Run plans for STAR in 2023-2025

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Plans for Run-23 and 25

Plans for Run-24

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U.S. DEPARTMENT OF ENERGY

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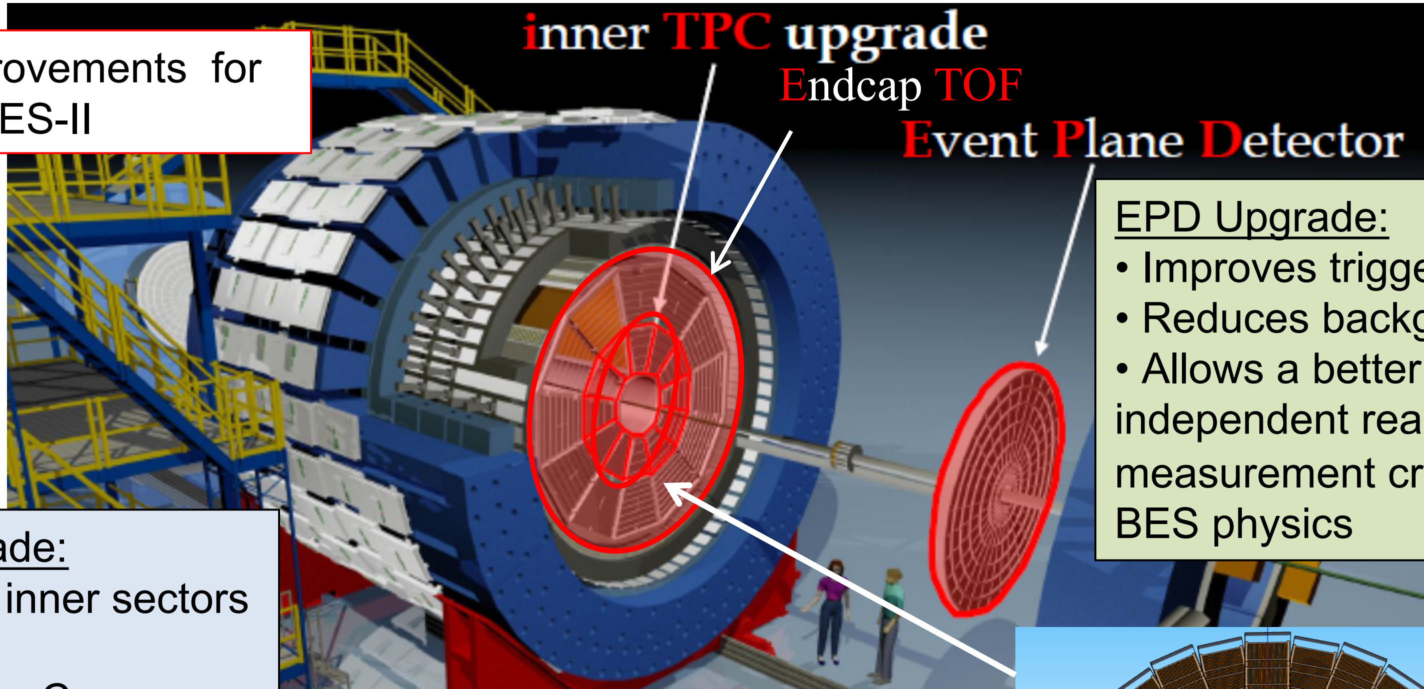
STAR detector at BESII

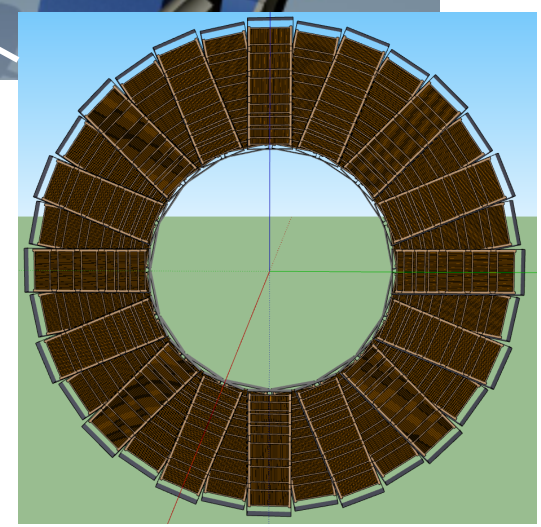
Major improvements for BES-II



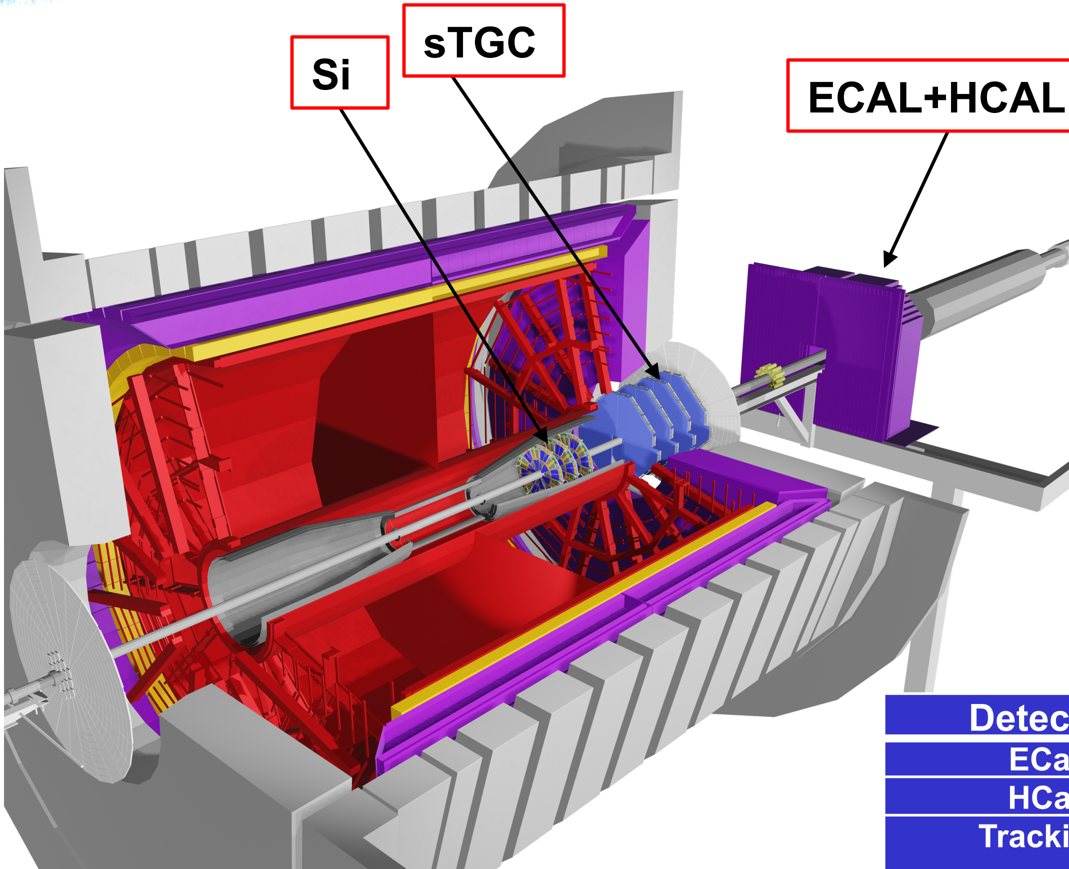
<u>EPD Upgrade:</u>
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

<u>iTPC Upgrade:</u>
- 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

<u>EndCap TOF Upgrade:</u>
- 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% $1/p_T$

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	26.5	19.1	15.7	**TPC+TOF+HFT+MTD**
2023	10	43	38	32	**iTPC+EPD+eTOF+TOF +MTD Forward upgrades**
2025	10	58	52	43	

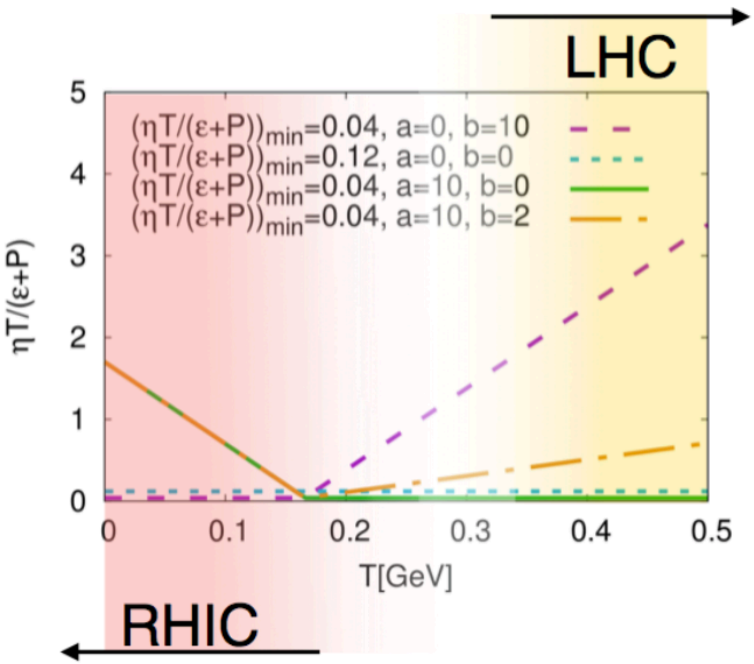
A factor of 10 more minimum bias data compare to Run-14 + Run-16
A factor of 4 more luminosity for high-p_T trigger

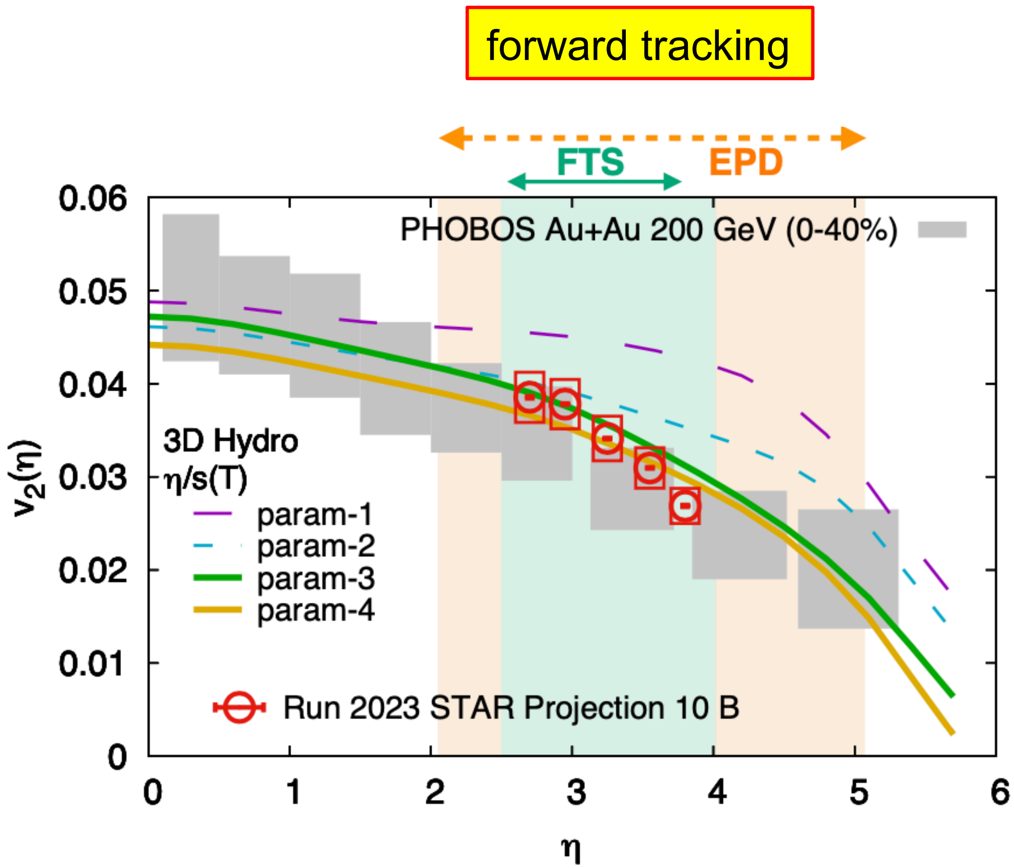
Physics Opportunities for 2023+2025

To address important questions about the inner workings of the QGP

- **What is the precise temperature dependence of shear and bulk viscosity?**
- **What is the nature of the 3-dimensional initial state at RHIC energies?**
- **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?**
- **What is the precise nature of the transition near μ_B=0?**
- **What is the electrical conductivity, and what are the chiral properties of the medium?**
- **What can be learned about confinement and thermalization in a QGP from charmonium measurement?**
- **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?**

Constrain temperature dependence of η/s

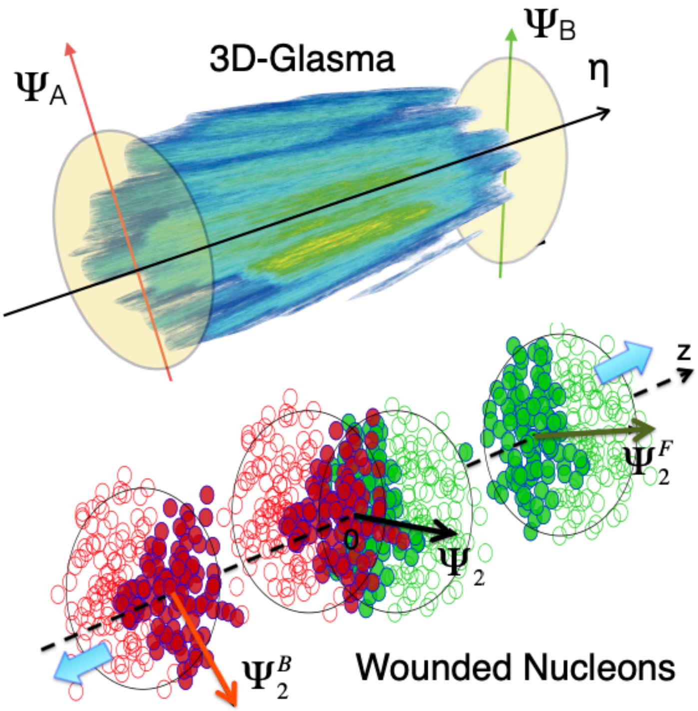




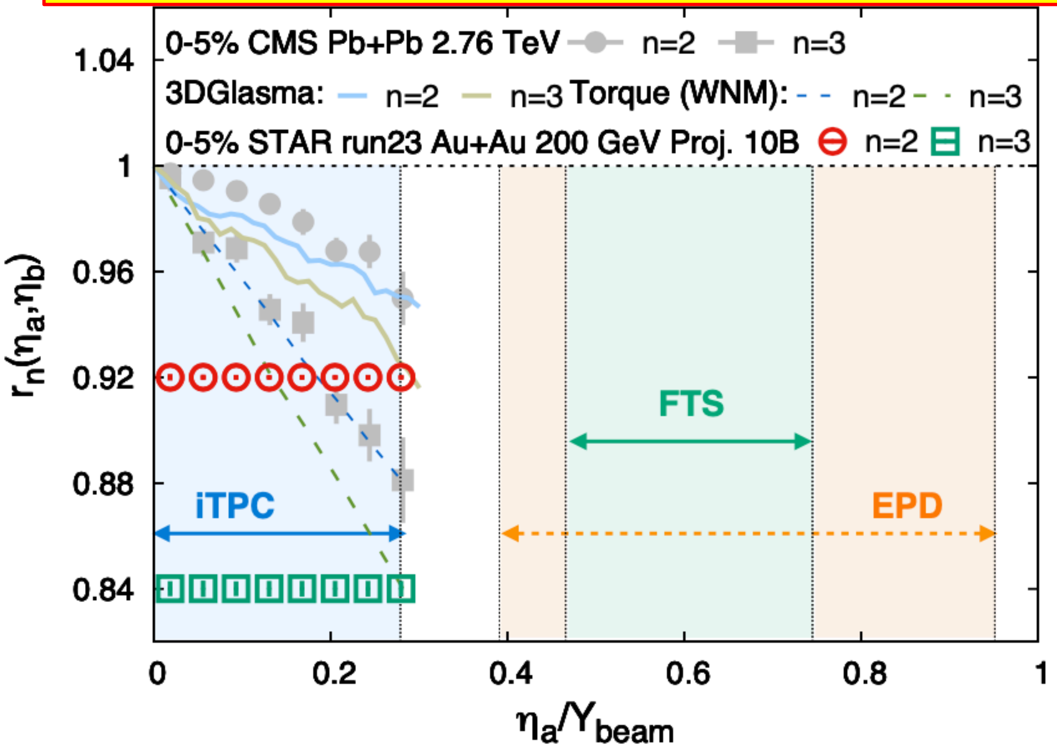
Flow measurements at forward rapidity sensitive to η/s as a function of T.

