Recent heavy-flavor measurements from STAR

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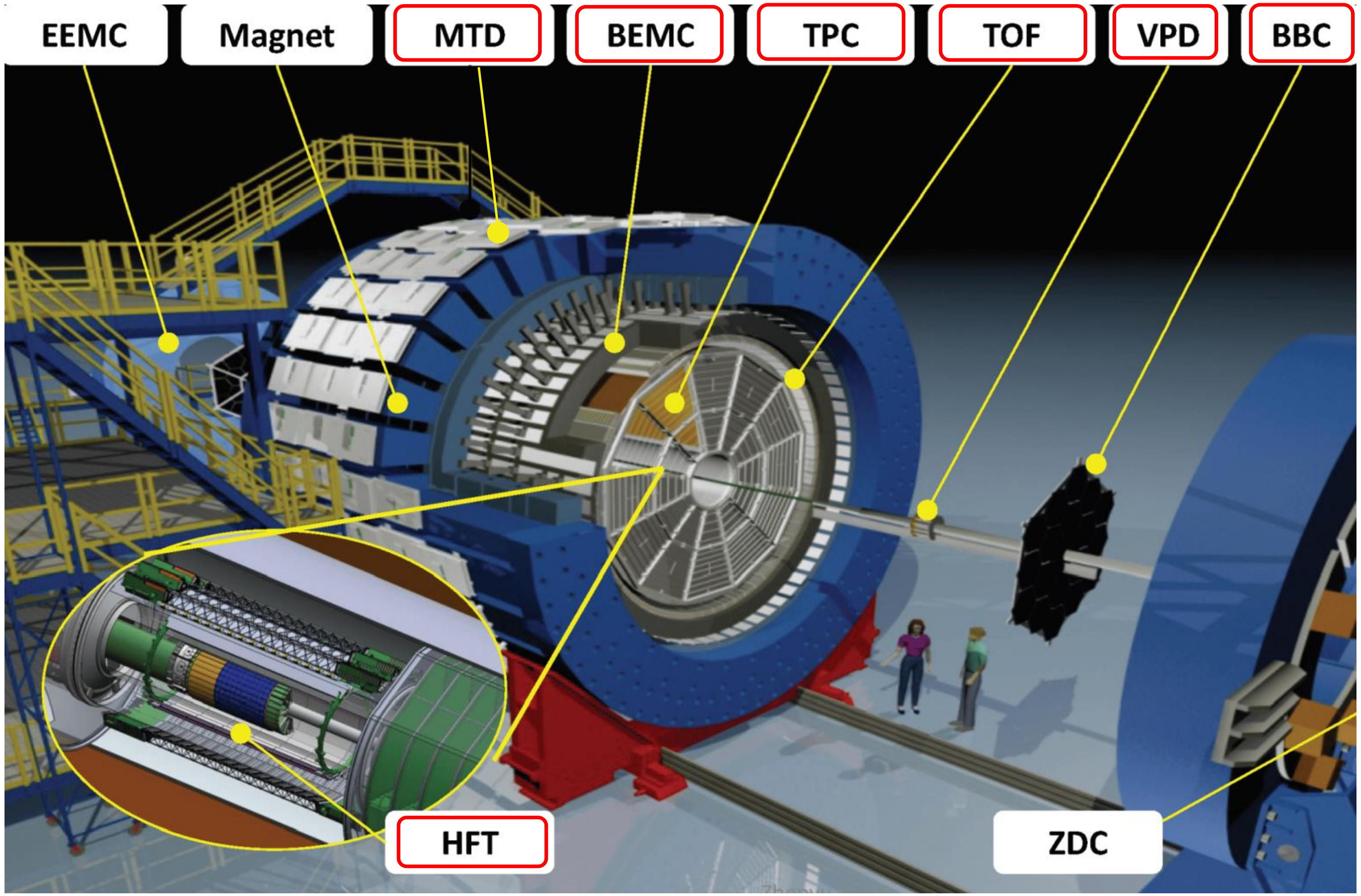
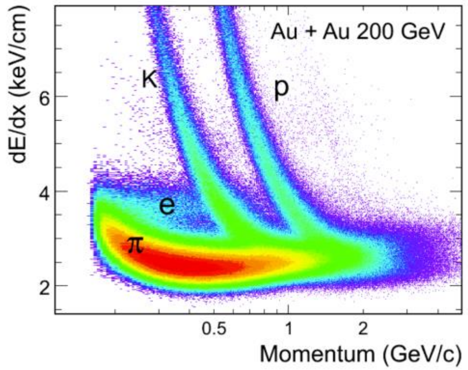
Outlook

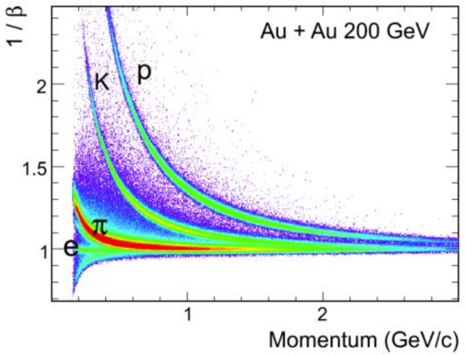
- STAR detector
- Why heavy quarks?
- Heavy-flavor electrons
- Recent results:
  - ➢ Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV arXiv:2303.03546 Accepted by PLB
  - ➢ Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV Phys. Rev. D 105, 032007
  - ➢ $e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV JHEP06(2023)176
  - ➢ Mass ordering of ***c*** and ***b*** quark energy loss *Eur. Phys. J. C* 82, 1150 (2022)
- Quarkonia
- Recent results:
  - ➢ CNM effects for inclusive J/ψ in p+Au @ 200 GeV Phys. Lett. B 825 (2022) 136865
  - ➢ Υ production in isobar collisions @ 200 GeV *STAR Preliminary*
  - ➢ J/ψ elliptic flow in isobar collisions @ 200 GeV *STAR Preliminary*
- Summary and future plans

The Solenoidal Tracker At RHIC (STAR)





- **TPC** – tracking and PID (dE/dx, **p**)
- **BEMC** – high p_T electron identification and triggering

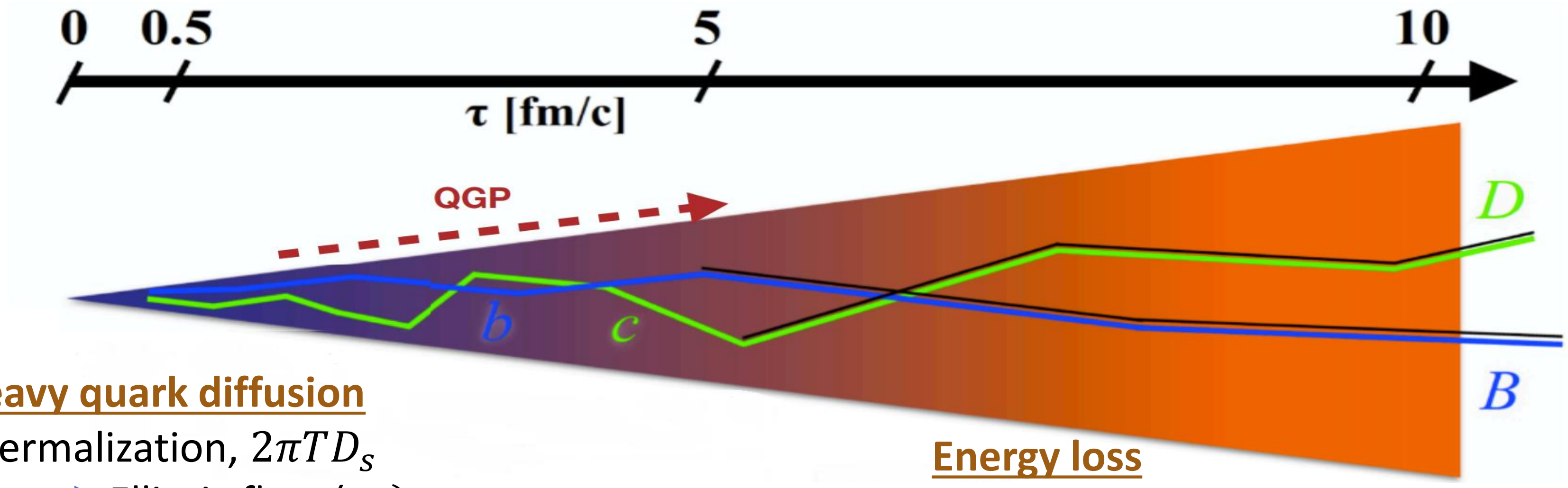


- **TOF** – PID (1/beta)
- **BBC & VPD** – minimum bias trigger
- **MTD** – muon identification and triggering
- **HFT** – topological reconstruction of heavy-flavor hadrons

Heavy quarks (*c* and *b*) = probes of QGP

- Dominantly produced in initial hard scatterings, $m_Q >> \Lambda_{QCD}, m_Q >> T_{QGP}$
- Production cross-sections can be calculated in pQCD
- Participate in the whole medium evolution

