STAR Beam Use Requests for Runs 23-25

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Executive summary

Table 1: Proposed Run-23 - Run-25 assuming 28 cryo-weeks of running every year, and 6 weeks set-up time to switch species in 2024. For p+p and p+Au sampled luminosities assume a "take all" trigger. For Au+Au we provide the requested event count for our minimum bias trigger, and the requested sampled luminosity from our a high-p_T trigger that covers all v_z.

Data Taking
48 weeks Au+Au
11 weeks pp
11 weeks p+Au

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024

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

Au+Au: probe the inner workings of the QGP
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

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

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

24 weeks data taking for Run-23 and 25 each

year	minimum bias [$\times 10^9$ events]	high-p_T int. luminosity [nb^{-1}] all vz	|vz|<70cm	|vz|<30cm
2014 2016	2	27	19	16
2023 2025	20	40	36	24

TPC+TOF+HFT+MTD

iTPC+EPD+eTOF+TOF +MTD

Forward upgrades

A factor of 10 more minimum bias data compare to Run-14 + Run-16
A factor of 1.5 more luminosity for high-p_T trigger

Improve the readout speed of TPC

With forward upgrades completed, we are in the process of doubling the TPC readout speed during this long summer shutdown. The upgrade consists of the following components:

- **Rewrite the FPGA firmware** of FEEs and RDOs. The FPGAs are different for the outer and inner sectors.
- **Rewrite DAQ online software** for TPC in framework as for FCS
- **Redo and evaluate cluster finder**
- **Improve network connectivity**
- **Add some DAQ PC and event builders** to handle increased data volume
- **Replaced the gating grid driver** for Run22 which can now handle more than 5 kHz (completed)

Task force formed in Feb. 2022 (co-chairs: Flemming Videbaek and Richard Witt)
Expect the development and system testing completed by the end of the year

The expectation of data rate:
20 B minimum bias data taken at low luminosity (10 kHz ZDC coincidence rate): record 5 kHz with 30% deadtime

40 nb^{-1} high luminosity data for rare triggers (100 kHz ZDC coincidence rate): record 3 kHz with 20% deadtime

Physics Opportunities for 2023+2025

Time

To address important questions about the inner workings of the QGP

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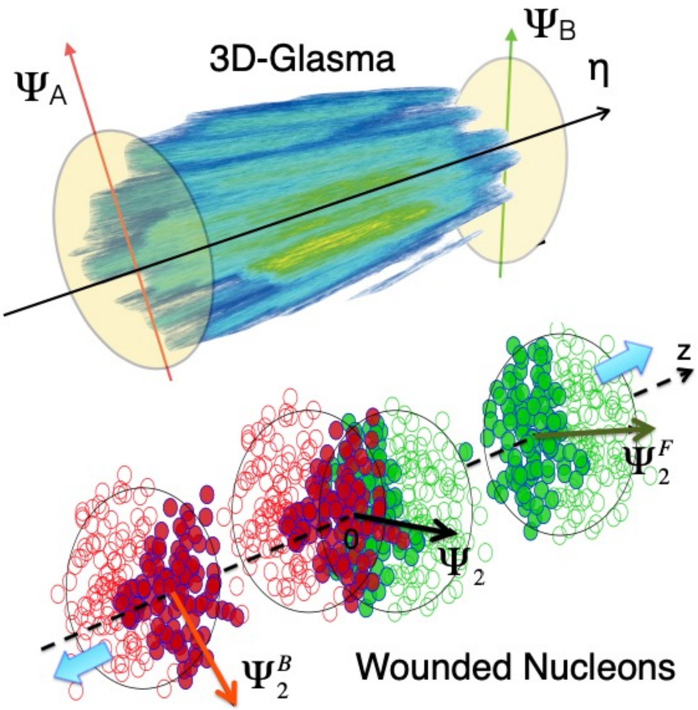
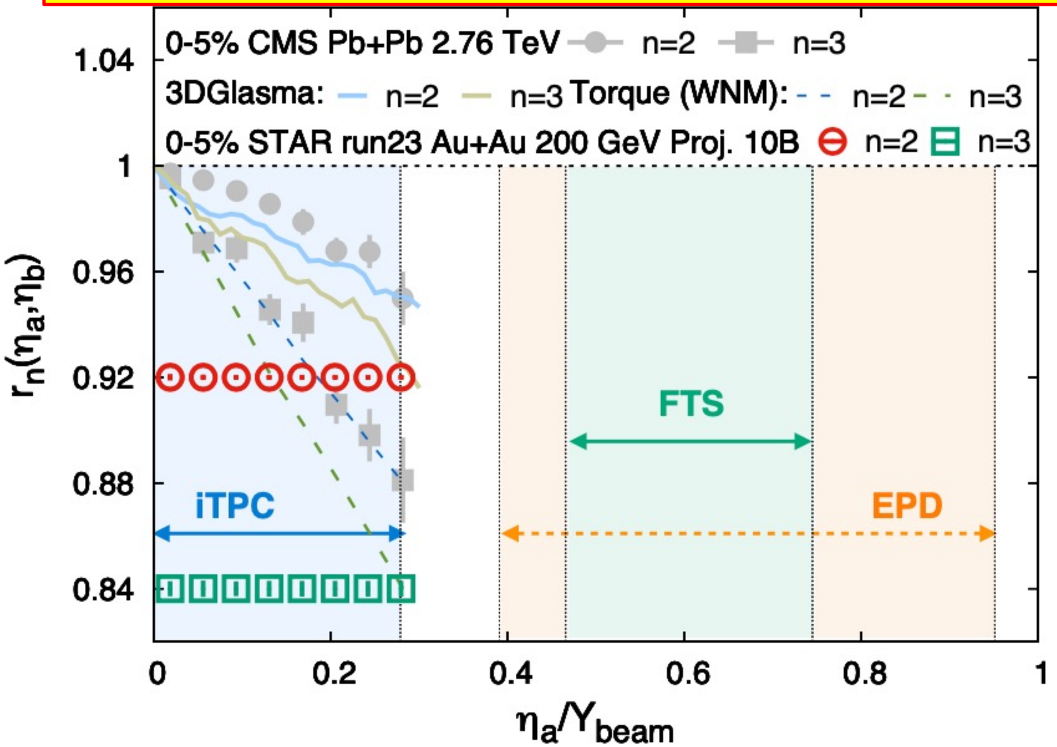
Constrain longitudinal structure of initial state

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

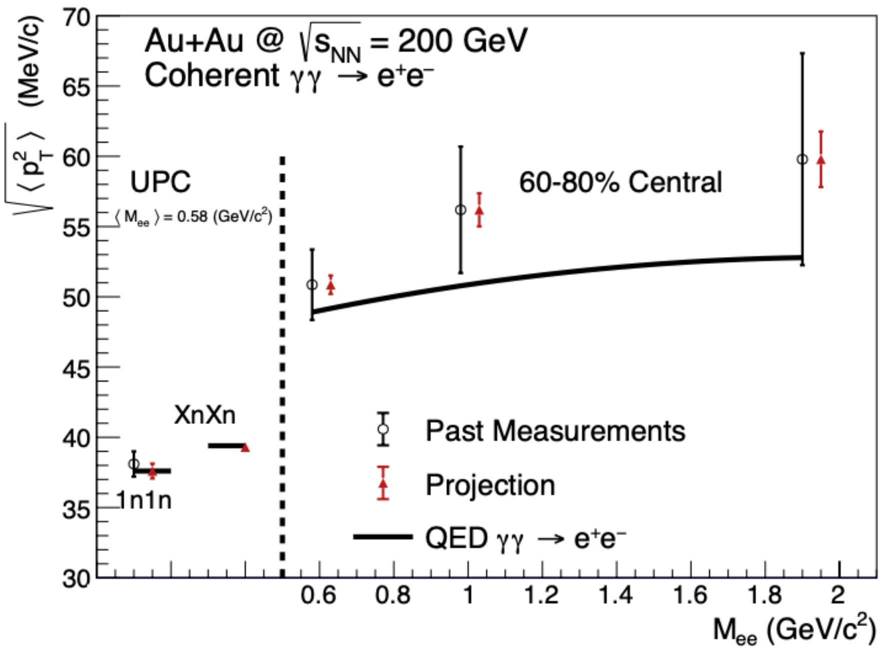
r_n sensitive to different initial state inputs:

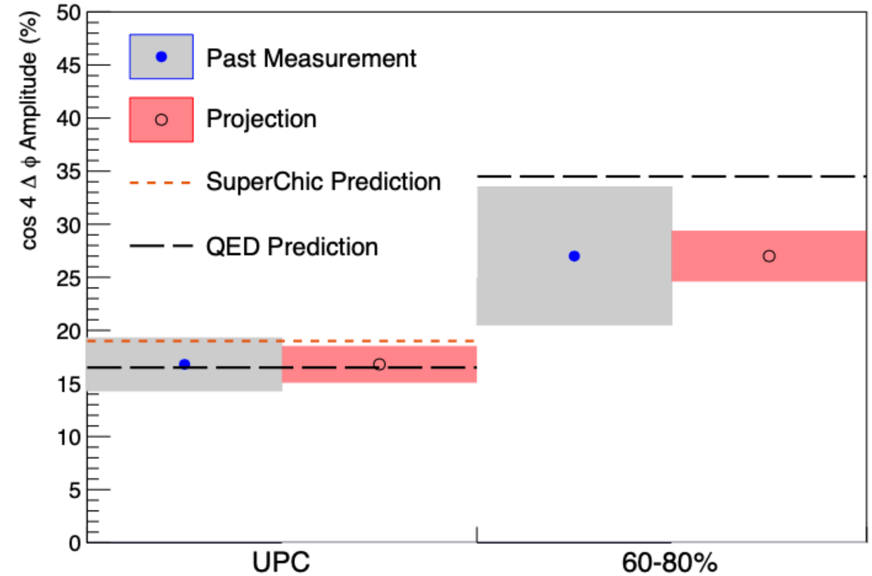
- **3D glasma model: weaker decorrelation, describes CMS r_2 but not r_3**
- **Wounded nucleon model: stronger decorrelation than data**

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.

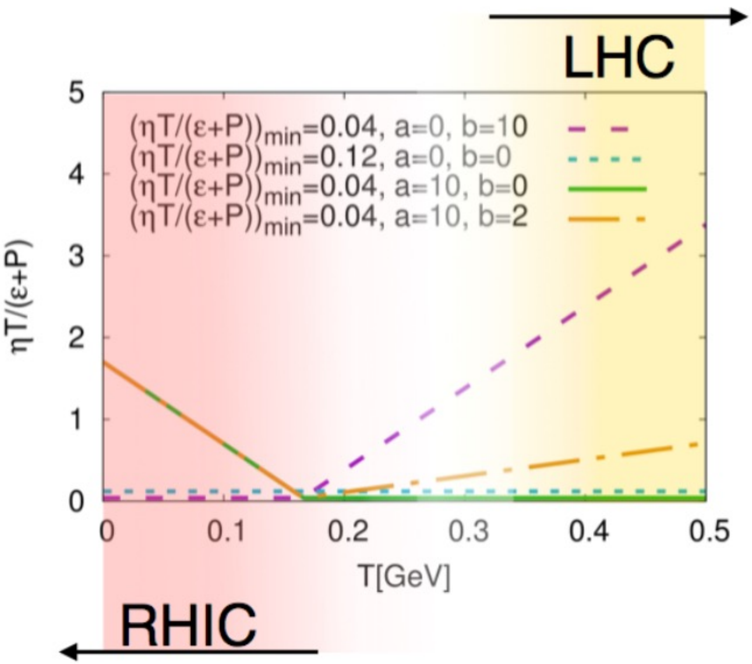
Is there a sensitivity to final magnetic field in QGP?

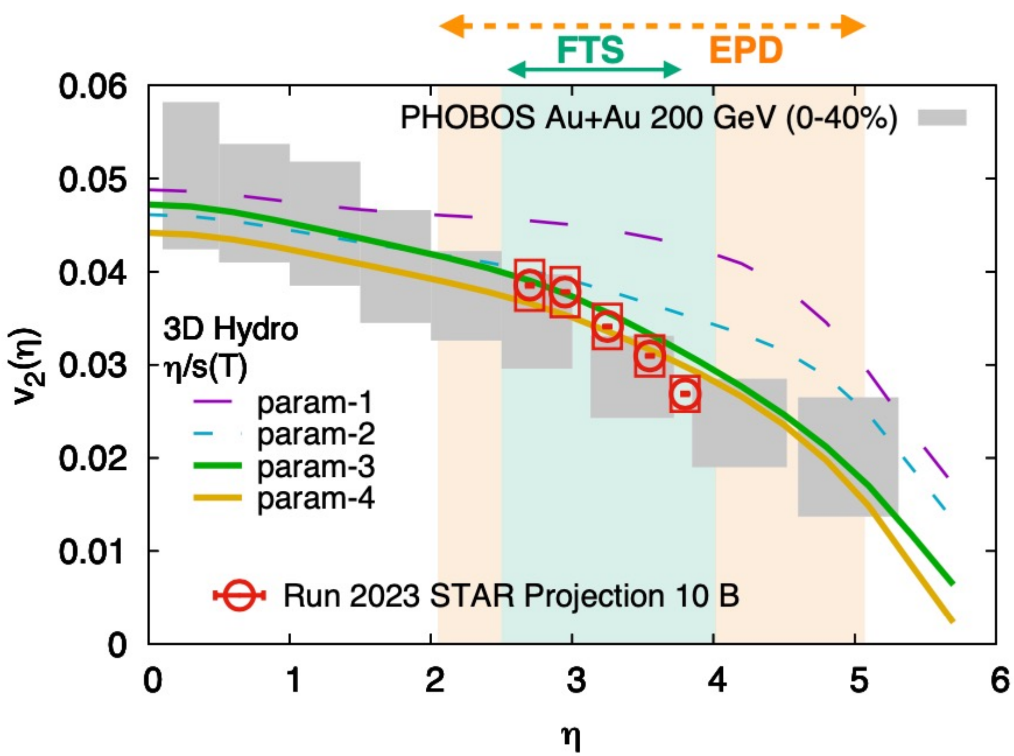
Precise measurement of p_T broadening and angular correlation will tell at $>3\sigma$ for each observable.

Fundamentally important and unique input to CME phenomenon.

Constrain temperature dependence of η/s

forward tracking



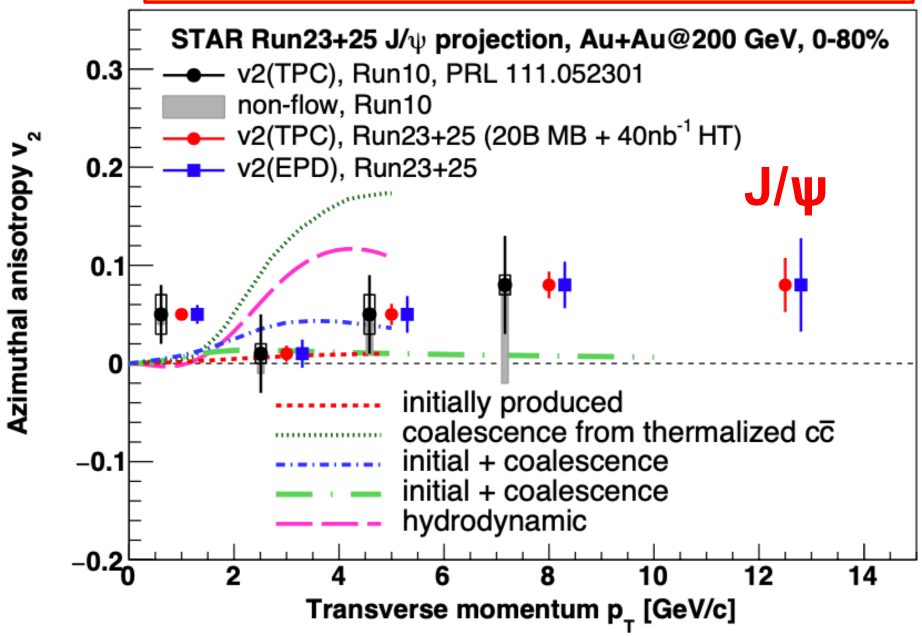


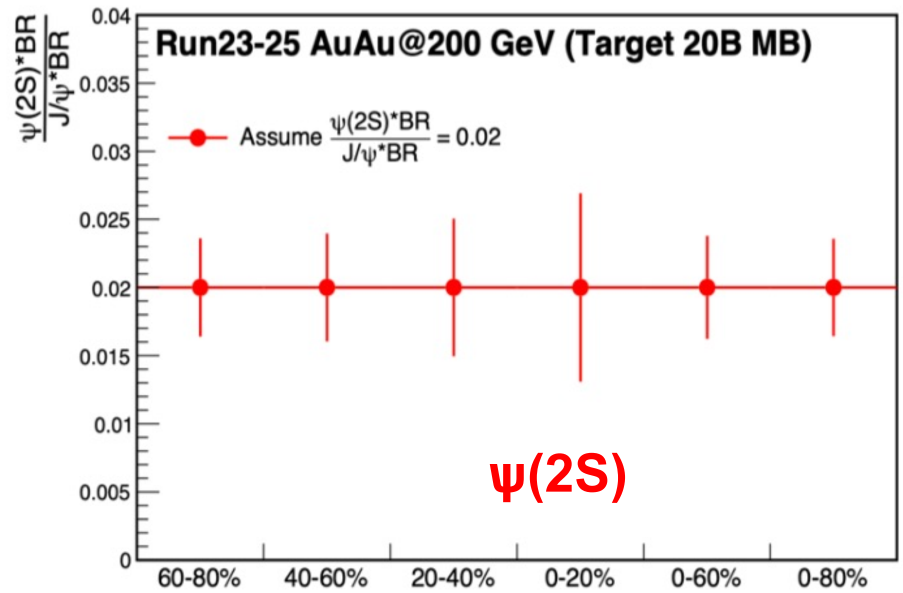
Flow measurements at forward rapidity sensitive to η/s as a function of T.

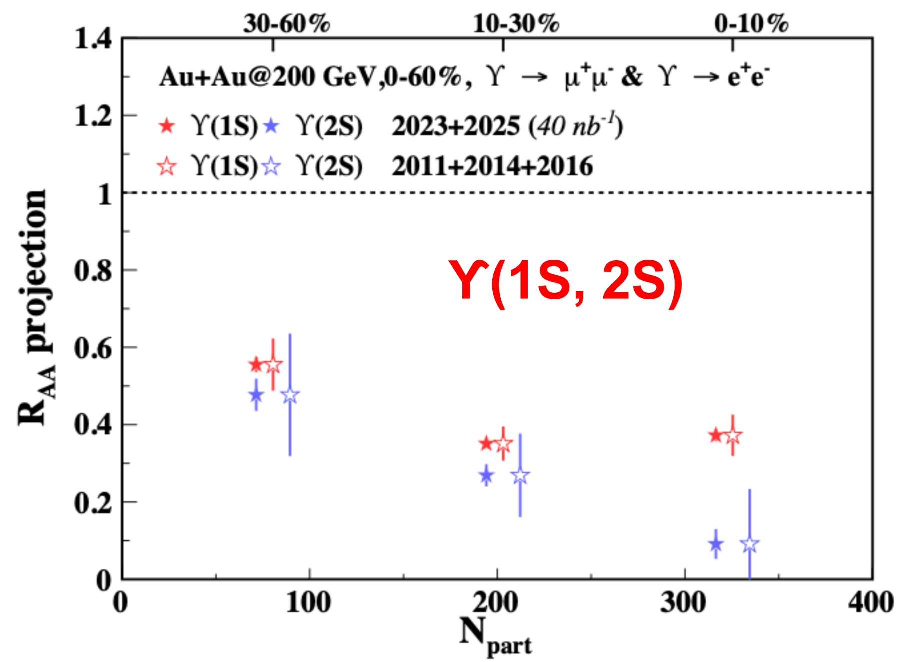
Much more precise than previous PHOBOS measurements.

