Future Physics Program at RHIC–STAR

KPS 70th Anniversary and 2022 Fall Meeting

Session – Pioneer: 50th Anniversary Division of Nuclear Physics II

Busan, South Korea – October 21, 2022

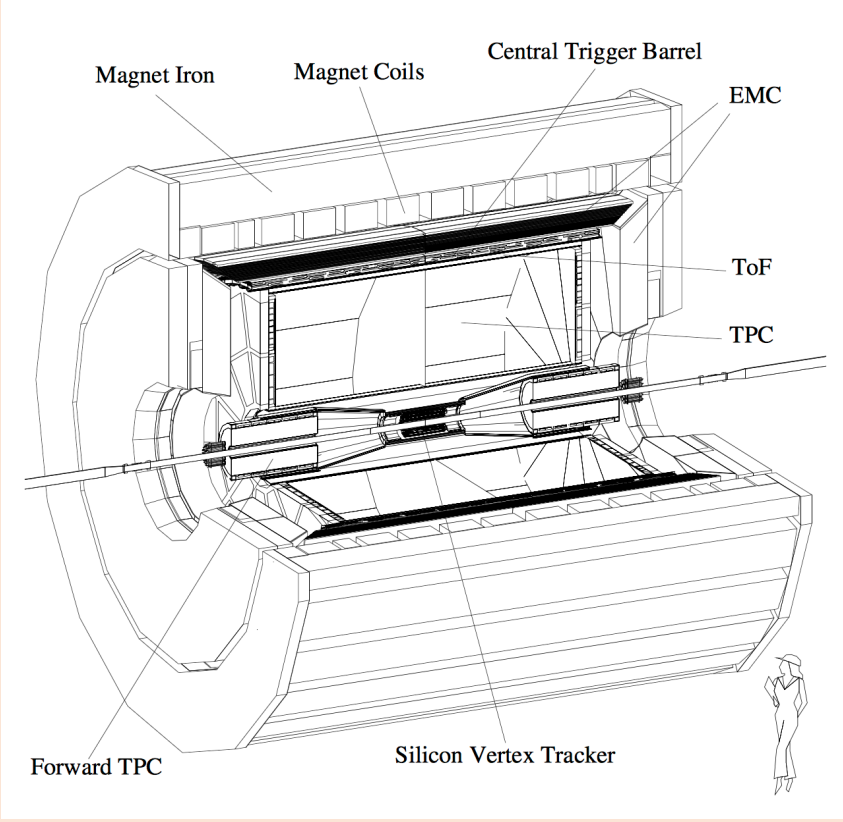
Saehanseul Oh (Sejong University, LBNL)

for the **STAR** Collaboration

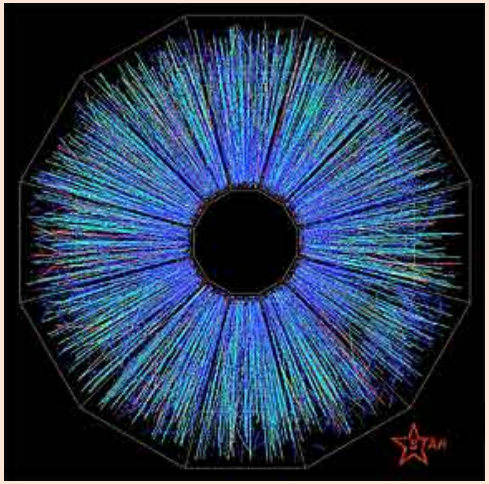
In part supported by

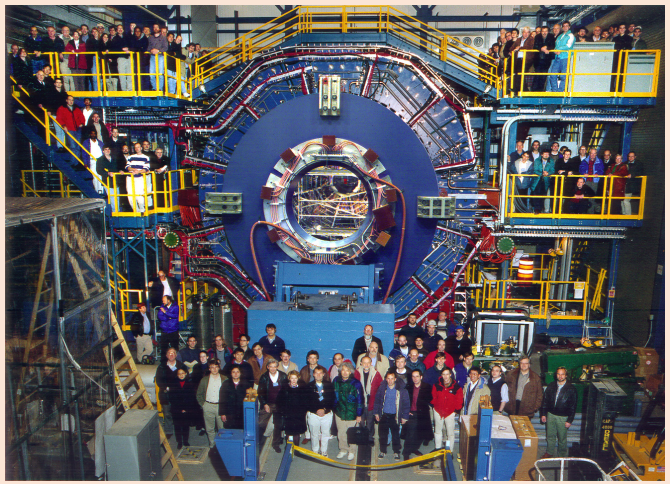
U.S. DEPARTMENT OF ENERGY | Office of Science

STAR has been taking data since the first day of the RHIC (Relativistic Heavy Ion Collider) operation, June 12, 2000

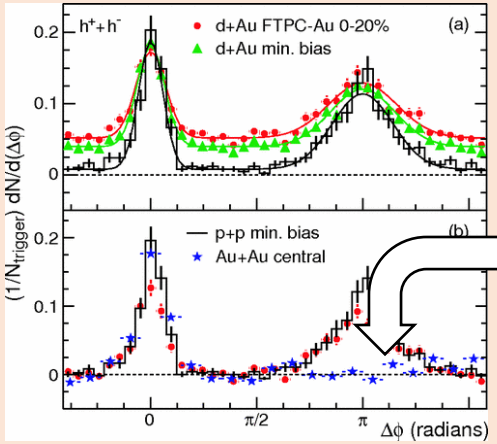


Acta Physica Hungarica Series A,
Heavy Ion Physics volume 14, pages 169–180 (2001)





STAR Collaboration in 2000



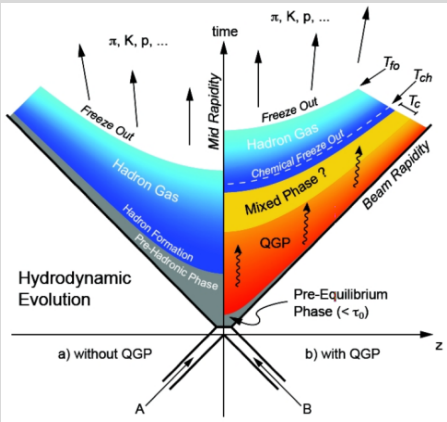
Evidence of Quark Gluon Plasma from jet quenching

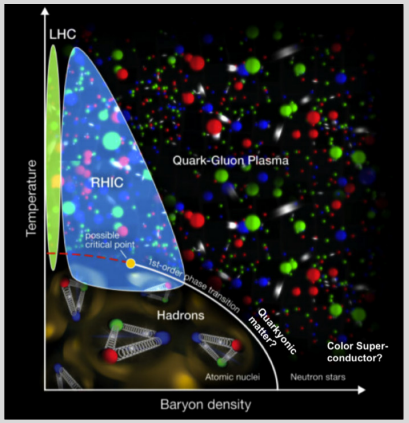
STAR, Phys. Rev. Lett. 91 (2003) 072304

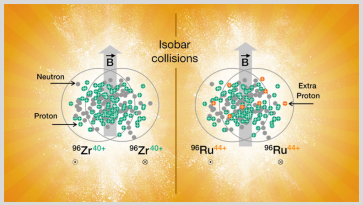
STAR highlights and future

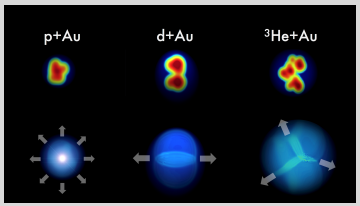
- Hot QCD topics at RHIC
  - Inner working of the QGP with hard probes
  - Mapping the QCD phase diagram
  - Study for the chiral properties of the medium
  - Vortical fluid and new probes to hydro paradigm

