Probing gluon and strange quark helicity distribution in the proton at STAR

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STAR

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NSFC National Natural Science Foundation of China

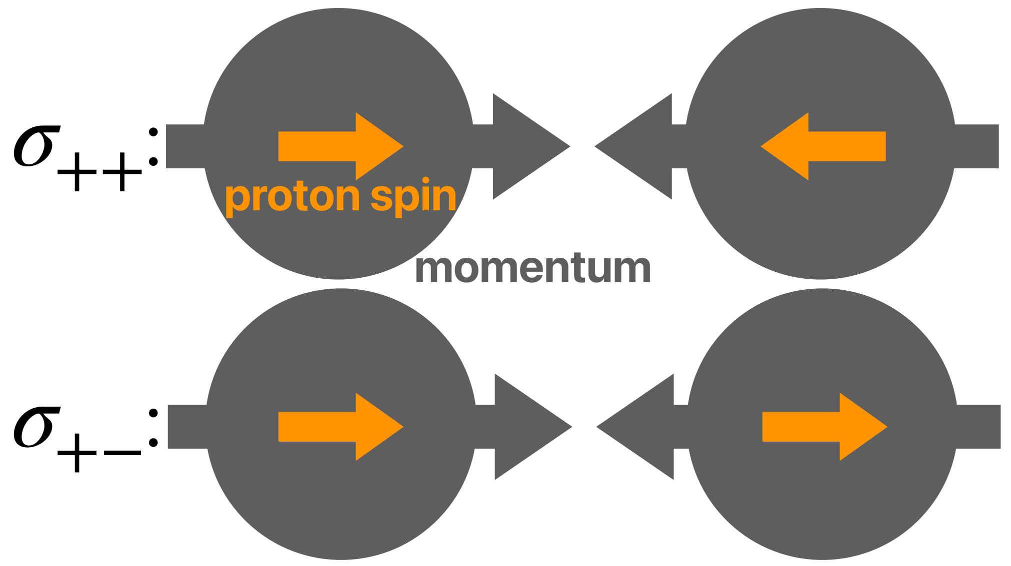
Outline

- Motivation
- Introduction to RHIC-STAR
- Longitudinal double spin asymmetry A_{LL} for $\pi^{\pm}$-tagged jets
- Longitudinal double spin asymmetry A_{LL} for Λ, $\overline{\Lambda}$ and K_S^0
- Longitudinal spin transfer D_{LL} of Λ and $\overline{\Lambda}$
- Summary

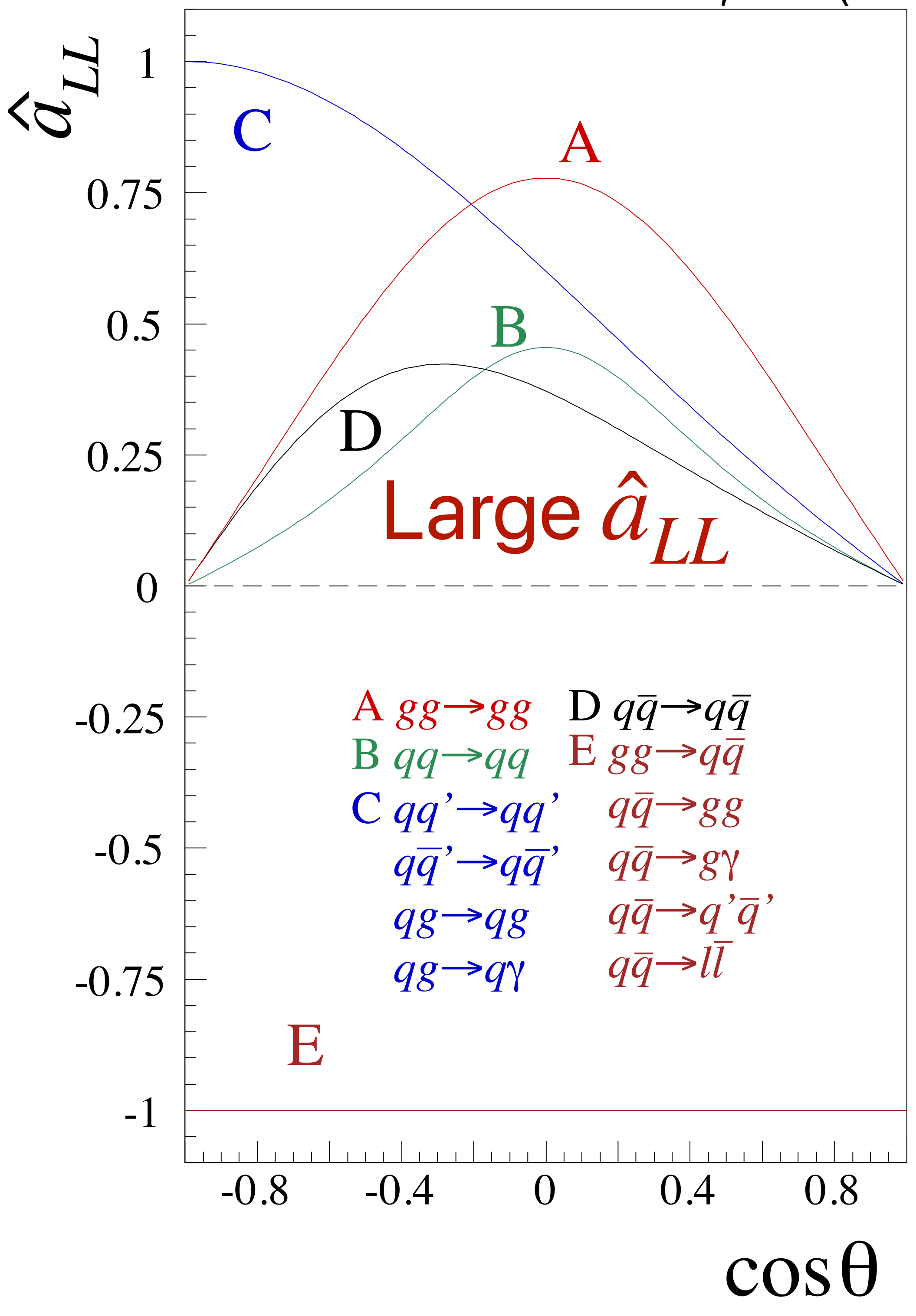
Probing gluon helicity with jets

- Longitudinal double spin asymmetry A_{LL} of inclusive jets and di-jets

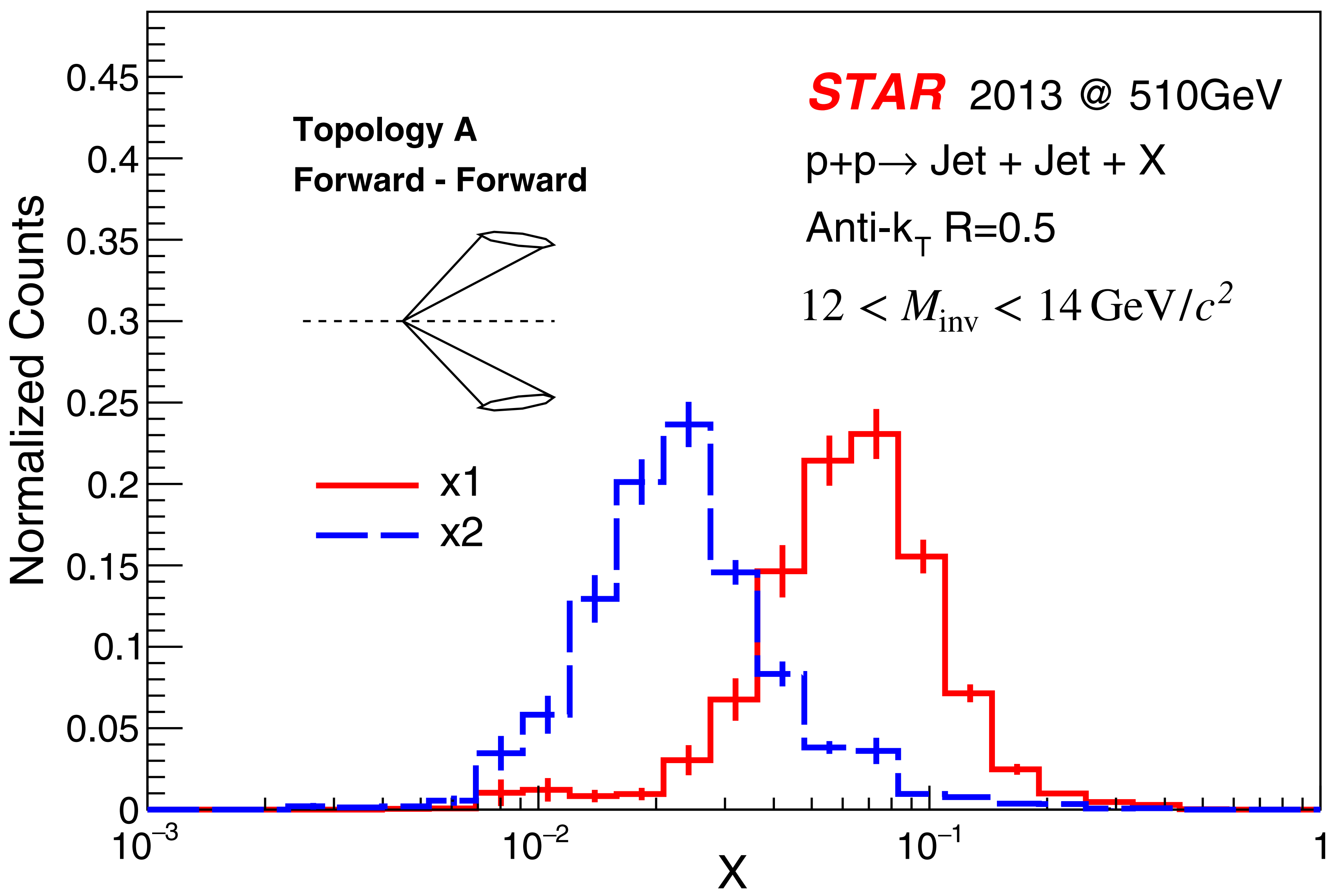
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma}\hat{a}_{LL}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$



G. Bunce, N. Saito, J. Soffer, and W. Vogelsang, Annu. Rev. Nucl. Part. Sci. 50, 525 (2000).

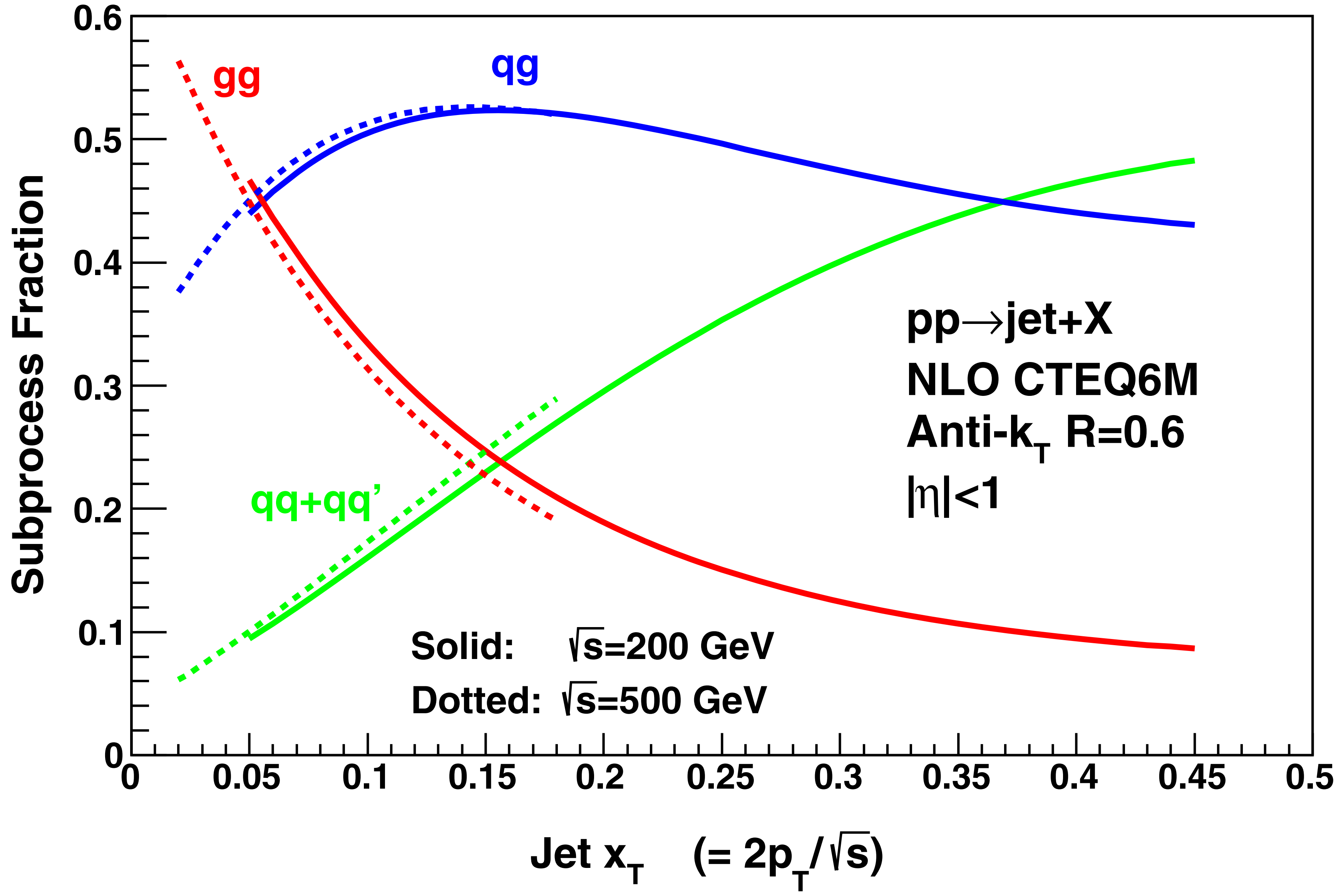


[STAR], Phys. Rev. D 105, 092011 (2022).