Deconfinement and thermalization

low material, improved PID, extended η coverage by iTPC







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

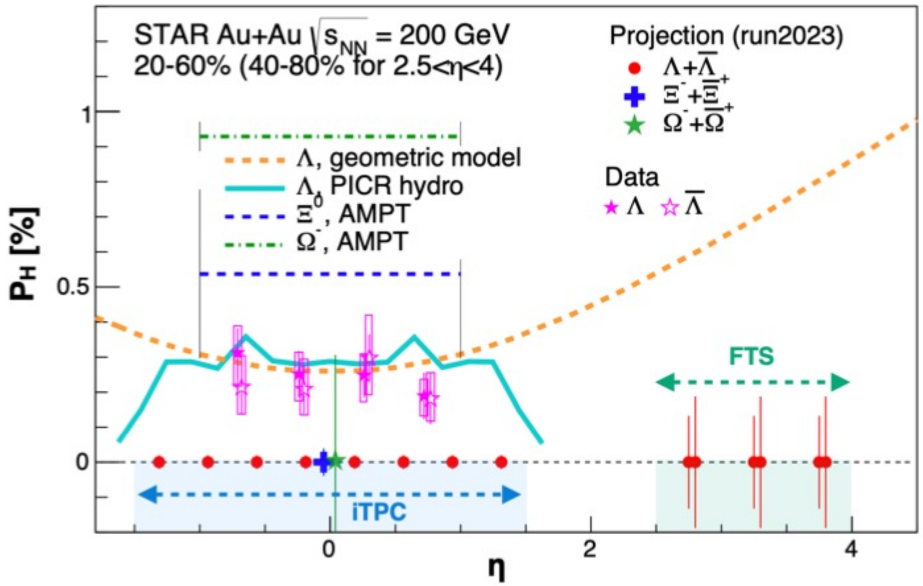
- **low p_T v_2: recombination**

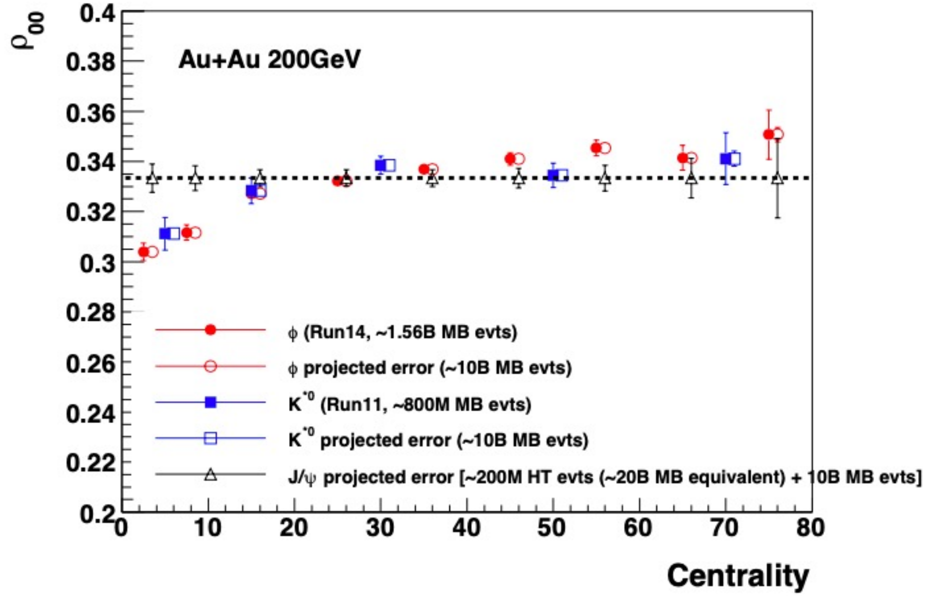
Explore temperature profile of the medium:

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

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.

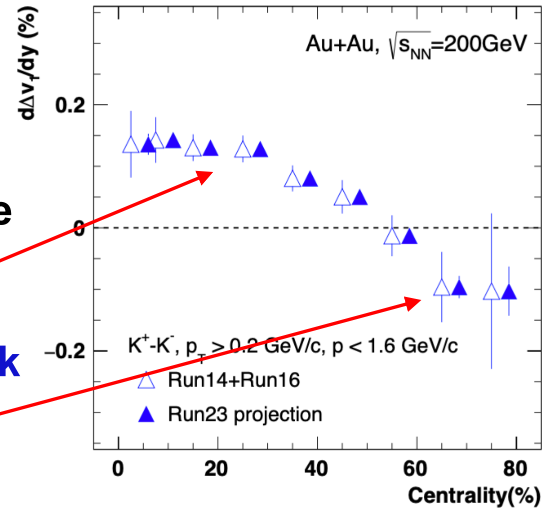
Charge dependent directed flow

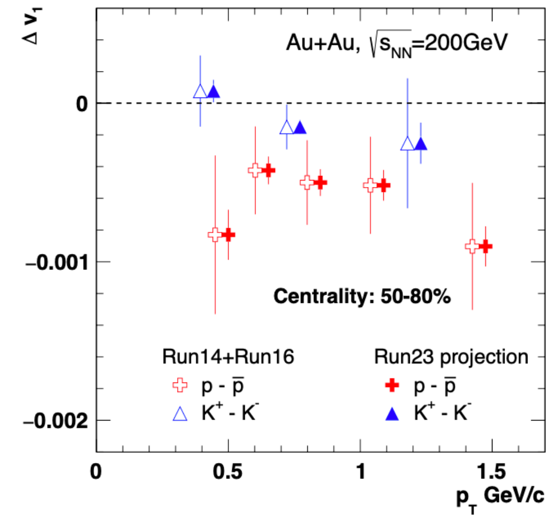
improved PID, extended η coverage by iTPC

Charge dependent v_1 slope sensitive to EM field

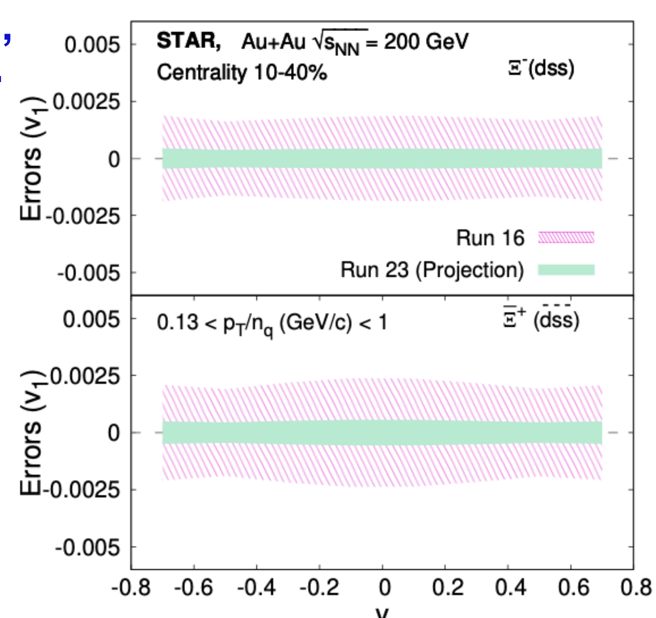
$d\Delta v_1/dy > 0$ due to transported quark

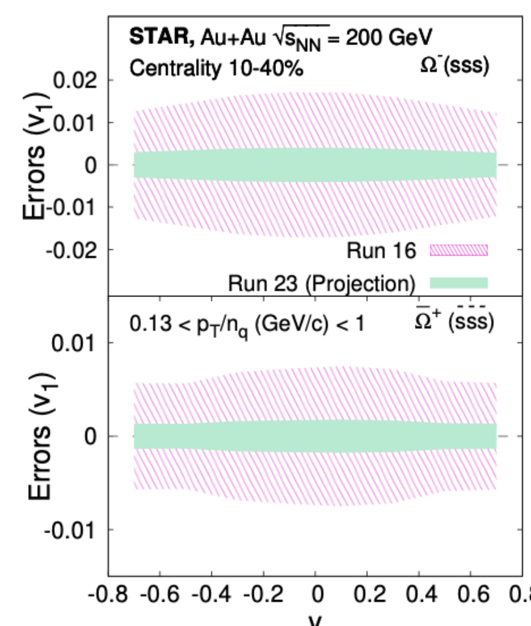
$d\Delta v_1/dy < 0$ due to EM field



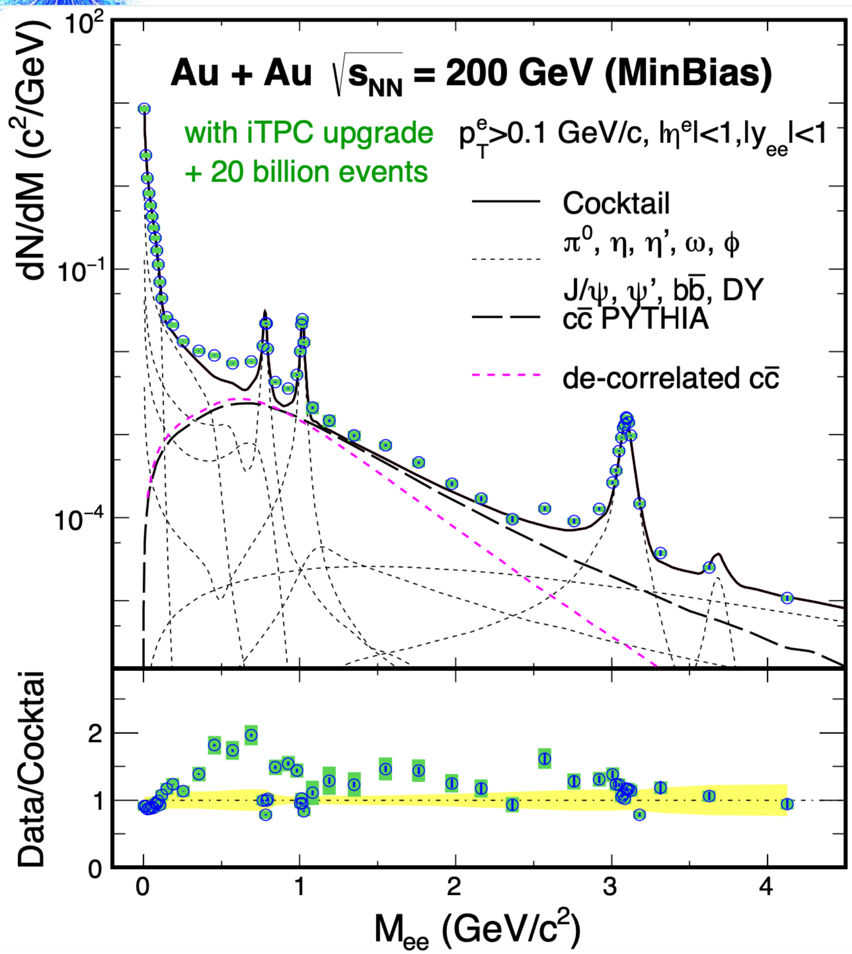


Runs 23+25: >5σ difference between K^+ and K^- in peripheral collisions, precise measurements for multi-strange particles.

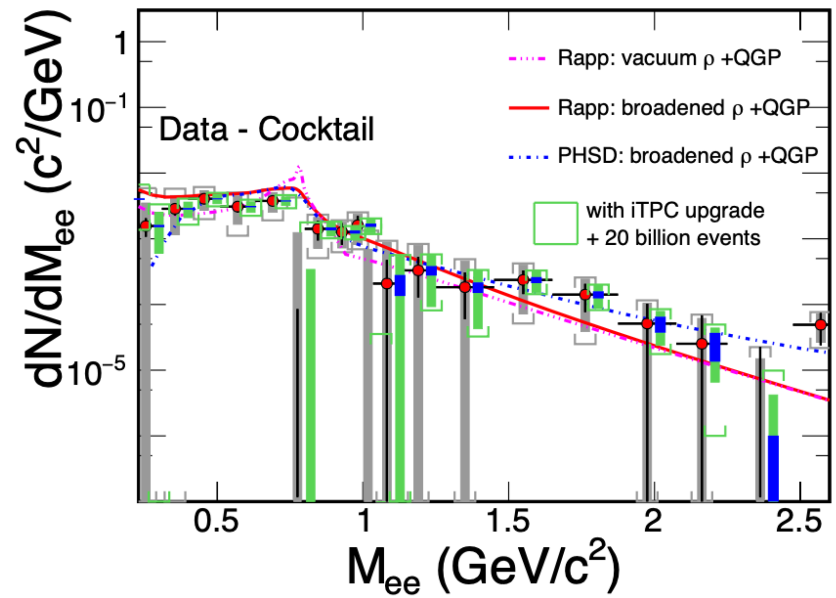




Chiral property



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



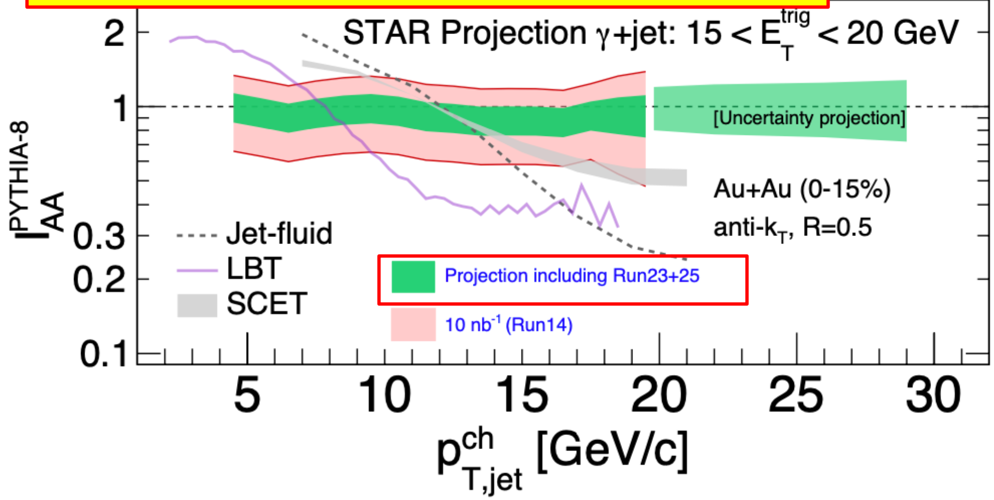
Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B=0

Intermediate mass: direct thermometer to measure temperature

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

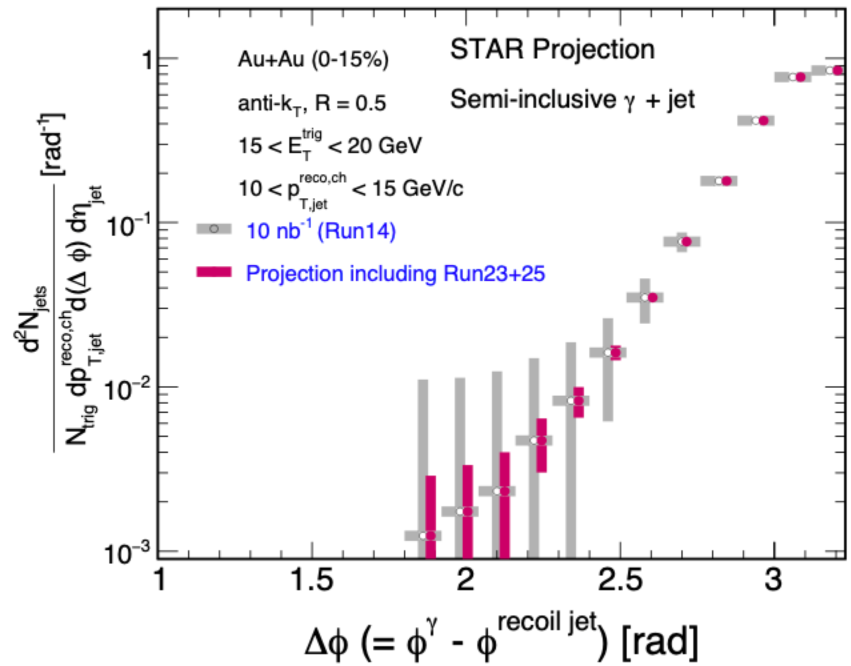
Jet quenching

low p_T, large R, extended to higher p_T

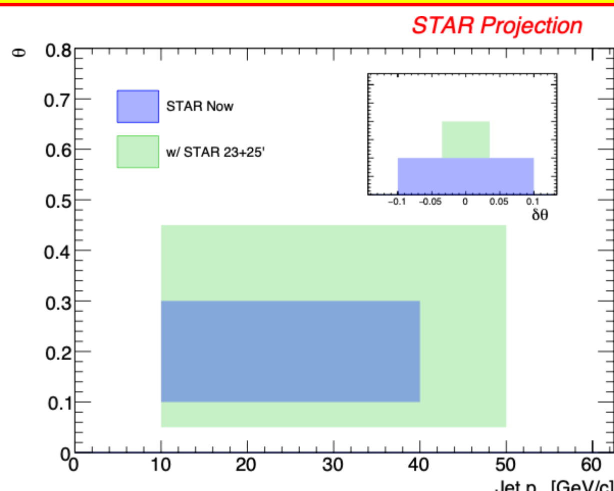


Semi-inclusive γ_{dir}+jet suppression

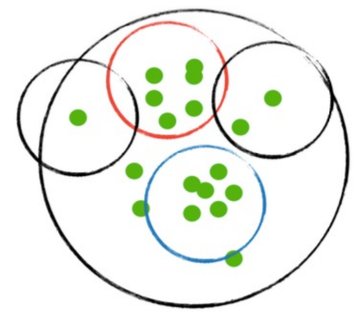
γ_{dir}+jet acoplanarity: constituents of medium



improved opening angle resolution by a factor of 4



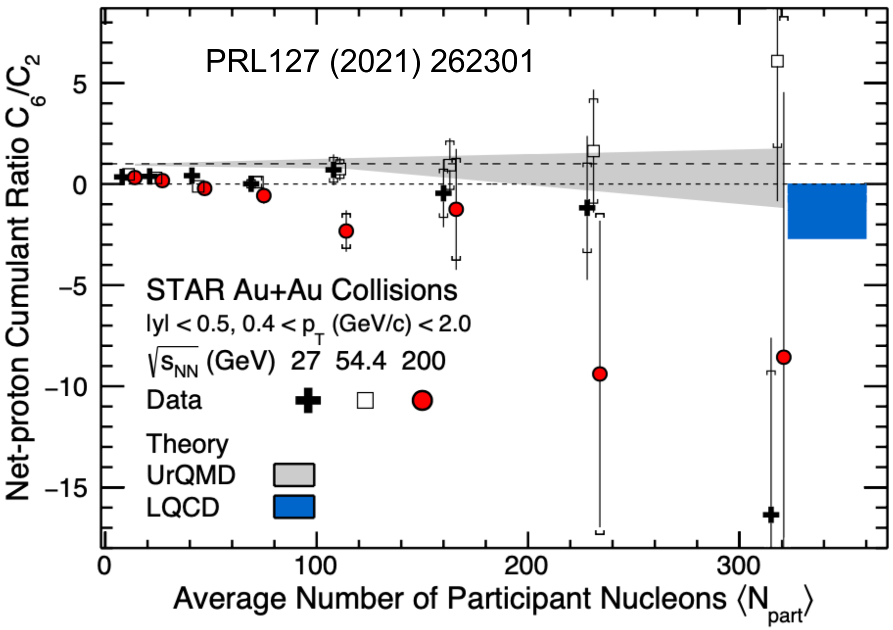
Jet substructure: coherence vs. de-coherence