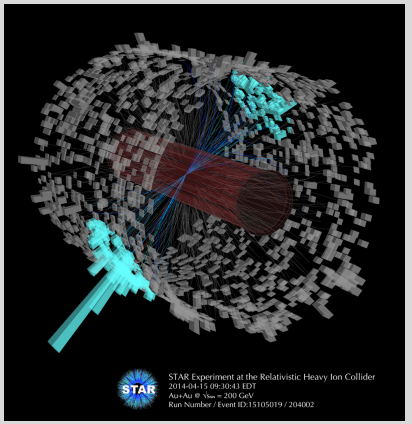
- Topics that bridge RHIC and EIC science
  - Origin of small system collectivity
  - Imaging nuclei in the pre-EIC era
  - Microscopic structure of a baryon











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- Unique hot QCD topics at RHIC
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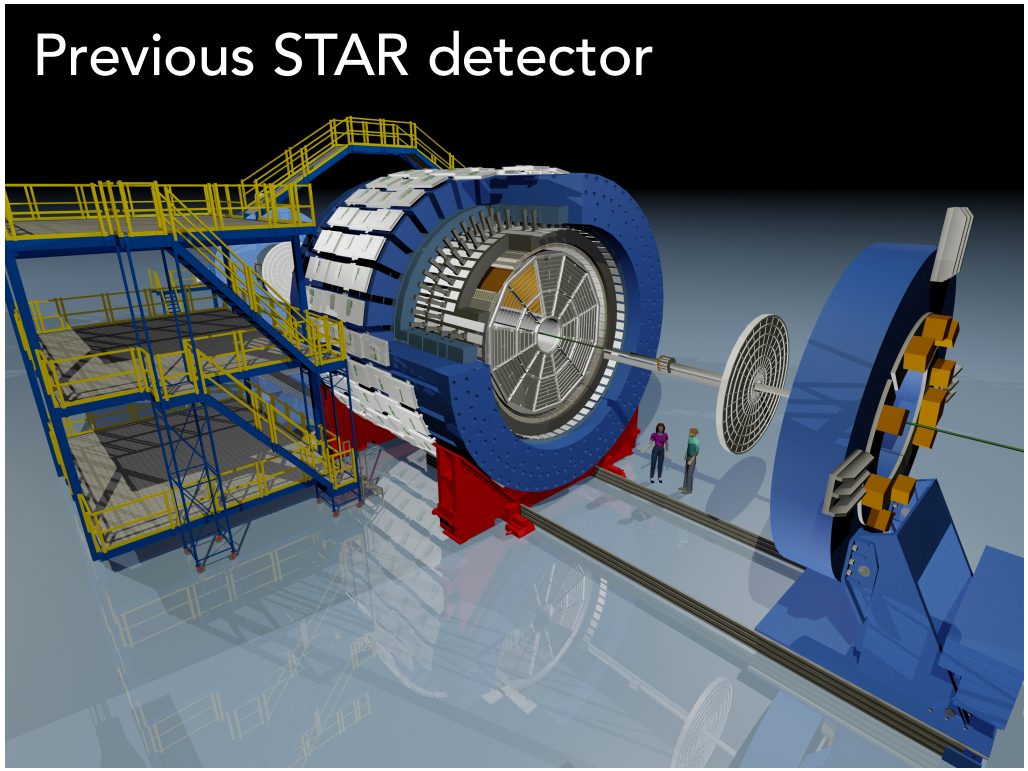
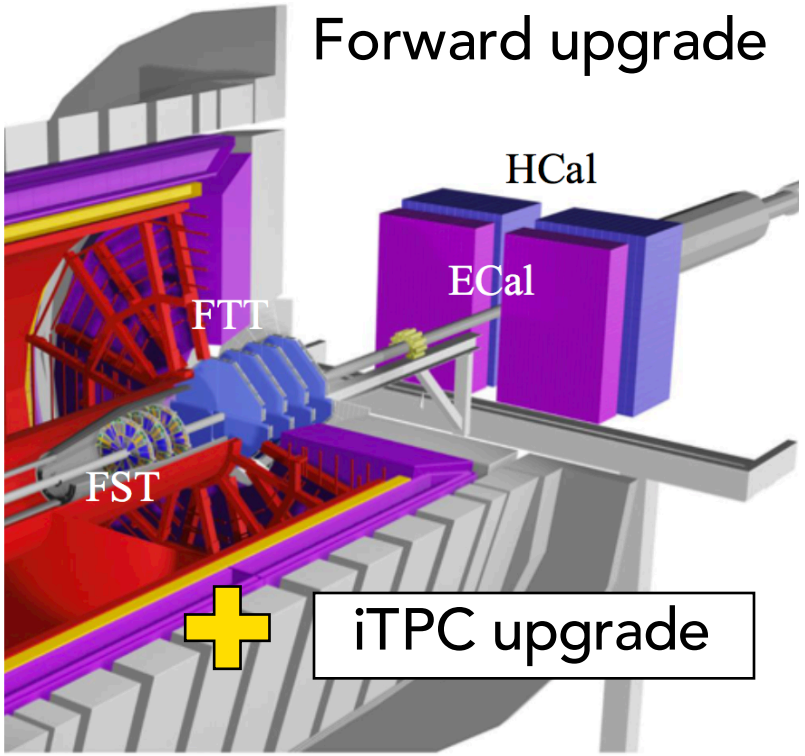
RHIC-STAR run plan for 2023-2025

Year	Species	$\sqrt{s_{NN}}$ (GeV)	Cryo weeks	Luminosity
2023	Au+Au	200	28	20 nb^{-1}
2024	p+p	200	28	235 pb^{-1}
2024	p+Au	200		1.3 pb^{-1}
2025	Au+Au	200	28	20 nb^{-1}

PAC recommendations: https://www.bnl.gov/npp/docs/2022-npp-pac-recommendations-final.pdf

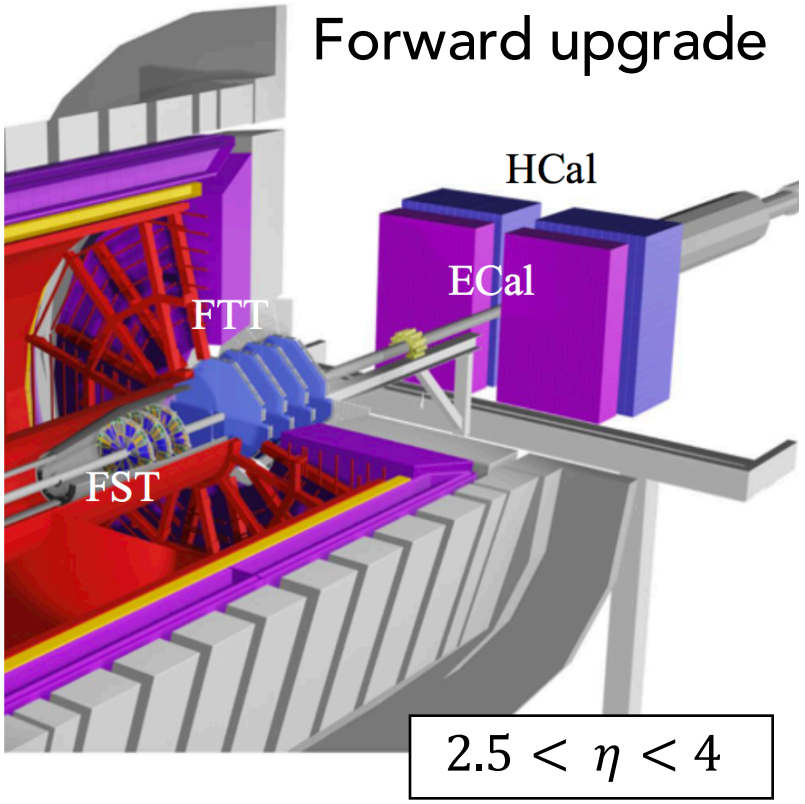
STAR detector and recent upgrade





STAR detector and recent upgrade

- Forward Tracking System (FTS)
  - Forward Silicon Tracker (FST)
  - Forward Small-strip Thin Gap Chambers Tracker (FTT)
- Forward Calorimeter System (FCS)
  - Electromagnetic Calorimeter (ECal)
  - Hadronic Calorimeter (HCal)



