2022 RHIC/AGS ANNUAL USERS' MEETING

From RHIC to EIC

At the QCD Frontiers

This meeting will be held virtually.
June 7–10, 2022

Jets and Heavy Flavor: Highlights and Prospects from STAR

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Overview

- **Jets and heavy quarks:** Hard probes to understand inner workings of QGP. Also inherently interesting in studies of QCD

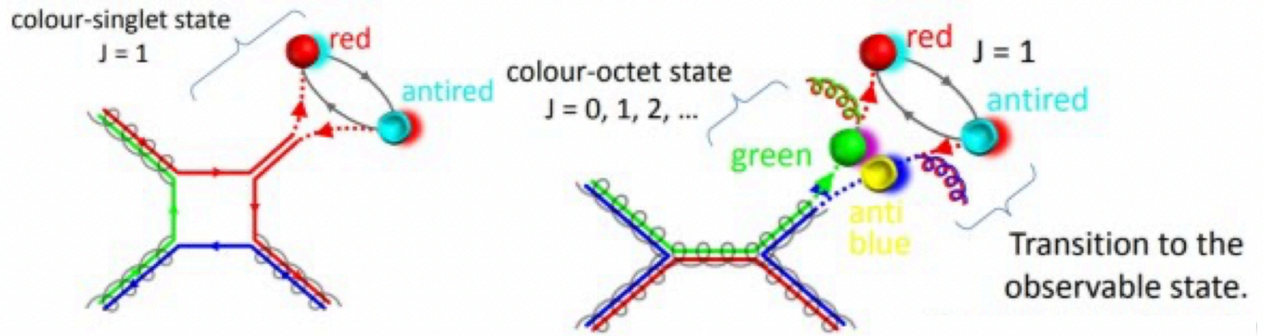
- **Questions STAR is focussed on/can answer:**

  - What is the quarkonium production mechanism in p+p collisions?
  - Impact of cold nuclear matter (CNM) effects on quarkonia production
  - Deconfinement, quarkonia dissociation, regeneration in the QGP
  - Using heavy flavor to access initial conditions in heavy-ion collisions

  - Better understand nature of jet energy loss and underlying mechanism of jet suppression in QGP
    - Lower p_T jets at STAR —> Study jet broadening and acoplanarity
    - Flavor dependence of jet modification
    - Jet substructure dependence of suppression

Recent Jets and HF Results from STAR

J/ψ Production with Jet Activity

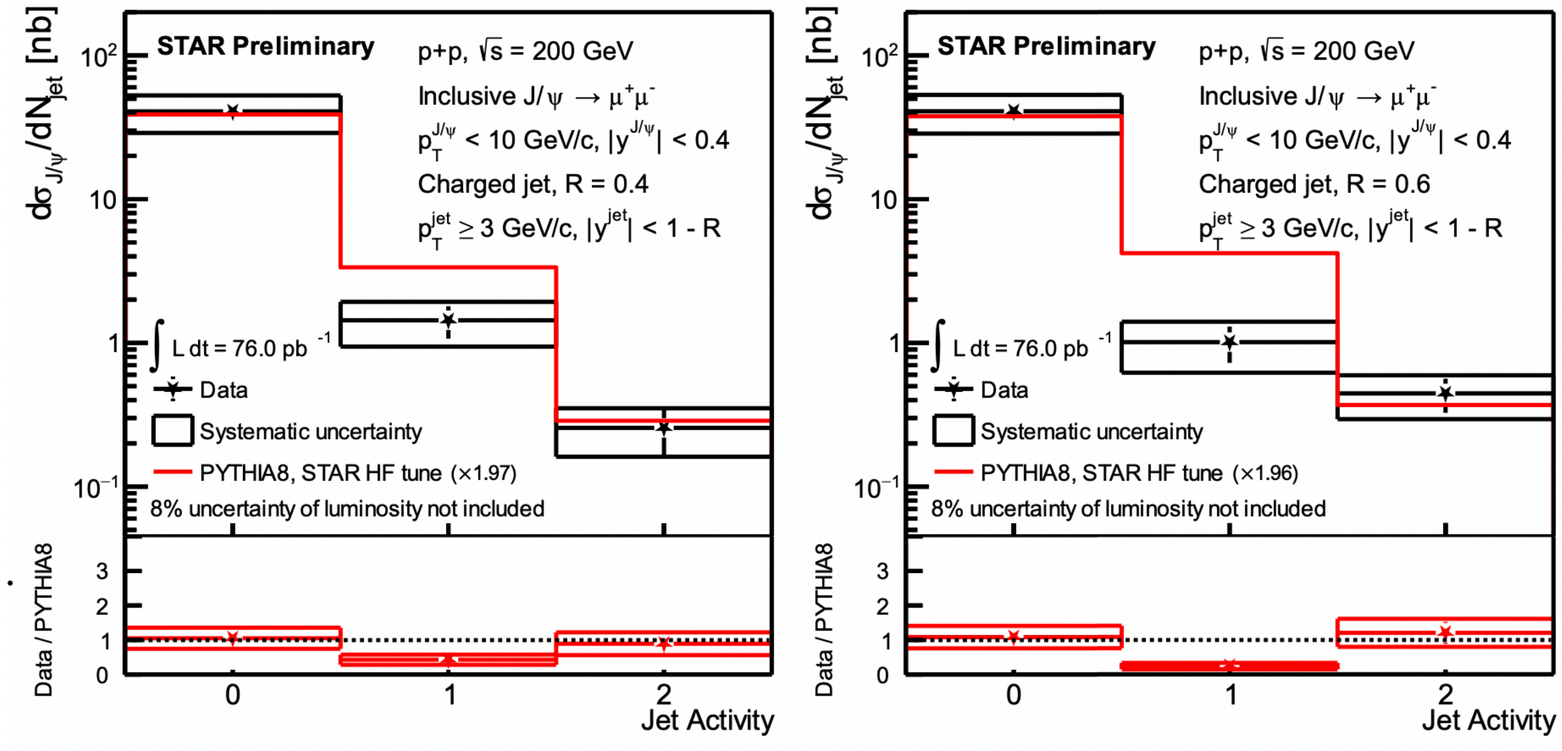


- J/ψ produced via intermediate color singlet or octet state

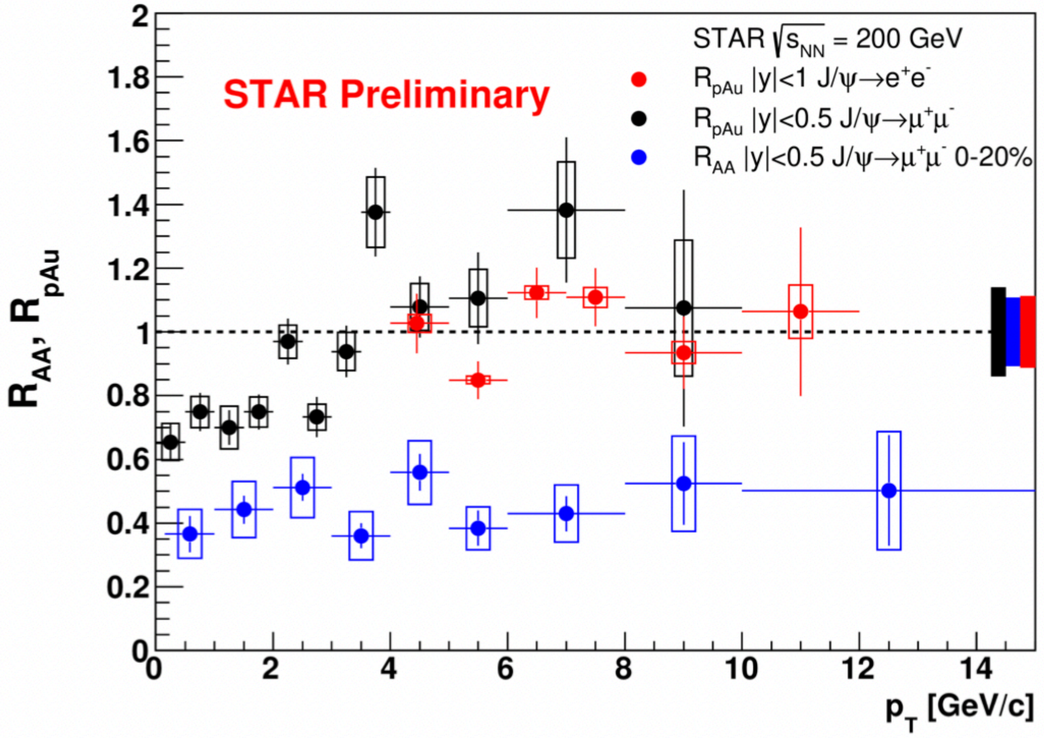
- Quarkonium production from the Color Singlet Model (CSM) should result in a larger jet activity (number of jets per event) than that from the Color Octet Mechanism (COM)

  J-P Lansberg, Physics Reports, 889, 1 (2020)

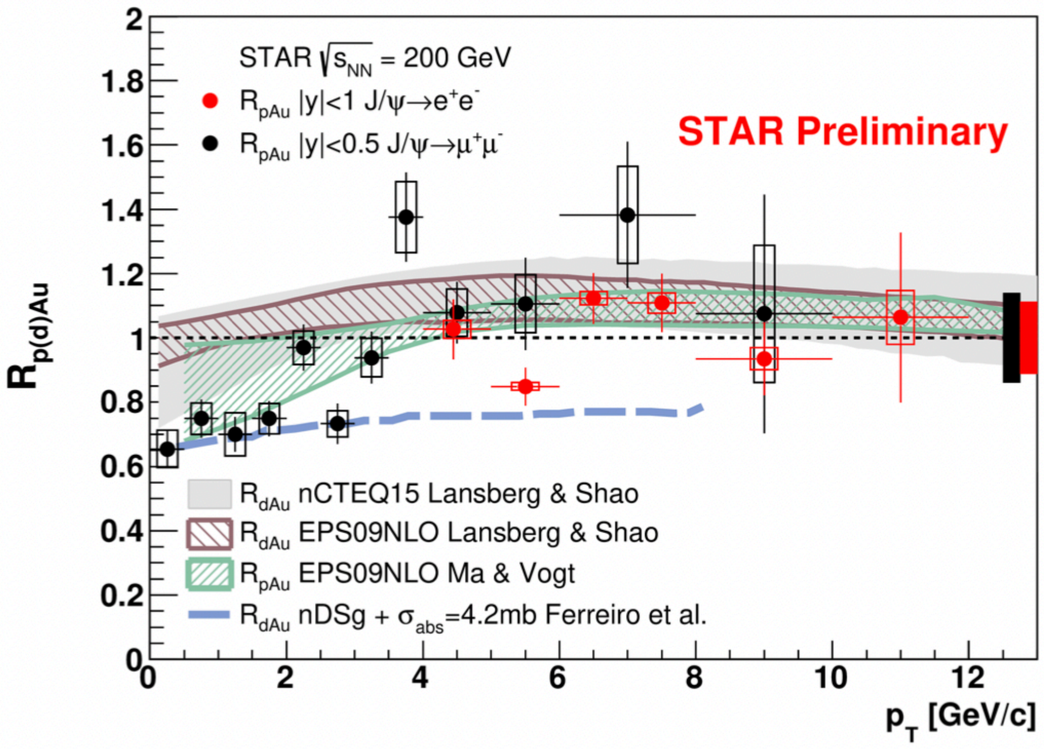
  - Compared to PYTHIA with same kinematics, a smaller fraction of J/ψ are produced associated with jets in data



