Recent Results on Open Heavy Flavor from STAR

Matthew Kelsey
(for the STAR collaboration)

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The Role of Heavy Flavor

Heavy quark production via the initial hard partonic scatterings in heavy-ion (HI) collisions \(\Rightarrow \) "External" probe of de-confined medium

Elementary collisions
\(\Rightarrow \) pQCD

Initial conditions
- Directed Flow
\(\Rightarrow \) B field
\(\Rightarrow \) Longitudinal profile

Heavy quark diffusion
- Elliptic Flow
\(\Rightarrow \) Thermalization
\(\Rightarrow \) 2\(\pi\)TDs

Energy loss
- \(R_{AA} + R_{CP}\)
\(\Rightarrow \) Collisional + radiative
\(\Rightarrow \Delta E(m)\)

Hadronization
- \(\Lambda_c + D_s\) production
\(\Rightarrow \) Coalescence vs. vacuum fragmentation
Outline of Measurements

Spectra of $D^\pm$ and $D_s^\pm$ mesons in Au+Au collisions

$b/c \rightarrow e$ $R_{AA}$ and $R_{AA}/CP$ double-ratios

Elliptic flow of non-photonics electrons in 54.4 and 27 GeV Au+Au collisions

$c \rightarrow e$ directed and $b/c \rightarrow e$ elliptic flow
The STAR Detector

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

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

PID achieved with TPC, Time-of-Flight (TOF), and Barrel Electromagnetic Calorimeter (BEMC)
D\(\pm\) Production in \(\sqrt{s_{NN}} = 200\) GeV Au+Au

D\(+\rightarrow K^{+}\pi^{+}\pi^{-}\) reconstructed topologically using HF decay vertex

- TMVA optimized selection
- Low p\(_{T}\) reach extended to 1 GeV/c
- Up to 3x improvement in signal significance at low p\(_{T}\)
$D^\pm$ Production in $\sqrt{s_{NN}} = 200$ GeV Au+Au

- Measured $D^+$ $R_{AA}$ comparable to $D^0$ within uncertainties
- Significant suppression in central Au+Au at high $p_T$

Measured $D^+/D^0$ yield ratio are consistent with PYTHIA 8 predictions across all collision centralities
$D_s^\pm$ Production in $\sqrt{s_{\text{NN}}} = 200$ GeV Au+Au

Good probe of strangeness enhancement + coalescence hadronization

Boosted decision tree optimized to select $D_s^+ \rightarrow \phi (K^+ K^-) \pi^+$ decays

- Improved signal significance by 30% compared to traditional cut-based approach
- Measured down to $p_T = 1$ GeV/$c$
D$_s^{\pm}$ Production in $\sqrt{s_{\text{NN}}} = 200$ GeV Au+Au

Significant enhancement in $D_{s^+}/D^0$ ratio compared to PYTHIA 6
- No strong centrality dependence
- Comparable to ALICE Pb+Pb data @ $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- Larger ratio than ALICE p+p @ $\sqrt{s} = 7$ TeV

Models including coalescence hadronization also show enhancement

Single Electrons from Bottom Hadrons

Log(3D DCA) distribution provides excellent separation between $c \rightarrow e$, $b \rightarrow e$, and BKG

Electron PID improved with likelihood MVA classifier; Hadron contamination reduced by factor of two

Photonic electron ($\pi^0$, $\eta$, and $\gamma$) background veto; Reduction by 60%
Fraction of $b \to e/c+c+b \to e$ significantly enhanced in central and min. bias $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions

Peripheral $b \to e/c+c+b \to e$ fraction consistent with $\sqrt{s} = 200$ GeV $p+p$ and FONLL

Bottom vs. Charm Energy Loss

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

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

Significant improvement in experimental uncertainties since QM17!
Bottom vs. Charm Energy Loss

\[ \frac{R_{CP}^{b\rightarrow e}}{R_{CP}^{c\rightarrow e}} = \frac{f_{central} b}{1 - f_{central}} \frac{1 - f_{peripheral}}{f_{peripheral}} \]

