Recent Transverse Spin Measurements in pp Collisions with *STAR*

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for the *STAR* Collaboration

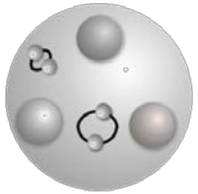
Outline

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

U.S. DEPARTMENT OF ENERGY | Office of Science

Complementarity of DIS and p+p

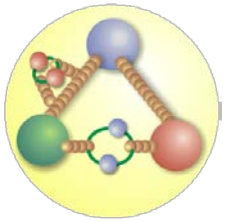
- **Deep-inelastic scattering** primarily probes via:



  - 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:

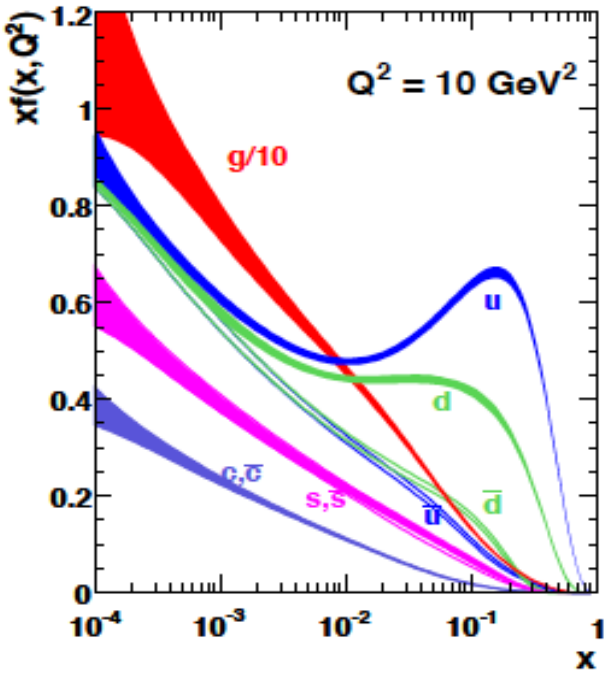


  - Strong interactions
    - Couple to color charge
    - Direct leading-order sensitivity to gluons
    - Insensitive to flavor

- **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



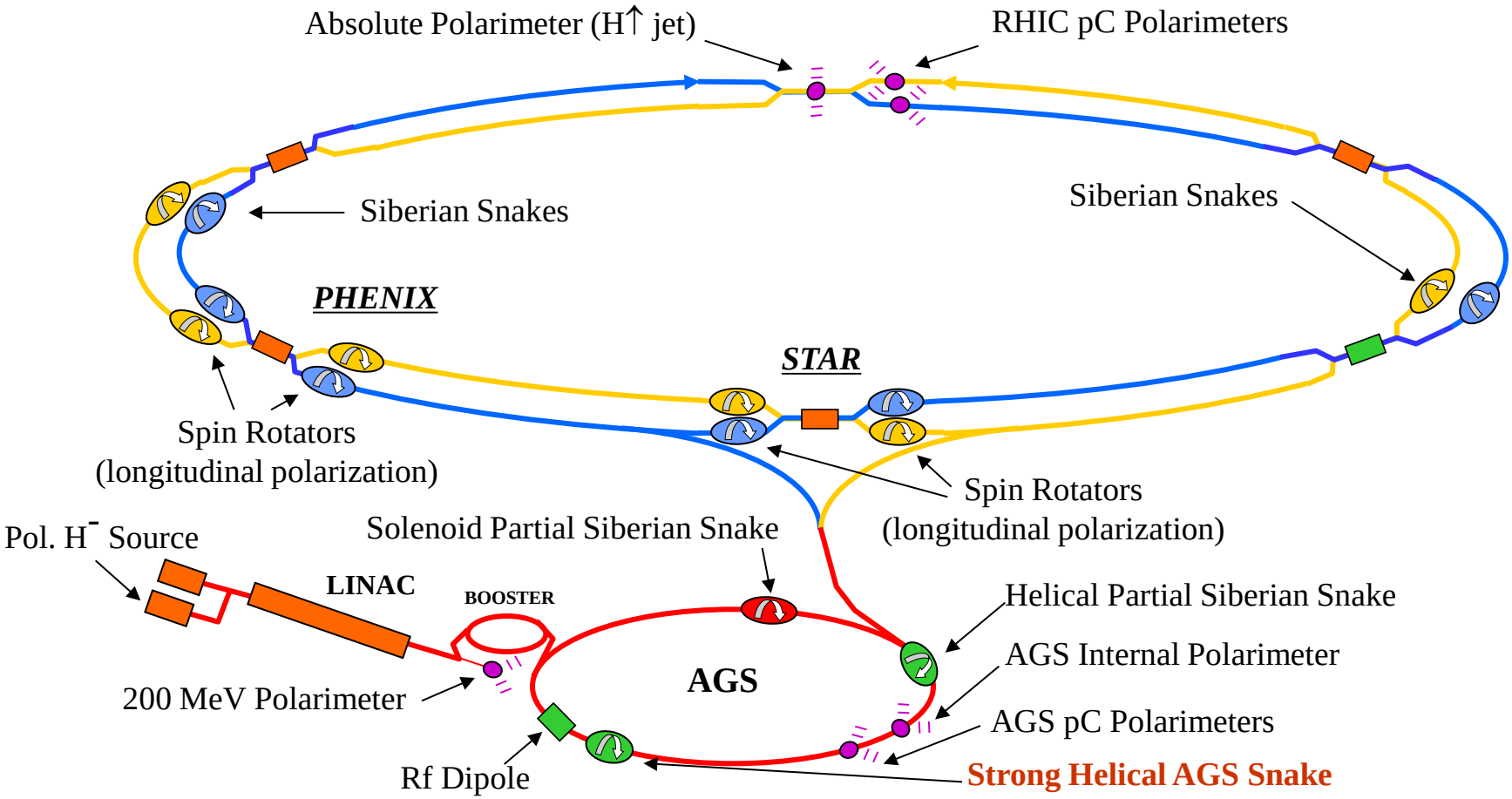
Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\}\to\ell^\pm X$	$\gamma^* q\to q$	$q,\bar{q},g$	$x\gtrsim 0.01$
$\ell^\pm n/p\to\ell^\pm X$	$\gamma^* d/u\to d/u$	d/u	$x\gtrsim 0.01$
$pp\to\mu^+\mu^- X$	$u\bar{u},d\bar{d}\to\gamma^*$	$\bar{q}$	$0.015\lesssim x\lesssim 0.35$
$pn/pp\to\mu^+\mu^- X$	$(u\bar{d})/(u\bar{u})\to\gamma^*$	$\bar{d}/\bar{u}$	$0.015\lesssim x\lesssim 0.35$
$\nu(\bar{\nu})N\to\mu^-(\mu^+)X$	$W^*q\to q'$	$q,\bar{q}$	$0.01\lesssim x\lesssim 0.5$
$\nu N\to\mu^-\mu^+ X$	$W^*s\to c$	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

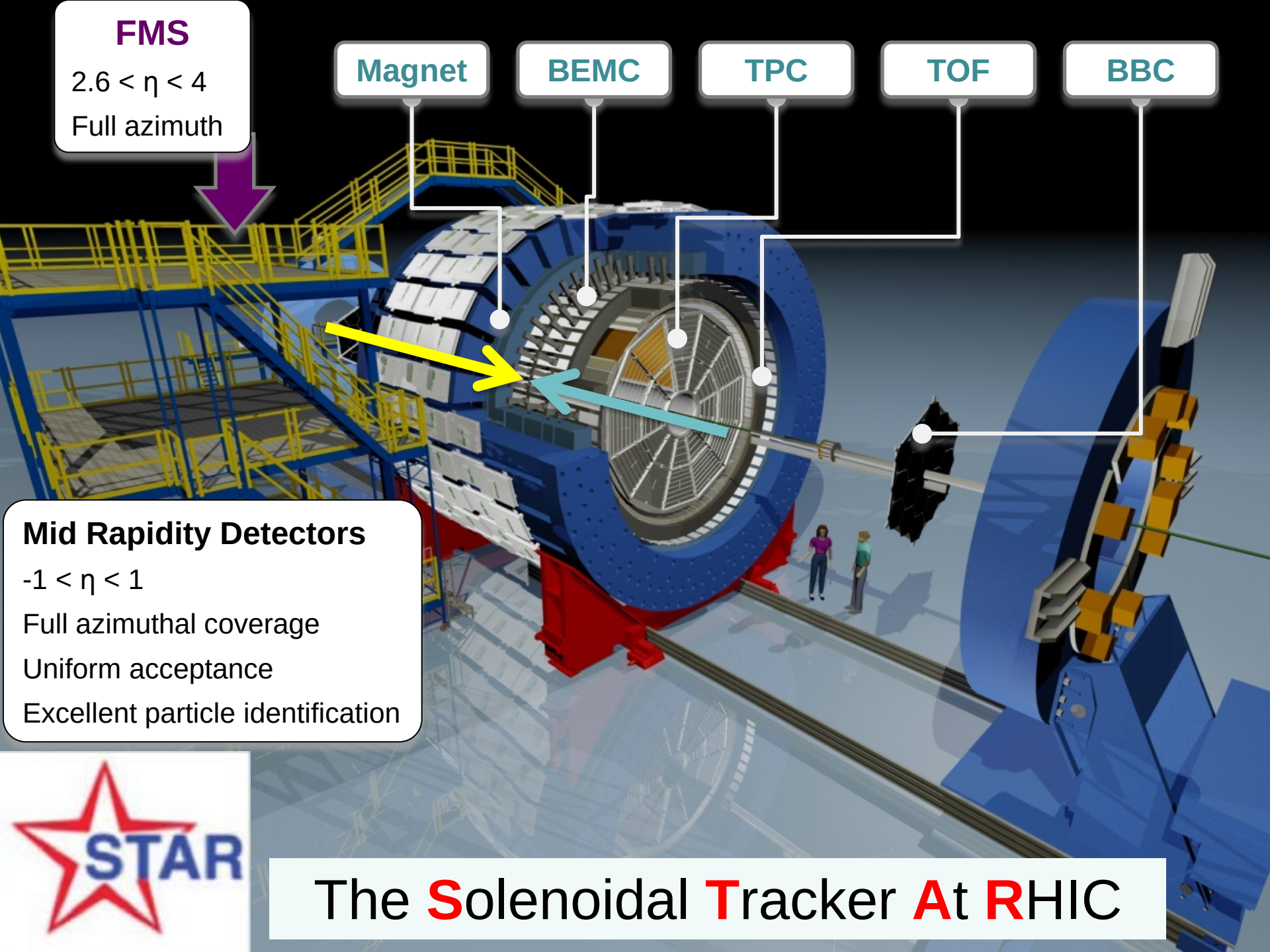
RHIC: the **R**elativistic **H**eavy **I**on **C**ollider