STAR detector and recent upgrade

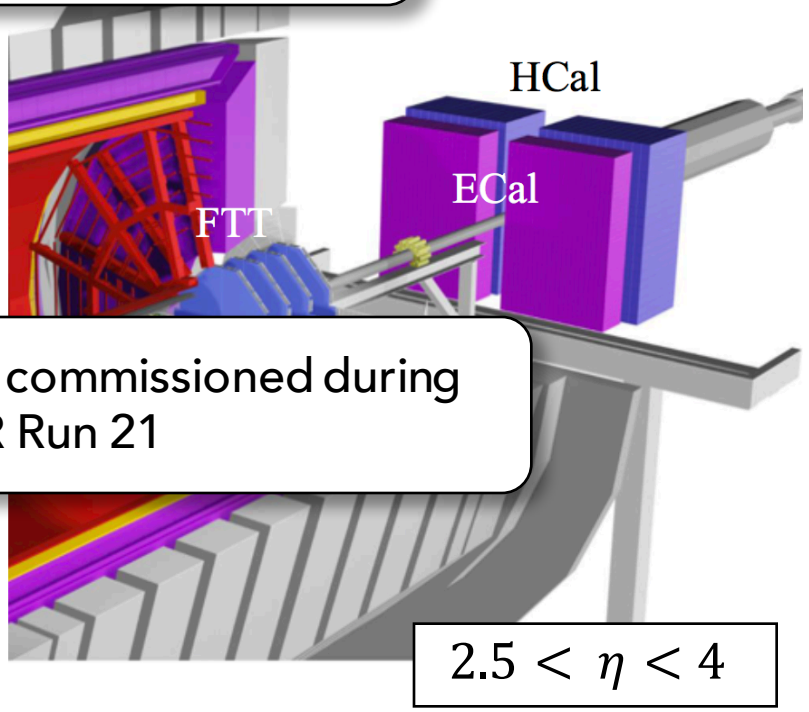
Fully commissioned and used for data taking at STAR Run 22

ward upgrade

- Forward Tracking System (FTS)
  - Forward Silicon Tracker (FST)
  - Forward Small-strip Thin Gap Chambers Tracker (FTT)

- Forward Calorimeter System (FCS)
  - Electromagnetic Calorimeter (ECal)
  - Hadronic Calorimeter (HCal)

Fully commissioned during STAR Run 21



$2.5 < \eta < 4$

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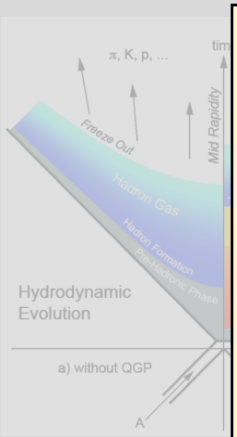
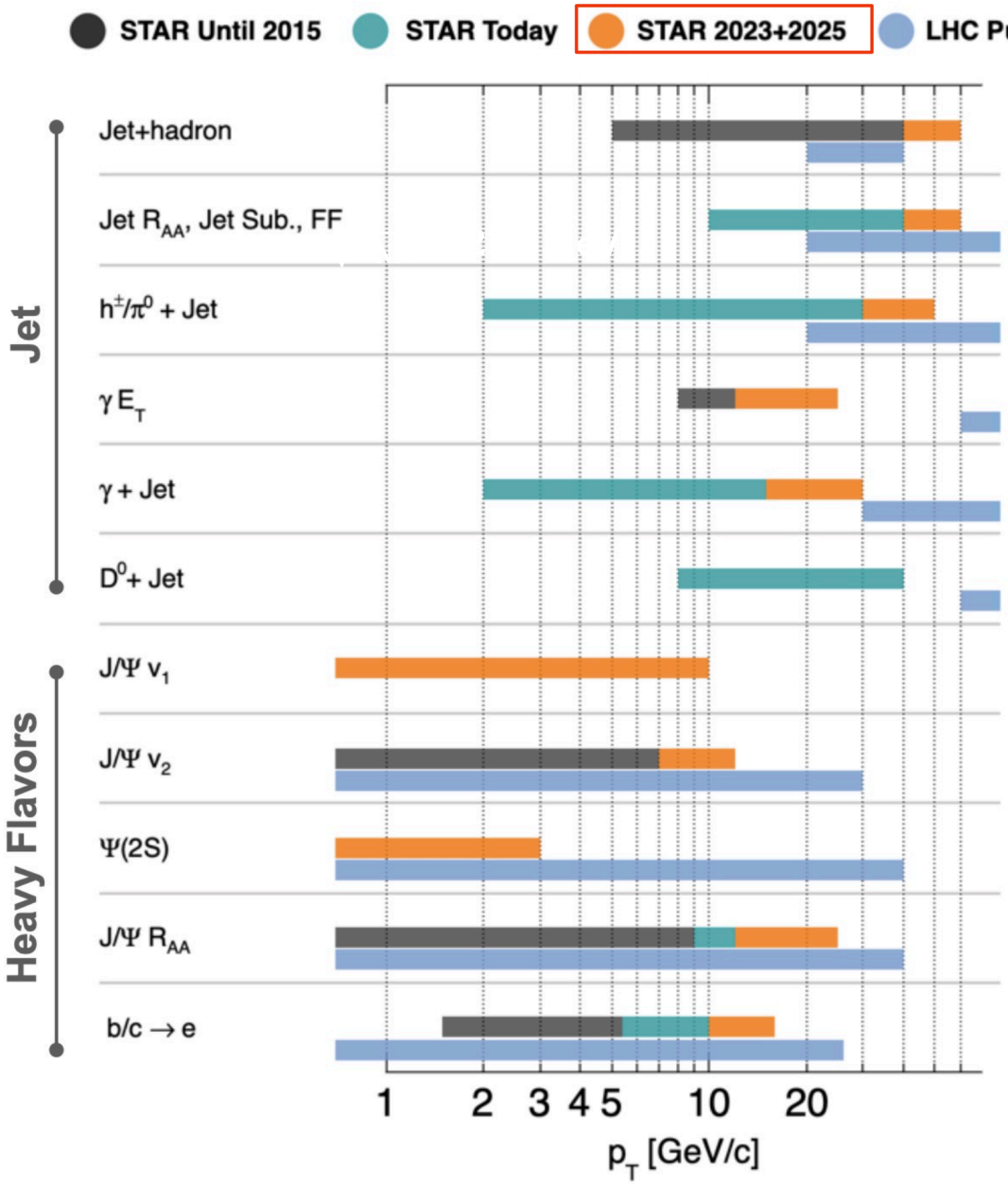


- Caveat
  - Topics discussed in the following slides are some of speaker's personal favorites, not covering every topics that STAR will explore
  - Cold QCD studies are not discussed in this talk
  - Focus on what physics questions we want to answer with each observable

