STAR Beam Use Requests for Runs 24-25

Lijuan Ruan (BNL)

Executive summary

28 cryo-weeks for p+p, p+Au in Run 24
28 cryo-weeks in Run 25 and 6 additional cryo-weeks in Run 24 for Au+Au

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	$p+p$	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

Transversely polarized pp and p+Au with equal nucleon-nucleon luminosities essential to optimize several critical measurements

p+p: enable detailed evolution studies, critical for precise factorization and universality tests, essential baseline for p+Au

p+Au: probe gluon saturation, quark-gluon structure of heavy nuclei, propagation and hadronization of colored partons

Au+Au: probe the inner workings of the QGP

Physics program

- quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions for initial and final state TMDs

  Test of Sivers non-universality: $Sivers_{SIDIS}$ = -- $Sivers_{DY, W+/-, Z0;}$ Full jet and dijet Sivers asymmetry

  Probe final state TMDs: Collins asymmetry for hadrons in jet
  - **Requirement:**
    - large data sets √s = 200 and 500 GeV $p^{\uparrow}p$
      → low to high x, highest and lowest x with fSTAR
    - A_{UT} for $W^{+/-}$ Z^0, A_{UT} for hadrons in jet
- First look Gluon GPD → E_g
  - **Requirement:**
    - data sets √s = 500 GeV $p^{\uparrow}p$ and √s = 200 GeV $p^{\uparrow}A$
    - A_{UT} for J/ψ in UPC
- Physics driving the large A_N at forward rapidities and high x_F
  - **Requirement:**
    - large data sets √s = 200 and 500 GeV $p^{\uparrow}p$
      → low to highest x_F → fSTAR
    - charge hadron A_N at forward rapidities
- Nuclear dependence of PDFs, FF, and TMDs
  - **Requirement:**
    - large equal data set of √s = 200 $p^{\uparrow}p$ and $p^{\uparrow}Au$
      → low to high x, highest and lowest x with fSTAR
    - R_{pA} direct photons and DY, hadrons in jet A_{UT}
- non-linear effects in QCD
  - **Requirement:**
    - large equal data set of √s = 200 $p^{\uparrow}p$ and $p^{\uparrow}Au$
      → lowest-x through fSTAR
    - dihadron correlations for $h^{+/-}$, γ-jet, di-jets

To address important questions about the inner workings of the QGP

- What is the nature of the 3-dimensional initial state at RHIC energies? r_n over a wide rapidity, J/ψ v_1, photon Wigner distributions
- What is the precise temperature dependence of shear and bulk viscosity? v_n as a function of η
- What can be learned about confinement from charmonium measurements? J/ψ v_2
- What is the temperature of the medium? Different ϒ states, ψ(2S), thermal dileptons
- What are the electrical, magnetic, and chiral properties of the medium? Λ, Ξ, Ω P_H and K*, ϕ, J/ψ ρ_{00}, thermal dileptons, CME observables
- What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale? γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure
- What is the precise nature of the transition near μ_B=0? Net-proton C_6/C_2
- What can we learn about the strong interaction? Correlation functions

To inform EIC physics with photon induced processes:

- Probe gluon distribution inside the nucleus: vector mesons (J/ψ), dijets (?)
- Search for collectivity and signatures of baryon junction: inclusive charge particles and cross sections, v_n , identified particle spectra

Plans for Run-24

28 cryo-weeks for p+p, p+Au in Run 24

28 cryo-weeks in Run 25 and 6 additional cryo-weeks in Run 24 for Au+Au

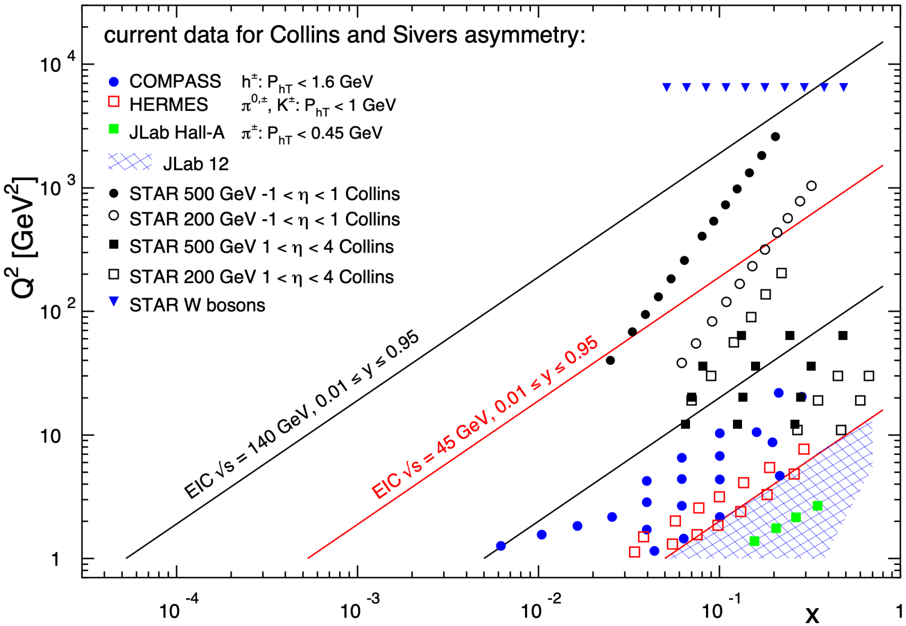
$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	$p+p$	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

1.2 (1.5) times the total luminosity in Run-15 p+p (p+Au)

2.7 (1.5) times the transverse lumi. in Run-15

Kinematic coverage for Collins and Sivers Asymmetry
STAR covers 0.005<x<0.5

Polarization:60%



Transversely polarized pp and p+Au with equal nucleon-nucleon luminosities essential to optimize several critical measurements

Physics Opportunities in 2024

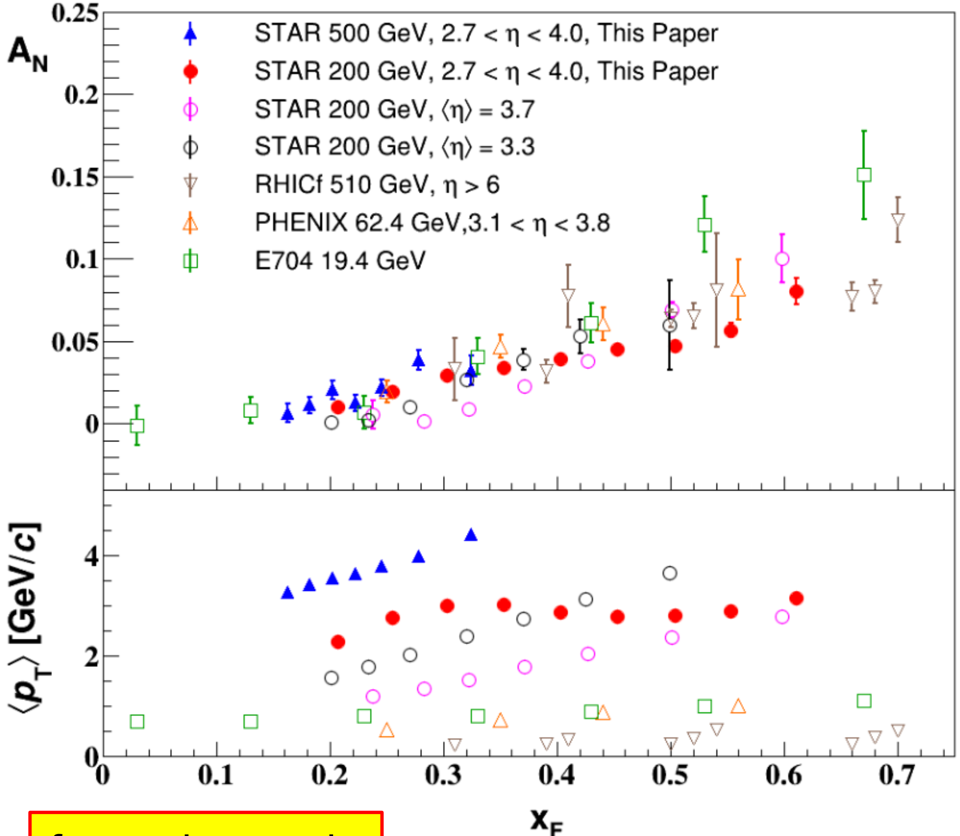
Central role played by 200 GeV pp:

- In most cases, similar measurements will be performed with 510 GeV and 200 GeV pp
- **Very wide *x* coverage ($0.005 < x < 0.5$)** by combining 200 and 510 GeV pp
  - 510 (200) GeV pp with the Forward Upgrade provides access to the lowest (highest) *x* value with jets and hadrons in jets over a wide range of perturbative scales
  - 200 GeV pp **provides best coverage for the intermediate *x* range**
  - provides **best overlap with the x-Q^2 coverage of EIC**
- Overlapping *x* coverage **enables detailed evolution studies**
- 200 GeV pp **critical for precise factorization and universality tests**
  - **Best statistical precision for much of the kinematics overlapping with EIC**

- 200 GeV pp essential baseline for 200 GeV p+Au
  - Must investigate **gluon saturation in both pA and eA to verify universality**
  - Precise probe of **the quark-gluon structure of heavy nuclei**
  - Explore the **propagation and hadronization of colored partons**

Must measure non-perturbative part of TMD experimentally!

Inclusive transverse single spin asymmetries at forward



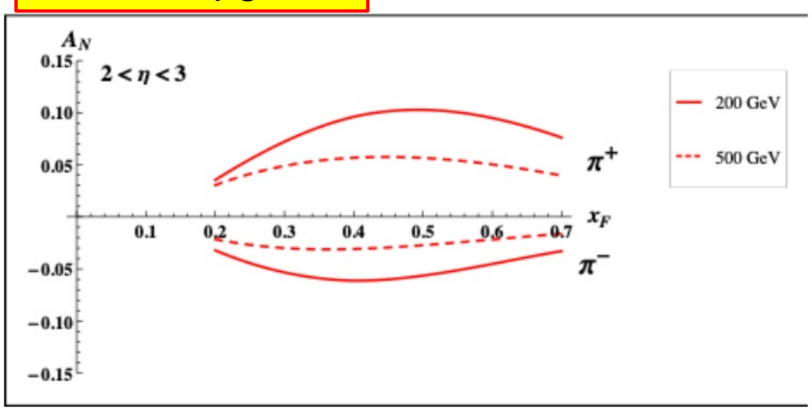
Interplay of
Initial state: Sivers distribution or its twist-3 analog, the Efremov-Teryaev-Qiu-Sterman (ETQS) function

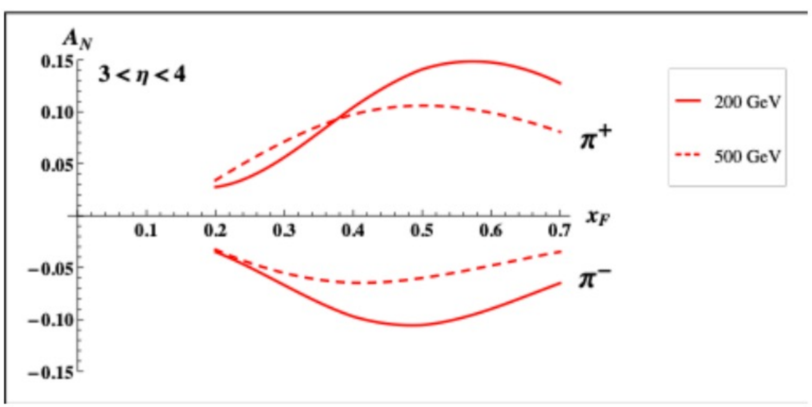
and/or

Final state: fragmentation of polarized quarks, Collins function or related twist-3 function H_{FU}

A_N for $h^{\pm}$, direct γ and π^0 :constrain the evolution and flavor dependence of ETQS distribution and determine the role of H_{FU}

forward upgrade

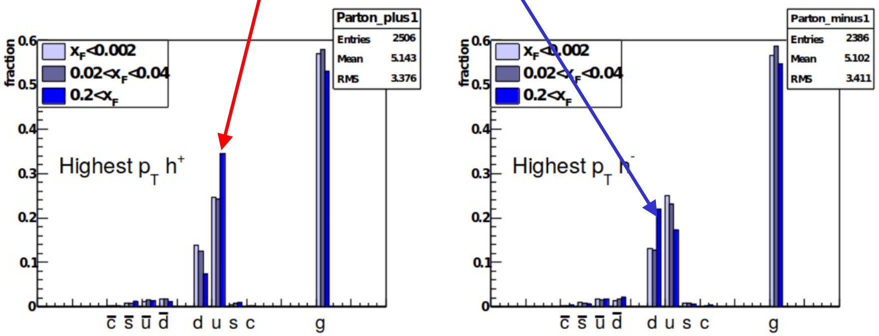


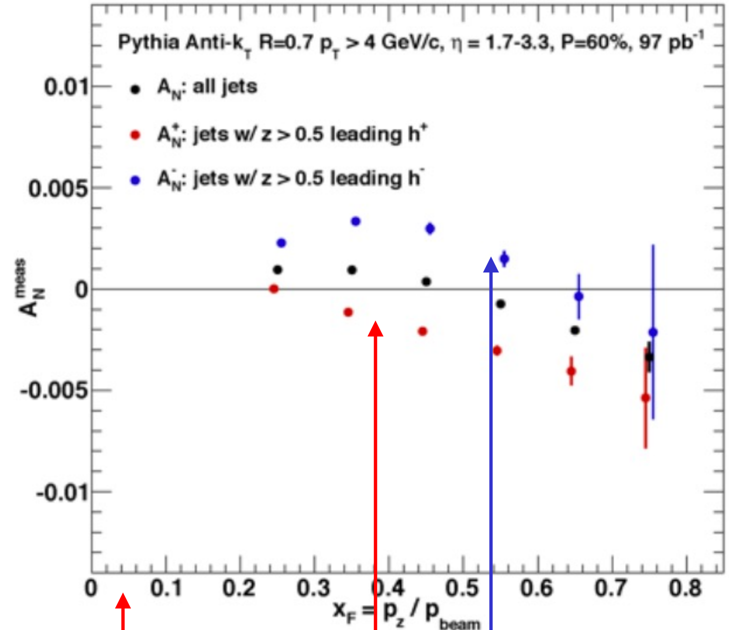


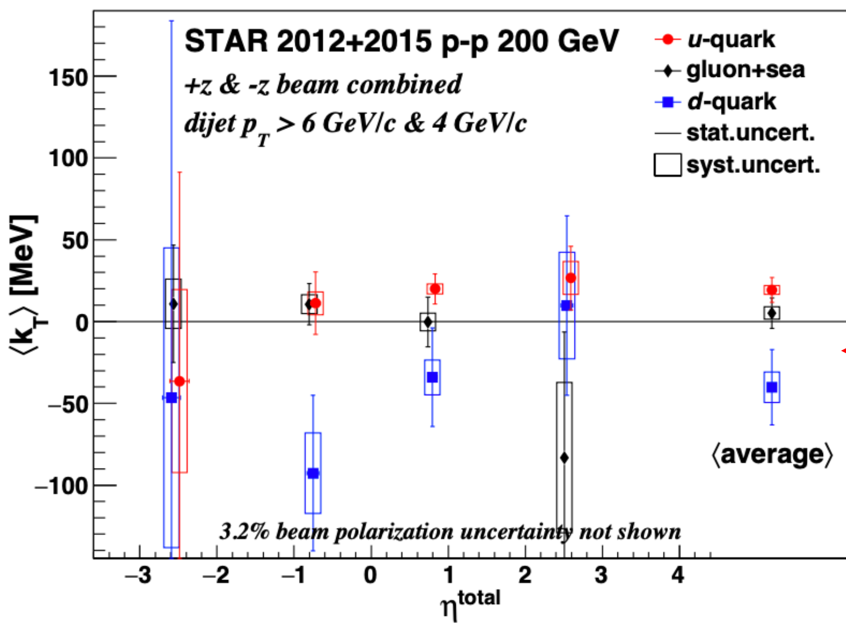
Sivers and ETQS function

forward upgrade

With positively/negatively charged leading hadron







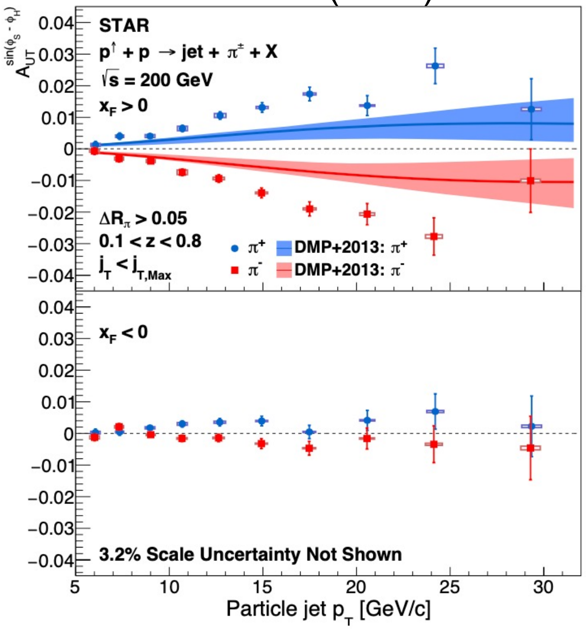
Full jet reconstruction, along with identification of a high-z hadron of known charge at forward rapidity, sensitive to u and d Sivers asymmetry

