The *STAR* Forward Upgrade

Carl Gagliardi

Texas A&M University

for the *STAR* Collaboration

Outline

- What is it?
- What is the current status?
- What science will it do?

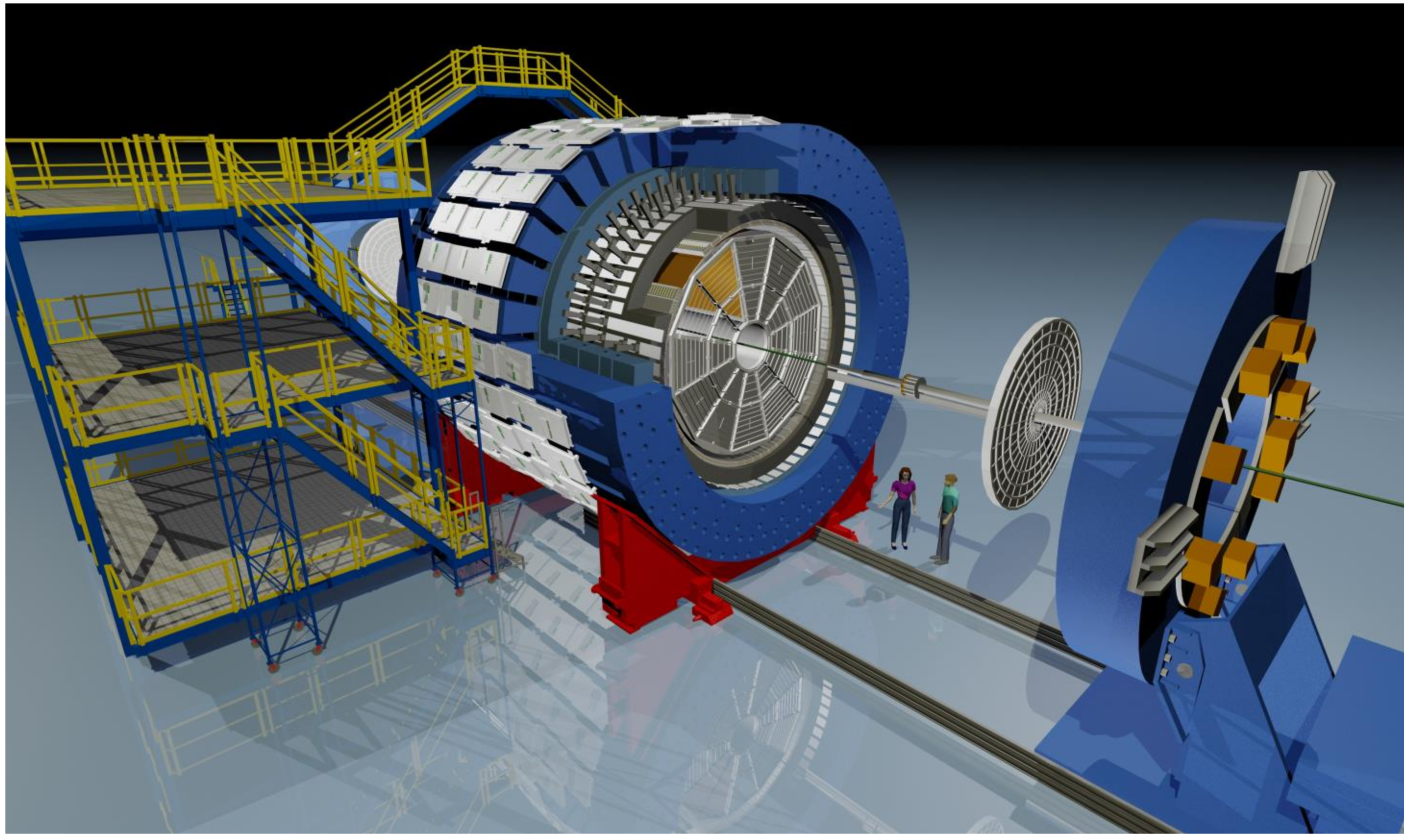
Supported in part by:

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

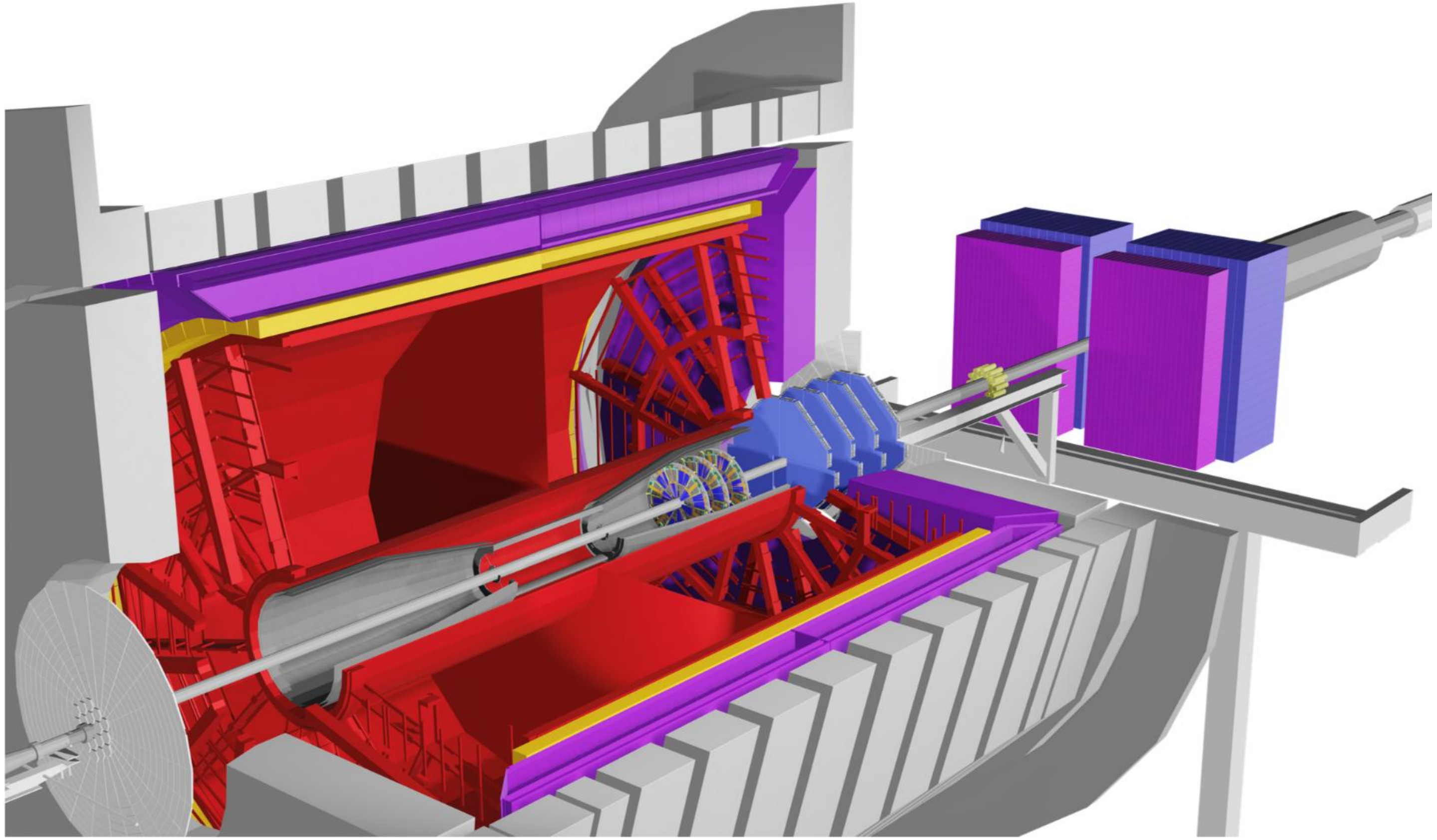
What is the *STAR* Forward Upgrade?

The *STAR* detector



- TPC provides tracking for $|\eta| < 1.5$
- Particle identification with dE/dx combined with Time-of-Flight
- Surrounded by electromagnetic calorimetry covering $-1 < \eta < 4$
- Complemented by many ancillary subsystems

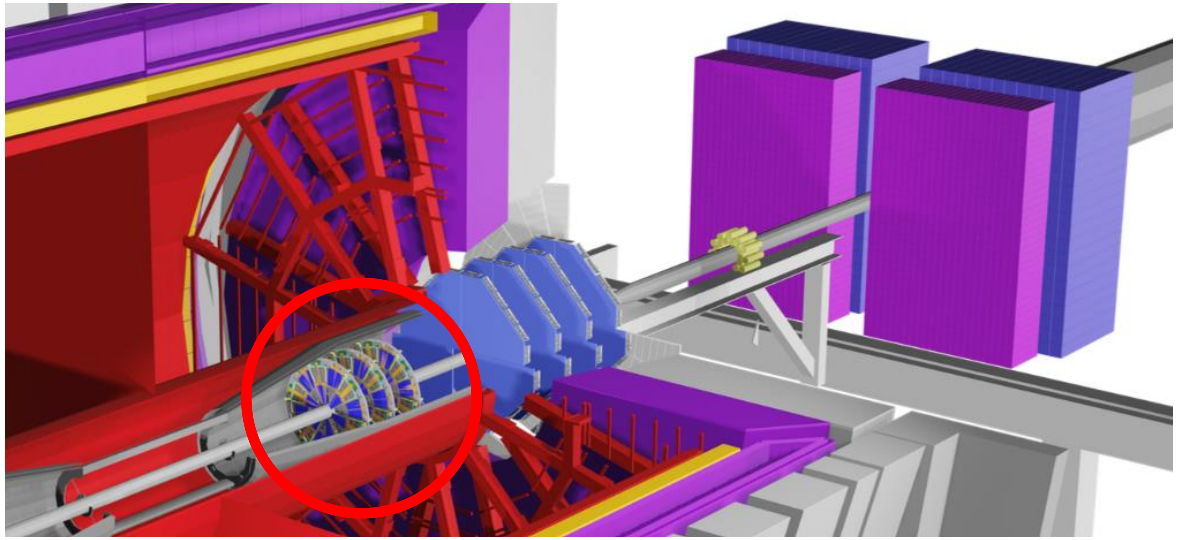
The *STAR* Forward Upgrade



- Covers the pseudorapidity region $2.5 < \eta < 4$ where ***STAR*** formerly only had Pb-glass electromagnetic calorimetry
  - Rapidity coverage is the same as the EIC hadron arm
- Combines:
  - Charged particle tracking using Si detectors and small-strip Thin Gap Chambers (sTGC)
  - Electromagnetic and hadronic calorimetry with SiPM readout and new ADC+trigger electronics
- Will measure $h^{+/-}$, $e^{+/-}$ (with good e/h discrimination), photons, π^0, jets

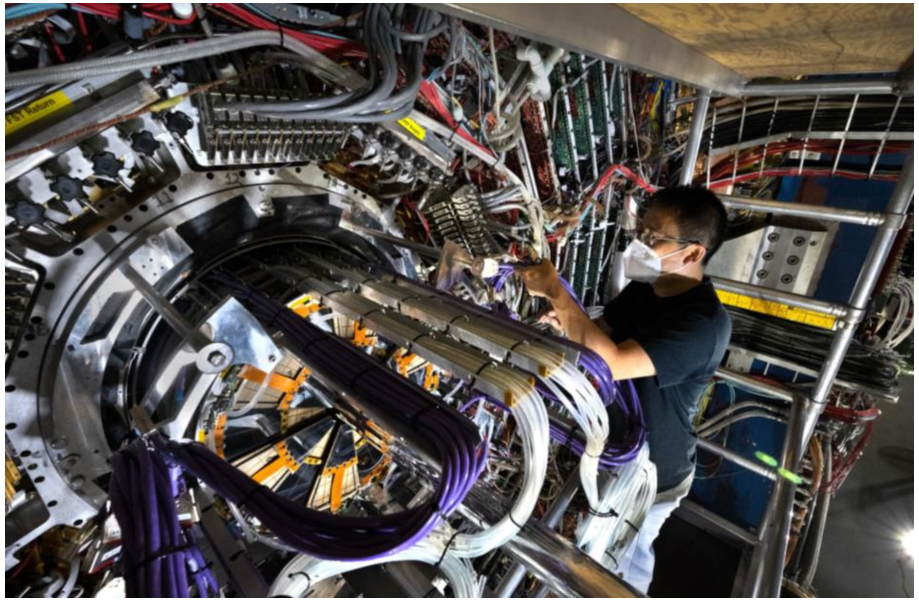
Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

