STAR Beam Use Requests for Runs 22-25

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Executive summary

Table 1: Proposed Run-22 assuming 20 cryo-weeks, including an initial one week of cool-down and a two weeks set-up time.

$\sqrt{s}$ (GeV)	Species	Polarization	Run Time	Sampled Luminosity	Priority
510	pp	Transverse	16 weeks	400 pb^{-1}	1

p+p 510 GeV: probe down to x~2×10^{-3} (gluons) and up to x~0.5 (valence quarks) regions

Table 2: Proposed Run-23 - Run-25 assuming 28 cryo-weeks of running every year, and 6 weeks set-up time to switch species in 2024. Sampled luminosities assume a "take all" triggers.

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

$\sqrt{s_{\rm NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	10B / 31 nb^{-1}	2023
200	pp	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024
200	Au+Au	10B / 31 nb^{-1}	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: $Sivers_{SiDIS}$ = -- $Sivers_{DY, W+/-, Z0}$
  - 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

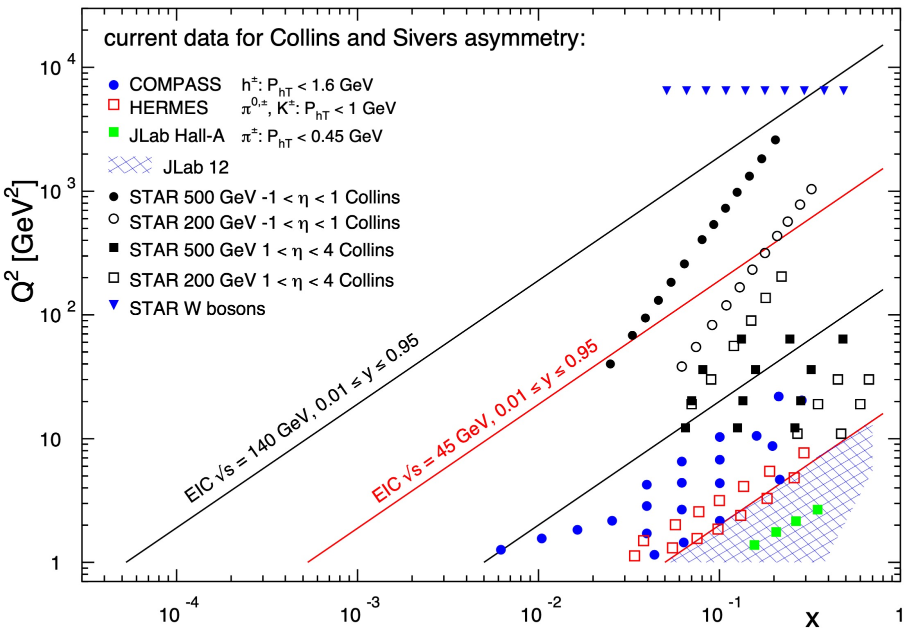
To address important questions about the inner workings of the QGP

- **What is the precise temperature dependence of shear and bulk viscosity?** v_n as a function of η
- **What is the nature of the 3-dimensional initial state at RHIC energies?** r_n over a wide rapidity
- **How is global vorticity transferred to the spin angular momentum of particles on such short time scales? How can the global polarization of hyperons be reconciled with the spin alignment of vector mesons?** Λ, Ξ, Ω P_H and ρ_{00} of K*, ϕ, J/ψ
- **What is the precise nature of the transition near μ_B=0?** Net-proton C_6/C_2
- **What is the electrical conductivity, and what are the chiral properties of the medium?** Dielectron
- **What can be learned about confinement and thermalization in a QGP from charmonium measurement?** J/ψ v_2 and v_1, ψ(2S)
- **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

BUR for Run-22

$\sqrt{s}$ (GeV)	Species	Polarization	Run Time	Sampled Luminosity	Priority
510	p+p	Transverse	16 weeks	400 pb^{-1}	1

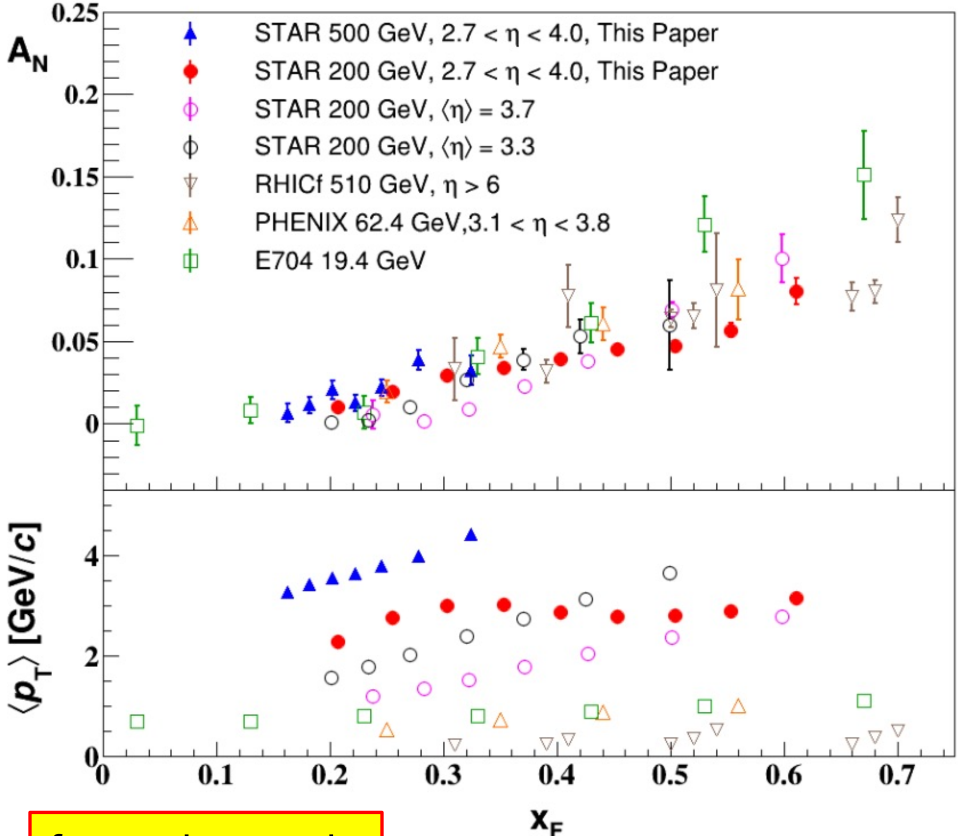
Kinematic coverage for Collins and Sivers Asymmetry
STAR covers 0.005<x<0.5



p+p 510 GeV up to η~4.2
probe down to x~2 × 10^{-3} (gluons)
and up to x~0.5 (valence quarks)

Forward upgrades will be ready for Run-22
First p+p run with BES-II upgrade detectors

Inclusive transverse single spin asymmetries at forward



Interplay of

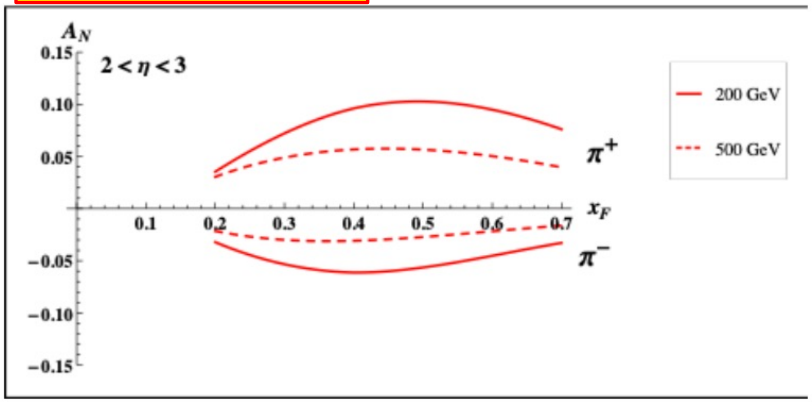
Initial state: Sivers distribution or its twist-3 analog, the Efremov-Teryaev-Qiu-Sterman (ETQS) function

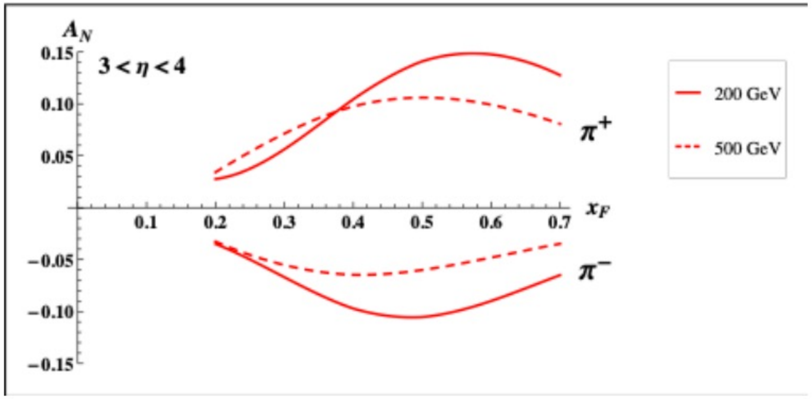
and/or

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}

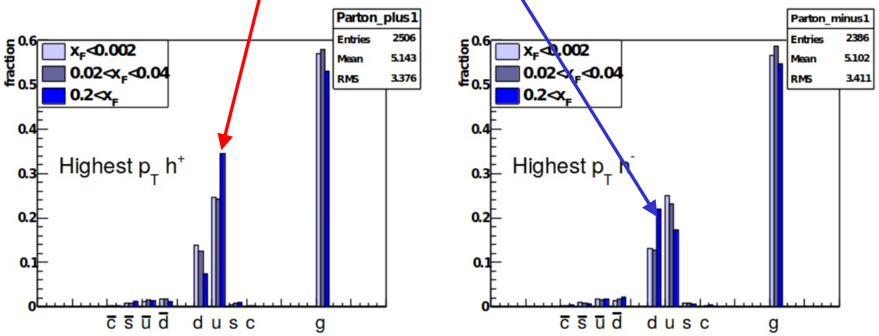
forward upgrade



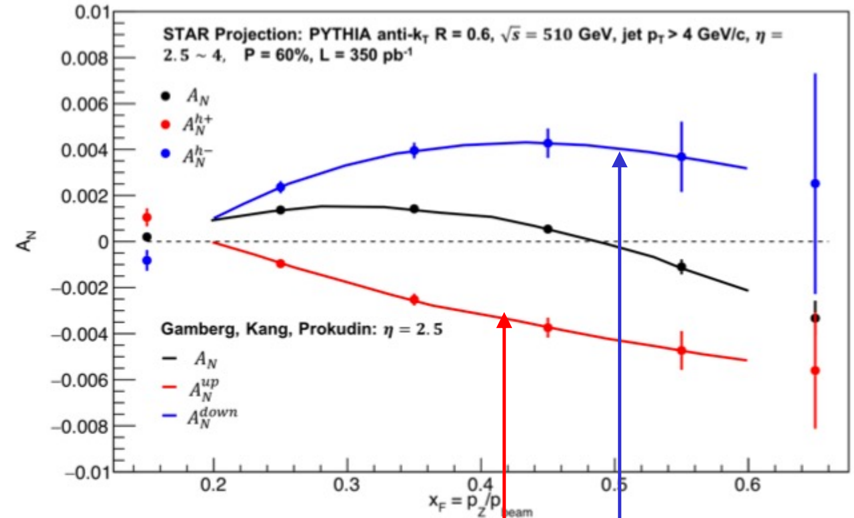


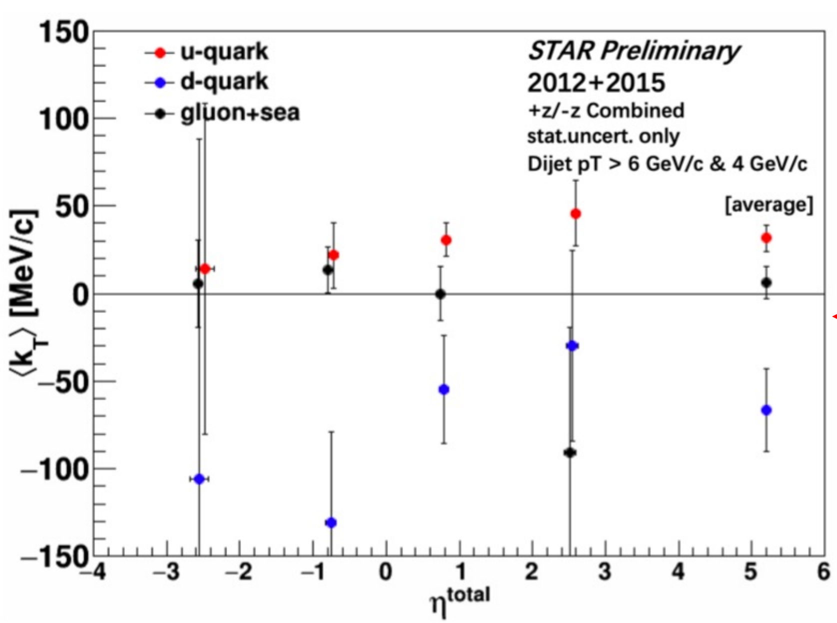
Sivers and ETQS function

With positively/negatively charged leading hadron



forward upgrade



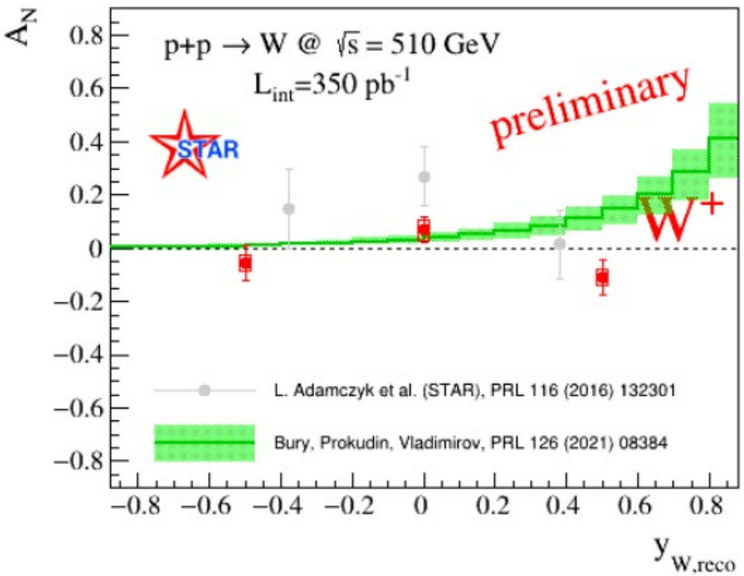


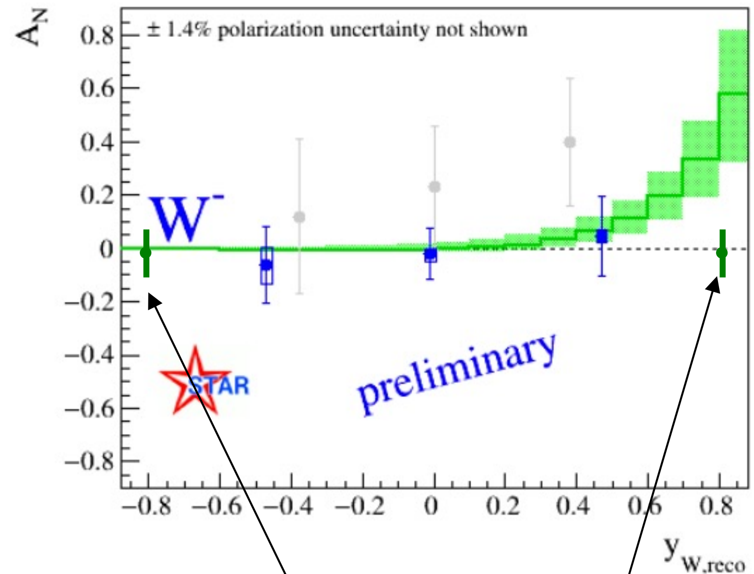
Full jet reconstruction, along with identification of a high-z hadron of known charge at forward rapidity, sensitive to u and d Sivers asymmetry

Charge tagging to separate u and d quark signals: $\langle k_T^u \rangle \sim$ 32 MeV/c, $\langle k_T^d \rangle \sim$ -67 MeV/c, $\langle k_T^{g+sea} \rangle \sim$ 0 MeV/c

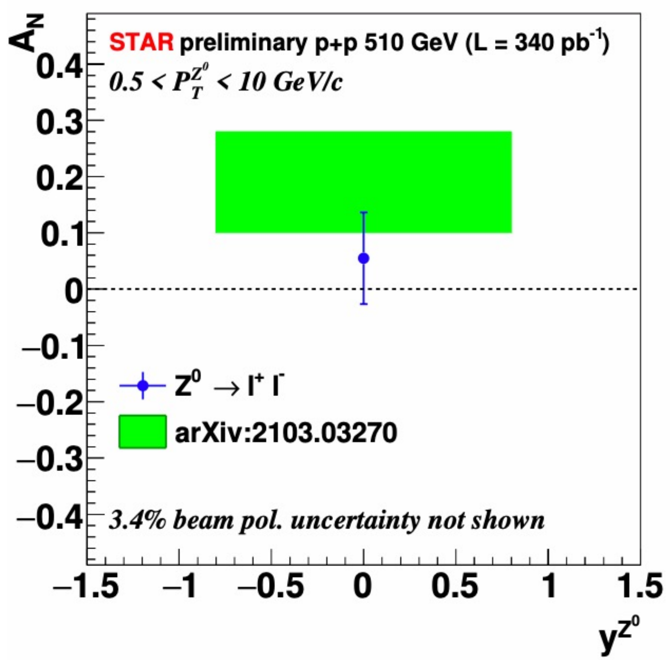
First observation of non-zero Sivers asymmetry in dijet production

Sivers effect





with iTPC



Run-22 will reduce red and blue uncertainties by 1.5

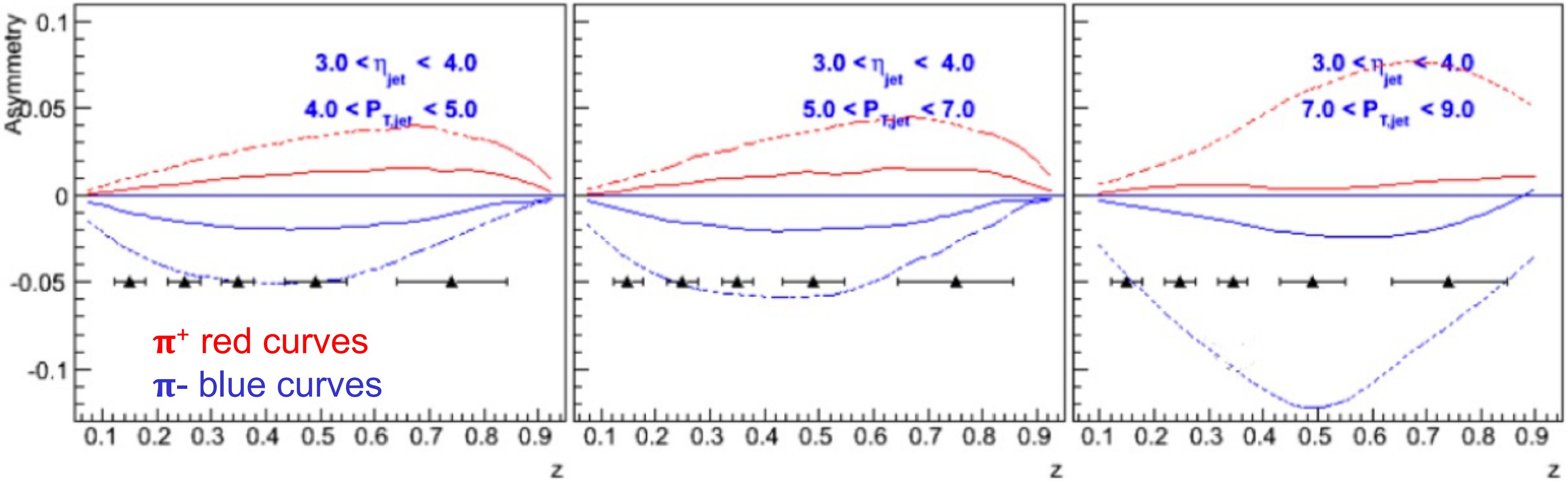
W/Z A_N provides important input for

- Confirmation of Sivers effect sign change
- Magnitude of TMD evolution

Collins effect at large x

forward upgrade

h^- in jets at forward rapidity



Extending Collins asymmetry measurements to the forward direction allows access to transversity at x>0.3.

