eff}(B, M, q)$ to be applied to Λ-Λ_{pC} asymmetry

$$\mathscr{A}_{eff}(B, M, q) \approx 1$$



spin direction of Λ & p is identical

$J^P = 0^-$

$$\mathscr{A}_{eff}(B, M, q) = \frac{\left\{ \int f(\theta_p) \sin^2\theta_p \, d\Omega_p \right\}_{@pC}}{\left\{ \int f(\theta_{\Lambda_{pC}}) \sin^2\theta_{\Lambda_{pC}} \, d\Omega_{\Lambda_{pC}} \right\}_{@pC}}$$

effective asymmetry
$\propto \sin^2\theta_\Lambda$

$J^P = 1^-$

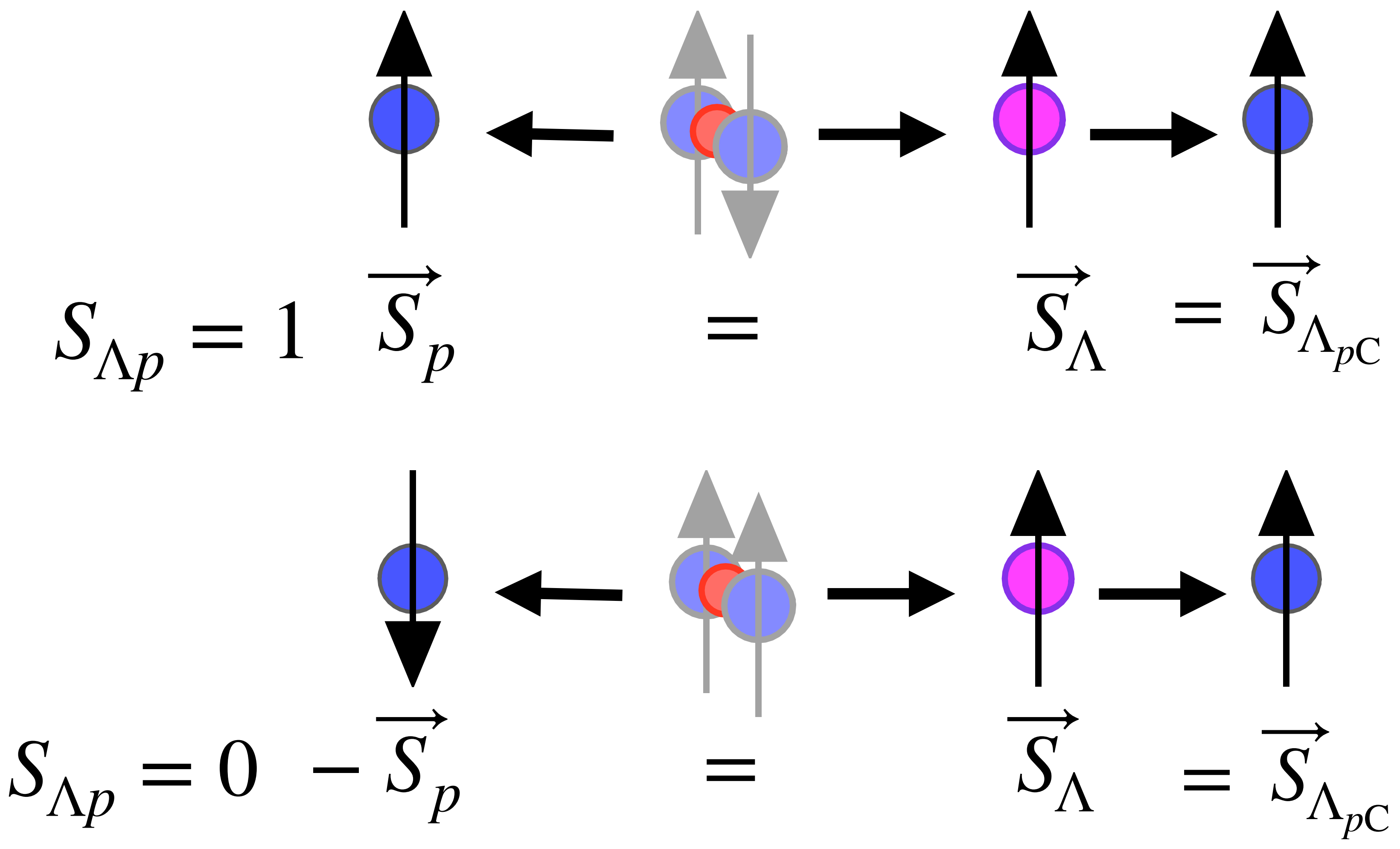
$$\mathscr{A}_{eff}(B, M, q) = \frac{\left\{ \int \left(f(\theta_p) + g(\theta_p) \right) \sin^2\theta_p \, d\Omega_p \right\}_{@pC}}{\left\{ \int \left(f(\theta_{\Lambda_{pC}} + g(\theta_{\Lambda_{pC}}) \right) \sin^2\theta_{\Lambda_{pC}} \, d\Omega_{\Lambda_{pC}} \right\}_{@pC}}$$

detail → Appendix:8

Short summary of $\alpha_{\Lambda p}$ calibration procedure

$$\alpha_{\Lambda p} \approx \overset{\textit{simulation}}{\mathscr{C}_{eff}(B,M,q)} \frac{n(\phi_{(\Lambda-p)})-1}{A_{(\Lambda-\Lambda_{pC})}\cos\phi_{(\Lambda-p)}}$$

$\Lambda \rightarrow p + \pi^-$



two experimental data

simulation

$$\mathscr{C}_{eff}(B,M,q) = \mathscr{A}_{eff}(B,M,q) \times \alpha_{cancel}(B,M,q)$$

correction = effective asymmetry × canceling facor

$$\mathscr{A}_{eff}(B,M,q) = \frac{A_{(\Lambda-\Lambda_{pC})}}{A_{(\Lambda-p)}}$$

experimental data

$n(\phi_{(\Lambda-p)}) - 1$: *bare asymmetry of* $\Lambda - p$

$A_{(\Lambda-\Lambda_{pC})}$: *asymmetry observed in* $\Lambda - \Lambda_{pC}$

$$\mathscr{C}_{eff} = 1.017 \quad (J^P = 0^-)$$

$$\mathscr{C}_{eff} = 1.431 \quad (J^P = 1^-)$$

Short summary of $\alpha_{\Lambda p}$ calibration procedure

bare asymmetry

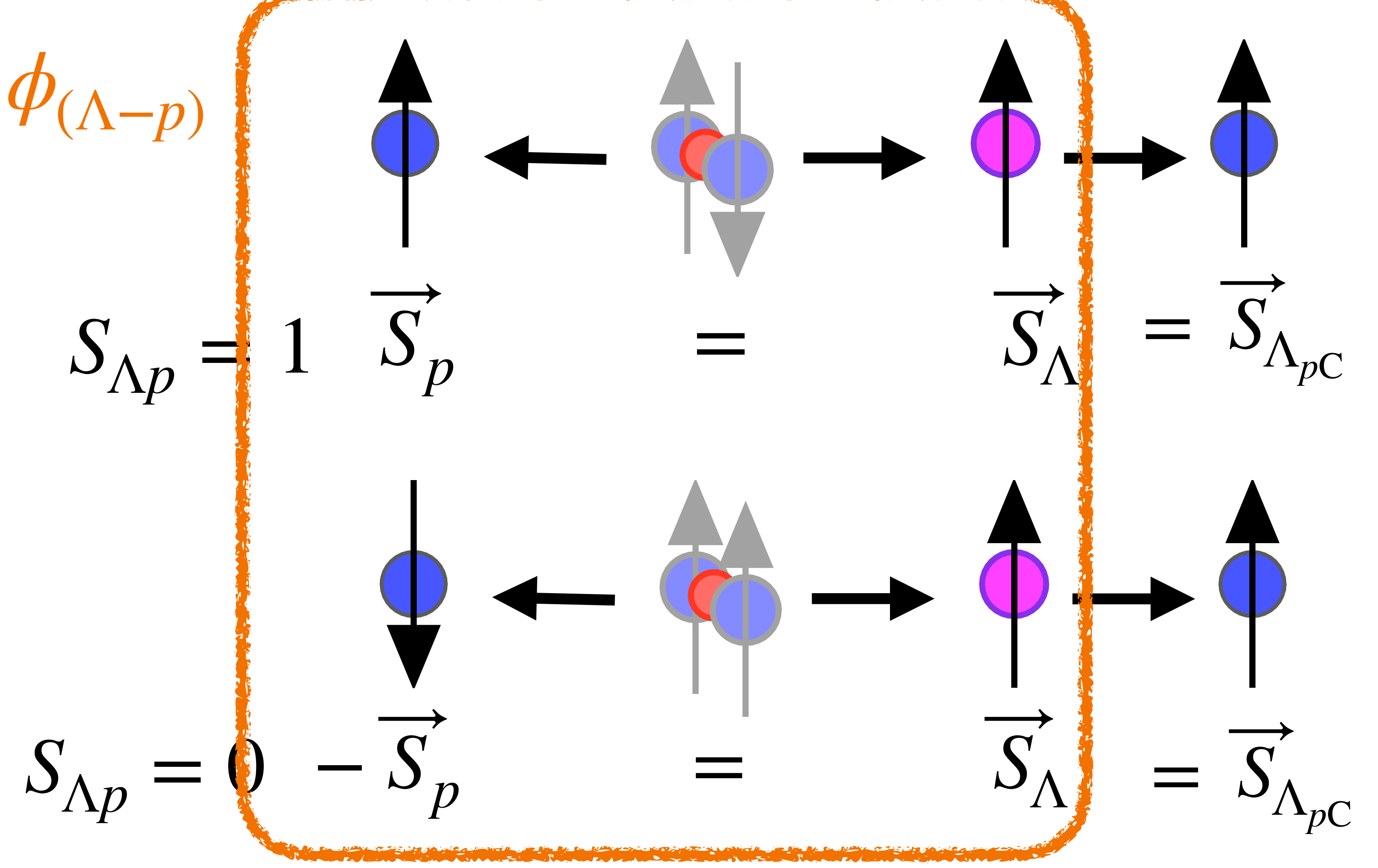
simulation

$$\alpha_{\Lambda p} \approx \mathscr{C}_{eff}(B, M, q)\,\frac{n(\phi_{(\Lambda-p)}) - 1}{A_{(\Lambda-\Lambda_{pC})}\cos\phi_{(\Lambda-p)}}$$

$n(\phi_{(\Lambda-p)}) - 1 \approx \alpha_{\Lambda p} A_{(\Lambda-p)} \cos\phi_{(\Lambda-p)}$

two experimental data

$\Lambda \rightarrow p + \pi^-$



bare asymmetry

simulation

$$\mathscr{C}_{eff}(B, M, q) = \mathscr{A}_{eff}(B, M, q) \times \alpha_{cancel}(B, M, q)$$

correction = effective asymmetry × canceling facor

$$\mathscr{A}_{eff}(B, M, q) = \frac{A_{(\Lambda-\Lambda_{pC})}}{A_{(\Lambda-p)}}$$ — *pC scattering*

experimental data

$n(\phi_{(\Lambda-p)}) - 1$: *bare asymmetry of* $\Lambda - p$

$A_{(\Lambda-\Lambda_{pC})}$: *asymmetry observed in* $\Lambda - \Lambda_{pC}$

$\mathscr{C}_{eff} = 1.017 \quad (J^P = 0^-)$

$\mathscr{C}_{eff} = 1.431 \quad (J^P = 1^-)$

Short summary of $\alpha_{\Lambda p}$ calibration procedure

bare asymmetry

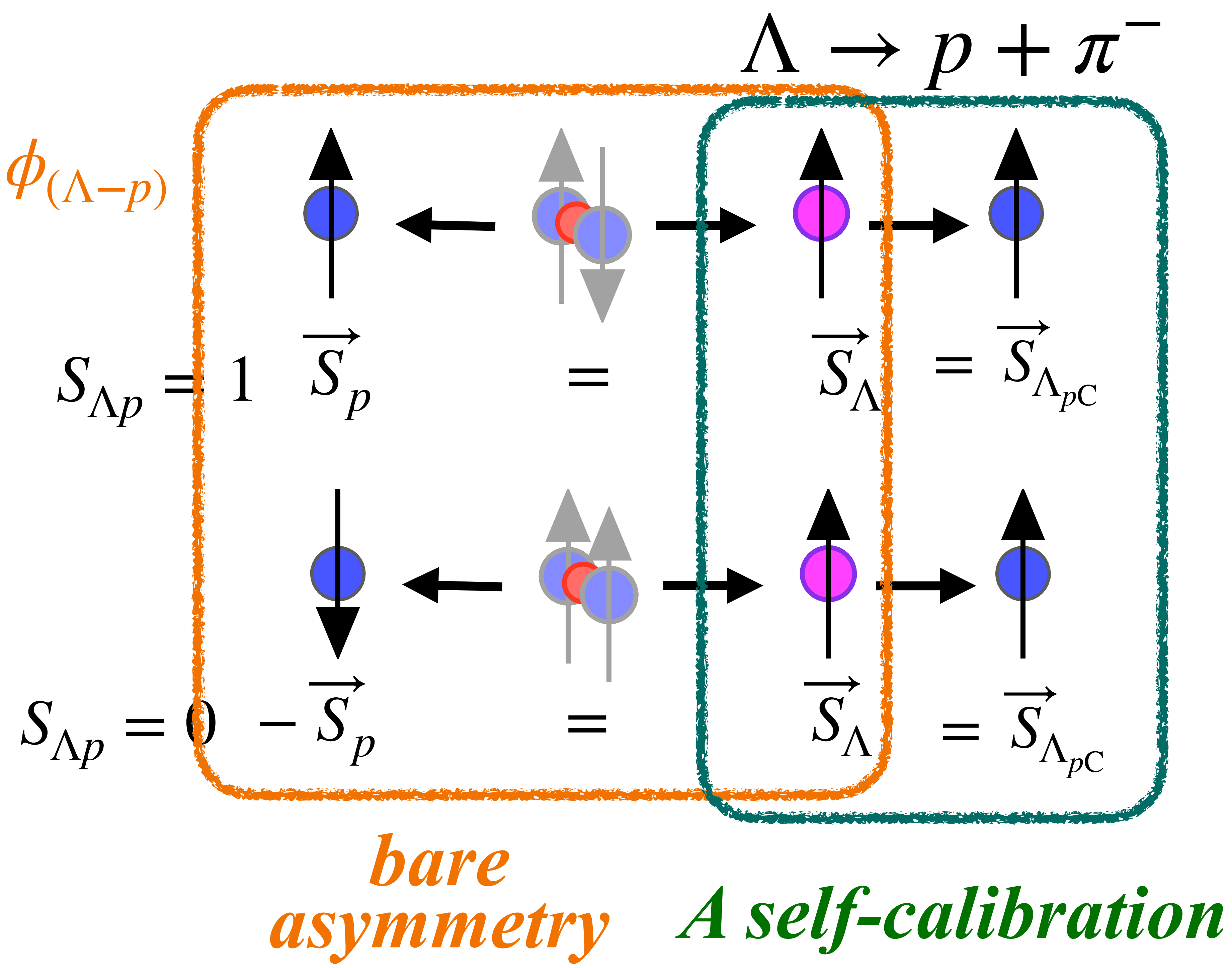
simulation

$$\alpha_{\Lambda p} \approx \mathscr{C}_{eff}(B, M, q) \frac{n(\phi_{(\Lambda-p)}) - 1}{A_{(\Lambda-\Lambda_{pC})} \cos\phi_{(\Lambda-p)}}$$

$n(\phi_{(\Lambda-p)}) - 1 \approx \alpha_{\Lambda p} A_{(\Lambda-p)} \cos\phi_{(\Lambda-p)}$

A self-calibration $\approx A_{(\Lambda-p)}$

two experimental data



simulation

$$\mathscr{C}_{eff}(B, M, q) = \mathscr{A}_{eff}(B, M, q) \times \alpha_{cancel}(B, M, q)$$

correction = effective asymmetry × canceling facor

$$\mathscr{A}_{eff}(B, M, q) = \frac{A_{(\Lambda-\Lambda_{pC})}}{A_{(\Lambda-p)}}$$

— *pC scattering*

— *pC scattering of Λ decay proton*

experimental data

$n(\phi_{(\Lambda-p)}) - 1$: *bare asymmetry of* $\Lambda - p$

$A_{(\Lambda-\Lambda_{pC})}$: *asymmetry observed in* $\Lambda - \Lambda_{pC}$

$$\mathscr{C}_{eff} = 1.017 \quad (J^P = 0^-)$$

$$\mathscr{C}_{eff} = 1.431 \quad (J^P = 1^-)$$

Short summary of $\alpha_{\Lambda p}$ calibration procedure

bare asymmetry

simulation

$$\alpha_{\Lambda p} \approx \mathscr{C}_{eff}(B, M, q)\frac{n(\phi_{(\Lambda-p)}) - 1}{A_{(\Lambda-\Lambda_{pC})}\cos\phi_{(\Lambda-p)}}$$

$\approx \alpha_{\Lambda p} A_{(\Lambda-p)} \cos\phi_{(\Lambda-p)}$

A self-calibration $\approx A_{(\Lambda-p)}$

two experimental data

simulation

$$\mathscr{C}_{eff}(B, M, q) = \mathscr{A}_{eff}(B, M, q) \times \alpha_{cancel}(B, M, q)$$

correction = effective asymmetry × canceling facor

$$\mathscr{A}_{eff}(B, M, q) = \frac{A_{(\Lambda-\Lambda_{pC})}}{A_{(\Lambda-p)}}$$

— *pC scattering*

— *pC scattering of Λ decay proton*

experimental data

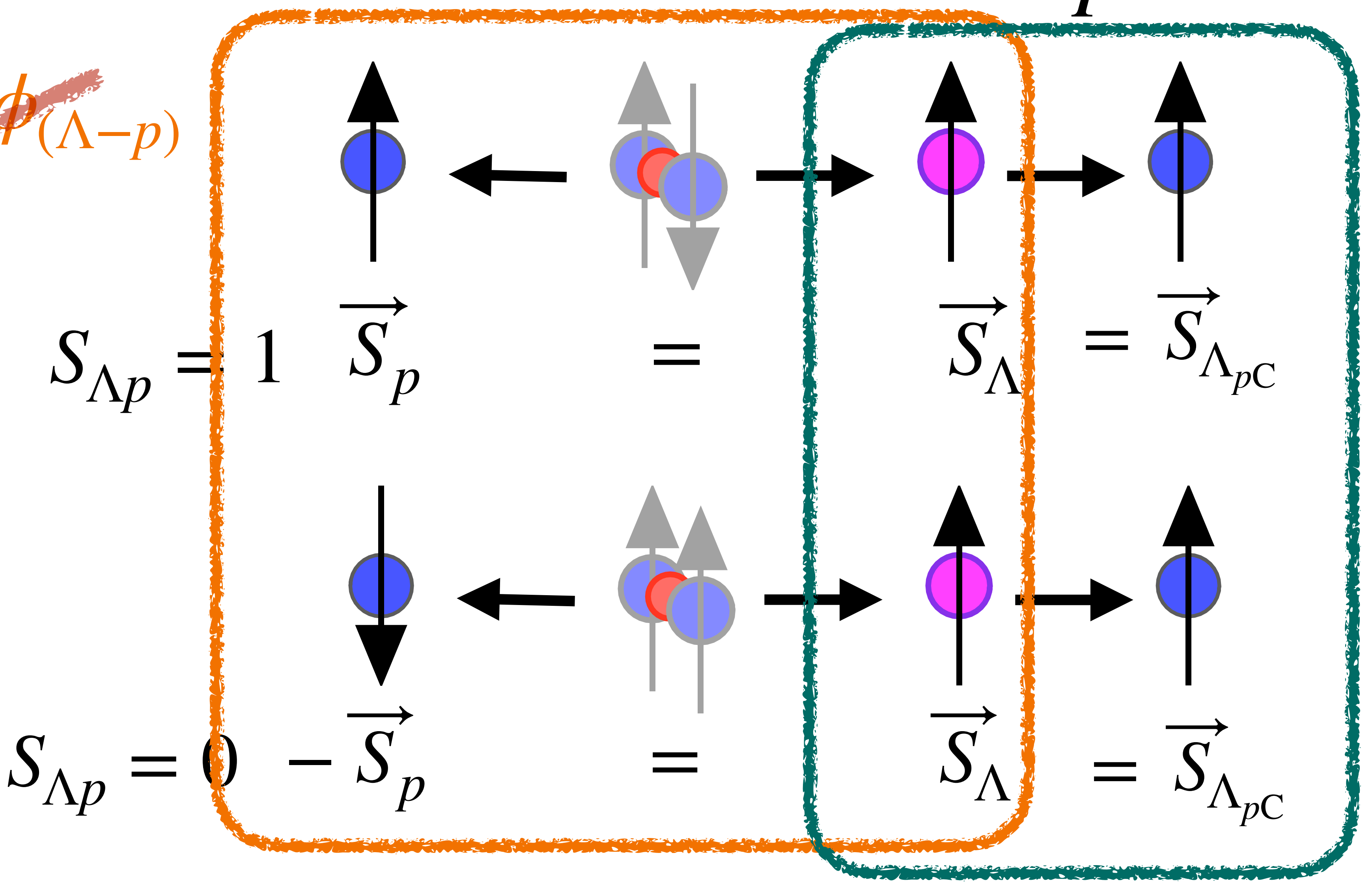
$n(\phi_{(\Lambda-p)}) - 1$: *bare asymmetry of* $\Lambda - p$

$A_{(\Lambda-\Lambda_{pC})}$: *asymmetry observed in* $\Lambda - \Lambda_{pC}$

$\mathscr{C}_{eff} = 1.017 \quad (J^P = 0^-)$

$\mathscr{C}_{eff} = 1.431 \quad (J^P = 1^-)$

$\Lambda \to p + \pi^-$



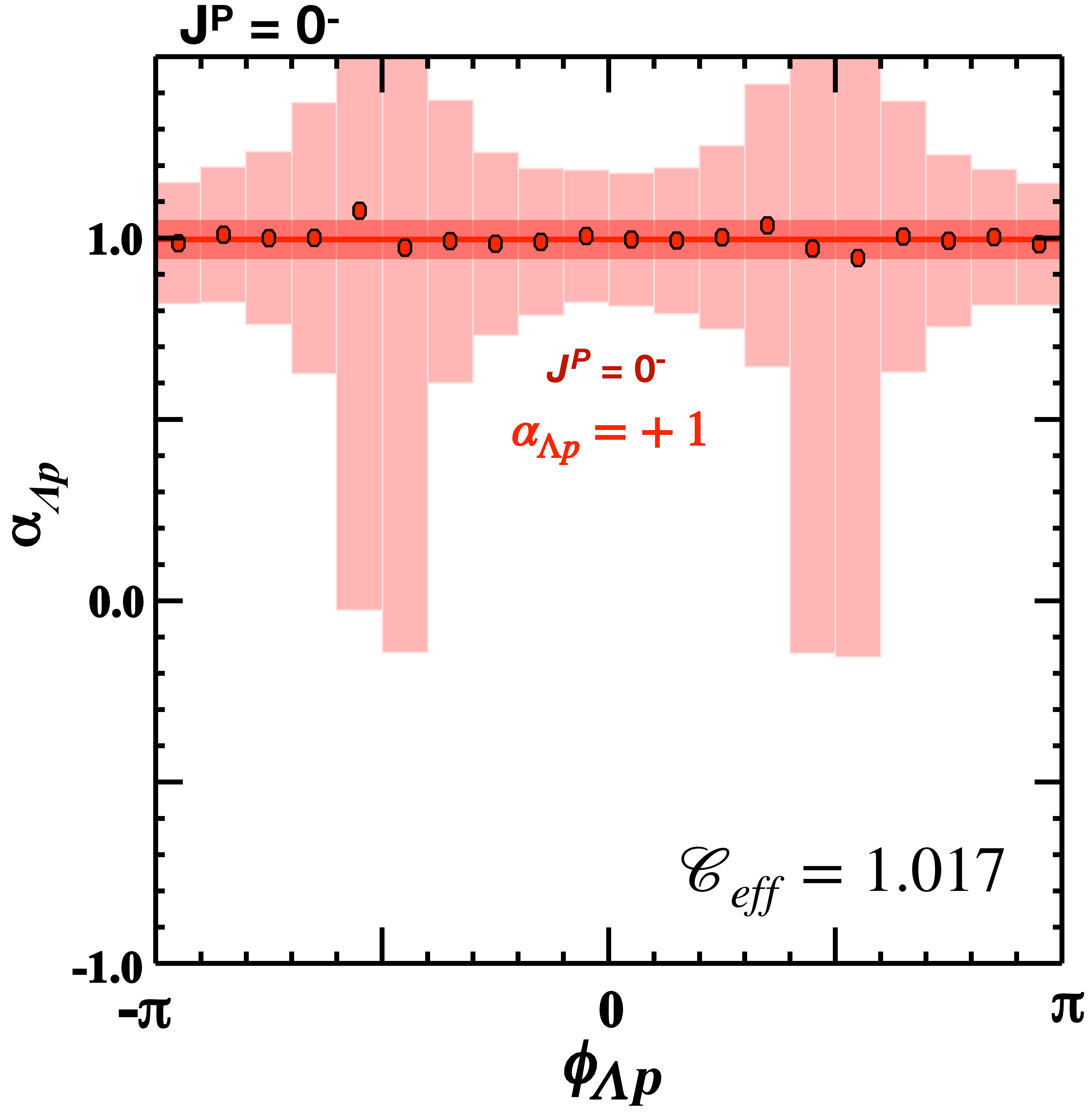
bare asymmetry

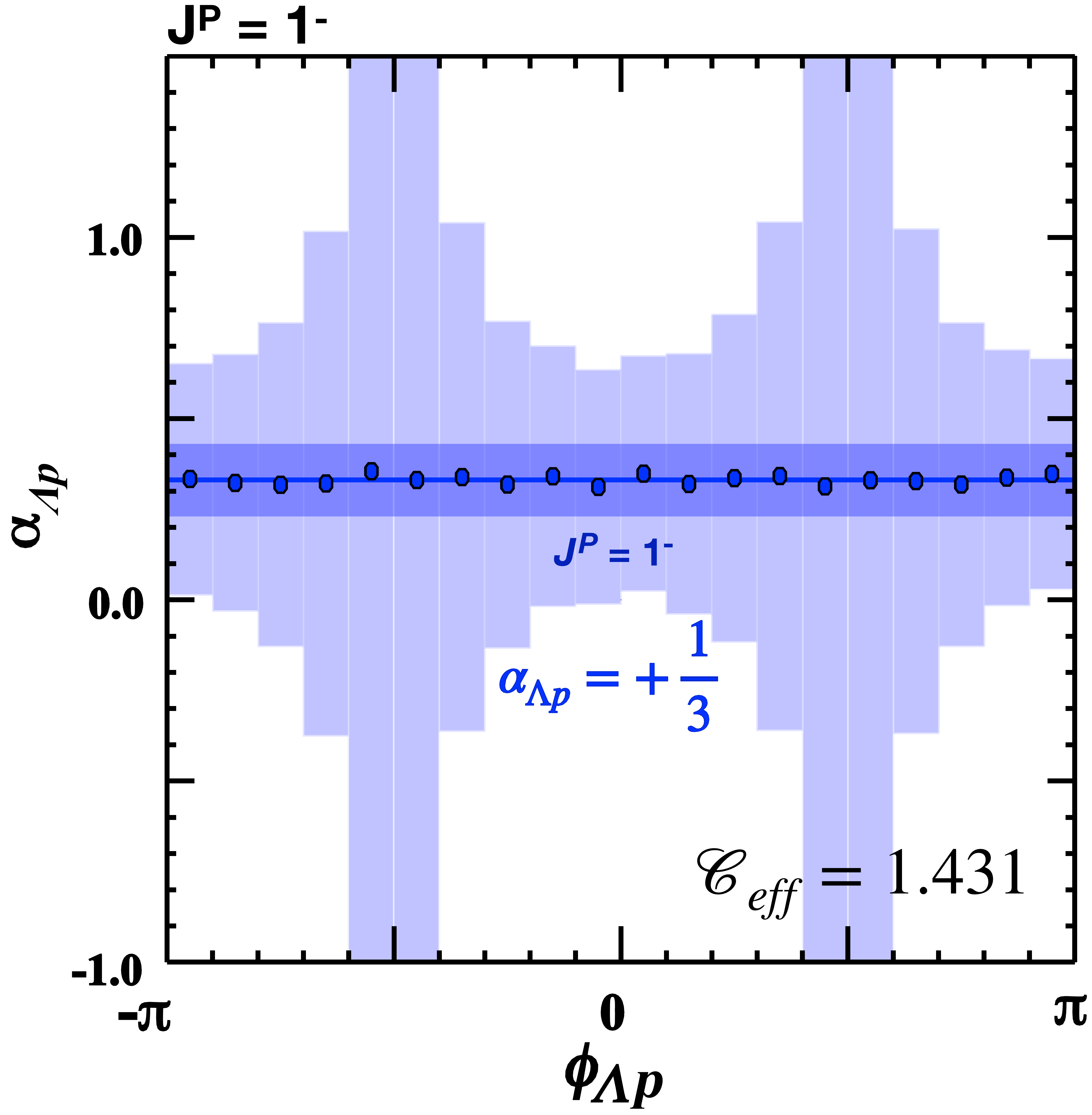
A self-calibration

efficient calibration can be done dominantly by data / data with small collection factor (for $J^P = 0^-$) given by simulation

Λp spin-spin correlation $\alpha_{\Lambda p}$

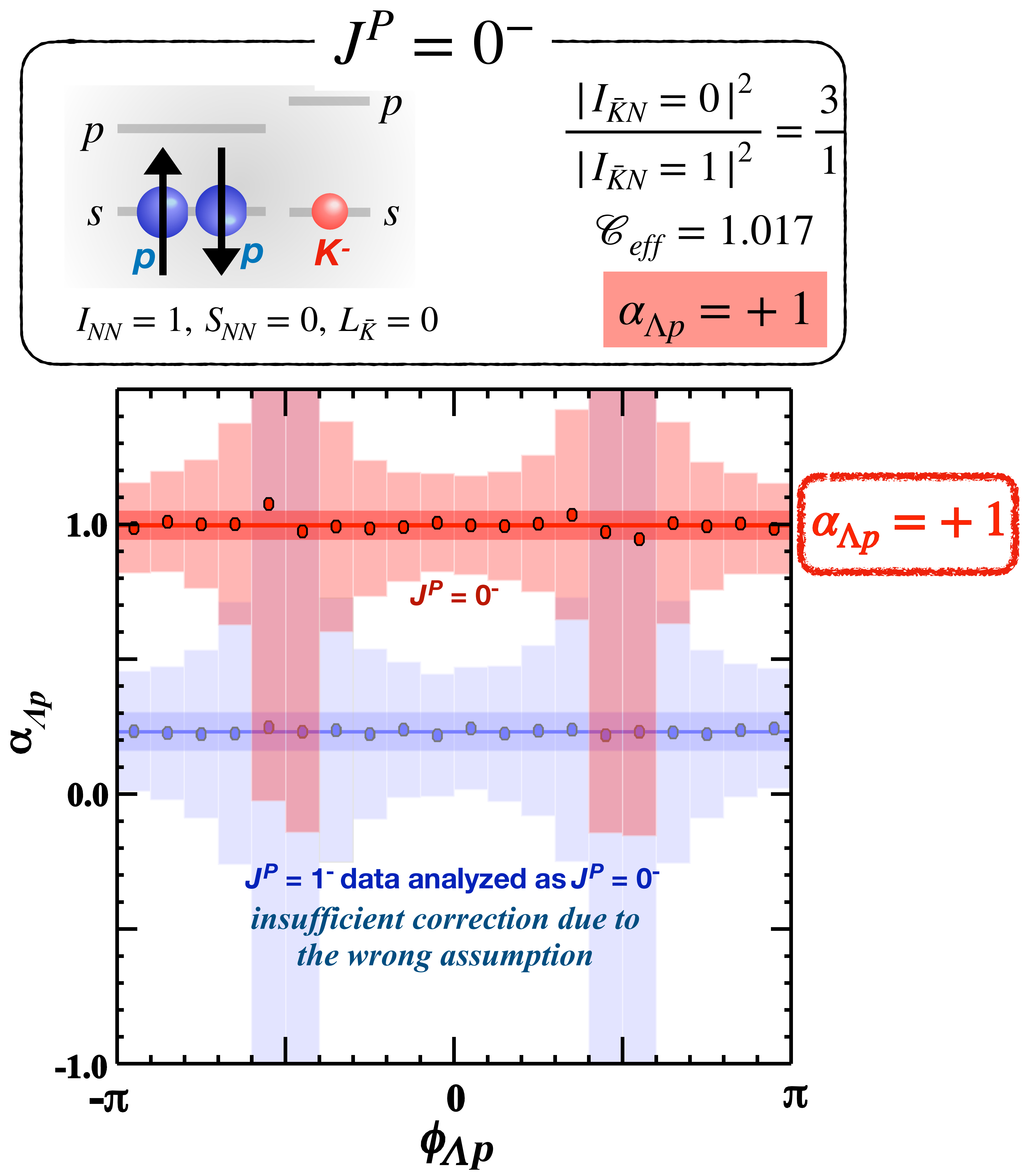
$$\alpha_{\Lambda p} \approx \mathscr{C}_{eff}(B, M, q)\,\frac{n(\phi_{(\Lambda-p)}) - 1}{A_{(\Lambda-\Lambda_{pC})}\cos\phi_{(\Lambda-p)}}$$



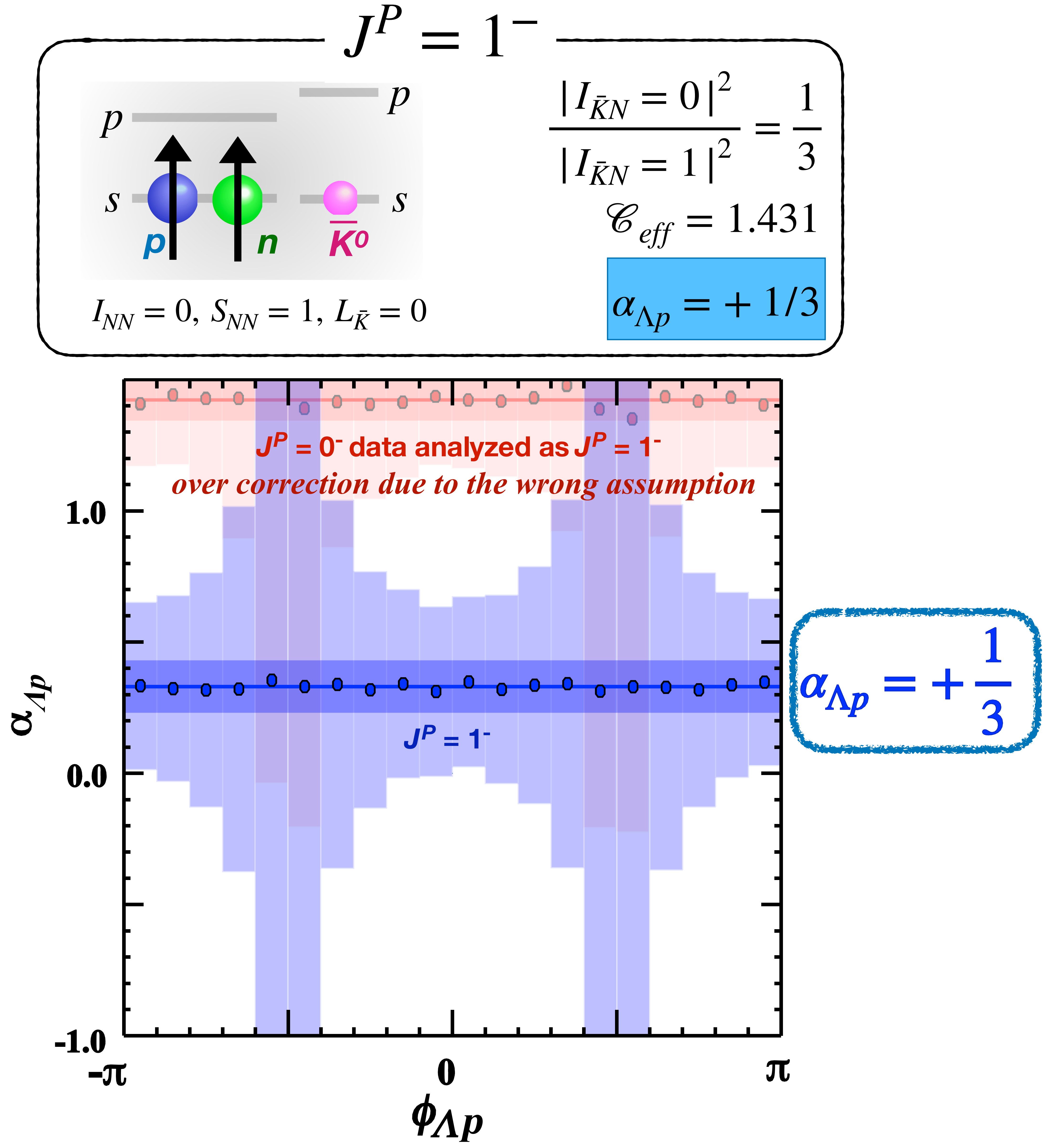


$\alpha_{\Lambda p}$ analysis for $J^P = 0^- / 1^-$

$\bar{K}NN$: $J^P = 0^-$, $I = 1/2$: $I_{NN} = 1$, $S_{NN} = 0$, $L_{\bar{K}} = 0$



$\bar{K}NN$: $J^P = 1^-$, $I = 1/2$: $I_{NN} = 0$, $S_{NN} = 1$, $L_{\bar{K}} = 0$



Summary

- *To establish K^-pp as a well defined quantum state, J^P should be experimentally studied*

- *J^P can be determined by using Λ-p spin-spin asymmetry $\alpha_{\Lambda\text{-}p}$ = +1 (for J^P=0^-) and $\alpha_{\Lambda\text{-}p}$ = +1/3 (for J^P=1^-)*

  - *For J^P=0^-, $\alpha_{\Lambda\text{-}p}$ can be calibrated by data (with small correction factor)*

  - *For J^P=1^-, correction factor for $\alpha_{\Lambda\text{-}p}$ is bit large, but it enables us to discriminate from J^P=0^- more easily*

- *The $\alpha_{\Lambda\text{-}p}$ analysis is insensitive to the spin uncorrelated backgrounds*

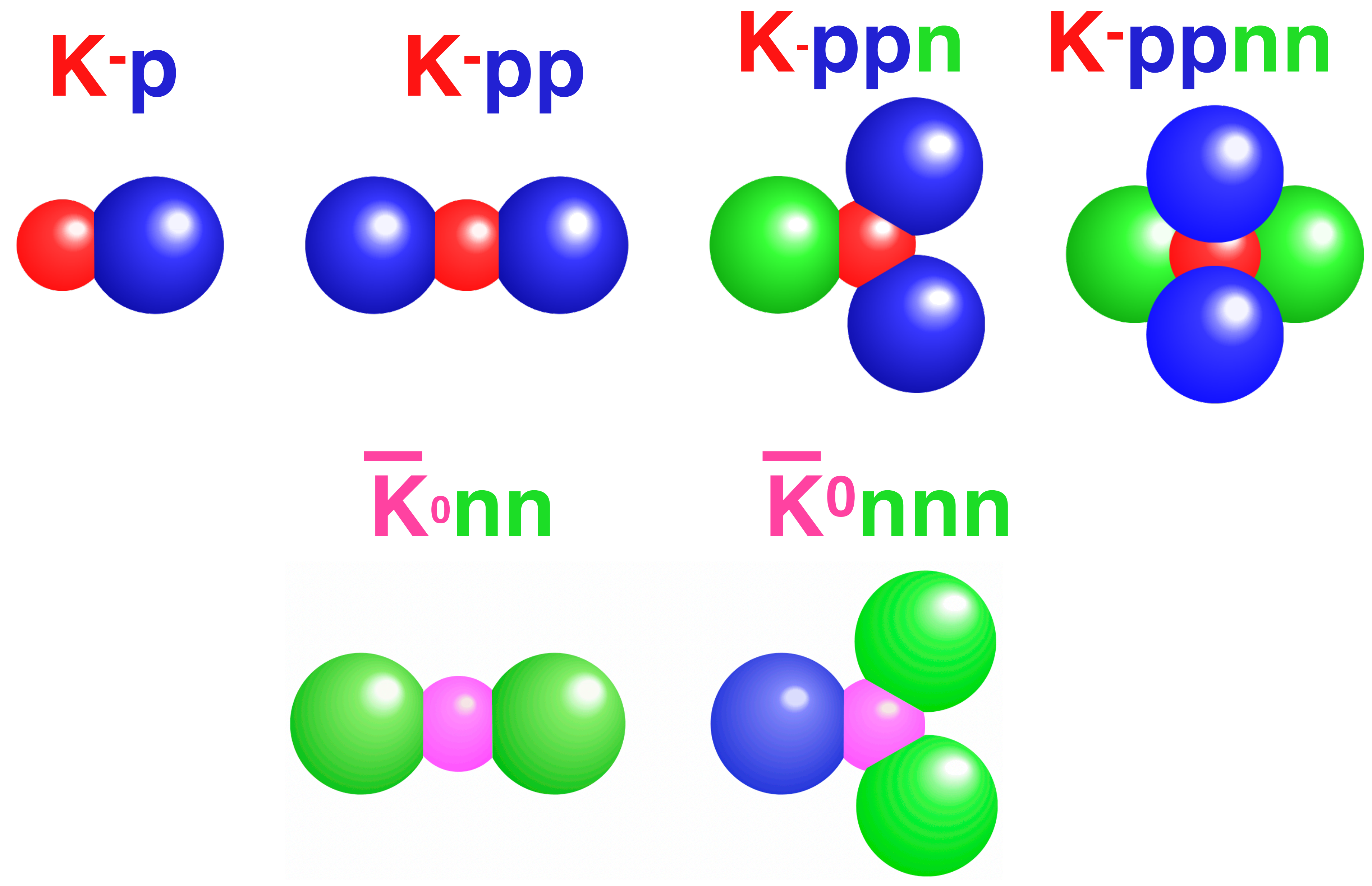
  (background removed automatically by $n(\phi_{(\Lambda-p)}) - 1$ procedure, although more sophisticated correction needed for $\alpha_{\Lambda p}$ calibration)