CNM Effects on J/ψ Production



STAR, Phys. Lett. B 825 (2022) 136865
STAR, Phys. Lett. B 797 (2019) 134917

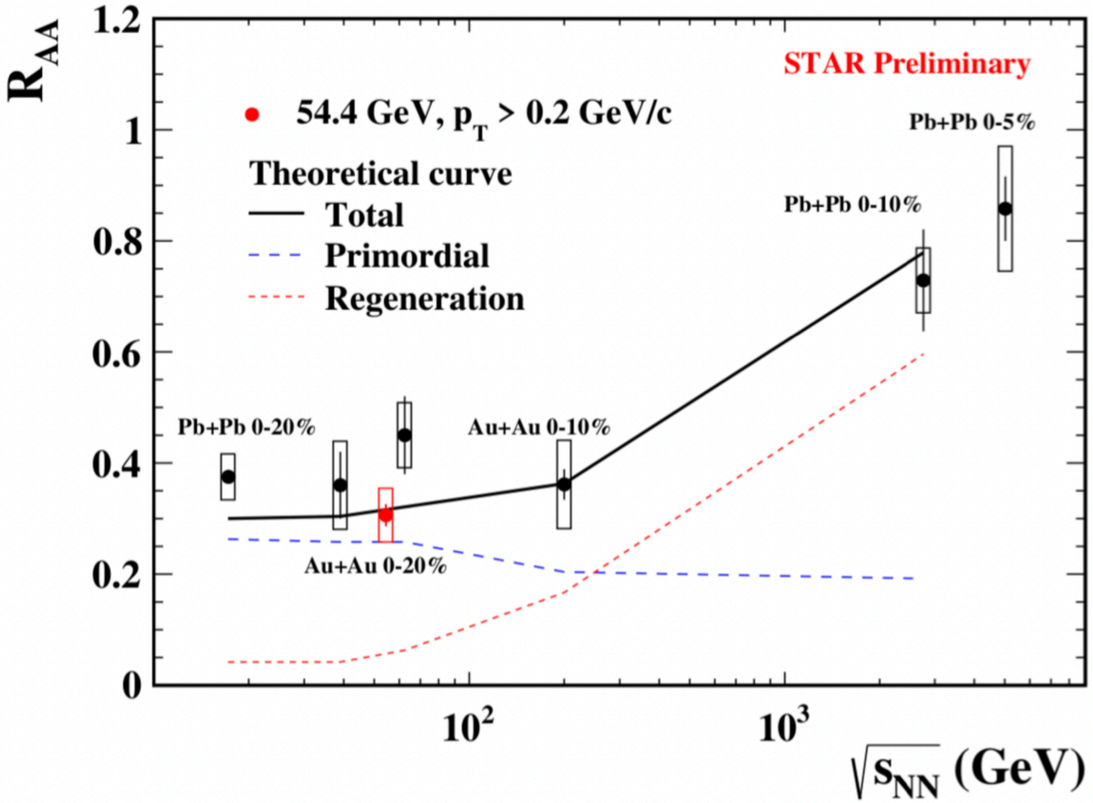


STAR, Phys. Lett. B 825 (2022) 136865
Ma & Vogt, EPS09+NLO, Private Comm.
Lansberg & Shao, nCTEQ15, EPS09+NLO, Eur.Phys.J. C77 (2017) no.1, 1
Ferreriro et al., nDSg+σ_{abs}, Few Body Syst. 53 (2012) 27

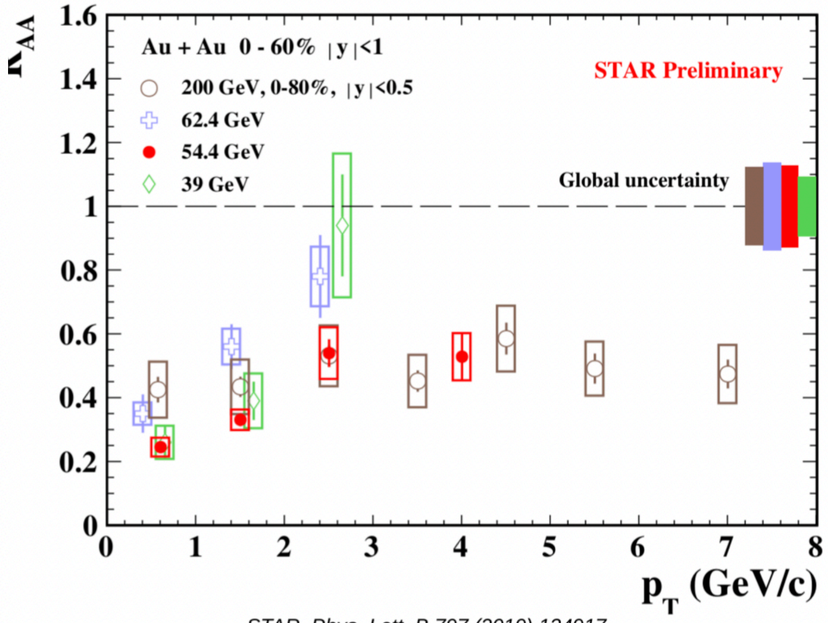
- Better precision measurements at higher p_T through dielectron channel
- $R_{pAu} < 1$ at low p_T (< 2 GeV/c), significant CNM effects
- R_{pAu} consistent with 1 at mid to high p_T, suppression in R_{AA} in this region is from QGP effects
- Model with nuclear absorption is consistent with R_{pAu} at low p_T, but not at high p_T

Collision Energy Dependence of J/ψ R_{AA}

- J/ψ dissociates in the QGP, but the deconfined heavy quark pairs also recombine to form J/ψ
- Collision energy dependence can help constrain the two



STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13-20
ALICE, Nucl. Phys. A 1005 (2021) 121769
ALICE, Phys. Lett. B 734 (2014) 314
X. Zhao, R. Rapp, Phys. Rev. C 82, 064905



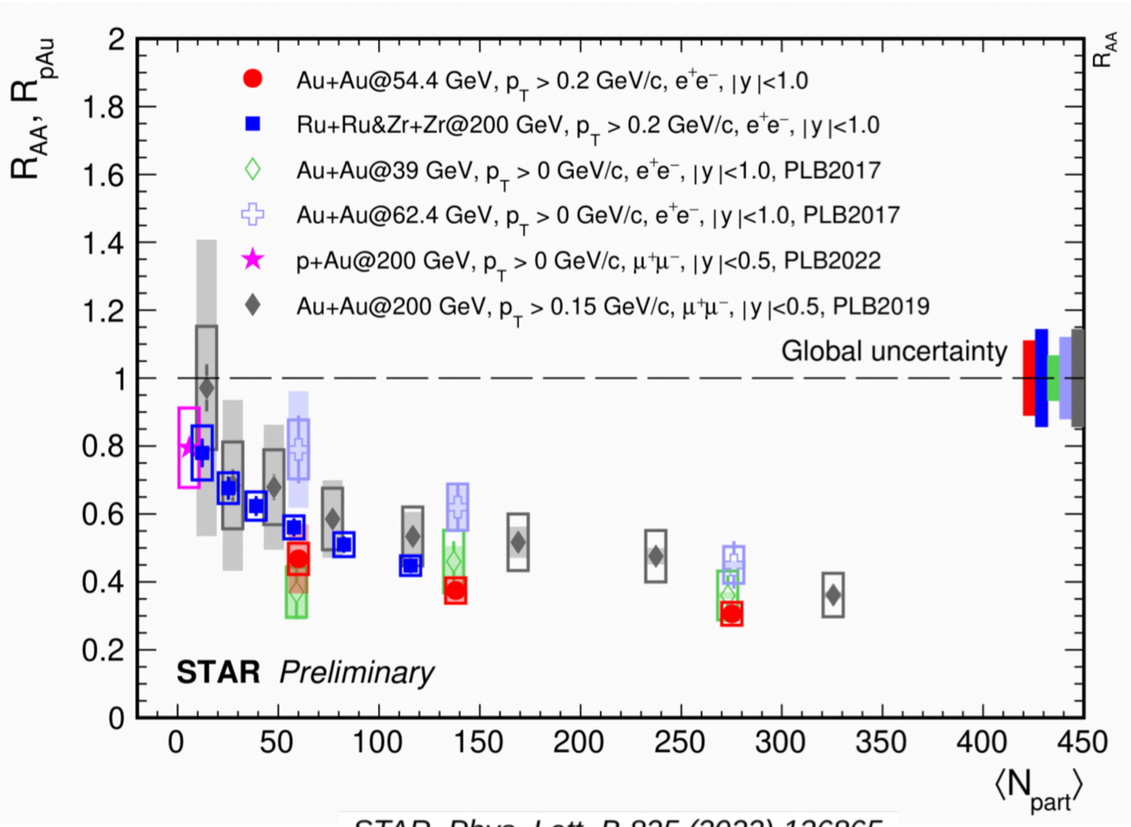
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13

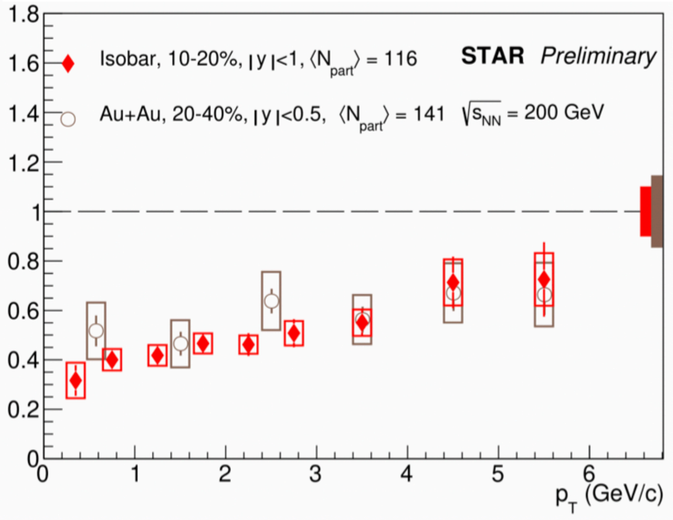
- Better precision for new measurement at 54.4 GeV compared to BES-I results

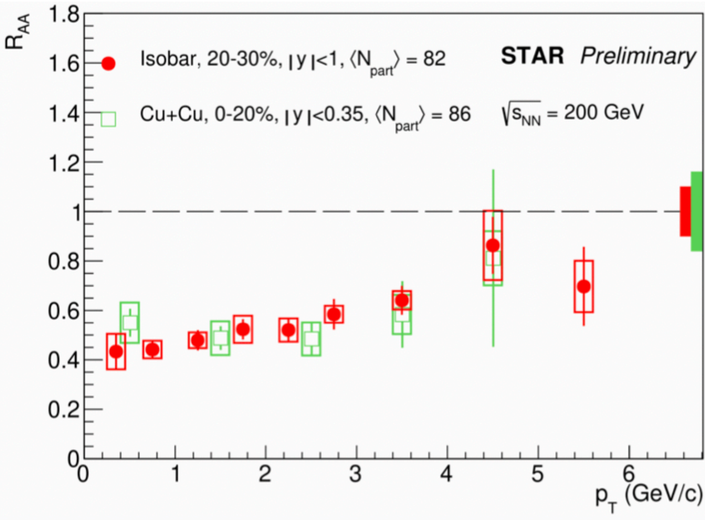
- No significant energy dependence of J/ψ R_{AA} below 200 GeV
- Transport model with both dissociation and regeneration effects describes the data

Isobar Collisions: System Size Dependence

- Large isobar dataset, about 4 billion minimum bias events.
- Ideal to study system size and geometry dependence of J/ψ suppression





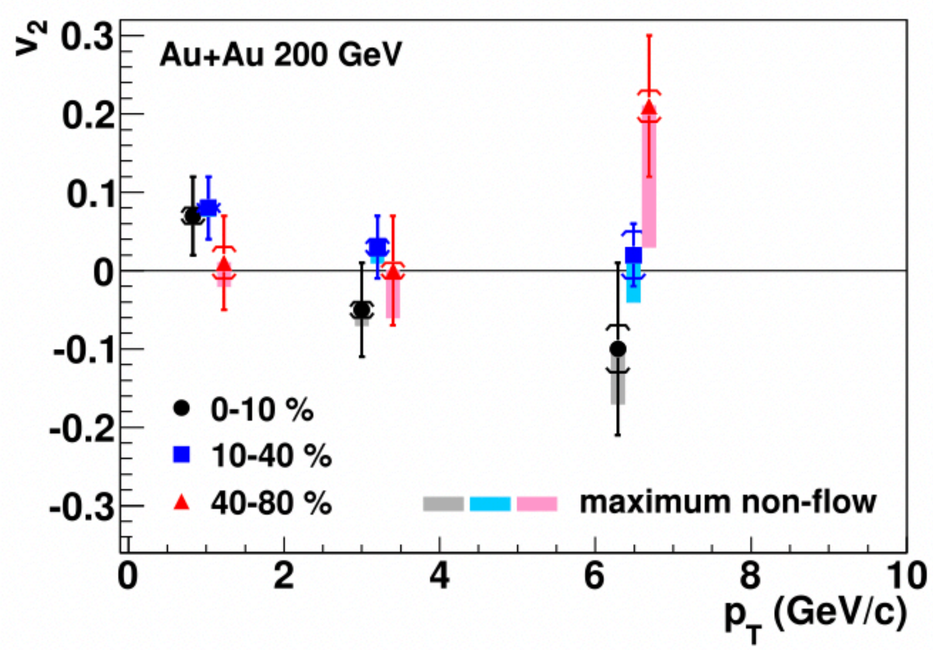


STAR, Phys. Lett. B 825 (2022) 136865
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13

- Good precision data from Isobar collisions
- J/ψ R_{AA} consistent between Au+Au, Cu+Cu and Isobar collisions at similar N_{part}
- J/ψ suppression driven by N_{part}

Isobar collisions: J/ψ v_2 to Constrain Regeneration Contribution

- Non zero J/ψ v_2 could arise from medium interactions of deconfined charm quarks
- Can give additional constraints to the regeneration component