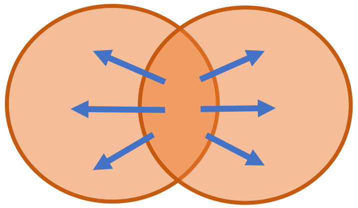
→ **Ideal probes of QGP**



Heavy quark diffusion

Thermalization, $2\pi T D_s$

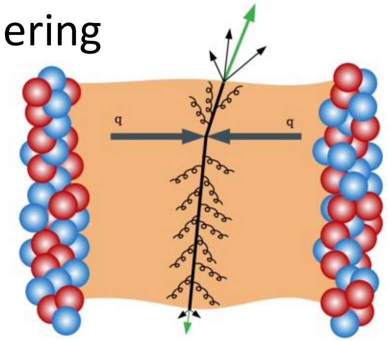
→ Elliptic flow (v_2)



Energy loss

R_{AA}, R_{CP}

Mass ordering



Heavy-flavor electrons (HFE)

- Electrons from semi-leptonic decays of heavy-flavor hadrons
- A mixture of electrons from both ***D*** and ***B*** hadron decays
- HFE BR > hadronic decays of open HF hadrons BR

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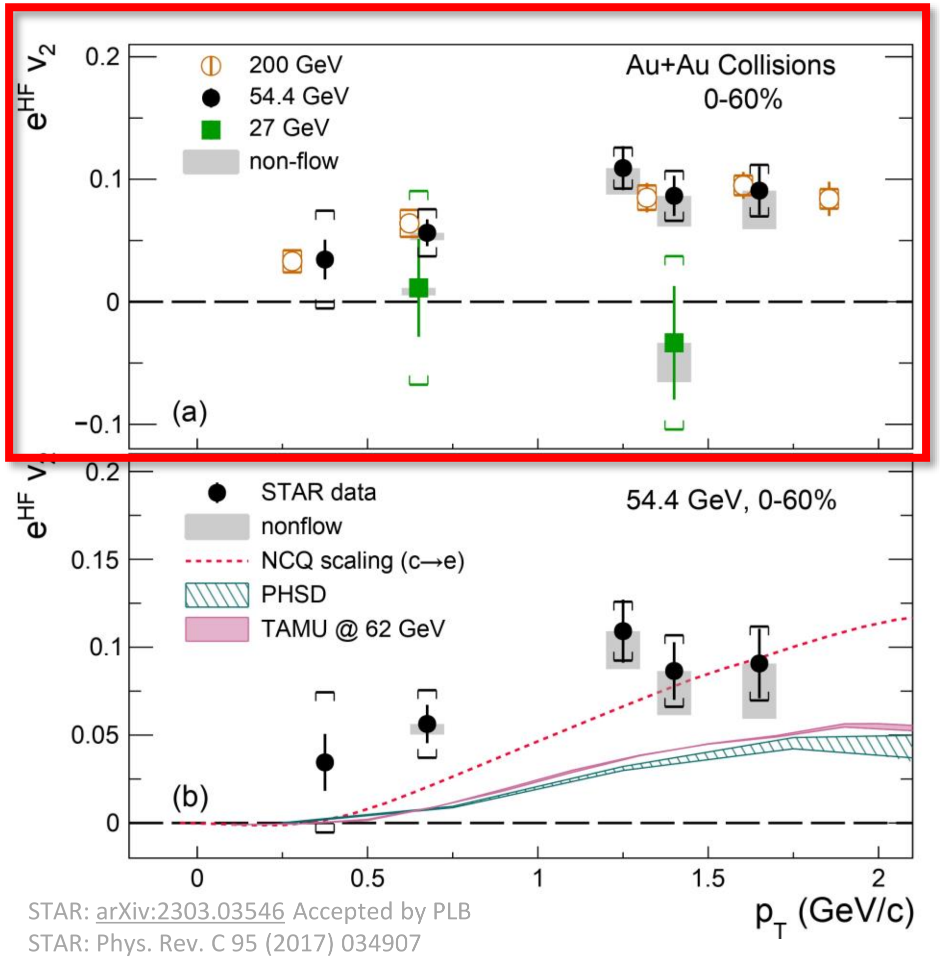
Widely used to study heavy quark (HQ) production

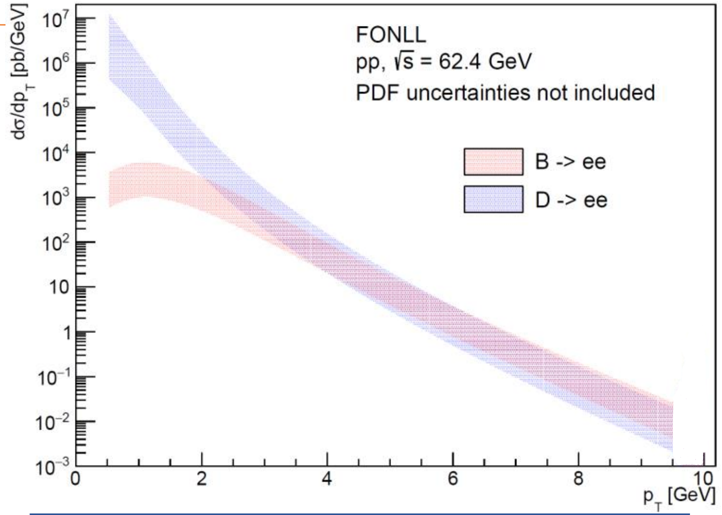
Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV

e^{HF} (HFE) – heavy-flavor electrons



STAR: arXiv:2303.03546 Accepted by PLB
STAR: Phys. Rev. C 95 (2017) 034907

In this $\sqrt{s_{NN}}$ and p_T range ***c*** quark is dominant



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]$$

$$v_2^{\text{non-flow}} = \frac{\langle \sum_i \cos 2(\varphi_e - \varphi_i) \rangle}{M \langle v_2 \rangle}$$

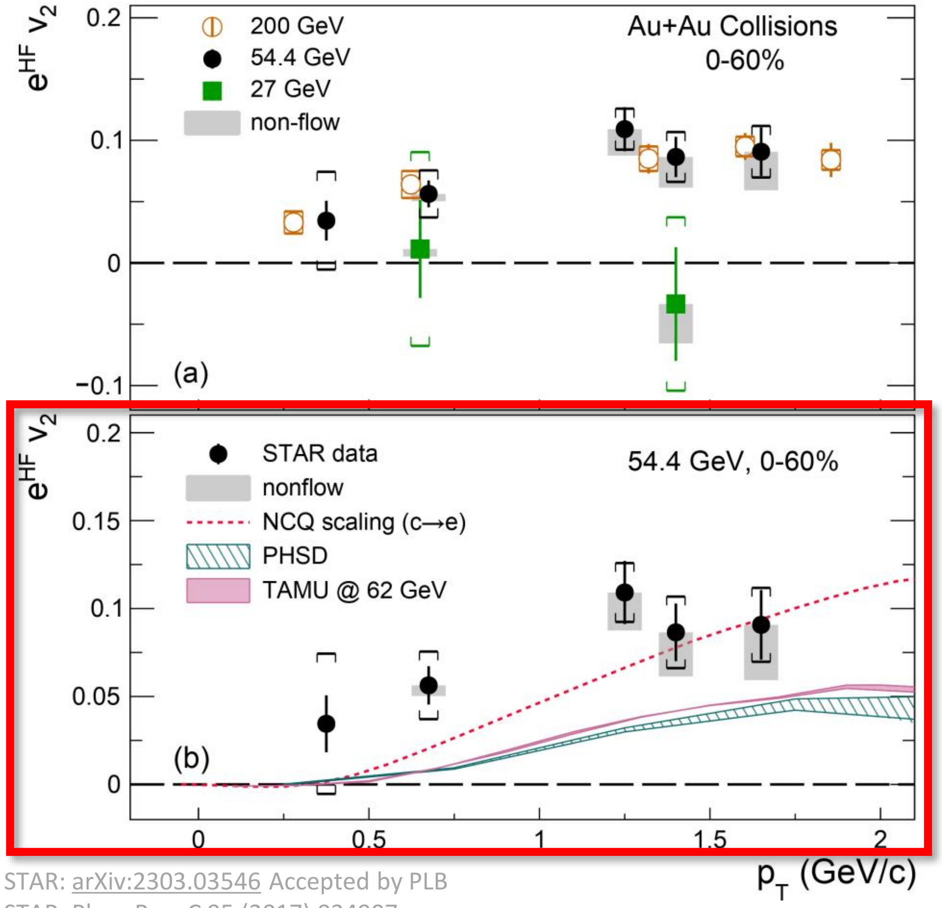
- 54.4 GeV : significant v_2 of e^{HF} →
  - **Strong interaction of *c* quark with QGP**
  - ***c* quarks gain most collectivity at $T \approx T_c$**

Phys. Rev. Lett. 118 (2017) 212301
Phys. Rev. C 91 (2015) 024904

- 27 GeV : v_2 is consistent with 0 →
  - **Deviation of *c* quarks from local thermal equilibrium ?**

Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV

e^{HF} (HFE) – heavy-flavor electrons



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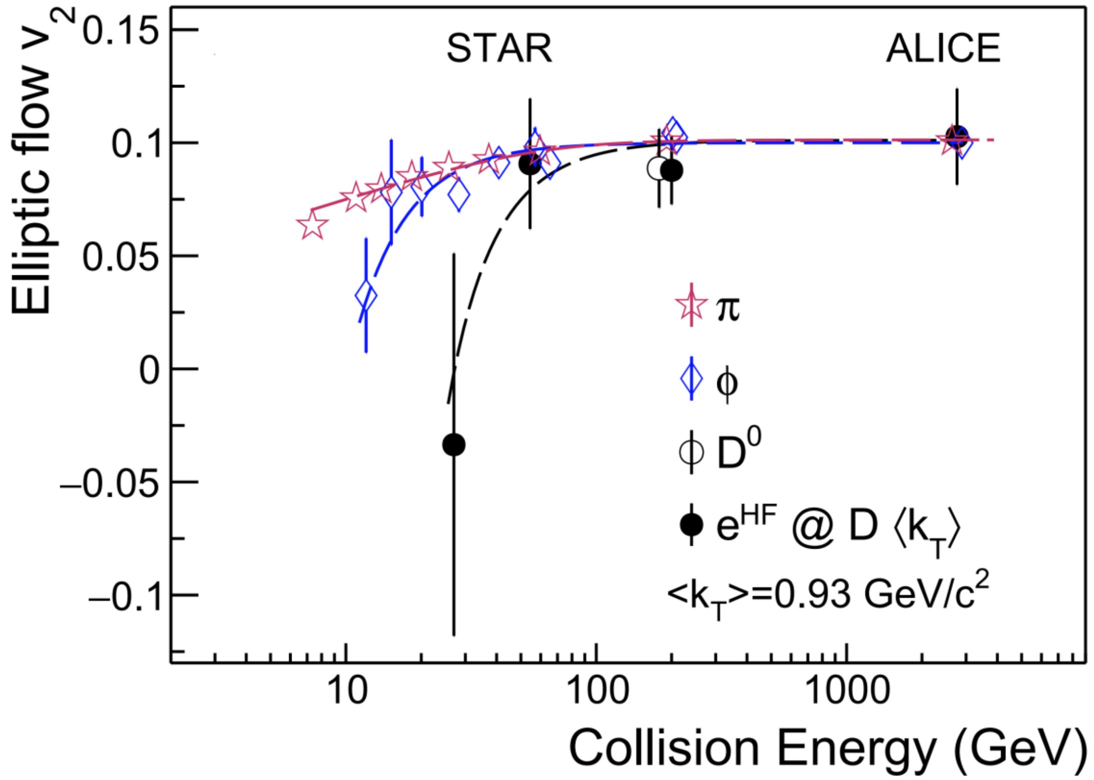
- 27 GeV : v_2 is consistent with 0 →
  - **Deviation of *c* quarks from local thermal equilibrium ?**

- Consistency of NCQ with $e^{HF} v_2$ →
  - ***c*** hadrons obtain significant v_2
  - **Hints of close to thermal equilibrium with the medium at 54.4 GeV**

Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV



STAR: arXiv:2303.03546
STAR: Phys. Rev. C 88 (2013) 014902
STAR: Phys. Rev. Lett. 92 (2004) 052302
STAR: Phys. Rev. C 103 (2021) 064907
ALICE: JHEP 06 (2015) 190
ALICE: Phys. Rev. C 88 (2013) 044910

Indication of v_2 of heavier particles drops faster with decreasing collision energy

↓

Mass hierarchy

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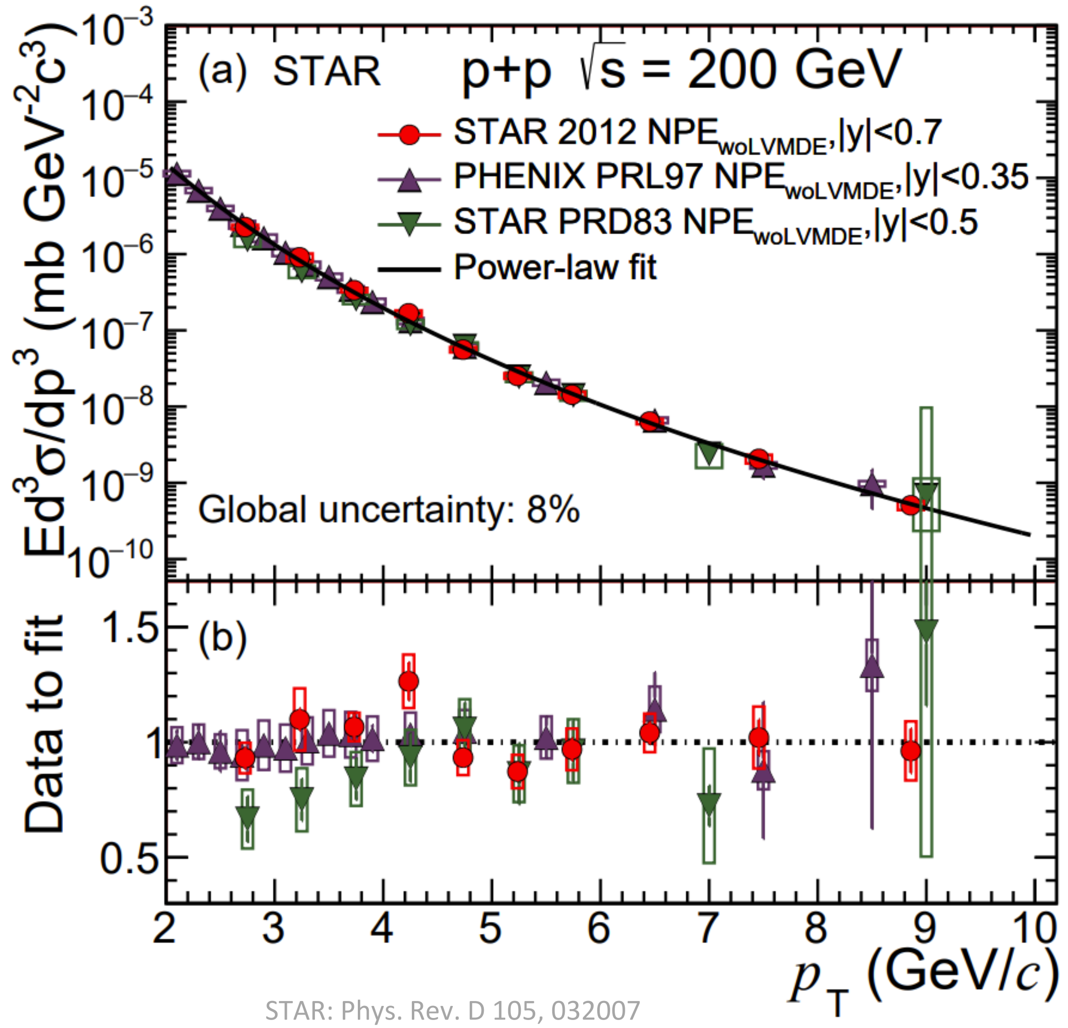
Collision-energy dependent properties of QGP:

The influence of QGP medium on final-state particle dynamics is reduced as the collision energies decrease

Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV



STAR: Phys. Rev. D 105, 032007
STAR: Phys. Rev. D 83, 052006 (2011)
PHENIX: Phys. Rev. Lett. 97, 252002 (2006)

$$E\frac{d^3\sigma}{dp^3}(\mathrm{NPE_{woLVMDE}}) = \frac{1}{2}\frac{1}{L}\frac{N_{NPE}}{2\pi p_T \Delta p_T \Delta y} - E\frac{d^3\sigma}{dp^3}(LVMDE)$$

