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Recent Hard Probes Results and Prospects from the STAR Experiment

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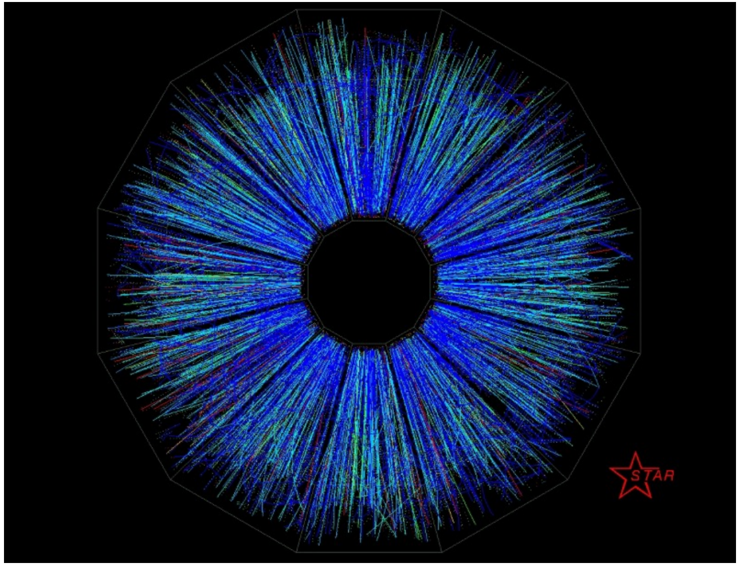
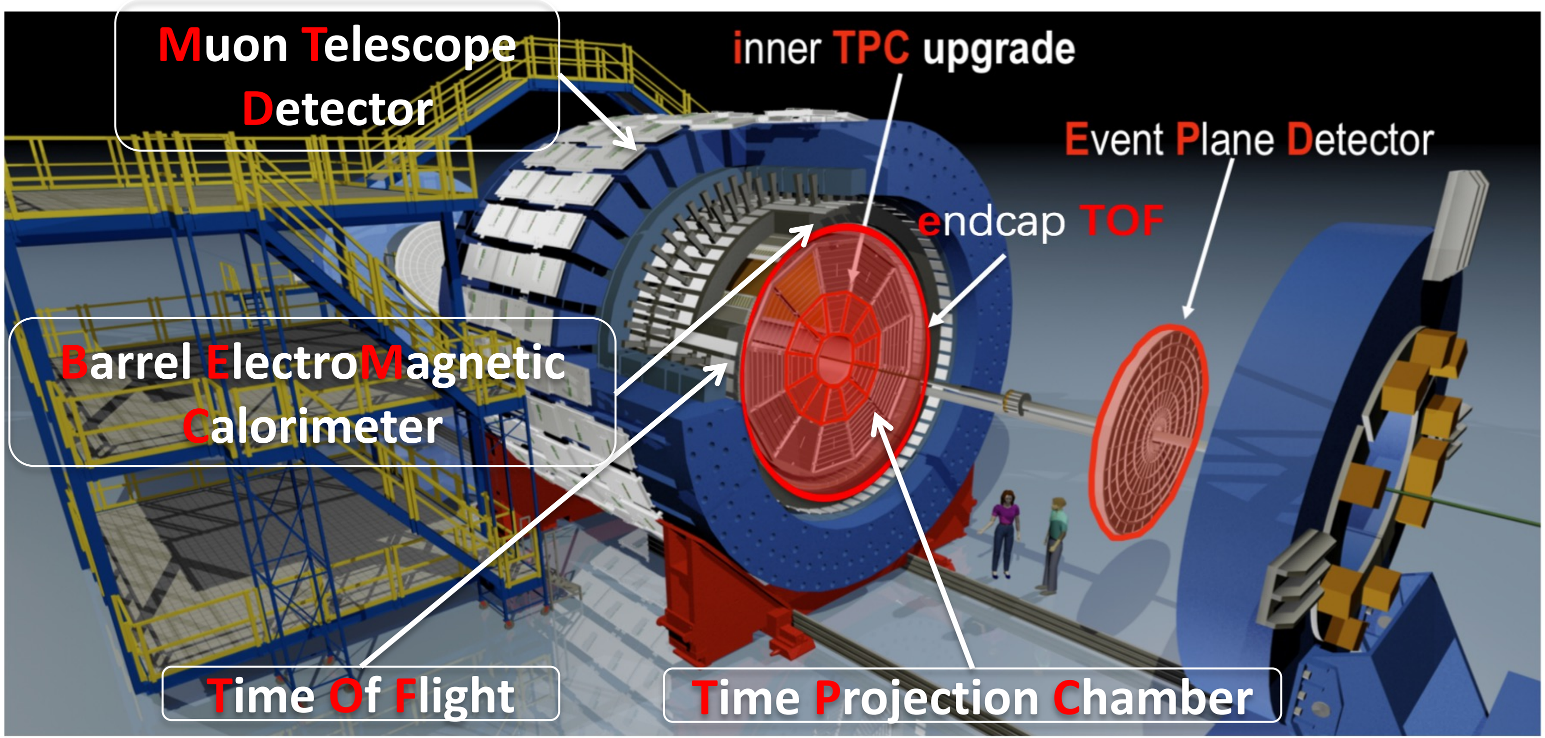
Brookhaven National Laboratory

Outline

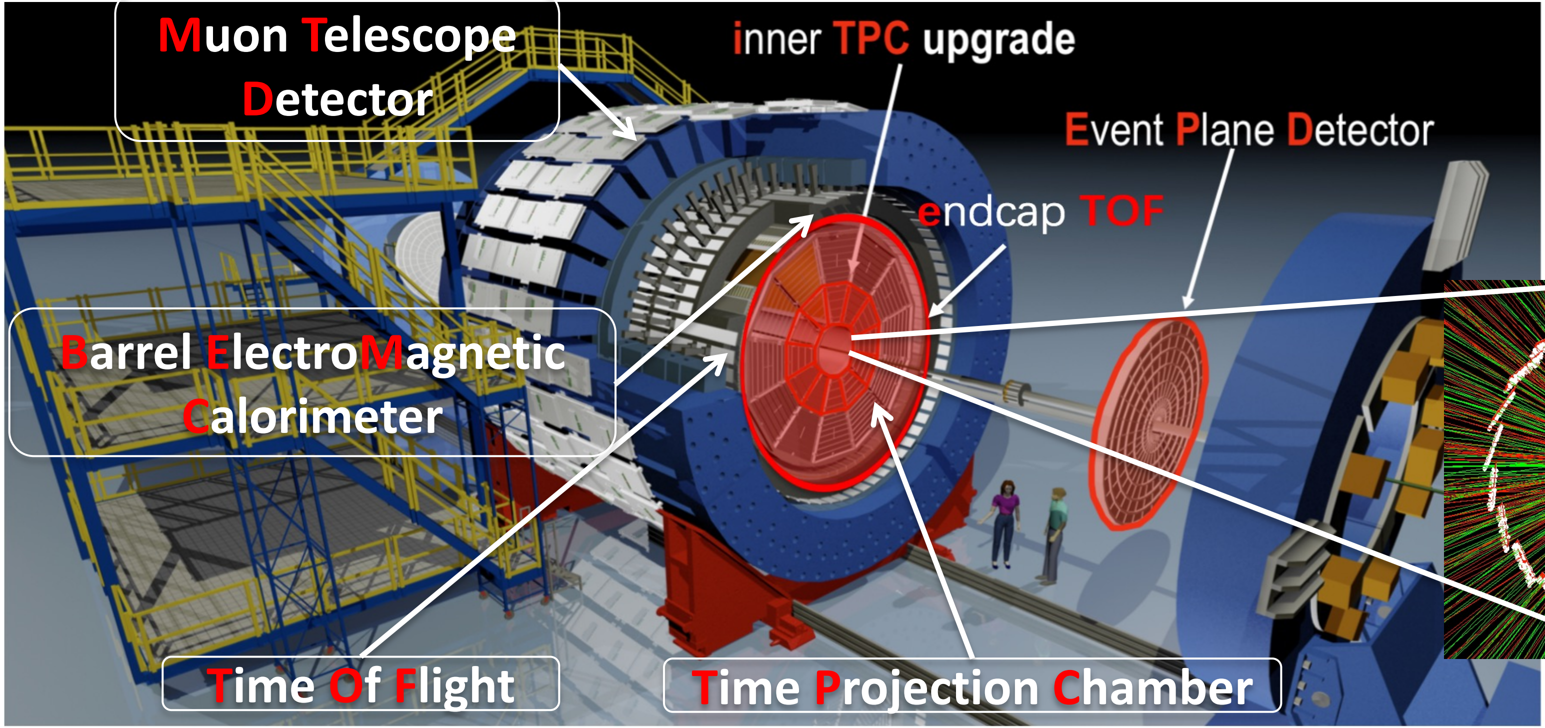
- STAR Detector
- Hard Probes
  - Jets
  - Heavy Flavor
- Future Plans (2023+25)



