STAR Beam Use Request for Run 25/26 (20 & 28 weeks)

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BNL NPP 2024 PAC meeting, November 7-8

STAR

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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Executive summary of plans for Run 25

STAR

Full detector capability with forward upgrades and excellent PID over an extended η coverage

Table 1: Proposed Run-25 assuming 20 or 28 cryo-weeks of running in 2025 and 2 weeks of set-up time to achieve minimum-bias running conditions. For both scenarios, we request 200 GeV Au+Au collisions. We provide the requested event count for our minimum bias (MB) trigger, and the requested sampled luminosity from our a high-p_T trigger that covers all v_z. During Runs 23 and 24, STAR collected 8 billion MB Au+Au events and achieved a sampled luminosity of 1.2 nb^{-1}.

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	8B+**5B** / 1.2 nb^{-1}+**20.8** $\mathbf{nb^{-1}}$	2023+2024+**2025 (20 cryo-weeks)**
200	Au+Au	8B+**9B** / 1.2 nb^{-1}+**28.6** $\mathbf{nb^{-1}}$	2023+2024+**2025 (28 cryo-weeks)**

Au+Au: probe the inner workings of the QGP;

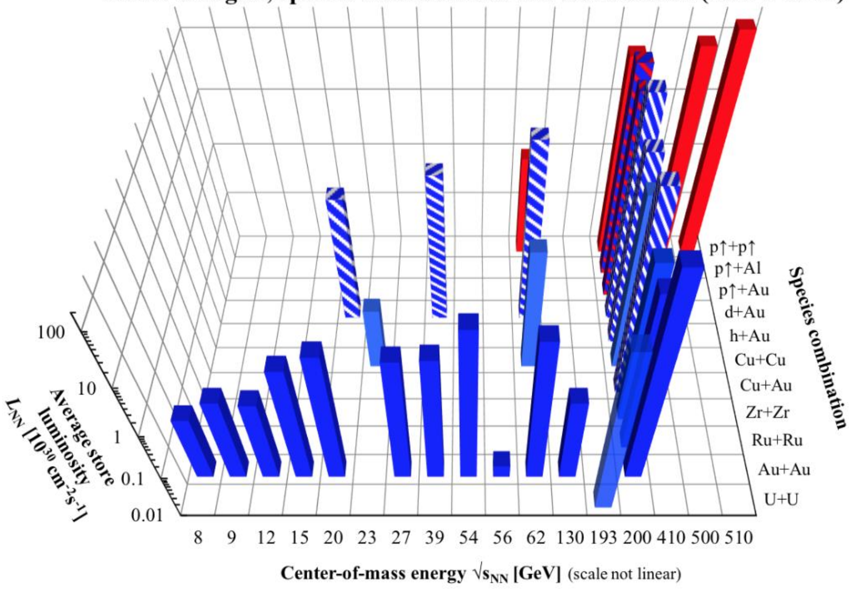
- original goals: 20 B MB events/40 nb^{-1}

STAR requests an extension of Run-25 beyond 28 cryo-weeks, allowing 5 weeks of p+Au physics data collection to achieve a sampled luminosity of 0.22 pb^{-1}

Evolution of the STAR Detector

major upgrades over the last twenty years to improve particle identification and vertex reconstruction, and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.

RHIC energies, species combinations and luminosities (Run-1 to 19)



Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\lvert\eta\rvert<1$ Tracking		1999-
Barrel EMC	$\lvert\eta\rvert<1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1<\eta<2$ jets/π^0/e	(NSF)	2005-
Roman Pots	diffractive		2009-
TOF	PID	(China)	2009-
FMS/Preshower	$2.5<\eta<4.2$	(Russia)	2008-2017
DAQ1000	x10 DAQ rate		2008-
HLT	Online Tracking	(China/Germany)	2012-
FGT	$1<\eta<2$ $W^{\pm}$		2012-2013
GMT	TPC calibration		2012-
HFT/SSD	open charm	(France/UIC)	2014-2016
MTD	muon ID	(China/India)	2014-
EPD	event plane	(China)	2018-
RHICf	$\eta>5$ π^0	(Japan)	2017
iTPC	$\lvert\eta\rvert<1.5$ Tracking	(China)	2019-
eTOF	$-2<\eta<-1$ PID	(Germany/China)	2019-
FCS	$2.5<\eta<4$ calorimeter	(NSF)	2021-
FTS	$2.5<\eta<4$ Tracking	(NCKU/SDU)	2021-

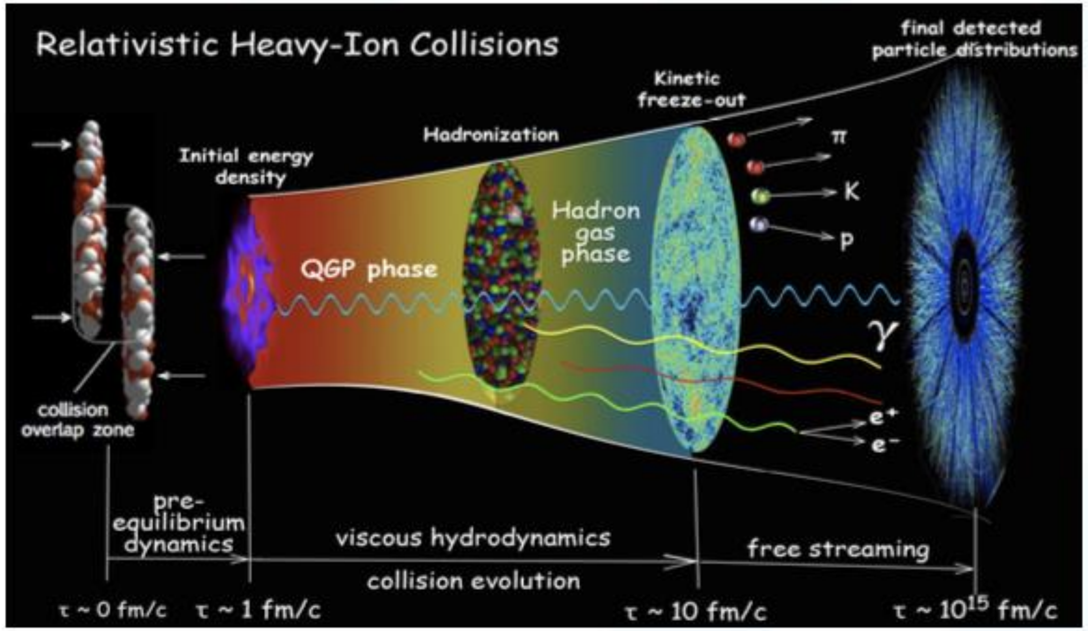
2

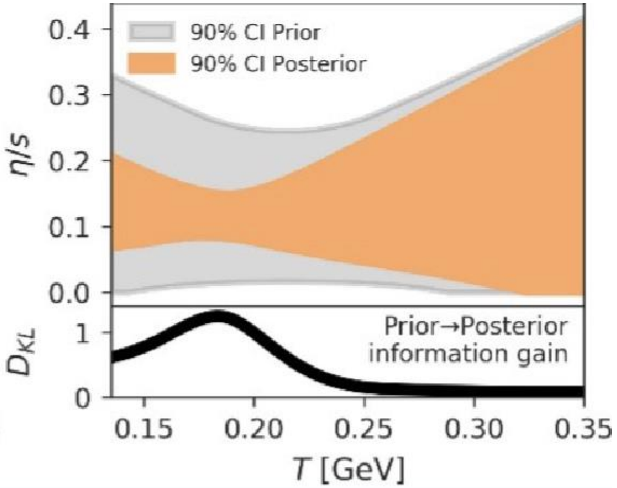
24 years of operation, major successful upgrades, vibrant physics programs

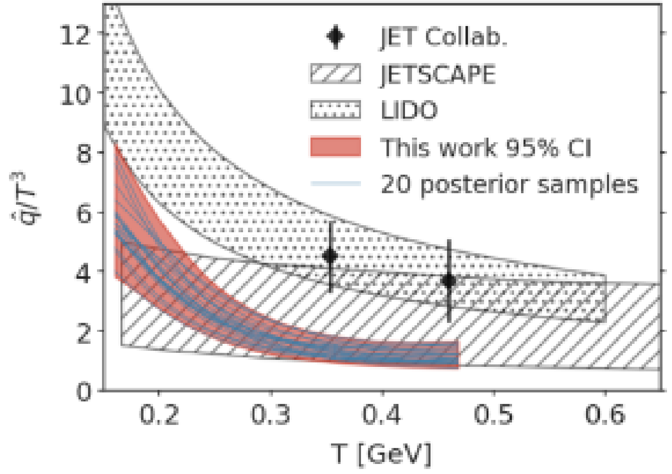
330 published papers, 321 PhD and 22 MS theses

The properties of perfect liquid

The 2023 NSAC Long Range Plan for Nuclear Science

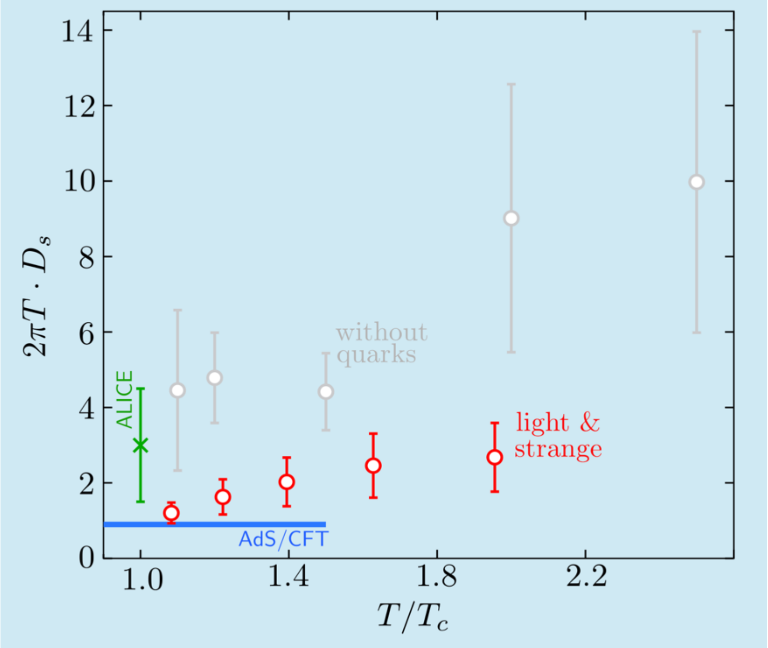






Essential questions to be addressed:

1. How do the fundamental interactions between quarks and gluons lead to the perfect fluid behavior of the quark-gluon plasma?
2. What are the limits on the fluid behavior of matter?
3. What are the properties of QCD matter?
4. What is the correct phase diagram of nuclear matter?



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Physics Opportunities for 2023+2024+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

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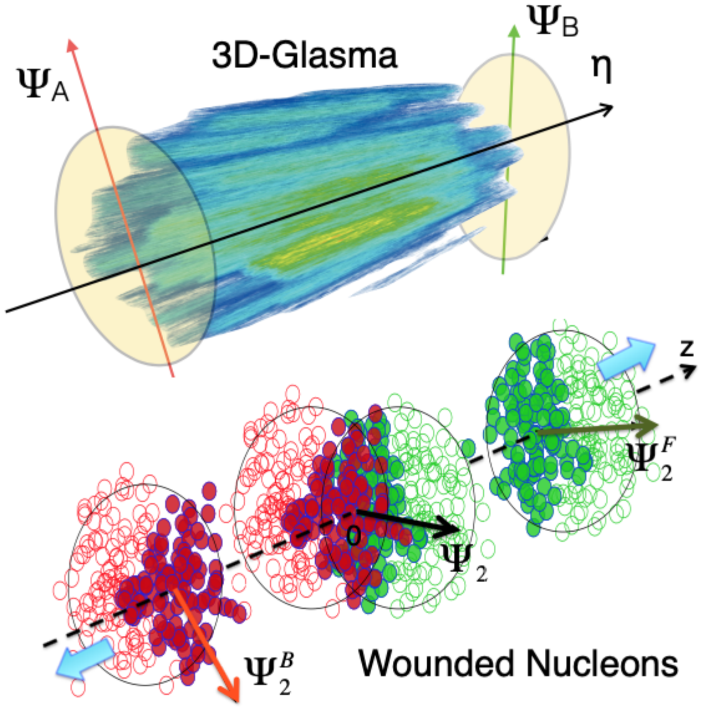
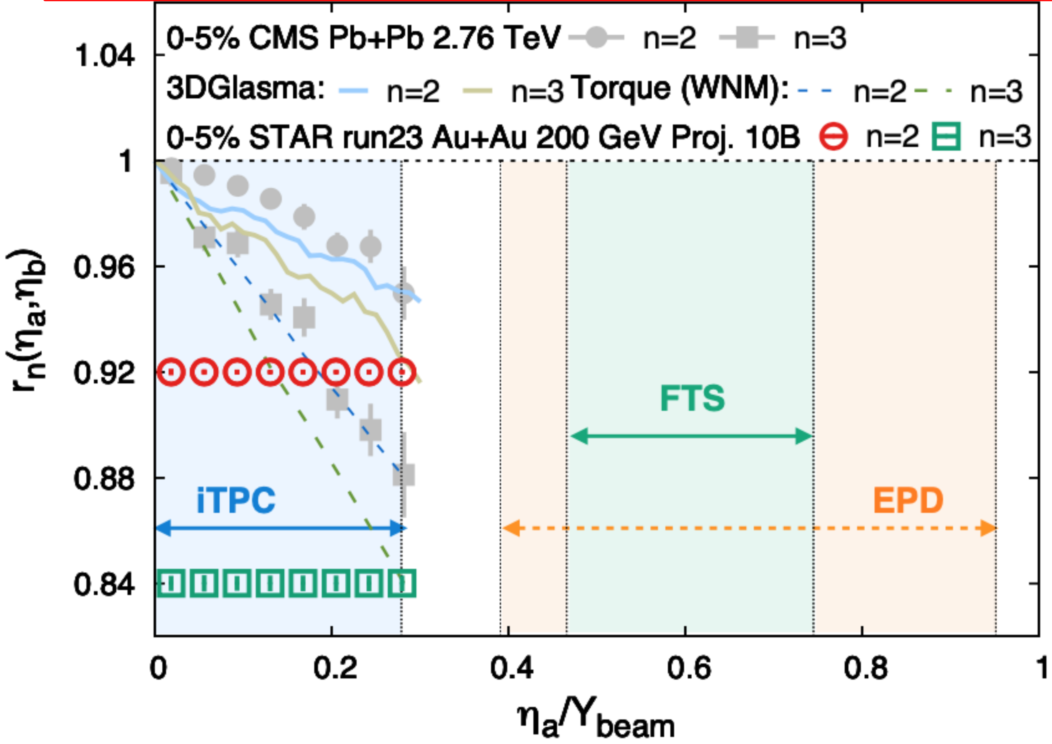
Constrain longitudinal structure of initial state



