Measurement of exclusive B-hadron production at 7 TeV with the CMS experiment

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for the CMS collaboration
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• The CMS detector
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• B⁰ → J/Ψ Kₛ(π⁺ π⁻)
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Introduction

- Early measurement possible due to large cross section
- Measurement at new energy allows tests of perturbative QCD and MC generators
- Improves understanding of b backgrounds for physics searches like Higgs, SUSY and other exotic physics
- Improves understanding of the detector, especially tracking and muon reconstruction
pp collisions @ a CM energy of 7 TeV/c\(^2\)
Data taken in 2010 with the CMS detector at the LHC

Main detector components for these analyses:
• Silicon tracker for |\(\eta|\) < 2.5 in a magnetic field of 3.8 T.
• Muon detector for |\(\eta|\) < 2.4

2008 JINST 3 S08004
Exclusive B decays

\[ \mu_1 \mu_2 \]

\[ J/\Psi K^+ \]

\[ J/\Psi \phi \]

\[ J/\Psi K_s \]

\[ B^+ PV \]

\[ B_0^+ PV \]

\[ B_0^0 PV \]
Exclusive B decays

- Goal: measuring differential production cross-section in bins of $p_T$ and $y$ of the B mesons

- Strategy:
  - Build $J/\Psi$ candidates from muons
  - Combine with 1 (2) tracks from same vertex to form $B^+$ ($B^0_s$) candidates or with 2 tracks from new vertex consistent with $K_s$ mass for $B^0$ candidates
  - Kinematic fit with mass and vertex constraints
  - Extract signal yields from unbinned 2 dimensional maximum likelihood fit in variables $m_B$ and $c_t$ with shape parameters determined from data as far as possible

- We don’t distinguish between a neutral B meson and its charge conjugate.
**J/Ψ reconstruction**

Common to all 3 analyses:

- **Trigger**: Di-muon, without explicit $p_T$ cut
- **Muon selection**:
  
  \[
  |\eta^\mu| < 1.3, \quad p_T^\mu > 3.3 \text{ GeV/c} \\
  1.3 < |\eta^\mu| < 2.2, \quad p^\mu > 2.9 \text{ GeV/c} \\
  2.2 < |\eta^\mu| < 2.4, \quad p_T^\mu > 0.8 \text{ GeV/c}
  \]

- **J/Ψ reconstruction**:
  
  Oppositely charged muons fitted to common vertex
  
  Muons matched to trigger objects
  
  \[
  |m_{\mu\mu} - m_{J/Ψ,PDG}| < 150 \text{ MeV/c}^2
  \]
Efficiency for J/Ψ

\[ \varepsilon_{J/\Psi} = \varepsilon_{\mu_1} \cdot \varepsilon_{\mu_2} \cdot \text{corr} \]

where \( \varepsilon_{\mu_i} \) are the single muon efficiencies and \( \text{corr} \) is a correction factor for di-muon correlation effects, determined from simulation.

The single muon efficiencies can be factorized as

\[ \varepsilon_{\mu_i} = \varepsilon_{\mu_i \text{ trigger}} \cdot \varepsilon_{\mu_i \text{ ID}} \cdot \varepsilon_{\mu_i \text{ tracking}} \]

and each term is measured independently from data using a tag & probe method.

Efficiency determined for each bin in \( p_T \) and \( y \) of the corresponding signal B meson.
$B^0 \rightarrow J/\Psi (\mu^+ \mu^-) K_s (\pi^+ \pi^-)$

- Accepted by PRL, preprint arXiv:1104.2892
- Integrated luminosity: $39.6 \pm 1.6 \text{ pb}^{-1}$
- Selection and reconstruction:
  - $J/\Psi$ candidate from above
  - $K_s$ candidate:
    - 2 oppositely charged tracks ($\geq 6$ hits, $\chi^2$/dof $< 5$, $d_0 > 0.5\sigma$)
    - Vertex fit ($\chi^2 < 7$, transverse distance from beamline $> 5\sigma$)
    - $478 \text{ MeV}/c^2 < M_{K_s} < 518 \text{ MeV}/c^2$
  - $B^0$ candidate:
    - Kinematic fit with constraints on $M_{J/\Psi}$ and $M_{K_s}$
    - $4.9 \text{ GeV}/c^2 < M_{B^0} < 5.7 \text{ GeV}/c^2$
    - $B^0$ decay vertex probability $> 1\%$.
- Total number of events after selection: 23174
\( \mathcal{B}^0 \to J/\Psi (\mu^+ \mu^-) K_s(\pi^+ \pi^-) \)

