



Spin Physics in Nuclear and Collider Experiments

- Spin as a probe of QCD matter and hadron structure -

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Contents of this lecture

- ▶ Day-1: The birth of spin physics: Stern-Gerlach to Wu
- ▶ Day-2: Spin structure of nucleon and Transverse spin phenomena
- ▶ Day-3: Spin polarization in relativistic heavy-ion collisions (1)
- ▶ Day-4: Spin polarization in relativistic heavy-ion collisions (2)
- ▶ Day-5: Spin correlations and Future directions

Before that...

Some more information related to yesterday's questions

How to measure decay parameter α ?

Traditional way

Cronin and Overseth, Phys.Rev.129, 1795 (1962)

$$\pi^- + p \rightarrow \Lambda + K^0$$

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

$$p + C \rightarrow p + X$$

$$P_z = [\gamma P_\Lambda + \alpha \cos\theta + P_\Lambda(1-\gamma) \cos^2\theta] / [1 + \alpha P_\Lambda \cos\theta],$$

$$P_x = [\alpha \sin\theta + P_\Lambda(1-\gamma) \sin\theta \cos\theta] / [1 + \alpha P_\Lambda \cos\theta],$$

$$P_y = [\beta P_\Lambda \sin\theta] / [1 + \alpha P_\Lambda \cos\theta],$$

$$\alpha = +0.62 \pm 0.07$$

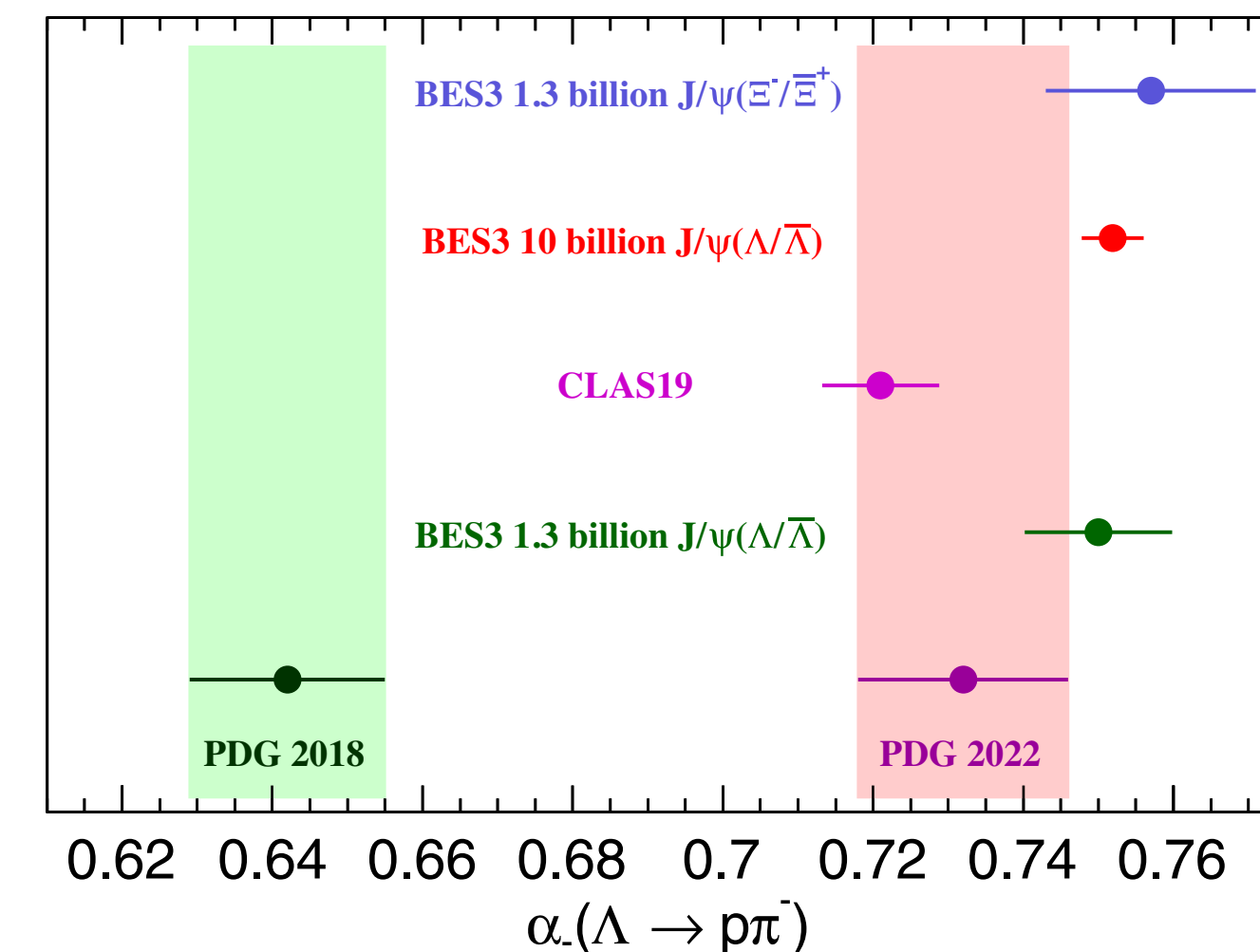
Daughter-proton polarization was measured with a pC polarimeter, to determine decay parameters

BES-III way

BESIII, PRL129, 131801(2022)

$$e^+ + e^- \rightarrow J/\psi \rightarrow \Lambda + \bar{\Lambda}$$

$$J^P=1^- \quad J^P=1/2^+ \quad J^P=1/2^-$$

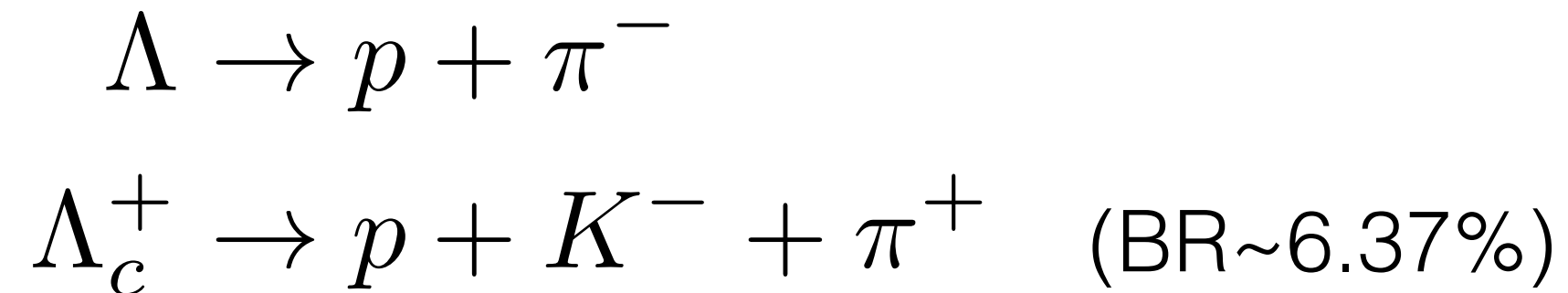


Λ and $\bar{\Lambda}$ spins are correlated in $J/\psi \rightarrow \Lambda \bar{\Lambda}$. Their joint decay angular distribution allows to determine α .

- Angular momentum and parity conservation constrain the $\Lambda \bar{\Lambda}$ system to $S=1$

How to measure polarization for 3-body decay like Λ_c ?

LHCb, JHEP07(2023)228



Because of 3-body decay, the decay cannot be simply characterized by one parameter like α_Λ

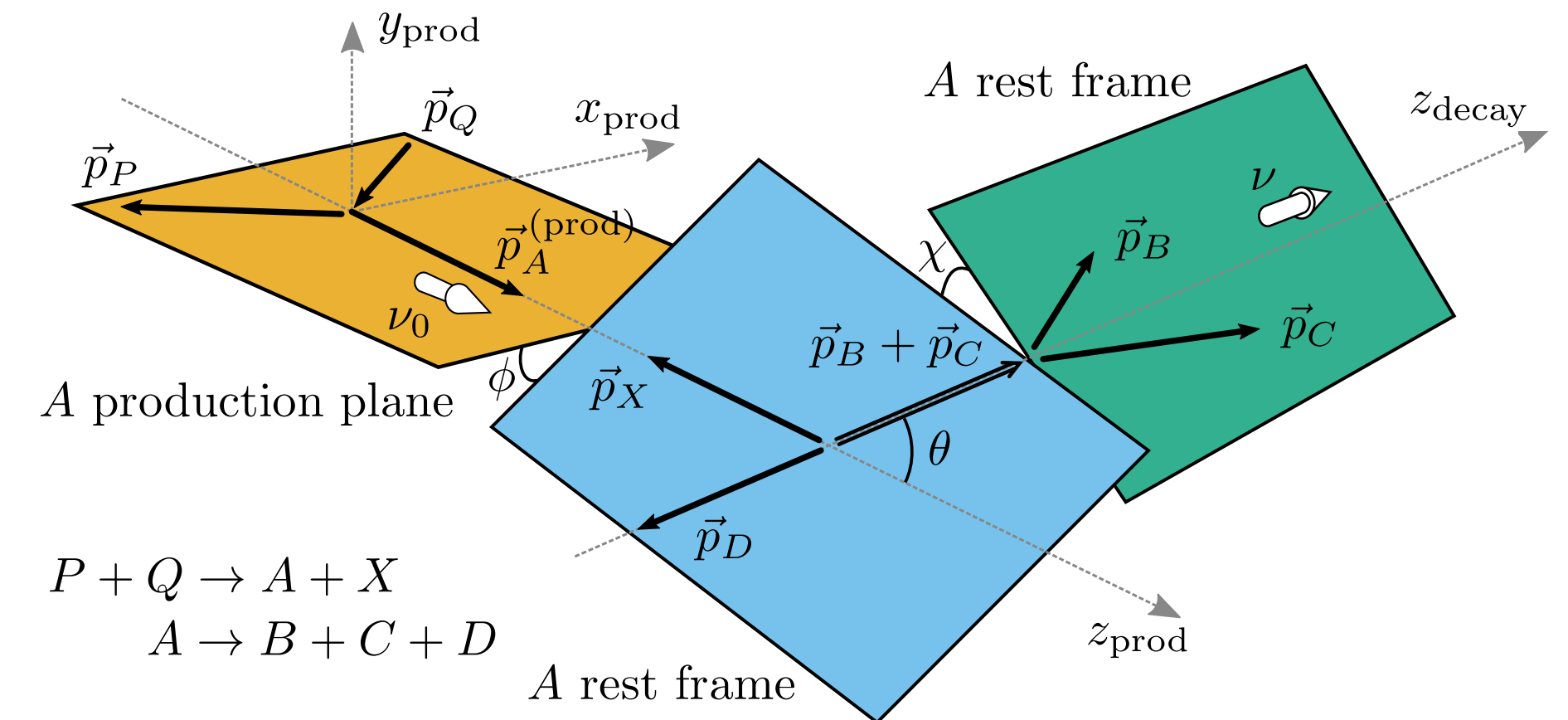
$$\frac{\Phi}{\Gamma} \frac{d\Gamma}{d\Phi} \propto 1 + \vec{P} \cdot \vec{h},$$

$$\vec{h} = R(\phi, \theta, \chi) \vec{\alpha},$$

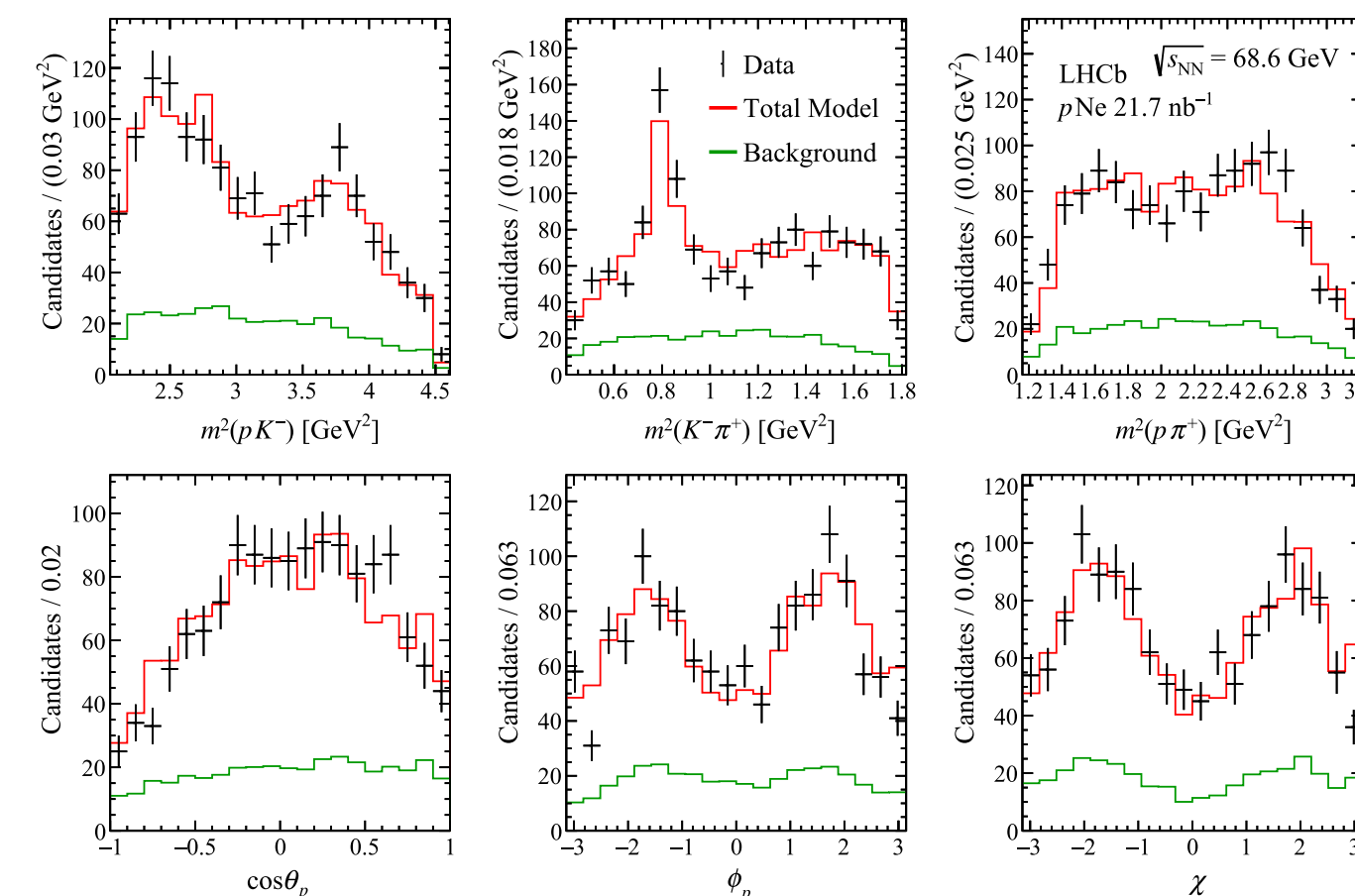
Γ : decay rate

$\vec{h}$: polarimeter vector

Φ : Lorentz-invariant phase space



Momentum distributions of 3 final-state particles carry the information of Λ_c spin



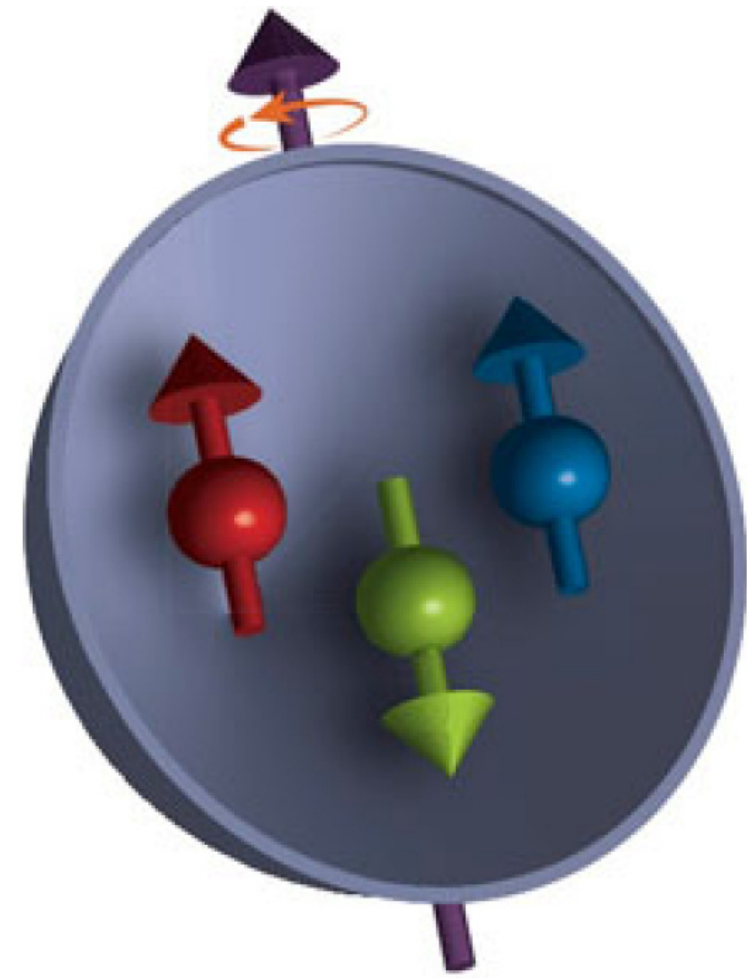
LHCb, PRL137.091901(2026)

The Dalitz plot reveals the resonant substructure of the three-body decay, which determines how sensitive each phase-space region is to the Λ_c polarization

Day-2

Spin structure of nucleon and Transverse spin phenomena

Where does proton spin come from?



1980s

p(uud)

Simplified form with the quark ordering fixed as uud:

$$|p^\uparrow\rangle = \frac{1}{\sqrt{6}}(2|u^\uparrow u^\uparrow d^\downarrow\rangle - |u^\uparrow u^\downarrow d^\uparrow\rangle - |u^\downarrow u^\uparrow d^\uparrow\rangle)$$

state	S_z^u	S_z^d
$u^\uparrow u^\uparrow d^\downarrow$	$1/2 + 1/2 = 1$	$-1/2$
$u^\uparrow u^\downarrow d^\uparrow$	$1/2 - 1/2 = 0$	$1/2$
$u^\downarrow u^\uparrow d^\uparrow$	$-1/2 + 1/2 = 0$	$1/2$

$$\langle S_z^u \rangle = \frac{4}{6}(1) + \frac{1}{6}(0) + \frac{1}{6}(0) = \frac{2}{3}$$

$$\langle S_z^d \rangle = \frac{4}{6}(-1/2) + \frac{1}{6}(1/2) + \frac{1}{6}(1/2) = -\frac{1}{6}$$

$$\langle S_z^u \rangle + \langle S_z^d \rangle = \frac{1}{2}$$

$$\Delta u = \frac{4}{3}, \quad \Delta d = -\frac{1}{3}, \quad \Delta s = 0$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$$

$$\Delta u = N(u^\uparrow) - N(u^\downarrow)$$

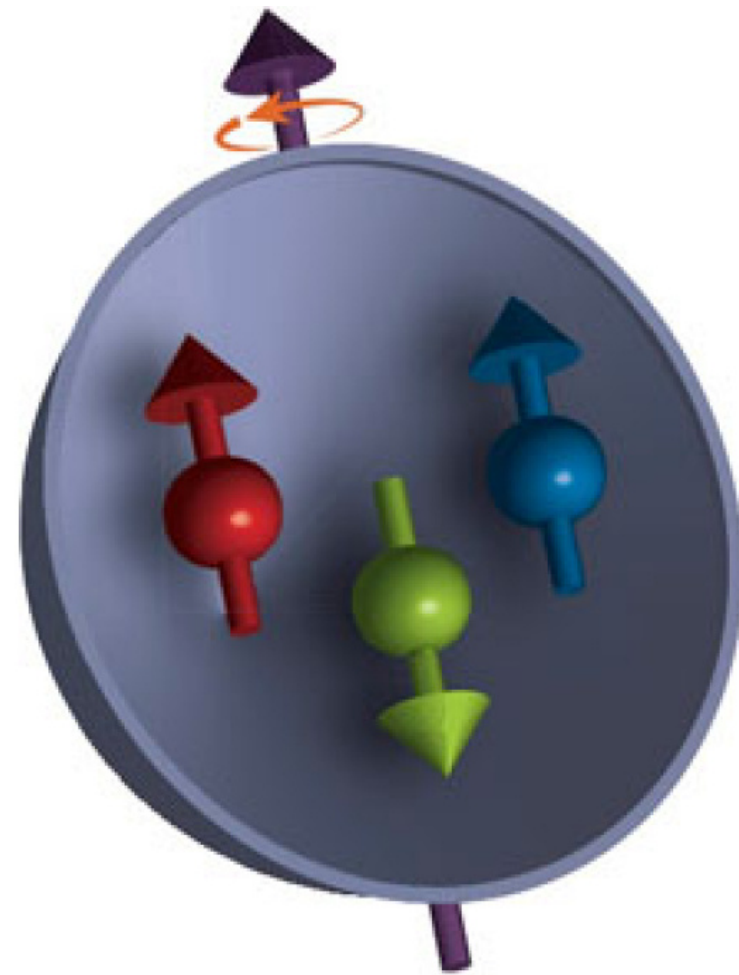
$$\text{quark spin contribution: } \langle S_z^q \rangle = \frac{1}{2}\Delta\Sigma = \frac{1}{2}$$

In naive quark model, quark spins account for 100% of proton spin.

Where does proton spin come from?

Simplified form with the quark ordering fixed as uud:

$$|p^\uparrow\rangle = \frac{1}{\sqrt{6}}(2|u^\uparrow u^\uparrow d^\downarrow\rangle - |u^\uparrow u^\downarrow d^\uparrow\rangle - |u^\downarrow u^\uparrow d^\uparrow\rangle)$$



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$$\Delta u = \frac{4}{3}, \quad \Delta d = -\frac{1}{3}, \quad \Delta s = 0$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$$

$$\Delta u = N(u^\uparrow) - N(u^\downarrow)$$

$$\text{quark spin contribution: } \langle S_z^q \rangle = \frac{1}{2}\Delta\Sigma = \frac{1}{2}$$

In naive quark model, quark spins account for 100% of proton spin.

But now we know that quark spins account for only ~30% of proton spin: $\Delta\Sigma \sim 0.3$

Deep inelastic scattering

Deep inelastic scattering of a lepton (l) on a hadron (h)

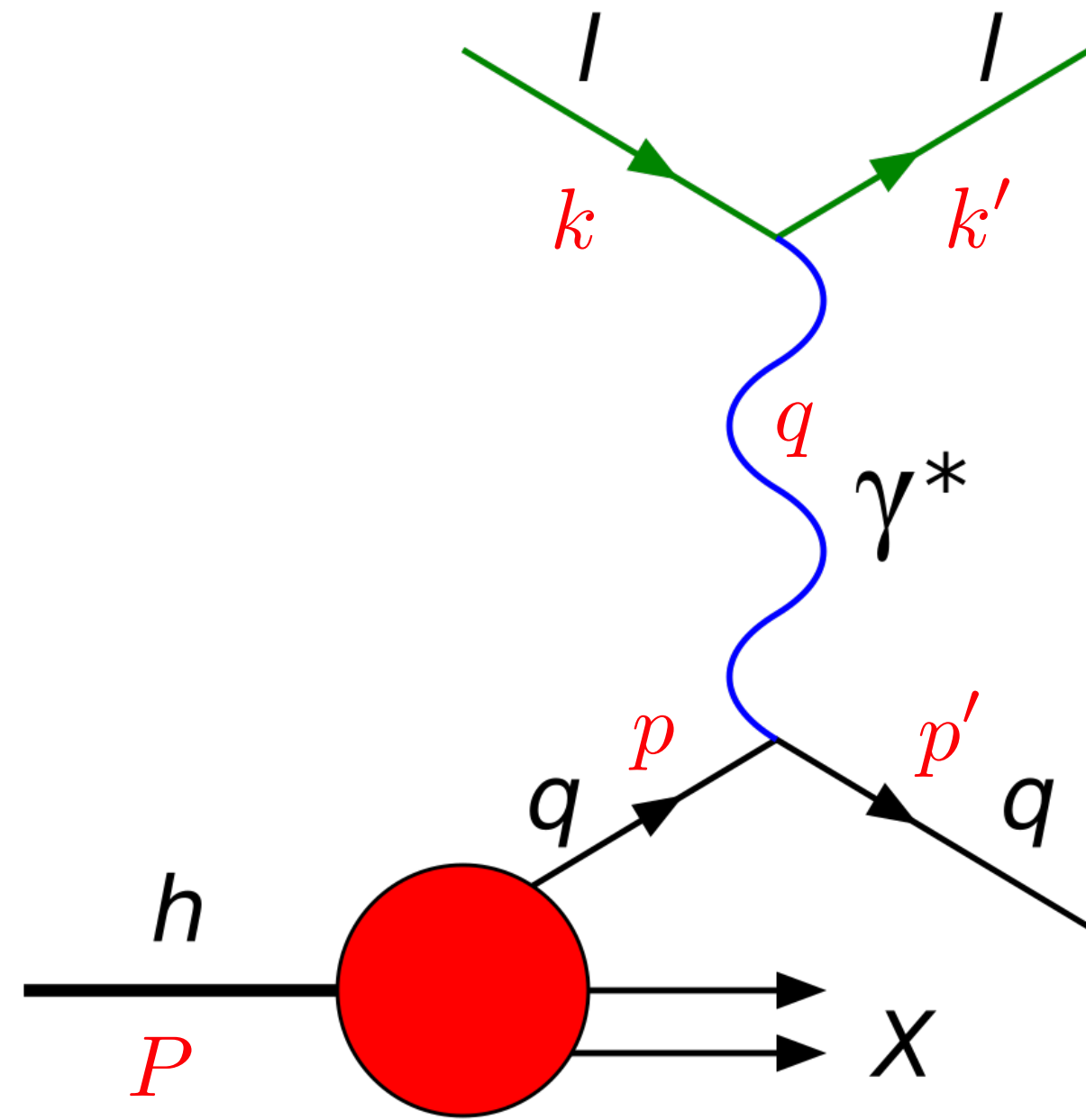
$$\ell(k) + h(P) \rightarrow \ell(k') + X$$

The lepton exchanges a virtual photon with a quark inside the hadron

$$Q^2 = -q^2 = -(k - k')^2$$

$$\Delta r \sim \frac{\hbar c}{Q}$$

higher $Q^2 \rightarrow$ shorter wavelength $\rightarrow$ higher spatial resolution



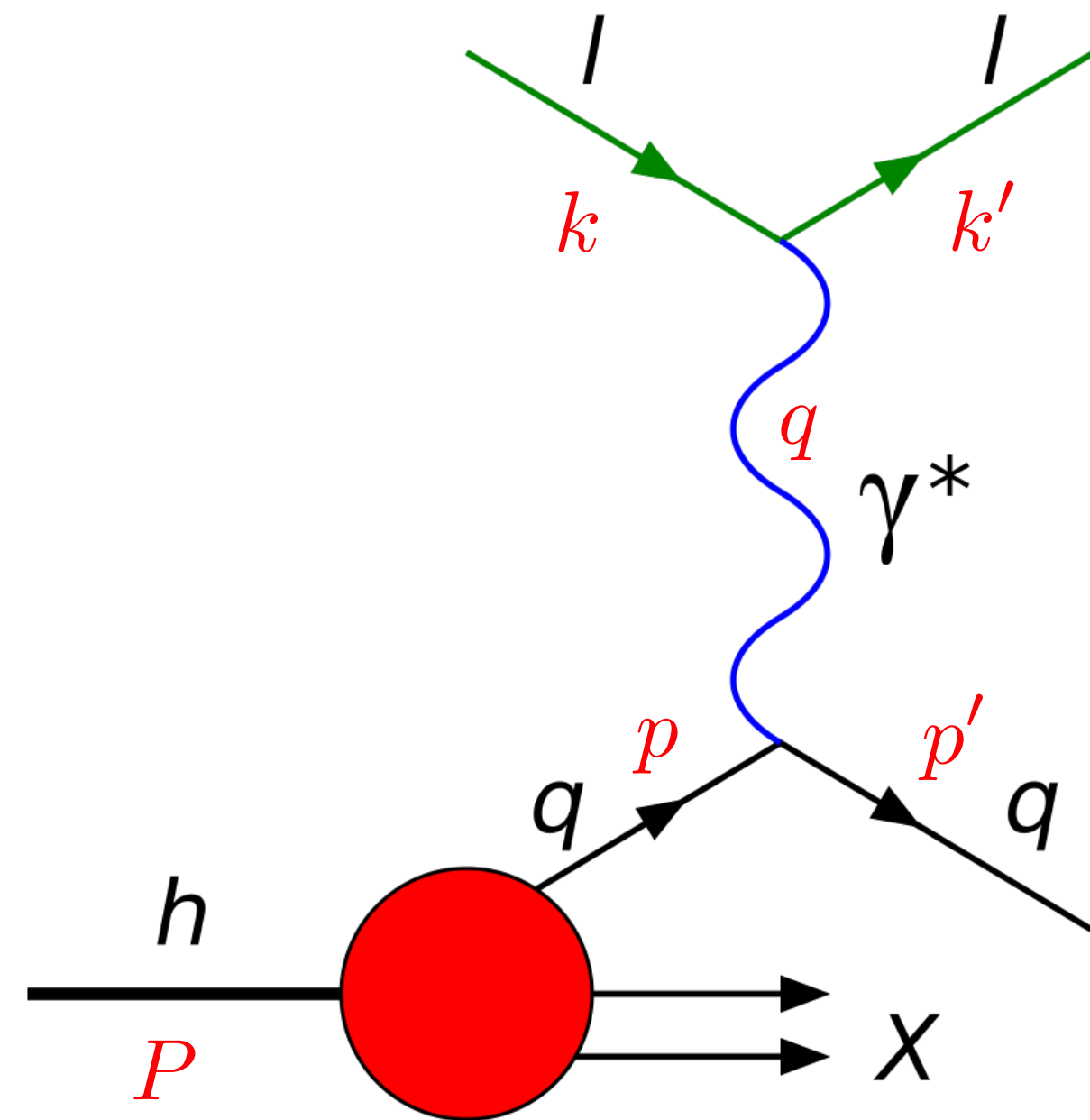
The virtual photon acts as a probe of the internal structure of the hadron