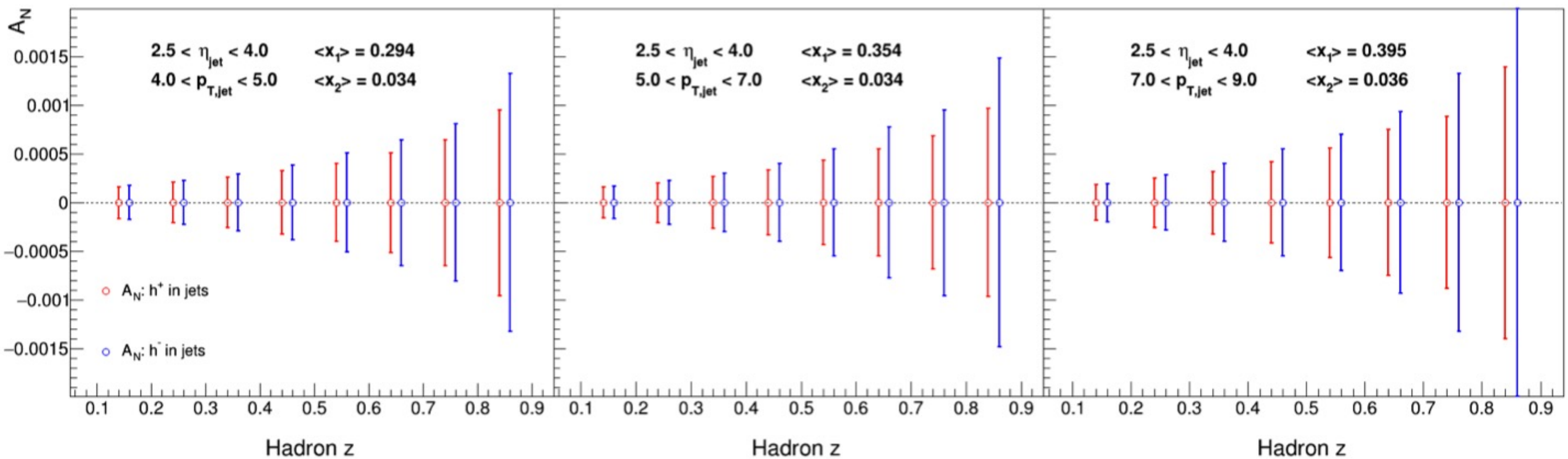
- Transversity at 0.3<x<0.5, never explored by SIDIS

Perform high precision "Collins-like" asymmetry measurement to access the distribution of linear polarized gluon down to x~0.005.

Collins effect at large x

forward upgrade

h⁻ in jets at forward rapidity



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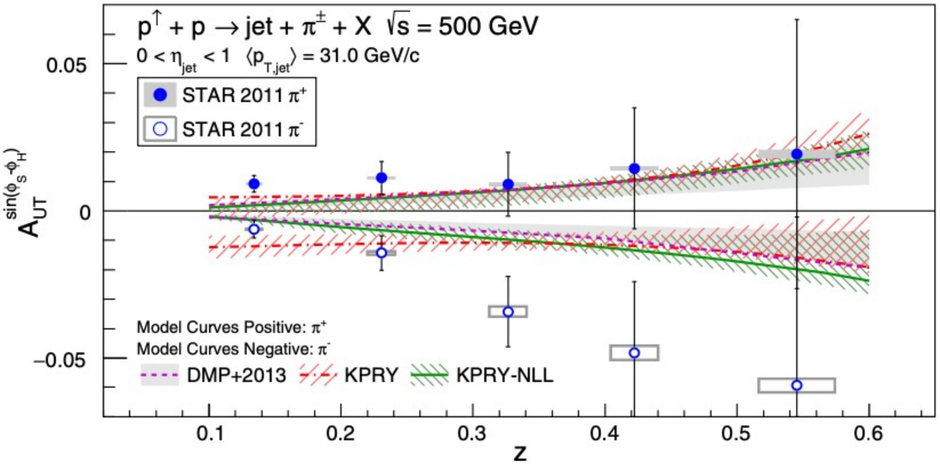
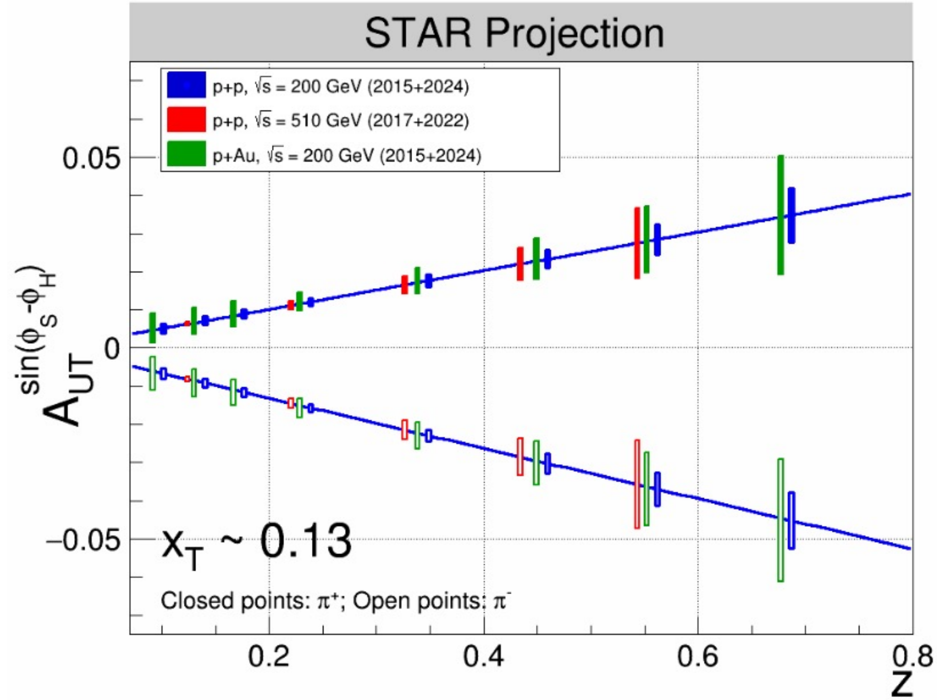
Collins asymmetry: $\pi^{\pm}$ in jets at mid-rapidity

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

Plans for Run-24

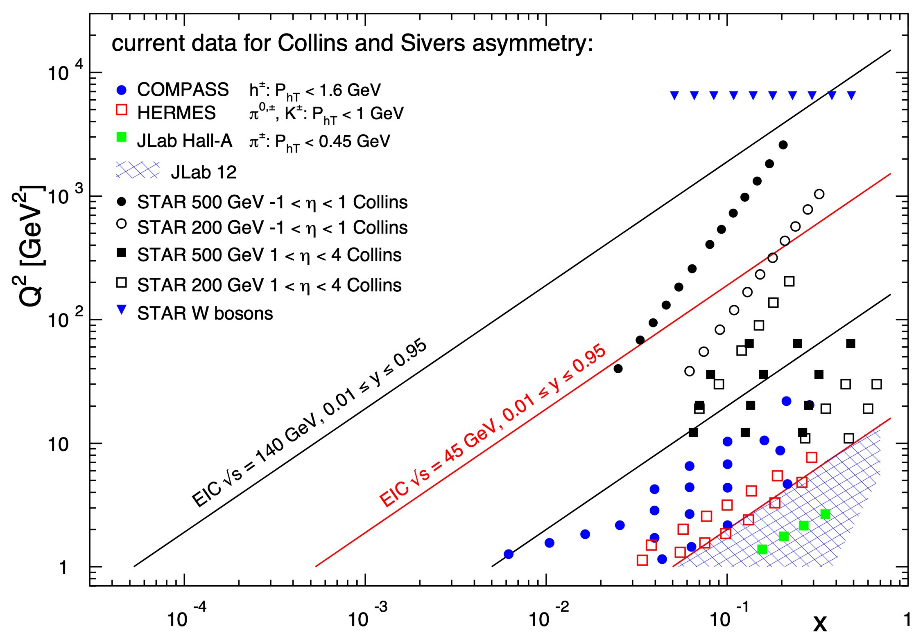
$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	10B / 31 nb^{-1}	2023
200	pp	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024
200	Au+Au	10B / 31 nb^{-1}	2025

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

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

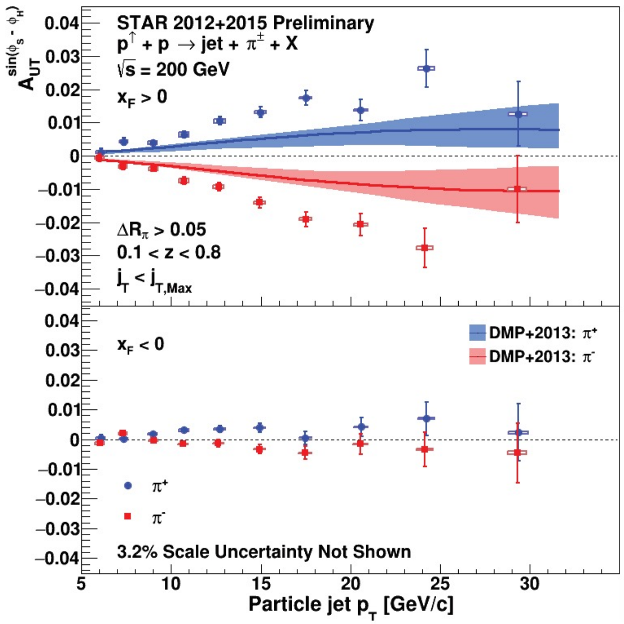
Central role played by 200 GeV pp:

- 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**

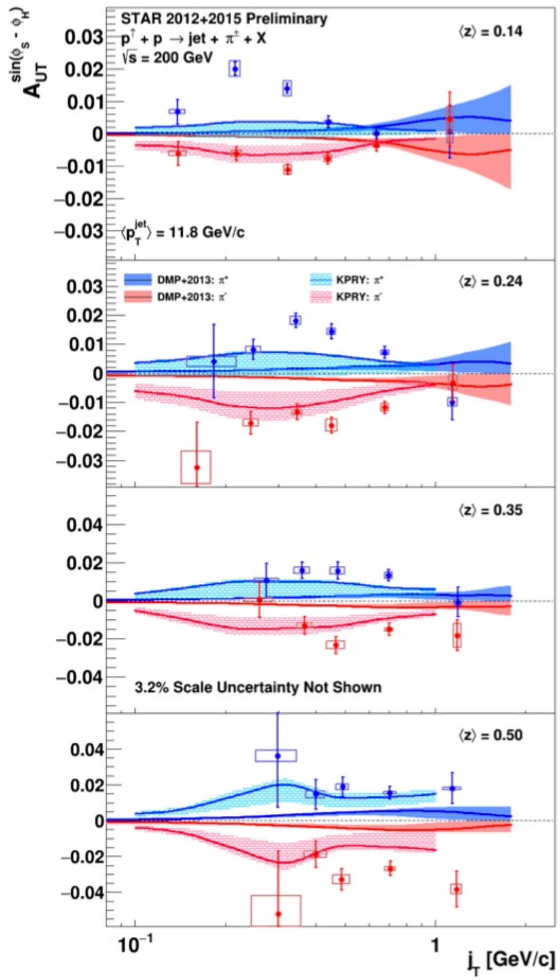
- 200 GeV pp essential baseline for 200 GeV p+Au
  - Must investigate **gluon saturation in both pA and eA to verify universality**
  - Precise probe of **the quark-gluon structure of heavy nuclei**
  - Explore the **propagation and hadronization of colored partons**

Must measure non-perturbative part of TMD experimentally!

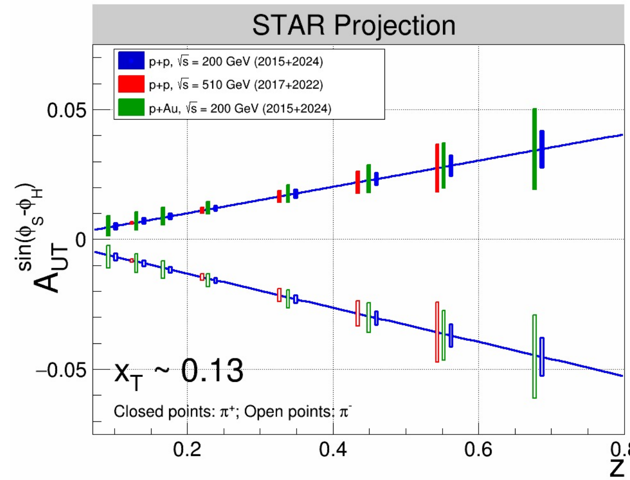
Example: mid-rapidity Collins effect at 200 vs 510 GeV



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



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



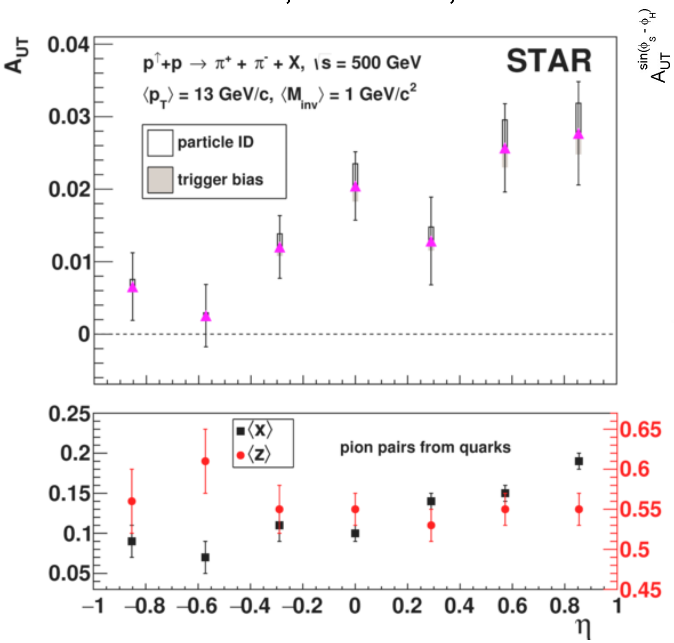
Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential x-Q^2 overlap with EIC

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

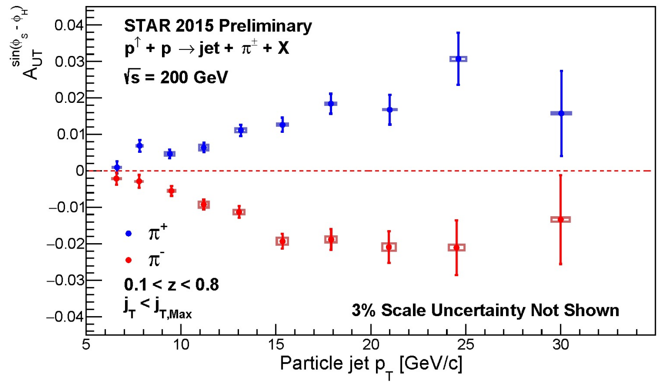
- **Run-24 will reduce these uncertainties at 200 GeV by a factor of 2.5, enabling the most sensitive universality test with EIC data**

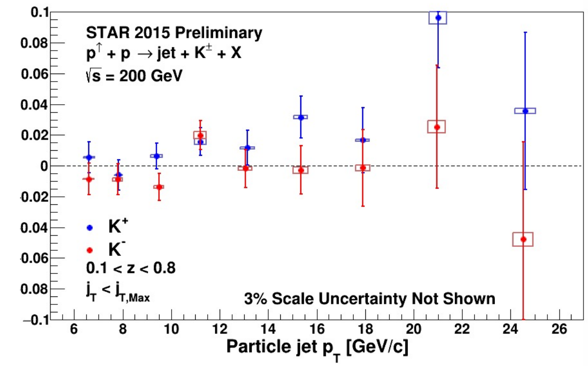
iTPC in mid-rapidity IFF and Collins: η dependence and PID

STAR IFF, PLB 780, 332



STAR 2015 Collins, preliminary





Forward η increases:

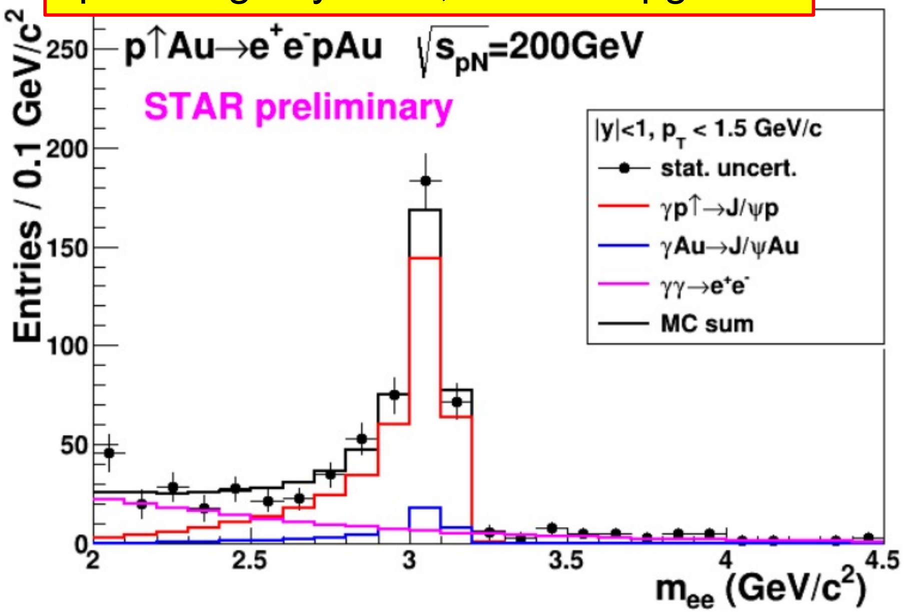
- Quark fraction (no gluon transversity)
- <x>
- Polarization transfer in hard scattering

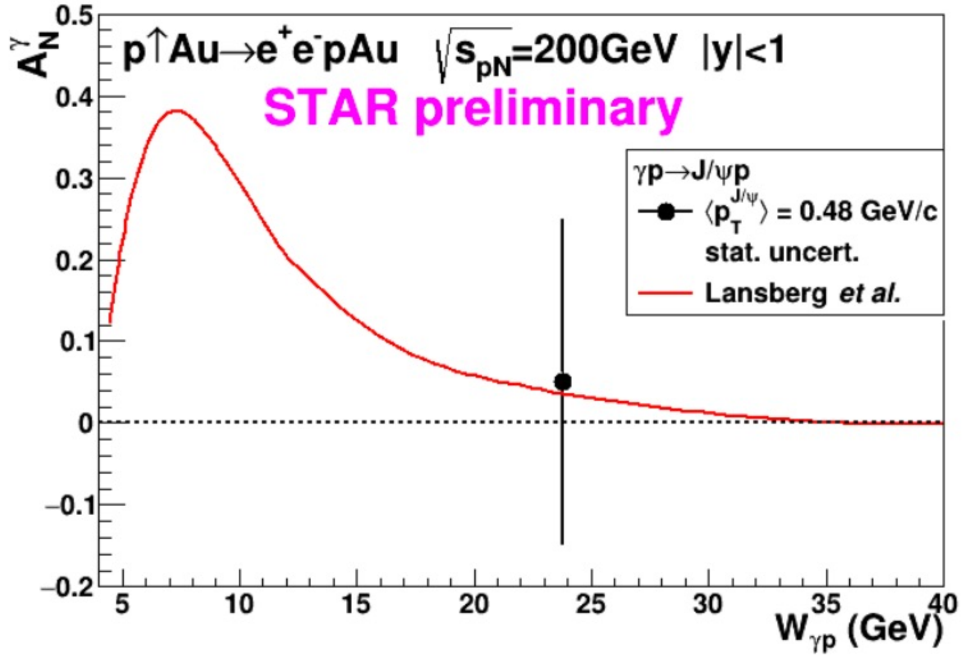
iTPC will add coverage of 1 < |η| < 1.5 for both IFF and Collins asymmetries

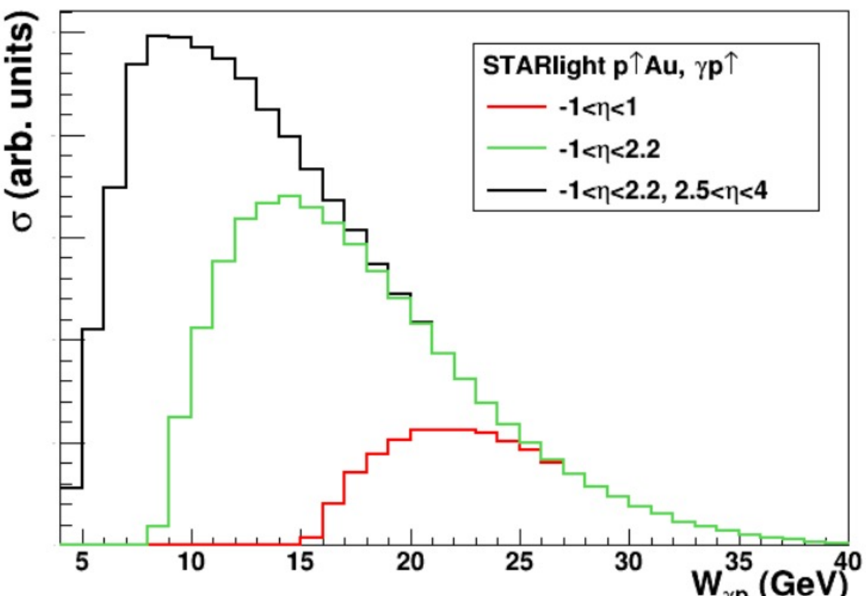
- Different Collins and IFF asymmetries for different particle types
  - K^+ about 1.5-sigma larger than π^+ (note diff vert scales)
  - K^- (and p/pbar in backup) consistent with zero in 2015
  - Similar π/K behavior seen in SIDIS
- Particle identification essential to maximize impact
- iTPC increases 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 $1/\sqrt{9}$ (!)

