Meson spectroscopy results from CMS

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In this presentation

I. Observation of well resolved signals consistent with $B_c^+(2S)$ and $B_c^{*+}(2S)$

II. Measurement of the $B_c^+(2S)$ mass

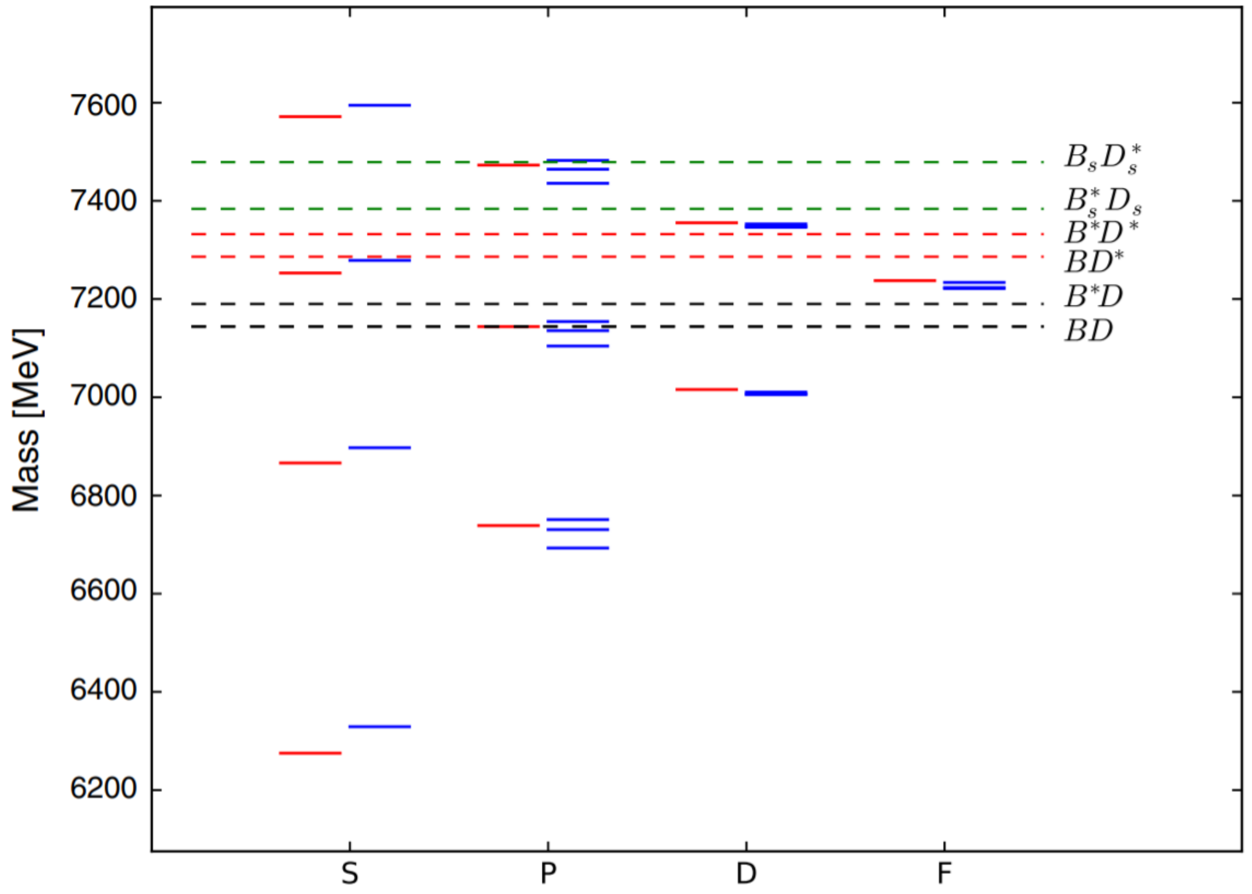
III. Measurement of the $B_c^+(2S)$ to B_c^+ and $B_c^{*+}(2S)$ to B_c^+ cross section ratios

IV. Invariant mass distributions of the pair of pions emitted in the $B_c^{*+}(2S) \rightarrow B_c^{*+}\pi^+\pi^-$ decay

Results published in:

- Physical Review Letters **122**, 132001 (2019) (results I and II)
- Physical Review D **102**, 092007 (2020) (results III and IV)