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

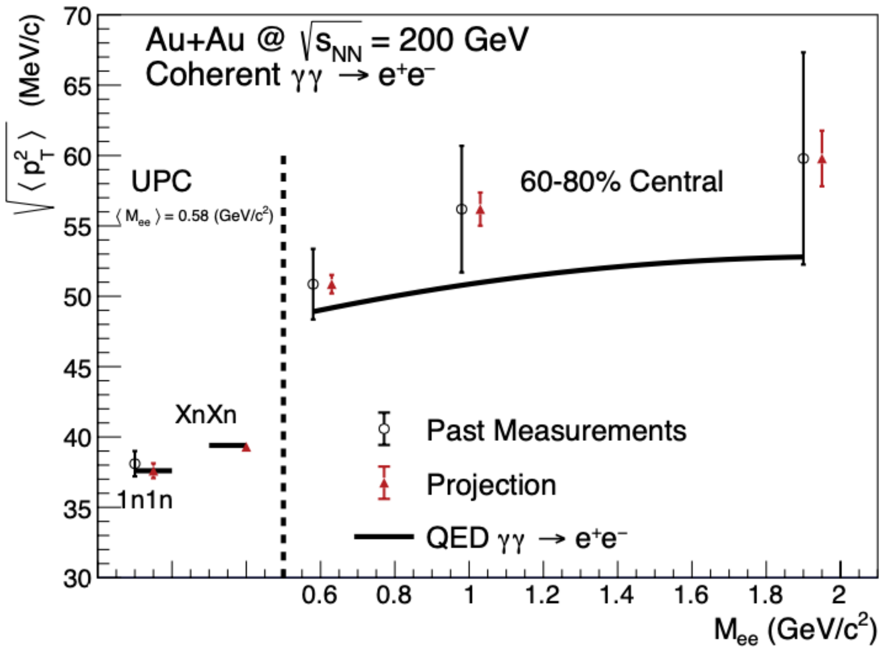
r_n sensitive to different initial state inputs:

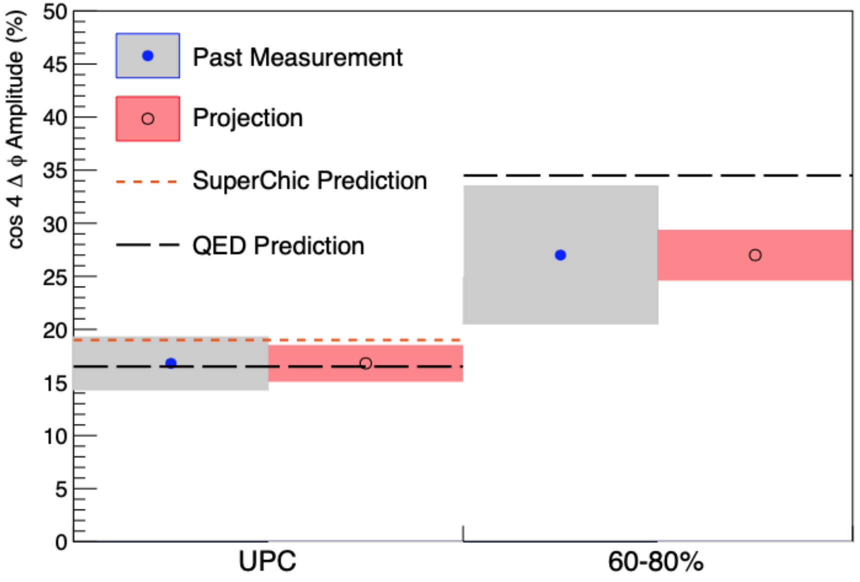
- **3D glasma model: weaker decorrelation, describes CMS r_2 but not r_3**
- **Wounded nucleon model: stronger decorrelation than data**

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.

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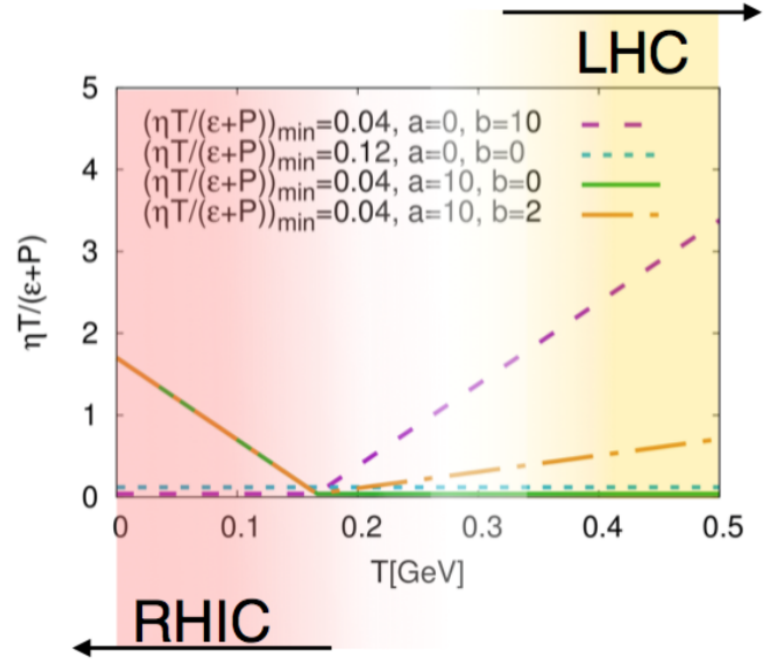
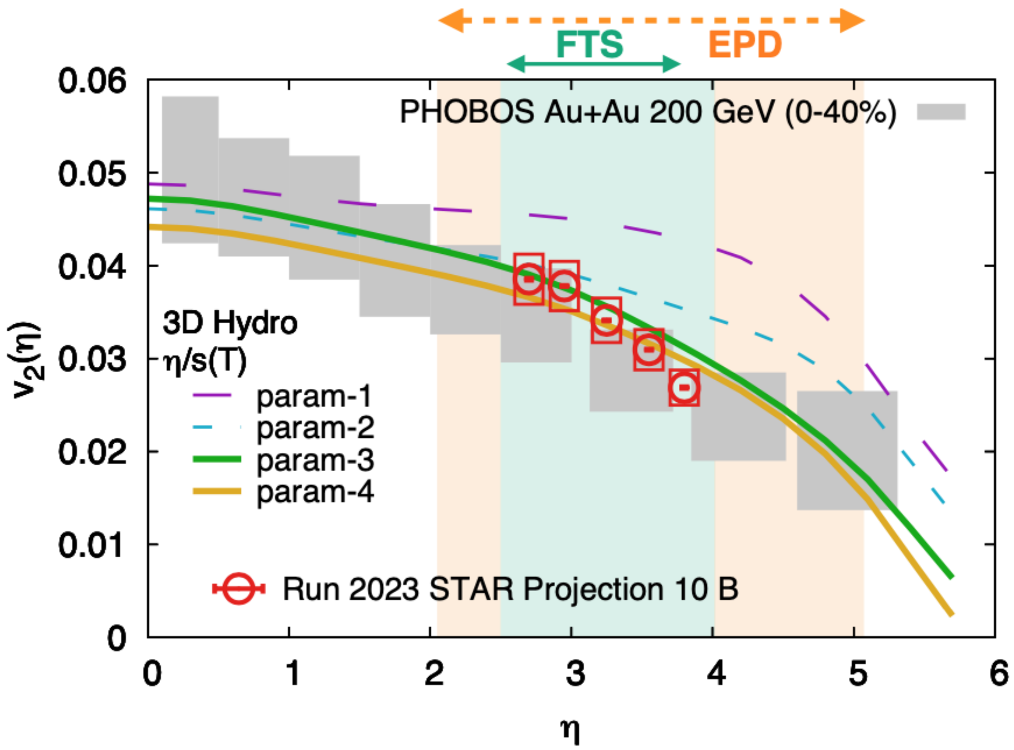
Constrain temperature dependence of η/s

forward tracking



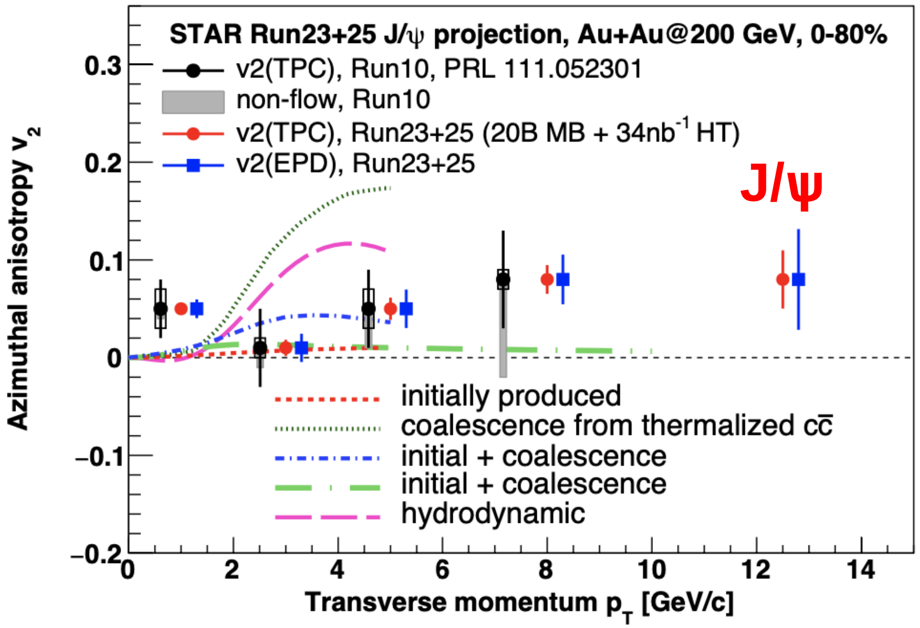


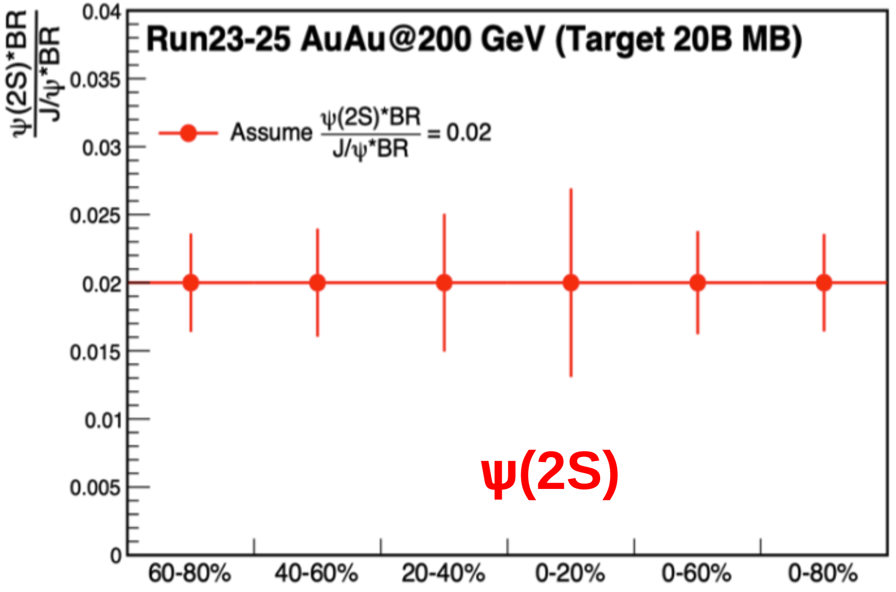
Flow measurements at forward rapidity sensitive to η/s as a function of T.

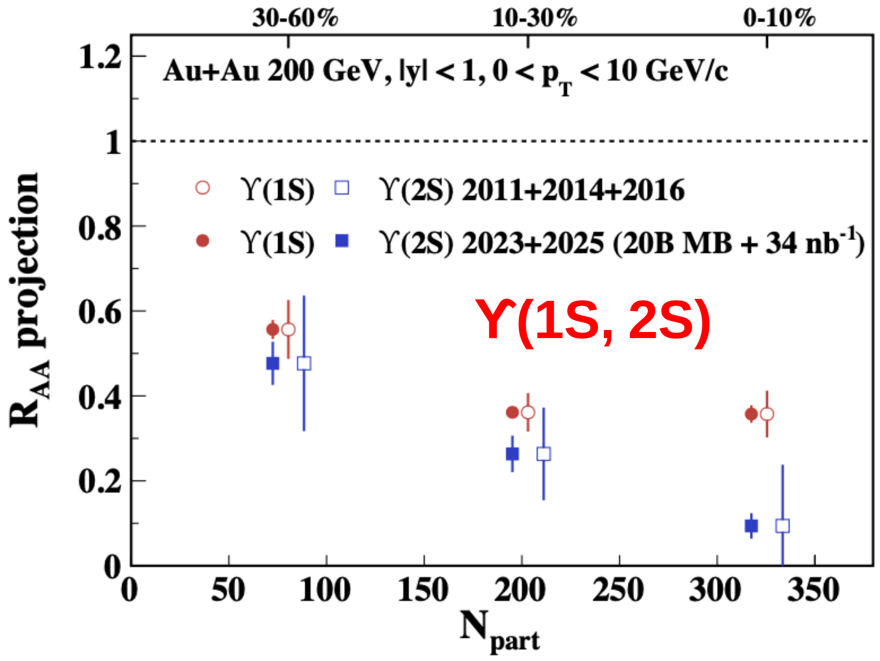
Much more precise than previous PHOBOS measurements.

