Overview of the STAR forward spin physics

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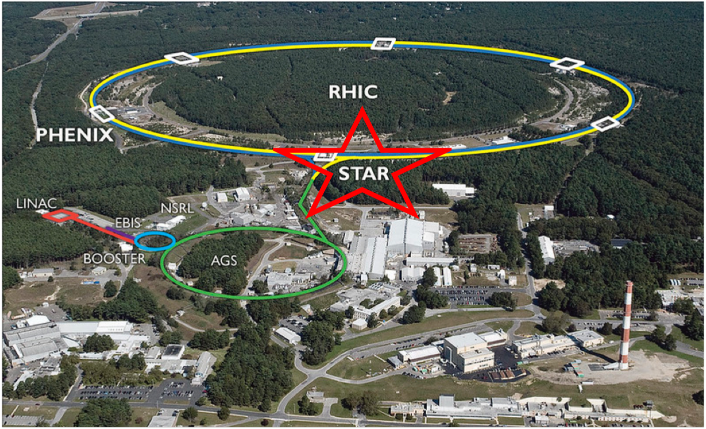
Supported in part by

RHIC: Relativistic Heavy Ion Collider

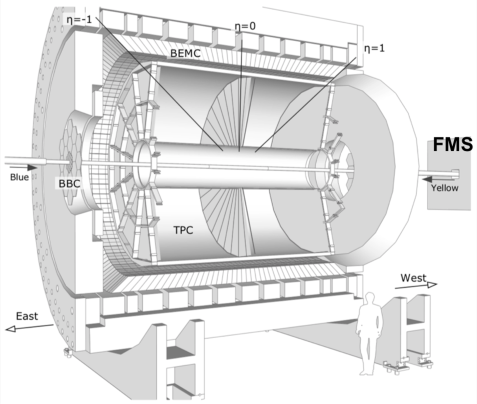
- Located at Brookhaven National Laboratory (BNL) in US
- World's only polarized proton-proton collider with transverse and longitudinal polarization



STAR Forward Detectors

Major STAR forward detectors used in the current STAR analyses:

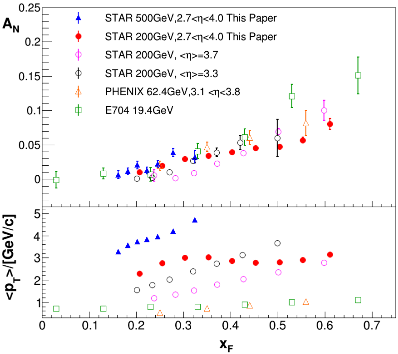
- Forward Meson Spectrometer (FMS): $2.6 < \eta < 4.2$, $\phi \in (0, 2\pi)$; Detect γ, π^0, η
- Roman Pot detector (RP): Located about 15 m away from Interaction Point on both sides; Detect slightly scattered protons



RP (not shown)

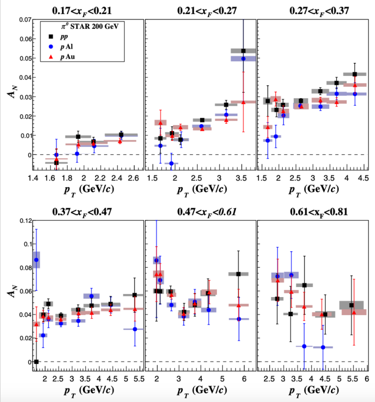
Transverse Single Spin Asymmetry (A_N) for Inclusive π^0

(STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)



- π^0 A_N depends on x_F for 200 GeV and 500 GeV results, consistent with previous STAR results
- π^0 A_N shows independence on $\sqrt{s}$

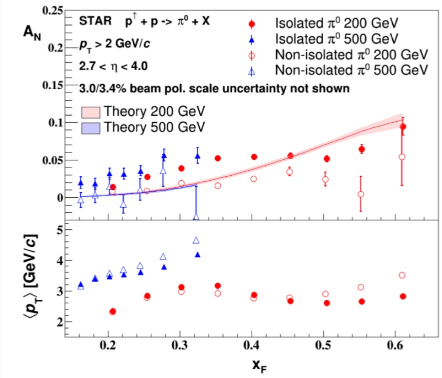
(STAR) J. Adam *et al.*, Phys. Rev. D 103, 072005 (2021)



