ATLAS results on charmonium and $B_c$ and exotic heavy hadrons

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on behalf of the ATLAS Collaboration

Outline:

Introduction

$J/\psi$ & $\psi(2S)$ at 13 TeV

$B_c^+ / B^+$ at 8 TeV

$P_c^+$ at 7-8 TeV

Summary

PHENO 2021

24-26 May 2021

Pittsburgh, USA

ATLAS-CONF-2019-047

arXiv:1912.02672 (subm. to PRD)

ATLAS-CONF-2019-048
Weight: ~ 7000 tons

Inner Detector (Pixel+SCT+TRT):
\[ p_T > 0.4 \ (0.1) \text{ GeV}, \ |\eta| < 2.5 \]

New for Run 2:
Insertable B-layer (IBL) – inner-most pixel layer (\( r = 33 \text{ mm} \)) and thinner beam-pipe
\[ m(\mu^+\mu^-) \text{ resolution: } \sim 50 \text{ MeV for } J/\psi \]
\[ \sim 150 \text{ MeV for } \Upsilon \]

Muon Spectrometer:
Offline tracking: \(|\eta| < 2.7\)
Triggering: \(|\eta| < 2.4\)
Data Taking and Heavy Flavor triggering

Peak Lumi: $7.73 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

$21.0 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
Charmonium production at 13 TeV with 139 fb⁻¹

Uses a single-muon trigger, with threshold at 50 GeV, un-prescaled on the full integrated luminosity of Run II, 139 fb⁻¹

\( p_T \) range covered: 60-360 GeV for J/ψ in 11 bins (60-140 GeV for ψ(2S))

Rapidity range \(|y| < 2\) covered in three bins

Yields for J/ψ and ψ(2S), prompt and non-prompt (from B decays), determined using 2D fit (mass and “pseudo-proper” lifetime)

\[ \tau = \frac{m L_{xy}}{c P_T} \]
Charmonium non-prompt fractions

Plateau $\sim 0.7$ for $p_T \gtrsim 40$ GeV

Similar behavior in pp and p\( \bar{p} \) collisions for $\sqrt{s}$ from 1.96 TeV till 13 TeV

No strong dependence from rapidity

Similar for $J/\psi$ and $\psi(2S)$
Charmonium non-prompt x-sections

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

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Non-prompt $J/\psi$ Cross-Section

FONLL predictions in general agreement, too high at high $p_T$

Deviations from data up to $\sim 2$

NNLO?
New fragmentation tuning?
Fixing of technical FONLL problems at high $p_T$?
Charmonium prompt x-sections

ATLAS and CMS agree in the range of overlap

Can be described by simple parametrization

\[ \sim (b+p_T)^{-n} \]

with \( b=4.4 \) and \( n=6 \)

Waiting NRQCD predictions for high-\( p_T \) charmonium production
$B_c^+ / B^+$ x-section ratios at 8 TeV with 20 fb$^{-1}$

$B_c^+ \rightarrow J/\psi \pi^+$  
$B^+ \rightarrow J/\psi K^+$

$B_c^+$ and $B^+$ yields measured using di-muon trigger

Their ratios, corrected for acceptances and efficiencies, measured in two $p_T$ bins (13-22 GeV, >22 GeV) and two $|y|$ bins (<0.75, 0.75-2.3)
$B_c^+ / B^+$ x-section ratios at 8 TeV

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

Compatible with CMS/LHCb

The ratio decreases with $p_T$

Differences in production? hadronization?