Deep inelastic scattering

Deep inelastic scattering of a lepton (l) on a hadron (h)

$$\ell(k) + h(P) \rightarrow \ell(k') + X$$

The muon exchanges a virtual photon with a quark inside the hadron



$$Q^2 = -q^2 = -(k - k')^2$$

$$\Delta r \sim \frac{\hbar c}{Q}$$

Suppose the parton carries a fraction ξ of hadron momentum: $p^\mu = \xi P^\mu$

$$p'^2 = (p + q)^2 \simeq 0$$

$$Q^2 = 2p \cdot q = 2\xi P \cdot q$$

$$\xi = \frac{Q^2}{2P \cdot q} = x$$

The struck quark can be approximately treated as massless in high-energy DIS

$$p^2 = E^2 - \mathbf{p}^2 = m_q^2 \simeq 0$$

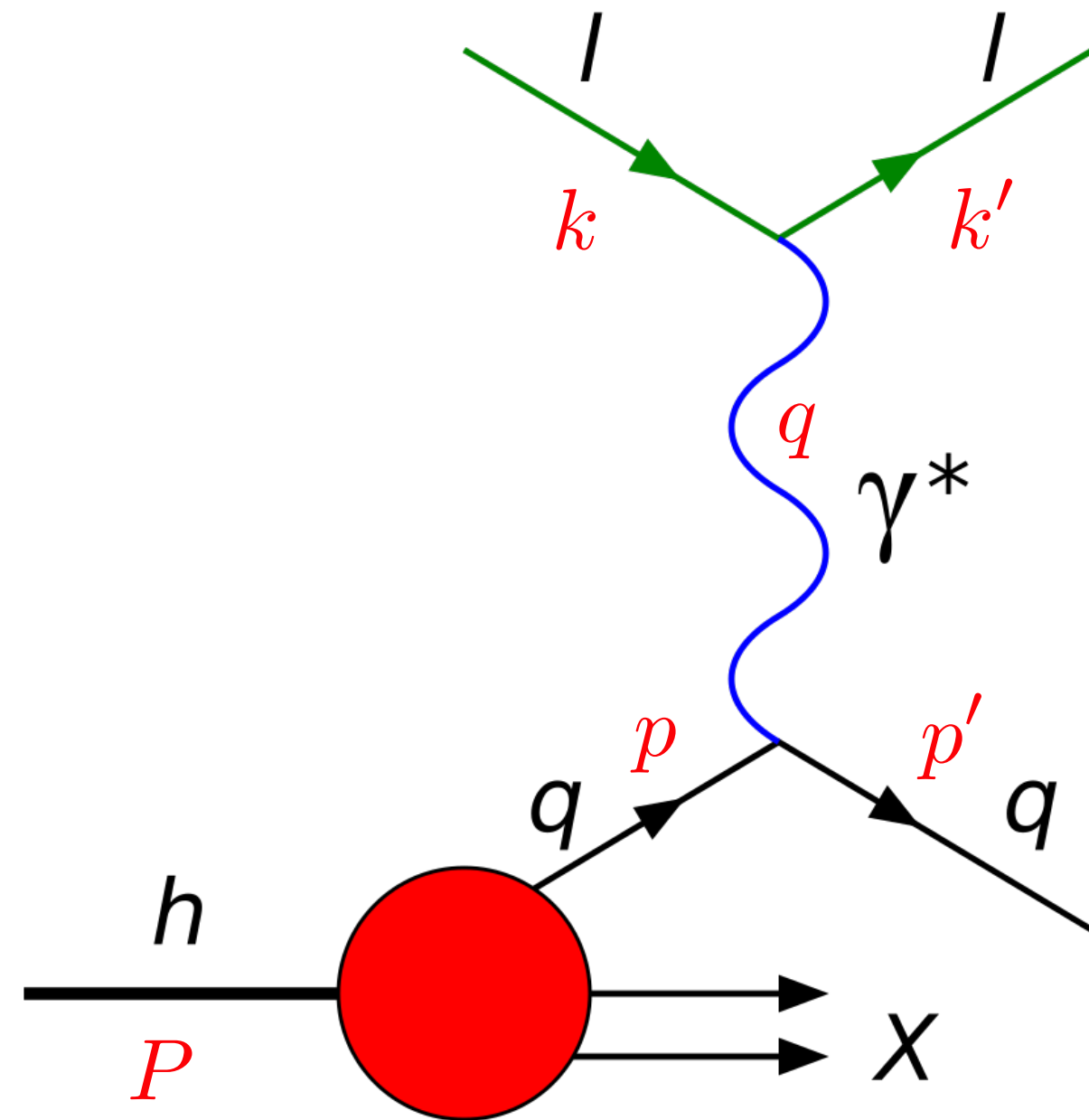
x: momentum fraction of the hadron carried by the struck parton

Deep inelastic scattering

Deep inelastic scattering of a lepton (l) on a hadron (h)

$$\ell(k) + h(P) \rightarrow \ell(k') + X$$

$$Q^2 = -q^2 = -(k - k')^2, \quad \nu = E - E', \quad x = \frac{Q^2}{2P \cdot q}$$



In **unpolarized DIS**, the cross section can be written as follows:

$$\frac{d^2\sigma}{d\Omega dE'} \propto 2F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{F_2(x, Q^2)}{\nu} \cos^2 \frac{\theta}{2}$$

Thus the structure functions $F_1(x)$, $F_2(x)$ can be obtained experimentally

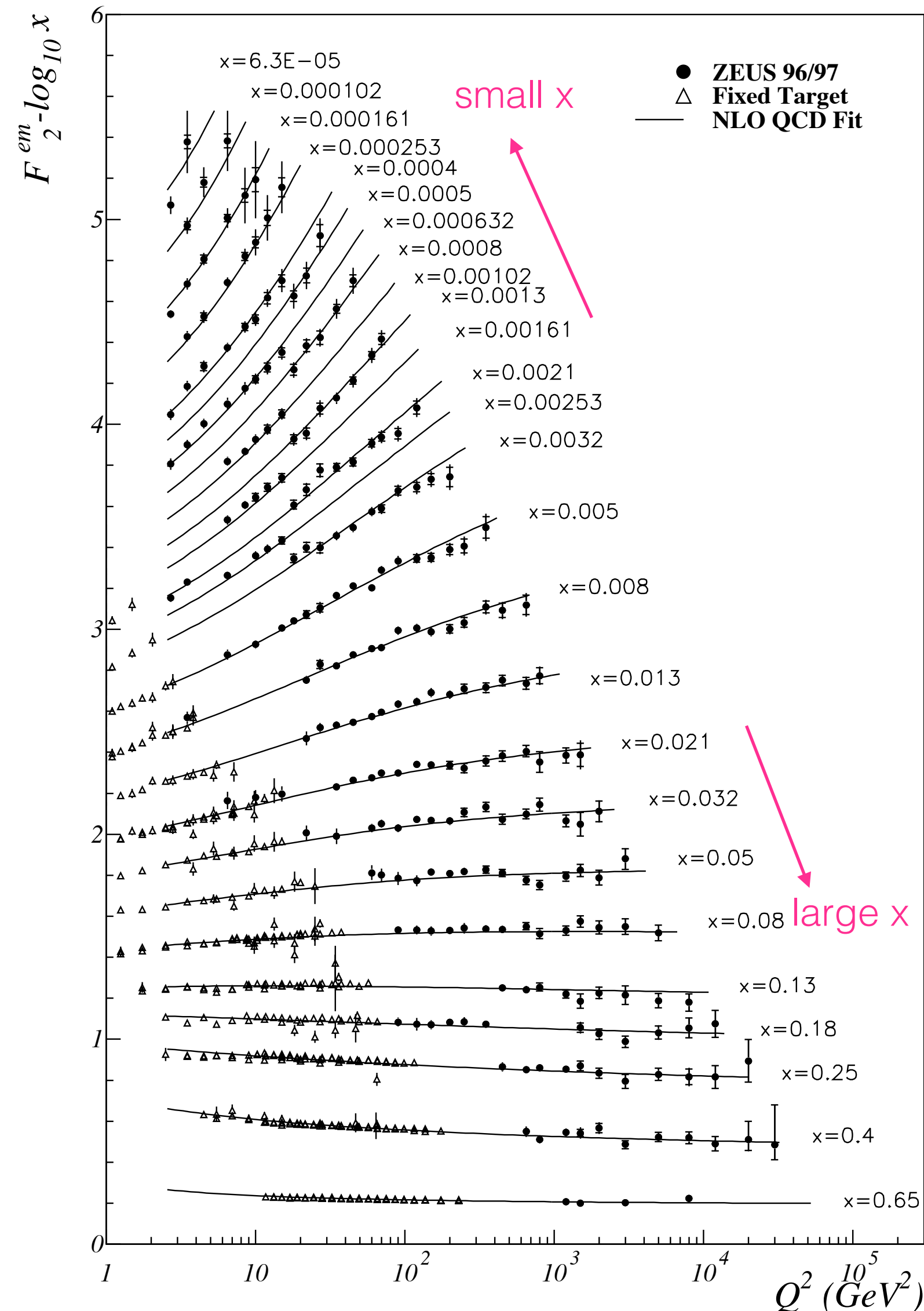
$$F_1(x) \sim \frac{1}{2} \sum_q e_q^2 [q(x) + \bar{q}(x)] \quad F_2(x) = 2xF_1(x)$$

$q(x)$, $\bar{q}(x)$: PDFs of quark and anti-quark

PDF: parton distribution function

$F_1(x)$ mainly probes charge-weighted unpolarized quark and anti-quark distributions

Structure function + QCD analysis

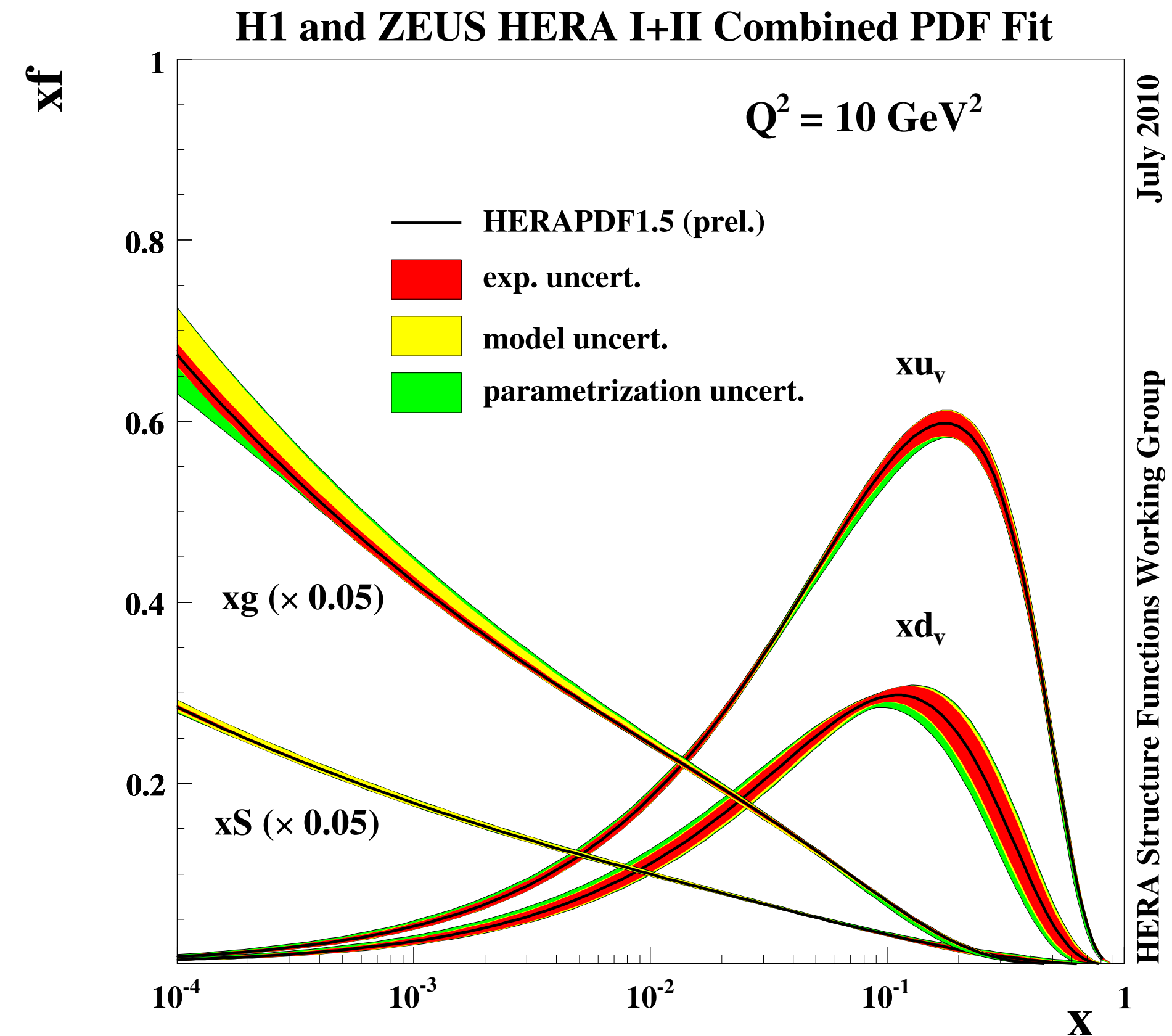
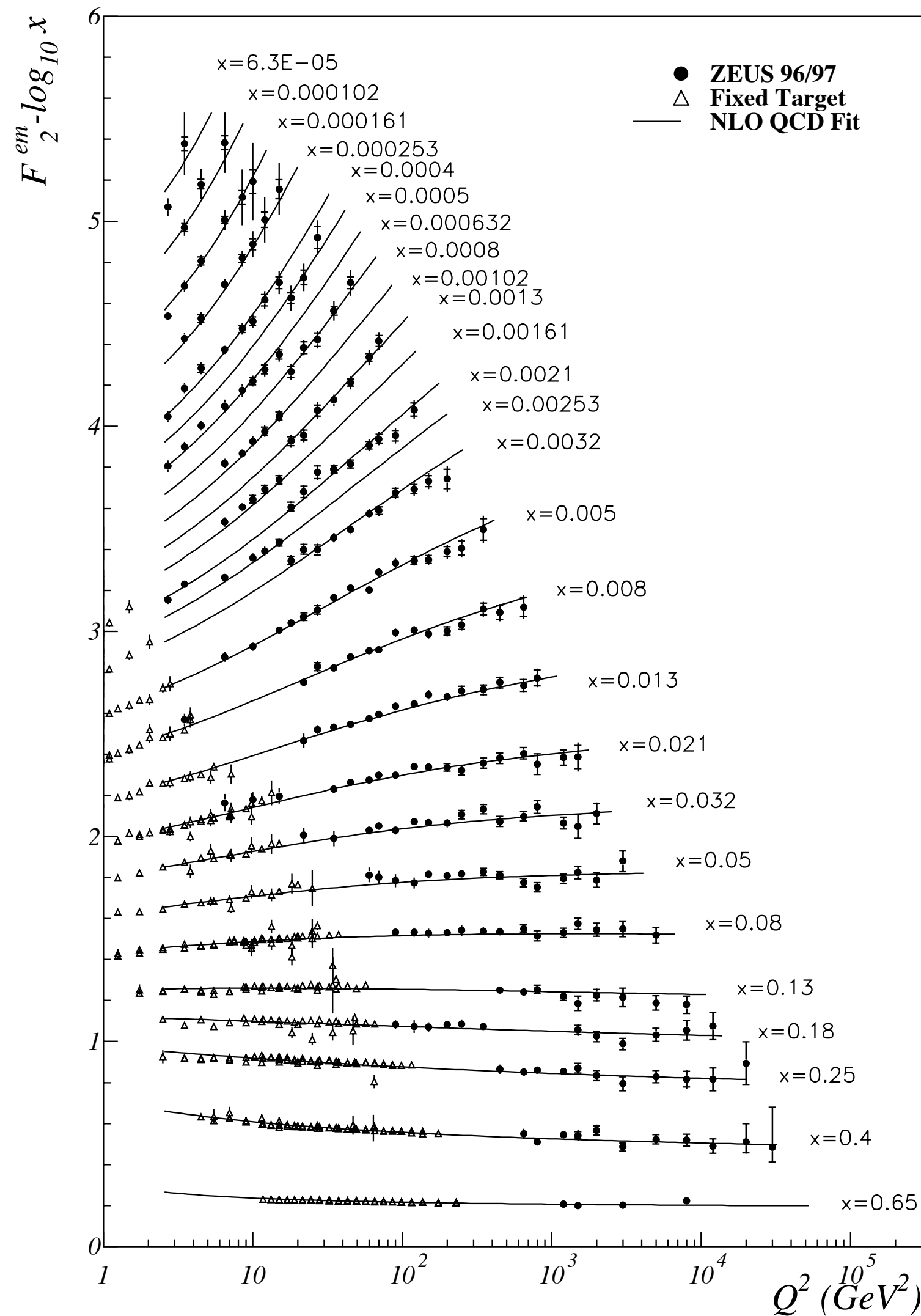


ZEUS, EPJC21, 443 (2001)

- In the naive parton model, F_2 is independent of Q^2 (Bjorken scaling)
- Partons are considered to be point-like and their distributions don't change with resolution scale
- The data show clear Q_2 dependence, especially at small x (scaling violation)
- The strong scaling violation at small x provides sensitivity to and constrains a large gluon distribution

Parton distribution function

ZEUS, EPJC21, 443 (2001)



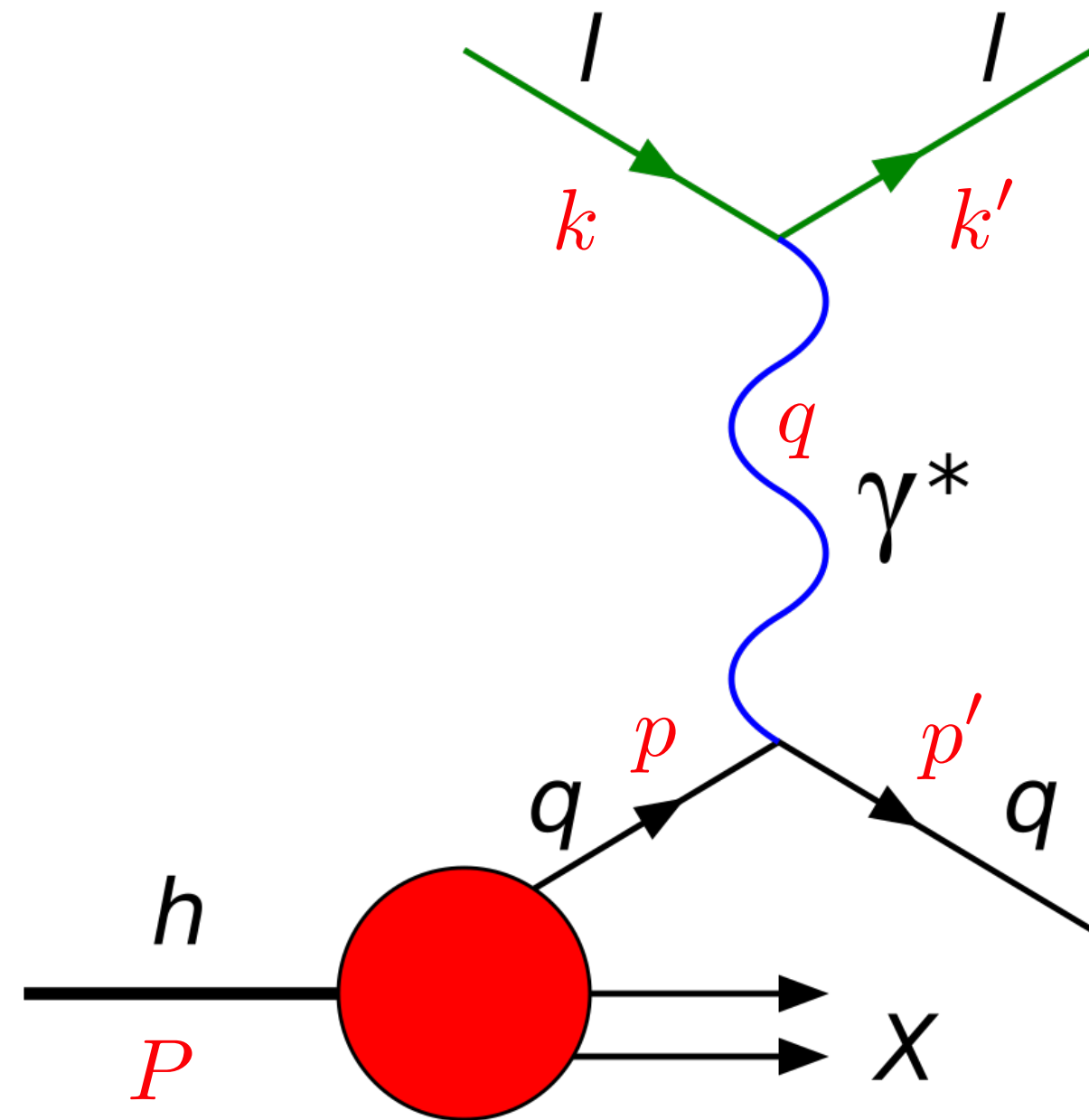
Valence quarks dominate at large x .
 Sea quarks and gluons become important at small x .

Deep inelastic scattering

Deep inelastic scattering of a lepton (l) on a hadron (h)

$$\ell(k) + h(P) \rightarrow \ell(k') + X$$

$$Q^2 = -q^2 = -(k - k')^2, \quad \nu = E - E', \quad x = \frac{Q^2}{2P \cdot q}$$



In **polarized DIS**,

spin-dependent structure functions $g_1(x)$ (& $g_2(x)$) is obtained

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 [\Delta q(x) + \Delta \bar{q}(x)]$$

$$\Delta q = q^+ - q^-$$

q^+ : quark helicity aligned with hadron helicity

q^- : quark helicity anti-aligned with hadron helicity

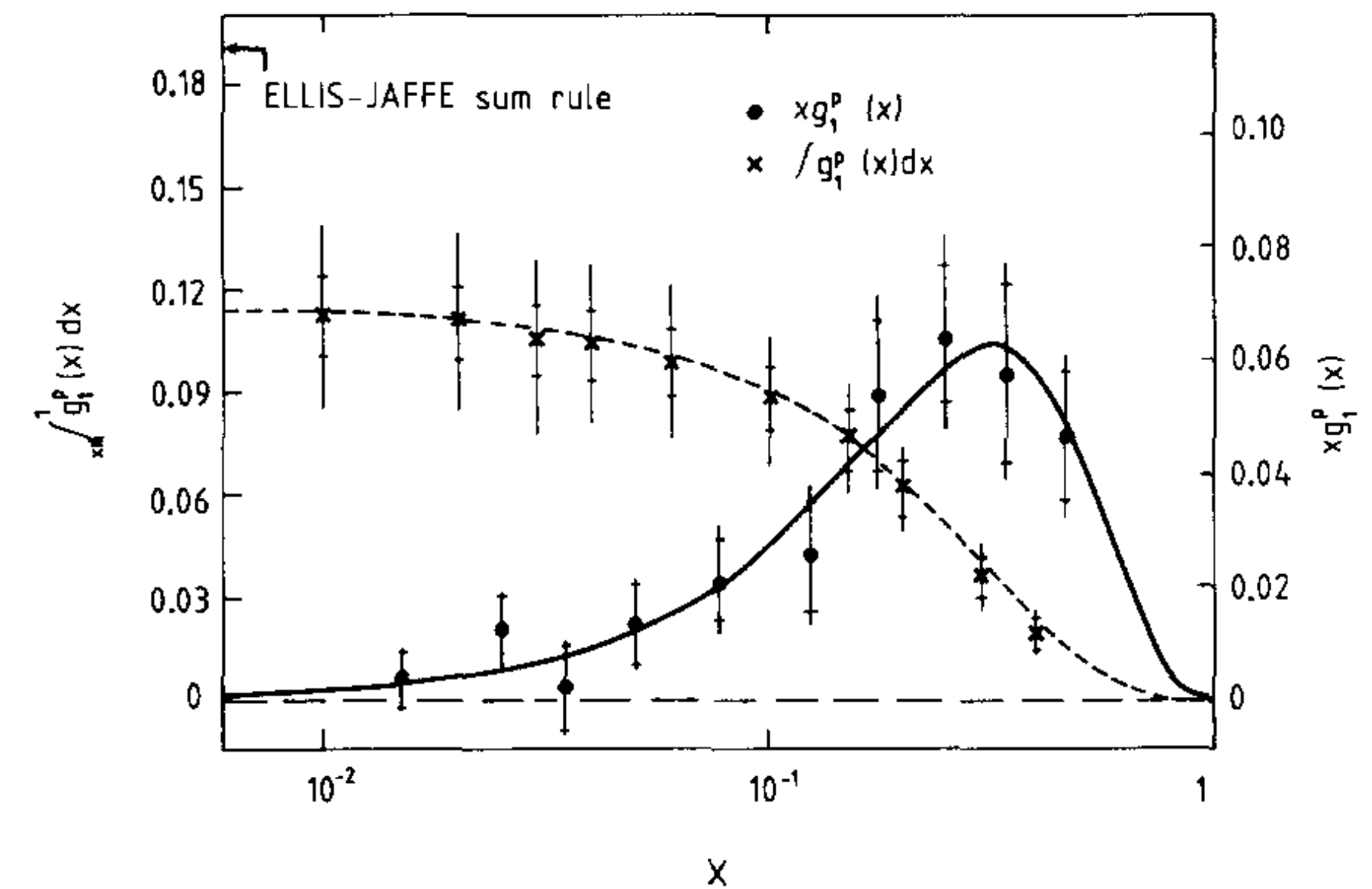
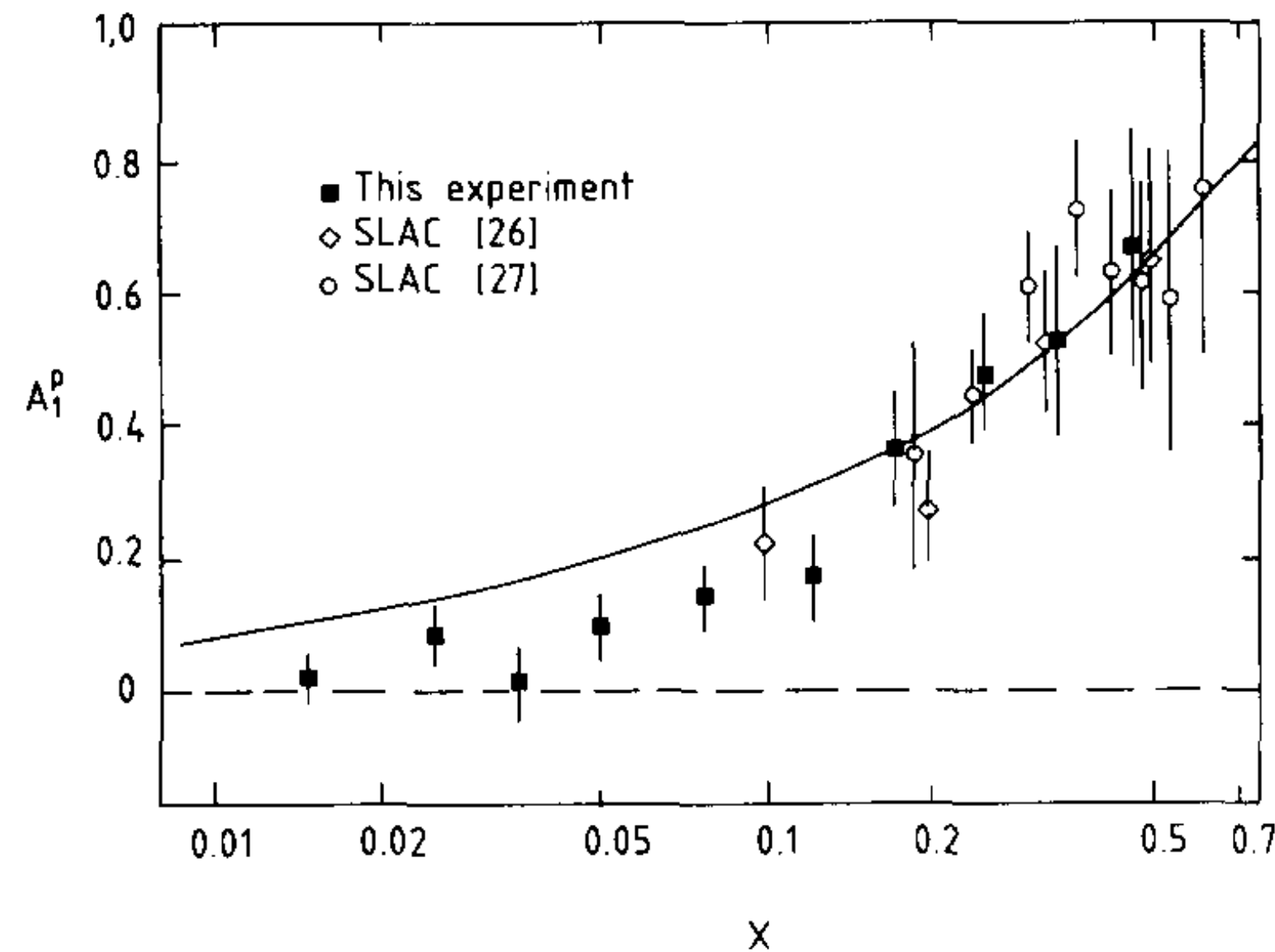
$g_1(x)$ mainly probes longitudinal quark helicity PDFs

