Measurements of heavy-flavor production at CMS

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Introduction

Heavy-flavor production studies are very important to improve understanding of QCD. These studies are becoming more feasible at CMS because of:

- Efficient and very flexible set of dimuon triggers
- Good resolution in $p_T \sim 1\%$ for central region tracker
- Remarkable vertexing efficiency
- Over 140 fb$^{-1}$ of data is recorded for physics data analysis during Run 2
Recent results in heavy-flavor sector from CMS

- Run 2 results:
  - Observation of two excited $B_C^+$ states and measurement of $B_C^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV. ([PRL 122 (2019) 132001](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.122.132001))

- Run 1 results:
  - Study of the $B^+ \to J/\psi \bar{\Lambda} p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV. ([CMS-PAS-BPH-18-005](https://cds.cern.ch/record/2666380))
  - Measurements of correlations between $J/\psi$ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions. ([CMS-PAS-BPH-15-003](https://cds.cern.ch/record/2274485))
Observation of two excited $B^+_C$ states and measurement of $B^+_C(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

[PRL 122 (2019) 132001]
Study focuses on $B_C^+(2S)$ and $B_C^*(2S)^+$ states.

- Decay modes are: $B_C^+(2S) \rightarrow B_C^+ \pi^+ \pi^-$ and $B_C^{++}(2S) \rightarrow B_C^{++} \pi^+ \pi^- \rightarrow B_C^+ \pi^+ \pi^- \gamma$, with a lost photon in the final state. Both $B_C^+(2S)$ and $B_C^{++}(2S)$ can be observed in the same mass distribution.


$$\Delta M = [M(B_C^*) - M(B_C)] - [M(B_C^{++}(2S)) - M(B_C(2S))] \approx 20 \text{ MeV}$$

$B_C^*(2S)^+$ state will be observed at lower reconstructed mass because the ground states splitting is expected to be greater than for $2S$ states.
Observation of two excited $B_C^+$ states and measurement of $B_C^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV

- First observation of well-separated $B_C^+(2S)$ and $B_C^{+(2S)}$ states, resolved at $> 5\sigma$ level
  - $M(B_C^+(2S)) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_C^+)$ MeV
  - $\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})$ MeV

Full Run 2 dataset analysis.
Latest LHCb results on Run1+Run2 data

CMS results were recently confirmed by LHCb collaboration:

\[ \Delta M = 31.0 \pm 1.4 \text{(stat)} \pm 0.0 \text{(syst)} \text{ MeV} \]

\[ M(B_c^{+}(2S)) = 6872.1 \pm 1.3 \text{(stat)} \pm 0.1 \text{(syst)} \pm 0.8(B_c^{+}) \text{ MeV} \]

\[ M(B_c^{*}(2S)^{+}) = 6841.2 \pm 0.6 \text{(stat)} \pm 0.1 \text{(syst)} \pm 0.8(B_c^{+}) \text{ MeV} \]

\[
\begin{array}{|c|c|c|}
\hline
& B_c^{+}(2S)^{+} & B_c^{*}(2S)^{+} \\
\hline
\text{Signal yield} & 51 \pm 10 & 24 \pm 9 \\
\text{Peak } \Delta M \text{ value (MeV/c}^2\text{)} & 566.2 \pm 0.6 & 597.2 \pm 1.3 \\
\text{Resolution (MeV/c}^2\text{)} & 2.6 \pm 0.5 & 2.5 \pm 1.0 \\
\text{Local significance} & 6.8 \sigma & 3.2 \sigma \\
\text{Global significance} & 6.3 \sigma & 2.2 \sigma \\
\hline
\end{array}
\]
Measurements of correlations between $\text{J}/\psi$ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

[CMS-PAS-BPH-15-003]
Models to describe J/ψ production

The mechanism of colorless c̅c state production from hadronic collisions has been a subject of extensive studies since 1974.

Overview:
- The original approach using the color-singlet (CS) model predicted J/ψ cross-sections significantly smaller than the Tevatron measurements.
- NRQCD approach (color-singlet+color-octet amplitudes) was able to describe the Tevatron data.
- NRQCD describes J/ψ production at LHC for $p_T > 10$ GeV.

