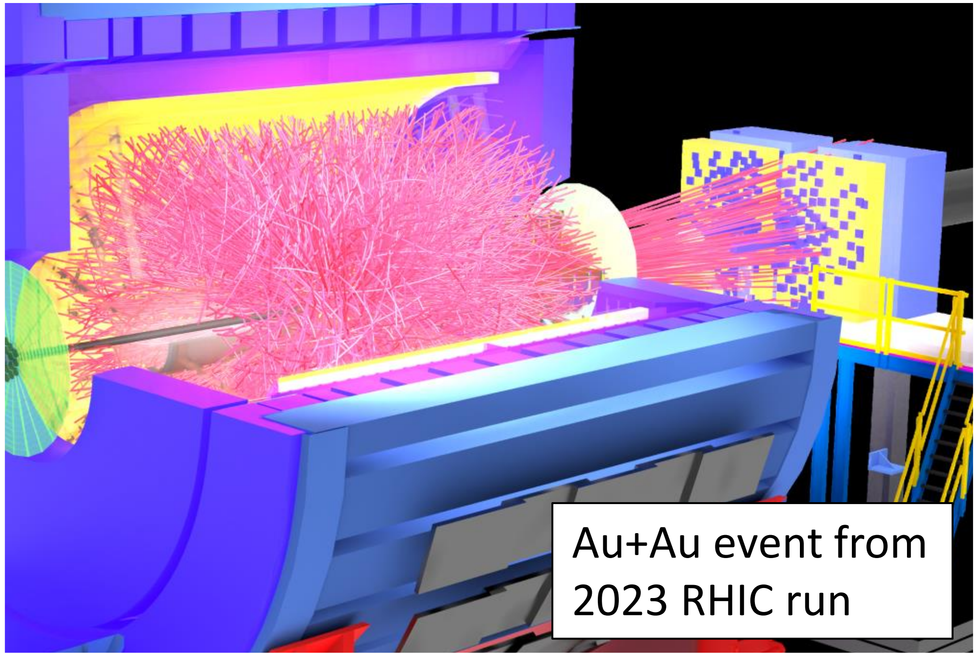
25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM



Au+Au event from 2023 RHIC run

The *STAR* Forward Upgrade

Carl Gagliardi

Texas A&M University

for the *STAR* Collaboration

Supported in part by:

U.S. DEPARTMENT OF ENERGY | Office of Science

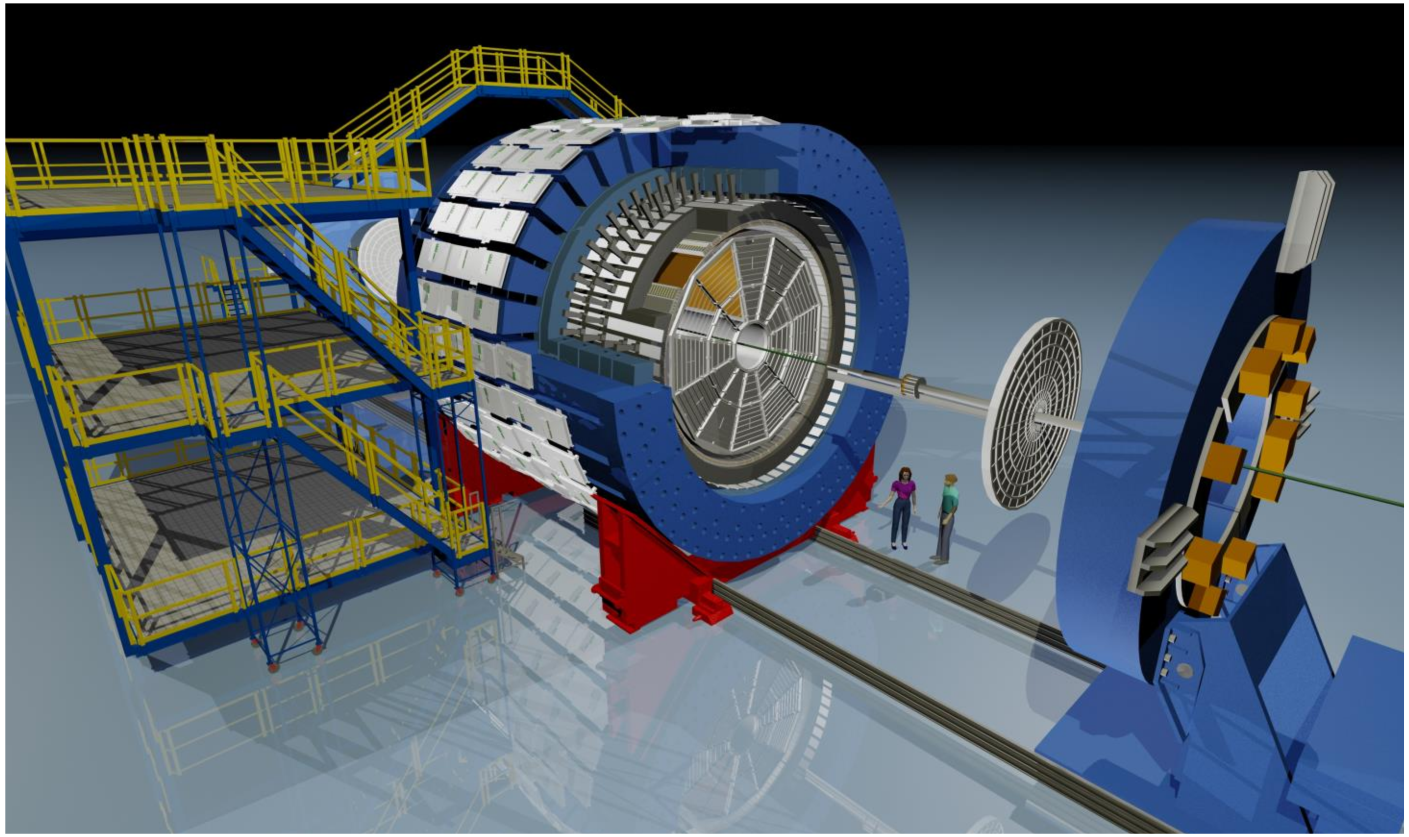
NSF

Outline

- What is it?
- What science is it doing?

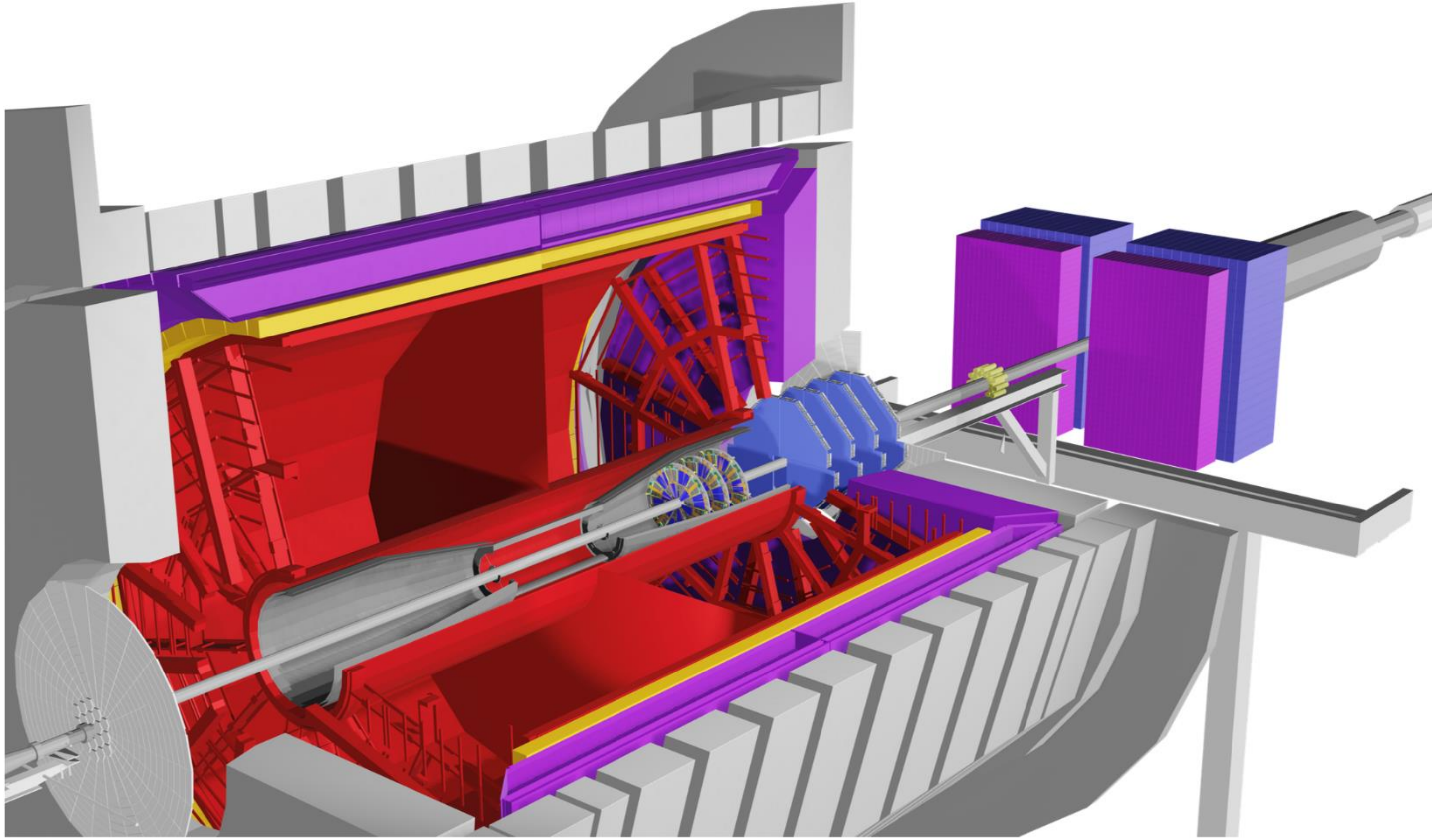
What is the *STAR* Forward Upgrade?

The *STAR* detector



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

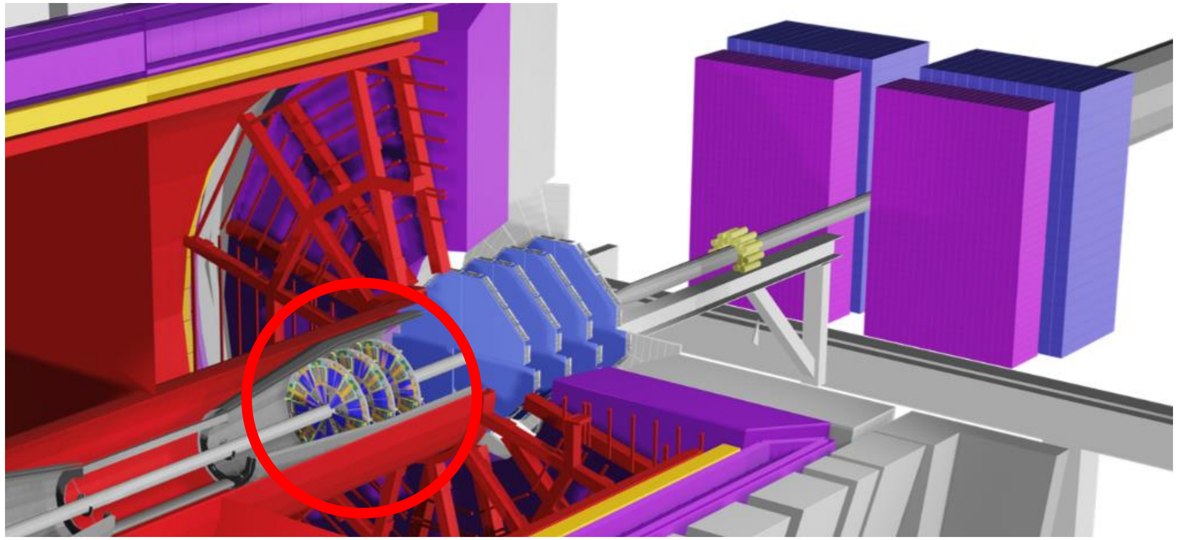
The *STAR* Forward Upgrade



- 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
- Measures $h^{+/-}$, $e^{+/-}$ (with good e/h discrimination), photons, π^0, jets

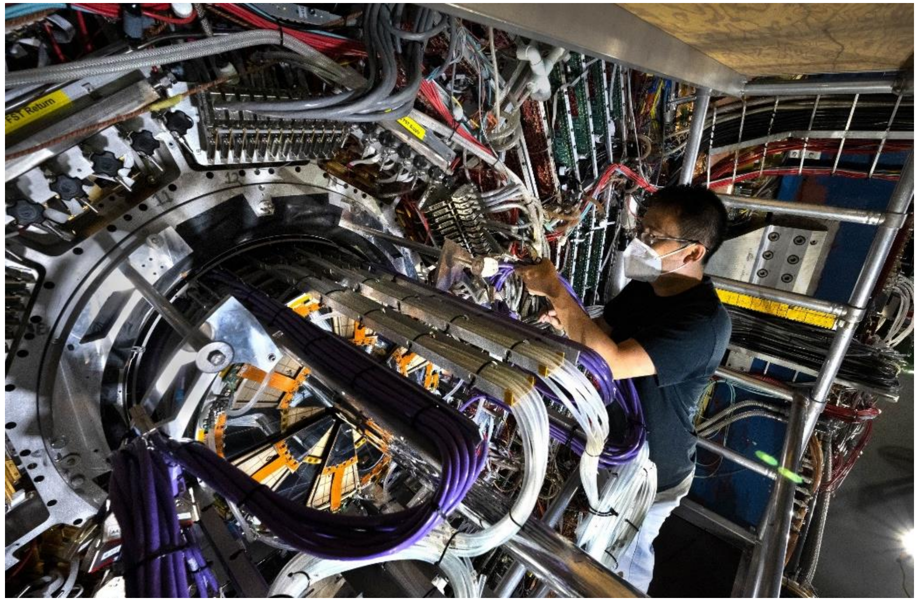
Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

