Inclusive $BB$ cross section at 8 TeV


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Aim: measure $b$-hadron production
- down to zero opening angle
- across a range of kinematics

Interested in $b$ production mechanisms
- particularly small angle $g \rightarrow bb$
  - important background for boosted searches
    eg boosted $H \rightarrow bb$

Previous measurements:
- limited by $b$-jet radius
  - small-\(R\) jet analyses in Run 2 will go to \(dR \sim 0.2\)
- stats & systs for inclusive vertexing
J/ψ → mumu is a clean signal
- use displaced J/ψ to tag B (include feed-down)
  … but low branching fraction \( Br( B \rightarrow J/ψ \rightarrow \mu\mu ) \sim 0.01 \times 0.06 \)

Use displaced muon to tag other B
- include cascades
  - \( Br ( B \rightarrow \mu + X ) \sim 0.2 \)

Analysis is based on 3 muons
- can measure muons down to ~zero BB opening angle

Measure differential, normalised cross sections:
- \( \Delta R(J/ψ, \mu) \) inclusively, for \( pT(J/ψ + \mu) > 20 \text{ GeV} \), and < 20 GeV
- \( \Delta \phi(J/ψ, \mu) \), \( y(J/ψ, \mu) \)
- \( y_{\text{boost}}(J/ψ, \mu) \)
- \( pT (J/ψ + \mu) \), mass(J/ψ + mu)
- \( pT / m \), and \( m / pT \)
\( B \rightarrow J/\psi + X \rightarrow \mu \mu + X \):

- clean signal, use dedicated B-physics triggers (prescaled in some runs)
- efficiencies measured using tag\&probe, applied as weights to data
- select muons with \( p_T > 6 \text{ GeV} \), \( |\eta| < 2.3 \)

**Backgrounds are small:**

- “fake \( J/\psi \)” : combinatorics, fake vertices etc
- prompt \( J/\psi \), ie not from \( B \) decay.
**B → μ + X:**

- select muon with $p_T > 6$ GeV, $|\eta| < 2.5$
- use transverse distance of closest approach to beam (d0) as discriminant

**Backgrounds are significant:**

- in-flight decay of $\pi/K$, punch-through, “sail-through”, pile-up, prompt muons...
- simplify picture by first cutting on $J/\psi \tau > 0.25$.  

![Graphs showing muon mass distribution and transverse separation](image-url)
Final signal yield determined by 2D fit to 3\textsuperscript{rd} muon:
- $d_0$ significance to separate prompt from non-prompt muons
- BDT output to separate “real” muons and “fakes”: in-flight decays, punch-through

Fake J/$\psi$ and pile-up contributions fixed in control regions

Extrapolation to full J/$\psi$ lifetime region after 3\textsuperscript{rd} muon fit
- small unfolding corrections also applied bin-by-bin
Irreducible backgrounds subtracted from the data post-fit:
- “sail-through” (e.g. π/K flying out through the muon system)
  - distribution and normalisation taken from MC (~1%)

- $B_c$ or $B_s \rightarrow J/\psi + \mu + X$
  - attempt to quantify looking for 4-muon events: $B_c \rightarrow J/\psi + \mu + X$ + $B(\rightarrow \mu + X)$
  - instead take from MC (<5%, all at low $\Delta R$)

- $B(\rightarrow J/\psi + X) + D(\rightarrow \mu + X)$
  - possible discrimination through shorter D lifetime
  - attempted to include in 3rd muon fit as separate template, struggle with stats
  - instead take from MC (~5%)
\[ \sigma(B(\rightarrow J/\psi[\rightarrow \mu^+\mu^-] + X)B(\rightarrow \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst}) \text{ nb.} \]

**Pythia 8.2, NNPDF2.3, A14 tune:**
- generate fully inclusive $2 \rightarrow 2$ process with very loose cuts
  - allow $b$-hadrons from ME and PS
- force one $b$-hadron to decay to $J/\psi$, with $J/\psi \rightarrow \mu\mu$.
  - still a significant amount of CPU time…

Generate samples with various settings for $g \rightarrow bb$ splitting kernel:

<table>
<thead>
<tr>
<th>Option label</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opt. 1</td>
<td>The same splitting kernel, $(1/2)(z^2 + (1 - z)^2)$, for massive as massless quarks, only with an extra $\beta$ phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [36] method.</td>
</tr>
<tr>
<td>Opt. 4</td>
<td>A splitting kernel $z^2 + (1 - z)^2 + 8r_q z(1 - z)$, normalised so that the $z$-integrated rate is $(\beta/3)(1+r/2)$, and with an additional suppression factor $(1-m_{qq}^2/m_{dipole}^2)^3$, which reduces the rate of high-mass $q\bar{q}$ pairs. This is the default setting in PYTHIA8.2.</td>
</tr>
<tr>
<td>Opt. 5</td>
<td>Same as Option 1, but reweighted to an $\alpha_s(km_{qq}^2)$ rather than the normal $\alpha_s(p_T^2)$, with $k = 1$.</td>
</tr>
<tr>
<td>Opt. 5b</td>
<td>Same as Option 5, but setting $k = 0.25$.</td>
</tr>
<tr>
<td>Opt. 8</td>
<td>Same as Option 4, but reweighted to an $\alpha_s(km_{qq}^2)$ rather than the normal $\alpha_s(p_T^2)$, with $k = 1$.</td>
</tr>
<tr>
<td>Opt. 8b</td>
<td>Same as Option 8, but setting $k = 0.25$.</td>
</tr>
</tbody>
</table>
mass kernels

pT kernels + best mass kernel

mass kernels
Samples using Herwig++2.7.1, CTE6L1, UE-EE-5 tune:
- again, fully inclusive $2\rightarrow 2$ process, loose cuts
- force one $b$-hadron $\rightarrow J/\psi$, with $J/\psi \rightarrow$ muumu

Madgraph5_aMC@NLO v2.2.2, CKKW-L merging @ 30 GeV, Pythia 8.186 A14 tune
- 5 and 4-flavour samples, using NNPDF3.0NLO (4fl) PDF for ME, NNPDF2.3LO for PS.
- no HFOR for 4-flavour, generate $b$’s in ME with ~no cuts

Shepa 2.1.1, CT10 PDF, MEPS@LO, default tune
- both MG & Sherpa: generate LO samples, up to 3 partons in ME.
- was not possible* to generate 3-muon predictions

Instead derive transfer functions:
- ratio of (3-muon cross section) / (2xb-hadron cross section)

Define a 2xb-hadron fiducial volume which reproduces 3-muon $\Delta R$ shape:

3-muon:
- muon $p_T>6$ GeV
- two muons from $J/\psi$: $|\eta|<2.3$
- 3rd muon from different $b$-hadron: $|\eta| < 2.5$

2xb-hadron:
- $b$-hadron $p_T> 15.5$ GeV
- $b$-hadron $|\eta| < 2.4$
- for $p_T$ and mass, scale down by 1.75
MG5 4-flavour
MG5 5-flavour
Sherpa 2.1 5-flavour

Herwig++
Pythia 8.2 opt.4
(default setting)

Note: no theory uncertainties!
Uncertainties on transfers applied to MG & Sherpa
Measurement of b-hadron pair production
- using 3-muon final state

Measure 10 normalised differential cross sections

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Rivet routine uploaded to contrib 30th August
- can be run in 3-muon mode
- or 2xb-hadron mode, with transfer functions applied.
What are the prospects for using these results in tuning?

Update to 13 TeV should be fairly easy (if people could be found…)
- driving down uncertainties at lowest $\Delta R$ should be relatively simple.

**Alternative is the CMS-style approach:**
- inclusive vertex finding
- would allow, eg $Z+bb$ measurement down to very small angles.

**Which is more interesting?**
- we are dominated by fairly low $p_T$ stuff
  - $b$-hadron $p_T > \sim 16.5$ GeV
- does this really tell us about the backgrounds to boosted topologies?

**Are there other kinematic variables of interest?**
Some backgrounds are fixed in the fit:

"Fake J/psi"
- determine from J/psi fit, applying tau cut

Signal region:
- 2.95 – 3.25 GeV
- Background normalisation from fit
- Background shapes from mass sidebands

Pile-up: J/psi and 3rd muon from different collisions

Determine yield by fitting Δz:
- gaussian, excluding range |Δz| < 40 mm

Signal region:
- cut |Δz| < 40 mm
- pileup normalisation from gaussian
- pileup shape from sidebands