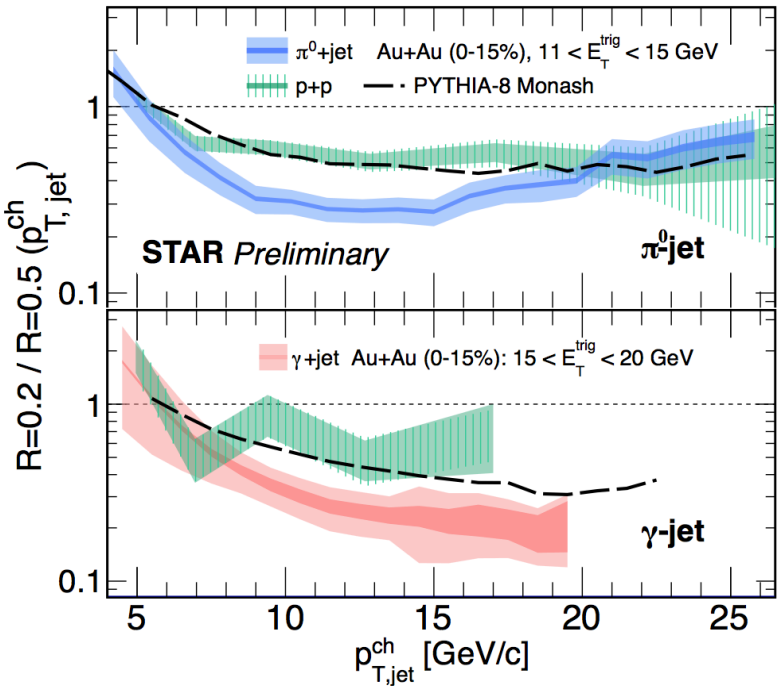
Hard probes: Jets and heavy flavors

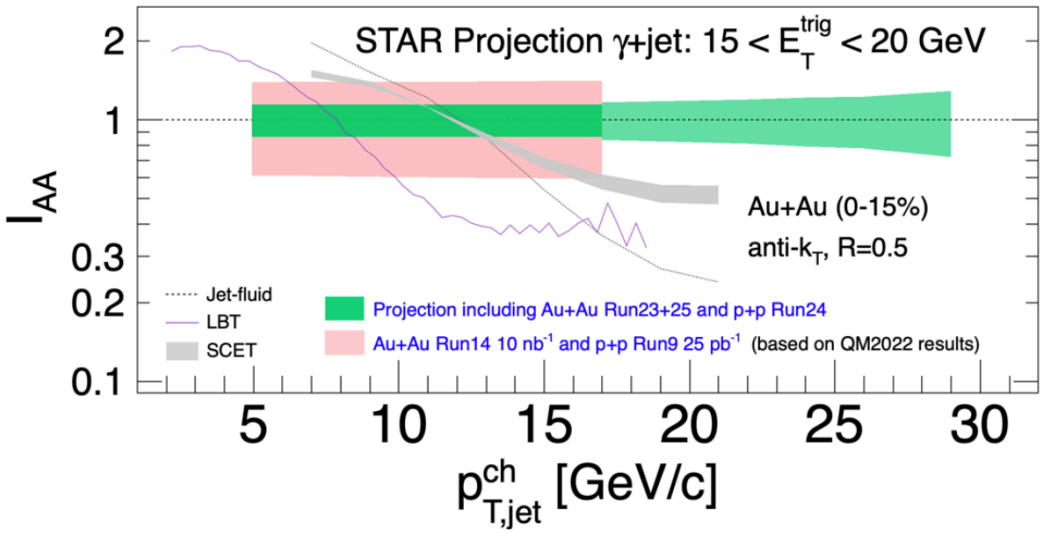


Hard probes program kinematic coverage

Photon-tagged jet spectra

What are the underlying mechanisms of jet quenching at RHIC energies?





- Semi-inclusive direct-photon+jet spectra
- Results based on Run 14 Au+Au data show medium-induced broadening of jet shower

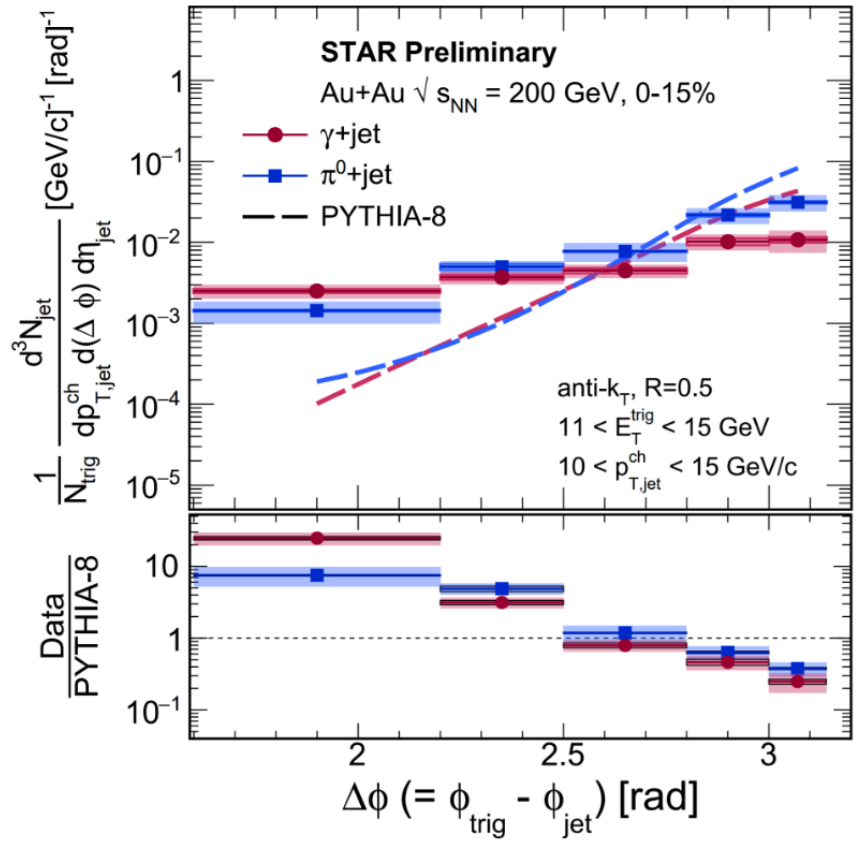
Anticipated uncertainties and kinematic reach with 2023–2025 data

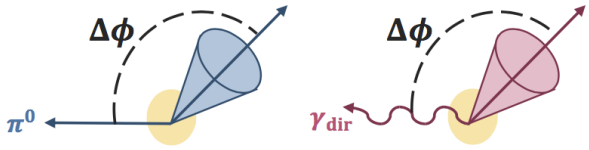
In-medium path-length, color factor, parton energy dependence of jet quenching

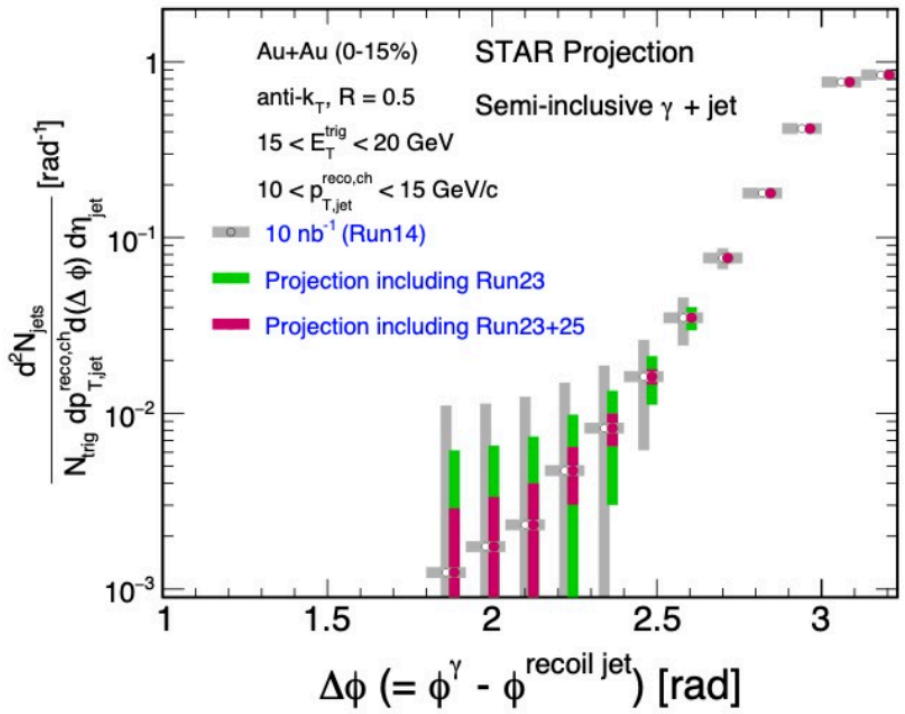
Low p_T, large R, extended to higher p_T with large sampled luminosity

Jet acoplanarity

What are the underlying mechanisms of jet quenching at RHIC energies?