- 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



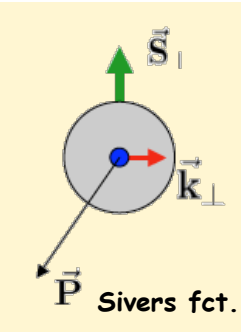
- Spin varies from rf bucket to rf bucket (9.38 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

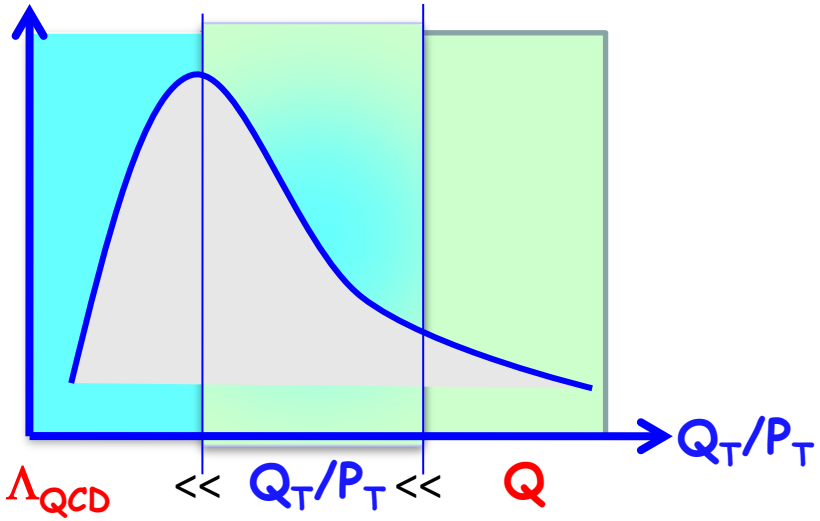

FMS
2.6 < η < 4
Full azimuth
Magnet
BEMC
TPC
TOF
BBC
Mid Rapidity Detectors
-1 < η < 1
Full azimuthal coverage
Uniform acceptance
Excellent particle identification
STAR
The Solenoidal Tracker At RHIC

Recent transverse spin measurements

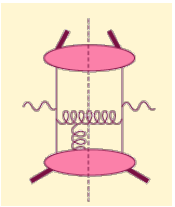
Initial state: TMDs and Twist-3

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 $\langle k_T \rangle$

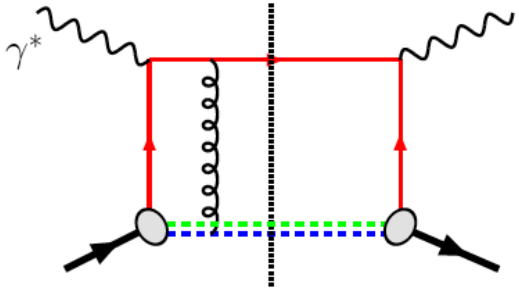
$$-\int d^2k_\perp \frac{{k_\perp}^2}{M} f_{1T}^{\perp q}\left(x, {k_\perp}^2\right)\Big|_{SIDIS} = T_{q,F}(x,x)$$

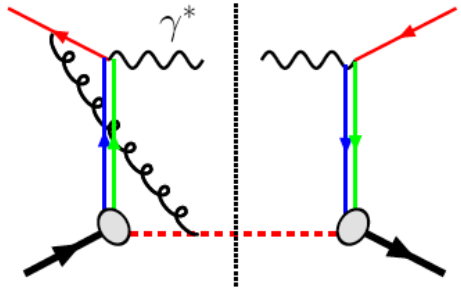
Color interactions in QCD

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

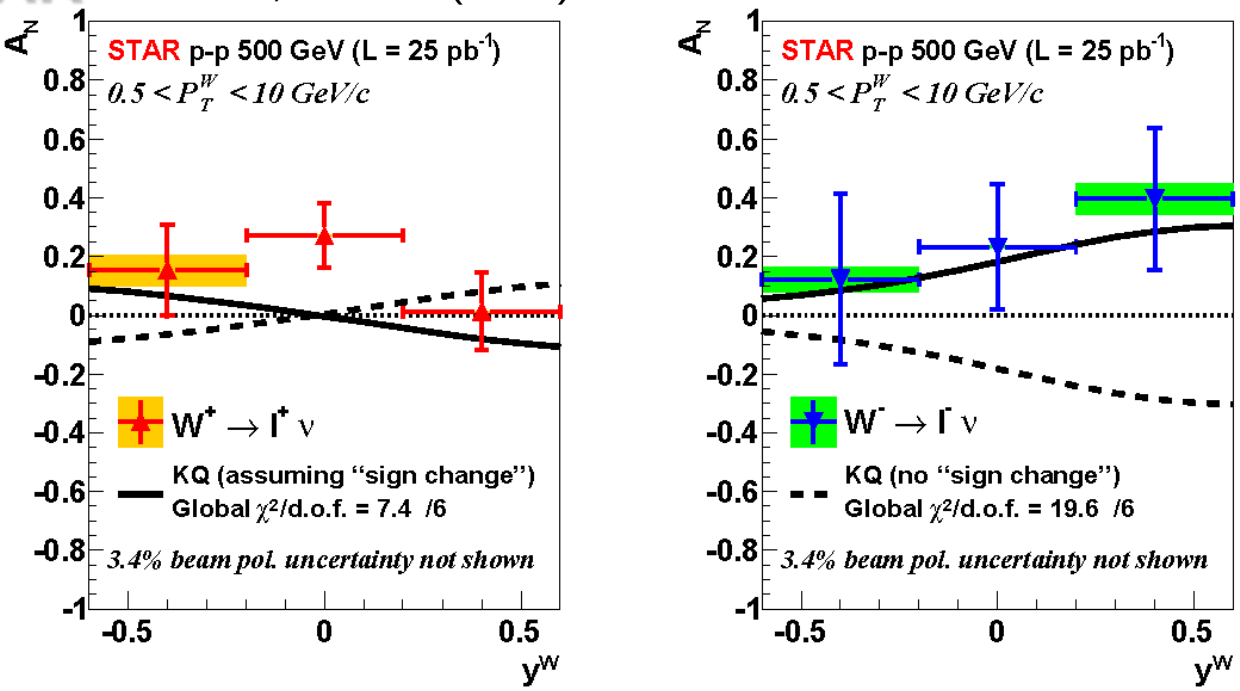
Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

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

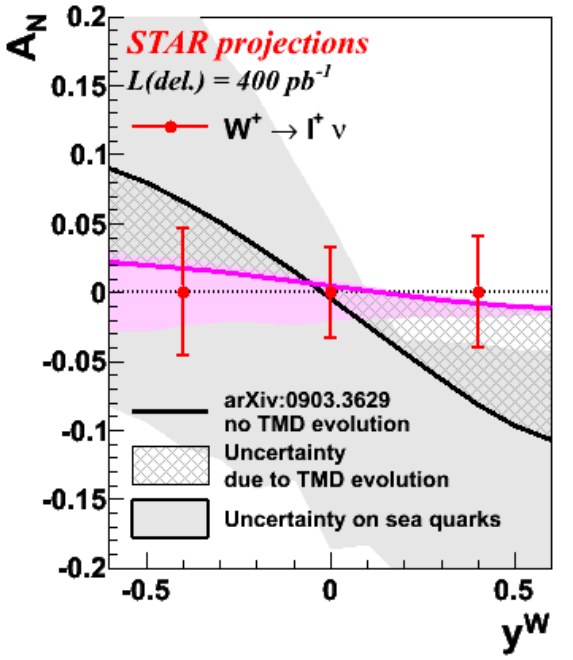
A_N for W production

STAR PRL 116, 132301 (2016)

