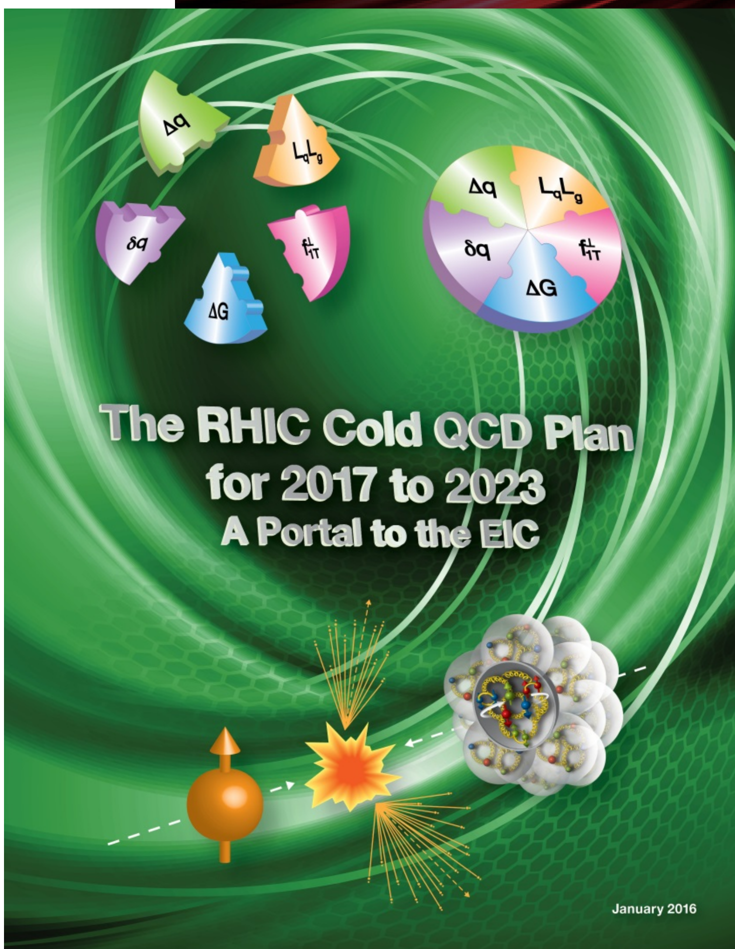


RHIC Cold QCD Plan: p+A Collisions

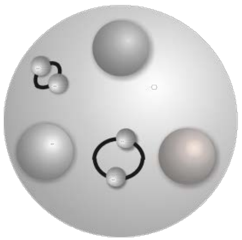
Carl Gagliardi
Texas A&M University

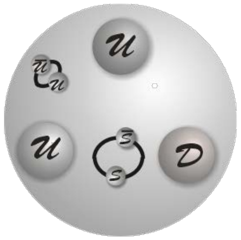
Primary goals of the plan

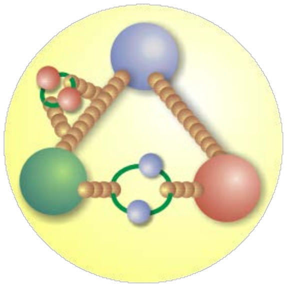
- Establish the validity - and limits - of **factorization and universality**
  - Essential to separate **intrinsic properties of hadrons** from **interaction-dependent dynamics**
  - Requires pushing the envelope beyond just those measurements that have been proven theoretically
    - Particularly relevant for transverse spin and **p+A**
  - 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 to significantly enhance the impact and interpretation of the future EIC data

Complementarity of DIS and p+p/p+A







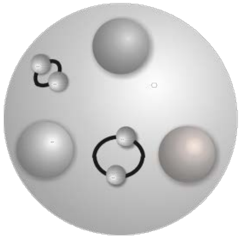
- Electromagnetic interactions
  - Sensitive to charge^2
  - Insensitive to color
- Weak interactions
  - Sensitive to weak charge (~flavor)
  - Insensitive to color

DIS

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

p+p
p+A

Complementarity of DIS and p+p/p+A



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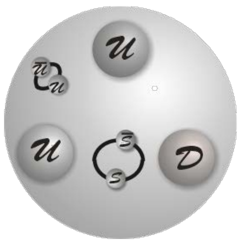

- Weak interactions
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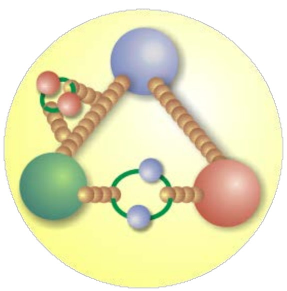
DIS



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

p+p
p+A

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

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

This talk:

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	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	$p^{\uparrow}p^{\uparrow}$ @ 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
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The plan in one table

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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-	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity	Yes Forward instrum. None
	202X	$\vec{p}p$ @ 510	1.1 fb^{-1} 10 weeks			

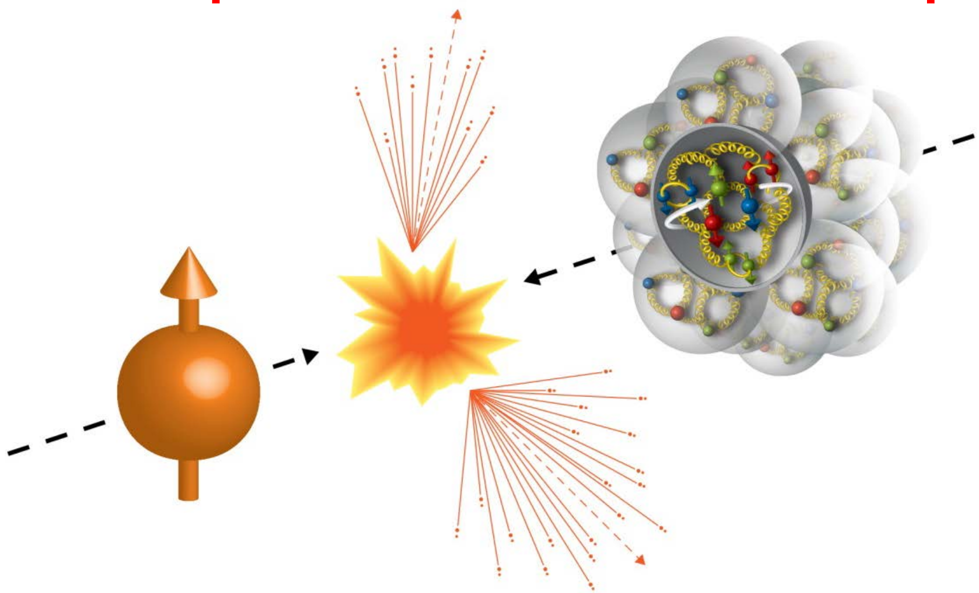
This talk:

The p+A running in the RHIC Cold QCD plan is already in the baseline RHIC schedule.

Headline questions for p+A

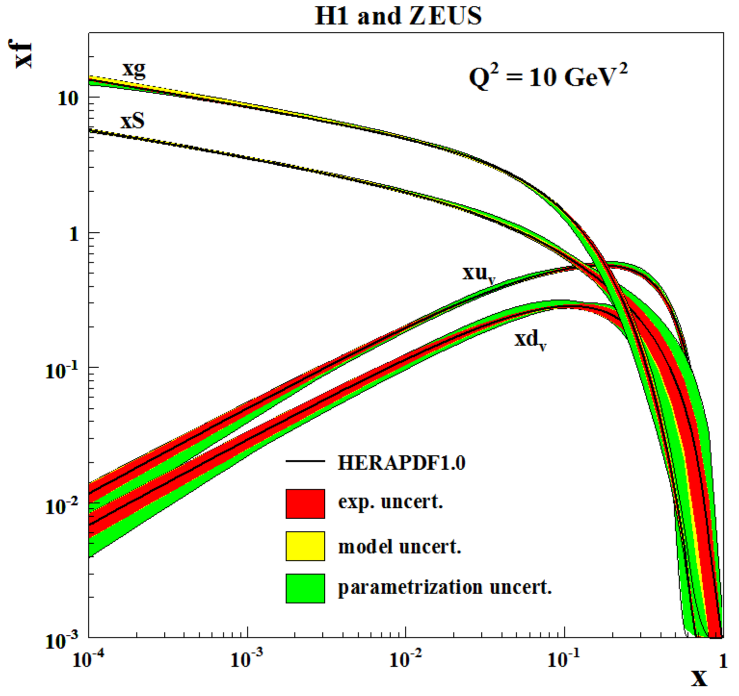
- Can we experimentally find evidence of a novel universal regime of non-linear QCD dynamics in nuclei?
- What is the role of saturated strong gluon fields, and what are the degrees of freedom in the high gluon density regime?
- What is the fundamental quark-gluon structure of light and heavy nuclei?
- Can a nucleus, serving as a color filter, provide novel insight into the propagation, attenuation, and hadronization of colored quarks and gluons?

