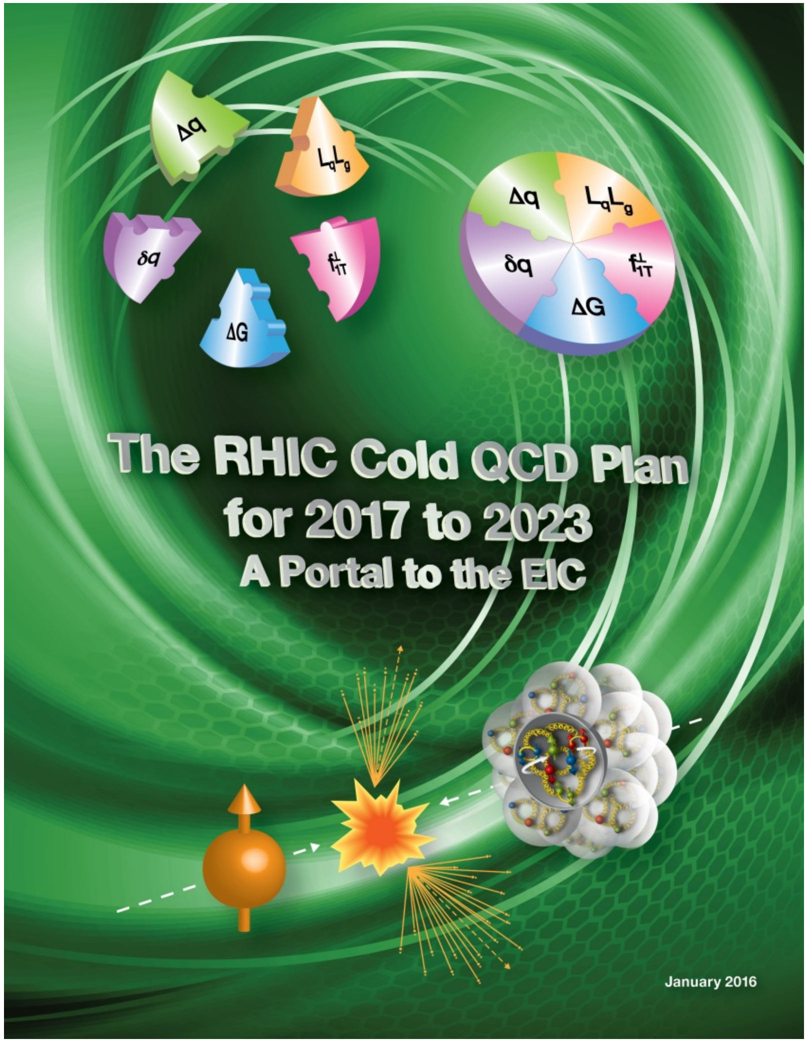
RHIC Cold QCD Plan for 2017 to 2023
A Portal to the EIC

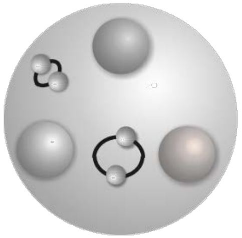


Carl Gagliardi
Texas A&M University

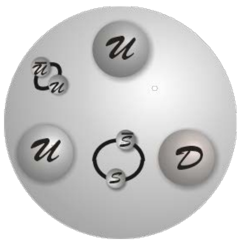
Outline

- Introduction
- A few recent achievements
- Opportunities with polarized protons
- Opportunities with p+A

Complementarity of DIS and p+p/p+A

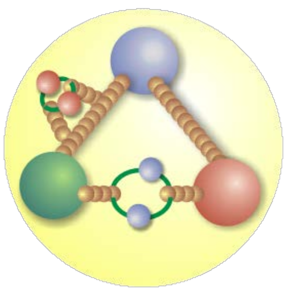


- Electromagnetic interactions
  - Sensitive to charge^2
  - Insensitive to color



- Weak interactions
  - Sensitive to weak charge (~flavor)
  - Insensitive to color

(Mostly) **DIS**



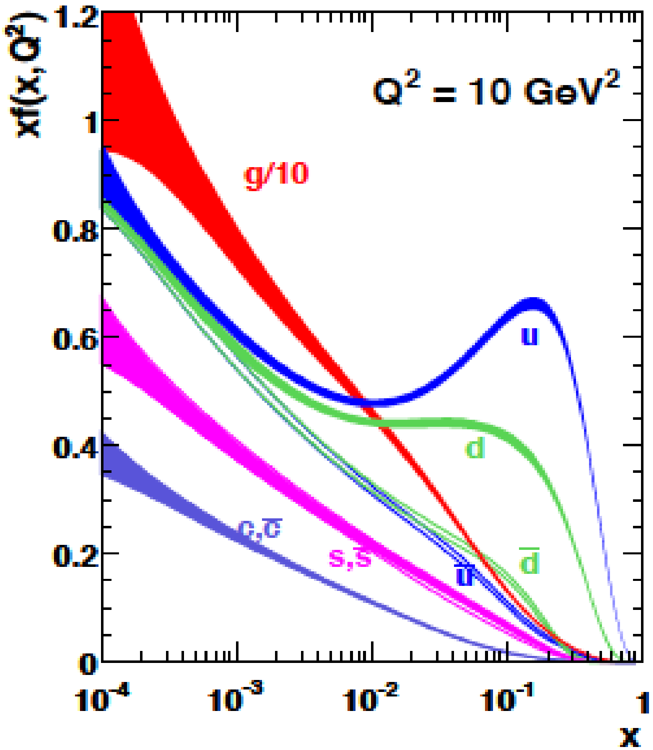
- Strong interactions
  - Sensitive to color charge
    - Unique sensitivity to gluons
  - Insensitive to flavor

(Mostly) **p+p** **p+A**

- **Need both for a consistent and complete picture**
- **Combine DIS and p+p/p+A** 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 and nuclear PDFs

Primary goals of the plan

- Establish the validity - and limits - of **factorization and universality**
  - Essential to separate **intrinsic properties of hadrons** from **interaction-dependent dynamics**
  - Requires pushing the envelope beyond just those measurements that have been proven theoretically
    - Particularly important for transverse spin and p+A measurements
  - Requires precision measurements to enable meaningful comparisons between RHIC data and future EIC data

- Perform **key measurements** with a **broader range of probes** and **wider kinematic coverage** than will be possible at the EIC alone
  - Significantly enhance the impact and interpretation of the future EIC data

The plan in one table

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linear pol Gluons, Gluon Sivers in Twist-3 First look on GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for diffractive events	Yes Forward instrum. **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

The plan in one table

In the baseline RHIC run plan

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linear pol Gluons, Gluon Sivers in Twist-3 First look on GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for diffractive events	Yes Forward instrum. **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

The plan in one table

In the baseline RHIC run plan

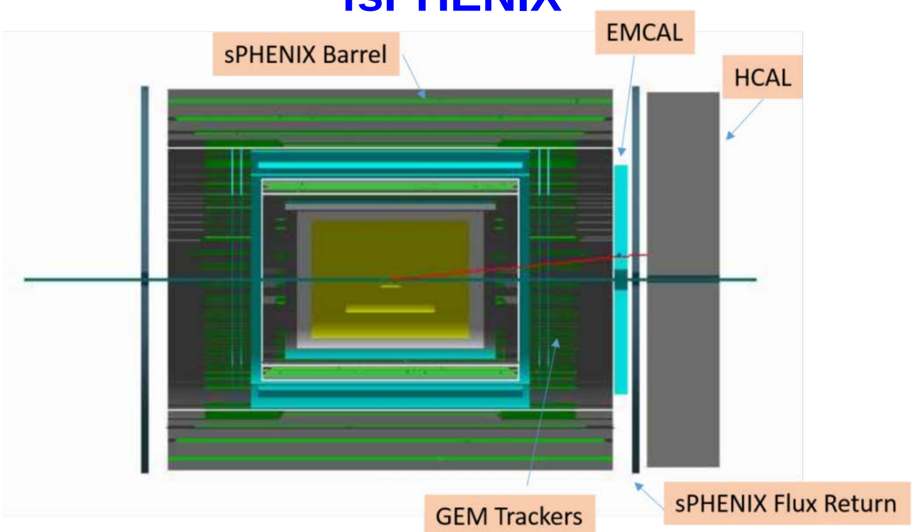
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linear pol Gluons, Gluon Sivers in Twist-3 First look on GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for diffractive events	Yes Forward instrum. **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

More high-impact science if the opportunity arises

What upgrades are necessary?

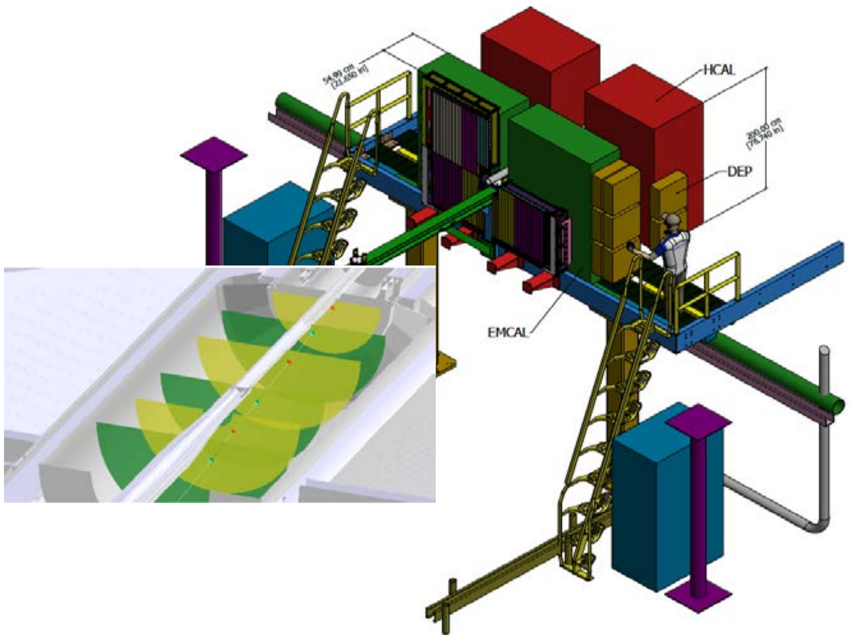
- Mid-rapidity
  - Baseline sPHENIX configuration can do those measurements that don't need π / *K* / p separation
  - STAR can do all proposed measurements

fsPHENIX



Est. cost: $12M + labor

STAR

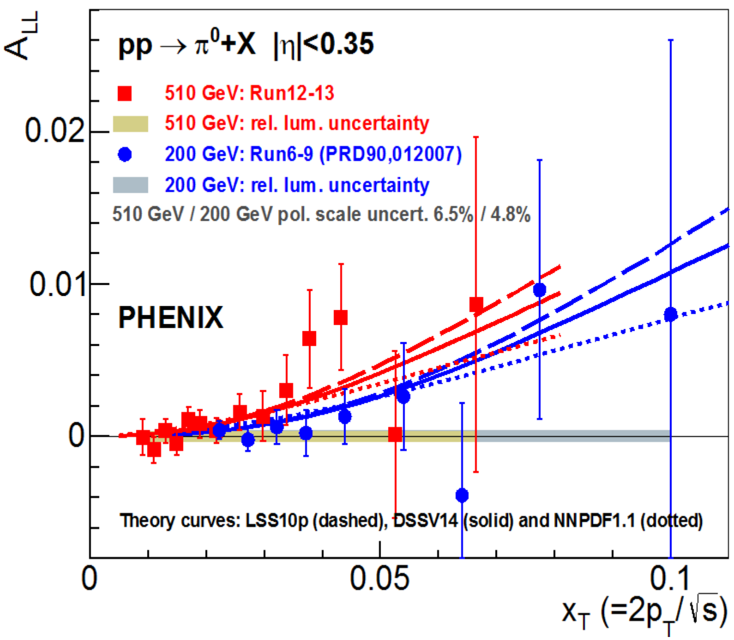


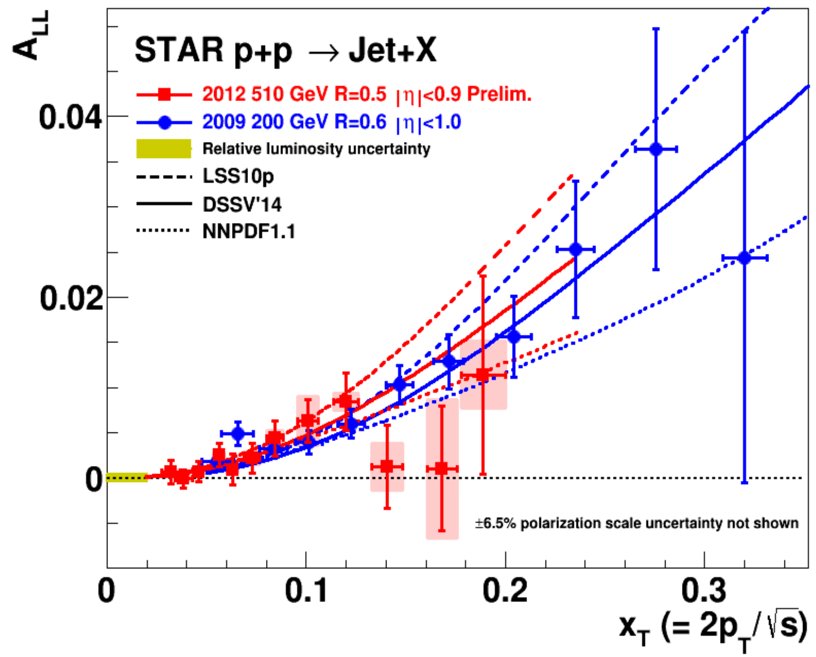
Est. cost: $6M

- Forward rapidity:
  - Both sPHENIX and STAR would need additional forward tracking + EM and hadronic calorimetry

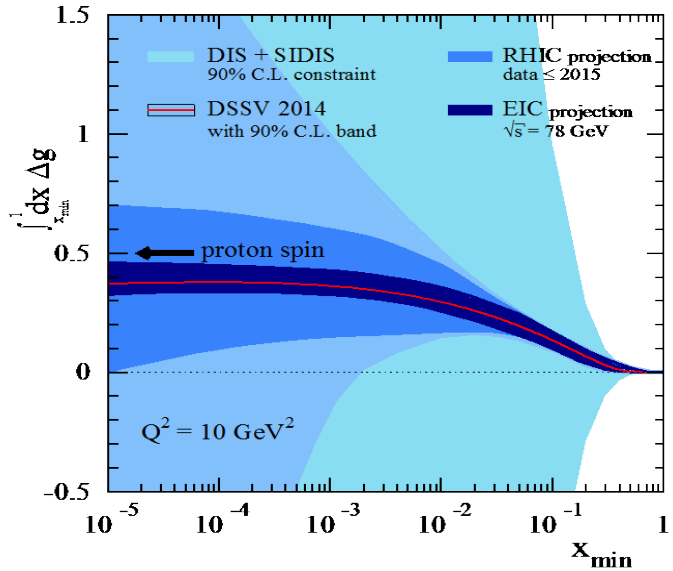
A few recent accomplishments

Gluon polarization in the proton

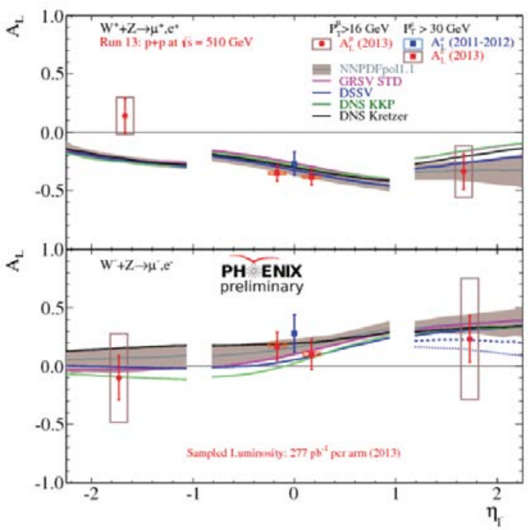


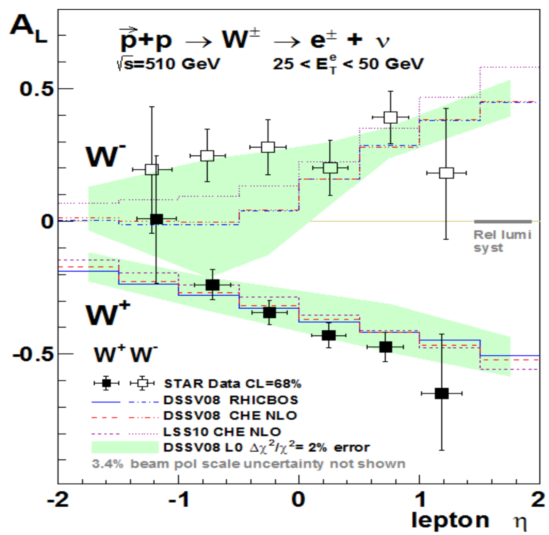


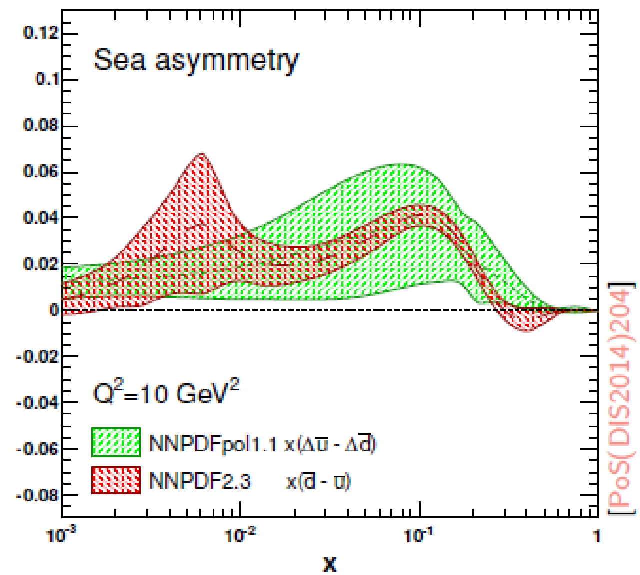
- Find Δg is positive in the region $x > 0.05$
  - Both DSSV14 and NNPDFpol1.1 draw same conclusion
- **2015 LRP: “a significant breakthrough”**



