Recent Jet and Heavy-Flavor Measurements from STAR

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for the STAR Collaboration

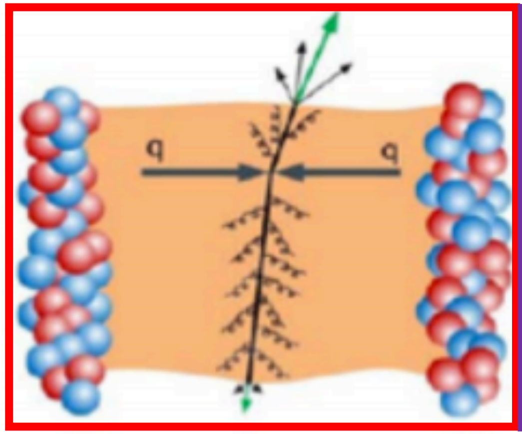
Santa Heavy-Flavor and Jets Workshop

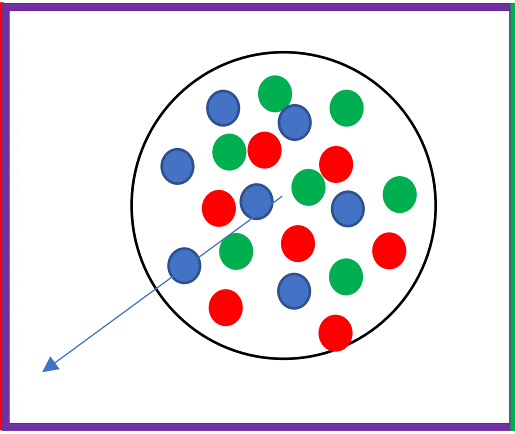
Feb. 2nd-5th, 2020

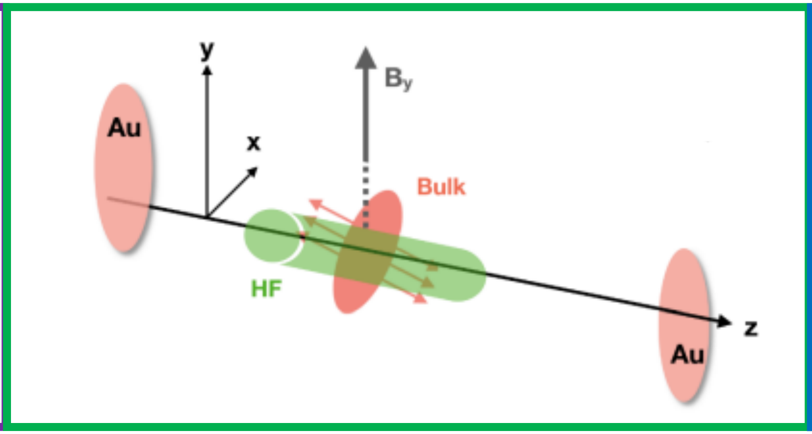
Supported by funding from the U.S. DEPARTMENT OF ENERGY

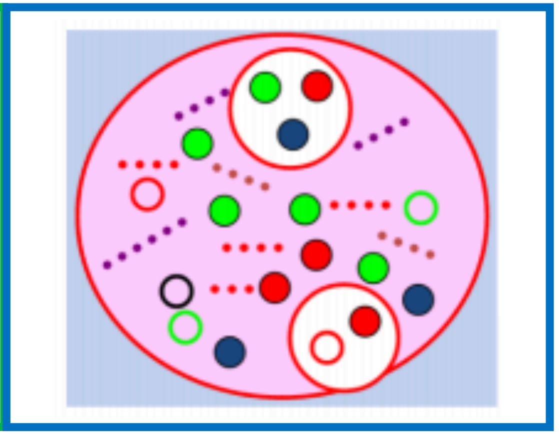
Why Heavy-Flavor and Jets?

- Formed in early, hard partonic scatterings (calculable in pQCD). → Probe entire evolution of the medium.
  - ➢ Partonic energy loss via modification of jets.
  - ➢ Flavor-dependent energy loss.
  - ➢ Bulk (transport) properties of heavy-quarks (i.e. anisotropic flow).
  - ➢ Initial conditions (i.e. directed flow).
  - ➢ Hadronization.







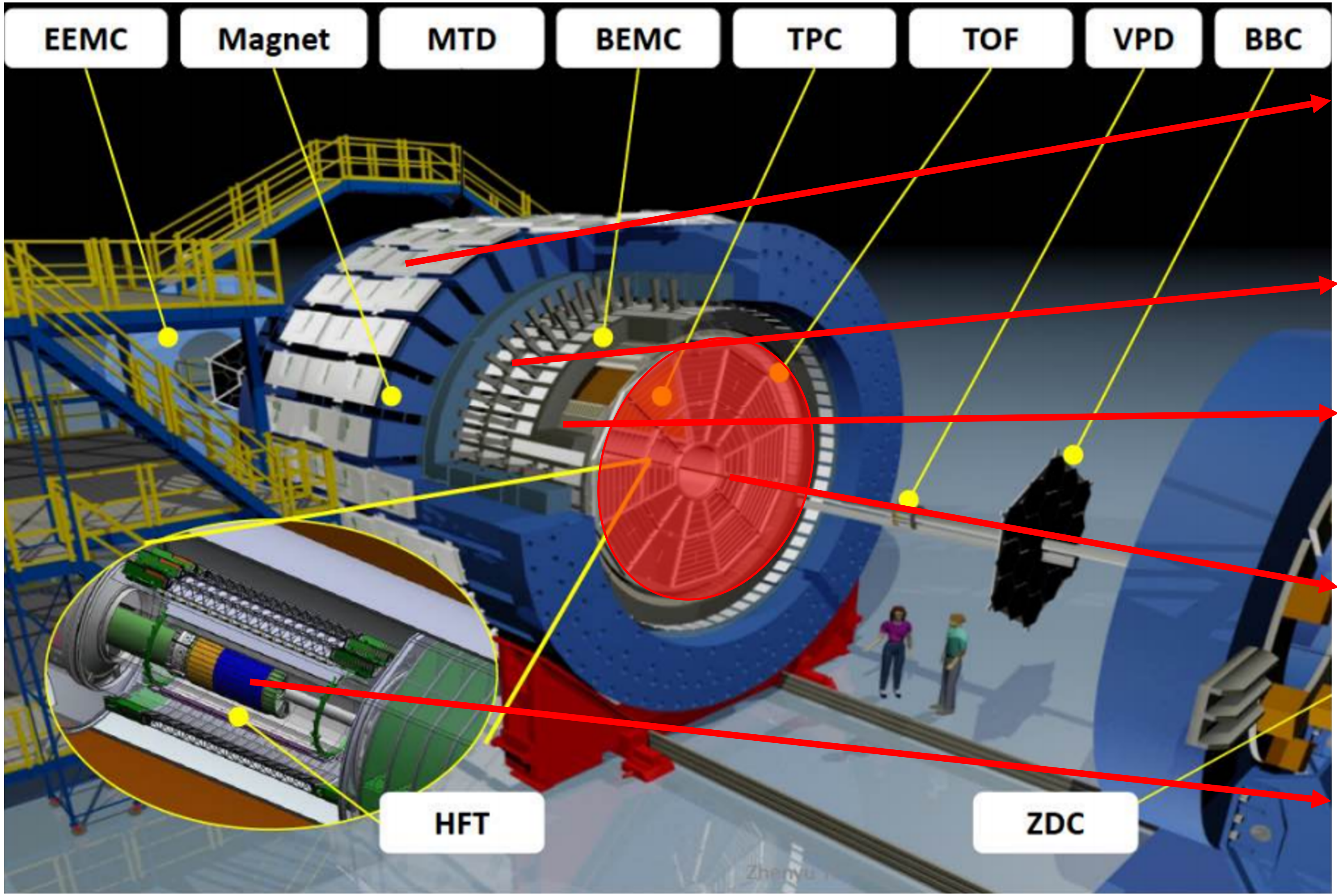


The "How": Overview of Measurements

- Jets
  - Di-jet imbalance
  - Semi-inclusive jet spectra
  - Event plane (path-length) dependence
  - Jet-flavor dependence
  - Angular scale of jets

- Heavy-flavor
  - Open heavy-flavor
    - Spectra and R_{AA}
    - Charm anisotropic flow (v_2)
    - Charm directed flow (v_1)
    - Charm & bottom HFE R_{AA}
  - Quarkonia
    - Spectra and R_{AA}
    - J/ψ polarization

The STAR Detector



Muon Telescope Detector (MTD)
- Used for identifying di-muon pairs from quarkonia decay.

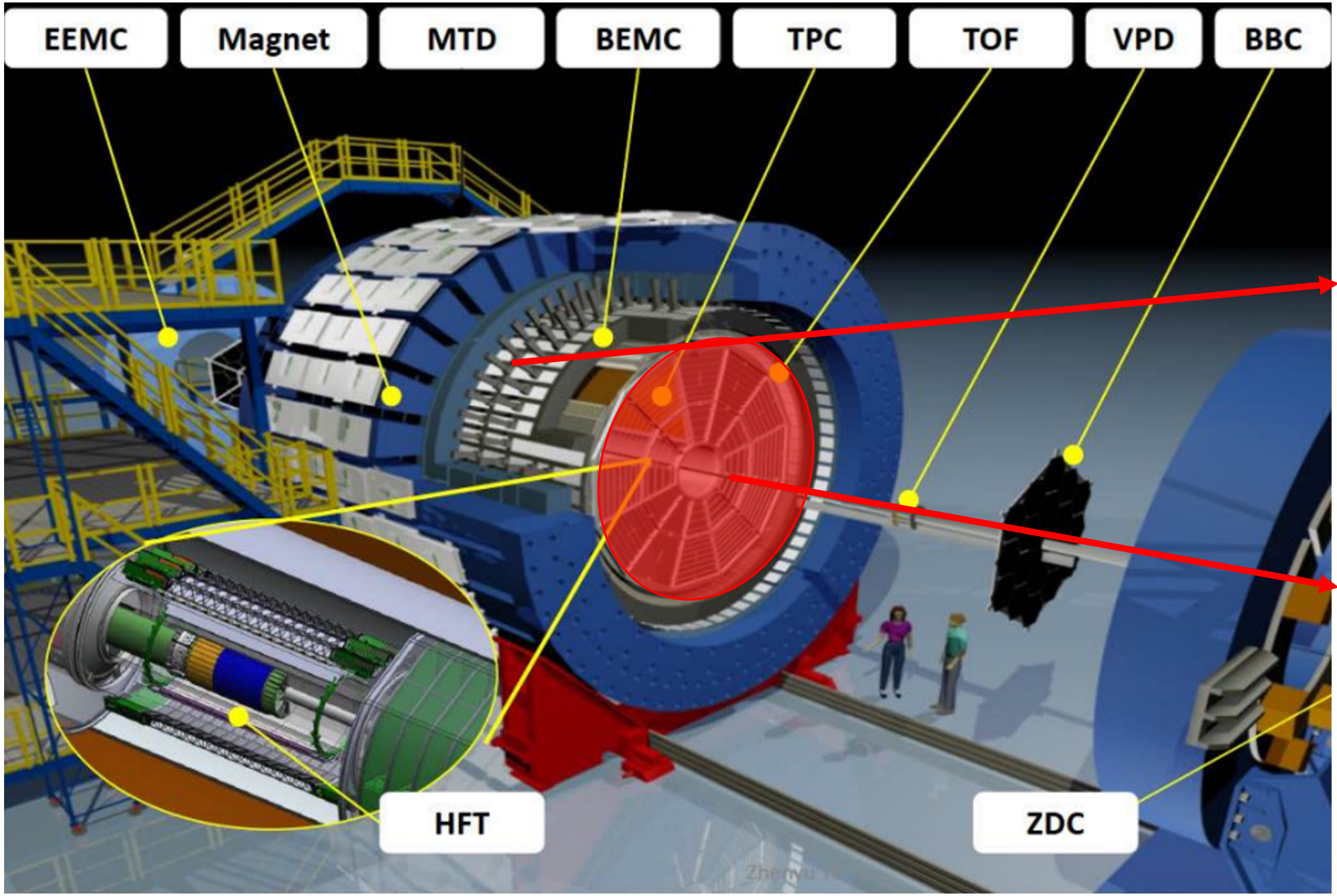
Barrel EM Calorimeter (BEMC)/EEMC
- Neutral particles, particle energy, jets.

Time of Flight (TOF)
- PID via measurement of velocity.

Time Projection Chamber (TPC)
- Main tracking volume.
- Allows extraction of $\vec{p}$.
- PID using TPC dE/dx.

Heavy Flavor Tracker (HFT)
- Used for rejecting enormous background in reconstructing open heavy-flavor mesons.

The STAR Detector



Barrel EM Calorimeter (BEMC)/EEMC
- Neutral particles, particle energy, jets.

Neutral Jets.

Time Projection Chamber (TPC)
- Main tracking volume.
- Allows extraction of $\vec{p}$.
- PID using TPC dE/dx.

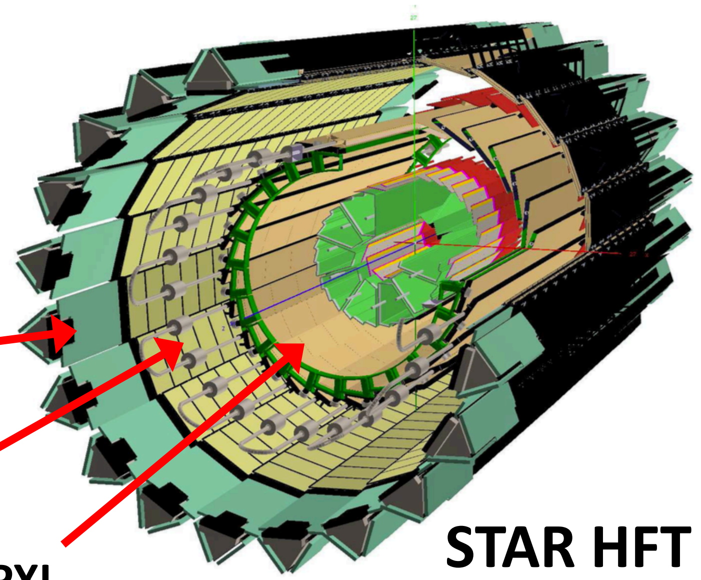
Charged Jets.