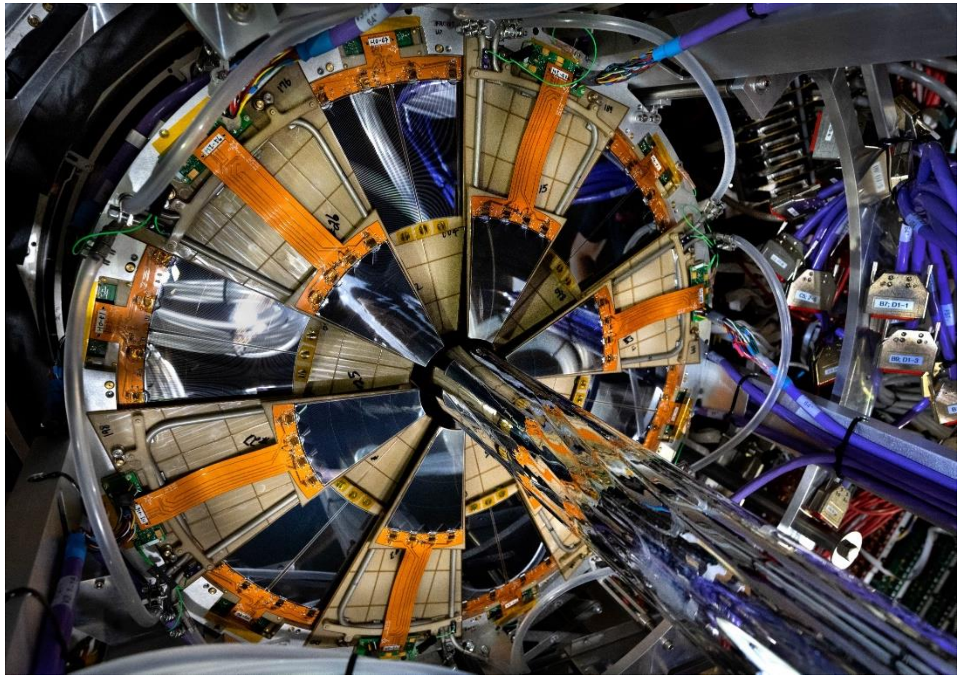
Silicon detector

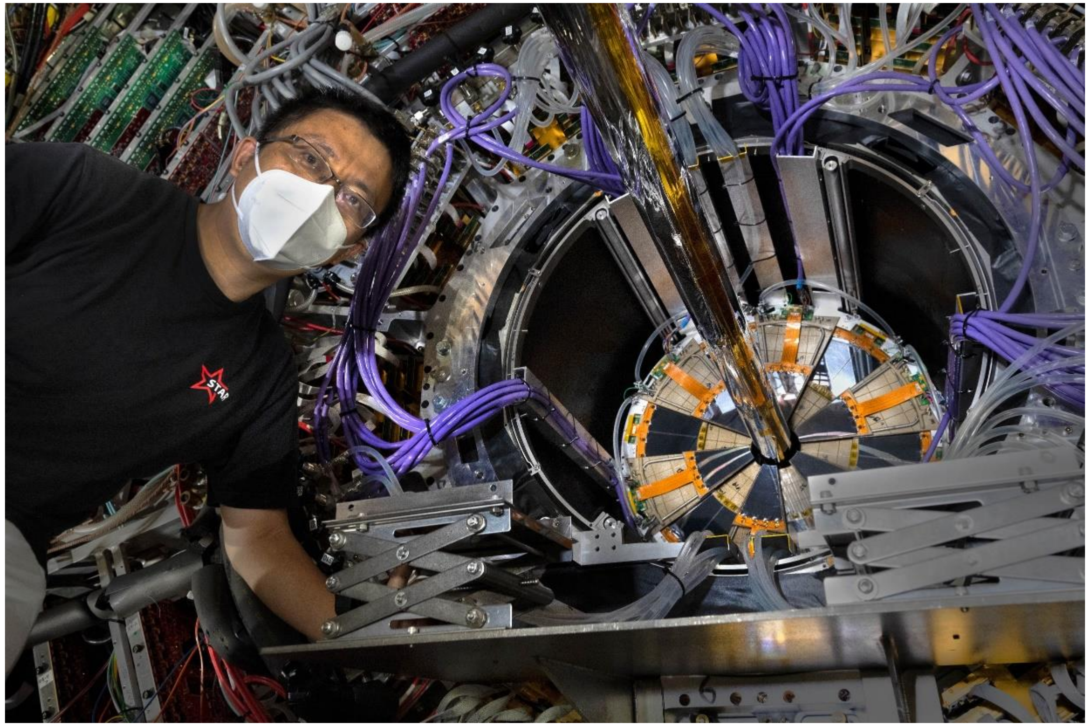


- Three disks, each with 12 modules
- Each module includes 3 single-sided double-metal mini-strip sensors (Si from Hamamatsu)
  - Fine granularity in φ and coarse in R
- Material budget ~1.5% X_0 per disk
- Technology is similar to ***STAR*** Intermediate Silicon Tracker
  - Same APV25-S1 front-end chip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

Silicon detector







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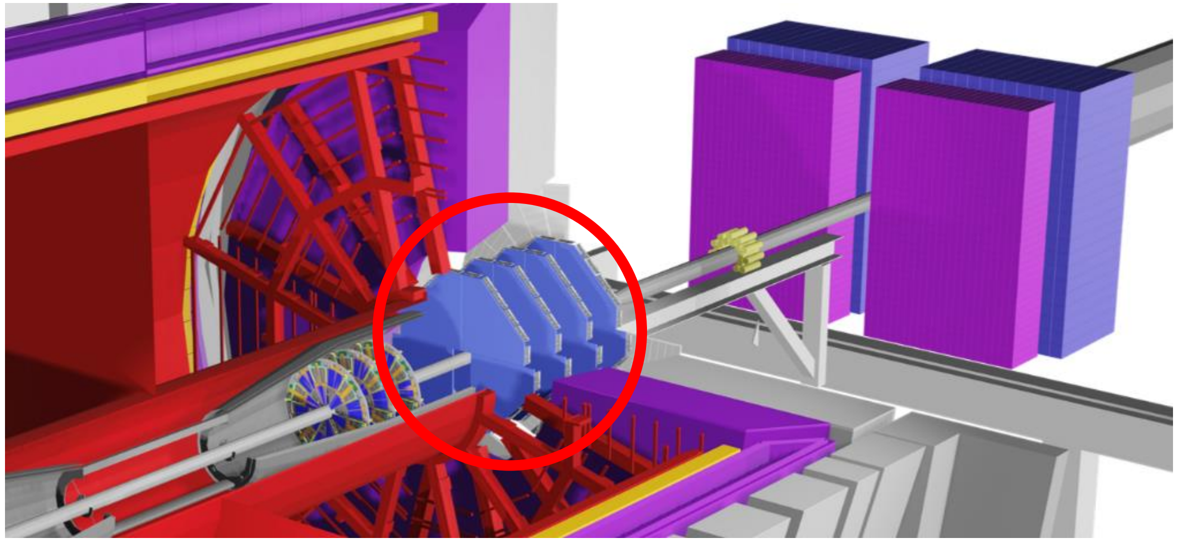
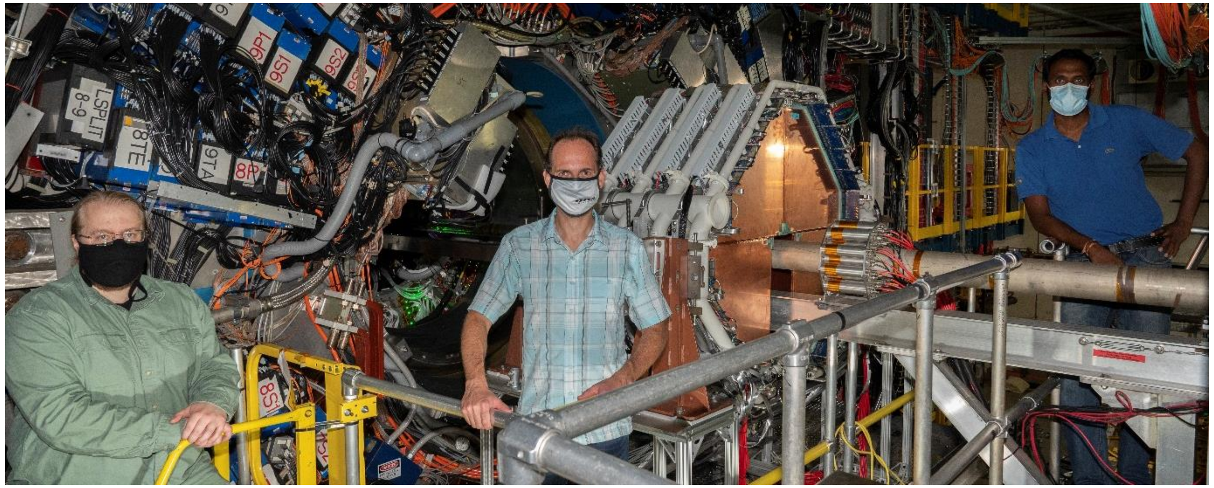
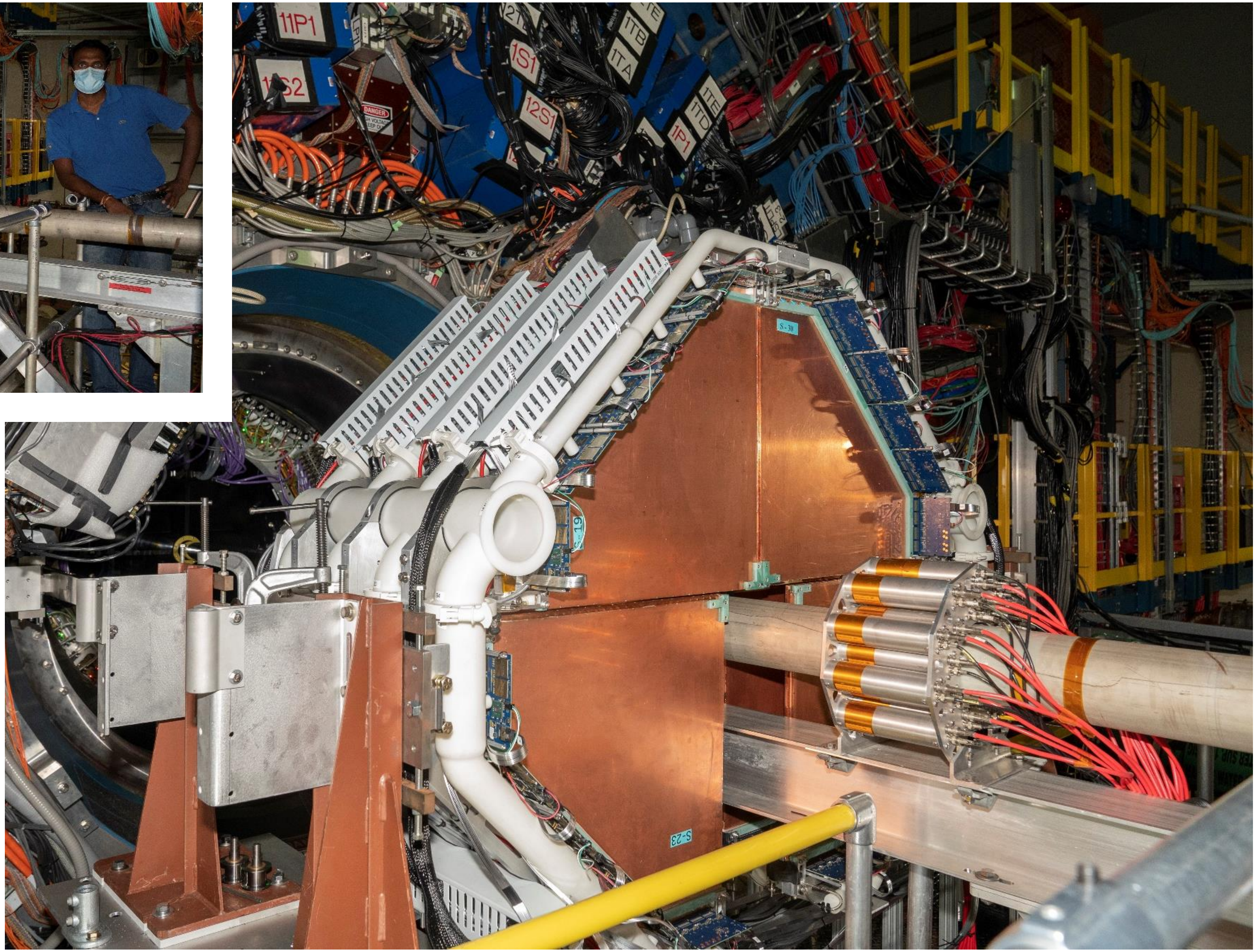
Small-strip Thin Gap Chambers



- 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

Small-strip Thin Gap Chambers





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sTGC gas system

Gas cabinet

Front of the controls cabinet

Gas distribution panel

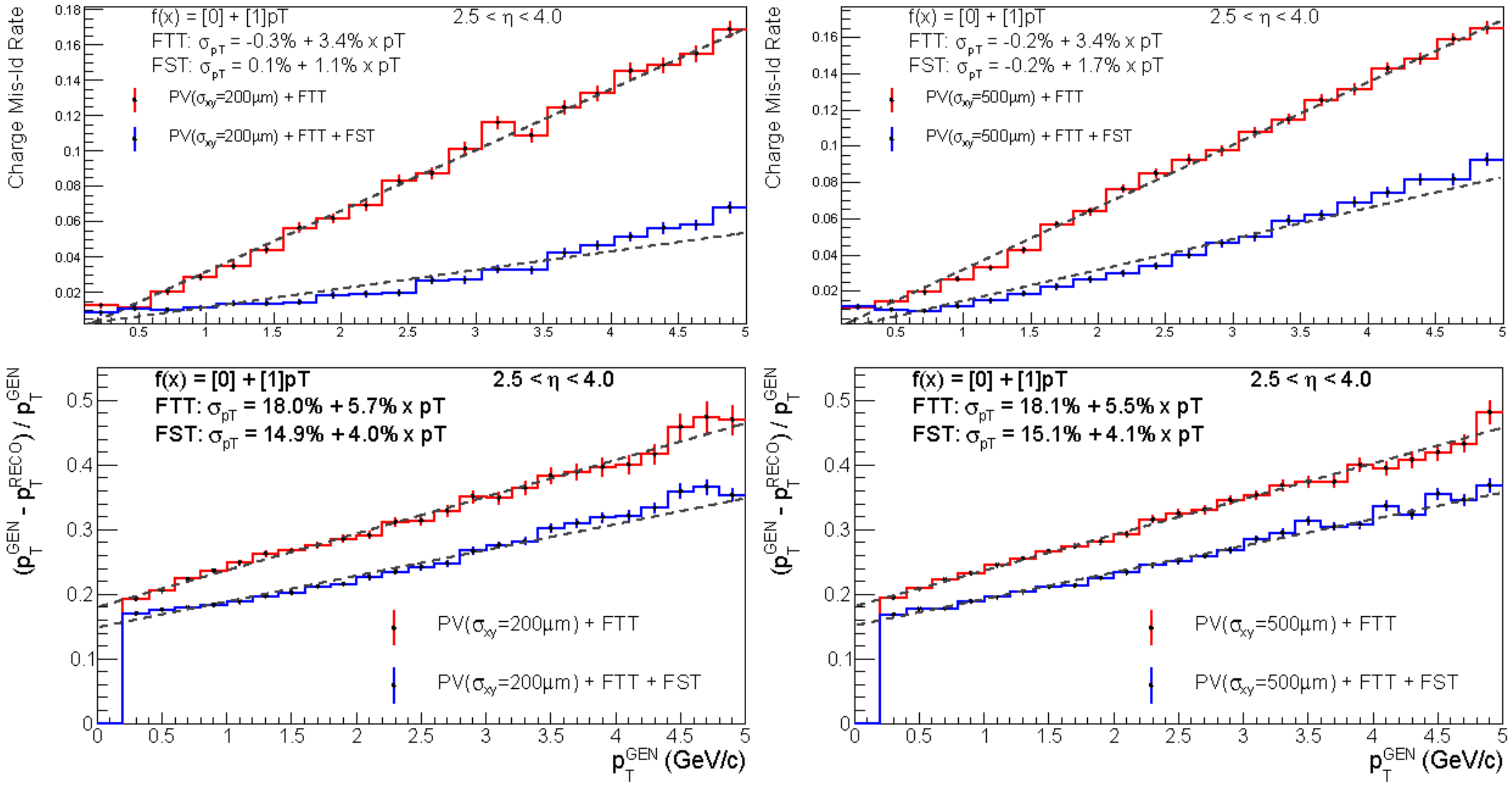
- sTGCs use a mixture of CO_2 and n-pentane
  - **Extreme care needed** for the **highly flammable n-pentane**!
    - Flash point 14 ^{0}C; explosive limits 1.5 – 7.8%
    - Boiling point of 36 ^{0}C further complicates things
- Has **operated extremely well** through major power failures and big storms