NRQCD and Fragmentation Jet Function (FJF) approach:
- J/ψ mesons are not produced directly but from high-$p_T$ jet fragmentation.
- The fragmentation function is decomposed in terms of NRQCD amplitudes and long-distance matrix elements (LDMEs). Depends on L and color configuration of c̅c pre-resonance state.
- LDME terms: $S^{(8)}_0, S^{(8)}_1, P^{(8)}_J, S^{(1)}_1$.
- Feature: J/ψ mesons are not isolated.
Measurements of correlations between J/ψ mesons and jets produced in \( \sqrt{s} = 8 \) TeV pp collisions

1. What fraction of J/ψ production is a result jet fragmentation?

\[
\Delta R = \sqrt{(\eta_{\text{jet}} - \eta_{\mu\mu})^2 + (\phi_{\text{jet}} - \phi_{\mu\mu})^2}
\]

Fragmentation is assumed if: \( \Delta R < 0.5 \) and muons are required to constitute jets

Results:
For events with 1 jet 84% of J/ψ with E>15 GeV and |y|<1 are fragments of jets produced in |\( \eta \)| < 1. When unobserved jets (p_T< 25 GeV) are taken into account → jet fragmentation is a source of >80% of J/ψ mesons
Measurements of correlations between $J/\psi$ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

2. Matching data with FJF predictions.

- Unfolded data are compared with BCKL and BK predictions in three $z$ ranges: 0.40-0.45; 0.50-0.55; 0.60-0.65;

- Only one NRQCD term $^1S_0^{(8)}$ using BCKL parameters is able to describe data for 3 measured ranges

- For $z > 0.5$ $^3S_1^{(1)}$ BK might play a role, but introduces polarization

- Further studies might eliminate ambiguity between $^3S_1^{(1)}$ BK and $^1S_0^{(8)}$ BCKL

BK and BCKL FJF - [Phys. Rev. D 96, 036020 (2017)]
Study of the $B^+ \rightarrow J/\psi \bar{\Lambda} p$ decay in proton-proton collisions at $\sqrt{s} = 8$ TeV

[CMS-PAS-BPH-18-005]
Previous results on $B^+ \rightarrow J/\psi \bar{\Lambda}p$ decay

The Belle Collaboration reported the observation of this decay in 2005

<table>
<thead>
<tr>
<th>mode</th>
<th>$Y$</th>
<th>$b$</th>
<th>$n_0$</th>
<th>$\epsilon$ (%)</th>
<th>$Y_{90}$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow J/\psi \Lambda \bar{p}$</td>
<td>$17.2 \pm 4.1$</td>
<td>$0.41 \pm 0.09$ (stat.)</td>
<td>$16$</td>
<td>$7.2^{+1.1}_{-1.4}$</td>
<td>$11.6 \pm 2.8$ (stat.) $^{+1.8}_{-2.3}$ (sys.) $\times 10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>
Study of the $B^+ \to J/\psi \bar{\Lambda}p$ decay

- Using $B^+ \to J/\psi K^{*+}$ decay as the normalisation channel with a similar topology:
  - $\mathcal{B}(B^+ \to J/\psi \bar{\Lambda}p) = (15.07 \pm 0.81\text{(stat)} \pm 0.40\text{(syst)} \pm 0.86\text{(br.)}) \times 10^{-6}$
- The most precise result to date and compatible with previous results:
  - PDG: $\mathcal{B}(B^+ \to J/\psi \bar{\Lambda}p) = (11.8 \pm 3.1) \times 10^{-6}$
  - Belle: $\mathcal{B}(B^+ \to J/\psi \bar{\Lambda}p) = (11.7 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$

- Allows to study intermediate invariant masses of $J/\psi + \text{baryon system}$
  - The masses are found to be inconsistent with pure 3-body PS with a significance $> 6.1$, 5.5 and 3.4 for $J/\psi p$, $J/\psi \bar{\Lambda}$ and $\bar{\rho} \Lambda$, respectively, including systematics
Study of the $B^+ \rightarrow J/\psi \bar{\Lambda}p$ decay. Model-independent approach

- $K^*$ resonances decaying to $p\bar{\Lambda}$ final states can contribute and alter 2-body invariant mass distributions
- Their possible contributions is taken into account by measuring $\cos \theta_{K^*}$ distribution in each $M(p\bar{\Lambda})$ bin on data

$$\frac{dN}{d \cos \theta_{K^*}} = \sum_{j=0}^{l_{\text{max}}} \langle P_j^U \rangle P_j(\cos \theta_{K^*})$$

- and reweighting pure 3-body phase space accordingly

$$w^i = 1 + \sum_{j=1}^{l_{\text{max}}} < P_j^N > P_j(\cos \theta_{K^*}) \quad l_{\text{max}} = 8, s \leq 4$$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass [MeV]</th>
<th>Natural width [MeV]</th>
<th>$j^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_4^*(2045)^+$</td>
<td>2045 ± 9</td>
<td>198 ± 30</td>
<td>4$^+$</td>
</tr>
<tr>
<td>$K_2^*(2250)^+$</td>
<td>2247 ± 17</td>
<td>180 ± 30</td>
<td>2$^-$</td>
</tr>
<tr>
<td>$K_3^*(2320)^+$</td>
<td>2324 ± 24</td>
<td>150 ± 30</td>
<td>3$^+$</td>
</tr>
</tbody>
</table>
Study of the $B^+ \rightarrow J/\psi \bar{\Lambda}p$ decay. 
Model-independent approach

PS - ----- 
8 moments in $\cos \theta_{K^*} -$ 
1D $\cos \theta_{K^*}$ reweighting - ----- 

The model-independent method is used to check the non-exotic hypothesis originated by the contributions of $K^*$ resonances to $p\bar{\Lambda}$ system.