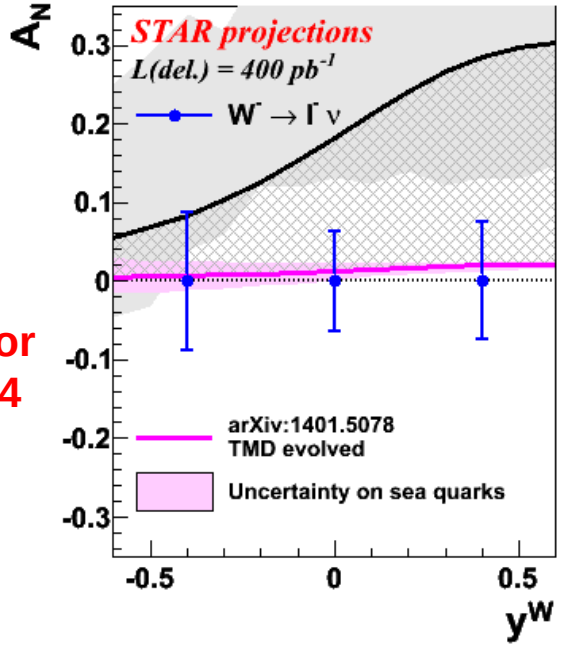


- STAR performed an exploratory measurement of A_N for W production with a small data set recorded in 2011
  - W kinematics fully reconstructed
- Favors **sign change** if evolution effects are modest
  - TMD evolution is non-perturbative at low k_T – no absolute theory predictions

Definitive measurement

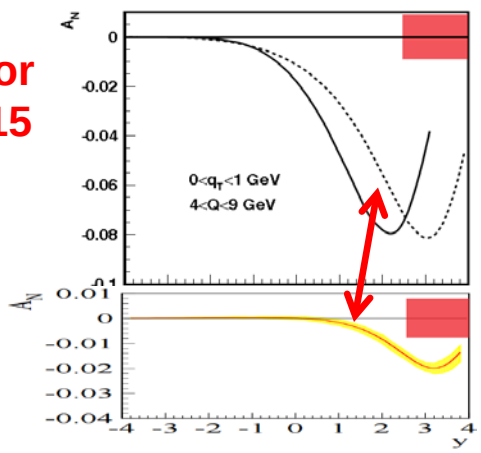


Factor of ~4



Factor of ~15

Drell-Yan

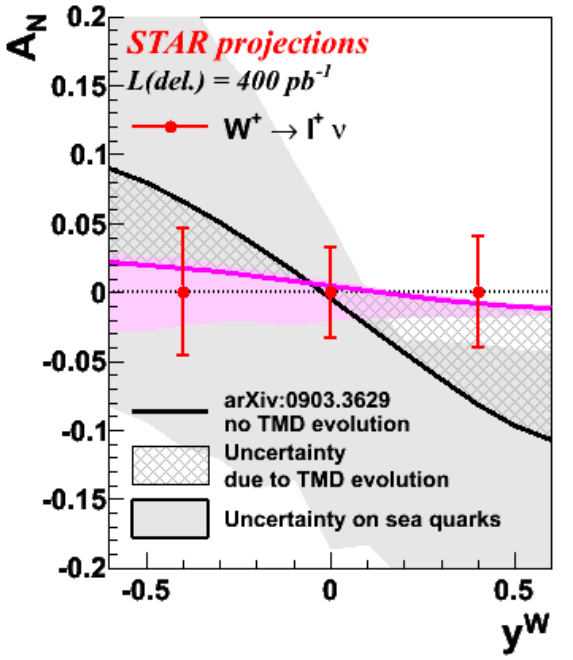


Factor of ~4

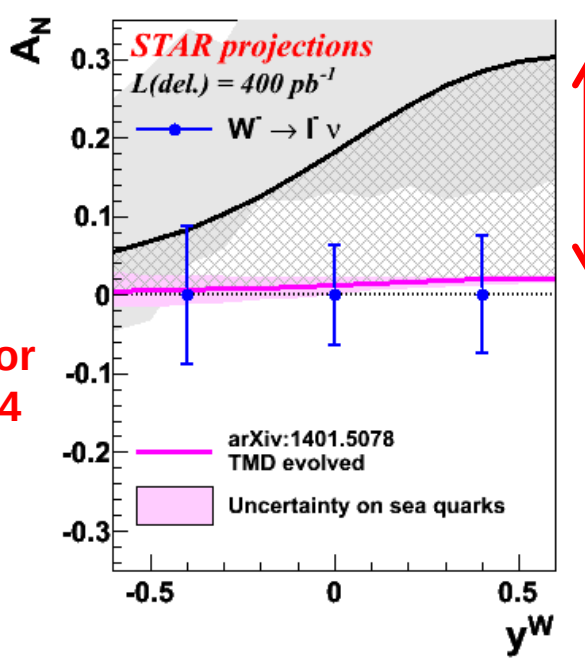
- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable *x* but very different Q^2
   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

2017 RHIC run, data currently under analysis

Definitive measurement

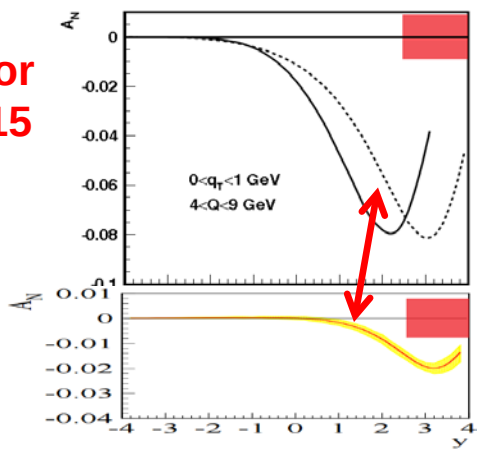


Factor of ~4



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

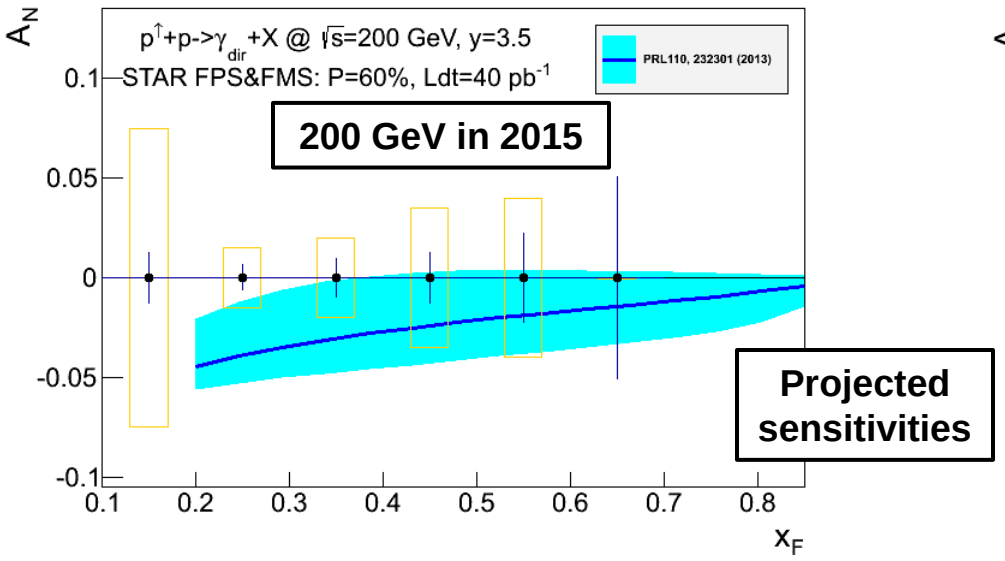
Are the magnitudes *really equal* in SIDIS and pp collisions?