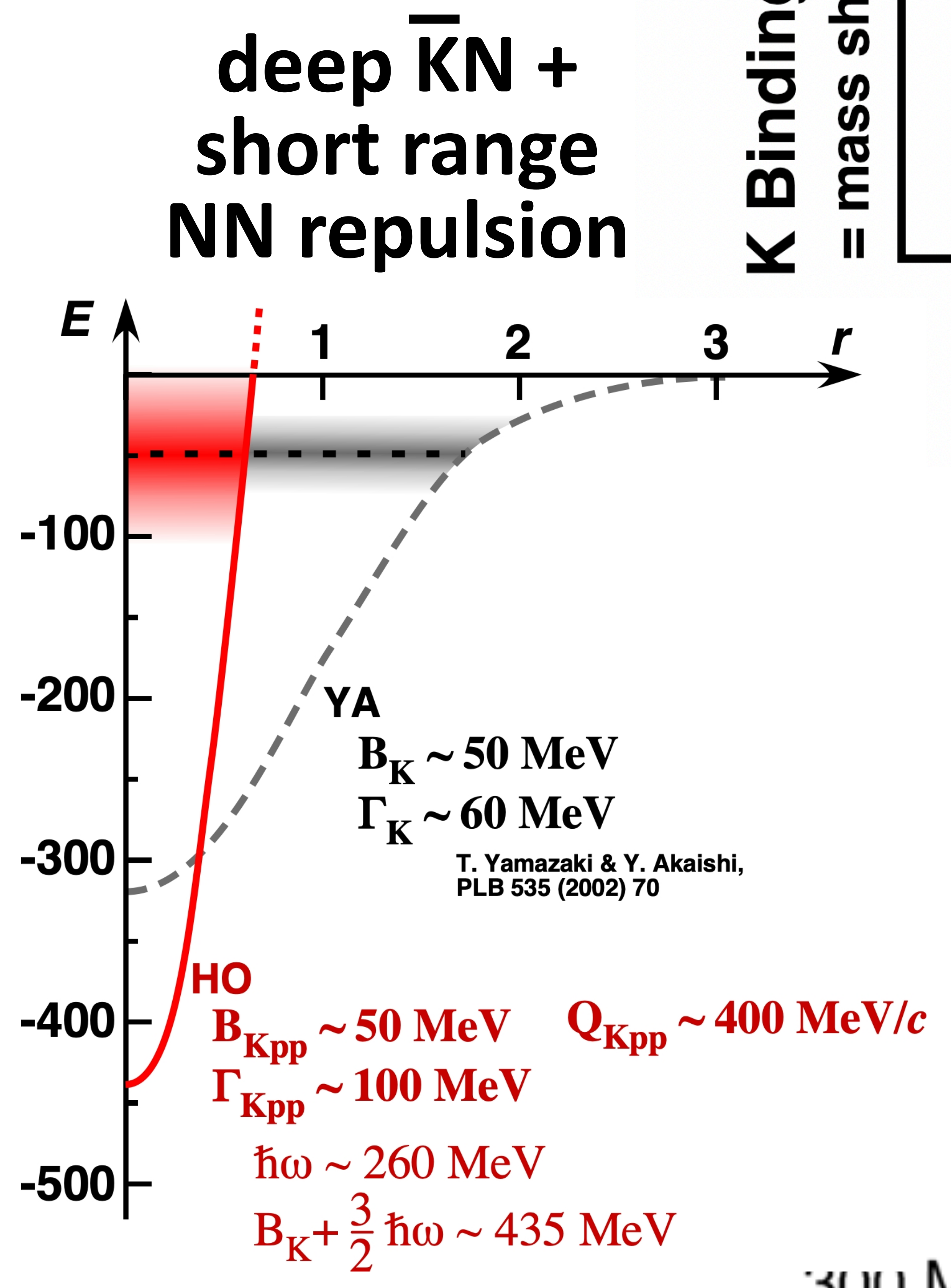
- *We wish to prepare the setup to achieve measurement within ~ two months*

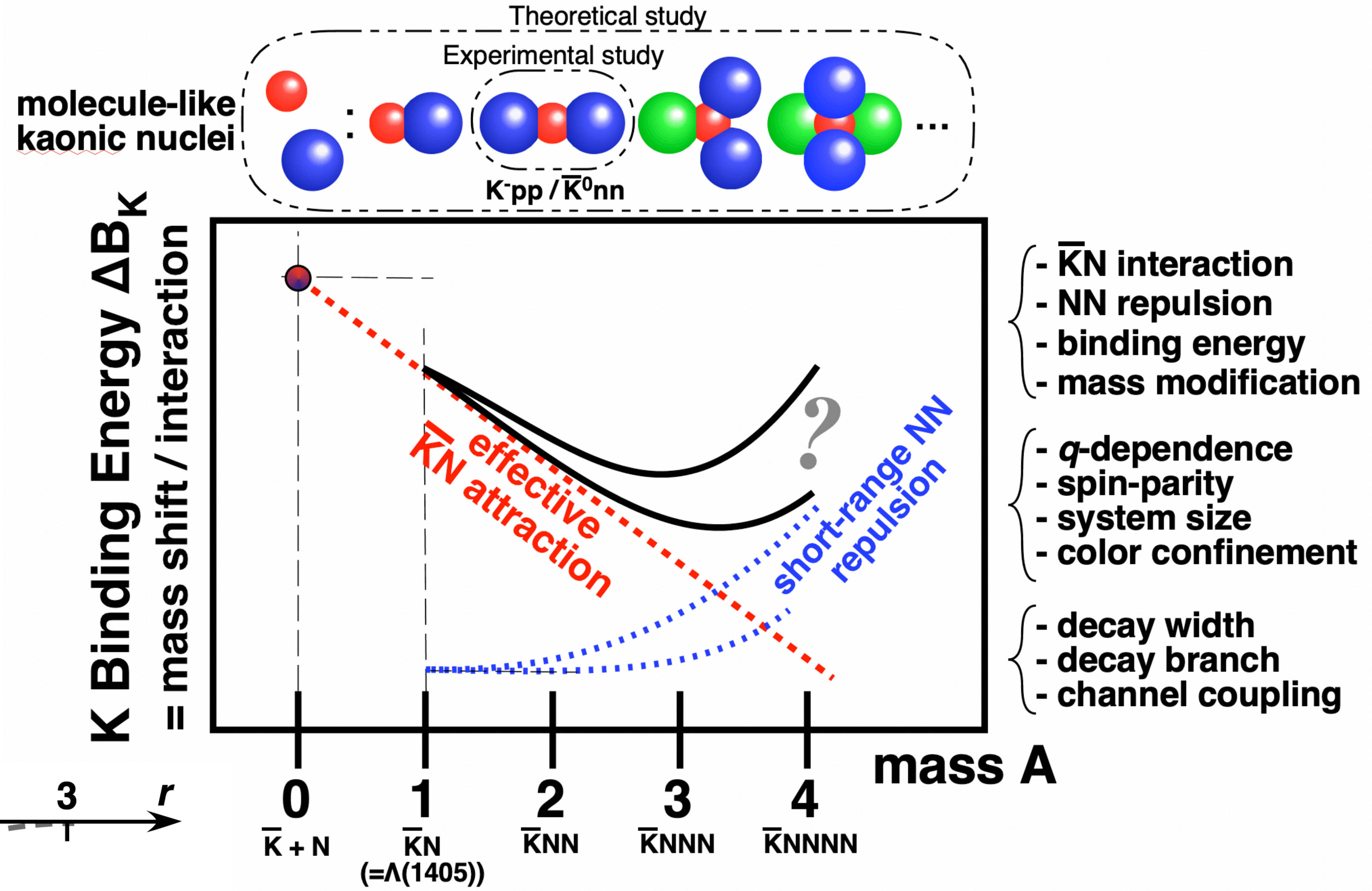
  (need to embed spin into GIANT)

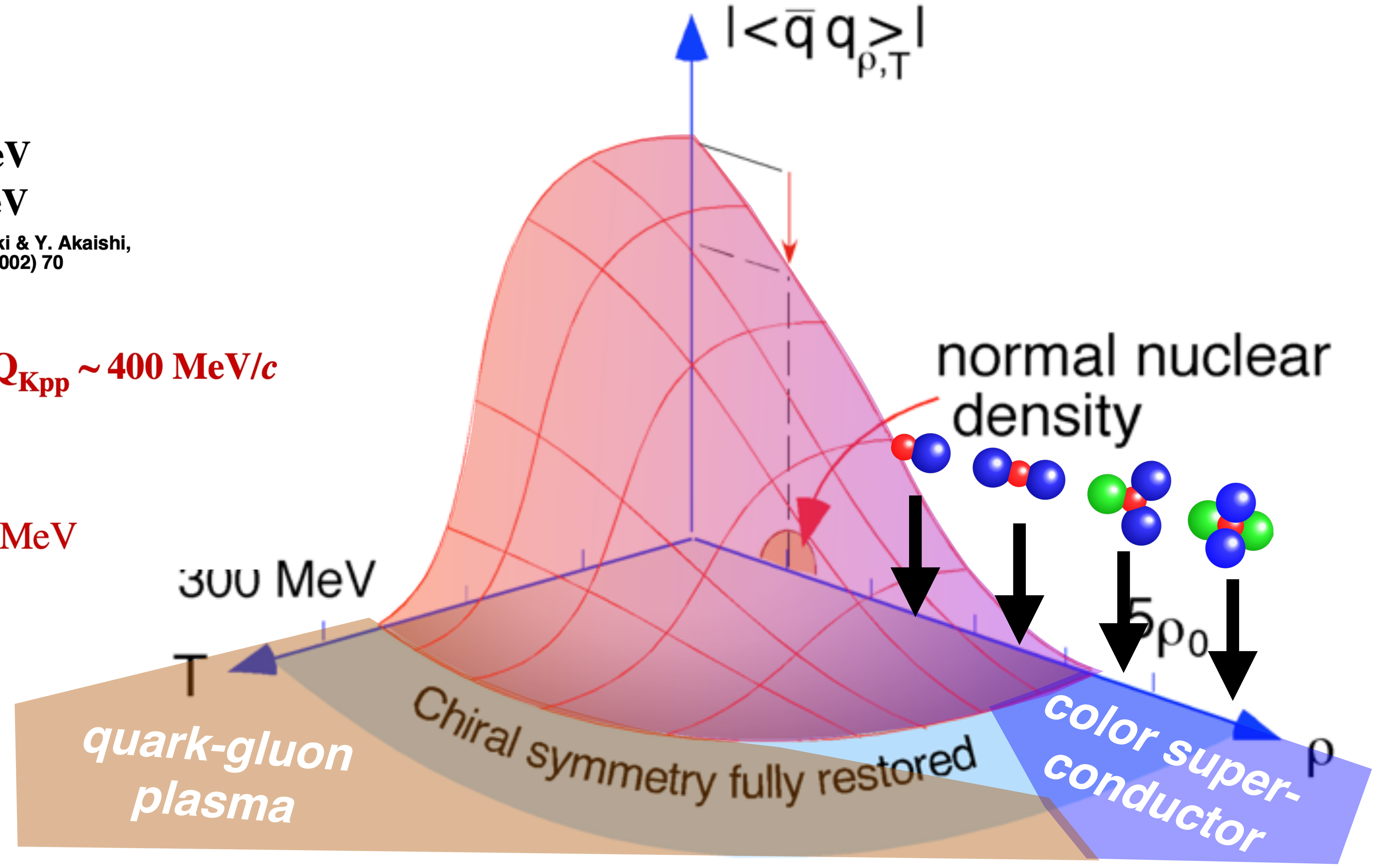
New programs for kaonic nuclei

molecule like structure expected due to NN repulsion









- understand origin of hadron mass
- understand high density baryonic matter (neutron star matter)

Many exotic study can be done at J-PARC,
why don't we do that?

Please join if you can

Thank you for attention

Appendix

Appendix 1:
Internal structure of K^-pp

$$\left(N(N\otimes\bar{K})+(N\otimes\bar{K})N\right)/\sqrt{2}=(NN)_{I.sym}\otimes\bar{K}$$

$\bar{K}NN$: $J^P = 0^-$, $I = +1/2$: $I_{NN} = 1$, $S_{NN} = 0$, $L_K = 0$

isospin singlet
$\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)$
isospin triplet
$p\bar{K}^0$
$\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)$
nK^-

$$I_{\bar{K}N}=0\qquad \left\{N\left\{(N\otimes\bar{K})_{I_{\bar{K}N}=0}\right\}+\left\{(N\otimes\bar{K})_{I_{\bar{K}N}=0}\right\}N\right\}/\sqrt{2}$$

$$=\frac{1}{\sqrt{2}}\left(p\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)+\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)p\right)$$

$I_N=|1/2,+1/2\rangle$ $I_{\bar{K}N}=0$ $I_{\bar{K}N}=0$ $I_N=|1/2,+1/2\rangle$

$$=\sqrt{\frac{1}{2}}\left(\frac{2ppK^- - (pn+np)\bar{K}^0}{\sqrt{2}}\right)_{(I.sym)}\otimes\left(\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}\right)_{(S.asym)}$$

$$I_{\bar{K}N}=1\qquad \left\{N\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}+\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}N\right\}/\sqrt{2}$$

$$=\frac{1}{\sqrt{2}}\left(\sqrt{\frac{2}{3}}\left(n\,(p\bar{K}^0)+(p\bar{K}^0)\,n\right)-\sqrt{\frac{1}{3}}\left(p\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)+\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)p\right)\right)$$

$I_{\bar{K}N}=|1,+1\rangle$ $I_N=|1/2,-1/2\rangle$ $I_{\bar{K}N}=|1,+1\rangle$ $I_N=|1/2,-1/2\rangle$ $I_N=|1/2,+1/2\rangle$ $I_{\bar{K}N}=|1,\pm0\rangle$ $I_{\bar{K}N}=|1,\pm0\rangle$ $I_N=|1/2,+1/2\rangle$

$$=-\sqrt{\frac{1}{6}}\left(\frac{2ppK^- - (pn+np)\bar{K}^0}{\sqrt{2}}\right)_{(I.sym)}\otimes\left(\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}\right)_{(S.asym)}$$

$1\times1/2$

m_1 m_2	3/2, +3/2	3/2, +1/2	1/2, +1/2	3/2, −1/2	1/2, −1/2	3/2, −3/2
+1 +1/2	1					
+1 −1/2		1/3	2/3			
0 +1/2		2/3	−1/3			
0 −1/2				2/3	1/3	
−1 +1/2				1/3	−2/3	
−1 −1/2						1

$$\therefore\ \bar{K}NN(J^P=0^-)\ldots\frac{|I_{\bar{K}N}=0|^2}{|I_{\bar{K}N}=1|^2}=\frac{3}{1}$$

$$\frac{\left|N\left\{(N\otimes\bar{K})_{I_{\bar{K}N}=0}\right\}+\left\{(N\otimes\bar{K})_{I_{\bar{K}N}=0}\right\}N\right|^2}{\left|N\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}+\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}N\right|^2}=\frac{3}{1}$$

expected to be deeper bound

strongly attractive in $I_{\bar{K}N}=0$

$$\left(N(N\otimes\bar{K})+(N\otimes\bar{K})N\right)/\sqrt{2} = (NN)_{I.sym}\otimes\bar{K}$$

$\bar{K}NN$: $J^P = 0^-$, $I = -1/2$: $I_{NN} = 1$, $S_{NN} = 0$, $L_K = 0$

isospin singlet
$\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)$
isospin triplet
$p\bar{K}^0$
$\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)$
nK^-

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

$$\left\{N\left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\} + \left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\}N\right\}/\sqrt{2}$$

$$= \frac{1}{\sqrt{2}}\left(n\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0) + \frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)n\right)$$

$I_N = |1/2, -1/2>$ $I_{\bar{K}N} = 0$ $I_{\bar{K}N} = 0$ $I_N = |1/2, -1/2>$

$$= -\sqrt{\frac{1}{2}}\left(\frac{2nn\bar{K}^0 - (pn+np)K^-}{\sqrt{2}}\right)_{(I.sym)} \otimes \left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)_{(S.asym)}$$

$I_{\bar{K}N} = 1$

$$\left\{N\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1} + \left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}N\right\}/\sqrt{2}$$

$$= \frac{1}{\sqrt{2}}\left(\left[-\sqrt{\frac{2}{3}}\right](p\,(nK^-) + (nK^-)\,p)\left[+\sqrt{\frac{1}{3}}\right]\left(n\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0) + \frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)n\right)\right)$$

$I_{\bar{K}N} = |1,-1>$ $I_{\bar{K}N} = |1,-1>$

$I_N = |1/2, +1/2>$ $I_N = |1/2, +1/2>$ $I_N = |1/2, -1/2>$ $I_{\bar{K}N} = |1, \pm 0>$ $I_{\bar{K}N} = |1, \pm 0>$ $I_N = |1/2, -1/2>$

$$= \sqrt{\frac{1}{6}}\left(\frac{2nn\bar{K}^0 - (pn+np)K^-}{\sqrt{2}}\right)_{(I.sym)} \otimes \left(\frac{\uparrow\downarrow - \downarrow\uparrow}{\sqrt{2}}\right)_{(S.asym)}$$

$1\times 1/2$

m_1 m_2	J M		
	3/2 +3/2		
+1 +1/2	1		
	3/2 +1/2	1/2 +1/2	
+1 −1/2	1/3	2/3	
0 +1/2	2/3	−1/3	
	3/2 −1/2	1/2 −1/2	
0 −1/2	2/3	1/3	
−1 +1/2	1/3	−2/3	
	3/2 −3/2		
−1 −1/2	1		

$$\therefore\ \bar{K}NN(J^P = 0^-)\ldots \frac{|I_{\bar{K}N} = 0|^2}{|I_{\bar{K}N} = 1|^2} = \frac{3}{1}$$

$$\frac{\left|N\left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\} + \left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\}N\right|^2}{\left|N\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1} + \left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}N\right|^2} = \frac{3}{1}$$

expected to be deeper bound

strongly attractive in $I_{\bar{K}N} = 0$

$$\left(N(N\otimes\bar{K})-(N\otimes\bar{K})N\right)/\sqrt{2}=(NN)_{I.asym}\otimes\bar{K}$$

$\bar{K}NN$: $J^P = 1^-$, $I = 1/2$: $I_{NN} = 0$, $S_{NN} = 1$, $L_K = 0$

isospin singlet
$\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)$
isospin triplet
$p\bar{K}^0$
$\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)$
nK^-

$$I_{\bar{K}N}=0 \quad \left\{N\left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\}-\left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\}N\right\}/\sqrt{2}$$

$$=\frac{1}{\sqrt{2}}\left(\underbrace{p\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)}_{I_N=|1/2,+1/2>\quad I_{\bar{K}N}=0}-\underbrace{\frac{1}{\sqrt{2}}(pK^- - n\bar{K}^0)p}_{I_{\bar{K}N}=0\quad I_N=|1/2,+1/2>}\right)$$

$$=\sqrt{\frac{1}{2}}\left(\frac{(np-pn)\bar{K}^0}{\sqrt{2}}\right)_{(I.asym)}\otimes\left(\uparrow\uparrow,\ \frac{\uparrow\downarrow+\downarrow\uparrow}{\sqrt{2}},\ \downarrow\downarrow\right)_{(S.sym)}$$

$$I_{\bar{K}N}=1 \quad \left\{N\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}-\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}N\right\}/\sqrt{2}$$

$$=\frac{1}{\sqrt{2}}\left(\sqrt{\frac{2}{3}}\left(\underbrace{n\left(p\bar{K}^0\right)}_{I_{\bar{K}N}=|1,+1>\ I_N=|1/2,-1/2>}-\underbrace{\left(p\bar{K}^0\right)n}_{I_{\bar{K}N}=|1,+1>\ I_N=|1/2,-1/2>}\right)-\sqrt{\frac{1}{3}}\left(\underbrace{p\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)}_{I_N=|1/2,+1/2>\quad I_{\bar{K}N}=|1,\pm0>}-\underbrace{\frac{1}{\sqrt{2}}(pK^- + n\bar{K}^0)p}_{I_{\bar{K}N}=|1,\pm0>\quad I_N=|1/2,+1/2>}\right)\right)$$

$$=\sqrt{\frac{3}{2}}\left(\frac{(np-pn)\bar{K}^0}{\sqrt{2}}\right)_{(I.asym)}\otimes\left(\uparrow\uparrow,\ \frac{\uparrow\downarrow+\downarrow\uparrow}{\sqrt{2}},\ \downarrow\downarrow\right)_{(S.sym)}$$

$1\times1/2$

m_1	m_2	$J=3/2$, $M=+3/2$	$J=3/2$, $M=+1/2$	$J=1/2$, $M=+1/2$	$J=3/2$, $M=-1/2$	$J=1/2$, $M=-1/2$	$J=3/2$, $M=-3/2$
+1	+1/2	1					
+1	−1/2		1/3	2/3			
0	+1/2		2/3	−1/3			
0	−1/2				2/3	1/3	
−1	+1/2				1/3	−2/3	
−1	−1/2						1

$$\therefore\ \bar{K}NN(J^P=1^-)\ldots\frac{|I_{\bar{K}N}=0|}{|I_{\bar{K}N}=1|}=\frac{1}{3}\qquad\frac{\left|N\left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\}+\left\{(N\otimes\bar{K})_{\ I_{\bar{K}N}=0}\right\}N\right|^2}{\left|N\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}+\left\{N\otimes\bar{K}\right\}_{I_{\bar{K}N}=1}N\right|^2}$$

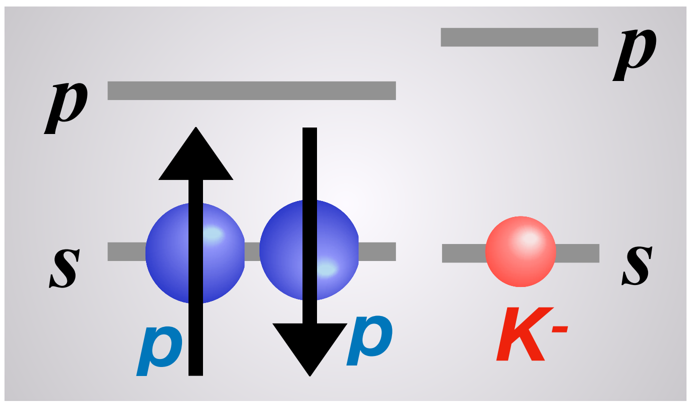
expected to be weaker bound

strongly attractive only in $I_{\bar{K}N}=0$

Appendix 2:
Decay axis & spin alignment

Λp decay of $\bar{K}NN$ $J^P = 0^-$

decay axis and spin direction

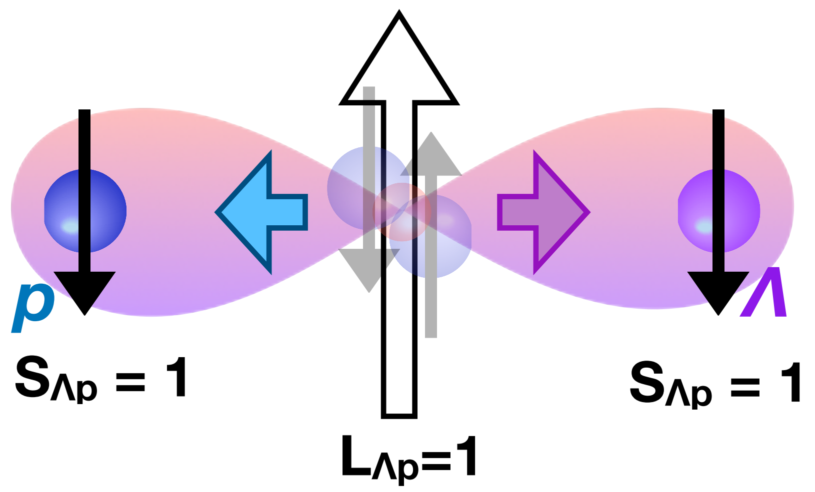


$I_{NN} = 1,\ S_{NN} = 0,\ L_{\bar{K}} = 0$

$J^P_{\bar{K}NN} = |0,\ 0>^-$

$L_{\Lambda p} = |1, +1> = Y_1^{+1}(\theta,\phi)$

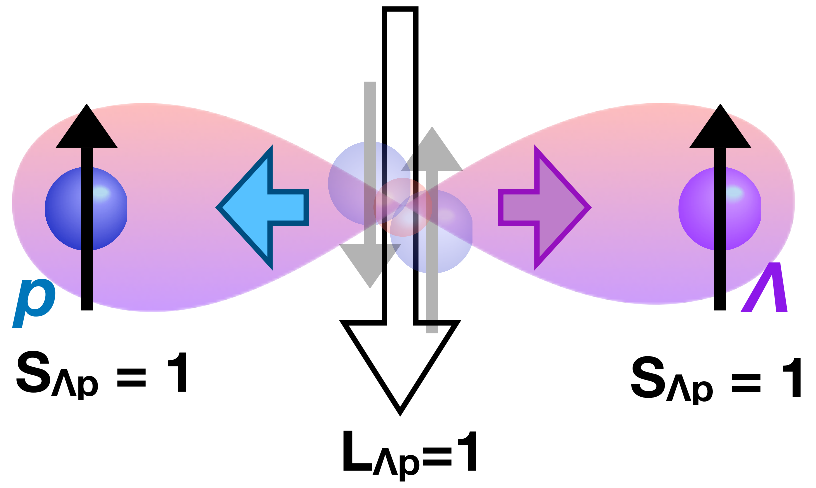
$S_{\Lambda p} = |1, -1>$



$Y_1^{+1}(\theta,\phi) = \sqrt{\frac{3}{4\pi}}\frac{\sin\theta}{\sqrt{2}}e^{+i\phi}$

$L_{\Lambda p} = |1, -1> = Y_1^{-1}(\theta,\phi)$

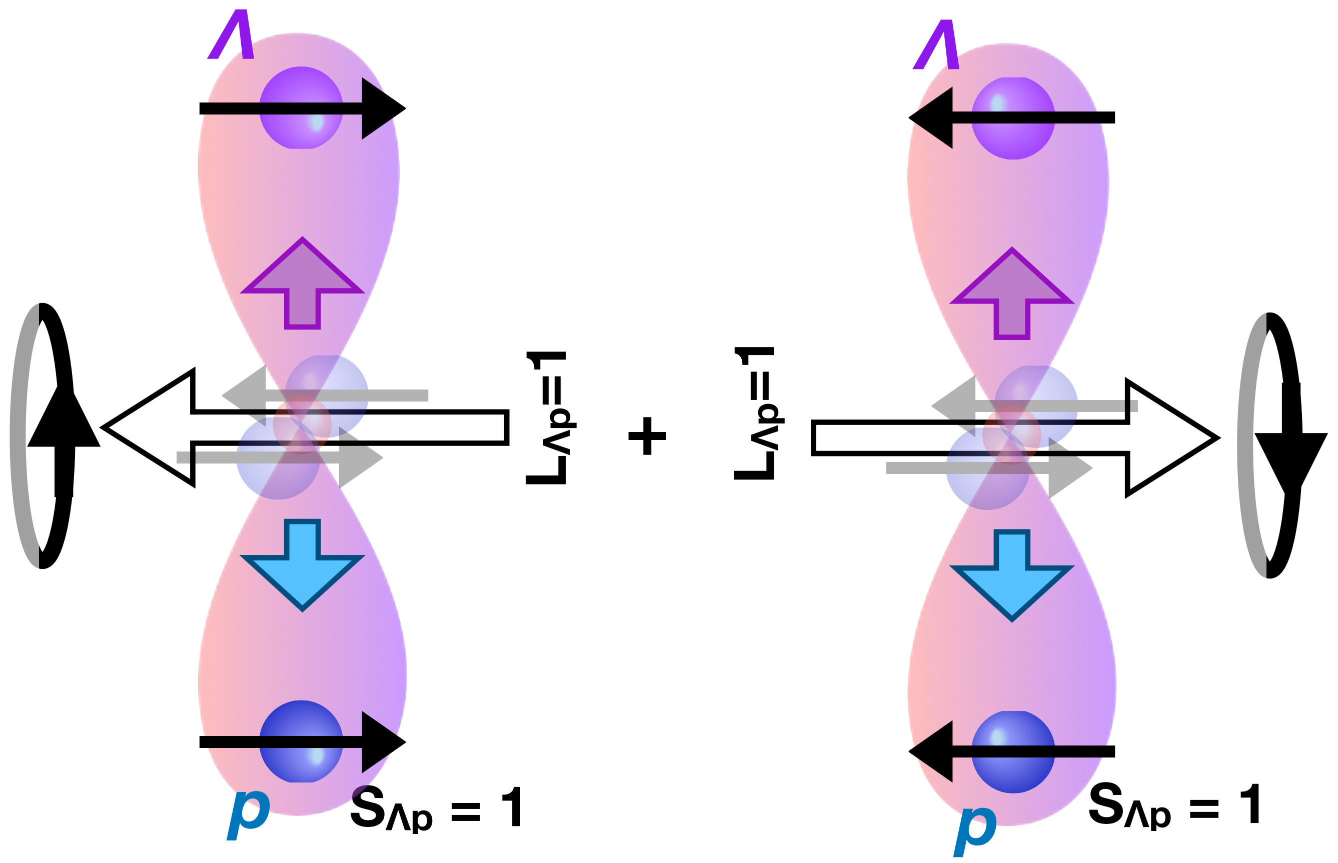
$S_{\Lambda p} = |1, +1>$



$Y_1^{-1}(\theta,\phi) = \sqrt{\frac{3}{4\pi}}\frac{\sin\theta}{\sqrt{2}}e^{-i\phi}$

$L_{\Lambda p} = |1,\ 0> = Y_1^0(\theta,\phi) = \sqrt{\frac{3}{4\pi}}\cos\theta$

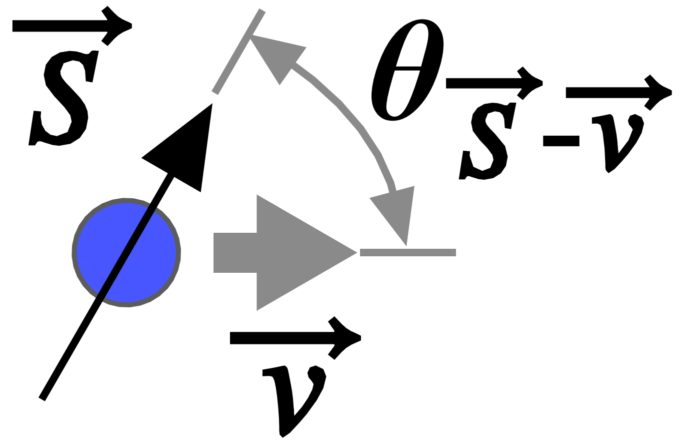
$S_{\Lambda p} = |1,\ 0>$



$= \sqrt{\frac{3}{4\pi}}\frac{1}{2}\left(|\substack{\rightarrow\\\rightarrow}> e^{+i\theta} + |\substack{\leftarrow\\\leftarrow}> e^{-i\theta}\right)$

$N(\vec{v}_\Lambda \cdot \vec{S}_\Lambda) \propto \sin^2\theta_{\vec{S}-\vec{v}}$, where $\theta_{\vec{S}-\vec{v}}$ is the angle between ($\vec{v}_p$ and $\vec{S}_p$)

$$\frac{N(\vec{v}_p \cdot \vec{S}_p)}{\sum N} = \frac{N(-\vec{v}_\Lambda \cdot \vec{S}_\Lambda)}{\sum N} = \frac{3}{4}\left(1 - (\vec{v} \cdot \vec{S})^2\right) = \frac{3}{4}\sin^2\theta_{\vec{S}-\vec{v}}$$



$J^P = 0^-$: decay-axis in P-wave & spin aligned to cancel L_z
i.e., spin ~ orthogonal to the decay axis

Λp decay of $\bar{K}NN$ $J^P = 1^-$

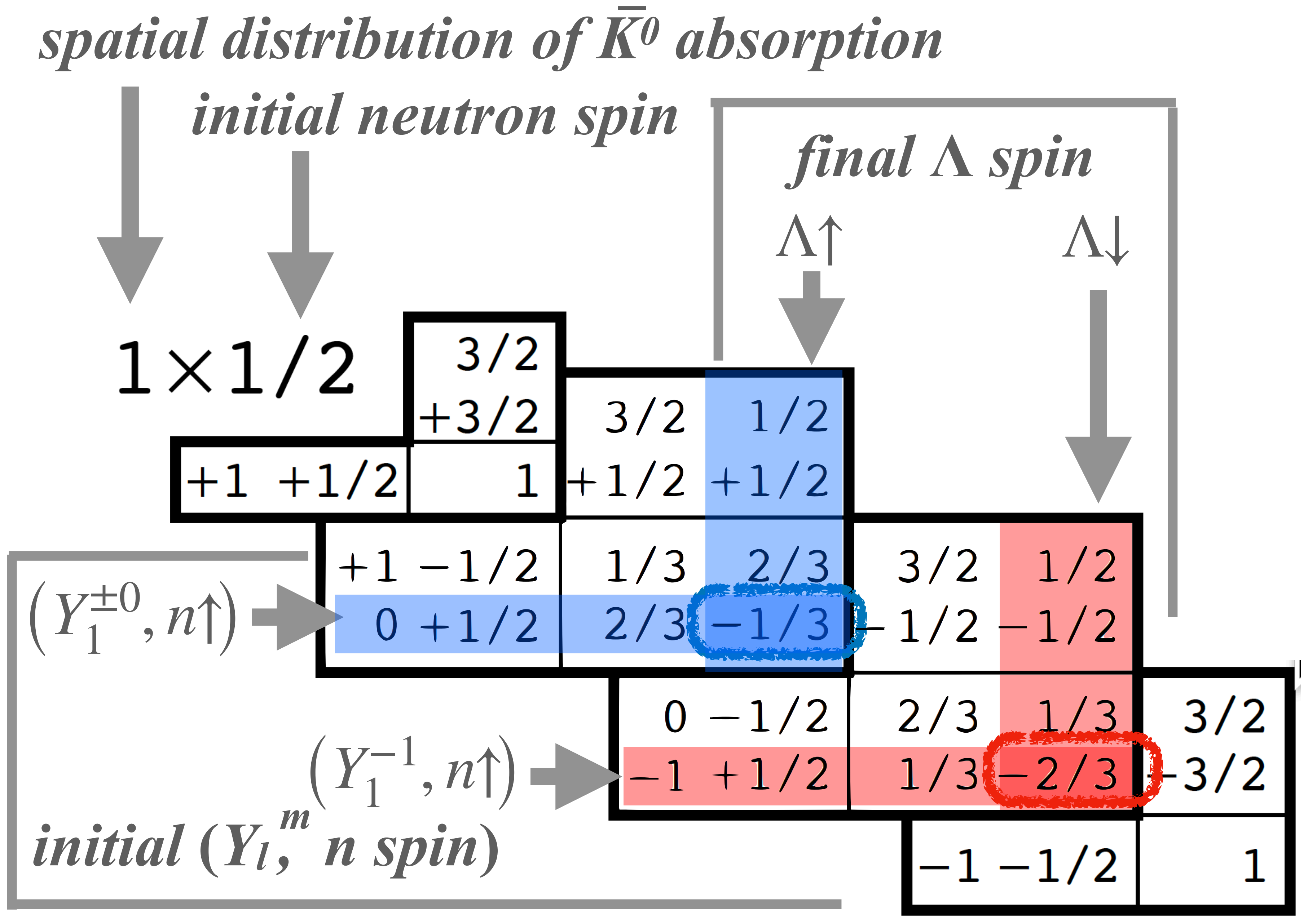
$$(J^P = 1^-) = (S_{\Lambda p} = 0 \; or \; 1) \otimes (L_{Kabs} = 1)$$

$$(S_{pn} = |1, +1\rangle)\bar{K}^0 = \frac{(p\!\uparrow\! n\!\uparrow - n\!\uparrow\! p\!\uparrow)}{\sqrt{2}}\bar{K}^0$$

quantum-axis = spin direction

$$\bar{K}^0 n \rightarrow \Lambda$$

P-wave absorption



$$-\sqrt{\frac{2}{3}}\sqrt{\frac{3}{4\pi}}\frac{\sin\theta}{\sqrt{2}}e^{-i\phi}\frac{(p\!\uparrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\uparrow)}{\sqrt{2}} - \sqrt{\frac{1}{3}}\sqrt{\frac{3}{4\pi}}\cos\theta\frac{(p\!\uparrow \Lambda\!\uparrow - \Lambda\!\uparrow p\!\uparrow)}{\sqrt{2}}$$

Clebsh-Gordan Y_1^{-1} $S_{p\Lambda}$ *Clebsh-Gordan* $Y_1^{\pm 0}$ $S_{p\Lambda}$

classification by symmetry

first term

$$S_{p\Lambda} = \frac{1}{\sqrt{2}}\left(\frac{(p\!\uparrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\uparrow) - (p\!\downarrow \Lambda\!\uparrow - \Lambda\!\uparrow p\!\downarrow)}{2} + \frac{(p\!\uparrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\uparrow) + (p\!\downarrow \Lambda\!\uparrow - \Lambda\!\uparrow p\!\downarrow)}{2}\right)$$

second term

$$S_{p\Lambda} = \frac{(p\!\uparrow \Lambda\!\uparrow - \Lambda\!\uparrow p\!\uparrow)}{\sqrt{2}}$$

this term should be $|1, +1\rangle$

examine first term by rotation $U(\theta', \phi')$

$$\uparrow \xrightarrow[U(\theta',\phi')]{} \cos(\theta'/2)\uparrow + e^{+i\phi'}\sin(\theta'/2)\downarrow$$

$$\downarrow \xrightarrow[U(\theta',\phi')]{} \cos(\theta'/2)\downarrow - e^{-i\phi'}\sin(\theta'/2)\uparrow$$

---

rotation of former component

$$\left(\frac{(p\!\uparrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\uparrow) - (\Lambda\!\uparrow p\!\downarrow - p\!\downarrow \Lambda\!\uparrow)}{2}\right) \xrightarrow[U(\theta',\phi')]{} \left(\cos^2\frac{\theta'}{2} + \sin^2\frac{\theta'}{2}\right)\left(\frac{(p\!\uparrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\uparrow) - (\Lambda\!\uparrow p\!\downarrow - p\!\downarrow \Lambda\!\uparrow)}{2}\right)$$

structure unchanged, so former component should be $|0, 0\rangle$

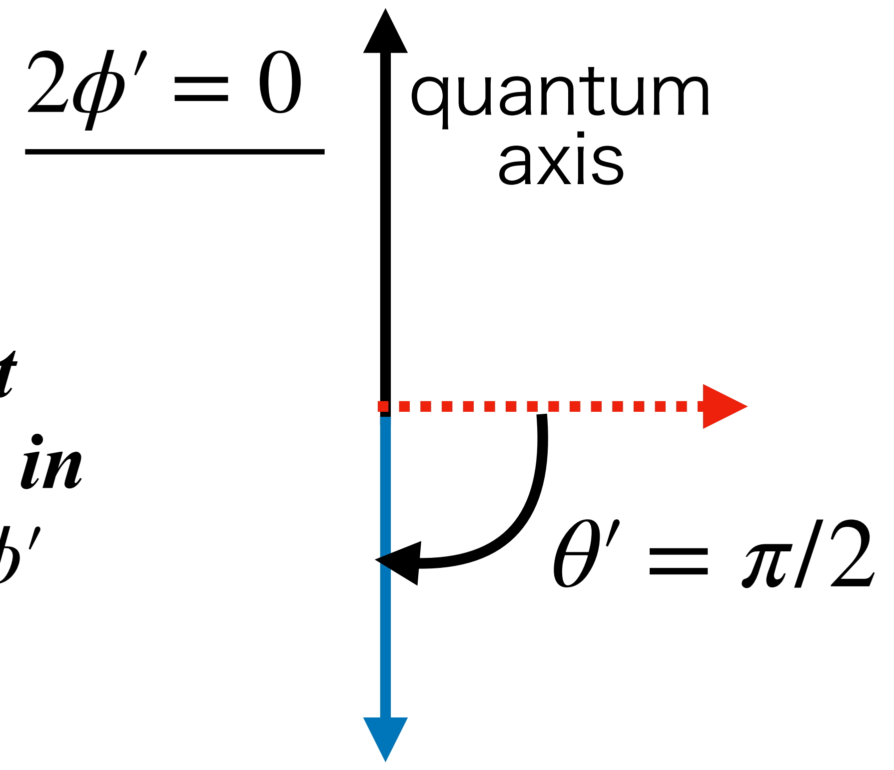
Let's examine $\theta = \pi/2$ *rotation to the latter component*

