STAR BUR 2022: 500 GeV $p + p$ Run

Jim Drachenberg

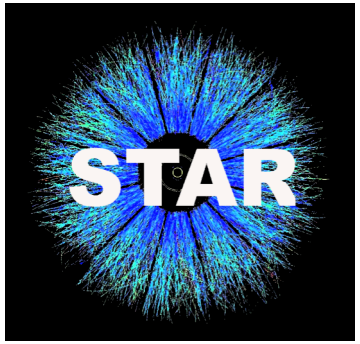
BNL NPP PAC Meeting

June 10, 2019

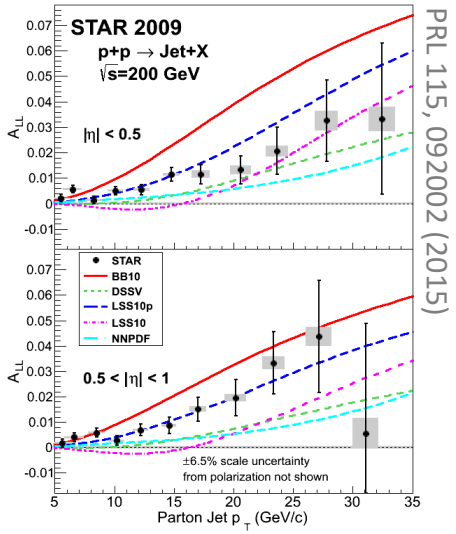
OUTLINE

- Open Questions in Cold QCD
- Timeframe and Vital Stats
- Transversity
- Gluon Helicity
- Summary

ABILENE CHRISTIAN UNIVERSITY



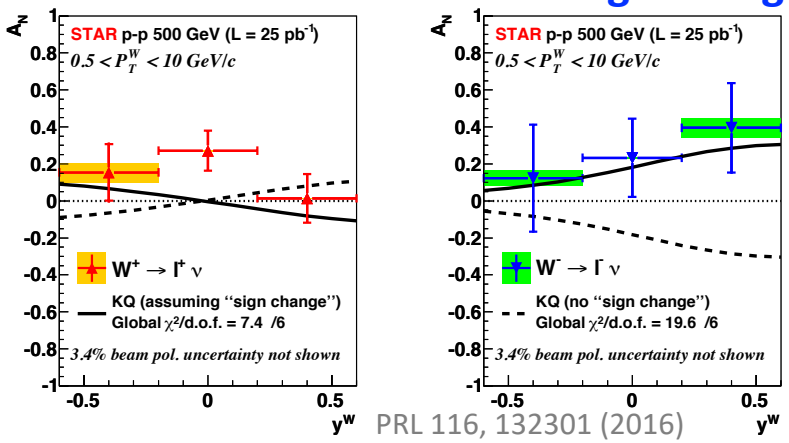
STAR Cold QCD results have significant impact!



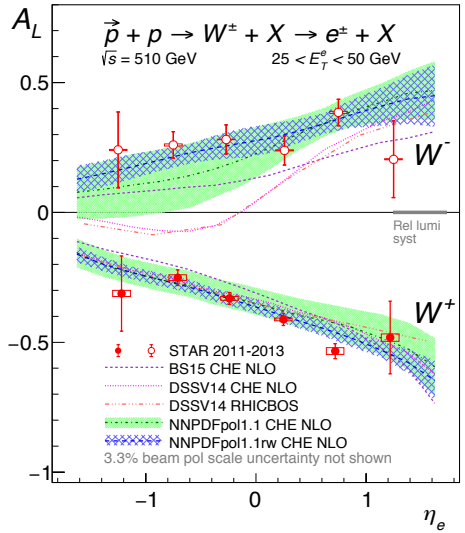
PRL 115, 092002 (2015)

First evidence of polarized gluons

Worldwide first hint of Sivers sign change

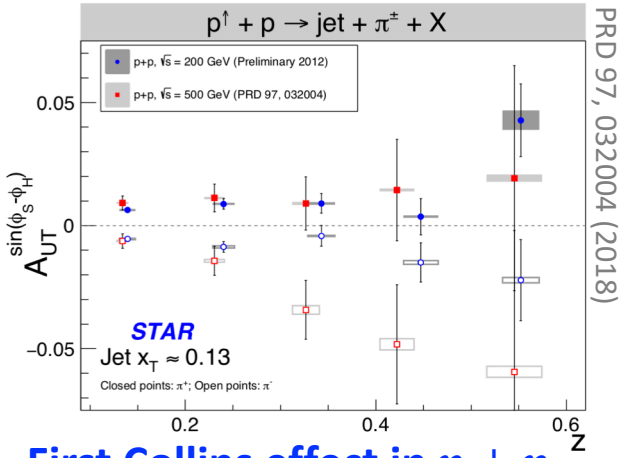


PRL 116, 132301 (2016)



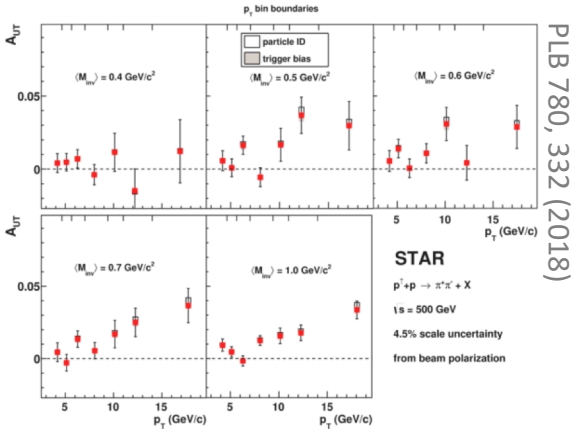
PRD 99, 51102 (2019)

Positive flavor asymmetry in the polarized sea



PRD 97, 032004 (2018)

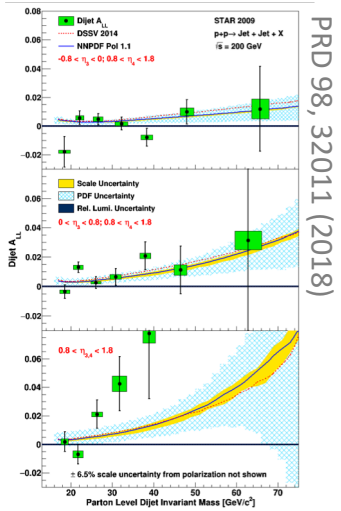
First Collins effect in $p + p$



PLB 780, 332 (2018)

Transversity via IFF

Fascinating questions remain…



PRD 98, 32011 (2018)

STAR dijets

Open Questions in Cold QCD

Deep and critical questions remain unanswered…

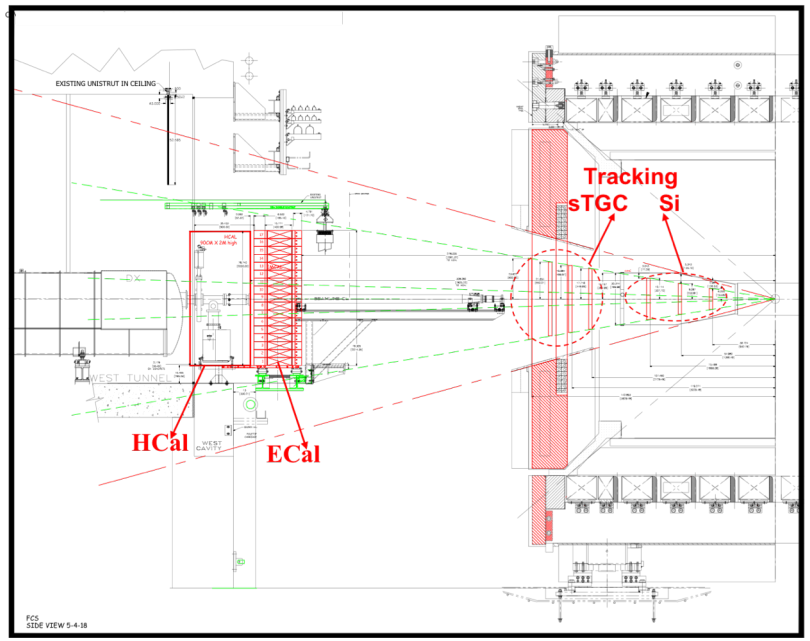
- Limited understanding of how quarks, gluons, and their spins are distributed in space and momentum inside the nucleon.
- How does partonic orbital motion contribute to the proton spin?
- Large transverse spin asymmetries observed at forward angles for inclusive hadron production remain poorly understood.
- Assumptions of universality and factorization for transverse-momentum-dependent (TMD) functions probed in $p + p$ collisions need to be tested and their evolution in Q^2 quantified.

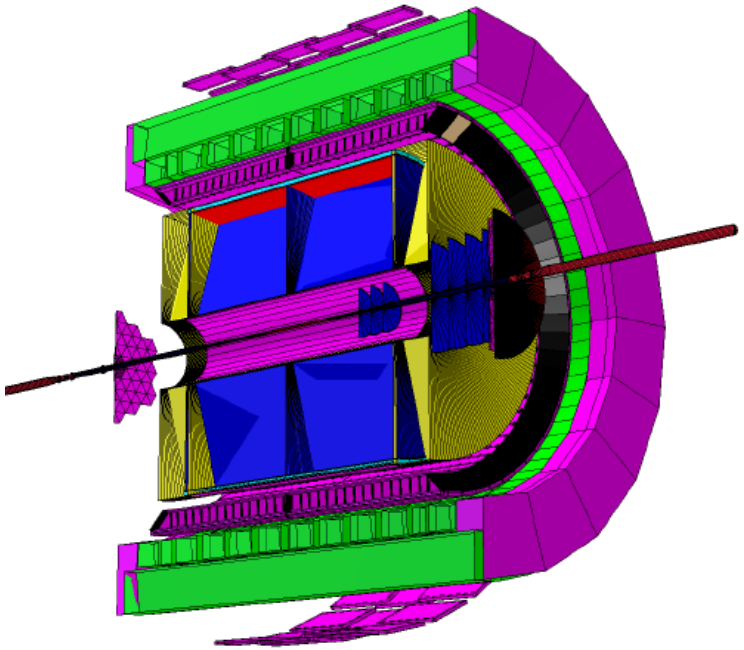
Open Questions in Cold QCD

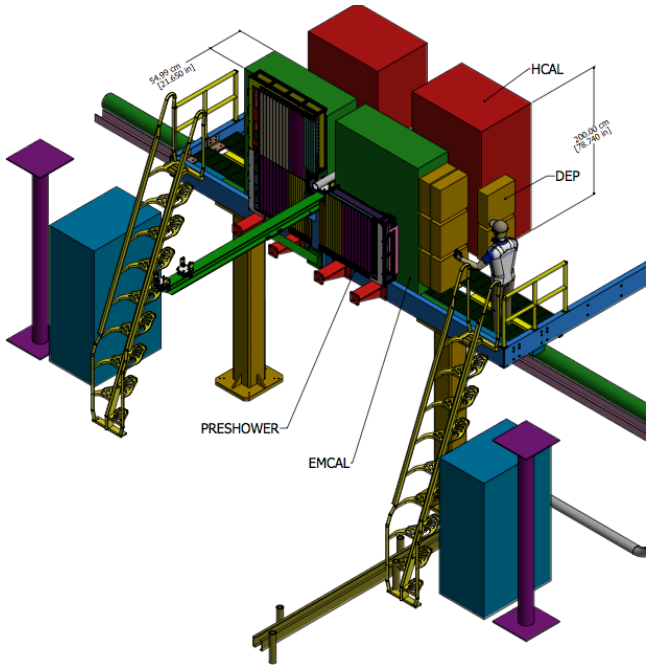
STAR detector post-BES-II well positioned to address many of these questions!