Generalized parton distribution

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







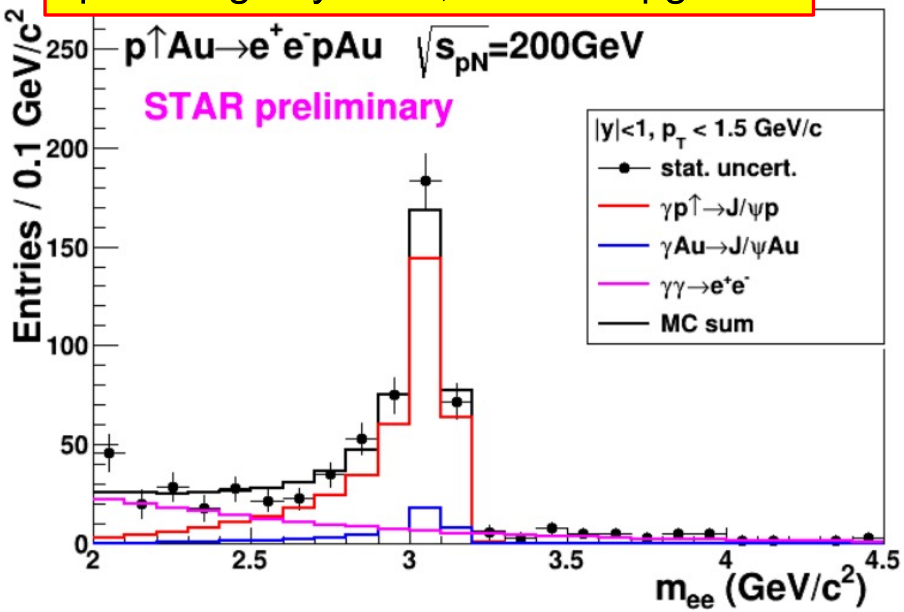
Exclusive J/ψ A_N in UPC, Q^2~10 GeV^2, $10^{-4}<x<10^{-1}$

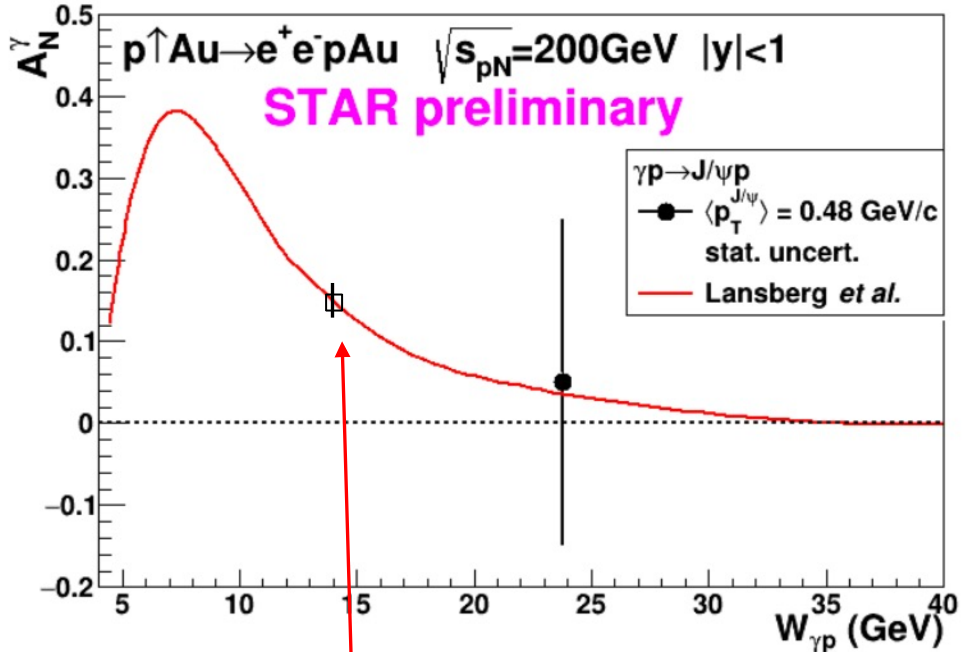
Access GPD Eg for gluons, sensitive to spin-orbit correlation

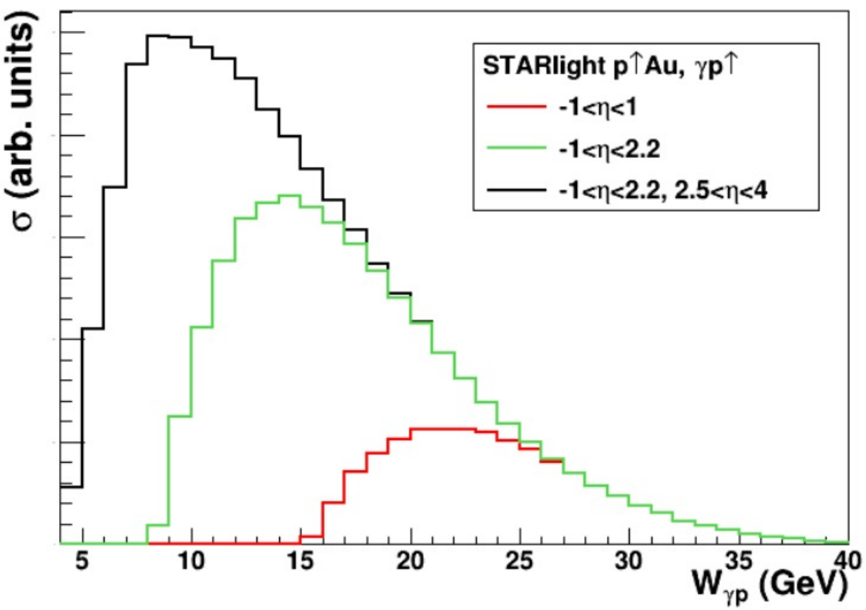
Run-24: a factor of 9-10 more data, combined with iTPC and forward upgrades, stat. error for A_N^{γ}: 0.02 for $<W_{\gamma p}>$=14 GeV, where the signal is expected to be large.

Generalized parton distribution

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







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

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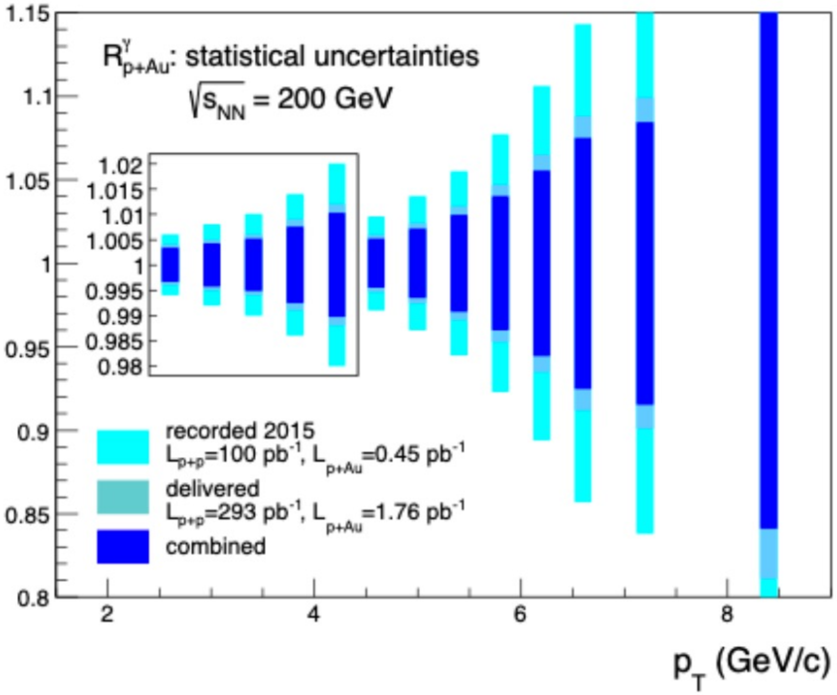
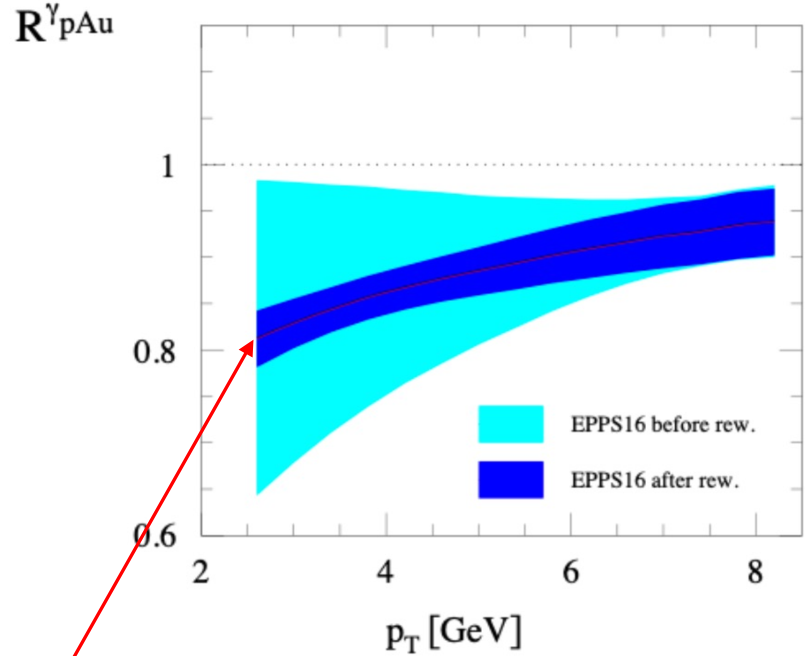
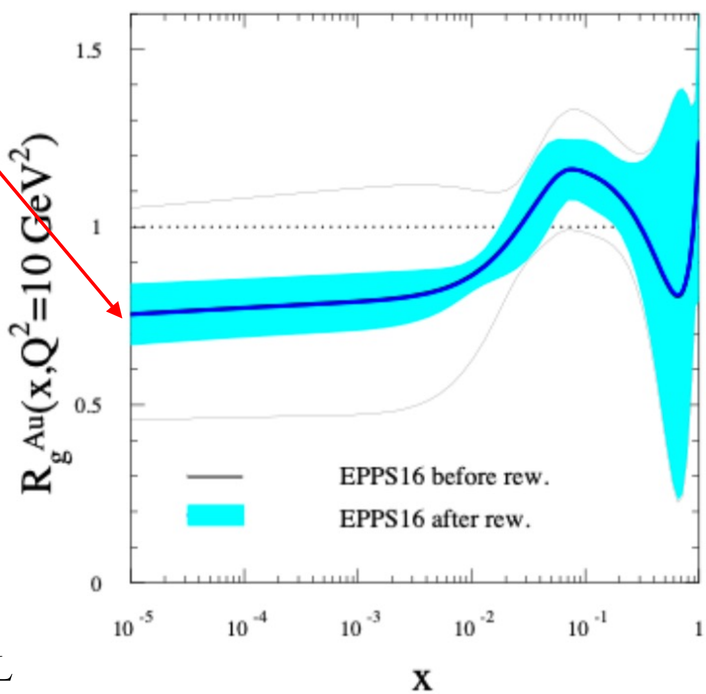
low material, forward upgrade

Nuclear PDF





Run-24 data impact

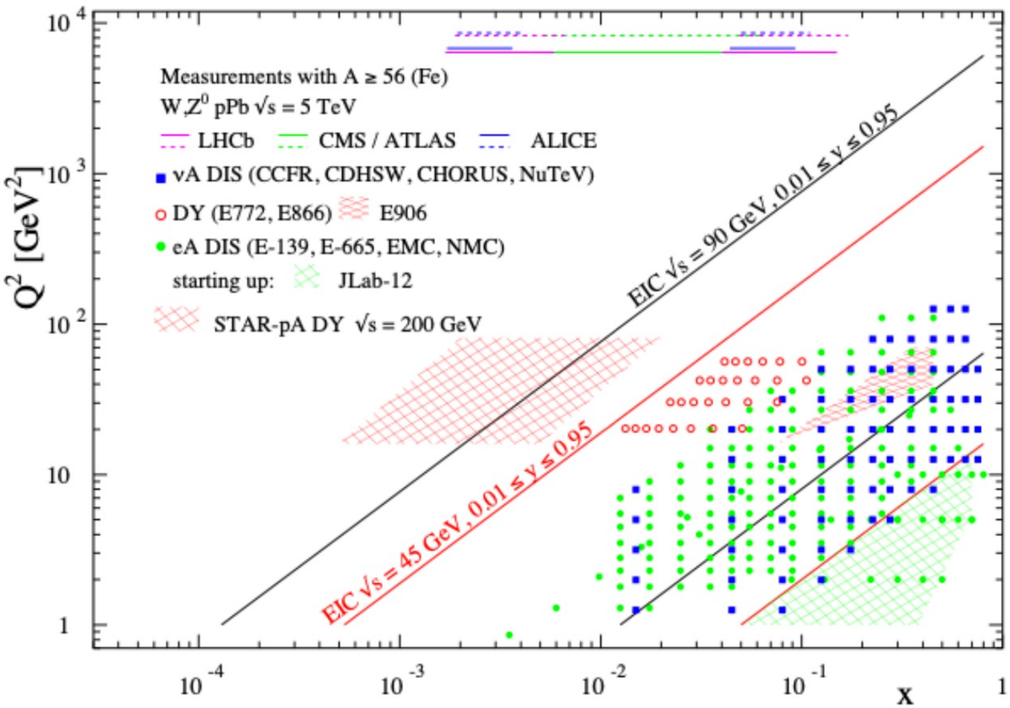


Direct photon measurement: constrain nuclear gluon distribution in a broad x range

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

Nuclear PDF

low material, forward upgrade



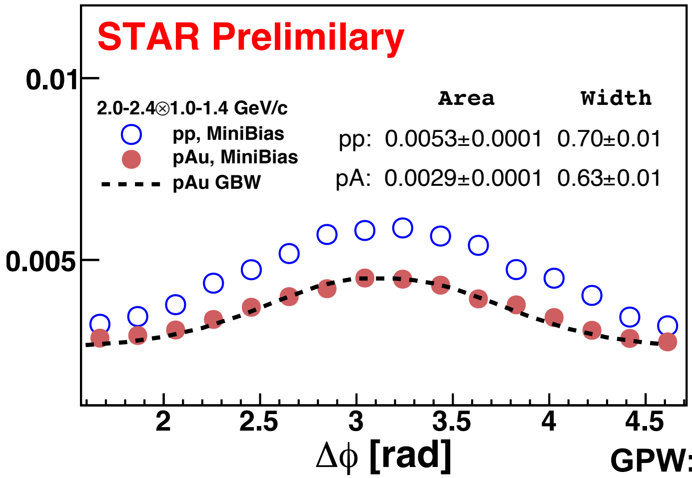
Small DY cross section (10^{-6}-10^{-5} of hadron): need suppress hadron to the order of 0.1% while maintaining a decent electron efficiency

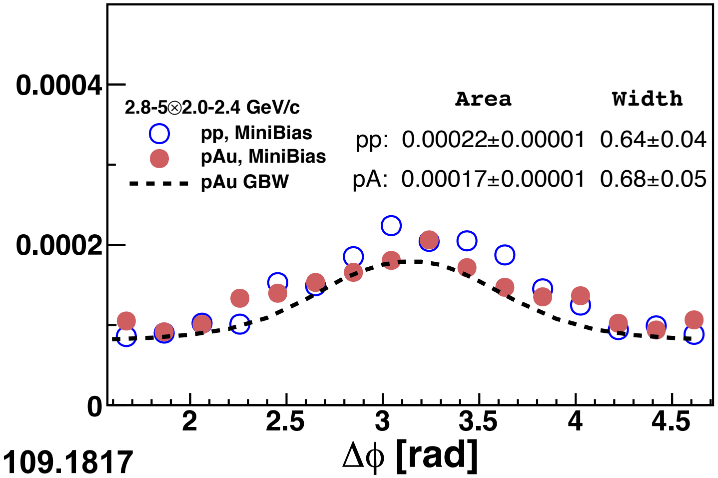
With forward upgrades:
hadron rejection power: 200-2000 for hadrons of 15-50 GeV
electron efficiency: 80%

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

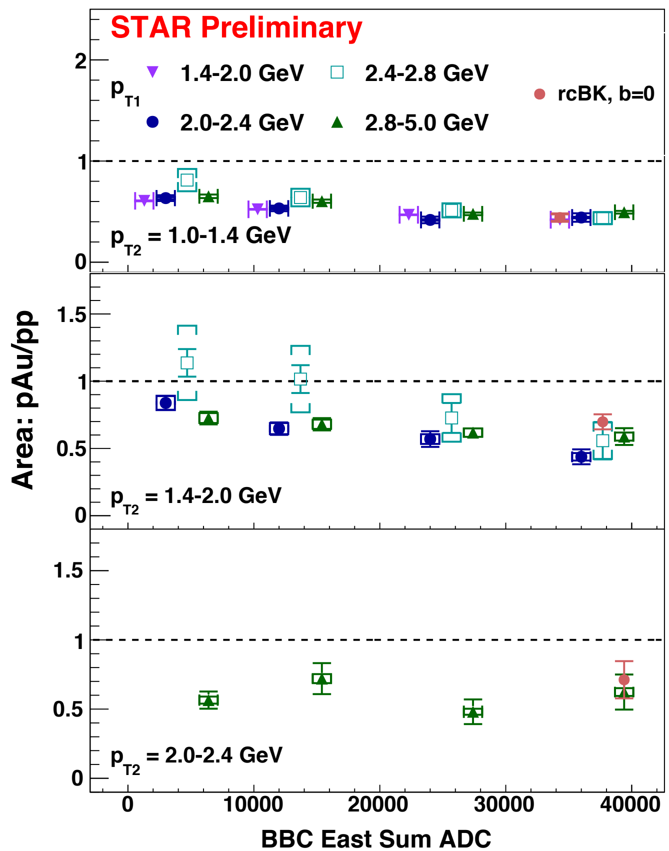
Essential in testing fundamental universality properties of nPDFs combined with data from EIC