LVMDE = ρ, ω, ϕ decays

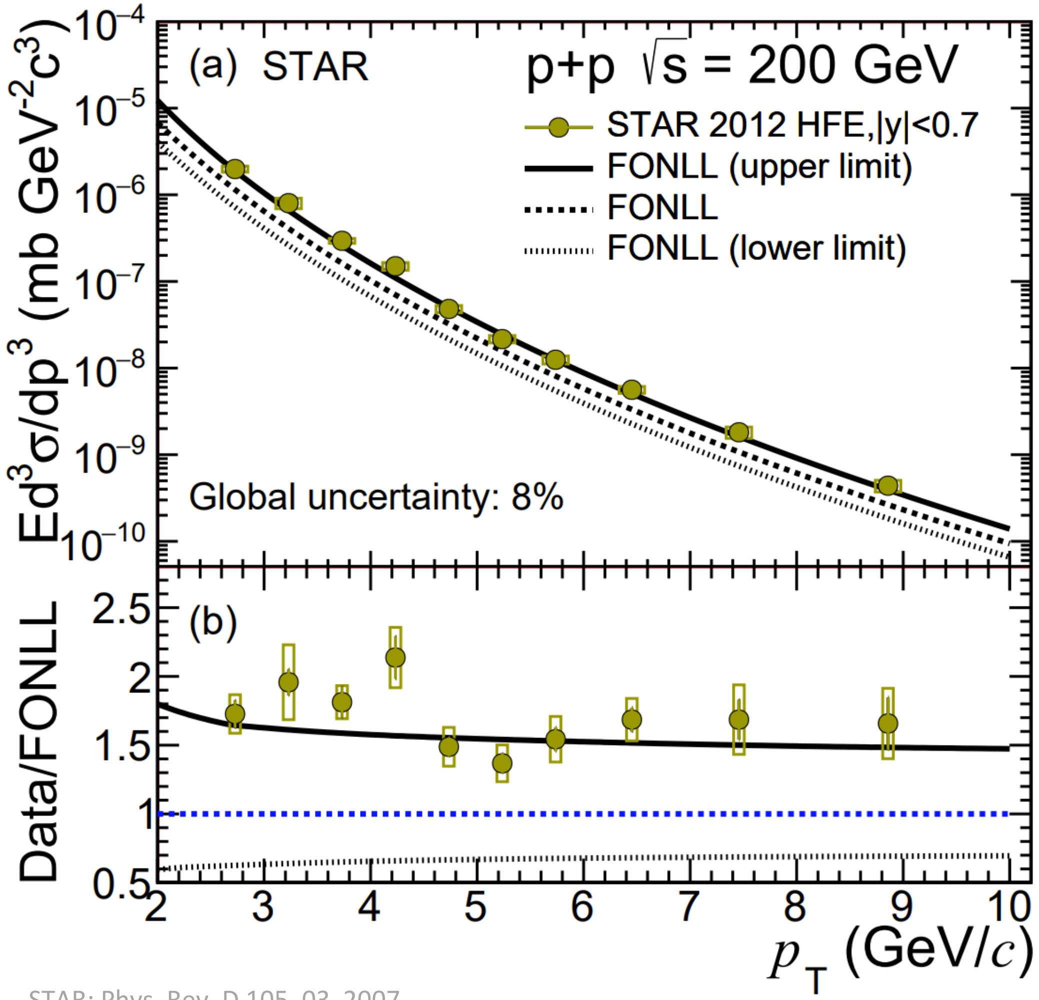
- Good agreement among the results
- Precision improvement at p_{T} > 6 GeV/c

Power-law fit:

$$f(p_T) = \frac{A}{(1 + p_T/B)^n}$$

$\boldsymbol{n = 8.99 \pm 0.26}$

Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV



STAR: Phys. Rev. D 105, 03 2007

$$E\frac{d^3\sigma}{dp^3}(\mathrm{HFE}) = \frac{1}{2}\frac{1}{L}\frac{N_{NPE}}{2\pi p_T \Delta p_T \Delta y} - E\frac{d^3\sigma}{dp^3}(HDE)$$

HDE = ρ, ω, ϕ + J/ψ, Υ + Drell-Yan + K_{e3}

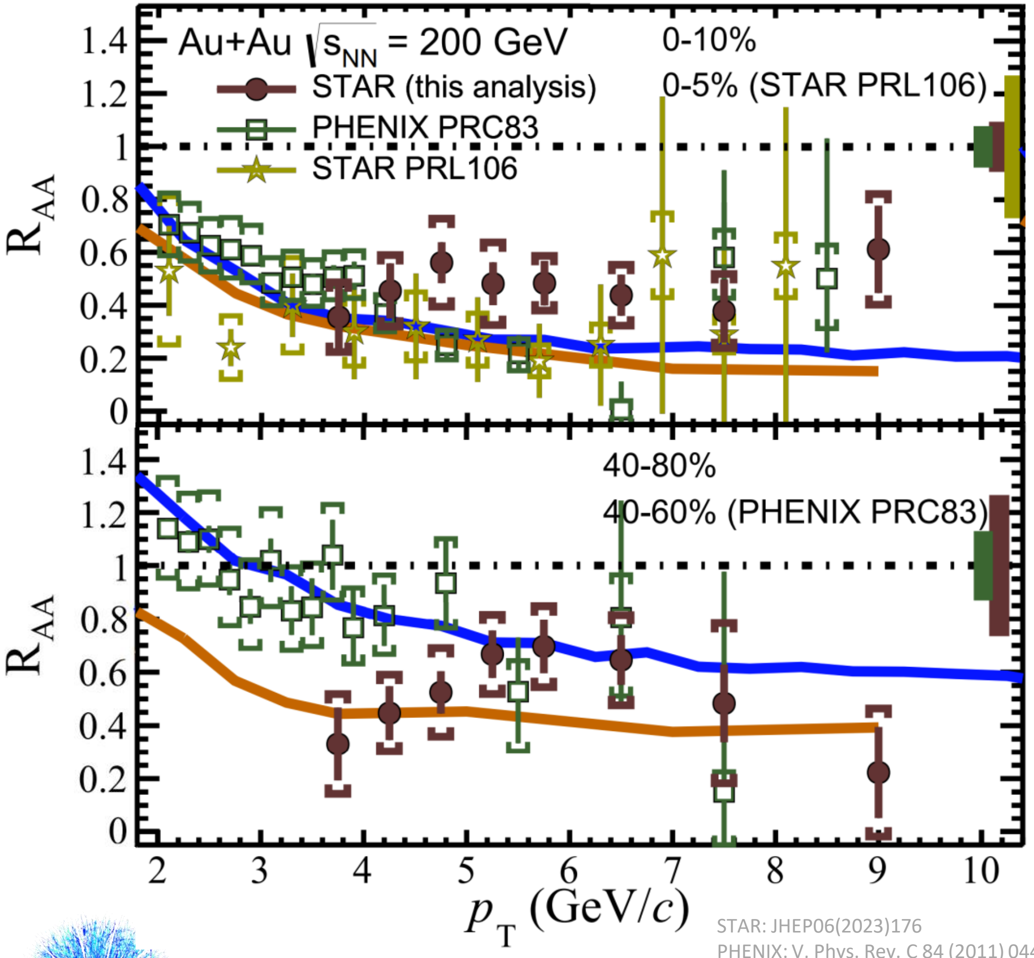
- Consistency with the upper limit of the FONLL uncertainty

- Further constraints on theoretical calculations
- Precise reference for R_{AA} measurements for HDE

$e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}^2/\, dp_T\, dy}{dN_{pp}^2/\, dp_T\, dy}$$

Duke model
PHSD model



STAR: JHEP06(2023)176
PHENIX: V, Phys. Rev. C 84 (2011) 044905
STAR: Phys. Rev. Lett. 98 (2007) 192301.

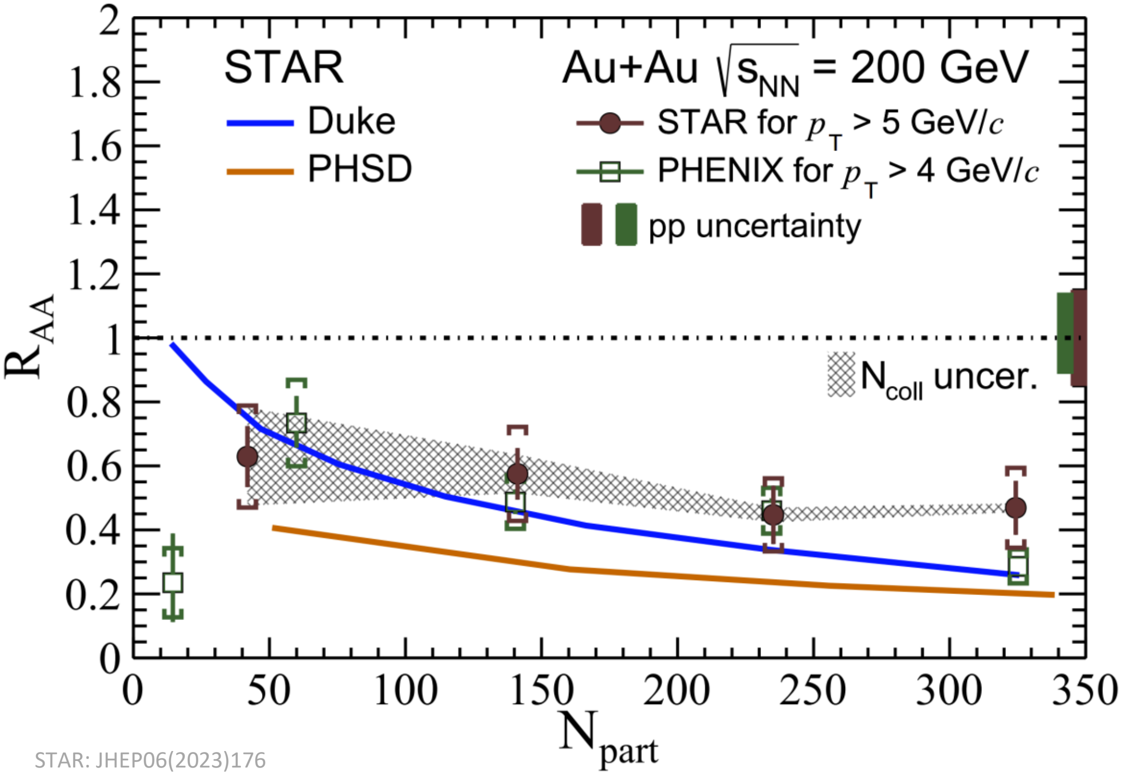
- Suppression by factor of 2 in central collisions within $3.5 < p_T < 8$ GeV/c

Significant energy loss of HQ in QGP

- **New results vs PHENIX:** precision improvement for $p_T > 6$ GeV/c
- **New results vs STAR:** reduction of uncertainties & measurement extension beyond central collisions
- **New results vs models:** agreement with data within uncertainties

$e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV

$$R_{AA}^{incl} = \frac{1}{N_{coll}} \times \frac{dN_{AA}^2/\,dp_T\,dy}{dN_{pp}^2/\,dp_T\,dy}$$



STAR: JHEP06(2023)176
PHENIX: V, Phys. Rev. C 84 (2011) 044905
STAR: Phys. Rev. Lett. 98 (2007) 192301.