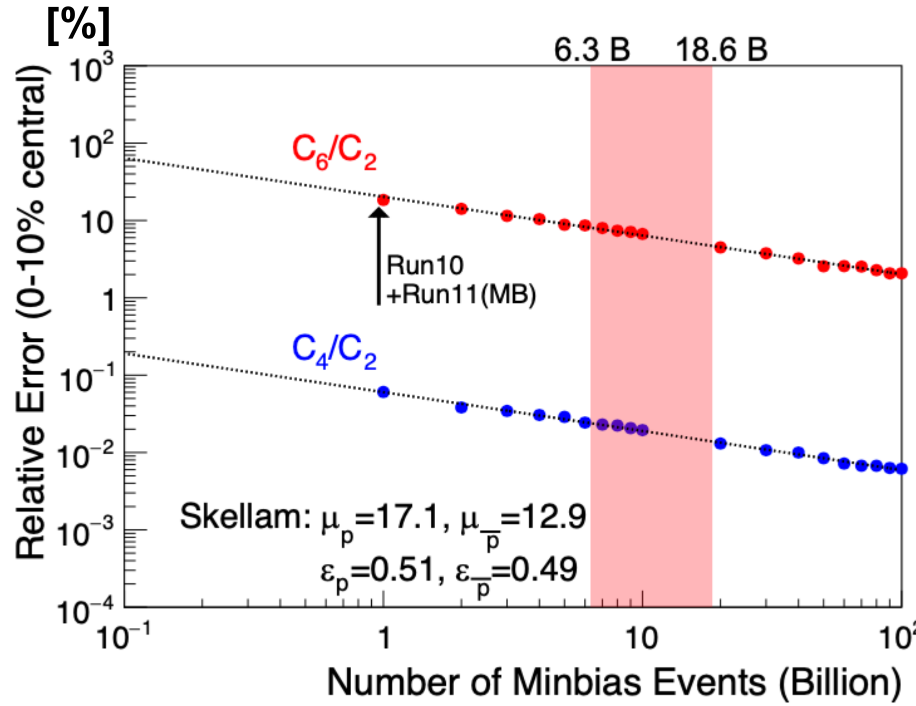


Red: leading sub-jet
Blue: sub-leading sub-jet
$Z_{SJ}=p_T^{blue}/(p_T^{blue}+p_T^{red})$
$\theta_{SJ}=\Delta R(blue,red)$

Chiral cross-over transition

Improved PID, extended η coverage by iTPC





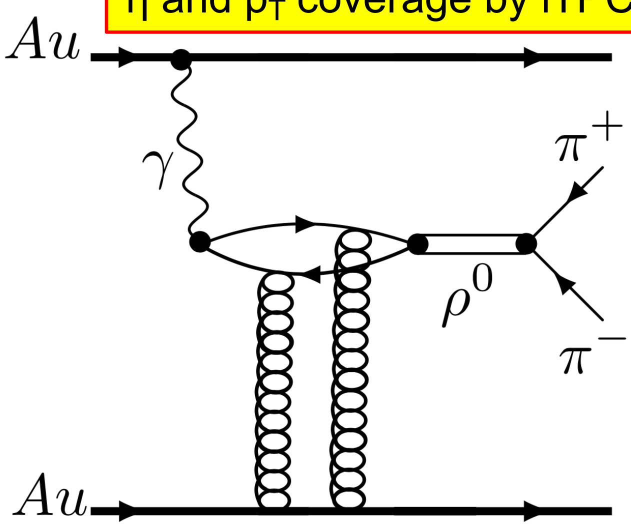
Lattice QCD predicts a sign change of susceptibility ratio χ_6^B/χ_2^B at T_C
The cumulants of net-proton distribution sensitive to chiral cross over transition at μ_B=0

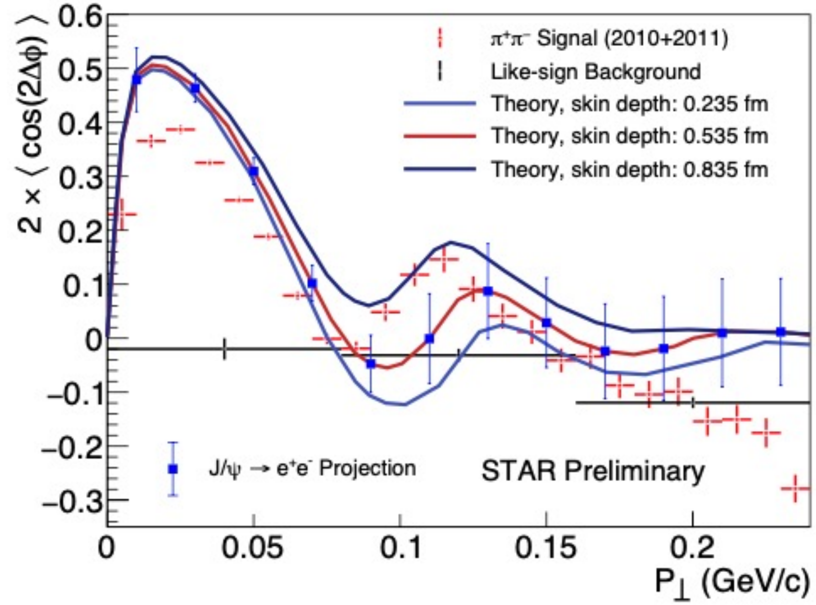
Observed a hint of a sign change from peripheral to central collisions at 200 GeV
$C_6/C_2 < 0$ at central collisions

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

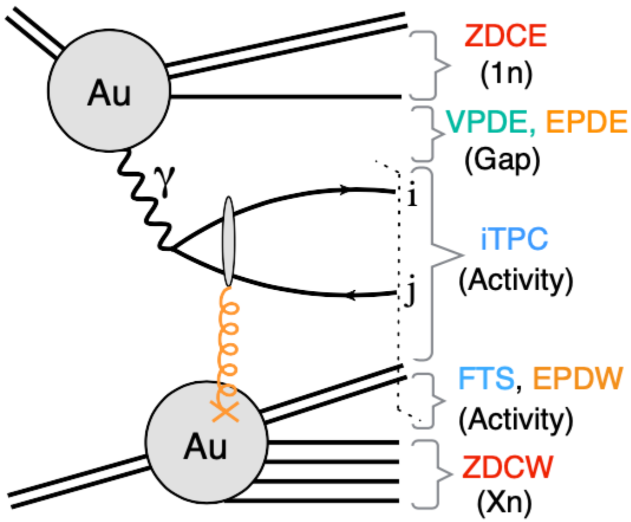
Theory (linear polarized photon + saturated gluons), sensitive to nuclear geometry and gluon distribution, closest to the gluon 3D tomography at EIC

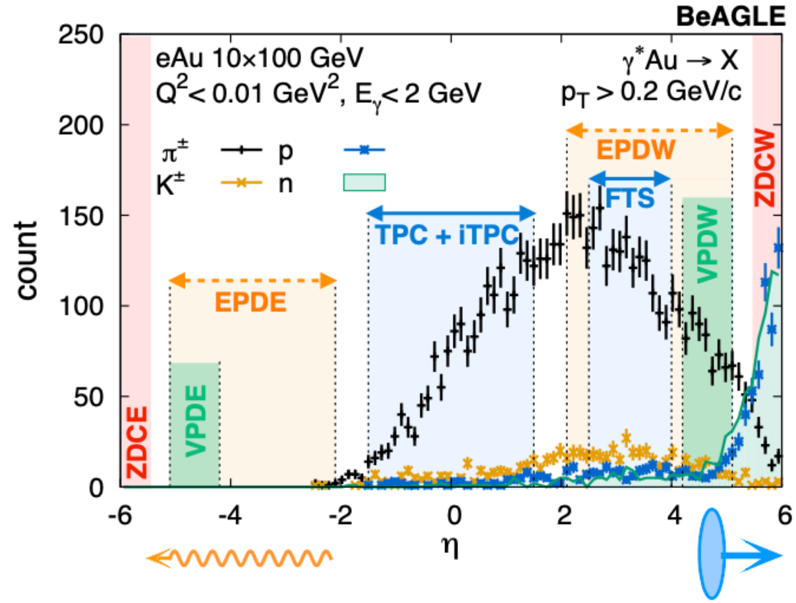
Run23+25:

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





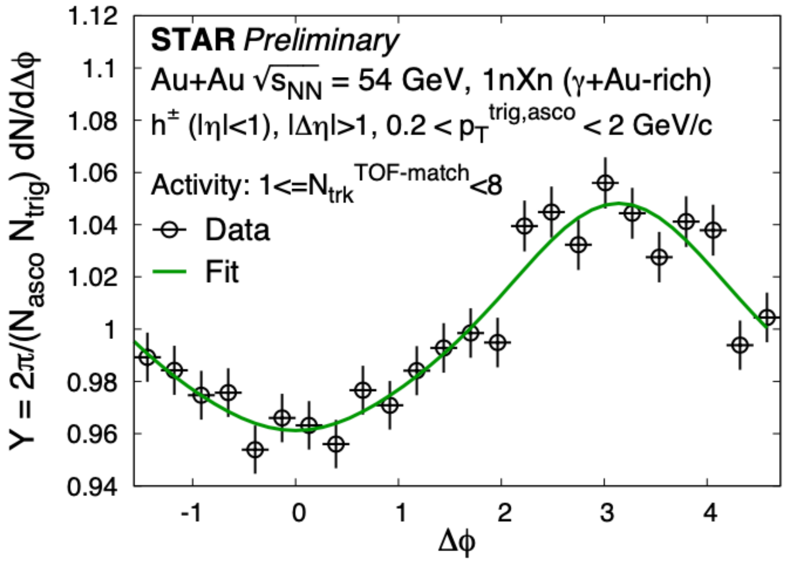
γ+Au process in UPC associated with a large rapidity asymmetry:

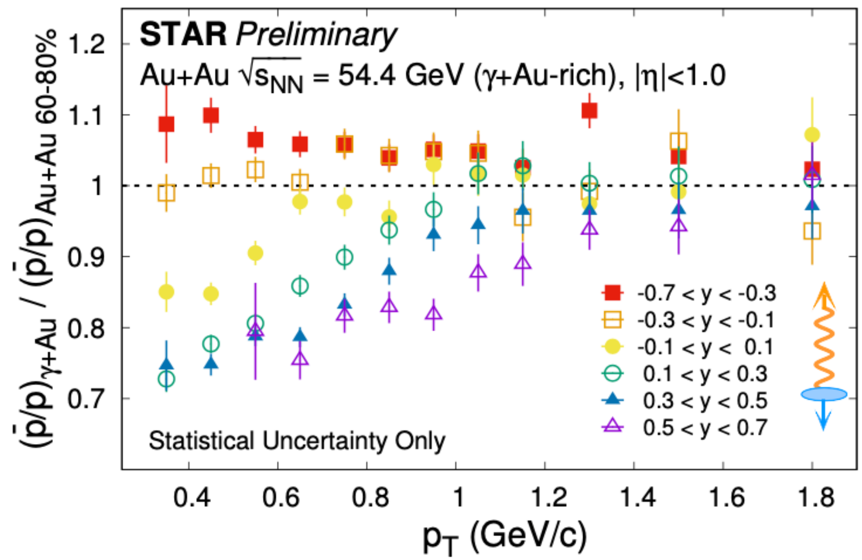
- Search for collectivity
- Study bulk observables

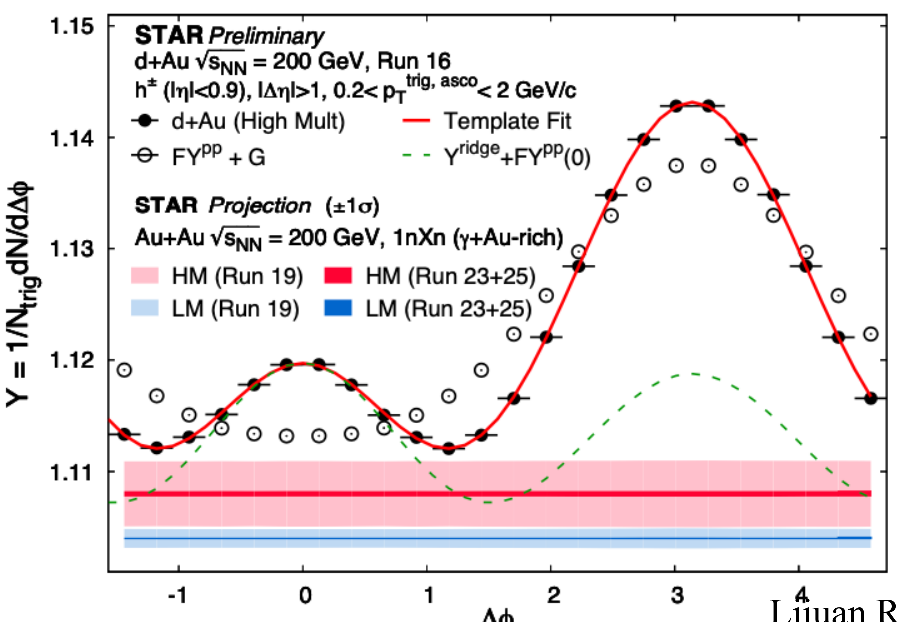
Further understand the origin of collectivity observed in small systems

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
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- **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.

Plans for Run-24

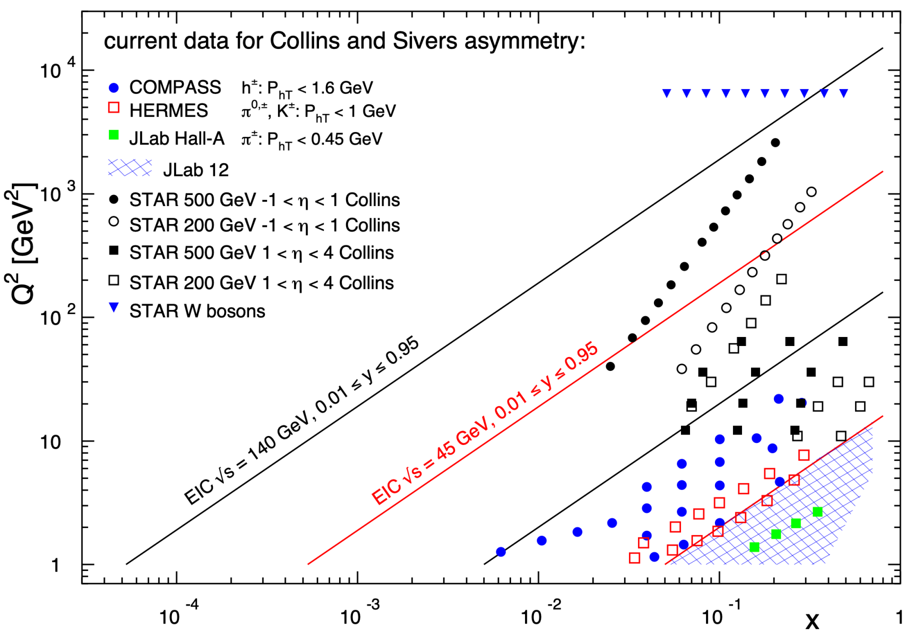
$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024

2 (3) times the total luminosity in Run-15 p+p (p+Au)
4.5 (3) times the transverse lumi. in Run-15

11 weeks each Polarization:60%

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

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



Physics Opportunities in 2024

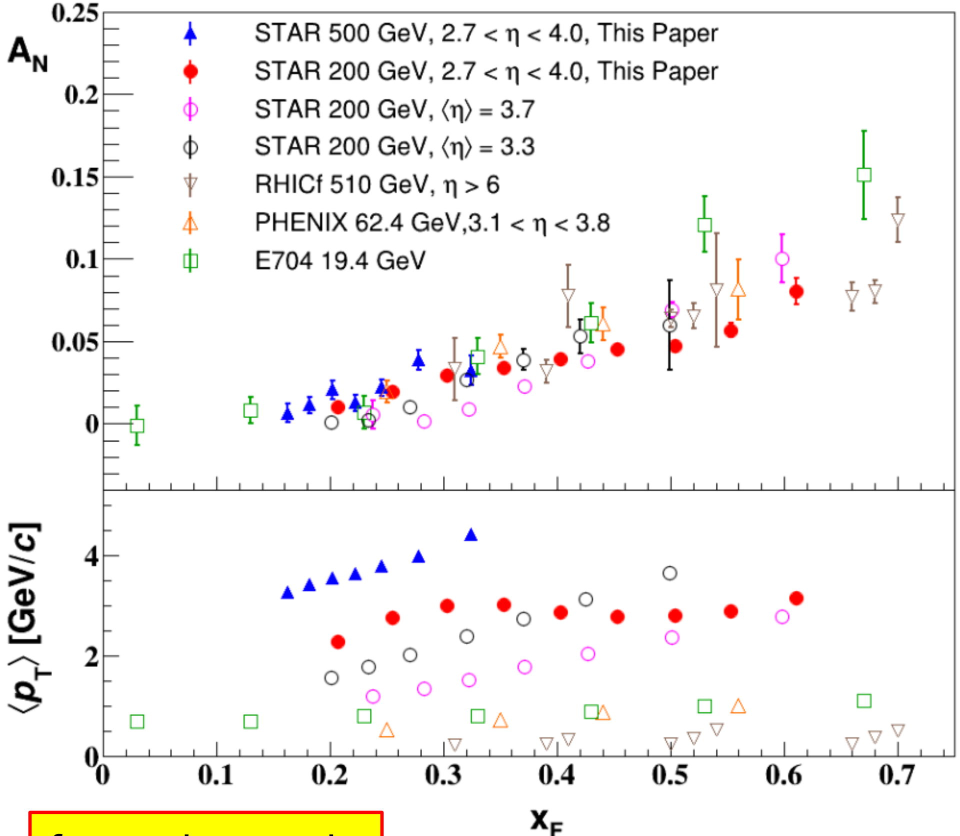
Central role played by 200 GeV pp:

- 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



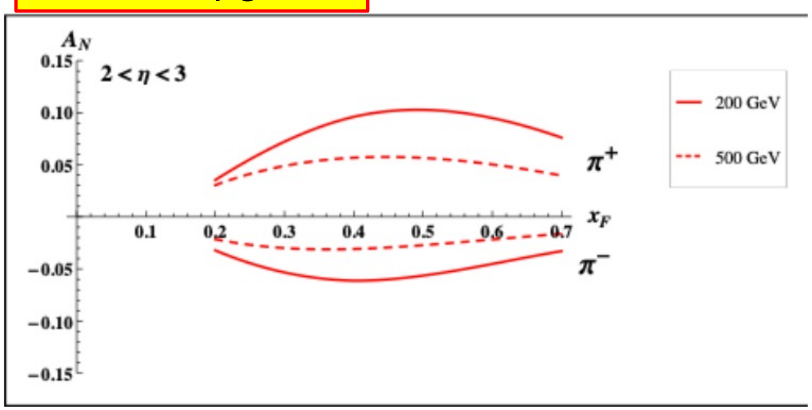
Interplay of
Initial state: Sivers distribution or its twist-3 analog, the Efremov-Teryaev-Qiu-Sterman (ETQS) function