QCD non-linear effects





GPW: arXiv:1109.1817

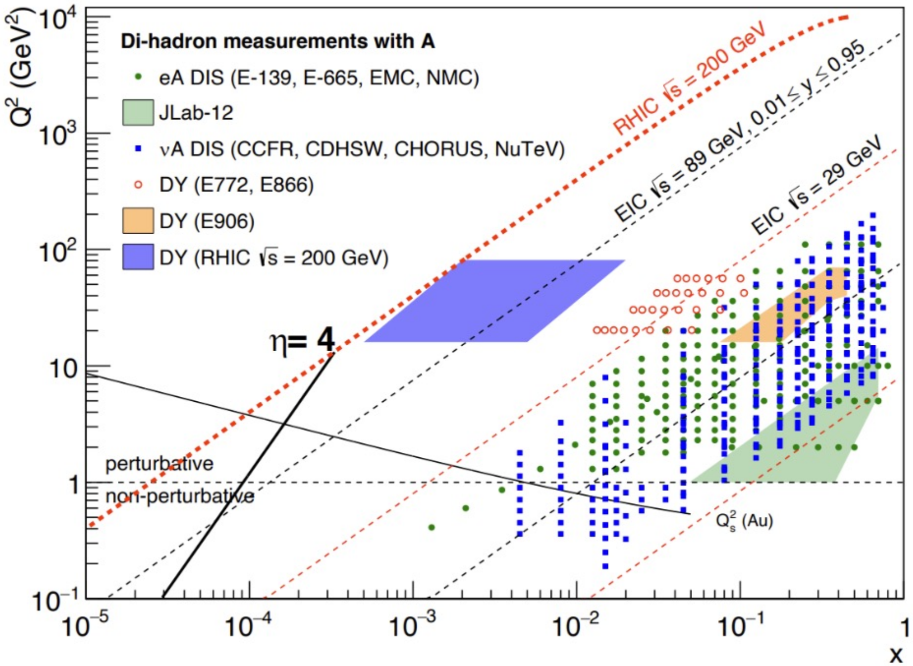


rcBK: arXiv:1805.05711

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

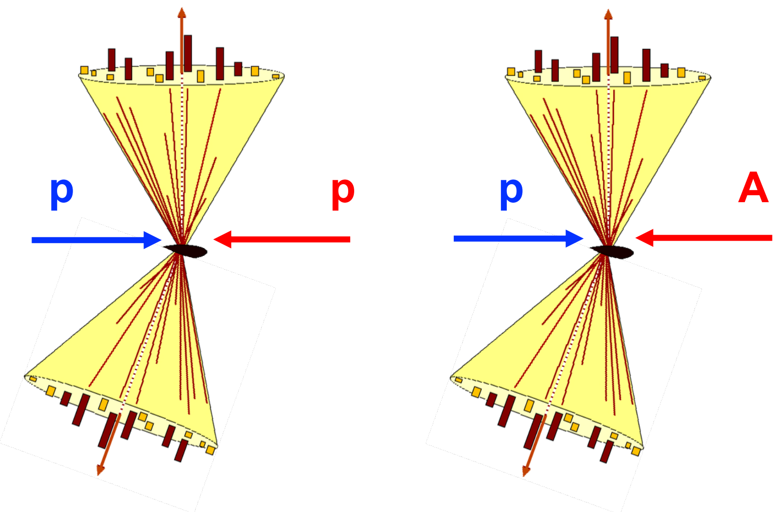
probe x down to 10^{-3}

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

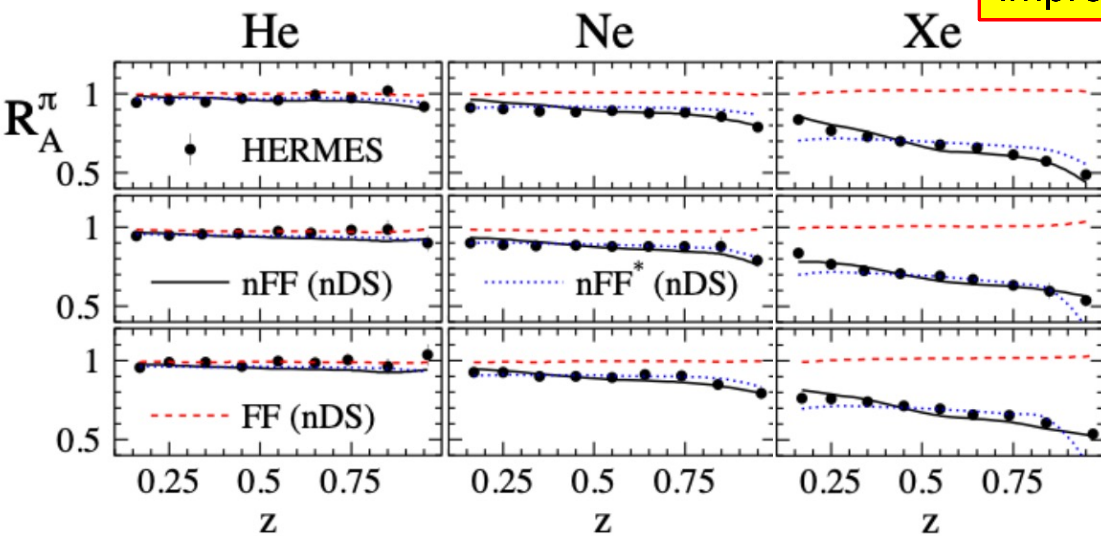
→ proton – Au collisions

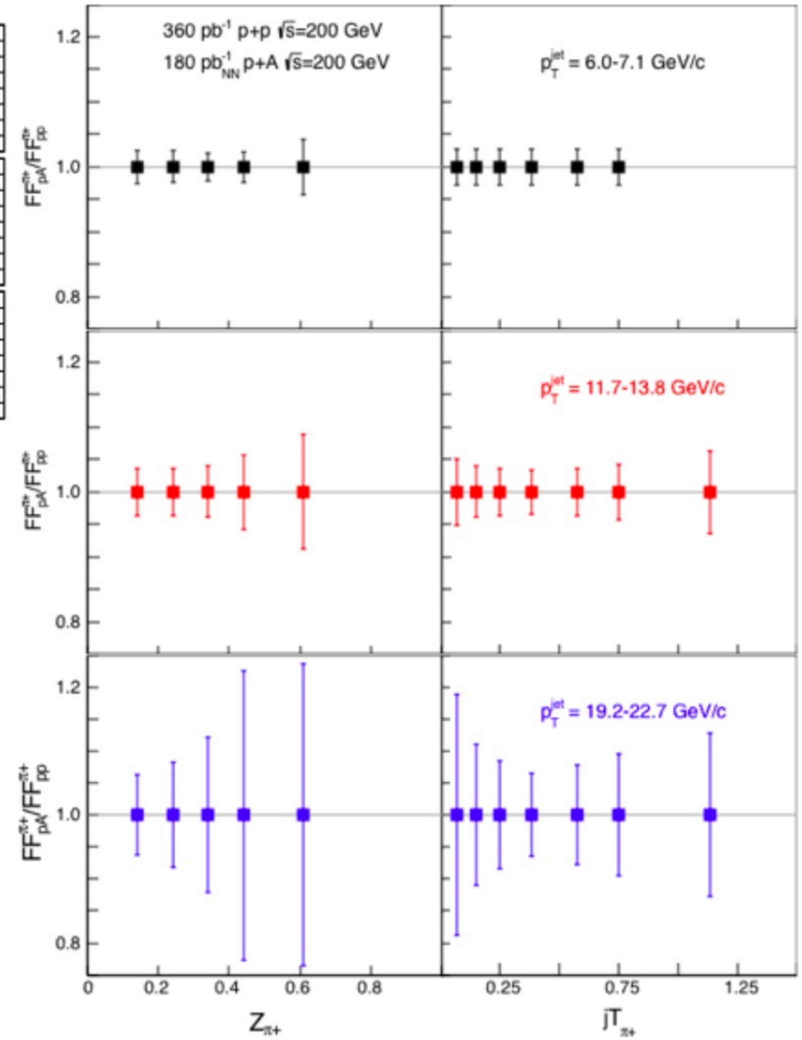
combined with an unambiguous observable

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

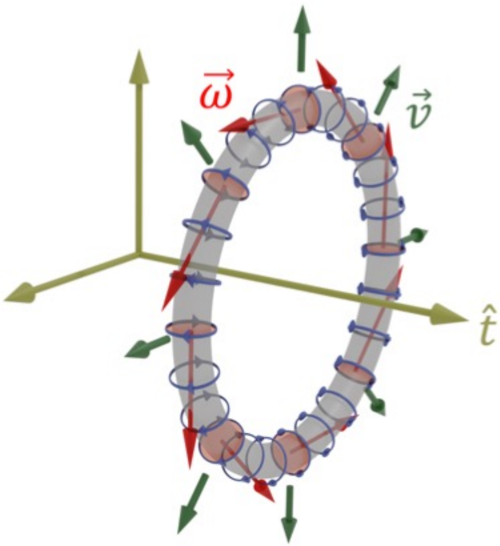
Universality has not been tested

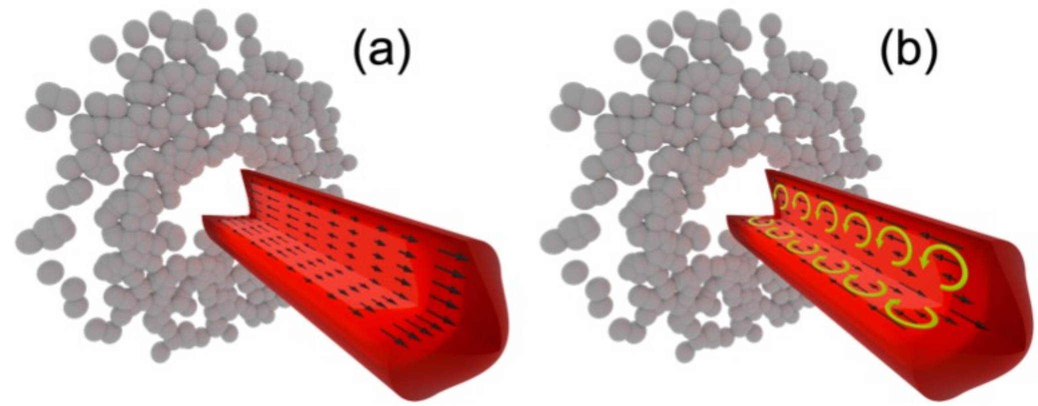
Run-24: study pion, kaon, and proton FF modification, constrain gluon FF.

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

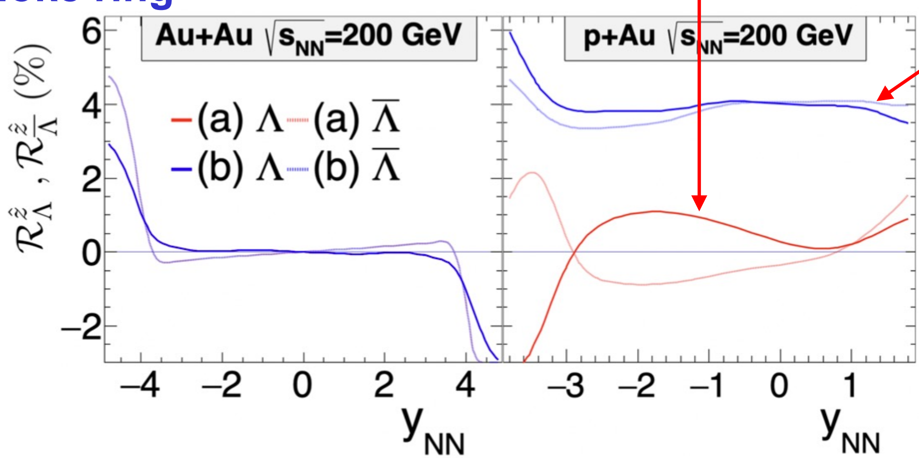




Toroidal vortex structure: smoke ring

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 2022 and 2024

200 and 510 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
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  - 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

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	$\lvert vz\rvert<70$cm	$\lvert vz\rvert<30$cm
2014 2016	2	27	19	16
2023 2025	20	63	56	38

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 2.3 more luminosity for high-p_T trigger

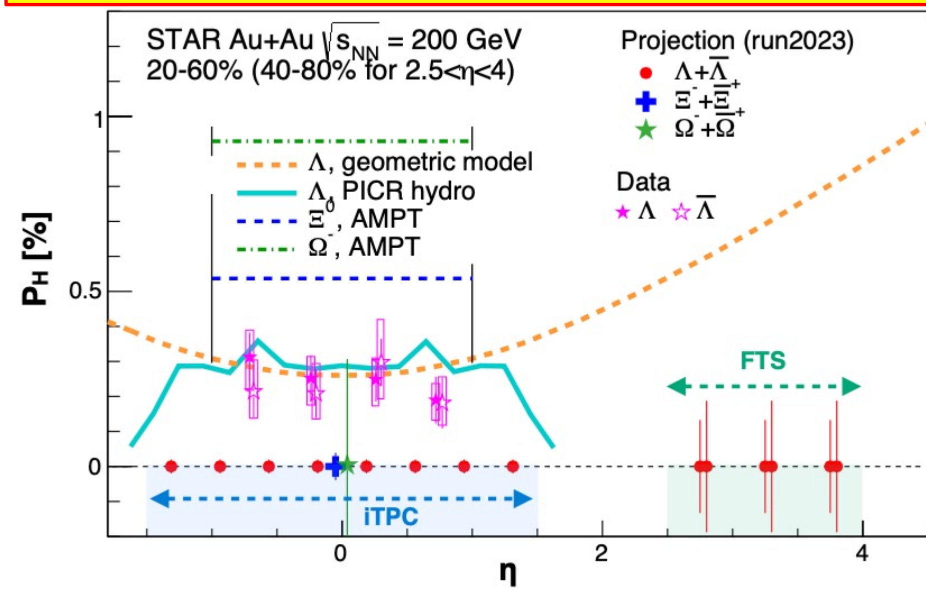
Physics Opportunities for 2023+2025

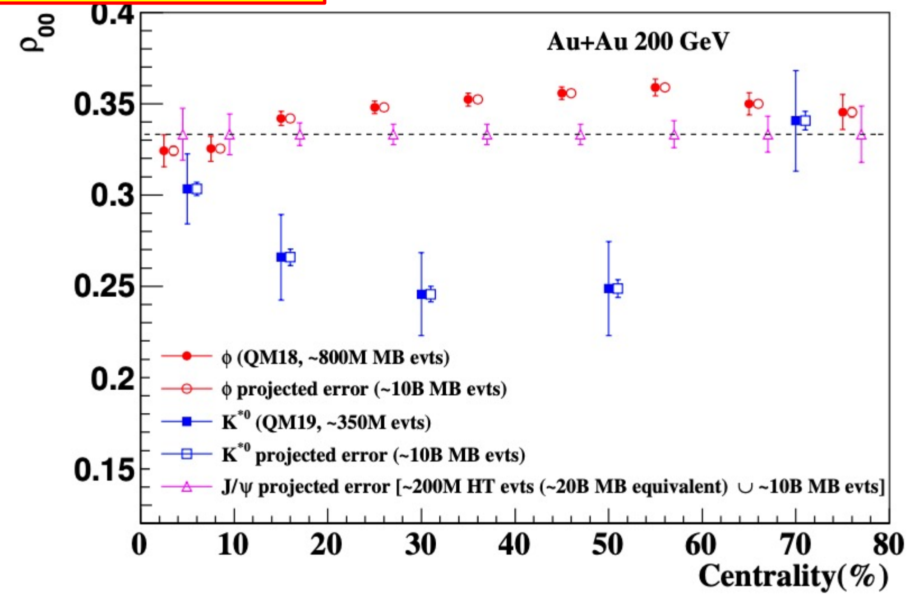
To address important questions about the inner workings of the QGP

- What is the precise temperature dependence of shear and bulk viscosity? v_n as a function of η
- What is the nature of the 3-dimensional initial state at RHIC energies? r_n over a wide rapidity
- How is global vorticity transferred to the spin angular momentum of particles on such short time scales? How can the global polarization of hyperons be reconciled with the spin alignment of vector mesons? Λ, Ξ, Ω P_H and ρ_{00} of K^*, ϕ, J/ψ
- What is the precise nature of the transition near μ_B=0? Net-proton C_6/C_2
- What is the electrical conductivity, and what are the chiral properties of the medium? Dielectron
- What can be learned about confinement and thermalization in a QGP from charmonium measurement? J/ψ v_2 and v_1, $\psi(2S)$
- 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

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?

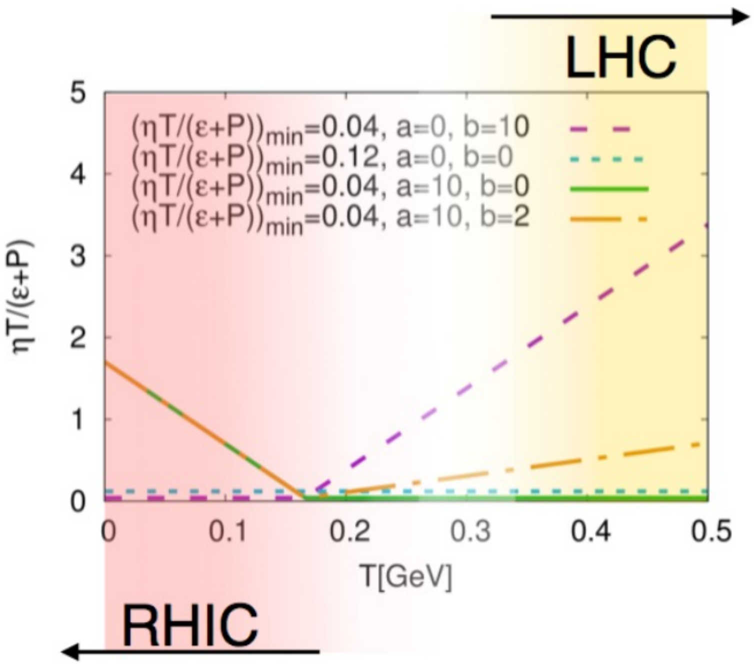
Rapidity dependence of Λ, Ξ, Ω P_H at STAR, probe the nature of global vorticity transfer:
Initial geometry and local thermal vorticity + hydro predict opposite trends.

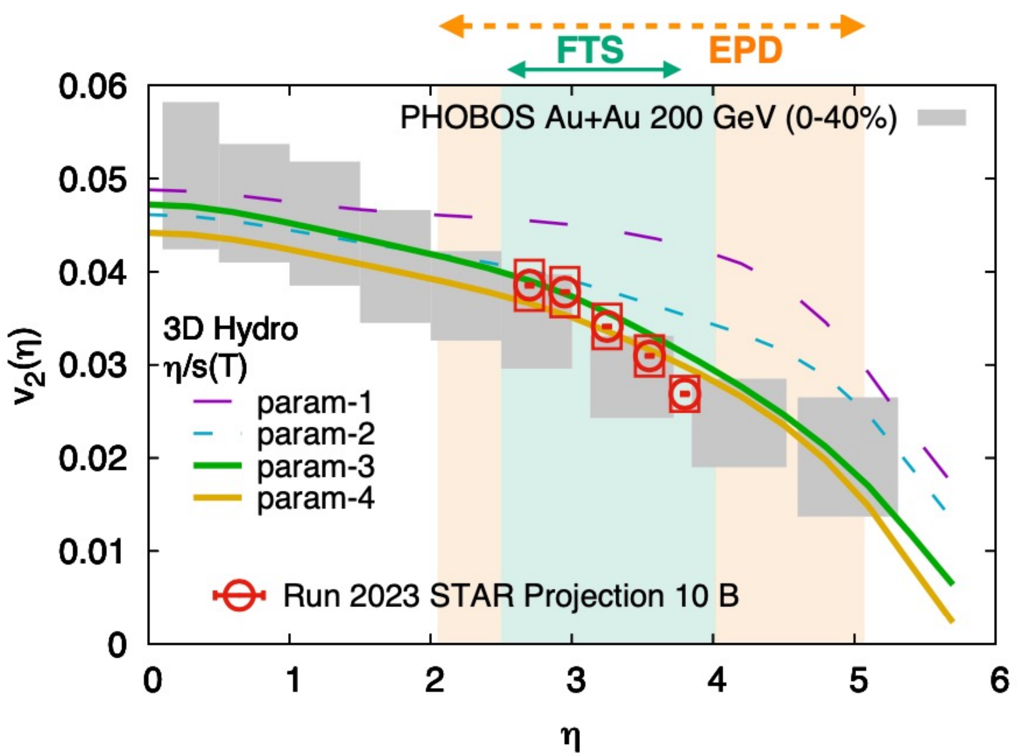
Can we reconcile P_H with vector meson spin alignment ρ_{00}? Strong force field effect?

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

Constrain temperature dependence of η/s

forward tracking

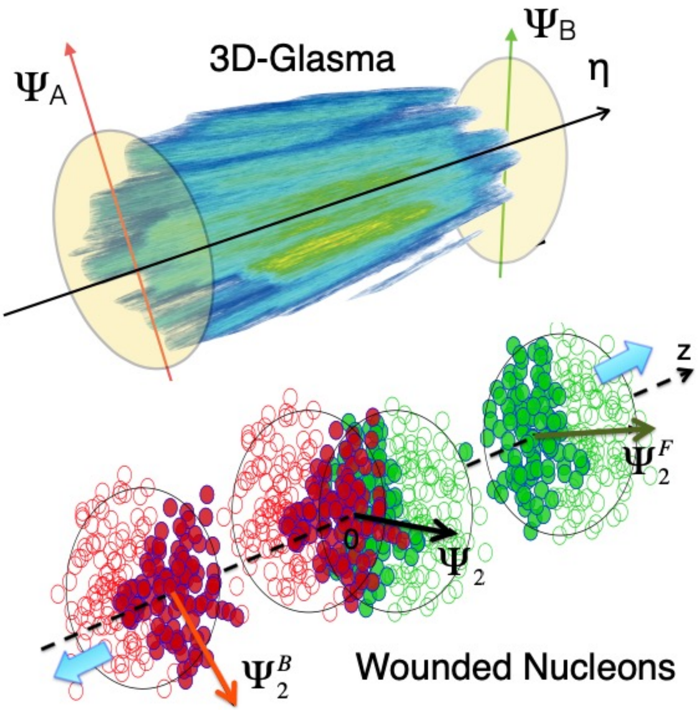




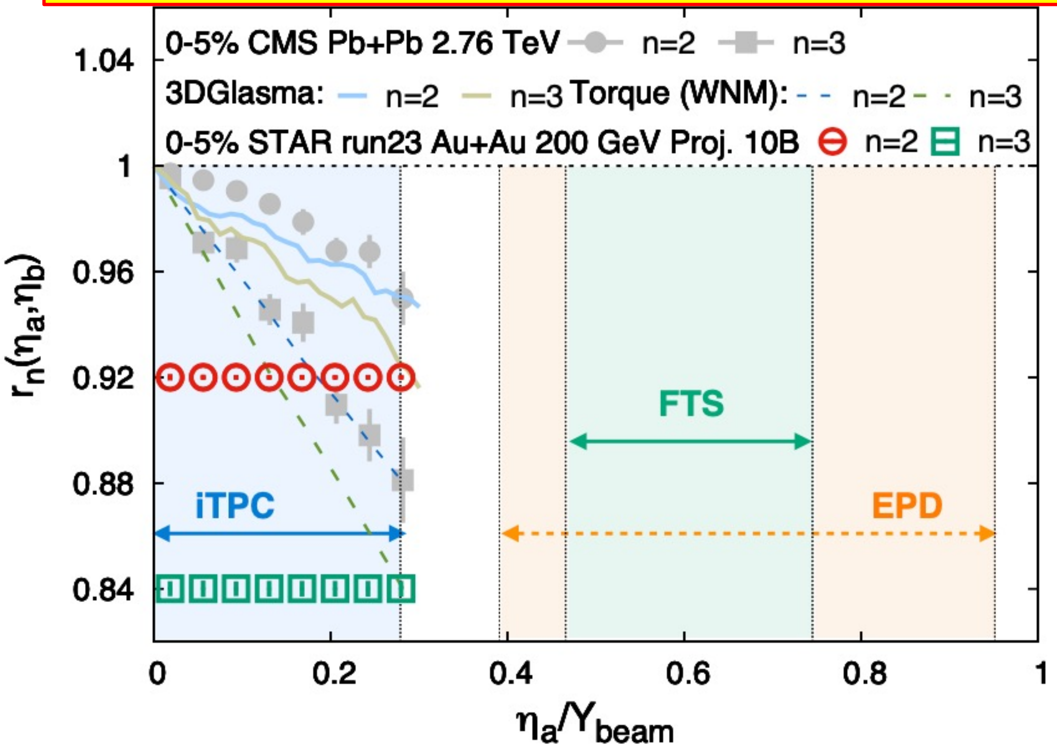
Flow measurements at forward rapidity sensitive to η/s as a function of T.

Much more precise than previous PHOBOS measurements.