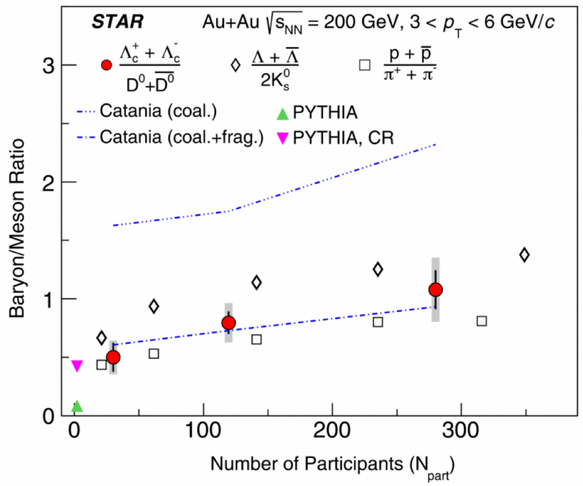
STAR, Phys. Rev. Lett., 111, 052301 (2013)

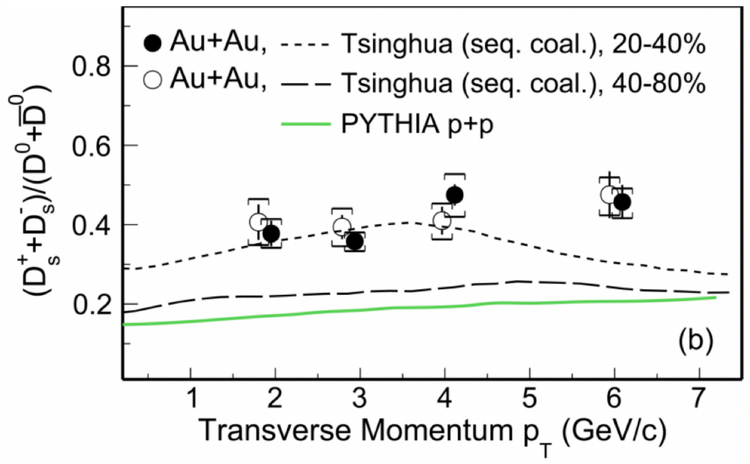
- Large uncertainties for existing measurements at RHIC
- Isobar collision data can reduce the error bars
- Also EPD for the isobar run, reduce non-flow effects

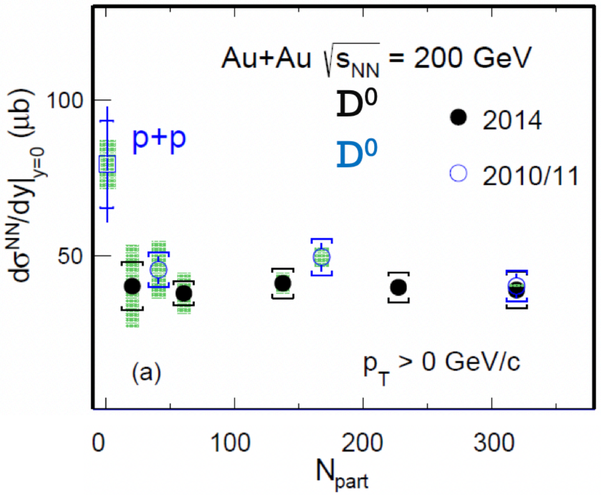
- Analysis ongoing, expect results in the upcoming conferences!

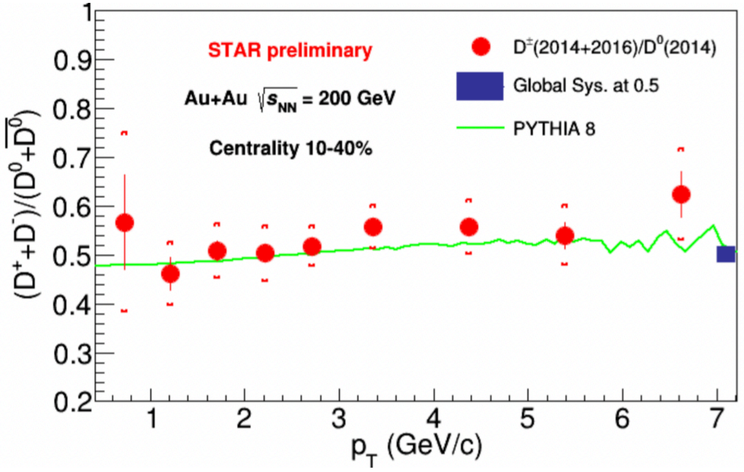
Open HF Production: Coalescence Hadronization

- All ground state open HF hadrons measured with HFT data









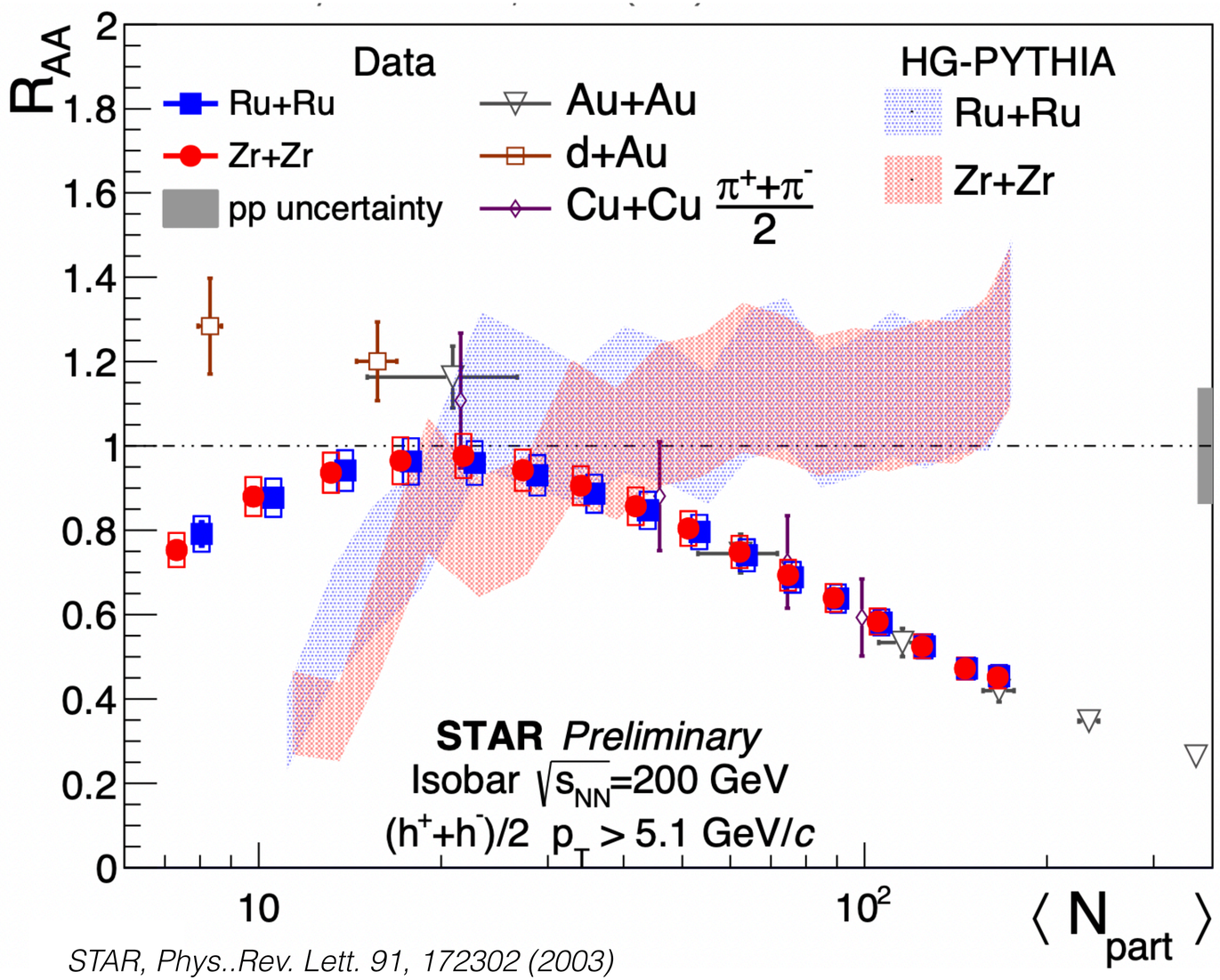
Coll. system	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3
	D_s	15 ± 2 ± 4
	Λ_c	40 ± 6 ± 27*
	Total:	**112 ± 6 ± 27**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

- D^0 and $D^{+/-}$ production suppressed relative to p+p
- Overall per nucleon charm production cross section in Au+Au consistent with that in p+p.

- Enhancement of Λ_c baryon and strange D meson (D_s) production —> Consistent with coalescence hadronization

D^0: STAR, Phys. Rev. C 99, 034908, (2019)
Λ_c: STAR, Phys. Rev. Lett. 124, 172301, (2020)
D_s: STAR, Phys. Rev. Lett. 127, 092301 (2021)

System Size Dependence of R_{AA}



STAR, Phys..Rev. Lett. 91, 172302 (2003)
STAR, Phys. Rev. Lett. 91, 072304 (2003)
STAR, Phys. Rev. C 81, 054907 (2010)

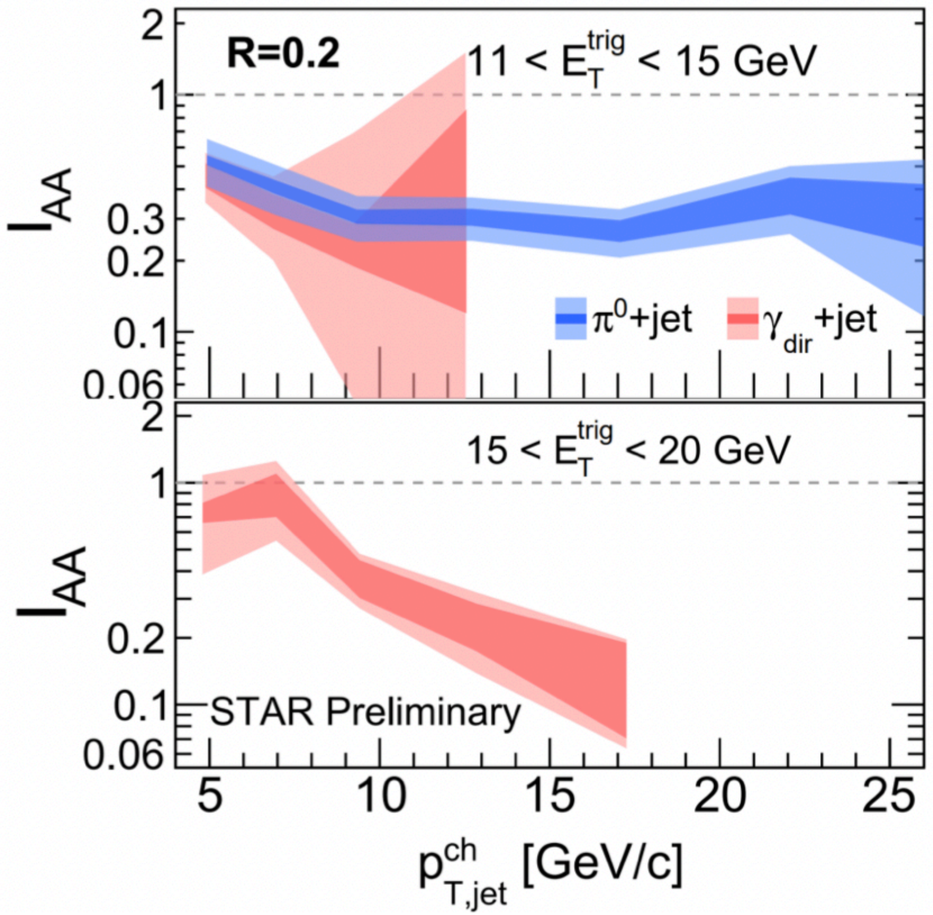
- **High p_T (> 5.1 GeV/c) charged hadron R_{AA}: Same value at same N_{part} irrespective of collision system, for $N_{part} > 20$**