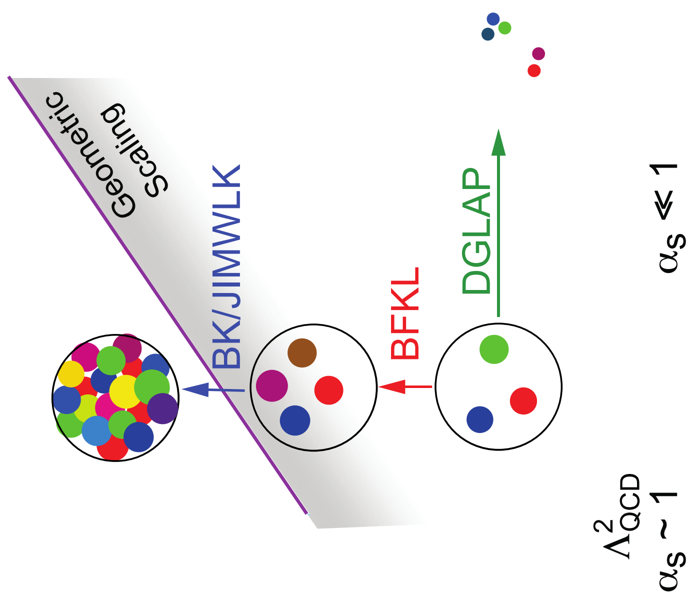
What's special about RHIC p+A?



- **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: plan to run d+Au this spring at 20, 39, 62, and 200 GeV in only 5 weeks

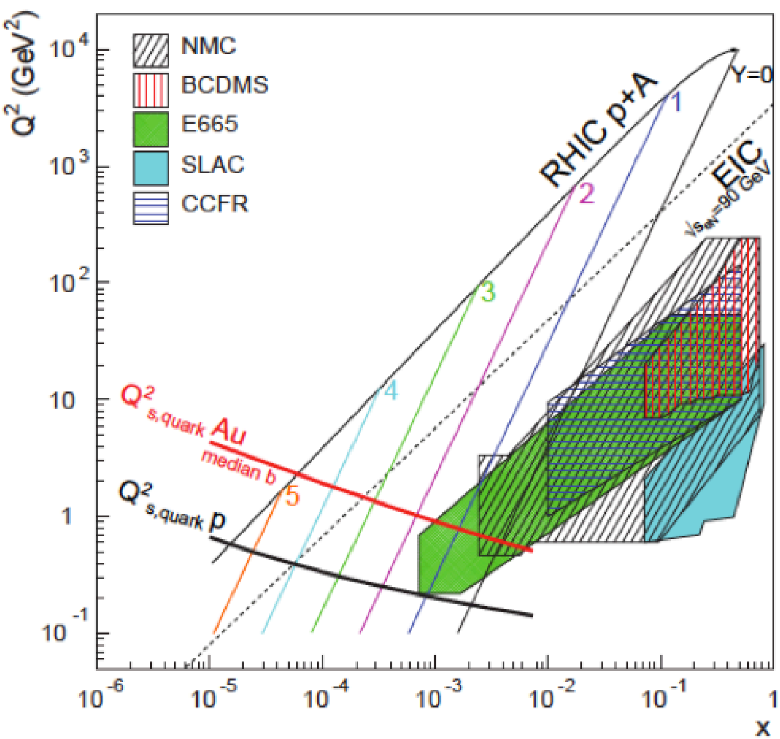
Where do gluons saturate?

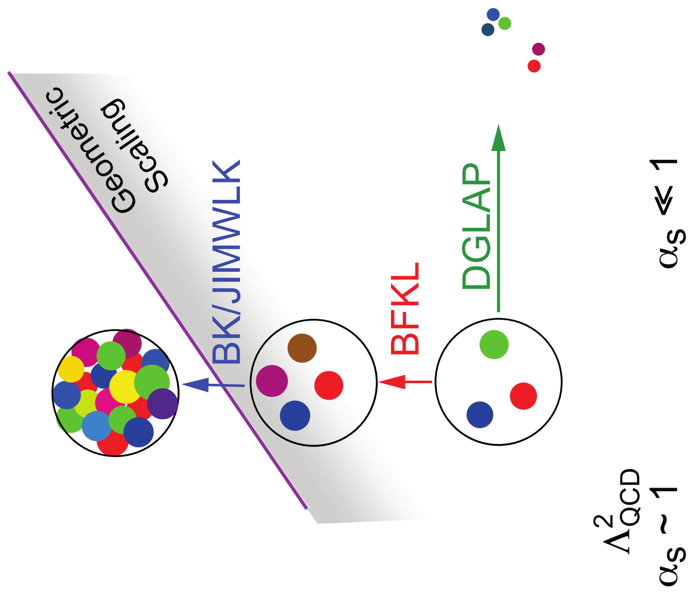




- Rapid rise of gluons is described by linear pQCD evolution equations
- Rise can't continue forever
  - Non-linear evolution must become important at some point
  - Introduces a new scale, $Q_s^2(x)$

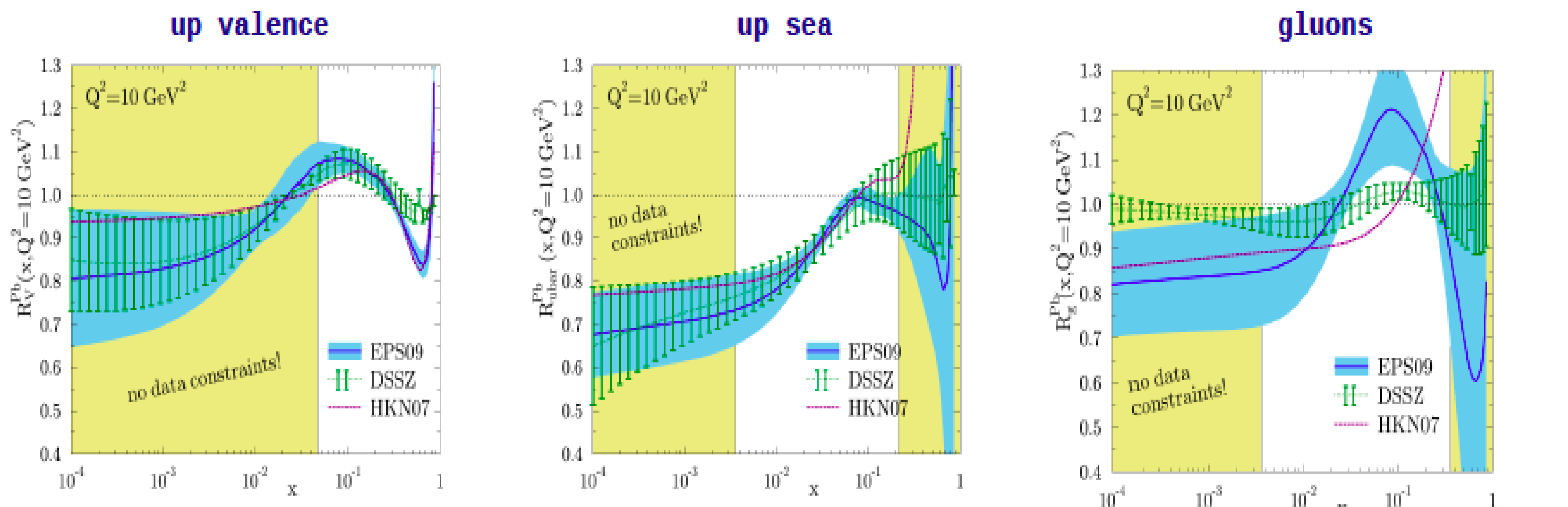
Where do gluons saturate?