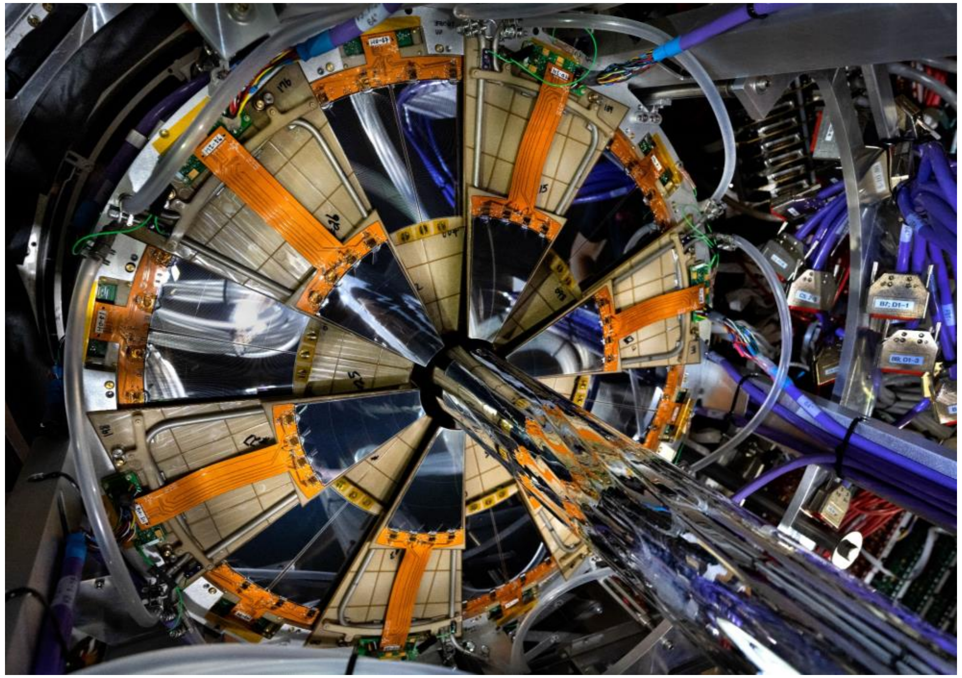
Silicon detector

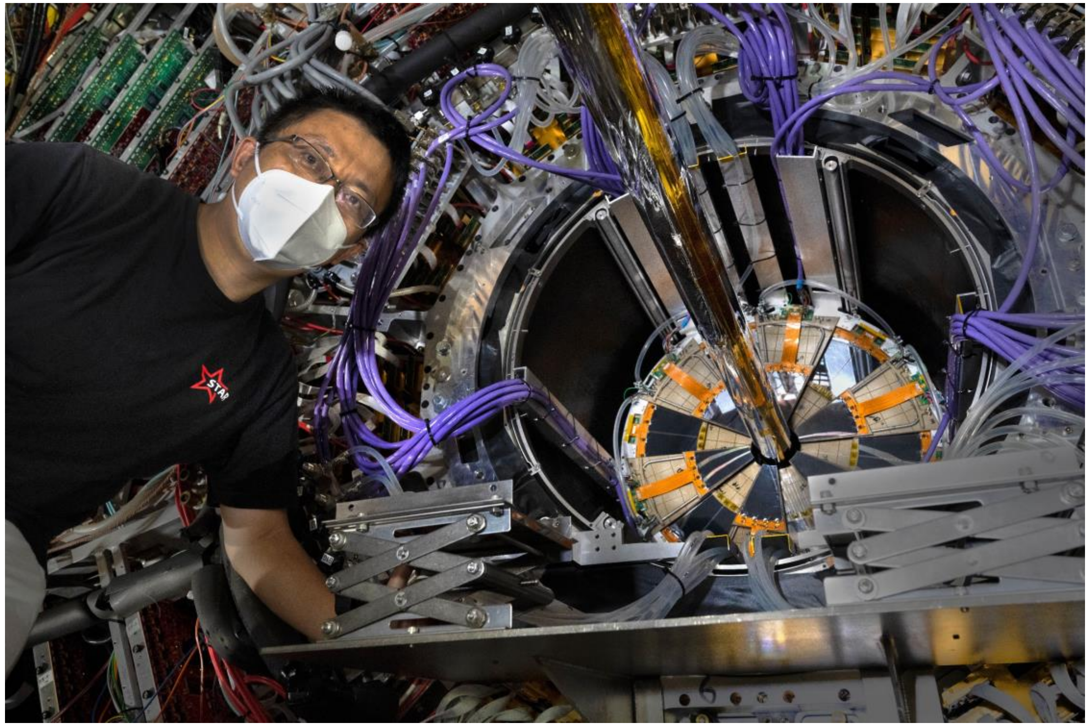


- Three disks, each with 12 modules
- Each module includes 3 single-sided double-metal mini-strip sensors (Si from Hamamatsu)
  - Fine granularity in φ and coarse in R
- Material budget ~1.5% X_0 per disk
- Technology is similar to STAR Intermediate Silicon Tracker
  - Same APV25-S1 front-end chip
  - Reusing the IST data acquisition and cooling systems
- Installed in ***STAR*** last month; under commissioning at present

Silicon detector







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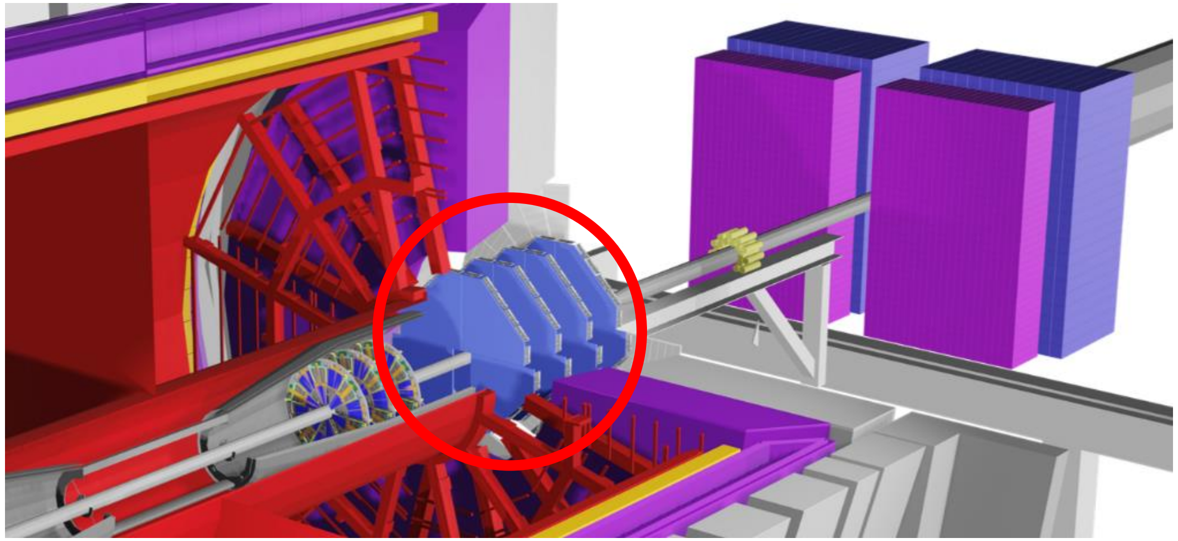
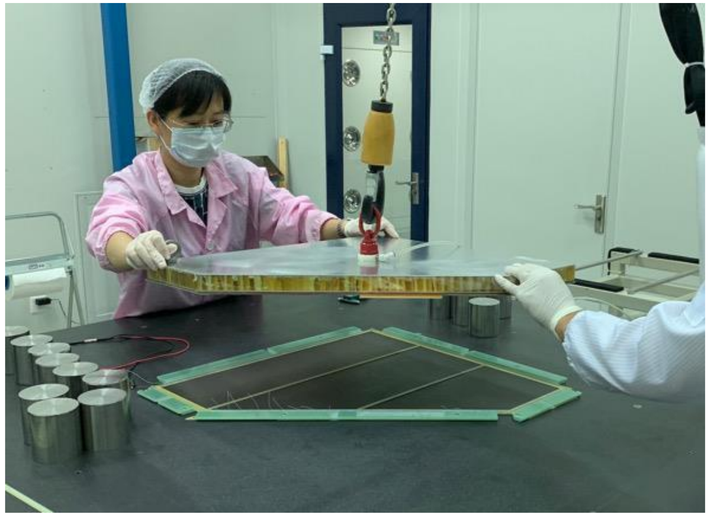
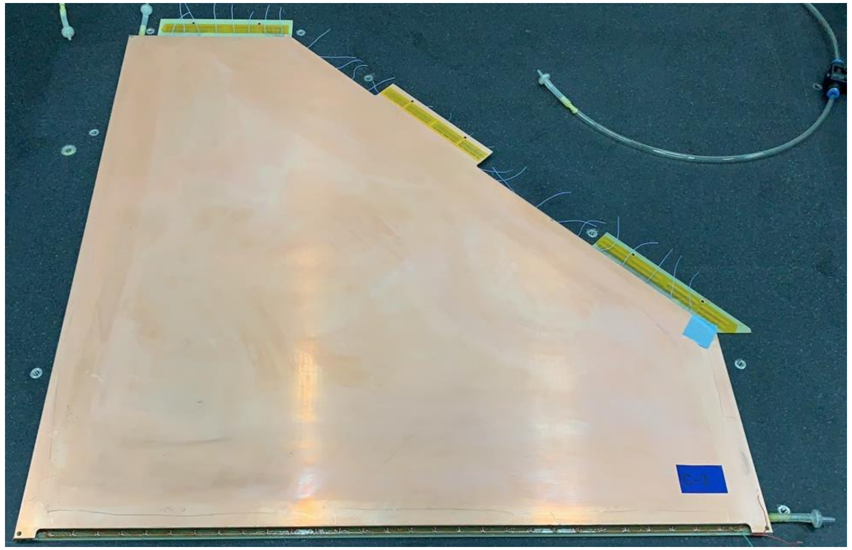
Small-strip Thin Gap Chambers

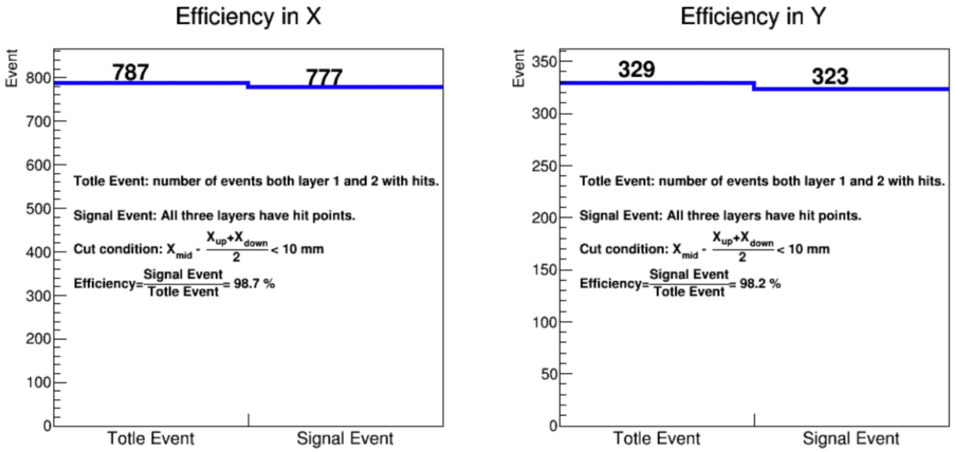


- Four planes, each consisting of four pentagonal modules
  - Double-sided sTGC with diagonal strips give *x*, *y*, *u* in each layer
  - Position resolution < 200 μm
- Material budget ~0.5% X_0 per layer
- Readout based on VMM chips
- Similar to the ATLAS sTGC system
- Final assembly onto its mounting frame underway
  - Will be mounted in position late this month

Small-strip Thin Gap Chambers







Efficiency > 97%

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Electronics under test

sTGC gas system

Gas cabinet

Front of the controls cabinet

Gas distribution panel

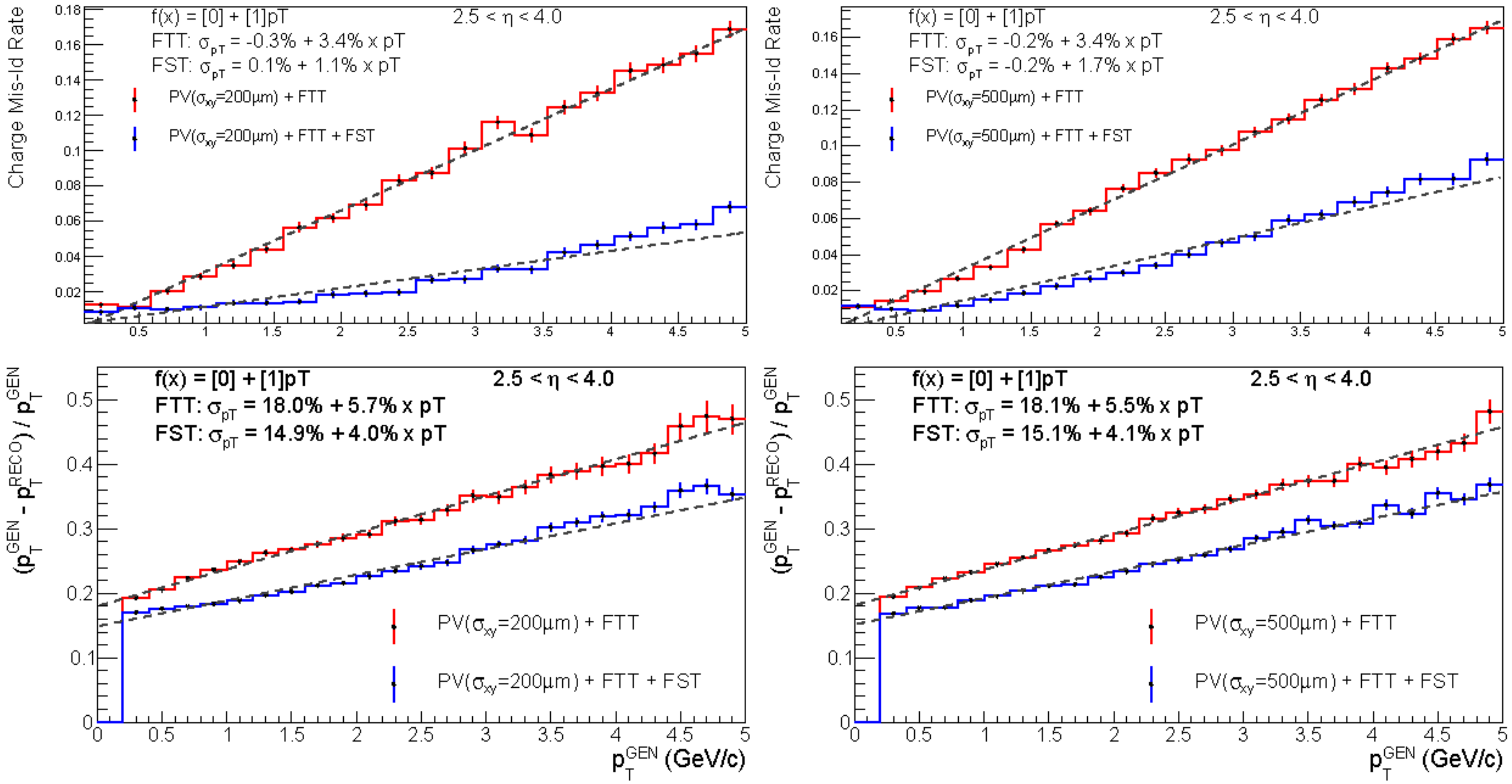
- sTGCs use a mixture of CO_2 and n-pentane
- Gas system has passed BNL flammable gas safety reviews
- Was used this spring to provide gas to a 60 x 60 cm^2 sTGC prototype module that was operated in ***STAR***
- Ready for operation with the full sTGC system

