Open Heavy Flavor at RHIC

Alan Dion

Recontres de Moriond, March 23, 2007

- Indirect measurement of heavy flavor mesons
- Medium modification of heavy flavor spectra
- Determining bulk medium properties
Heavy Quarks

**c\bar{c}, b\bar{b} from hadronic collisions**

- Hard process
- Quark-antiquark annihilation
- Gluon fusion (dominates at large energy)
- Higher-order processes? (small at large energy)

**General strategy to study heavy quarks**

- Calibrate the heavy quark production in p+p collisions
- Probe the medium from A(d)(p)+A collisions, using known initial yield

**Theoretical Expectation**

- Large mass ⇒ less E-loss from gluon radiation ("Dead-cone" effect)
- Some medium-induced radiation
- Elastic scattering? (depends on $\alpha_s$)
**Direct Reconstruction**

\[ \overline{D^0} \rightarrow K^+\pi^- \]

STAR employs this method

Difficult without measure of vertex displacement \((c\tau \sim 123 \mu m)\)

**Alternative Indirect Method**

Measure contribution of semileptonic decays from heavy flavor to lepton spectra

Both single and pair spectra

PHENIX and STAR
PHENIX and STAR

**PHENIX**
electrons in central arms: tracking, eID with RICH, EMC
muons in forward arms: tracking, $\mu$ID with absorber

**STAR**
large acceptance tracking with TPC
hadrons and muons: TPC, TOF
eID with EMC

Heavy Flavor at RHIC  Alan Dion  2007-03-23
Electron Identification in PHENIX

Detectors

Tracking in drift chamber. Track matching to RICH & EMC.
Ring size/shape in RICH
E/p distribution from the EMC and DC.

Heavy Flavor at RHIC

Alan Dion

2007-03-23
Electron Identification in PHENIX

The E/p distribution gives strong evidence that we understand our eID. Kaons which decay far from the collision have mis-reconstructed momentum. Most tracks passing eID cuts form a gaussian centered at 0.98 (EMC calibrated for hadrons).

Hadronic Background

Some hadronic tracks are randomly associated with a ring in the RICH. These are statistically subtracted by swapping the north and south sides of the RICH in software.
Electron sources

- Dalitz decay of light neutral mesons
  \( \pi^0 \rightarrow \gamma e^+ e^- \)
  also from \( \eta, \omega, \eta', \phi \)

- \( \gamma \rightarrow e^+ e^- \) in material
  main photon source: \( \pi^0 \rightarrow \gamma \gamma \)
  beampipe, detector material, air

- Weak kaon decays
  \( K^\pm \rightarrow \pi^0 e^\pm \nu_e \)

- Di-electron decays of vector mesons
  \( \rho, \omega, \phi \rightarrow e^+ e^- \)

- Direct/thermal radiation

- Heavy flavor decays
Cocktail Method

Method

All relevant background sources are measured

Decay kinematics and photon conversion rate are calculated (simulated)

Background cocktail is subtracted from inclusive spectrum

Performs well at high $p_T$ where signal/background is large

Not limited by statistics
Converter Method

**Method**

Add material of known thickness around the beampipe and compare the electron spectra with and without the material installed

\[
N_{\text{non-photonic}} = \frac{R_\gamma N_{\text{inclusive}} - N_{\text{converter inclusive}}}{R_\gamma - 1}
\]

Works best at low \( p_T \) where photonic sources are significant

Limited by statistics of converter run

Converter method is used to normalize the cocktail method
PHENIX $e^\pm$ consistent with FONLL

STAR $e^\pm$ above FONLL

PHENIX has better signal to background, and the data is accepted by PRL. STAR has a direct D-meson measurement...
Prompt muons
- mainly from c, b
- PYTHIA: <15% from $\rho, \omega, \phi \to \mu^+\mu^-$ for $p_T > 0.9$ GeV/c

Decay muons
- From $\pi, K$
- Important at all $p_T$

Punch-through hadrons
- small, uncertain contribution

Stopped hadrons
Decay muons obtained from vertex distribution

- Yield of decay muons increases linearly with distance between collision vertex and absorber