Anti-quark polarization

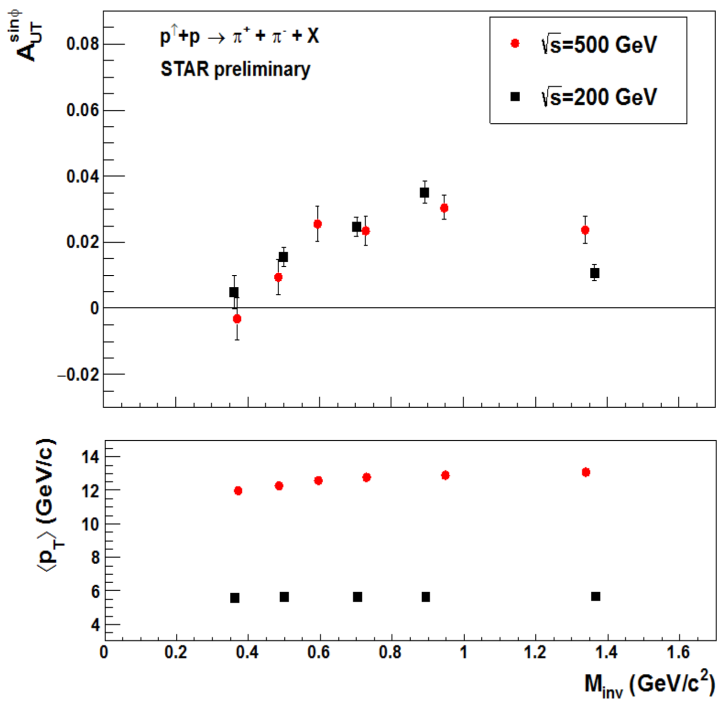


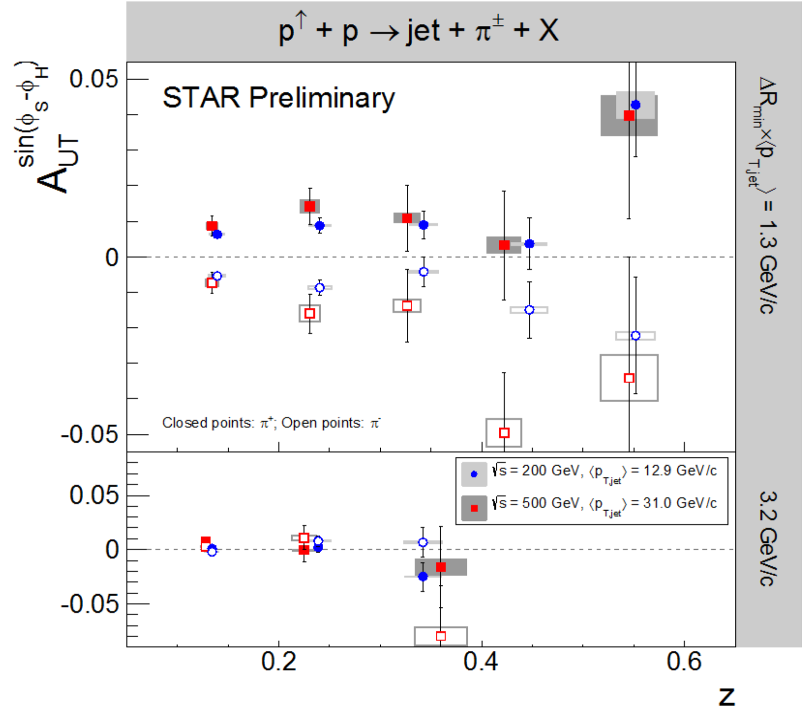




- $W^{+/-}$ asymmetries hint at $\Delta\bar{u} > \Delta\bar{d}$
  - This is opposite from the unpolarized distributions
  - Uncertainties will shrink by factor of 2 when all existing data are analyzed

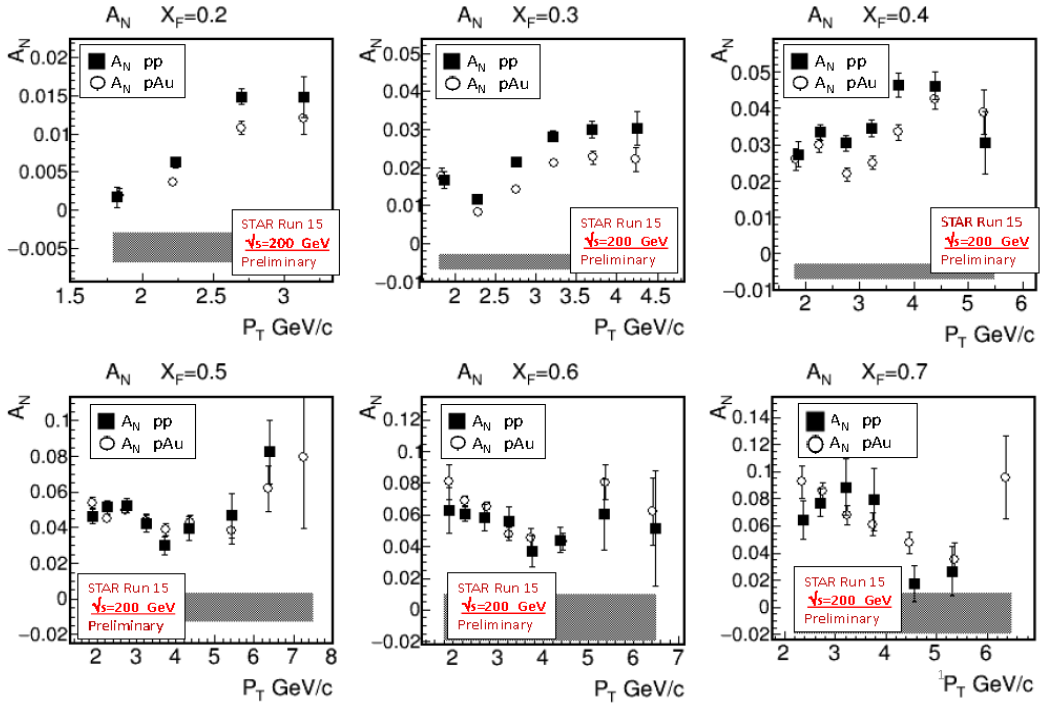
First transversity signals in hadronic collisions





- 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
- Observations of transversity at very high scales
  - Q^2 up to 900 GeV^2 for Collins at 500 GeV
- Complementary results that obey different evolution equations

First results from *polarized* p+Au



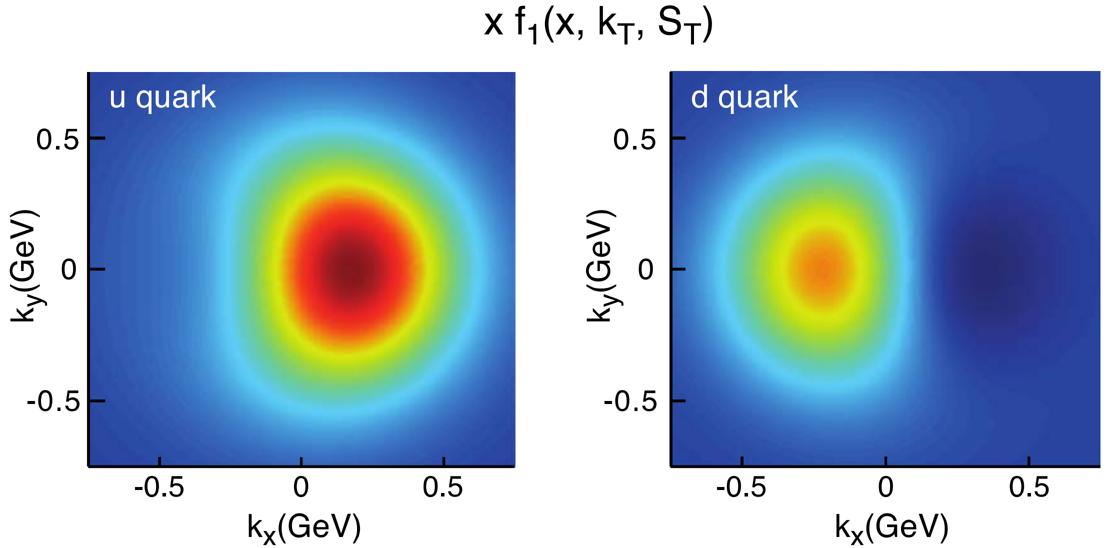
- Large transverse single-spin asymmetries for forward inclusive hadron production were an early driver of the RHIC transverse spin program
  - Nearly independent of $\sqrt{s}$ from 5 GeV (ZGS) to 500 GeV (RHIC)
    - At RHIC energies, the unpolarized cross section described by pQCD
  - Various initial and final-state effects have been proposed
- CGC calculations in some of the possible channels predicted that A_N would be suppressed when scattering off a saturated gluon field
  - Preliminary results from 2015 find little suppression

Opportunities with polarized protons

Limited time:

- Focus on TMD, Twist-3, and related measurements
- Diffraction, GPDs and gluon polarization in back-up

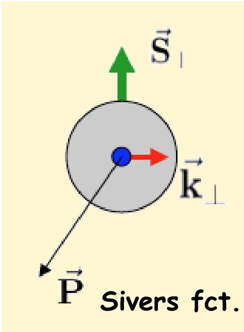
Why TMDs?

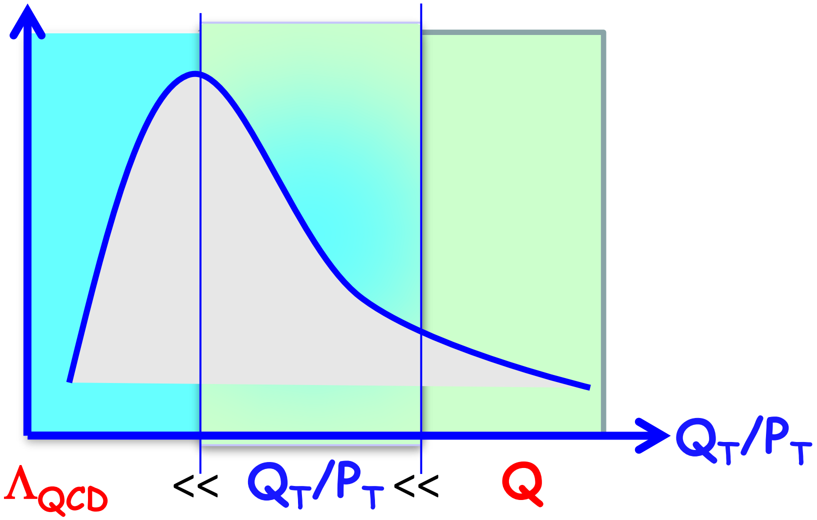


- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei
  - **Tomography of the nucleon!**
- Access to transverse momenta at non-perturbative scales
  - Probe at the confinement scale
- Exhibit correlations arising from spin-orbit effects
- Close connection to Twist-3 quark-gluon-quark correlations
- Un-integrated gluon density $g(x,Q^2,k_T)$ critical for physics at small x
  - Connection with saturation (CGC)

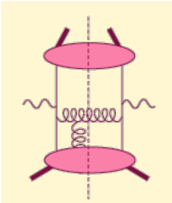
Initial state: TMDs and Twist-3

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

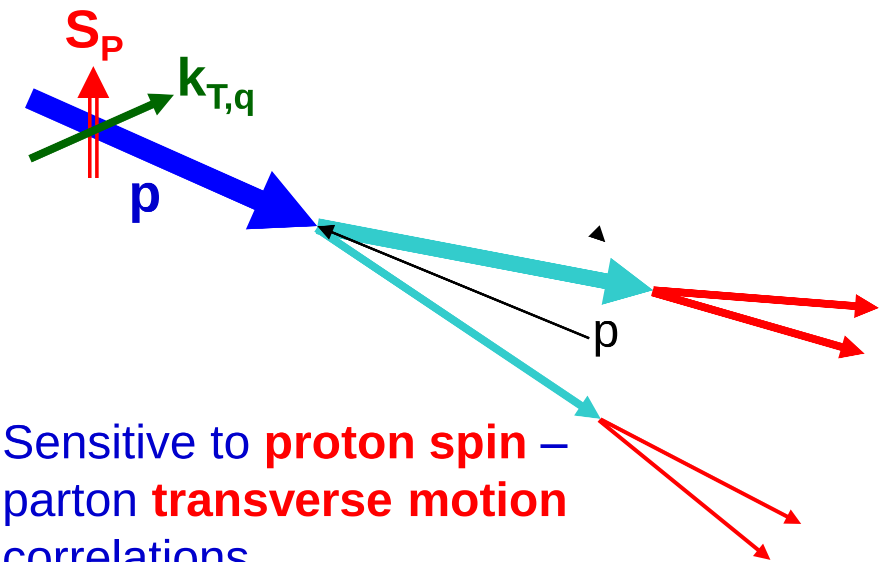
Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$

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

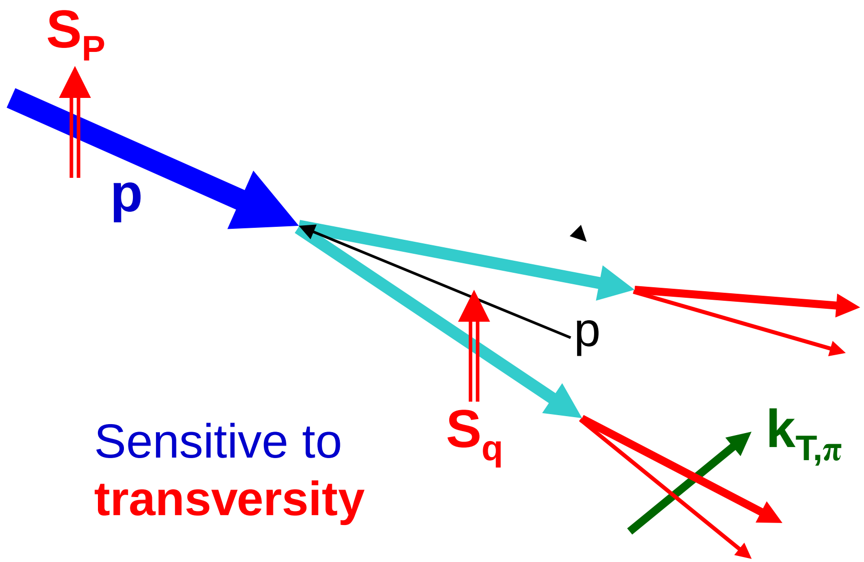
Sivers or twist-3 mechanisms:



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**

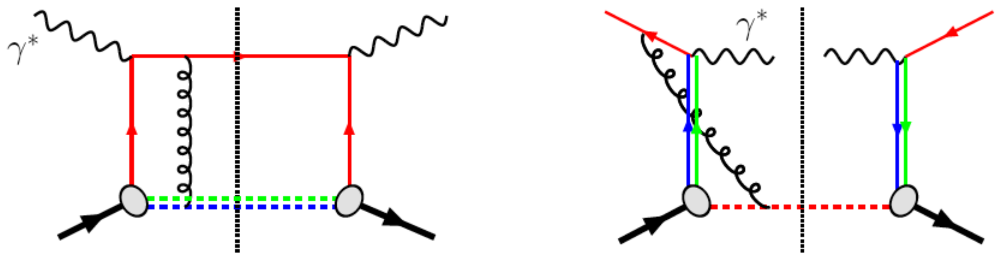
- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - A_N for pions → novel FF
- Collins predicted to be universal

Color interactions in QCD

Controlled non-universality of the Sivers function

QCD:

DIS Final-state interaction	**Drell-Yan, W or Z** Initial-state interaction



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

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

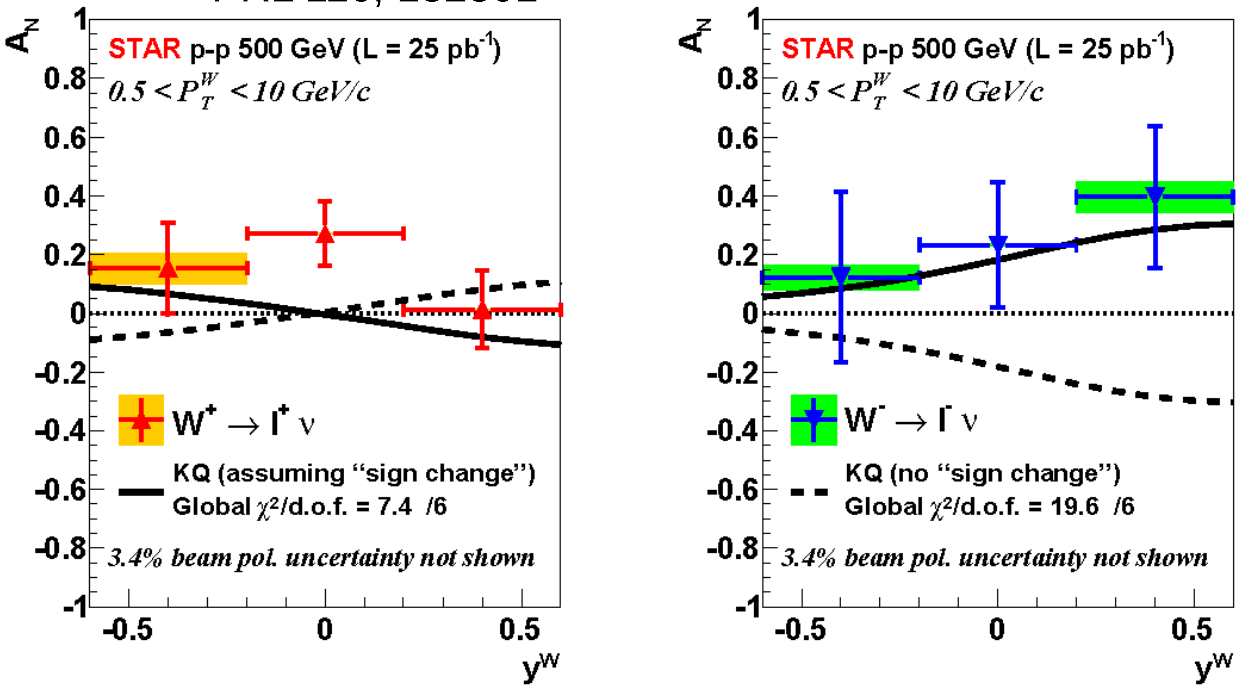
Critical test of factorization

Opportunity to visualize the repulsive interaction between like color charges

Can explore all of these observables in 500 GeV pp collisions at RHIC

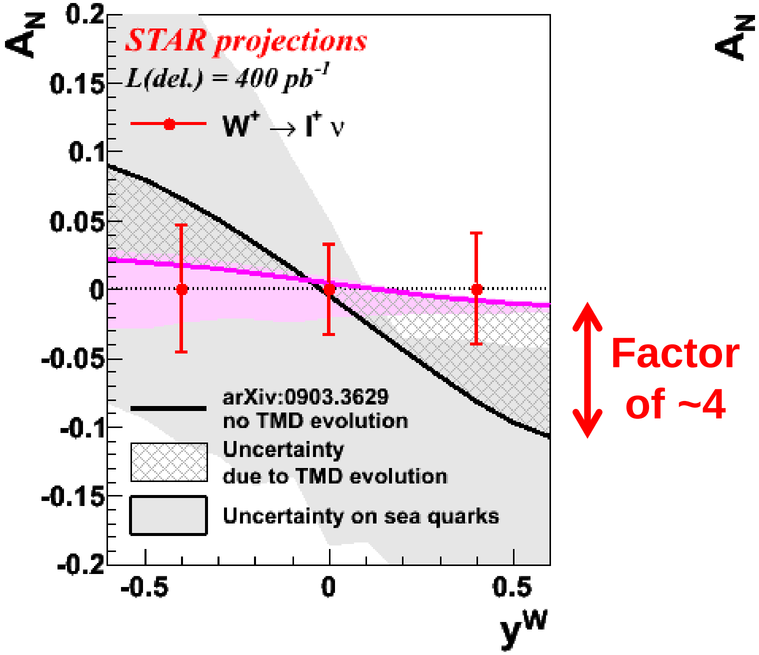
A_N for W production

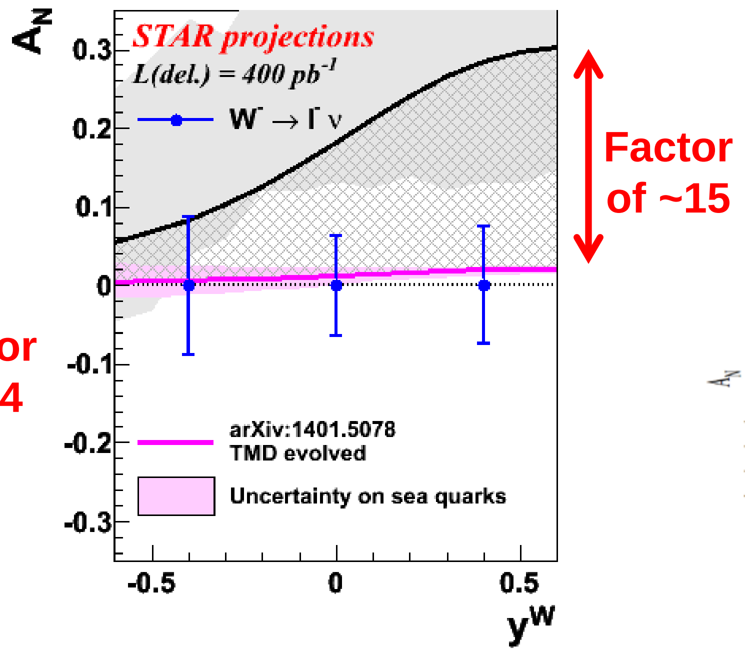
PRL 116, 132301

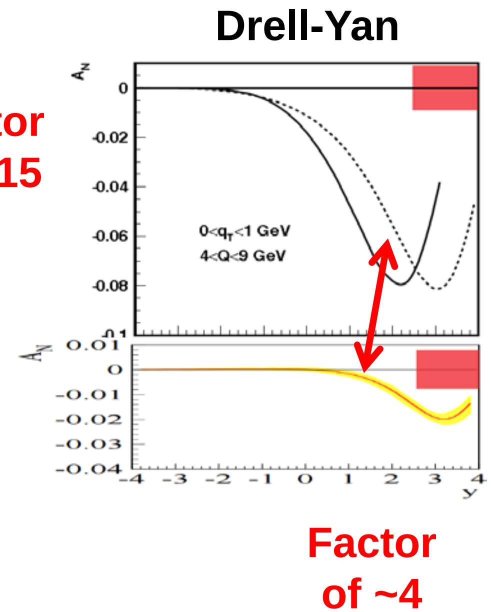


- STAR performed an exploratory measurement of A_N for W production with a small data set recorded in 2011
  - W kinematics fully reconstructed
- Favors **sign change** if evolution effects are modest
  - TMD evolution is non-perturbative at low $k_\perp$ - no absolute theory predictions

Definitive measurement in 2017



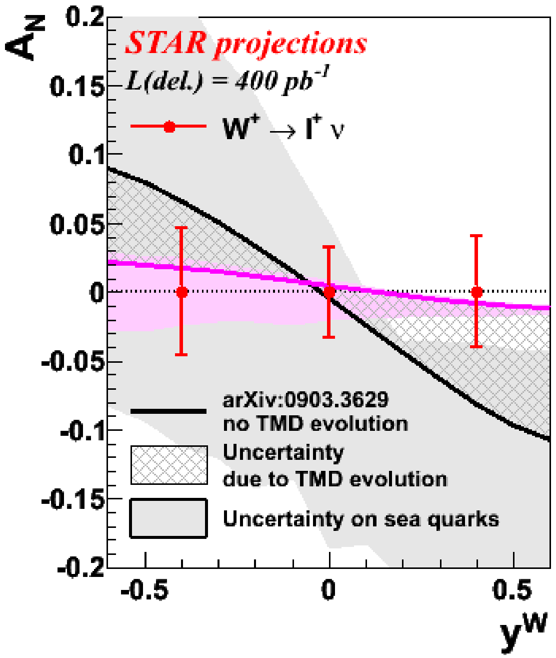




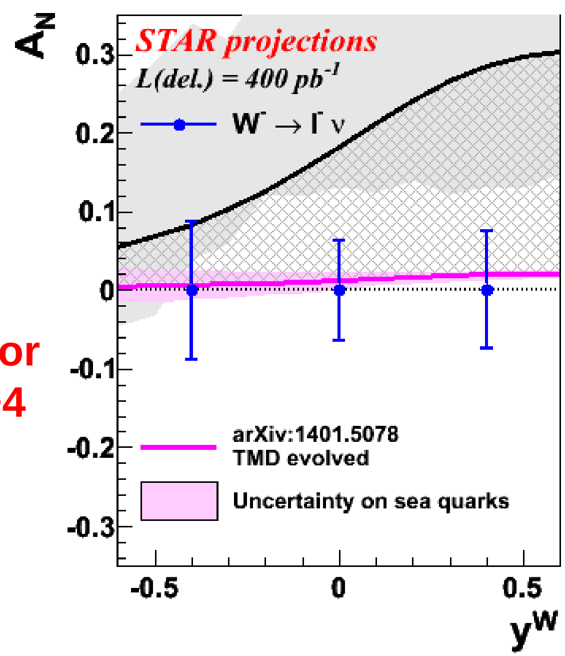
- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable *x* but very different Q^2
    - W and Z A_N at 500 GeV
    - Drell-Yan at 500 GeV

2017 RHIC run

Definitive measurement in 2017

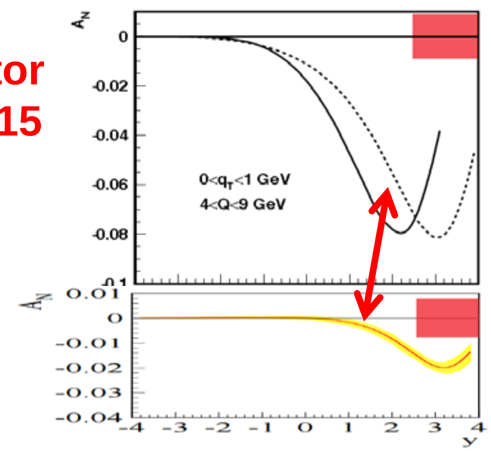


Factor of ~4



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

Return to 500 GeV in 202X:

Go beyond testing the sign

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

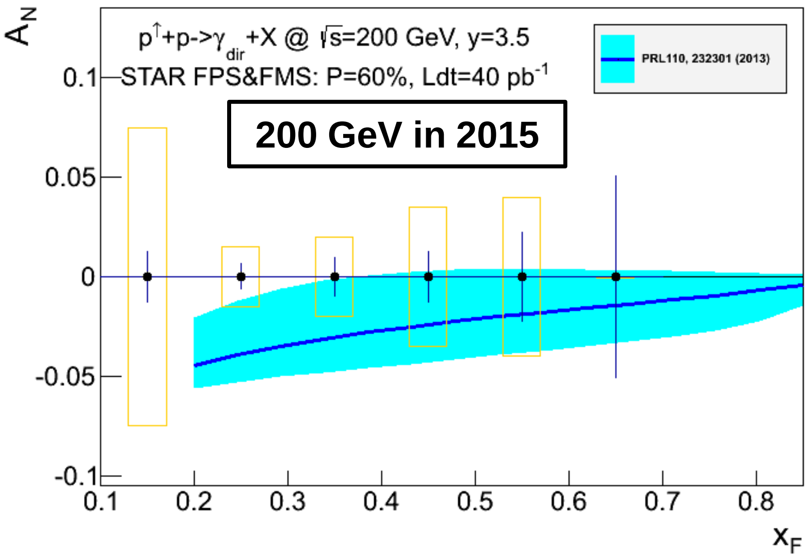
202X DY would benefit from forward upgrade

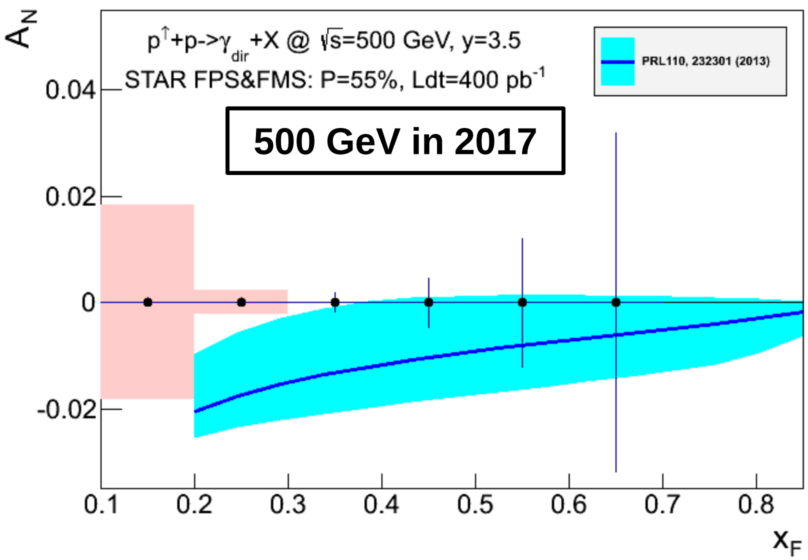
different Q^2

- W and Z A_N at 500 GeV
- Drell-Yan at 500 GeV

} **2017 RHIC run**

A_N for direct photon

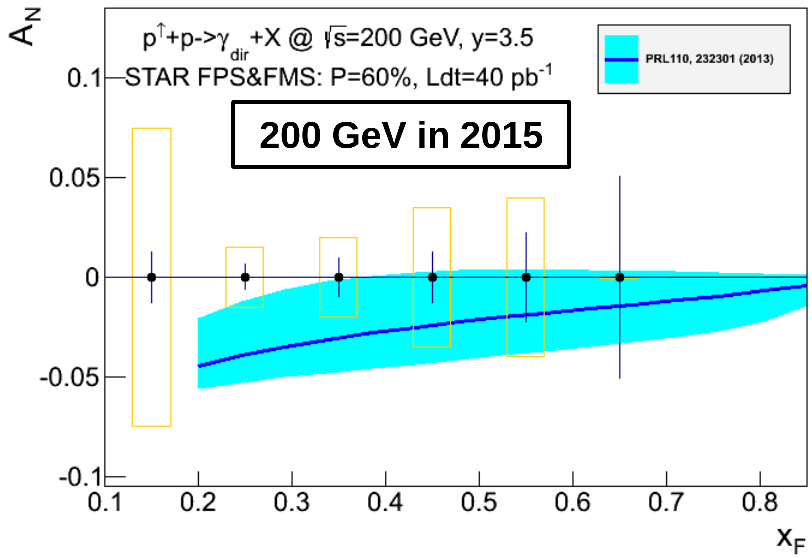


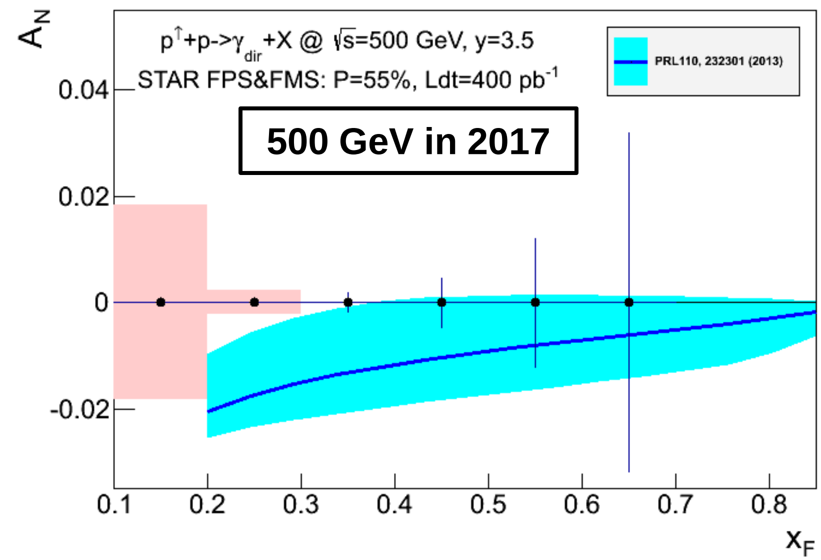


- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

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 evolutions than DGLAP
  - Not sensitive to TMD evolution
- Provid… eir integra…

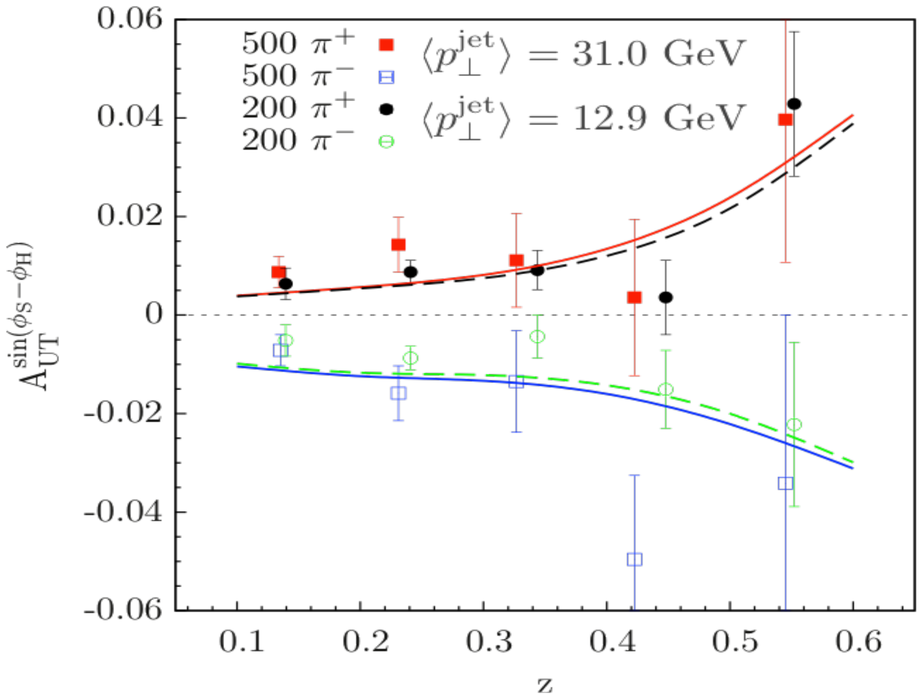
Return to 200 GeV in 2023:

Reduce 200 GeV uncertainties by ~3

Precision measurement of Twist-3 evolution

important complementary piece of the puzzle

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



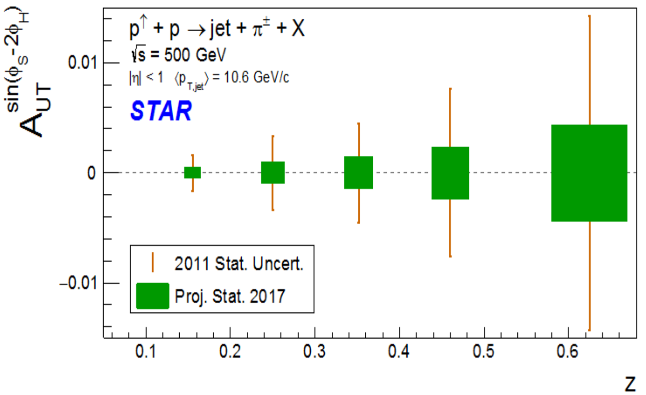
Calculations from Kang et al, in preparation

- First Collins effect measurements in pp collisions are well described by calculations that convolute the transversity distribution from SIDIS with the Collins FF from e^+e^- collisions
  - Tests the predicted **universality of the Collins FF**
  - No TMD evolution in this calculation
    - Maybe small?
    - Maybe cancels between numerator and denominator for asymmetries?