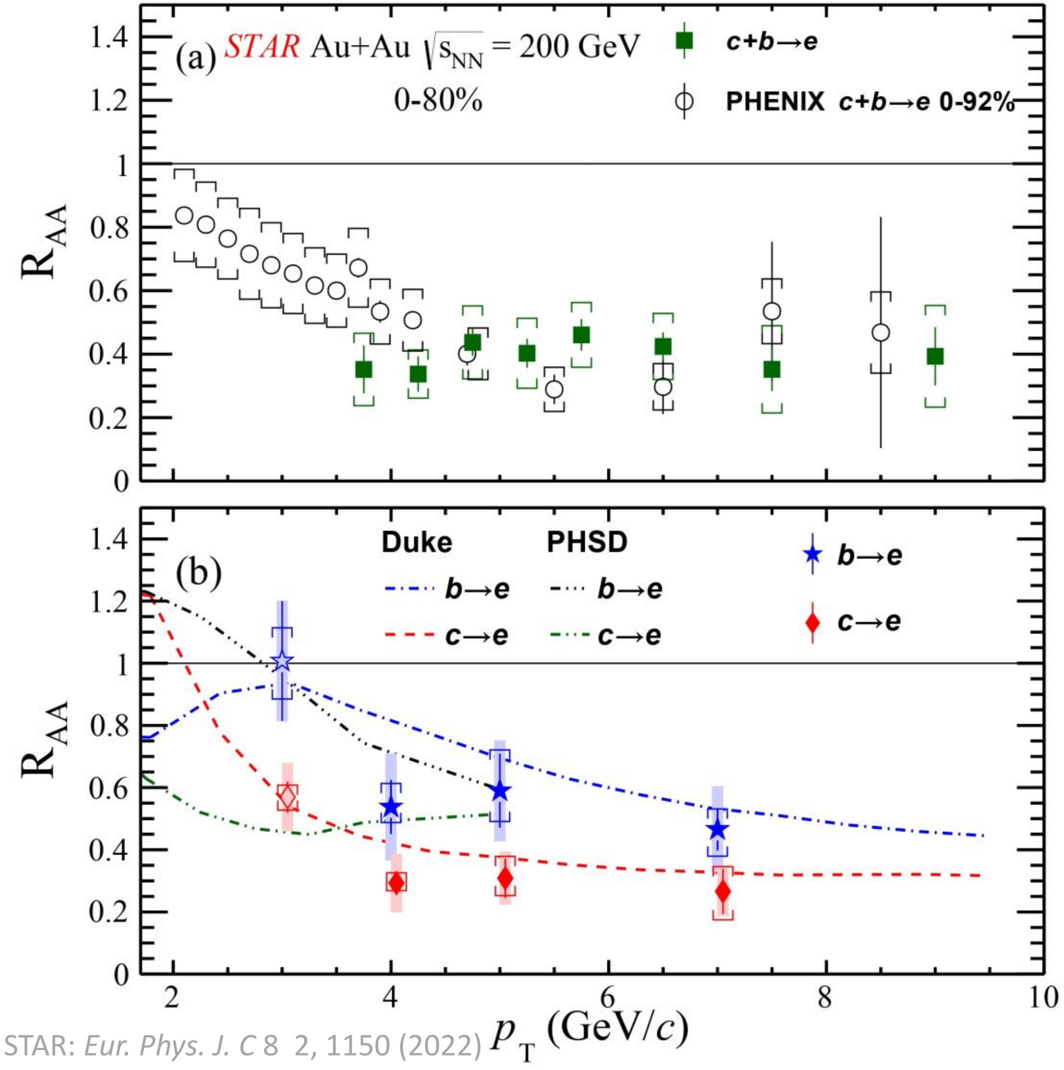
- A hint of HFE R_{AA} decreasing from peripheral to central collisions

Stronger parton energy loss in central collisions

- Consistency with PHENIX results
- Qualitative description of data by Duke and PHSD models

Mass ordering of *c* and *b* quark energy loss

$$R_{AA}^{incl} = \frac{1}{N_{coll}} \times \frac{dN_{AA}^2/\,dp_T\,dy}{dN_{pp}^2/\,dp_T\,dy}$$



STAR: *Eur. Phys. J. C* 8 2, 1150 (2022)
PHENIX: Phys. Rev. C 8 4, 044905 (2011)

$$R_{AA}^{b\to e} = f_b^{AA}/f_b^{pp} \times R_{AA}^{incl}$$

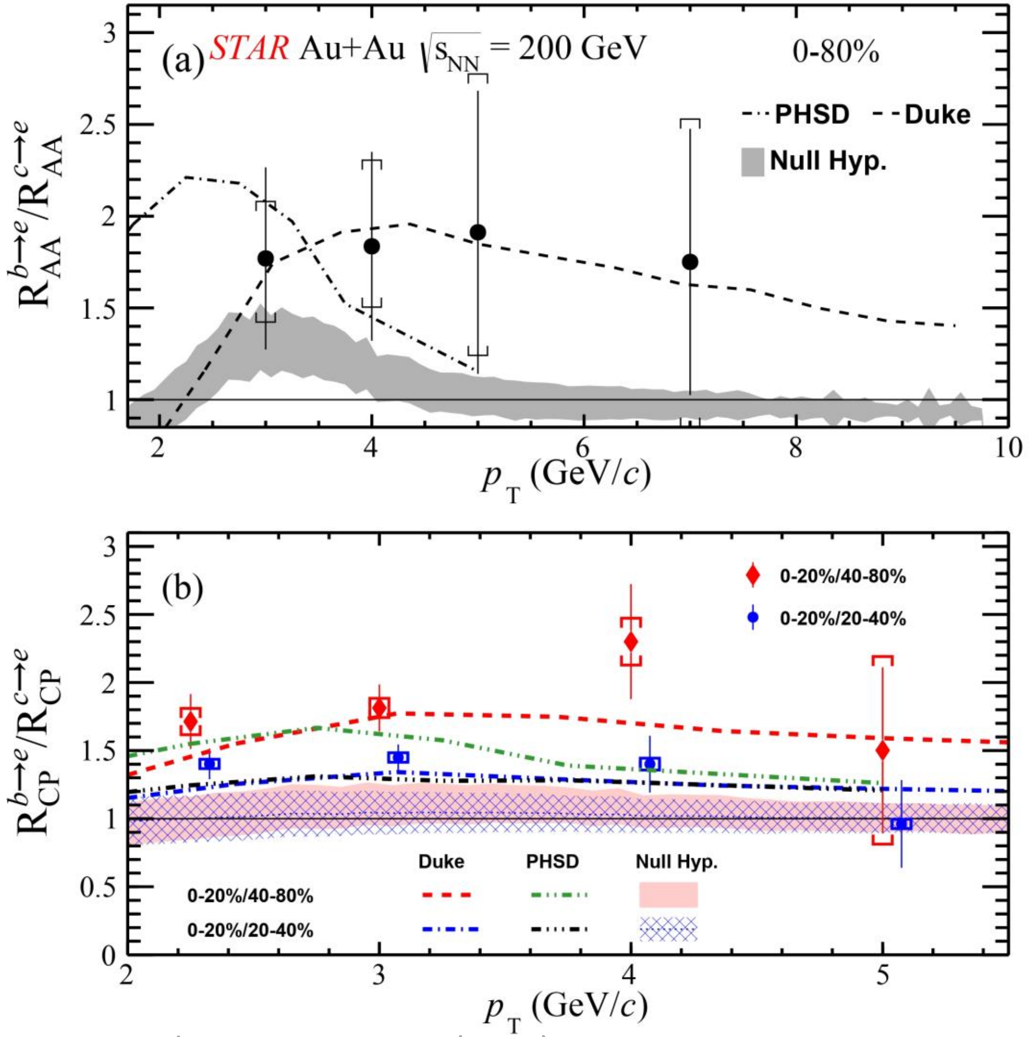
$$R_{AA}^{c\to e} = (1 - f_b^{AA})/(1 - f_b^{pp}) \times R_{AA}^{incl}$$

f_b^{AA} - fraction measured in Au+Au

Possible to measure **thanks to HFT!**

- Compatibility with PHENIX measurement
- Larger suppression of *c-decay* $e^{\pm}$ than *b-decay* $e^{\pm}$
- Improved precision
- Good agreement with both Duke and PHSD models