Simulated performance of the Forward Tracker

√*s* = 500 GeV √*s* = 200 GeV

Charge mis-ID rate vs. p_T

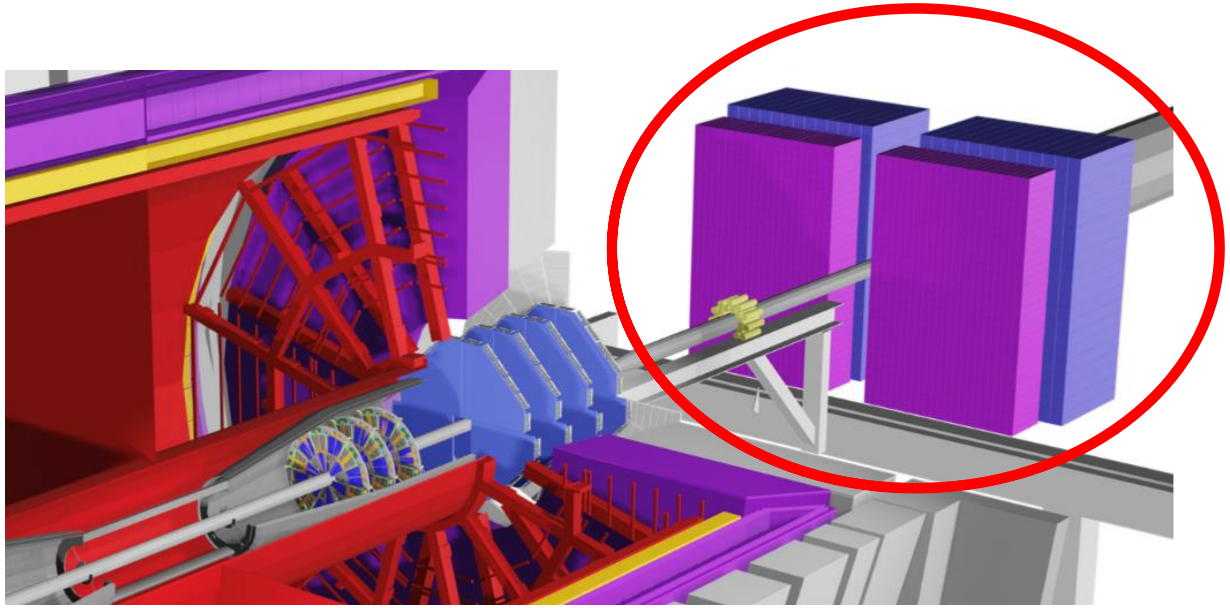
p_T resolution vs. p_T



Red: sTGCs only
Blue: sTGCs+Si disks

- Charge mis-ID rate less than 6% (8%) for p_T < 5 GeV/c and √*s* = 500 GeV (200 GeV)
- p_T resolution better than 35% for p_T < 5 GeV/c for both beam energies

Forward Calorimeter System (FCS)



- 7 m from the center of ***STAR***
  - Split into 2 movable halves
  - Slightly projective
- ECal:
  - Reuse PHENIX Pb-Scintillator calorimeter
    - 1496 channels: 5.52 x 5.52 x 33 cm^3
    - 66 sampling cells with 1.5 mm Pb / 4 mm Sc
    - 36 wavelength-shifting fibers per cell
    - 18 X_0; 0.85 nuclear interaction lengths
  - Replaced PMTs with SiPM readout
- HCal:
  - Fe/Sc (20 mm/3 mm) sandwich
    - 520 channels: 10 x 10 x 84 cm^3
    - Approximately 4.5 nuclear interaction lengths
  - Uses same SiPM readout as ECal
  - Developed in collaboration with EIC R&D
- Preshower:
  - Split signals off from ***STAR*** EPD for triggering

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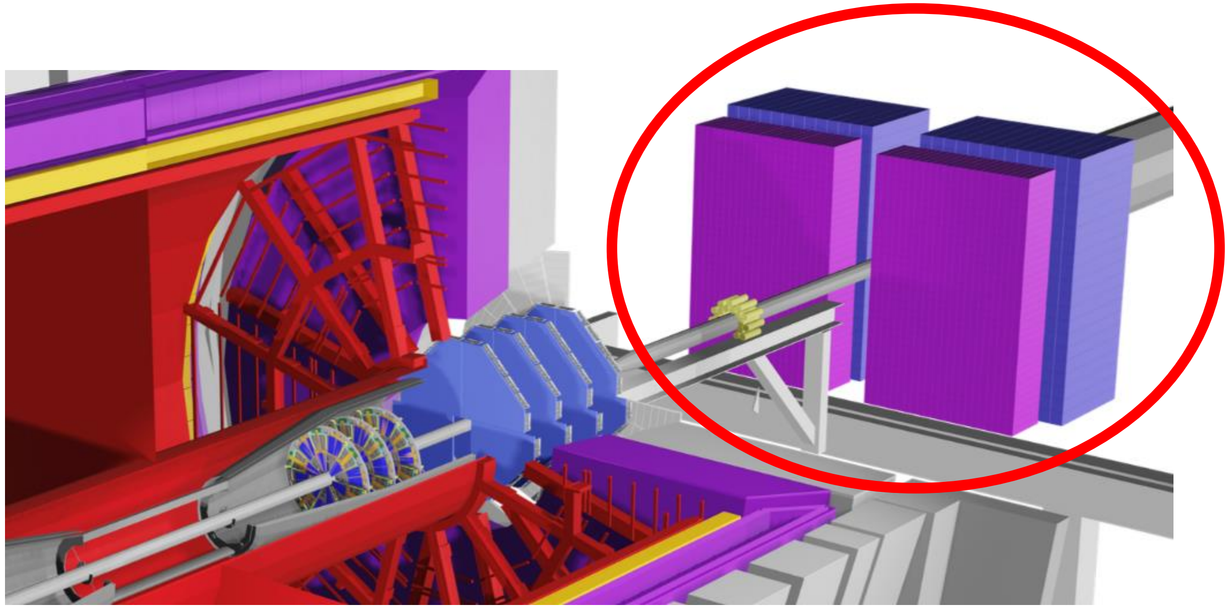

- **Entire FCS (ECal + HCal + electronics) was installed during 2020**
  - Commissioned during recent RHIC run
    - Extensive running with Au+Au at $\sqrt{s_{NN}}$ = 7.7 GeV
    - Brief runs with O+O and *d*+Au at $\sqrt{s_{NN}}$ = 200 GeV

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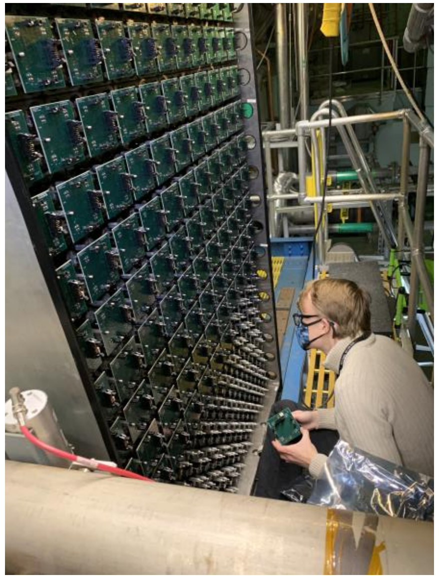
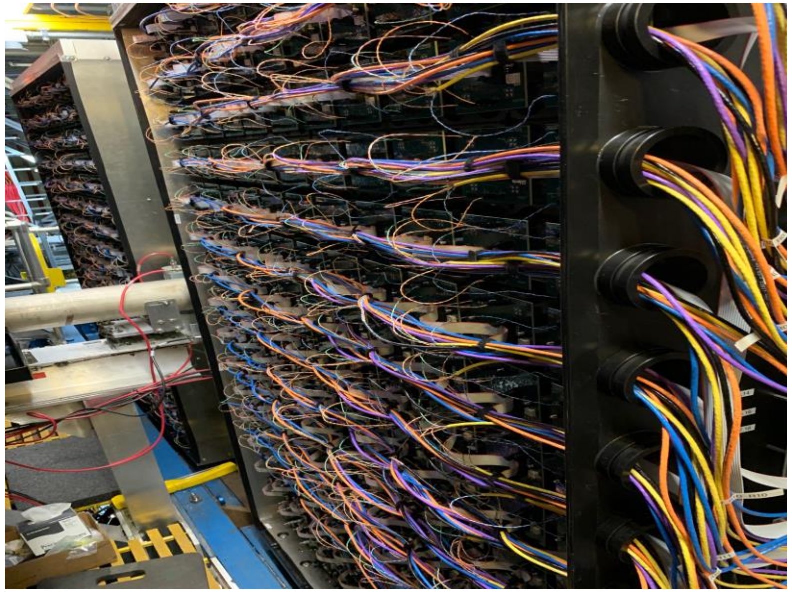
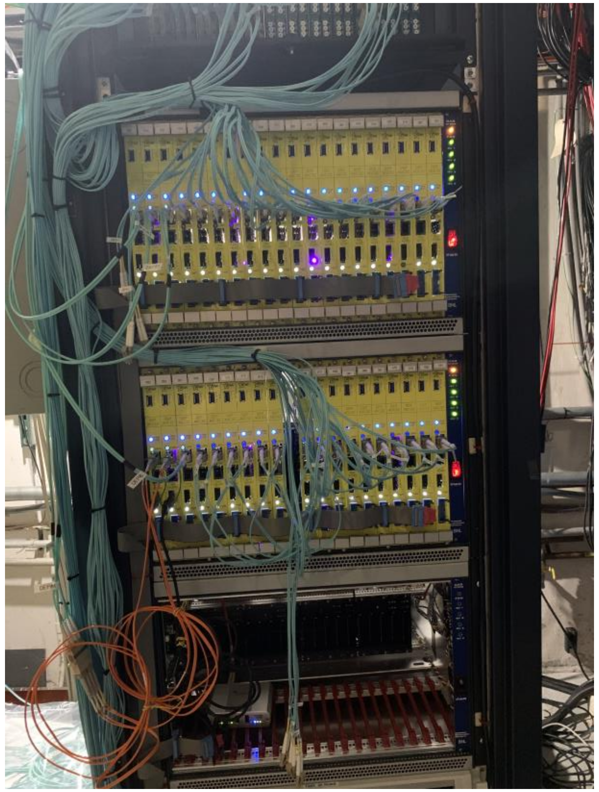
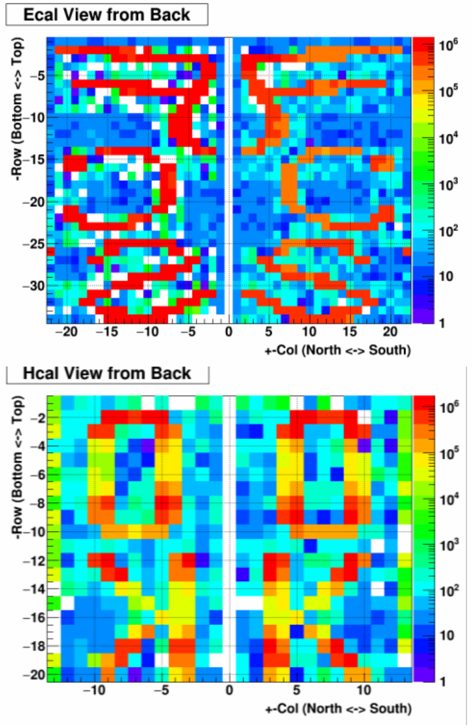