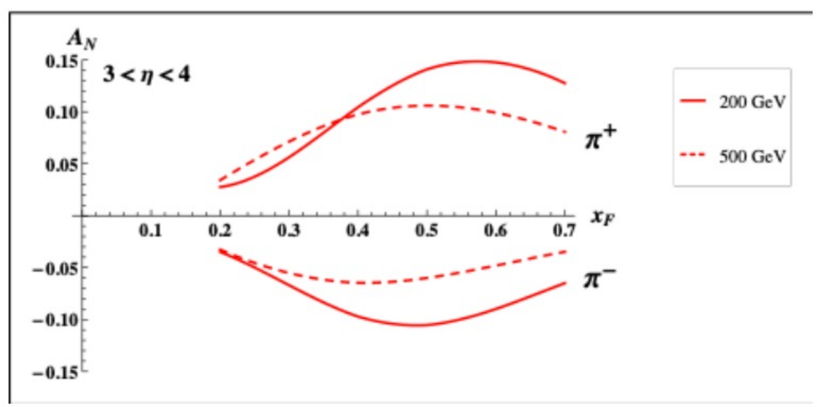
and/or

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

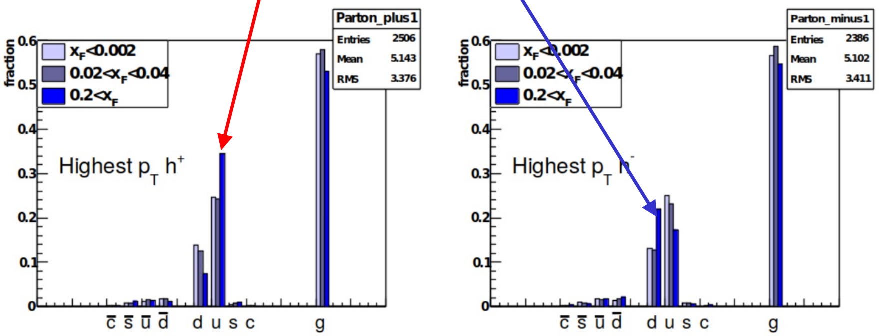


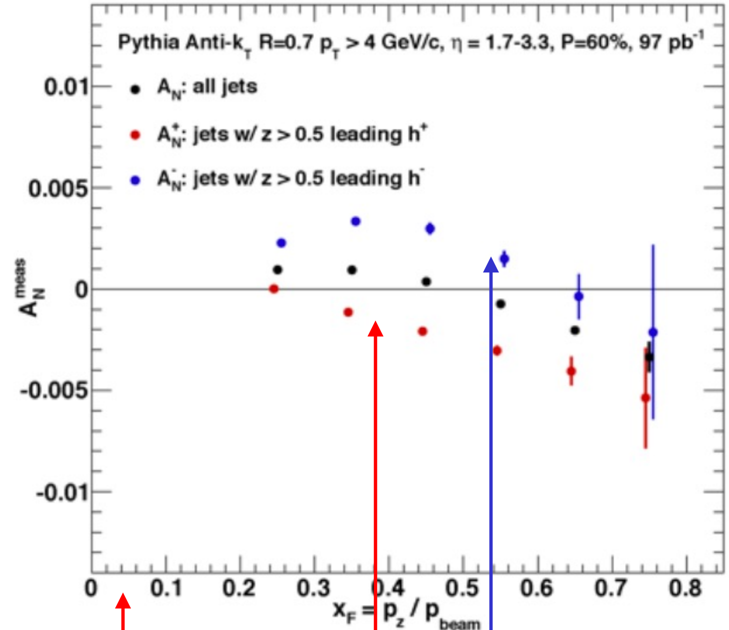


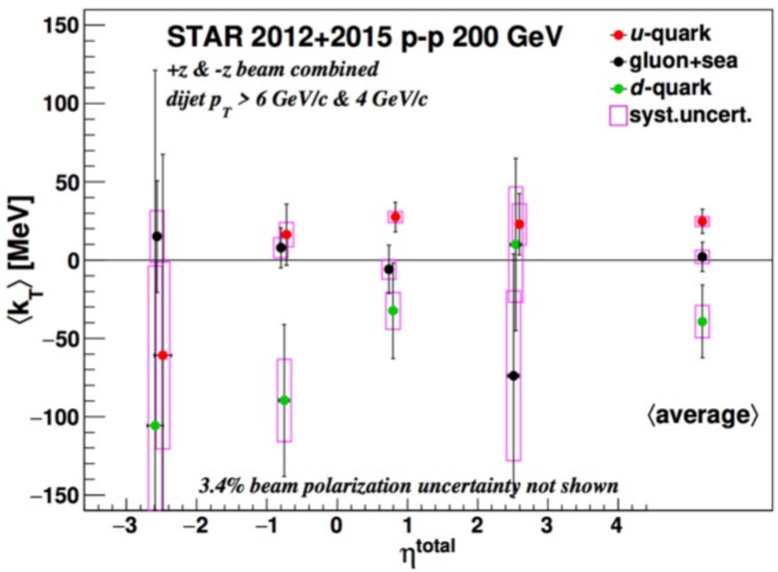
Sivers and ETQS function

forward upgrade

With positively/negatively charged leading hadron







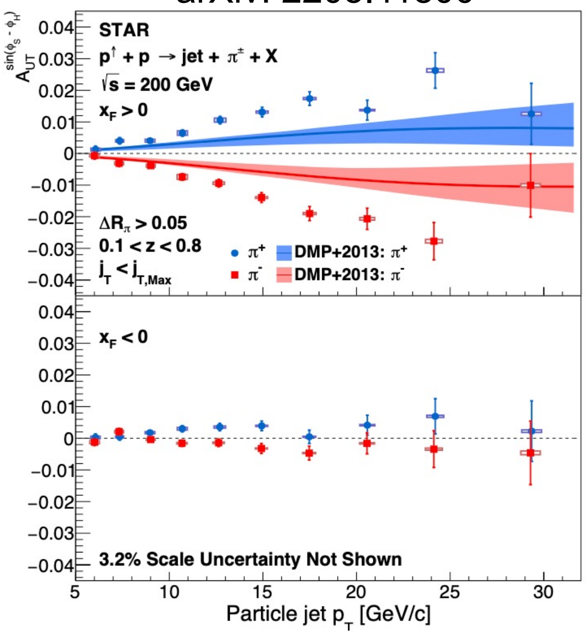
Full jet reconstruction, along with identification of a high-z hadron of known charge at forward rapidity, sensitive to u and d Sivers asymmetry

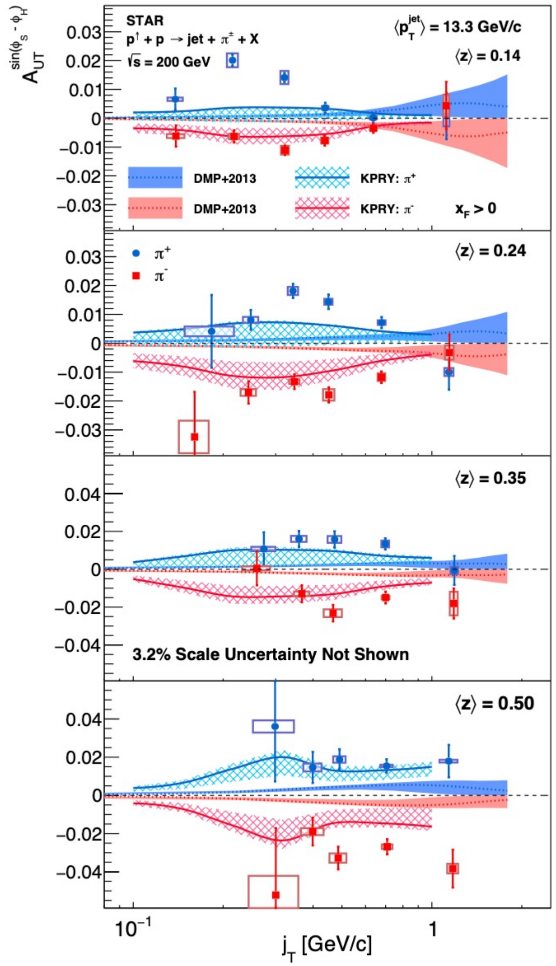
Charge tagging to separate u and d quark signals: $<k_T^u>$~ 32 MeV/c, $<k_T^d>$~ -67 MeV/c, $<k_T^{g+sea}>$~ 0 MeV/c

First observation of non-zero Sivers asymmetry in dijet production

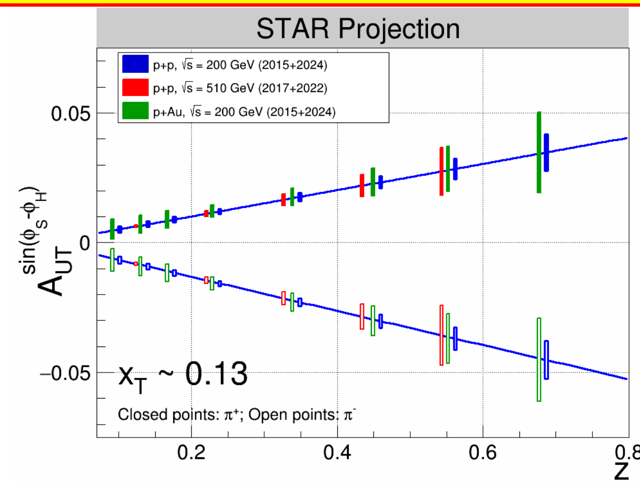
Mid-rapidity Collins effect at 200 vs 510 GeV

arXiv: 2205.11800





improved PID, extended η coverage by iTPC



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

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

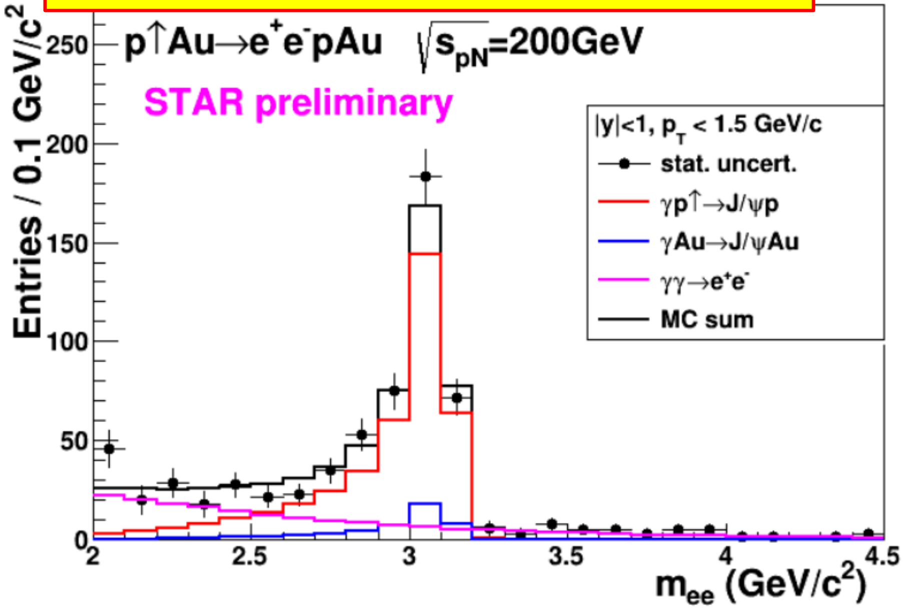
Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential x-Q^2 overlap with EIC

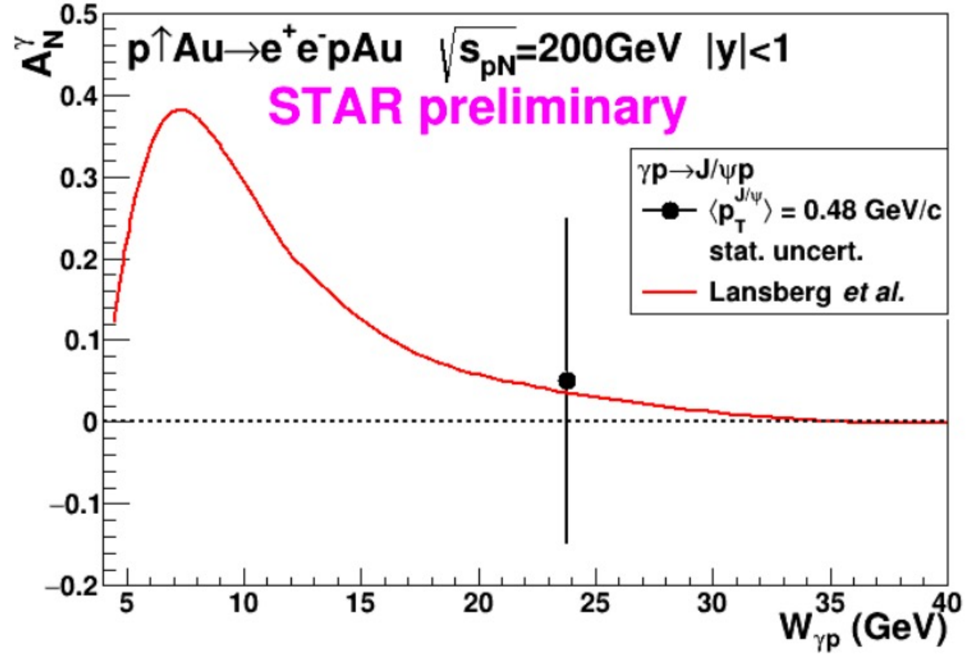
A_{UT} in p+Au: an alternative universality test and a unique look at spin-dependent hadronization

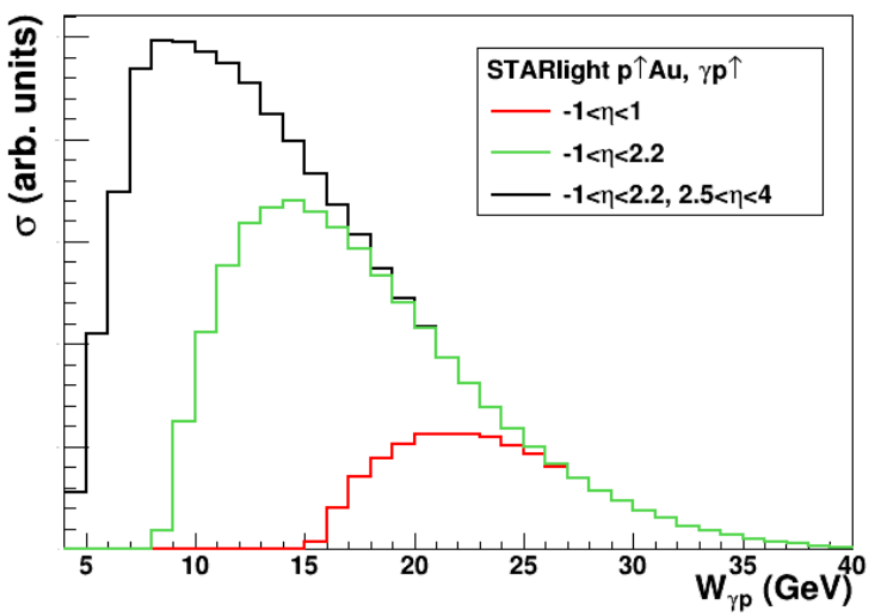
- **Run-24 will reduce these uncertainties at 200 GeV by a factor of 2.5, enabling the most sensitive universality test with EIC data**

Generalized parton distribution

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







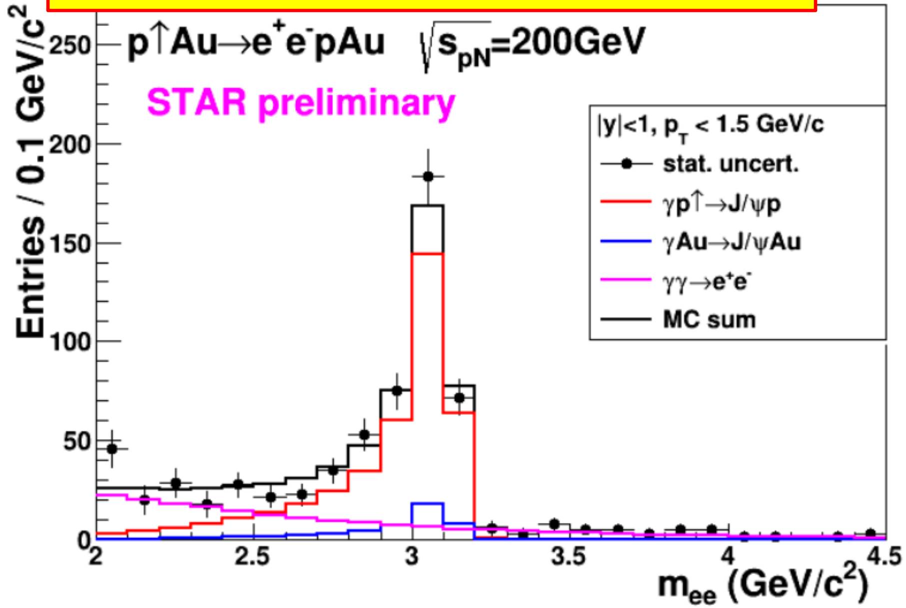
Exclusive J/ψ A_N in UPC, Q^2~10 GeV^2, $10^{-4}<x<10^{-1}$

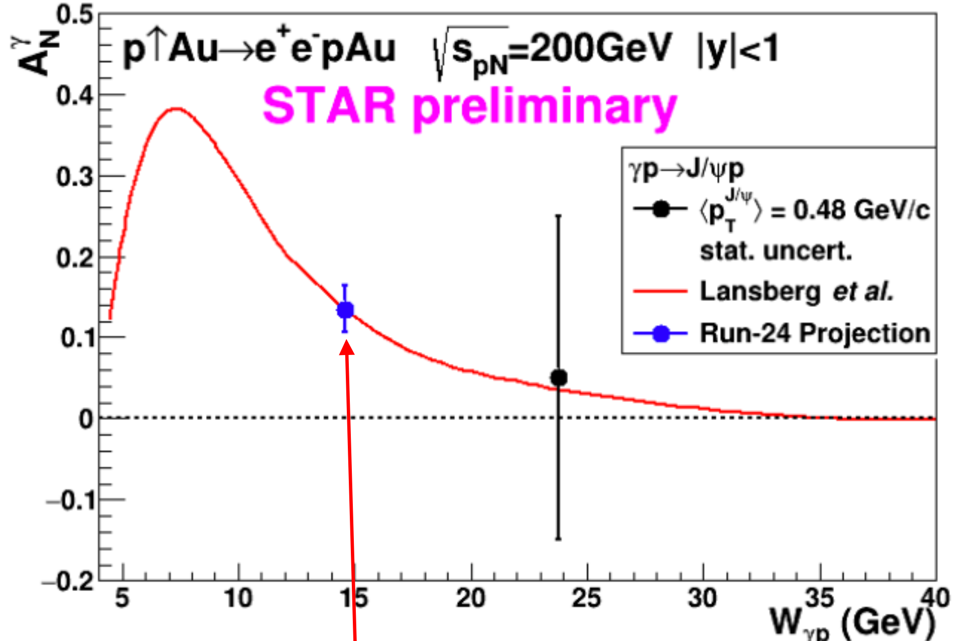
Access GPD Eg for gluons, sensitive to spin-orbit correlation

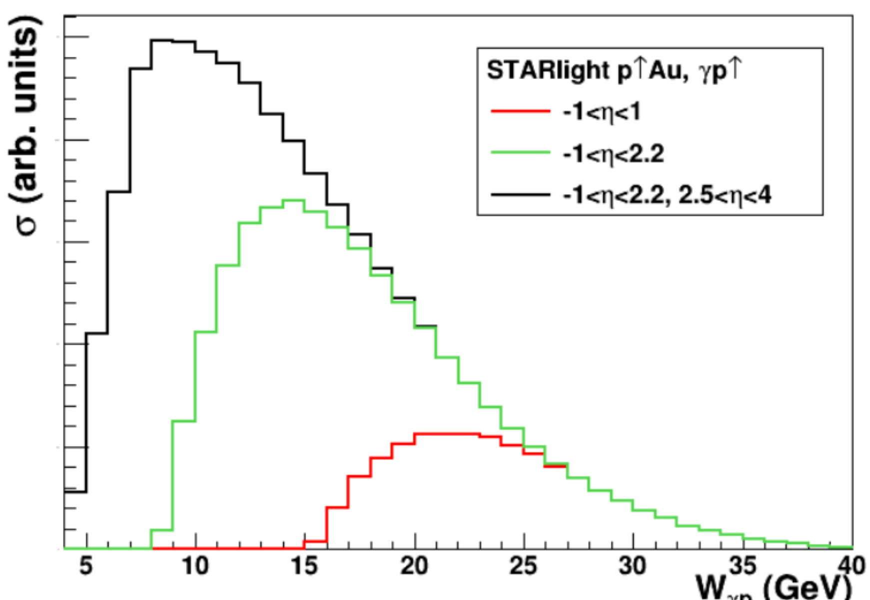
Run-24: a factor of 9-10 more data, combined with iTPC and forward upgrades, stat. error for A_N^{γ}: 0.02 for $<W_{\gamma p}>$=14 GeV, where the signal is expected to be large.