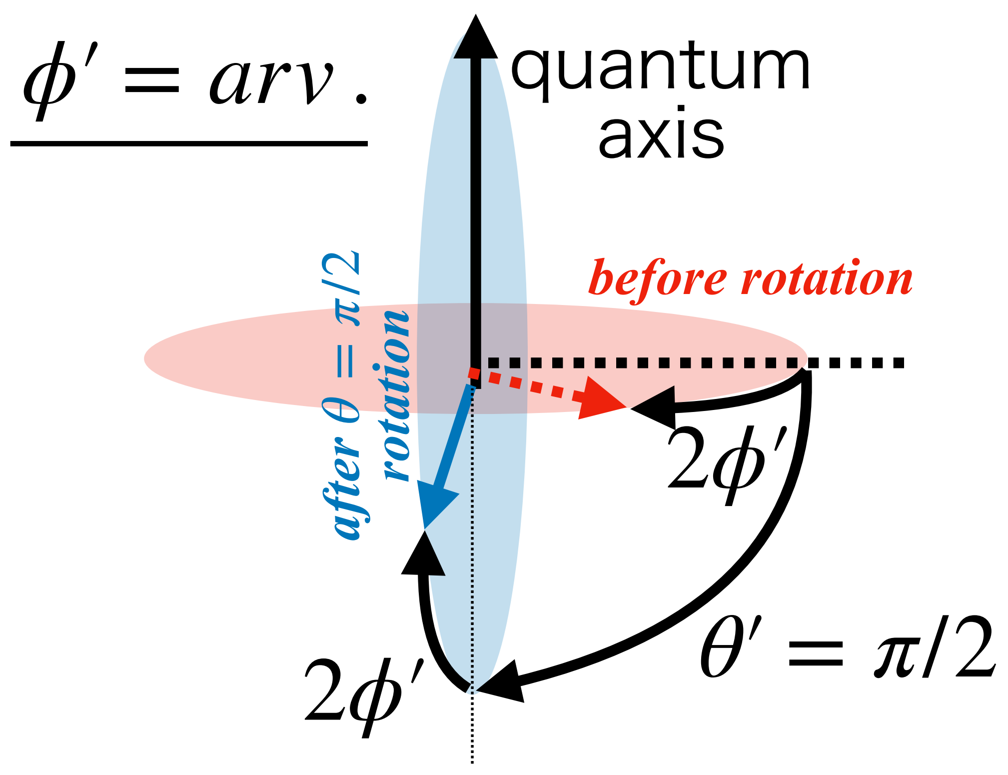
after $\theta = \pi/2$ *rotation*

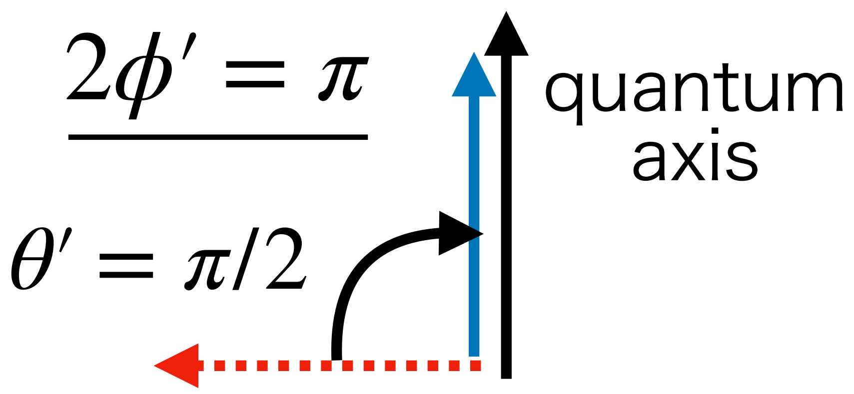
$$\left(\frac{(p\!\uparrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\uparrow) + (\Lambda\!\uparrow p\!\downarrow - p\!\downarrow \Lambda\!\uparrow)}{2}\right) \xrightarrow[U(\pi/2,\phi')]{} \frac{\cos\phi'(p\!\downarrow \Lambda\!\downarrow - \Lambda\!\downarrow p\!\downarrow) + i\sin\phi'(\Lambda\!\uparrow p\!\uparrow - p\!\uparrow \Lambda\!\uparrow)}{2}$$

before rotation

after $\theta = \pi/2$ *rotation, this component becomes normalized vector in x-y plane, in between all up or down at the phase* $2\phi'$







latter component: normalized vector in x-y plane

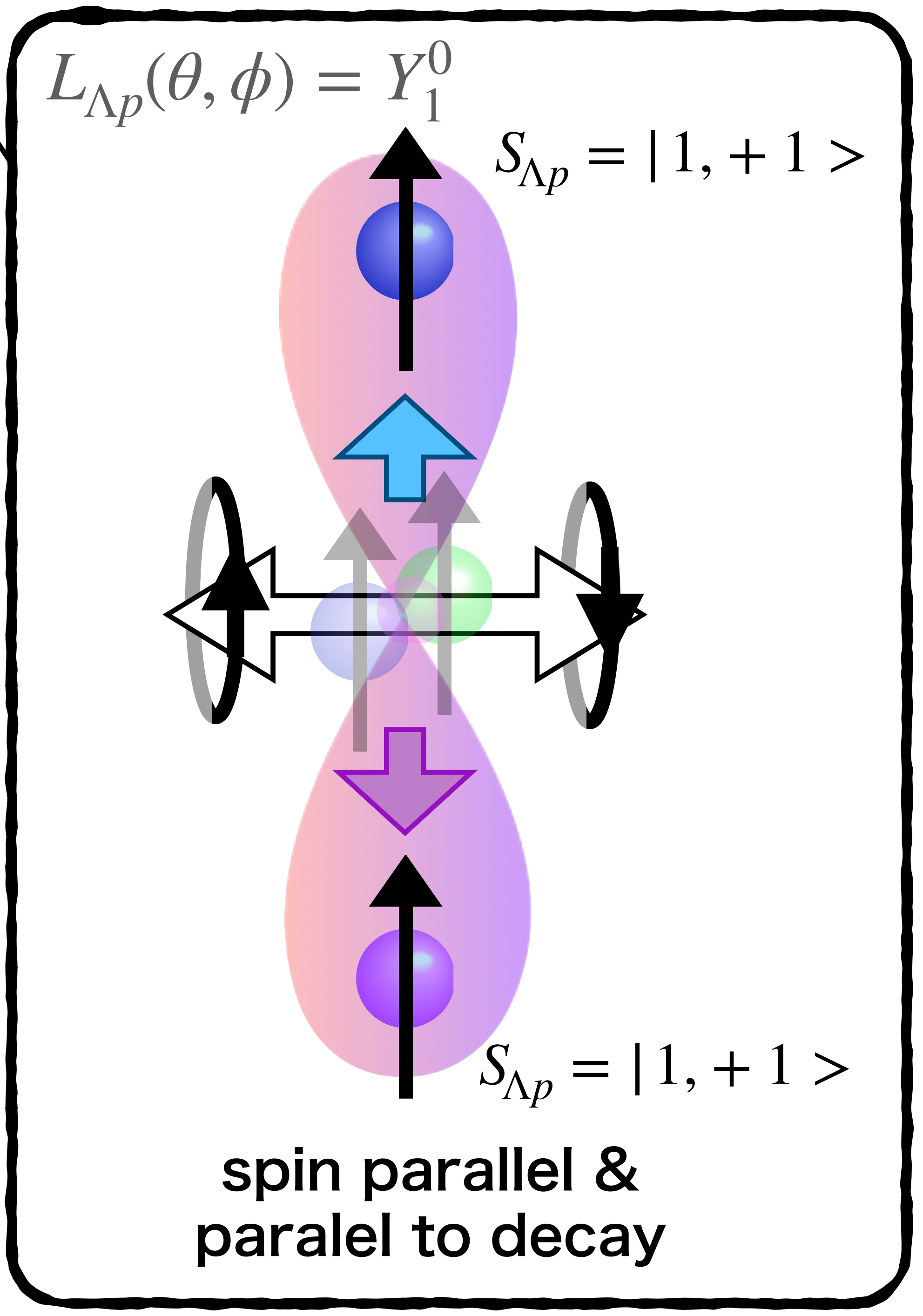
$$-\sqrt{\frac{2}{3}}\sqrt{\frac{3}{4\pi}}\frac{\sin\theta}{\sqrt{2}}e^{-i\phi}\left(\frac{|0,0\rangle+|1,0\rangle}{\sqrt{2}}\right)-\sqrt{\frac{1}{3}}\sqrt{\frac{3}{4\pi}}\cos\theta\,|1,0\rangle$$

summary of $J^P = 1^-$

$\theta_{(v-S)}$ は 崩壊軸とスピン ($\vec{v}_\Lambda$と$\vec{S}_\Lambda$) の成す角

1/3 : S=1 parallel to quantum axis

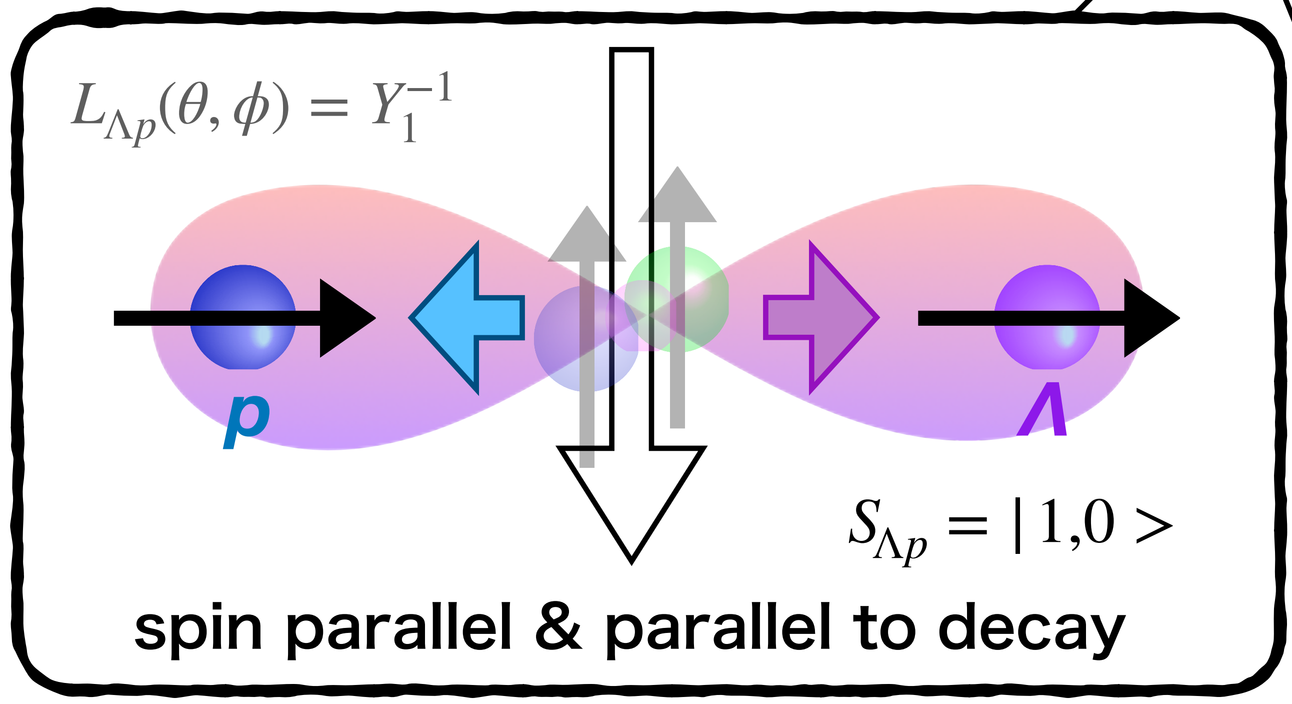
$N\left(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_{(\Lambda,p)}\right) \propto \cos^2\theta_{(v-S)}$



1/3 : S=1 & uniform in a plane orthogonal to quantum axis

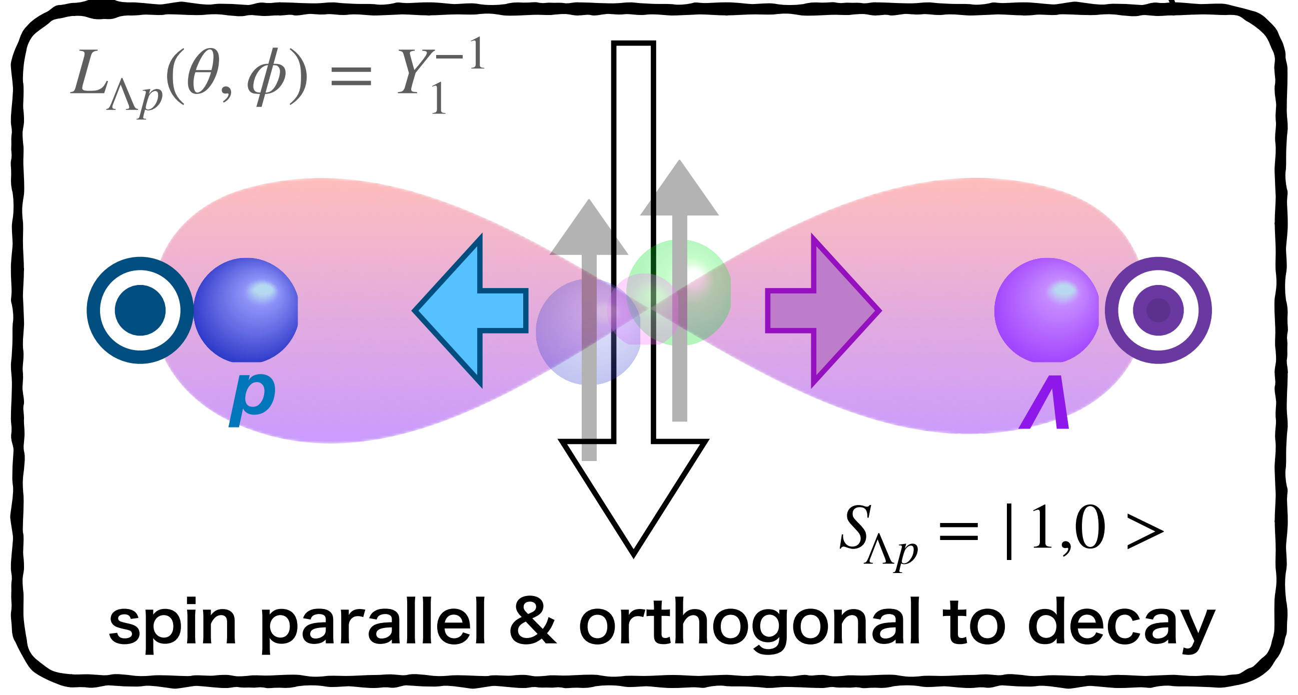
1/2

$N\left(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_{(\Lambda,p)}\right) \propto \cos^2\theta_{(v-S)}$



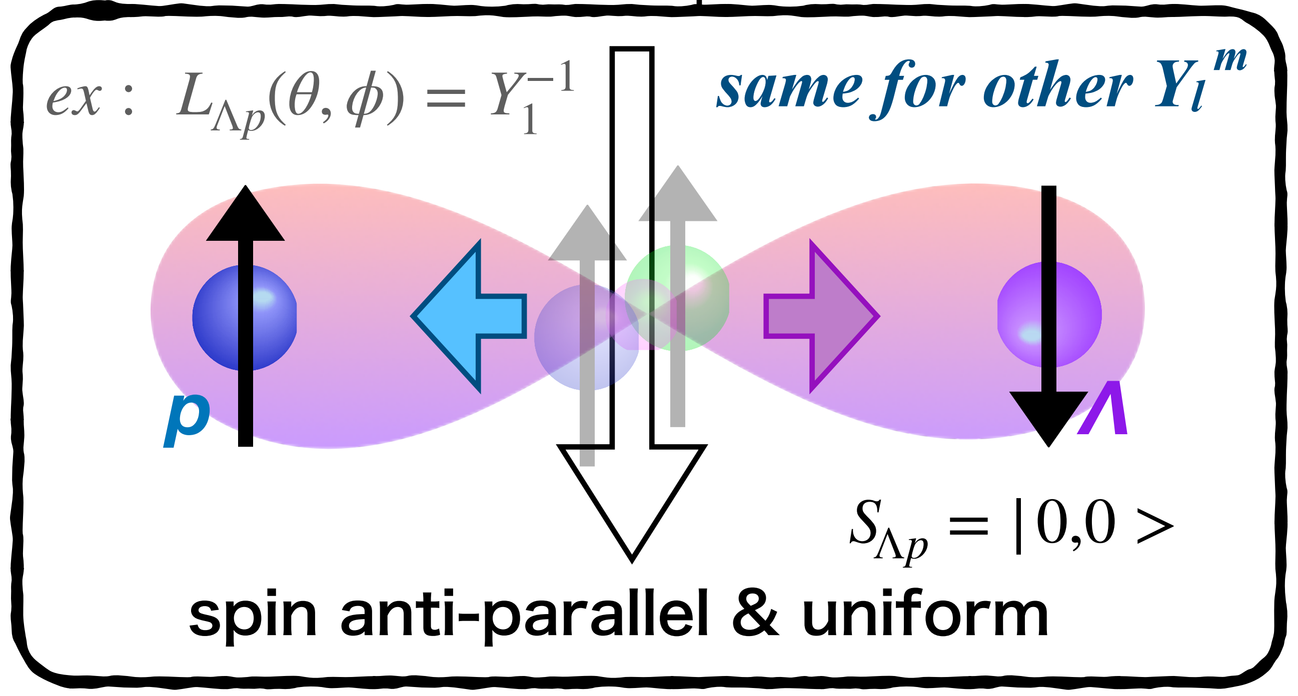
1/2

$N\left(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_{(\Lambda,p)}\right) \propto \sin^2\theta_{(v-S)}$



1/3 : S=0

$N\left(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_{(\Lambda,p)}\right) \propto flat$



In total, $\alpha_{\Lambda p} = +\frac{1}{3}$

$$S_{\Lambda p}=0:\ \frac{N(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_\Lambda)}{\sum N}=\frac{1}{3},$$

uniform distribution

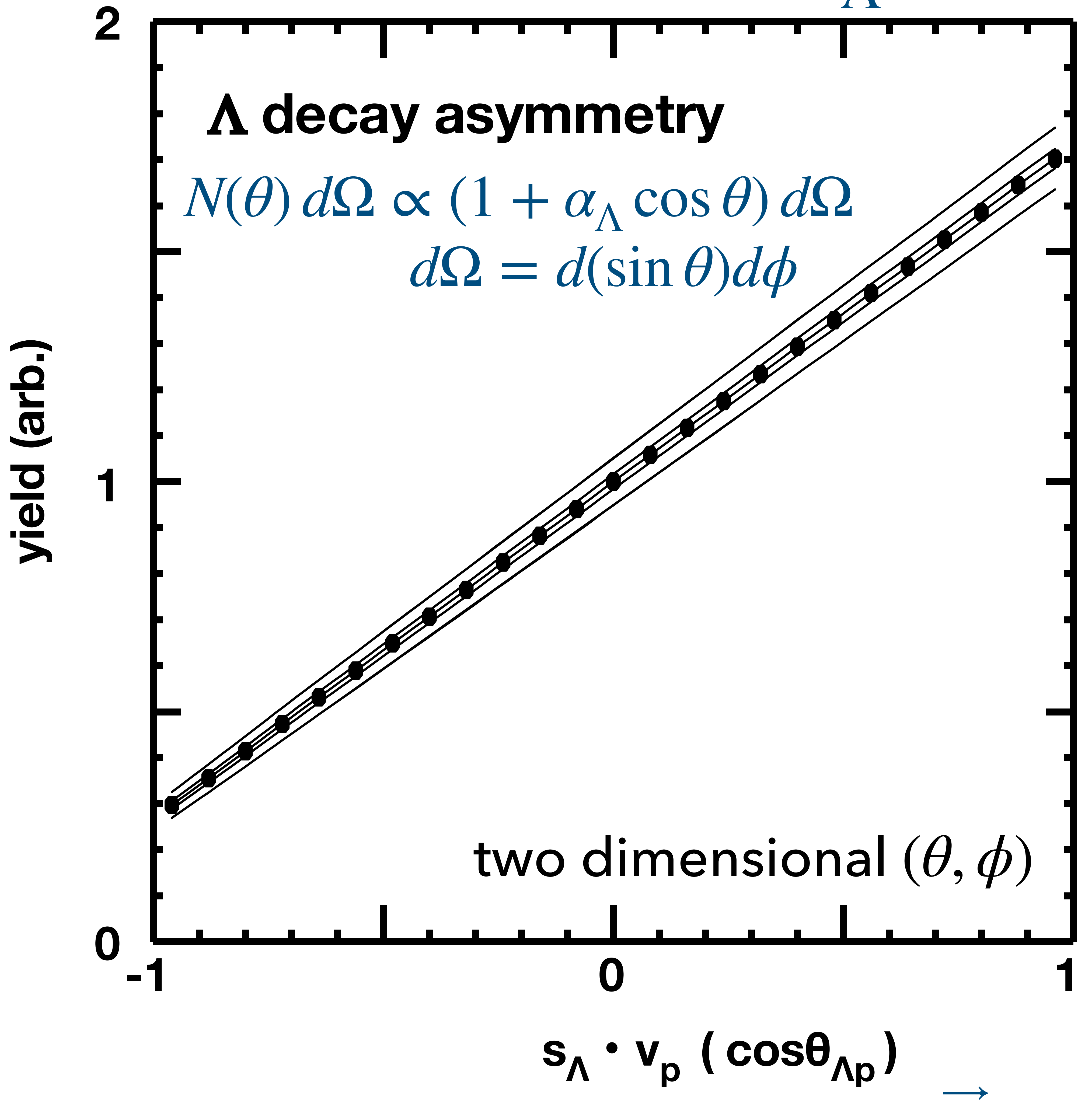
$$S_{\Lambda p}=1:\ \frac{N(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_\Lambda)}{\sum N}=\frac{1}{8}\sin^2\theta_{(v-S)}+\left(\frac{1}{4}+\frac{1}{2}\right)\cos^2\theta_{(v-S)}=\frac{1+5(\vec{v}_{(\Lambda-p)}\cdot\vec{S}_\Lambda)^2}{8}$$

mostly parallel to decay axis

Appendix 3:
Λ & *p* spin Asymmetry

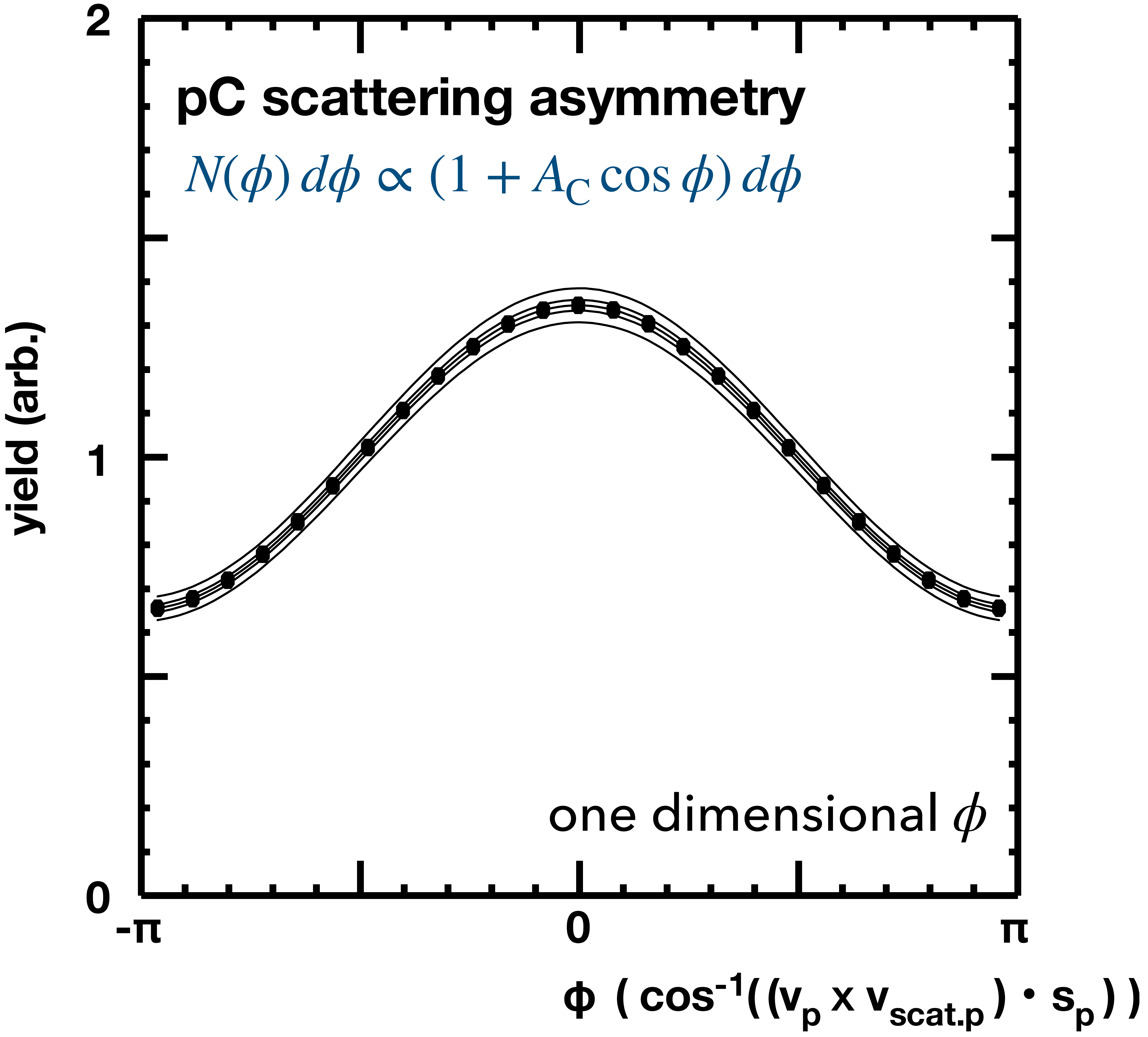
Λ & *p* spin Asymmetry

$\alpha_\Lambda \sim 0.7$



$\vec{v}_p \equiv \frac{\vec{p}_p}{|\vec{p}_p|}$

$A_C \sim 0.4$

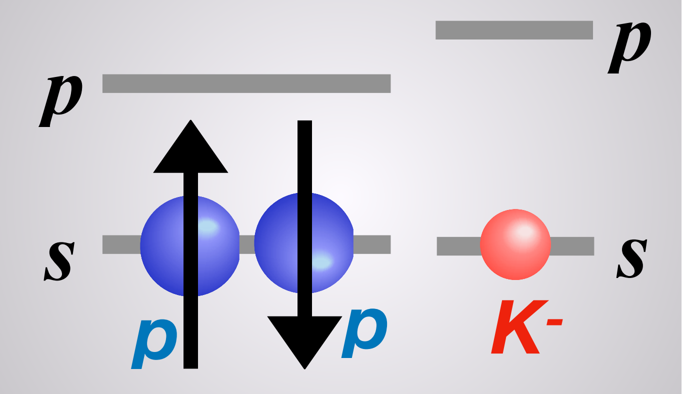


Appendix 4:
Difficulty to measure spin axis

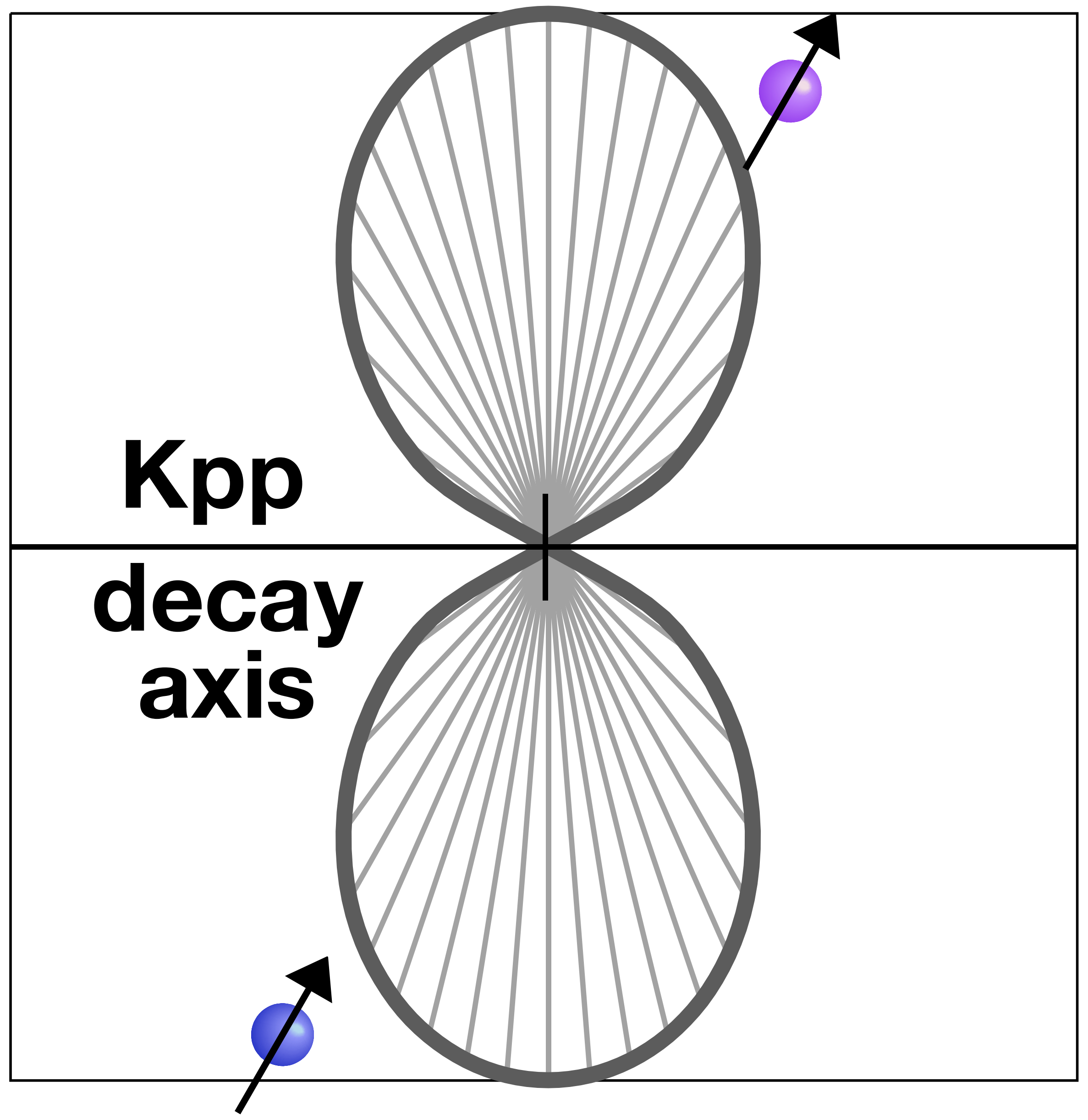
Can spin distribution be measured?

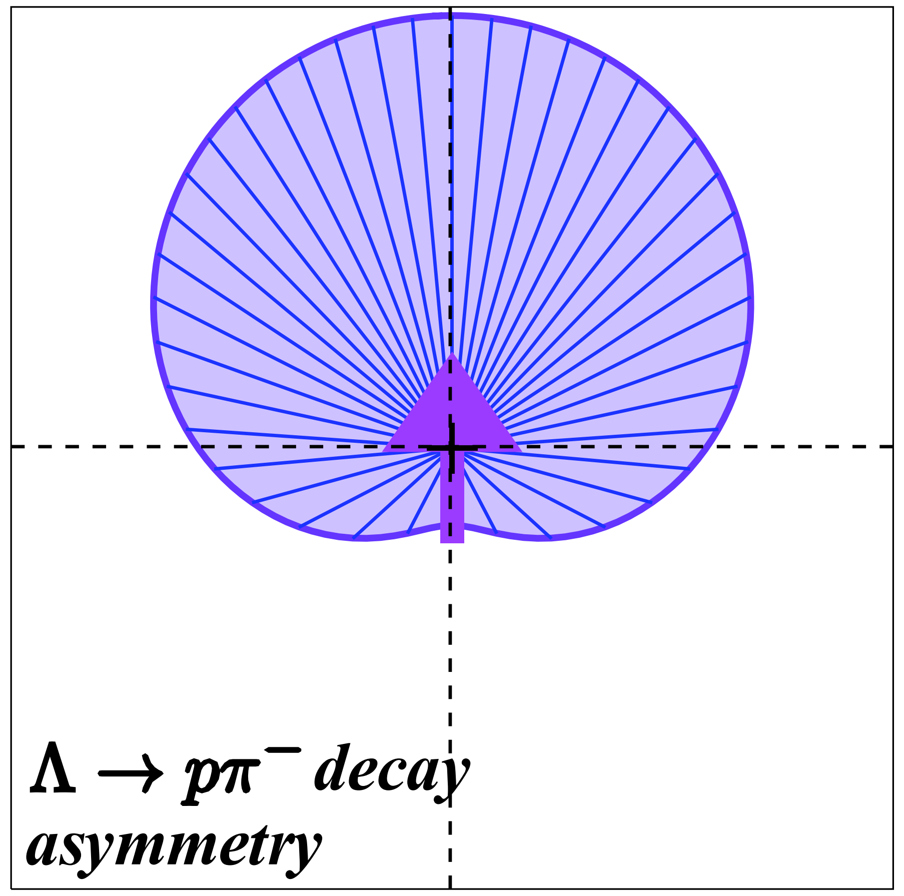
If possible, the experiment is just simple…

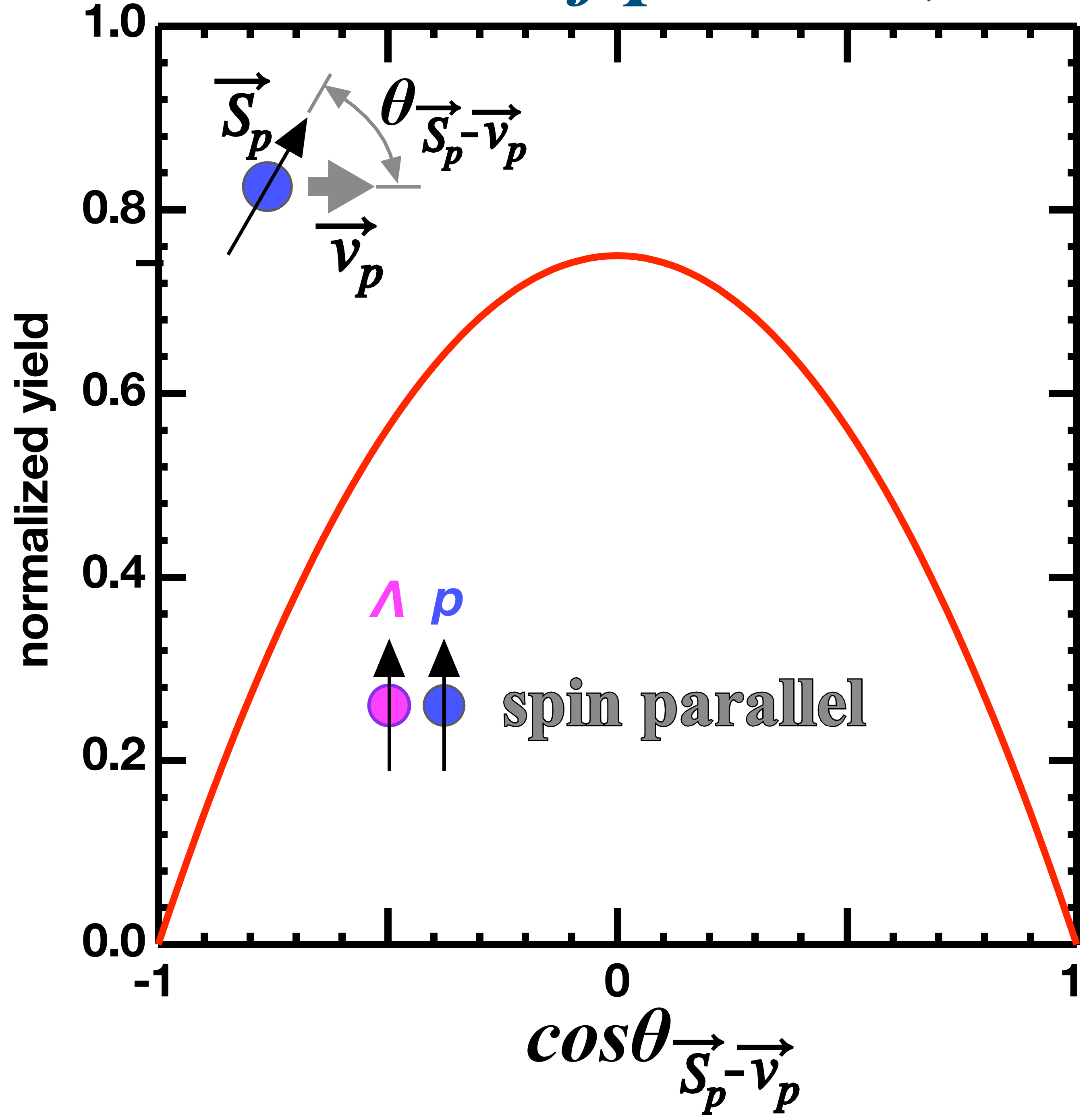
KNN : $J^P = 0^-$,



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





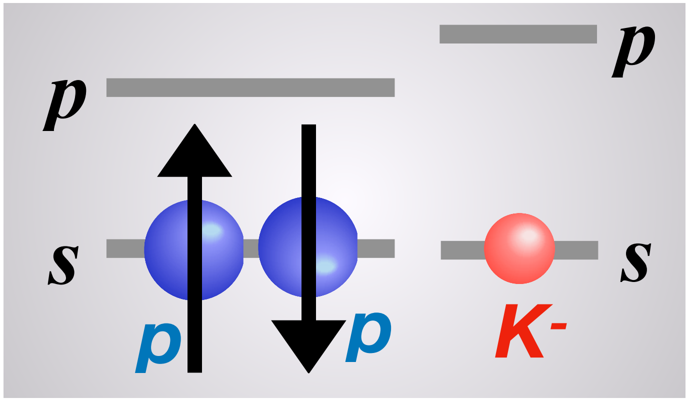


$$N(\theta)\, d\Omega \propto (1 + \alpha_\Lambda \cos\theta)\, d\Omega$$

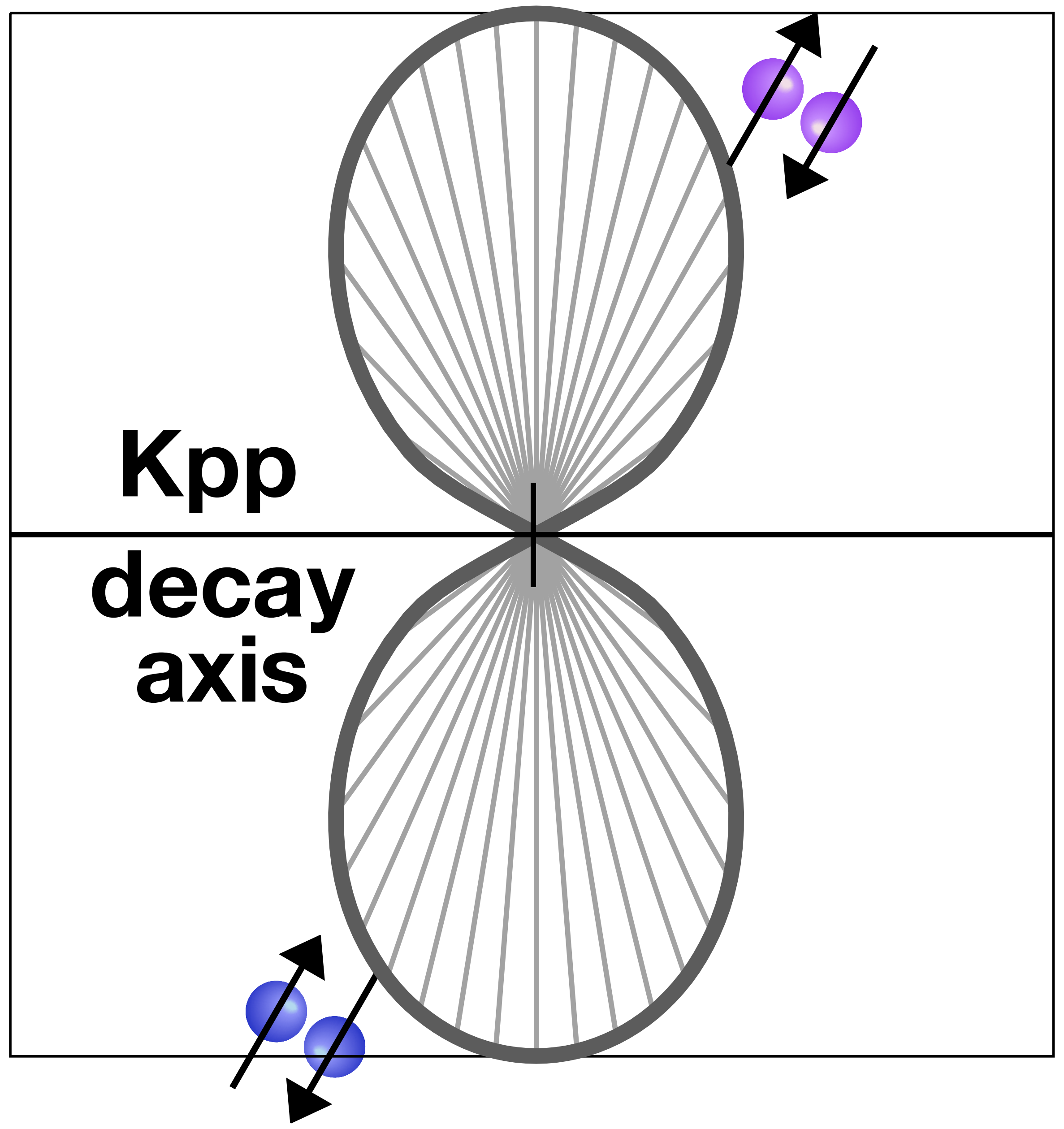
Can spin distribution be measured?

