b Production Studies With Early Data At CMS

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On behalf of the CMS Collaboration

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Why study $b$ production at LHC?

- $b$ quarks are a key ingredient at LHC either as direct signal (top physics, low mass Higgs)... Or background to New Physics searches (SUSY...)

- Large $bb$ cross-section allow study of $b$ production and $bb$ correlations with early data
- Test of QCD predictions at LHC energy
- Test detector performance: help with calibration, alignment, trigger
Three dominant production mechanisms:

LO:
Flavor Creation (FC): gluon fusion (dominant) and qq annihilation

NLO:
Flavor Excitation (FE): \( \bar{b} b \) from the sea, only one \( b \) participates to the hard scatter, asymmetric \( p_T \) for the \( b \)'s
Gluon Splitting (GS): \( g \rightarrow b \bar{b} \) in initial or final state, \( b \) at low \( p_T \) and close in the azimuthal angle (\( \Delta \phi \))

Measurement of \( b \) production:
Differential cross-section \( d\sigma/dp_T, d\sigma/d\eta \)

\( b\bar{b} \) correlations:
Azimuthal correlation between the two \( b \)'s (high sensitivity to NLO/LO ratio)
**b production at the Tevatron**

- Studied since the first data in late 80s

- Single b production
  - Exclusive, fully reconstructed $B \rightarrow J/\Psi K$
  - Inclusive $b \rightarrow J/\Psi X$ (lifetime)
  - Inclusive $b \rightarrow (e, \mu)X$ (impact parameter)
  - Inclusive $b \rightarrow \mu + \text{jet}$

- Correlated $b\bar{b}$ production
  - Dimuons (impact parameter)
  - $J/\Psi$ + lepton (lifetime + impact parameter)
  - $\mu + \text{b-tagged jet}$ (secondary vertex)
  - Two b-tagged jet

Results have been compared with “classic” NLO QCD (MNR), and newer FONLL (Cacciari et al., JHEP 0407,033) to determine if QCD correctly predicts the data

CDF PRL 75, 1451(1995)
CDF PRL 79, 572(1997)
CDF PRL 71, 2396(1993), D0 PRL 74, 3548 (1995)
D0 PRL 85, 5068(2000)
CDF PRD 53, 1051(1996)
CDF PRD 69, 072004(2004)
We quote the ratio $R=\text{data}/\text{theory}$, as reported by Happacher et al. (PRD 73, 014026), who performed a consistent evaluation of all existing data as of 2006 using a common theory benchmark. Data consistently above simulation. Agreement improves slightly at large $p_T$. Problem even in D0 $\mu+$jet that should be less sensitive to the exact features of the $b$ fragmentation.

Data consistently above simulation. Agreement improves slightly at large $p_T$. Problem even in D0 $\mu+$jet that should be less sensitive to the exact features of the $b$ fragmentation.
Similar situation for $b\bar{b}$ correlation measurements with $\mu$, but not for only-jet analysis!

Recent measurement from CDF with tighter cuts on muon in good agreement with NLO

Problem with $\mu$ in old analysis ("Ghost muon" puzzle)? Similarly, single $b$ analysis with $\mu$ yields larger $R$ values...
Analysis Examples:

- Cross-section for bottom, charm and quarkonia
  Inclusive J/Ψ, Exclusive B decays (J/ΨK(*)): \(O(10 \text{ pb}^{-1})\)
- Quarkonia studies: polarization, production mechanisms
- \(b\bar{b}\) correlations:
  - J/Ψ+\(\mu\)
  - \(\mu + \text{jet}\)
  - \(\text{jet} + \text{jet}\)
- Lifetime and properties of \(b\) hadrons: \(B_u, B_d, B_s, B_c, \Lambda_b\)
- \(B_s\) oscillations, CP violation: \(O(1 \text{ fb}^{-1})\)
- FCNC rare decays: \(B \rightarrow K^{(*)}\mu\mu, B_s \rightarrow \Phi\mu\mu\)
- FCNC very rare decays: \(B_{s/d} \rightarrow \mu\mu\): \(O(10 \text{ fb}^{-1})\)
- \(\tau \rightarrow 3\mu\) LFV
**Trigger @ CMS**