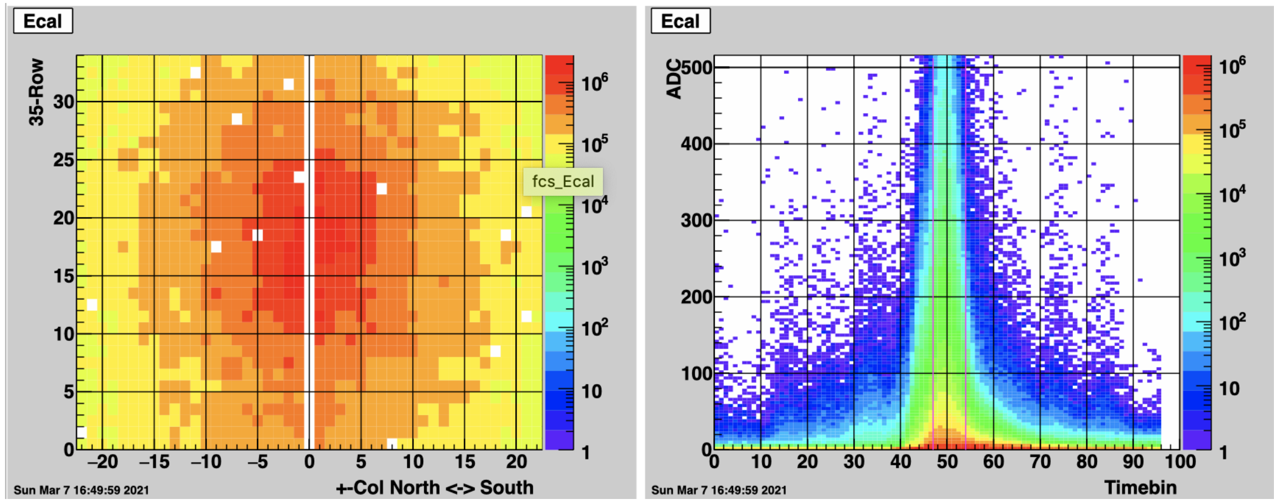
FCS readout and commissioning



LED mapping check

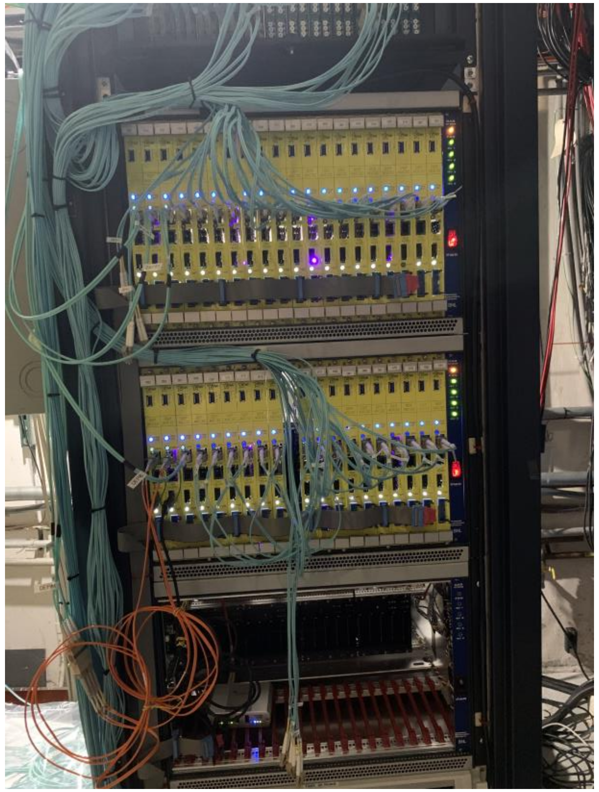


Online monitoring plots during 7.7 GeV Au+Au



- During the recent RHIC run, we:
  - Exercised the on-line machinery, monitoring systems, and slow controls
  - Off-line and Monte Carlo machinery also in place
  - Trigger system was commissioned
- Analysis of the O+O data is underway

FCS readout and commissioning



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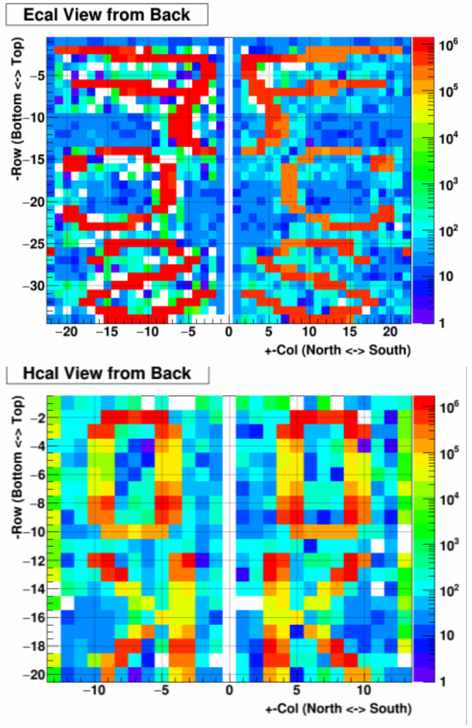

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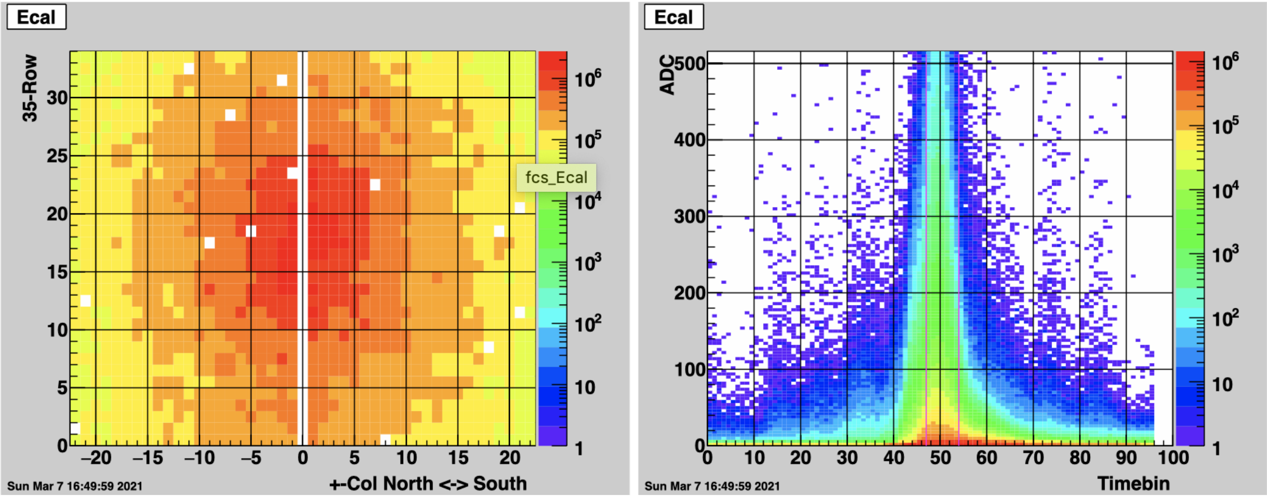

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- **FCS is ready for data taking**

What science will the *STAR* Forward Upgrade enable?

STAR Forward Upgrade physics program

Forward-rapidity: 2.5 < η < 4

A+A

Beam:
Full Energy AuAu

Physics Topics:
- **Temperature dependence of viscosity through flow harmonics up to η~4**
- **Longitudinal decorrelation up to η~4**
- **Global Lambda Polarization**
  → strong rapidity dependence

p+p & p+A

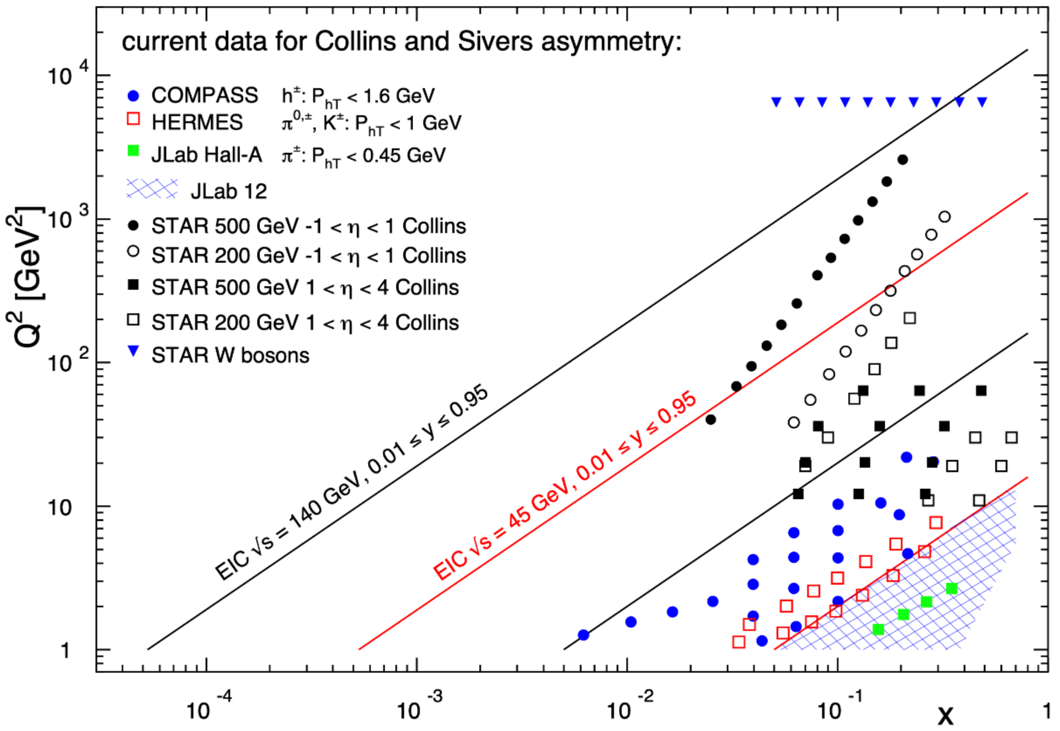
Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- **Sivers asymmetries for hadrons, (tagged) jets, and di-jets**
- **TMD measurements at high x**
  transversity → tensor charge
- **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**

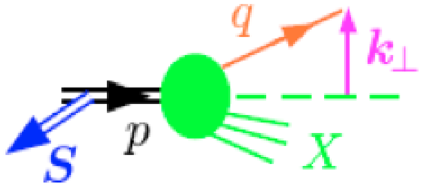
- Observables:
  - Charged and neutral hadrons
  - Inclusive jets and di-jets
  - Hadrons in jets
  - Photons
  - Drell-Yan and J/Ψ di-electrons
  - Lambda's
  - Mid-forward and forward-forward rapidity correlations

- Running periods:
  - ***STAR*** alone:
    - 500 GeV polarized *pp*: 20 week run starts November 15
  - ***STAR*** in parallel with sPHENIX:
    - 2023 and 2025: 200 GeV Au+Au
    - 2024: 200 GeV polarized *pp* and *p*+Au

Transverse momentum dependent PDFs and FFs



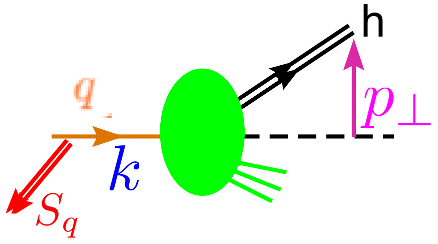
Sivers effect:



Unpolarized partons with a spin-dependent intrinsic k_T

Non-universal:
Sign change between initial- and final-state interactions

Collins effect:



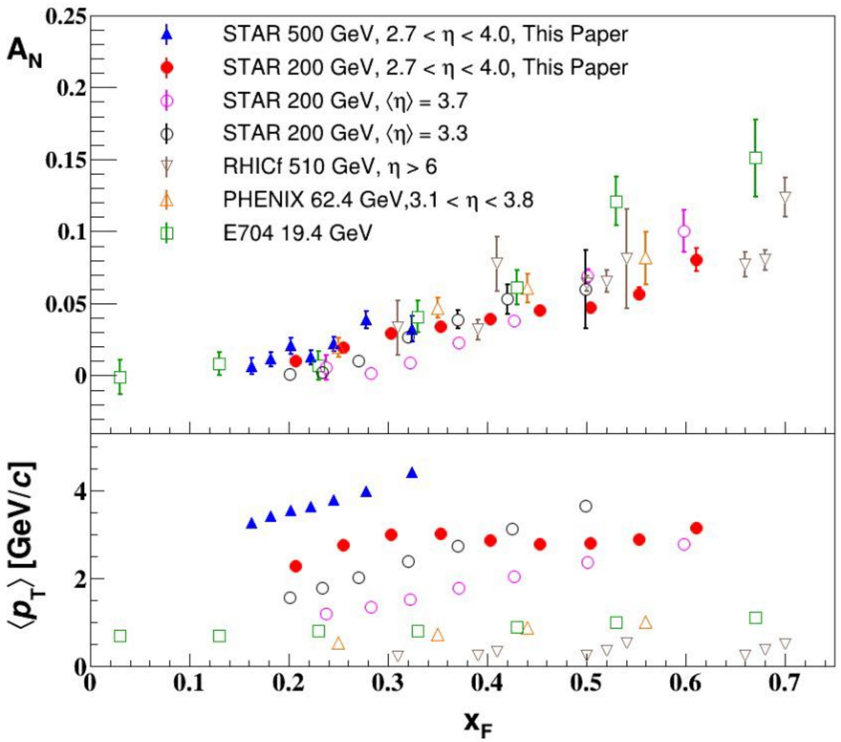
Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the quark momentum. Requires quark transversity.