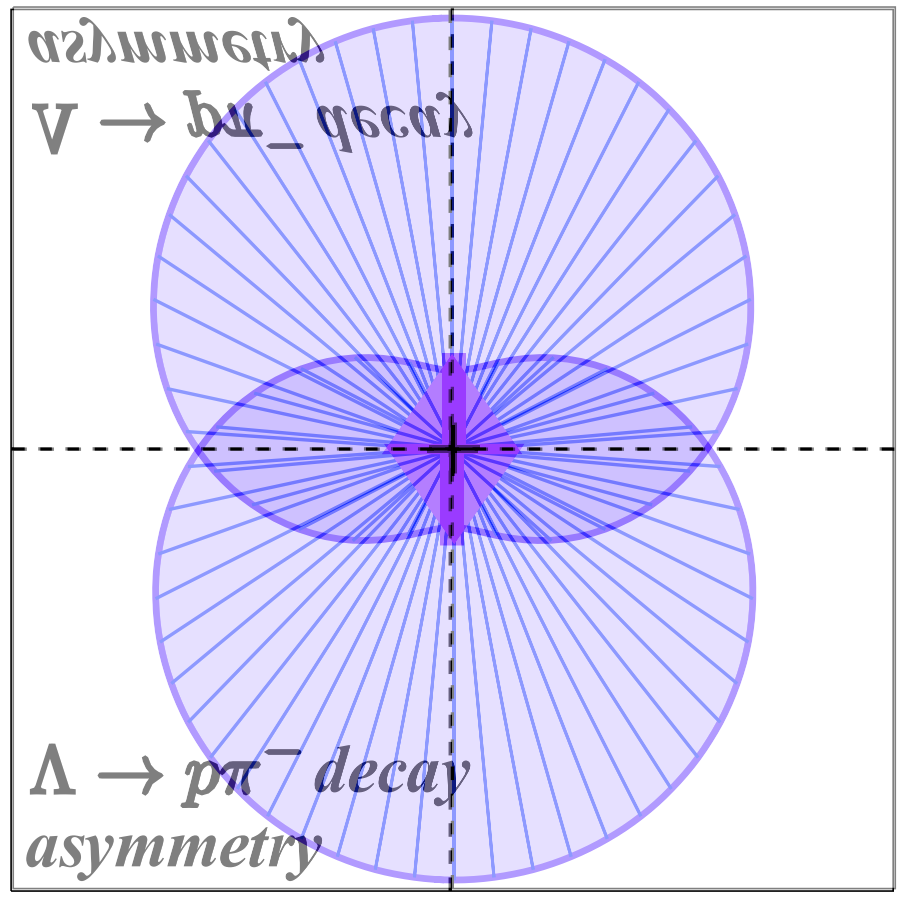
If possible, the experiment is just simple…

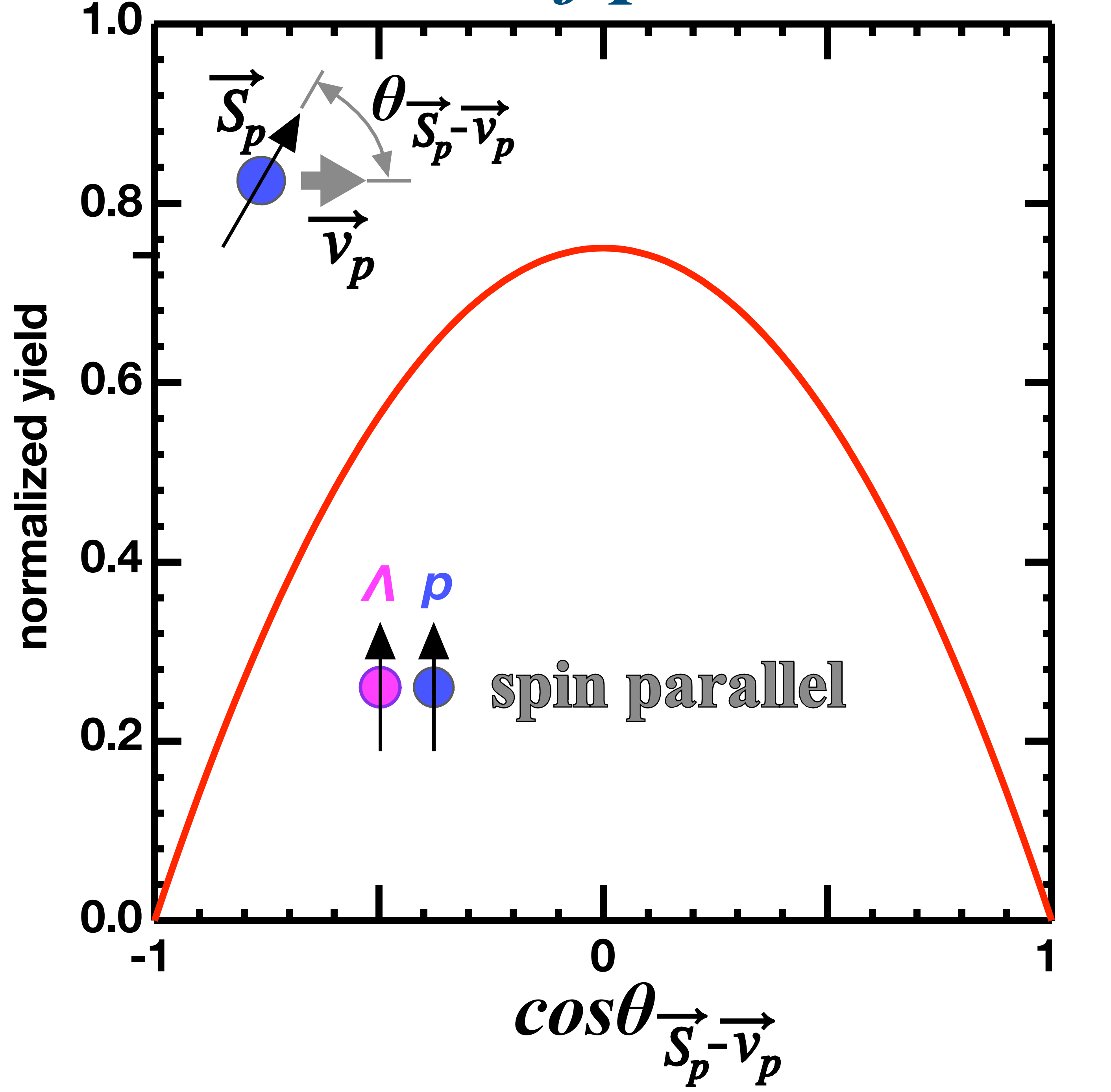
KNN : $J^P = 0^-$,



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







$$N(\theta)\, d\Omega \propto (1 + \alpha_\Lambda \cos\theta)\, d\Omega$$

$$+$$

$$N(\theta)\, d\Omega \propto (1 - \alpha_\Lambda \cos\theta)\, d\Omega$$

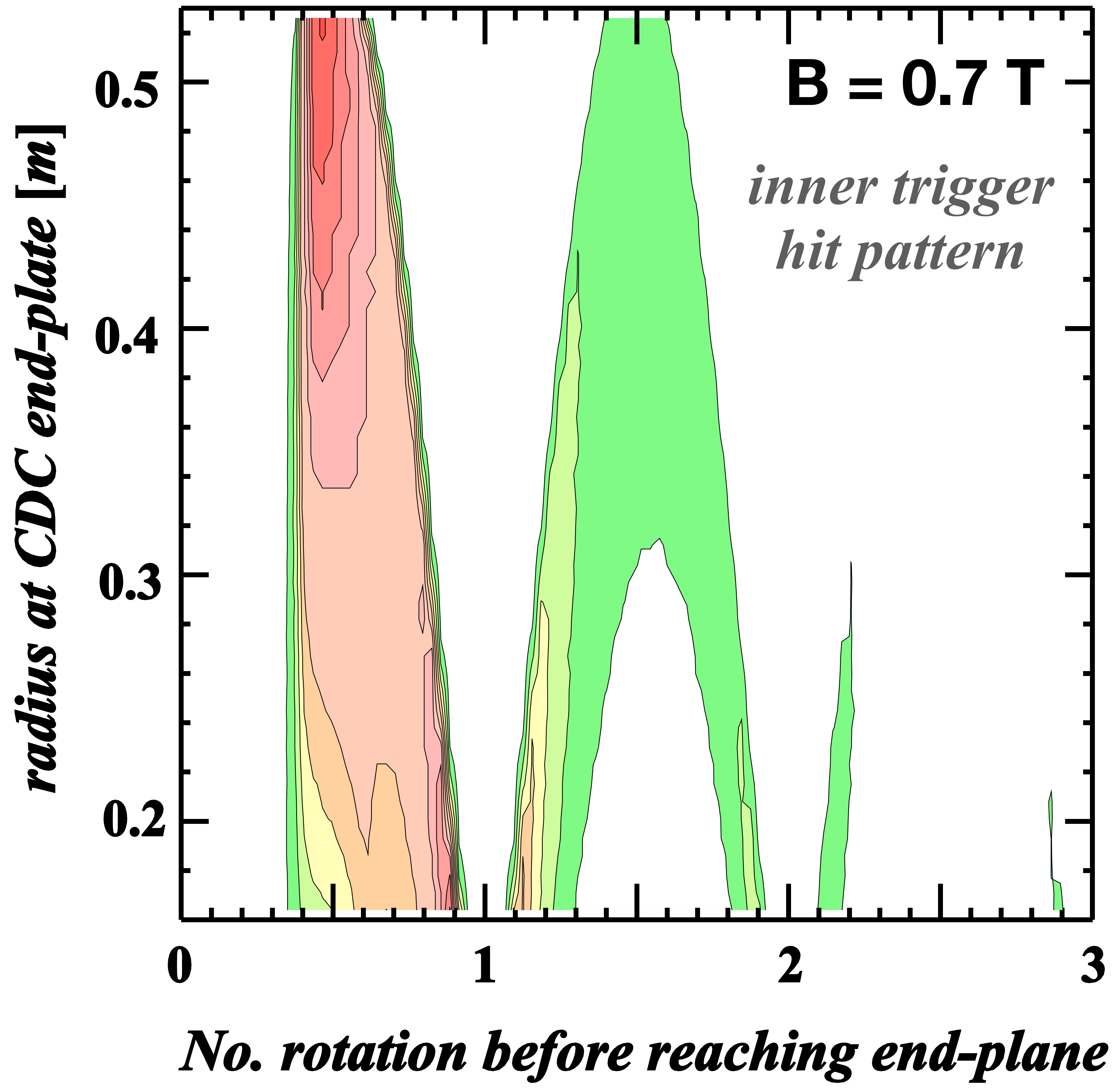
$$=$$

$$N(\theta)\, d\Omega \propto d\Omega$$

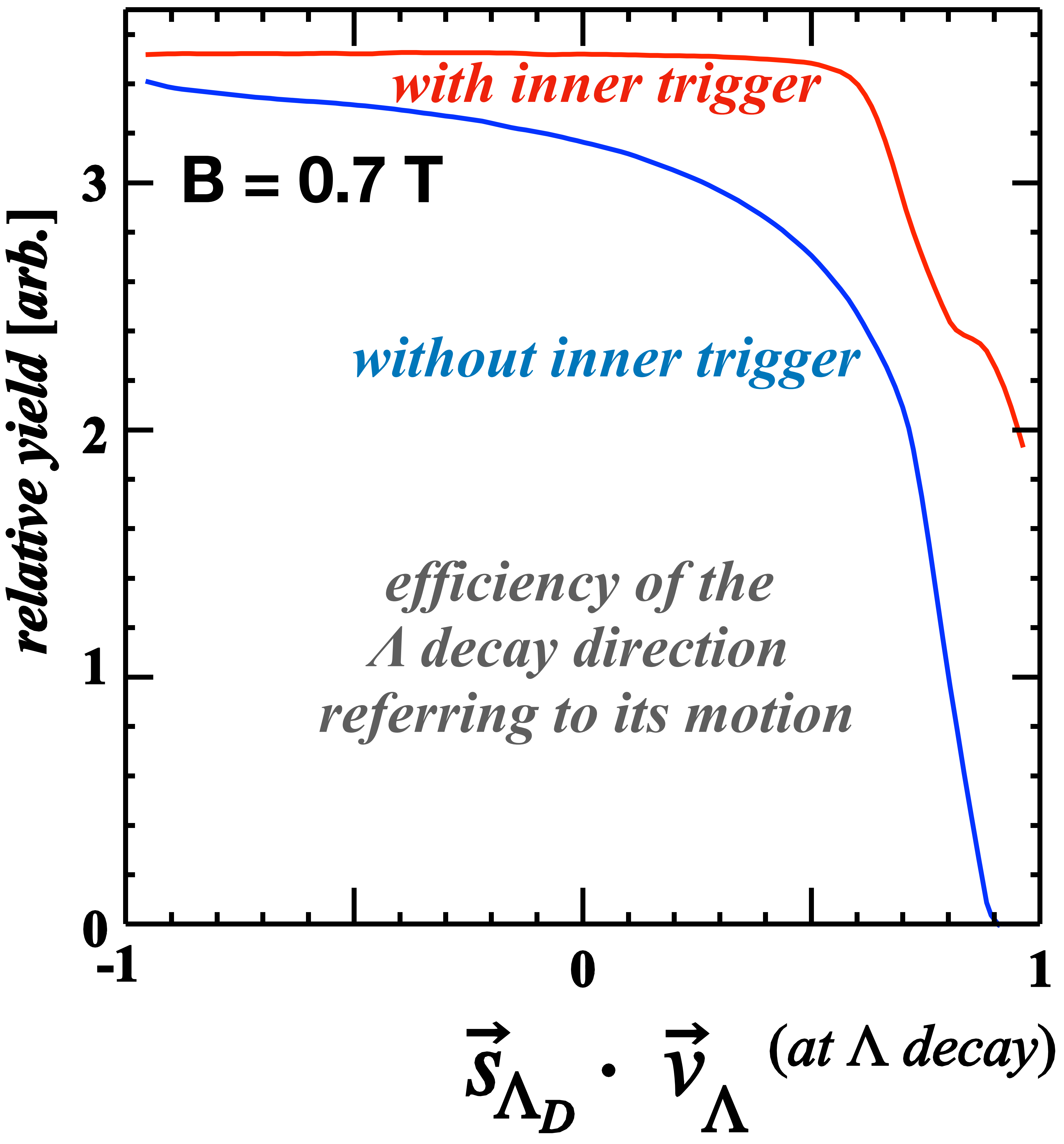
Unfortunately, no way to access quantum axes! → spin-spin

Appendix 5:
Improved acceptance due to inner Z trigger counter

When we trigger pion inside CDC, acceptance of Λ decay angle drastically improves

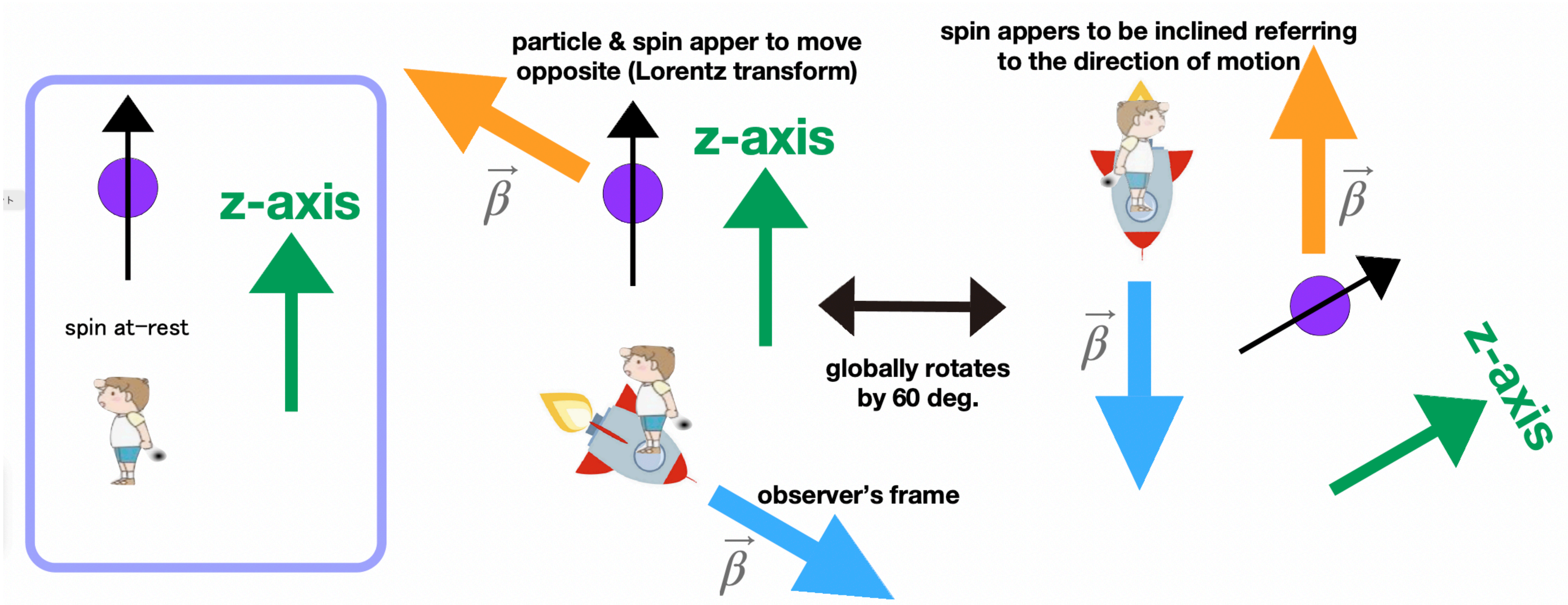


CDC inner pion trigger helps a lot

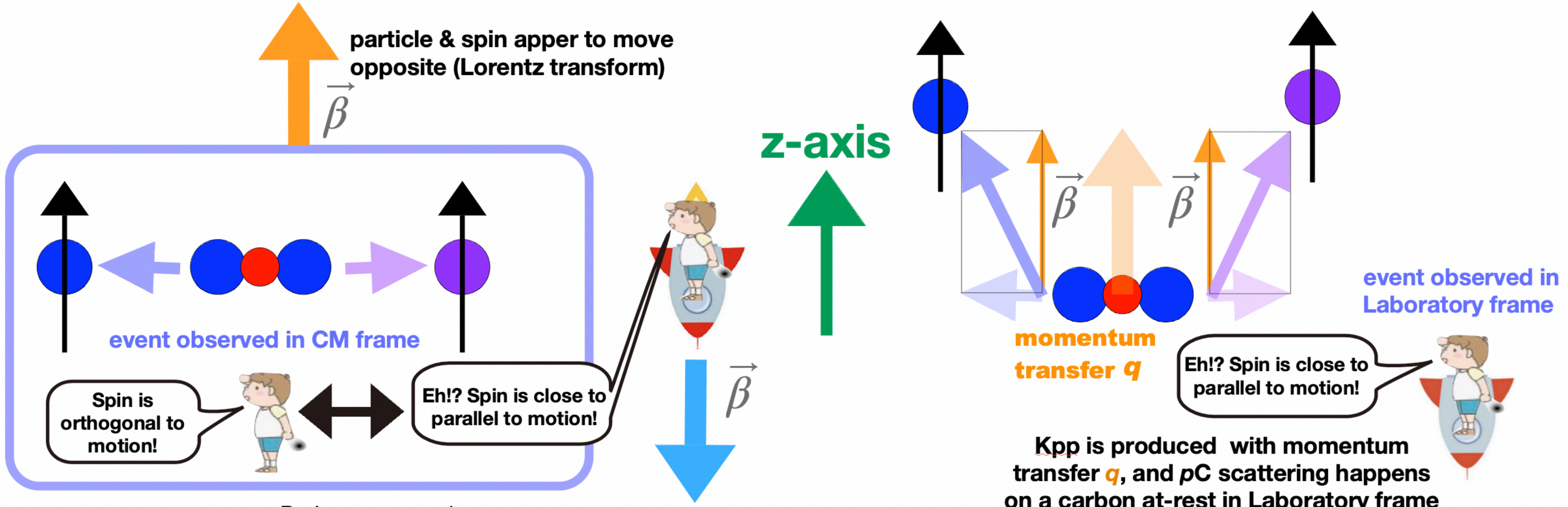


Appendix 6:
Spin and Frame to observe that

Lorentz transforms do not change spin direction to the global axis, but do changes angle between spin direction and direction of motion



Lorentz transforms do not change spin direction to the global axis, but do changes angle between spin direction and direction of motion

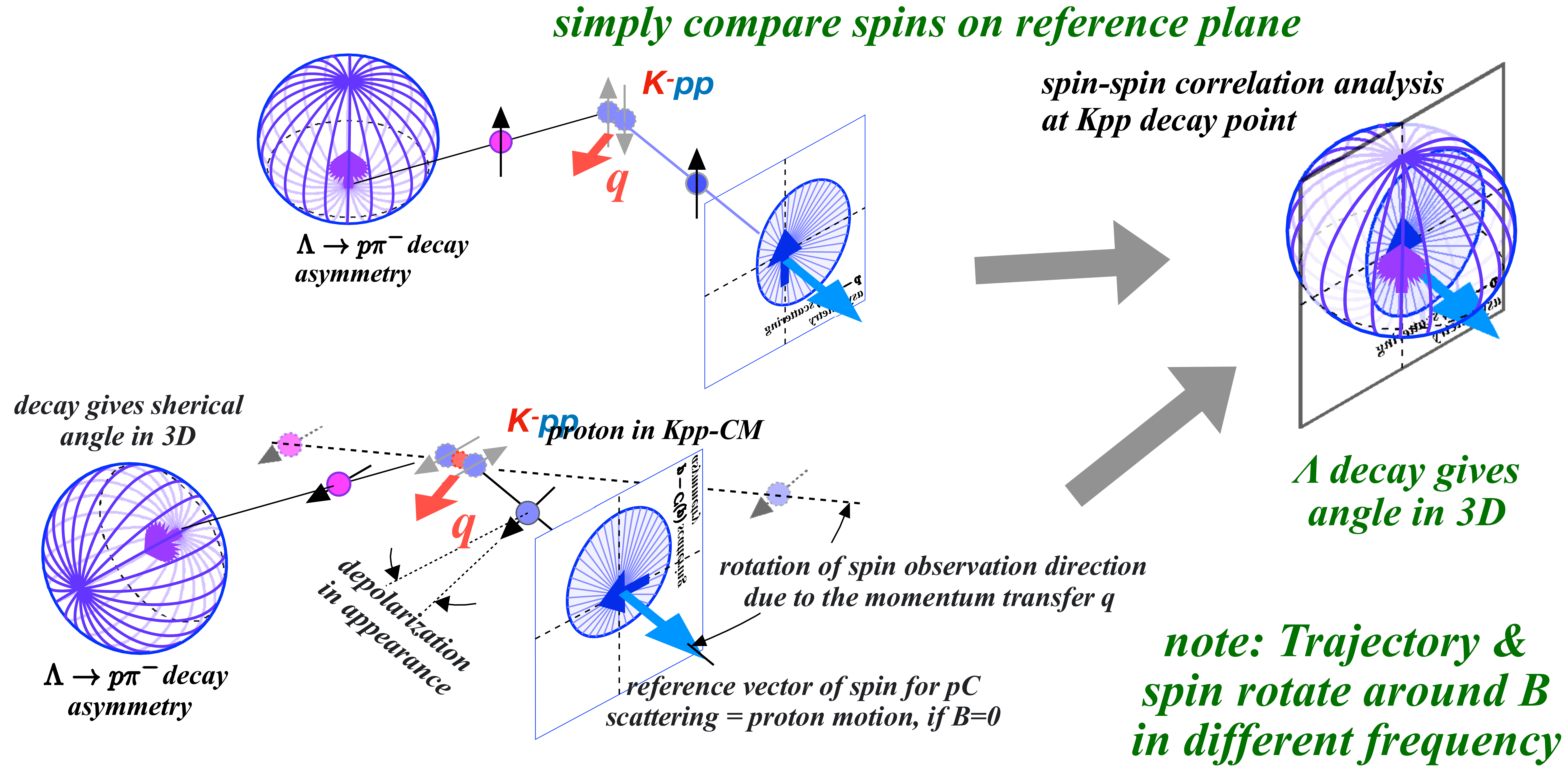


Both are correct in a sence...

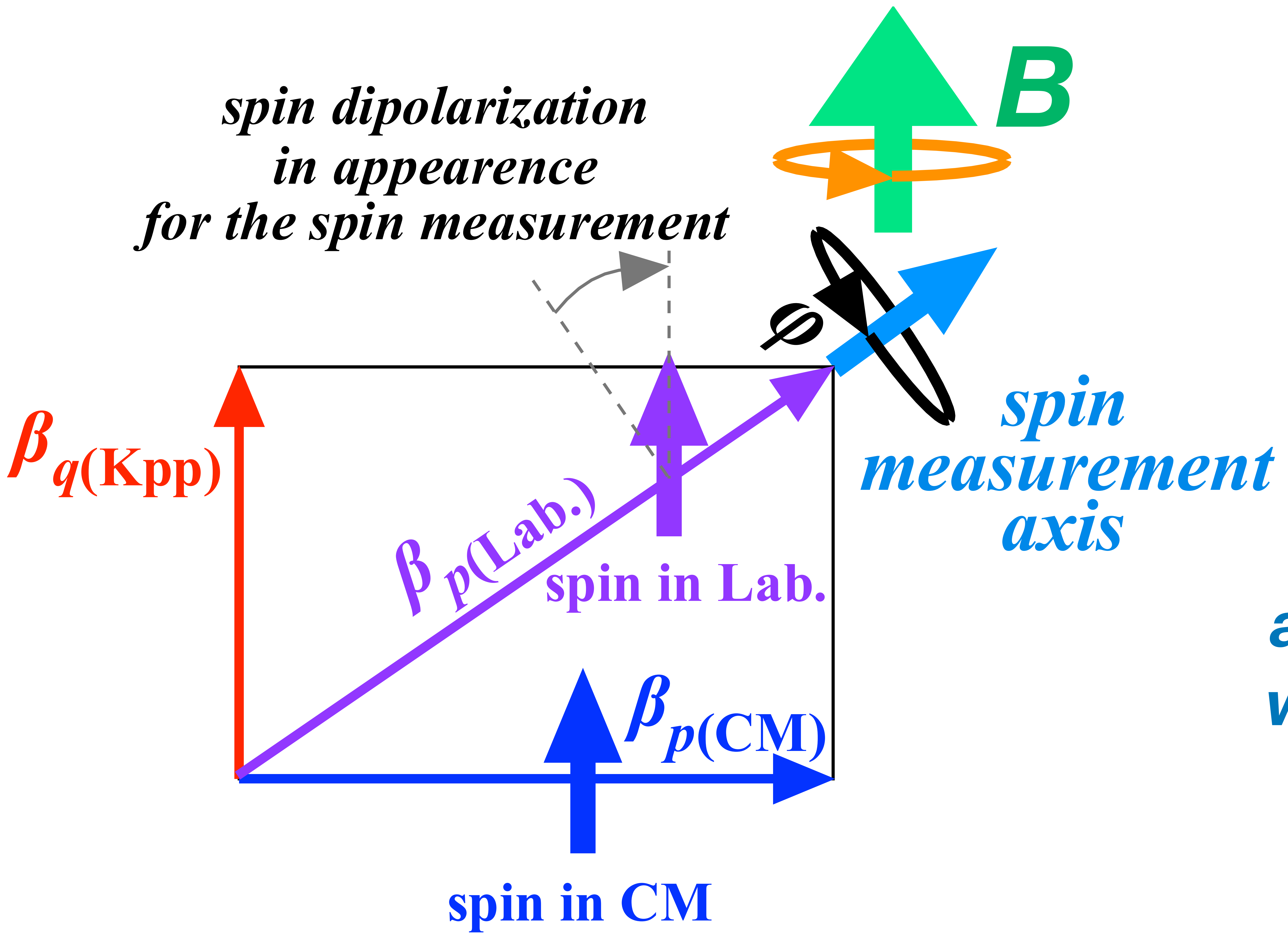
Kpp is produced with momentum transfer q, and pC scattering happens on a carbon at-rest in Laboratory frame
(*q* is relatively small compared to the decay momentum, in fact)

Λ-p spin correlation analysis

detail → Appendix: 6

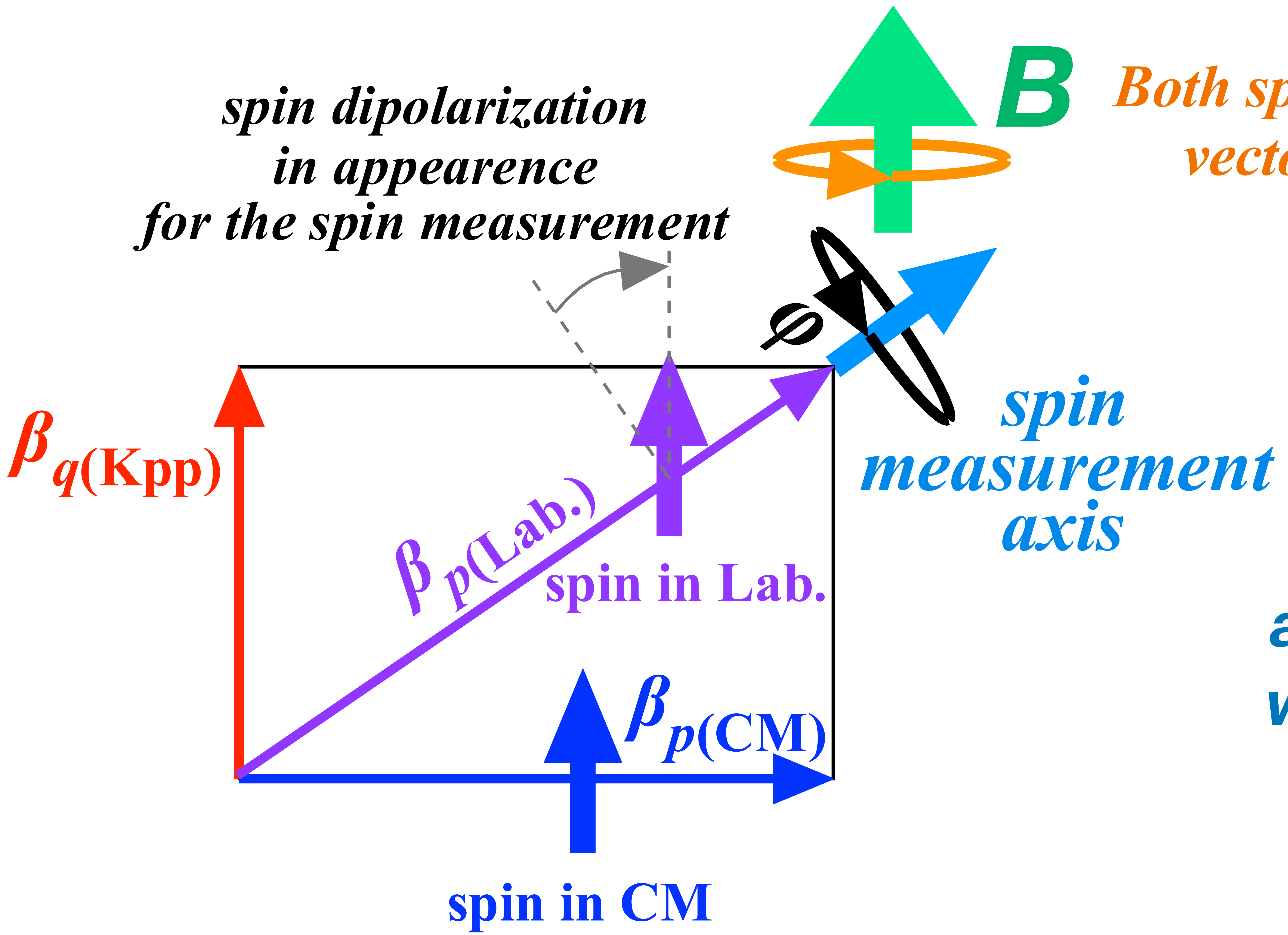


Small, but unpreferable reduction of spin correlation due to apparent depolarization



Large scattering asymmetry is expected when directions of spin and motion are orthogonal

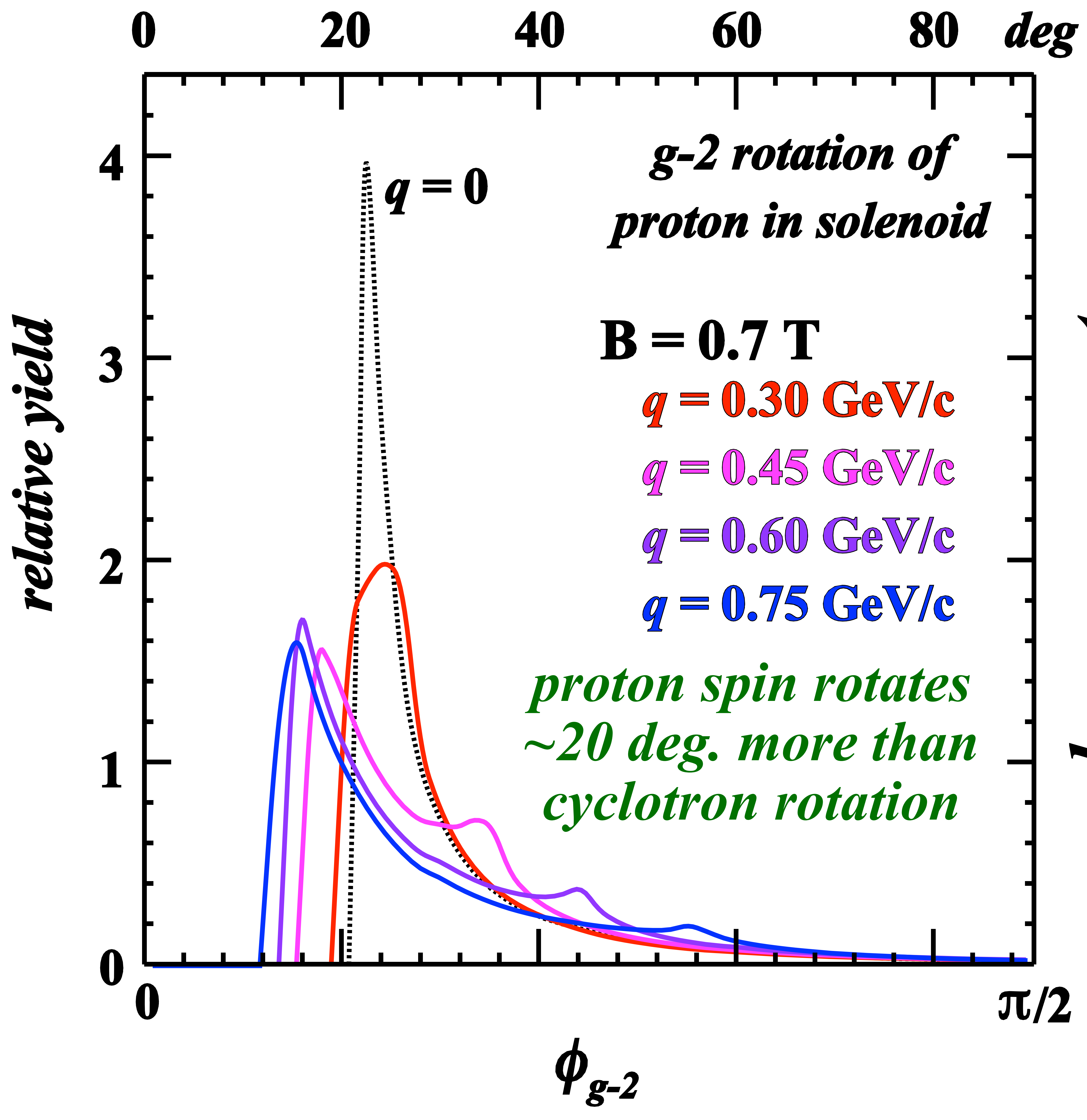
Small, but unpreferable reduction of spin correlation due to apparent depolarization



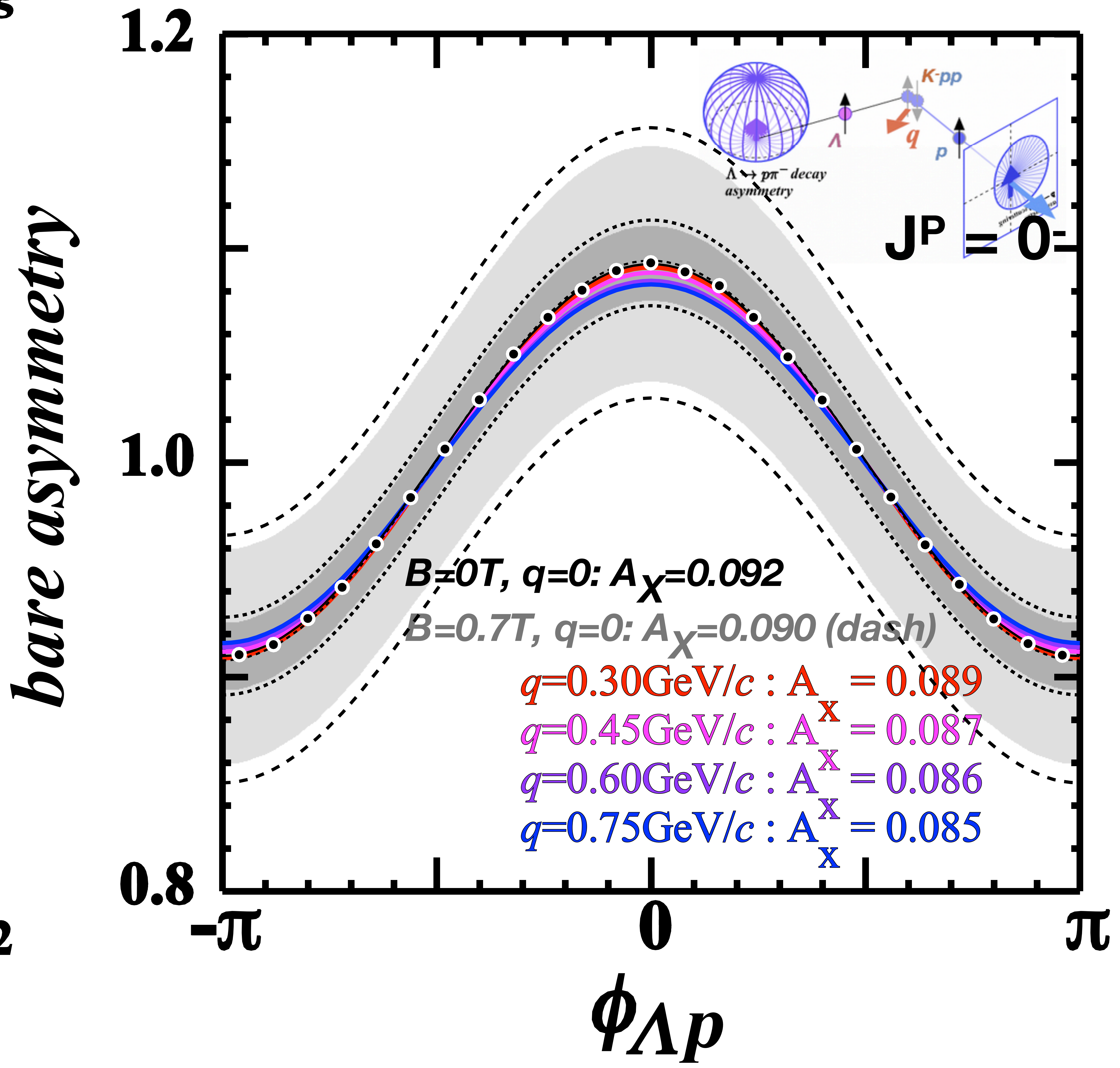
Both spin and spin-measurement-vector rotate around B field.