Backgrounds and probability density functions in \( m_B \) and ct
All shape parameters are extracted from data, except for the peaking background and the PDF for the signal \( m_B \), which are taken from MC

<table>
<thead>
<tr>
<th>Component</th>
<th>P.D.F. for ( m_B )</th>
<th>P.D.F. for ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>Sum of 2 Gaussians</td>
<td>( R \otimes \text{Exponential} )</td>
</tr>
<tr>
<td>Peaking B</td>
<td>Sum of 3 Gaussians</td>
<td>( R \otimes \text{Exponential} )</td>
</tr>
<tr>
<td>Like ( \mathcal{B}^0 \to J/\Psi K^*(892) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt ( J/\Psi )</td>
<td>Exponential</td>
<td>( R )</td>
</tr>
<tr>
<td>Combinatorial BB</td>
<td>Exponential</td>
<td>( R \otimes (\text{sum of 2 exponentials}) )</td>
</tr>
</tbody>
</table>

where \( R \) is a common resolution function = sum of two Gaussians
$B^0 \rightarrow J/\Psi (\mu^+ \mu^-) K_S (\pi^+ \pi^-)$

2D unbinned maximum likelihood fit: data driven fit procedure in 3 steps
1. High mass side band fit in $m_B$ and ct to determine effective lifetime of combinatorial background
2. Full mass range fit to determine signal lifetime
3. Extract yields from full fit in bins of $p_T^B$ and $|y_B|$ with (effective) lifetimes fixed from above.
# Systematic uncertainties

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF parameters and potential fit bias</td>
<td>4 – 7 %</td>
</tr>
<tr>
<td>Effect of final state radiation on signal mass shape</td>
<td>1 %</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2 – 3 %</td>
</tr>
<tr>
<td>Muon identification</td>
<td>1 %</td>
</tr>
<tr>
<td>Muon tracking efficiency</td>
<td>1 %</td>
</tr>
<tr>
<td>$K_s$ selection</td>
<td>5 %</td>
</tr>
<tr>
<td>$B^0$ selection</td>
<td>3 %</td>
</tr>
<tr>
<td>Acceptance</td>
<td>2 – 3%</td>
</tr>
<tr>
<td>Di-muon correlation</td>
<td>1 – 5 %</td>
</tr>
<tr>
<td>Mismeasurement of $p_T^B$ and $y^B$</td>
<td>1 %</td>
</tr>
<tr>
<td>Kinematic reweighting</td>
<td>3 – 5 %</td>
</tr>
<tr>
<td>Total uncorrelated error</td>
<td>10 - 12 %</td>
</tr>
<tr>
<td>Branching fractions</td>
<td>3.8 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4 %</td>
</tr>
</tbody>
</table>
\[ B^0 \rightarrow J/\Psi \ (\mu^+ \ \mu^-) \ K_s (\pi^+ \ \pi^-) \]

Total cross section for \( p_T(B^0) > 5 \text{ GeV}/c \) and \( |y_{B0}| < 2.2 \) :

\[ \sigma(B^0 \rightarrow J/\Psi \ X) = 33.2 \pm 2.5(\text{stat}) \pm 3.5(\text{syst}) \mu\text{b} \]

Prediction from MC@NLO = \( 25^{+9.6}_{-6.2} \ \mu\text{b} \)
$$B^+ \rightarrow J/\Psi(\mu^+ \mu^-) K^+$$

