Recent results on the physics of the proton's spin at the STAR experiment

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QCD-N2021
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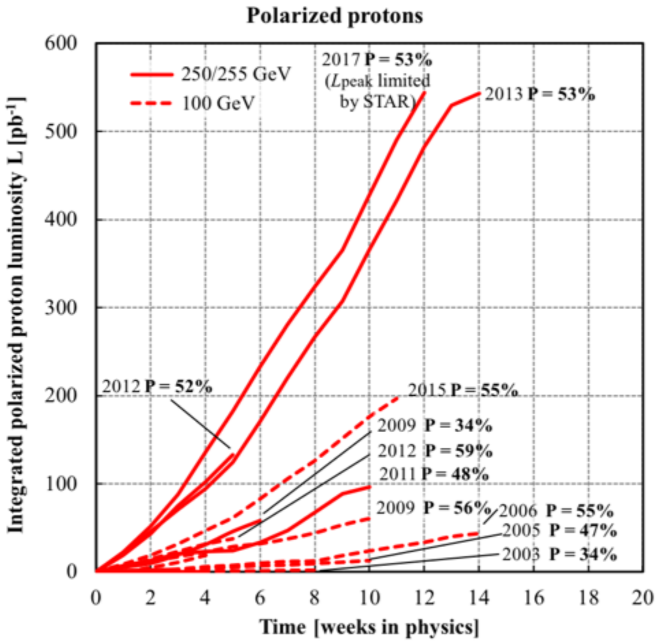
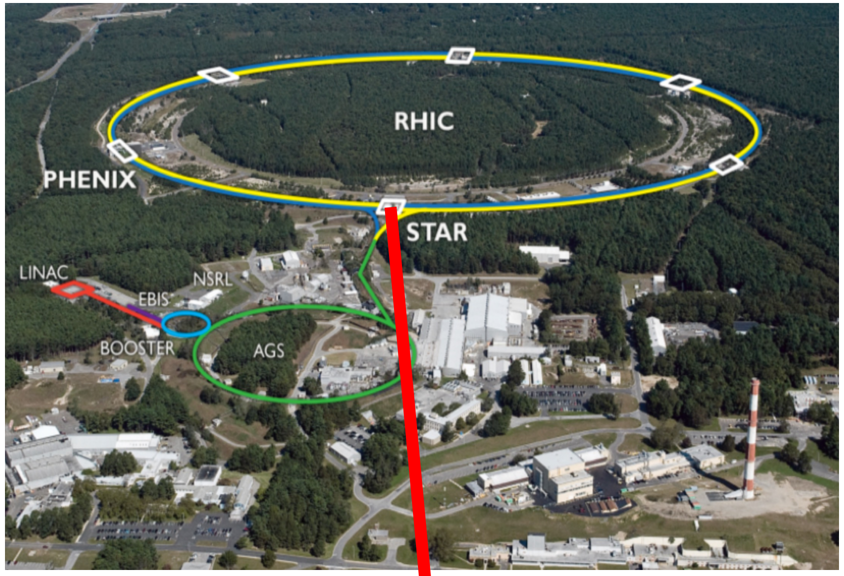
RHIC and the STAR experiment

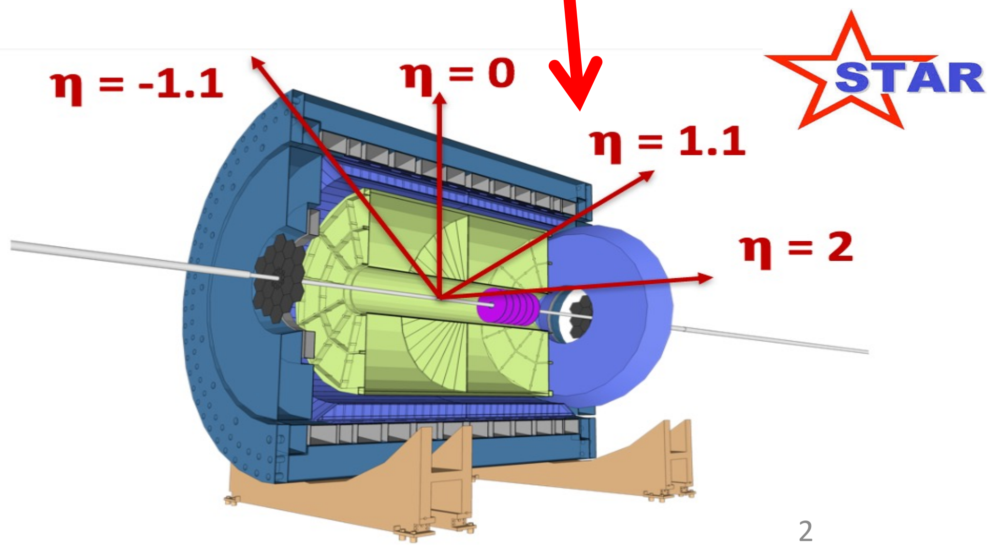
RHIC is the world's first and only polarized hadron collider

Beams: √s = 200 - 510 GeV *p+p*; 50-60% polarization





- 2π coverage Electromagnetic Calorimeter
  - Barrel: -1 < η< 1
  - End-cap: 1.1 < η < 2
- Main tracker – Time Projection Chamber (TPC): |η| < 1.3

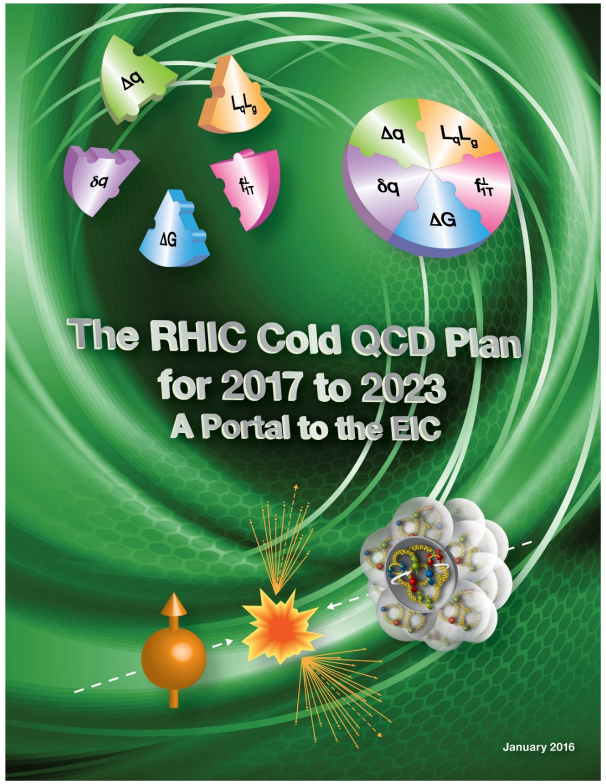


The Cold QCD program

Probing the cold nuclear matter via strong interactions in p+p and p+A collisions

- What is the origin of the proton spin?
- What is the landscape of the (un)polarized see quarks in a nucleon?
- Understand QCD processes in cold nuclear matter
  - Investigate transverse-spin effects in QCD
- What is the initial state in nuclear collisions?

arXiv:1501.01220



arXiv:1602.03922

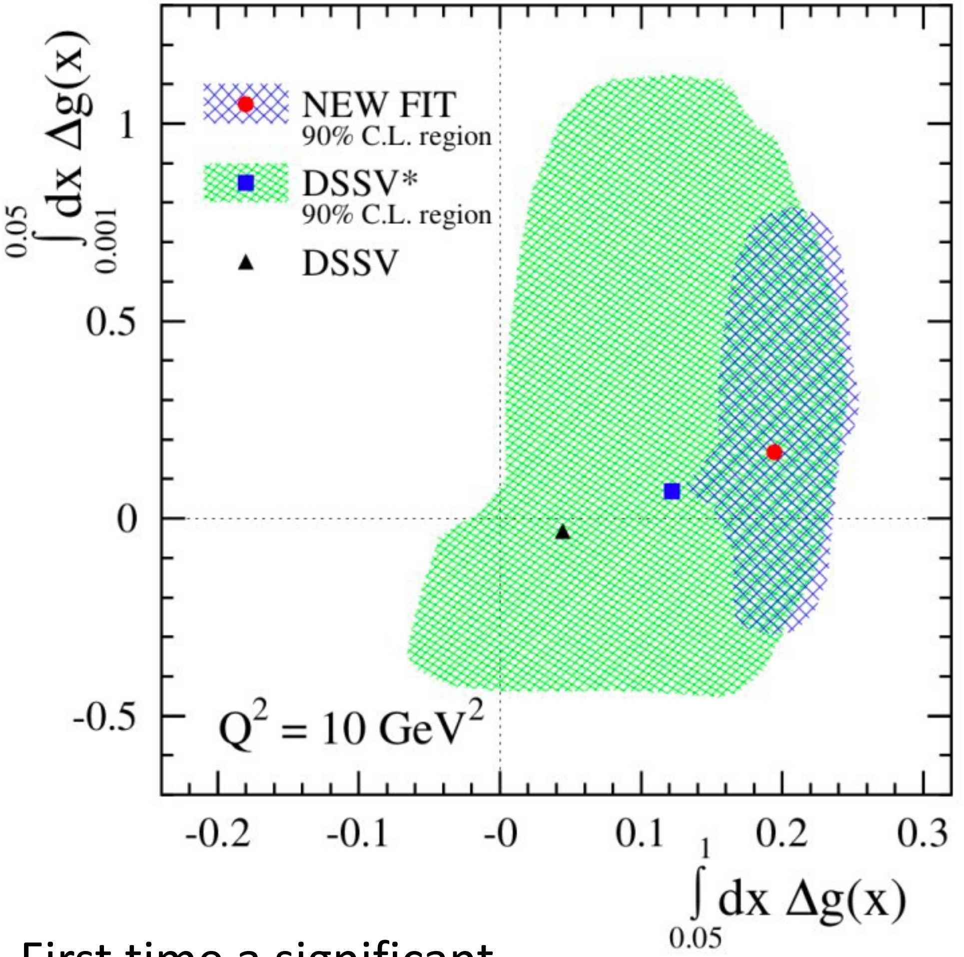
Helicity of gluons

Jaffe-Manohar Spin Sum Rule:

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2} | J^z_{QCD} | P,\frac{1}{2} \right\rangle = \sum_q \frac{1}{2} S^z_q + S^z_g + \sum_q L^z_q + L^z_g$$

New Fit: DIS (fixed targ.) + RHIC (till 2009)

Phys.Rev.Lett. 113 (2014) no.1, 012001



Process:

$\vec{p} + \vec{p} \rightarrow$ jets,dijets $+ X$

Observable:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

- RHIC energies are sensitive to qg, gg interactions
  → access to $\frac{\Delta g(x)}{g(x)}$

- First evidence for gluon polarization driven by STAR inclusive jet measurements at √s = 200 GeV (2009 run data) – [PRL 115 (2015) 9, 092002]

