Recent Jet and Heavy-Flavor Measurements from STAR

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for the STAR Collaboration

Santa Fe Heavy-Flavor and Jets Workshop
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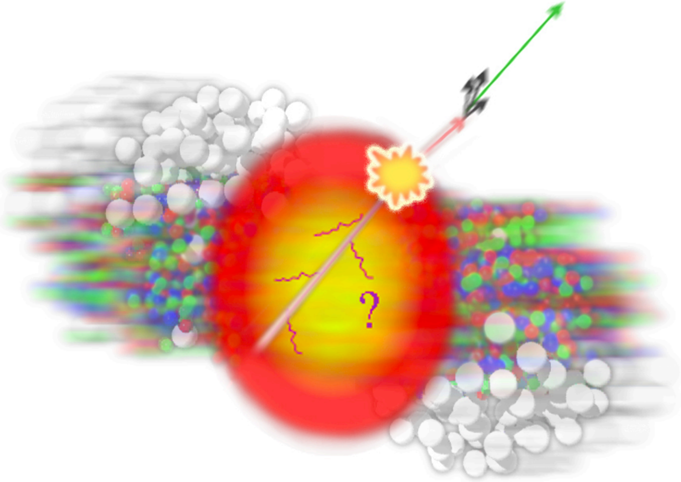
Supported by funding from the U.S. DEPARTMENT OF ENERGY

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.
  - Modification of jet fragmentation.
  - Flavor-dependent energy loss.

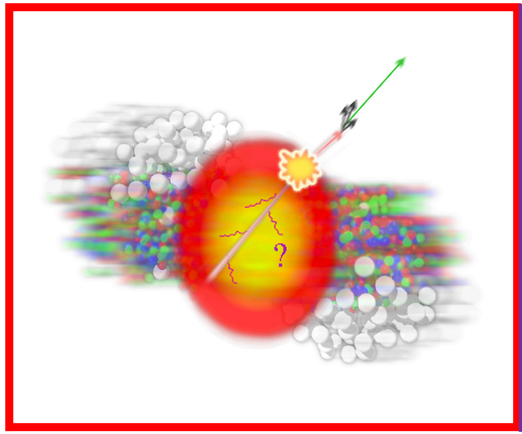


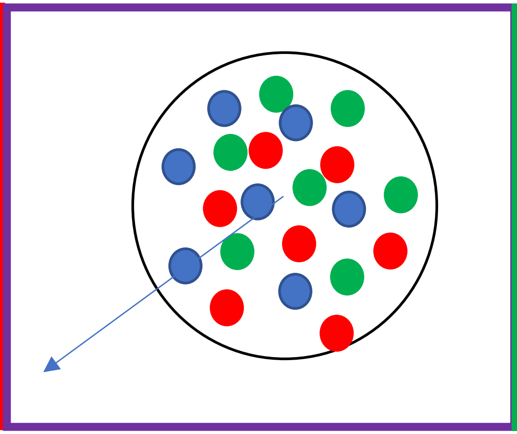
- Jets
  - Di-jet imbalance
  - Semi-inclusive jet spectra
  - Jet fragmentation functions
  - Jet+hadron correlations (jet shape)
  - Angular scale of jets
  - D^0+hadron correlations

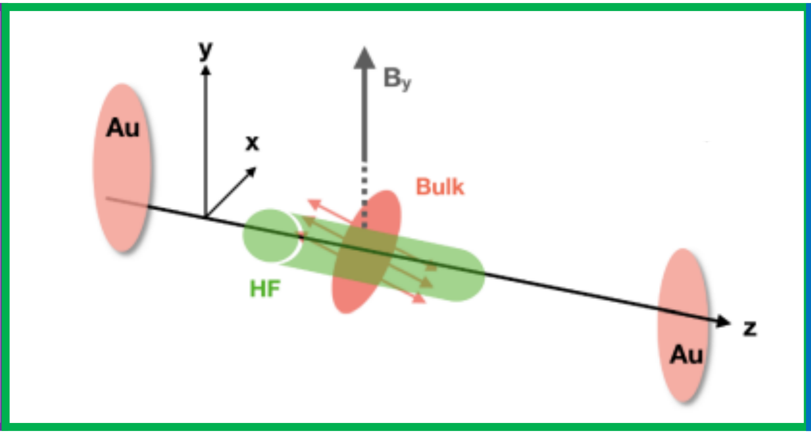
Why Heavy-Flavor and Jets?

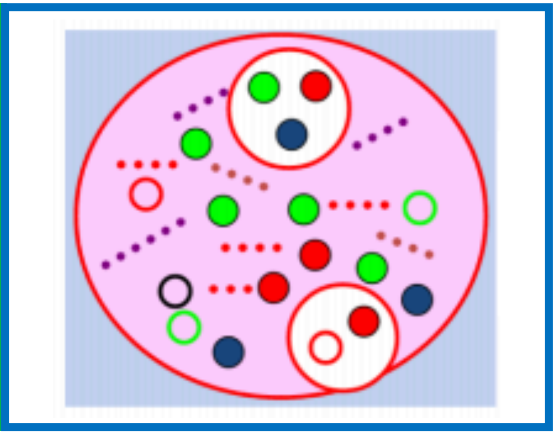
- Formed in early, hard partonic scatterings (calculable in pQCD). → Probe entire evolution of the medium.
  - Partonic energy loss via modification of jets.
  - Modification of jet fragmentation.
  - Flavor-dependent energy loss.
  - Bulk (transport) properties of heavy-quarks.
  - Initial conditions.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

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

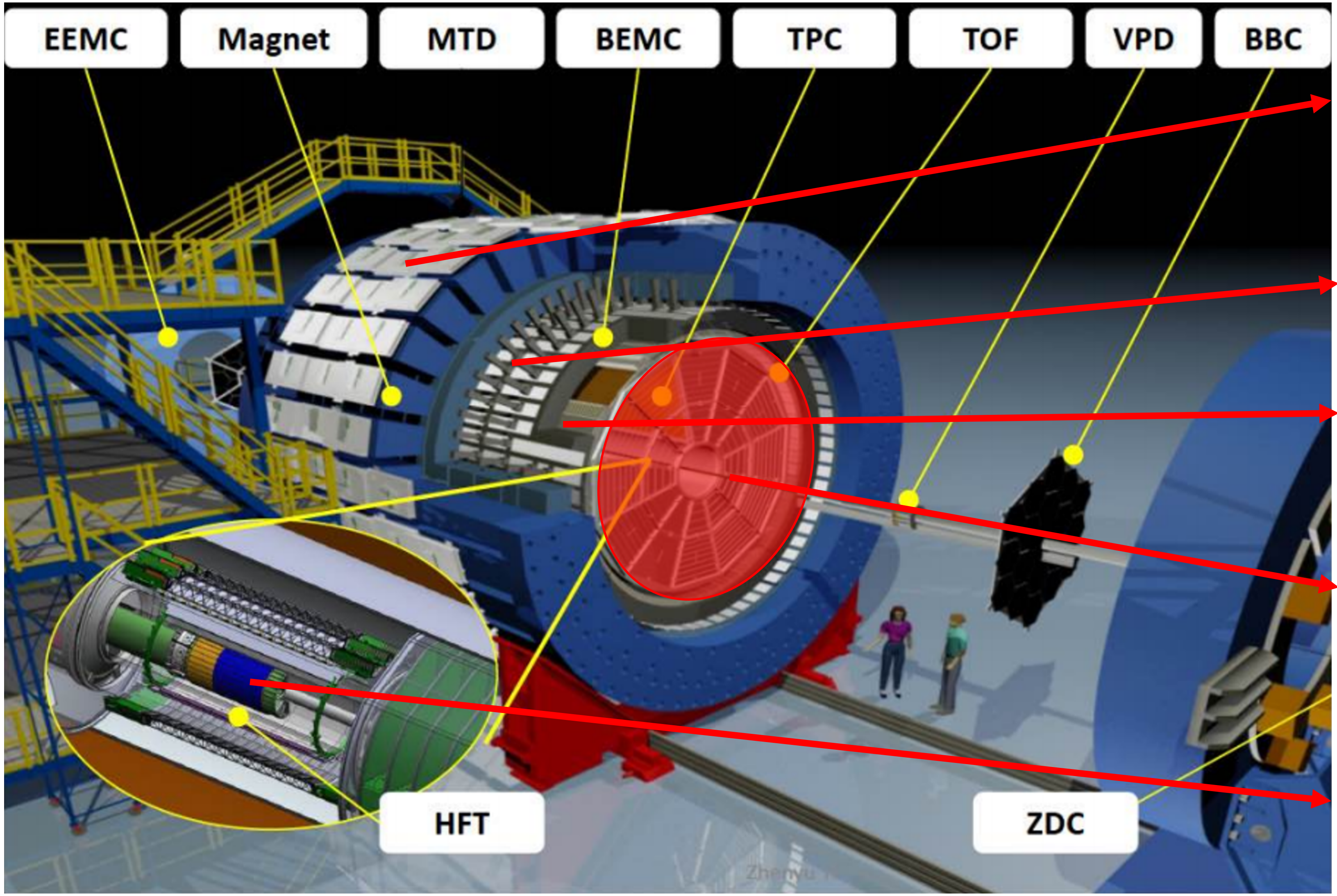








The STAR Detector



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.

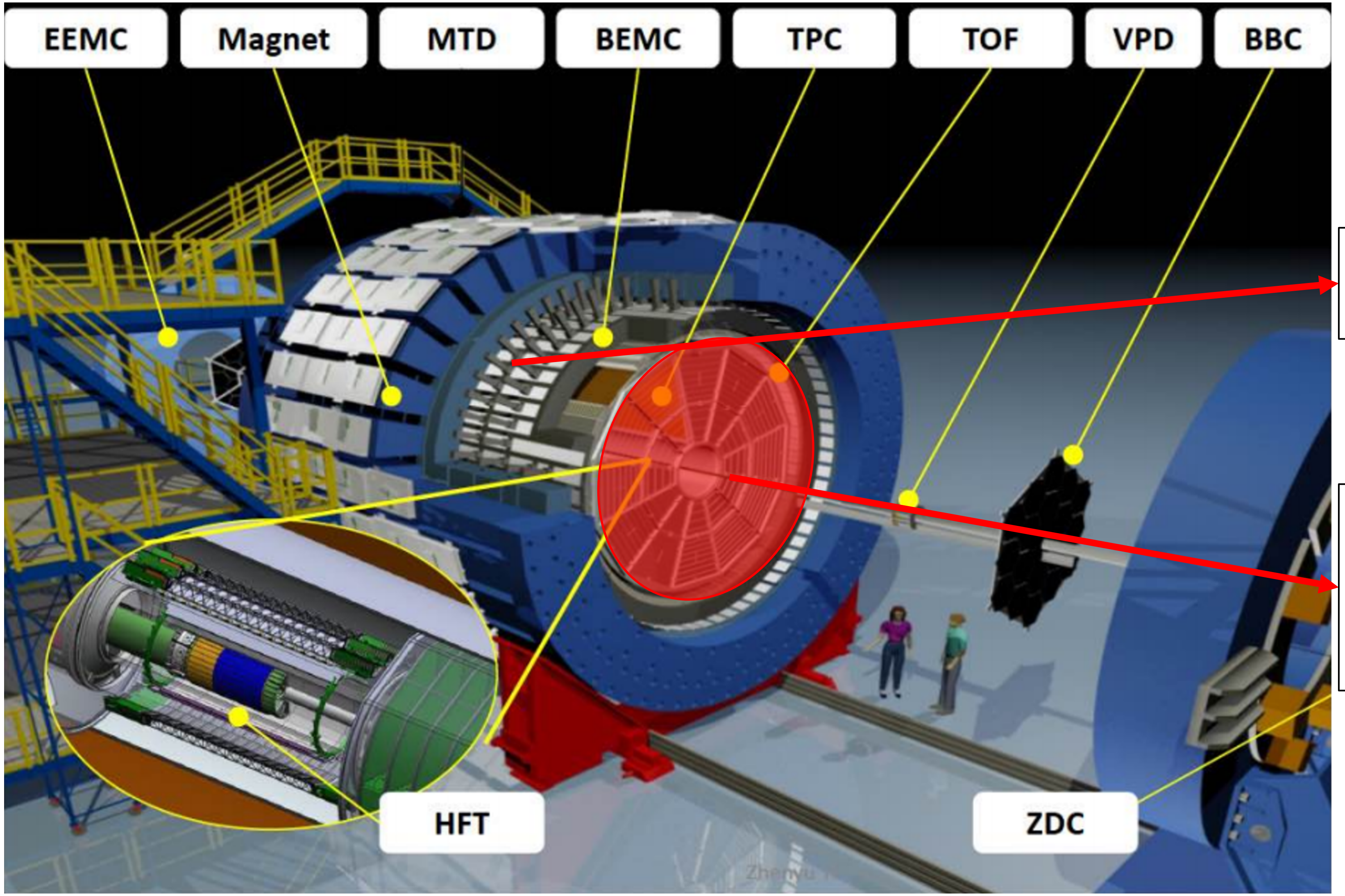
Time Projection Chamber (TPC)

- 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 particles.

Time Projection Chamber (TPC)

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

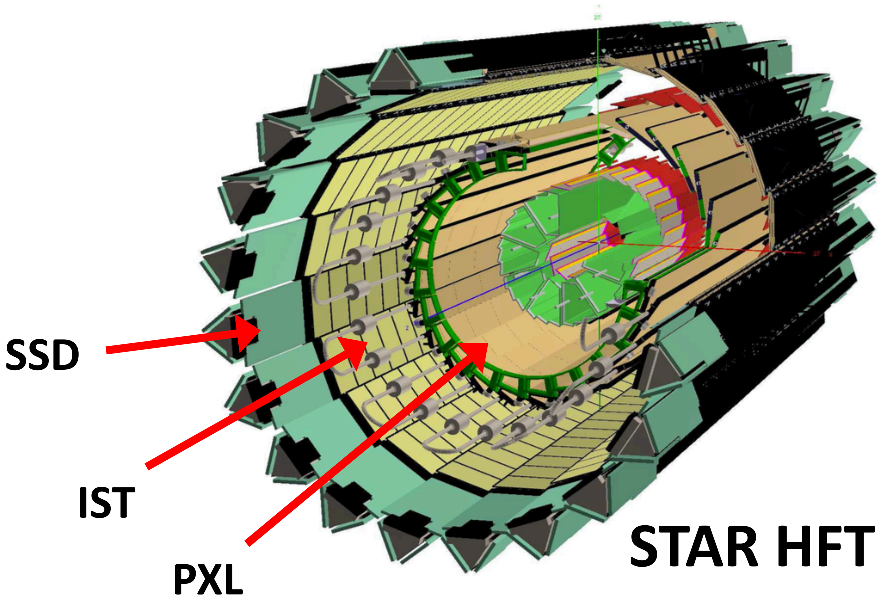
Charged particles.