EMC experiment

Polarized deep-inelastic scattering by EMC (European Muon Collaboration) in 1988

$$\mu^{\rightarrow} + p^{\rightarrow} \rightarrow \mu' + X$$

EMC, Phys. Lett. B206, 2 (1988)



$$A = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

$$A_1 \simeq A/D.$$

D: depolarization factor

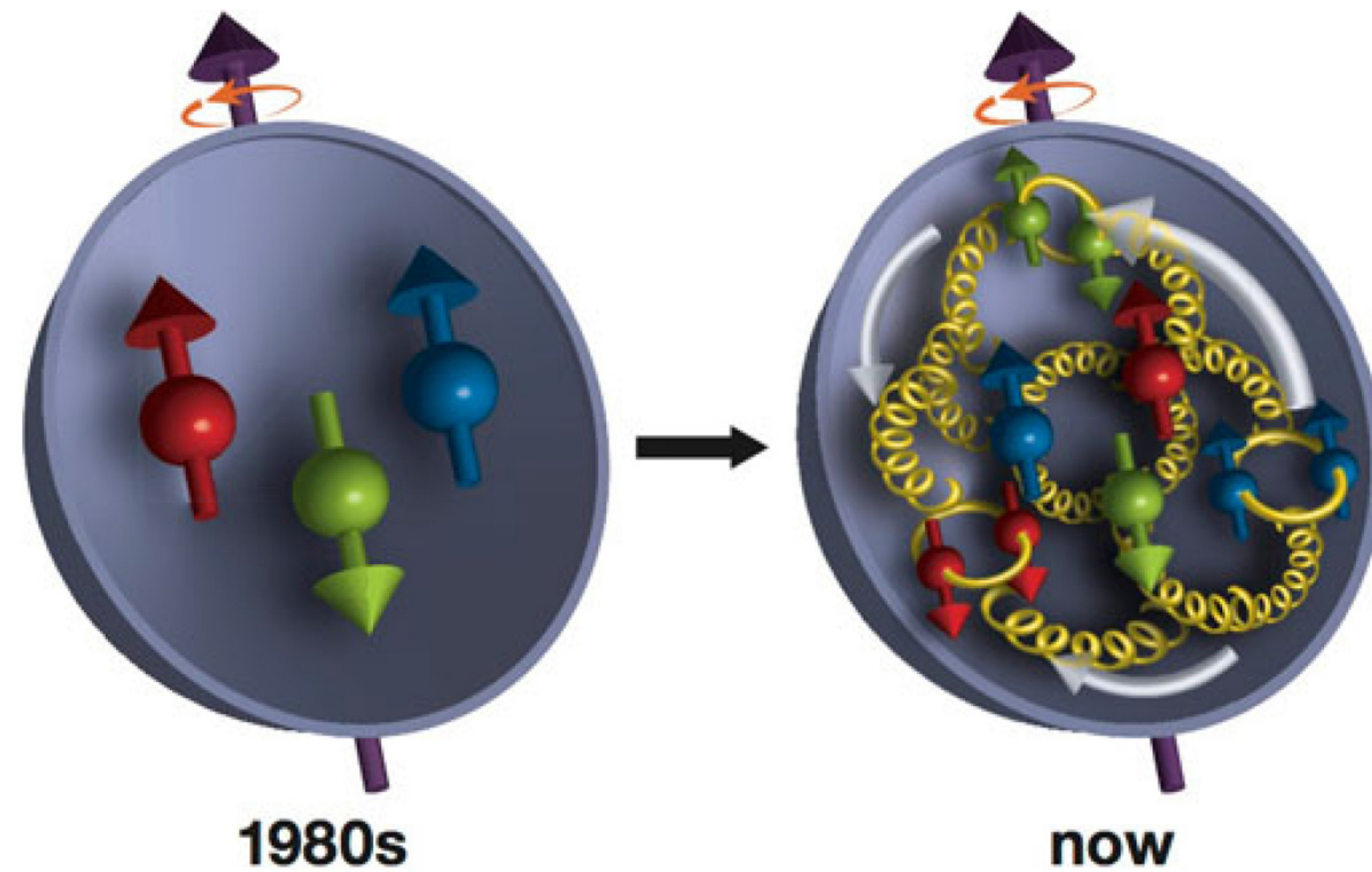
$$g_1 \simeq \frac{F_2 A_1}{2x(1+R)}$$

$$\int_0^1 g_1^p(x) dx \Rightarrow \Delta\Sigma \simeq 0.14$$

Longitudinal double-spin asymmetry

Only ~14% of proton spin carried by quark spins (spin crisis!)

Where is the rest of proton spin?



$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

Quark spin **Gluon spin** **Orbital angular momentum**

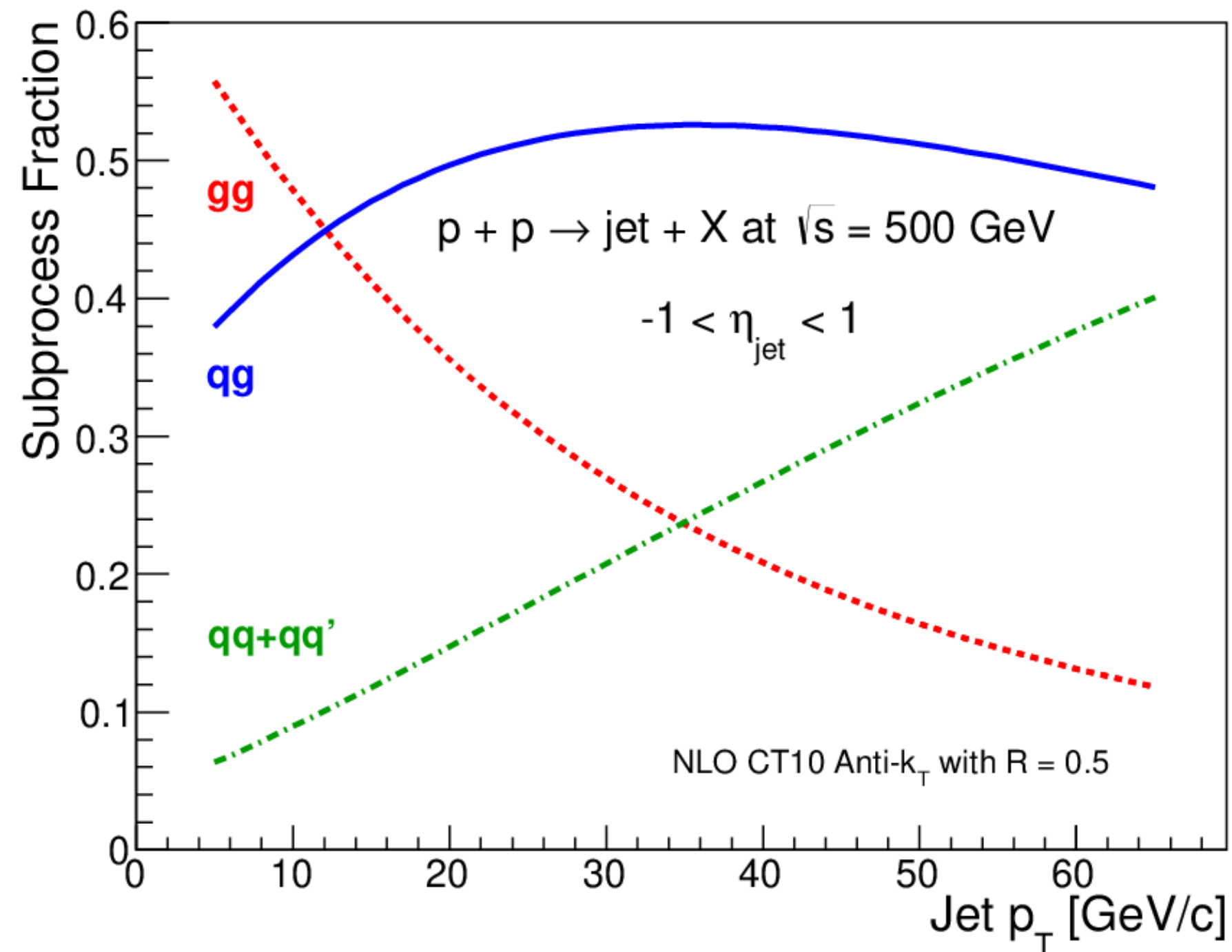
Quark spin: Known to be $\Delta \Sigma \sim 30\%$ by more DIS data with improved QCD analysis

Gluon spin: Can be constrained by polarized pp collisions

Orbital angular momentum: Little known

How to probe gluon helicity?

Mukherjee and Vogelsang, PRD86, 094009 (2012)
Plot from STAR, PRD97, 032004 (2018)



Jet and high- p_T hadron production is dominated by gluon-gluon (gg) and quark-gluon (qg) hard scattering process at RHIC energies

Longitudinally polarized proton-proton collisions

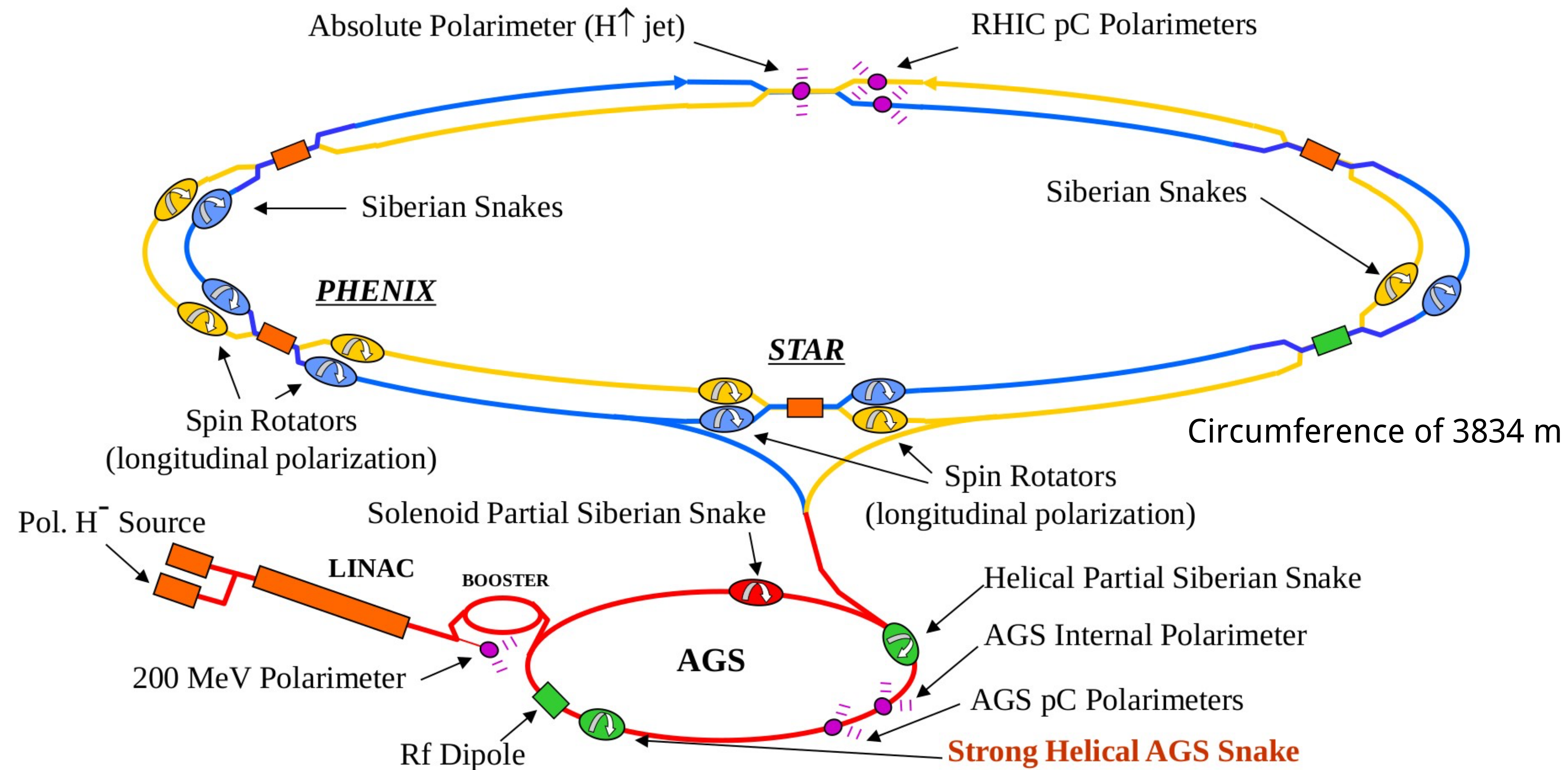
$$p^{\rightarrow} + p^{\rightarrow} \rightarrow \text{jet}/\pi^0 + X$$

$$gg \rightarrow gg, \quad qg \rightarrow qg$$

One can study gluon-related spin effects

→ RHIC spin program

Relativistic Heavy Ion Collider (RHIC) - Polarized proton collider



- The only polarized high-energy proton-proton collider
- Polarization: transverse and longitudinal
- Center-of-mass energy for pp collisions: $\sqrt{s} = 62, 200, 500/510$ GeV

Longitudinal double-spin asymmetry

$$p^{\rightarrow} + p^{\rightarrow} \rightarrow \text{jet}/\pi^0 + X$$

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

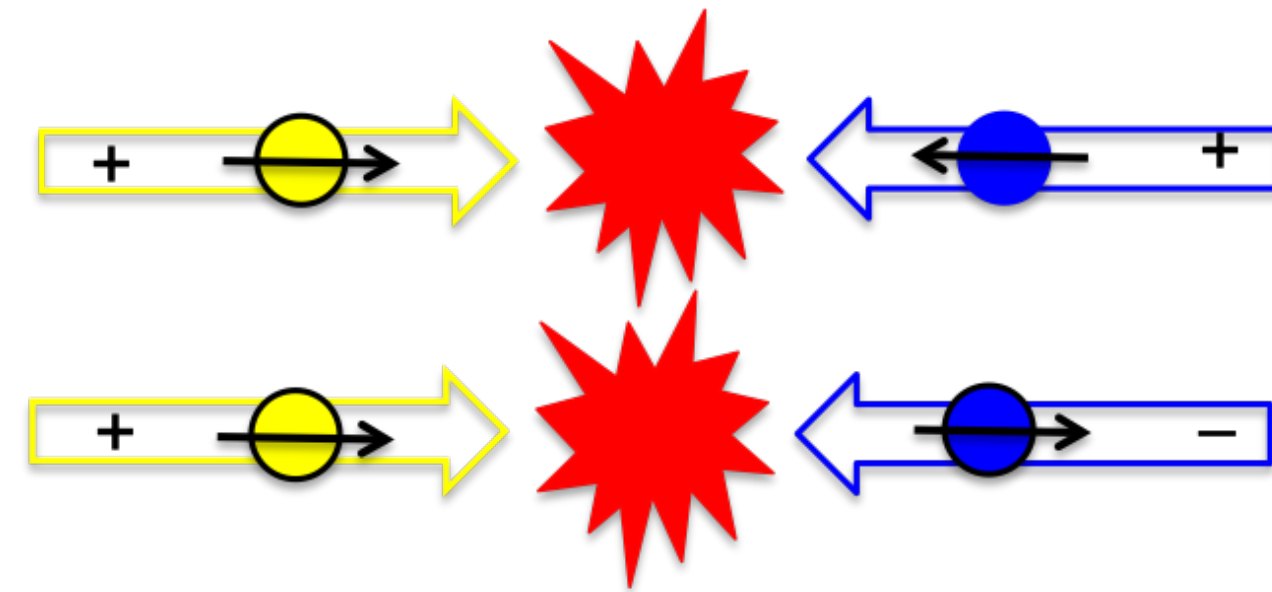
$$A_{LL} \sim \frac{\sum_{a,b} \Delta f_a \Delta f_b d\Delta \hat{\sigma}_{ab}}{\sum_{a,b} f_a f_b d\hat{\sigma}_{ab}} = \frac{\sum_{a,b} \Delta f_a \Delta f_b}{\sum_{a,b} f_a f_b} \hat{a}_{LL}$$

parton-level double spin asymmetry

e.g. for $qg \rightarrow qg$ process

$$A_{LL} \sim \frac{\Delta q}{q} \frac{\Delta g}{g} \hat{a}_{LL}$$

A_{LL} is sensitive to gluon helicity distribution Δg



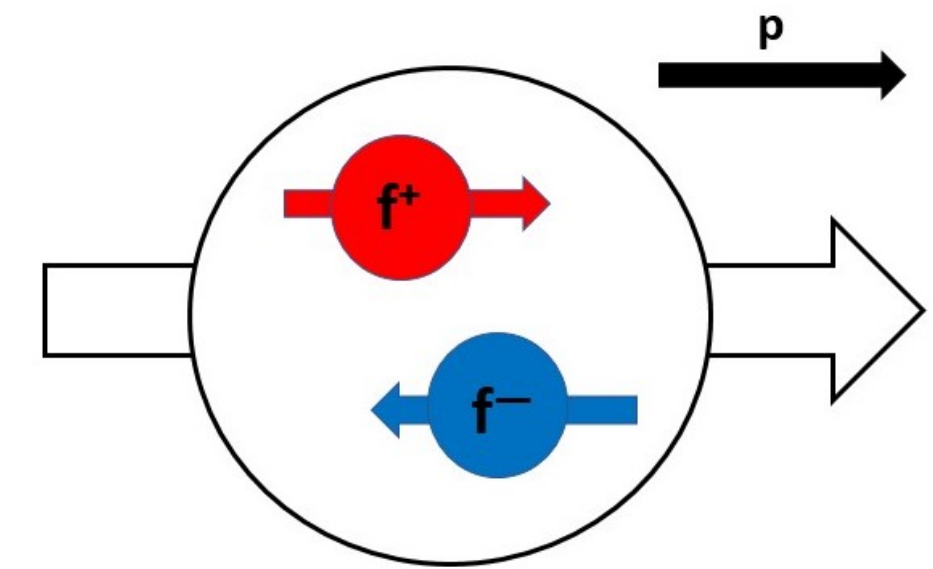
++: beam has the same helicity
+-: beam has the opposite helicity

Polarized parton distribution function Δf

$$\Delta f = f^+(x) - f^-(x)$$

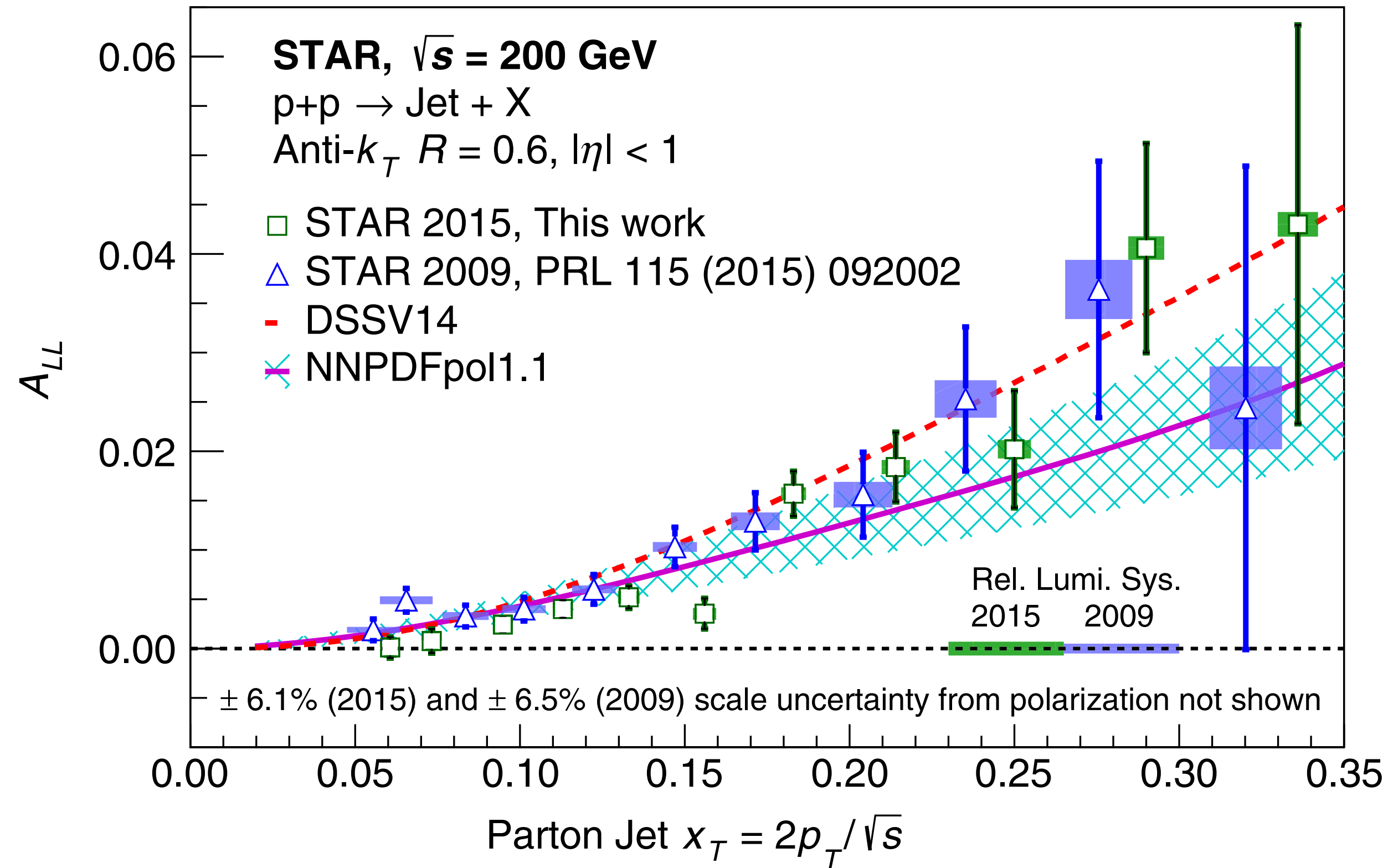
“+”: parton helicity aligned with proton helicity
(anti-aligned for “-”)

$\hat{\sigma}_{ab}$: cross section of parton-parton hard scattering
(a, b denote quark or gluon)



Jet A_{LL} from STAR

STAR, PRL115, 092002 (2015)
 STAR, PRD103, L091103 (2021) and more...



$$A_{LL} = \frac{\sum_{a,b} \Delta f_a \Delta f_b}{\sum_{a,b} f_a f_b} \hat{a}_{LL}$$

Jet A_{LL} : Sum over subprocesses gg , qg , qq

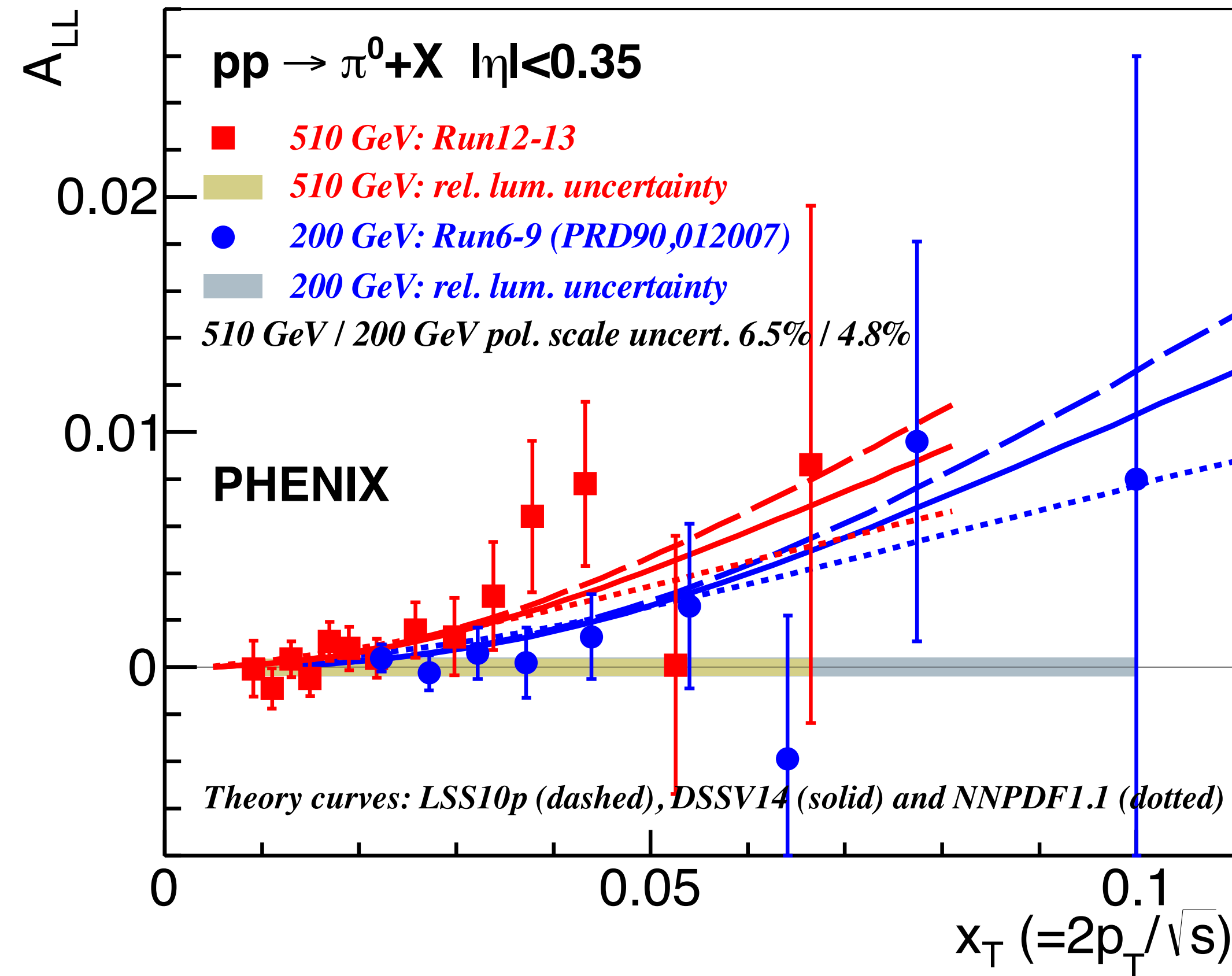
$$\begin{aligned} gg &: \Delta g(x_1) \Delta g(x_2) \\ qg &: \Delta q(x_1) \Delta g(x_2) \\ qq &: \Delta q(x_1) \Delta q(x_2) \end{aligned}$$

dominant

Positive jet A_{LL} at $x > 0.05$ provides evidence for a nonzero and positive Δg , when interpreted together with known quark helicities and QCD calculations

$\pi^0 A_{LL}$ from PHENIX

PHENIX, PRD90, 012007 (2014)
PHENIX, PRD93, 011501(R) (2016)



$$qg \rightarrow qg \rightarrow \pi^0 + X$$

$\underbrace{\hspace{1.5cm}}$
fragmentation

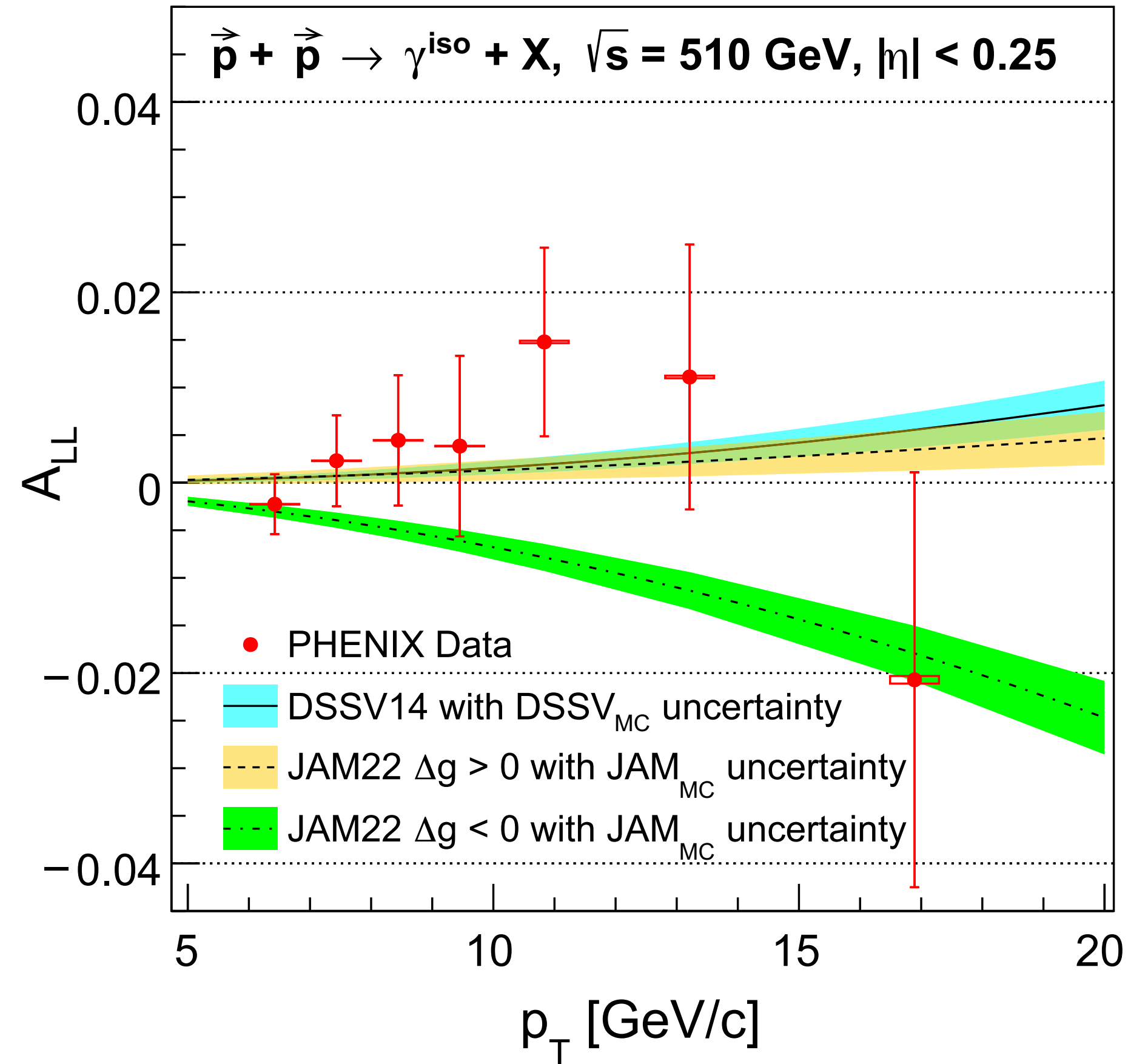
$$d\Delta\sigma \sim \Delta f_a \otimes \Delta f_b \otimes d\Delta\hat{\sigma}_{ab \rightarrow cX} \otimes D_{c \rightarrow \pi^0}$$