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

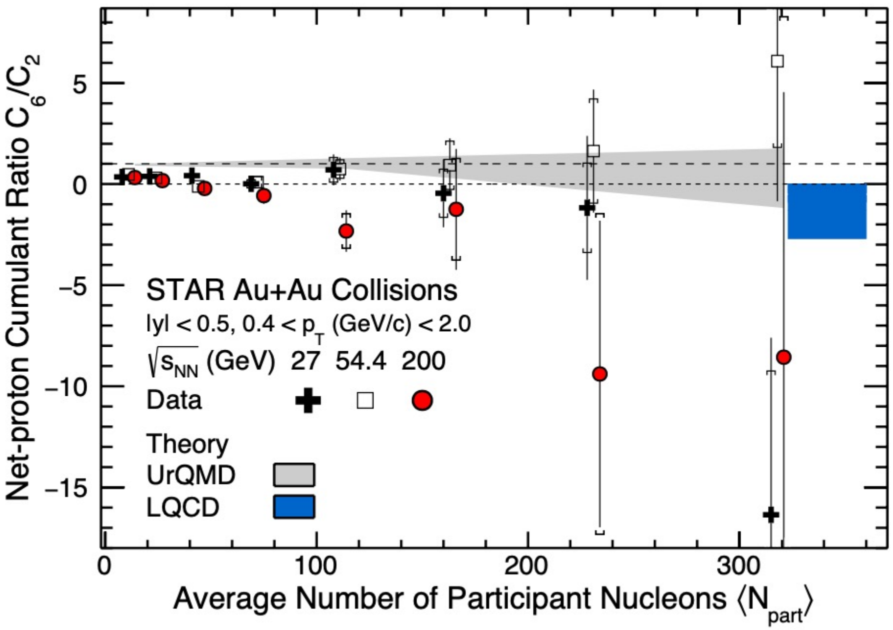
r_n sensitive to different initial state inputs:

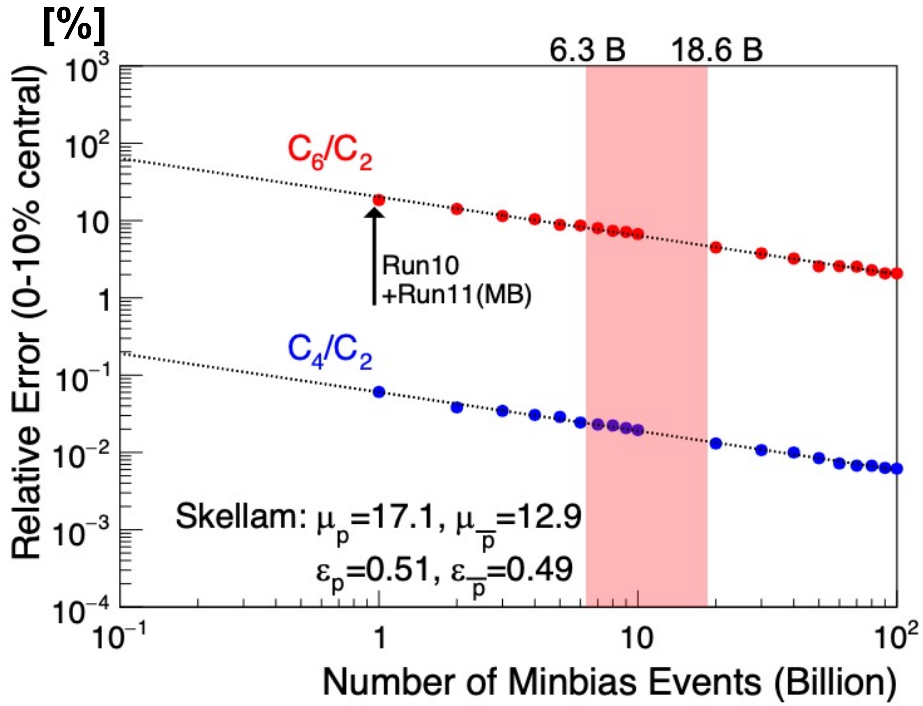
- **3D glasma model: weaker decorrelation, describes CMS r_2 but not r_3**
- **Wounded nucleon model: stronger decorrelation than data**

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

Chiral cross-over transition

Improved PID, extended η coverage by iTPC



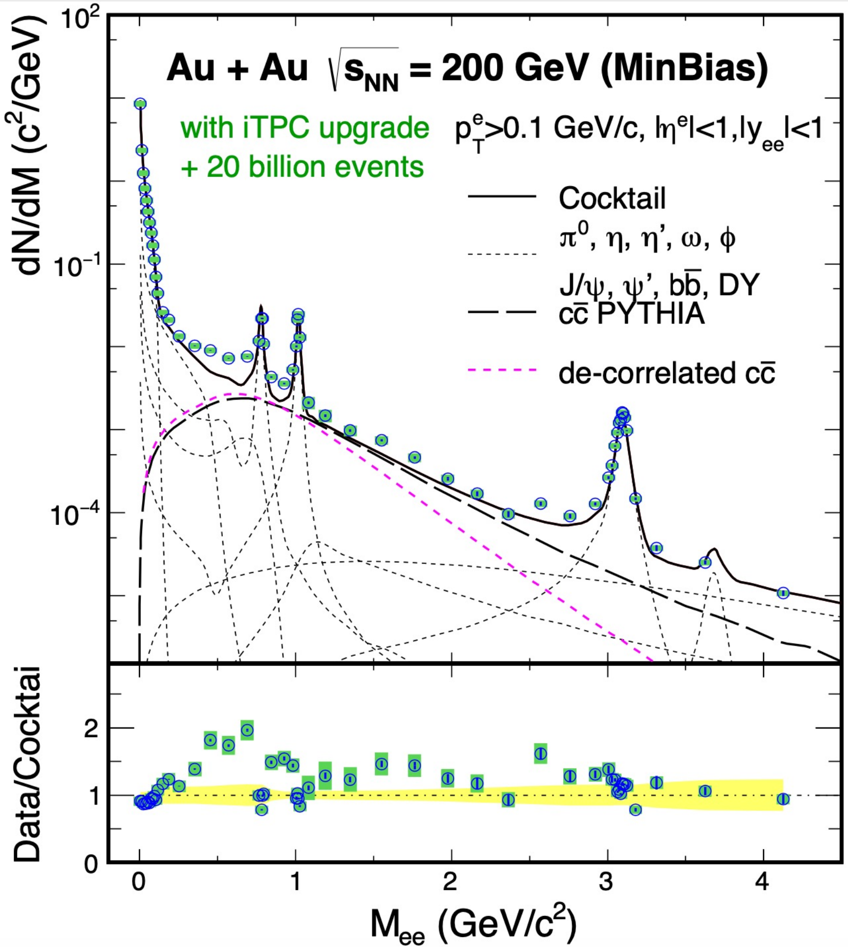


Lattice QCD predicts a sign change of susceptibility ratio χ_6^B/χ_2^B at T_C
The cumulants of net-proton distribution sensitive to chiral cross over transition at μ_B=0

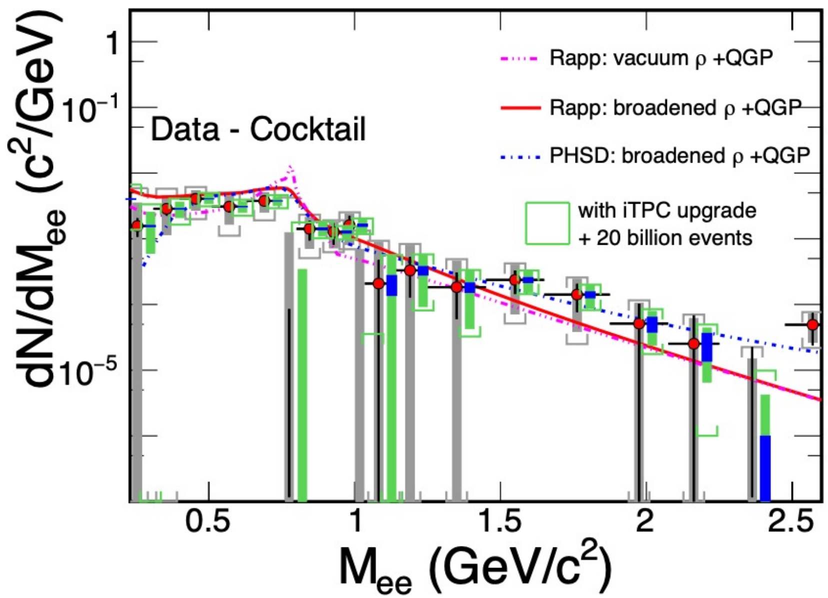
Observed a hint of a sign change from peripheral to central collisions at 200 GeV
$C_6/C_2 < 0$ at central collisions

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

Chiral property



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



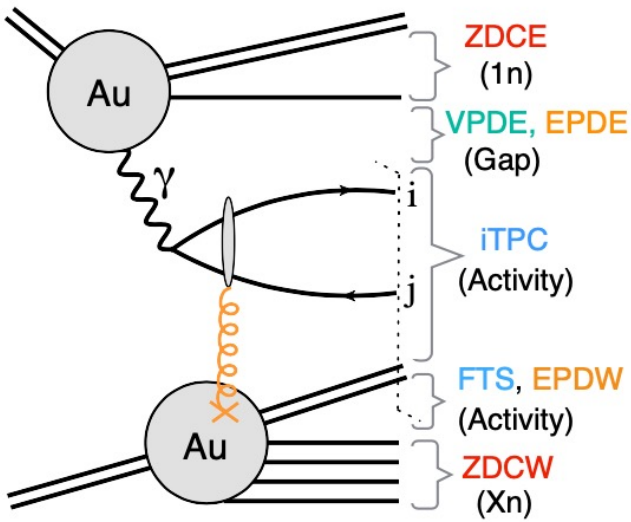
Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B=0

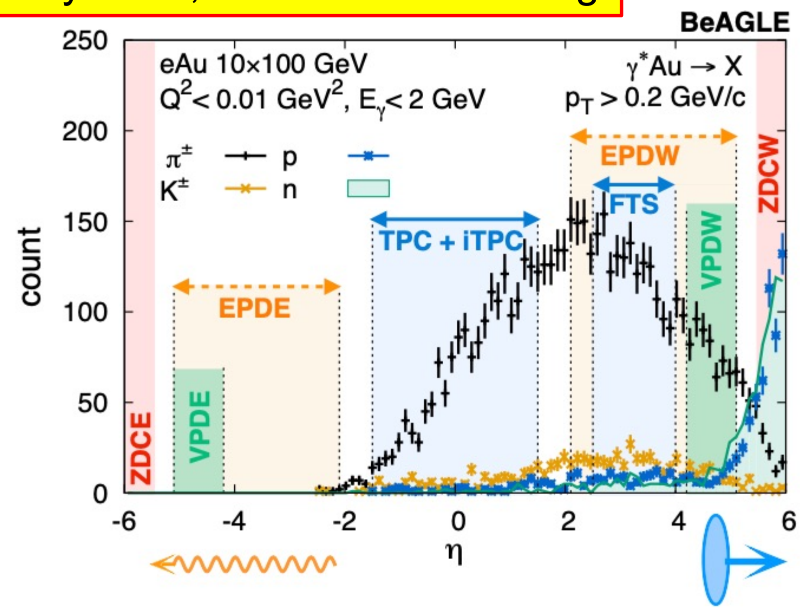
Intermediate mass: direct thermometer to measure temperature

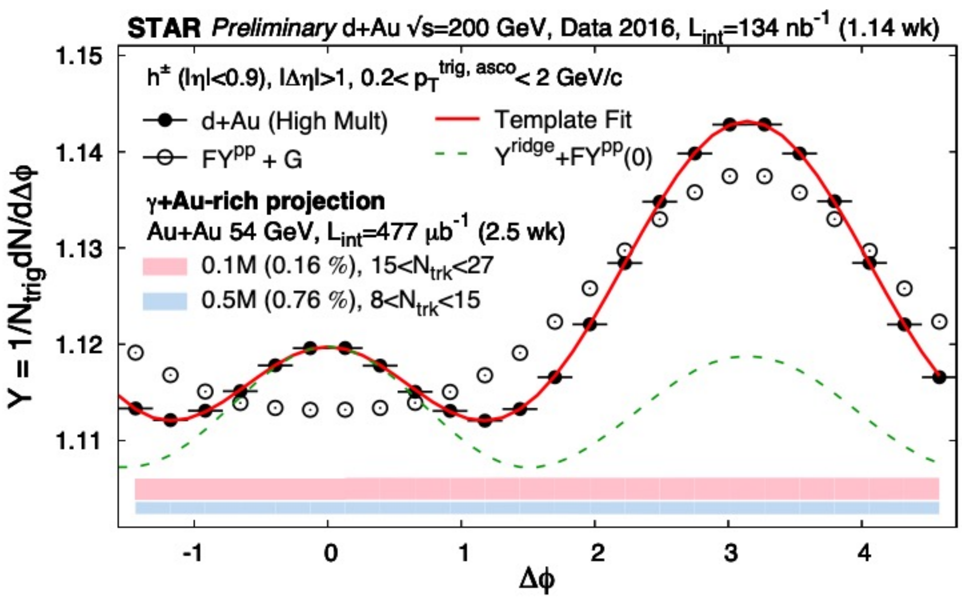
Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

Search for collectivity in photo-nuclear processes

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







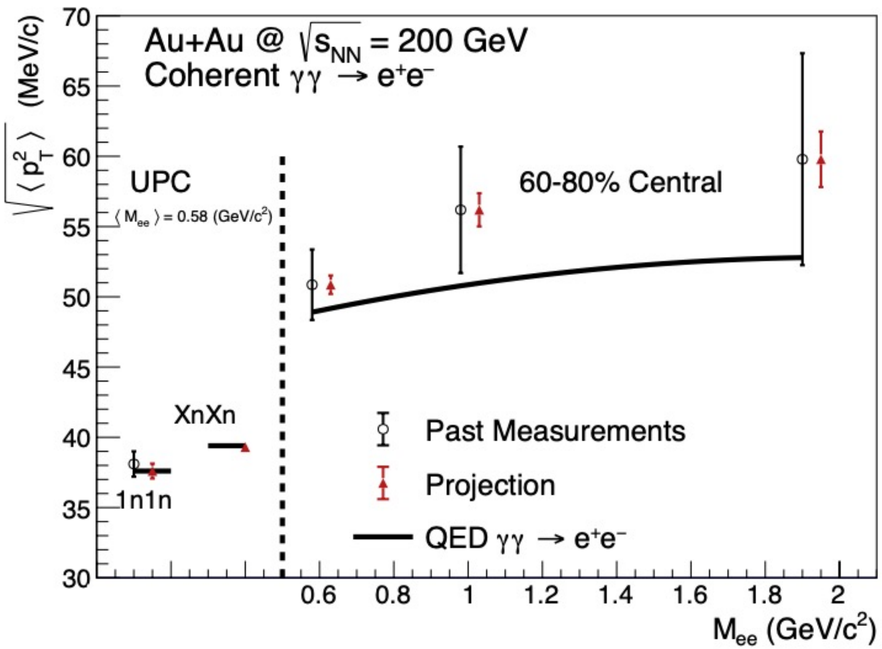
γ+Au process in UPC associated with a large rapidity asymmetry:
- **Search for collectivity**
- **Study bulk observables**

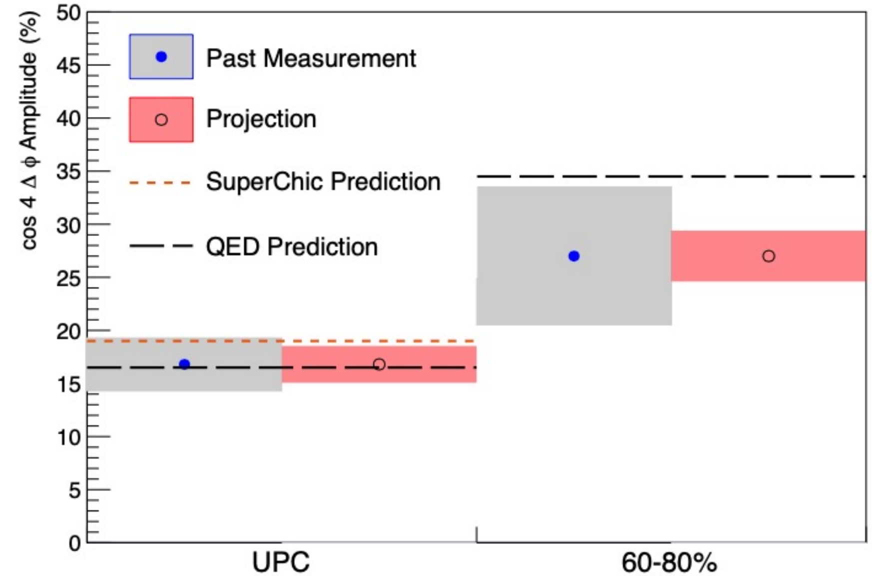
Further understand the origin of collectivity observed in small systems

Run23+25: errors will be reduced by a factor of 17

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.

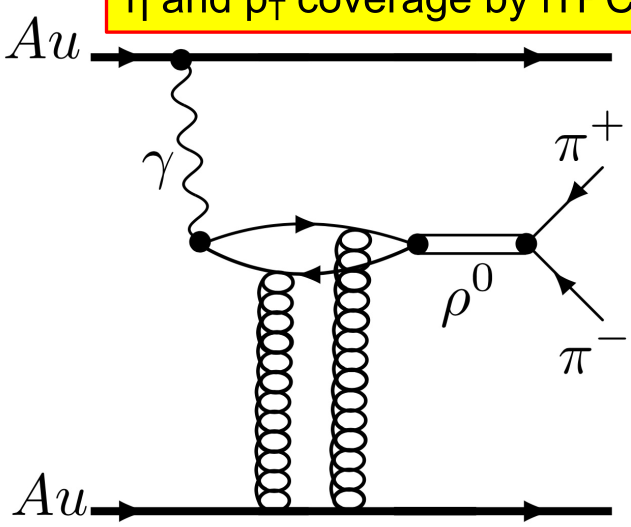
Is there a sensitivity to final magnetic field in QGP?

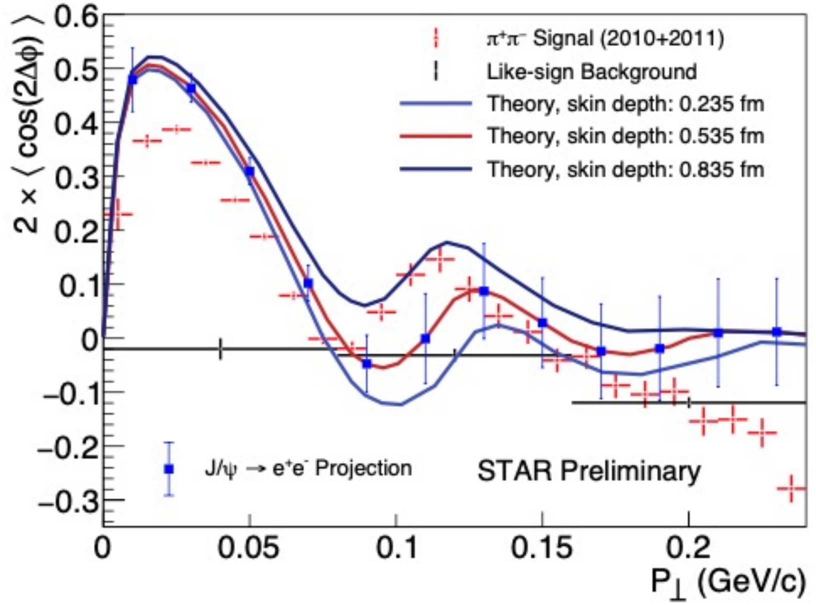
Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.

Fundamentally important and unique input to CME phenomenon.

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

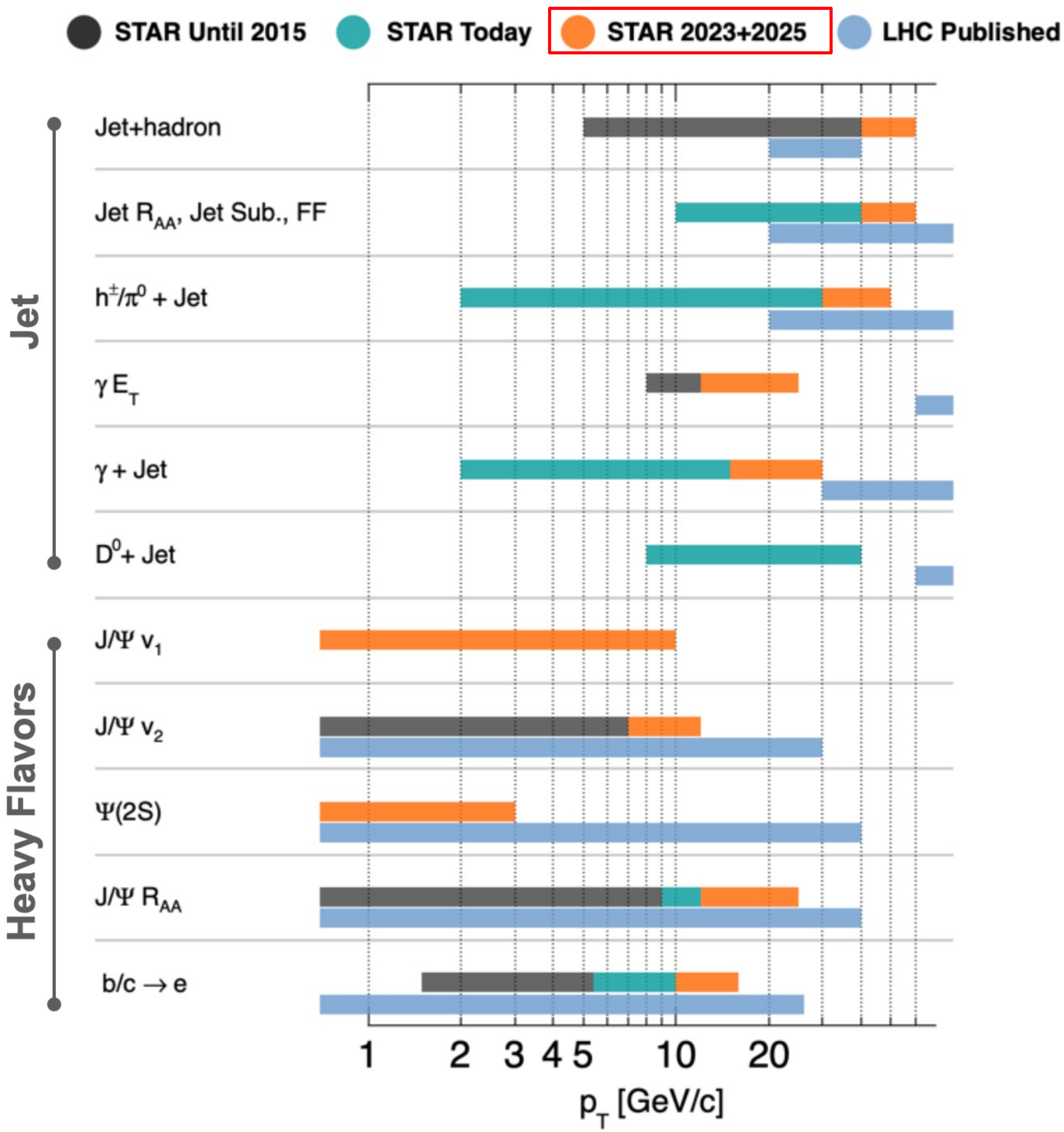
Theory (linear polarized photon + saturated gluons), sensitive to nuclear geometry and gluon distribution, closest to the gluon 3D tomography at EIC