Much more precise than previous PHOBOS measurements.

Constrain longitudinal structure of initial state



extended η coverage by iTPC and forward tracking



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

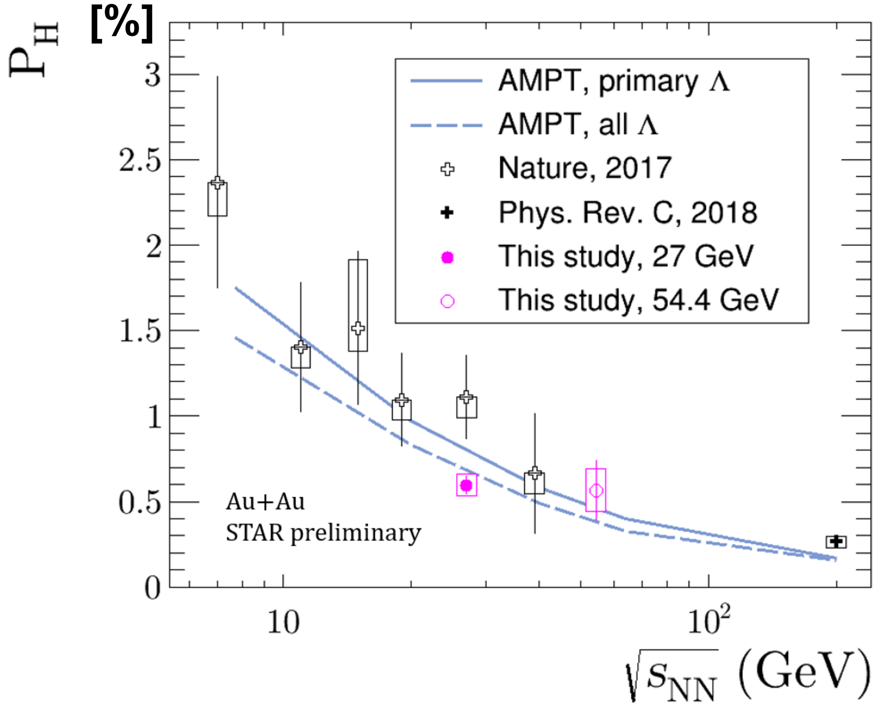
$V_{n\Delta}$ the Fourier coefficient calculated with pairs of particles in different rapidity regions

r_n sensitive to different initial state inputs:

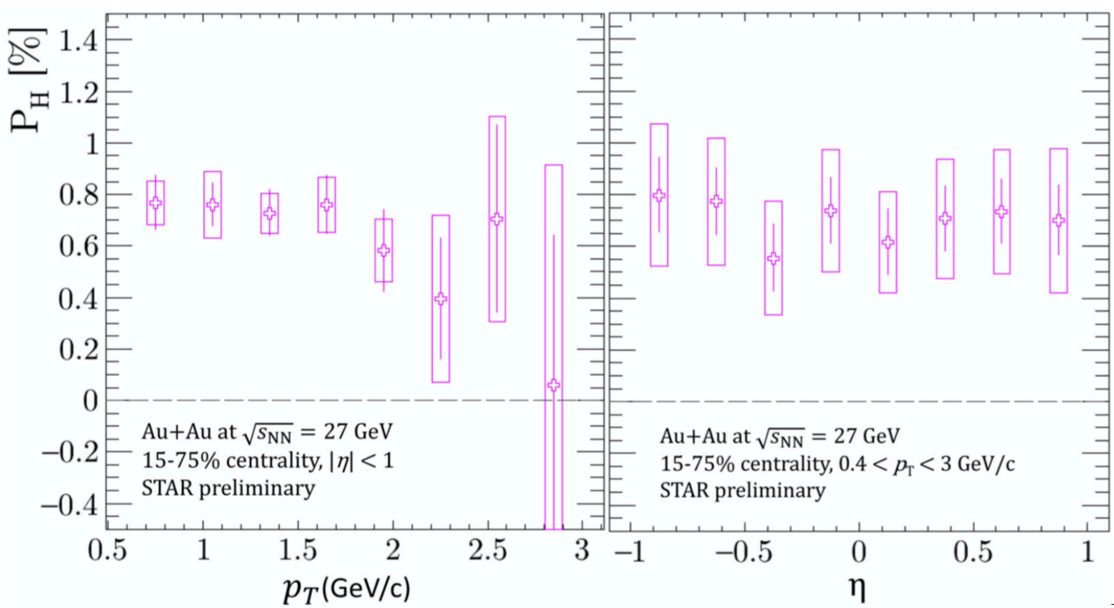
- **3D glasma model: weaker decorrelation, describes CMS r_2 but not r_3**
- **Wounded nucleon model: stronger decorrelation than data**

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

Vortical fluid: global vorticity transfer

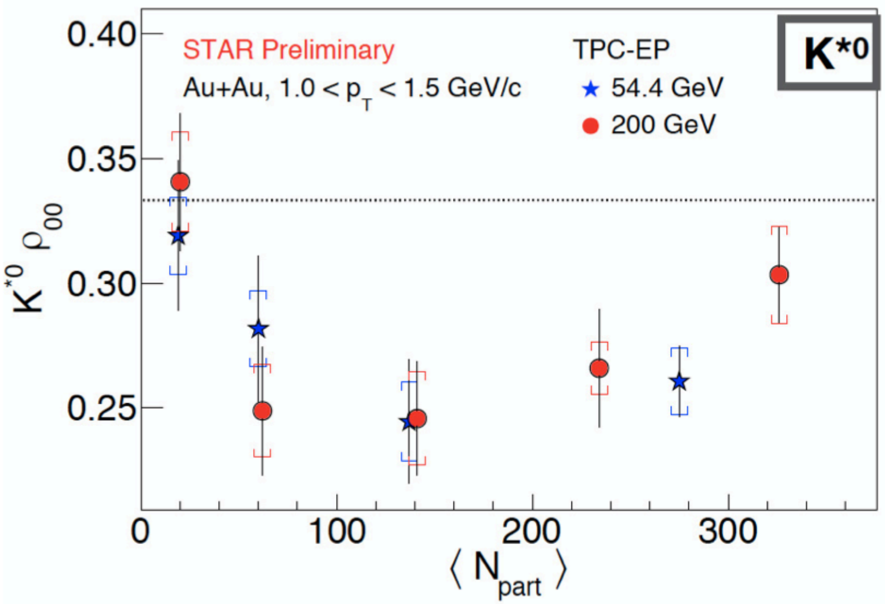


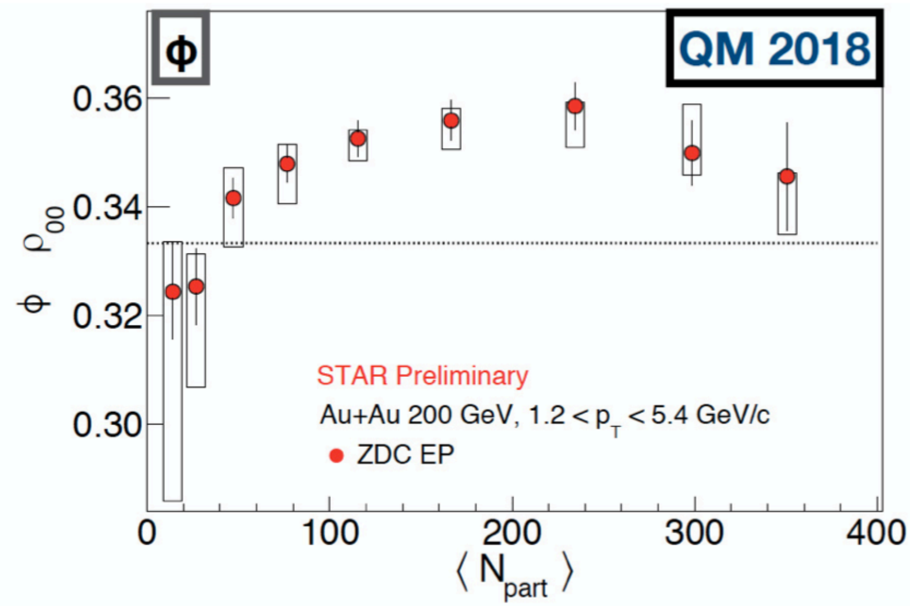
Λ Global polarization: strong energy dependence



Weak p_T and η dependence

Vortical fluid: global vorticity transfer





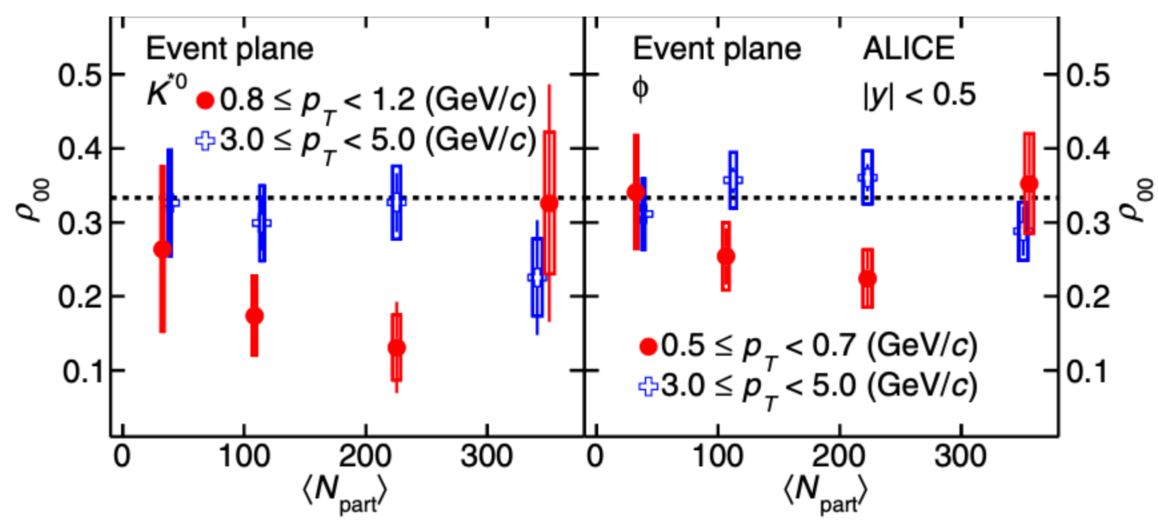
Vector meson spin alignment ρ_{00} from STAR

>1/3 for ϕ

<1/3 for K*

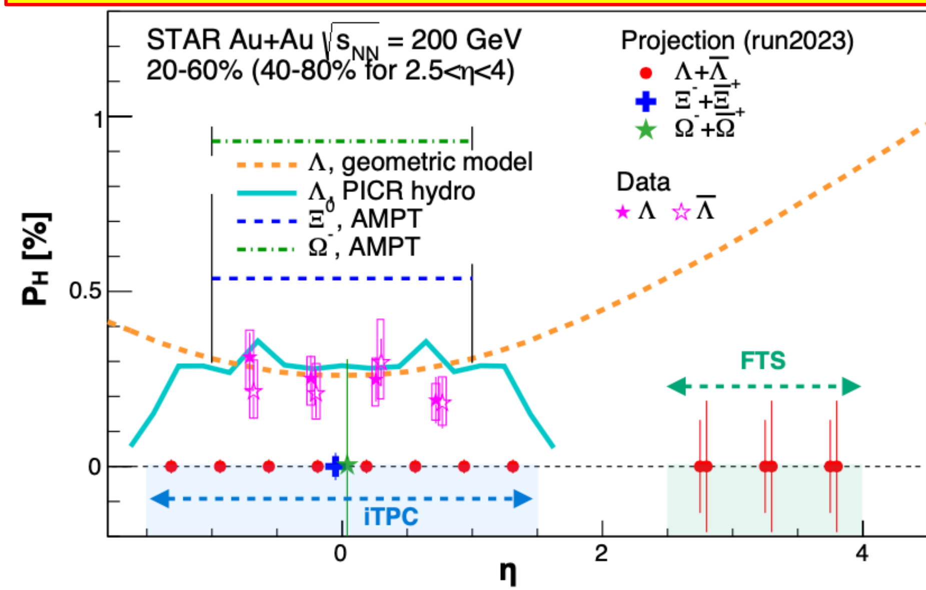
Can we reconcile P_H with vector meson spin alignment ρ_{00}?

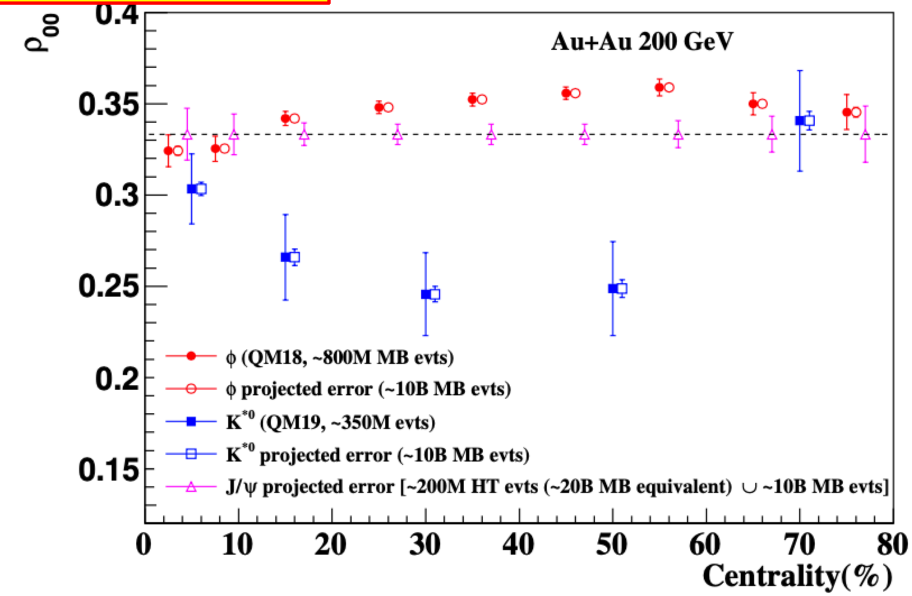
Strong vector meson field?



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?

