Measurement of inclusive $b$-quark production at $\sqrt{s} = 7$ TeV with the CMS experiment

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- Cross sections from:
  - Correlated $b\bar{b}$ with dimuons
  - Single muons
  - Inclusive $b$-jet
- $B\bar{B}$ angular correlations
Correlated $b\bar{b}$ cross section with dimuons

- Cross section for $b\bar{b}$ production from both $b$ quarks decaying into muons
- $\mathcal{L} = 28 \, pb^{-1} @ \sqrt{s} = 7$ TeV
- Flavor composition of the dimuon sample in data $\rightarrow$ fit to the muon transverse impact parameters with respect to primary vertex ($d_{xy}$)
- Both muons need to satisfy: $p_T^{\mu} > 4$ GeV and $|\eta^{\mu}| < 2.1$ and from same PV
- Cuts on $M_{\mu\mu}$ remove backgrounds from $Z$ ($M_{\mu\mu} > 70$ GeV), $\Upsilon$ ($8.9 < M_{\mu\mu} < 10.6$ GeV), charmonium resonances and sequential decays ($M_{\mu\mu} < 5$ GeV)
Correlated $b\bar{b}$ cross section with dimuons

- Single muon events in MC are classified as:
  - **B**: $b \rightarrow \mu$
  - **C**: $c \rightarrow \mu$
  - **D**: meson decay in flight
- Impact parameter distribution for **B**, **C** and **D** from simulation. Distribution for **P** extracted from data: $\Upsilon(1s)$ decays
- Dimuon templates ($BB, CC, PP, DD$) and combinations ($BD, BC, CD...$)

- Binned maximum likelihood fit using the 2D distributions
Correlated $b\bar{b}$ cross section with dimuons: results

- CMS-PAS-BPH-10-015

$$\sigma(pp \rightarrow b\bar{b}X \rightarrow \mu\mu Y) = 26.18 \pm 0.14(\text{stat.}) \pm 2.82(\text{syst.}) \pm 1.05(\text{lumi.}) \text{ nb}$$

$$\sigma_{\text{PYTHIA}} = 48.2 \text{ nb}$$

$$\sigma_{\text{MC@NLO}} = 19.95 \pm 0.46(\text{stat.}) \pm 4.68(\text{scale+pdf+m}_{b}) \text{ nb}$$

- Fraction of $BB$ from fit: 65%
- BP, CP and PD can be neglected
- Constraints: BC/BB, BD/BB and CD/CC from MC
- Largest systematic uncertainty from trigger efficiency ($\approx 8.3\%$)
Open beauty production with muons

- $\mathcal{L} = 85 \text{ nb}^{-1} \oplus \sqrt{s} = 7 \text{ TeV}$
- Signal events discriminated using muon transverse momentum relative to the jet direction $p_T^{\text{rel}}$:

$$p_T^{\text{rel}} = \frac{|\vec{p}_\mu \times \vec{p}_\text{jet}|}{|\vec{p}_\text{jet}|}$$

- $p_T^{\text{rel}}$ is harder in $b$-events than in background due to larger mass of $b$-quark
- Binned maximum likelihood fit to measure $p_T^{\text{rel}}$ distribution based on templates
Open Beauty production with muons

- $p_T^\mu > 6$ GeV and $|\eta^\mu| < 2.1$
- $\mu$ IP requirement: $|d_0| < 2$ mm, $|d_z| < 1$ cm
- Track Jets:
  - Determine $\vec{p}_{\text{jet}}/|\vec{p}_{\text{jet}}|$
  - Tracks with $p_T > 300$ MeV, anti-$k_T$ with $R = 0.5$, $E_T^{\text{jet}} > 1$ GeV (without muon)

- Shape of the light quark/gluon component is evaluated from minimum bias data → misidentification probability for hadrons to be selected as muons
- Templates for $c$ and light quark/gluon events are combined
- $b$ fraction from the fit= 46%
Open Beauty production with muons: results

\( \sigma = 1.32 \pm 0.01(\text{stat.}) \pm 0.30(\text{syst.}) \pm 0.15(\text{lumi.}) \ \mu b \)

\( \sigma_{\text{PYTHIA}} = 1.9 \ \mu b \)