Simulated performance of the Forward Tracker

√*s* = 510 GeV   √*s* = 200 GeV

Charge mis-ID rate vs. p_T

p_T resolution vs. p_T

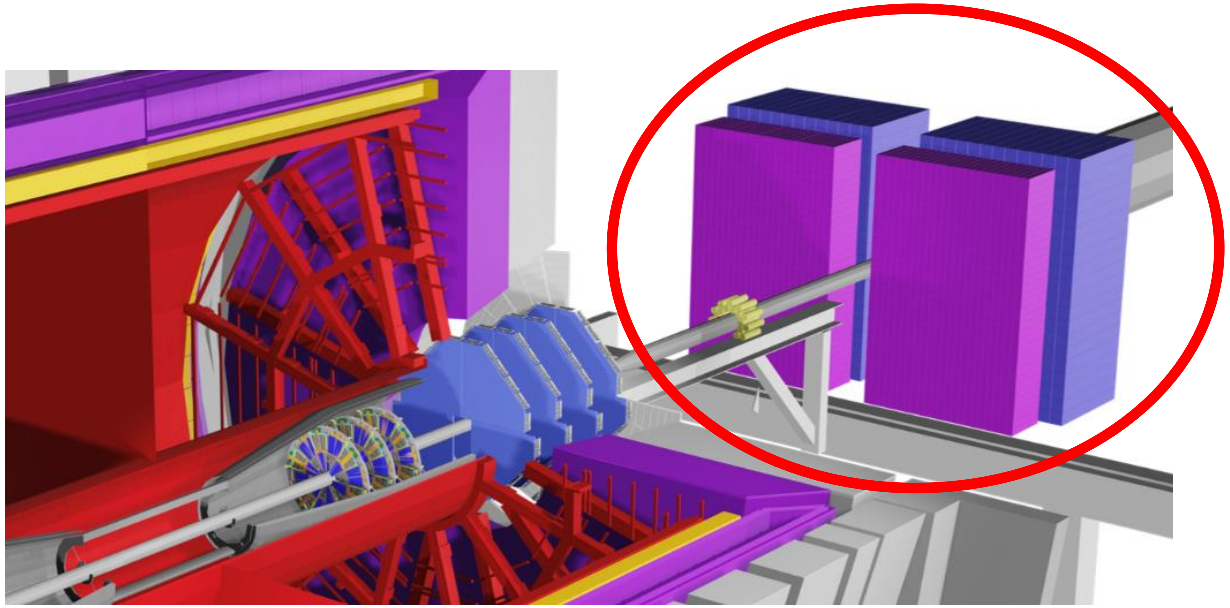


Red: sTGCs only

Blue: sTGCs+Si disks

- Charge mis-ID rate less than 6% (8%) for p_T < 5 GeV/c and √*s* = 510 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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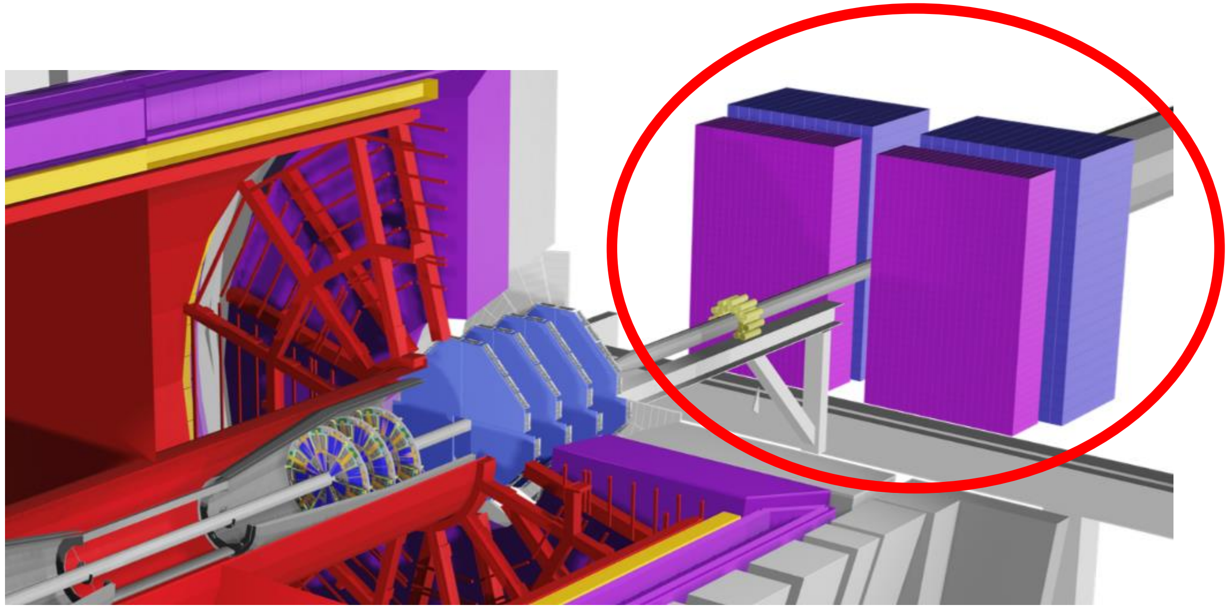

- **Entire FCS (ECal + HCal + electronics) was installed during 2020**
  - Commissioned during the 2021 RHIC run
    - Extensive running with Au+Au at $\sqrt{s_{NN}}$ = 7.7 GeV
    - Brief runs with O+O and *d*+Au at $\sqrt{s_{NN}}$ = 200 GeV

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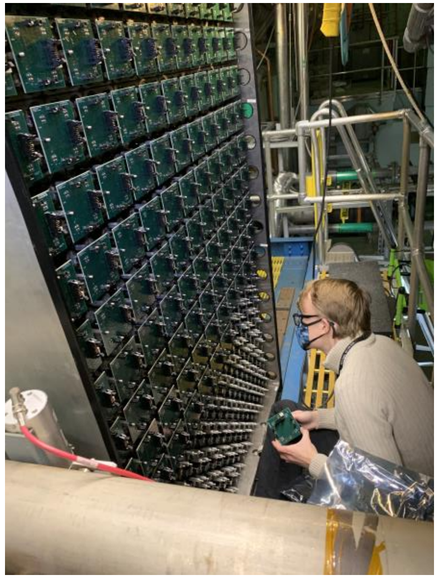
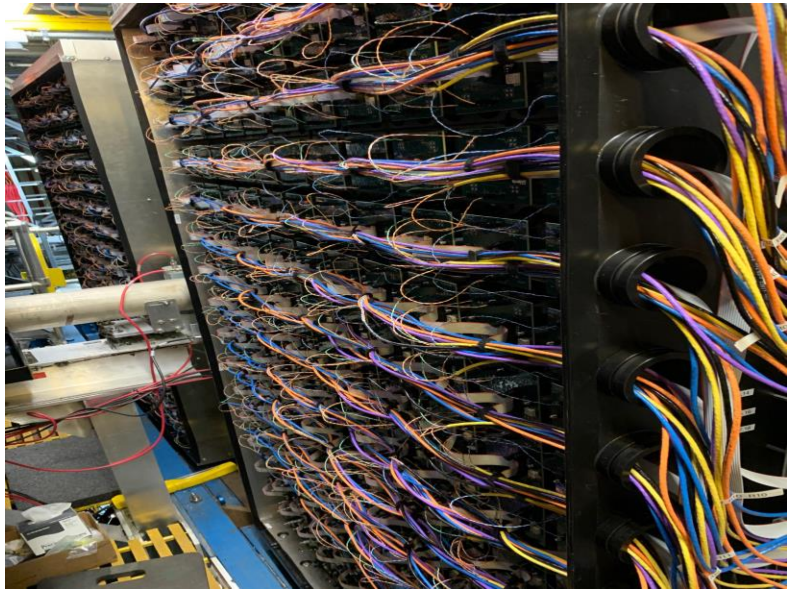
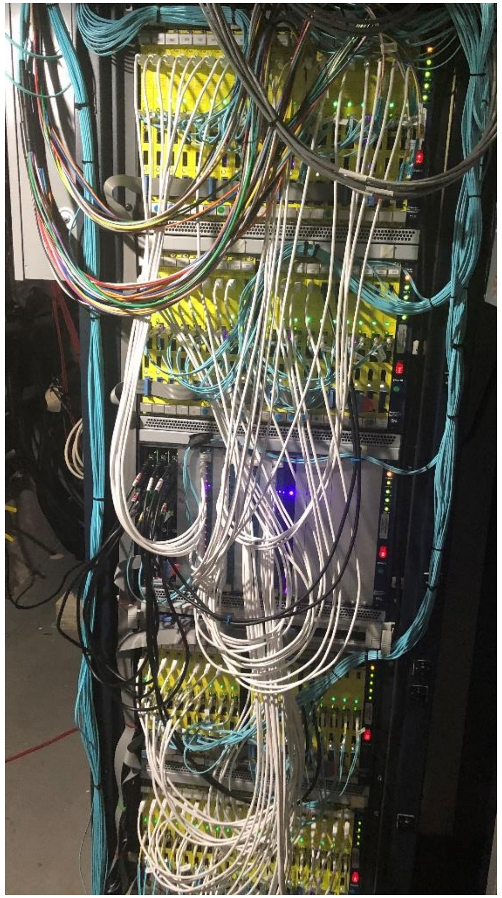
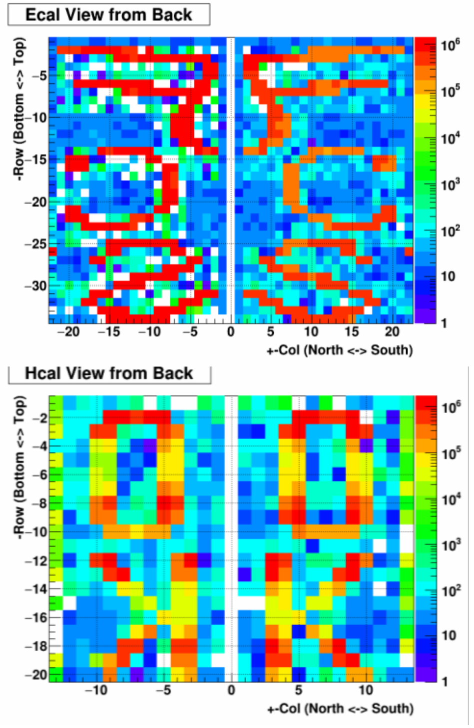




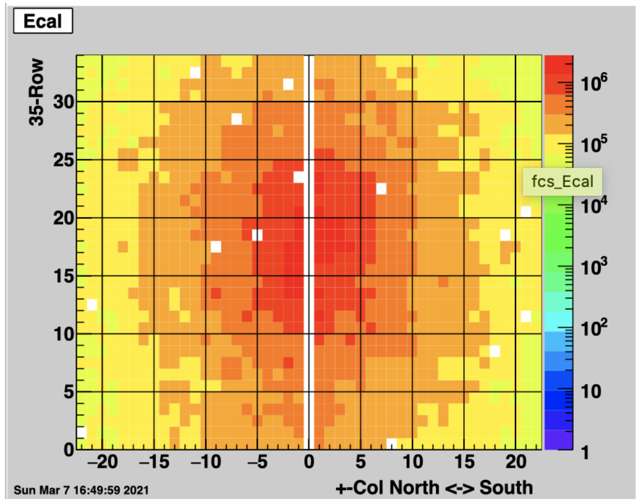
FCS readout and commissioning

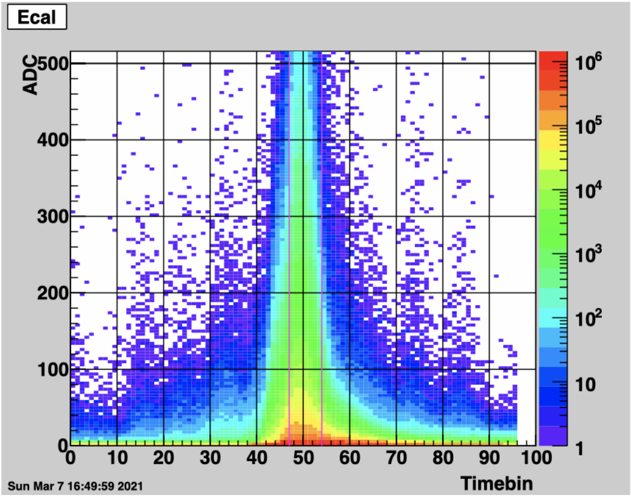


LED mapping check



Online monitoring plots during 7.7 GeV Au+Au





- During the 2021 RHIC run, we:
  - Exercised the on-line machinery, monitoring systems, and slow controls
- Was ready to go on Day-1 of the 508 GeV *pp* run in 2022 (except for some gain tweaks)

Forward Upgrade timeline

- Summer, 2019: final funding was secured
- Fall, 2020: FCS and associated electronics installed
- Spring, 2021: FCS commissioned with beam
- August, 2021: FST installed
- October, 2021: sTGC installed
- November, 2021: FST and sTGC commissioned with cosmic rays

- November 29, 2021: cool down began for the 2022 RHIC run with 508 GeV *pp* collisions
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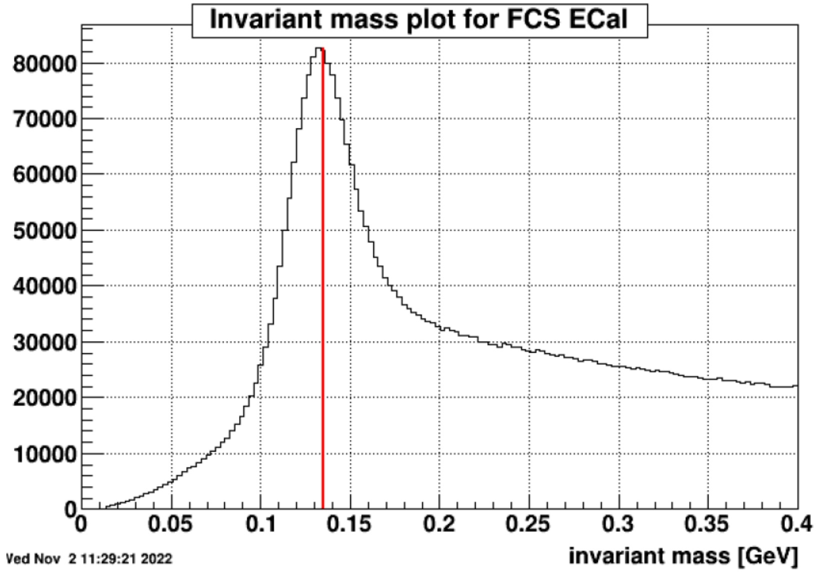
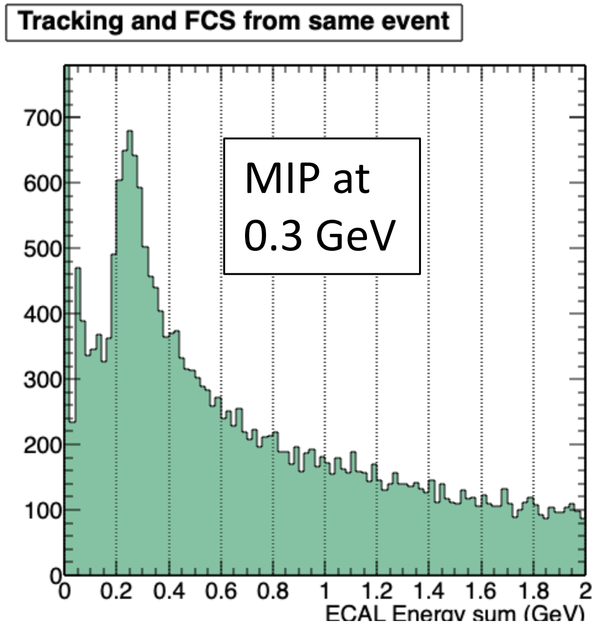
- The ***STAR*** Forward Upgrade was **completed on time and on budget, in spite of the pandemic**!