The average $\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6$ MeV/c, $\langle k_T^d \rangle = -40.2 \pm 23.0 \pm 9.3$ MeV/c, $\langle k_T^{g+sea} \rangle = 5.2 \pm 9.3 \pm 3.8$ MeV/c

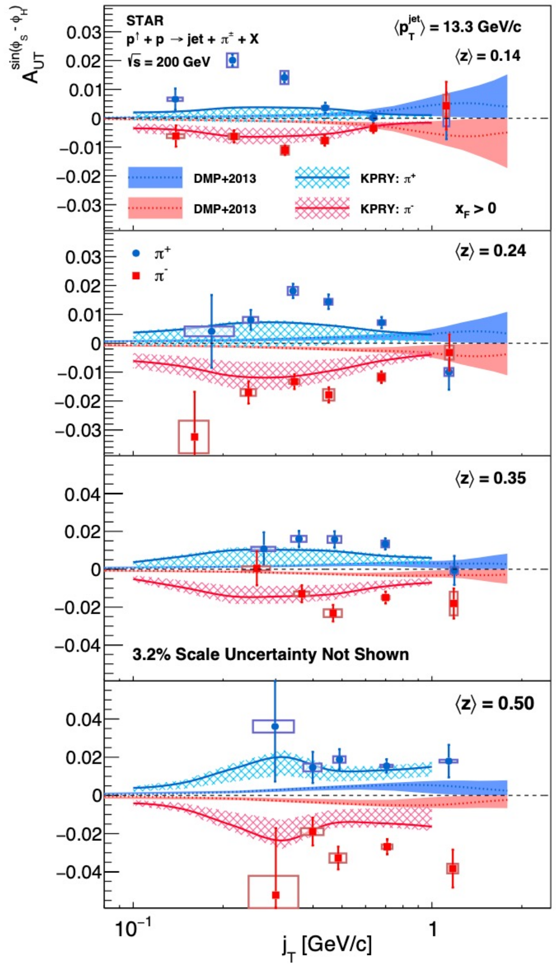
First observation of non-zero Sivers asymmetry in dijet production

Mid-rapidity Collins effect at 200 vs 510 GeV

PRD106 (2022) 72010

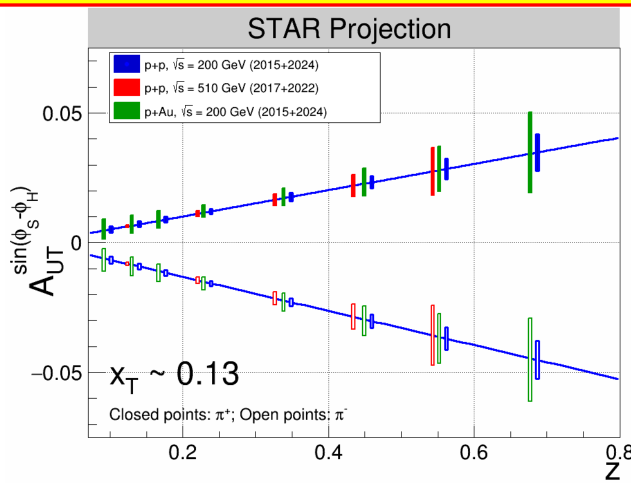


A_{UT} vs jet (p_T,η) measures the collinear transversity distribution



A_{UT} vs hadron (z,j_T) maps the Collins fragmentation function

improved PID, extended η coverage by iTPC



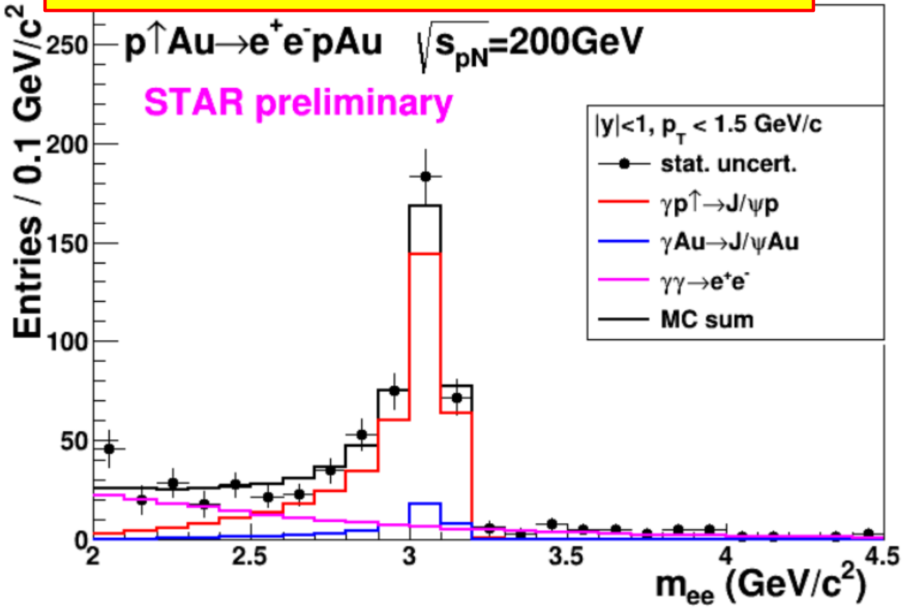
Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential x-Q^2 overlap with EIC

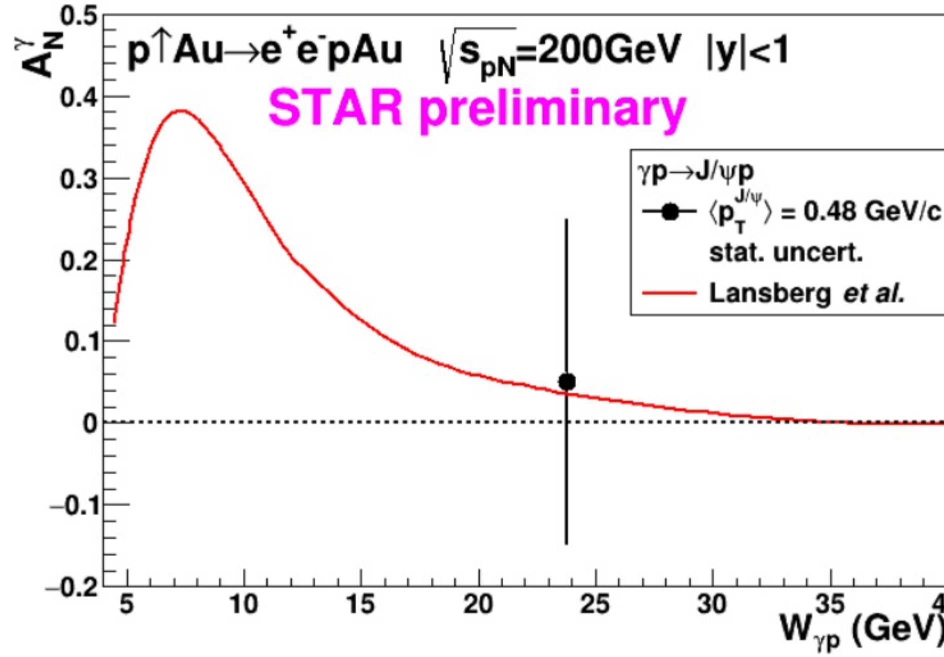
A_{UT} in p+Au: an alternative universality test and a unique look at spin-dependent hadronization

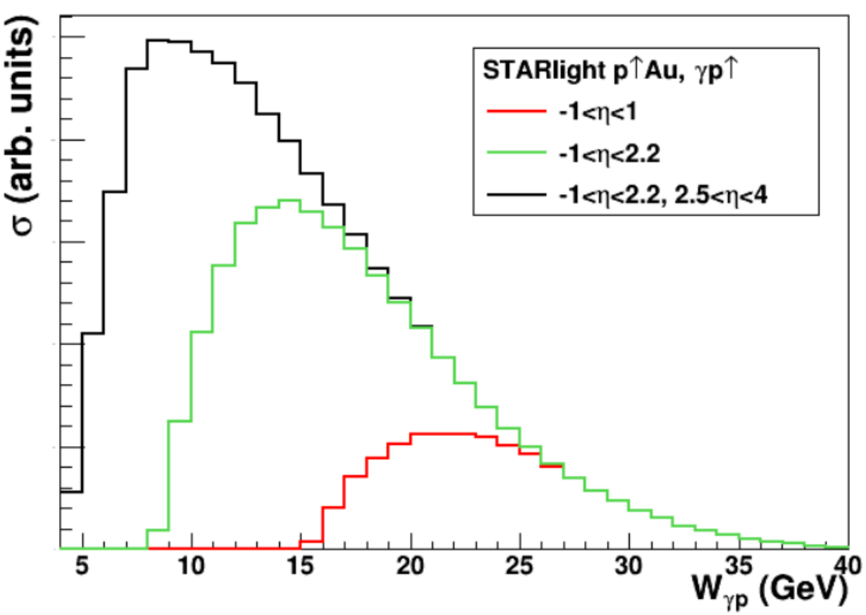
- **Run-24 will reduce these uncertainties at 200 GeV by a factor of 2, enabling the most sensitive universality test with EIC data**

Generalized parton distribution

low material, improved PID, extended η coverage by iTPC, forward upgrade







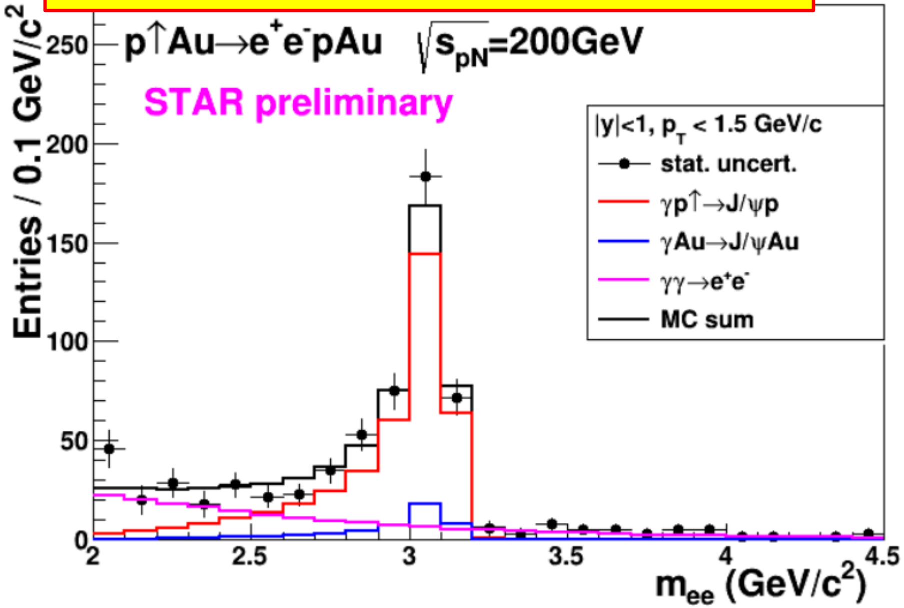
Exclusive J/ψ A_N in UPC, Q^2~10 GeV^2, $10^{-4}<x<10^{-1}$

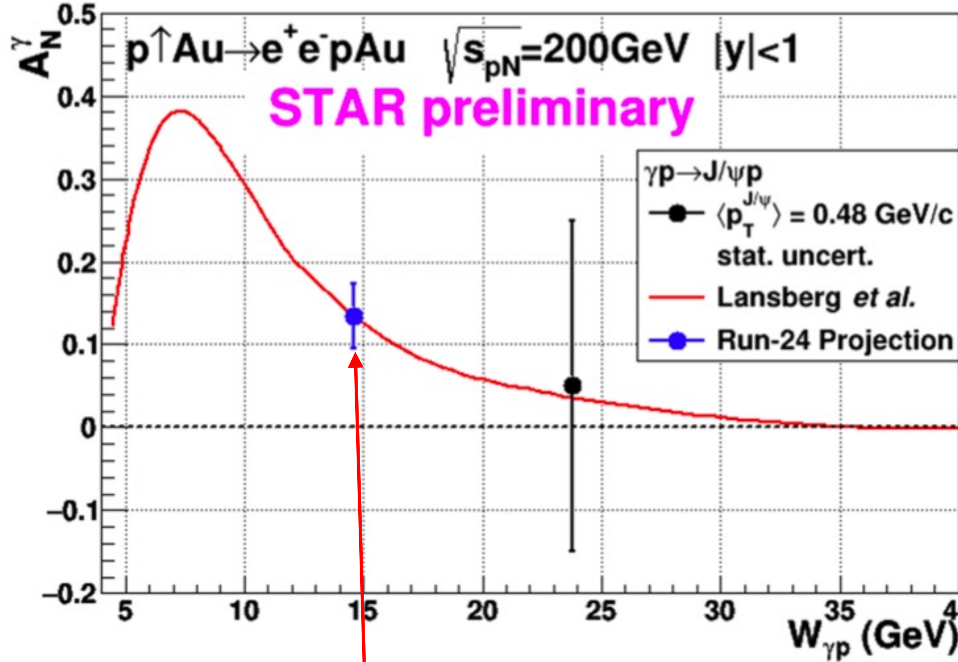
Access GPD Eg for gluons, sensitive to spin-orbit correlation

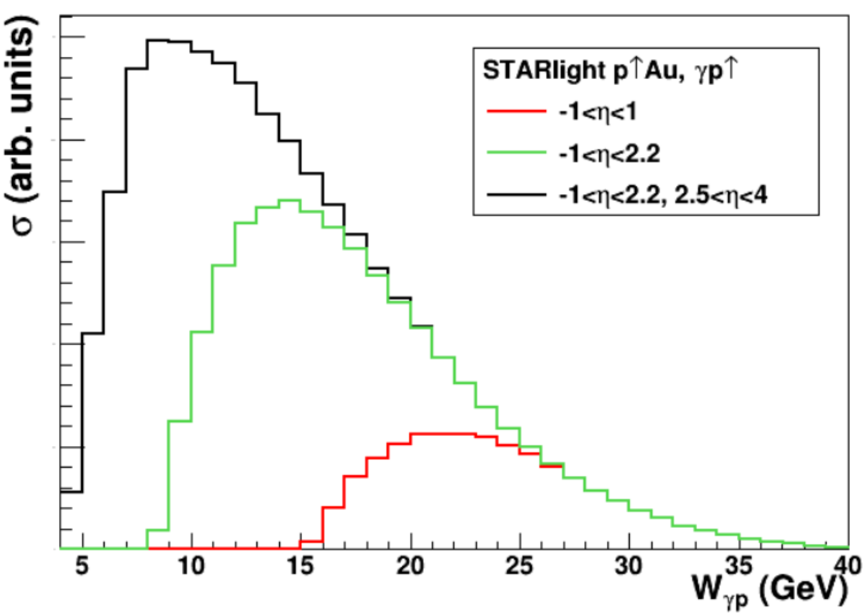
Run-24: a factor of 9-10 more data, combined with iTPC and forward upgrades, stat. error for A_N^{γ}: 0.04 for $<W_{\gamma p}>$=14 GeV, where the signal is expected to be large.