- Integrated luminosity: 5.8 pb$^{-1}$
- Selection and reconstruction:
  - $J/\Psi$ candidate from above
  - $B^+$ candidate:
    - Combine with track ($\geq$ 4 hits, $\chi^2$/ndof < 5) with kaon mass hypothesis and $p_T > 0.9$ GeV/c
    - Kinematic fit with constraint on $M_{J/\Psi}$
    - $4.95$ GeV/$c^2 < m_{B^+} < 5.55$ GeV/$c^2$
    - $B^+$ decay vertex probability > 0.1%. Choose candidate with highest $p_T$
- Total number of events after selection: 35406
$\mathbf{B}^+ \rightarrow \mathbf{J}/\Psi(\mu^+ \mu^-) \mathbf{K}^+$

Backgrounds and probability density functions in $m_B$ and ct

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<thead>
<tr>
<th>Component</th>
<th>P.D.F. for $m_B$</th>
<th>P.D.F. for ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>Sum of 3 Gaussians</td>
<td>R $\otimes$ Exponential</td>
</tr>
<tr>
<td>$\mathbf{J}/\Psi \pi$</td>
<td>Sum of 2 Gaussians</td>
<td>R $\otimes$ Exponential</td>
</tr>
<tr>
<td>Cabbibo suppressed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peaking B</td>
<td>Sum of 2 Gaussians + exponential</td>
<td>R $\otimes$ Exponential</td>
</tr>
<tr>
<td>Mainly $B^0 \rightarrow \mathbf{J}/\Psi \ K^*$, $B^0 \rightarrow \chi_c X$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt $\mathbf{J}/\Psi$</td>
<td>Exponential</td>
<td>R</td>
</tr>
<tr>
<td>Combinatorial BB</td>
<td>Exponential</td>
<td>R $\otimes$ (sum of 2 exponentials)</td>
</tr>
</tbody>
</table>

where $R$ is a common resolution function = sum of two or three Gaussians
B$^+ \rightarrow J/\Psi(\mu^+ \mu^-) K^+$

2D unbinned maximum likelihood fit: data driven fit procedure in 3 steps
1. High mass side-band fit in ct to determine effective lifetime of combinatorial background.
2. Same fit in bins of $p_T$ and $|y|$ but with ct fixed from above to determine resolution function
3. Extract yields from full fit with $m_B$ PDFs for signal, $J/\Psi \pi$ and peaking background from MC, ct parameters from above
# Systematic uncertainties

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>PDF parameters and potential fit bias</td>
<td>2 – 5 %</td>
</tr>
<tr>
<td>ct resolution function</td>
<td>1 – 2 %</td>
</tr>
<tr>
<td>Effect of final state radiation on signal mass shape</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2 %</td>
</tr>
<tr>
<td>Muon identification</td>
<td>1 %</td>
</tr>
<tr>
<td>Tracking efficiency for muon and hadron</td>
<td>1 - 4 %</td>
</tr>
<tr>
<td>B(^+) momentum spectrum</td>
<td>1 - 4 %</td>
</tr>
<tr>
<td>Efficiency of vertexing</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Misalignment</td>
<td>2 %</td>
</tr>
<tr>
<td>Total uncorrelated errors</td>
<td>6 - 10 %</td>
</tr>
<tr>
<td>Branching fractions</td>
<td>3.5 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>11 %</td>
</tr>
</tbody>
</table>
\[ B^+ \rightarrow J/\Psi(\mu^+ \mu^-) K^+ \]

Total cross section for \( p_T(B^+) > 5 \text{ GeV/c} \) and \( |y_{B^+}| < 2.4 \):

\[ \sigma(B^+ \rightarrow J/\Psi \ X) = 28.1 \pm 2.4 \text{(stat)} \pm 2.0 \text{(syst)} \pm 1.1 \text{(lumi)} \ \mu \text{b} \]

Prediction from MC@NLO = 25.5^{+9.2}_{-5.7} \mu \text{b}
\[ B^0_s \rightarrow J/\Psi(\mu^+ \mu^-) \phi(K^+ K^-) \]