- And since then, it has **operated very smoothly** and taken excellent data throughout the **2022** (508 GeV polarized *pp* collisions) and **2023** (200 GeV Au+Au collisions) RHIC runs

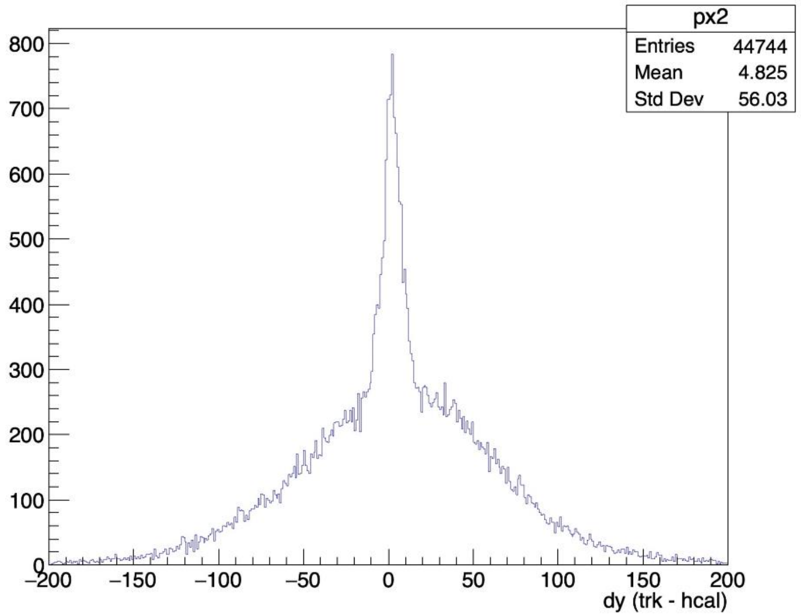
Analysis status for the 2022 RHIC run



Energy of small (1-2 cell) ECal cluster with track pointing



Y of track projected to HCal – Y of HCal cluster



- FCS ECal π^0 calibration complete
- Track finder and fitter can use sTGC first, then add FST, or the reverse
- Find nice correlations between reconstructed tracks and FCS hits
- Working on precise final alignments of sTGC and FST
- Working toward HCal MIP and J/ψ reconstruction

What is the science of the *STAR* Forward Upgrade?

STAR Forward Upgrade physics program

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

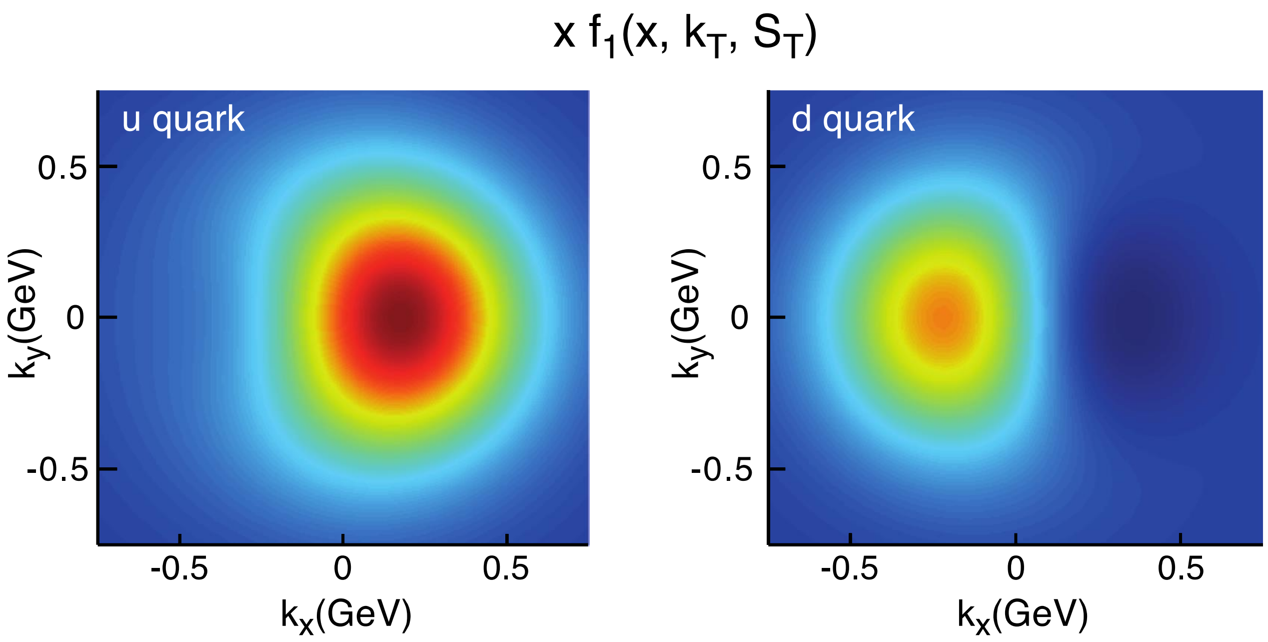
Beam:
508 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- **Sivers asymmetries for hadrons, (tagged) jets, and di-jets**
- **Collins asymmetries 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:
    - 2021-22: 508 GeV polarized *pp*
  - ***STAR*** in parallel with sPHENIX:
    - 2023 and 2025: 200 GeV Au+Au
    - 2024: 200 GeV polarized *pp*
    - Hope for polarized *p*+Au during 2024 or '25 (but not guaranteed)

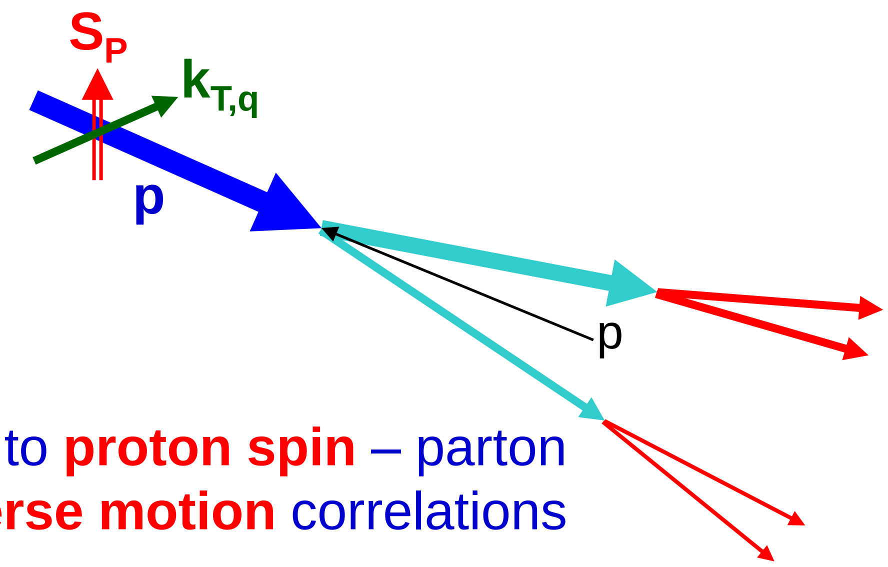
Why Transverse Momentum Dependent (TMD) phenomena?



- 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

Separating initial- and final-state effects

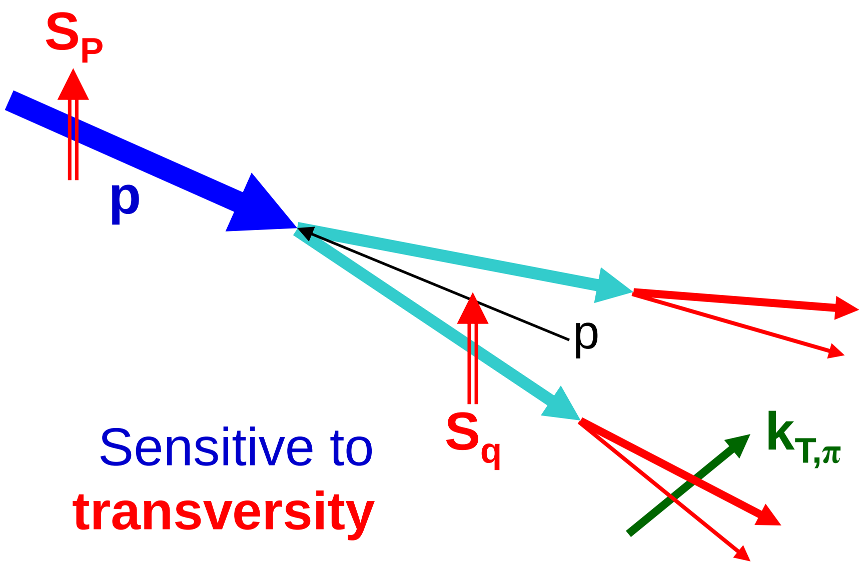
Sivers or twist-3 mechanisms:



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

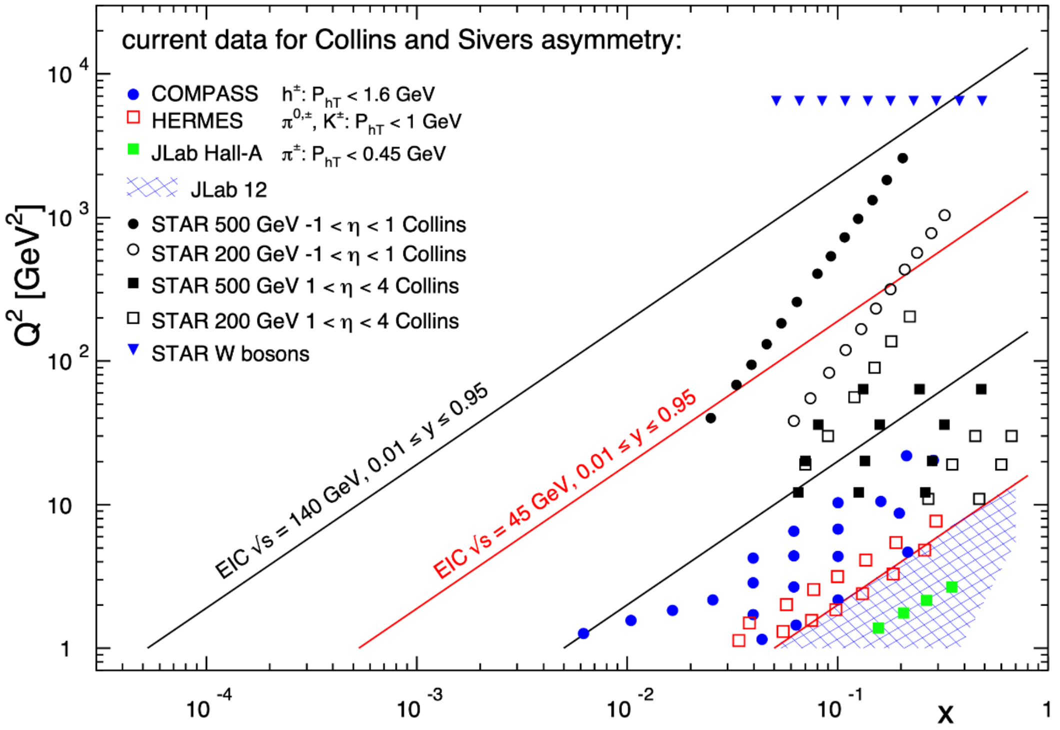
Collins or novel FF mechanisms:



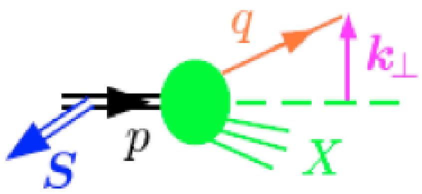
Sensitive to **transversity**

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

Transverse momentum dependent PDFs and FFs

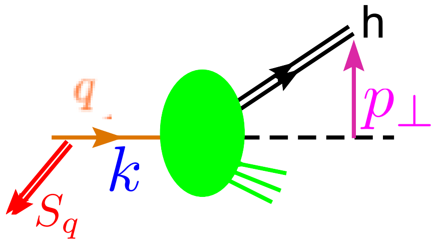


Sivers effect:



Unpolarized partons with a spin-dependent intrinsic k_T

Collins effect:

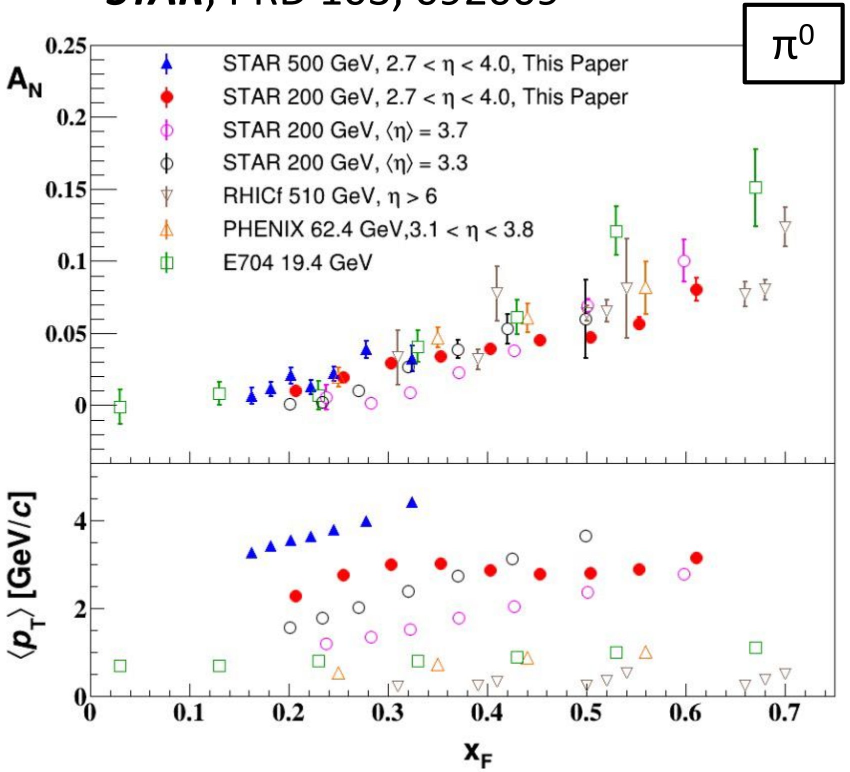


Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the quark momentum. Requires quark transversity.

