Measurement of Charms and Bottoms with Semi-leptonic Decay Modes in p+p Collisions at $\sqrt{s} = 200$ GeV

2014/02/21
Ryohji Akimoto
Heavy quark (charm & bottom)

- Heavy quark (HQ): created at initial hard process
  - Interaction between parton & QGP can be clearly extracted by comparing initial and final states.
- HQ production: well evaluated by $p+p \times N_{\text{coll}}$
  - Result of $p+p$ collision can provide information of initial state of A+A collision.
- The interaction depends on many factors.
  → Multiple information is necessary to test interaction models & to extract QGP properties.
- HQ measurement: electrons from charm or bottom decay (heavy-quark electrons)
  - small $R_{AA}$ at high $p_T$: large energy loss (same suppression level as $\pi^0$)
  - large $v_2$ at $p_T < 3$ GeV/c: largely affected by QGP

\[
R_{AA} = \frac{d^3 N_{AA}/dp^3}{\langle N_{\text{coll}} \rangle \cdot d^3 N_{pp}/dp^3}
\]

\[
E \frac{d^3 N}{dp^3} = \frac{d^2 N}{2\pi p_T dp_T dy} \left( 1 + 2v_2 \cos(2\phi) + \cdots \right)
\]
Measurement of charm & bottom

- **charm & bottom measurement**: important to test interaction between HQ and QGP
  - measure electron/positron from semi-leptonic decay.

- **Distance of Closest Approach (DCA)**
  - c/b contributions are evaluated with DCA distribution.
  - depends on life-time and q-value of parent hadrons.

  → DCA can be used to distinguish charm & bottom

  ✓ $D^\pm$: $c\tau=311.8\mu m$, $D^0$: $c\tau=122.9\mu m$
  ✓ $B^\pm$: $c\tau=491.1\mu m$, $B^0$: $c\tau=457.2\mu m$
Overview of data analysis

- \( E \frac{d^3\sigma}{dp^3} |_{b \rightarrow e} = E \frac{d^3\sigma}{dp^3} |_{c,b \rightarrow e} \times (b \rightarrow e)/(c,b \rightarrow e) \)
  - \( E \frac{d^3\sigma}{dp^3} |_{c,b \rightarrow e} \) : already reported (PRL 103, 082002 (2009))
  - \( (b \rightarrow e)/(c,b \rightarrow e) \) : evaluate by using DCA distribution

- \( (b \rightarrow e)/(c,b \rightarrow e) \)
  
  (1) measure inclusive electron, and DCA distribution of inclusive electrons
  
  (2) yield ratio & DCA distribution of each electron component by simulation
  
  (3) fit DCA distribution of inclusive electron by using the yield ratio and DCA distribution of each electron component, then evaluate \( (b \rightarrow e)/(c,b \rightarrow e) \)

✓ free parameter of the fitting : only \( (b \rightarrow e)/(c,b \rightarrow e) \)
Analyzed data

- **p+p collisions collected at 2012**
  - collision energy : $\sqrt{s} = 200$ GeV
  - integrated luminosity : 2.2 pb$^{-1}$

- **trigger**
  - base trigger : BBC
    - ✓ data collection : $|z\text{-vertex}| < 15$ cm
    - ✓ data analysis : $|z\text{-vertex}| < 8$ cm
  - electron trigger : RICH & EMCal
Electron ID

- **RICH**
  - Gas : CO\(_2\) (\(\beta \gamma > 35\))
    - ✓ electron : \(p > 18\) MeV/c
    - ✓ \(\pi^\pm\) : \(p > 4.9\) GeV/c

- **EMCal**
  - energy measurement : \(E/p=1\)
  - shower shape

- performance
  - reconstruction efficiency : 90%
  - hadron contamination : ~1%
DCA measurement

- interpolate by using $p_T$ from VTX hit point.
  
  - position resolution ($\phi$) : $14\mu$m @ $r=2.6$cm
  - $p_T$ : measured by DC/PC
    
   ✓ $\frac{\delta p_T}{p_T} \approx 1.5\%$ @ $p_T=1$GeV/c
  
  - beam collision point : evaluated for run-by-run (center of beam spot (beam center))
    
   ✓ beam size : $115\sim129$ $\mu$m

• DCA resolution
  
  - hadron : $63.8/p_T \oplus 128.3$ $\mu$m
  
  - difference between data & sim. : $\pm 5\mu$m
    
   ✓ effect from the difference is included in systematic error.
Beam center measurement

- beam center (center of beam spot)

1. evaluate beam collision point for events with more than 1 tracks

2. create distribution of beam collision point run-by-run.