\( \sigma_{\text{MC@NLO}} = 0.95^{+0.41}_{-0.21}(\text{scale}) \pm 0.09(m_b) \pm 0.05(\text{pdf}) \ \mu b \)

- Major systematic uncertainties are \( b p_T^{\text{rel}} \) shape uncertainty (21%) and luminosity (11%)
- Data and MC@NLO compatible within uncertainties

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Inclusive \( b \)-quark production at \( \sqrt{s} = 7 \) TeV

August 12, 2011
Inclusive $b$-jet production

- $\mathcal{L} = 60$ nb$^{-1}$ @ $\sqrt{s} = 7$ TeV
- Minimum bias and jet triggers
- Particle flow jets. Jet reconstruction using anti-$k_T$ algorithm, with $R = 0.5$
- Jet required to have:
  $18 < p_T^{\text{jet}} < 300$ GeV and rapidity $|y| < 2$
- $b$ jets identified using a secondary vertex tagger:
  - Secondary vertex fitted with at least 3 charged particle tracks
  - 3D decay length significance cut is applied
Inclusive $b$-jet production

- $b$-tagging efficiency as a function of $p_T^{\text{jet}}$ and $y^{\text{jet}}$ is from MC → verified in a subsample using data/MC scale factors based on $p_T^{\text{rel}}$
- $b$-content (purity) in selected jets is estimated in data by fitting the secondary vertex mass distribution after the selection

![Secondary vertex mass distribution](image)

| $|y| < 2.0$ | $37 \leq p_T < 56$ GeV | $\chi^2 / \text{NDF} = 18.9 / 17$ |
|---|---|---|
| Data / MC = 0.976 ± 0.022 | $\chi^2 / \text{NDF} = 1.2 / 3$ |
Inclusive $b$-jet production: results

CMS-PAS-BPH-10-009

MC@NLO describes well the overall fraction of $b$-jets, but shape differences in $p_T^{\text{jet}}$ and $y^{\text{jet}}$

Main systematic uncertainties from $b$-tag efficiency (20%), jet energy scale (5%) and luminosity (11%)
$B\bar{B}$ angular correlations

- $\mathcal{L} = 3.1\, \text{pb}^{-1}$ at $\sqrt{s} = 7\, \text{TeV}$
- Use single jet triggers: jet only used to set the energy scale
- Measure $\Delta \phi$ and $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between flight directions of the two $B$-hadrons
- Secondary vertices (SV) reconstructed using an inclusive vertex finder (jet independent): SV reconstructed even if the two $B$-hadrons are in the same jet
**$\bar{B}B$** angular correlations: results

- JHEP03 (2011) 136
- Differential production cross section in bins of opening angle of $B\bar{B}$ pairs
- MC@NLO does not describe the data well, particularly at low $\Delta R$, where large gluon splitting contribution is dominant
Conclusions

- Inclusive $b$-quark production at $\sqrt{s} = 7$ TeV has been measured:
  - Correlated $b \bar{b}$ production with dimuons
  - Open Beauty production with muons
  - Inclusive $b$-jet production
- Inclusive measurements are in overall agreement with MC@NLO
- MC@NLO does not describe data well at low $B \bar{B}$ opening angles (gluon splitting)
Backup slides
Correlated $b\bar{b}$ cross section with dimuons

- 2D symmetrized distributions populated according to:

$$T_{12,ij} = \frac{S_{1,i} \cdot S_{2,j} + S_{1,j} \cdot S_{2,i}}{2}$$

- Real data events fill the $T_{12,ij}$ distribution by assigning the muon in a random order.
Correlated $b\bar{b}$ cross section with dimuons

- **Efficiencies:**
  - $\varepsilon_i = \varepsilon_{i,MuSel} \cdot \varepsilon_{i,EvSel} \cdot \varepsilon_{i,Trg}$
  - $\varepsilon_i = 44.3 \pm 0.1\%$
  - $\varepsilon_{i,MuSel} = 64.8 \pm 0.1\%$
  - $\varepsilon_{i,EvSel} = 78.0 \pm 0.1\%$
  - $\varepsilon_{i,Trg} = 87.7 \pm 0.1\%$

