Heavy-Ion Proposal Runs 23-25
Exploring the QCD Microstructure

Opportunities:

- Upgraded STAR detector (BES-II upgrades, upgraded DAQ, Forward Upgrades)
- Low internal material budget
- Improved RHIC Luminosities

Goals/Questions in the 22-25 BUR:

1. What is the precise temperature dependence of η/s and ζ/s? (v_n vs. η)
2. What is the nature of the 3D initial state? (r_n vs. η)
3. How is the global vorticity transferred to the spin alignment of vector mesons? (Λ vs. J/Ψ)
4. What is the nature of the phase transition near $\mu_B = 0$? (C_6)
5. What are the electrical and chiral properties of the medium? (Dielectrons)
6. What can charmonium tell us about confinement and thermalization of the QGP? (J/ψ)
7. What are the underlying mechanisms of jet quenching? (IAA, acoplanarity, substructure)

Proposed Change in Structure

Last year's proposal was organized in topics by working group and then by "opportunity".

Proposal → Organize the proposal by scientific questions. Go from initial to late stage

Goals/Questions:

1. What is the nature of the 3D initial state? (r_n vs. η) (UPC J/Ψ)
2. What is the precise temperature dependence of η/s and ζ/s? (v_n vs. η)
3. What are the underlying mechanisms of jet quenching? (IAA, acoplanarity, substructure)
4. What can charmonium tell us about confinement (J/ψ v_2)
5. What is the temperature of the medium? (Dielectrons, ψ(2S) suppression)
6. What are the electrical and magnetic properties of the QGP? (Dielectrons, γ Wigner function, Λ and J/Ψ global polarization)
7. What is the nature of the phase transition near μ_B = 0? (C_6)
8. What can we learn about the strong interaction? (Baryon Correlation Functions)

Observable	PGW	MB/H$\mathcal{L}$	Coverage	
$v_2(\eta)$	FCV	Min bias	iTPC FTS	
$r_n(\eta a,\eta b)$	FCV	Min Bias	iTPC, FTS	
v_2 in γ+Au	FCV	Min Bias	iTPC, FTS	
$P_H(h)$	FCV	Min Bias	iTPC, FTS	
P_H of J/Ψ	FCV	Luminosity	iTPC	
Net-p C_6	CF	Min Bias	iTPC	
Baryon CF	CF	Min Bias	iTPC	
γ_{Dir} + jet I_{AA}	Jet Corr	Luminosity		
γ_{Dir} + jet acopl.	Jet Corr	Luminosity		
Jet substruct.	Jet Corr	Luminosity		
J/Ψ v_2	HF	Luminosity	iTPC	
Y(2s) suppress.	HF	Luminosity	iTPC	
Di-elec IMR	LFSUPC	Min bias	iTPC	
Di-elec	LFSUPC	Min Bias	iTPC	
Photon WF	LFSUPC	Min Bias	iTPC	
UPC J/Ψ	LFSUPC	Min Bias	iTPC	

Need to check whether these estimates are consistent with the DAQ expectations.

Need to verify that all subsections use the same numbers of events (or make a table).

Performance assumptions:

- 24 weeks of running
- 85% X 60% (STAR X RHIC) Uptime
- Minimum Bias Rate: 1.5 kHz
- High and low luminosity running periods

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

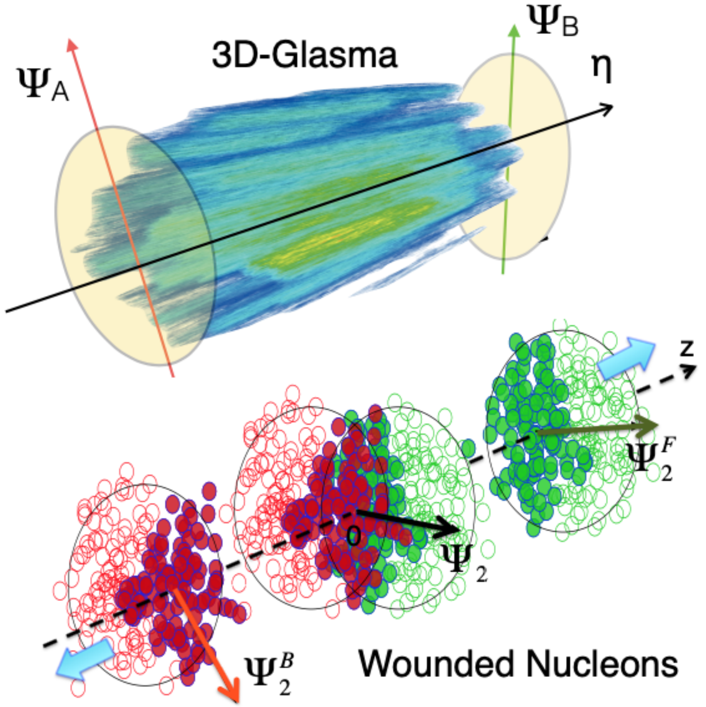
Table 9: STAR minimum bias event statistics and high-p_T luminosity projections for the 2023 and 2025 Au+Au runs. For comparison the 2014/2016 event statistics and luminosities are listed as well.

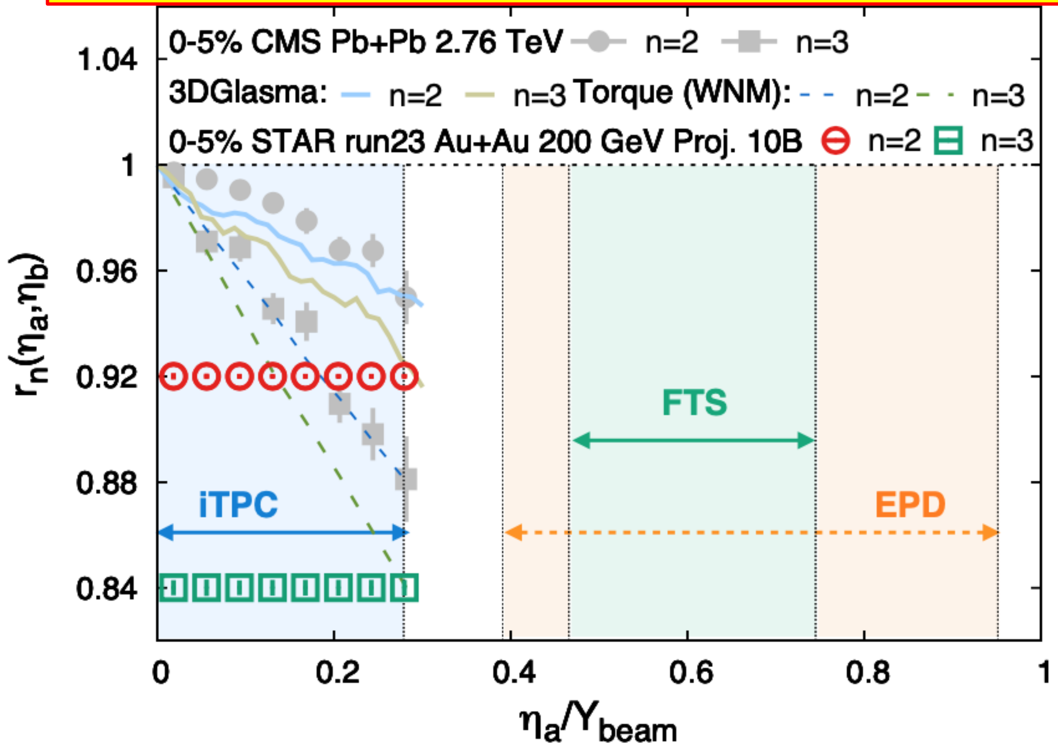
- A factor of 10 more minimum bias data compare to Run-14 + Run-16
- A factor of 2.3 more luminosity for high-p_T trigger

Q1: What is the nature of the 3D initial state?

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:

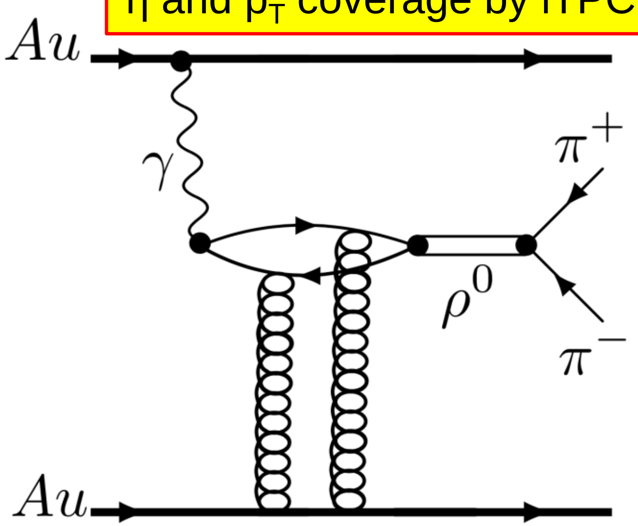
- **3D glasma model: weaker decorrelation, describes CMS r_2 but not r_3**
- **Wounded nucleon model: stronger decorrelation than data**

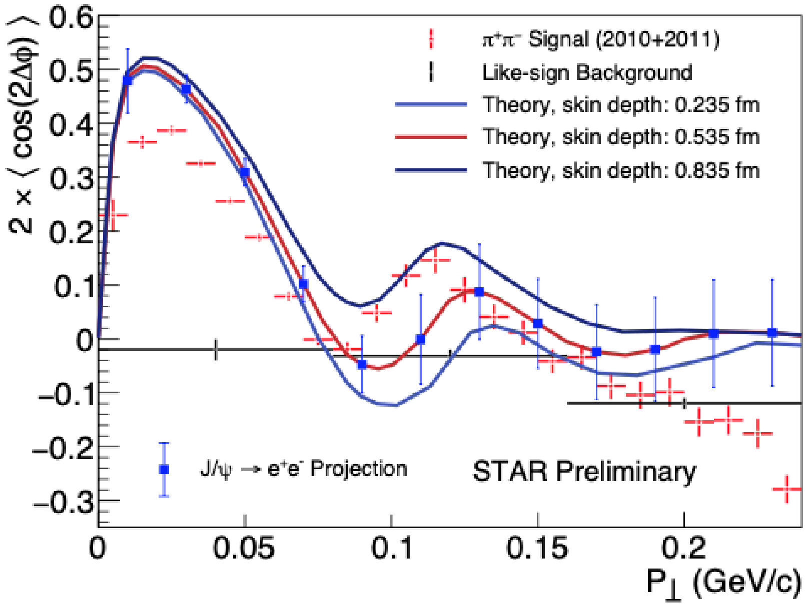
Precise measurement of r_n over a wide rapidity window will provide a stringent constraint

Q1: What is the nature of the 3D initial state?