Mass ordering of c and b quark energy loss



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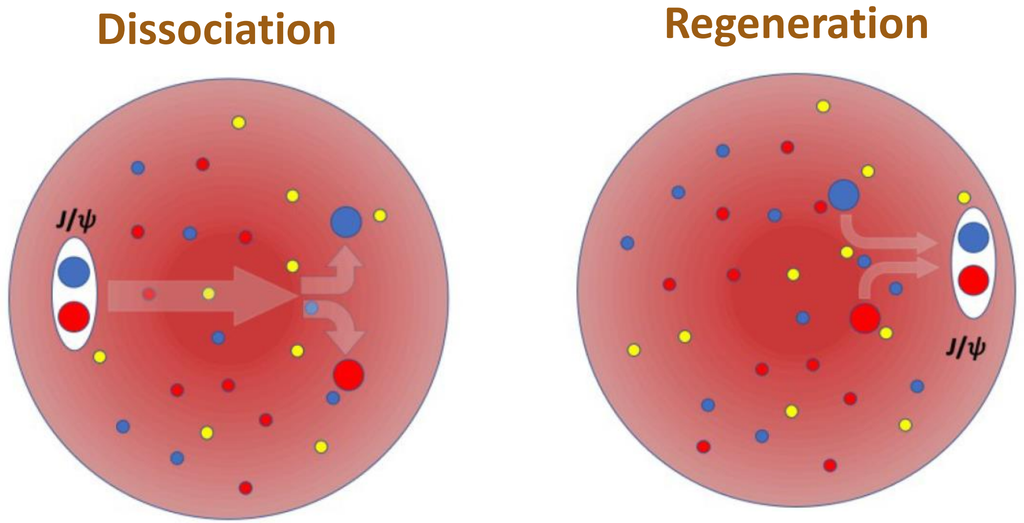
$$R_{AA}^{b\to e} = f_b^{AA}/f_b^{pp} \times R_{AA}^{incl}$$

$$R_{AA}^{c\to e} = (1 - f_b^{AA})/(1 - f_b^{pp}) \times R_{AA}^{incl}$$

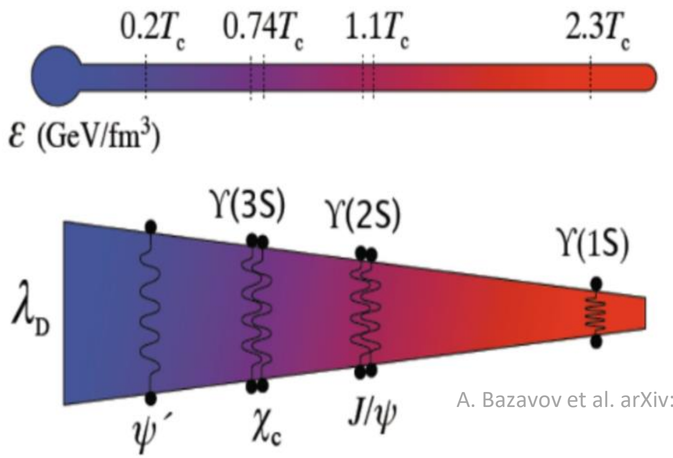
- $R_{AA}^{b\to e} > R_{AA}^{c\to e}$ → **Evidence of mass ordering!**
- Significant deviation of both R_{CP} from unity
- Good agreement with both Duke and PHSD models

Why quarkonia?

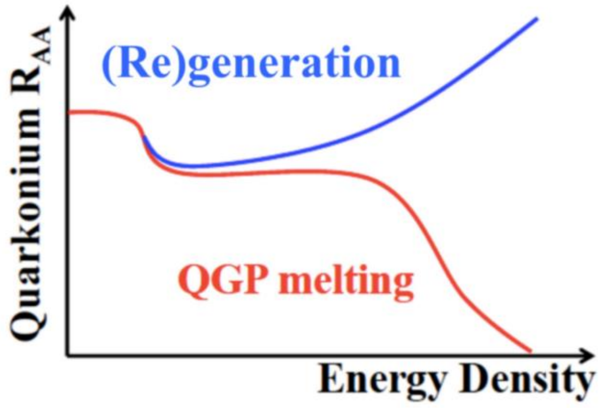
- Observation of quarkonium suppression in HIC = strong evidence for QGP formation, important probes of the medium T
- Hot nuclear matter effects:
  - ➢ **Dissociation** due to color screening and **regeneration**



- Sequential quarkonium suppression due to different binding energies (quarkonium state size > $\lambda_D \sim 1/T_C$)



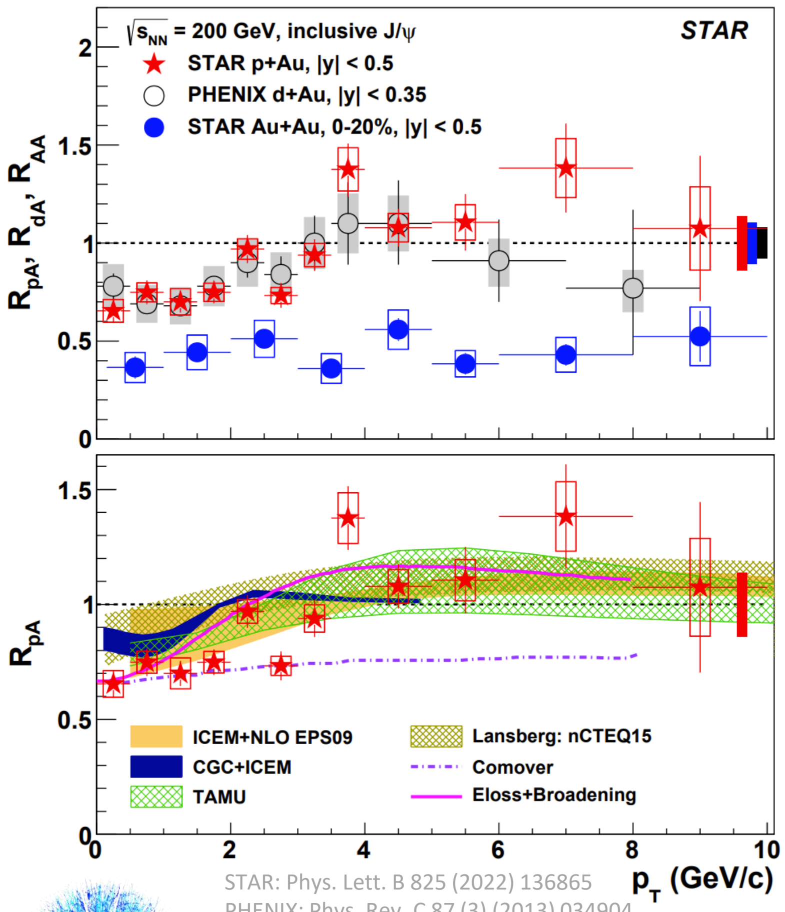
A. Bazavov et al. arXiv:1904.09951



- Cold Nuclear Matter (CNM) effects:
  - ➢ Modification of PDFs, nuclear absorption, coherent energy loss, co-mover absorption, ... - study in p+A collisions
- Production mechanism - study in p+p collisions

CNM effects for inclusive J/ψ in p+Au @ 200 GeV

$$\bigstar\ R_{pAu} = \frac{1}{<T_{AA}>} \times \frac{\left(\frac{d^2 N_{J/\psi}}{dp_T\, dy}\right)_{p+Au}}{\left(\frac{d^2 \sigma_{J/\psi}}{dp_T\, dy}\right)_{p+p}}$$



STAR: Phys. Lett. B 825 (2022) 136865
PHENIX: Phys. Rev. C 87 (3) (2013) 034904
STAR: Phys. Lett. B797 (2019) 134917

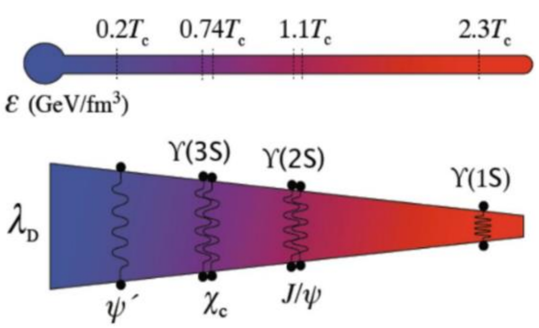
- Suppression of ~ 30 % below 2 GeV/c
- Consistency with 1 above 3 GeV/c →
  - Little CNM effects on J/ψ production
  - Similar CNM effects as for d+Au
- Better precision than for R_{dAu}
- Consistency with the model calculations within uncertainties
- The Comover model: underprediction of the data above 3.5 GeV/c by 2.3σ
- Au+Au: large suppression of J/ψ yield above 3 GeV/c due to hot medium effects
- First measurement within 0 < p_T < 10 GeV/c