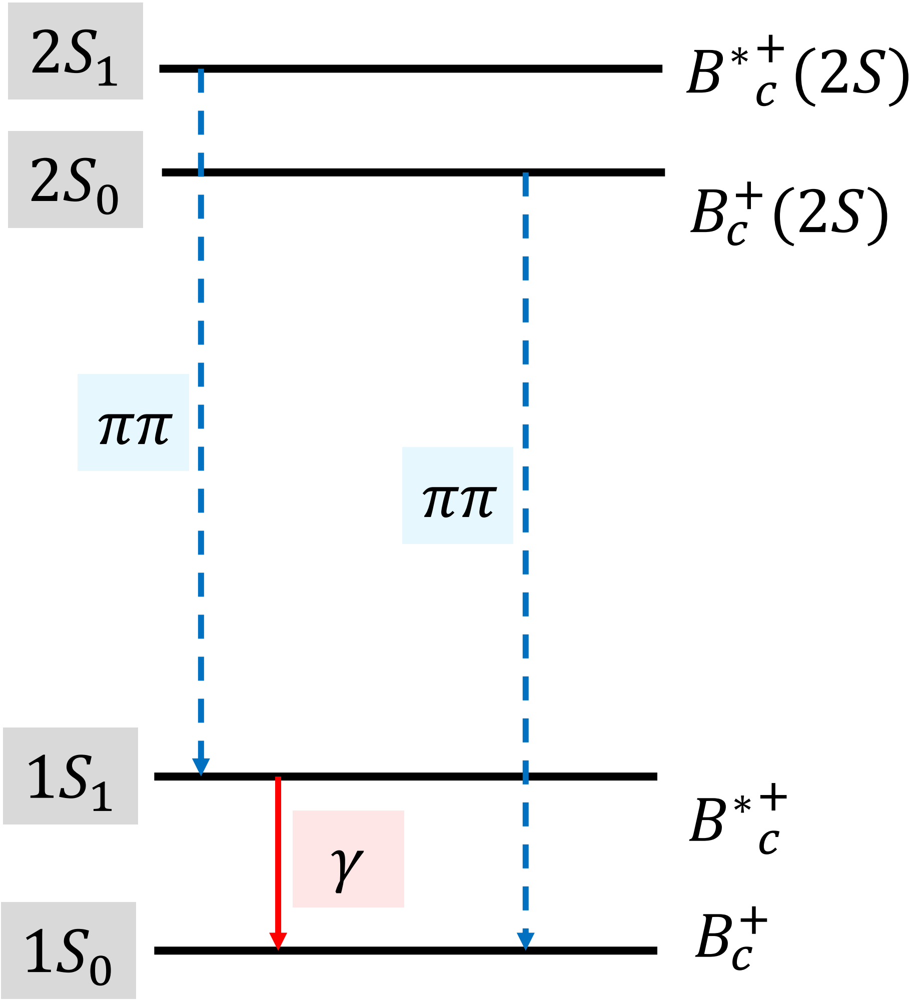
Introduction



$c\bar{b}$ spectrum calculated by Eichten and Quigg. ***Spin-singlet*** *(**-triplet**) state are displayed in **red** (**blue**)*

- $\boldsymbol{B_c^+}$ is the **lighest meson** of the $\boldsymbol{\bar{b}c}$ **family**
- **Why** is it **interesting**?
  - ➢ It's the only heavy meson consisting of two **heavy quarks** with **different flavours**
  - ➢ Transitions from excited states allow to **study** the **QCD potential**
  - ➢ Only **weak decay** is allowed for the **ground state**
  - ➢ All **excited $\boldsymbol{B_c}$ states** (below the BD threshold) **decay** to the ground state via **electromagnetic** or **hadronic** transitions
- Rather **small production cross section** at hadron colliders:
  - ➢ B_c mesons mainly produced via **gg** $\rightarrow$ $\boldsymbol{B_c\,\bar{c}b}$ at LHC
  - ➢ Production cross section $\sim \boldsymbol{\alpha_s^4}$