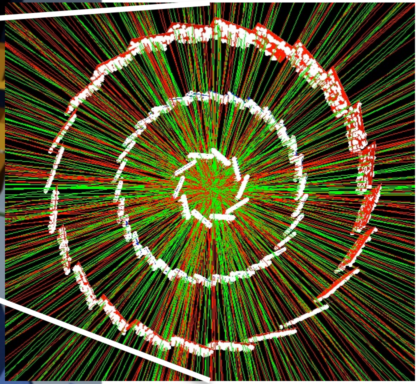
STAR Detector



STAR Detector



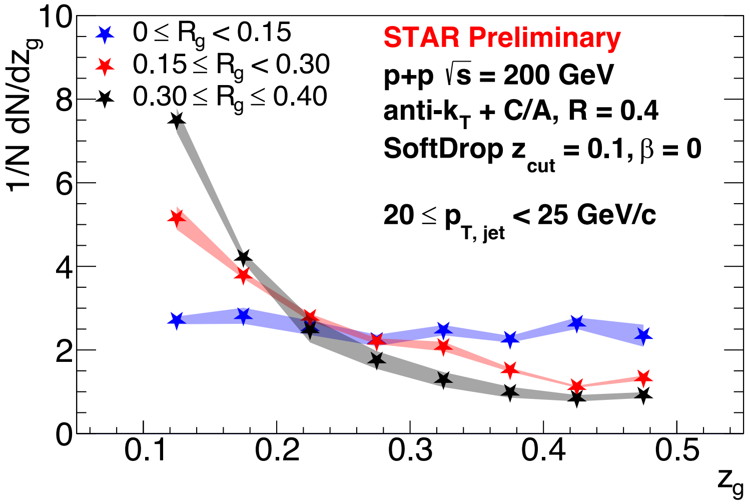
Heavy Flavor Tracker (2014-2016)



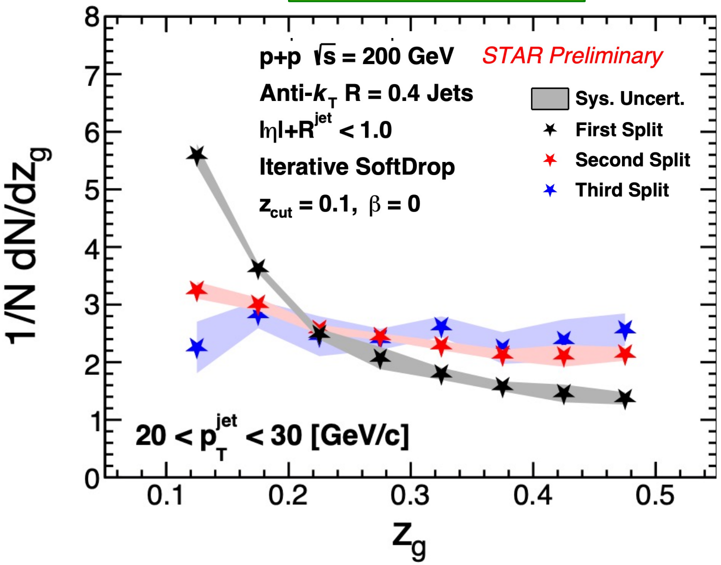
Hard Probes
-- Jets

Jet Sub-structure in p+p Collisions

First split



Different splits

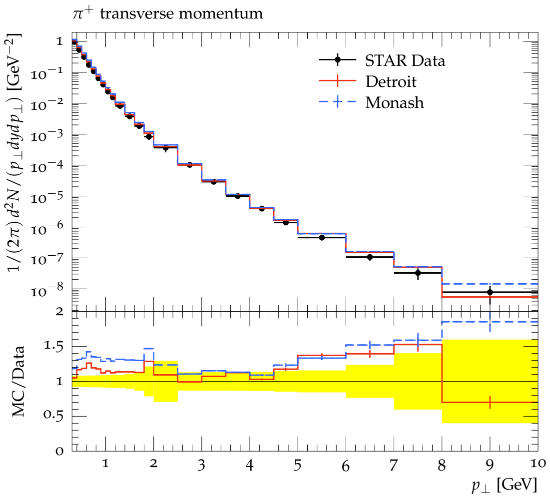


- First split: smaller R_g → flatter z_g
- First → third split: flatter z_g
- One can control z_g by selecting on R_g or split number

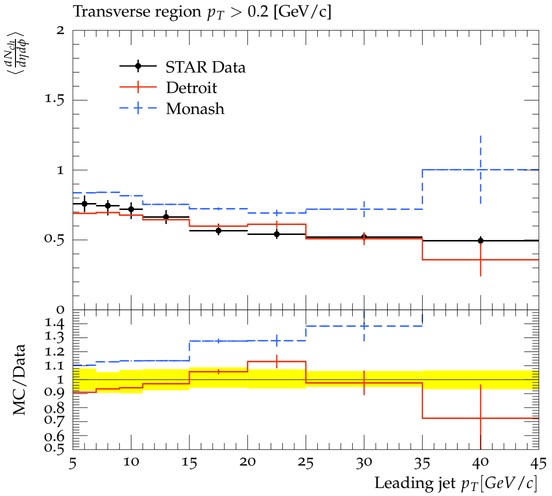
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}\left(\frac{R_g}{R_{jet}}\right)^{\beta}; R_g = \Delta R(1,2)$$

Detroit Tune for RHIC

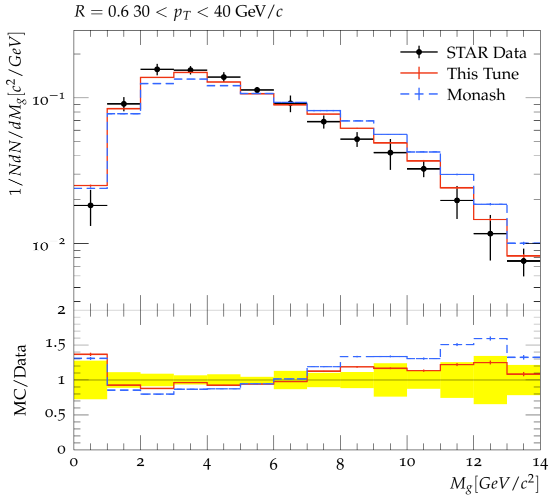
Pion



UE



Jet Mass

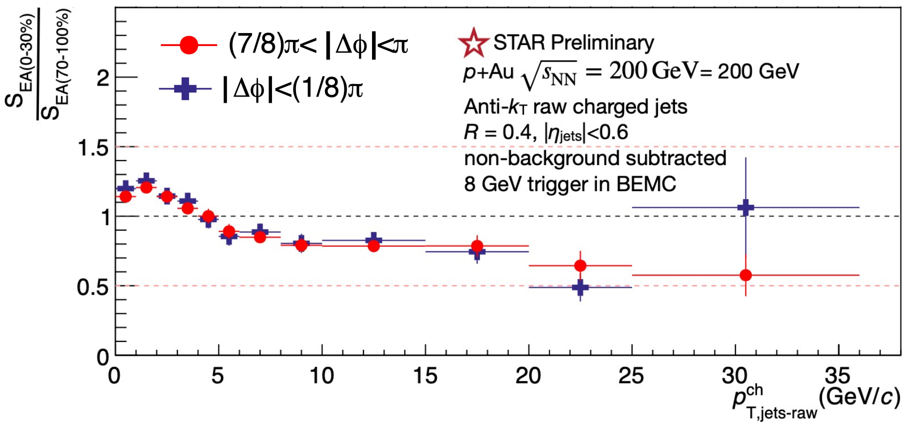


- A new PYTHIA 8 tune based on RHIC and CDF data, with MPI/UE parameters adjusted and PDF updated
- **Provide a good description of RHIC data at midrapidity**

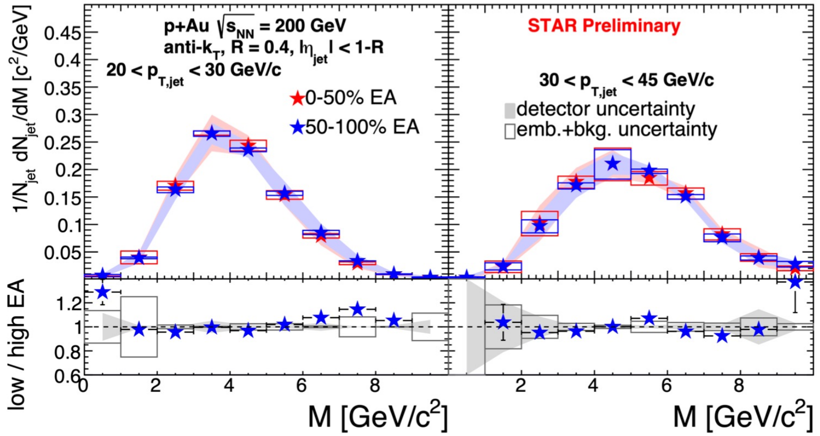
STAR, PRD 105 (2022) 016011

Are Jets Quenched in p+Au?

Semi-inclusive jet suppression



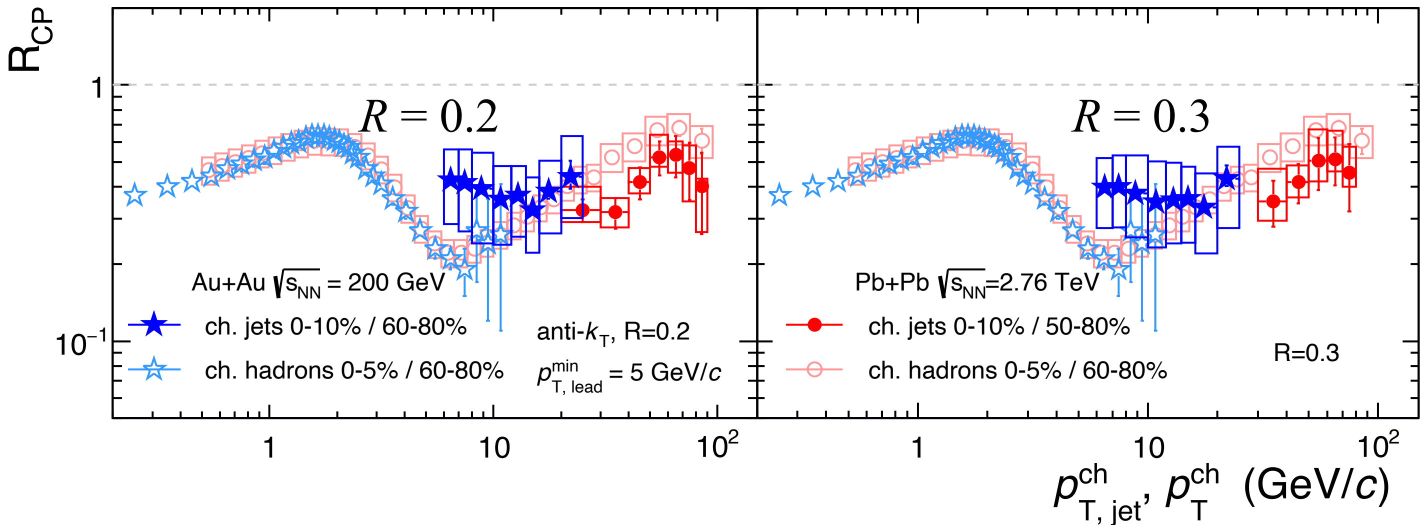
Jet Mass



- High vs. low event activity events
  - Similar level of suppression for trigger-side and recoil-side semi-inclusive jets
  - Similar jet mass distributions
- **Jet quenching picture is disfavored in 200 GeV p+Au collisions**