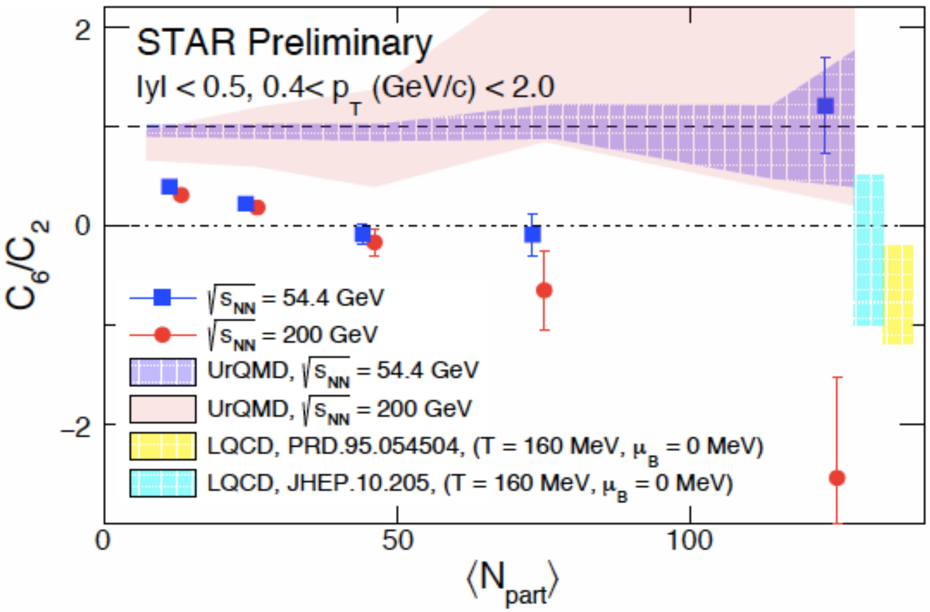
Rapidity dependence of Λ, Ξ, Ω P_H at STAR, probe the nature of global vorticity transfer:
Initial geometry and local thermal vorticity + hydro predict opposite trends.

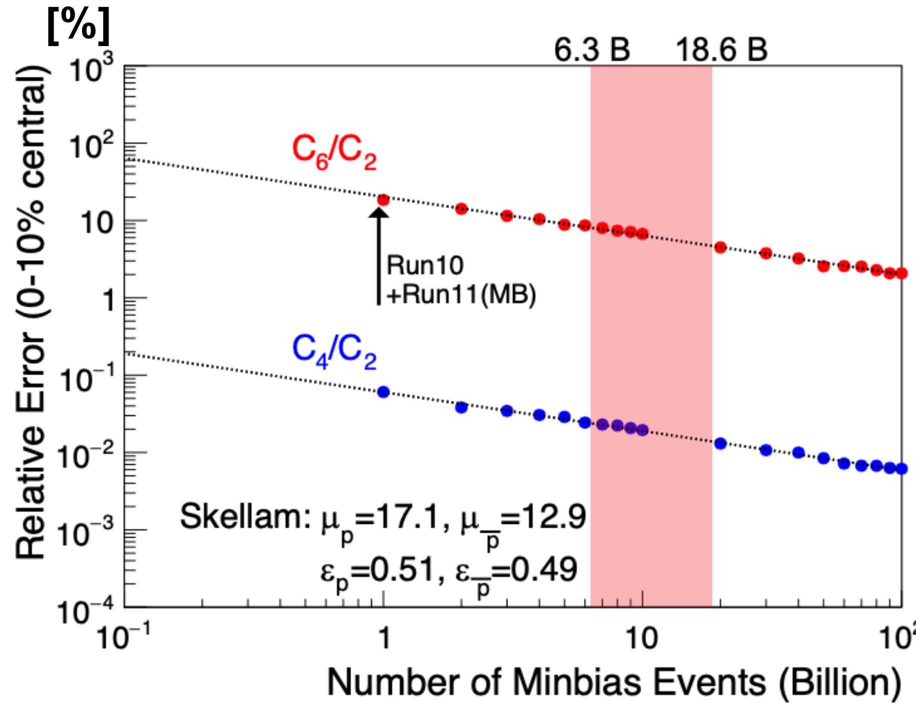
Can we reconcile P_H with vector meson spin alignment ρ_{00}? Strong force field effect?

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

Chiral cross-over transition

Improved PID, extended η coverage by iTPC



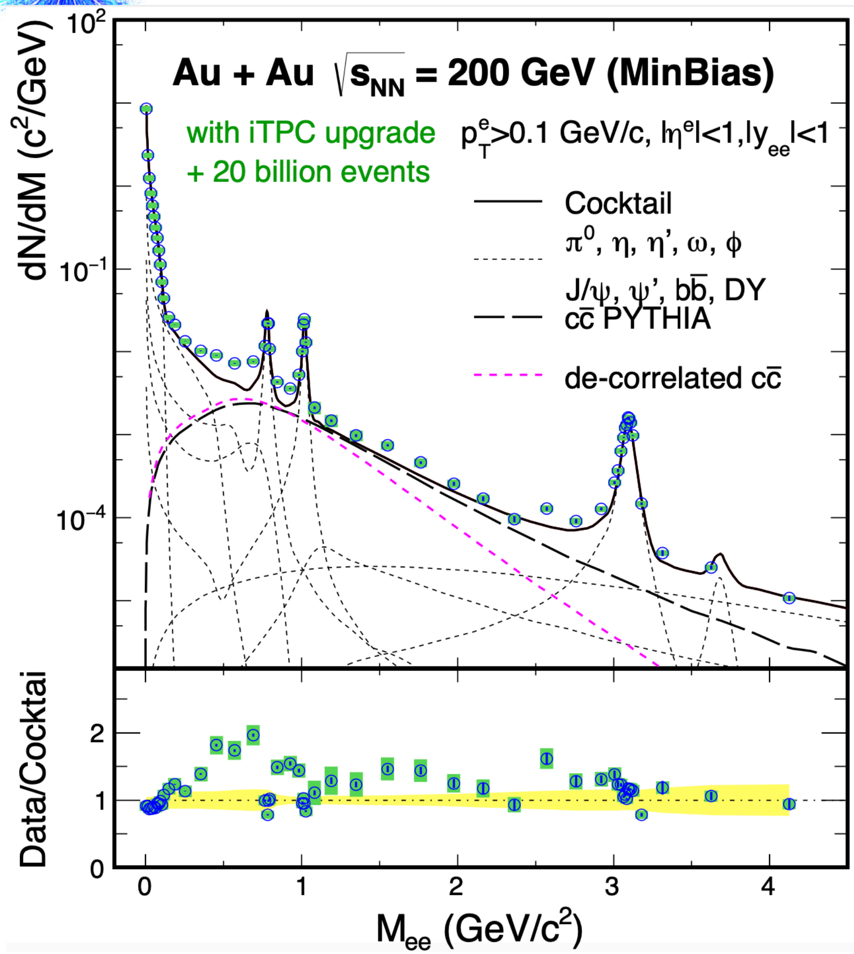


Lattice QCD predicts a sign change of susceptibility ratio χ_6^B/χ_2^B at T_C
The cumulants of net-proton distribution sensitive to chiral cross over transition at μ_B=0

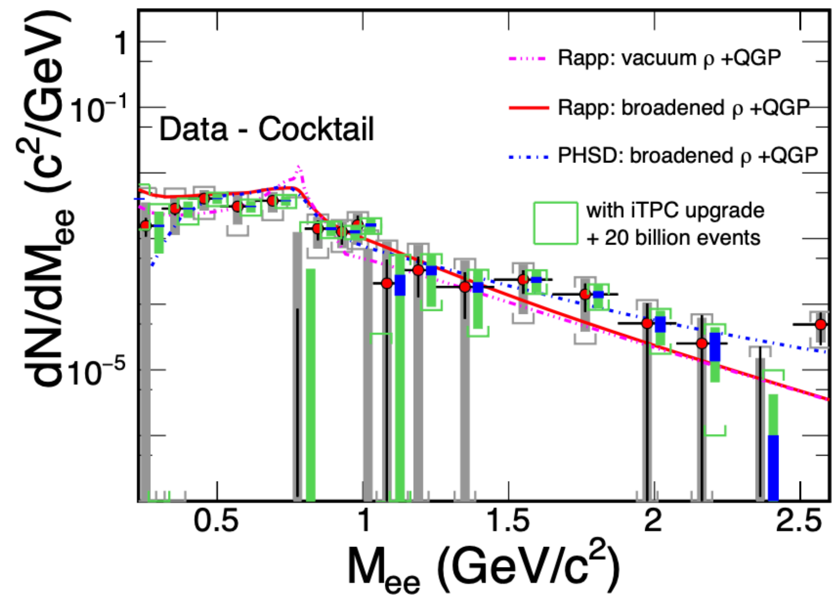
Observed a hint of a sign change from 54 GeV to 200 GeV
C_6/C_2 < 0 at central 200 GeV
C_6/C_2 > 0 at central 54.4 GeV

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



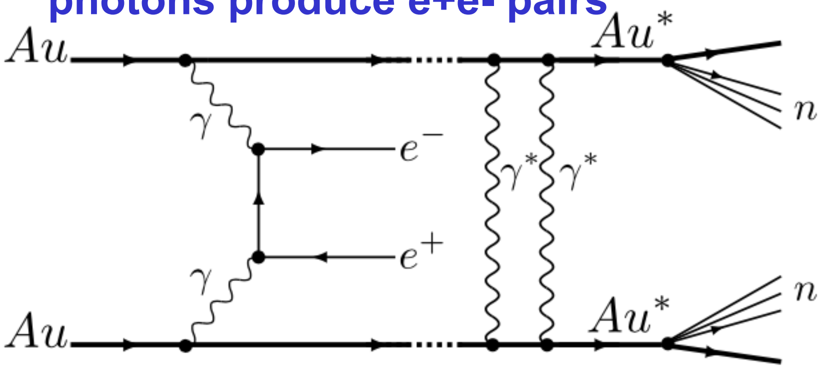
Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B=0

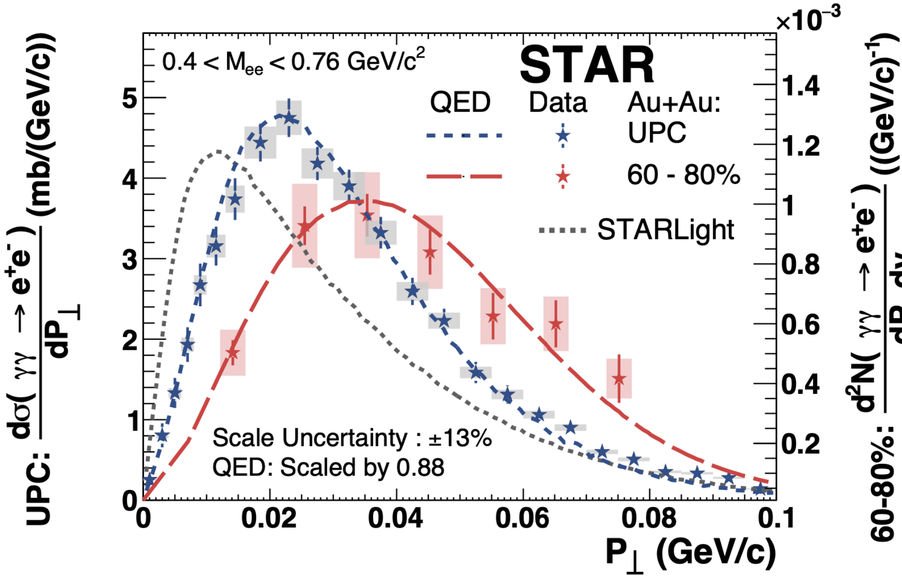
Intermediate mass: direct thermometer to measure temperature

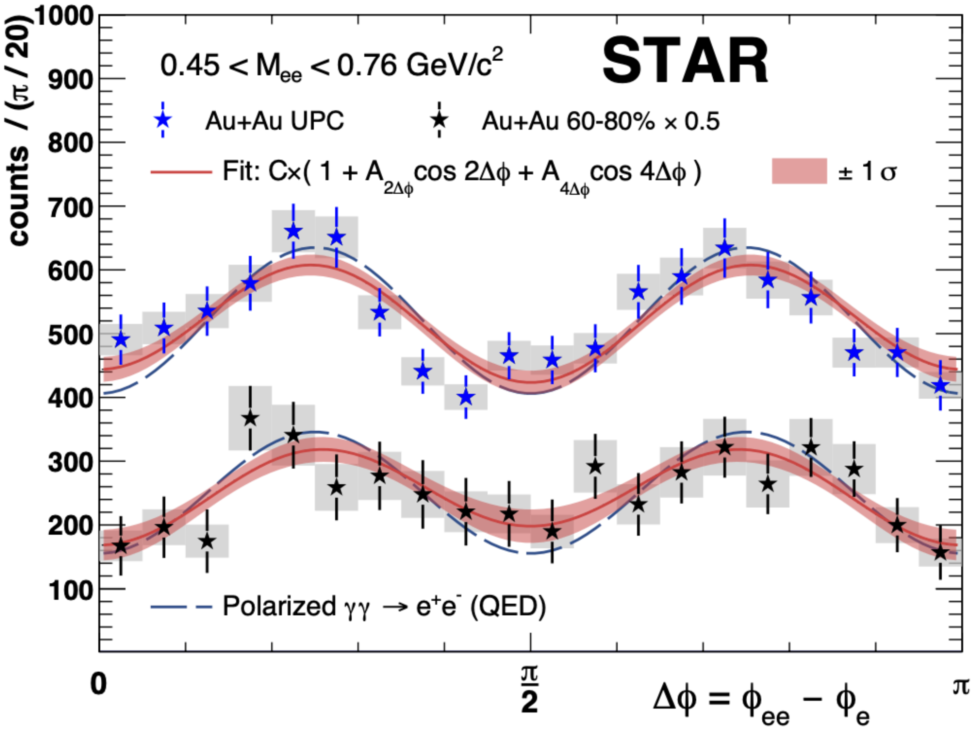
Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

Discoveries of Breit-Wheeler process and vacuum birefringence

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







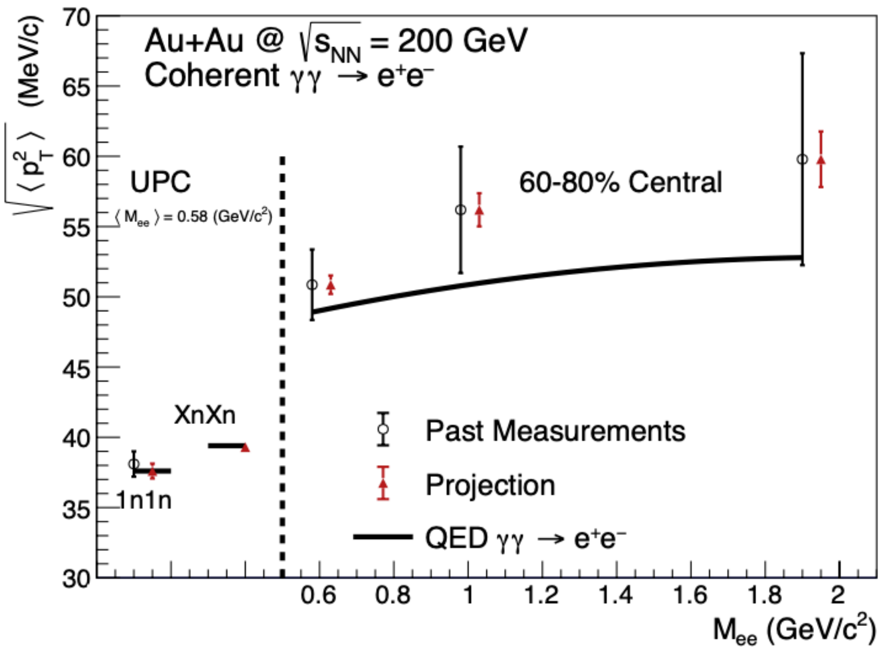
arXiv: 1910.12400

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

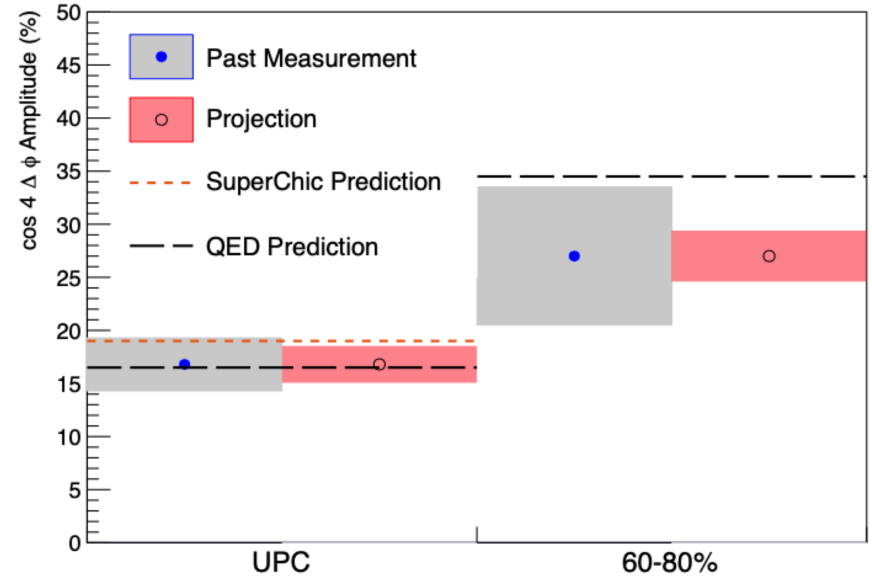
Dielectron p_T spectrum: broadened from large to small impact parameters

