Recent STAR Cold QCD Results and Forward Upgrade

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Supported by
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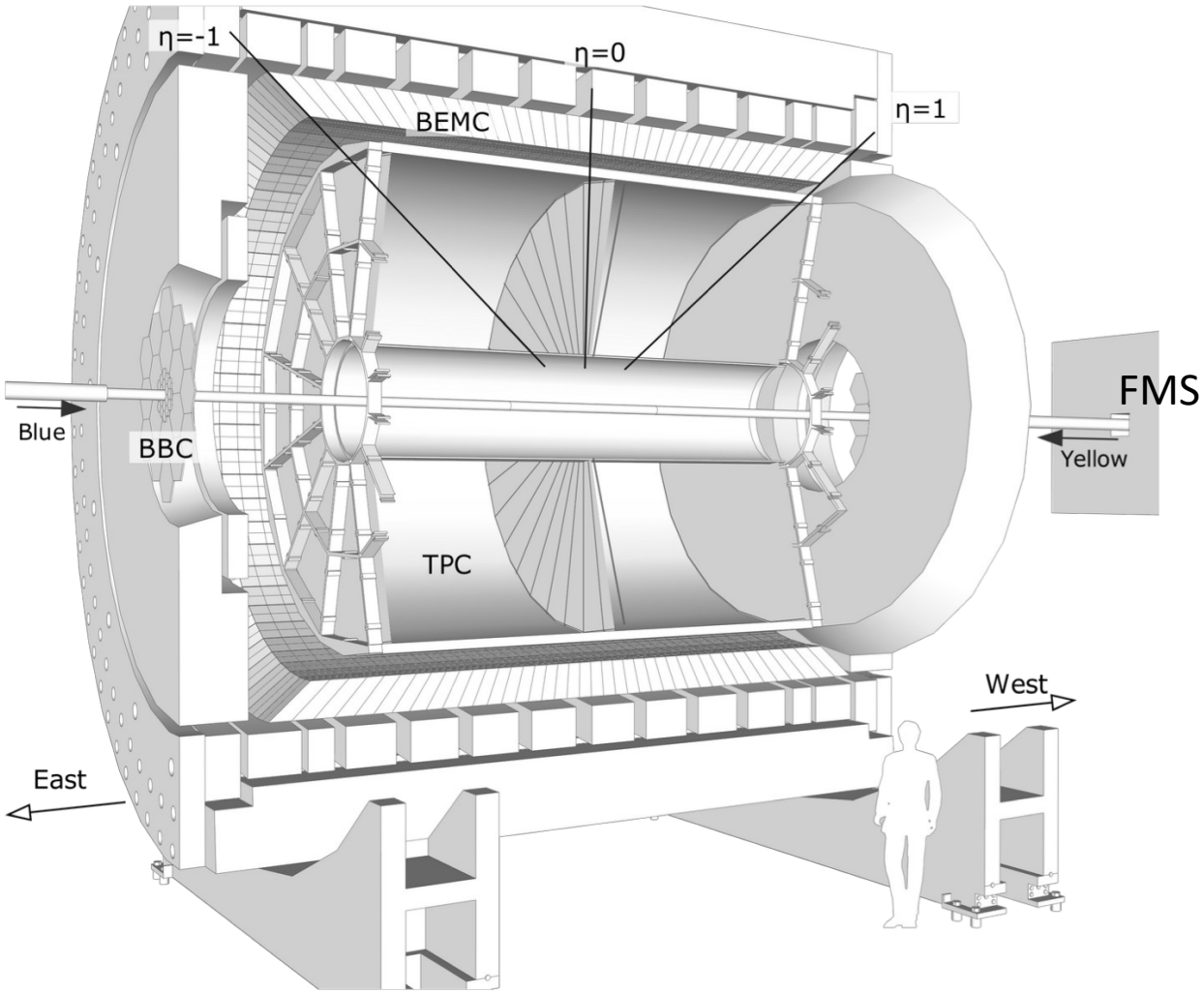
Outline:

- Results on longitudinally polarized program
- Results and Forward Upgrade on
  - Transversely polarized program
  - Unpolarized program

The STAR detector



Time Projection Chamber: $|\eta| < 1$, $\Delta\phi = 2\pi$
- Tracking, PID, vertex reconstruction

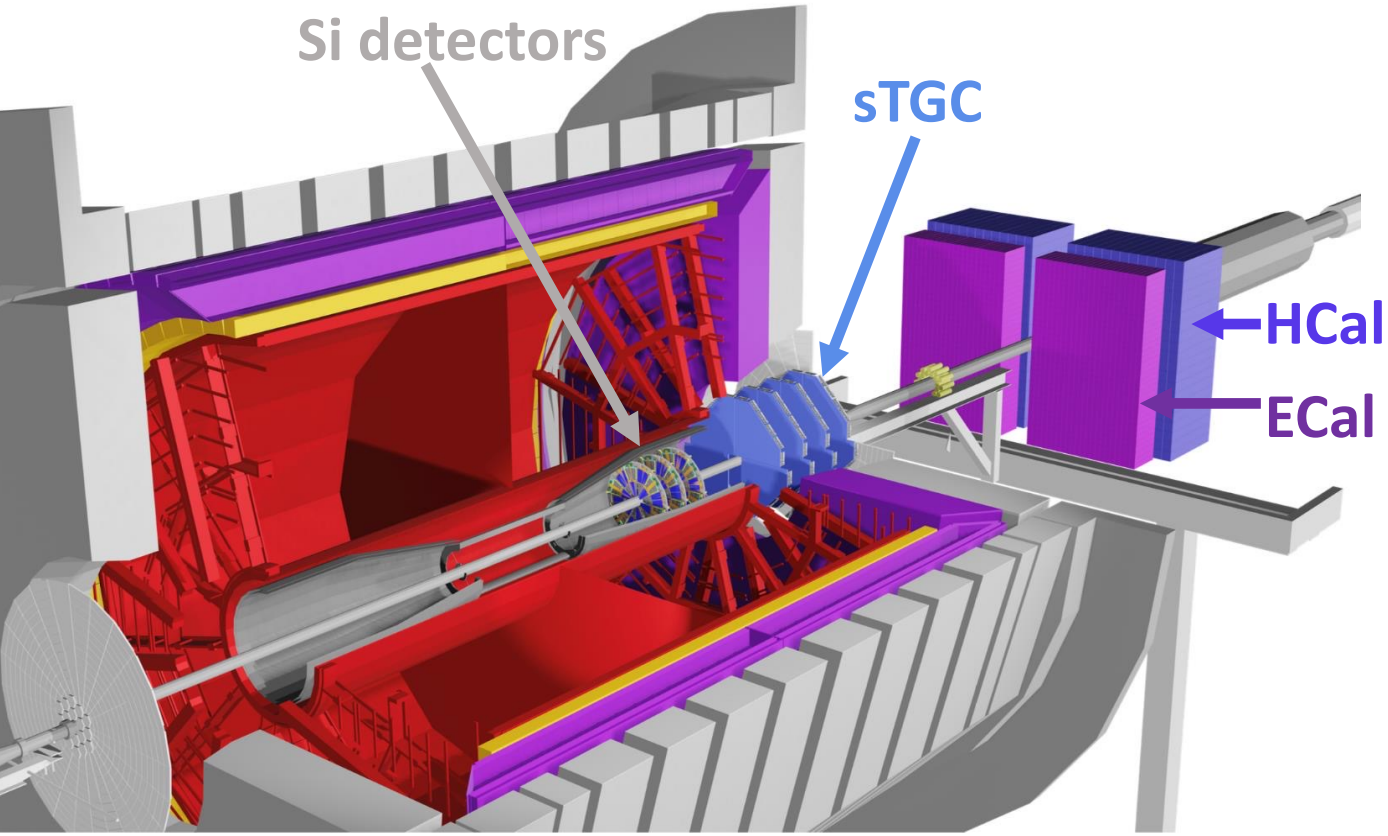
Electromagnetic Calorimeter: $-1 < \eta < 2$, $\Delta\phi = 2\pi$
- Energy measurement

Time-of-Flight: $|\eta| < 1$, $\Delta\phi = 2\pi$
- Particle identification

Forward Meson Spectrometer: $2.6 < \eta < 4$, $\Delta\phi = 2\pi$
- Energy measurement

Complemented by many ancillary subsystems:
- Beam-Beam Counter
- Vertex Position Detector
- Zero Degree Calorimeter
- Roman Pots

STAR Forward Upgrade



Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

STAR Forward Upgrade: $2.5 < \eta < 4$

Four new systems:

- Electromagnetic and Hadronic Calorimetry
- Tracking: Si detectors and small-strip Thin Gap Chambers (sTGC)

What we can measure:

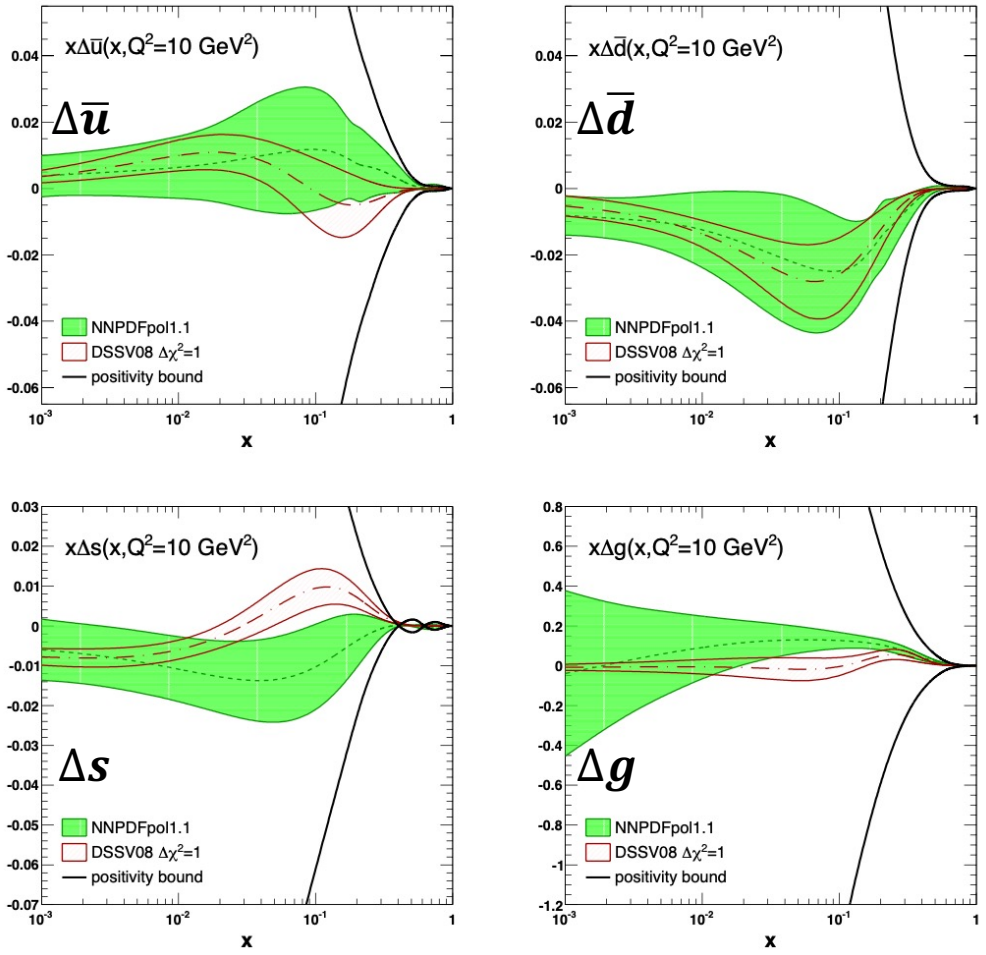
- $h^{+/-}$, $e^{+/-}$ (with good e/h discrimination)
- Photons, π^0
- Jets, h in jets
- Lambda's
- Drell-Yan and J/Ψ di-electrons
- Mid-forward and forward-forward correlations

Run period:

- STAR alone (**NOW**): 2022 → 510 GeV polarized p+p
- STAR in parallel with sPHENIX:
  - 2023 and 2025 → 200 GeV Au+Au
  - 2024 → 200 GeV polarized p+p and p+Au

Longitudinally polarized program

NNPDFpol1.1, NPB887,276 (2014)



