Measurements of beauty quark production at CMS

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for the CMS collaboration
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• Introduction/Overview
• Selected Results
  – inclusive $b$–jets
  – $\Lambda_b$ production
  – $b\bar{b} \rightarrow$ muon pairs
• Conclusion
b-quark production at the LHC

LHC: pp collisions at $\sqrt{s} = 7$ TeV

- large $b$ cross-section dominated by gluon fusion

- test (LO/NLO)QCD based predictions in a new kinematical region

Data taking

- 2010: 34 pb$^{-1}$
  - low trigger thresholds (increasing with time)
  - negligible pile-up
  $\rightarrow$ ideal for low $p_T$ production cross section

- 2011: 5 fb$^{-1}$
  - more restrictive/ specialized triggers
b-physics:
central region
$|\eta| < 2.4$:
- muons
- tracking
- b-tagging

$\sim 15 \, \mu m \, d_{xy}, d_z$
3.8 T B-field,
excellent mass resolution

**Trigger**

- first level, hardware: muons, calorimeter (1 kHz output)
- higher level trigger, software: near offline reco
  e.g., inv. mass, impact parameters (300 Hz output, 10% b-physics)
# CMS b-production measurements

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<tr>
<th>$pp \to b + X$</th>
<th>$b \to \mu X$</th>
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<td>$b \to \text{muon}$</td>
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<td>JHEP03(2011)090</td>
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<td>$b \to \text{jet}$</td>
<td>b-tagged jets, $\mu$-jet</td>
<td>arXiv:1202.4617</td>
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<td>$b \to \text{hadrons}$</td>
<td>$B^+$</td>
<td>PRL106(2011)112001</td>
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<td>$B^0$</td>
<td>PRL106(2011)252001</td>
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<td>$\Lambda_b$</td>
<td>CMS-BPH-11-007*</td>
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<td>$b \to J/\psi X$</td>
<td>non-prompt $J/\psi$</td>
<td>JHEP02(2012)011</td>
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<td>$b\bar{b} \to \text{di-hadrons}$</td>
<td>angular correlations</td>
<td>arXiv:1203.3458</td>
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* [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11007](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11007)
b-jet cross sections

- less affected by hadronization, decay details
  (compared to more exclusive modes)
- b-tagging calibration crucial, sizeable sys. uncertainty (10%)
- CMS jet measurements
  - anti-kt (R=0.5), particle flow algorithm (calorimeter + identified objects)
  - corrected to generator-level jets (stable particles), same jet algorithm
    LO (PYTHIA) and NLO (MC@NLO)
  - jet energy corrections contributes (4–6%)/(6–8%) to cross section uncertainty
- two approaches
  - jet trigger(s)
  - single muon trigger
- very small overlap, essentially independent samples
Inclusive b-jet cross section


- fully inclusive jet sample
  - jet trigger(s), $L = 34 \text{ pb}^{-1}$
  - $p_T(jet) > 18 \text{ GeV}$
  - high purity b-tagging: 3-track vertex
    $\epsilon(btag) = 5\%(18\text{GeV}) \ldots 56\%(100\text{GeV})$
  - b-fraction from fit to the vertex mass distribution
    tagged sample well described by PYTHIA

- muon sample
  - single muon trigger, $L = 3.0 \text{ pb}^{-1}$
  - $p_T(\mu) > 9 \text{ GeV}$
  - associate nearest b-tagged jet
  - high efficiency b-tagging (2-track vertex):
    $\epsilon(btag) = 50\%(30\text{GeV}) \ldots 75\%(100\text{GeV})$
  - b-fraction from fit to muon $p^\text{rel}_T$ distribution ($\rightarrow$)
    negligible light-quark component
Muon analysis: visible cross section

CMS \( L = 3.0 \text{ pb}^{-1} \)
\( \sqrt{s} = 7 \text{ TeV} \)

- **visible**: muon acceptance varies from 5\% (low \( p_T \)) to 20 \%
- total rate and jet \( p_T \) spectrum in good agreement with MC@NLO
- rapidity shape not well described by MC@NLO
  - PYTHIA describes \( y \) shape better but is too high
  - \( b \to \mu, p_T(\mu) > 6 \text{ GeV} \)

JHEP03(2011)090 →
Reasonable agreement with MC@NLO

- below data for central rapidities (near the upper uncertainty band)
- different \( p_T \) slope at high \( |y| \)

