Nuclear modification factors, directed and elliptic flow of electrons from open heavy-flavor decays in Au+Au collisions from STAR

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Heavy-Flavor quarks in the QGP

- Precise measurements of HF hadron production essential for understanding non-perturbative regime of hot QCD
- Measurements of charm $R_{AA}$ and $v_2$ similar to light-hadrons in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions
  
  $\Rightarrow$ Bottom quark ultimate HF probe of QGP at RHIC

\[ m_{c,b} >> \Lambda_{QCD} \]
\[ m_{c,b} >> T_{QGP} \]
\[ \tau_{\text{relaxation}} \approx \tau_{\text{QGP}} \]
Electrons at STAR

- **Time Projection Chamber**
  - Full $2\pi$ azimuthal coverage at mid-rapidity

- **Heavy Flavor Tracker in 2014+2016 data**
  - First application of thin MAPS detector in collider experiment
  - Excellent pointing resolution for HF vertex and displaced daughter reconstruction

**Good electron PID at mid-rapidity**
- Ionization energy loss in TPC ($dE/dx$)
- $1/\beta$ from Time-Of-Flight detector
- Energy deposition in Barrel EM Calorimeter ($p$/Energy)

**Figures**
- Tracking
- Phys. Rev. C 99, 034908

0-80% Au+Au $\sqrt{s_{NN}}=200$ GeV
Outline of measurements

• Nuclear modification factors of charm and bottom electrons in √s_{NN} = 200 GeV Au+Au collisions
• Charm electron directed flow in √s_{NN} = 200 GeV Au+Au collisions
• Charm and bottom electron elliptic flow in √s_{NN} = 200 GeV Au+Au collisions
• Inclusive HF electron elliptic flow in √s_{NN} = 54.4 GeV Au+Au collisions

With HFT
NPE @ 200 GeV with HFT

Combined 2014+2016 RHIC Runs

- 2014: ~0.9 B minimum bias + ~0.2 nb\(^{-1}\) BEMC triggered events
- 2016: ~1.1 B minimum bias + ~1.2 nb\(^{-1}\) BEMC triggered events
Extraction of $b$- and $c$-decayed electrons with template fit to log of 3D Distance of Closest Approach

- Larger $\tau$ of $b$-hadrons w.r.t. $c$-hadrons
  - $\langle DCA(b \rightarrow e) \rangle > \langle DCA(c \rightarrow e) \rangle$

- Large separation from backgrounds (hadrons and photonic electrons)

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STAR Preliminary
Au+Au $\sqrt{s_{NN}} = 200$ GeV
0-80%
Combined 2014+2016 RHIC Runs

- 2014: ~0.9 B minimum bias + ~0.2 nb\(^{-1}\) BEMC triggered events
- 2016: ~1.1 B minimum bias + ~1.2 nb\(^{-1}\) BEMC triggered events

Hadron background reduced with Likelihood MVA PID

Photonic electron background rejection with single electron isolation cuts

See Yingjie Zhou’s poster (HF32) for details!

- Large separation from backgrounds (hadrons and photonic electrons)

### Events / (0.04 GeV)

- \( p_T \in [3.5,4.5] \) GeV/c
- STAR Preliminary
- Au+Au \( \sqrt{s_{NN}} = 200 \) GeV
- 0-80%

### DCA/cm

- \( \log_{10}(DCA/cm) \)}
Bottom Electron Fraction

- Bottom fraction in MB Au+Au enhanced compared to p+p measurement and FONLL prediction
  - p+p from combined STAR 2006 published and 2012 preliminary data

- Bottom fraction significantly enhanced in central collisions
  - Bottom fraction in peripheral collisions consistent with p+p data

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STAR Preliminary 0-80%

\[ \frac{N(b \rightarrow e)}{N(b+c \rightarrow e)} \] as a function of \( p_T \) (GeV/c)

- STAR preliminary
- Au+Au \( \sqrt{s_{NN}} = 200 \) GeV
- FONLL

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See Yingjie Zhou’s poster (HF32) for details!
Nuclear Modification Factors

Bottom electron fraction translated to $b,c\rightarrow e$ $R_{AA}$ with preliminary STAR inclusive NPE $R_{AA}$

$R_{AA}^{b\rightarrow e} = \frac{f_{b}^{AA}}{f_{b}^{pp}} R_{AA}^{NPE}$

$R_{AA}^{c\rightarrow e} = \frac{1 - f_{b}^{AA}}{1 - f_{b}^{pp}} R_{AA}^{NPE}$

- Increased precision from QM2017 preliminary
  - Increased statistics with 2014+2016 data
  - Reduced backgrounds from MVA PID and photonic electron rejection
  - Increased sensitivity to HF electrons with log(DCA) fit

Const. fit = $1.92\pm0.25$(stat.)$\pm0.21$(syst.)