Longitudinally polarized p+p → $\Delta f(x, Q^2)$

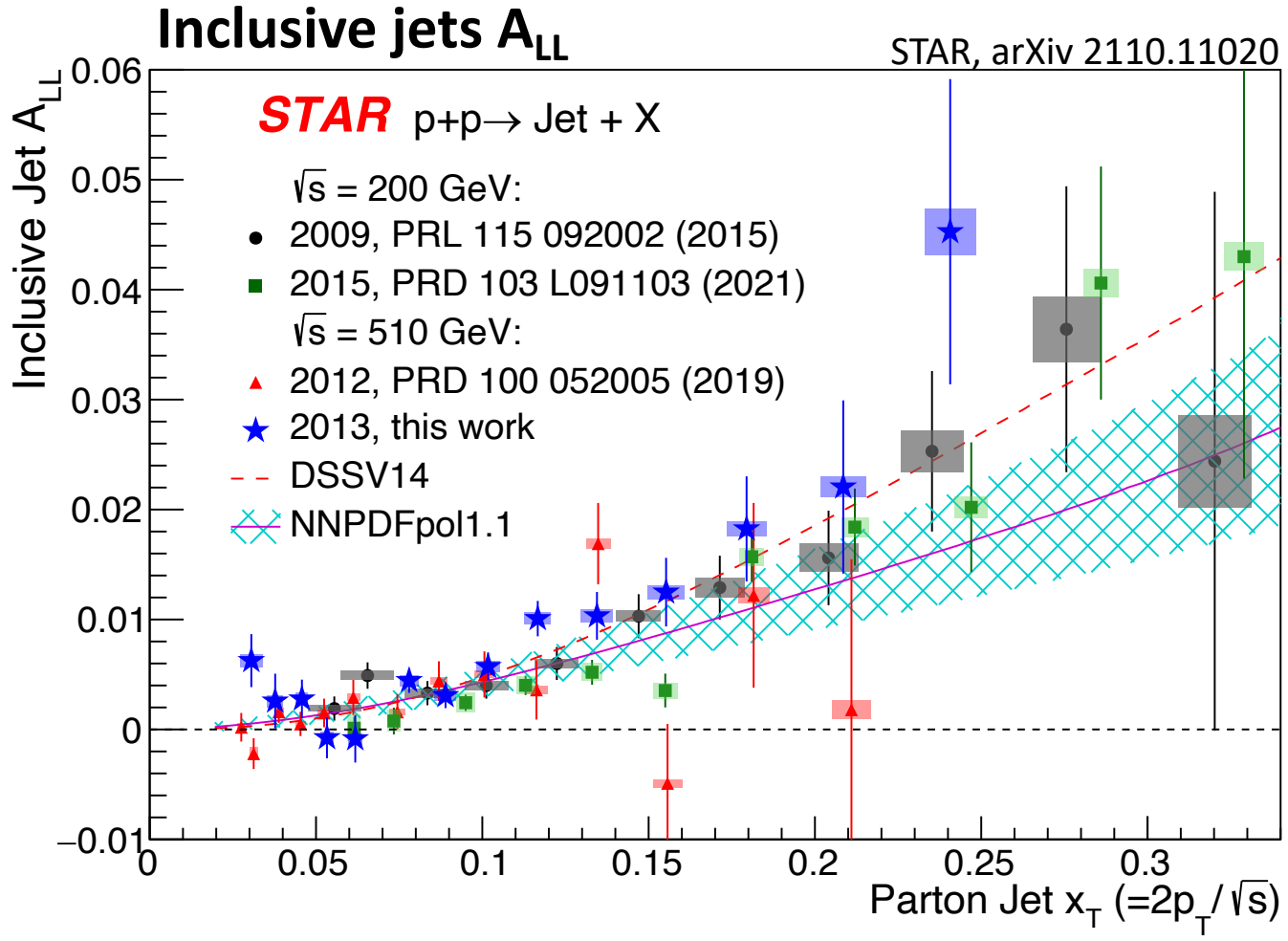
Polarized gluon distribution Δg

- $\vec{p}$+$\vec{p}$ → jet/dijet/hadron + X: $A_{LL} = \frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}} \propto \frac{\Delta f_a \otimes \Delta f_b}{f_a \otimes f_b}$

Polarized sea quark distributions

- **$\Delta\bar{u}$ and $\Delta\bar{d}$**
  - $\vec{p}$+p → W + X: $A_L = \frac{\sigma_+-\sigma_-}{\sigma_++\sigma_-}$
  - $W^{+/-}$→ natural flavor separation
- **Δs**
  - Λ ($\bar{\Lambda}$) production: $D_{LL} = \frac{\sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}}{\sigma_{p^+p\to\Lambda^+X} + \sigma_{p^+p\to\Lambda^-X}}$
  - Sensitive to polarized fragmentation functions (FF) and the helicity distributions of s ($\bar{s}$)

Helicity Δg



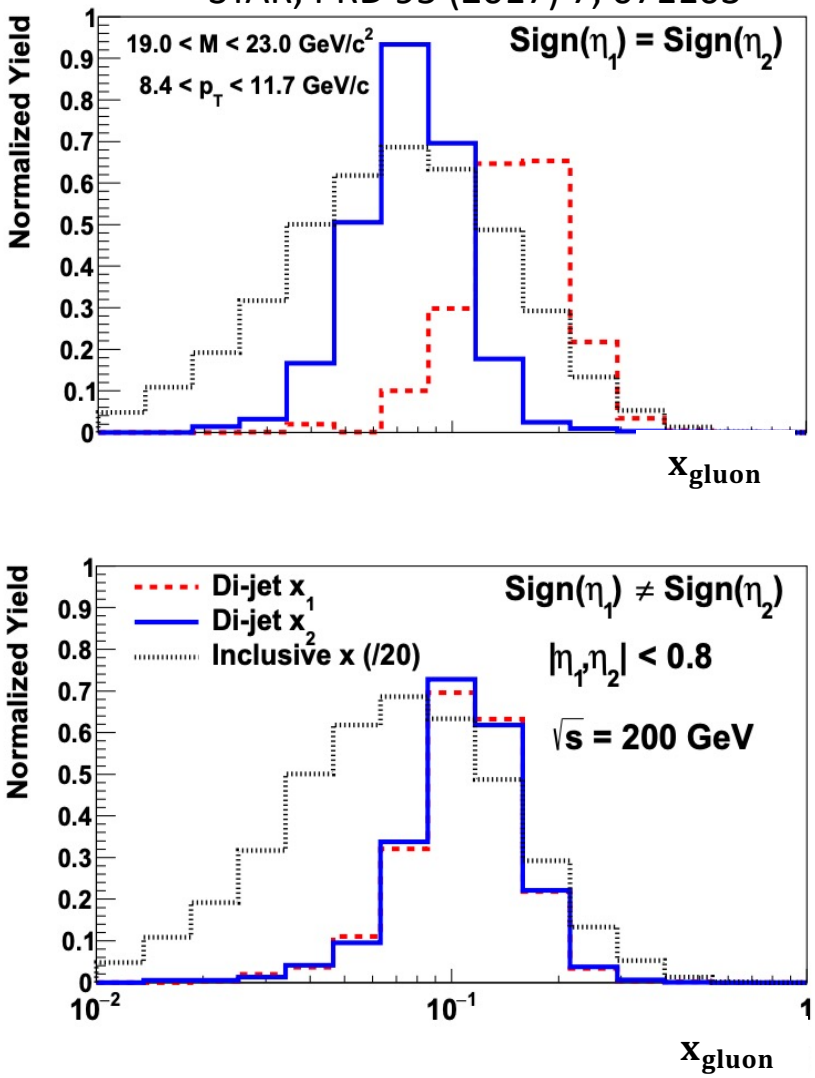
STAR inclusive jets A_{LL} at 200 and 510 GeV from 2009 to 2015:

- Consistent results from both energies
- 200 GeV data constrain Δg(x) for $x > 0.05$; 510 GeV data push sensitivity to lower $x \rightarrow 0.02$

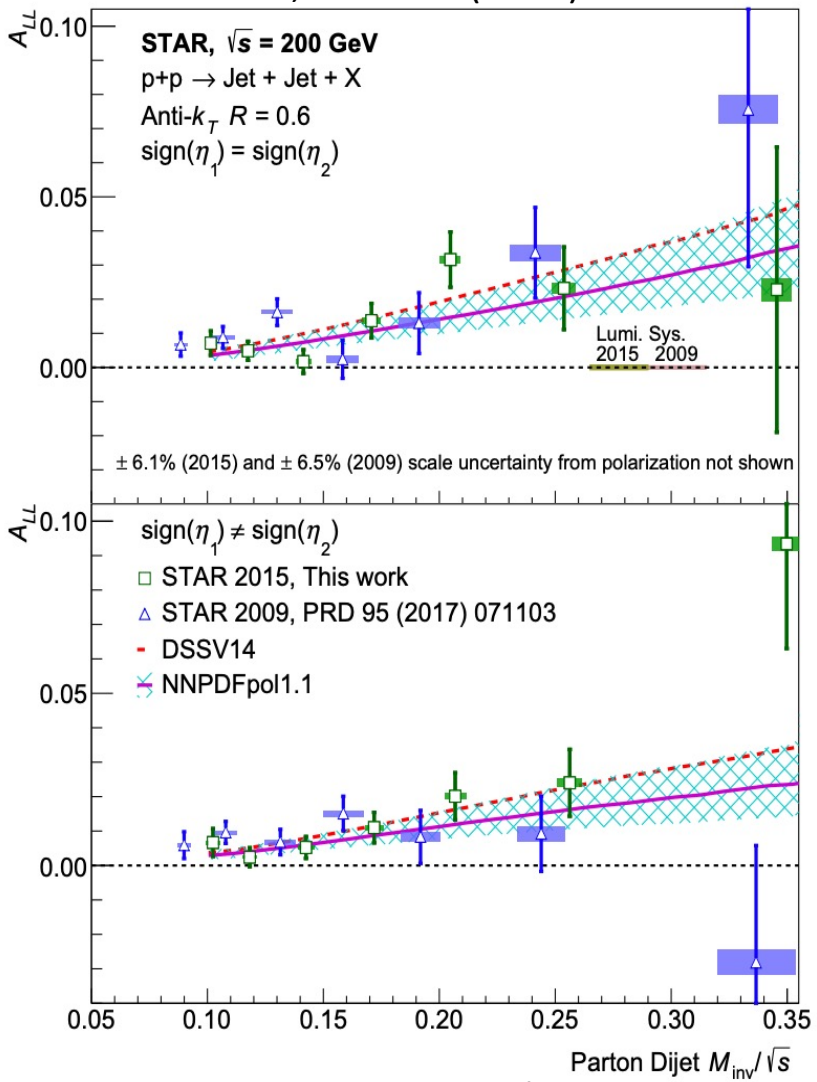
Helicity Δg

Dijets A_{LL}

STAR, PRD 95 (2017) 7, 071103



STAR, PRD 103 (2021) L091103

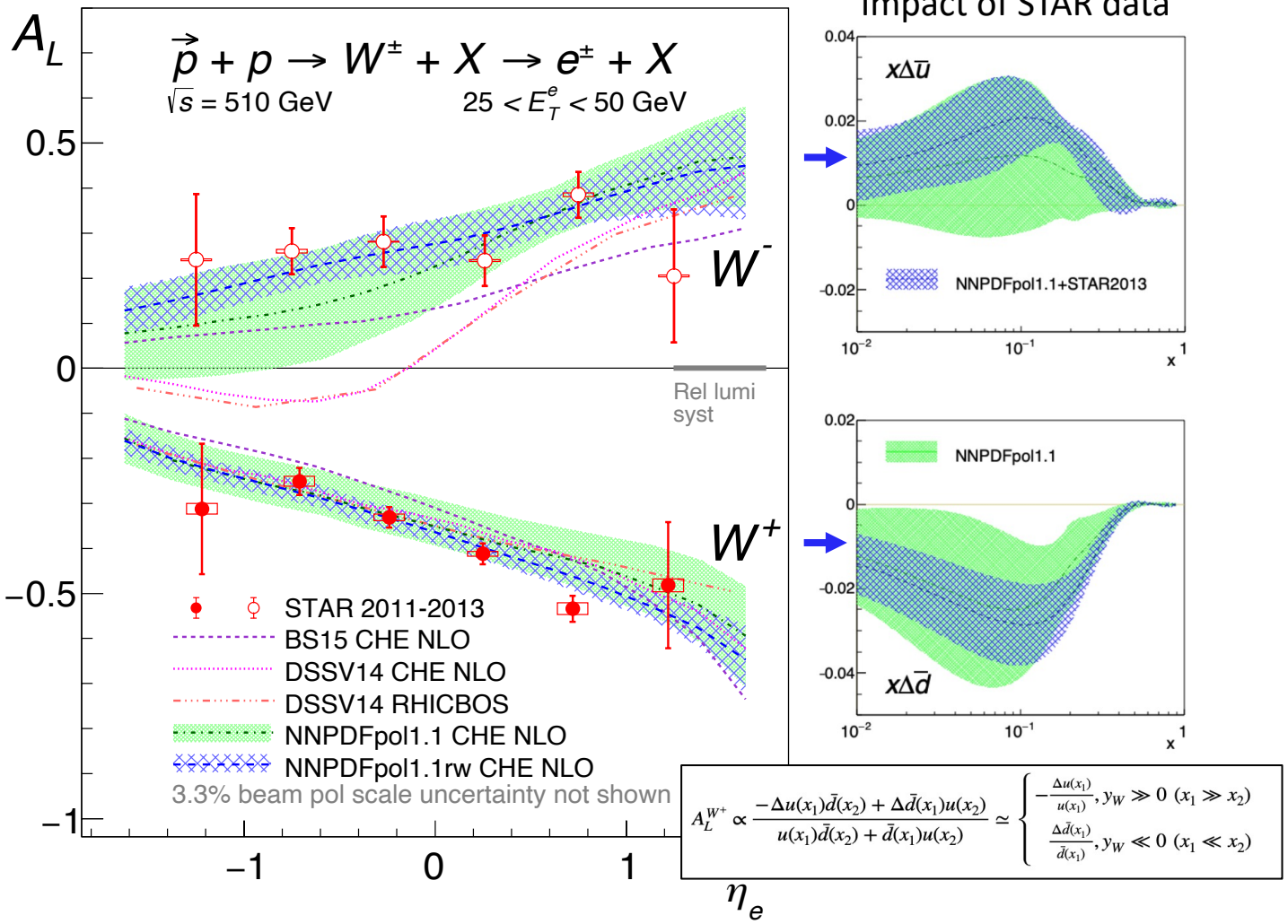


Dijets provide stricter constraints to underlying **partonic kinematics:**

- Narrow ranges of initial state partonic momentum fraction probed
- More-forward production: lower $x \rightarrow 0.01$ (PRD 98 (2018), 032011)