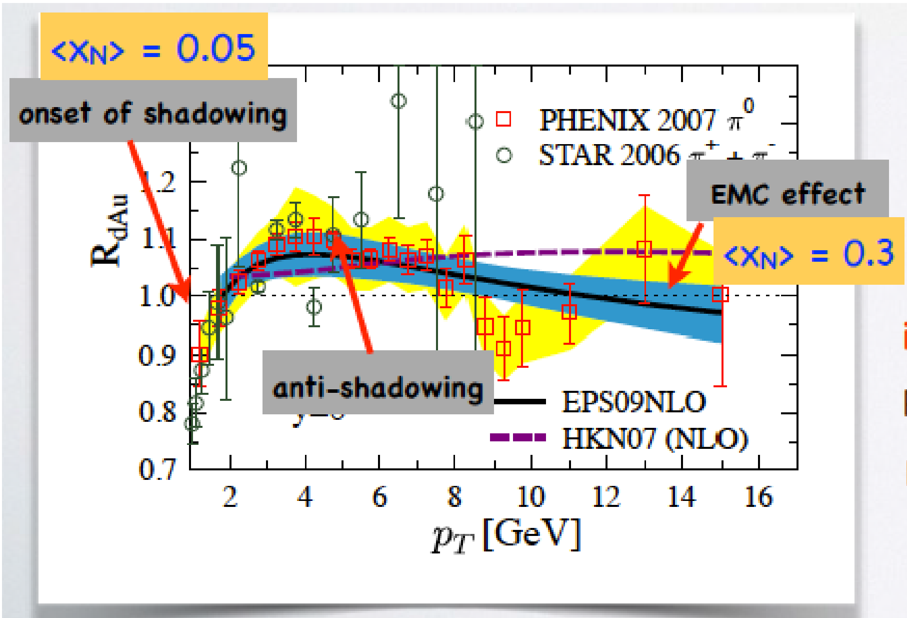
- Need measurements over a wide range of x,Q^2 to constrain "standard" nuclear PDFs
- Must go to forward rapidities and moderate transverse momenta to probe the saturation regime