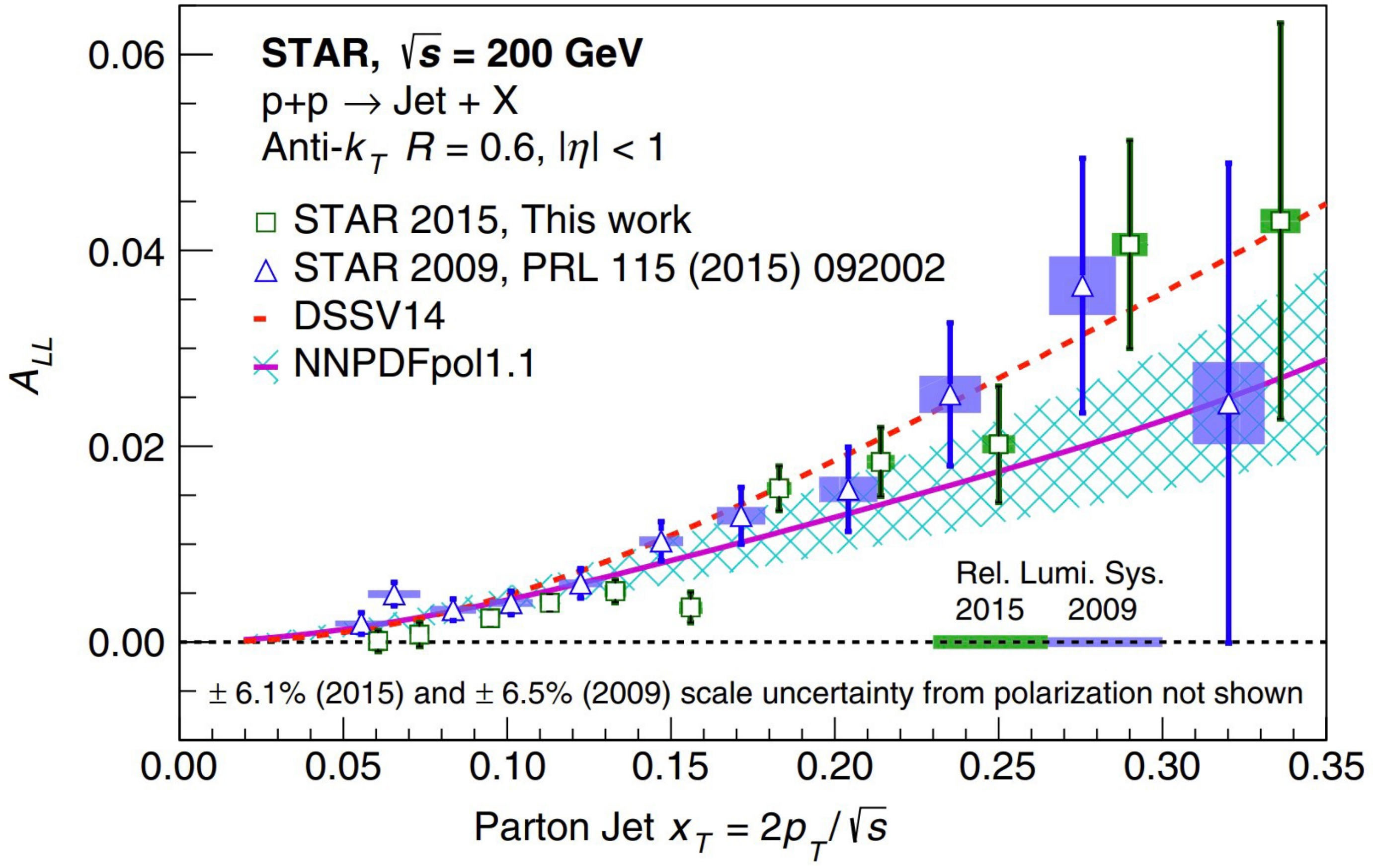
  → global fits: $\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07}$ $@Q^2 = 10$ GeV^2

First time a significant non-zero $\Delta g(x)$

Inclusive jets from run 2015 at 200 GeV

$\vec{p} + \vec{p} \rightarrow \text{jets} + X$

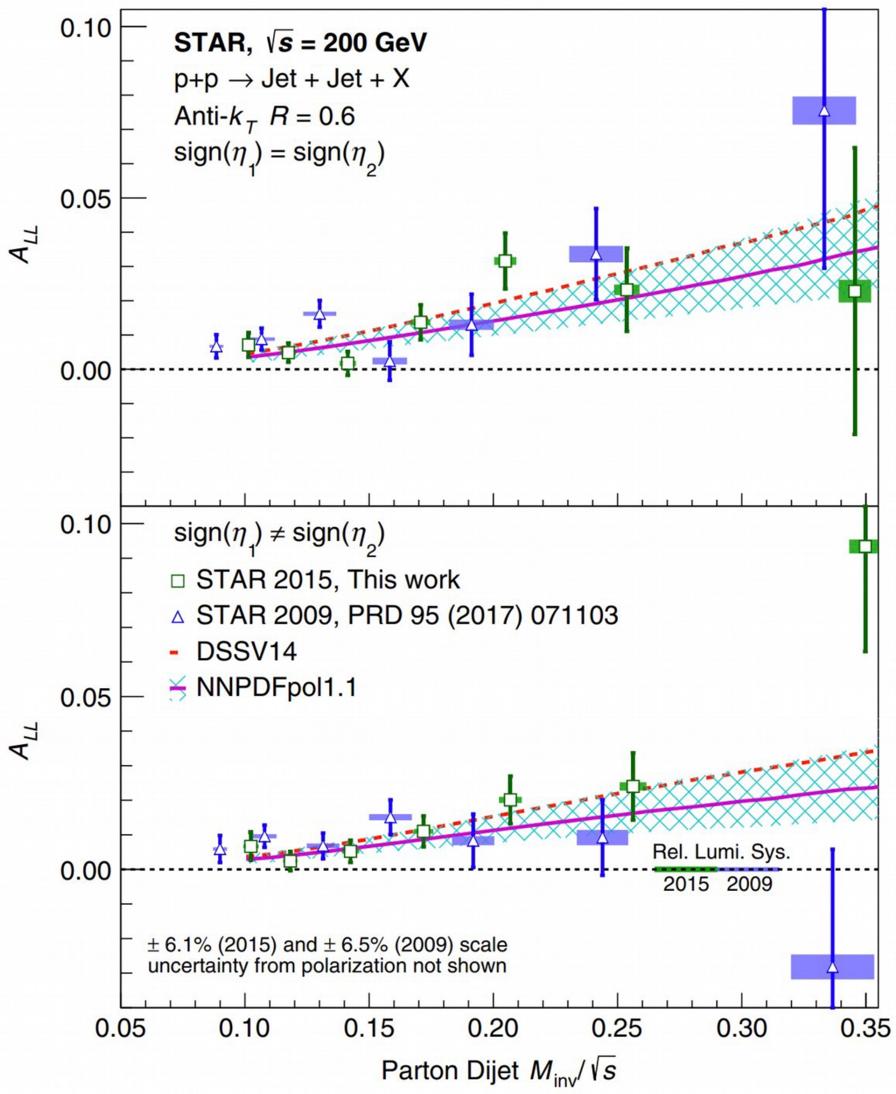
Phys. Rev. D 103, L091103 (2021)



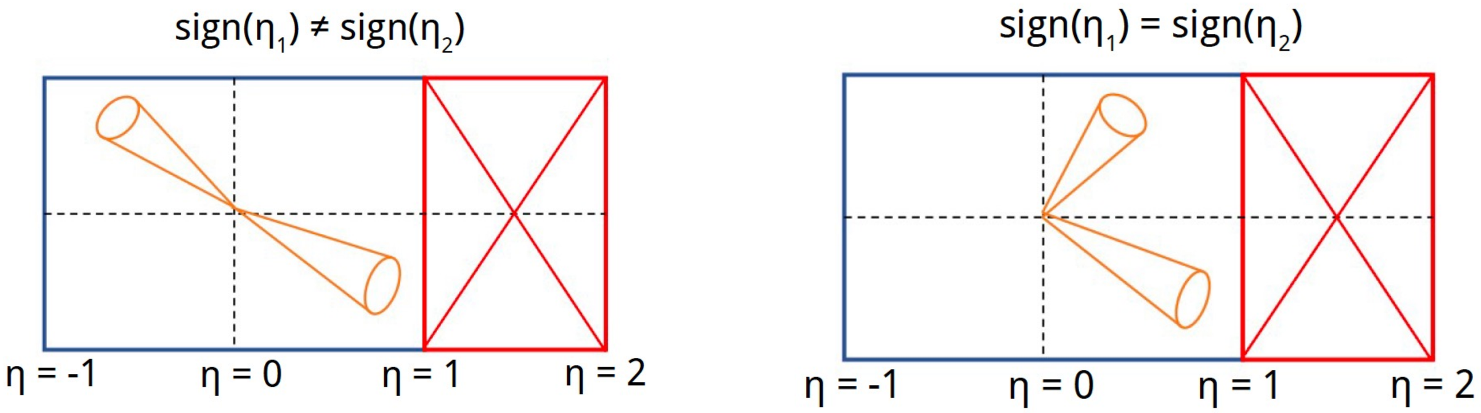
- Newly published 2015 data consistent with results from 2009
- Twice larger figure-of-merit (LP^4) and improved systematics
- When included into global fits, will further reduce uncertainty on $\frac{\Delta g(x)}{g(x)}, x > 0.05$

Dijets from run 2015 at 200 GeV

Phys. Rev. D 103, L091103 (2021)