Analysis strategy

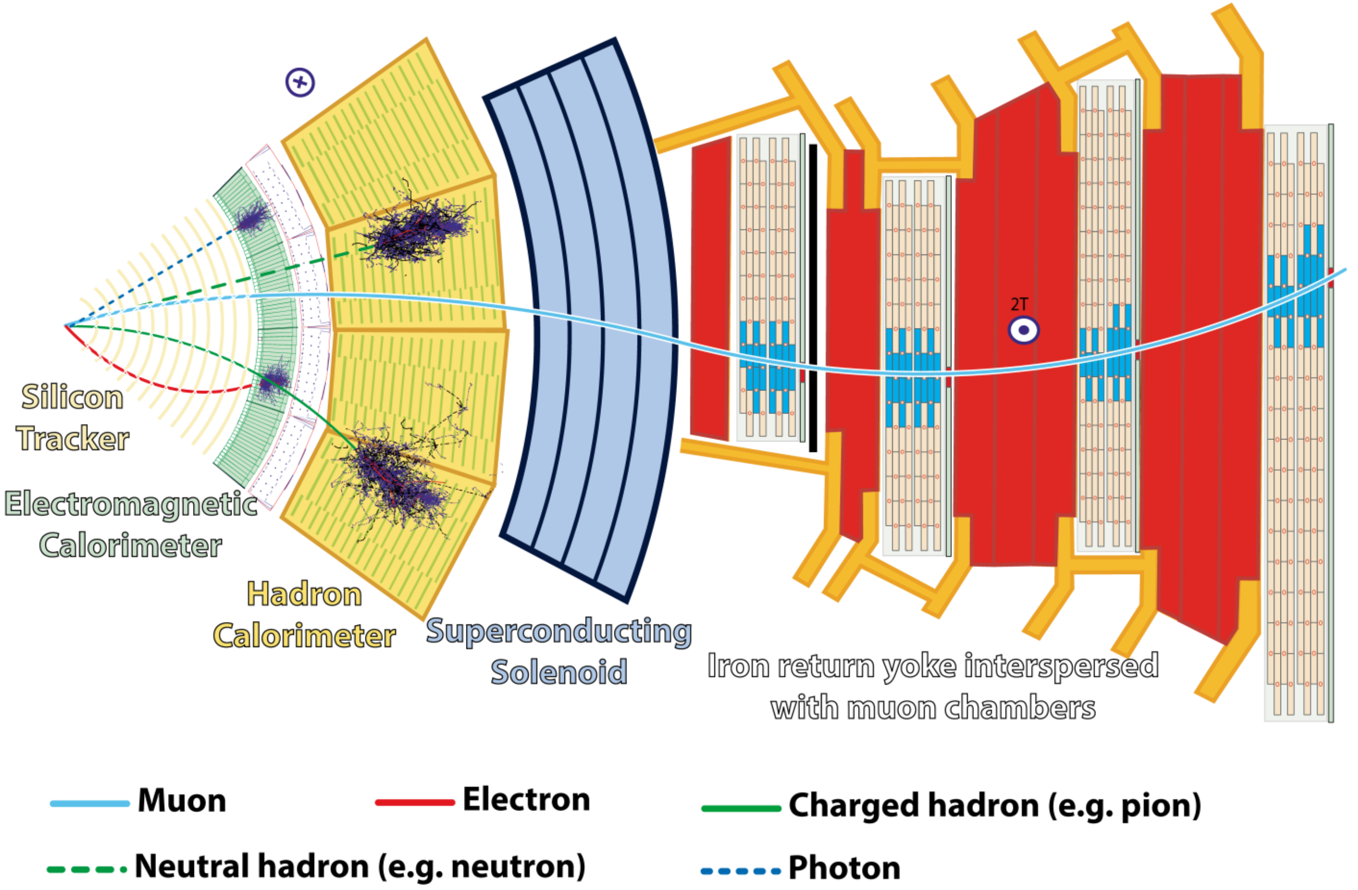


- $\boldsymbol{B_c^+(2S)}$ **decays** directly to $\boldsymbol{B_c^+\pi^+\pi^-}$ while the $\boldsymbol{B_c^{*+}(2S)}$ is expected to decay predominantly to $\boldsymbol{B_c^{*+}\pi^+\pi^-}$ **followed by** the $\boldsymbol{B_c^{*+} \rightarrow B_c^+\gamma}$ decay
- The $\boldsymbol{\gamma}$ **from** the $\boldsymbol{B_c^{*+}}$decay has very **low energy** ($54\ \mathrm{keV}$) and its detection is very challenging
- The two states can be seen as two **separate peaks** in the $B_c^+\pi^+\pi^-$ mass distribution if $\boldsymbol{\Delta M \equiv [M(B_c^{*+}) - M(B_c^+)] - [M(B_c^{*+}(2S)) - M(B_c^+(2S))]}$ is **larger than** the **experimental resolution**
- Since $M(B_c^{*+}) - M(B_c^+)$ is predicted to be larger than $M(B_c^{*+}(2S)) - M(B_c^+(2S))$, the $\boldsymbol{B_c^{*+}(2S)}$ state will be the **lower mass peak**
- Expected resolution ($\sim 6\ \mathrm{MeV}$) smaller than the expected mass difference ($\sim 23\ \mathrm{MeV}$)→ the **peaks are resolved**
- **Total width** predicted to be in the $50 - 90\ \mathrm{keV}$ range→ **cannot be measured**

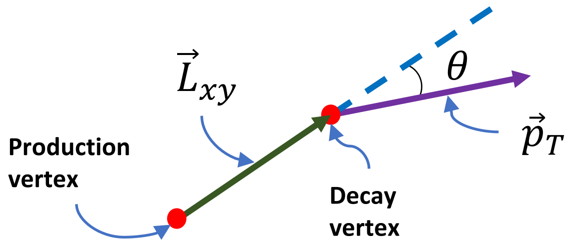
Experimental apparatus, data sample and event selection

Trigger selection targeting $\mathbf{J/\psi \rightarrow \mu^{+}\mu^{-}}$ decay

- **Level-1**: custom hardware processors select **events with two muons**
- **High-level trigger** requires a pair of **opposite-sign muon** having
  - ➢ invariant mass in the range $2.9 - 3.3$ GeV
  - ➢ vertex fit χ^2 probability $< 10\%$
  - ➢ distance of closest approach < 0.5 cm
  - ➢ $L_{xy} > 3\delta_{L_{xy}}$ and $\cos\theta > 0.9$
- **Additional track compatible** with being produced at the **dimuon vertex**



- **Proton-proton** collisions collected by **CMS** at a center of mass energy of $\mathbf{13\ TeV}$ in 2015, 2016, 2017 and 2018
- **Total** integrated **luminosity** of $\mathbf{146.6\ fb^{-1}}$