Current state of nuclear PDFs

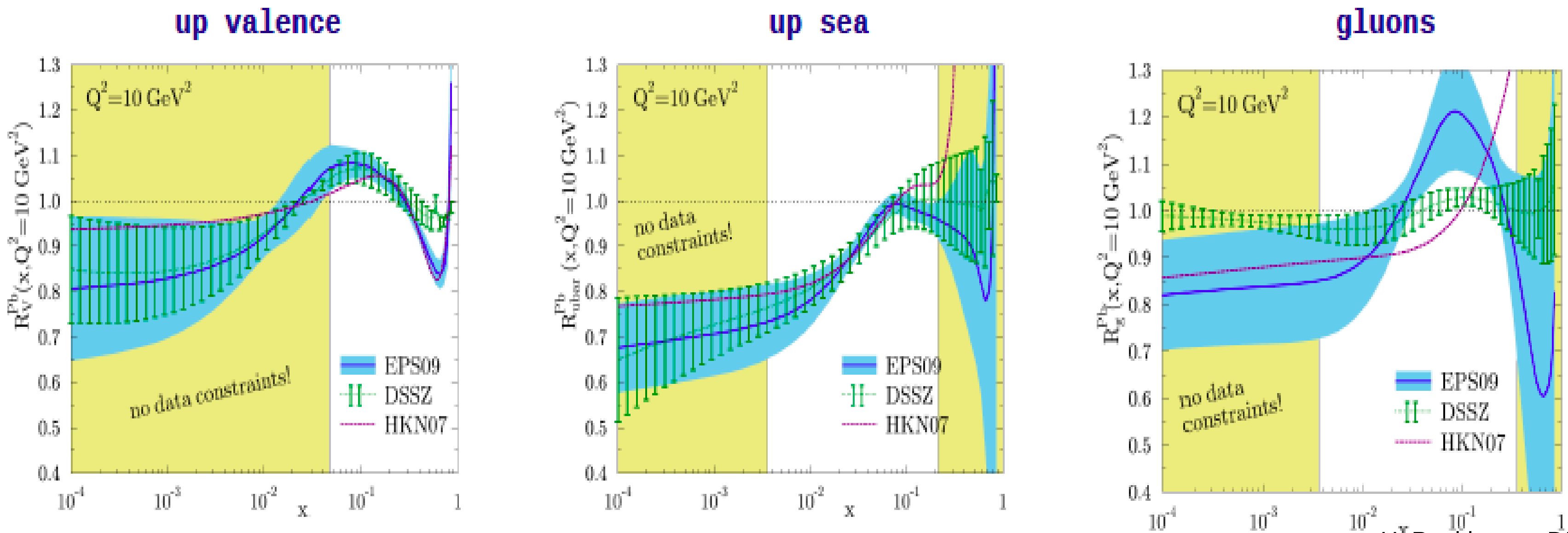


H. Paukkunen, DIS-2014

- 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



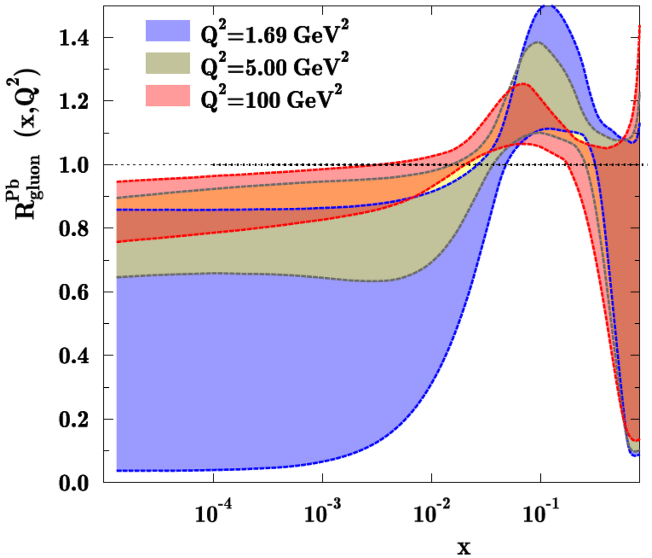
H. Paukkunen, DIS-2014

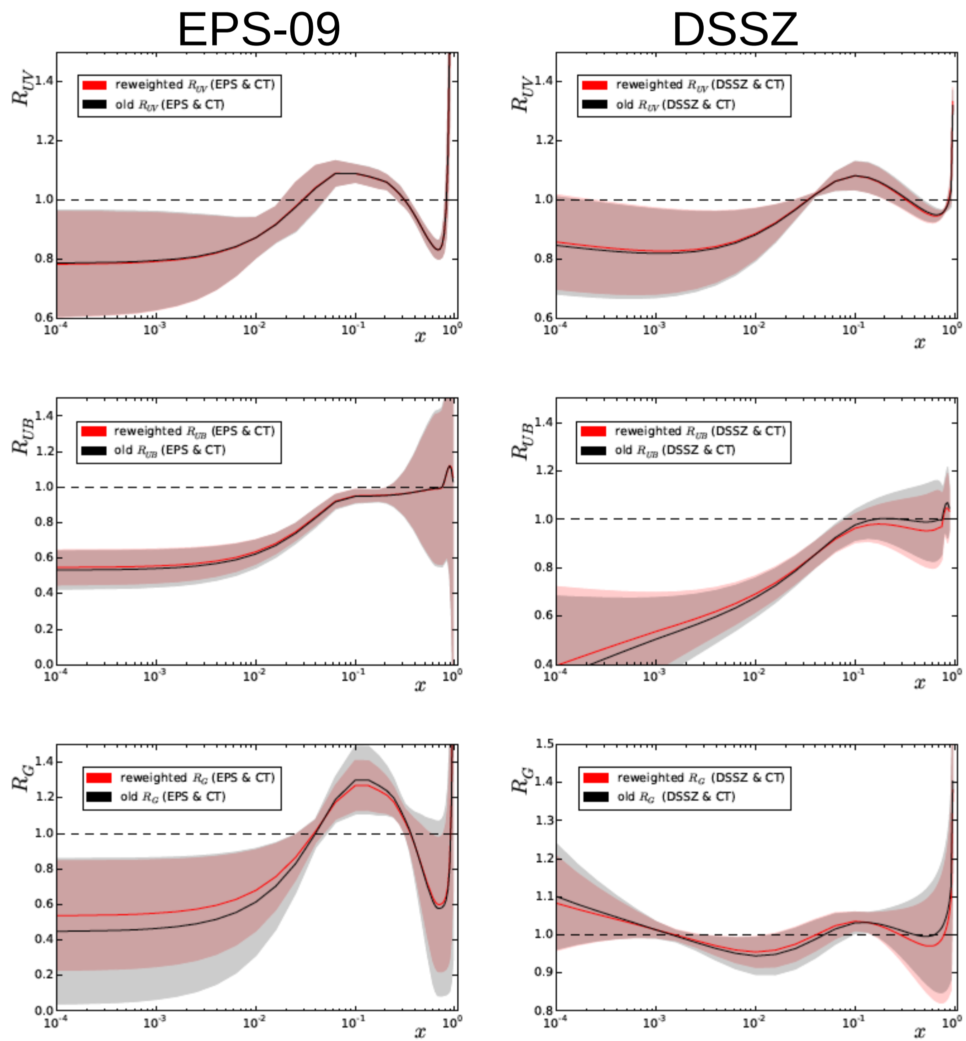
- **DGLAP** predicts **Q^2 dependence**, but **NOT A- or x-dependence**
- **Saturation models** predict the **A- and x-dependence**, but **NOT Q^2**

- **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 GeV^2

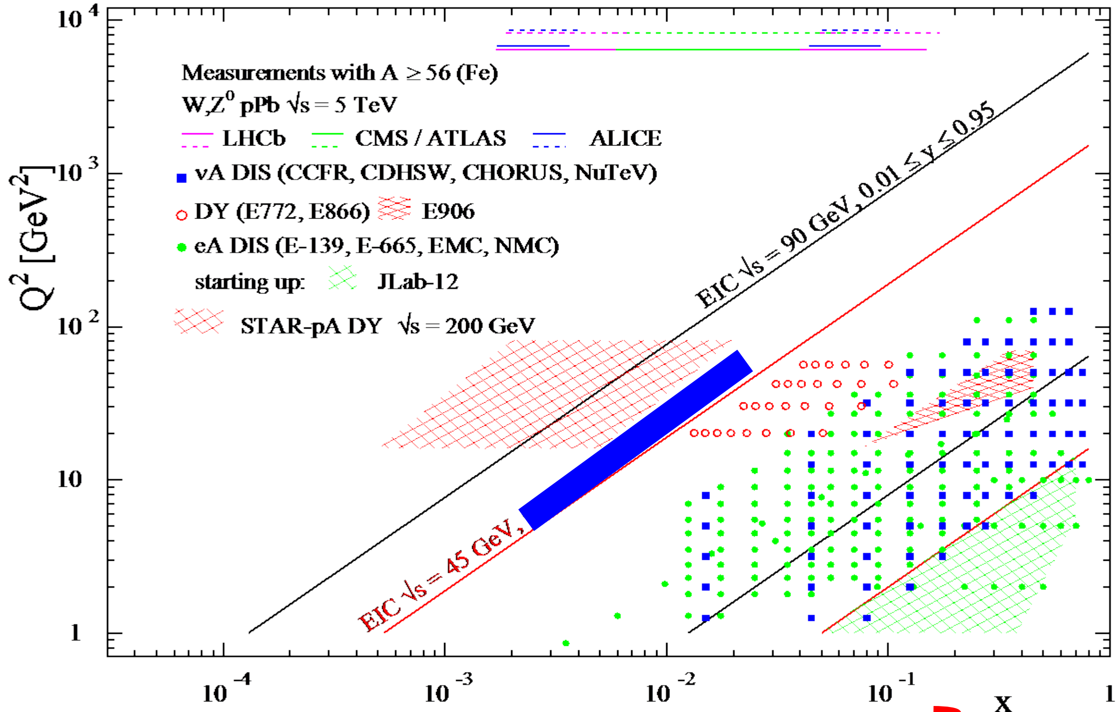




N. Armesto, *et al.*, arXiv:1512.01528

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

Key RHIC nPDF and saturation observables



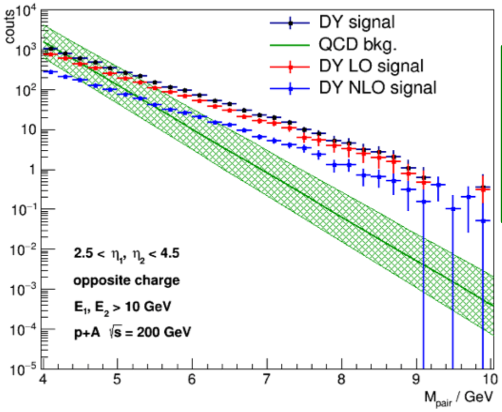
Direct photon
$2.8 < \eta < 3.8$

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

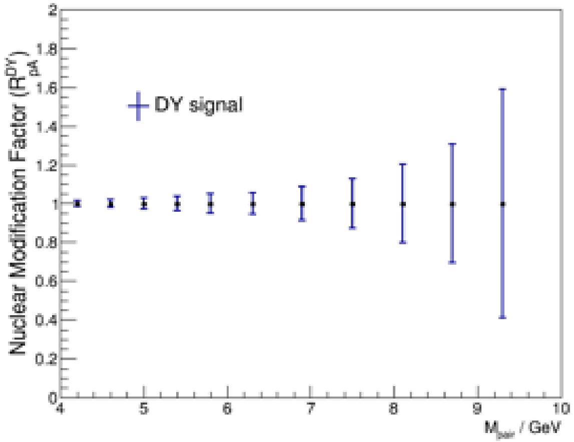
No final-state effects!

