U.S. DEPARTMENT OF ENERGY | Office of Science

Recent Transverse Spin Measurements in pp Collisions with *STAR*

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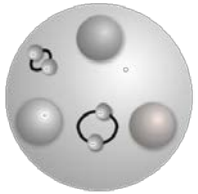
Outline

- Introduction
- Recent (and near future) measurements
- ***STAR*** Forward Upgrade plans

Complementarity of DIS and p+p

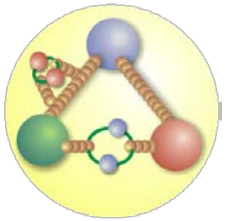
- **Deep-inelastic scattering** primarily probes via:



  - Electromagnetic interactions
    - Couple to charge^2
    - Insensitive to color

  - Weak interactions
    - Couple to weak charge (~flavor)
    - Insensitive to color
  - Only accesses gluons through higher-order effects

- **pp collisions** primarily probe via:

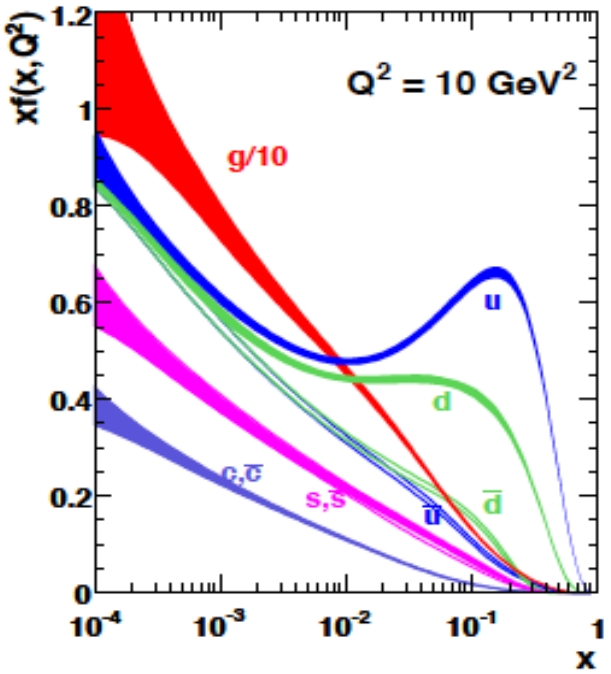


  - Strong interactions
    - Couple to color charge
    - Direct leading-order sensitivity to gluons
    - Insensitive to flavor

- **Need both for a consistent and complete picture**
- **Combine DIS and p+p** to explore **universality** and separate **interaction-dependent phenomena from intrinsic properties**

A well-proven method

MSTW 2008



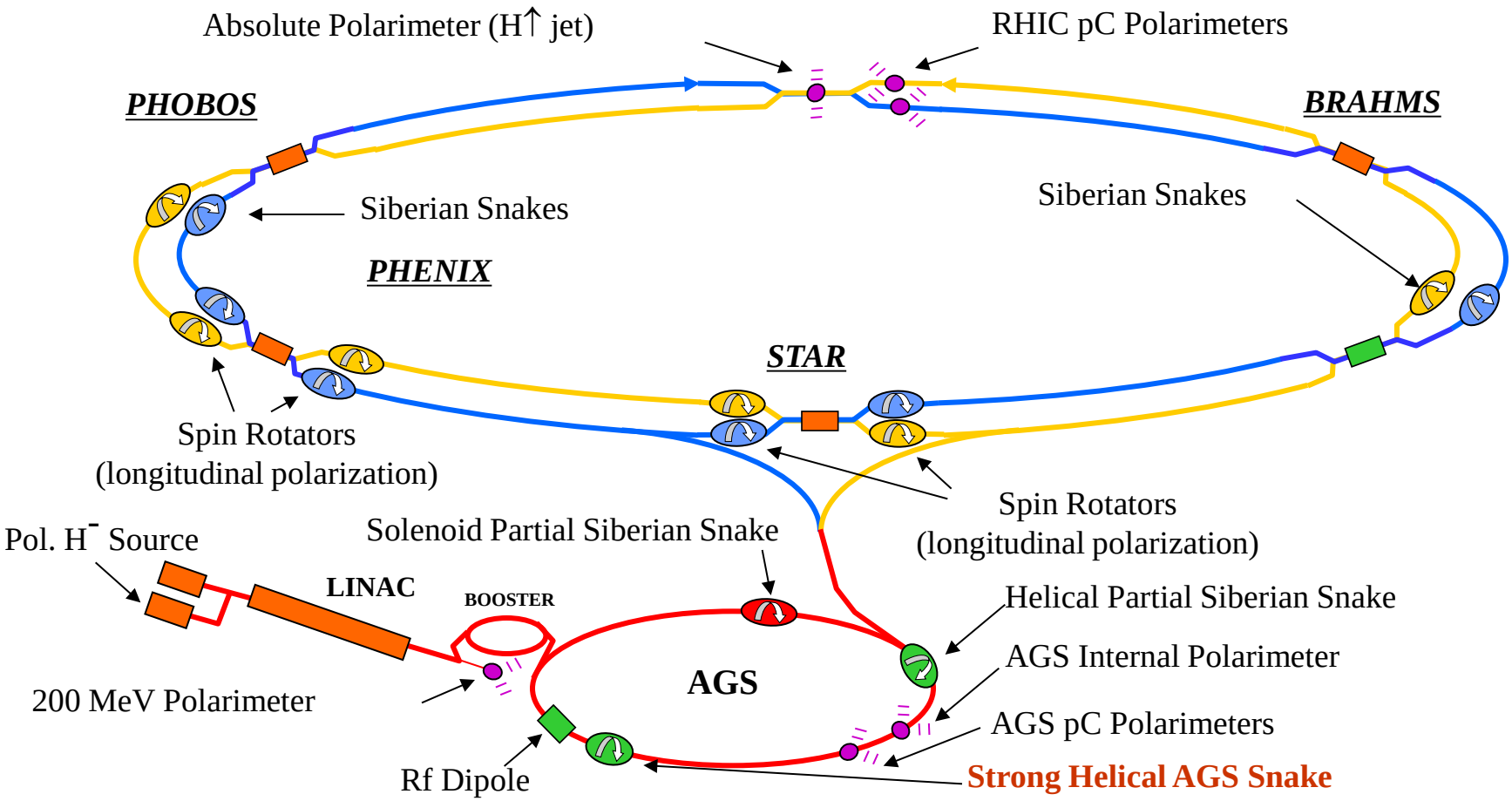
Process	Subprocess	Partons	x range
$\ell^{\pm}\{p,n\} \to \ell^{\pm} X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^{\pm} n/p \to \ell^{\pm} X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})\, N \to \mu^-(\mu^+)\, X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^{\pm} p \to e^{\pm} X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
$e^{\pm} p \to e^{\pm} c\bar{c} X$	$\gamma^* c \to c,\ \gamma^* g \to c\bar{c}$	$c,\ g$	$0.0001 \lesssim x \lesssim 0.01$
$e^{\pm} p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^{\pm} \to \ell^{\pm}\nu) X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-) X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

- The key role of hadronic collision data to determine the unpolarized PDFs of the proton has long been exploited
- RHIC provides equally critical data to determine polarized PDFs
  - Have provided essential constraints on gluon and anti-quark polarizations
  - Now also providing critical insights in transverse spin phenomena

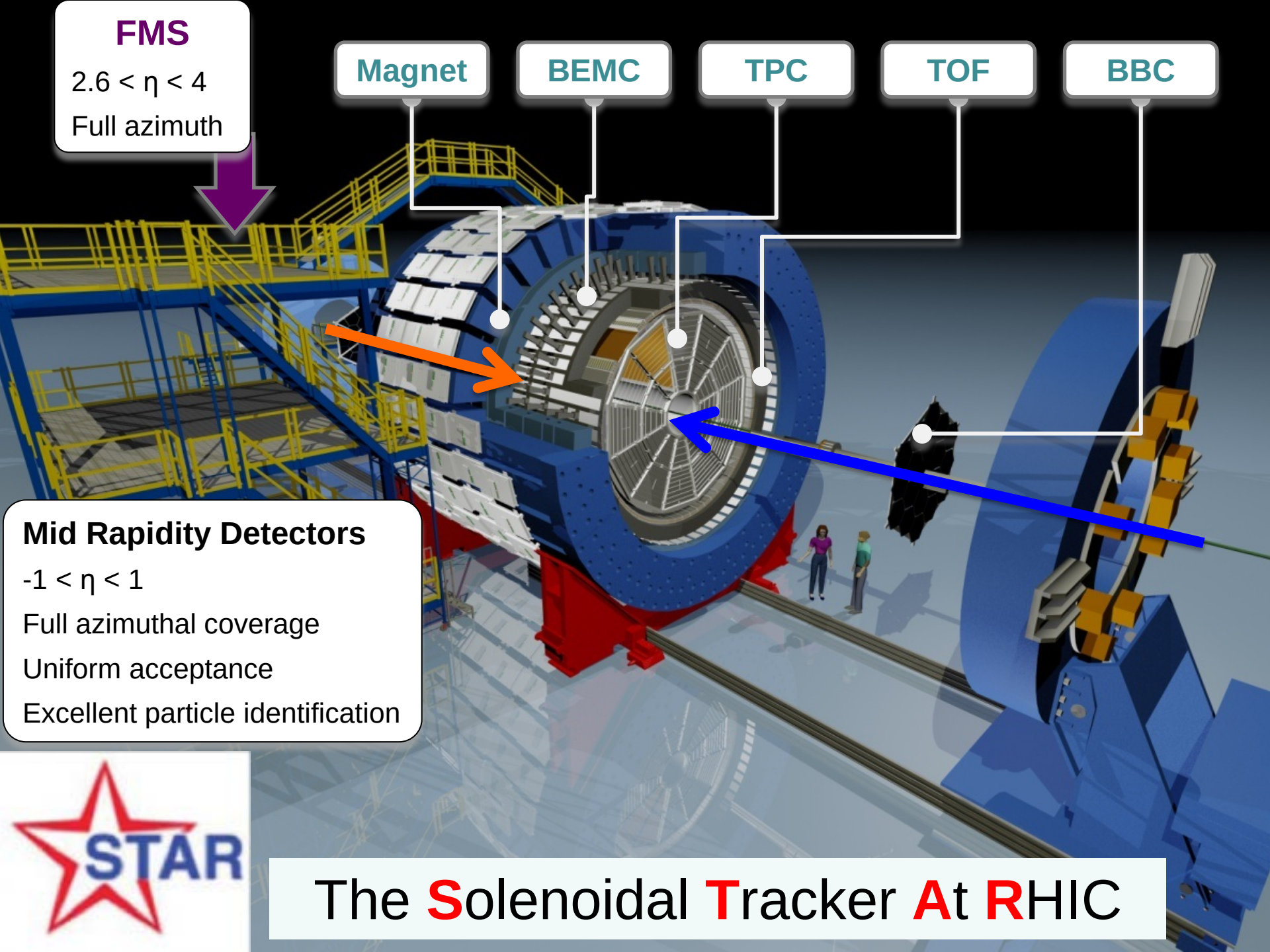
RHIC: the **R**elativistic **H**eavy **I**on **C**ollider

