Longitudinal double spin asymmetry A_{LL} of $\pi^{\pm}$-tagged jet, Λ, $\overline{\Lambda}$, and K_S^0 in polarized p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ at STAR

Yi Yu (于毅), for the STAR Collaboration

Shandong University (山东大学)

2023-09-26

Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

SHANDONG UNIVERSITY

NSFC National Natural Science Foundation of China

Outline

- $\pi^{\pm}$-tagged jet A_{LL}
  - Focus on the gluon helicity distribution
- Λ, $\overline{\Lambda}$ and K_S^0 A_{LL}
  - Provide constraints on the strange quark helicity distributions
- Summary & outlook

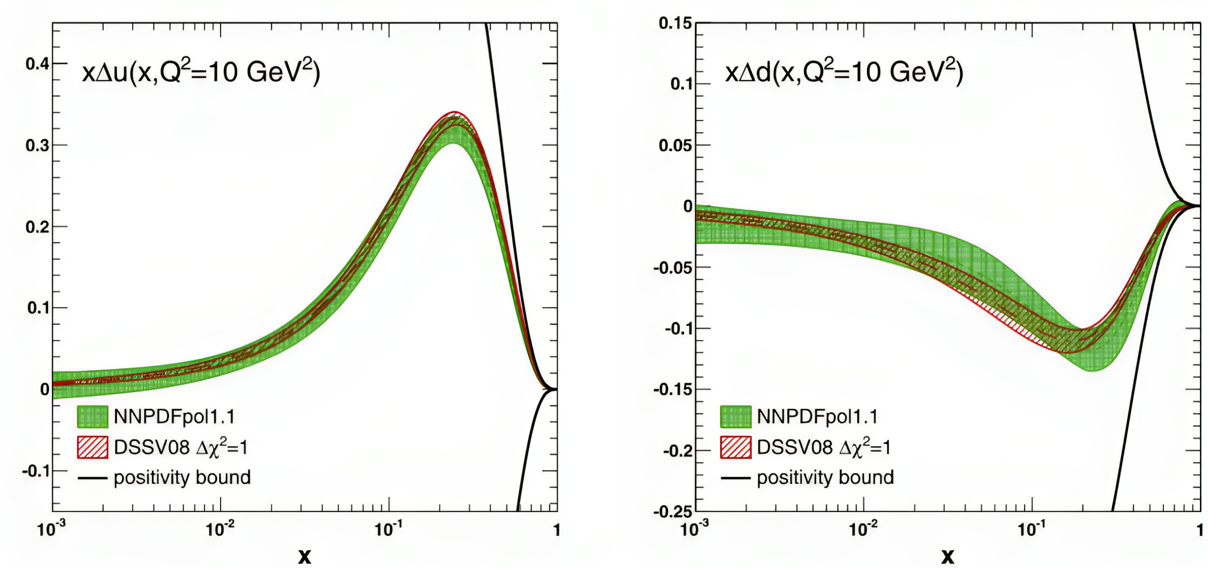
Constrain the gluon helicity and its sign

$$\vec{p}+\vec{p} \rightarrow \textbf{jet} + \pi^{\pm} + X$$

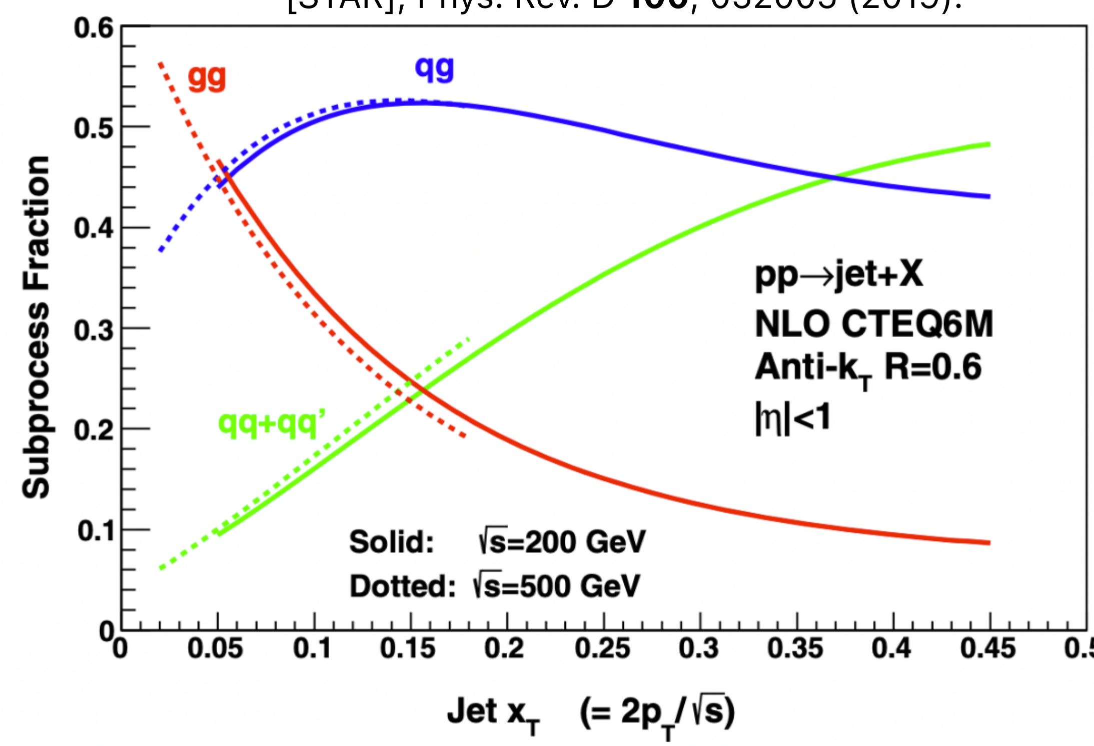
$$A_{LL}^{\pi^{\pm}} = \frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}} = \frac{\Sigma \Delta f_i \otimes \Delta f_j \otimes \Delta\hat{\sigma} \otimes D_k^{\pi^{\pm}}}{\Sigma f_i \otimes f_j \otimes \hat{\sigma} \otimes D_k^{\pi^{\pm}}}$$

- $\Delta u > 0$ 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 in p+p $\sqrt{s} = 200\,\mathrm{GeV}$
- $\Delta g > 0 \rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
- $\Delta g < 0 \rightarrow A_{LL}^{\pi^+} < A_{LL}^{\pi^-}$

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

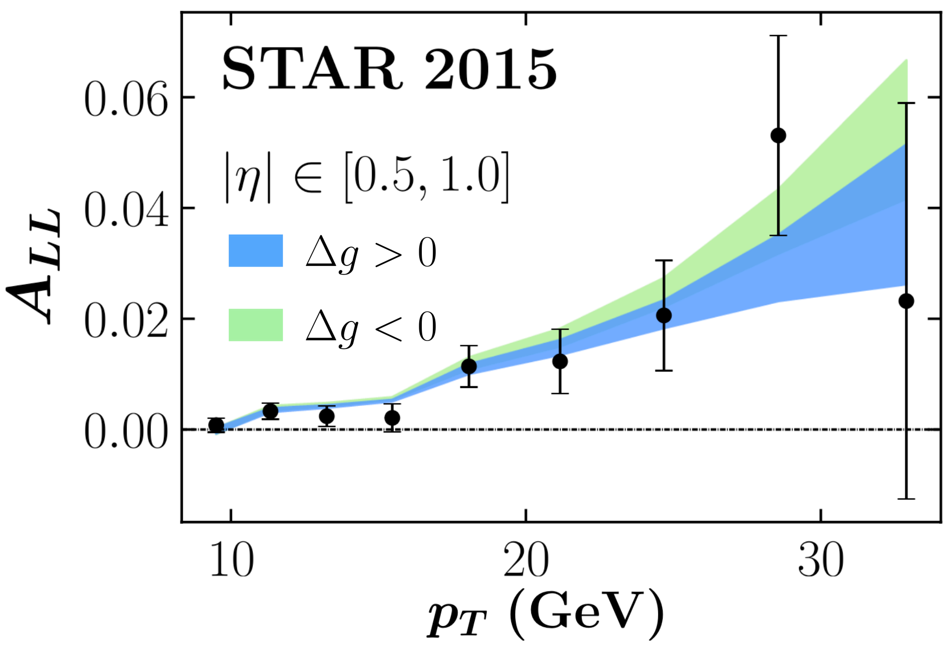


[STAR], Phys. Rev. D **100**, 052005 (2019).



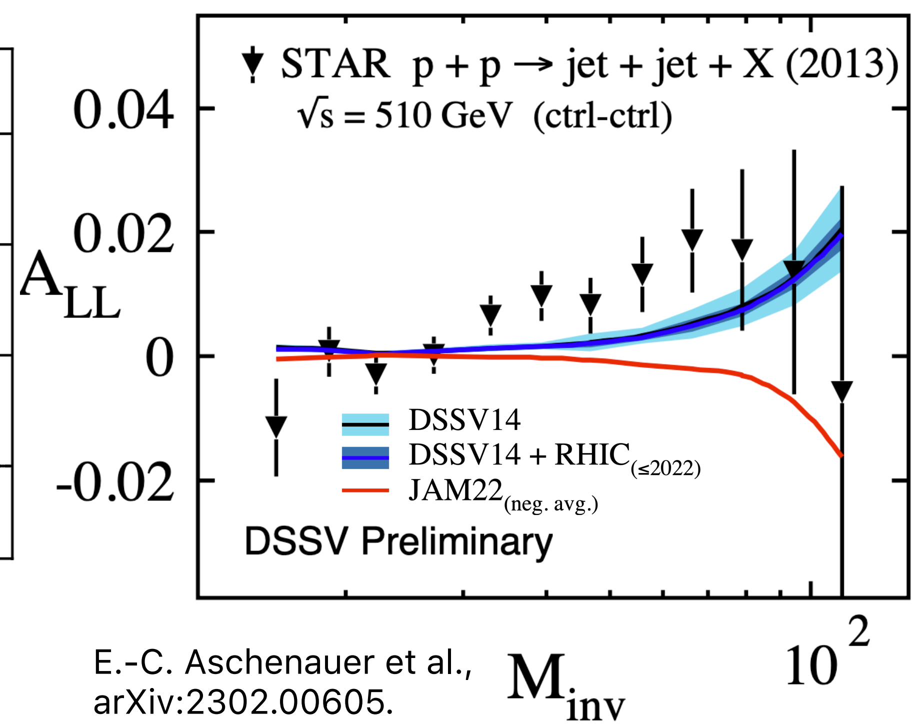
Constrain the gluon helicity and its sign