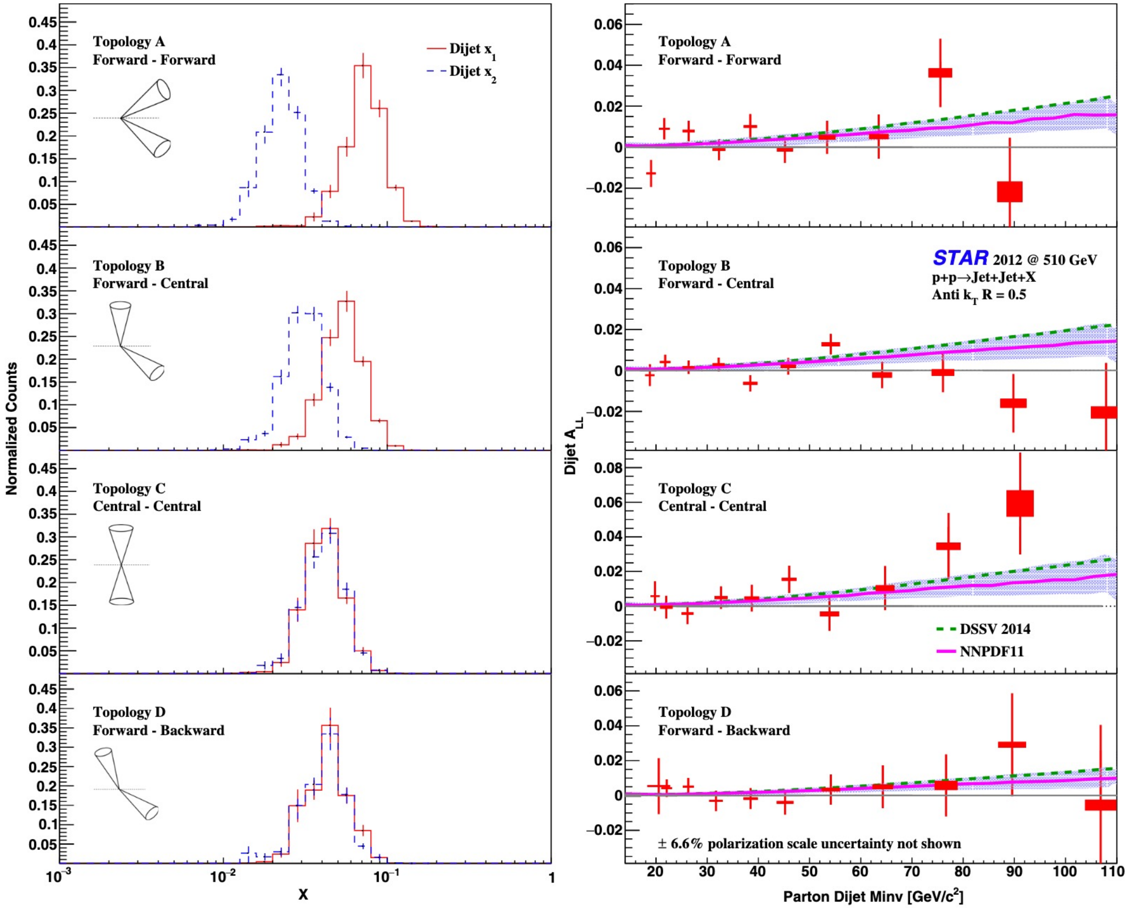


$$\vec{p} + \vec{p} \to \text{jet} + \text{jet} + X$$

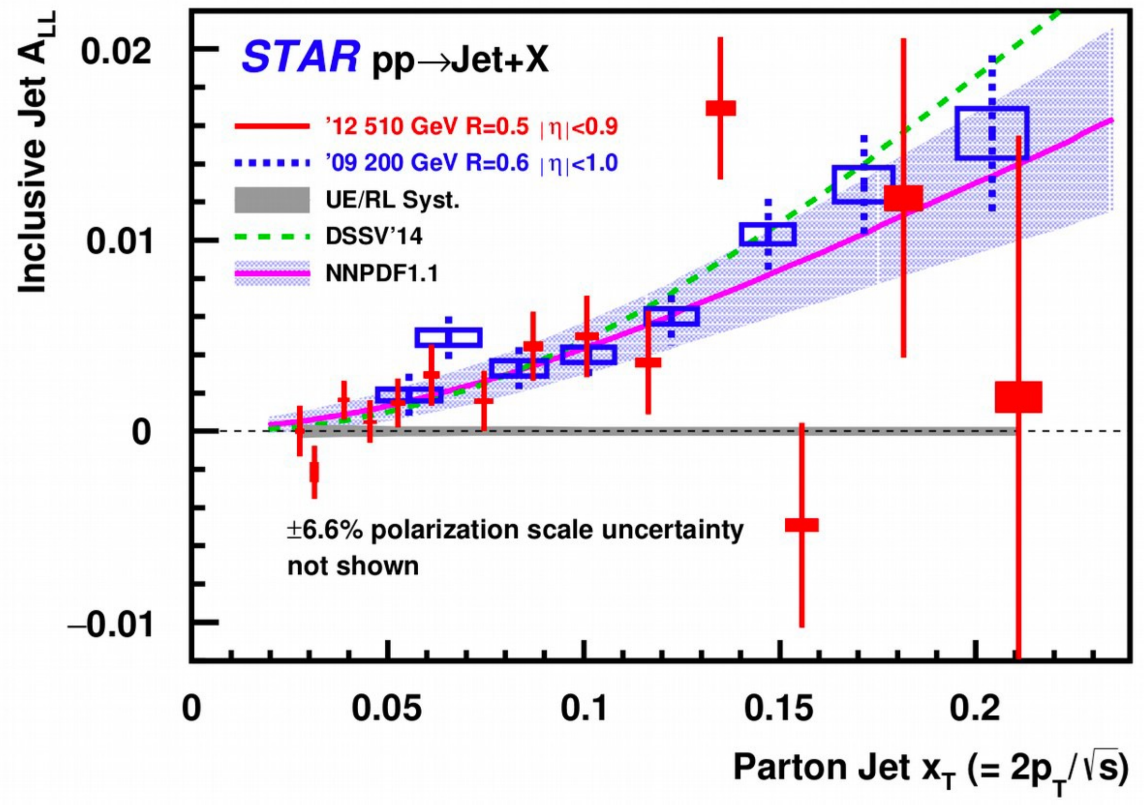


- Dijets give more stringent constraints to underlying partonic kinematics
  - Better constraints on functional form of $\Delta g(x)$ - narrow ranges of initial state partonic momentum probed
- Will further improve precision of $\Delta g(x)$ at $x > 0.05$
- STAR forward endcap: extends coverage down to $x \gtrsim 0.01$

Inclusive jets and dijets from run 2012 at 510 GeV



Phys Rev. D 100 (2019), 052005

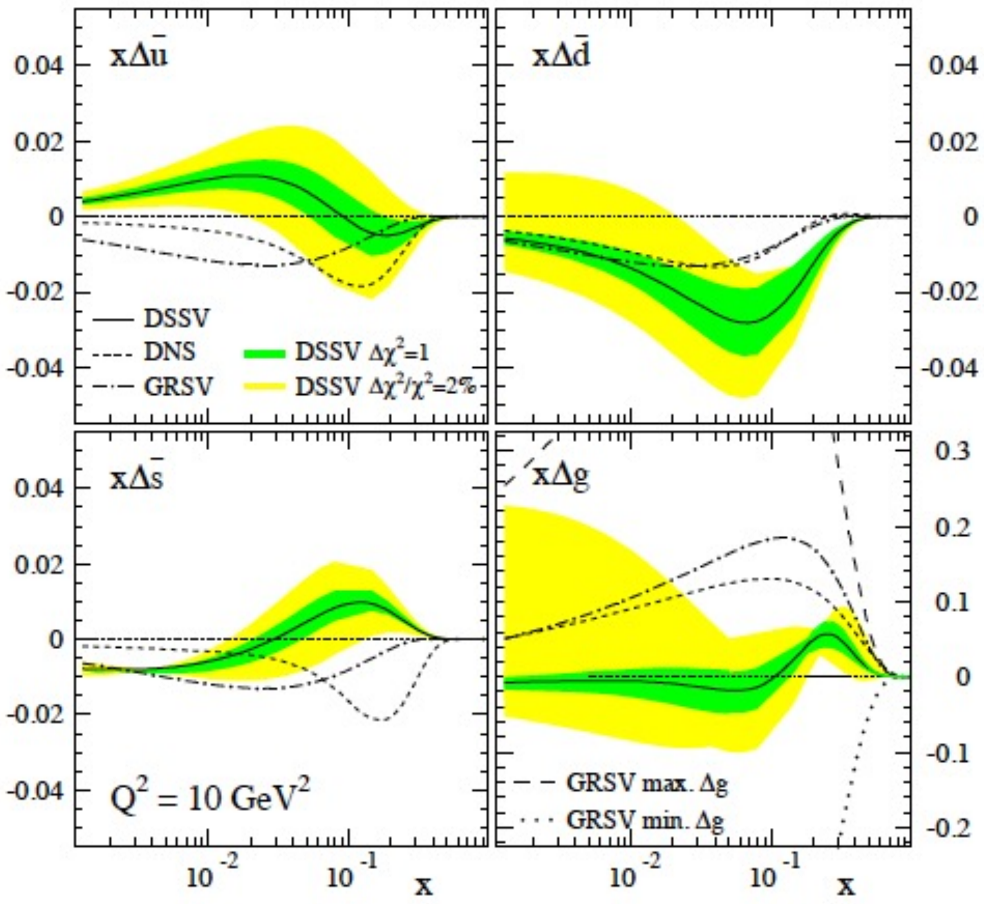


- Higher c.o.m. energy → smaller *x* [$x \gtrsim 0.004$ with STAR endcap dijets]
- Results from 510 GeV compatible with 200 GeV at the same x_T
- Analysis of run 2013 will add f.c.t. ~3.5 more statistics with respect to run 2012

Helicity of sea quarks

Jaffe-Manohar Spin Sum Rule:

$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} | J^z_{QCD} | P, \frac{1}{2} \right\rangle = \sum_q \frac{1}{2} S^z_q + S^z_g + \sum_q L^z_q + L^z_g$$



Observable: $A_L = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$

At LO:

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

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

- A_L of $W^{\pm}$ bosons → decompose quark flavors
  - Decay process is easily calculable: no fragmentation fcn.
  - flavor asymmetry of the light quark sea in the proton

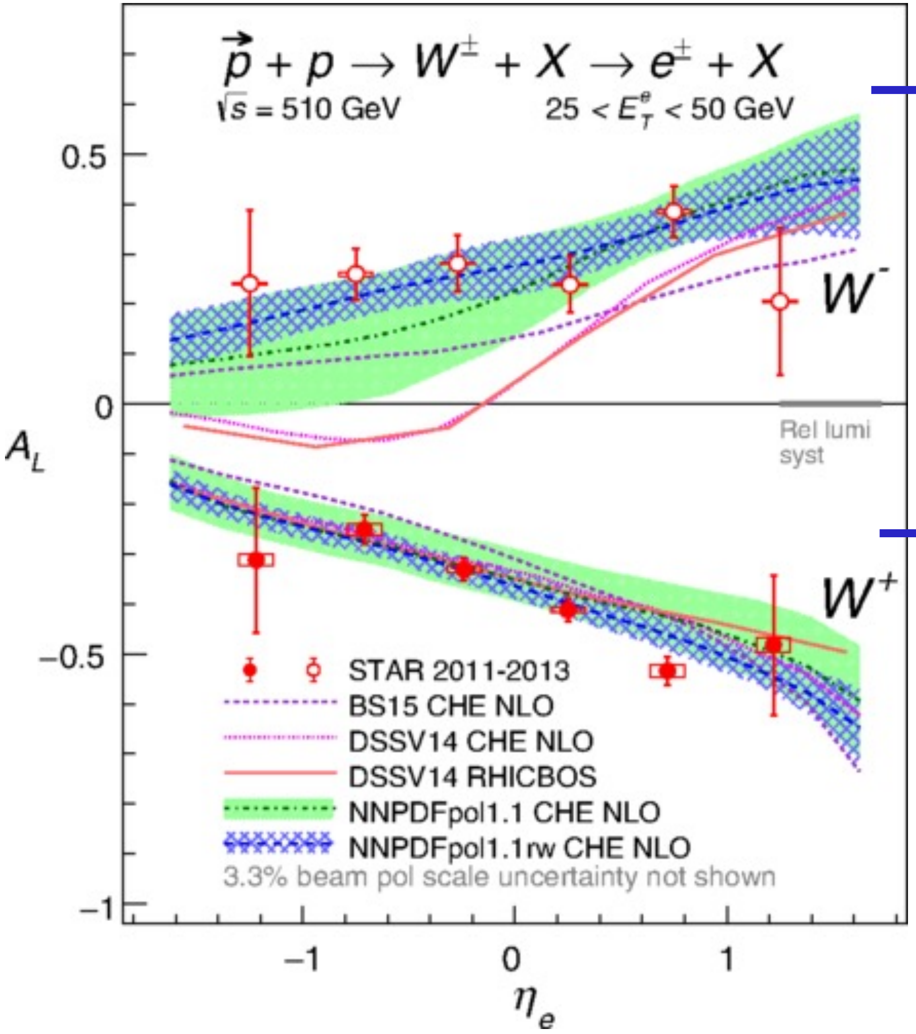
unpolarized: ubar ≠ dbar

polarized case?

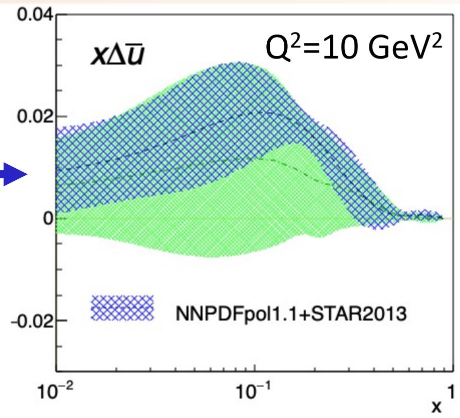
A_L in W production

NNPDFpol1.1 reweighting

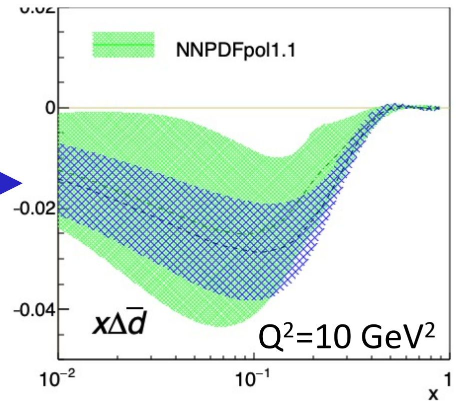
Phys, Rev. D 99, 051102(R) (2019)