- Search for and study the Quark-Gluon Plasma
- **Explore the partonic structure of the proton**
- **Determine the partonic structure of nuclei**

RHIC: the world's first (and only!) polarized hadron collider



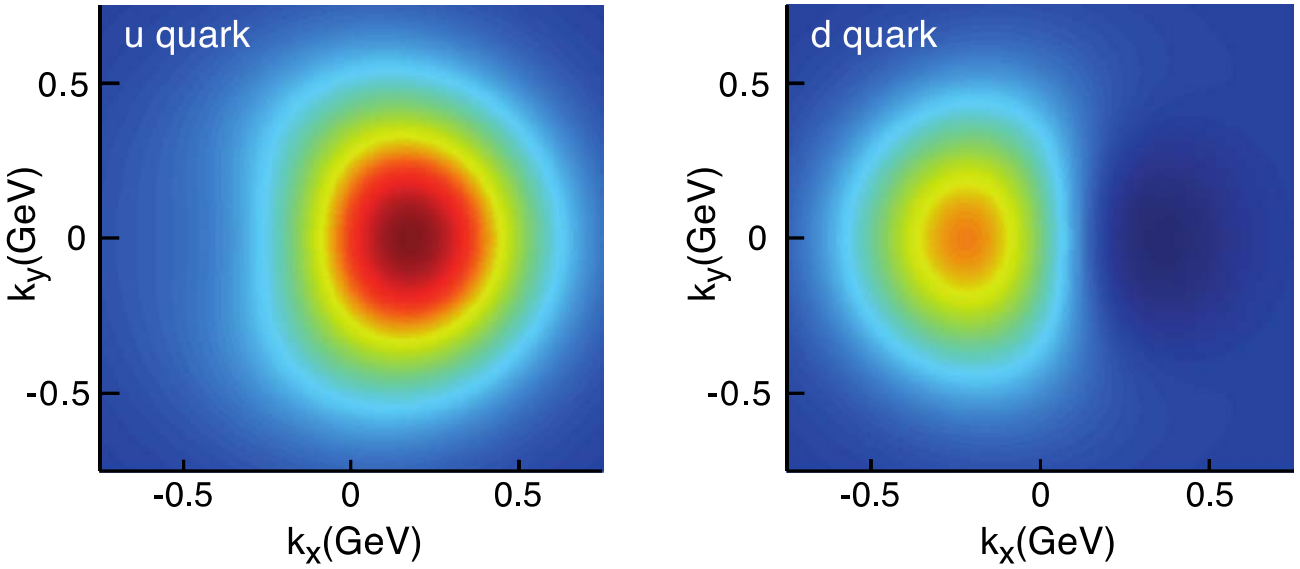
- Spin varies from rf bucket to rf bucket (9.38 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization


FMS
2.6 < η < 4
Full azimuth
Magnet
BEMC
TPC
TOF
BBC
Mid Rapidity Detectors
-1 < η < 1
Full azimuthal coverage
Uniform acceptance
Excellent particle identification
STAR
The Solenoidal Tracker At RHIC

Recent transverse spin measurements

Why TMDs?

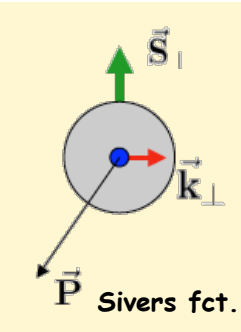
$x\, f_1(x, k_T, S_T)$

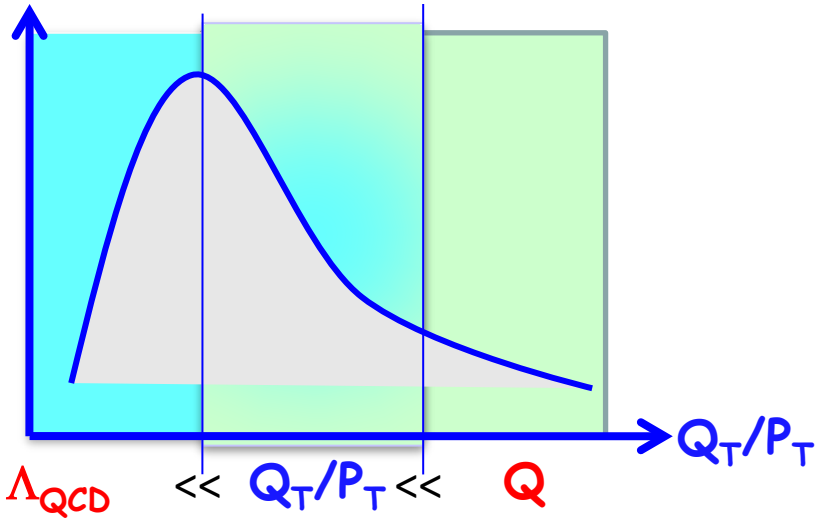


- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei
  - **Tomography of the nucleon!**
- Access to transverse momenta at non-perturbative scales
  - Probe at the confinement scale
- Exhibit correlations arising from spin-orbit effects
- Close connection to Twist-3 quark-gluon-quark correlations

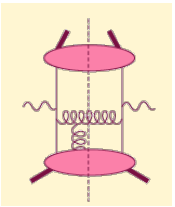
Initial state: TMDs and Twist-3

TMD





Twist-3



Efremov, Teryaev;
Qiu, Sterman
or
Twist-3 FF

Requires 2 scales:
- **Hard scale Q^2**
- **Soft scale p_T**

SIDIS, Drell-Yan, W/Z, …

Access the full transverse momentum dynamics k_T

Single hard scale: p_T

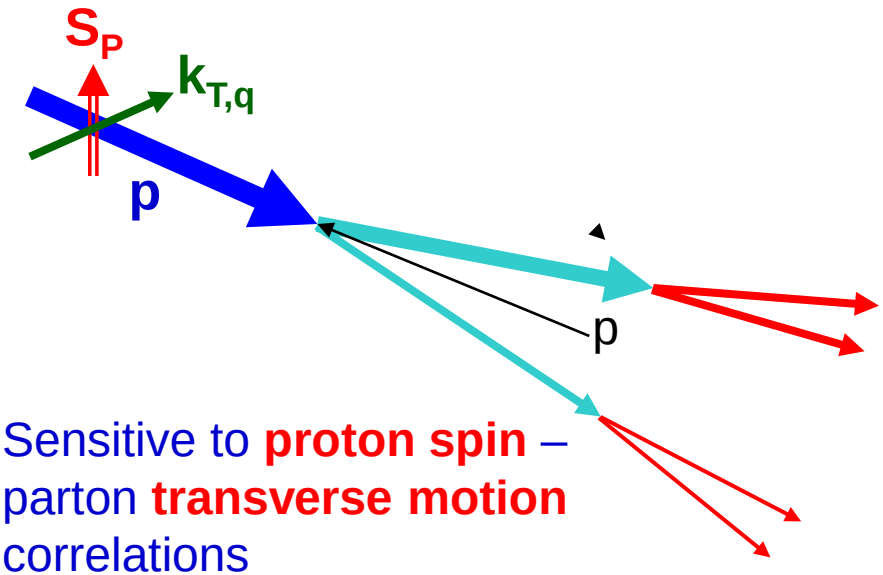
Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$

Access the average transverse momentum $\langle k_T \rangle$

$$-\int d^2k_\perp \frac{{k_\perp}^2}{M} f_{1T}^{\perp q}(x, {k_\perp}^2)|_{SIDIS} = T_{q,F}(x,x)$$

Separating initial- from final-state effects

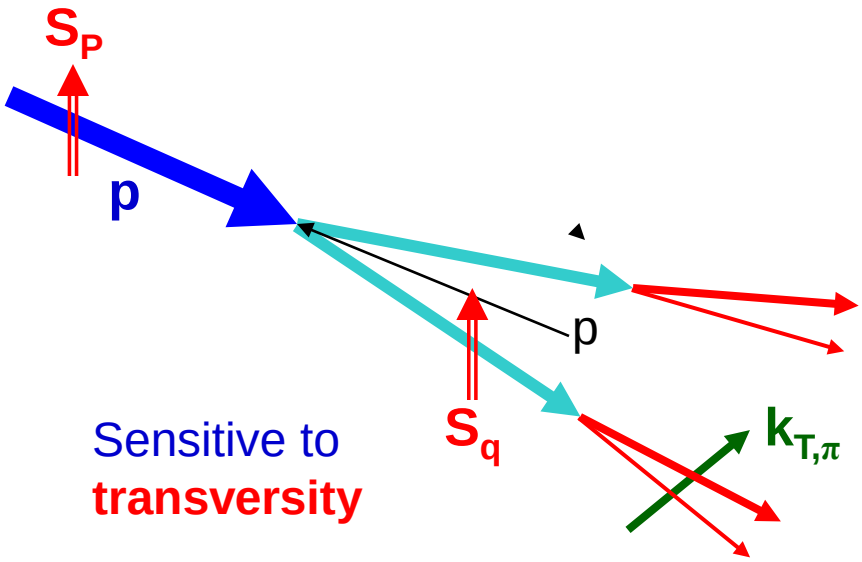
Sivers or twist-3 mechanisms:



Sensitive to **proton spin** – parton **transverse motion** correlations

- Signatures:
  - A_N for jets or direct photons
  - A_N for $W^{+/-}$, Z^0, Drell-Yan
  - A_N for heavy flavor (gluon)
- Sivers NOT universal
  - Sign change from SIDIS to W, Z, and Drell-Yan