Inclusive Charged Jet R_{CP}

STAR, PRC 102 (2020) 054913

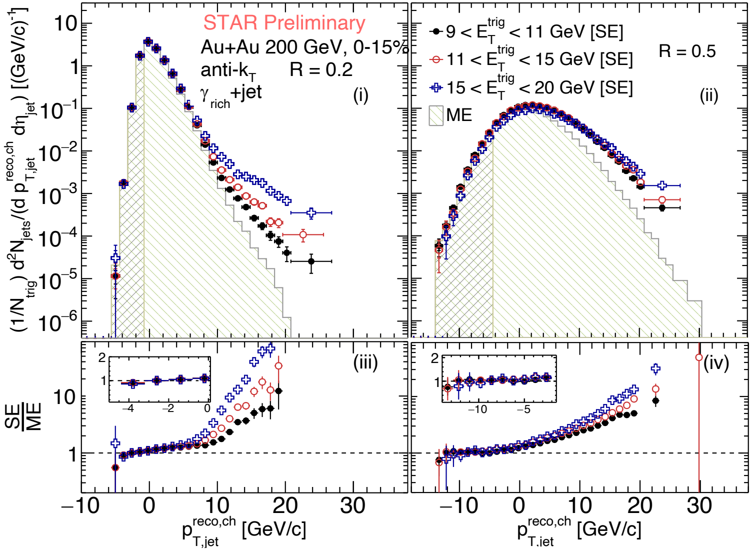


- Combinatorial jets removed by requiring high-p_T leading constituent
- **Strong suppression in central collisions**
  - Consistent with LHC measurements in the overlapping kinematic range
  - Different p_T dependence compared to inclusive charged hadrons

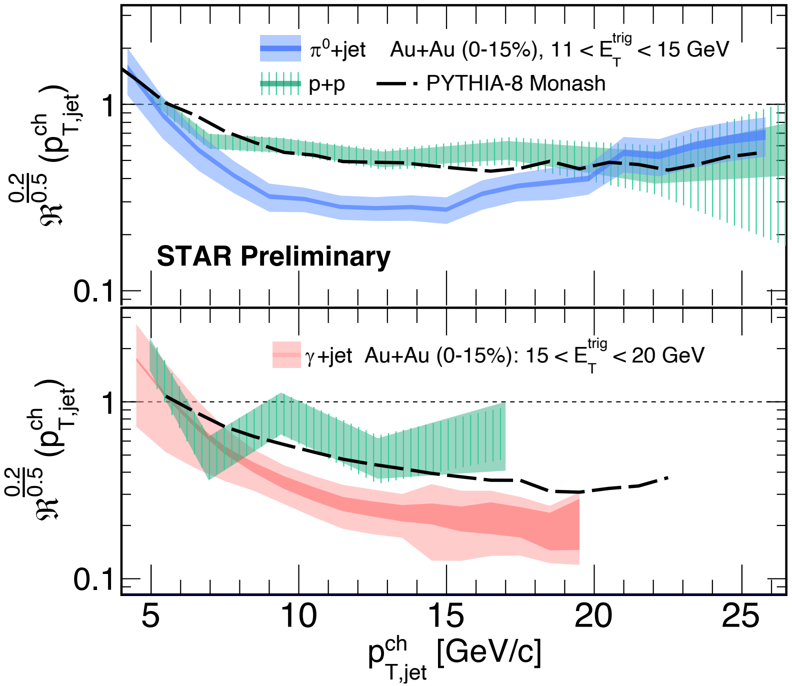
Semi-inclusive γ-jet vs. π^0-jet I_{AA}

✓ Vary parton flavor, path length
  - ➢ Different spectrum shapes

- Combinatorial jets removed statistically with event mixing
  - Mix tracks from events of similar characteristics
  - Remove combinatorial jets precisely on an ensemble basis
  - Does not impose any fragmentation bias
  - Enable jet measurements down to low p_T and up to large radius



Intra-jet Broadening

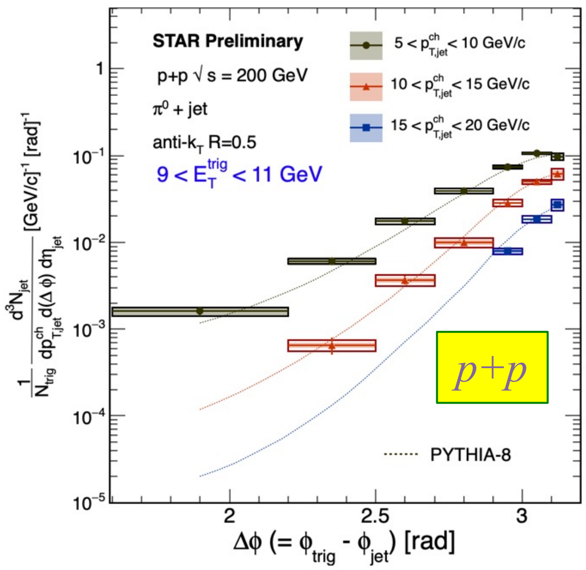


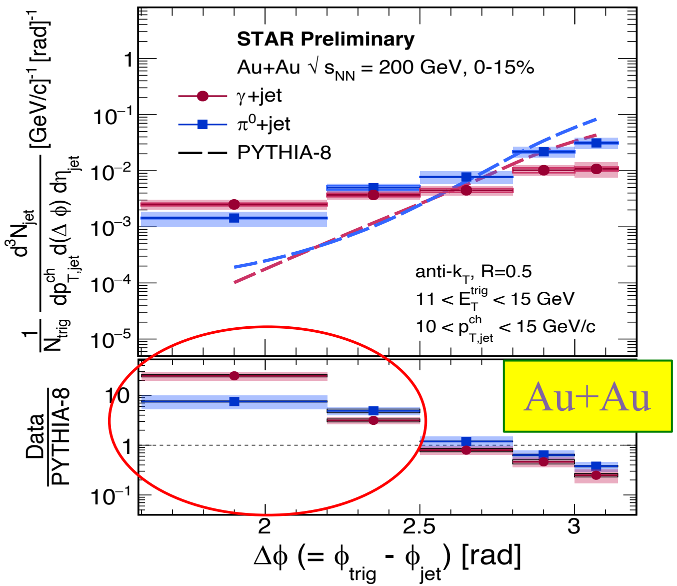
$$\Re^{0.2}_{0.5} = \frac{dN/dp_T\ (R = 0.2)}{dN/dp_T\ (R = 0.5)}$$

- Ratio of yields: calculable in pQCD
- Smaller ratios in Au+Au compared to p+p → **redistribution of energy to larger angles**
- Similar behavior for both γ and π^0 triggers

Jet Acoplanarity

R = 0.5



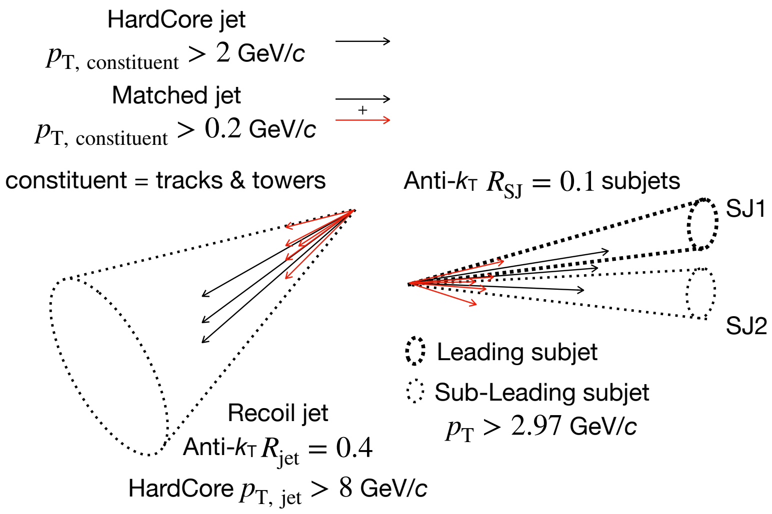


- Significant broadening of acoplanarity distributions in Au+Au collisions for $R = 0.5$ jets with $10 < p_T < 15$ GeV/c → **Medium wake? Scattering off medium constituents?**