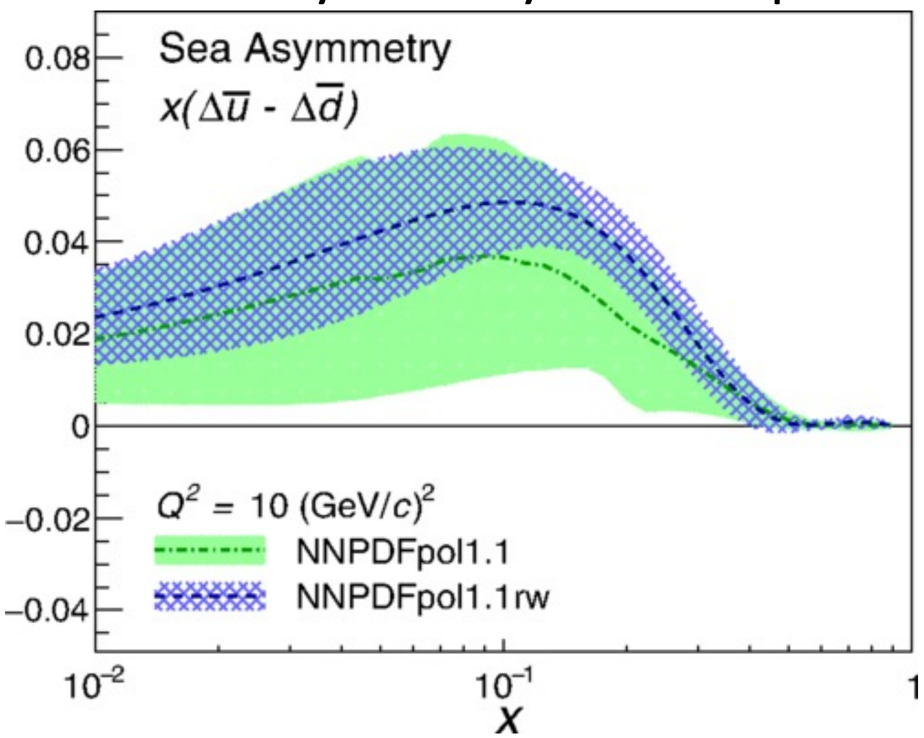
$\Delta\bar{u}$



$\Delta\bar{d}$



Flavor asymmetry for sea quarks

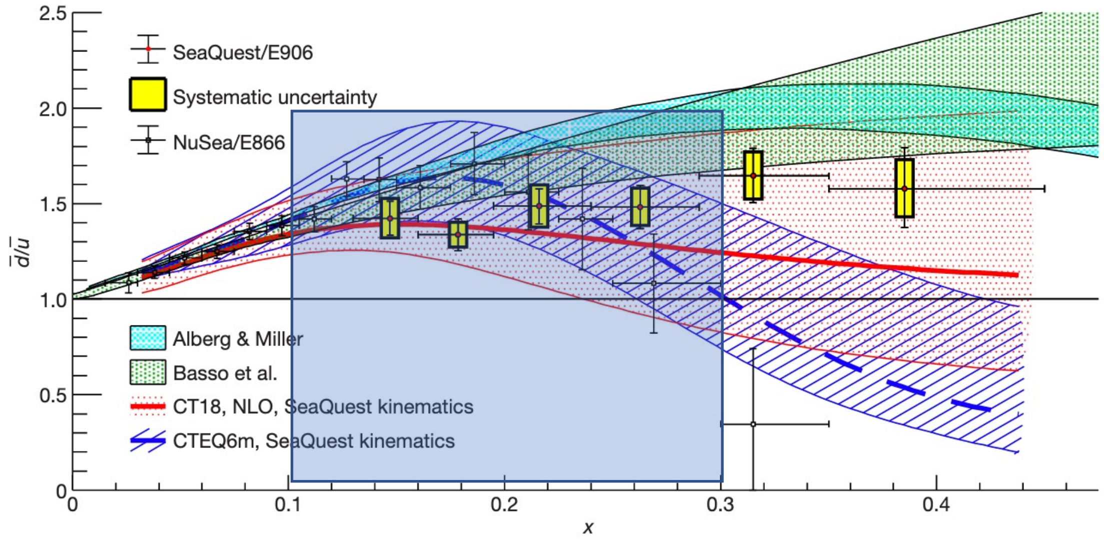


- **40% reduced uncertainties** after adding STAR run 2013
- Good agreement with DSSV and NNPDF
- **First evidence for polarized flavor asymmetry**
  - Data show a **significant preference** for $\Delta\bar{u} > \Delta\bar{d}$ for $0.05 < x < 0.25$ at $Q^2 = 10$ GeV^2

Quark flavor ratio in PDFs

- Unpolarized $\bar{d}/\bar{u}$ in PDFs can be probed via Drell-Yan
- **E-866** suggests a trend where the $\bar{d}/\bar{u}$ ratio appears to be decreasing at large-*x*, but **new SeaQuest** trend appears to level out at **higher *x***.
- **Unpolarized W cross-section charge ratios** are also **sensitive** to **quark/anti-quark** distributions.

Nature 590, 561–565 (2021)



LO:

$$\frac{\sigma(W^+)}{\sigma(W^-)} = \frac{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)}$$

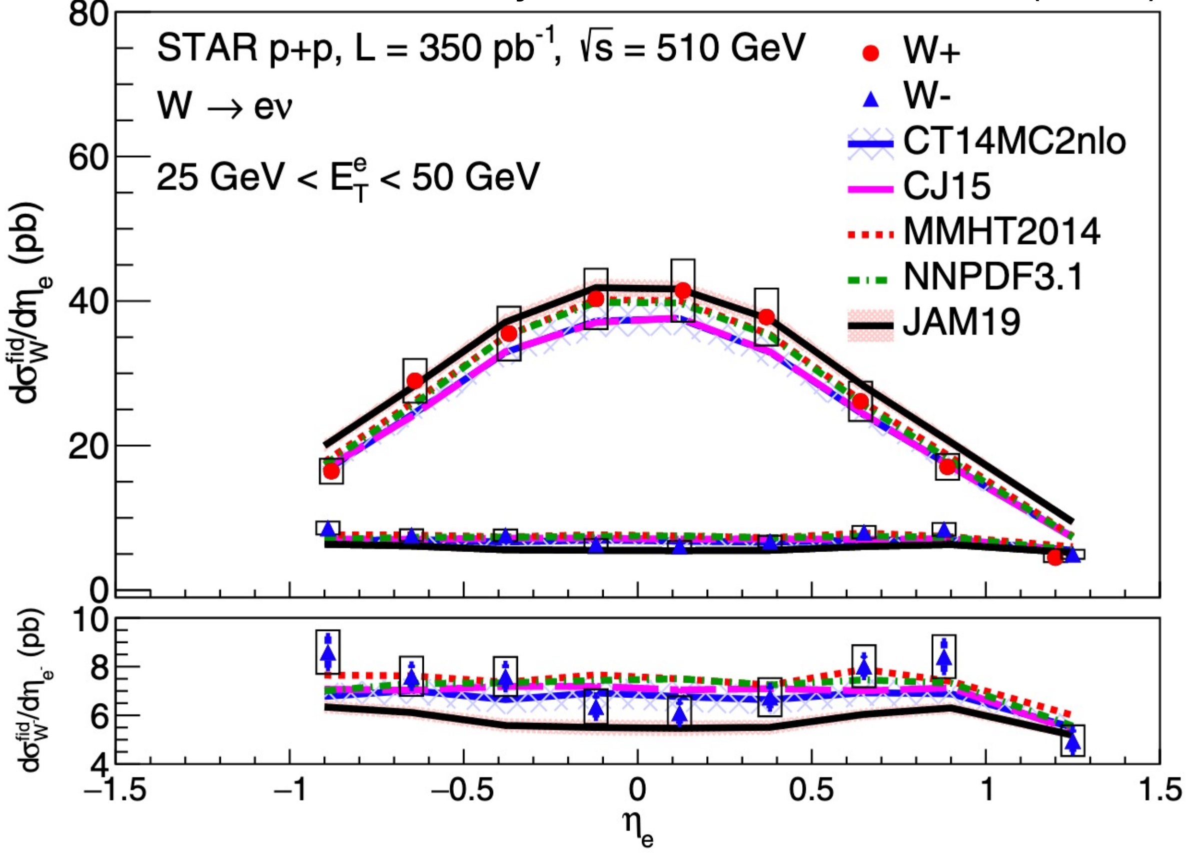
- Complementary to Drell-Yan data: $|\eta| < 1$: 0.1 < x < 0.3, at higher $Q^2 = M_W^2$
  - **LHC coverage:** ~10^{-3} < x < 10^{-1}

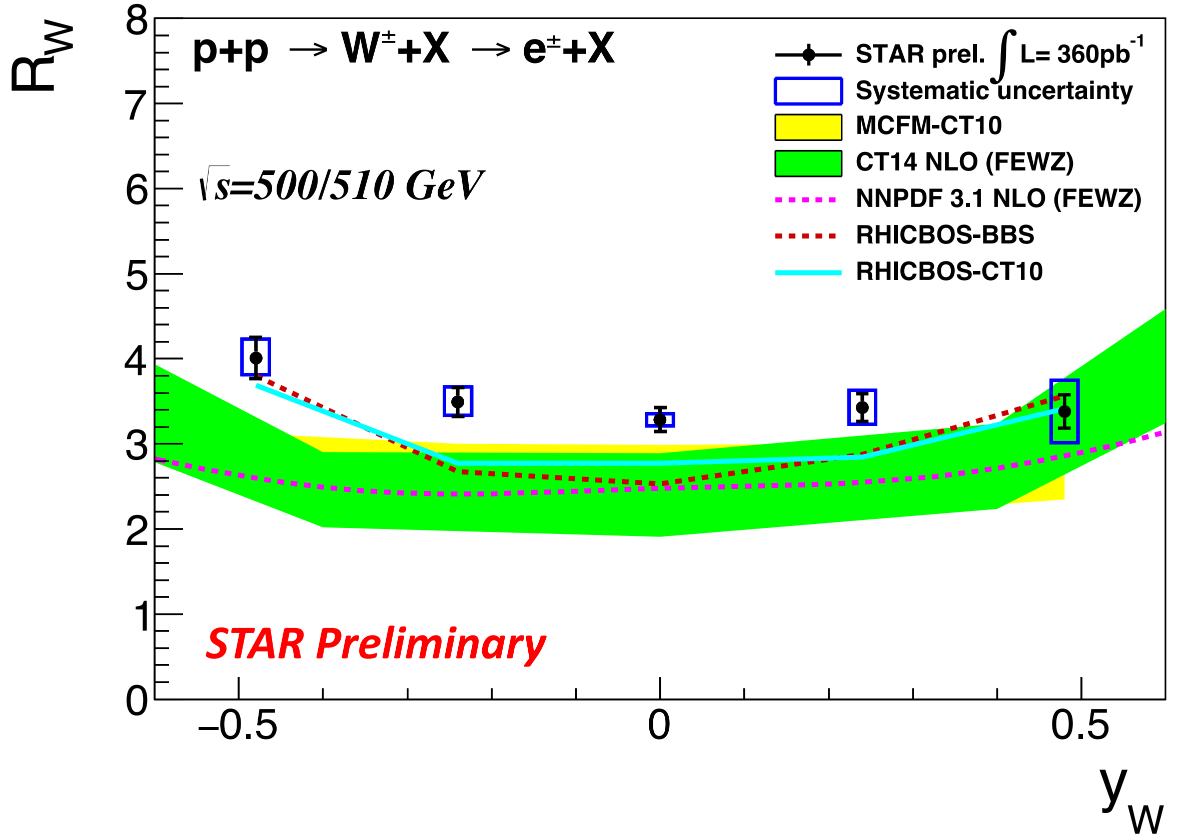
    $$\langle x_{1,2}\rangle = \frac{M_W}{\sqrt{s}} e^{-\eta_l/2}$$

  - **STAR coverage:**
    - **Mid-rapidity** $-1 < \eta < 1$ (**TPC +BEMC**) : 0.1 < x < 0.3
    - **Forward EEMC** $1.1 < \eta < 2$: 0.06 < x < 0.4
- Differential cross sections of weak bosons are key inputs in global fits of **unpolarized TMDs**