Inclusive jet A_{LL}

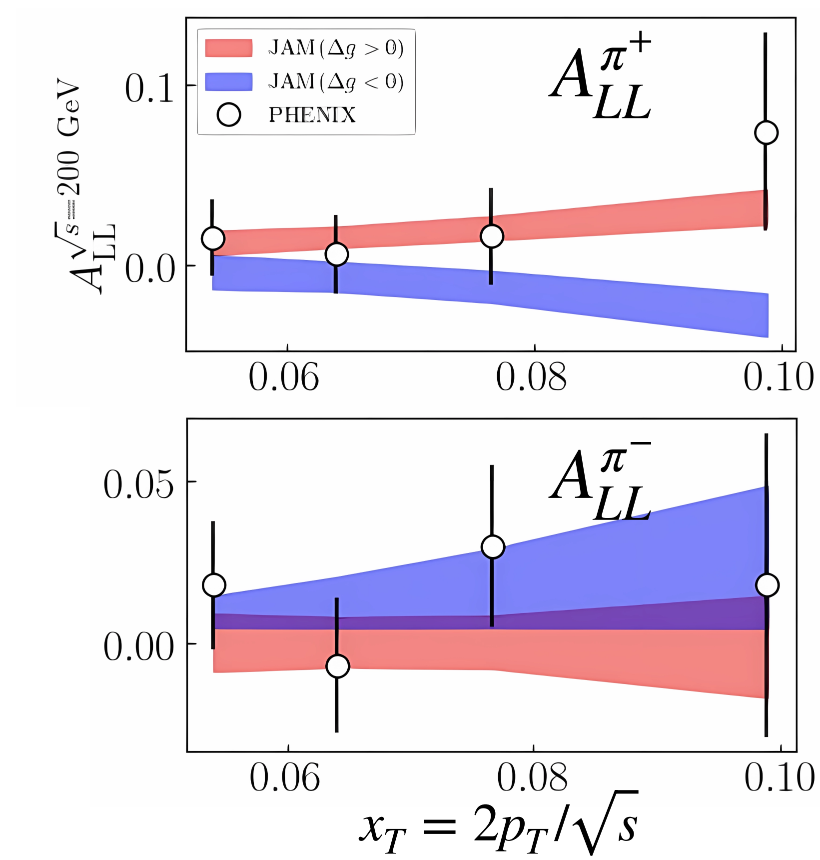


[JAM], Phys. Rev. D **105**, 074022 (2022).

di-jet A_{LL}



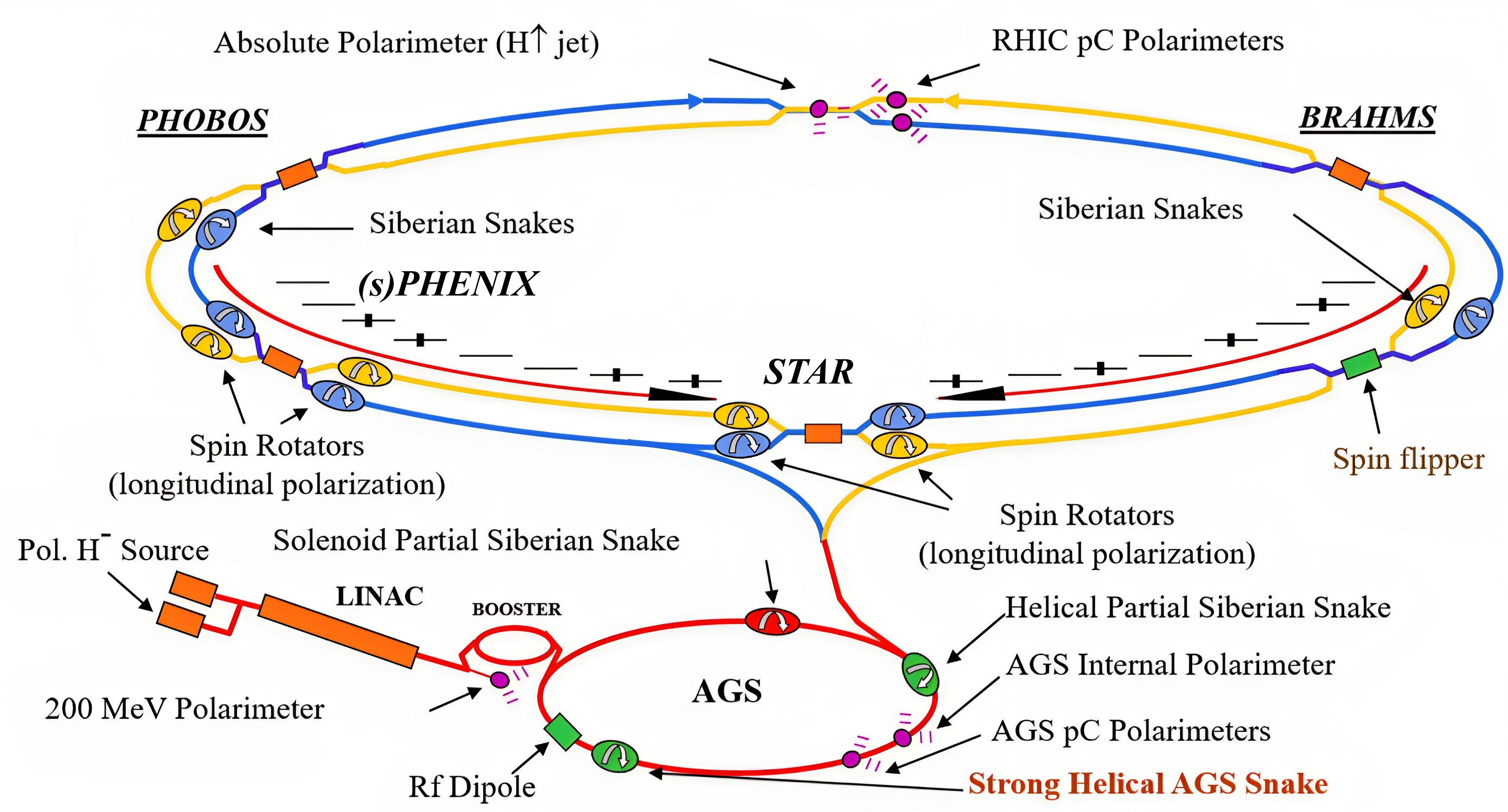
E.-C. Aschenauer et al., arXiv:2302.00605.



[PHENIX], Phys. Rev. D **91**, 032001 (2015).

- Inclusive jet A_{LL} is insensitive to the sign of the Δg
- Di-jet A_{LL} disfavors negative Δg solution
- $\pi^{\pm}$-tagged jet A_{LL} provides an additional way to constrain the sign of Δg

Relativistic Heavy Ion Collider



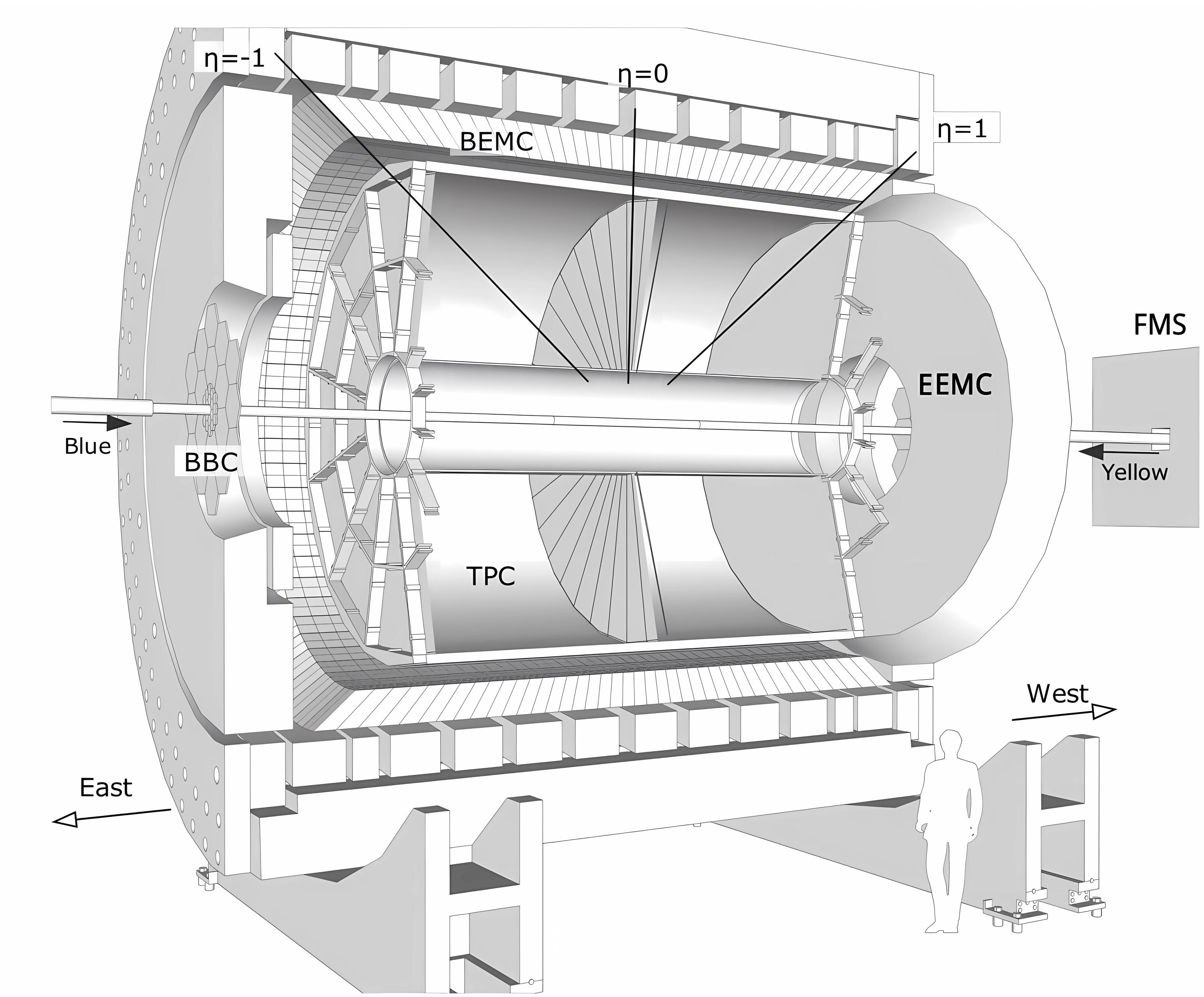
- The first and only polarized p+p collider in the world
- Collides both longitudinally and transversely polarized proton beams at $\sqrt{s} = 200\,\mathrm{GeV}$ and $500/510\,\mathrm{GeV}$

Longitudinally polarized pp collision samples taken at STAR

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

used in this analysis

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 photon, 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