Punch-through hadrons calculated from a data-driven absorption model:

- Tracks reaching gap 2 (3), but not gap 3(4)
- Tracks reaching gap 4
- Nuclear interaction lengths (FLUKA, GHEISHA)

Decay muons obtained from vertex distribution

- Subtract decay muons and punch-through hadrons from inclusive yield at gap 4
Prompt $\mu^-$ spectrum from p+p collisions at $\sqrt{s} = 200$ GeV

Prompt $\mu^+$ spectrum has much larger uncerntainty due to punch-through hadrons

Prompt $\mu^-$ spectrum at $\eta = -1.65$ is comparable to heavy flavor $e^\pm$ spectrum at $y=0$

Excess over PYTHIA and FONLL

Heavy flavor rapidity distribution wider than expected from pQCD
Cold Nuclear Matter

$R_{dAu}$ from STAR

Consistent with binary scaling

but also some indication for Cronin enhancement

PHENIX also observes no strong centrality dependence of $e^\pm$ from d+Au

No strong cold nuclear matter effects
$R_{AA} \equiv \frac{\text{Yield in } A+A}{N_{\text{binary}} \times \text{Yield in } p+p}$
D meson reconstruction

\[ \text{Counts} [10^5/(5 \text{ MeV/c}^2)] \]

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

\[ \text{Au+Au minbias} \]

\[ \text{STAR Preliminary} \]

\[ (d^2N)/(N_{ev} d^2p_T dy) (\text{GeV/c})^{-2} \]

\[ p_T \text{ (GeV/c)} \]

\[ K\pi \text{ Inv. Mass (GeV/c}^2) \]

\[ 1.7 \quad 1.75 \quad 1.8 \quad 1.85 \quad 1.9 \quad 1.95 \quad 2 \]

\[ 10^7 \quad 10^5 \quad 10^3 \quad 10^{-1} \quad 0 \quad 10^{-3} \quad 10^{-7} \]

\[ \pm \mu \pm e \]

\[ \text{D}^0(\text{D}^0) \rightarrow K\pi, p_T < 3 \text{ GeV/c, } |y| < 1 \]

\[ \text{Event-Mixing Background Subtracted} \]

\[ \text{Event-Mixing+Linear Background Subtracted} \]

\[ \text{Gaussian+Linear Fit} \]

\[ \text{Gaussian Fit} \]

\[ \text{Systematic Error} \]
No discrepancy in $R_{AA}$ between PHENIX and STAR.
e-h Correlations from STAR

separating charm and bottom cross section

subtraction of large background

model dependent (PYTHIA)
Intermediate-mass di-electrons mostly come from charm...perhaps a significant thermal radiation contribution

what can the di-electrons tell us about the medium properties and heavy quark energy loss?
Azimuthal Anisotropy

quantify azimuthal dependence of observed particles with respect to the reaction plane of the collision by the Fourier expansion

\[
\frac{dN}{d\phi} \propto 1 + \sum_i v_i \cos(i(\phi - \Psi))
\]

We are mostly interested in \(v_2\), as the other coefficients will either be small or masked by the reaction plane resolution.

the measurement

Measure reaction plane with BBC at forward and backward rapidity

Measure electrons in similar way as the singles spectra, with “cocktail” and “converter” method.
Some Models for $R_{AA}$ and $v_2$

Caveats

The Rapp/van Hees model seems to do pretty well, but it is missing a few things:

- radiative energy loss
- more realistic geometry/density

Also, the model uses a given impact parameter for “0-10%” and “minimum-bias”.