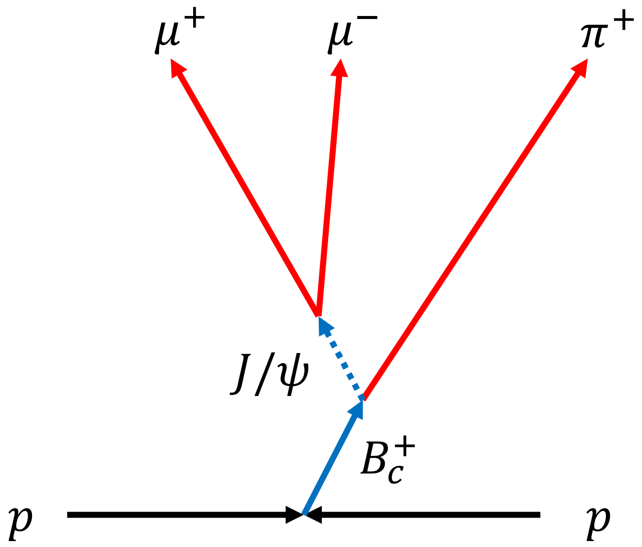


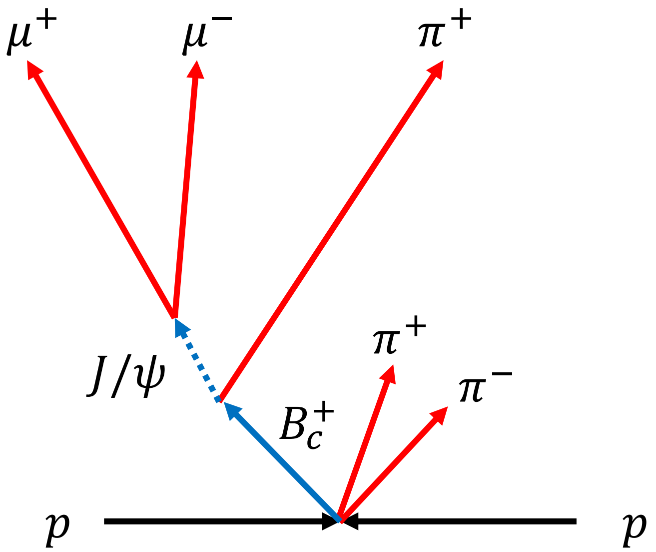
$$\cos\theta = \frac{\vec{L}_{xy} \cdot \vec{p}_T}{L_{xy} p_T}$$

Observation of two excited B_c states: event selection

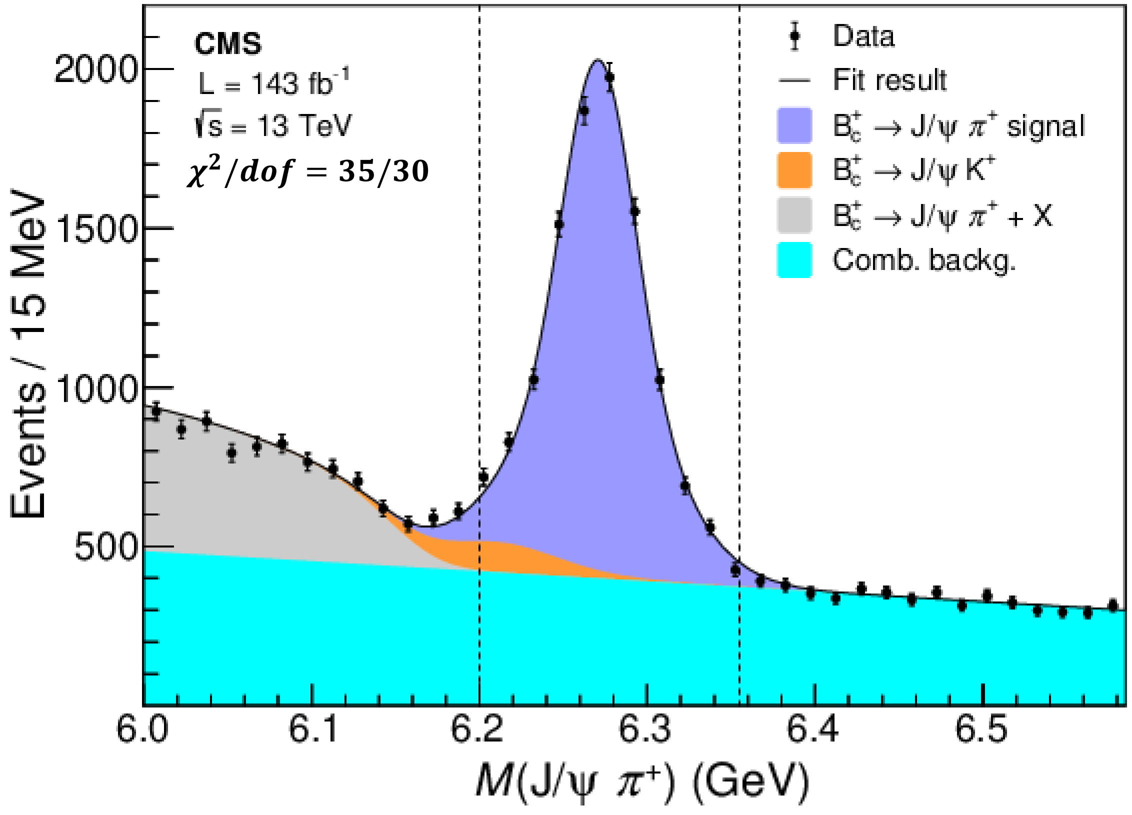
- $\boldsymbol{B_c^+}$ candidate reconstructed combining **dimuon+track**
- $\boldsymbol{\mu^+\mu^-}$ invariant **mass constrained** to the $\boldsymbol{J/\psi}$ **mass**
- **Primary vertex** selected as the one with the **largest** $\boldsymbol{\cos\theta}$
- $\boldsymbol{B_c^+}$ **selection cuts**:
  - $p_T > 15$ GeV, $|y| < 2.4$ and decay length < 100 μm
  - Kinematic fit probability $\chi^2 > 10\%$
  - If more than one candidate per event, the one with the higest p_T is selected