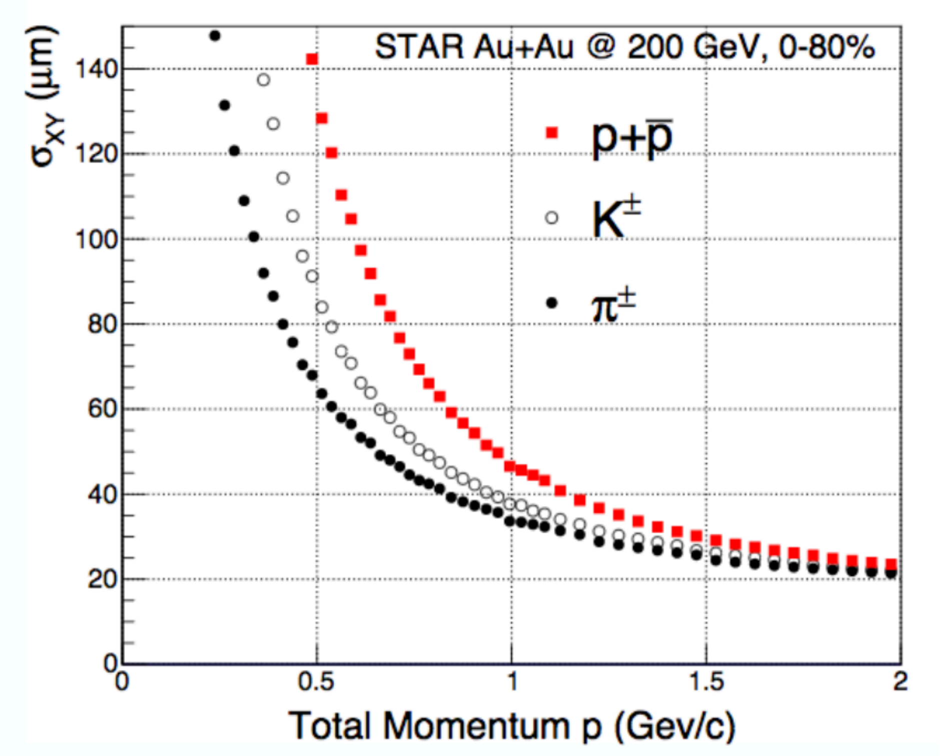
TPC+BEMC(EEMC) → Full Jets!

The STAR Detector

Phys. Rev. Lett. 118 (2017) 212301

Heavy Flavor Tracker





- Provides the pointing resolution needed for open heavy-flavor reconstruction.

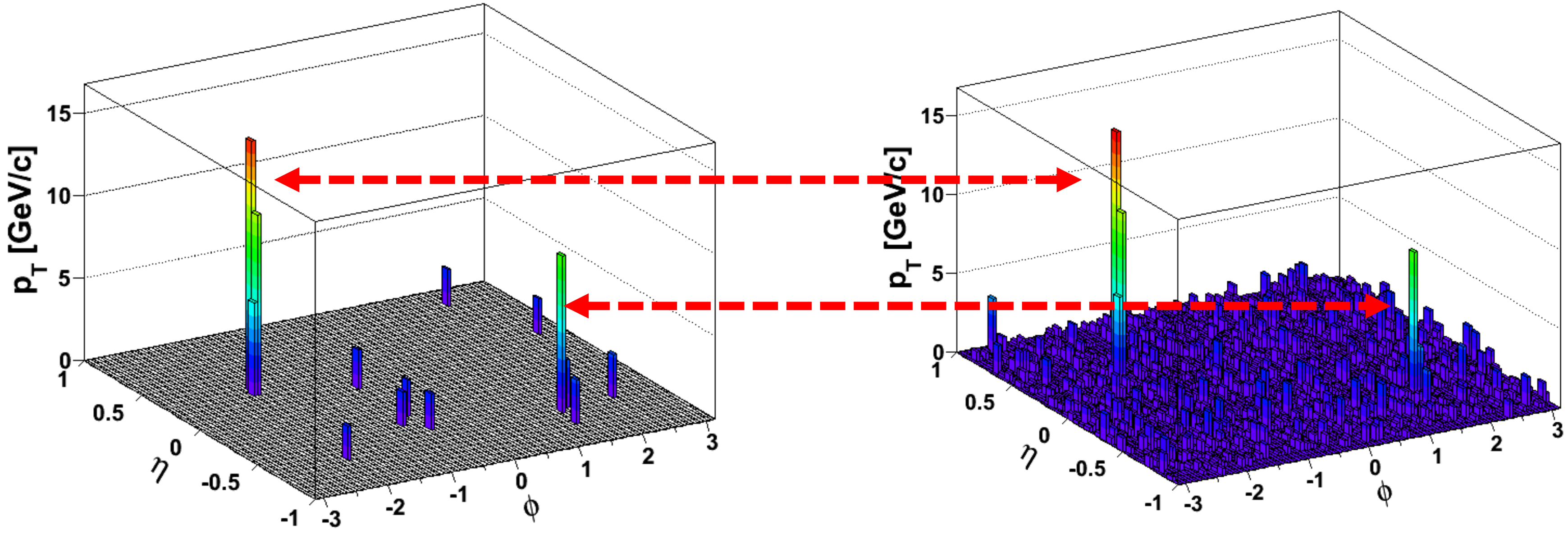
Jets in Heavy-Ion Collisions at STAR

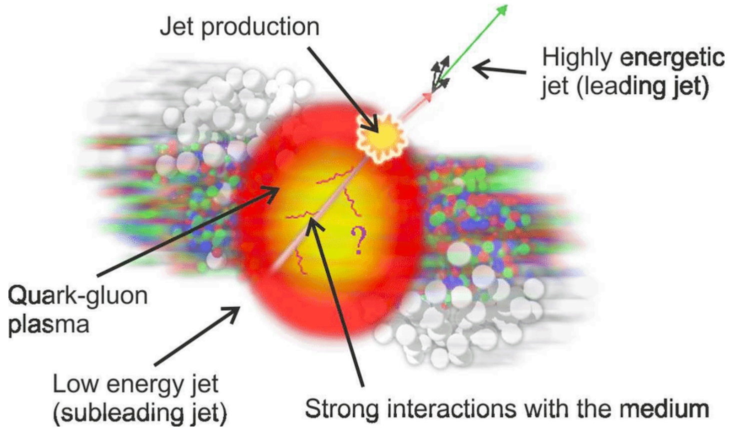
Di-Jet Imbalance

- Constituent p_T^{Cut} > 2 GeV/c (***hard-core***)
- Reduce BG and combinatorial jets

- Constituent p_T^{Cut} > 0.2 GeV/c
- Geometrically matched to the hard-core jet

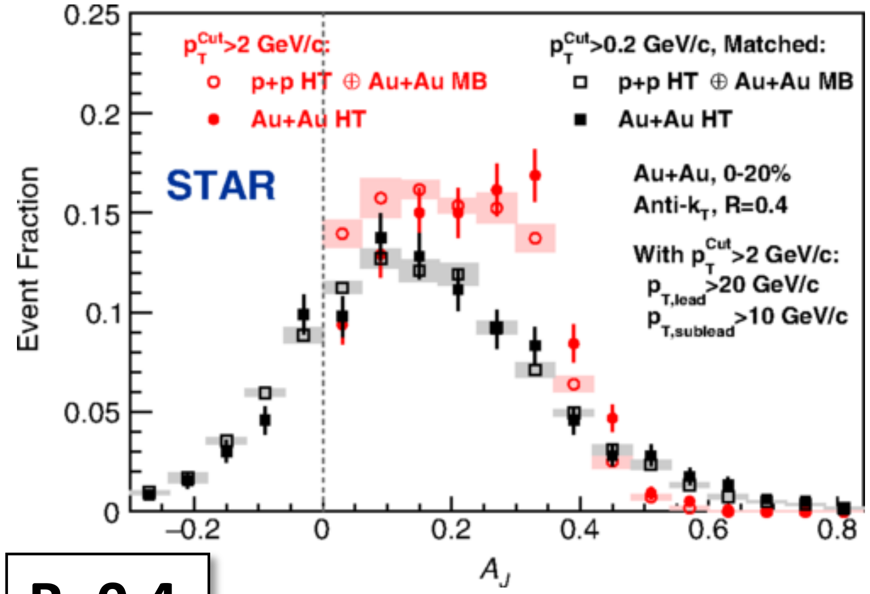
- $A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$
- **Hard-core jet** vs. **Matched jet**



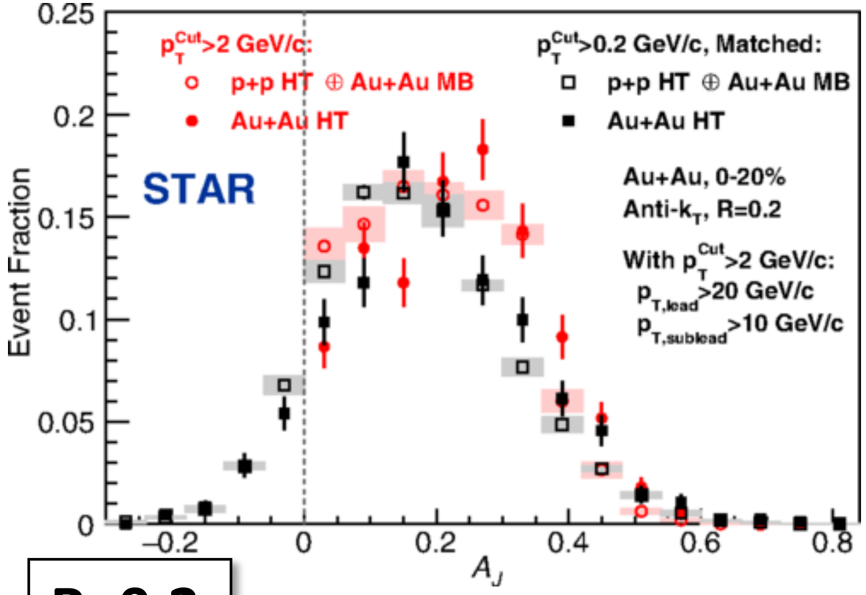


Di-Jet Imbalance

STAR, Phys. Rev. Lett. **119** (2017) 062301

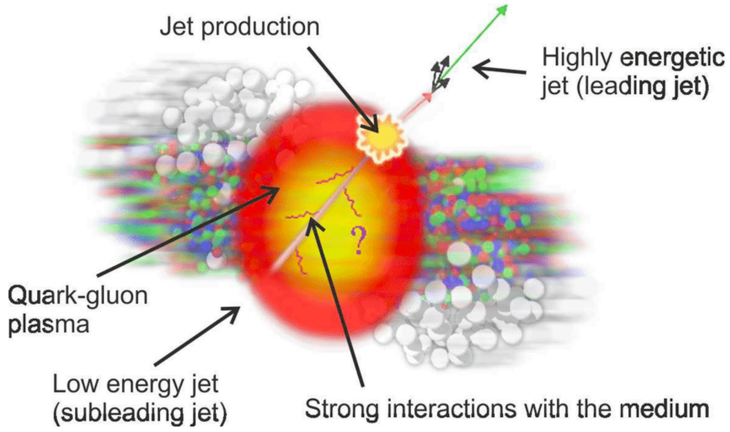


R=0.4



R=0.2

- $A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$
- **Hard-core jet** vs. **Matched jet**

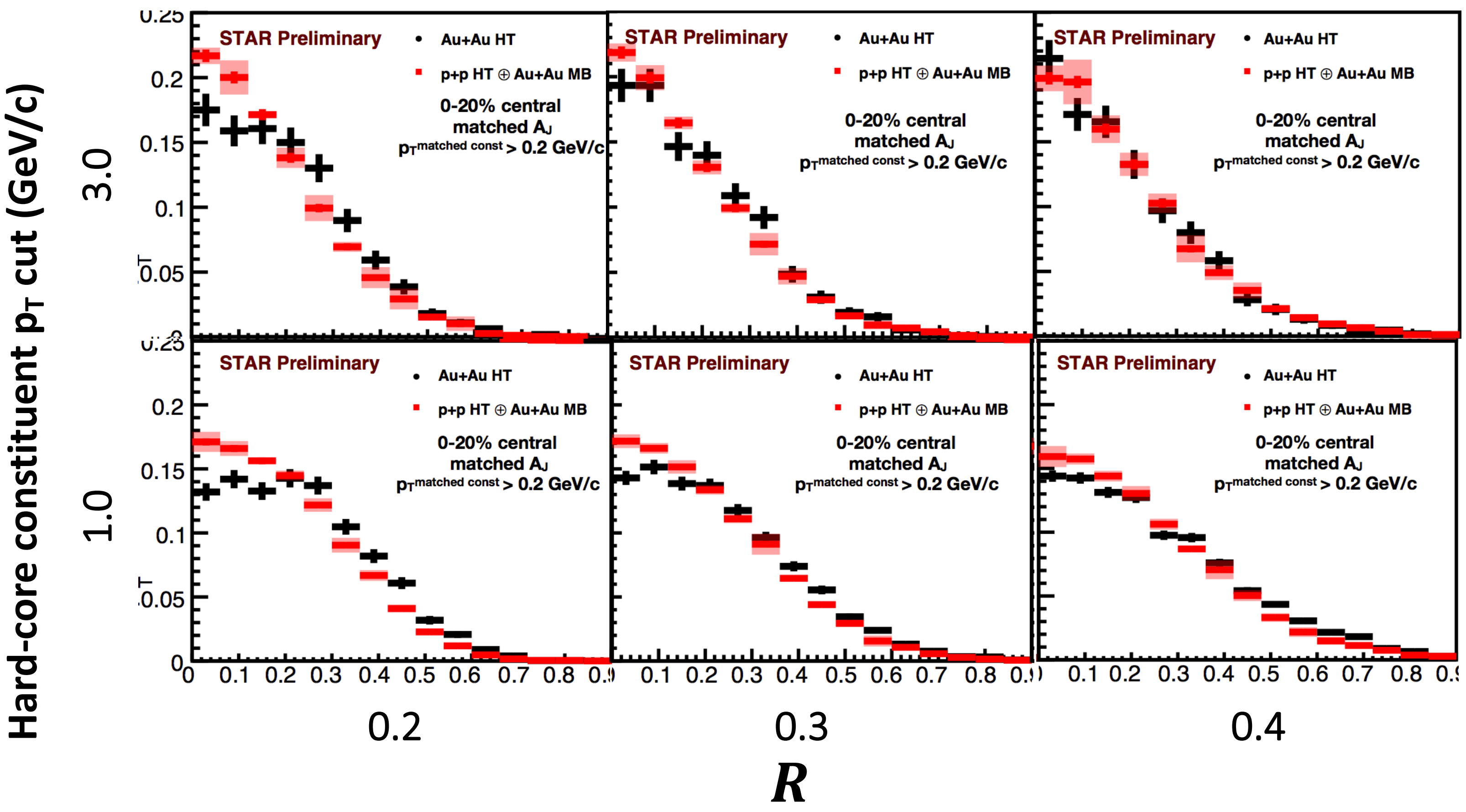


- For $R = 0.4$ hard-core jet, more di-jet momentum imbalance compared to p+p
  - Balance recovered when soft constituents are included (matched-jet)
- For $R = 0.2$, balance no longer recovered in matched-jet