Believed to be universal

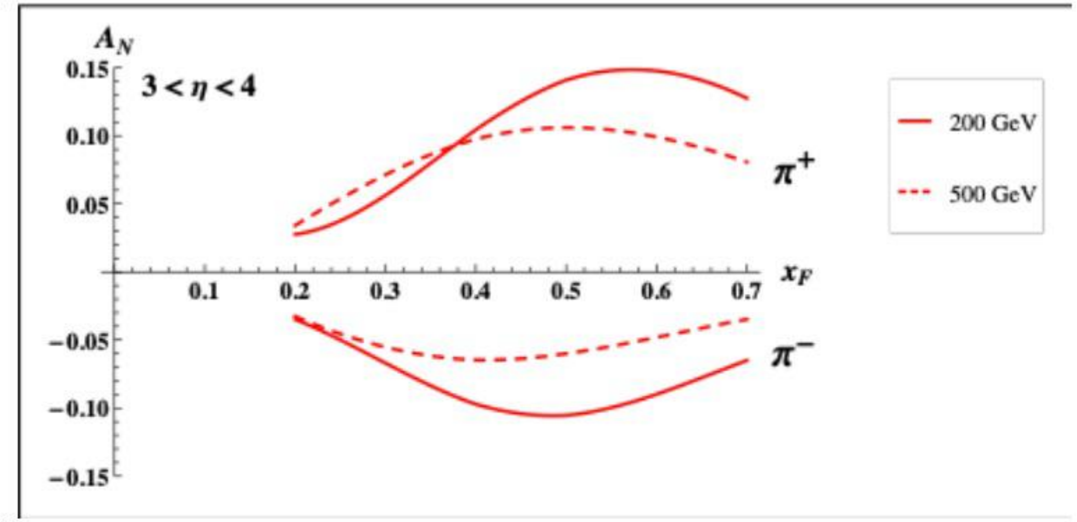
- Before ***STAR***, TMDs came only from fixed target ep data: high x and low Q^2
  - Need measurements at high Q^2 and a broad x range
- ***STAR*** mid- plus forward rapidity provides excellent kinematic overlap with future EIC measurements
  - Forward upgrade provides access to **quarks up to *x* ~ 0.5 and gluons down to *x* ~ 0.005**
  - Need **high precision data in *pp* and DIS@EIC** to establish universality of TMDs

Inclusive transverse spin asymmetries at forward rapidities

STAR, PRD 103, 092009



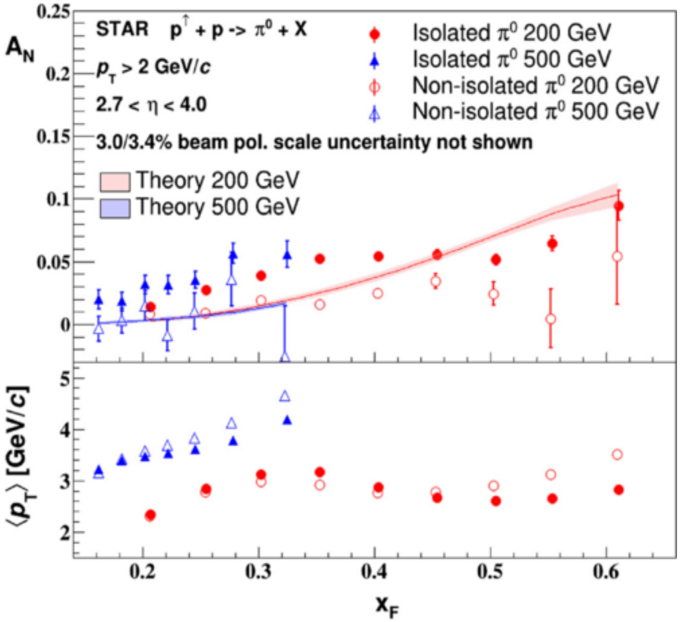
Predicted asymmetries for $\pi^{+/-}$ from Kanazawa et al, PRD 89, 111501



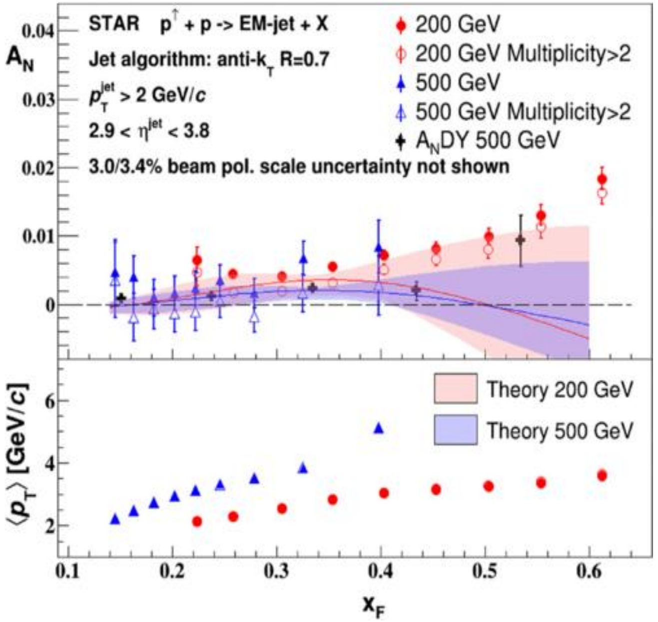
- Described by an interplay of initial-state Sivers distribution or its Twist-3 analog, the Efremov-Teryaev-Qiu-Sterman (ETQS) function, and final-state Collins effect or the related Twist-3 function H_{FU}
- A_N for $h^{+/-}$, direct photon, and π^0 can constrain the evolution and flavor dependence of the ETQS distribution and determine the role of H_{FU}