K. Rajagopal, Jet Quenching in QGP, ECT 2022*

STAR, PRC 105 (2022) 044906

Jet Sub-structure in Au+Au

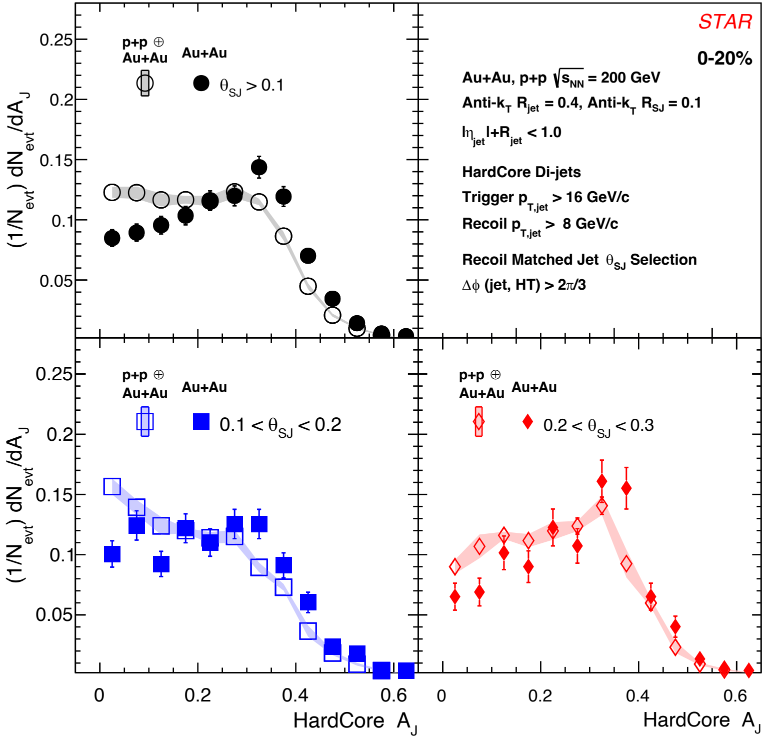


- ✓ Suppress combinatorial jets
  - ✓ HardCore jet: negligible background contribution
  - ✓ Matched jet: all constituents down to 0.2 GeV/c
- ✓ Study energy loss for wide (large θ_{SJ}) and narrow (small θ_{SJ}) recoil jets

$$z_{SJ} = \frac{\min(p_{T,SJ1}, p_{T,SJ2})}{p_{T,SJ1}+p_{T,SJ2}}, \ \theta_{SJ} = \Delta R(SJ1, SJ2)$$

HardCore Jet A_J: Au+Au vs. p+p

STAR, PRC 105 (2022) 044906

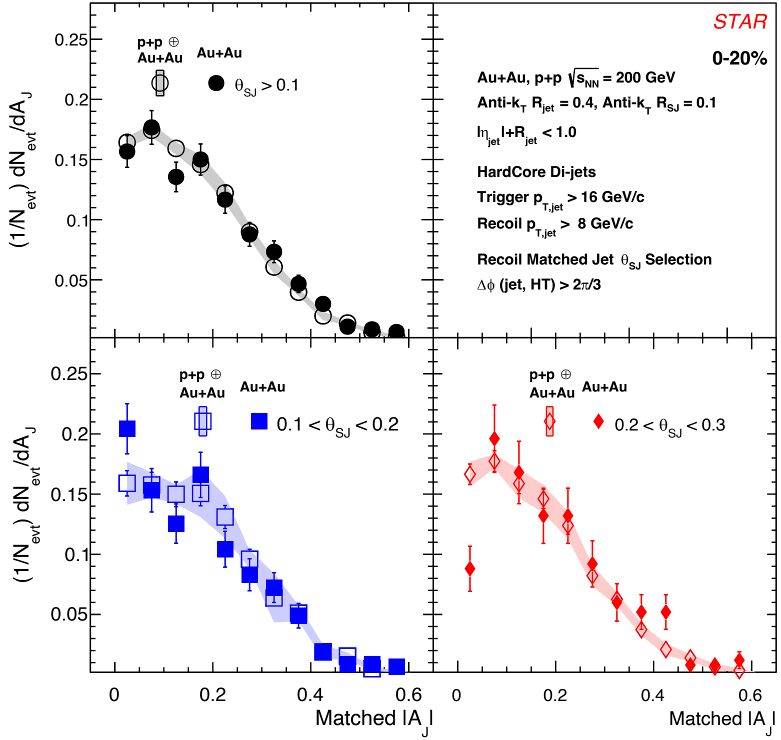


$$A_J \equiv \frac{p_{\mathrm{T,jet}}^{\mathrm{trigger}} - p_{\mathrm{T,jet}}^{\mathrm{recoil}}}{p_{\mathrm{T,jet}}^{\mathrm{trigger}} + p_{\mathrm{T,jet}}^{\mathrm{recoil}}}$$

- Different A_J distributions for narrow and wide jets
- Larger $< A_J >$ in Au+Au compared to p+p, **due to jet quenching**, for both narrow and wide HardCore jets

Matched Jet A_J: Au+Au vs. p+p

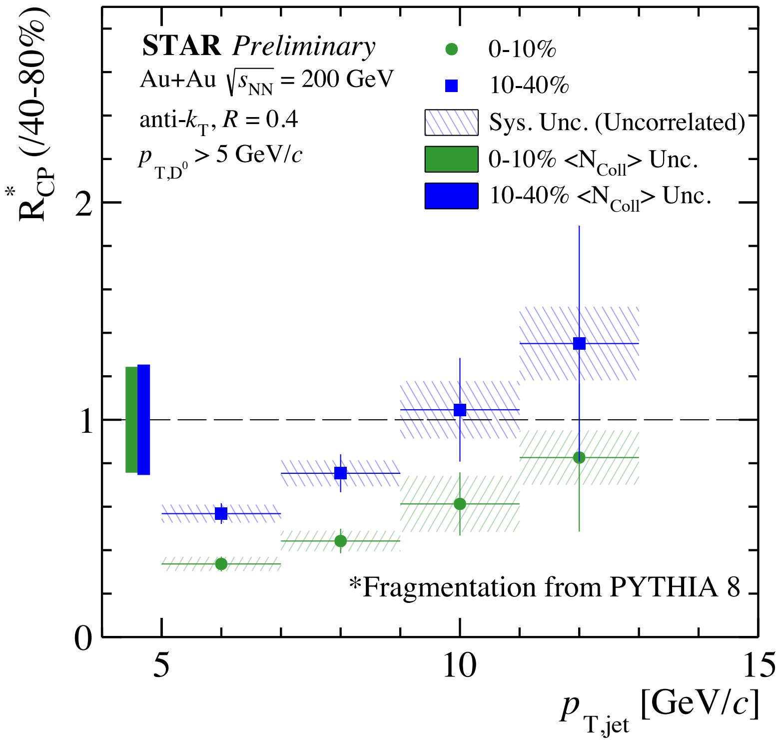
STAR, PRC 105 (2022) 044906



$$A_J \equiv \frac{p_{\mathrm{T,jet}}^{\mathrm{trigger}} - p_{\mathrm{T,jet}}^{\mathrm{recoil}}}{p_{\mathrm{T,jet}}^{\mathrm{trigger}} + p_{\mathrm{T,jet}}^{\mathrm{recoil}}}$$

- Similar A_J distributions for narrow and wide jets
- Similar $< A_J >$ in Au+Au compared to p+p → **lost energy recovered by low-p_T constituents in the selected jet population**

Yield Suppression of D^0-tagged Jets

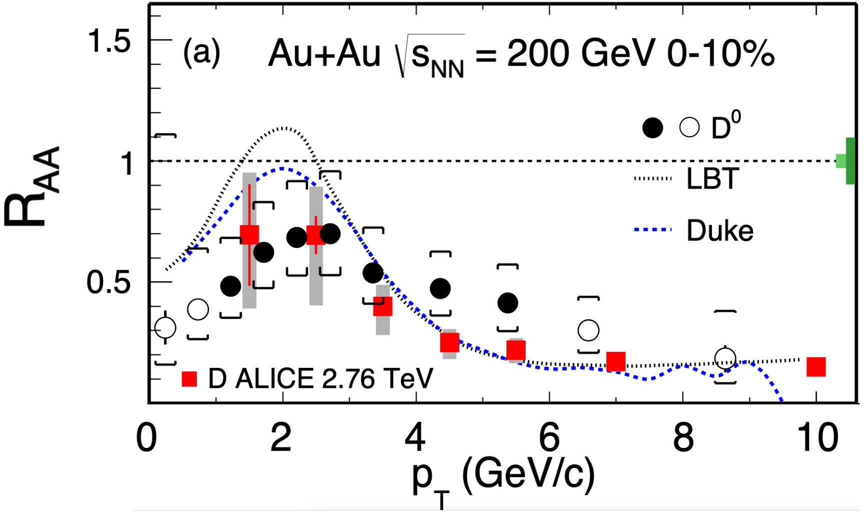


- Only look at jets containing a D^0 above 5 GeV/c
  - No combinatorial jets by definition
- Unfolded with PYTHIA8 fragmentation: need to be improved
- **Strong suppression at low $p_{T,jet}$; hint of a rising R_{CP} with $p_{T,jet}$**

