ATLAS results on charmonium production and $B_C^+$ production and decays

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on behalf of ATLAS Collaboration

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19th International Conference on Hadron Spectroscopy and Structure
26-31 July 2021
Introduction

**B-physics at ATLAS**

- Possible to measure heavy flavour (HF) production at high energy
- Much higher HF yields in $pp$ environment compared to B-factories
- Extended spectroscopy studies are possible
- ATLAS and CMS, although not specially optimized for B-physics, provide complementary kinematic region to LHCb
  - Benefit from higher statistics in certain analyses
- This talk covers a selection of ATLAS results
  - Relative $B_c/B^+$ production measurement at 8 TeV – Phys. Rev. D 104, 012010
  - Study of the $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ decays in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector ATLAS-CONF-2021-046
High-$p_T$ $J/\psi$ and $\psi(2S)$ production measurement

- Two different mechanisms for charmonium production:
  - **Prompt**: directly in $pp$ interaction or via feed-down from heavier states
  - **Non-prompt**: from decays of $b$ hadrons
    - Can be distinguished by fitting the pseudo proper lifetime
  - FONLL calculations within the framework of perturbative QCD have been reasonably successful in describing the non-prompt contributions
  - Satisfactory understanding of the prompt production mechanisms is still to be achieved

  - Overall reasonable agreement with theoretical predictions for prompt and non-prompt production
  - Di-muon triggers with low thresholds – could not reach beyond $p_T$ of $\sim 100$ GeV

- New measurement focuses on high-$p_T$ charmonia
  - Help to discriminate various theoretical models
  - Use single-muon triggers (50 GeV muon $p_T$ threshold) to cover the range 60–360 GeV
  - Full Run-2 dataset, 139 fb$^{-1}$ at 13 TeV
High-$p_T$ $J/\psi$ and $\psi(2S)$ measurement

- Measured are:
  - Prompt and non-prompt $J/\psi$ and $\psi(2S)$ double-differential $\times$-sections
  - Non-prompt fraction for $J/\psi$ and $\psi(2S)$
  - $\psi(2S)/J/\psi$ production ratio for prompt and non-prompt

- $\rho_T$ ranges extend significantly
- FONLL consistent at low-$\rho_T$, over-estimates high-$\rho_T$ production
Relative $B_C^+/B^+$ production measurement at 8 TeV

- $B_C^+$ is the only known weakly decaying particle made of two heavy quarks
- Motivation:
  - test of the QCD prediction;
  - important input for heavy quark production models;
  - complements CMS and LHCb measurements;

- Measure the ratio: $\frac{\sigma(B_C^+) \cdot B(B_C^+ \rightarrow J/\psi \pi^+) \cdot B(J/\psi \rightarrow \mu^+ \mu^-)}{\sigma(B^+) \cdot B(B^+ \rightarrow J/\psi K^+) \cdot B(J/\psi \rightarrow \mu^+ \mu^-)}$
  - Common systematic uncertainties mostly cancel

- Fiducial region of the measurement:
  - $p_T(B) > 13 \text{ GeV}$, $|y(B)| < 2.3$
  - In addition to the full bin two bins in $p_T$ ($13 < p_T(B) < 22 \text{ GeV}$ and $p_T > 22 \text{ GeV}$) and two bins in rapidity ($|y| < 0.75$ and $0.75 < |y| < 2.3$) were defined
$B_c^+ / B^+$ production: results

- Production ratio in the fiducial region

$$\frac{\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}{\sigma(B^+) \cdot \mathcal{B}(B^+ \rightarrow J/\psi K^+) \cdot \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)} = (0.34 \pm 0.04(\text{stat.})^{+0.06}_{-0.02}(\text{syst.}) \pm 0.01(\text{lifetime}))\%$$

- Lower than the LHCb result for more forward and lower-$p_T$ fiducial volume: $(0.683 \pm 0.018 \pm 0.009)\%$,
  $0 < p_T(B) < 20\,\text{GeV}$, $2 < |y(B)| < 4.5$

- Fairly consistent with the CMS result in a similar (but not identical) fiducial volume:
  $(0.48 \pm 0.05(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.05(\text{lifetime}))\%$ at $\sqrt{s} = 7\,\text{TeV}$, $p_T(B) > 15\,\text{GeV}$, $|y(B)| < 1.6$