**Level 1 Triggers:**
- Hardware based
- Muons and Calorimeters
- 40 MHz $\rightarrow$ 200 kHz

**High Level Triggers (L2,L3):**
- Software based
- Fast (local) reconstruction in the tracker included
- 200 kHz $\rightarrow$ 100 Hz

- Different trigger menu under study, depending on the luminosity (e.g. 8E29, 1E31...)

**Relevant Triggers for heavy flavor physics:**

**Dimuon triggers**
- L1: 2 muons $p_T > 3$ GeV/c ($2\mu 3$)
- HLT: Normal dimuon trigger: 2 muons $p_T > 3$ GeV/c
  - Displaced dimuon vertex trigger

**Single muon triggers**
- L1 & HLT: 1 muon with $p_T > 9$ GeV/c (other threshold available, with different pre-scaling factors)
Inclusive b production

Measure inclusive differential b cross-section: dσ/dη, dσ/dp_T

- Study performed at 14 TeV collisions and high lumi
- L1 Trigger: single μ with p_T > 14 GeV/c
- HLT: μ + b-jet: 1 non isolated μ (with p_T > 19 GeV/c) plus a b-tagging requirement on a jet (E_T > 50 GeV and |η| < 2.4, Track counting from pixel tracks)
Inclusive $b$ production

- Select events with at least one $b$-tagged jet and one $\mu$
- Select $b$-tagged jet with highest $p_T$, $\mu$ associated to jet ($\Delta R$)
- B-tag efficiency is about 65% (55%) in barrel (end-caps), Total efficiency $\sim 25$
- Use $p_T$(Rel) to distinguish between $b, c$, and light quark events

- B purity between 55 and 70%
- $b$-hadron $p_T$ range accessible up to 1.5 TeV/c
- $t\bar{t}$ contamination $< 1\%$

<table>
<thead>
<tr>
<th></th>
<th>MC Gen, $120 &lt; \hat{p}_T &lt; 170$</th>
<th>Fit</th>
</tr>
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<tbody>
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<td>$N_{bb}</td>
<td>2503</td>
<td>$2750 \pm 346$</td>
</tr>
<tr>
<td>$N_{cc}</td>
<td>965</td>
<td>$702 \pm 513$</td>
</tr>
<tr>
<td>$N_{uds}</td>
<td>299</td>
<td>$329 \pm 235$</td>
</tr>
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</table>
Inclusive $b$ production

Systematics uncertainties at 14 TeV dominated by:
- JES uncertainty
- b-quark fragmentation
- MC modeling
- B-tagging, luminosity, trigger, etc.

<table>
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<tr>
<th>Source</th>
<th>uncertainty, %</th>
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<td>event selection</td>
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<td>luminosity</td>
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<td>muon Br</td>
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<tr>
<td>muon efficiency</td>
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<tr>
<td>$t\bar{t}$ background</td>
<td>0.7</td>
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<tr>
<td>fragmentation</td>
<td>9</td>
</tr>
<tr>
<td>total</td>
<td>18</td>
</tr>
</tbody>
</table>

Prospects:
\[ \int \mathcal{L} dt \quad 1 \text{fb}^{-1} \quad 1.6 \text{ M} \]
**Strategy**

Measure $bb$ azimuthal correlation using clean full leptonic signature in final state

**Goal**

Measure $bb$ cross-section, estimate NLO contribution

Sensitive to $\Delta \phi$ region $\sim 0$

Allow measurement of GS contribution

Commissioning with early data (first $\mathcal{O}(10)$ pb$^{-1}$)