Softening of jet constituents and **Broadening** of the jet structure

Jet Geometry Engineering

- Building off the previous work, do this analysis more differentially!
  - Vary the jet definition (R, constituent p_T cut, …) → effectively control the path length and vertex of jets in the medium (Jet Geometry Engineering)



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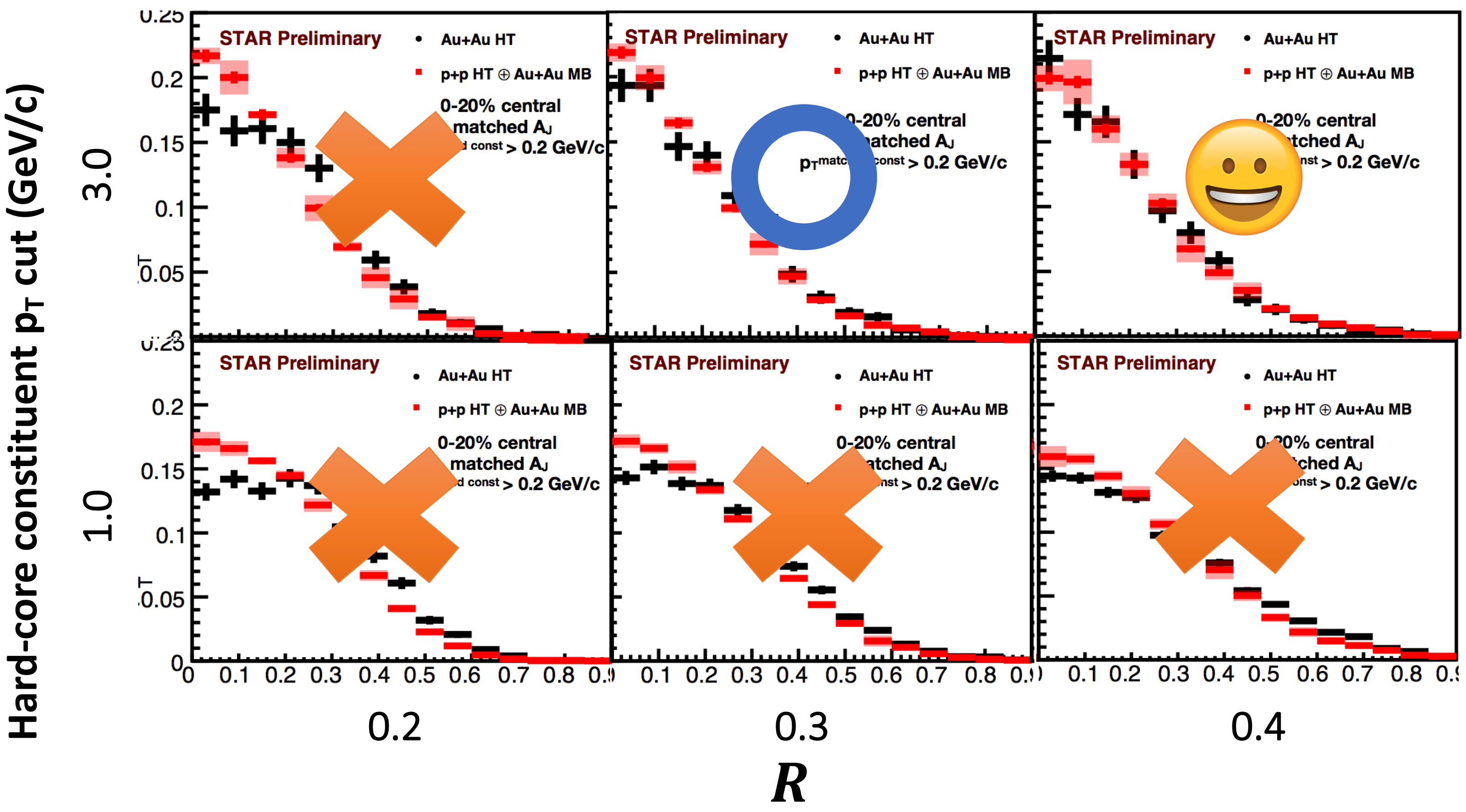


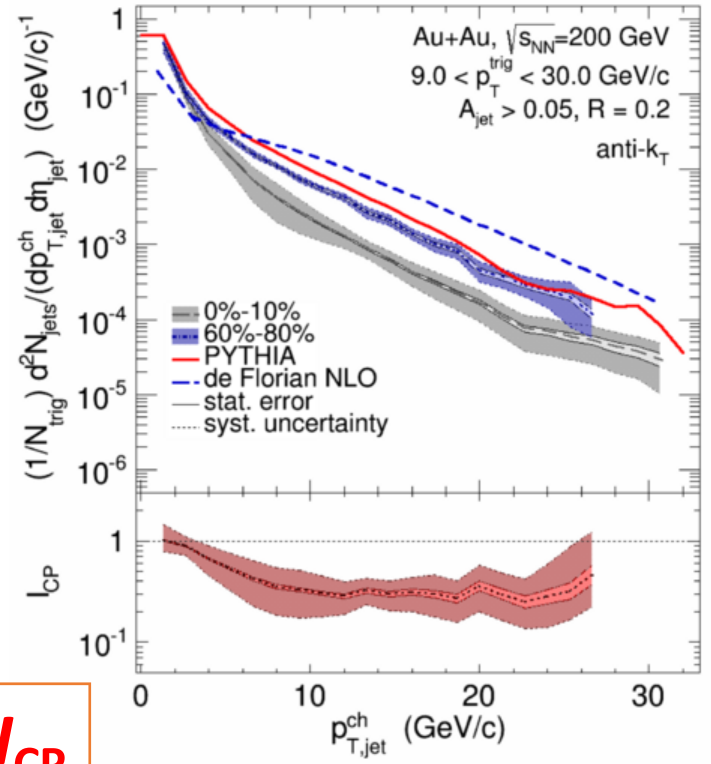
- Matched jet with various hard-core constituent p_T cut and R

> - Imbalance at small R.
> - Balance ONLY restored with increased R (~0.35) when soft particles are included.

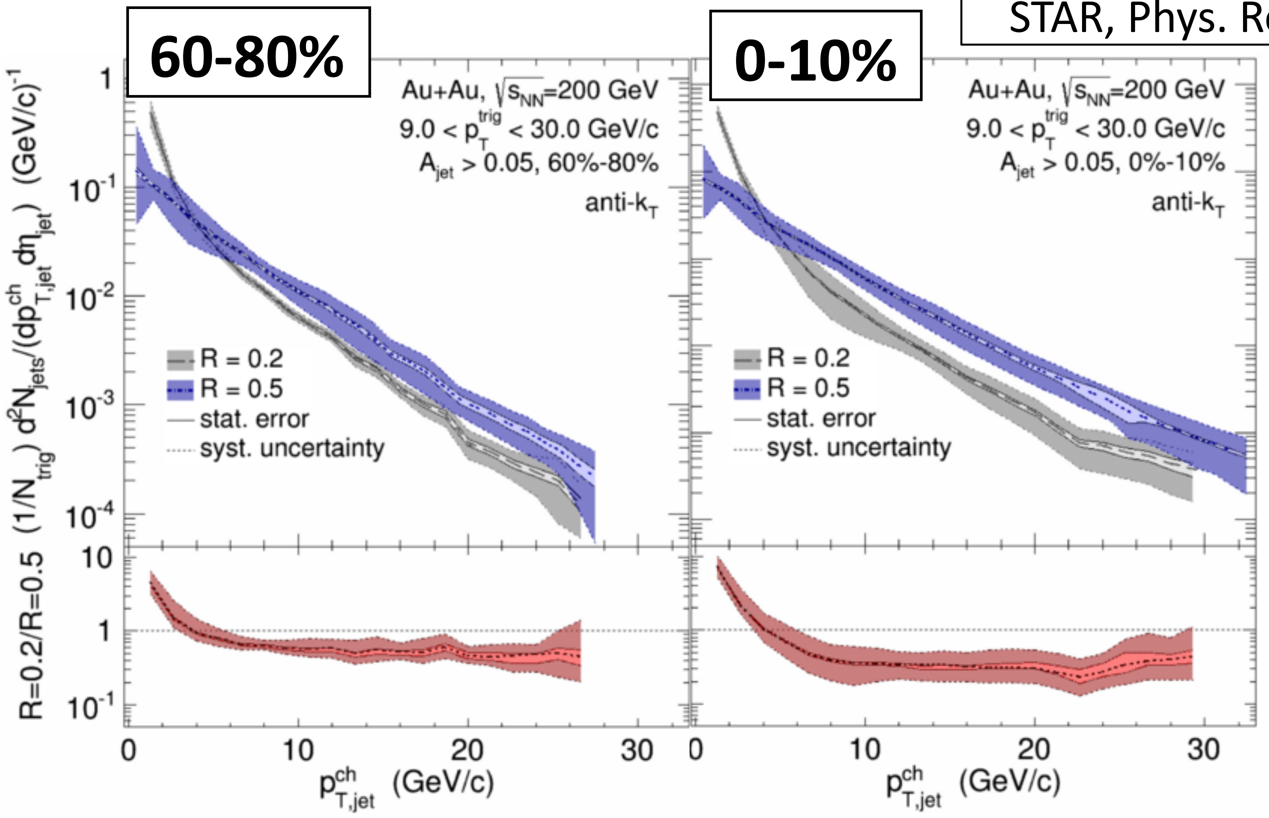
Semi-Inclusive Spectra

h-Triggered Recoil Jets

STAR, Phys. Rev. C **96** (2017) 24905



I_{CP}



***R*=0.2 vs. *R*=0.5**

Charged Jet

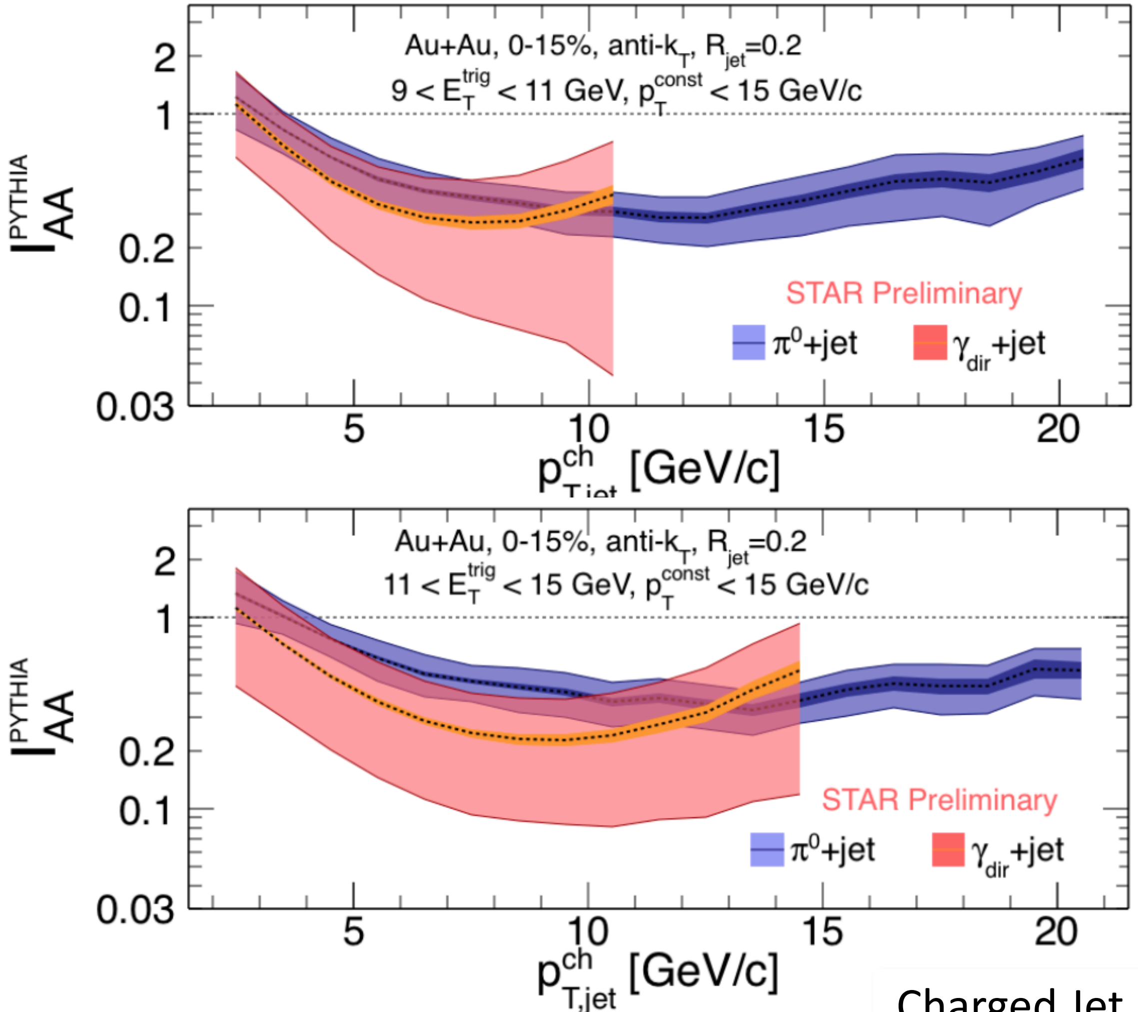
- Fully corrected $h^{\pm}$-triggered charged recoil jet
  - Strong suppression via I_{CP}
  - Medium-induced broadening ⇦ Comparison between $R = 0.2$ and $R = 0.5$

Semi-Inclusive Spectra

γ-Triggered Recoil Jets

- γ_{dir}+jet and p^0+jet
  - Path length
  - Color factor (toward *q*-jet)
  - Parton energy