- $B_c^+$ production decreases faster with $p_T$ than that for $B^+$

- No evident rapidity dependence

<table>
<thead>
<tr>
<th>Analysis bin</th>
<th>$\sigma(B_c^+) / \sigma(B^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) / \mathcal{B}(B^+ \rightarrow J/\psi K^+) \times B(B_c^+ \rightarrow J/\psi \pi^+) / B(B^+ \rightarrow J/\psi K^+) \times 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B) &gt; 13,\text{GeV},</td>
<td>y(B)</td>
</tr>
<tr>
<td>$13 &lt; p_T(B) &lt; 22,\text{GeV},</td>
<td>y(B)</td>
</tr>
<tr>
<td>$p_T(B) &gt; 22,\text{GeV},</td>
<td>y(B)</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13,\text{GeV},</td>
<td>y(B)</td>
</tr>
<tr>
<td>$p_T(B) &gt; 13,\text{GeV}, 0.75 &lt;</td>
<td>y(B)</td>
</tr>
</tbody>
</table>
New: Study of the $B_c^+ \rightarrow J/\psi D_s^{(*)+}$

- Decays $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ can occur through $b$ decay with $c$ as spectator, or through annihilation diagram.

- Only $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays observed earlier by LHCb (PRD 87 (2013) 112012) and ATLAS (EPJC 76 (2016) 4).

- This analysis aims at more precise measurement of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ branching fraction and polarization with full Run-2 data.
  - Test various approaches predicting these (perturbative QCD calculation, relativistic potential models, sum rules calculations...).
Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ decays

- $B_c^+ \to J/\psi (\mu^+ \mu^-) D_s^+(\to \phi (\to K^+ K^-) \pi^+)$
- $B_c^+ \to J/\psi (\mu^+ \mu^-) D_s^{*+}(\to D_s^+ \gamma/\pi^0)$
  - Same reconstructed final state, soft neutral particle escapes detection
- **Reference channel:** $B_c^+ \to J/\psi \pi^+$
  - Use it for $B$ measurement
- Define fiducial range of the measurement: $p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.0$
- Measured quantities:
  - Ratios b/w $B$ of signal channels and $B(B_c^+ \to J/\psi \pi^+)$: $R_{D_s^{(*)+}/\pi^+}$
  - Ratios b/w $B$’s of signal channels (to cancel some of the uncertainties): $R_{D_s^{*+}/D_s^+}$
  - Transverse polarisation fraction $\Gamma_{\pm\pm}/\Gamma$ for $B_c^+ \to J/\psi D_s^{*+}$
Study of the $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ decays

- **Dataset 1**: candidates in the events collected by the standard dimuon or three-muon triggers without requirements on additional ID track.
  - can be safely used to measure $R_{D_s^+/\pi^+}$, $R_{D_s^{*+}/\pi^+}$

- **Dataset 2**: candidates collected only by the dedicated $B_s^0 \rightarrow \mu^+ \mu^- \phi$ triggers and not by other ones used in the analysis.
  - improve sensitivity to $R_{D_s^{*+}/D_s^+}$, $\Gamma_{\pm\pm}/\Gamma$
Study of the $B_c^+ \to J/\psi D_s^{(*)+}$ decays: results

$R_{D_s^+}/\pi^+ = 2.76 \pm 0.33\,(\text{stat.}) \pm 0.29\,(\text{syst.}) \pm 0.16\,(\text{br.f.})$

$R_{D_s^{(*)+}/\pi^+} = 5.33 \pm 0.61\,(\text{stat.}) \pm 0.67\,(\text{syst.}) \pm 0.32\,(\text{br.f.})$

$R_{D_s^{(*)+}/D_s^+} = 1.93 \pm 0.24\,(\text{stat.}) \pm 0.10\,(\text{syst.})$

$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10\,(\text{stat.}) \pm 0.04\,(\text{syst.})$

- All results are consistent with the earlier measurements of ATLAS and LHCb.
- The precision of the measurement exceeds that of all previous studies of these decays.
Summary

- A selection of ATLAS results on heavy flavour production was presented
  - Production of hidden charm
  - Physics of $B_c^+$ mesons
- More can be found here:
  - ATLAS B-physics public results page
- Many interesting results are still to come!
Backup slides
ATLAS detector and trigger