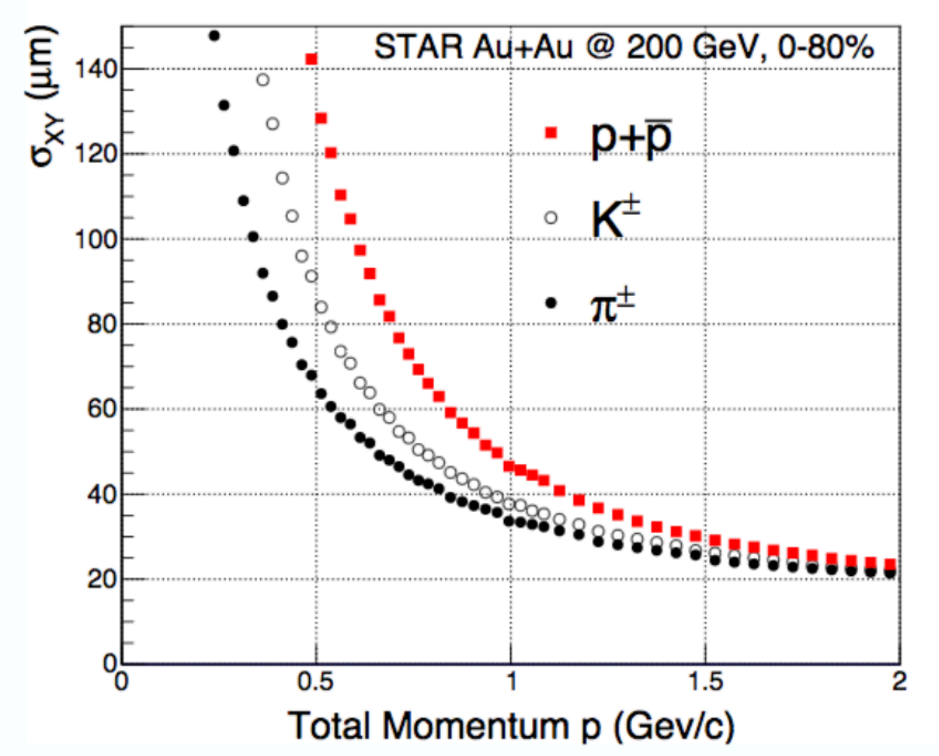
Need combined TPC and BEMC information to reconstruct a full jet.

The STAR Detector

Phys. Rev. Lett. 118 (2017) 212301

Heavy Flavor Tracker





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

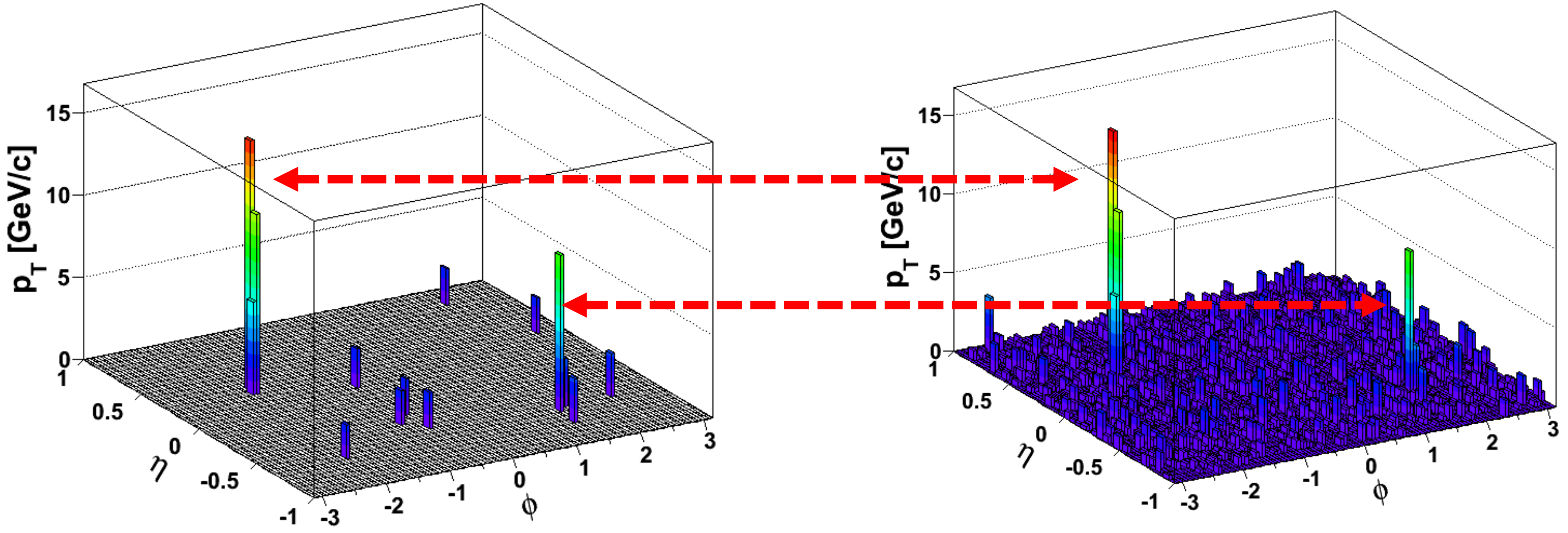
Jets in Heavy-Ion Collisions at STAR

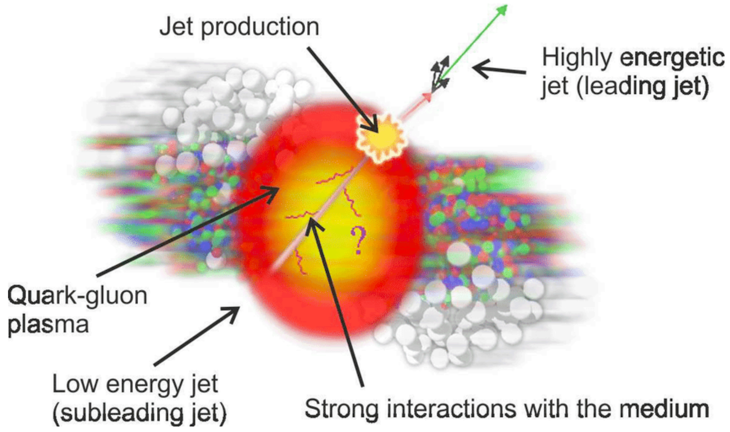
Di-Jet Imbalance

- 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

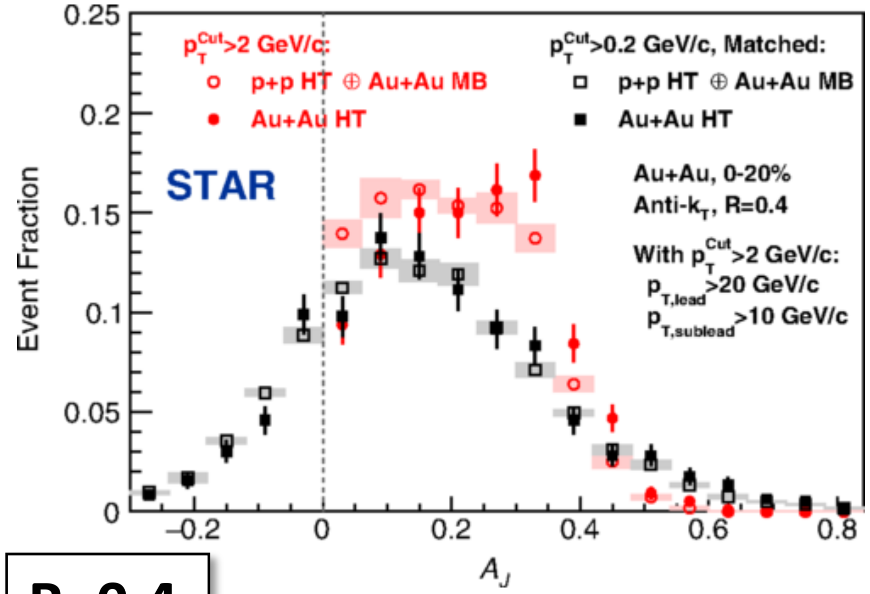
- $A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$
- **Hard-core jet** vs. **Matched jet**



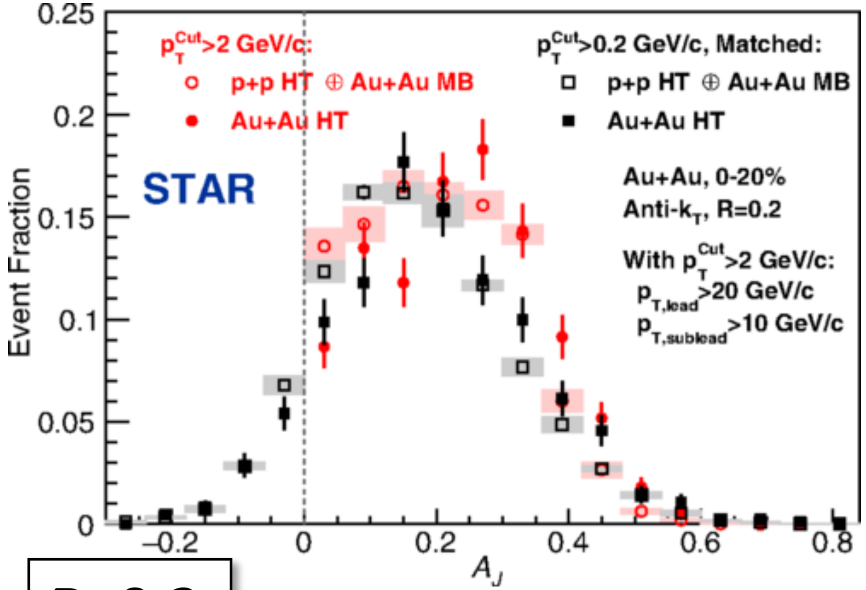


Di-Jet Imbalance

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

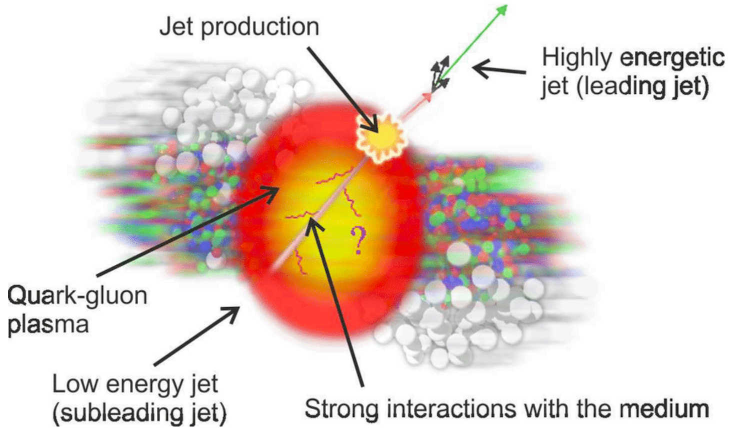


R=0.4



R=0.2

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

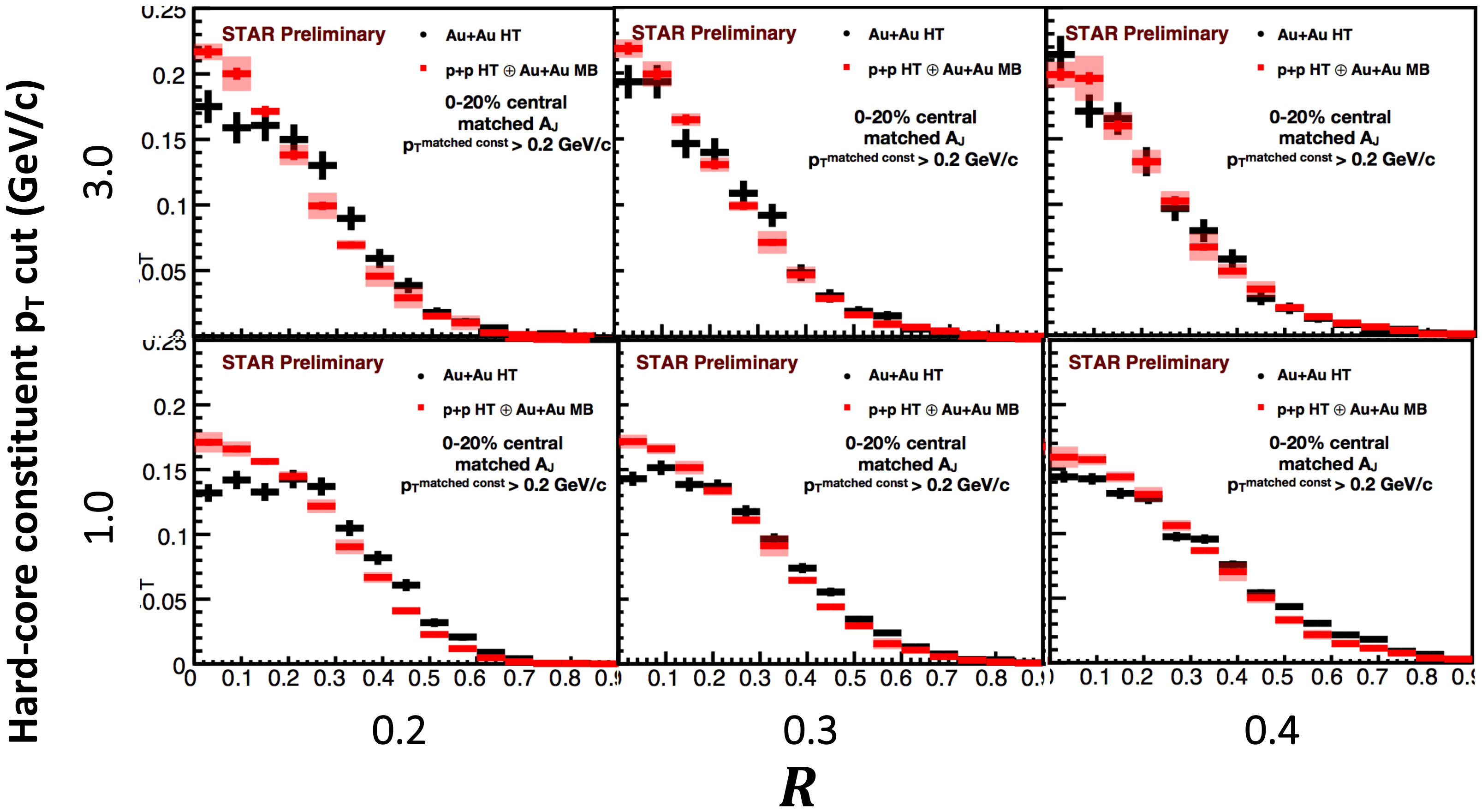


- ➢ For $R = 0.4$ hard-core jet, more di-jet momentum imbalance compared to p+p
  - ➢ Balance recovered when soft constituents are included (matched-jet)
- ➢ For $R = 0.2$, balance no longer recovered in matched-jet