Collins or novel FF mechanisms:



Sensitive to **transversity**

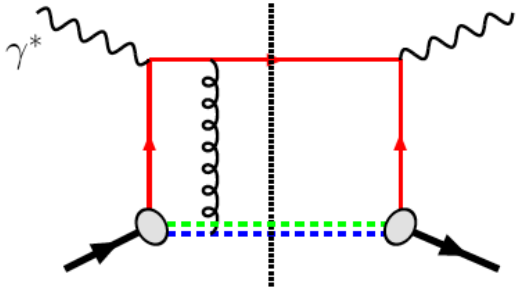
- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - A_N for pions → novel FF
- Collins predicted to be universal

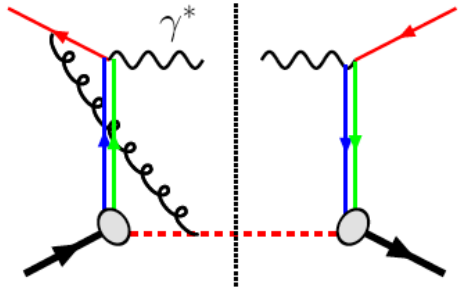
Color interactions in QCD

Controlled non-universality of the Sivers function

QCD:

DIS	Drell-Yan, W or Z
Final-state interaction	Initial-state interaction
Opposite colors attract	Like colors repel





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

A_N for direct photon has related sign change in Twist-3

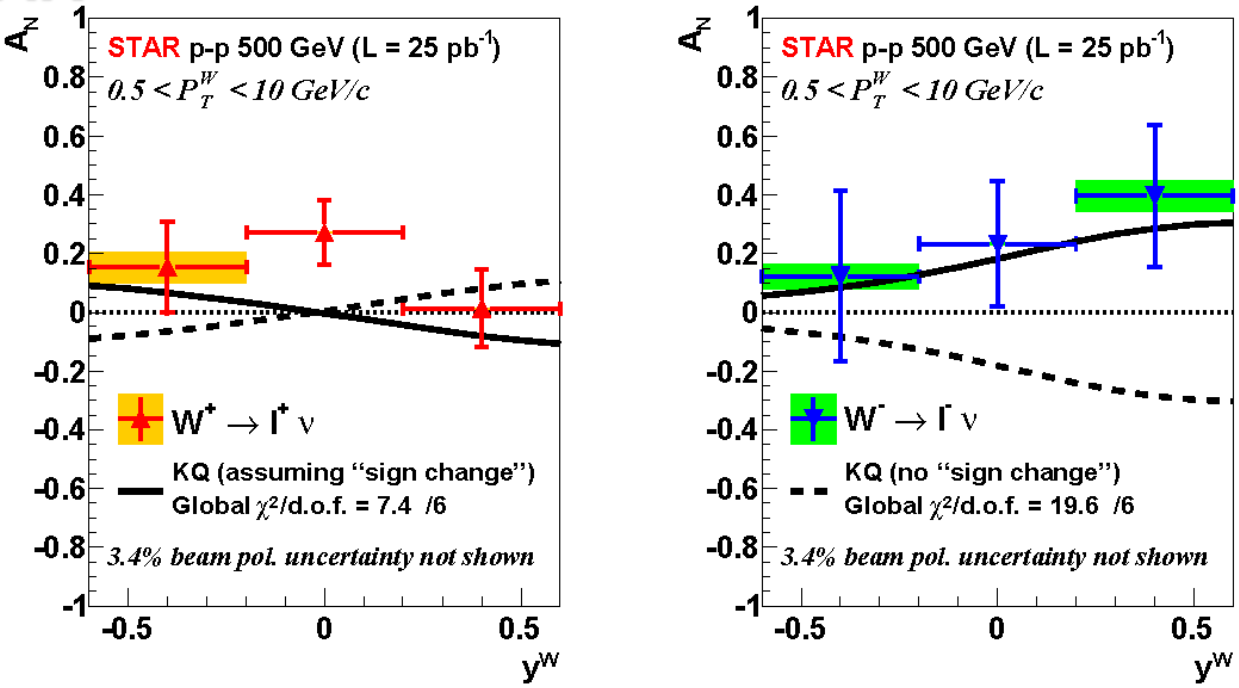
Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

Can explore all of these observables in 510 GeV pp collisions at RHIC

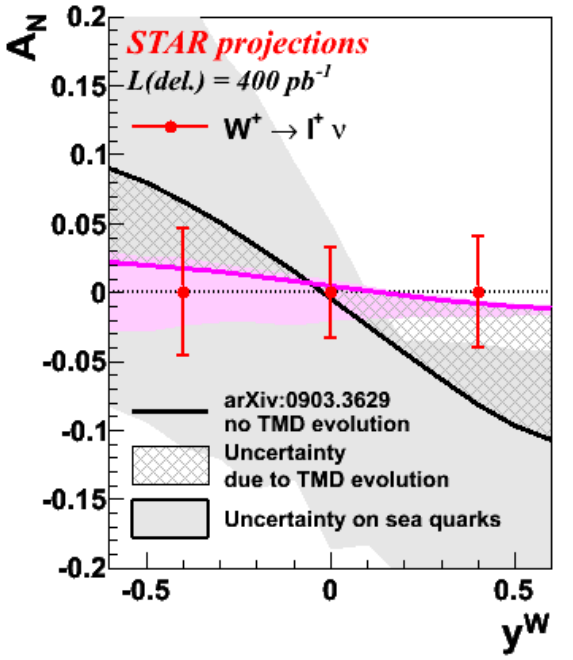
A_N for W production

STAR PRL 116, 132301

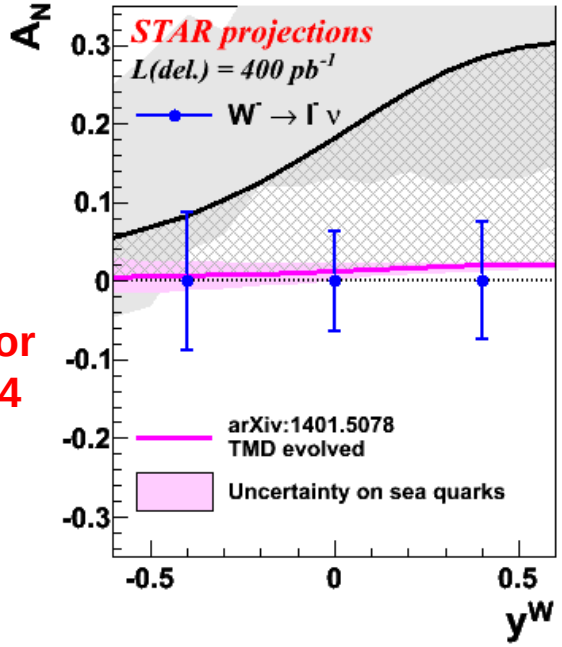


- STAR performed an exploratory measurement of A_N for W production with a small data set recorded in 2011
  - W kinematics fully reconstructed
- Favors **sign change** if evolution effects are modest
  - TMD evolution is non-perturbative at low k_T – no absolute theory predictions

Definitive measurement

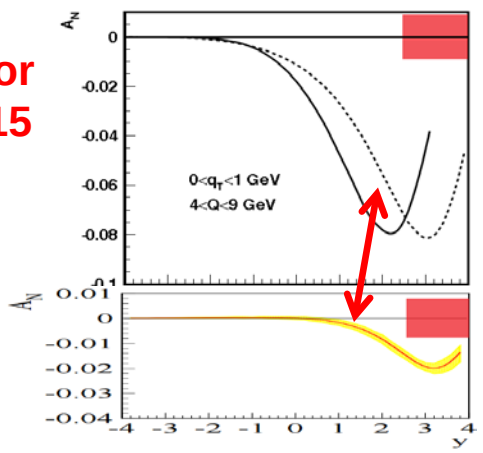


Factor of ~4



Factor of ~15

Drell-Yan

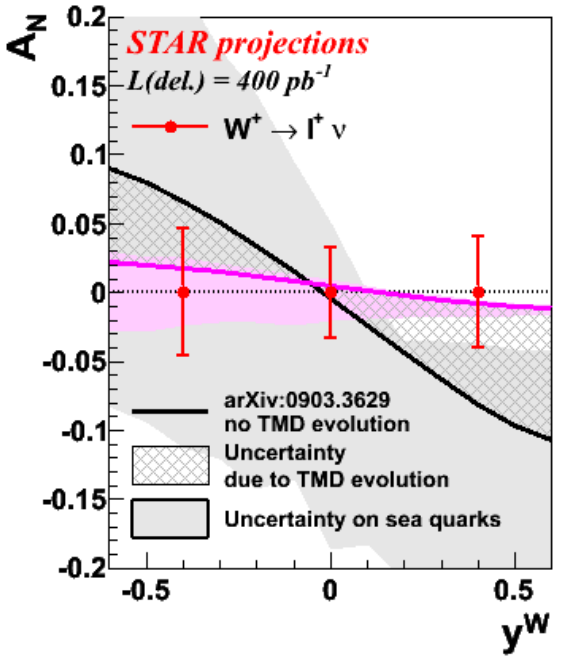


Factor of ~4

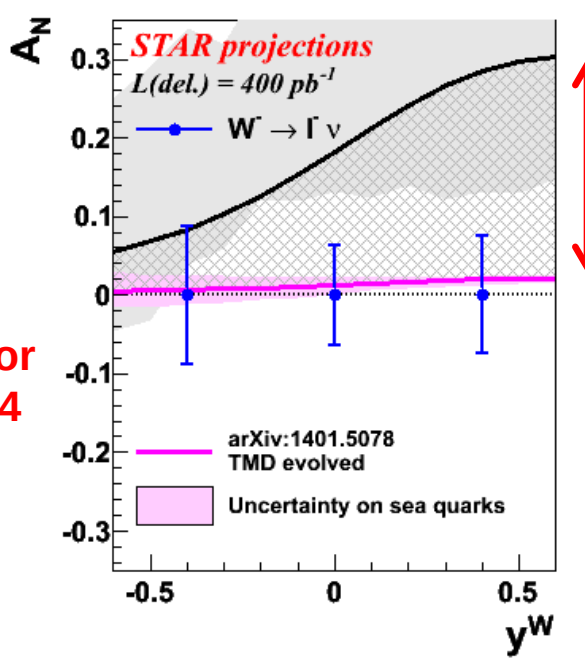
- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable *x* but very different Q^2
    - W and Z A_N at 510 GeV
    - Drell-Yan at 510 GeV