3. fit the distribution by a Gaussian, and the center of the Gaussian is used as beam center.

- width (= beam size $\oplus$ resolution of beam collision point) : $\sim 200$μm

- simulate p+p collision by PYTHIA : well reproduces data.
Electron components

- electron components
  - non-photonic electron
    ✓ heavy quark (charm, bottom)
    ✓ kaon (Ke3)
  - photonic electron
    ✓ photon conversion ($\gamma \rightarrow e^+e^-$)
    ✓ Dalitz decay from light mesons ($\pi^0$, $\eta$, $\eta' \rightarrow \gamma e^+e^-$)
  - light vector meson
  - heavy quarkonia ($J/\psi$, $\psi'$, $\Upsilon$)
  - others
    ✓ hadron contamination
    ✓ fake track

- $p_T$ distribution of inclusive electrons can be explained by the sum of these components (PRC 84, 044905 (2011))
  - increase of material: evaluated by using distributions of pair-mass & $\phi_V$ of $e^+-e^-$ pairs.
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Isolation cut

- require empty hit around associated VTX hits.
  - a large part of photonic electrons is rejected: improve S/N
    ✓ Rejected tracks are used to evaluate DCA distribution of conversion electrons.
  - hit distribution around associated hit: well reproduced by simulation.
- rejection fraction by isolation cut
  - photonic electron: ~80%
  - HQ: ~10%
- S/N of heavy-quark electron: ~3 times larger

- data
- sim. all conversion
  - B1: 1<p_T<2 GeV/c

![Graph showing survival fraction and S/N vs electron p_T](image)
Yield ratio after isolation cut

- **yield ratio after iso. cut = (yield ratio before iso. cut) \times (survival fraction)**
  - HQ electron: > 50%
    - large S/N ratio even at low $p_T$ region.
  - background
    - $p_T < 3\text{GeV/c}$: photonic electron (< 40%)
    - $p_T > 3\text{GeV/c}$: heavy quarkonia (~15%)

- $dN/dp_T$ of inclusive electrons after isolation cut
  \[
  = \Sigma \{(dN/dp_T \text{ before iso. cut}) \times (\text{yield ratio before iso. cut}) \times (\text{survival fraction})\}
  \]

**Fractions in total**

**dN/dp_T after iso. cut**

- data
- sim. all
- c+b
- conversion
- $\pi^0 \rightarrow \gamma e^+e^-$
- heavy quarkonia
DCA distribution of each electron component

- **electrons from hadron decay**: evaluated with simulation
  - Smearing by detectors is approximated by a Gaussian.
    - width: use width in simulation.
    - mean: correct mean of simulation to reproduce data.
- **conversion electron**: use tracks rejected by the isolation cut.
  - A large part of the tracks which are not rejected at B0 and are rejected at outer layers, is conversion electron.
  - width & mean: consistent with simulation
- **fake track**: make fake tracks deliberatively by rotating CNT projection.
- **hadron contamination**: use DCA distribution of hadron
Comparison of DCA distribution

sum of DCA distributions of all components 
→ reproduce DCA distribution of inclusive electrons of data.
Systematic error evaluation

• Uncertainties of yield ratio and DCA distribution of each electron component are transferred to the systematic error of \((b \rightarrow e)/(c, b \rightarrow e)\).

(1) Each of items is changed within its uncertainty.

(2) Then evaluate \((b \rightarrow e)/(c, b \rightarrow e)\) by the DCA fitting.

(3) A difference of \((b \rightarrow e)/(c, b \rightarrow e)\) values before and after the change is assigned as the systematic error.
Systematic error

1. Yield ratios of each electron component
2. Mean of DCA distribution
3. **DCA resolution**
4. DCA distribution of conversion electron
5. DCA distribution of fake track
   i. Mean
   ii. Width
6. HQ electron
   i. Production ratio of hadrons
   ii. **Quark p_T distribution**
   iii. Quark mass
7. Fitting region
8. Isolation cut efficiency