- Approved result
- Integrated luminosity: 39.6 ± 1.6 pb\(^{-1}\)
- Selection and reconstruction:
  - \( J/\Psi \) candidate from above with \( p_T > 0.5 \) GeV/c
  - \( \phi \) candidate:
    - 2 oppositely charged tracks (≥5 hits, \( \chi^2/dof < 5 \)) with kaon mass hypothesis, \( p_T > 0.7 \) GeV/c
    - 1009 MeV/c\(^2\) < \( M_\phi \) < 1029 MeV/c\(^2\)
  - \( B_s^0 \) candidate:
    - Kinematic fit with constraint on \( M_{J/\Psi} \)
    - \( B_s^0 \) decay vertex probability > 2%. Choose candidate with highest probability
    - 8 GeV/c < \( p_T \) < 50 GeV/c, \( |y_{B_s}| < 2.4 \)
    - 5.20 GeV/c\(^2\) < \( M_{B_s} \) < 5.65 GeV/c\(^2\)
- Total number of events after selection: 6200
$$B^0_s \rightarrow J/\Psi(\mu^+ \mu^-) \phi(K^+ K^-)$$

Backgrounds and probability density functions in $m_B$ and $ct$

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<tr>
<td>Signal</td>
<td>Sum of 2 Gaussians</td>
<td>$R \otimes$ exponential</td>
</tr>
<tr>
<td>Non-prompt $J/\Psi$</td>
<td>Second order polynomial</td>
<td>$R \otimes$ (sum of 2 exponentials)</td>
</tr>
<tr>
<td>Misreconstructed $B$ decays to $J/\Psi$ and higher mass $K$- mesons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt $J/\Psi$</td>
<td>First order polynomial</td>
<td>$R$</td>
</tr>
</tbody>
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where $R$ is a common resolution function = sum of two Gaussians
$B^0_s \rightarrow J/\Psi(\mu^+ \mu^-) \phi(K^+ K^-)$

2D unbinned maximum likelihood fit: data driven fit procedure in 3 steps

2. Same fit in bins of $p_T$ and $|y|$ but with ct fixed from above to determine resolution function.
3. Extract yields from full fit with $m_B$ PDF for signal from MC, ct parameters from above.

Preliminary
## Systematic uncertainties

**Preliminary**

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<tr>
<td>PDF parameters and potential fit bias</td>
<td>2 – 4 %</td>
</tr>
<tr>
<td>Muon efficiency (trigger + ID + tracking)</td>
<td>3 - 5 %</td>
</tr>
<tr>
<td>Tracking efficiency for hadron pair, including misalignment</td>
<td>9 %</td>
</tr>
<tr>
<td>$B^0_s$ momentum spectrum</td>
<td>2 - 3 %</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>3 %</td>
</tr>
<tr>
<td>Total uncorrelated error</td>
<td>9 - 12 %</td>
</tr>
<tr>
<td>Branching fractions</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4 %</td>
</tr>
</tbody>
</table>
\[ B^0_s \rightarrow J/\Psi(\mu^+ \mu^-) \phi(K^+ K^-) \]

**Preliminary**

Total cross section for \( 8 \text{ GeV}/c < p_T(B^0_s) < 50 \text{ GeV}/c \) and \( |y_{B_s}| < 2.4 \):

\[ \sigma(B^0_s \rightarrow J/\Psi \phi) = 6.9 \pm 0.6(\text{stat}) \pm 0.6(\text{syst}) \text{ nb} \]

Prediction from MC@NLO = \( 4.6^{+1.9}_{-1.7} \text{ nb} \)
Conclusion

• First measurements of total and differential cross sections for \( B^+, B^0 \) and \( B_{s}^0 \) at the LHC

• Good agreement with predictions from MC@NLO

• Results show the great performance of the CMS detector
Outlook

Coming soon:

$$\Lambda_b \rightarrow J/\Psi \ (\mu^+ \mu^-) \ \Lambda^0(p \pi)$$

Differential cross section and lifetime measurement

Using data taken in 2010-2011

\[
\mu_{\text{Gauss}} = 5.617 \pm 0.003 \text{ GeV/c}^2 \\
\sigma_{\text{Gauss}} = 0.021 \pm 0.002 \text{ GeV/c}^2 \\
N_{\text{signal}} = 106 \pm 12 \\
N_{\text{background}} = 32 \pm 3 \\
S/\sqrt{S+B} = 9.0 \pm 1.1 \\
S/B = 3.3 \pm 0.5
\]