Unlike jets,
 π^0 production involves parton fragmentation

Positive $\pi^0 A_{LL}$ provides complementary evidence for a positive gluon helicity distribution Δg

A cleaner probe: Direct photon A_{LL}

PHENIX, PRL 130, 251901 (2023)



$$A_{LL} = \frac{\sum_{a,b} \Delta f_a \Delta f_b}{\sum_{a,b} f_a f_b} \hat{a}_{LL}$$

$$gg : \Delta g(x_1) \Delta g(x_2)$$

$$qg : \Delta q(x_1) \Delta g(x_2)$$

$$qq : \Delta q(x_1) \Delta q(x_2)$$

Jet/ π^0 A_{LL} cases, gg contribution is insensitive to the sign of Δg

Direct-photon A_{LL} case, $q + g \rightarrow q + \gamma$ is dominant

$$A_{LL}^{\gamma} \sim \Delta q \Delta g$$

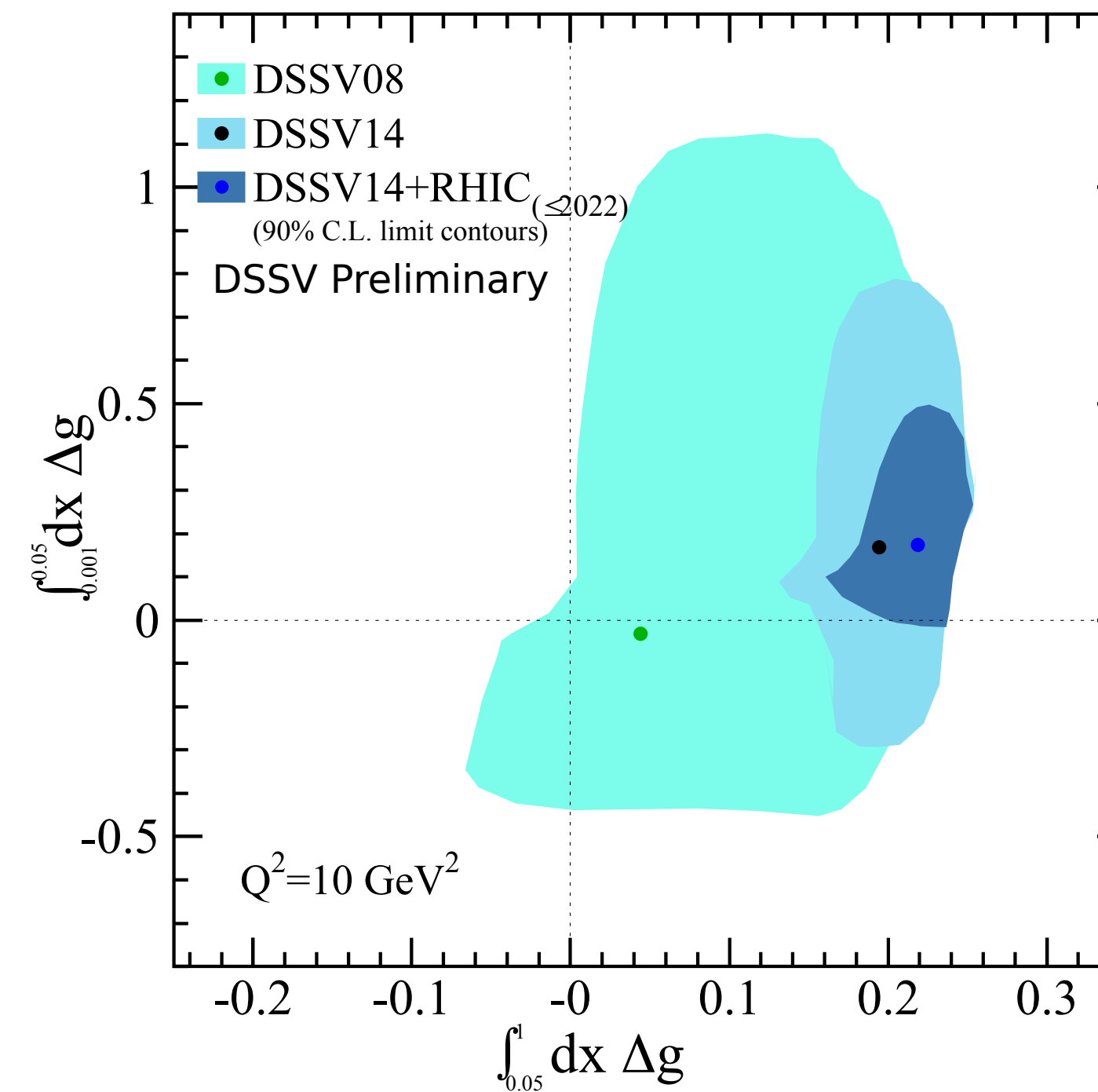
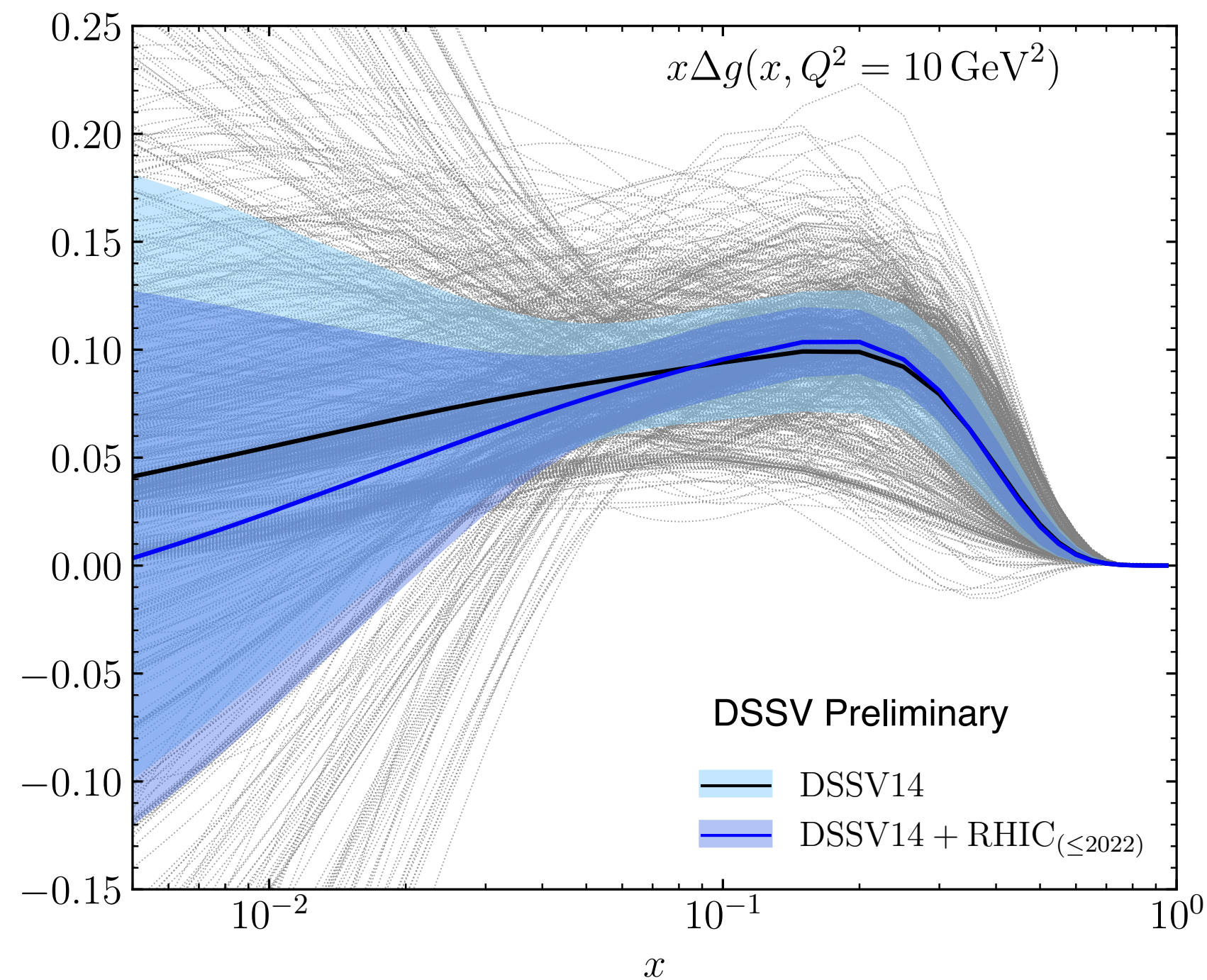
Despite the relatively large uncertainties, positive direct-photon A_{LL} favors a positive Δg (2.8σ level).

A clean and independent probe to determine the sign of Δg

Constrain ΔG by global QCD analysis

Global QCD analysis: Simultaneous analysis of various experimental data within the QCD framework to extract (helicity) PDFs

QCD framework: factorization + pQCD + Q^2 evolution of PDFs



$$\Delta G = \int_0^1 dx \Delta g(x)$$

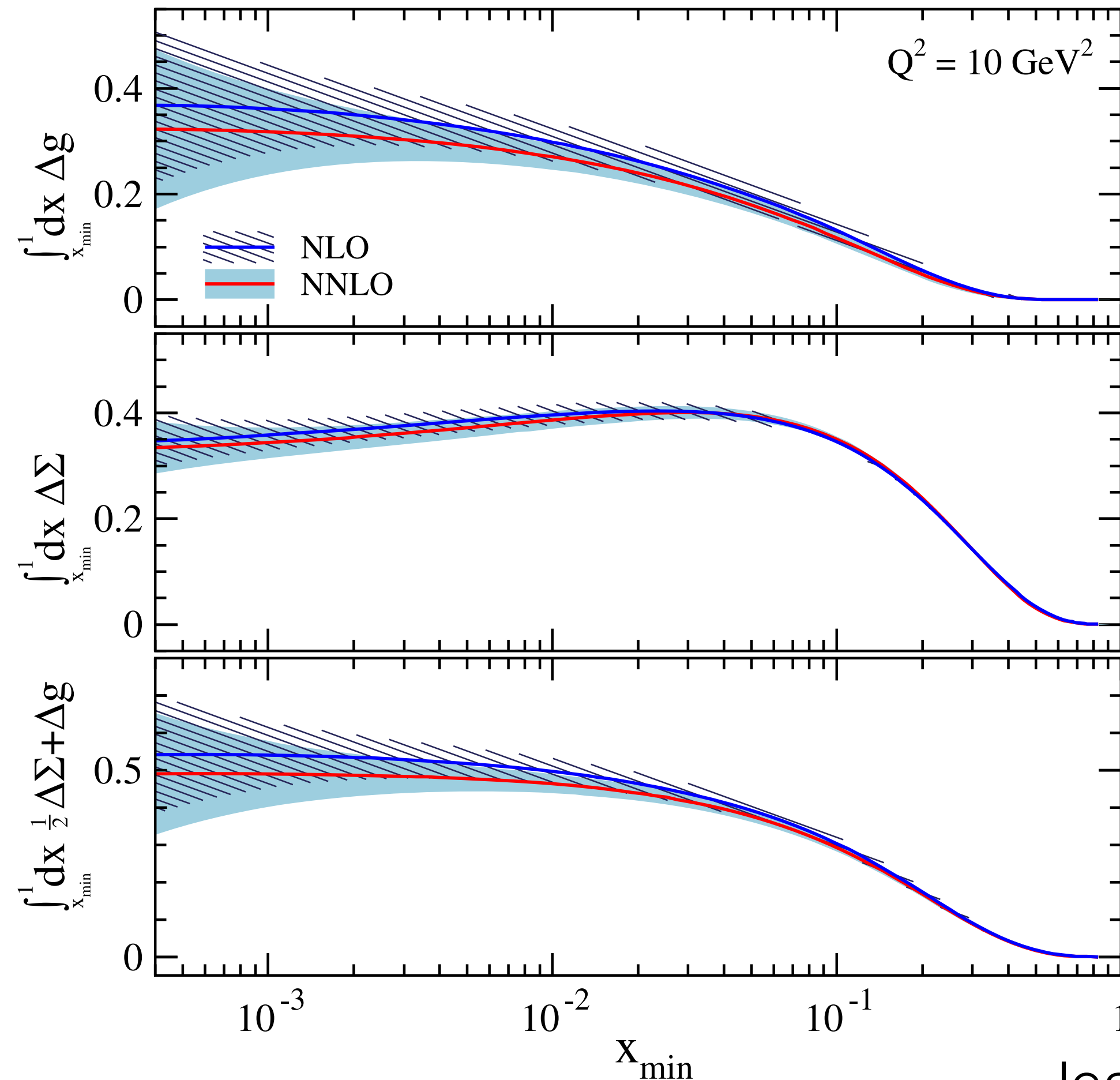
Plots from RHIC ColdQCD white paper, arXiv:2302.00605

Significant improvements on ΔG using RHIC A_{LL} data

Recent update on ΔG using NNLO

Borsa et al., PRL133, 151901 (2024)

NNLO global QCD analysis



$$\Delta G = \int_0^1 dx \Delta g(x)$$

$$\frac{1}{2} = \frac{1}{2} \underbrace{\Delta \Sigma}_{\sim 0.34} + \underbrace{\Delta G}_{\sim 0.3} + L_q + L_g$$

~ 0.47

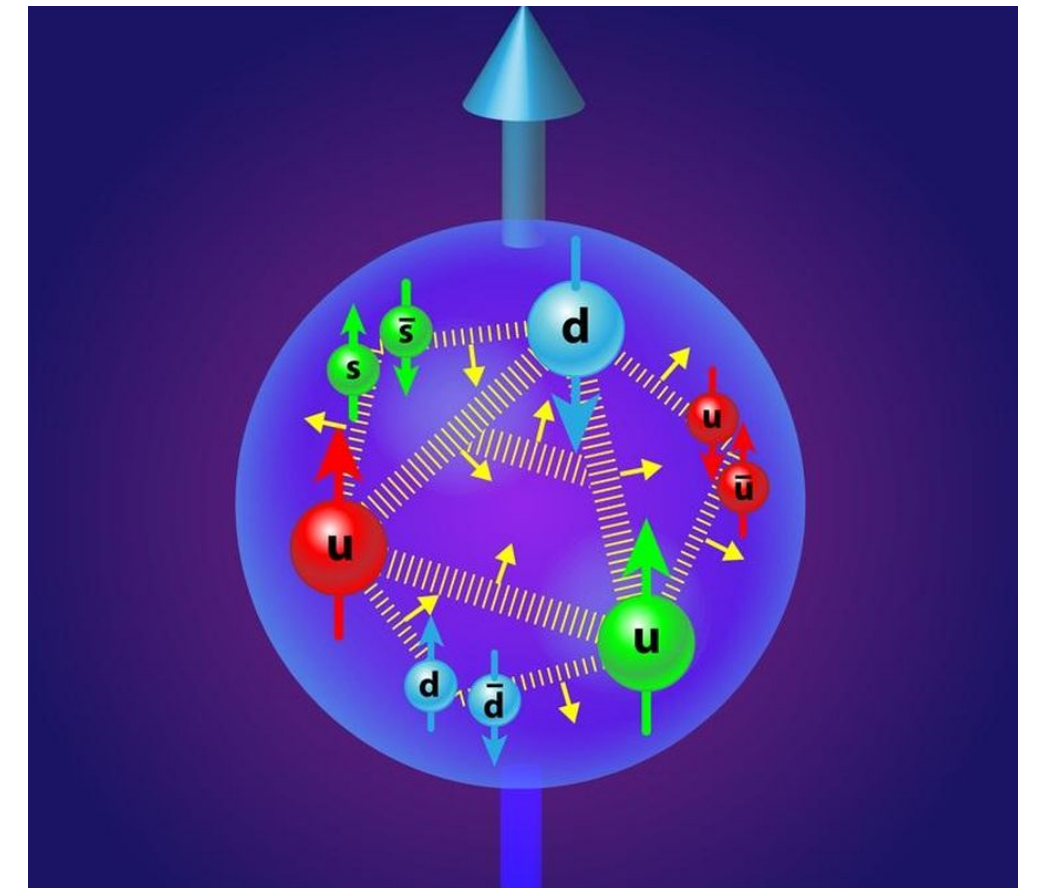
The central values suggest that quark and gluon helicities together may account for most of the proton spin.

However, the small- x region remains poorly constrained, leaving uncertainty in the total quark and gluon helicity contributions.

What about sea-quark helicities?

$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \boxed{\Delta\bar{u} + \Delta\bar{d}} + \Delta\bar{s})dx$$

Total quark helicity contribution is well constrained by DIS ($\Delta\Sigma \sim 0.3$).
Semi-inclusive DIS provides some flavor separation but
sea-quark helicities remain less well constrained.



Sea-quark helicities accessible via W production at RHIC: $\Delta\bar{u}$, $\Delta\bar{d}$

$$p^{\rightarrow} + p \rightarrow W^{\pm} + X$$

Probing sea-quark helicities via W production

$$p^{\rightarrow} + p \rightarrow W^{\pm} + X$$

Why $W^{\pm}$ production? Bourrely and Soffer, NPB423, 329-348 (1994)

✓ **$W^{\pm}$ couple directly to specific quark flavors**

$$u + \bar{d} \rightarrow W^{+}$$

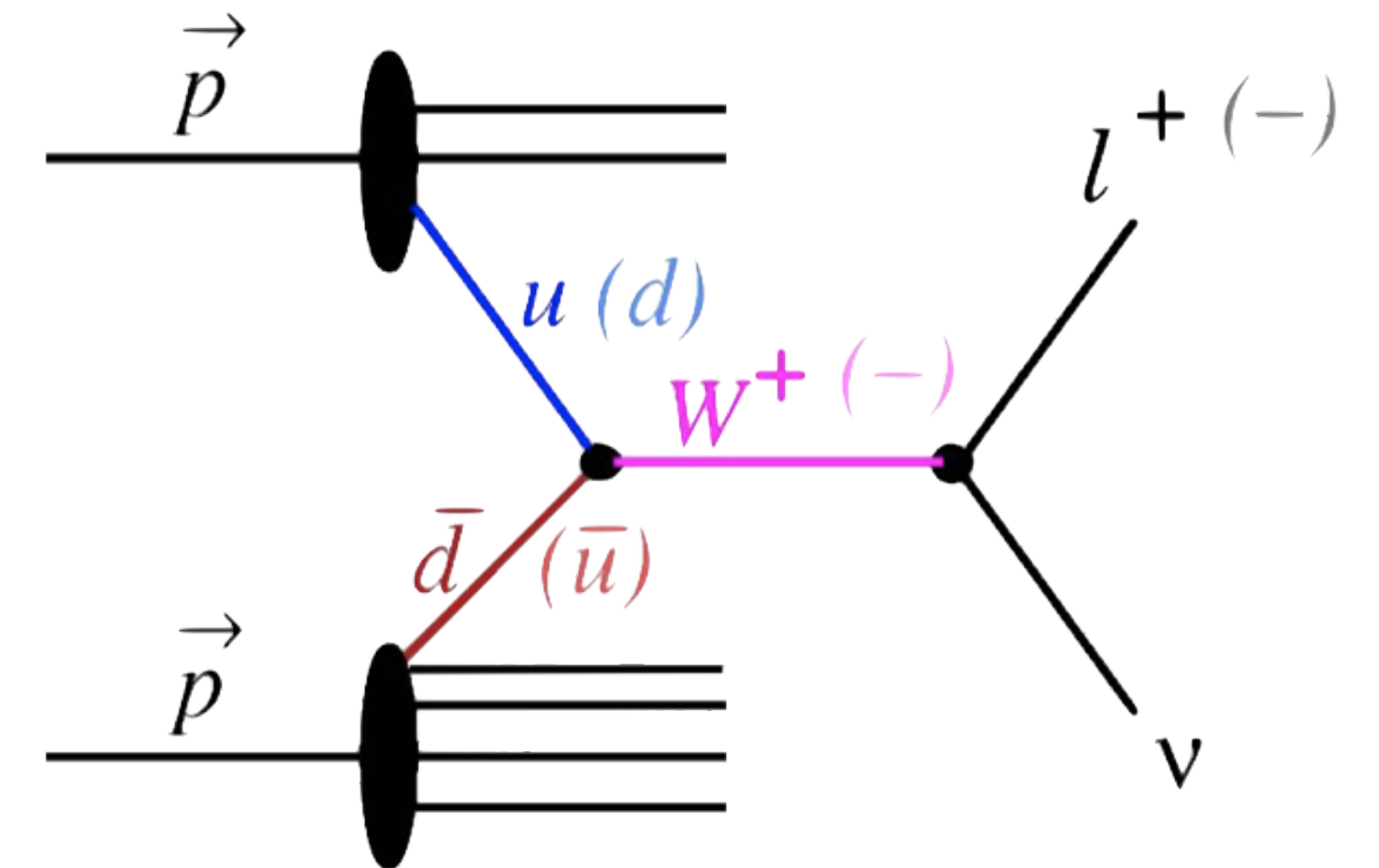
$$d + \bar{u} \rightarrow W^{-}$$

✓ **V-A interaction acts as a helicity selector**

Only left-chiral quarks and right-chiral anti-quarks couple to W

$$u_L + \bar{d}_R \rightarrow W^{+}$$

~~$$u_R + \bar{d}_L$$~~



Recall “helicity and Goldhaber experiment” in day-1

Longitudinal single-spin asymmetry of W bosons

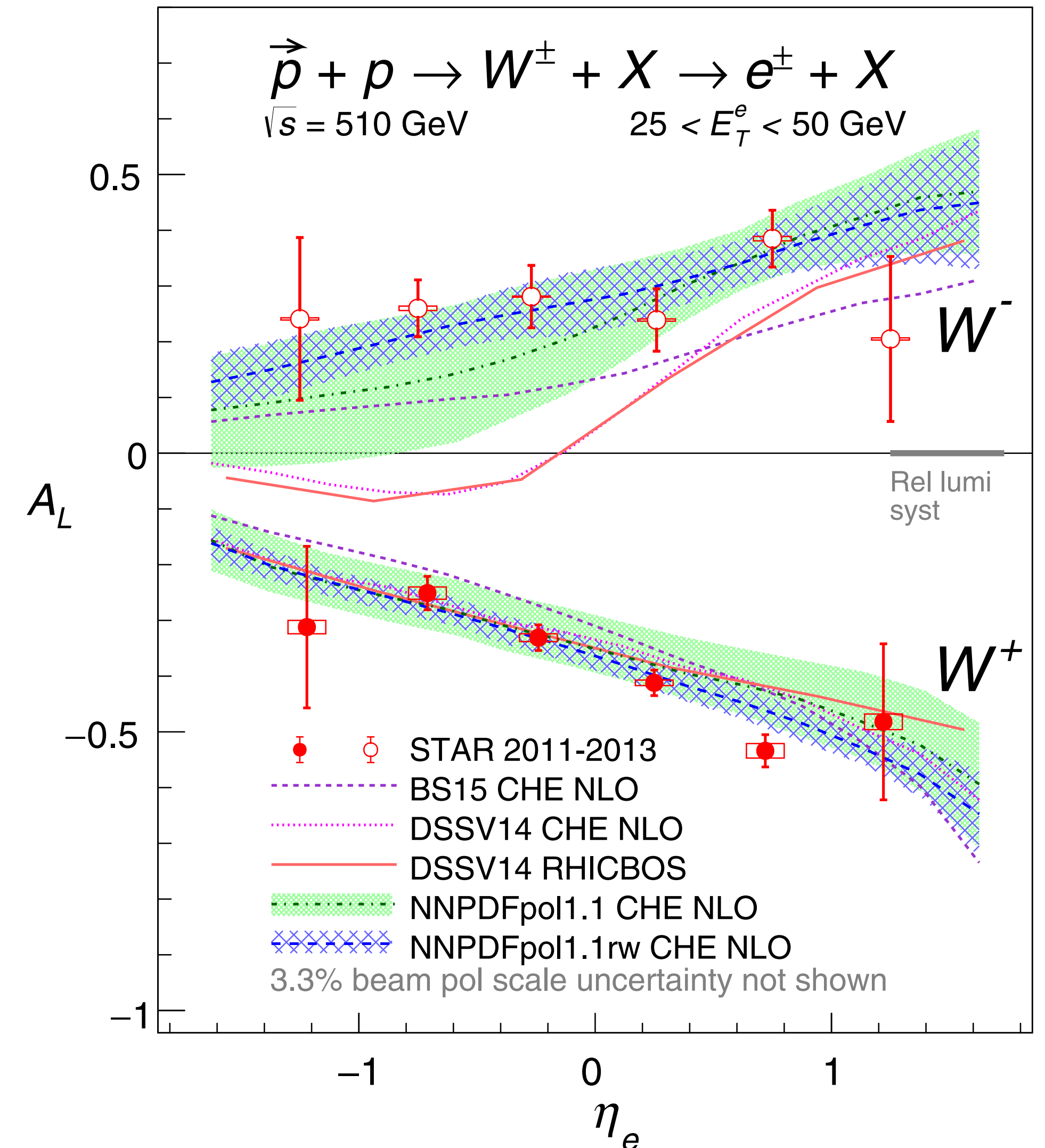
STAR, PRD99, 051102 (2019)

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_L^{W^+} \sim \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \sim \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

- Large parity-violating single-spin asymmetries are observed
- Opposite sign for W^+ A_L and W^- A_L
- η dependence provides sensitivity to different quark and anti-quark helicities



Longitudinal single-spin asymmetry of W bosons

STAR, PRD99, 051102 (2019)

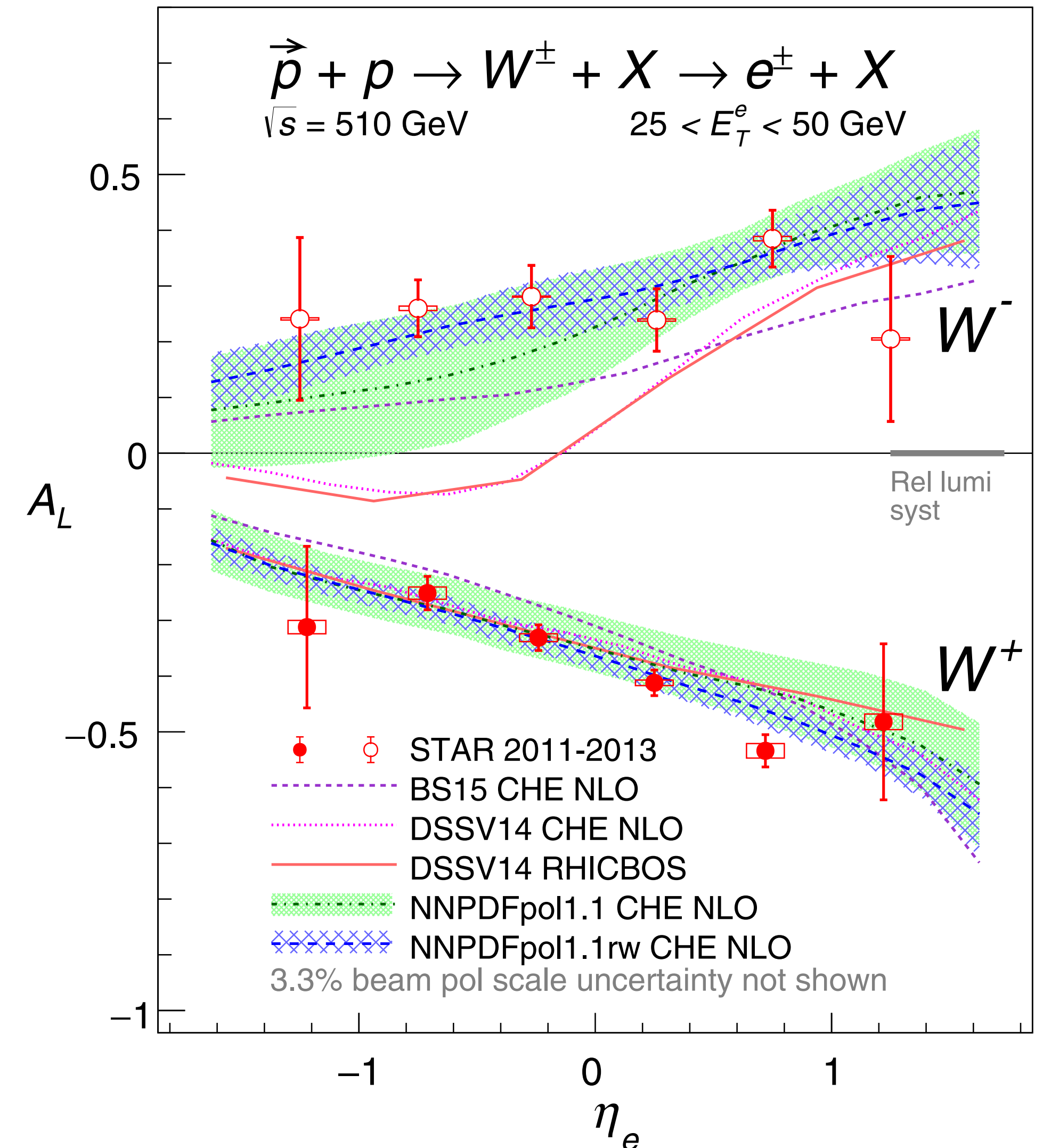
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_L^{W^+} \sim \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \sim \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