Generalized parton distribution

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







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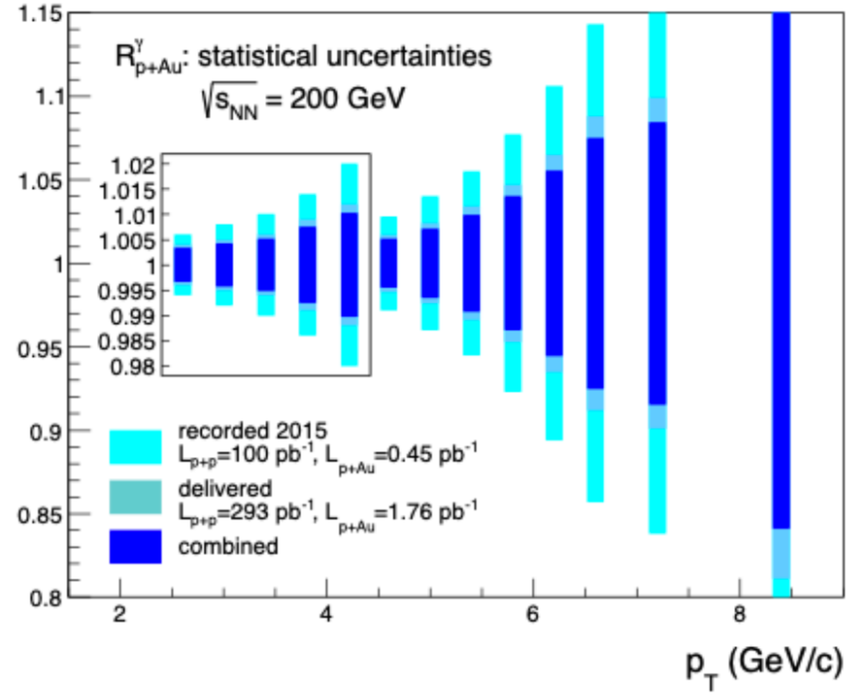
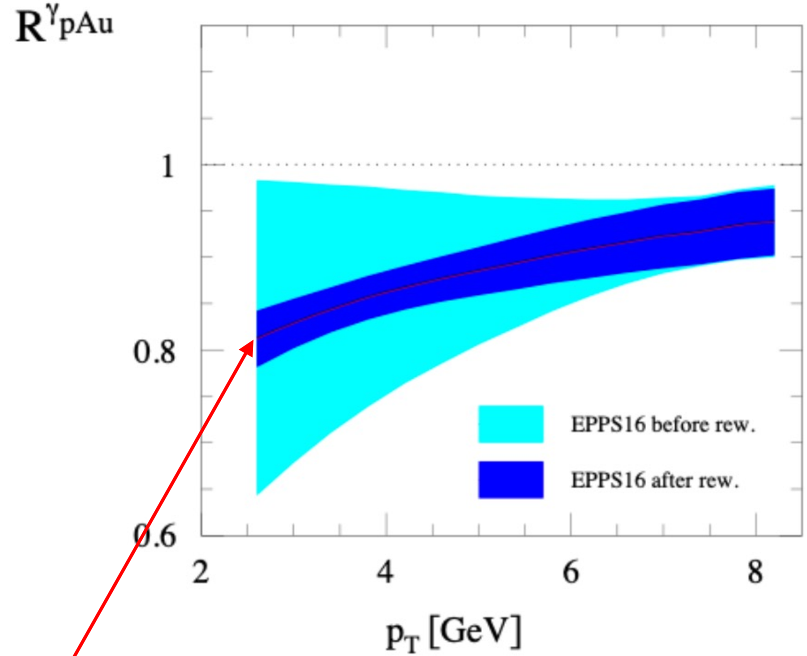
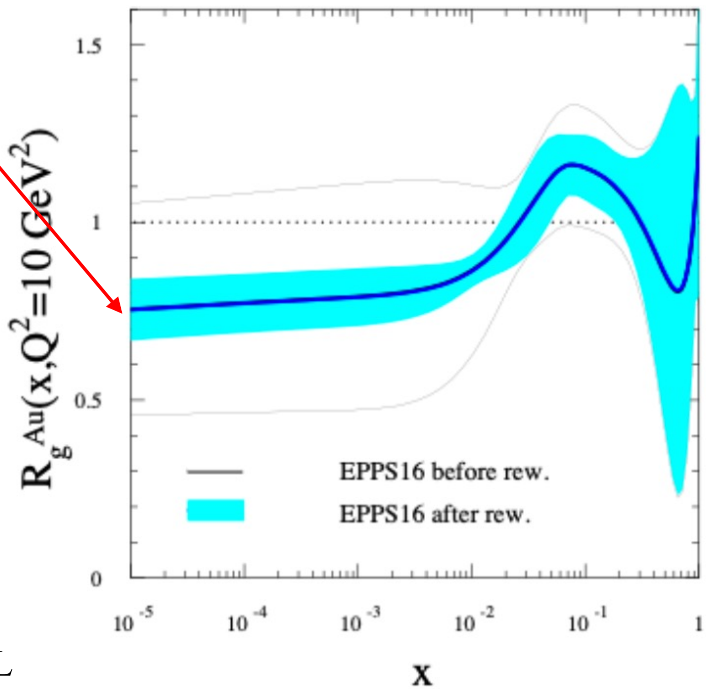
low material, forward upgrade

Nuclear PDF





Run-24 data impact

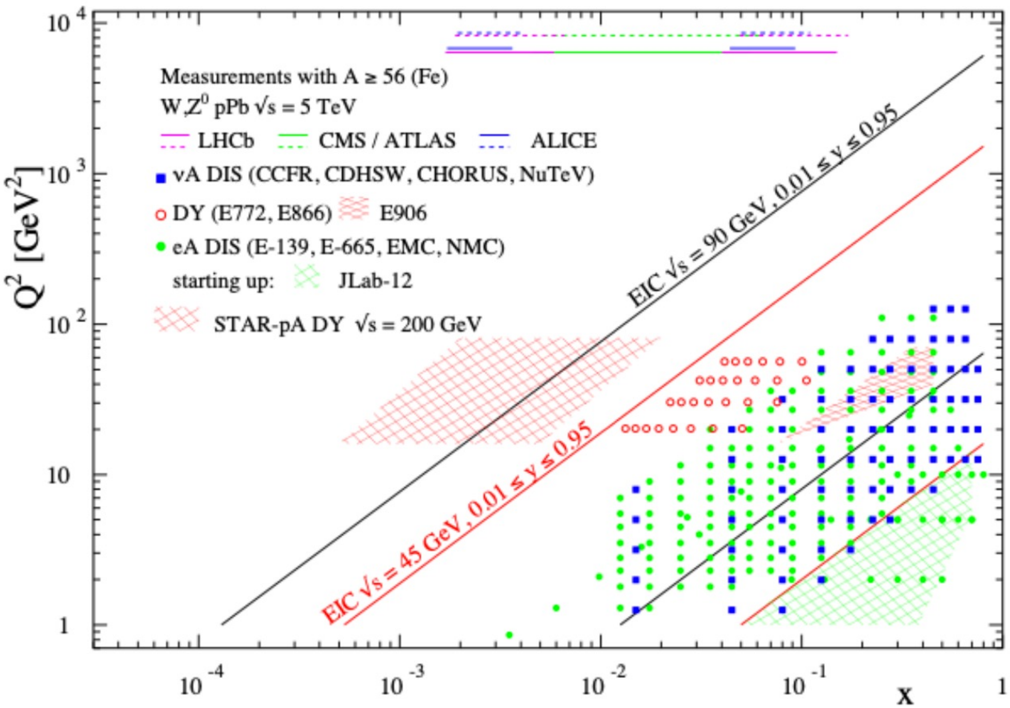


Direct photon measurement: constrain nuclear gluon distribution in a broad x range

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

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

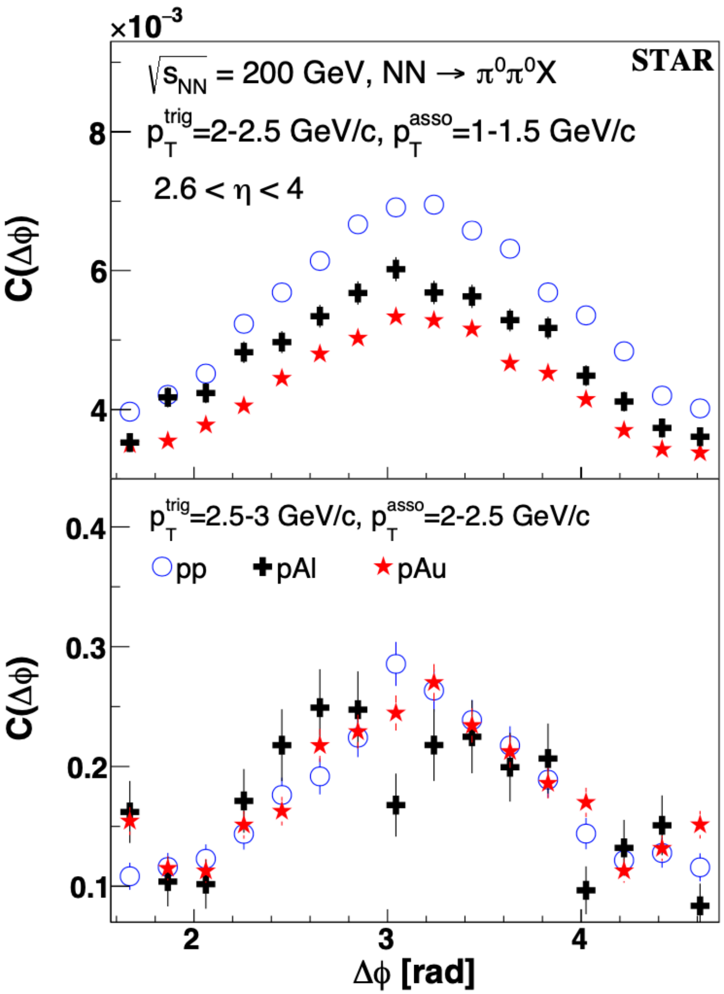
With forward upgrades:
hadron rejection power: 200-2000 for hadrons of 15-50 GeV
electron efficiency: 80%

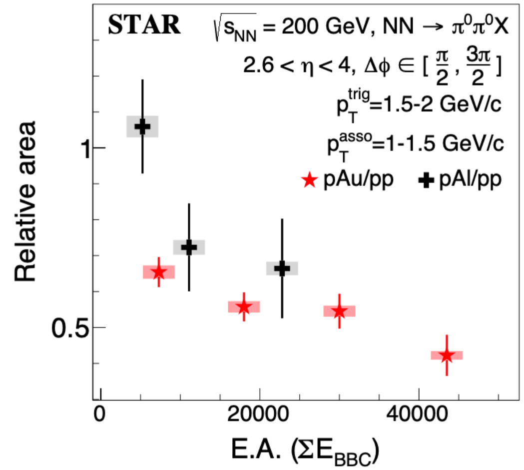
Drell-Yan : constrain nuclear sea quark distribution in a broad x range

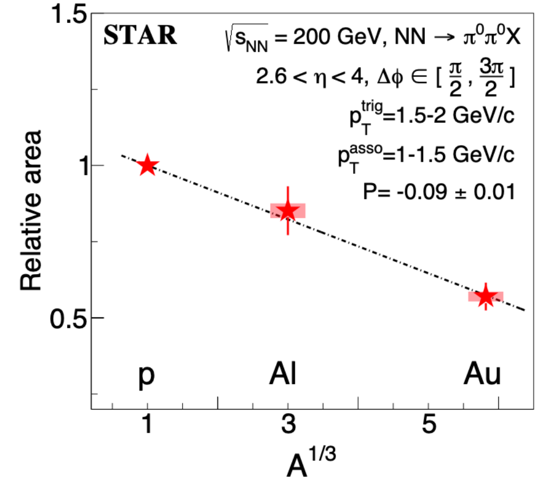
Essential in testing fundamental universality properties of nPDFs combined with data from EIC

QCD non-linear effects

arXiv: 2111.10396



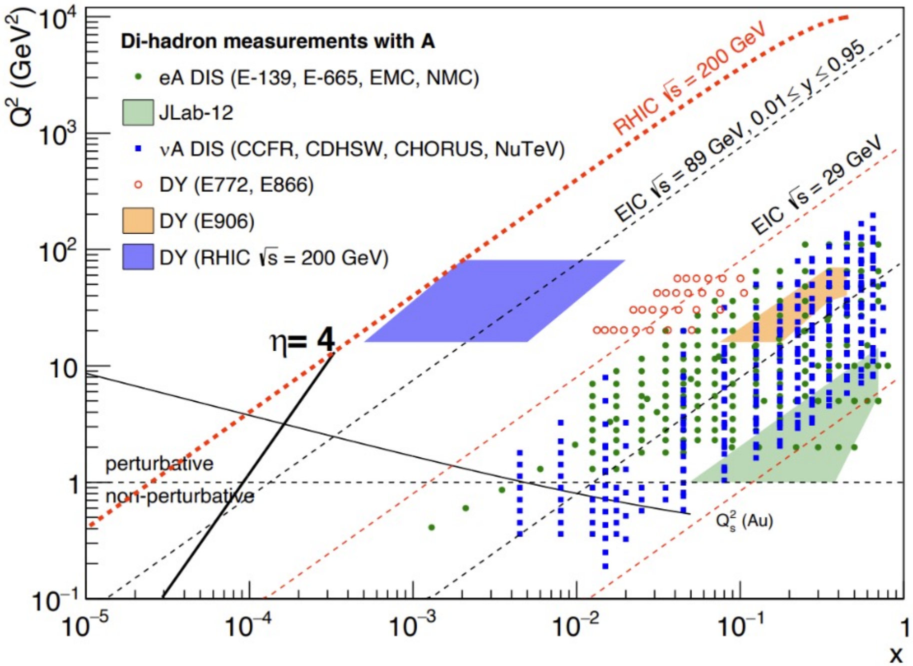




Run-15 di-π^0 correlation:
away side area suppressed significantly, while the pedestal and away side widths change very little.

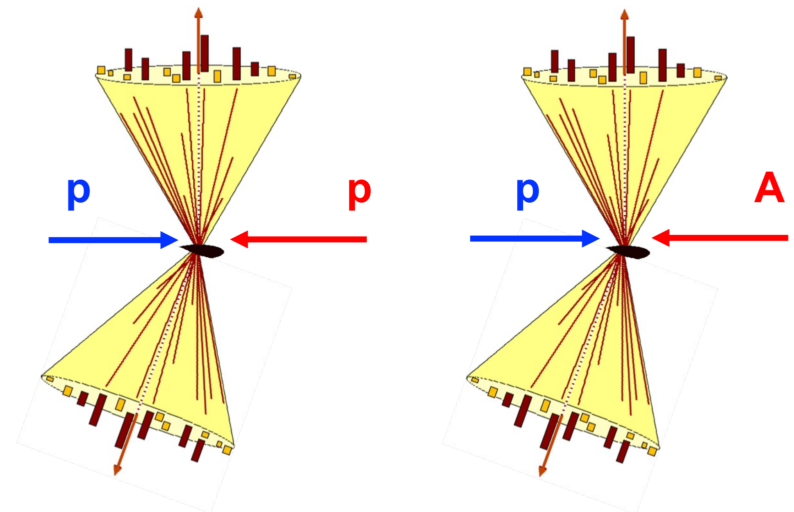
probe x down to 10^{-3}

QCD non-linear effects



counting experiment of Di-jets in pp and pA

Saturation: Disappearance of backward jet in pA



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

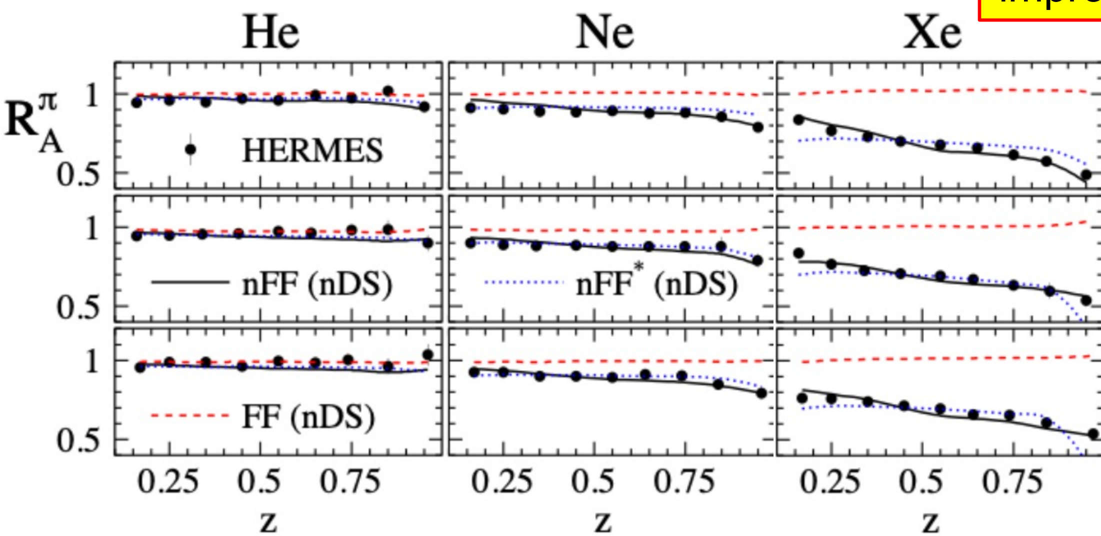
→ proton – Au collisions

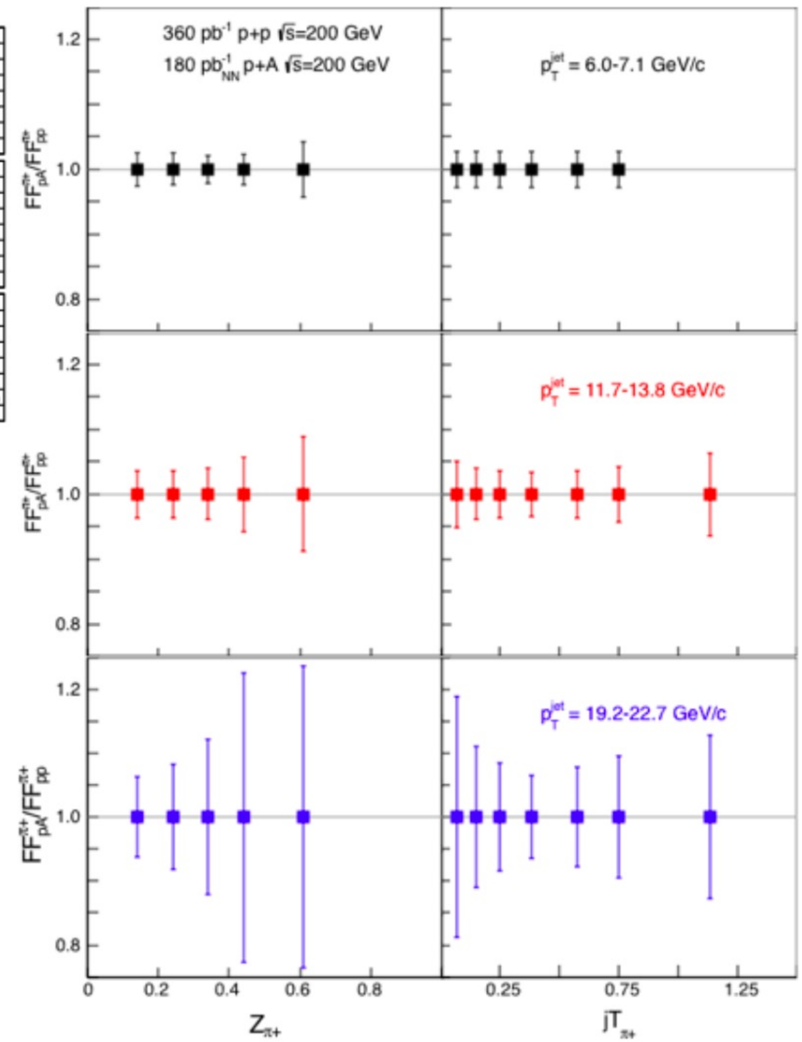
combined with an unambiguous observable

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

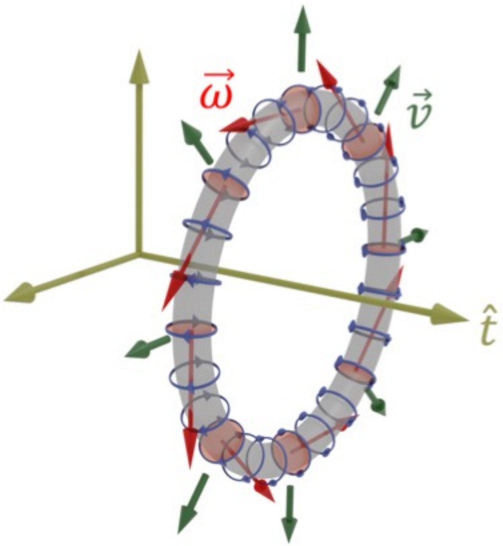
Universality has not been tested

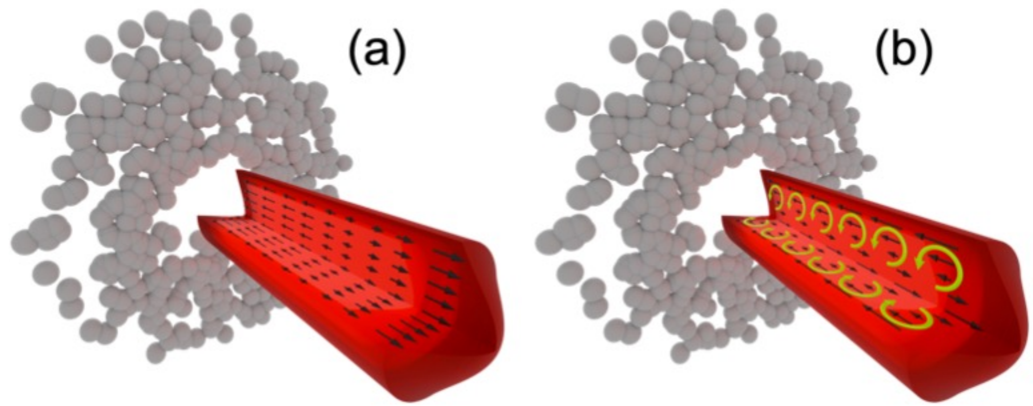
Run-24: study pion, kaon, and proton FF modification, constrain gluon FF.