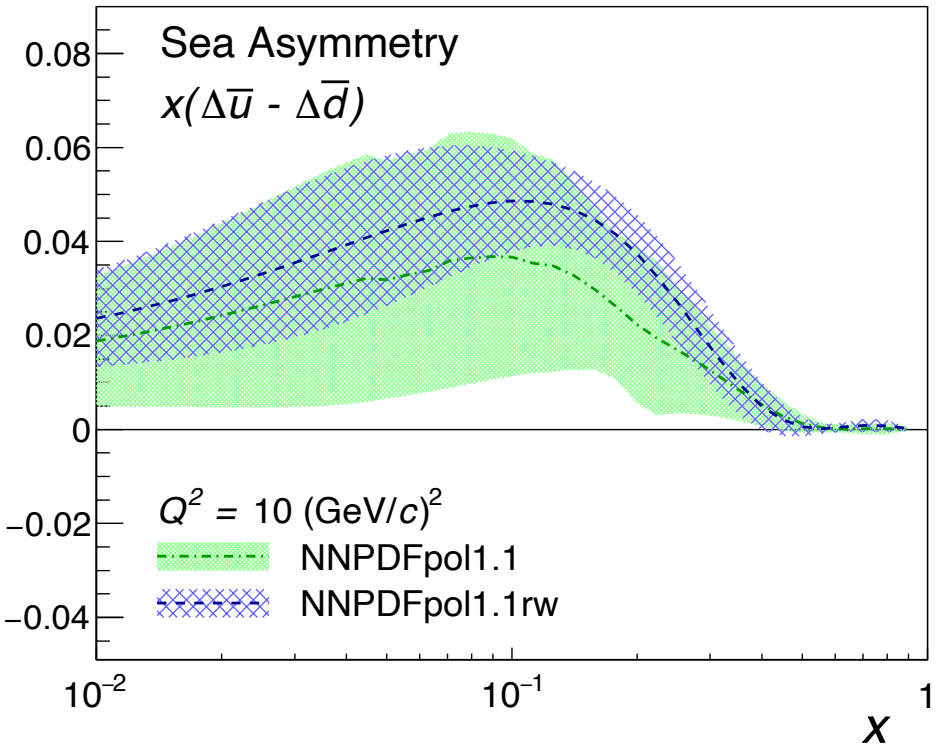
Helicity PDFs: $\Delta\bar{u}$ and $\Delta\bar{d}$

STAR, PRD 99 (2019), 051102(R)



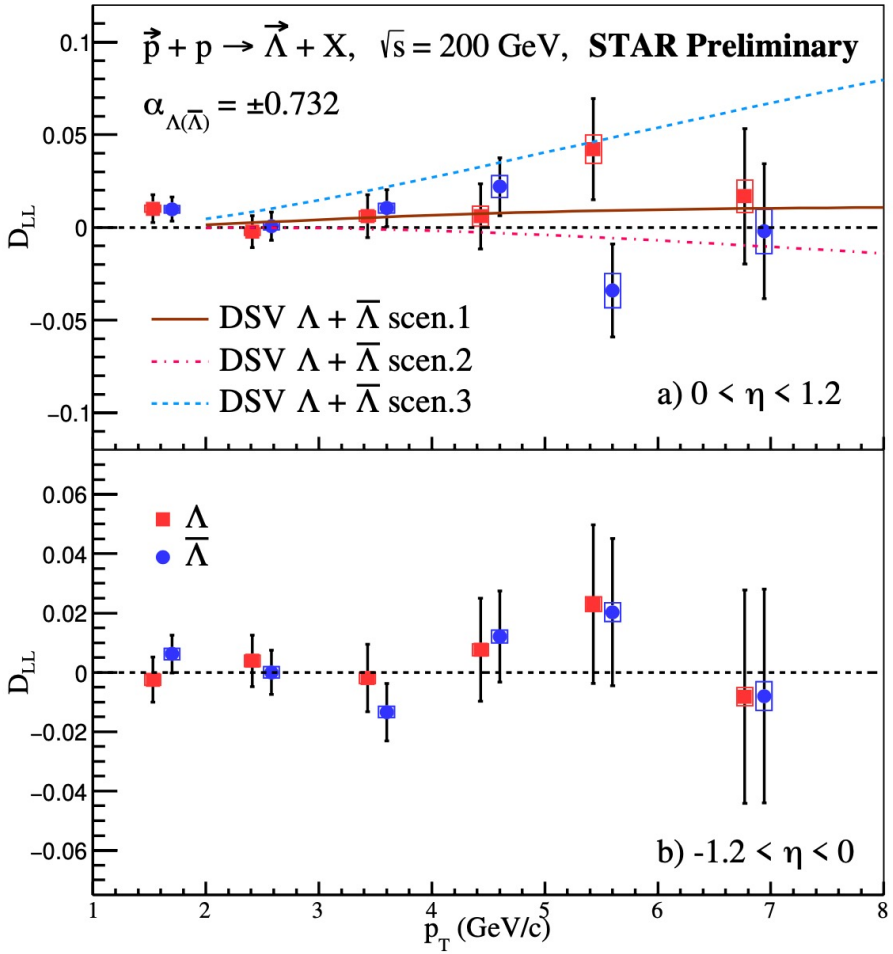
Impact of STAR data

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \simeq \begin{cases} -\frac{\Delta u(x_1)}{u(x_1)}, y_W \gg 0 \ (x_1 \gg x_2) \\ \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

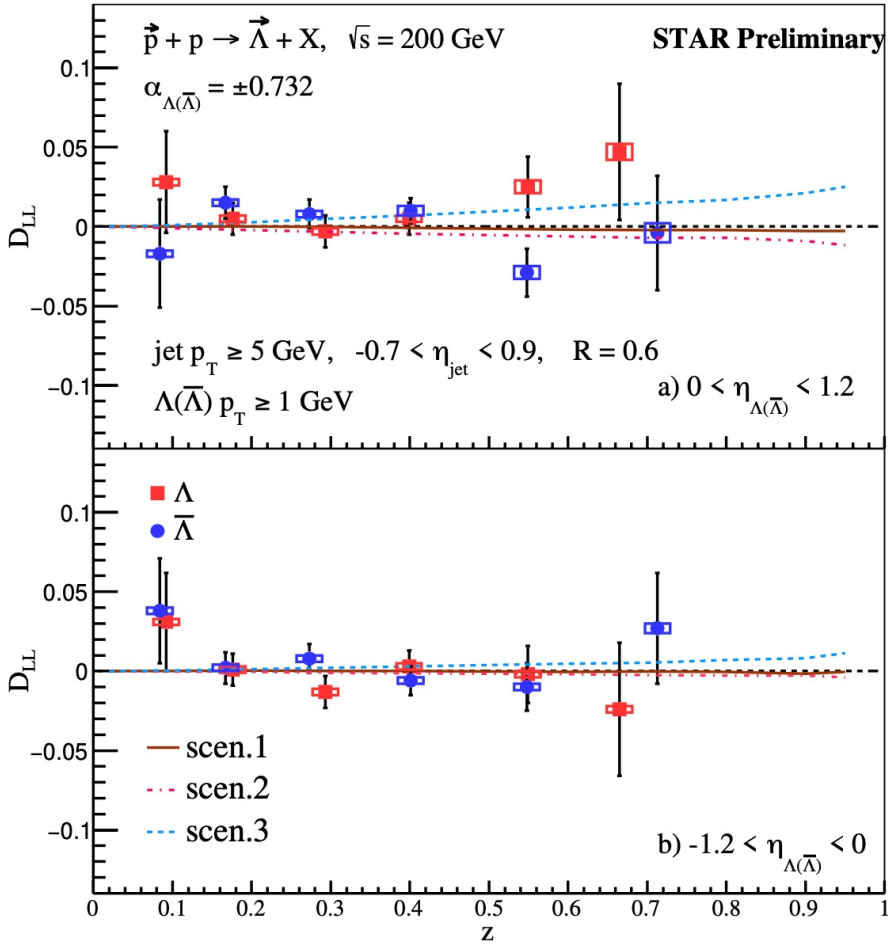


- **Polarized flavor asymmetry**:
  - $\Delta\bar{u} > \Delta\bar{d}$ for $0.05 < x < 0.25$
  - Opposite to the unpolarized flavor asymmetry: $\bar{u} < \bar{d}$

Helicity PDFs: Δs



Theory curves: D. de Florian et al, PRL 81, 530 (1998)



Theory curves: Z.B. Kang et al, PLB 809, 135756 (2020)

$$z = \frac{\vec{p}_\Lambda \cdot \vec{p}_{jet}}{\vec{p}_{jet} \cdot \vec{p}_{jet}}$$

- Results show consistency between Λ and $\bar{\Lambda}$
- Data agree with various models within uncertainties
- Most precise measurements to date with twice the statistics of the 2009 dataset (STAR, PRD 98 (2018) 112009)

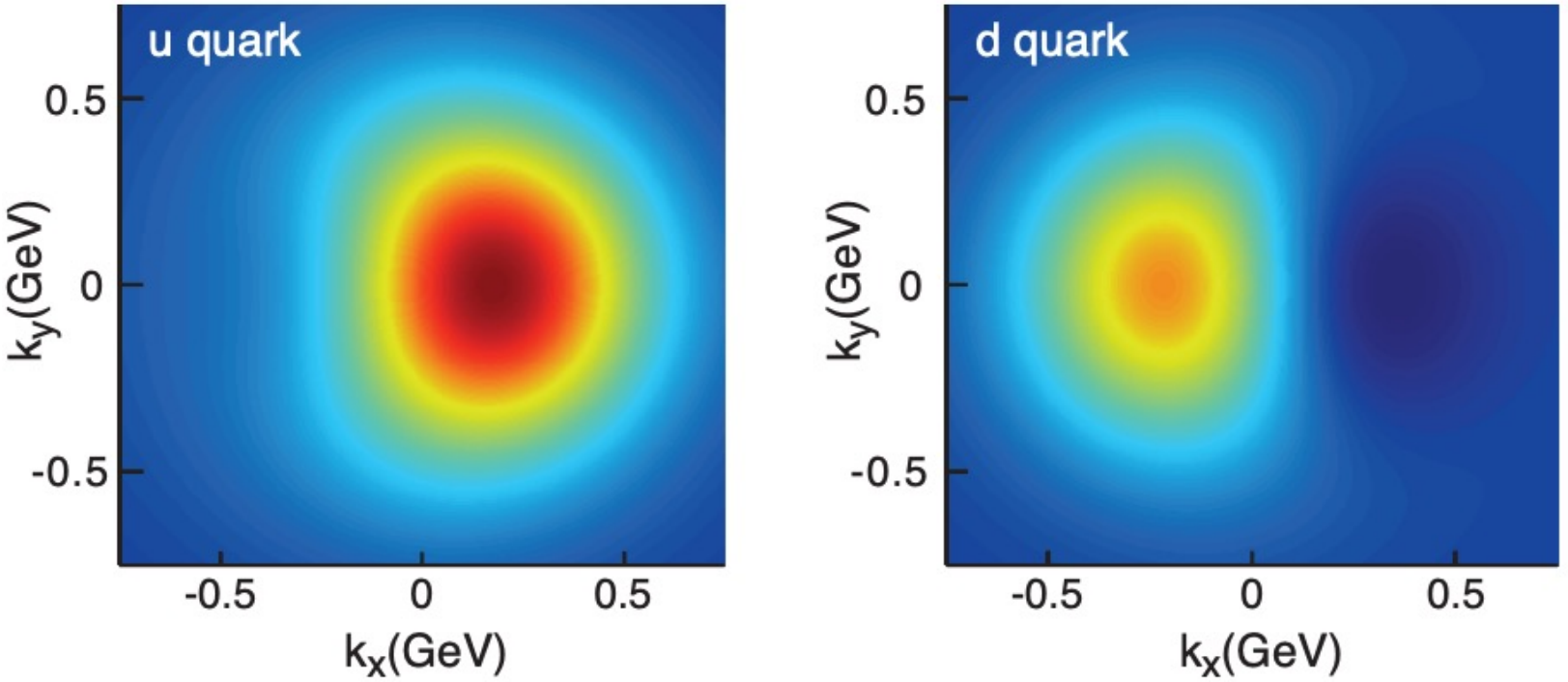
STAR has concluded the collection of longitudinally polarized data

