XI International Conference on New Frontiers in Physics

Recent heavy-flavor results from STAR

Barbara Trzeciak, for the STAR Collaboration
Czech Technical University in Prague

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

ICNFP 2022
8.9.2022, Kolymbari, Crete

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

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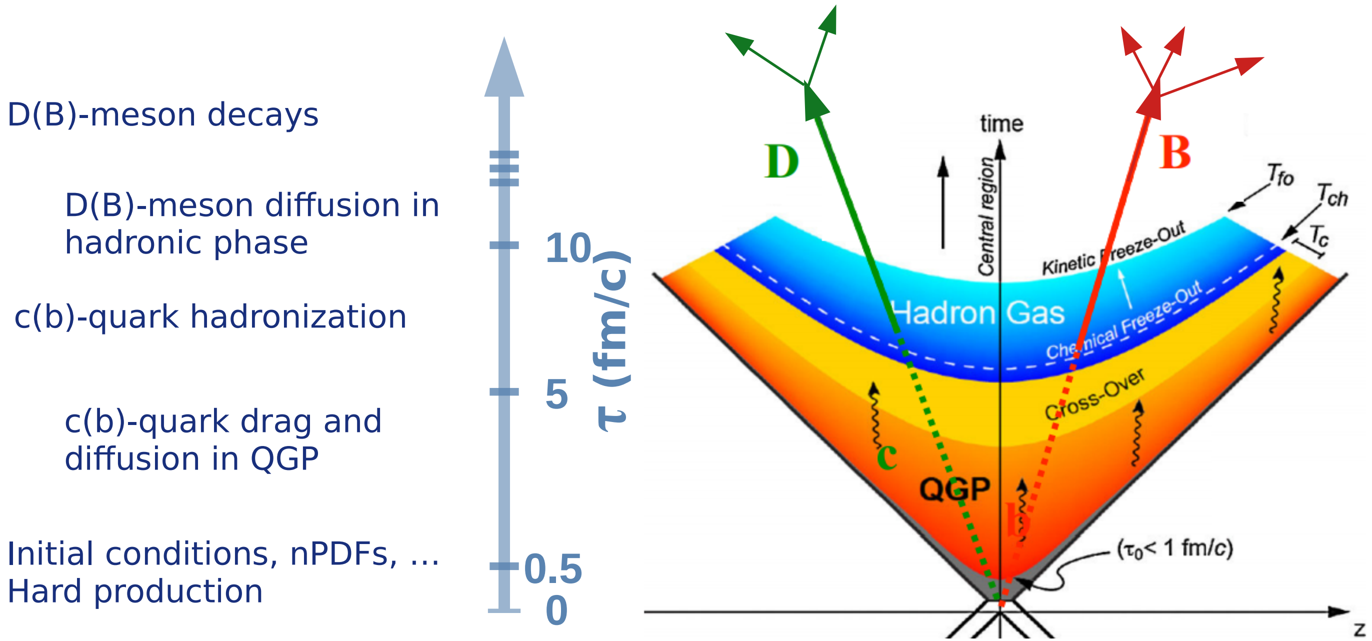
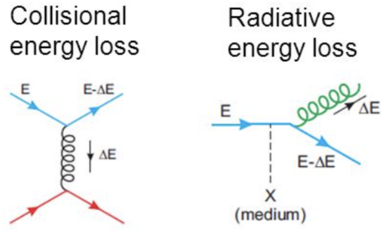
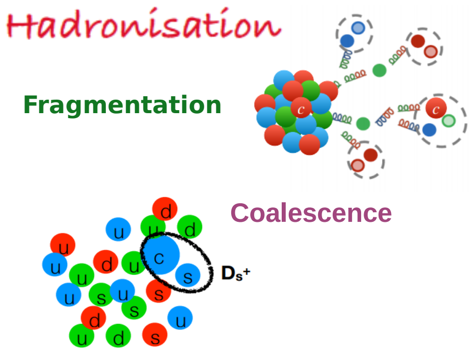
Why heavy flavor ?

- Heavy-flavor quarks (c,b), $m_Q >> \Lambda_{QCD}$, T_{QGP}: produced dominantly in initial hard scatterings (negligible thermal production), production cross section calculable with pQCD.
- Interactions with the medium → parton energy loss, flow.
  - ➔ Constraints on energy loss mechanisms: collisional vs radiative process.
  - ➔ Medium thermalization and transport coefficient $D_s(2\pi T)$.
  - ➔ Hadronization: fragmentation vs coalescence.



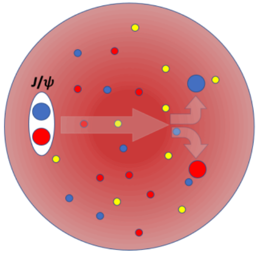




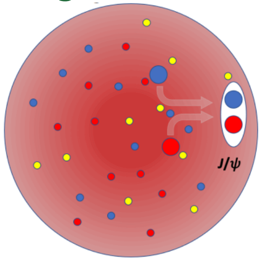
Why quarkonia ?

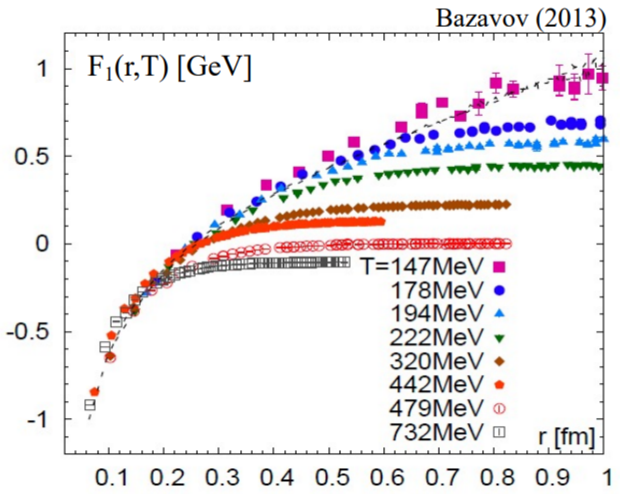
- QQbar potential and spectral function modified in the QGP medium w.r.t. vacuum.
- Hot nuclear matter effects:
  - ➔ Dissociation due to color screening, regeneration.