- **Problem:** existing detectors access limited range of $x = p_{\mathrm{parton}}/p_{\mathrm{proton}}$!
- Full understanding of hadrons and hadronic matter: probe high-x ***and*** low-x
  - Most direct access through asymmetric collisions, i.e. $x_1 \gg x_2$
  - Outgoing particles emitted at ***far forward angles***

→ ***STAR Forward Upgrade!***







Timeframe and Vital Stats

From the BUR charge…

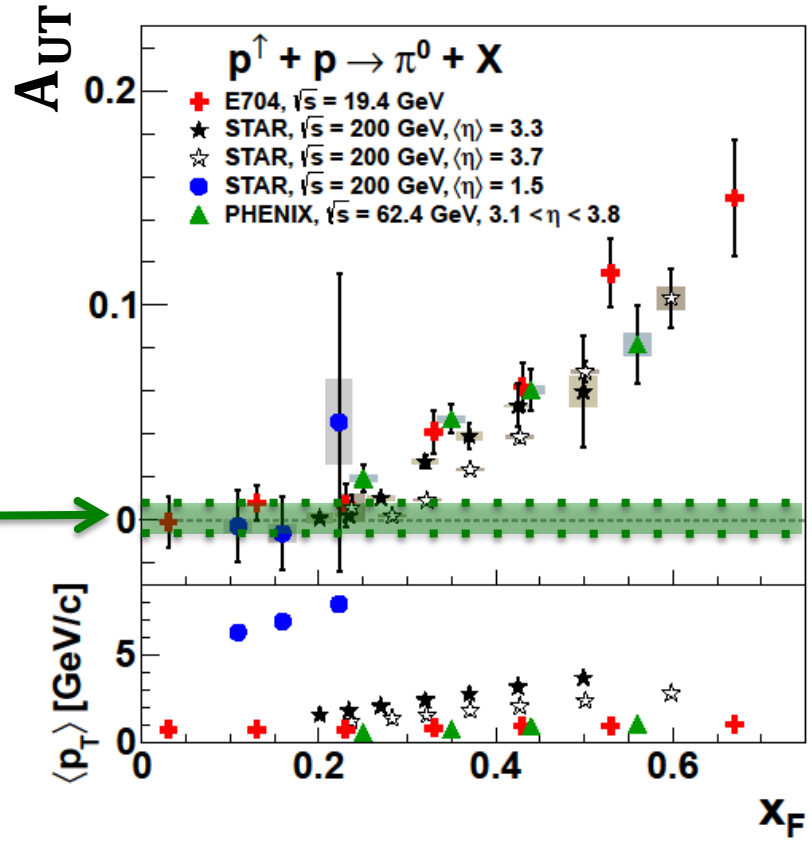
In addition, I request presentations on…an update of the physics goals for a short (16 cryo-weeks) forward Spin physics run in FY22 with 500 GeV $p+p$ collisions.

- Follows completion of BES-II
  - Possible last opportunity for extended 500 GeV running at RHIC
- Inaugural physics run with full suite of upgraded forward detectors
  - ***Very positive feedback from NSF and fully expect to receive funding!***
- First $p+p$ run able to exploit capabilities of iTPC, eTOF, and EPD
- Anticipate a total delivered luminosity of 1.2 fb^{-1}
  - Roughly double that of the 2017 run
  - Significantly improve precision of midrapidity measurements
    - Weak boson A_N (Sivers), Collins, IFF, Collins-like, (di)jet A_{LL}, etc.
    - *Not shown here for reasons of time*

A Surprise from Transverse Single-spin Asymmetries

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$d\sigma^{\uparrow(\downarrow)}$ -- cross section for ***leftward*** scattering when beam polarization is spin-***up***(down)



Collinear pQCD at leading twist: very small A_{UT}

Sizeable A_{UT} at forward pseudorapidity across a large range of $\sqrt{s}$

Measurements at RHIC in region where NLO pQCD cross-section provides a reasonable description of the data

→ Go beyond collinear pQCD at leading twist

→ Insight into transverse polarization structure?

Shown results from
E704, PLB 261, 201 (1991)
STAR, PRL 101, 222001 (2008)
STAR, PRD 89, 012001 (2014)
PHENIX, PRD 90, 012006 (2014)

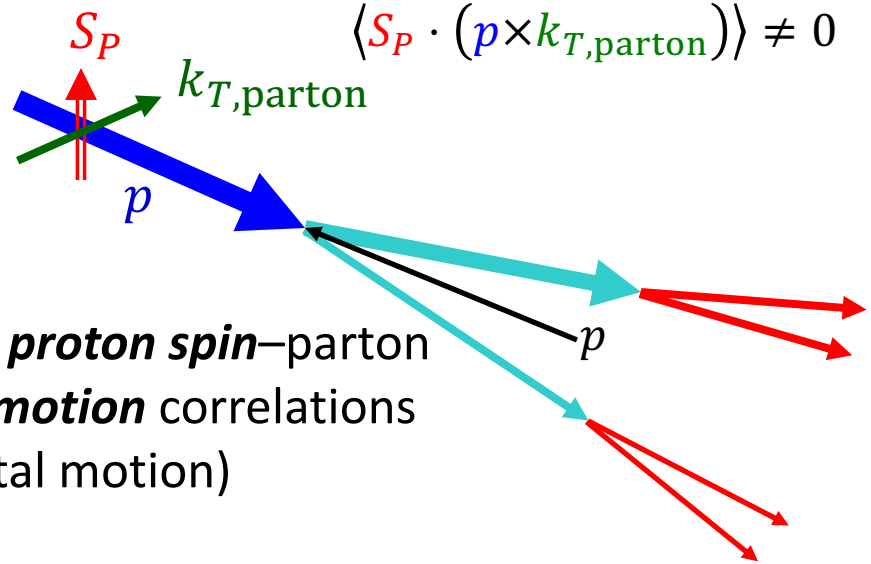
Mechanisms for Transverse Single-spin Asymmetries

Transverse Momentum Dependent (TMD) Distributions and FFs

Sivers mechanism: asymmetry in the jet or γ *production*

D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)

$\langle S_P \cdot (p \times k_{T,\text{parton}}) \rangle \neq 0$

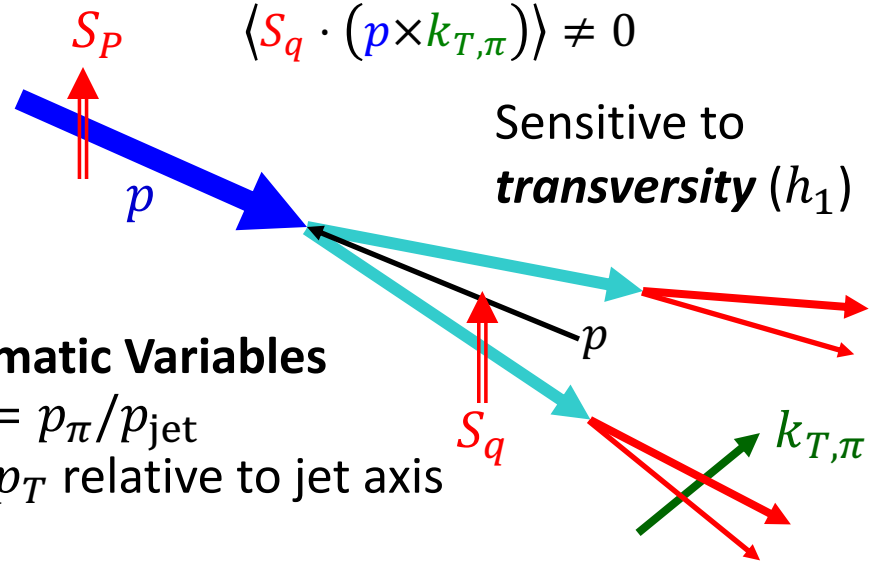


Sensitive to ***proton spin***–parton ***transverse motion*** correlations (needs orbital motion)

Collins mechanism: asymmetry in the jet *fragmentation*

J. Collins, NP B396, 161 (1993)

$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$



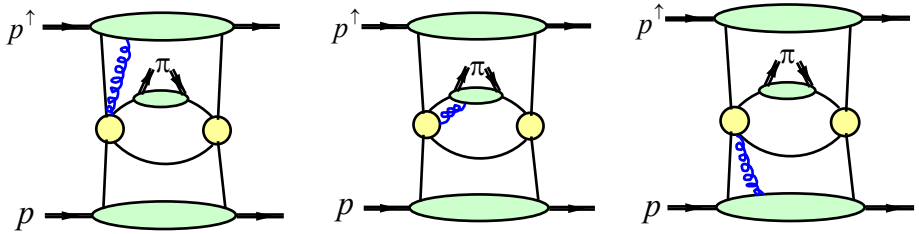
Sensitive to ***transversity*** (h_1)

$\pi^{\pm}$ **Kinematic Variables**

$z = p_\pi / p_{\text{jet}}$

$j_T\ (k_{T,\pi}) = \pi\ p_T$ relative to jet axis

Twist-3 Distributions and FFs



Y. Koike, RSC Discussion (2004)

Asymmetry from multi-parton correlation functions

e.g. Qiu and Sterman, PRL 67, 2264 (1991); PRD 59, 014004 (1998)

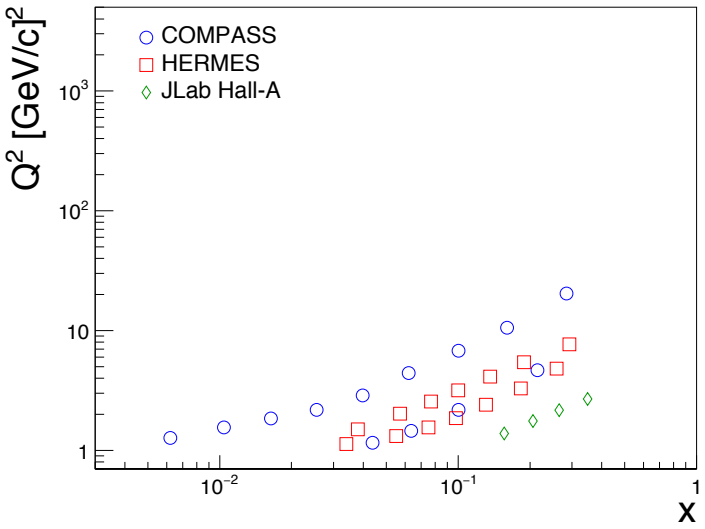
Correlators closely related to k_T moments of TMD's

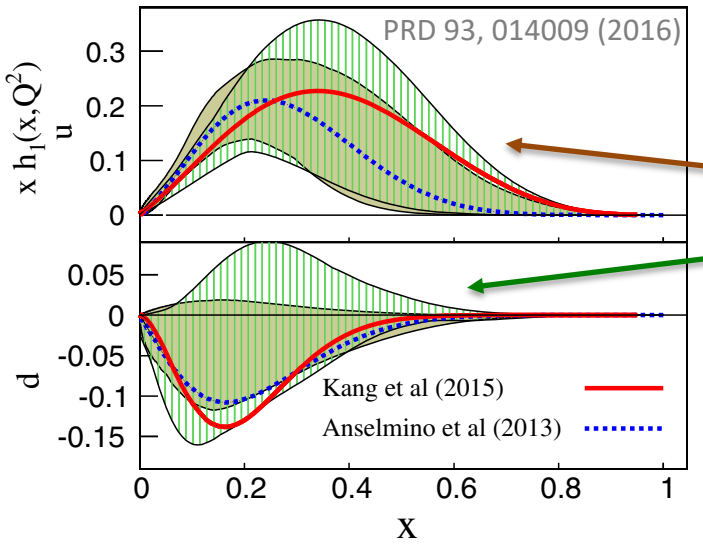
Boer, Mulders, Pijlman, NPB 667, 201 (2003)

Transversity

Complete understanding of nucleon structure requires knowledge of

- Unpolarized PDF, $f(x)$
- Helicity PDF ($\Delta f(x)$)
- Transversity ($h_1(x)$ or $\delta q(x)$) – chiral odd → requires another chiral-odd distribution
  - $\Delta q(x) - \delta q(x)$: direct connection to *non-zero OAM components* of proton wave function
  - Tensor charge, $\delta q = \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$





Large uncertainties for u-quark at high x and d-quark everywhere!