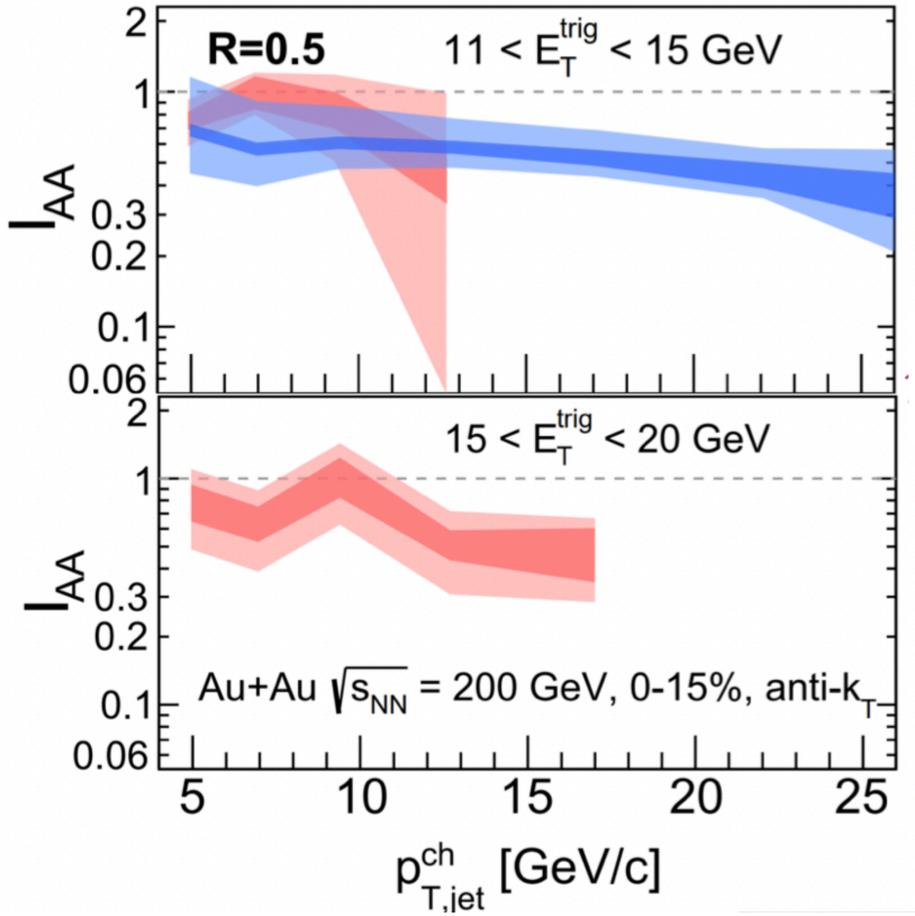
- Different trends and suppression below $N_{part} \sim 20$ in isobar collisions
  - **Possible event selection bias in peripheral centralities**
  - HG-PYTHIA reproduces trend, but predicts larger bias/suppression
  - More studies ongoing

Medium-induced Intrajet Broadening and Acoplanarity

- Study semi-inclusive recoil jet distributions to π^0 and γ^{dir} triggers
  - Different q/g jet fractions, different path lengths in medium
  - π^0 trigger: less quark jets in recoil jet distribution, surface bias for triggers

$I_{AA} = Yield_{Au+Au}/Yield_{p+p}$



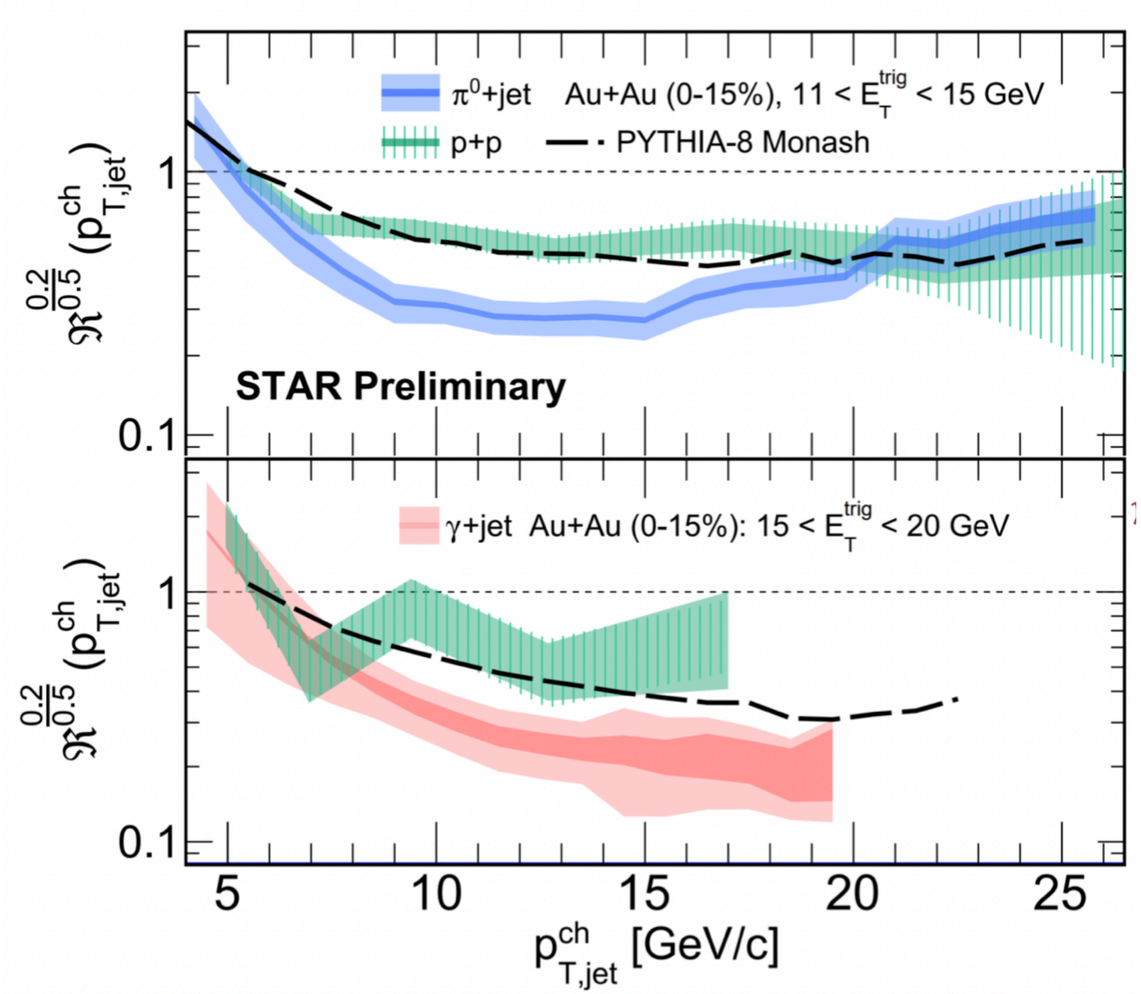


- **R = 0.2 jets suppressed more than R = 0.5 jets**
  - Redistribution of energy to wider angles in A+A
- **Similar suppression for π^0 and γ^{dir} triggered cases**
  - Interplay of differing spectrum shape, path lengths and q/g fractions

Medium-induced Intrajet Broadening and Acoplanarity

- Study semi-inclusive recoil jet distributions to π^0 and γ^{dir} triggers
  - Different q/g jet fractions, different path lengths in medium
  - π^0 trigger: Less quark jets in recoil jet distribution, surface bias for triggers

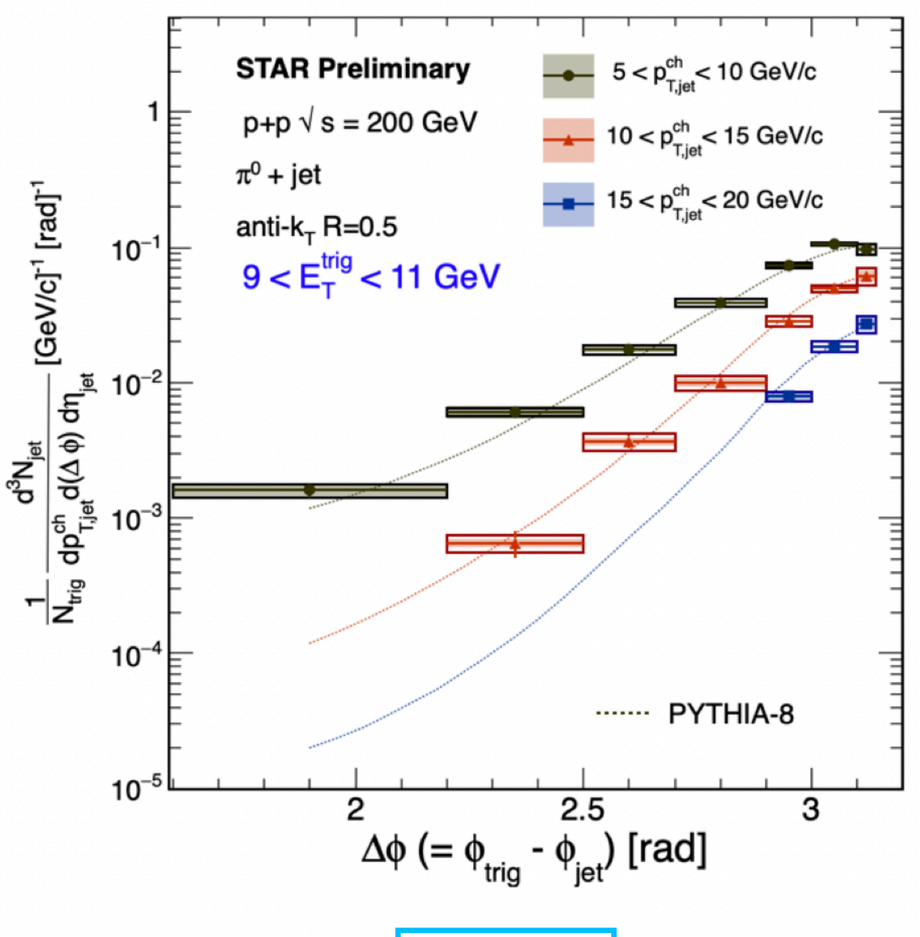
$$R^{0.2/0.5} = \text{Yield}_{R=0.2}/\text{Yield}_{R=0.5}$$



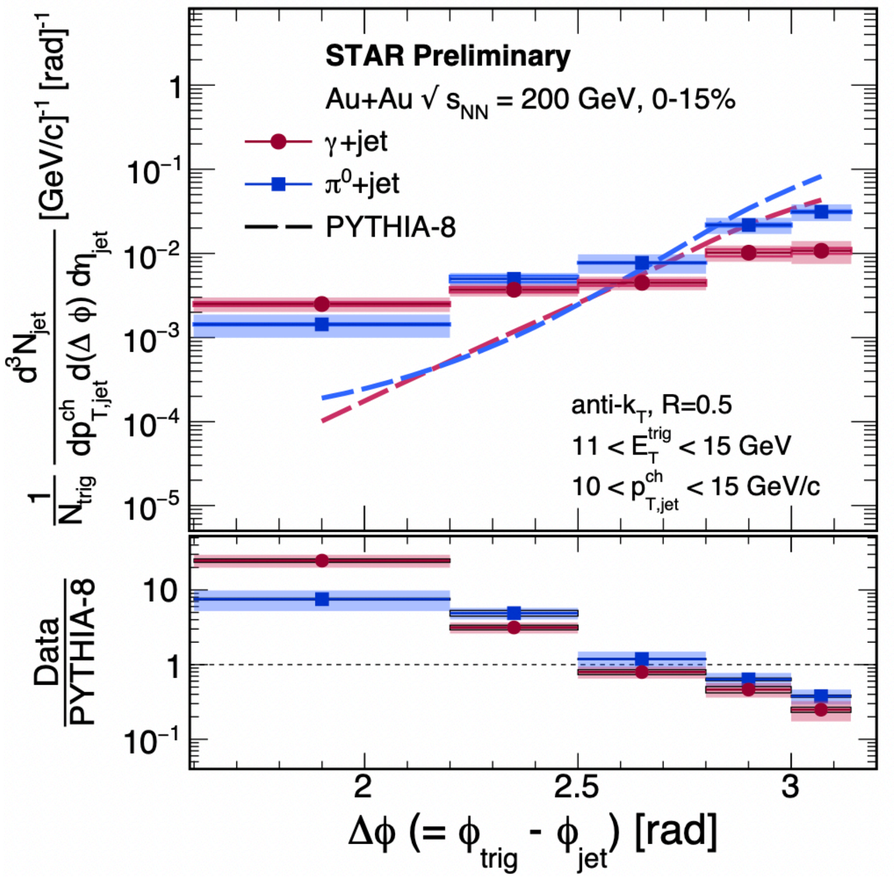
- **Ratio less than 1 in p+p due to jet shape in vacuum**
  - Well reproduced by PYTHIA-8
- **Observation of medium induced intrajet broadening in Au+Au collisions**
  - Observed for both π^0 and γ^{dir} triggered jets