} **2017 RHIC run, data currently under analysis**

Definitive measurement

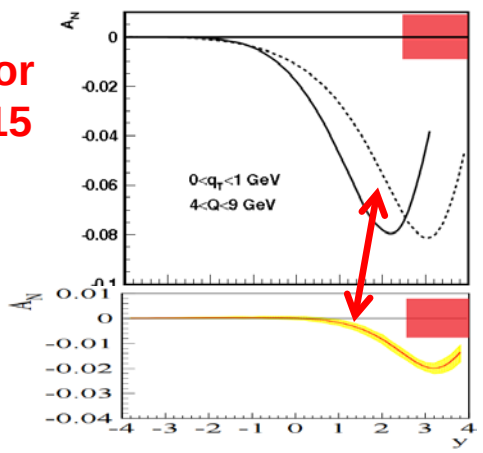


Factor of ~4



Factor of ~15

Drell-Yan



Factor of ~4

- See the sign change if evolution effects are less than factor of 5

Propose a return to 510 GeV in 2021:

Go beyond testing the sign

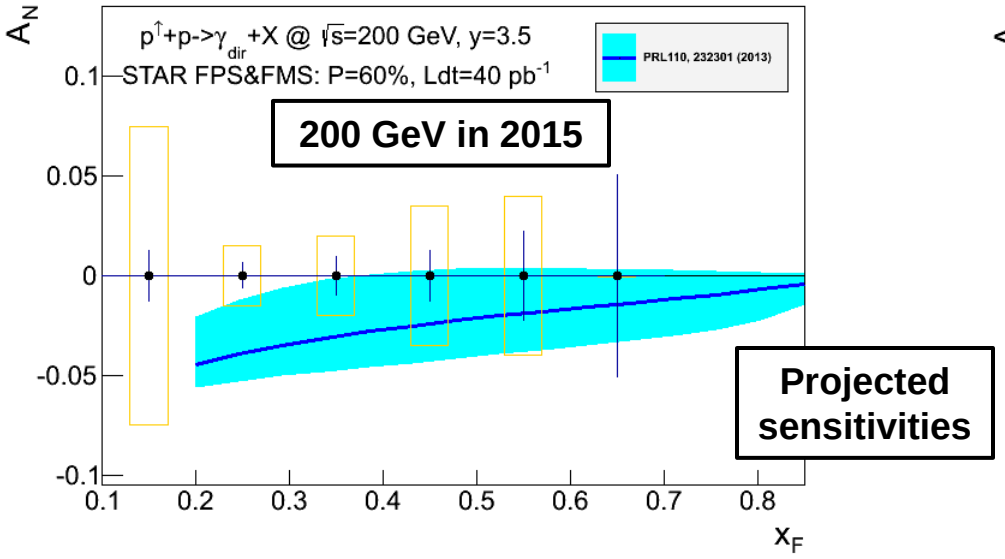
Are the magnitudes *really equal* in SIDIS and pp collisions?

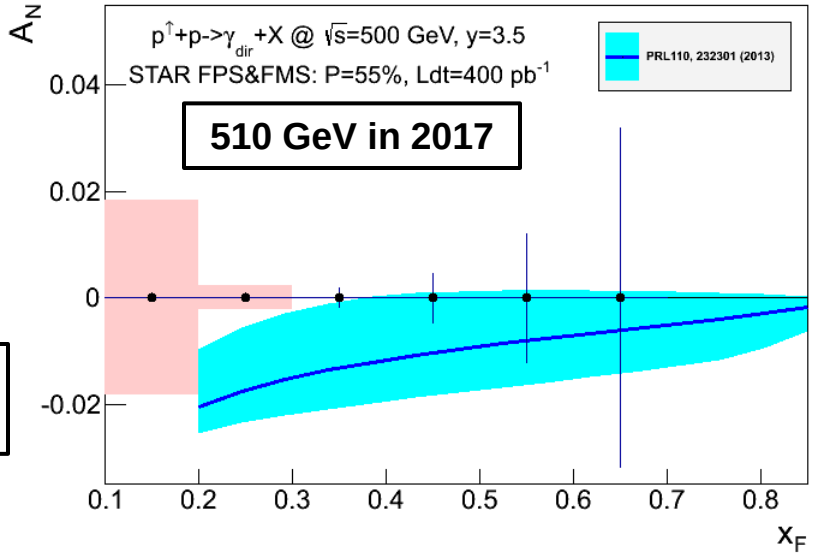
– Access similar observables at comparable x but very different Q^2

- W and Z A_N at 510 GeV
- Drell-Yan at 510 GeV

} **2017 RHIC run, data currently under analysis**

A_N for direct photon

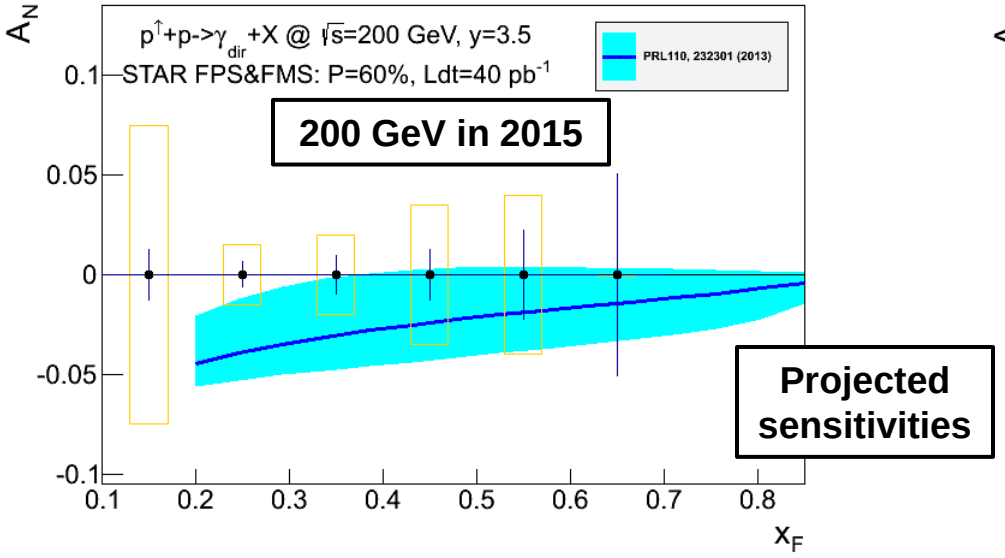


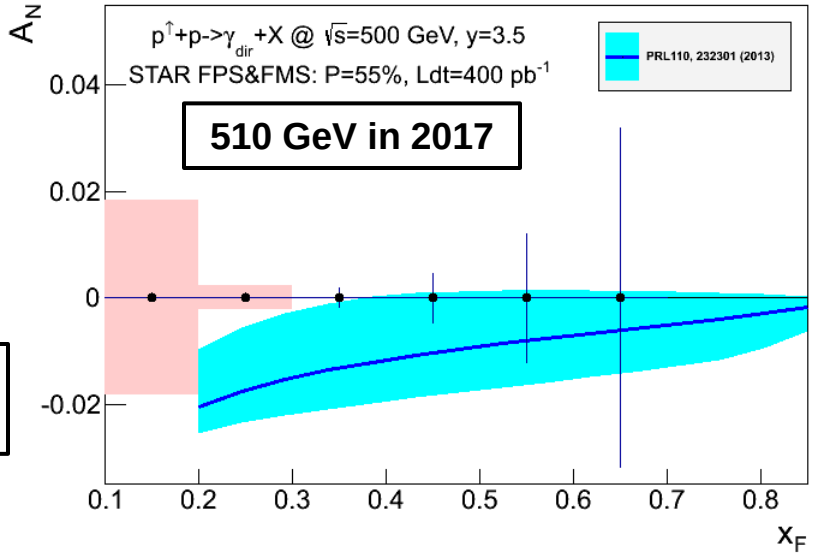


- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

Not a replacement for A_N(W, Z, DY), but an
important complementary piece of the puzzle

A_N for direct photon





- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provid… eir integra…

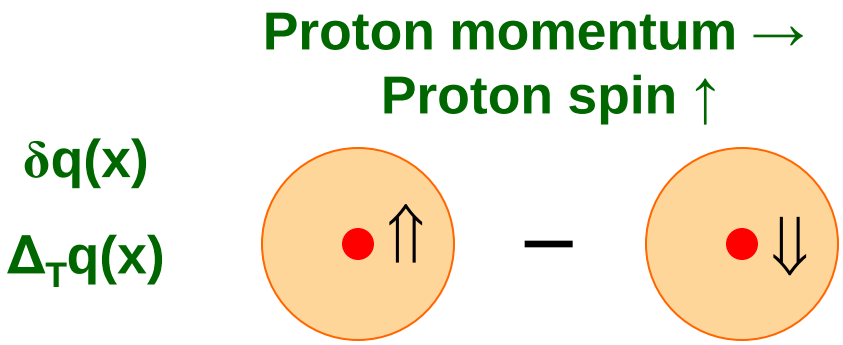
Expect to return to 200 GeV in 2023:

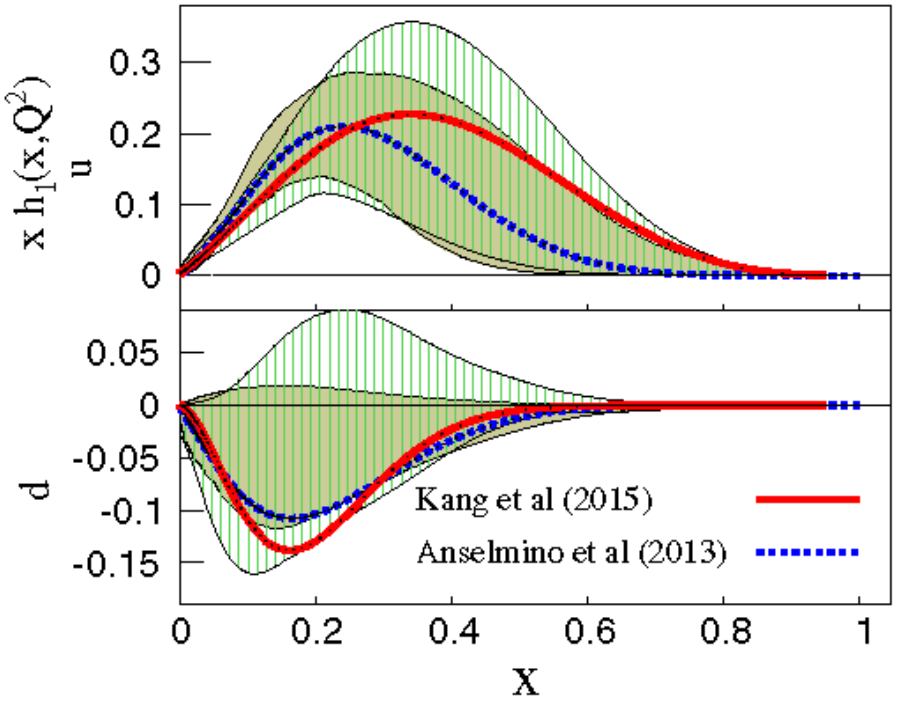
Reduce 200 GeV uncertainties by ~3

Precision measurement of Twist-3 evolution

important complementary piece of the puzzle

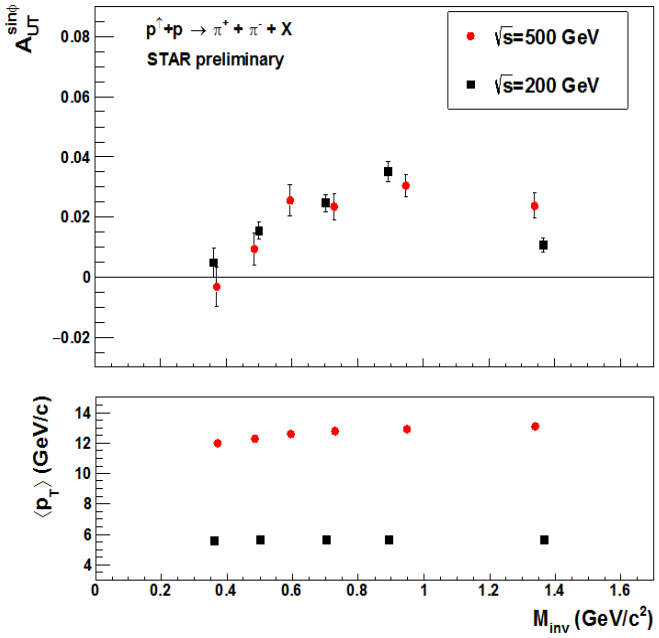
Transversity

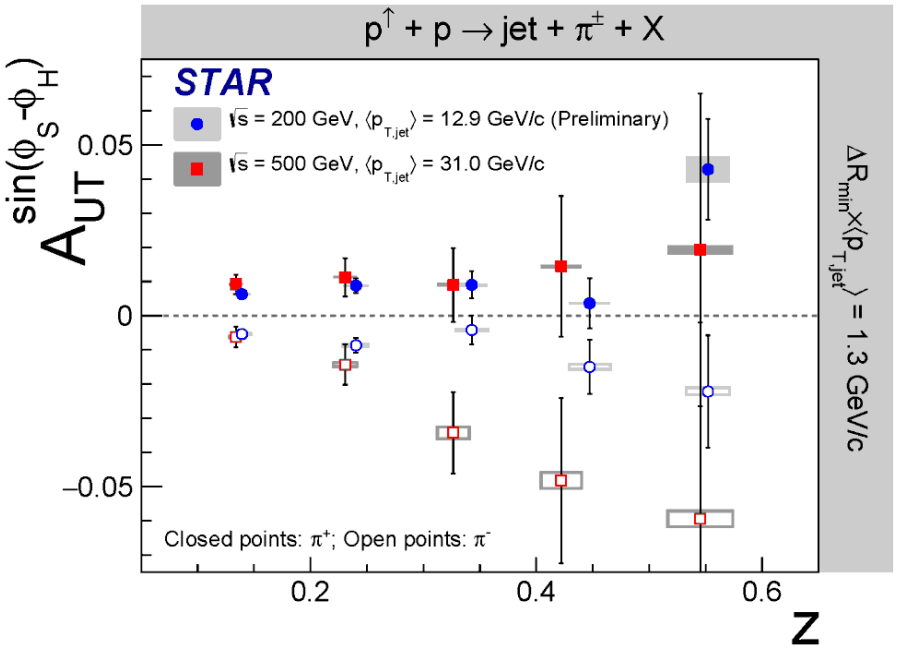




- Quark polarization along spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Chiral odd
- Before ***STAR***, only observed in SIDIS combined with e^+e^-
- Much less data than for helicity
- Several recent global analyses including:
  - Collins effect input:
    - PRD 93, 014009
    - PRD 92, 114023
  - IFF input:
    - arXiv:1802.05212
  - All show large uncertainties

First transversity signals in hadronic collisions

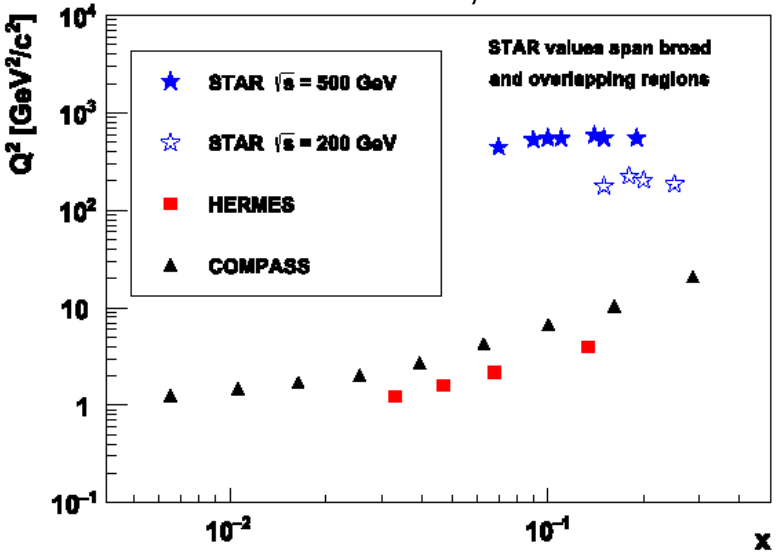




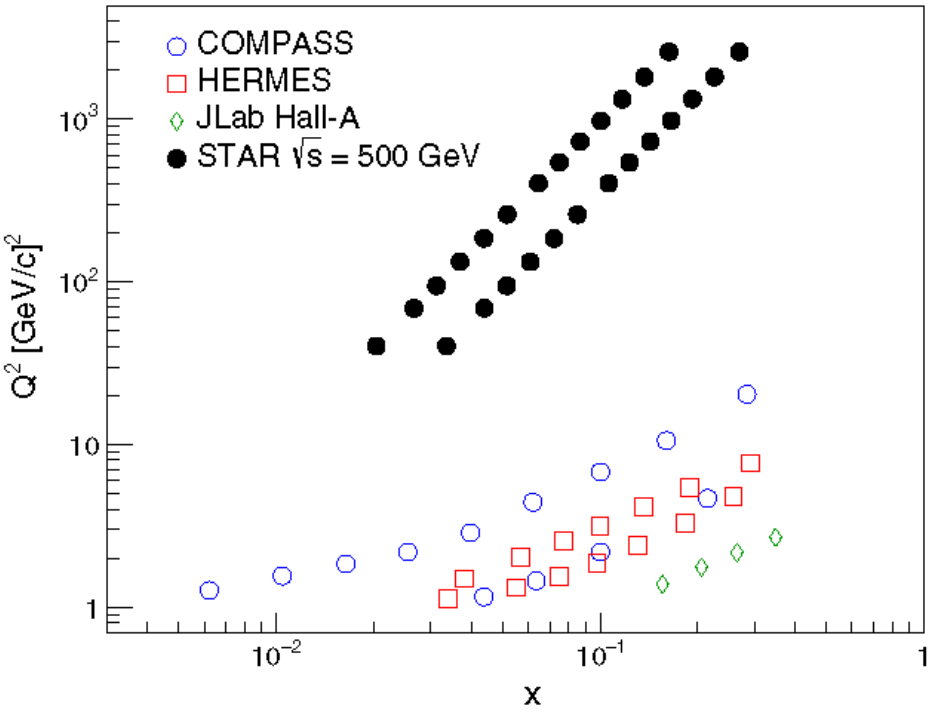
- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Complementary results that obey different evolution equations

x – Q^2 coverage for IFF and Collins effect

PLB 780, 332



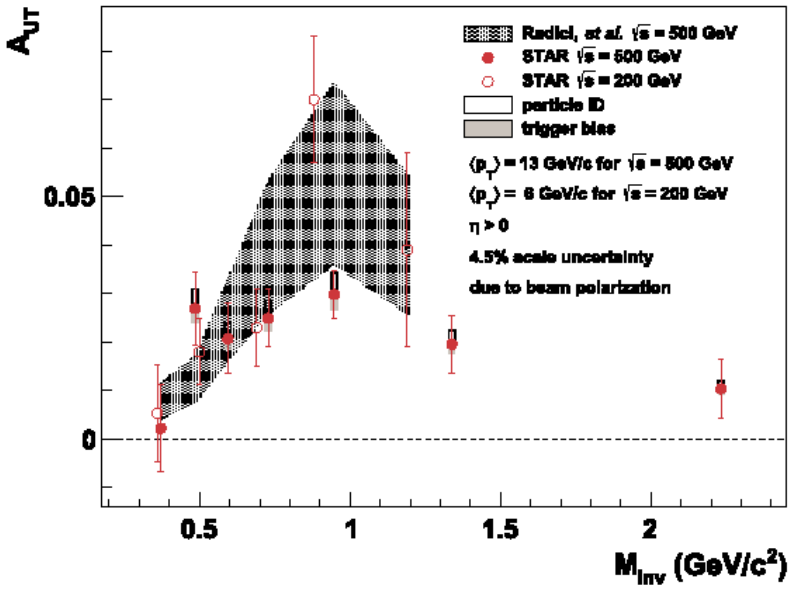
PRD 97, 032004

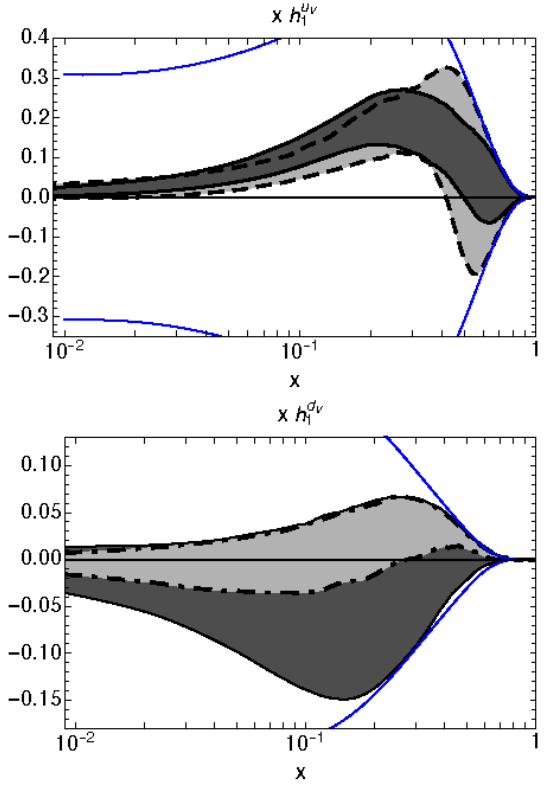


- STAR measurements provide the first observations of transversity at very high scales
  - One to two orders of magnitude higher than COMPASS measurements