Transversely polarized program

Transversely polarized p+p → $f(x, k_T, S_T)$

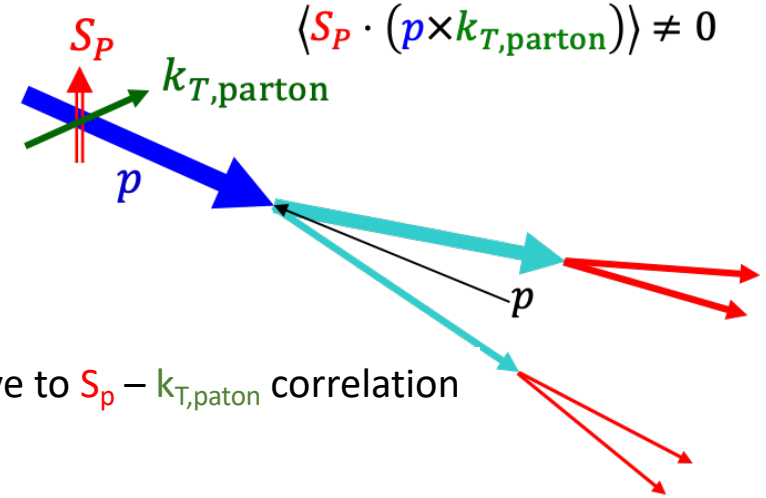
- Transverse Momentum Dependent parton distribution functions (TMDs):
  - Sivers effect
  - Collins fragmentation functions (FF)
- What measurements will Forward Upgrade enable?

arXiv:1212.1701



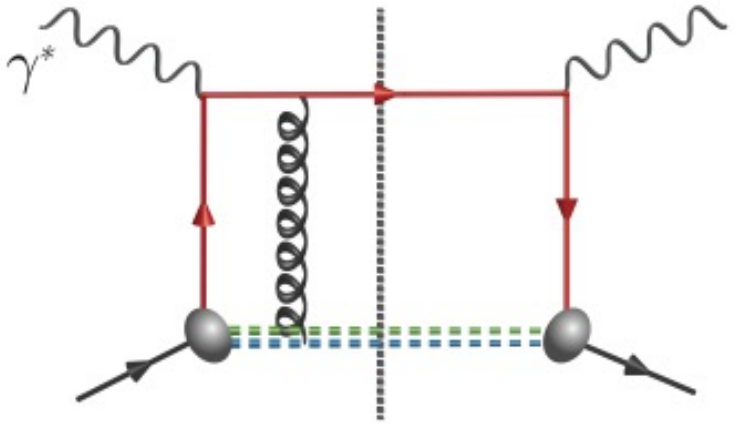
Sivers

Initial state TMD



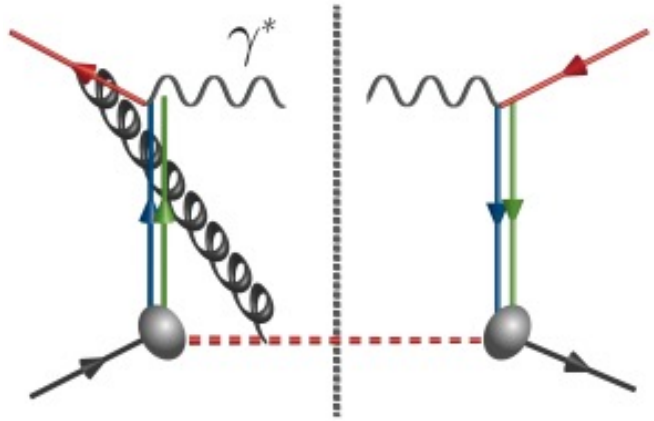
Sensitive to S_p – $k_{T,paton}$ correlation

DIS



Final-state interaction
Color attractive

DY, W, Z^0



Initial-state interaction
Color repulsive

One of the 8 TMDs known as **Sivers function:**

- Observables: transverse single spin asymmetry (TSSA) for jets, $W^{+/-}$, Z^0, Drell-Yan

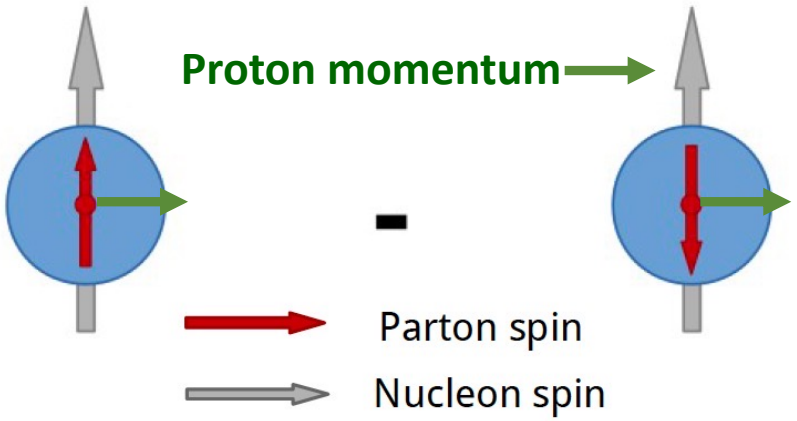
$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi+\pi)}{d\sigma(\phi) + d\sigma(\phi+\pi)}$$

Sivers effect:

- Not universal→ $\text{Sivers}_{DIS} = -(\text{Sivers}_{DY} \text{ or } \text{Sivers}_{W,Z0})$

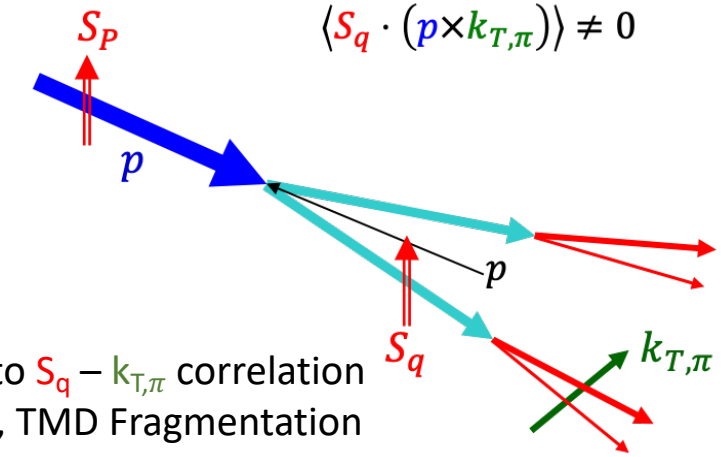
Transversity and Collins fragmentation functions

Transversity

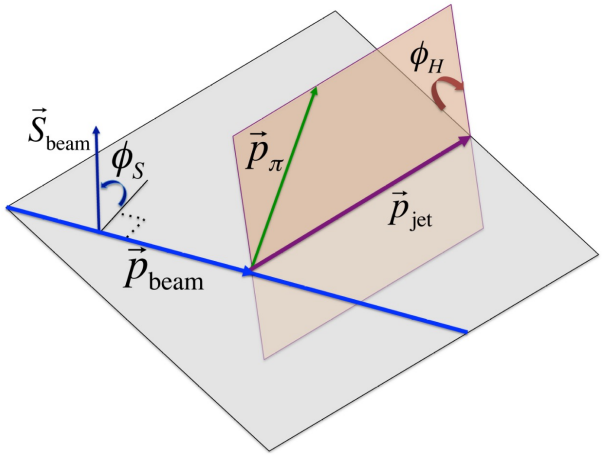


Quark polarization along the spin of a transversely polarized proton

Final state: Collins



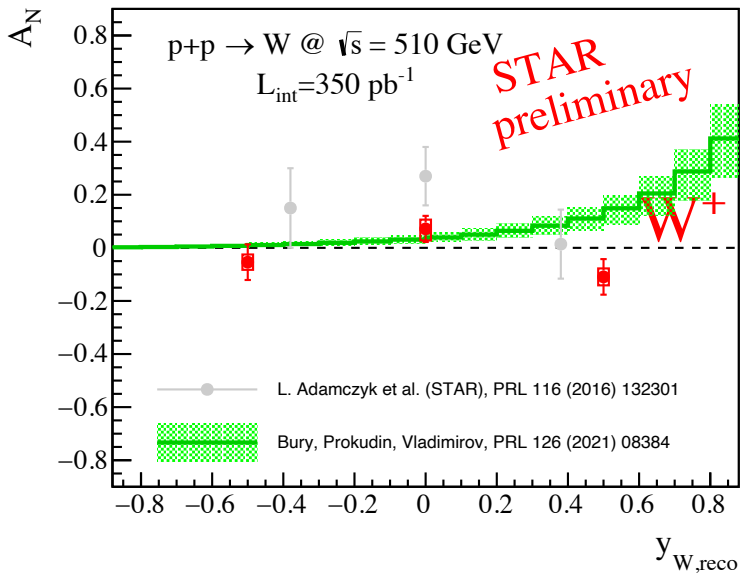
Sensitive to S_q – $k_{T,\pi}$ correlation
Transversity, TMD Fragmentation

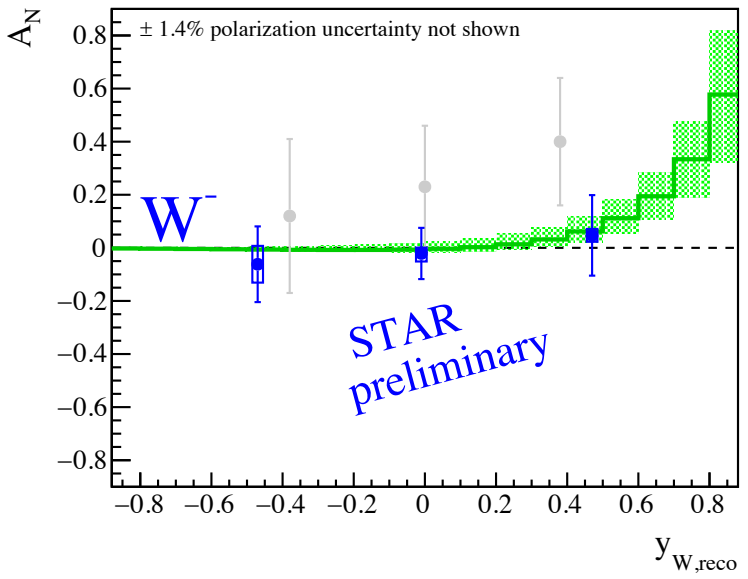


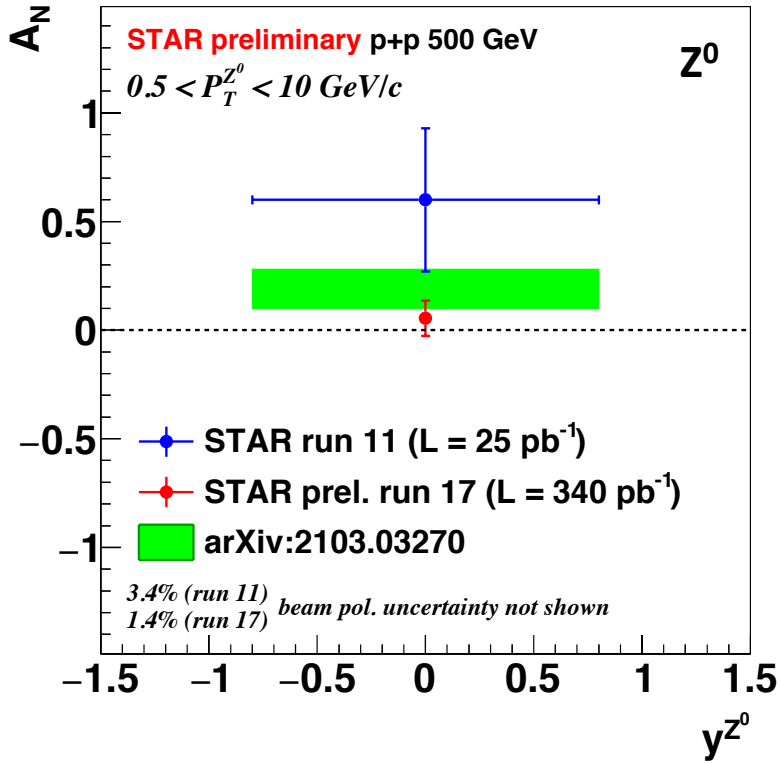
$$\phi = \phi^S - \phi^H$$

- Observables: $A_{UT}^{\sin(\phi)}$ for pions
- Collins function predicted to be universal