Large scattering asymmetry is expected when directions of spin and motion are orthogonal

B field effect



B & q effects to bare asymmetry are weak



Appendix 7:
Spin convolution

spin asymmetry around motional axis ***… for B=0, q=0, parallel*** $(\vec{s}_\Lambda = \vec{s}_p)$***, but uniform***

$$P = \left(1 + A_\Lambda \cos\theta_{(\Lambda-\Lambda_D)}\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

$$\vec{s}_\Lambda(\theta_\Lambda, \phi_\Lambda) = \cos\theta_\Lambda\,\vec{v}_p^{(ref)} + \sin\theta_\Lambda\left(\cos(\phi_\Lambda - \phi_{\Lambda_D})\,\vec{s}_{\Lambda_D}^{(proj)} + \sin(\phi_\Lambda - \phi_{\Lambda_D})\,\vec{s}_{\Lambda_D}^{(ortho)}\right)$$

$$\vec{s}_{\Lambda_D}(\theta_{\Lambda_D}, \phi_{\Lambda_D}) = \cos\theta_{\Lambda_D}\,\vec{v}_p^{(ref)} + \sin\theta_{\Lambda_D}\,\vec{s}_{\Lambda_D}^{(proj)}$$

$$\cos\theta_{(\Lambda-\Lambda_D)} = \vec{s}(\theta,\phi)\cdot\vec{s}_{\Lambda_D}(\theta_{\Lambda_D}, \phi_{\Lambda_D})$$

$$\int \cos\theta_\Lambda d(\cos\theta_\Lambda) = 0$$

$$P(\theta_{\Lambda_D}, \phi_{\Lambda_D}, \theta_\Lambda, \phi_\Lambda) = \frac{1}{(4\pi)^2}\left(1 + A_\Lambda(\cos\theta_\Lambda\cos\theta_{\Lambda_D} + \sin\theta_\Lambda\sin\theta_{\Lambda_D}\cos(\phi_\Lambda - \phi_{\Lambda_D}))\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

$$\int P(\theta_{\Lambda_D}, \phi_{\Lambda_D}, \theta_\Lambda, \phi_\Lambda)\,d(\cos\theta_{\Lambda_D}) = P(\phi_{\Lambda_D}, \theta_\Lambda, \phi_\Lambda)$$ *… pC scattering do not have sensitivity in* θ_{Λ_D} *direction*

$$P(\phi_{\Lambda_D}, \theta_\Lambda, \phi_\Lambda) = \frac{2}{(4\pi)^2}\left(1 + \frac{\pi}{4}A_\Lambda\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{\Lambda_D})\right)\left(1 + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})\right)$$

$$= \frac{2}{(4\pi)^2}\Big[1 + \frac{\pi}{4}A_\Lambda\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{\Lambda_D}) + A_{pC}\sin\theta_\Lambda\cos(\phi_\Lambda - \phi_{pC})$$
$$+\frac{\pi}{4}A_\Lambda A_{pC}\sin^2\theta_\Lambda\left\{\cos(2\phi_\Lambda - \phi_{\Lambda_D} - \phi_{pC}) + \cos(\phi_{\Lambda_D} - \phi_{pC})\right\}\Big]$$

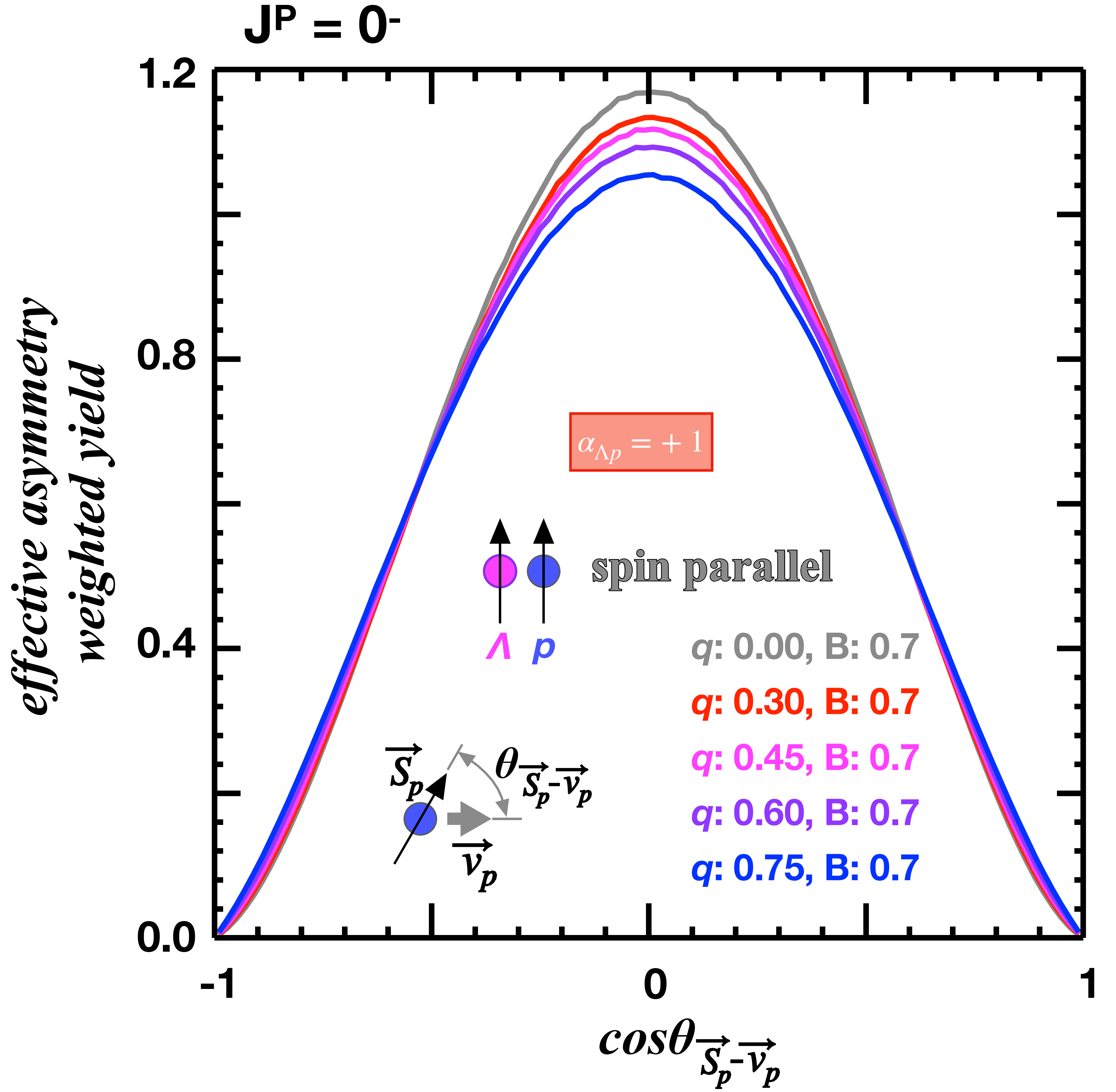
$$\int X'(\phi_\Lambda)d\phi_\Lambda = 0$$

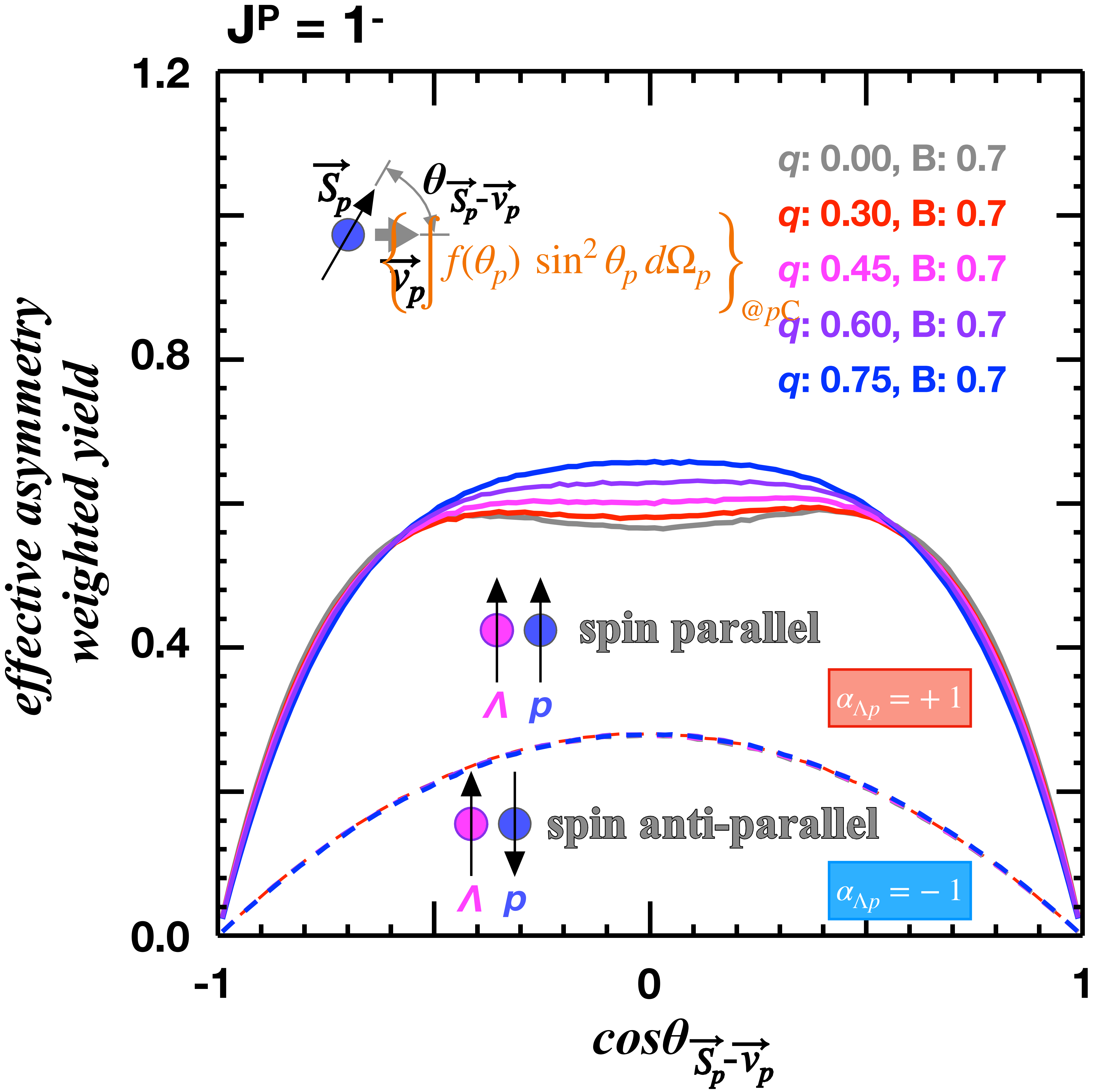
$$P(\phi_{\Lambda_D}) = \int d(\cos\theta_\Lambda)\int d\phi_\Lambda P(\phi_{\Lambda_D}, \theta_\Lambda, \phi_\Lambda) = \frac{1}{4\pi}\int d(\cos\theta_\Lambda)\left[1 + \frac{\pi}{4}A_\Lambda A_{pC}\sin^2\theta_\Lambda\cos(\phi_{\Lambda_D} - \phi_{pC})\right]$$

$$P(\phi_{\Lambda_D}) = \frac{1}{2\pi}\left(1 + \frac{\pi}{12}A_\Lambda A_{pC}\cos(\phi_{\Lambda_D} - \phi_{pC})\right)$$

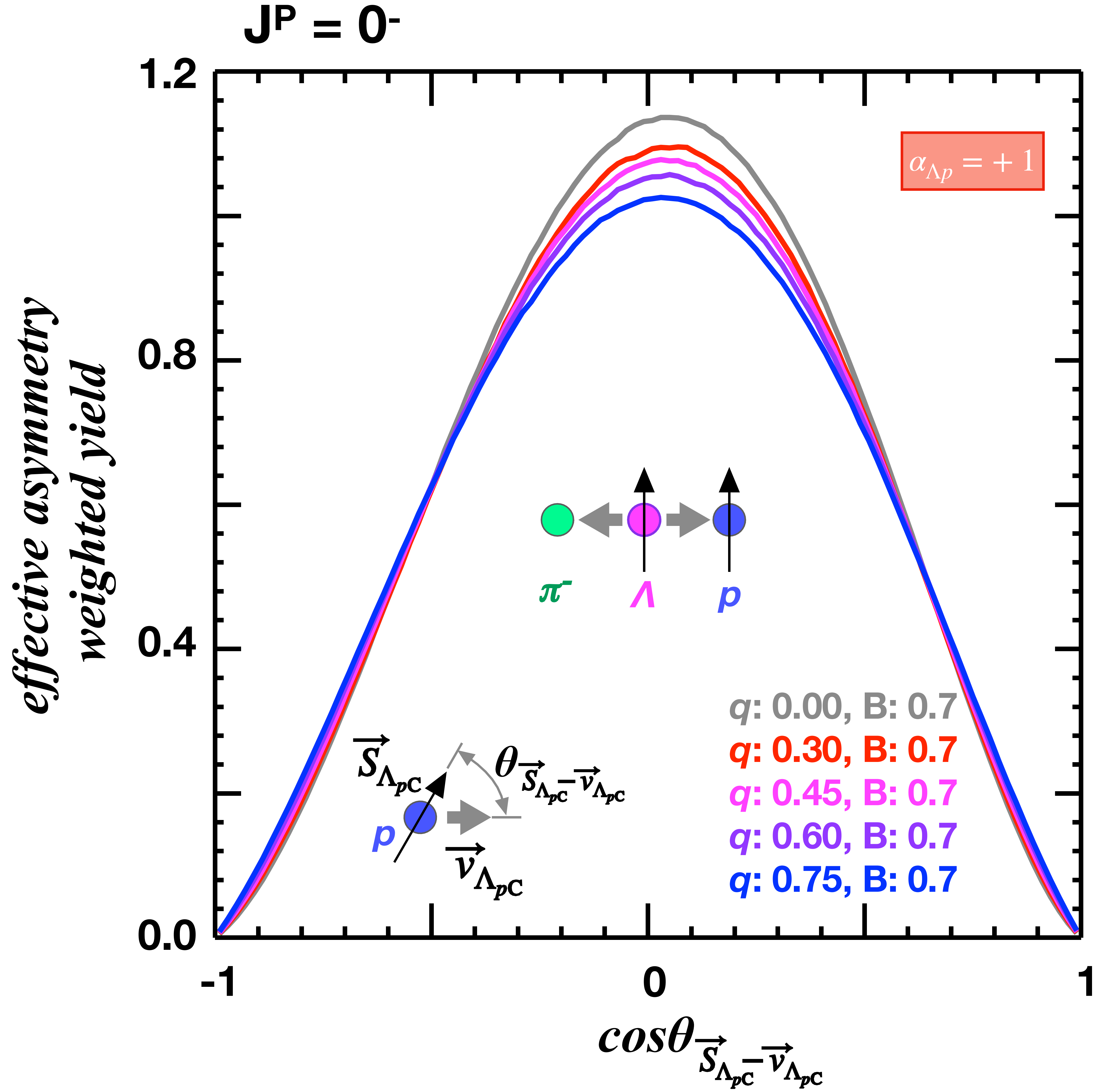
Appendix 8:
Simulated polarization spectra to derive $\mathscr{A}_{eff}(B, M, q)$

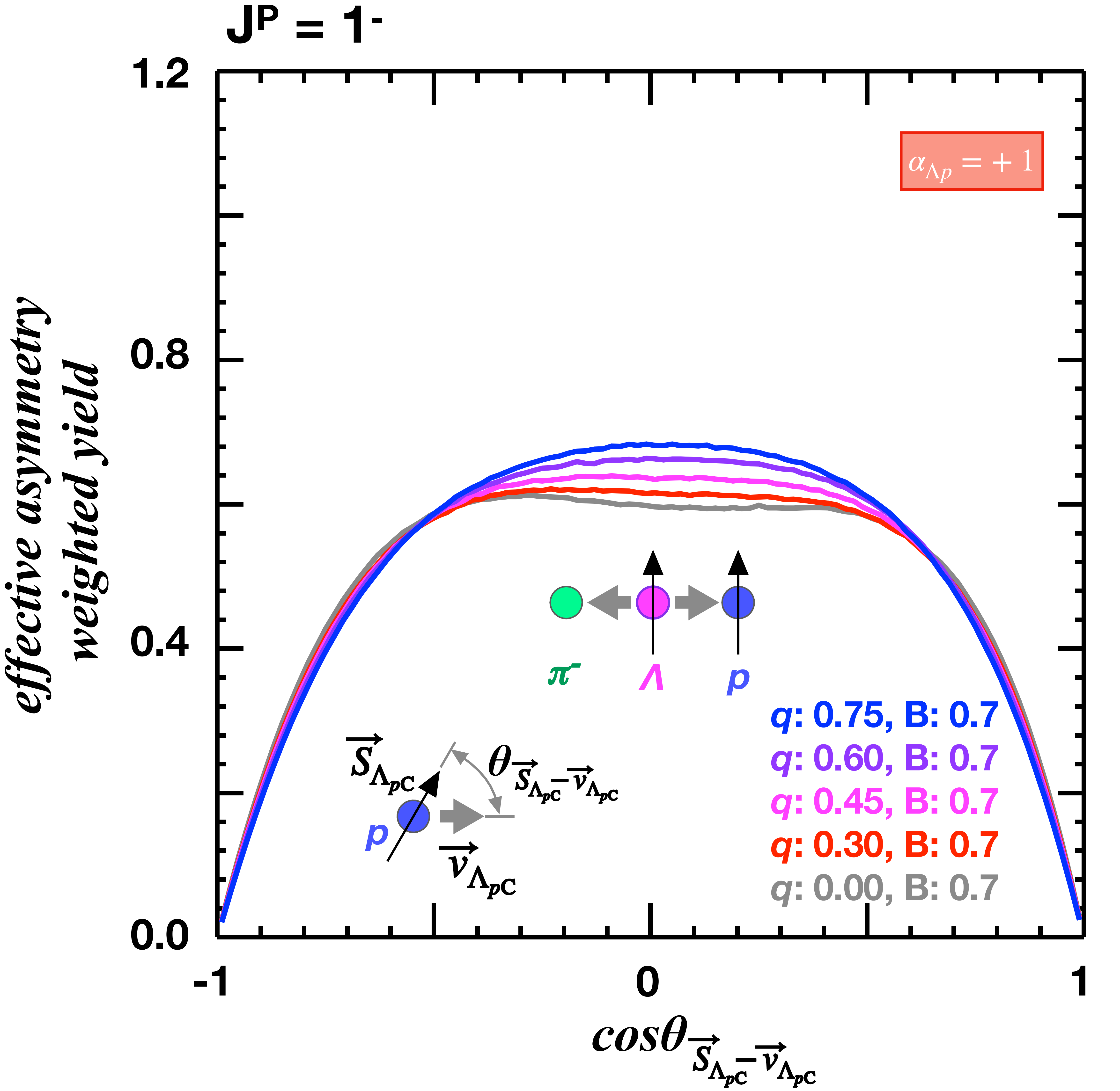
Eff. asymmetry $\left\{ \int f(\theta_p)\ \sin^2\theta_p\, d\Omega_p \right\}_{@pC}$: p from Kpp decay





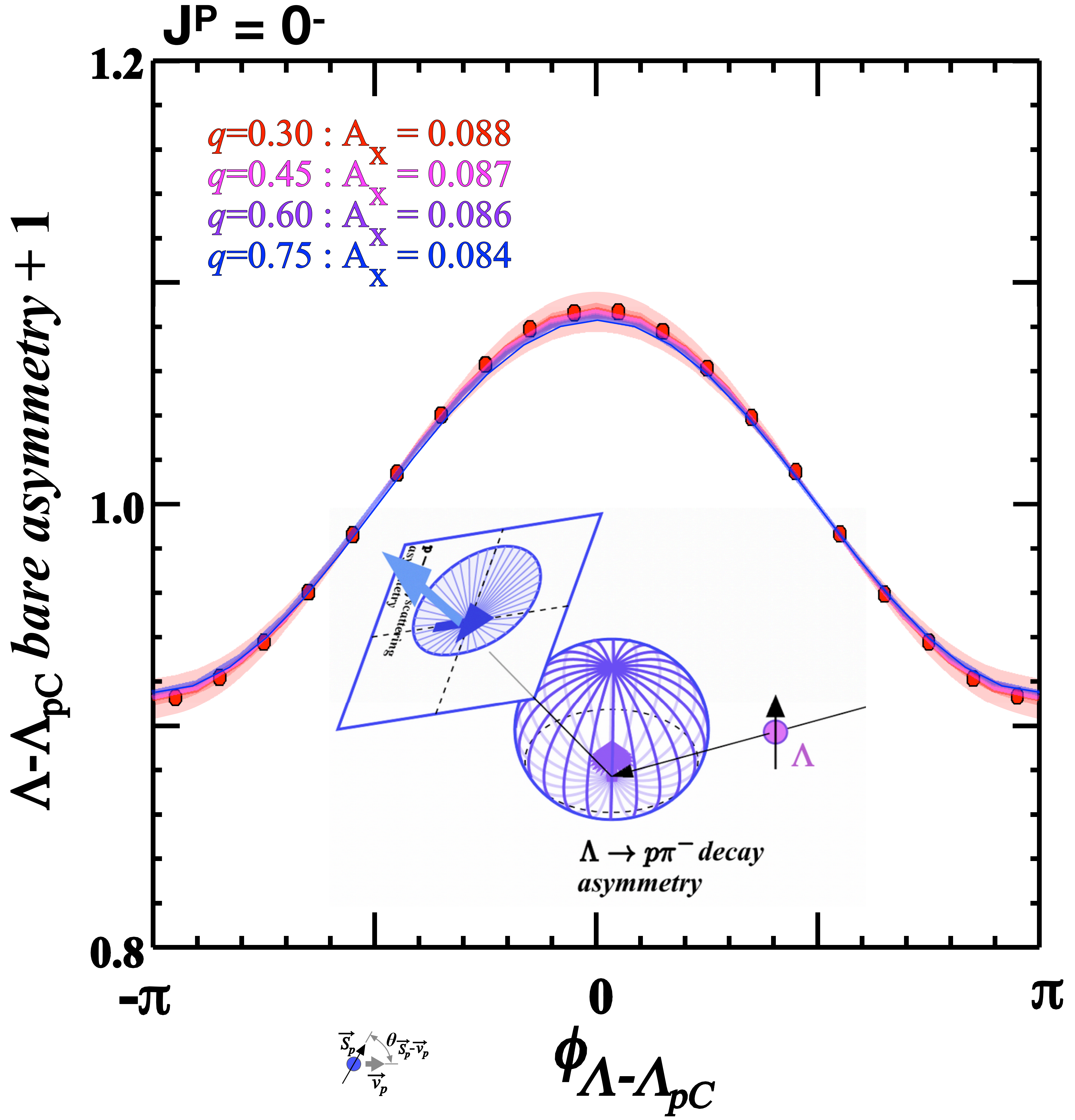
Eff. asymmetry $\left\{ \int \left(f(\theta_{\Lambda_{pC}} + g(\theta_{\Lambda_{pC}}) \right) \sin^2 \theta_{\Lambda_{pC}} \, d\Omega_{\Lambda_{pC}} \right\}_{@pC}$ **p from Λ decay**

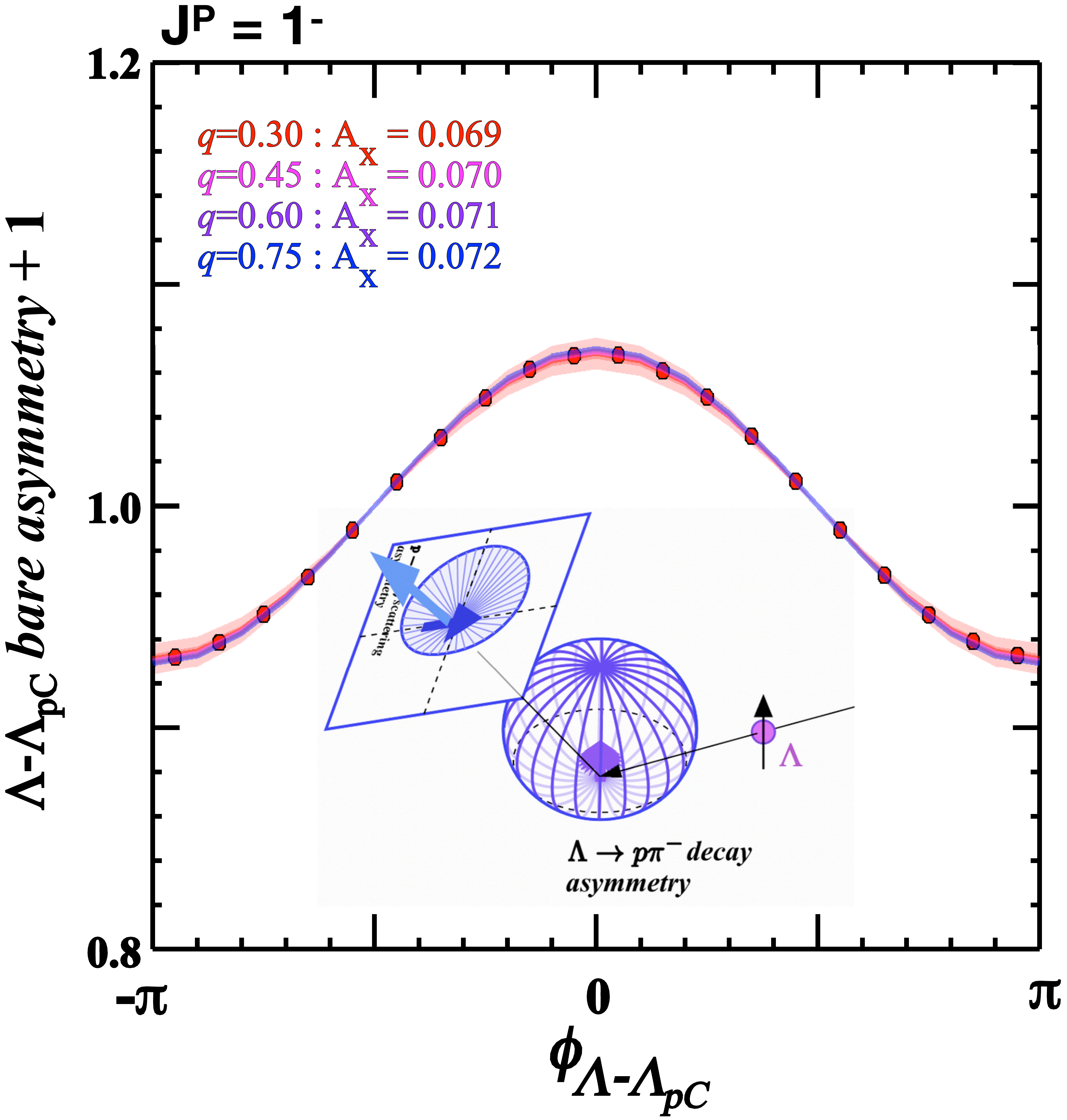




Λ-Λ_{pC} data for self-calibration of asymmetries

correlation of observed spins by Λ decay and pC scattering





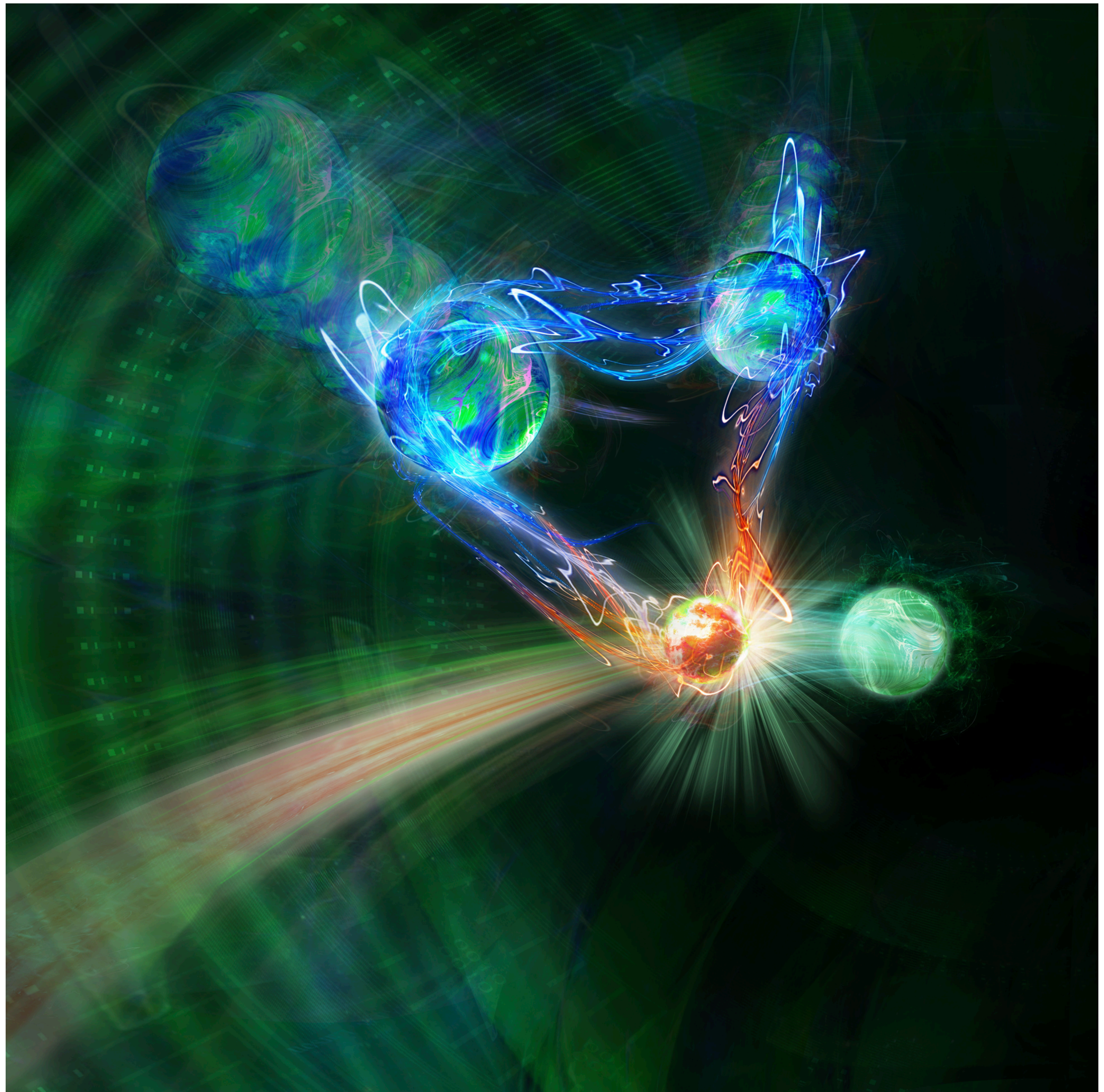
Appendix 9:
K^-pp observed in E15

“K⁻pp” search

$K^- + {}^3He \rightarrow$ “K^-pp” $+ n$

via $\bar{K}N \rightarrow \bar{K}N$ reaction

illustration of the reaction



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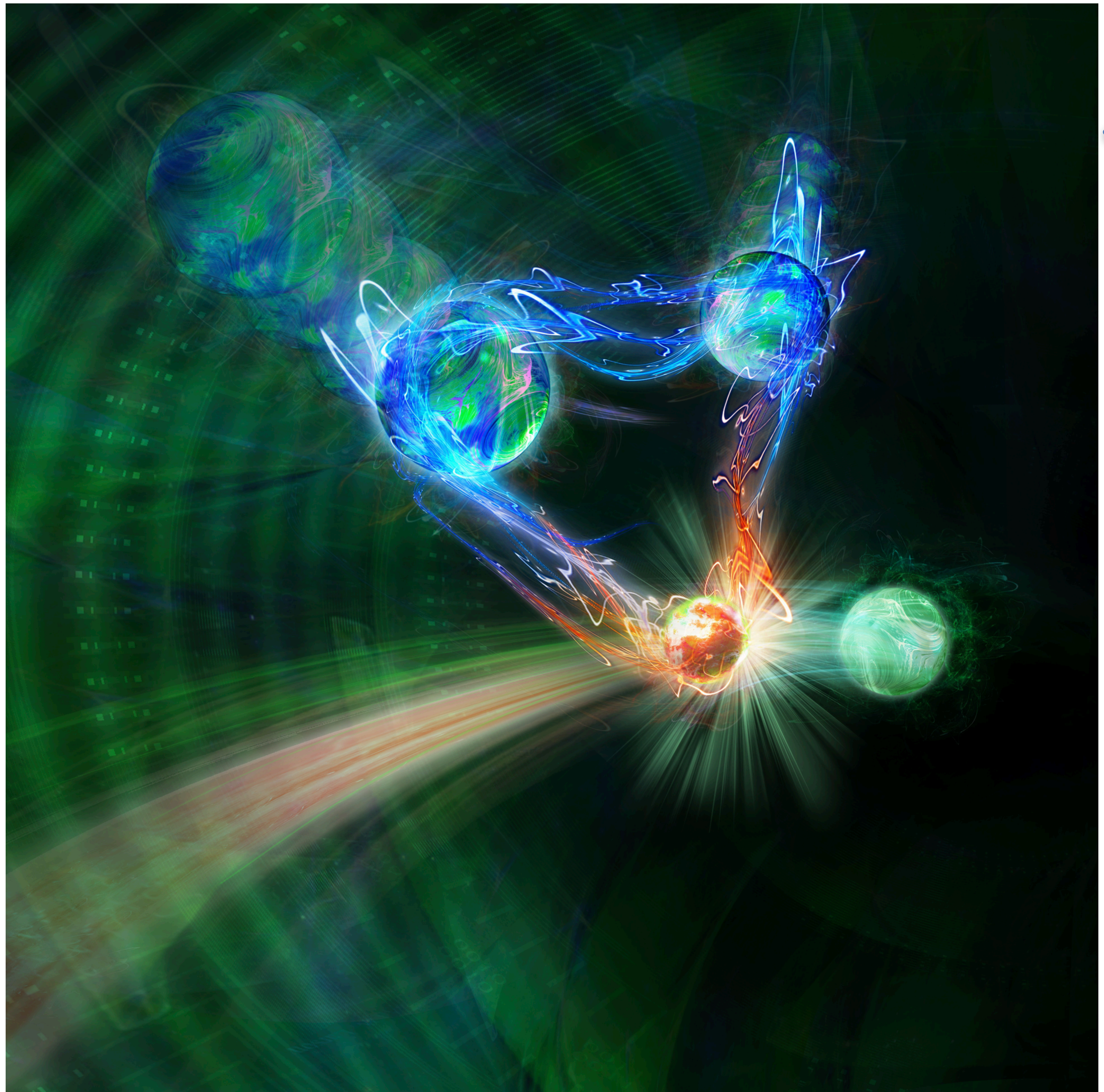

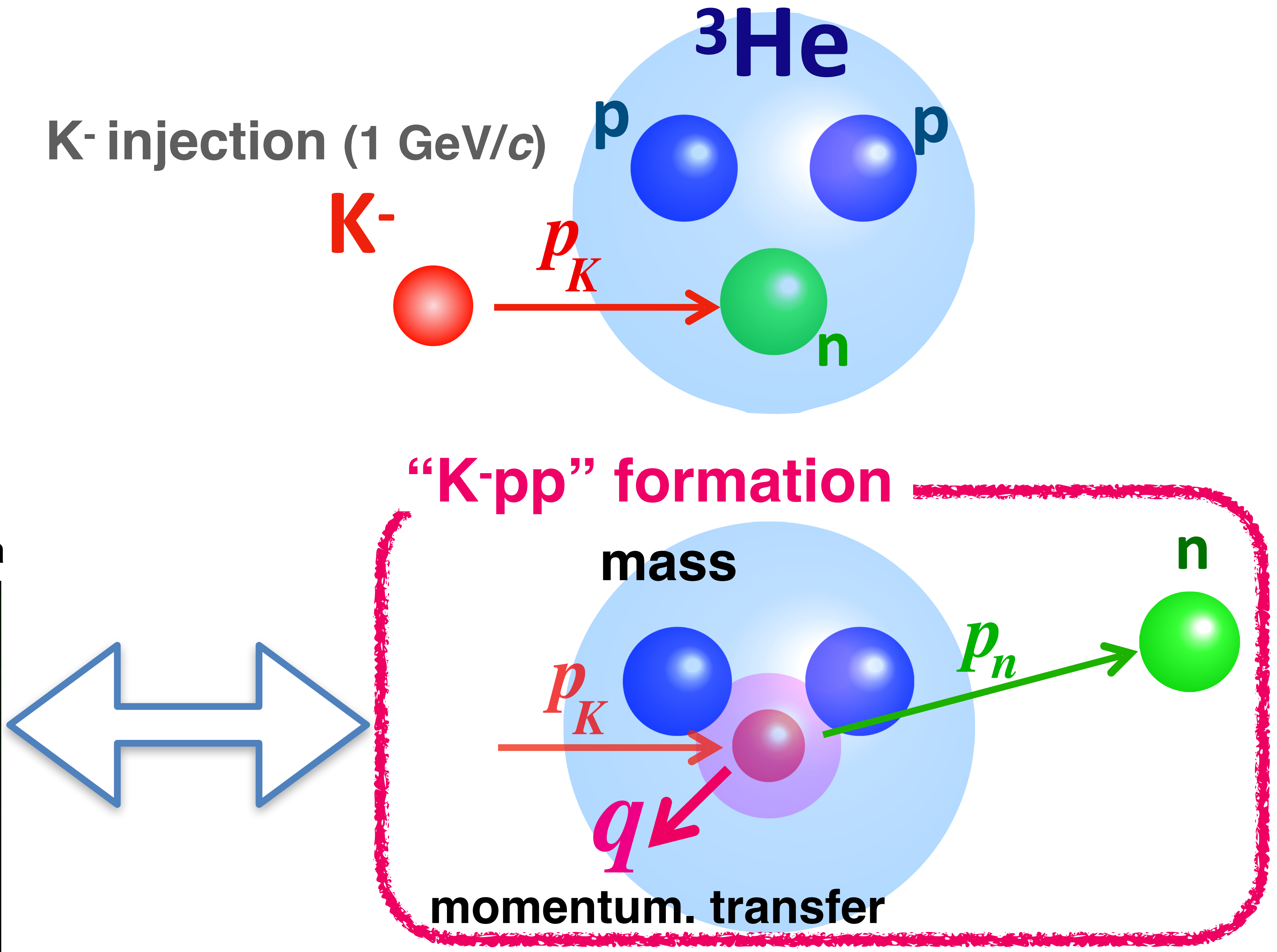

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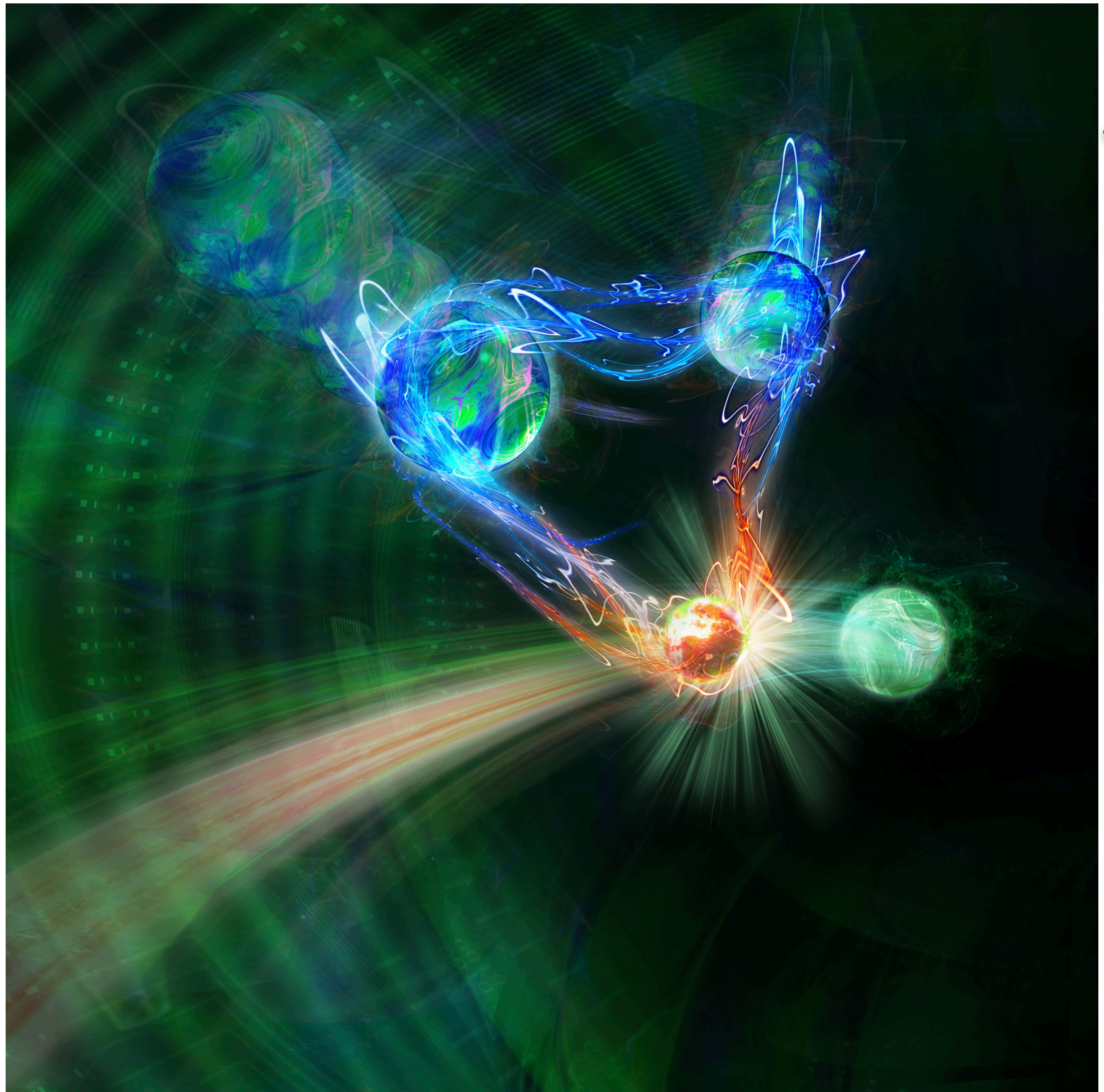

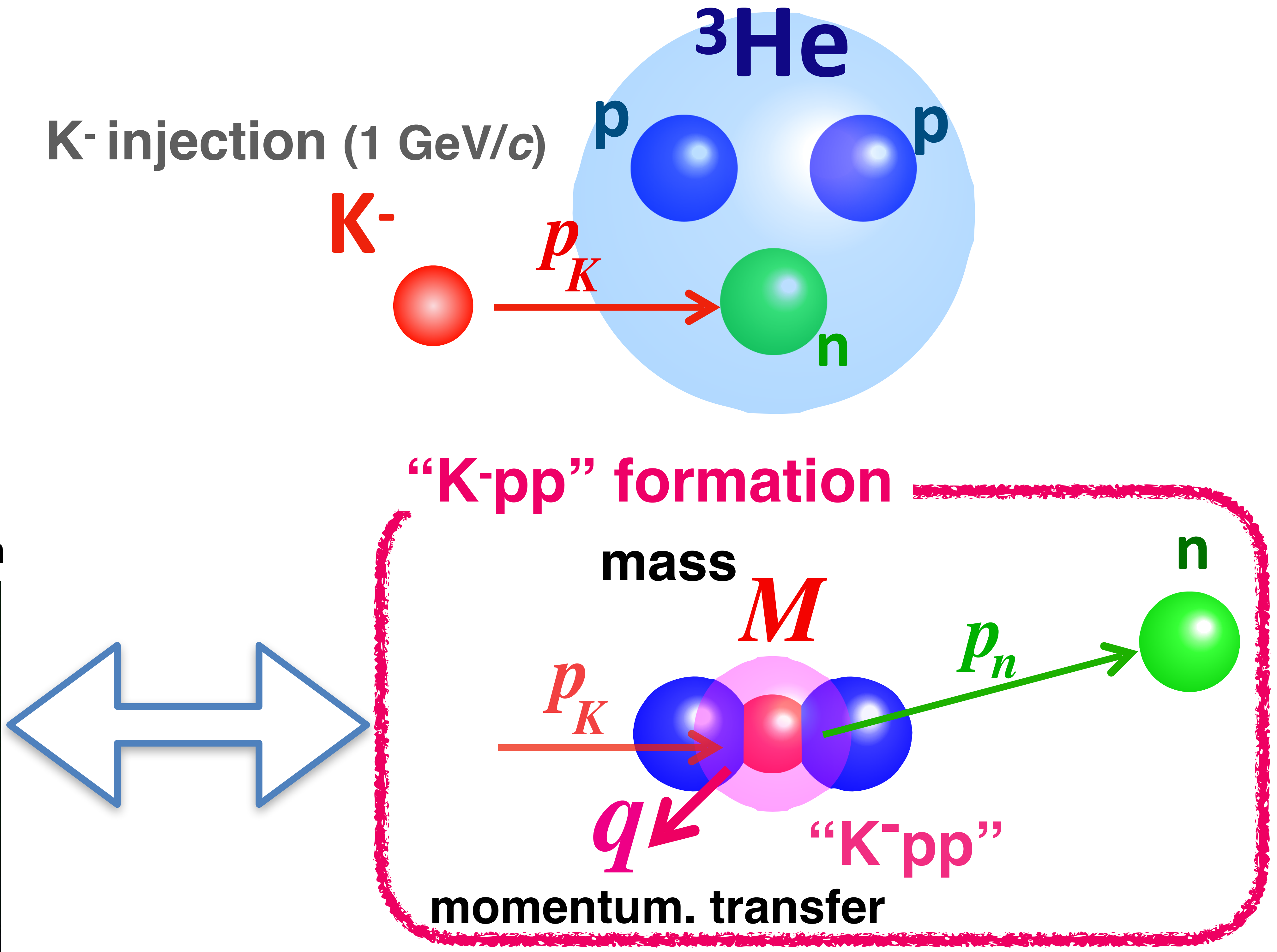

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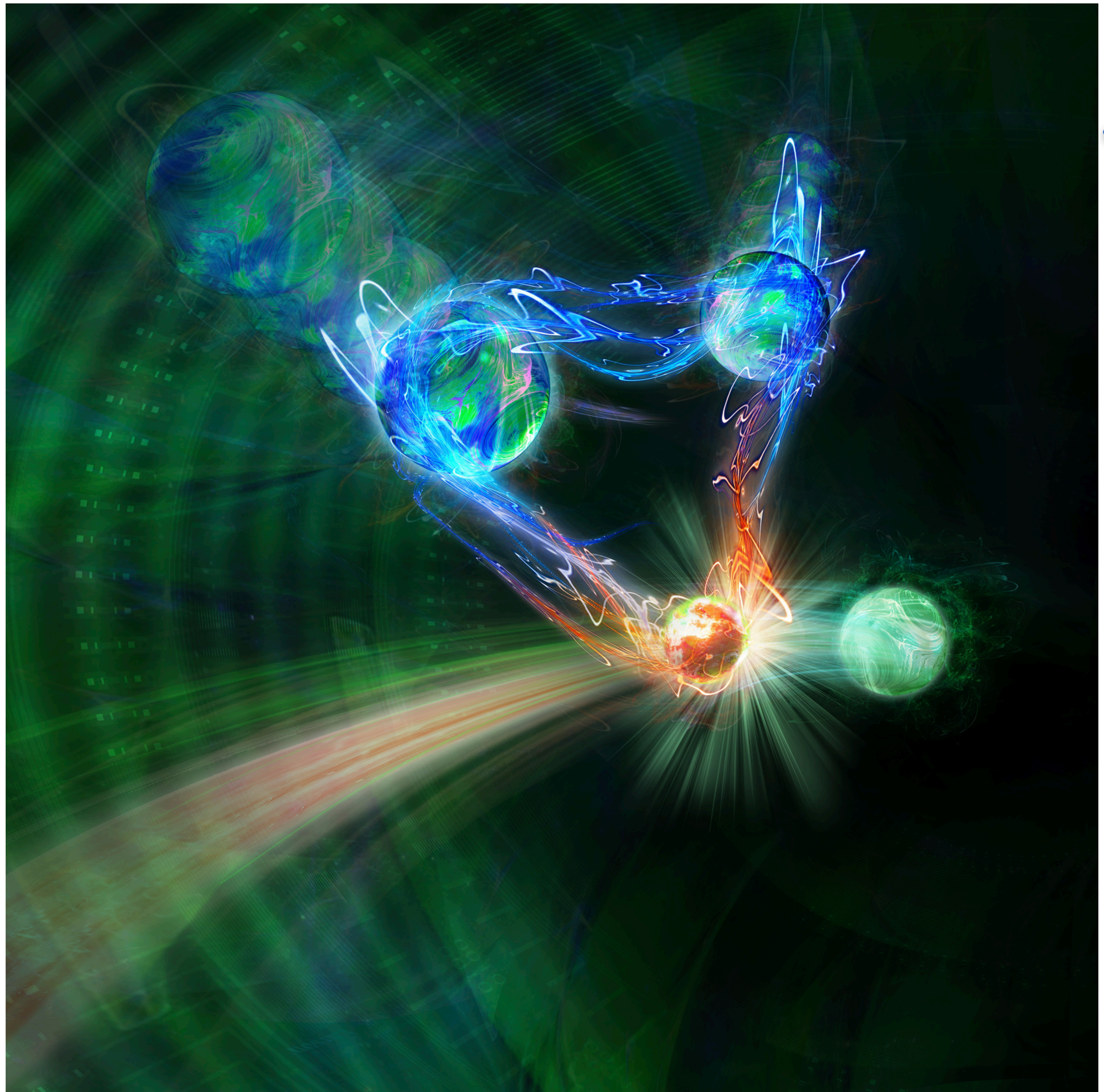