Anselmino et al: PRD 87, 094019 (2013)
Kang et al: PRD 93, 014009 (2016)
Radici et al: JHEP 05, 123 (2015)

Global analyses access in SIDIS + e^+e^-, e.g. via "Collins" or IFF asymmetries

Currently limited reach in (x, Q^2)

Transversity

Complete understanding of nucleon structure requires knowledge of

- Unpolarized PDF, $f(x)$
- Helicity PDF ($\Delta f(x)$)
- Transversity ($h_1(x)$ or $\delta q(x)$) – chiral odd → requires another chiral-odd distribution
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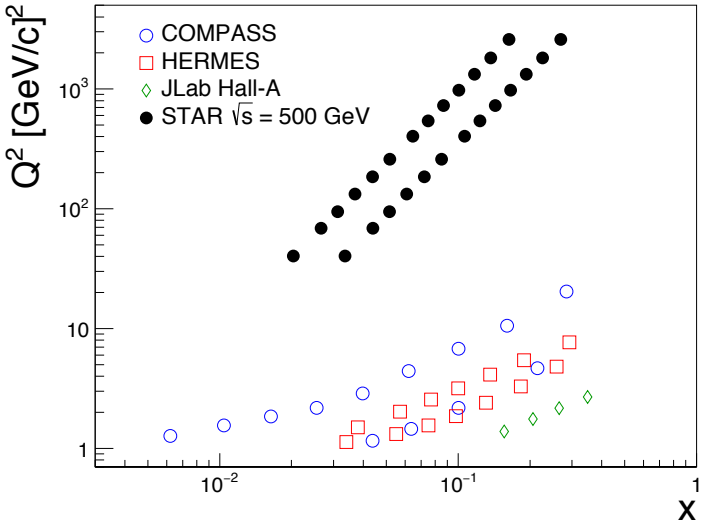
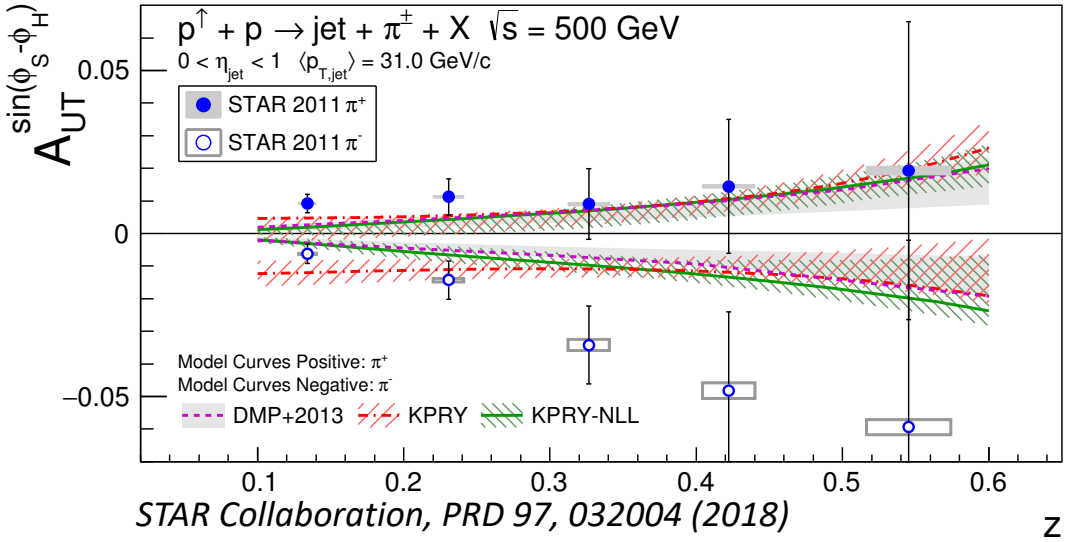
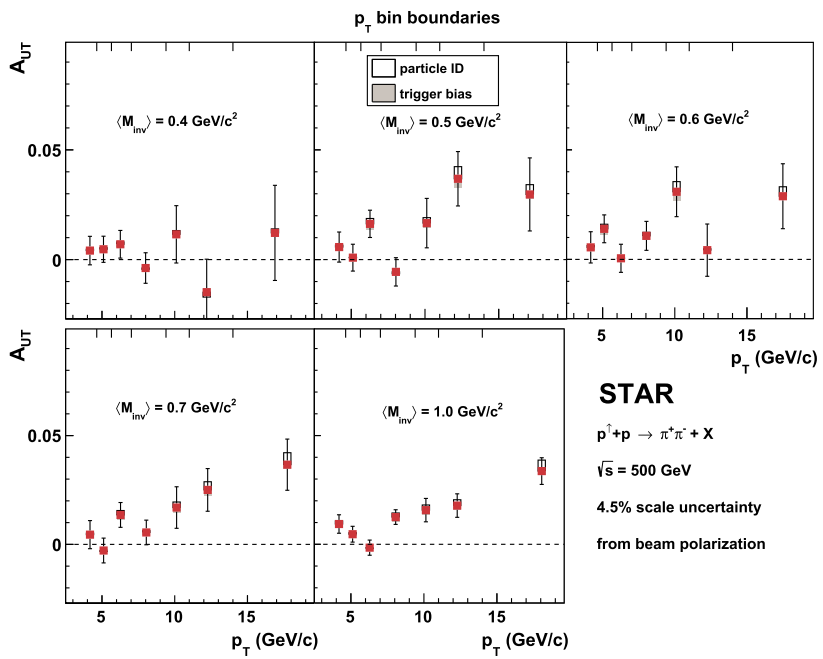


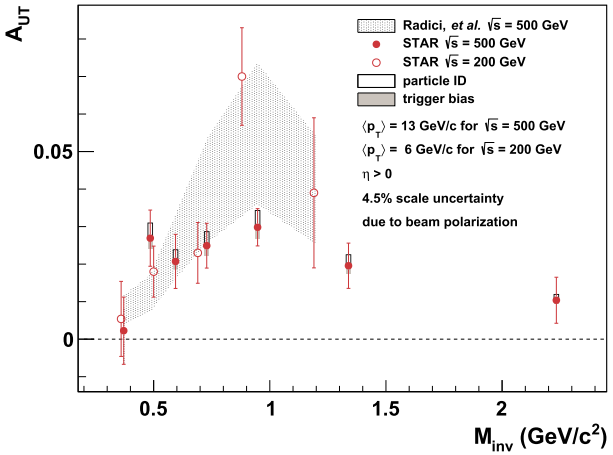


Collins effect, now observed in pp and largely consistent with SIDIS+e^+e^-

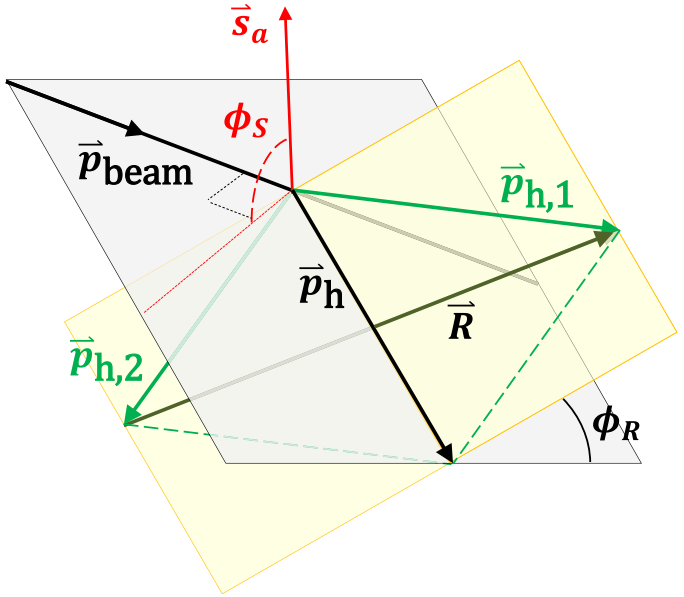
- Tests of TMD factorization and universality
- Sample wider kinematic space → insight into TMD evolution

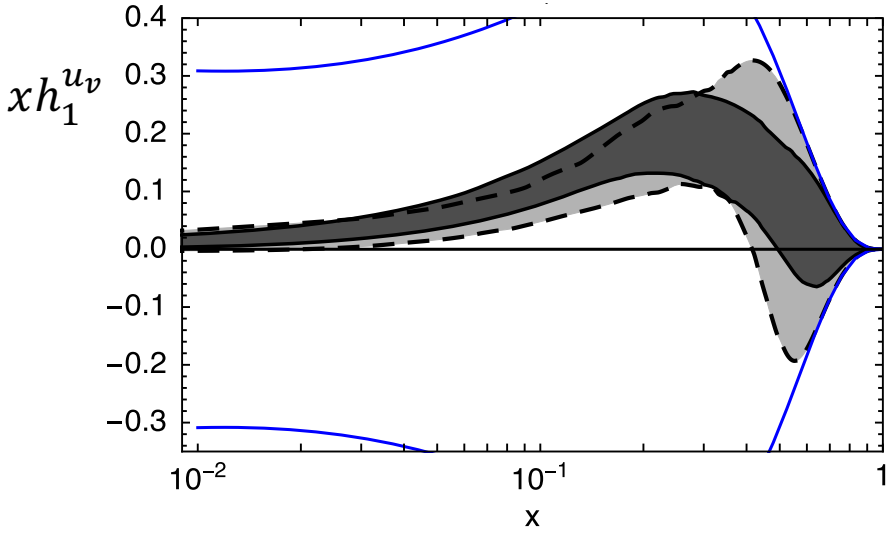
Transversity





STAR Collaboration, PLB 780, 332 (2018)





Radici and Bacchetta, PRL 120, 192001 (2018)

Significant dihadron asymmetries at RHIC (200 & 500 GeV)

- *Strong dependence on pair p_T*
- In terms of invariant mass, data are consistent with 68% of replicas based on SIDIS & e^+e^- data

  → Same as in SIDIS!
- 200 GeV: ***Significant impact*** on global transversity analysis!
  - Improved precision of valence u-quark
  - Improved behavior of valence d-quark