Unpolarized W^+/W^- differential cross-section ratios

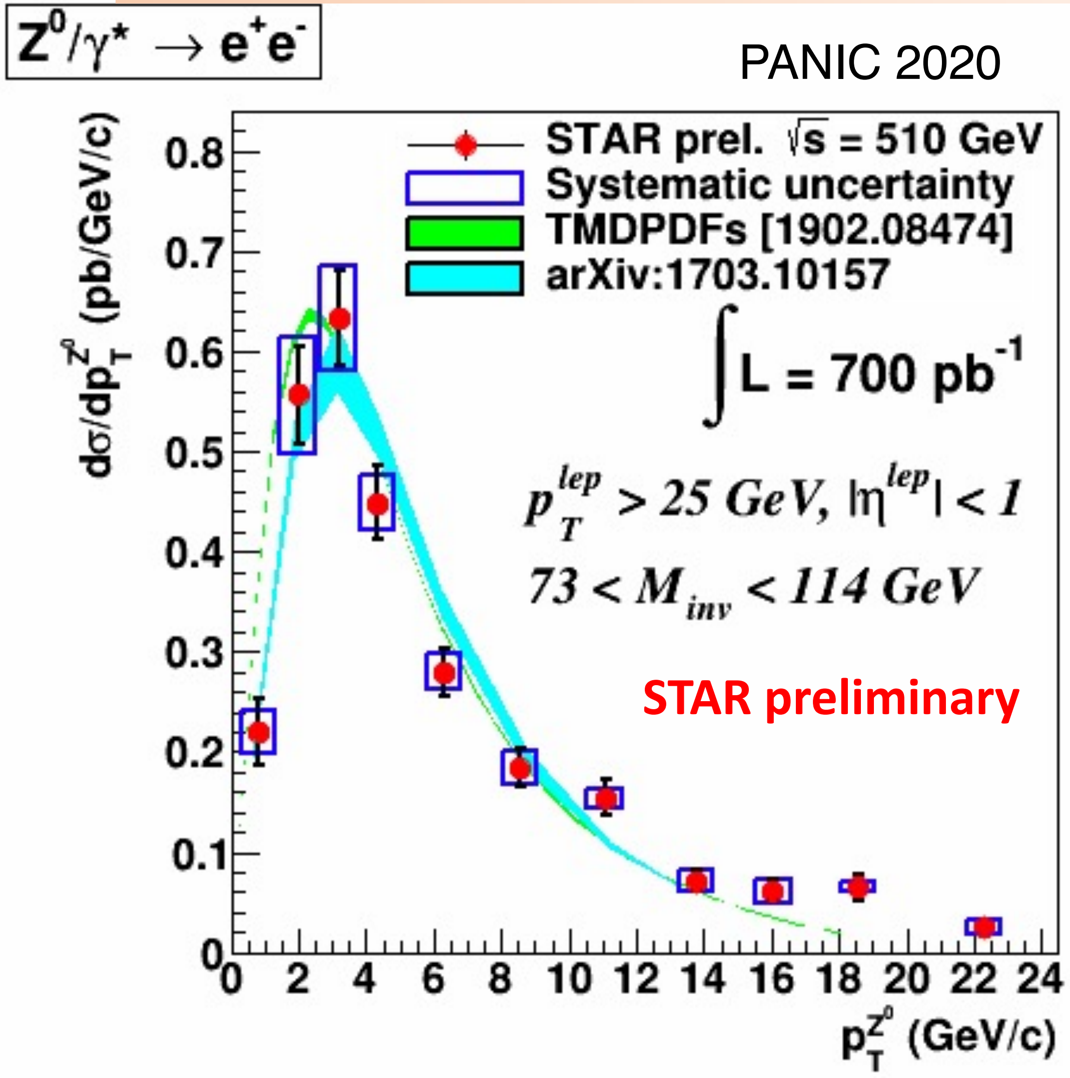
Phys. Rev. D 103, 012001 (2021)

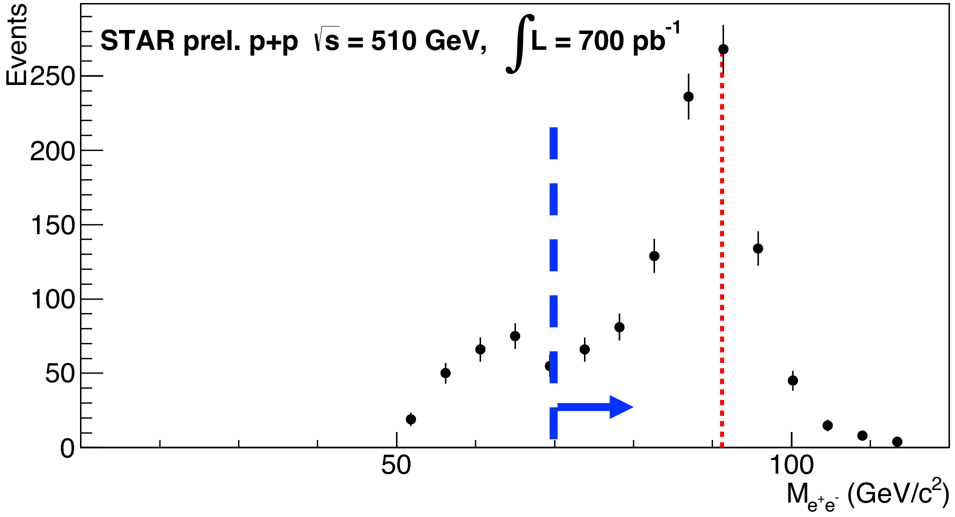




- Cross section charge ratio measured vs. both the decay lepton and the boson's kinematics
- Will provide insights into unpolarized light quark distributions *d(x), u(x),* and $\frac{\bar{d}}{\bar{u}}$ at $x > 0.05$
- Run-17 will add an additional ~350 pb^{-1}, Run-22 expected to add another ~400 pb^{-1}

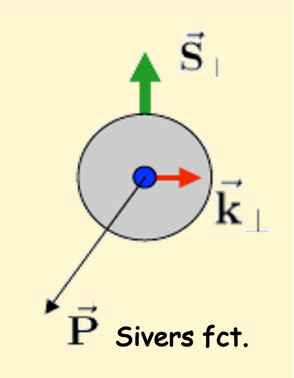
Unpolarized Z^0 p_T-differential cross section





- **Now includes data from 2017:** ~2 more statistics compared to previous release
  - Unfolded p_T spectrum
  - Systematics from energy resolution and electron selection
- Key input to global fits of unpolarized TMDs
- New theory fits including all STAR measurements will be added as they become available

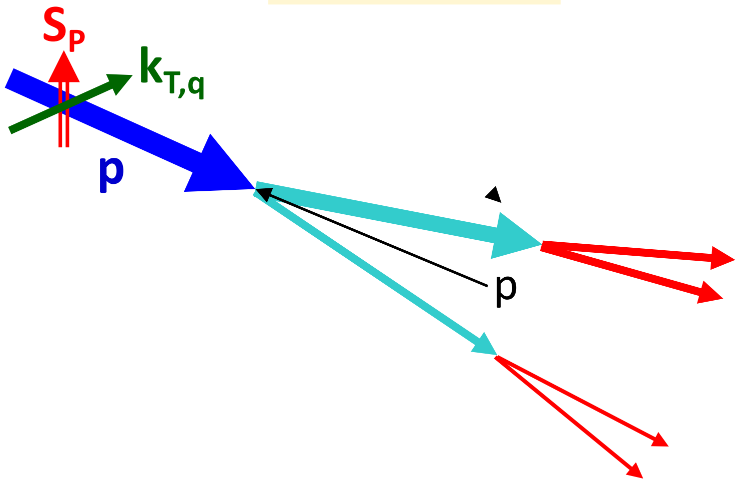
Sivers function



8 Transverse Momentum Dependent distribution functions (TMDs) are allowed by gauge invariance

The TMD known as **Sivers function** is

- Sensitive to **transverse proton spin** – parton **transverse motion** correlations
- Predicted not to be universal between SIDIS & p+p
  - **Sivers$_{DIS}$ = - Sivers (DY or W or Z)**
- Weak bosons:
  - less background compared to DY
  - higher $Q^2 = M_W^2$: can test evolution effects
  - sensitive to sea quarks
  - but: need for reconstructing produced boson's kinematics

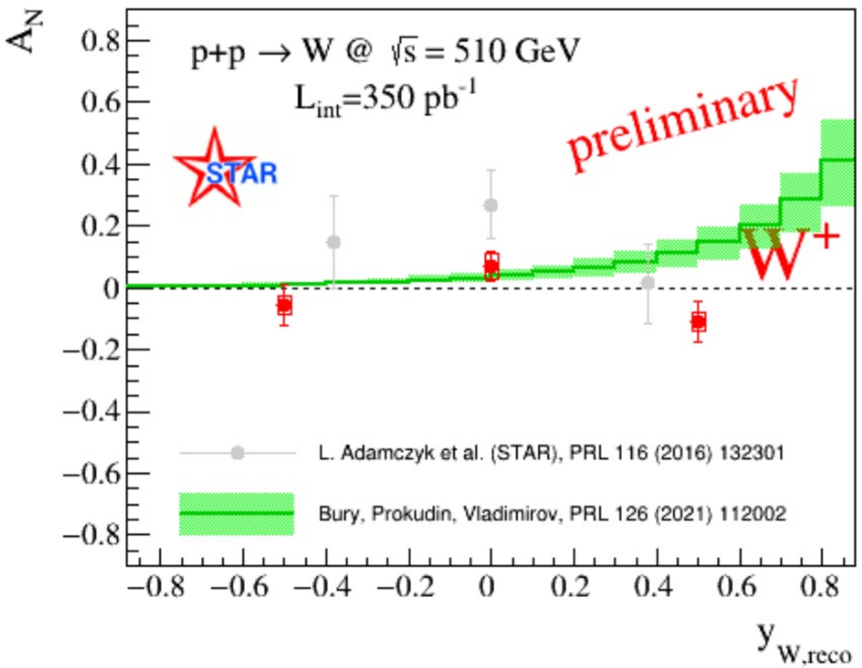


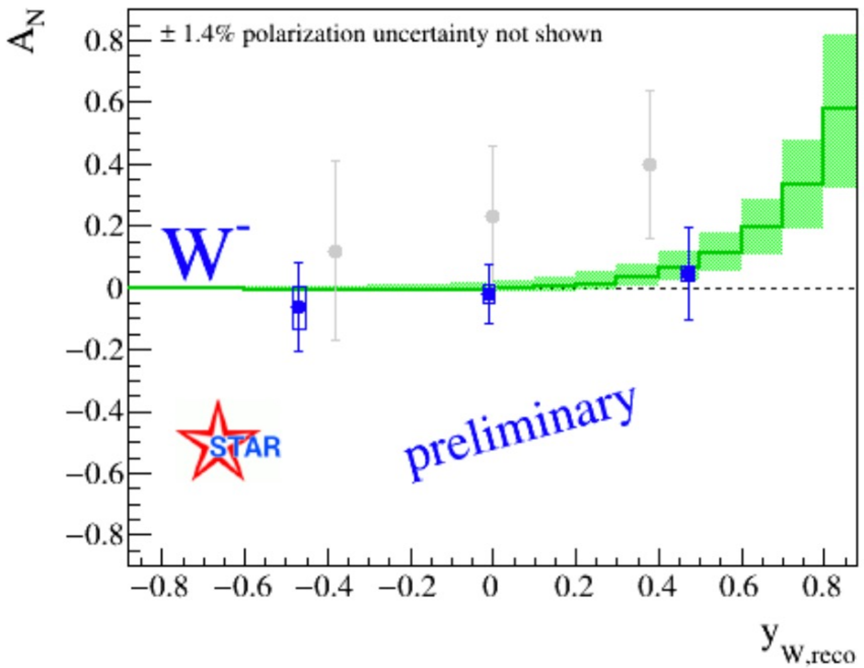
Tools to measure Sivers:

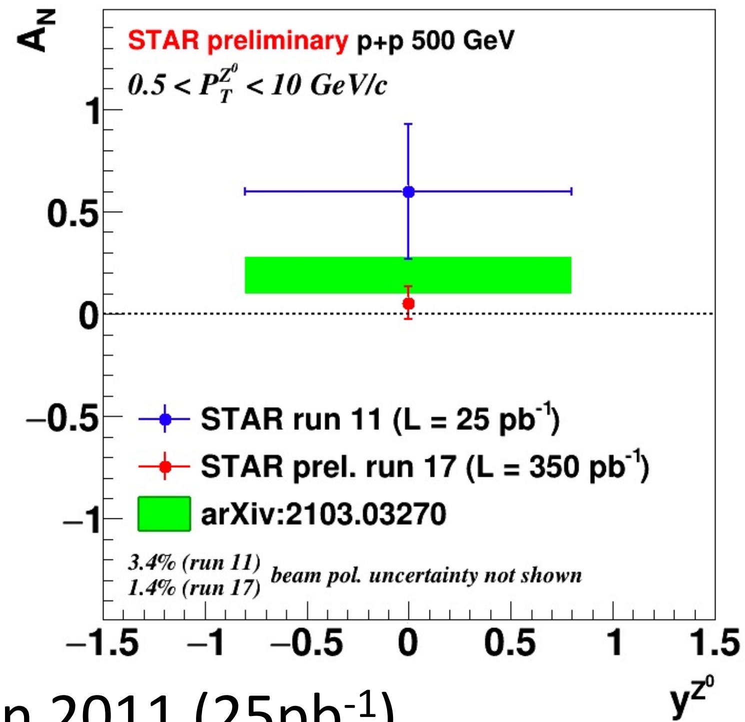
Transverse single-spin asymmetry amplitude (azimuthal modulation)

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

A_N in weak boson production





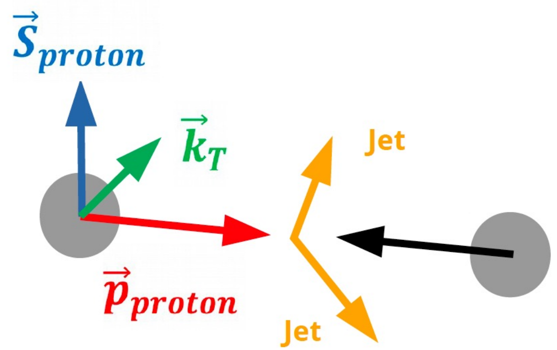


- **Statistics much improved with run 2017 (350pb^{-1})** compared to run 2011 (25pb^{-1})
- Prediction by Bury, Prokudin, and Vladimirov PRL 126, 112002 (2021) – assumes sign change
  - Extraction includes SIDIS, DY and STAR run 2011 results
  - Comparison with other fits will be added as they become available
- Current STAR data not yet significant enough to make claims on the sign-change
  - Expect ~400 pb^{-1} more data from run 2022, with η coverage extended by STAR iTPC

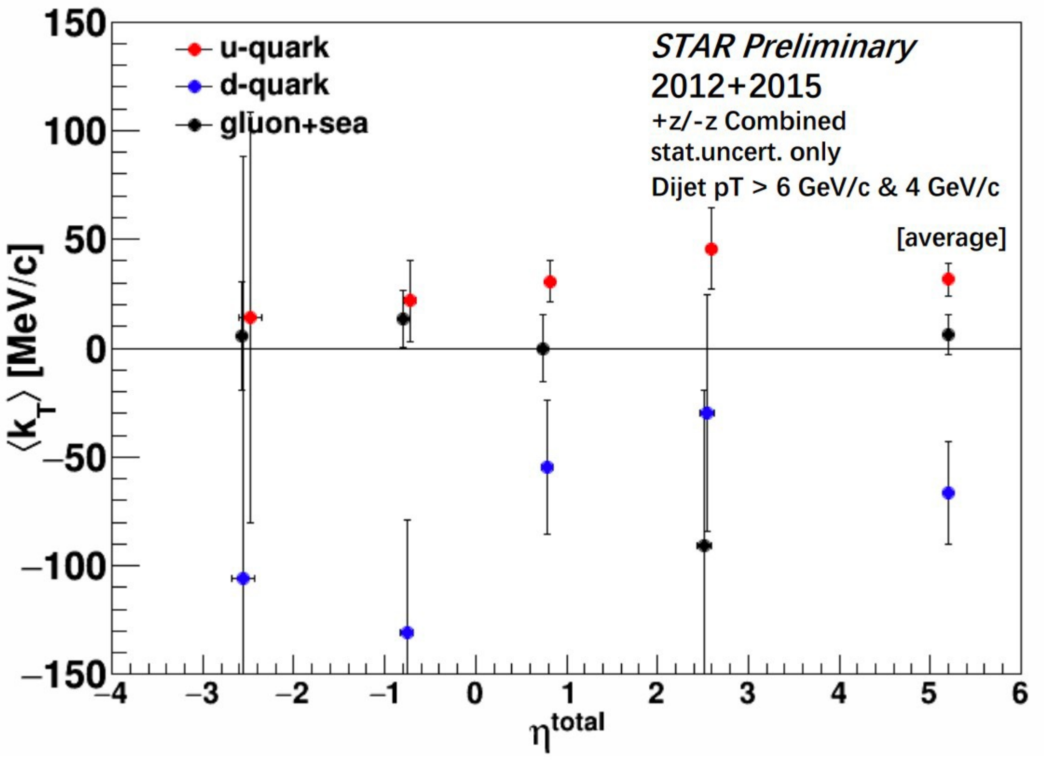
Asymmetry in dijets opening angle

Sivers fnc. is sensitive to correlation between transverse **proton spin** (initial state) and **parton transverse momentum**

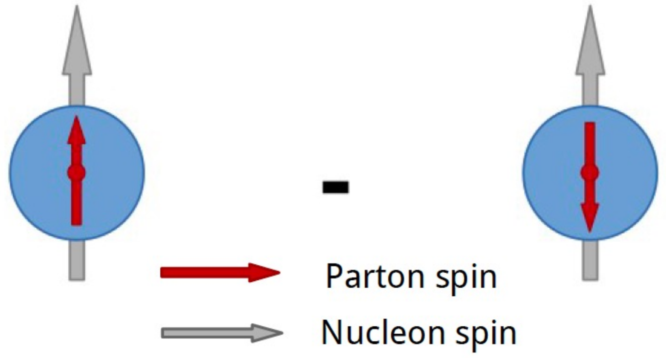
$$\langle \vec{S}_{proton} \cdot (\vec{p}_{proton} \times \vec{k}_T) \rangle \neq 0$$



- Non-zero k_T leads to a spin-dependent tilt of dijet opening angle in transverse plane
- Enhancing contribution of *u* or *d* quarks by sorting jets by their net charge
- Tilt unfolded for the k_T of individual partons
- **Results:** k_T for *d quark* opposite in sign, and twice larger than the average k_T for u quarks
- Constraints for the Sivers fnc. at a high Q^2 scale (Q^2 > 160 GeV^2)



Transversity



Describes the net density of **quarks with spin aligned with the transversely polarized nucleon** (leading twist)

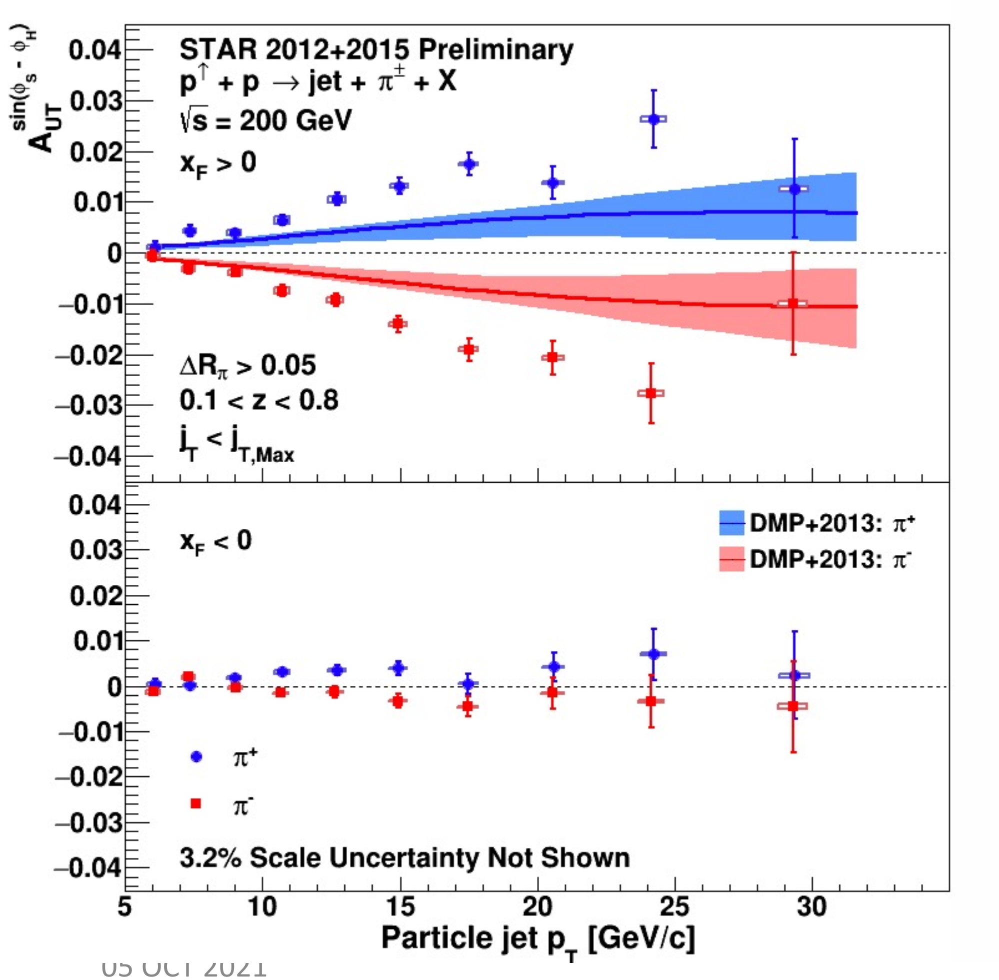
- **Tools:** azimuthal modulation of **transverse single-spin asymmetry amplitude (A_{UT})**

- **At RHIC:** sensitivity via two A_{UT} amplitudes:
  - **Spin-dependent modulation of hadrons in jets**
    - **Collins function (TMD FF) -** Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron
  - **Di-hadron correlation measurements**
    - **"interference FF"** (collinear framework) - Correlation of transverse spin of fragmenting quark and momentum cross-product of di-hadron pair

Transversity

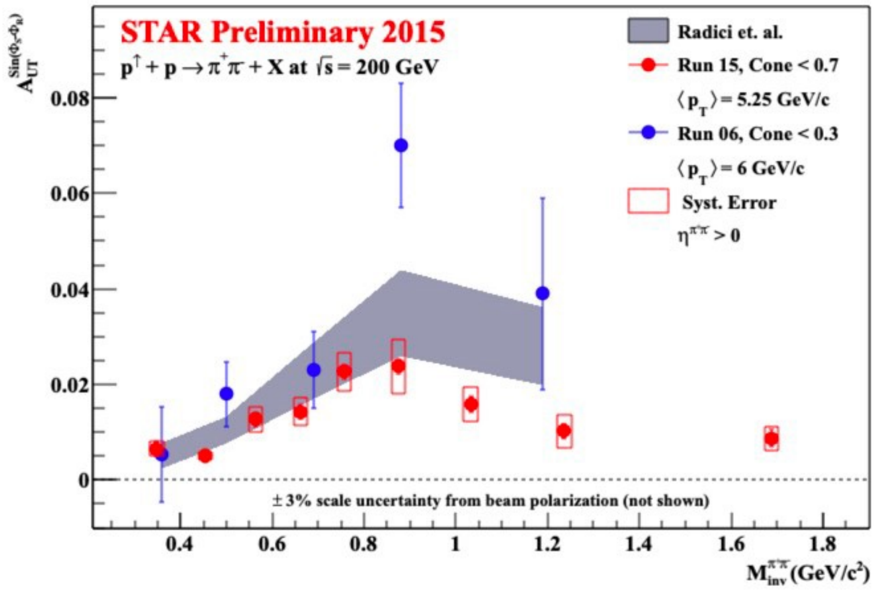
Spin-dependent modulation of hadrons in jets

Collins function (TMD FF)



Di-hadron correlation measurements

"interference FF"

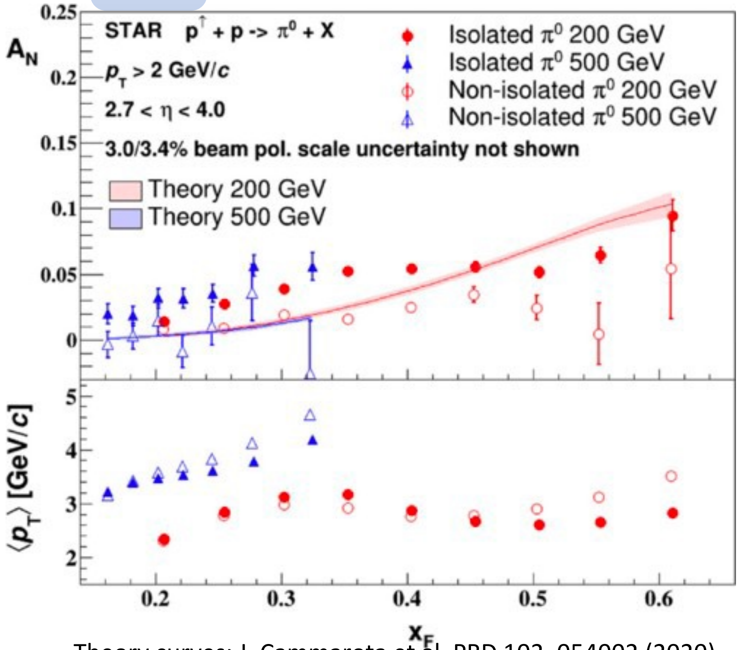


- Significant Collins asymmetries have been observed from 200 GeV data:
  - Collinear transversity is probed most directly in the jet p_T dependence;
  - Collins TMD FF is sensitive to the (j_T, z) dependence.