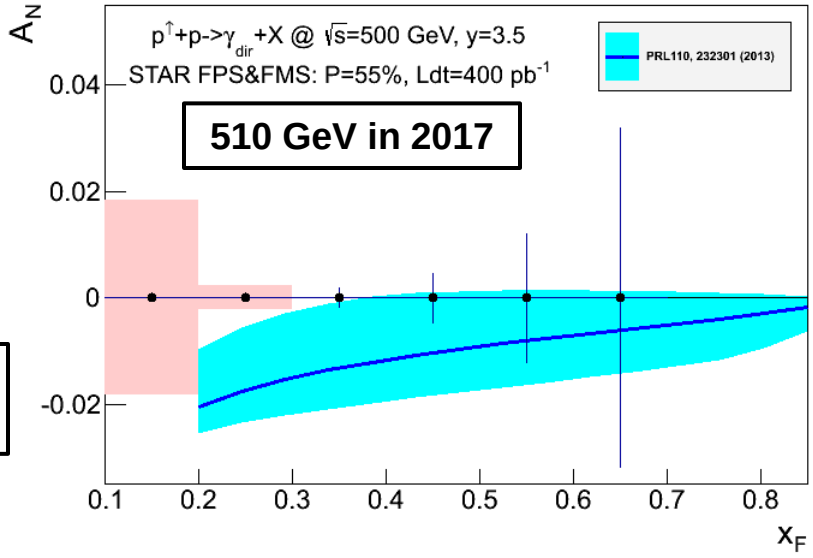
– Access similar observables at comparable x but very different Q^2

- 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

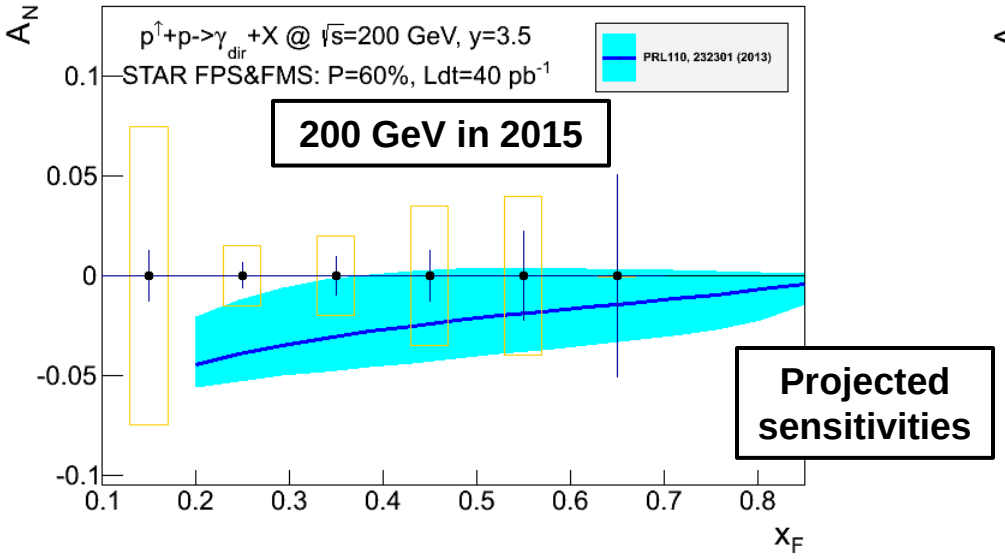


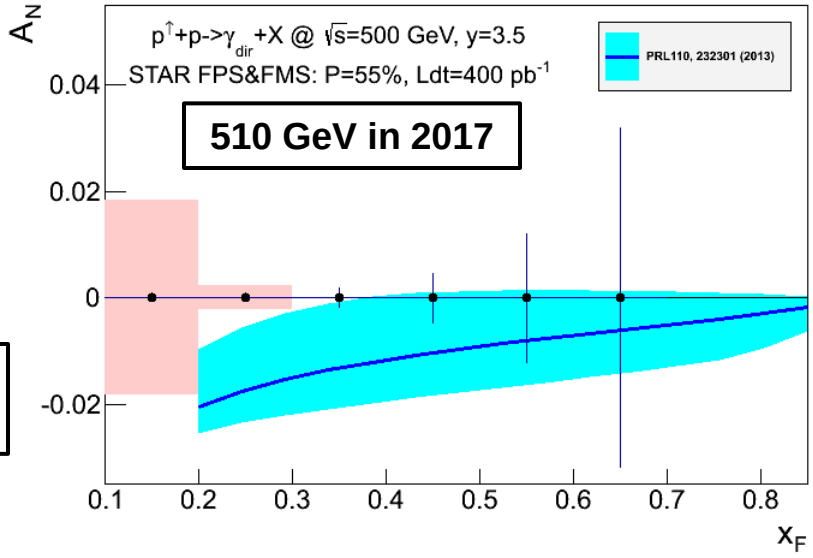


- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

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…

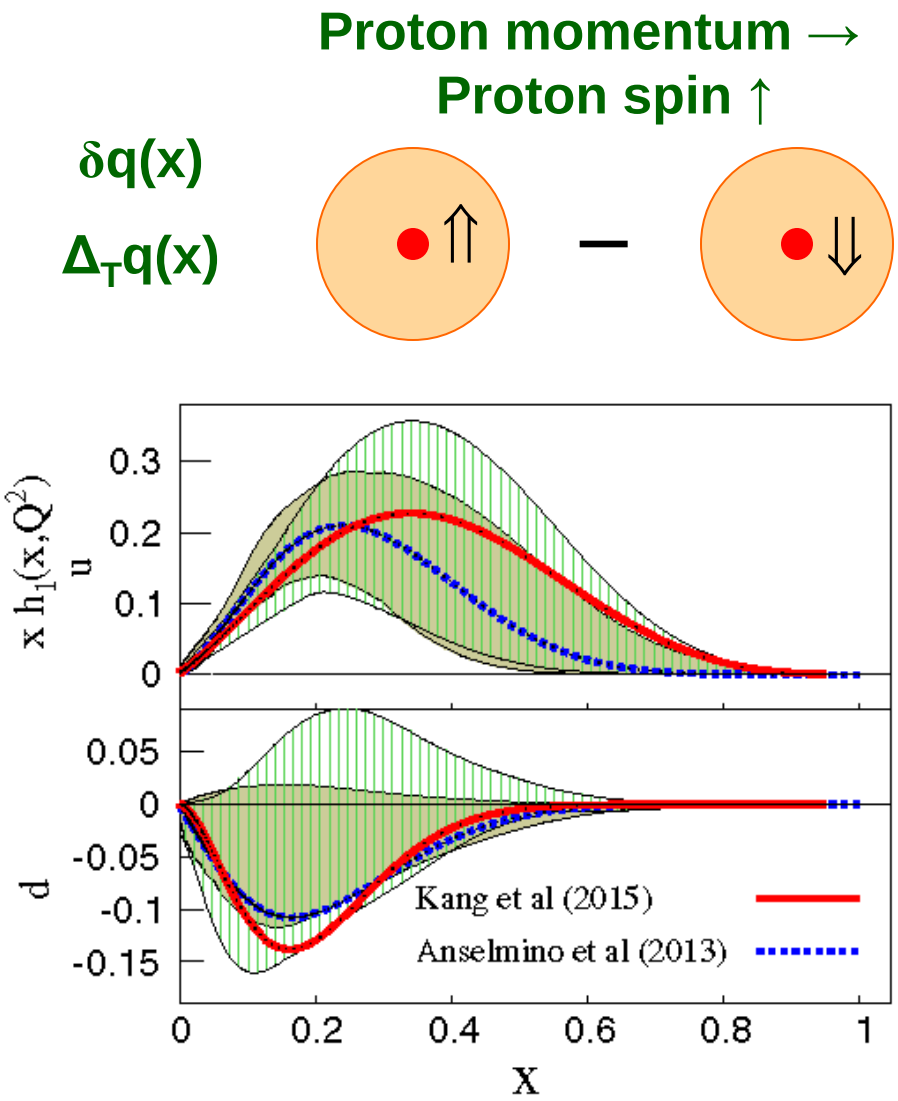
Expect to return to 200 GeV in 2023:

Reduce 200 GeV uncertainties by ~3

Precision measurement of Twist-3 evolution

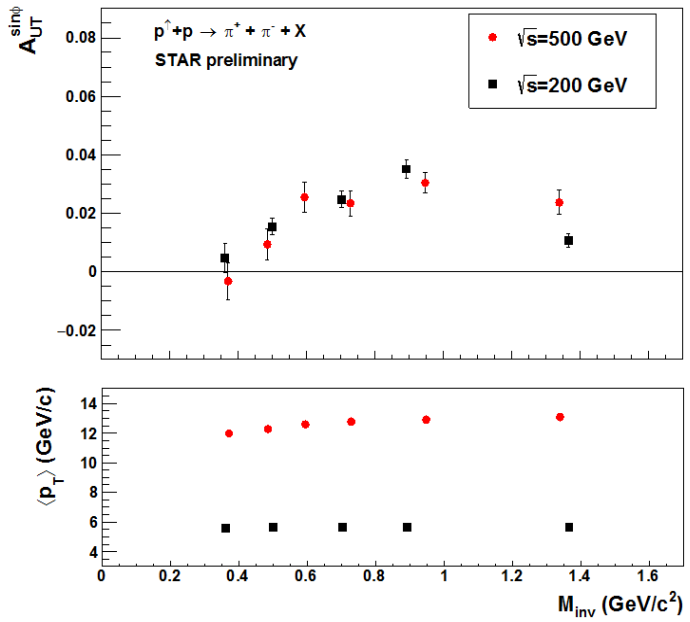
important complementary piece of the puzzle