Observation of vacuum birefringence: 6.7σ in UPC

Photon Wigner function and magnetic effects in QGP



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



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

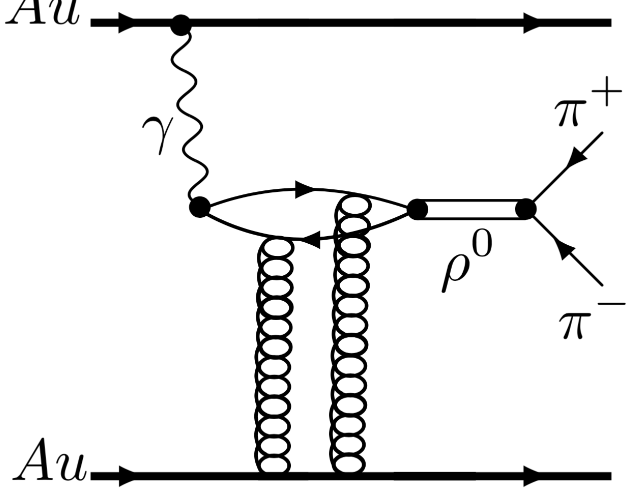
Is there a sensitivity to final magnetic field in QGP?

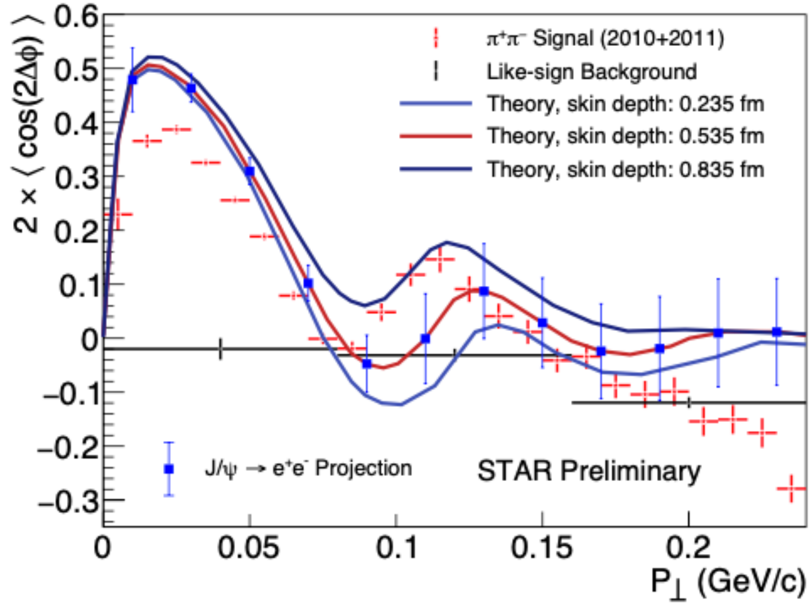
Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.

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

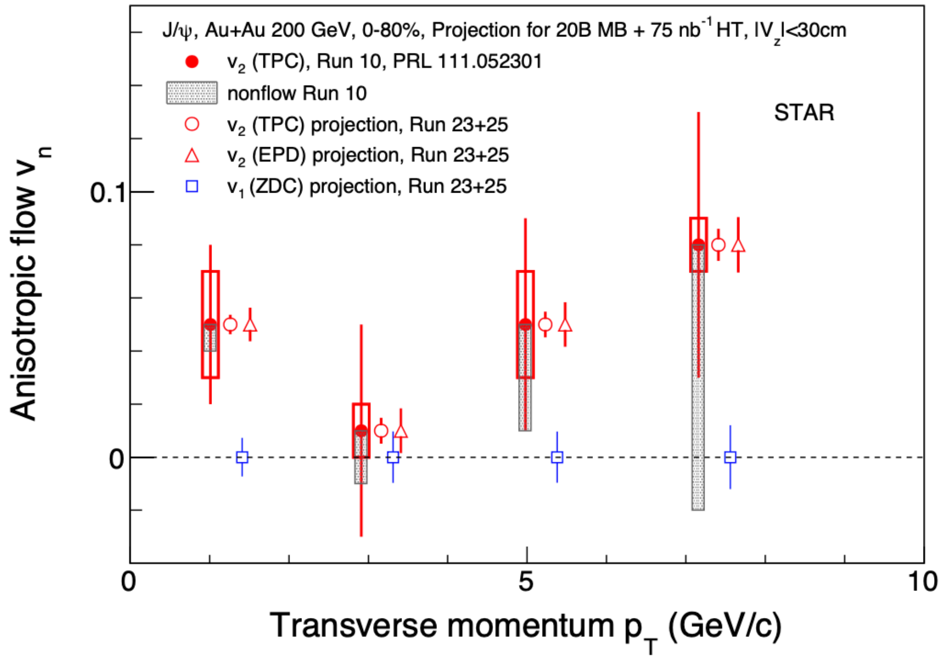
Run23+25:

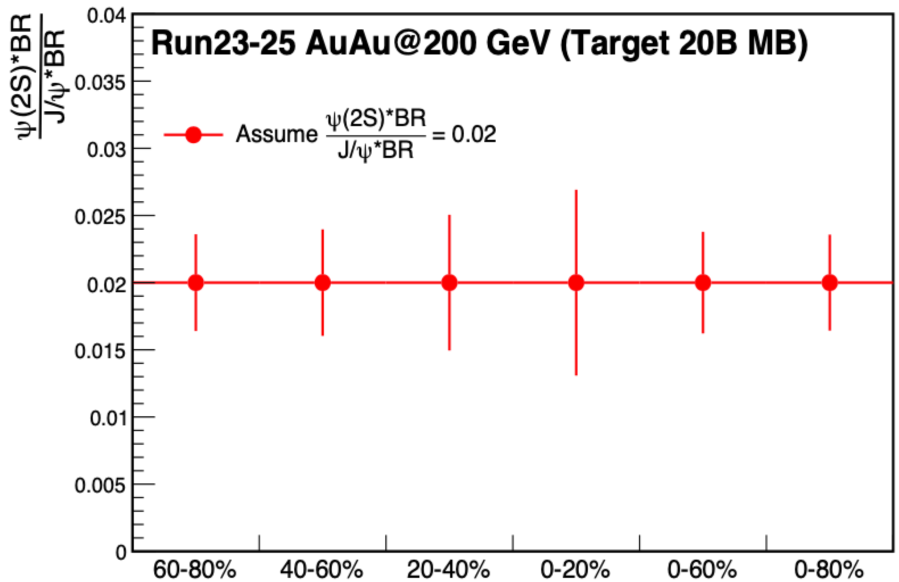
multi-differential measurements (vs. mass, rapidity, p_T): provide strong theoretical constraints, separate ρ^0 from continuum (Drell-Soding), investigate how double-slit interference mechanism affects the structure

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

Deconfinement and thermalization

low material, improved PID, extended η coverage by iTPC





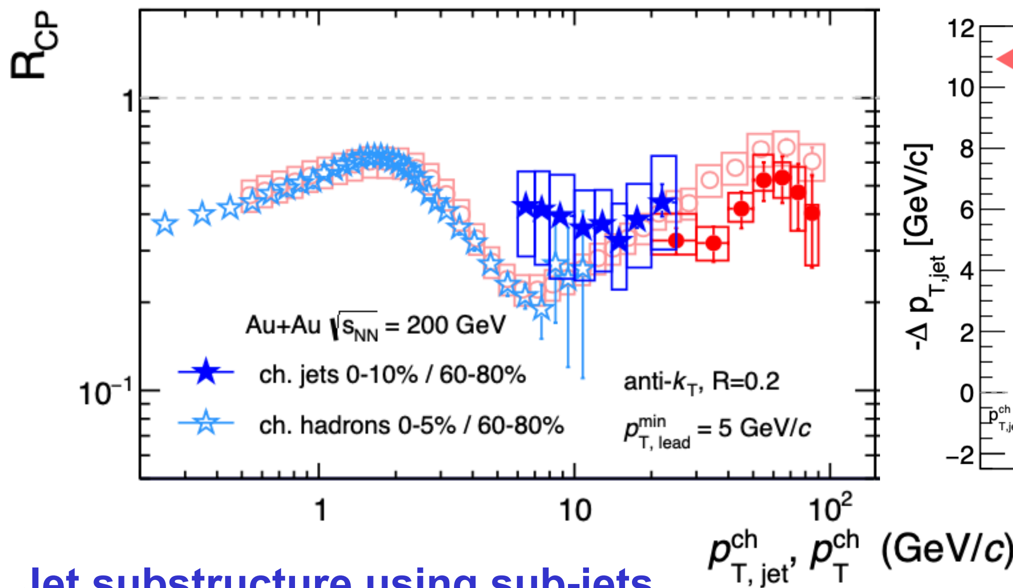
J/ψ: interplay of color-screening and recombination, signature of deconfinement

- **low p_T v_2: recombination**
- **v_1: initial tilt of the bulk medium**

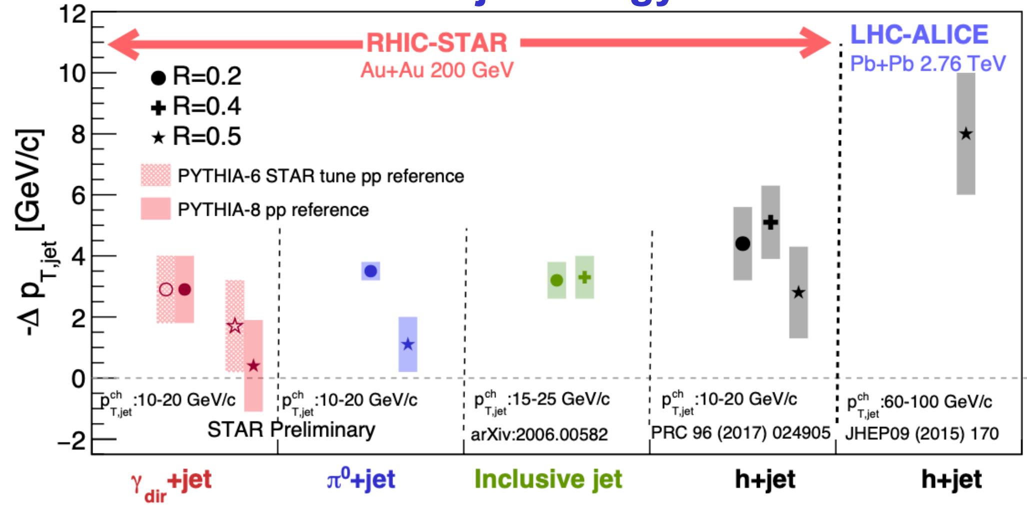
ψ(2S) suppression: explore temperature profile of the medium

Jet quenching: recent measurements

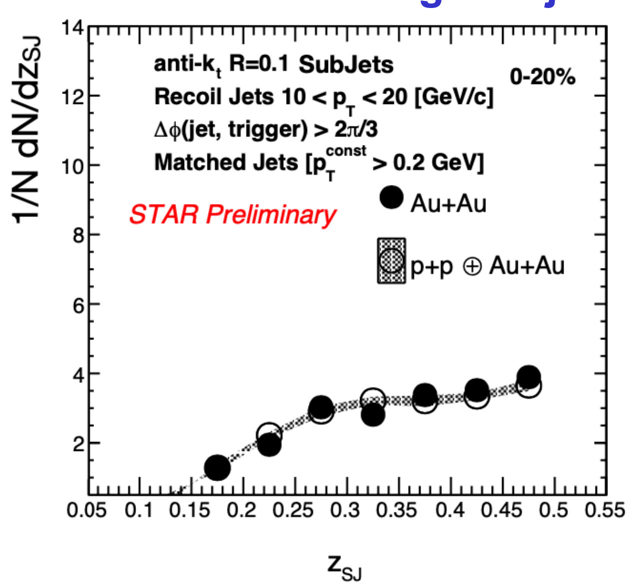
inclusive charged jet suppression

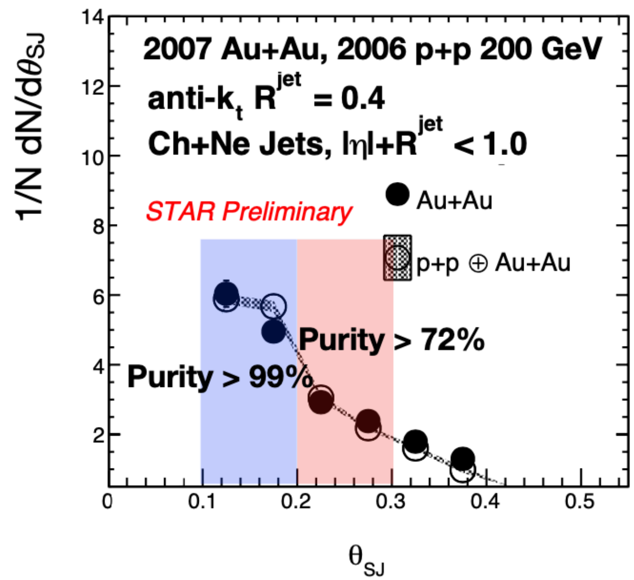


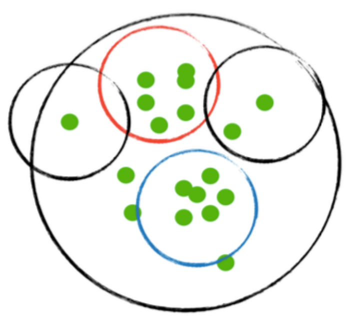
Out-of-cone jet energy loss



Jet substructure using sub-jets







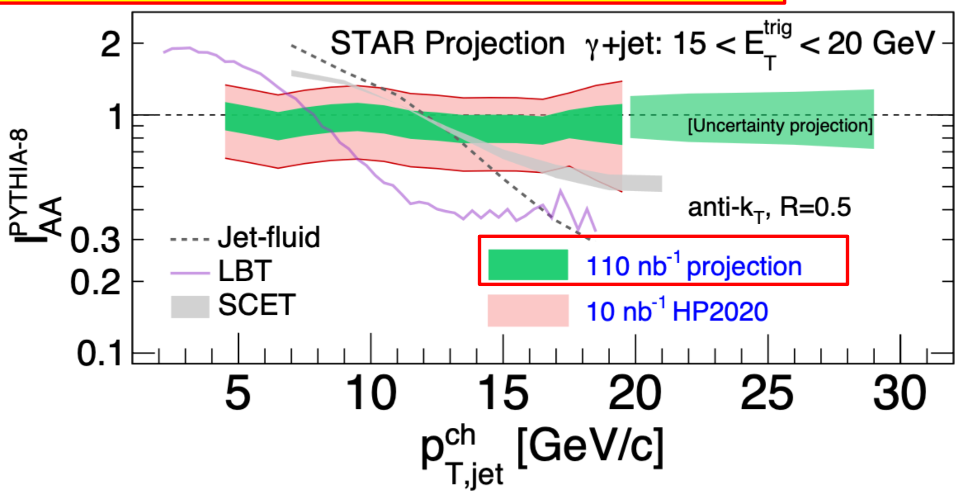
Red: leading sub-jet
Blue: sub-leading sub-jet
$Z_{SJ}=p_T^{blue}/(p_T^{blue}+p_T^{red})$
$\theta_{SJ}=\Delta R(\text{blue,red})$