Medium-induced Intrajet Broadening and Acoplanarity

- Study semi-inclusive recoil jet distributions to π^0 and γ^{dir} triggers
  - Dijet acoplanarity measured in p+p and Au+Au collisions at RHIC



p+p

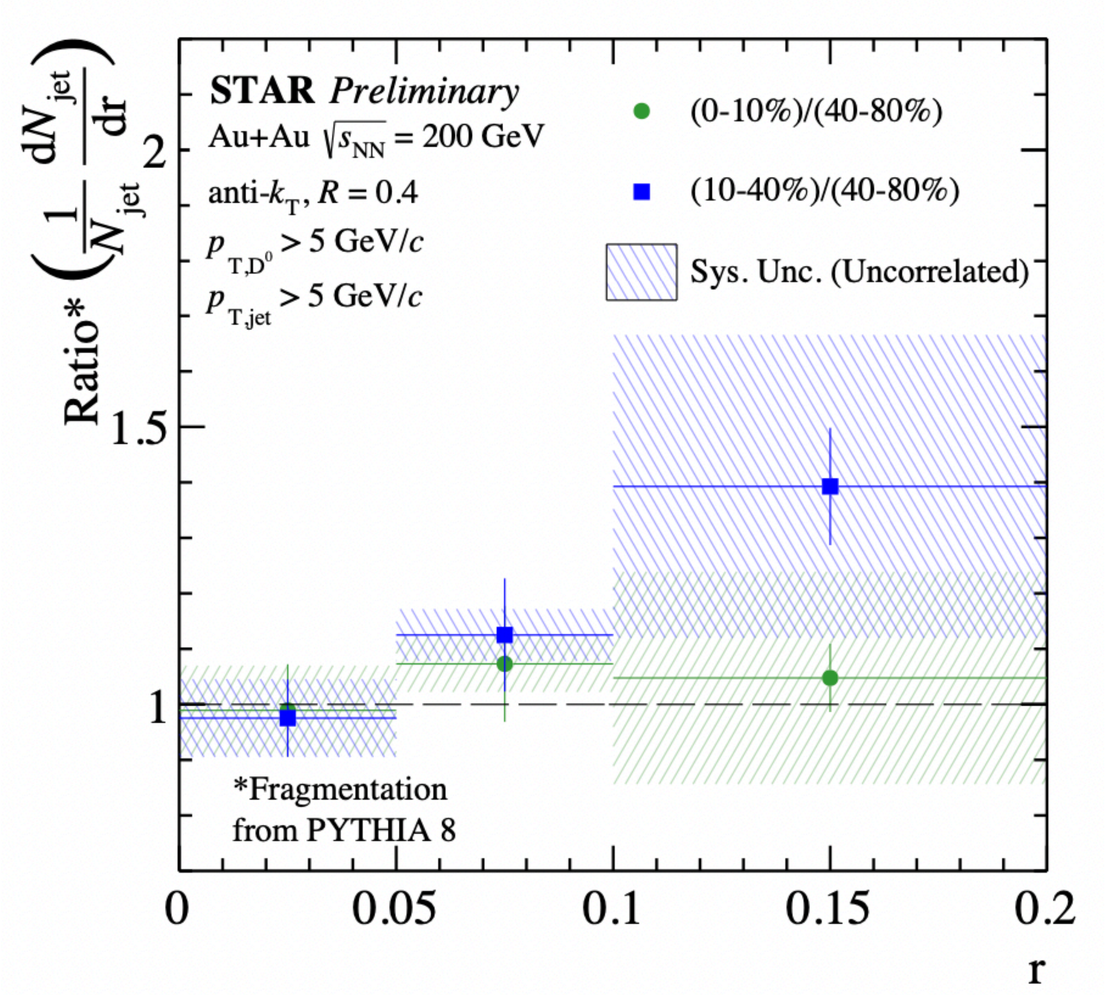


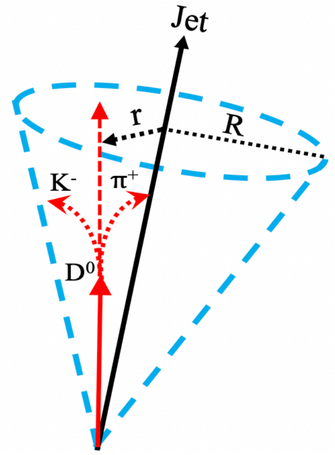
Au + Au

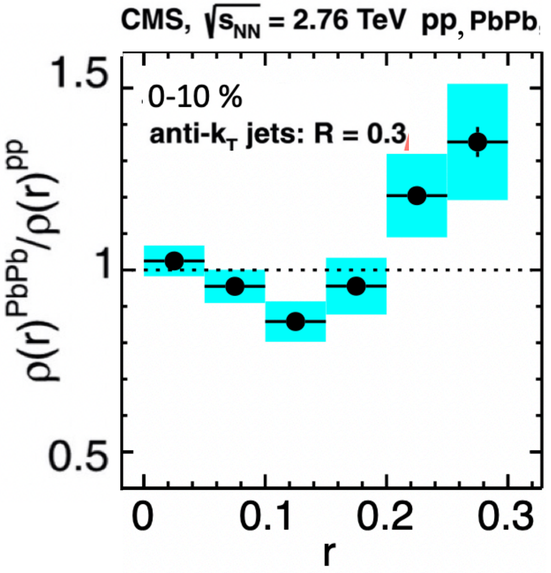
- Δφ distributions in p+p consistent with that from PYTHIA
- **Significant medium induced acoplanarity in Au+Au collisions for R = 0.5 jets**

Heavy Flavor Jet Modification

- Jet energy redistributed away from the jet axis in central A+A collisions
- Study D^0 tagged jets to understand the flavor dependence of redistribution







CMS, Phys. Lett. B 730 (2014) 243

- Ratios of radial distributions in central to peripheral collisions consistent with unity for D^0 tagged jets
- Extending the analysis to lower D^0 kinematics is essential to study D^0 diffusion
- 2016 data to be analyzed, also p+p baseline with improved precision possible with high statistics p+p dataset in 2024

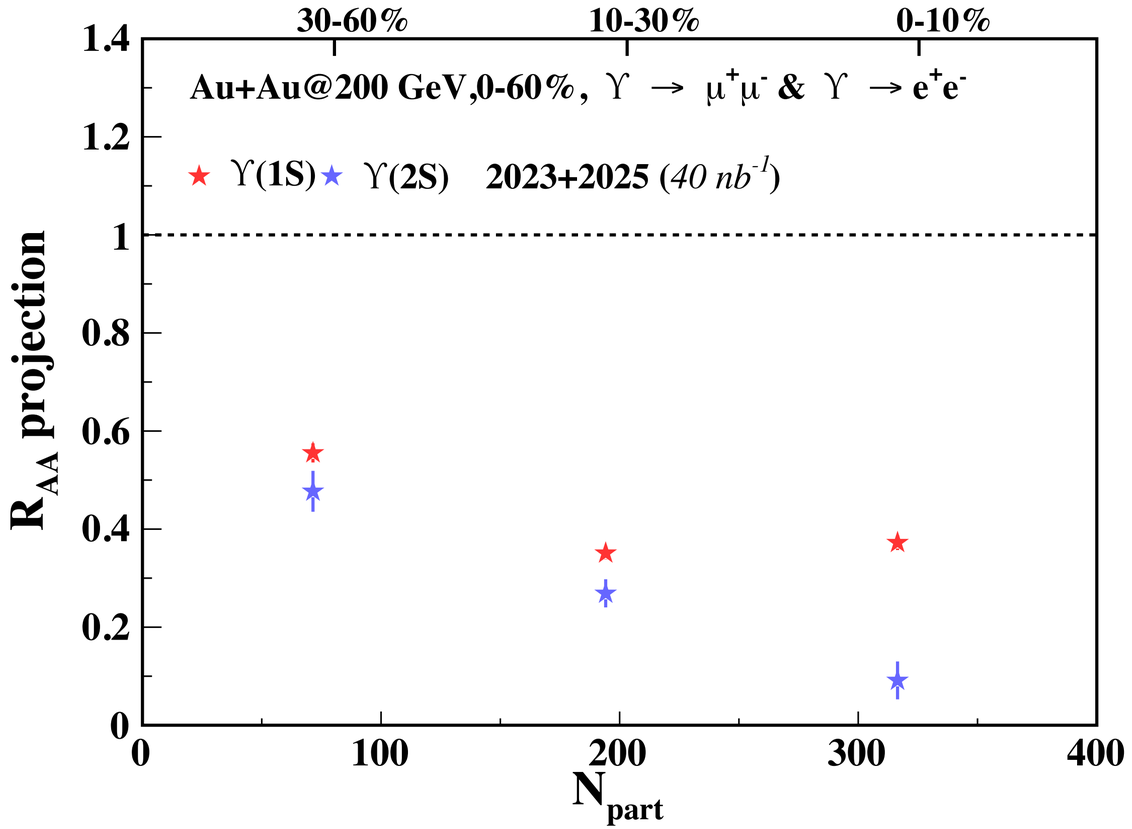
RHIC Runs 23 - 25:
What can we learn from STAR Jets & HF measurements

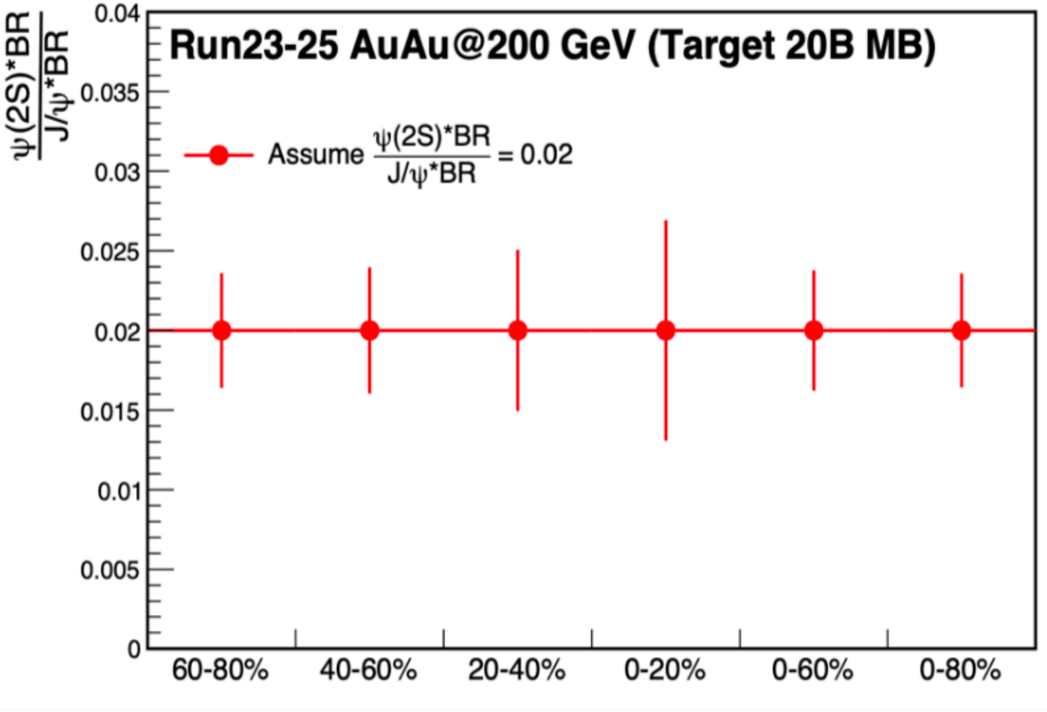
STAR BUR for 2023-25

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

Improved tracking and mid-rapidity acceptance with iTPC, EPD for triggering and independent EP determination, forward detectors