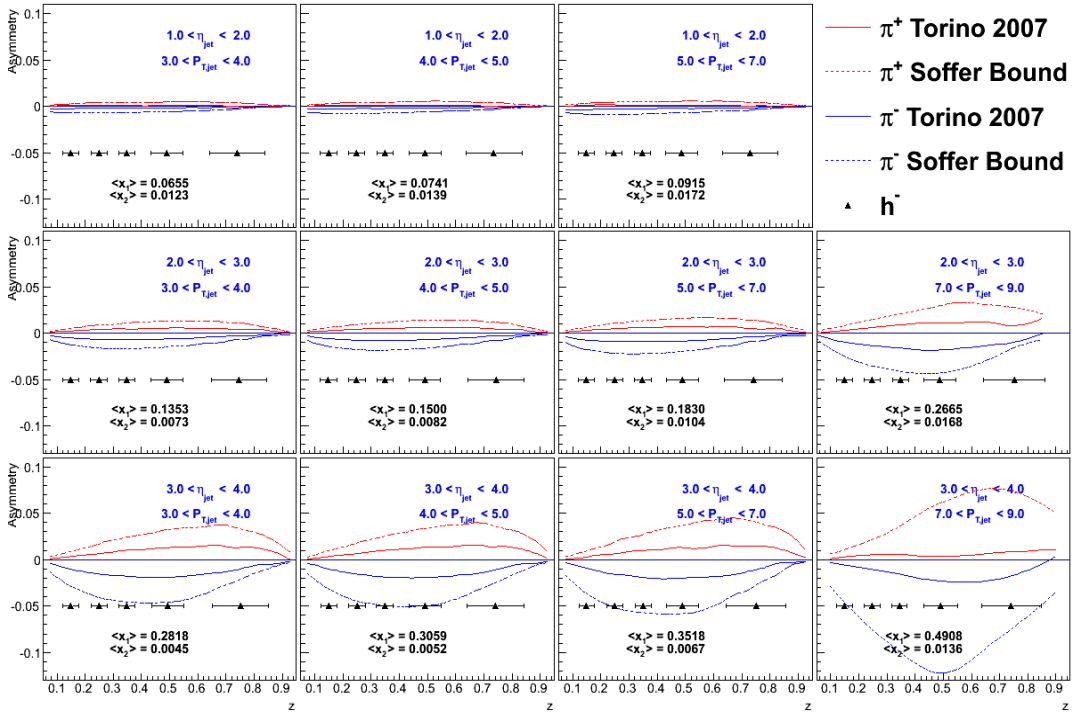
Transversity

Utilize $p + p \rightarrow \mathrm{jet}(h^{\pm})$, as at midrapidity

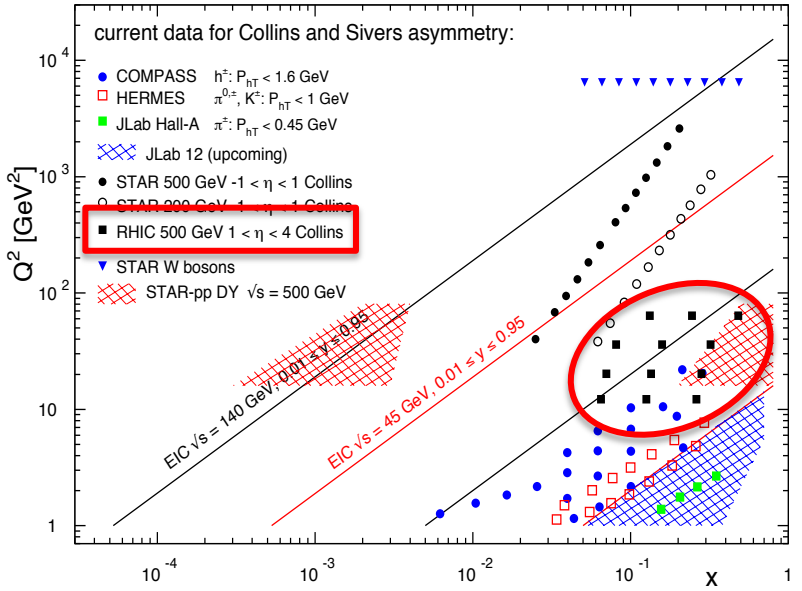
Pushing forward = higher x:

Simulation Studies

- Precision for 385 pb^{-1} delivered lumi (16 weeks $= 1.2\ \mathrm{fb}^{-1}$)
- Momentum smearing of hadrons & jets
- Dilution due to beam remnant, underlying event, and kaon+proton contamination



500 GeV: $1 < \eta < 4$



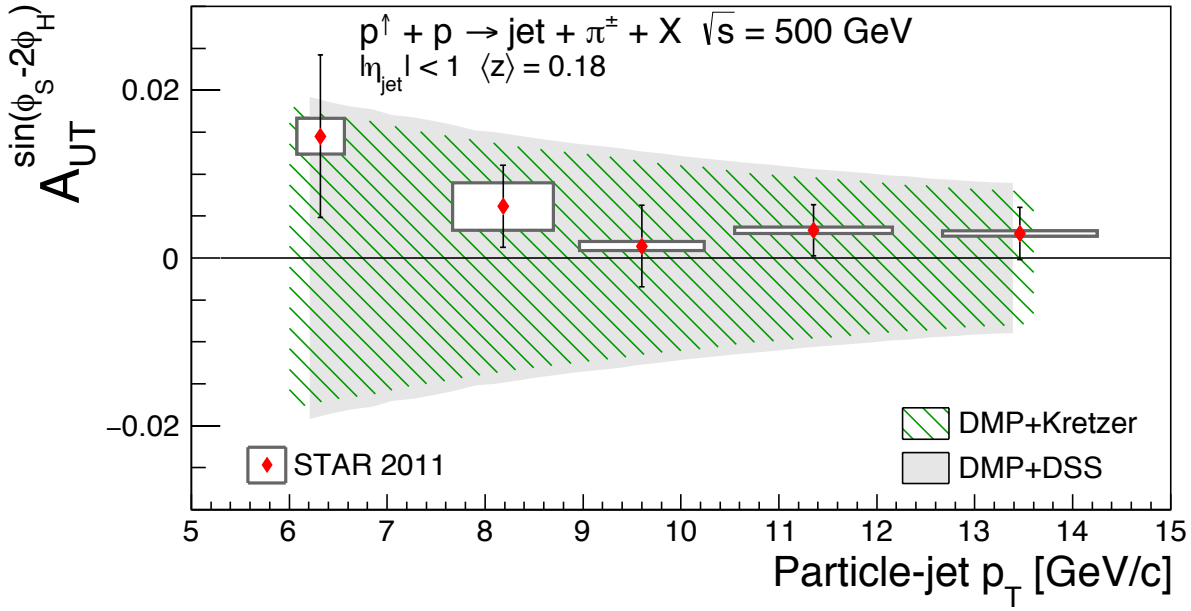
New with STAR forward upgrade:

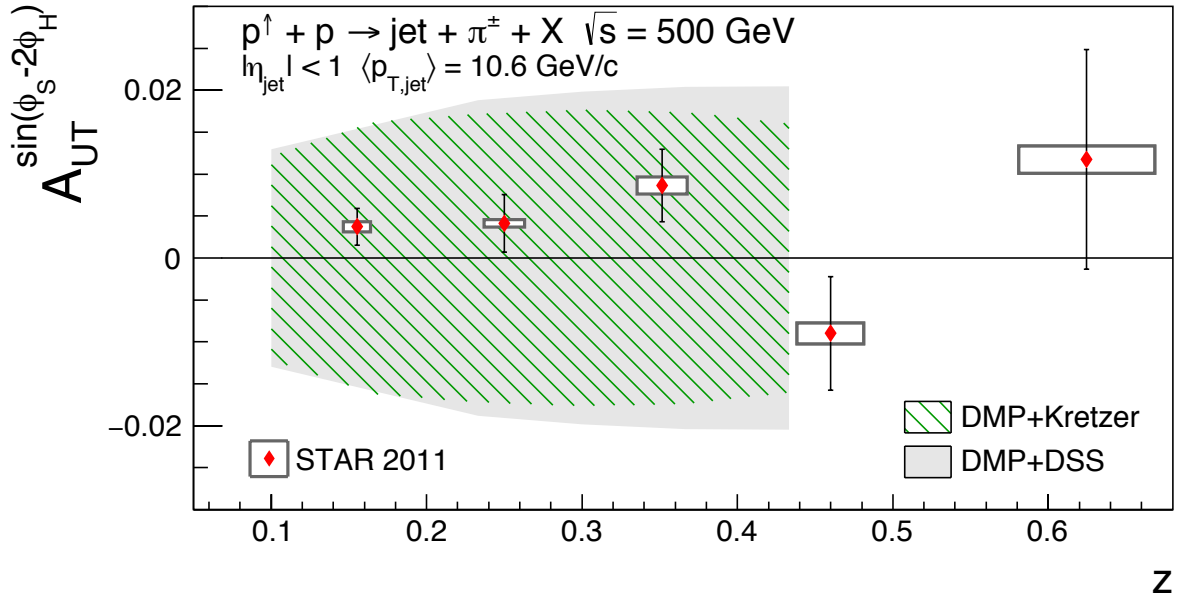
- Probe transversity at high x (0.05 to 0.5) and Q^2 (10 to 100 GeV^2)
- Quantitative test of Collins function universality and evolution
- ***Critical information for the lead-up to EIC!***

Gluon Linear Polarization

Collins-like asymmetries

- Sensitive to linearly polarized gluons in a transversely polarized proton
- Asymmetries consistent with zero in 500 GeV (shown) and (preliminary) 200 GeV
- STAR data provide first-ever constraints