Recoiled jets within selected di-jets

Recoiled jet p_T>10 GeV constituents p_T>0.2 GeV

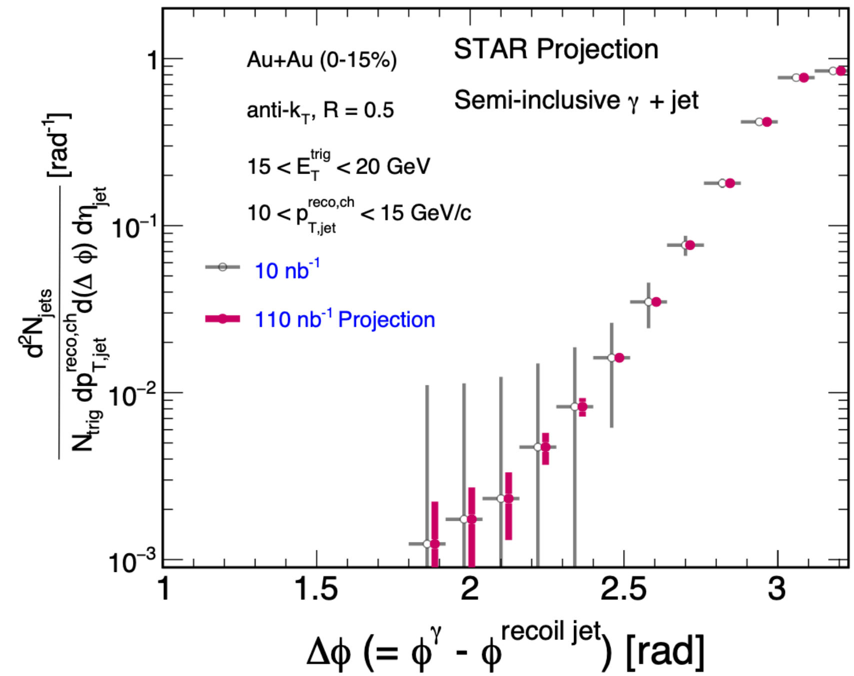
Jet quenching

low p_T, large R, extended to higher p_T

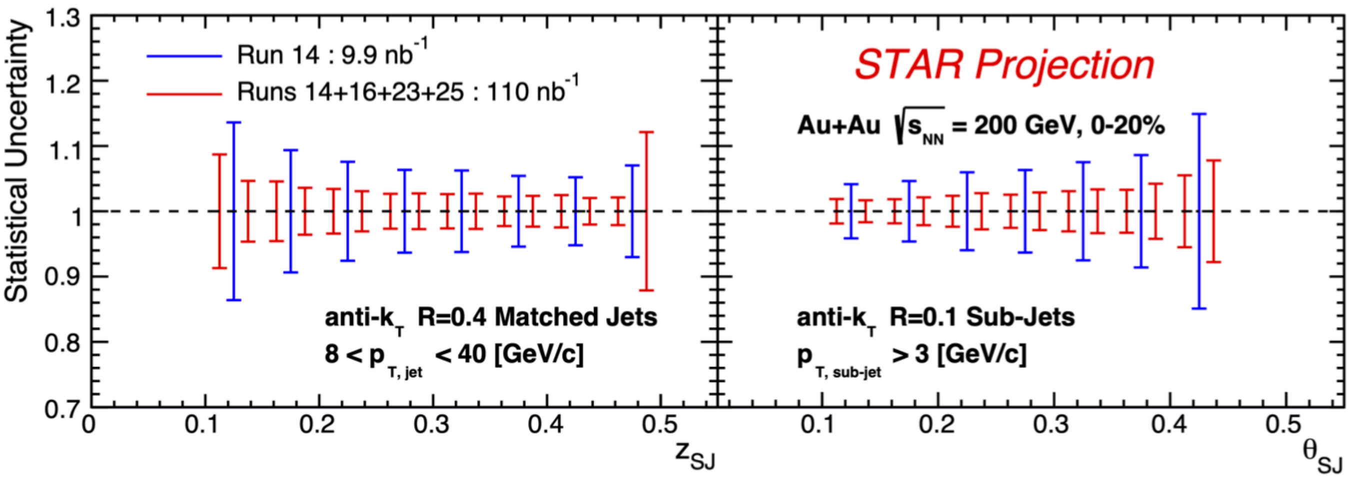


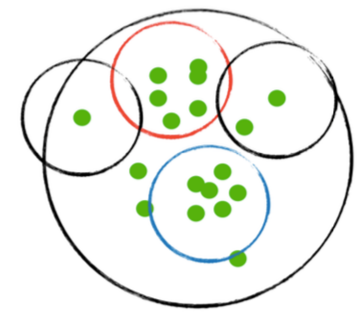
Semi-inclusive γ_{dir}+jet suppression

γ_{dir}+jet acoplanarity: constituents of medium



improved opening angle resolution by a factor of 4





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Jet substructure: coherence vs. de-coherence

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?
- What is the nature of the 3-dimensional initial state at RHIC energies?
- 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?
- What is the precise nature of the transition near μ_B=0?
- What is the electrical conductivity, and what are the chiral properties of the medium?
- What can be learned about confinement and thermalization in a QGP from charmonium measurement?
- 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?

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

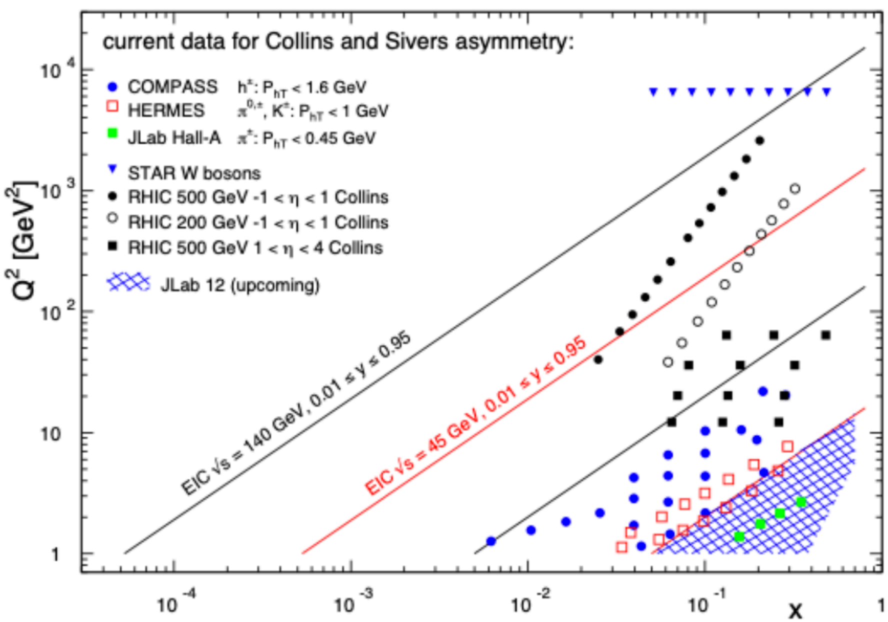
Plans for Run-24

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Date
200	Au+Au	10B / 38 nb^{-1}	2023
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024
200	Au+Au	10B / 52 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

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



Physics Opportunities in 2024

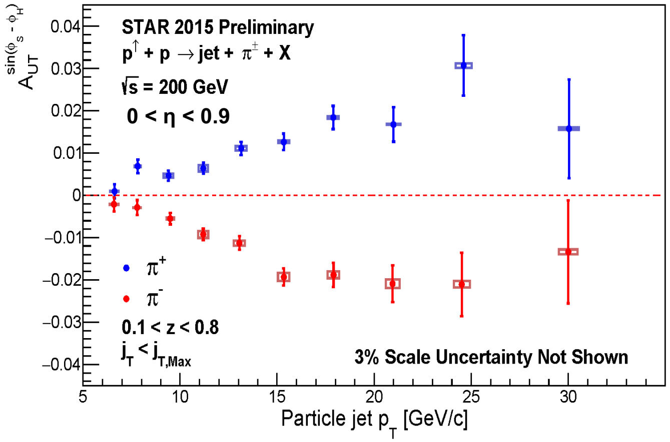
Central role played by 200 GeV pp:

- 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 GeV pp with the Forward Upgrade provides access to the highest and lowest *x* values 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**

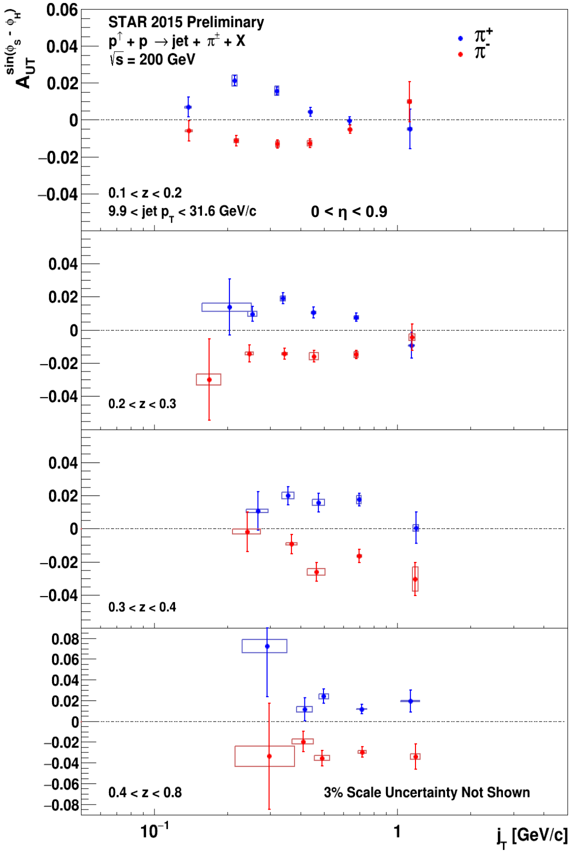
- 200 GeV pp essential baseline for 200 GeV p+Au
  - Must investigate **gluon saturation in both pA and eA to verify universality**
  - Precise probe of **the quark-gluon structure of heavy nuclei**
  - Explore the **propagation and hadronization of colored partons**

Must measure non-perturbative part of TMD experimentally!

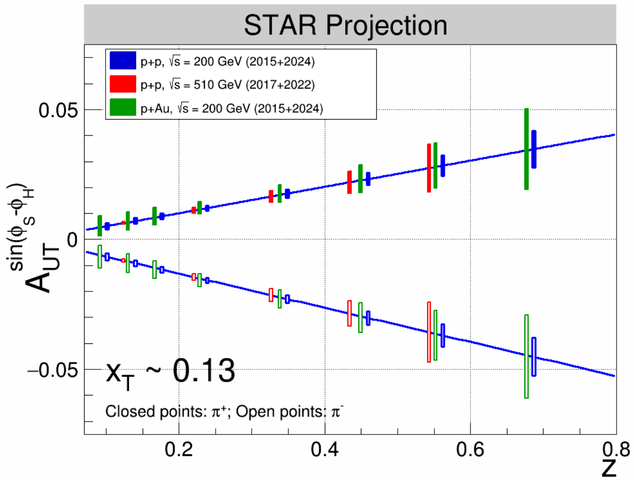
Example: mid-rapidity Collins effect at 200 vs 510 GeV



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



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



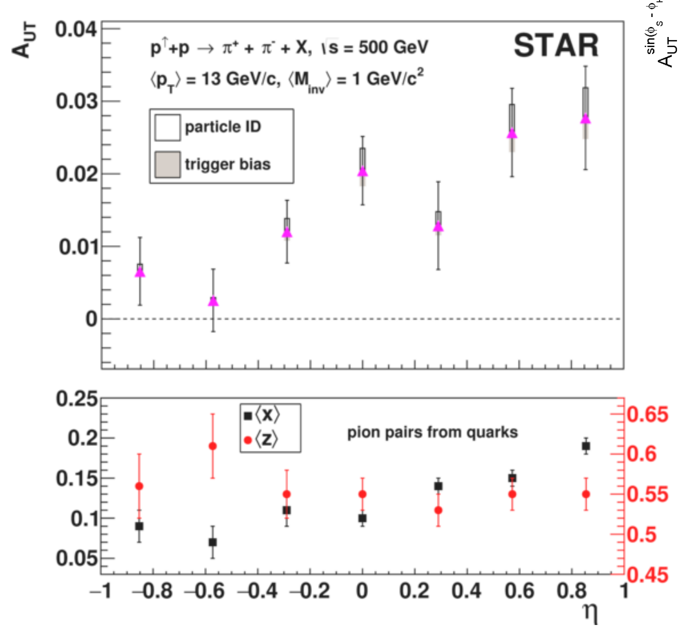
Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential x-Q^2 overlap with EIC

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

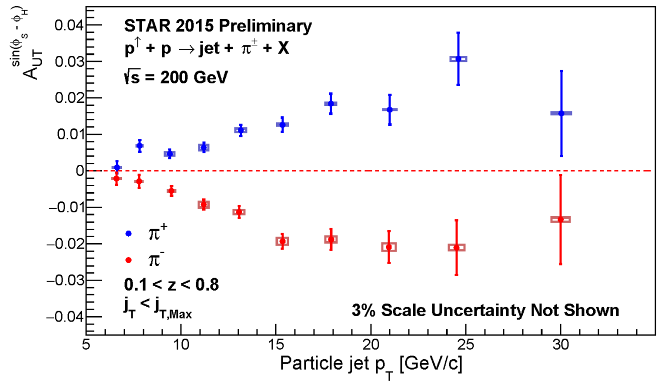
- **Run-24 will reduce these uncertainties at 200 GeV by a factor of 2.5, enabling the most sensitive universality test with EIC data**

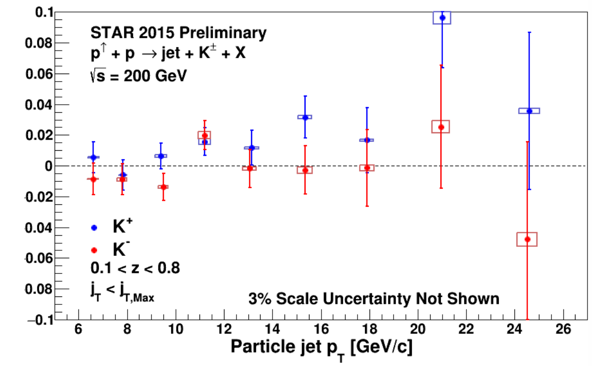
iTPC in mid-rapidity IFF and Collins: η dependence and PID