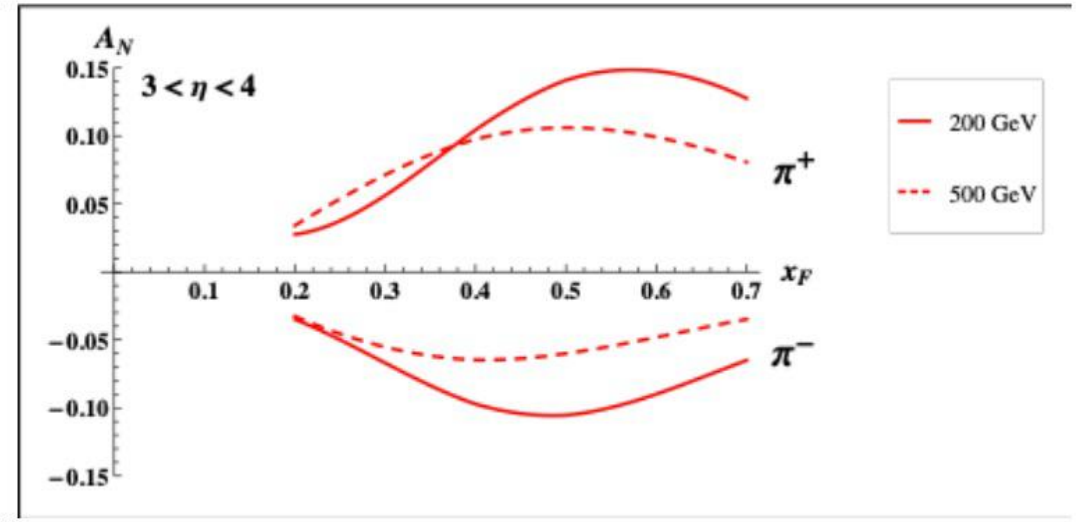
- Before ***STAR***, spin-dependent TMDs came only from fixed target ep data: high x and low Q^2
  - Need measurements at high Q^2 and a broad x range
- ***STAR*** mid- plus forward rapidity provides excellent kinematic overlap with future EIC measurements
  - Forward upgrade provides access to **quarks up to x ~ 0.5 and gluons down to x ~ 0.001**
  - 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



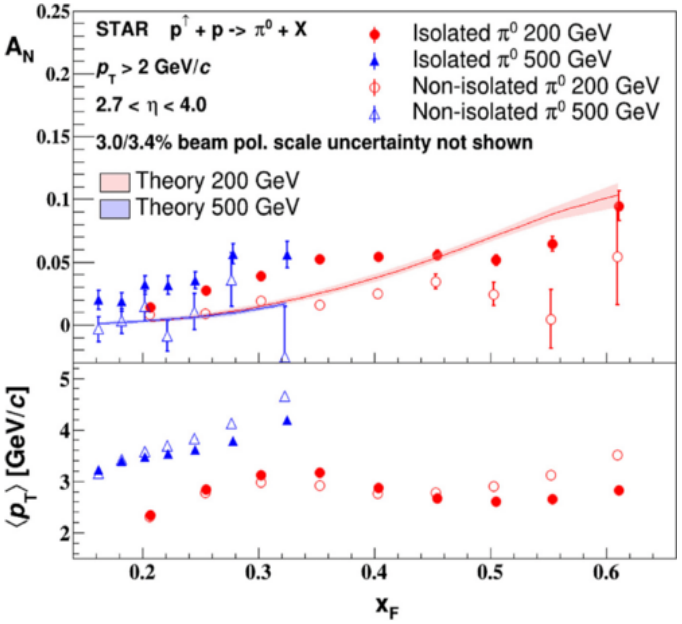
Predicted asymmetries for $\pi^{+/-}$ from Kanazawa et al, PRD 89, 111501



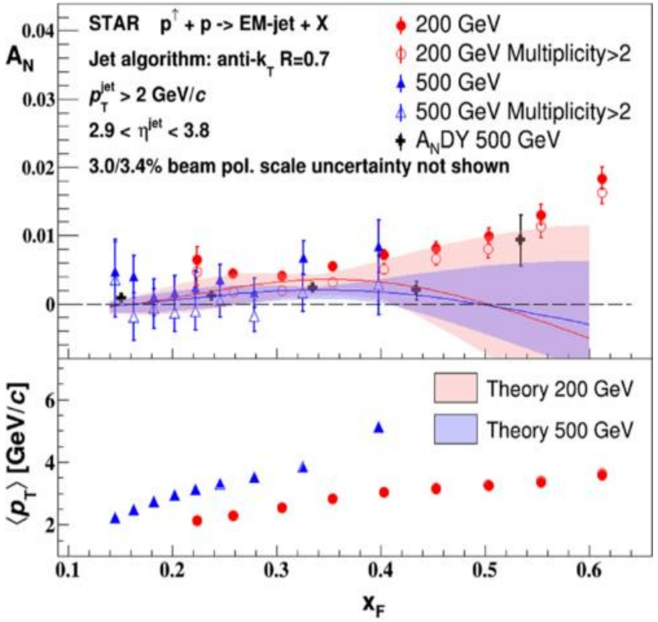
- Described by an interplay of initial-state Sivers distribution or its Twist-3 analog, the Efremov-Teryaev-Qiu-Sterman (ETQS) function, and final-state Collins effect or the related Twist-3 function H_{FU}
- A_N for $h^{+/-}$, direct photon, and π^0 can constrain the evolution and flavor dependence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

Underlying mechanism for the large forward rapidity A_N ?

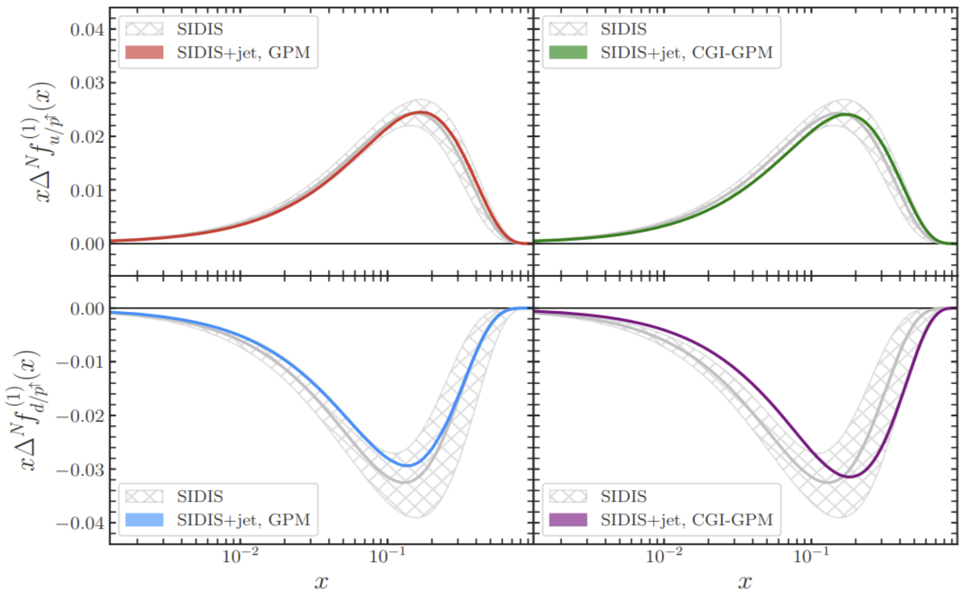
STAR, PRD 103, 092009
π^0 A_N



STAR, PRD 103, 092009
EM-jet A_N

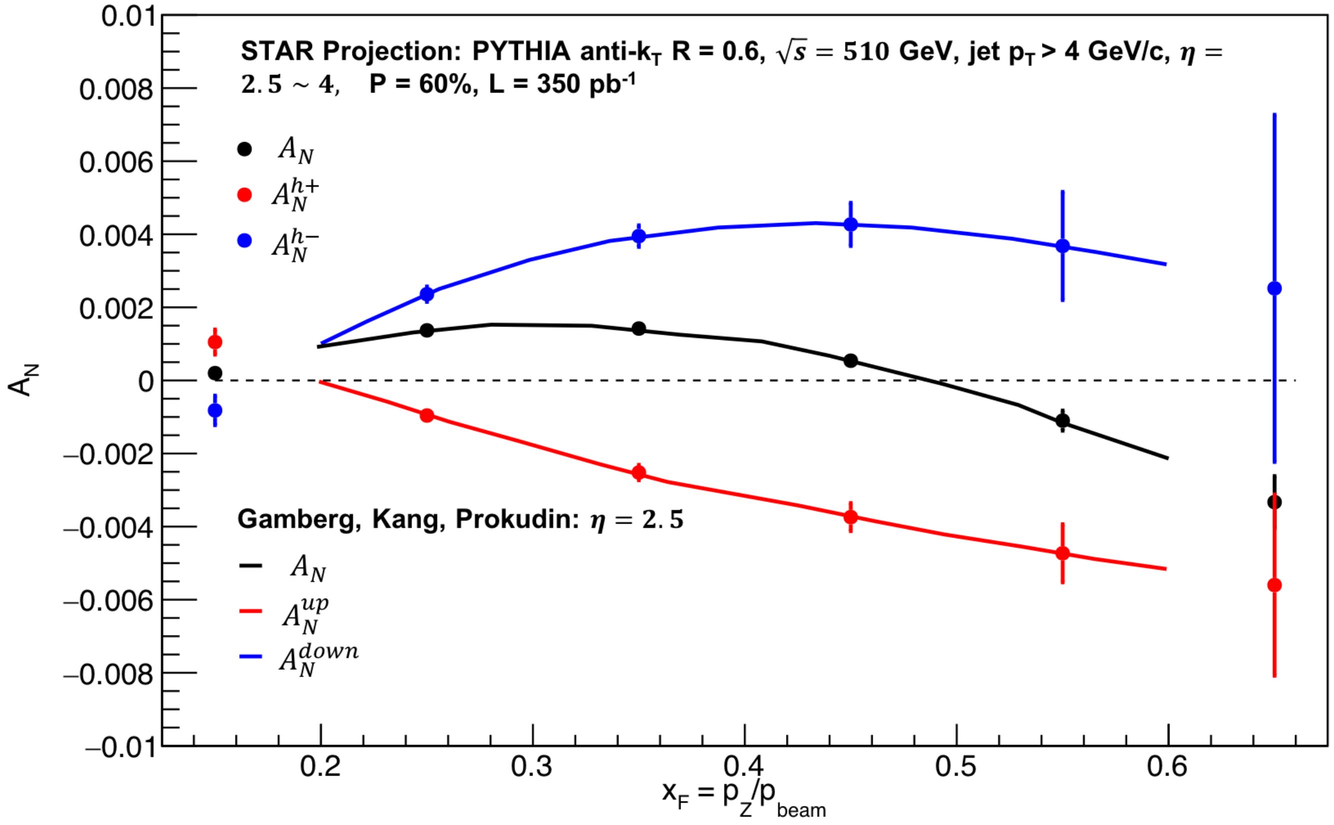


Boglione et al, PLB 815, 136135



- ***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

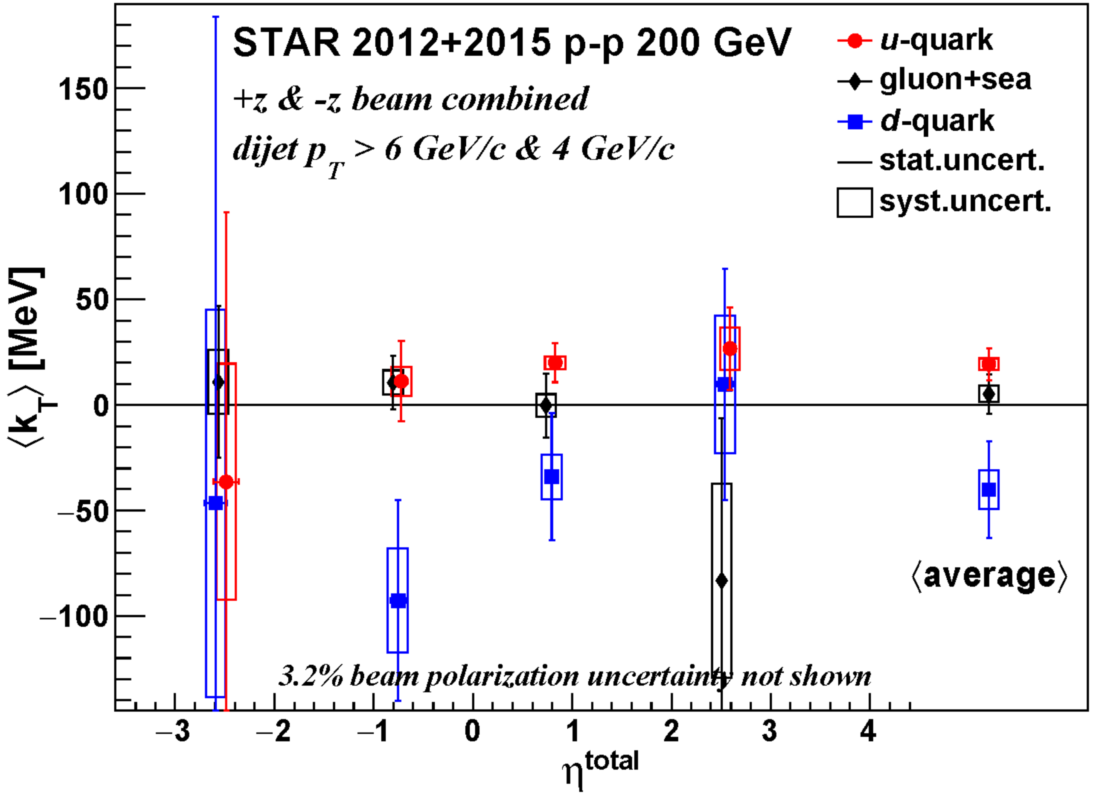
How well can the Forward Upgrade do?

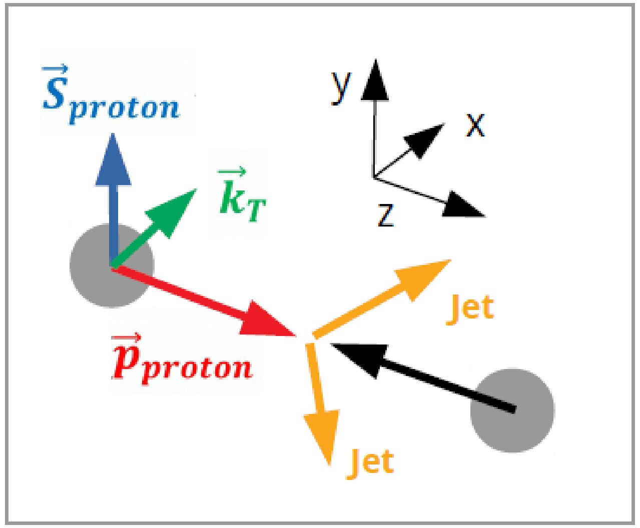


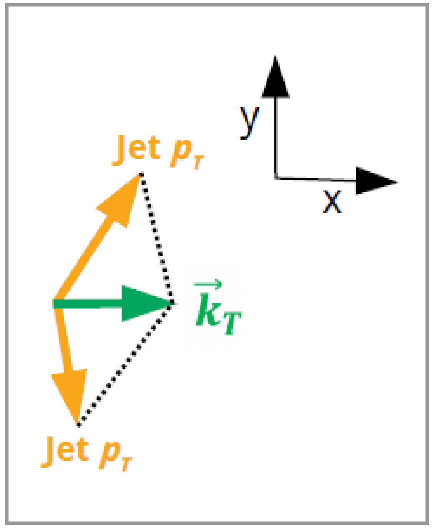
- A_N for full jet reconstruction, combined with charge-sign tagging of a hadron fragment with *z* > 0.5
  - Projected statistical uncertainties drawn on twist-3 predictions from Gamberg et al
  - Up to 10 σ separation between plus-tagged and minus-tagged jet A_N

