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Latest results on B_c at ATLAS and CMS

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CMS Collaboration

Latest results from CMS and ATLAS

Production

- **ATLAS**: Measurement of the relative $B_c^{\pm}/B^{\pm}$ production cross section with the ATLAS detector at $\sqrt{s}$ = 8 TeV [PRD 104 (2021) 012010]
- **CMS**: Observation of the B_c^+ meson in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and Measurement of its nuclear modification factor [PRL 128 (2022) 252301]

Decays

- **ATLAS**: 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 [JHEP 08 (2022) 087]

Spectroscopy

- **CMS**: Observation of two excited B_c states and measurement of the $B_c(2S)$ mass in pp collisions at $\sqrt{s}$ = 13 TeV [PRL 122 (2019) 132001]
- **CMS**: Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s}$ = 13 TeV [PRD 102 (2020) 092007]

Relative $B_c^{\pm}$ / $B^{\pm}$ production at ATLAS

B_c meson production is possible at LHC via gluon-gluon fusion (proportional to α_s^4):
unique probe for Heavy Flavour physics, as it requires collinear production of two different heavy quarks

Measurement of the total and differential **production cross section for the $B_c^{\pm}$** ($B_c^{\pm} \rightarrow J/\psi\pi^{\pm}$) relative to $B^{\pm} \rightarrow J/\psi K^{\pm}$ using 20.3 fb^{-1} of pp collisions data collected at **ATLAS** at $\sqrt{s}$ = 8 TeV (LHC Run-1/2012)

Relative production cross section calculated as

$$\frac{\sigma(B_c^{\pm}) \cdot \mathcal{B}(B_c^{\pm} \to J/\psi\pi^{\pm}) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\sigma(B^{\pm}) \cdot \mathcal{B}(B^{\pm} \to J/\psi K^{\pm}) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)} = \frac{N^{\mathrm{reco}}(B_c^{\pm})}{N^{\mathrm{reco}}(B^{\pm})} \cdot \frac{\epsilon(B^{\pm})}{\epsilon(B_c^{\pm})}.$$

Signal yield (N^{reco}) are extracted with a Extended 1D Unbinned Maximum Likelihood (UML) fit

Efficiency ϵ describes the detector effects, the trigger efficiency, π/K differences and the selection criteria

Differential production cross section in transverse momentum p_T and rapidity y bins:

- $13 < p_T(B) < 22$ GeV and $p_T(B) > 22$ GeV
- $|y(B)| < 0.75$ and $0.75 < |y(B)| < 2.3$

$B_c^{\pm}$ and $B^{\pm}$ signal yield extraction

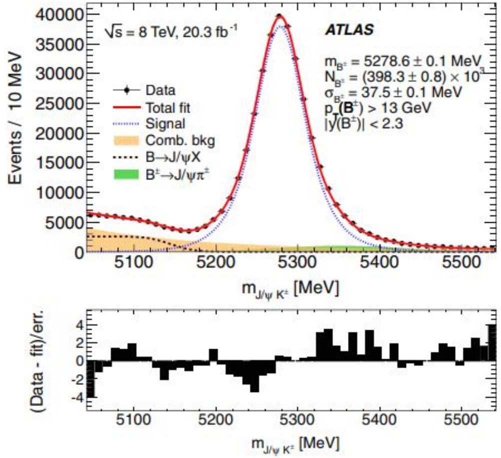
B^+ UML fit (top):

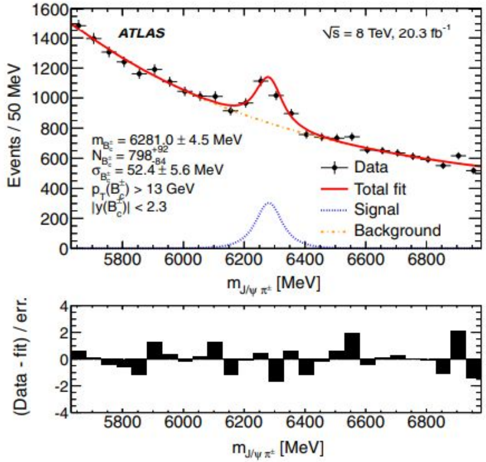
- Signal: Gaussian
- Background: falling exponential
- Partially reco'd decays: error function
- $B^{\pm} \rightarrow J/\psi\pi^{\pm}$ (Cabibbo-suppressed): Gaussian

B_c^+ UML fit (bottom):

- Signal: Gaussian
- Background: falling exponential

Analysis bin	Number of the $B^{\pm}$ candidates	Number of the $B_c^{\pm}$ candidates
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$	$(398.3 \pm 0.8) \times 10^3$	798^{+92}_{-84}
$13 < p_T(B) < 22$ GeV, $\lvert y(B)\rvert < 2.3$	$(207.6 \pm 0.6) \times 10^3$	417^{+68}_{-63}
$p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$	$(190.9 \pm 0.6) \times 10^3$	363^{+59}_{-56}
$p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$	$(147.9 \pm 0.5) \times 10^3$	319^{+57}_{-52}
$p_T(B) > 13$ GeV, $0.75 < \lvert y(B)\rvert < 2.3$	$(248.8 \pm 0.6) \times 10^3$	454^{+71}_{-66}