STAR IFF, PLB 780, 332



STAR 2015 Collins, preliminary



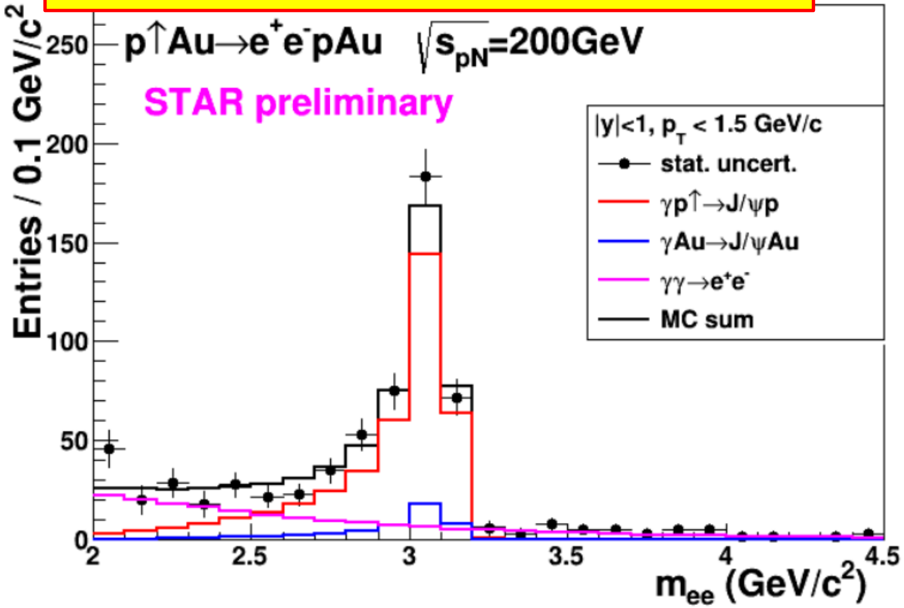


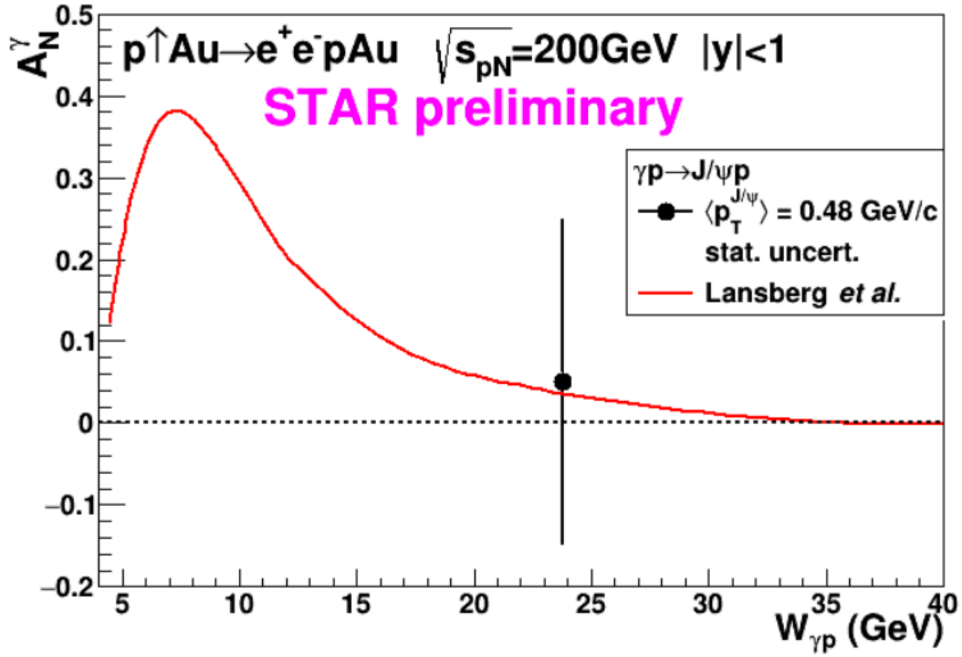
- Forward η increases:
  - Quark fraction (no gluon transversity)
  - <x>
  - Polarization transfer in hard scattering
- iTPC will add coverage of 1 < η < 1.5 for both IFF and Collins asymmetries

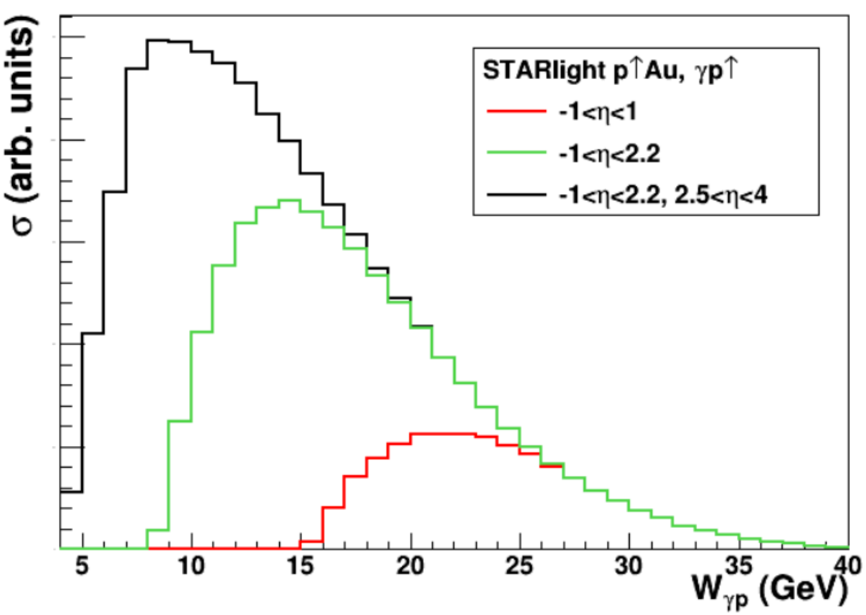
- Different Collins and IFF asymmetries for different particle types
  - K^+ about 1.5-sigma larger than π^+ (note diff vert scales)
  - K^- (and p/pbar in backup) consistent with zero in 2015
  - Similar π/K behavior seen in SIDIS
- Particle identification essential to maximize impact
- iTPC increases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







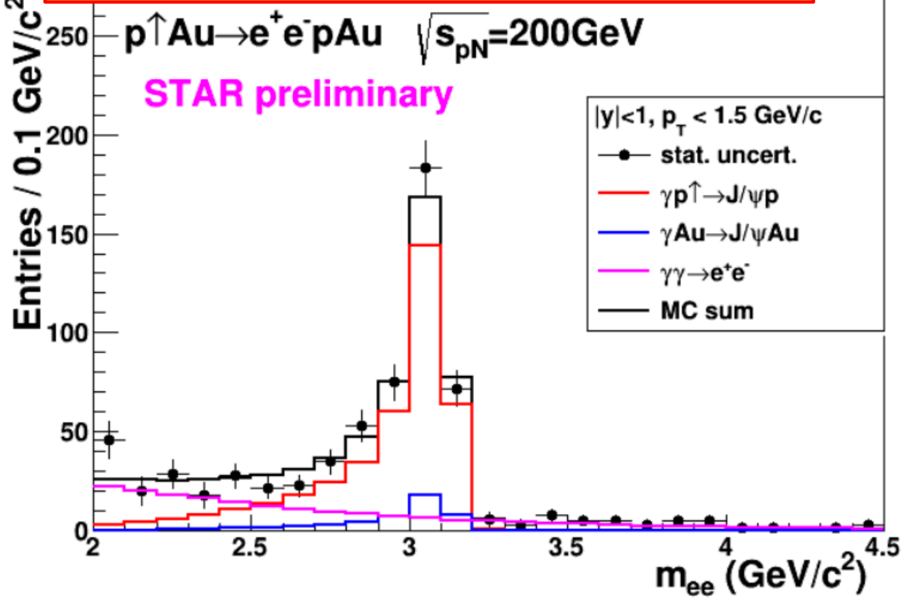
Exclusive J/ψ A_N in UPC, Q^2~10 GeV^2, $10^{-4}<x<10^{-1}$

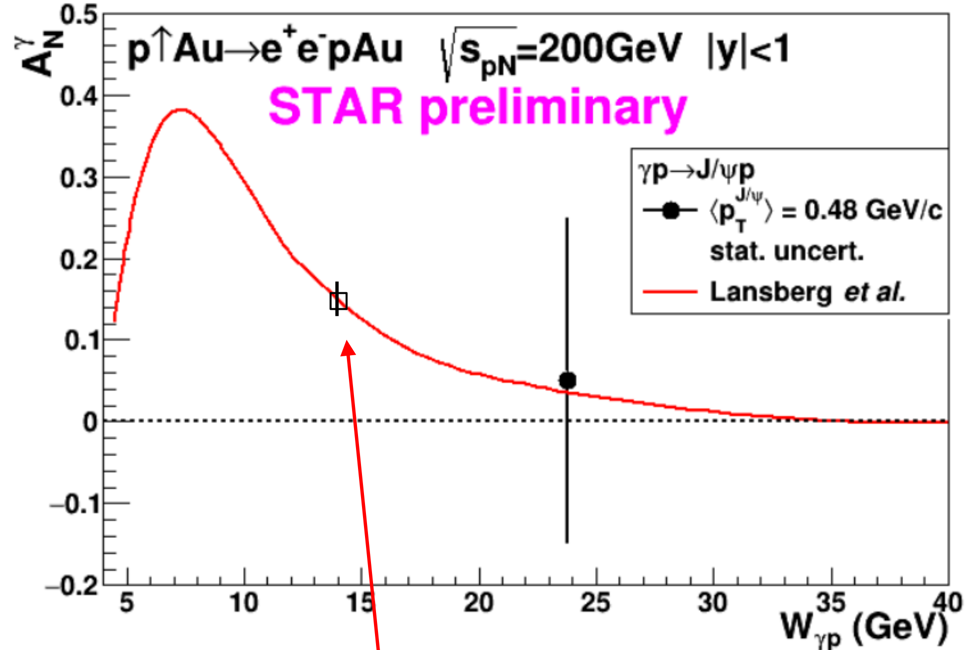
Access GPD Eg for gluons, sensitive to spin-orbit correlation

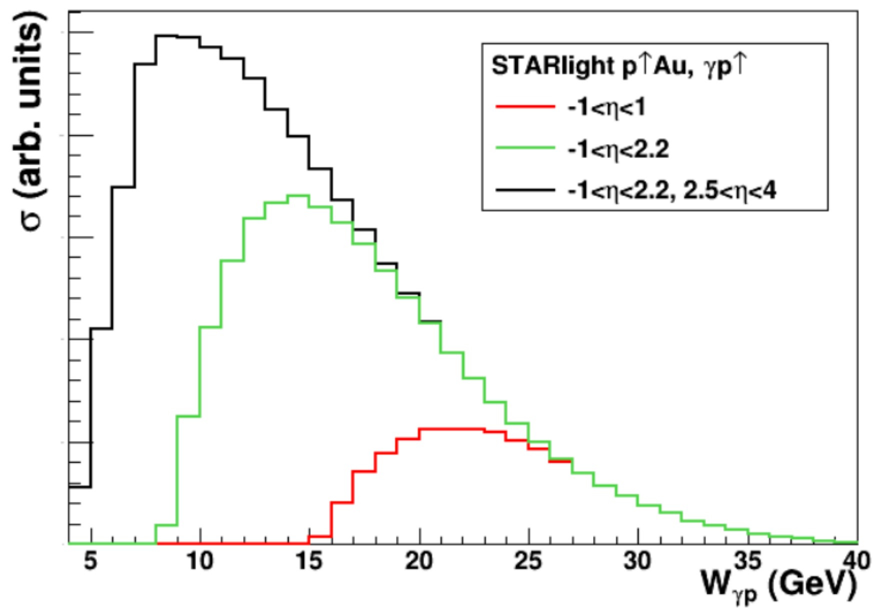
Run-24: a factor of 9-10 more data, combined with iTPC and forward upgrades, stat. error for A_N^{γ}: 0.02 for $<W_{\gamma p}>$=14 GeV, where the signal is expected to be large.

Generalized parton distribution

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







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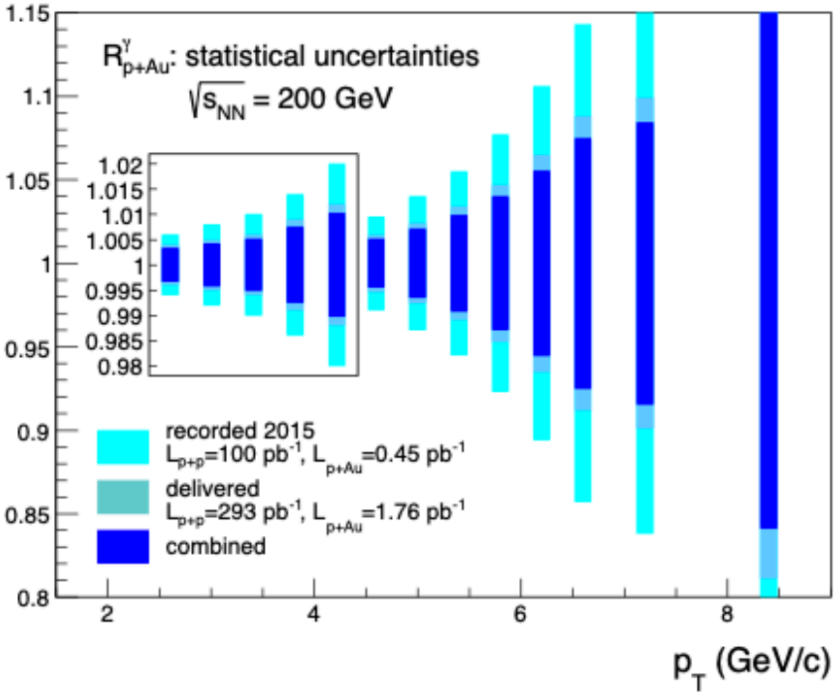
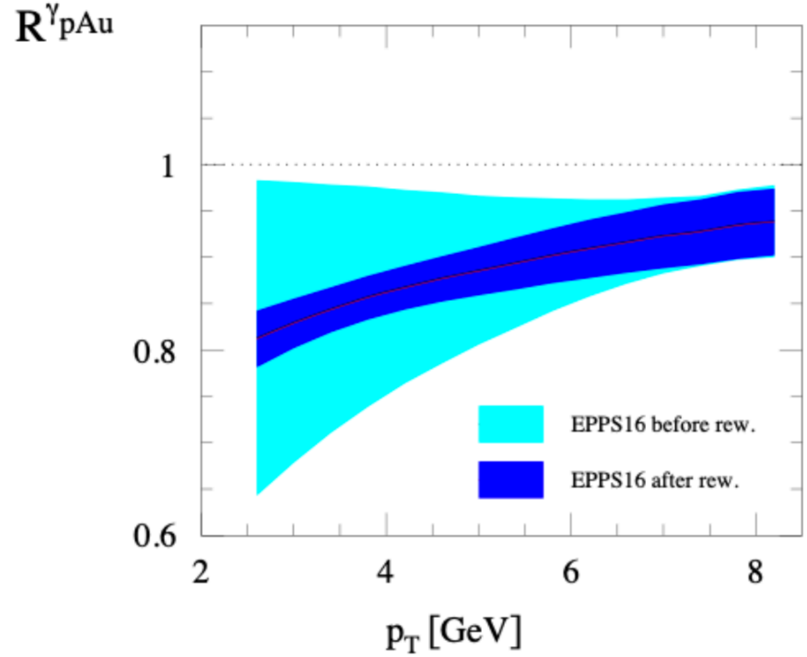
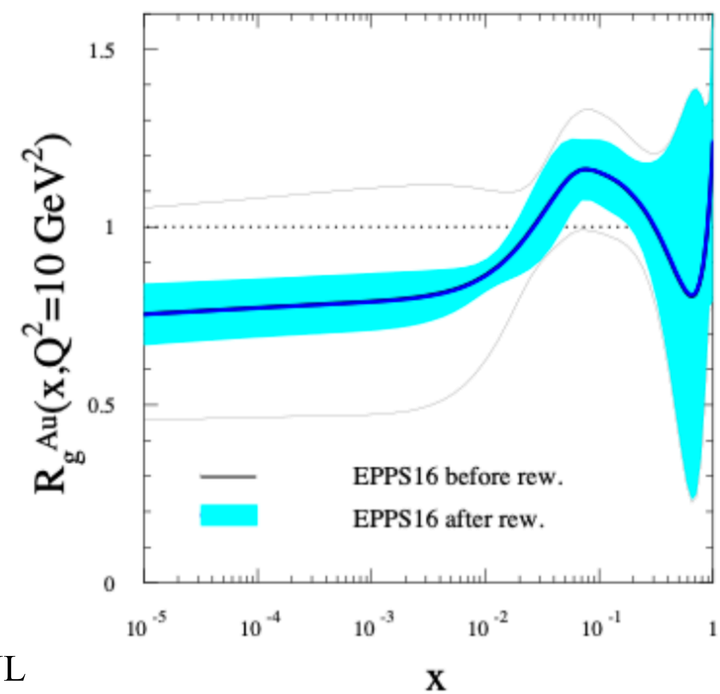
low material, forward upgrade