No significant $|y|$ dependence
\( B_c^+ / B^+ \) x-section ratios at LHC

\[
\frac{\sigma(B_c^\pm) \cdot \mathcal{B}(B_c^\pm \rightarrow J/\psi \pi^\pm)}{\sigma(B^\pm) \cdot \mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)} =
\]

\[0.683 \pm 0.018 \pm 0.009\] \( p_T < 20 \text{ GeV}, \ 2.0 < |y| < 4.5 \) \( \text{LHCb at 8 TeV} \)

\[0.48 \pm 0.05 \pm 0.03 \pm 0.05\] \( p_T > 15 \text{ GeV}, \ |y| < 1.6 \) \( \text{CMS at 7 TeV} \)

\[0.44 \pm 0.07 +0.09 -0.04 \pm 0.01\] \( 13 < p_T < 22 \text{ GeV}, \ |y| < 2.3 \) \( \text{ATLAS at 8 TeV} \)

\[0.24 \pm 0.04 +0.05 -0.01 \pm 0.01\] \( p_T > 22 \text{ GeV}, \ |y| < 2.3 \) \( \text{ATLAS at 8 TeV} \)

The ratio decreases with \( p_T \)

Differences in production? hadronization?
Pentaquarks with hidden charm ($c\bar{c}uud$) at 7 - 8 TeV with 25 fb$^{-1}$

\[ m(K\pi) > 1.55 \&\& m(\pi K) > 1.55 \rightarrow m(pK) > 2.0 \text{ GeV} \]

\[ \Lambda_b \rightarrow J/\psi \ p \ K^- \text{ signal is seen on the top of} \]

- large combinatorial background
- very large $B \rightarrow J/\psi K^+ \pi^-$ contribution
- large $B_s \rightarrow J/\psi K^+ K^-$ contribution
- tails from small $B \rightarrow J/\psi \pi^+ \pi^-$ and $B_s \rightarrow J/\psi \pi^+ \pi^-$ contributions
$P_c^+$ at 7 - 8 TeV

\[ N(\Lambda_b \rightarrow J/\psi, p, K) = 2270 \pm 300 \]

\[ N( B^0 \rightarrow J/\psi, K, \pi) = 10770, \]
\[ N( B_s \rightarrow J/\psi, K, K) = 2290, \]
\[ N( B^0 \rightarrow J/\psi, \pi, \pi) = 1070, \]
\[ N( B_s \rightarrow J/\psi, \pi, \pi) = 1390; \]

1010$\pm$140 direct $\Lambda_b \rightarrow J/\psi, p, K$
**$\Lambda_b \to J/\psi, p, K$ decays analysis: 2 pentaquark hypothesis**

\[ \chi^2/N_{dof} = 49.0/43 \text{ (p-value = 0.25)} \]

### $P_c$ signal parameters and yields from fit:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>LHCb value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(P_{c1})$</td>
<td>$400^{+130}<em>{-140}(\text{stat})^{+110}</em>{-100}(\text{syst})$</td>
<td>--</td>
</tr>
<tr>
<td>$N(P_{c2})$</td>
<td>$150^{+170}<em>{-100}(\text{stat})^{+50}</em>{-90}(\text{syst})$</td>
<td>--</td>
</tr>
<tr>
<td>$N(P_{c1} + P_{c2})$</td>
<td>$540^{+80}<em>{-70}(\text{stat})^{+70}</em>{-80}(\text{syst})$</td>
<td>--</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>$2.8^{+1.0}<em>{-1.6}(\text{stat})^{+0.2}</em>{-0.1}(\text{syst})$ rad</td>
<td>--</td>
</tr>
<tr>
<td>$m(P_{c1})$</td>
<td>$4282^{+33}<em>{-26}(\text{stat})^{+28}</em>{-7}(\text{syst})$ MeV</td>
<td>$4380 \pm 8 \pm 29$ MeV</td>
</tr>
<tr>
<td>$\Gamma(P_{c1})$</td>
<td>$140^{+77}<em>{-50} (\text{stat})^{+41}</em>{-33}$ (syst) MeV</td>
<td>$205 \pm 18 \pm 86$ MeV</td>
</tr>
<tr>
<td>$m(P_{c2})$</td>
<td>$4449^{+20}<em>{-29} (\text{stat})^{+18}</em>{-10}$ (syst) MeV</td>
<td>$4449.8 \pm 1.7 \pm 2.5$ MeV</td>
</tr>
<tr>
<td>$\Gamma(P_{c2})$</td>
<td>$51^{+59}<em>{-48} (\text{stat})^{+14}</em>{-46}$ (syst) MeV</td>
<td>$39 \pm 5 \pm 19$ MeV</td>
</tr>
</tbody>
</table>
$\Lambda_b \rightarrow J/\psi, p, K$ decays analysis: 4 pentaquark hypothesis

Similar fits (no interference, Breit-Wigner amplitudes) has been performed on our data with masses, widths and relative yields of narrow states fixed to LHCb values. Parameters of $P_c(4380)$ kept free.

