PHENIX measurements of $b\bar{b}$ production in $p+p$ collisions

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Motivation

- Bottom quark production is very useful tool to test pQCD theories.
  \[ m_b \sim 5\text{GeV} \gg \Lambda_{QCD} \]

- Large semi-leptonic branching ratio \( b \rightarrow e/\mu \), BR\(\sim 10\% \).

- Focus on PHENIX open bottom measurements from di-leptons.

- Di-leptons are a unique probe
  - Allow access to diverse physics signal
  - Exploring the mass and \( p_T \) phase space simultaneously provides separation of charm and bottom.
The PHENIX detector

Electron acceptance:
• $|\eta|<0.35$
• $p_e > 0.2\ \text{GeV/c}$
• $\Delta \phi = \pi(2\ \text{arms} \times \pi/2)$

Muon acceptance:
• $1.2 < |\eta| < 2.2$
• $p_\mu > 1\ \text{GeV/c}$
• $\Delta \phi = 2\pi$

Outline of this talk

$b\bar{b}$ measurements in p+p collisions:
- At $\sqrt{s} = 200\ \text{GeV}$ using unlike-sign $e^+e^-$ pairs.
- At $\sqrt{s} = 500\ \text{GeV}$ using like-sign $\mu^\pm \mu^\pm$ pairs from B oscillation.
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Uniqueness:
- No secondary vertex determination required.
- Results have smaller statistical uncertainties.
$b\bar{b}$ measurement using unlike-sign electron pairs
Unlike-sign di-electron spectra

- High quality, large mass range e^+e^- pair data from 2006.
- Very well understood in terms of
  - Hadronic cocktail at low masses
  - DY, charm and bottom at high masses
- Same technique as PRC 91, 2015, 014907 (d+Au)
Isolating charm and bottom contributions

- Subtract the yield of
  - Vector and pseudo-scalar mesons
  - Drell-Yan
- Left with the electron pairs from charm and bottom.
- Separate charm and bottom by fitting mass and $p_T$ simultaneously.
**Heavy flavor mass spectra in $p_T$ bins**

**Heavy flavor mass spectra**

\[ \text{DATA} - (\pi, \eta, \eta', \rho, \omega, \phi, J/\psi, \psi', \Upsilon, DY) \]

- $0.0 < p_T < 0.5$ GeV/c
- $2.0 < p_T < 2.5$ GeV/c
- $1.0 < p_T < 1.5$ GeV/c
- $3.5 < p_T < 5.0$ GeV/c

**DATA (c $\bar{c}$ + b$b'$ pairs)**

$p+p, \sqrt{s}=200$ GeV

**PHENIX acceptance**

- $90\% \text{ CL}$
- $1.2<y<2.2$ (p-going)
- $-2.2<y<-1.2$ (Au-going)

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**PHENIX preliminary**

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Heavy flavor mass spectra in $p_T$ bins

**Heavy flavor mass spectra**

*DATA* — ($\pi, \eta, \eta', \rho, \omega, \phi$, $J/\psi, \psi', \Upsilon, DY$)

**PYTHIA Shapes:**
- Charm
- Bottom
- Total

**PHENIX acceptance**

- $0.0 < p_T < 0.5$ GeV/c
- $0.5 < p_T < 1.0$ GeV/c
- $1.0 < p_T < 1.5$ GeV/c
- $1.5 < p_T < 2.0$ GeV/c
- $2.0 < p_T < 2.5$ GeV/c
- $2.5 < p_T < 3.0$ GeV/c
- $3.0 < p_T < 3.5$ GeV/c
- $3.5 < p_T < 4.0$ GeV/c
- $4.0 < p_T < 4.5$ GeV/c
- $4.5 < p_T < 5.0$ GeV/c

**Fit Range**
- $1.15 < m_{ee} < 2.4$ GeV/c$^2$
- $4.1 < m_{ee} < 8.0$ GeV/c$^2$

**Legend**
- DATA (c $\bar{c}$ + b $\bar{b}$ pairs)
- $c\bar{c}$ (PYTHIA)
- $b\bar{b}$ (PYTHIA)

**p+p, $\sqrt{s}=200$ GeV**
Heavy flavor mass spectra in $p_T$ bins

Heavy flavor mass spectra

$DATA - (\pi, \eta, \eta', \rho, \omega, \phi, J/\psi, \psi', \Upsilon, DY)$

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$1.15 < m_{ee} < 2.4 \text{ GeV/c}^2 \& \& 4.1 < m_{ee} < 8.0 \text{ GeV/c}^2$