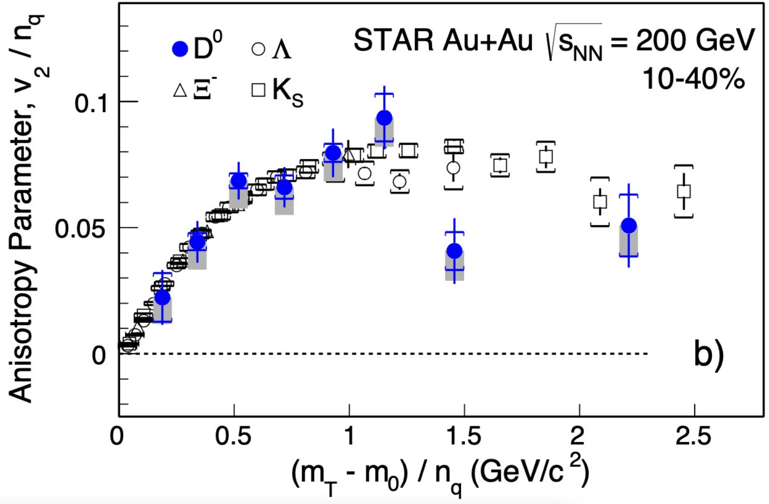
Hard Probes
-- Heavy Flavor

D^0 R_{AA} & v_2 in Au+Au Collisions

STAR, PRC 99 (2019) 034908



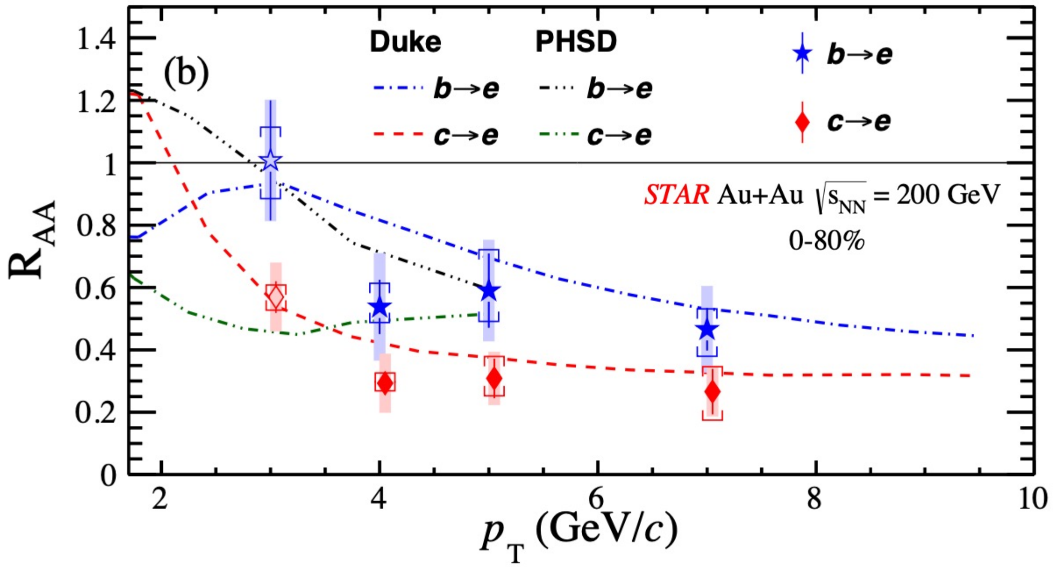
STAR, PRL 118 (2017) 212301



- Significant suppression of D^0 at high p_T; v_2 follows NCQ scaling
  → **Strong interactions between charm quarks and QGP; constrain diffusion coefficient**

Mass Dependence of Parton Energy Loss

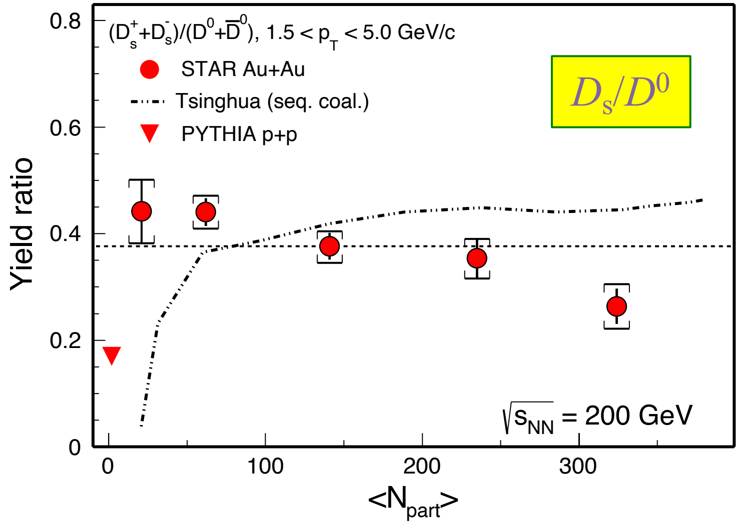
STAR, arXiv:2111.14615



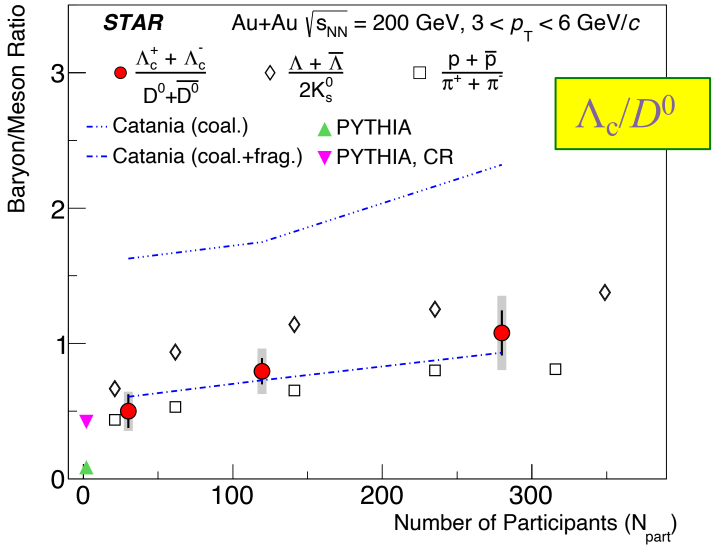
- Clear mass hierarchy of HF electron R_{AA} → ***b* quarks lose less energy than *c* quarks**
- b→e could be used for tagging *b*-jets

Charm Hadrochemistry

STAR, PRL 127 (2021) 092301

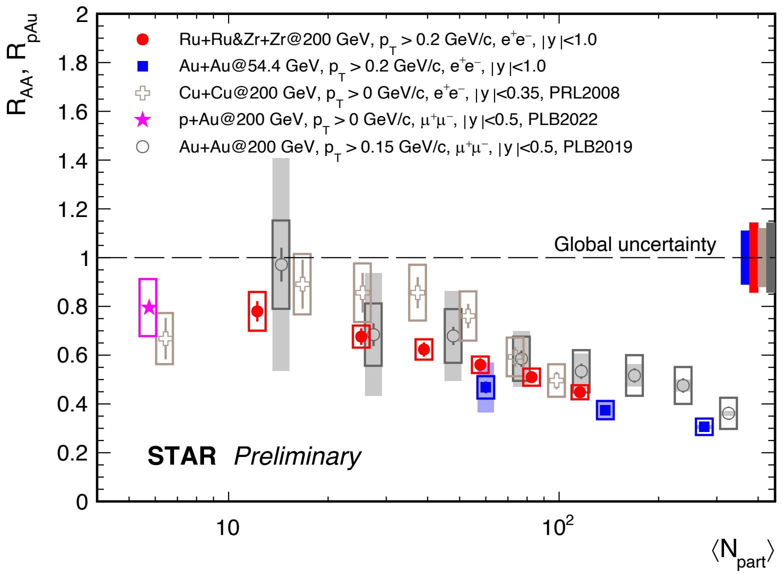


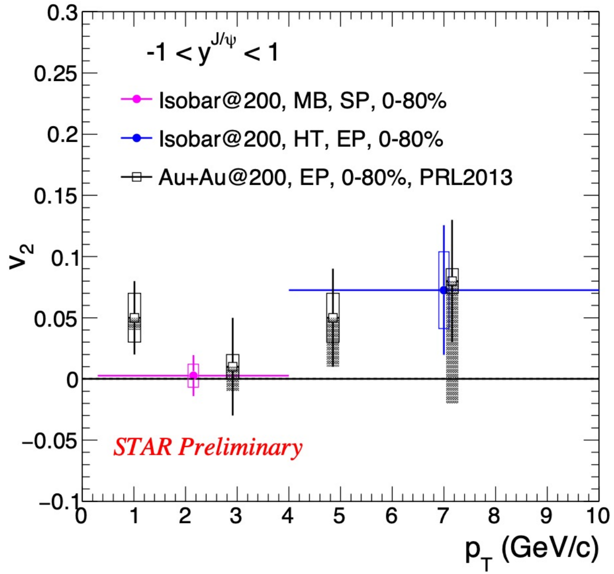
STAR, PRL 124 (2020) 172301



- Clear enhancements of D_s and Λ_c to D^0 ratios compared to PYTHIA (coalescence is important)
  → Redistribution of charm quarks in HI collisions?
- Need to extend measurements down to zero p_T (total charm cross section). How about p+p at RHIC?

Isobar Collisions: J/ψ R_{AA} & v_2

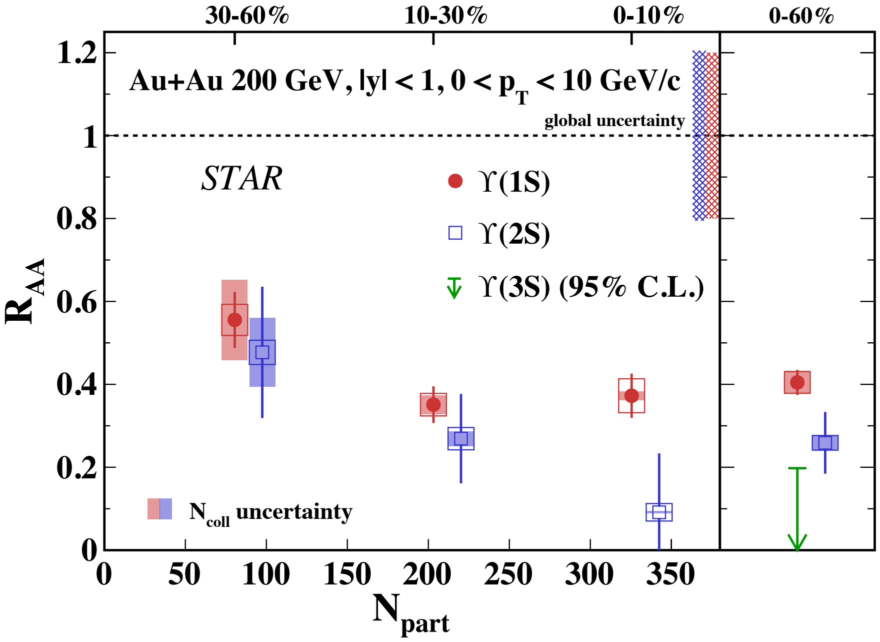




- Indication of a global trend of R_{AA} vs. N_{part} for different colliding systems and energies
  → Interplay of dissociation, regeneration and cold nuclear matter effects
- v_2 consistent with zero below 4 GeV/c → Small regeneration and/or small charm quark flow