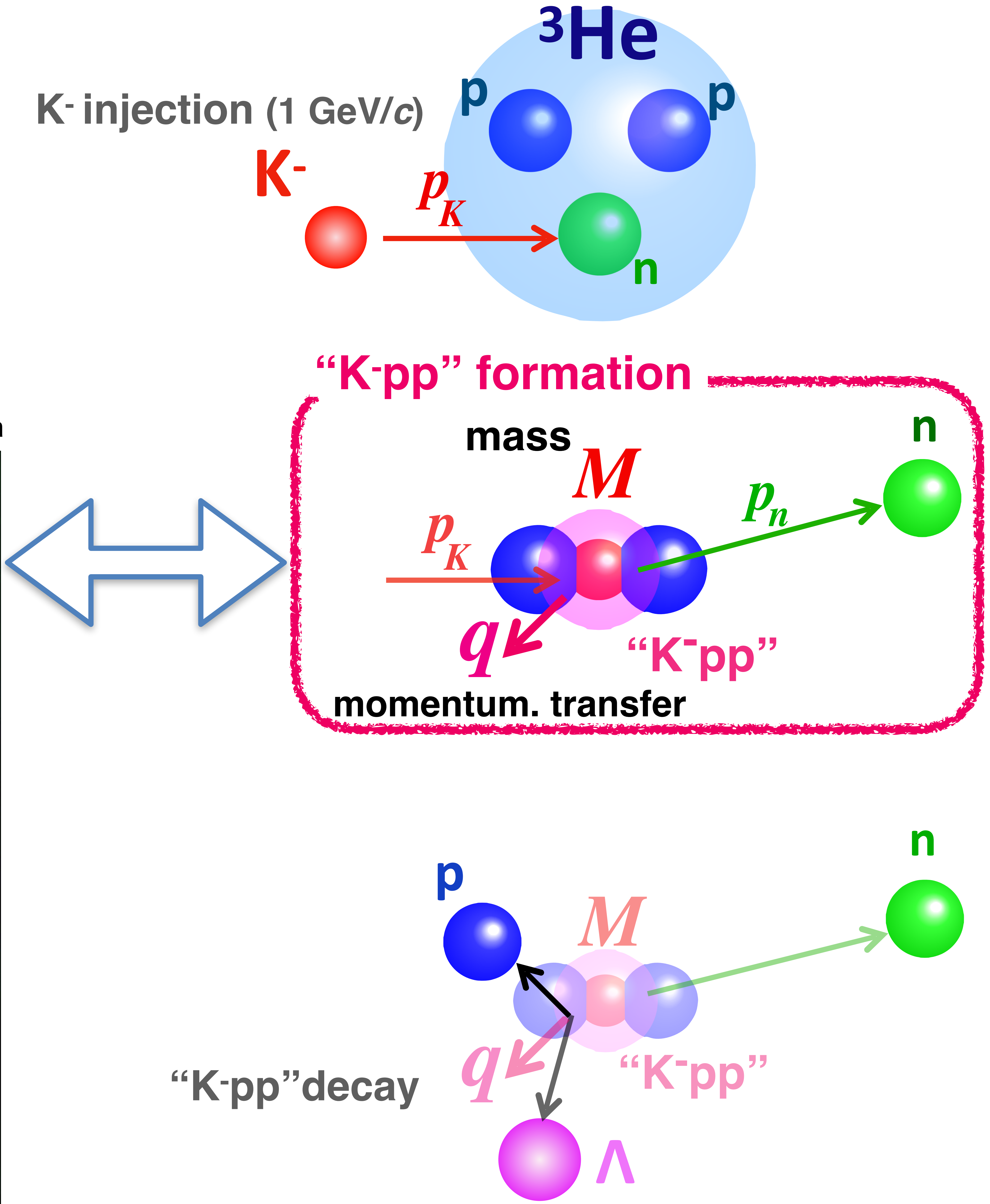

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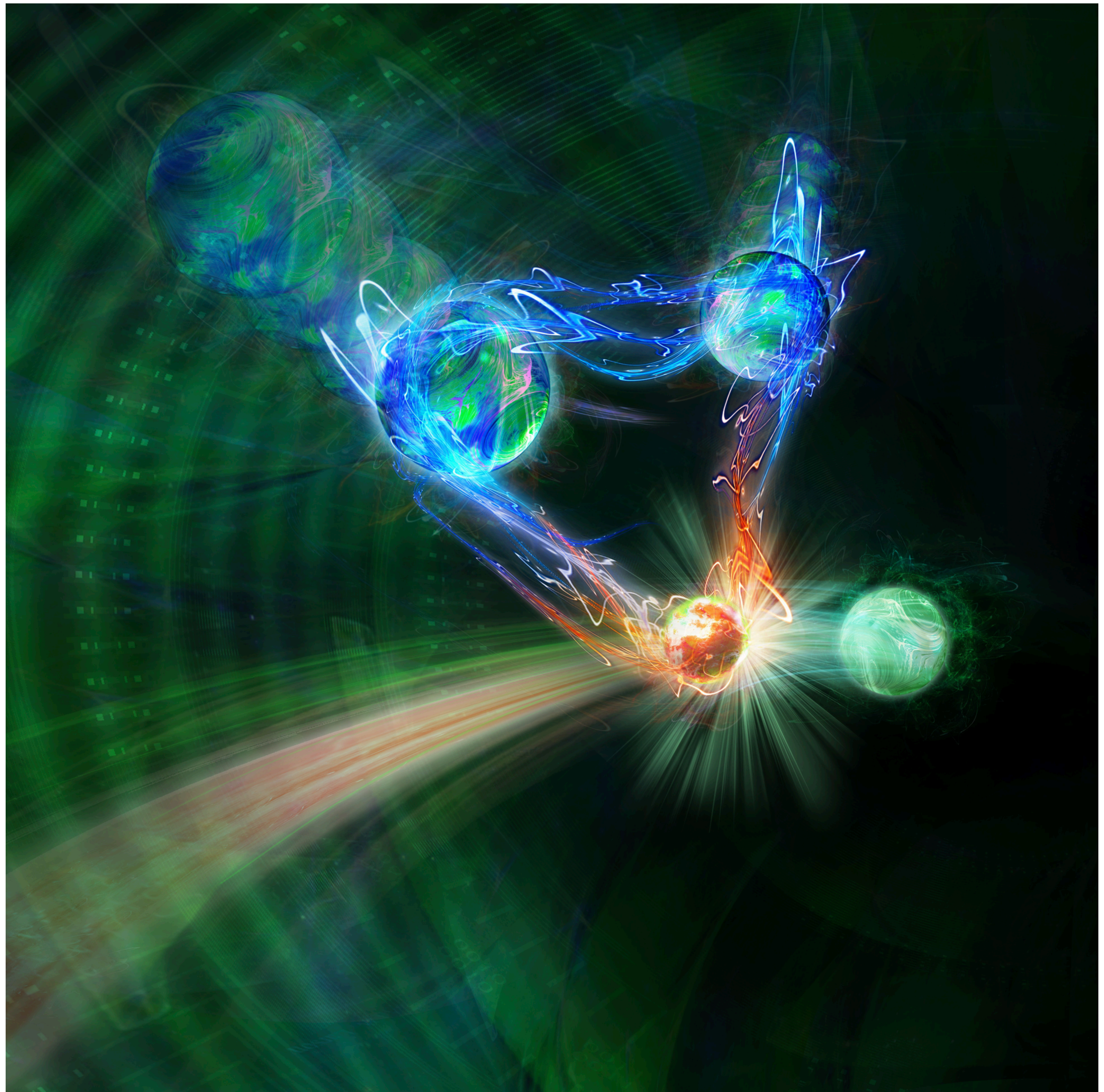

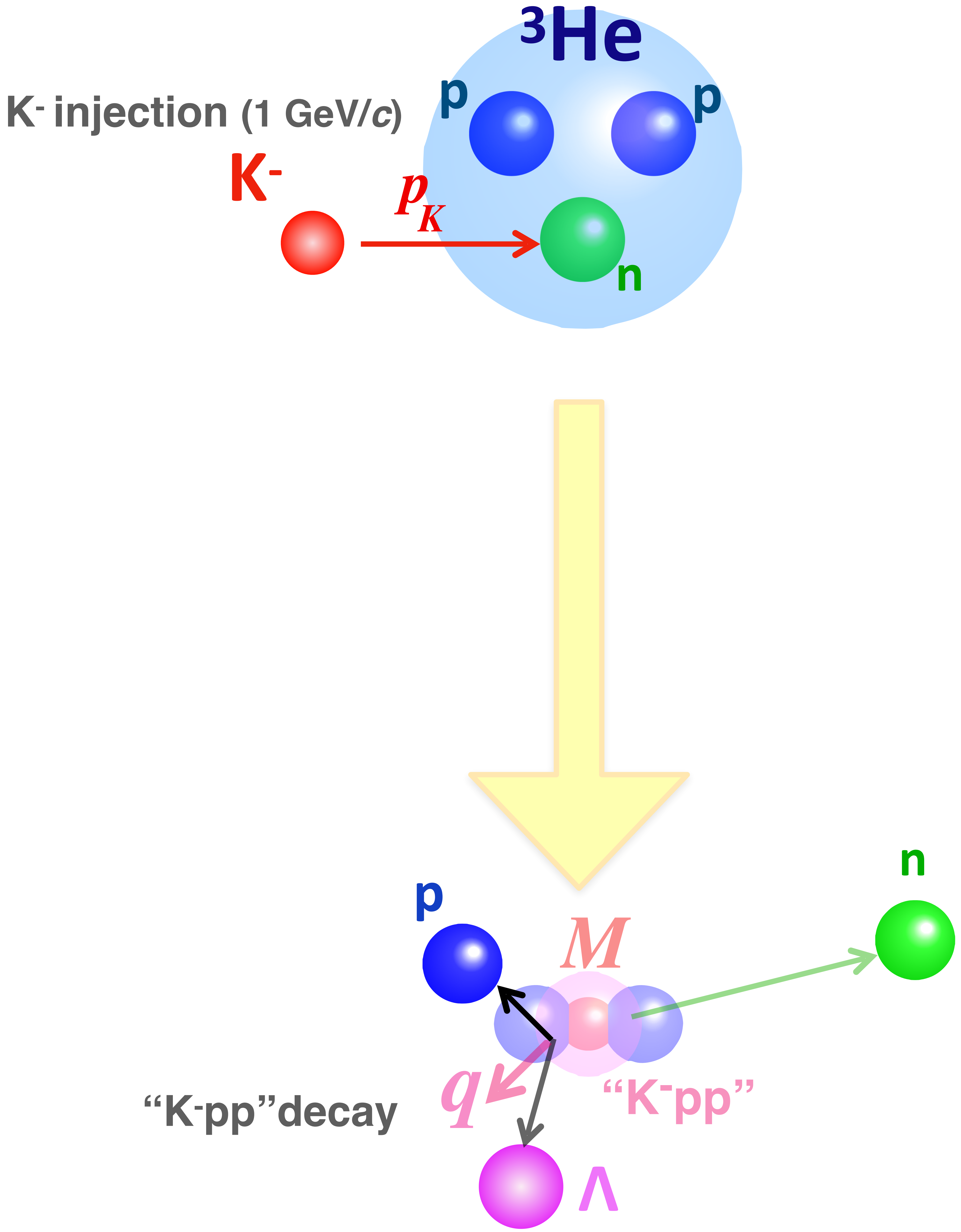

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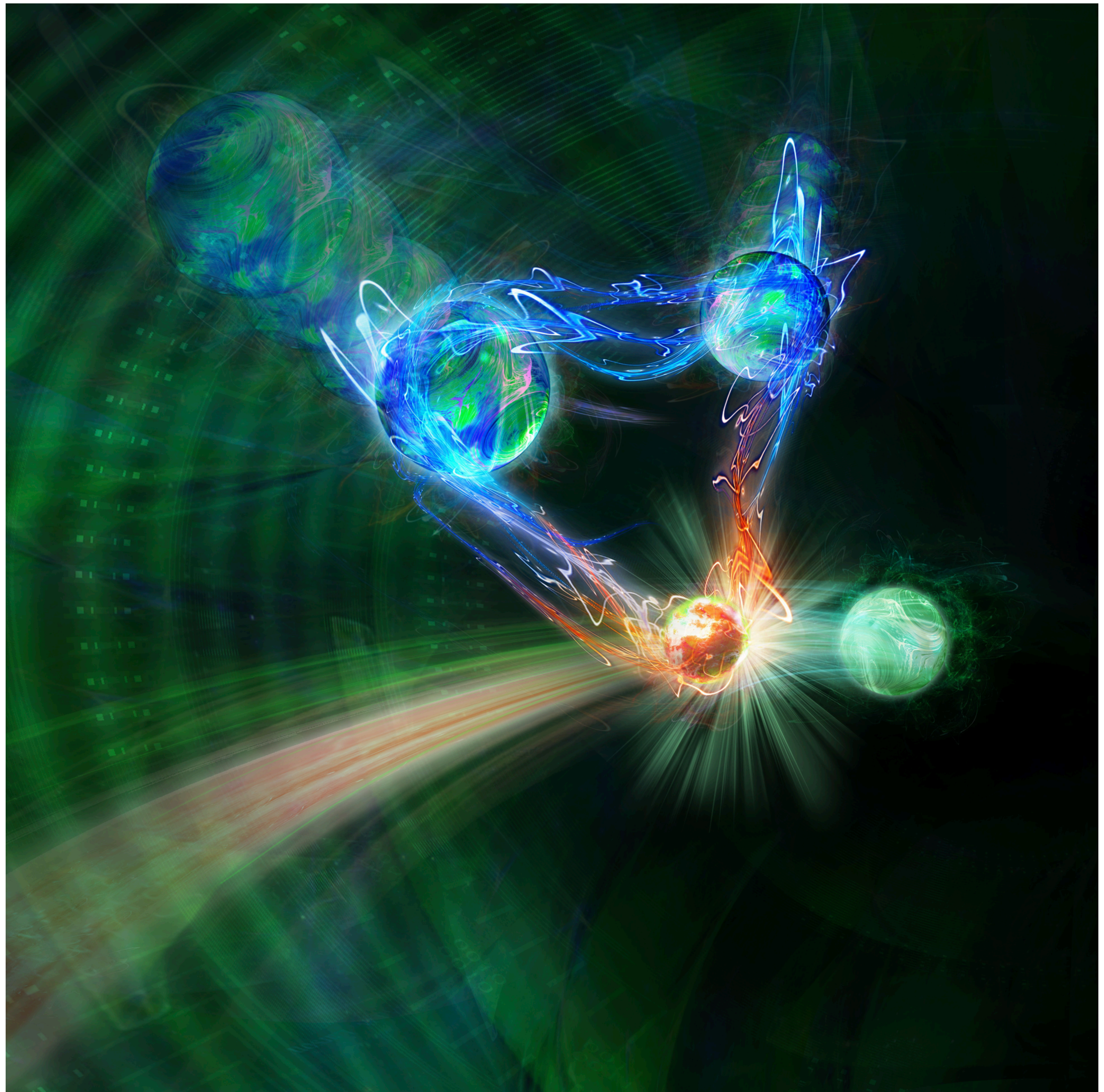

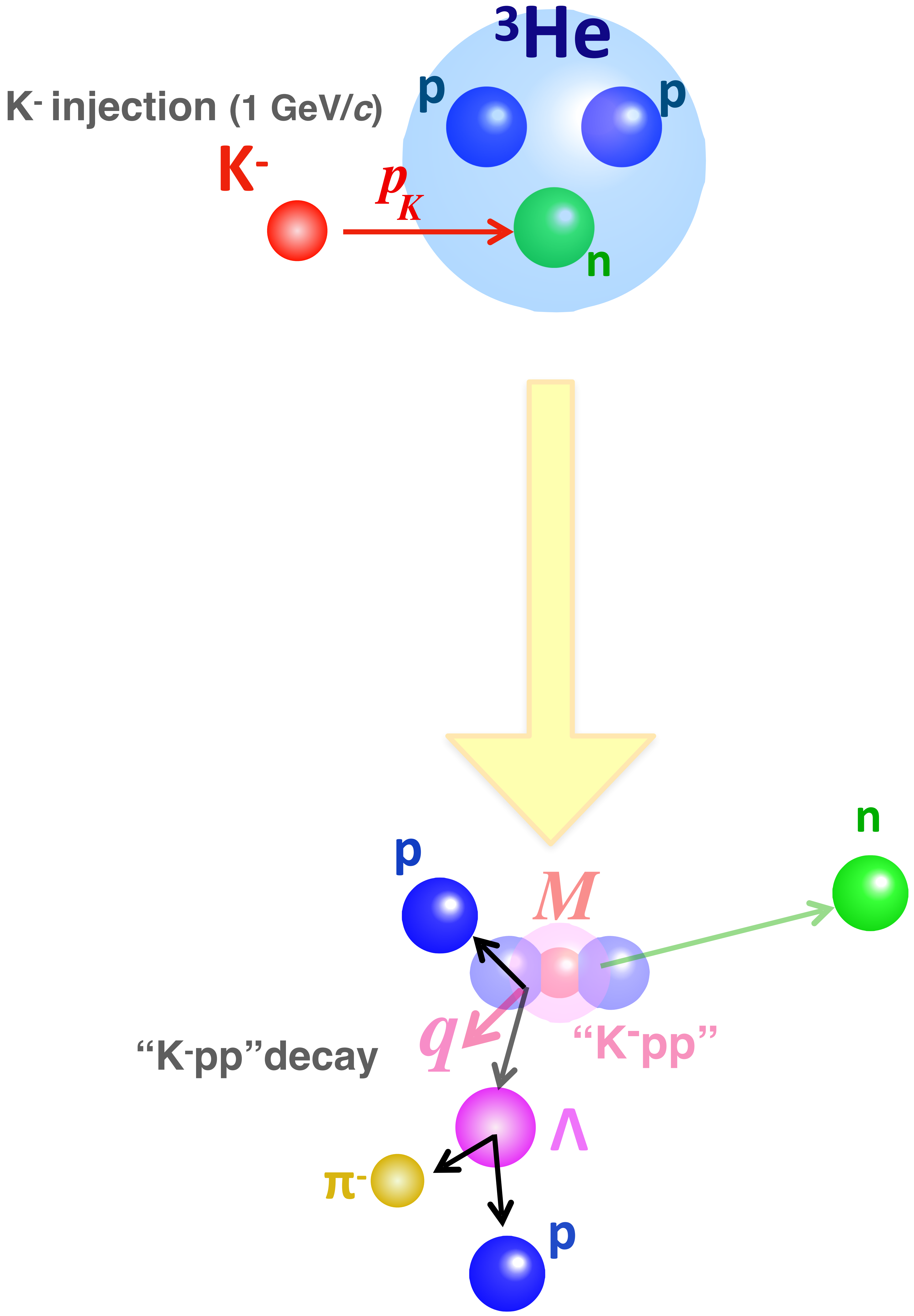

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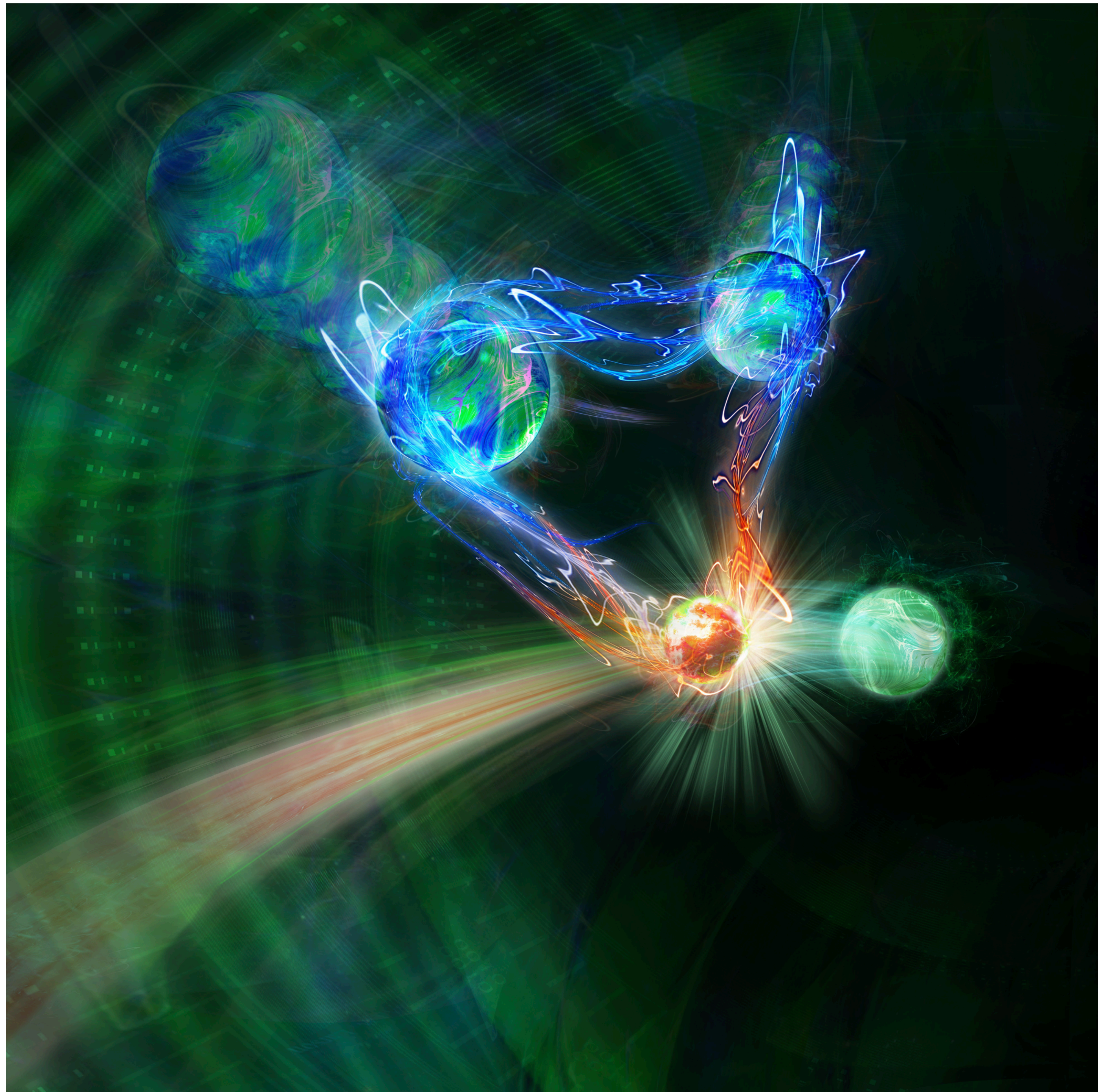

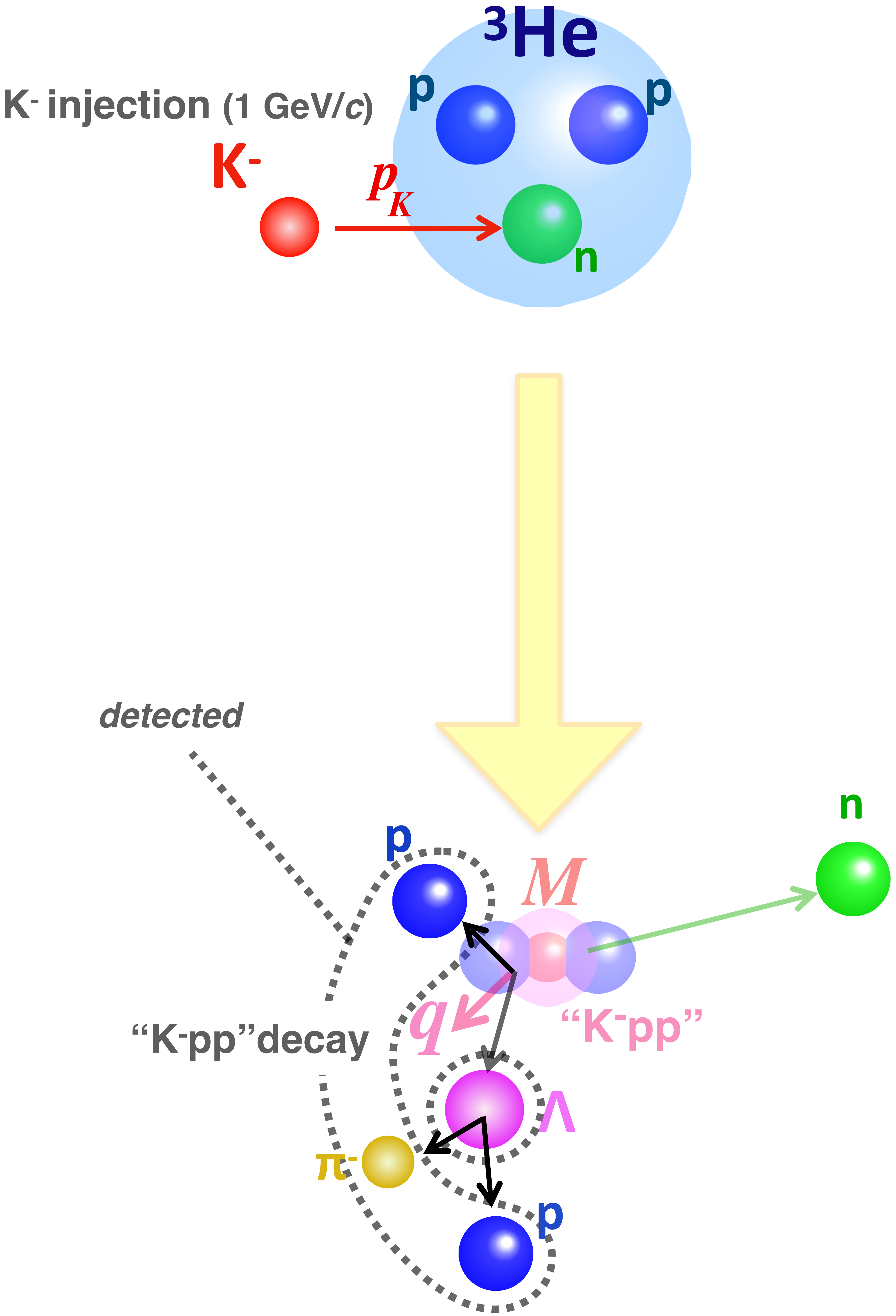

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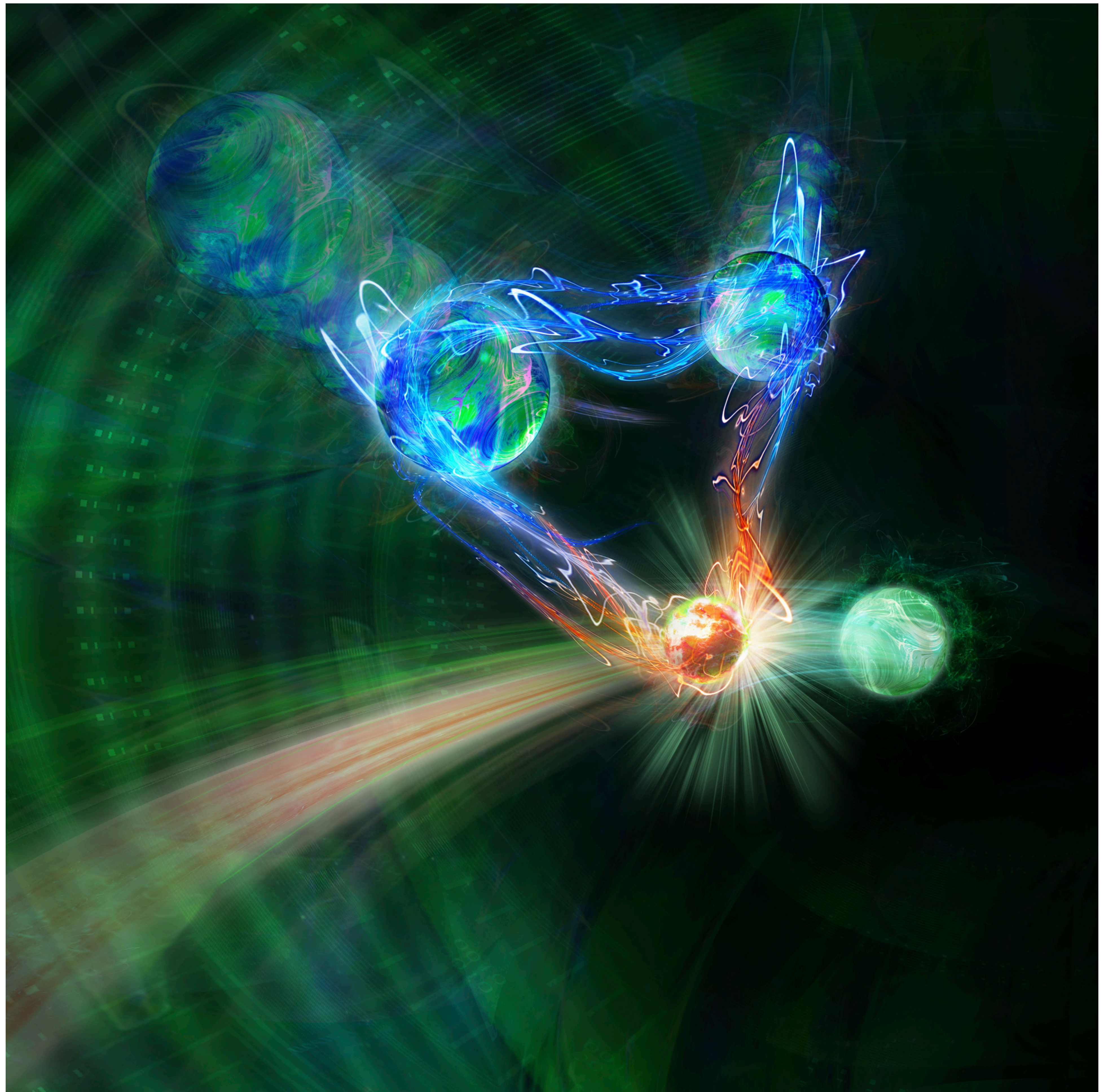

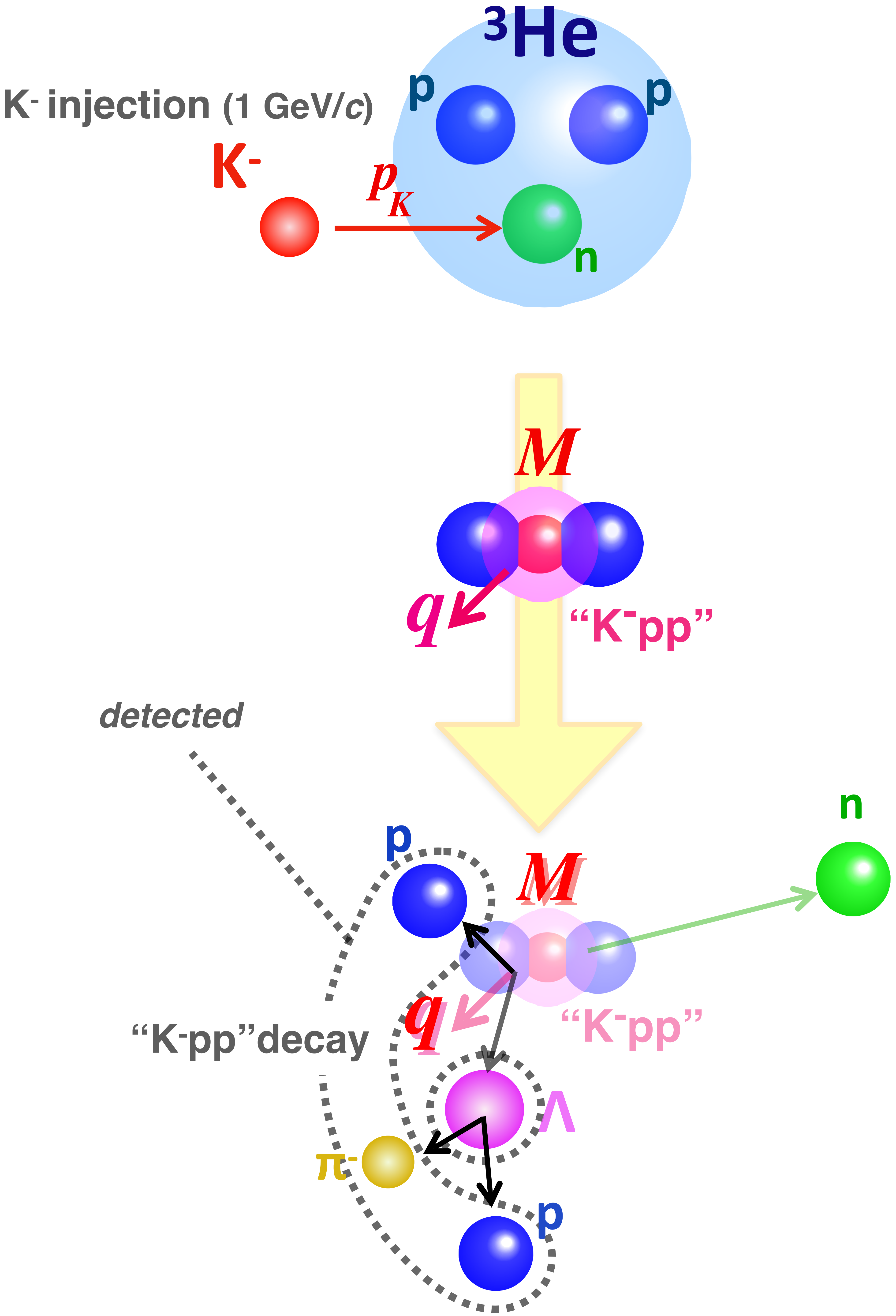

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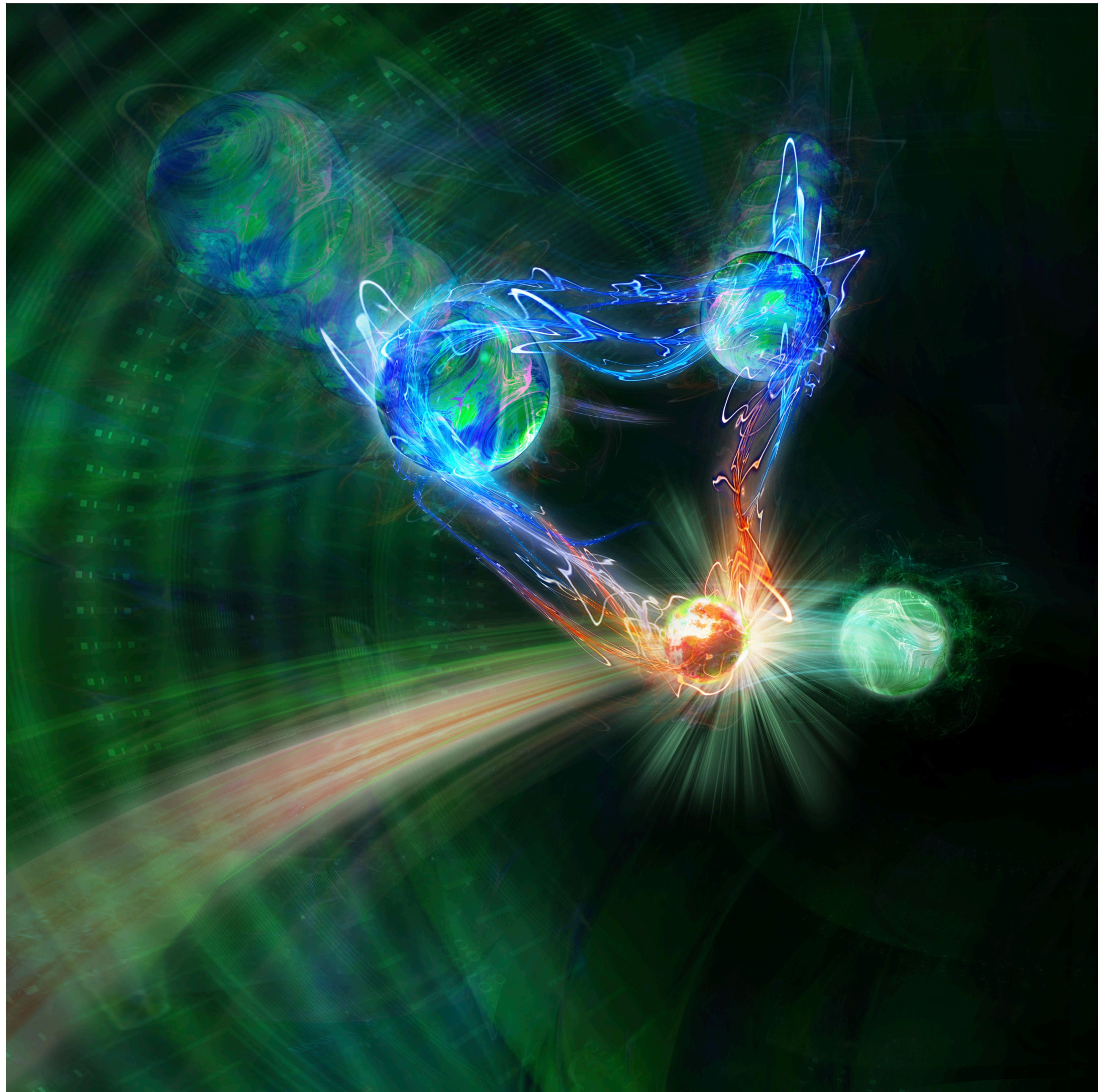