Nuclear PDF





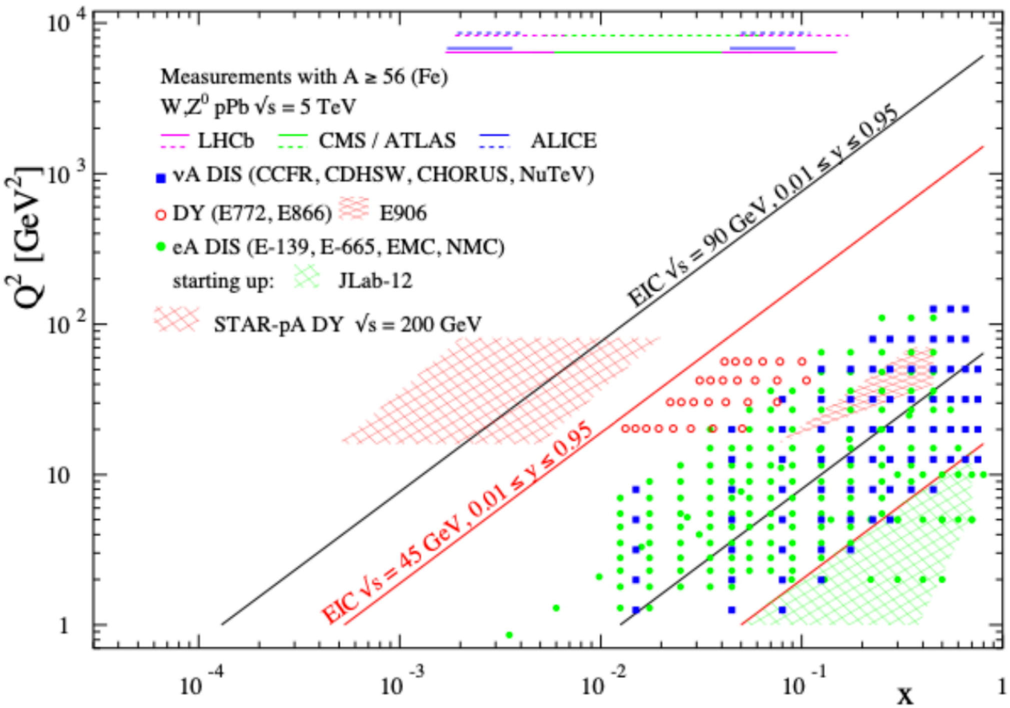


Direct photon measurement: constrain nuclear gluon distribution in a broad x range

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

Nuclear PDF

low material, forward upgrade



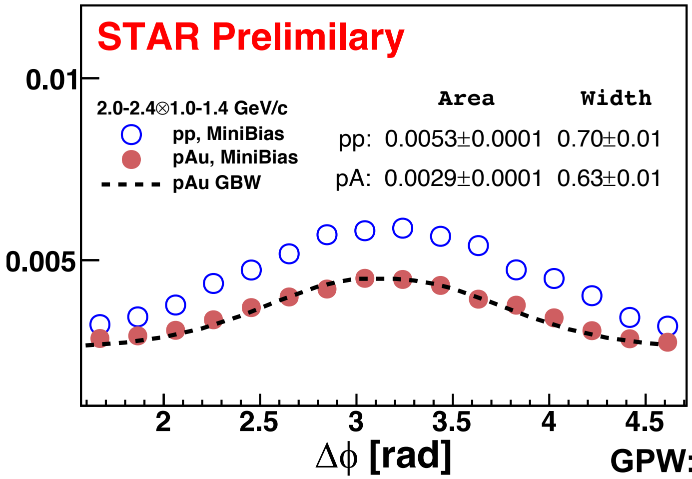
Small DY cross section (10^{-6}-10^{-5} of hadron): need suppressed hadron to the order of 0.1% while maintaining a decent electron efficiency

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

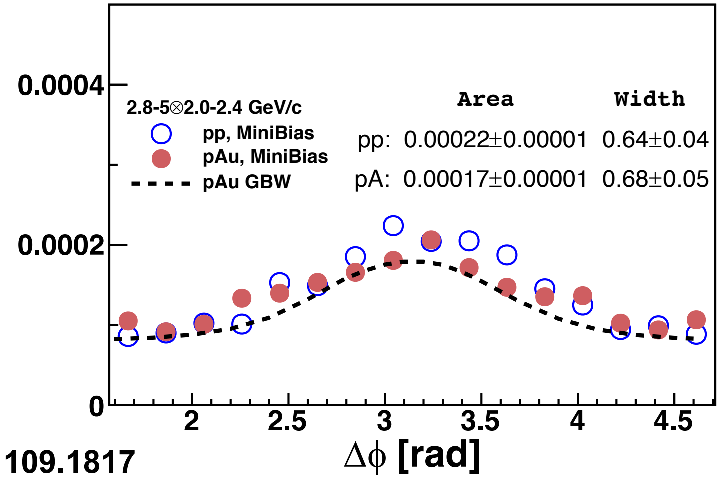
Drell-Yan : constrain nuclear sea quark distribution in a broad x range

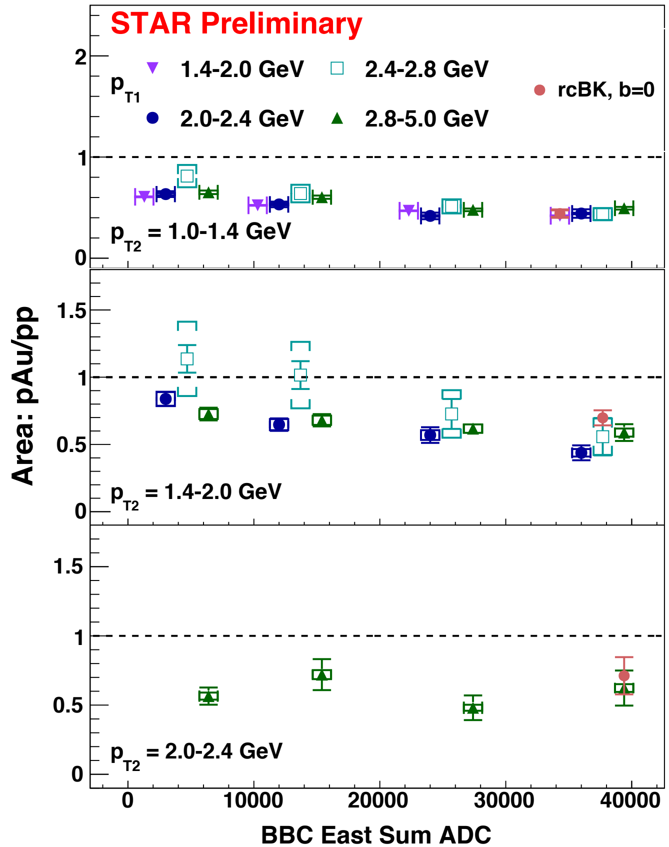
Essential in testing fundamental universality properties of nPDFs combined with data from EIC

Gluon saturation



GPW: arXiv:1109.1817



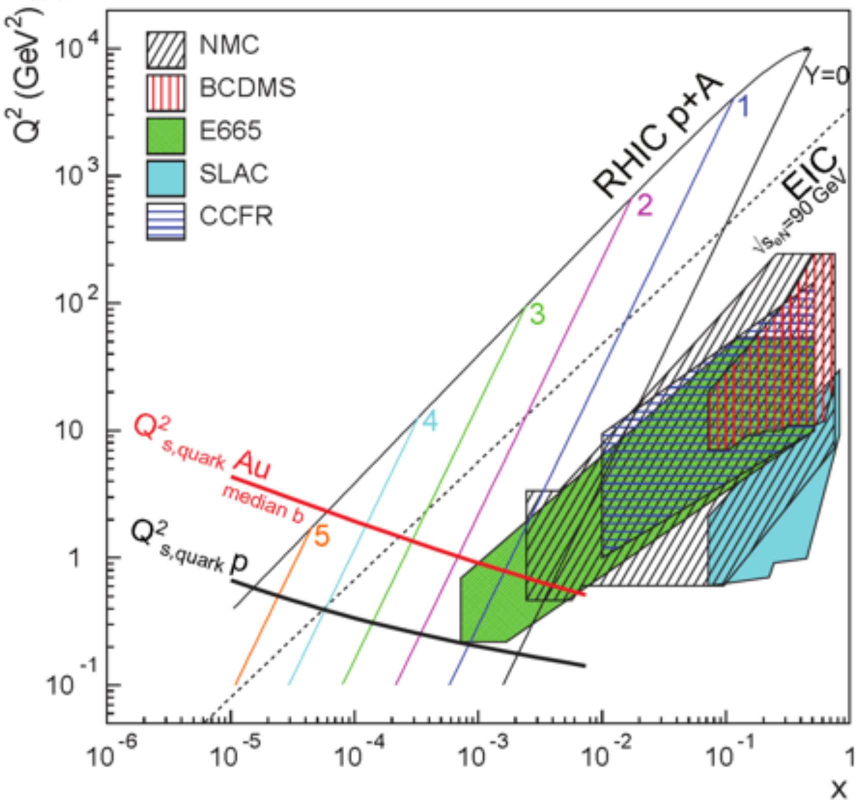


rcBK: arXiv:1805.05711

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

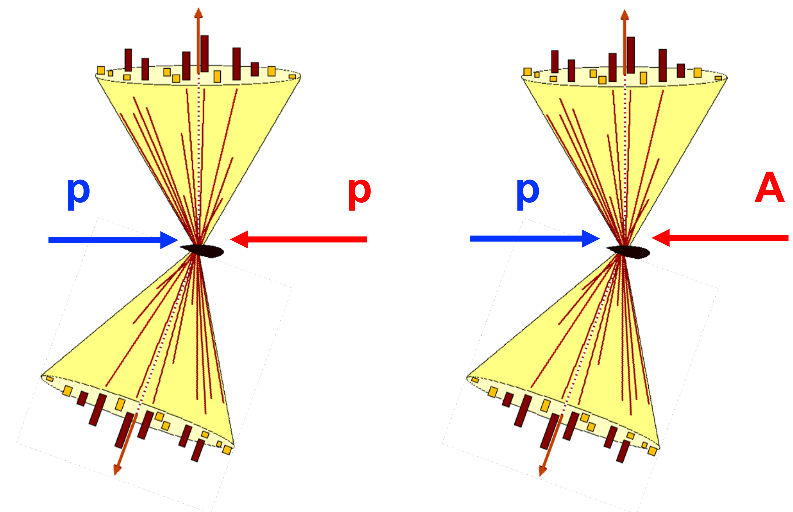
probe x down to 10^{-3}

Gluon saturation



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

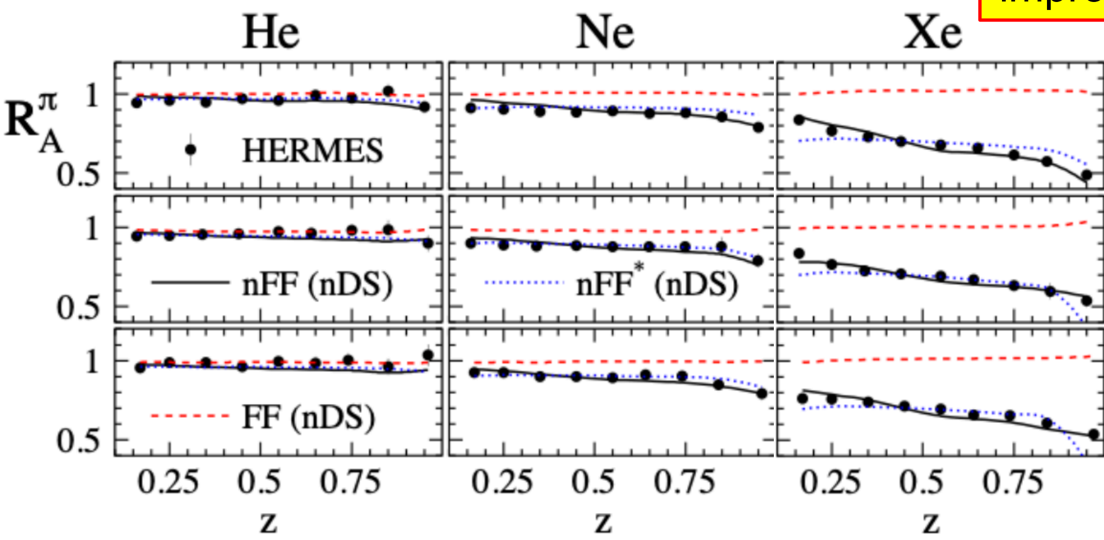
→ proton – Au collisions

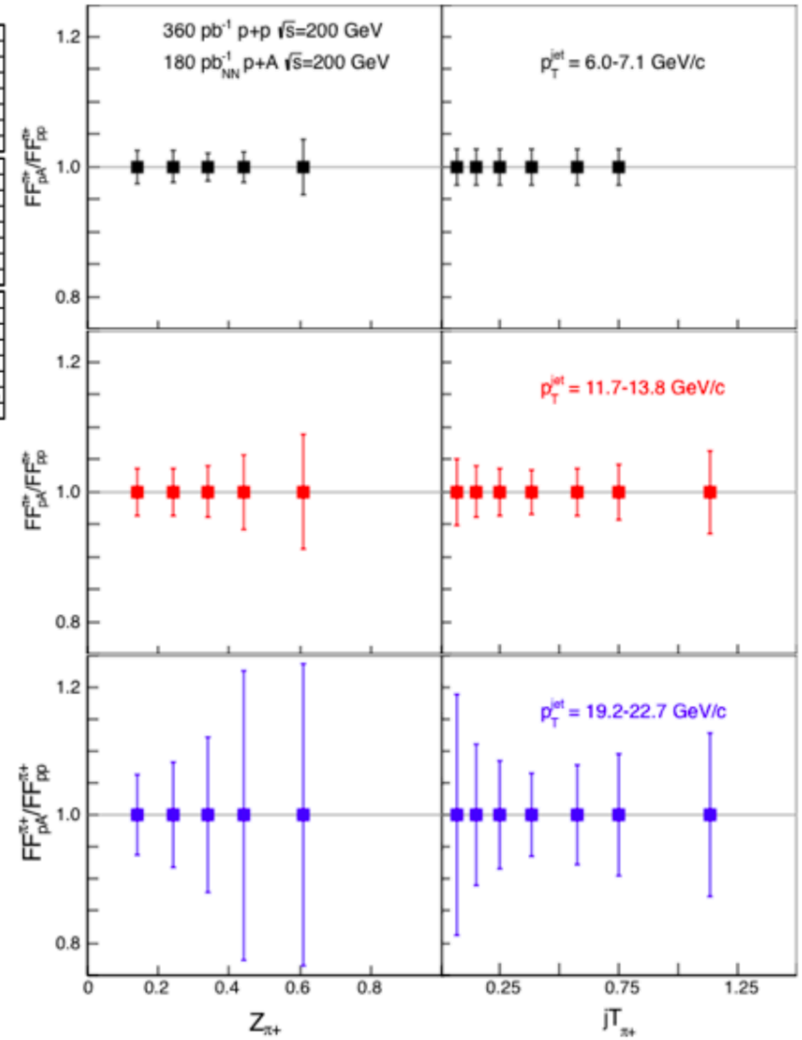
combined with an unambiguous observable

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.