Generalized parton distribution

low material, improved PID, extended η coverage by iTPC, forward upgrade







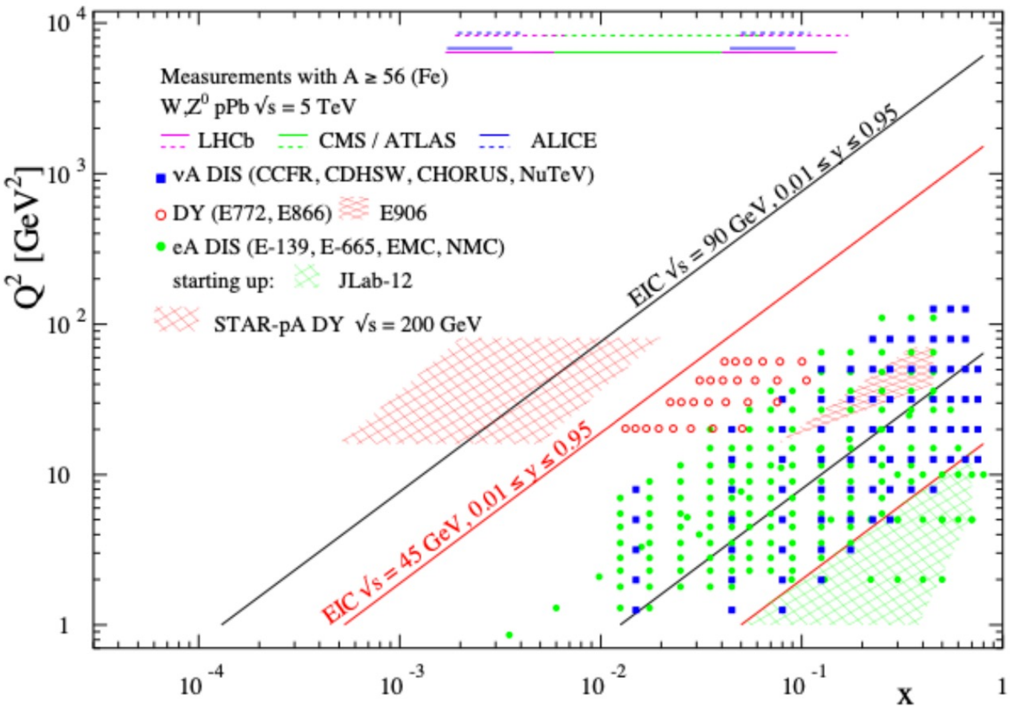
Exclusive J/ψ A_N in UPC, Q^2~10 GeV^2, $10^{-4}<x<10^{-1}$

Access GPD Eg for gluons, sensitive to spin-orbit correlation

Run-24: a factor of 9-10 more data, combined with iTPC and forward upgrades, stat. error for A_N^{γ}: 0.04 for $<W_{\gamma p}>$=14 GeV, where the signal is expected to be large.

Nuclear PDF

low material, forward upgrade



Small DY cross section (10^{-6}-10^{-5} of hadron): need suppress hadron to the order of 0.1% while maintaining a decent electron efficiency

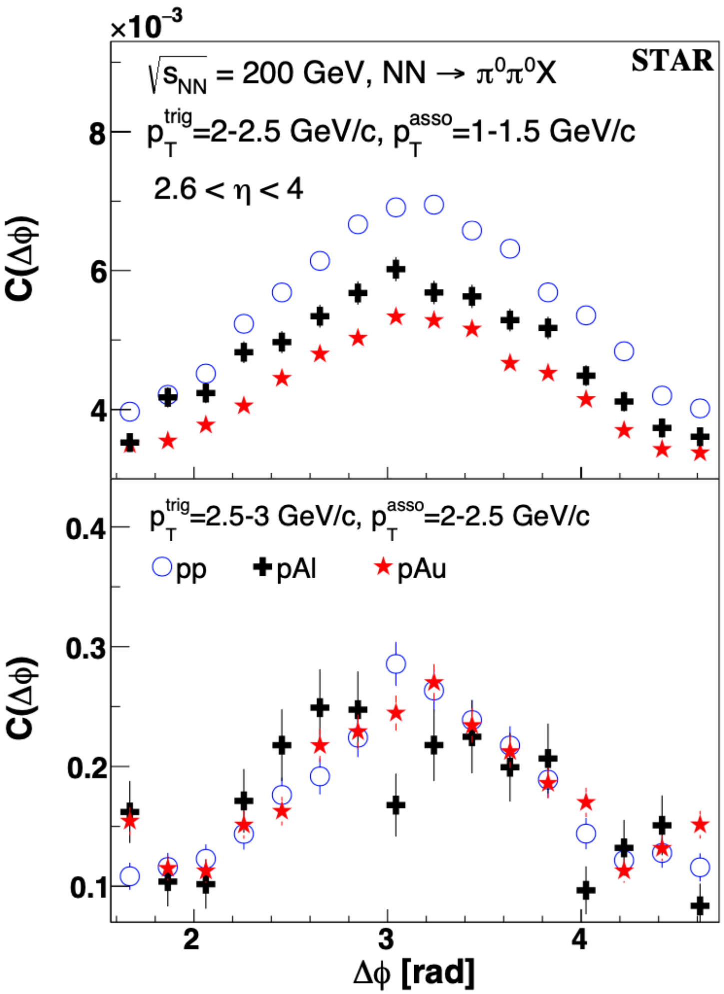
With forward upgrades:
hadron rejection power: 200-2000 for hadrons of 15-50 GeV
electron efficiency: 80%

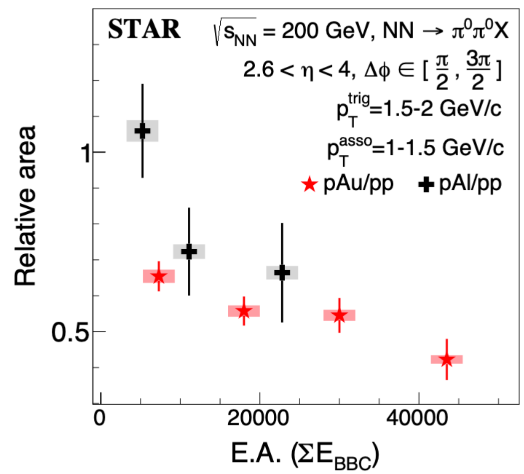
Drell-Yan : constrain nuclear sea quark distribution in a broad x range

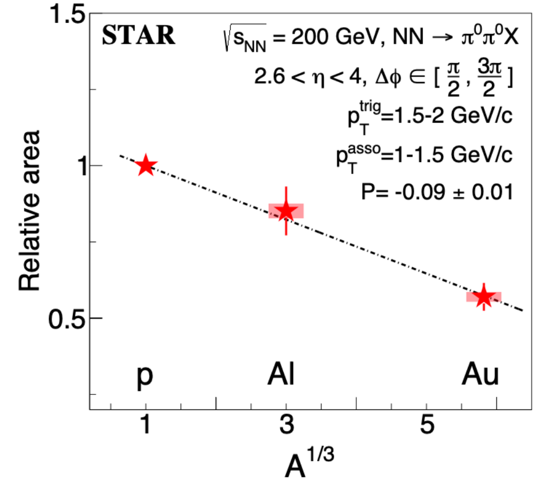
Essential in testing fundamental universality properties of nPDFs combined with data from EIC

QCD non-linear effects

STAR, PRL129 (2022) 92501



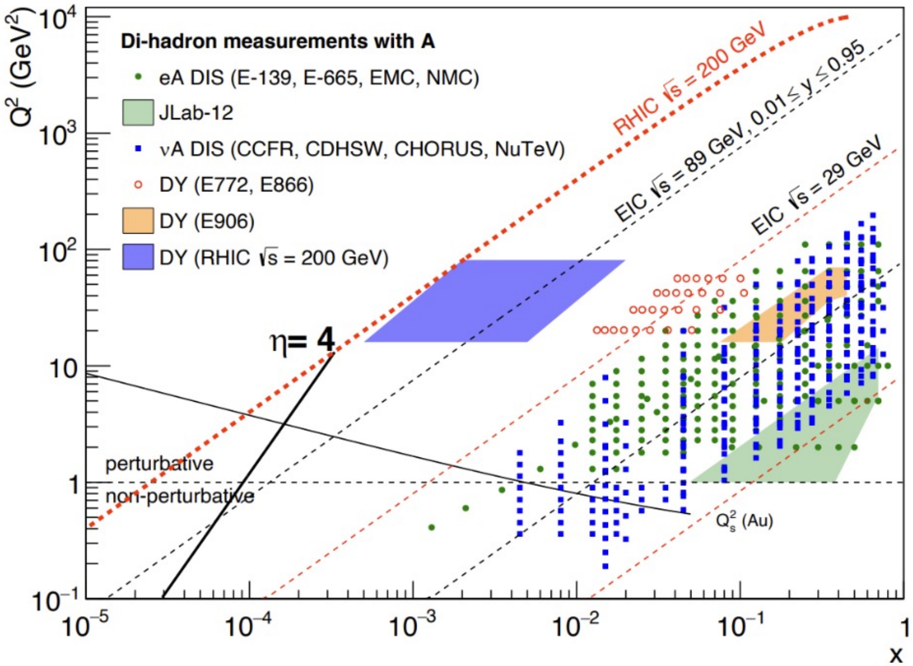




Run-15 di-π^0 correlation:
away side area suppressed significantly, while the pedestal and away side widths change very little.

probe x down to 10^{-3}

QCD non-linear effects



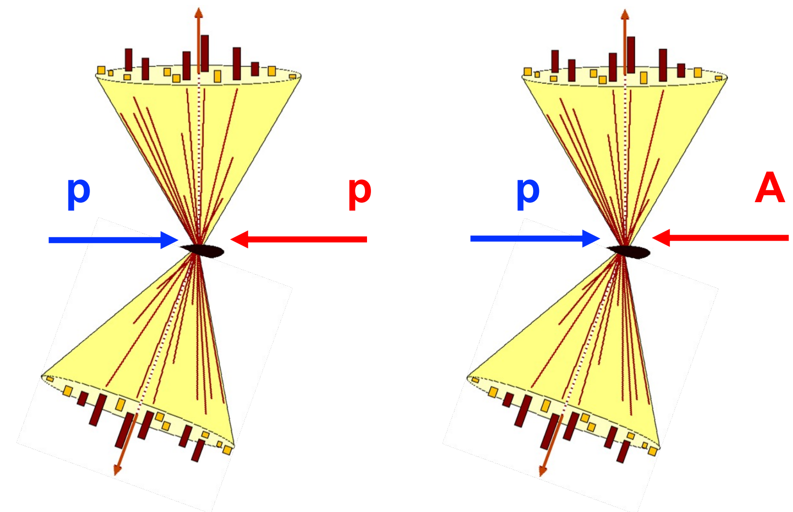
Forward rapidities at STAR provide an absolutely unique opportunity to have very high gluon densities

→ proton – Au collisions

combined with an unambiguous observable

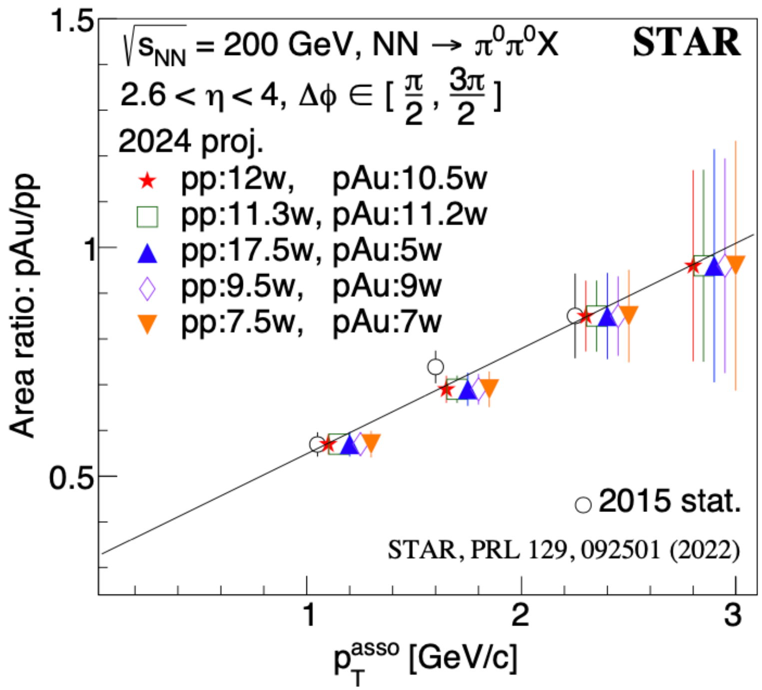
counting experiment of Di-jets in pp and pA

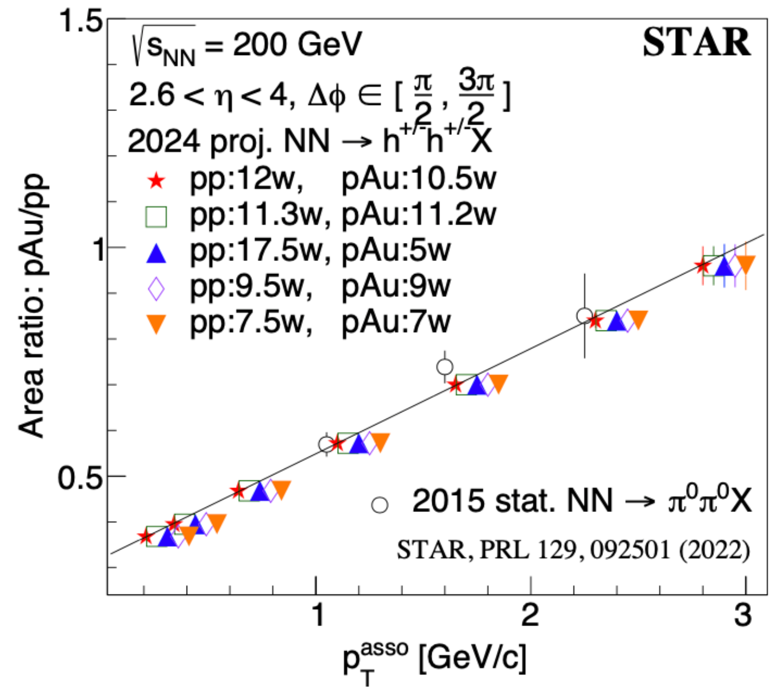
Saturation: Disappearance of backward jet in pA