Dissociation

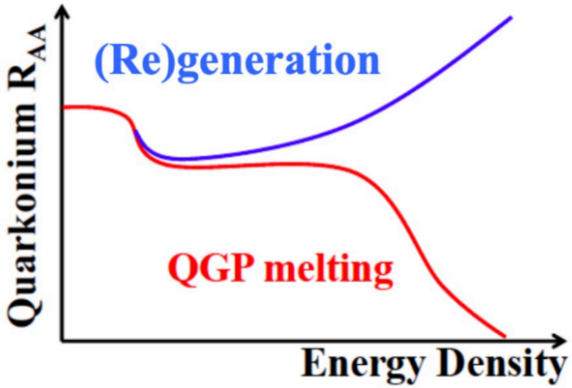


Regeneration

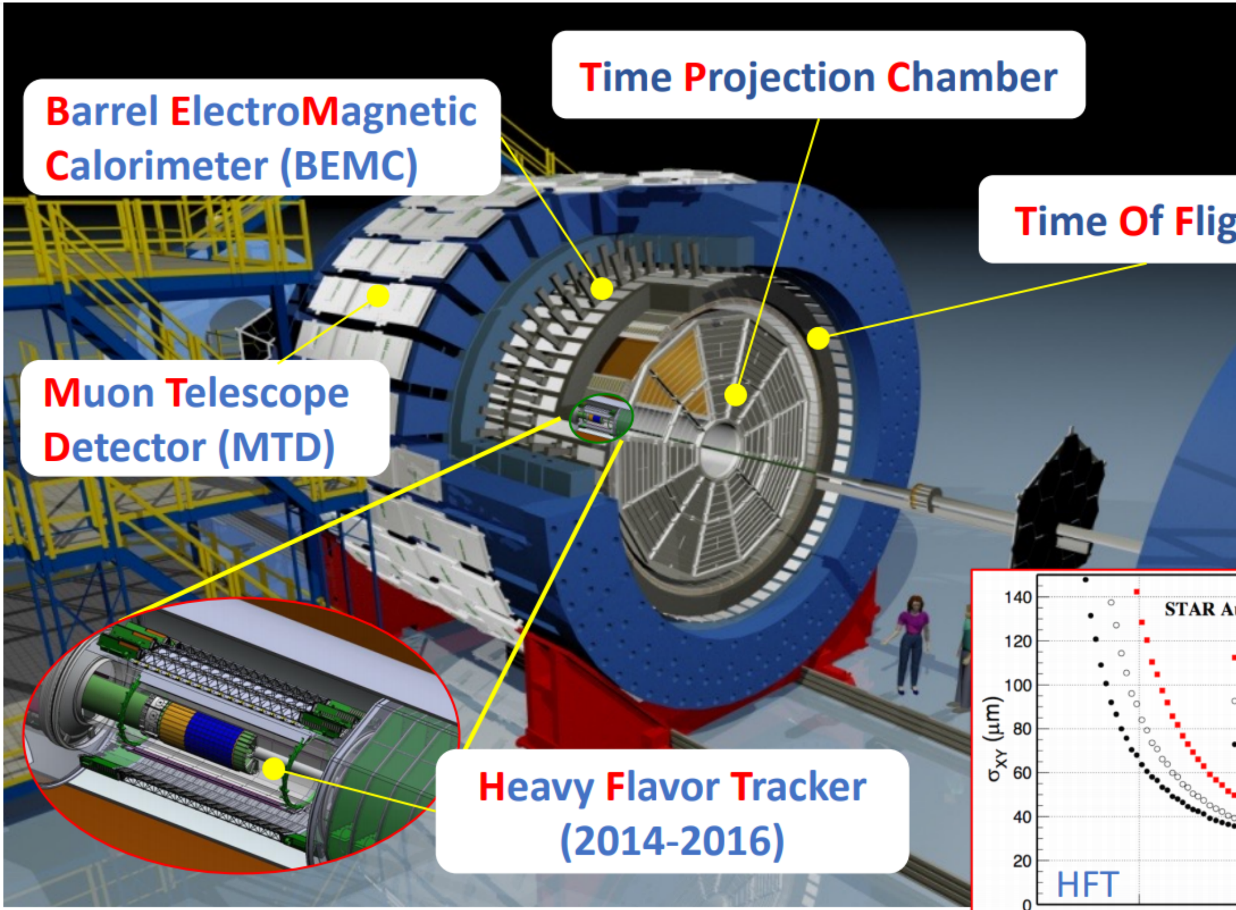




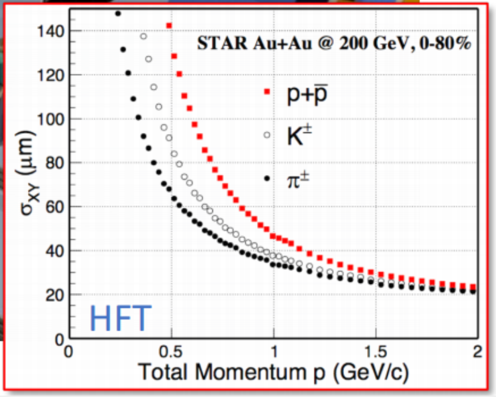
- Sequential quarkonium suppression due to different binding energies.
- Cold nuclear matter effects:
  - ➔ Modification of PDFs, nuclear absorption, coherent energy loss, co-mover absorption, … .

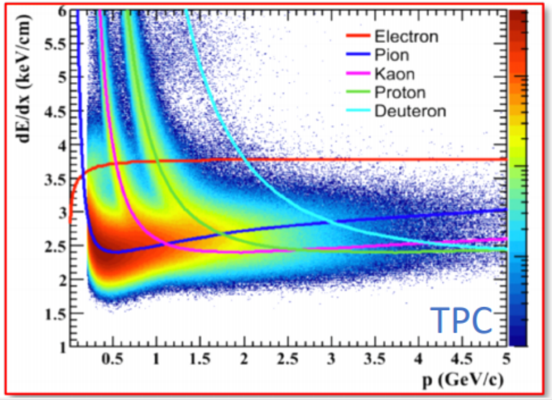


STAR detector at RHIC



- TPC – momentum and PID (dE/dx)
- TOF – PID (1/β)
- BEMC – trigger on and identify high p_T electrons
- HFT – excellent pointing resolution for secondary vertex reconstruction
- MTD – trigger on and identify muons

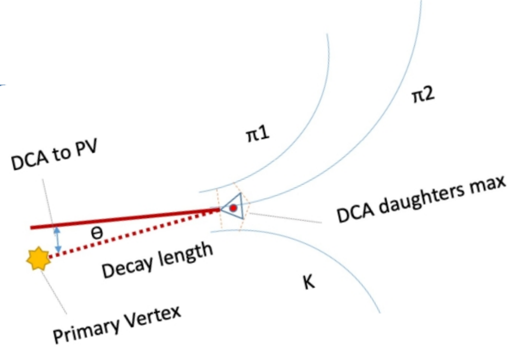


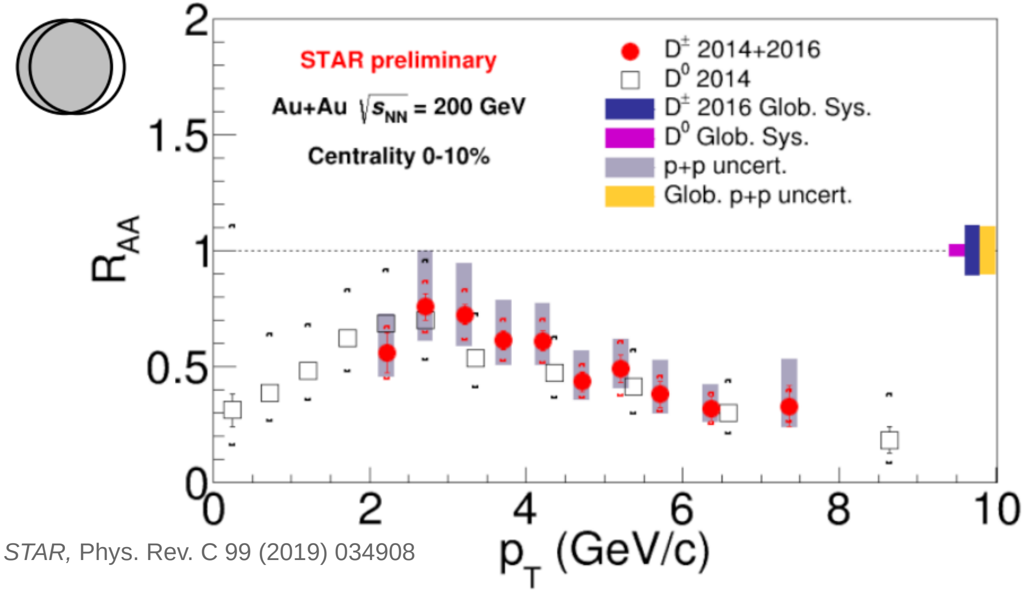


Open heavy flavor

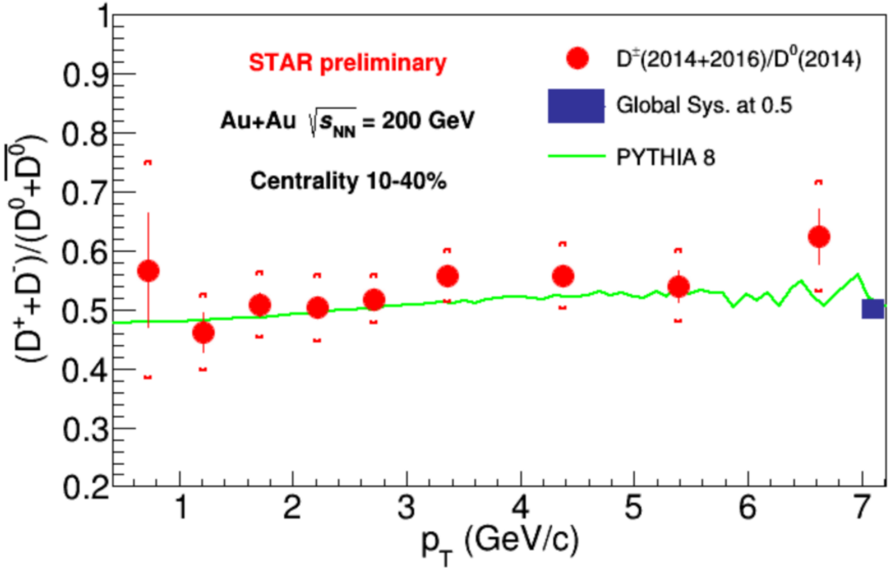
Open heavy-flavor hadrons

$$R_{AA} = \frac{1}{N_{coll}} \frac{d^2N_{AA}/(dp_T dy)}{d^2N_{pp}/(dp_T dy)}$$ QGP Medium / QCD Vacuum





STAR, Phys. Rev. C 99 (2019) 034908



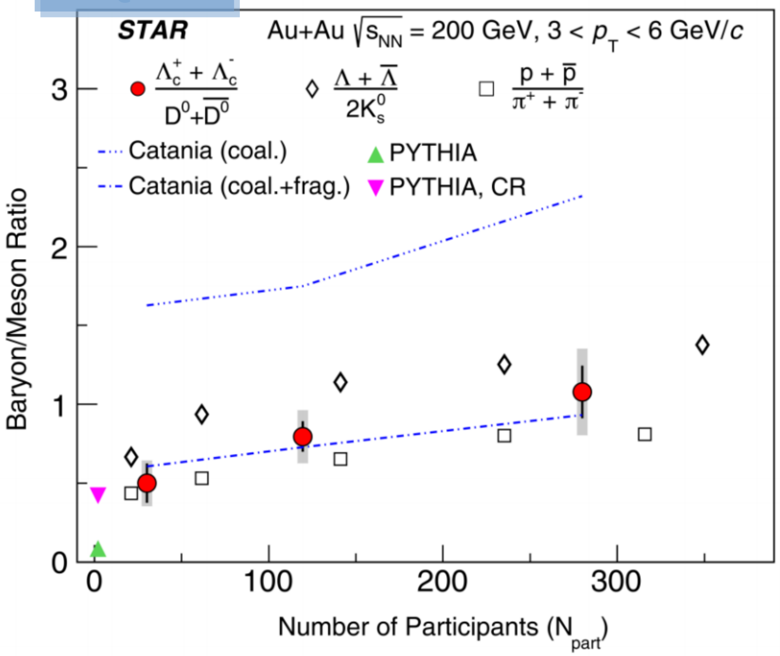
➔ Strong suppression of D^0 and $D^{+/-}$ at high p_T → strong interaction of charm quarks with the medium.