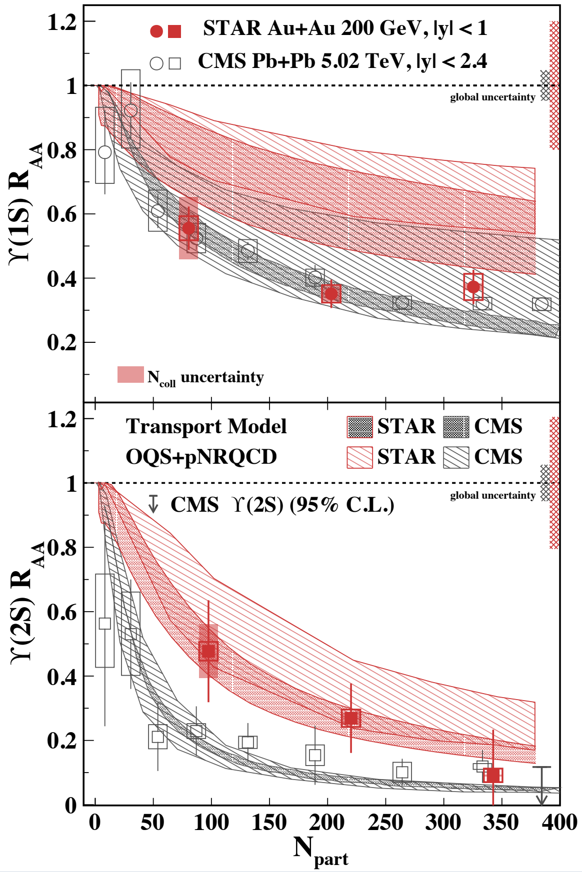
Au+Au Collisions: Υ R_{AA} vs. N_{part}

STAR, arXiv:2207.06568



- All three Υ states are suppressed
- Hint of increasing suppression from peripheral to central collisions
- **First observation of sequential suppression for three Υ states at RHIC**
  - Upper limit for Υ(3S) in 0-60%
  - $>3\sigma$ difference between Υ(1S) and Υ(3S)
  - Υ(2S) R_{AA} is in between

Υ R_{AA} vs. N_{part}: RHIC vs. LHC



STAR, arXiv:2207.06568

- **Υ(1S): similar level of suppression between RHIC and LHC**
  - Mostly due to strong suppression of excited states and cold nuclear matter effects
  - Primordial Υ(1S) not significantly suppressed
- Υ(2S): indication of less suppression at RHIC in peripheral collisions
- Model calculations
  - Υ(1S): larger separation between RHIC and LHC
  - Υ(2S): tend to undershoot data at the LHC

Transport Model: PRC 96 (2017) 054901
OQS+pNRQCD: 2205.10289

Future Plans (2023+25)

STAR Beam Use Request 2022

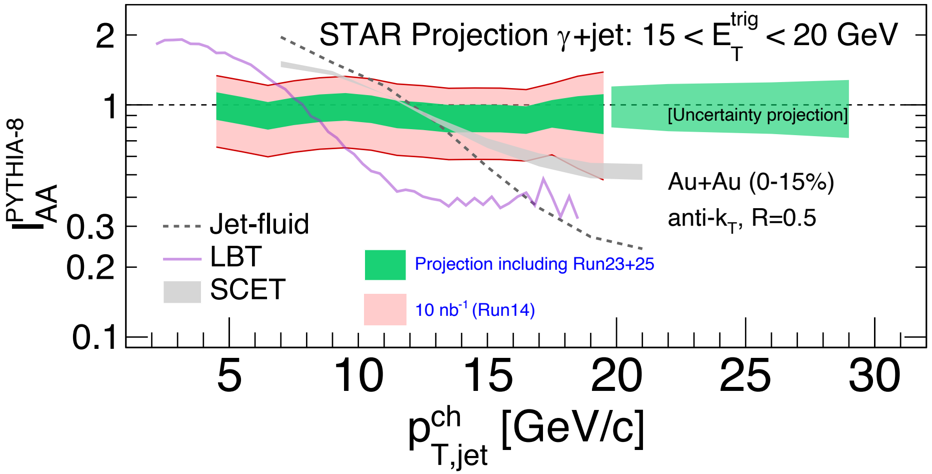
Table 1: Proposed Run-23 - Run-25 assuming 28 cryo-weeks of running every year, and 6 weeks set-up time to switch species in 2024. For $p+p$ and $p+$Au sampled luminosities assume a "take all" trigger. For Au+Au we provide the requested event count for our minimum bias trigger, and the requested sampled luminosity from our a high-p_T trigger that covers all v_z.

$\sqrt{s_{NN}}$ (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

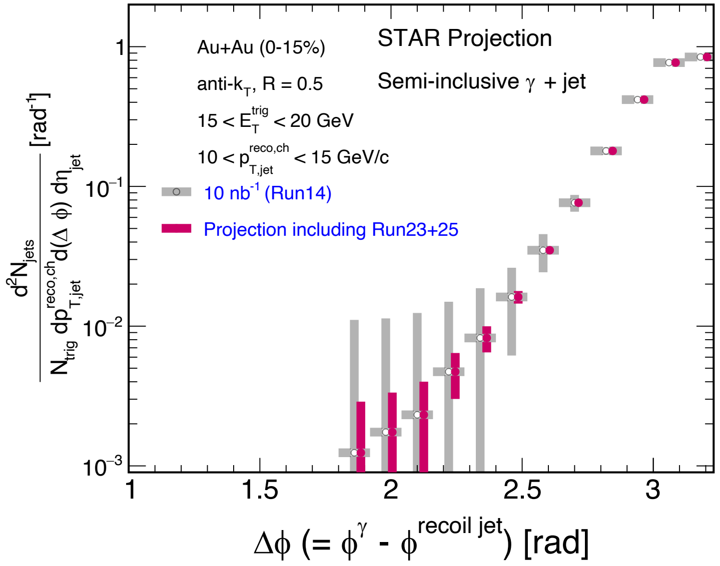
- All projections are based on existing measurements

Projection: *γ-jet*

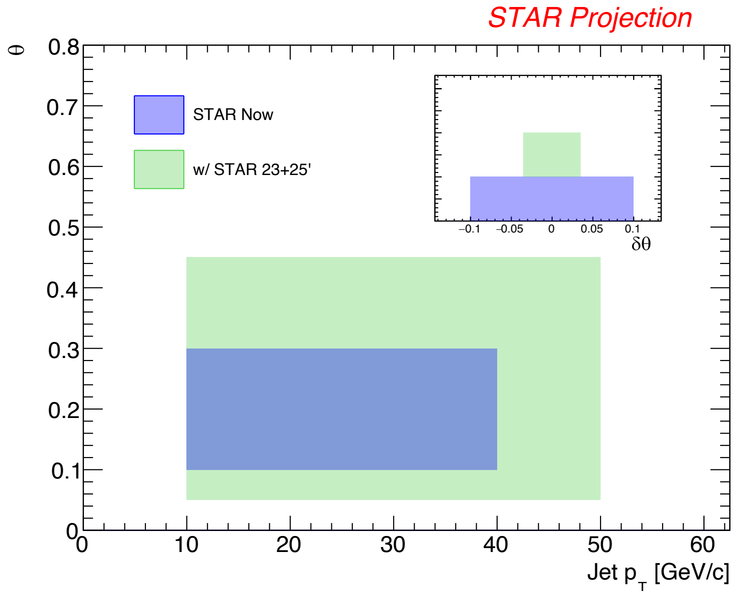
Suppression & intra-jet broadening



Jet acoplanarity

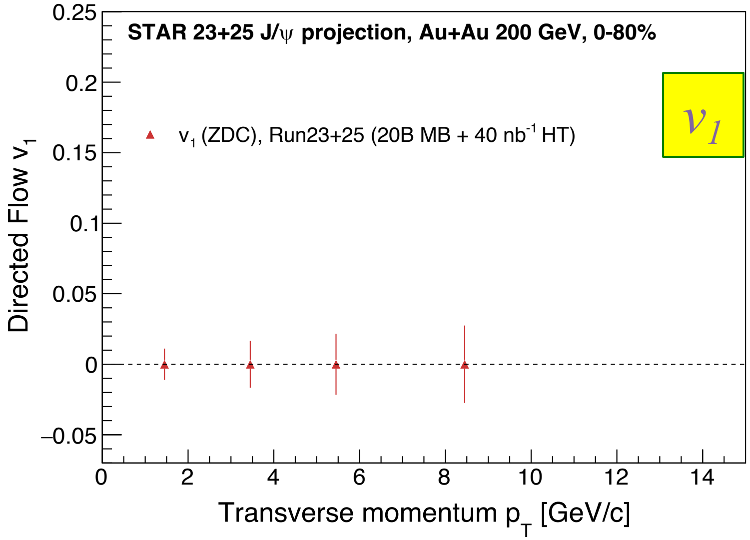


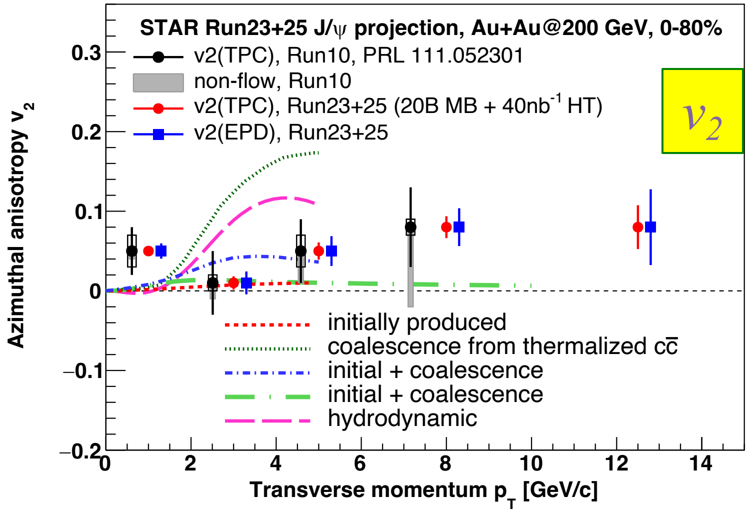
Projection: *Jet Substructure Dependent Energy Loss*