QGP Temperature and Temperature Profile

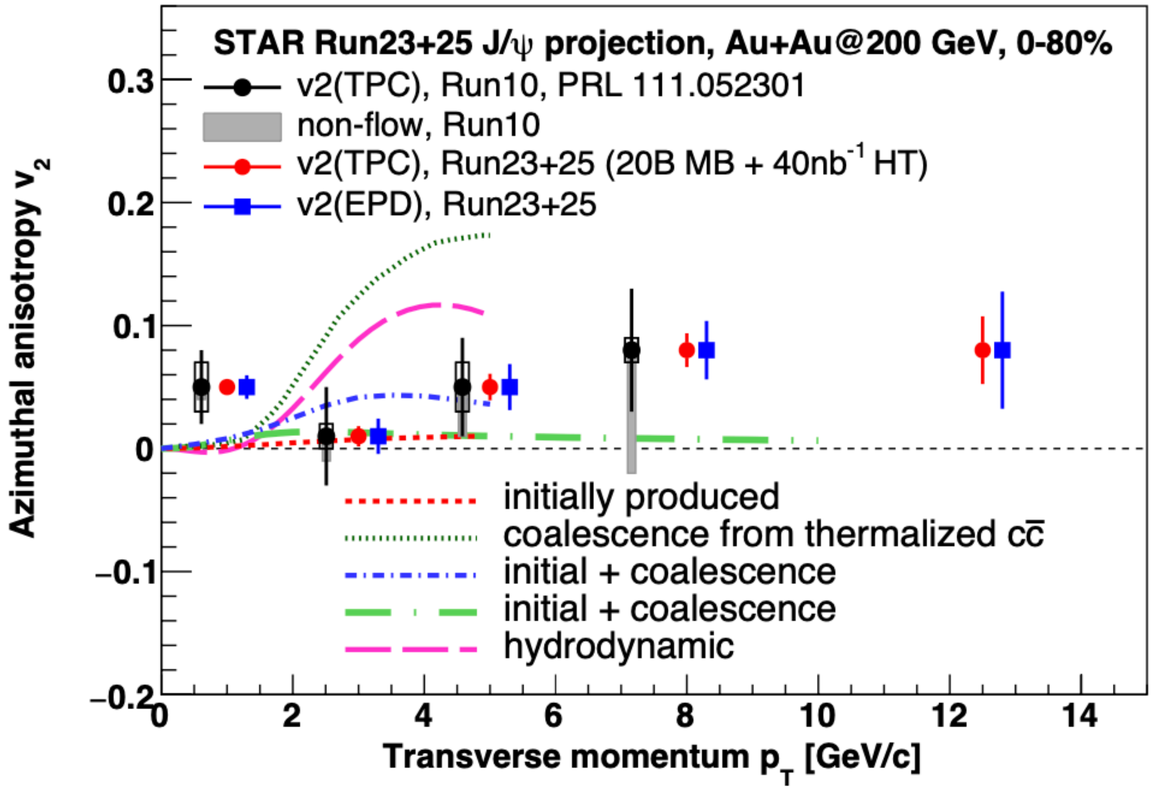


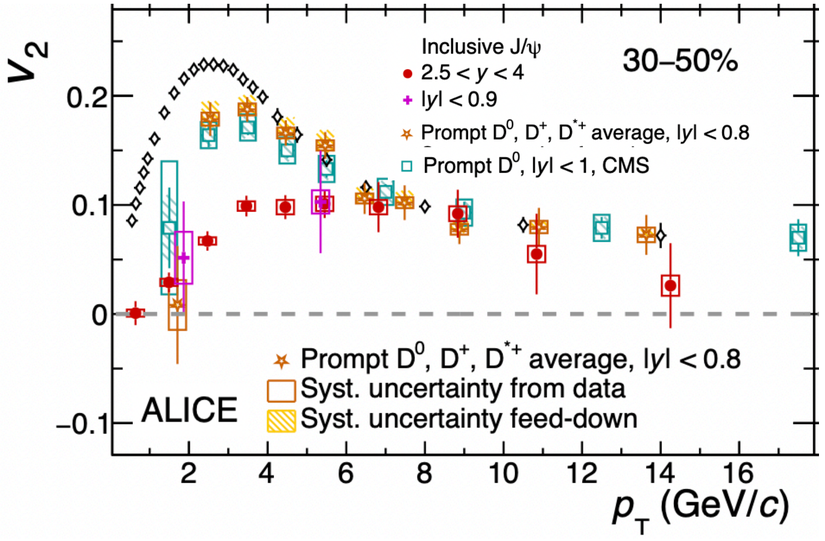


- Factor of 17 (1.5) improvement in statistics compared to existing dielectron (dimuon) measurements with Run 23+25 data
- Sequential suppression of Y states depending on temperature of the medium
- Very small regeneration contribution at RHIC energy

- Lower binding energy for ψ(2S) compared to J/ψ and Y states
- Sensitive to regeneration contribution and temperature profile of QGP

Deconfinement and Charmonia Regeneration



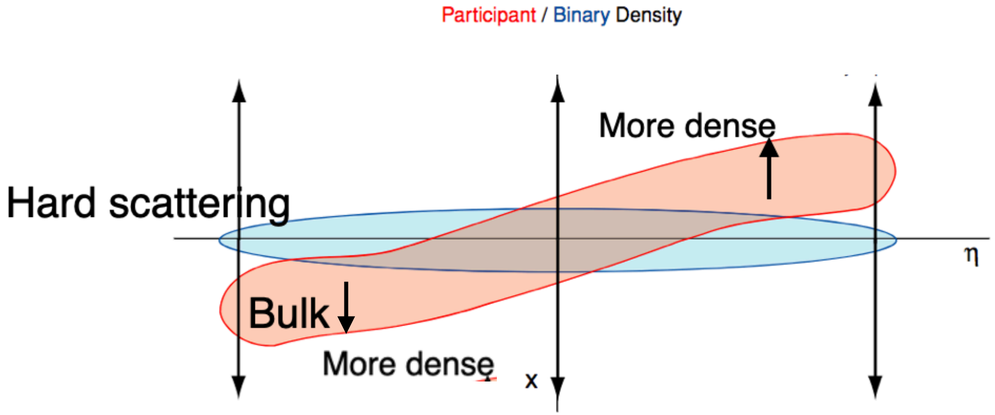


- If J/ψ is regenerated from deconfined charm in medium, J/ψ can gain collectivity
- Large J/ψ v_2 measured at LHC

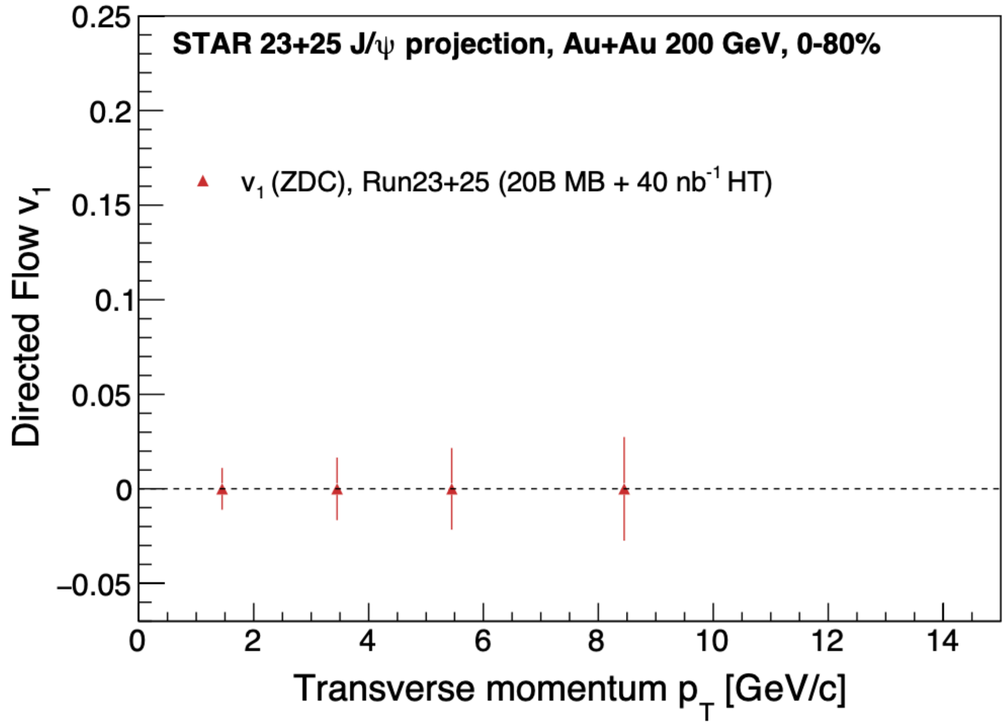
- Precise measurements of J/ψ v_2 at RHIC possible with Run 23+25 STAR data
- Important for constraining regeneration contribution to J/ψ production and charm quark thermalization in QGP

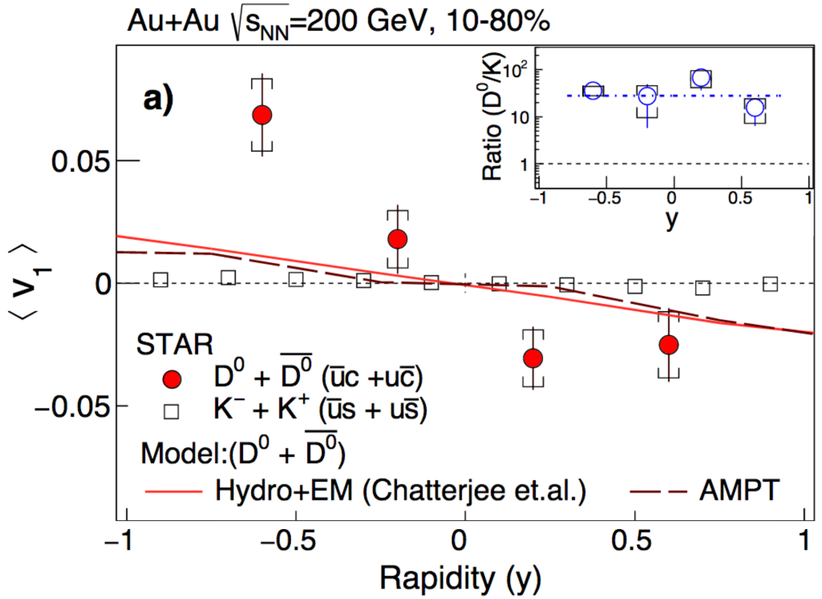
Initial Longitudinal Density Profile of the Medium

- Initial longitudinal density profile of the medium tilted w.r.t the reaction plane
- Hard-scattering profile not tilted
- Produces large ‘anti-flow’ for hard probes, increased sensitivity to the initial tilt of the medium



From M.Gyulassy et.al Phys Rev C 72, 034907 (2005)



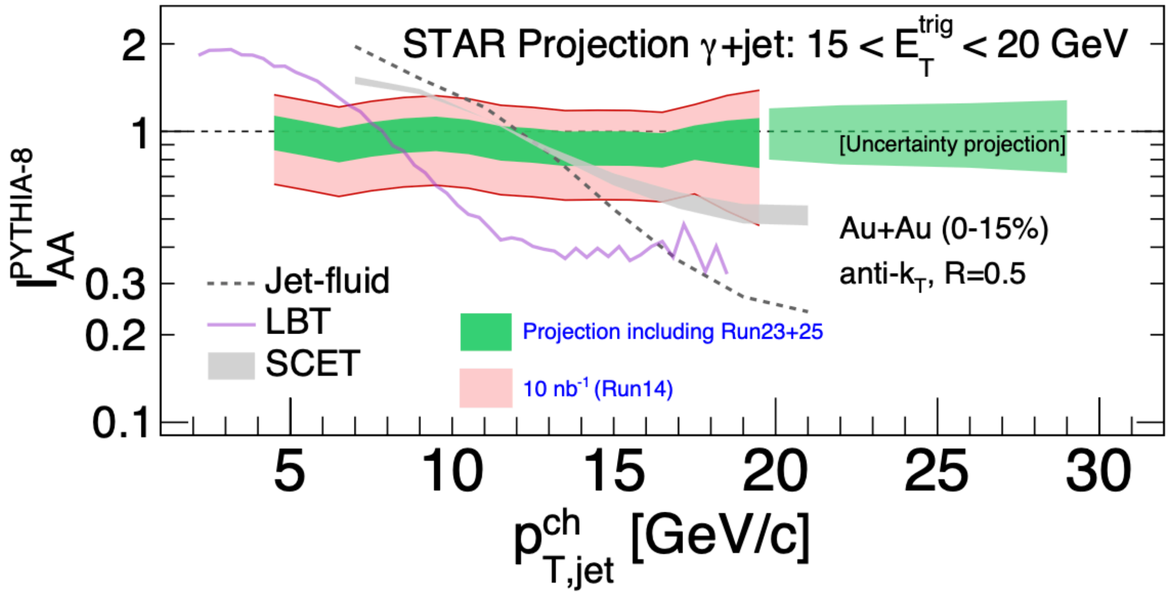


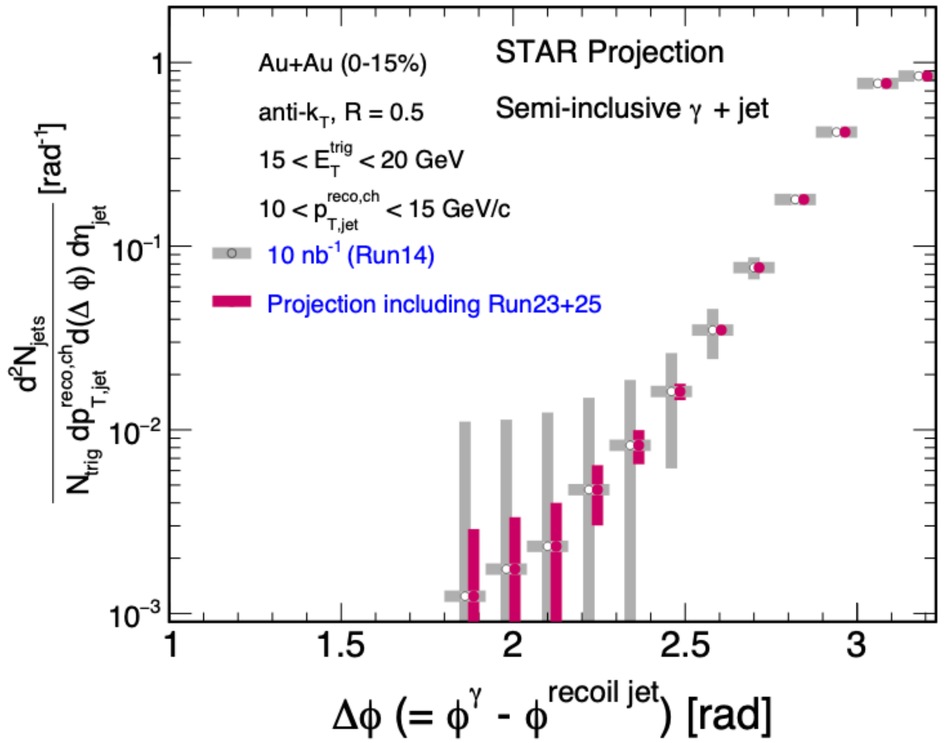
STAR, Phys. Rev. Lett. 123, 162301 (2019)