Complementary to charmonium inclusive study for lifetime/IP fits

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$bb$ Correlations using $J/\Psi + \mu$

Pythia, $2\mu$ $2.5$ filter

$\sigma = 0.20$
**bb Correlations using $J/\Psi + \mu$**

**Event Selection:**
- **Trigger:** $2\mu 3$
- Vertex $\mu\mu$ pairs to build $J/\Psi$ candidate
- Require only match between pixel track and one muon segment to increase Sensitivity at low $p_T$
- Look for a third $\mu$ in the event
- Quality cuts on the third muon track

**Stacked histograms**

**Backgrounds:**
- **Misassigned muons**
- **Real $J/\Psi$** and Fake 3rd muon (hadronic punch-through/Decay in flight),
- **Real $J/\Psi$** from prompt decays
- Irreducible background from Bc $J/\Psi X\mu$ decays

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Signal Extraction

Extract signal in several $\Delta \phi$ bins by simultaneous 3-d unbinned maximum LH fit to $J/\Psi$ invariant mass, $L_{xy}$ transverse flight length, soft $\mu$ Impact Parameter

PDF shapes fixed on MC sample, yields for signal, real $J/\Psi$+ fake $\mu$, prompt $J/\Psi$, and fake $J/\Psi$ floated PDF Shapes:

- Triple Gaussian for $J/\Psi$ invariant mass
- Single(double) tail exponential convoluted with 2 Gaussians for $J/\Psi$ $L_{xy}$ ($\mu$ Impact Parameter)
- Use error/event for gaussian resolution

Validate Fit by fitting independent MC samples, and by using a toy MC study
bb Signal Yield Fit Example

Integrated luminosity ~ 13 pb$^{-1}$

<table>
<thead>
<tr>
<th>Category</th>
<th>Gen Yield</th>
<th>Fitted Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>1865</td>
<td>1924 ± 147</td>
</tr>
<tr>
<td>Fake $\mu$</td>
<td>674</td>
<td>642 ± 140</td>
</tr>
<tr>
<td>Fake $J/\psi$</td>
<td>1576</td>
<td>1543 ± 47</td>
</tr>
<tr>
<td>Prompt $J/\psi$</td>
<td>330</td>
<td>334 ± 25</td>
</tr>
</tbody>
</table>

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Unfolding the $\Delta \phi$ Distribution

Acceptance sculpts reconstructed $\Delta \phi$ distribution

How to get the true spectrum (a) from the measured spectrum (b)?

\[ A: \text{detector/resolution matrix} \rightarrow \text{must be inverted:} \]

\[ \hat{A}a = b \]

(problems: statistical fluctuations, oscillatory solutions...)


Comparison before and after unfolding

- Normalized to the same area
- 13 pb$^{-1}$
Sources of systematic uncertainty (estimated in each $\Delta \phi$ bin):

- Luminosity, tracking and trigger efficiency
- Fraction of muons produced in cascade decays $b \rightarrow cX \rightarrow \mu X'$
- $b$-quark fragmentation
- Uncertainty in the PDF shapes
- $J/\Psi$ polarization and misalignment effects

Compute $pp \rightarrow b\bar{b}X$ cross-section

According to

$$\frac{d\sigma}{d\Delta \phi} = \frac{N_{\text{fit}}}{\mathcal{L} \cdot \epsilon_{\text{trg}} \cdot \epsilon_{\text{reco}}}$$

Uncertainty between 15 and 25% in each $\Delta \phi$ bin, for an integrated luminosity of 50 pb$^{-1}$

Expect an uncertainty of 10% for the integrated $pp \rightarrow b\bar{b}X$ cross-section

$\sigma(pp \rightarrow b\bar{b}X) = (451 \pm 50) \mu$b

(Gen: 438 mb)
Conclusions

- **b-quark** crucial ingredient for LHC goals
- Large bb cross-section makes b production studies ideal test for LHC first run
  - Better understanding of the detector
  - Competitive results with the Tevatron with $O(10 \text{ pb}^{-1})$ data
- Tevatron data on b production and quarkonium still need to be reconciled with theory
- Measurement of b production and bb correlations is an important test of QCD
  - Important to disentangle vanilla QCD effects from real new physics
- Signatures
- We are all waiting for LHC run at the end 2009!
Backup Slides
Requiring tight SVX selection removes events with $\mu^\dagger$ IP > 1.5 cm. Old CDF results suffered from large bkg (1:1) of long-lived real (fake) $\mu$.

