Thesis title

“Nuclear modification of electron yields from charm and bottom hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”

(based on PPG182 paper)

(English ver. slides)

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Contents

- motivation
  -- brief introduction to heavy ion collisions
  -- why heavy quark?
- analysis
  -- single electron measurement with VTX
-discussions & conclusions
1. After the nucleus-nucleus collisions, multiple parton scatterings take place.
2. They are supposed to be in the thermal equilibrium (QGP phase)
3. The system expands rapidly along the beam axis and cools. Finally, it is converted into normal hadronic phase.
Time evolution of heavy quarks

- Since charm quark ($m_c \approx 1.3$ GeV) and bottom quark ($m_b \approx 5$ GeV) mass are much larger than QGP’s temperature ($300\sim600$ MeV), they are dominantly produced via the hard scatterings at the initial nucleon-nucleon collisions.
- They interact with QGP, but the number heavy quarks are conserved because they are not destroyed by the strong interaction.
- Thus, heavy quarks are suitable probes to study the evolution of the matter.

radlab meeting
Single electrons from **Charm** and **Bottom**

Previous PHENIX measurement (2004/2005 data)

- Single electrons from combined charm and bottom hadron decays are strongly suppressed in Au+Au compared to p+p.

-> unexpected, because the expectation was

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

- Results are challenging for theoretical models
- bottom is suppressed ??
parton energy loss mechanisms

1. Radiative energy loss
   - energy loss via gluon emission
   - qualitatively, dominant in higher pT

2. Collisional energy loss
   - qualitatively, dominant in lower pT
   - neglected before the PHENIX discovery (in pQCD-based calculations)
   - the relative importance is expected to increase if non-perturbative effects become relevant.
     (Ralf, Rapp, arXiv:0930.1096)

- There are many models for radiative/collisional energy loss.
- Although radiative energy loss is believed to be more dominant in higher pT than collisional energy loss, it is not know at which pT this transition occurs.
radiative energy loss model (example)

DGLV theory

This model puts gluons as a static scattering center and assumes the medium expands uniformly and cylindrically along with the beam axis.

The free parameter of this model is initial gluon density \( \left( \frac{dN_g}{dy} \right) \).

- evaluate radiative energy loss of charm and bottom quarks separately.
collisional energy loss (examples)


Langevin –type approach
Brownian motion of heavy quarks are considered for the collisional; energy loss

\[ \frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}. \]

(\(\eta_D\): friction coefficient , \(\xi\): noise term)

- In this model, the (spatial) diffusion coefficient D is free parameter.
- describe R_AA of charm and bottom depending on their mass

\[ D = \frac{T}{M\eta_D(0)} \]


T-matrix approach

- consider hadronic resonance states in the QGP
- larger scattering amplitude
- This non-perturbative process is calculated using T-matrix.
motivation of separating charm/bottom

- The contributions of collisional energy loss and radiative energy loss for heavy quarks are unclear.
- Different models predict different energy loss for charm and bottom quarks.
- Thus, the charm and bottom separation in single electron spectrum plays an important role to discriminate those models or limit their model parameters.
PHENIX Silicon Vertex Tracker (VTX)

- installed in 2010.
- Inner 2 layers composed of Pixel (B0/B1)
- Outer 2 layers composed of Stripixel (B2/B3)

Reconstruct precise tracking as well as precise collision vertex.

In 2011 Au+Au collisions data, we analyzed $2.4 \times 10^9$ events.
Analysis strategy to separate $c \rightarrow e$ / $b \rightarrow e$

Utilize their different lifetimes and decay kinematics

- Measure displaced tracking of electron with VTX + Central arms
  - $1.5 < p_T < 5.0$ [GeV/c] in 2011 Au+Au data.

  **charm hadron**
  \[ c\tau_{D^0} = 123 \, \mu m, \quad c\tau_{D^\pm} = 312 \, \mu m \]

  **bottom hadron**
  \[ c\tau_{B^0} = 455 \, \mu m, \quad c\tau_{B^\pm} = 491 \, \mu m \]

- Use published invariant yield of single electrons from combined charm and bottom decays in 2004 data.
  - $1.0 < p_T < 9.0$ [GeV/c]
    - Higher pT reach
    - Efficiency corrected (absolute normalization)

Use unfolding techniques to simultaneously take into account both pieces and statistically separate charm and bottom.

PRL 98, 172301 (2007)
Precise displaced tracking with VTX

- reconstruct collision vertex position in 3D with the VTX hit information alone.
- Calculate the Distance of Closest Approach (DCA) of a track to the collision vertex.

Calculated separately in transverse plane ($DCA_T$) and longitudinal plane ($DCA_L$).


![Graph showing DCA_T resolution](image)

achieved ~60 μm $DCA_T$ resolution
electron $DCA_T$ distribution

Measured $DCA_T$ distribution of electrons from 2011
(Run 11) Au + Au MB data, ( $|\eta|<0.35$ )

- 5 electron pT bins  $1.5 < p_T < 5.0$ [GeV/c]
- no efficiency correction
- At first, determine normalized background contributions and then subtract.