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)

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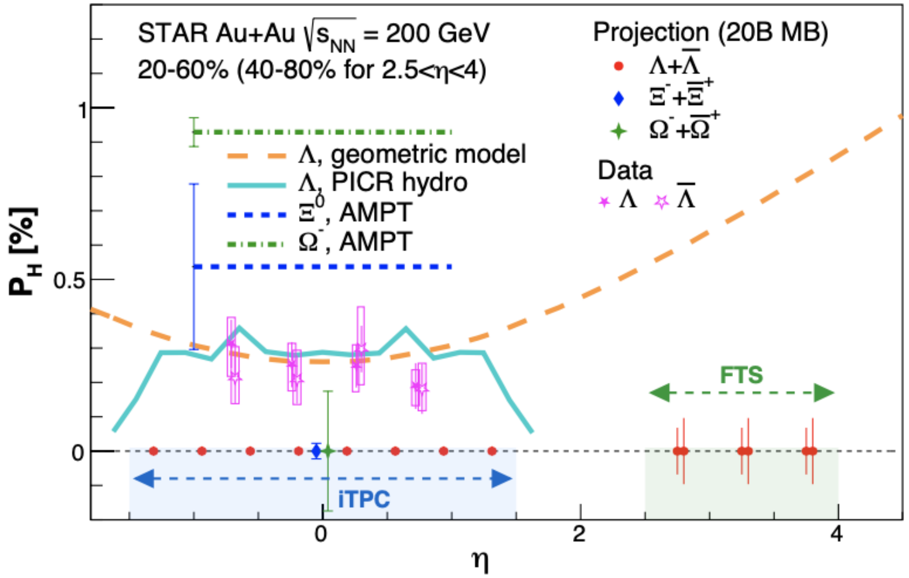
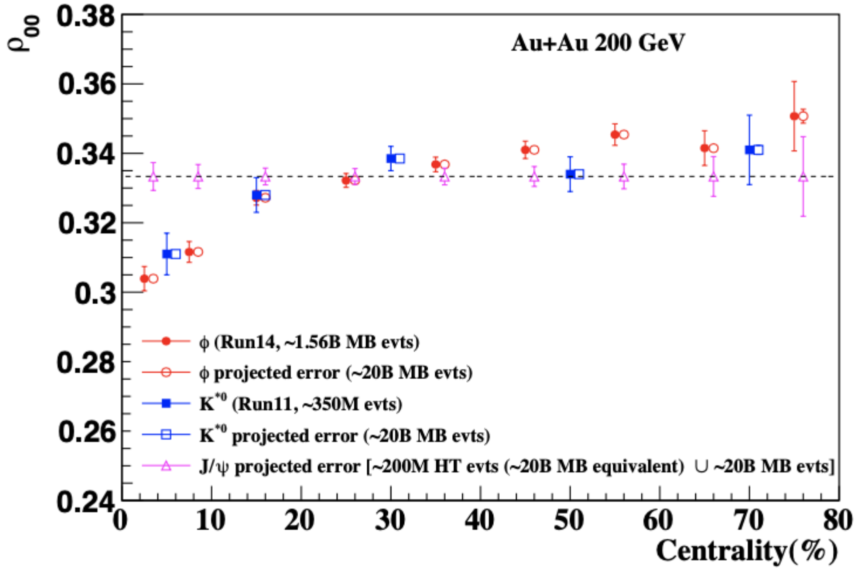
Global vorticity transfer

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.

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Charge dependent directed flow

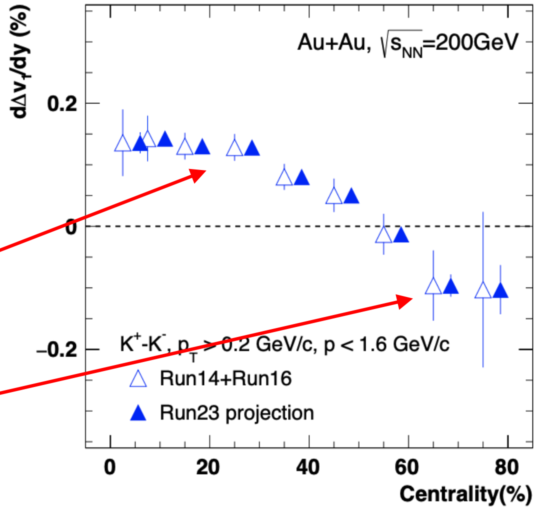
improved PID, extended η coverage by iTPC

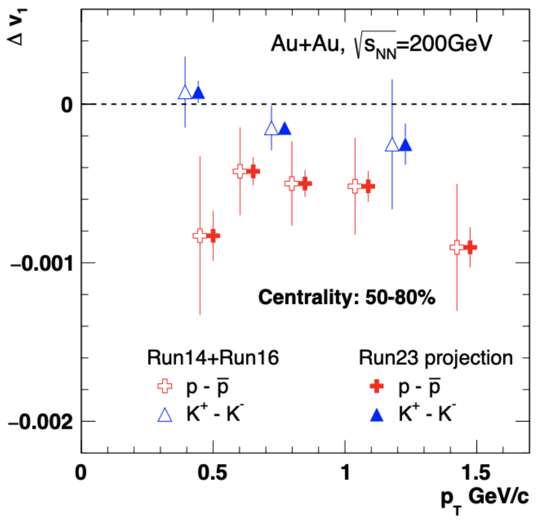
Charge dependent v_1 slope sensitive to EM field

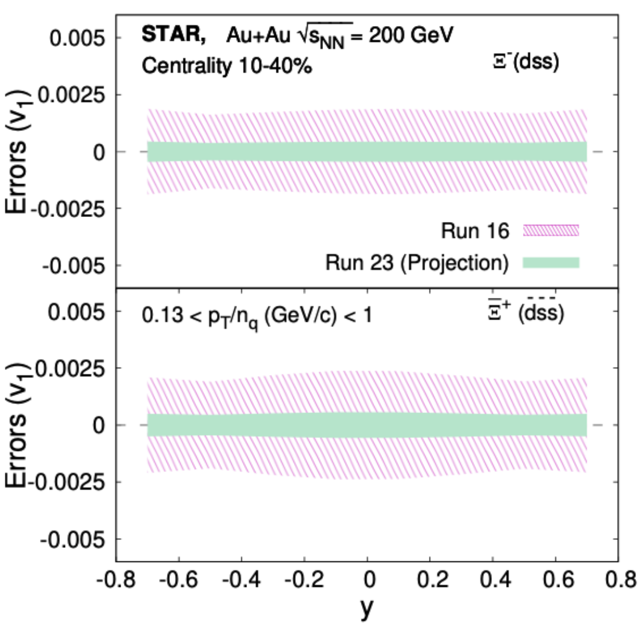
$d\Delta v_1/dy > 0$ due to transported quark

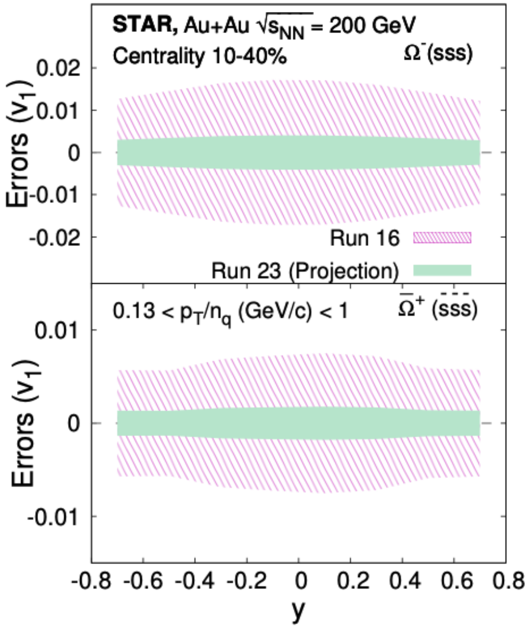
$d\Delta v_1/dy < 0$ due to EM field

Runs 23+24+25: >5σ difference between K^+ and K^- in peripheral collisions, precise measurements for multi-strange particles.









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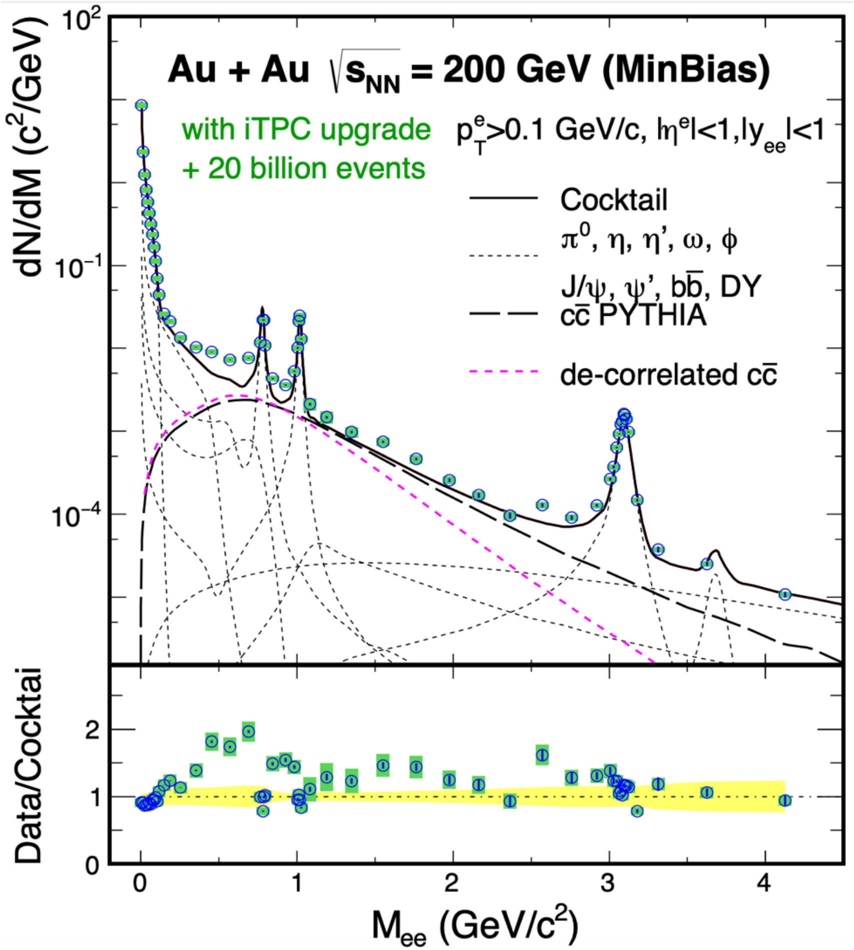
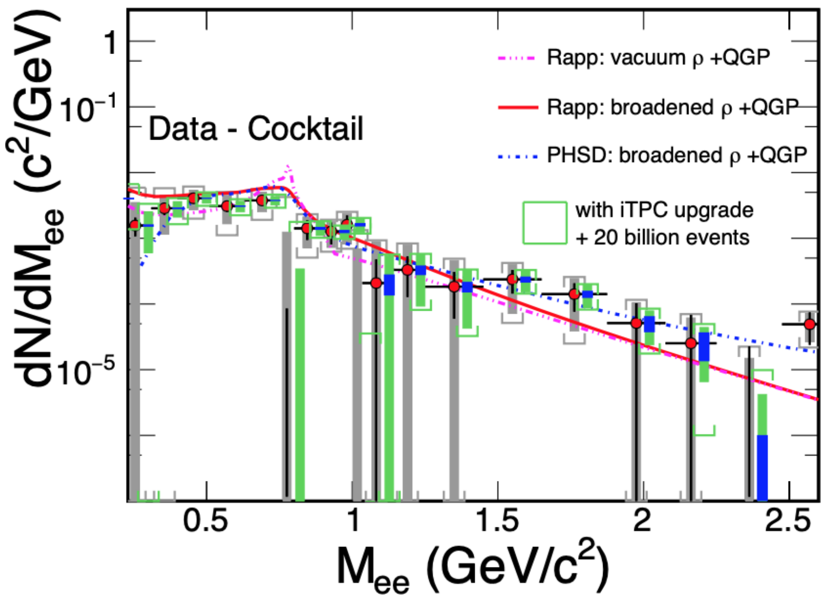
Chiral property



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



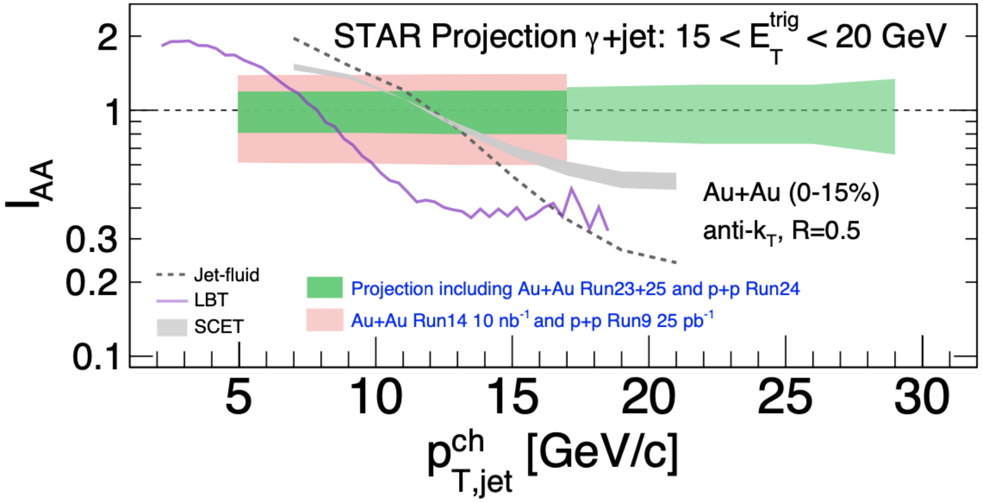
Low-mass dielectron measurement: **lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B~0**

Intermediate mass: **direct thermometer to measure temperature**

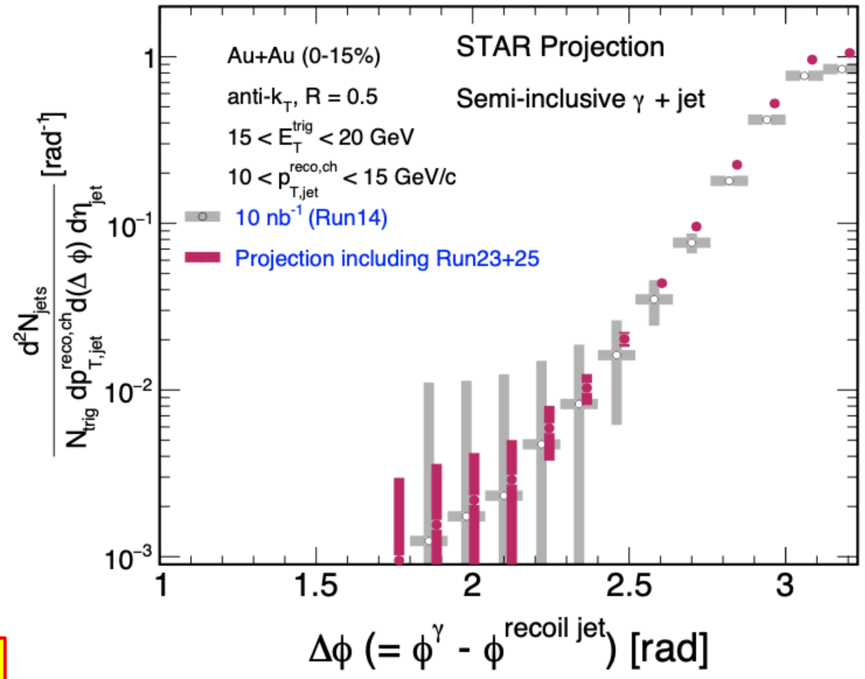
Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

Jet quenching

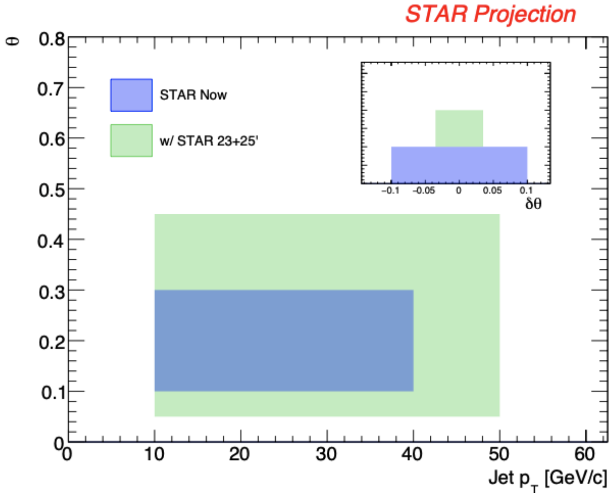
low p_T, large R, extended to higher p_T