- Possible to measure J/ψ v_1 with good precision with Run 23+25 data

Underlying Mechanism of Jet Quenching

- Much improved precision for γ^{dir} triggered jet measurements

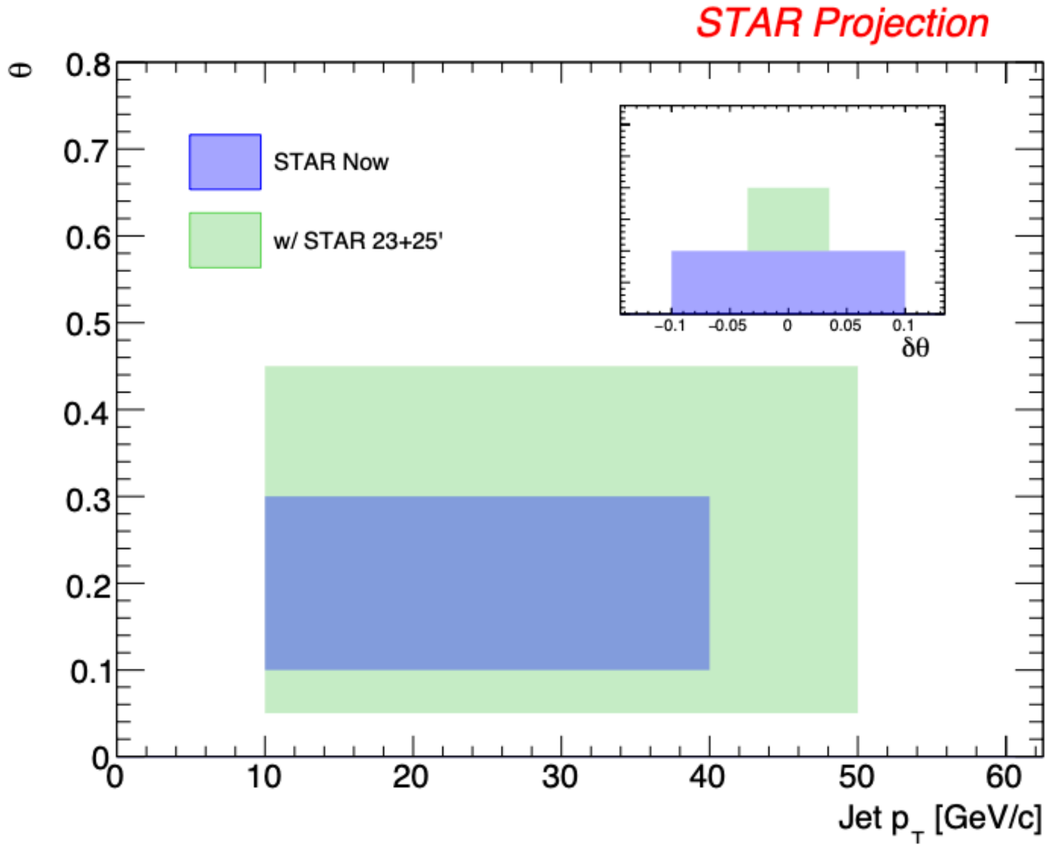




- Broad kinematic range accessible for I_{AA} and acoplanarity measurements. Also access to forward rapidity
- Far improved uncertainties for jet acoplanarity measurements: extraction of in-medium jet scatterings

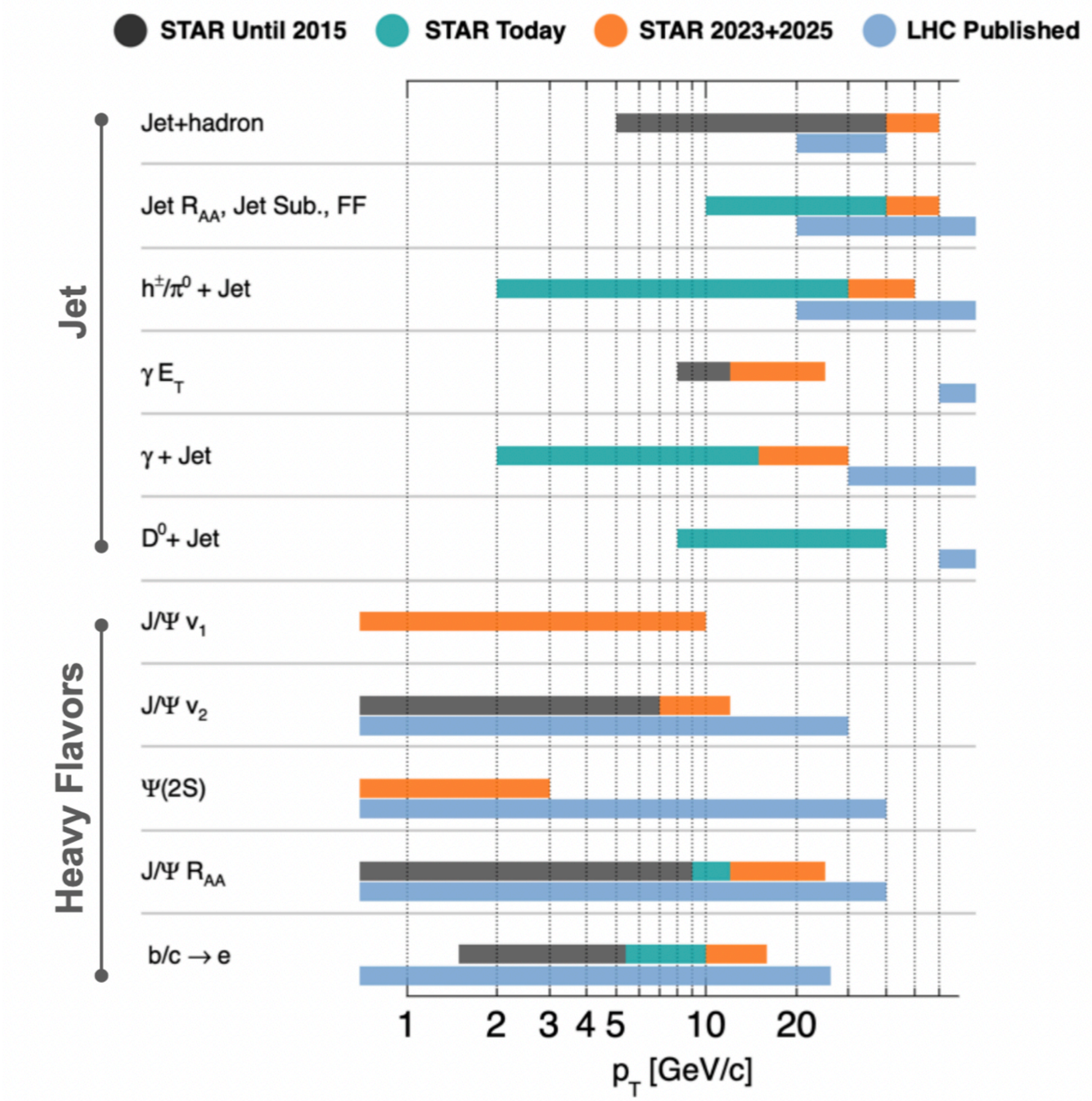
Underlying Mechanism of Jet Quenching

- Study in-medium jet modification for jets with different sub-structures —> can use jet-substructure as classifiers
  - Probe different aspects of energy loss



- Extended p_T range and higher statistics with Run 23+25 data
- Allows access to wide angle emissions and high p_T jets
- Also allows resolution in angular scale to be improved from 0.1 to 0.025

STAR Hard Probes Program Kinematic Coverage



Summary

- **New jet and HF results from STAR**
  - Less production of J/ψ in events with jets in data compared to PYTHIA
  - High p_T (> 4 GeV/c) R_{pAu} consistent with unity. Suppression in A+A in this region from QGP medium effects
  - J/ψ R_{AA} in Au+Au collisions at 54.4 GeV with improved precision consistent with that at 200 GeV: interplay of in-medium dissociation and regeneration components

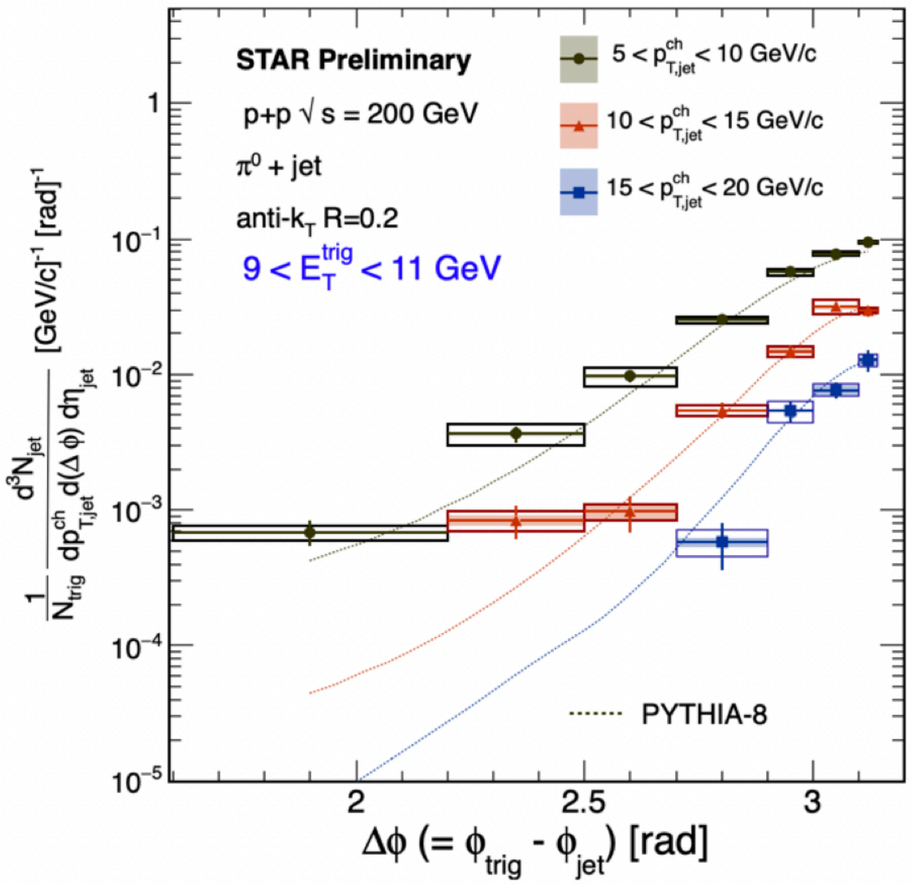
  - Charged hadron and J/ψ R_{AA} same for different collision systems at same N_{part} (for $N_{part} > 20$)
  - Observation of medium induced intrajet broadening in Au+Au collisions
  - Significant medium induced acoplanarity for jets in Au+Au collisions for R = 0.5 jets