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

Novel QGP droplet substructure: toroidal vorticity

improved PID, extended η coverage by iTPC

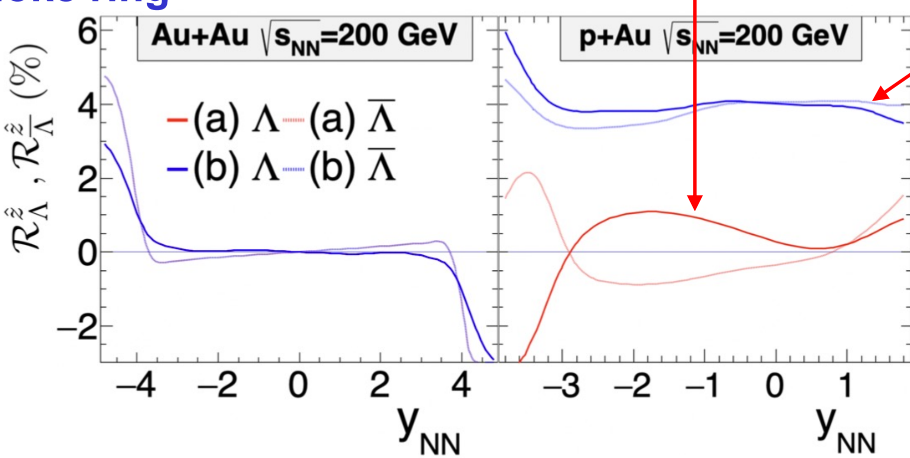




Toroidal vortex structure: smoke ring

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 $\overline{\mathcal{R}}^{z}_{\Lambda}$~1% with 7 σ significance

A unique 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

A shorter run scenario

Runs 23-25: 24 cryo-weeks each

Data taking:
40 weeks Au+Au
9 weeks pp
9 weeks p+Au

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity
200	Au+Au	17B / 34 nb^{-1}
200	p+p	176 pb^{-1}
200	p+Au	0.98 pb^{-1}

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

Au+Au: Decrease statistics by at least 16%, 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 22-25%, 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

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 at the mini-retreat on "Nuclear Physics Computing from RHIC to EIC" in January 2022

Impact on SDCC resources shown at backup

Network and HPSS capability	2022 capacity	2023-2025 needs
DAQ to SDCC network upload	40 Gbps	40 Gbps
SDCC to DAQ local network	28×1 Gbps	48×1 Gbps
Tape Drive Capacity	20 Gbps	40 Gbps

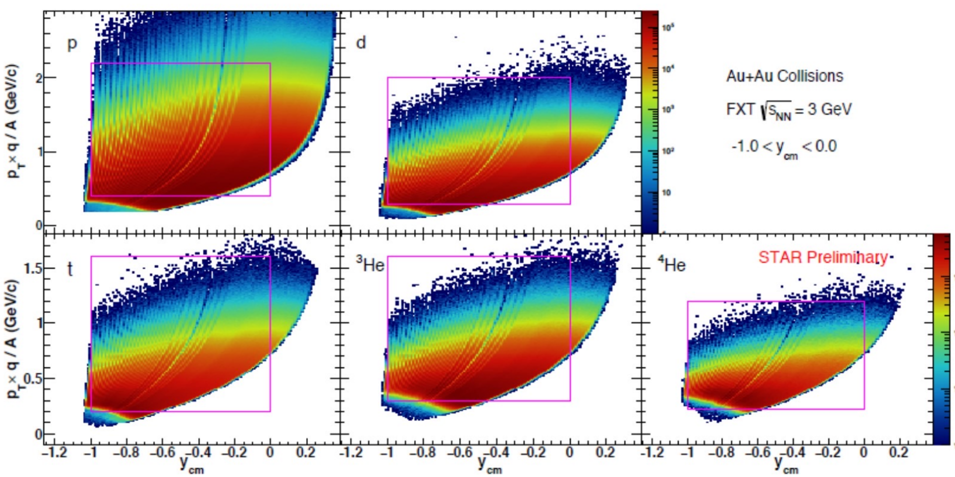
Year	Species	Additional HPSS Space Needed (RAW+DST) (PB)	Total Storage Space Needed (Xrootd) (PB)	Total Storage Space Needed (NFS/Central) (PB)	Required CPU Total [kHS06]
2021	BES-II	0.43	3.06	3.504	203
2022	500 GeV p+p	11.07	3.63	3.854	295
2023	200 GeV Au+Au	55.4	7.0	4.75	626
2024	200 GeV p+p/p+Au	35.5	9.1	4.75	626
2025	200 GeV Au+Au	73.8	13.5	4.75	626

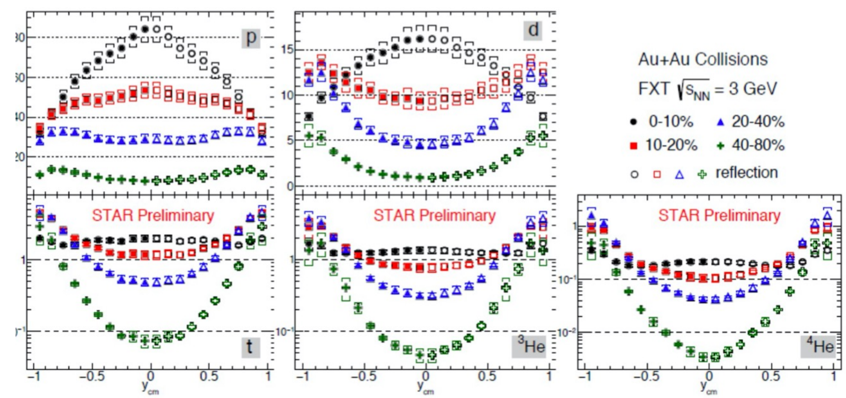
After 2025, we could do with what we have in 2025 but it must be preserved for +3 years for CPU. HPSS storage does not change. The Xrootd/central storage will be needed for at least a decade; **need to maintain software and computing person power for at least 5 years, for STAR data calibration, production,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

Future opportunity I

Light fragment yields from C, Al, and Fe on C, Al, and Fe targets with beam energies from 3 to 50 GeV

- **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 can install the targets of interest (C, Al, Fe)**





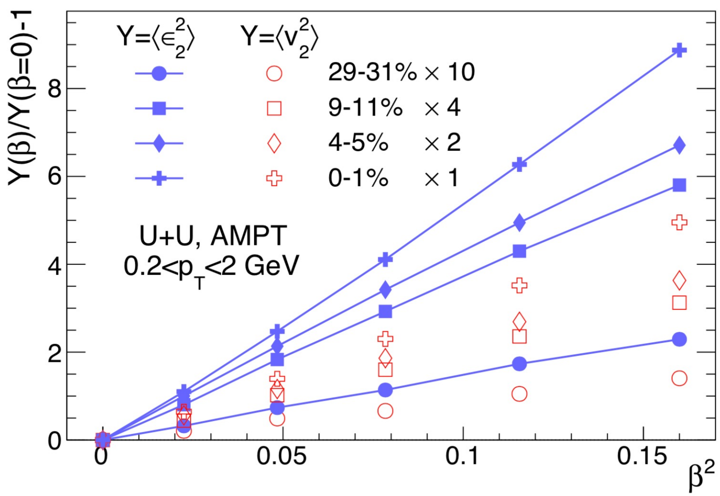
In total, two weeks of running including machine setup

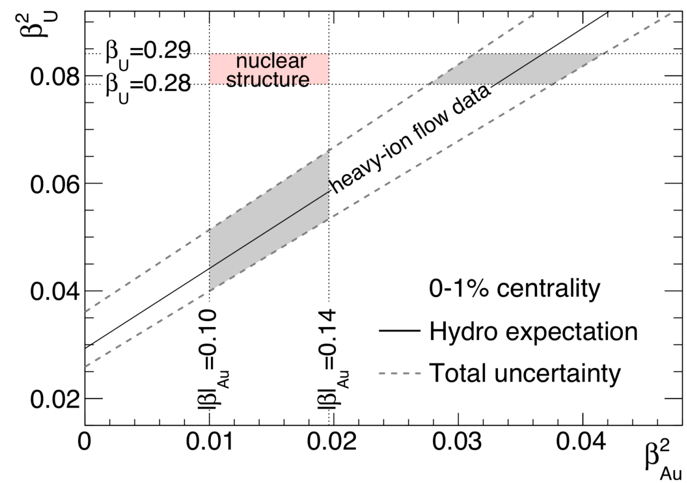
Future opportunity II

Shape tomography of atomic nuclei using collective flow measurements

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

- 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 √s = 200 and 500 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 Gluon GPD → E_g
  - ❑ Requirement:
    - ➢ data sets √s = 500 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 500 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
    - ➢ 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

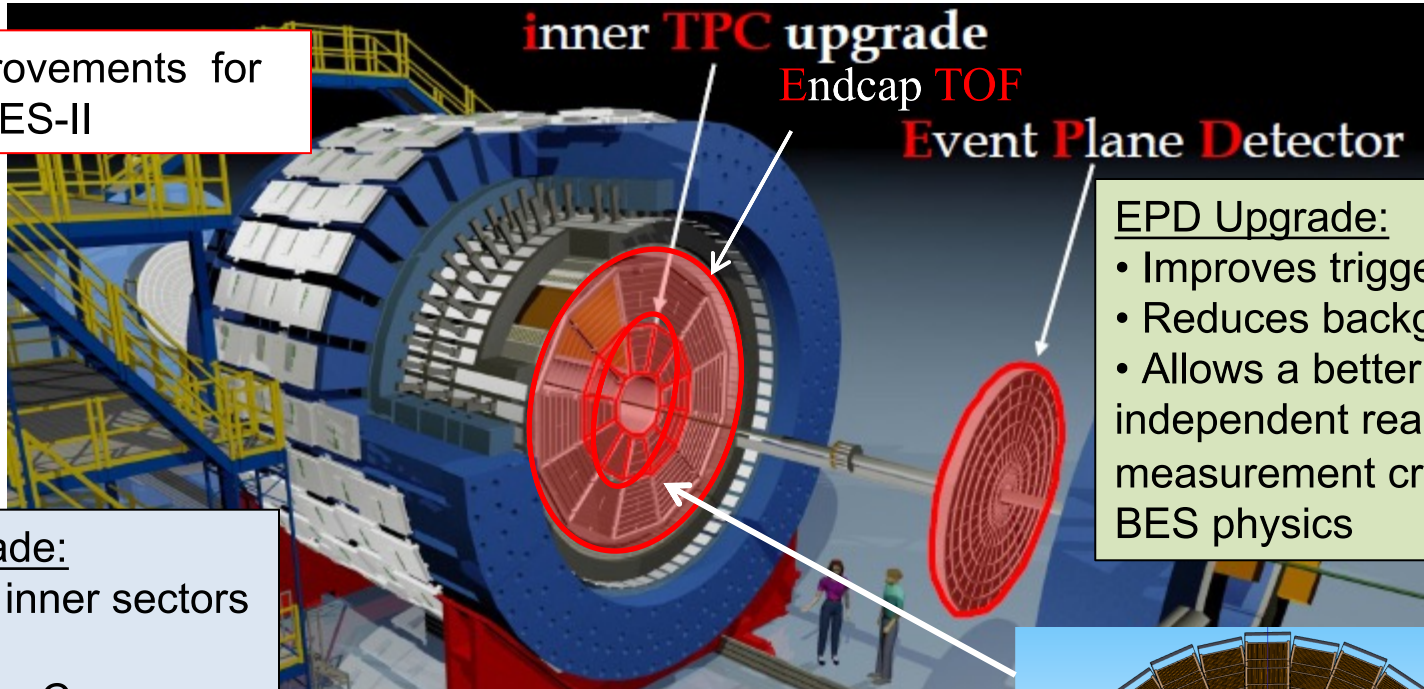
To inform EIC physics with photon induced processes:

- 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

Backup

STAR detector at BESII

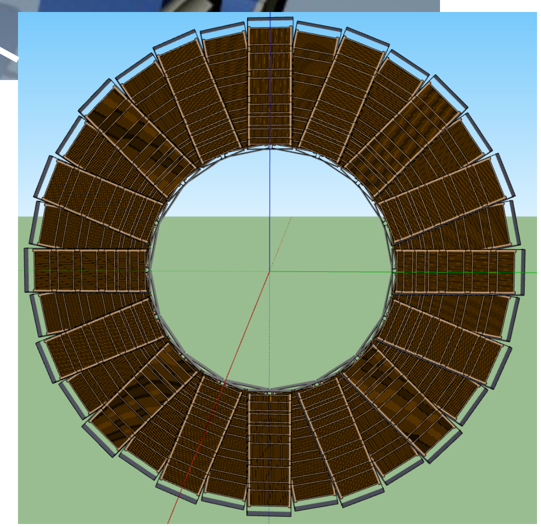
Major improvements for BES-II



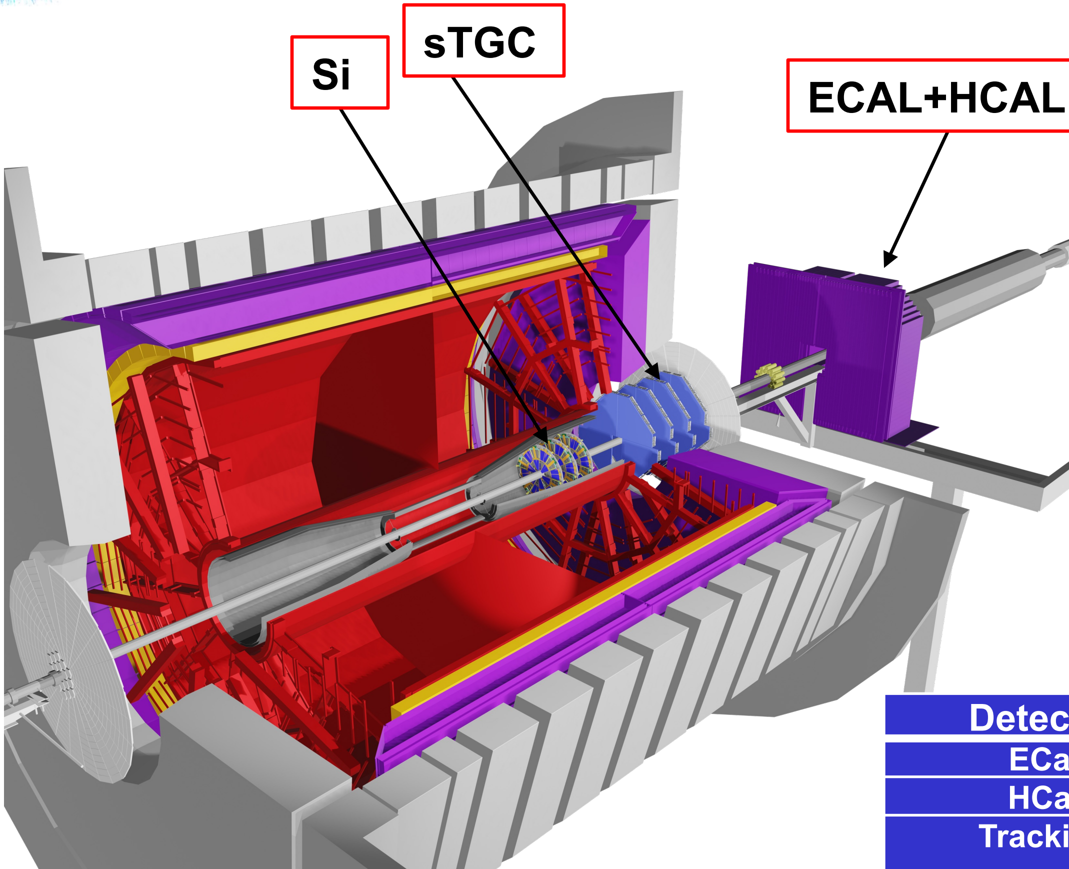
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

iTPC Upgrade:
- Replaced inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



STAR forward upgrades

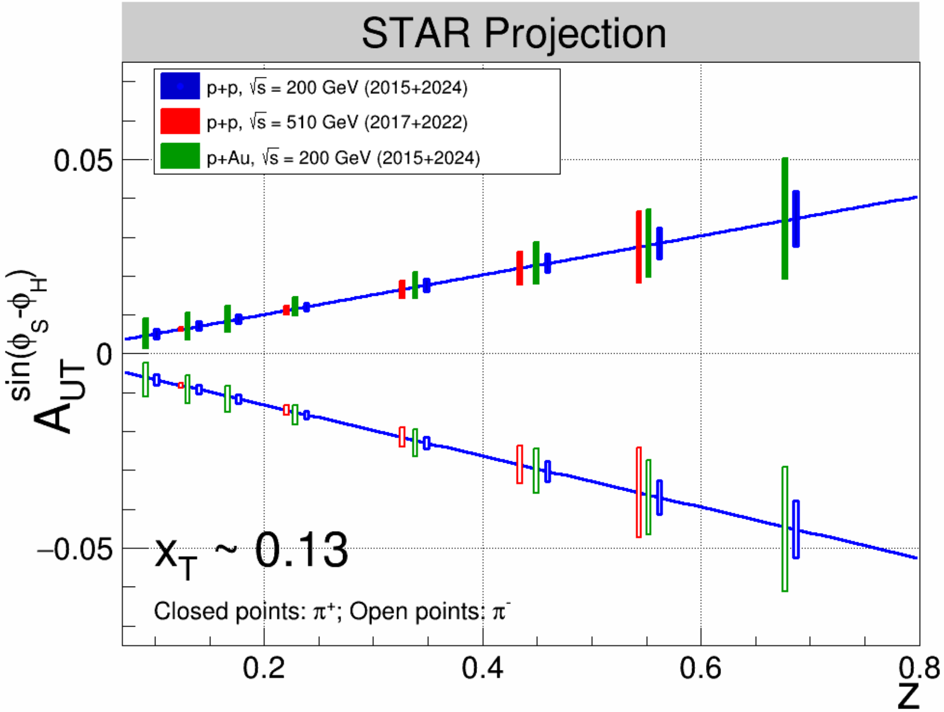


At $2.5<\eta<4$
- Jets
- PID (π^0, γ, e, Λ)
- charged particle momentum resolution 20-30% at $0.2<p_T<2$ GeV/c
- event-plane reconstruction and trigger capability

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% $1/p_T$

Collins asymmetry: $\pi^{\pm}$ in jets at mid-rapidity

improved PID, extended η coverage by iTPC

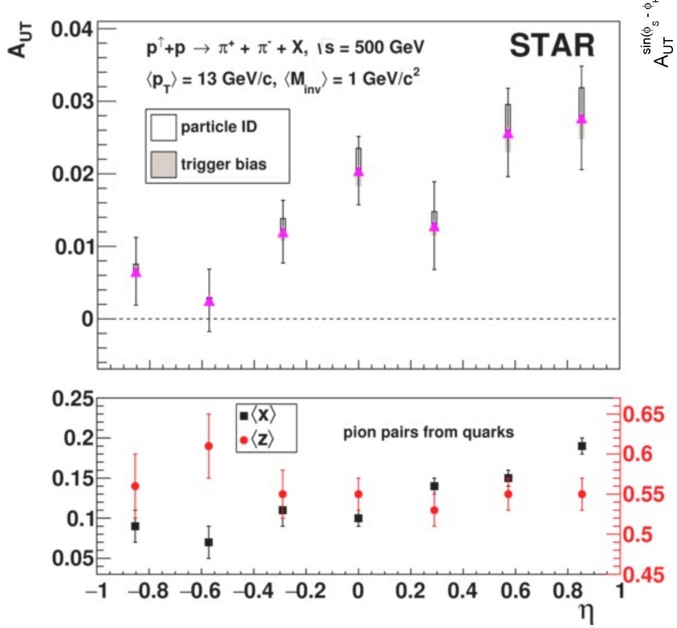


Multi-differential (p_T, η, z, j_T, Q^2) precise Collins asymmetry measurements at mid-rapidity will probe TMD factorization, universality, and evolution.