A_N for $W^{+/-}$ and Z^0







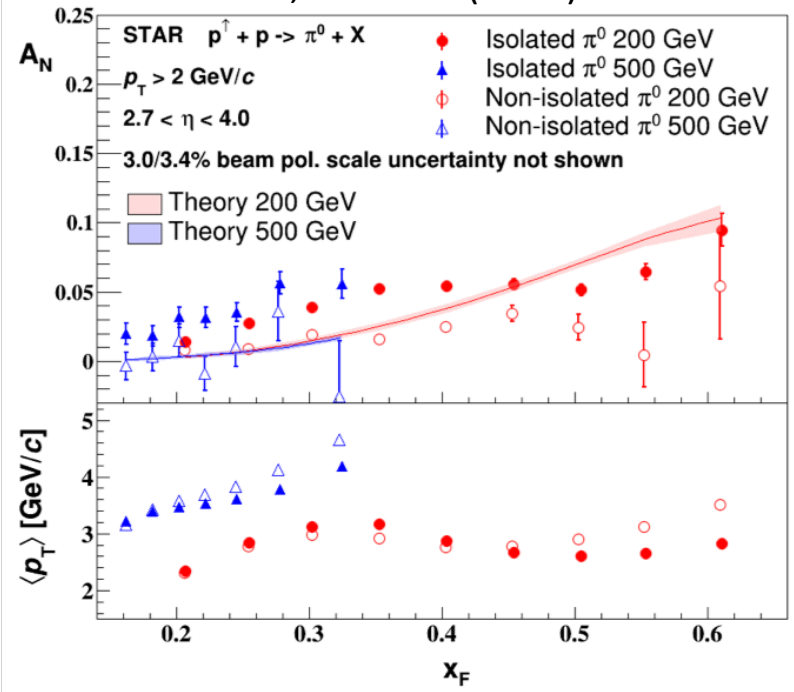
Mid-rapidity $W^{+/-}$ and Z^0 A_N:

- Statistics much improved with run 2017 (350 pb^{-1}) compared to run 2011 (25 pb^{-1})
- Predictions from PRL 126, 112002 (2021)
  - Extraction includes SIDIS, DY and STAR run 2011 results
  - N^3LO accuracy of the TMD evolution assuming sign-change

Expect ~350 pb^{-1} more data from run 2022 with Forward Upgrade and η coverage extended by STAR iTPC

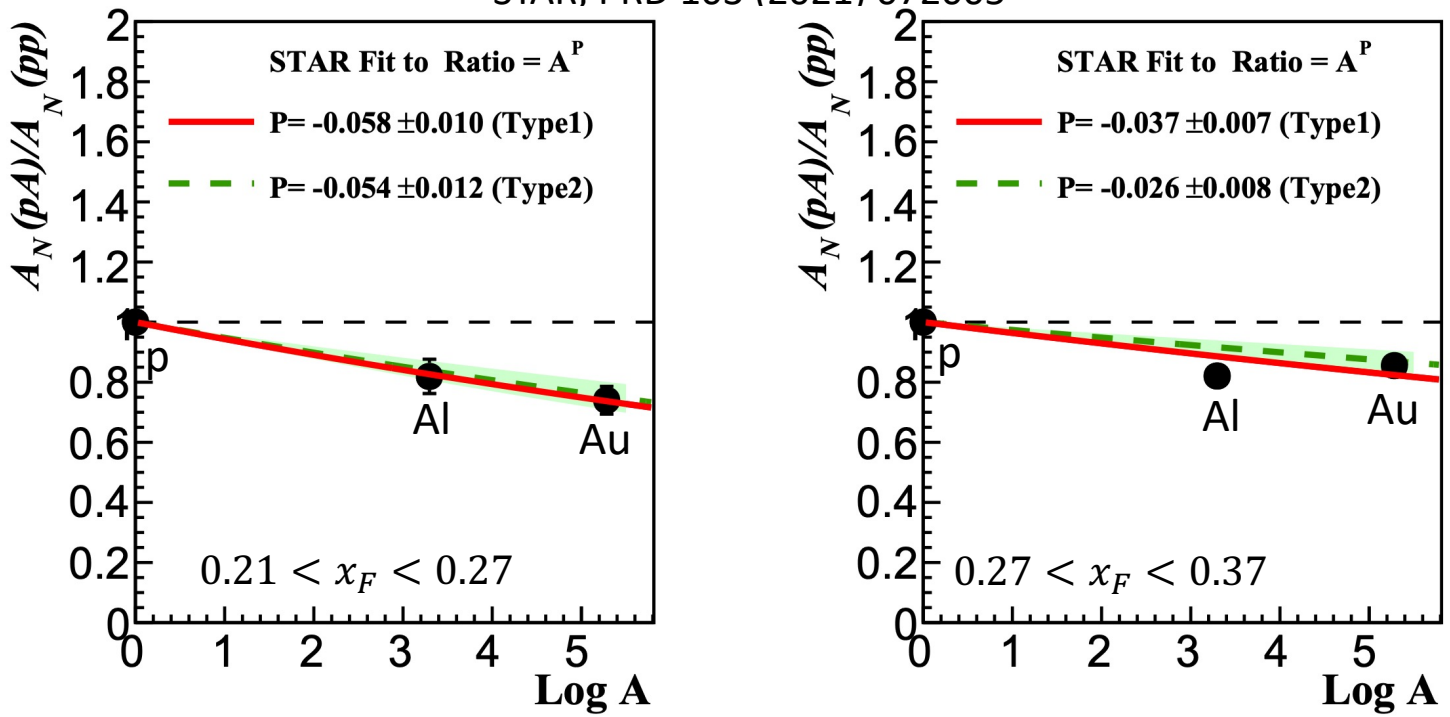
A_N for π^0

STAR, PRD 103 (2021) 92009



Theory curves: J. Cammarota et al, PRD 102, 054002 (2020)

STAR, PRD 103 (2021) 072005



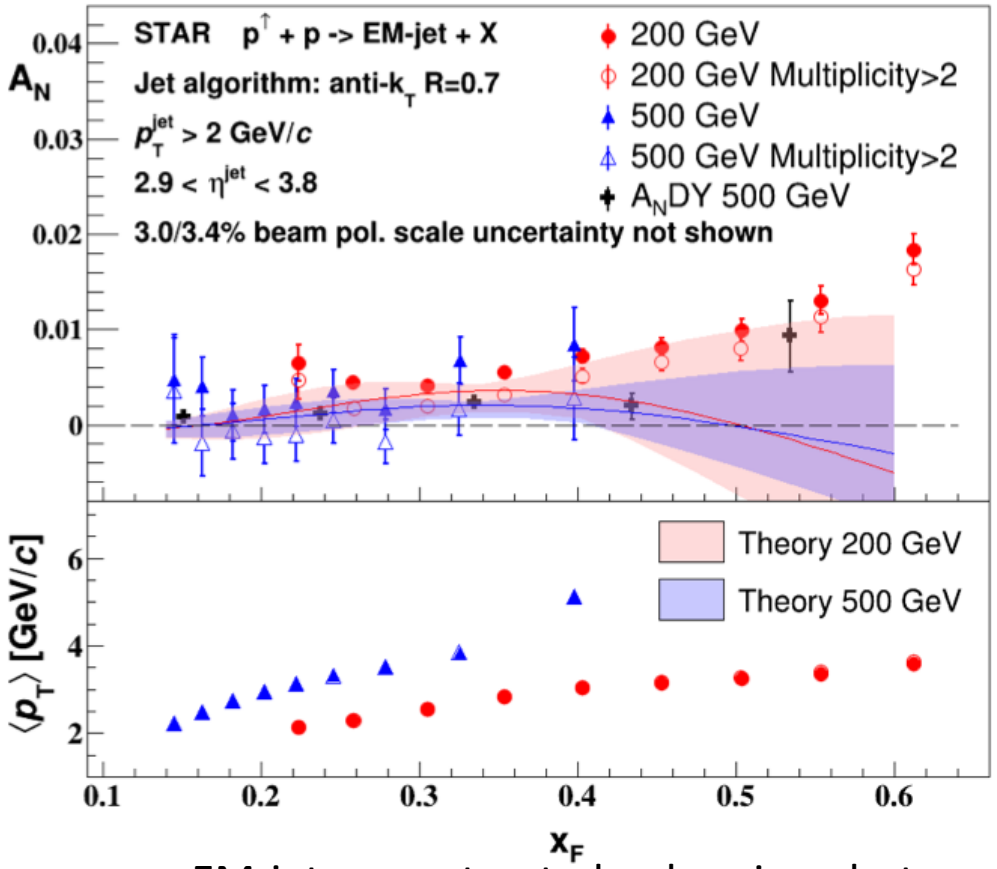
Type1: correlated uncertainties in the ratio; Type2: without correlated uncertainties

Forward π^0 A_N:

- Weak dependence on the center-of-mass energy
- Larger A_N for isolated π^0: additional mechanism needed to explain asymmetries → diffractive processes?
- Suppression of A_N in p+A to A_N in p+p collisions is observed → nuclear dependence of TMDs?