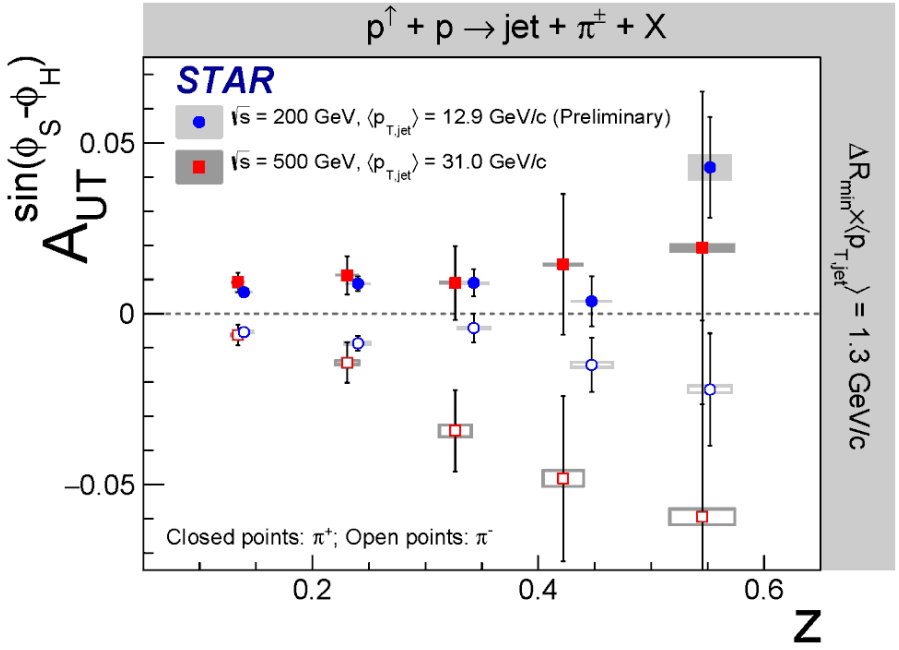
Transversity



- Quark polarization along spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Chiral odd
- Much less data than for helicity
- Before ***STAR***, only observed in SIDIS combined with e^+e^-
- Several recent global analyses including:
  - Collins effect SIDIS input:
    - PRD 93, 014009 (2016)
    - PRD 92, 114023 (2015)
  - IFF SIDIS + ***STAR*** pp input:
    - PRL 120, 192001 (2018)
  - All show large uncertainties

First transversity signals in hadronic collisions

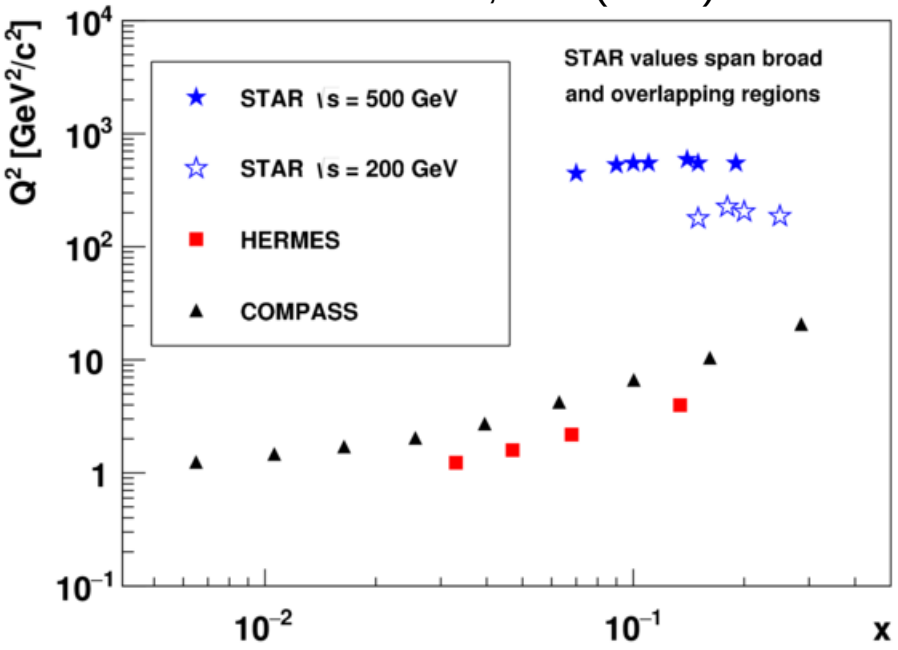


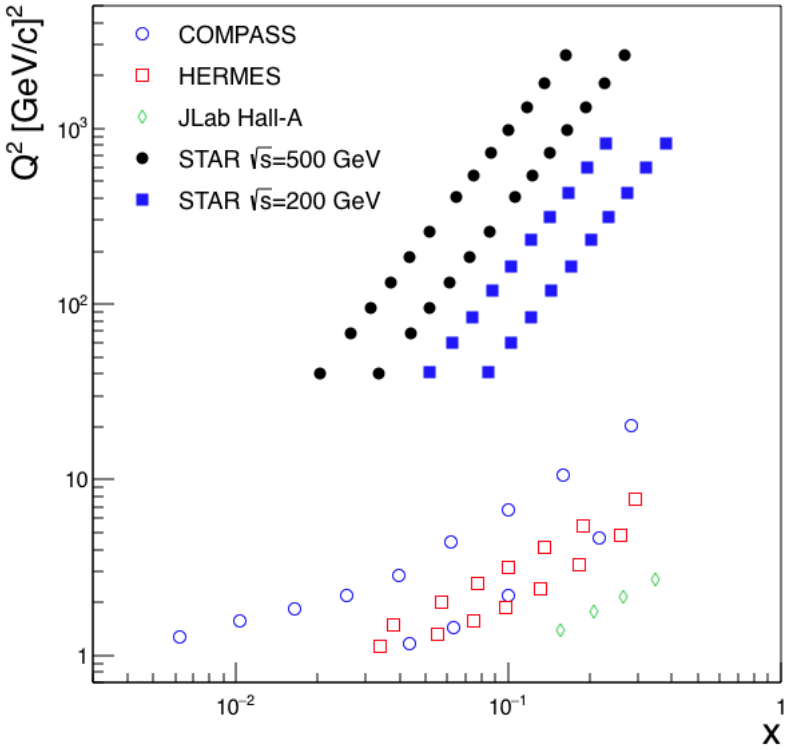


- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Complementary results that obey different evolution equations

x – Q^2 coverage for IFF and Collins effect

PLB 780, 332 (2018)

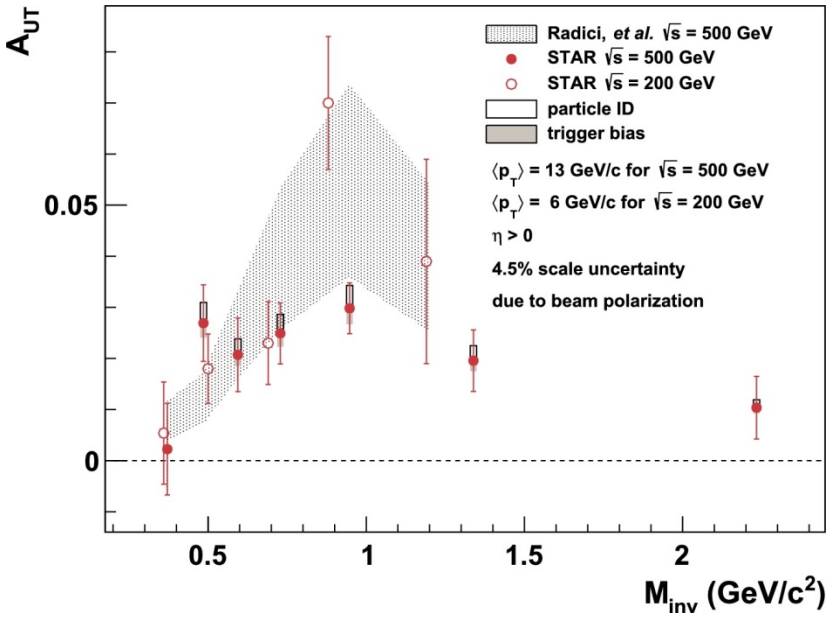


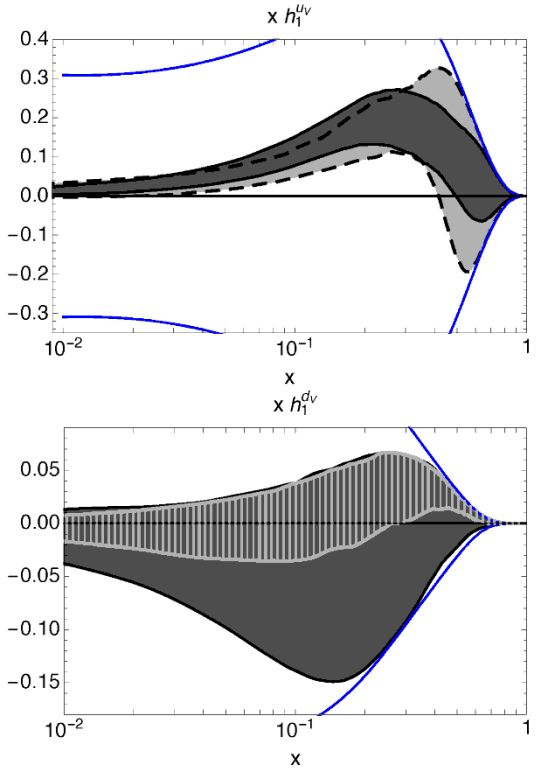


- STAR measurements provide the first observations of transversity at very high scales
  - One to two orders of magnitude higher than all previous measurements