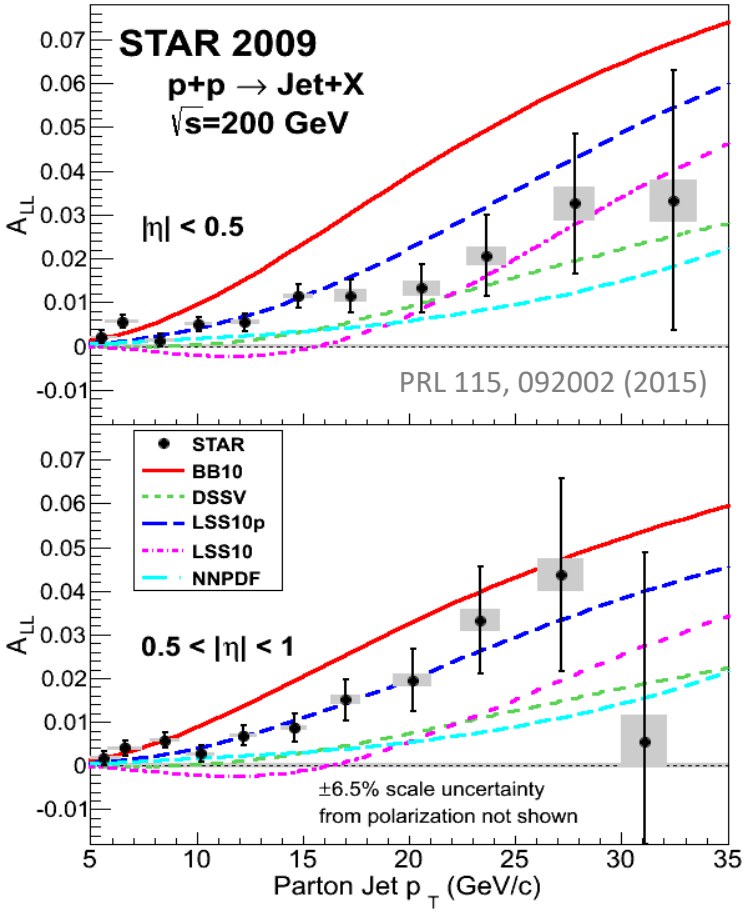


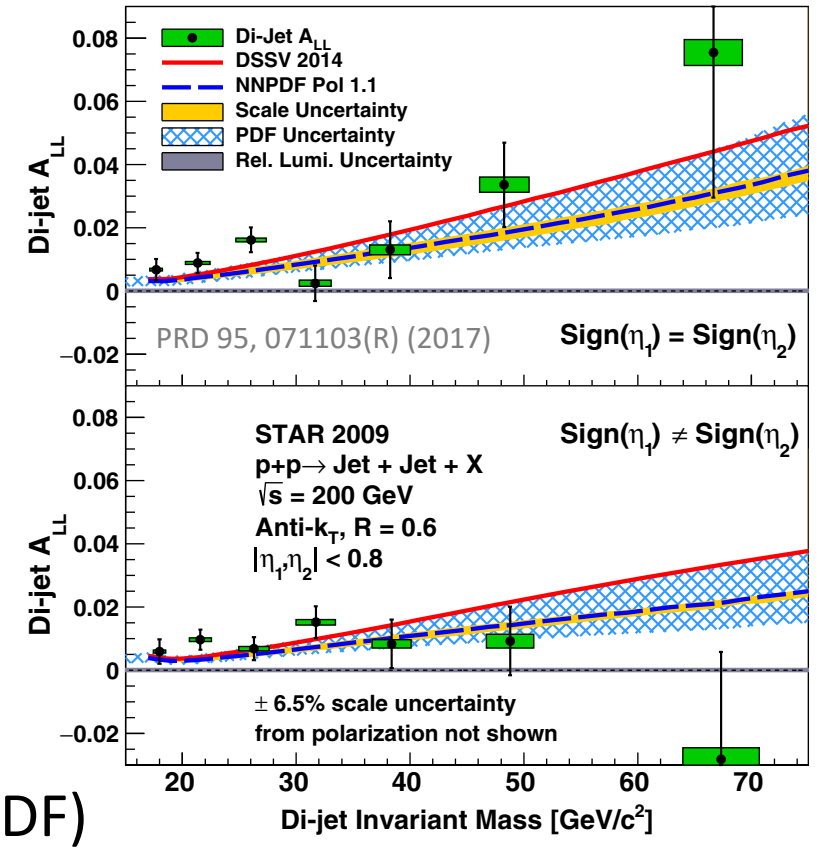
New with STAR forward upgrade:

- Probe Collins-like asymmetries to $x \lesssim 2\times10^{-3}$
- *Important for gluon linear polarization*

STAR Collaboration, PRD 97, 032004 (2018)

Gluon Helicity





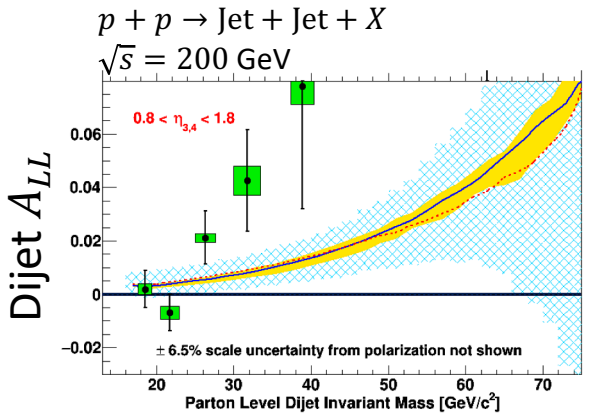
RHIC data through 2009:

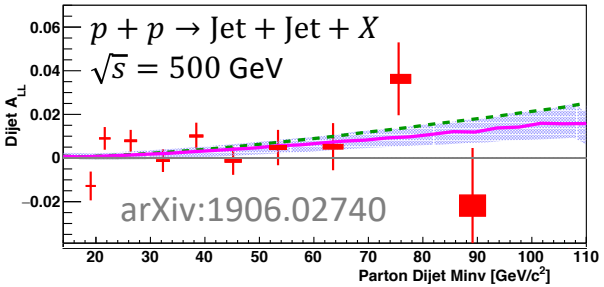
$$\int_{0.05}^{1} \Delta g(x)dx = 0.23 \pm 0.06 \text{ (NNPDF)}$$

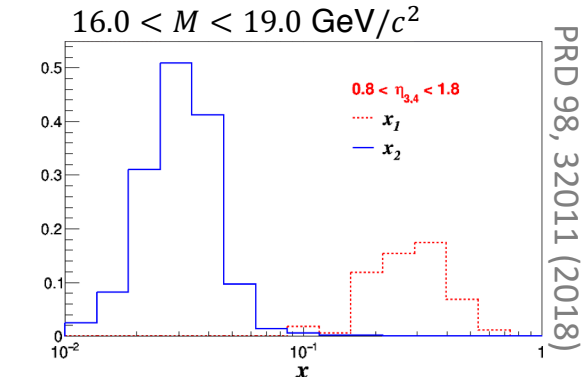
$$\int_{0.05}^{1} \Delta g(x)dx = 0.20^{+0.06}_{-0.07} \text{ (DSSV)}$$

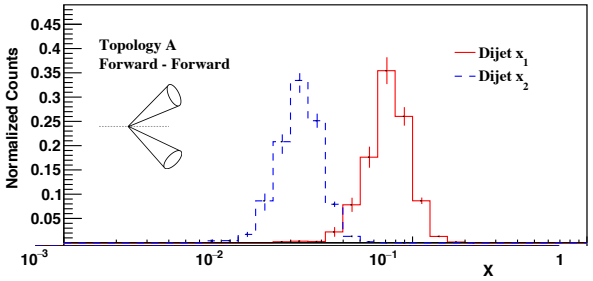
Recent data will improve uncertainties further…

Gluon Helicity

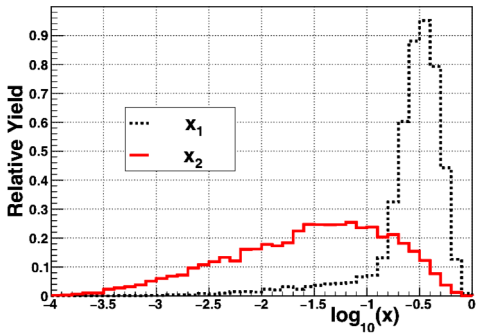


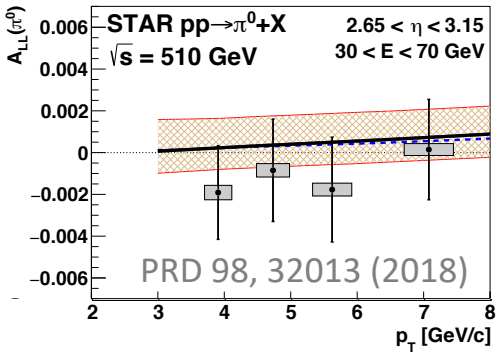




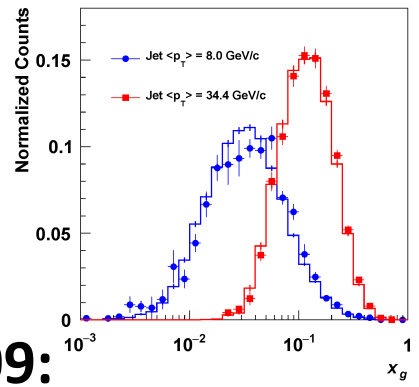


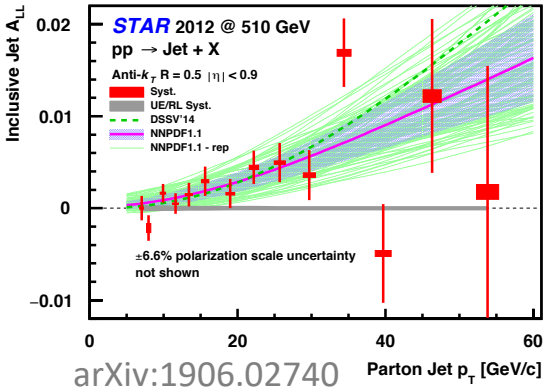
PRD 98, 32011 (2018)





PRD 98, 32013 (2018)





arXiv:1906.02740

RHIC data through 2009:

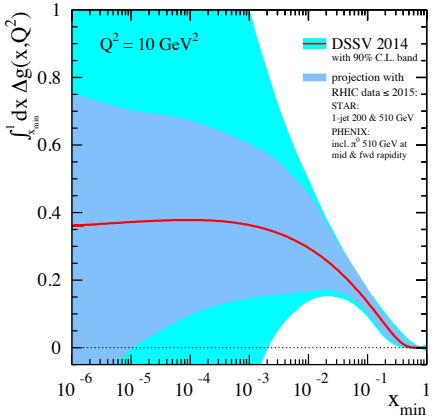
$$\int_{0.05}^{1} \Delta g(x)dx = 0.23 \pm 0.06 \text{ (NNPDF)}$$

$$\int_{0.05}^{1} \Delta g(x)dx = 0.20^{+0.06}_{-0.07} \text{ (DSSV)}$$

Recent data will improve uncertainties further…

…but Δg at very low x still largely unconstrained!

For lower x: push forward!



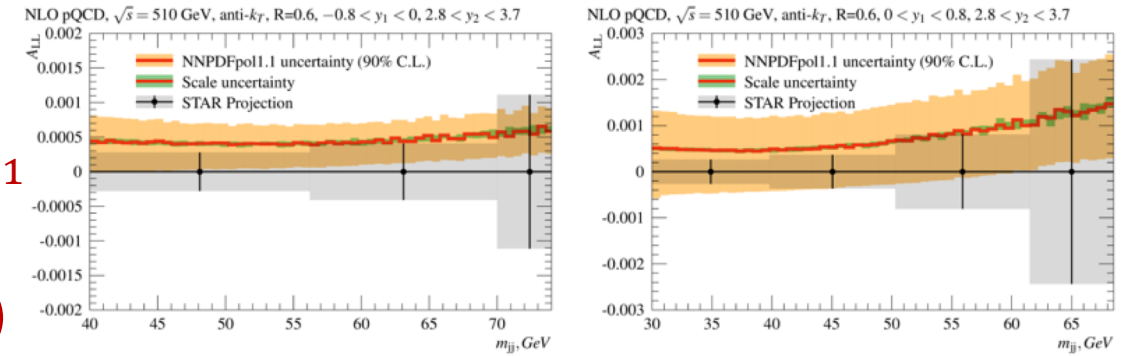
Add'l Results:

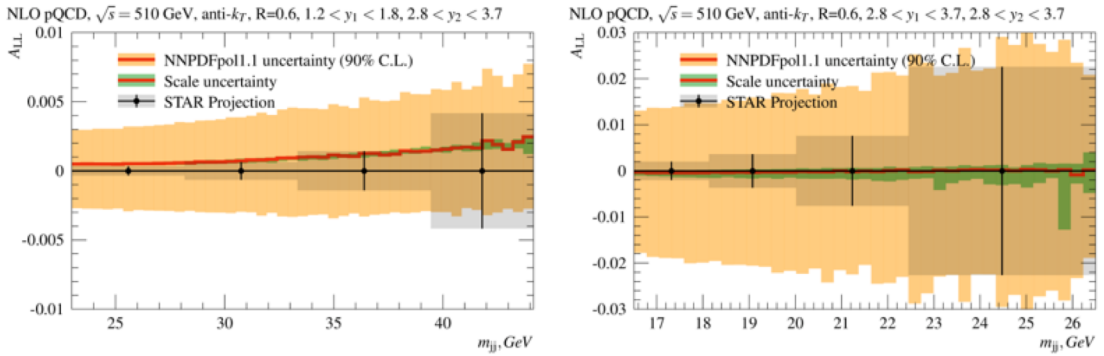
- Intermed.-η dijets at 500 GeV
- Intermed.- η π^0
- High stats 200 GeV in 2015