- Larger jet kinematic reach and finer resolution

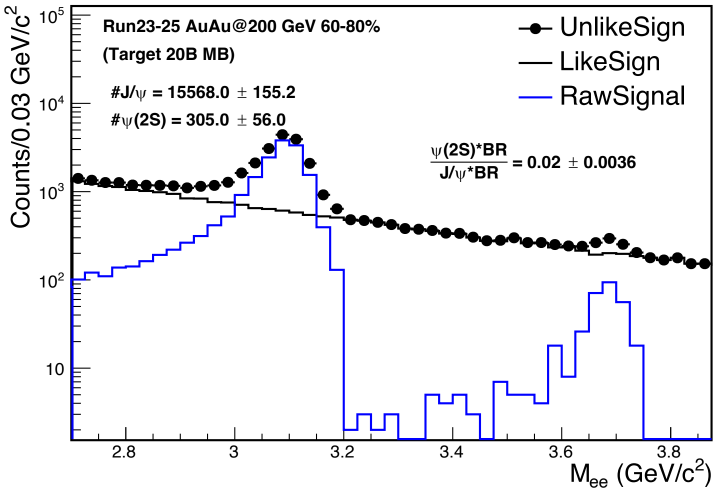
Projection: J/ψ v_1 and v_2

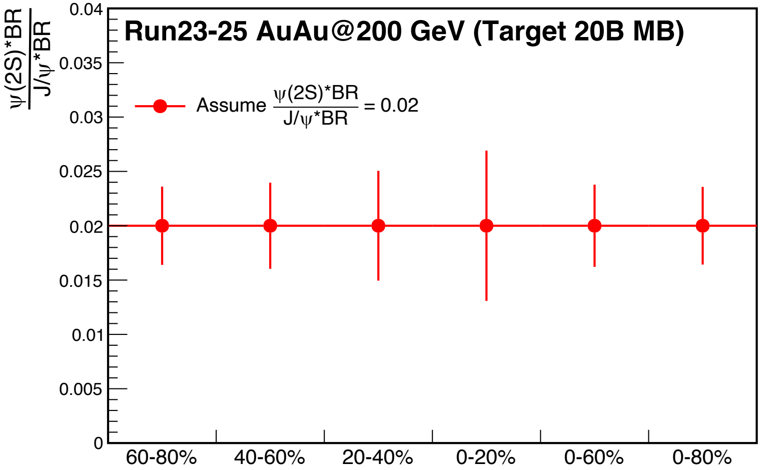




- v_1: probe initial tilt of the medium
- v_2: good precision to distinguish models (EPD can greatly suppress non-flow)
  - Connection to D^0 v_2 through regenerated J/ψ

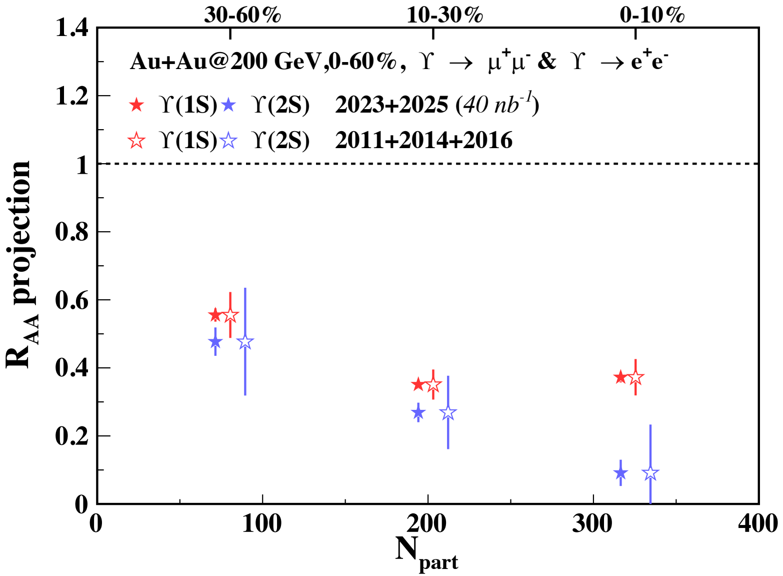
Projection: $\psi(2S)$ Suppression

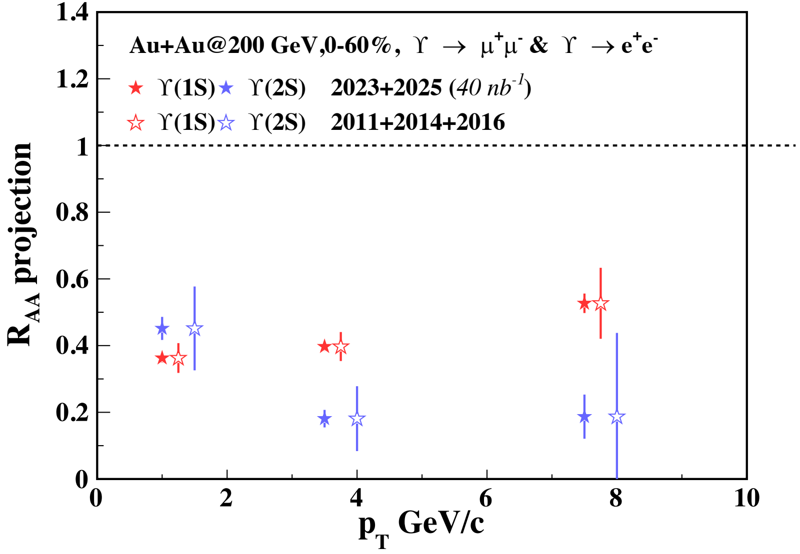




- First of such measurement in Au+Au collisions at RHIC

Projection: Υ *Suppression*





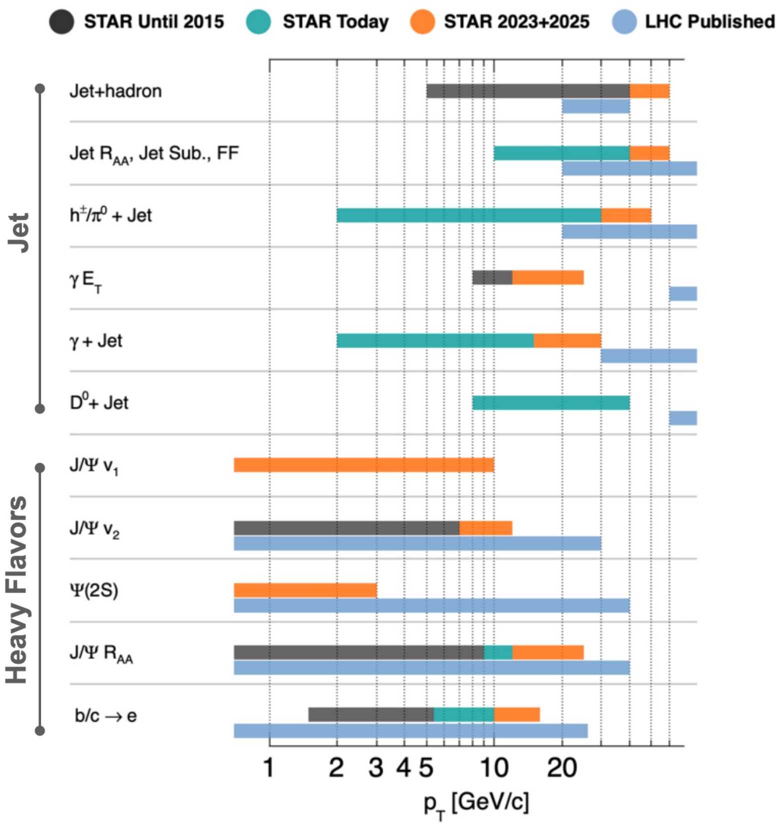
- Entering precision era
- Expect a precision of 30% statistical uncertainty for Υ(3S) measurements

Summary

- **High-impact and insightful hard probes program at STAR**
  - Jets: study parton shower in vacuum and energy loss mechanism in QGP through (semi-)inclusive and substructure measurements
  - Open HF: constrain spatial diffusion coefficient; change of hadronization process
  - Quarkonia: probe in-medium QCD force and medium temperature

- **Bright future ahead**
  - Precision era
  - Extended kinematic reach
  - New channels
  - More differential measurements
  - …