Transverse 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:

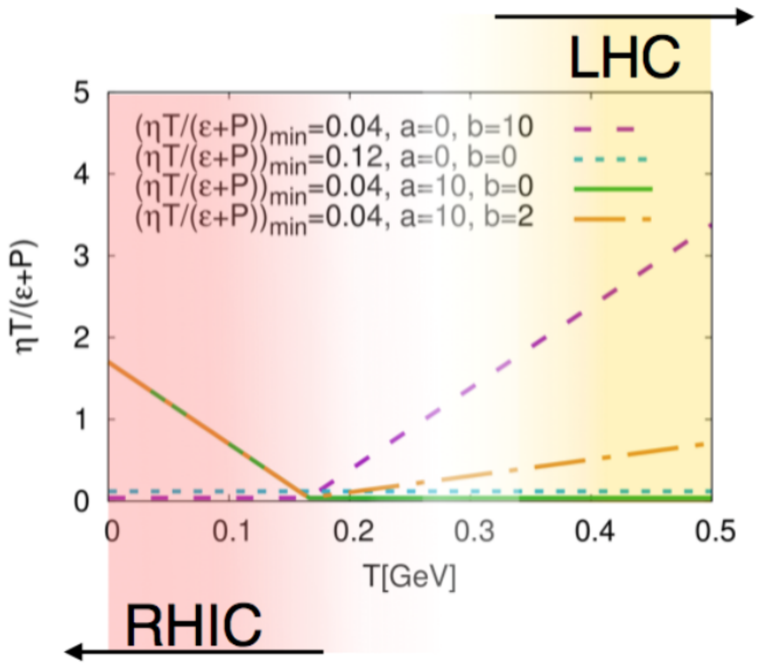
multi-differential measurements (vs. mass, rapidity, p_T): provide strong theoretical constraints, separate ρ^0 from continuum (Drell-Soding), investigate how double-slit interference mechanism affects the structure

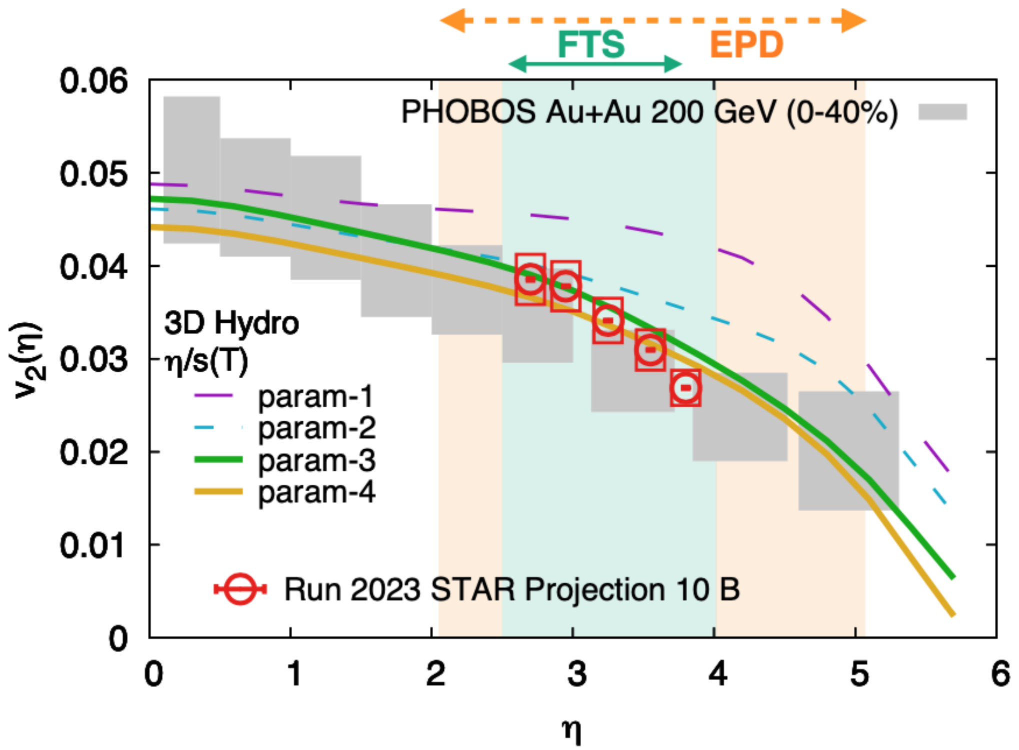
Enable a similar measurement for J/ψ, a cleaner probe for gluon spatial distribution

Q2: What is the precise temperature dependence of *η/s* and *ζ/s*?

Constrain temperature dependence of η/s

forward tracking



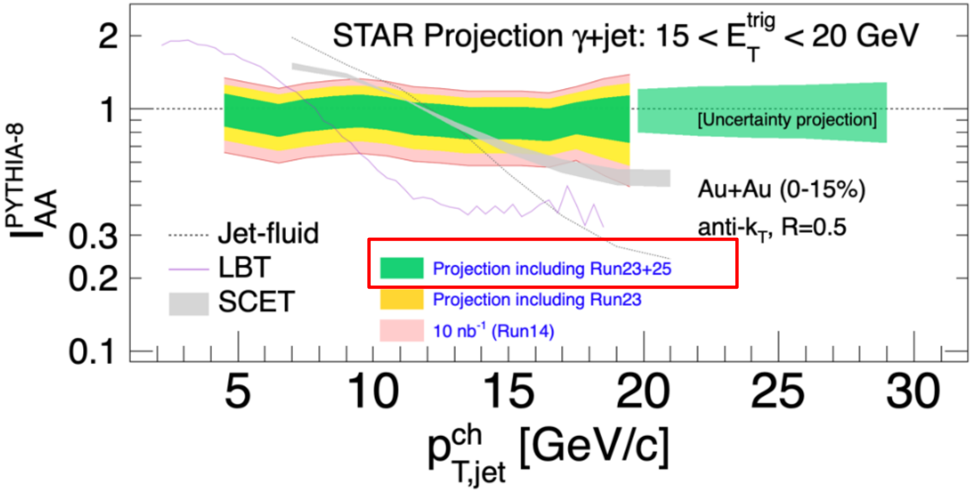


Flow measurements at forward rapidity sensitive to η/s as a function of T.

Much more precise than previous PHOBOS measurements.

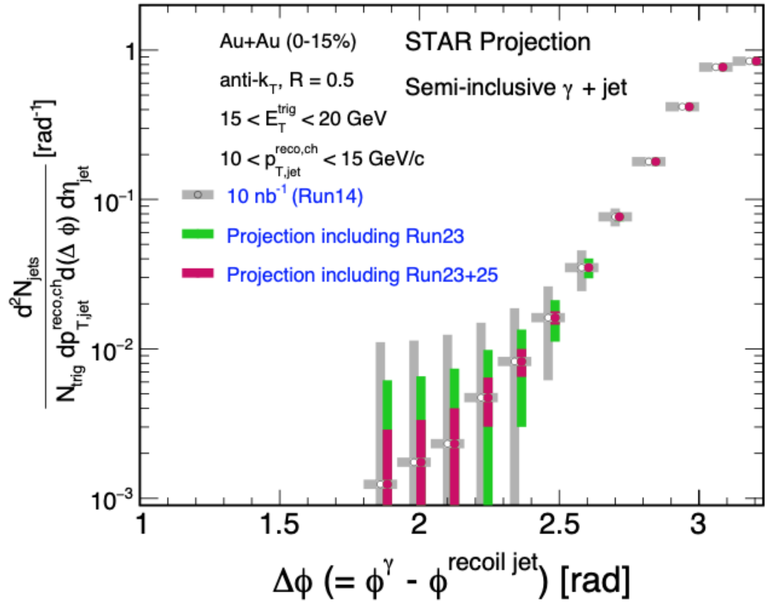
Q3: What are the underlying mechanisms of jet quenching?

low p_T, large R, extended to higher p_T

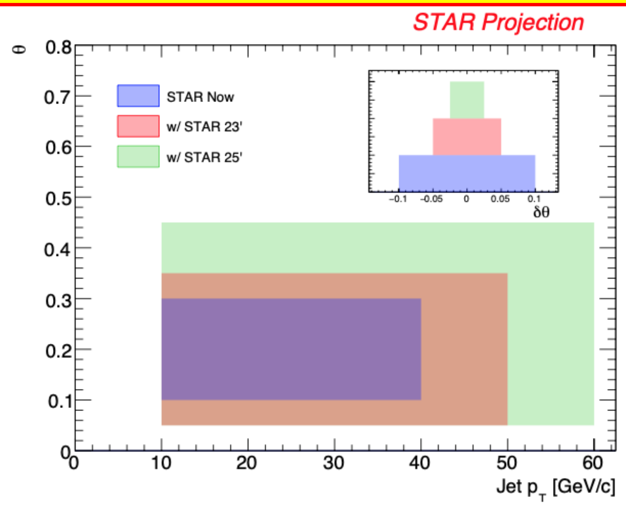


Semi-inclusive γ_{dir}+jet suppression

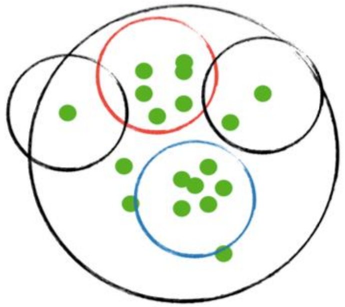
γ_{dir}+jet acoplanarity: constituents of medium



improved opening angle resolution by a factor of 4



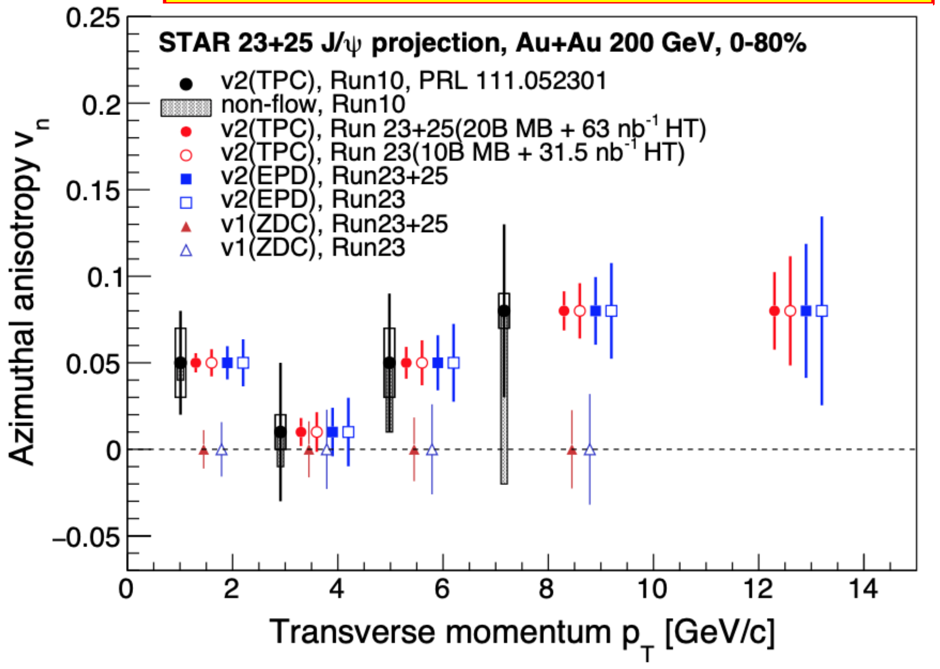
Jet substructure: coherence vs. de-coherence