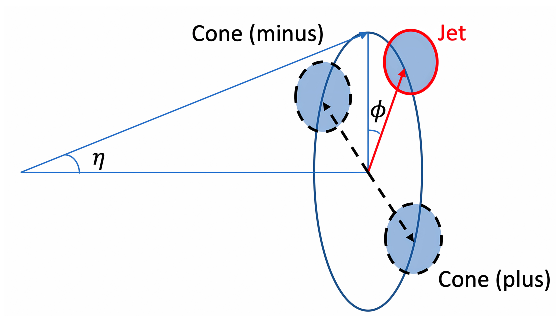
Longitudinal double spin asymmetry

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

- $+(-)$ denotes the beam helicity
- N_{++} etc are the jet yields for different beam helicity configurations
- P_B and P_Y are beam polarizations
- $R_3 = \dfrac{L_{++} + L_{--}}{L_{+-} + L_{-+}}$ is the relative luminosity calculated with the VPD

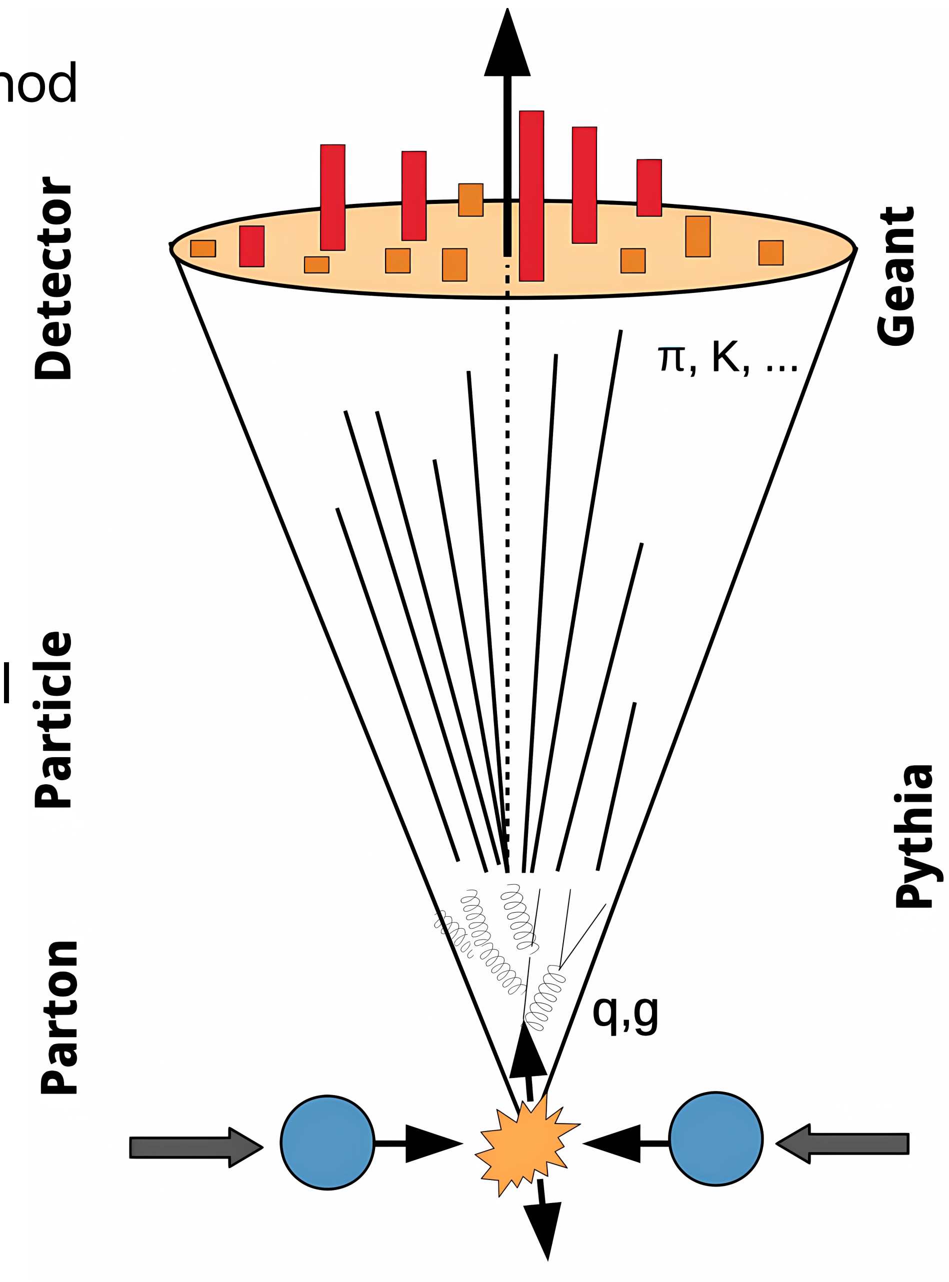
Jet reconstruction

- Jet reconstruction (TPC tracks + energy deposits in EMC)
  - Anti-k_T algorithm, with $R = 0.6$
  - Jet-by-jet underlying event correction with off-axis cone method



[ALICE], PRD 91 (2015), 112012

  - Simulation: PYTHIA6 + GEANT3 + Zero-bias events
    - Perugia 2012 with additional tuning to STAR data
    - Jet was reconstructed at parton, particle and detector level
  - Jet p_T was corrected back to particle level



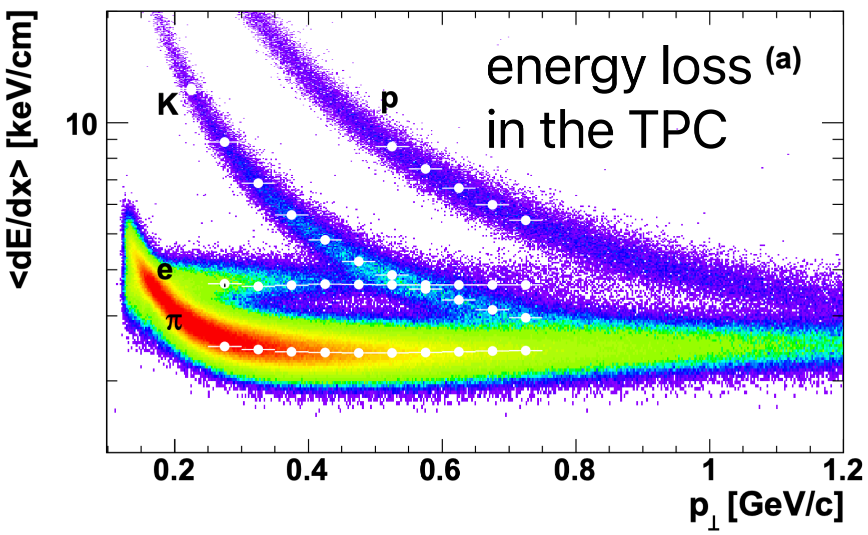
- Jets tagged with high z $\pi^{\pm}$ are required

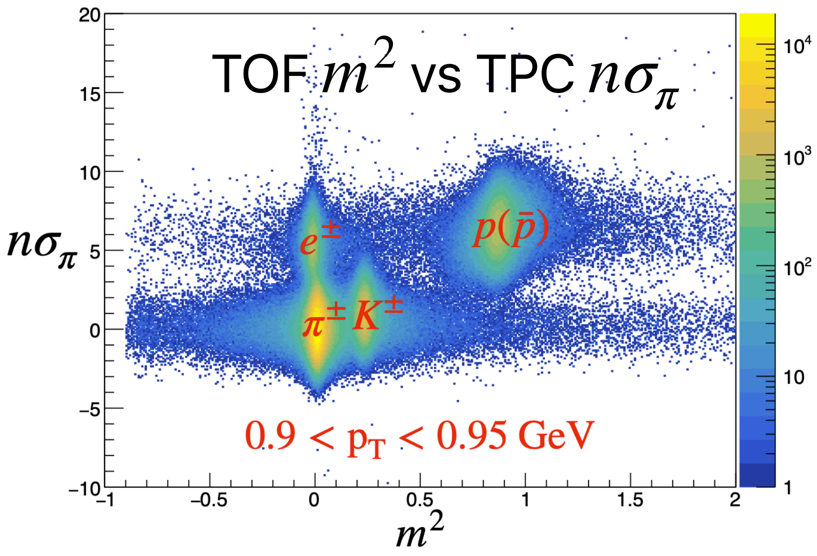
$$z \equiv \frac{\vec{p}_\pi \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2}$$

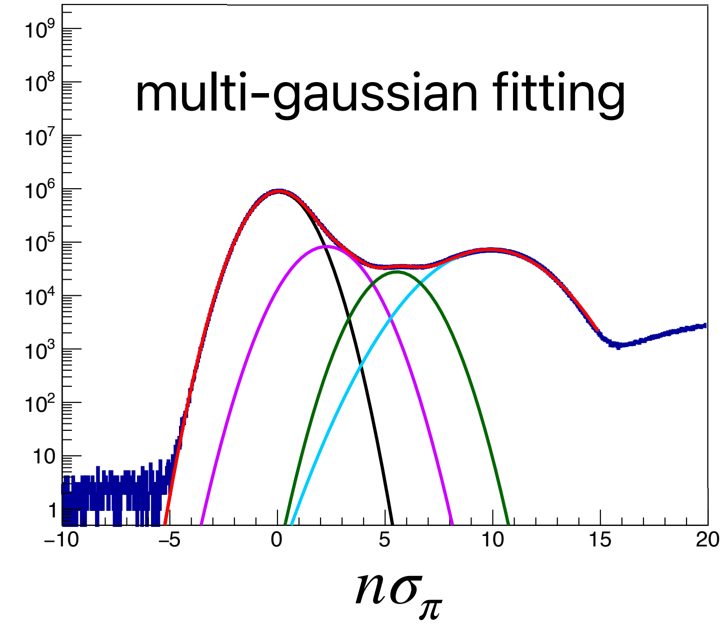
$\pi^{\pm}$ PID

- Energy loss inside the TPC + the flight time recorded by TOF

[STAR], Phys. Rev. C **79**, 034909 (2009)