Most recent CDF results on single $b$ and $b\bar{b}$ correlation using jets close to NLO prediction.
The CMS Detector

Diameter = 15 m, length = 21.6 m, Weight = 12000 t
3.8 T solenoidal magnetic field
Steel Return Yoke (2T) instrumented with Muon spectrometer
Tracker, ECAL, HCAL inside coil
CMS Detector Slice

Key:
- Muon
- Electron
- Charged Hadron (e.g., Pion)
- Neutral Hadron (e.g., Neutron)
- Photon

START from Tracker

ECAL

HCAL

HO (barrel only)

Muon system

Transverse slice through CMS

Iron return yoke interspersed with Muon chambers

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7 May 2009
### The CMS Muon System

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift Tube Chambers (DT)</td>
<td>Precise tracking</td>
</tr>
<tr>
<td>250 chambers</td>
<td>4 stations in the muon barrel</td>
</tr>
<tr>
<td>8-12 layers/station</td>
<td></td>
</tr>
<tr>
<td>Resistive Plate Chambers (RPC)</td>
<td>Fast response &lt; 10 ns</td>
</tr>
<tr>
<td>540 chambers</td>
<td>6 layers in muon barrel</td>
</tr>
<tr>
<td>4 layers in muon endcap</td>
<td></td>
</tr>
<tr>
<td>Cathode Strip Chambers (CSC)</td>
<td>Precise tracking</td>
</tr>
<tr>
<td>540 chambers</td>
<td>4 stations in muon endcap</td>
</tr>
<tr>
<td>6 layers in muon endcap</td>
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</tr>
</tbody>
</table>

![Diagram of CMS Muon System](image-url)
CMS Muon Reconstruction

Standard approach: Outside-in

- **Local Reconstruction**
  Combine hits in muon chambers into segments (2-d projections and then 3-d segments)

- **Standalone muon reconstruction**
  Build muon seeds from segments in DT, CSC, RPC hits
  Backward Kalman filter to innermost muon station, followed by fit with vertex constraint

- **Global muon reconstruction**
  Extrapolate back to tracker surface
  Look for compatible tracks in region of interest
  Perform global fit, select final candidates based on $\chi^2$
Alternative approach: Inside-out

- Extrapolate every track outward
- Find compatible deposits in ECAL, HCAL, HO, muon hits
- Determine muon “compatibility”

Recover muon inefficiencies at muon chamber boundaries and low $p_T$ (e.g. muons which only reach the first muon station)
## Systematic Uncertainties

### Relative Errors (in %)

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \phi$ Bin 1</th>
<th>$\Delta \phi$ Bin 2</th>
<th>$\Delta \phi$ Bin 3</th>
<th>$\Delta \phi$ Bin 4</th>
<th>$\Delta \phi$ Bin 5</th>
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<td>bottom hadron rate</td>
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<tr>
<td>$J/\psi L_{xy}$</td>
<td>4.8</td>
<td>2.6</td>
<td>4.1</td>
<td>2.6</td>
<td>2.6</td>
<td>0.9</td>
<td>1.8</td>
<td>0.7</td>
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<td>$\mu$ IP</td>
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<td>PDF shape</td>
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<td>$J/\psi$ invariant mass</td>
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<tr>
<td>$J/\psi L_{xy}$</td>
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<td>0.3</td>
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