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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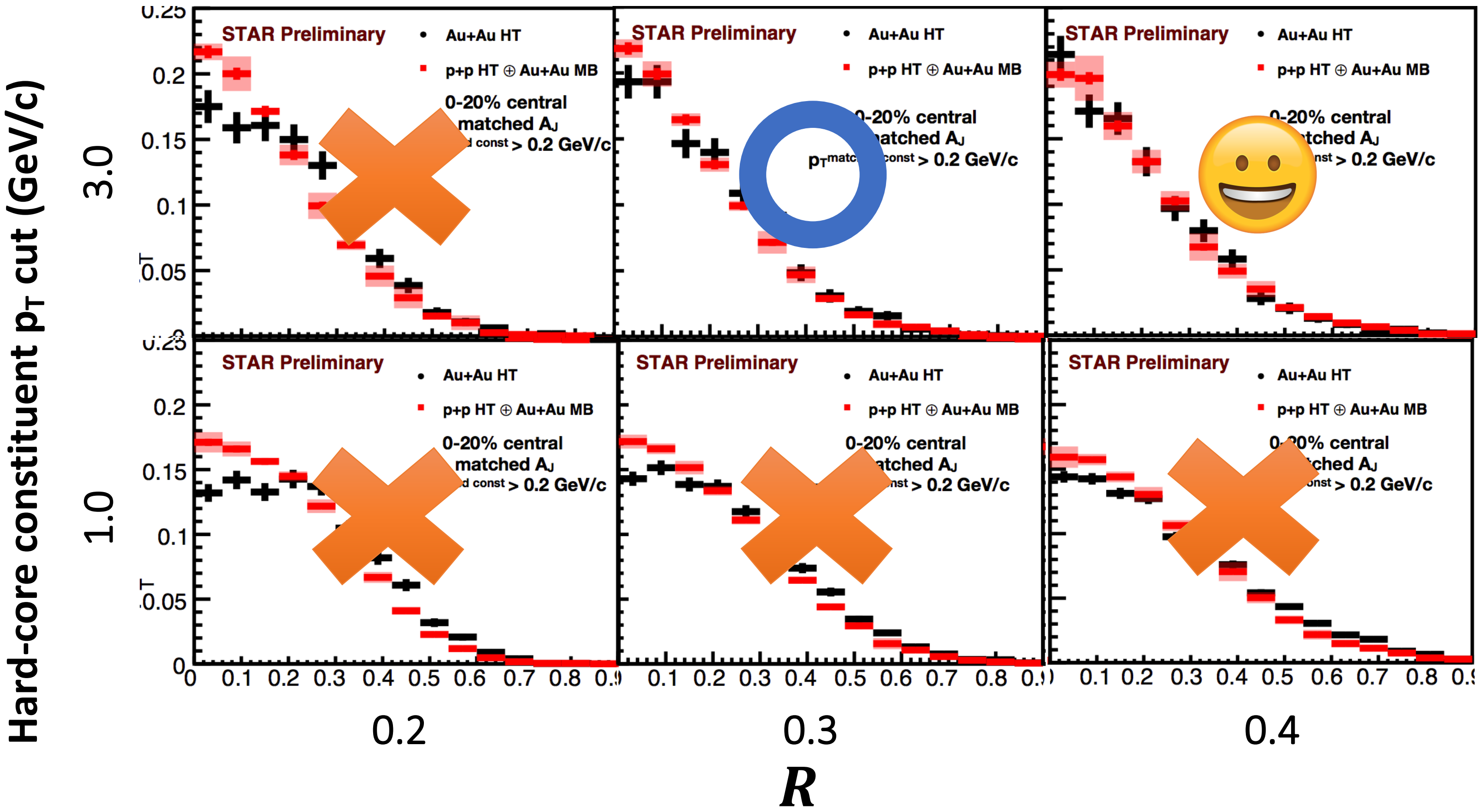


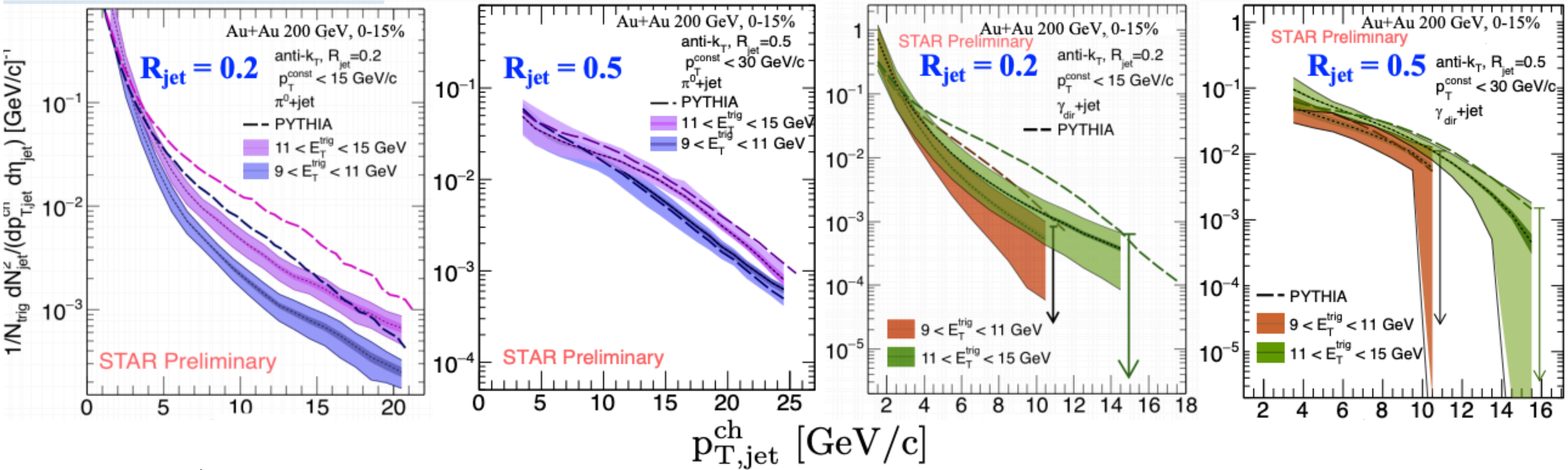
- Matched jet with various hard-core constituent p_T cut and R

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

Semi-Inclusive Spectra

Comparison of correlations of a neutral hadron (π^0) and a γ with jets provides quantitative understanding of parton energy loss in the QCD medium.

π^0-Triggered Recoil Jets **γ-Triggered Recoil Jets**



- A clear difference between recoil-jet spectra for different trigger E_T: 9-11 GeV and 11-15 GeV.
- γdir+jet: downward arrow represents upper limit in the yield at: $p_{T,jet\ ch}$ = 11 GeV/c for 9-11 GeV, $p_{T,jet\ ch}$ = 15 GeV/c for 11-15 GeV.

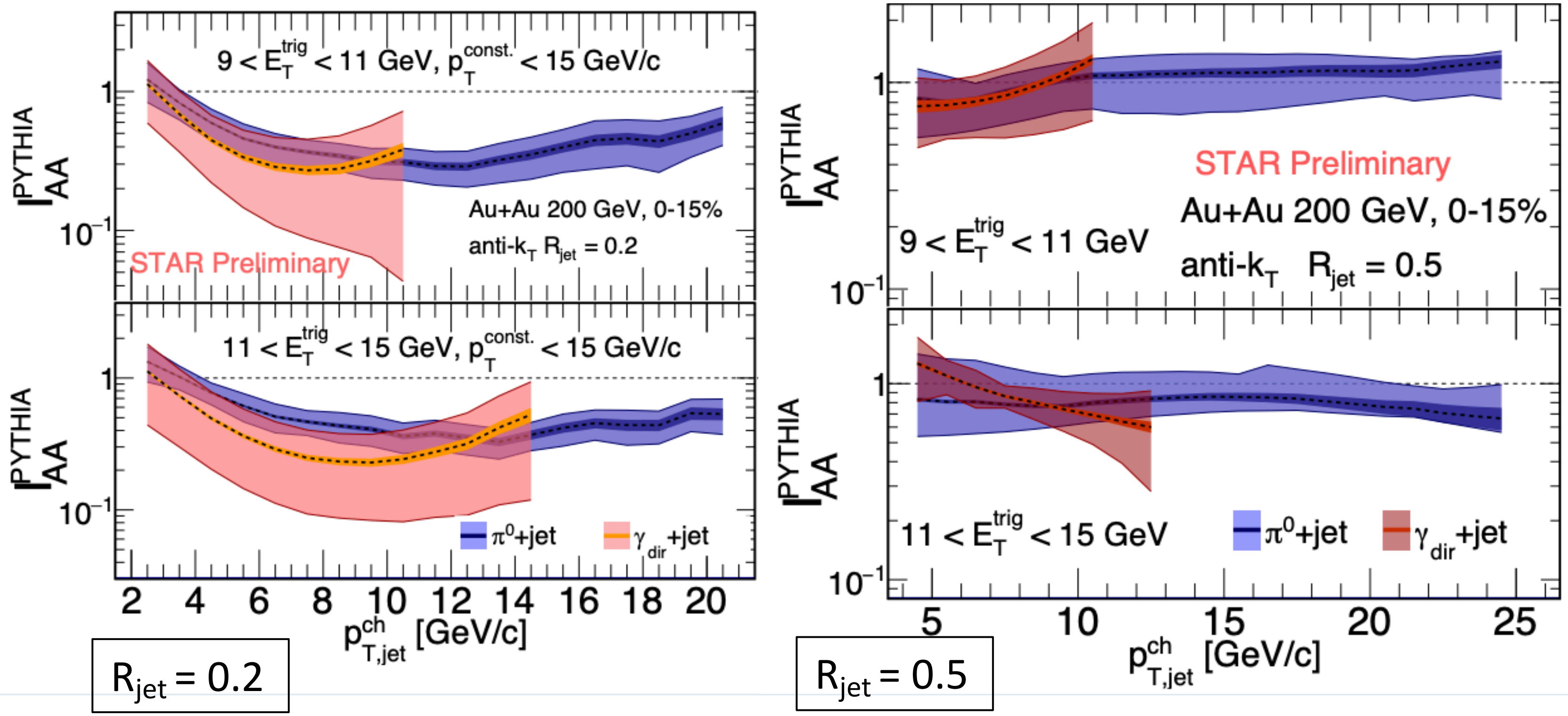
Semi-Inclusive Spectra

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

$$I_{AA}(p^{ch}_{T,jet}) = \frac{Y(p^{ch}_{T,jet})^{Au+Au}}{Y(p^{ch}_{T,jet})^{p+p}}$$

$Y(p^{ch}_{T,jet})$ are the jet per-trigger yields in Au+Au and p+p (with PYTHIA8 used for p+p).

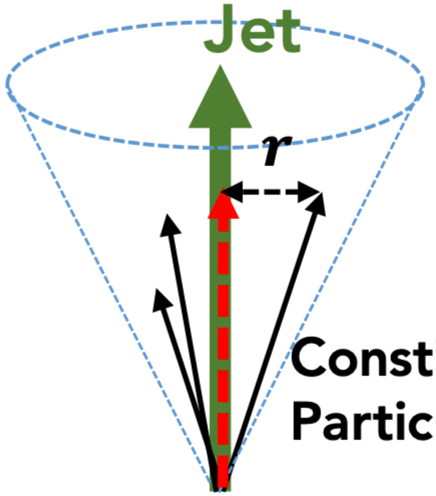
γ_{dir}+jet vs. π^0+jet: Recoil jet suppression for two jet radii



- Recoil jet with a jet resolution parameter of $R_{jet} = 0.2$ shows strong suppression, whereas a negligible suppression is observed for $R_{jet} = 0.5$, within uncertainties.
- I_{AA}^{PYTHIA} values are comparable between the two E_T trig bins.
- The same level of suppression is seen between γ_{dir}+jet and π^0+jet for different E_T trig bins and the two jet resolution parameters within uncertainties.

Jet Fragmentation Functions

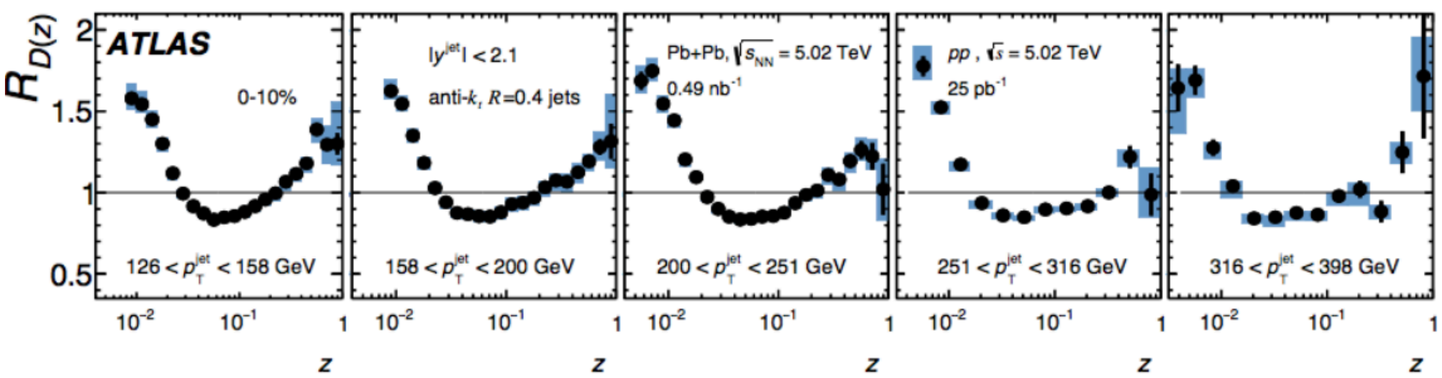
Jet Fragmentation Functions



Constituent Particle

$$z = \frac{p_{\mathrm{T,track}} \cos(r)}{p_{\mathrm{T,jet}}}$$

ATLAS, Phys. Rev. C 98 (2018) 024908

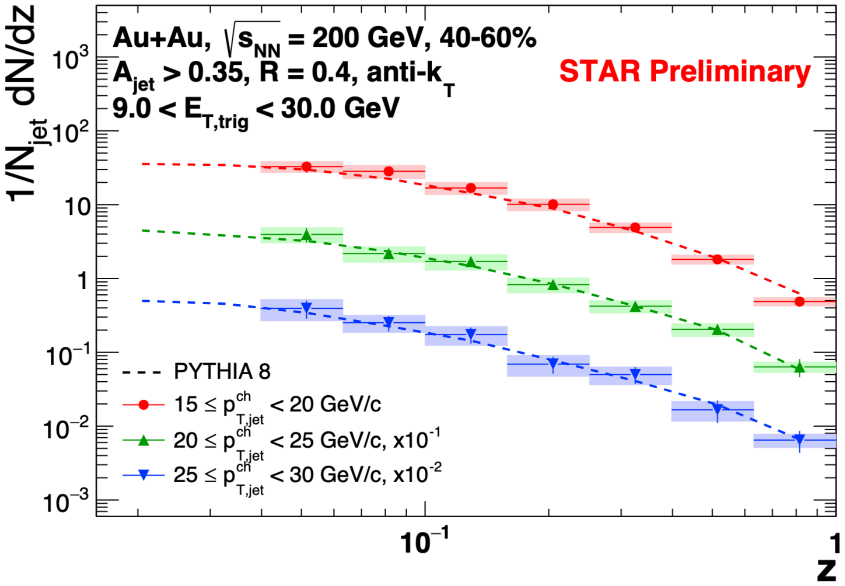


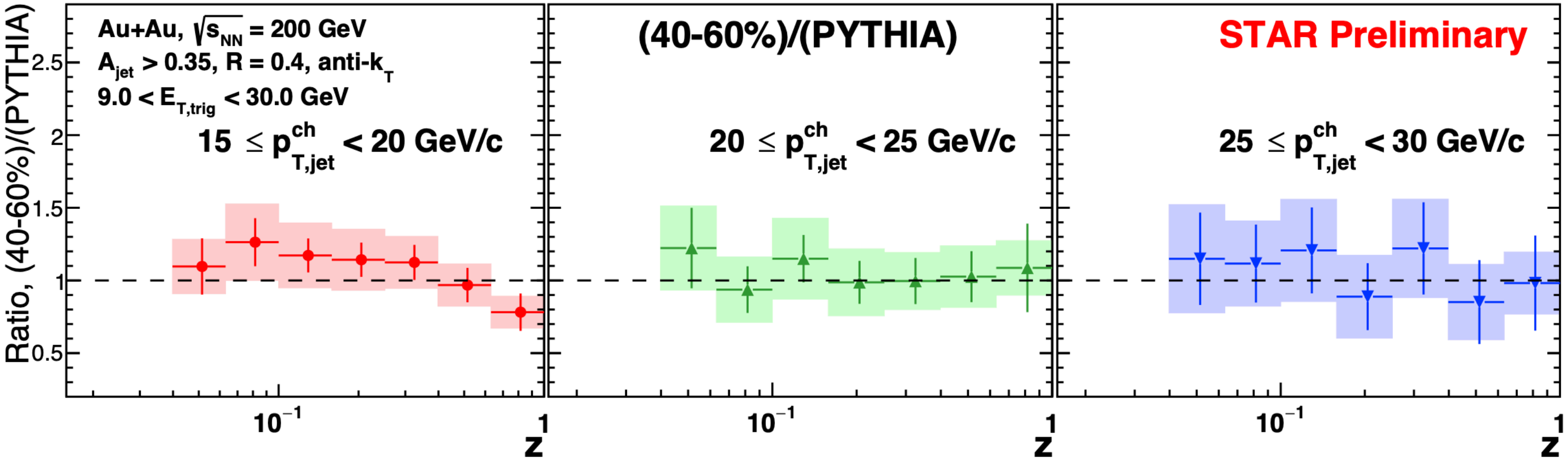
Pb+Pb/*p*+*p* @5.02 TeV

- **Fragmentation function**[1], $\frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N}{\mathrm{d}z}$
- Distribution of longitudinal momentum fraction of particles with respect to the jet

Not previously measured at RHIC energy!