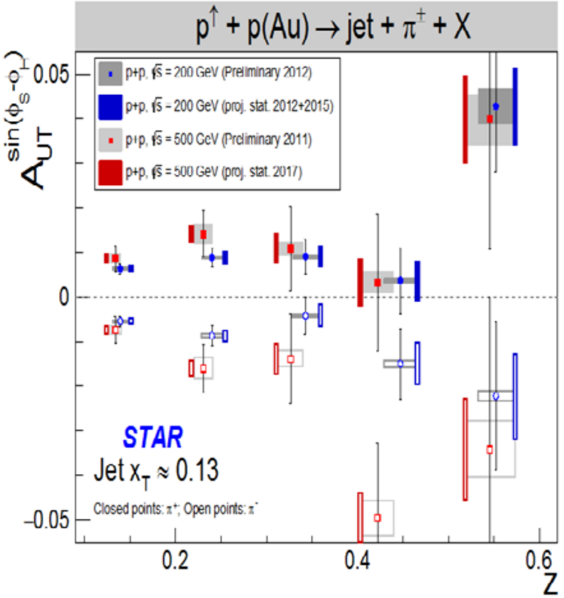
Many azimuthal modulations possible

Needs π / *K* / p PID

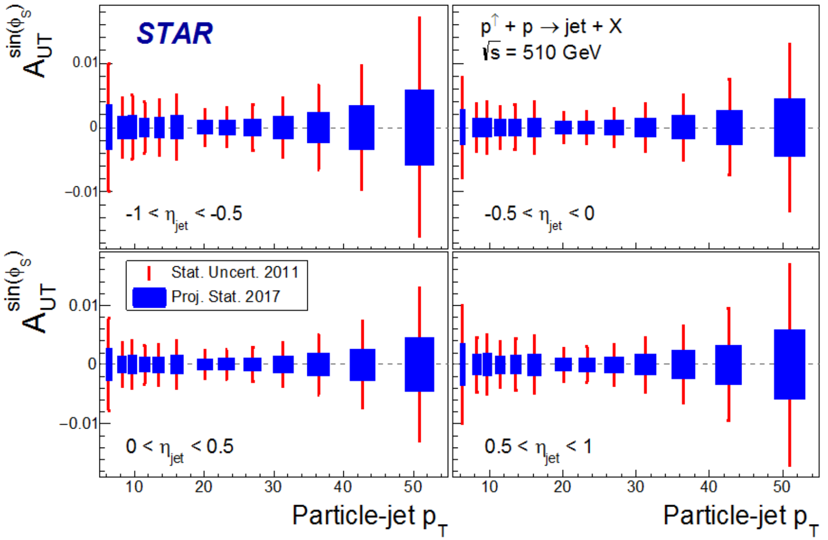
Linearly polarized gluons:
Possible explanation for the ridge in pp/pA?



Transversity x Collins



Gluon Sivers function via Twist-3 relationship

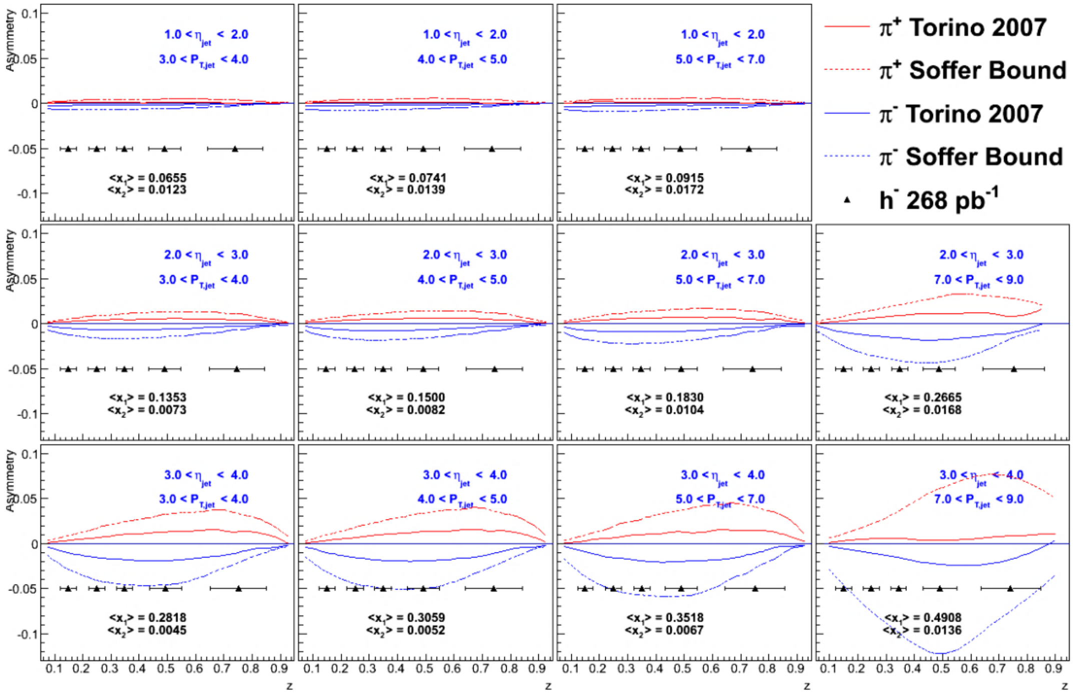


- Precision data at fixed *x*, different √*s* **ideal to constrain TMD evolution**
- Run 17, combined with 2011, ‘12, and ‘15 data will provide initial look
- **Reduce uncertainties** by a **further** factor of ~3 at 200 GeV in 2023 and ~2 at 500 GeV in 202X

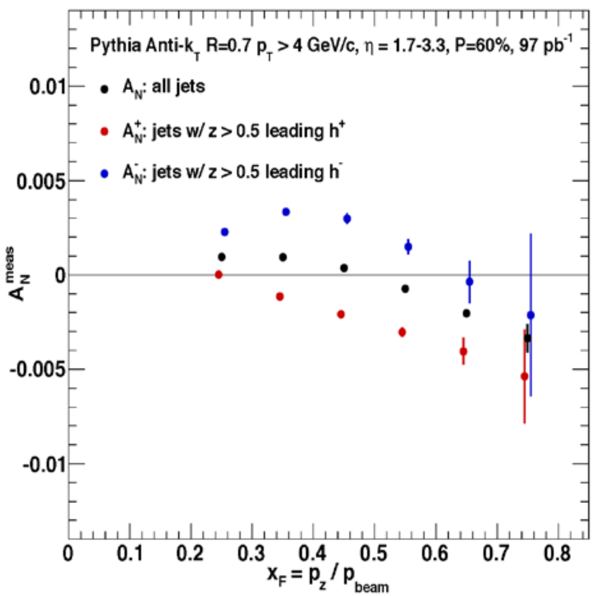
202X: TMDs and Twist-3 at forward rapidity

Assumes forward upgrade

Forward Transversity x Collins FF

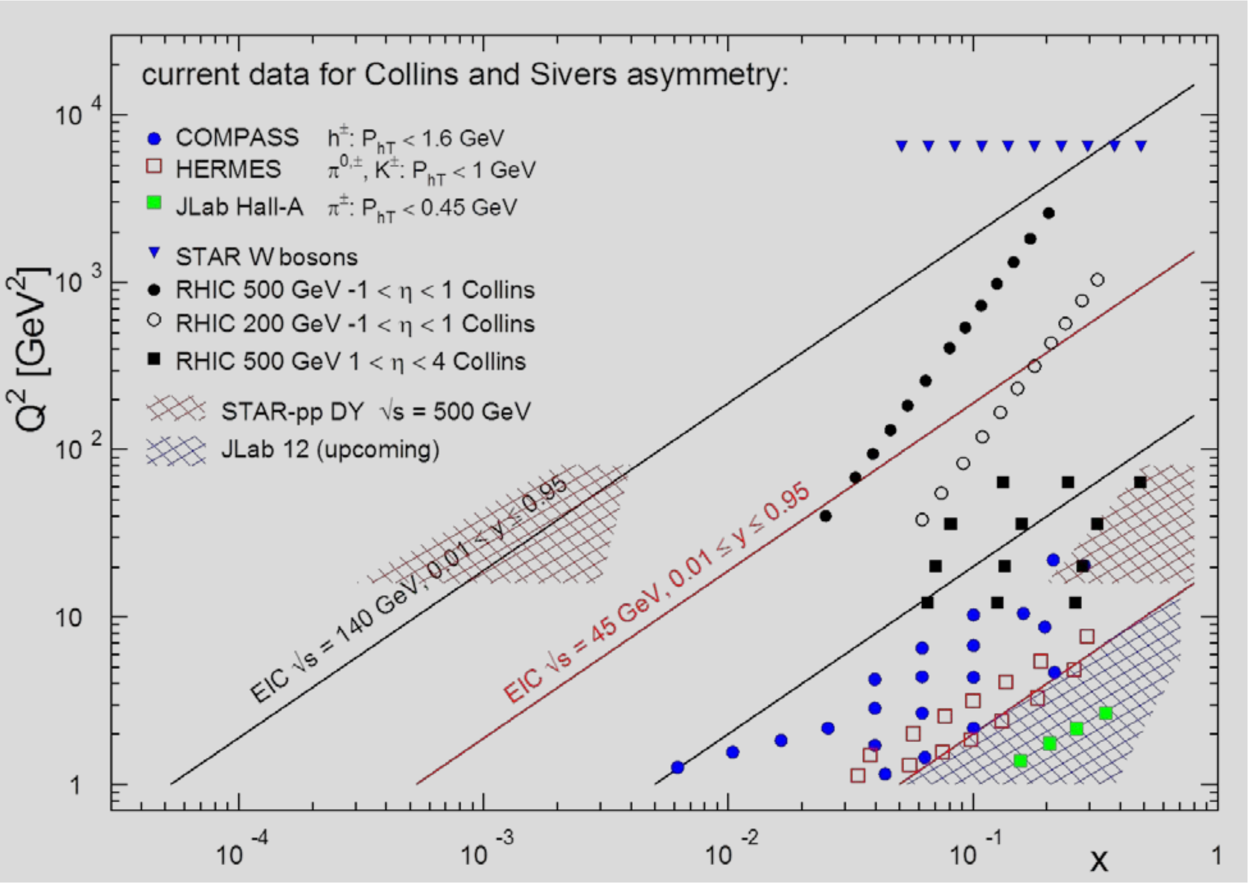


Forward A_N for jets with high-z $h^{+/-}$



- 500 GeV Collins effect
  - Access high *x* (0.05-0.5) at high Q^2 (10-100 GeV^2)
  - Strong constraint on the tensor charge
- *u*- and *d*-quark enriched jet A_N probes Sivers function via Twist-3 to very high *x*

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

Opportunities with p+A

Headline questions for p+A

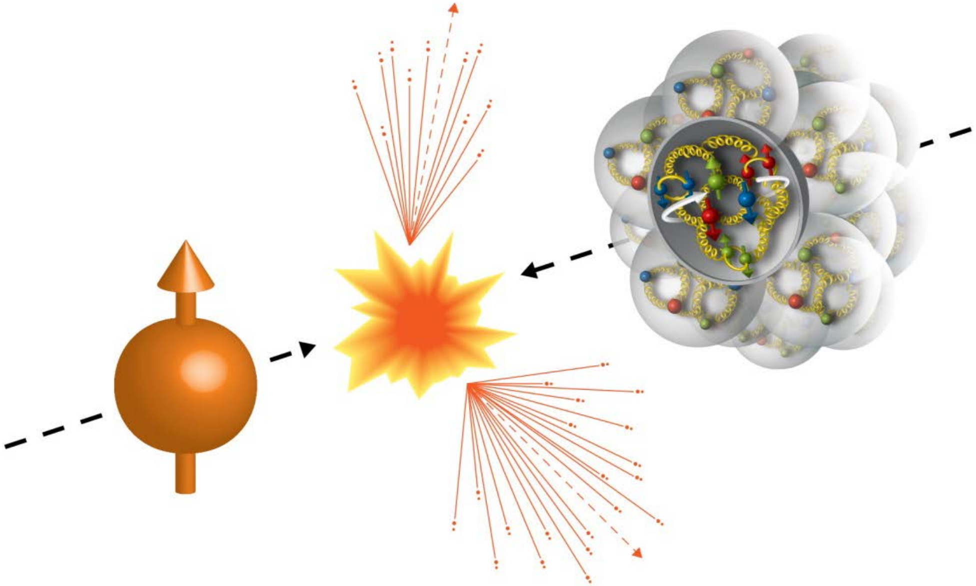
- Can we experimentally find evidence of a novel universal regime of non-linear QCD dynamics in nuclei? Can we describe this dynamics quantitatively?

- What is the role of saturated strong gluon fields, and what are the degrees of freedom in the high gluon density regime?

- What is the fundamental quark-gluon structure of light and heavy nuclei?

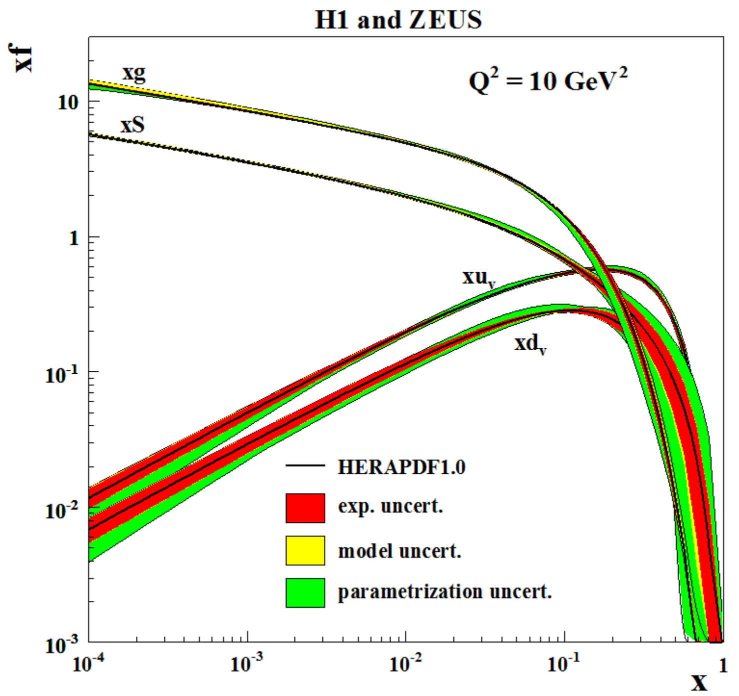
- Can a nucleus, serving as a color filter, provide novel insight into the propagation, attenuation, and hadronization of colored quarks and gluons?