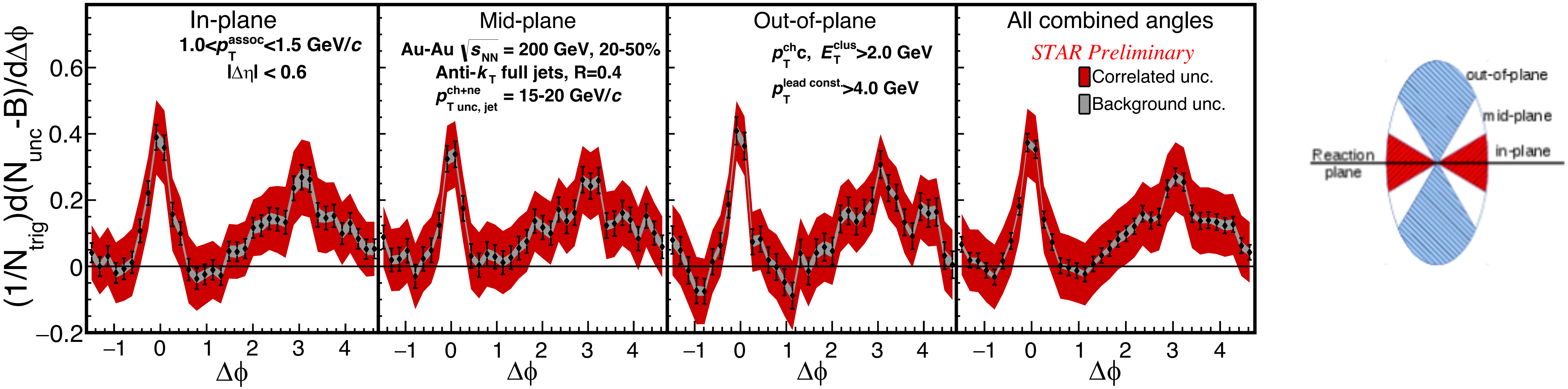
- Similar level of suppression observed



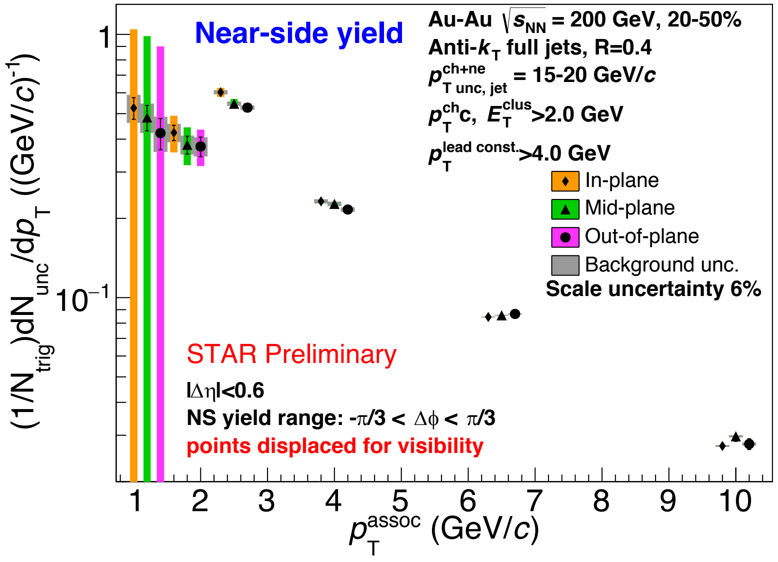
Charged Jet

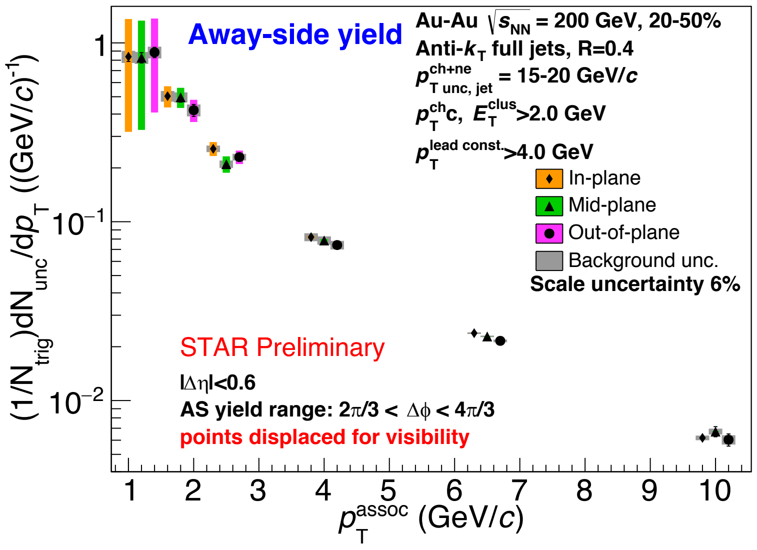
Event-plane Dependent Jet-hadron Correlations

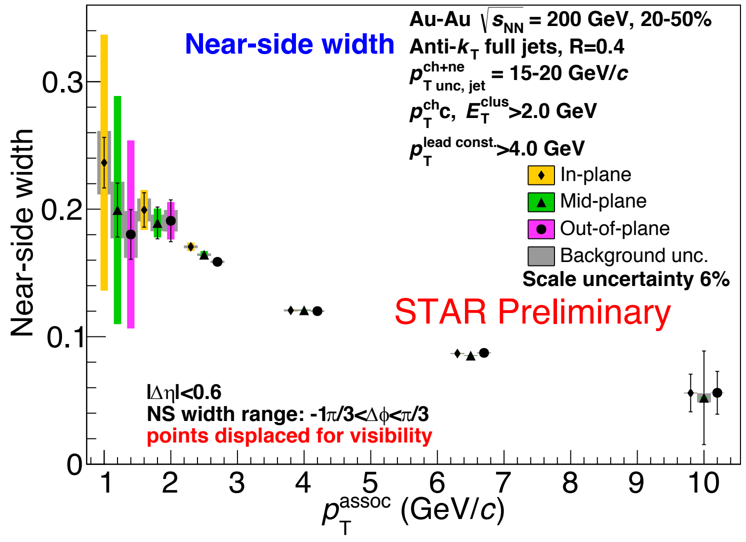
- Previous jet-hadron correlations by STAR (Phys. Rev. Lett. 112 (2014) 122301)
  - Suppression of high-p_T associated particle yield is balanced by low p_T associated particle enhancement

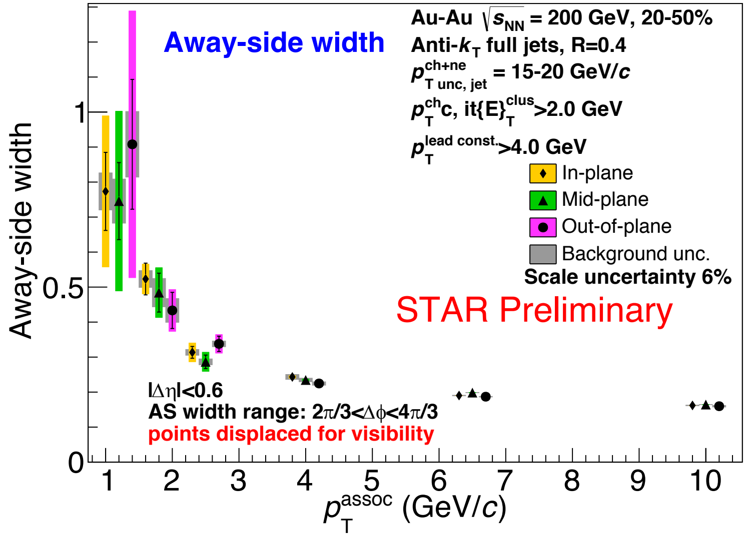


Event-Plane Dependence









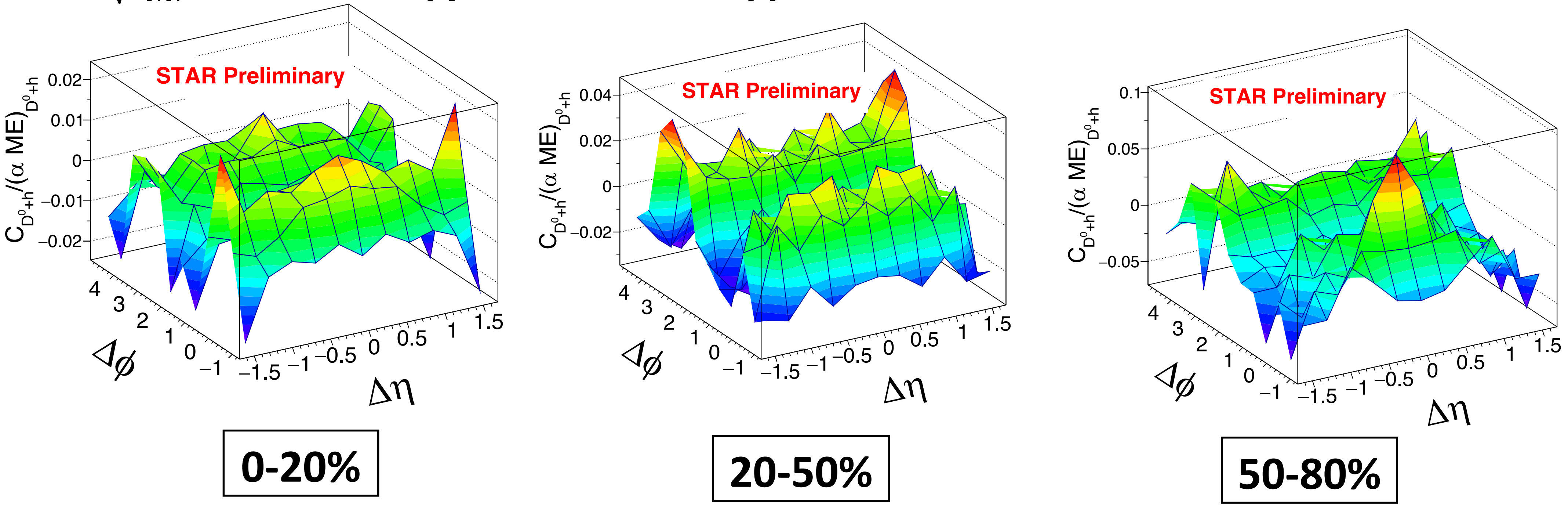
No significant event plane dependence is observed within uncertainties

Flavor Dependence: D^0+h Correlations

Submitted to PRC (arXiv: 1911.12168)

- Heavy Flavor Tracker (HFT) provides significantly better identification of heavy-flavor particles.
- D^0-hadron two-particle angular correlations with $D^0 \rightarrow \pi^{\pm}K^{\mp}$ channel.
- Correlations compared to light-flavor di-hadron correlations with similar trigger p_T.

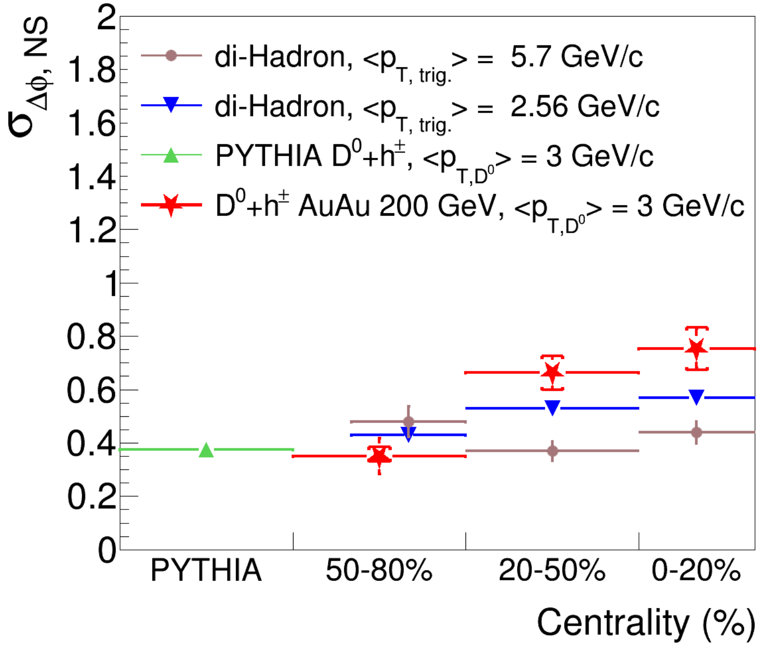
Au+Au, $\sqrt{s_{NN}} = 200$ GeV, D^0 $p_T = 2$–10 GeV/c, $h^{\pm}$ $p_T > 0.15$ GeV/c



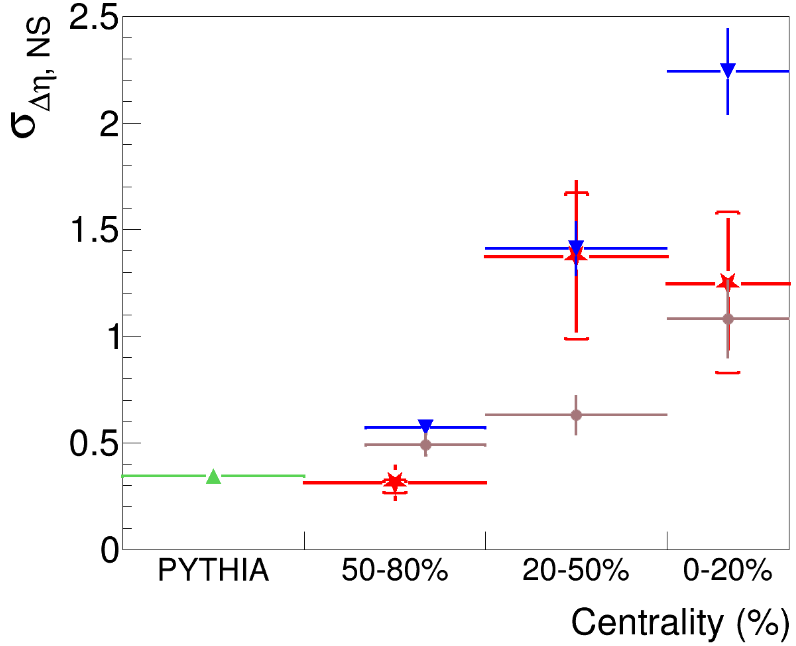
Flavor Dependence: D^0+h Correlations

arXiv: 1911.12168

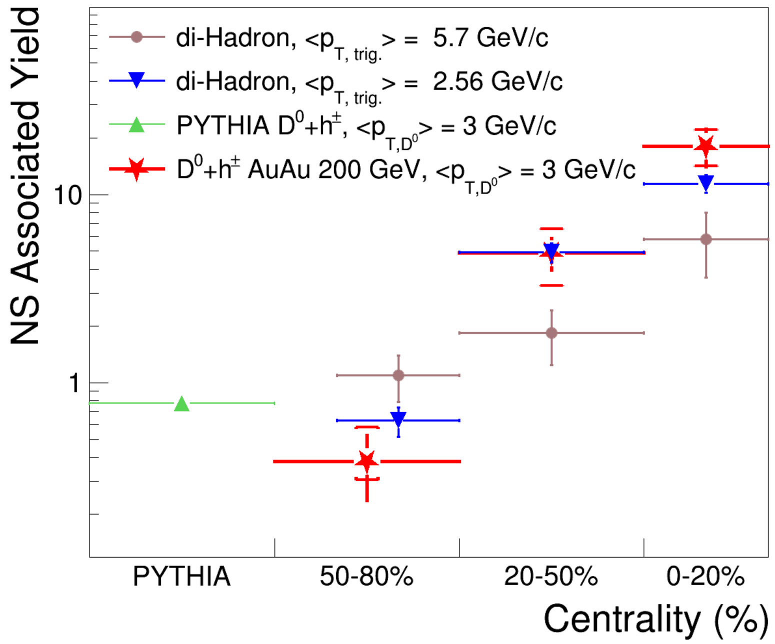
Near-side width (phi)