STAR IFF and global analysis

STAR PLB 780, 332



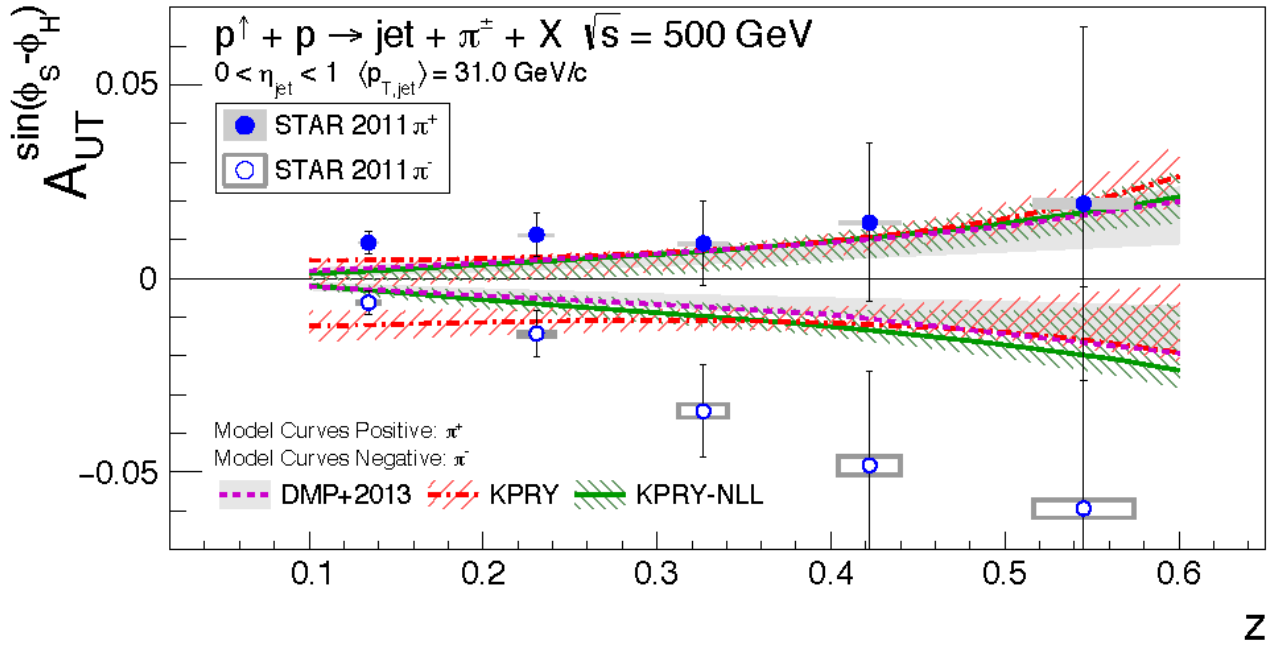


Radici and Bacchetta, arXiv:1802.05212

- ***STAR*** IFF measurements in 200 and 500 GeV pp collisions are well described by recent IFF calculations
- Radici and Bacchetta have performed a global analysis including the ***STAR*** IFF results from 200 GeV pp collisions (PRL 115, 242501)
  - ***STAR*** data significantly reduce the uncertainty for $h_1^{u\text{-}val}$
  - $g \rightarrow \pi^+ \pi^-$ FF dominates the uncertainty for $h_1^{d\text{-}val}$

$\pi^{+/-}$ azimuthal distribution in jets

STAR PRD 97, 032004

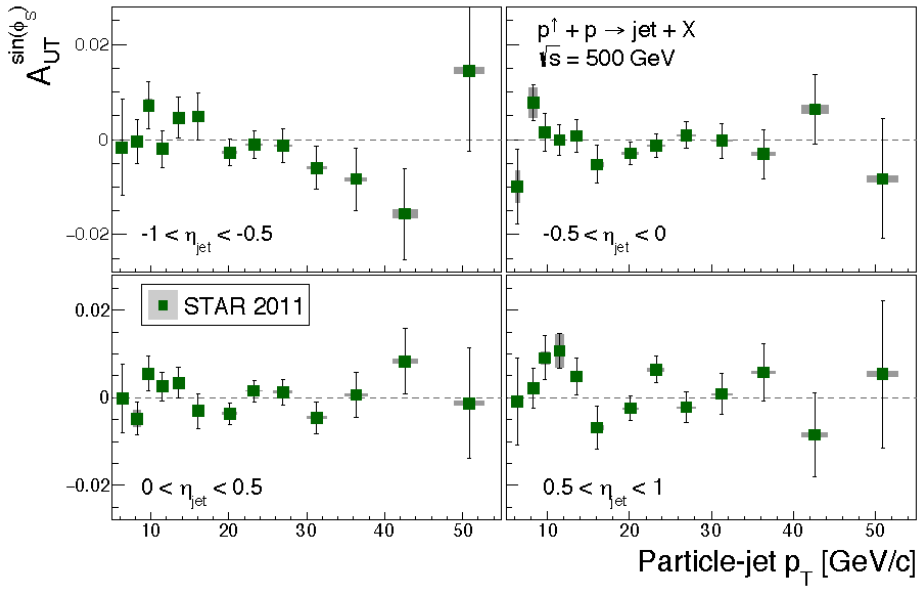


DMP: arXiv:1707.00914
KPRY: arXiv:1707.00913

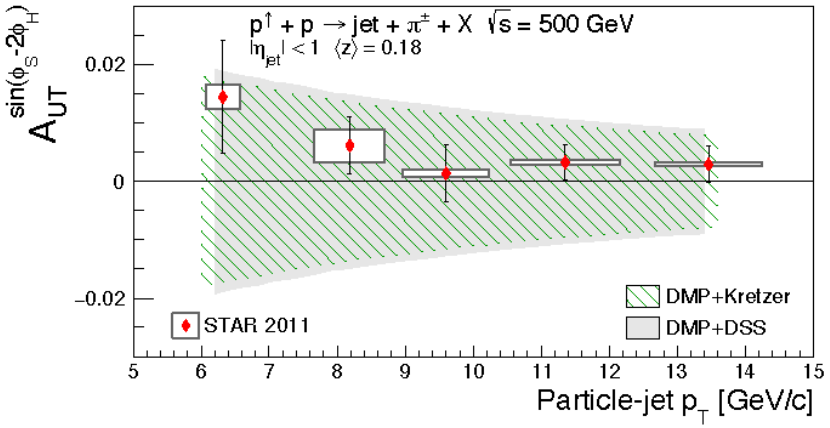
- First Collins effect measurements in pp collisions are reasonably described by two recent calculations that convolute the transversity distribution from SIDIS with the Collins FF from e^+e^- collisions
  - Tests the predicted **universality of the Collins FF**
    - Kang et al, JHEP 1711, 068
  - TMD evolution effects appear to be small