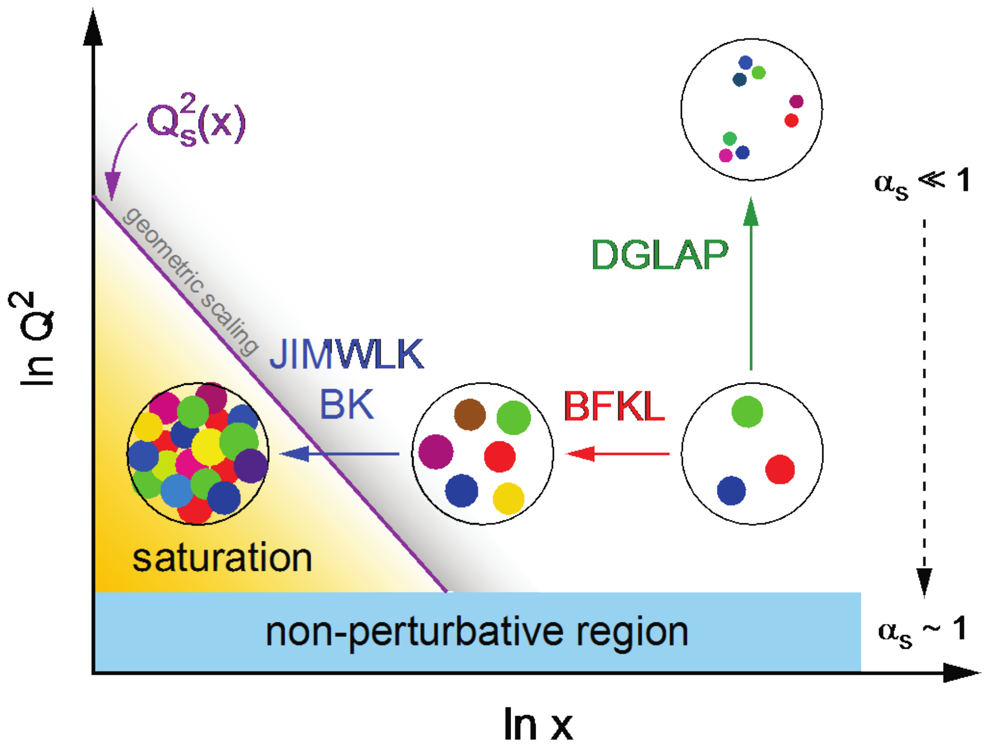
What's special about **RHIC** p+A?



- **Unique RHIC opportunities**:
  - A-scan (Au, Cu, Al, He, d beams have been run; more available)
    - Nuclear dependence of PDFs is not predicted by pQCD
    - Important test for saturation models
  - Polarized proton beams
  - Energy scan is straightforward if necessary to separate different underlying mechanisms
    - Example: studied d+Au at 20, 39, 62, and 200 GeV in just 5½ weeks

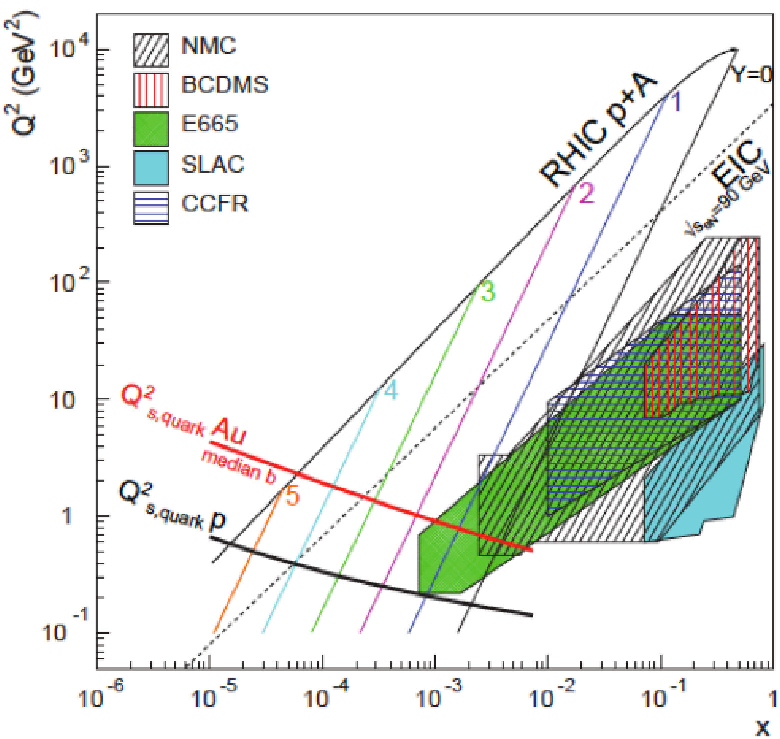
Where do gluons saturate?

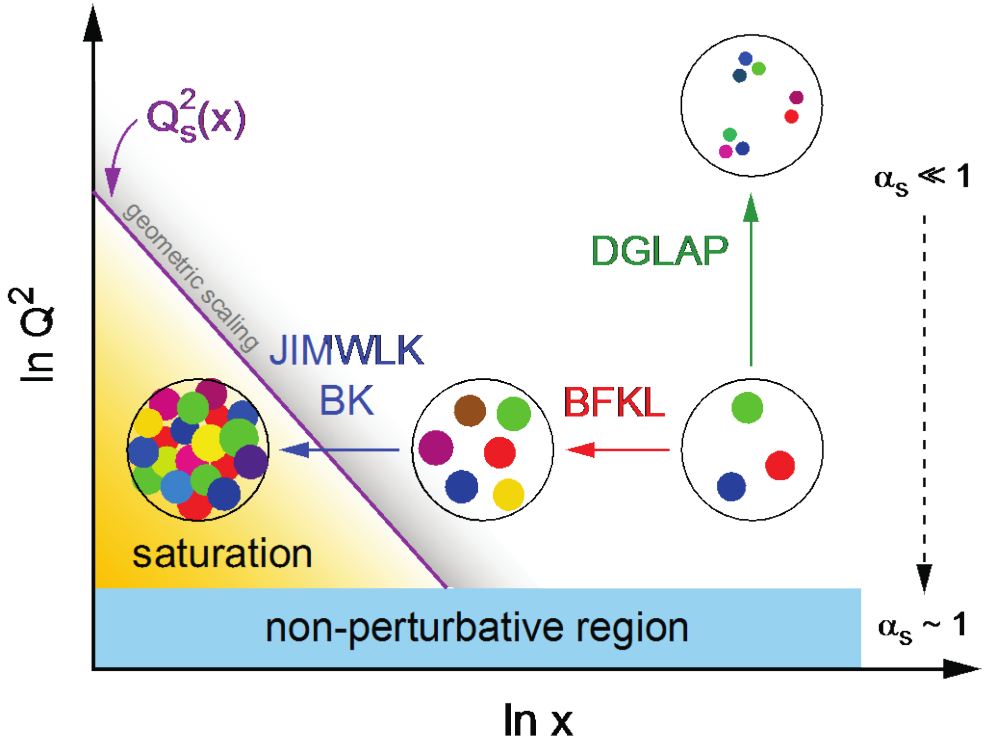




- Rapid rise of gluons is described by linear pQCD evolution equations
- Rise can't continue forever
  - Non-linear evolution must become important at some point
  - Introduces a new scale, $Q_s^2(x)$

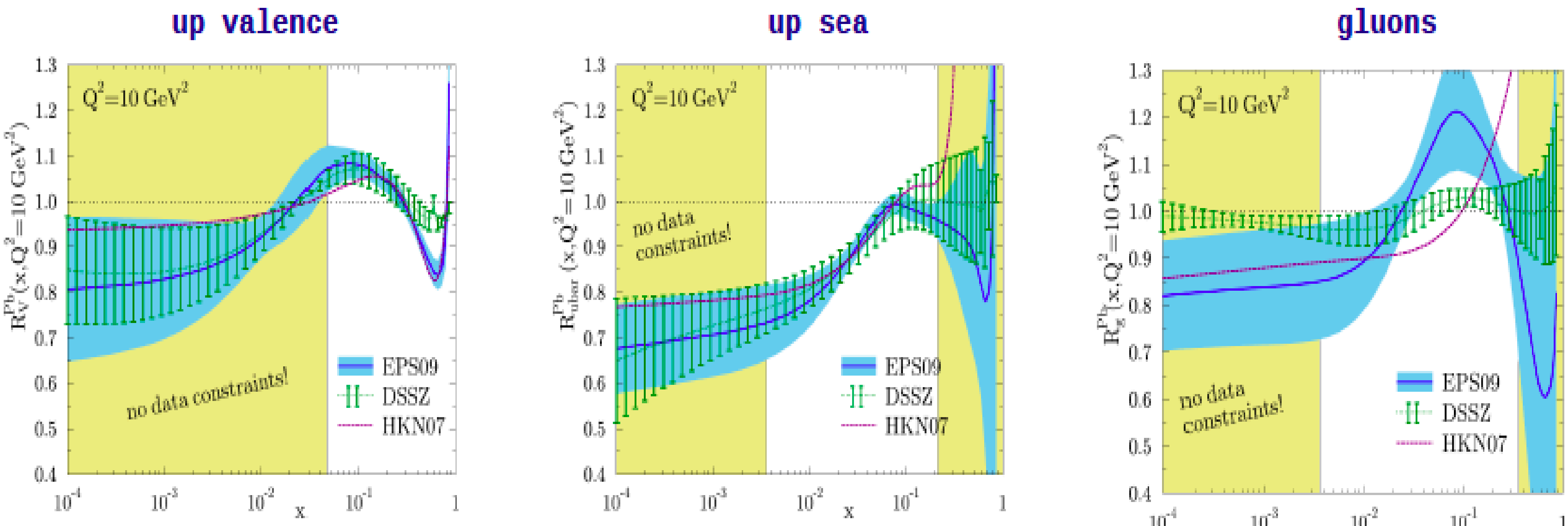
Where do gluons saturate?





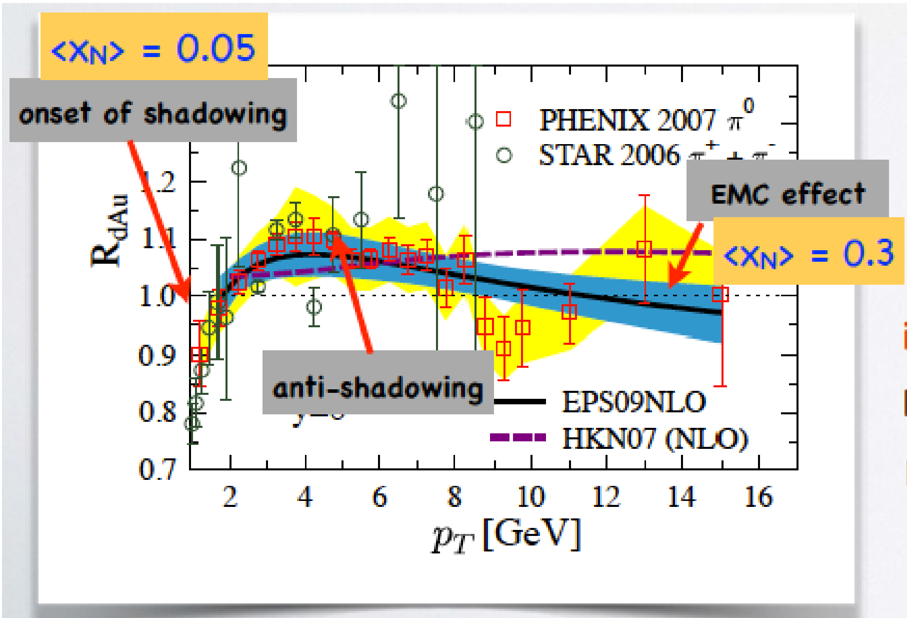
- Need measurements over a wide range of x,Q^2 to constrain "standard" nuclear PDFs
  - Crucial to **separate initial and final state effects**
- Must go to forward rapidities and moderate transverse momenta to probe the saturation regime

Current state of nuclear PDFs

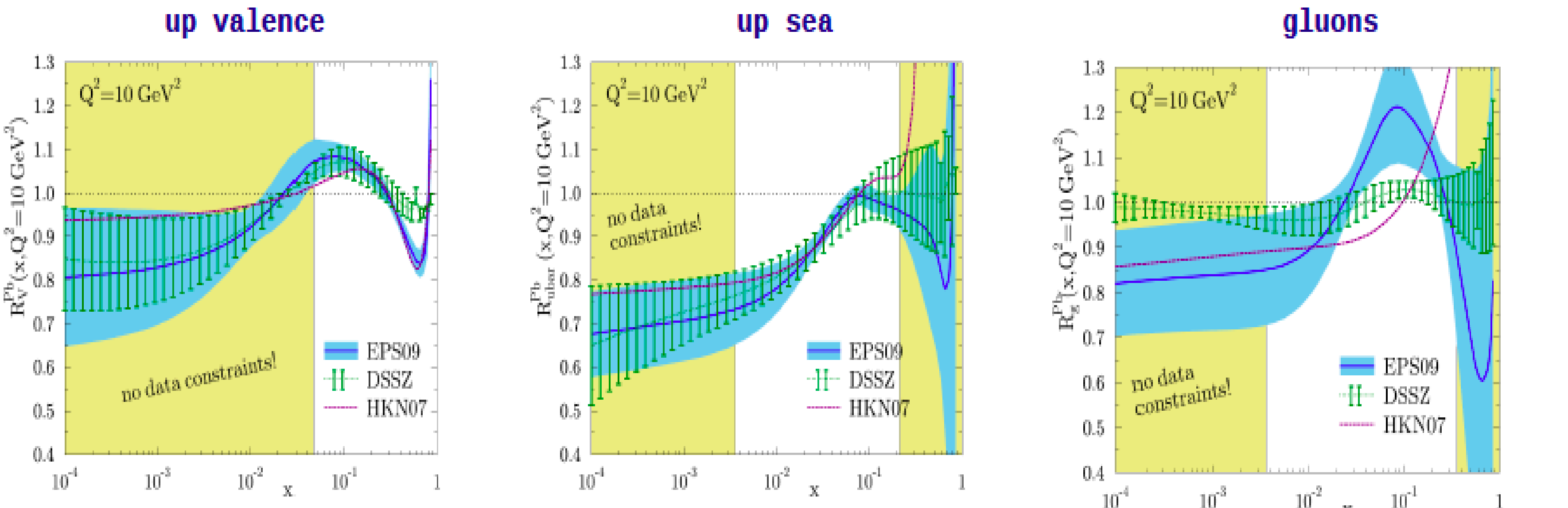


H. Paukkunen, DIS-2014

- EPS-09 includes PHENIX mid-rapidity π^0 R_{pA} with a weight of 20
  - Produces the large suppression / enhancement of the gluon distribution in the shadowing / anti-shadowing regimes



Current state of nuclear PDFs

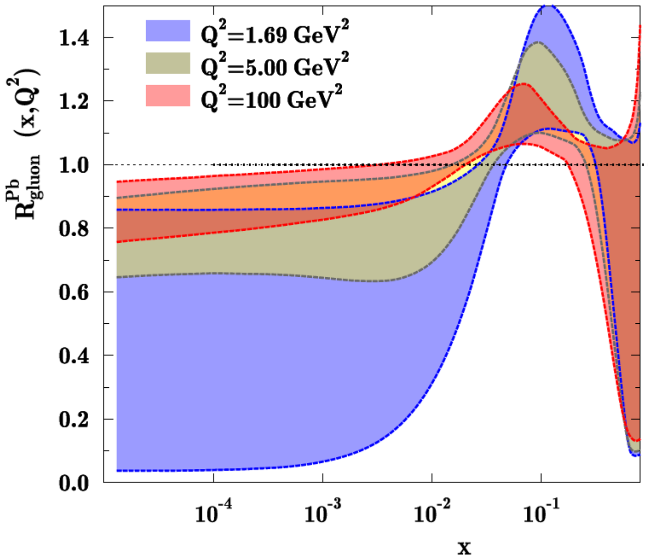


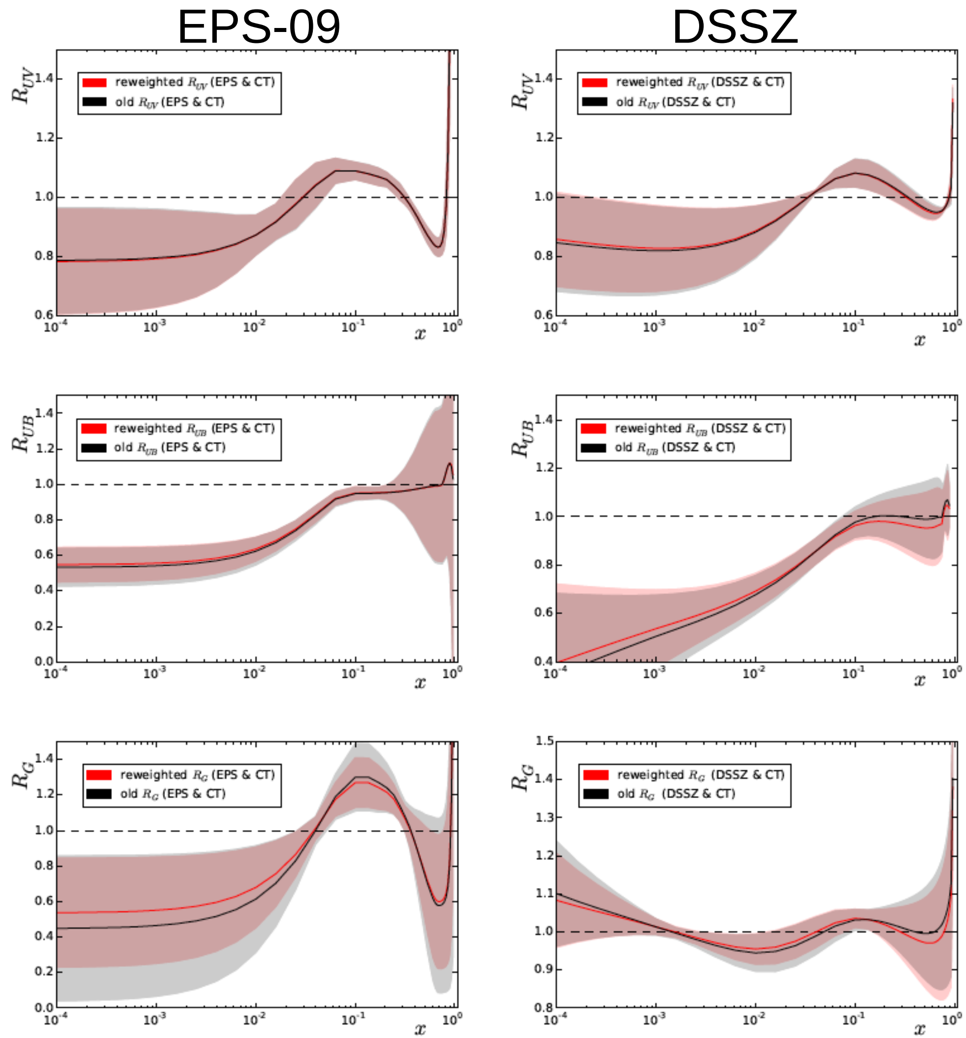
H. Paukkunen, DIS-2014

- **DGLAP** predicts ***Q*² dependence**, but **NOT A- or x-dependence**
- **Saturation models** predict the **A- and *x*-dependence**, but **NOT *Q*²**
- **Need a wide *Q*² lever arm at fixed *x*, together with an A-scan**

What about LHC p+Pb data?