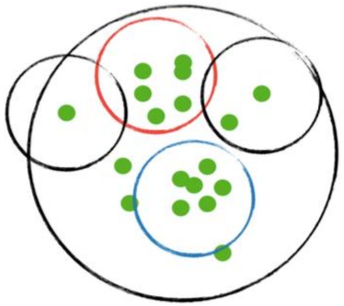


γ_{dir}+jet acoplanarity: constituents of medium



improved opening angle resolution by a factor of 4

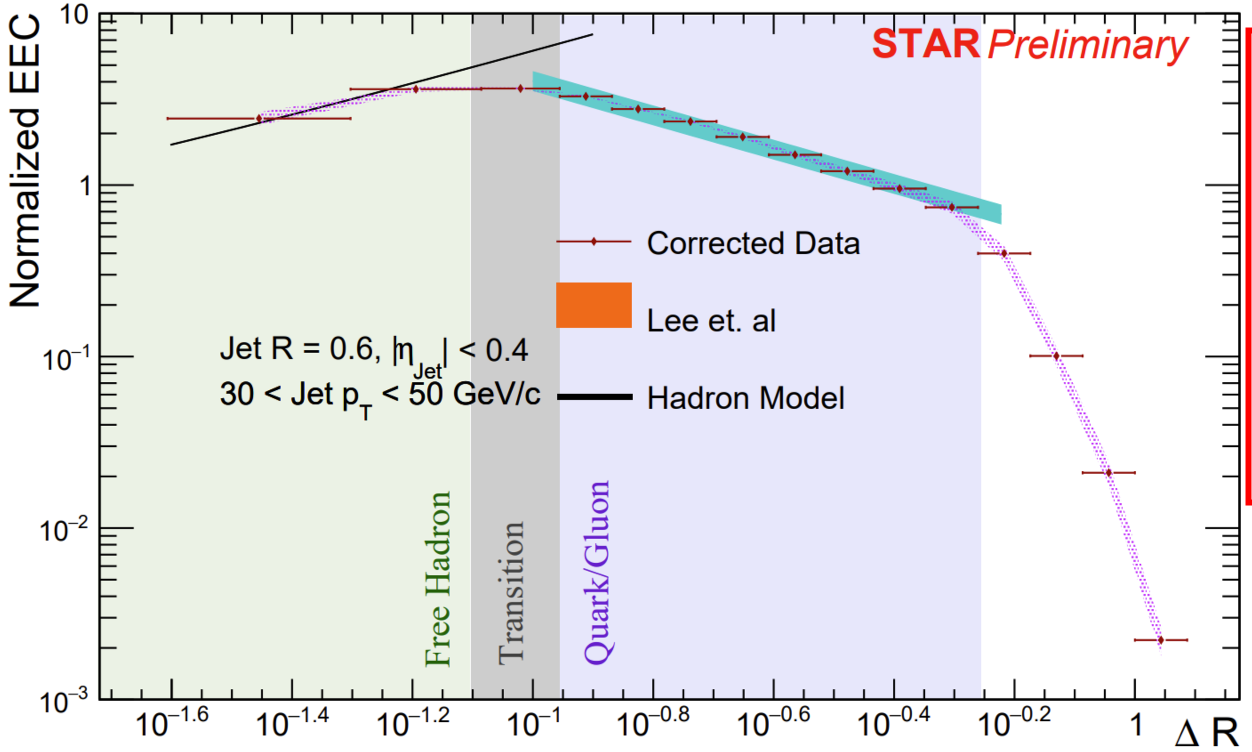




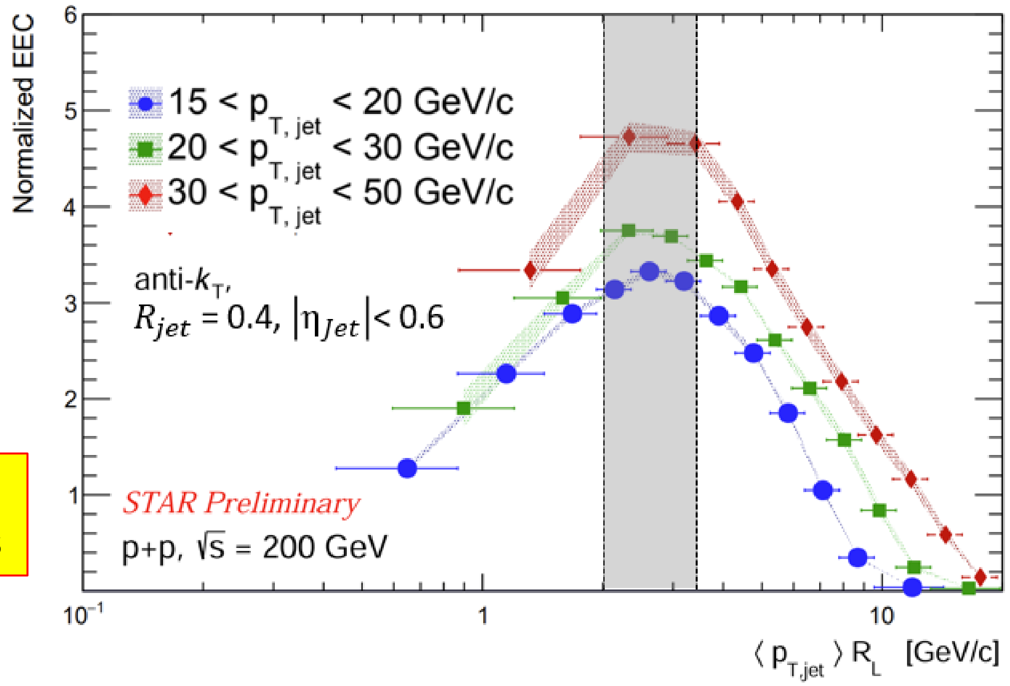
Red: leading sub-jet
Blue: sub-leading sub-jet
$Z_{SJ}=p_T^{blue}/(p_T^{blue}+p_T^{red})$
$\theta_{SJ}=\Delta R$(blue,red)

Jet substructure: coherence vs. de-coherence

Jet evolution and hadronization



- Separates evolution of jet into angular regimes
  - **Analyze both perturbative and non-perturbative**
  - **Locate transition between them – hadronization**
- Peak moves as a function of jet momentum
  - **Consistent transition regime within STAR**
  - **Dependent on initiator flavor – compare between experiments**



- Heavy-Ion data will show modification at discrete angles
  - **Onset of coherence**
  - **Diffusion wake**

High statistics, improved opening angle and momentum resolution, unbiased centrality determination, forward and mid-rapidity comparisons

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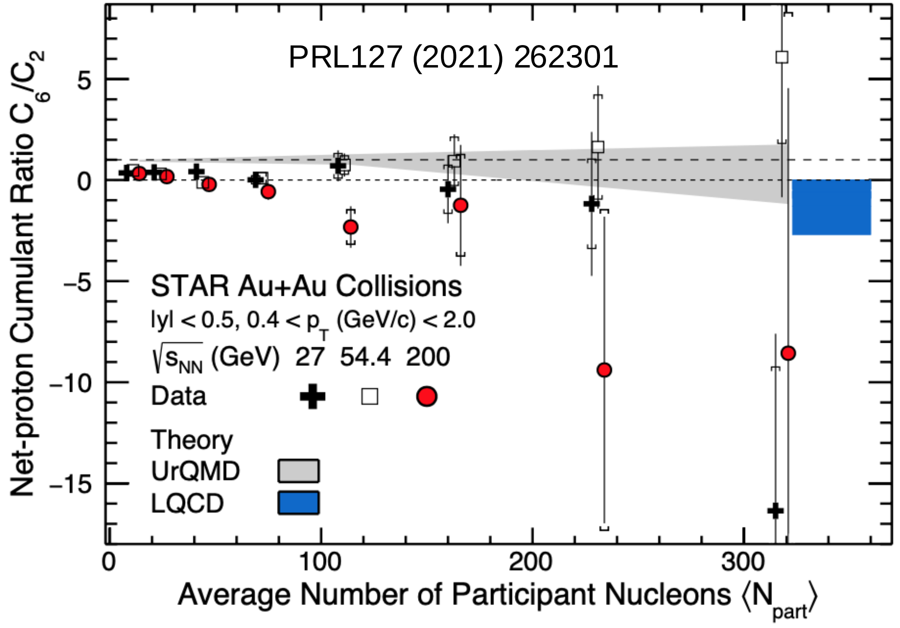
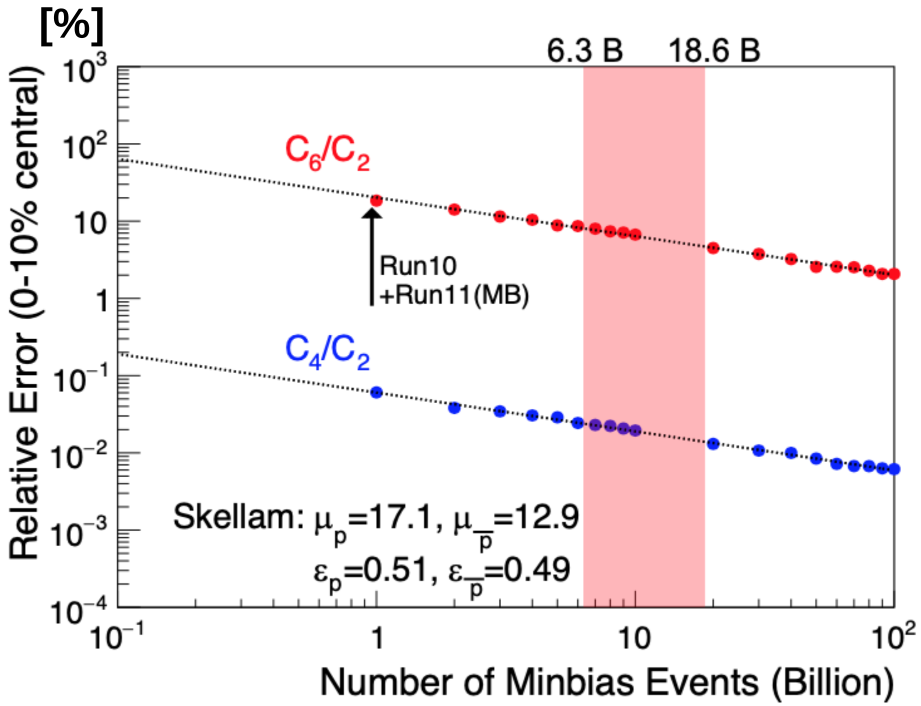
Chiral cross-over transition

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

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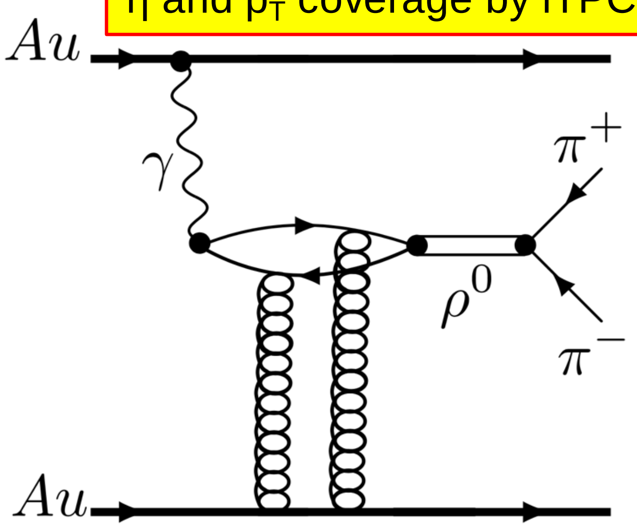
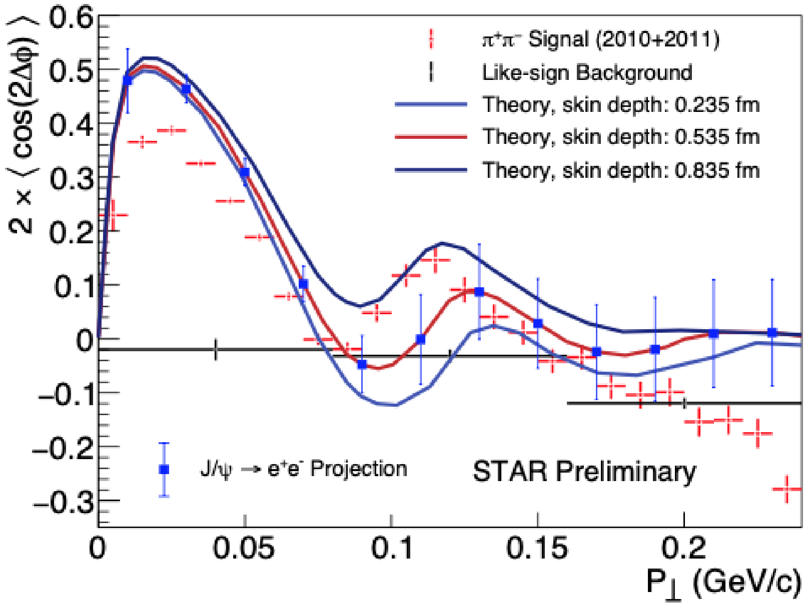
Gluon distribution inside nucleus

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





Significant cos2Δϕ azimuthal modulation in $\pi^+\pi^-$ pairs from photonuclear ρ^0 and continuum
Modulation vs. p_T, shows a diffractive pattern structure

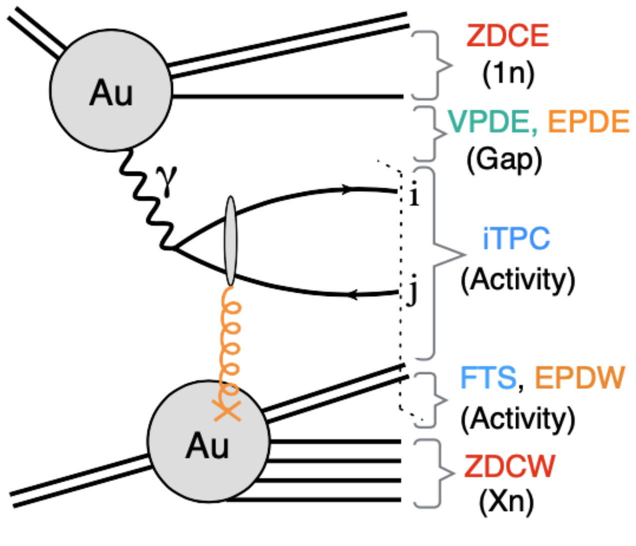
Theory (linear polarized photon + saturated gluons), sensitive to nuclear geometry and gluon distribution, closest to the gluon 3D tomography at EIC