- 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)**

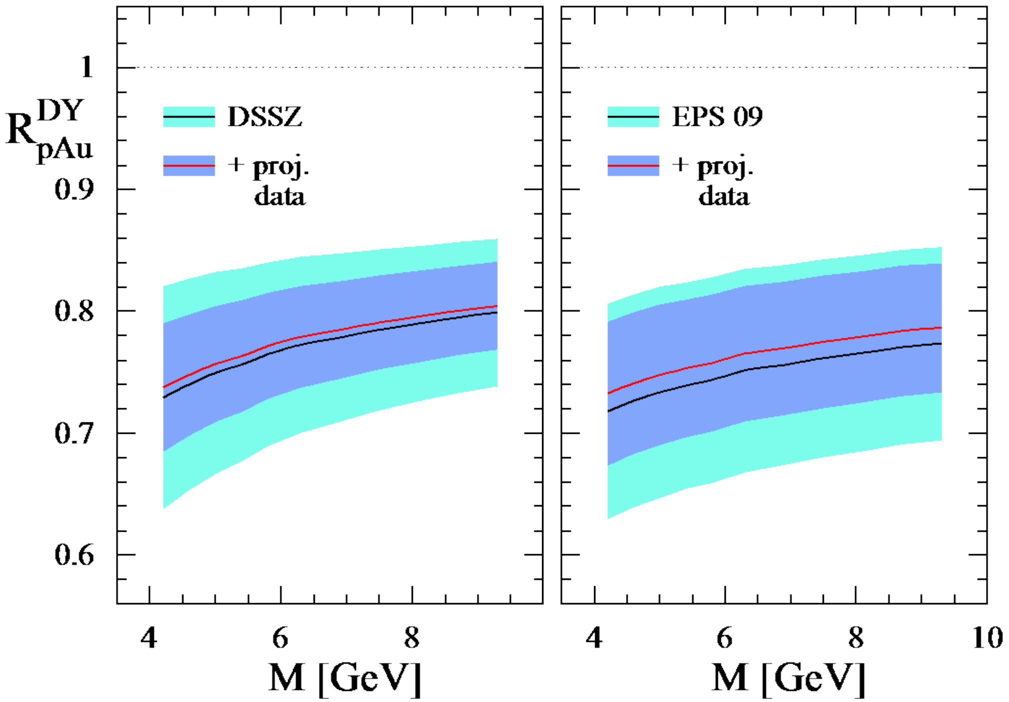
Drell-Yan R_{pA} at 200 GeV



Assumes forward upgrade



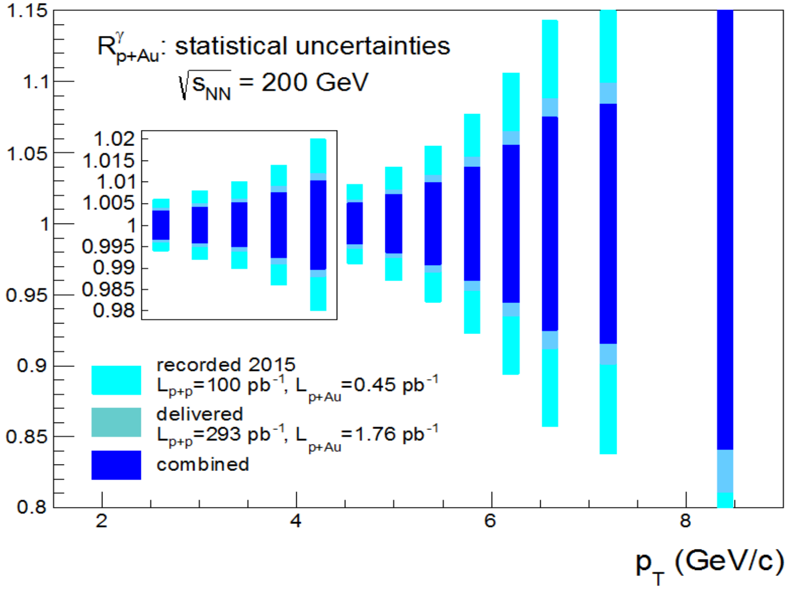
Projected impact on sea quark nPDFs



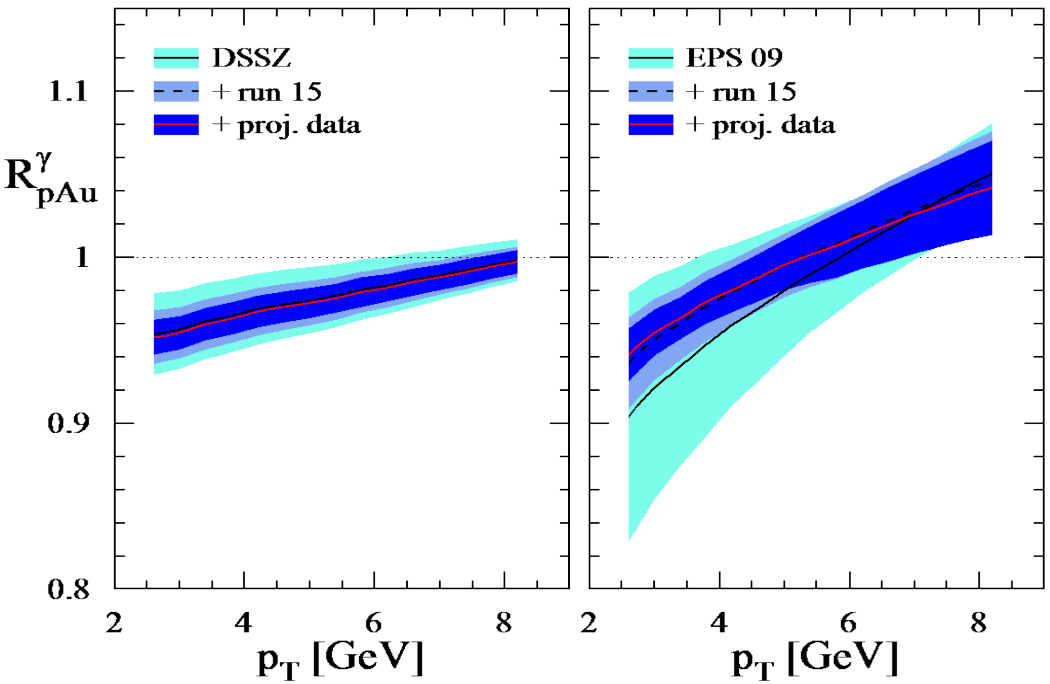
- Will obtain similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the low-x Q^2 lever arm relative to future EIC data

Direct photons

Data from p+Au run in 2015 and 2023



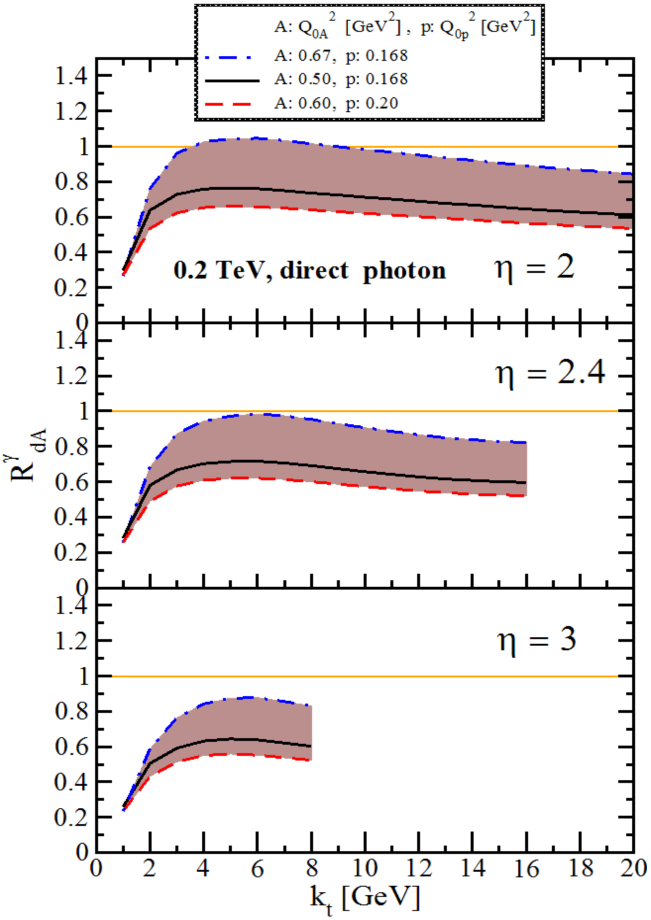
Projected impact on gluon nPDFs



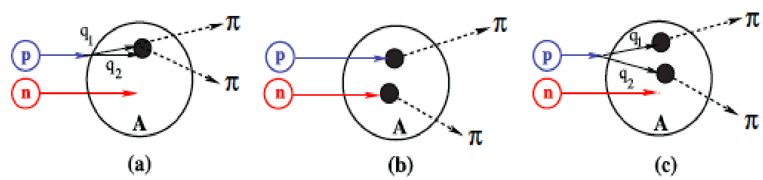
- Both direct photon and Drell Yan will provide:
  - Substantial improvements in our understanding of nuclear PDFs in the near term
  - Alternative observables and kinematics to EIC in the long term