- Large parity-violating single-spin asymmetries are observed
- Opposite sign for W^+ A_L and W^- A_L
- η dependence provides sensitivity to different quark and anti-quark helicities

$$p_z^W = \frac{\sqrt{s}}{2}(x_1^{\text{pol}} - x_2^{\text{unpol}})$$



Longitudinal single-spin asymmetry of W bosons

STAR, PRD99, 051102 (2019)

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_L^{W^+} \sim \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \sim \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

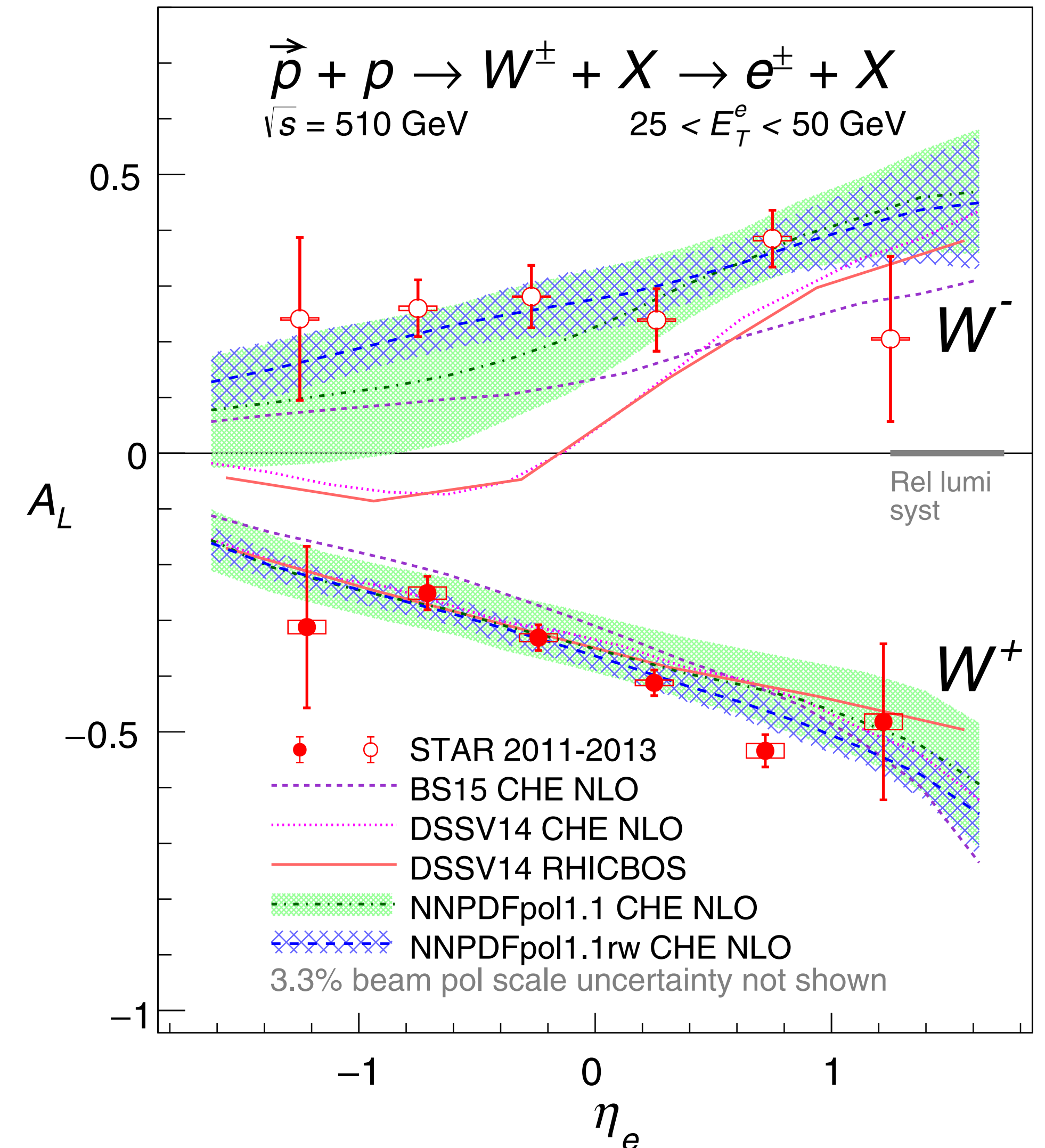
- Large parity-violating single-spin asymmetries are observed
- Opposite sign for W^+ A_L and W^- A_L
- η dependence provides sensitivity to different quark and anti-quark helicities

$$p_z^W = \frac{\sqrt{s}}{2}(x_1^{\text{pol}} - x_2^{\text{unpol}})$$

W^+ case

Forward $\eta \rightarrow (x_1^{\text{pol}} - x_2^{\text{unpol}}) > 0$ (large x_1) $\rightarrow$ sensitive to Δu

Backward $\eta \rightarrow (x_1^{\text{pol}} - x_2^{\text{unpol}}) < 0$ (small x_1) $\rightarrow$ sensitive to $\Delta\bar{d}$



Longitudinal single-spin asymmetry of W bosons

STAR, PRD99, 051102 (2019)

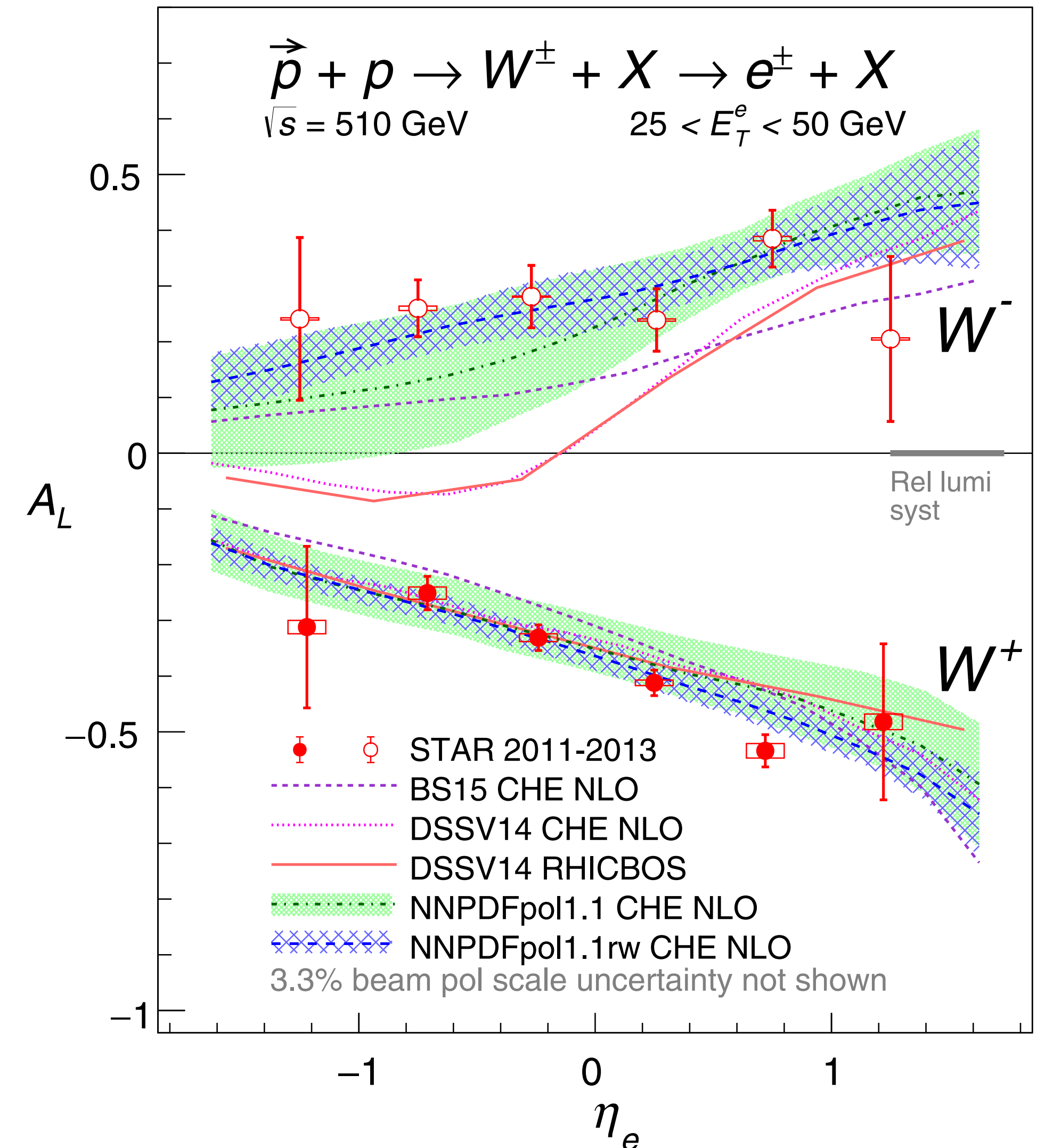
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_L^{W^+} \sim \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$A_L^{W^-} \sim \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

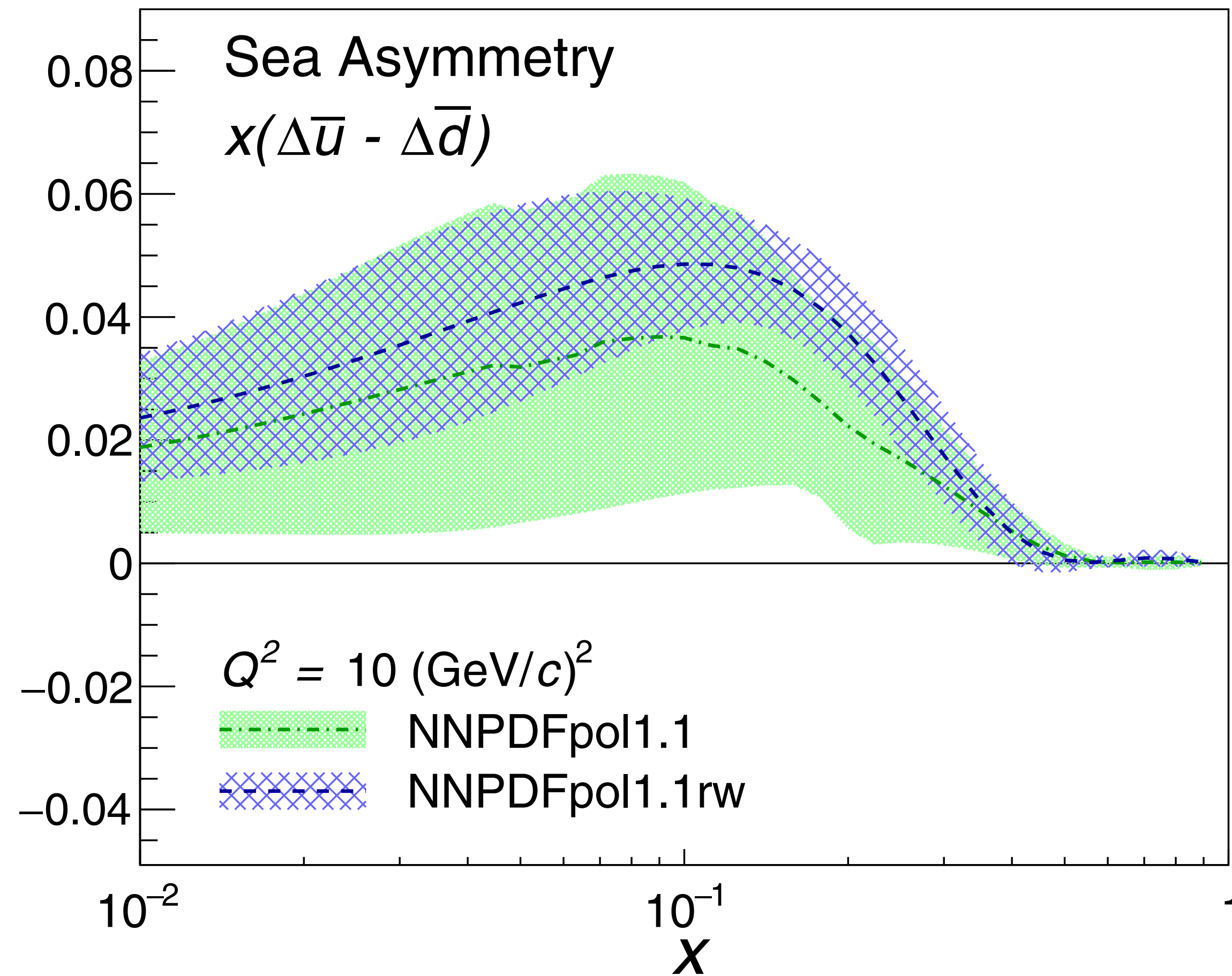
- Large parity-violating single-spin asymmetries are observed
- Opposite sign for W^+ A_L and W^- A_L
- η dependence provides sensitivity to different quark and anti-quark helicities

Opposite signs of backward W^+ and W^- asymmetries
reflect signs of Δd and $\Delta\bar{u}$



Flavor asymmetry in the polarized sea

STAR, PRD99, 051102 (2019)



STAR W data significantly constrain sea-quark helicities

$$\Delta\bar{u}(x) > \Delta\bar{d}(x) \quad (0.05 < x < 0.25)$$

Flavor asymmetry in the polarized light-quark sea

Beyond longitudinal spin structure

Longitudinally polarized protons $p^{\rightarrow} + p^{\rightarrow} \rightarrow \text{jet}/\pi^0 + X$

$$\Delta q(x) = q^{+}(x) - q^{-}(x), \quad \Delta g(x) = g^{+}(x) - g^{-}(x)$$

- DIS $\rightarrow$ quark helicity
- A_{LL} $\rightarrow$ gluon helicity
- $W A_L \rightarrow$ flavor-separated quark/antiquark helicity

What about transverse spin?

Beyond longitudinal spin structure

Longitudinally polarized protons $p^{\rightarrow} + p^{\rightarrow} \rightarrow \text{jet}/\pi^0 + X$

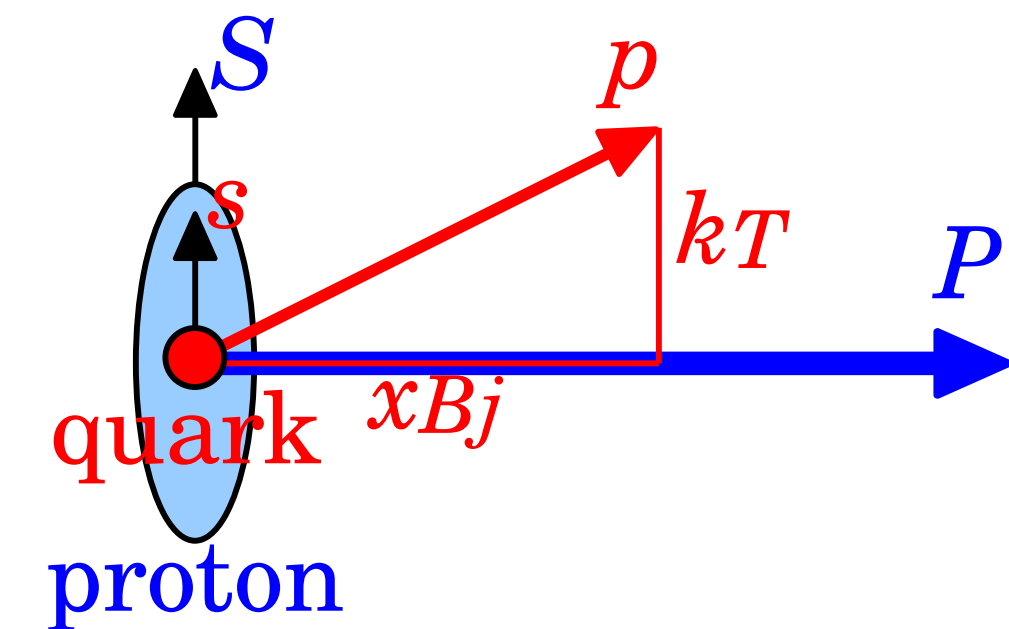
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- DIS $\rightarrow$ quark helicity
- A_{LL} $\rightarrow$ gluon helicity
- $W A_L \rightarrow$ flavor-separated quark/antiquark helicity

What about transverse spin?

Transversely polarized protons $p^{\uparrow} + p \rightarrow h + X$

- Protons have transverse motion: k_T
 - Spin can be correlated with k_T
- $\rightarrow$ Transverse-momentum-dependent distributions (TMDs)



Sivers effect:
Correlation between nucleon spin (S) and
parton transverse momentum (k_T)

Beyond longitudinal spin structure

Longitudinally polarized protons $p^{\rightarrow} + p^{\rightarrow} \rightarrow \text{jet}/\pi^0 + X$

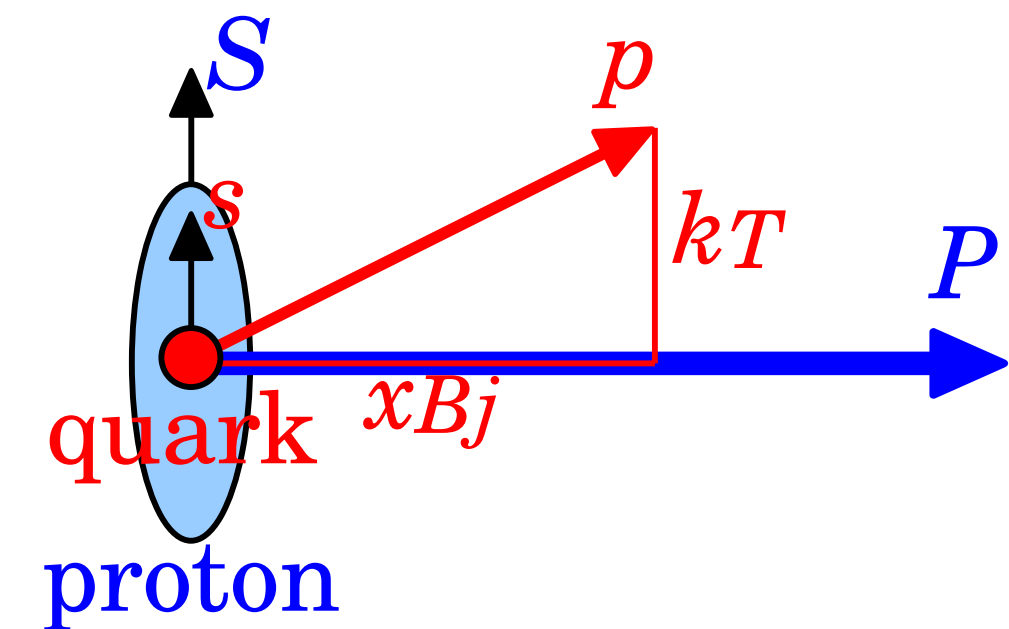
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Sivers effect:
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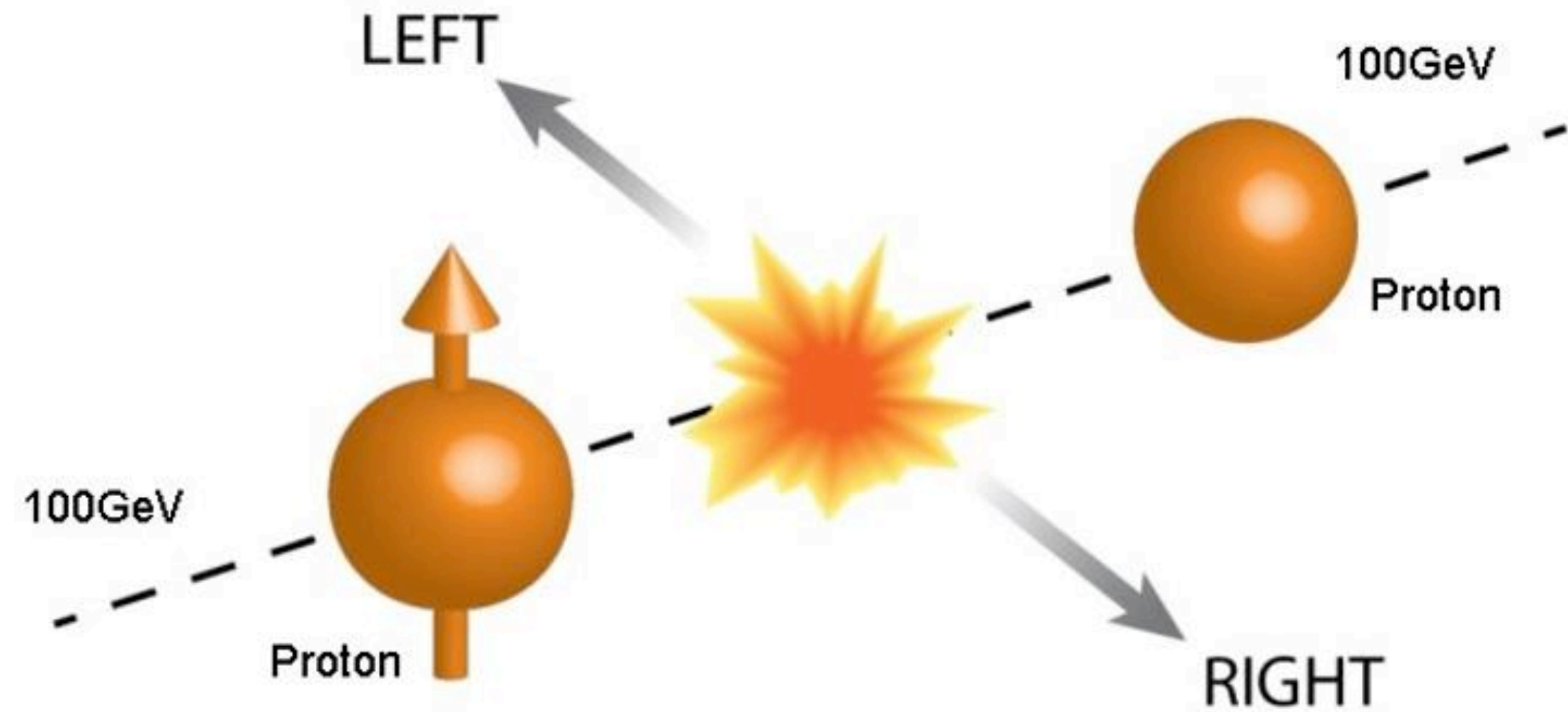
Spin structure is not only about helicity.
Spin can also correlate with transverse parton motion

Transverse single-spin asymmetry

$$p^\uparrow + p \rightarrow h + X$$

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

$$\boldsymbol{n} = \frac{\boldsymbol{p}_{\text{beam}} \times \boldsymbol{p}_h}{|\boldsymbol{p}_{\text{beam}} \times \boldsymbol{p}_h|}$$



In pQCD, transverse spin effect was naively expected to be small at high energies...

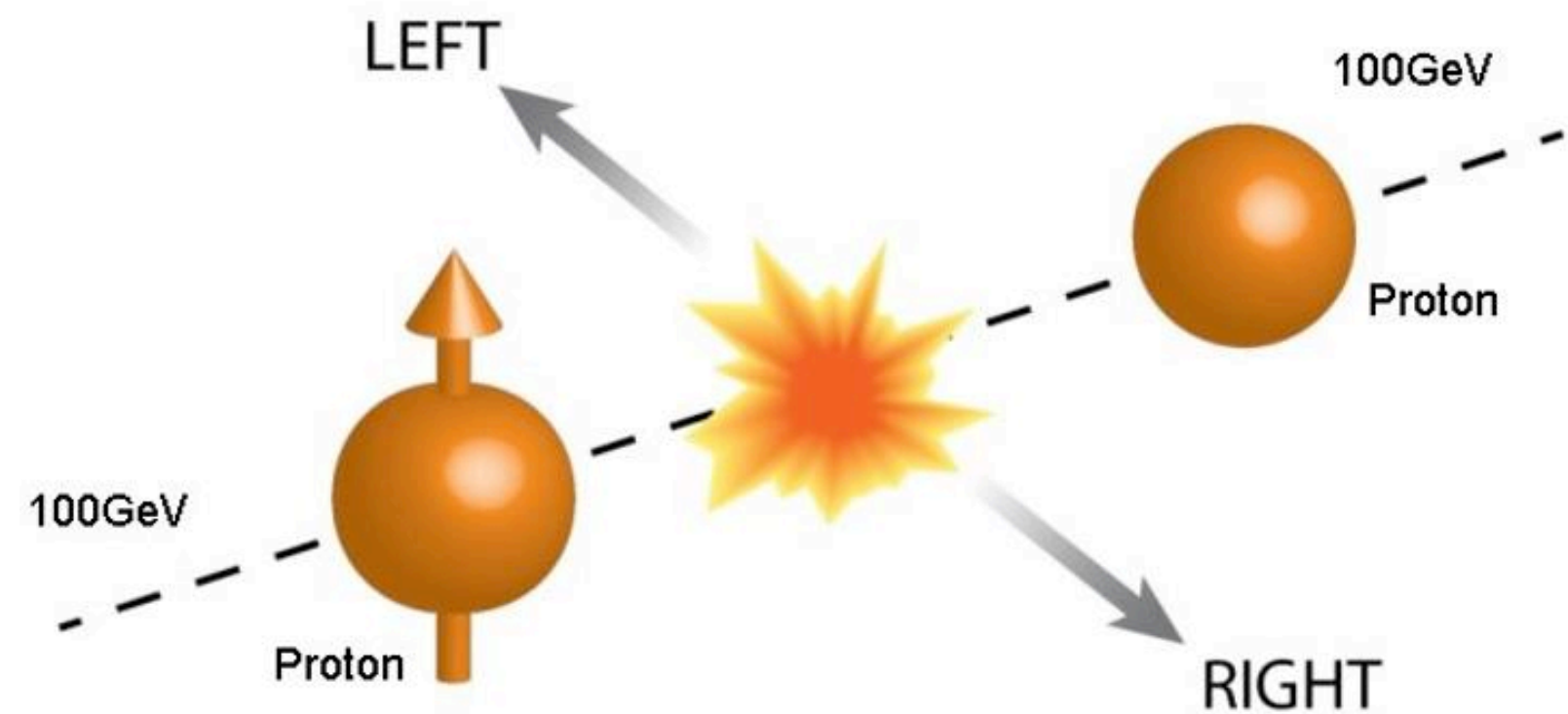
$$\text{In naive pQCD: } A_N \sim \alpha_s \frac{m_q}{p_T}$$

Kane, Pumplin, and Repko, PRL41, 1689 (1978)