TMDs at forward rapidity

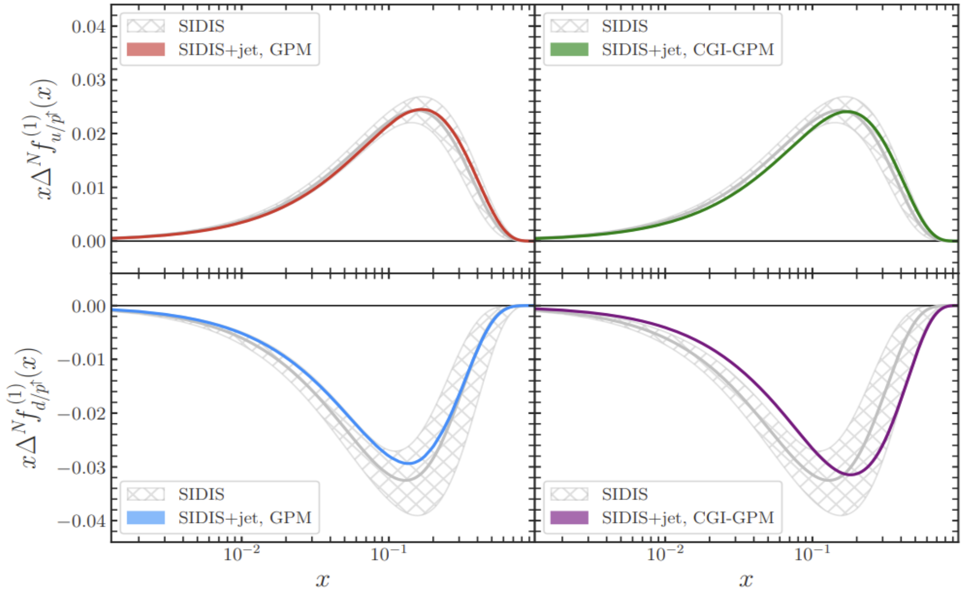
STAR, PRD 103, 092009
π^0 A_N



STAR, PRD 103, 092009
EM-jet A_N

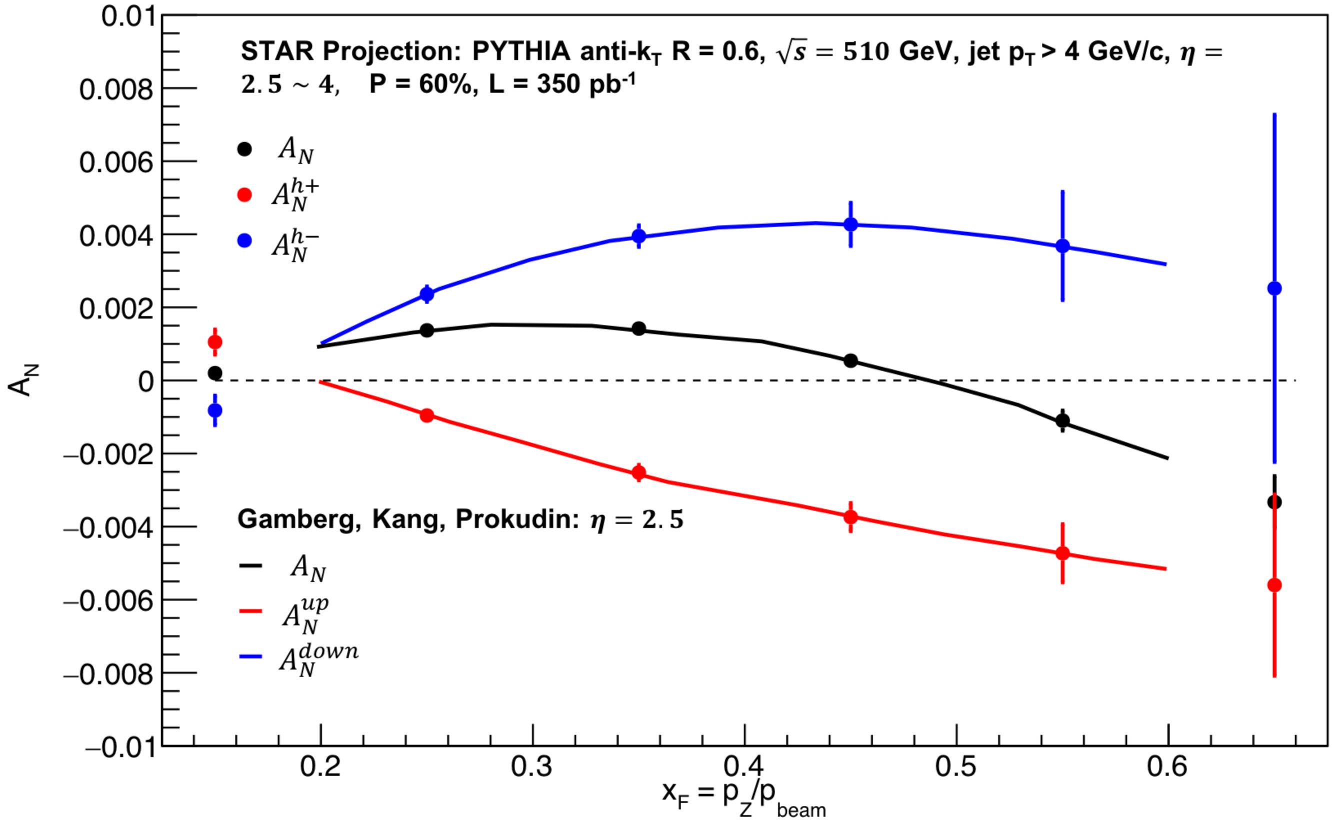


Boglione et al, PLB 815, 136135



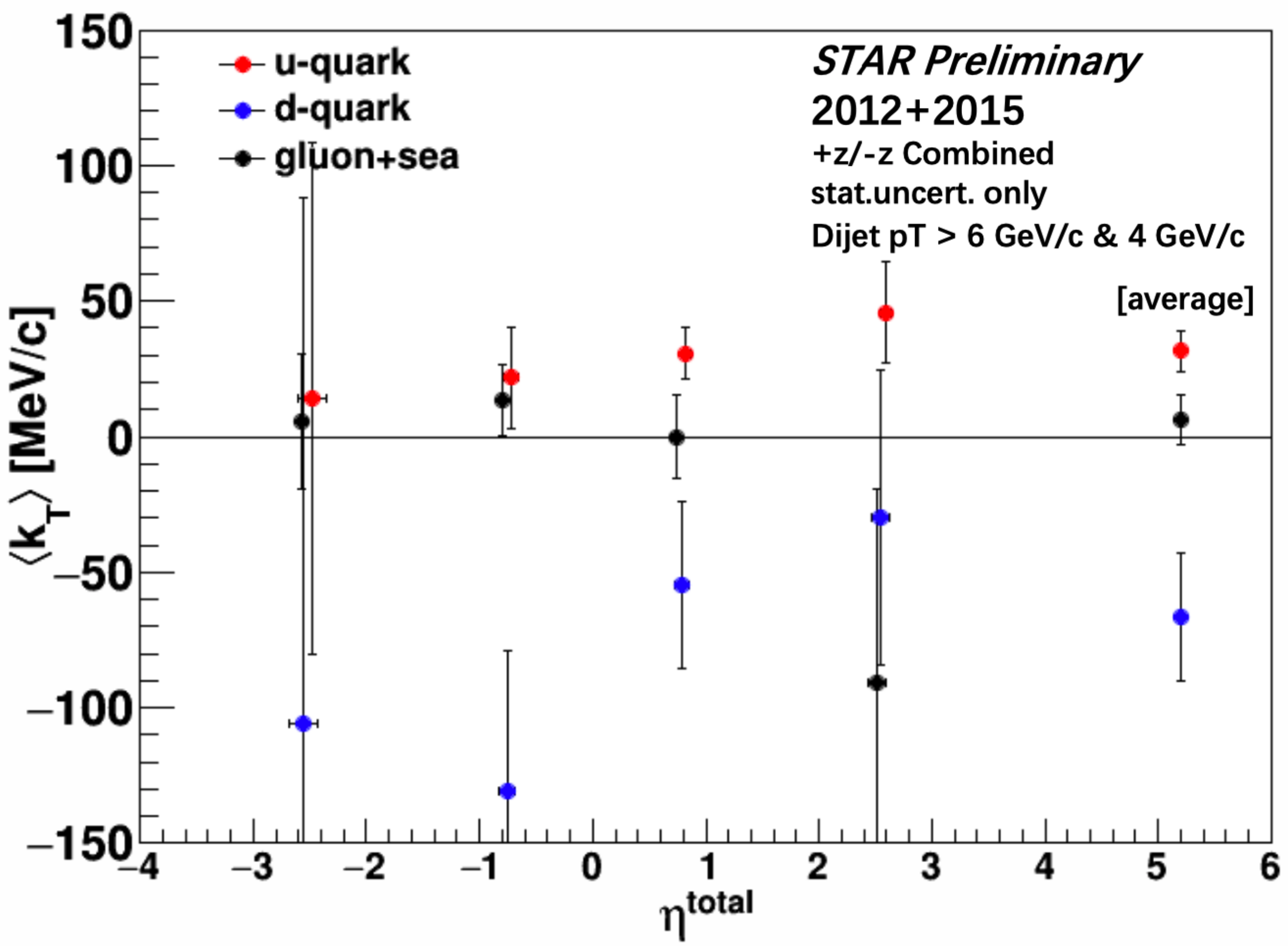
- ***STAR*** finds A_N lower for non-isolated π^0 and higher multiplicity EM-jets
  - Provide substantial constraints on the Sivers effect at high *x*
  - Additional mechanism to produce large A_N for isolated π^0 ?
- ***STAR*** has also measured small Collins asymmetry for π^0 in EM-jet (not shown)
- ***STAR*** Forward Upgrade will enable forward rapidity asymmetry measurements of charged-tagged jets and di-jets, hadron in jet Collins asymmetry, and diffractive processes with rapidity gaps

How well can the Forward Upgrade do?



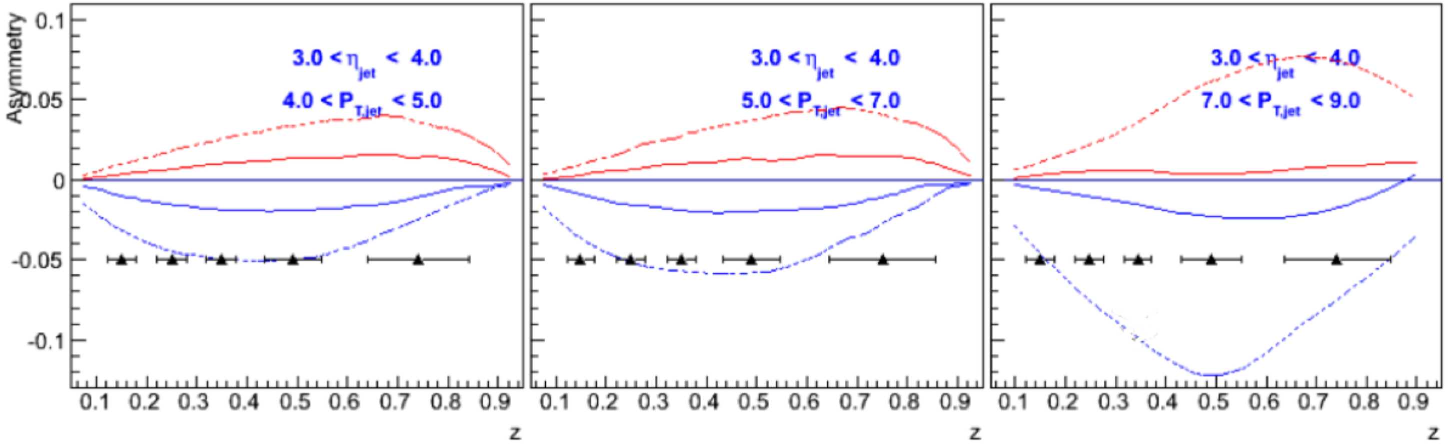
- A_N for full jet reconstruction, combined with charge-sign tagging of a hadron fragment with $z > 0.5$
  - Projected statistical uncertainties drawn on twist-3 predictions from Gamberg et al
  - Up to 10 σ separation between plus-tagged and minus-tagged jet A_N

Di-jet Sivers effect



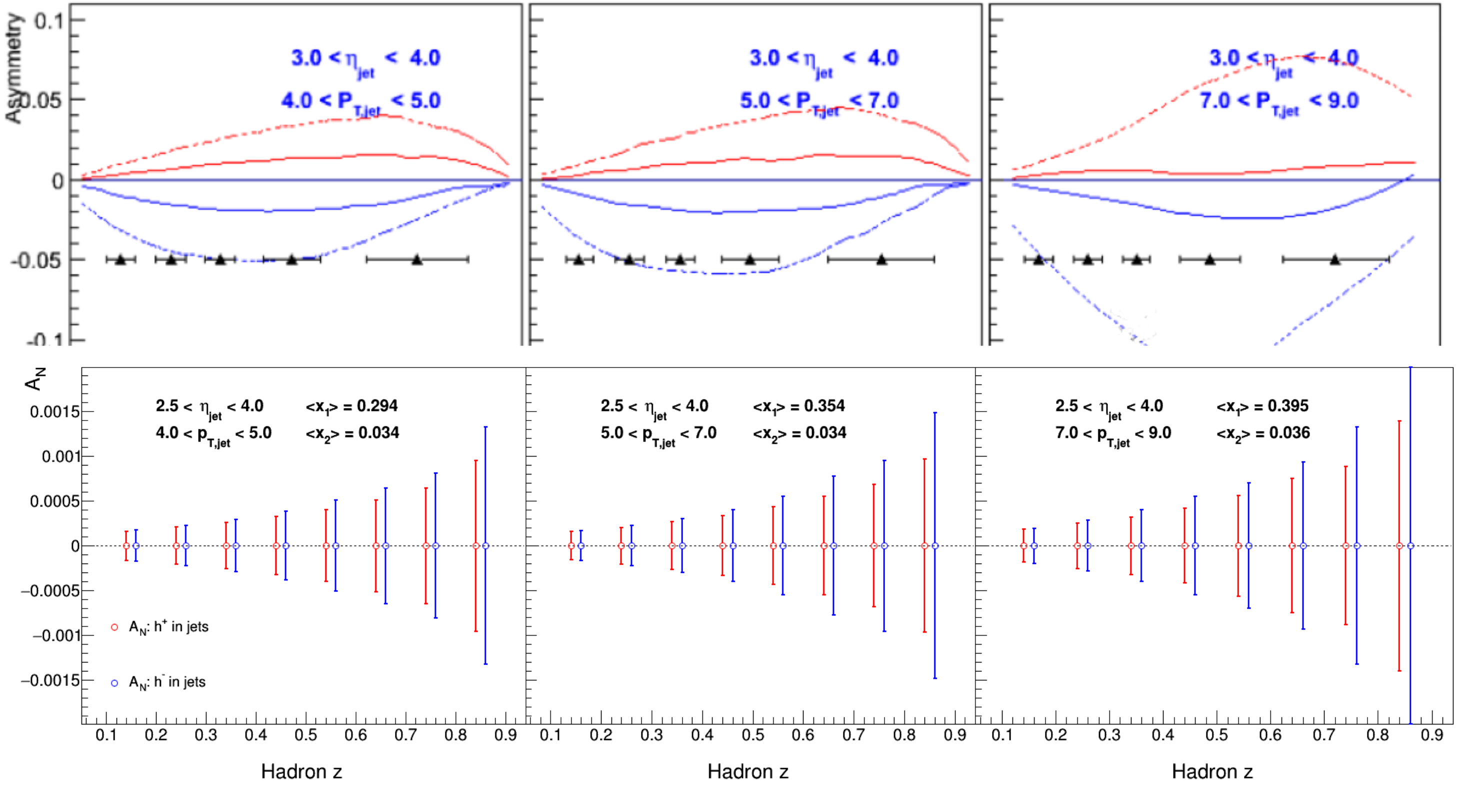
- ***STAR*** has performed the first ever observation of the Sivers effect in di-jet production
- Mid-rapidity results at √s = 200 GeV show that up and down quarks have opposite sign spin-dependent $\langle k_T \rangle$
    - $\langle k_T \rangle_d \sim -2 \langle k_T \rangle_u$
    - Gluon+sea quarks have $\langle k_T \rangle \sim 0$
- $\eta^{total} = \eta_1 + \eta_2 \sim \ln(x_1/x_2)$
    - Mid-rapidity STAR only covers $|\eta_1 + \eta_2| < 3$
    - Forward upgrade will provide access to $|\eta_1 + \eta_2| \sim 6$
        - Sample much higher (and lower) *x* values

Collins effect at high *x*



- Extending Collins asymmetry measurements to forward rapidities provides direct access to transversity in the region $0.3 < x < 0.5$
  - Has never been explored in SIDIS
  - Essential to constrain experimental measurements of the nucleon tensor charge
- Will simultaneously perform measurements with similar uncertainties of the “Collins-like” asymmetries to access linearly polarized gluons in transversely polarized protons down to $x \sim 0.005$

Collins effect at high *x*



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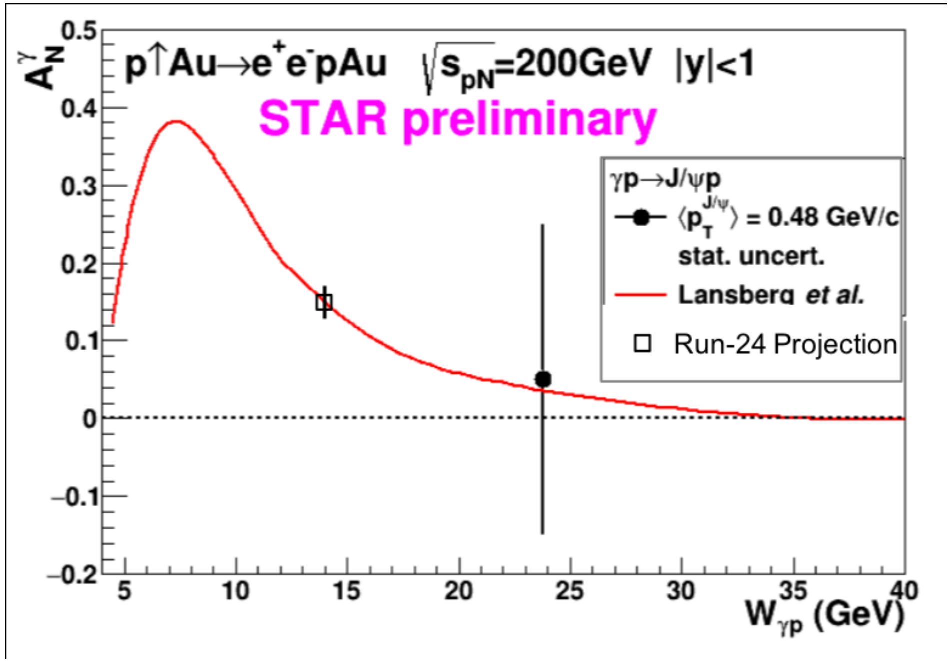
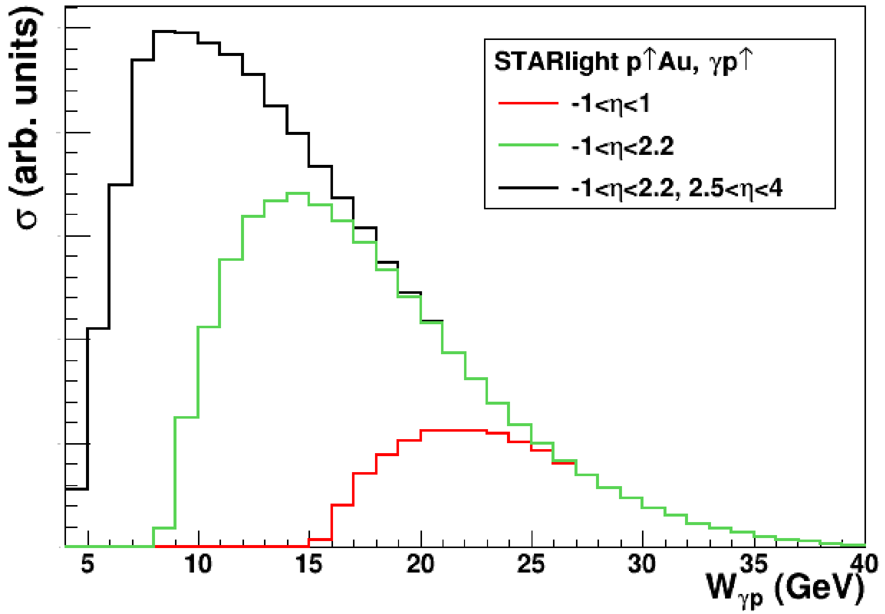
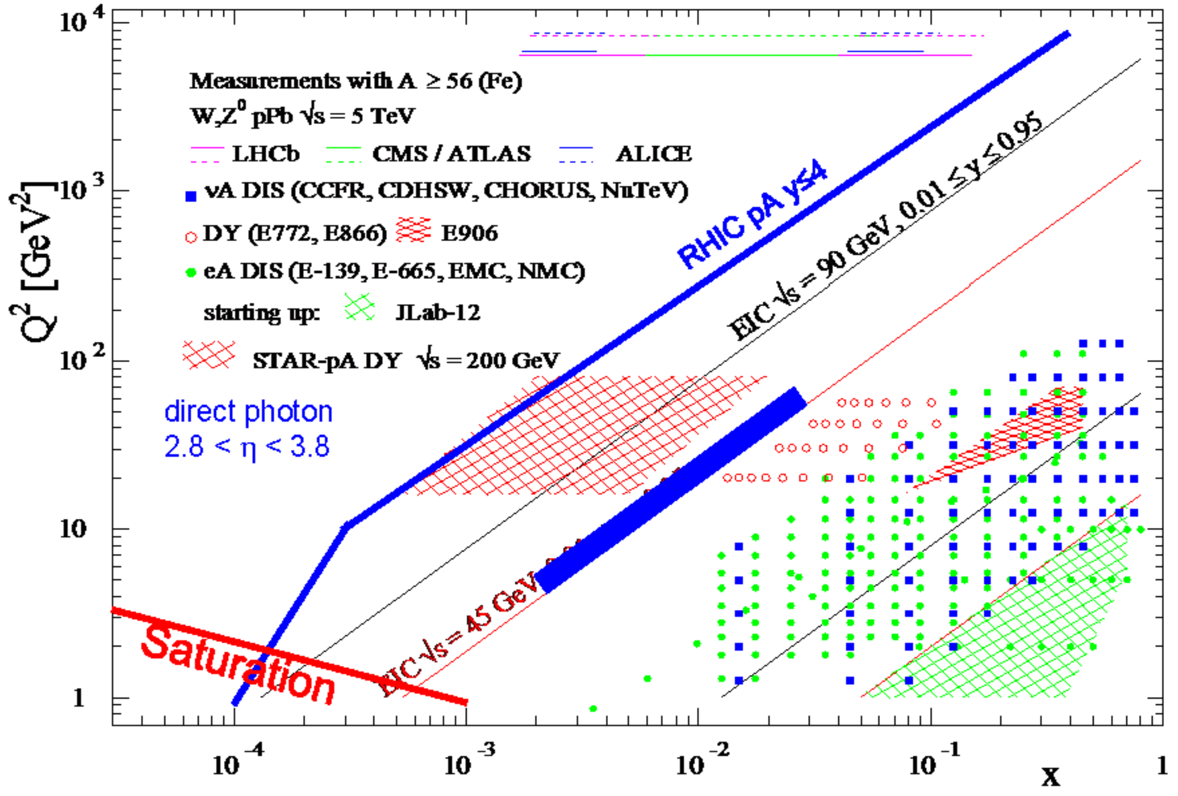
Generalized parton distribution E_g