Saturation probes

CGC prediction for direct photon R_{pA}

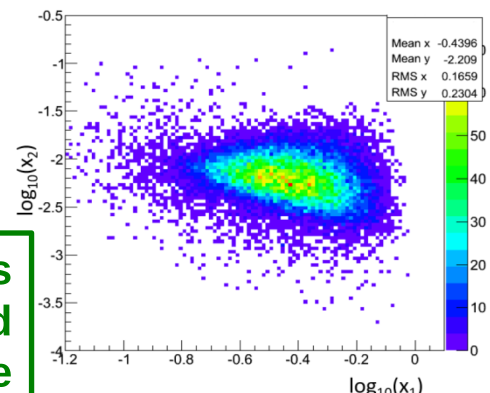


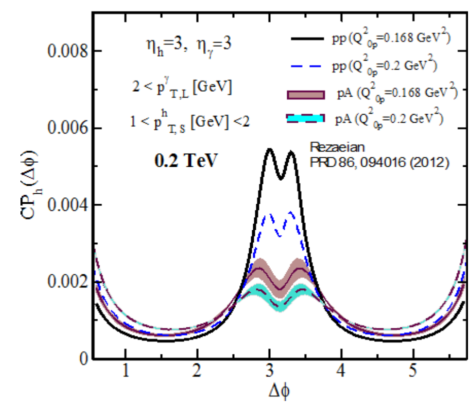
- Forward-forward correlation measurements
  - Di-hadron correlations in p+A
    - First data from 2015 p+Au
    - Reduced pedestal compared to d+Au
    - Eliminate double-interaction mechanism



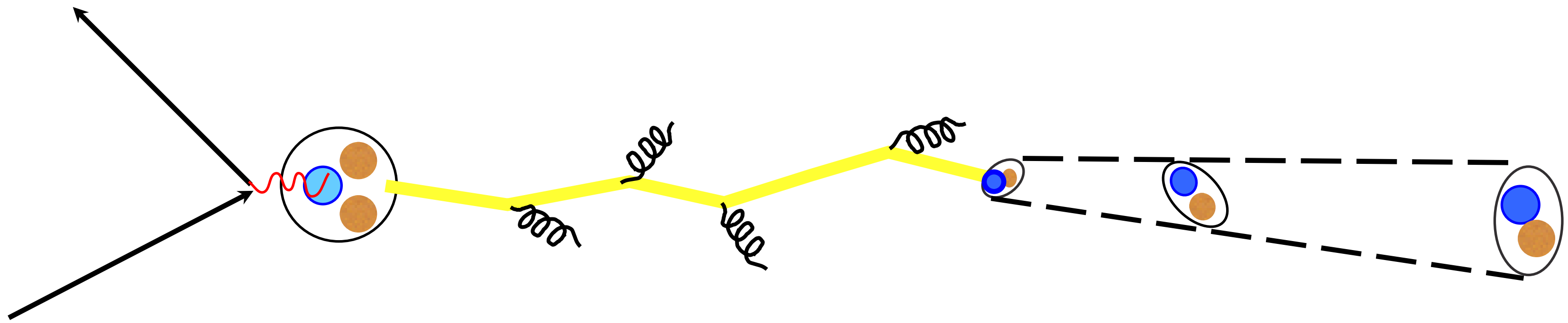
  - Photon-jet and jet-hadron correlations
    - 1M forward-forward gamma+jet events in 2023 p+Au and p+Al

Assumes forward upgrade



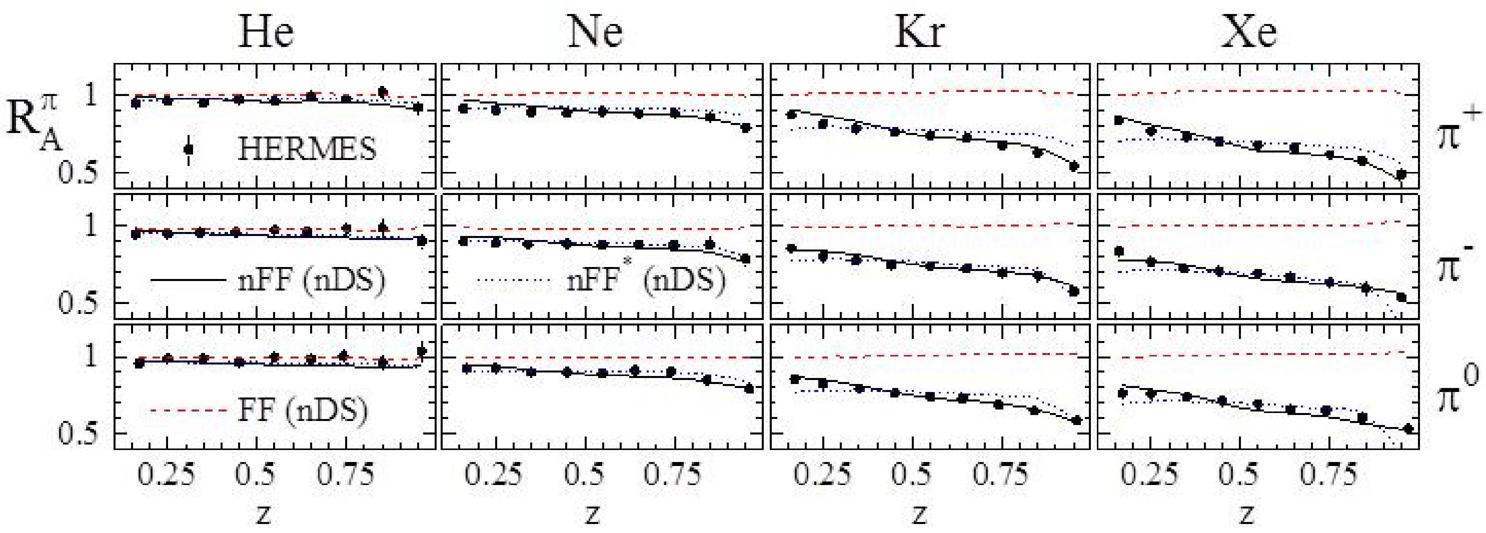


What about final state effects?



- 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

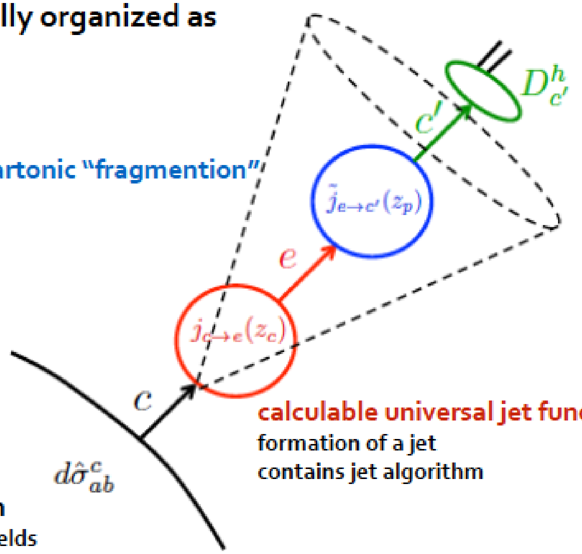


- Examining the fragmentation distribution isolates final-state hadronization contributions from initial-state nPDF modifications
- Large nuclear effects have been seen in *e*A scattering
- Can be described in terms of an effective nuclear fragmentation function
  - Don't know the underlying QCD process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