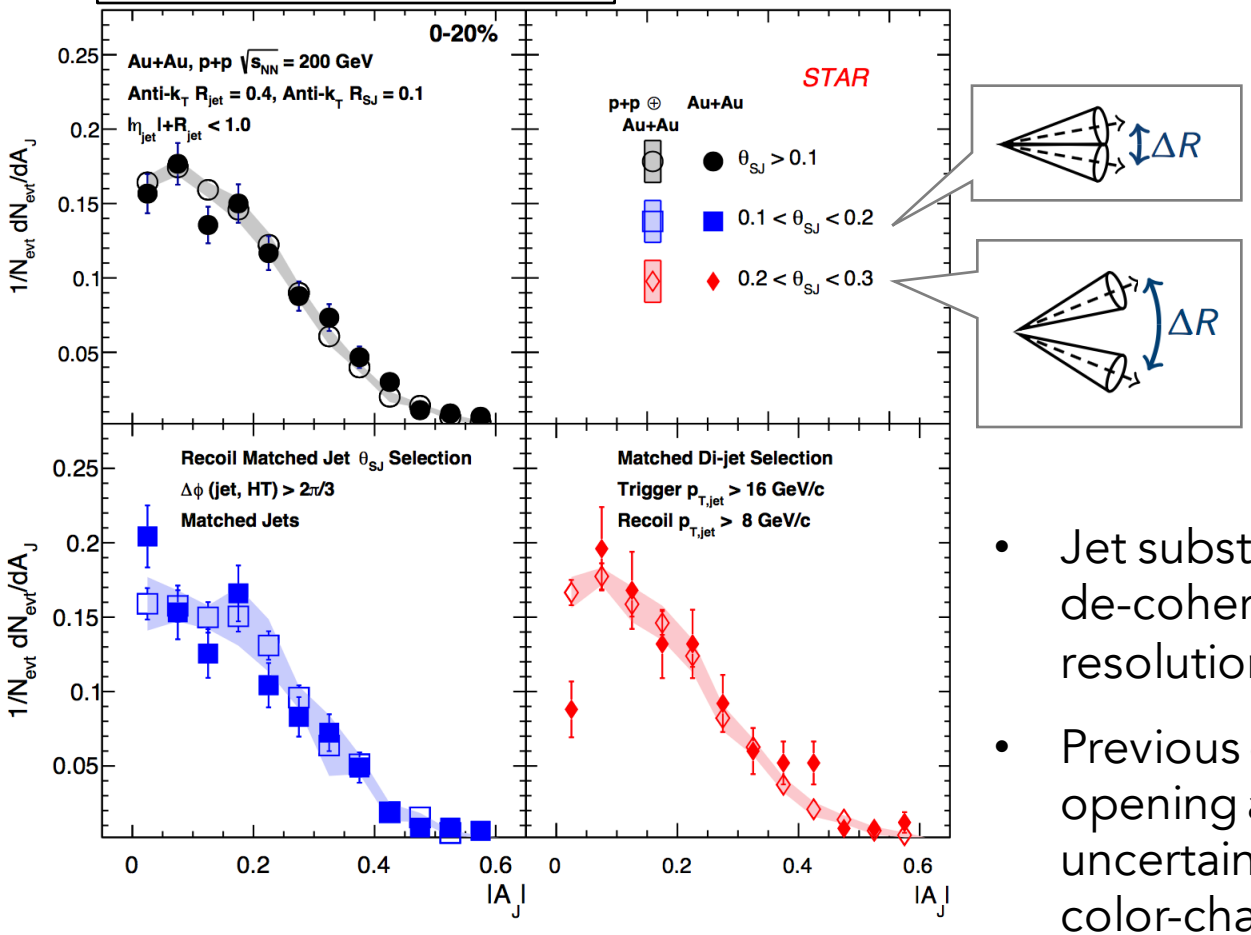
- Direct-photon+jet acoplanarity – Constituents of medium (Discrete scattering centers or effectively continuous medium?)

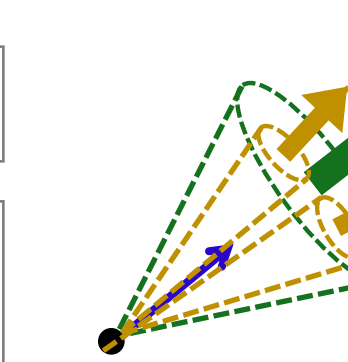
Anticipated uncertainties with 2023–2025 data

Jet substructure

What does jet study tell us about the microscopic structure of the QGP as a function of resolution scale?

STAR, Phys. Rev. C 105 (2022) 44906

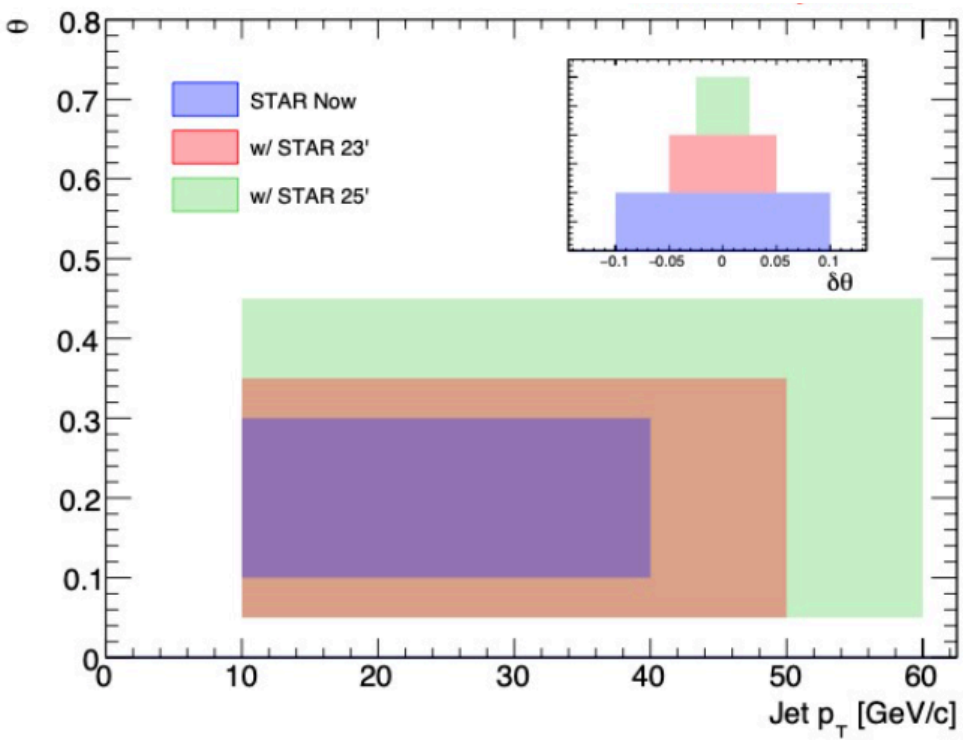


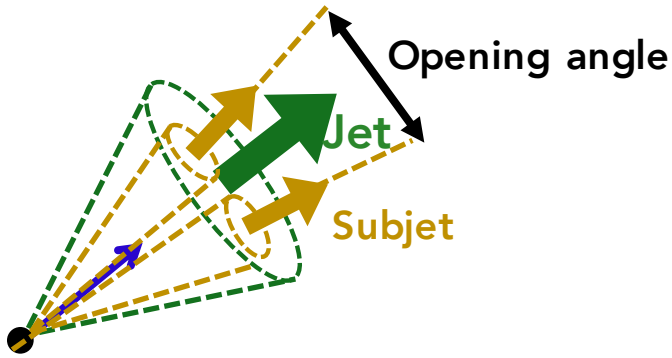


- Jet substructure: distinguishing coherence vs. de-coherence picture connected to medium's resolution scale
- Previous di-jet imbalance for jets of different opening angles – No dependence within the uncertainties → Energy loss from a single color-charge as it traverses the medium

Jet substructure

What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale?