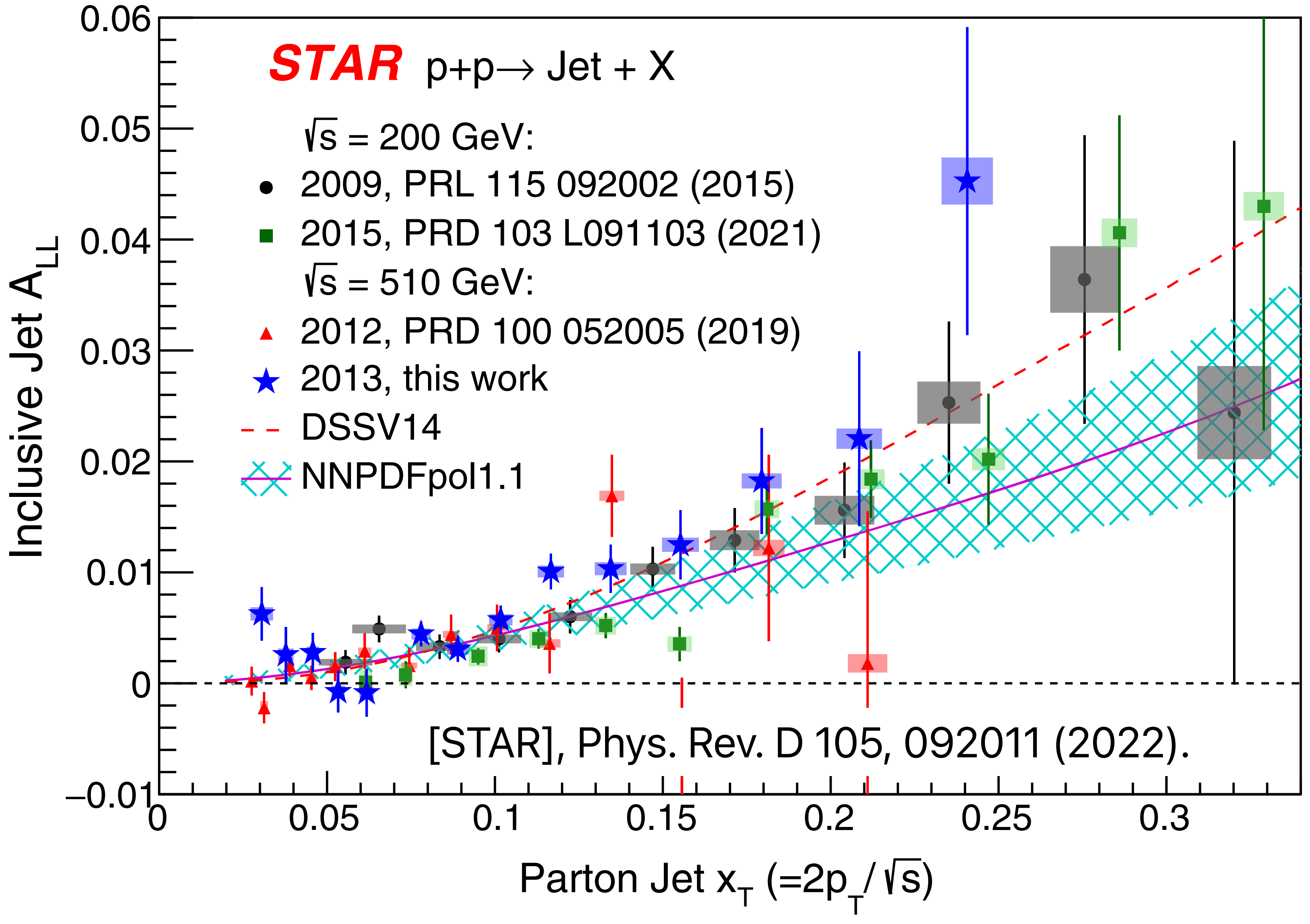
sampled gluon x

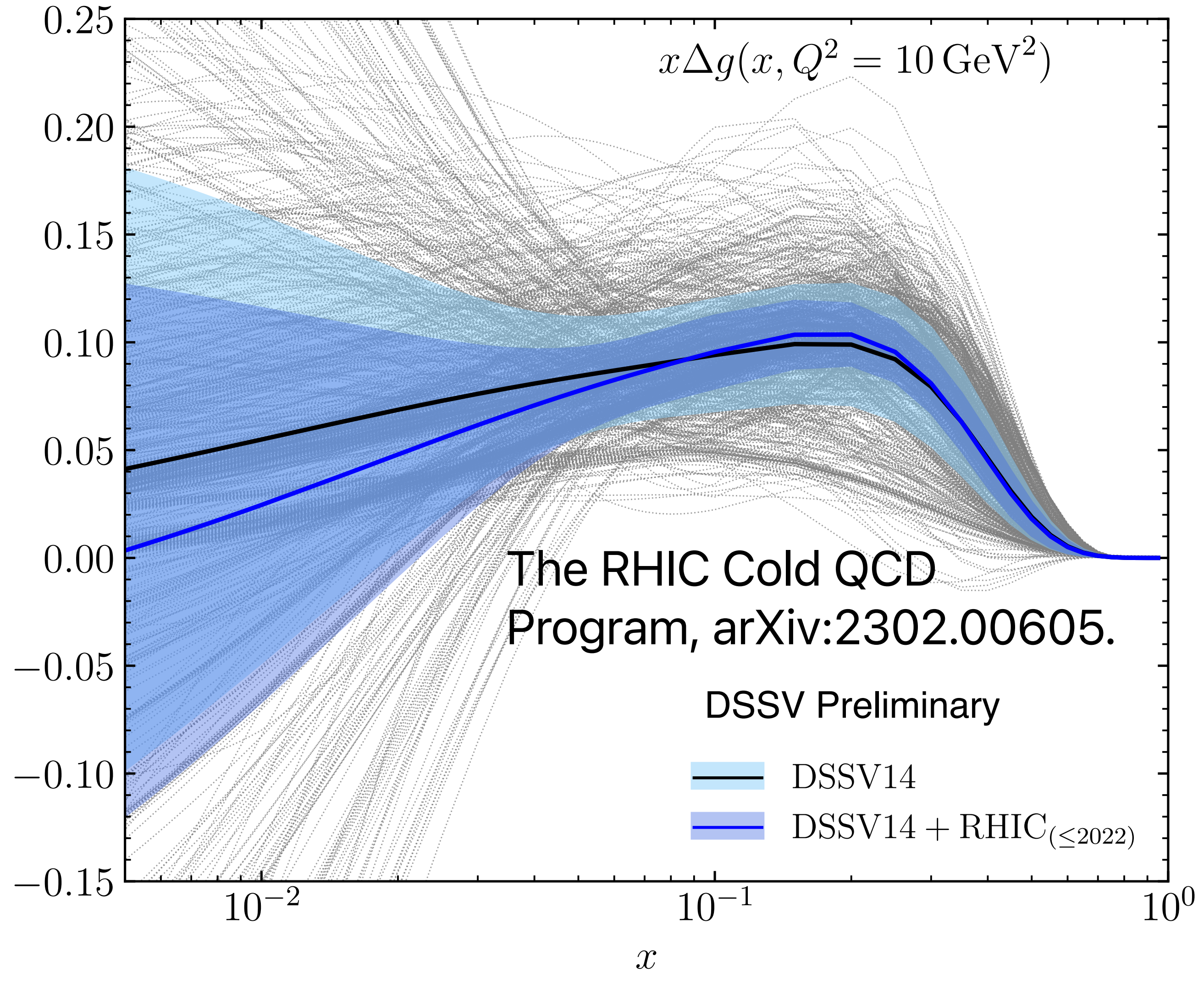
[STAR], Phys. Rev. D **100**, 052005 (2019).



- Relative large cross section of jets
- No hadronization effect
- gg and gq are sensitive to gluon helicity Δg
- Large $\hat{a}_{LL}$ ➡ sizable A_{LL} with small $\frac{\Delta f}{f}$
- Dijets extends sensitivity to x-dependence of Δg

Gluon helicity: positive or negative?

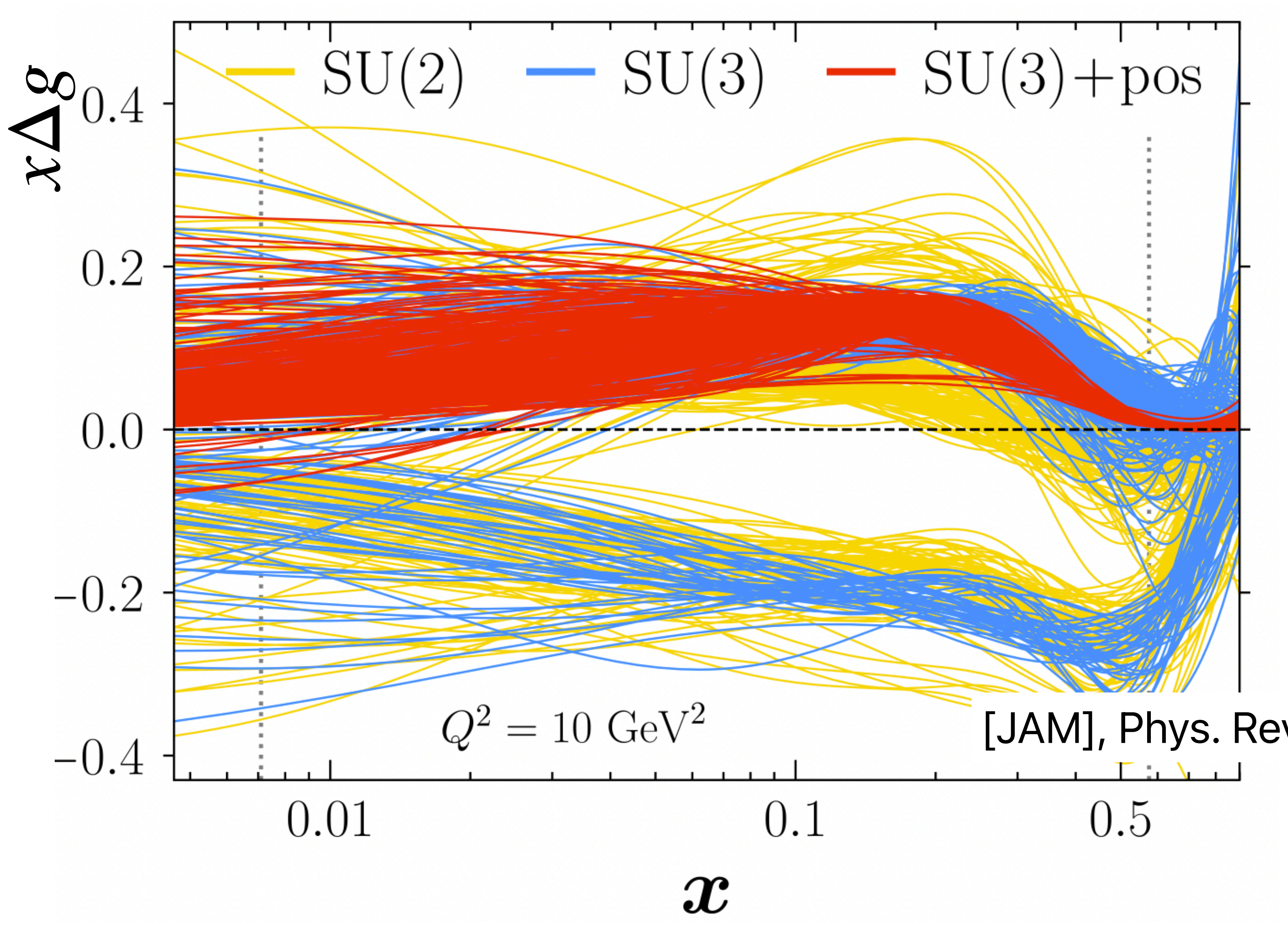


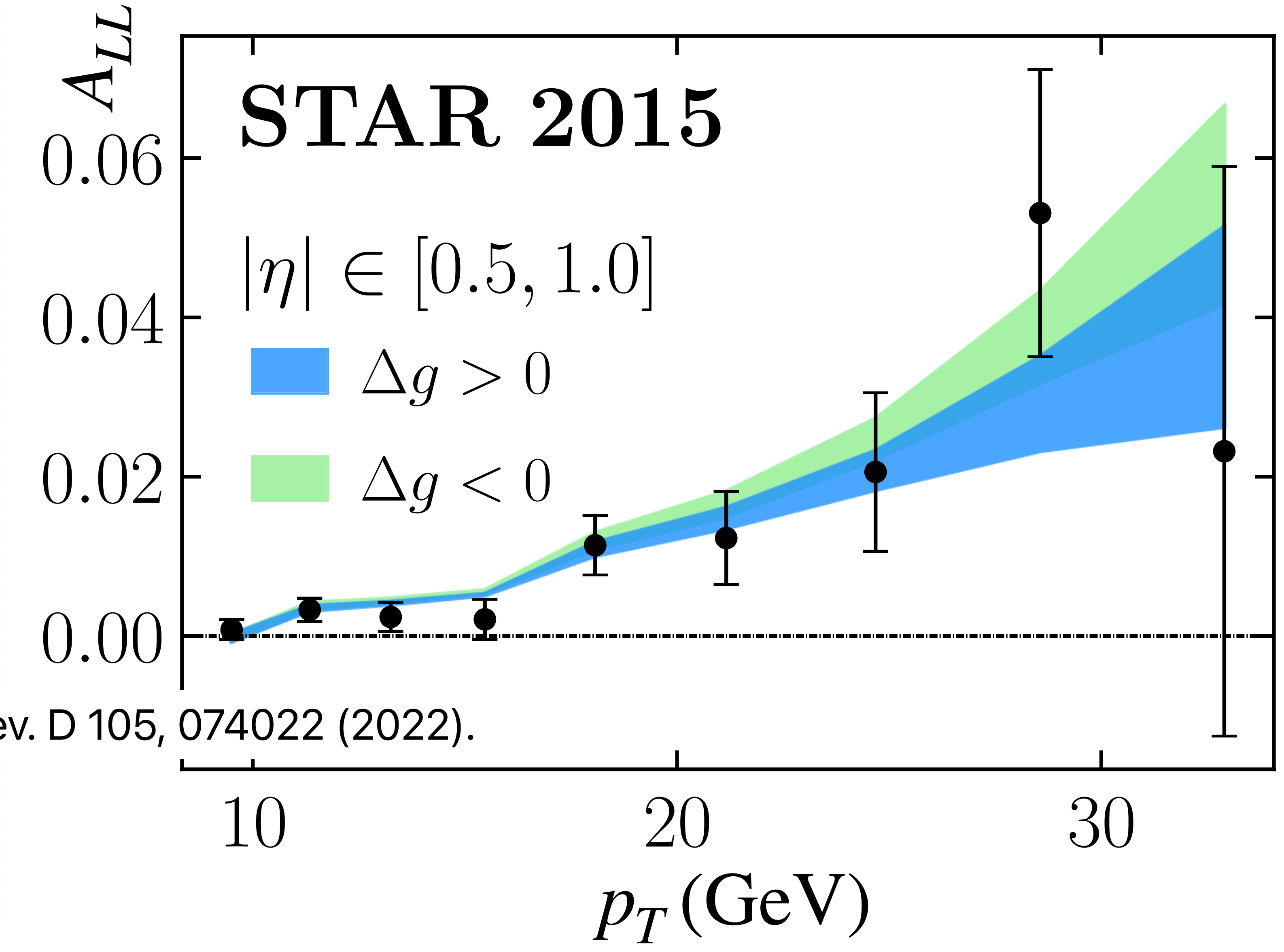


DSSV2014

$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.20^{+0.06}_{-0.07},\ Q^2 = 10\,\text{GeV}^2$$

- $|\Delta f| < f$ ➡ **Positive ΔG**
- 40% contribution to proton spin

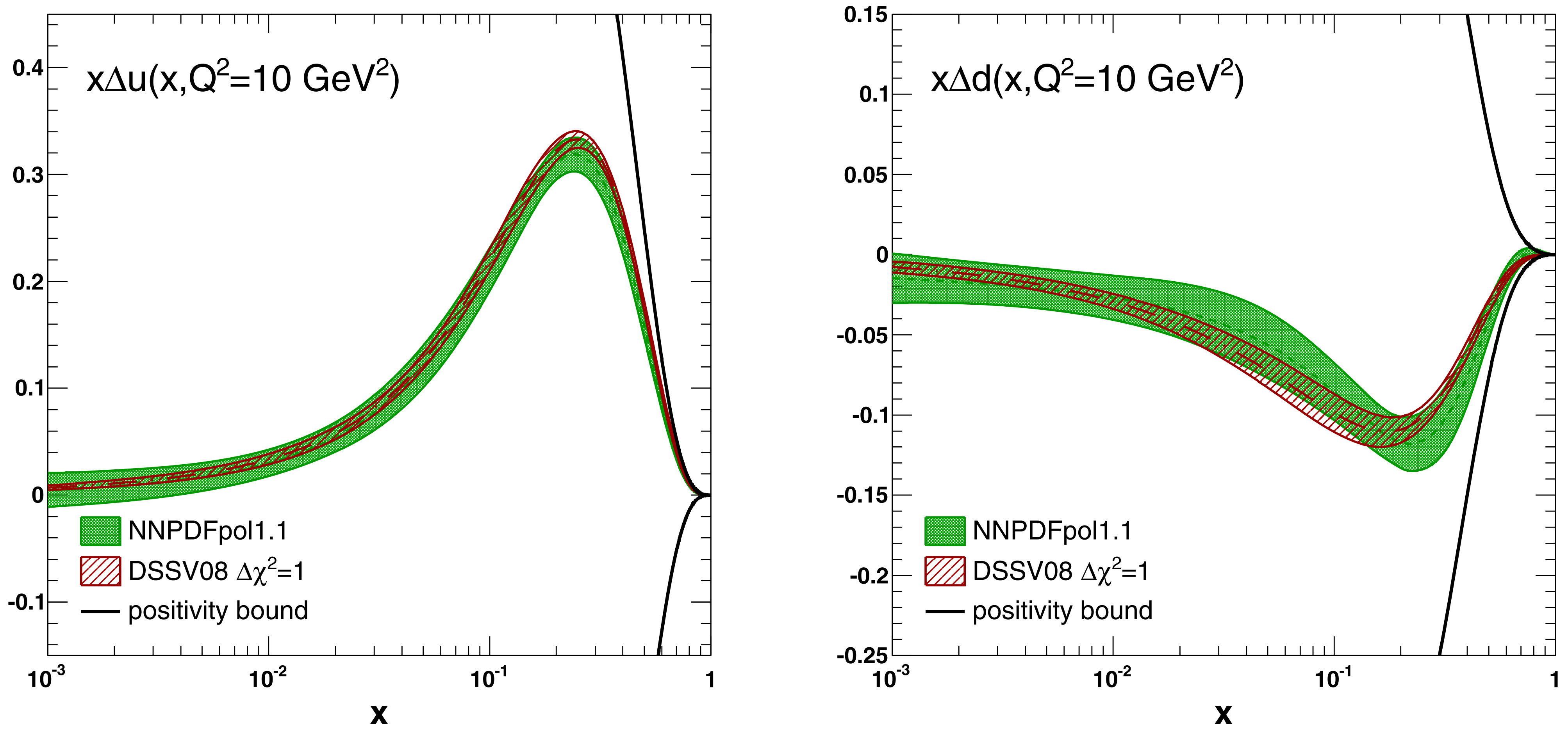




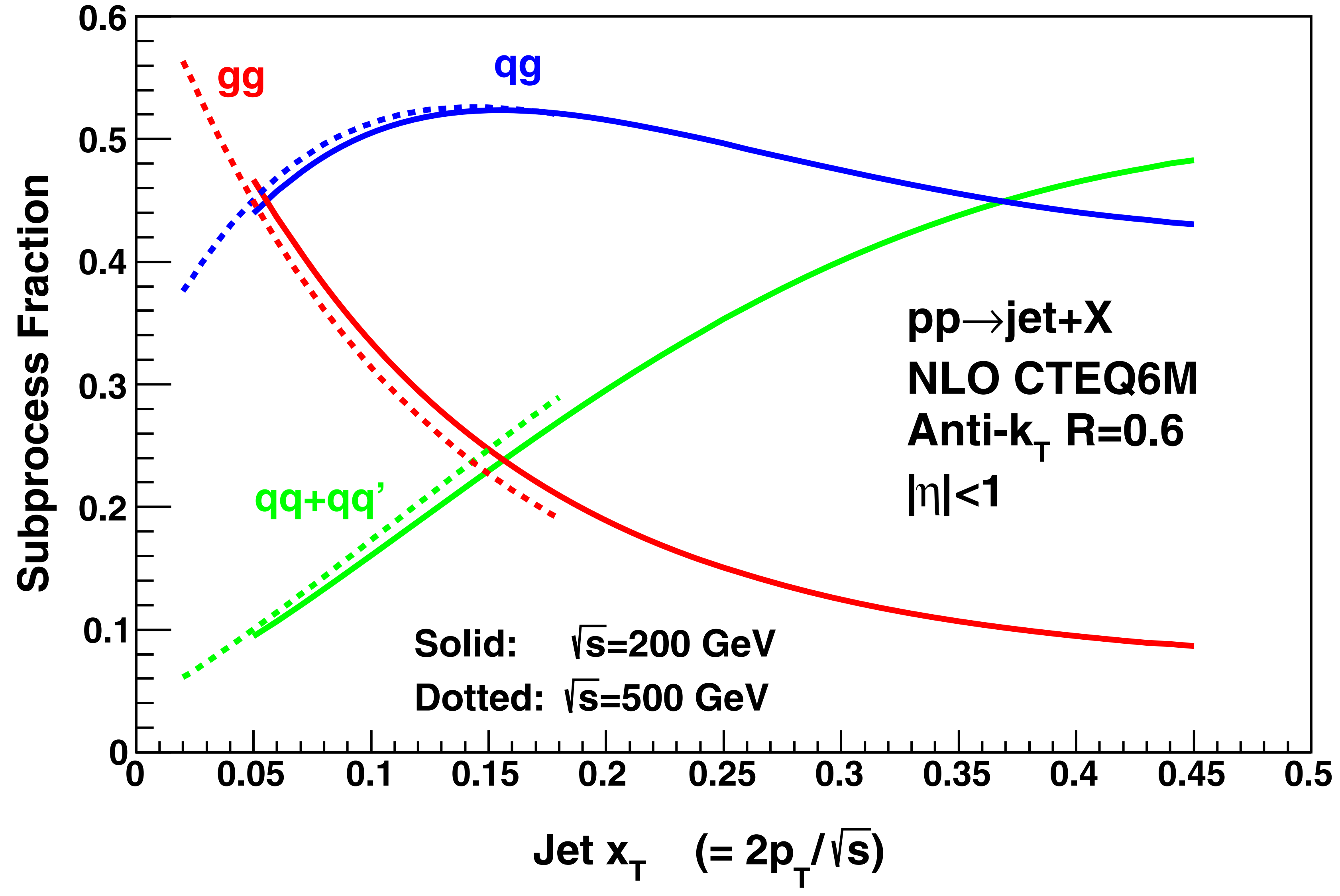
- ~~$|\Delta f| < f$~~ ➡ **Negative ΔG**
- Inclusive jets A_{LL} is not sensitive to the sign of Δg

Constraining gluon polarization with $\pi^{\pm}$-tagged jet A_{LL}

[NNPDF], Nucl. Phys. B 887, 276 (2014).