STAR IFF and global analysis

STAR PLB 780, 332 (2018)



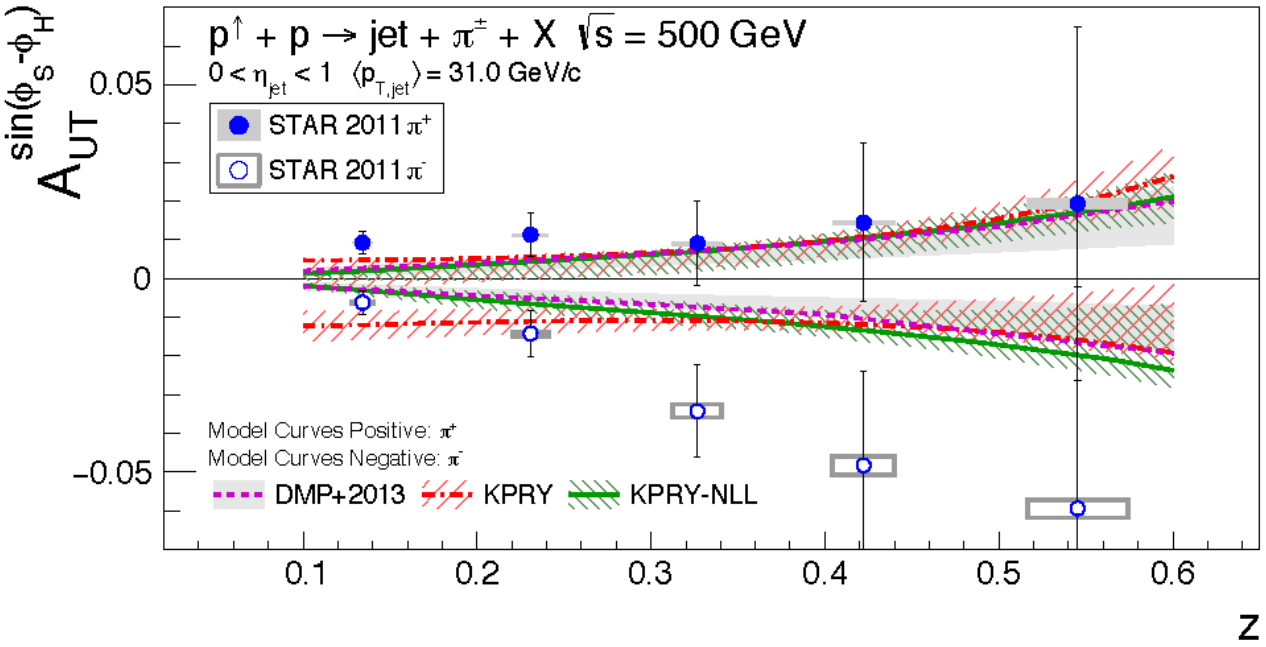


Radici and Bacchetta, PRL 120, 192001 (2018)

- ***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 (2015)]
  - ***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

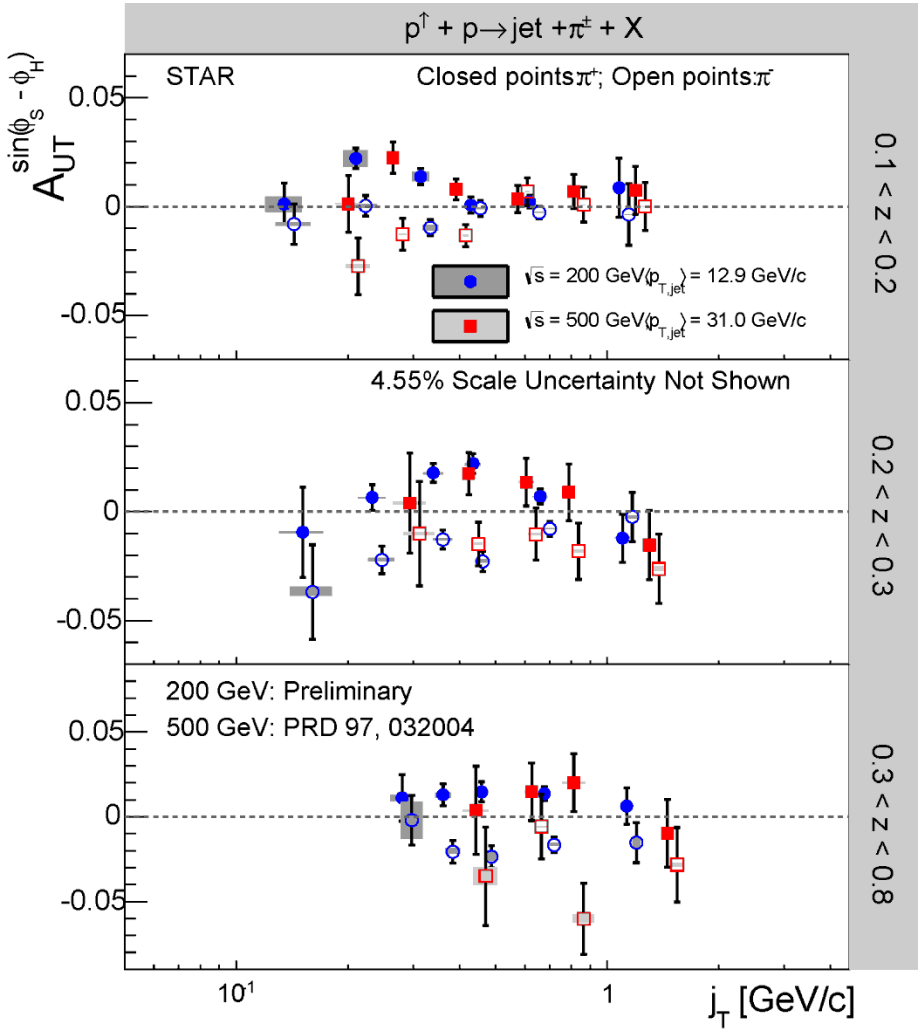
STAR PRD 97, 032004 (2018)



DMP: PLB 773, 300 (2017)
KPRY: PLB 774, 635 (2017)

- 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 11, 068 (2017)
  - TMD evolution effects appear to be small

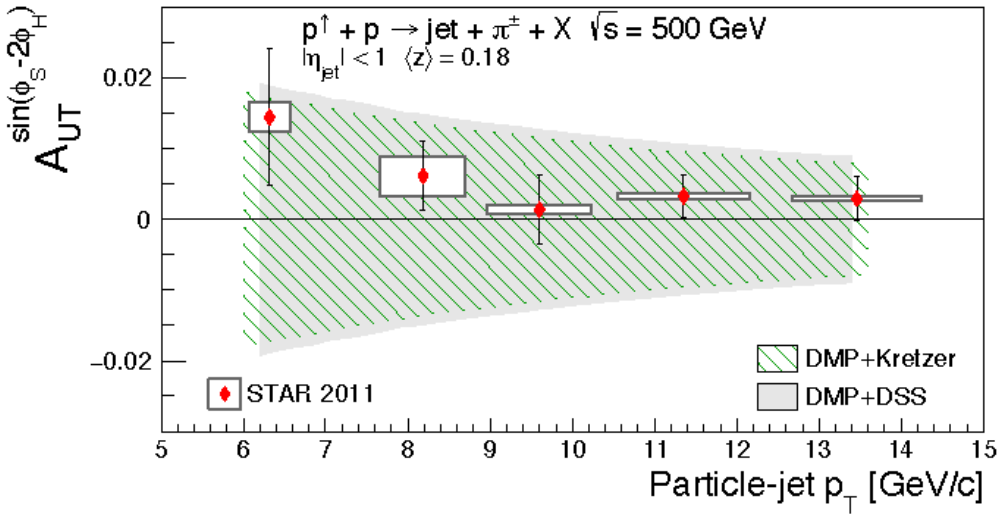
Collins effect vs. j_T in separate z bins