Summary of 2024

200 GeV pp:

- Very wide x coverage ($0.005 < x < 0.5$) by combining 200 and 510 GeV pp
  - 510 GeV pp with the Forward Upgrade provides access to the highest and lowest x values 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
- Essential baseline for 200 GeV p+Au

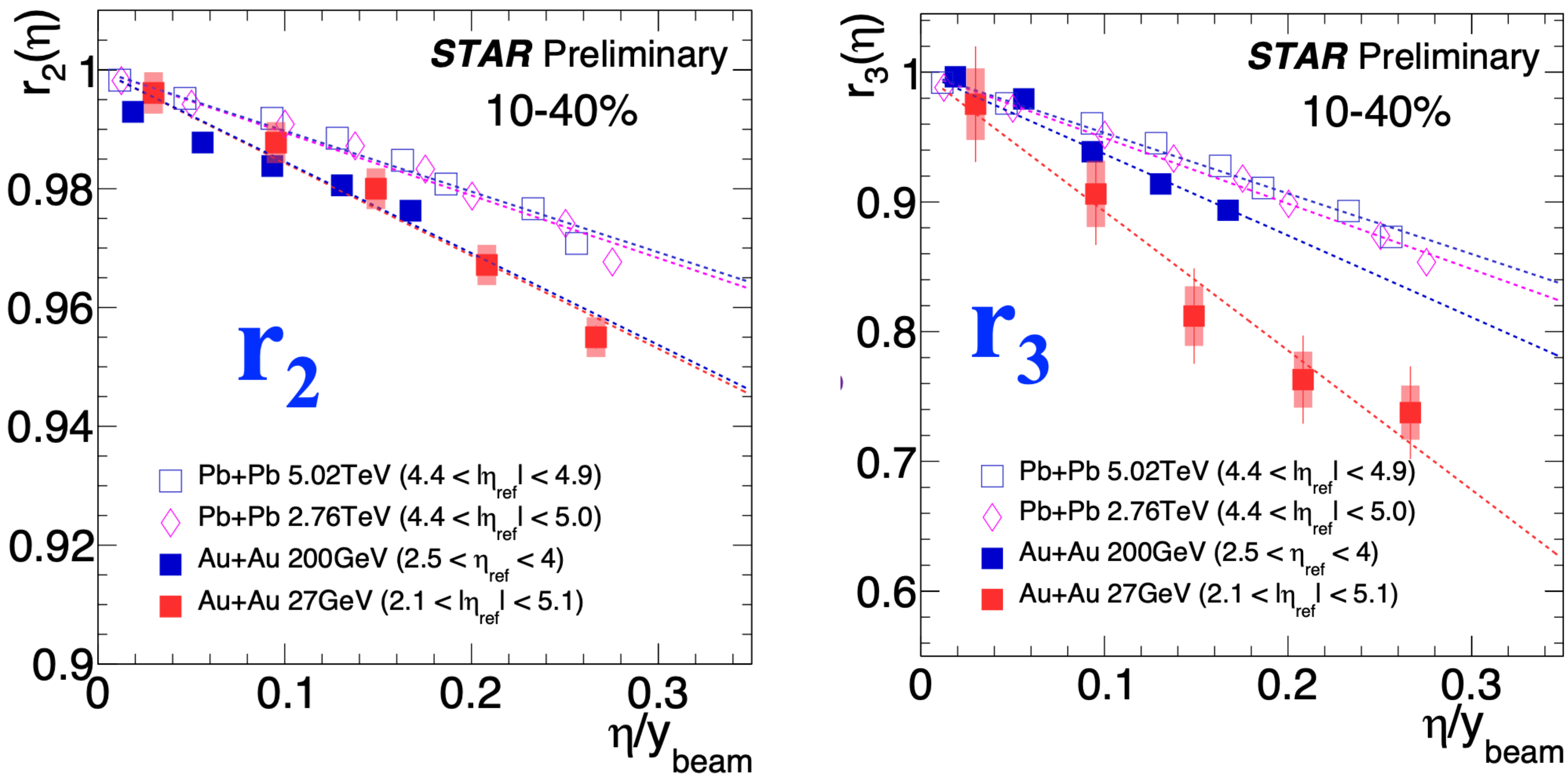
200 GeV p+Au:

- **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

Fully utilize forward upgrades and excellent PID over extended η coverage

Backup

De-correlation in 27 and 200 GeV Au+Au



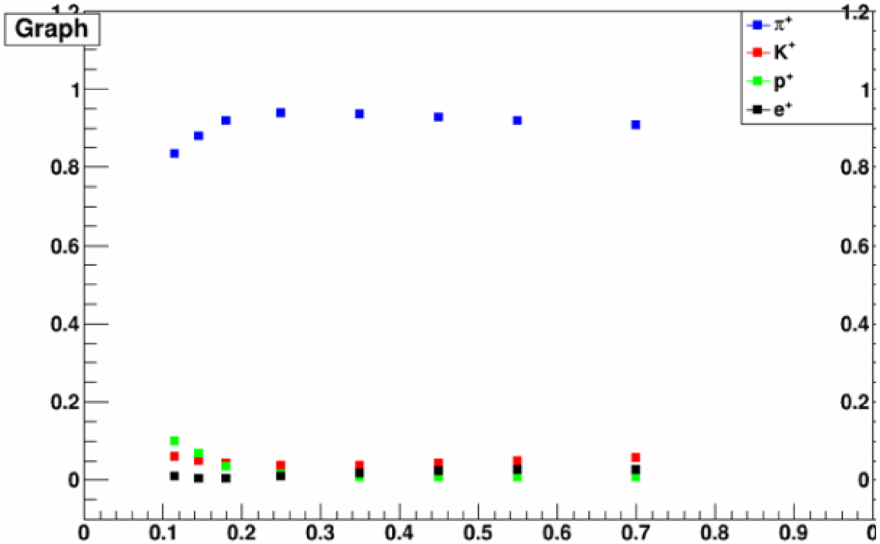
200 GeV AuAu in 2023-2025

STAR is in a unique position to measure

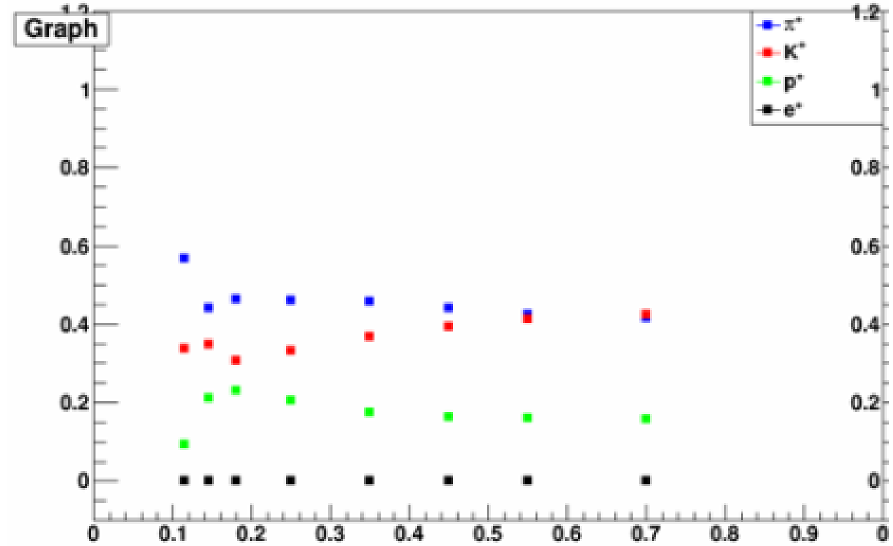
- **v_n vs. η at forward**
- **Decorrelation vs. η up to forward**
- **Net-proton C_6/C_2**
- **Dielectron**
- **$\gamma\gamma \rightarrow e^+e^-$**
- **$\gamma p \rightarrow \rho X \rightarrow \pi^+\pi^- X$ and $\gamma p \rightarrow J/\psi X \rightarrow e^+e^- X$**
- **Parton energy loss for jets of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

Identified particle composition in one jet p_T bin

Pion-rich dE/dx region

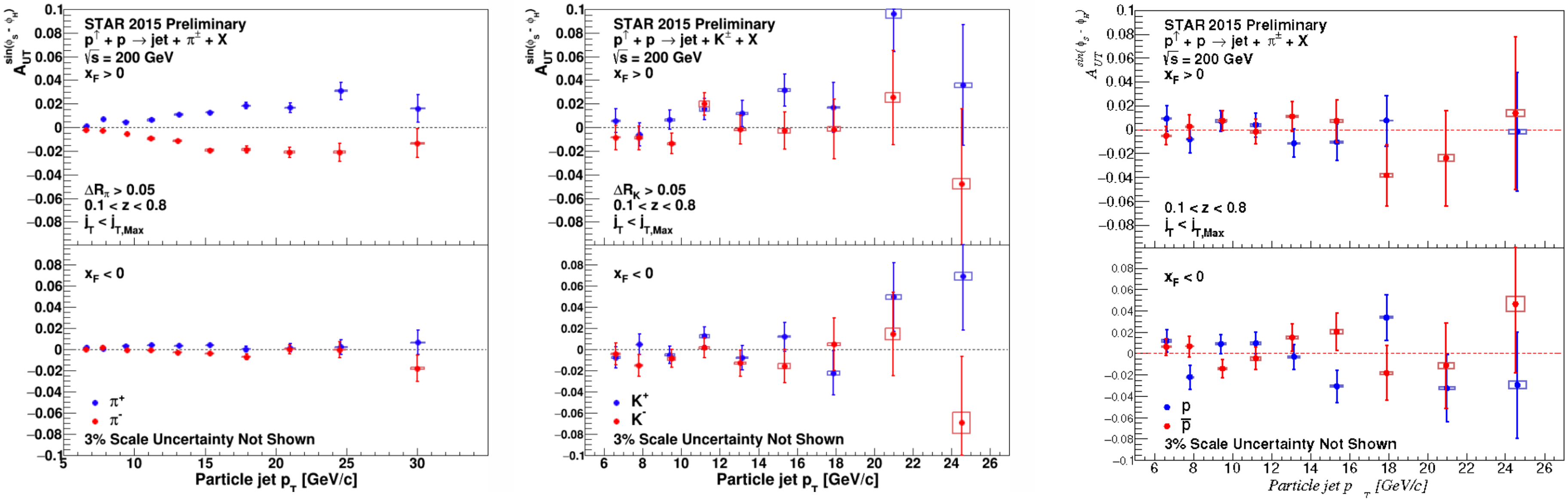


Kaon-rich dE/dx region



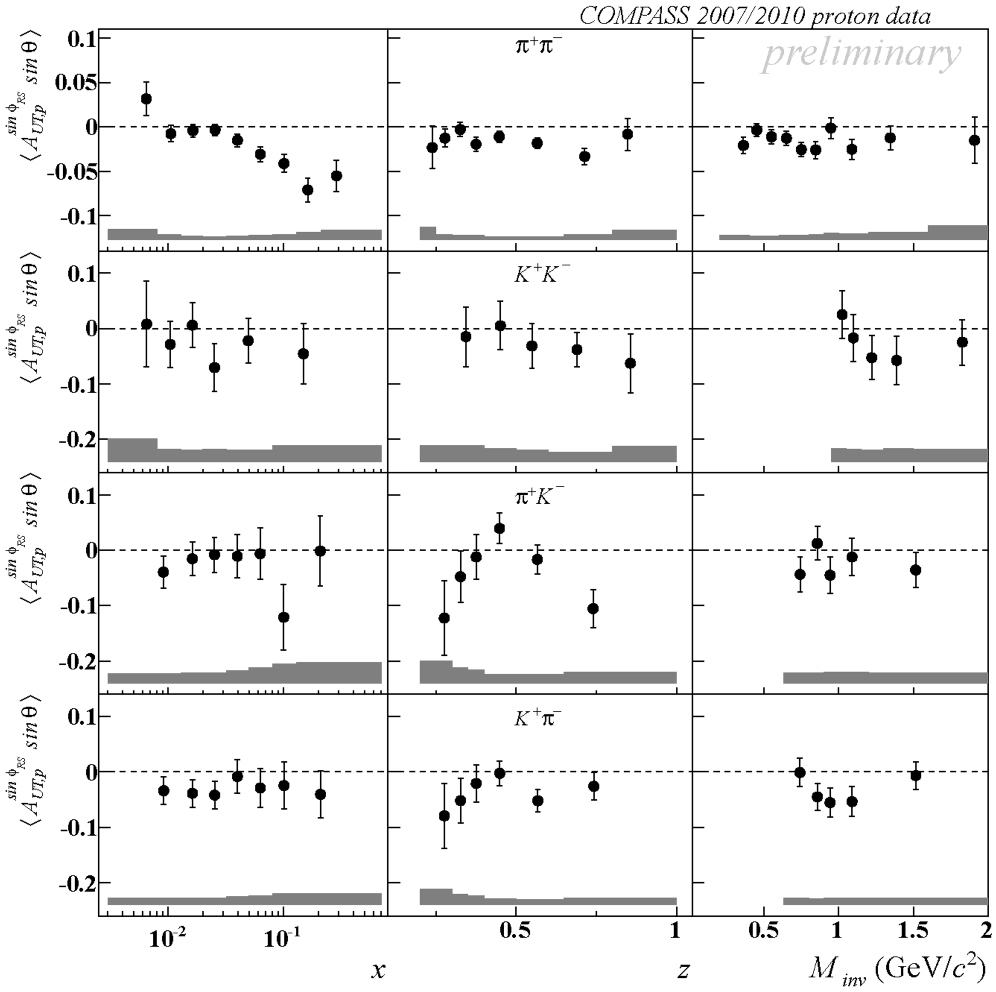
- Fractions of π^+, K^+, p, and e^+ in jets with $11.7 < p_T < 13.8$ GeV/c as a function of z in the 200 GeV 2015 Collins effect measurement (negative hadrons behave similarly)
- Note that, with 2015 dE/dx resolution, the kaon-rich region contains more pions than anything else, but far fewer than in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