- Exclusive J/Ψ A_N in 200 GeV ultra-peripheral p+Au collisions is sensitive to the GPD E_g
  - $Q^2 \sim 10$ GeV^2; $10^{-4} < x < 10^{-1}$
  - GPD E_g determines gluon spin-orbit correlations in the proton
- ***STAR*** performed a proof-of-principle measurement with the TPC during 2015
- ***STAR*** Forward Upgrade will enable measurement at smaller $W_{\gamma p}$, where both the cross section and the signal are expected to be much larger

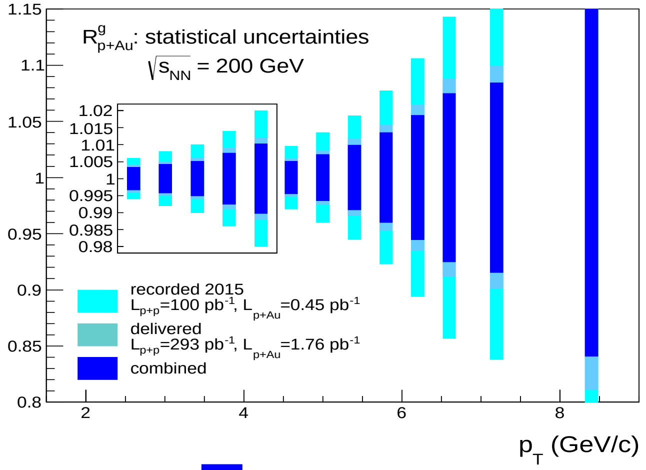
Nuclear parton distribution functions



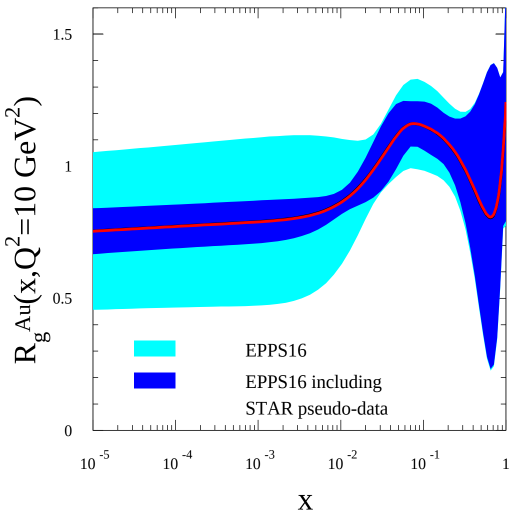
- The Forward Upgrade will enable measurements of R_{pAu} for direct photon and Drell-Yan production at $\sqrt{s_{NN}}$ = 200 GeV
  - Direct photons will constrain the nuclear gluon distribution over 0.0025 <~ x <~ 0.025
  - Drell-Yan di-electrons will constrain the nuclear sea quark distribution over 0.001 <~ x <~ 0.01

Nuclear parton distribution functions

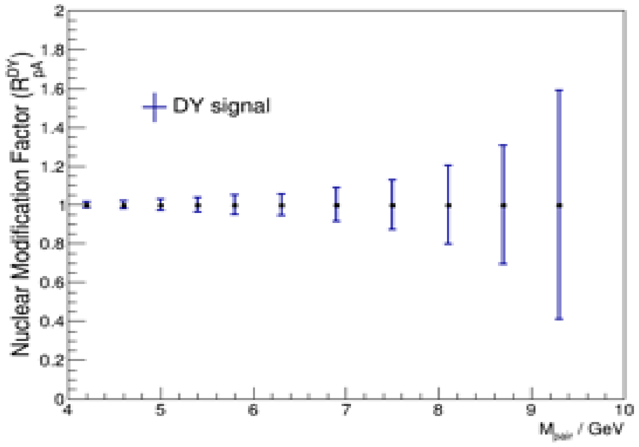
Direct photons in pA at 2.5<η<4.5



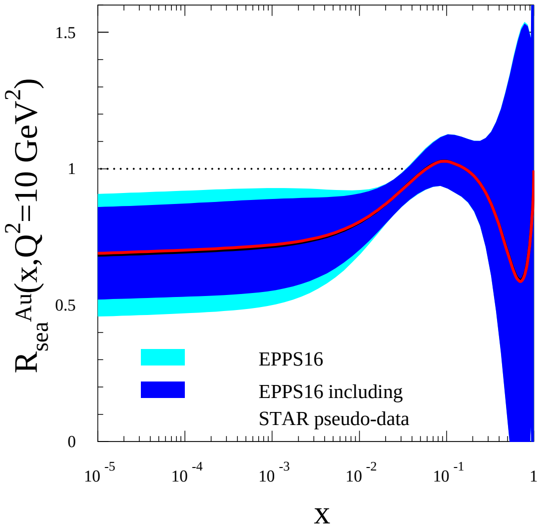
to constrain gluons



Drell-Yan in pA at 2.5<η<4.5

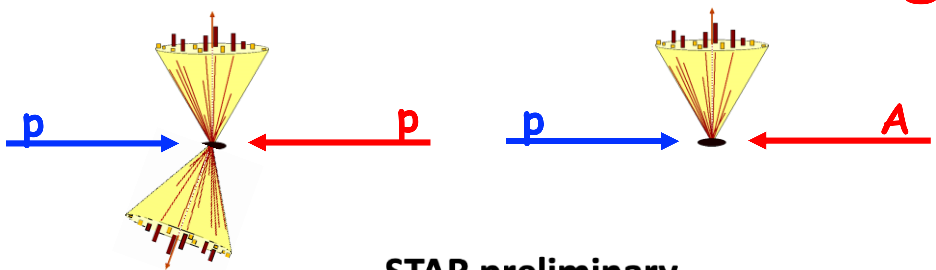


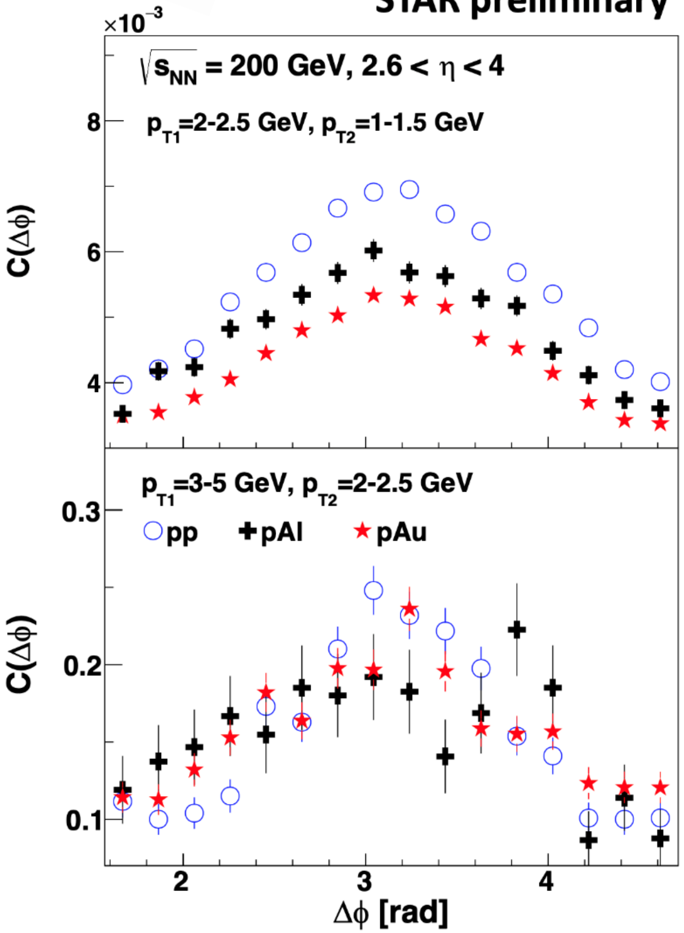
to constrain sea quarks

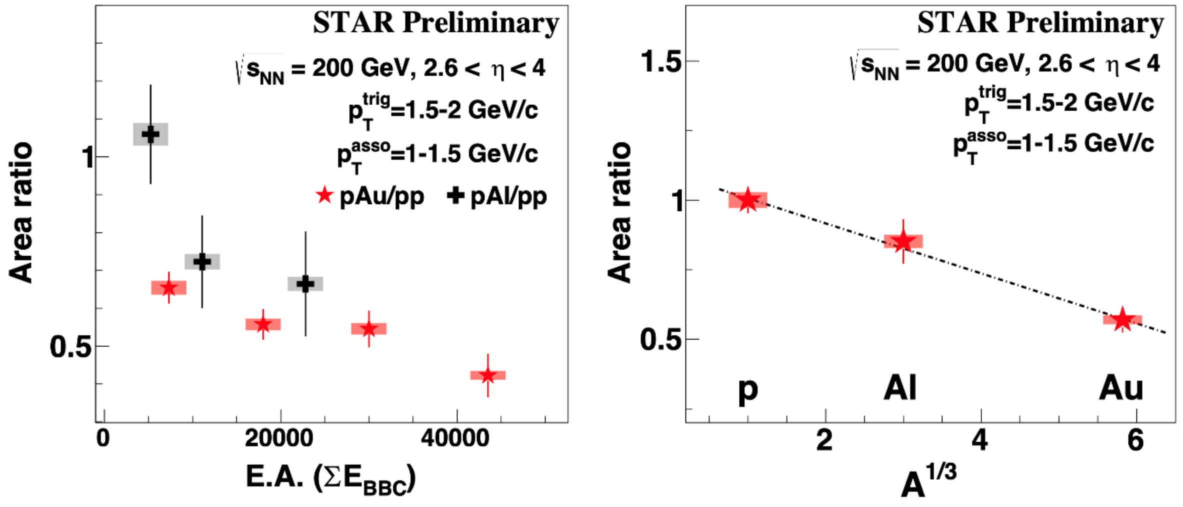


- Precision measurements of nuclear gluon and sea quark distributions
  - Essential for a **stringent test of nPDF universality** at EIC