[STAR], Phys. Rev. D 100, 052005 (2019).

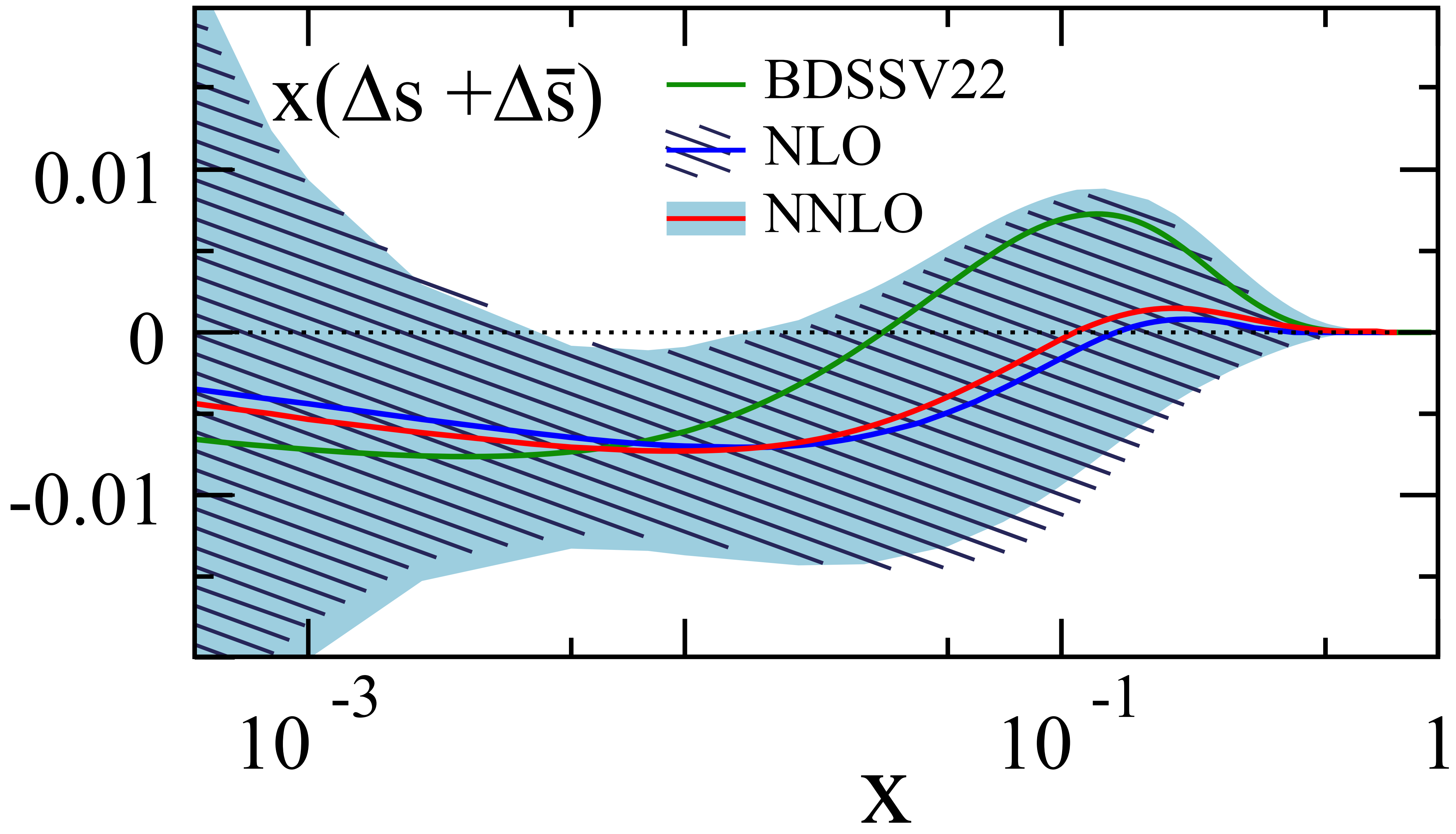


$$A_{LL}^{\pi^{\pm}} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_i \otimes \Delta f_j \otimes \Delta\hat{\sigma} \otimes D_k^{\pi^{\pm}}}{\Sigma f_i \otimes f_j \otimes \hat{\sigma} \otimes D_k^{\pi^{\pm}}}$$

- $\Delta u > 0$ and $\Delta d < 0$
- u-g and d-g scatterings are sensitive to the sign of Δg
- u quark favors π^+, d quark favors π^-
- q-g scattering is the dominated process at RHIC energy
- $\Delta g > 0 \rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
- $\Delta g < 0 \rightarrow A_{LL}^{\pi^+} < A_{LL}^{\pi^-}$

Probing strange quark helicity distribution

I. Borsa, M. Stratmann, W. Vogelsang, D. De Florian, and R. Sassot, Phys. Rev. Lett. 133, 151901 (2024).



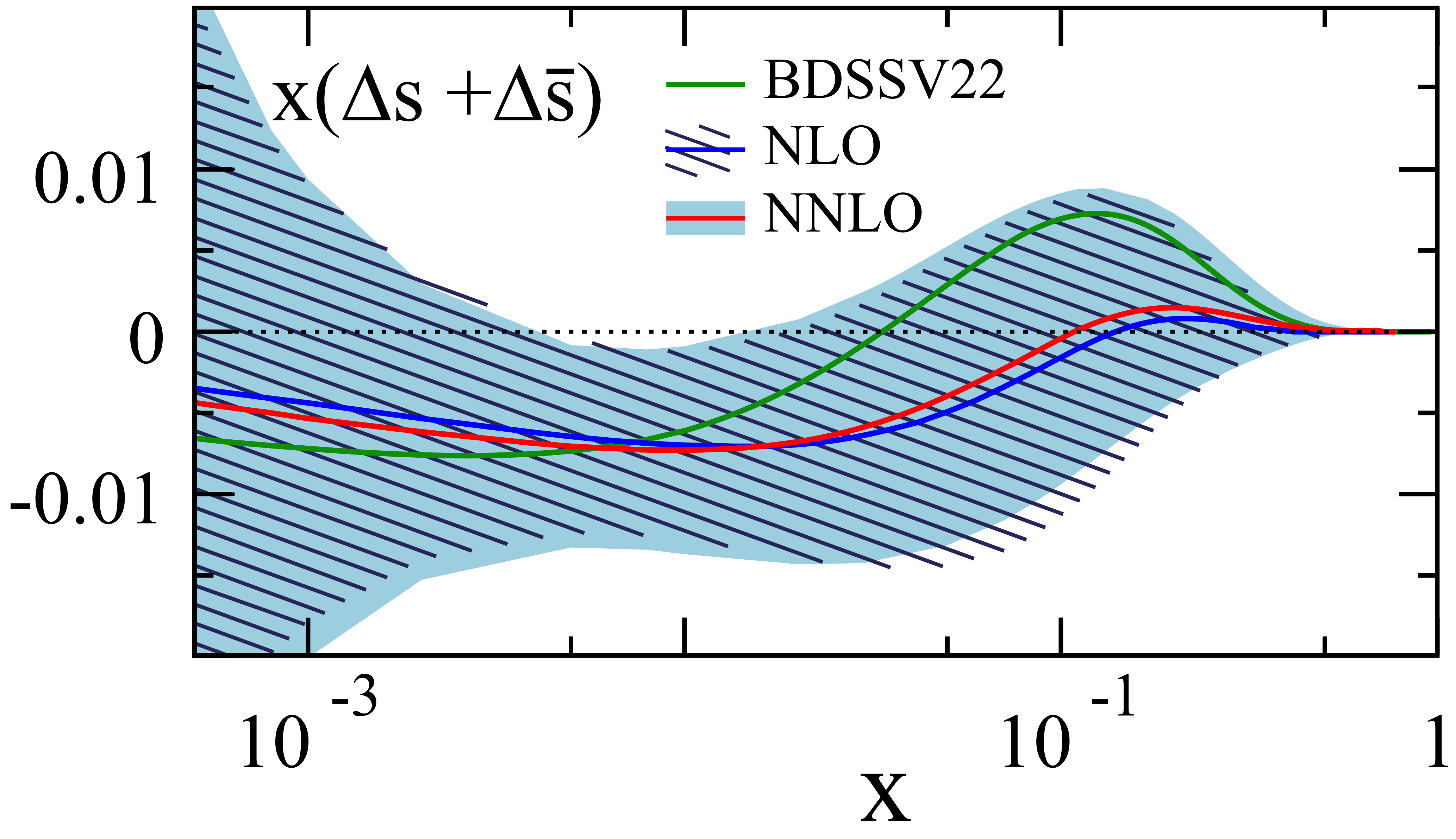
- Poor constraints on the (anti-)strange quark helicity distributions $(\Delta\bar{s})\ \Delta s$
- A_{LL} of Λ, $\overline{\Lambda}$ and K_S^0

$$A_{LL}^{\Lambda} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_i \otimes \Delta f_j \otimes \Delta\hat{\sigma} \otimes D_k^{\Lambda}}{\Sigma f_i \otimes f_j \otimes \hat{\sigma} \otimes D_k^{\Lambda}}$$

  - Valence s or $\bar{s}$ inside Λ, $\overline{\Lambda}$ and K_S^0
  - s or $\bar{s}$ prefers Λ, $\overline{\Lambda}$ and K_S^0 in the fragmentation process
  - A_{LL} of Λ, $\overline{\Lambda}$ and K_S^0 can shed light on the Δs and $\Delta\bar{s}$

Probing strange quark helicity distribution

I. Borsa, M. Stratmann, W. Vogelsang, D. De Florian, and R. Sassot, Phys. Rev. Lett. 133, 151901 (2024).



- Longitudinal spin transfer D_{LL} of Λ and $\overline{\Lambda}$ in $p + p$ collisions

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma^{p^+p\to\Lambda^+X} - d\sigma^{p^+p\to\Lambda^-X}}{d\sigma^{p^+p\to\Lambda^+X} + d\sigma^{p^+p\to\Lambda^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

$$d\Delta\sigma \propto \Delta f_a(x_a) f_b(x_b) \Delta\sigma^{ab\to cd} \Delta D^{\Lambda}(z)$$

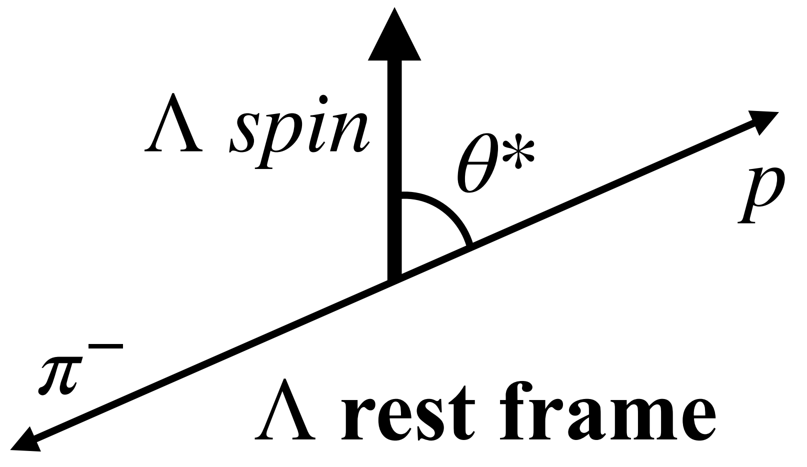
helicity distribution — pQCD calculable — longitudinally polarized FFs