$Q^2 = 1.69\ \text{GeV}^2$

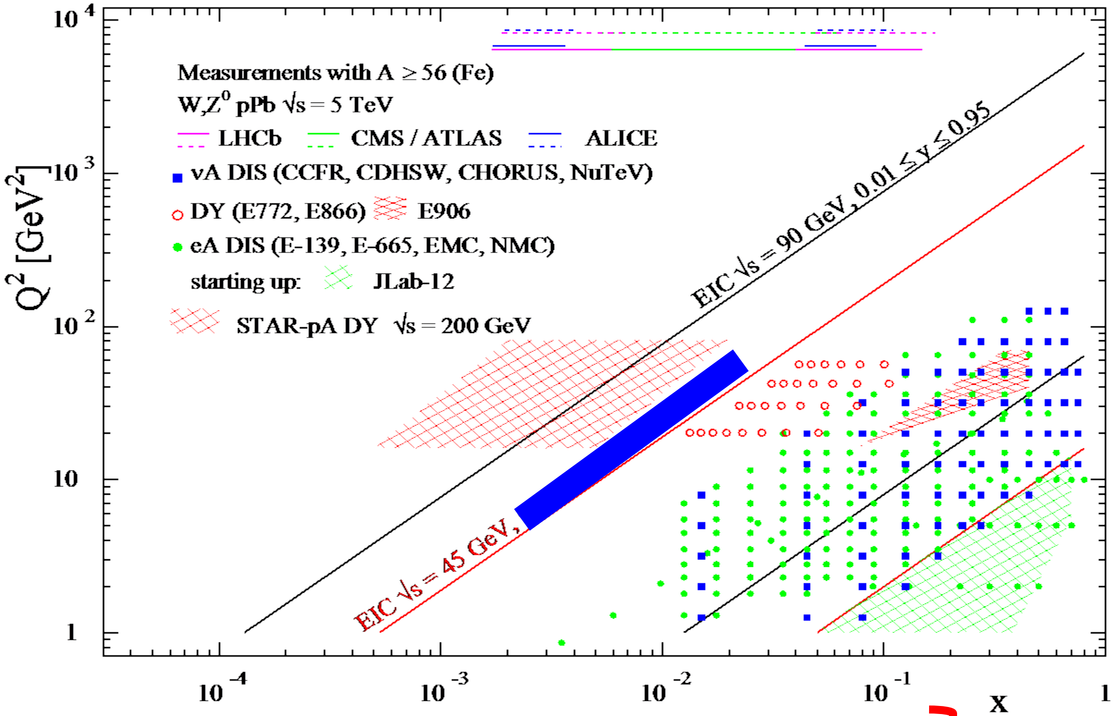




N. Armesto, *et al.*, arXiv:1512.01528

- Nuclear effects evolve away quickly with Q^2
- LHC data provide only minimal constraints to the nuclear PDFs

Key RHIC nPDF and saturation observables



Direct photon
$2.8 < \eta < 3.8$

- Direct photon R_{pA}
- R_{pA} for Drell-Yan **(needs forward upgrade)**

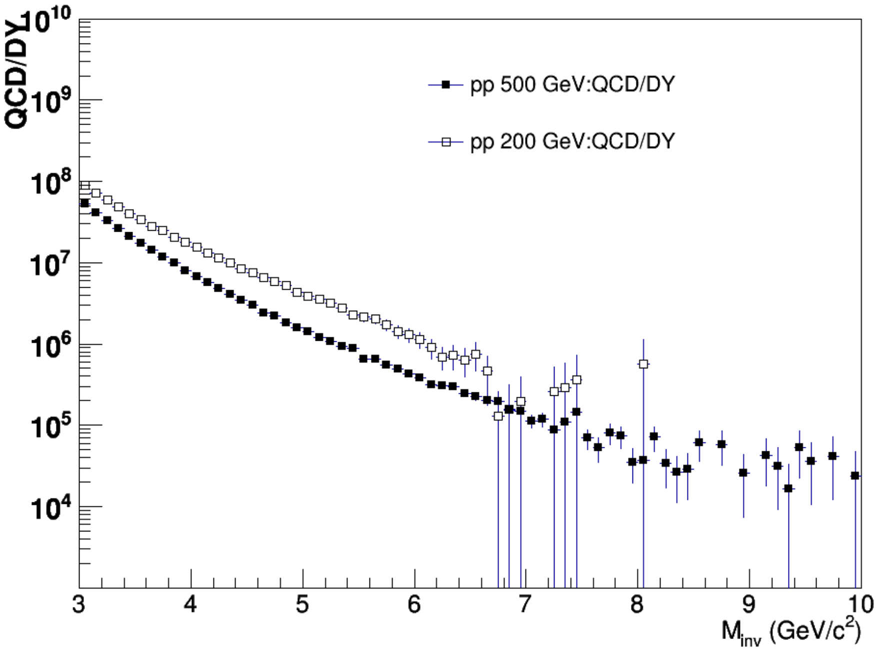
No final-state effects!

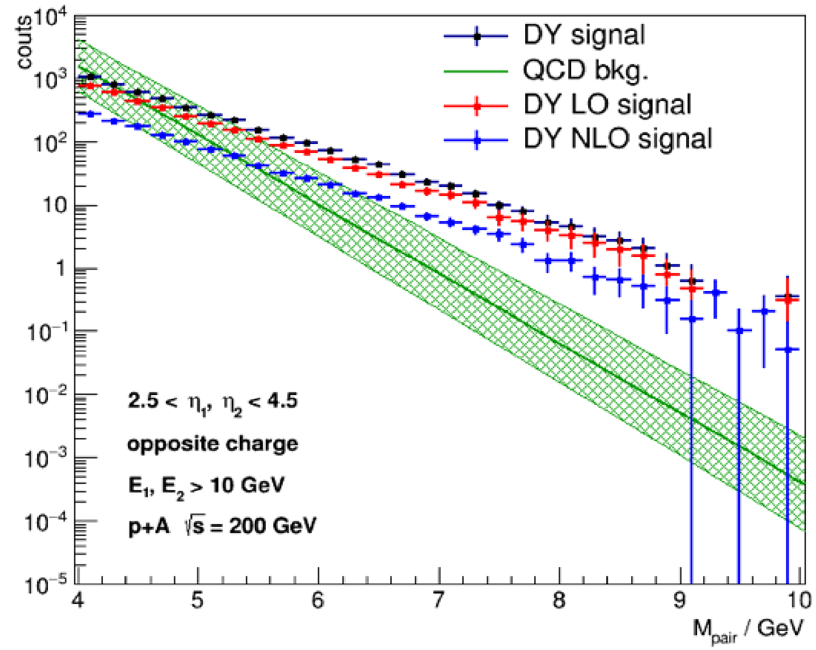
- pA ultra-peripheral collisions: $g(x,Q^2,b)$
- Di-hadron correlation measurements
- $A_N^{pA}(\pi^0) / A_N^{pp}(\pi^0)$
- Direct-photon + jet correlations **(needs forward upgrade)**

Drell-Yan R_{pA} at 200 GeV

Assumes forward upgrade

QCD/DY at 2.5 < η < 4.5

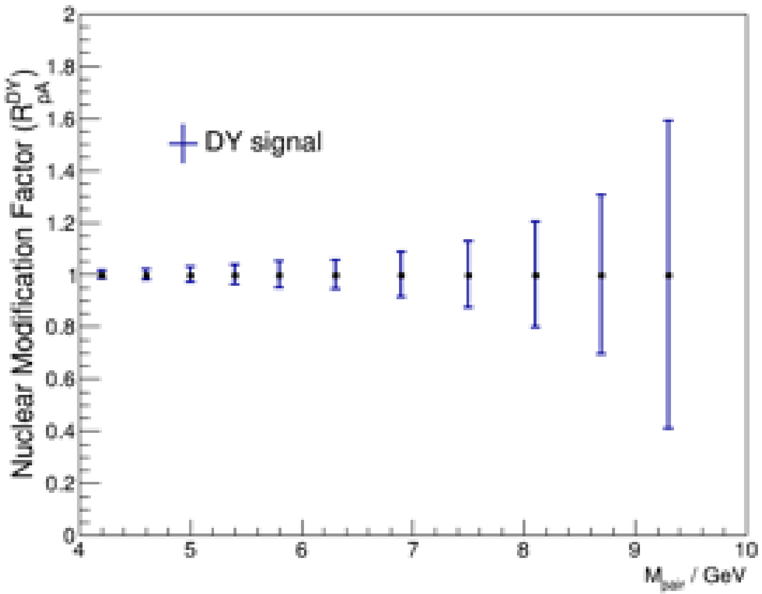




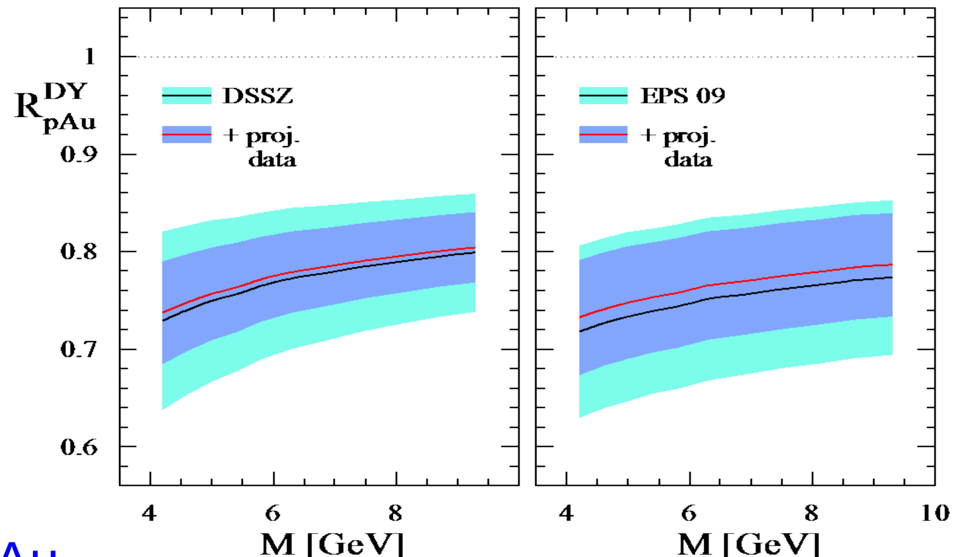
- Challenge is to reject intense hadronic backgrounds
- Proposed forward upgrades will do the job

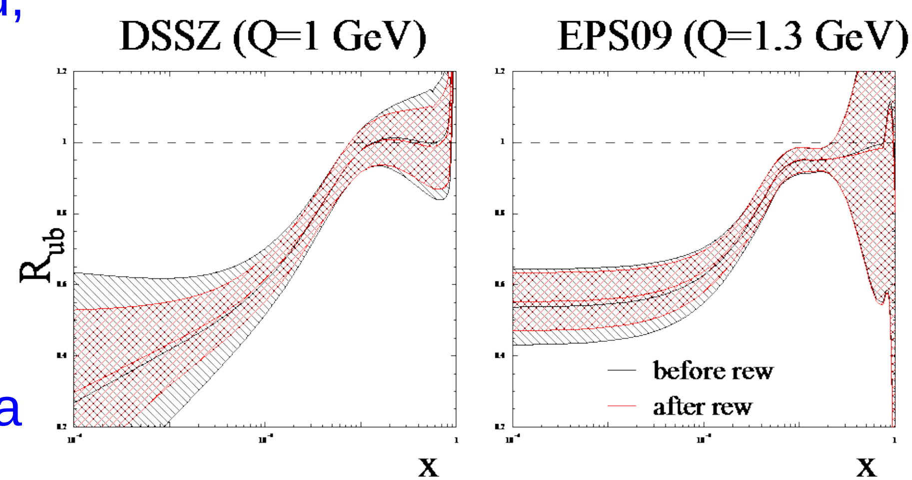
Drell-Yan R_{pA} at 200 GeV

Assumes forward upgrade



Projected impact on sea quark nPDFs

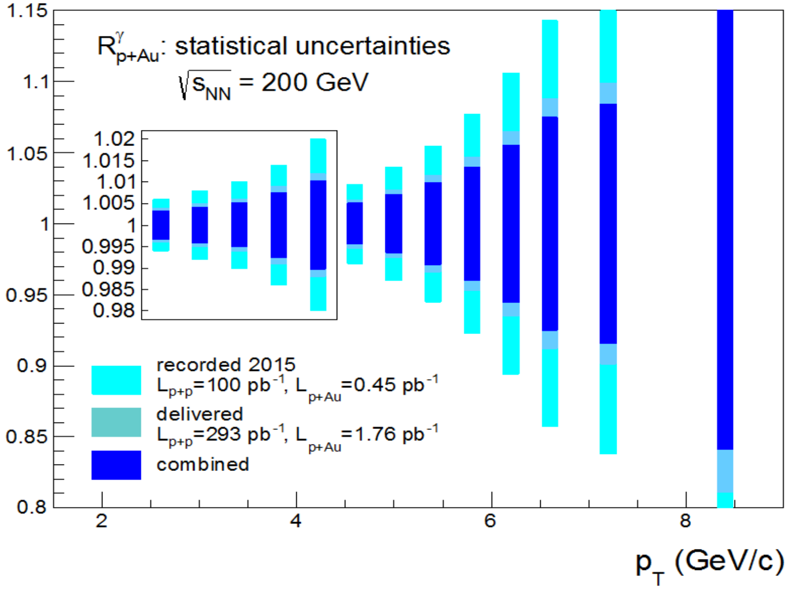




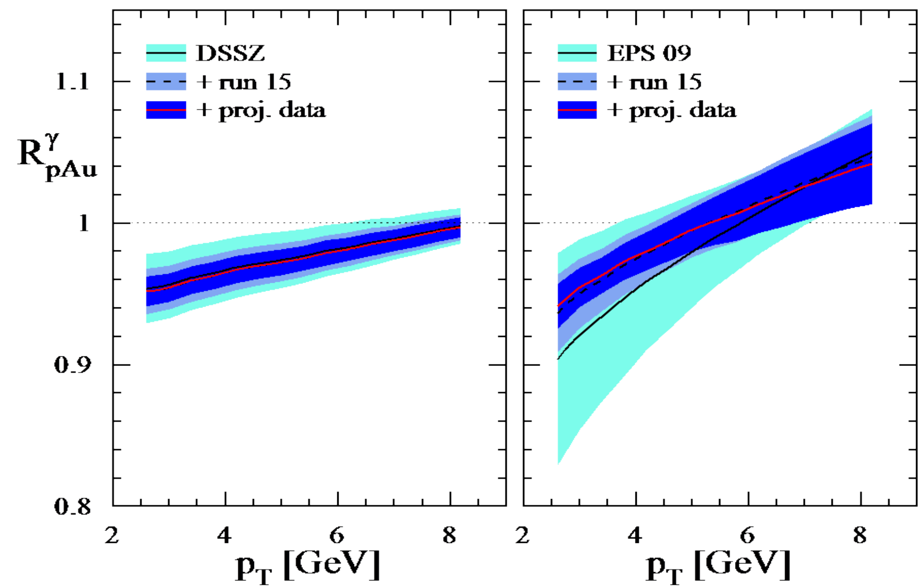
- Similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the Q^2 lever arm at low x relative to future EIC data