Jet Fragmentation Functions





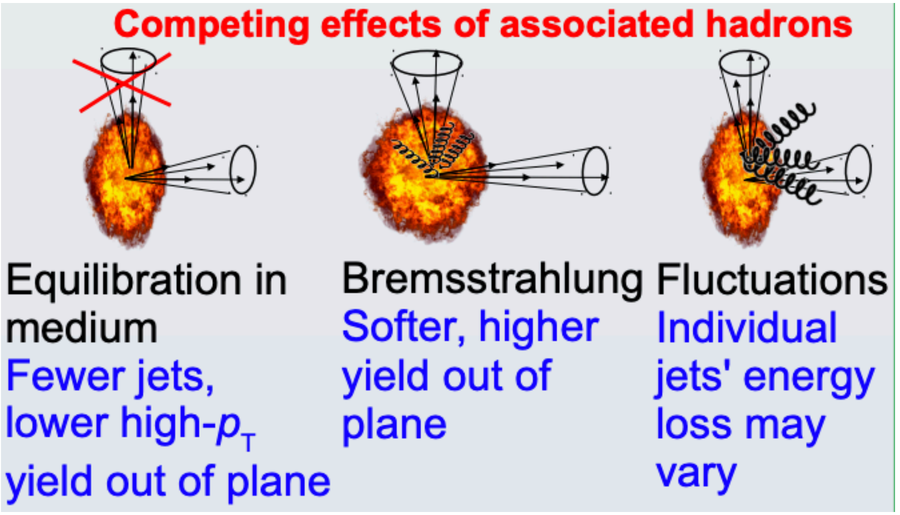
Au+Au 40-60%/PYTHIA8

- Jet fragmentation functions for the 40-60% centrality class for three $p_{T,jet}$ ranges.
- PYTHIA8 is tuned using LHC data – needs further tuning for RHIC energy.
- Ratios consistent with 1 for all p_T ranges.
  - 40-60% too peripheral?
- Results for p+p and more-central events + higher statistics in progress!

Jet-Hadron Correlations

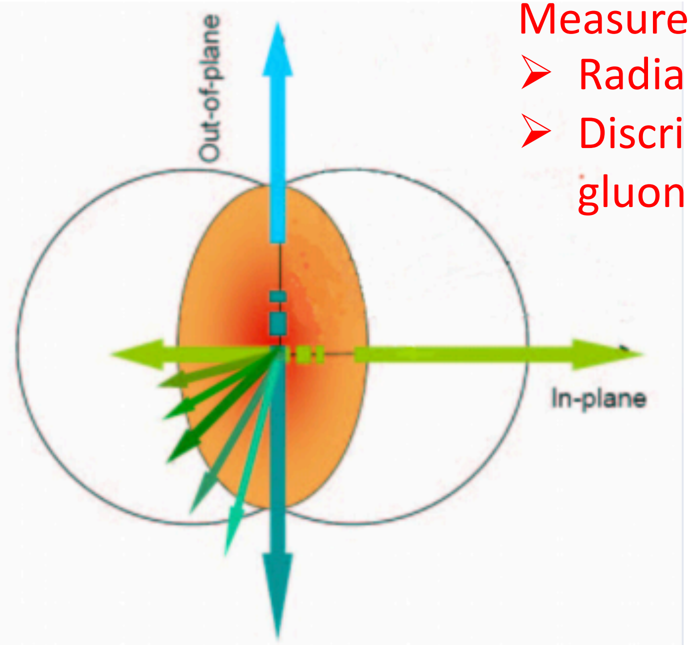
Event-plane (EP) Dependent Jet-hadron Correlations

- Previous jet-hadron correlations by STAR (Phys. Rev. Lett. 112 (2014) 122301)
- Can control the path-length of jet quenching by measuring as a function of centrality and event-plane angle.
  - Average path length out-of-plane > average path length in-plane



Competing effects of associated hadrons

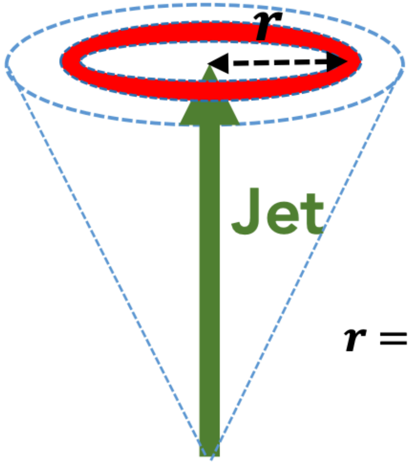
Equilibration in medium	Bremsstrahlung	Fluctuations
Fewer jets, lower high-p_T yield out of plane	Softer, higher yield out of plane	Individual jets' energy loss may vary



Measure the EP dependence as a function of jet shape.

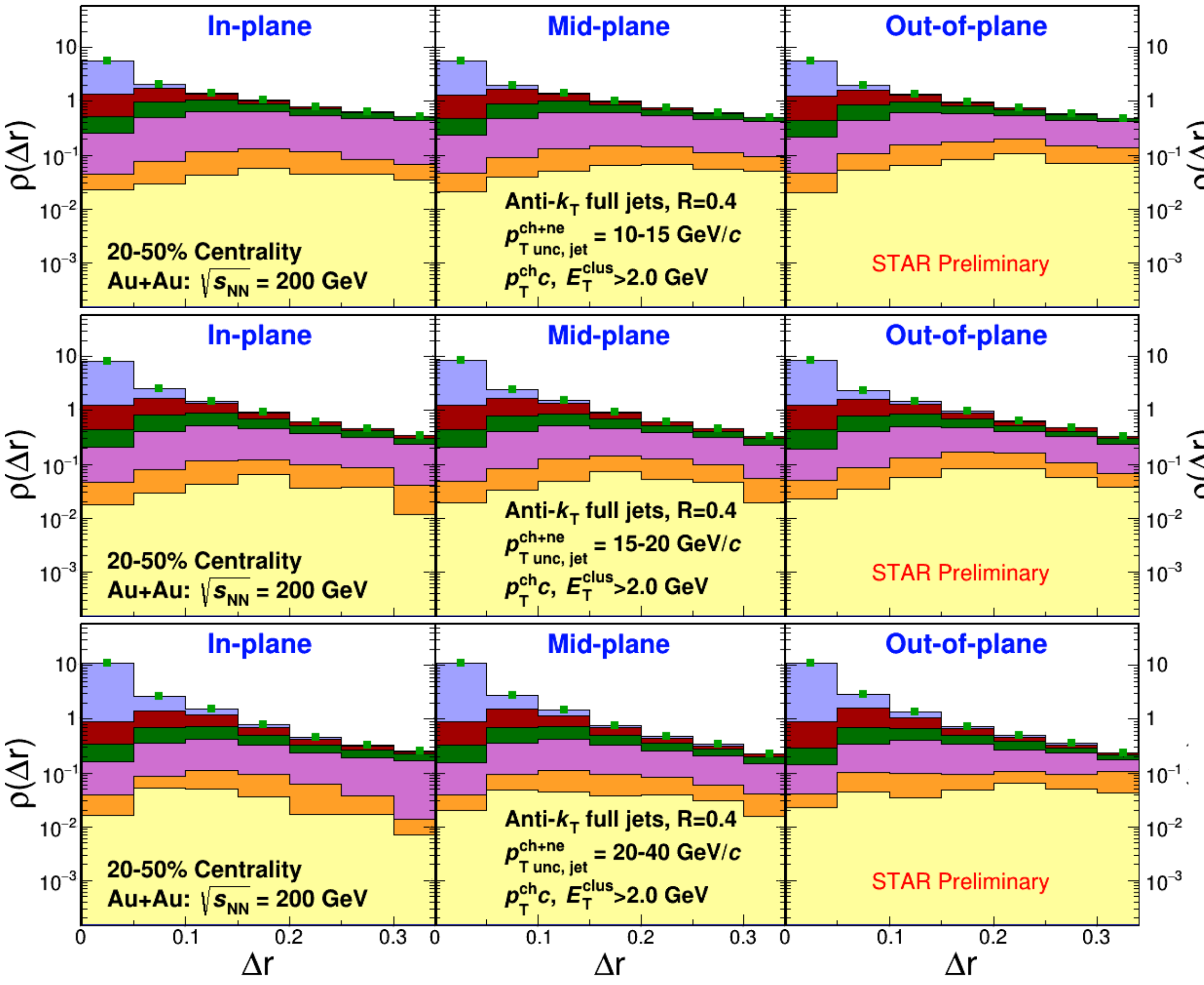
- Radial momentum distribution of the constituents.
- Discriminate models for quenching and quark vs. gluon energy loss.

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(r-\delta r/2,\,r+\delta r/2)} p_{\text{T,track}}}{p_{\text{T,jet}}}$$



$$r = \sqrt{(\Delta\varphi)^2+(\Delta\eta)^2}$$

Jet-Hadron Correlations

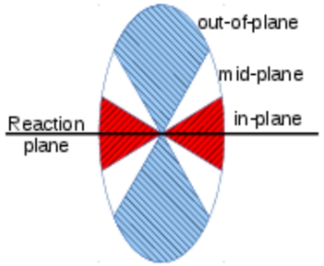


🟨 $1.0 < p_T^{\mathrm{assoc}} < 1.5$ GeV/c
🟧 $1.5 < p_T^{\mathrm{assoc}} < 2.0$ GeV/c
🟪 $2.0 < p_T^{\mathrm{assoc}} < 3.0$ GeV/c
🟩 $3.0 < p_T^{\mathrm{assoc}} < 4.0$ GeV/c
🟥 $4.0 < p_T^{\mathrm{assoc}} < 6.0$ GeV/c
🟦 $p_T^{\mathrm{assoc}} > 6.0+$ GeV/c
■ Total: $p_T^{\mathrm{assoc}} > 1.0+$ GeV/c

Leading Jets
EP resolution corr.

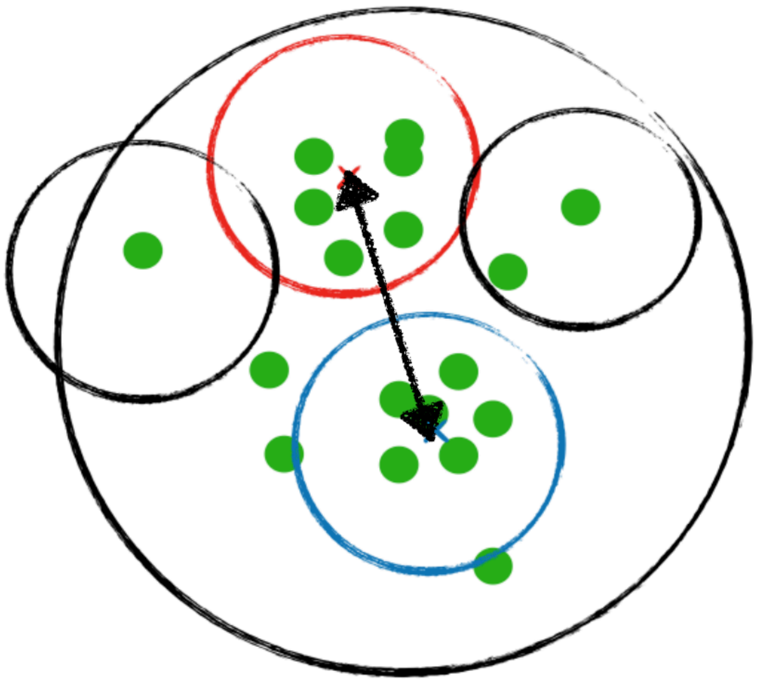
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}}\frac{\sum_{\mathrm{track}\in(r-\delta r/2,\,r+\delta r/2)} p_{\mathrm{T,track}}}{p_{\mathrm{T,jet}}}$$

- Low-p_T (1.0-2.0 Ge/c) associated hadrons are dominated by background at $\Delta r > 0.1$.
- high-p_T hadrons are located closer to jet core.
- Below 2 GeV/c, EP ordering: out > mid > in-plane.
  - out-of-plane jets have more low-p_T hadrons than in-plane jets.
- Above 2 GeV/c, the distributions are consistent as a function of EP.
- Jets at higher p_T are more collimated.

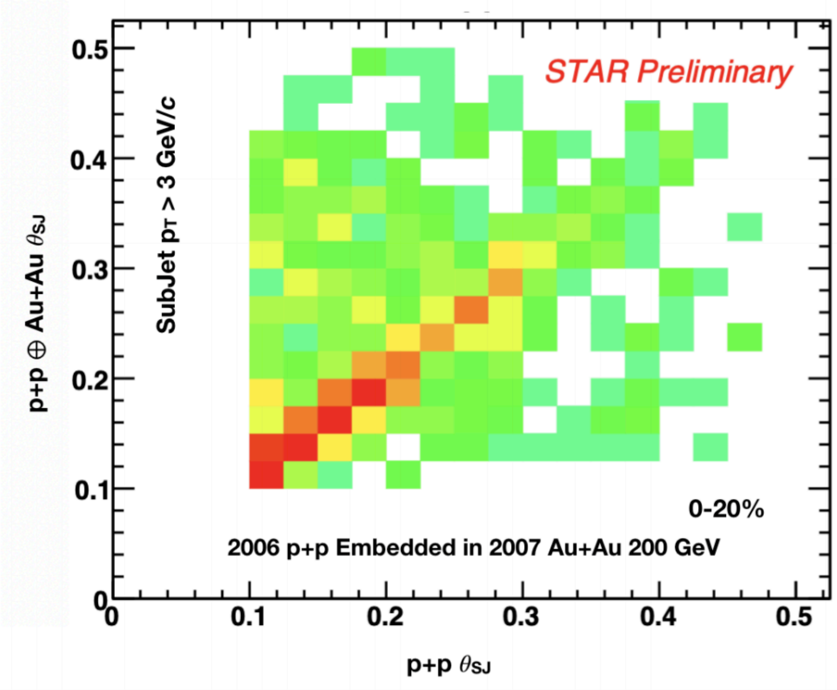


Jet Substructure in Au+Au

Need observables that are robust to underlying event background.