➔ $D^{+/-}/D^0$ yield ratio in Au+Au consistent with PYTHIA8.

Charm hadrochemistry

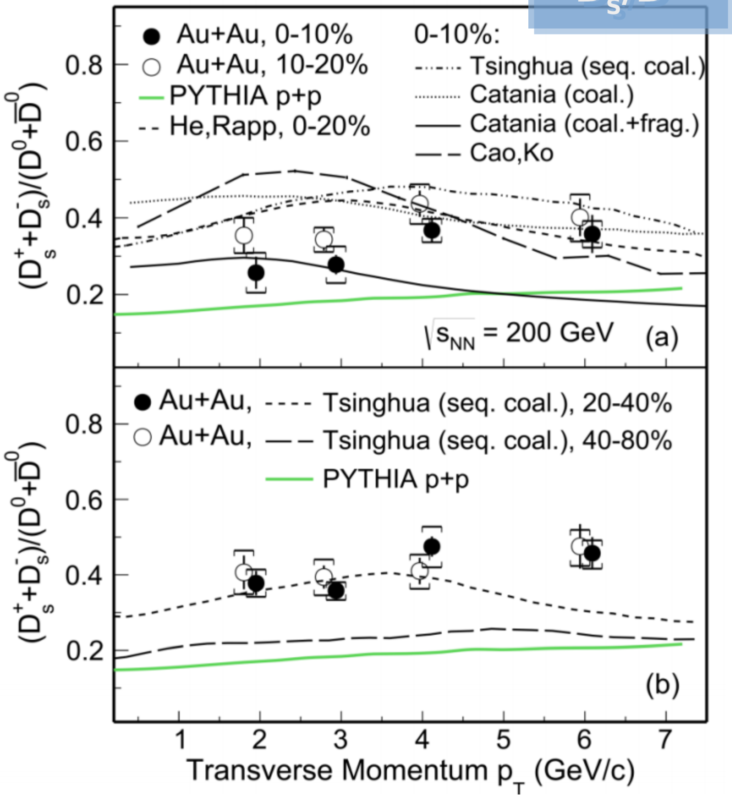
- Insight into hadronization mechanism of charm quarks.

Λ_c/D^0



STAR, Phys. Rev. Lett. 124 (2020) 172301

D_s/D^0



STAR, Phys. Rev. Lett. 127 (2021) 092301

➔ **Enhancement of Λ_c/D^0 and D_s/D^0** ratios compared to PYTHIA.

➔ Consistent with models including coalescence hadronization.

Total charm production cross section

➔ Total charm production cross section per binary collision in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.
- **Consistent with p+p collisions.**

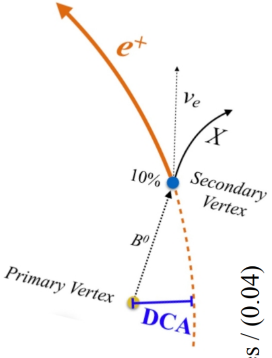
Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

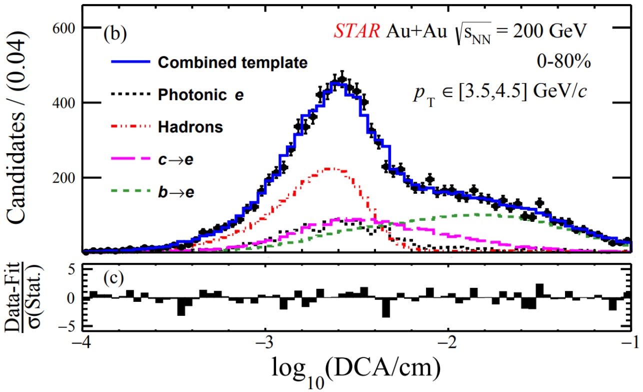
D^0 [1] STAR, Phys. Rev. C 99 (2019) 034908
D_s [2] STAR, Phys. Rev. Lett. 127 (2021) 092301
Λ_c [3]STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p [4] STAR, Phys. Rev. D 86 (2012) 072013

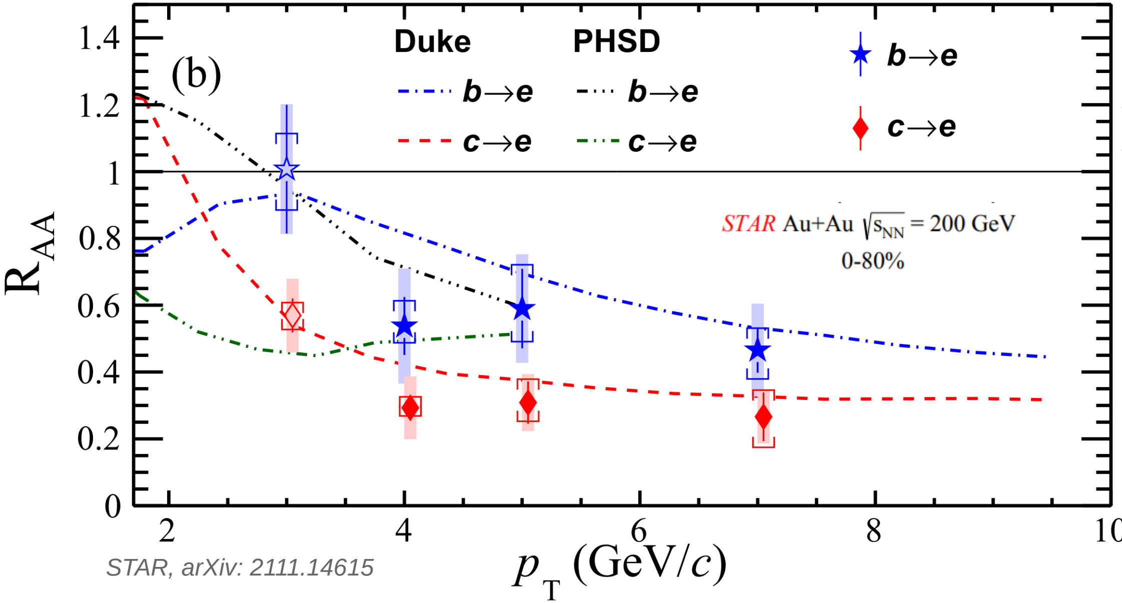
** Preliminary $D^{+/-}$ results*
*** Λ_c cross section derived from Λ_c/D^0 yield ratio*

Mass dependence of parton energy loss

- Heavy-flavor hadron decayed electrons: c → e and b → e separation thanks to HFT.







STAR, arXiv: 2111.14615

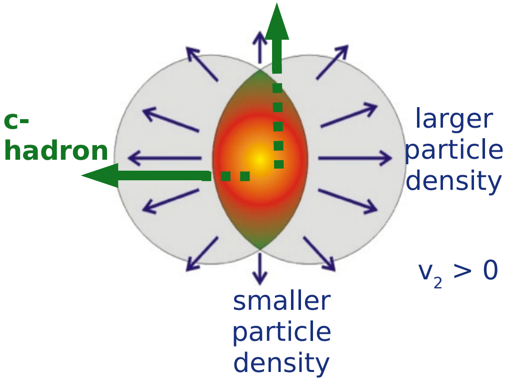
Duke, Phys. Rev. C 92, 024907 (2015)
PHSD, Phys. Rev. C 78, 034919 (2008), Nucl. Phys. A 831, 215 (2009)

➔ Clear mass hierarchy of c → e and b → e R_{AA} observed. Consistent with model predictions.

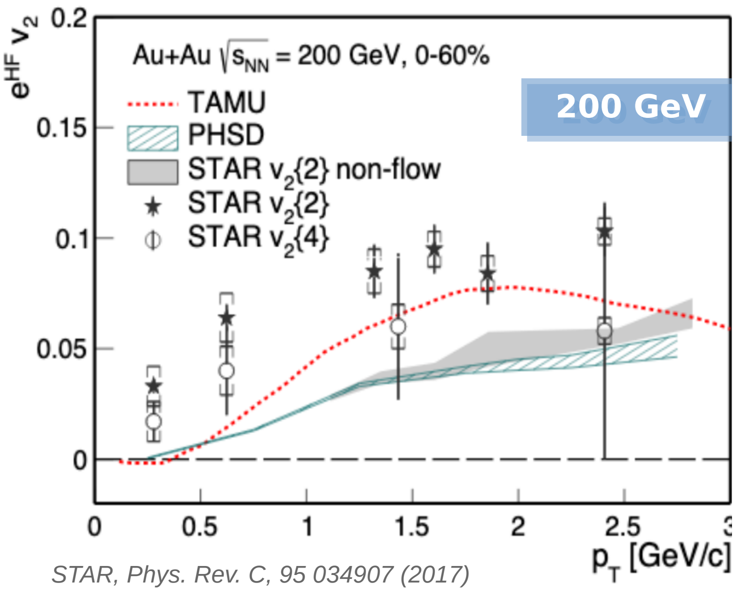
➔ b quarks lose less energy than c quarks.