Near-side width (eta)



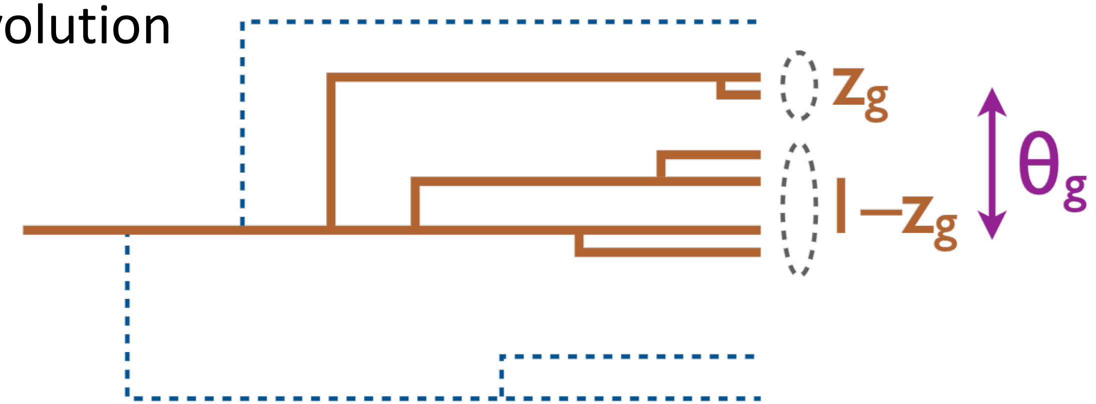
Near-side yield



- Significant increase in both near-side width and yield as a function of centrality.
- Similar width and yield results to light-flavor correlations – Indication of similar behavior of correlations between light-flavor and charm-quarks

Jet Substructure in p+p

- Experimental observables related to quantities in jet evolution
  - With SoftDrop algorithm (Phys. Rev. D 91, 111501 (2015))
    - ✓ Momentum scale, $\boldsymbol{z_g}$
    - ✓ Angular scale, $\boldsymbol{R_g}$
  - Invariant jet mass, ***M***

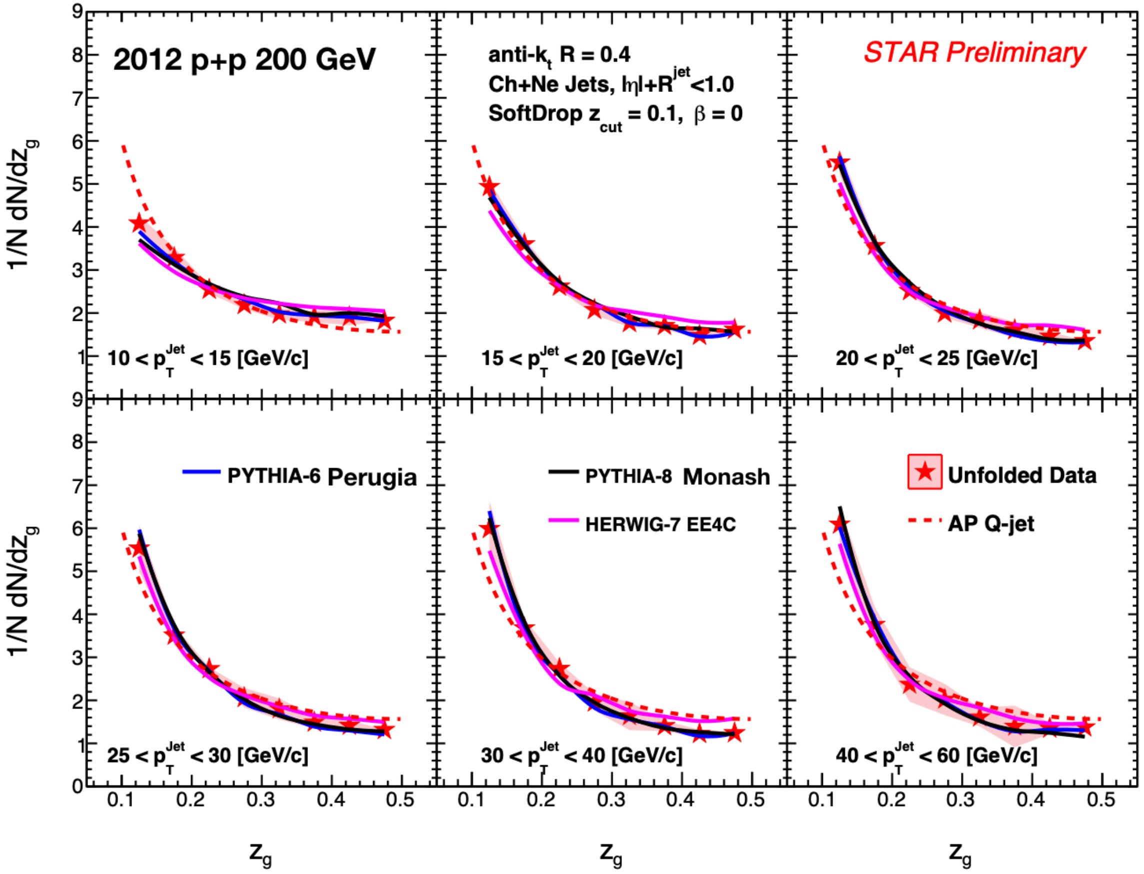


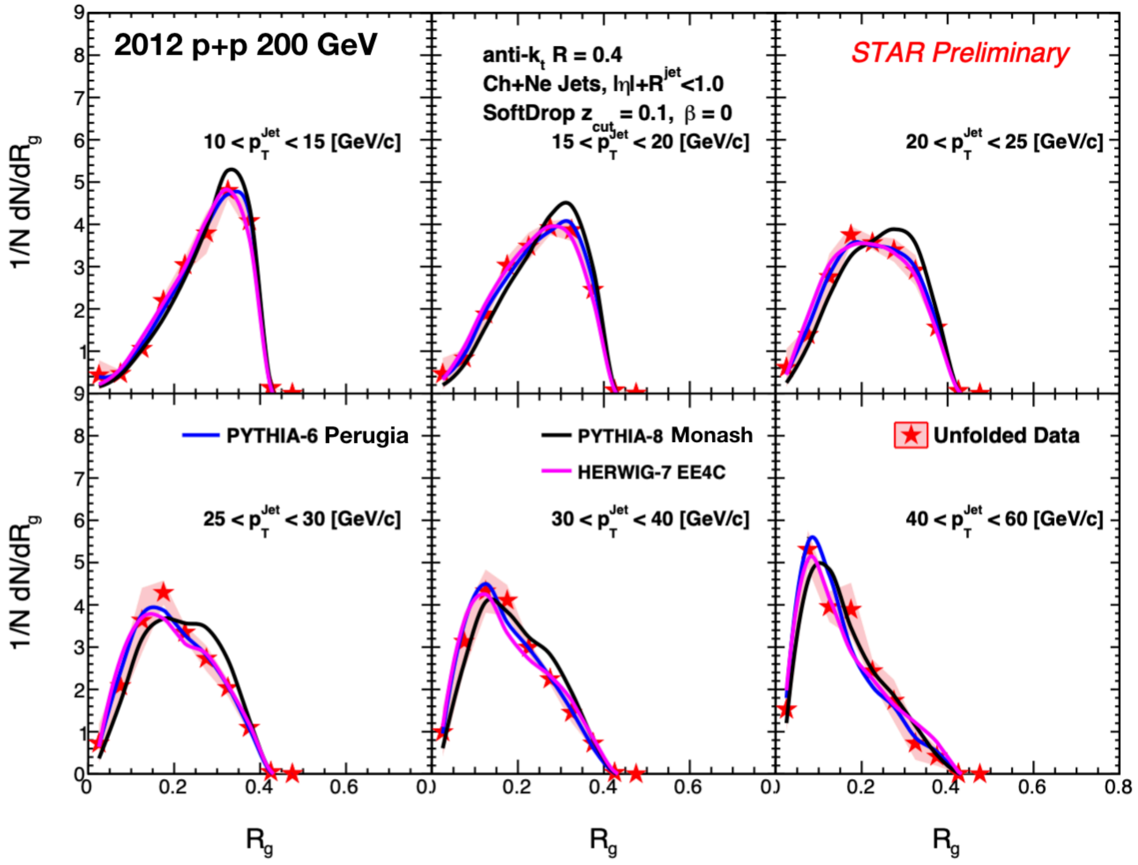
Based on declustering an angular-ordered tree

- Measurements of these observables in *pp* set a vacuum baseline

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

Other Jet Observables





- *1/z* behavior recovered for jet p_T > 20 GeV/*c*
- z_g in *pp* described by leading order MC generators

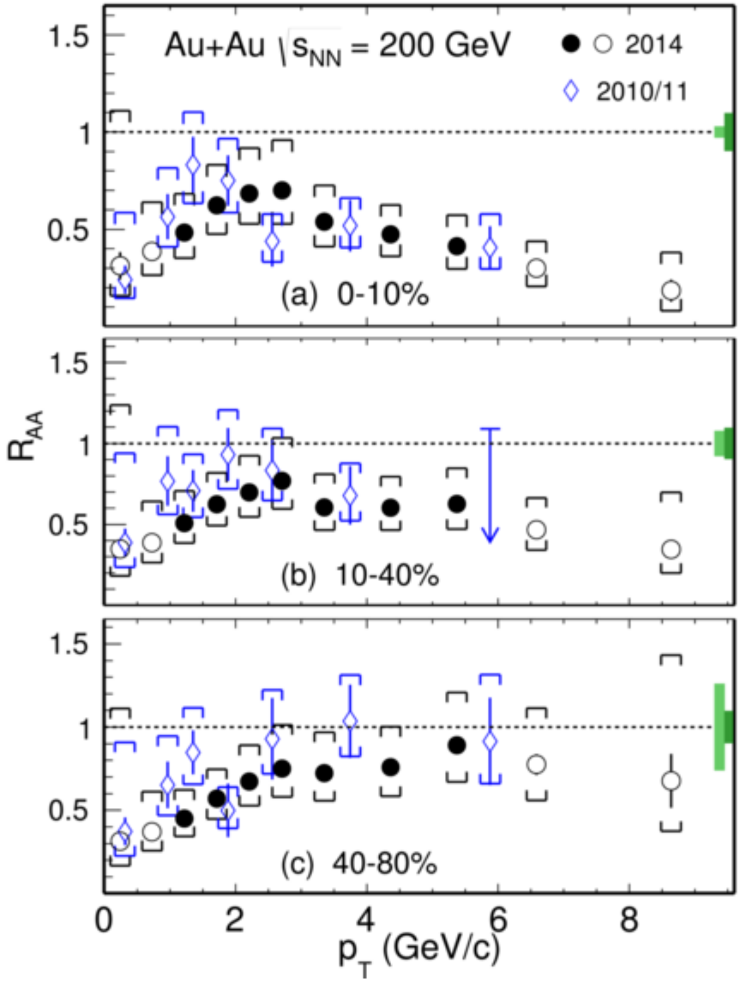
- Momentum dependent narrowing of jet angular structure
- R_g overall shape in *pp* described by leading order MC generators

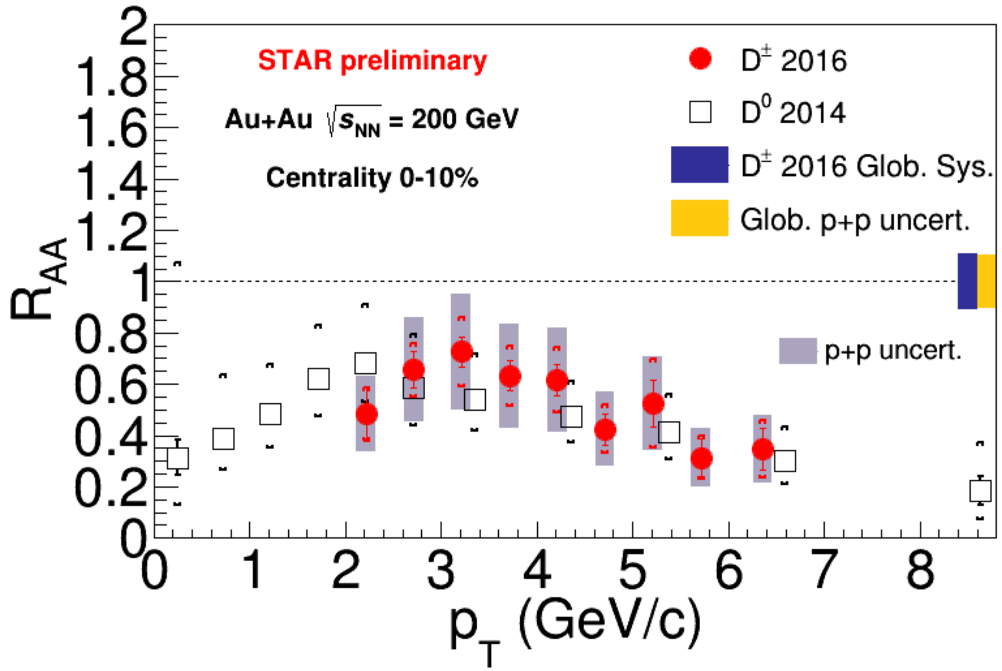
Open Heavy-Flavor in STAR

D^0 and $D^{\pm}$ meson production

Decay channel	$c\tau$ [µm]	Branching ratio [%]
$D^0 \longrightarrow K^- + \pi^+$	122.9 ± 0.4	3.93 ± 0.04
$D^+ \longrightarrow K^- + \pi^+ + \pi^+$	311.8 ± 2.1	9.46 ± 0.24