- **Scaling factors obtained by Tag-and-Probe ($J/\psi$)**
  - $SF_{TP,Data}^{Global} = 1.082 \pm 0.082$
  - $\varepsilon = \varepsilon_{MC} \cdot SF_{TP,Data}^{Global} = 47.9 \pm 0.1\%$
Correlated $b\bar{b}$ cross section with dimuons

- MC@NLO+Herwig
  - CTEQ6.6 PDF, $m_b = 4.75$ GeV
- PYTHIA 6.4
  - Z2 tune, CTEQ6L1 structure function
- Systematic error on MC@NLO: $m_b = [4.5, 5]$ GeV, PDF → MSTW2008, renormalization:
- Small error on the scale+pdf seems to come from requiring both the 2 muons with low $p_T$
Correlated $b\bar{b}$ cross section with dimuons

- Systematic errors:
  - Template shapes 5.1%
  - Fit Method 4.7%
  - Efficiencies and normalization 8.3%
  - $\mathcal{L}$ 4%
  - Total 11.4%
Open Beauty production with muons: efficiency measurement $\varepsilon$

\[ \varepsilon = \varepsilon_{\text{trigger}} \cdot \varepsilon_{\mu,\text{reco}} \cdot \varepsilon_{\mu,\text{jet}} \]

- $\varepsilon_{\text{trigger}} = (88 \pm 5) \%$ from data
- $\varepsilon_{\mu,\text{reco}} = (94 \pm 3) \%$ from MC
- $\varepsilon_{\mu,\text{jet}} = (77 \pm 8) \%$ from MC
Open Beauty production with muons: efficiency measurement $\varepsilon$

- **PYTHIA**
  - CTEQ6L1 PDF
  - $m_b = 4.8$ GeV
  - Peterson et al fragmentation function ($\varepsilon_c = 0.05$ and $\varepsilon_b = 0.005$)
  - D6T tune (underlying events)

- **MC@NLO + HERWIG**
  - $m_b = 4.75$ GeV
  - CTEQ6M PDF
Open Beauty production with muons: comparison with the theory

- Comparison with MC@NLO

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Inclusive $b$-jet production

Unfolding

- Ansatz method to correct jet $p_T$ back to particle level
- Phenomenological power law motivated by parton model (Feynman, Field, Fox), extended at the Tevatron and updated at CMS for low $p_T$ and $b$-jets

$$f(p_T) = N_0 p_T^{-\alpha} \left( 1 - \frac{2p_T \cosh(y_{\text{min}})}{\sqrt{s}} \right)^B \exp(-\gamma/p_T)$$

\[ f(p_T) \] : Ansatz function to parametrize true jet $p_T$ spectrum

\[ F(p_T) = \int_0^{\infty} f(p_T') R(p_T' - p_T; \sigma) dp_T' \]

\[ R(p_T' - p_T; \sigma) \] : smearing function

\[ C_{\text{res}} = f(p_T)/F(p_T) \]
Inclusive $b$-jet production

- **MC@NLO**
  - CTEQ6M PDF
  - $m_b = 4.75$ GeV
  - $\mu_F = \mu_R = p_T$

- **PYTHIA**
  - D6T

- **Systematics:**
  - $\mu_R \rightarrow [0.5,2] : +40\%, -25\%$
  - CTEQ PDF: $+10\%, -6\%$
  - $m_b \rightarrow [4.5,5]$ GeV: $+17\%,-14\%$
Inclusive $b$-jet production

- Systematics
Inclusive $b$-jet production

- Ratio to inclusive jets

![Graph showing the ratio of $b$-jet production to inclusive jets as a function of $p_T$ (GeV) with different $|y|$ ranges. The graph includes data points and fits from MC@NLO, Pythia, and experimental uncertainties.](image-url)
**Heavy Quark Production**

- **LO**
  - Flavor creation (FCR): $gg$ fusion (dominant) and $q\bar{q}$ annihilation

- **Large NLO contributions**
  - Flavor excitation (FEX): $b\bar{b}$ from the sea, only one $b$ participates in hard scattering
  - Gluon splitting (GSP): $g \rightarrow b\bar{b}$ in initial or final state

- Production mechanism not separated in analyses presented here

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![Graph showing b-jet pt distribution with FEX, GSP, and Herwig 6.5](image-url)