Measured DCA$_T$ distribution of electrons from 2011 (Run 11) Au + Au MB data , ( |η|<0.35 )

**Mis-reconstructed components**
- Hadrons identified as electrons
- Wrong VTX hit association

**Prompt components**
- Dalitz decay ($\pi, \eta \rightarrow e^+e^-\gamma$)
- $J/\psi \rightarrow e^+e^-$

**Non-prompt components**
- Conversions $\gamma \rightarrow e^+e^-$
- Ke3

Remaining components come from charm + bottom

Unfolding

Use Bayesian inference methods to determine parent charm and bottom hadron $p_T^h$ distributions.
- use PYTHIA 6 to make model of yield of c/b vs pT, as well as electron’s pT and DCA$_T$
- sample model parameters and compared with data using likelihood function.

Example:

Probability distribution of Invariant yield of charm and bottom hadrons and their correlations
Charm and Bottom Hadrons Yield

Yields for Min. bias Au+Au at 200 GeV, integrated over all rapidities.

- Using PYTHIA + Charm hadron yield
- Calculate $D^0$ yield within $|y| < 1$
- Compare with $D^0$ measurement from STAR

(Phys. Rev. Lett. 113, 142301)

Very good agreement!
Unfolding consistency check

simultaneous fit of pT distribution and DCA_T distribution works well.
electrons from **bottom** fraction

In electron’s pT space

**Fraction of electrons from bottom**

\[
F = \frac{b \rightarrow e}{b \rightarrow e + c \rightarrow e}
\]

Apparent shape difference when compared to p+p data from e-h correlation measurements.
Charm electron and Bottom electron $R_{AA}$

\[ F = \frac{b\rightarrow e}{b\rightarrow e + c\rightarrow e} \]

red line (uncertainty band) is the VTX result in Au+Au collisions.

\[ R_{AA}^{b\rightarrow e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF} \]

previous PHENIX result (c->e + b->e) in Au+Au

PHYS. REV. C 84, 044905 (2011).

STAR b->e fraction in p+p

PHYS. REV. LETT. 105, 202301 (2010).

\[ R_{AA}^{c\rightarrow e} < R_{AA}^{b\rightarrow e} \]

at 3 < pT < 4 GeV/c

\[ R_{AA}^{c\rightarrow e} \sim R_{AA}^{b\rightarrow e} \]

above 4 GeV/c

First measurement that b->e are suppressed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV!
comparison with theoretical models
comparison with theoretical models

DGLV model
(only radiative energy loss)
Below 4 GeV/c
initial gluon density
dNg/dy = 1000, 3500
agree with data but slightly above and outside the uncertainty band

+ added collisional energy loss

(Note) those calculations are for 0-10% central collisions, while data are for MB.
comparison with theoretical models

only collisional energy loss

Brownian motion of heavy quarks are considered.
(Langevin –type approach)

D: diffusion constant $D(2\pi T) \sim 6$ agree with data.
comparison with theoretical models

collisional energy loss

T-Matrix approach (consider hadronic resonance in the QGP)

In (b), D=4~6 agree with data below ~ 3, 4 GeV/c

Only model (d) shows a slight decrease in the bottom fraction at high pT.
- we limit several model parameters.

-those models predict different bottom fraction at $p_T > 4$ GeV/c, it is important to reduce the uncertainty of the bottom fraction in higher $p_T$ region for future measurement.
future:
- high statistic data (~x10) in Au+Au (2014)
  -> significantly improve uncertainties in $c\rightarrow e$, $b\rightarrow e$
- p+p data (2015)
  -> provide baseline with same method.

Those data should provide new constraints on theoretical description of charm and bottom energy loss.
Conclusion

- We have succeeded in measuring the electrons from charm and bottom hadrons decay separately as a function of p T from Au+Au data taken at √sNN = 200 GeV in 2011 by the VTX detector.

- first observation of electrons from bottom is suppressed at RHIC!

- 3 < pT < 4 GeV/c electron \( R^{c\rightarrow e}_{AA} < R^{b\rightarrow e}_{AA} \)

- 4 GeV/c < pT \( R^{c\rightarrow e}_{AA} \sim R^{b\rightarrow e}_{AA} \)

- We have found that the extracted bottom electron fraction agrees with a number of models within the relatively large uncertainties, while it provides new constraints on some model parameters.
backup
parton energy loss

- In the central Au+Au collisions at RHIC, high pT hadrons are strongly suppressed compared to p+p or d+Au collisions.
- one of the most important phenomena in heavy ion collisions

- Nuclear modification factor

\[ R_{AA}(p_T, y; b) = \frac{d^2 N_{AA}/dydp_T}{N_{coll} \times d^2 N_{pp}/dydp_T}. \]

Number of binary collisions

PHENIX measurement of $\pi^0$ $R_{AA}$

DCA distribution w/ backgrounds