Apolinario et al. 1710.07607



anti-k_T R=0.4, 20 < p_T < 30 GeV/c
Constituent-Subtracted Jets

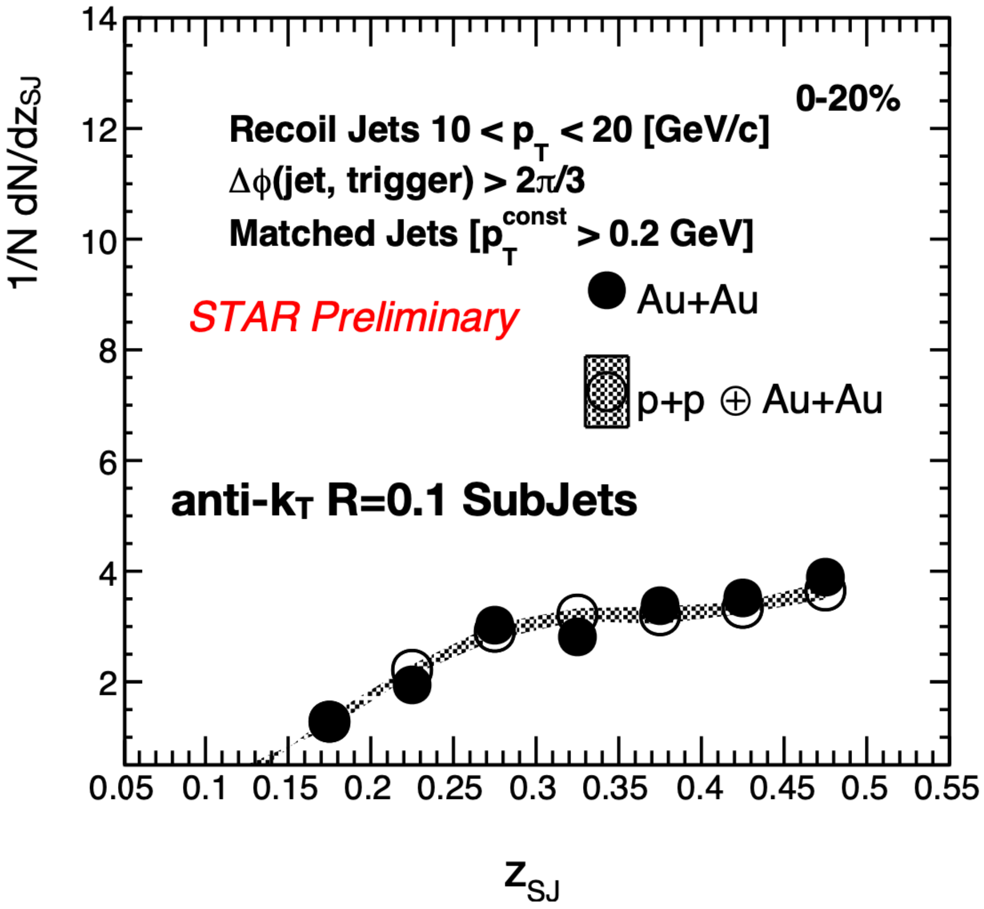
Berta, P et al. JHEP 06 (2014) 092

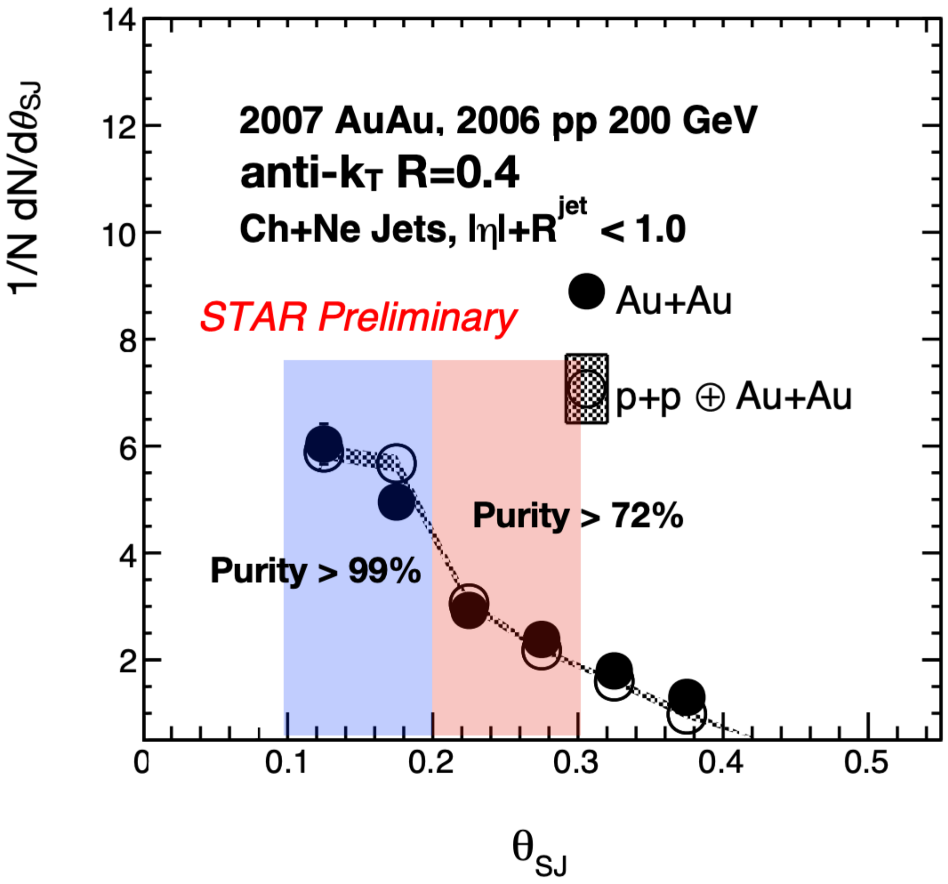
θ_{SJ} (w/ R=0.1 subjets) less sensitive Au+Au underlying event

Comparisons between Au+Au and p+p embedded in Au+Au to isolate quenching effects

- **Recluster jet constituents with a smaller radius** - identify regions of jet-like features within the mother jet
- Choose the **leading** and **subleading** Subjets
- z_{SJ} = **subleading p_T** / (**subleading p_T** + **leading p_T**); **θ_{SJ} = ΔR (subleading, leading)**

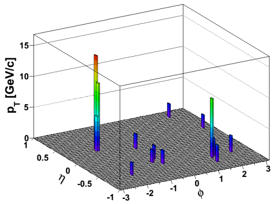
Jet Substructure in Au+Au



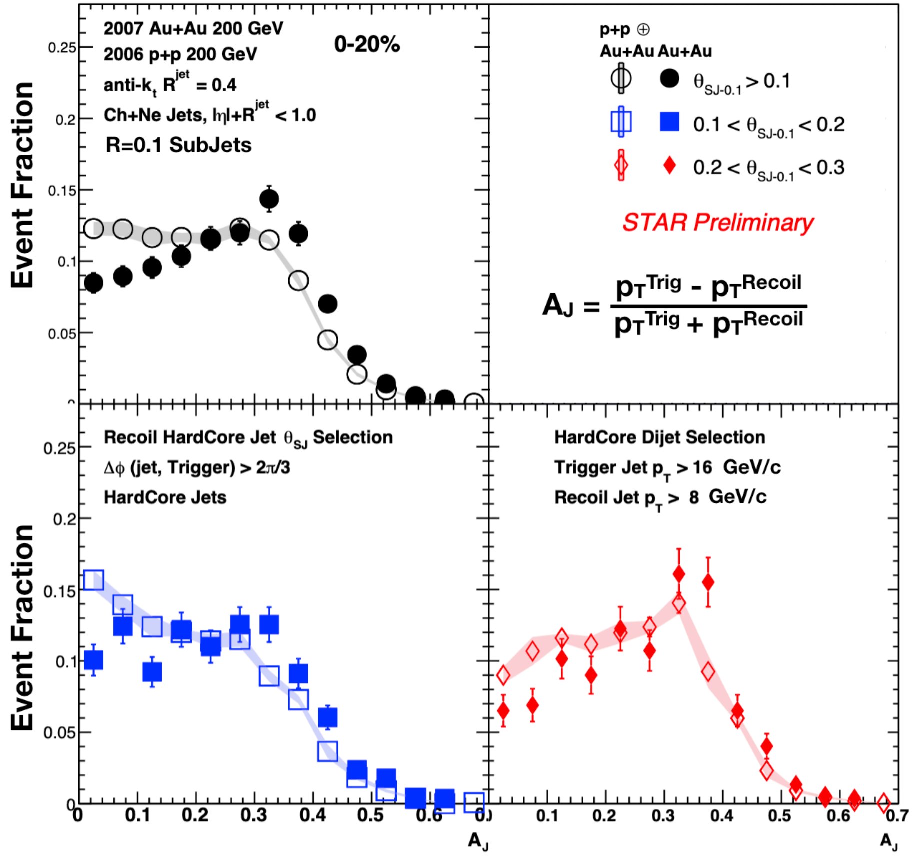


- The z_{SJ} distribution is biased toward harder splits.
- For both z_{SJ} and θ_{SJ}, no significant difference in shape due to jet quenching.

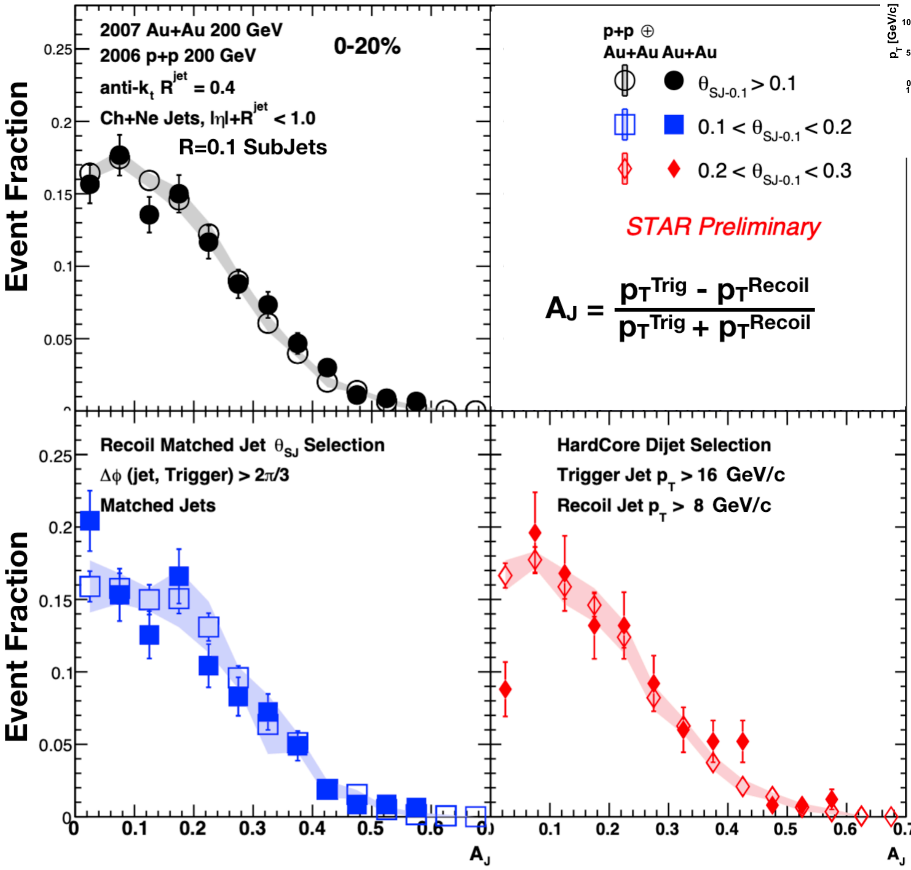
Di-Jet Imbalance as a Function of θ_{SJ}

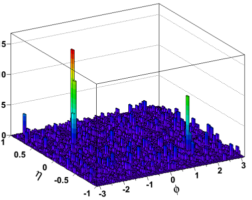


Hardcore Jets



Matched Jets





- ➢ A_J shape different for wide vs. narrow jets.
- ➢ Significant imbalance for all θ_{SJ}

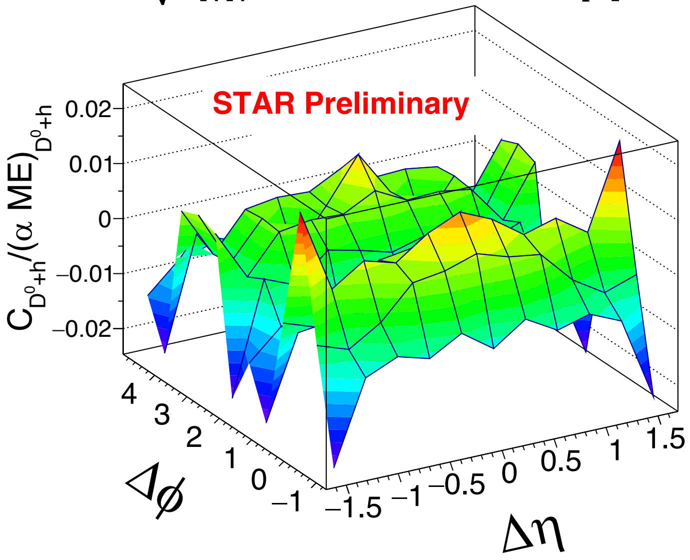
- ➢ Matched A_J similar for wide vs. narrow jets.
- ➢ Balance indicating recovery for all θ_{SJ}

Flavor Dependence: D^0+h Correlations

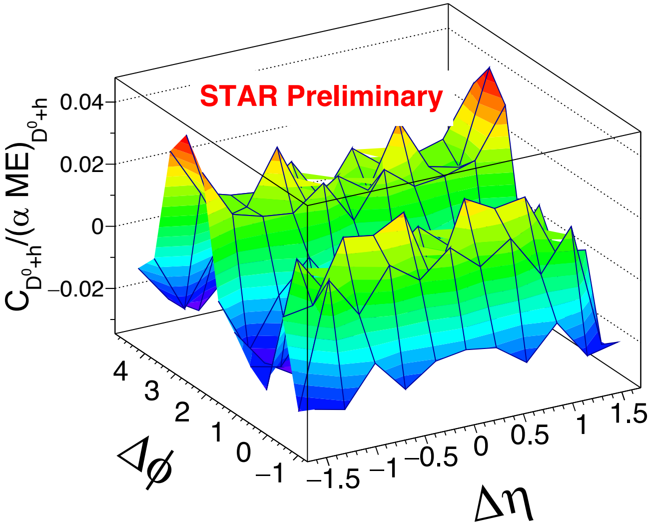
Submitted to PRC (arXiv: 1911.12168)

- 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.