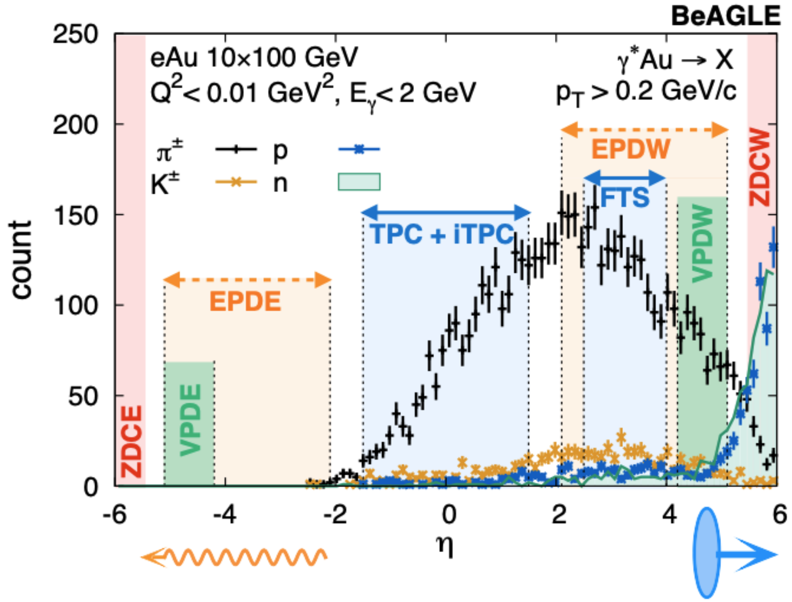
Run23+25:

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:

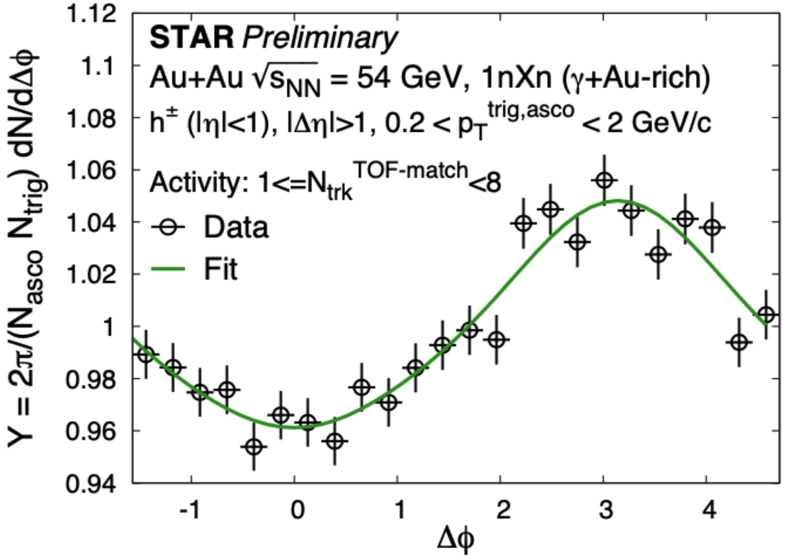
- Search for collectivity
- Study bulk observables

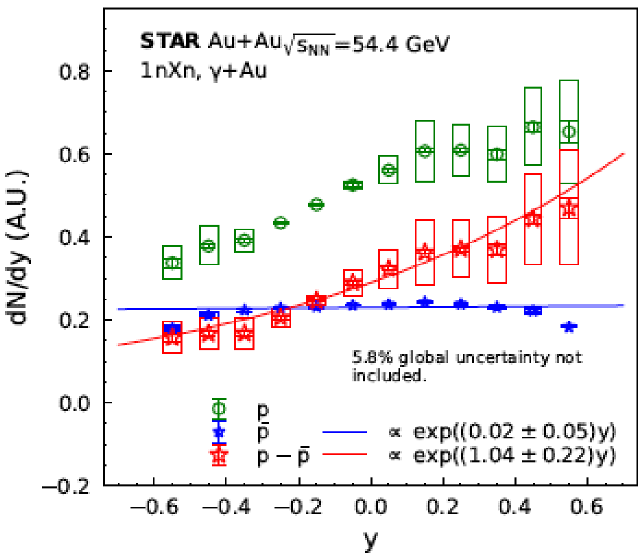
Further understand the origin of collectivity observed in small systems in addition to testing the baryon junction conjecture

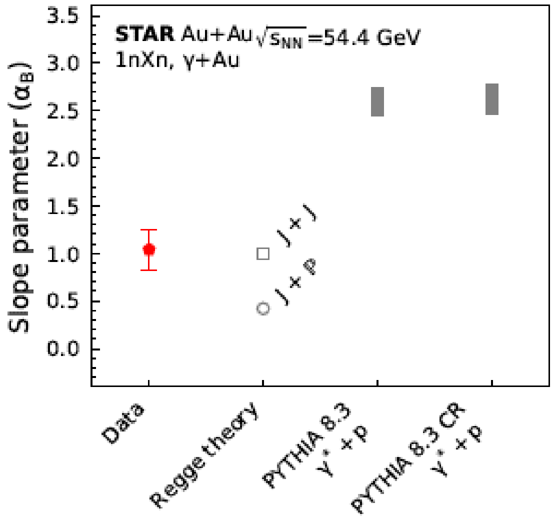
Search for collectivity and signatures of baryon junction in photo-nuclear processes

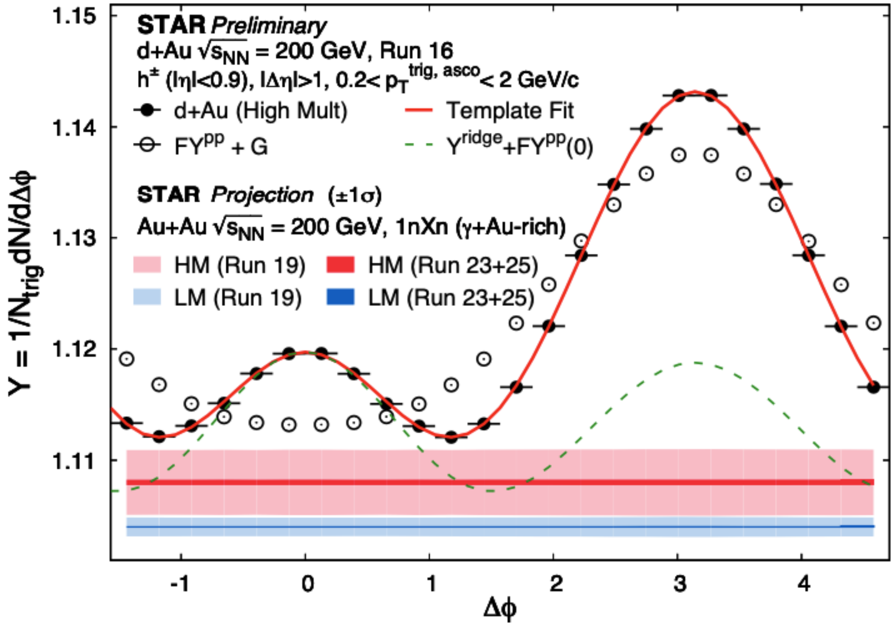
improved PID, extended η coverage by iTPC, and forward tracking

arXiv: 2408.15441









γ+Au 54 GeV:

- **No signature of collectivity**
- **Net-proton rapidity distribution consistent with the Regge theory prediction incorporating the baryon junction**

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

Search for collectivity in addition to testing the baryon junction conjecture

Physics Opportunities for 2023+2024+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
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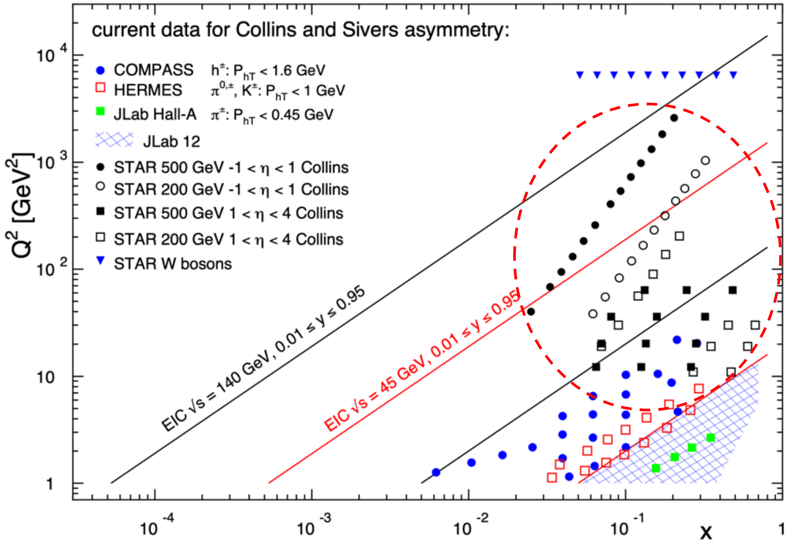
Plans for Run 24

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

Full detector capability with forward upgrades and excellent PID over an extended η coverage

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



Based on the presentations of STAR and sPHENIX and their full detector capabilities in Sep. 2023:

The PAC recommends that the top priority for Run 24 is to complete the commissioning of sPHENIX and to collect the high statistics pp dataset necessary as a reference for all the sPHENIX hard probes Au+Au measurements in Run 25, and simultaneously allow STAR to make landmark polarized proton measurements using its new forward instrumentation. We recommend p+Au running in Run 24 if, and only if, the top priority above has been completed and a p+Au run of at least 5 weeks can be accomplished.

We note that the p+Au run identified as the second priority for Run 24 is not a necessary precursor to Run 25. *Looking at the compelling scientific case for this run, and in particular its importance to the science of the future EIC, if the p+Au run is not done in Run 24 there will be a compelling case for running RHIC beyond the completion of the Run 25 Au+Au data-taking in order to include at least five weeks of p+Au running, even if doing so extends Run 25 beyond June 2025.*

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Physics program for 2022+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

Full detector capability with forward upgrades and excellent PID over an extended η coverage

The RHIC cold QCD plan for 2024 to 2028:
https://drupal.star.bnl.gov/STAR/starnotes/public/SN0837

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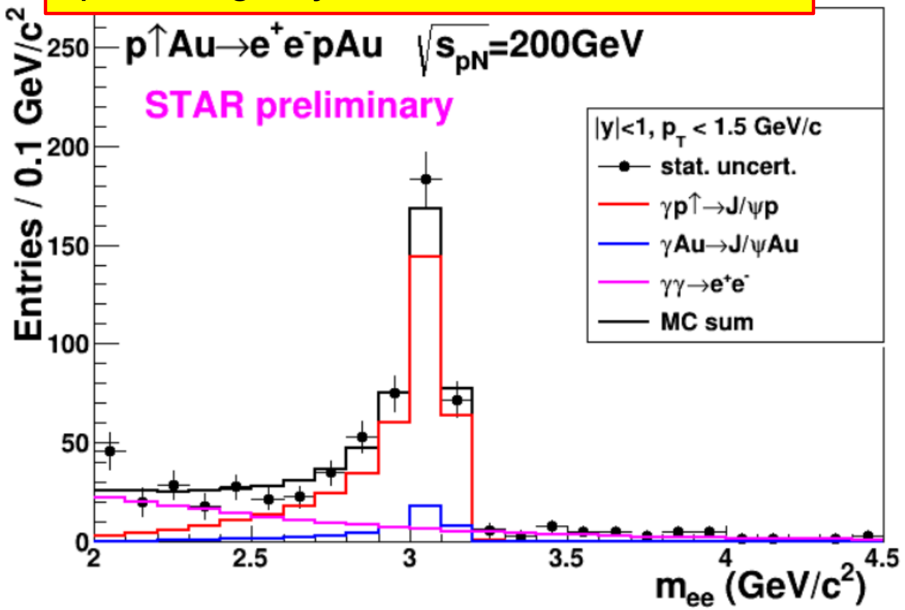
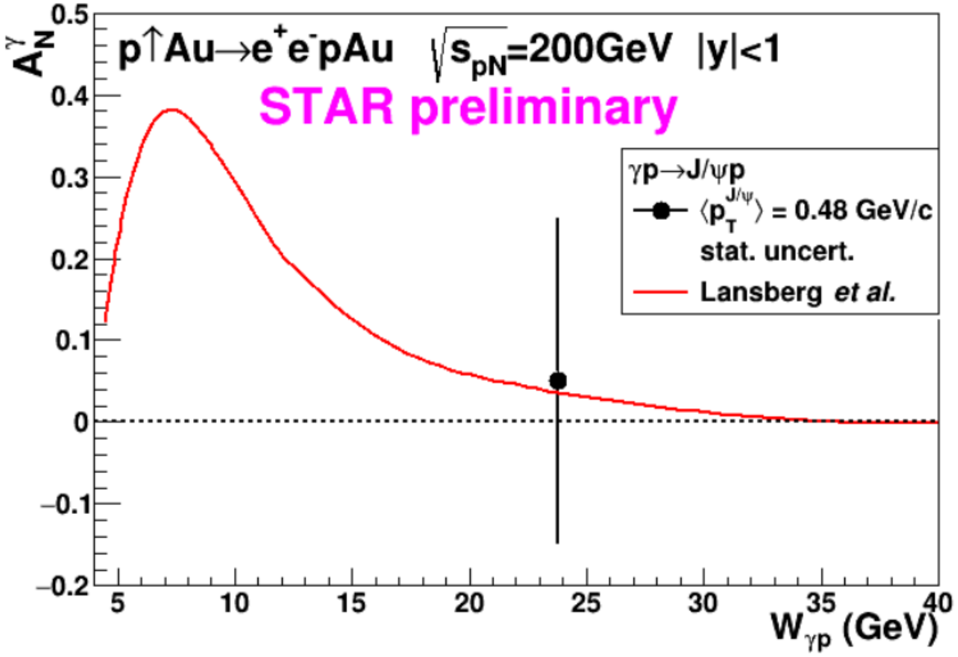
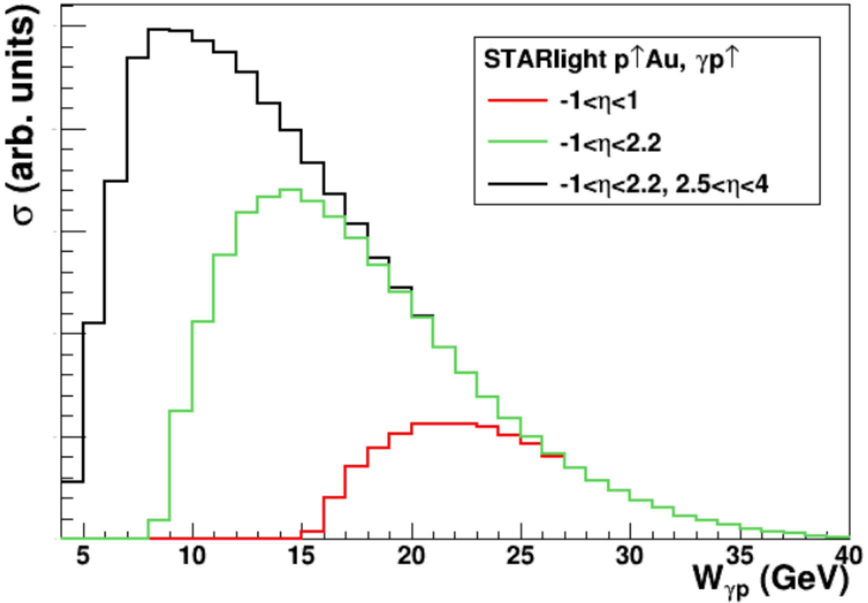
Generalized parton distribution

