Heavy Flavor production at RHIC

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Heavy quark production at RHIC

Cold nuclear matter effects for bottom quarks
Relativistic Heavy Ion Collisions

- $c$, $b$ quarks produced early
- $D$, $B$ production in $A+A \rightarrow QGP$ properties

UrQMD, http://urqmd.org/
Experimental approach

1. baseline – \( p+p \)

2. “cold” nuclear matter effects – \( d+Au \)

\[
R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{dAu}}{dN/dy^{pp}}
\]

\( R_{AA}(dAu) = 1 \) if no modification in the medium

3. modification in the hot/dense medium – \( Au+Au \)

\[
R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dy^{AuAu}}{dN/dy^{pp}}
\]
Cold nuclear matter effects

Shadowing

antishadowing

Fermi motion

EMC effect

Cronin effect

Electrons from semi-leptonic heavy flavor hadrons decay ($b \rightarrow e$, $c \rightarrow e$)

Direct open charm reconstruction

Courtesy of David Tlusty
$e^{HF}$: Cold vs Hot Nuclear matter

$e^{HF} (b \rightarrow e, c \rightarrow e)$ suppressed at high $p_T$ in Au+Au 200 GeV
U+U \rightarrow \sim 20\% \text{ larger energy density for the same centrality class than Au+Au}
Open charm suppression

Suppression at high $p_T$ in central and mid-central collisions

Enhancement at intermediate $p_T$:  
→ Radial flow (?)  
→ Cronin enhancement + suppression at high $p_T$ (?)

arXiv: 1404.6185
HFT available for RHIC Run-14 (a long Au-Au 200 GeV run)

charm → e and bottom → e separation in Au+Au

Cold nuclear matter effects for $c \rightarrow e$ and $b \rightarrow e$?
d+Au: reference or “mini-QGP”? 

**Charged hadron**


**Heavy flavor decay electron**

*Possible evidence for radial flow of heavy mesons in d+Au collisions*

Cold nuclear matter effects for charm and bottom

D. K., Andrzej Lipiec
Input:
- charm spectrum in $p+p$
- $b \rightarrow e$ and $c \rightarrow e$ in $p+p$
- $R_{pA}$ for charm quarks: initial $k_T$ broadening and shadowing (EKS98)
- $e^\text{HF}$ in $d+Au$

Charm spectrum in $d+Au$: \[rac{dN^{dAu}}{dp_T} = R_{pA} \langle N_{\text{bin}} \rangle \frac{dN^{pp}}{dp_T}\]

Decay kinematics: PYTHIA8, BR = 10.5%
- Input:

- charm spectrum in $p+p$

- $R_{pA}$ for charm quarks: initial $k_T$ broadening and shadowing (EKS98)
Inclusive NLO c quark production at $\sqrt{s} = 5.5$ TeV

$e^{HF}$ $p_T$ spectrum in p+p 200 GeV
$e^{HF}$ $p_T$ spectrum in $p+p$ 200 GeV

Good agreement considering difference in charm cross section:

\[
\text{STAR: } \frac{d\sigma^{c\bar{c}}}{dy} = 161 \pm 20 (\text{stat.}) \pm 34 (\text{syst.}) \mu b
\]
Good agreement considering difference in charm cross section:

**STAR:** \( \frac{d\sigma^{c\bar{c}}}{dy} = 161 \pm 20 \text{ (stat.)} \pm 34 \text{ (syst.)} \mu b \)

**PHENIX:** \( \frac{d\sigma^{c\bar{c}}}{dy} = 119 \pm 12 \text{ (stat.)} \pm 38 \text{ (syst.)} \mu b \)
STAR $c \rightarrow e$ / Simulated $c \rightarrow e$

Good agreement

Limited precision at high $p_T$
$e^{\text{HF}} p_T$ spectrum in d+Au 200 GeV

Enhancement for $p_T < 2.5$ GeV/c $\rightarrow$ shadowing + initial $k_T$ breadboarding for charm quarks due to multiple scattering of incoming partons.
Enhancement for $p_T < 2.5 \text{ GeV/c}$ → shadowing + initial $k_T$ breadboarding for charm quarks due to multiple scattering of incoming partons.
$R_{dAu}$ for $c \rightarrow e$ and $b \rightarrow e$

$b \rightarrow e$: moderate enhancement, still comparable with unity

$c \rightarrow e$: consistent with no modification in $d+Au$
$R_{dAu}$ for $c \rightarrow e$ and $b \rightarrow e$

**RHIC: $d+Au \sqrt{5} \text{ TeV}$**

**LHC: $p+Pb \sqrt{5} \text{ TeV}$**

RHIC: $b \rightarrow e$: moderate enhancement, still comparable with unity

Similar behavior at LHC
Summary

- Strong suppression of charmed mesons and $e^{HF}$ at RHIC at high $p_T$

- $e^{HF}$ enhancement in d+Au at low-$p_T$ → consistent with initial $k_T$ breadboarding for charm quarks

- Enhancement expected for $b \rightarrow e$ for $3 < p_T < 8$ GeV/c in d+Au 200 GeV
Backup
STAR Experiment

Magnet  MTD  BEMC  TPC  TOF  BBC  EEMC

HFT  FMS  HLT
Initial $k_T$ broadening

Arises from multiple scattering of the projectile partons in the target:

$$\langle k_T^2 \rangle_A = \langle k_T^2 \rangle_p + (\langle \nu \rangle - 1) \Delta^2(\mu)$$

$$\langle k_T^2 \rangle_p = 1 \text{ GeV}^2$$

$$\langle \nu \rangle = \sigma_{NN} \frac{\int d^2b T_A^2(b)}{\int d^2b T_A(b)} = \frac{3}{2} \frac{\sigma_{NN} \rho_0 R_A}{\sigma_{NN}}$$

$$\Delta^2(\mu) = 0.225 \frac{\ln^2(\mu/\text{GeV})}{1 + \ln(\mu/\text{GeV})} \text{GeV}^2$$

$$\mu = 2m_Q \quad - \text{scale, } m_c = 1.2 \text{ GeV}$$

number of collisions in a p-A interaction
Phys. Rev. D 83 (2011) 52006
Heavy Flavor decay electrons in Au+Au 200 GeV

Strong suppression at high $p_T$ in central collisions

$D^0$ and $e^{HF}$ suppression $\rightarrow$ similar
STAR Preliminary

- **U+U 193 GeV** $D^0$: $|y|<1$, $3<p_{T}<5$ GeV/$c$
- **Au+Au 200 GeV** $D^0$: $|y|<1$, $3<p_{T}<8$ GeV/$c$, arXiv:1404.6185 (submitted to PRL)
- **Au+Au 200 GeV** $\pi^-$: $|y|<0.5$, $p_{T}>6$ GeV/$c$, PLB655, 104 (2007)

Quark Matter 2014, Zhenyu Ye
Large suppression at high $p_T$ points to strong charm-medium interaction;
Indication of enhancement $p_T \approx 0.7-2$ GeV/c, described by models with charm quarks coalescence with light quarks;
CNM effects could be important.

arXiv:1404.6185 (submitted to PRL)
arXiv:1405.6348