Measuring fragmentation functions at RHIC

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

pQCD calculation can be schematically organized as

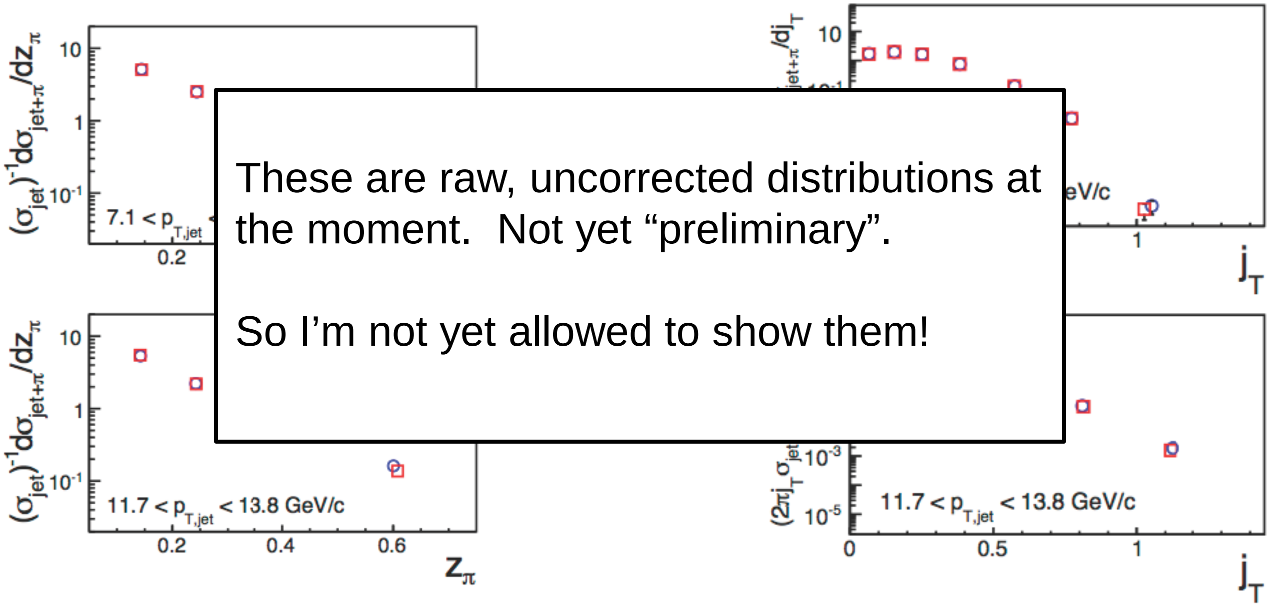


considerable theoretical activity recently:

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



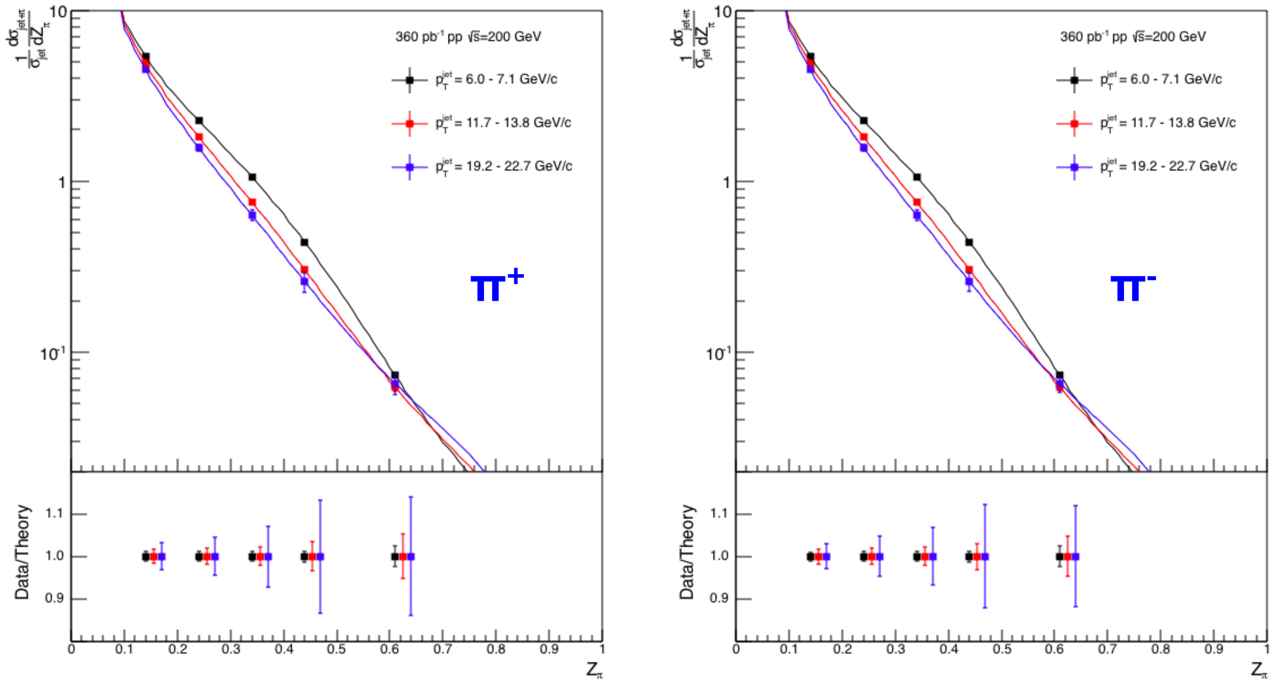
These are raw, uncorrected distributions at the moment. Not yet "preliminary".

So I'm not yet allowed to show them!

- 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

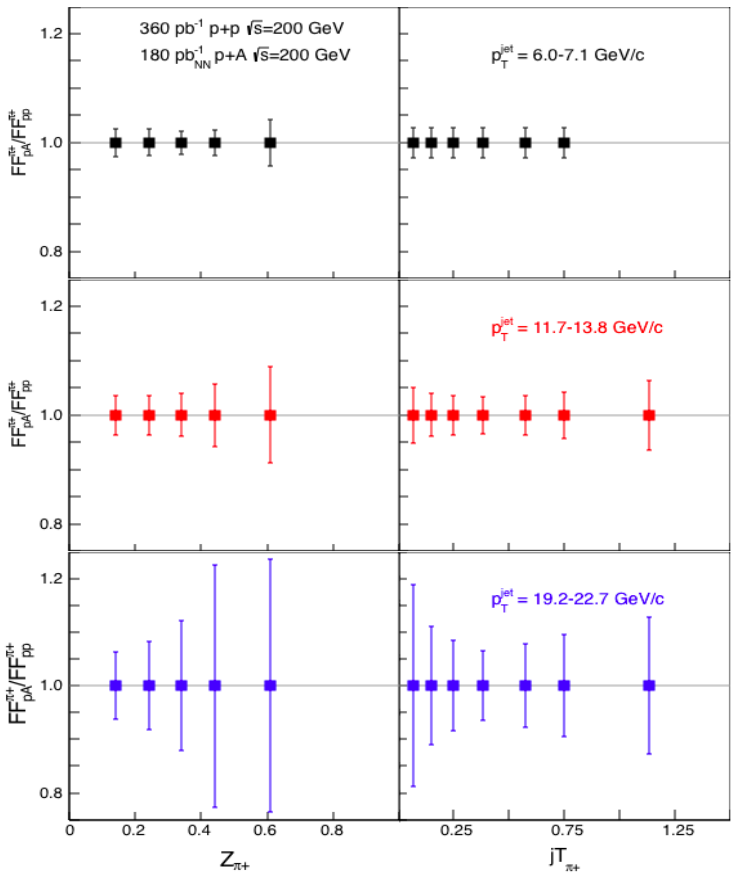
- Probes similar kinematics as EIC cold-nuclear matter energy loss, but with a gluon-rich probe

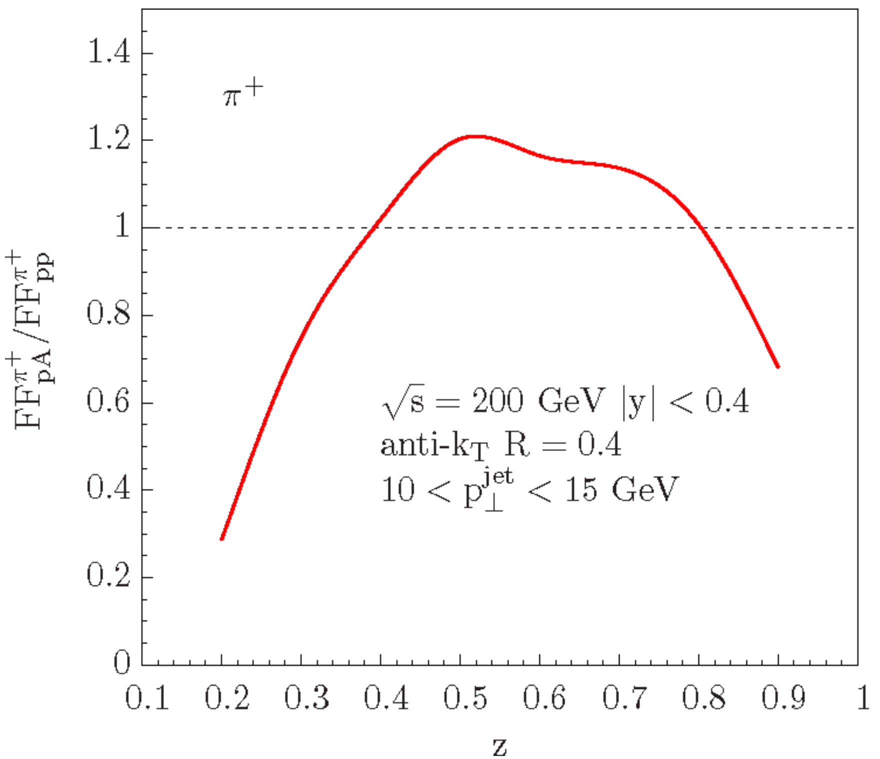
How well can we do in pp?