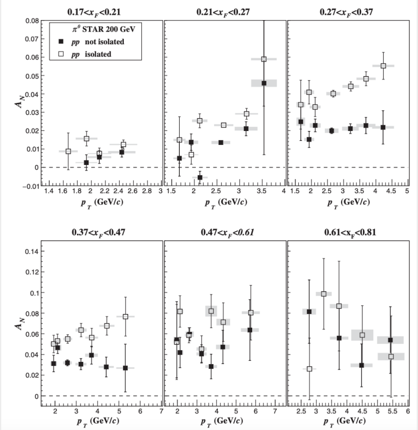
- π^0 A_N for $p+p$, $p+Al$, and $p+Au$ increases with increasing p_T at $0.17 < x_F < 0.47$, but flattens or falls with p_T for larger x_F

Isolated and Non-isolated π^0 A_N

(STAR) J. Adam *et al.*,Phys. Rev. D 103, 092009 (2021)



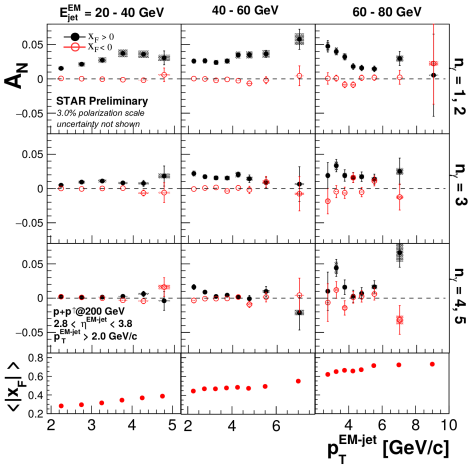
(STAR) J. Adam *et al.*,Phys. Rev. D 103, 072005 (2021)

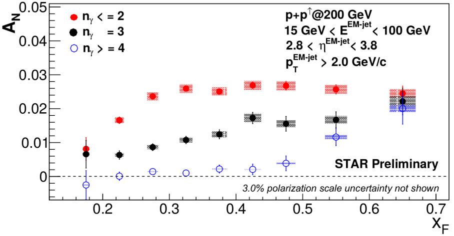


- A_N for isolated π^0 is significantly larger than that for non-isolated π^0 regardless of x_F and p_T
  - Isolated π^0: No other nearby photons
- Indication for large A_N from diffraction?

Multi-dimensional Studies for Inclusive EM-jet A_N at 200 GeV

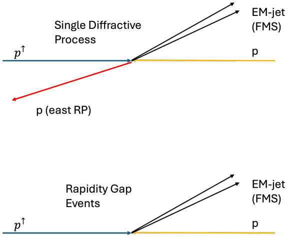
The Electromagnetic jets (EM-jets) are the jets reconstructed using only photons

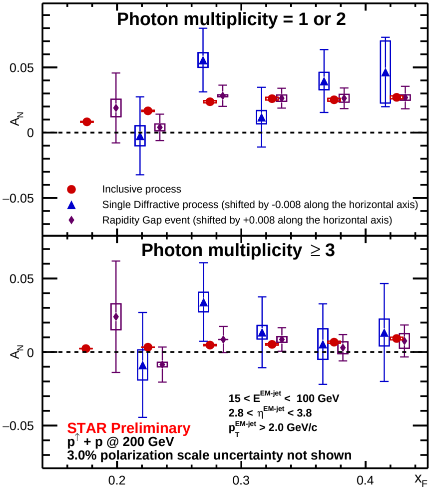




- The EM-jet A_N decreases with increasing photon multiplicity for $x_F > 0$
  - A_N is larger for the EM-jets consisting of 1 or 2 photons
- A_N increases with x_F for all the cases of photon multiplicity

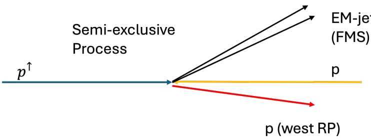
Single Diffractive EM-jet A_N at 200 GeV

