Measurement of $b\bar{b}$ cross section in LHCb

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for the LHCb collaboration

3rd Workshop on the implications of HERA for LHC physics
DESY, Hamburg, 12th-16th March 2007
Physics interest of production studies

- Measurements of heavy-quark production are essential for testing predictions based on perturbative QCD, and for constraining fragmentation models
- Significant improvements in theoretical calculations, and their inputs, over past few years
  - Better knowledge of fragmentation, structure functions and $\alpha_S$
  - Calculations performed fixed-order with next-to-leading log (FONLL)
  - Consequent improved agreement with Tevatron data for central $b\bar{b}$ production

- Need more precise measurements before ruling out contributions from new physics
- Need to improve understanding of forward production
  - D0 measurement for $2.4 < |\eta| < 3.2$ factor 4 higher than suggested by theory
Measuring $\sigma_{bb}$ in LHCb

- LHCb is designed for high-precision measurements of b-hadron decays
  ‣ Will record enormous data samples useful for $bb$ production studies
- Experiment is optimised for acceptance in forward region, and in a single hemisphere
  ‣ Take advantage of correlation between $b$ and $\bar{b}$
  ‣ Measure $\sigma_{bb}$ in region of phase space not accessible to previous hadron-collider experiments, or to other LHC experiments
- Measurement of $\sigma_{bb}$ is complementary to other production measurements
  ‣ Production fractions for different species of $b$ hadron
  ‣ Differential cross sections
  ‣ Correlations between pairs
LHCb detector

Muon Detector

Calorimeters

Vertexing

Tracking

Hadron Identification

e/\gamma

\mu

Hadron triggering

proton beam

250 mrad

15 mrad

cavern wall

interaction region

Trigger Tracking

Tracking stations

Cavern wall

interaction region

Hadron triggering
Average luminosity = $2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \approx 2 \text{ fbarn}^{-1}$ per year of data taking ($10^7 \text{s}$)

<table>
<thead>
<tr>
<th>Cross section (mbarn)</th>
<th>Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch crossings</td>
<td>40000.</td>
</tr>
<tr>
<td>All interactions</td>
<td>100.</td>
</tr>
<tr>
<td>Visible interactions</td>
<td>60.</td>
</tr>
<tr>
<td>bb events</td>
<td>0.5</td>
</tr>
<tr>
<td>cc events</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Approximate cross sections and production rates

$\geq 2$ charged tracks in VELO

- Hardware trigger
- High $E_T$ particles
- Partial information

- Software trigger
- High $E_T$ and IP
- Full information

Trigger rates

<table>
<thead>
<tr>
<th>Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 triggers</td>
</tr>
<tr>
<td>HLT</td>
</tr>
<tr>
<td>Exclusive B</td>
</tr>
<tr>
<td>Dimuon</td>
</tr>
<tr>
<td>Single muon</td>
</tr>
<tr>
<td>Inclusive D</td>
</tr>
</tbody>
</table>

Overall trigger efficiency in range 0.3-0.8 for hadronic and semi-leptonic $b$ decays of interest to LHCb
Determination of $\sigma_{bb}$

- Measurement of cross section for a process $X$ is conceptually simple
- Use: $\sigma_X = N_X / (L \varepsilon_X)$
  - $\sigma_X$: cross section
  - $L$: integrated luminosity
  - $N_X$: number of times process is detected
  - $\varepsilon_X$: Detection efficiency
- Outline how each of these will be evaluated in LHCb for measurement of $\sigma_{bb}$
  - Deal with general strategy rather than precise numbers, as studies are still at an early stage
- Note that work to measure $\sigma_{bb}$ is work to understand the detector (acceptances) and the environment (luminosity)
  - Essential for all LHCb physics studies
Number of bb pairs using inclusive muons

- Approaches based on analysis of inclusive muon samples have historically been very successful
  - Used by UA1, CDF and D0 in their first measurements of $\sigma_{bb}$
  - LHCb has dedicated muon stream in trigger, and good muon identification in offline reconstruction
- Aim to identify muons from $b$ using cuts on $P_T$ and impact parameter

![Diagram of impact-parameter resolution](image)

$\mu_{\text{eff}} = 0.94$

$\pi_{\text{misid}} = 0.01$
- LHCb is able to reconstruct $J/\psi$ decays both to muons and to electrons.
- In addition to cuts on $P_T$ and impact parameter, will use cuts on separation between primary vertex and $J/\psi$ vertex to identify $J/\psi$ from $b$.