PYTHIA overestimates at low \( p_T \), good agreement at high \( p_T \)
• Integrated over $|y| < 2.2$
• muon based result extrapolated over unobserved muon acceptance (using PYTHIA)
• muon and jet-based measurements consistent
• MC@NLO agrees within uncertainties prediction tends to lie below data
Λ_b production

\[ Λ_b \rightarrow Λ J/ψ \]

\[ J/ψ \rightarrow μ^+μ^- \]
\[ Λ \rightarrow pπ \]

\[ p_T(Λ_b) > 10 \text{ GeV} \]
\[ |η(Λ_b)| < 2.0 \]
\[ L = 1.78 \pm 0.08 \text{ fb}^{-1} \]

\[ <\text{efficiency}> \sim 0.7\%, (0.3\% \ldots 4\%) \]
1252 ± 59 signal events (err. stat. only)
low background

\[ Λ \rightarrow pπ \]
\[ p_T(p) > 1.0 \text{ GeV} \]
\[ p_T(p) > p_T(π) \]
vertex
\[ l_{xy}/σ(l_{xy}) > 5 \]

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\( \Lambda_b \rightarrow \Lambda J/\psi \) and \( \Lambda_b \rightarrow \Lambda J/\psi \)

- event yield from unbinned fit of \( m_{\Lambda_b} \) distribution (projection shown)
- \( \epsilon(\Lambda_b) \) 15\% lower than \( \epsilon(\Lambda_b) \) (\( \vec{p} \) nuclear interactions)
  good agreement between corrected rates
differential cross sections × $BR(Λ_b \to Λ J/ψ)$

- correlated uncertainties not shown (54% $BR(Λ_b \to Λ J/ψ)$, 4.5% Luminosity)
- data softer than PYTHIA simulation, good agreement in $|y|$
Comparison with b-meson production

CMS results for b-hadron production

\[ p_T > 10 \text{ GeV and } |\eta| < 2.0 \]

\[
\begin{align*}
\sigma(pp \rightarrow B^+ X) &= 6.7 \pm 1.0 \text{ pb} \\
\sigma(pp \rightarrow B^0 X) &= 6.7 \pm 0.8 \text{ pb} \\
\sigma(pp \rightarrow B_s X) &= 2.5 \pm 1.0 \text{ pb} \\
\sigma(pp \rightarrow \Lambda_b X) &= 2.1 \pm 1.1 \text{ pb}
\end{align*}
\]

- softer \( p_T \) spectrum for \( \Lambda_b \) than \( B^0, B^+ \)

- phase space corrections wrt to original measurements applied using \texttt{MC@NLO}

- statistical and systematic uncertainties in quadrature
$b\bar{b}$ production with muon pairs


5 GeV < $m(\mu\mu)$ < 70 GeV, $\Upsilon$–veto
remaining $\mu\mu$ sources:

- (B) $b \rightarrow \mu X$
- (C) charm
- (P) prompt muons (DY, resonances)
- (D) light hadron decay-in-flight

disentangled using $\mu$ impact parameters

- 2D fit, symmetrized 1D templates

muon $d_{xy}$ templates, $p_T > 4$ GeV

B,C,D from simulation

P from data
\[
\sigma(pp \to b\bar{b}X \to \mu\mu X',|\eta| < 2.1, p_T > 6 \text{ GeV} \ (4 \text{ GeV})
\]

\[p_T > 4 \text{ GeV}\]

Data \qquad 25.7 \pm 0.1 \ (\text{stat.}) \pm 2.2 \ (\text{syst.}) \pm 1.0 \ (\text{lumi.}) \ \text{nb}

MC@NLO \qquad 19.7 \pm 0.3 \ (\text{stat.}) \pm 6.5 \ (\text{syst.}) \ pm 4.1 \ (\text{syst.}) \ \text{nb}

\[p_T > 6 \text{ GeV}\]

Data \qquad 5.03 \pm 0.05 \ (\text{stat.}) \pm 0.46 \ (\text{syst.}) \pm 0.20 \ (\text{lumi.}) \ \text{nb}

MC@NLO \qquad 4.40 \pm 0.14 \ (\text{stat.}) \pm 1.10 \ (\text{syst.}) \pm 0.84 \ (\text{syst.}) \ \text{nb}(\text{MC@NLO})

- very precise experimental cross section result
- largest systematic uncertainty from muon efficiency
- MC@NLO agrees within uncertainty, below data
Summary

- CMS has studied b-production in $pp$ collisions at 7 TeV
  - b-tagged jets, two independent measurements
  - all ground state b-hadrons (except $B_c$)
    new result on $\Lambda_b$, steep $p_T$ dependence
  - muons pairs, very precise cross section result

- general picture
  - NLO QCD based prediction ($\text{mc@nlo}$) agrees with data within uncertainties
    tends to underestimate b-production for central rapidities
  - PYTHIA tends to overestimate b-production at low $p_T$