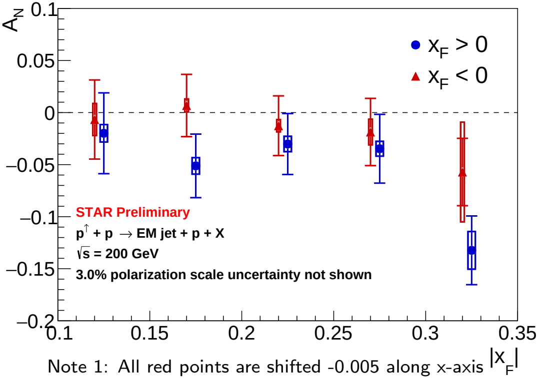




- The EM-jet A_N for $x_F > 0$ ($> 2\ \sigma$ significance of non-zero) is observed for 1 or 2 photon multiplicity EM-jets in the single diffractive process
- A_N for the three processes consistent with each other within uncertainty
- The single diffractive processes fail to provide evidence for its significant contribution to large A_N in the inclusive processes

Semi-exclusive Process EM-jet A_N at 200 GeV



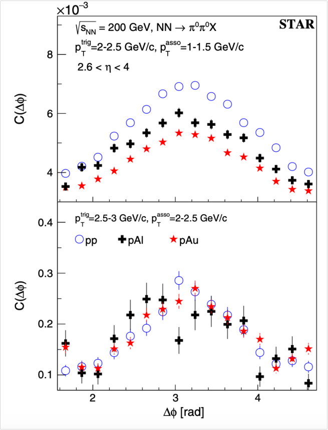


Note 1: All red points are shifted -0.005 along x-axis
Note 2: The rightmost point is for $0.3 < |x_F| < 0.45$

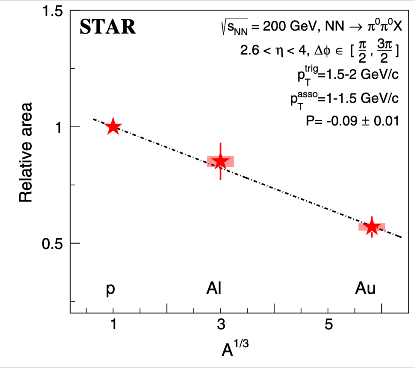
- Semi-exclusive process: Polarized proton intact; constrain the energy of EM-jet at FMS and west side proton to less than beam energy
- A non-zero A_N for $x_F > 0$ is observed with 3.3 σ significance for semi-exclusive process
- Sign of A_N is negative. Theoretical inputs are needed to understand the different sign

Nonlinear Gluon Effects in QCD

(STAR) M.S. Abdallah *et al.*, Phys. Rev. Lett. 129, 092501



- First measurement of the A dependence of nonlinear gluon effects



- At low p_T regime, a clear suppression is observed in p + A compared to the p + p data
- Such suppression scaling with $A^{1/3}$ matches gluon saturation models

Current and Future: STAR Forward Upgrade

Coverage: $2.5 < \eta < 4.0$

Status:

- Installation and commission completed in 2021
- Start taking data since 2022

Requirement:

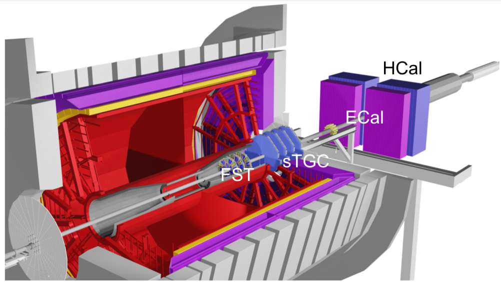
Detector	pp and pA	AA
ECal	$\sim$10 % / $\sqrt{E}$	$\sim$20 % / $\sqrt{E}$
HCal	$\sim$50 % / $\sqrt{E}$ + 10%	-
Tracking	Charge separation photon suppression	$\delta p_T/p_T$ $\sim$20 - 30% for $0.2 < p_T < 2$ GeV/c

Combines:

1. Forward Tracking System (FTS)
   - Forward Silicon Tracker (FST)
   - small-strip Thin Gap Chambers (sTGC)
2. Forward Colorimeter System (FCS)
   - Electromagnetic Calorimeter (ECal)
   - Hadronic Calorimeter (HCal)

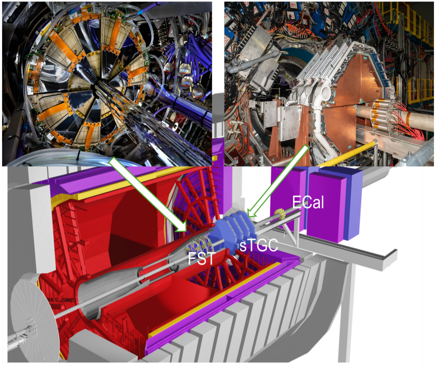
Measures:

- $h^{+/-}$, $e^{+/-}$ (with good e/h separation)
- Photon, π^0, jets



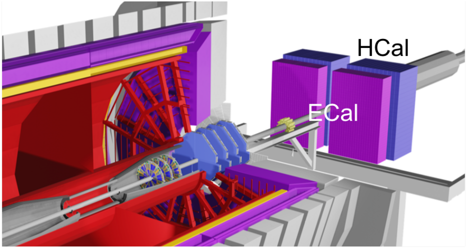
STAR Forward Upgrade: Forward Tracking System (FTS)

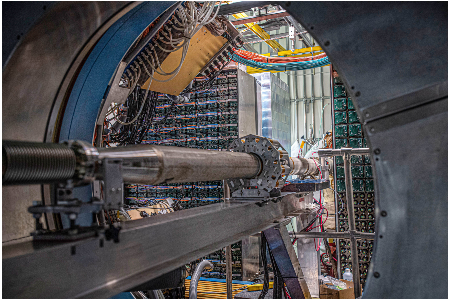
- Forward Tracking System (FTS):
  1. Forward Silicon Tracker (FST)
  2. small-strip Thin Gap Chambers (sTGC)



- Forward Silicon Tracker (FST):
  - 3 disks, each with 12 modules
  - Each module includes 3 single-sided double-metal mini-strip sensors (Si from Hamamatsu)
    - Fine granularity in ϕ and coarse in R
  - Material budget $\sim 1.5\%\ X_0$ per disk
- small-strip Thin Gap Chambers (sTGC):
  - 4 planes, each with 5 pentagonal modules
    - Double-sided sTGC with diagonal strips give x, y, u in each layer
    - Position resolution $< 200\ \mu$m
  - Material budget $\sim 0.5\%\ X_0$ per layer
  - Readout based on VMM chips

Forward Calorimeter System (FCS)





ECal:

- Reuse PHENIX Pb-Scintillator calorimeter
  - 1496 channels: $5.52 \times 5.52 \times 33\ cm^3$
  - 18 X_0; 0.85 nuclear interaction lengths
- SiPM readout

HCal:

- Fe/Sc (20 mm/3 mm) sandwich
  - 520 channels: $10 \times 10 \times 84\ cm^3$
  - $\sim$ 4.5 nuclear interaction lengths
- Same SiPM readout as ECal

Data Taking and Physics Opportunities with STAR Forward Upgrade

Data taking with STAR Forward Upgrade:

- 2022: $p + p\ \sqrt{s} = 508$ GeV
- 2023: $Au + Au\ \sqrt{s} = 200$ GeV
- 2024: $p + p\ \sqrt{s} = 200$ GeV & $Au + Au\ \sqrt{s} = 200$ GeV
- 2025: $Au + Au\ \sqrt{s} = 200$ GeV & possible $p + Au\ \sqrt{s} = 200$ GeV

Cold QCD:

- Sivers asymmetries for hadrons, (tagged) jets, and di-jets
- Collins measurements at high x
- GPD E_g: gluon spin-orbit correlations
- Gluon PDFs for nuclei: R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-jets

Hot QCD:

- Temperature dependence of viscosity through flow harmonics up to $\eta \sim 4$
- Longitudinal decorrelation up to $\eta \sim 4$
- Global Lambda Polarization: test predictions of strong rapidity dependence