STAR forward upgrade characterize non-linear effects with charged di-hadrons, γ-jet, di-jet

QCD non-linear effects



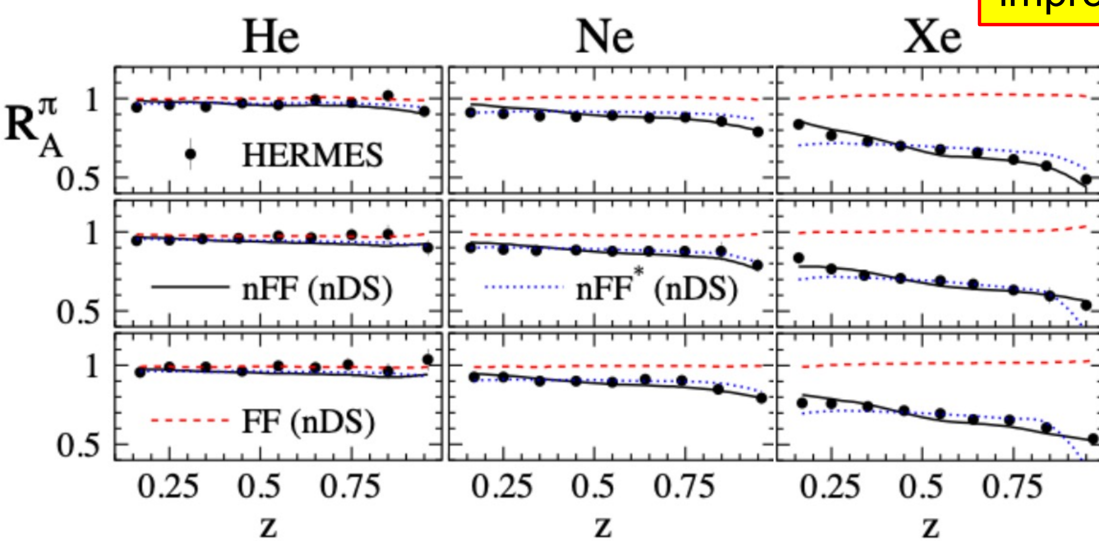


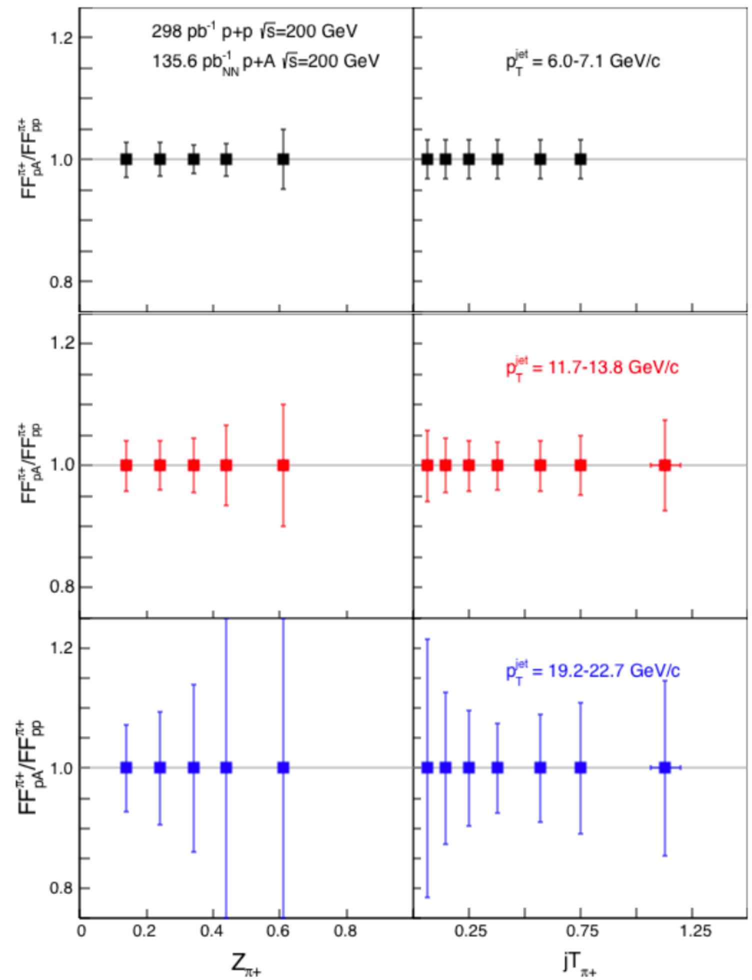
Forward rapidities at STAR provide an absolutely unique opportunity to have very high gluon densities
→ proton – Au collisions
combined with an unambiguous observable

STAR forward upgrade characterize non-linear effects with charged di-hadrons, γ-jet, di-jet

Nuclear FF

improved PID, extended η coverage by iTPC





Modified FF is needed to explain SIDIS data by HERMES

Underlying mechanism is not understood

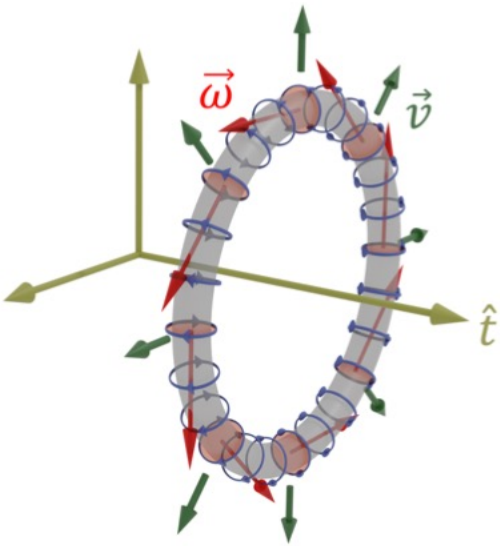
Universality has not been tested

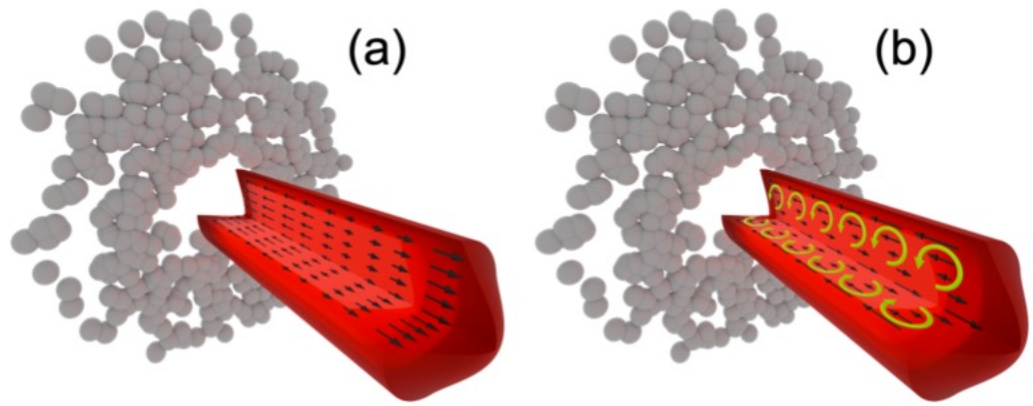
Run-24: study pion, kaon, and proton FF modification, constrain gluon FF.

RHIC is in the ideal kinematic region to measure nuclear effects compared to LHC

Novel QGP droplet substructure: toroidal vorticity

improved PID, extended η coverage by iTPC

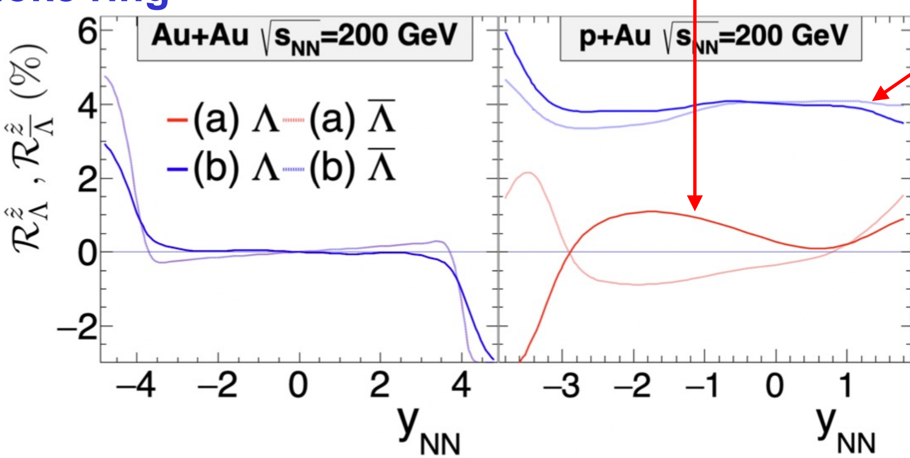




Toroidal vortex structure: smoke ring

Bjorken flow profile

Radial-gradient flow profile



Ring structure

$$\mathcal{R}^{z}_{\Lambda} \equiv \left\langle \frac{\vec{S}'_{\Lambda} \cdot (\hat{z} \times \vec{p}'_{\Lambda})}{|\hat{z} \times \vec{p}'_{\Lambda}|} \right\rangle$$

300 M p+Au central events at each field polarity: enable us to measure $\overline{\mathcal{R}}^{z}_{\Lambda}$~1% with 7 σ significance

Opportunity to discover a novel vortical configuration in the subatomic fluid

Summary of 2024

200 pp:

- Very wide *x* coverage (0.005 < *x* < 0.5) by combining 200 and 510 GeV pp
  - 510 (200) GeV pp with the Forward Upgrade provides access to the lowest (highest) *x* value with jets and hadrons in jets over a wide range of perturbative scales
  - 200 GeV pp provides best coverage for the intermediate *x* range
  - provides best overlap with the x-Q^2 coverage of EIC
- Overlapping *x* coverage enables detailed evolution studies
- 200 GeV pp critical for precise factorization and universality tests
  - Best statistical precision for much of the kinematics overlapping with EIC
- 200 GeV pp essential baseline for 200 GeV p+Au

Equal nucleon-nucleon luminosities in pp and pAu in Run-24 essential to optimize several critical measurements

200 GeV p+Au:

- **Gluon saturation in both pA and eA to verify universality**
- Precise probe of quark-gluon structure of heavy nuclei
- Explore the propagation and hadronization of colored partons
- A unique opportunity to discover toroidal vorticity

Fully utilize forward upgrades and excellent PID over extended η coverage

STAR detector and Au+Au data sets

Low material, PID capability over extended η and p_T, improved trigger capability
forward π^0, γ, e, Λ, charged hadron, jets

40 weeks physics data taking for 200 GeV Au+Au: 10 (Run 23) + 4 (Run 24) + 26 (Run 25)

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	p+p	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

iTPC + EPD + eTOF
Forward upgrades
DAQ5k

A factor of 9 more minimum bias data compared to Run-14 + Run-16
A factor of 1.2 more luminosity for high-p_T trigger

Physics Opportunities for 2023 + 2025

Time

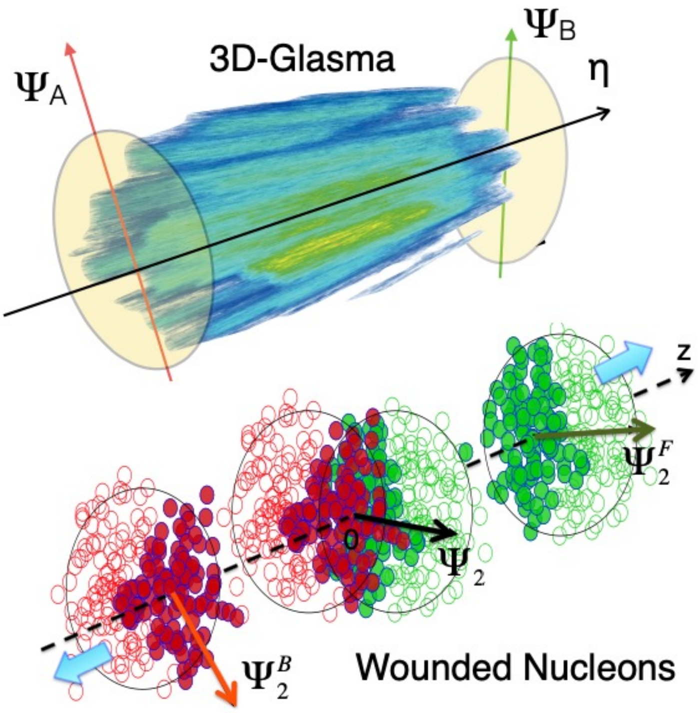
To address important questions about the inner workings of the QGP

- What is the nature of the 3-dimensional initial state at RHIC energies? r_n over a wide rapidity, J/ψ v_1, photon Wigner distributions
- What is the precise temperature dependence of shear and bulk viscosity? v_n as a function of η
- What can be learned about confinement from charmonium measurements? J/ψ v_2
- What is the temperature of the medium? Different ϒ states, ψ(2S), thermal dileptons
- What are the electrical, magnetic, and chiral properties of the medium? Λ, Ξ, Ω P_H and K*, ϕ, J/ψ ρ_{00}, thermal dileptons, CME observables
- What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale? γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure
- What is the precise nature of the transition near μ_B=0? Net-proton C_6/C_2
- What can we learn about the strong interaction? Correlation functions

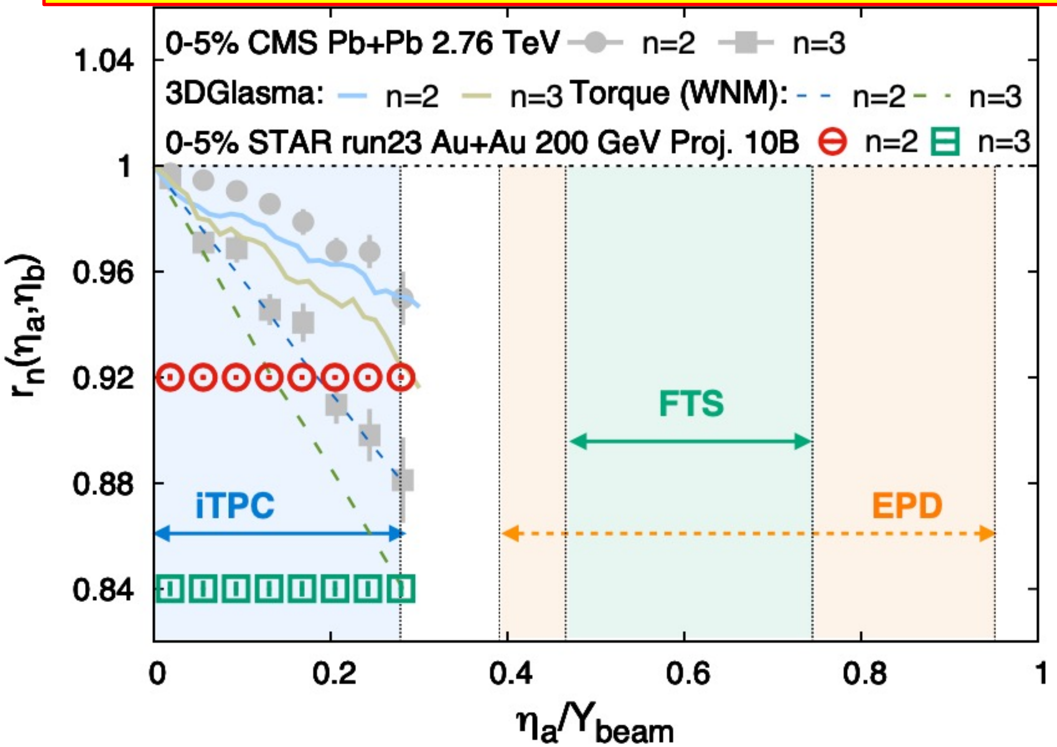
To inform EIC physics with photon induced processes:

- Probe gluon distribution inside the nucleus: vector mesons (J/ψ), dijets (?)
- Search for collectivity and signatures of baryon junction: inclusive charge particles and cross sections, v_n , identified particle spectra

Constrain longitudinal structure of initial state



extended η coverage by iTPC and forward tracking



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

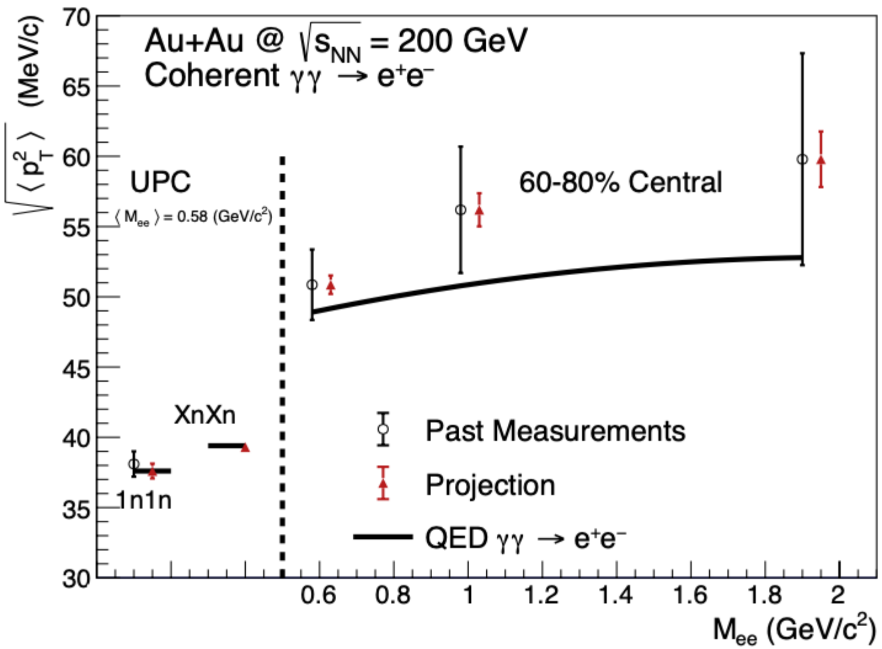
$V_{n\Delta}$ the Fourier coefficient calculated with pairs of particles in different rapidity regions

r_n sensitive to different initial state inputs:

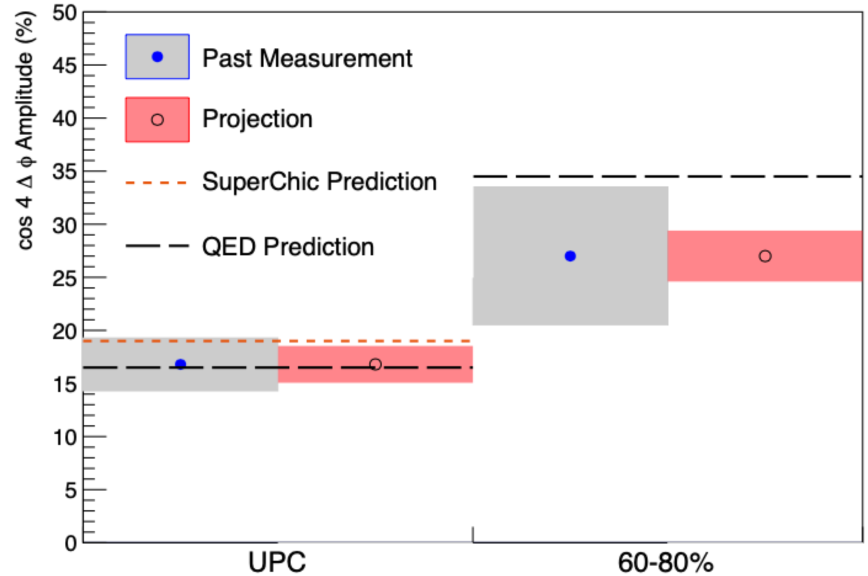
- **3D glasma model: weaker decorrelation, describes CMS r_2 but not r_3**
- **Wounded nucleon model: stronger decorrelation than data**

Precise measurement of r_n over a wide rapidity window will provide a stringent constraint

Photon Wigner function and magnetic effects in QGP



low material, improved PID, extended η and p_T coverage by iTPC



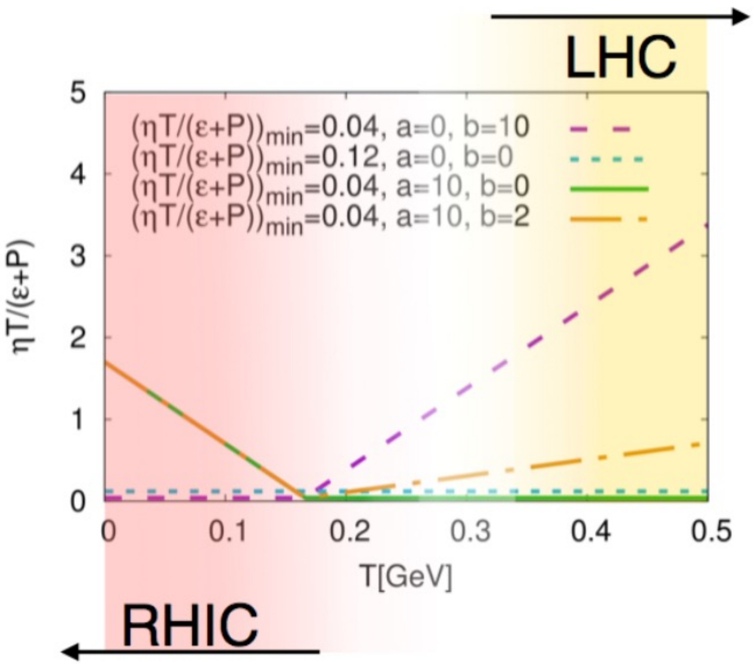
Impact parameter dependence of transverse momentum distribution of EM production is the key component to describe data;
p_T broadening and azimuthal correlations of e^+e^- pairs sensitive to electro-magnetic (EM) field.

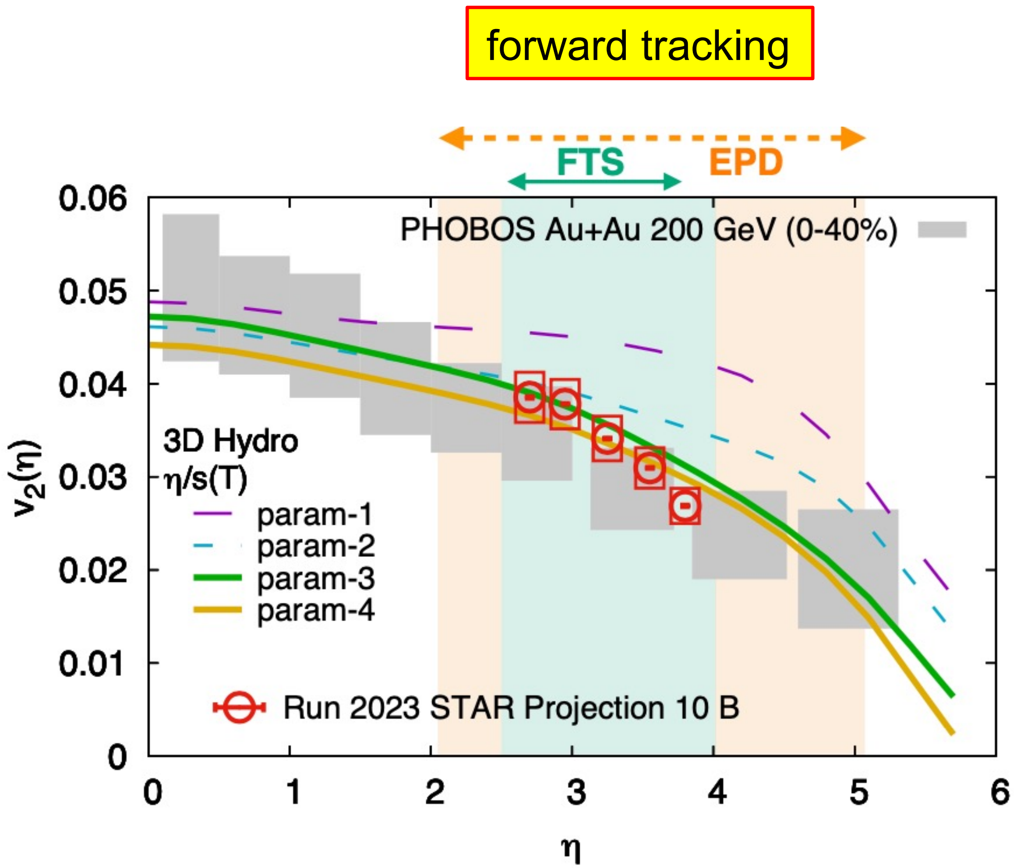
Is there a sensitivity to final magnetic field in QGP?

Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.

Fundamentally important and unique input to CME phenomenon.

Constrain temperature dependence of η/s



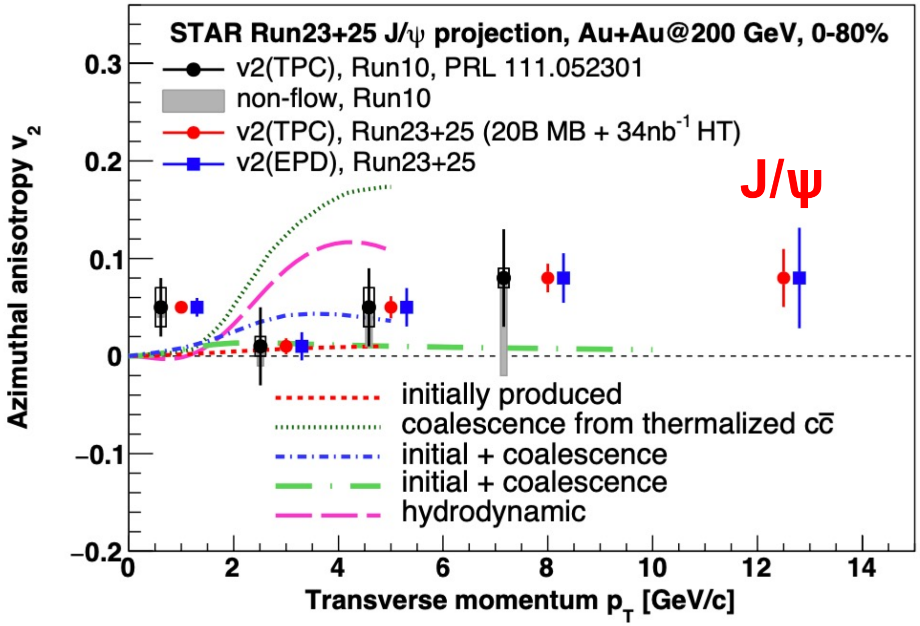


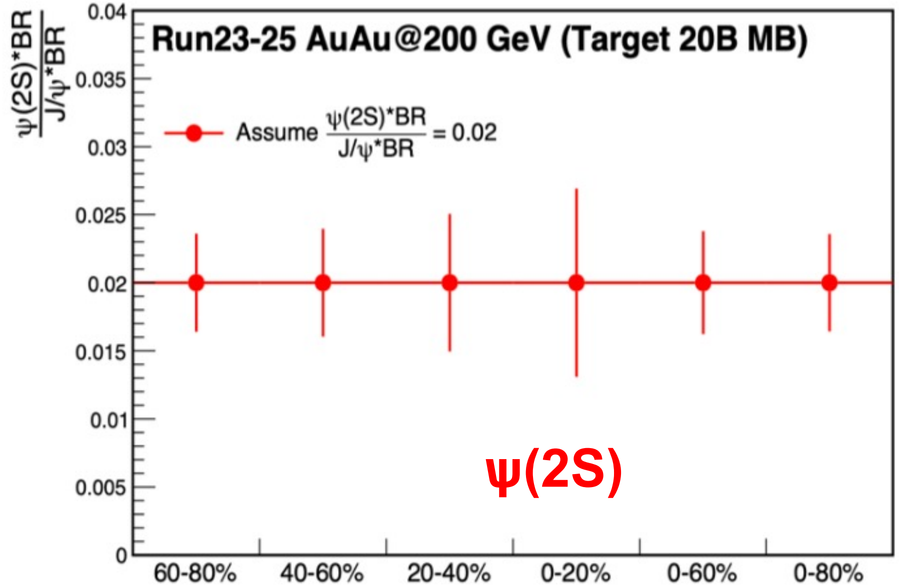
Flow measurements at forward rapidity sensitive to η/s as a function of T.

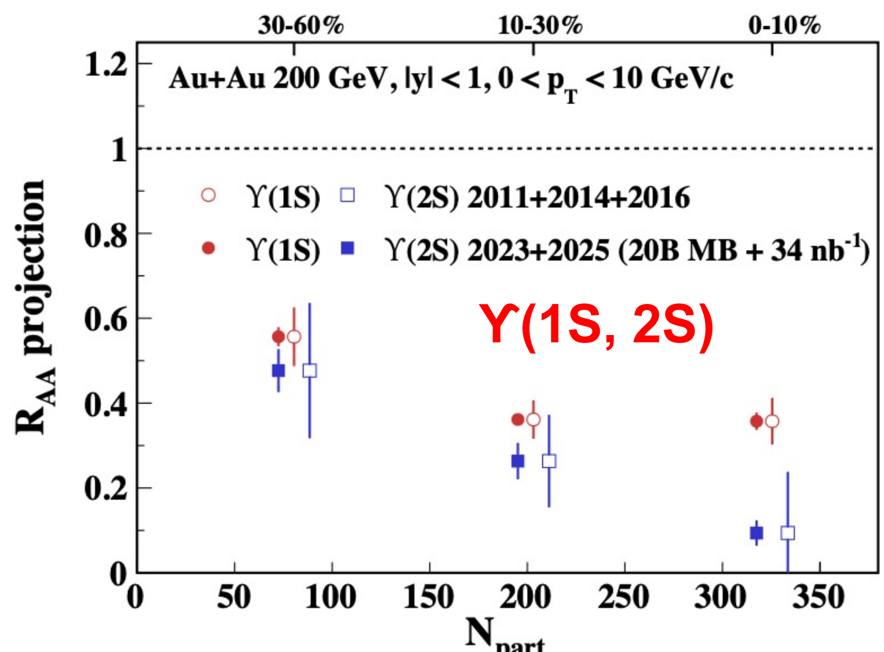
Much more precise than previous PHOBOS measurements.