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<table>
<thead>
<tr>
<th>p_T range (GeV/c)</th>
<th>1.5-2.0</th>
<th>2.0-2.5</th>
<th>2.5-3.0</th>
<th>3.0-4.0</th>
<th>4.0-5.0</th>
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<td>±7%</td>
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<tr>
<td>3</td>
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<td>±18%</td>
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<tr>
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<td>&lt; 1%</td>
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<tr>
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<td>&lt; 1%</td>
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<tr>
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</tr>
<tr>
<td>6-1 (D^+/D^0)</td>
<td>±3%</td>
<td>±1%</td>
<td>±1%</td>
<td>±1%</td>
<td>&lt; 1%</td>
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<tr>
<td>6-1 (Λ_c/D^0)</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
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<tr>
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<tr>
<td>6-1 (B_s/B^0)</td>
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<td>6-1 (Λ_b/B^0)</td>
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<td>±4%</td>
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<td>±5%</td>
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<td>6-2 (charm)</td>
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<td>±7%</td>
<td>±8%</td>
<td>±10%</td>
<td>±1%</td>
</tr>
<tr>
<td>6-2 (bottom)</td>
<td>±36%</td>
<td>±38%</td>
<td>±40%</td>
<td>±43%</td>
<td>±41%</td>
</tr>
<tr>
<td>6-3 (charm)</td>
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<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>±4%</td>
</tr>
<tr>
<td>6-3 (bottom)</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>&lt; 1%</td>
<td>±9%</td>
</tr>
<tr>
<td>7</td>
<td>±6%</td>
<td>±12%</td>
<td>±9%</td>
<td>±6%</td>
<td>±4%</td>
</tr>
<tr>
<td>8</td>
<td>±27%</td>
<td>±9%</td>
<td>±8%</td>
<td>±8%</td>
<td>±6%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>66%</td>
<td>46%</td>
<td>48%</td>
<td>54%</td>
<td>48%</td>
</tr>
</tbody>
</table>

**Large contribution**: DCA resolution & p_T distribution of bottom quark
(b→e)/(c,b→e) & differential cross section

measurement of (b→e)/(c,b→e) & differential cross sections of c→e & b→e at 1.5 < p_T < 5 GeV/c.
Comparison with reported results

- \( p_T < 2.5 \text{ GeV/c} \) : achieved at lower \( p_T \) region.
- \( p_T > 2.5 \text{ GeV/c} \) : consistent with the reported results.

- estimation of pQCD : consistent with experimental results.
Comparison with pQCD: differential cross section

- comparison with pQCD calculation
  - reproduce experimental results within uncertainty
  - central value: ~50% smaller than experimental results
Comparison with pQCD : total cross section (bottom)

\[ \sigma_{bb} = 3.14 \pm 0.53\text{(stat)} \pm 1.96\text{(sys)} \mu b \]

• consistent with our result as well as results with different collision energies
Conclusion

Cross sections of charm→e & bottom→e in p+p collisions with √s=200GeV has been measured.

• achieved at 1.5 < p_T < 5 GeV/c
  
  - achieved at the low p_T region where large v2 of HQ electrons has been observed (p_T<3GeV/c).

  ✔ The base line for A+A collisions at 1.5 < p_T < 2.5 GeV/c can be provided.

• comparison with pQCD
  
  - Both total & differential cross sections are consistent with experimental results.
Backup
Quark Gluon Plasma (QGP)

• **QGP : deconfined phase of QCD matter**
  - achieved at extremely high temperature and density from lattice QCD calculation (T>~170MeV, $\varepsilon$>~1GeV/fm$^3$)

• **High-energy heavy-ion collision**
  - an unique experimental method to achieve such high temperature and density.
    - RHIC : Au+Au ($\sqrt{s_{NN}}$ = 200 GeV), Cu +Cu, U+U
    - LHC : Pb+Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)
Heavy quark (charm & bottom)

- Heavy quark (HQ) : created at initial hard process
  - HQ production : well evaluated by p+p × N_{coll}
  - difference between p+p & A+A : modification from initial state

  ✓ measurement of p+p : base line for A+A

- HQ measurement : electrons from charm or bottom decay (heavy-quark electrons)
  - small R_{AA} at high p_T : same suppression level as π^0
  - ✓ large energy loss
  - large v_2 at p_T < 3 GeV/c

  ✓ largely affected by expanding medium

\[
R_{AA} = \frac{d^3N_{AA}/dp^3}{\langle N_{coll}\rangle \cdot d^3N_{pp}/dp^3}
\]
\[
E \frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy} (1 + 2v_2 \cos(2\phi) + \cdots)
\]
Heavy quark in QGP

• smaller energy loss than light quarks due to dead cone effect: longer thermalization time
  - different from particles composing QGP

• interaction between QGP and HQ: depends on quark mass
  - evaluate $R_{AA}$, $v2$ of charm & bottom separately → test of the interaction from quark-mass dependence.