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

Q4: What can charmonium tell us about confinement

low material, improved PID, extended η coverage by iTPC

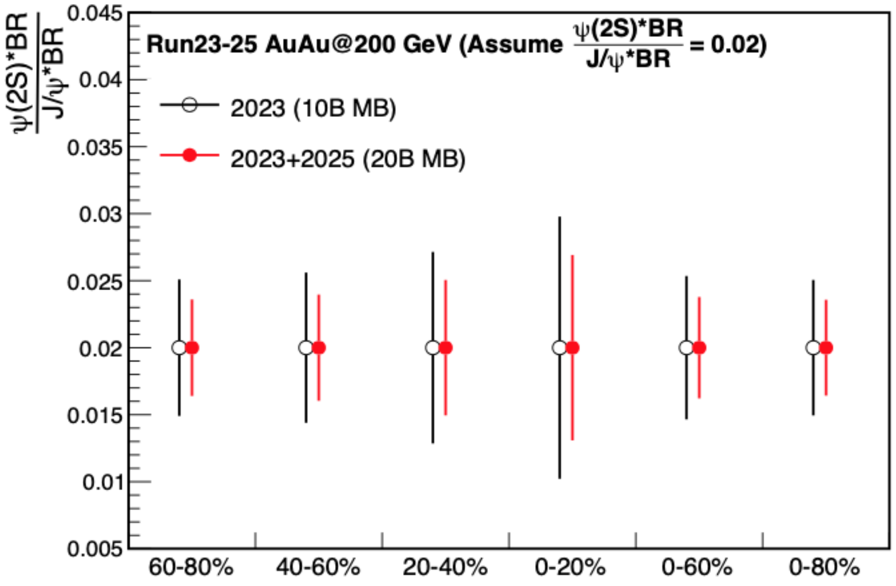


J/ψ: interplay of color-screening and recombination, signature of deconfinement

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

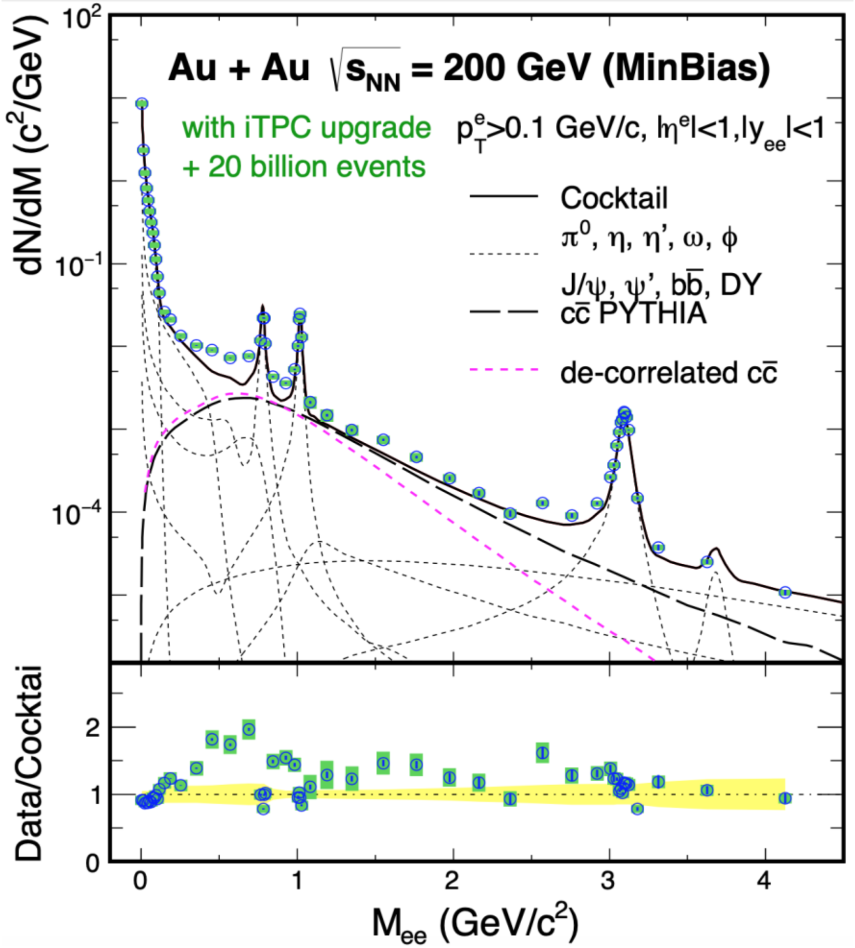
Q5: What is the temperature of the medium?

low material, improved PID, extended η coverage by iTPC

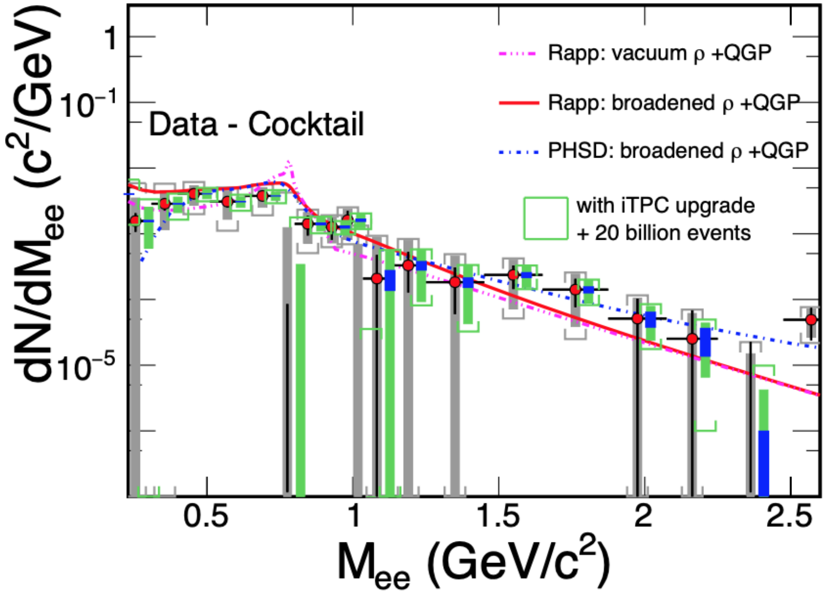


ψ(2S) suppression: explore temperature profile of the medium

Q5: What is the temperature of the medium?



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**

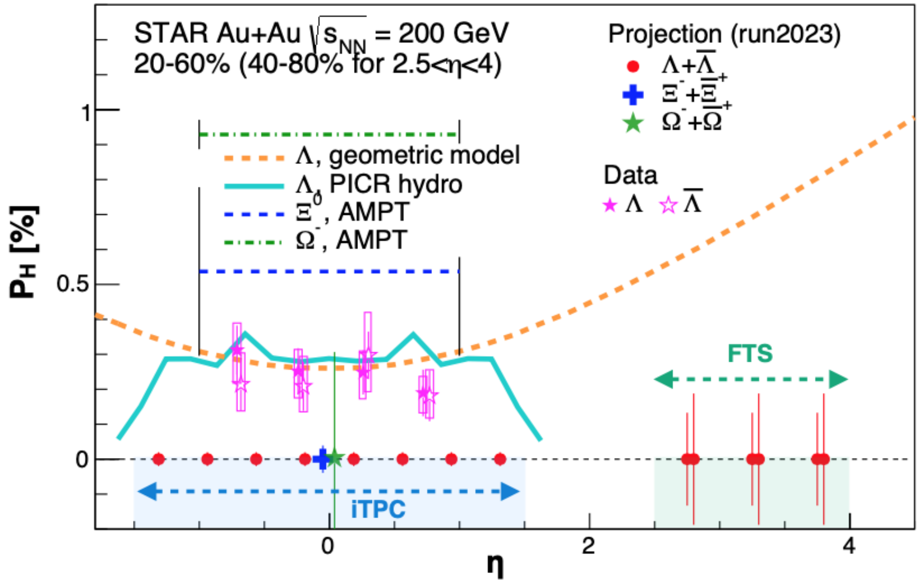
Intermediate mass: **direct thermometer to measure temperature**

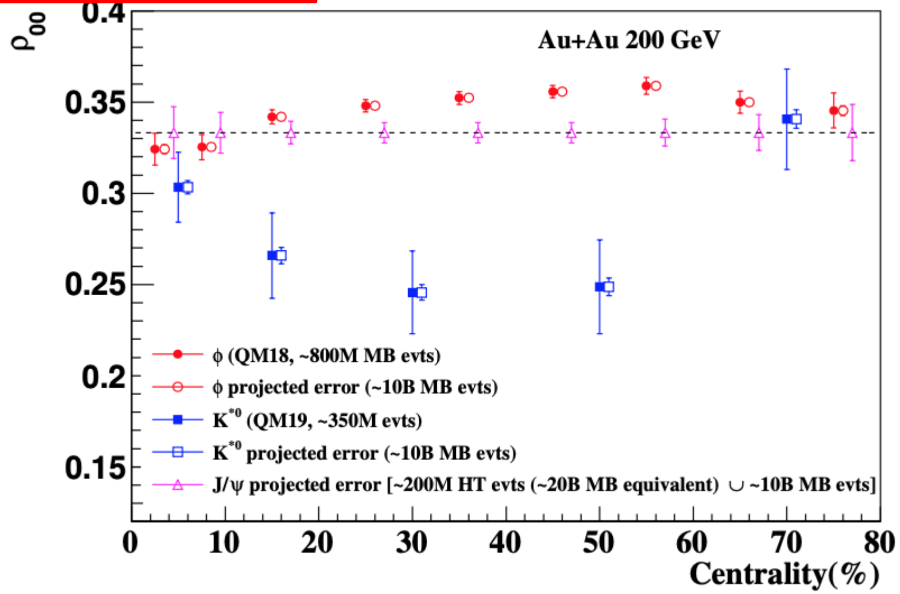
Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

Q6: What are the electrical and magnetic properties of the QGP?

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?

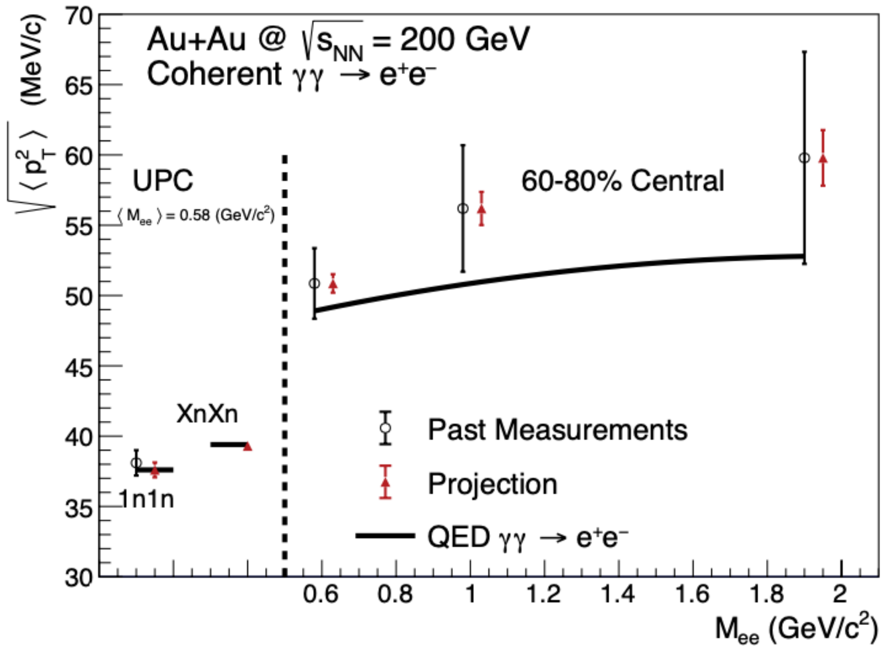
Precise measurements of ρ_{00} of K*, ϕ, J/ψ will tell.

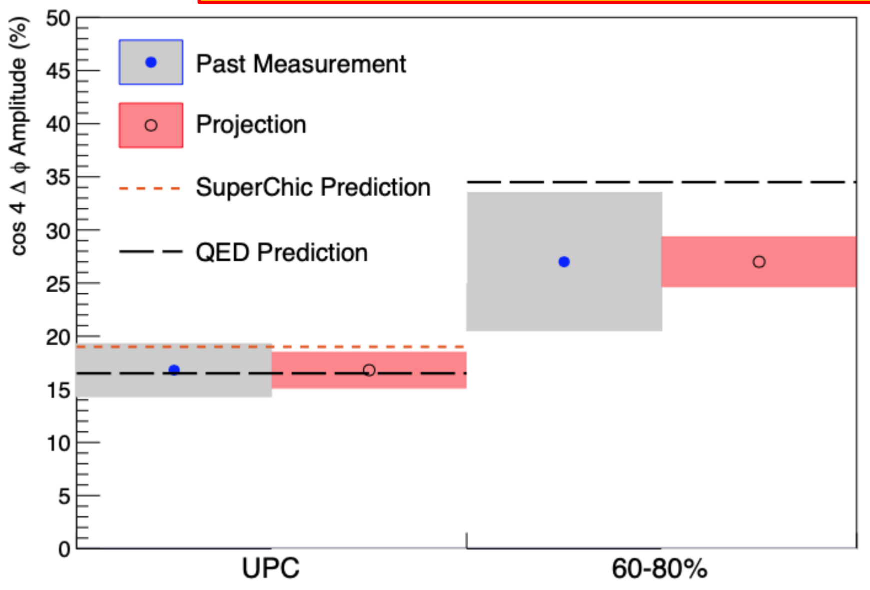
From Lijuan Ruan, BNL

Q6: What are the electrical and magnetic properties of the QGP?