**J/\psi \rightarrow \mu^+\mu^-$**
in minimum-bias events

**J/\psi \rightarrow e^+e^-**
in inclusive $J/\psi$ events
Number of bb pairs using inclusive D mesons

- Reconstruct $D \to K\pi\pi$, $D \to K\pi$, $D \to K\pi\pi\pi$, $D_s \to KK\pi$, then identify D mesons from b by again using cuts on $P_T$, impact parameter and vertex separation
- D-meson reconstruction uses RICH for kaon identification

Kaon identification with RICH

$D_s \to KK\pi$ in $B_S \to D_s(KK\pi)K$ events

$\text{efficiency} \approx 88\%$

$\text{pion mis-ID: 3\%}$

$m_{D_s} = 1.97\,\text{GeV}/c^2$

$\sigma_{D_s} = 5.5\,\text{MeV}/c^2$
Number of bb pairs using exclusive B decays

- Use channels with well-measured branching fractions, for example: 
  \( B^+ \rightarrow J/\psi K^+ \) (3.5% uncertainty), \( B^0 \rightarrow J/\psi K^0 \) (3.8% uncertainty)
- For these channels, expect to reconstruct >100k decays per year

\[ B^+ \rightarrow J/\psi K^+ \]
Efficiency estimates

- Efficiency estimates rely heavily on simulation studies
- Most LHCb studies to date have used Pythia for particle production
- Studies for b production based on other packages also
  - HERWIG/MC@NLO/Jimmy, Sherpa, etc
  - Essential for understanding systematic uncertainties
    - Two generators can give same inclusive distributions, but different correlations
- Use EvtGen for particle decays, and Geant 4 for detector simulation
Luminosity from decays of $Z^0$ and $W^\pm$

- Take theoretical predictions for $Z$ and $W$ cross sections and muonic branching fractions
  - Theoretical uncertainty of ~4%
- Measure yields of $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$, and correct for experimental acceptance
  - Detection rate, after selection cuts, of about 0.05 Hz for $Z \rightarrow \mu\mu$, and 0.25 Hz for single $\mu$ from $Z$ or $W$
  - To match theoretical uncertainty, require data taking for about 3.75 hours for $Z \rightarrow \mu\mu$ and 45 minutes for single $\mu$
- Combine numbers from theory and experiment to determine luminosity

![Dimuon Invariant Mass](image1)

<table>
<thead>
<tr>
<th>Dimuon Invariant Mass (GeV/c²)</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15607</td>
</tr>
<tr>
<td>$N$</td>
<td>477.4 ± 6.5</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>3.66 ± 0.04</td>
</tr>
<tr>
<td>$M_{\mu\mu}$</td>
<td>91.09 ± 0.02</td>
</tr>
</tbody>
</table>

![Muon P_T](image2)

<table>
<thead>
<tr>
<th>MuPt (MuPt&gt;2 &amp; MuPt&lt;2.5 &amp; MuPt/signal&lt;3)</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>43782</td>
</tr>
<tr>
<td>Mean</td>
<td>34.32</td>
</tr>
<tr>
<td>RMS</td>
<td>12.75</td>
</tr>
</tbody>
</table>

![Signal and Background](image3)
- Consider two counter-rotating bunches, with velocity ~c in beams with crossing angle $\phi$ and revolution frequency $f$
- Bunches have populations $N_1, N_2$, and are described by normalised density functions $\rho_1(x,t), \rho_2(x,t)$
- Luminosity obtained as:

$$L = f \frac{N_1 N_2}{4} \frac{2c \cos^2(\phi/2)}{\sin^2(\phi/2)} \int \rho_1(x,t) \rho_2(x,t) \, d^3x \, dt$$

- Use residual gas into region of vertex locator, or inject additional gas
- Reconstruct beam-gas interaction to determine vertices beam angles, profiles and relative positions, and so evaluate overlap integral
  - Use Hijing to generate beam-gas interactions
Conclusions

- LHCb is designed for high-precision measurements of b-hadron decays, and will have large data samples for studies of b production characteristics
- To keep systematic uncertainties under control, each of the quantities contributing to the measurement of $\sigma_{bb}$ will be evaluated in more than one way
  - Determine number of bb pairs using inclusive muons, inclusive J/$\psi$, inclusive D mesons, and exclusive B decays
  - Determine efficiencies using different packages for particle production
  - Determine absolute luminosity using decays of $Z^0$ and $W^\pm$, and using beam-gas interactions in region of vertex locator
- LHCb will measure $\sigma_{bb}$ in the forward region, where the only previous measurement suggests disagreement with predictions based on perturbative QCD