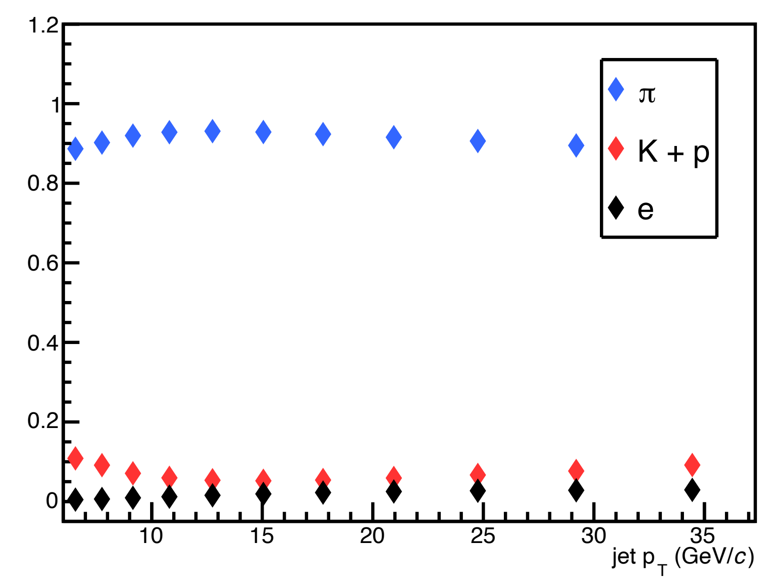




- Particle contaminations fraction (f)
  - Determined with multi-gaussian fitting and PID info from TOF
  - 3 particle-rich regions are used ($\pi^\pm$, $K^\pm + p(\bar{p})$, $e^\pm$)
  - $A_{LL}^{raw} = \sum_{\pi,K+p,e} f_i A_{LL}^i$