Energy dependence of HFE v_2

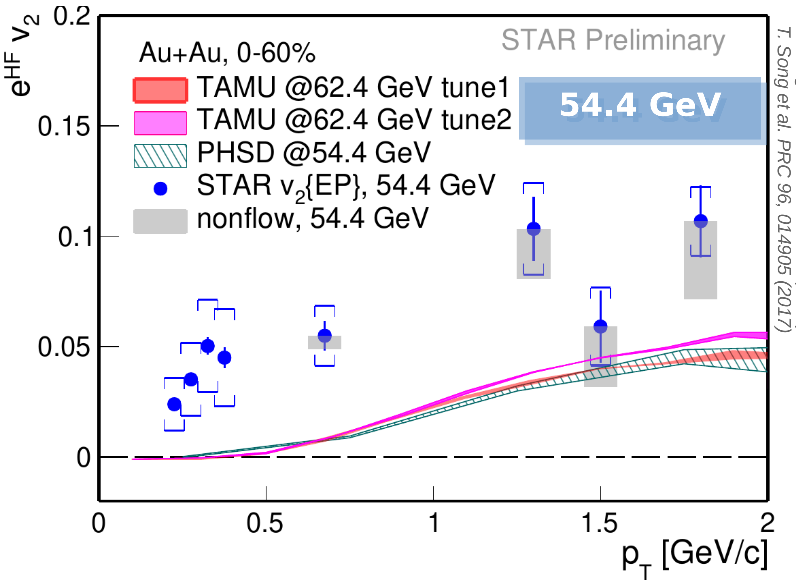
- v_2 vs coll. energy → temperature dependence of charm quark diffusion coefficient.



$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$



STAR, Phys. Rev. C, 95 034907 (2017)



M. He et al. PRC 91, 024904 (2015)
T. Song et al. PRC 92, 014910 (2015)
T. Song et al. PRC 96, 014905 (2017)

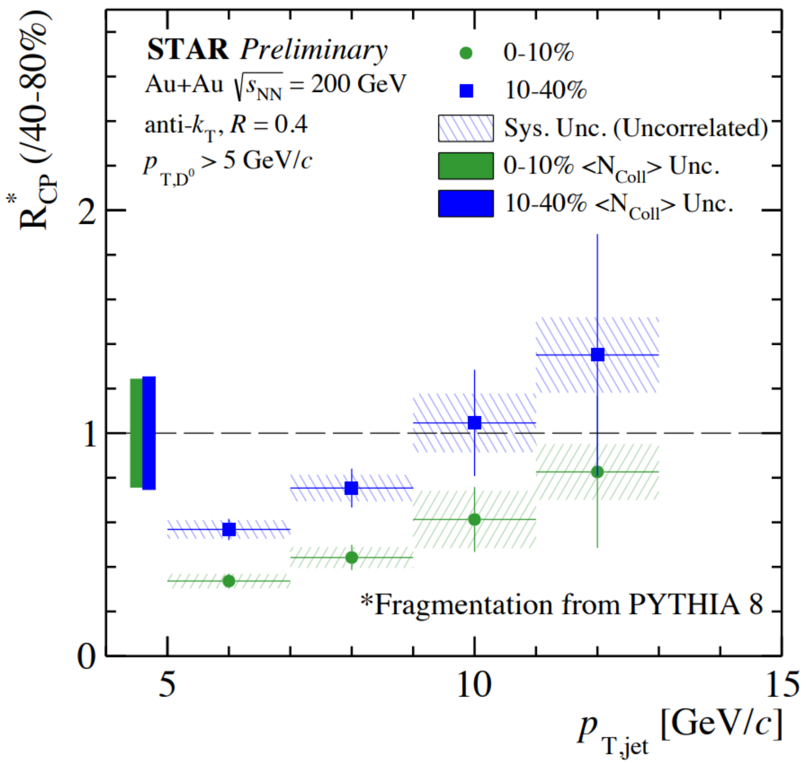
➔ **Significant non-zero v_2 of c,b → e at 54.4 – 200 GeV.**

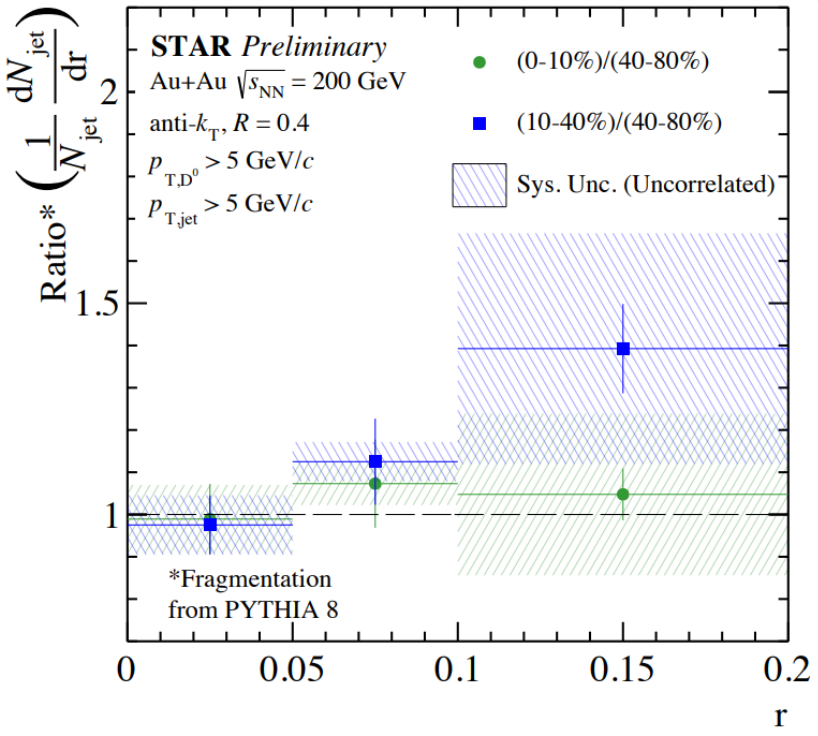
➔ At low p_T models underestimate data.

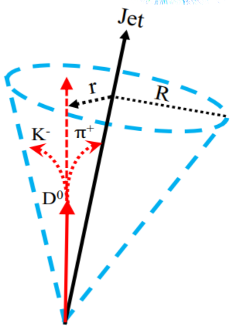
➔ HF quarks interact strongly with the medium at 54.4 – 200 GeV.

D^0-meson tagged jets

- D^0-jet radial profile: charm quark diffusion in QGP.





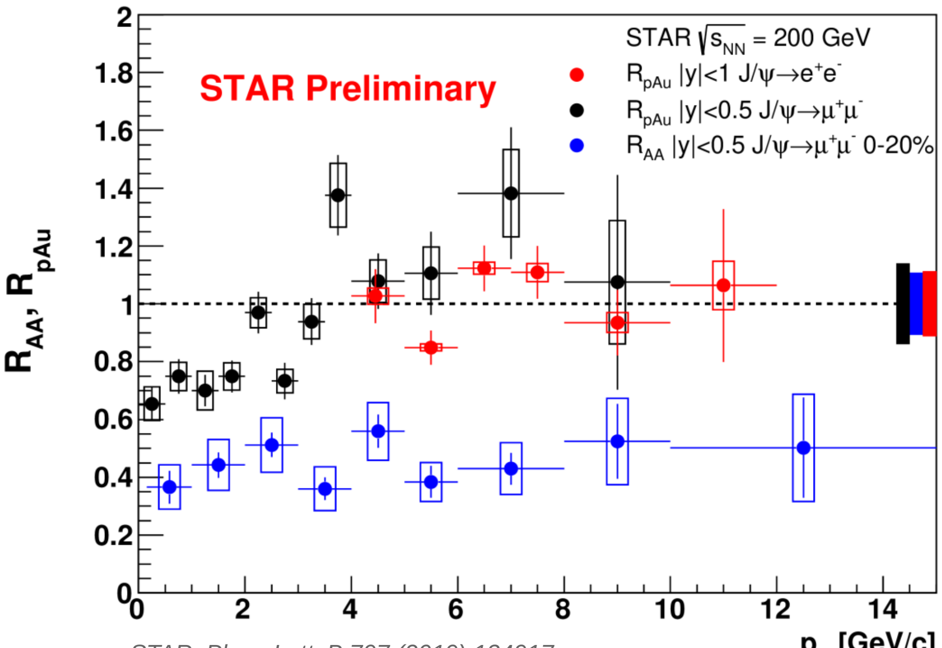


➔ R_{CP}: **strong suppression at low jet p_T**, hint of increasing trend.