- Polarization of Λ can be measured via its weak decay

$$dN \sim (1 + \alpha P_{\Lambda} \cos\theta^*) d\cos\theta^*$$

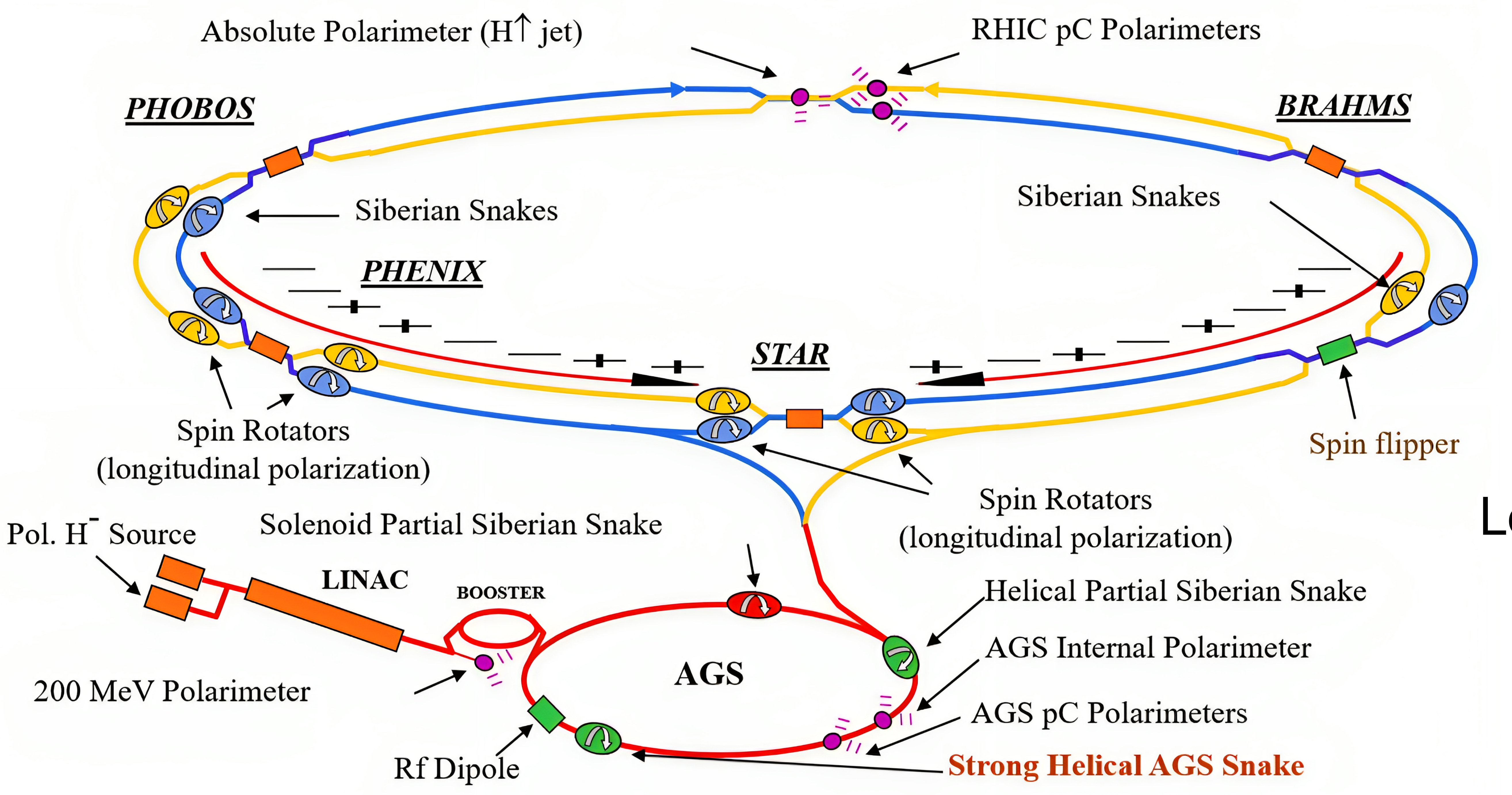
α: weak decay constant

P_{Λ}: Λ polarization



- Large fraction of Λ spin is carried by its s quark

The Relativistic Heavy Ion Collider



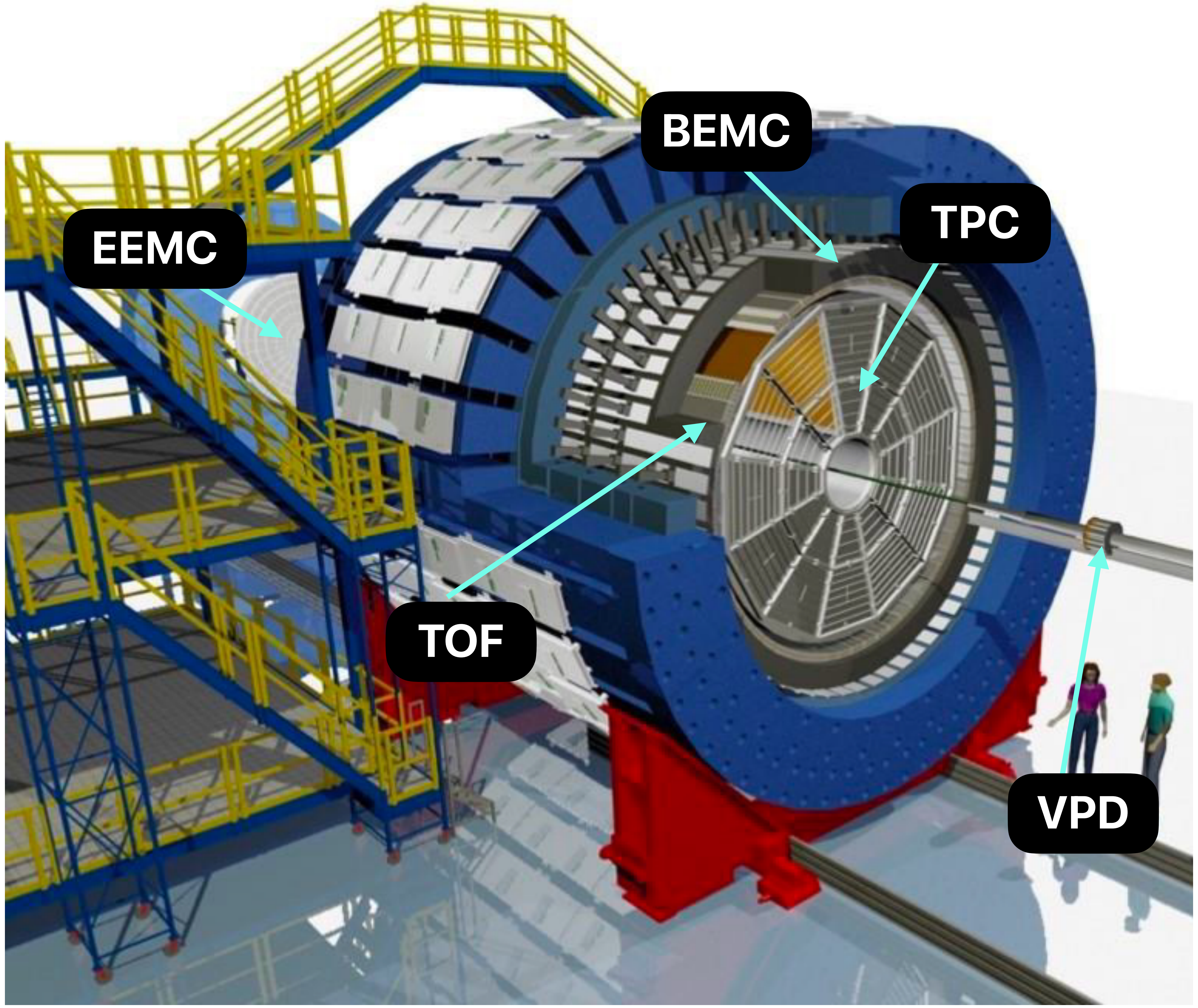
- The first and only polarized $p+p$ collider in the world
- Collides both longitudinally and transversely polarized proton beams at $\sqrt{s} = 200\,\mathrm{GeV}$ and $500/510\,\mathrm{GeV}$

Longitudinally polarized $p+p$ collision samples taken at STAR

Year	$\sqrt{s}$ (GeV)	$\int L\,(\mathrm{pb}^{-1})$	P_{beam}
2009	200	19	57% / 57%
2015	200	52	52% / 56%
2012	510	82	50% / 53%
2013	510	300	51% / 52%

used in the measurements → (2015)

The Solenoidal Tracker at RHIC

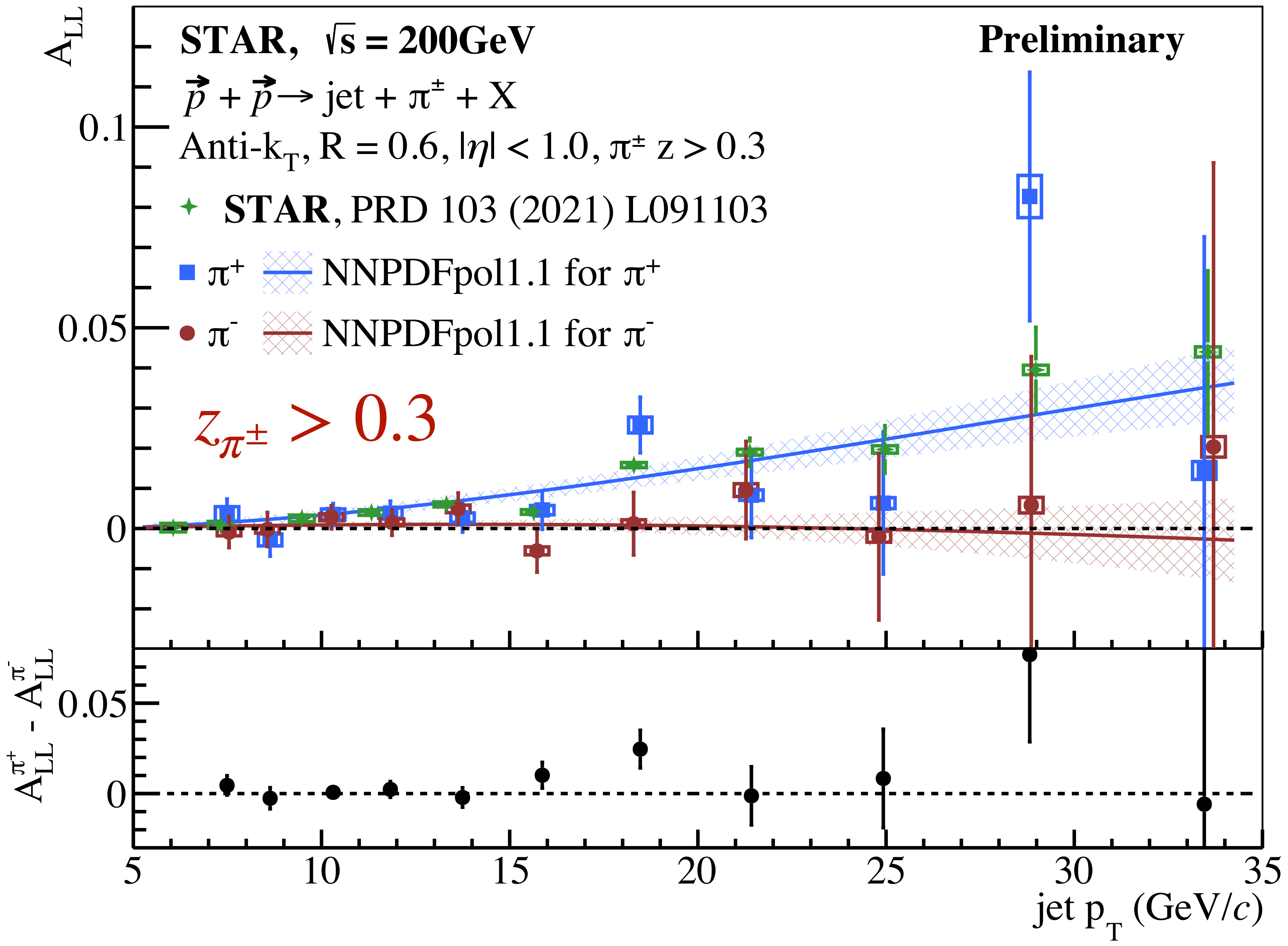


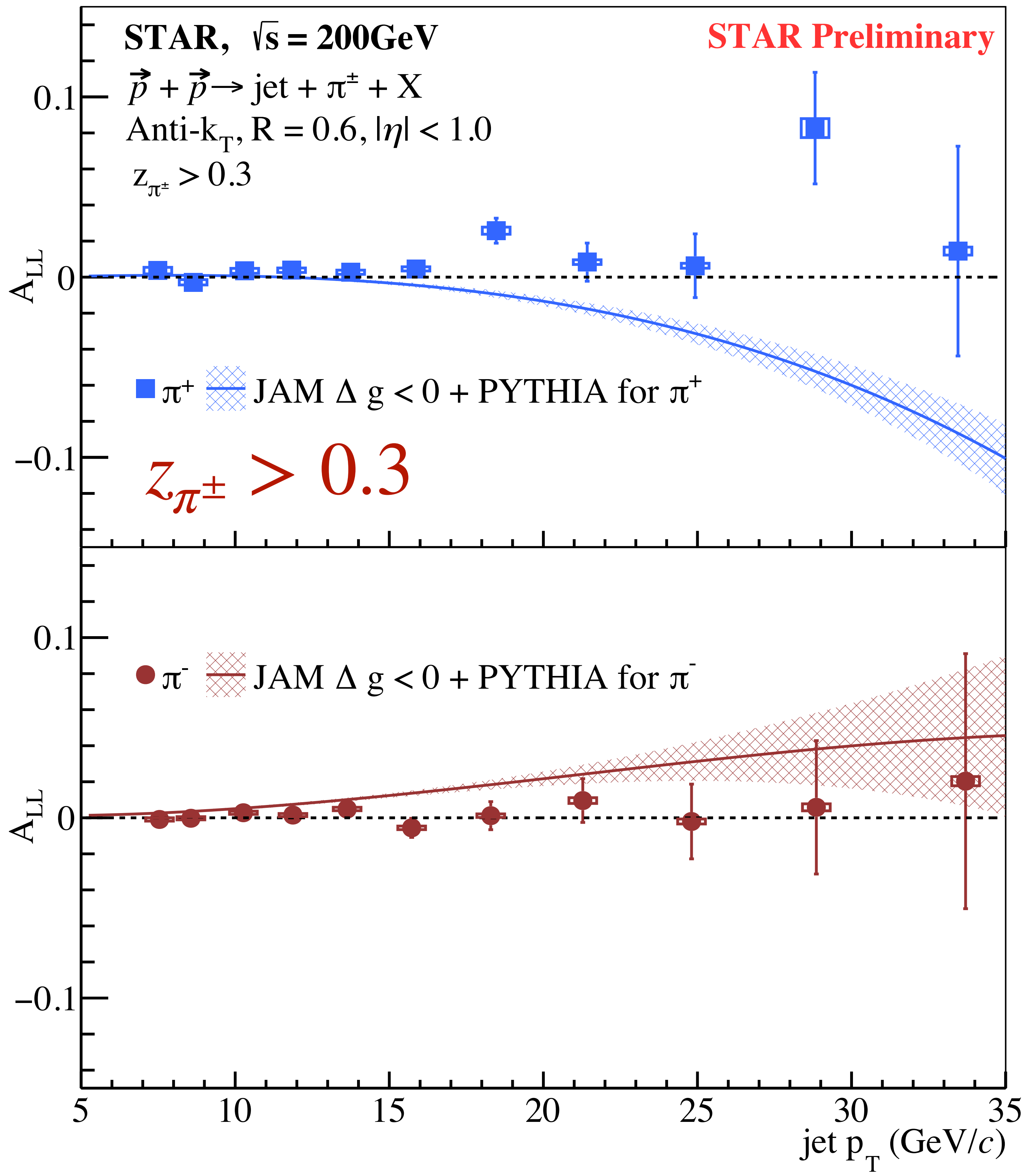
- Time Projection Chamber (TPC)
  - $|\eta| < 1.3$ and $0 \leq \phi \leq 2\pi$
  - Tracking and particle identification (PID)
- Time of Flight detector (TOF)
  - $|\eta| < 0.9$ and $0 \leq \phi \leq 2\pi$
  - Particle identification
- Electromagnetic Calorimeter (EMC)
  - Barrel EMC (BEMC): $|\eta| < 1.0$ and $0 \leq \phi \leq 2\pi$
  - Endcap EMC (EEMC): $1.086 < \eta < 2.0$ and $0 \leq \phi \leq 2\pi$
  - Reconstruction of γ, π^0, jet ..., and serves as trigger detectors
- Vertex Position Detector (VPD)
  - $4.24 < |\eta| < 5.1$
  - Monitor the relative luminosities and determine the primary vertex

Part I: Longitudinal double spin asymmetry A_{LL} of $\pi^{\pm}$-tagged jets, $\Lambda(\overline{\Lambda})$ and K_S^0