Forward transverse single spin asymmetries

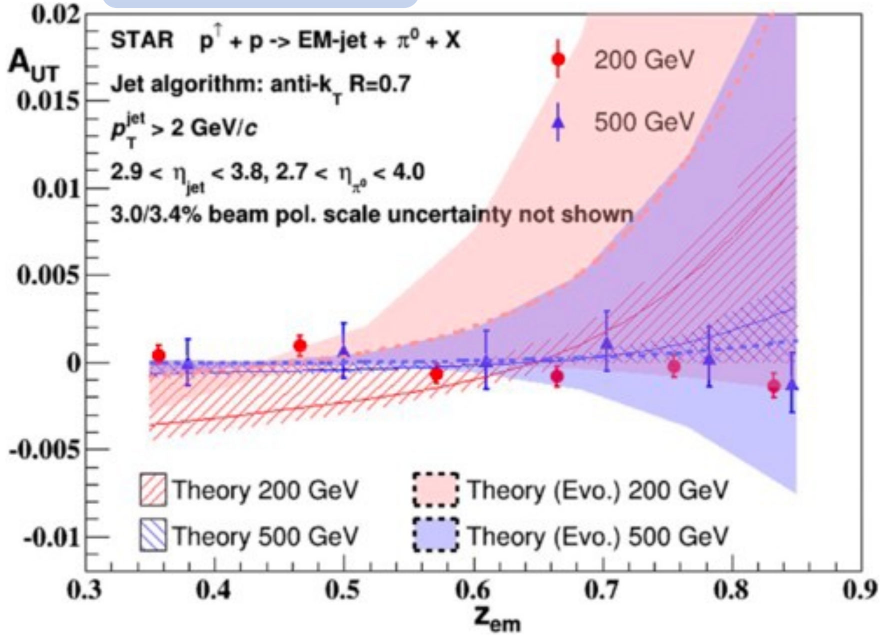
Phys. Rev. D 103 (2021) 92009

π^0



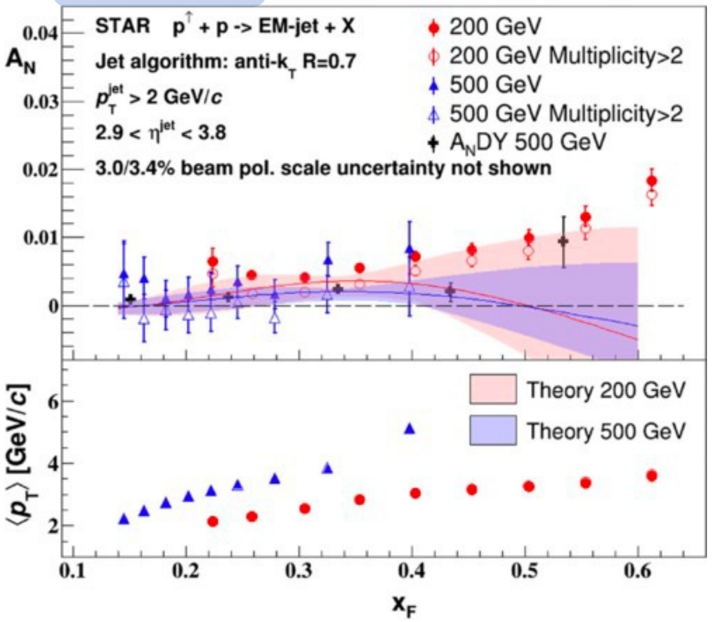
Theory curves: J. Cammarota et al. PRD 102, 054002 (2020)

π^0 in EM-jet



Theory curves : Z. Kang, et al. PLB 774, 635 (2017)

EM-jet



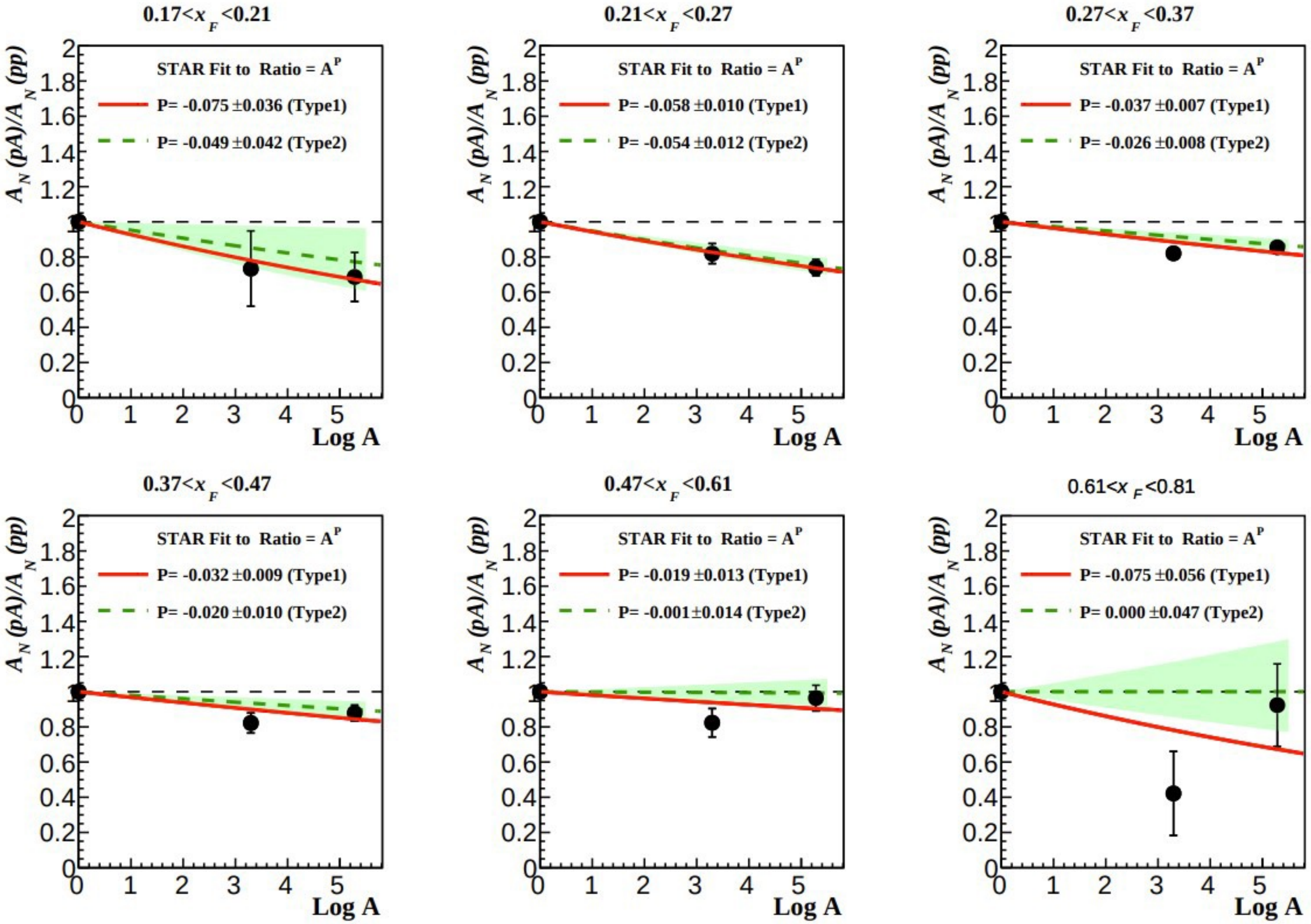
Theory curves : L. Gamberg, Z. Kang, A. Prokudin,PRL 110 23, 232301 (2013)

- Investigating the origin of the large asymmetries
- **Results:**
  - Observed A_N for EM-jets and Collins asymmetry for π^0 within EM jets are small
  - A_N for non-isloated π^0 and for π^0 within higher-multiplicity jets are even smaller
  - Weak dependence of the collision energy

Nuclear dependence of forward transverse asymmetries

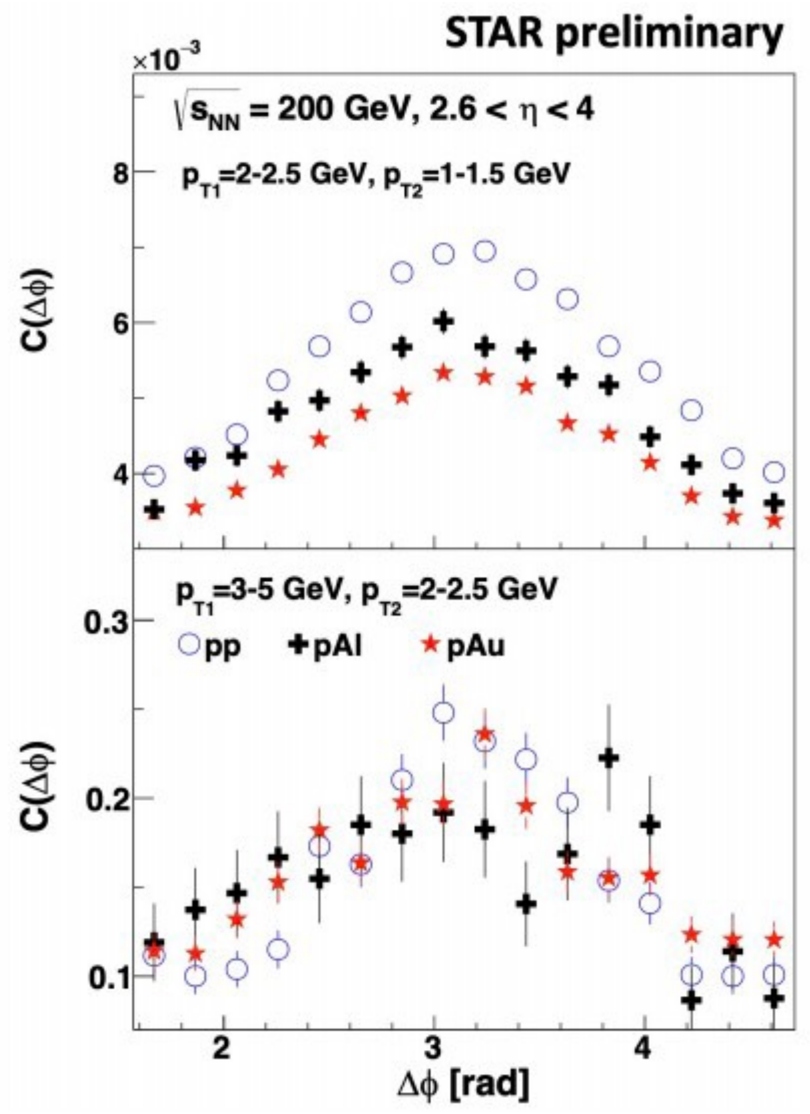
Phys. Rev. D 103 (2021) 92009

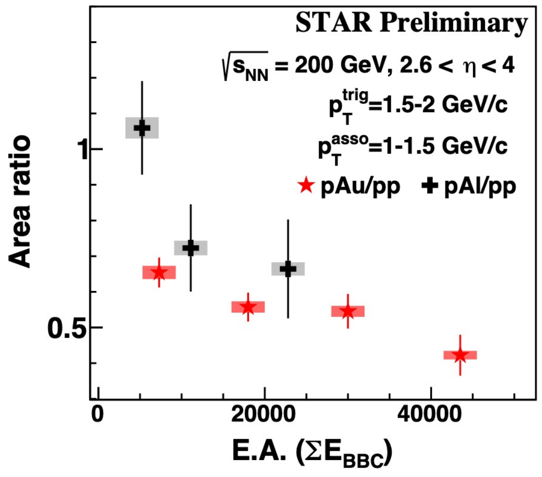
Investigating the **nuclear dependence** $A_N(p+A)/A_N(p+p)$