ϒ production in isobar collisions @ 200 GeV

Sequential ϒ states suppression observed at RHIC energies in Au+Au

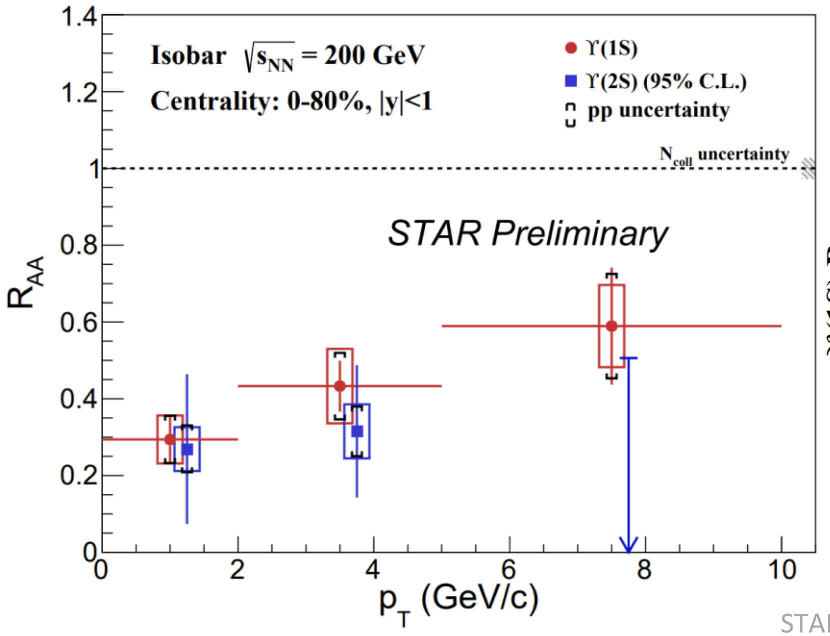
STAR: Phys. Rev. Lett. 130 (2023) 112301

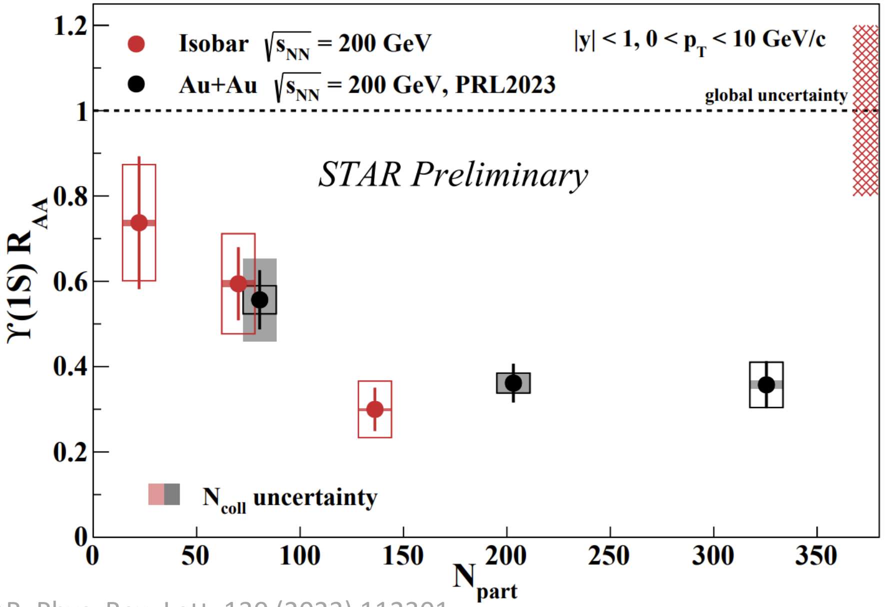
- Dissociation of quarkonium states (quarkonium state size > $\lambda_D \sim 1/T_C$)



- Different levels of suppression of quarkonium states of different sizes

STAR: Phys. Rept. 858 (2020) 1–117





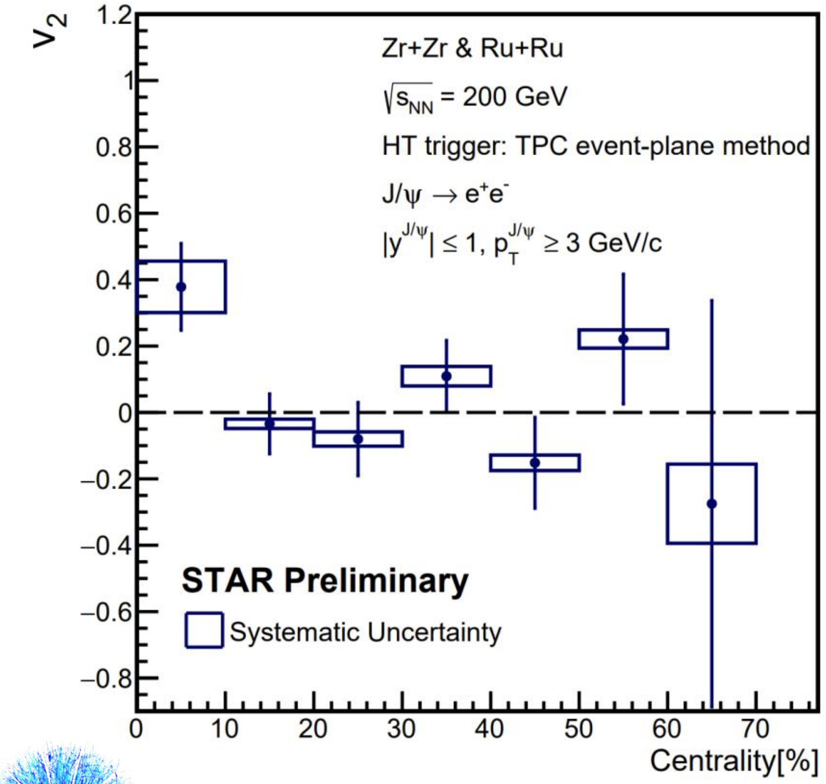
STAR: Phys. Rev. Lett. 130 (2023) 112301

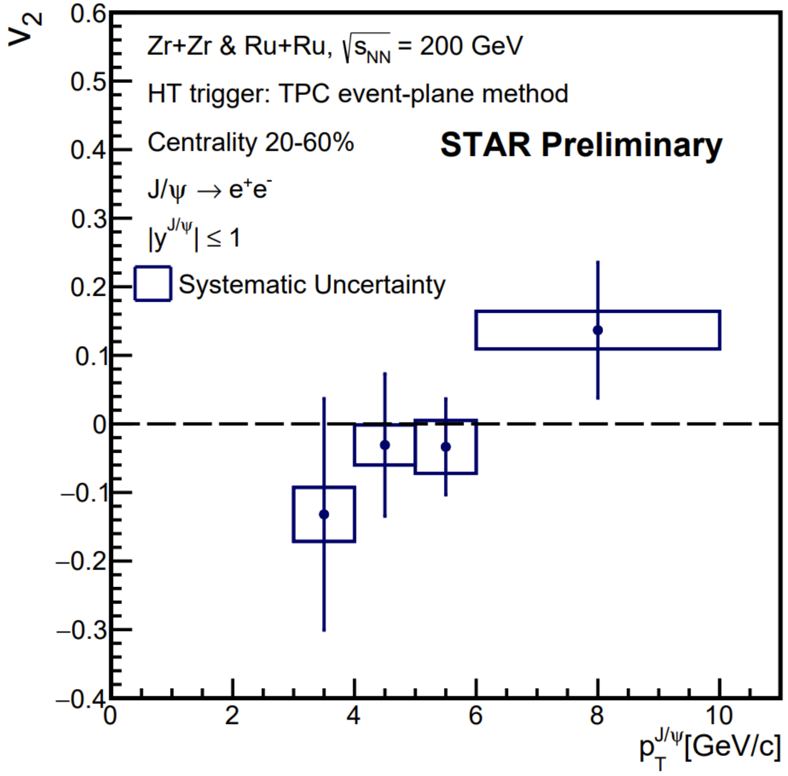
- No significant p_T dependence
- No significant species dependence at the same $<N_{part}>$
- Suppression driven by collision energy density