Results of $A_{LL}^{\pi^\pm}$ vs jet p_T

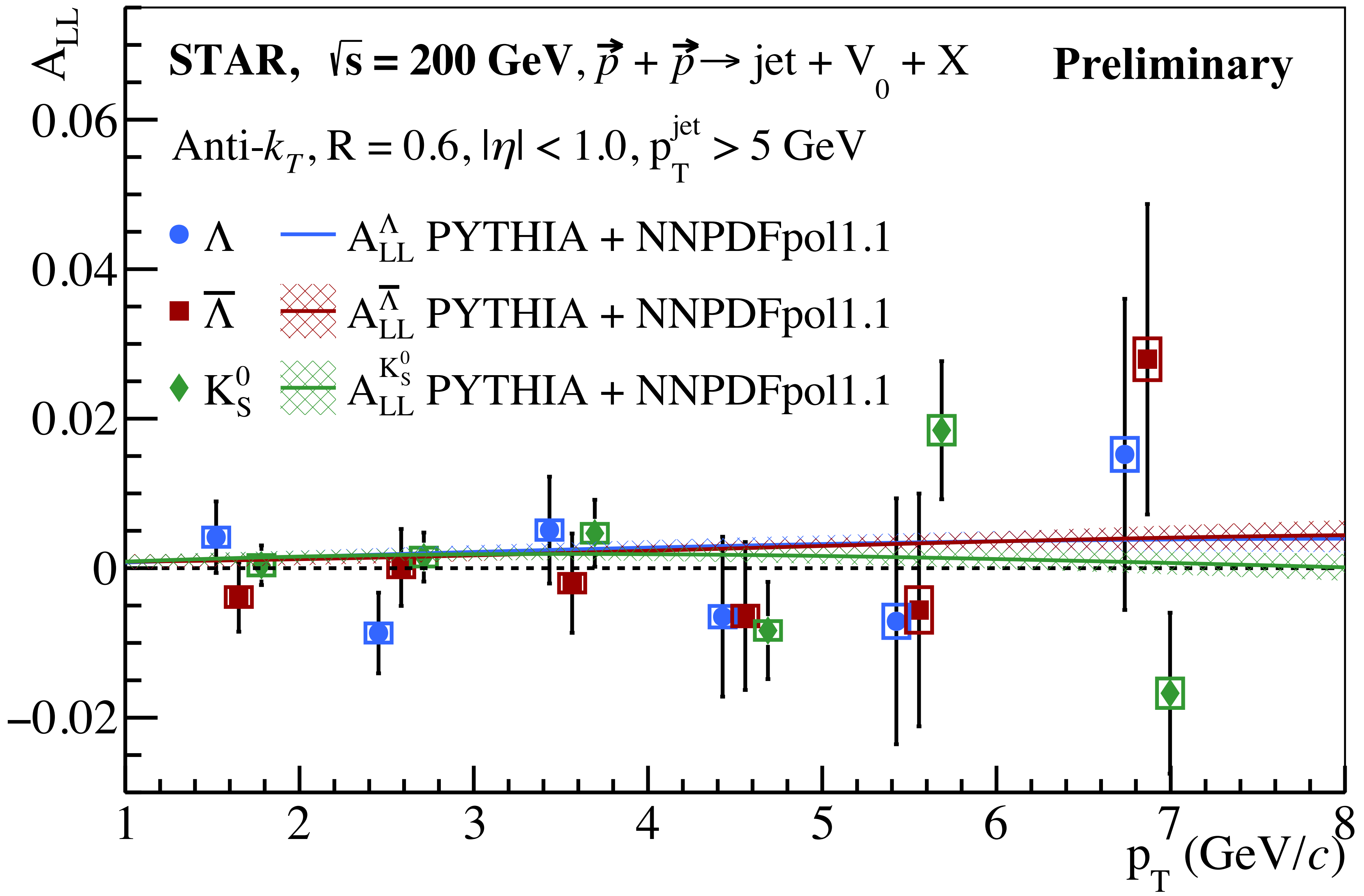
arxiv:2408.15479

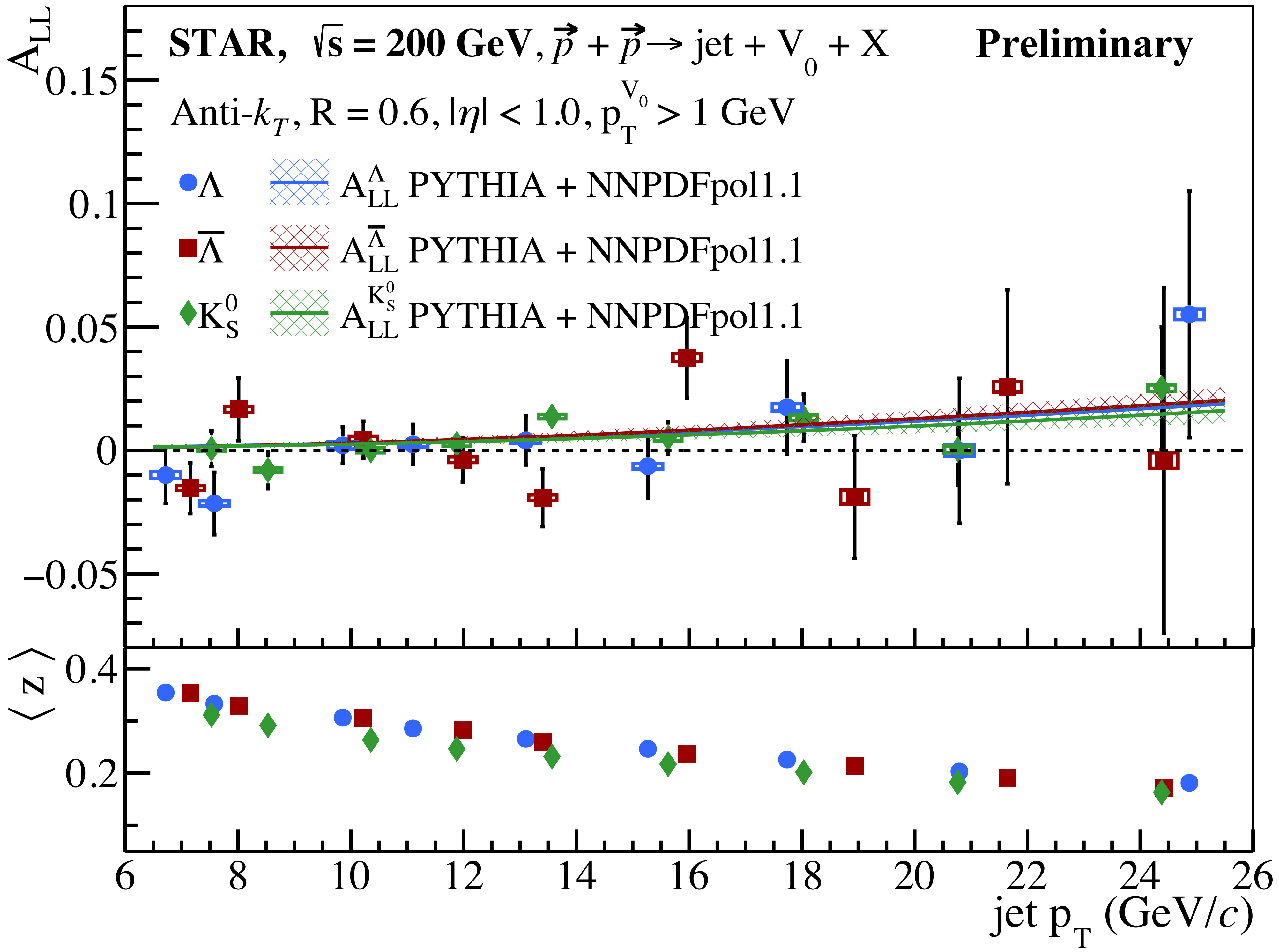




- Indication of $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
- Agreement with NNPDFpol1.1 predictions: $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$ with positive gluon helicity Δg
- Strongly disfavors predictions of JAM with negative Δg

A_{LL} for $\Lambda, \overline{\Lambda}$ and K_S^0





- First measurement A_{LL} vs p_T for $\Lambda, \overline{\Lambda}$ and K_S^0 in polarized $p+p$ collisions
- The results are independent of particle p_T and jet p_T
- The results are consistent with zero and agree with the NNPDFpol1.1 predictions
- Indication of small helicity distributions of s and $\bar{s}$

Part II: Longitudinal spin transfer D_{LL} of Λ and $\overline{\Lambda}$

D_{LL} in $p+p$ collision

- Definition

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma^{p^+p\to\Lambda^+X} - d\sigma^{p^+p\to\Lambda^-X}}{d\sigma^{p^+p\to\Lambda^+X} + d\sigma^{p^+p\to\Lambda^-X}} = \frac{d\Delta\sigma}{d\sigma}$$

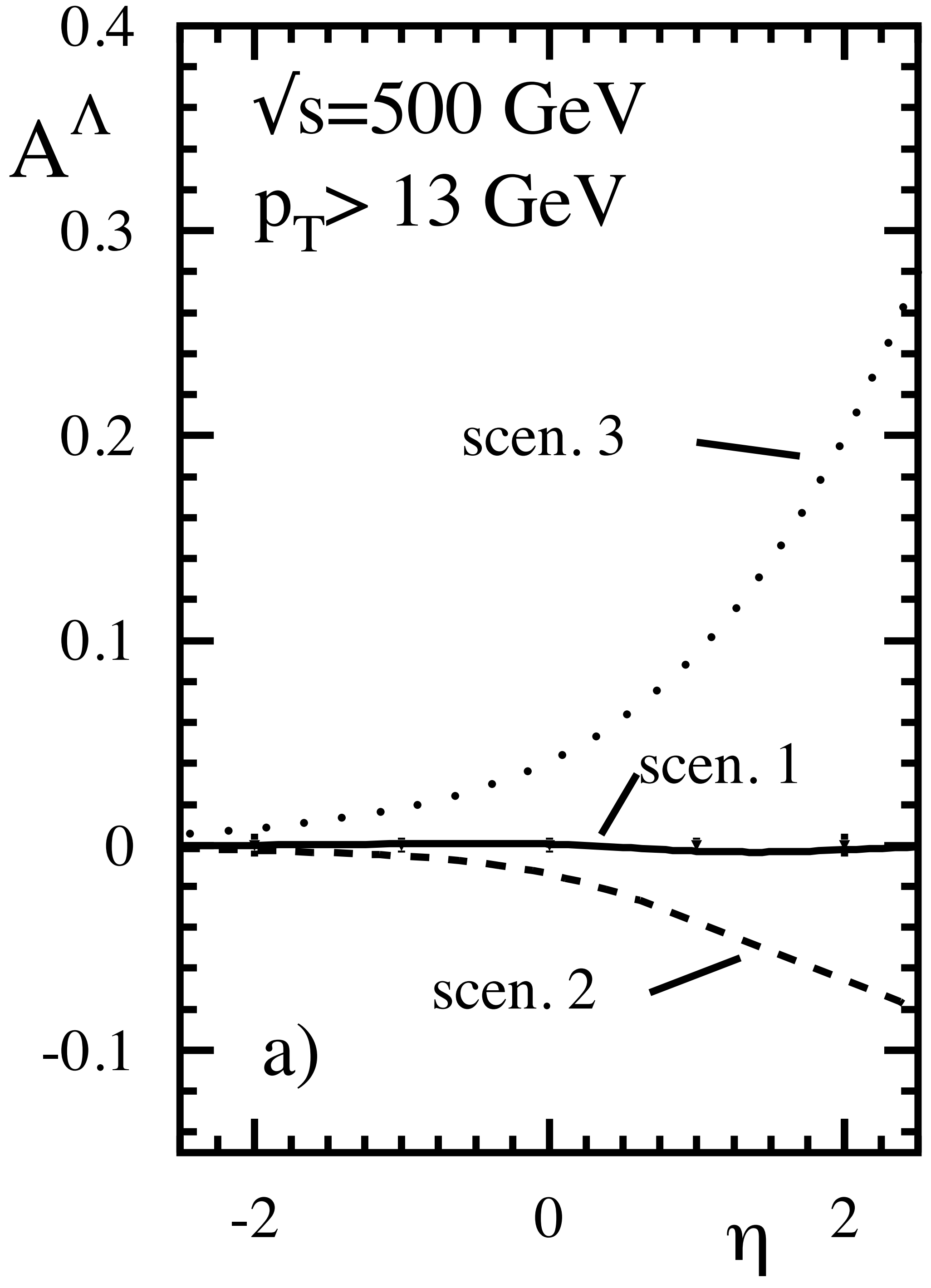
$$d\Delta\sigma \propto \Delta f_a(x_a) f_b(x_b) \Delta\sigma^{ab\to cd} \Delta D^{\Lambda}(z)$$

helicity distribution — pQCD calculable — longitudinally polarized FFs

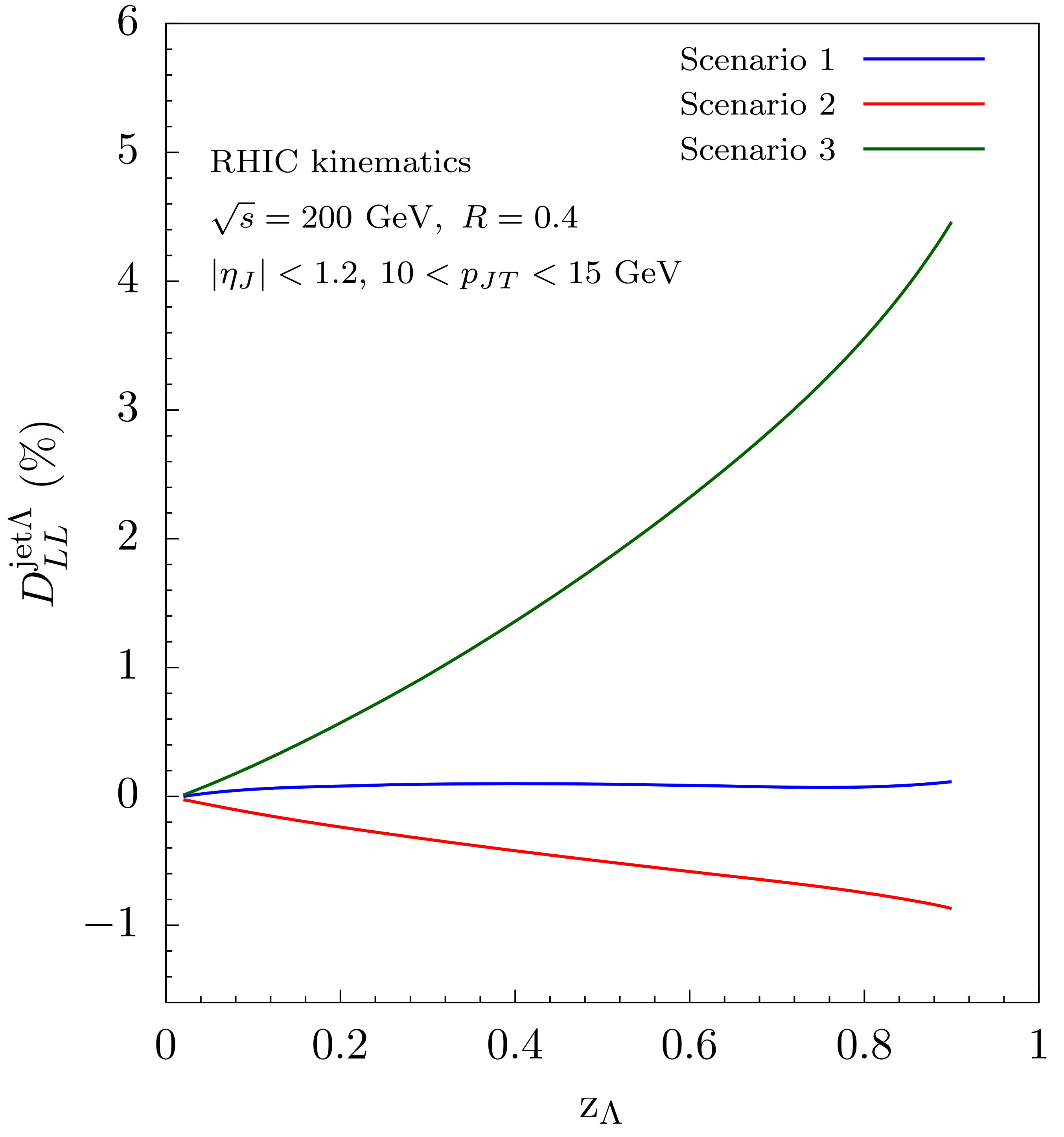
- D_{LL} can shed light on both polarized fragmentation functions (FFs) and the helicity distributions of $s(\bar{s})$
- D_{LL} vs z can provide direct probe to the polarized FFs

Prediction of D_{LL} at RHIC energy

D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **81**, 4 (1998).



Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B **809**, 135756 (2020).



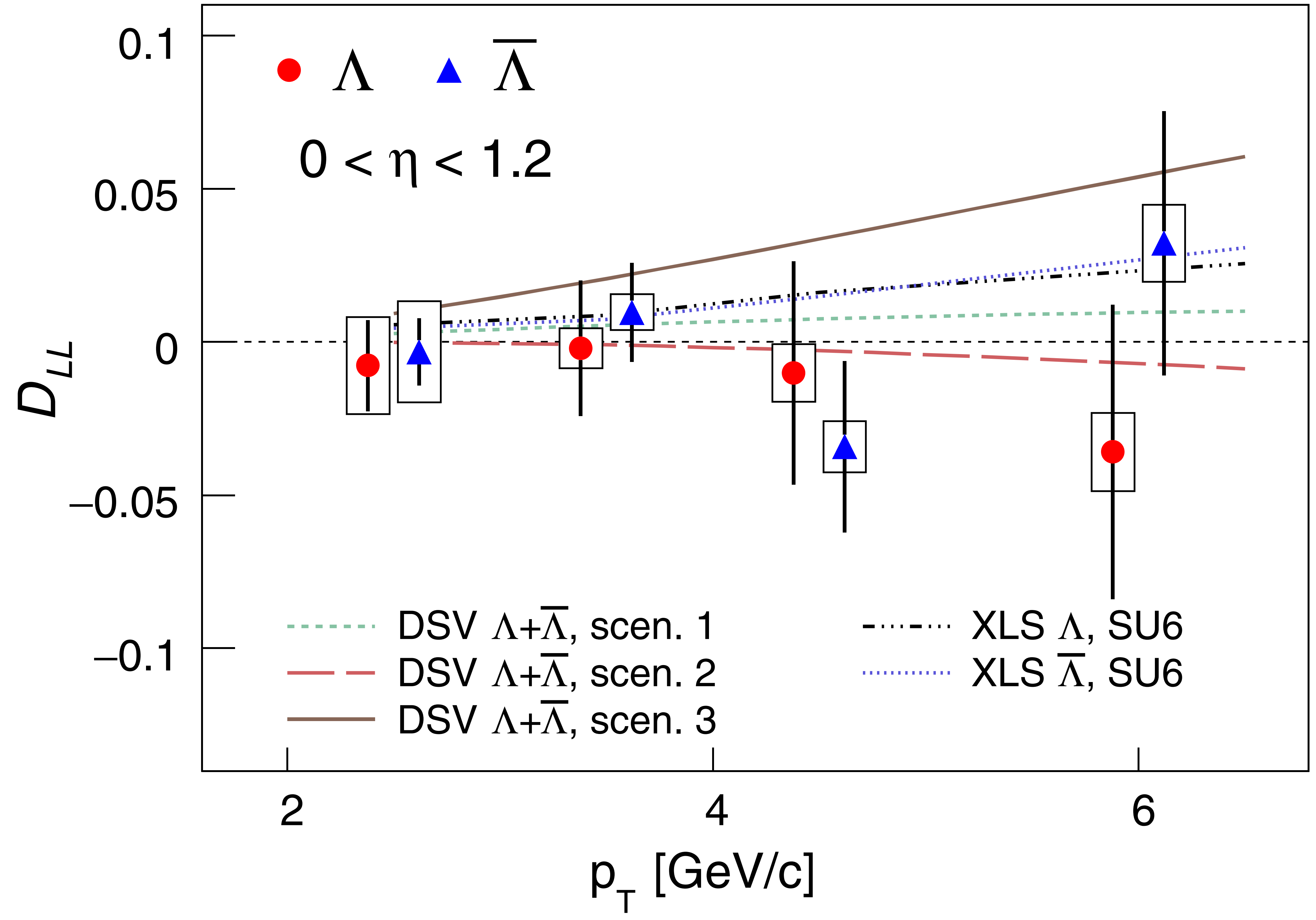
scenario 1: only s quark can contribute to Λ polarization.

scenario 2: u and d quarks have the same contribution to polarized Λ but u and d have an opposite sign from s quark.

scenario 3: u, d and s quarks have the same contribution to the polarized Λ

Previous D_{LL} results with STAR 2009 data

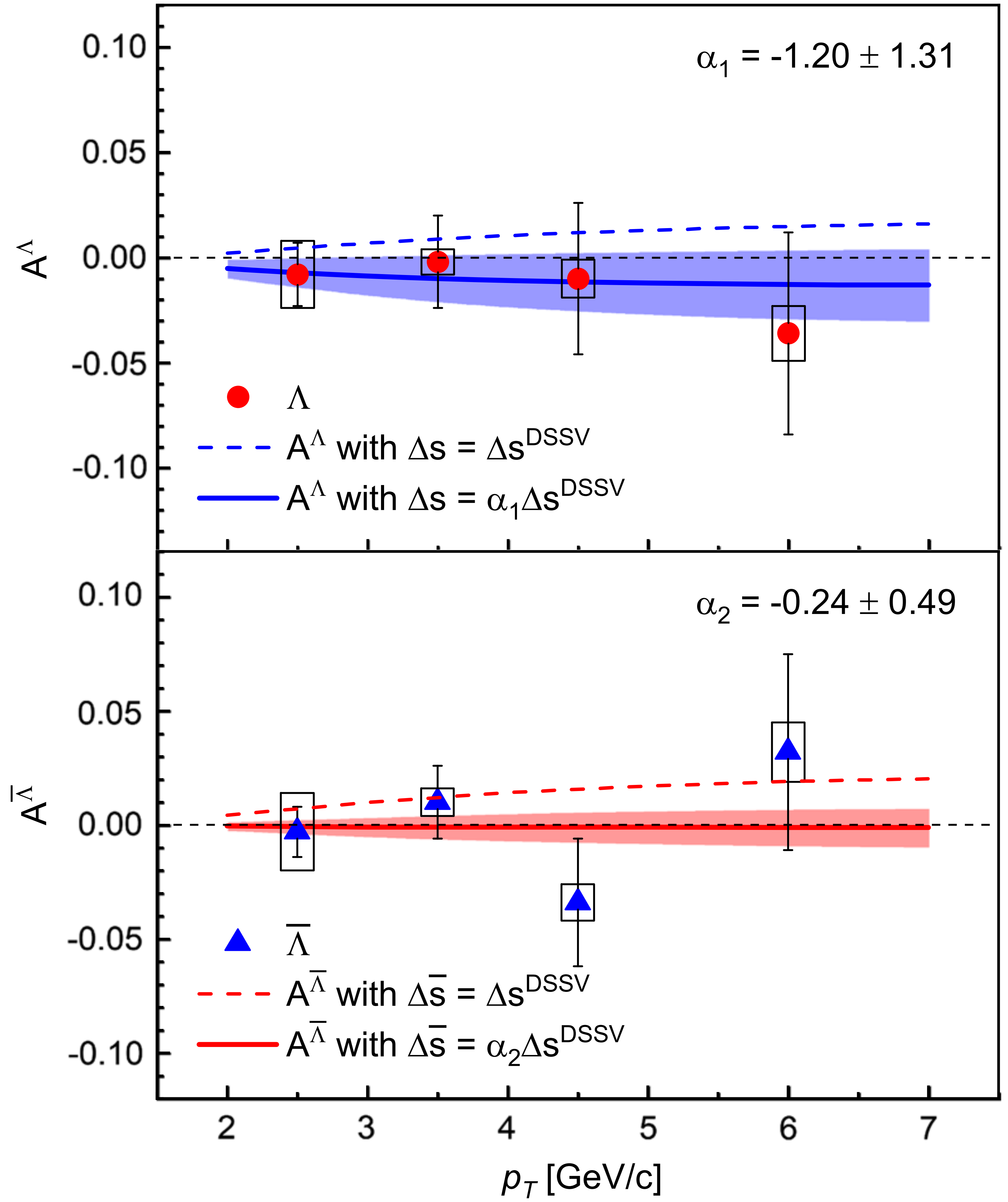
STAR, *Phys. Rev. D* **98**, 112009 (2018).