\( R_{AA} \) double ratios deviate from unity by \( 3\sigma \); null hyp. (assumption of same \( R_{AA} \) for bottom/charm) by \( 2\sigma \)

- Fixed electron \( p_T \) probes roughly same charm and bottom hadron average \( p_T \) (within relative 12%)

\[ R_{CP}[0-20%/40-80%(20-40%)] \] double ratios deviate from unity by \( 4.4(3.5)\sigma \)

- \( R_{CP} \) null hyp. consistent with unity (not shown)

Data consistent with Duke Langevin model prediction

Provide a conclusive picture of \( c \) and \( b \) quark energy loss consistent with \( \Delta E(b) < \Delta E(c) \)
Low Energy Electron Elliptic Flow

\( D^0 \) \( v_2 \) well described by models including \( c \) quark diffusion

Low energy non-photonic electron (NPE) \( v_2 \) good probe of temperature dependence

RHIC Run17+18: Au+Au collisions at \( \sqrt{s_{NN}} = 54.4 \pm 27 \) GeV; 10x increase in statistics compared to previous STAR low energy measurements
Low Energy Electron Elliptic Flow

Significant NPE $v_2$ at 54.4 GeV; comparable to those at $\sqrt{s_{NN}} = 200$ data

NPE $v_2$ at 27 GeV consistent with zero within experimental uncertainties

Above $p_T=1$ GeV/$c$ model comparisons consistent considering non-flow and all uncertainties; disagreement at $p_T<1$ GeV/$c$

TAMU: M. He et al. PRC 91, 024904 (2015)
PHSD: T. Song et al. PRC 92, 014910 (2015)
T. Song et al. PRC 96, 014905 (2017)
Charm Quark Directed Flow

Electrons from charm hadron semileptonic decays excellent proxy for parent hadron $v_1$
- Beneficial channel due to improved statistics; requires good single track pointing resolution to isolate signal

Average $c \rightarrow e$ $v_1$ comparable to measured $D^0$ $v_1$ from STAR in $\sqrt{s_{NN}} = 200$ GeV $Au+Au$ collisions
- Similar hadron $p_T$ probed: $\langle p_T(D) \rangle = 2.5$ GeV/$c$ in $c \rightarrow e$ vs. 2.2 GeV/$c$ for $D^0$ measurement
- Improved precision offers improved constraint to initial tilt of QGP bulk
Charm Quark Directed Flow

Initial EM field predicted to affect $c$ and anti-$c$ quarks differently

Electron charge tags initial heavy quark flavor in semileptonic decays

Electron $v_1$ difference trend same as $D^0$ measurement; consistent with zero at 1σ level

$D^0 \rightarrow K^- e^+ \nu_e$

$\bar{D}^0 \rightarrow K^+ e^- \bar{\nu}_e$

Hydo+EM: Chatterjee, Bojek: arXiv1804.04893v1
Bottom-decayed Electron Elliptic Flow

$\bar{c} \rightarrow e v_2$ consistent with STAR $D^0$ measurement folded to decay electron

Non-zero $b \rightarrow e v_2$ with significance $>3\sigma$ (first significant bottom $v_2$ at RHIC)

Consistency with Duke model considering non-flow


STAR $D^0$ PRL 118 (2017) 212301

FMS = Forward (2.5 < $\eta$ < 4) Meson Spectrometer
Summary

✓ Significant suppression of $D^+$ in central HI collisions; Similar $D^+/D^0$ yield to PYTHIA 8
✓ Significant enhancement of $D_{s}^+/D^0$ ratios in HI collisions w.r.t. $p+p$
✓ Separation of $b/c\rightarrow e$ $R_{AA}$ and significant $R_{AA}/CP$ double ratios > unity
✓ Elliptic flow of NPE: Non-zero in 54.4 GeV collisions; Consistent with zero in 27 GeV collisions
✓ $c\rightarrow e$ $v_1$ and $v_2$ consistent with previous STAR measurement
✓ First significant non-zero $b\rightarrow e$ $v_2$ @ RHIC