Di-jet Sivers effect

STAR, arXiv:2305.10359

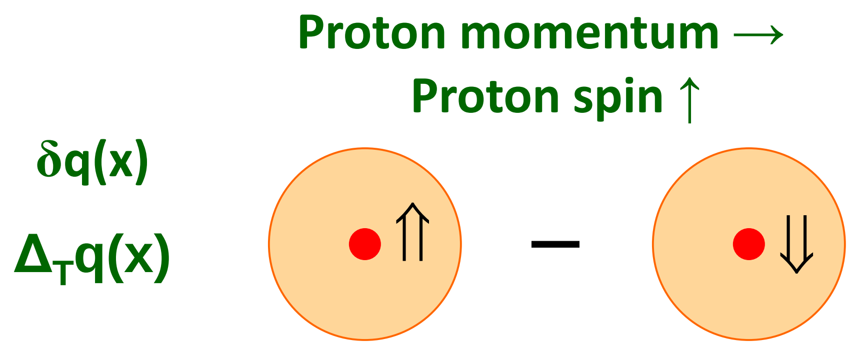


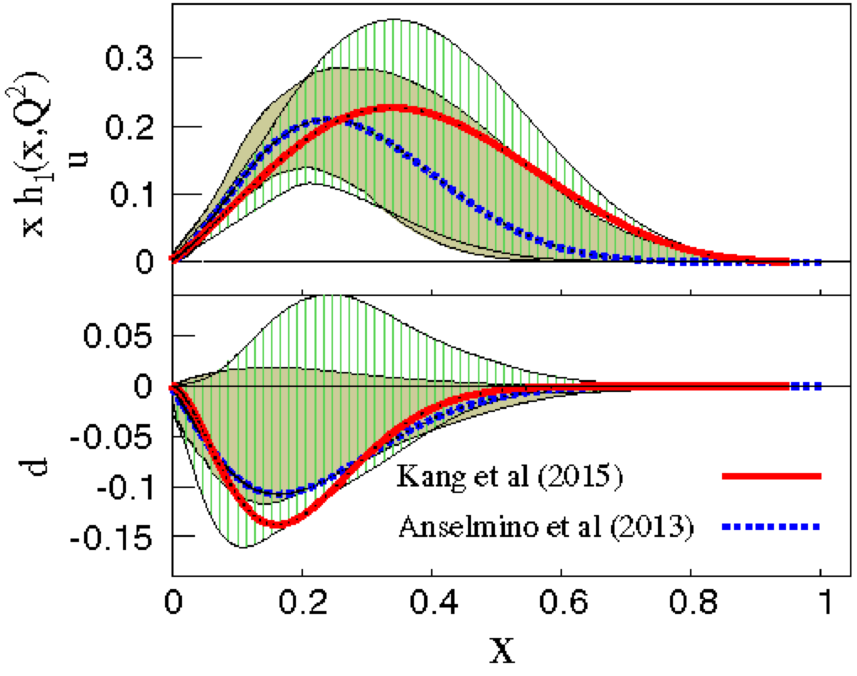




- ***STAR*** has performed the first ever observation of the Sivers effect in di-jet production
- Mid-rapidity results at √s = 200 GeV show that up and down quarks have opposite sign spin-dependent $\langle k_T \rangle$
  - $\langle k_T \rangle_d \sim -2 \langle k_T \rangle_u$
  - Gluon+sea quarks have $\langle k_T \rangle \sim 0$
- $\eta^{total} = \eta_3 + \eta_4 \sim \ln(x_1/x_2)$
  - Mid-rapidity STAR only covers $|\eta_3 + \eta_4| < 3$
    - Sample x up to 0.21 (and down to 0.02)
- **Forward Upgrade provides access to $|\eta_3 + \eta_4| \sim 6$**
  - **Sample x values from 0.001 to 0.5**

Transversity and the Collins fragmentation function

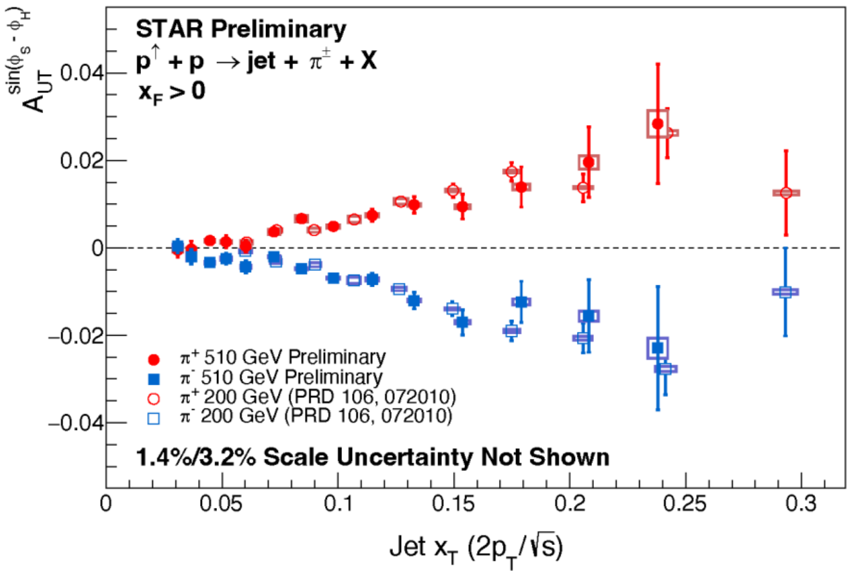


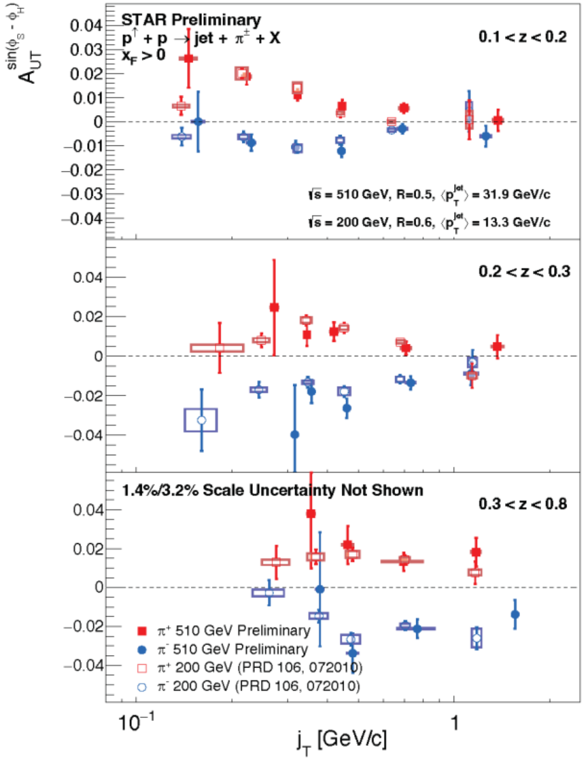


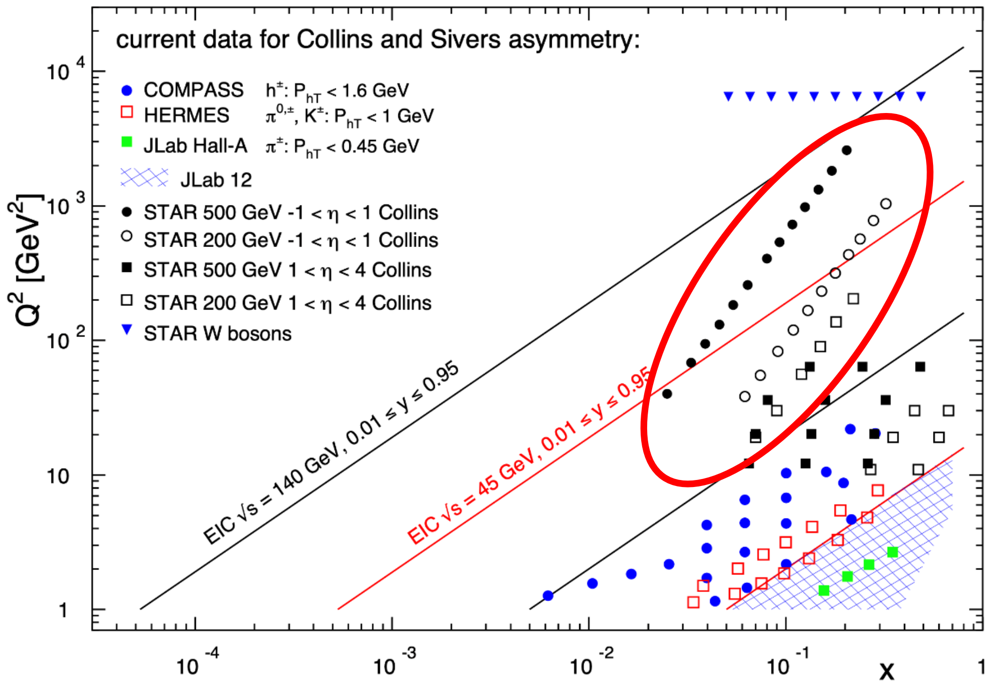
- Quark polarization along the spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Integral gives tensor charge – critical input for low-energy beyond the Standard Model calculations
  - Difference between helicity and transversity directly related to parton orbital angular momentum
- Chiral odd
  - Much less data than for helicity
- Collins FF: azimuthal modulation of hadron fragments
  - Excellent testing ground for TMD factorization, universality, and evolution
- Before ***STAR***, transversity only observed in SIDIS + e^+e^-
- Several recent global analyses, including:
  - Collins effect SIDIS input:
    - PRD 93, 014009 (2016)
    - PRD 92, 114023 (2015)
    - PRD 102, 054002 (2020)
  - IFF SIDIS + ***STAR*** pp input:
    - PRL 120, 192001 (2018)
  - All show large uncertainties

***STAR* Collins asymmetry measurements**

STAR, PRD 106, 070210; and prelim.







- ***STAR*** has performed detailed measurements of the Collins asymmetry at mid-rapidity in both 200 and 510 GeV *pp* collisions
  - Span 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 Collins asymmetry measurements

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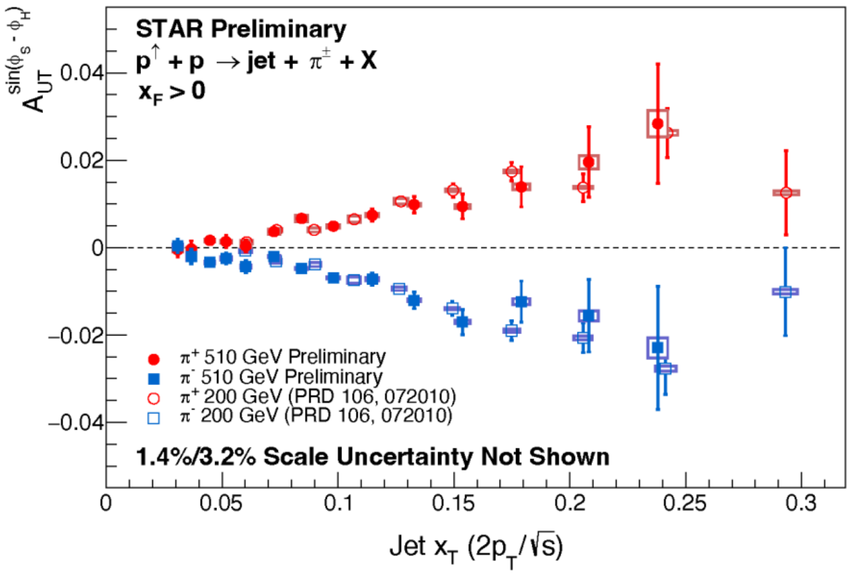

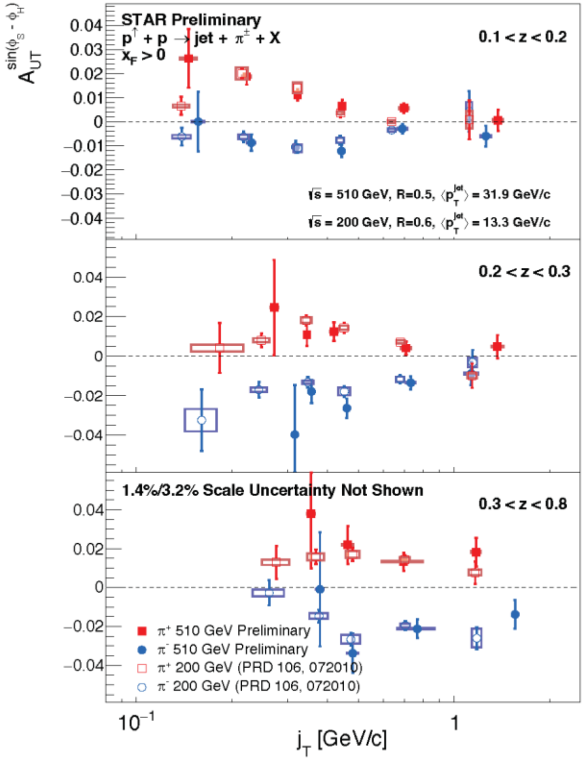

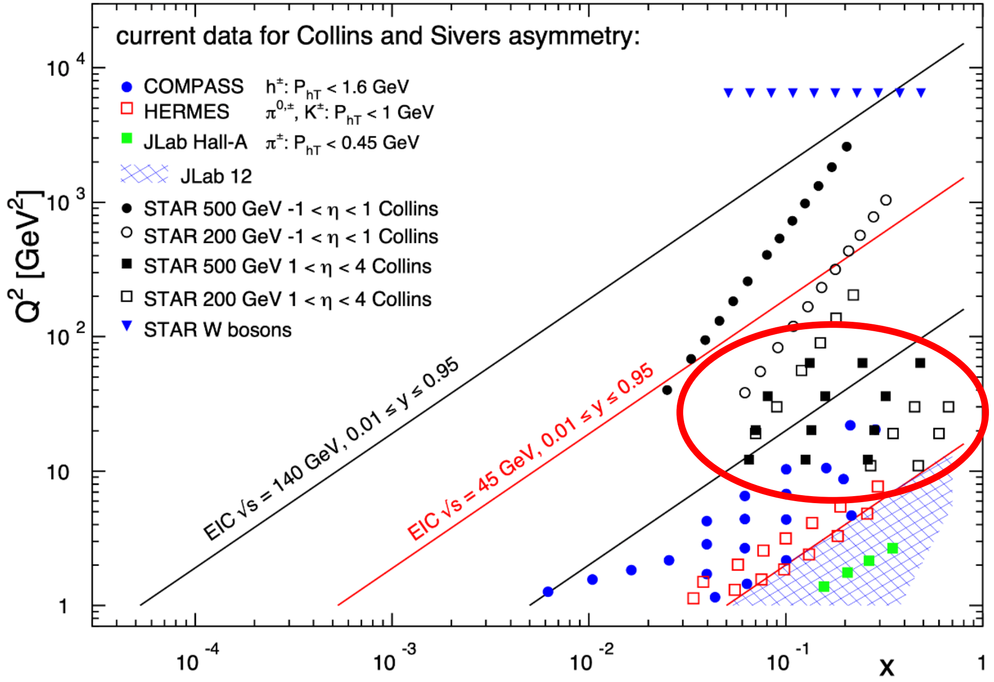

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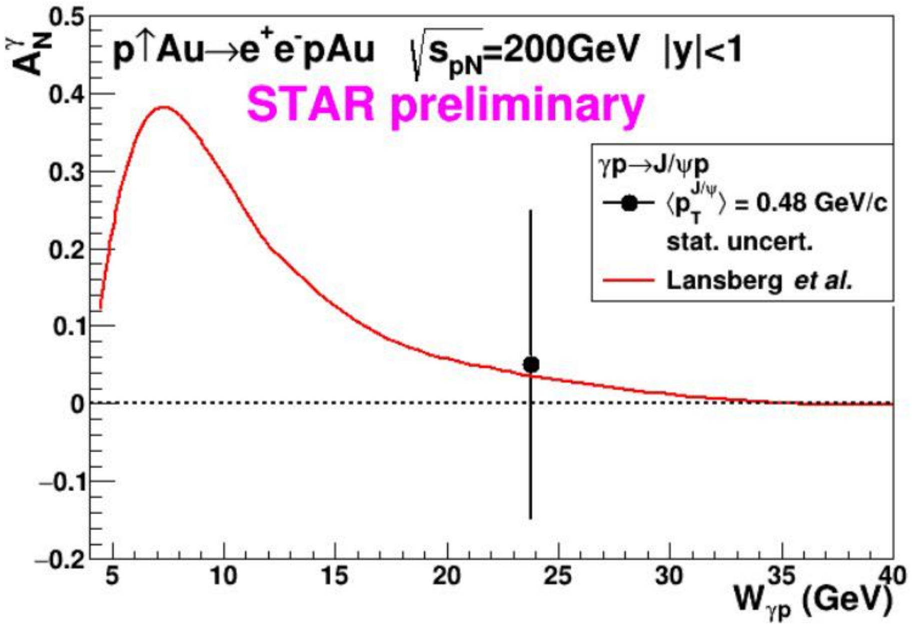
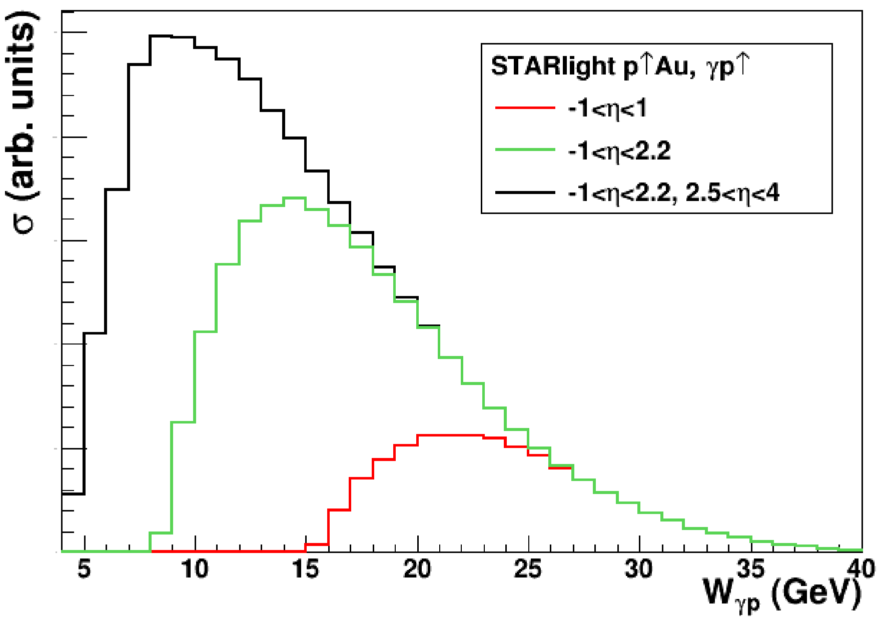
  - Span similar *x* range as existing SIDIS measurements
  - Q^2 values are one to two orders of magnitude higher than SIDIS at the same *x*
- The Forward Upgrade will extend the ***x* range to above 0.5**, while **filling in the Q^2 region** between SIDIS and mid-rapidity ***STAR***
- Essential input for **future universality studies at the EIC**