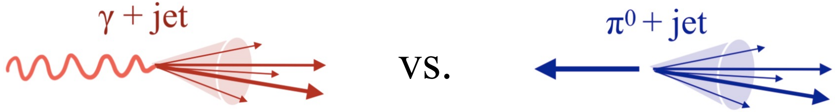
Projected Kinematic Reach



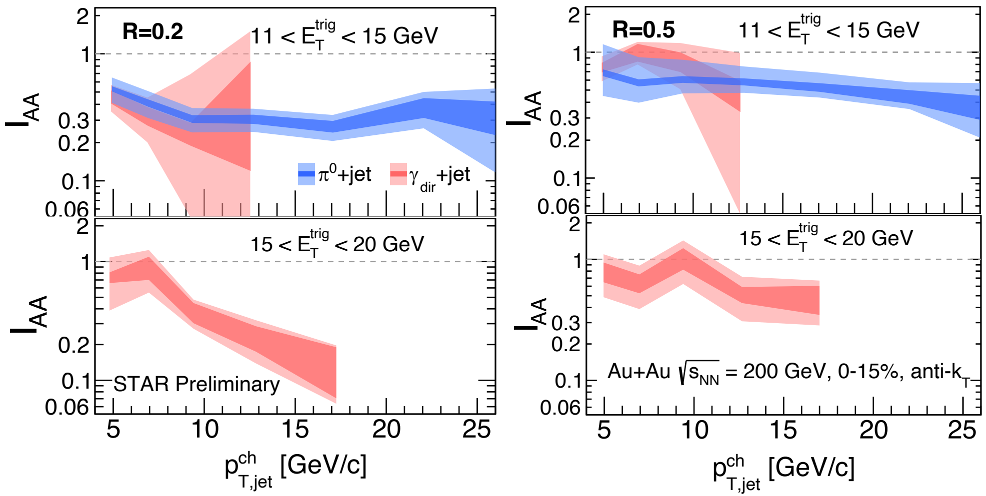
Backup

Semi-inclusive γ-jet vs. π^0-jet I_{AA}

- ✓ Vary parton flavor, path length
  - ➢ Different spectrum shapes



- Combinatorial jets removed statistically with event mixing

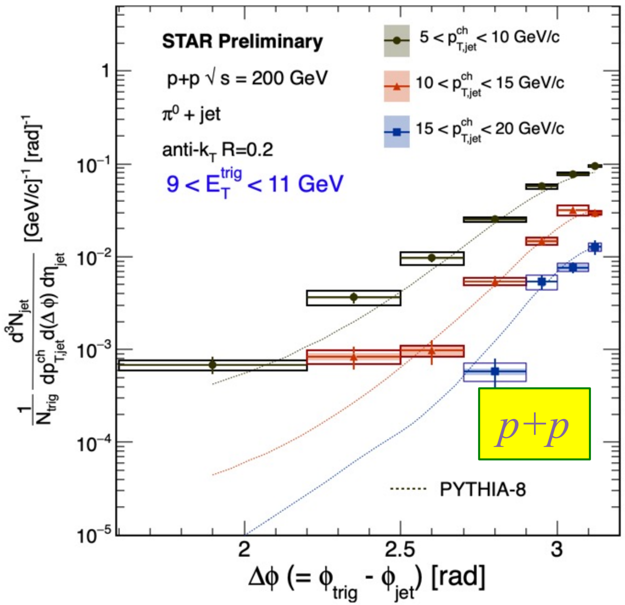


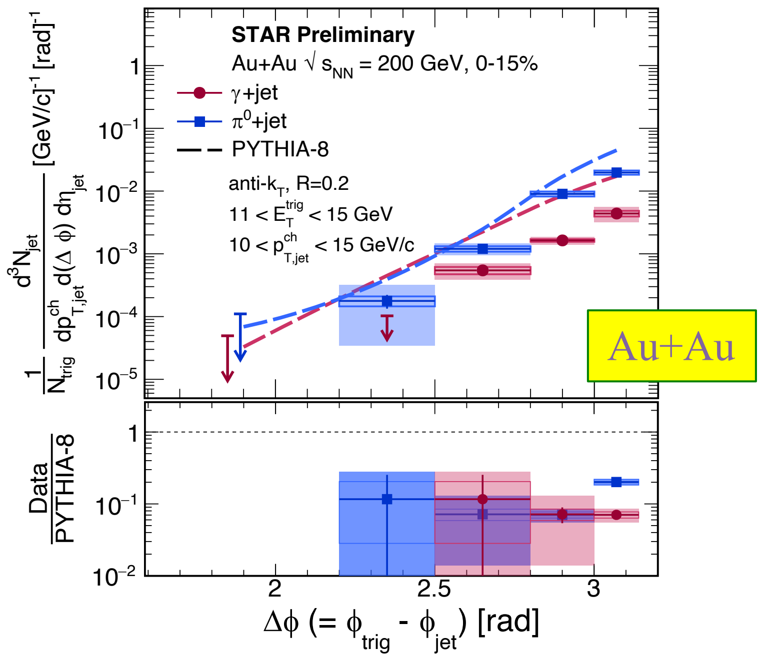
$$I_{AA} = \frac{dN/dp_{T\,AA}}{dN/dp_{T\,pp}}$$

- Strong suppression at high p_T
- Larger suppression for $R = 0.2$ than $R = 0.5$; different shapes
- **Similar suppression** for γ-jet and π^0-jet within uncertainties
- No significant trigger E_T dependence

Jet Acoplanarity

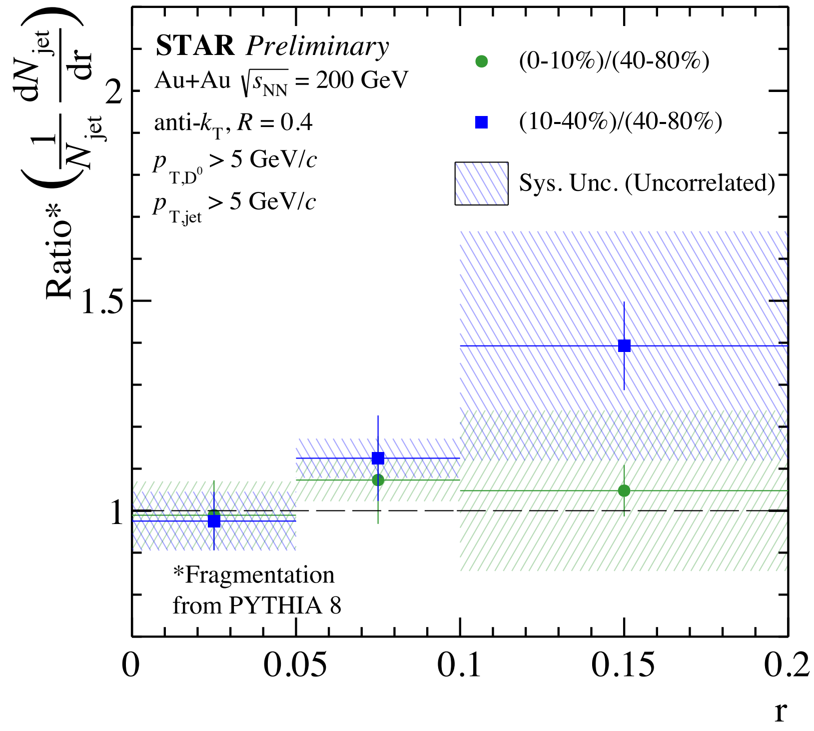
$R = 0.2$





- No obvious sign of broadening for $R = 0.2$ jets

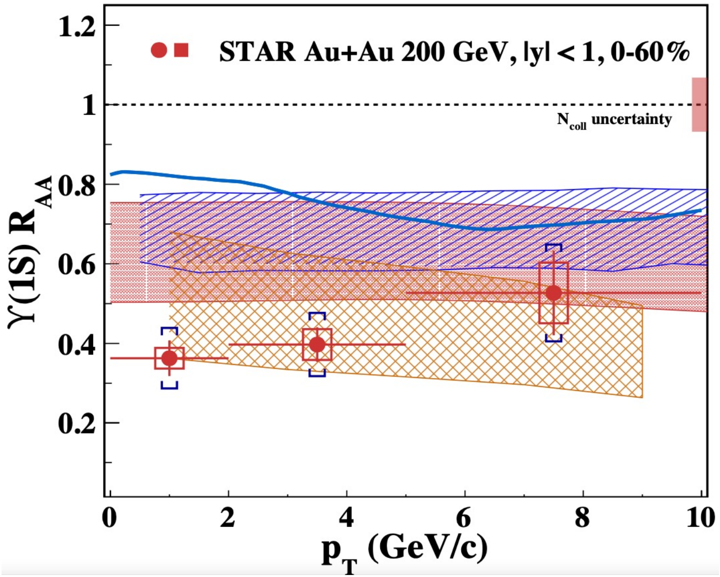
Radial Profile of D^0-tagged Jets

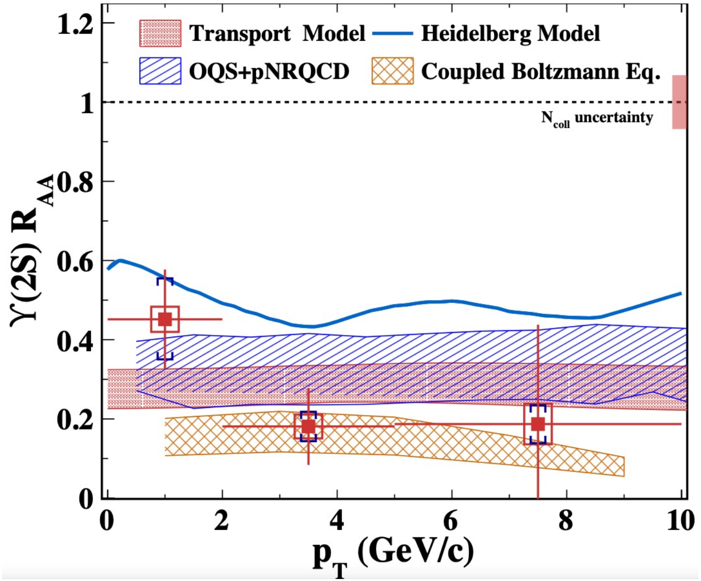


- Distance between D^0 and jet axis
- Unfolded with PYTHIA8 fragmentation: need to be improved
- No significant difference between central and peripheral collisions
  - Will extend to lower D^0 p_T

Au+Au Collisions: Υ R_{AA} vs. p_T

STAR, arXiv:XXXX





- No significant p_T dependence seen
- Can constrain model calculations

Transport Model: PRC 96 (2017) 054901
OQS+pNRQCD: 2205.10289
Coupled Boltzmann Eq: JHEP 01 (2021) 046
Heidelberg Model: PRC 95 (2017) 024905