Study of $B^+_c \rightarrow J/\psi D_s^+$ and $B^+_c \rightarrow J/\psi D_s^{**}$ decays in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

1. Introduction

The $B^+_c$ meson is the only known weakly decaying particle consisted of two heavy quarks. It affects theoretical calculations of its decay properties. Various model predictions are available. Leading Feynman diagrams for $B^+_c \rightarrow J/\psi D_s^{(*)}$ decays:

- **Signal process**: $B^+_c \rightarrow J/\psi D_s^+$ and $B^+_c \rightarrow J/\psi D_s^{**}$
  - Daughters are reconstructed via $J/\psi \rightarrow \mu^+ \mu^-$ and $D_s^{(*)} \rightarrow \phi K$ with $\phi \rightarrow K^+ K^-$
  - 2 distinct decay vertices of $B^+_c$ and $D_s^{(*)}$
  - Masses of $J/\psi$ and $D_s^{(*)}$ candidates are constrained in the vertex to their nominal values
- $D_s^{(*)}$ decays into $J/\psi$ or $D_s^{(*)}$ with the neutral particle escaping detection, i.e. incomplete reconstruction

2. Reconstruction and measurement strategy

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**Reference mode**: $B^+_c \rightarrow J/\psi c\bar{s}$
- Decay $J/\psi$ is constrained in the fit to the nominal value
- The model provides large statistics and thus used for normalisation in the branching fractions measurement

**Polarisation in $B^+_c \rightarrow J/\psi D_s^{(*)}$**
- Scalar $B^+_c$ decays into two vector particles - three possible helicity amplitudes $A_{00}, A_{+-}, A_{++}$
- Longitudinal $A_{00}$ and transverse $A_{+-,++}$ components have different kinematics
- Shape of $J/\psi D_s^{(*)}$ invariant mass and $J/\psi$ helicity angle
- They can be distinguished in the fit to these variables

3. Event selection

**J/ψ candidates**
- The $J/ψ$ candidates are built from pairs of oppositely charged momen
t candidates that are reconstructed using information from the MS and the ID. Muon candidates must satisfy the Loose identification working point

**D_s^{(*)} candidates**
- $p_T(B^+_c) > 1$ GeV, $|\eta(B^+_c)| < 2.5$
- $L_{tr,vis}(B^+_c) > 0$ min, (wrt the $B^+_c$ vertex)
- $m(B^+_c)$ in $1$% FFWHM around nominal mass
- $1.05 \times m(B_s) < m(D_s^{(*)}) < 1.016$ GeV

**B_s candidates**
- $p_T(B_s) > 15$ GeV, $|\eta(B_s)| < 2.1$
- $m(B_s) > 5$ and $m(B_s') < 5$ wrt the $B^+_c$
- $V_r < 2.0$, $c_t < 2$, $c_t = B$
- $L_{tr,vis}(B_s) > 0.3$ mm, $L_{tr,vis}(B_s') > 10$ mm
- Exclude 5.34 GeV in the $J/\psi(\gamma)$ by $5.40$ GeV to suppress $B^+_c \rightarrow J/\psi c\bar{s}$

To further suppress the combinatorial background, a multivariate classifier based on boosted decision trees (BDT) as implemented in the TMVA framework is employed.

**BDT input variables**
- $p_T(J/\psi), L_{tr,vis}(B^+_c)$
- $m(J/\psi)/m(D_s^{(*)})$ (for $D_s^{(*)}$)
- $m(B^+_c)/m(D_s^{(*)})$, $m(D_s^{(*)})/m(B^+_c)$

4. Signal

An extended unbinned maximum-likelihood fit to the two-dimensional distribution of $m(J/\psi)$ and $cos(\theta)$ is performed to extract the signal yields as well as the transverse momentum fraction in the $B^+_c \rightarrow J/\psi D_s^{(*)}$ decay. The helicity angle $cos(\theta)$ is defined as the angle between $\mu^+$ and $D_s^{(*)}$ candidate momenta in the rest frame of the muon pair.

**Mass part**

- $B^+_c \rightarrow J/\psi D_s^{(*)}$ signal modified Gaussian function

**Angular part**

- Shapes of $cos(\theta)$ can be predicted analytically

**Background**

- Second-order polynomial shapes

5. Normalisation using reference decay

Selection of the reference decay candidates is close to that of signal for better cancellation of uncertainties

**Same cuts as in $B^+_c \rightarrow J/\psi D_s^{(*)}$**
- $J/\psi$ candidate selection
- $p_T(B^+_c)$, $\langle p_T(B^+_c) \rangle$ region, $L_{tr,vis}(B^+_c)$
- Further cuts
- $|\delta_{1b}^u(B^+_c)|/\delta_{2b}^u(B^+_c) < 3$ and $|\delta_{1b}^u(B^+_c)|/\delta_{2b}^u(B^+_c) < 3$
- $\chi^2_{1b,2b} < 1.8$, $p_T(J/\psi) > 3.5$ GeV
- Veto $B^+_c$ candidate tracks identified as low-$p_T$ muons to suppress $B^+_c \rightarrow J/\psi \mu^+ \mu^-$

**Ratios of branching fractions**

- $R_{D_s^{(*)}} = \frac{B(B^+_c \rightarrow J/\psi D_s^{(*)})}{B(B^+_c \rightarrow J/\psi D_s^{(*)})}$
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6. Systematics

**Measured ratios of branching fractions**

- $R_{D_s^{(*)}}/R_{D_s} = 2.78 \pm 0.33$ (stat.) $\pm 0.29$ (syst.) $\pm 0.06$ (lumi.) $\pm 0.04$ (SF)
- $R_{D_s^{**}}/R_{D} = 3.33 \pm 0.61$ (stat.) $\pm 0.07$ (syst.) $\pm 0.03$ (SF)
- $BR(B^+_c \rightarrow J/\psi D_s^{(*)}) = 1.03 \pm 0.24$ (stat.) $\pm 0.06$ (syst.)

The measurement of $R_{D_s^{(*)}}$, and $R_{D_s^{**}}$ agree with ATLAS Run 1 [1] and LHCB [2]. The obtained values of $R_{D_s^{(*)}}$ is smaller and $BR(B^+_c \rightarrow J/\psi D_s^{(*)})$ is larger than the ATLAS Run 1 measurement, although in both cases the difference does not exceed 1.5 standard deviations taking the Run 1 uncertainty. All the ratios of branching fractions are well described by the QCD relativistic potential model predictions [3].

7. References