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

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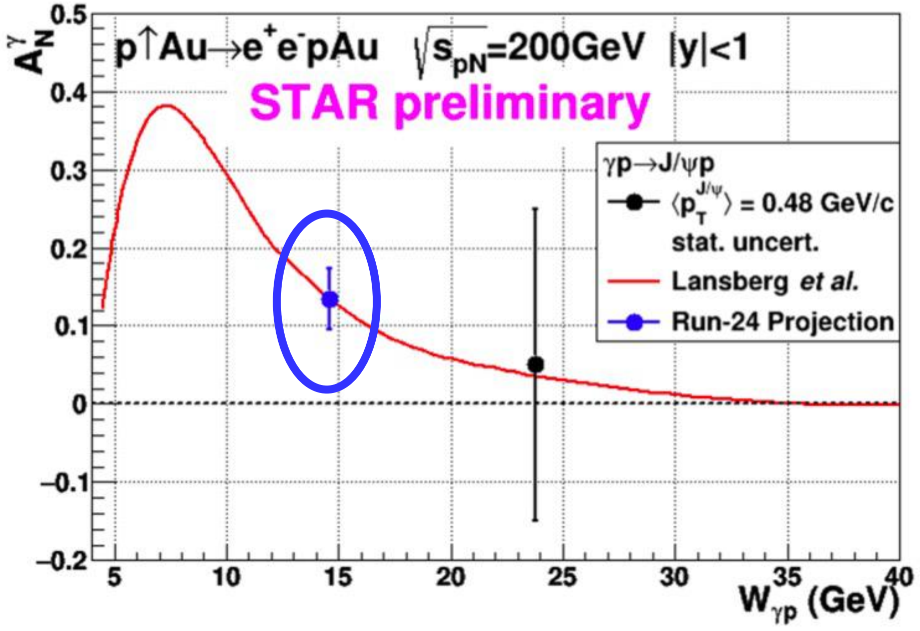

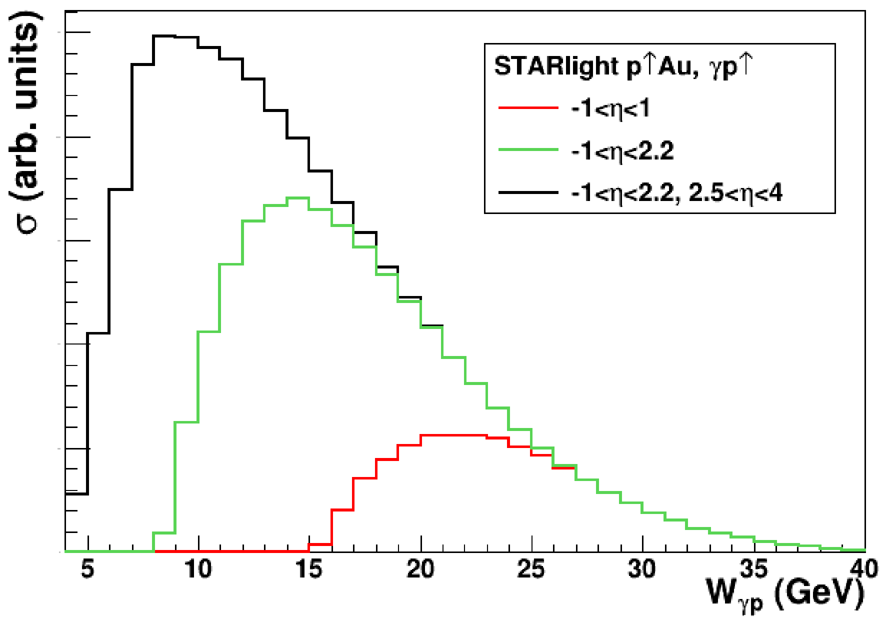

- Exclusive J/Ψ A_N in 200 GeV ultra-peripheral *p*+Au collisions is sensitive to the GPD E_g
  - $Q^2 \sim 10$ GeV^2; $10^{-4} < x < 10^{-1}$
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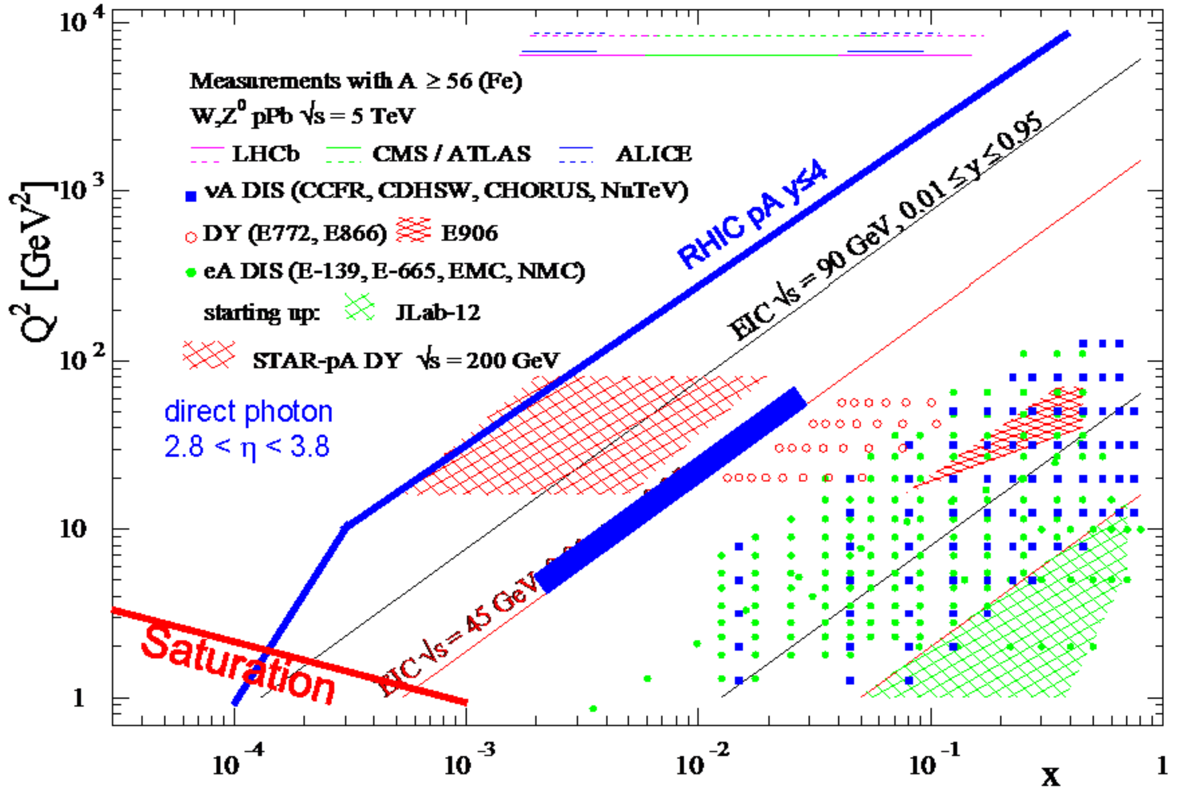
- ***STAR*** performed a proof-of-principle measurement with the TPC during 2015
- ***STAR*** Forward Upgrade will enable measurement at smaller $W_{\gamma p}$, where both the cross section and the signal are expected to be much larger

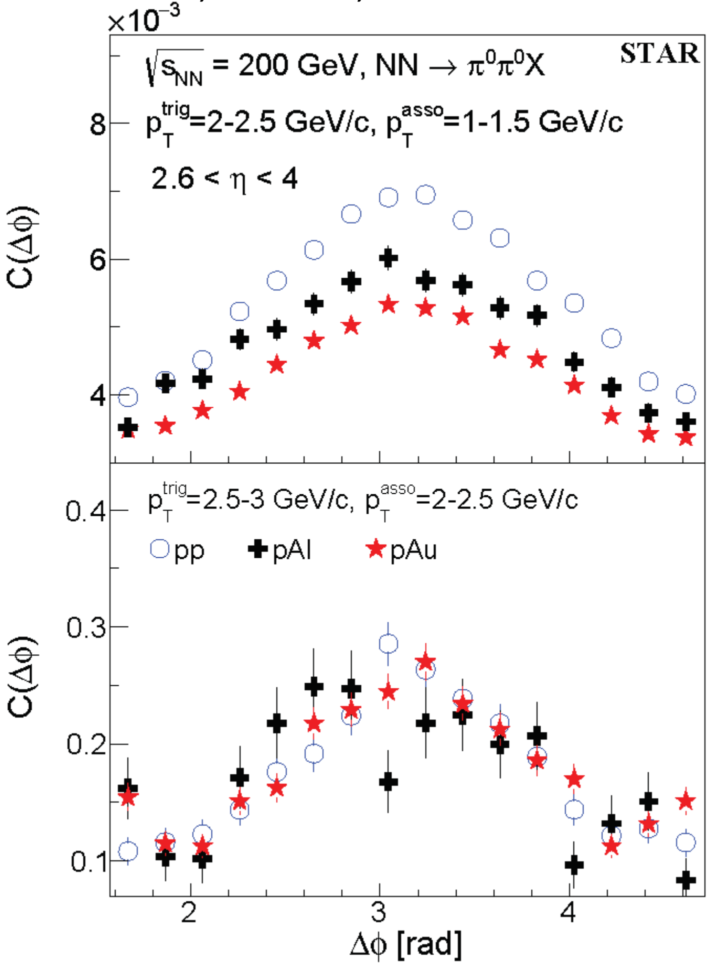
Nuclear parton distribution functions

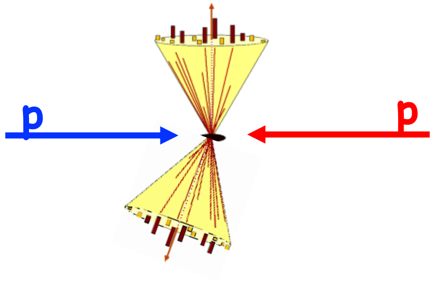


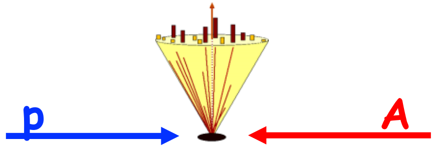
- The Forward Upgrade will enable measurements of R_{pAu} for direct photon and Drell-Yan production at $\sqrt{s_{NN}}$ = 200 GeV
  - Direct photons will constrain the nuclear gluon distribution over 0.0025 <~ x <~ 0.025
  - Drell-Yan di-electrons will constrain the nuclear sea quark distribution over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