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?

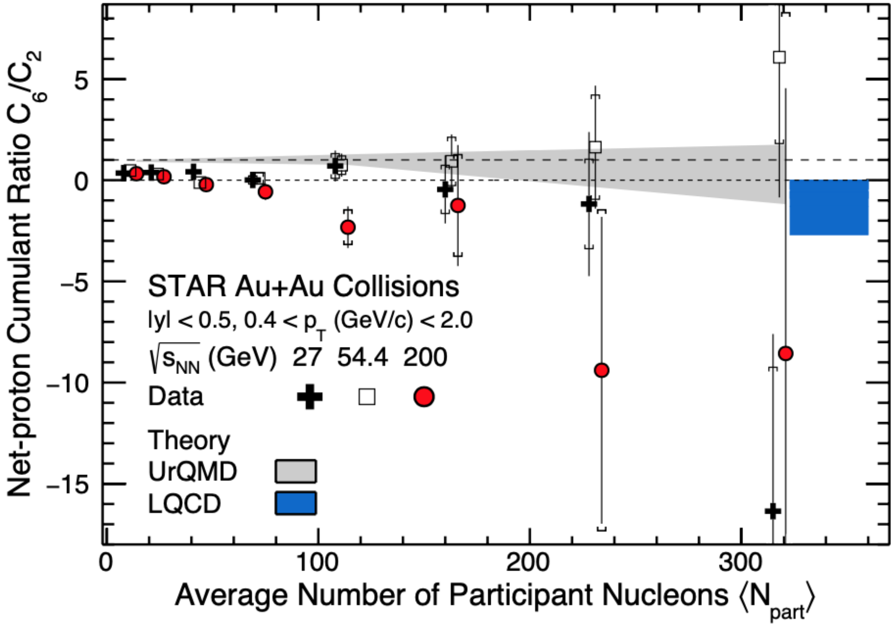
Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.

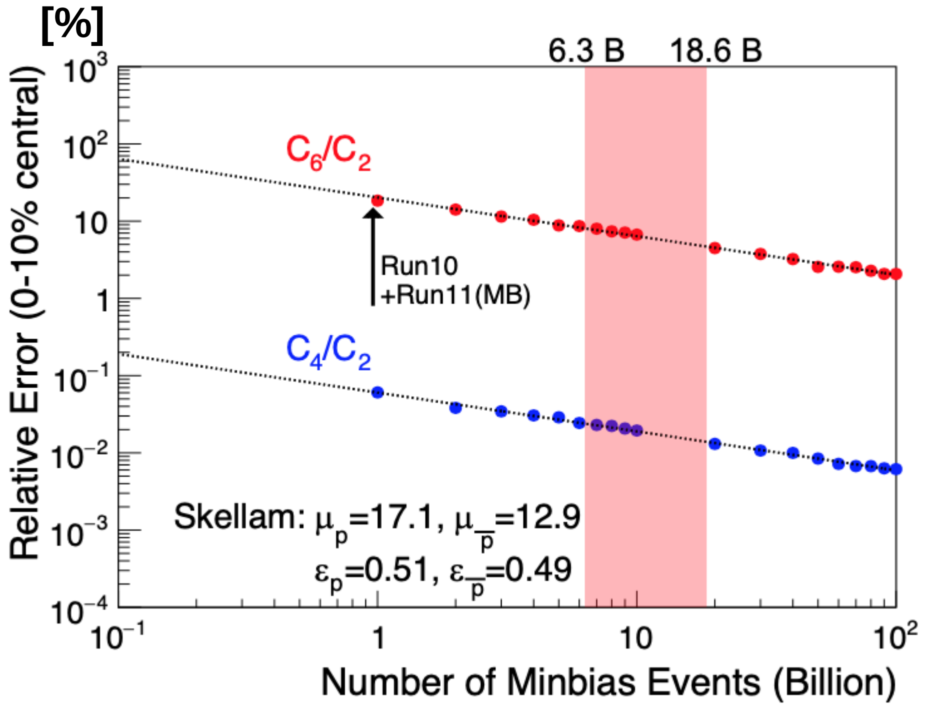
Fundamentally important and unique input to CME phenomenon.

Q7: What is the nature of the phase transition near $\mu_B = 0$?

Chiral cross-over transition

Improved PID, extended η coverage by iTPC



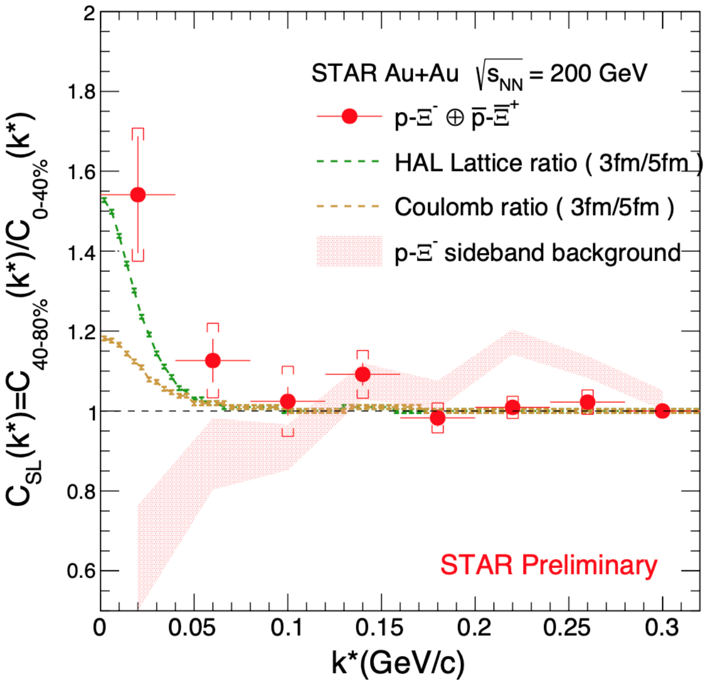


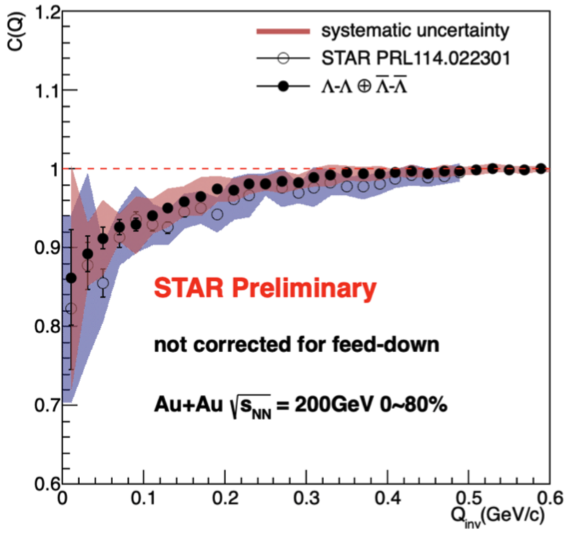
Lattice QCD predicts a sign change of susceptibility ratio χ_6^B/χ_2^B at T_C
The cumulants of net-proton distribution sensitive to chiral cross over transition at μ_B=0

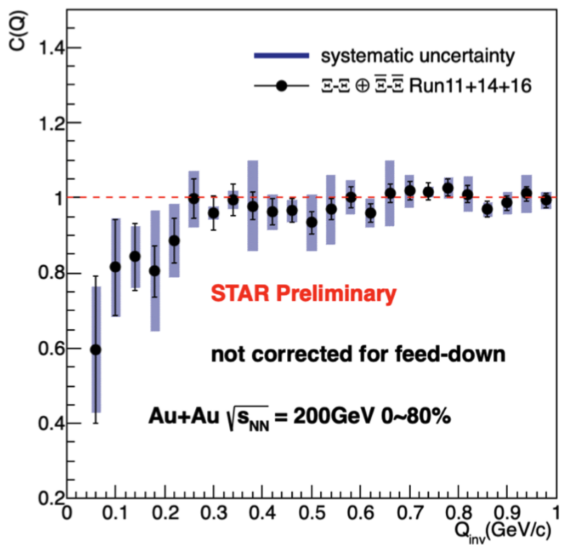
Observed a hint of a sign change from peripheral to central collisions at 200 GeV
$C_6/C_2 < 0$ at central collisions

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

Q8: What can we learn about the strong interaction?







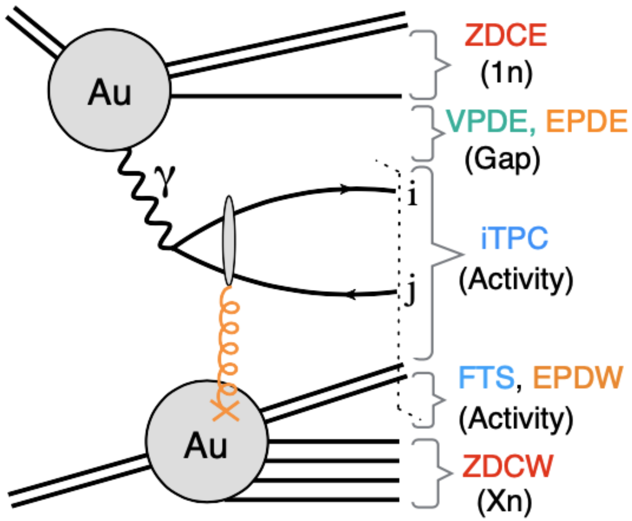
Constrain hyperon-nucleon and hyperon-hyperon interactions, important for the study exotic hadronic states and understanding of the EoS of neutron stars

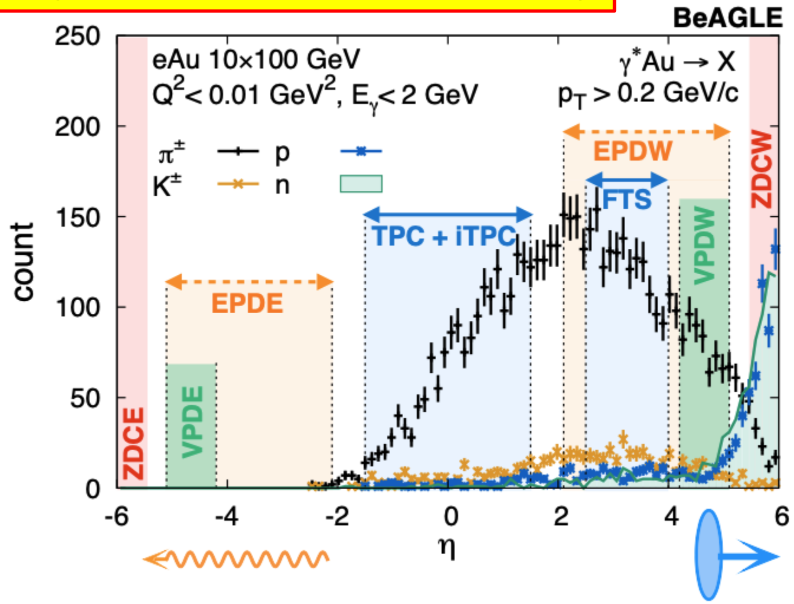
- **A factor of 7 more data in Runs 23 and 25**
- **Systematic uncertainties will be significantly reduced.**