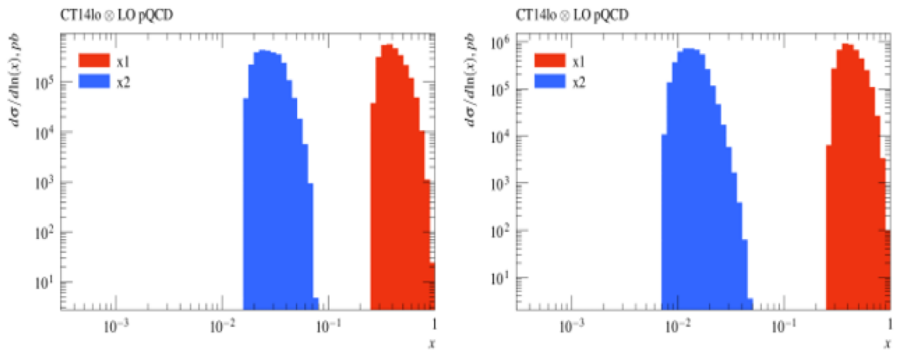
Gluon Helicity

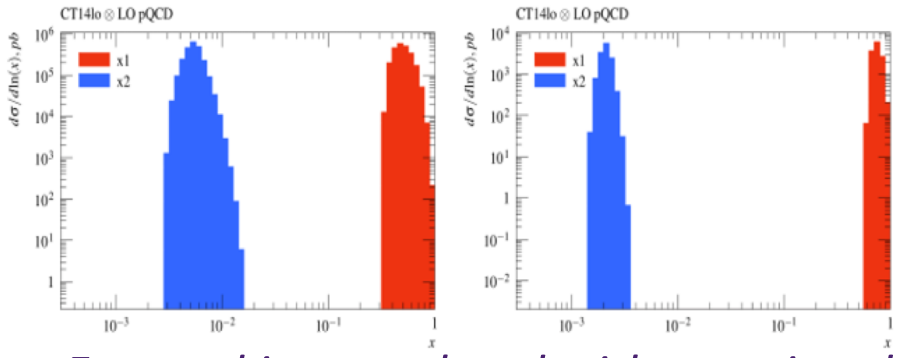
Simulation Studies

- Precision for 1 fb^{-1} delivered lumi (16 wk = 1.2 fb^{-1})
- Assume 60% pol
- Rel. lumi. syst: 5×10^{-4}







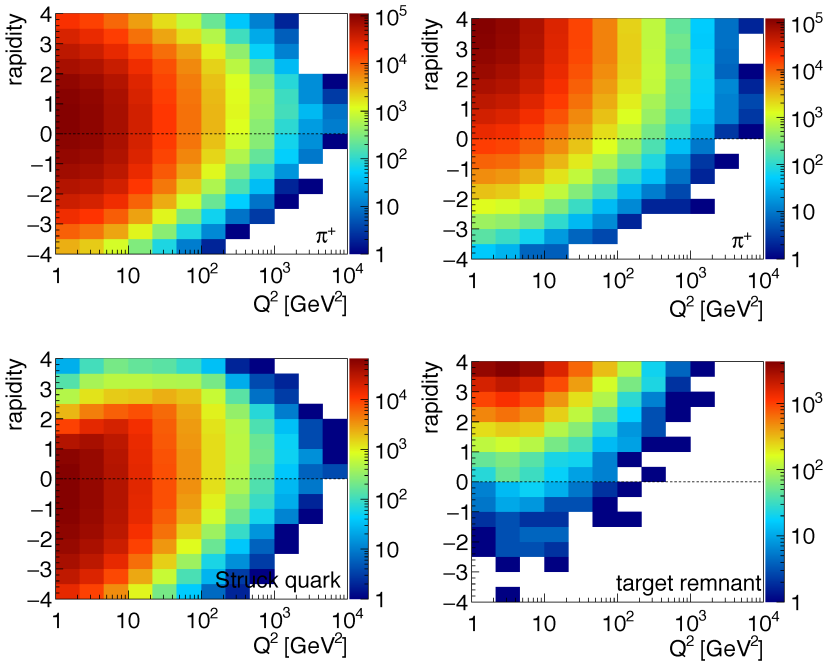


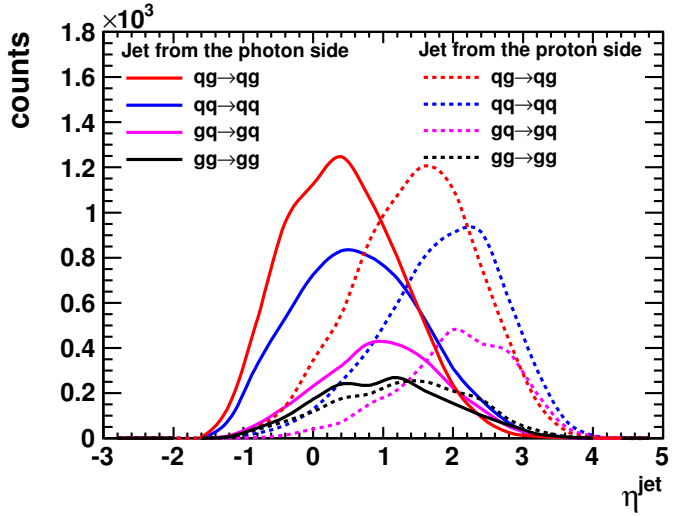
Forward jet correlated with associated jet in different rapidity ranges samples a varied range of x

New with STAR forward upgrade:

- Constrain Δg at low x with forward dijets
- More sensitive to ***shape*** of $\Delta g(x)$ than inclusive probes
- Pushing both jets to $\eta > 2.8$ allows sensitivity of $x \sim 10^{-3}$

Forward Dijets: Prelude to the EIC





Dijets at EIC: a promising tool

- Excellent surrogate for partons
- Jets from γ and p side are well-separated in η
- Potential for probing (un)polarized PDFs, FFs, and much more

Dijets with STAR forward upgrade

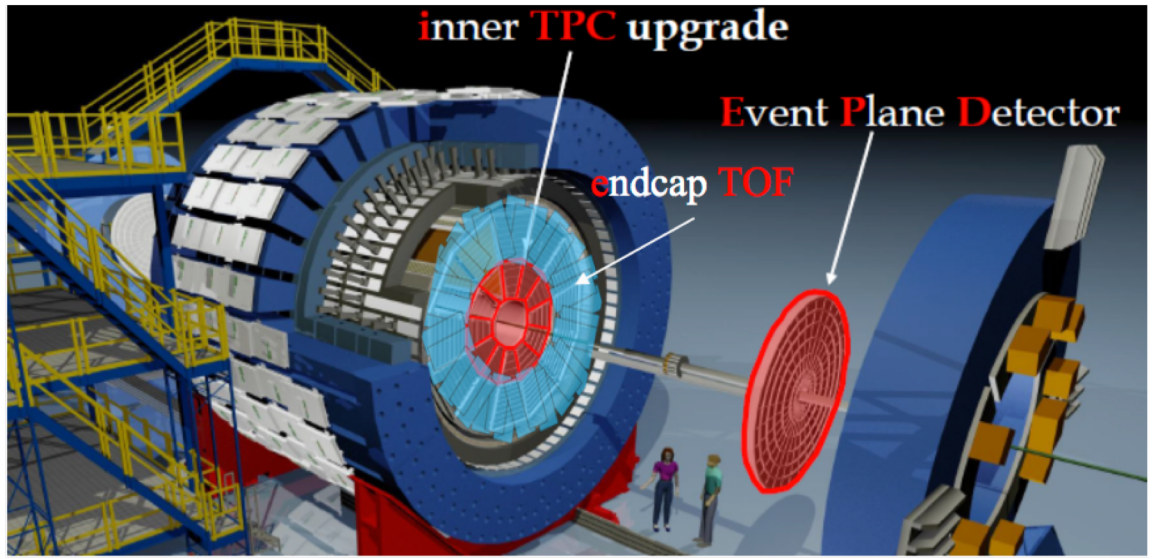
- Same range of η as dijets with EIC
- Understand dijets physics at EIC kinematics
- *Critical for maximizing impact of the EIC era*

Summary

- Fascinating open questions in cold-QCD remain
  - STAR poised to continue to play a significant role after BES-II
  - Critical to investigate at high and low x
- Physics goals for a 16-week run in FY22 (estimated 1.2 fb^{-1})
  - Transversity at high x via hadron-in-jet ("Collins") and dihadron ("IFF") A_{UT}
    - *Improved understanding of nucleon spin structure*
    - *Deeper Insight into large forward inclusive hadron asymmetries*
    - *Experimental tests of TMD factorization and universality in $p+p$*
  - Gluon linear polarization at low x, e.g. via "Collins-like" effect
    - *Improved understanding of nucleon spin structure*
  - Gluon helicity at low x via forward dijet A_{LL}
    - *Improved understanding of nucleon spin structure*
  - *Opportunity to gain insight critical for maximizing impact of EIC*
- ***Significant progress*** already on the forward upgrade! (*Elke's talk at 15:45*)

Back-up Slides

Cold-QCD Physics with Existing Upgrades



EPD

- Enhanced ability to identify rapidity gaps for diffractive measurements

iTPC

- Improve dE/dx PID resolution and extend η reach of mid-rapidity Collins and IFF measurements
- Substantially increase reconstruction efficiency and reduce need for corrections for intermediate η jets
- Provide tracking efficiency overlapping kinematic region where PHENIX observes strong A dependence of A_N for h^+
- Extend rapidity reach of W measurements, e.g. A_L and A_N
- Improved tracking substantially reduces size of the "second EEMC" correction for W measurements

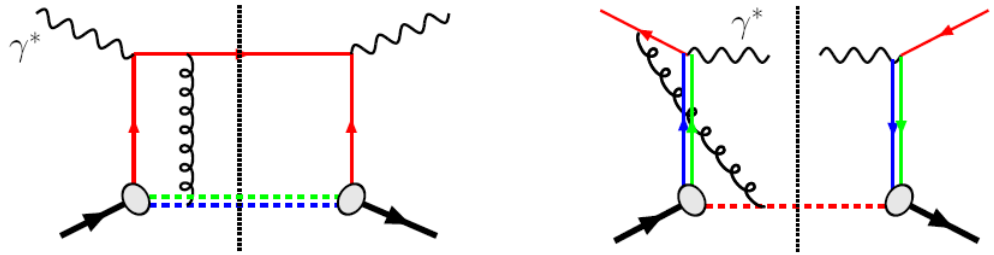
Sivers Effect

Color interactions in QCD

"Modified-universality" of the "Sivers" function

QCD:

DIS: Final-state interaction	Drell-Yan or W: Initial-state interaction



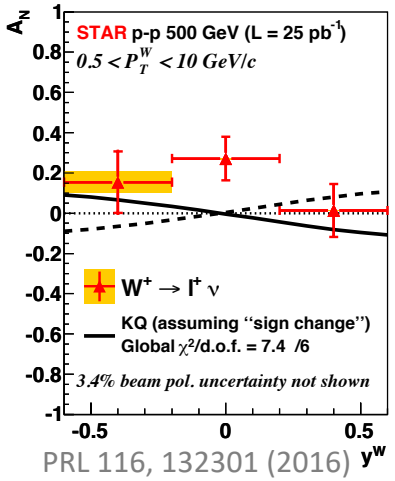
$\text{Sivers}_{DIS} = -\text{Sivers}_{Drell\text{-}Yan}$ or Sivers_{W}

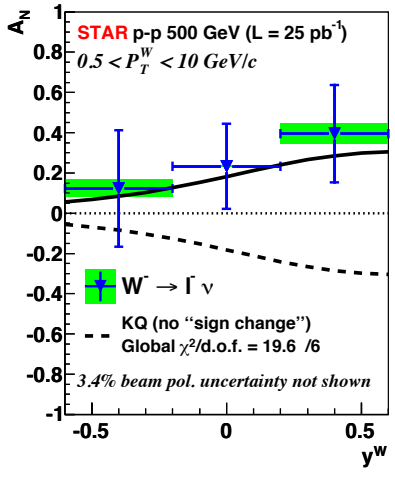
A_N for direct photon also has a closely related "sign change"

Opportunity to see the repulsive interaction between like color charges for the first time!