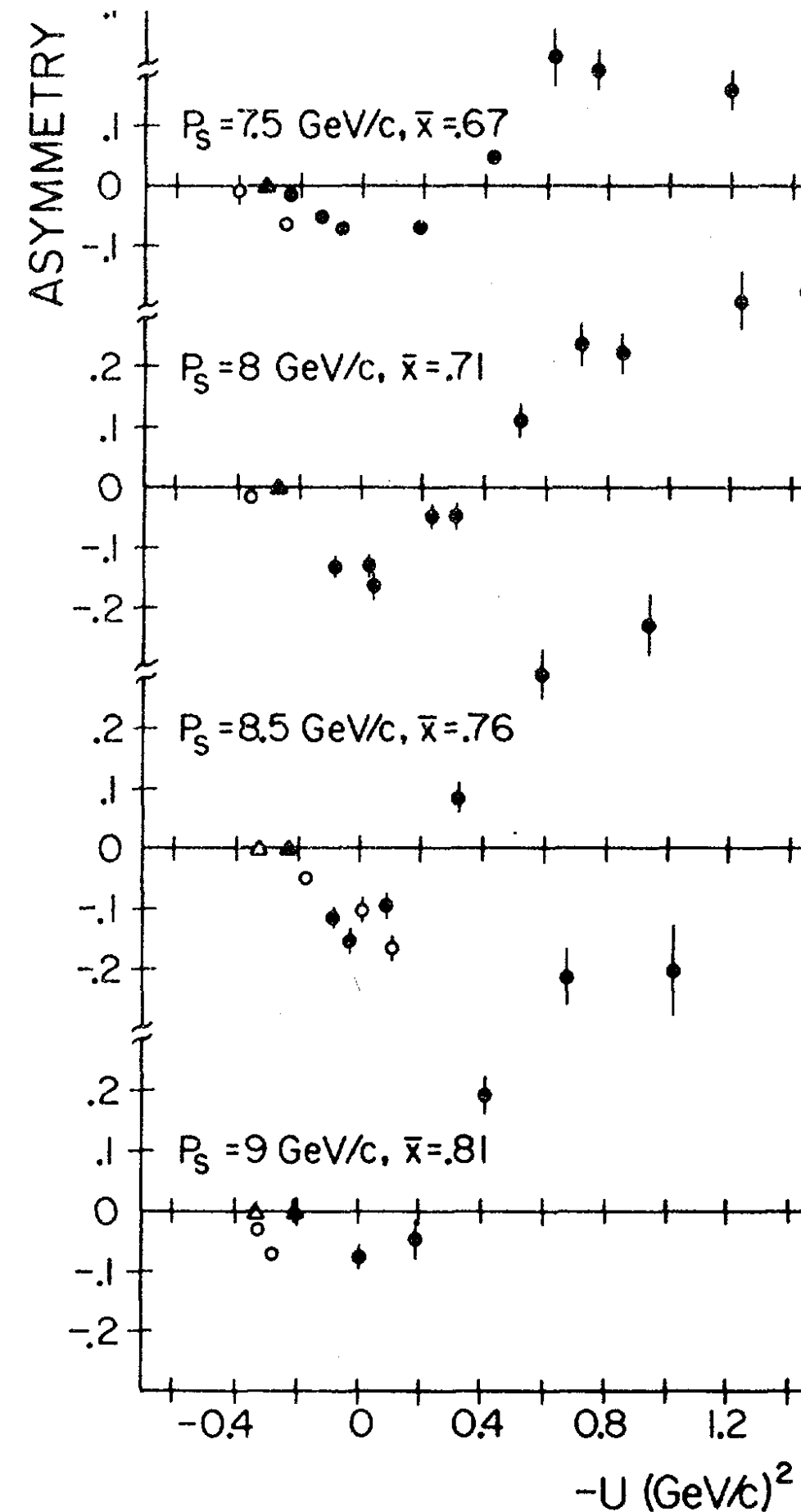
Transverse single-spin asymmetry

$$p^\uparrow + p \rightarrow h + X$$

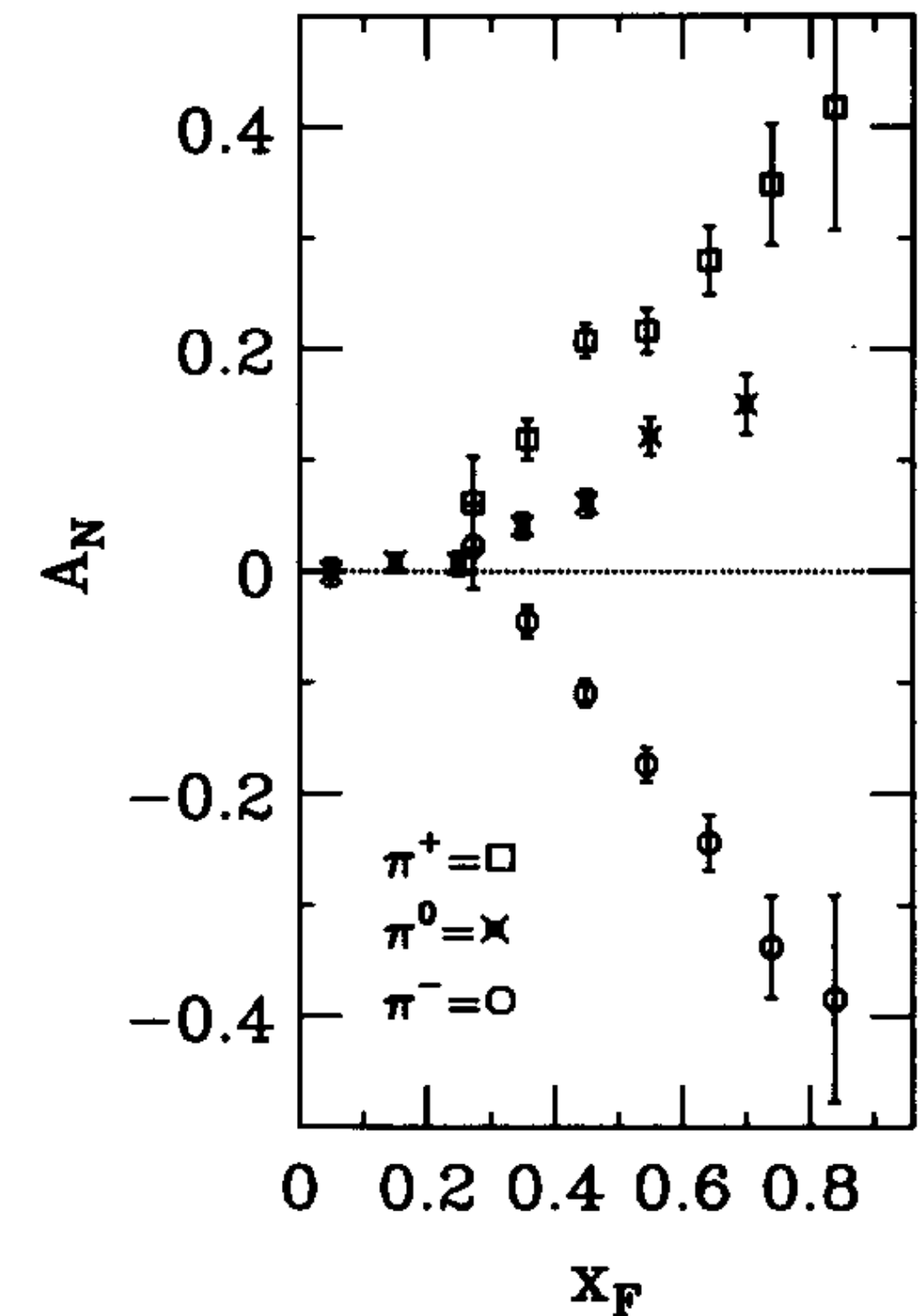
$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



Klem et al. (ZGS), PRL36, 929 (1976)



Adams et al. (FNAL E704),
PLB264, 929 (1991)



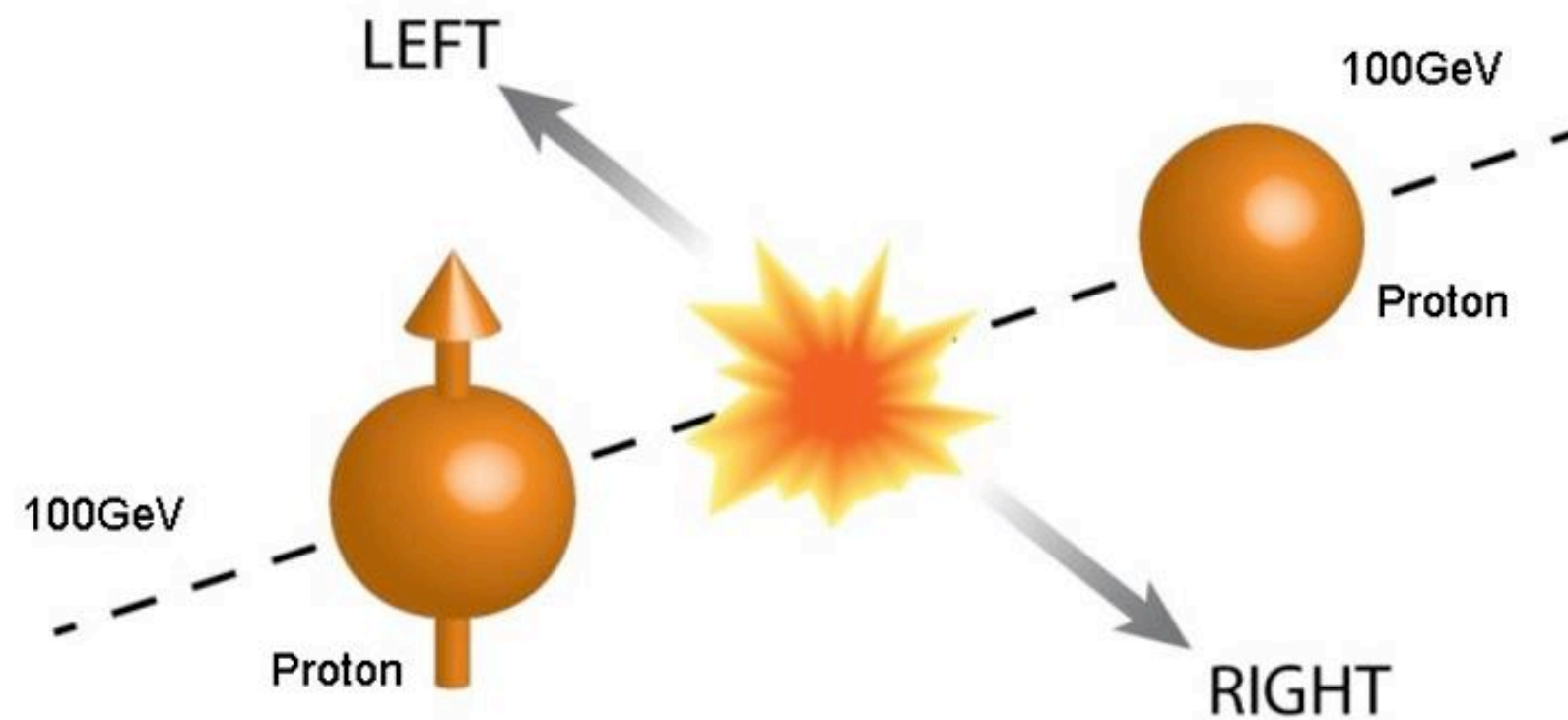
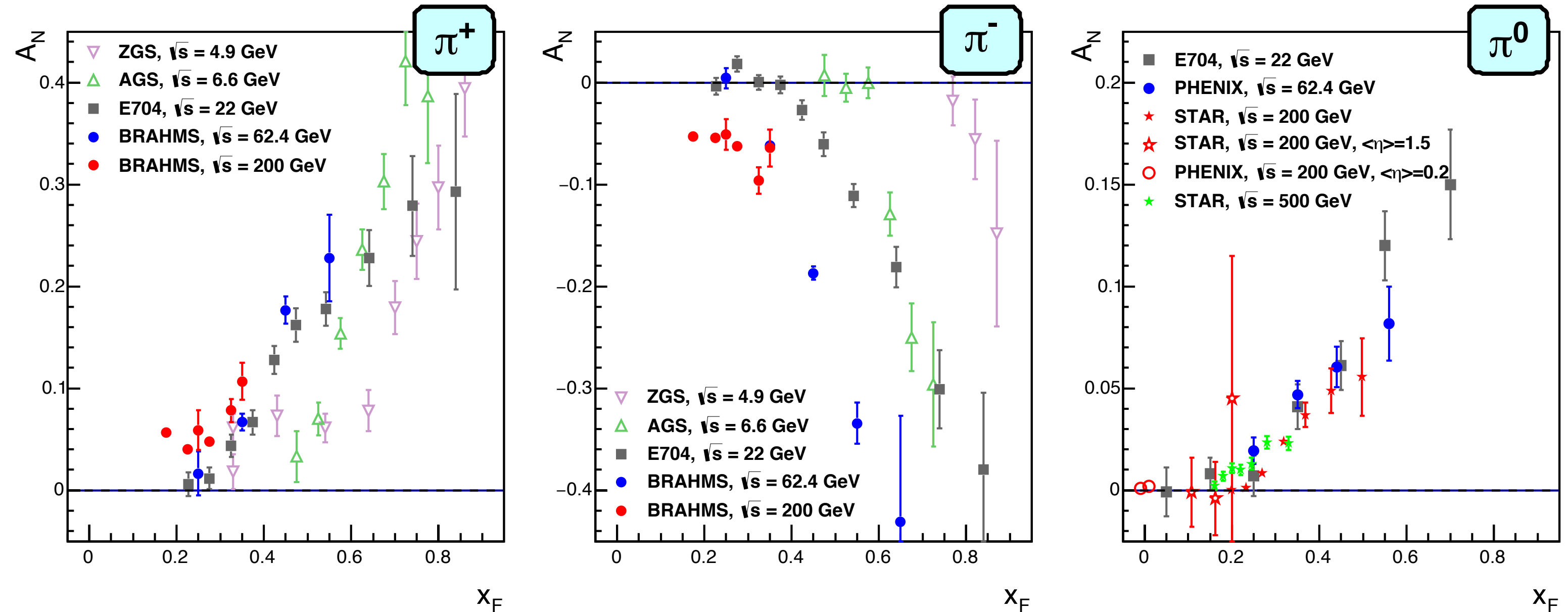
Surprisingly large A_N was observed at forward rapidity
at Argonne National Lab. ZGS experiment, and later at FNAL E704!

Transverse single-spin asymmetry

RHIC ColdQCD WhitePaper (2016), arXiv1602.03922

$$p^\uparrow + p \rightarrow h + X$$

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



Large A_N was also observed at forward rapidity at RHIC

→ Spin-momentum correlation

Initial state: quark-gluon correlations (related to Sivers effect)

Final state: fragmentation correlations (related to Collins effect)

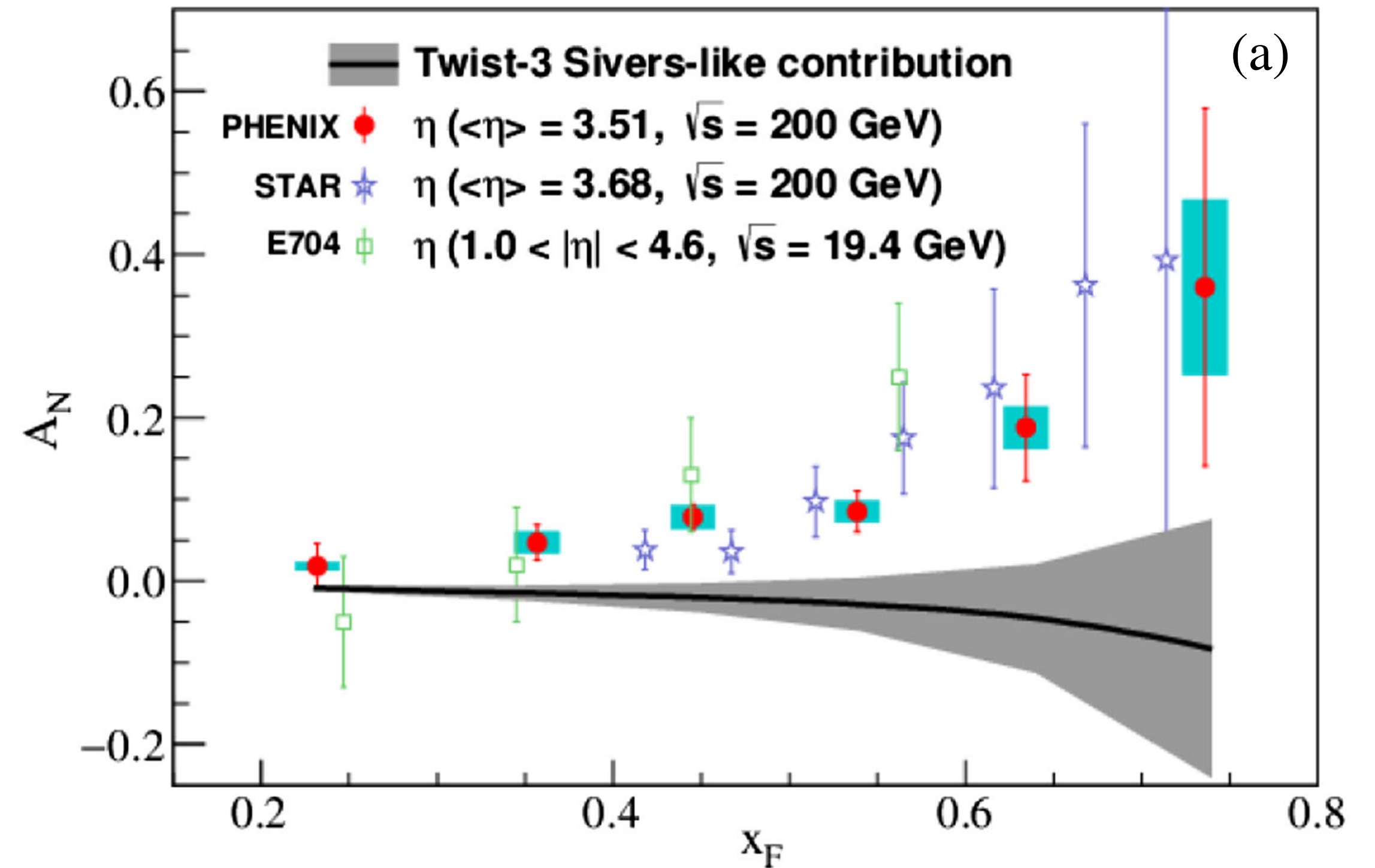
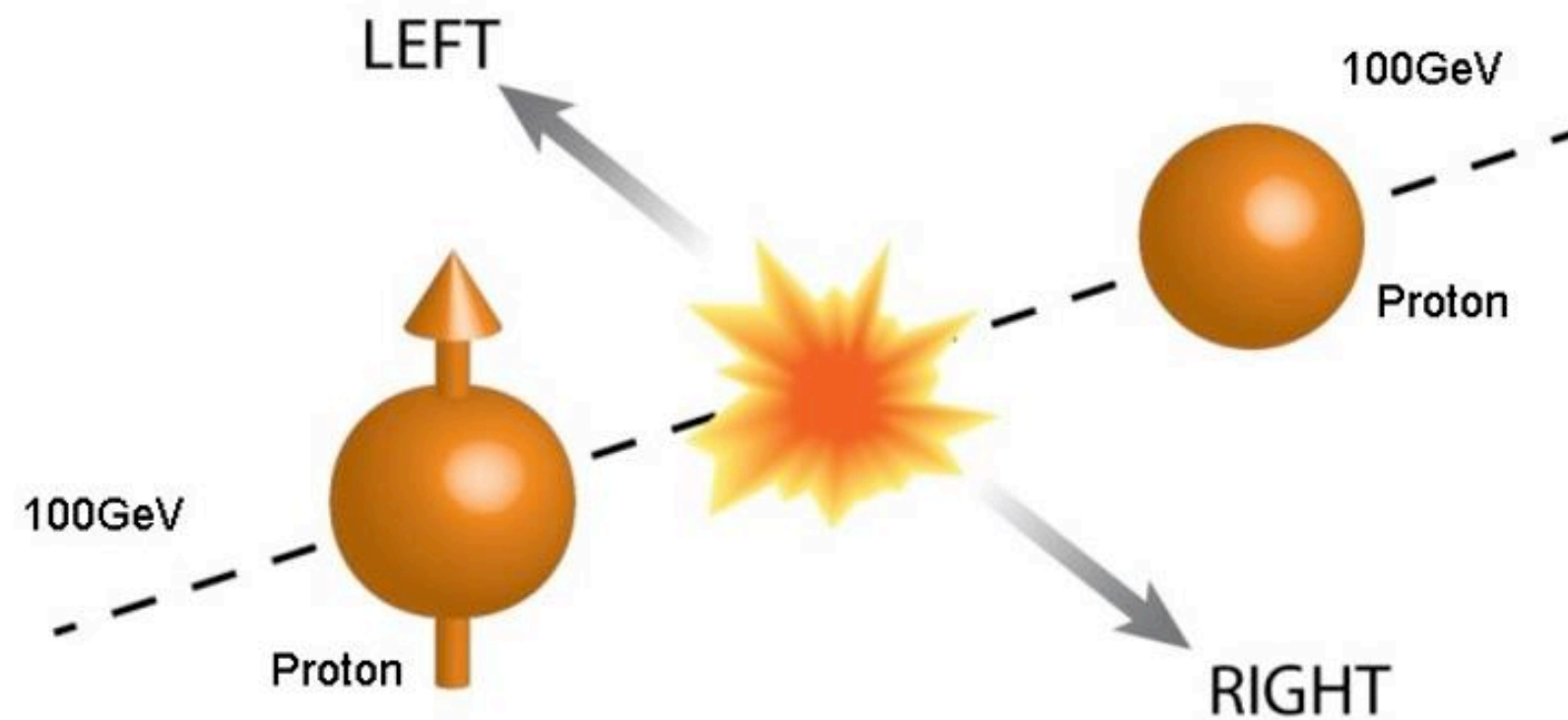
The origin of the large A_N is not yet fully understood

Transverse single-spin asymmetry

PHENIX, PRD113, 072006 (2026)

$$p^\uparrow + p \rightarrow h + X$$

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



Initial-state correlations alone cannot explain the data

$$S_p \cdot (p_p \times k_{T,q})$$

Can polarization be produced without a polarized beam?

- ▶ Transverse single-spin asymmetry

$$p^{\uparrow} + p \rightarrow h + X \qquad A_N \neq 0$$

Initial-state proton is polarized $\rightarrow$ spin asymmetry

- ▶ Can a polarized particle be produced from unpolarized collisions?

Can polarization be produced without a polarized beam?

- Transverse single-spin asymmetry

$$p^{\uparrow} + p \rightarrow h + X \qquad A_N \neq 0$$

Initial-state proton is polarized $\rightarrow$ spin asymmetry

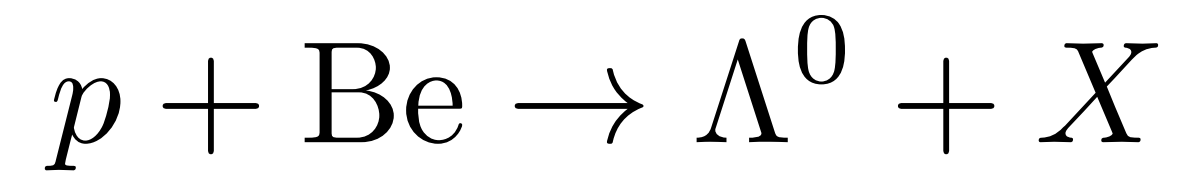
- Can a polarized particle be produced from unpolarized collisions?

Yes. Large transverse Λ polarization was observed!

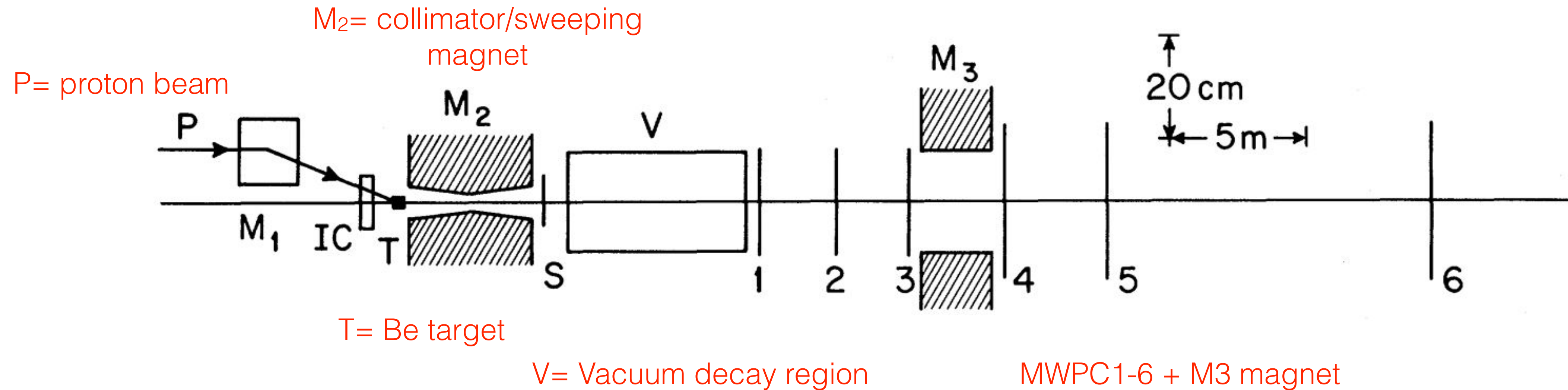
$$p + p \rightarrow \Lambda^{\uparrow} + X$$

The first measurement in 1976

- ▶ Bunce et al., Phys. Rev. Lett. 36, 1113 (1976)
- ▶ 300 GeV unpolarized proton beam at unpolarized Be target

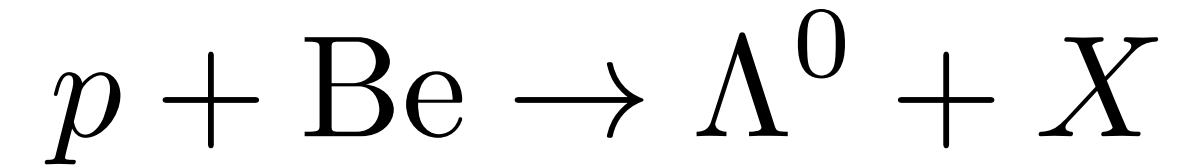


- ▶ Experimental apparatus below



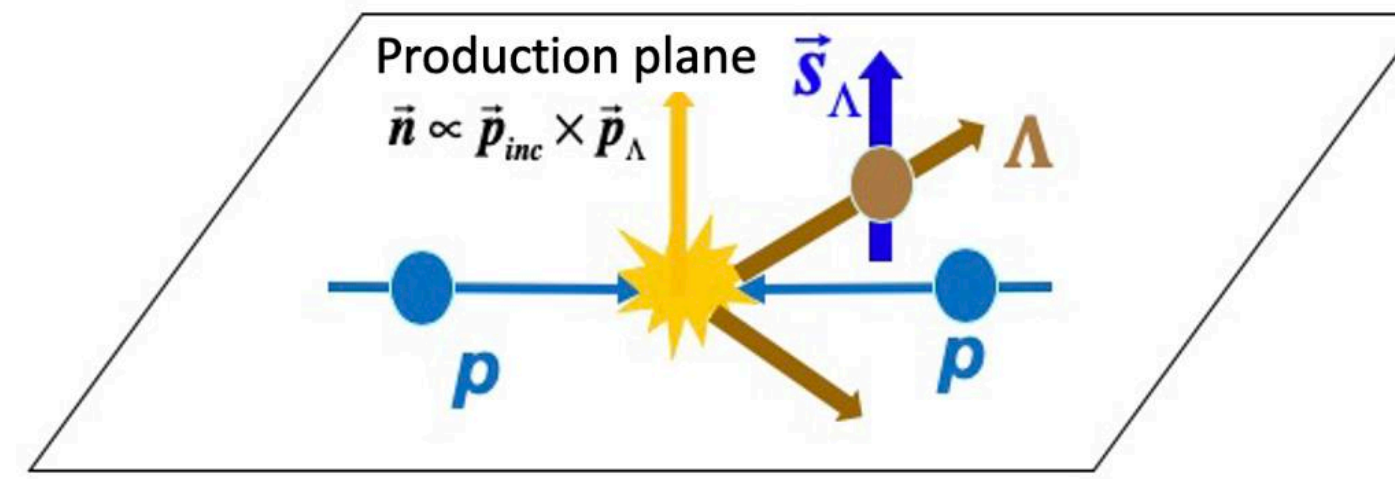
The first observation of transverse Λ polarization

Bunce et al., Phys. Rev. Lett. 36, 1113 (1976)



- Large polarization normal to production plane was observed!