- Statistically limited
- In agreement with models

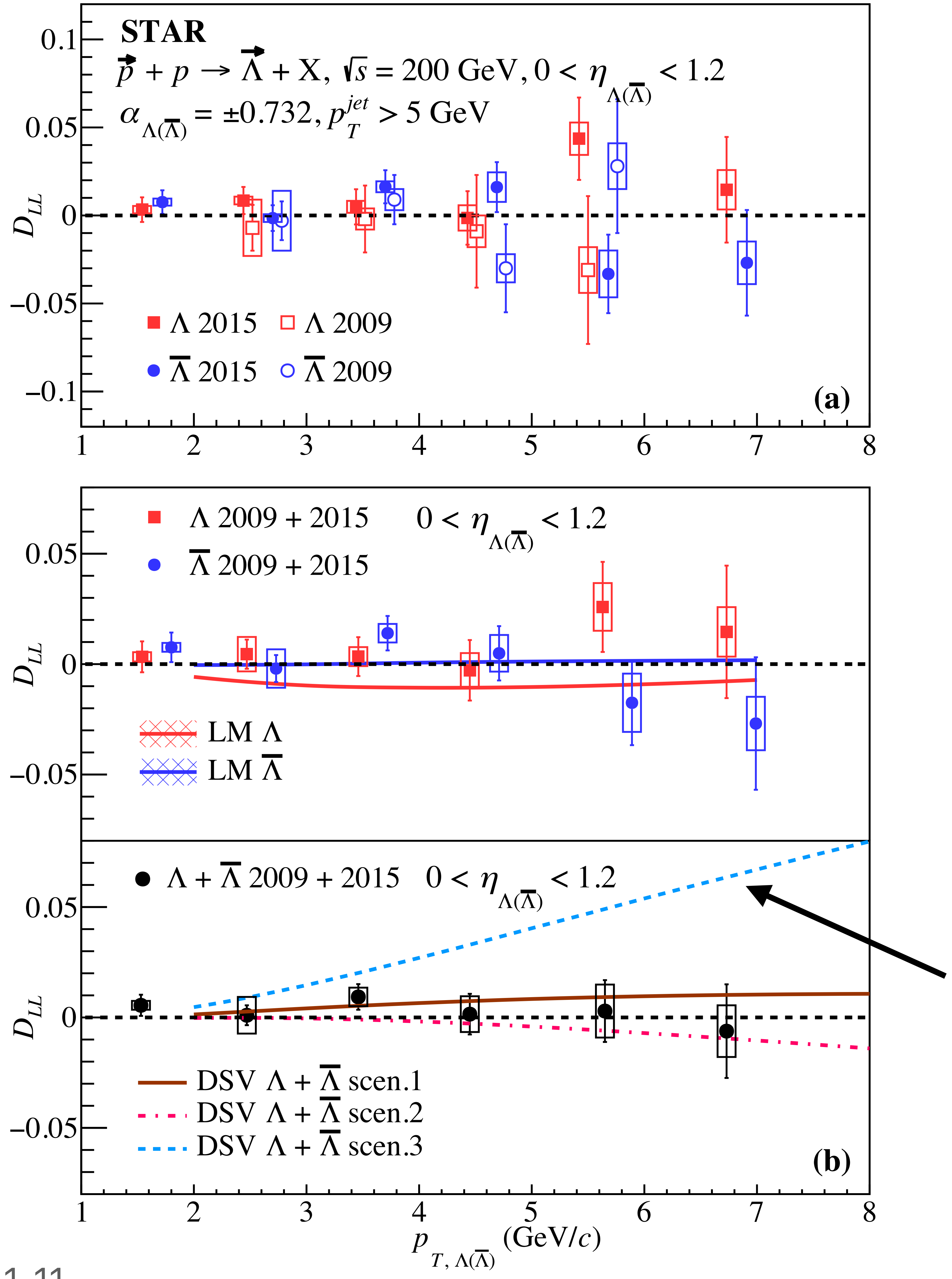
- Theoretical models, when fit to data, provide constraints on (anti)strange quark polarization

X.N. Liu, B.Q. Ma. *Eur. Phys. J. C* 10 (2019).



New results of D_{LL} vs p_T

[STAR], Phys. Rev. D 109, 012004 (2024).



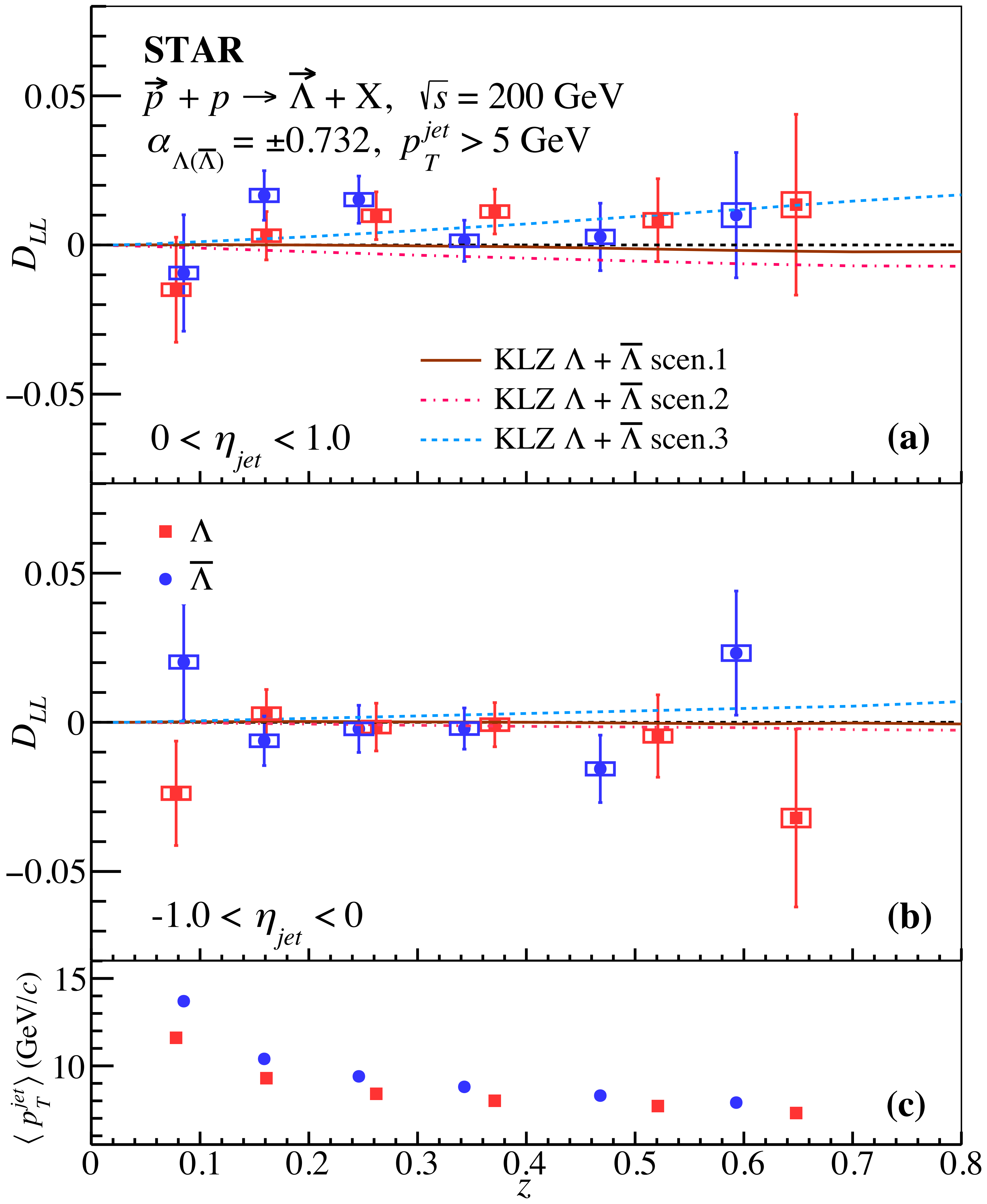
- Twice larger statistics than STAR 2009 data
- Most precise measurements up to date
- Consistent results between Λ and $\bar{\Lambda}$
- Consistency between the two STAR measurements
- Results are consistent with LM calculation
- Strongly disfavors the scenario 3 of the polarized FFs

Model predictions:
X.N. Liu, B.Q. Ma. *Eur. Phys. J. C* 10 (2019).
D. de Florian, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. 81, 530 (1998).

scenario 3: u, d and s equally contribute to the Λ polarization

First measurement of D_{LL} vs z

[STAR], Phys. Rev. D 109, 012004 (2024).



- The results **directly probe the polarized fragmentation functions**
- Results are in agreement with KLZ model predictions within uncertainties
- Indication of small helicity distributions of (anti-) strange quark and/or small polarized fragmentation functions

KLZ model predictions: Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B 809, 135756 (2020).

Summary

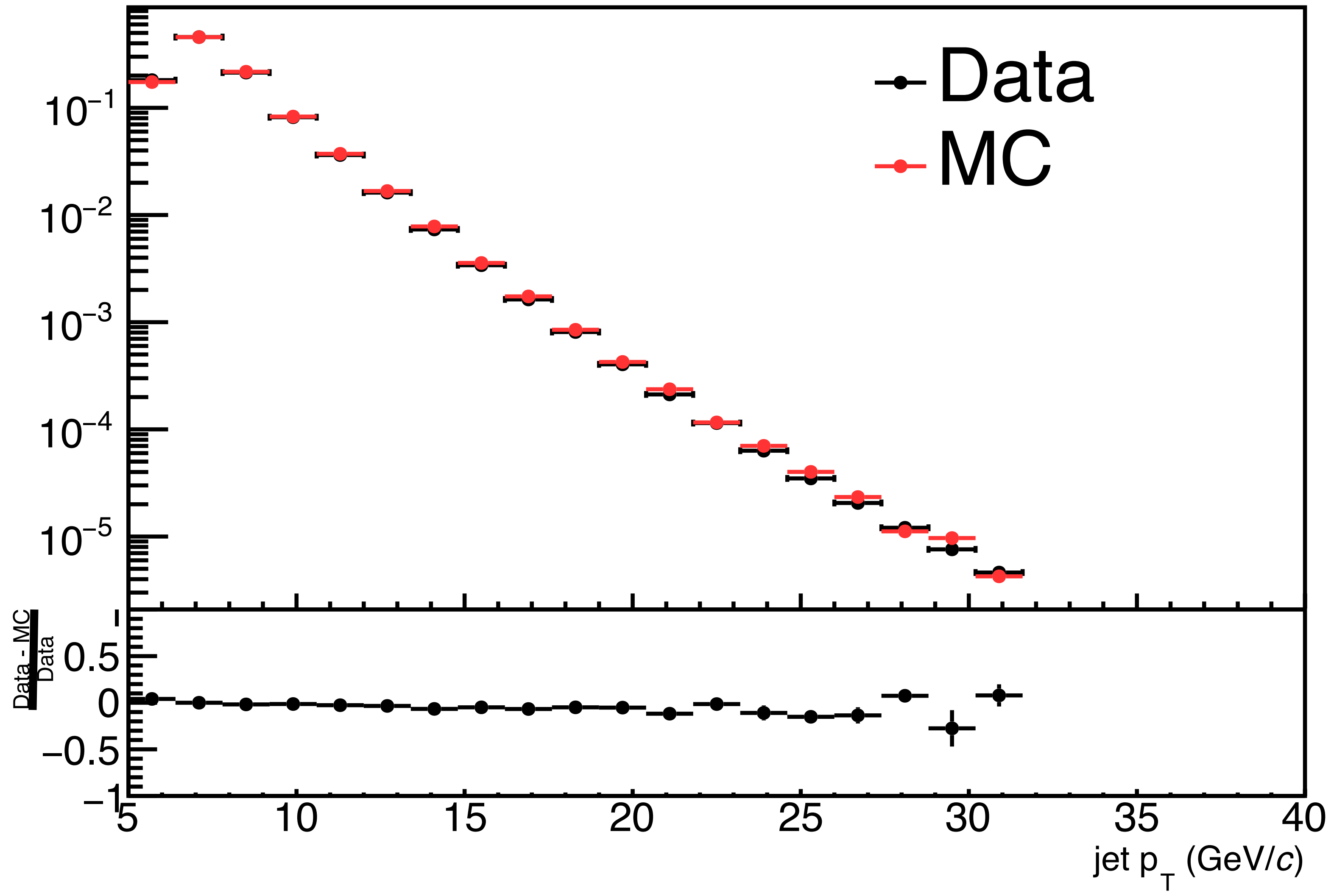
- $\pi^{\pm}$-tagged jet A_{LL} in $p+p$ collisions at $\sqrt{s}=200\text{ GeV}$ at STAR → **gluon helicity Δg**
  - The results support positive Δg
  - A_{LL} is consistent with the prediction with NNPDFpol1.1 ($\Delta g > 0$)
  - Disagreement with predictions of JAM negative Δg
  - $\pi^{\pm}$-tagged jet A_{LL} provides a complementary constraints on Δg
- Λ, $\overline{\Lambda}$ and K_S^0 A_{LL} and D_{LL} → **strange quark helicity $\Delta s(\Delta \bar{s})$**
  - First measurements of A_{LL} in polarized $p+p$ collisions at $\sqrt{s}=200\text{ GeV}$
  - Indication of small strange quark and anti-quark helicity distribution
  - D_{LL} disfavors the extreme scenario about the polarized FFs
  - First measurement of D_{LL} vs z provides direct access to the polarized FFs
- Larger data samples of $p+p$ collisions at 510 GeV taken in 2012 and 2013 will improve higher precision and extend to lower x region

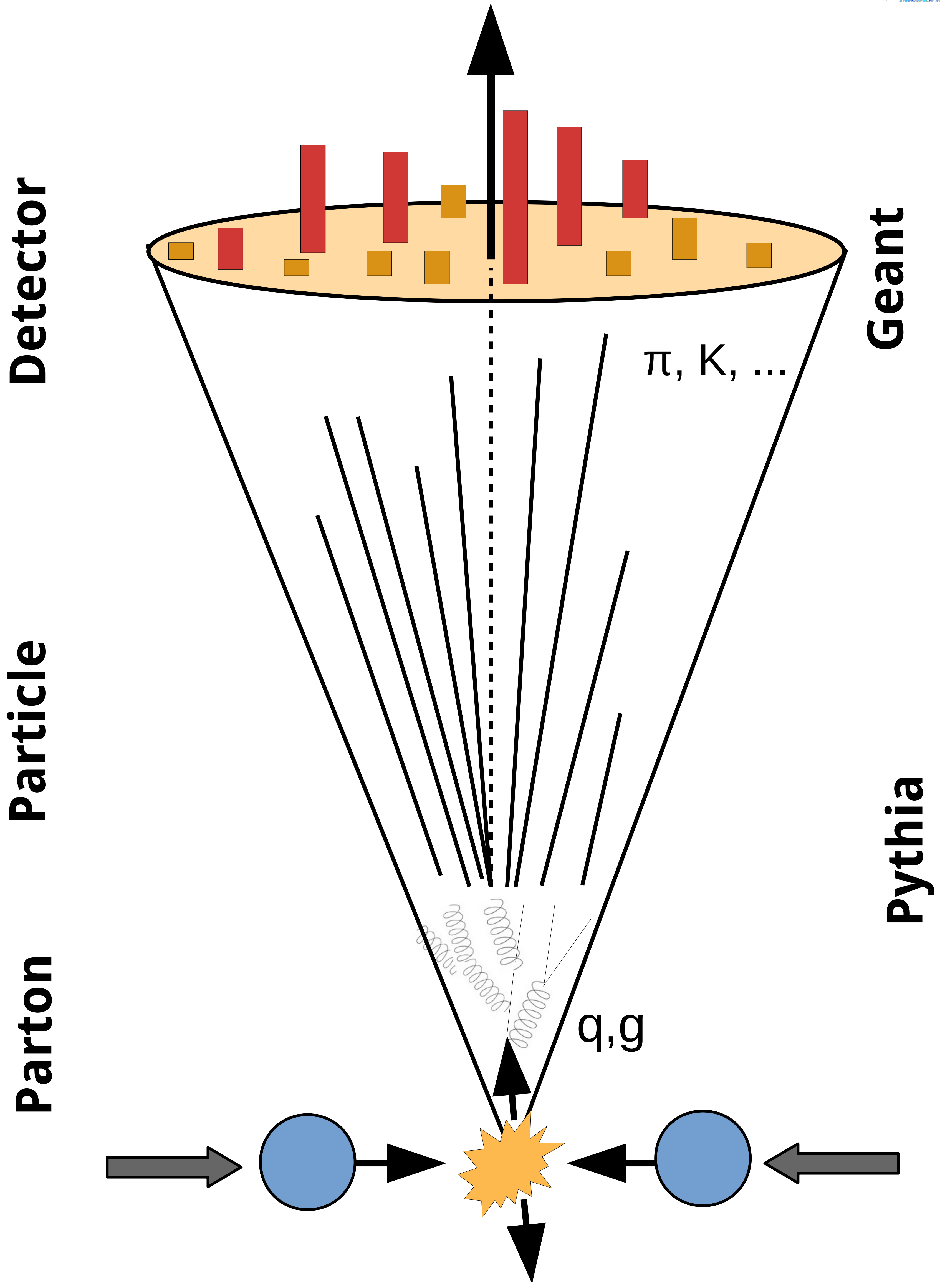
Backup

Jet Reconstruction

- High-p_T jet triggers (JP1 and JP2) are used based on energy deposits in EMC
- Jet reconstruction (TPC tracks + energy deposits in EMC)
  - Anti-k_T algorithm, with $R = 0.6$
  - Simulation: PYTHIA6 + GEANT3 + Zero-bias events
    - Jet was reconstructed at parton, particle and detector level
  - Jet p_T was corrected back to particle level
- Jets tagged with $\pi^{\pm}$ with $z > 0.2$ or $z > 0.3$

$$z \equiv \frac{\vec{p}_{\pi} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2}$$