- $\boldsymbol{B_c^{(*)+}(2S)}$ reconstructed combining $\boldsymbol{B_c^+}$ candidate **+ two opposite-sign tracks** from a common vertex
- $\boldsymbol{B_c^+}$ in the $\boldsymbol{6.2 - 6.355}$ **GeV** mass window
- $\boldsymbol{B_c^{(*)+}(2S)}$ **selection cuts**:
  - Leading (subleading) pion $p_T > 0.8\ (0.6)$GeV
  - $|y| < 2.4$
  - Kinematic vertex fit χ^2probability $> 10\%$
  - Only $B_c^+\pi^+\pi^-$ candidate with highest p_T is kept





$B_c^+ \to J/\psi\pi^+$ mass distribution: signal and background fit



$N(B_c^+) = 7629 \pm 225$
$M(B_c^+) = 6271.1 \pm 0.5$ MeV

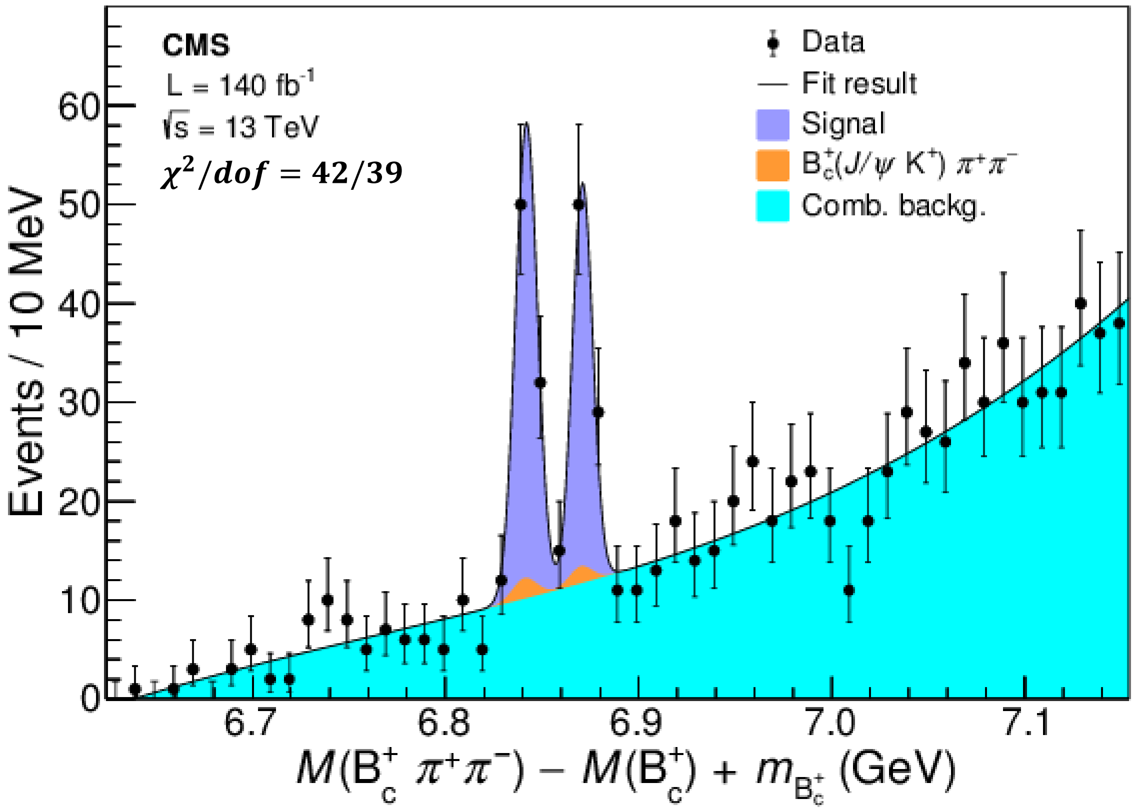
B_c^+ signal peak

- Sum of two gaussian functions with a common mean

Background

- Combinatorial J/ψ + uncorrelated charged track paramatrized by first order Chebyshev polynomial
- Partially reconstructed B_c^+ described by generalized ARGUS function (ARGUS Coll.)
- $B_c^+ \to J/\psi K^+$ decays modelled using custom shape determined from simulation studies