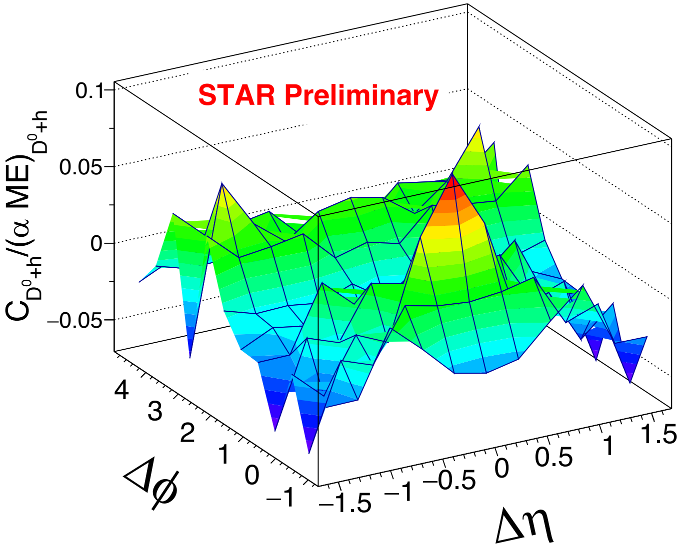
Au+Au, $\sqrt{s_{NN}} = 200$ GeV, D^0 $p_T = 2–10$ GeV/c, $h^{\pm}$ $p_T > 0.15$ GeV/c



0-20%



20-50%

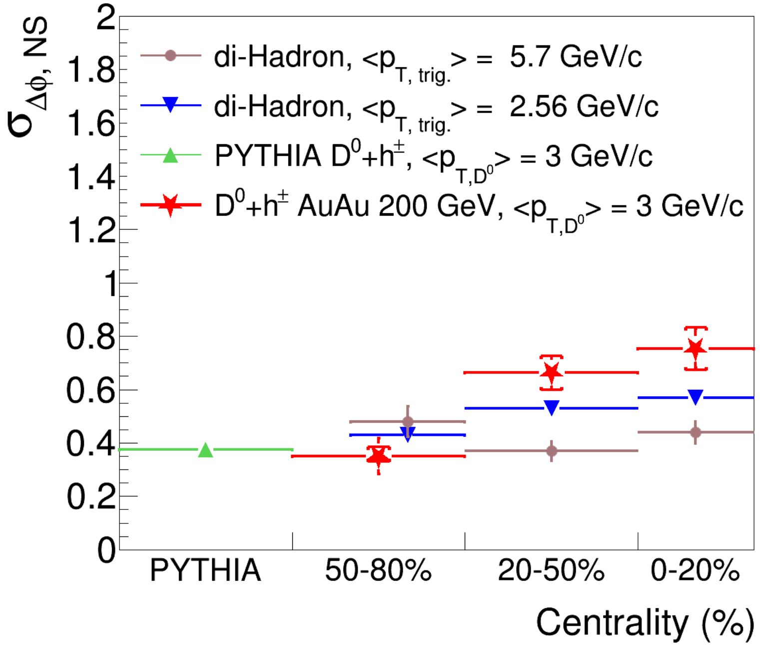


50-80%

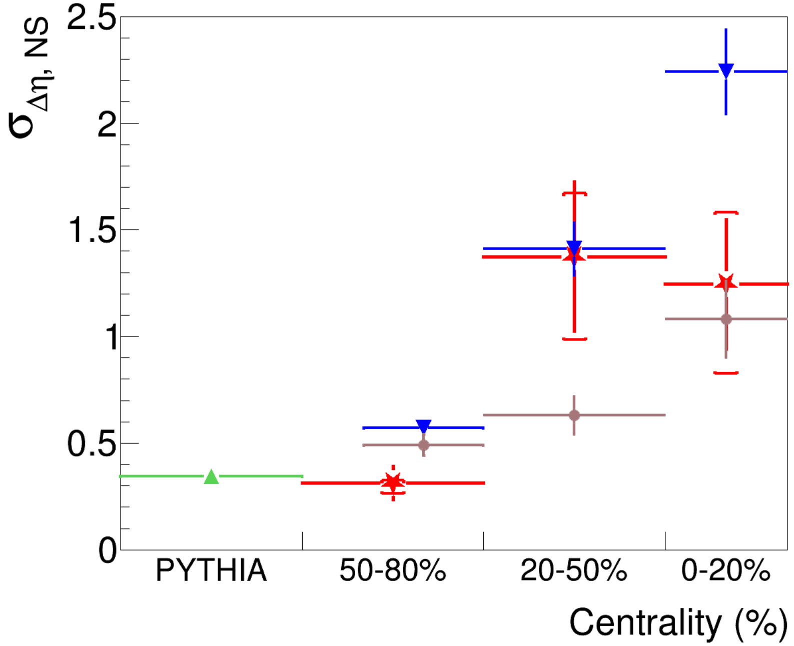
Flavor Dependence: D^0+h Correlations

arXiv: 1911.12168

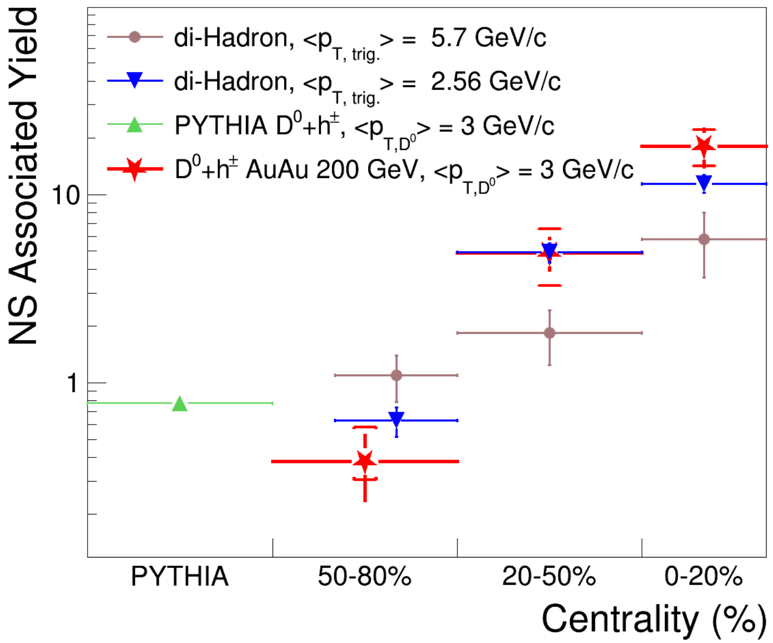
Near-side width (phi)



Near-side width (eta)



Near-side yield



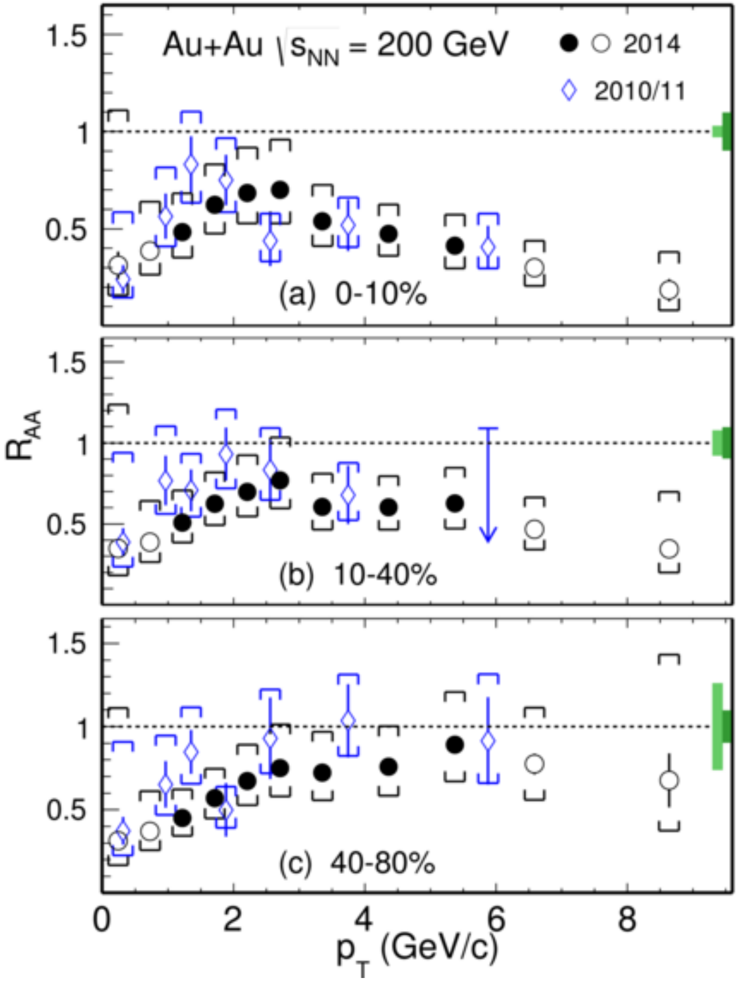
- Significant increase in both near-side width and yield as a function of centrality.
- Similar width and yield results to light-flavor correlations – Indication of similar behavior of correlations between light-flavor and charm-quarks

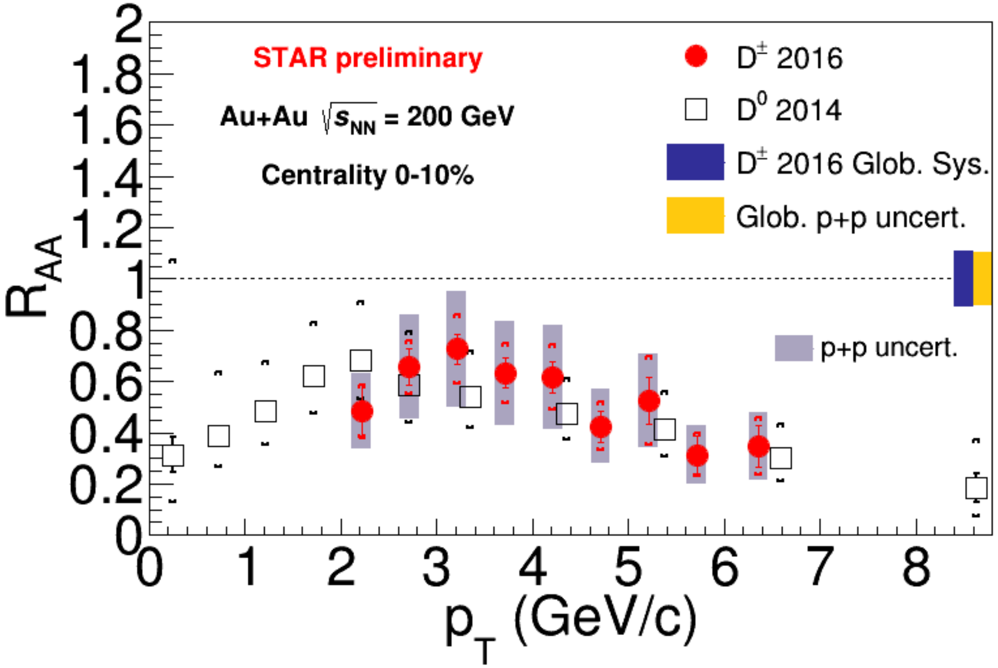
Open Heavy-Flavor in STAR

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

STAR, PRC99 (2019) 034908

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

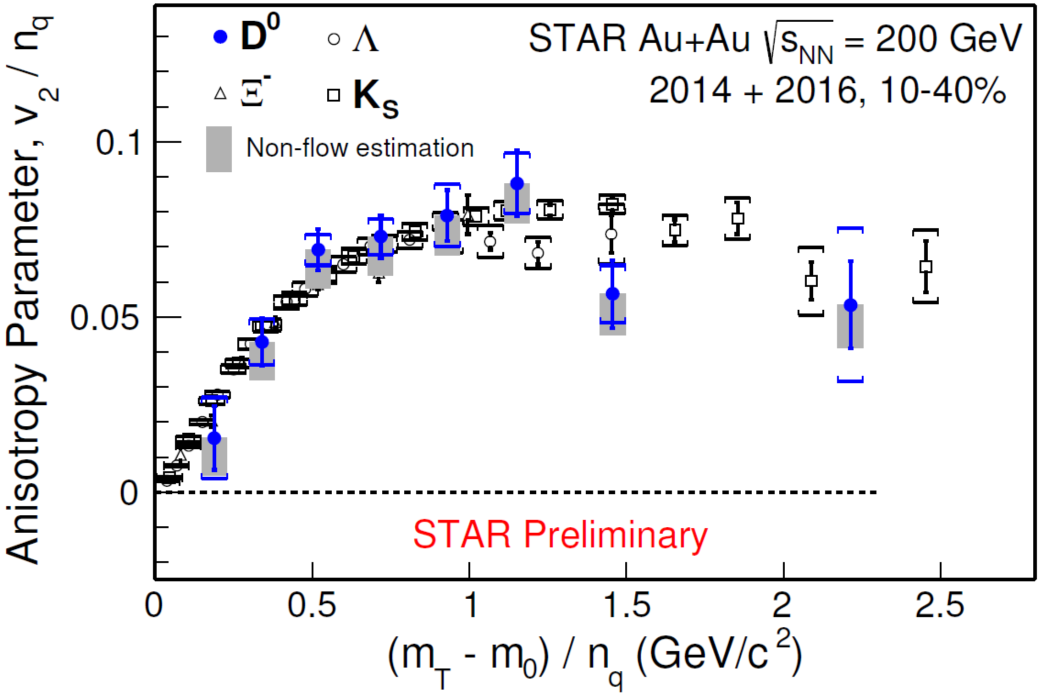


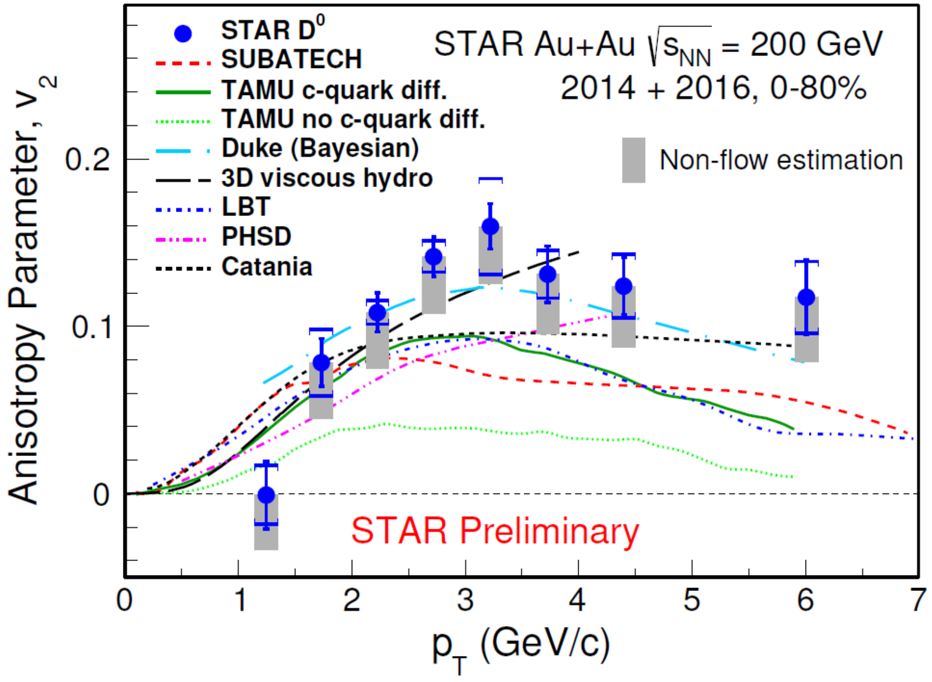


- ➢ Suppression at high p_T increases towards more central collisions.
- ➢ $R_{AA} < 1$ in the 0-10% Au+Au centrality interval for all p_T.
- ➢ D^0 and $D^{\pm}$ mesons show same level of suppression.

D^0 Anisotropic Flow

2014: STAR, PRL 118 (2017) 212301



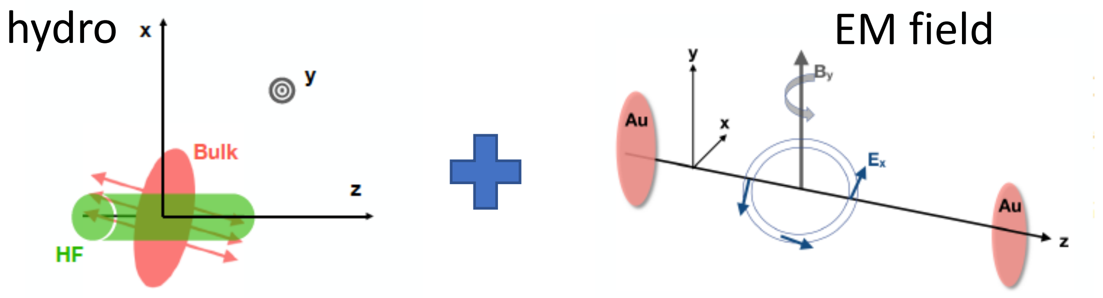


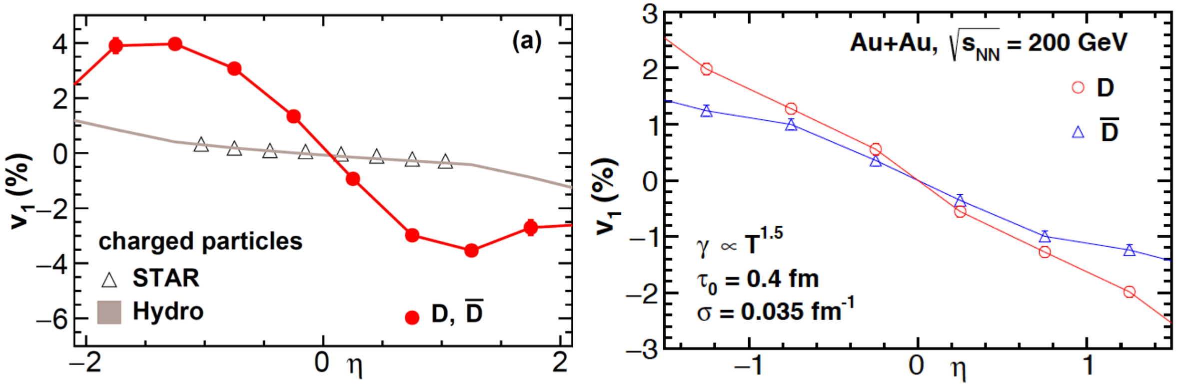
Charm quarks acquire similar elliptic flow as light flavor quarks
→ data suggest strong interaction of charm quarks with QGP.