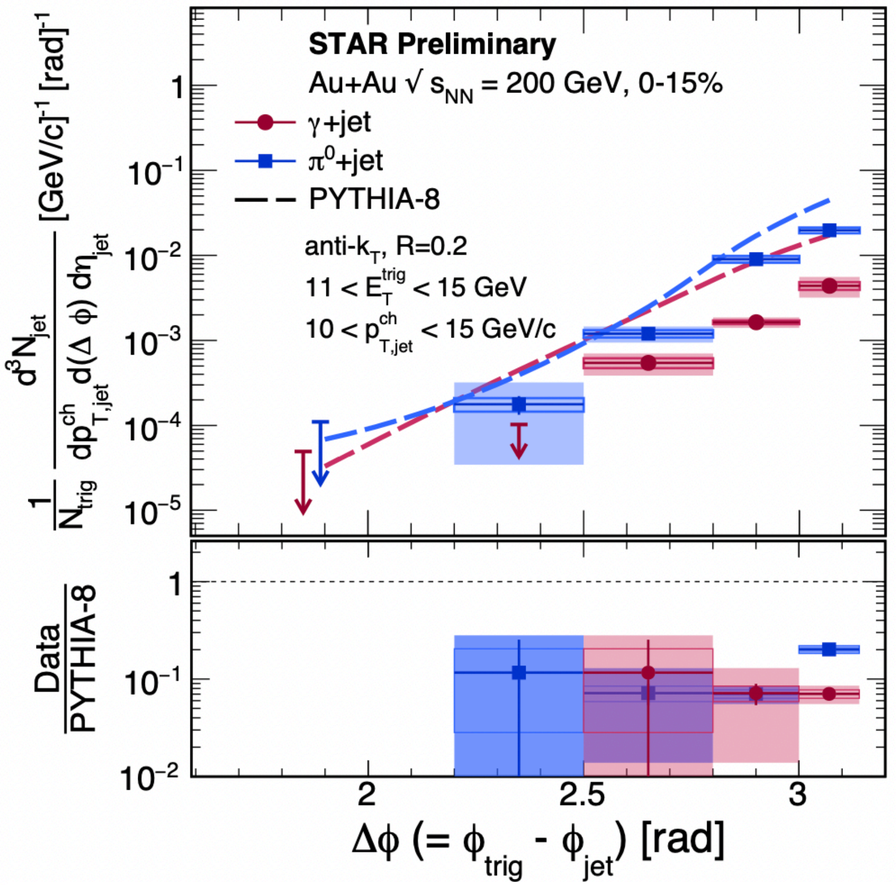
- **Prospects for Run 23 - 25**
  - Improved constraints for QGP temperature, charm quark thermalization and charmonia regeneration, and initial longitudinal density profile of the fireball from Υ and J/ψ measurements
  - Improved precision for γ^{dir} triggered and sub-structure selected jet measurements: better understanding of underlying mechanism of jet quenching

Back Up

Medium-induced Acoplanarity

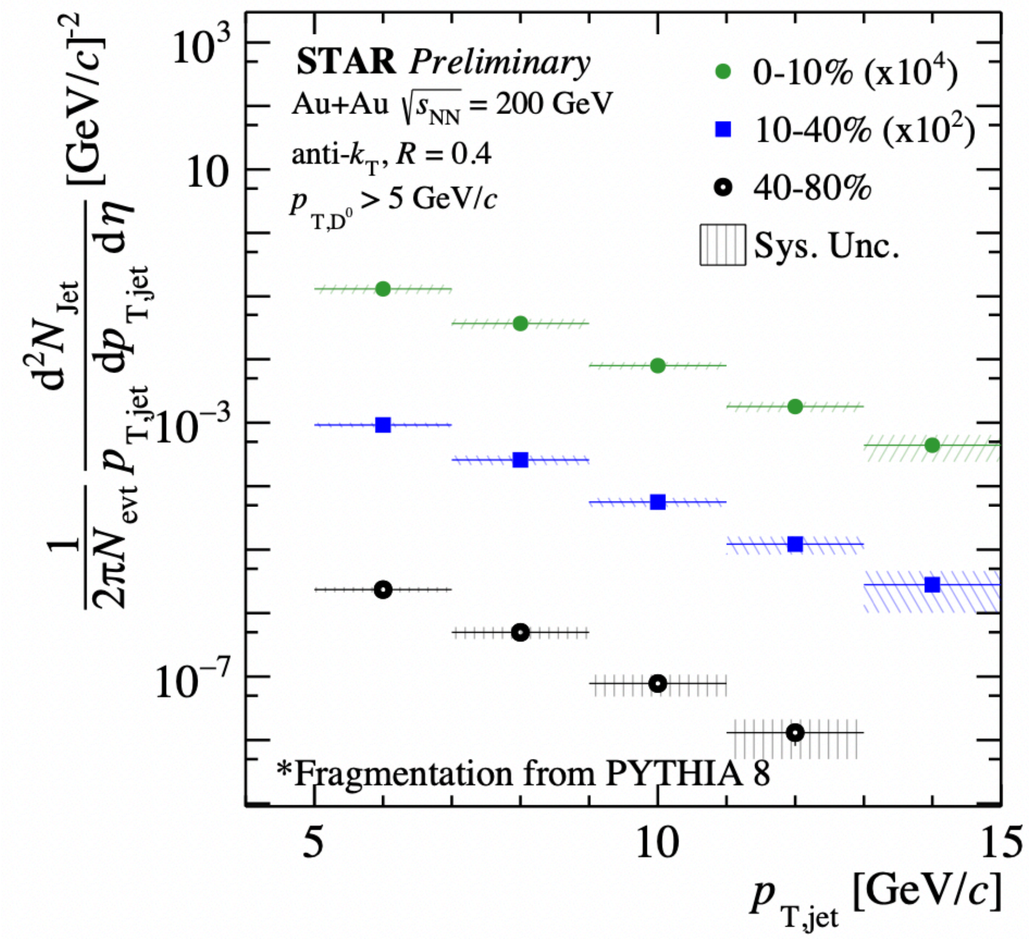
- Study semi-inclusive recoil jet distributions to π^0 and γ^{dir} triggers
  - Dijet acoplanarity measured in p+p and Au+Au collisions at RHIC

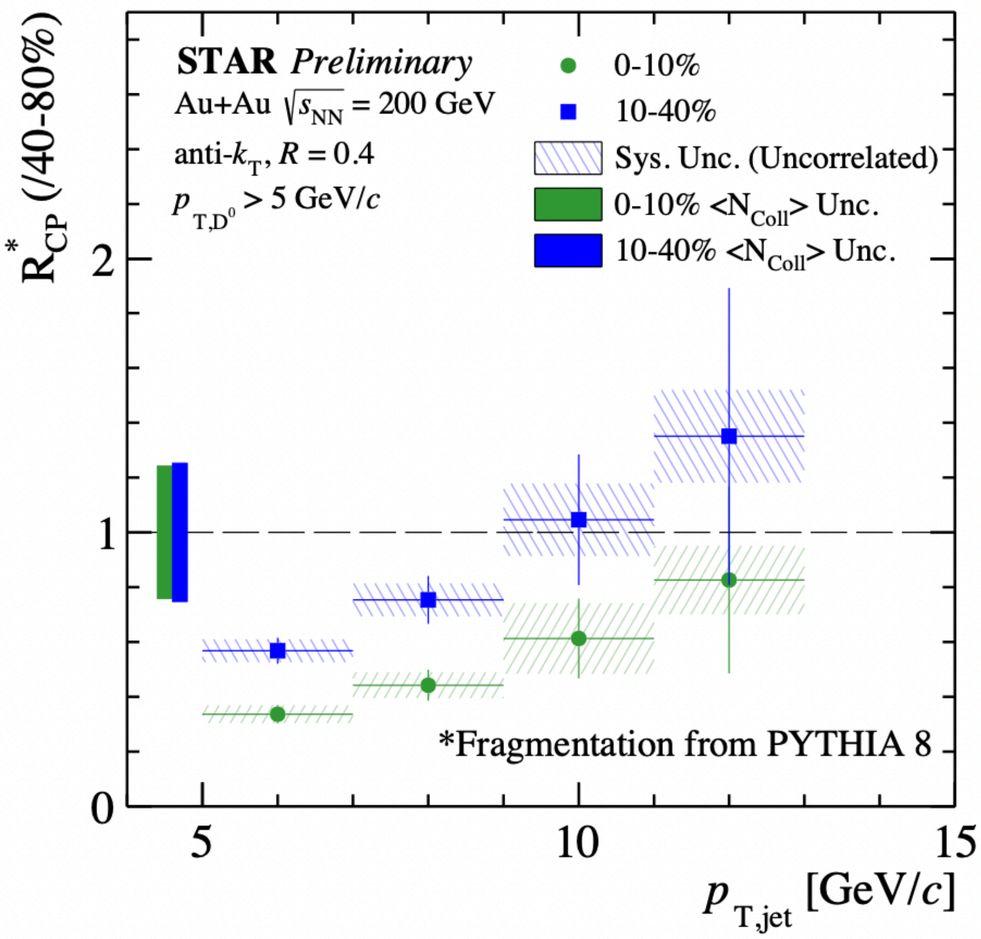




R = 0.2 jets

Heavy Flavor Jet Modification - R_{CP}

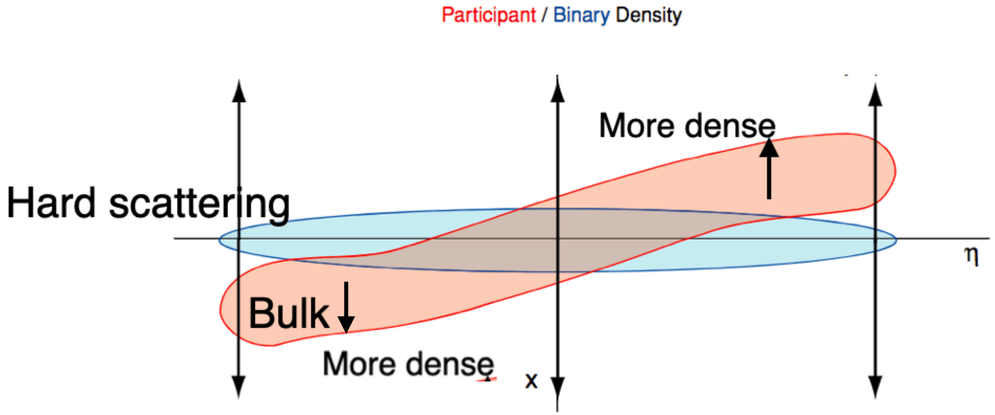


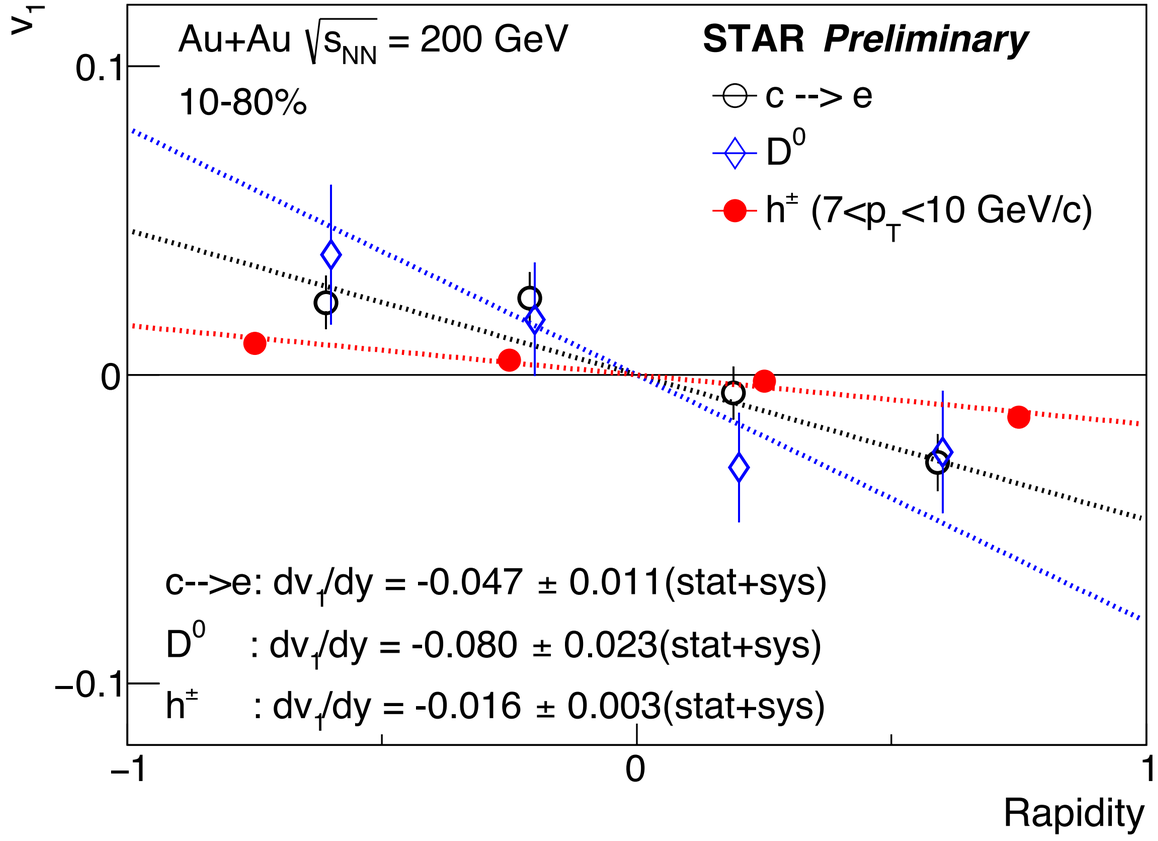


- R_{CP} for D^0 tagged jets show more suppression in central collisions than in mid-central collisions
- R_{CP} shows strong suppression at low p_T and an increasing trend with p_T

Initial Longitudinal Density Profile of the Medium

- Initial longitudinal density profile of the medium tilted w.r.t the reaction plane
- Hard-scattering profile not tilted
- Produces large ‘anti-flow’ for hard probes, increased sensitivity to the initial tilt of the medium





- Observed for different hard probes