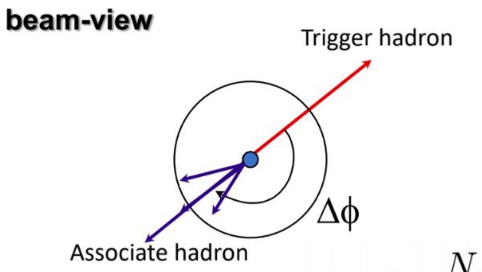


- The nuclear modification of transverse spin asymmetries is related to parton saturation in the color glass condensate
- **STAR π^0 coverage:**
  - **$2.6 < \eta < 4.0$**
  - $0.2 < x_F < 0.7$
  - $1.5 < p_T < 7$ GeV
- A mild nuclear dependence observed in a regime where perturbative effects are relevant
- New opportunities to use p+A collisions as a tool to investigate the rich phenomena behind TSSAs in hadronic collisions

Di-hadron correlations







$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}}$$

Area: integral from $\frac{\pi}{2}$ to $\frac{3\pi}{2}$

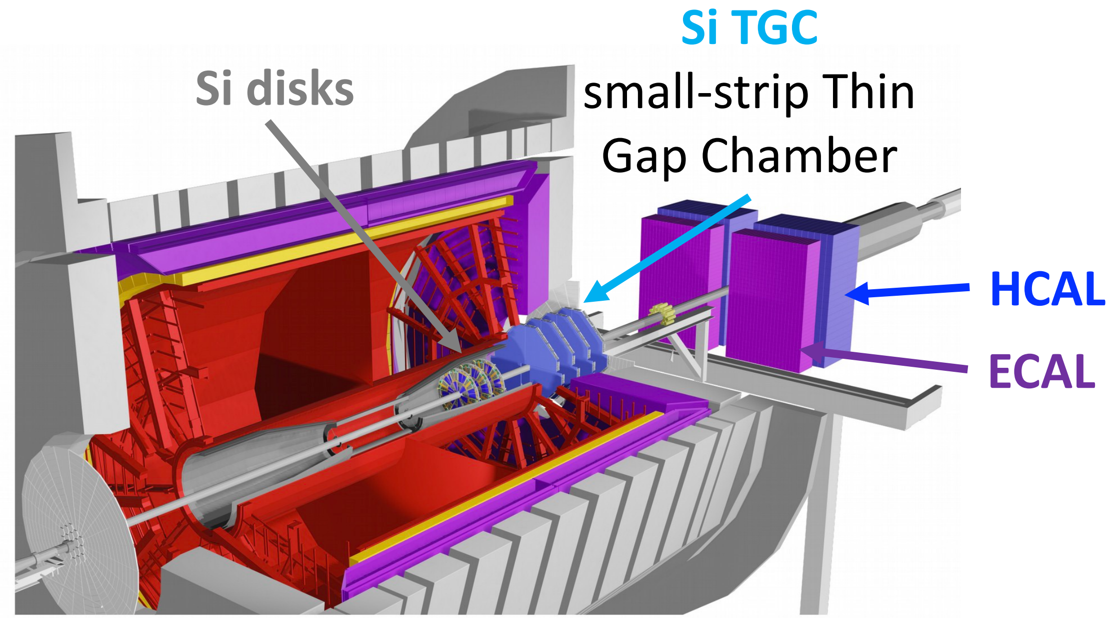
- Measure the azimuthal correlation between two final hadrons in p+p and p+A
  - **p+p:** 2→2 process ⇒ back-to-back di-hadron
  - **p+A:** back-to-back configuration is smeared by multiple gluon interactions
- Access to non-linear gluon dynamics at small *x* (e.g. gluon saturation)
  - Remember: saturation scale grows with *A* and decreases with x

Results

- Clear signature of non-linear gluon dynamics with di-hadron correlation
- Evidence for a nuclear **dependence:** stronger suppression in p+Au than p+Al
- **Event activity dependence:** suppression enhanced in "high activity" collisions at low p_T

STAR forward upgrade

Run 2022: p↑+p↑ collisions at 510 GeV with forward upgrade and enhanced PID at mid-rapidity



Forward rapidity 2.5 < η < 4
TMD measurements at high *x*   • Sivers through tagged Drell-Yan, jets, direct photon   • Transversity at high *x* + Collins/IFF
Mid rapidity -1.5 < η < 1.5
Improved statistical precision and the extended η acceptance of iTPC   • Sivers measurements with *W/Z* and dijets   • Transversity + Collins/IFF   • Unpolarized *W/Z* cross section

Enhanced capabilities:

- Forward jet capability and charge-sign discrimination of charged particles
  - **Tracking:** Si disks + small Thin Gap Chambers
  - **Calorimetry:** hadronic and electromagnetic
- Access to highly asymmetric partonic collisions: high-*x* quark and low-*x* gluon interactions

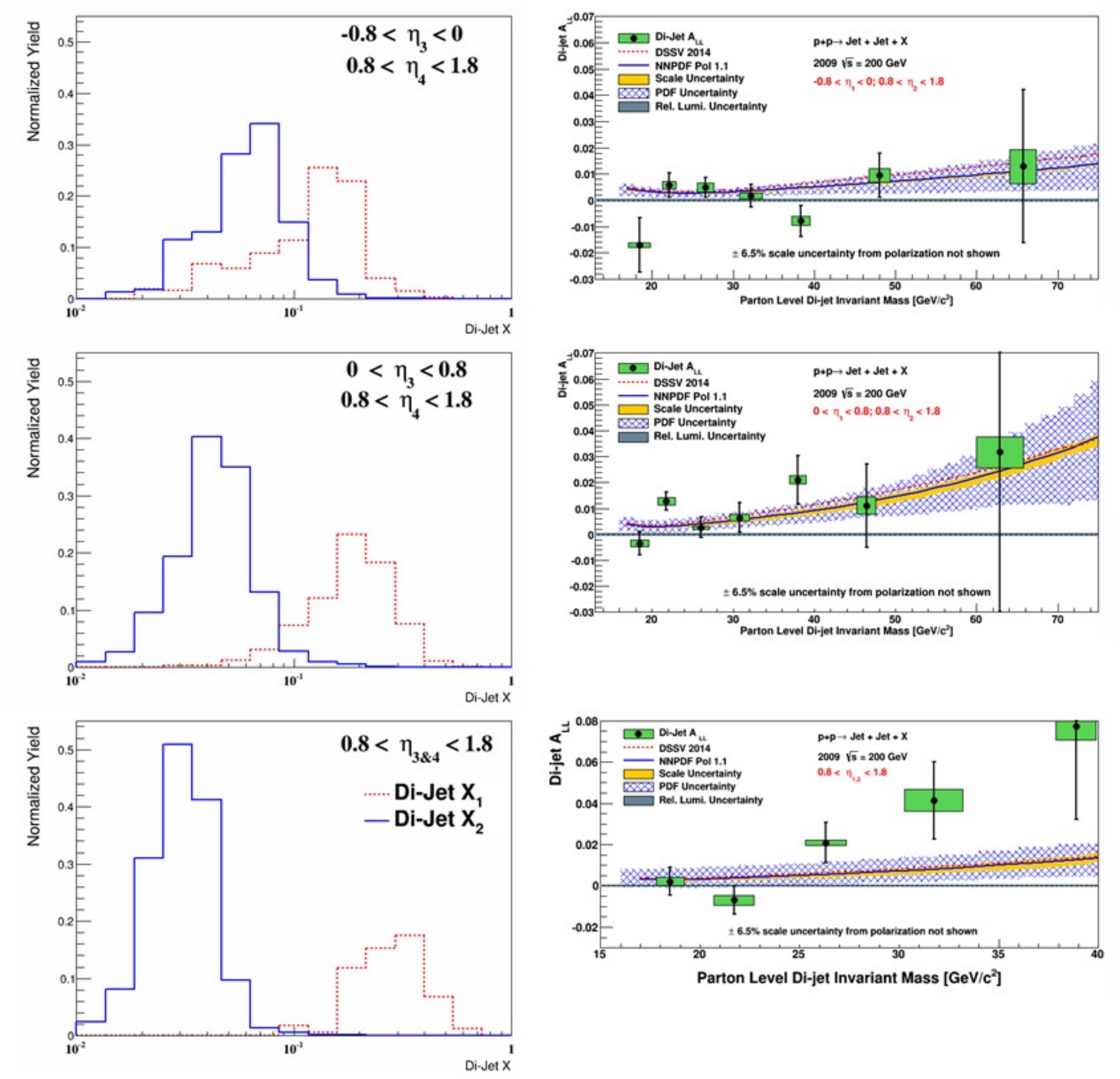
Conclusions

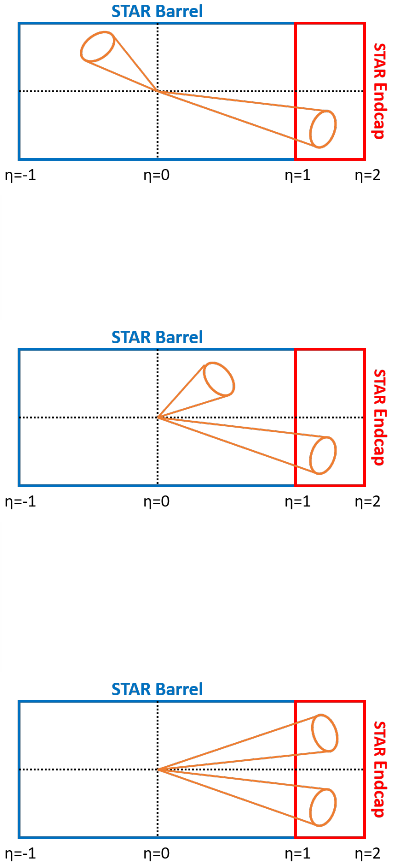
- **Rich Cold QCD program at STAR**
- **STAR data have provided key (often unique) insight into the spin structure of a proton**
  - Evidence for the positive gluon polarization for $x > 0.05$
  - The polarized and unpolarized sea quark distributions via W/Z production
- **Sivers function**
  - A_N from weak bosons consistent with sign change
  - Non-zero Sivers effect observed in dijets
- **Transversity through the Collins and IFF asymmetry**
  - Non-zero asymmetries at mid-η that are sensitive to quark transversity at hard scales
- **Non-linear gluon dynamics via di-hadron correlations**
  - Observed suppression in p+A over p+p at small x and grows with A
- **Forward upgrade provides new physics opportunities**


BACKUP

Dijets at moderate forward rapidity

Phys. Rev. D**98** (2018) 032011





- **Inclusive jets**

$$x \approx x_T e^{\pm\eta}$$

$$x_T = 2p_T/\sqrt{s}$$

- **Dijets**

$$x_1 = (p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})/\sqrt{s}$$

$$x_2 = (p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})/\sqrt{s}$$

$$M = \sqrt{x_1 x_2 s}$$

$$|\cos\theta^*| = \tanh(|\eta_3 - \eta_4|/2)$$