Open Heavy Flavor Production In Heavy-Ion Collisions from STAR

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- Introductions
- Recent measurements
- Near future HF program
- Summary
Light flavor behavior in strongly coupled medium

- **High $p_T$:**
  - Light quark e-loss, Jet quenching
- **Low $p_T$:**
  - Hydrodynamics works
  - Multi-strange hadrons flow
- **Intermediate $p_T$:**
  - Number of Constituent Quark scaling
  - $s \sim u,d$

$\sqrt{s_{NN}} = 200$ GeV $^{197}$Au+$^{197}$Au Collisions at RHIC

(a) Light quarks

(b) Strange quarks

$V_2$ (%)

Transverse Momentum $p_T$ (GeV/c)

QM09
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Large partonic collective flow observed.
$u, d, s$ quarks strongly interact with hot/dense medium.

What about heavy quarks?
Is the medium hot/dense enough to modify heavy quarks at RHIC energy?

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QM09
Why are heavy quarks important?

- Higgs mass: electro-weak symmetry breaking (current quark mass).
- QCD mass: Chiral symmetry breaking (constituent quark mass).
- Strong interactions impact little on heavy quark mass.

- Production cross section can be evaluated by pQCD. Provide reference for charmonium calculations.
- Sensitive to initial gluon density and distribution.
- Probe for studying medium properties.
- Charm collectivity => sensitive to the thermalization of the medium.
The STAR detector for open HF measurement

**Time Projection Chamber:**
- $|\eta|<1$, full azimuth
- Tracking.
- PID through $dE/dx$

**Time of Flight:**
- $|\eta|<1$, full azimuth
- PID through TOF
- Timing resolution: ~85 ps.

**Barrel Electromagnetic Calorimeter**
- $|\eta|<1$, full azimuth
- **BTOW:**
  - Tower matching
  - $p/E$ for electron ID
  - Fast online trigger
- **BSMD:**
  - Double layer High spatial resolution MWPC.
  - $e/h$ separation.
Particle Identification

\[ n\sigma = \ln\left(\frac{dE^{\text{Measured}}}{dx} - \frac{dE^{\text{Exp}}}{dx}\right) / \sigma \]
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- Low \( p_T \) e

D meson hadronic daughter ID.
Particle Identification

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\[ \sqrt{s_{NN}} = 200\text{GeV} \]

Low \( p_T \) e

High \( p_T \) e

D meson hadronic daughter ID.
D⁰ signals in Au+Au 200 GeV

- Combining data from Year 2010 & 2011.

- Total: ~ 800 M Min.Bias events

- Significant signals are observed Total ~ 14σ in 0<p_T<8 GeV/c.
Nuclear modification of $D^0$

Au+Au 200 GeV $(D^0+\overline{D^0})/2$, $|y| < 1$

- 0-80% $y_{10}$
- 0-80% $y_{10+y_{11}}$
- 0-10% $\times 20$
- 10-40% $\times 5$
- 40-80% $\div 2$

$\frac{d^2N}{N_{ev}(2\pi p_T dp_T dy)} (\text{GeV/c})^2$

STAR Preliminary

- p+p $D^0+D^*$ $\times 2$
- p+p Levy scaled by $\langle N_{bin} \rangle$

pp reference:
PRD 86, 072013 (2012)
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Low $p_T$ enhancement, radial flow of light quarks coalescence with charm (models).
Charm cross section versus $N_{\text{bin}}$ at 200 GeV

The charm cross section at mid-rapidity:

$$\left. \frac{d\sigma}{dy} \right|_{y=0}^{pp} = 170 \pm 45_{-59}^{+38} \mu b \quad \left. \frac{d\sigma}{dy} \right|_{y=0}^{AuAu} = 175 \pm 13 \pm 23 \mu b$$

The total charm cross section (extrapolate from PYTHIA F^~4.7):

$$\sigma_{cc}^{pp} = 797 \pm 210_{-295}^{+208} \mu b \quad \sigma_{cc}^{AuAu} = 822 \pm 62 \pm 192 \mu b$$

Assuming $N_{D0} / N_{cc} = 0.56$ does not change for total cross section.


Charm cross section follows number of binary collisions scaling $\Rightarrow$

Charm quarks are mostly produced via initial hard scatterings
Non-photonic electron $R_{AA}$ in Au+Au 200 GeV
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- Strong suppression at high $p_T$ in central collisions
- $D^0$, NPE results seems to be consistent, in spite of kinematics smearing & charm/bottom mixing
- Models with radiative energy loss underestimate the suppression
- Uncertainty dominated by $p+p$ result.
- High quality $p+p$ data from Run12 are on disk.

DGLV: Djordjevic, PLB632, 81 (2006)
CUJET: Buzzatti, arXiv:1207.6020
D⁰ v₂ measurement in Au+Au 200 GeV

Need HFT for more precise measurement:
- to confirm the coalescence scenarios.
- to confirm the energy dependence.