Deconfinement and thermalization

low material, improved PID, extended η coverage by iTPC







J/ψ: interplay of color-screening and recombination, signature of deconfinement

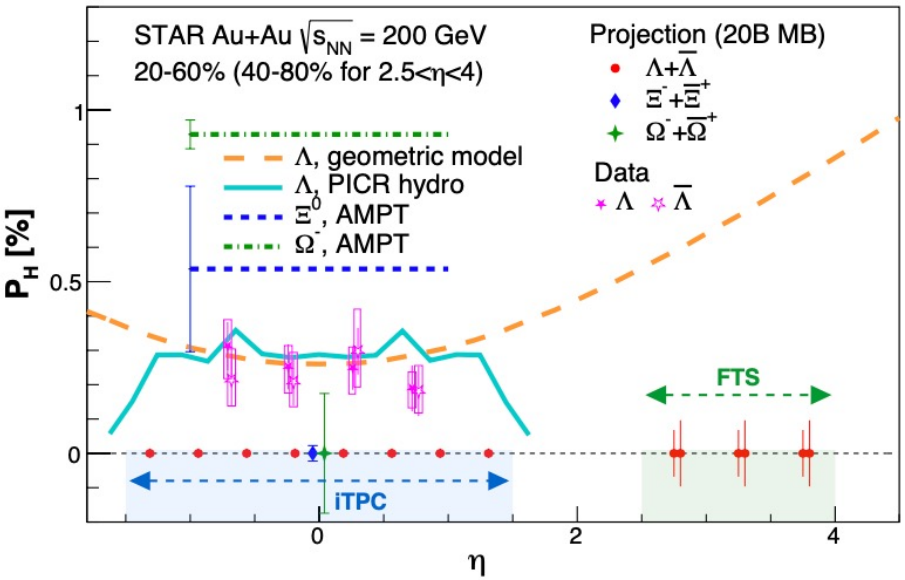
- low p_T v_2: recombination

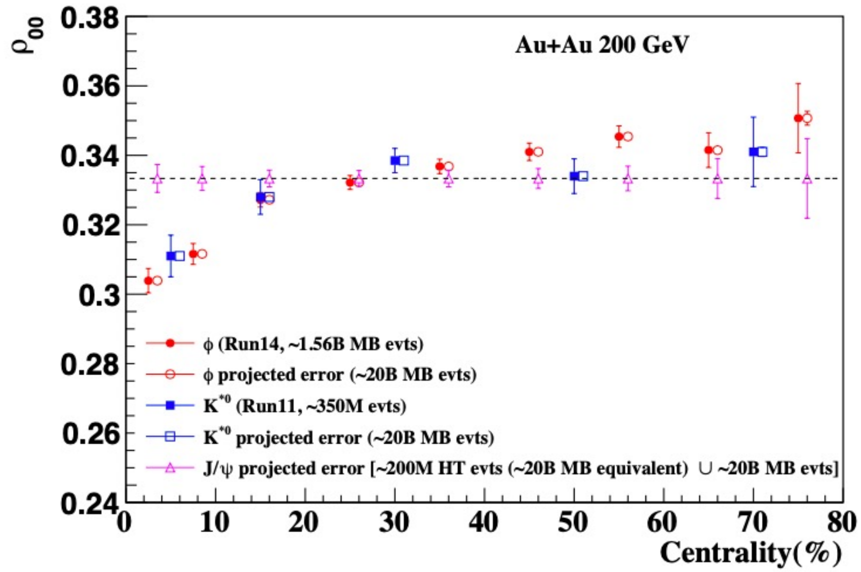
Explore temperature profile of the medium:

ψ(2S) suppression, different ϒ states, thermal dileptons (see slides later)

Global vorticity transfer

improved PID, extended η coverage by iTPC, and forward tracking





How exactly the global vorticity is dynamically transferred to fluid?
How does the local thermal vorticity of the fluid gets transferred to the spin angular momentum?

Rapidity dependence of Λ, Ξ, Ω P_H at STAR, probe the nature of global vorticity transfer:
Initial geometry and local thermal vorticity + hydro predict opposite trends.

Can we reconcile P_H with vector meson spin alignment ρ_{00}? Strong force field effect?

Precise measurements of ρ_{00} of K*, ϕ, J/ψ will tell.

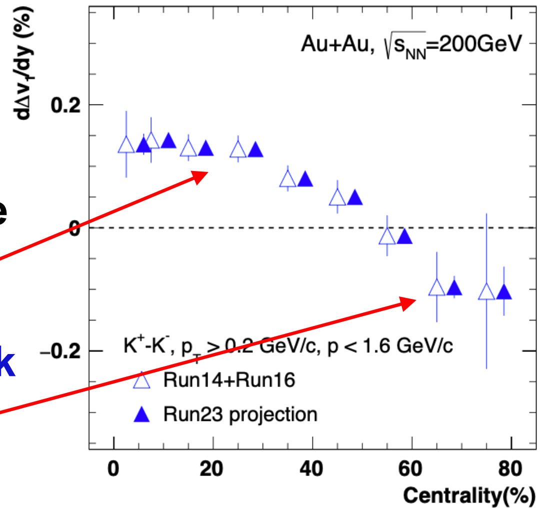
Charge dependent directed flow

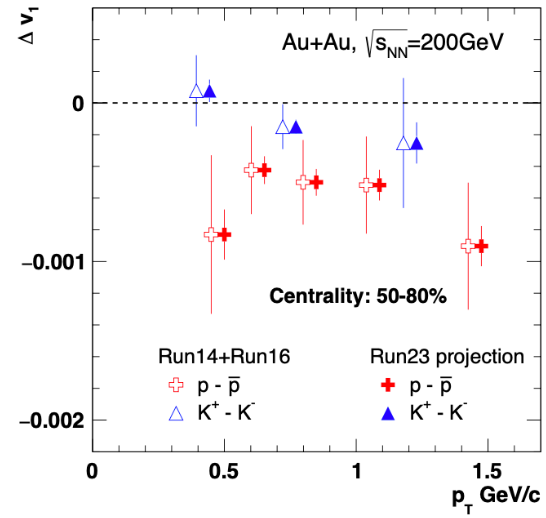
improved PID, extended η coverage by iTPC

Charge dependent v_1 slope sensitive to EM field

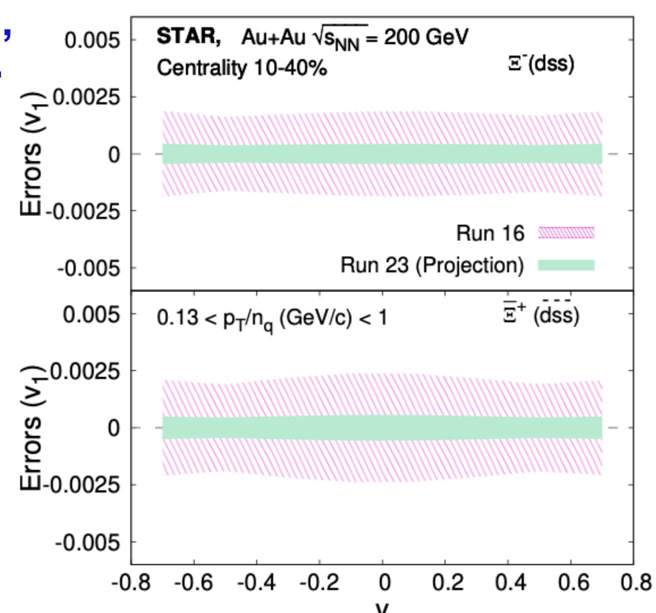
$d\Delta v_1/dy > 0$ due to transported quark

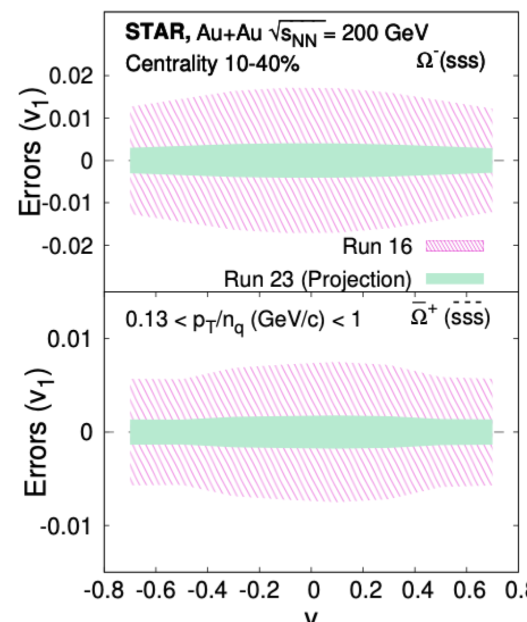
$d\Delta v_1/dy < 0$ due to EM field



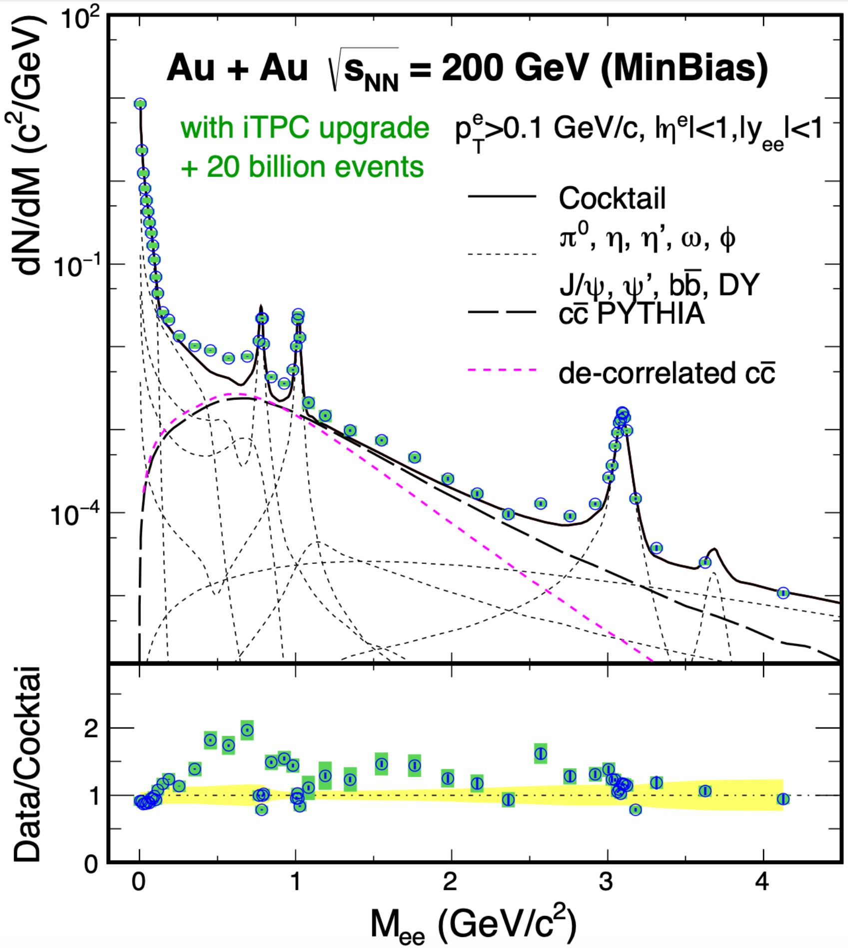


Runs 23+25: >5σ difference between K^+ and K^- in peripheral collisions, precise measurements for multi-strange particles.

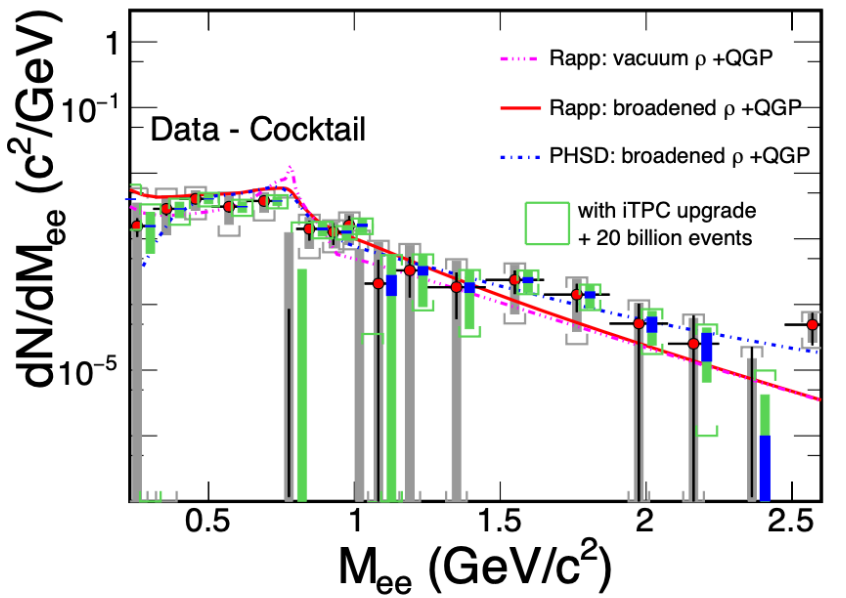




Chiral property



low material, improved PID, extended η and p_T coverage by iTPC



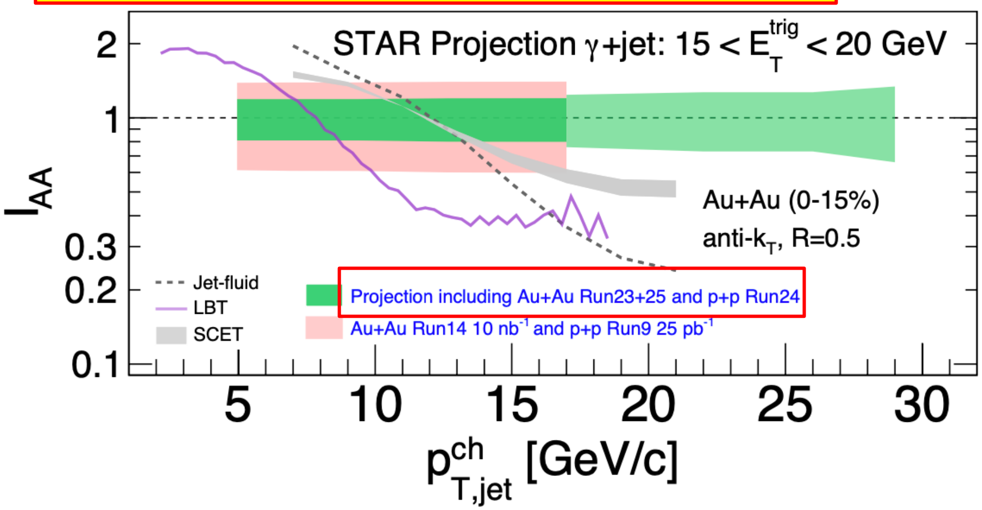
Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B=0