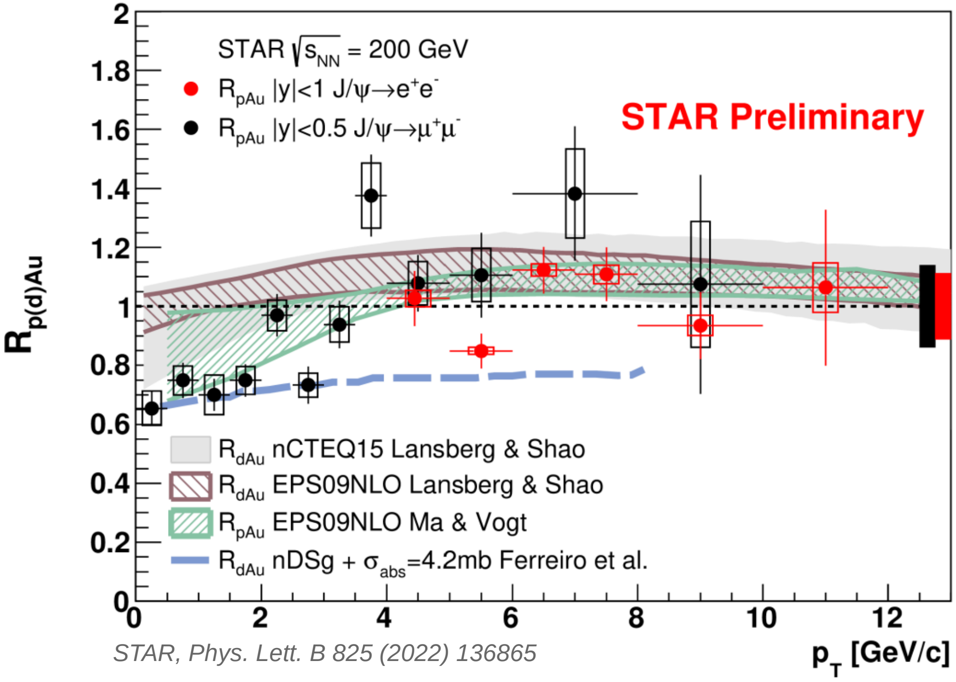
➔ Ratio of radial distributions consistent with unity. Potential to go to lower D^0 p_T.

Quarkonia

CNM effects on J/ψ production



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

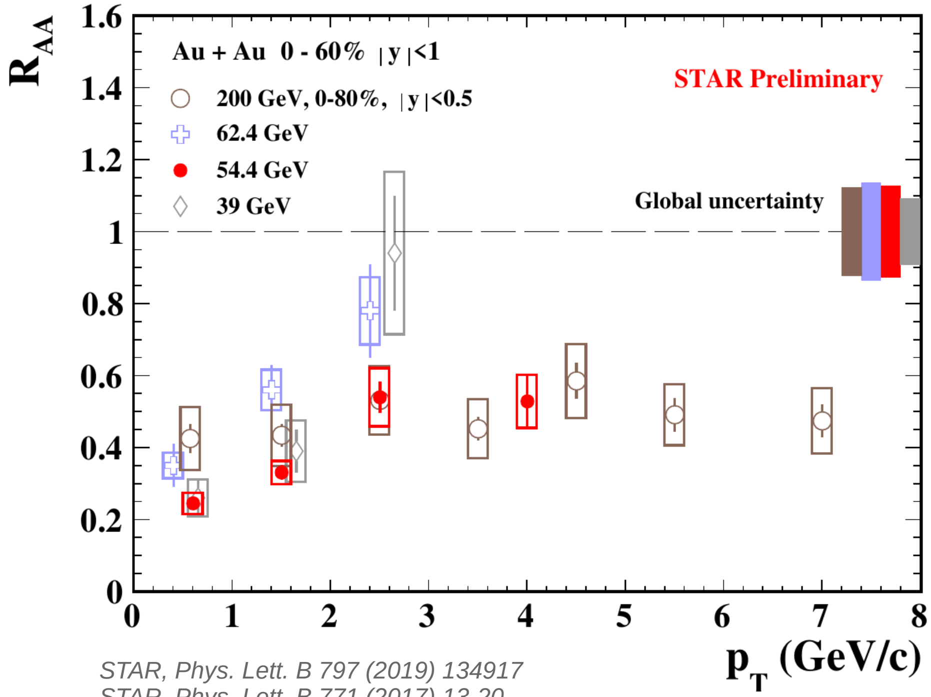


STAR, Phys. Lett. B 825 (2022) 136865

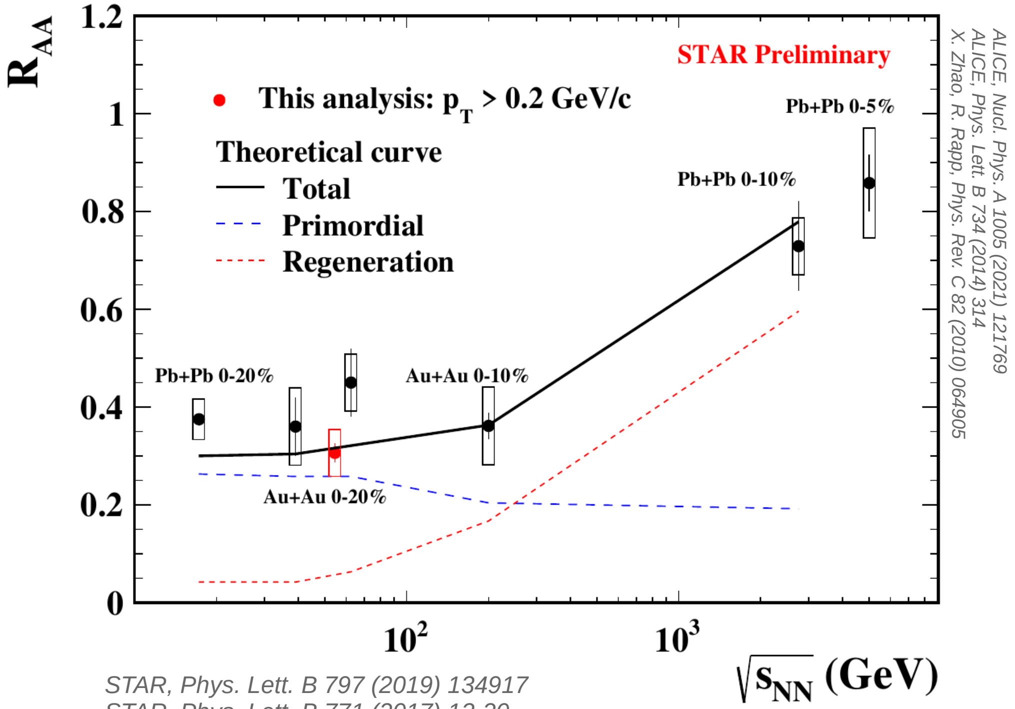
Ma & Vogt, EPS09+NLO, Private Comm.
Lansberg & Shao, nCTEQ15, EPS09+NLO, Eur.Phys.J. C77 (2017) no.1, 1
Ferreiro et al., nDSg+σ abs, Few Body Syst. 53 (2012) 27

- ➔ **Low p_T (< 2 GeV/c): significant CNM effects**. Consistent with nPDFs and nuclear absorption models.
- ➔ High p_T: R_{pAu} consistent with unity → **suppression in AA due to QGP effects**.

Energy dependence of J/ψ R_{AA}



STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13-20



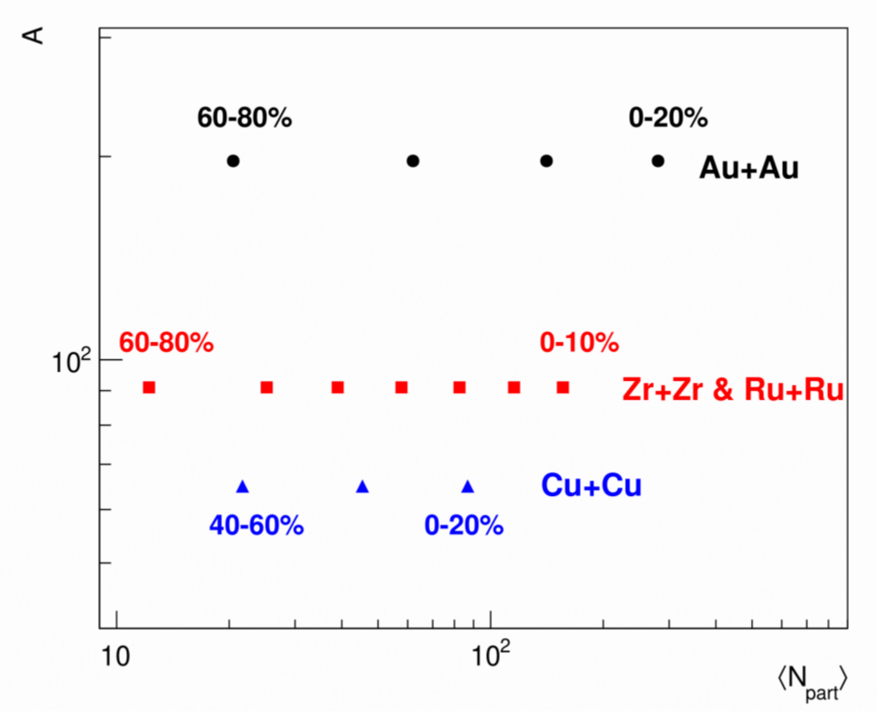
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 771 (2017) 13-20

- ➔ R_{AA} increases with p_T below 3 GeV/c at 39 - 62.4 GeV, less p_T dependence at 200 GeV.
- ➔ **No significant colliding energy dependence** of the J/ψ suppression between 39-200 GeV → interplay of dissociation and regeneration effects.