DATA ($c \bar{c} + b \bar{b}$ pairs)
- $2.0 < p_T < 2.5 \text{ GeV/c}$
  - $c \bar{c} + b \bar{b}$ (PYTHIA)
  - $c \bar{c}$ (PYTHIA)
  - $b \bar{b}$ (PYTHIA)

$p+p, \sqrt{s}=200 \text{ GeV}$
Heavy flavor mass spectra in $p_T$ bins

**Data –** ($\pi, \eta, \eta', \rho, \omega, \phi, J/\psi, \psi', \Upsilon, DY$)

PYTHIA Shapes:
- Charm
- Bottom
- Total

Heavy flavor mass spectra

![Graph showing heavy flavor mass spectra in $p_T$ bins]
Heavy flavor mass spectra in $p_T$ bins

**Heavy flavor mass spectra**

*DATA* – ($\pi$, $\eta$, $\eta'$, $\rho$, $\omega$, $\phi$, $J/\psi$, $\psi'$, $\Upsilon$, $DY$)

**PYTHIA Shapes:**
- **Charm**
- **Bottom**
- **Total**

Charm dominates
- Low $p_T$, low mass

Bottom dominates
- Low $p_T$, high mass
- High $p_T$, low mass
Heavy flavor mass spectra in $p_T$ bins

**Heavy flavor mass spectra**

*DATA* — ($\pi, \eta, \eta', \rho, \omega, \phi, J/\psi, \psi', \Upsilon, D\ Y$)

**PYTHIA Shapes:**

**Charm**

- Low $p_T$, low mass

**Bottom**

- Low $p_T$, high mass
- High $p_T$, low mass

Charm dominates

Bottom dominates

This behavior is model independent.
Double differential spectra

**MC@NLO**

- $0.0 < p_T < 0.5$ GeV/c
- $0.5 < p_T < 1.0$ GeV/c
- $1.0 < p_T < 1.5$ GeV/c
- $1.5 < p_T < 2.0$ GeV/c

**PYTHIA**

- $0.0 < p_T < 0.5$ GeV/c
- $0.5 < p_T < 1.0$ GeV/c
- $1.0 < p_T < 1.5$ GeV/c
- $1.5 < p_T < 2.0$ GeV/c

Data (c+ b pairs) $\sqrt{s}=200$ GeV

- Fit Range $1.15 < m_{ee} < 2.4$ GeV/c² & $1.15 < m_{ee} < 3.5$ GeV/c²
- Fit Range $1.15 < m_{ee} < 2.4$ GeV/c² & $1.15 < m_{ee} < 8.0$ GeV/c²

In PHENIX acceptance

$\frac{1}{N_{\text{evt}}} \frac{dN}{dm_{ee}} [c^2/\text{GeV}]$ versus $m_{ee} [\text{GeV/c}^2]$
Both PYTHIA and MC@NLO describe the data equally well. Shaded region in the mass region is excluded in the fits.
Extrapolation to total cross-section

Bottom cross-section is model independent. Charm is not!
If $m_q \gg p$, the $e^+e^-$ decay randomizes the opening angle.
- Otherwise, the opening angle between electrons depends on the opening angle between quark pair.

The rapidity shapes between PYTHIA and MC@NLO are different for charm pairs.
- This implies a larger model dependence for $c\bar{c}$ than $b\bar{b}$ pairs.

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See poster by Deepali Sharma (ID:256)
$b \bar{b}$ measurement using like-sign muon pairs from B oscillation
**Advantages of like-sign pairs**

Like-sign pairs: no contamination from Quarkonia, DY or vector mesons.

Like-sign pairs consists of
- Combinatorial pairs
  - Estimated from event mixing
- Correlated pairs
  - Charm pairs:
    - Negligible.
    - <1% in PHENIX acceptance
  - Bottom pairs.
  - Jet pairs.