low material, improved PID, extended η coverage by iTPC, fSTAR







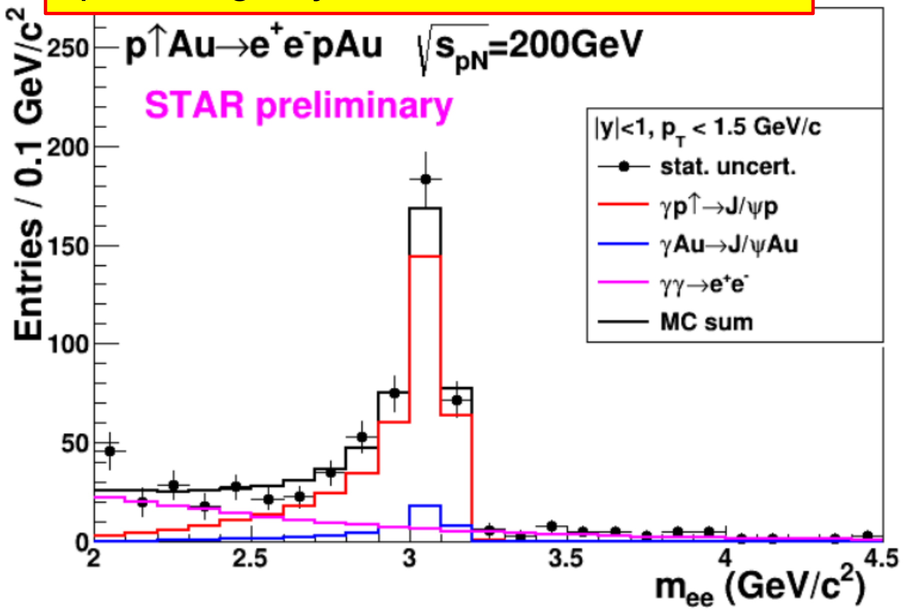
Exclusive J/ψ A_N in UPC, Q^2~10 GeV^2, $10^{-4}<x<10^{-1}$

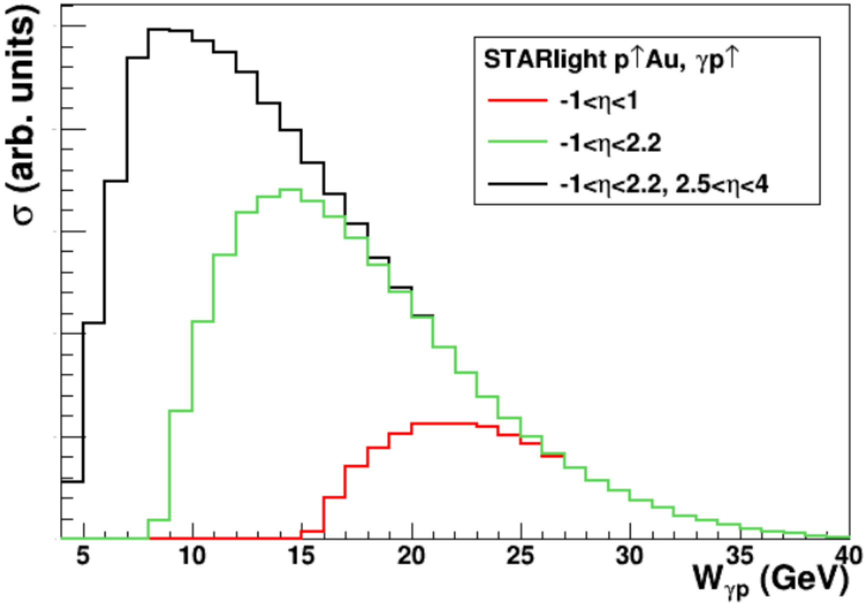
Access GPD Eg for gluons, sensitive to spin-orbit correlation

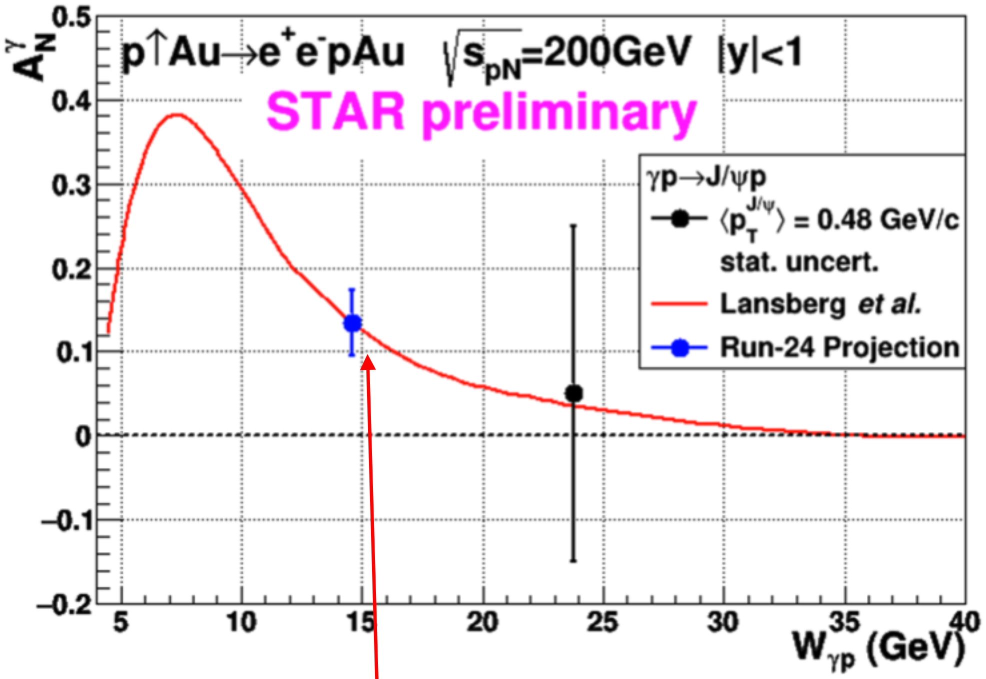
Run-24: acceptance improved by a factor of 9-10, combined with iTPC and forward upgrades, stat. error for A_N^{γ}: 0.04 for $<W_{\gamma p}>$=14 GeV, where the signal is expected to be large.

Generalized parton distribution

low material, improved PID, extended η coverage by iTPC, fSTAR







Exclusive J/ψ A_N in UPC, Q^2~10 GeV², $10^{-4}<x<10^{-1}$

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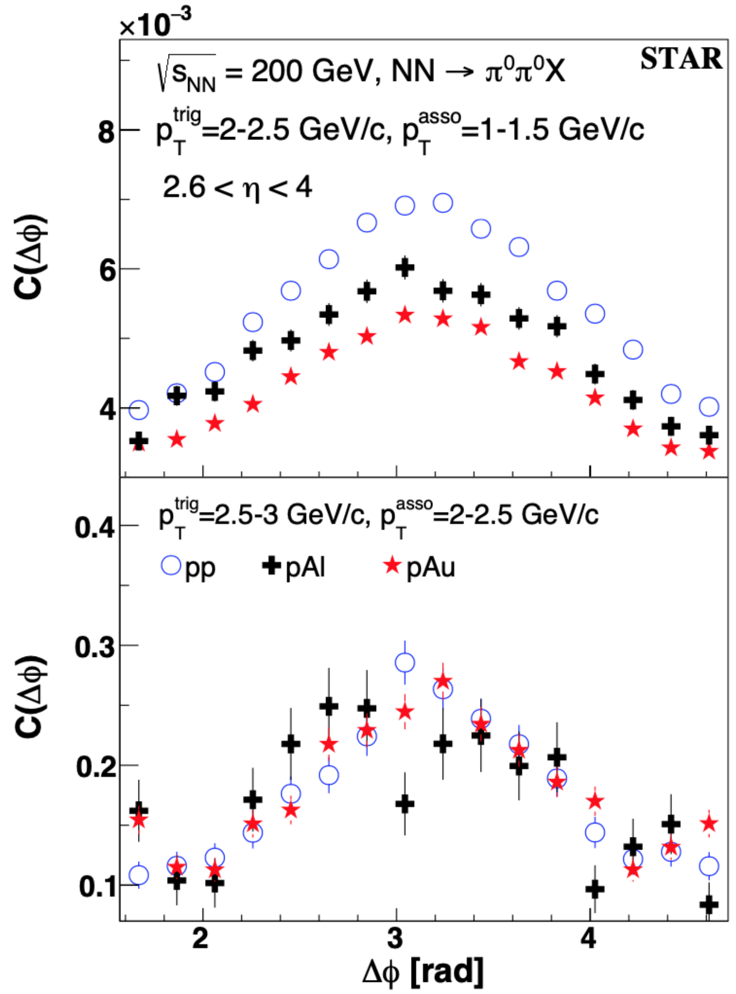
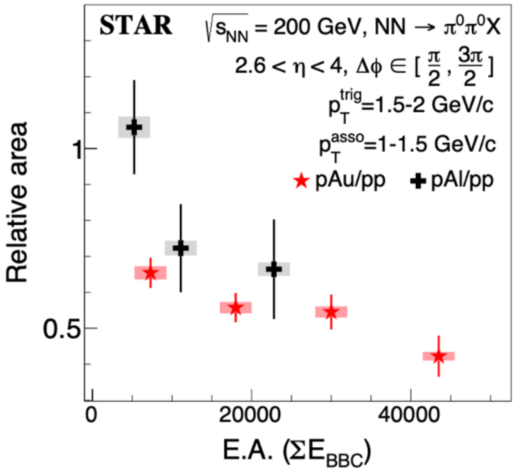
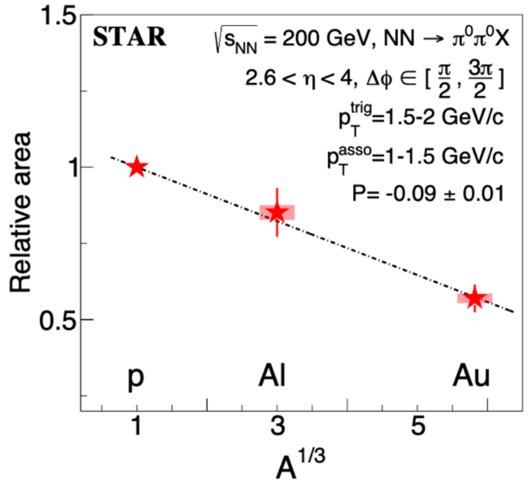
QCD non-linear effects

STAR, PRL129 (2022) 92501



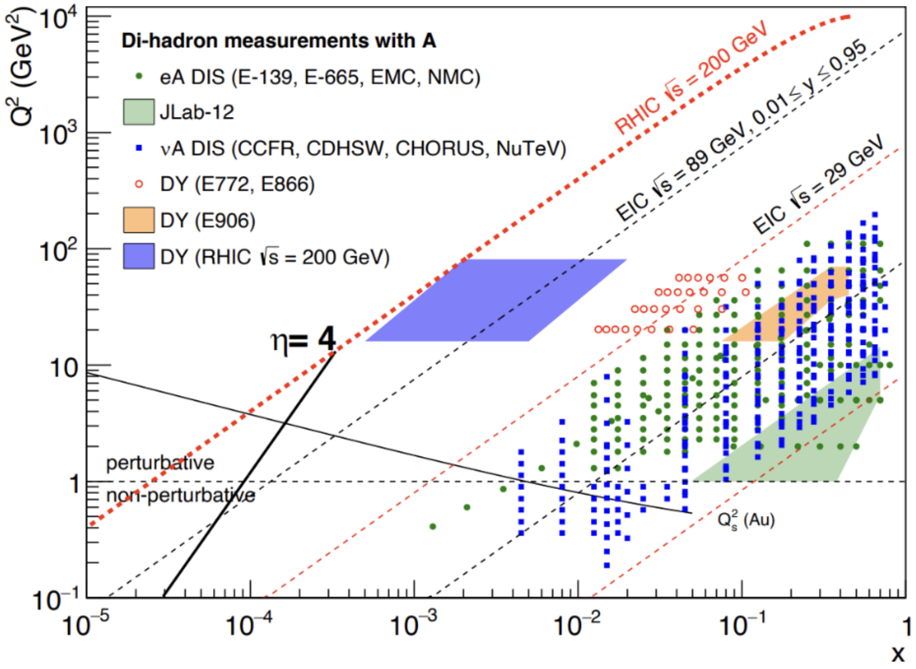


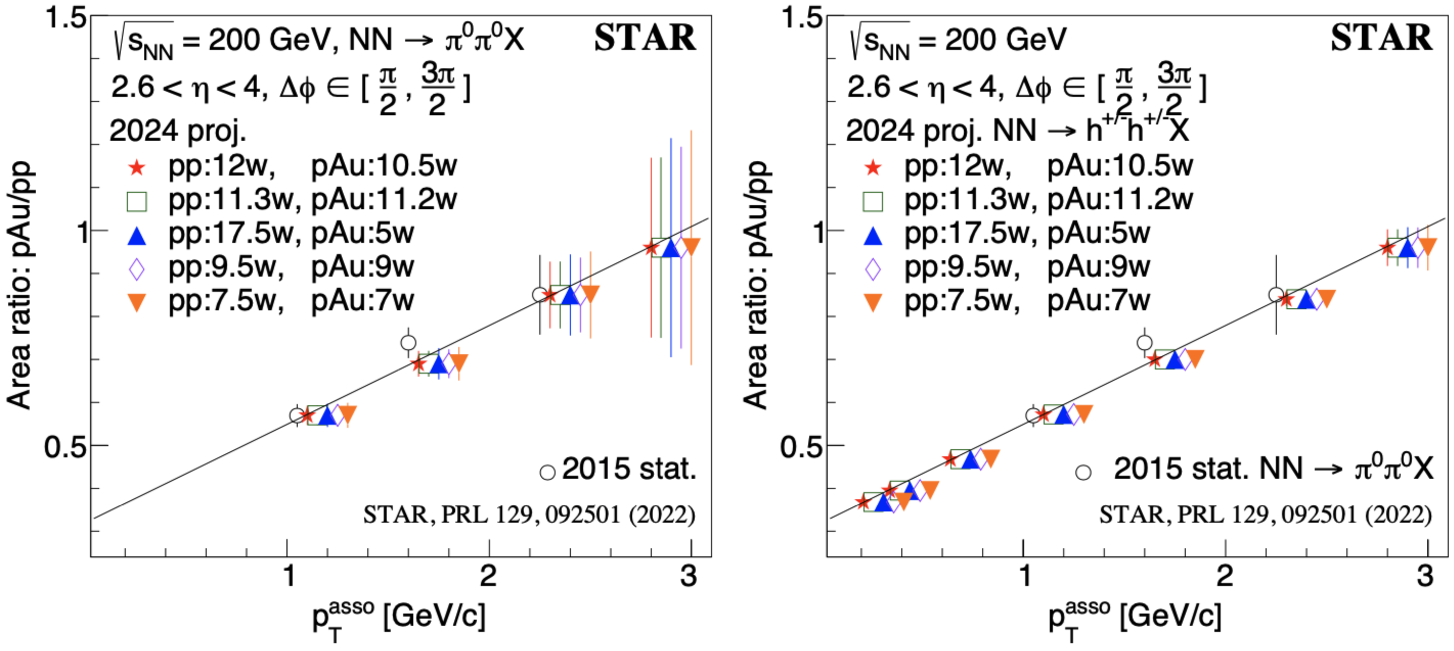


Run-15 di-π^0 correlation:
away side area suppressed significantly, while the pedestal and away side widths remain unchanged.