STAR, PRC99 (2019) 034908

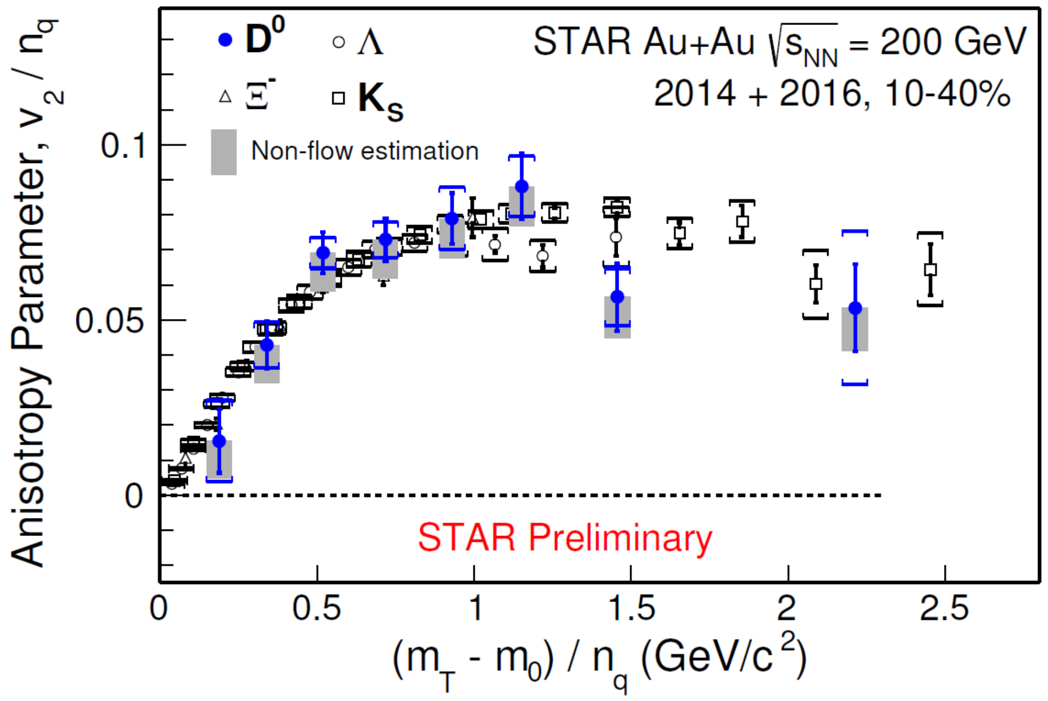


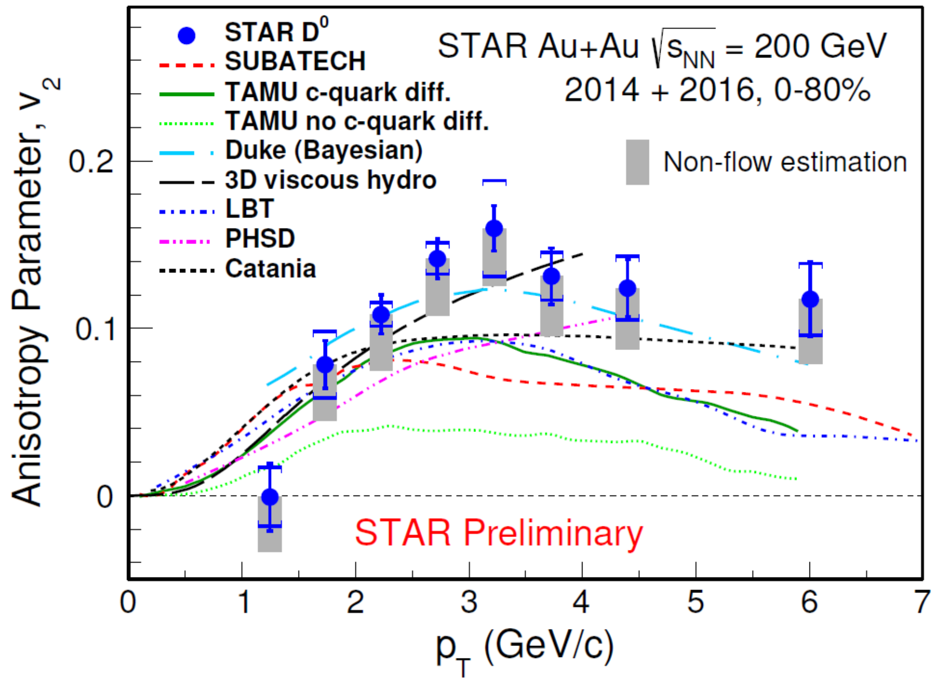


- Suppression at high p_T increases towards more central collisions.
- $R_{AA} < 1$ in the 0-10% Au+Au centrality interval for all p_T.
- D^0 and $D^{\pm}$ mesons show same level of suppression.

D^0 Anisotropic Flow

2014: STAR, PRL 118 (2017) 212301





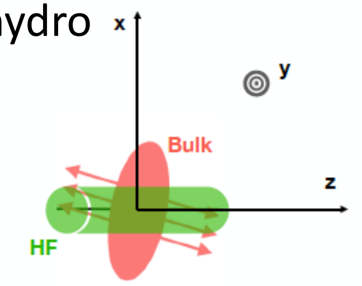
Charm quarks acquire similar elliptic flow as light flavor quarks
→ data suggest strong interaction of charm quarks with QGP.

n_q = number of constituent quarks
m_0/m_T = particle/transverse particle mass

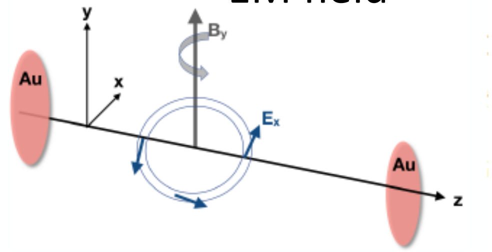
Data described by models with temperature dependent charm diffusion coefficient $2\pi TD_s \sim 2$–12 predicted by lattice QCD.

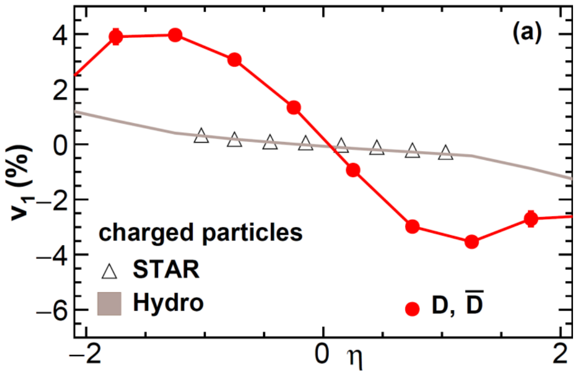
D^0 Directed Flow

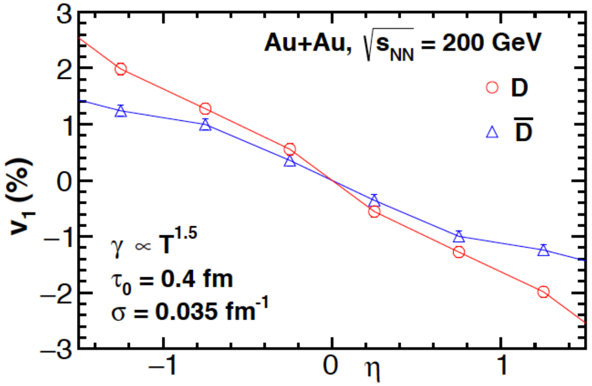
hydro



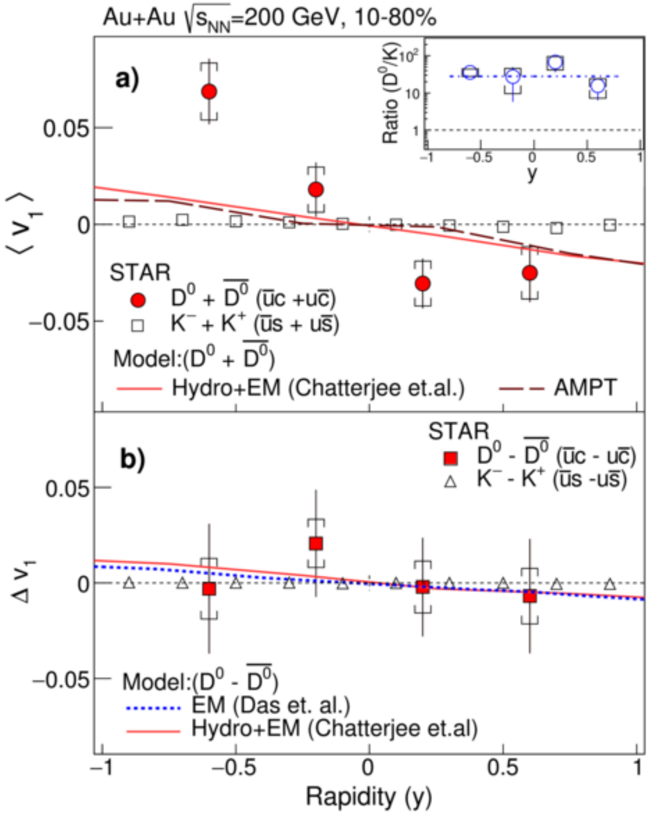
EM field



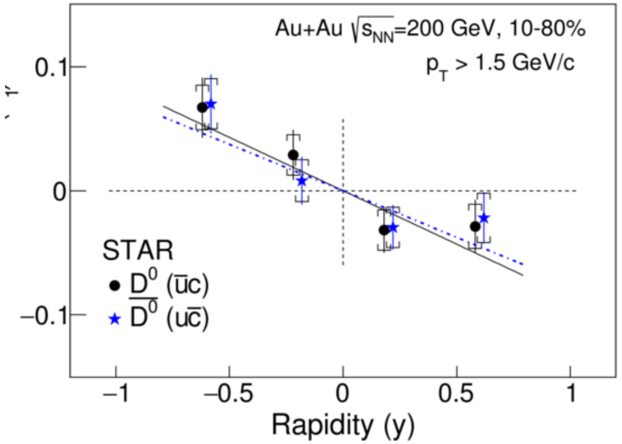




Chatterjee, Bozek: PRL 120, 192301 (2018)
PLB 798, 134955 (2019)



STAR, PRL 123 (2019) 162301



dv_1/dy

D^0: −0.086 ± 0.025 (stat) ± 0.018 (syst)

$\bar{D^0}$: −0.075 ± 0.024 (stat) ± 0.020 (syst)

- Sensitive to initial tilt of fireball and viscous drag on charm quarks in QGP.
- Effect of EM fields is of opposite sign on D^0 and anti-D^0 mesons and would not influence the average v_1 of D^0 mesons.

D^0 mesons exhibit much larger v_1 than light flavor hadrons → strong interaction of c-quarks with initially tilted source.

More data needed to draw conclusions on magnetic field induced v_1 splitting of c and anti-c quarks.

D_s/D^0 enhancement

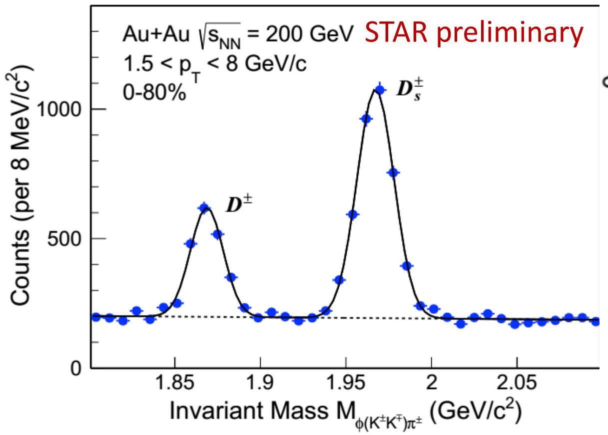
- Strangeness enhancement in QGP is expected to affect the yield of D_S (if c quarks participate in coalescence).
- D_S freezes out early and has smaller hadronic interaction cross-section compared to D^0.

D_s/D^0 ratio:

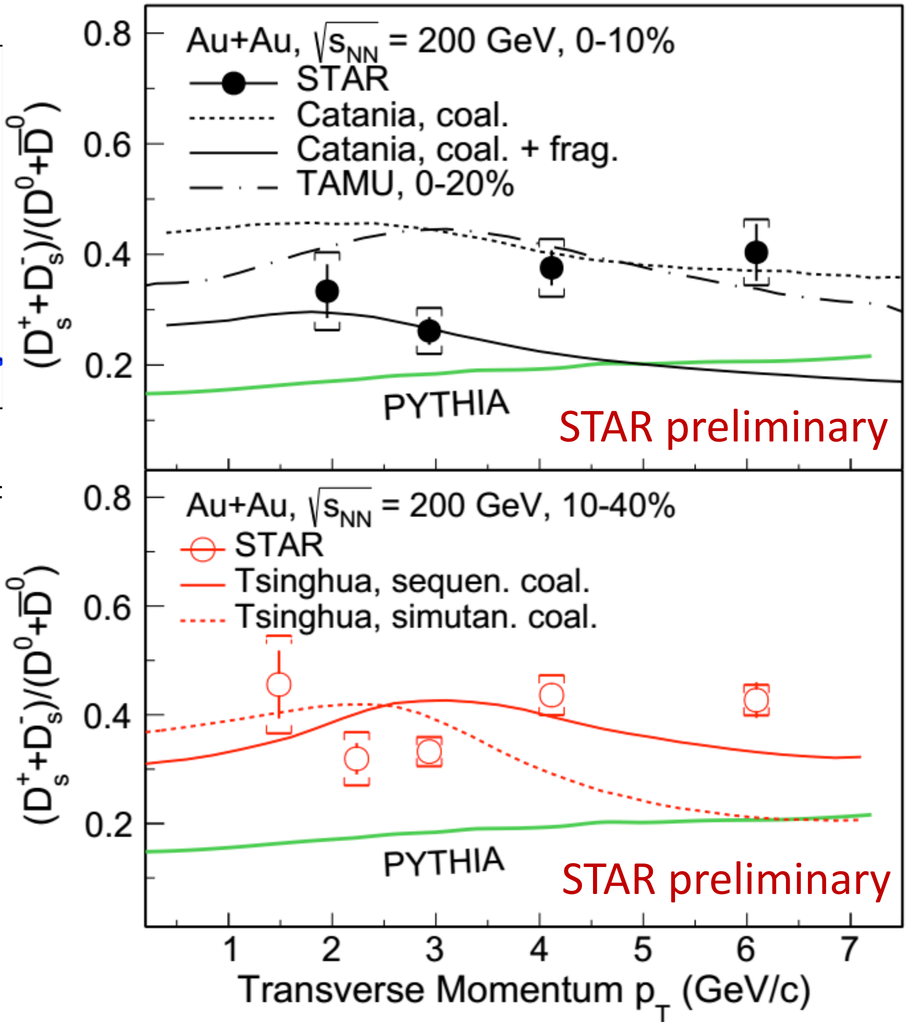
- strong enhancement observed in central Au+Au collisions relative to PYTHIA
- qualitatively described by model calculations incorporating strangeness enhancement and (sequential) coalescence hadronization of charm quarks
- data suggest important role of coalescence in charm quark hadronization at RHIC energy.