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

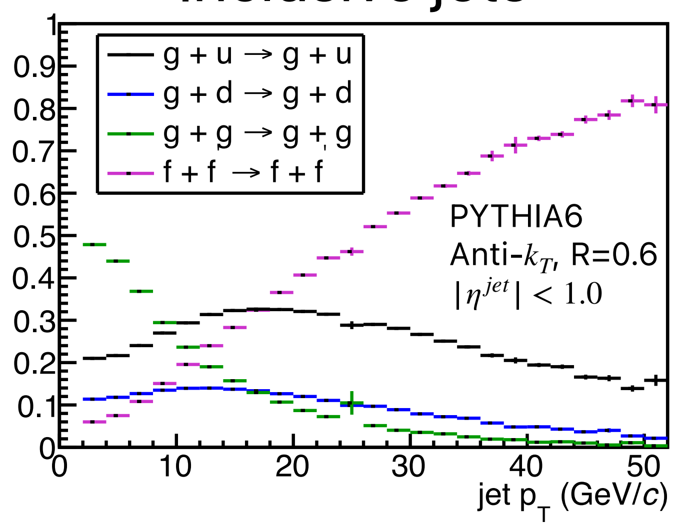
particle fraction in π-rich region



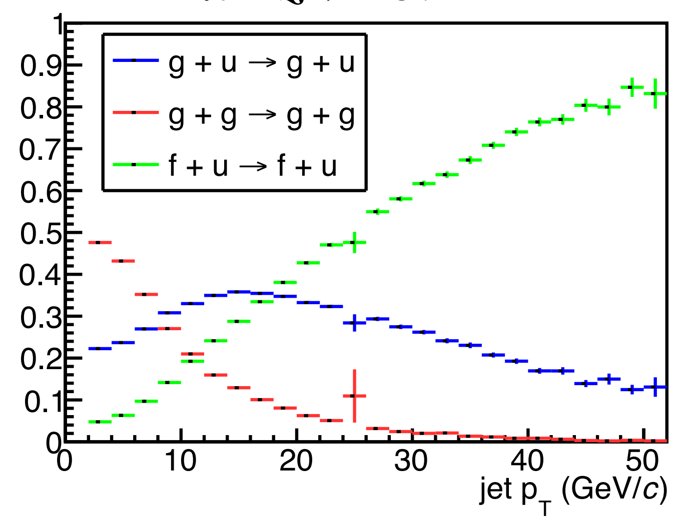
Impact of $\pi^{\pm}\ z > 0.2$ tagging

subprocess fraction from simulation based on PYTHIA6

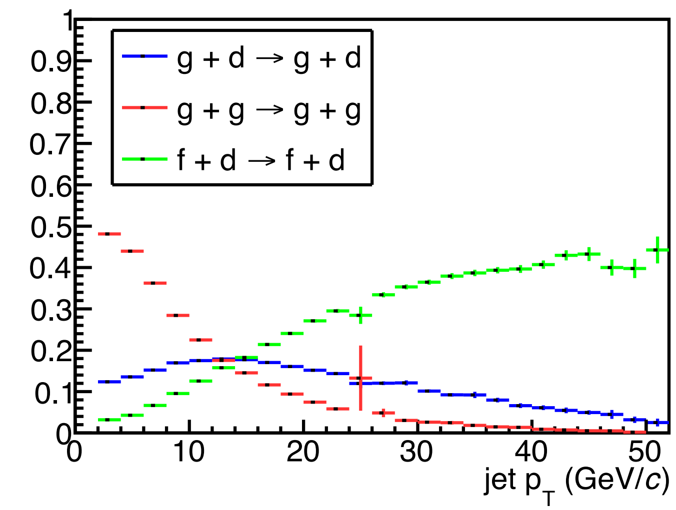
Inclusive jets



$\pi^{+}\ z > 0.2$

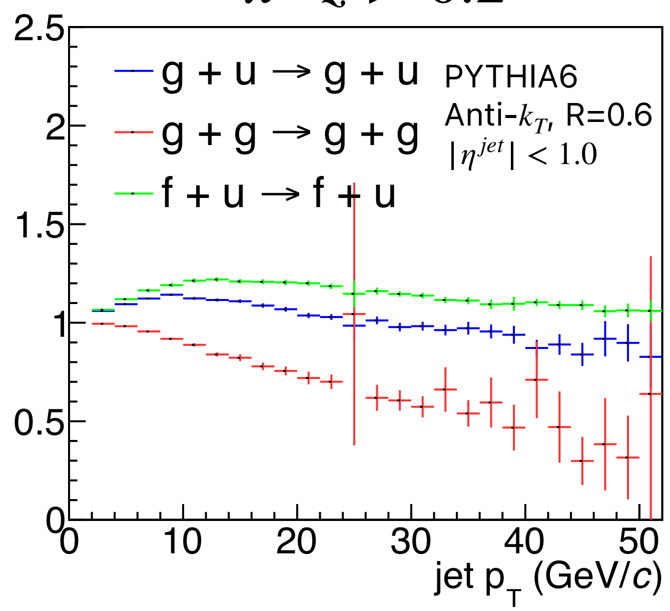


$\pi^{-}\ z > 0.2$

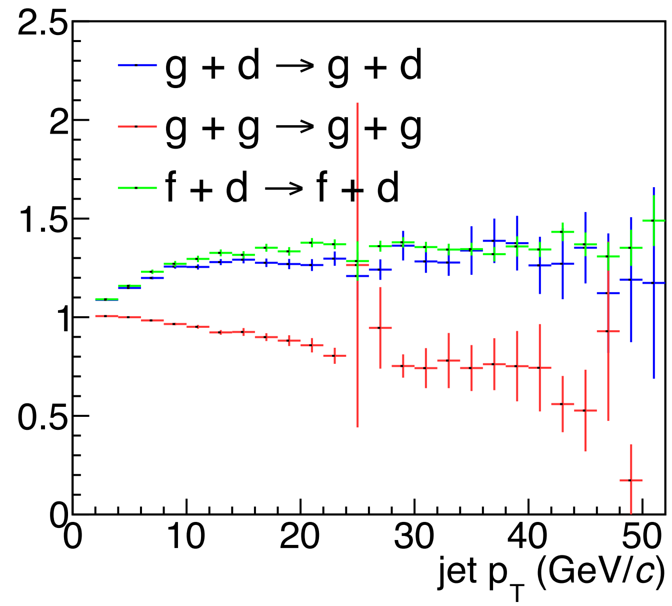


subprocess ratio to inclusive jet

$\pi^{+}\ z > 0.2$



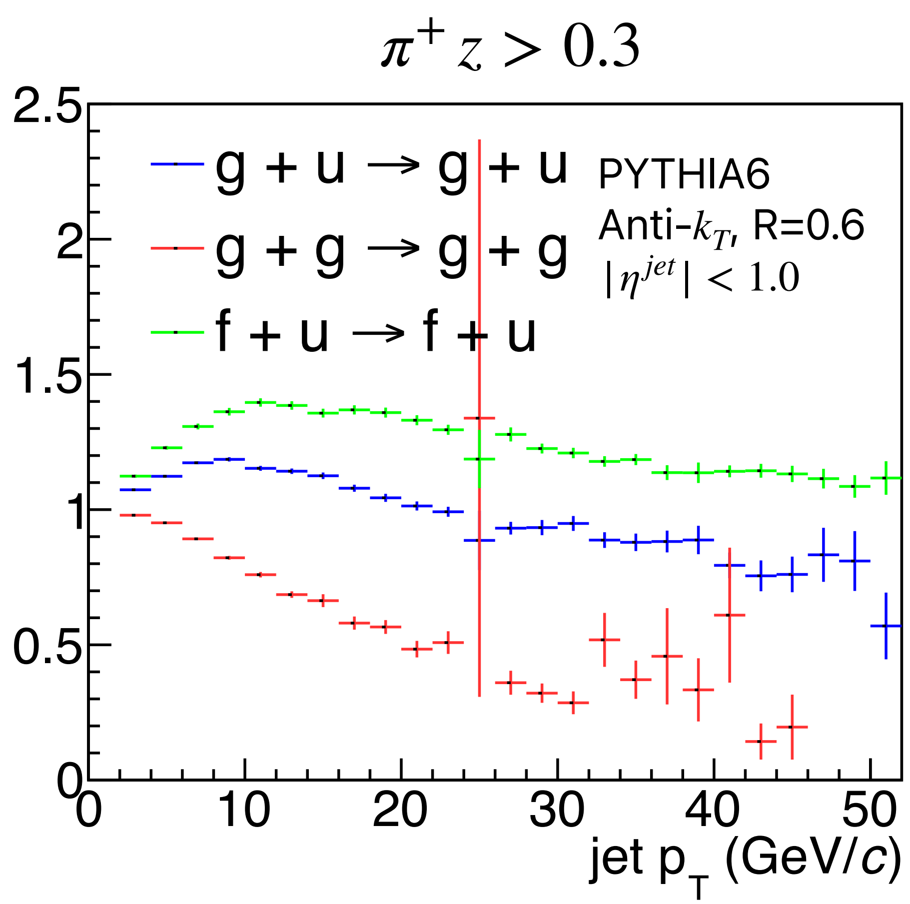
$\pi^{-}\ z > 0.2$

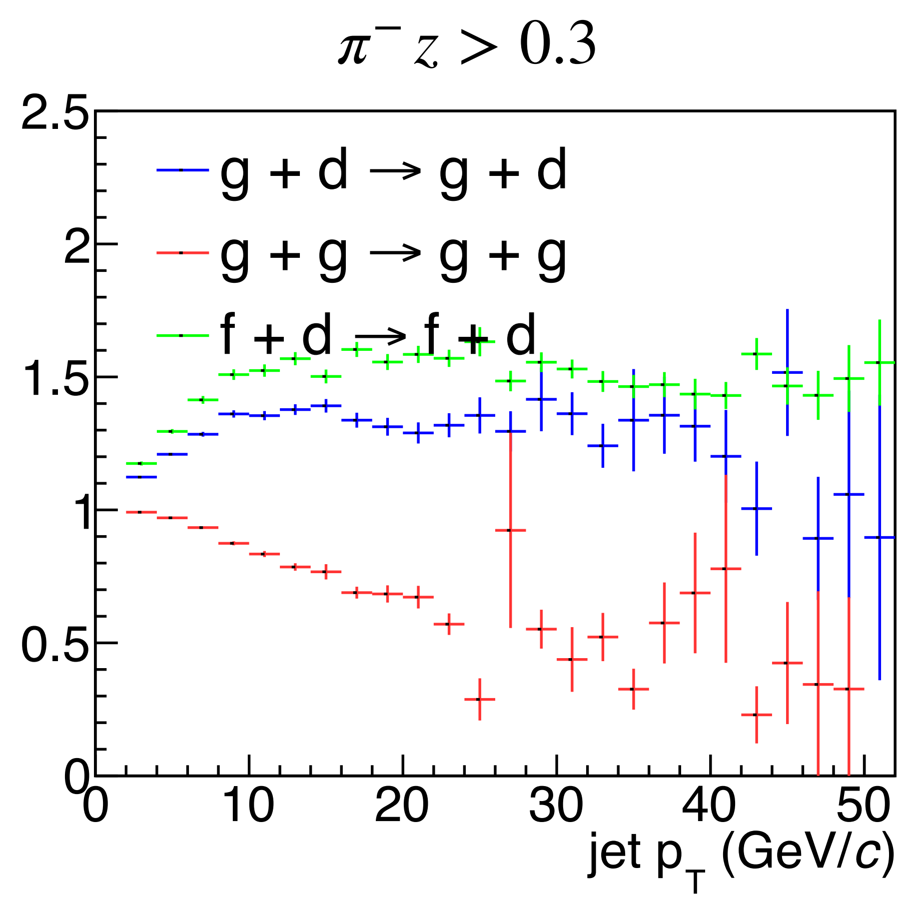


- Tagging suppresses g-g scattering
- π^{+} tagging enhances u quark related subprocess up to 20%
- π^{-} tagging enhances d quark related subprocess up to 40%

Raising z_{min} from 0.2 to 0.3

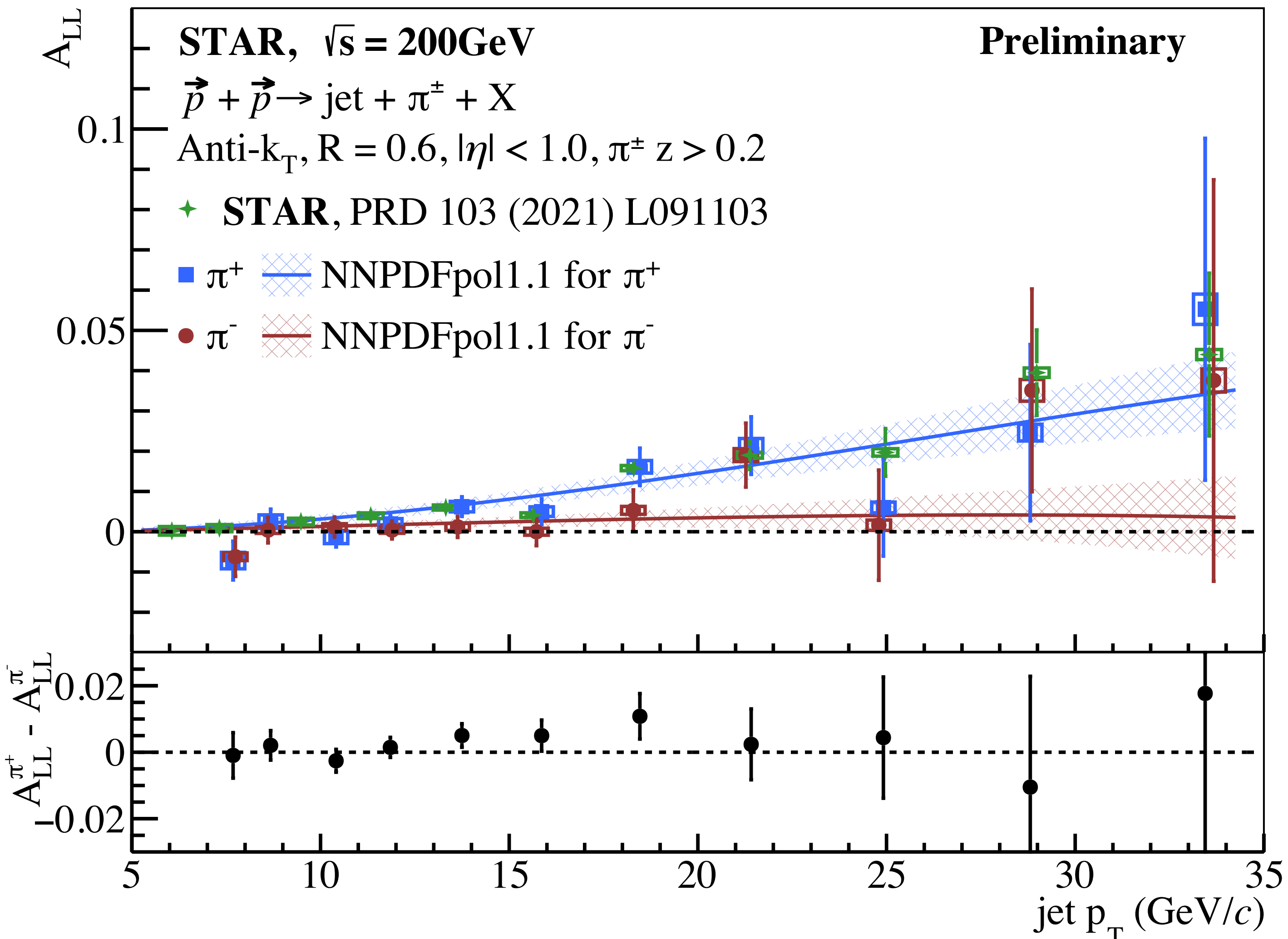
subprocess ratio to inclusive jet





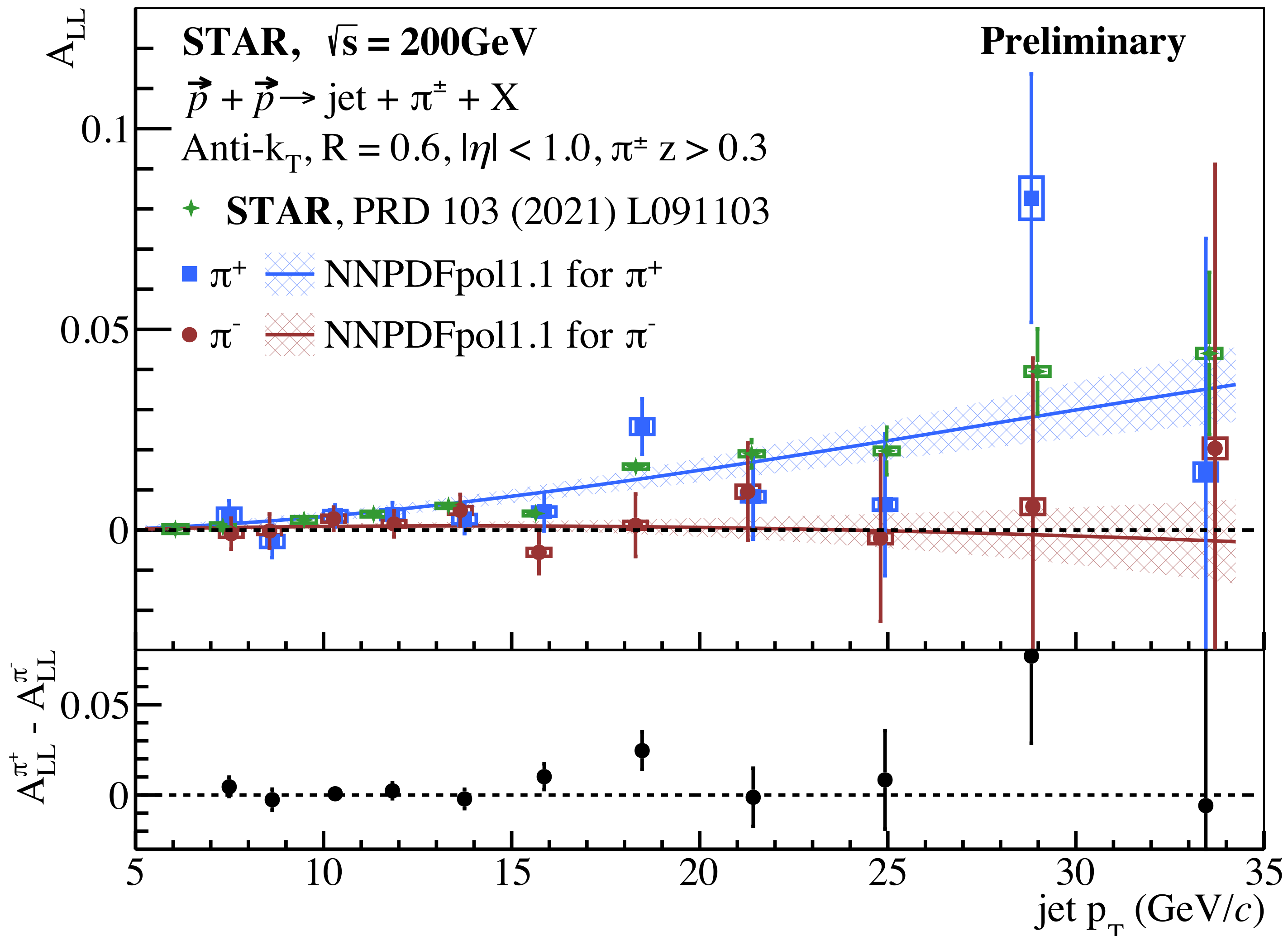
- Enhancements and suppressions are further strengthen with higher z cut
- Tagging can increase the sensitivity to the sign of Δg

$\pi^{\pm}$-tagged A_{LL} with $z > 0.2$



- Indication of $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
- NNPDFpol1.1 predicts $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$ with positive Δg
- The results are close to the predictions