Cold QCD Physics Opportunities with STAR Forward Upgrade

Cold QCD Physics with p + p:

- ★ Sivers asymmetries for charged hadrons, (tagged) jets, di-jets, and diffractive process
  - Allows spin-dependent TMDs for quarks up to x $\sim$ 0.5 and gluons down to x $\sim$ 0.001
  - Allows to understand better underlying mechanism for the large forward A_N
- ★ Collins measurements at high x
  - Allow full jet Collins measurements in forward rapidity
  - Similar x range as existing SIDIS measurements, with Q^2 values are one to two orders higher
  - Similar kinematic coverage with future EIC, enable sensitive universality test with EIC data

Cold QCD Physics with p + A:

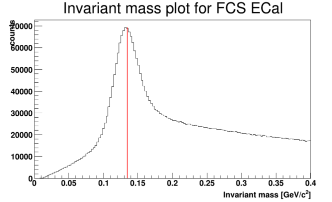
- ★ GPD E_g: gluon spin-orbit correlations
  - Enable measurement at smaller $W_{\gamma p}$, where both the cross section and the signal are expected to be much larger
- ★ Gluon PDFs for nuclei: R_{pA} for direct photons & DY
  - Allow to constrain the nuclear gluon / sea quark distribution at low x
- ★ Test of Saturation predictions through di-hadrons, γ-jets
  - The di-$h^{+/-}$ measurement can extend both lower and higher (x, Q^2) to map out the Q^2 boundary

Status of the STAR Forward Upgrade

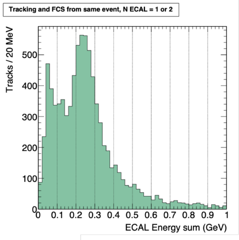
Data production, calibration, and analysis are in progress:

- Data (pre-)productions for p + p $\sqrt{s} = 510$ GeV (2022) are ready for Forward Upgrade software developments, calibrations, and analyses
- π^0 reconstruction for FCS ECal calibration is developed
- MIP study is ongoing
- Jet reconstruction & energy calibration are in progress
- J/ψ analysis is in progress
- Track matching studies between Forward Tracking and Calorimeter, as well as within calorimeters, are in progress

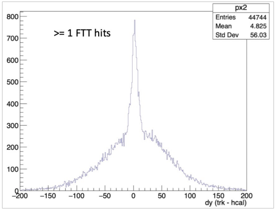
π^0 reconstruction for FCS ECal



ECal MIP at around 0.3 GeV



Y(track project to HCal) - Y(HCal cluster)



Conclusion and Outlook

Fruitful results in forward region at STAR:

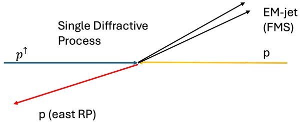
- Large A_N observed in forward π^0 and EM-jets
- First diffractive A_N is studied, but diffractive A_N can not have significant contribution to large A_N
- STAR di-π^0 correlation study shows strong suppression at low p_T in $p + A$, following expected $A^{1/3}$ dependence

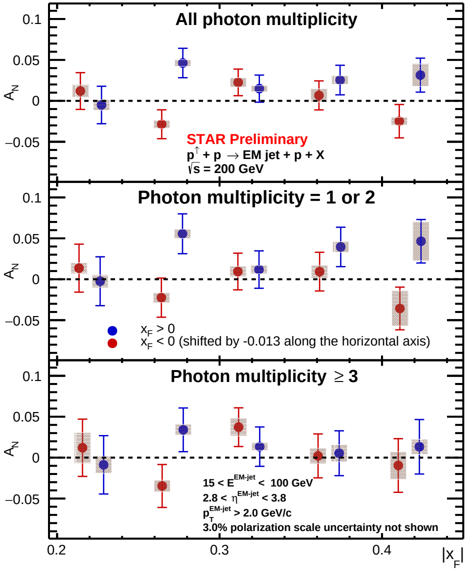
STAR Forward Upgrade will enable a wide range of high-impact measurements, shining light to the future EIC:

- The STAR Forward Upgrade was installed in 2021 and collected data successfully in 2022 and 2023
- The STAR Forward Upgrade will continue to collect data in 2024 and 2025

Back up

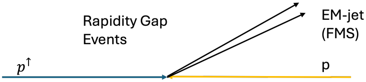
Single Diffractive EM-jet A_N at 200 GeV



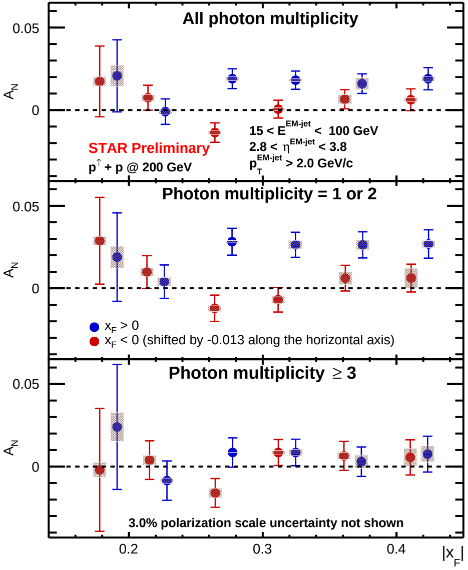


- Single diffractive process: Unpolarized proton intact, with the rapidity gap on the east side ($-5 < \eta < -2.1$)
- The EM-jet A_N for $x_F > 0$ (> 2 σ significance of non-zero) is observed for the case of all photon multiplicity and 1 or 2 photon multiplicity
- The EM-jet with 1 or 2 photon multiplicity has larger A_N than with 3 or more photon multiplicity

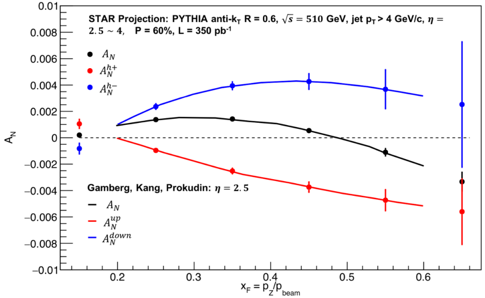
Rapidity Gap Event EM-jet A_N at 200 GeV



- Rapidity gap events: Rapidity gap on the east side $(-5 < \eta < -2.1)$
- About 70% of the rapidity gap events are single diffractive process events
- The size of EM-jet A_N for rapidity gap events is similar to that for inclusive process
- The A_N for the EM-jet with 1 or 2 photon multiplicity is the largest



TSSA (A_N) with STAR Forward Upgrade

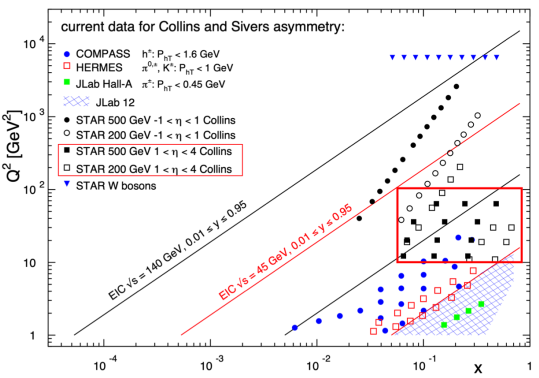


What can be measured with STAR Forward Upgrade for A_N?

- (isolated)π^0, EM-jets
- (isolated)$h^{+/-}$
- Full jets
- Diffractive process

- A_N for full jet reconstruction, combined with charge-sign tagging of a hadron fragment with $z > 0.5$
  - Projected statistical uncertainties drawn on twist-3 predictions
  - Up to 10 σ separation between plus-tagged and minus-tagged jet A_N
- With STAR Forward Upgrade, it can access to higher x_F with $p + p$ at $\sqrt{s} = 200$ GeV; and access to higher p_T with $p + p$ at $\sqrt{s} = 508$ GeV