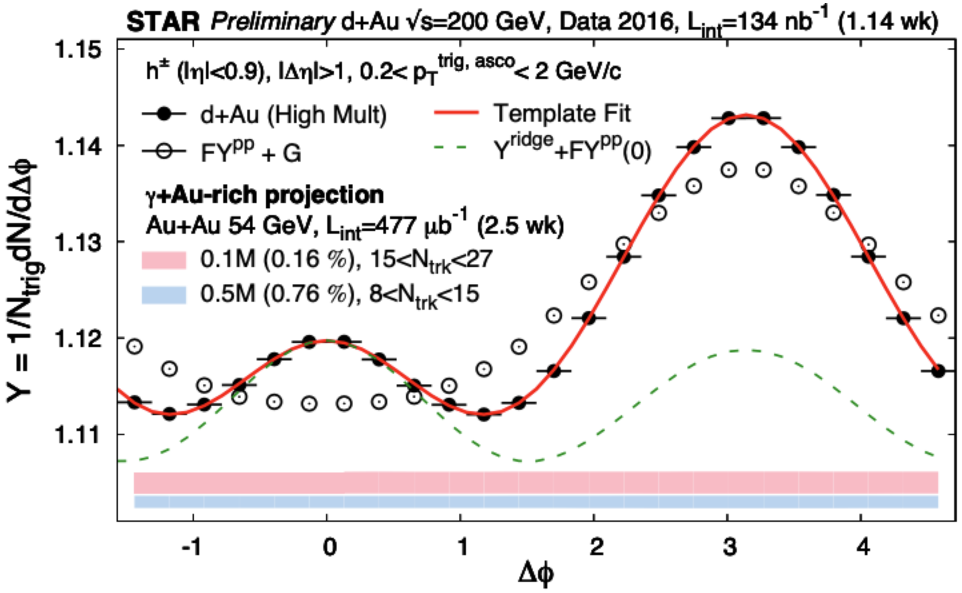
END

Search for collectivity in photo-nuclear processes

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







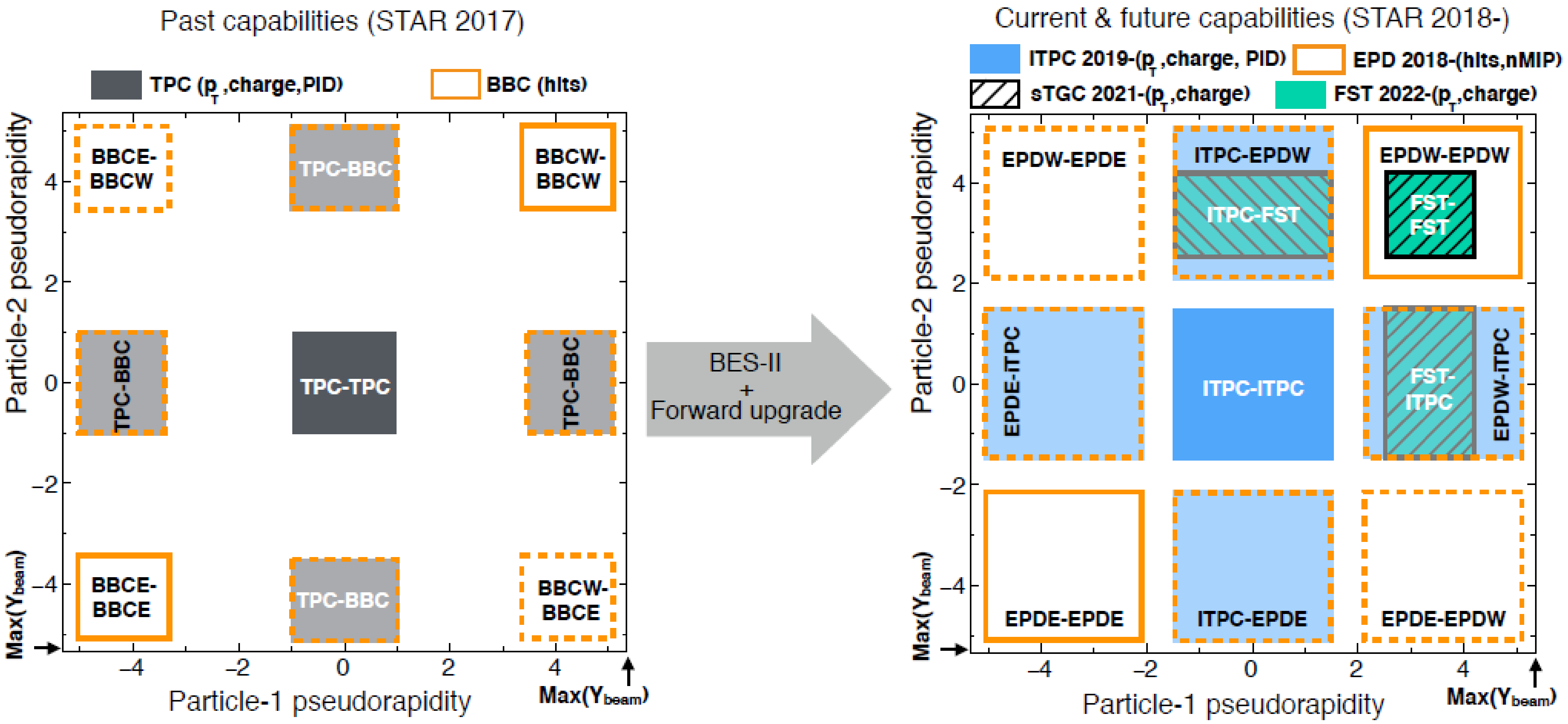
γ+Au process in UPC associated with a large rapidity asymmetry:

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

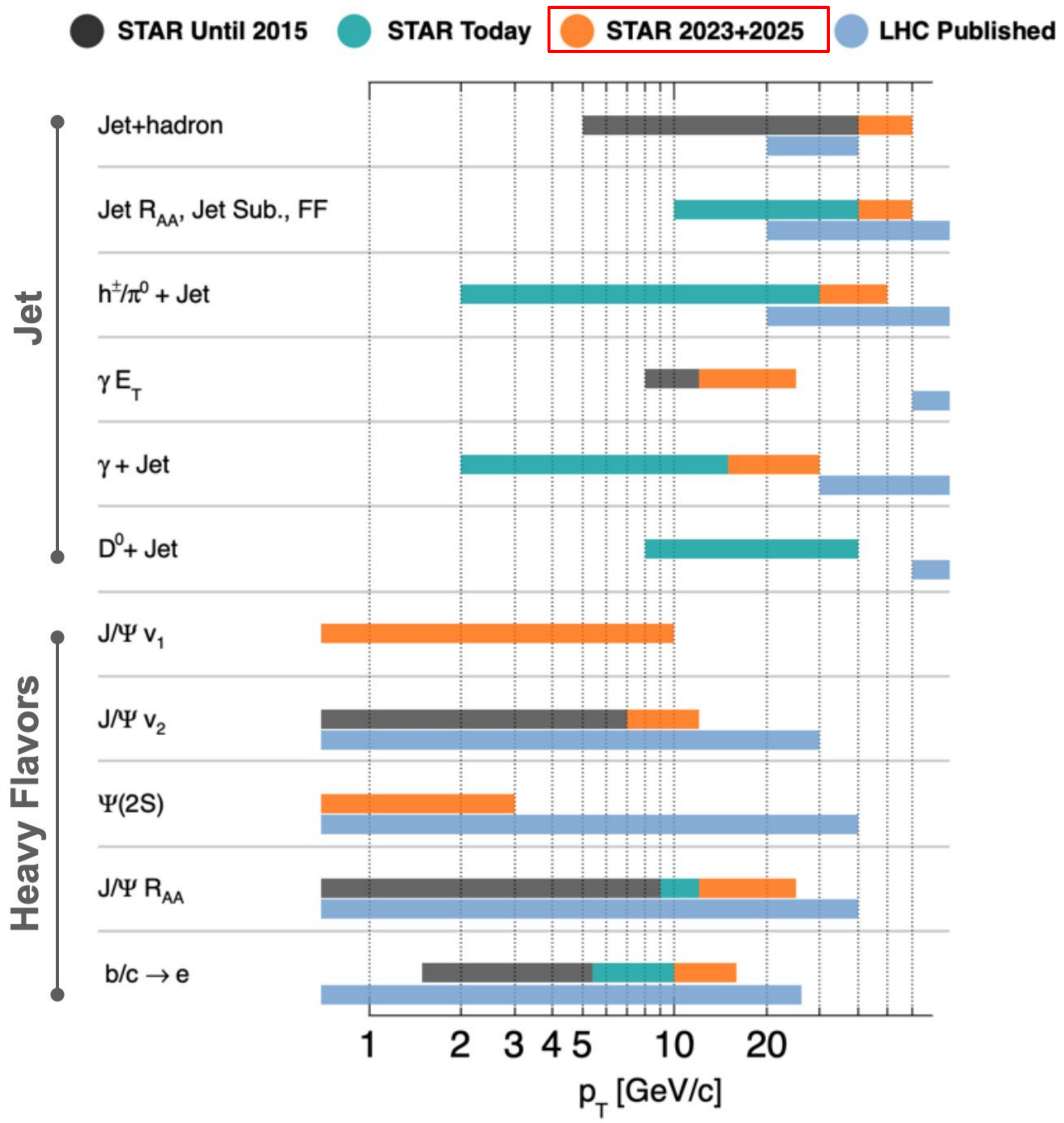
Further understand the origin of collectivity observed in small systems