Diffusion/drag are connected through pQCD. What happens for higher orders?
**Hadron Blind Detector**
- Dalitz/conversion background rejection for single electrons and electron pairs

**Silicon Vertex Tracker**
- Direct tagging of charm/bottom decays → distinguish charm from bottom signal and measure $v_2$ of D meson

**New reaction plane detector**
- High $p_T$ non-photonic electron $v_2$
Measurement of electrons at $y=0$ and muons at $\eta = -1.65$ from semileptonic heavy flavor decays from p+p collisions

- $p_T$ spectra agrees pretty well with FONLL, but some indication that spectra are harder than FONLL
- Rapidity distribution is wider than expected from pQCD
- PHENIX/STAR yield discrepancy needs to be worked out

Electrons from heavy flavor at $y=0$ from Au+Au collisions

- Yield follows binary scaling (hard probe)
- $p_T$ spectra strongly modified by the medium
- $v_2$ indicates charm flow

Charm quarks seem to interact with the medium similarly to light quarks

What is the bottom quark distribution?
Backup Slides
Efficiency Correction

Acceptance $\times$ Efficiency

Simulate single electrons/positrons in full azimuth and PHENIX rapidity

run through GEANT

make eID cuts

Multiplicity Dependence

Simulate single electrons/positrons in full azimuth and PHENIX rapidity

embed into real data

run reconstruction software

make eID cuts

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>0.751</td>
</tr>
<tr>
<td>10-20%</td>
<td>0.810</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.874</td>
</tr>
<tr>
<td>40-60%</td>
<td>0.935</td>
</tr>
<tr>
<td>60-93%</td>
<td>0.976</td>
</tr>
</tbody>
</table>
Hadron E/p determined from CNTs

get a hadron sample from CNT’s by a RICH veto

eID cuts are the same as electron analysis except for inverse prob and RICH veto
Hadrons with inverse prob cut

Blue points are the E/p of tracks which pass normal eID cuts. Red points are the E/p of tracks which pass eID cuts with the inverse prob cut, divided by the ratio shown on slide 1.

E/p for 8 GeV/c < p_T < 9 GeV/c

Data from cEWG with eID cuts, but prob<0.01
8 GeV/c < p_T < 9 GeV/c

E/p [c]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 2 4 6 8

10 12 14

E/p for 8 GeV/c < p_T < 9 GeV/c

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 2 4 6 8 10 12 14

total signal
hadron background

eID cuts are the same as electron analysis except for inverse prob
Constraining $\eta/s$

Rapp & van Hees

describe $R_{AA}$ and $v_2$ with heavy quark diffusion constant $D_{HQ}(2\pi T) \sim 4 - 6$

Teaney & Moore

Find $\frac{D_{HQ}}{\eta/(\epsilon+p)} \sim 6$

Perturbative calculation, but error from non-perturbative effects cancel in ratio (?)

Combining

$\epsilon + p = Ts$ at $\mu_B = 0$

This gives $\eta/s \sim (1 - 2)/4\pi$

This is very close to the conjectured quantum bound of $\eta/s = 1/4\pi$
Medium-induced radiative energy loss (BDMPS)

No medium effects on fragmentation

pQCD calculation (works at high $p_T$)

The light hadron spectra are quite insensitive to the value of $\hat{q}$
Model Description

Same model used as for the light hadrons

charm/bottom separation from FONLL calculation

Heavy quarks are less suppressed than the light quarks ⇒ less sensitive to surface bias

Single electrons from heavy flavor are more sensitive to the transport coefficient than the light hadrons

however, the admixture of charm and bottom confuses things
Other suppression models

Collisional Dissociation

heavy quarks fragment inside the medium and are suppressed by dissociation

\[ \frac{dN_q}{dy} = 1000 \]

B mesons are suppressed as much as D mesons at high \( p_T \)

DGLV

radiative energy loss

pQCD calculation

elastic scattering included

next step

charm and bottom signals need to be disentangled to distinguish various models
Other suppression models

- PHENIX data

--- \( \Lambda_c/D \) enhancement factor of 5

--- \( \Lambda_c/D \) enhancement factor of 12

Baryon Enhancement

Could enhancement of the \( \Lambda_C \) explain the suppression of the non-photonic electrons?

- Smaller leptonic branching ratio
- Softer leptonic decay spectrum