$B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-$ mass distribution: signal and background fit



$$N_{\text{low-mass}} = 67 \pm 10$$
$$N_{\text{high-mass}} = 51 \pm 10$$
$$\Delta M = 29.1 \pm 1.5 \text{ MeV}$$
$$M\left(B_c^+(2S)\right) = 6871.0 \pm 1.2 \text{ MeV}$$

$B_c^+(2S)$ and $B_c^{*+}(2S)$ signal peaks

- Two gaussian superposition for $B_c^+(2S)$ and $B_c^{*+}(2S)$ peaks

Background

- Third order Chebyshev polynomial modelling the combinatorial background
- The shape used for modelling $B_c^+ \to J/\psi K^+$ decay identical to the signal
  - ➢ normalization fixed by the ratio of $B_c^+ \to J/\psi K^+$ and $B_c^+ \to J/\psi\pi^+$ yields

Observation of **two peaks** rather than one is established with a significance of **6.5 standard deviations**

Measurement of $B_c^+(2S)$ mass

Systematic uncertainties

- **Event selection criteria**
- **Normalization** of the $B_c^+ \to J/\psi K^+$ **channel**
- **Contamination** from **partially reconstructed** B_c^+
- Possible **misalignements** of the **tracker** detectors
- **Shape** used to **fit** various **background** contributions

→ Found to be negligible

- **Shape** used to **fit** the **signal peaks** → ± 0.8 MeV for $\mathrm{M}(B_c^+(2S))$ and ± 0.7 MeV for ΔM
- **Uncertainty** on the **world-average** B_c^+ **mass** → Additional ± 0.8 MeV for $\mathrm{M}(B_c^+(2S))$

⇒ $$M\left(B_c^+(2S)\right) = 6871.0 \pm 1.2\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst}) \pm 0.8\ (B_c^+)\,\mathrm{MeV}$$

Cross section ratios: reconstruction efficiency

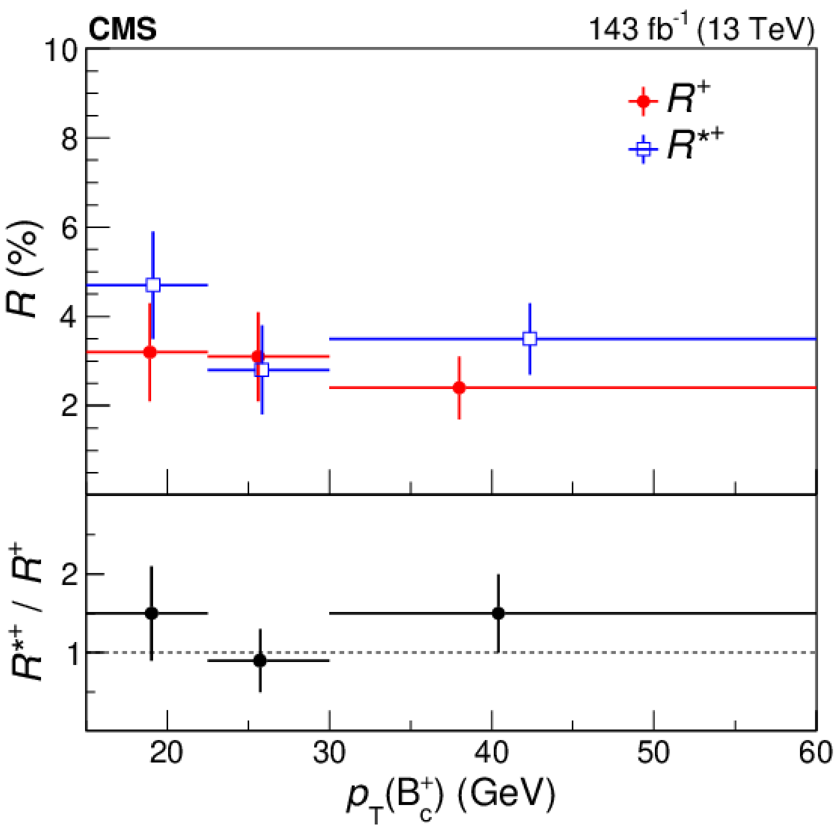
$$R^{(*)+} = \frac{\sigma\left(B_c^{(*)+}(2S)\right)}{\sigma(B_c^+)}\mathcal{B}\left(B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-\right) = \frac{N\left(B_c^{(*)+}(2S)\right)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon\left(B_c^{(*)+}(2S)\right)}$$