$\pi^{\pm}$-tagged A_{LL} with $z > 0.3$

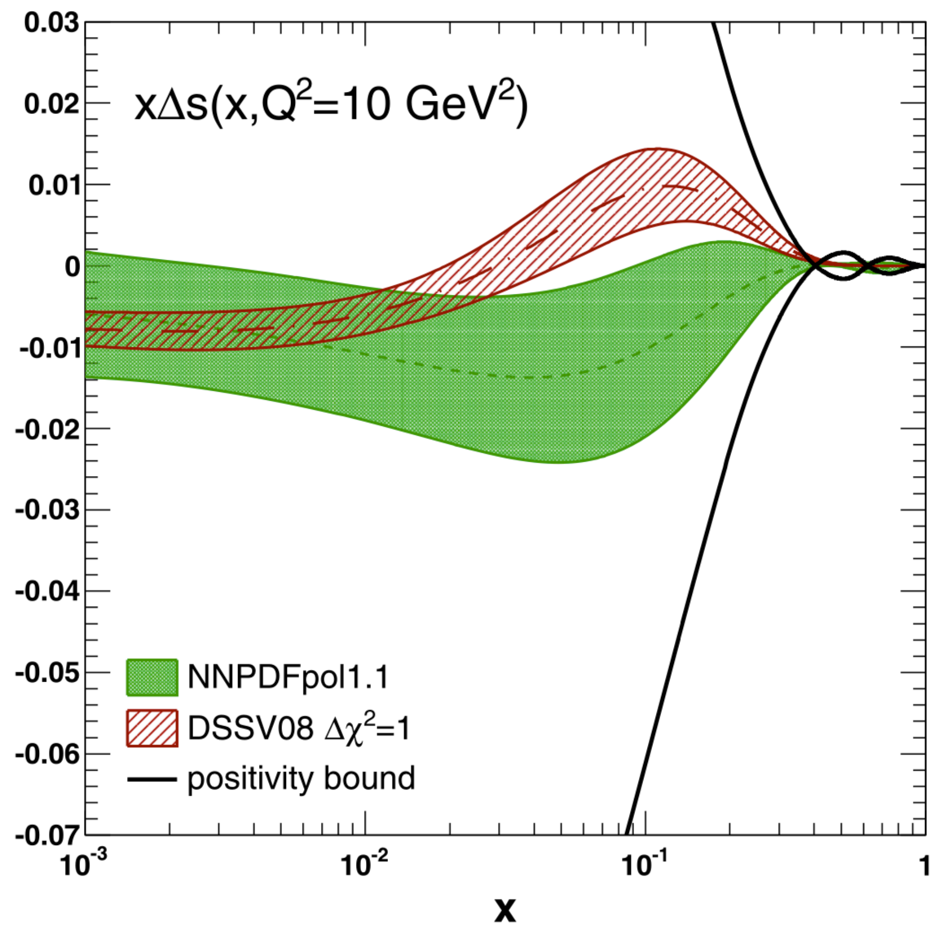


- Indication of $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
- Larger separation between predictions
- The results are close to the predictions

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

Constrain strange quark helicity distribution

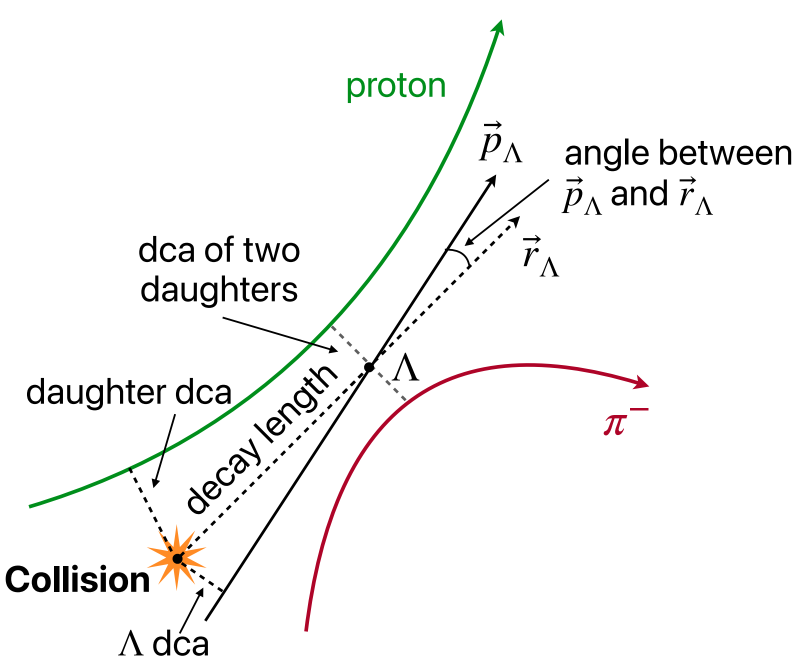
- Poor constraints on the (anti-)strange quark, $s(\bar{s})$, helicity distributions
- Valence s or $\bar{s}$ inside Λ, $\overline{\Lambda}$ and K_S^0
- A_{LL} of Λ, $\overline{\Lambda}$ and K_S^0 may shed light on the helicity distributions of s or $\bar{s}$
- Hyperon spin transfer D_{LL} can also provide constraints on helicity distribution of the s or $\bar{s}$



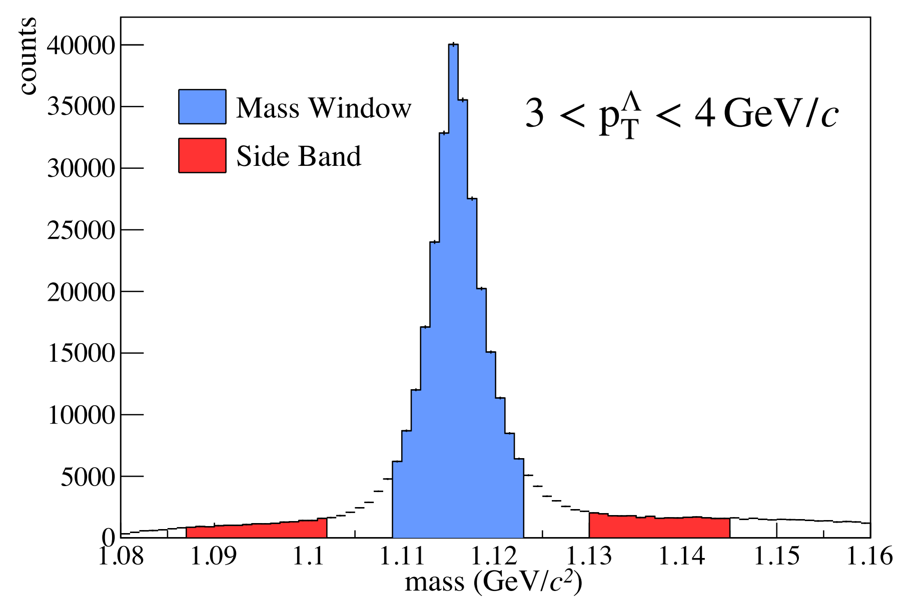
[NNPDF], Nucl. Phys. B **887**, 276 (2014).

Λ hyperon and K_S^0 selection

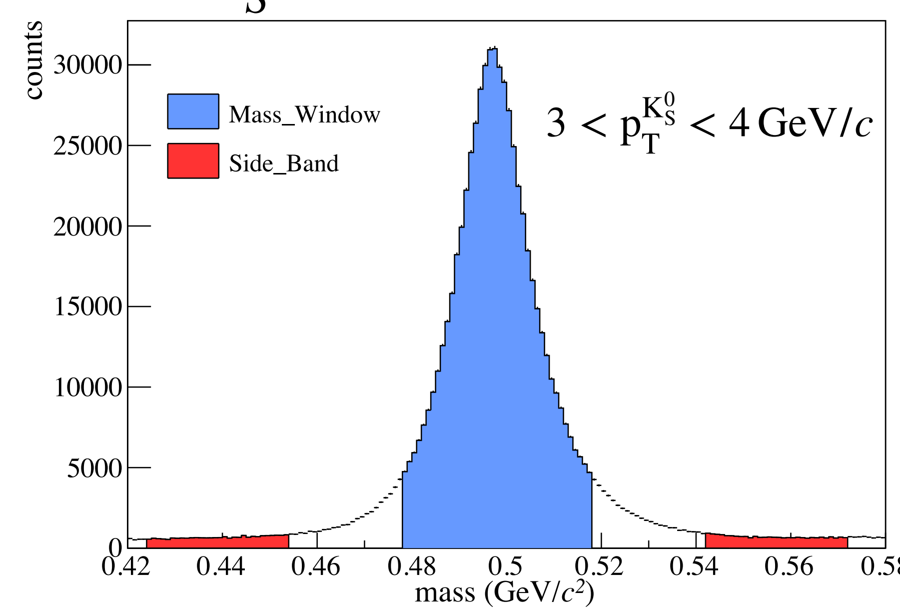
- $\Lambda(\overline{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(\pi^+), K_S^0 \rightarrow \pi^+ + \pi^-$
- Proton and $\pi^\pm$ tracks were measured with the TPC
- Sets of topological cuts were applied to reduce background
- Residual background fraction r was estimated with side-band method