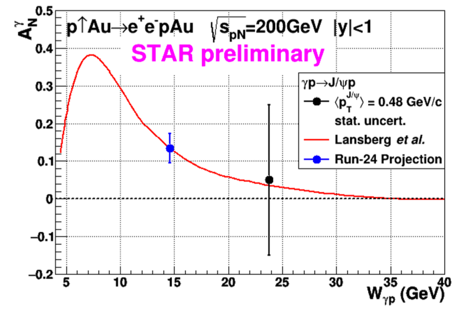
Collins Asymmetry with STAR Forward Upgrade

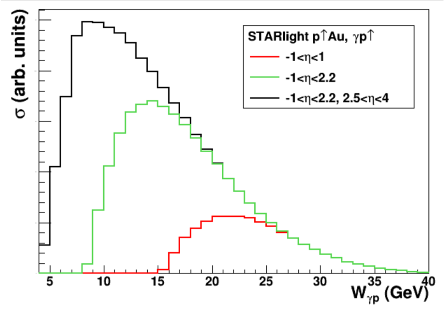


- STAR has performed Collins asymmetry measurement at mid-rapidity
- Similar x range as existing SIDIS measurements
- Q^2 values are one to two orders of magnitude higher than SIDIS at the same x

- STAR forward upgrade will provide unique kinematics coverage for Collins asymmetry measurement
- x up to $\sim 0.5 \rightarrow$ sensitive to valence quark
- Spans in Q^2 by a factor of 6

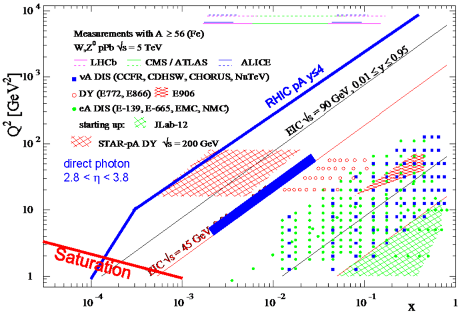
Generalized Parton Distribution E_g with STAR Forward Upgrade





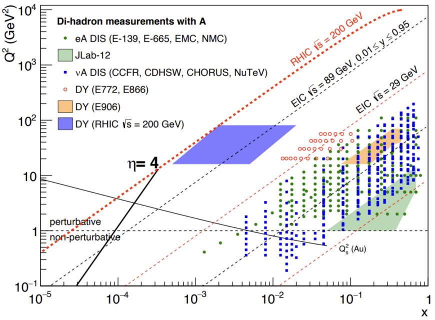
- Exclusive J/Ψ A_N measurement in ultra-peripheral p + Au collision
  - $Q^2 \sim 10 GeV^2$ and $10^{-4} < x < 10^{-1}$
  - Non-zero A_N would be the first signature of a non-zero GPD E_g for gluons
  - GPD E_g is sensitive to spin-orbit correlations
- STAR Forward Upgrade will enable measurement at smaller $W_{\gamma p}$. Both the cross section and the signal are expected to be much larger

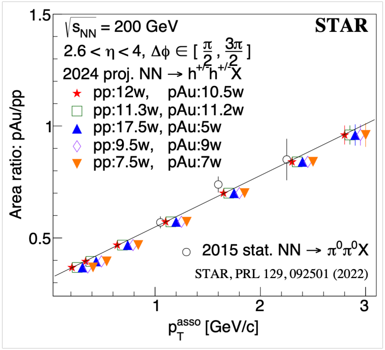
Nuclear Parton Distribution Functions with STAR Forward Upgrade



- The STAR Forward Upgrade will enable measurements of R_{pAu} for direct photon and Drell-Yan production at $\sqrt{s_{NN}} = 200$ GeV
  - Moderate Q^2 and medium-to-low x regime
  - Direct photons will constrain the nuclear gluon distribution
  - Drell-Yan di-electrons will constrain the nuclear sea quark distribution

Non-linear QCD with STAR Forward Upgrade





- Previous STAR measurements used di-π^0 ; STAR Forward Upgrade will enable studies with di-$h^{+/-}$ with $p + Au$ collisions (possibly in Run-25)
- The di-$h^{+/-}$ measurement can extend both lower and higher (x, Q^2) to map out the Q^2 boundary
- STAR hadro-production measurements are essential to explore the universality of non-linear effects along with the future EIC