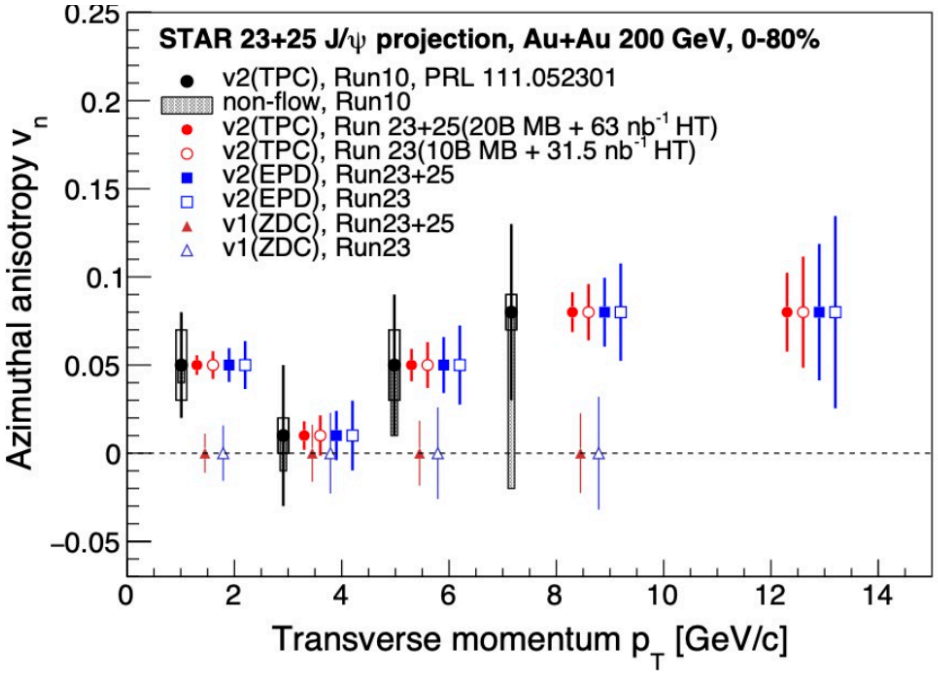
Jet substructure: distinguish coherence vs. de-coherence picture connected to medium's resolution scale

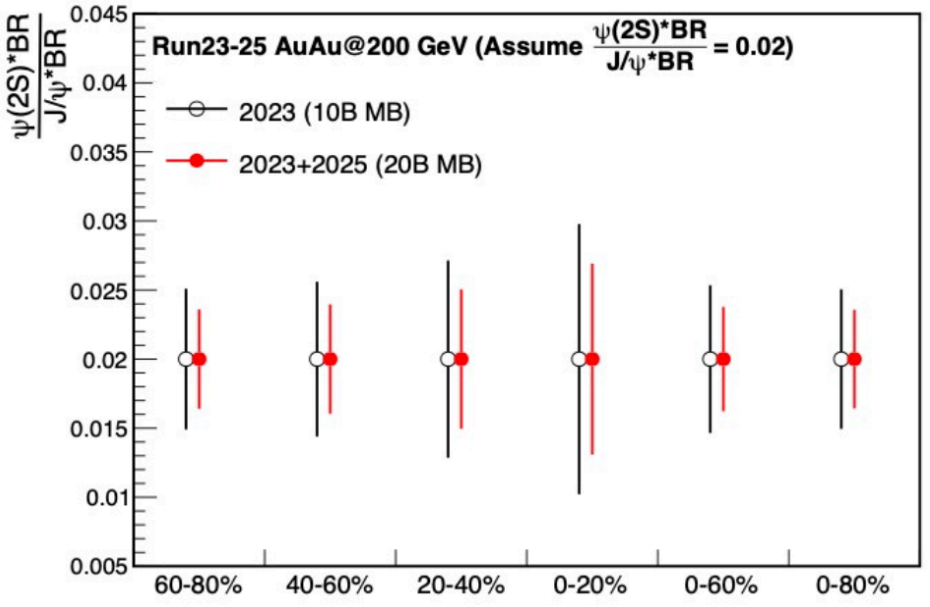
Improved opening angle resolution by a factor of 4 with 2023-2025 data

Pre
op in the previous uncertainties → Energy loss from a single color-charge as it traverse the medium

J/ψ v_2 and v_1, ψ(2S)

What can be learned about deconfinement and thermalization in a QGP from charmonium measurements?





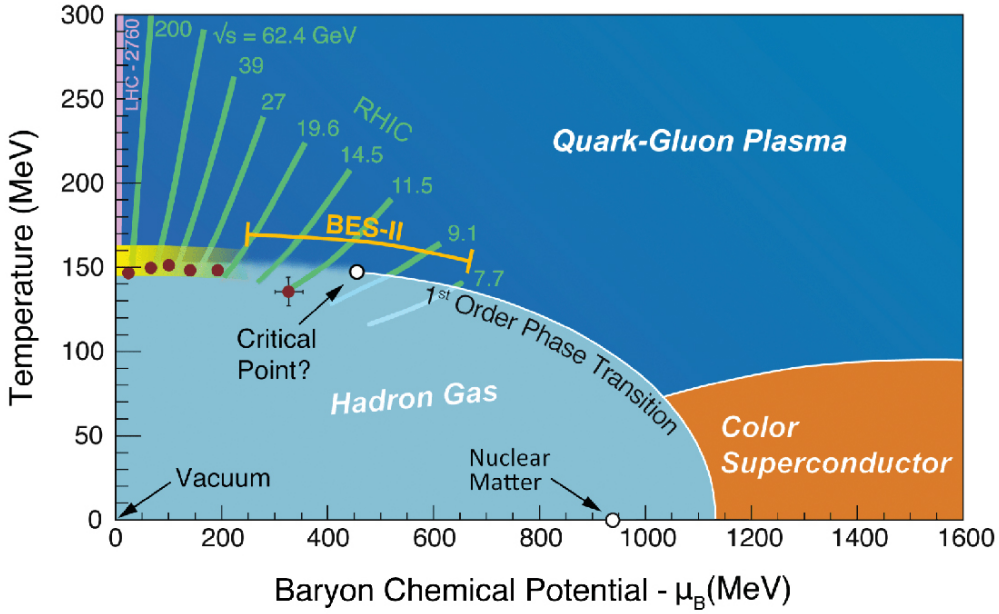
- J/ψ – interplay of dissociation and recombination → signature of deconfinement
- Low p_T v_2 – Attributing to recombination
- v_1 – initial tilt of the bulk medium

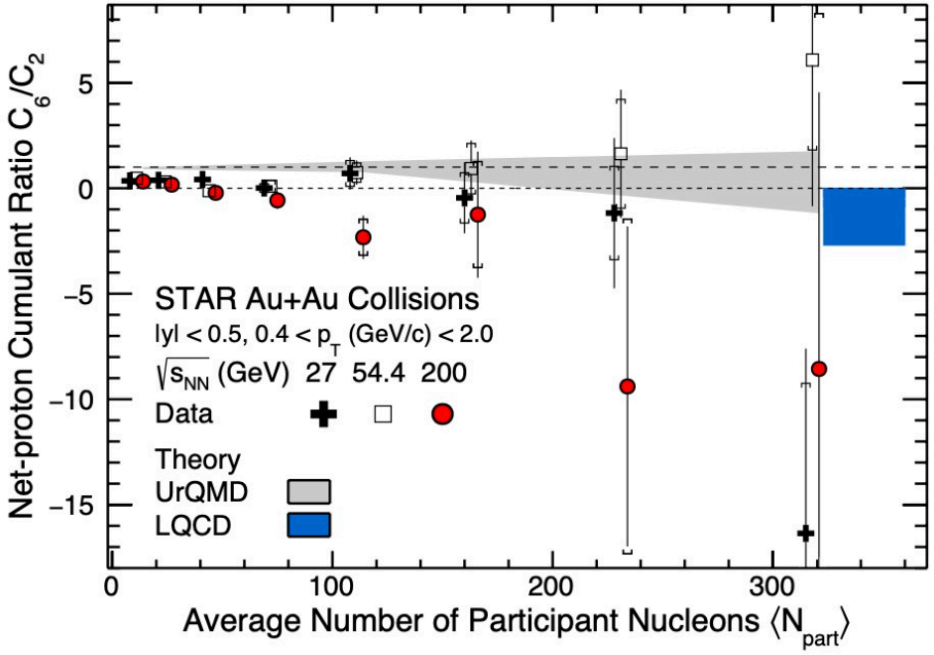
- ψ(2S) suppression – exploring temperature profile of the medium