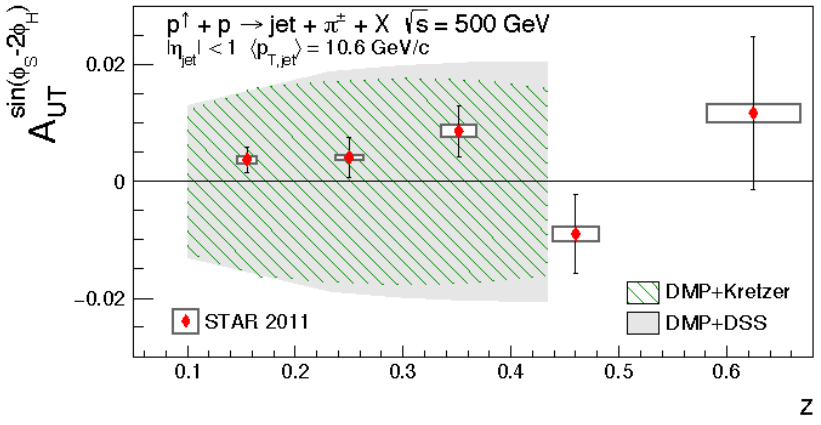
Additional azimuthal modulations

STAR PRD 97, 032004

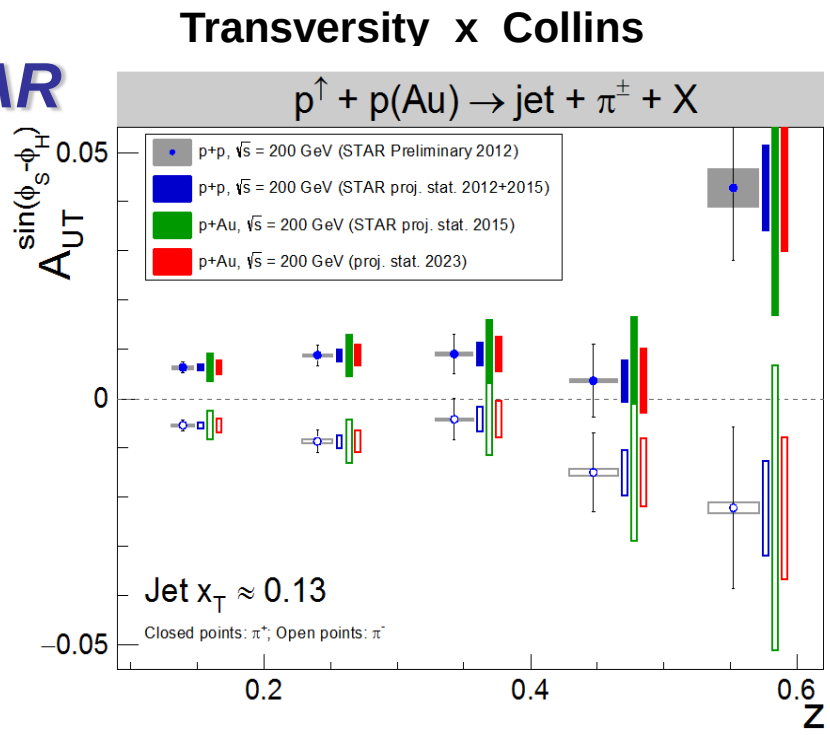


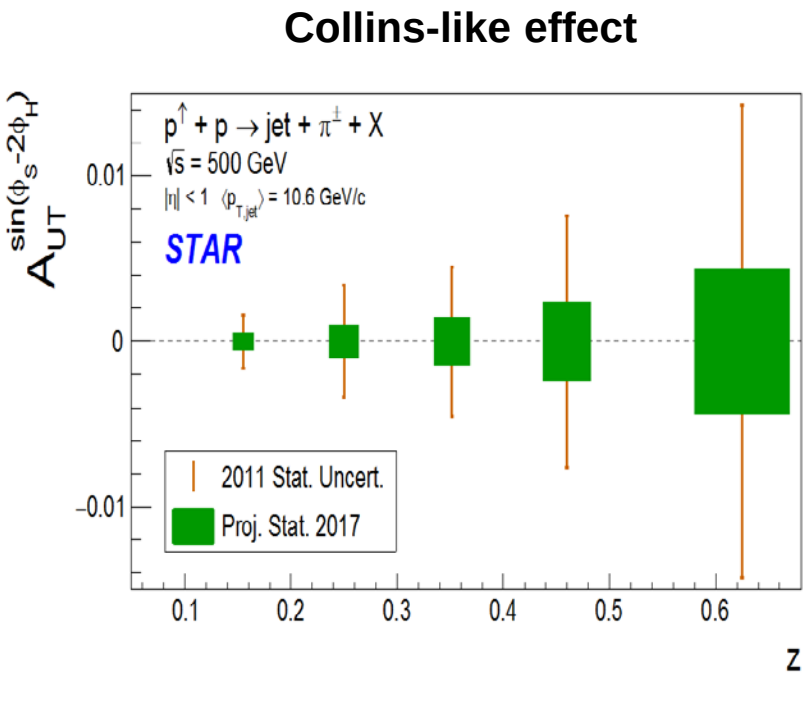
- Inclusive jet A_N
  - Sensitive to the gluon Sivers function via the Twist-3 relationship
- "Collins-like" effect
  - World's first ever limit on linearly polarized gluons in a polarized proton





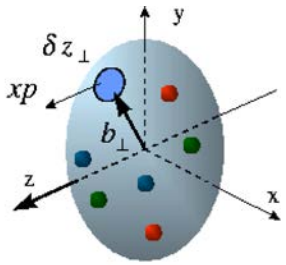
Projected uncertainties for upcoming results

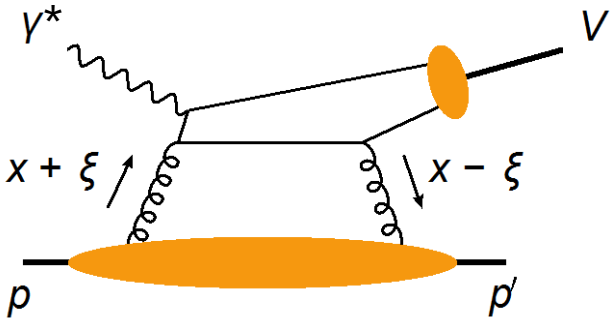


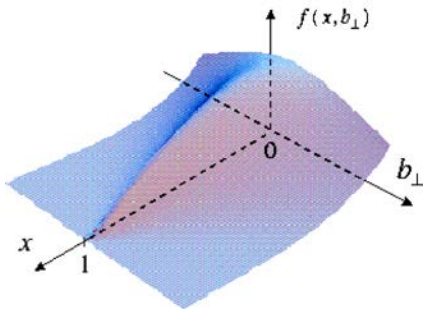


- Final Collins results from 200 GeV collisions will be coming soon
- Recorded > 10 times as much data at 510 GeV in 2017 as in 2011
  - Precision data at fixed *x*, different √*s* **ideal to constrain TMD evolution**
  - Much tighter limits (or first observation?) for Collins-like effect
- Also have data for a first look at the Collins effect in p+Au collisions

What about orbital angular momentum?







quark contribution

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

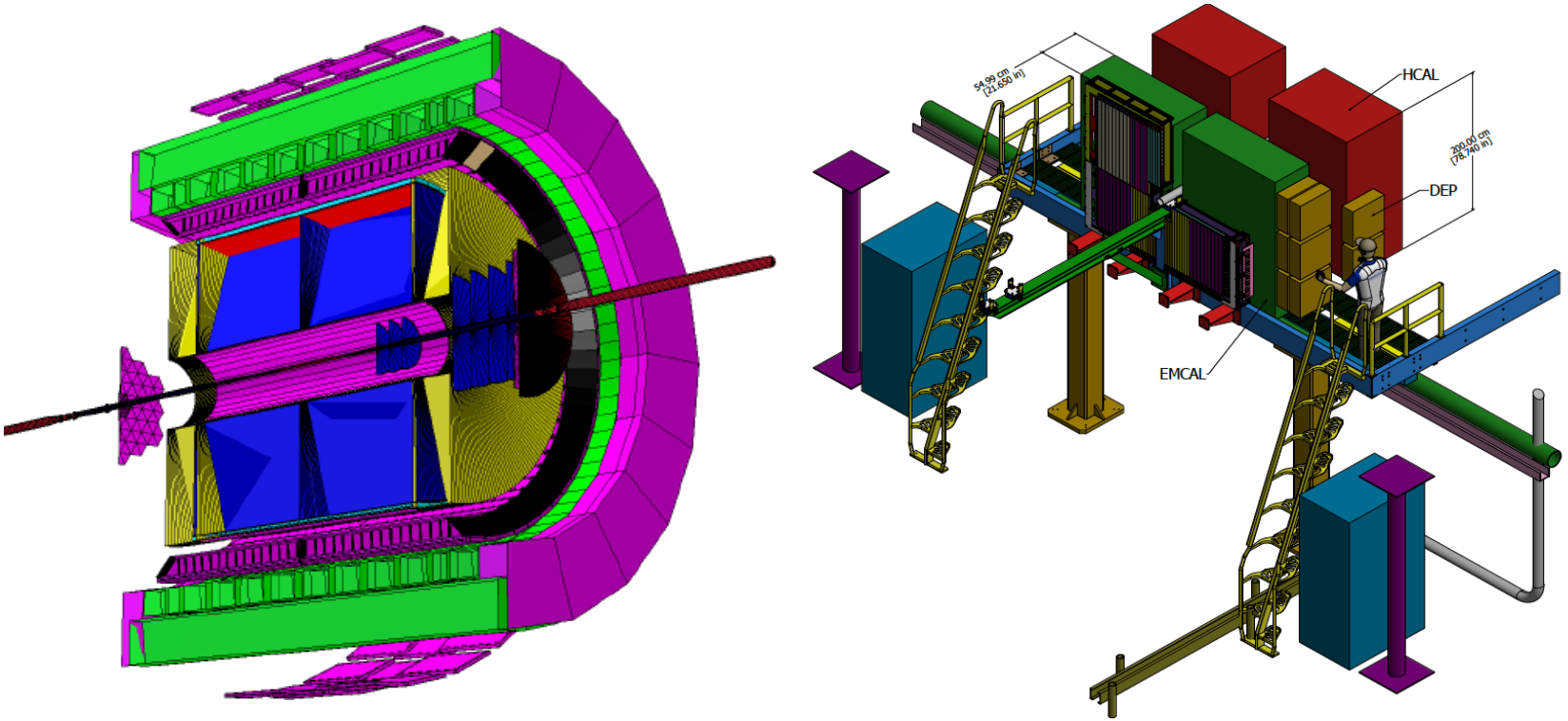
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$

- Generalized parton distributions (GPDs), measured via exclusive reactions, provide **access to L_q and L_g**
- Exclusive J/ψ production in ultra-peripheral collisions with transversely polarized p+p and p+Au provides access to the GPD E_g
  - The GPD E is responsible for orbital angular momentum
  - **Access to E_g before EIC**
    - Set the scale to inform EIC detector and experiment planning
- Data from the 2015 and 2017 RHIC runs are under analysis