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

Correlation Measurements Using Extended Phase Space

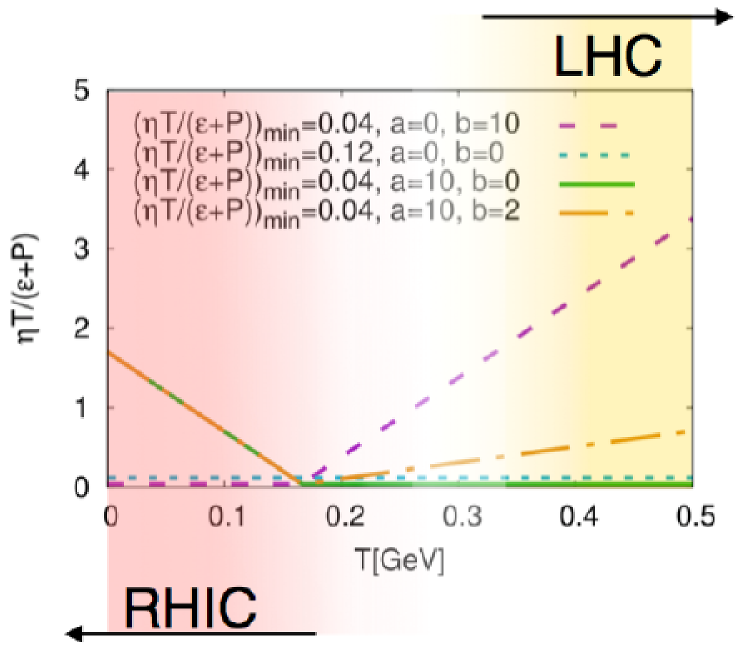


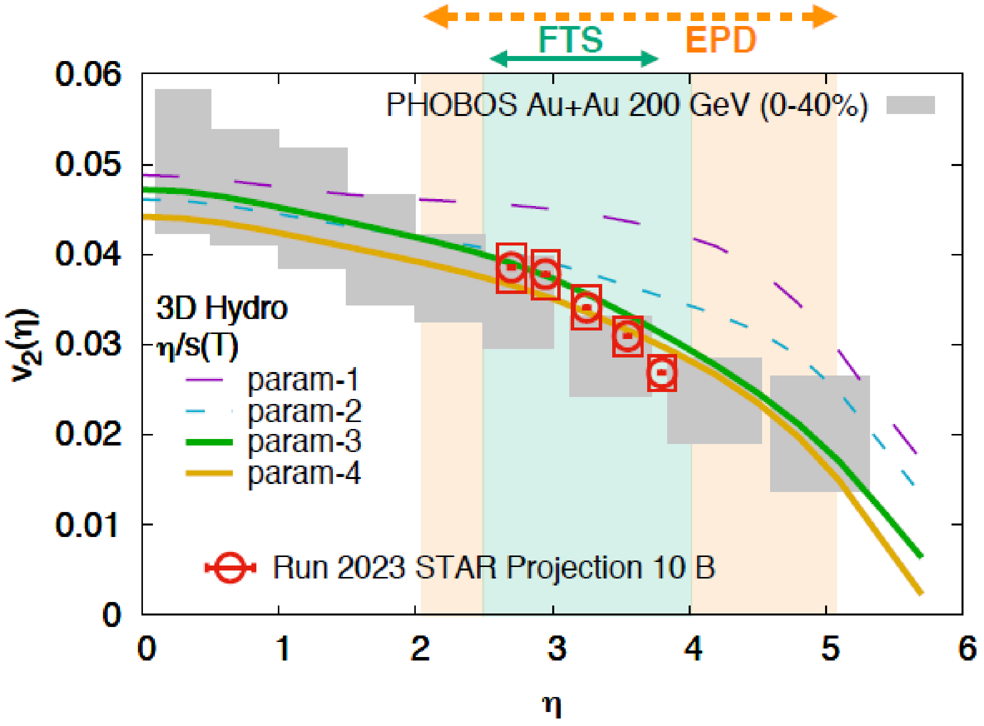
Hard probes: jets and heavy flavor



Pseudo-rapidity azimuthal correlations to tightly constrain the viscosity

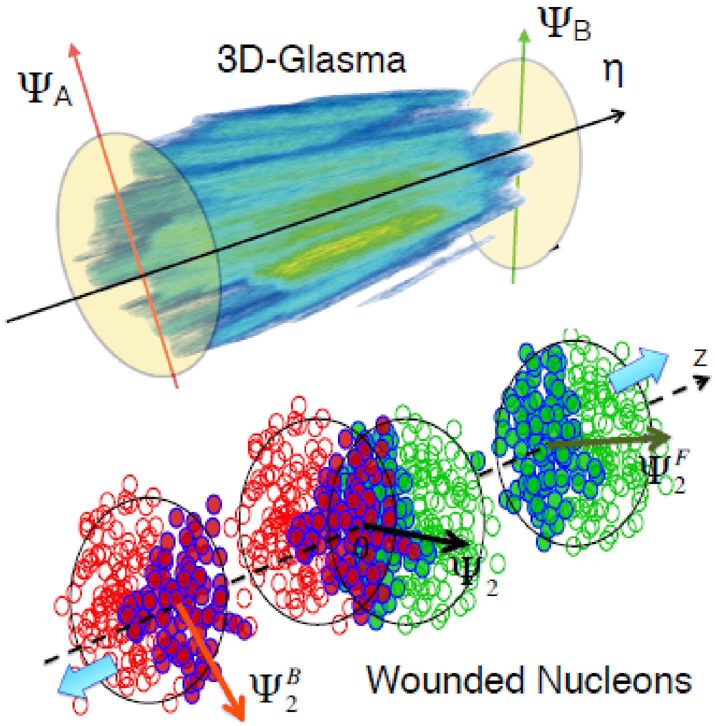
Where are the iTPC and EPD projections

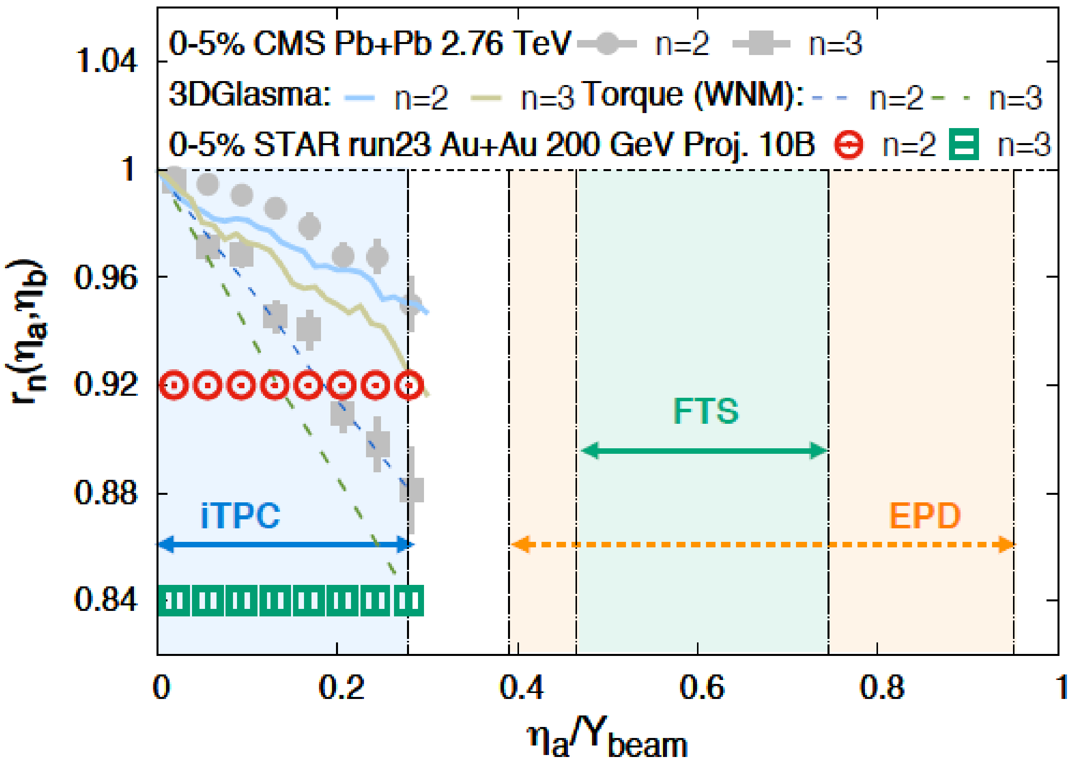




LRP goal ➔ constraint viscosity vs. temperature
Temperature of the plasma varies with rapidity ➔ rapidity dependent measurements can study viscosity vs. temperature
Use average pT to constrain zeta/s
Need 10B min bias events

Pseudo-rapidity dependent azimuthal correlations to constrain the longitudinal structure of the initial state