$R_{AA}(b\rightarrow e) > R_{AA}(c\rightarrow e)$ significant at $\sim 3\sigma$
Nuclear Modification Factors

Bottom electron fraction translated to $b,c\rightarrow e$ $R_{AA}$
with preliminary STAR inclusive NPE $R_{AA}$

$$R_{AA}^{b\rightarrow e} = \frac{f_{b}^{AA}}{f_{b}^{pp}} R_{AA}^{NPE}$$

$$R_{AA}^{c\rightarrow e} = \frac{1 - f_{b}^{AA}}{1 - f_{b}^{pp}} R_{AA}^{NPE}$$

- Data consistent with DUKE Langevin model prediction (consistent with $\Delta E(b) < \Delta E(c)$)
- Null hypothesis [$R_{AA}(B) = R_{AA}(D)$] for $p_T(e) \in [2.5,5.5]$ GeV/c:
  - $\chi^2/\text{ndof} = 8.6/2$, p-value = .014

See Yingjie Zhou’s poster (HF32) for details!
Double Ratio of $R_{CP}$

- Calculated from centrality dependent bottom fraction
- Large cancelation of correlated systematic uncertainties

⇒ Constant fit to double ratio >1 significant at $3.5\sigma$ and $4.4\sigma$ for $R_{CP}(0\text{-}20\%/40\text{-}80\%)$ and $R_{CP}(0\text{-}20\%/20\text{-}40\%)$

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Anisotropic Flow Strategy

- HFT enables study of $v_1$ and $v_2$ in log(DCA) regions rich with charm and bottom electrons and with little backgrounds
- Observed flow corrected for flow from background

$$v_2(\text{obs.}) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$
Charm→e Directed Flow

Background $\langle p_T \rangle \sim 1.5 \text{ GeV}/c$

$\Rightarrow v_1(\text{hadron}) \sim 0$

$v_1(\text{obs.}) = f_c v_1^c$
Charm→e Directed Flow

- Charm-decayed electron $dv_1/dy$ non-zero $\sim 5\sigma$ level
  - $\langle p_T(D) \rangle = 2.5$ GeV/$c$ for electron $p_T > 1.2$ GeV/$c$
  - Magnitude consistent with STAR $D^0$ measurement ($\langle p_T(D^0) \rangle = 2.2$ GeV/$c$)

$v_1(\text{obs.}) = f_c v_1^c$

$D^0$ points shifted from bin center

$\langle p_T(D) \rangle = 0.051 \pm 0.009$(stat.$) \pm 0.005$(syst.$)$

$D^0$ points shifted from bin center

$D^0$ $v_1$: Phys. Rev. Lett. 123, 162301
Charm→e Directed Flow

- Initial EM field predicted to alter $c/\bar{c} v_1$ oppositely
- Electron charge tags parent hadron flavor allowing $c/\bar{c} v_1$ probe
  - $e^+(\bar{c}) - e^-(\bar{c}) v_1$ difference at $<1\sigma$

$\nu_1 (obs.) = f_c v_1^c$

$D^0$ vs. Rapidty

$e^+ dv/dy = -0.059\pm0.013$(stat.$)\pm0.004$(syst.)
$e^- dv/dy = -0.044\pm0.013$(stat.$)\pm0.006$(syst.)

$D^0$ vs. Rapidty

$10-80\%$ Au+Au

$0-80\%$ Au+Au

$e^\pm$ points shifted from bin center
Charm→e Elliptic Flow

- Second order event plane measured with TPC tracks using $\eta$-sub event method
- Simultaneous fit to two log(DCA) regions; solve for $v_2(c\rightarrow e)$
Charm → e Elliptic Flow

• Non-flow estimated with two-particle (e-h) correlations in PYTHIA

• Measured $D^0v_2$ folded to decayed electron with simulated semileptonic decays in EvtGen

$\Rightarrow$ Charm electron $v_2$ consistent with folded $D^0v_2$ and DUKE model

$\nu_2^{I}(\text{obs.}) = f_b^{I}v_2^b + f_c^{I}v_2^c + f_{bkg}^{I}v_2^{bkg}$

$\nu_2^{II}(\text{obs.}) = f_b^{II}v_2^b + f_c^{II}v_2^c + f_{bkg}^{II}v_2^{bkg}$
Bottom→e Elliptic Flow

\[ v_2(\text{obs.}) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg} \]
Bottom→e Elliptic Flow