ATLAS data is consistent with LHCb Run II results.
No pentaquark fits: extended $\Lambda^*$ decay model

Projection of 2D $M(J/\psi,p)$ vs $M(J/\psi,K) + 1D M(p,K)$ fit w/o pentaquarks using extended $\Lambda^*$ decay model (left)

Result of 1D $\chi^2$ $M(J/\psi,p)$ fit with the same model (right): $\chi^2$/NDF = 42.0/23

$p$-val = $9.1 \times 10^{-3}$

This model shows a ‘border-line agreement’ with data.
Summary

**J/ψ & ψ(2S) at 13 TeV**
- non-prompt fraction: plateau \( \sim 0.7 \) for \( p_T > \sim 40 \) GeV
- non-prompt x-sections: FONLL predictions too high at high \( p_T \)
- prompt x-sections: \( \sim (b+p_T)^{-n} \), waiting for NRQCD

**B_c^+ / B^+ at 8 TeV**
- \( \sim 0.3\% \) (\( \sigma \) * Br)
- the ratio decreases with \( p_T \)
- no significant |\( y \)| dependence

**P_c^+ at 7-8 TeV**
- measured parameters of two pentaquarks agree with LHCb;
- do not contradict to the 3 narrow pentaquarks LHCb measurement;
- model w/o pentaquarks in border-line agreement (p-val = 9.1 x 10^{-3})

New exciting results for summer/fall conferences
Back-up Slides
Charmonium production

Non-prompt (from B decays) – probes open b quark production, fragmentation and B-decay kinematics
FONLL, matched NLO+NLL ("massive" NLO + resummation)
GM-VFNS ("massless" NLO + mass-dependent terms)
Charmonium production

**Non-prompt** (from B decays) – probes open b quark production, fragmentation and B-decay kinematics
- FONLL, matched NLO+NLL (“massive” NLO + resummation)
- GM-VFNS (“massless” NLO + mass-dependent terms)

**Prompt** (not from B decays) – probes specific mechanisms of Q̅Q system production and transformation to a meson
- NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data.
- Color Singlet Model (CSM) – only CS diagrams.
- Color Evaporation Model (CEM) – only one LDME.
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NRQCD: Color Singlet (CS) and Color Octet (CO) terms. Long-distance matrix elements (LDME) determined from experimental data.
Color Singlet Model (CSM) – only CS diagrams.
Color Evaporation Model (CEM) – only one LDME.

Ψ(2S) – nearly feed-down free
J/ψ – feed-downs ~35%
- Systematics due to fit model variation, muon and track reconstruction efficiency determination, trigger efficiency determination, and bin-to-bin migration have been studied.

- Systematic uncertainties dominate for $J/\psi$ up to $p_T$ of about 140 GeV.

- At higher $p_T$ of $J/\psi$, and also for full range of $p_T$ for $\psi(2S)$, statistical errors are dominant.

- Overall uncertainties for $J/\psi$ start at the level of 5-7%, increasing at the highest $p_T$ to 30%.