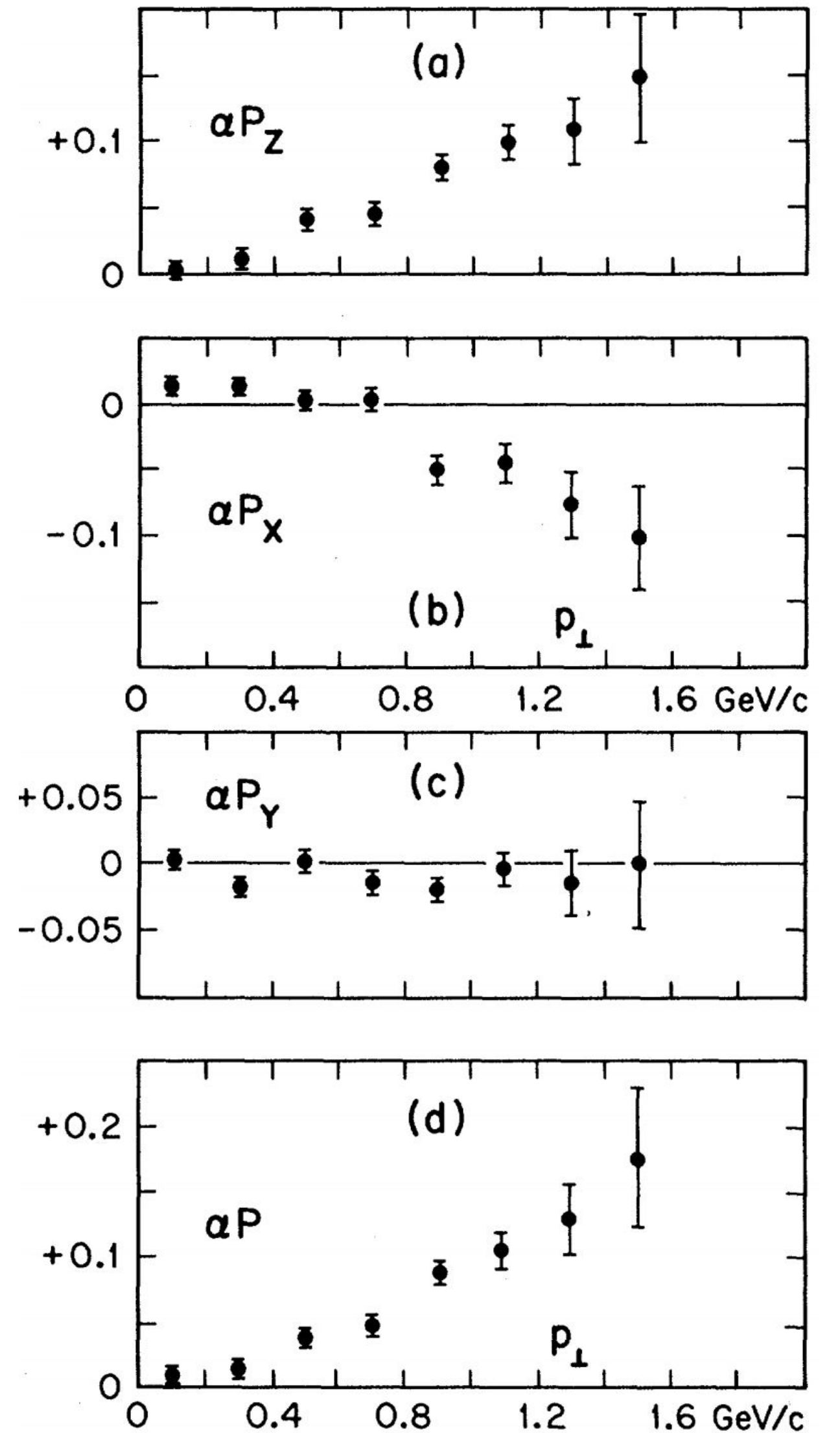
$$\hat{z} \parallel \vec{p}_\Lambda \quad \hat{x} = \frac{\vec{p}_p \times \vec{p}_\Lambda}{|\vec{p}_p \times \vec{p}_\Lambda|}$$



- Due to spin precession by magnet, (P_x, P_y) originate from polarization at production
- $$|\alpha P| = \sqrt{(\alpha P_x)^2 + (\alpha P_z)^2}$$

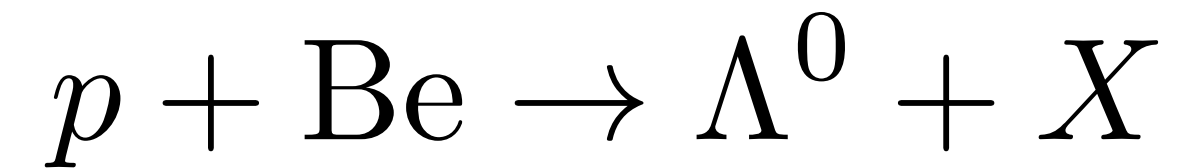
- $|P_\Lambda|$ increases with p_T , reaching $\sim 30\%$ ($0.3 < x < 0.7$)

Final-state Λ is transversely polarized even from unpolarized initial state



The first observation of transverse Λ polarization

Bunce et al., Phys. Rev. Lett. 36, 1113 (1976)

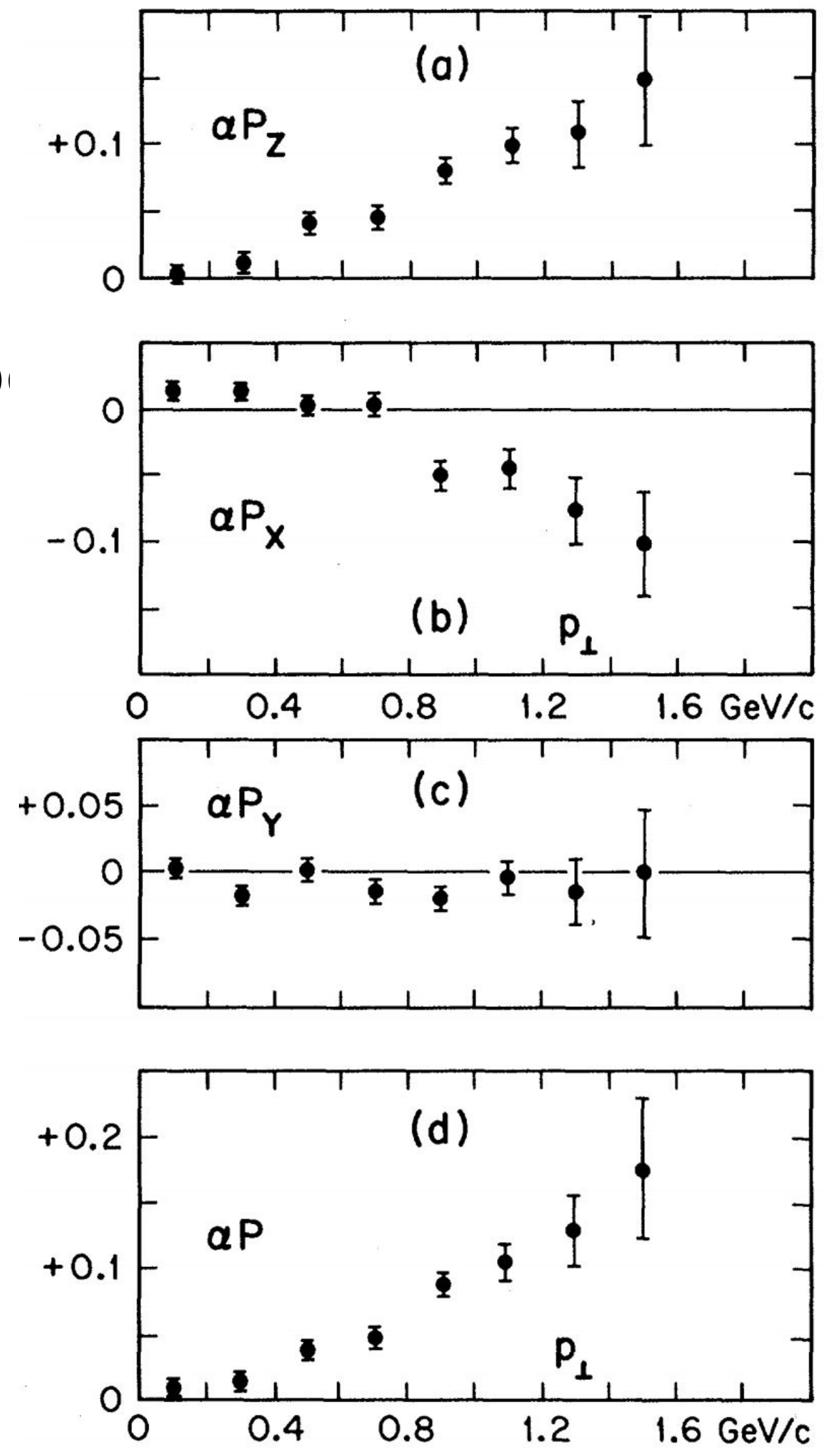


► Large transverse polarization relative to production plane was observed!

□ In a simple perturbative picture, transverse polarization was expected high p_T , roughly suppressed by m_q/p_T

$$P \sim \alpha_s \frac{m_q}{p_T} \sim O(10^{-2})$$

► So it was unexpectedly large!



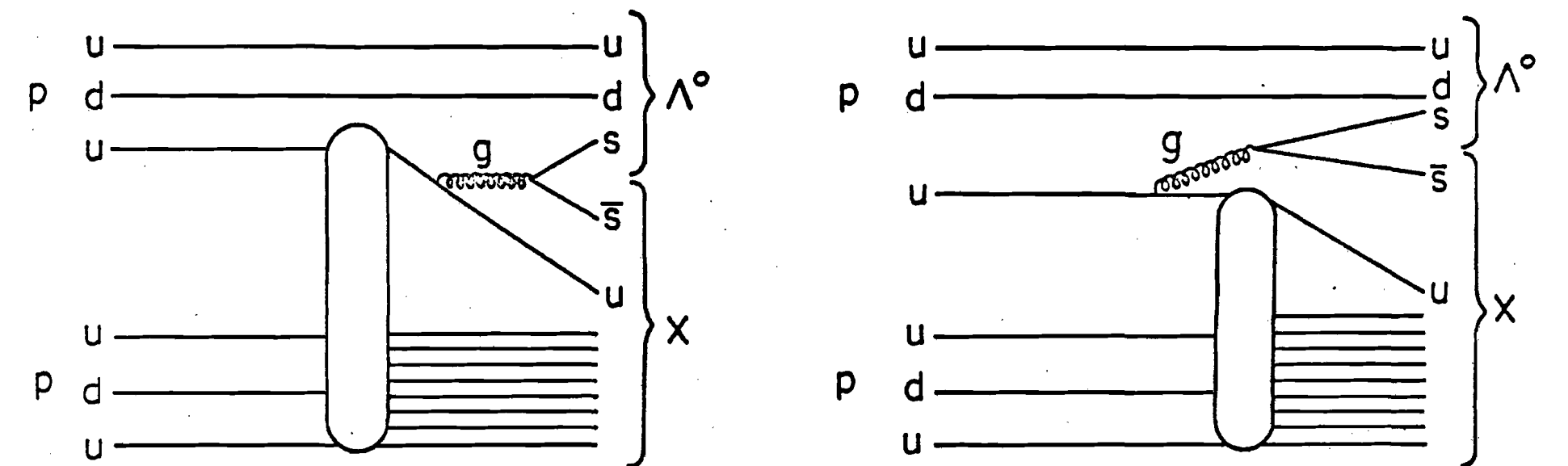
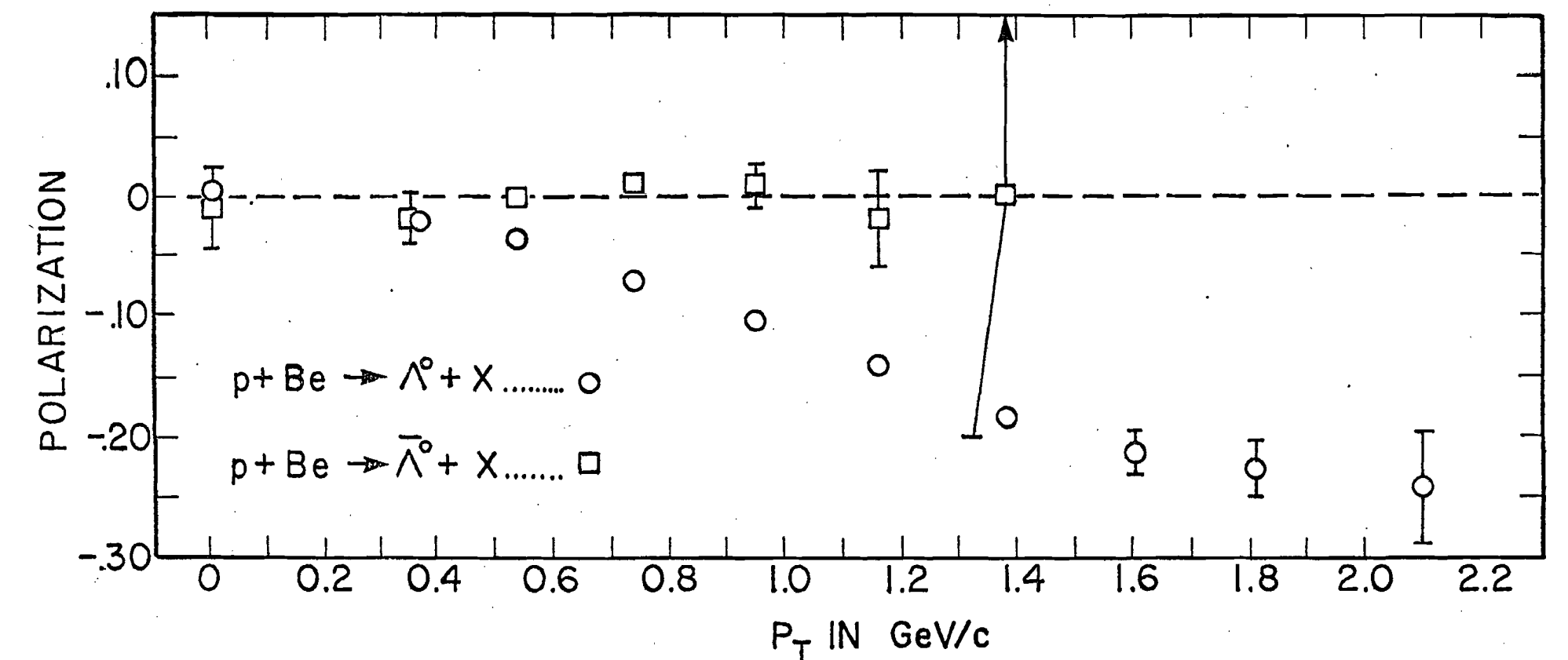
How about polarization of anti- Λ ?

► Since then, a series of experimental studies have been conducted

► Heller et al. (1978)

- ❑ 400 GeV proton beam on a Be target
- ❑ Λ transverse polarization $\sim 24\%$ ($0.1 < x < 0.7$)
- ❑ $\bar{\Lambda}$ was found to have zero polarization

Phys. Rev. Lett. 41, 607 (1978)



How about other hyperons?

► Since then, a series of experimental studies have been conducted

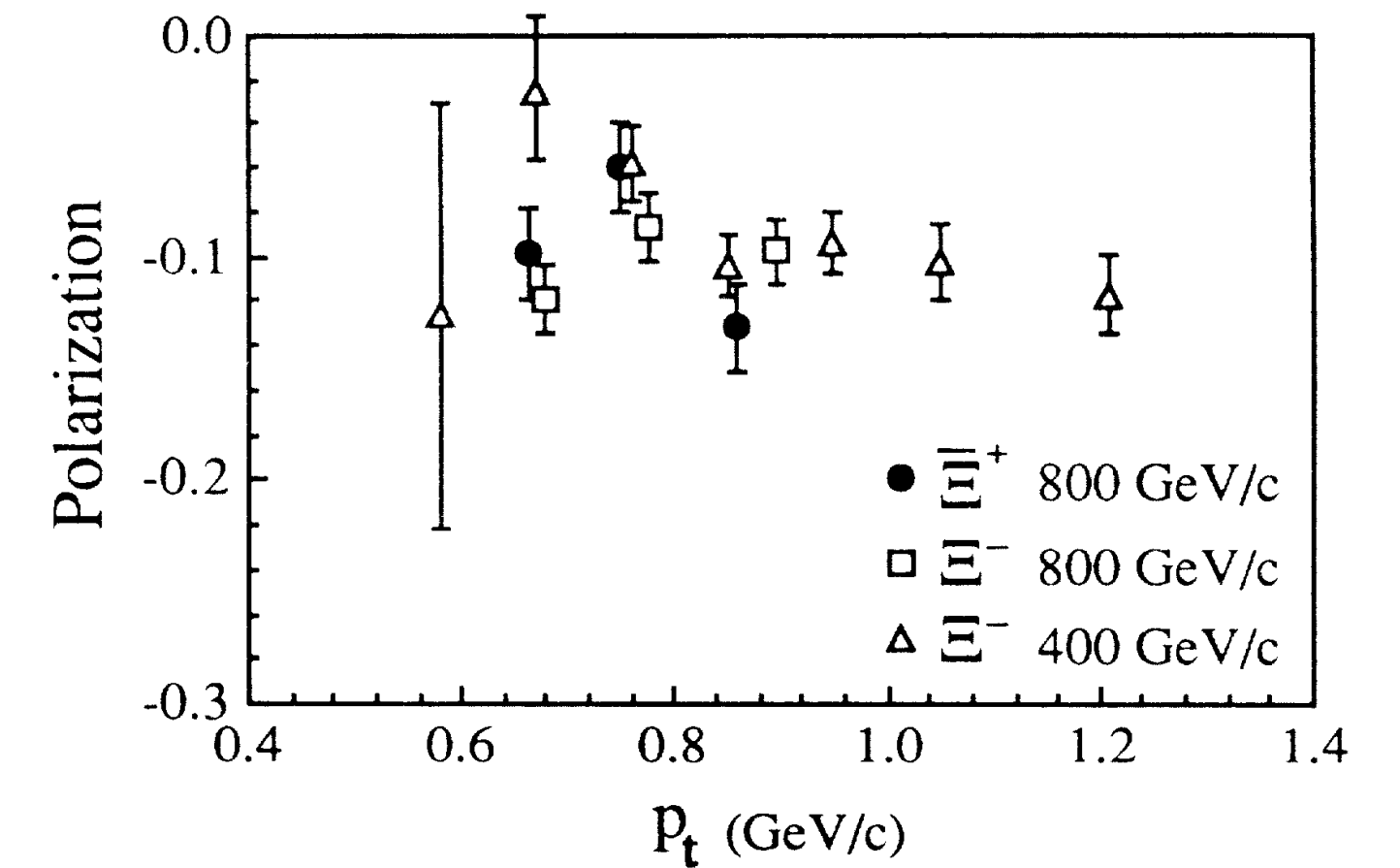
► Ho et al. (1990)

□ 800 GeV proton beam on a Be target

□ $p + \text{Be} \rightarrow \Xi^- (\bar{\Xi}^+) + X$

□ Both Ξ and anti- Ξ show positive/comparable polarization

Ho et al., Phys. Rev. Lett. 65, 1713 (1990)



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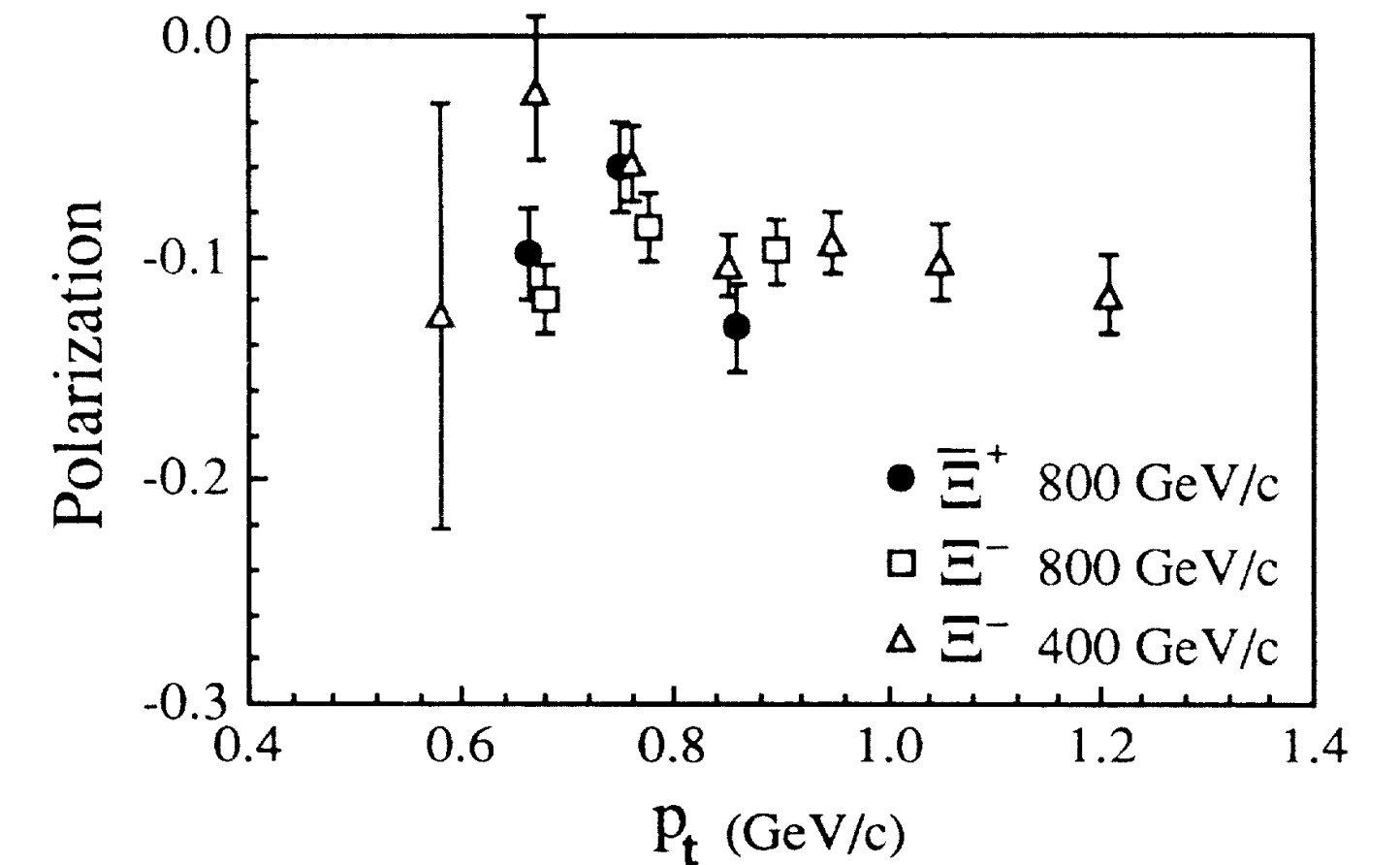
□ 800 GeV proton beam on a Cu target

□ $p + \text{Cu} \rightarrow \Sigma^- (\bar{\Sigma}^+) + X$

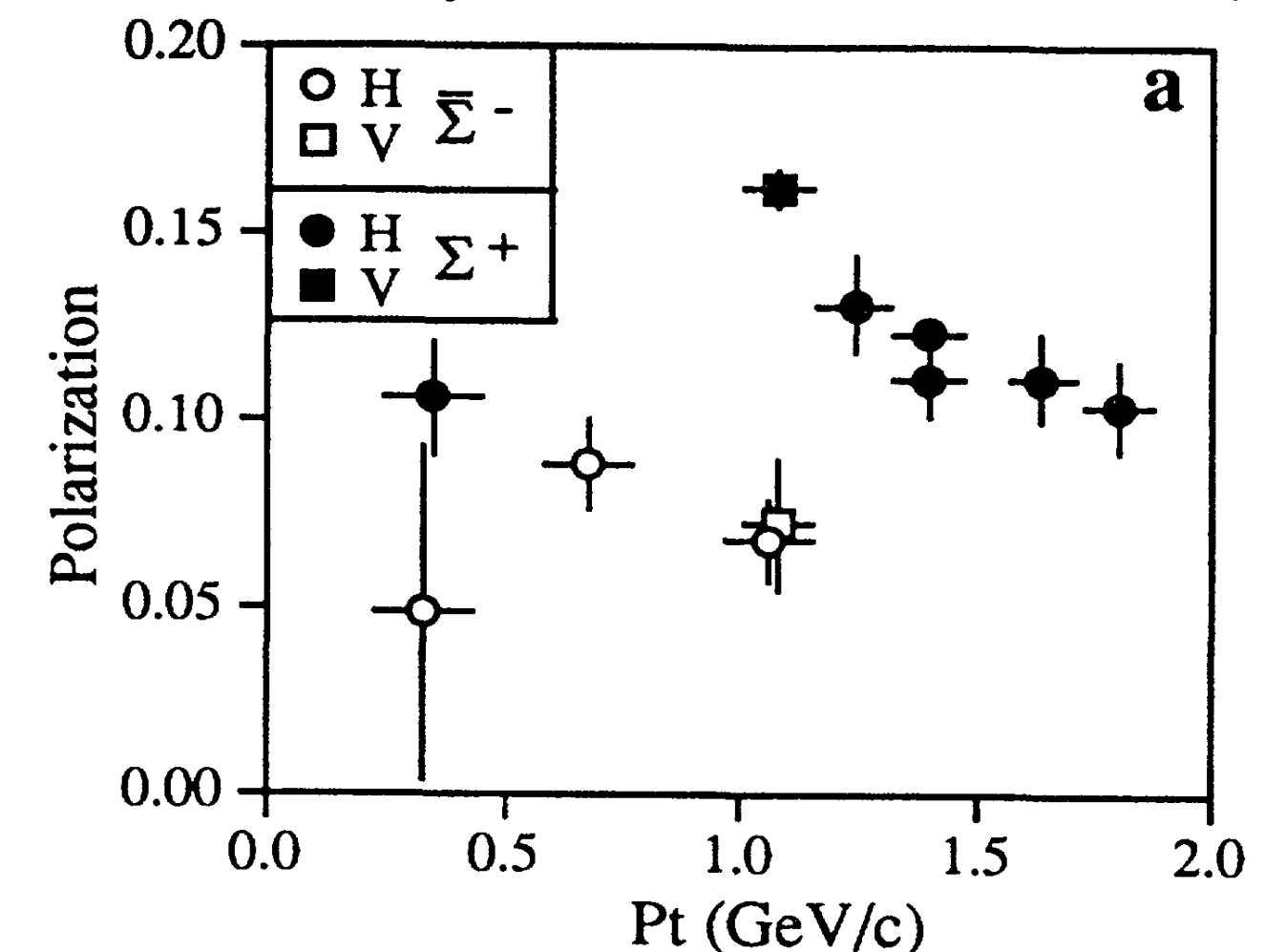
□ Both Σ and anti- Σ show non-zero positive polarization

Hyperon transverse polarization has non-trivial flavor dependence!

Ho et al., Phys. Rev. Lett. 65, 1713 (1990)



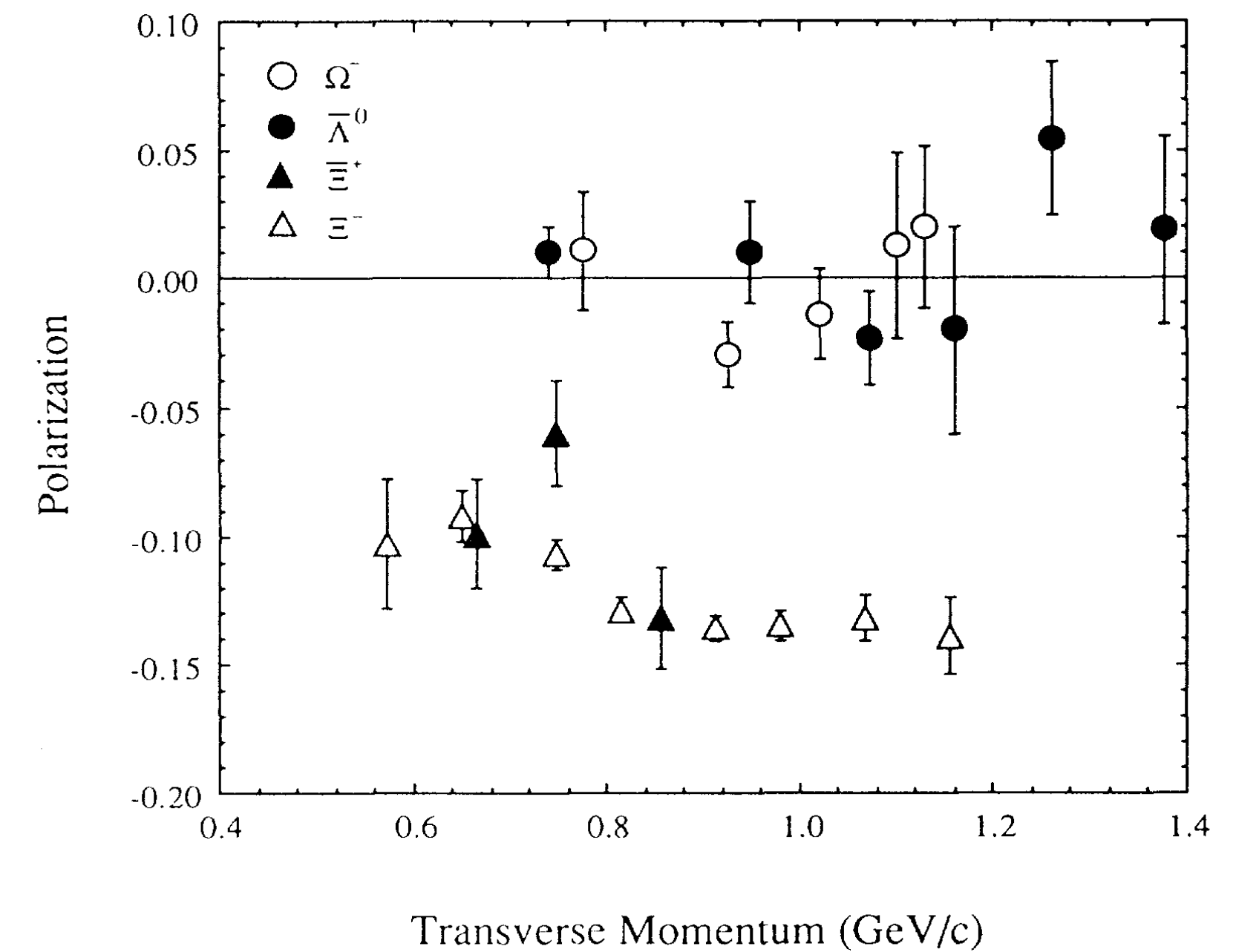
Morelos et al., Phys. Rev. Lett. 71, 2172 (1993)



How about other hyperons?