The inclusion of first eight moments corresponding to already known resonances decaying to $p\bar{\Lambda}$ improved the description of the data in $J/\psi p$ and $J/\psi \bar{\Lambda}$ systems, the significance of incompatibility is less than 2.8 standard deviations. 
→ No need for additional exotic resonances
Conclusion

Presented results which demonstrate high potential of upcoming studies using full Run 2 data:

- Observation of two excited $B_C^+(2S)$ states and measurement of $B_C^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV
  - Well-resolved $B_C^+(2S)$ and $B_C^{+(*\pm)}(2S)$ states
    - $M(B_C^+(2S)) = 6871.0 \pm 1.2$(stat) $\pm 0.8$(syst) $\pm 0.8(B_C^+)$ MeV
    - $\Delta M = 29.1 \pm 1.5$(stat) $\pm 0.7$(syst) MeV

- Measurements of correlations between $J/\psi$ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions
  - Concluded that more than 80% of $J/\psi$ mesons are produced by jet fragmentation in the central region
  - Shown that NRQCD term $s^{(8)}_0$ using BCKL can describe the data for three different $z$ regions

- Study of the $B^+ \rightarrow J/\psi \Lambda p$ decay
  - The most precise measurement of branching fraction
  - Study of potentially exotic intermediate states shows that no additional resonances are needed
Backup
S-wave $B_C$ spectroscopy (before CMS results)

**ATLAS**


\[ \int_{L_{\text{tot}} = 19.2 \text{ fb}^{-1}} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ m_{B_C} = 6277 \pm 6 \text{ MeV} \]

\[ N_{B_C} = 227 \pm 25 \]

\[ \sigma = 50 \pm 8 \text{ MeV} \]

**LHCb Collaboration**


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\[ \frac{\sqrt{s} = 7 \text{ TeV}}{\sqrt{s} = 8 \text{ TeV}} \]

\[ \text{ATLAS} \quad (0.22 \pm 0.08 \text{ (stat)})/\varepsilon_7 \]

\[ \text{LHCb} \quad (0.15 \pm 0.06 \text{ (stat)})/\varepsilon_8 \]

\[ \frac{\text{ATLAS}}{\text{LHCb}} \]

\[ \text{ATLAS} \quad (0.22 \pm 0.08 \text{ (stat)})/\varepsilon_7 \]

\[ \text{LHCb} \quad < [0.04, 0.09] \]
Measurements of correlations between J/ψ mesons and jets produced in $\sqrt{s} = 8$ TeV pp collisions

2. Matching data with FJF predictions

Set of variables:

- Theory uses $E_{\text{jet}}$ and $z = E_{J/\psi}/E_{\text{jet}}$ as independent variables
- FJF differential cross section for each LDME term: $z < 0.8$

\[
\frac{d\tilde{\sigma}_i(E; z_1)}{dE} = \frac{d\sigma_i(E; \zeta)}{dE} \bigg|_{z_1} / \sum_{i=1}^{4} \int_{0.3}^{0.8} \frac{d\sigma_i(E; \zeta)}{dE} d\zeta
\]

- Experimentally, a ratio function is used:

\[
\Xi(E_1, z_1) \equiv \frac{N(E_1, z_1)}{\int_{0.3}^{0.8} N(E_1, z) dz} \equiv \left. \frac{d\tilde{\sigma}}{dE d\zeta} \right|_{E_1, z_1}.
\]

$N_{\text{corr}}(E; z_1)$ is the number of events in $\pm \Delta z = 0.25$ about $z_1$.

$R_{\text{corr}}(E; 0.3 - 0.8)$ is the number of events $0.3 - 0.8$ excluding $N_{\text{corr}}(E; z_1)$.

Two different LDMEs sets from Bodwin, Chung, Kim and Lee (BCKL) [Phys. Rev. Lett. 113, 022001 (2014)] and Butenschoen and Kniehl (BK) [Phys. Rev. Lett. 108, 242004 (2012)] are used to compare with data (differ in production mechanisms)