BDT method, data 2014+2016

Significance = 45



$D_S^\pm \longrightarrow \phi\ (\longrightarrow K^+ + K^-) + \pi^\pm$



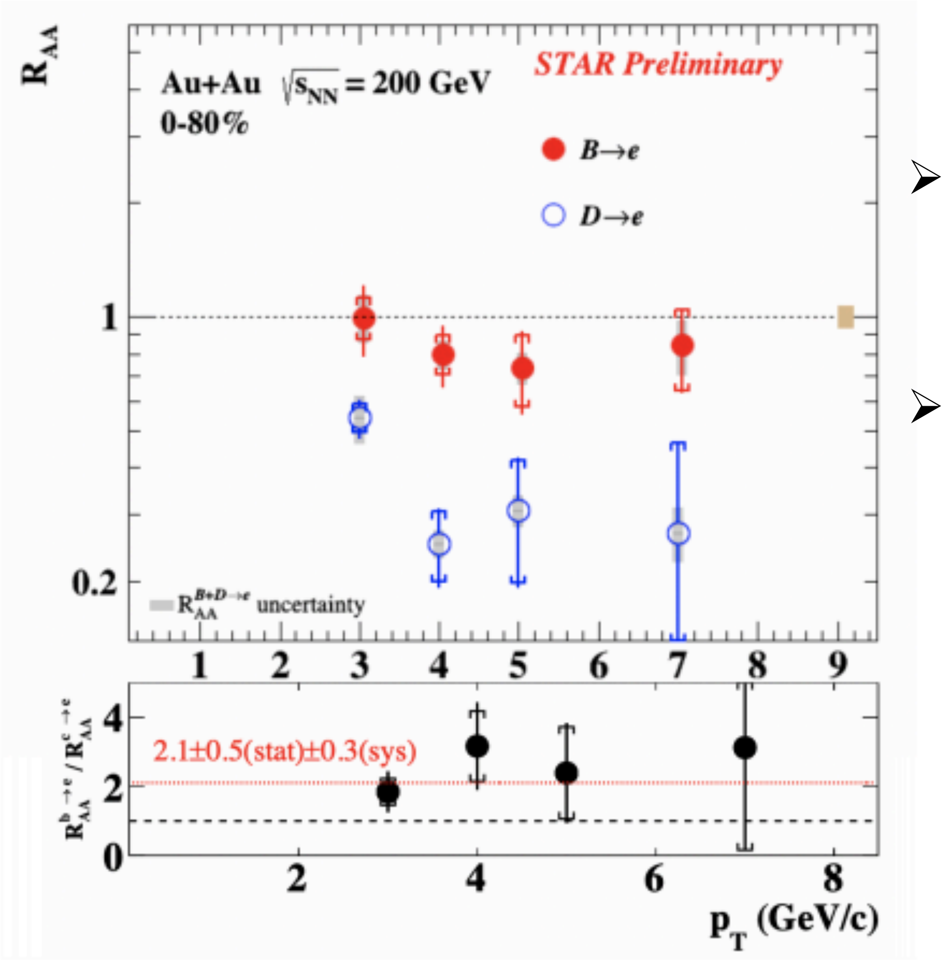
Model calculations:

Catania: *S. Plumari, V. Minissale V, S.K. Das et al., EPJ C78 (2018) 348*

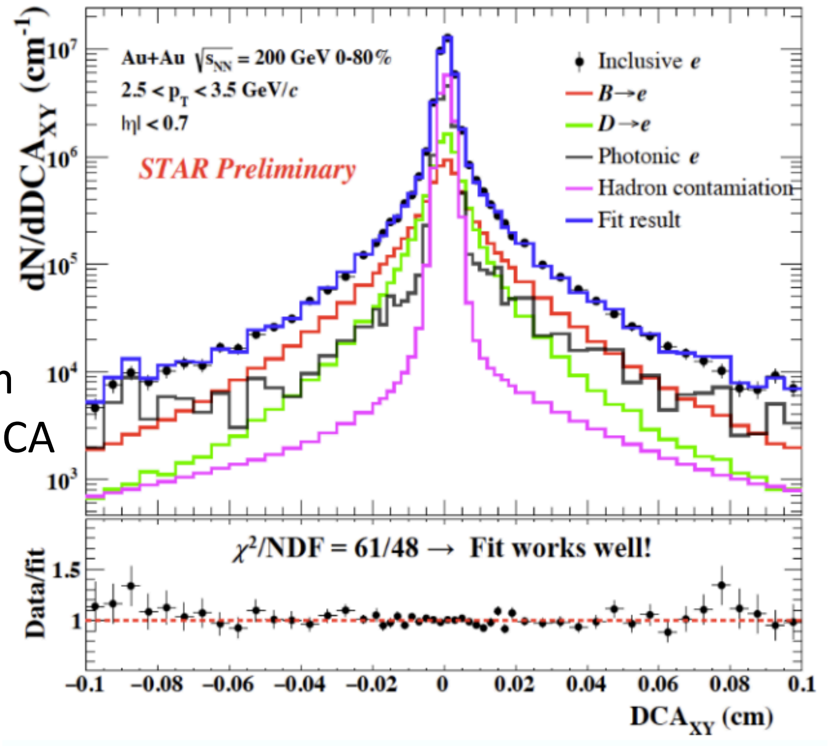
TAMU: *M. He, R. Rapp, in preparation*

Tsinghua: *J. Zhao, S. Shi, N. Xu, P. Zhuang, arXiv:1805.10858.*

Charm to Bottom via Single HFE

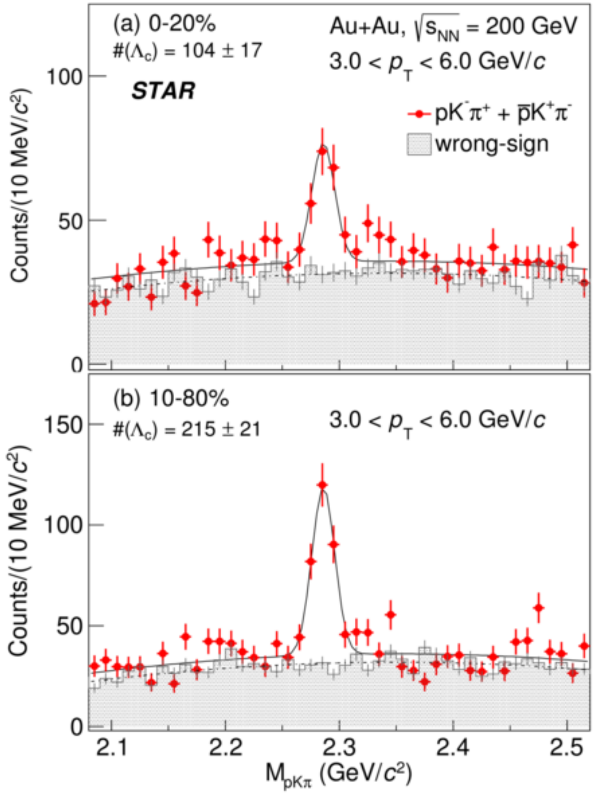


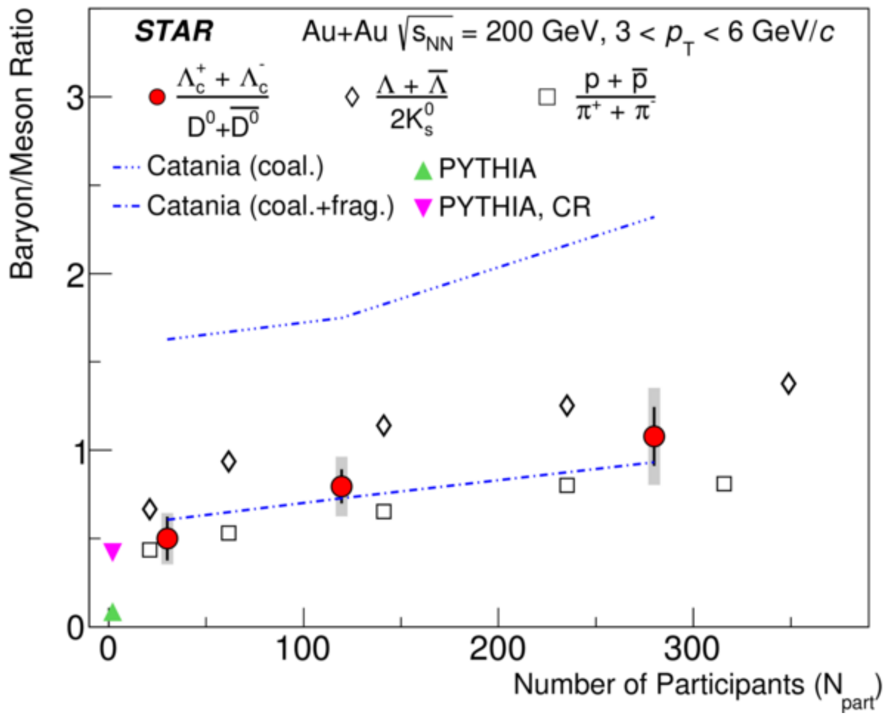
- ➢ It's been established that charm still interacts strongly with the medium, against early predictions – do we still expect a mass hierarchy with bottom?
- ➢ Using HFE, separate contributions from D→e and B→e using template fits to DCA distribution.



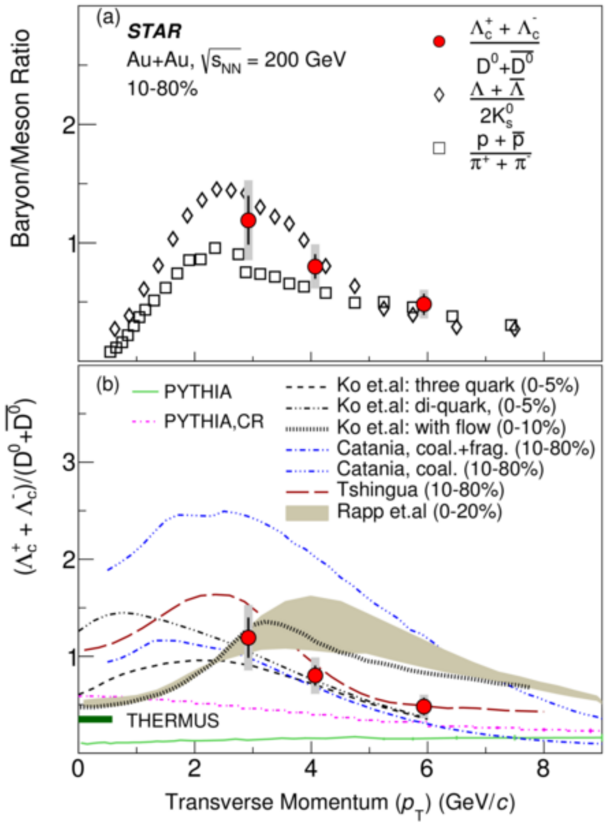
- ➢ Indication of higher R_{AA} for B→e compared to D→e (2σ significance): consistent with $\Delta E_c > \Delta E_b$
- ➢ Better precision measurements on the way with combined 2014+2016 datasets!

Λ_c and heavy quark hadronization





STAR, arXiv:1910.14628



Supervised machine learning TMVA BDT analysis used to improve signal extraction.

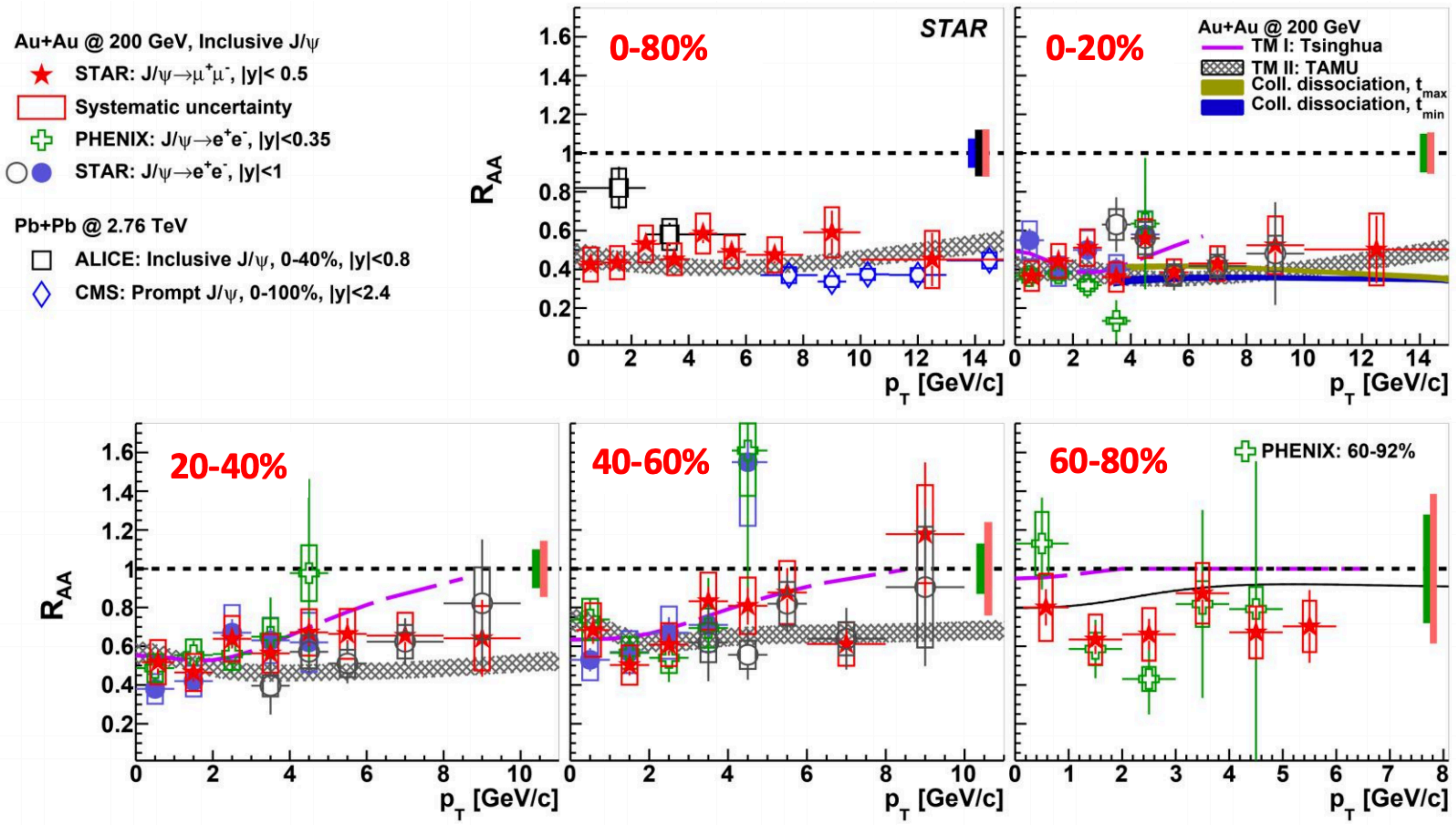
- Strong enhancement of Λ_c/D^0 production in Au+Au collisions compared to PYTHIA with/without color-reconnection (CR).
- Data suggest coalescence hadronization of charm quarks in QGP at intermediate p_T (2-6 GeV/c) similar to light-flavor quarks.