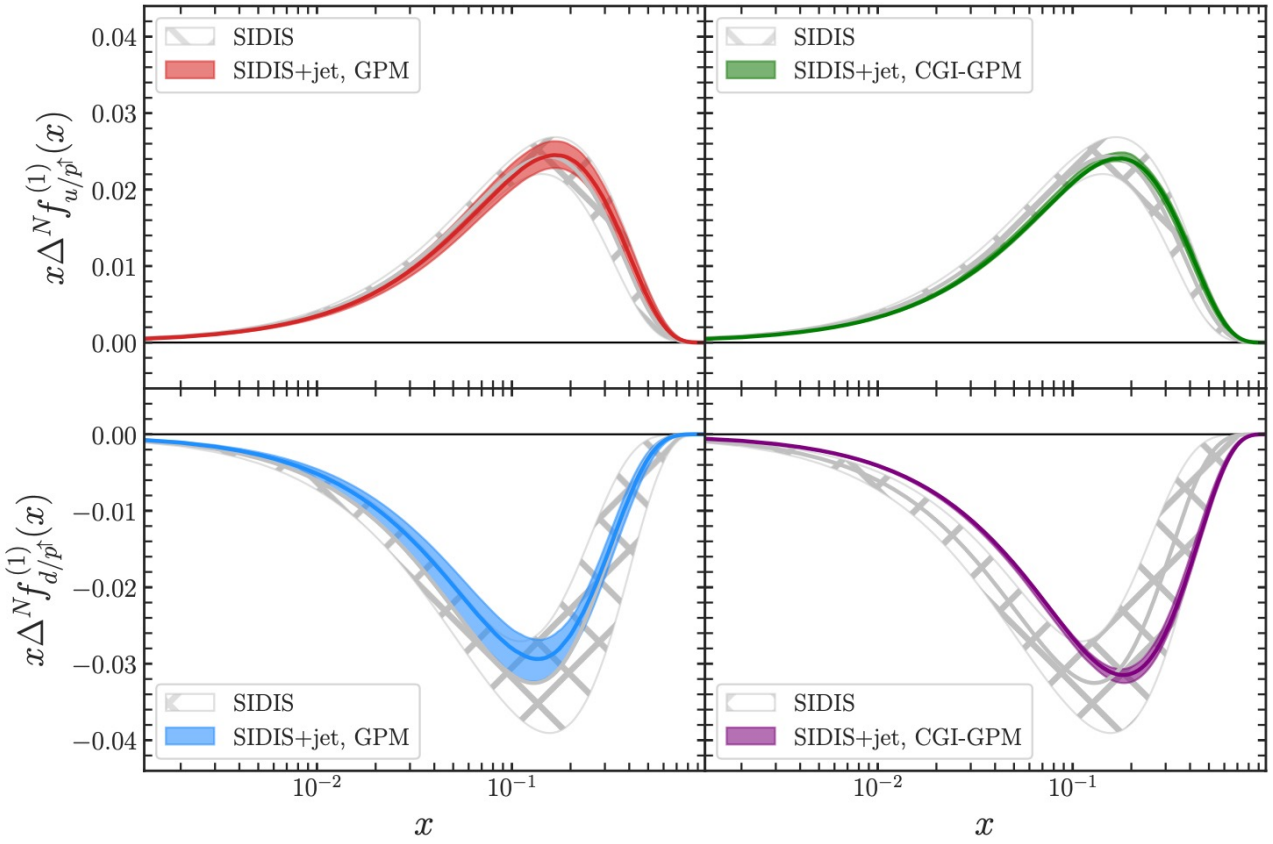
A_N for EM-jet

STAR, PRD 103 (2021) 92009



EM-jet reconstructed only using photons

M.Boglione et al, PLB 815 (2021), 136135

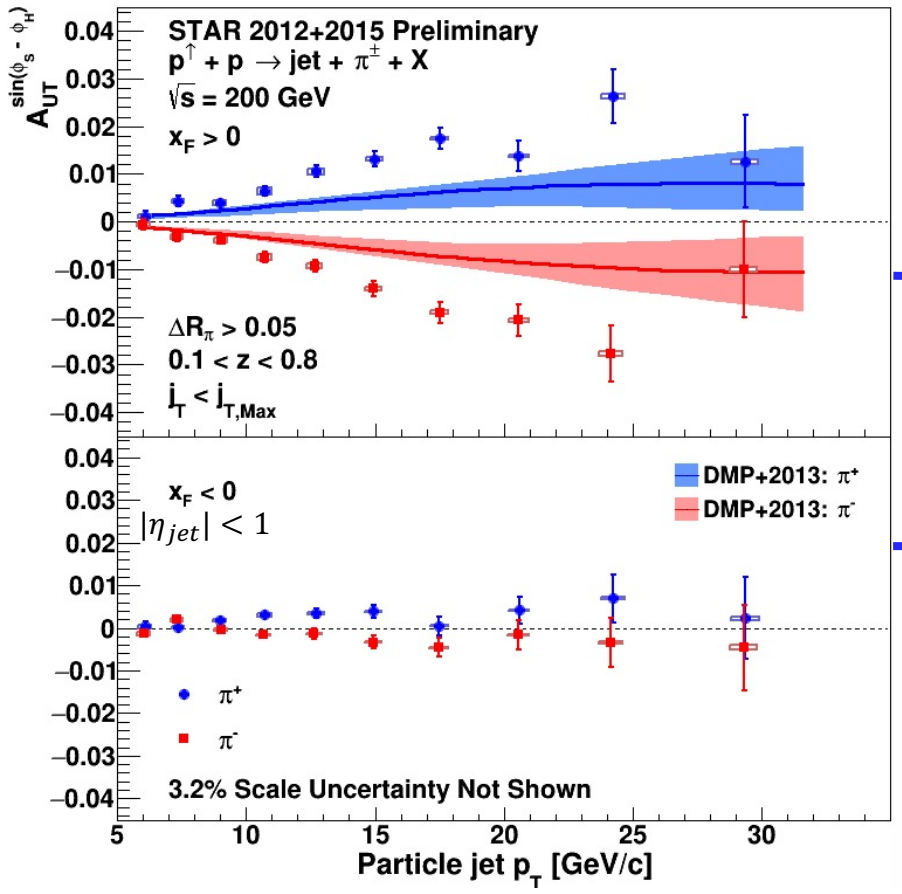


Impact of EM-jet A_N

Forward EM-jet A_N:

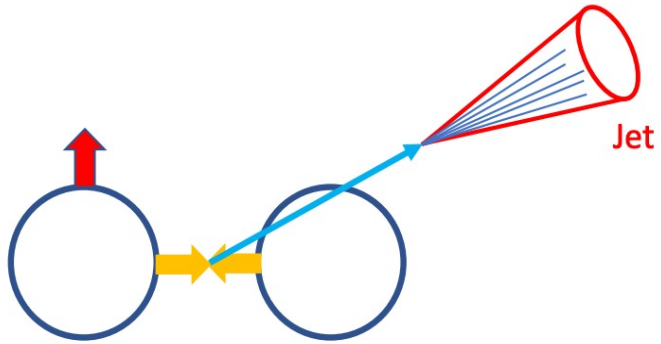
- Decreases with increasing photon multiplicity
- Provides substantial constraints on the Sivers effect at high x

Collins asymmetry for $\pi^{\pm}$ in jets



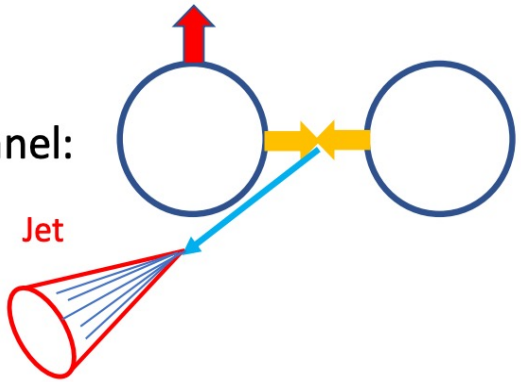
Top panel:

$x^F > 0$



Bottom panel:

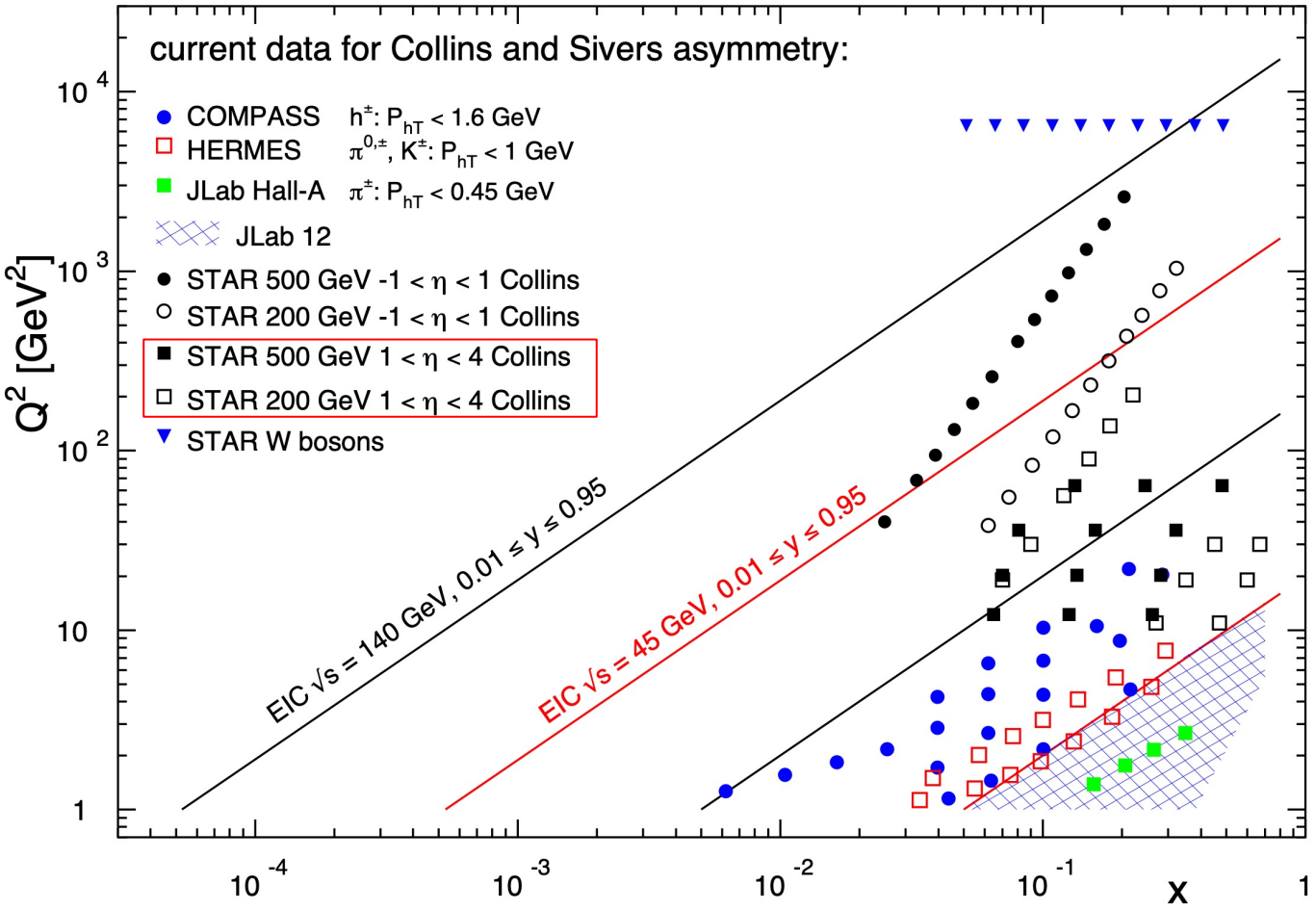
$x^F < 0$



Spin-dependent modulation of $\pi^{\pm}$ in jets at mid-rapidity ($|\eta_{jet}| < 1$):

- Significant Collins asymmetries for $\pi^{\pm}$ measured with high precision
- Stringent constraints on theoretical calculations of transversity and Collins FF

Transverse physics with Forward Upgrade

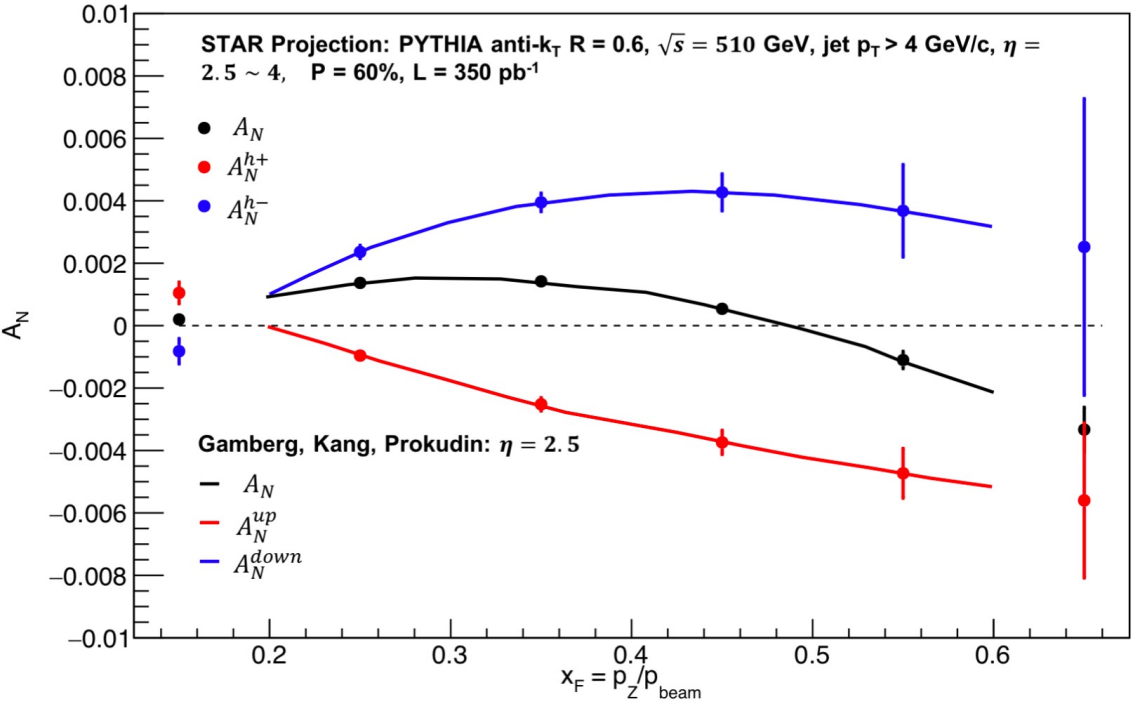


STAR Forward Upgrade capabilities with jets and hadrons for transverse asymmetries:

- Study forward Sivers, Collins and diffractive processes → charge-tagged jets and di-jets, hadron in jets, and diffractive processes with rapidity gaps
- Before STAR: TMDs only came from fixed target e+p data with low Q^2
- STAR's unique kinematics with Forward Upgrade: low to high x at moderate and high Q^2 → TMD evolution:
  - x up to ~0.5 → sensitive to valence quark

How well Forward Upgrade will do?