- For $\psi(2S)$, uncertainties fairly stable at around 10%.
### $B_c^+ / B^+$ x-section ratios at 8 TeV with 20 fb$^{-1}$

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B_c^\pm$</td>
</tr>
<tr>
<td></td>
<td>$13 \text{ GeV} &lt; p_T &lt; 22 \text{ GeV}$</td>
</tr>
<tr>
<td>Signal model of the fit</td>
<td>2.4%</td>
</tr>
<tr>
<td>CS and PRD components</td>
<td>+19.3%</td>
</tr>
<tr>
<td></td>
<td>-2.4%</td>
</tr>
<tr>
<td>Background model of the fit</td>
<td>1.7%</td>
</tr>
<tr>
<td>Trigger and reconstruction effects</td>
<td>0.9%</td>
</tr>
<tr>
<td>$B$-meson lifetime uncertainty</td>
<td>1.1%</td>
</tr>
</tbody>
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<td>$B_c^\pm$</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Signal model of the fit</td>
<td>2.5%</td>
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<tr>
<td>CS and PRD components</td>
<td>+11.2%</td>
</tr>
<tr>
<td></td>
<td>-2.4%</td>
</tr>
<tr>
<td>Background model of the fit</td>
<td>2.8%</td>
</tr>
<tr>
<td>Trigger effects and reconstruction effects</td>
<td>1.1%</td>
</tr>
<tr>
<td>$B$-meson lifetime uncertainty</td>
<td>1.0%</td>
</tr>
</tbody>
</table>
LHCb results on pentaquarks with hidden charm

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays

Model-Independent Evidence for $J/\psi p$ Contributions to $\Lambda_b^0 \rightarrow J/\psi p K^-$ Decays

Study of the production of $\Lambda_b^0$ and $B^0$ hadrons in pp collisions and first measurement of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ branching fraction

Evidence for Exotic Hadron Contributions to $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ Decays

Significance is convincing

However, in PDG

Status: *

* Evidence of existence is poor.
Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$

**arXiv:** [hep-ex]

LHCb selected 9 times more $\Lambda_b$ candidates in Run II compared to Run I.

The $J/\psi p$ mass resolution is 2.3–2.7 MeV (RMS) in 4.3–4.6 GeV region.

New data showed evidence for a new narrow state: $P_c(4312)$.

Moreover, the former $P_c(4450)$ state revealed substructure: 2 narrow states $P_c(4440)$ and $P_c(4457)$ have been observed.

Signal parameters are obtained using non-coherent sum of Breit-Wigner amplitude. Presence of the broad state $P_c(4380)$ is not confirmed...

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>(95% CL)</th>
<th>$R$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>4311.9 ± 0.7$^{+6.8}_{-0.6}$</td>
<td>9.8 ± 2.7$^{+3.7}_{-4.5}$</td>
<td>(&lt; 27)</td>
<td>0.30 ± 0.07$^{+0.34}_{-0.09}$</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>4440.3 ± 1.3$^{+4.1}_{-4.7}$</td>
<td>20.6 ± 4.9$^{+8.7}_{-10}$</td>
<td>(&lt; 49)</td>
<td>1.11 ± 0.33$^{+0.22}_{-0.10}$</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>4457.3 ± 0.6$^{+4.1}_{-1.7}$</td>
<td>6.4 ± 2.0$^{+5.7}_{-1.9}$</td>
<td>(&lt; 20)</td>
<td>0.53 ± 0.16$^{+0.15}_{-0.13}$</td>
</tr>
</tbody>
</table>

**Helicity formalism is not (yet) used in Run II analyses**
First measurement of near-threshold $J/\psi$ exclusive photoproduction off the proton


We report on the measurement of the $\gamma p \to J/\psi p$ cross section from $E_\gamma = 11.8$ GeV down to the threshold at 8.2 GeV using a tagged photon beam with the GlueX experiment. We find the total cross section falls toward the threshold less steeply than expected from two-gluon exchange models. The differential cross section $d\sigma/dt$ has an exponential slope of $1.67 \pm 0.39$ GeV$^{-2}$ at 10.7 GeV average energy. The LHCb pentaquark candidates $P_c^+$ can be produced in the s-channel of this reaction. We see no evidence for them and set model-dependent upper limits on their branching fractions $\mathcal{B}(P_c^+ \to J/\psi p)$ and cross sections $\sigma(\gamma p \to P_c^+) \times \mathcal{B}(P_c^+ \to J/\psi p)$.