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

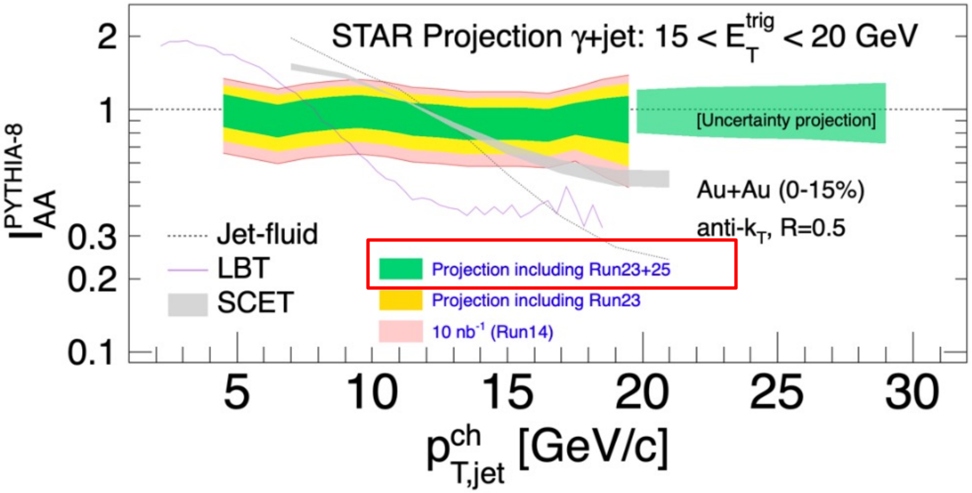
Enable a similar measurement for J/ψ, a cleaner probe for gluon spatial distribution

Hard probes: jets and heavy flavor



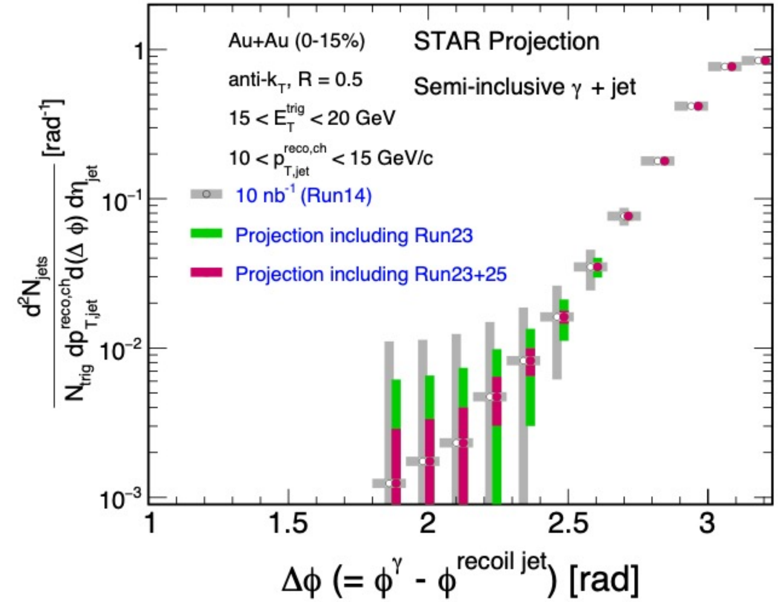
Jet quenching

low p_T, large R, extended to higher p_T

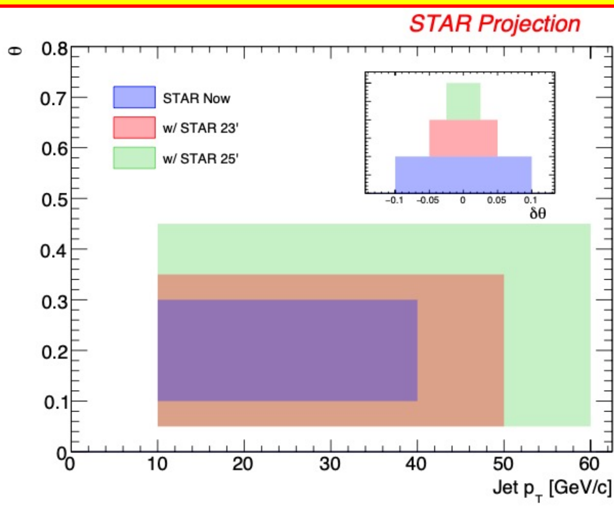


Semi-inclusive γ_{dir}+jet suppression

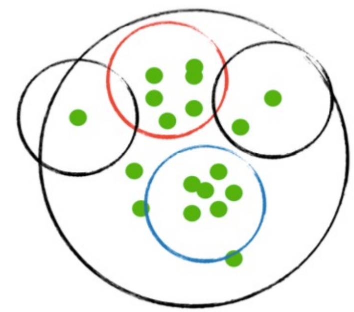
γ_{dir}+jet acoplanarity: constituents of medium



improved opening angle resolution by a factor of 4



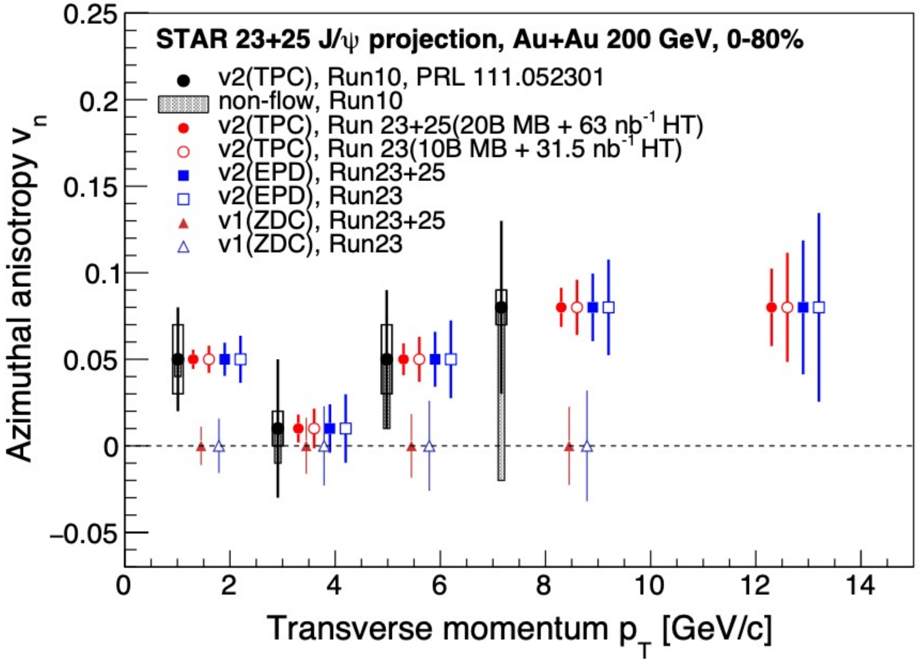
Jet substructure: coherence vs. de-coherence

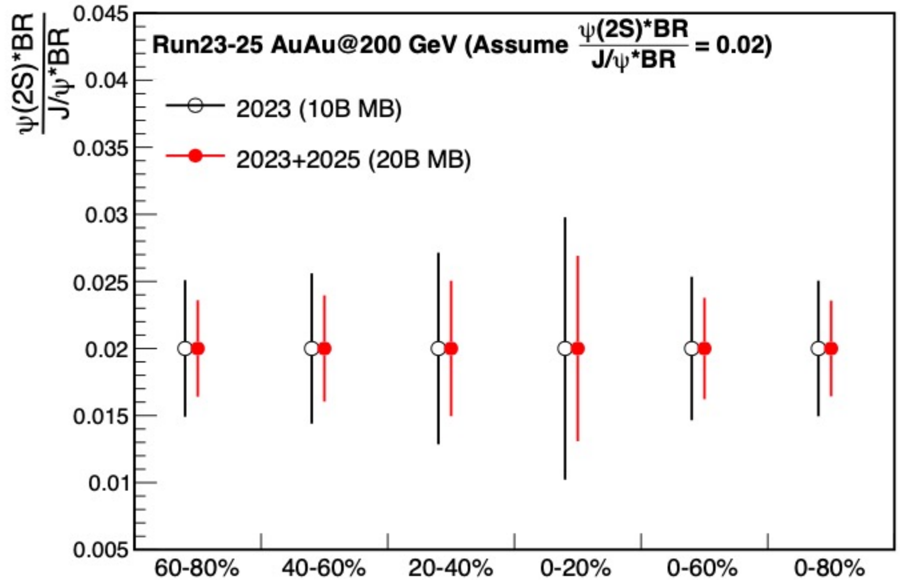


Red: leading sub-jet
Blue: sub-leading sub-jet
$Z_{SJ}=p_T^{blue}/(p_T^{blue}+p_T^{red})$
$\theta_{SJ}=\Delta R(blue,red)$

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**
- **v_1: initial tilt of the bulk medium**

ψ(2S) suppression: explore temperature profile of the medium

Summary of 2023-2025

STAR is in an excellent position to address important questions about the inner workings of the QGP

- What is the precise temperature dependence of shear and bulk viscosity? v_n as a function of η
- What is the nature of the 3-dimensional initial state at RHIC energies? r_n over a wide rapidity
- How is global vorticity transferred to the spin angular momentum of particles on such short time scales? How can the global polarization of hyperons be reconciled with the spin alignment of vector mesons? Λ, Ξ, Ω P_H and ρ_{00} of K^*, ϕ, J/ψ
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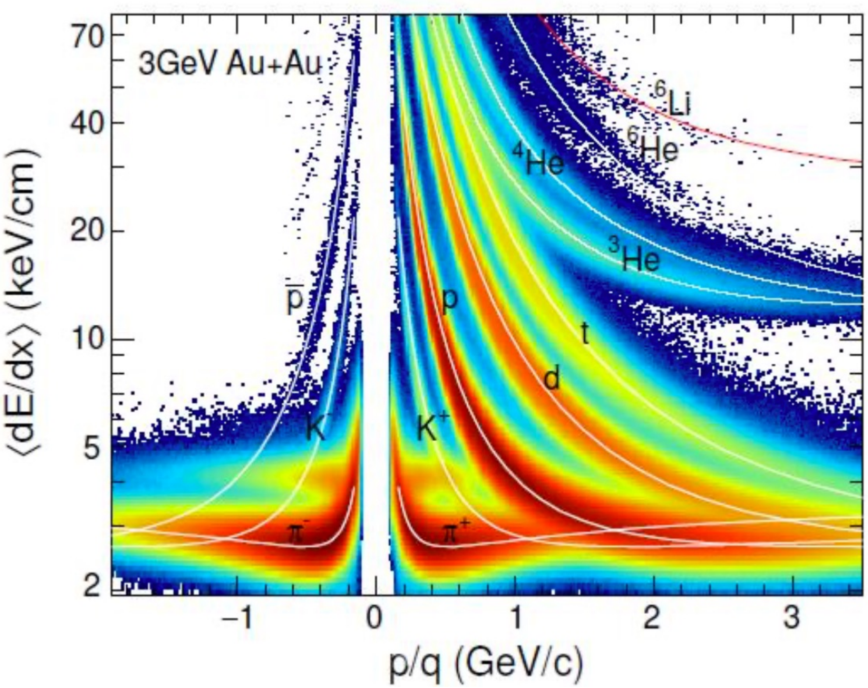
- What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale? γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure

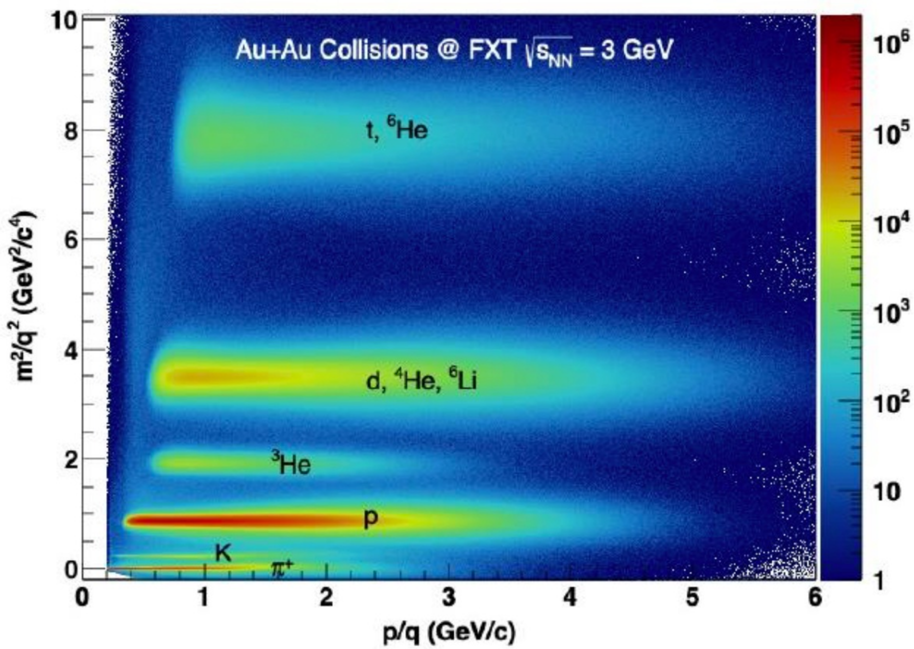
Proposed measurements based on our detector performances in past years and/or forward capabilities.

Future opportunity I

Light fragment yields from He, Si, 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 (He, Si, 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)



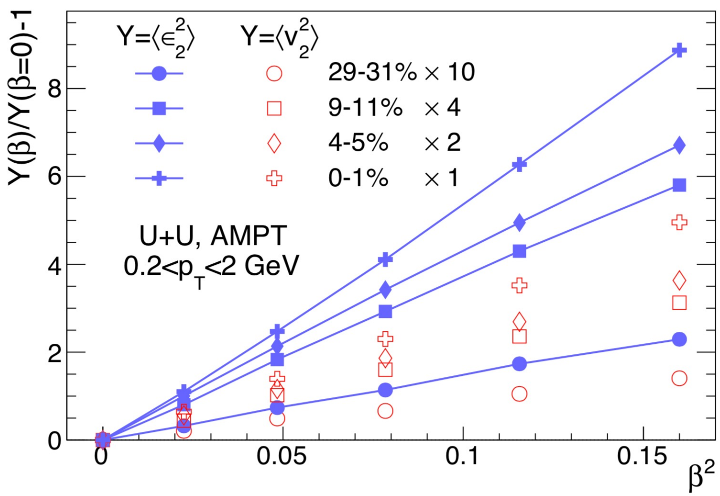


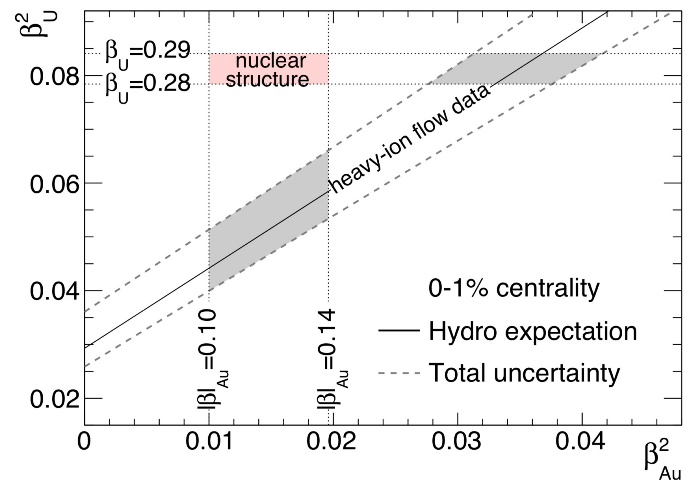
Future opportunity II

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.

A shorter run scenario

Run-22: 18 cryo-weeks

- **Detrimental to STAR achieving all our physics goals.**
- **Need commission forward detectors**
- **Results in more than 15% reduction in sampled luminosity**

Runs 23-25: 20 cryo-weeks each

Data taking:
29 weeks Au+Au
10 weeks pp
10 weeks p+Au

$\sqrt{s_{\mathrm{NN}}}$ (GeV)	Species	Number Events/ Sampled Luminosity
200	Au+Au	12B / 37 nb^{-1}
200	pp	214 pb^{-1}
200	p+Au	1.2 pb^{-1}

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

Very detrimentally impact the following physics programs:
Hard probes, thermal di-lepton, photon-induced di-lepton and J/ψ in Au+Au
Nuclear PDFs, fragmentation functions, and gluon saturation measurements

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: $Sivers_{SIDIS}$ = -- $Sivers_{DY, W+/-, Z0}$
  - 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

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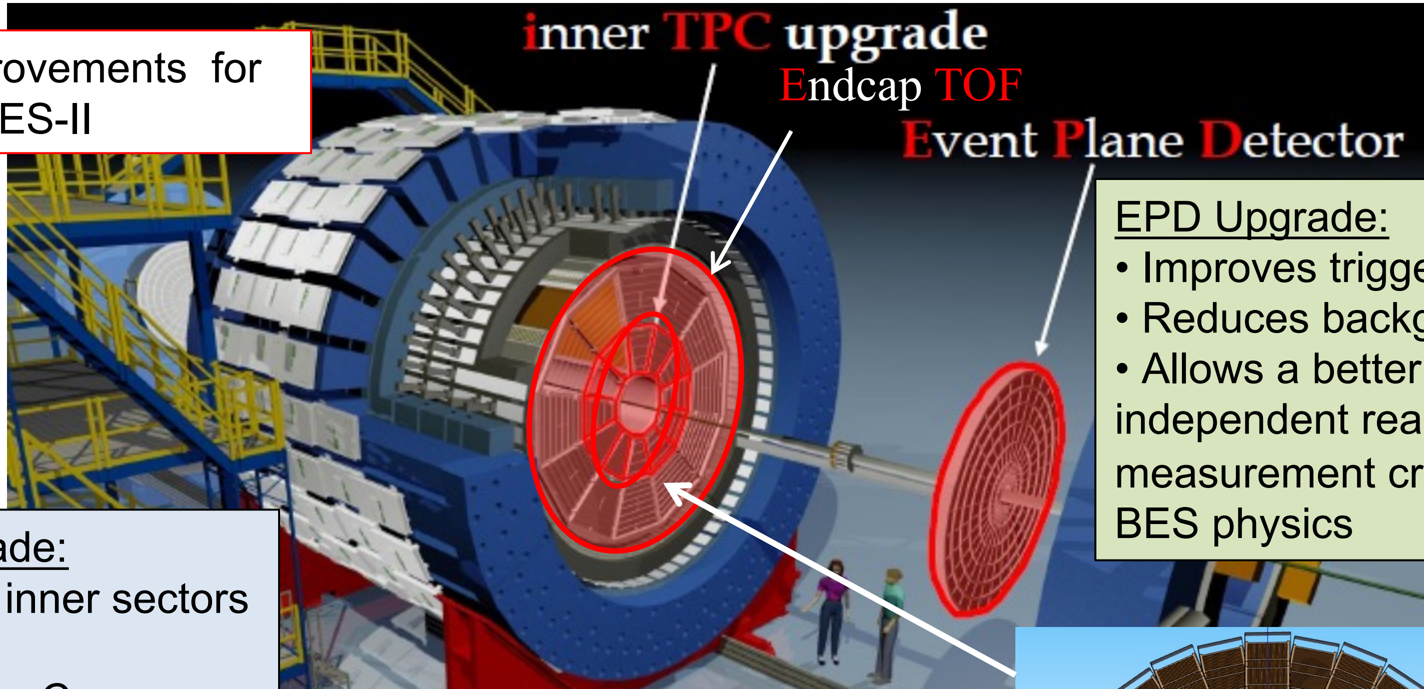
Backup