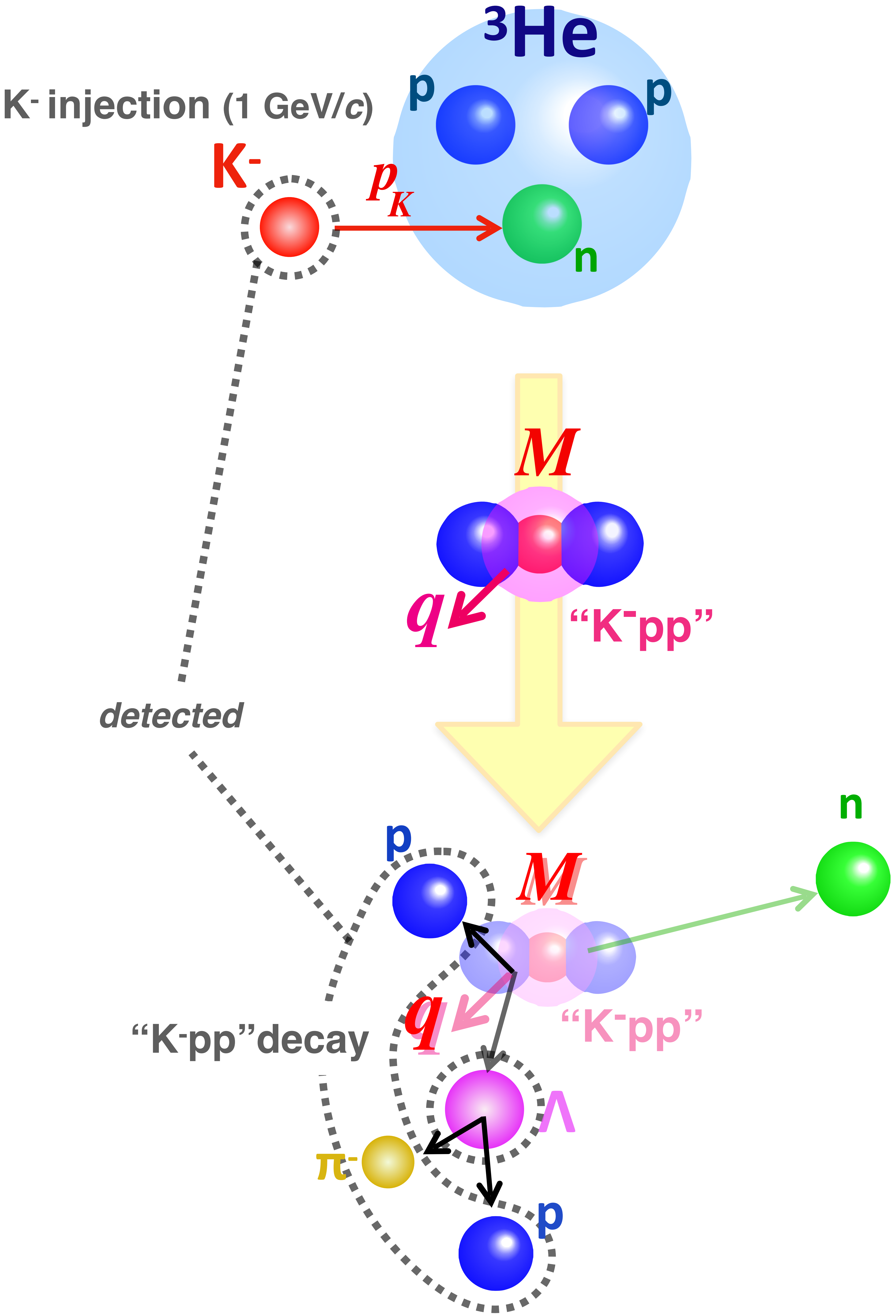

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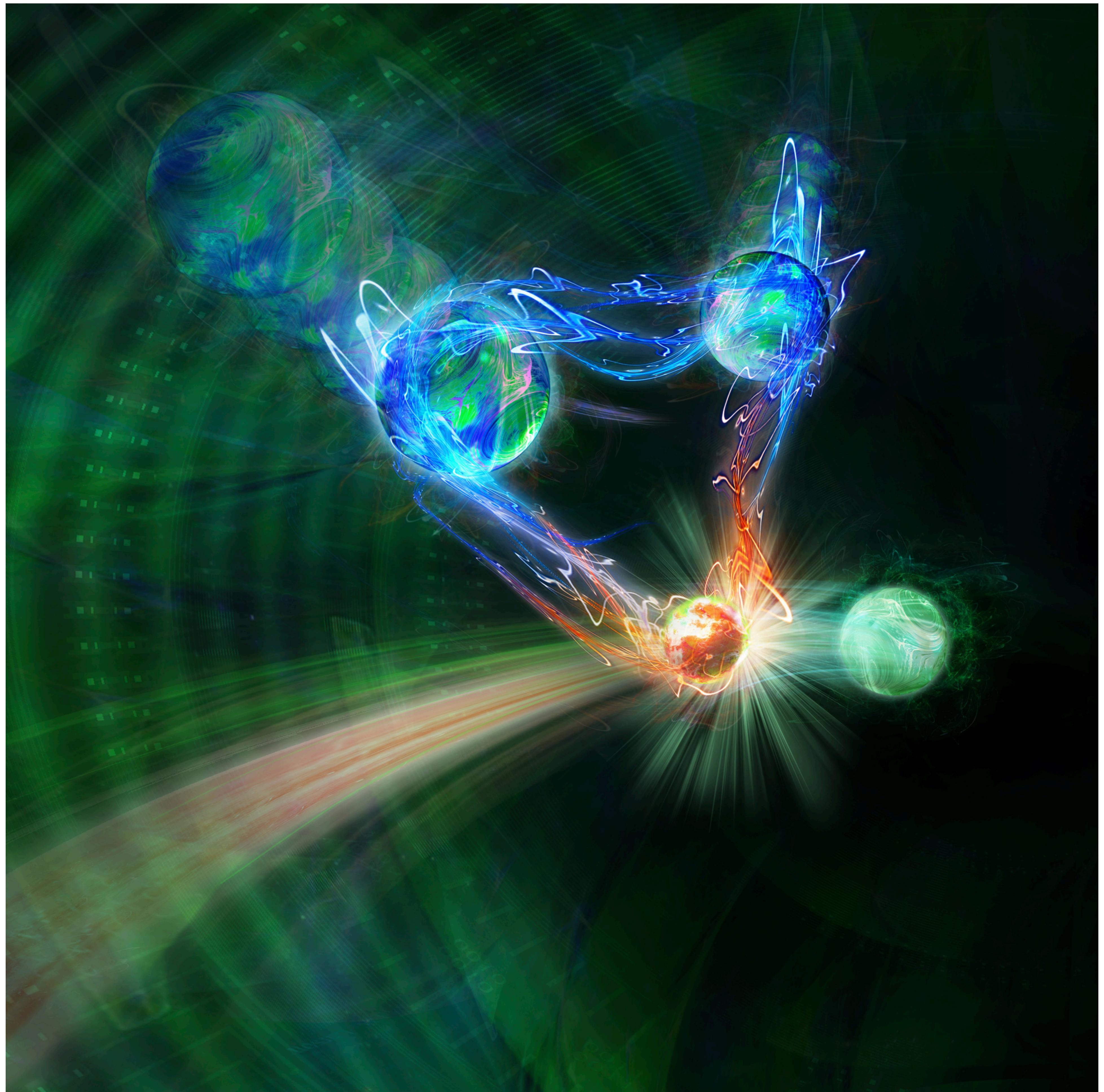
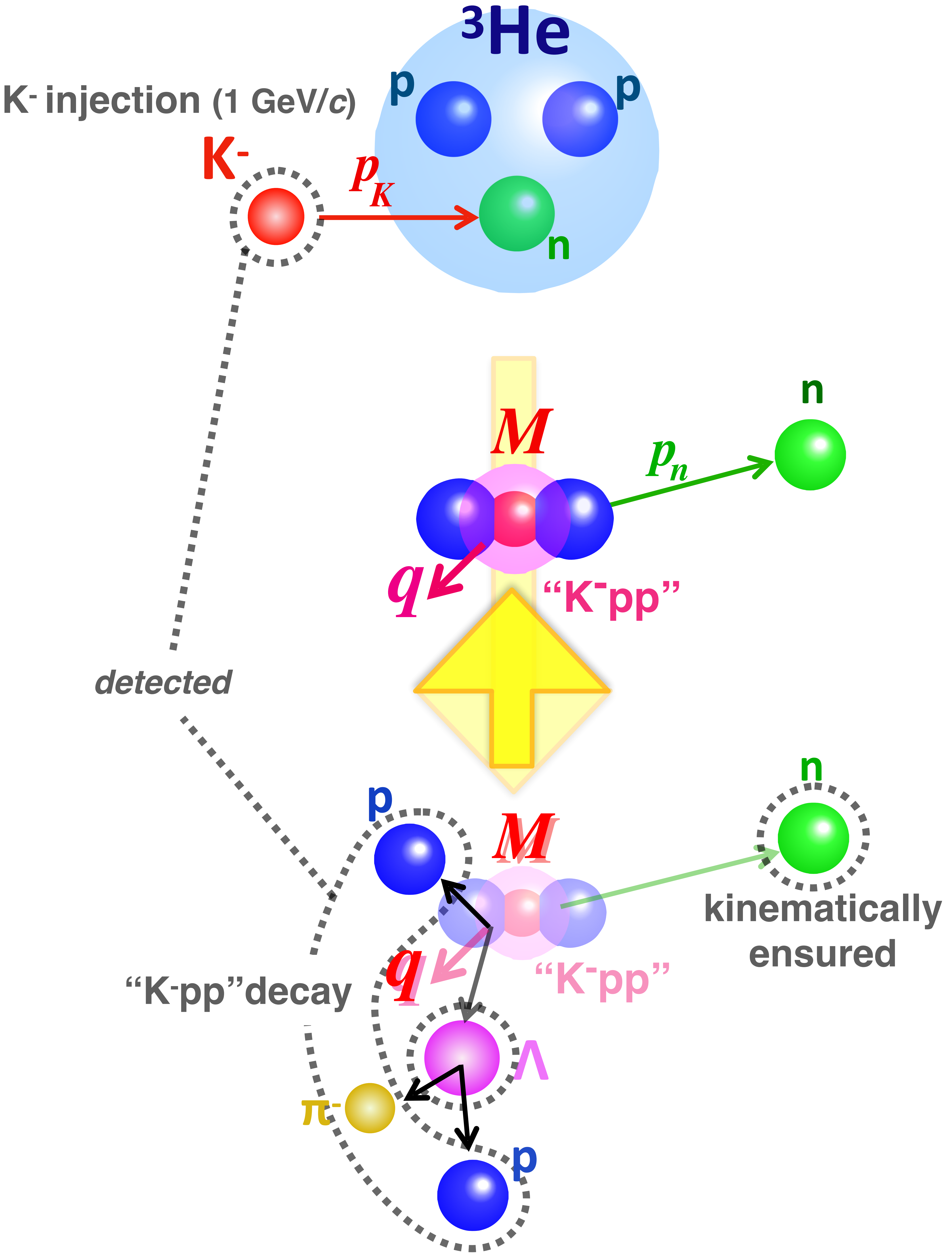
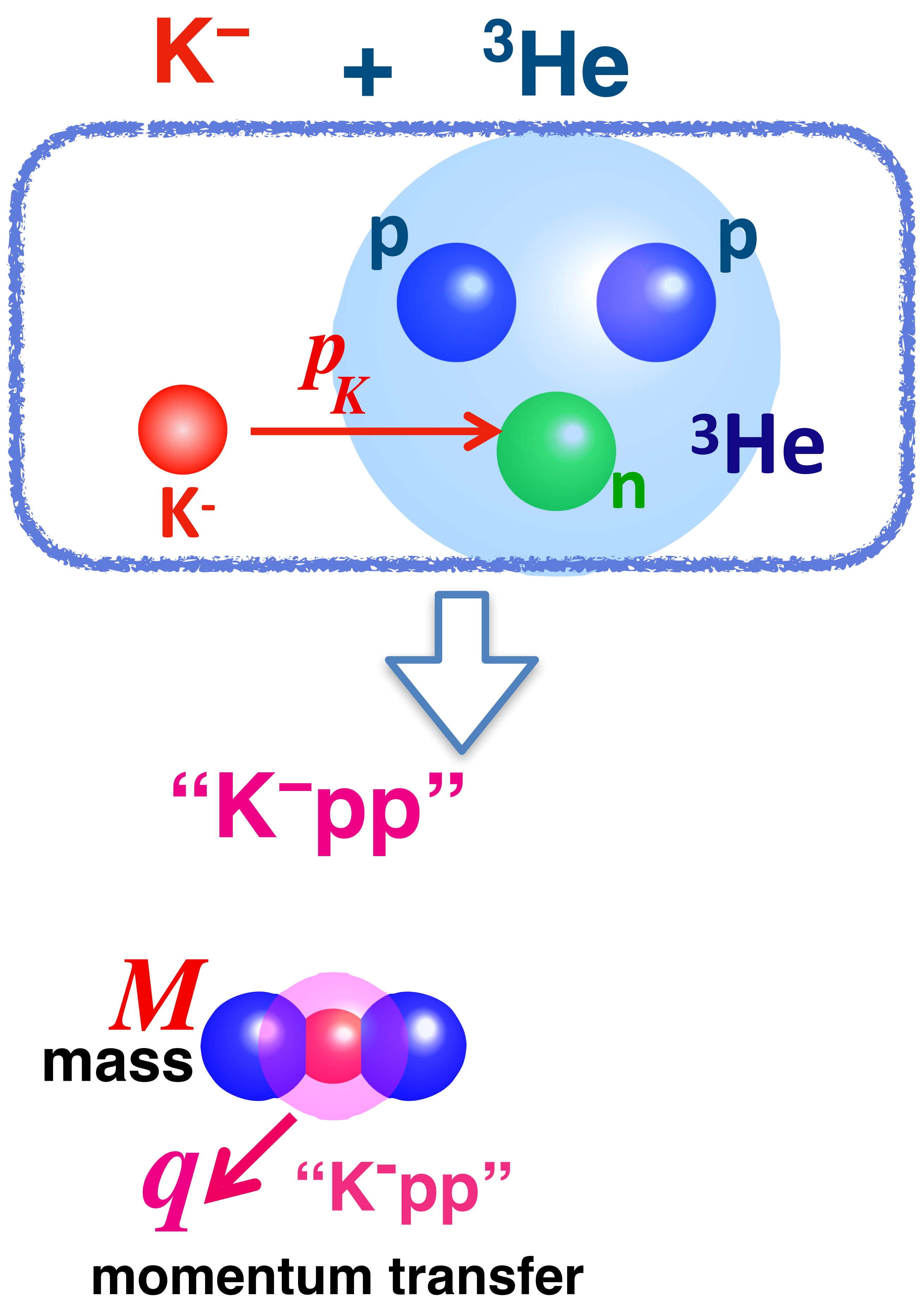
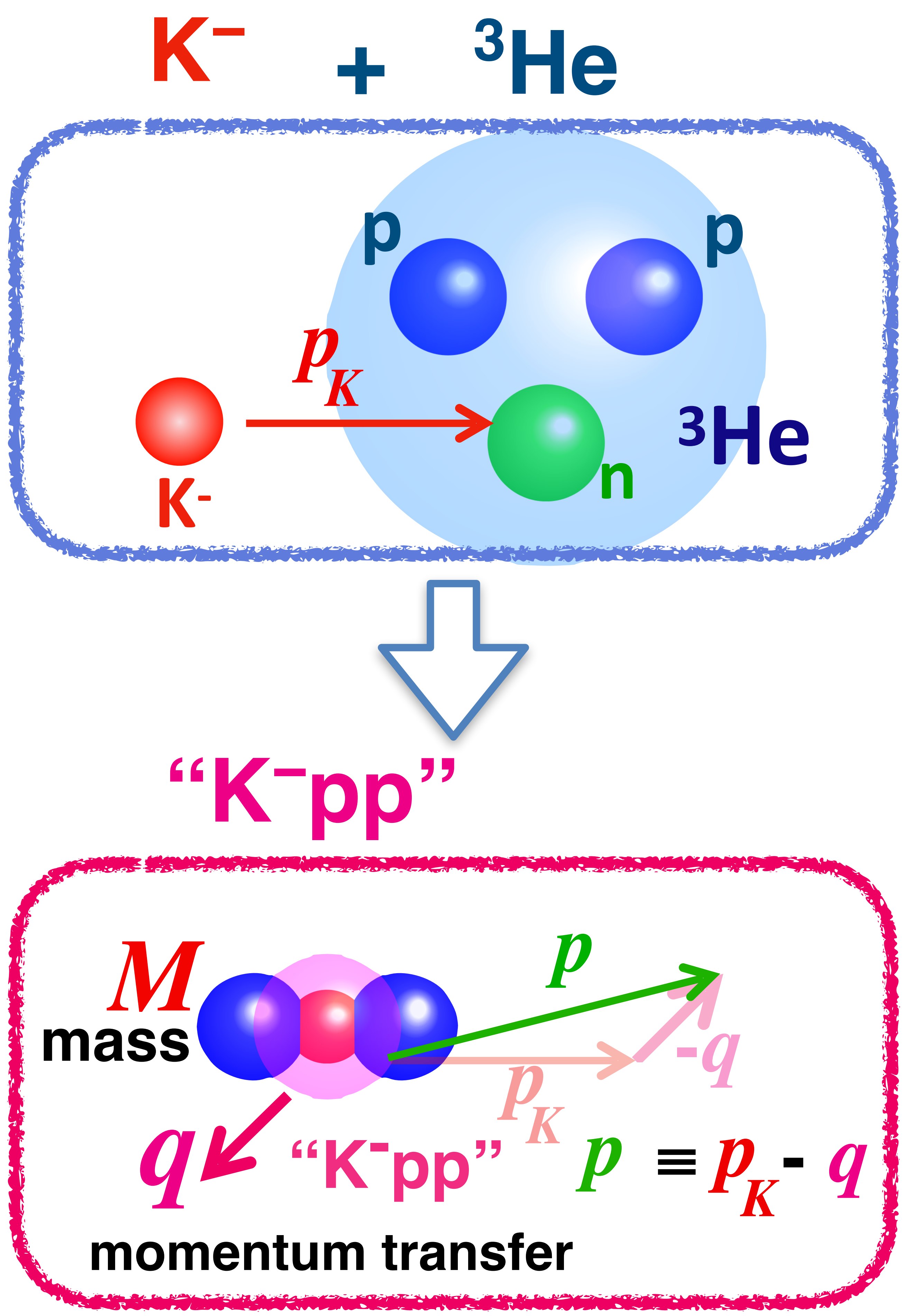
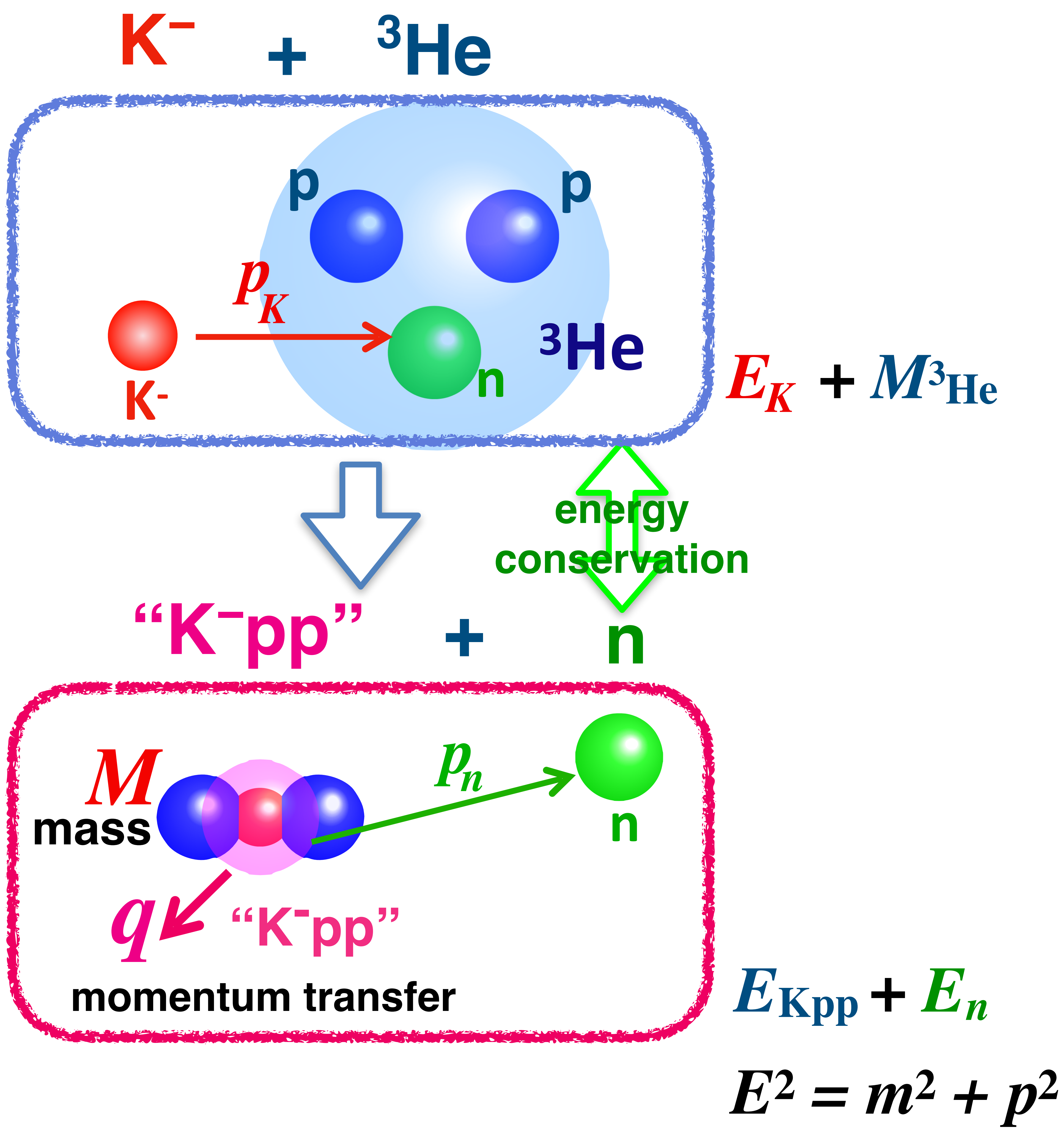


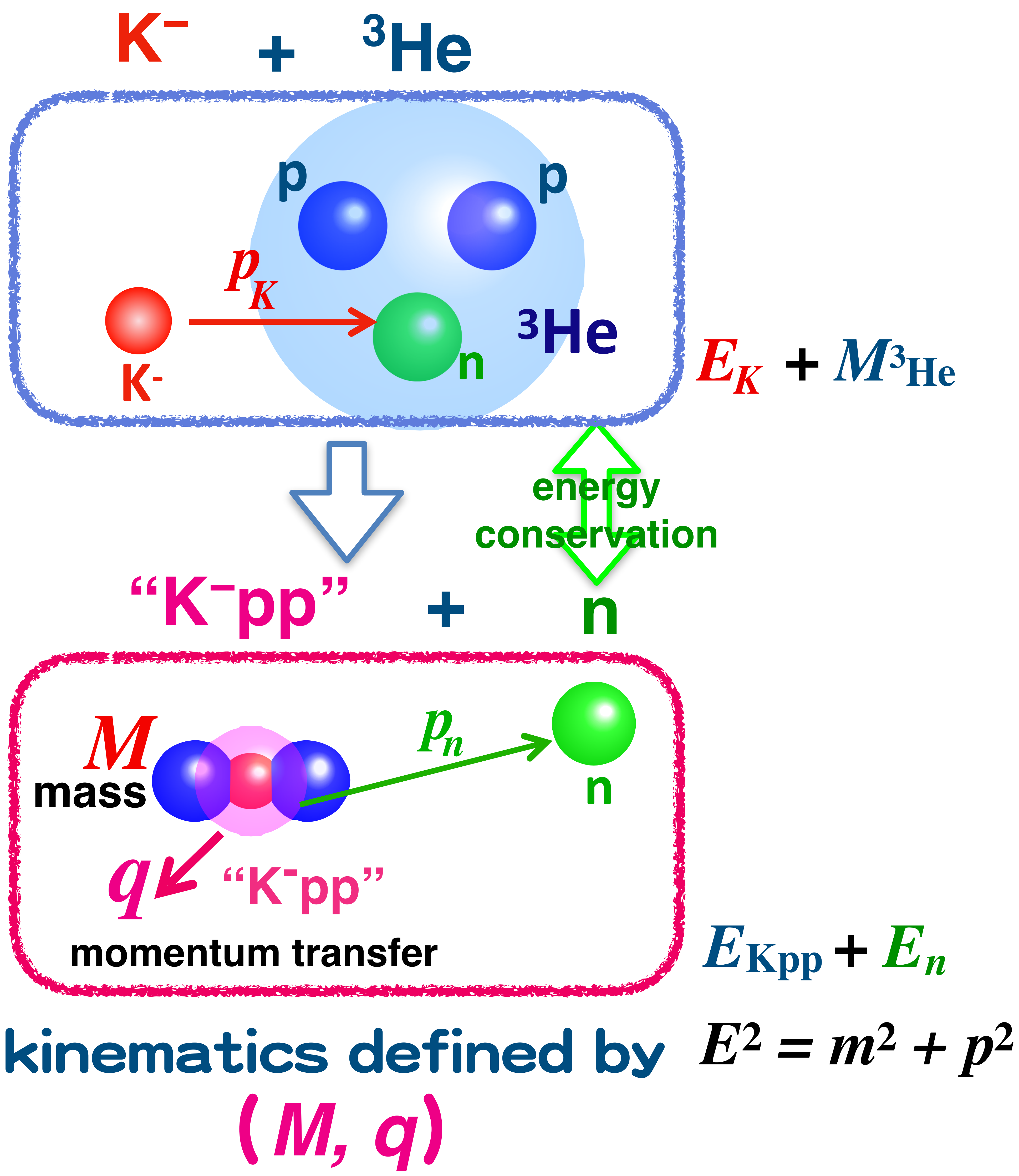



K⁻ + ³He
p
p
p_K
K-
n
³He
"K⁻pp"
M
mass
q
"K⁻pp"
momentum transfer



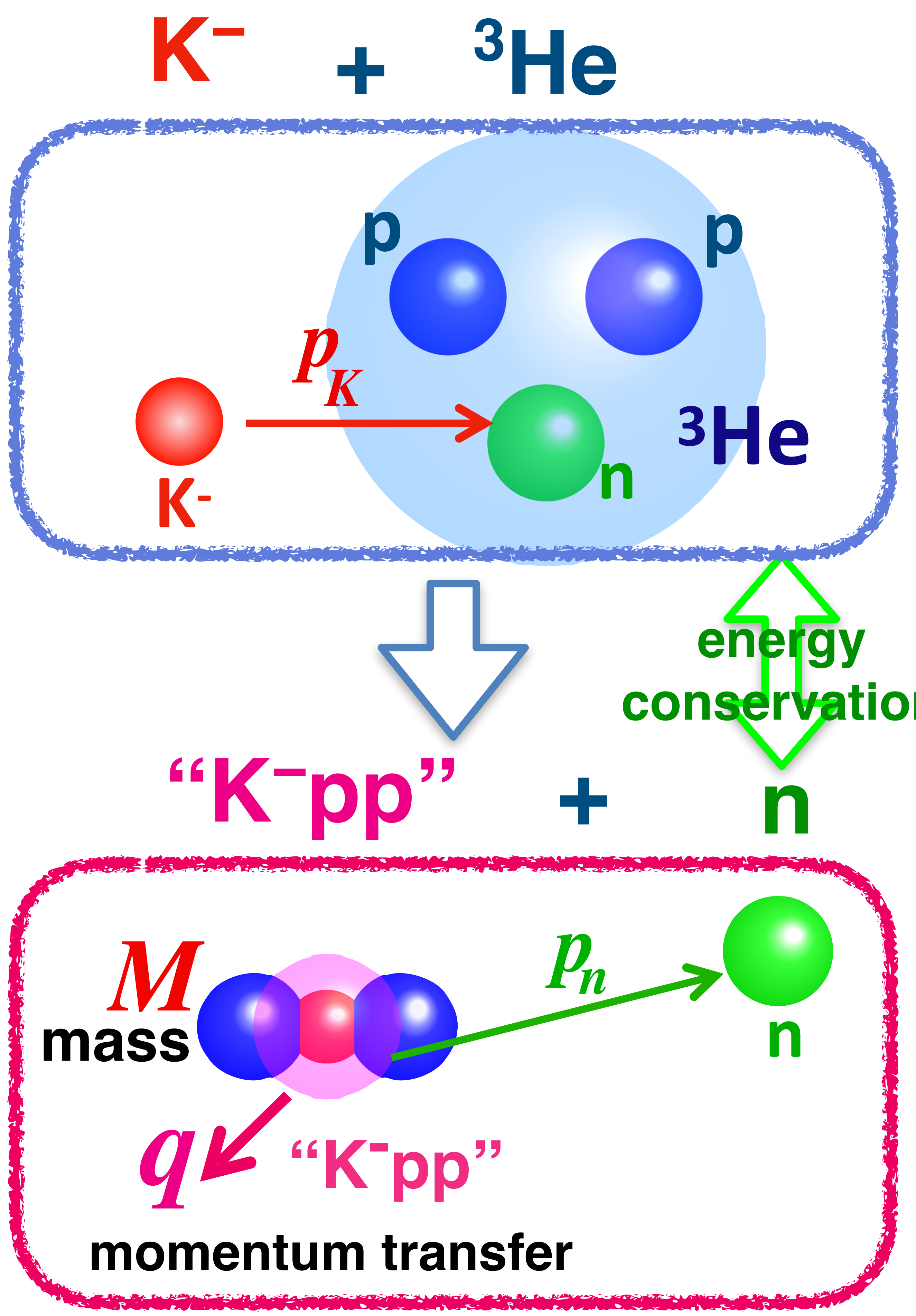
K⁻ + ³He
p
p
p_K
K⁻
n
³He
"K⁻pp"
M
mass
p
-q
p_K
q
"K⁻pp"
p ≡ p_K - q
momentum transfer


K⁻ + ³He
p
p
p_K
K⁻
n
³He
$E_K + M_{^3\mathrm{He}}$
energy
conservation
"K⁻pp" + n
M
mass
p_n
n
q
"K⁻pp"
momentum transfer
$E_{\mathrm{Kpp}} + E_n$
$E^2 = m^2 + p^2$

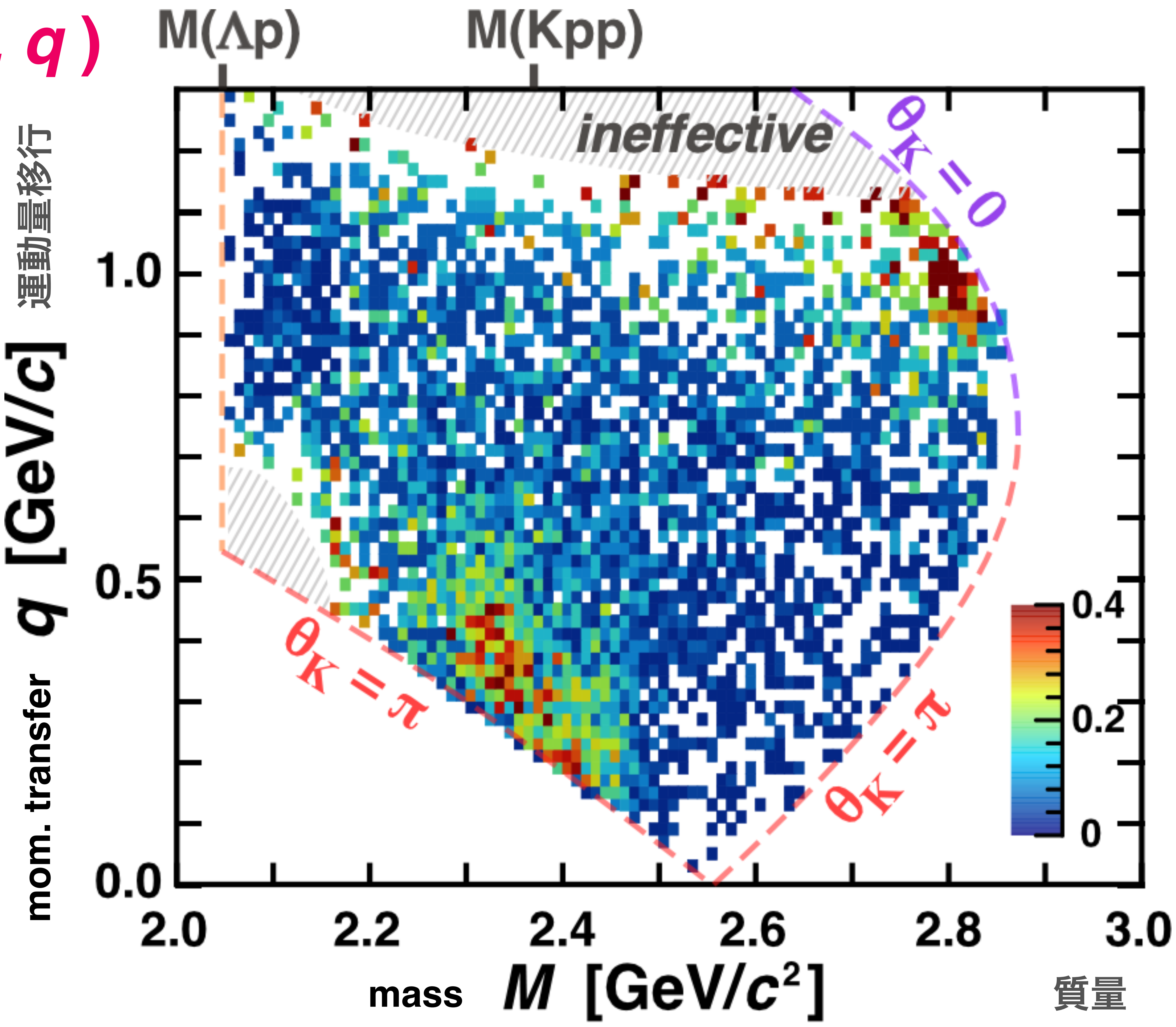


K⁻ + ³He
p
p
p_K
K⁻
n
³He
E_K + M_³He
energy conservation
"K⁻pp" + n
M
mass
p_n
n
q
"K⁻pp"
momentum transfer
E_Kpp + E_n
kinematics defined by
E² = m² + p²
(M, q)

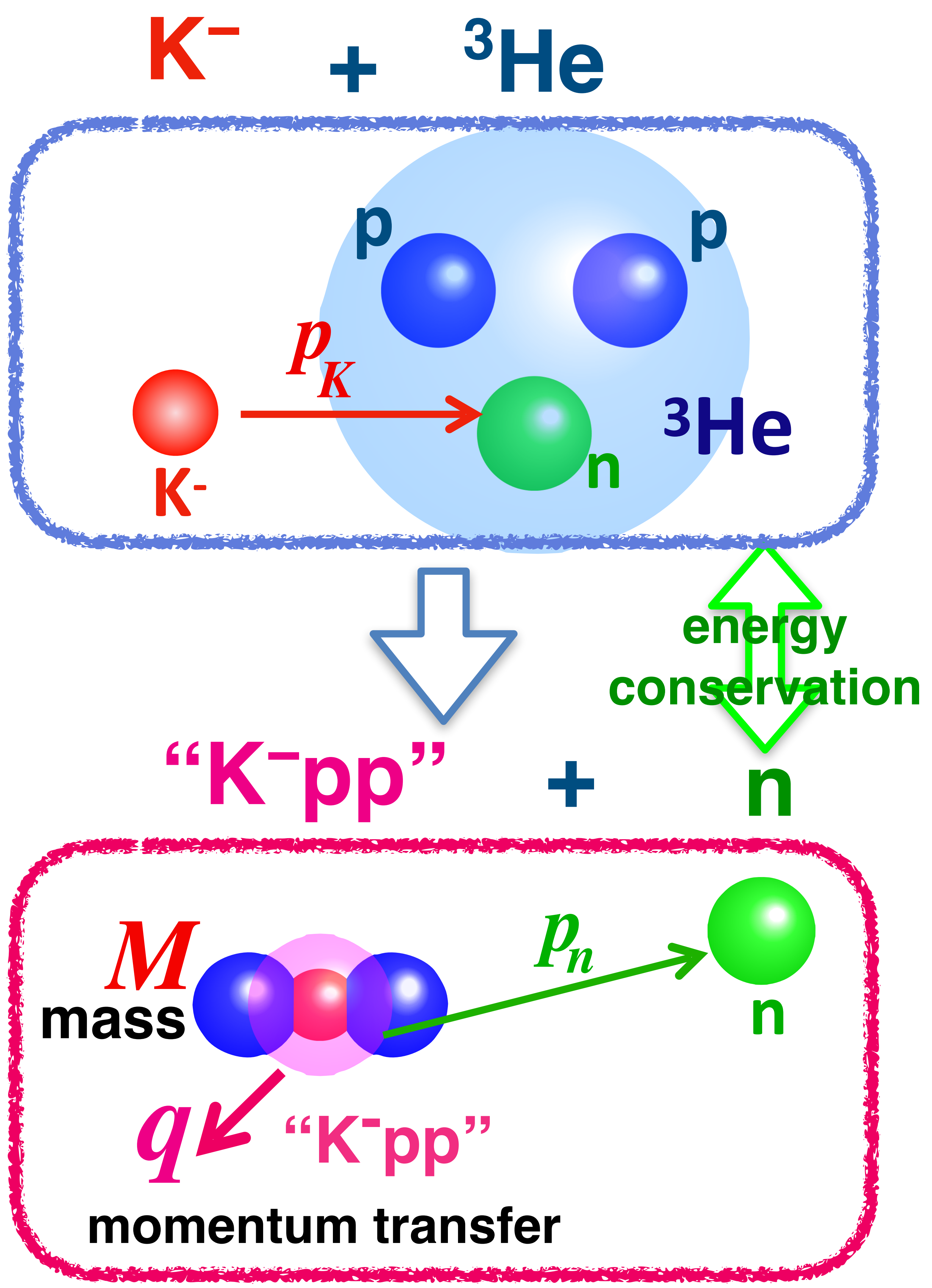
2D analysis on (*M*, *q*)

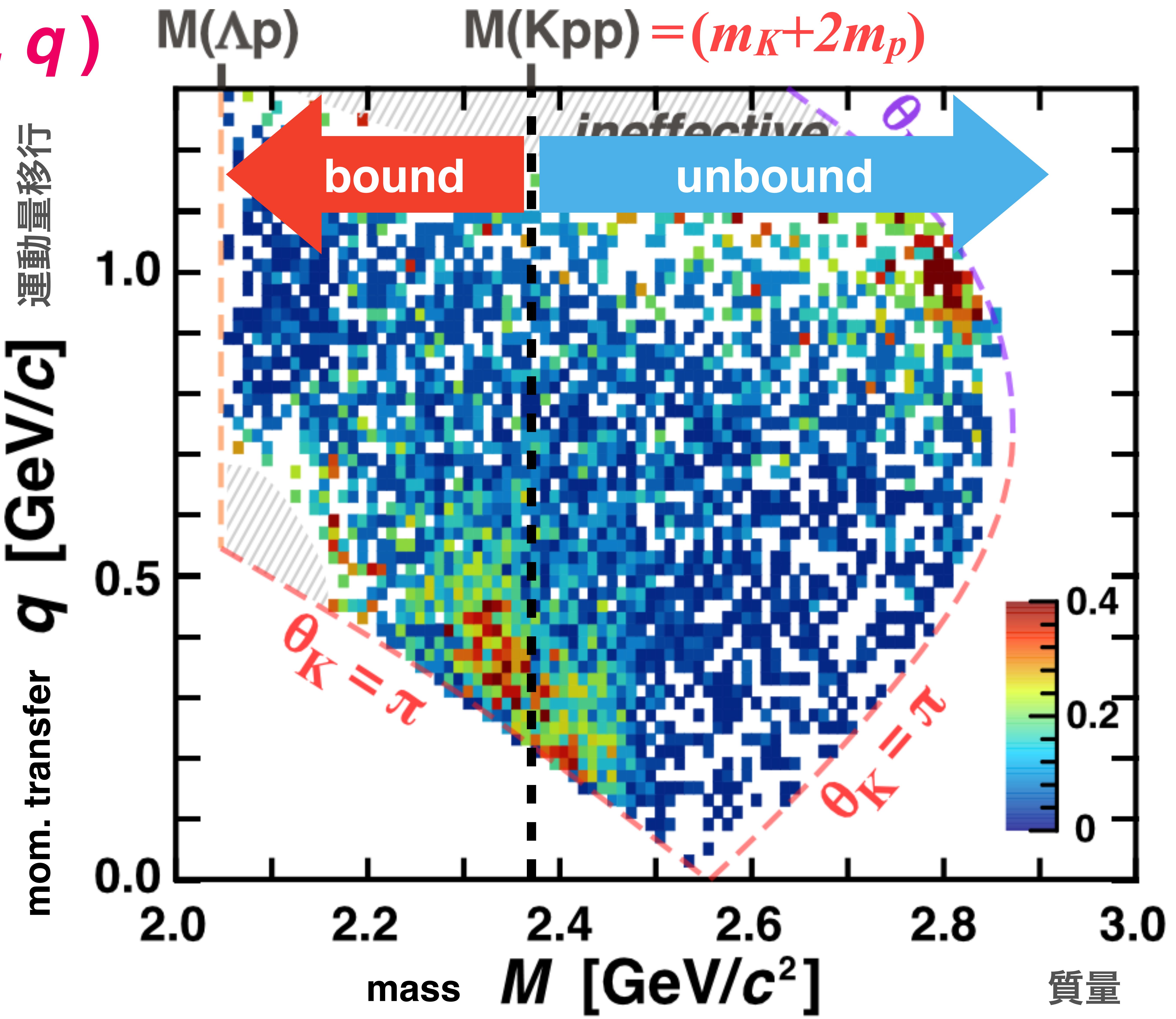


kinematics defined by (*M*, *q*)