<table>
<thead>
<tr>
<th>$B(P_c^+ \to J/\psi p)$ Upper Limits, %</th>
<th>p.t.p. only</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c^+(4312)$</td>
<td>2.9</td>
<td>4.6</td>
</tr>
<tr>
<td>$P_c^+(4440)$</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>$P_c^+(4457)$</td>
<td>2.7</td>
<td>3.8</td>
</tr>
</tbody>
</table>

upper limits for the $P_c^+$ states
at 90% confidence level
Inclusive production of the $P_c$ resonances in $p\bar{p}$ collisions (The D0 Collaboration*)


“displaced vertex” candidates with a superimposed fit

candidates of the decay $\Lambda_b^0 \rightarrow J/\psi p K^-$

$82 \pm 37$

$2.3\sigma$
Selection criteria

- $\chi^2(H_b)/N_{\text{dof}} < 2$, where $\chi^2$ is the quality of the fit to the $H_b$ topology with $N_{\text{dof}} = 8$.
- $L_{xy}(H_b) > 0.7$ mm, where $L_{xy}(H_b)$ is the transverse decay length of the $H_b$ vertex measured from the primary vertex.
- $p_T(H_b)/\sum p_T(\text{track}) > 0.2$, where the sum in the denominator is taken over all tracks originating from the primary vertex (tracks of the $H_b$ candidate are included in the sum). The requirement removes a sizeable fraction of combinatorial background while having a smaller effect on the signal due to the characteristic hard fragmentation of $b$ quarks.
- $p_T(p) > 2.5$ GeV and $p_T(K^-) > 1.8$ GeV, assuming proton and kaon masses for the additional tracks in turn.
- $\cos \theta_{P_c} < 0.5$, where $\theta_{P_c}$ is the angle between $J/\psi$ momentum in the $P_c$ candidate rest frame and $P_c$ candidate momentum in $\Lambda_b$ candidate rest frame;
- $\cos \theta_{\Lambda_b} < 0.8$, where $\theta_{\Lambda_b}$ is the angle between $P_c$ candidate momentum and $\Lambda_b$ candidate momentum in laboratory frame;
- $|\cos \theta_{\Lambda^*}| < 0.85$, where $\theta_{\Lambda^*}$ is the angle between kaon momentum in $\Lambda^* \rightarrow pK$ candidate rest frame and $\Lambda^*$ candidate momentum in $\Lambda_b$ candidate rest frame.

$$p_T(\mu^\pm) > 4 \text{ GeV}, \ |\eta(\mu^\pm)| < 2.3.$$ 

The kinematic range of the $H_b$ measurement is fixed to

$$p_T(H_b) > 12 \text{ GeV}, \ |\eta(H_b)| < 2.1.$$
Fit structure – iterations of 4 steps

1. To tune parameters of B and $B_s$ decays (background):

Unbinned likelihood for the sum

\[
[2D \, m(J/\psi \, K \, \pi) + m(J/\psi \, \pi \, \pi \, K)] + [2D \, m(J/\psi \, K \, K) + m(J/\psi \, \pi \, \pi)] + [2D \, m(J/\psi \, \pi_1) + m(J/\psi \, \pi_2)] + [1D \, m(K\pi)] + [1D \, m(\pi K)] + [2D \, m(J/\psi \, K_1) + m(J/\psi \, K_2)] + [1D \, m(KK)]
\]

overall normalization

B signal mass region

$B_s$ signal mass region

2. To determine number of $\Lambda_b$ baryons

$\chi^2$ fit of m(J/ψ p K−) (fully statistically correct)

3. To tune $\Lambda^*$ parameters ($\Lambda_b$ signal region)

Unbinned likelihood fit for the sum

\[
[2D \, m(J/\psi \, p) + m(J/\psi \, K)] + [1D \, m(pK)]
\]

4. To determine pentaquark parameters ($\Lambda_b$ signal region)

$\chi^2$ fit of m(J/ψ p) (fully statistically correct)
Step 1: To tune parameters of B and Bs decays (background):
Step 1: To tune parameters of B and Bs decays (background):