Different production mechanisms compared with hidden charm?
NPE $v_2$ in Au+Au 200 GeV

**200 GeV Au+Au:**
- Large NPE $v_2$ observed at low $p_T$ => strong charm-medium interaction
- $v_2$ increase at $p_T > 3$ GeV/c
  - path length of energy loss
  - Jet-like correlation.
Peripheral is consistent with no suppression.
Minbias and central 0-10% show no obviously larger suppression compared with D$^0$ $R_{AA}$.
We expect more precise measurement with Heavy Flavor Tracker.
Assuming $D^0$ $R_{cp}$ distribution as charged hadron.

1B Au+Au m.b. events at 200 GeV.

- Charm $R_{AA} \Rightarrow$
  
  *Energy loss mechanism!*

  *Charm interaction with QCD matter!*

Assuming $D^0$ $v_2$ distribution from quark coalescence.

1B Au+Au m.b. events at 200 GeV.

- Charm $v_2 \Rightarrow$
  
  *Medium/light flavor thermalization*

  *Drag coefficients!*

12 weeks, expected to get ~1B MB events
Summary

- Charm cross sections at mid-rapidity follow number of binary collisions scaling, which indicates charm quarks are mostly produced via initial hard scatterings.

- Observed large high-$p_T$ suppression of heavy quark production via NPE and $D^0$ meson measurement in 200 GeV central Au+Au collisions.

- Low-$p_T$ enhanced structure of $D^0 R_{AA}$ is consistent with coalescence picture that charm recombined with thermalized light quarks in the medium.

- First separation of $b$ & $c$ contribution in NPE analysis directly from experiment although with limited statistics. Bottom does not suppress more in central collisions compared to charm, but no suppression is seen in peripheral collisions.

- HFT upgrade with increasing RHIC luminosity is expected to provide much more precise measurement on open heavy flavor properties.
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More exciting results are coming soon!

Thank you for your attention!
Backup Slides
Non-photonic electron spectra in Au+Au 200 GeV

Non-photonic electron (NPE): electron from HF decays

- ~1 nb$^{-1}$ sampled luminosity in Run2010 Au+Au collisions.
- ~6 pb$^{-1}$ sampled luminosity in Run2005 and Run2008 p+p collisions.
**D⁰ and D* signals in p+p 200 GeV**

- **K*⁰**
  - Unlike Sign (US)
  - Like Sign (LS)
  - Rotation (Rot)

- **K₂*⁰(1430)**

- **D⁰**

- **D*⁺ → D⁰(Bar D⁰) + π⁻ → K⁺π⁻π⁻**

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p+p minimum bias 105 M

Different methods reproduce comb. background.
Consistent between two background methods.

- ✧ No secondary vertex reconstruction so far.
- ✧ STAR took advantage of the large acceptance, and beat combinatorial background with statistics

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PRD 86, 072013 (2012)
D⁰ and D* p_T spectra in p+p 200 GeV

The charm cross section at mid-rapidity:
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The total charm cross section:
\[ \sigma^{pp}_{cc} = 797 \pm 210_{-295}^{+208} \mu b \]

D⁰ scaled by \( N_{cc} / N_{D^0} = 1 / 0.565 \)[1]
D* scaled by \( N_{cc} / N_{D^*} = 1 / 0.224 \)[1]

Xsec = dN/dy|_{y=0}^{cc} \times F \times \sigma_{pp}
F = 4.7 \pm 0.7 scale to full rapidity.
\( \sigma_{pp}(NSD) = 30 \) mb

D, B and B->D are generated from PYTHIA. Normalized by FONLL cross section, the band indicate uncertainty of Strong pT dependence, but contribution is small, less than 10%. Low pT only contributes a few percent, which will not affect cross section result. Assuming B feeddown fraction is the same for p+p and Au+Au, then RAA will not be affected. The B feeddown will be in the systematic uncertainty.
Heavy Flavor Tracker

## Detector Specifications

<table>
<thead>
<tr>
<th>Detector</th>
<th>Radius (cm)</th>
<th>Hit Resolution $R/\phi - Z$ ((\mu m - \mu m))</th>
<th>Radiation length</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSD</td>
<td>22</td>
<td>20 / 740</td>
<td>1% $X_0$</td>
</tr>
<tr>
<td>IST</td>
<td>14</td>
<td>170 / 1800</td>
<td>&lt;1.5% $X_0$</td>
</tr>
<tr>
<td>PIXEL</td>
<td>8</td>
<td>12 / 12</td>
<td>~0.4% $X_0$</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>12 / 12</td>
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</tbody>
</table>
Statistic projection of $e_D$, $e_B$ $R_{CP}$ & $v_2$


- (B→e) spectra obtained via the subtraction of charm decay electrons from inclusive NPEs:
  - no model dependence, reduced systematic errors.

- Unique opportunity for bottom e-loss and flow.
  - Charm may not be heavy enough at RHIC, but how is bottom?
Charmed baryons – Y14

$\Lambda_c \rightarrow pK\pi$  Lowest mass charm baryons  $c\tau = 60 \mu m$

$\Lambda_c/D$ enhancement?

- $0.11$ (pp PYTHIA) $\rightarrow$ $0.4-0.9$  (Di-quark correlation in QGP)
  S.H. Lee etc. PRL 100, 222301 (2008)

- Total charm yield in heavy ion collisions