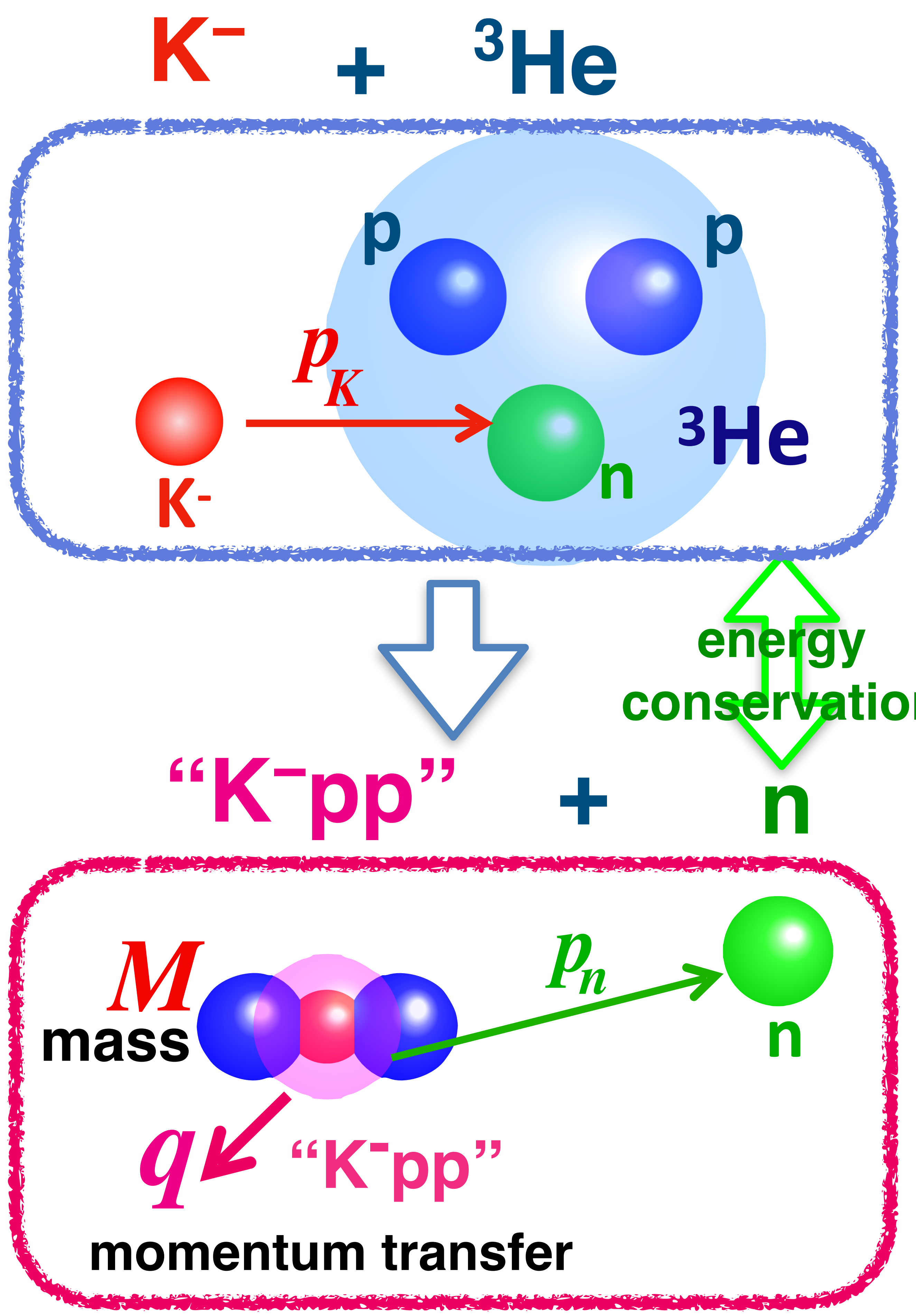
2D analysis on (*M*, *q*)



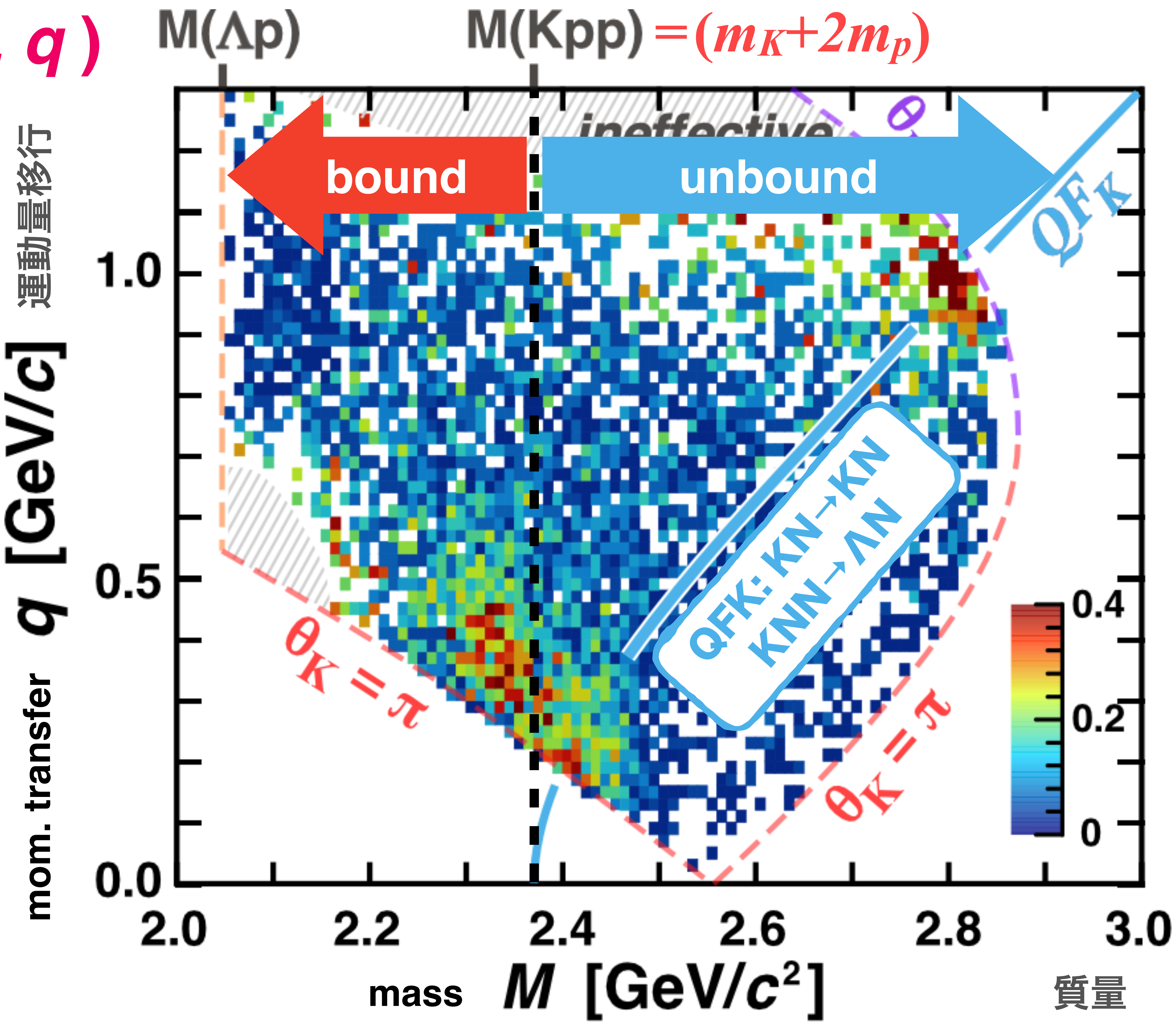


kinematics defined by
(*M*, *q*)

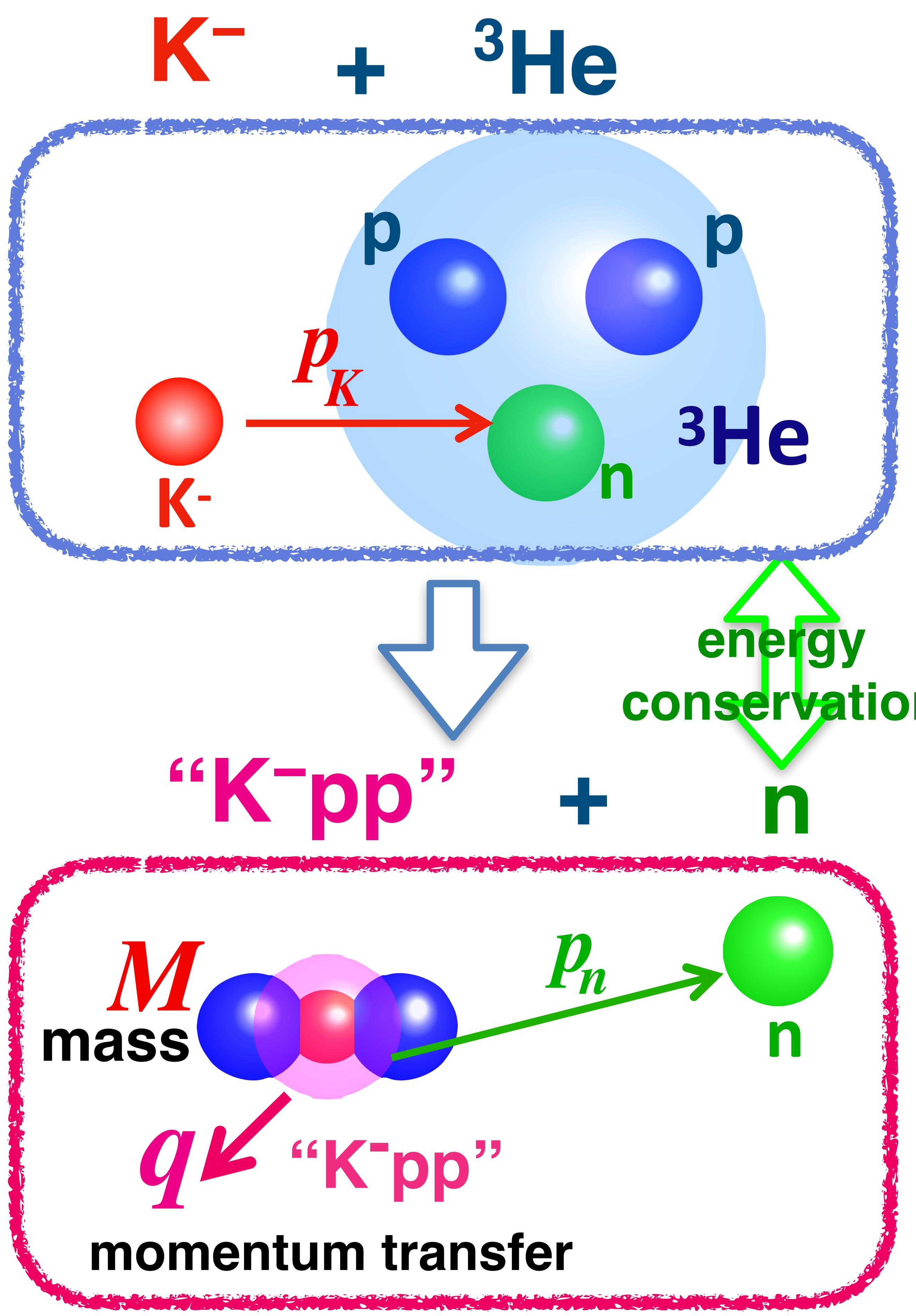
2D analysis on (*M, q*)



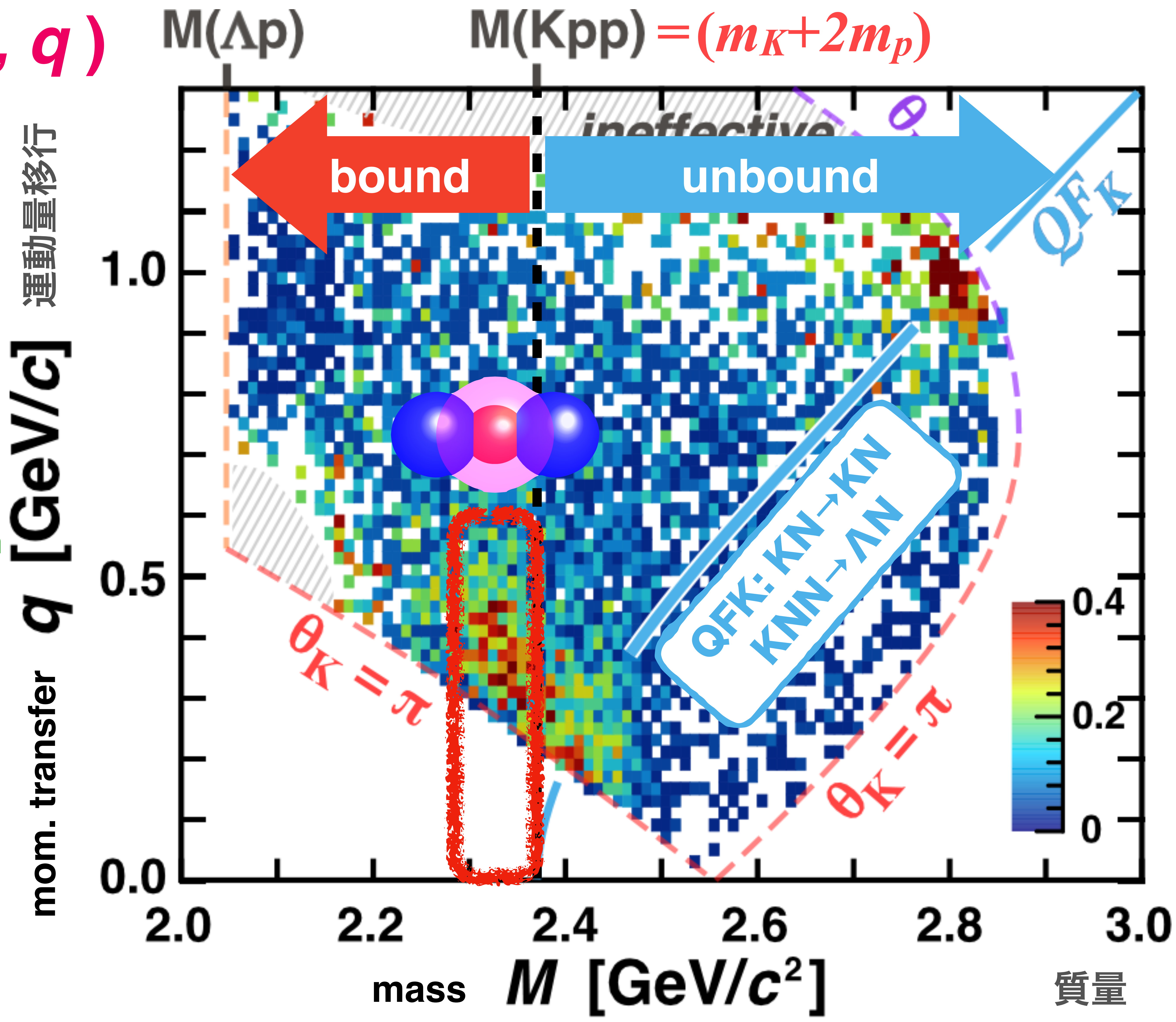
kinematics defined by (*M, q*)



2D analysis on (*M, q*)



kinematics defined by
(*M, q*)



$$M = m_K + 2m_p - B_K$$

PWIA
(plane wave impulse approximation)

$$\sigma(M, q) \propto \rho_{3B}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

Differential cross section

PWIA

(plane wave impulse approximation)

$$\sigma(M, q) \propto \rho_{3B}(M, q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

Differential cross section

Lorentz invariant phase space (Λpn)

PWIA

(plane wave impulse approximation)

B.W. / Lorentzian

$$\sigma\,(M,\,q) \propto \rho_{3B}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q^2_{Kpp}}\right)$$

Differential cross section

Lorentz invariant phase space (Λpn)

PWIA

(plane wave impulse approximation)

B.W. / Lorentzian

form factor / structure factor

$$\sigma(M, q) \propto \rho_{3B}(M, q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times \exp\left(-\frac{q^2}{Q^2_{Kpp}}\right)$$

Differential cross section

Lorentz invariant phase space (Λpn)

PWIA

(plane wave impulse approximation)

B.W. / Lorentzian   form factor / structure factor

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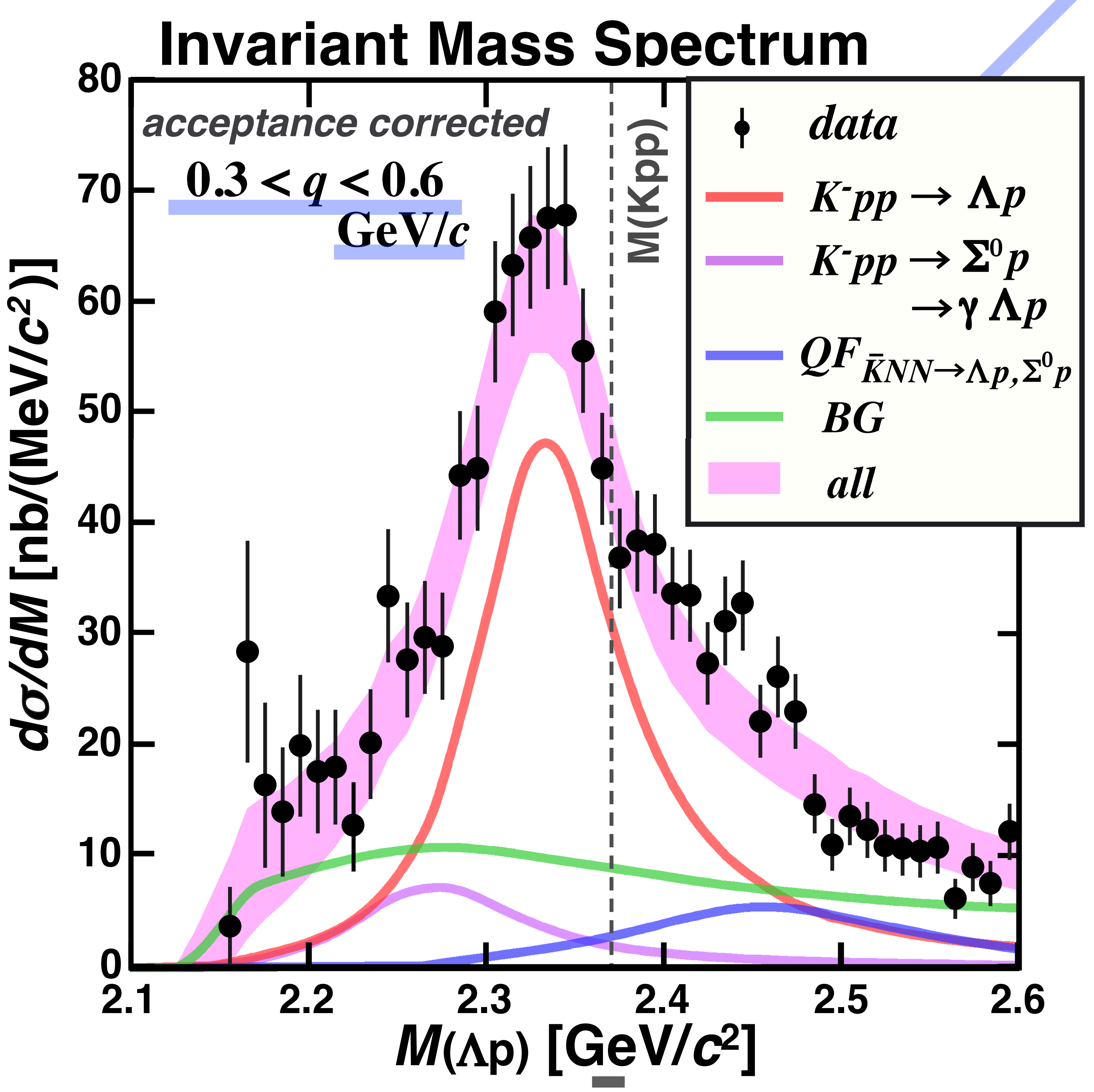
Differential cross section   Lorentz invariant phase space (Λpn)



strong binding (K̄N attraction)

B_{Kpp} ~40 MeV, Γ_{Kpp}~ 90MeV

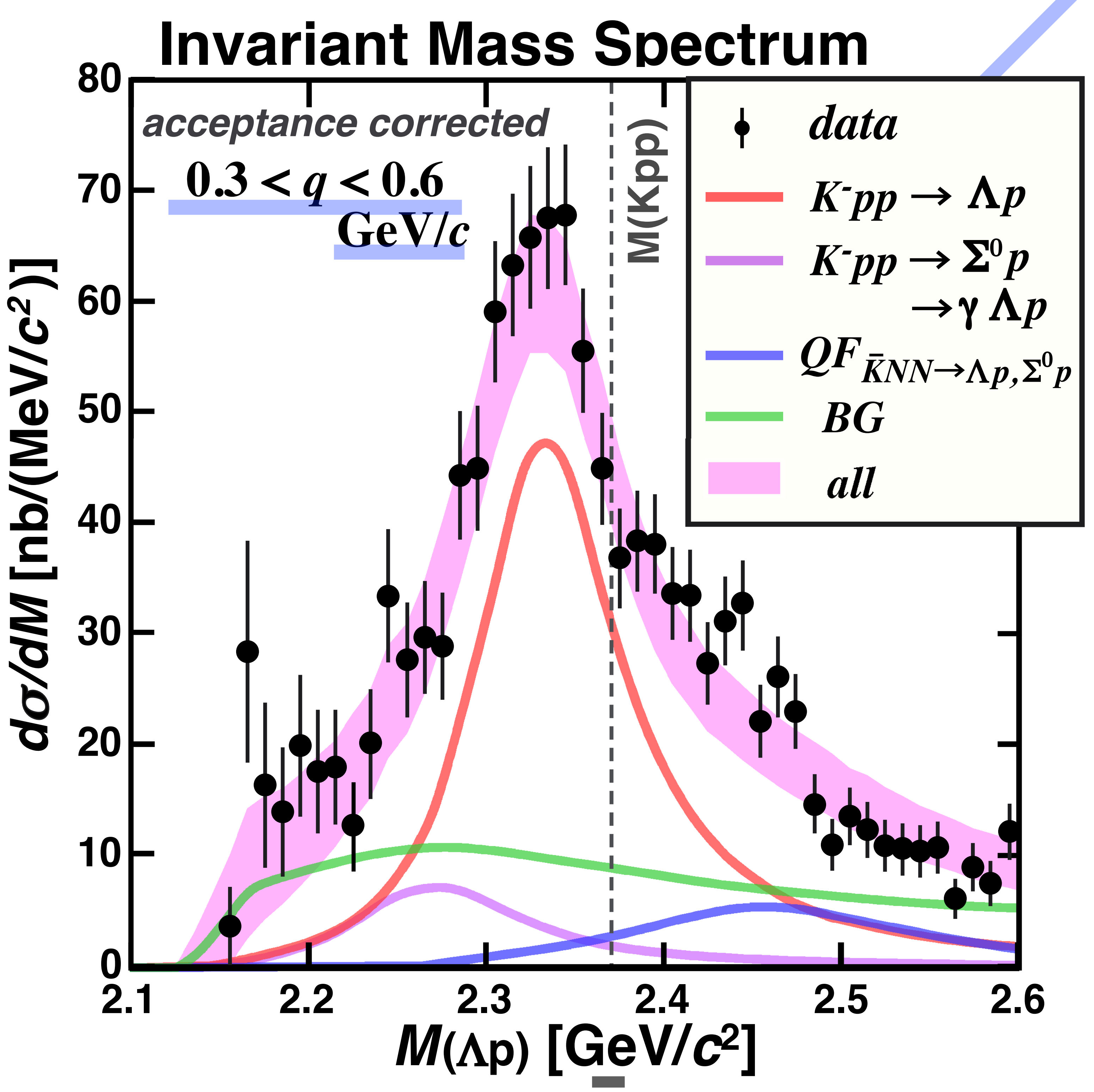
PWIA

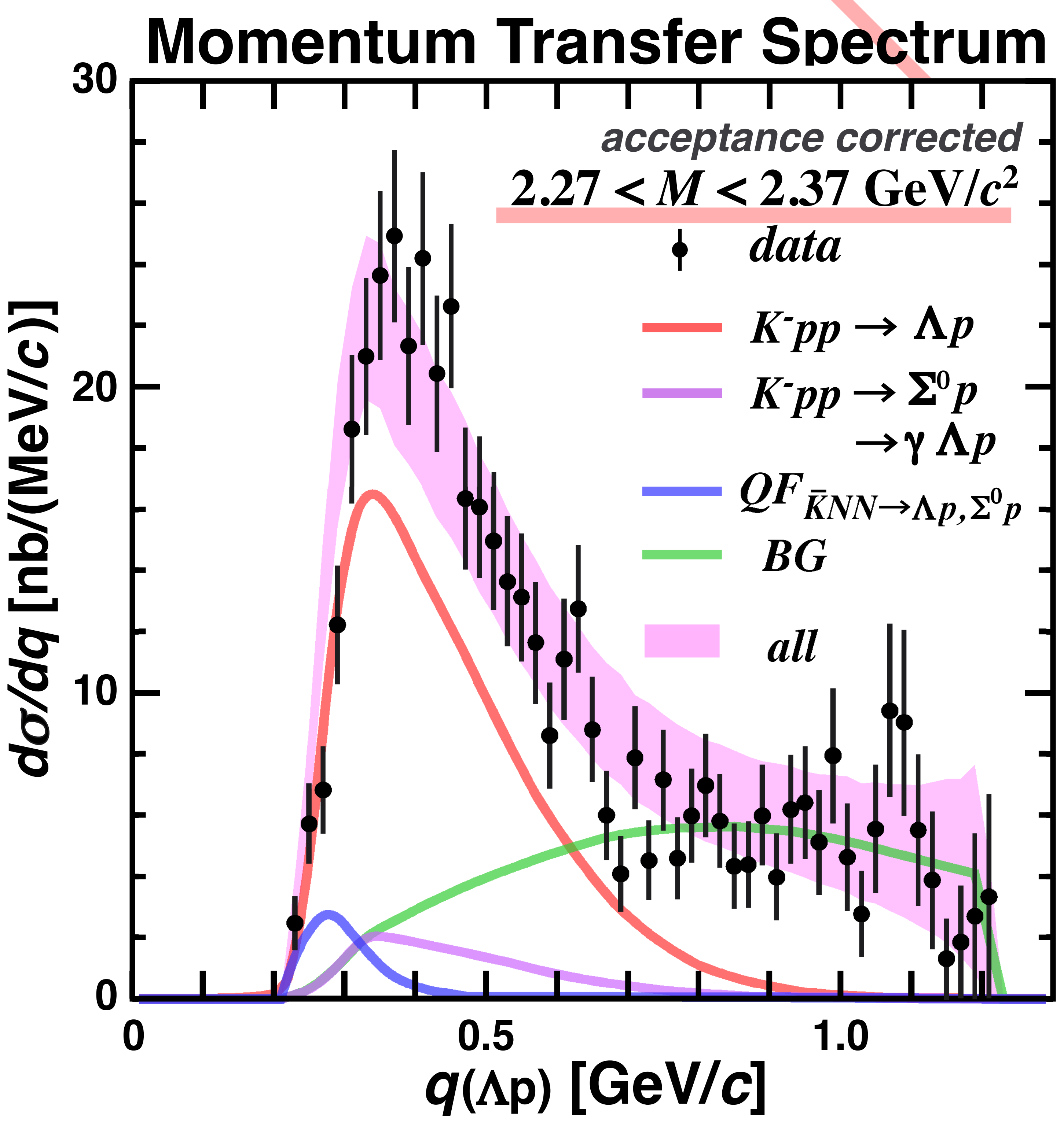
(plane wave impulse approximation)

B.W. / Lorentzian — form factor / structure factor

$$\sigma(M, q) \propto \rho_{3B}(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2} \times \exp\left(-\frac{q^2}{Q^2_{Kpp}}\right)$$

Differential cross section — Lorentz invariant phase space (Λpn)





strong binding (K̄N attraction) — wide momentum width — quite compact?

B_{Kpp} ~40 MeV, Γ_{Kpp} ~ 90 MeV — Q_{Kpp} ~ 400 MeV/c (R_{Kpp} ~ 0.6 fm (H.O.))

We introduce three model functions to fit

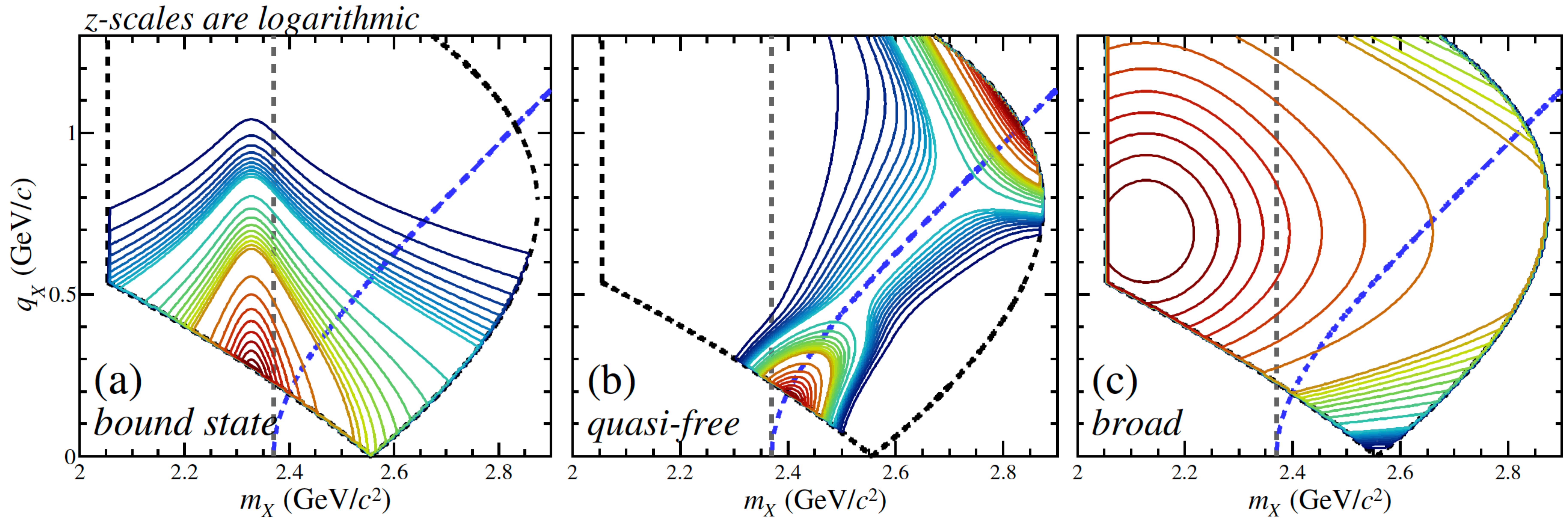
$$\mathcal{E}(M,q) \times \rho_3(M,q) \times phys_X(M,q)$$

detector efficiency | Λpn 3-body phase space | physics process

“Kpp” — KN→KN, KNN→“Kpp”

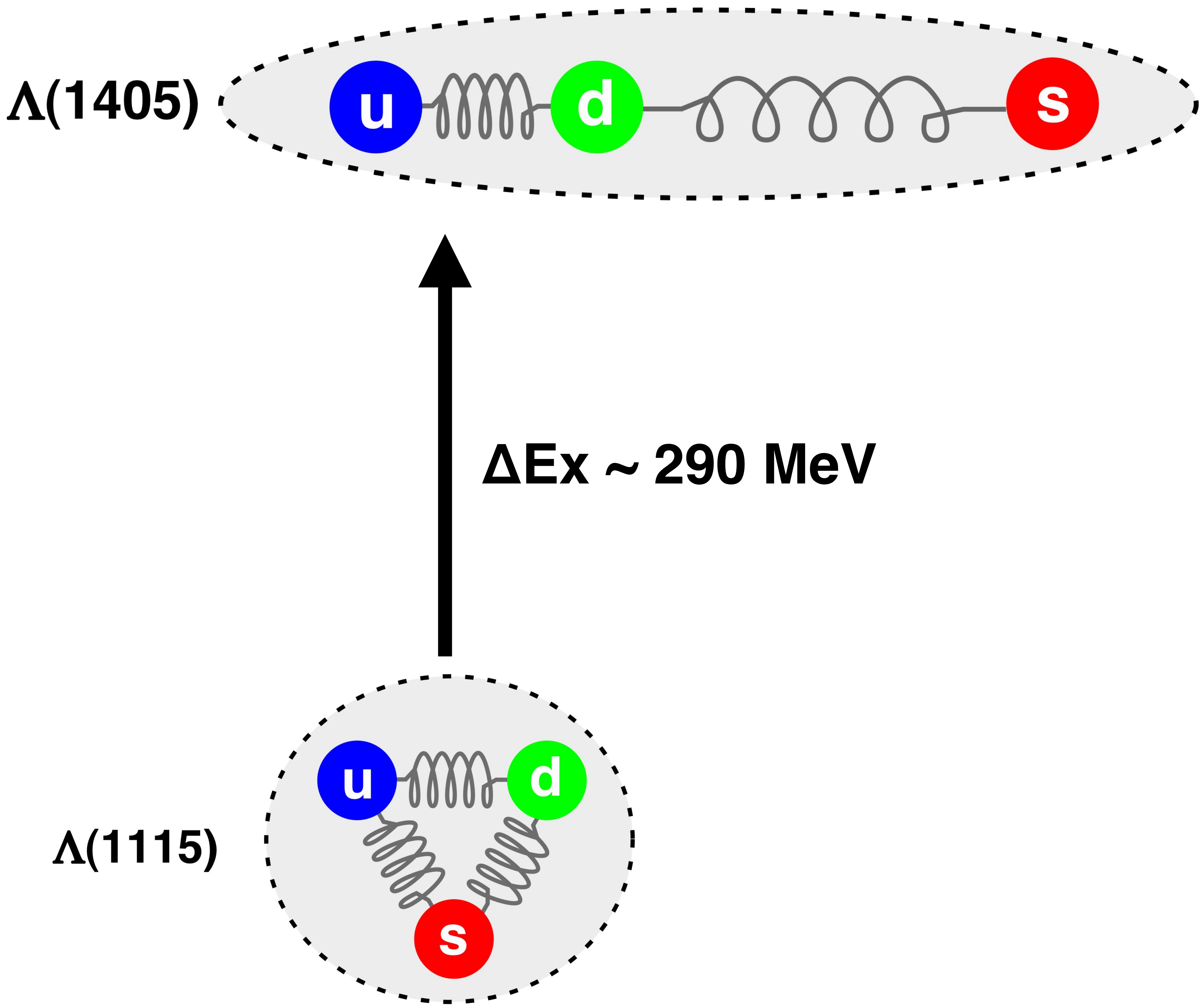
QF$_{\bar{K}\Lambda}$ — KN→KN, KNN→Λp

broad(BG) — K ^{3}He→Λpn ?



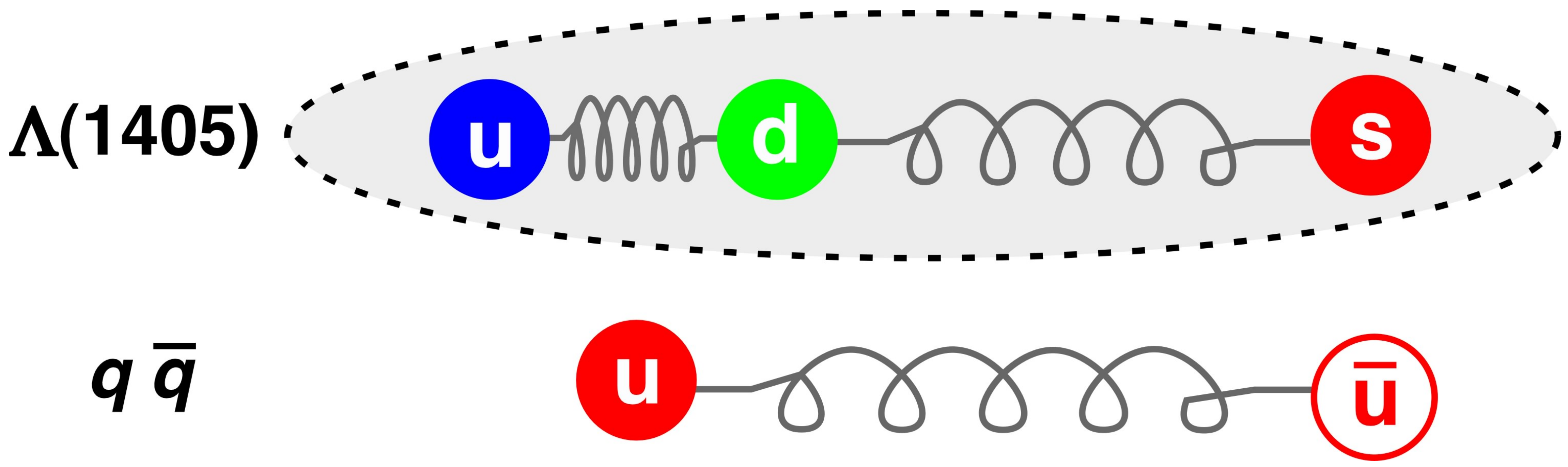
From Λ(1405) to kaonic nuclei

Is Λ(1115) an excited state of *uds*?



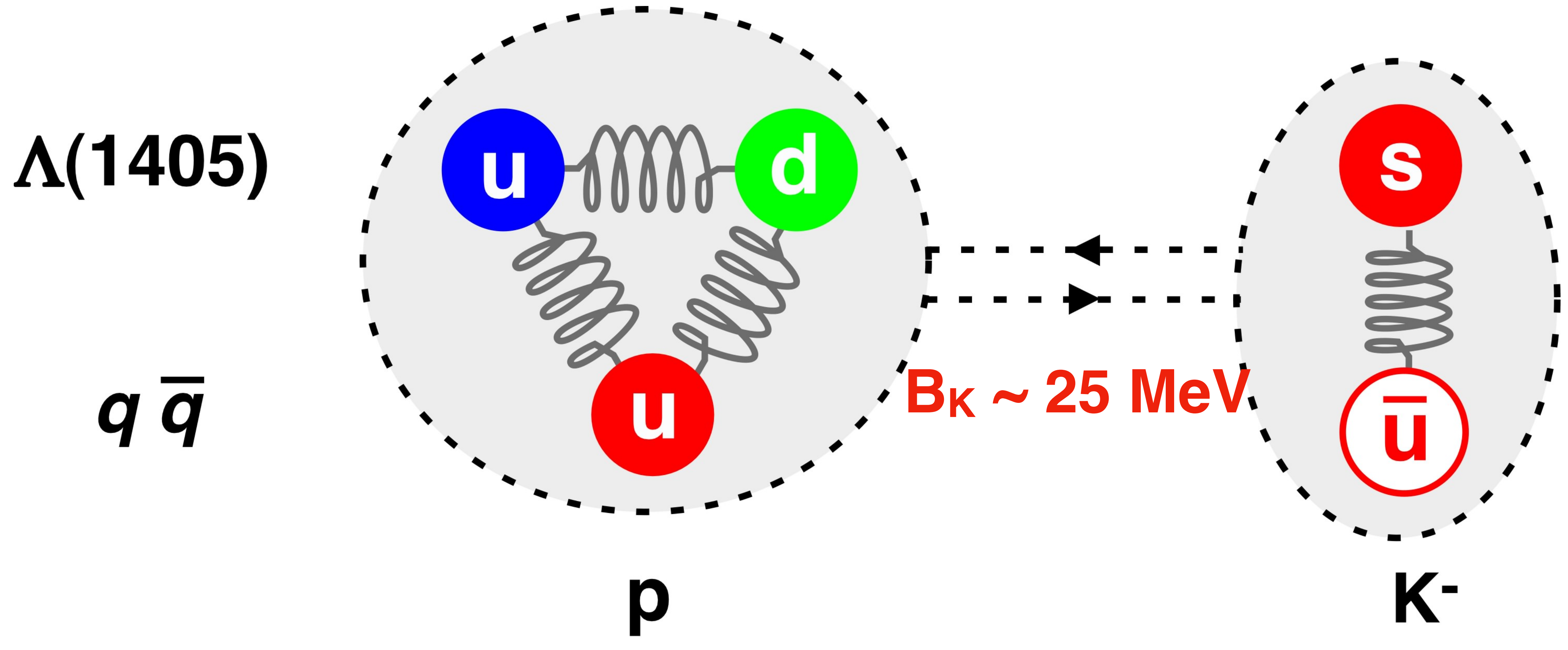
From Λ(1405) to kaonic nuclei

with $\bar{q}q$ (χ-condensate) in vacuum



From Λ(1405) to kaonic nuclei

two color-singlet objects bound by meson exchange : p = K⁻



M(pK⁻) = 1432 MeV/c²

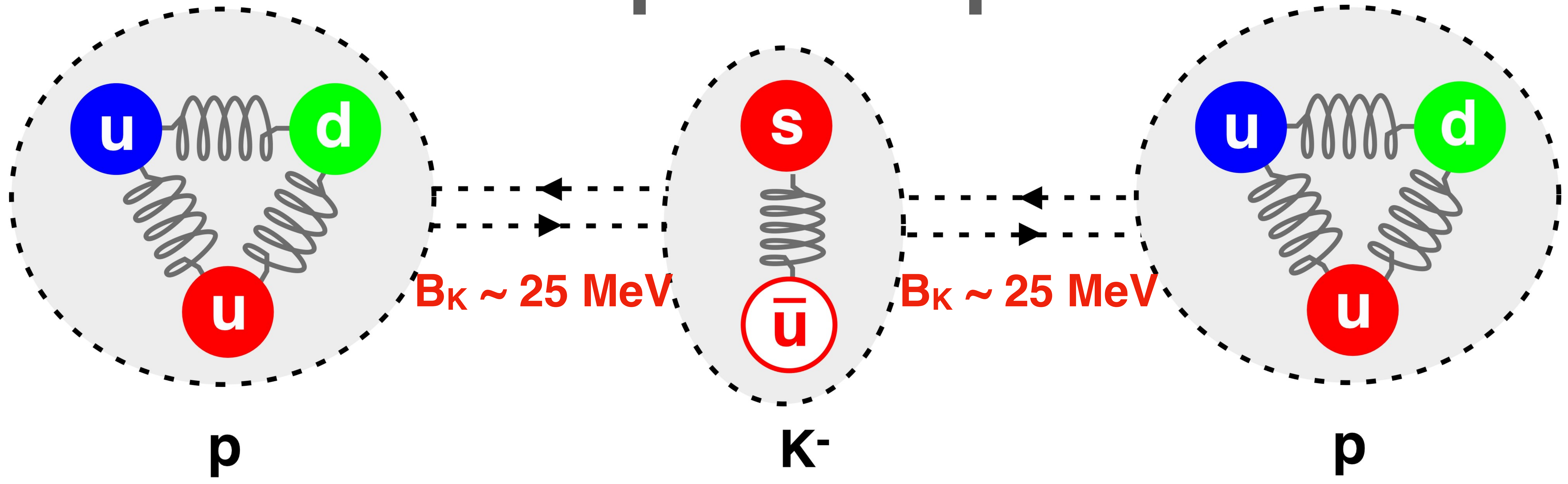
From Λ(1405) to kaonic nuclei

kaonic nucleus “Kpp”

$p = K^{-} = p$: *nuclecule*

Λ(1405)

$q\,\bar{q}$



$M(pK^{-}) = 1432\ \mathrm{MeV}/c^2$

$M(ppK^{-}) = 2370\ \mathrm{MeV}/c^2$

$M_{Kpp} \sim 2320\ \mathrm{MeV}/c^2$

$B_{Kpp} \sim 50$ MeV

$\Gamma_{Kpp} \sim 100$ MeV

and “Kp” = Λ(1405)