Entries / 50 MeV

2 4 6 8 10 12

ATLAS Preliminary

\[ \sqrt{s} = 7 \text{ TeV} \quad L dt \approx 2.3 \text{ fb}^{-1} \]

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JINR 13 / 11
### $J/\psi$ and $\psi(2S)$ fits

<table>
<thead>
<tr>
<th>i</th>
<th>Type</th>
<th>P/NP</th>
<th>$f_i(m)$</th>
<th>$h_i(\tau)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$J/\psi$</td>
<td>P</td>
<td>$\omega G_1(m) + (1 - \omega)CB_1(m)$</td>
<td>$\delta(\tau)$</td>
</tr>
<tr>
<td>2</td>
<td>$J/\psi$</td>
<td>NP</td>
<td>$\omega G_1(m) + (1 - \omega)CB_1(m)$</td>
<td>$E_1(\tau)$</td>
</tr>
<tr>
<td>3</td>
<td>$\psi(2S)$</td>
<td>P</td>
<td>$\omega G_2(m) + (1 - \omega)CB_2(m)$</td>
<td>$\delta(\tau)$</td>
</tr>
<tr>
<td>4</td>
<td>$\psi(2S)$</td>
<td>NP</td>
<td>$\omega G_2(m) + (1 - \omega)CB_2(m)$</td>
<td>$E_2(\tau)$</td>
</tr>
<tr>
<td>5</td>
<td>Bkg</td>
<td>P</td>
<td>$B$</td>
<td>$\delta(\tau)$</td>
</tr>
<tr>
<td>6</td>
<td>Bkg</td>
<td>NP</td>
<td>$E_4(m)$</td>
<td>$E_5(\tau)$</td>
</tr>
<tr>
<td>7</td>
<td>Bkg</td>
<td>NP</td>
<td>$E_6(m)$</td>
<td>$E_7(</td>
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</table>

#### Notation & Function

<table>
<thead>
<tr>
<th>Notation</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>Gaussian</td>
</tr>
<tr>
<td>$CB$</td>
<td>Crystal Ball</td>
</tr>
<tr>
<td>$E$</td>
<td>Exponential</td>
</tr>
<tr>
<td>$B$</td>
<td>Bernstein polynomials</td>
</tr>
</tbody>
</table>

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ATLAS Preliminary

$pp \sqrt{s} = 13$ TeV, 139 fb$^{-1}$

0.75 < $|y|$ < 1.50
140.0 < $p_T$ < 160.0 GeV

**Left Panel:**

- Data
- Fit Projection
- Prompt $\psi$ (nS)
- Non-prompt $\psi$ (nS)
- Prompt Bkg
- Non-Prompt Bkg

**Right Panel:**

- Data
- Fit Projection
- Prompt $\psi$ (nS)
- Non-prompt $\psi$ (nS)
- Prompt Bkg
- Non-Prompt Bkg

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ATLAS Preliminary

$pp \sqrt{s} = 13$ TeV, 139 fb$^{-1}$

0.00 < $|y|$ < 0.75
180.0 < $p_T$ < 200.0 GeV

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High-$p_T$ $J/\psi$ and $\psi(2S)$ measurement

- Measured are
  - Prompt and non-prompt $J/\psi$ and $\psi(2S)$ double-differential $x$-sections
  - Non-prompt fraction for $J/\psi$ and $\psi(2S)$
  - $\psi(2S)/J/\psi$ production ratio for prompt and non-prompt

- $p_T$ ranges extend significantly
- FONLL consistent at low-$p_T$, over-estimates high-$p_T$ production

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**ATLAS Preliminary**

*Prompt $J/\psi$ Cross-Section*

| $p_T$ (GeV) | Data $10^3$, $|y| < 0.75$ | FONLL
|------------|--------------------------|------
| 1.50 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |
| 0.00 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |

*Non-prompt $J/\psi$ Cross-Section*

| $p_T$ (GeV) | Data $10^3$, $|y| < 0.75$ | FONLL
|------------|--------------------------|------
| 1.50 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |
| 0.00 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |

---

**ATLAS Preliminary**

*Prompt $\psi(2S)$ Cross-Section*

| $p_T$ (GeV) | Data $10^3$, $|y| < 0.75$ | FONLL
|------------|--------------------------|------
| 1.50 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |
| 0.00 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |