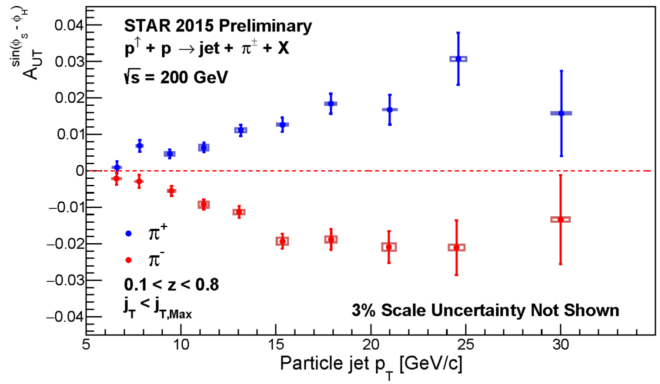
- Similar x coverage but much larger Q^2 compared to SIDIS measurements

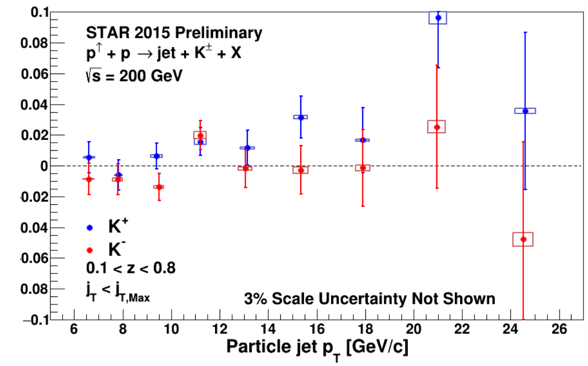
iTPC in mid-rapidity IFF and Collins: η dependence and PID

STAR IFF, PLB 780, 332



STAR 2015 Collins, preliminary





- Different Collins and IFF asymmetries for different particle types
  - K^+ about 1.5-sigma larger than π^+ (note diff vert scales)
  - K^- (and p/pbar in backup) consistent with zero in 2015
  - Similar π/K behavior seen in SIDIS
- Particle identification essential to maximize impact
- iTPC increases FoM by improving dE/dx resolution
- Propose to take 4.5 times the 2015 luminosity, but
  - Pion uncertainties will drop by $1/\sqrt{5.4}$
  - Kaon and proton uncertainties will drop by $1/\sqrt{9}$ (!)

Forward η increases:

- Quark fraction (no gluon transversity)
- <x>
- Polarization transfer in hard scattering

iTPC will add coverage of 1 < |η| < 1.5 for both IFF and Collins asymmetries

The impact on SDCC resource

- The maximum data throughput of STAR as a whole will increase a factor of 2 from a peak rate of ~16Gbps to a peak rate of ~32Gbps.

- The needed network bandwidth to HPSS, the tape drive bandwidth, and tape storage for analyzed data will scale directly with the increased STAR data rates.

- 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.

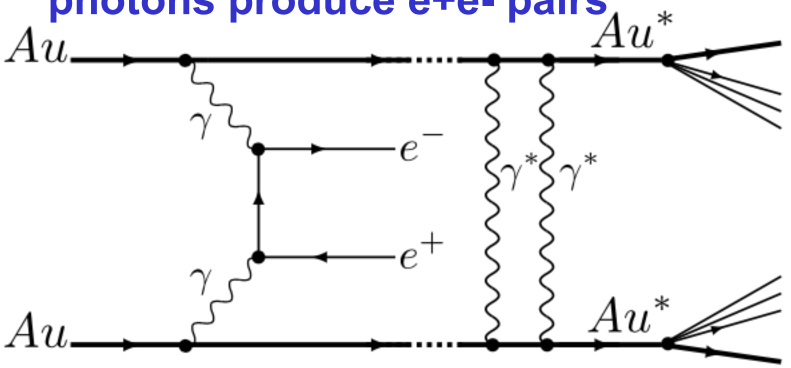
- Xrootd and NFS disk storage, however, does not scale as directly with the data volume because of the potential for summarized information and because not all data sets have to be present at the same time for analysis. We have assumed that the planned incremental increases must scale with the data volume rather than the total storage.

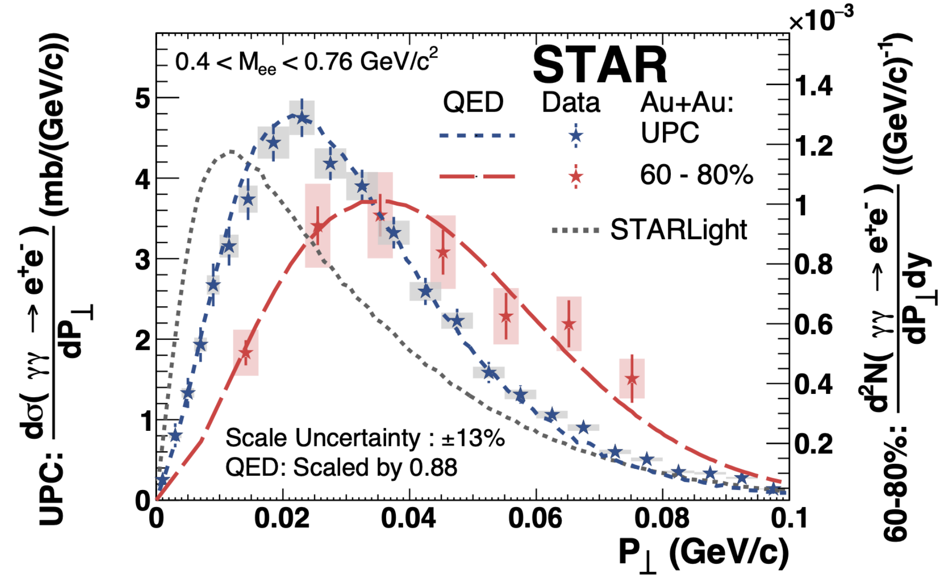
- The current network infrastructure will need to be reconfigured but will support the full 32Gbps rate. The current network connection between SDCC and the STAR DAQ consists of 4 nominal 10Gbit upload links. The existing switches also have the capacity to add at least 2 addition 10Gbit upload links supplying sufficient network capacity. The local DAQ connections currently consist of 28x1Gbps links. These would need to upgraded to at least 40 links. The existing switches provide sufficient capability.

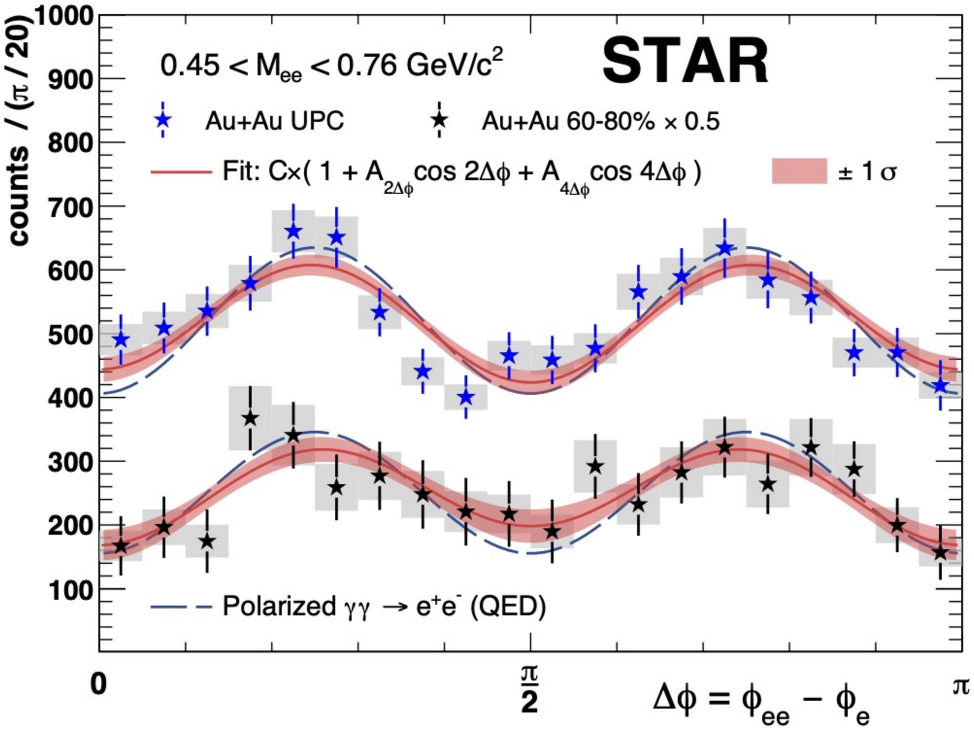
- The number of tape drives in the HPSS system would need to be increased to provide the full 40Gbps throughput capability.

Discoveries of Breit-Wheeler process and vacuum birefringence

linearly polarized quasi-real photons produce e+e- pairs







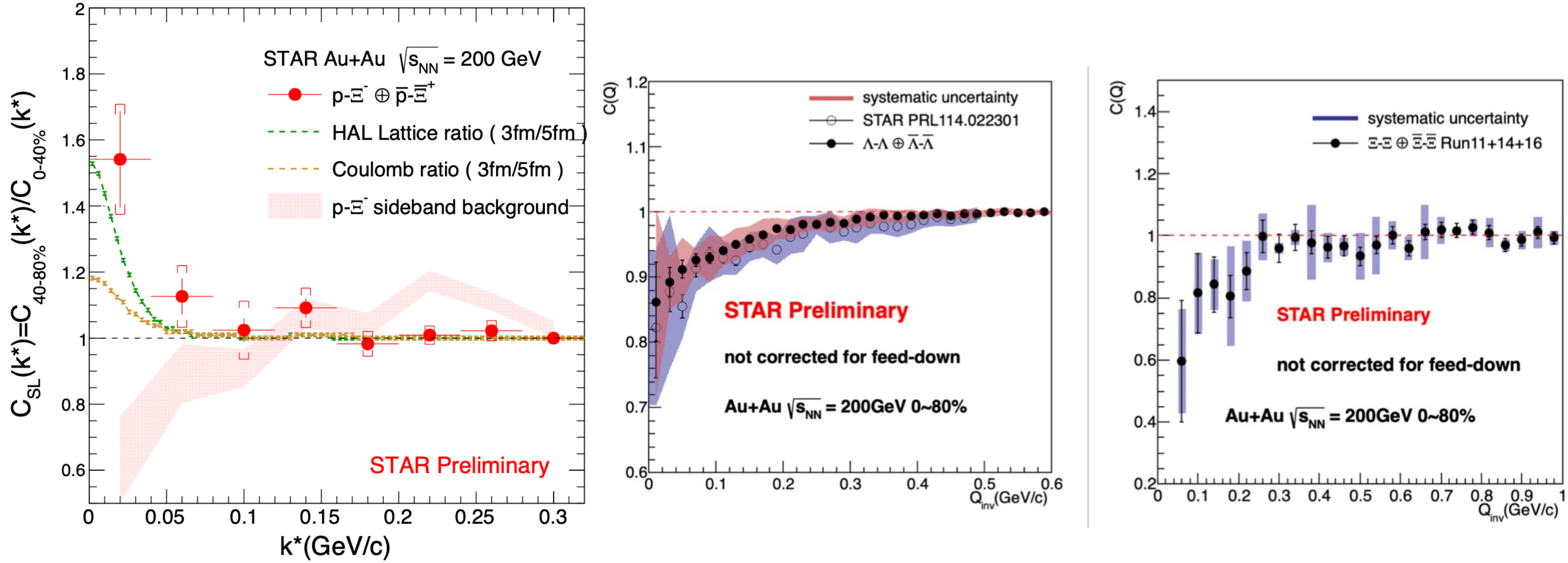
arXiv: 1910.12400

Observation of Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, p_T, angle)

Dielectron p_T spectrum: broadened from large to small impact parameters

Observation of vacuum birefringence: 6.7σ in UPC

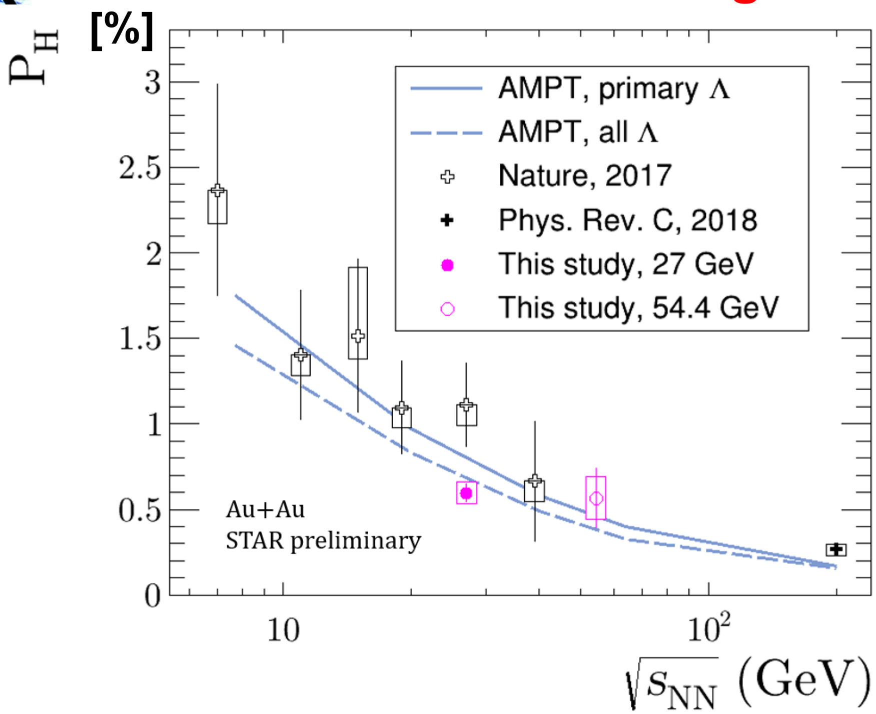
Strong interactions



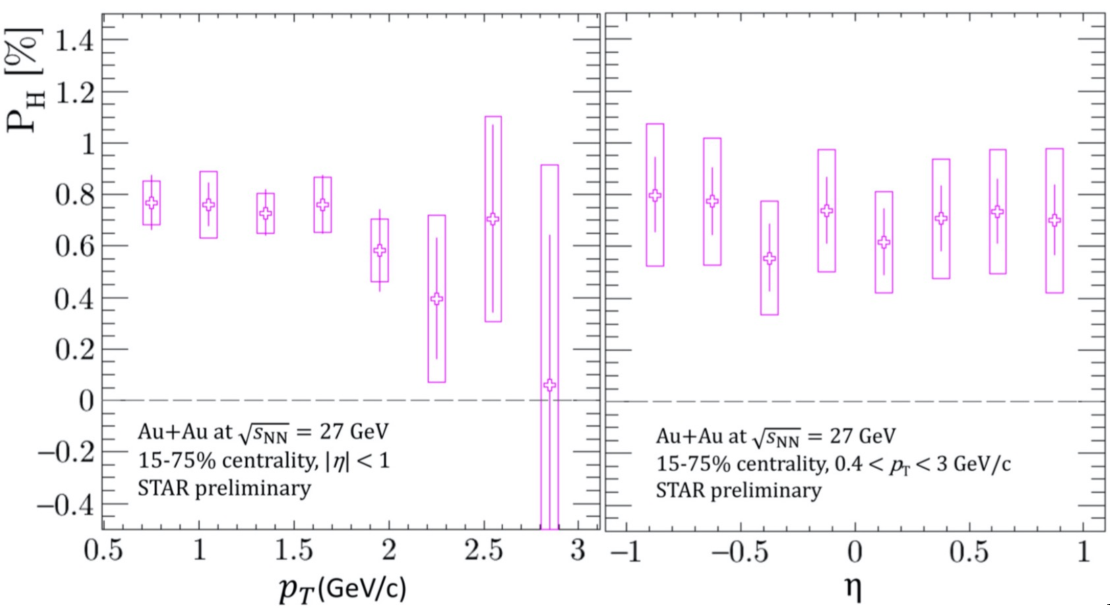
Constrain hyperon-nucleon and hyperon-hyperon interactions, important for the study exotic hadronic states and understanding of the EoS of neutron stars

- **A factor of 7 more data in Runs 23 and 25**
- **Systematic uncertainties will be significantly reduced.**

Vortical fluid: global vorticity transfer

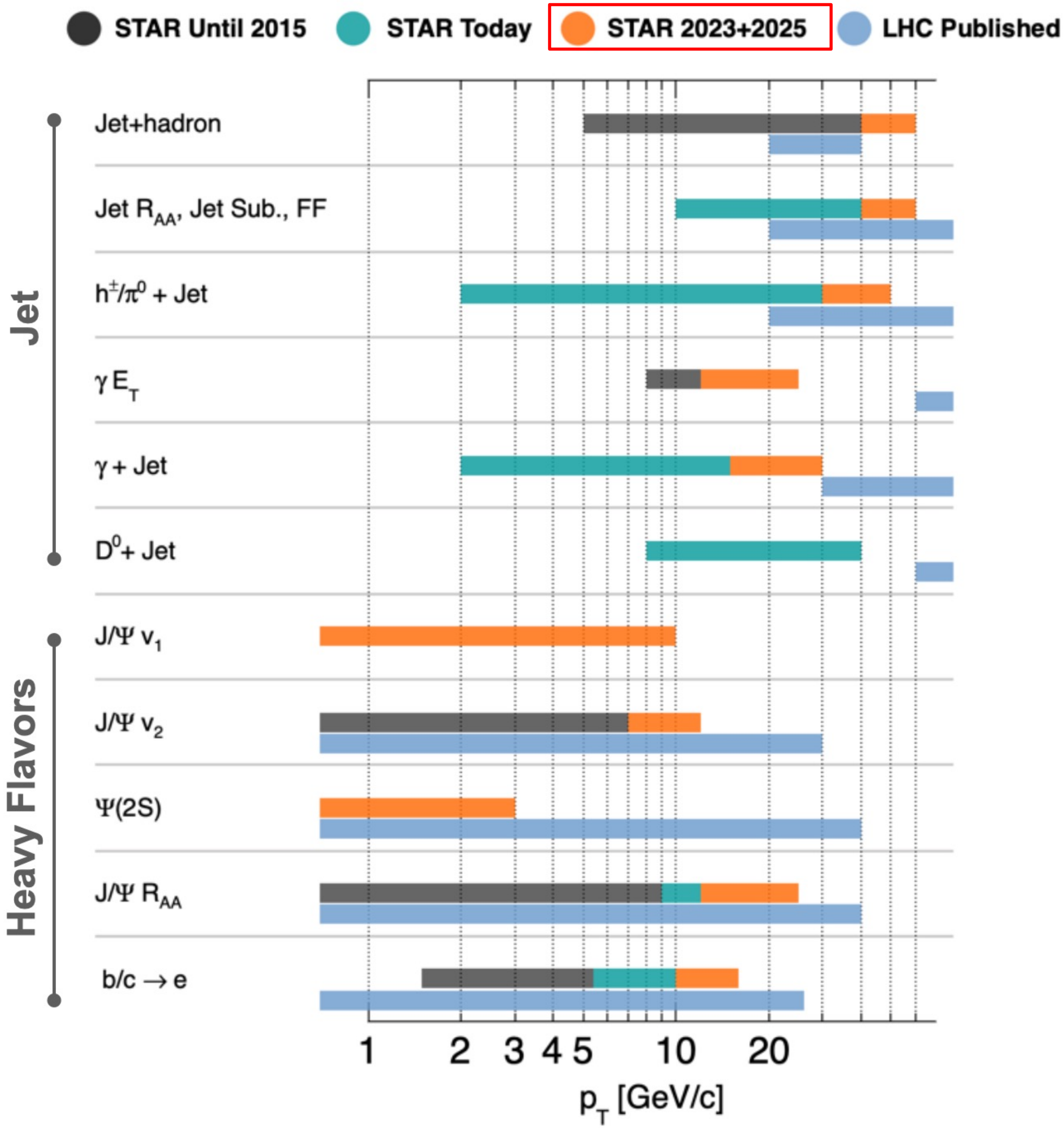


Λ Global polarization: strong energy dependence



Weak p_T and η dependence

Hard probes: jets and heavy flavor



200 GeV AuAu in 2023-2025

STAR is in a unique position to measure

- v_n vs. η at forward
- Decorrelation vs. η up to forward
- Net-proton C_6/C_2
- Dielectron
- $\gamma\gamma \rightarrow e^+e^-$
- $\gamma p \rightarrow \rho X \rightarrow \pi^+\pi^- X$ and $\gamma p \rightarrow J/\psi X \rightarrow e^+e^- X$
- Parton energy loss for jets of varying topologies selected via substructure