Λ mass distribution



K_S^0 mass distribution

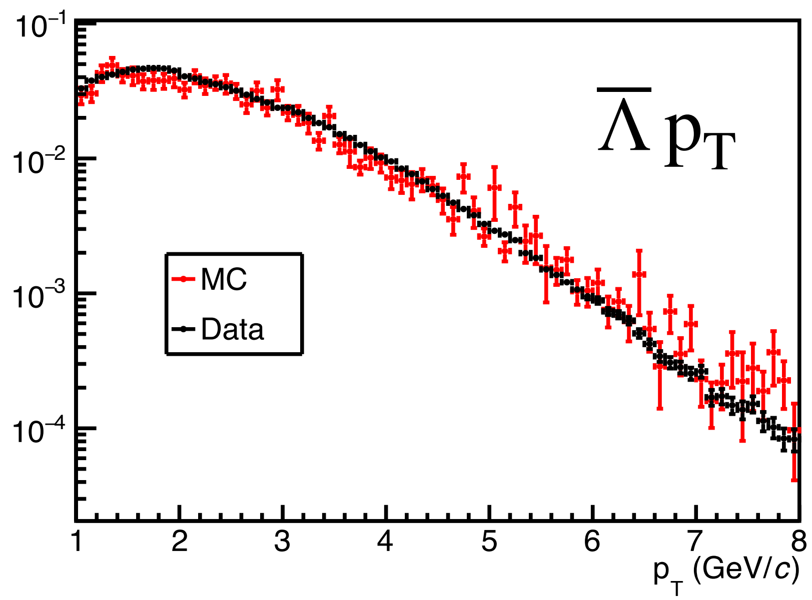


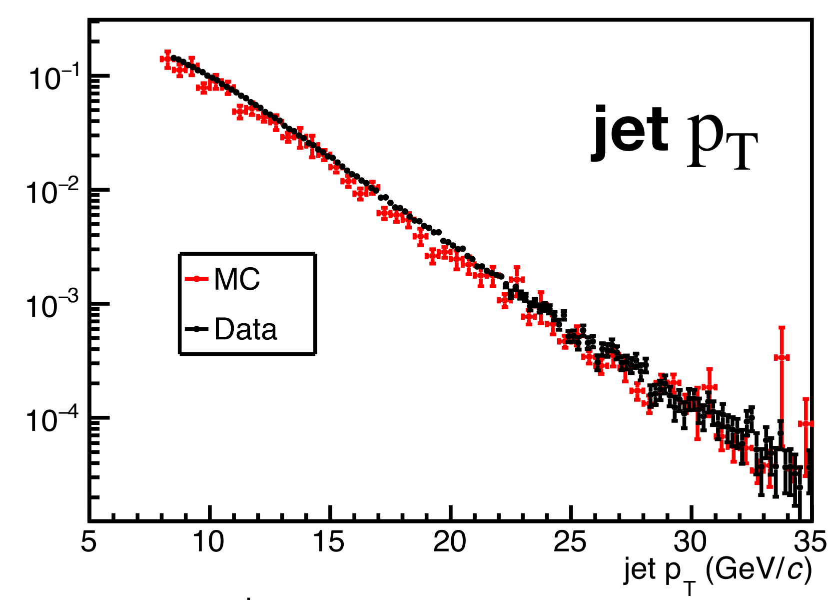
Background subtraction →

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

Λ, $\overline{\Lambda}$ and K_S^0 as inputs in jet reconstruction

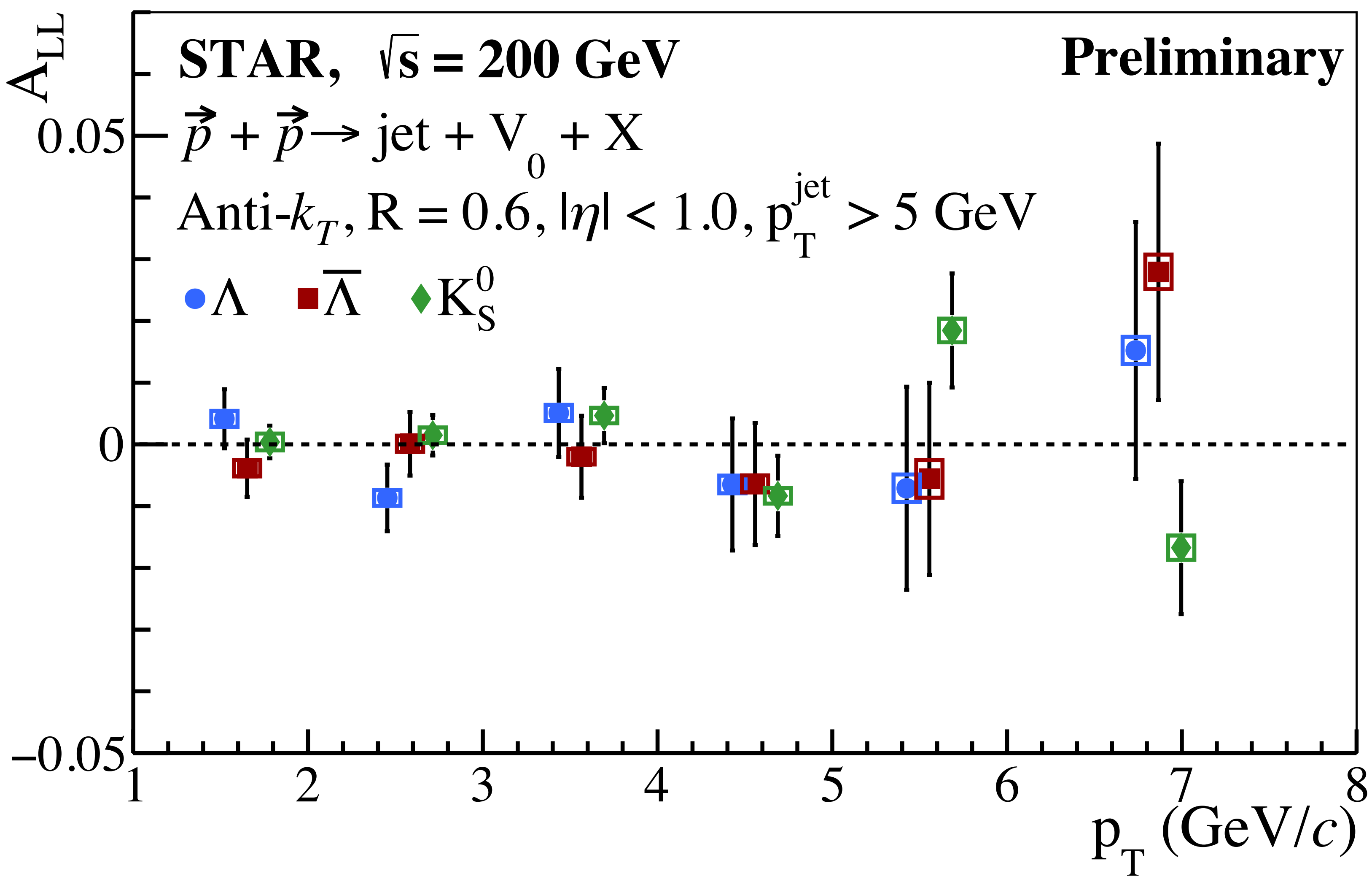
- Jets are reconstructed with anti-k_T algorithm ($R = 0.6$)
- Inputs for jets reconstruction: TPC tracks, EMC energy deposits, Λ, $\overline{\Lambda}$, and K_S^0
- Double counting correction
  - Daughters removed from the jet reconstruction inputs list
  - EMC energy deposits matched to anti-proton were removed
- Jet-by-jet underlying event correction with off-axis cone method [ALICE], PRD 91 (2015), 112012
- Jets $\mathrm{p_T}$ and particle z are corrected back to particle level $z \equiv \dfrac{\vec{p}_\Lambda \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|^2}$





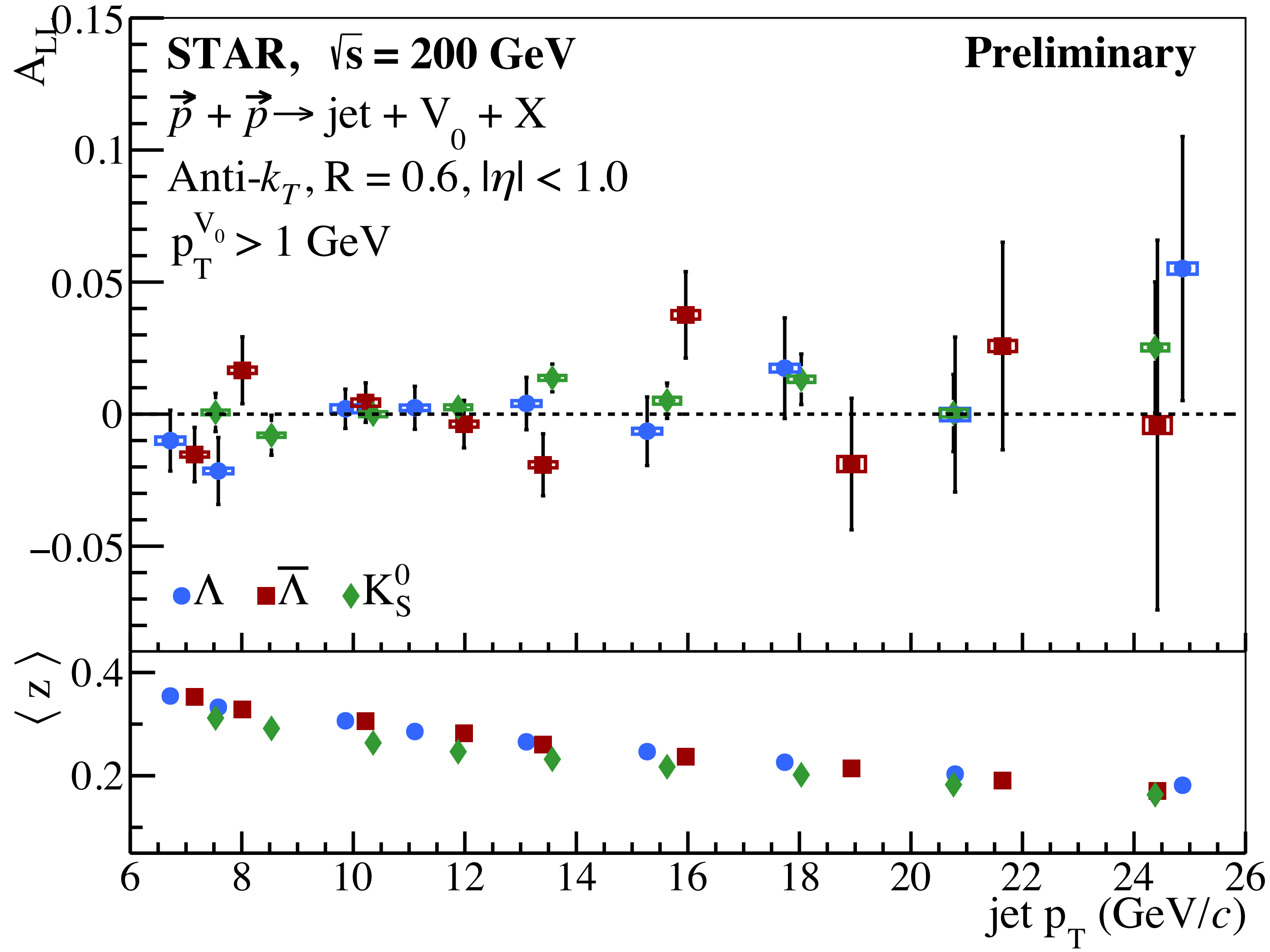
Same simulation samples used in $A_{LL}^{\pi^\pm}$ measurement

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



- First measurement A_{LL} vs $\mathrm{p_T}$ in polarized p+p collisions
- The results are independent of particle $\mathrm{p_T}$
- The results are consistent with zero
- Indication of small helicity distributions of s and $\bar{s}$

jet A_{LL} with Λ, $\overline{\Lambda}$ and K_S^0 tagging



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

- A subset of inclusive jets
- No jet pt dependence.
- Results are consistent with zero
- Indication of small helicity distribution of s and $\bar{s}$

Λ hyperon spin transfer D_{LL}

See talk of Qinghua Xu at Sep 26 TMDs session

- s quark is expected to carry a large fraction of Λ spin
  - Λ polarization can be measured via its weak decay