STAR detector at BESII

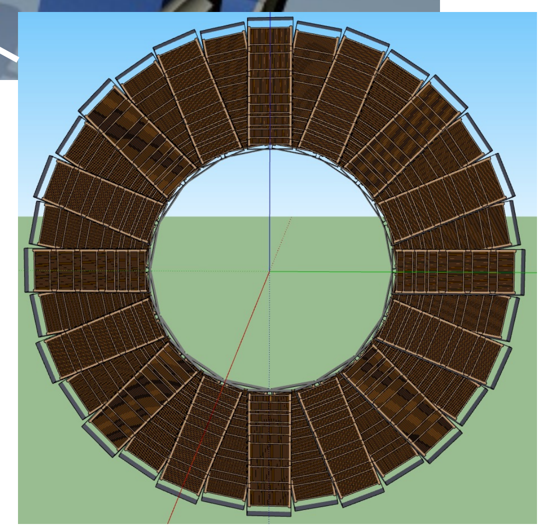
Major improvements for BES-II



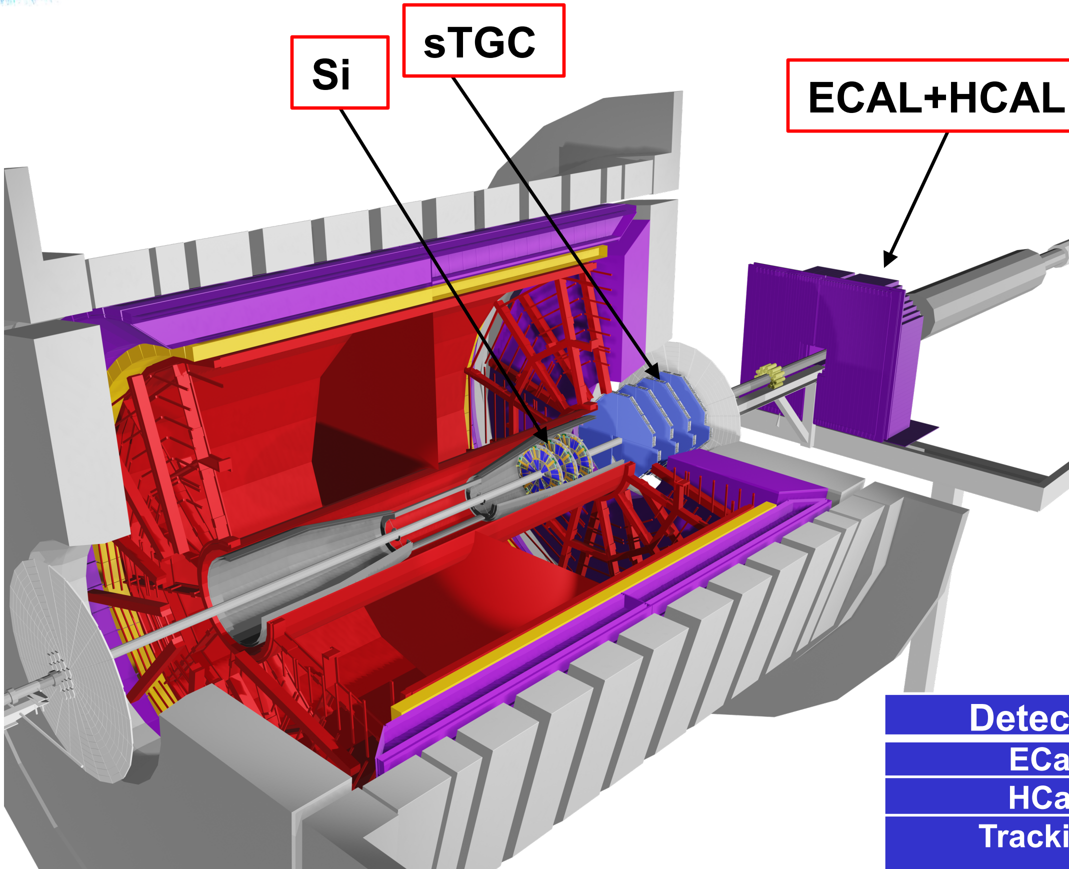
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

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



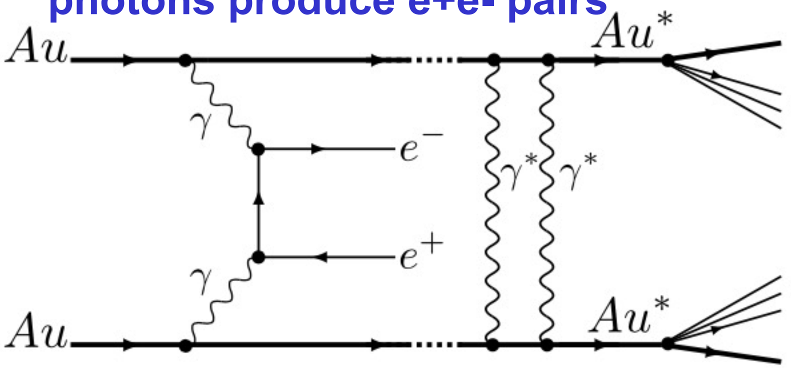
At $2.5<\eta<4$

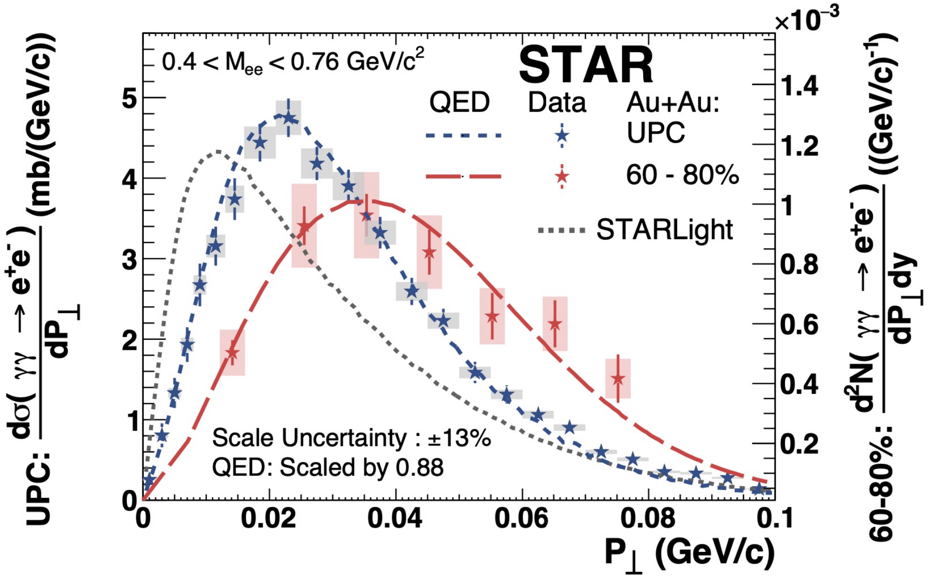
- Jets
- PID (π^0, γ, e, Λ)
- charged particle momentum resolution 20-30% at $0.2<p_T<2$ GeV/c
- event-plane reconstruction and trigger capability

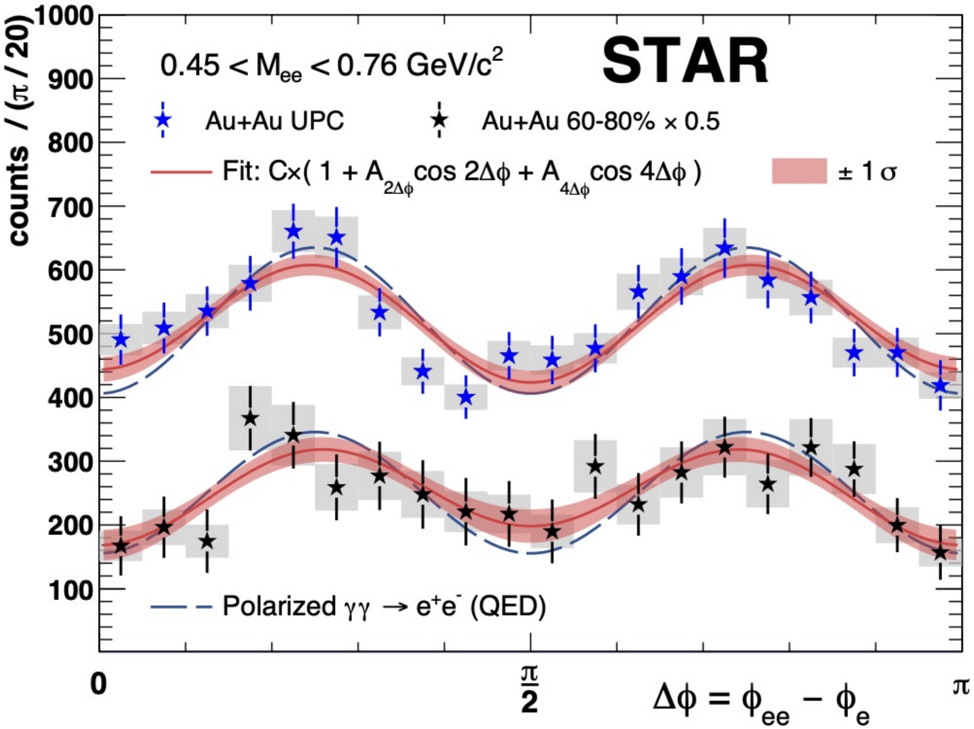
Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

Discoveries of Breit-Wheeler process and vacuum birefringence

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







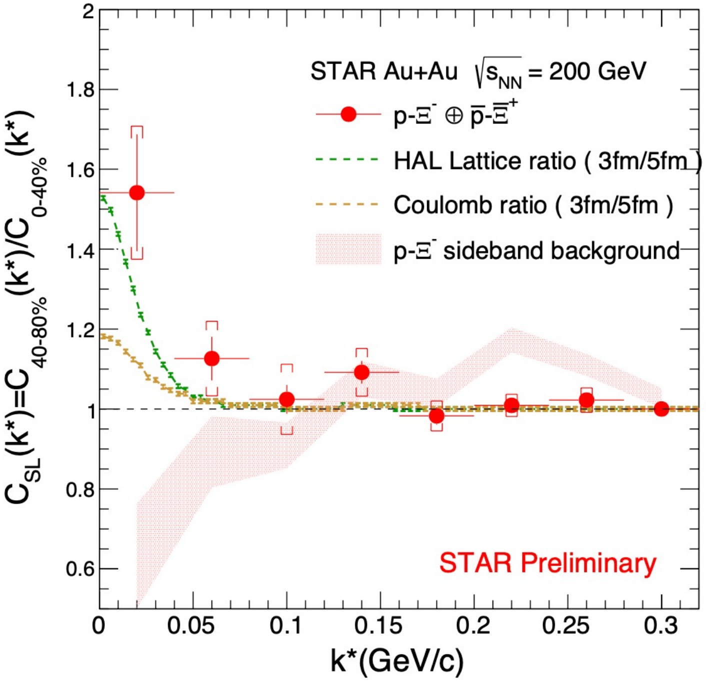
arXiv: 1910.12400

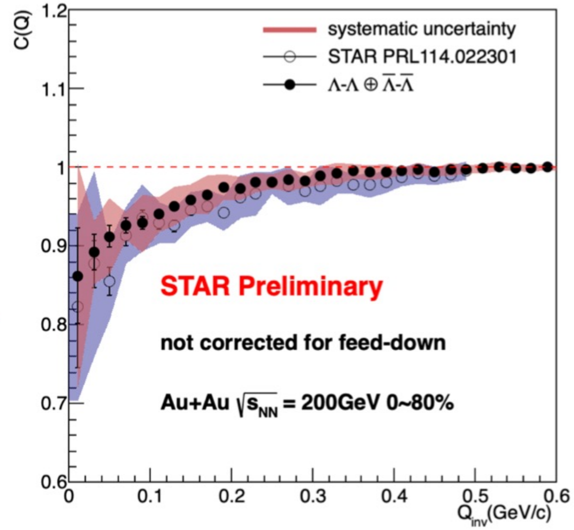
Observation of Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, p_T, angle)

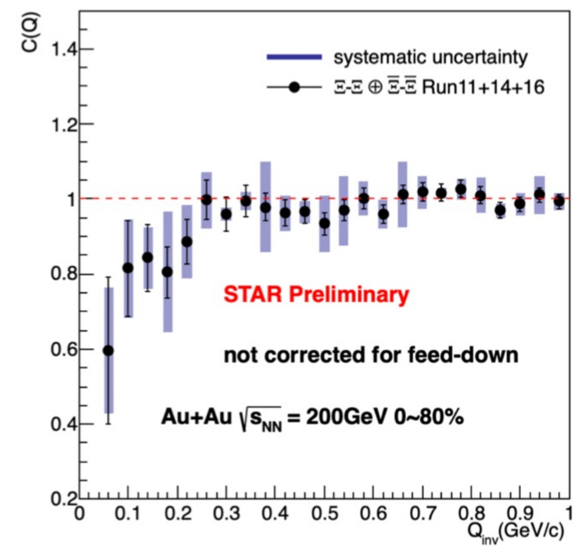
Dielectron p_T spectrum: broadened from large to small impact parameters

Observation of vacuum birefringence: 6.7σ in UPC

Strong interactions



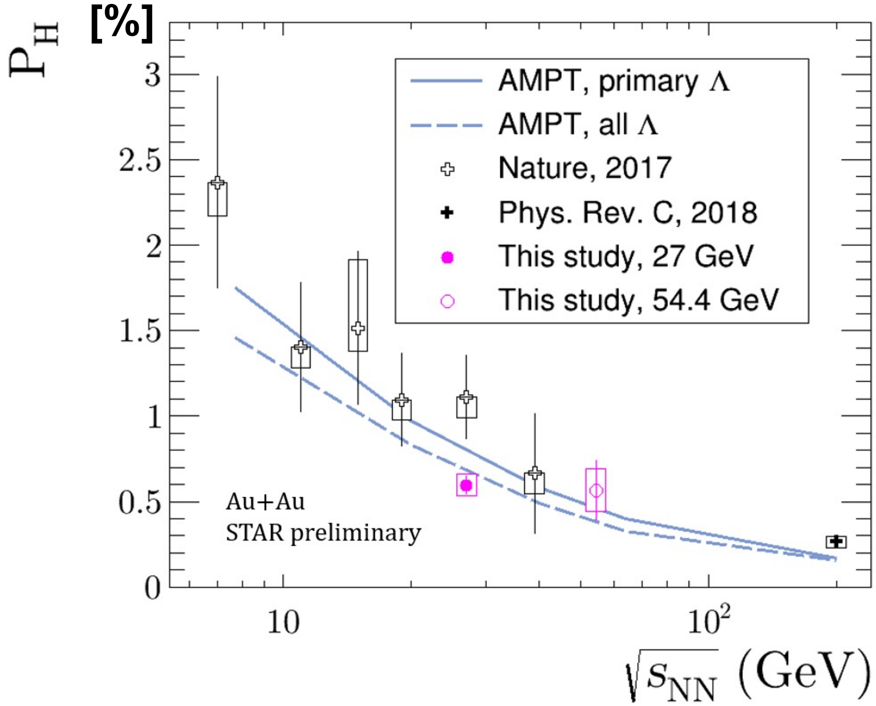




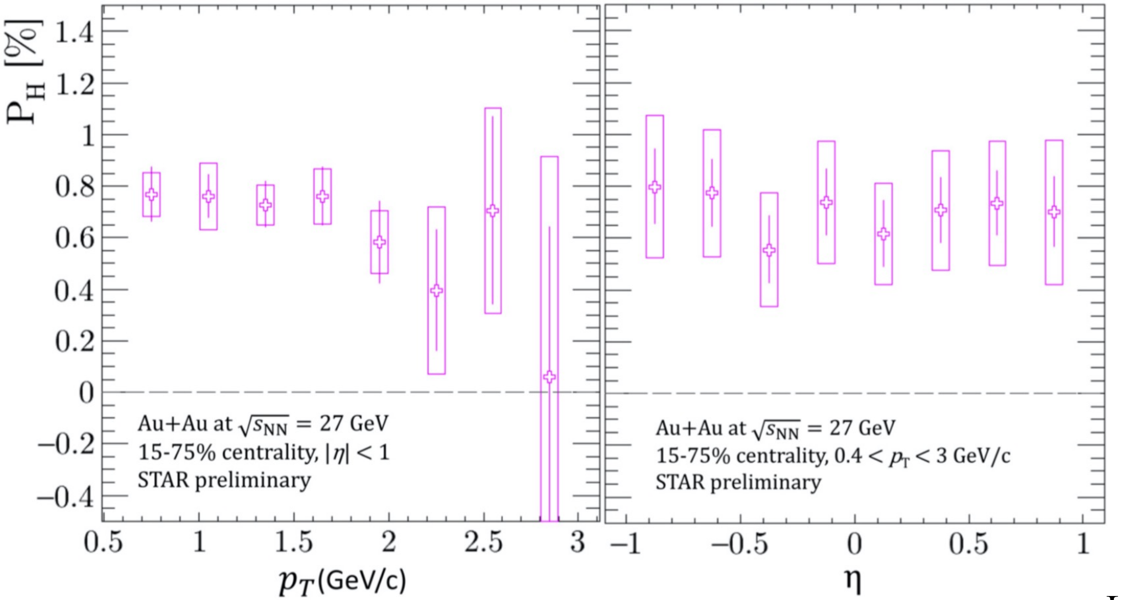
Constrain hyperon-nucleon and hyperon-hyperon interactions, important for the study exotic hadronic states and understanding of the EoS of neutron stars

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

Vortical fluid: global vorticity transfer

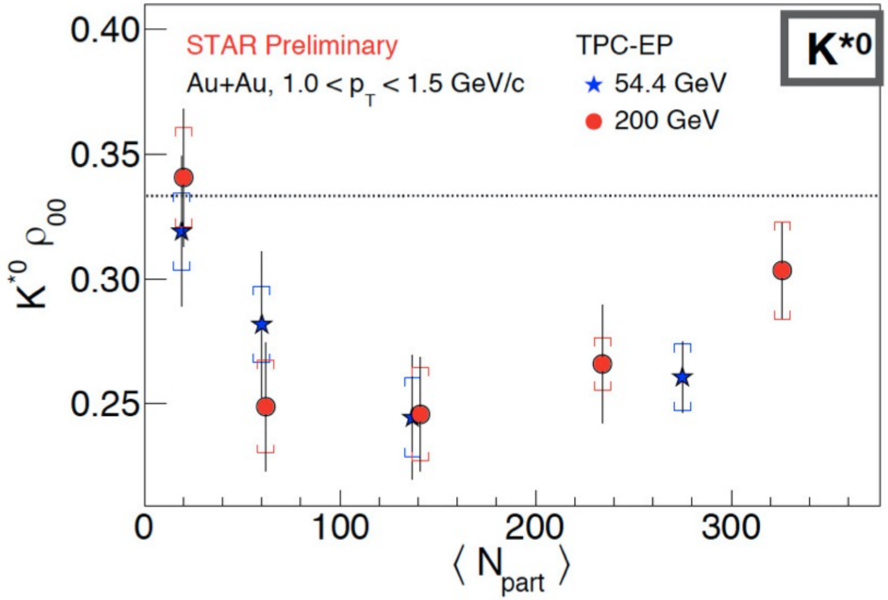


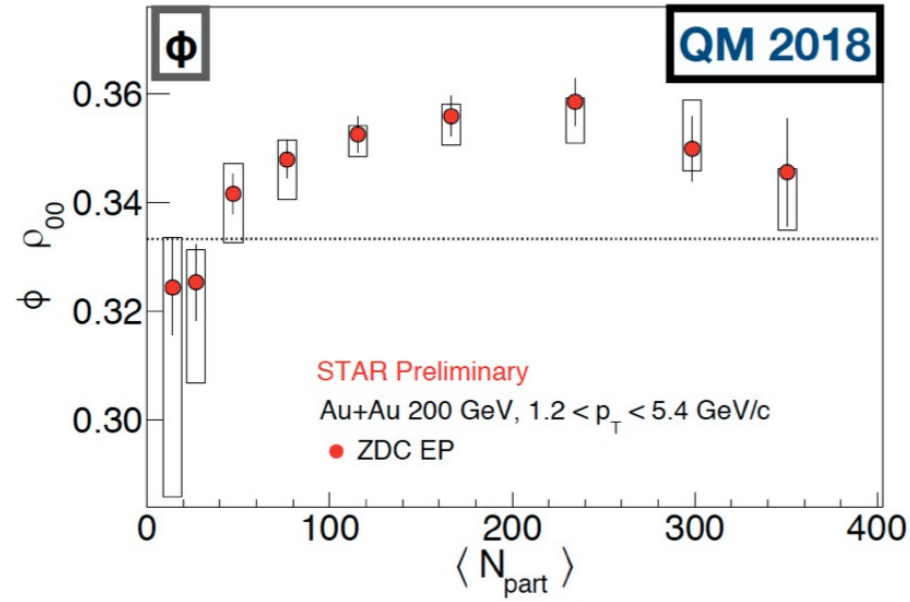
Λ Global polarization: strong energy dependence



Weak p_T and η dependence

Vortical fluid: global vorticity transfer





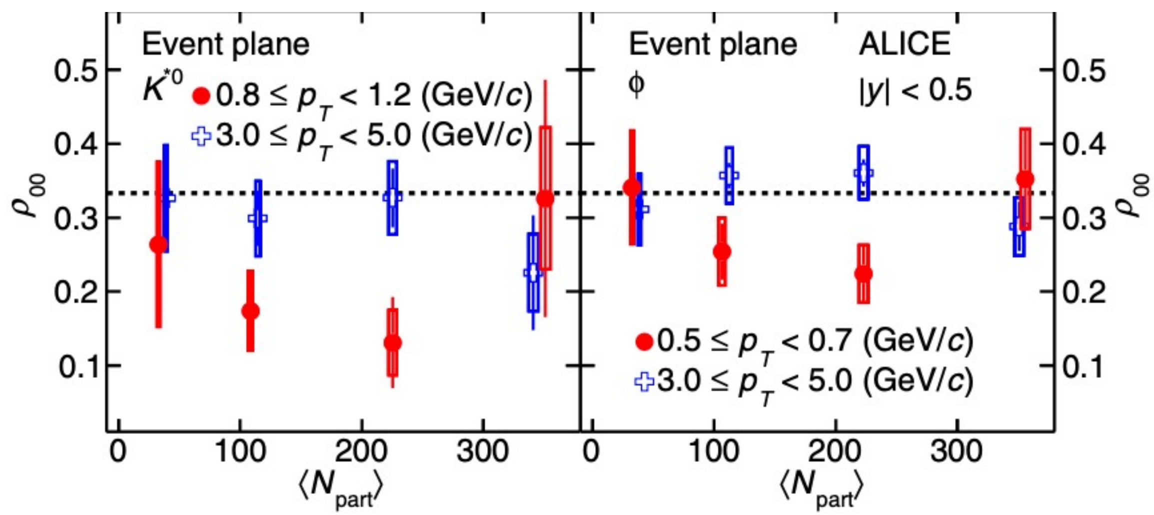
Vector meson spin alignment ρ_{00} from STAR