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

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

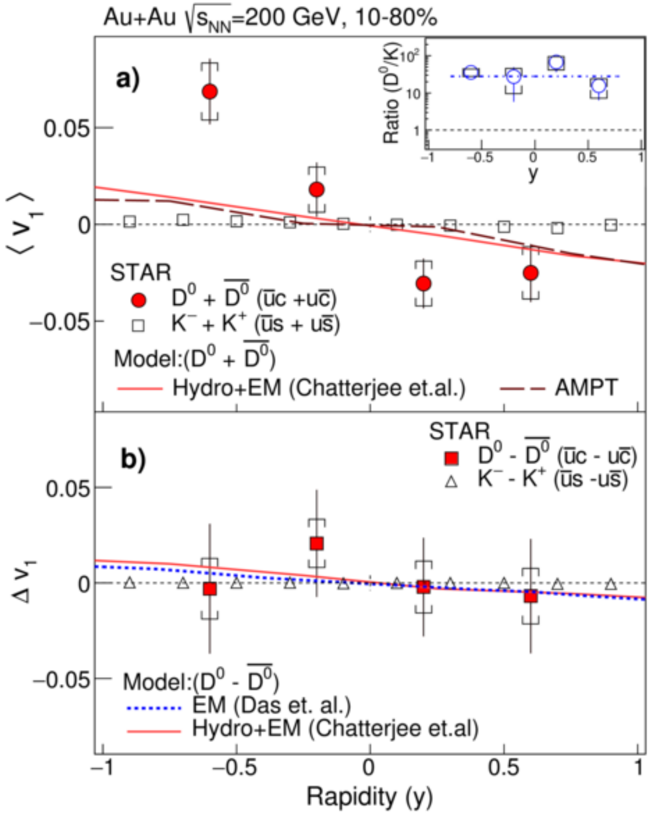
D^0 Directed Flow

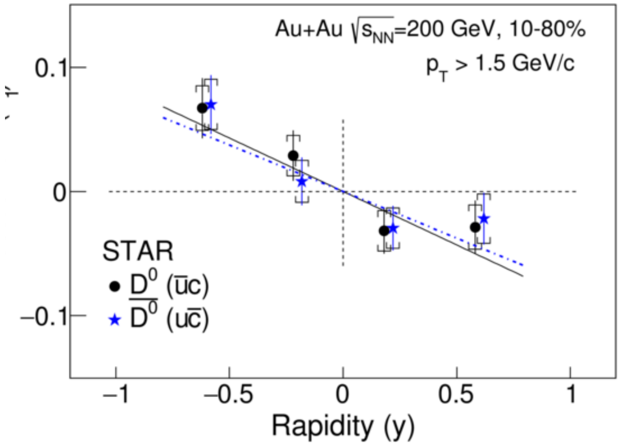




Chatterjee, Bozek: PRL 120, 192301 (2018)
PLB 798, 134955 (2019)

STAR, PRL 123 (2019) 162301





dv_1/dy

$\overline{D}^0$: −0.086 ± 0.025 (stat) ± 0.018 (syst)

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.

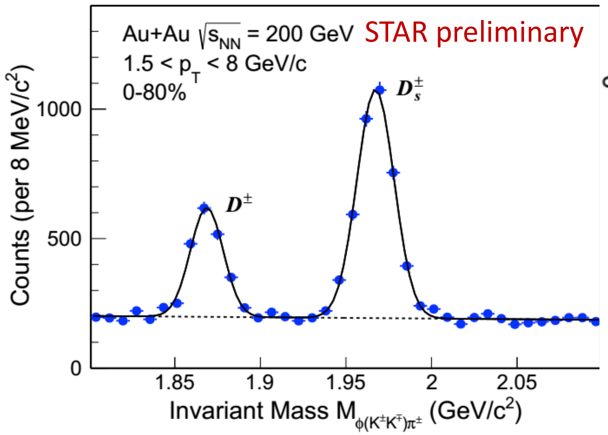
D_s/D^0 enhancement

- 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.

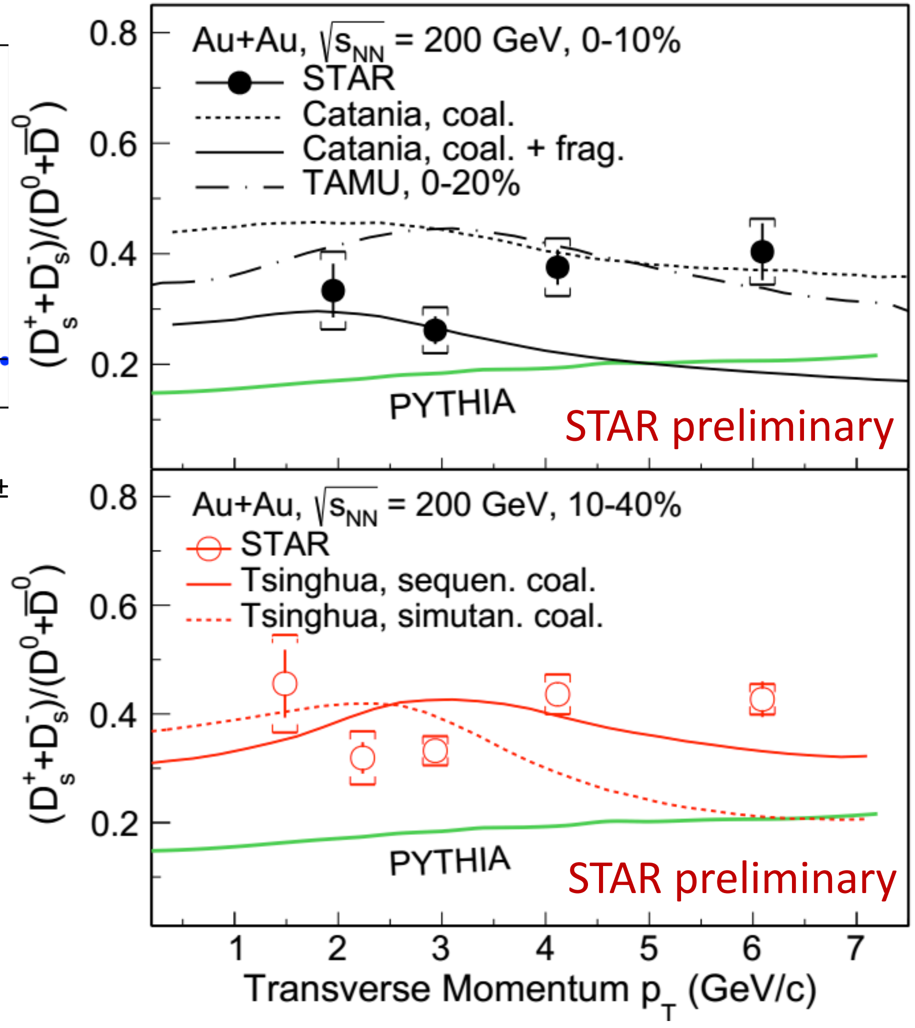
D_s/D^0 ratio:

- 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



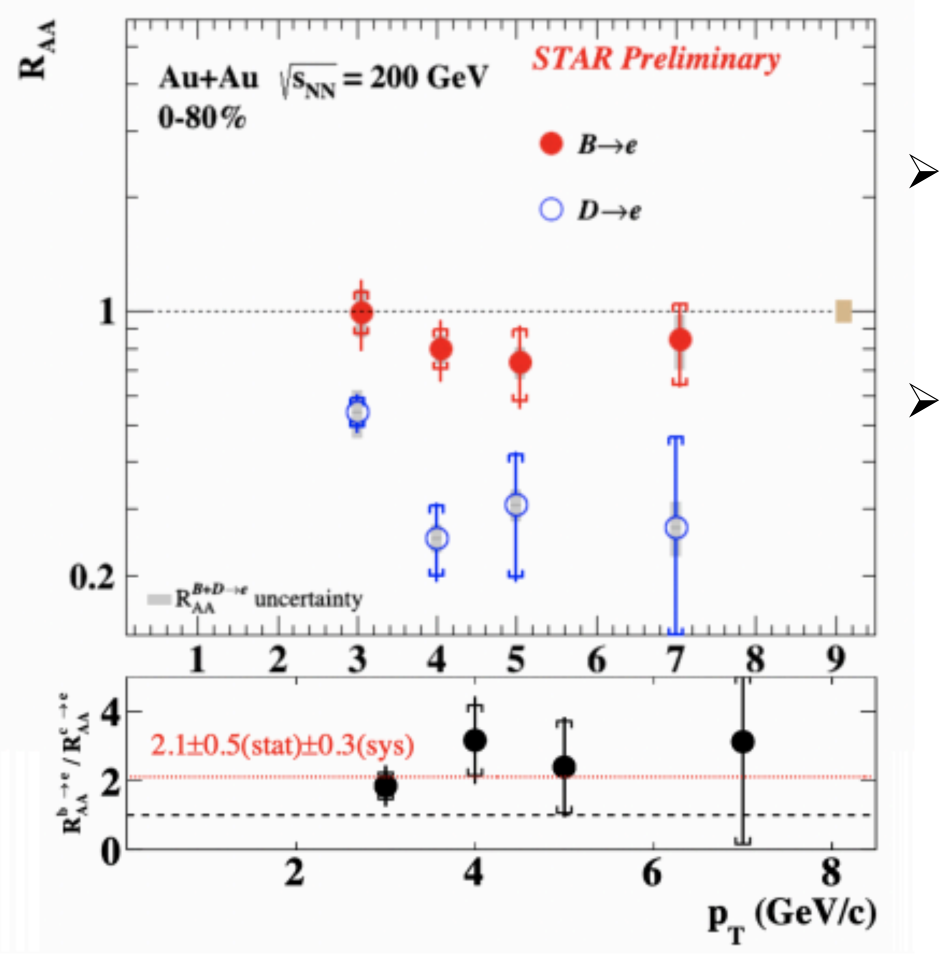
$D_S^\pm \longrightarrow \phi\ (\longrightarrow K^+ + K^-) + \pi^\pm$



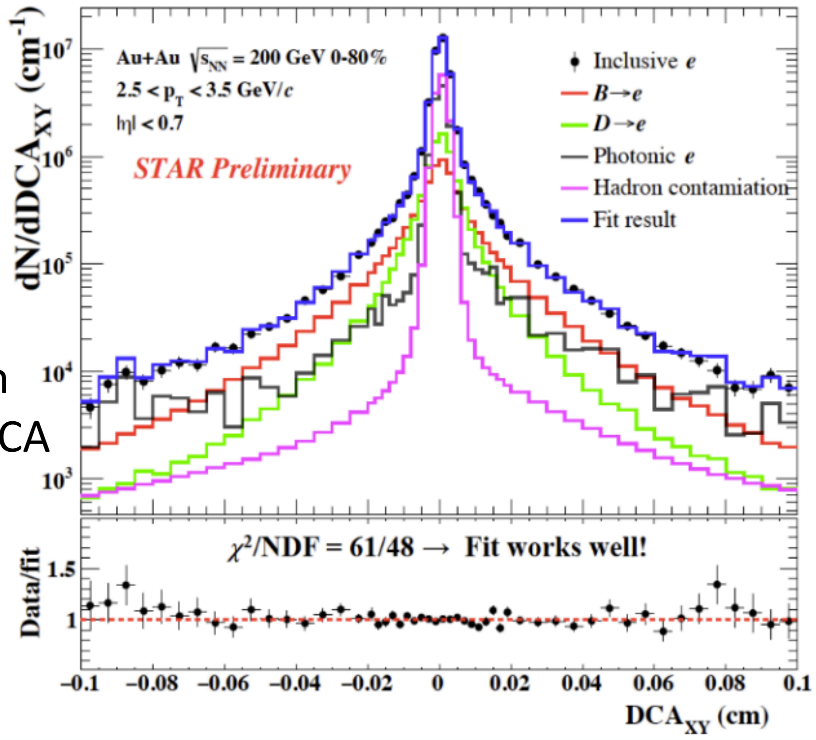
Model calculations:

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



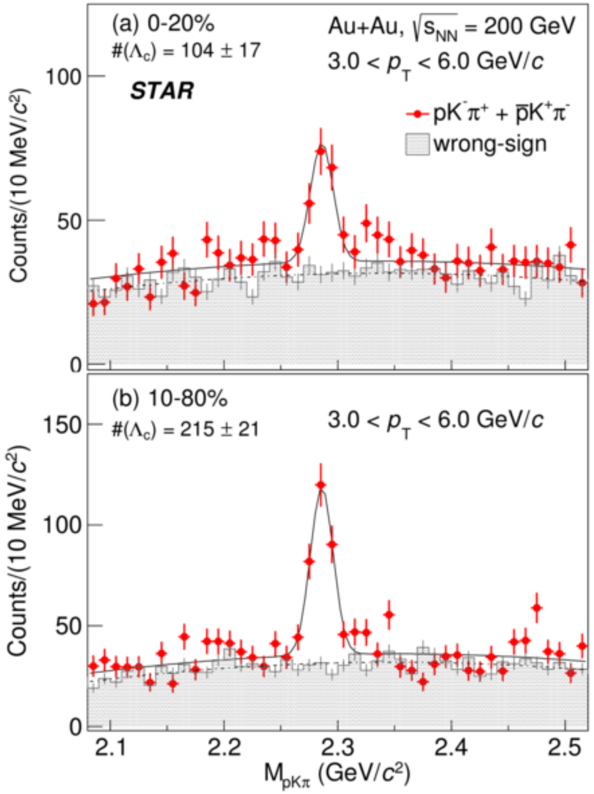
- It's been established that charm still interacts strongly with the medium, against early predictions – do we still expect a mass hierarchy with bottom?
- Using HFE, separate contributions from D→e and B→e using template fits to DCA distribution.