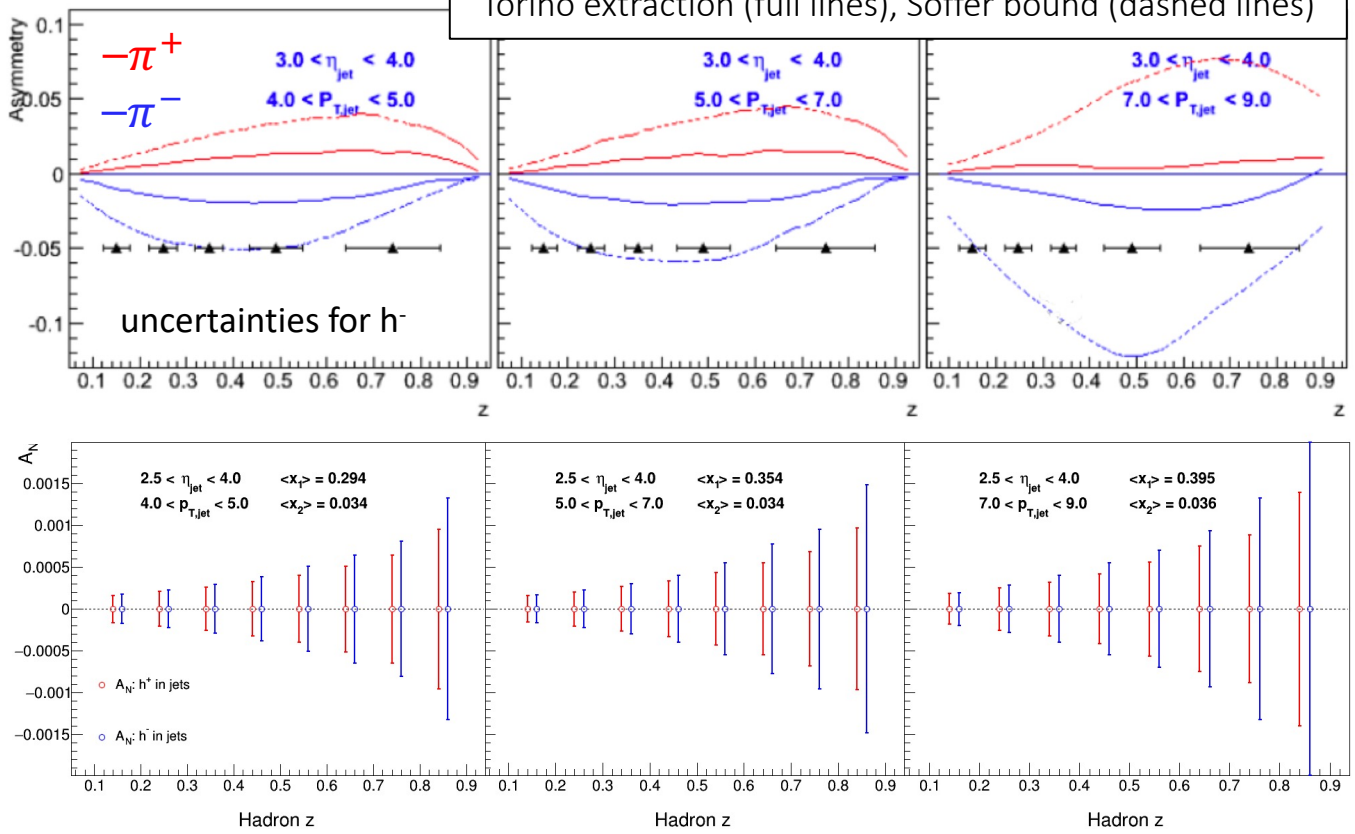
Sivers



All Plots: STAR Beam Use Request for Run 2022

Transversity and Collins

Torino extraction (full lines), Soffer bound (dashed lines)



Projected uncertainty of the data from 2022

Forward Upgrade enables full jet reconstruction with charge-sign tagging (no PID) of a hadron fragment:

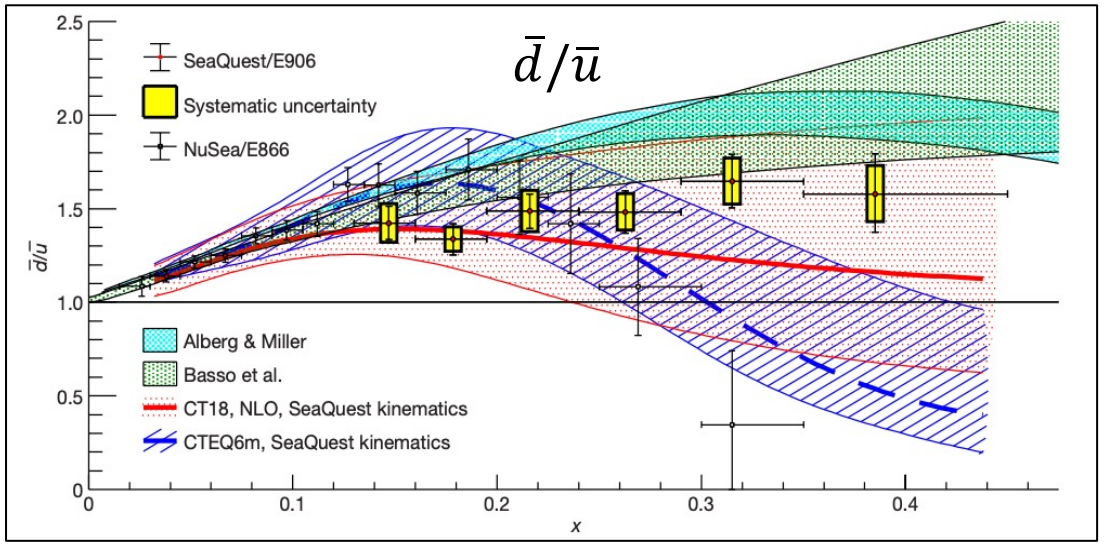
- Sivers: projected statistical uncertainties drawn on twist-3 predictions from Gamberg et al; up to 10 σ separation between plus-tagged and minus-tagged jet A_N
- Transiversity: precise measurements at high x with uncertainties $\sim< 10^{-3}$

Unpolarized program

Unpolarized p+p and p+A → $f(x, Q^2)$

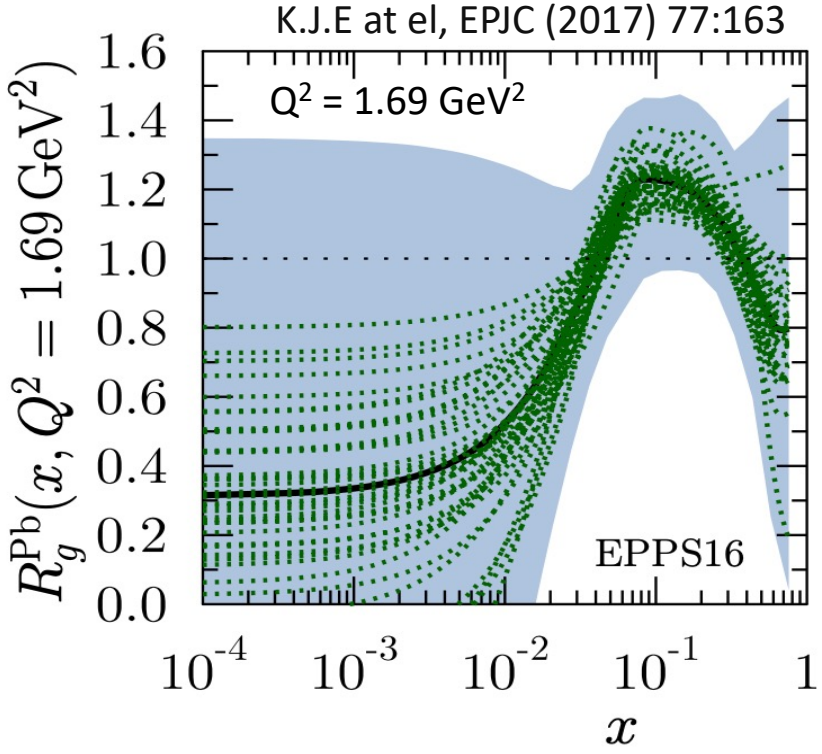
- Sea quark distributions and nuclear parton distributions
- What measurements will Forward Upgrade enable?

SeaQuest, Nature 590, 561–565 (2021)



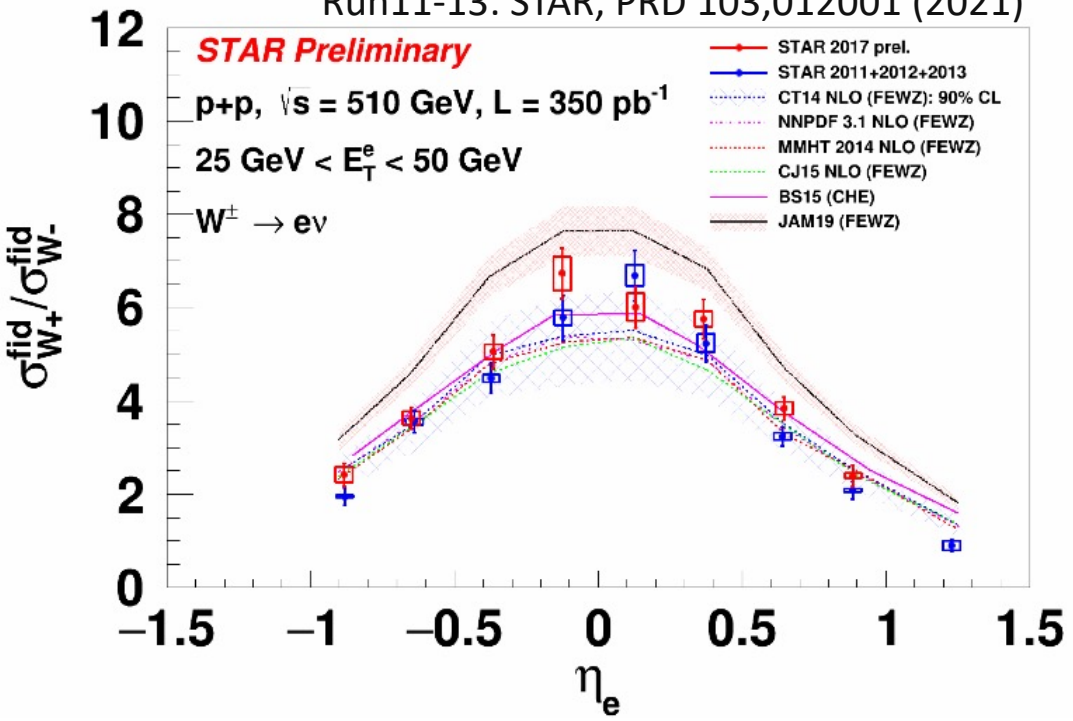
x

K.J.E at el, EPJC (2017) 77:163



W and Z^0 cross section

Run11-13: STAR, PRD 103,012001 (2021)

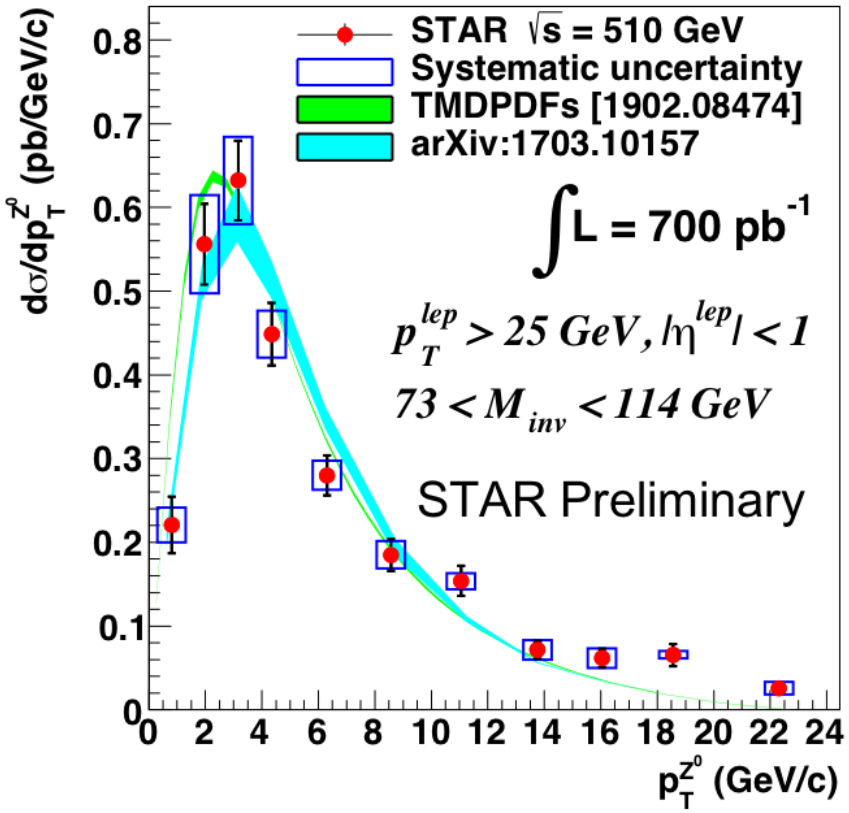


$W^+/ W^- \rightarrow \bar{d}/\bar{u}$:

- Sensitive to the region $0.1 < x < 0.3$ in STAR mid-rapidity ($|\eta| < 1$) at $Q^2 = M_W^2$
- Clean theoretical and experimental observable

$$\sigma_{W^+}/\sigma_{W^-} \approx \frac{u(x_1)\,\bar{d}(x_2) + u(x_2)\,\bar{d}(x_1)}{\bar{u}(x_1)\,d(x_2) + \bar{u}(x_2)\,d(x_1)}$$