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

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

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Impact of STAR science goals without pA data in Run 24

- 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

Full detector capability with forward upgrades and excellent PID over an extended η coverage

Without pA 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

Physics priorities

Table 1: Proposed Run-25 assuming 20 or 28 cryo-weeks of running in 2025 and 2 weeks of set-up time to achieve minimum-bias running conditions. For both scenarios, we request 200 GeV Au+Au collisions. We provide the requested event count for our minimum bias (MB) trigger, and the requested sampled luminosity from our a high-p_T trigger that covers all v_z. During Runs 23 and 24, STAR collected 8 billion MB Au+Au events and achieved a sampled luminosity of 1.2 nb^{-1}.

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	8B+**5B** / 1.2 nb^{-1}+**20.8 nb^{-1}**	2023+2024+**2025 (20 cryo-weeks)**
200	Au+Au	8B+**9B** / 1.2 nb^{-1}+**28.6 nb^{-1}**	2023+2024+**2025 (28 cryo-weeks)**

- **Priority for Runs 23+24+25: meet Hot QCD goals in 200 GeV Au+Au.**
  - minimum bias data and high luminosity data are equally important and will be reduced proportionally for a shorter run scenario.
  - original goals: 20 B MB events/40 nb^{-1}

- **STAR requests an extension of Run-25 beyond 28 cryo-weeks, allowing 5 weeks of p+Au physics data collection to achieve a sampled luminosity of 0.22 pb^{-1}**

- **STAR is ready for the opportunistic fixed target program, which is important for NASA.**

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.**

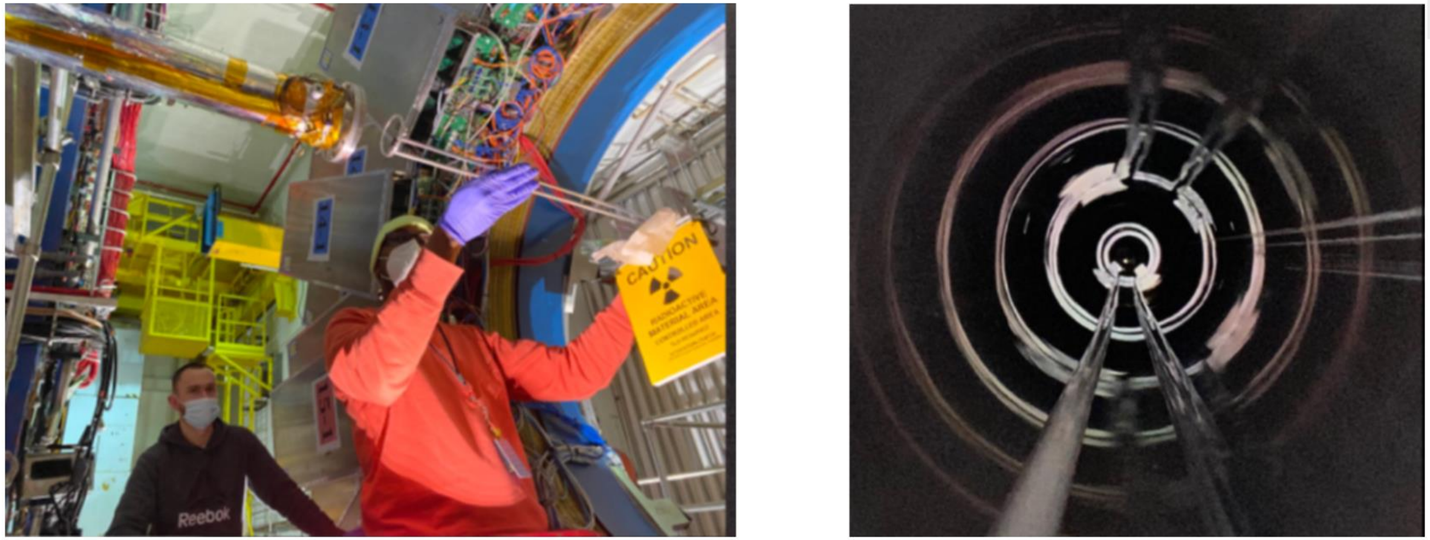


Figure 112: Left panel: Installation of the targets and holder on the East side of the STAR detector. Right Panel: A view down the beam pipe showing the three targets (C, Al, and Ni) installed at STAR.

In total, two weeks of running including machine setup

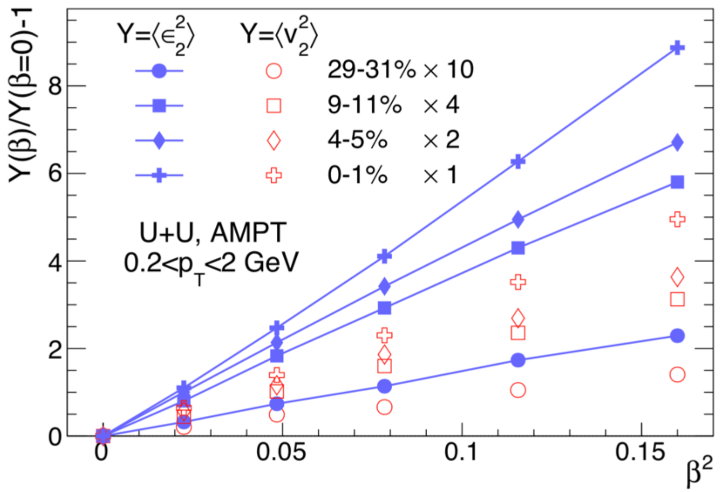
Future opportunity II

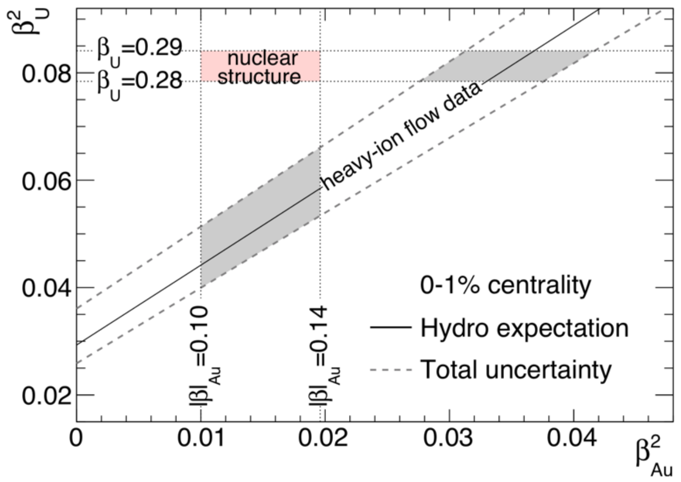
STAR

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 ^{208}Pb at 200 GeV

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

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

- Step2: uncover the nuclear force: triaxiality in rare earths

  Run alternatively Pb+Pb, ^{154}Sm (β_2=0.34) + Sm, ^{166}Er (β_2=0.34) + Er

  - To discover experimentally the triaxiality of well-deformed rare-earth nuclei

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

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Summary

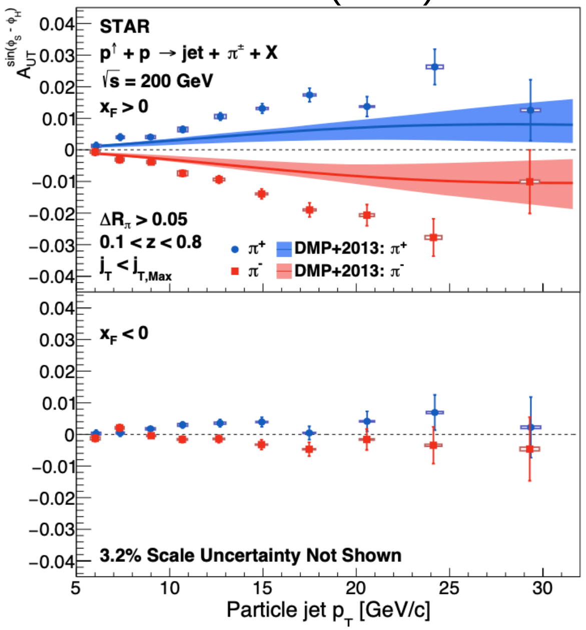
- **STAR forward upgrades were completed on schedule despite pandemic and took data successfully for all of Runs 22-24.**
- **DAQ5k commissioned and operated successfully during Runs 23 and 24.**
- **Those upgrades will enable diverse, broad, and vibrant physics programs in both cold and hot QCD, which will bridge RHIC physics and EIC science.**
- **Run-23, 24 and 25: STAR is in an excellent position to address important questions about the inner workings of the QGP in 200 GeV Au+Au.**
- **STAR requests an extension of Run-25 beyond 28 cryo-weeks, allowing 5 weeks of p+Au physics data collection.**

> We note that the p+Au run identified as the second priority for Run 24 is not a necessary precursor to Run 25. *Looking at the compelling scientific case for this run, and in particular its importance to the science of the future EIC, if the p+Au run is not done in Run 24 there will be a compelling case for running RHIC beyond the completion of the Run 25 Au+Au data-taking in order to include at least five weeks of p+Au running, even if doing so extends Run 25 beyond June 2025.*

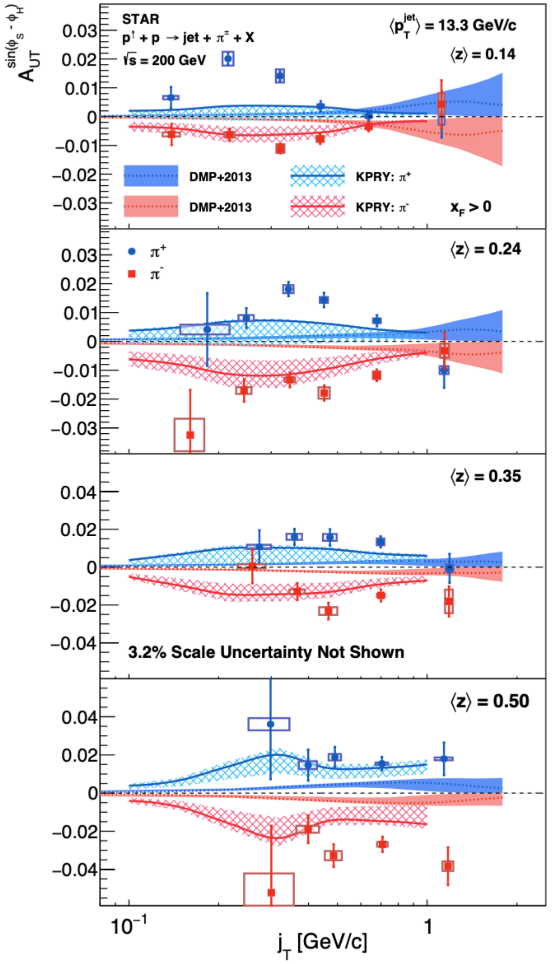
Backup

Mid-rapidity Collins effect at 200 vs 510 GeV

PRD106 (2022) 72010

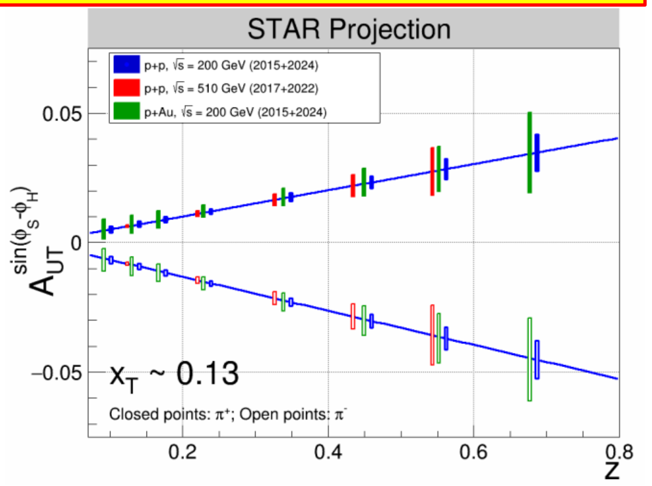


A_{UT} vs jet (p_T,η) measures the collinear transversity distribution



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**

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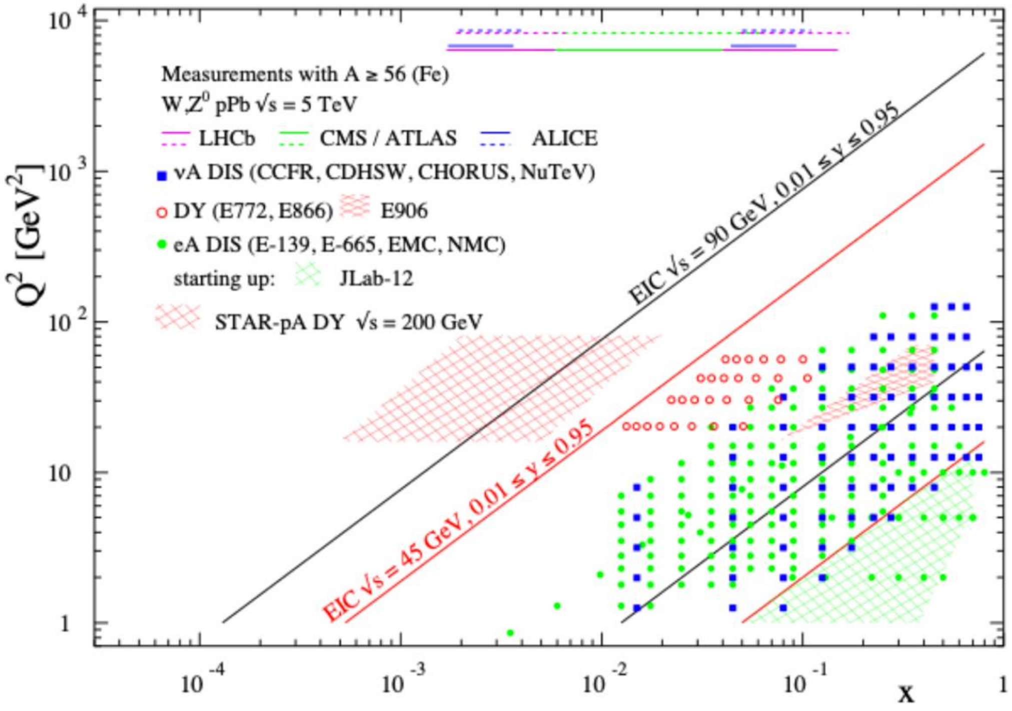
Nuclear PDF