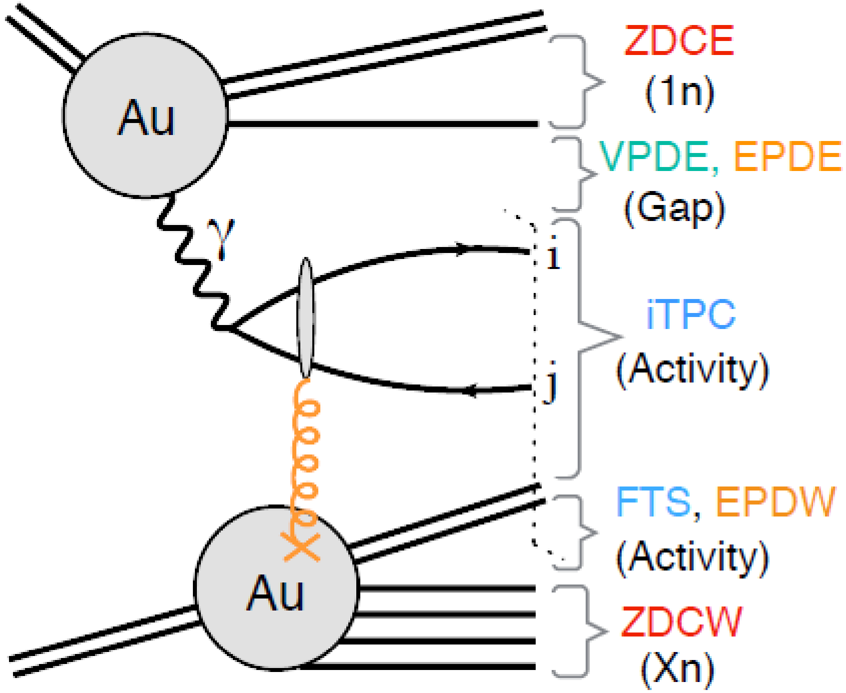


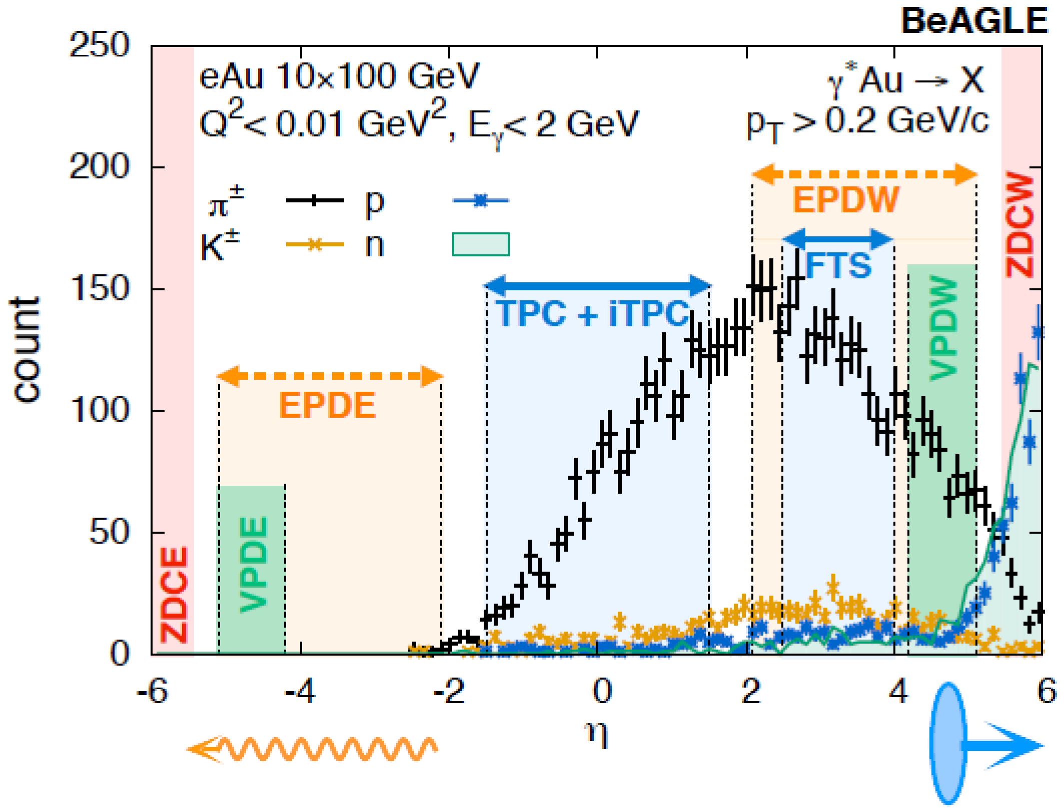


20 B events

Search for Collectivity on Photo-nuclear (γ + Au) Processes

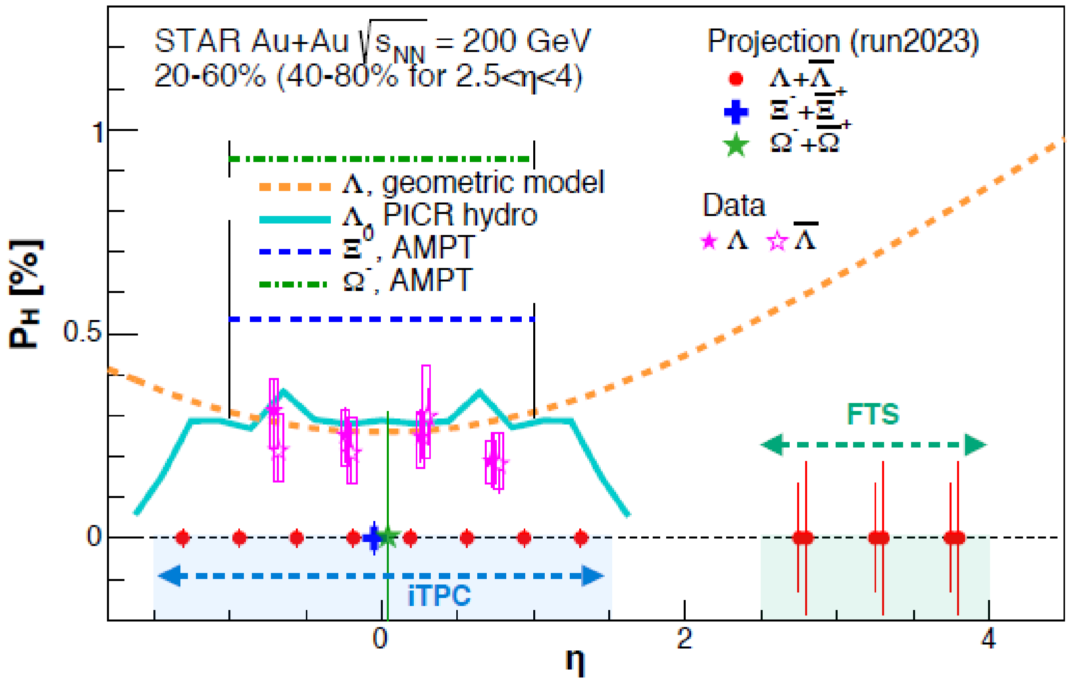
What question does this answer?

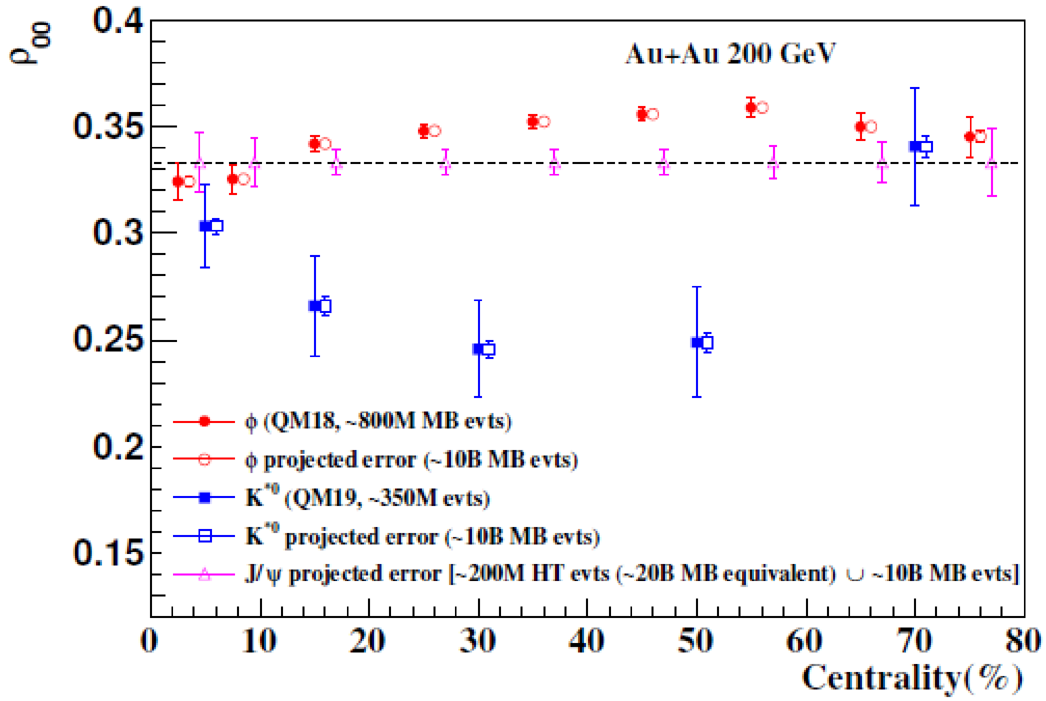




20 B min bias

Pseudo-rapidity Dependence of the Global Lambda Polarization





10 B

Correlation Measurements Using Enhanced Statistics

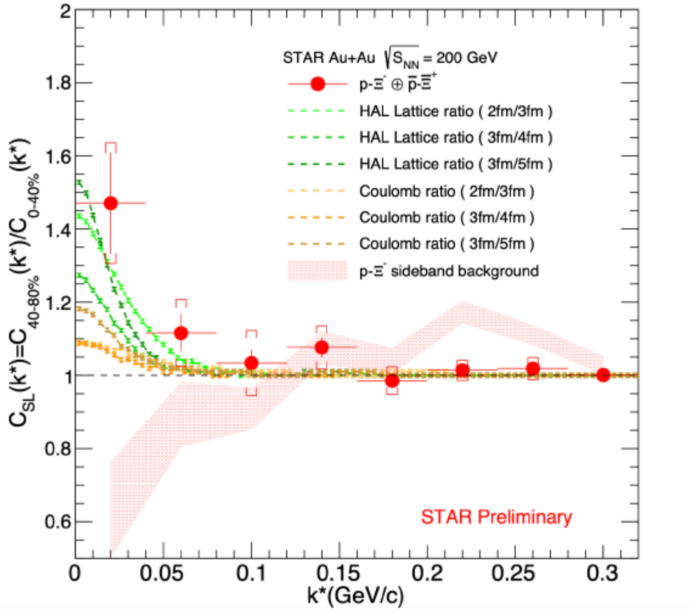
What Does This Mean?