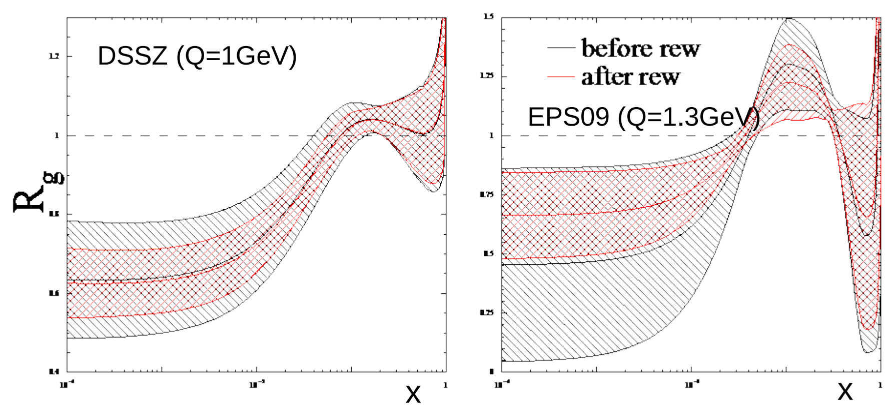
Direct photons

Data from p+Au run in 2015 and 2023



Projected impact on gluon nPDFs

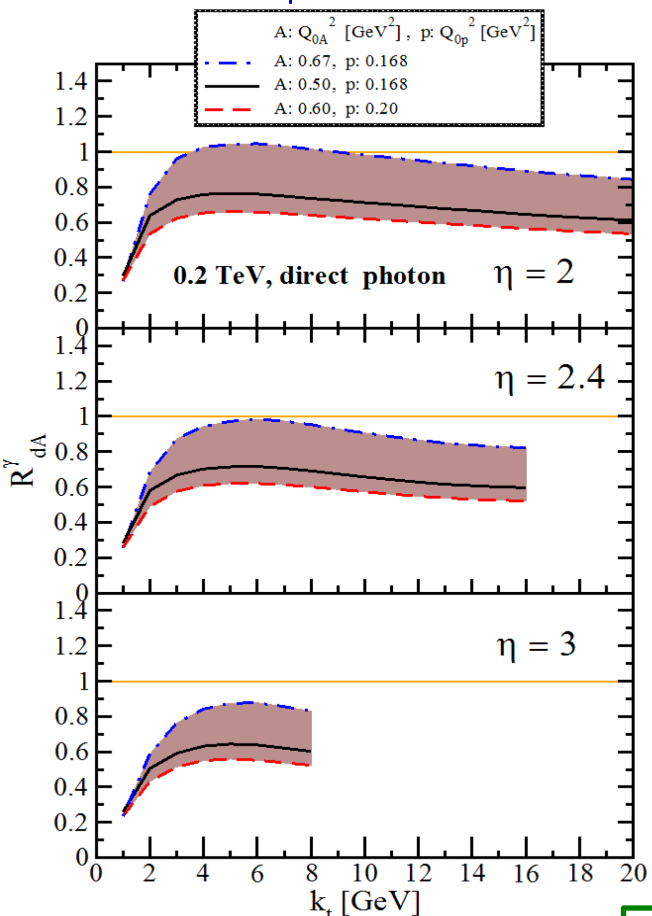




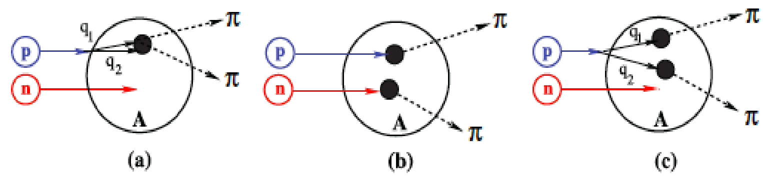
- Direct photon and Drell-Yan will provide:
  - Substantial improvements in our understanding of nuclear PDFs in the near term
  - Alternative observables and kinematics to EIC in the long term

Saturation probes

CGC prediction for direct photon R_{pA}

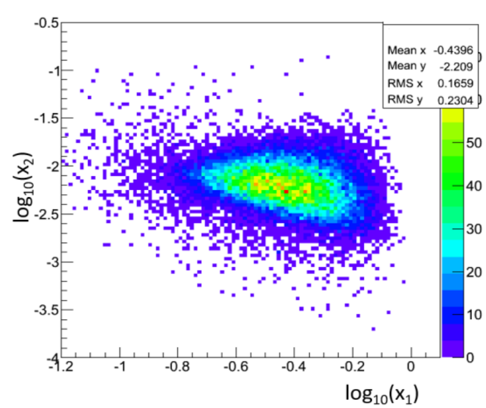


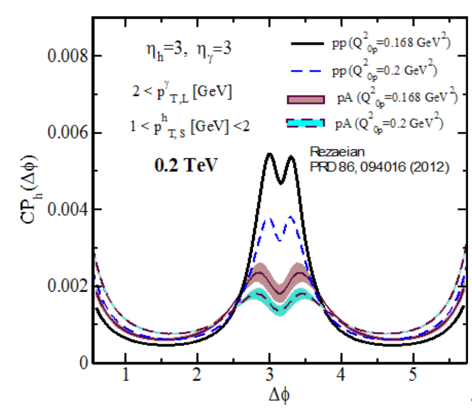
- Forward-forward correlation measurements
  - Di-hadron correlations in p+A
    - First data from 2015 p+Au
    - Reduced pedestal compared to d+Au
    - Eliminate double-interaction mechanism



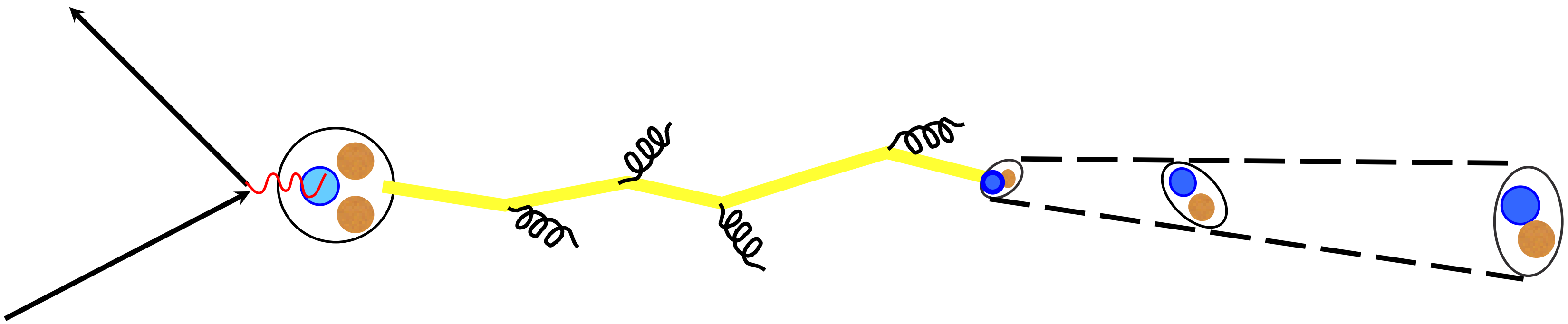
  - Photon-jet and jet-hadron correlations
    - 1M forward-forward gamma+jet events in 2023 p+Au and p+Al
    - Gamma+jet has no final state contribution

Assumes forward upgrade





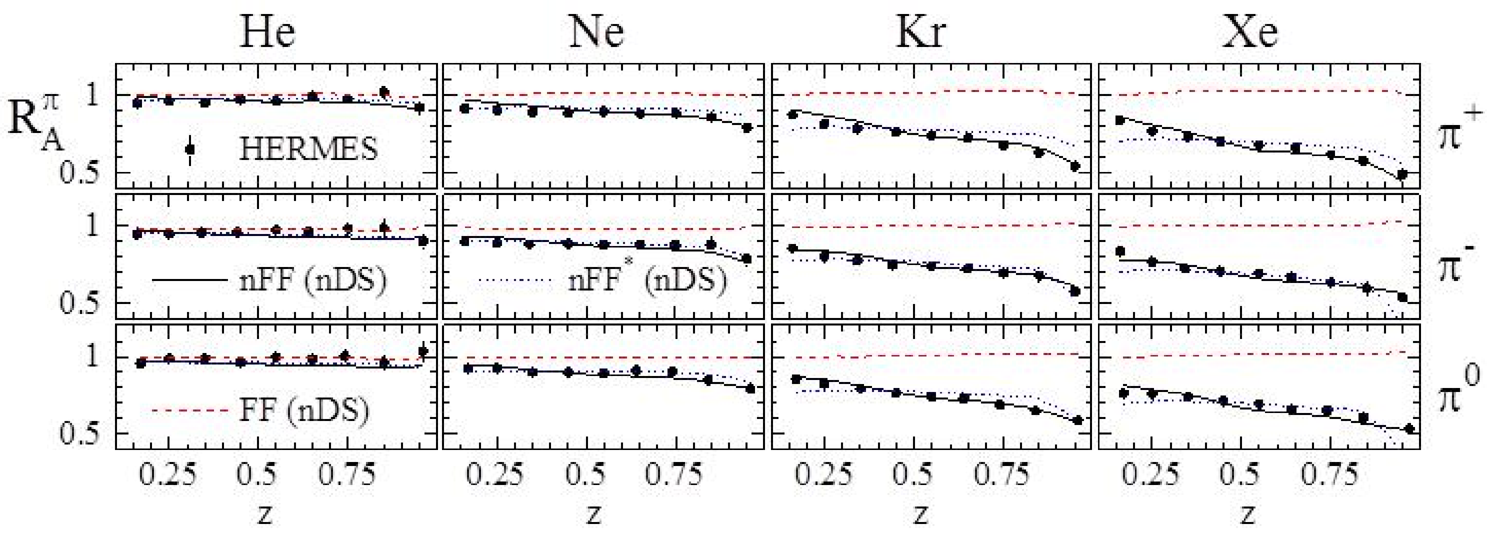
What about final state effects?



- JLab 12-GeV and EIC both anticipate major programs to explore the hadronization process
  - Probe the mechanism for confinement

- What can we learn at RHIC?

Hadronization in the nuclear environment

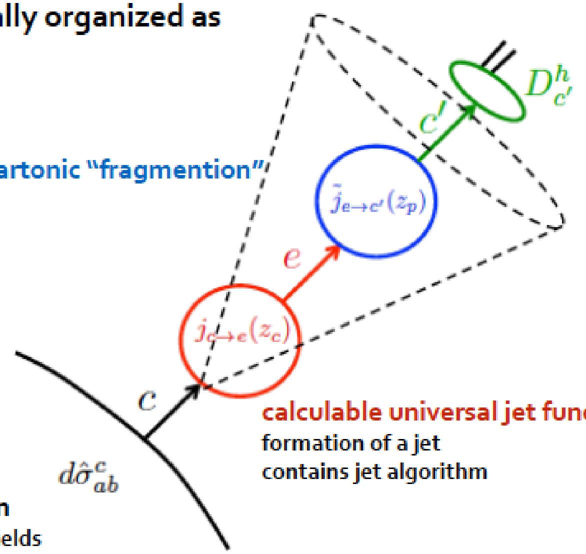


- Examining the fragmentation distribution isolates final-state hadronization contributions from initial-state nPDF modifications
- Large nuclear effects have been seen in *e*A scattering
- Can be described in terms of an effective nuclear fragmentation function
  - Don't know the **underlying QCD process**
  - Don't know if these effects survive to high √s
  - Don't know how **gluons might differ from quarks**
    - Difficult to access gluon FF in DIS

Measuring fragmentation functions at RHIC

observable: $$\frac{d\sigma^{pp}}{dp_T^{\rm jet}\, d\eta^{\rm jet}\, dz_H}$$ identified hadron in a jet with $$z_H \equiv \frac{p_T^H}{p_T^{\rm jet}}$$

pQCD calculation can be schematically organized as

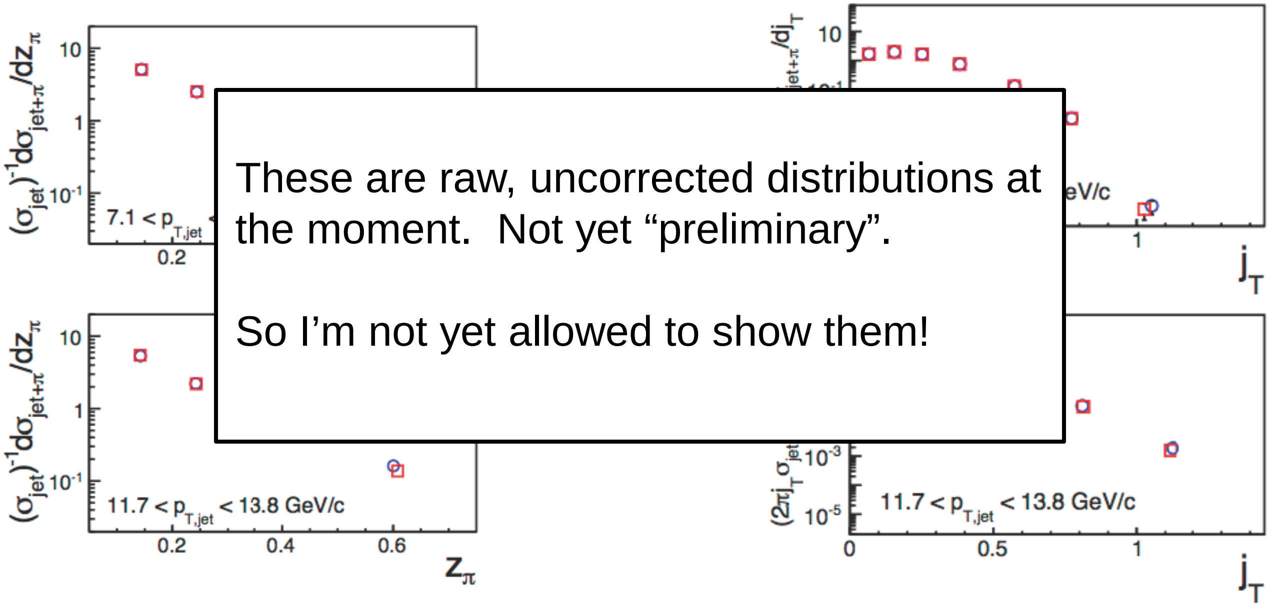


considerable theoretical activity recently:

MC techniques: Procura, Stewart; Jain et al.; Arleo et al.; Ritzmann, Waalewijn, ...
anal. calc. (small jet approx.): Kaufmann, Mukherjee, Vogelsang 1506.01415 arXiv:1506.01415

- Recently the formalism has been developed to relate the distribution of hadrons inside a jet quantitatively to the fragmentation function

Fragmentation functions at RHIC

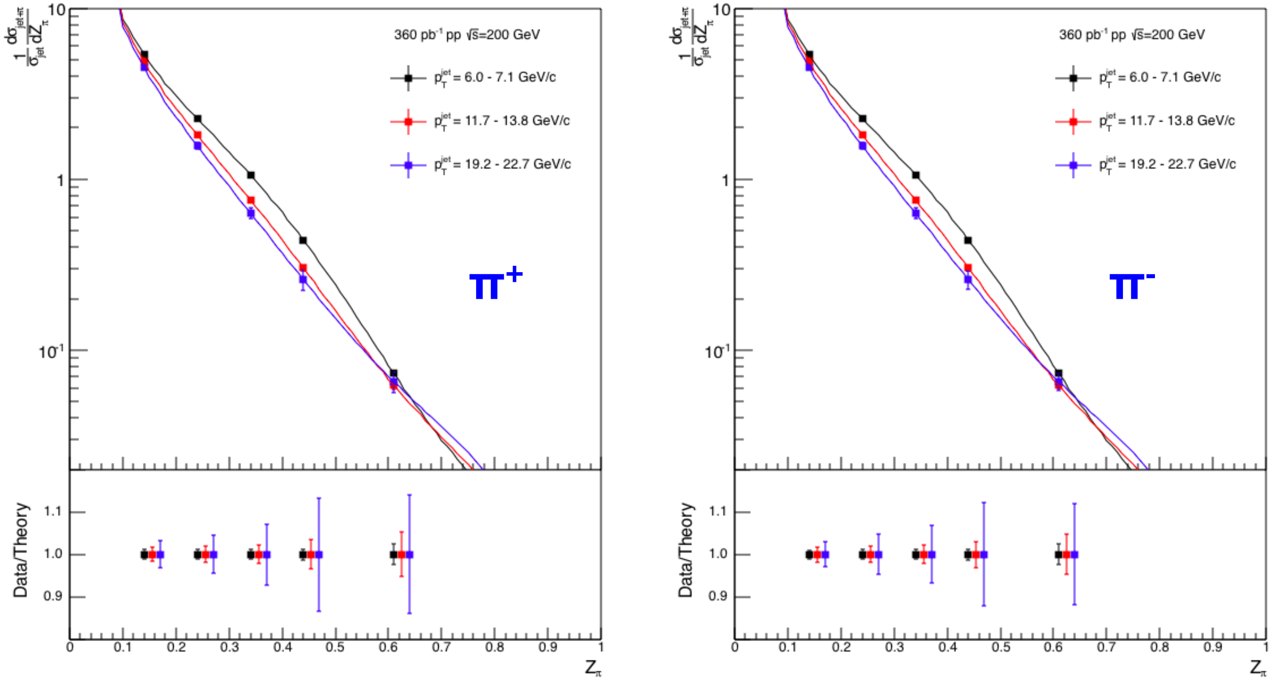


- STAR has initiated a series of fragmentation function measurements
  - First step: access to gluon FF in 500 GeV pp collisions
    - Measuring both longitudinal and transverse jet structure
  - Will follow with 200 GeV pp and **p+Au** collisions
    - Can also measure longitudinal-transverse correlations
    - Critical input for unpolarized TMD calculations

- RHIC p+A fragmentation measurements probe similar kinematics as EIC cold-nuclear matter energy loss, but with a **gluon-rich probe**

How well can we do in pp?