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

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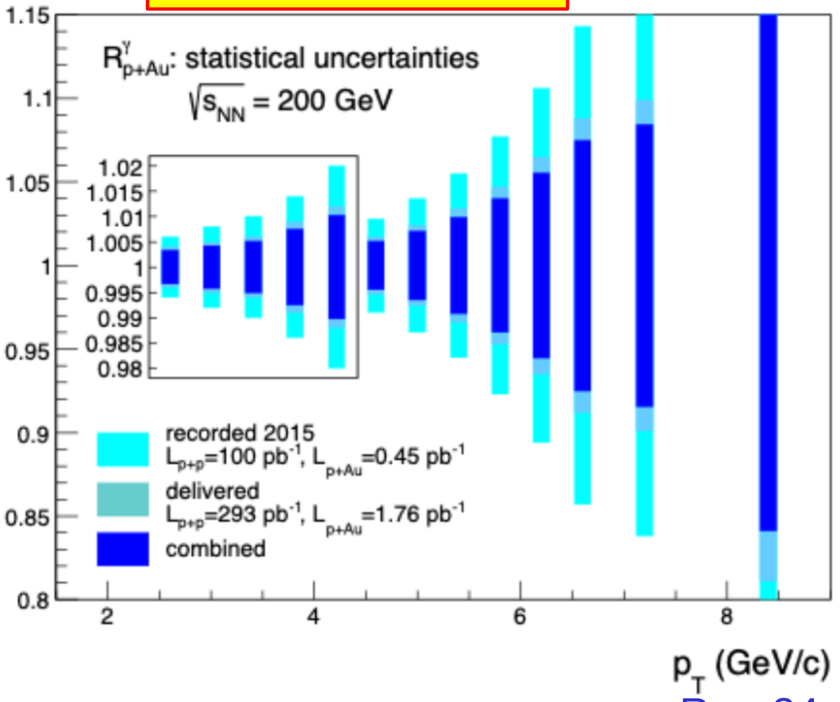
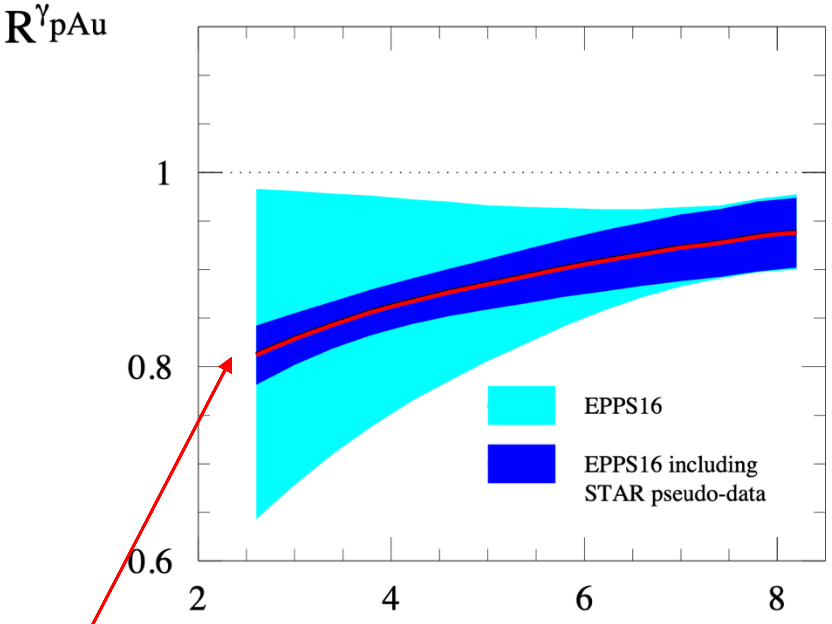
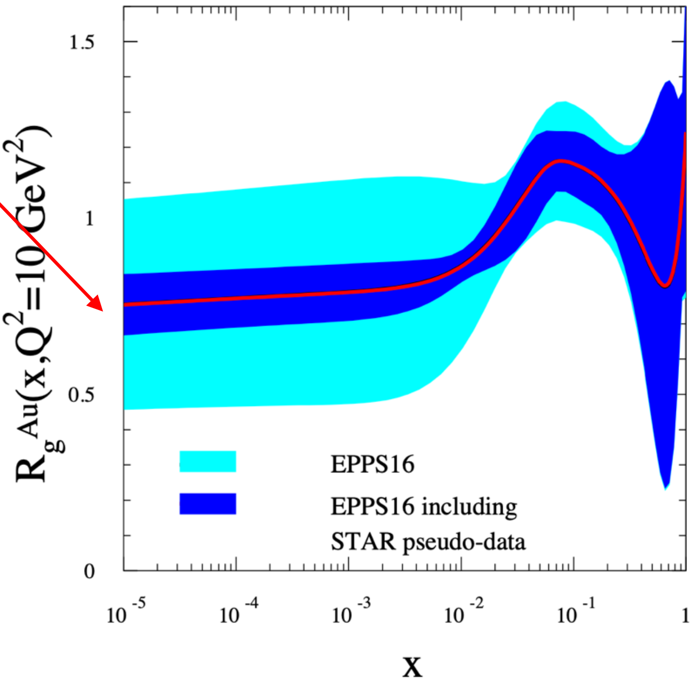
Nuclear PDF

low material, fSTAR



Run-24 data impact





Direct photon measurement: constrain nuclear gluon distribution in a broad x range

Contribute to a stringent test of the universality of nuclear PDFs when combined with data from EIC

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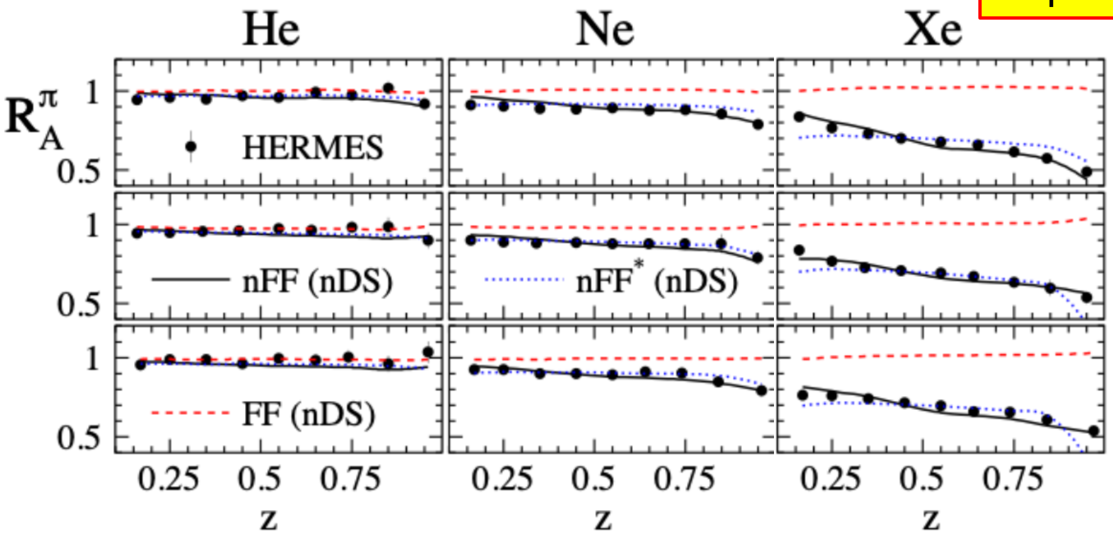
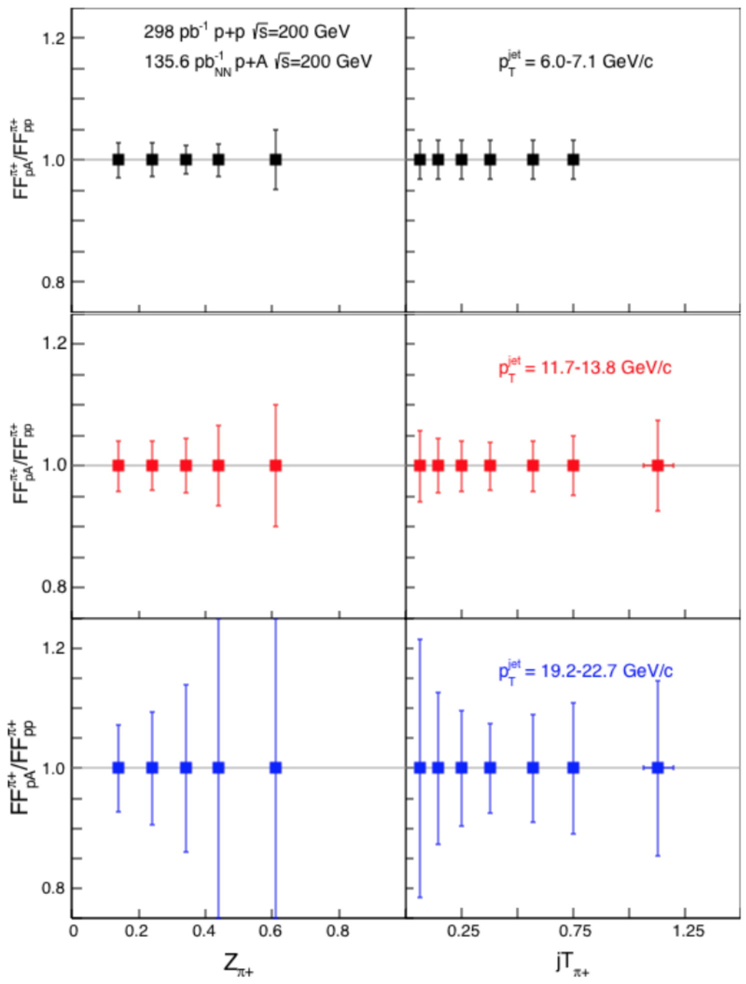
Nuclear FF

improved PID, extended η coverage by iTPC





Modified FF is needed to explain SIDIS data by HERMES

Underlying mechanism is not understood

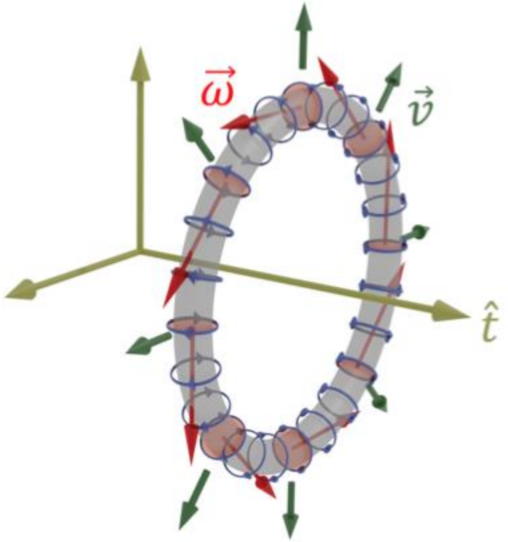
Universality has not been tested

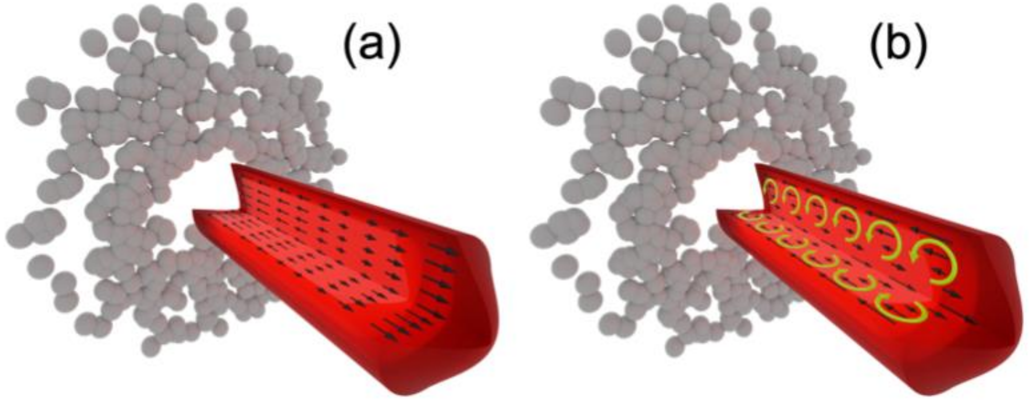
Run-24: study pion, kaon, and proton FF modification, constrain gluon FF.

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

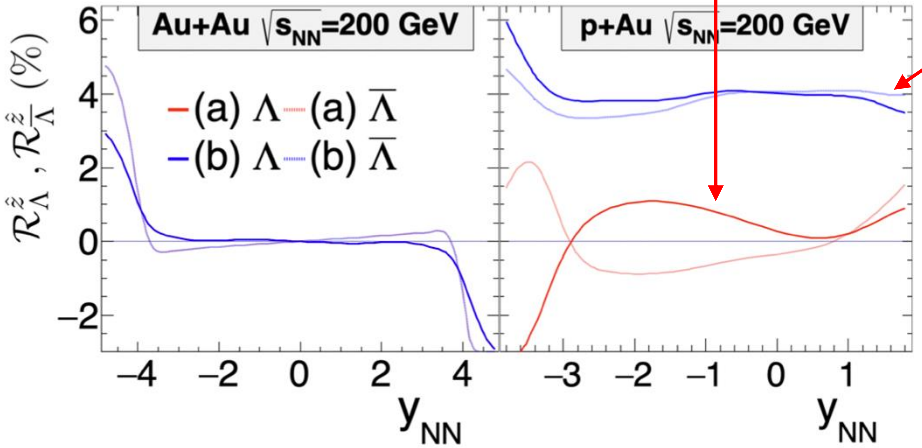




Toroidal vortex structure: smoke ring

Bjorken flow profile

Radial-gradient flow profile



Ring structure

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

300 M p+Au central events at each field polarity: enable us to measure ~1% with 7 σ significance

Opportunity to discover a novel vortical configuration in the subatomic fluid

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