• low $p_T$ region ($< 3\text{GeV/c}$): largely affected by expanding medium.
  - important region to understand properties of QGP.
Evaluation of charm/bottom

- evaluation of charm/bottom contributions
  - p+p : N(b→e)/N(c,b→e) is evaluated by using e-h correlations.
    ✓ partial reconstruction of D^0 (e+K)
    ✓ angle correlation of e-h

- evaluation in p+p collision
  - only for high p_T region (> 2.5 GeV/c) : smaller difference between c/b as decrease p_T

- can not be carried out in A+A collision
  - large combinatorial BG
    ✓ multiplicity of Au+Au : \times 100 larger than that of p+p
    ✓ S/N ratio at Au+Au : 1/100 of p+p
      → statistical error : \times 10
Distance of Closest Approach (DCA)

- **DCA**: distance between track and beam collision point
  - \( DCA = d \cdot \sin \theta \) (\( B=0 \))

- separation charm/bottom by using DCA
  - utilize large difference of life-times of charm & bottom
    - ✓ width of DCA distribution: depends on life-time
      - \( D^\pm = 311.8 \mu m, D^0 = 122.9 \mu m \)
      - \( B^\pm = 491.1 \mu m, B^0 = 457.2 \mu m \)
    - ✓ large difference even at low \( p_T \) region
  - not pair analysis: promising also at A+A collision.
Summary of motivation

- separation of charm & bottom contributions
  - test of interaction between QGP and HQ
    - important to understand behavior of HQ in QGP
    - p+p collision: measured only at $p_T > 2.5$ GeV/c
      - not measured at low $p_T$ region where a large v2 has been observed.
  - A+A collision: not achieved

- evaluate c/b contributions in $c+b \rightarrow e$ at p+p collisions.
  - provide the base line for A+A result via measurement at p+p.
Overview of measurement

• measure electrons from charm or bottom decay
  - large branching ratio (BR>10%)
  - small background (S/N>1 for p_T>1 GeV/c)
• evaluate yields of charm and bottom by using DCA distribution.
  - different life-times → different widths of DCA distributions.
• measurement
  - electron ID: RICH, EMCal
  - DCA measurement: track reconstruction around beam collision + correct bending by magnetic field.
    ✓ VTX: track reconstruction around beam collision
    ✓ DC, PC: momentum measurement

<table>
<thead>
<tr>
<th>BR(h→e+X)</th>
<th>life-time (cτ)</th>
</tr>
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<tbody>
<tr>
<td>D⁰</td>
<td>6.47% 122.9μm</td>
</tr>
<tr>
<td>D⁺</td>
<td>16.07% 311.8μm</td>
</tr>
<tr>
<td>B⁰</td>
<td>10.33% 457.2μm</td>
</tr>
<tr>
<td>B⁺</td>
<td>10.99% 491.1μm</td>
</tr>
</tbody>
</table>
PHENIX detector complex

- **PHENIX central arm**
  - $|\eta| < 0.35$
  - $\Delta\phi = 90^\circ \times 2$

- **DC, PC**
  - momentum measurement
  - track reconstruction

- **RICH, EMCal**
  - electron ID
  - electron trigger

- **VTX**
  - tracking around beam collision
  - measurement of beam collision point

- **BBC**
  - event trigger
  - measurement of beam collision point (z direction)
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- **VTX**
  - tracking around beam collision
  - measurement of beam collision point

- **BBC**
  - event trigger
  - measurement of beam collision point (z direction)
**Silicon Vertex Tracker (VTX)**

- installed for DCA measurement
  - track reconstruction around beam collision & reconstruction of beam collision
  - installed at 2011

- silicon detector with 4 layers
  - **pixel detector** : inner 2 layers
  - **stripixel detector** : outer 2 layers

<table>
<thead>
<tr>
<th>barrel</th>
<th>B0</th>
<th>B1</th>
<th>B2</th>
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<tr>
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<td>2.6cm</td>
<td>5.1cm</td>
<td>11.8cm</td>
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<tr>
<td>pixel size</td>
<td>50μm(ϕ) × 425μm(z)</td>
<td>80μm(ϕ) × 1000μm(z)</td>
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<tr>
<td>rad. length</td>
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<tr>
<td>occupancy</td>
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<td>0.16%</td>
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<tr>
<td>thickness</td>
<td>200μm</td>
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<td>625μm</td>
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DCA distribution : fake track