STAR Forward Upgrade plans

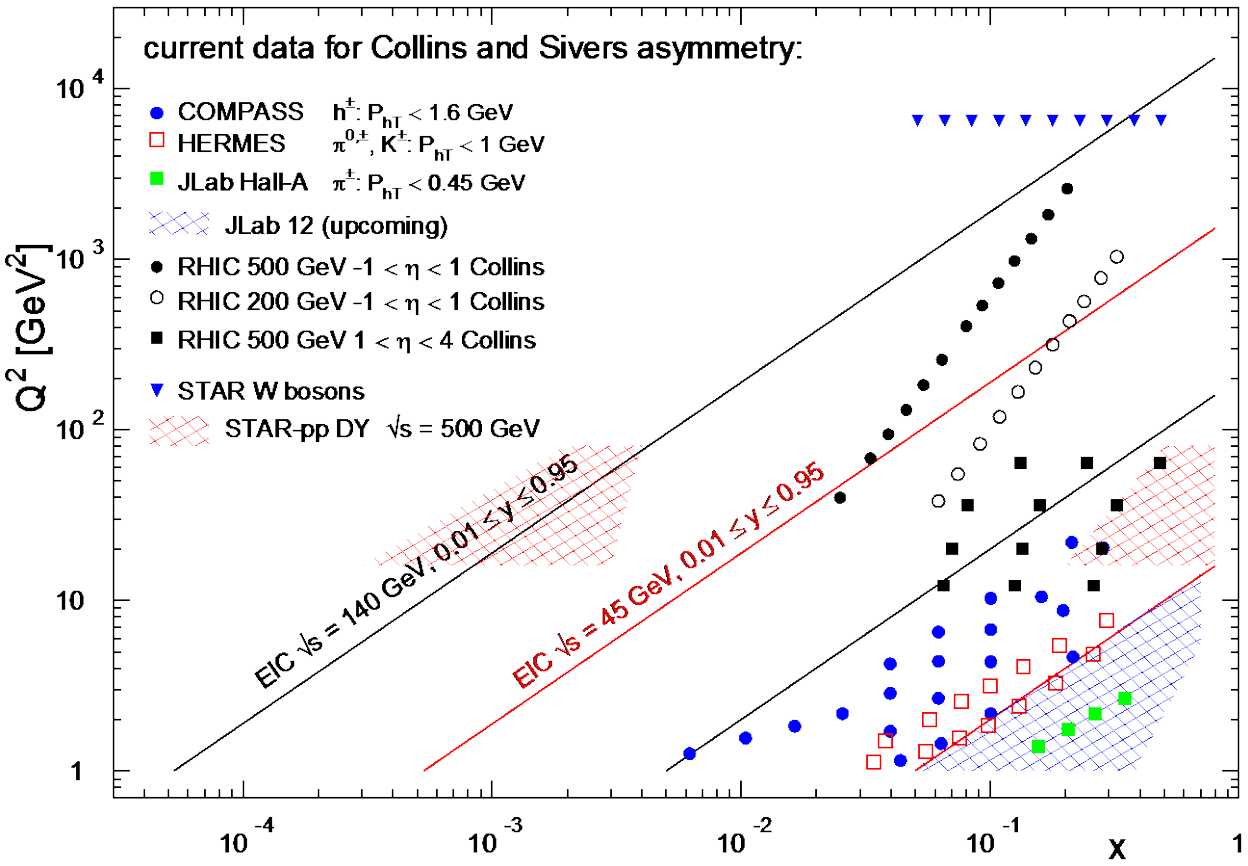
For a more detailed discussion, see:
E.-C. Aschenauer, WG6-WG7 Joint Session, 14:00-14:30 today

Planned forward upgrade for the 2020's



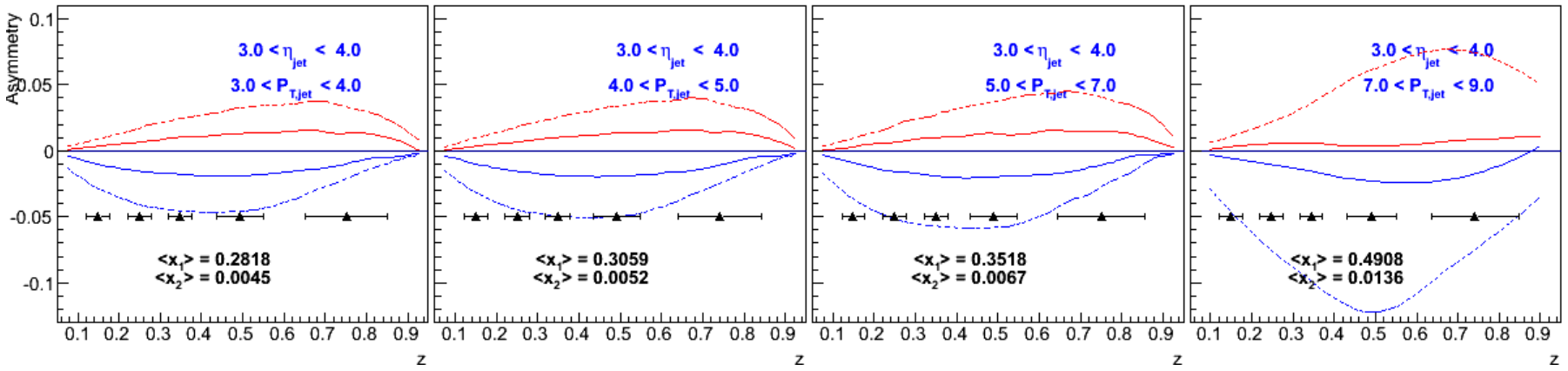
- Si disks + small Thin Gap Chambers for tracking
- Compact electromagnetic and hadronic calorimeters
- Transverse spin phenomena:
  - Precision TMDs through jets at forward rapidity
  - Precision A_N(Drell-Yan) to complete the Sivers measurements

Sivers and Collins coverage at RHIC



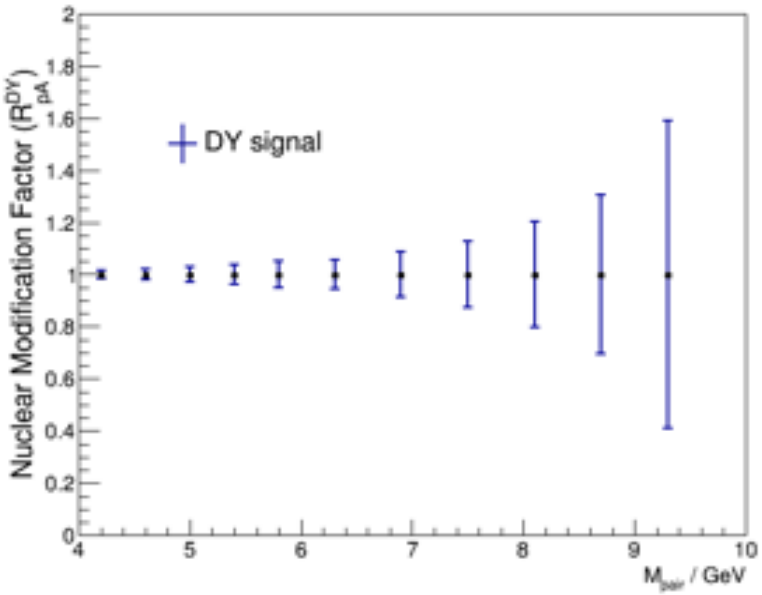
- Kinematics of RHIC
  - Dramatic extension in (x, Q^2) reach before EIC
  - W production probes the highest Q^2 over a wide x range
  - **Precision tests of universality** when EIC data become available

Future precision with the Forward Upgrade

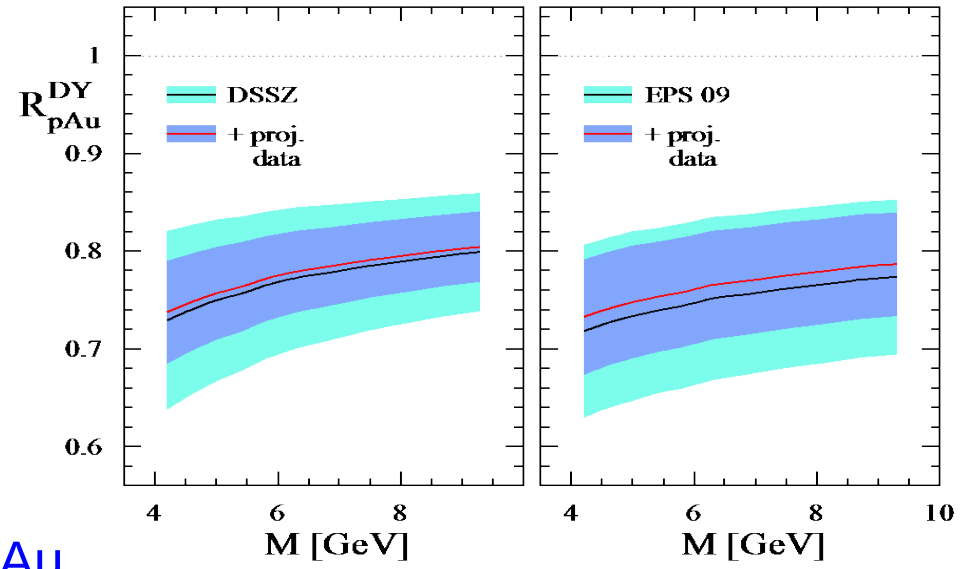


- Measurements of the Collins effect in forward jets will sample transversity at high scales over a very wide *x* range
- Will also much higher precision Drell-Yan and direct photon A_N measurements

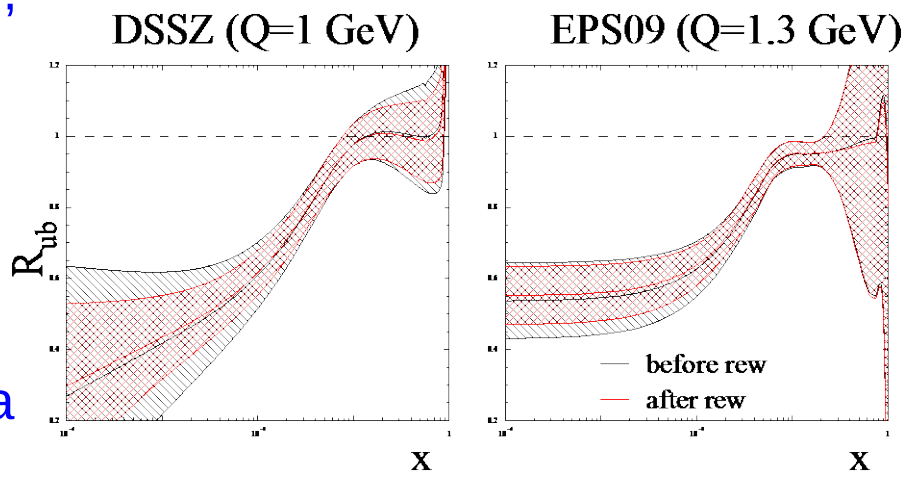
Drell-Yan R_{pA} at 200 GeV



Projected impact on sea quark nPDFs



- Similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the Q^2 lever arm at low x relative to future EIC data



Conclusions

- The ***STAR*** transverse spin program has made a number of striking observations
- ***STAR*** has a huge body of additional spin data under analysis
- The ***STAR*** Forward Upgrade will provide a bright future for ***STAR*** in the coming decade
- ***STAR*** is a key component of the RHIC Cold QCD program: an essential bridge between the physics of RHIC and the physics of the future Electron Ion Collider