Global Spin Alignment of J/Ψ

Sixth Order Cumulant of the Net-proton Distribution

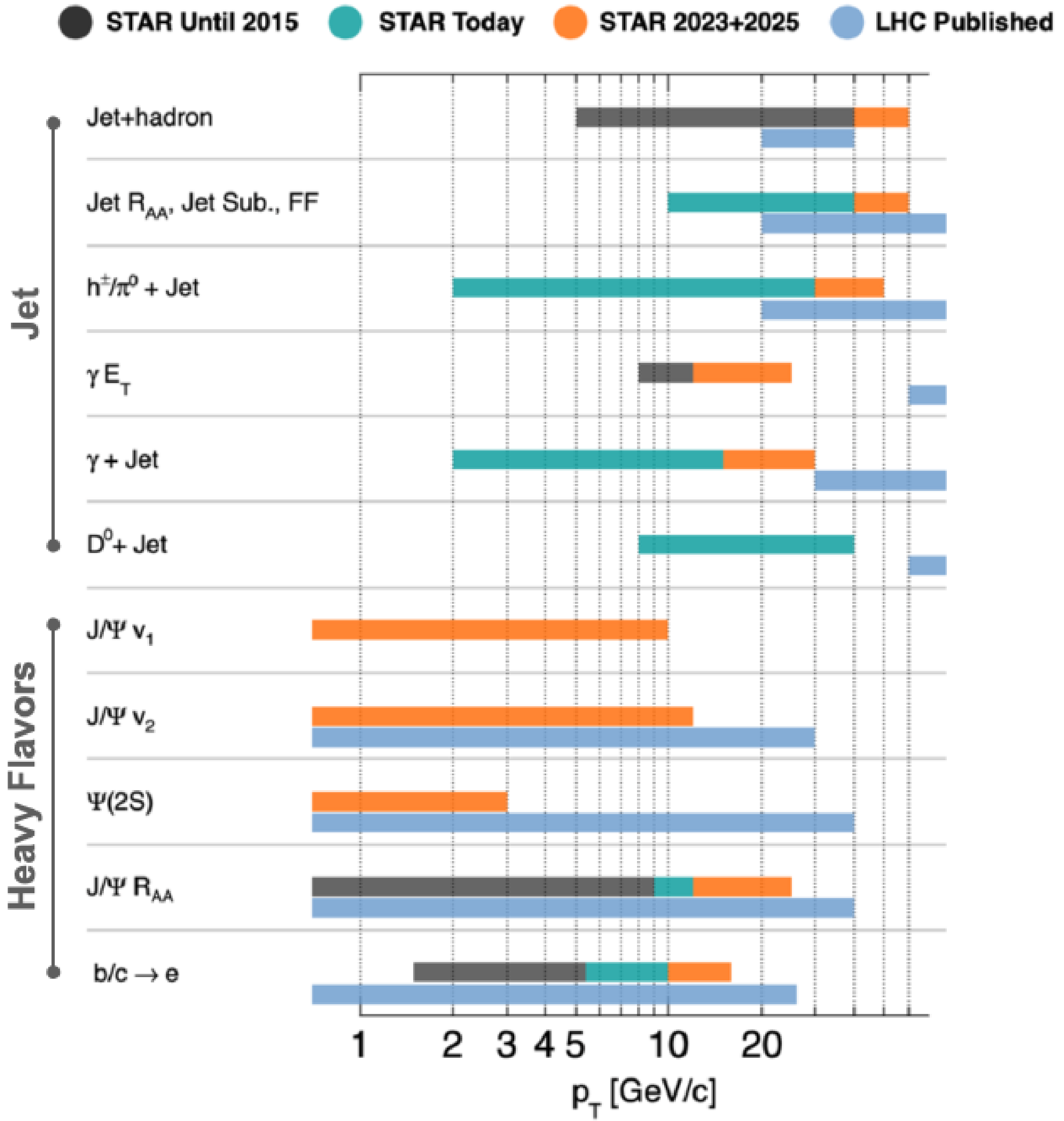
Strong Interaction Measurements

$p\Lambda,\ p\Sigma,\ p\Omega,\ p\Xi,\ \Lambda\Lambda,\ \Xi\Xi.$

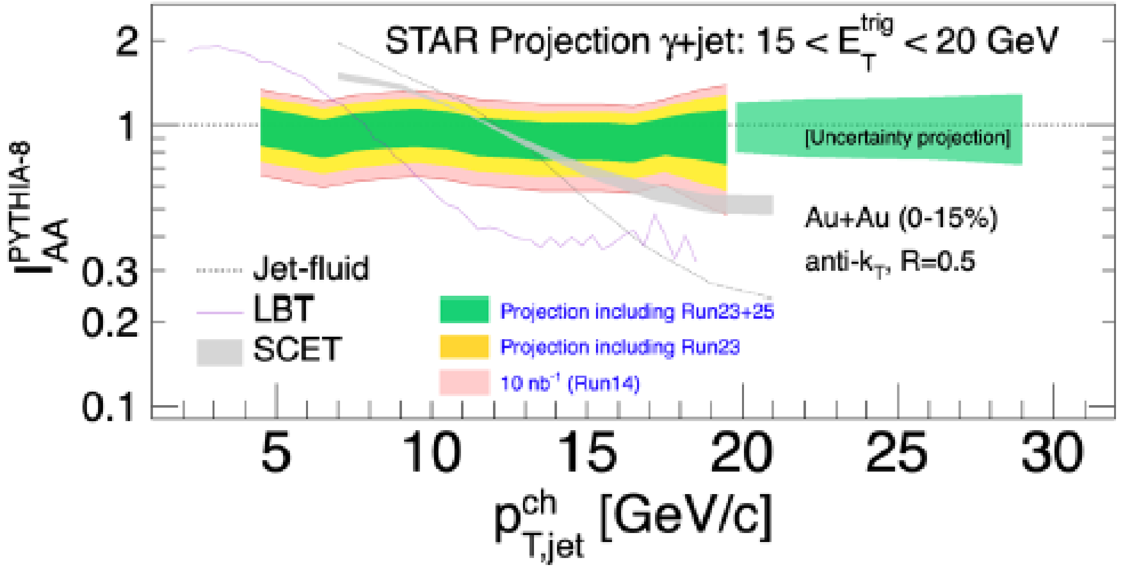


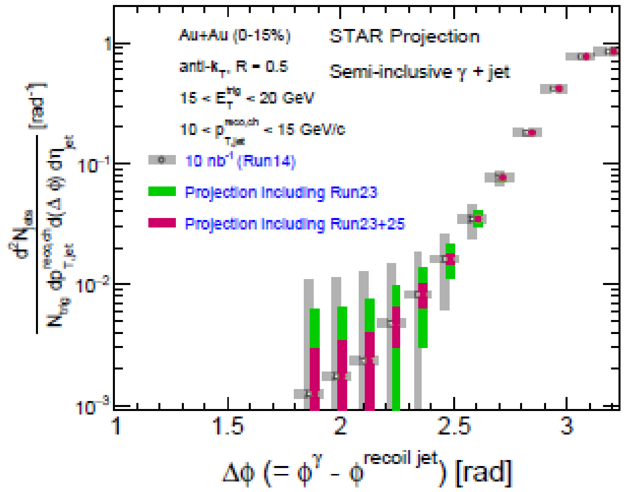
Hard Probes: Jets and Heavy Flavor

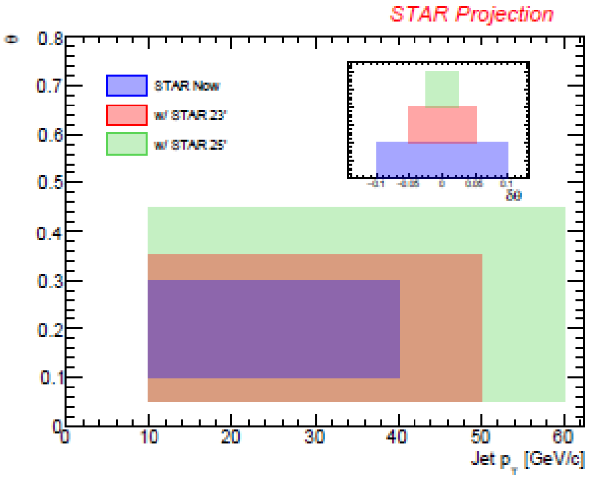
LRP goal



Semi-inclusive γ_{Dir} + jet measurements

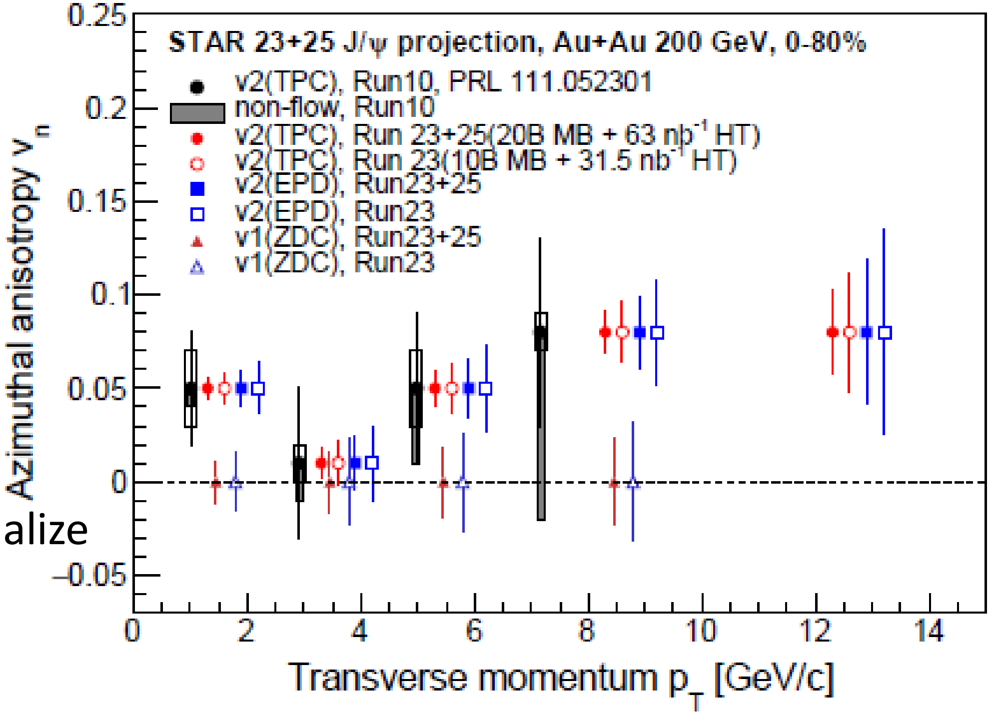






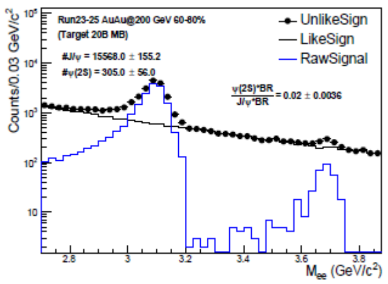
Differential Measurements of Energy Loss Tagged with a Sub-structure Metric

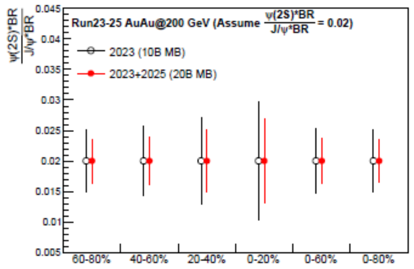
Deconfinement and Thermalization with Chamonium Measurements



Charm quarks partially thermalize

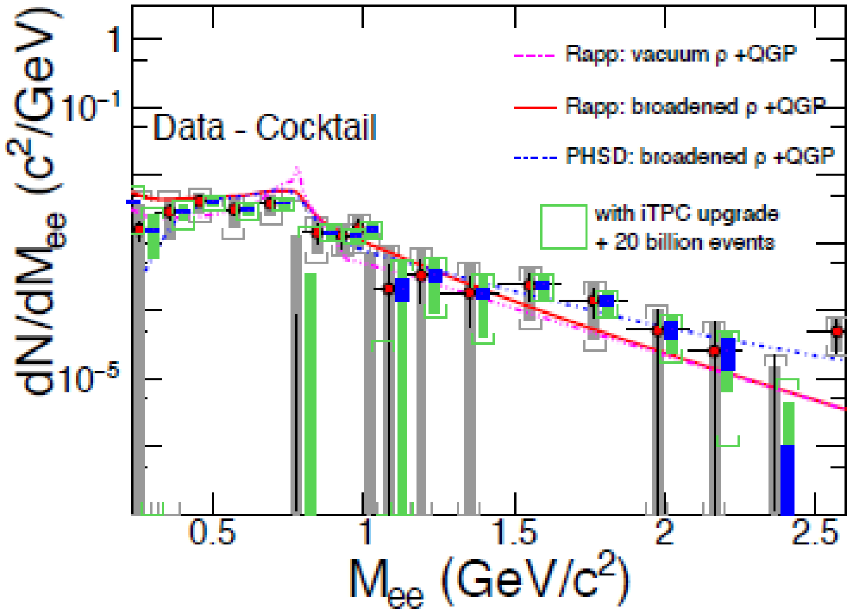
Psi(2s) suppression





Electromagnetic Probes and Ultra-peripheral Collisions

Probing the degrees of Freedom of the medium and its transport properties

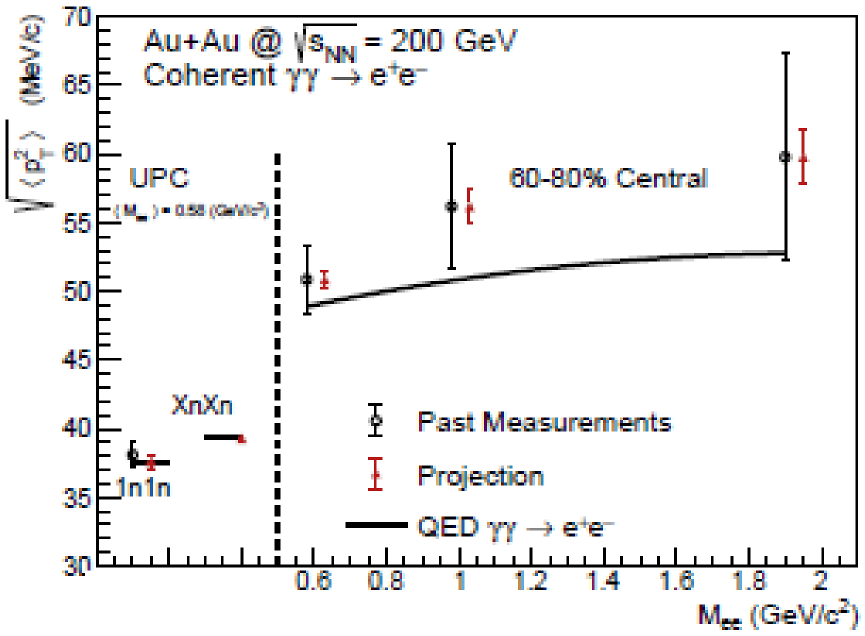


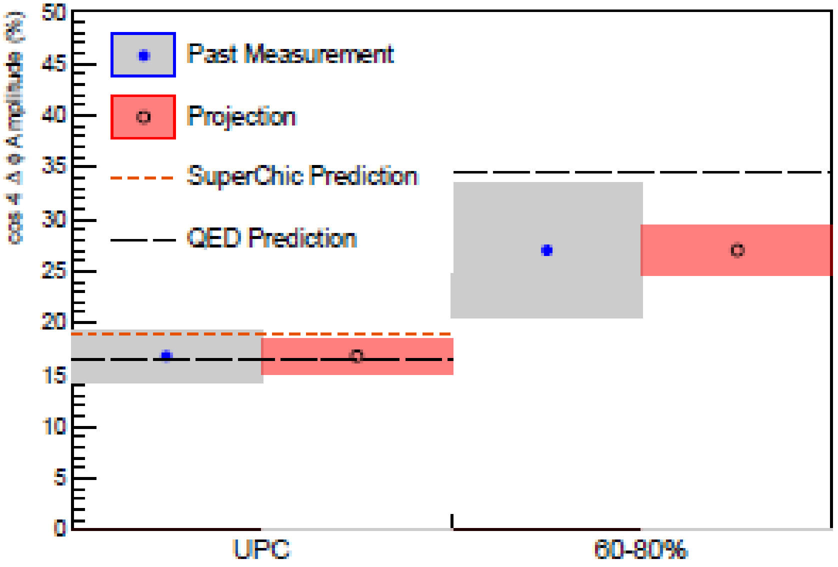
Temperature

Fireball lifetime

Transport properties – electrical conductivity

Probing the Photon Wigner Function and Final State Magnetic Fields in the QGP





Residual magnetic field trapped in electrically conducting QGP

Ultraperipheral Collisions: Probing the Gluon Distribution Function Inside the Nucleus