*Non-prompt $\psi(2S)$ Cross-Section*

| $p_T$ (GeV) | Data $10^3$, $|y| < 0.75$ | FONLL
|------------|--------------------------|------
| 1.50 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |
| 0.00 < $|y|$ | 0.00 < $|y|$ | 0.00 < $|y|$ |
$B_c^+ \rightarrow J/\psi\pi^+$ fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{B_c^+}$ [MeV]</td>
<td>$6274.5 \pm 1.5$</td>
</tr>
<tr>
<td>$\sigma_{B_c^+}$ [MeV]</td>
<td>$47.5 \pm 2.5$</td>
</tr>
<tr>
<td>$N_{B_c^+ \rightarrow J/\psi\pi^+}$</td>
<td>$8440^{+550}_{-470}$</td>
</tr>
</tbody>
</table>
$B^+_c \rightarrow J/\psi D_s^{(*)+}$ fit PDF

- 2D unbinned ML fit of $m(J/\psi D_s^+)$ and $|\cos \theta'(\mu^+)|$; mass and angular PDF are factorized
- ratio between $B^+_c \rightarrow J/\psi D_s^+$ and $B^+_c \rightarrow J/\psi D_s^{*+}$ yield and $f_{\pm\pm}$ are the same in DS1 and DS2
- $B^+_c \rightarrow J/\psi D_s^+$ signal
  - mass: modified Gaussian\(^1\)
  - $|\cos \theta'(\mu^+)|$: MC kernel template (same in DS1 and DS2)
- $B^+_c \rightarrow J/\psi D_s^{*+}$ signals, separately $A_{\pm\pm}$ and $A_{00}$ components
  - mass: MC kernel templates (same in DS1 and DS2)
  - $|\cos \theta'(\mu^+)|$: MC kernel templates (same in DS1 and DS2)
- Background
  - mass: exponential (same slope in DS1 and DS2)
  - $|\cos \theta'(\mu^+)|$: 2nd order polynomial (same parameters in DS1 and DS2)

\(^1\) Gauss\(_{\text{mod}}^\text{mod}\) $\propto \exp(-0.5 \times t^{1+1/(1+t/2)})$, where $t = |m(J/\psi D_s^+) - m_{B^+_c}|/\sigma_{B^+_c}$
$B_c^+ \rightarrow J/\psi D_s^{(*)+}$ fit result

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{B_c^+}$ [MeV]</td>
<td>6274.8 ± 1.4</td>
</tr>
<tr>
<td>$\sigma_{B_c^+}$ [MeV]</td>
<td>11.5 ± 1.5</td>
</tr>
<tr>
<td>$r_{D_s^{(*)+}/D_s^+}$</td>
<td>1.76 ± 0.22</td>
</tr>
<tr>
<td>$f_{+}\pm$</td>
<td>0.70 ± 0.10</td>
</tr>
<tr>
<td>$N_{D_{S1}}^{B_c^+\rightarrow J/\psi D_s^+}$</td>
<td>193 ± 20</td>
</tr>
<tr>
<td>$N_{D_{S2}}^{B_c^+\rightarrow J/\psi D_s^+}$</td>
<td>49 ± 10</td>
</tr>
<tr>
<td>$N_{D_{S1&amp;2}}^{B_c^+\rightarrow J/\psi D_s^{(*)+}}$</td>
<td>338 ± 32</td>
</tr>
<tr>
<td>$N_{D_{S1&amp;2}}^{B_c^+\rightarrow J/\psi D_s^{(*)+}}$</td>
<td>241 ± 28</td>
</tr>
<tr>
<td>$N_{D_{S1&amp;2}}^{B_c^+\rightarrow J/\psi D_s^{(*)+}}$</td>
<td>424 ± 46</td>
</tr>
</tbody>
</table>
Ratios calculation

\[ R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{N_{D_{s1}}^{D_{s1}}}{N_{B_c^+ \to J/\psi D}^{B_c^+ \to J/\psi D_s^{(*)+}}} \times \frac{\varepsilon_{B_c^+ \to J/\psi \pi^+}}{\varepsilon_{D_{s1}}^{D_{s1}}} \times \frac{1}{\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)} , \]  