Isobar collisions at 200 GeV

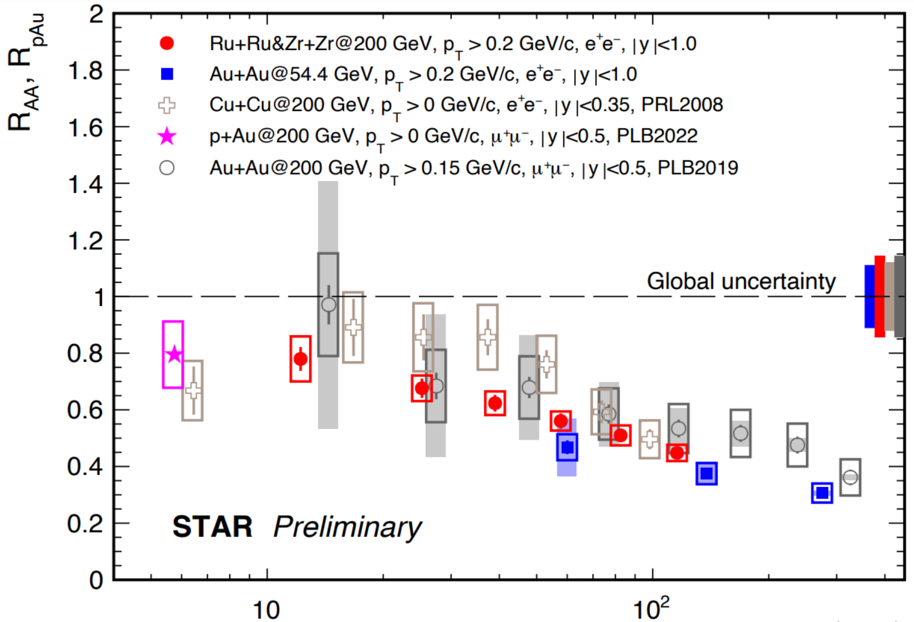
$^{96}_{44}Ru + ^{96}_{44}Ru$ **and** $^{96}_{40}Zr + ^{96}_{40}Zr$

- Moderate size collision system, between Au+Au and Cu+Cu.
- Large sample: ~ 4 billion minimum bias events and high-tower trigger events.
- Event Plane Detector: reduction of non-flow effects in v_2 analysis.
- Study dependence of hot nuclear medium effects on medium size and geometry.

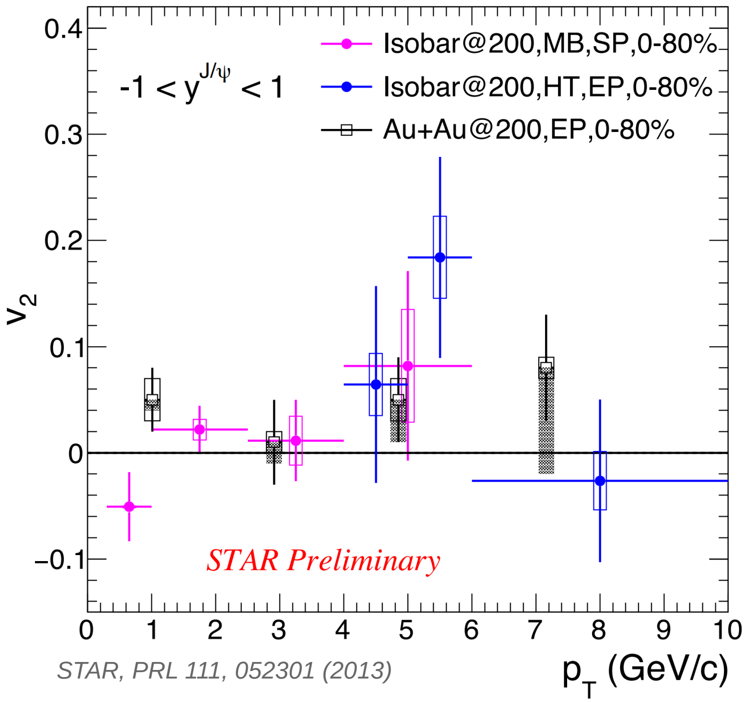


J/ψ R_{AA} and v_2 in isobar collisions

- Dissociation vs regeneration effects: system size and geometry dependence.



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

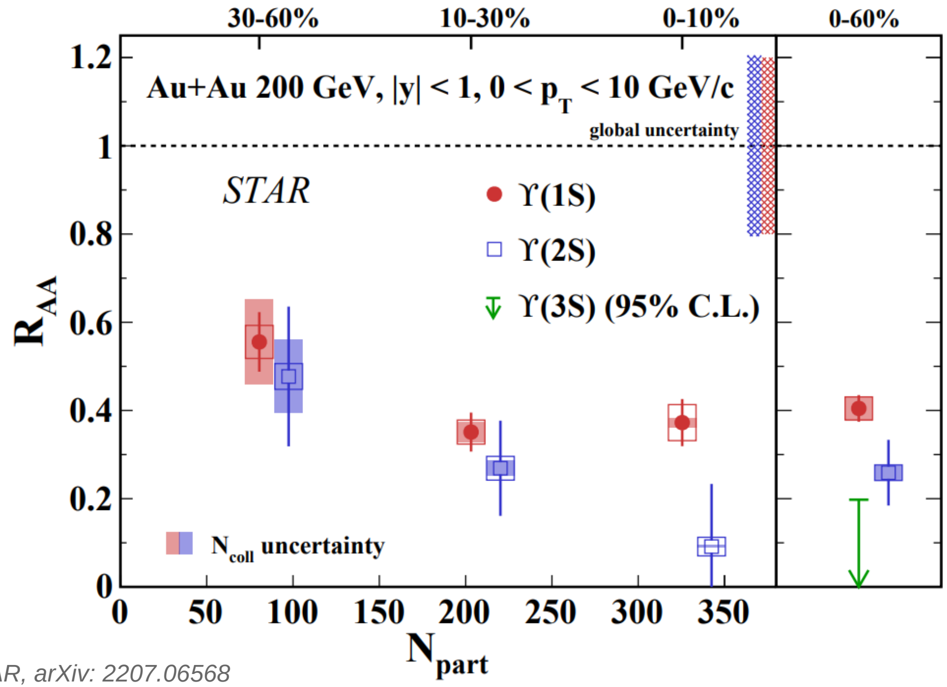


STAR, PRL 111, 052301 (2013)

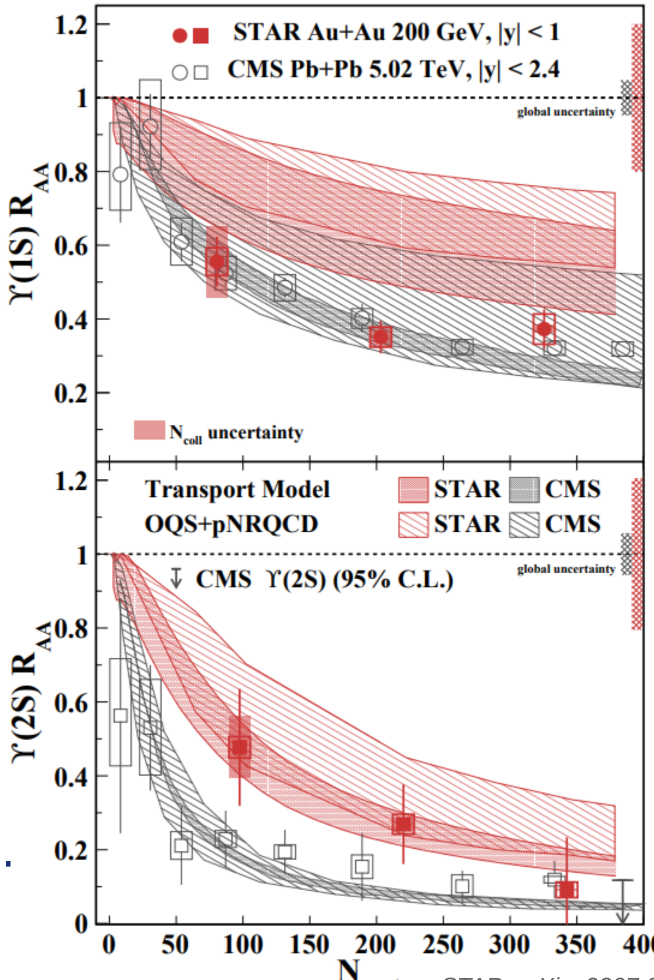
→ **No significant collision system dependence** of the J/ψ suppression at similar N_{part}.

→ Elliptic flow (v_2) consistent with zero for p_T < 4 GeV/c at $\sqrt{s_{NN}}$ = 200 GeV → small regeneration or/and small charm quark flow.