>1/3 for ϕ

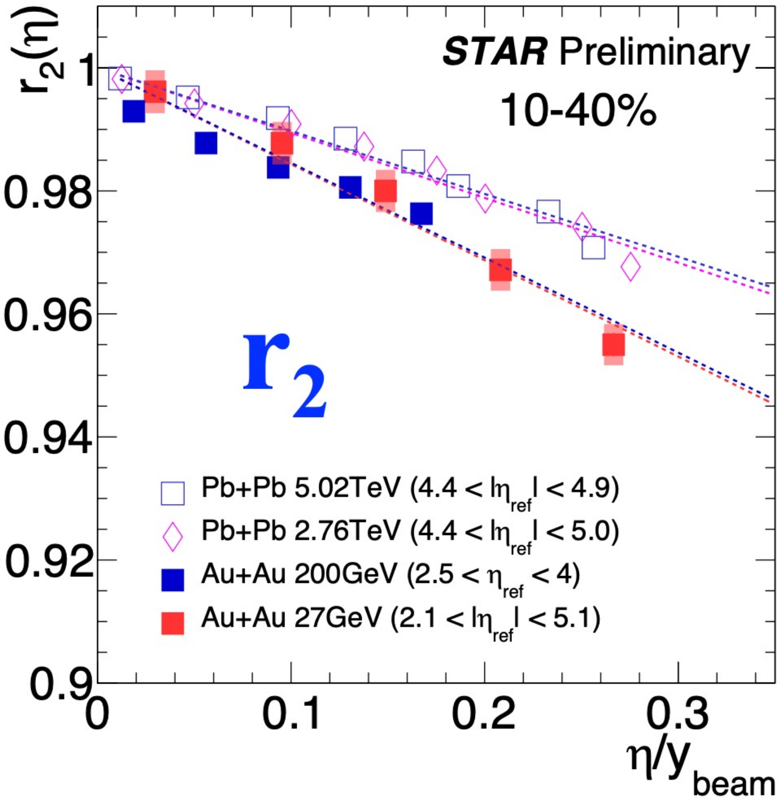
<1/3 for K*

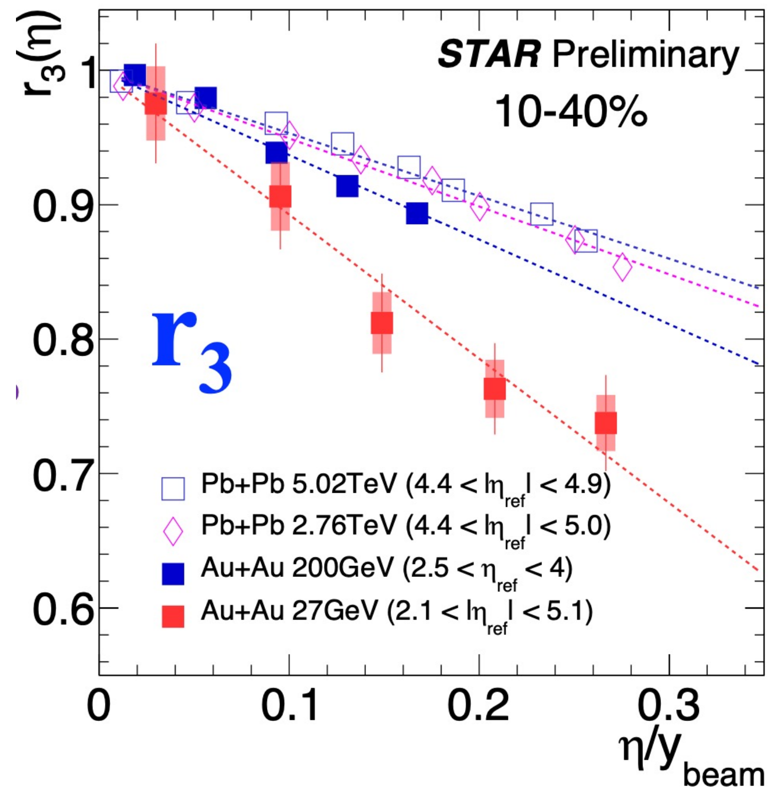
Can we reconcile P_H with vector meson spin alignment ρ_{00}?

Strong vector meson field?



De-correlation in 27 and 200 GeV Au+Au





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

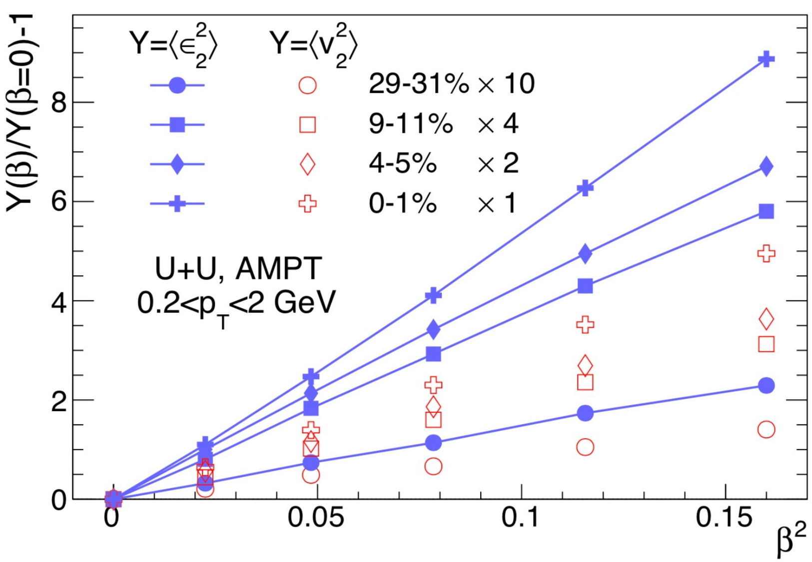
Shape tomography of atomic nuclei using collective flow measurements

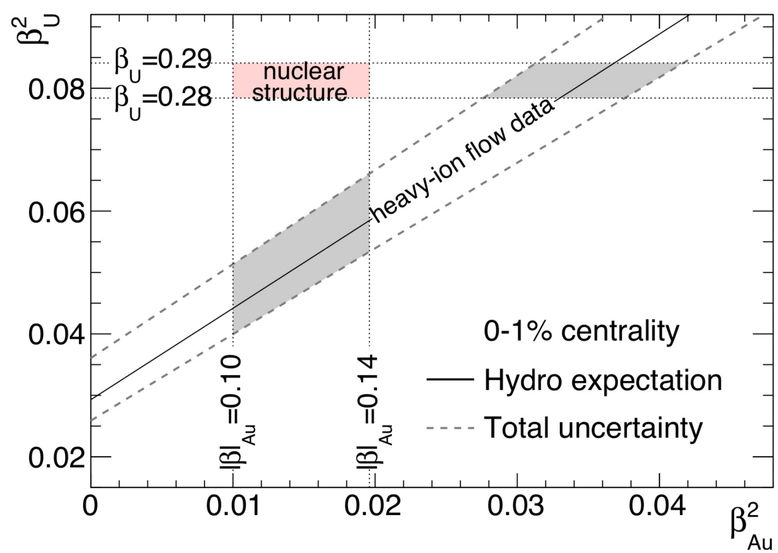
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi)/a}}$$

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

- **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

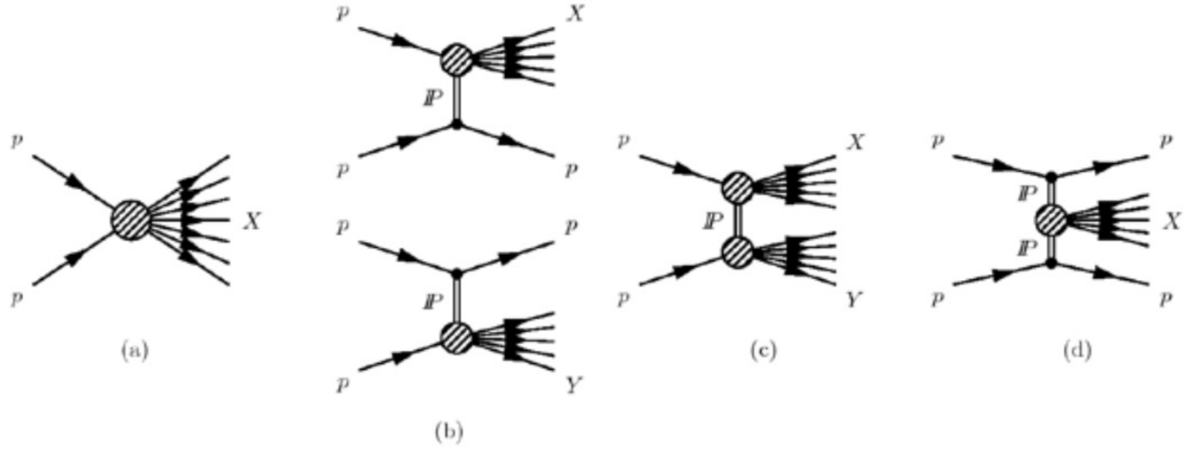
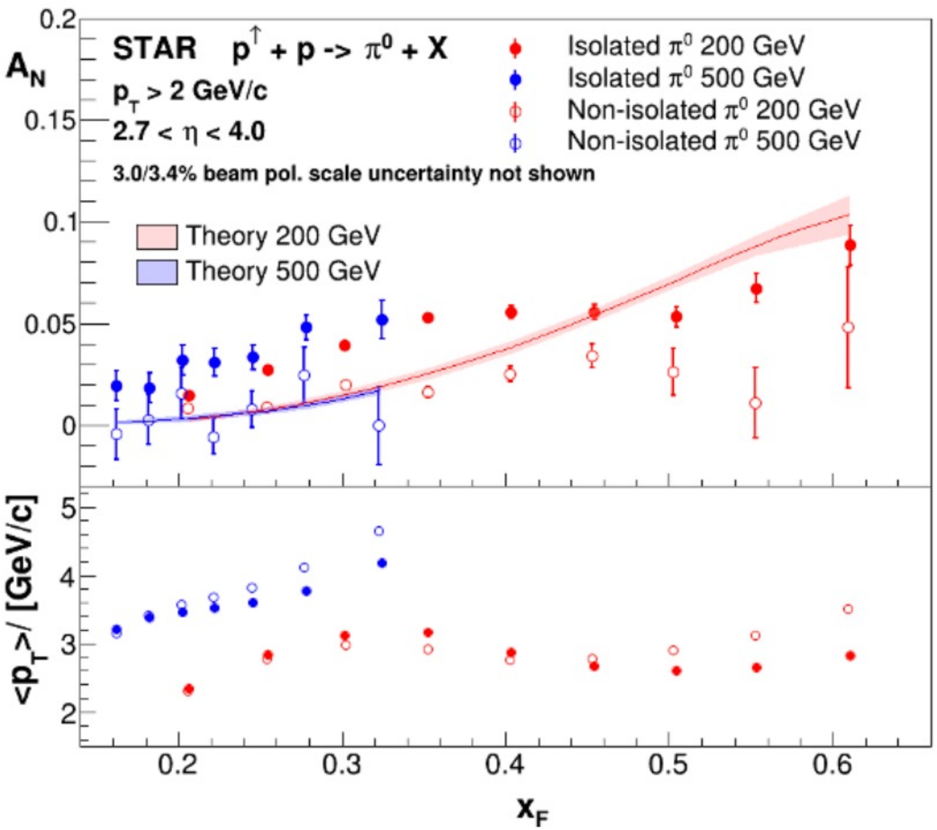


Figure 71: Schematic diagrams of (a) nondiffractive, $pp \to X$, (b) singly diffractive, $pp \to Xp$ or $pp \to pY$, (c) doubly diffractive, $pp \to XY$, and (d) centrally diffracted, $pp \to pXp$, events.



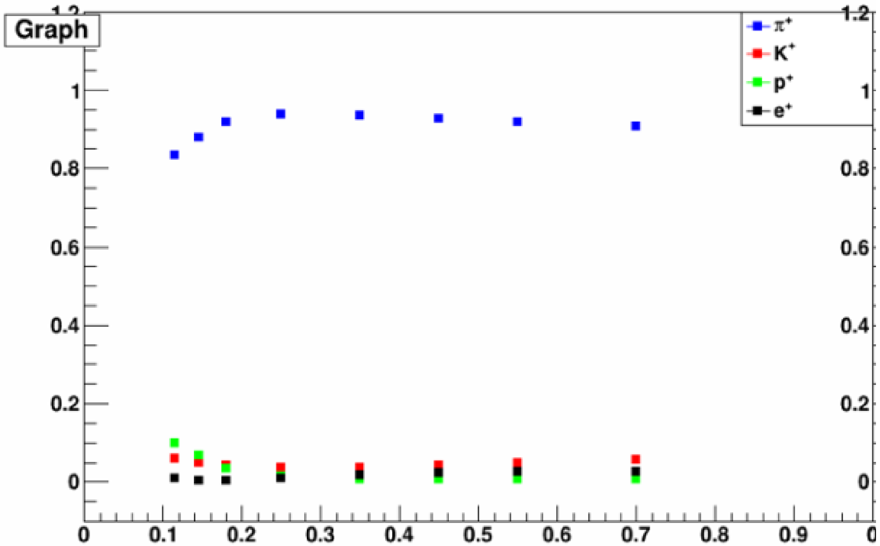
Model with initial and final state effect can only explain the non-isolated π^0 A_N

Significantly larger value of A_N for isolated π^0

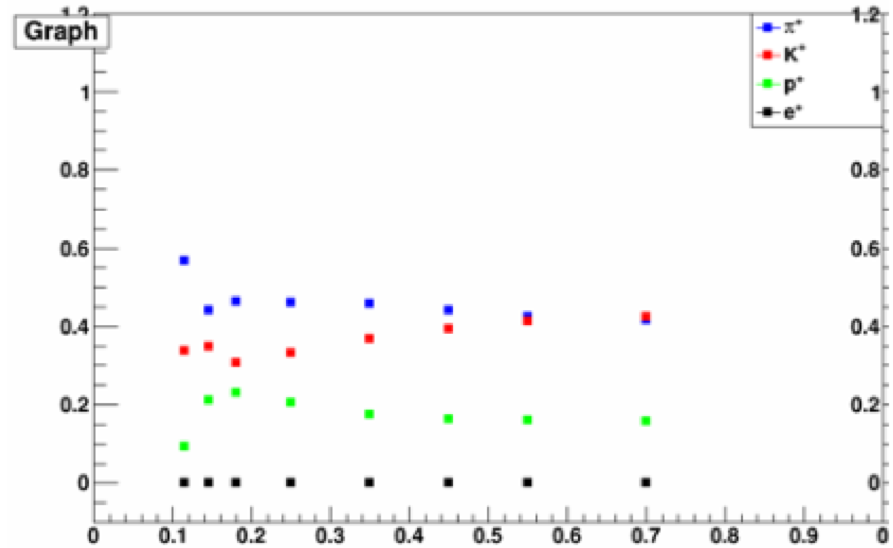
Plan to reconstruct jets produced with scattered proton tagged in Roman Pots with/without rapidity gaps

Identified particle composition in one jet p_T bin

Pion-rich dE/dx region

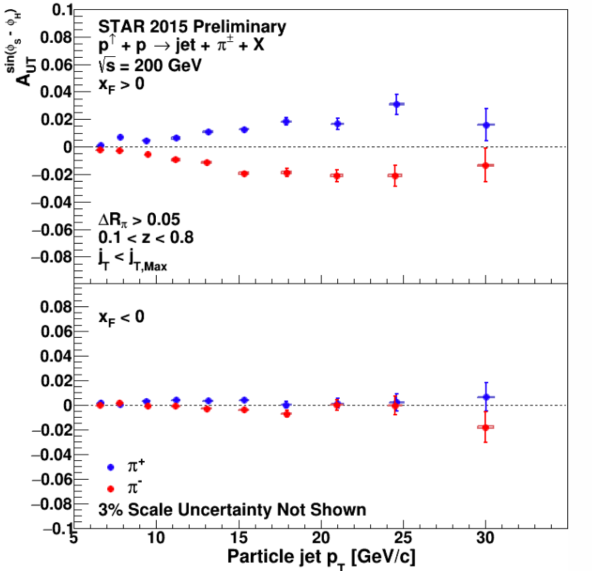


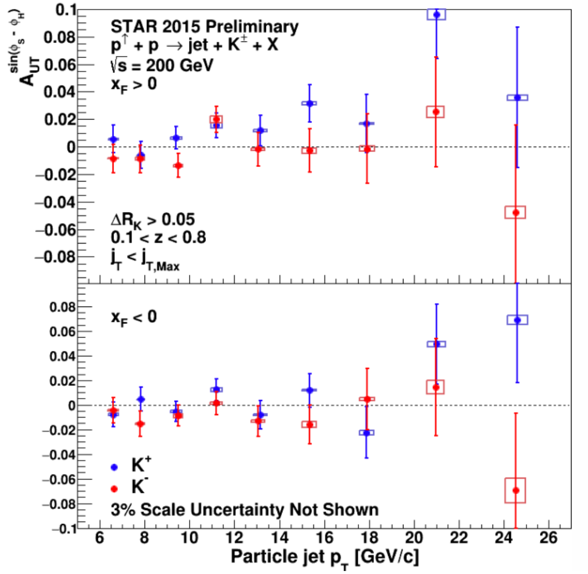
Kaon-rich dE/dx region

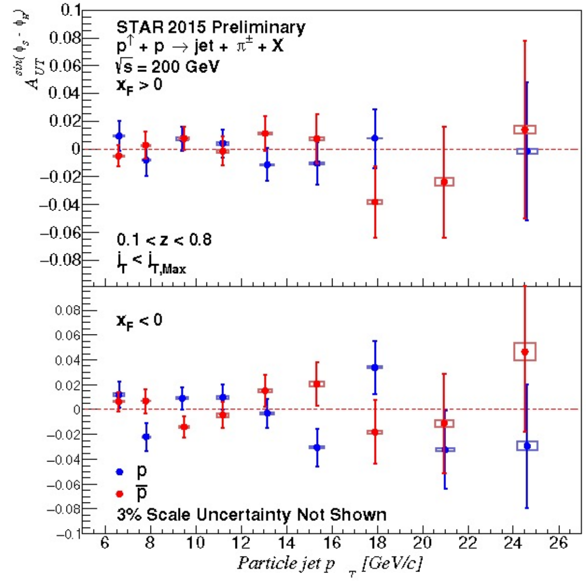


- Fractions of π^+, K^+, p, and e^+ in jets with $11.7 < p_T < 13.8$ GeV/c as a function of z in the 200 GeV 2015 Collins effect measurement (negative hadrons behave similarly)
- Note that, with 2015 dE/dx resolution, the kaon-rich region contains more pions than anything else, but far fewer than in 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

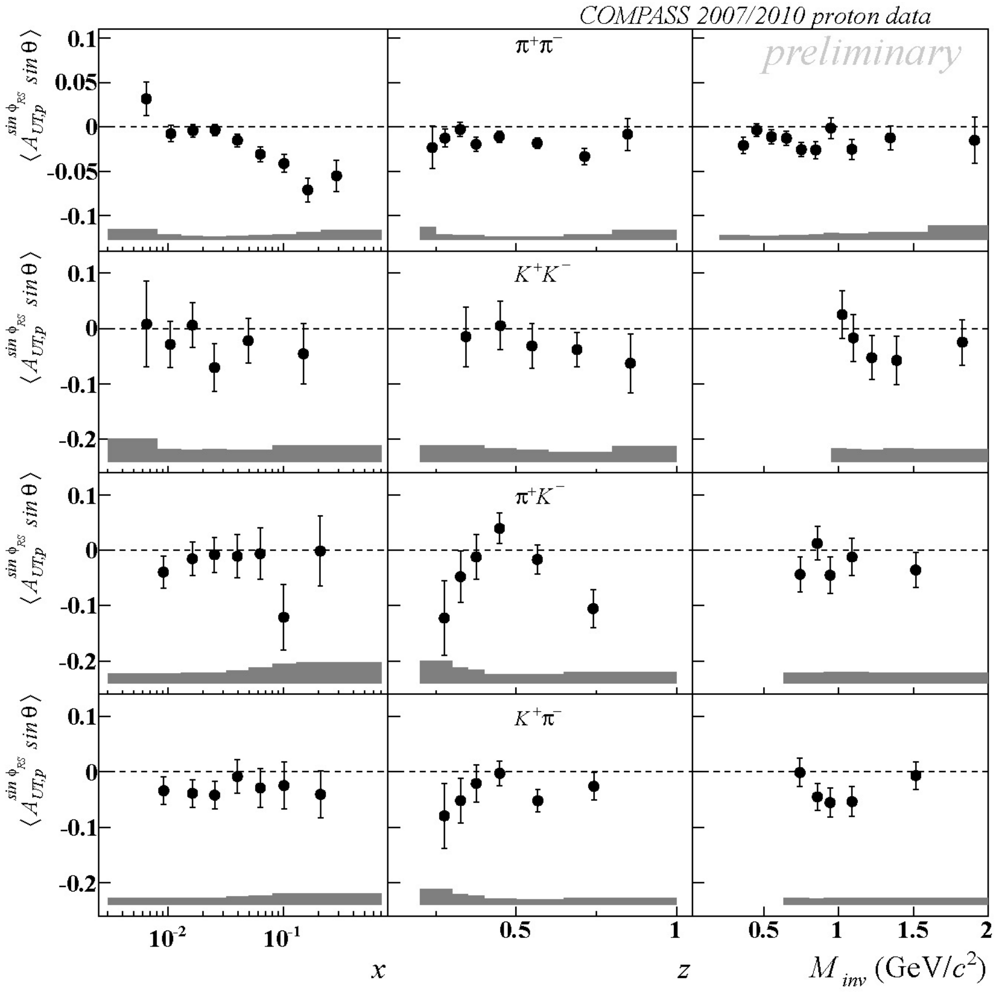






- pi^+, pi^-, K^+, K^-, p, pbar for both rapidity bins and with the same vertical scale

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