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

α : weak decay parameter of Λ

P_Λ: the polarization of Λ

- Longitudinal spin transfer D_{LL} in p+p collisions

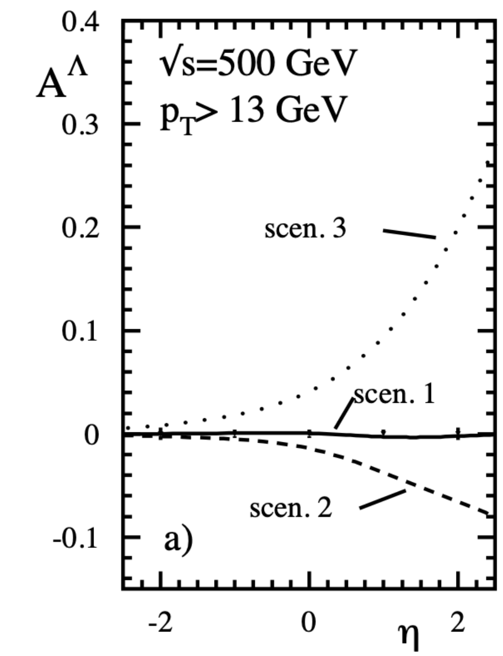
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^\Lambda}{d\sigma^\Lambda}$$

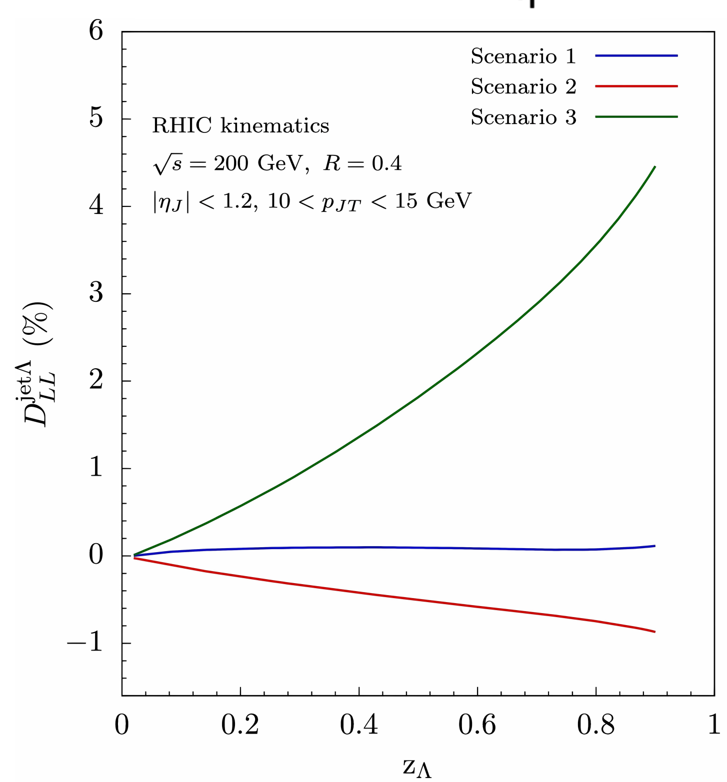
$$d\Delta\sigma^\Lambda = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^\Lambda(z)$$

PDFs — polarized partonic cross — polarized FFs

  - D_{LL} can shed light on the helicity distributions of s or $\bar{s}$
  - D_{LL} can provide constraints on polarized fragmentation functions (FFs)

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

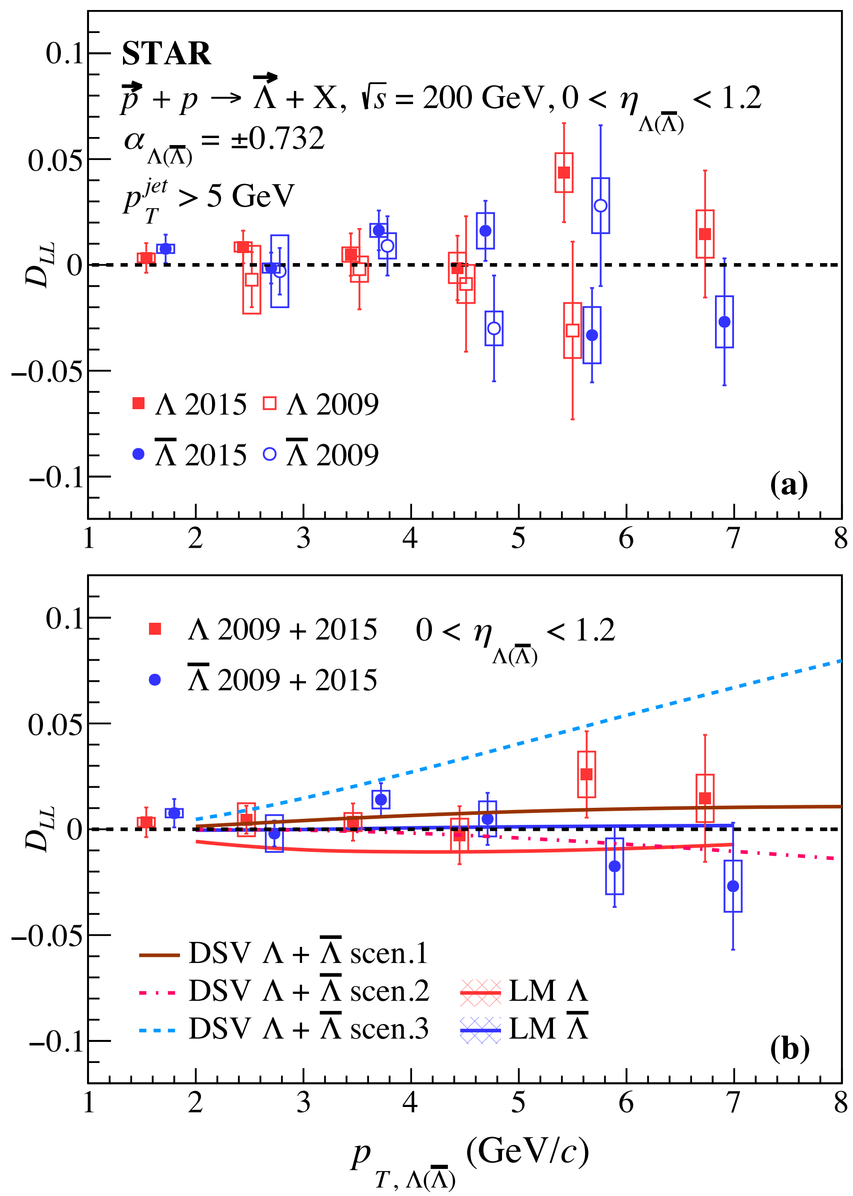


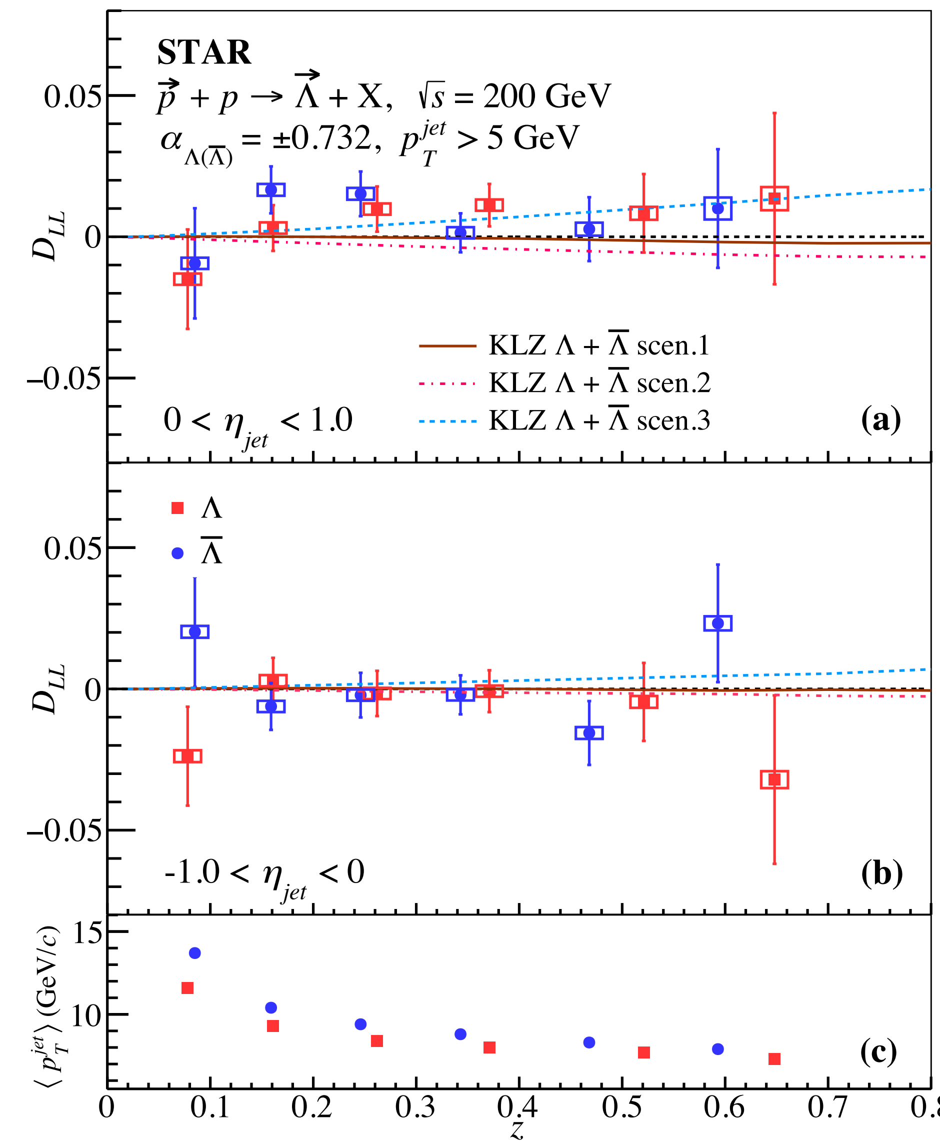


Z.-B. Kang, K. Lee, and F. Zhao, Physics Letters B **809**, 135756 (2020).

New D_{LL} measurements with 2015 data

D_{LL} vs p_T — STAR, arXiv: 2309xxx — D_{LL} vs z





- New measurements are consistent with previous measurements
- Results are in agreement with model prediction except 'DSV scen.3', which is predicted with flavor-independent polarized FFs
- Indications of small s and $\bar{s}$ helicity distributions and/or small polarized FFs

Summary & outlook

- $\pi^{\pm}$-tagged jet A_{LL}
  - $\pi^{\pm}$-tagged jet A_{LL} is measured indicating of $A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$
  - The results support positive Δg
- Λ, $\overline{\Lambda}$ and K_S^0 A_{LL} and D_{LL}
  - First measurements of A_{LL} in polarized p+p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$
  - Indication of small strange quark and anti-quark helicity distribution
  - 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 the precision and extend to lower x region