Suppression of ϒ states in Au+Au



STAR, arXiv: 2207.06568



Transport, PRC 96 (2017) 054901
OQS+pQCD, arXiv:2205.10289

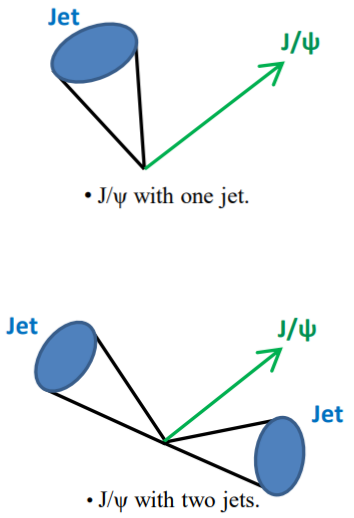
STAR, arXiv: 2207.06568

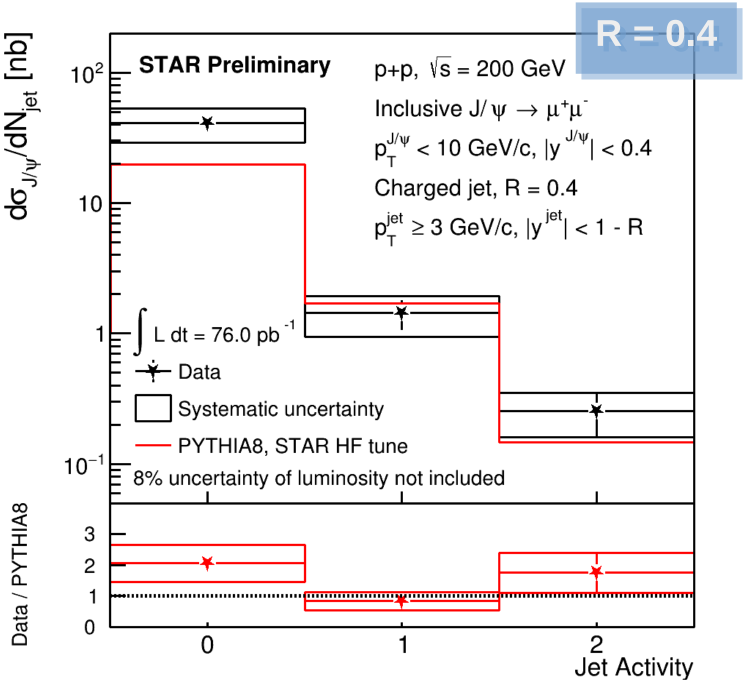
- Sequential suppression of ϒ states at RHIC.
- ϒ(1S): similar magnitude of suppression at RHIC and LHC.
- ϒ(2S): hint of less suppression at RHIC in peripheral collisions.

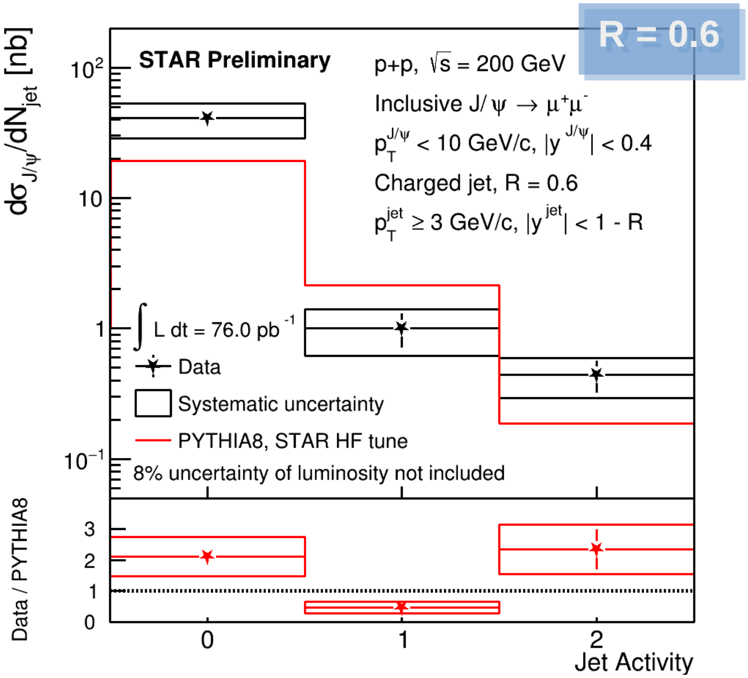
J/ψ production with jet activity in p+p

- Constraining J/ψ production mechanism: color singlet vs color octet state.

Lansberg, Physics Reports, 889, 1 (2020)





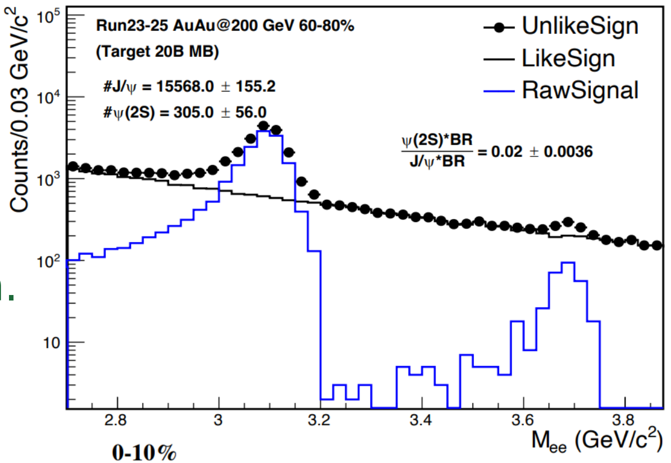


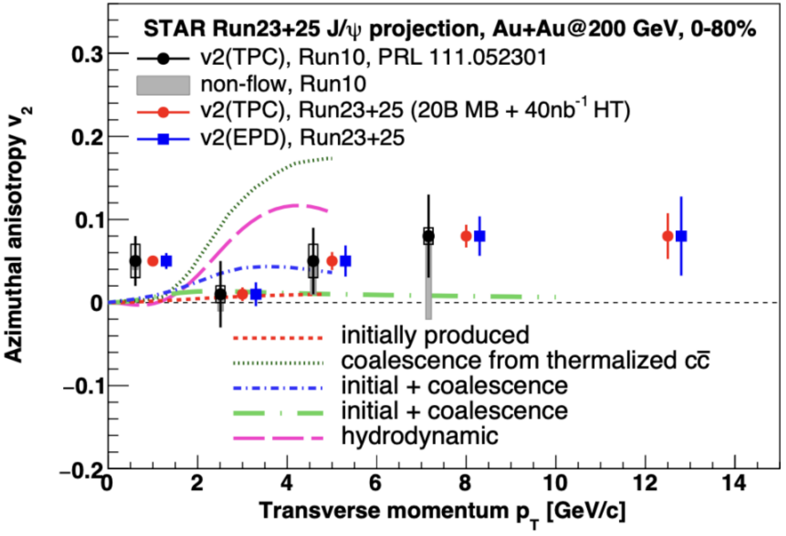
➔ J/ψ production cross section as a function of jet activity for R = 0.4 and R = 0.6 jets.

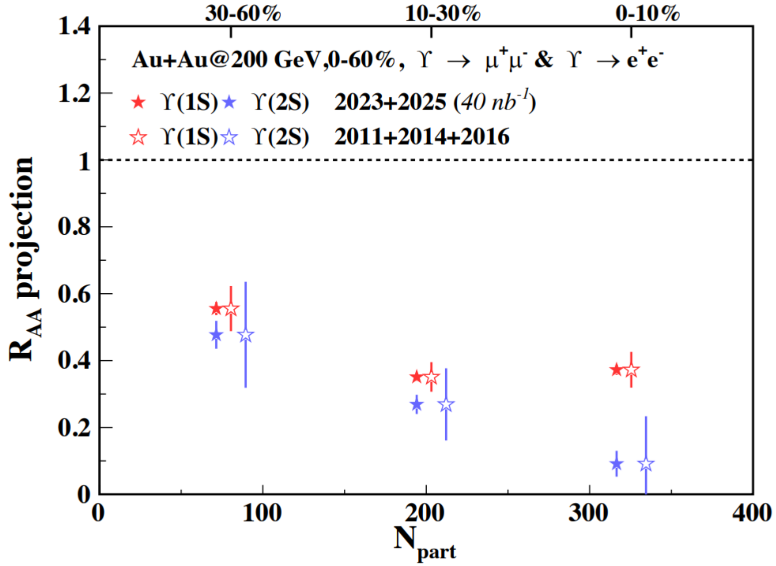
➔ **For the measured kinematics, PYTHIA8 predicts larger fraction of J/ψ produced in association with jets than that observed in data.**

Outlook – 2023 and 25

- High luminosity Au+Au runs at 200 GeV
  1. First ψ(2S) measurement in Au+Au at RHIC.
     - ➔ Regeneration contribution and temperature profile of QGP.
  2. Improved J/ψ v_2 measurement with reduced non-flow effects.
     - ➔ Regeneration contribution and charm quark thermalization.
  3. Precision ϒ measurements (~30% statistical uncertainty for ϒ(3S)).
     - ➔ Medium temperature.