Improved PID and extended rapidity and p_T coverage by iTPC

Net-proton C_6/C_2

What is the the precise nature of the transition near $\mu_B = 0$? (i.e. search for crossover)



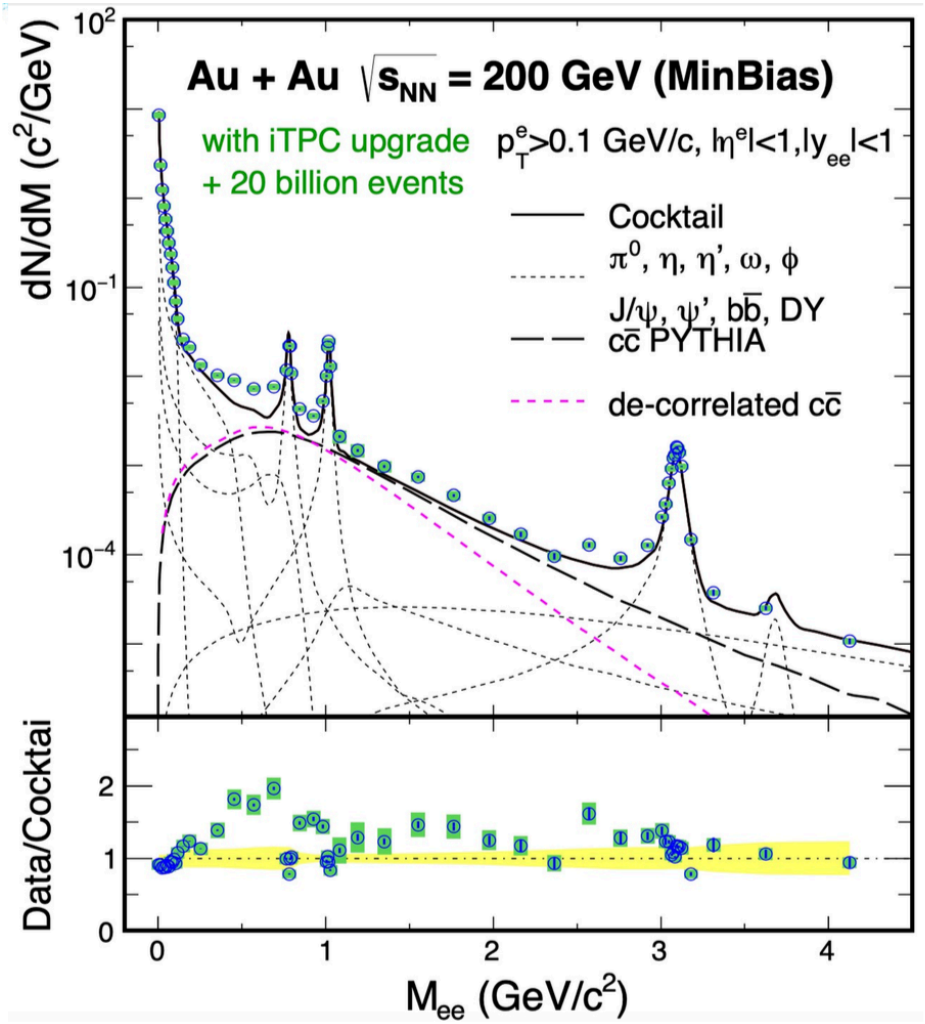


- Net-proton cumulants are sensitive to chiral crossover transition at $\mu_B = 0$, lattice QCD predicts a chiral crossover at $\mu_B/T \leq 2$ with negative 6th-order net proton cumulants
- Previous results showed a hint of a sign change from peripheral to central collisions at 200 GeV
- High statistics measurements with 2023-2025 data will pin down the sign change

Di-electron

What are the chiral properties of the medium?

What is the QGP temperature?

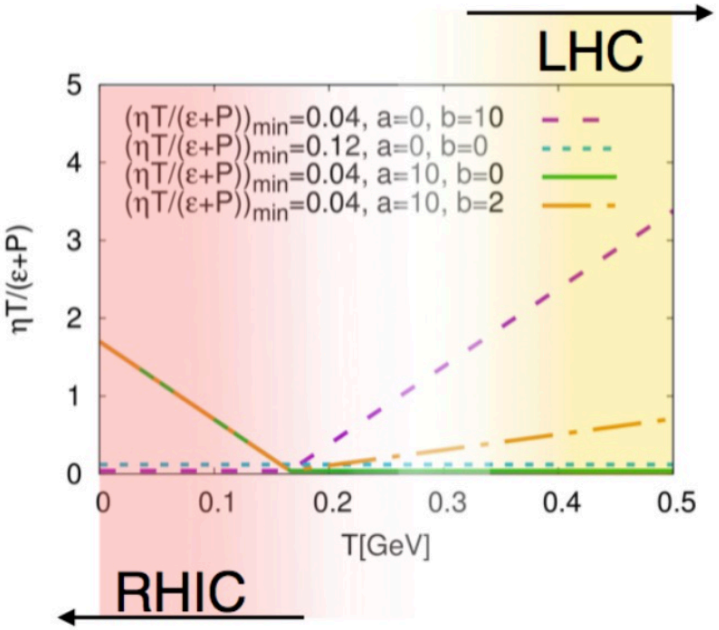


- **Low-mass dielectron** – temperature indicator near chiral crossover, providing constraints to theories regarding chiral symmetry restoration at $\mu_B = 0$
- **Intermediate-mass dielectron** – direct thermometer to the QGP temperature
- Results from BES-II data are coming

Improved PID and extended rapidity and p_T coverage by iTPC

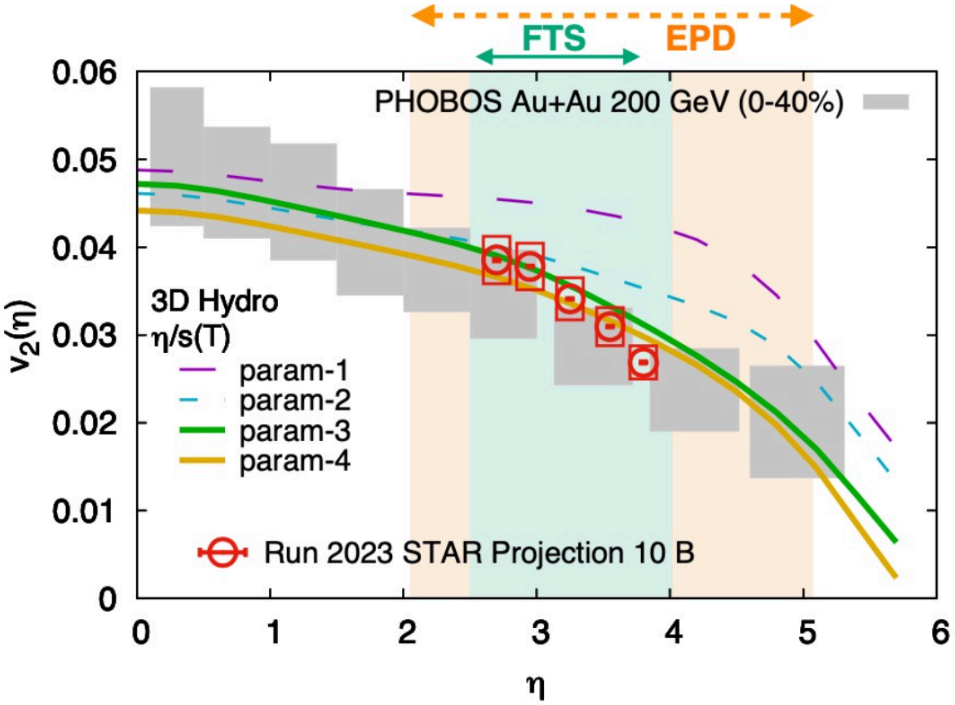
v_n as a function of η

What is the precise temperature dependence of shear and bulk viscosity?