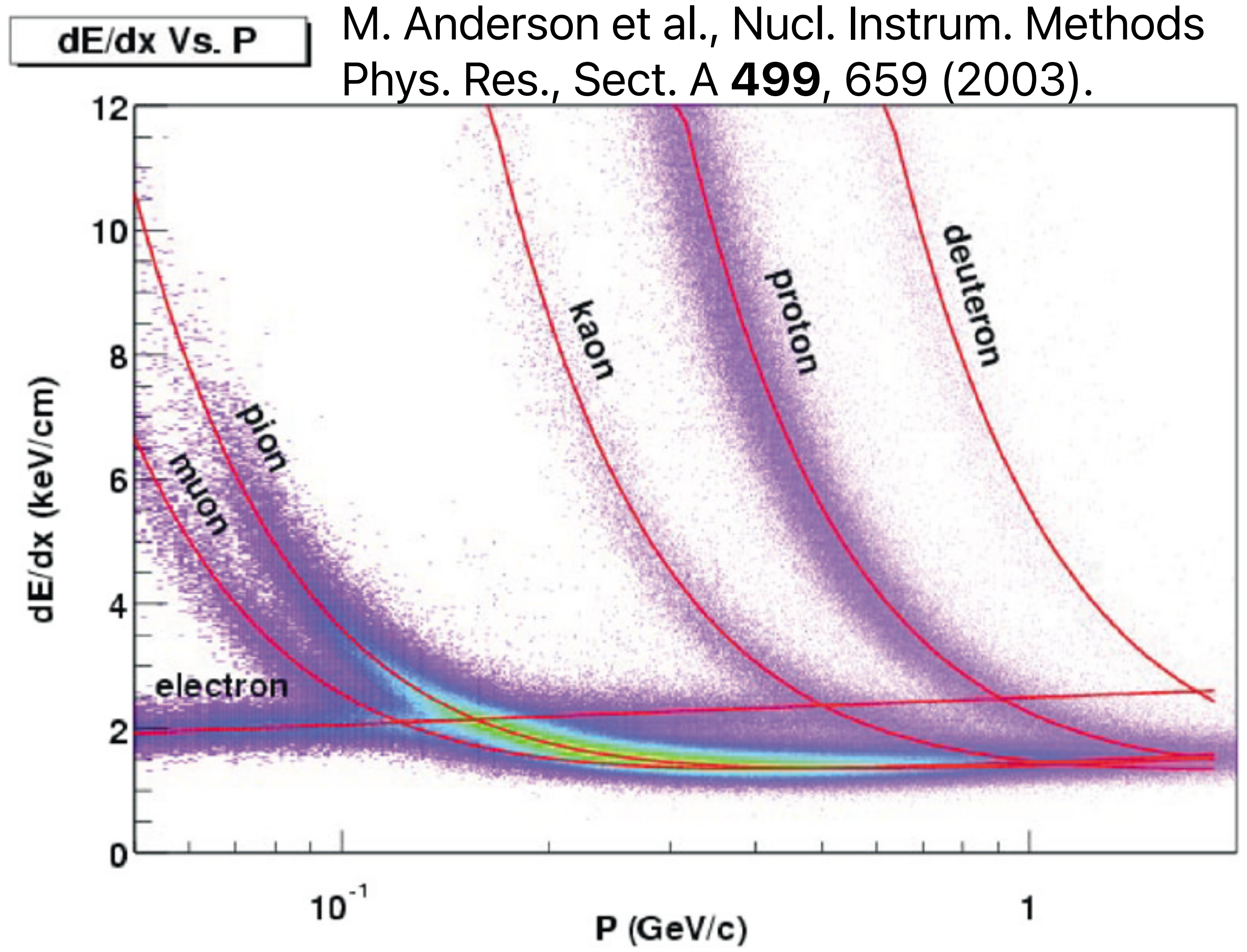


$\pi^{\pm}$ PID

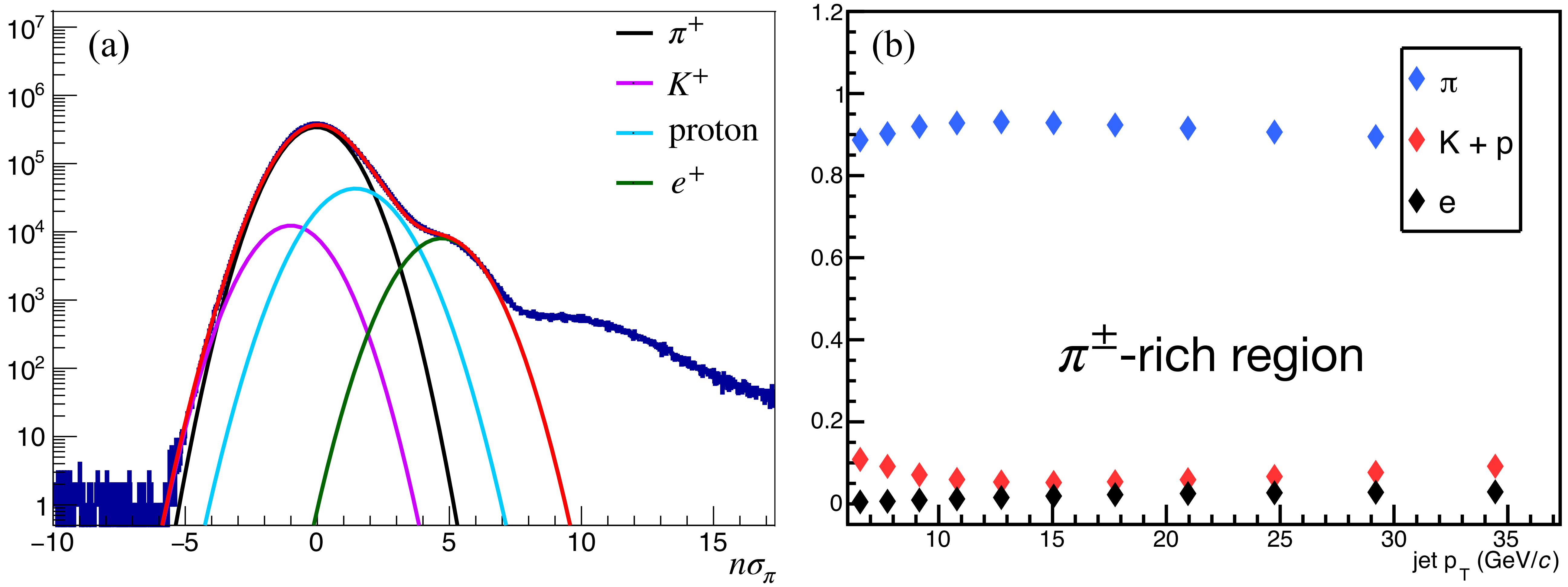
- $\pi^{\pm}$ are identified based on their energy loss inside the TPC

$$n\sigma(\pi) = \frac{1}{\sigma_{\exp}} \ln\left(\frac{dE/dx_{\rm obs}}{dE/dx_{\pi,\rm cal}}\right)$$

- Particle purity is estimated with multi-Gaussian fitting of the $n\sigma_{\pi}$ distribution
- 3 particle rich regions ($\pi^{\pm}$, $K^{\pm} + p(\bar{p})$, $e^{\pm}$)



M. Anderson et al., Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 659 (2003).



$$A_{LL} = \frac{1}{P_B P_Y} \frac{(N_{++} + N_{--}) - R_3(N_{+-} + N_{-+})}{(N_{++} + N_{--}) + R_3(N_{+-} + N_{-+})}$$

$+(-)$ denotes the beam helicity

N_{++} etc are the jet yields for different beam helicity configurations

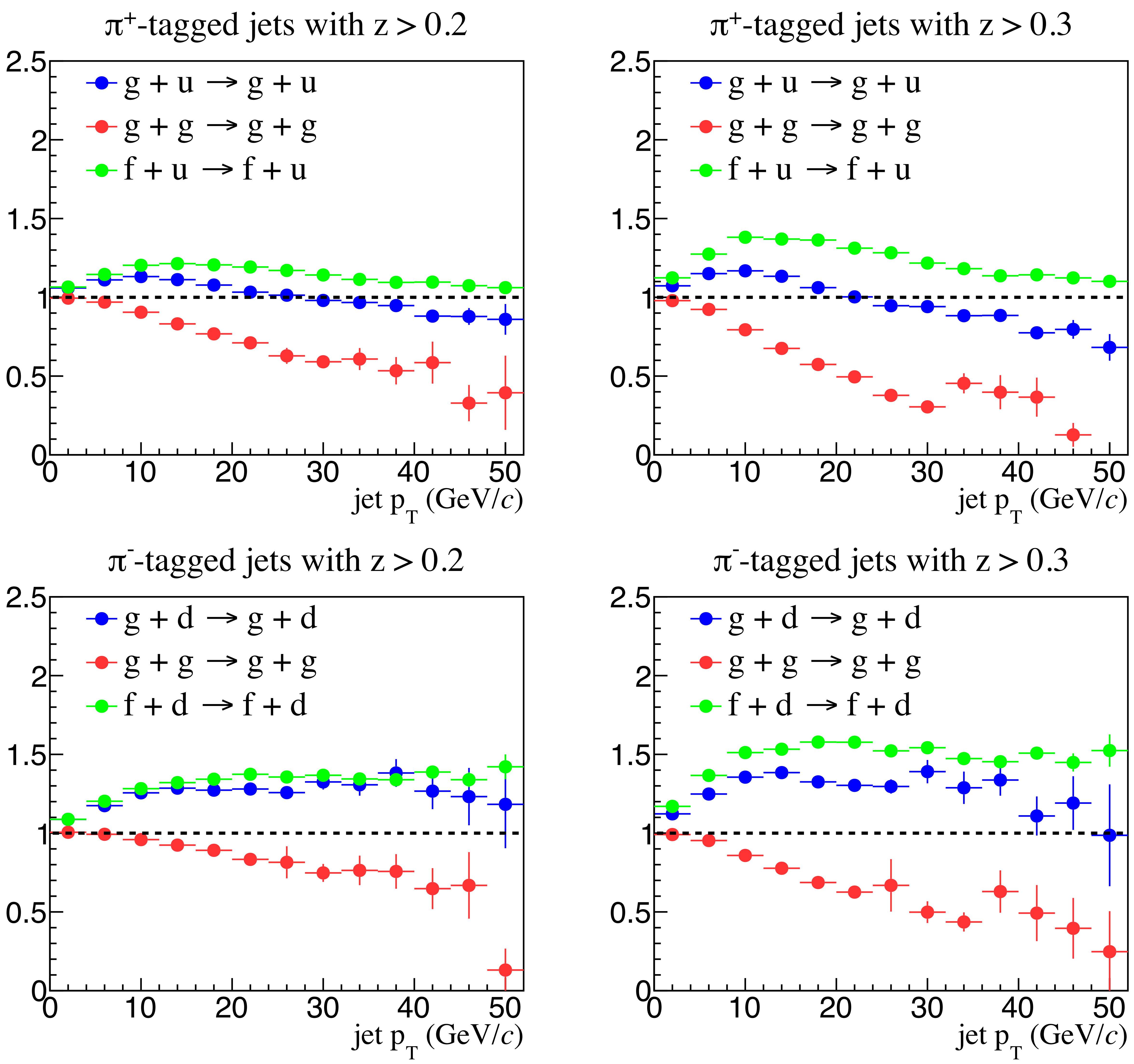
P_B and P_Y are beam polarizations

R_3 is the relative luminosity calculated with the VPD

$$A_{LL}^{raw} = \sum_{\pi,K+p,e} f_i A_{LL}^i$$

$$\begin{bmatrix} f^{\pi}_{\pi_{rich}} & f^{K+p}_{\pi_{rich}} & f^{e}_{\pi_{rich}} \\ f^{\pi}_{K+p_{rich}} & f^{K+p}_{K+p_{rich}} & f^{e}_{K+p_{rich}} \\ f^{\pi}_{e_{rich}} & f^{K+p}_{e_{rich}} & f^{e}_{e_{rich}} \end{bmatrix} \begin{bmatrix} A_{\pi} \\ A_{K+p} \\ A_e \end{bmatrix} = \begin{bmatrix} A^{raw}_{\pi_{rich}} \\ A^{raw}_{K+p_{rich}} \\ A^{raw}_{e_{rich}} \end{bmatrix}$$

Impact of the $\pi^{\pm}$ tagging



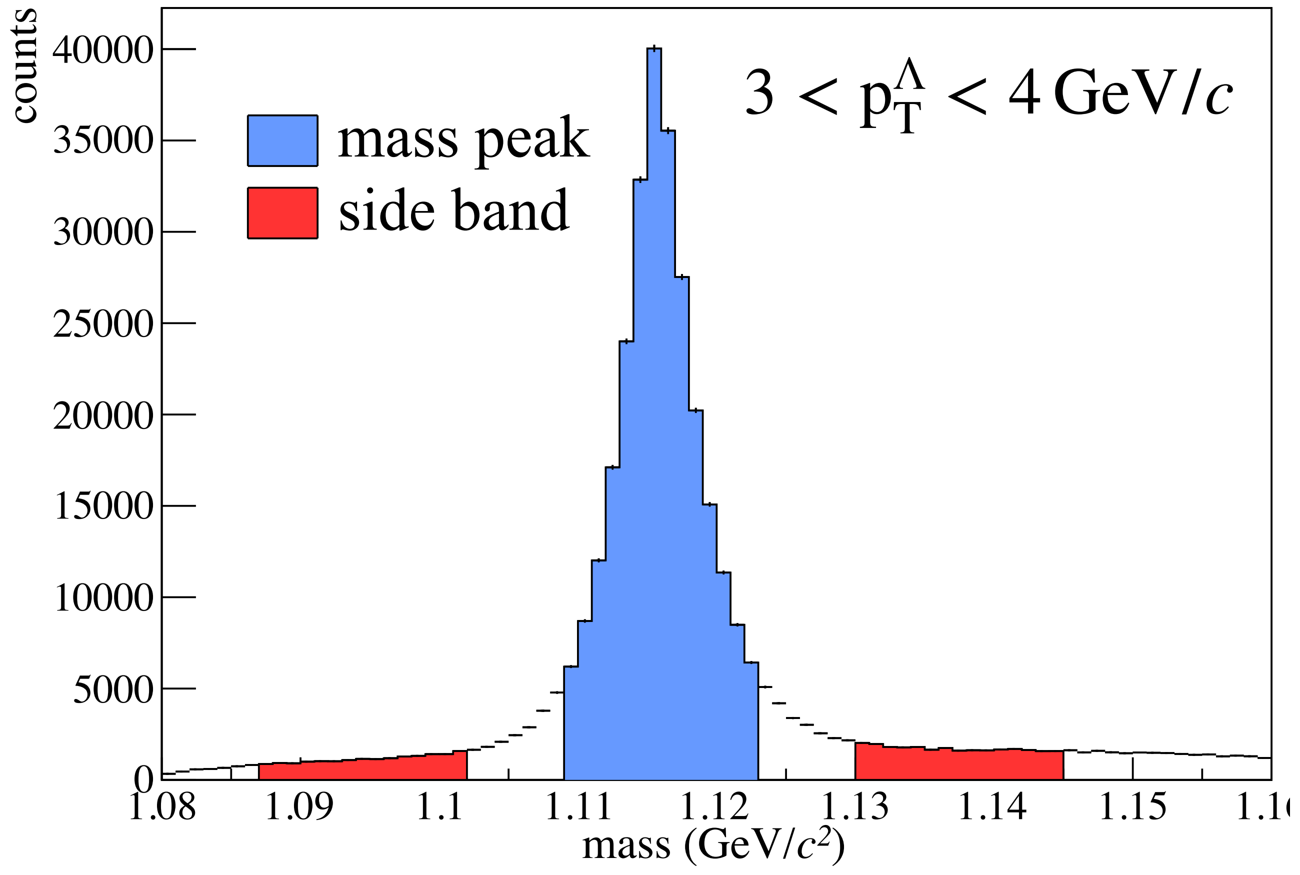
Λ and K_S^0 Selection & Jet Reconstruction