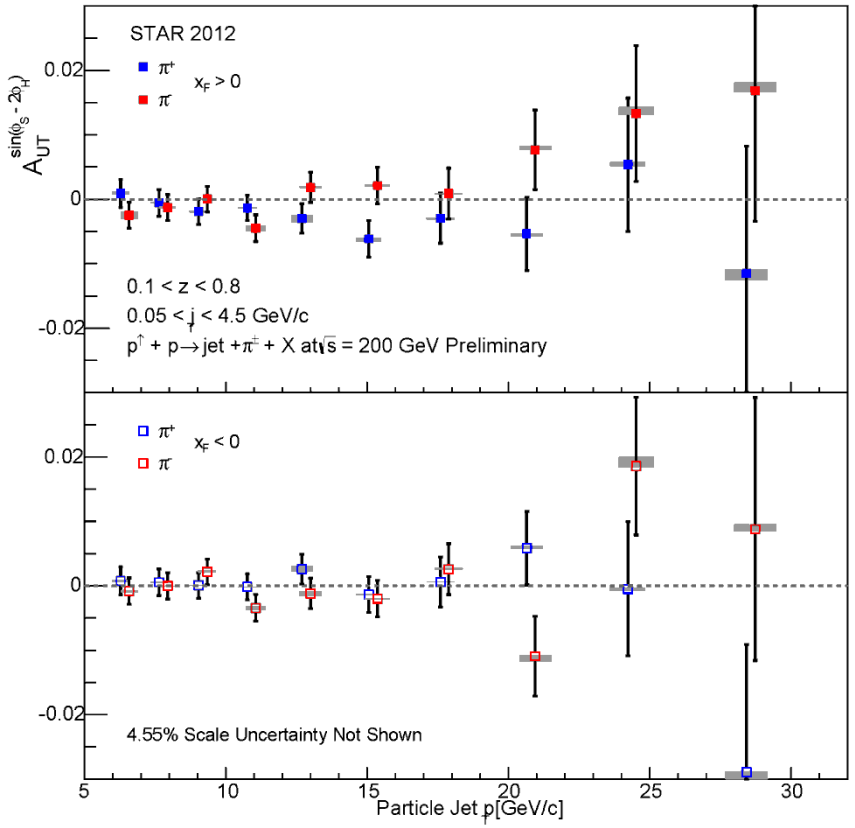
- 500 GeV pp results hinted the A_{UT} peak shifts to higher j_T as z increases
- New preliminary **200 GeV pp results provide confirming evidence**

Additional modulations: "Collins-like" effect

500 GeV: PRD 97, 032004 (2018)



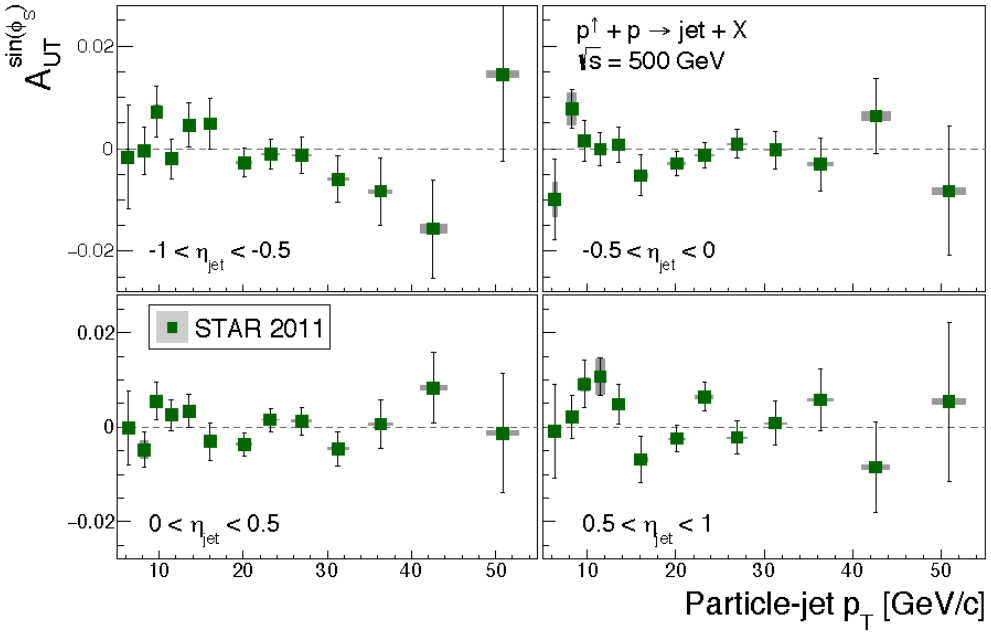
200 GeV: Preliminary



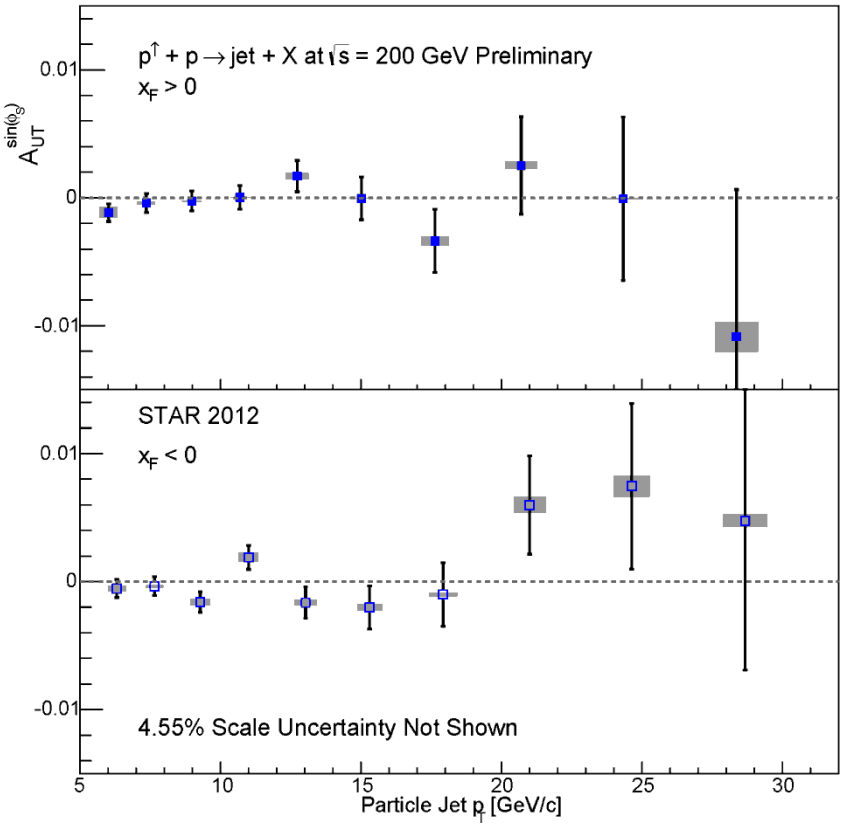
- Collins-like effect
  - **World's first ever limit** on linearly polarized gluons in a polarized proton
  - New preliminary results from 200 GeV pp collisions
    - Will provide much stronger limits