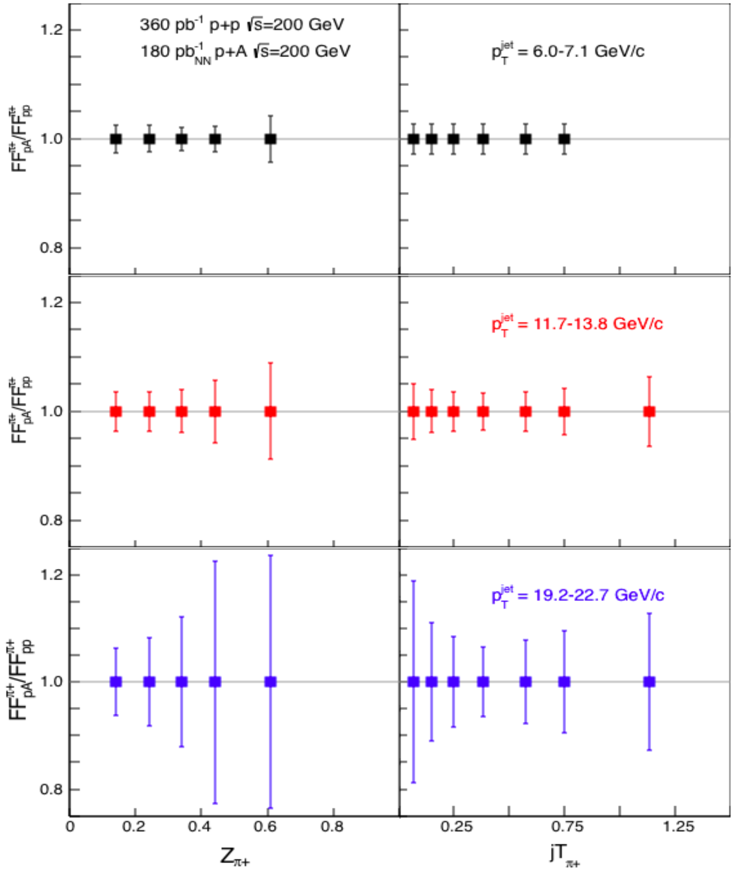
Needs π / *K* / p PID

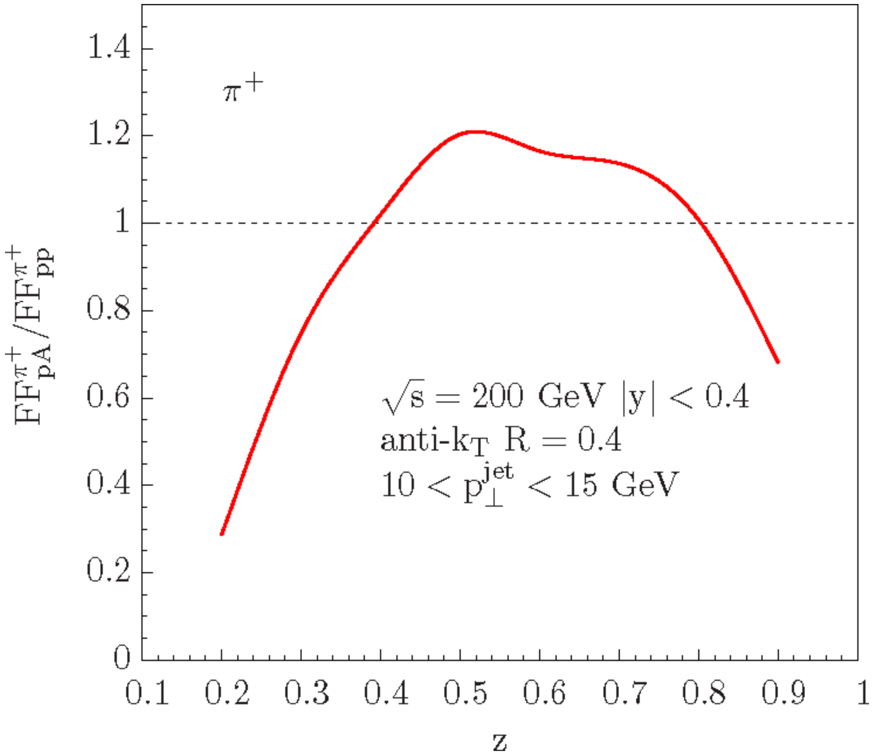


- Projected measurement of identified pions in mid-rapidity jets at 200 GeV with 2023 data included
  - Theoretical curves for DSS14 FF calculated using code from Kaufmann et al
  - Will also measure identified kaons and (anti-)protons with reduced precision over a more limited z range

How well can we do in p+A?

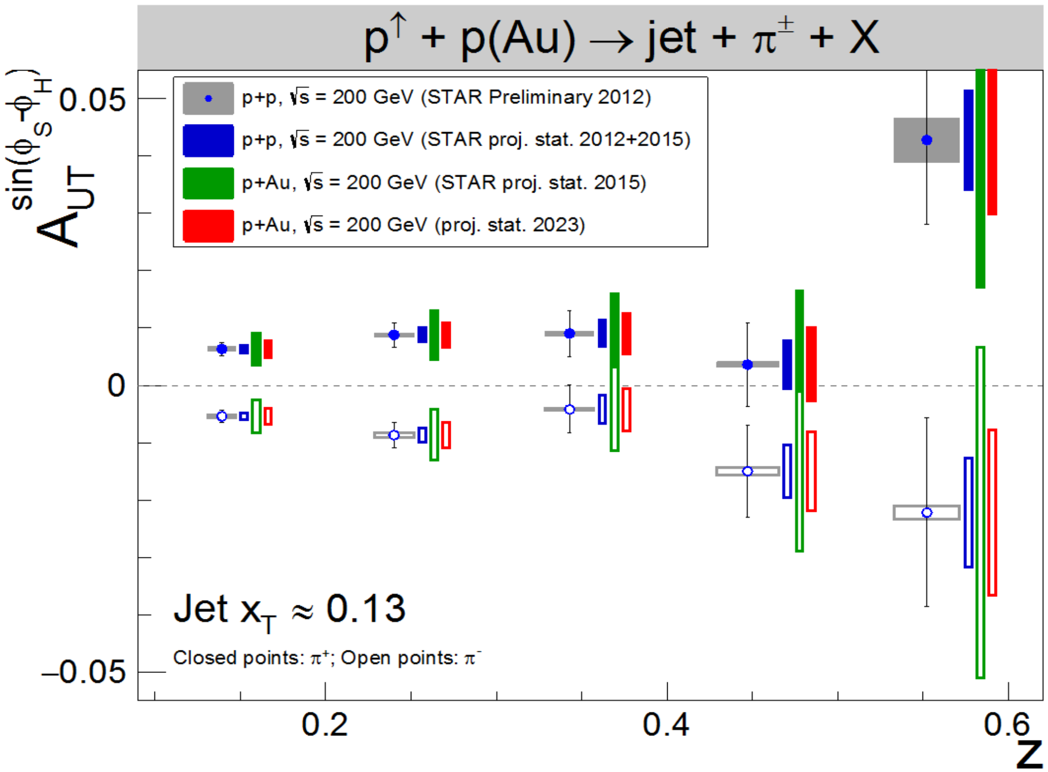
Needs π / *K* / p PID





- π^+ FF in p+A / FF in pp for $|eta_{jet}| < 0.4$ in three representative jet p_T bins (will have comparable statistics for π^-)
- Model prediction calculated by Z.-B. Kang, using nFF from M. Stratmann

Can even measure polarized nuclear FF



Needs π / *K* / p PID

- Collins effect in p+A
  - Extreme test of factorization / universality !
  - Unique at RHIC
- STAR took a first opportunistic look for p+Au during 2015 run
- Will obtain much better statistics, plus a lighter nucleus, in 2023

Summary

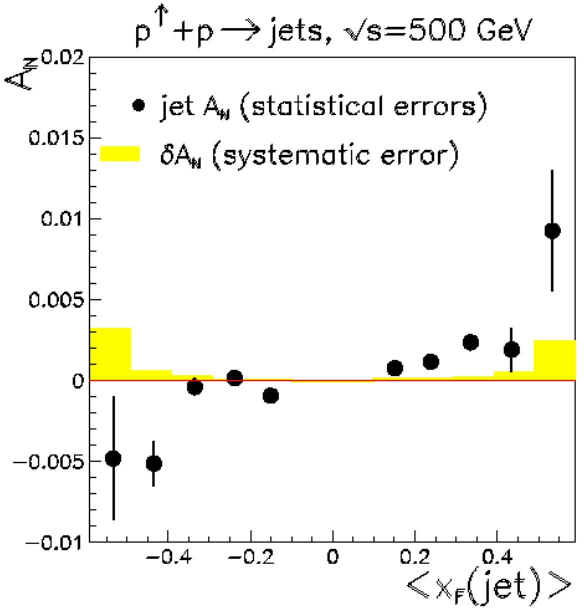
In the baseline RHIC run plan

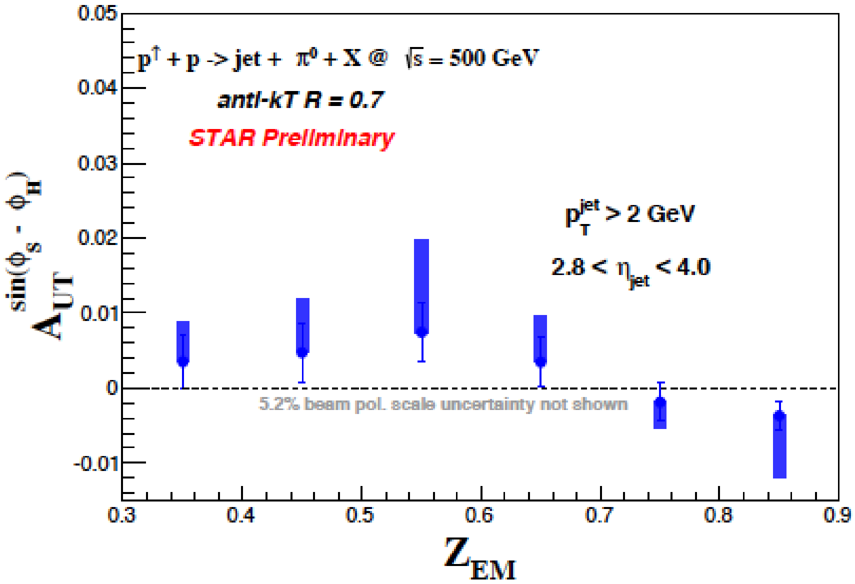
	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linear pol Gluons, Gluon Sivers in Twist-3 First look on GPD E_g	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_S-2\phi_h)}$ $A_{UT}^{\sin(\phi_S-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_S)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR None None
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for diffractive events	Yes Forward instrum. None
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_S-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY): Yes Forward instrum. None Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_S-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. None Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity	Yes Forward instrum. None
	202X	$\vec{p}\vec{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

More high-impact science if the opportunity arises

Origin of forward hadron asymmetries ?

A_NDY, PLB B750, 660

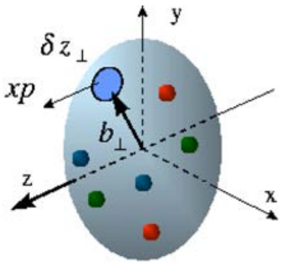


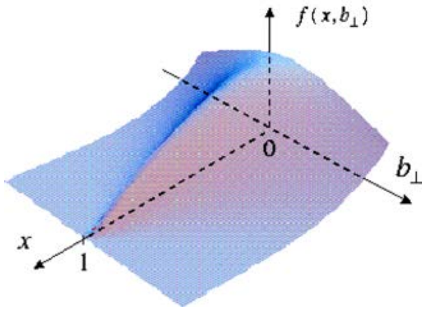


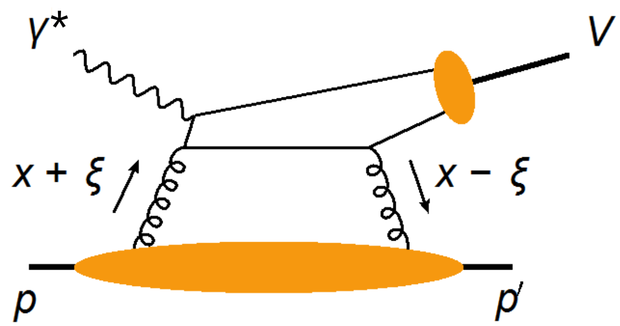
- A_N for forward jets is factor of ~10 smaller than for π^0
- Collins for π^0 in forward EM jets is too small to explain π^0 A_N
- **Maybe the π^0 A_N arises from diffraction?** (~20% of cross section)

- Combination of Roman pots with **forward upgrade** will open a **new era of diffractive jet spin asymmetries**

What about orbital angular momentum?







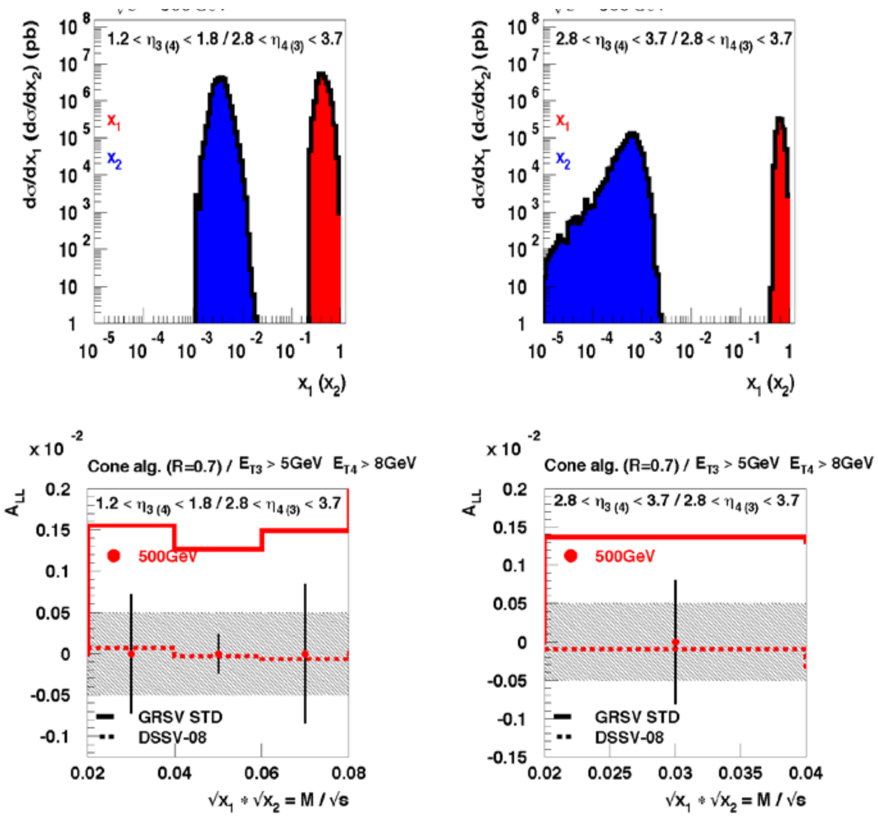
quark contribution

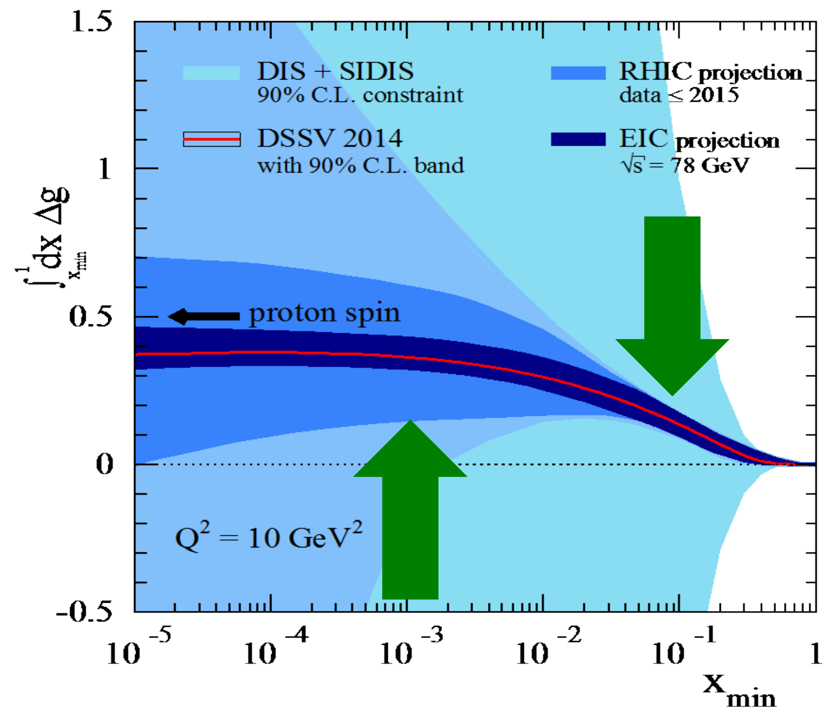
$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

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

- 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
  - **Only access world-wide to E_g before EIC**
- First measurements started in 2015 enabled by the Roman Pot phase II* upgrade to STAR

Gluon polarization in 2020+





- If run longitudinal during 200 GeV pp running, can reduce π^0/jet uncertainties a further factor of 2
- Forward-forward di-jets in 500 GeV pp running can directly sample Δg at $x \sim 10^{-3}$ **(needs forward upgrade)**