- Λ and K_S^0 selection
  - $\Lambda(\overline{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(\pi^+), K_S^0 \rightarrow \pi^+ + \pi^-$
  - $p(\bar{p})$ and $\pi^{\pm}$ tracks were measured with the TPC
  - Sets of topological cuts were applied to reduce background
  - Residual background fraction r was estimated with side-band method
- Jet reconstruction
  - Jet reconstructed with anti-k_T algorithm with $R = 0.6$
  - Λ and K_S^0 candidate as input for jet reconstruction
  - In-jet Λ and K_S^0 are used to make sure they are originate from the hard scattering

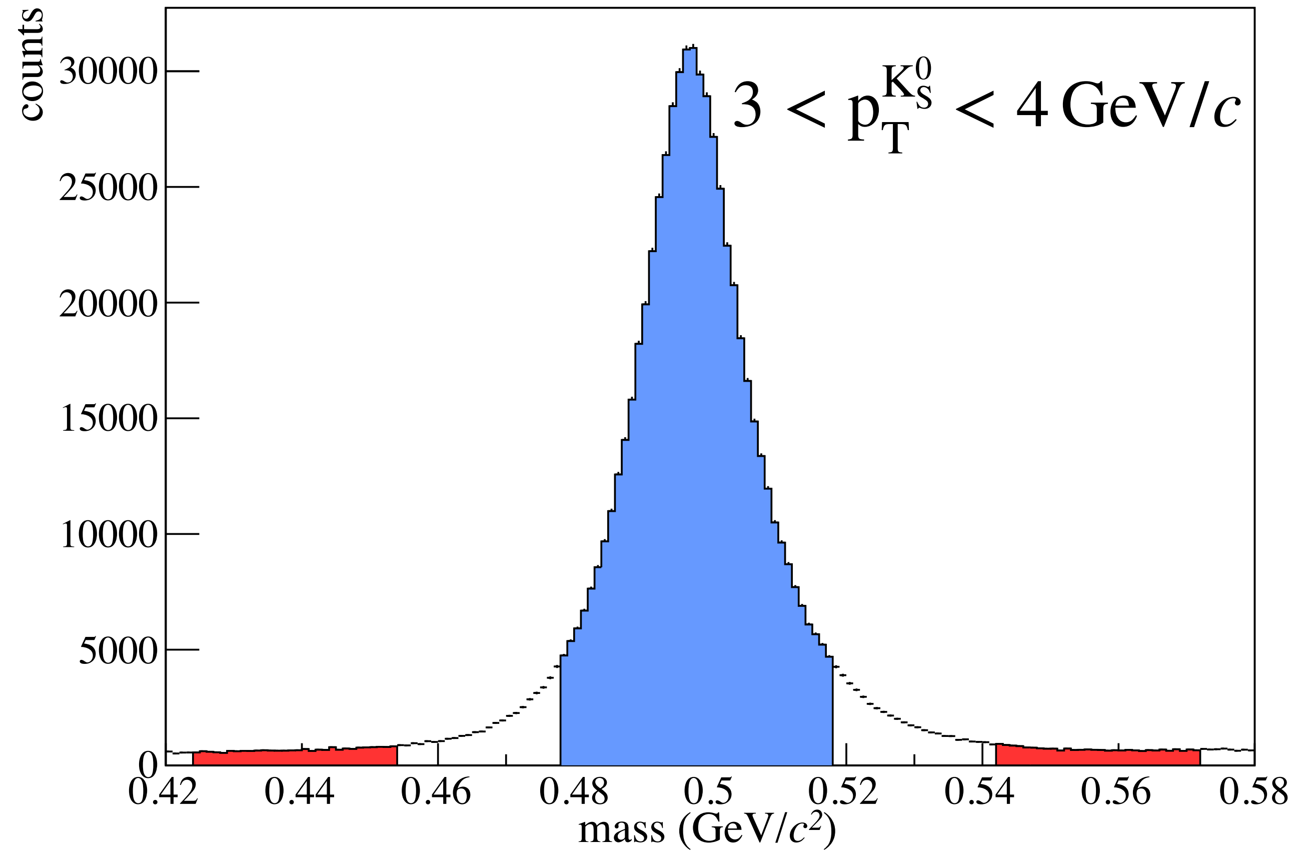
Background subtraction →

$$A_{LL} = \frac{A_{LL}^{raw} - rA_{LL}^{bkg}}{1 - r}$$

Λ mass distribution



K_S^0 mass distribution



D_{LL} Extraction

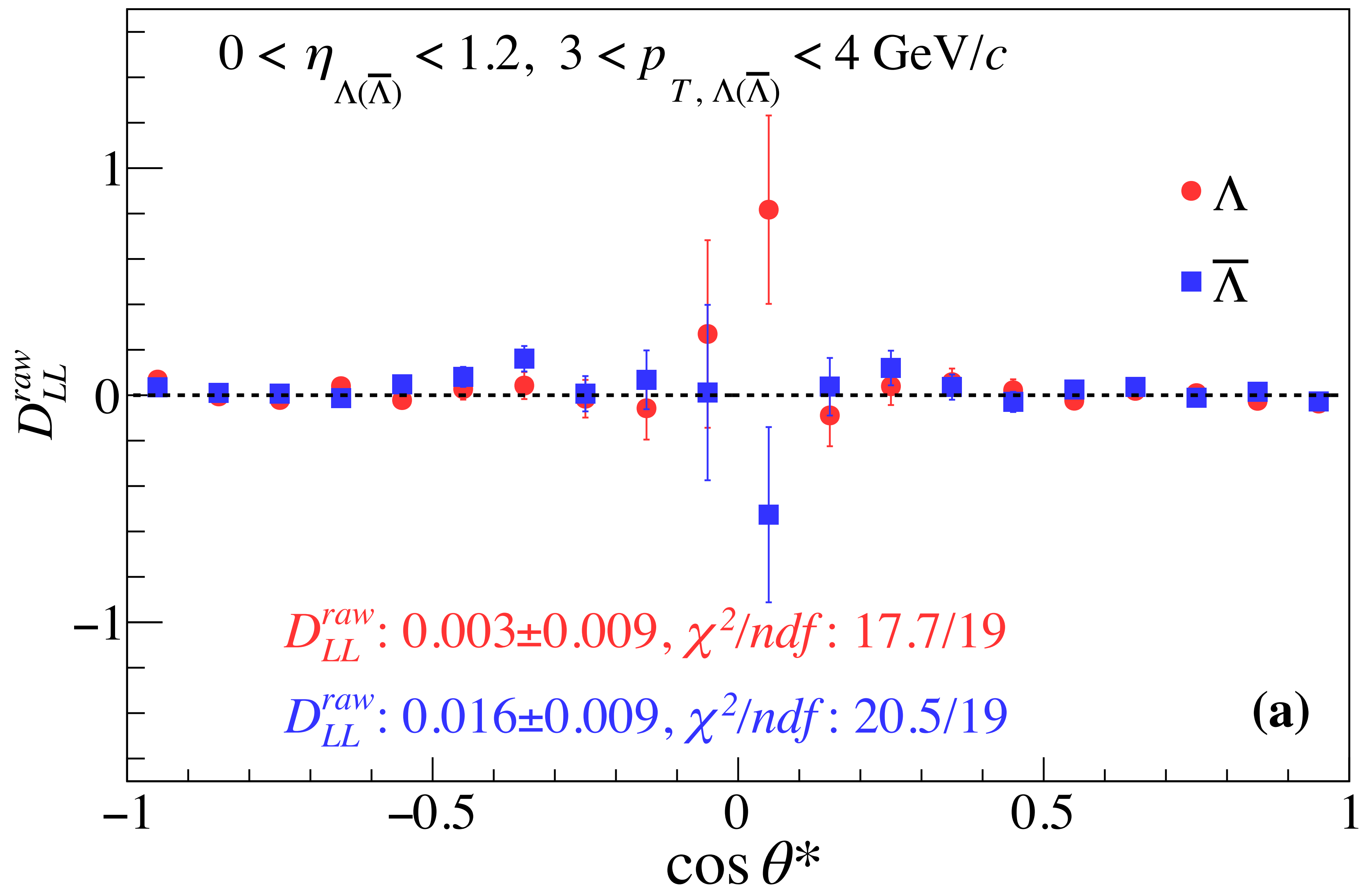
- D_{LL} is measured with the asymmetry of $\Lambda(\overline{\Lambda})$ yields as a function of $\cos\theta^*$

$$D_{LL} = \frac{1}{\alpha P_{beam}\langle\cos\theta^*\rangle}\frac{N^+ - RN^-}{N^+ + RN^-}$$

Acceptance canceled

firstly used in STAR, *Phys. Rev. D* 80, 111102 (2009).

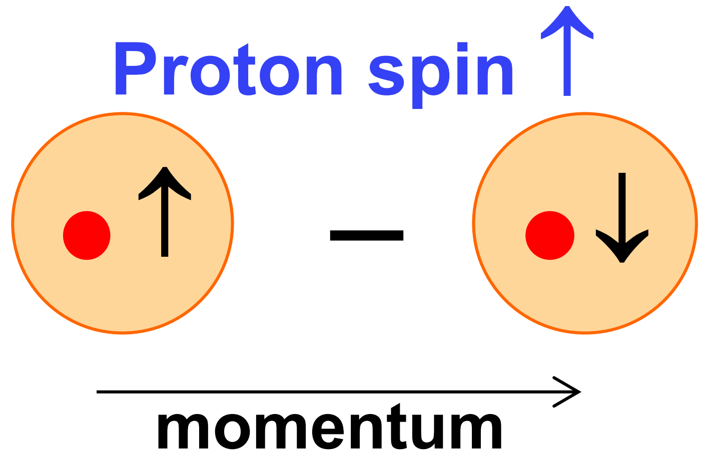
Background subtraction $$D_{LL} = \frac{D_{LL}^{raw} - rD_{LL}^{bkg}}{1-r}$$



- $N^{+(-)}$: the Λ yields with positive (negative) beam helicity
- R: relative luminosity measured by the VPD
- α: decay parameter of Λ, $\alpha_\Lambda = 0.732$, $\alpha_\Lambda = -\alpha_{\overline{\Lambda}}$
- P_{beam}: the beam polarization

Transverse spin transfer D_{TT} in $p+p$ collisions

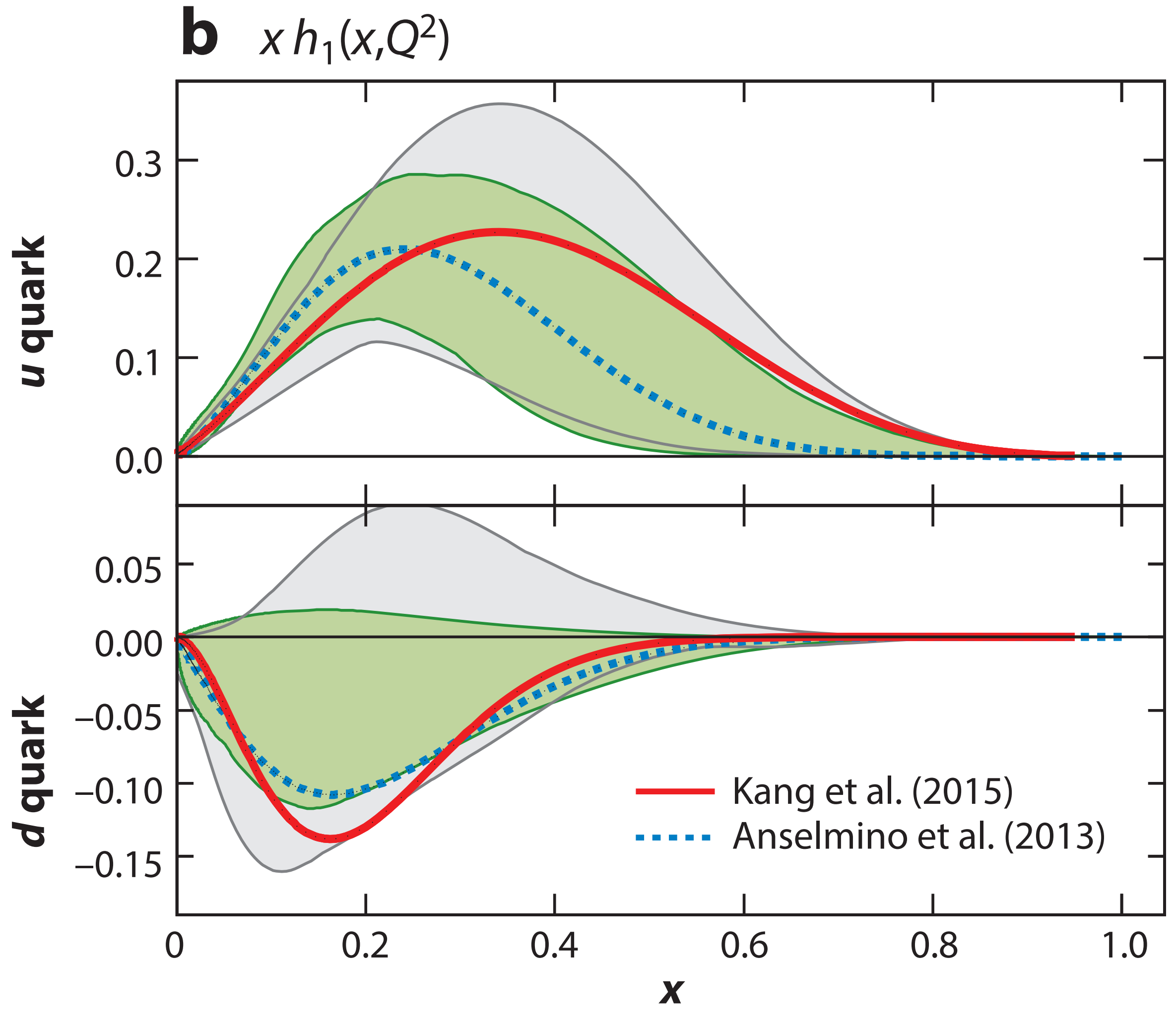
- Transversity: least known leading twist parton distribution functions



$\delta f(x) = f^{\uparrow}(x) - f^{\downarrow}(x)$

Poor constraints on u and d

Little info about s quark



- D_{TT} can probe transversity

$$D_{TT}^{\Lambda} \equiv \frac{d\sigma^{p^{\uparrow}p\to\Lambda^{\uparrow}X} - d\sigma^{p^{\uparrow}p\to\Lambda^{\downarrow}X}}{d\sigma^{p^{\uparrow}p\to\Lambda^{\uparrow}X} + d\sigma^{p^{\uparrow}p\to\Lambda^{\downarrow}X}} = \frac{d\Delta_T\sigma}{d\sigma}$$

$$d\Delta_T\sigma \propto \delta f_a(x_a) f_b(x_b) \delta\sigma_T^{ab\to cd} \Delta_T D_c^{\Lambda}(z)$$

transversity — pQCD calculable — transversely polarized FFs

New D_{TT} measurements at STAR

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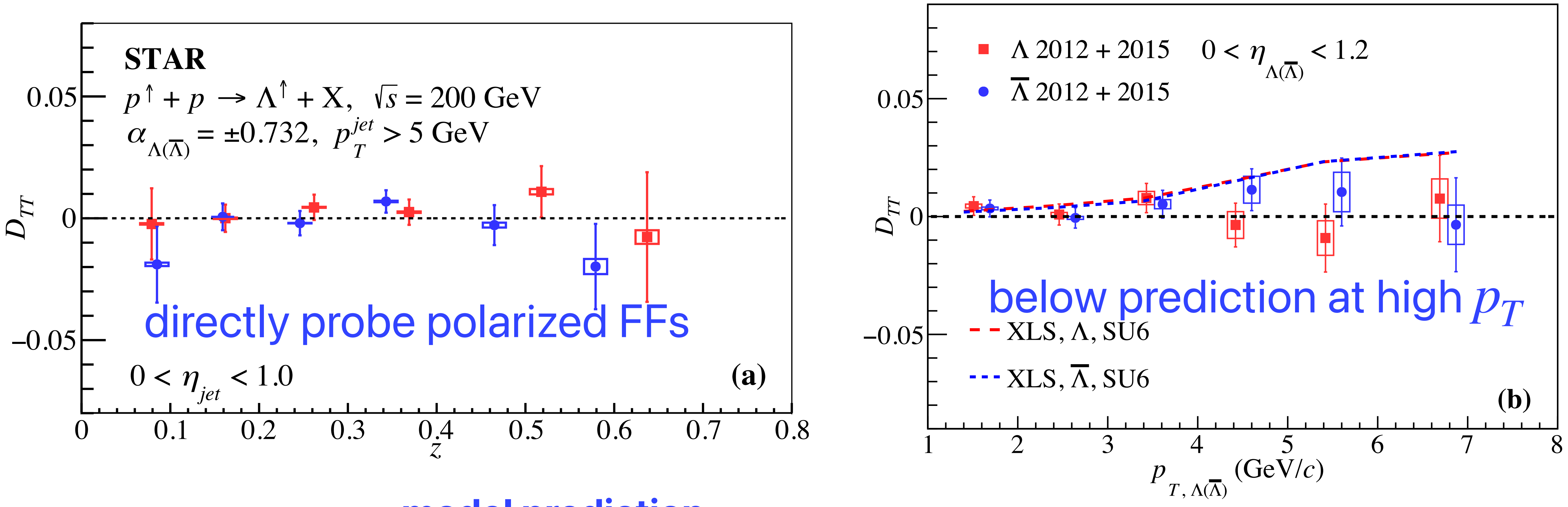

model prediction

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