Additional modulations: inclusive jet A_N

500 GeV: PRD 97, 032004 (2018)

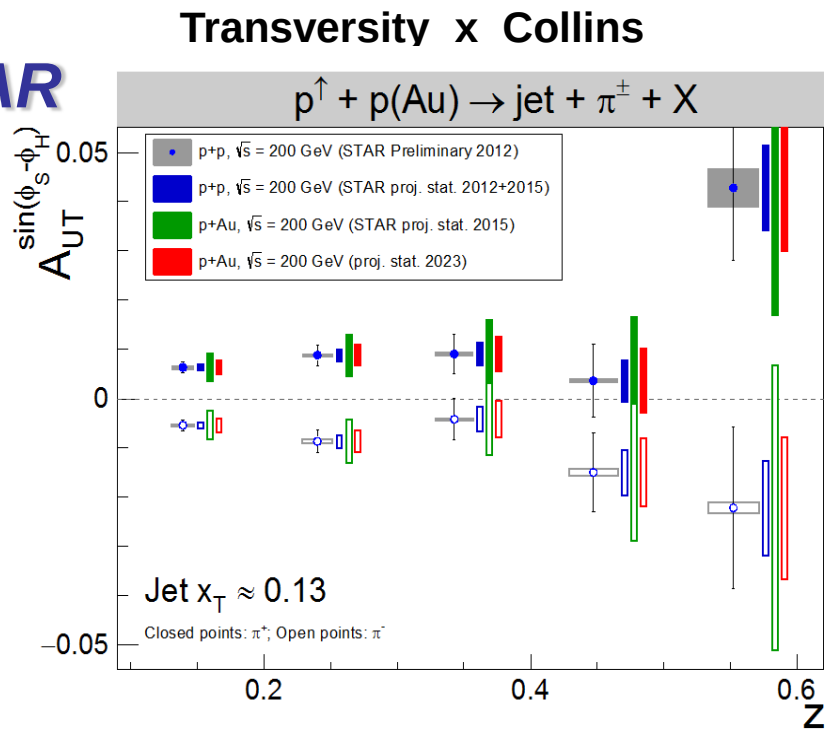


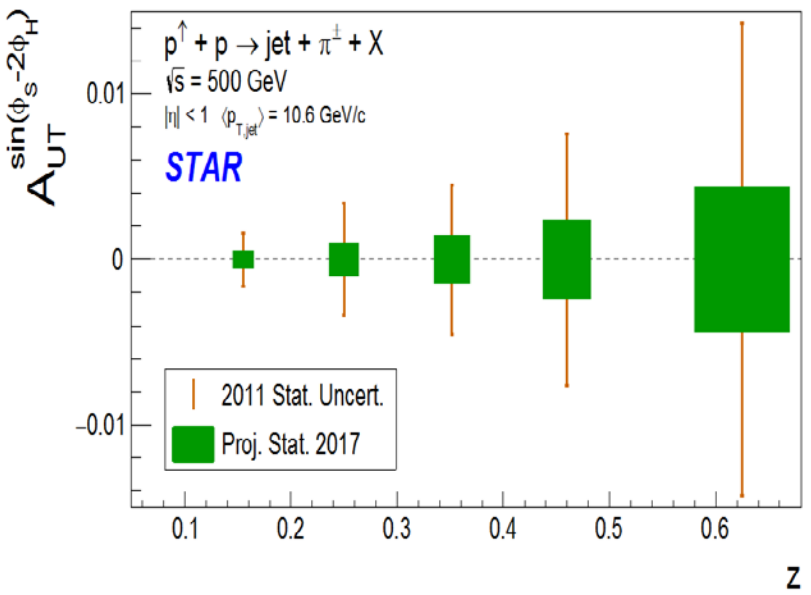
200 GeV: Preliminary



- Inclusive jet A_N
  - Sensitive to the gluon Sivers function via the Twist-3 relationship
  - New preliminary results in 200 GeV pp collisions
    - Far more precise than 500 GeV results
    - Still consistent with zero

Projected uncertainties for upcoming results





- Final Collins results from 2012 200 GeV run will be coming soon
  - 200 GeV data from 2015, with twice the FoM, under analysis
- 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**
- Also have data for a first look at the Collins effect in p+Au collisions

STAR Forward Upgrade plans

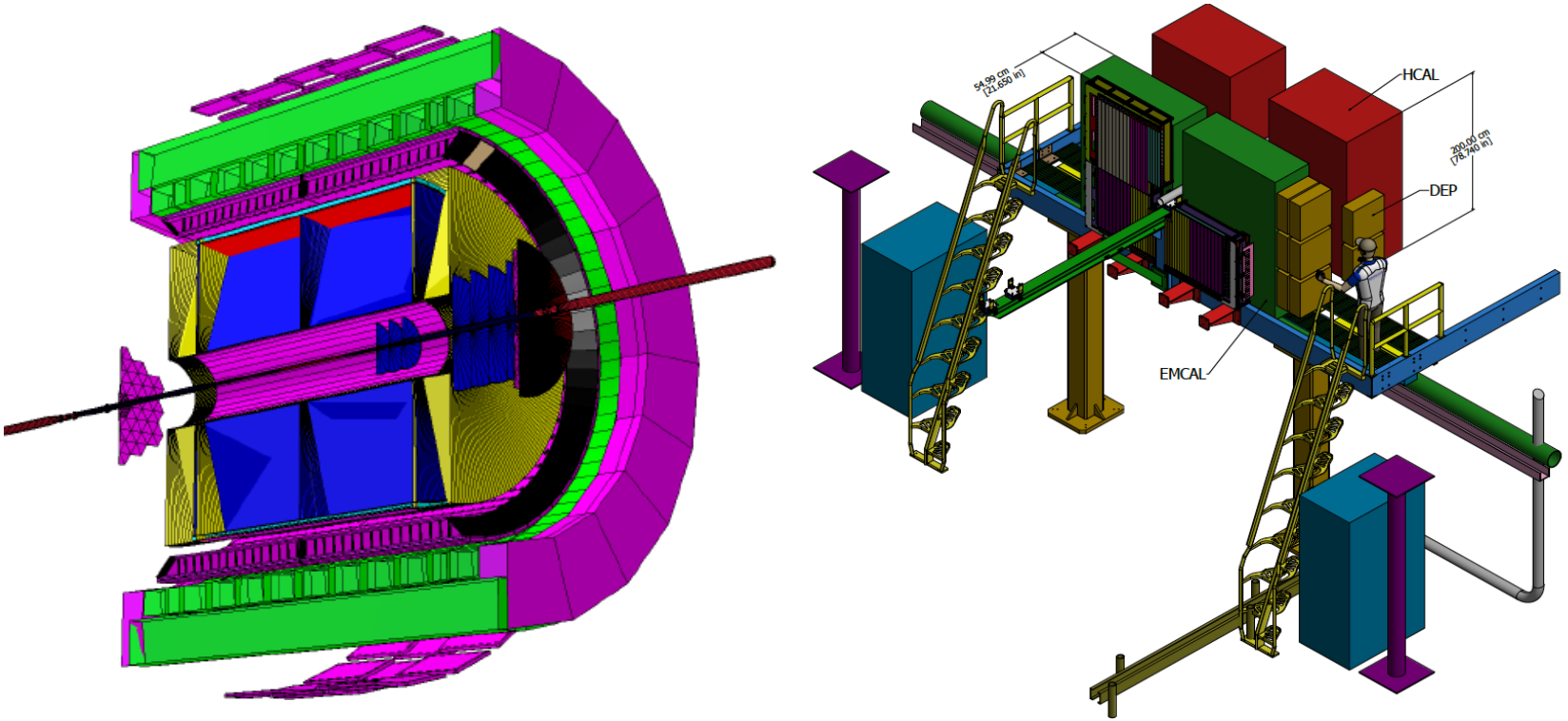
For a more detailed discussion, see:

The STAR Forward Rapidity Upgrade

Ken Barish (sub for Elke Aschenauer)

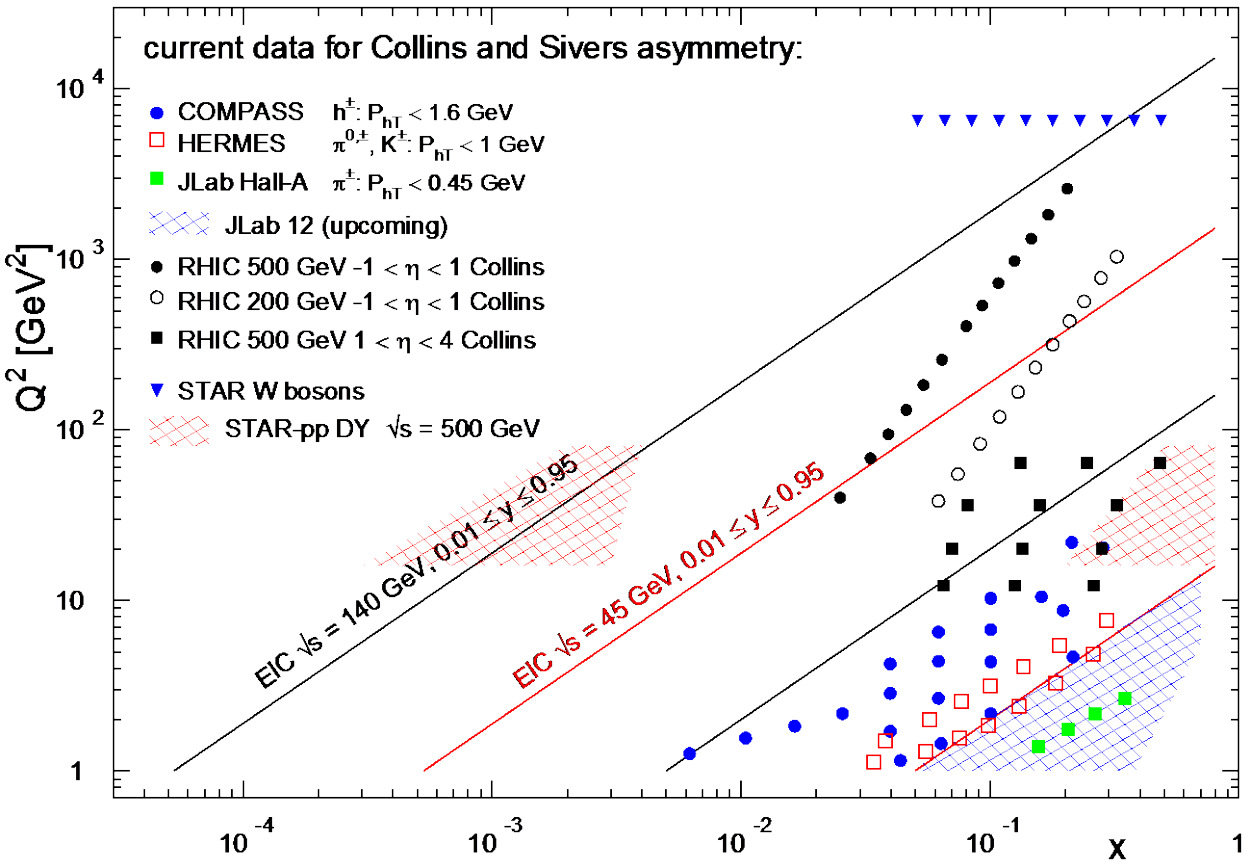
Future Facilities and Experiments, Wed, 17:40

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

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