G. Denicol, et. al, Phys. Rev. Lett. 116 (2016) 212301

PHOBOS, Phys. Rev. C 72 (2005) 051901

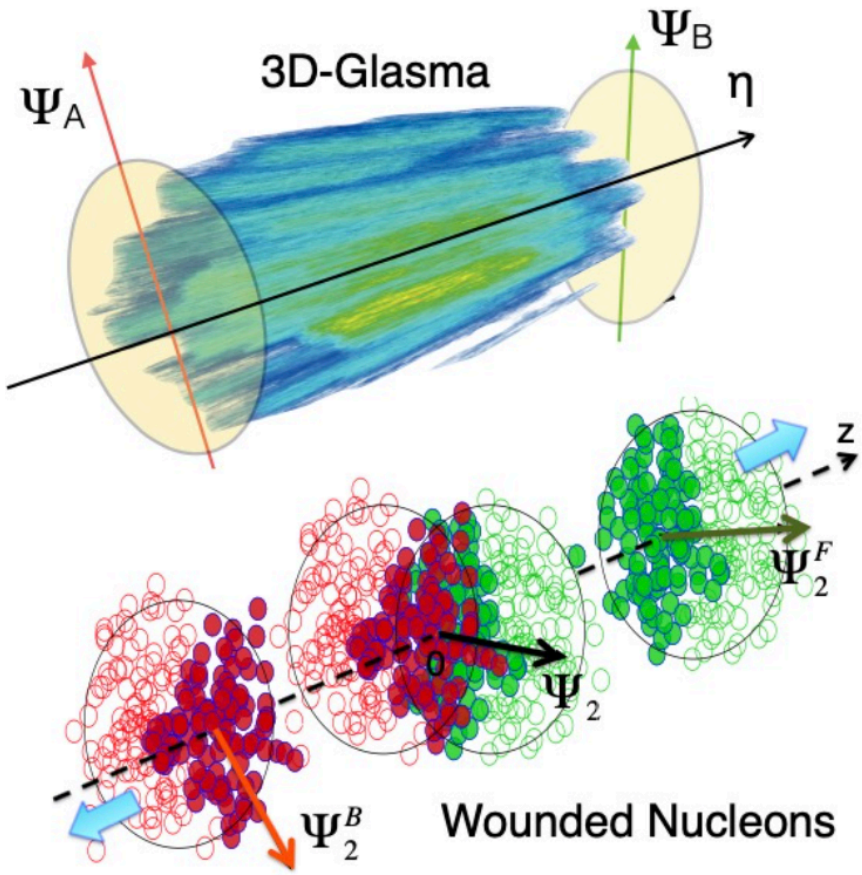


- Flow measurements at forward rapidity are sensitive to shear viscosity (η/s) as a function of temperature (T)
- Significantly more precise results than previous PHOBOS results with 2023–2025 data

Forward upgrade

r_n over a wide η window

What is the nature of the 3-dimensional initial state at RHIC energies?



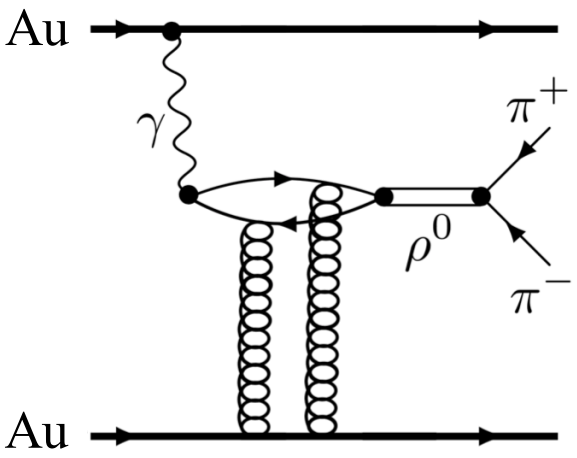
$$r_n(\eta_a, \eta_b) = V_{n\Delta}(-\eta_a, \eta_b)/V_{n\Delta}(\eta_a, \eta_b)$$

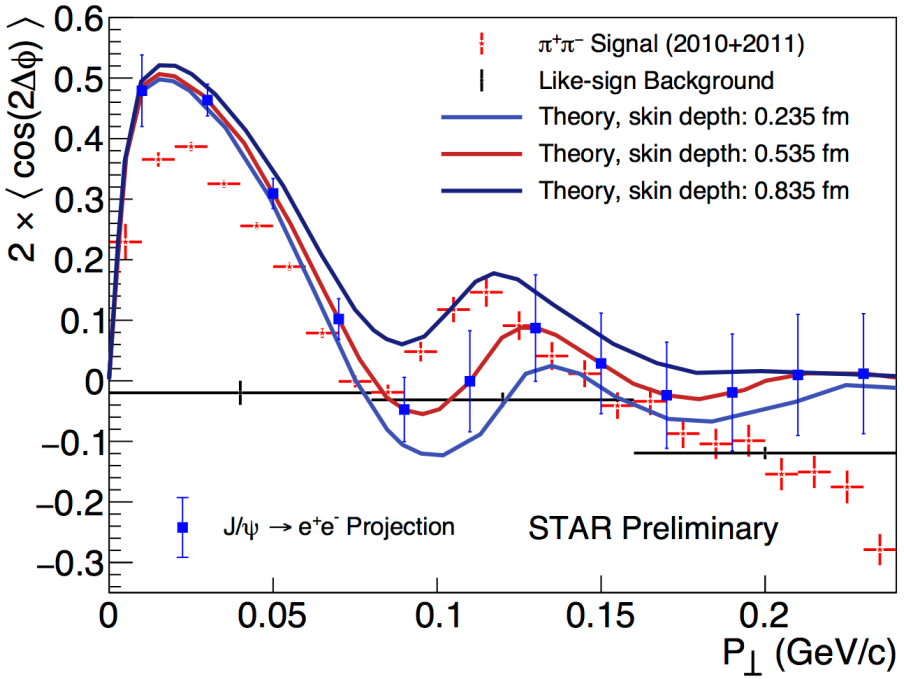
- $V_{n\Delta}$: Fourier coefficient calculated with pairs of particles in different rapidity regions
- r_n is sensitive to the initial state (e.g. 3D Glasma model – weaker decorrelation, Wounded nucleon model – stronger decorrelation, …)
- Precise measurement of r_n over a wide rapidity window with 2023–2025 data

Extended η coverage with iTPC and Forward upgrade

Vector meson decay

What can we learn about the gluon distribution inside the nucleus?





- $\cos(2\Delta\phi)$ modulation in $\pi^+\pi^-$ pairs from photonuclear ρ^0 meson and continuum (Drell-Soding production) observed
- Theoretical calculation (linearly polarized photon interacting with the saturated gluons) qualitatively agrees with the data – Model sensitive to the spatial gluon distribution
- Multi-differential measurements (η, mass, p_T) with 2023–2025 data will provide further constraints to theoretical calculations

Bridging RHIC and EIC science

Summary

- STAR Collaboration will continue to explore characteristics of Quark-Gluon Plasma and QCD phase diagram with existing and upcoming data, as well as provide opportunity to identify and perform measurements informative towards EIC science

- Key questions and observables:
  - What are the underlying mechanisms of jet quenching at RHIC energies? What does jet study tell us about the microscopic structure of the QGP as a function of resolution scale? γ_{dir}+jet I_{AA}, γ_{dir}+jet acoplanarity, jet substructure
  - What can be learned about deconfinement and thermalization in a QGP from charmonium measurement? J/ψ v_2 and v_1, ψ(2S)
  - What is the precise nature of the transition near μ_B=0? Net-proton C_6/C_2
  - What are the chiral properties of the medium? What is the QGP temperature? Di-electron
  - 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
  - What can we learn about the gluon distribution inside the nucleus? Vector meson decay
  - And there are more!

Thank you!

STAR detector and recent upgrade

- Physics goals of forward upgrade for hot QCD studies
  - Flow harmonics up to $\eta \sim 4$
  - Longitudinal decorrelation up to $\eta \sim 4$
  - Global Lambda polarization: strong rapidity dependence…
  - Charged and neutral hadrons
  - Inclusive jets and di-jets
  - Mid-forward and forward-forward rapidity correlations
  - …
- Also, cold QCD studies