Model calculations:
Ko: *PRC 79, 044905 (2009), arXiv:1905.09774*
Catania: *EPJ C78 (2018) 348*
Tshingua: *arXiv:1805.10858*
Rapp: *arXiv:1910.14628*

Heavy Quarkonia in STAR

J/ψ Suppression in Au+Au Collisions

STAR, PLB 797 (2019) 134917

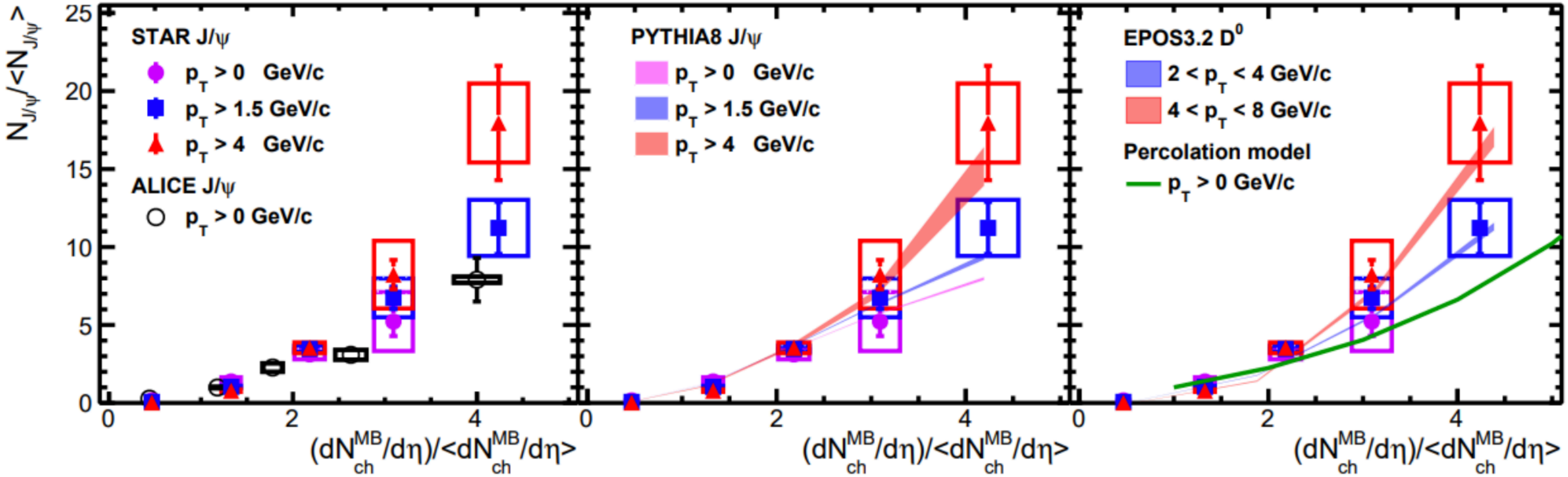


First final results from MTD in Au+Au collisions

- In more central collisions (0-40%), suppression is roughly constant with both centrality and p_T.
- Different effects at play
  - Dissociation: decreases with p_T due to formation time.
  - Regeneration at low p_T.
  - Cold nuclear matter effects.

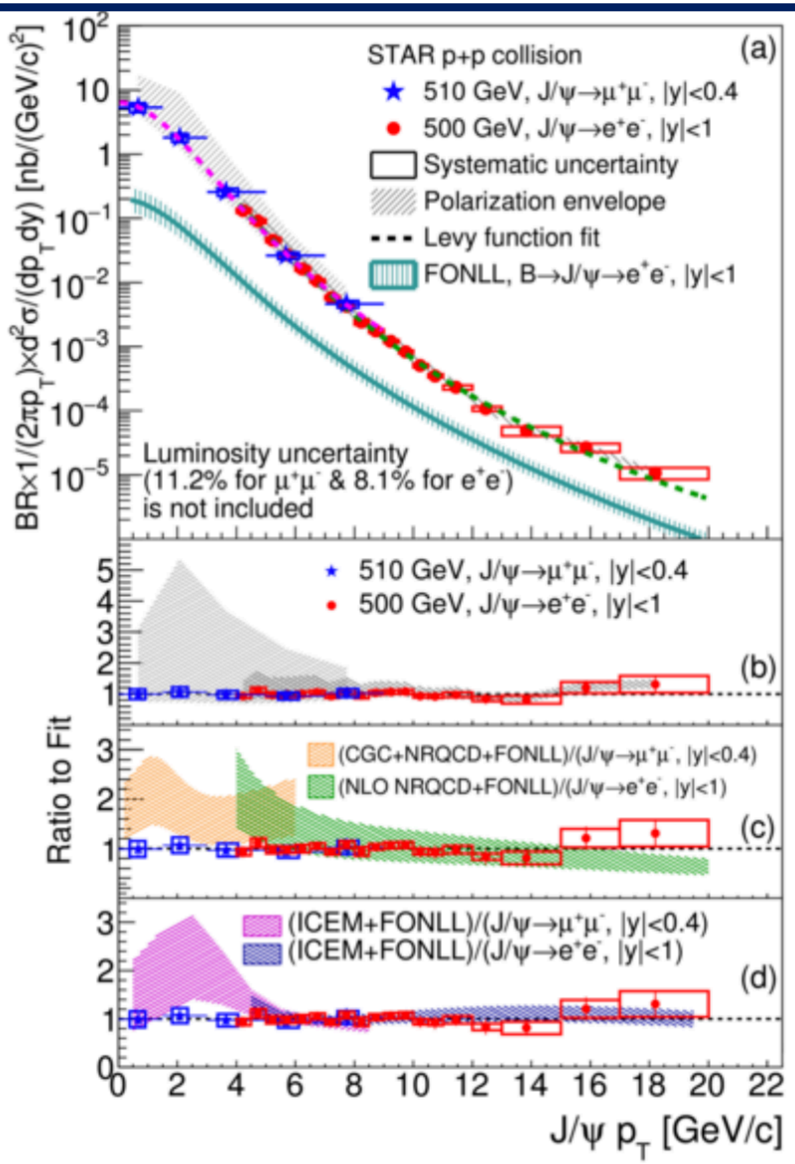
J/ψ Suppression in Au+Au Collisions

STAR, PLB 786 (2018) 87



- J/ψ yield rises faster than linear vs. mid-rapidity activity.
  - Fastest rise at higher-p_T
- Possible reasons why
  - Quarkonia produced in multi-parton interactions (MPI): PYTHIA8 and EPOS
  - String percolation
  - Color glass condensate (CGC)/saturation.

J/ψ Cross Section in p+p



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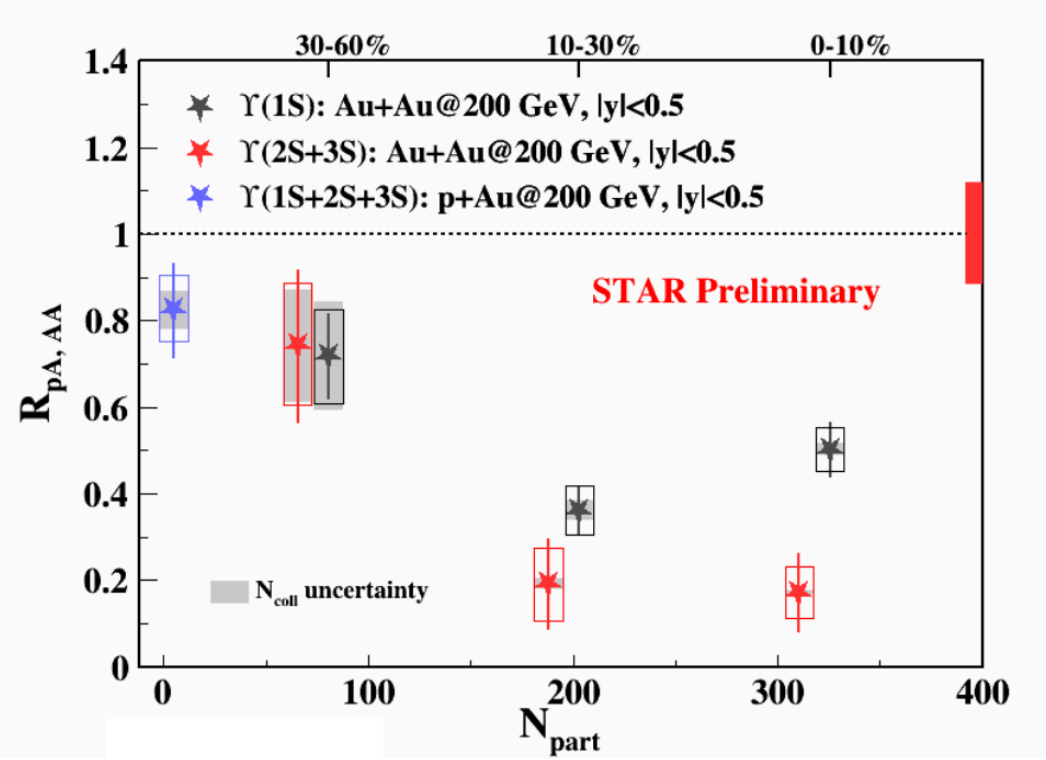
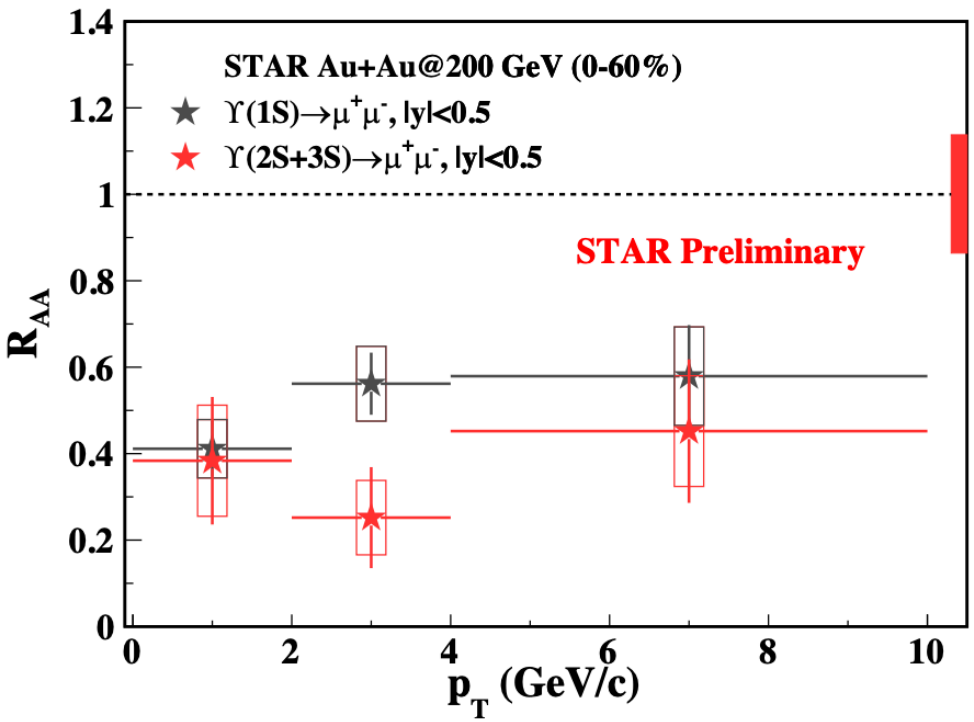
- Inclusive J/ψ cross-section with $\mu^{+}\mu^{-}$ decay channel at low-p_T and $e^{+}e^{-}$ decay channel at high-p_T.
- Several models available
  - Improved color evaporation model (ICEM)
  - NLO non-relativistic QCD (NRQCD) – applicable at high-p_T
  - CGC+NRQCD at low-p_T
- ICEM and NRQCD calculations are compared to data with b-hadron feed-down contributions from FONLL added
  - Low-p_T: ICEM and CGC+NRQCD over-predict data assuming zero polarization.
  - High-p_T: ICEM and NLO NRQCD are consistent with data.

Υ(1S) & Υ(2S+3S)





- Combined results from e^+e^- and $\mu^+\mu^-$ decay channels.
- More suppression seen in more central events.
- No significant dependence on p_T.
- Υ(2S+3S) more suppressed than Υ(1S) in more central collisions.
    - Consistent with sequential melting.

Conclusions & Takeaways

STAR has a robust physics program for both jets and heavy-flavor.
There are things I did not have time to cover!

- Jets
  - Differential di-jet imbalance
  - Semi-inclusive spectra
  - Event plane dependence
  - Flavor dependence
  - substructure

Jet energy loss, partonic energy loss, flavor dependent energy loss.

- Open heavy-flavor
  - D-meson spectra and R_{AA}
  - HFE charm vs. bottom
  - Charm anisotropic flow
  - Charm directed flow
  - Charm baryon spectra

Charm suppression, mass hierarchy (bottom and charm), bulk charm properties, hadronization

- Heavy quarkonia
  - J/ψ R_{AA}
  - Υ(1S) vs. Υ(2S+3S)
  - J/ψ cross section

J/ψ suppression, sequential melting

Stayed tuned for more exciting results from STAR!