- Non-flow estimated from two particle correlations (e-h) in PYTHIA
- Data qualitatively consistent with Duke model considering non-flow

\[ v_2(\text{obs.}) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg} \]

DUKE: Phys. Rev. C 92, 024907
Private Communication
Bottom→e Elliptic Flow

- **Forward Meson Spectrometer** (2.5<\(\eta\)<4) as EP detector reducing non-flow to <0.5%
  - ~1/4 sample size w.r.t. total minimum bias

- **FMS EP data consistent within uncertainties with TPC EP measurement**

\[ v_2(\text{obs.}) = f_b v_2^b + f_c v_2^c + f_{\text{bkg}} v_2^{\text{bkg}} \]

DUKE: Phys. Rev. C 92, 024907
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**Bottom→e Elliptic Flow**

\[ v_2(\text{obs.}) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg} \]

- **TPC EP measurement null hypothesis with full non-flow subtraction:**
  \[ \chi^2/\text{ndof} = 17.1/3, \text{p-value} = .00067 (\sim 3.4\sigma) \]

⇒ **Observation of non-zero bottom electron \( v_2 \)!**

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DUKE: Phys. Rev. C 92, 024907
Private Communication
Energy dependence of HF $v_2$

- Probe of temperature dependence of diffusion coefficient
- Previous HF $v_2$ measurements in 62.4 and 39 GeV Au+Au collisions inconclusive with limited statistics

Dataset at 54.4 GeV allows more precise measurement at lower energy

15x increase in statistics compared to 62.4 GeV!
Inclusive NPE $v_2 @ 54.4$ GeV

- Significant non-zero values of NPE $v_2$ in 54.4 GeV Au+Au collisions
- Similar magnitude as NPE $v_2 @ 200$ GeV

$\Rightarrow$ HF($c$) quarks interact strongly with the medium in 54.4 GeV Au+Au collisions

See Yuanjing Ji’s poster (HF29) for details!
Summary

- Measured $b \rightarrow e$ suppression less than $c \rightarrow e$ with $\geq 3\sigma$ significance (consistent with $\Delta E(b) < \Delta E(c)$)!
- First observation of non-zero bottom electron $v_2$ significant at $3.4\sigma$!

- Anisotropic flow for charm-decayed electrons
  - $dv_1/dy$ at $\sim 5\sigma$; consistent with $D^0$ measurement
  - $v_2$ consistent with measured $D^0 v_2$

- Significant NPE $v_2$ in Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV
  - Consistent with NPE $v_2$ at $\sqrt{s_{NN}} = 200$ GeV
Backup slides follow
Comparisons to PHENIX

- Preliminary PHENIX $b, c \rightarrow e$ from Hard Probes 2018
- Excellent consistency between experiments within uncertainties
HF log(DCA) template model

- HF decayed electron DCA templates from EvtGen generator corrected for efficiency and momentum/position resolution determined from data.

- Ground state $B/D^+/0$, $B_s/D_s$, and $\Lambda_{b,c}$ hadron decays simulated with all known semileptonic decays:
  - Charm re-weighted with measured $D^0$ spectra and preliminary hadron fractions from STAR in Au+Au collisions @ $\sqrt{s_{NN}} = 200$ GeV
  - $\Lambda_c$ corrected using $\Lambda_c/D_0$ preliminary measurement from STAR + model calculations in Au+Au collisions @ $\sqrt{s_{NN}} = 200$ GeV
  - Bottom spectra from FONLL; hadron fractions from LHCb p+p measurement

*Less sensitive to $b$ hadron fractions

Large uncertainty coming from $D^+/D^0$ ratio

LHCb: PhysRevD.100.031102
FONLL: JHEP 1210 (2012)
Charm→e Directed Flow Simulation

- Measured $D^0 v_1$ fit folded into $D \rightarrow e$ simulation
- Electrons with $p_T > 1.2$ GeV/c show little loss of parent hadron $v_1$ due to decay
Inclusive NPE $v_2 \phi 54.4$ GeV

- Significant non-zero values of NPE $v_2$ in 54.4 GeV Au+Au collisions
- Similar magnitude as NPE $v_2 \phi 200$ GeV

$\rightarrow$ HF$(c)$ quarks interact strongly with the medium in 54.4 GeV Au+Au collisions

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Non-flow estimated using electron-hadron correlations in 200 GeV pp data