(1)

\[ \mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+) \text{ taken as } m(K^+K^-)\text{-dependent, using CLEO measurement, recalculated to } \pm 7 \text{ MeV} \]

\[ R_{D_s^{(*)+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} = \frac{N_{D_{s1\&2}}^{D_{s1\&2}}}{N_{B_c^+ \to J/\psi D_s^+}} \times \frac{\varepsilon_{D_{s1\&2}}^{D_{s1\&2}}}{\varepsilon_{B_c^+ \to J/\psi D_s^+}} \times \frac{\varepsilon_{D_{s1\&2}}^{D_{s1\&2}}}{\varepsilon_{D_{s1\&2}}^{D_{s1\&2}}} , \]  

(2)

\[ \varepsilon_{B_c^+ \to J/\psi D_s^{(*)+}} = \frac{1}{f_{\pm\pm}/\varepsilon_{B_c^+ \to J/\psi D_s^{(*)+}, A_{\pm\pm}} + (1 - f_{\pm\pm})/\varepsilon_{B_c^+ \to J/\psi D_s^{(*)+}, A_{00}}} , \]  

(3)

\[ \Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \times \frac{\varepsilon_{D_{s1\&2}}^{D_{s1\&2}}}{\varepsilon_{D_{s1\&2}}^{D_{s1\&2}}} . \]  

(4)

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\varepsilon_{B_c^+ \to J/\psi X}^{D_{s1}}) [%]</th>
<th>(\varepsilon_{B_c^+ \to J/\psi X}^{D_{s1&amp;2}}) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_c^+ \to J/\psi D_s^+)</td>
<td>0.971 ± 0.012</td>
<td>1.163 ± 0.013</td>
</tr>
<tr>
<td>(B_c^+ \to J/\psi D_s^{(*)+}, A_{00})</td>
<td>0.916 ± 0.012</td>
<td>1.088 ± 0.012</td>
</tr>
<tr>
<td>(B_c^+ \to J/\psi D_s^{(*)+}, A_{\pm\pm})</td>
<td>0.868 ± 0.010</td>
<td>1.049 ± 0.011</td>
</tr>
<tr>
<td>(B_c^+ \to J/\psi \pi^+)</td>
<td>2.169 ± 0.018</td>
<td>-</td>
</tr>
</tbody>
</table>
Table of Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>( R_{D_s^+/\pi^+} )</th>
<th>( R_{D_s^{++}/\pi^+} )</th>
<th>( R_{D_s^{++}/D_s^+} )</th>
<th>( \Gamma \pm \pm /\Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated ( p_T(B_c^+) ) spectrum</td>
<td>1.5</td>
<td>1.9</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Simulated (</td>
<td>\eta(B_c^+)) spectrum</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>( B_c^+ ) lifetime</td>
<td>0.1</td>
<td>&lt; 0.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( D_s^{++} ) lifetime</td>
<td>0.4</td>
<td>0.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>1.0</td>
<td>1.0</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Pile-up effects</td>
<td>1.0</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( \chi^2/ndf ) cut efficiency</td>
<td>3.2</td>
<td>3.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Impact parameter cuts efficiency</td>
<td>0.2</td>
<td>0.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BDT cut efficiency</td>
<td>1.3</td>
<td>1.3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0</td>
<td>1.0</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

- \( B_c^+ \to J/\psi D_s^{(*)+} \) signal fit:
  - \( D_s^{(*)+} \) signal mass modelling: 1.8, 0.5, 1.3, 0.8
  - \( D_s^{(*)+} \) signal mass modelling: 0.6, 1.2, 1.7, 2.7

- \( B_c^+ \to J/\psi \pi^+ \) signal fit:
  - Signal modelling: 4.2, 4.2, –, –
  - PRD/comb. background modelling: 5.8, 5.8, –, –
  - CKM-suppr. background modelling: 1.0, 1.0, –, –

- MC statistics: 1.5, 1.5, 1.7, 1.5

- Total: 10.7, 12.6, 5.0, 5.8

- \( B(D_s^+ \to \phi(K^+K^-)\pi^+) \): 5.9, 5.9, –, –

> Effect of muon reconstruction and identification efficiency uncertainty affects individual channel efficiencies by about 1–2%. However, for the measured quantities, due to cancellation in the efficiency ratios, it is found to be negligible.