Is X(4200)$^\pm$ here?
### Summary of systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$N(P_{c1})$</th>
<th>$N(P_{c2})$</th>
<th>$N(P_{c1} + P_{c2})$</th>
<th>$\Delta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of $\Lambda^0_{b} \rightarrow J/\psi pK^-$ decays ($\delta_1$)</td>
<td>$+1.8% \pm 0.6%$</td>
<td>$+6.6% \pm 9.2%$</td>
<td>$+1.6% \pm 0.8%$</td>
<td>$+0.3% \pm 0.0%$</td>
</tr>
<tr>
<td>Pentaquark modelling ($\delta_2$)</td>
<td>$+21%$</td>
<td>$+1% \pm 22%$</td>
<td>$+8.7% \pm 4.4%$</td>
<td>$+1.6% \pm 0.0%$</td>
</tr>
<tr>
<td>Non-pentaquark $\Lambda^0_{b} \rightarrow J/\psi pK^-$ modelling ($\delta_3$)</td>
<td>$+14% \pm 2%$</td>
<td>$+5% \pm 44%$</td>
<td>$+9.2% \pm 9.1%$</td>
<td>$+3.6% \pm 1.6%$</td>
</tr>
<tr>
<td>Combinatorial background ($\delta_4$)</td>
<td>$+0.7% \pm 4.0%$</td>
<td>$+18% \pm 5%$</td>
<td>$+4.2% \pm 4.8%$</td>
<td>$+3.2% \pm 0.0%$</td>
</tr>
<tr>
<td>$B$ meson decays modelling ($\delta_5$)</td>
<td>$+13% \pm 25%$</td>
<td>$+28% \pm 35%$</td>
<td>$+1.6% \pm 9.3%$</td>
<td>$+0.5% \pm 2.1%$</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$+28% \pm 25%$</td>
<td>$+35% \pm 61%$</td>
<td>$+14% \pm 15%$</td>
<td>$+5.1% \pm 2.7%$</td>
</tr>
</tbody>
</table>

### Summary of nuisance uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$m(P_{c1})$</th>
<th>$\Gamma(P_{c1})$</th>
<th>$m(P_{c2})$</th>
<th>$\Gamma(P_{c2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of $\Lambda^0_{b} \rightarrow J/\psi pK^-$ decays ($\delta_1$)</td>
<td>$+0.06% \pm 0.03%$</td>
<td>$+3.5% \pm 2.5%$</td>
<td>$+0.07% \pm 0.04%$</td>
<td>$+7% \pm 13%$</td>
</tr>
<tr>
<td>Pentaquark modelling ($\delta_2$)</td>
<td>$+0.6%$</td>
<td>$+18% \pm 0%$</td>
<td>$+0.2% \pm 0.0%$</td>
<td>$+0% \pm 33%$</td>
</tr>
<tr>
<td>Non-pentaquark $\Lambda^0_{b} \rightarrow J/\psi pK^-$ modelling ($\delta_3$)</td>
<td>$+0.23% \pm 0.05%$</td>
<td>$+9.2% \pm 1.2%$</td>
<td>$+0.24% \pm 0.02%$</td>
<td>$+2% \pm 62%$</td>
</tr>
<tr>
<td>Combinatorial background ($\delta_4$)</td>
<td>$+0.03% \pm 0.15%$</td>
<td>$+0% \pm 11%$</td>
<td>$+0.01% \pm 0.17%$</td>
<td>$+22% \pm 4%$</td>
</tr>
<tr>
<td>$B$ meson decays modelling ($\delta_5$)</td>
<td>$+0.24% \pm 0.00%$</td>
<td>$+21% \pm 21%$</td>
<td>$+0.27% \pm 0.14%$</td>
<td>$+17% \pm 57%$</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>$+0.7% \pm 0.2%$</td>
<td>$+30% \pm 24%$</td>
<td>$+0.4% \pm 0.2%$</td>
<td>$+28% \pm 91%$</td>
</tr>
</tbody>
</table>