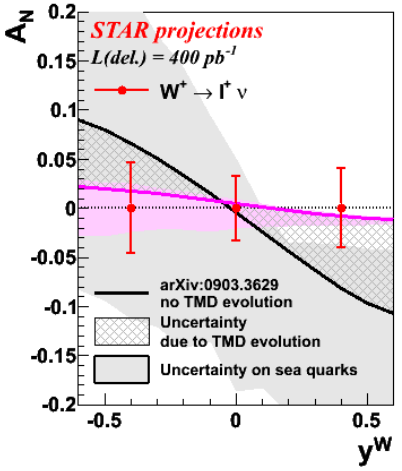
Can explore all of these observables in 500 GeV $p + p$ collisions at RHIC!

Sivers Effect at RHIC

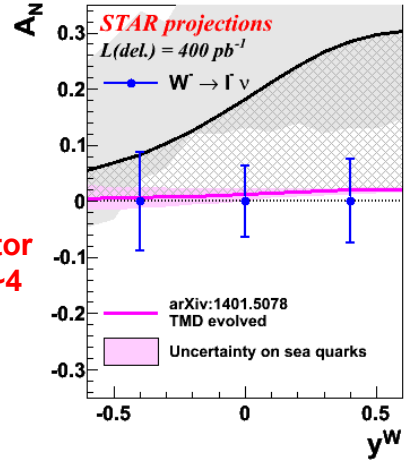




PRL 116, 132301 (2016)



Factor of ~4



Factor of ~15

Sivers through weak bosons

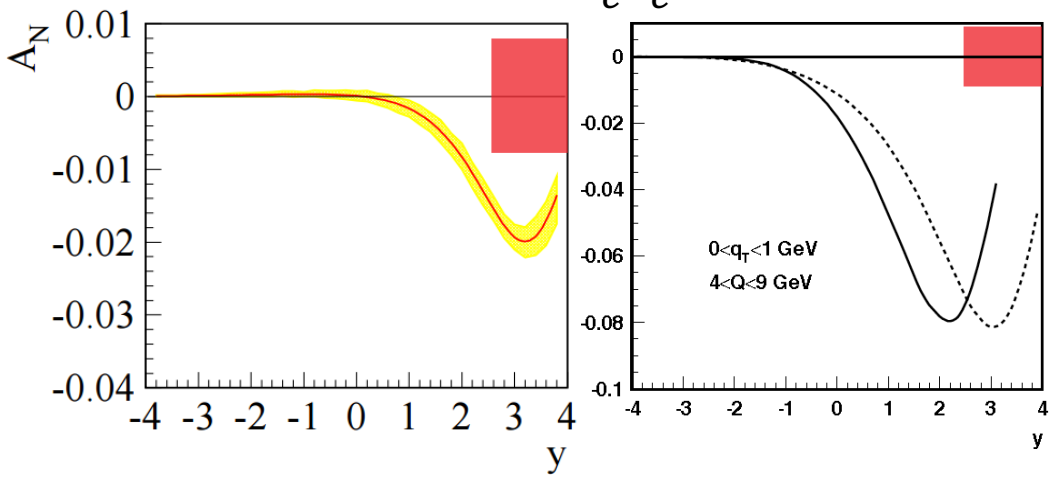
- Higher scale than DY
- Sensitivity to evolution!
- **Test through W/Z, DY, and direct photon (twist-3)**

Proposal for 2022

- Go beyond simply testing sign-change
- Test the magnitudes between SIDIS and $p + p$

A_N for DY to ± 0.008

- DY e^+e^-
- $2.5 < \eta < 4.0$ (*FMS+FPre+FPost*)
- $4.0\ \text{GeV} < M_{e^+e^-} < 9.0\ \text{GeV}$



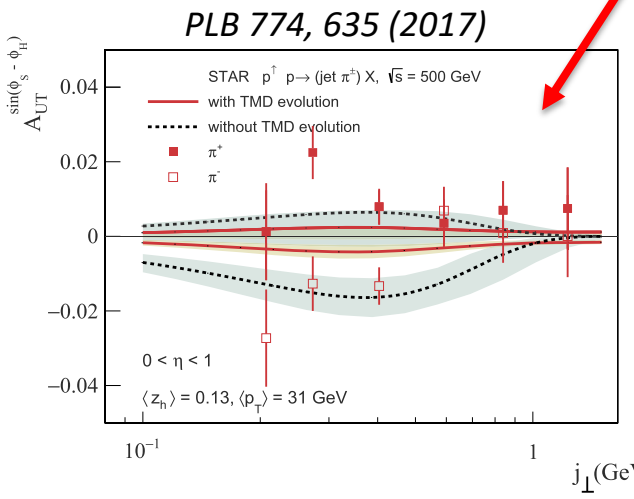
Collins Effect at RHIC

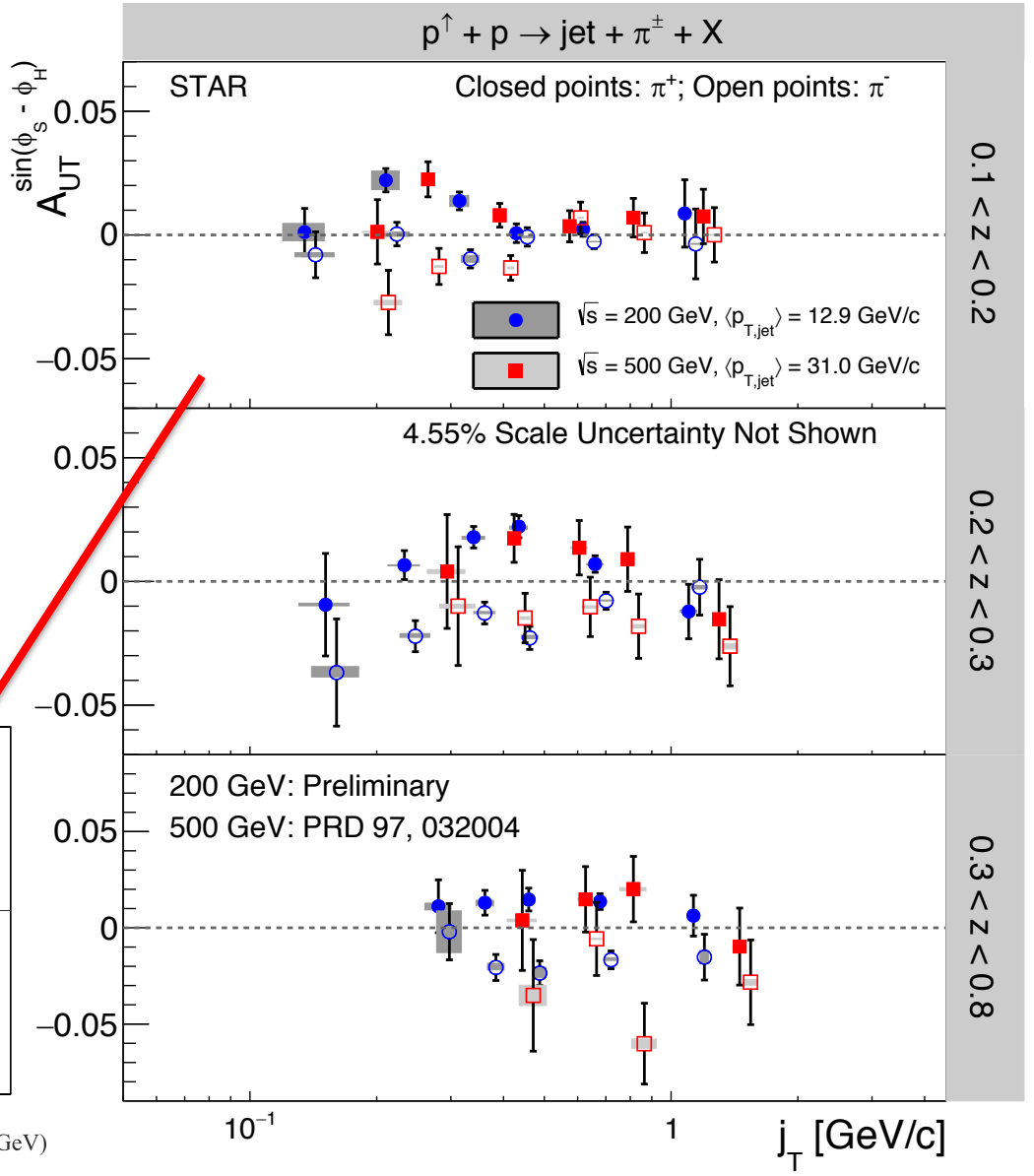
Evaluate the j_T dependence directly

- 200 and 500 GeV in ***complete agreement*** for common x_T
- Shape of asymmetries vs. j_T changes with z
  - Peak appears to shift to higher j_T for increasing z
  - Suggests asymmetry does not factorize as

$$A_{UT} \sim f(j_T) \times f(z)?!$$

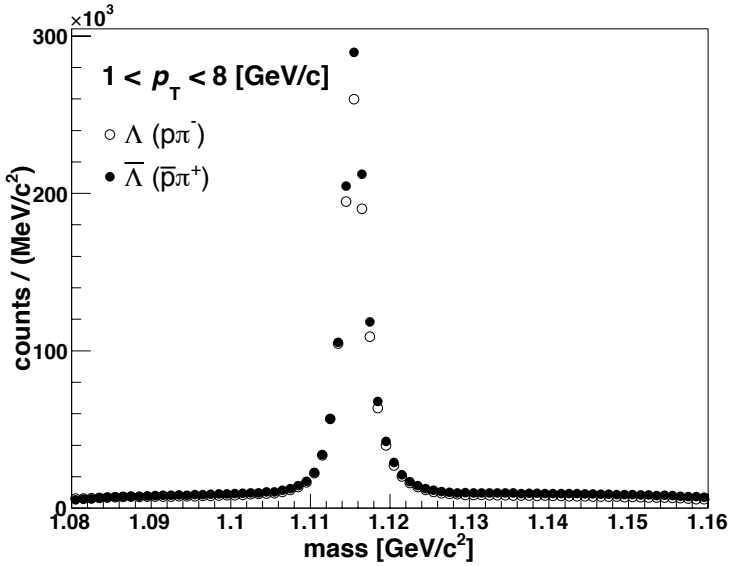
- Models agree relatively well but more work needed
  - ***More unpolarized data!***
  - More thought at low j_T