- 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

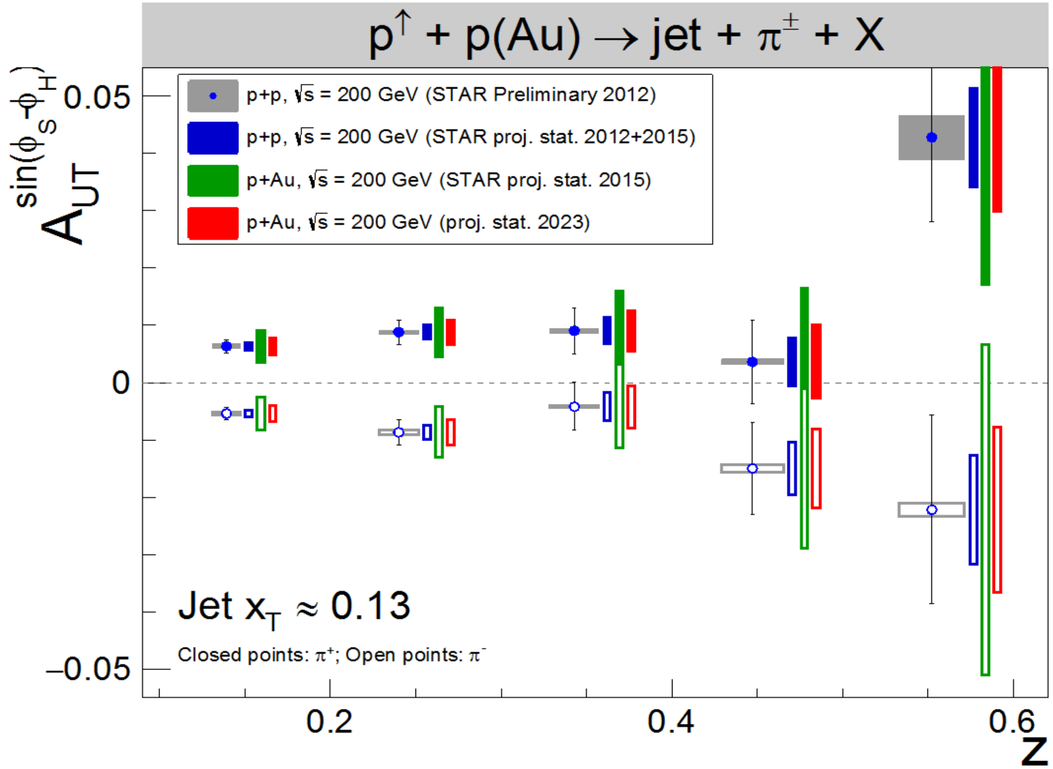
How well can we do in p+A?





- 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

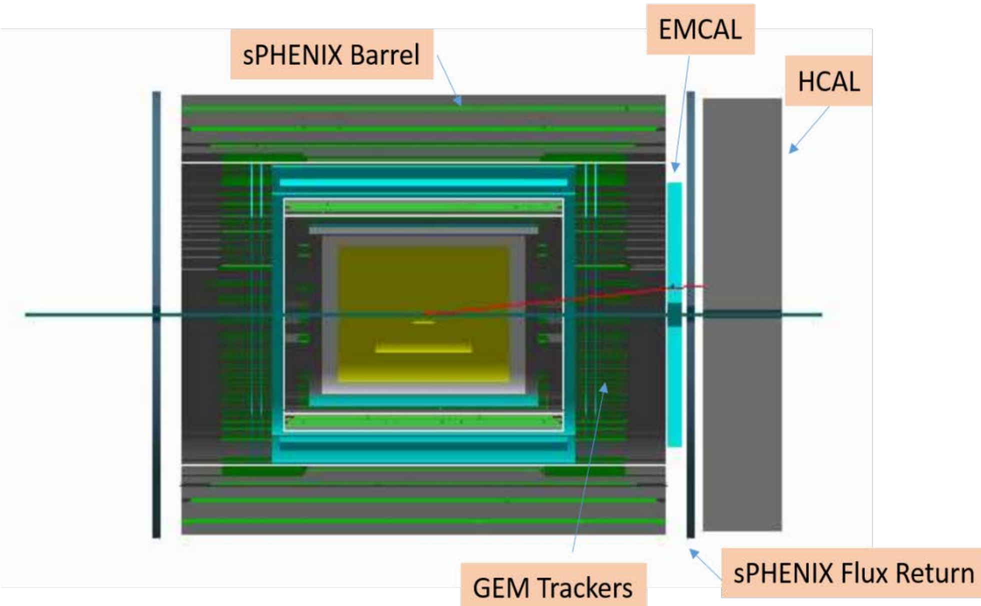
Can even measure polarized nuclear FF



- 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

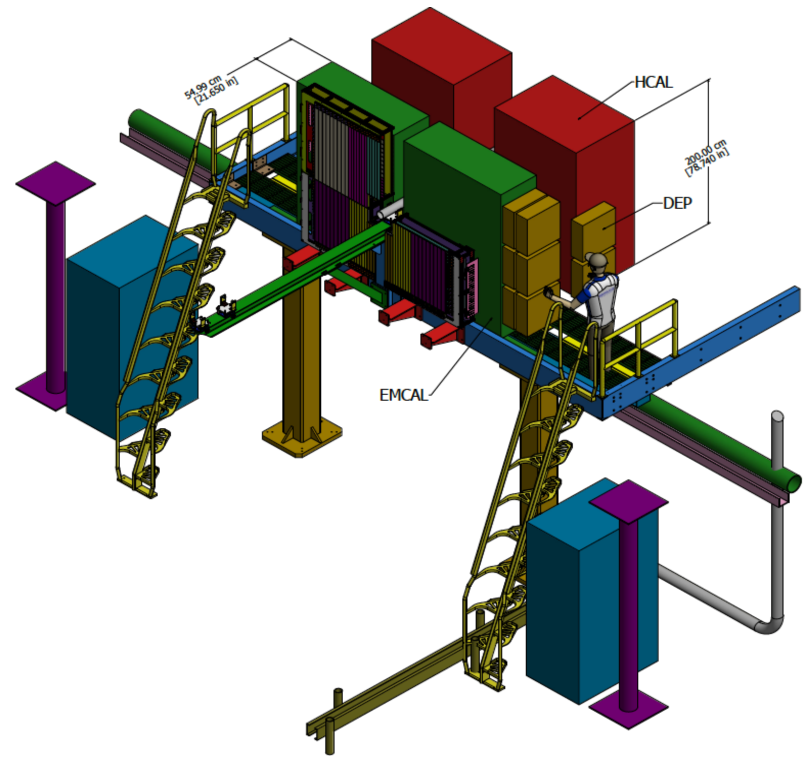
Forward upgrade options

fsPHENIX



Est. cost: $12M + labor

STAR



Est. cost: $6M

- Both sPHENIX and STAR would need additional forward tracking + calorimetry for some of the proposed measurements

Conclusion

	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 Eg	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.