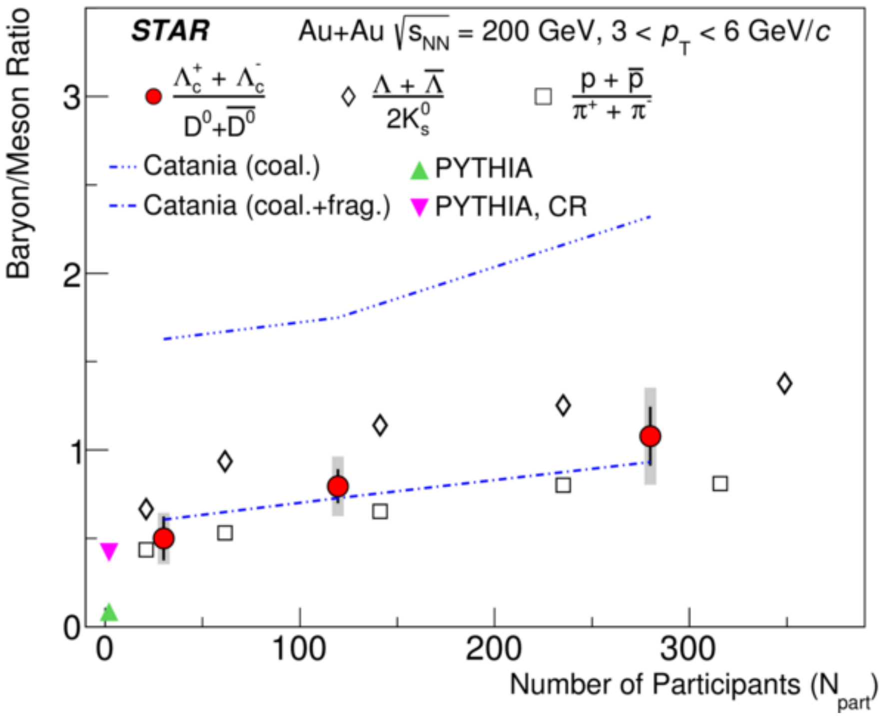
- Indication of higher R_{AA} for B→e compared to D→e (2σ significance): consistent with $\Delta E_c > \Delta E_b$
- Better precision measurements on the way with combined 2014+2016 datasets!

Λ_c and heavy quark hadronization

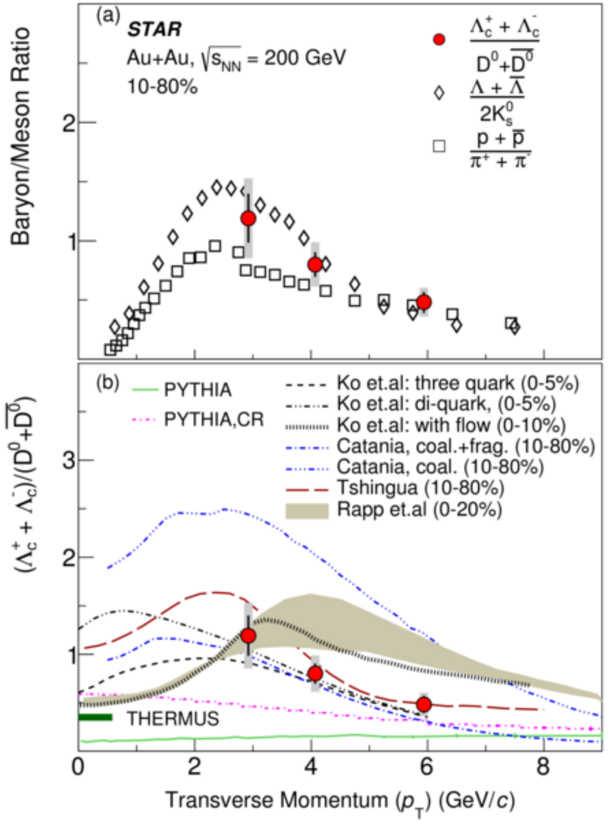
STAR, arXiv:1910.14628



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.

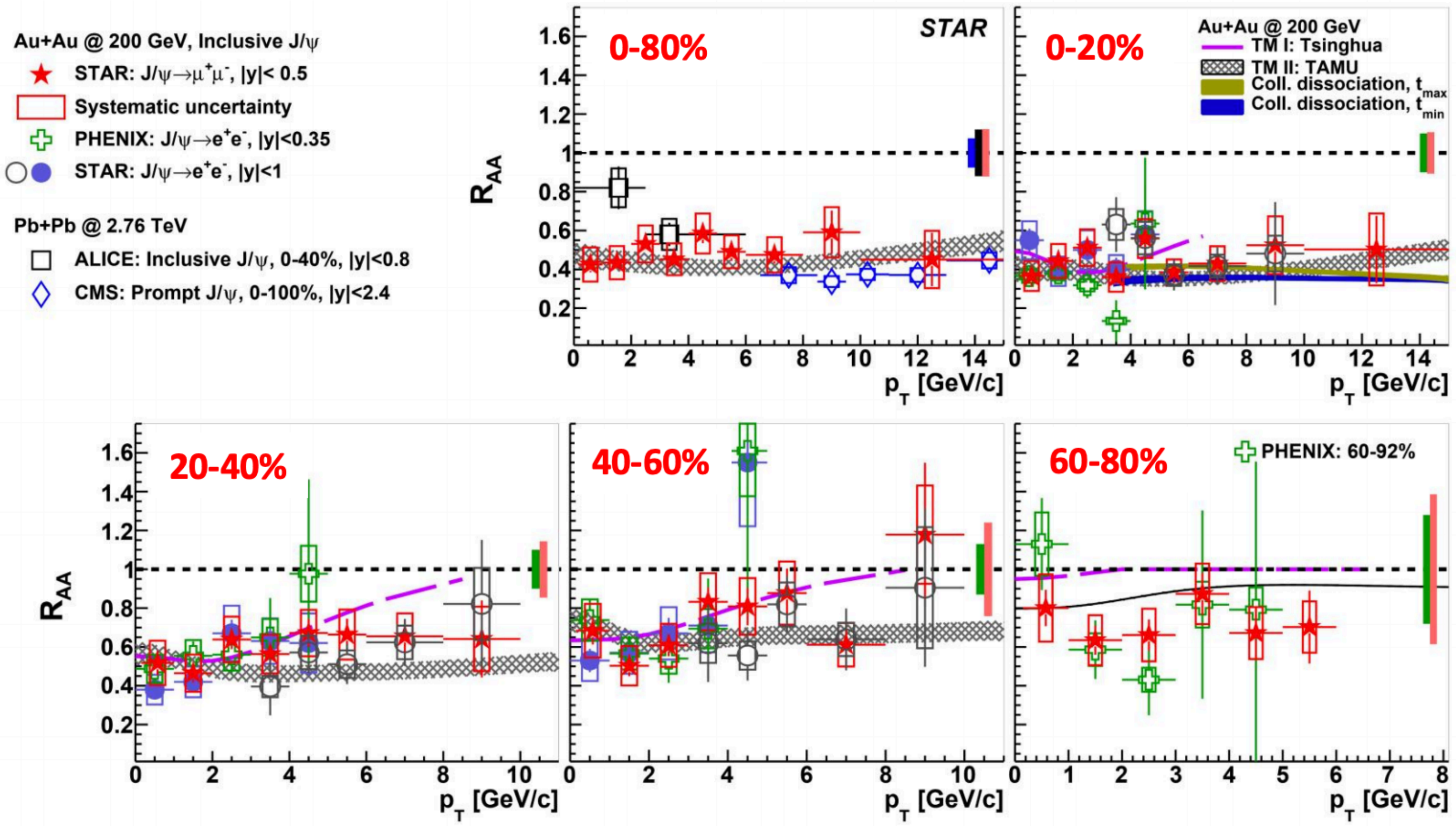


Model calculations:
Ko: *PRC 79, 044905 (2009), arXiv:1905.09774*
Catania: *EPJ C78 (2018) 348*
Tshingua: *arXiv:1805.10858*
Rapp: *arXiv:1910.14628*

Heavy Quarkonia in STAR

J/ψ Suppression in Au+Au Collisions

STAR, PLB 797 (2019) 134917

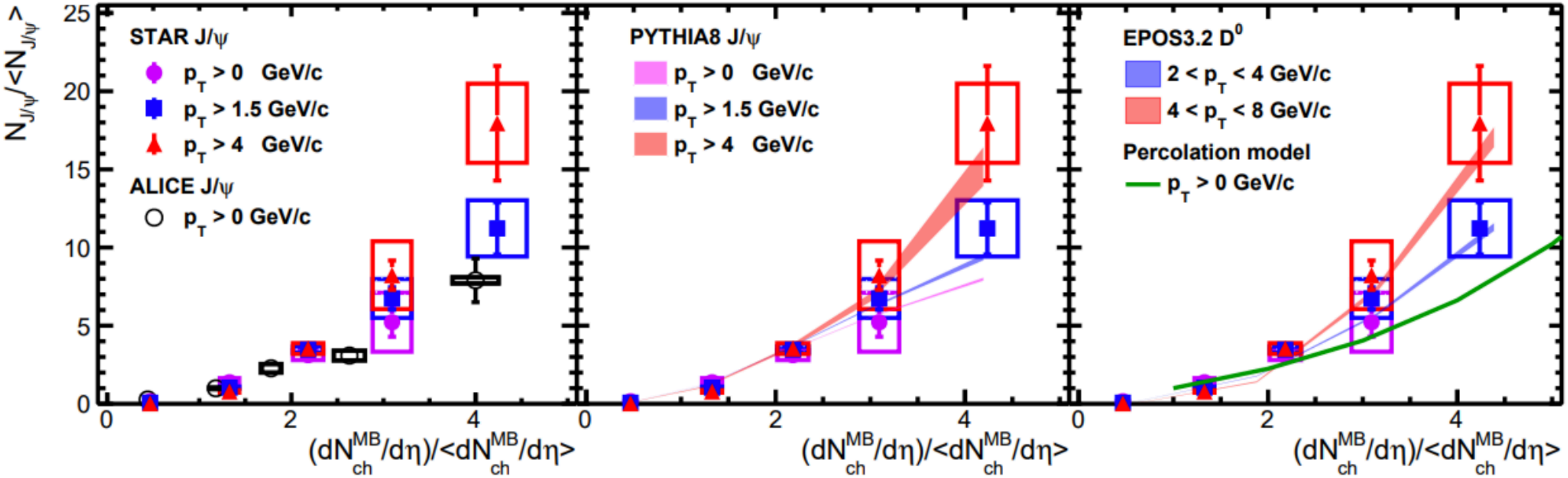


First final results from MTD in Au+Au collisions

- 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.

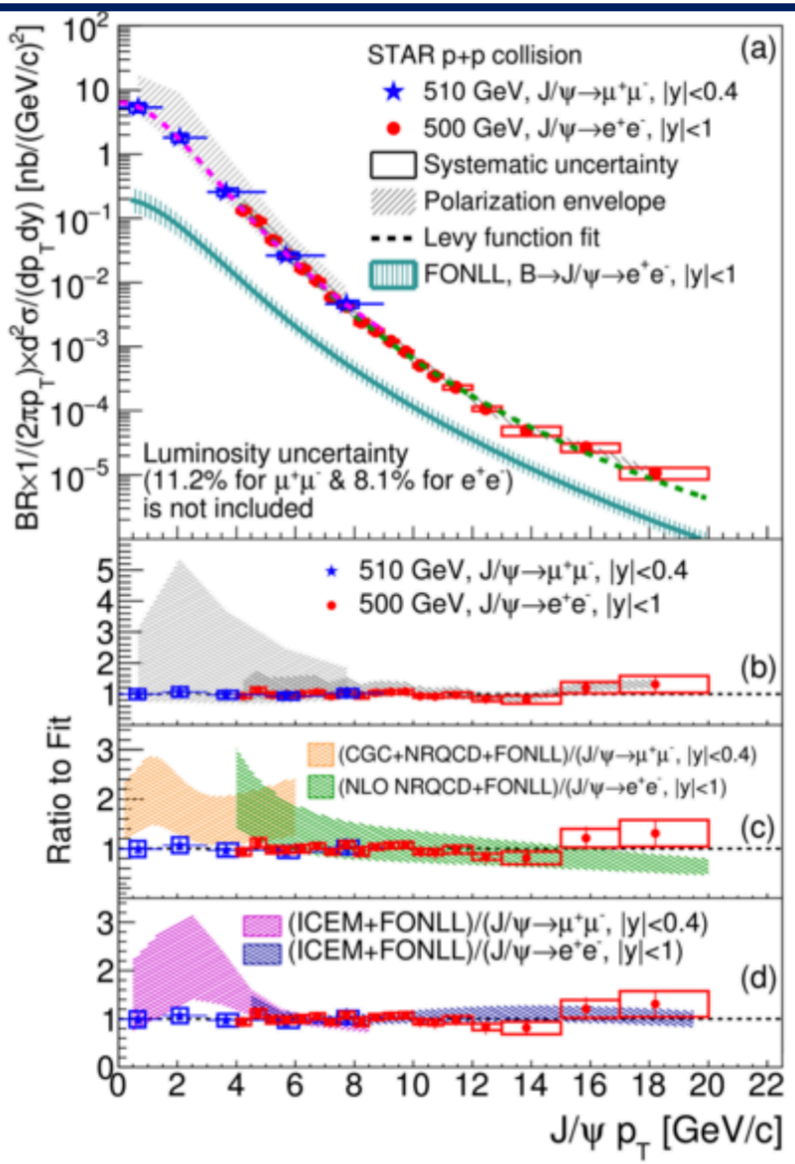
J/ψ Suppression in Au+Au Collisions

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.

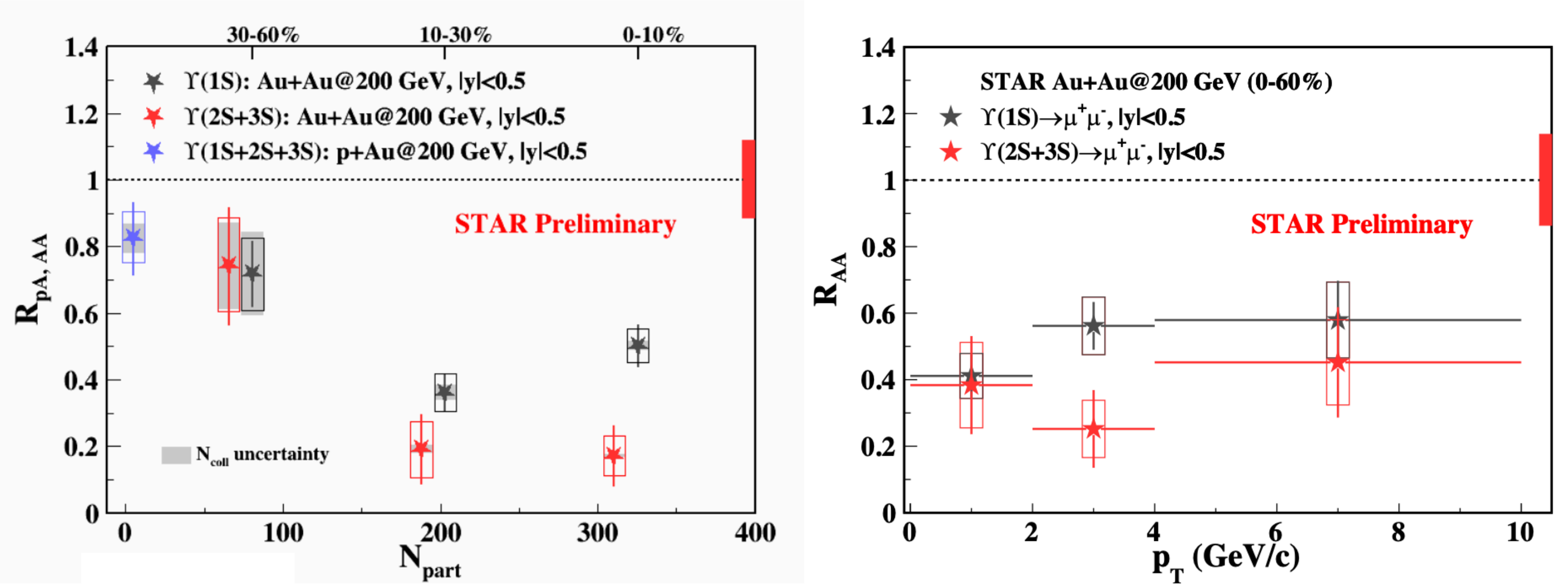
J/ψ Cross Section in p+p



STAR, PRD 100 (2019) 52009

- 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!