Probing non-linear effects in QCD

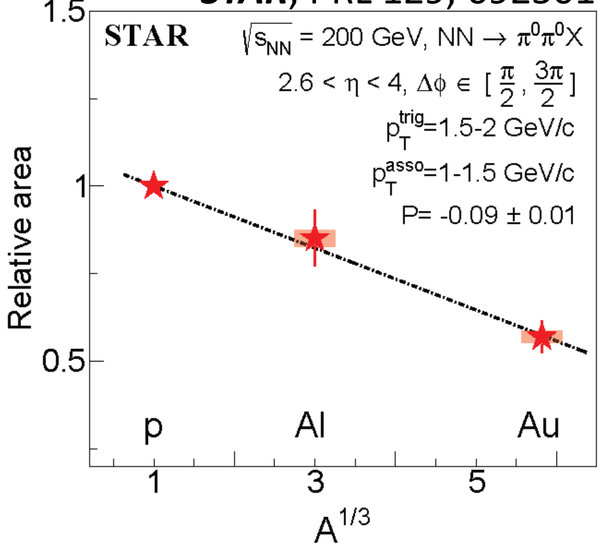
***STAR*, PRL 129, 092501**





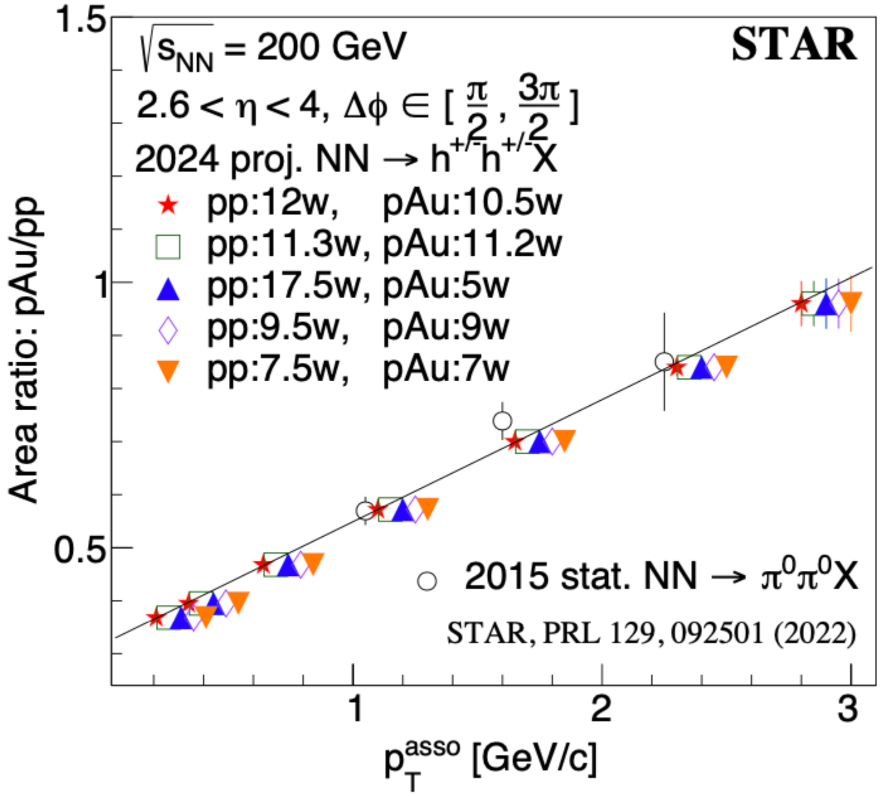


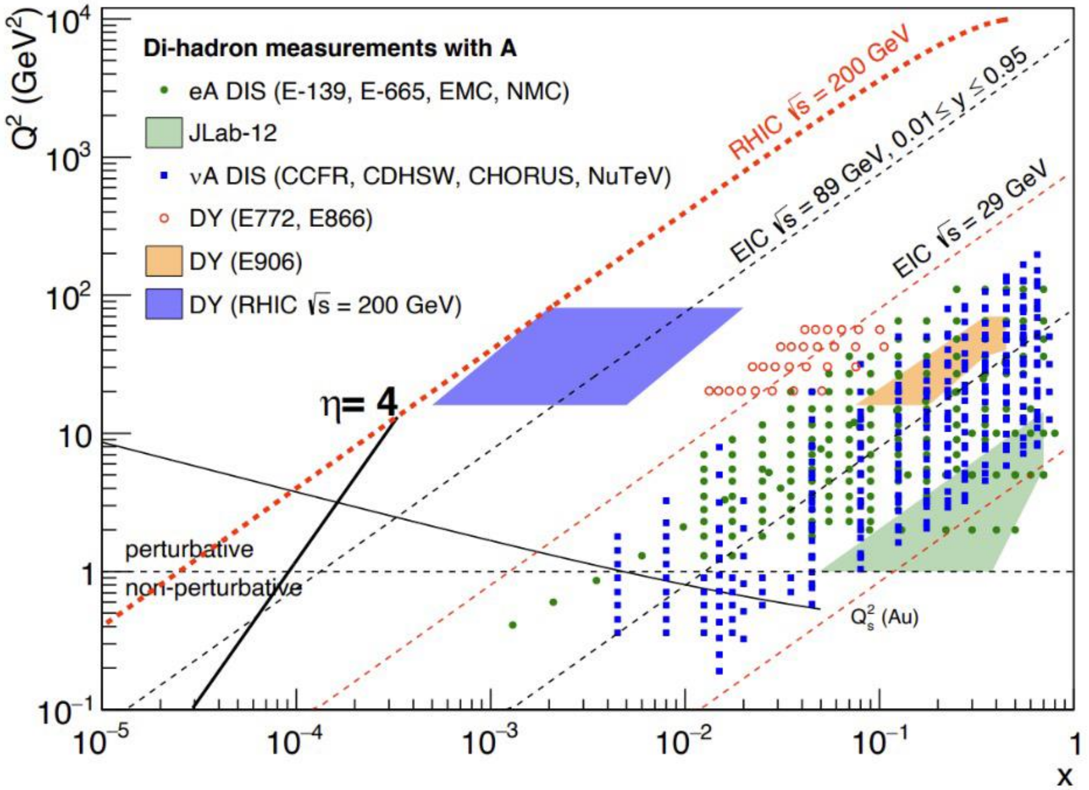
***STAR*, PRL 129, 092501**



- 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
    - The suppression follows the expected $A^{1/3}$ dependence
  - 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

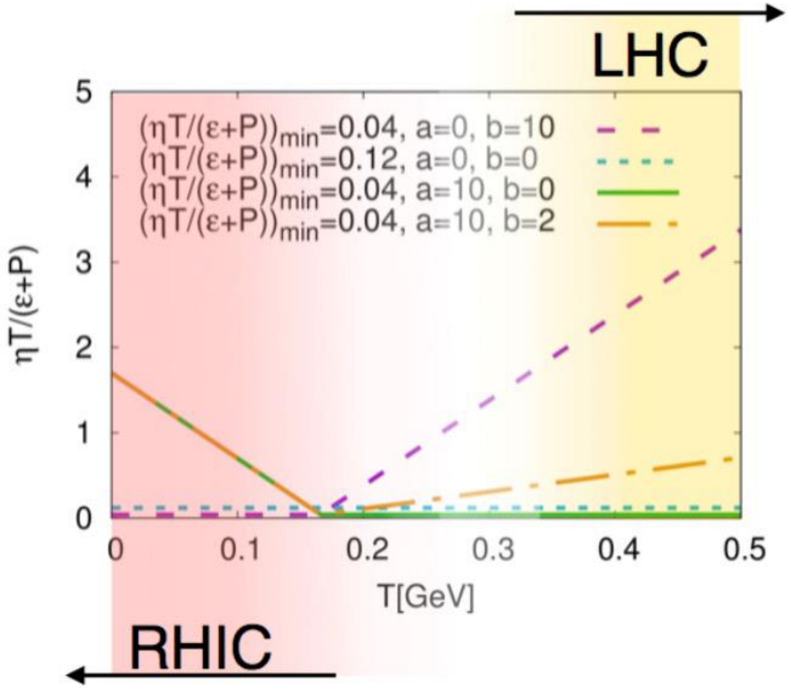
Non-linear QCD with the Forward Upgrade

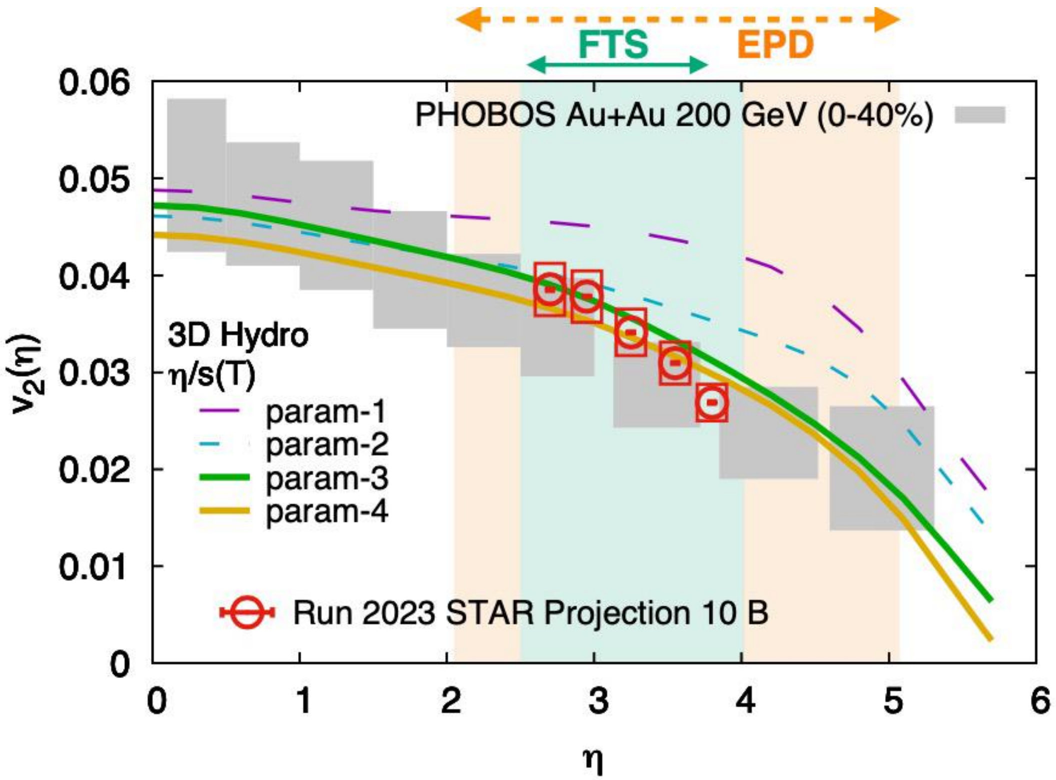




- The Forward Upgrade enables similar studies in $h^{+/-}$-$h^{+/-}$, di-jets, and γ-jet
- $h^{+/-}$-$h^{+/-}$ can extend measurements to both lower and higher (x, Q^2) to **map out the Q_s^2 boundary**
- **Di-jet and γ+jet** are important complements: sample different mixes of WW and dipole gluon distributions

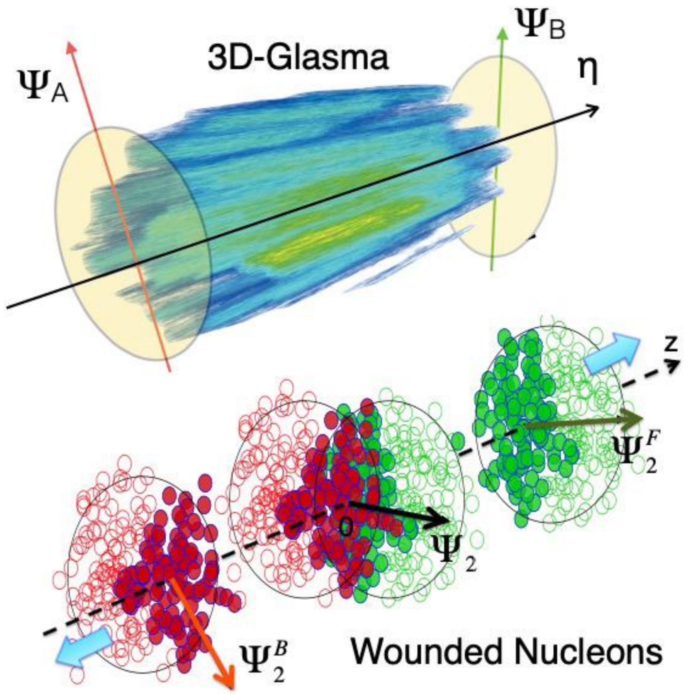
Flow measurements in Au+Au to constrain η/s

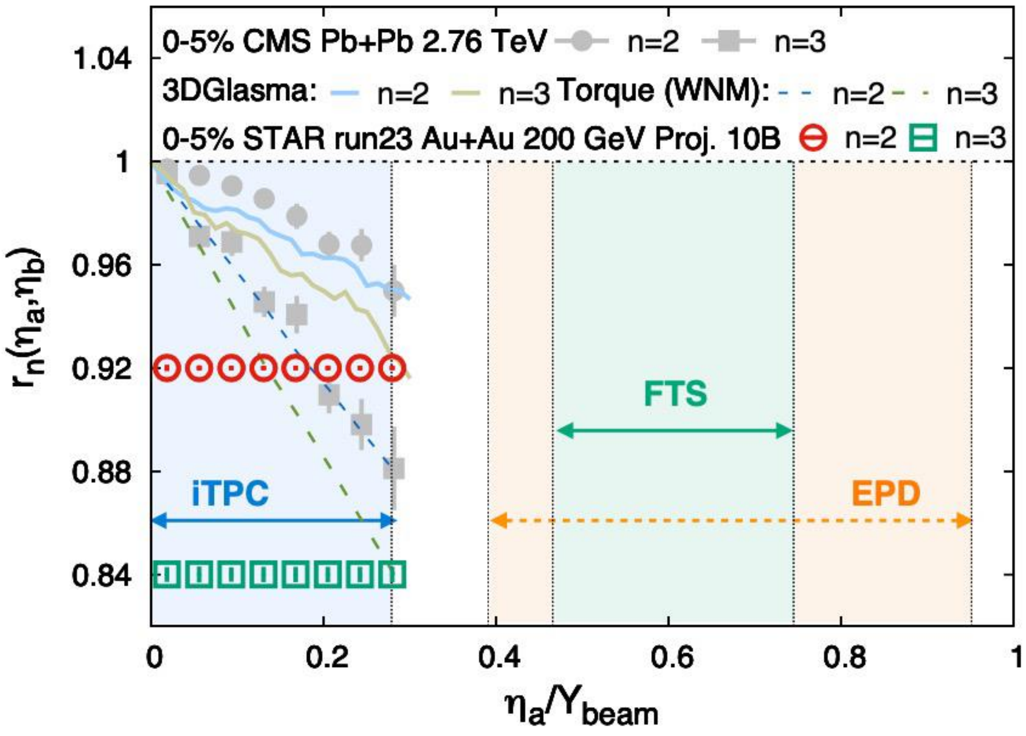




- η/s is expected to be smallest in the RHIC energy regime
- Flow measurements at forward rapidity are sensitive to the temperature dependence of η/s
- ***STAR*** Forward Upgrade measurements will be far more precise than previous PHOBOS measurements

Constrain the longitudinal structure of the initial state



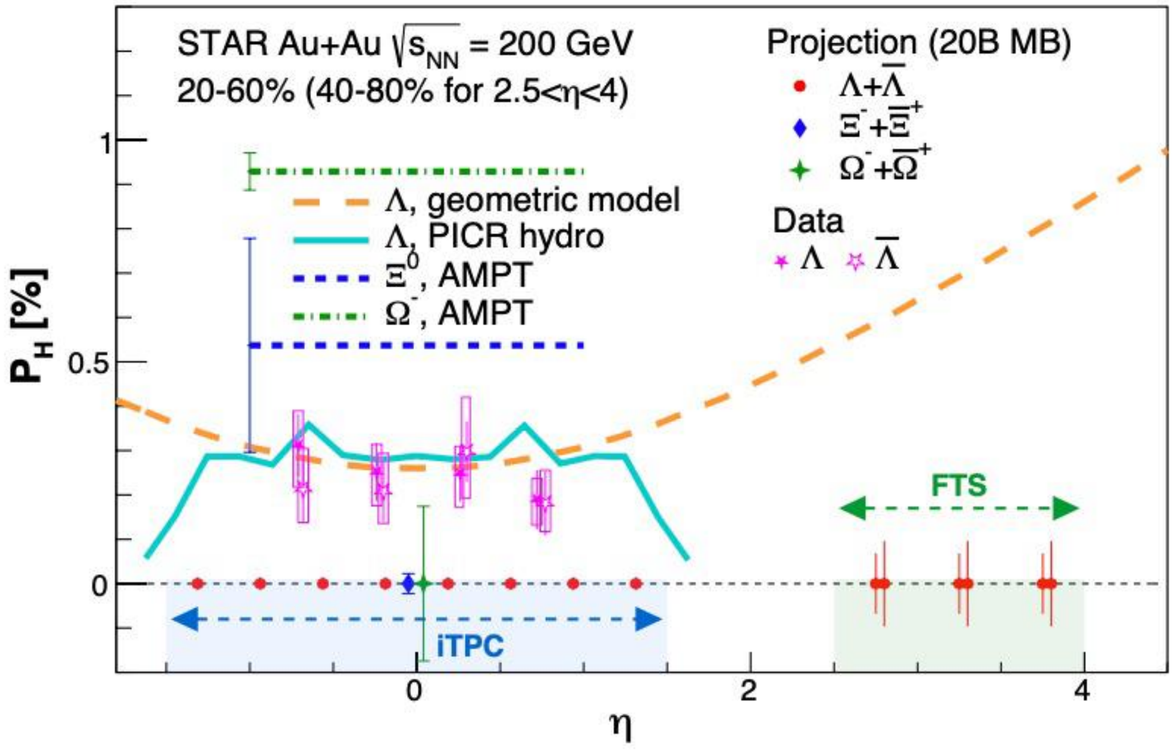


$$r_n(\eta_a, \eta_b) = V_{n\Delta}(-\eta_a, \eta_b)/V_{n\Delta}(\eta_a, \eta_b)$$

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 < 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:
508 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- **Sivers asymmetries for hadrons, (tagged) jets, and di-jets**
- **Collins asymmetries 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 was **completed on time** and **on budget**, in spite of the pandemic
- The ***STAR*** Forward Upgrade has **operated very well** during the 2022 and '23 RHIC runs
- The ***STAR*** Forward Upgrade **enables** 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!**