- **fake track** : make fake tracks deliberatively by rotating CNT projection.
シリコンピクセル検出器

• ピクセル検出器：VTXの内側2層
  - binaryのヒット情報を出力
• 動作環境
  - バイアス電圧: 30V / 200μm
  - 温度: ~5℃
• 有感領域：全体の約60%
• threshold値：タイミングをずらして測定、ヒットレートから値を決定
  - 0.1~0.3 MIP（検出効率 > 99%）
• noise hit rate：ビームが入っていないbunchでヒットレートを評価
  - 0.012 (B0), 0.02 (B1) → occupancy: ~10^{-8}
各成分のDCA分布：photon conversion

• isolation cutによりrejectされた電子を利用
  - 特にB1以降でrejectされた電子の多くがconversion成分
• B0（最内層）以外でrejectされたものの分布から、他の成分の寄与を除く
  - 他の成分：π⁰→γe⁺e⁻, random association
• GEANT simulationの結果と一致（中心値、幅）

![Graphs showing DCA distribution and pT distributions for total, random, and conversion components.](image-url)
hadron $p_T$ vs. electron $p_T$
Example of the stable run selection (B1-west)
Electron rate after good run selection ($p_T>0.5\text{GeV/c}$)

- electron rate ($=(\text{number of electrons ($p_T>0.5\text{GeV/c}$)}) / (\text{number of MB equivalent events})$) was checked for all good runs.
  - checked with ERT trigger data.
- The rates were fitted by pol0 (red line), and the deviations of all runs from the line were less than $3.3\times\text{(stat. error)}$. 
hit map (run group 7)
重イオン衝突への適用（DCA分解能）

• DCA分解能：ビーム衝突点の使用で分解能が改善

  - ビーム衝突点の分布の分解能 (p+p)：
    \[ \sqrt{(200^2 - 125^2)} = 156\mu m \]
  - ビーム衝突点の分解能が (飛跡数)^{-1/2} に比例すると仮定

    \[ \sqrt{(60^2 + 15^2)} = 62\mu m \] (p+pのときの~1/2)

\[ p_T = 1\text{GeV/c} \]

\[ \text{single track DCA resolution} \]
重イオン衝突への適用（DCA分解能）

- DCA分解能が変わることによる影響
  - DCA分解能の不定性：p+pと同程度の不定性（±5μm）を考える
  - b/(c+b) を求める手順を簡略化、c→e + b→eのサンプルに対して、

\[
\begin{align*}
\sigma^2_{\text{data}} &= (1-f) \cdot \sigma^2(c) + f \cdot \sigma^2(b) \\
&= (1-f) \cdot (\sigma_0^2(c) + \sigma_{\text{DCA}}^2) + f \cdot (\sigma_0^2(b) + \sigma_{\text{DCA}}^2) \\
&= f \cdot \left( \sigma_0^2(b) - \sigma_0^2(c) \right) \quad (f = b/(c+b))
\end{align*}
\]

\[
\rightarrow f = \frac{\sigma^2_{\text{data}} - \sigma_{\text{DCA}}^2 - \sigma_0^2(c)}{\sigma_0^2(b) - \sigma_0^2(c)}
\]

- \( \sigma_{\text{DCA}} \)に\( \delta \sigma_{\text{DCA}}=5\mu m \)の不定性があるとすると、\( \sigma_{\text{DCA}}^2 \)には2\( \sigma_{\text{DCA}} \cdot \delta \sigma_{\text{DCA}} \)の不定性がつく

\[
\rightarrow \text{DCA分解能の不定性が} b/(c+b) \text{に与える影響は} p+p \text{の} \sim 1/2 \text{となる}
\]
重イオン衝突への適用（S/N）

- background: \( \pi^0 \)の抑制により、BGは減少
  \( R_{AA}(\pi^0) \approx 0.3 \)
- multiplicityの増加から、多くのトラックがisolation cutでカットしてしまう → より狭いisolation領域の設定が必要
  \( \approx 1/30 \)のisolation領域を設定：\( \approx 60\% \)のphotonic electronが除去

- S/N: \( p_T > 1 \text{GeV/c} \)でS/N > 1が得られると期待 → p+pと同程度