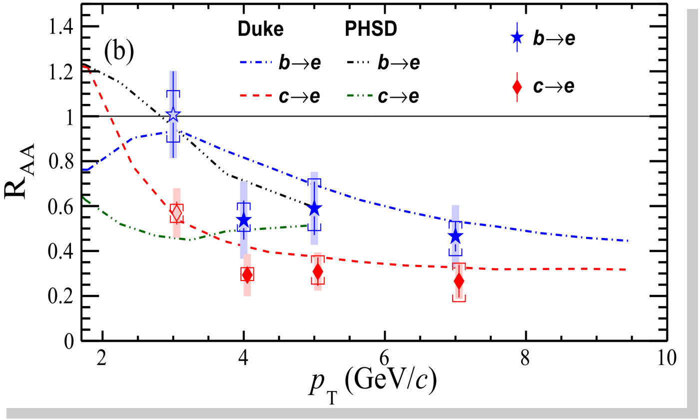


Summary of heavy flavor in STAR

1 Strong charm quark interactions with QGP
- Constrains on diffusion coefficient

2 b quarks loose less energy than c quarks
- Mass dependent parton energy loss

3 Λ_C/D^0 and D_s/D^0 enhancement
- Importance of charm quark coalescence



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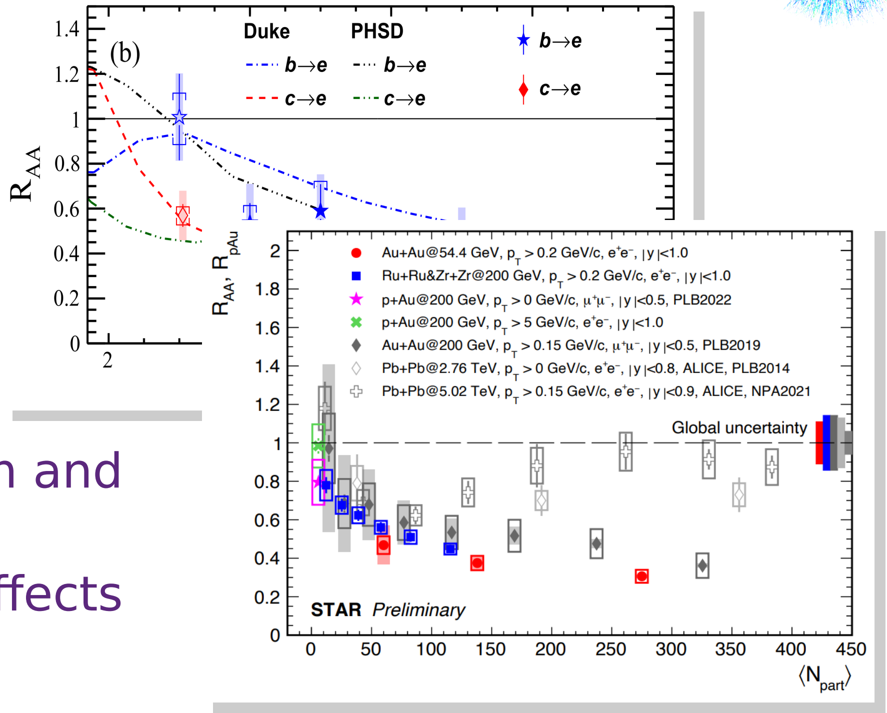
- Interplay of dissociation and regeneration effects

5 J/ψ v_2 consistent with zero in isobar collisions
- Small regeneration effects



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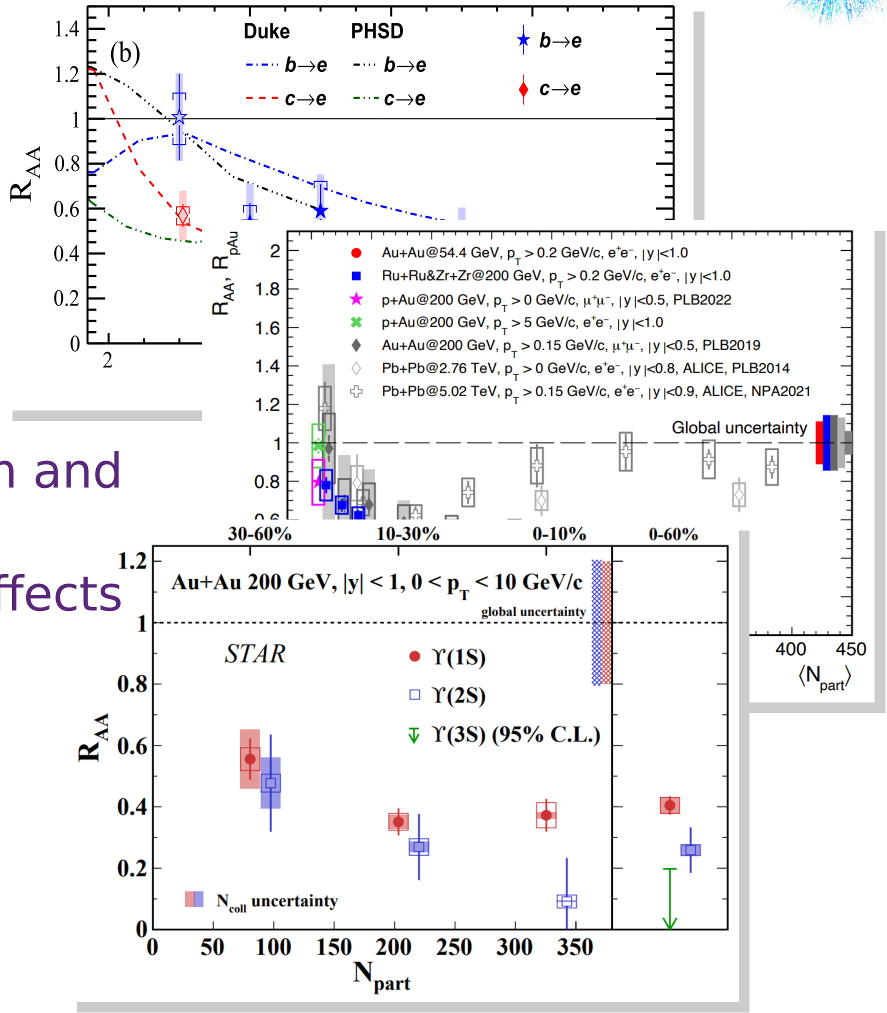
- Small regeneration effects

6 Sequential Υ suppression at RHIC
- Thermodynamic properties of the medium



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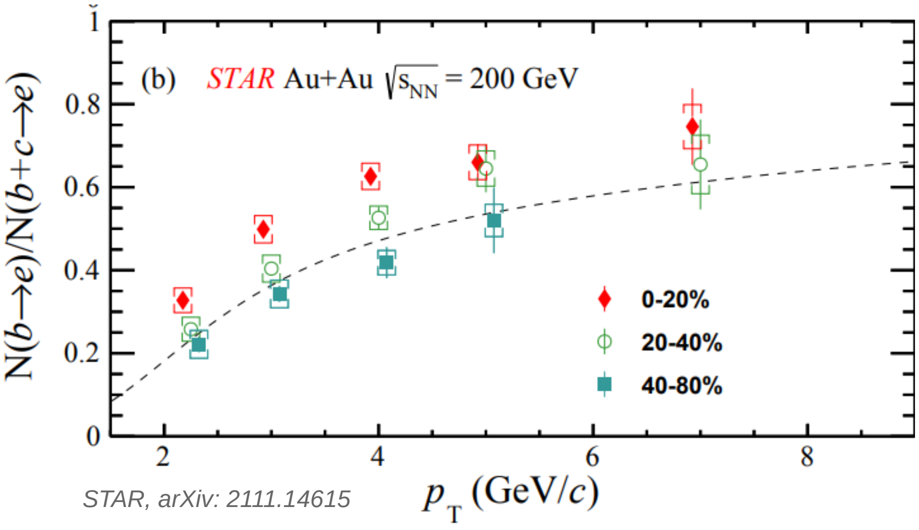
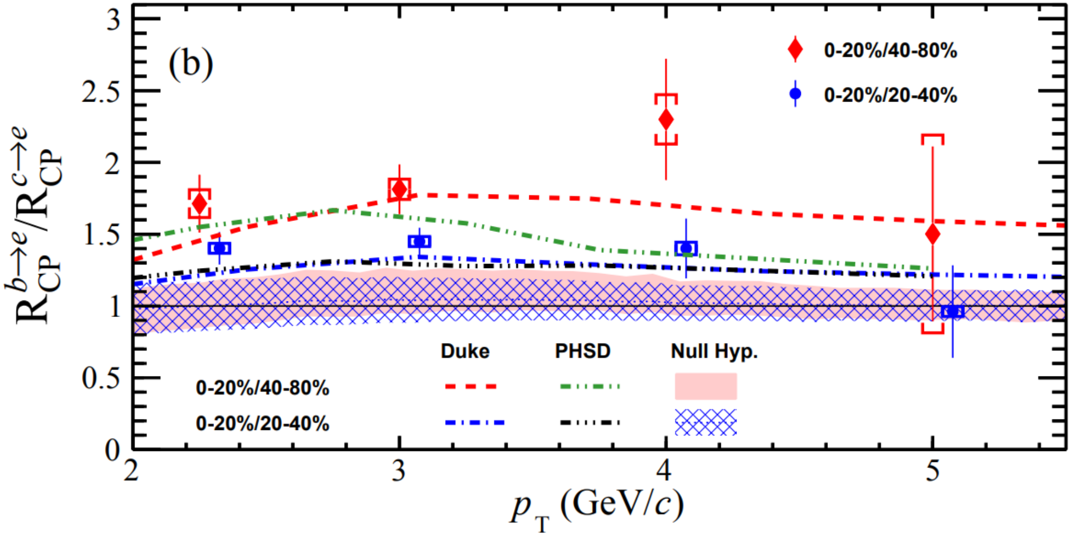
Backup

Mass dependence of parton energy loss

- Heavy-flavor hadron decayed electrons: c → e and b → e separation thanks to HFT.



STAR, arXiv: 2111.14615



Duke, Phys. Rev. C 92, 024907 (2015)
PHSD, Phys. Rev. C 78, 034919 (2008), Nucl. Phys. A 831, 215 (2009)

➔ Bottom-to-charm R_{CP}(0–20%/40–80%) and R_{CP}(0–20%/20–40%) ratios in p_T range 2 - 4.5 GeV/c reject null hypothesis at 4.2 and 3.3σ, respectively.

➔ b quarks lose less energy than c quarks.

Outlook – 2023 and 25

- High luminosity Au+Au runs at 200 GeV
  - ➔ Projected kinematic coverage of the heavy-flavor program.