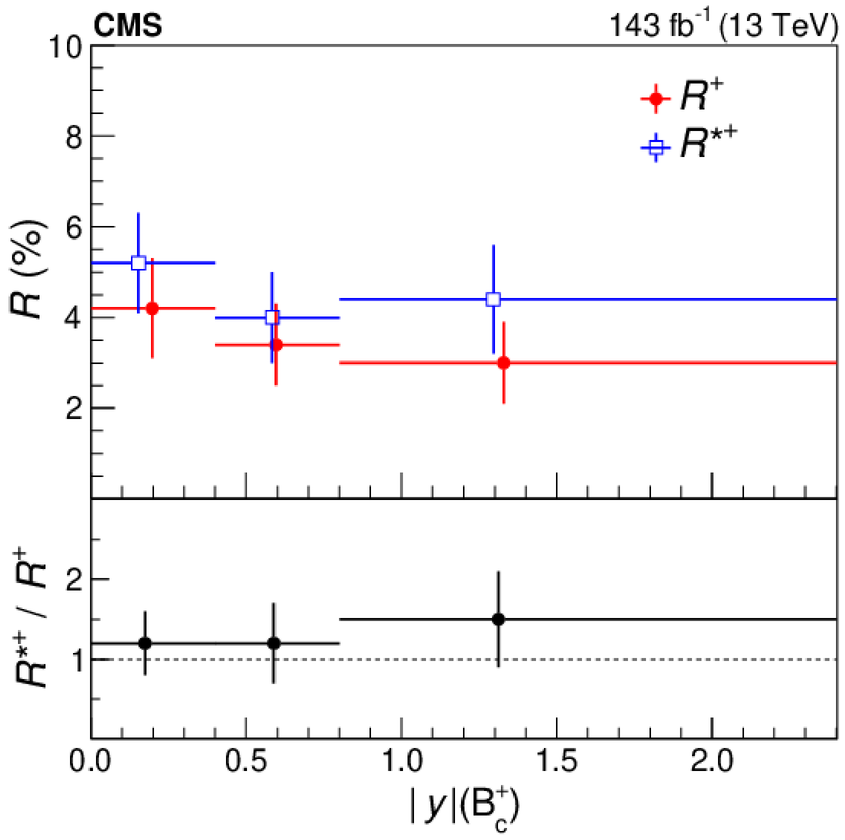
- Efficiencies evaluated by computing the **fraction** of **generated** $\boldsymbol{B_c^{*+}(2S)}$ events (within the phase space region of the analysis) that **survive** all the **reconstruction** and **selection** steps
- **Reconstruction efficiencies systematics**
  - Potential residual **mismatches** between the **running conditions** and the settings used in **simulations** (*Spread*)
  - Uncertainty in the **reconstruction efficiency** of the **two pions** emitted in the $B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-$ decay (*Pions*)

	Central	Stat.	Spread	Pions
$\epsilon(\mathrm{B_c(2S)^+})/\epsilon(\mathrm{B_c^+})$	0.196	1.1%	1.8%	4.2%
$\epsilon(\mathrm{B_c^*(2S)^+})/\epsilon(\mathrm{B_c^+})$	0.187	1.0%	1.6%	4.2%
$\epsilon(\mathrm{B_c^*(2S)^+})/\epsilon(\mathrm{B_c(2S)^+})$	0.955	1.4%	0.9%	—

$$R^+ = (3.47 \pm 0.63\,(\mathrm{stat}) \pm 0.33\,(\mathrm{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\mathrm{stat}) \pm 0.56\,(\mathrm{syst}))\%, \quad \text{and}$$
$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}).$$

Cross section ratios: dependence on B_c^+ kinematics





Probing the **cross section ratios dependence** on the **kinematics** of the B_c^+ meson

- **Events splitted** into **three** B_c^+ meson $\boldsymbol{p_T}$ **bins** and (independently) into **three** $|\boldsymbol{y}|$ **bins**:
  - p_T bins = $[15, 22.5, 30, 60]$ GeV
  - $|y|$ bins = $[0, 0.4, 0.8, 2.4]$

None of the measured ratios show **significant variations** with the $\boldsymbol{p_T}$ or $|\boldsymbol{y}|$ of the $\boldsymbol{B_c^+}$ **meson**

Cross section ratios: systematics

- $B_c^+ \to J/\psi\pi^+$
  - ➢ 1st order polynomial → exponential
  - ➢ Double-gaussian → Student
- $B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-$
  - ➢ Double gaussian → single gaussian
  - ➢ Signal yield evaluated by subtracting the background after side-band fit only
  - ➢ Chebyshev polynomial → $\delta^\lambda \exp(\nu\delta)$ where $\delta \equiv M(B_c^+\pi^+\pi^-) - q_0$

- **Reconstruction efficiencies systematics** (slide 10)

- Assuming $\pi^+\pi^-$ **kinematics reflect** the existence of an **intermediate resonance**
  - ➢ Generated $B_c^{(*)+}(2S)$ events reweighted so that their $\pi^+\pi^-$ invariant mass distribution match that in the data