Future opportunity II

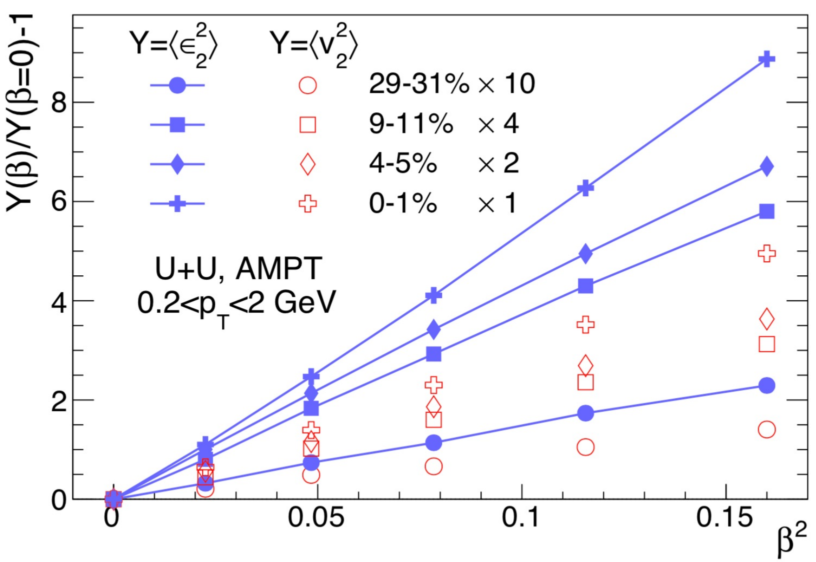
Shape tomography of atomic nuclei using collective flow measurements

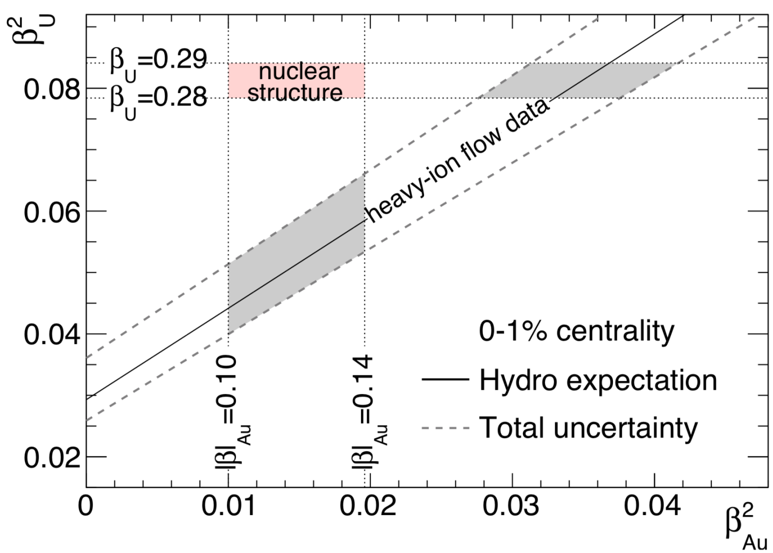
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi)/a}}$$

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3 Y_{3,0}+\beta_4 Y_{4,0}\right)$$

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

	β_2	β_3	β_4		β_2	β_3	β_4		β_2	β_3	β_4
^{238}U	0.286 [9]	0.078 [10]	0.094 [10]	^{208}Pb	0.06 [9]	0.04[11]	?	^{197}Au	-(0.13-0.16) [12, 13]	?	-0.03 [12]
^{129}Xe	0.16 [12]	?	?	^{96}Ru	0.05-0.16 [14]	?	?	^{96}Zr	0.08-0.22 [14]	?	0.06 [12]





Future opportunity II

Shape tomography of atomic nuclei using collective flow measurements

- Step1: calibrate systematics two species around 197Au: 208Pb & 198Hg (β_2=-0.11)
  - 208Pb $\sqrt{s}$=0.2 RHIC vs 5 TeV @LHC: precision on IS and pre-equilibrium dynamics?
  - 208Pb $\sqrt{s}$=0.2 vs 197Au $\sqrt{s}$=0.2 TeV: control on effects of Au deformation
  - 198Hg $\sqrt{s}$=0.2 TeV: 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: 144Sm (β_2=0.08),148Sm (β_2=0.14,triaxial),154Sm (β_2=0.34)
  - These elements in region Z~56/N~88, where large octuple is expected/predicted.
  - Compare a pair with equal mass: 154Sm (β_2 = 0.34) and 154Gd (β_2 = 0.31)

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

A_N in diffractive events

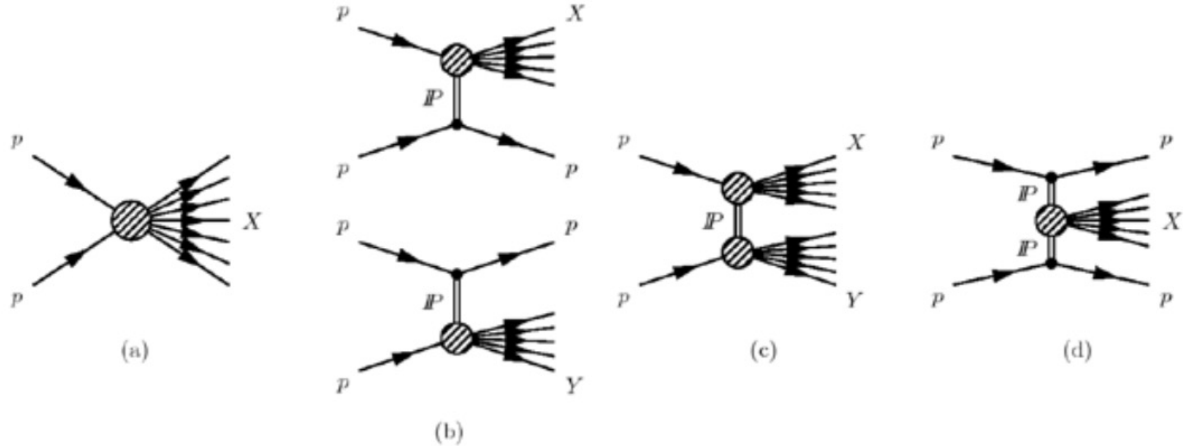
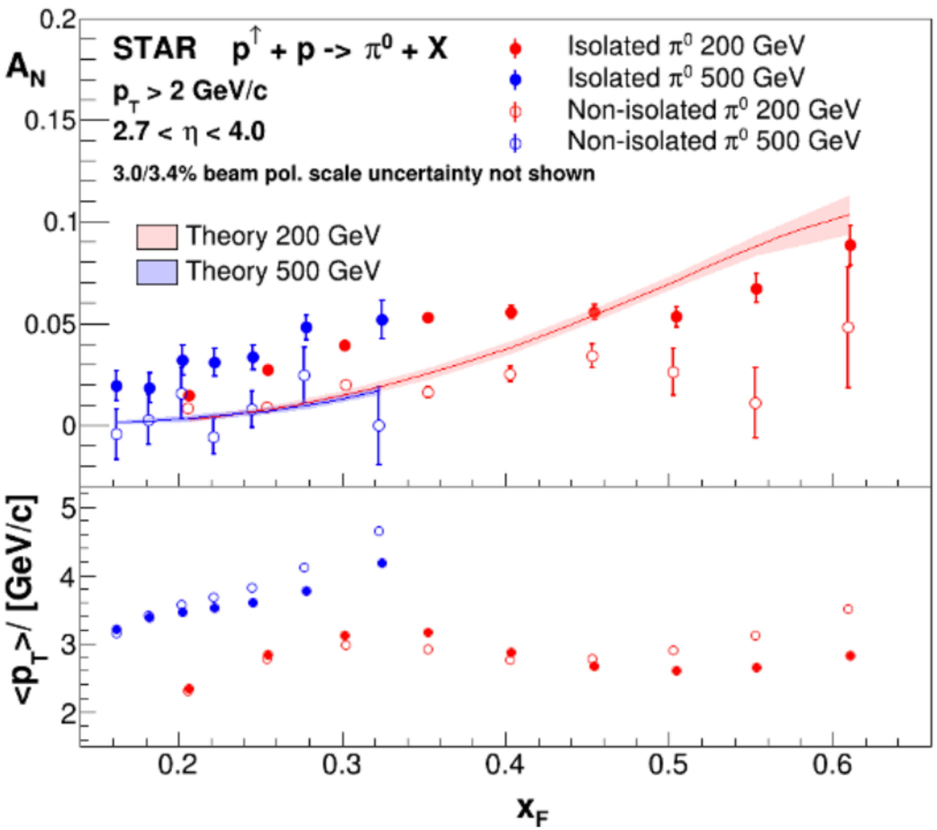


Figure 71: Schematic diagrams of (a) nondiffractive, $pp \to X$, (b) singly diffractive, $pp \to Xp$ or $pp \to pY$, (c) doubly diffractive, $pp \to XY$, and (d) centrally diffracted, $pp \to pXp$, events.



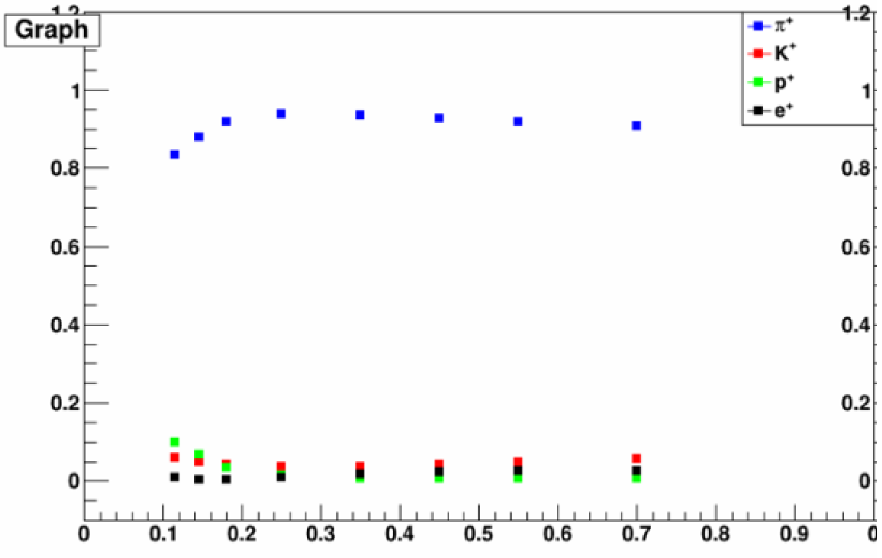
Model with initial and final state effect can only explain the non-isolated π^0 A_N

Significantly larger value of A_N for isolated π^0

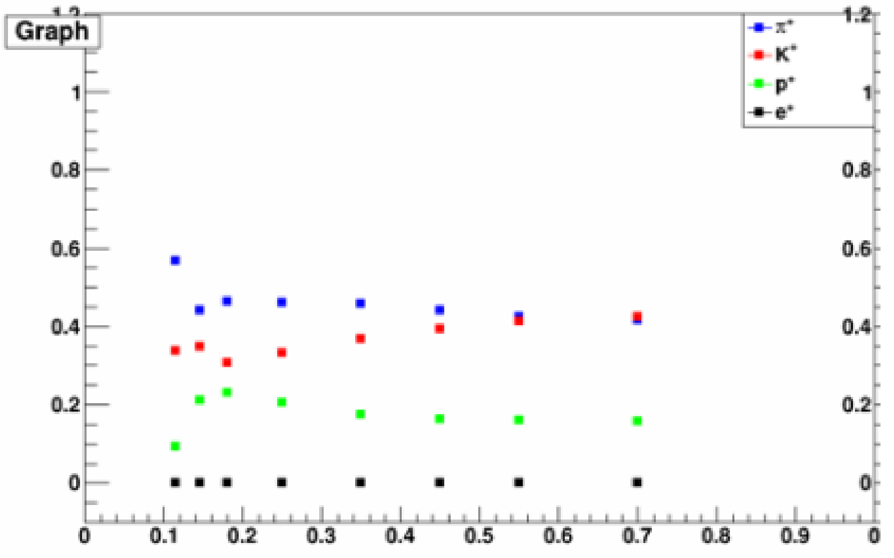
Plan to reconstruct jets produced with scattered proton tagged in Roman Pots with/without rapidity gaps

Identified particle composition in one jet p_T bin

Pion-rich dE/dx region

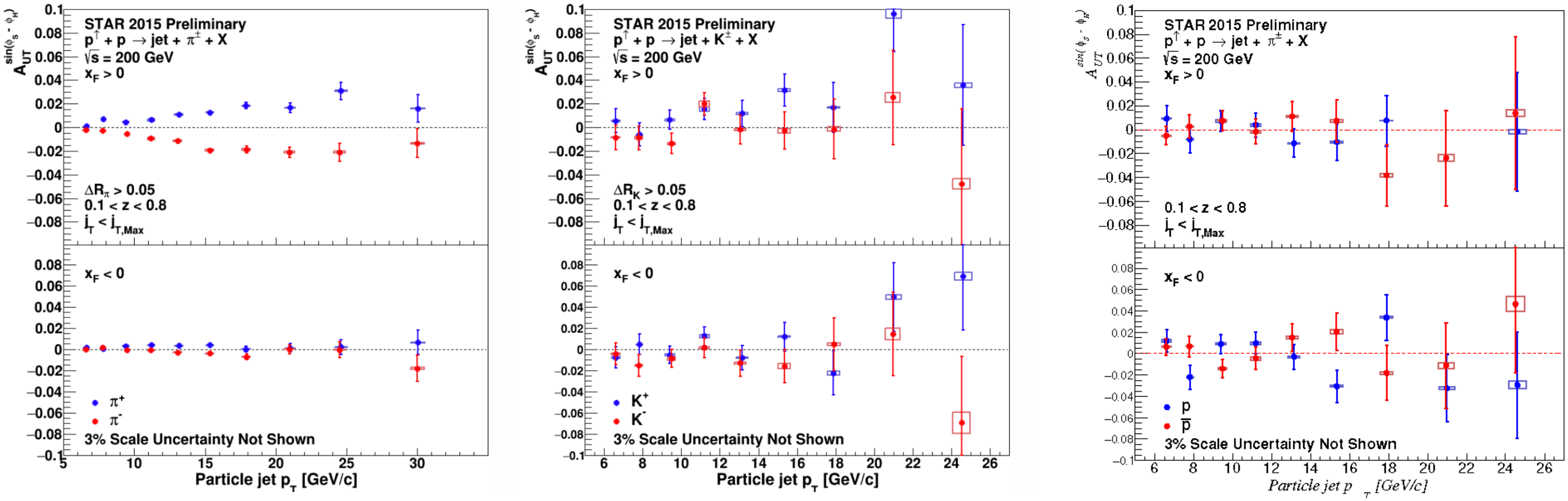


Kaon-rich dE/dx region



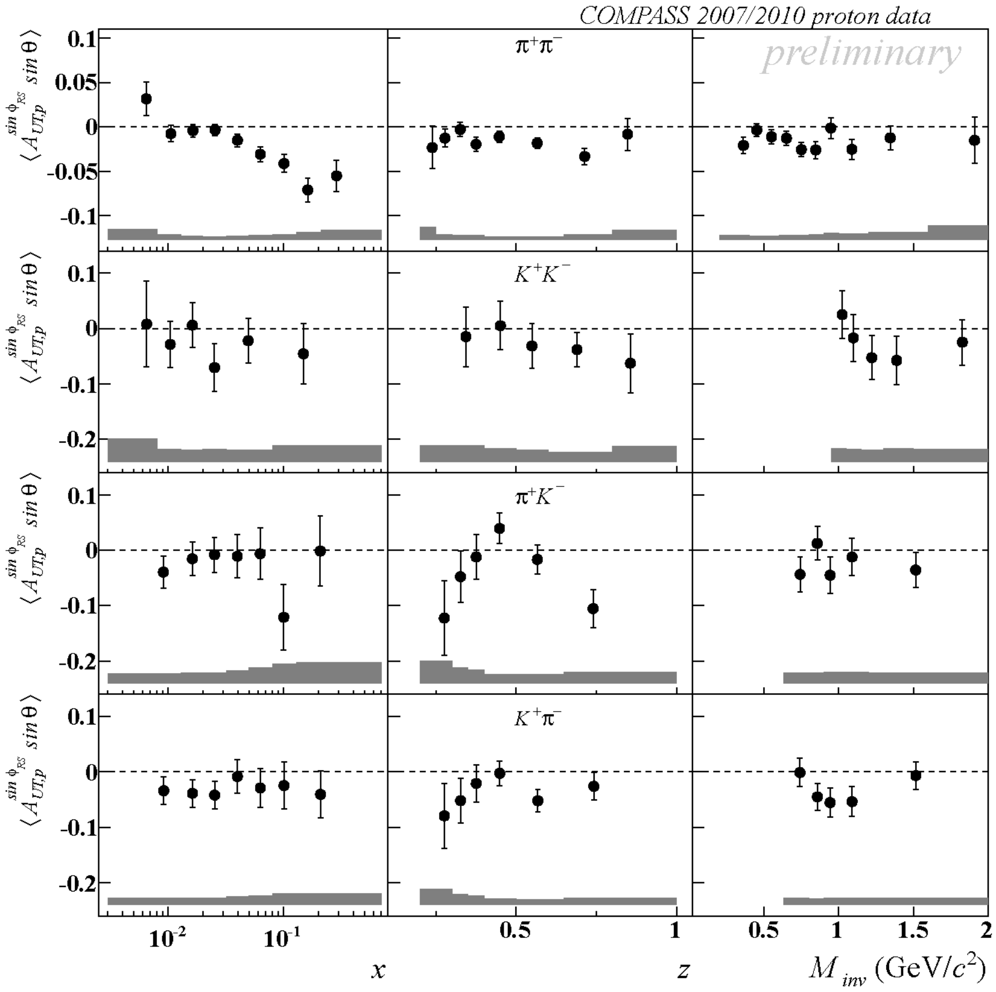
- Fractions of π^+, K^+, p, and e^+ in jets with $11.7 < p_T < 13.8$ GeV/c as a function of z in the 200 GeV 2015 Collins effect measurement (negative hadrons behave similarly)
- Note that, with 2015 dE/dx resolution, the kaon-rich region contains more pions than anything else, but far fewer than in the pion-rich region
- With the iTPC, the pion fraction in the pion-rich region will increase, and for most z bins there will be more kaons than pions in the kaon-rich region
  - After matrix inversion, the pion uncertainties will shrink by ~9% for the same integrated luminosity, and the kaon uncertainties will shrink by ~30%

STAR 200 GeV Collins asymmetries vs. p_T from 2015



- pi+, pi-, K+, K-, p, pbar for both rapidity bins and with the same vertical scale

Identified particle IFF asymmetries from COMPASS



C. Braun for COMPASS, DIS-2014

- **Different particle-type pairs yield different IFF asymmetries**

Species dependence in HERMES nFF measurements

HERMES, NPB 780, 1