Probing non-linear effects in QCD

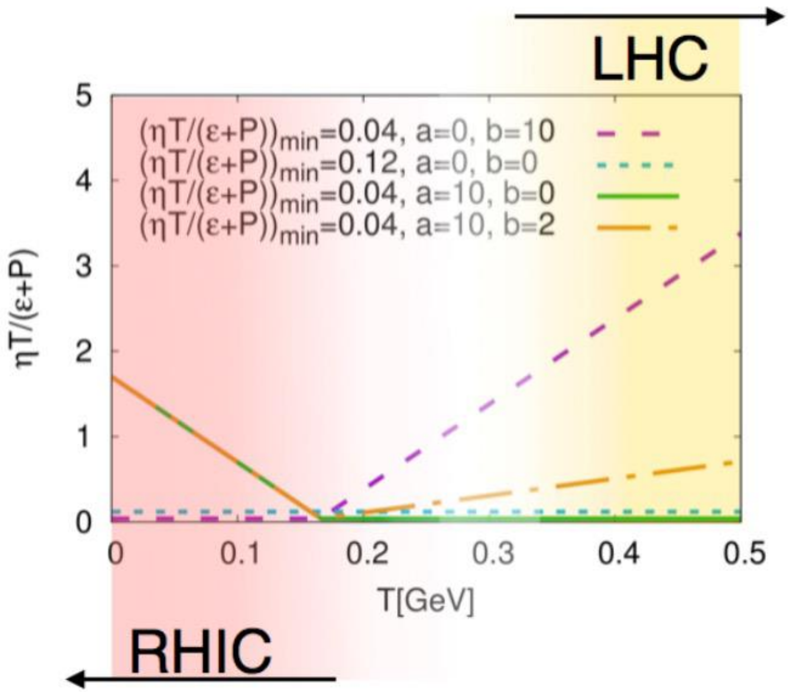


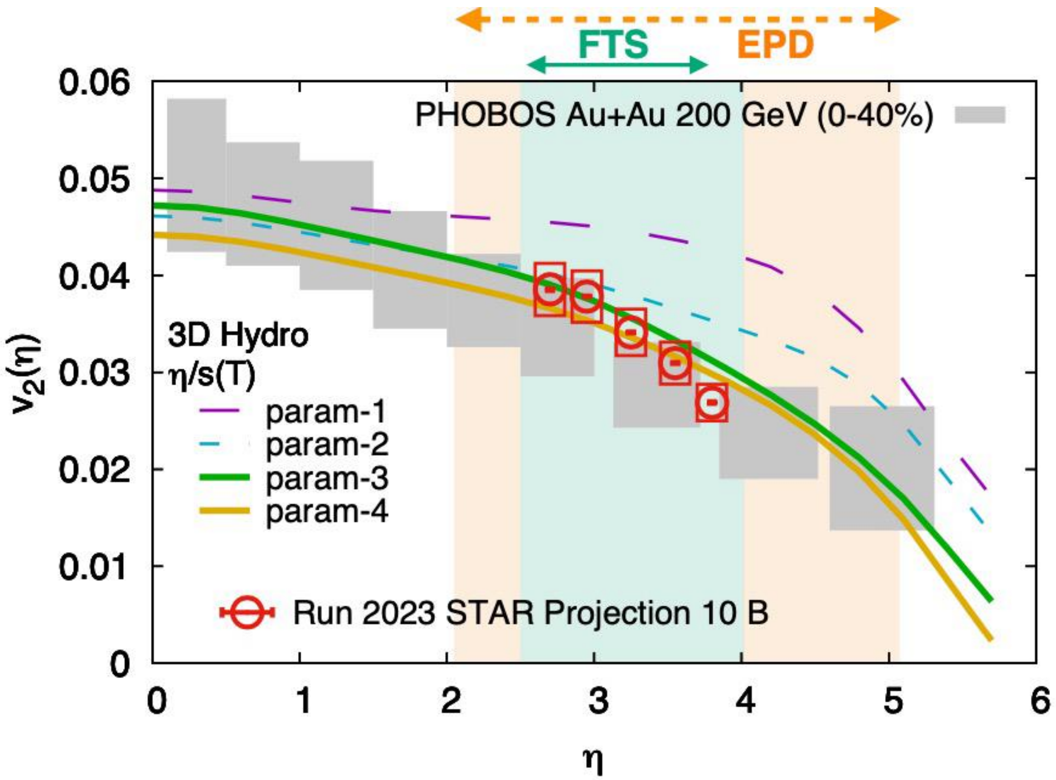




- Forward rapidities at ***STAR*** provide the unique opportunity to investigate very high gluon densities with an unambiguous probe
  - Disappearance of the backward jet in p+A
- ***STAR*** π^0 - π^0 correlations find:
  - Strong suppression at low p_T in p+A where gluon saturation is expected
  - No suppression at high p_T (larger *x*) outside the non-linear domain
- Such **hadro-production measurements are essential** to explore the **fundamental universality of non-linear effects** at EIC
- Forward Upgrade will enable similar studies in $h^{+/-}$-$h^{+/-}$, di-jets, and γ-jet

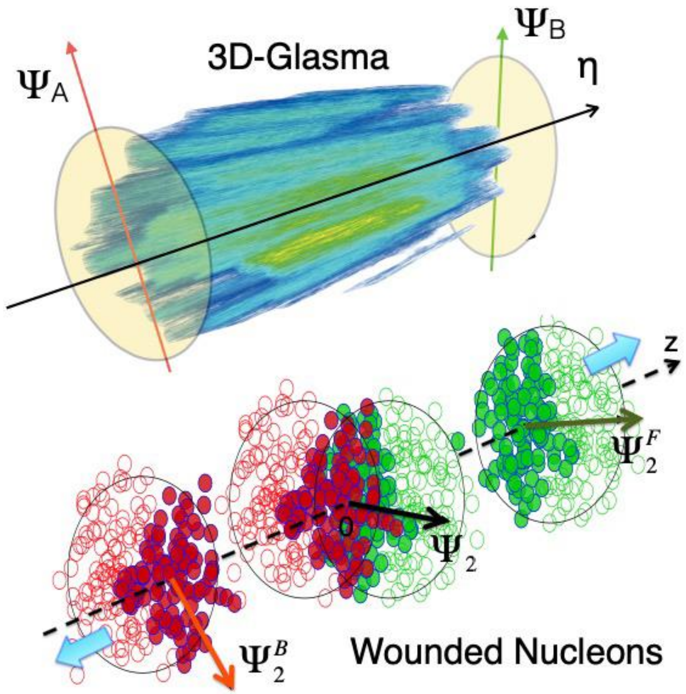
Flow measurements in Au+Au to constrain η/s

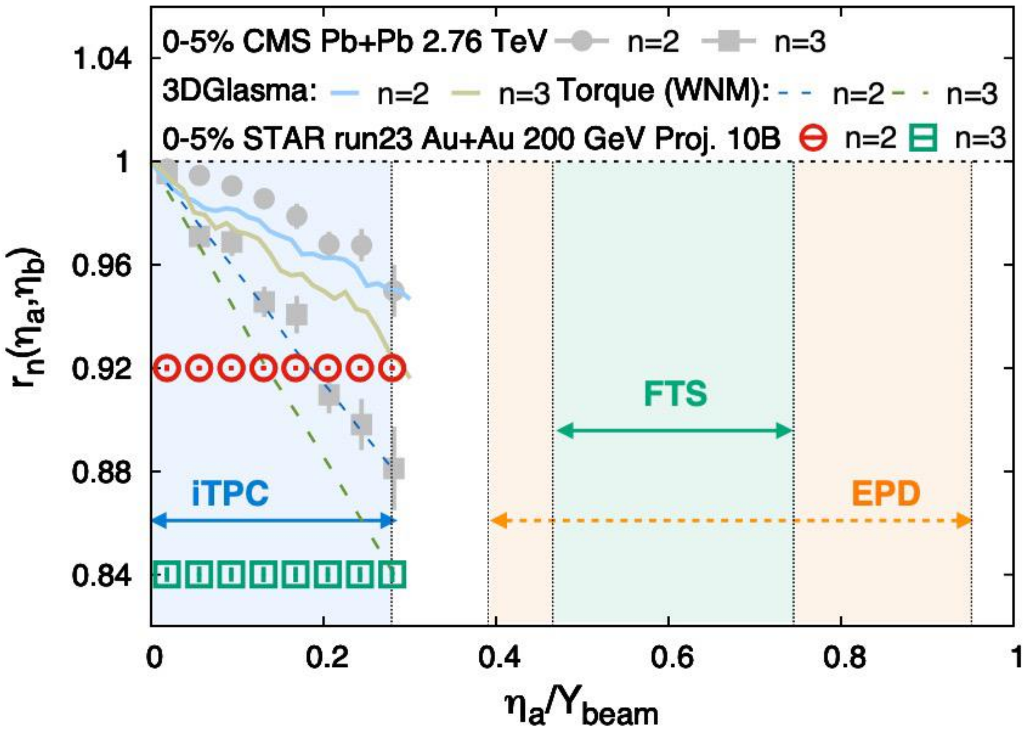




- *η/s* is expected to be smallest in the RHIC energy regime
- Flow measurements at forward rapidity are sensitive to the temperature dependence of η/s
- ***STAR*** Forward Upgrade measurements will be far more precise than previous PHOBOS measurements

Constrain the longitudinal structure of the initial state



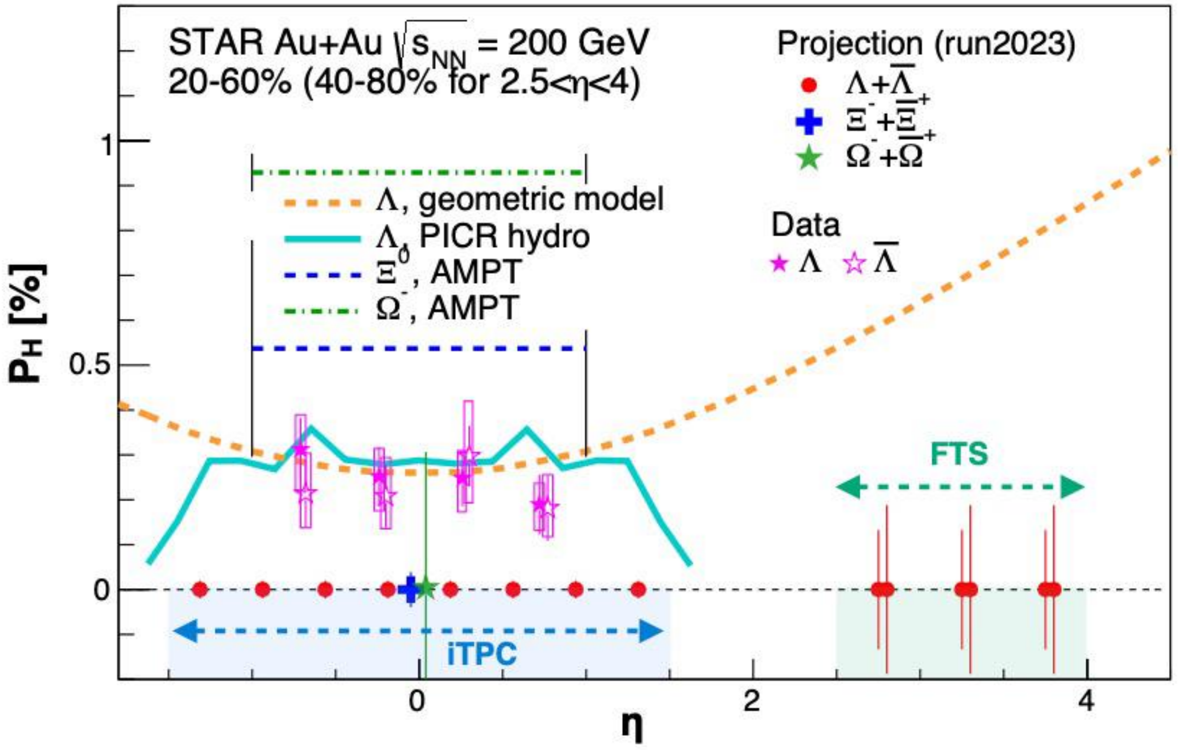


$$r_n(\eta_a, \eta_b) = V_{n\Delta}(-\eta_a, \eta_b)/V_{n\Delta}(\eta_a, \eta_b)$$

where $V_{n\Delta}$ is the Fourier coefficient calculated with pairs of particles in different rapidity ranges

- r_n is sensitive to different initial state inputs
  - 3D glasma model: weaker decorrelation, describes CMS r_2, but not r_3
  - Wounded nucleon model: stronger decorrelation than seen in the data
- Precise measurement over a wide rapidity window will provide a stringent constraint

Global vorticity transfer



- How is the global vorticity transferred to the fluid?
- How does the local thermal vorticity of the fluid get transferred to spin angular momentum?
- Rapidity dependence of Λ global polarization will probe the nature of the global vorticity transfer
  - Initial geometry and local thermal vorticity + hydro predict opposite trends

Conclusion

Forward-rapidity: $2.5 < \eta < 4$

A+A

Beam:
Full Energy AuAu

Physics Topics:
- **Temperature dependence of viscosity through flow harmonics up to η~4**
- **Longitudinal decorrelation up to η~4**
- **Global Lambda Polarization**
  → **strong rapidity dependence**

p+p & p+A

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- **Sivers asymmetries for hadrons, (tagged) jets, and di-jets**
- **TMD measurements at high x**
  transversity → tensor charge
- **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**

- The ***STAR*** Forward Upgrade will be **ready for physics** when the upcoming RHIC run begins on November 15
- The ***STAR*** Forward Upgrade **will enable** a wide range of **high-impact measurements** in polarized *pp* collisions, in polarized and unpolarized *p*+Au collisions, and in Au+Au collisions
- **Stay tuned!**