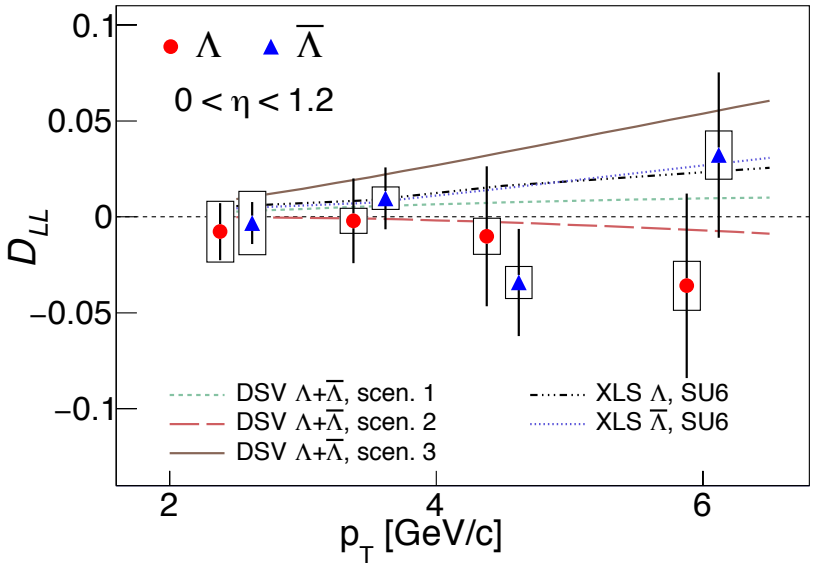


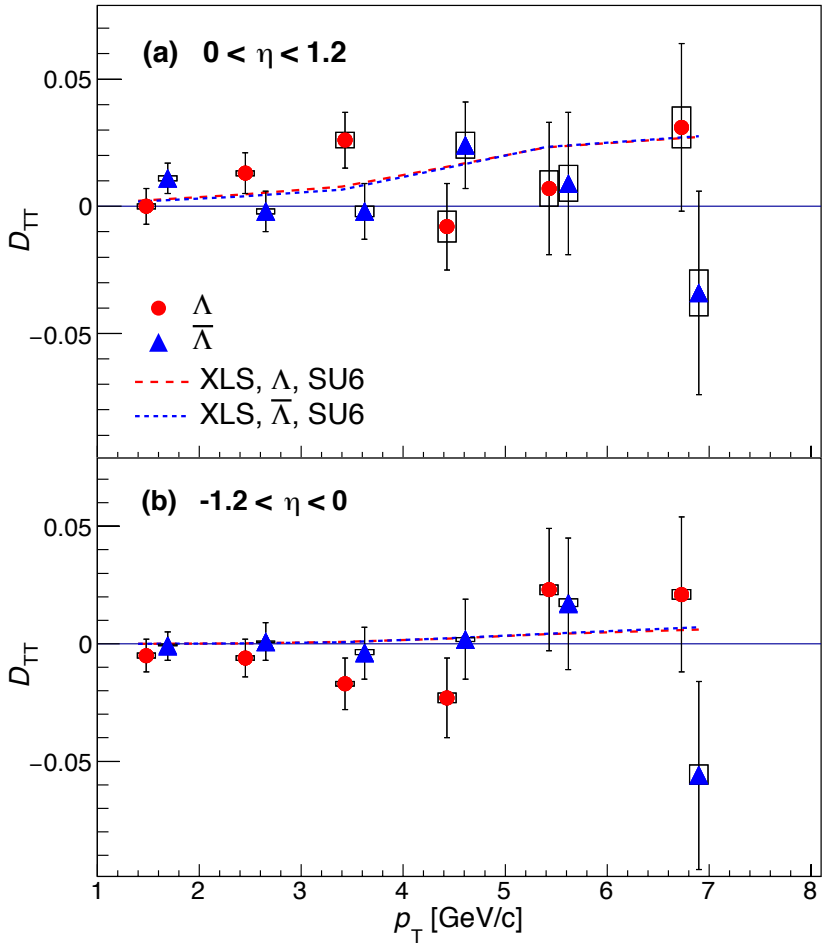


500 GeV: STAR Collaboration, PRD 97, 032004 (2018)
200 GeV: Int. J. Mod. Phys. Conf. Ser. 40, 1660040

Hyperons







First measurement of Λ D_{TT} at RHIC!

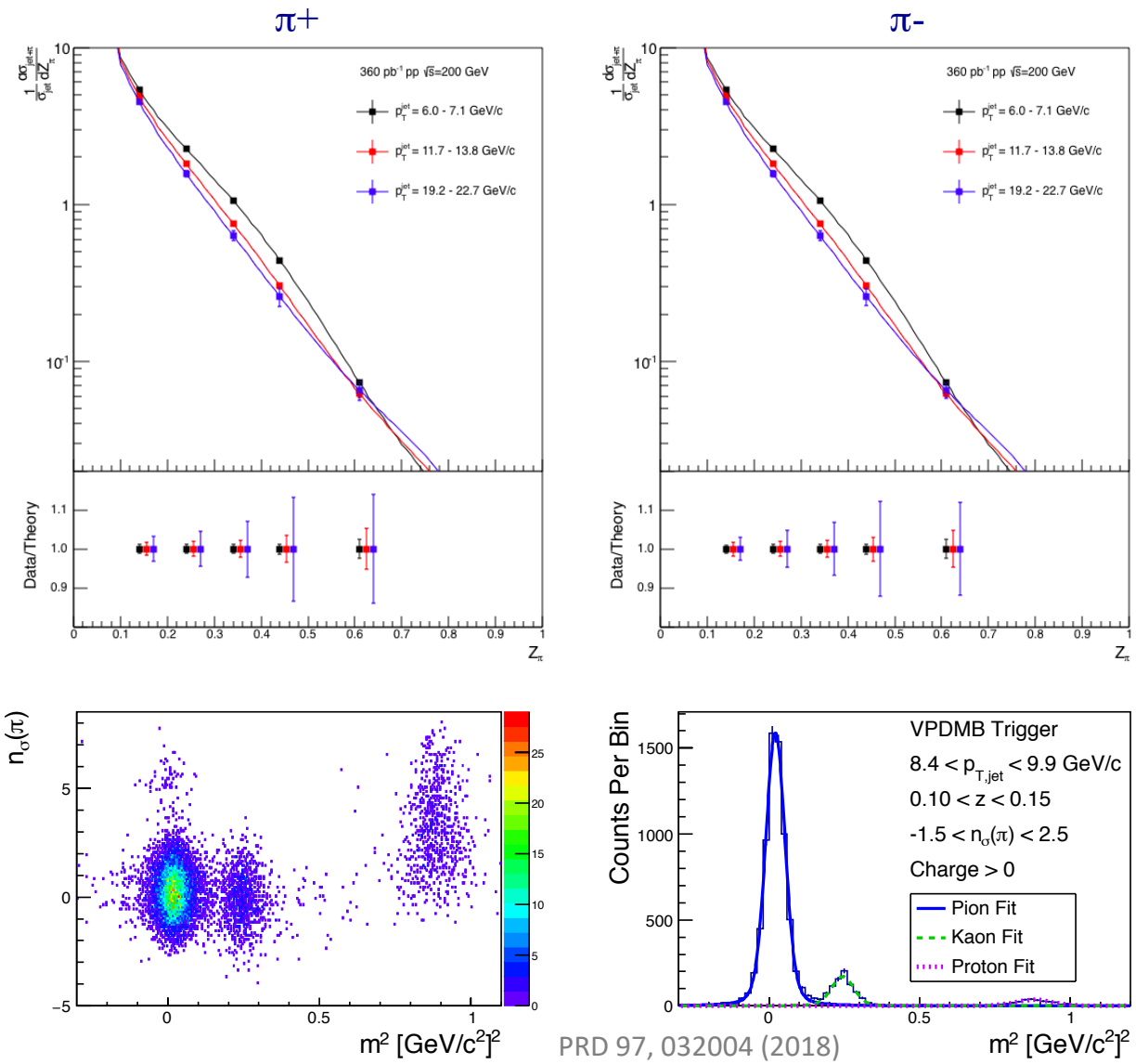
- Sensitive to transversity and transversely polarized FF
- Possible channel to constrain transversity of strange quarks
- Consistent with model calculation from PRD 70, 034015 (2004) and PRD 73, 077503 (2006)

Improved precision for Λ D_{LL}

- Sensitive to polarized PDF and polarized FF

STAR Collaboration, PRD 98, 91103 (2018)
STAR Collaboration, PRD 98, 112009 (2018)

Hadron-in-jet Fragmentation Functions



PRD 97, 032004 (2018)

The RHIC Spin Collaboration, arXiv:1602.03922

Unpolarized in-jet & dihadron fragmentation functions

- STAR equipped with ***particle ID***, e.g. time-of-flight (TOF) and energy-loss (dE/dx) in TPC
- Use PID to identify pion-in-jet, kaon-in-jet, etc.
  - *Enhance sensitivity to strangeness w/ K-tag*

pp/pA Physics in 2020+

RHIC Cold QCD physics after BES-II at Mid & Forward Rapidities:

The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC (*arXiv:1602.03922*)

→ Critical to the mission of the RHIC physics program

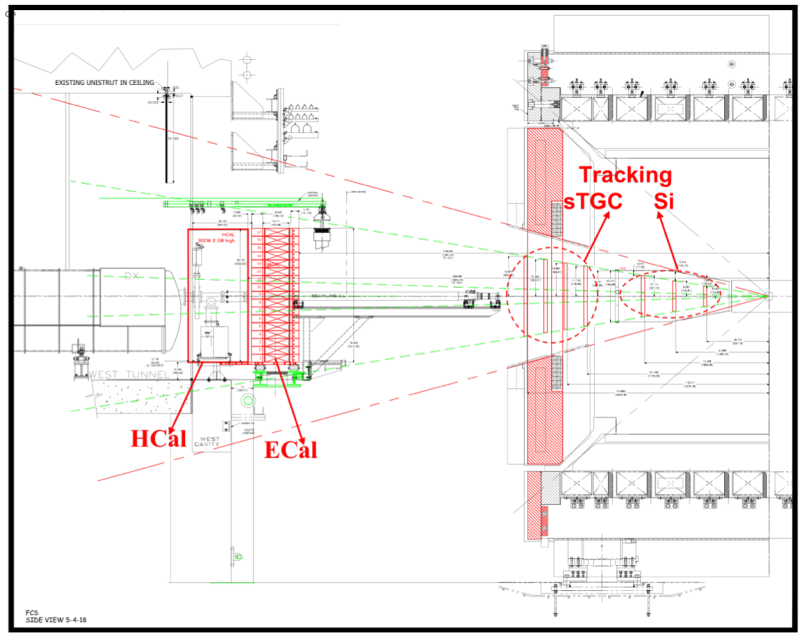
→ ***Fully realize*** the scientific promise of the EIC

Midrapidity: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669

- *Based on existing STAR detectors, utilizing recent BES II upgrades (iTPC, eTOF, EPD)*

Forward-rapidity: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

- *Upgrades consist of **HCal** + **ECal** + **Tracking*** in range of $2.5 < \eta < 4.5$



Positive endorsement by 2018 PAC:

- STAR presented a ***rich program*** for future operation after BES II that addresses many ***important and innovative topics*** in $p+p$, $p+A$ and $A+A$ physics.
- …would enable studies of ***novel reaction channels*** including several specific diffractive reactions and ultra-peripheral collisions of interest to hadron structure and QGP physics alike.