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 [HEP06(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 $J/\psi$ in p+Au @ 200 GeV [Phys. Lett. B 825 (2022) 136865]
  ➢ $\Upsilon$ production in isobar collisions @ 200 GeV [STAR Preliminary]
  ➢ $J/\psi$ 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, $m_Q \gg \Lambda_{QCD}, m_Q \gg T_{QGP}$
- Production cross-sections can be calculated in pQCD
- Participate in the whole medium evolution

Heavy quark diffusion
Thermalization, $2\pi T D_s$
Energy loss
$R_{AA}, R_{CP}$
Mass ordering

Elliptic flow ($v_2$)
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

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

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

- 54.4 GeV: significant $v_2$ of $e^{HF}$
- 27 GeV: $v_2$ is consistent with 0

In this $\nu_{NN}$ and $p_T$ range $c$ quark is dominant

- Strong interaction of $c$ quark with QGP
- $c$ quarks gain most collectivity at $T \approx T_c$
- 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

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

- 54.4 GeV: significant \( \nu_2 \) of \( e^{HF} \)
- 27 GeV: \( \nu_2 \) is consistent with 0
- Consistency of NCQ with \( e^{HF} \nu_2 \)

\[ \nu_2 \text{ non-flow} = \frac{\langle \sum_i \cos 2(\varphi_e - \varphi_i) \rangle}{M \langle \nu_2 \rangle} \]

- Strong interaction of \( c \) quark with QGP
- \( c \) quarks gain most collectivity at \( T \approx T_c \)
- Deviation of \( c \) quarks from local thermal equilibrium?
- \( c \) hadrons obtain significant \( \nu_2 \)
- Hints of close to thermal equilibrium with the medium at 54.4 GeV

STAR: arXiv:2303.03546 Accepted by PLB

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

Collision-energy dependent properties of QGP:

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

Mass hierarchy

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

References:
- STAR: arXiv:2303.03546
- ALICE: JHEP 06 (2015) 190
Inclusive $e^\pm$ from open HF hadron decays in $p+p$ @ 200 GeV

- Good agreement among the results
- Precision improvement at $p_T > 6$ GeV/c

Power-law fit:

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

$n = 8.99 \pm 0.26$

$LVMDE = \rho, \omega, \phi$ decays
Inclusive $e^\pm$ from open HF hadron decays in $p+p$ @ 200 GeV

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

- Consistency with the upper limit of the FONLL uncertainty
- Further constraints on theoretical calculations
- Precise reference for $R_{AA}$ measurements for HDE

$e^±$ from open HF hadron decays in Au+Au @ 200 GeV

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

- 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

STAR: JHEP06(2023)176
$e^\pm$ from open HF hadron decays in Au+Au @ 200 GeV

$R^{incl}_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}^2}{dp_T dy} \cdot \frac{dN_{pp}^2}{dp_T dy}$

- 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

STAR: JHEP06(2023)176

08/02/2023

Veronika Prozorova, 2023   RHIC & AGS AUM
Mass ordering of $c$ and $b$ quark energy loss

- 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

\[ R_{AA}^{c\to e} = \frac{(1 - f_b^{AA})}{(1 - f_b^{pp})} \times R_{AA}^{incl} \]

\[ f_b^{AA} \text{ - fraction measured in Au+Au} \]

Possible to measure thanks to HFT!
Mass ordering of c and b quark energy loss

\[ R_{AA}^{b\to e} = \frac{f_b^{AA}}{f_b^{PP}} \times R_{AA}^{incl} \]

\[ R_{AA}^{c\to e} = \frac{(1 - f_c^{AA})}{(1 - f_c^{PP})} \times R_{AA}^{incl} \]

- \( R_{AA}^{b\to e} > R_{AA}^{c\to e} \) → 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 > $\lambda_D \sim 1/T_C$)

• 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

A. Bazavov et al. arXiv:1904.09951
CNM effects for inclusive $J/\psi$ in $p+Au$ @ 200 GeV

- Suppression of $\sim 30\%$ below 2 GeV/c
- Consistency with 1 above 3 GeV/c
- 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 $2.3\sigma$
- Au+Au: large suppression of $J/\psi$ yield above 3 GeV/c due to hot medium effects
- First measurement within $0 < p_T < 10$ GeV/c

$R_{pAu} = \frac{1}{<T_{AA}>} \times \left( \frac{d^2N_{J/\psi}}{dp_T \, dy} \right)_{p+Au} \times \left( \frac{d^2\sigma_{J/\psi}}{dp_T \, dy} \right)_{p+p}$
Sequential $\Upsilon$ states suppression observed at RHIC energies in Au+Au

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

- Different levels of suppression of quarkonium states of different sizes

- No significant $p_T$ dependence

- No significant species dependence at the same $\langle N_{\text{part}} \rangle$

- Suppression driven by collision energy density

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


STAR Preliminary
**J/ψ elliptic flow in isobar collisions @ 200 GeV**

**Why J/ψ v₂?**

Distinguish J/ψ from pQCD process or recombination

- J/ψ v₂ 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 $J/\psi$:**
  - First measurement within $0 < p_T < 10$ GeV/c
  - Little CNM effects on $J/\psi$ production above 3 GeV/c

- **$\Upsilon$ production in isobar collisions:**
  - Suppression of $\Upsilon$ states comparable to Au+Au
  - No significant $p_T$ and species dependence

- **$J/\psi$ elliptic flow in isobar collisions:**
  - $J/\psi$ $v_2$ 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..)

**Run 24 p+Au:** higher statistics than in Run 15

- Potential enhancement at high $p_T$ for the STAR results

- E.g. precise $J/\psi \, v_2$ measurement at RHIC energies
- EPD for event plane reconstruction → less non-flow effect contribution

- 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 ($\rho, \omega, \phi$), quarkonium decays ($J/\psi, \Upsilon$), Drell-Yan processes and kaon semi-leptonic decays ($K_{e3}$)