$Z^0/\gamma^* \rightarrow e^+e^-$



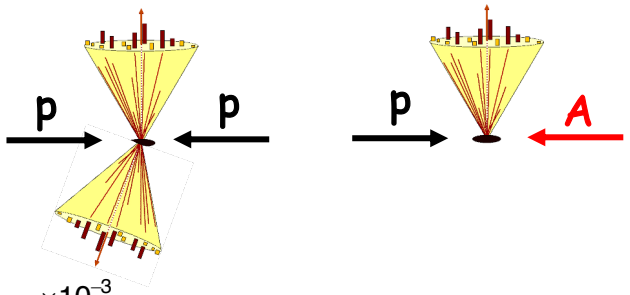
The differential Z^0 cross section:

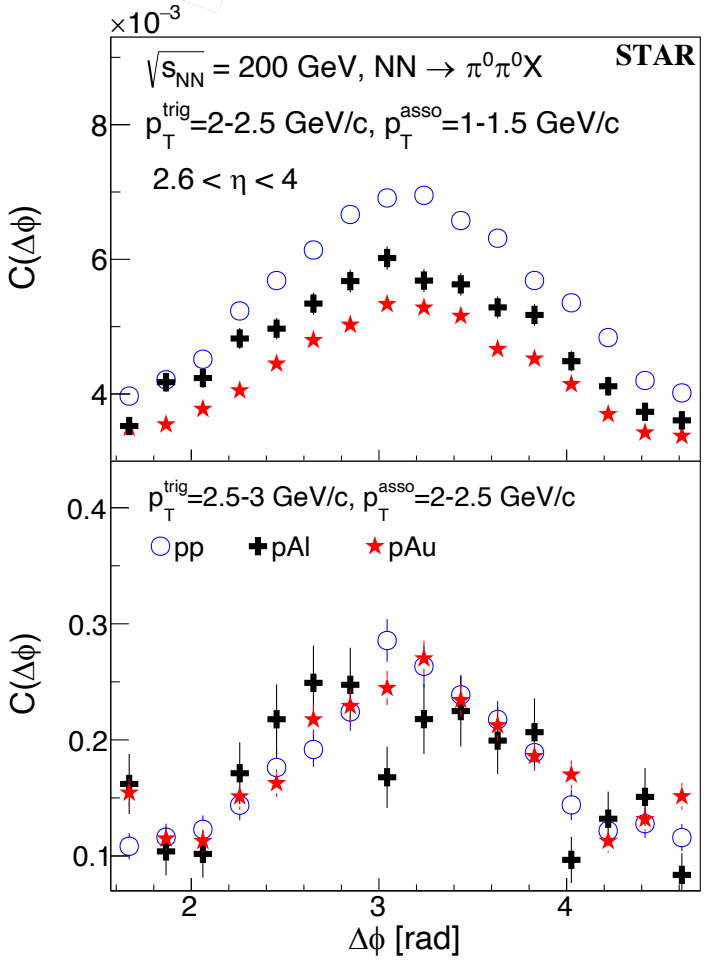
- Constrain on the energy scale dependence of TMDs

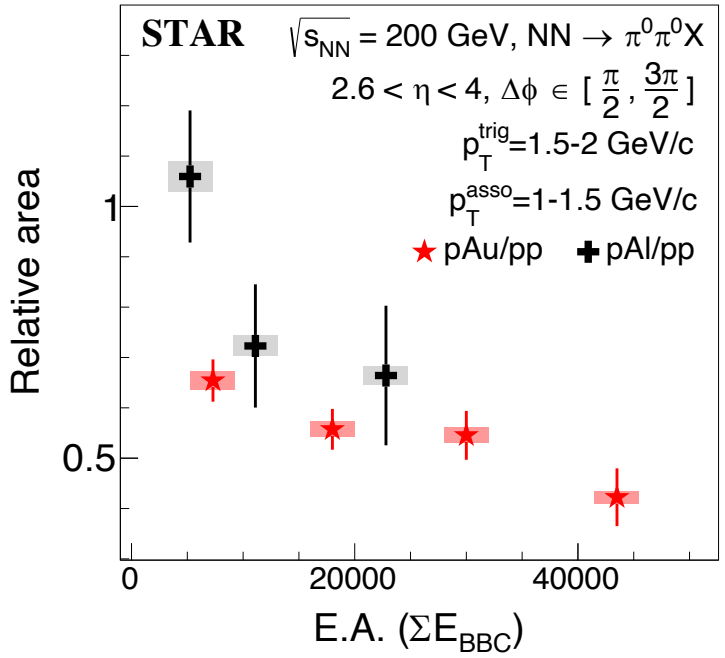
Expect ~350 pb^{-1} more data from run 2022 with Forward Upgrade

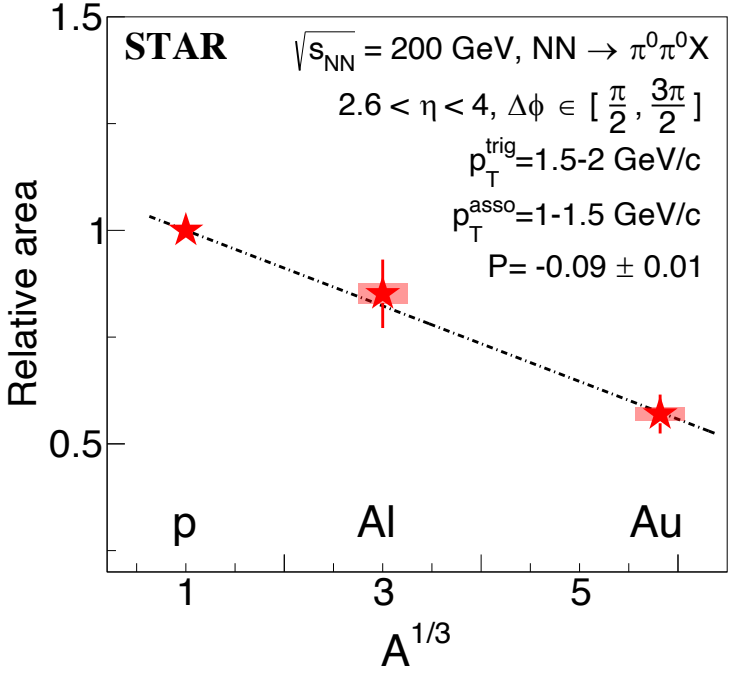
STAR, arXiv: 2111.10396

Nonlinear gluon dynamics in QCD



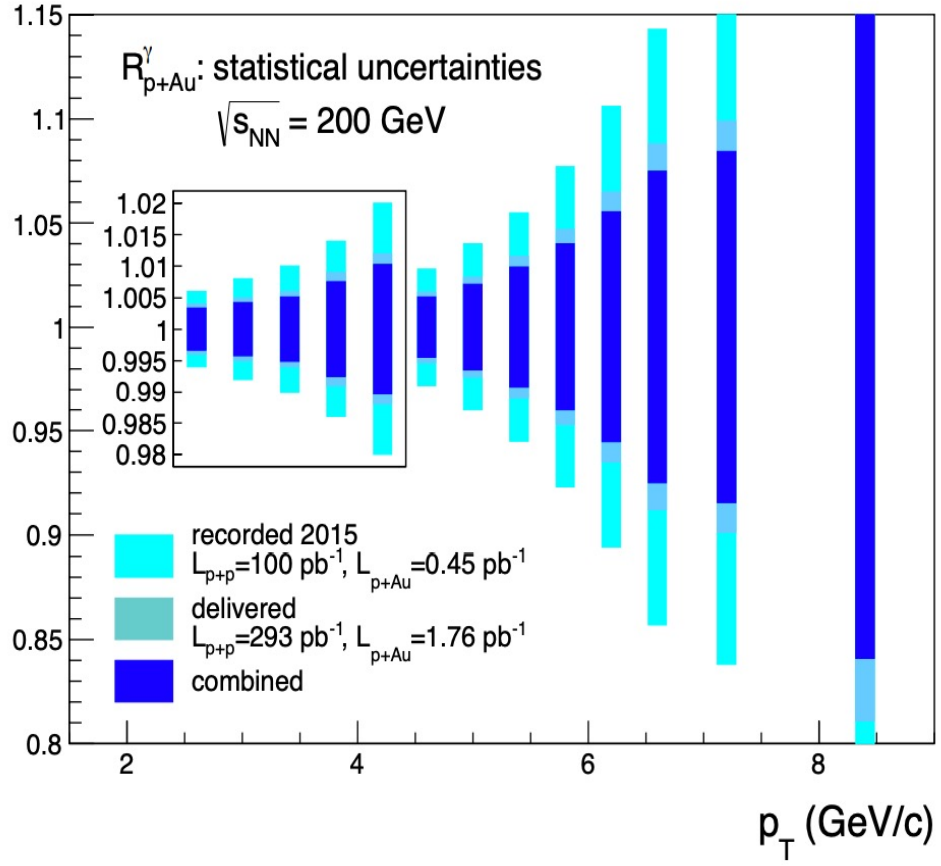




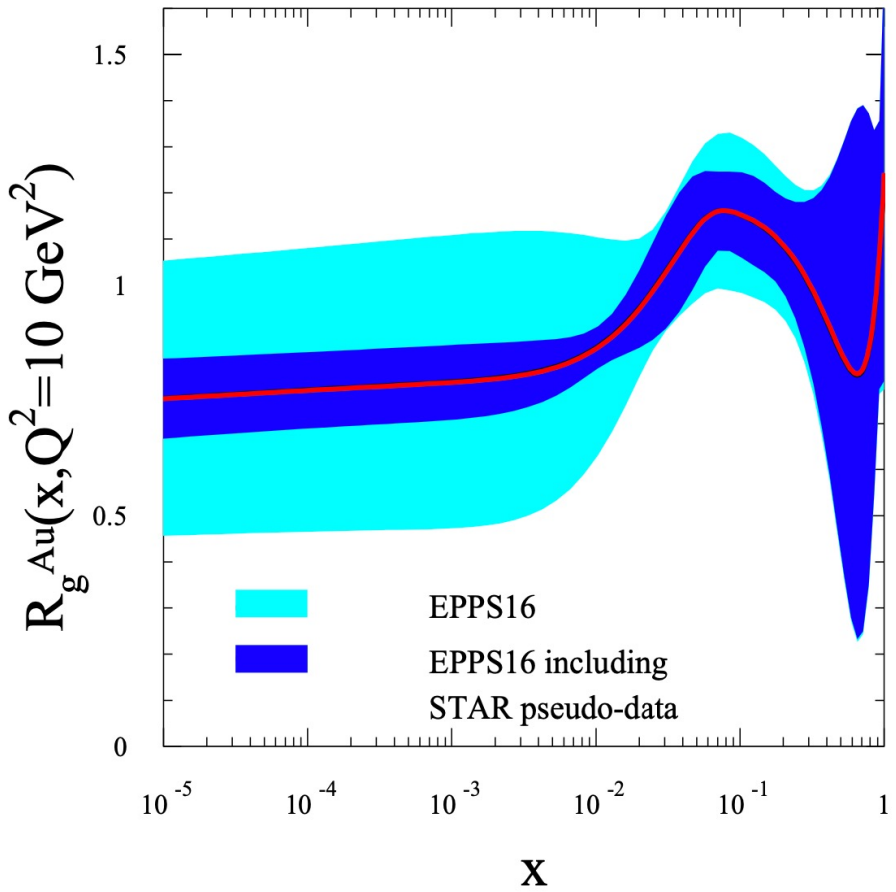


- Forward rapidities → high gluon densities
- STAR π^0- π^0 correlations: p_T, E.A. and A dependence
- This measurement is essential to explore the universality of nonlinear effects along with the future EIC

Future measurements with Forward Upgrade



arxiv:1602.03922



Expanded observables by Forward Upgrade: di-hadron, di-jet, γ-hadron/jet, inclusive γ…

- R^{γ}_{pAu} of direct photon: free from the final state effects; precise measurements of nuclear gluon distribution

Summary

High impact of STAR Cold QCD program:
Longitudinally polarized: insights in Δg; $\Delta\bar{u} > \Delta\bar{d}$ and $\Delta s \sim 0$

Transversely polarized:
- A_N for W and Z boson → precise measurement to investigate Sivers effect
- Non-zero Collins asymmetry for $\pi^{\pm}$

Unpolarized:
- W^+/ W^- ratio → constrain sea quark distributions
- Forward π^0- π^0 correlation → evidence of nonlinear gluon dynamics

STAR is taking data with the Forward Upgrade. The upgrade will provide insights in:
- Understanding the origin of large forward A_N
- Testing TMD evolution and universality
- Constraining transversity at high x
- Understanding the nature of the initial state in nucleon and nucleus