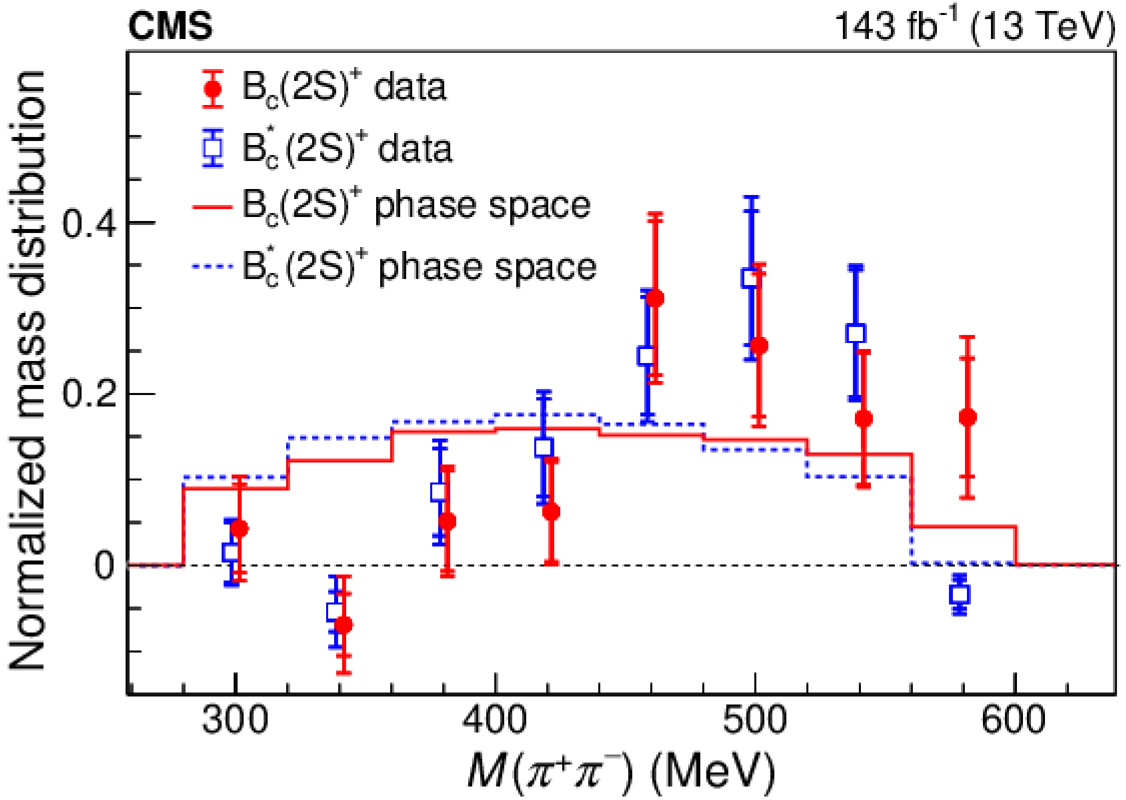
Relative systematic uncertainties given in %

	R^+	R^{*+}	R^{*+}/R^+
$J/\psi\pi^+$ fit model	5.5	5.5	···
$B_c^+\pi^+\pi^-$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: spread among years	1.8	1.6	0.9
Efficiencies: pion tracking	4.2	4.2	···
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total	9.5	12.0	6.4

- Assuming $\pi^+\pi^-$ **kinematics** are **dependent** on the **spins** of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states
  - ➢ Generated $B_c^{(*)+}(2S)$ events reweighted so that ditribution of the angle between π^- and π^+, in the dipion rest frame, match that in the data

Invariant mass distribution of the dipion system

- Data derived **from $B_c^+\pi^+\pi^-$ mass distribution**
- **Background subtraction**
  - Shape evaluated measuring the $B_c^+\pi^\pm\pi^\pm$ invariant mass
  - Normalization to the $B_c^+\pi^+\pi^-$ spectrum in the invariant mass sideband region
- **Systematic uncertainties** evaluated by **varying** the **models** used to **fit** the invariant $B_c^+\pi^+\pi^-$ mass distribution
  - signal and the background composition of the $B_c^+\pi^+\pi^-$ mass distribution
  - contributions from $B_c^+ \to J/\psi K^+$ and partially reconstructed B_c^+ decays



- $B_c(2S)^+$ and $B_c^*(2S)^+$ dipion **invariant mass distributions** are **compatible with each other** within the uncertainties
- They have **shapes different** from the distributions predicted from the **phase space simulations**

Summary

- **Signals** consistent with the $\boldsymbol{B_c^+(2S)}$ and $\boldsymbol{B_c^{*+}(2S)}$ **states** have been seperately **observed** for the first time by **CMS**
  - The **two peaks** are **well resolved**, with a measured mass differenece of
  $$\Delta M = 29.1 \pm 1.5\ (\text{stat}) \pm 0.7(\text{syst})\ \text{MeV}$$
  - The $\boldsymbol{B_c^+(2S)}$ **mass** is **measured** to be $6871.0 \pm 1.2\ (\text{stat}) \pm 0.8(\text{syst}) \pm 0.8\ (B_c^+)\ \text{MeV}$
  - Because of the low-energy photon emitted in the $B_c^{*+} \rightarrow B_c^+\gamma$ radiative decay is not reconstructed, the **true value** of the $\boldsymbol{B_c^{*+}(2S)}$ **mass** remains **unknown**

- The **ratios** of the $\boldsymbol{B_c^+(2S)}$ **to** $\boldsymbol{B_c^+}$, $\boldsymbol{B_c^{*+}(2S)}$ **to** $\boldsymbol{B_c^+}$ and $\boldsymbol{B_c^{*+}(2S)}$ **to** $\boldsymbol{B_c^+(2S)}$ **production cross section** have been **measured** by **CMS**
  - **No significant dependences** on the **transverse momentum** or **rapidity** of the B_c^+ mesons have been observed for any of these ratios