Nearly half of the total bottom yield is like-sign!
Closer look at $b$ decay

(a)

Decay chain

Primary: $B \rightarrow l^+ X$
Feed down: $B \rightarrow \bar{D}X \rightarrow l^- X$
Primary: $B \to l^+ X$
Feed down: $B \to \bar{D}X \to l^- X$

Primary-Primary decay only produces like-sign pairs via oscillation.
**Closer look at $b$ decay**

- **Decay chain**
  - Primary: $B \rightarrow l^+ X$
  - Feed down: $B \rightarrow D X \rightarrow l^- X$

- **Oscillation**
  - Primary-Primary decay only produces like-sign pairs via oscillation.

**Total number of bottom pairs:**

$$N_{b\bar{b}} = N_{primary-primary}/(BR(B \rightarrow \mu))^2$$

**Fraction of like-sign pairs comes from oscillations**

$$\alpha(m) = \frac{b\bar{b} \rightarrow B\bar{B} \rightarrow \mu^\pm \mu^\pm (osc)}{b\bar{b} \rightarrow B\bar{B} \rightarrow \mu^\pm \mu^\pm}.$$
Dimuons at $\sqrt{s} = 500$ GeV

- Combinatorial background was subtracted out using event mixing method.

$$N_{\pm\pm}^{corr} = N_{\pm\pm}^{like} - N_{\pm\pm}^{mixed}$$

- In high mass region, correlated pairs contains:
  - Bottom pairs
  - Jet pairs

- Jet pair contribution is estimated from hadronic simulation
Extracting the bottom contribution

- Mass region between 5 and 10 GeV
  - B oscillation pairs dominate

- Slopes were fixed from simulation.

- Extracted hadronic and open bottom contribution.

- Forward/backward rapidity hadronic background differ due to different amount of absorber material.
Total cross-section:

\[ \sigma_{bb} = \frac{d\sigma_{bb \rightarrow \mu\mu}}{dy} \times \frac{1}{\text{scale}} \times \frac{1}{\text{BR}_{(B \rightarrow \mu)}} \]

Extrapulated using PYTHIA (scale~0.2%) to calculate the total cross-section.

Bottom cross-section from primary-primary decay

\[ N_{\pm \pm}^{\text{osc}} = \alpha(m) \times N_{\pm \pm}^{B,\text{corr}} \]

\[ N_{BB \rightarrow \mu\mu} = N_{\pm \pm}^{\text{osc}} \times \left( \frac{1}{\beta} \right) \]

\( \beta \) is the fraction of primary-primary B decay from oscillation.
Results are consistent with the NLO pQCD calculation within uncertainties.
Summary

- Dileptons provides a low background measurement of $b\bar{b}$.
- Measurements does not require secondary vertex determination.
- Both PYTHIA and MC@NLO describe the data nicely,
  - Precise measurement of bottom cross-section.
  - Large model uncertainty in charm cross-section.
- Measured bottom cross-section from like-sign dimuon pairs via oscillation.
  - Extrapolation of the bottom cross-section is higher than pQCD value but consistent within uncertainties.

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BACKUP
Figure 33: Invariant mass plots of the unlike-sign (black) and all like-sign (green) dimuons from open charm mesons generated in Pythia. The small number of counts in the high mass region are due to underlying events and are not correlated.
Normalization

(a)

PHENIX

p+p at \( \sqrt{s} = 500 \text{ GeV} \)

1.2 < y < 2.2

\( 1 \frac{dN}{N_{MB} dm} \) (GeV/c^2)^{-1}

\( A \in \)

\( -1 \times 10^{-9} \)

m_{\mu^+\mu^-} (GeV/c^2)

m_{\mu^+\mu^-} (GeV/c^2)
Hadron background
cocktail

Systematic source | Uncertainty (Mass ≤ 1.0 GeV/c^2) | Uncertainty (Mass > 1.0 GeV/c^2)
---|---|---
Data systematics

| eID | 15% | 10% |
| ERT | 10% | 3% |
| Fiducials | 8.6% | |
| α− correction | 5% | |

Cocktail systematics

| Hadronic cocktail | 20% |
| cc cross-section | 32% |
| bb cross-section | 36% |