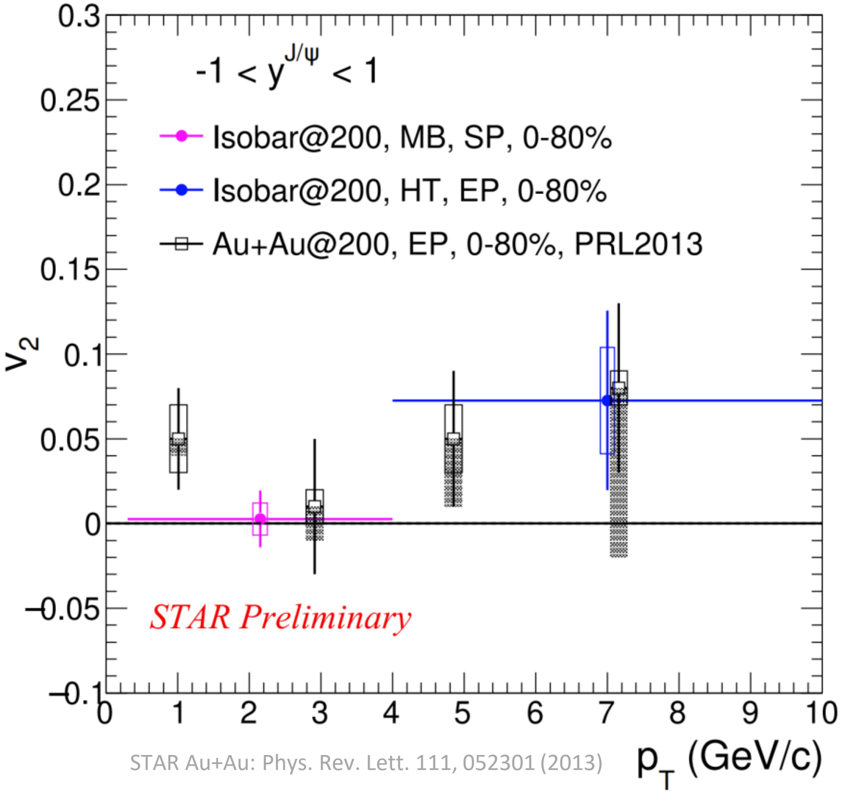
J/ψ elliptic flow in isobar collisions @ 200 GeV

Why J/ψ v_2 ?

Distinguish J/ψ from pQCD process or recombination







STAR Au+Au: Phys. Rev. Lett. 111, 052301 (2013)

- J/ψ v_2 is consistent with 0 and with Au+Au results
- Uncertainty is dominated by statistical error
- **Indication of small regeneration effects**

Summary

Open Heavy-flavor

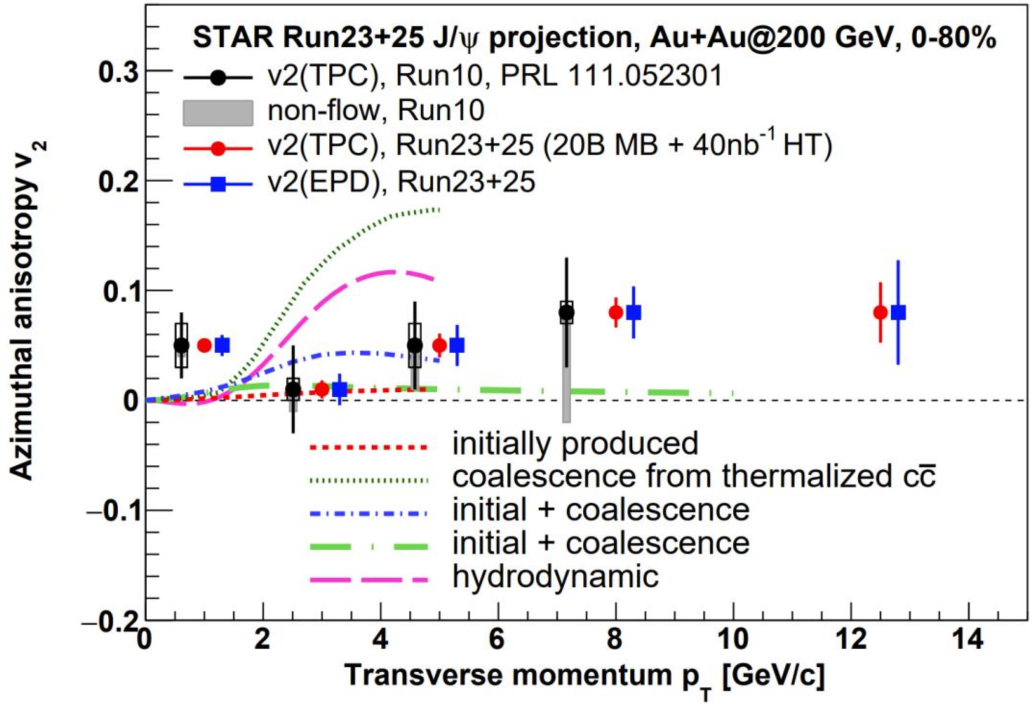
- **Elliptic flow:**
  - 54.4 GeV : significant v_2 of e^{HF}
  - 27 GeV : v_2 is consistent with 0
- **HFE in p+p:**
  - Precision improvement at p_{T} > 6 GeV/c
  - Further constrains on theoretical calculations
  - Precise reference for R_{AA} measurements
- **HFE in Au+Au:**
  - Significant energy loss of HQ in QGP
  - Improvement of precision for p_{T} > 6 GeV/c
  - **Mass ordering of c and b quark energy loss**

Quarkonium

- **CNM effects for inclusive *J/ψ* :**
  - First measurement within 0 < p_{T} < 10 GeV/*c*
  - Little CNM effects on *J/ψ* production above 3 GeV/*c*
- **ϒ production in isobar collisions:**
  - Suppression of ϒ states comparable to Au+Au
  - No significant p_{T} and species dependence
- ***J/ψ* elliptic flow in isobar collisions:**
  - *J/ψ* v_2 consistent with 0

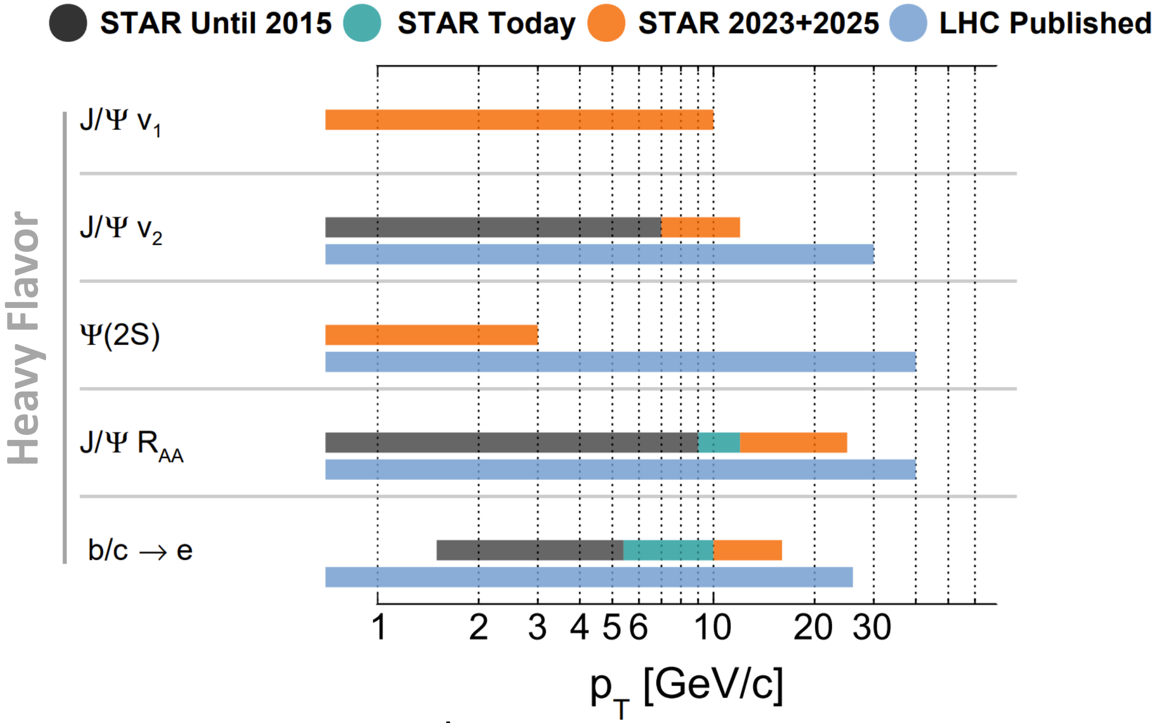
STAR Heavy Flavor program for Runs 23-25

- Run 23 + 25 Au+Au at 200 GeV: 20B MB and 40nb^{-1} HT events projected
- Detector upgrades (EPD, iTPC..)



- E.g. precise J/ψ v_2 measurement at RHIC energies
- EPD for event plane reconstruction ⟶ less non-flow effect contribution

- Run 24 p+Au: higher statistics than in Run 15
- Potential enhancement at high p_T for the STAR results



- Broader momentum coverage at RHIC

BACKUP

HFE analysis steps

1. Identification and purity correction of inclusive electrons (INCL)

2. Identification and efficiency correction of photonic electrons (PE)

3. Subtraction of PE from INCL sample

4. Efficiency correction of non-photonic electrons (NPE)

5. Subtraction of remaining background sources, hadron-decayed electrons (HDE), including dielectron decays of light-vector mesons (ρ, ω, ϕ), quarkonium decays ($J/\psi, \Upsilon$), Drell-Yan processes and kaon semi-leptonic decays (K_{e3})