Intermediate mass: direct thermometer to measure temperature

Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

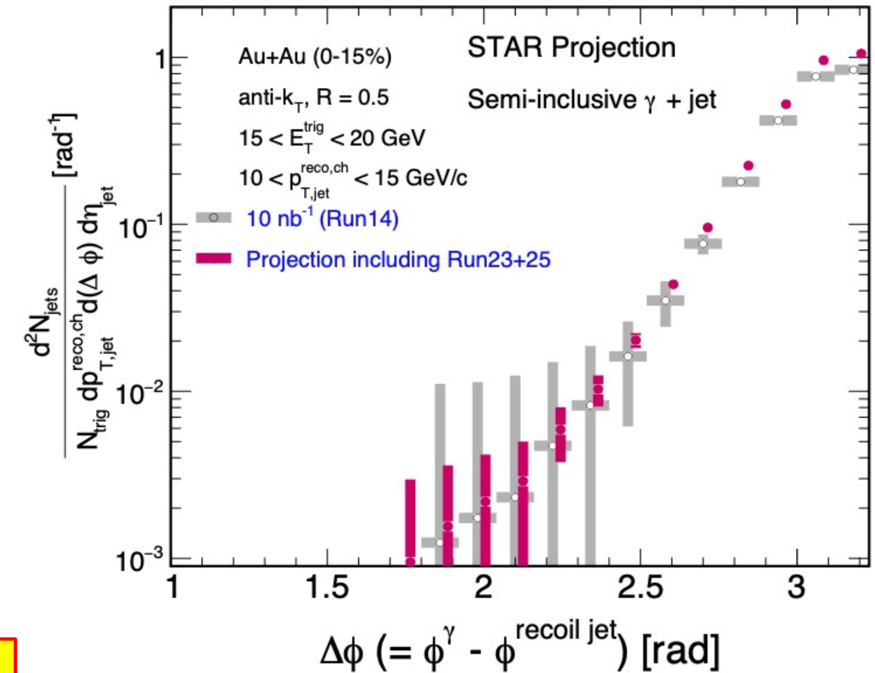
Jet quenching

low p_T, large R, extended to higher p_T

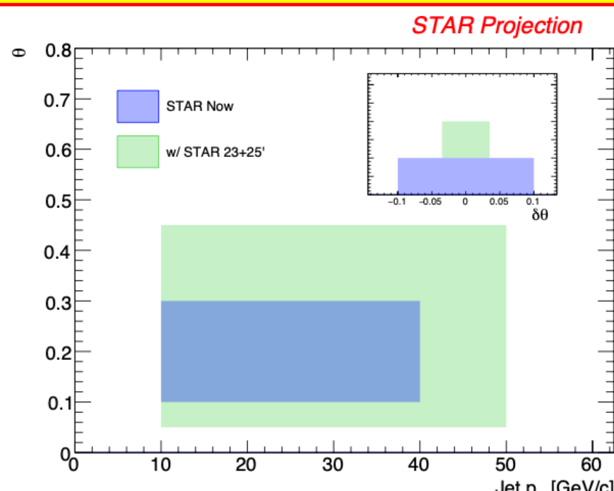


Semi-inclusive γ_{dir}+jet suppression

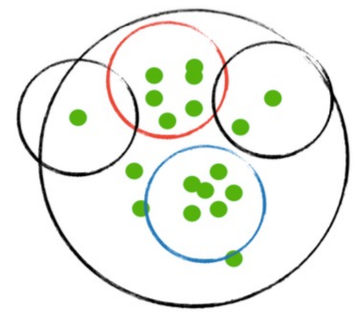
γ_{dir}+jet acoplanarity: constituents of medium



improved opening angle resolution by a factor of 4



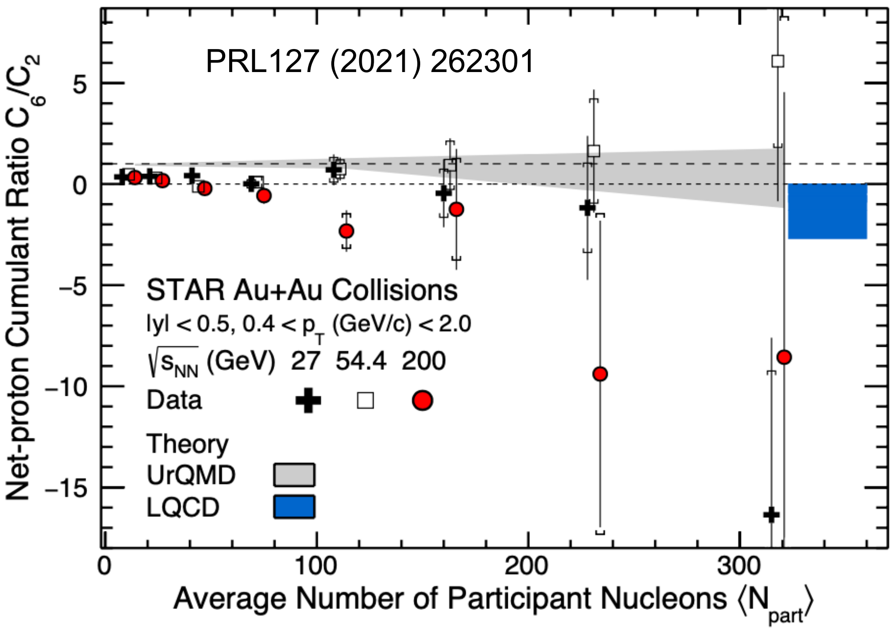
Jet substructure: coherence vs. de-coherence

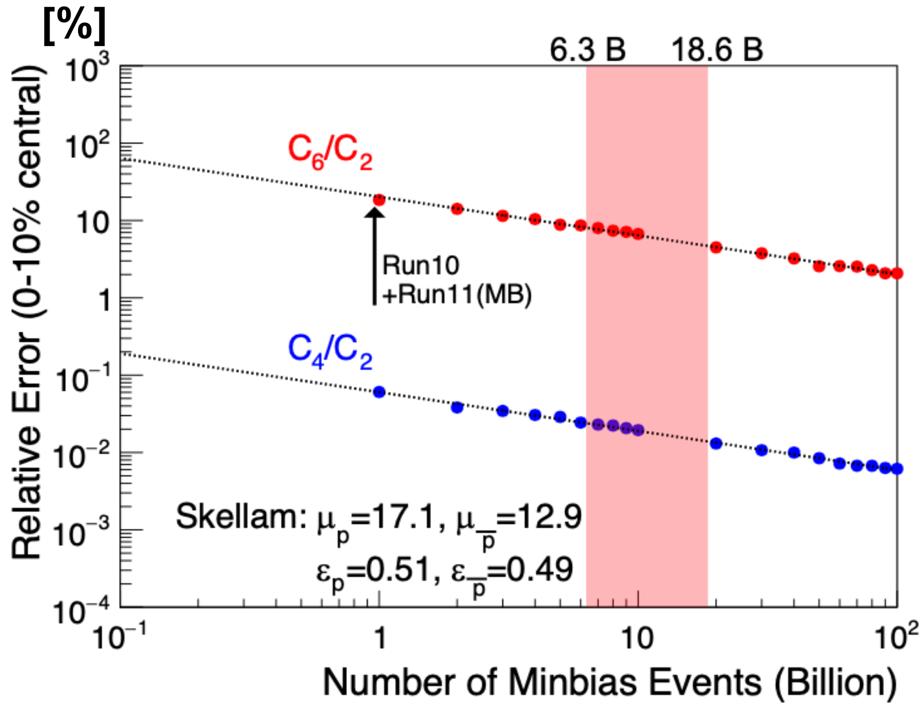


Red: leading sub-jet
Blue: sub-leading sub-jet
$Z_{SJ}=p_T^{blue}/(p_T^{blue}+p_T^{red})$
$\theta_{SJ}=\Delta R(\text{blue,red})$

Chiral cross-over transition

Improved PID, extended η coverage by iTPC





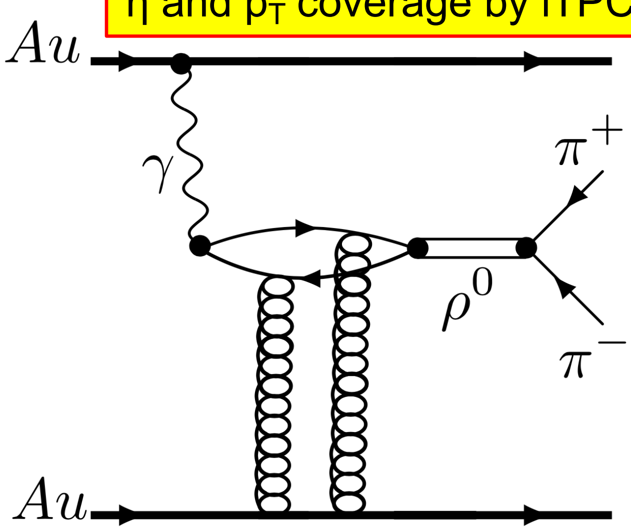
Lattice QCD predicts a sign change of susceptibility ratio χ_6^B/χ_2^B at T_C
The cumulants of net-proton distribution sensitive to chiral cross over transition at μ_B=0

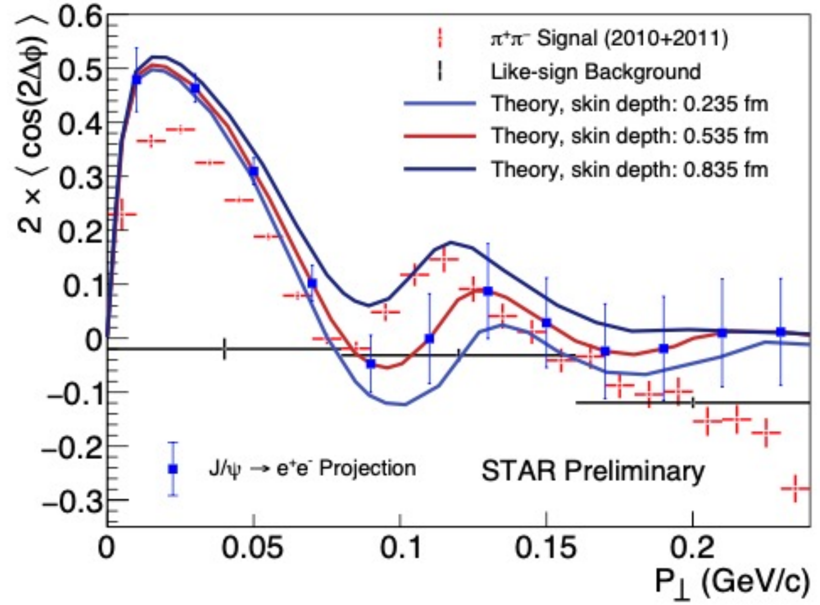
Observed a hint of a sign change from peripheral to central collisions at 200 GeV
$C_6/C_2 < 0$ at central collisions

High statistics measurements (10% statistical error for C_6/C_2 in central) will pin down the sign change

Gluon distribution inside nucleus

low material, improved PID, extended η and p_T coverage by iTPC





Significant cos2$\Delta\phi$ azimuthal modulation in $\pi^+\pi^-$ pairs from photonuclear ρ^0 and continuum Modulation vs. p_T, shows a diffractive pattern structure

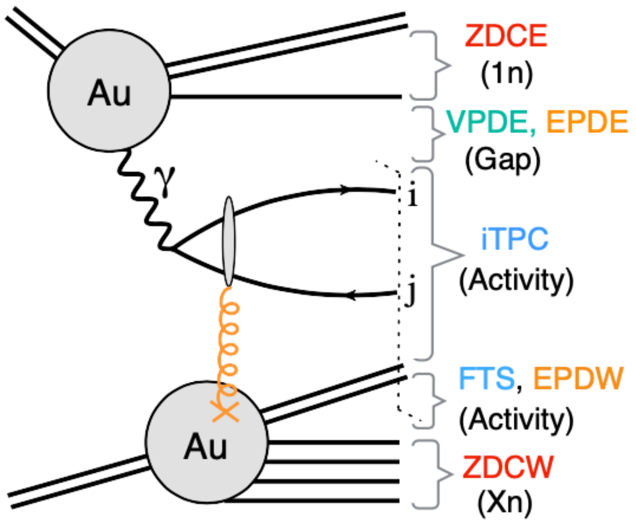
Theory (linear polarized photon + saturated gluons), sensitive to nuclear geometry and gluon distribution, closest to the gluon 3D tomography at EIC

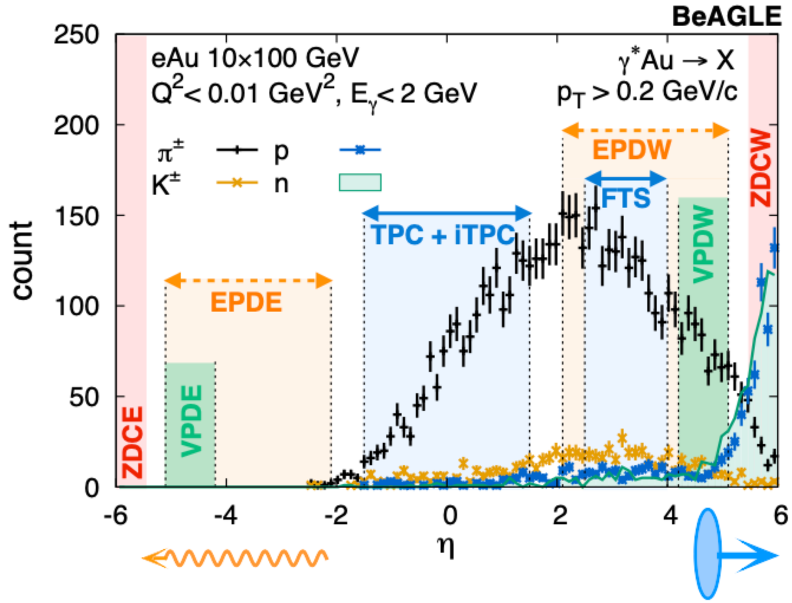
Run23+25:

multi-differential measurements (vs. mass, rapidity, p_T): provide strong theoretical constraints, separate ρ^0 from continuum (Drell-Soding), investigate how double-slit interference mechanism affects the structure

Enable a similar measurement for J/ψ, a cleaner probe for gluon spatial distribution

Search for collectivity and signatures of baryon junction in photo-nuclear processes





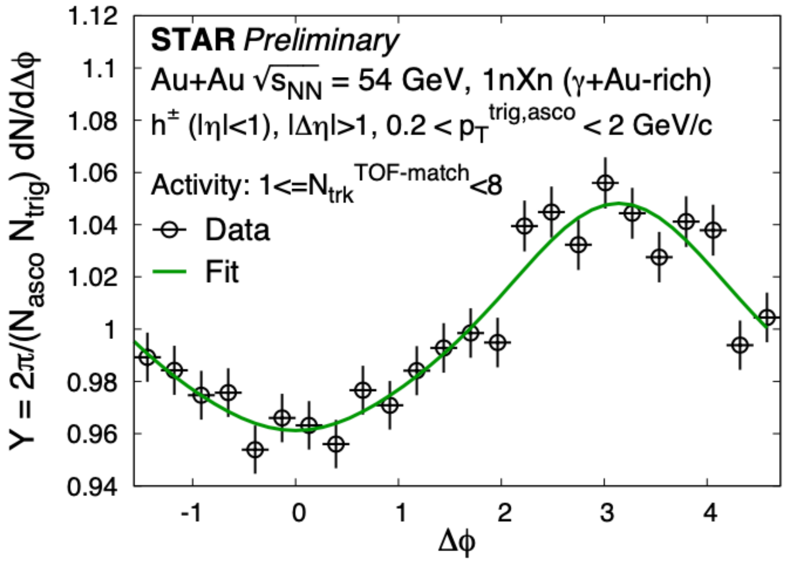
γ+Au process in UPC associated with a large rapidity asymmetry:

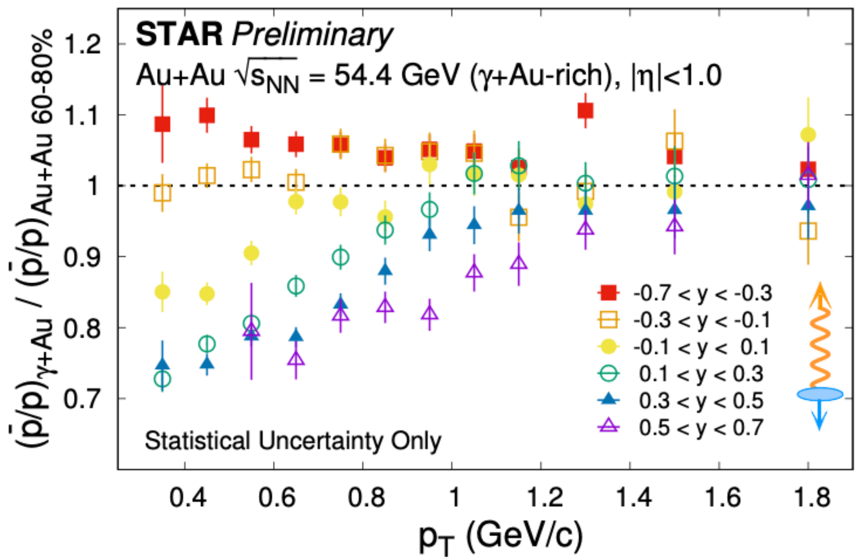
- **Search for collectivity**
- **Study bulk observables**

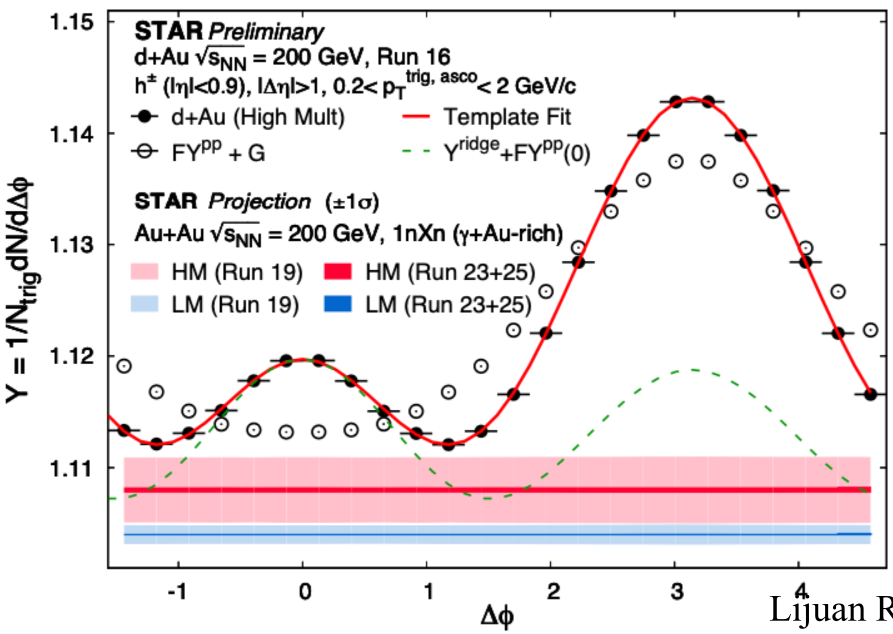
Further understand the origin of collectivity observed in small systems

Search for collectivity and signatures of baryon junction in photo-nuclear processes

improved PID, extended η coverage by iTPC, and forward tracking







γ+Au 54 GeV:

- **No signature of collectivity**
- **Significant enhancement of protons at low p_T at mid-rapidity compared to peripheral Au+Au**

Run23+25: enable differential measurements of di-hadron correlations

Search for collectivity in addition to testing the baryon junction conjecture

Summary of 2023 + 2025

STAR is in an excellent position to address important questions about the inner workings of the QGP and inform EIC physics with photon induced processes

- **What is the nature of the 3-dimensional initial state at RHIC energies?** r_n over a wide rapidity, J/ψ v_1, photon Wigner distributions
- **What is the precise temperature dependence of shear and bulk viscosity?** v_n as a function of η
- **What can be learned about confinement from charmonium measurements?** J/ψ v_2
- **What is the temperature of the medium?** Different ϒ states, ψ(2S), thermal dileptons
- **What are the electrical, magnetic, and chiral properties of the medium?** Λ, Ξ, Ω P_H and K*, ϕ, J/ψ ρ_{00}, thermal dileptons, CME observables
- **What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale?** γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure
- **What is the precise nature of the transition near μ_B=0?** Net-proton C_6/C_2
- **What can we learn about the strong interaction?** Correlation functions
- **Probe gluon distribution inside the nucleus**: vector mesons (J/ψ), dijets (?)
- **Search for collectivity and signatures of baryon junction**: inclusive charge particles and cross sections, v_n , identified particle spectra

Proposed measurements based on our detector performances in past years and/or forward capabilities. STAR will be ready for physics data taking within a week.

A shorter run scenario

Runs 24-25: 24 cryo-weeks each

Data taking:
9.5 weeks pp
9 weeks p+Au
22 weeks Au+Au

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity
200	p+p	108 pb^{-1}/9.5w
200	p+Au	0.58 pb^{-1}/9w
200	Au+Au	16B / 29.4 nb^{-1}/36w

Equal nucleon-nucleon luminosities in pp and p+Au essential to optimize several critical measurements

Au+Au: Decrease statistics by at least 11%, hard probes (jets and quarkonia), thermal di-lepton, photon-induced processes (di-lepton and J/ψ) most impacted

p+p and p+Au: Decrease statistics by at least 24-16%, even larger impact on nuclear PDFs, fragmentation functions, and gluon saturation measurements since these require comparisons of the same observables measured in both p+p and p+Au

Run 24: 20 cryo-weeks

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity
200	p+p	81 pb^{-1}/7.5w
200	p+Au	0.42 pb^{-1}/7w

The computing plan updates

The current goals of data analysis call for timely analysis and publication of data taken. The data processing will have to keep pace with data taking, therefore the CPU processing will also have to scale with the data taken.
We updated computing plan in November 2021 and discussed with NPP management and SDCC.

After 2025, we could do with what we have in 2025 but it must be preserved for +3 years for CPU. HPSS storage does not change. The Xrootd/central storage will be needed for at least a decade**; need to maintain software and computing person power for at least 5 years, for STAR data calibration, production, simulation, embedding, and analysis.**

Future opportunity I

Nuclear data for space radiation protection

Not part of STAR physics program in the final RHIC phase but represents an opportunity for RHIC to contribute with some important nuclear data

- **The Space Radiation Protection community has identified 3-50 GeV/n region as an area of need. https://doi.org/10.3389/fphy.2020.565954**
- **STAR has excellent light fragment capabilities.**
- **RHIC can deliver the ion beam species (C, Al, Fe) and energies (3-50 GeV/n) of need to the Space Radiation Protection community. STAR installed the targets of interest (C, Al, Ni) and is ready to take FXT data when opportunities arise.**

Figure 112: Left panel: Installation of the targets and holder on the East side of the STAR detector. Right Panel: A view down the beam pipe showing the three targets (C, Al, and Ni) installed at STAR.

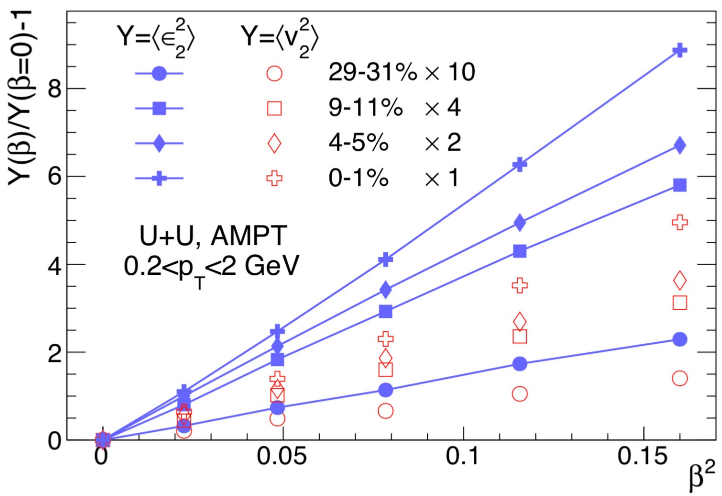
In total, two weeks of running including machine setup

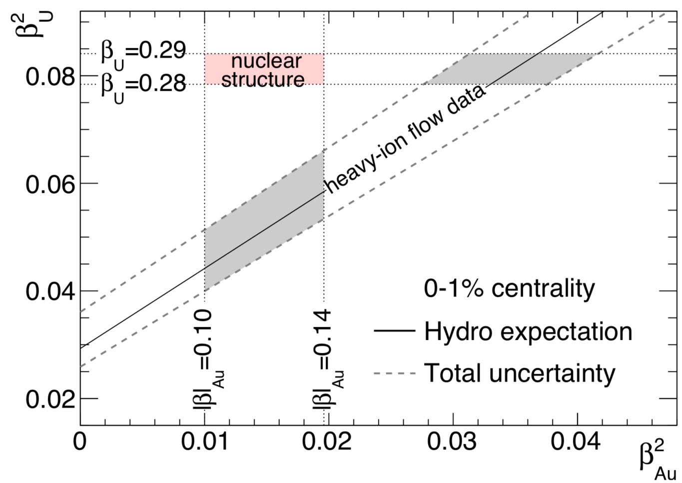
Future opportunity II

Imaging shape and radial profile of atomic nuclei

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi)/a}} \qquad R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3 Y_{3,0}+\beta_4 Y_{4,0}\right)$$

- **Collective flow measurements sensitive to nuclear deformation**
- **Understanding of the nuclear shape of current available systems not ideal: impact η/s extraction**





- Step1: calibrate systematics using two species around ^{197}Au: ^{208}Pb & ^{198}Hg (β_2=-0.11) at 200 GeV

  Pb: control on effects of Au deformation; precision on initial state and pre-equilibrium dynamics (energy dependence) vs. LHC

  Hg: two systems with known β_2 can triangulate the consistency of β_{2Au}.

  Constrain **η/s** with improved understanding of initial state.

- Step2: explore more exotic regions for triaxiality and octuple

  Scan an isotopic chain: ^{144}Sm (β_2=0.08), ^{148}Sm (β_2=0.14,triaxial), ^{154}Sm (β_2=0.34)

  - large octuple expected/predicted for Z~56/N~88; compare ^{154}Sm (β_2 = 0.34) with ^{154}Gd (β_2 = 0.31)

  Use hydrodynamics and flow measurements to perform precision cross-check of low energy nuclear physics.

Summary

- quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions for initial and final state TMDs

  Test of Sivers non-universality: $Sivers_{SIDIS}$ = -- $Sivers_{DY, W+/-, Z0;}$ Full jet and dijet Sivers asymmetry

  Probe final state TMDs: Collins asymmetry for hadrons in jet
  - Requirement:
    - large data sets $\sqrt{s}$ = 200 and 500 GeV $p^{\uparrow}p$

      → low to high x, highest and lowest x with fSTAR
    - A_{UT} for $W^{+/-}$ Z^0, A_{UT} for hadrons in jet
- First look Gluon GPD → E_g
  - Requirement:
    - data sets $\sqrt{s}$ = 500 GeV $p^{\uparrow}p$ and $\sqrt{s}$ = 200 GeV $p^{\uparrow}A$
    - A_{UT} for J/ψ in UPC
- Physics driving the large A_N at forward rapidities and high x_F
  - Requirement:
    - large data sets $\sqrt{s}$ = 200 and 500 GeV $p^{\uparrow}p$

      → low to highest x_F → fSTAR
    - charge hadron A_N at forward rapidities
- Nuclear dependence of PDFs, FF, and TMDs
  - Requirement:
    - large equal data set of $\sqrt{s}$ = 200 $p^{\uparrow}p$ and $p^{\uparrow}Au$

      → low to high x, highest and lowest x with fSTAR
    - R_{pA} direct photons and DY, hadrons in jet A_{UT}
- non-linear effects in QCD
  - Requirement:
    - large equal data set of $\sqrt{s}$ = 200 $p^{\uparrow}p$ and $p^{\uparrow}Au$

      → lowest-x through fSTAR
    - dihadron correlations for $h^{+/-}$, γ-jet, di-jets

To address important questions about the inner workings of the QGP

- **What is the nature of the 3-dimensional initial state at RHIC energies?** r_n over a wide rapidity, J/ψ $v_{1,}$ photon Wigner distributions
- **What is the precise temperature dependence of shear and bulk viscosity?** v_n as a function of η
- **What can be learned about confinement from charmonium measurements?** J/ψ v_2
- **What is the temperature of the medium?** Different ϒ states, ψ(2S), thermal dileptons
- **What are the electrical, magnetic, and chiral properties of the medium?** Λ, Ξ, Ω P_H and K*, ϕ, J/ψ ρ_{00}, thermal dileptons, CME observables
- **What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale?** γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure
- **What is the precise nature of the transition near μ_B=0?** Net-proton C_6/C_2
- **What can we learn about the strong interaction?** Correlation functions

To inform EIC physics with photon induced processes:

- **Probe gluon distribution inside the nucleus**: vector mesons (J/ψ), dijets (?)
- **Search for collectivity and signatures of baryon junction**: inclusive charge particles and cross sections, v_n , identified particle spectra

Impact of STAR science goals with no pAu data in Run 2024

- Quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions for initial and final state TMDs

  Test of Sivers non-universality: $Sivers_{SIDIS}$ = -- $Sivers_{DY, W+/-, Z0;}$ Full jet and dijet Sivers asymmetry

  Probe final state TMDs: Collins asymmetry for hadrons in jet

  - Requirement:
    - large data sets √s = 200 and 508 GeV p↑p
      → low to high x, highest and lowest x with fSTAR
    - A_{UT} for $W^{+/-}$ Z^0, A_{UT} for hadrons in jet
- ~~First look at gluon GPD → E_g~~
  - Requirement:
    - data sets √s = 508 GeV p↑p and √s = 200 GeV p↑A
    - A_{UT} for J/ψ in UPC
- Physics driving the large A_N at forward rapidities and high x_F
  - Requirement:
    - large data sets √s = 200 and 508 GeV p↑p
      → low to highest x_F → fSTAR
    - charge hadron A_N at forward rapidities
- ~~Nuclear dependence of PDFs, FF, and TMDs~~
  - Requirement:
    - large equal data set of √s = 200 p↑p and p↑Au
      → low to high x, highest and lowest x with fSTAR
    - R_{pA} direct photons and DY, hadrons in jet A_{UT}
- ~~Non-linear effects in QCD~~
  - Requirement:
    - large equal data set of √s = 200 p↑p and p↑Au
      → lowest-x through fSTAR
    - correlations for $h^{+/-}$, γ-jet, di-jets

Without pAu data, STAR's forward upgrade will not be fully utilized for its discovery potential and RHIC will lose important physics opportunities on the following:

- **First look at gluon GPD → E_g**
- **Probe Nuclear dependence of PDFs, FF, and TMDs**
- **Study Non-linear effects in QCD**
- **Discover a novel vortical configuration**