- Luk et al. (1993)
 - ❑ 800 GeV proton beam on a Be target
 - ❑ $p + \text{Be} \rightarrow \Omega^- + X$
 - ❑ Ω^- polarization is consistent with zero ($0.3 < x < 0.7$)
- Λ , Σ^+ , Ξ^- share at least one valence quark with the incident proton while Ω does not

Luk et al., Phys. Rev. Lett. 70, 900 (1993)



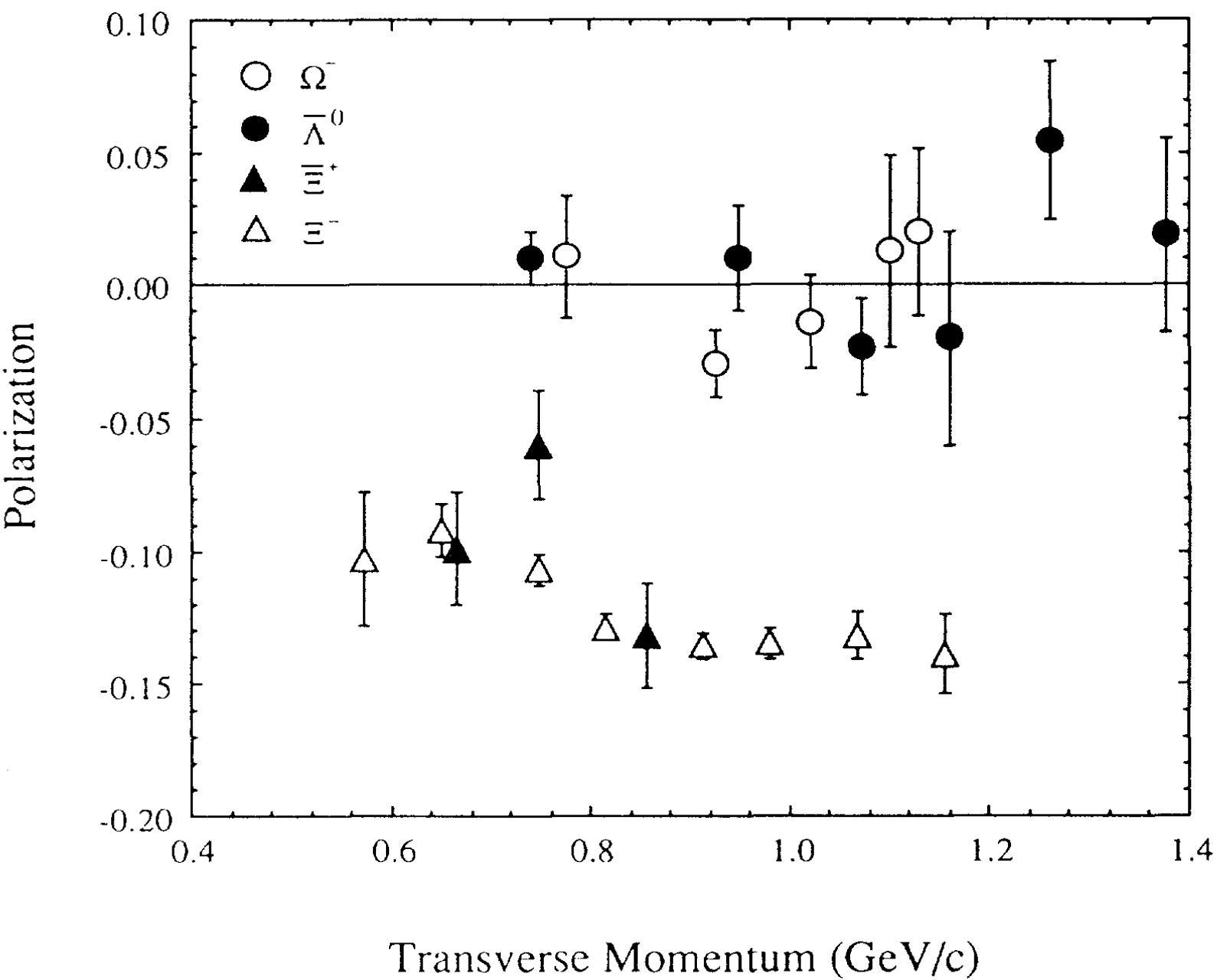
Hyperon	quark content	P
Λ	uds	<0
Σ^+	uus	>0
Ξ^-	dss	<0
Ω^-	sss	~ 0

How about other hyperons?

- ▶ Luk et al. (1993)
 - ❑ 800 GeV proton beam on a Be target
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 - ❑ Ω^- polarization is consistent with zero ($0.3 < x < 0.7$)
- ▶ Λ , Σ^+ , Ξ^- share at least one valence quark with the incident proton while Ω does not

But anti-hyperon polarization cannot be simply understood in terms of shared valence quarks

Luk et al., Phys. Rev. Lett. 70, 900 (1993)



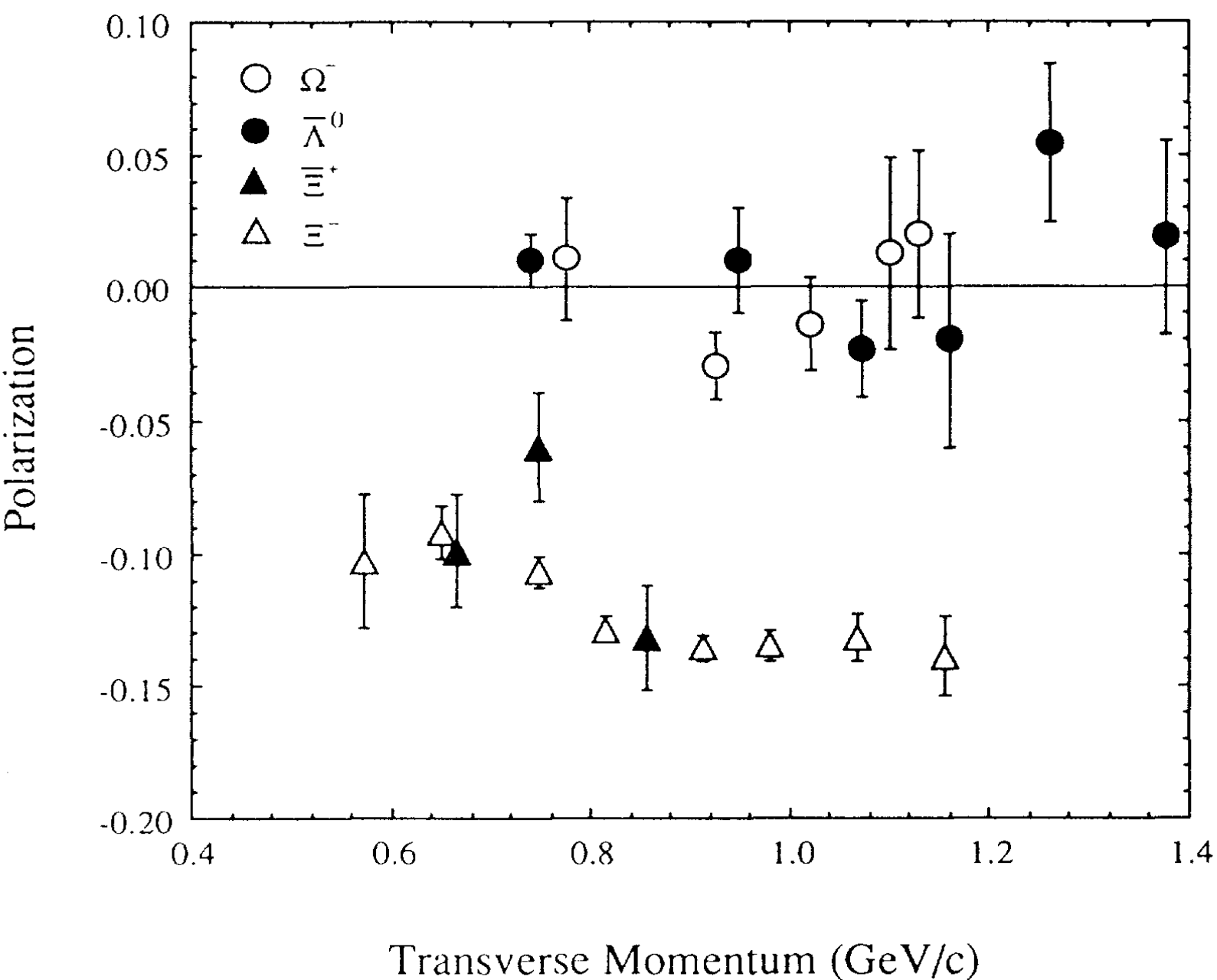
Hyperon	quark content	P
Λ	uds	<0
Σ^+	uus	>0
Ξ^-	dss	<0
Ω^-	sss	~0

Hyperon	quark content	P
$\bar{\Lambda}$	$\bar{u}\bar{d}\bar{s}$	~0
$\bar{\Sigma}^-$	$\bar{d}\bar{s}\bar{s}$	>0
$\bar{\Xi}^-$	$\bar{u}\bar{u}\bar{s}$	<0

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- ▶ Luk et al. (1993)
 - ❑ 800 GeV proton beam on a Be target
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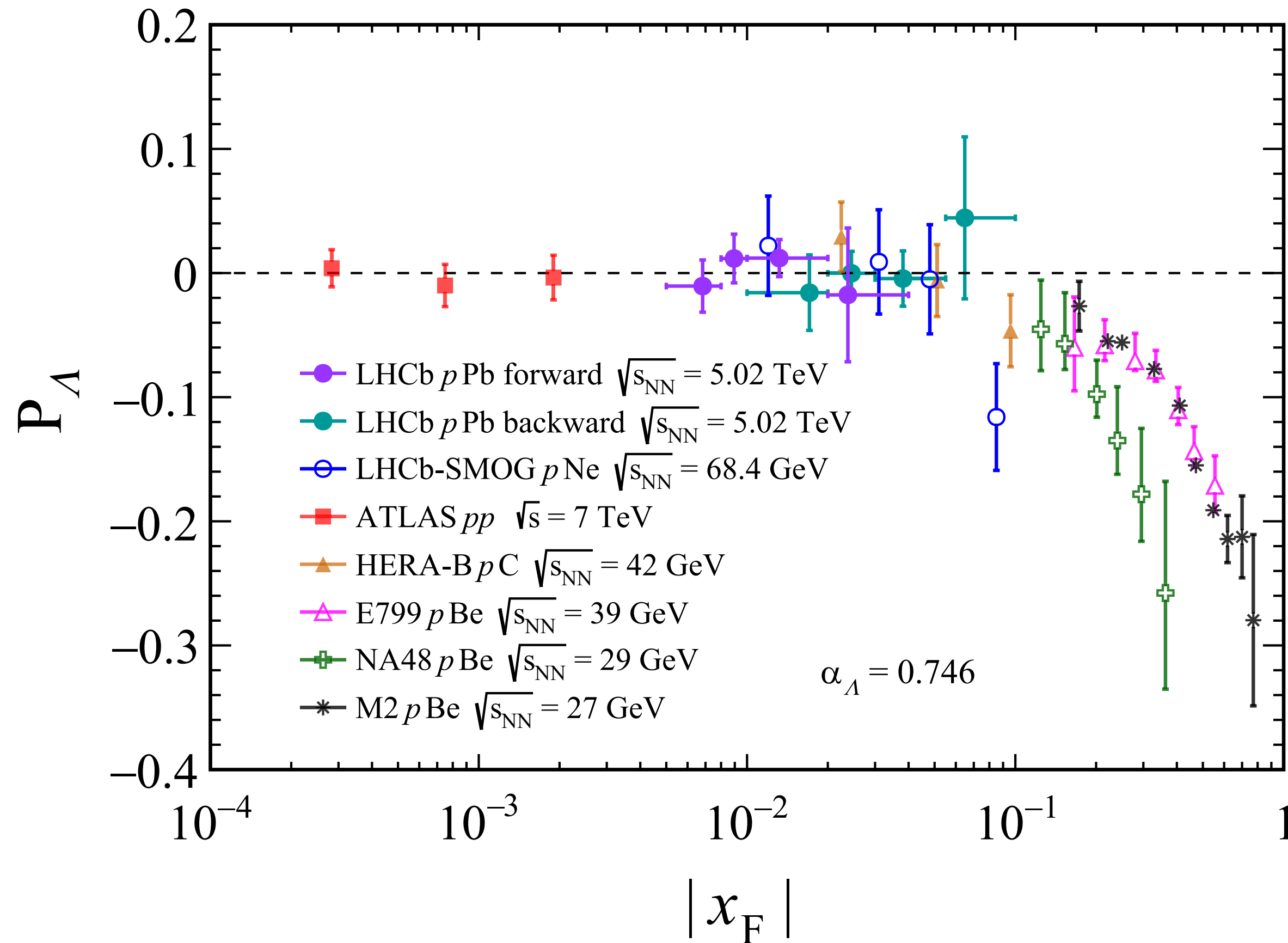
Hyperon	quark content	P
Λ	uds	<0
Σ^+	uus	>0
Ξ^-	dss	<0
Ω^-	sss	~ 0

Hyperon	quark content	P
Λbar	$\bar{u}\bar{d}\bar{s}$	~ 0
Σbar^-	$\bar{d}\bar{s}\bar{s}$	>0
Ξbar^-	$\bar{u}\bar{u}\bar{s}$	<0

Longstanding hyperon polarization puzzle for nearly 50 years

The study continues...

LHCb, PRD112, 112022 (2025)

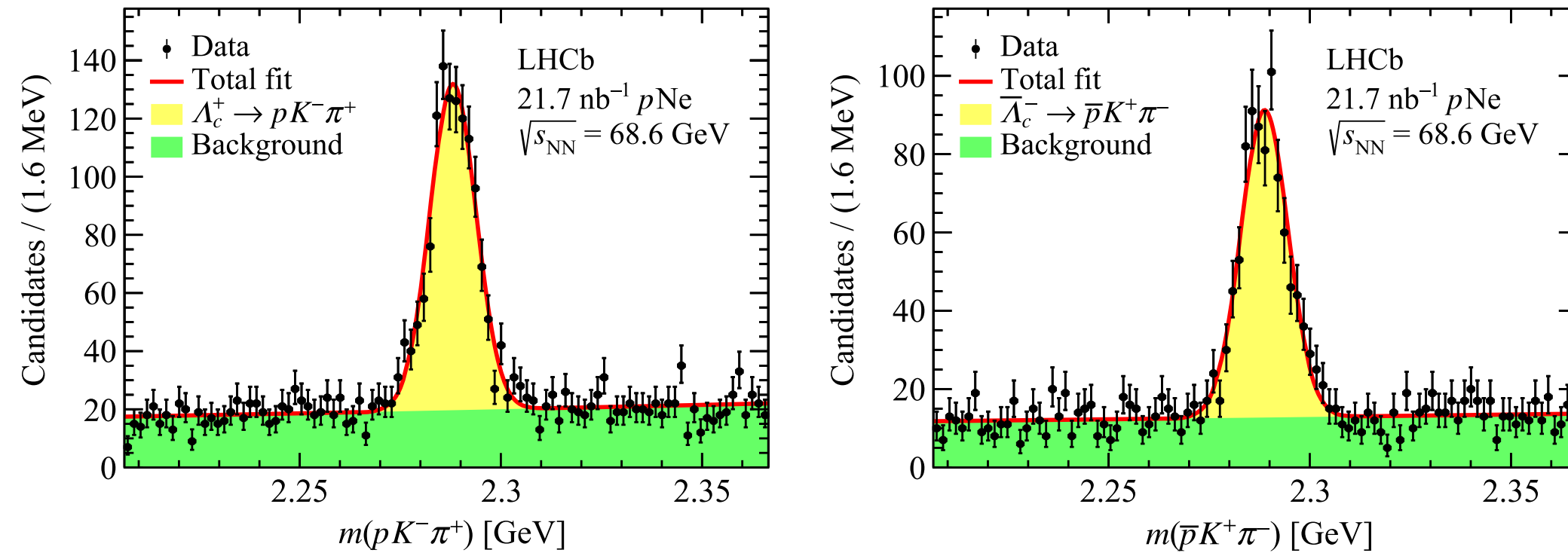


$$x_F = \frac{2p_z}{\sqrt{s}}$$

- ▶ Little or no polarization at small x_F (midrapidity)
- ▶ The polarization becomes increasingly negative toward large x_F (beam-fragmentation region)
- ▶ Similar trend over a wide range of $\sqrt{s_{NN}}$

Λ_c^+ polarization from LHCb

LHCb, PRL 137, 091901 (2026)

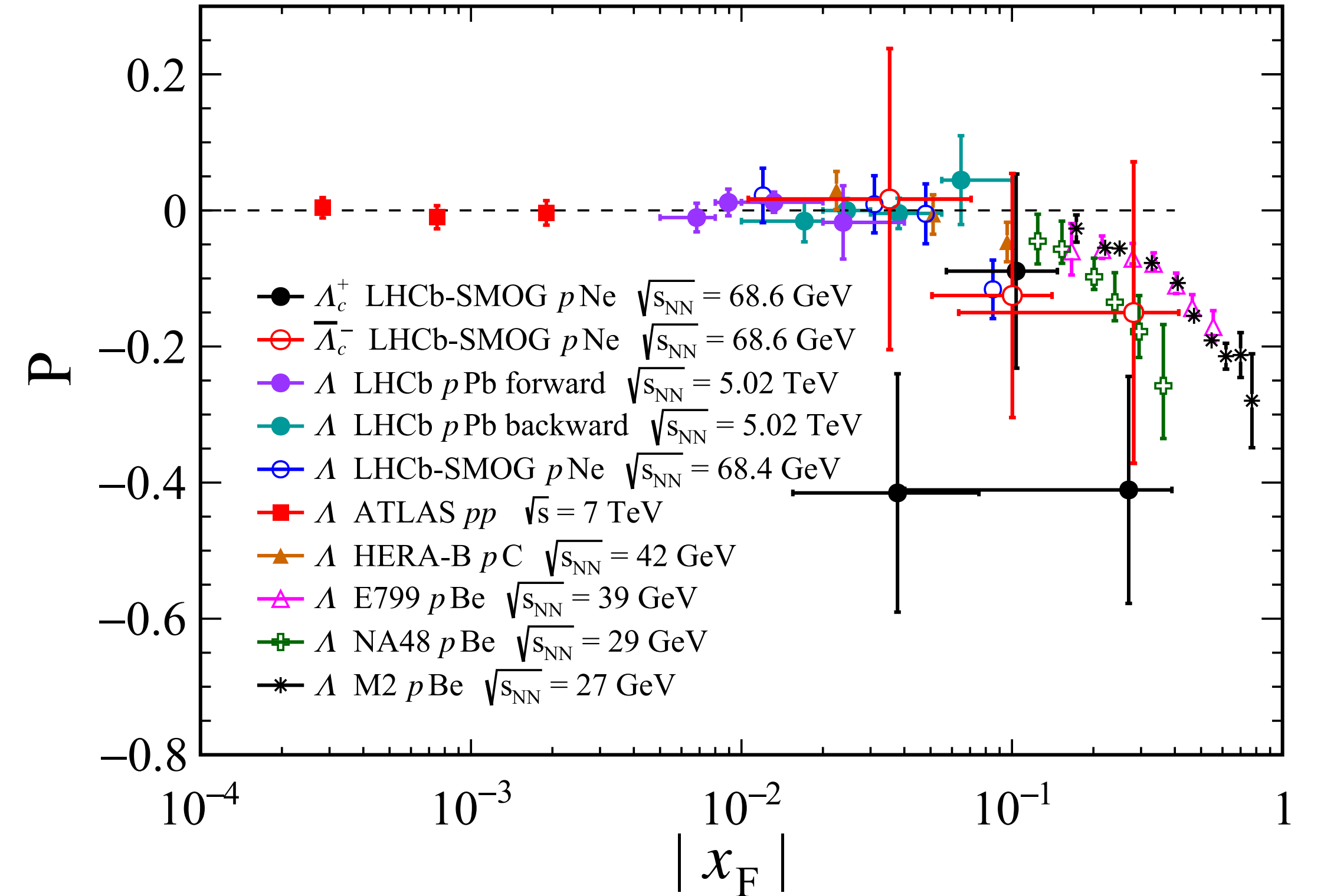


- First separate measurement of Λ_c^+ and Λ_c^- transverse polarization in p+Ne at $\sqrt{s_{NN}} = 68.6$ GeV

$$P_{\Lambda_c^+} = (24 \pm 9 \pm 2)\%, P_{\Lambda_c^-} = (-8 \pm 12 \pm 3)\%$$

- Polarization extracted from 5D amplitude analysis of $\Lambda_c^+ \rightarrow pK^-\pi^+$

- First study of x_F dependence of charmed-baryon polarization



Possible explanation

- ▶ Many models have been proposed but no single model can explain all the data
 - e.g. parton recombination model DeGrand, Markkanen, and Miettinen (1985)
- ▶ The large polarization cannot be explained by a simple perturbative picture. Spin-momentum correlations may arise from initial- and/or final-state effects
 - Polarization originates from the initial hadronic state?
 - Or can it be generated at the final state?
An unpolarized parton fragments into a polarized hadron

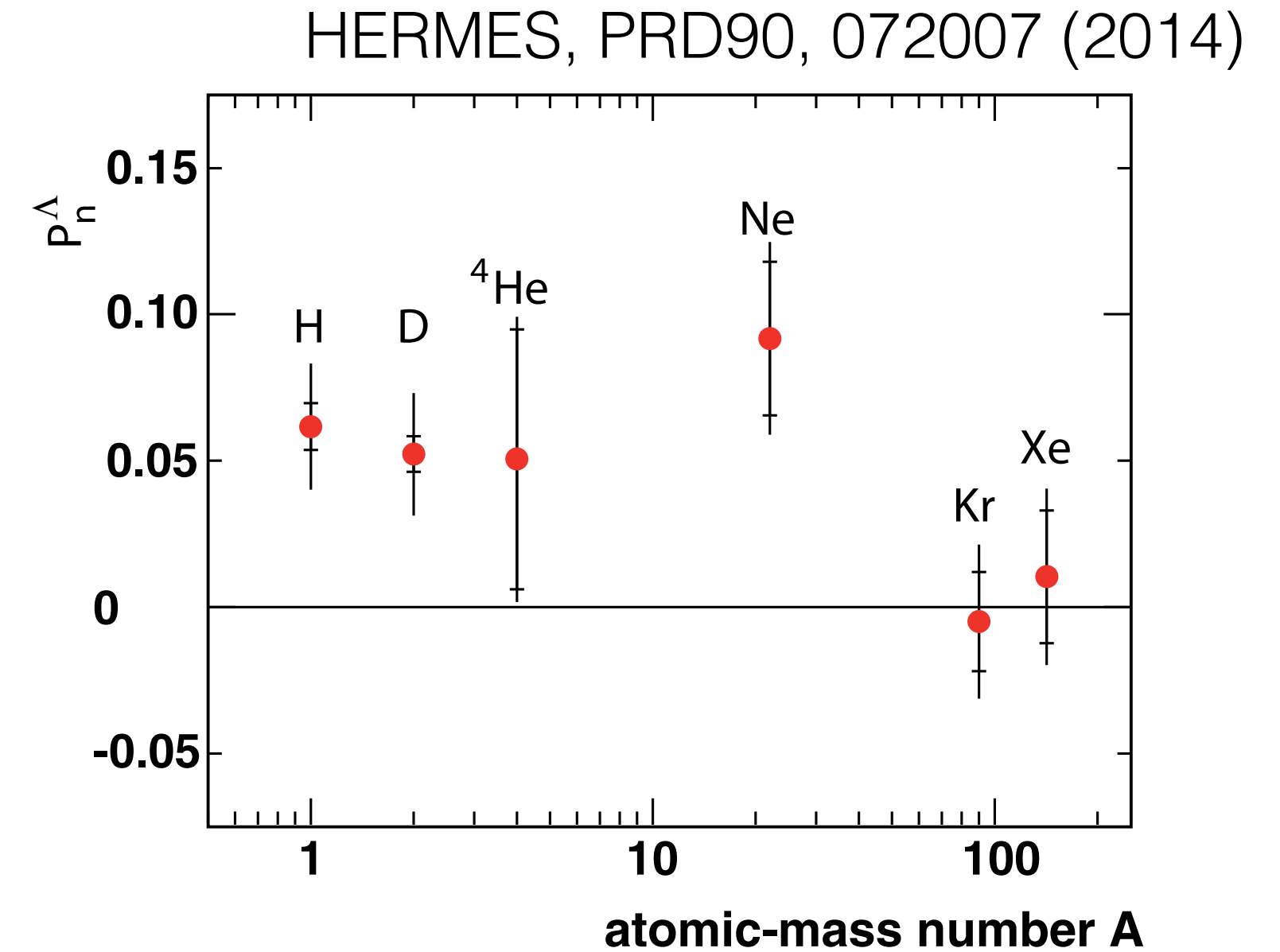
Polarization is not unique to hadron-induced reactions

► HERMES (2007, 2014)

- Positron beam on a gas target (^1H , ^2H , and heavier gas). Positron emits a quasi-real photon, which interacts with the nucleon

$$e^+ N \rightarrow e^+ \Lambda X \quad (\gamma^* N \rightarrow \Lambda N, \quad Q^2 \simeq 0)$$

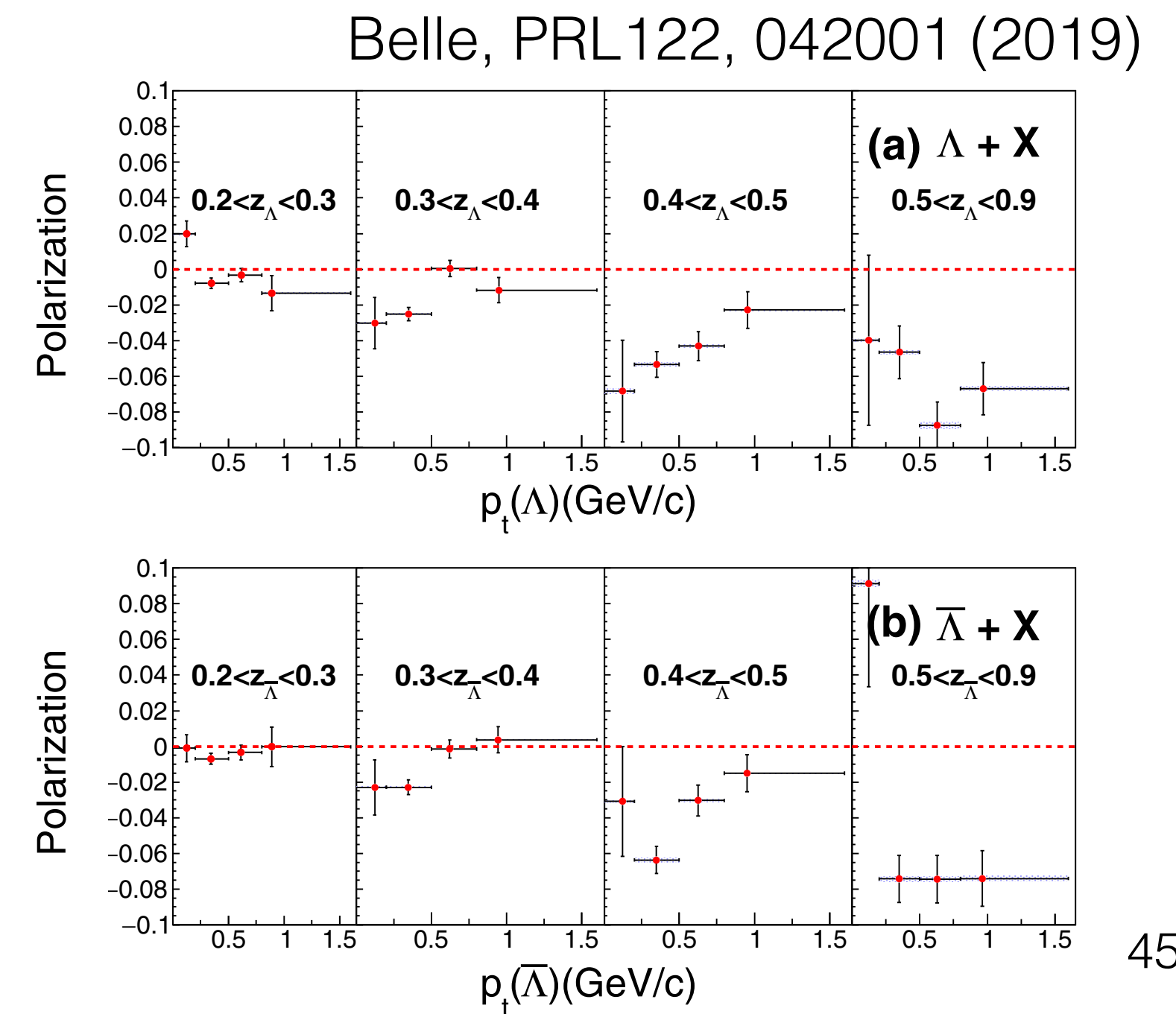
- Polarization was also observed in photoproduction, with a positive sign and an indication of decreasing polarization with increasing A



► Λ transverse polarization was found even in e^+e^- annihilation by Belle Collaboration (2019)

$$e^+e^- \rightarrow q\bar{q} \rightarrow \Lambda^\uparrow + X$$

- Polarization can be generated during fragmentation or hadronization
→ polarizing fragmentation function



This supports the idea that transverse Λ polarization can be generated in the fragmentation process

Summary of day-2

► Spin structure of nucleon

- ❑ Quark helicity constrained by polarized DIS: $\Delta\Sigma \sim 0.3$
- ❑ Gluon helicity probed by ALL in polarized pp collisions: $\Delta g(x) > 0$ in the x region probed by RHIC
- ❑ Sea-quark flavor asymmetry probed by $W^\pm A_L$: $\Delta\bar{u} > \Delta\bar{d}$

► Transverse spin phenomena

- ❑ Large transverse spin asymmetries (A_N) were unexpected in a simple perturbative picture
- ❑ Large Λ transverse polarization is observed even with unpolarized beams
- ❑ Spin-momentum correlations in the initial and/or fragmentation provide possible explanations but the origin of large transverse spin effects is not yet fully understood