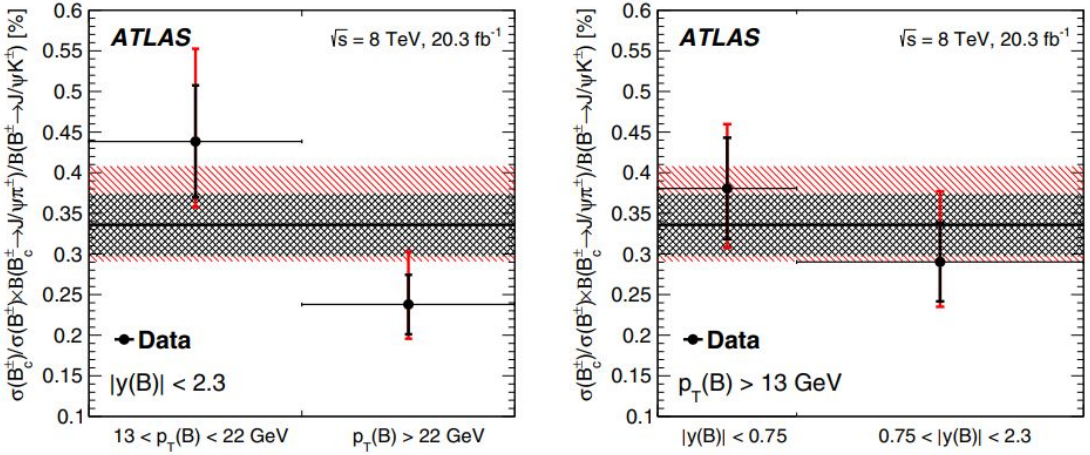
$B_c^{\pm}$ / $B^{\pm}$ production cross section

Relative total production cross section

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

Differential production cross section:

- decreasing with B meson transverse momentum
- no significant dependence on B meson rapidity



Points: result in p_T / y bins
Shaded area: result in the entire fiducial region

Black: statistical uncertainties
Red: systematic uncertainties

Comparison with other experiments

The result from ATLAS 8 TeV can be compared to previous results from:

- LHCb 7 TeV [PRL 114, 132001 (2015)]
- LHCb 8 TeV [PRL 109, 232001 (2012)]
- CMS 7 TeV [JHEP 01 (2015) 063]

Measurement	$p_T(B)$	$\|y(B)\|$	B_c^+/B^+ Ratio [%]
LHCb 8 TeV	< 20 GeV	$2.0 - 4.5$	$(0.683 \pm 0.018 \pm 0.009)$
CMS 7 TeV	> 15 GeV	< 1.6	$(0.48 \pm 0.05 \pm 0.03 \pm 0.05)$
ATLAS	$13 - 22$ GeV	< 2.3	$(0.44 \pm 0.07 \pm^{+0.09}_{-0.04} \pm 0.01)$
ATLAS	> 22 GeV	< 2.3	$(0.24 \pm 0.04 \pm^{+0.05}_{-0.01} \pm 0.01)$

LHCb fiducial region has slight overlap with ATLAS measurement and shows no p_T-dependence in the common phase-space region; but LHCb dataset is dominated by low-p_T B mesons ($p_T(B) > 4$ GeV)

ATLAS results are smaller if compared to CMS and LHCb and **p_T-dependence is shown for the first time**

$B_c^{\pm}$ production in PbPb collisions at CMS

B_c^+ meson observed for the first time in PbPb collisions via the $B_c^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\mu^+\nu_\mu$ (+ c.c) using 1.61 nb^{-1} of PbPb collisions data collected at **CMS** at $\sqrt{s_{NN}}$ = 5.02 TeV (2018)

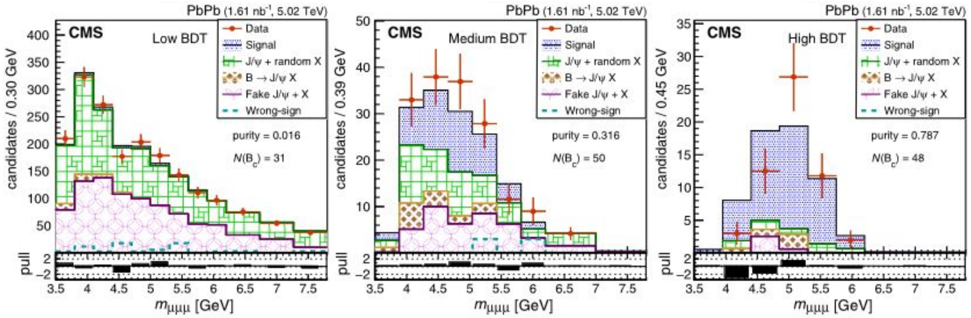
The result is compared to the measurement in pp collisions (302 pb^{-1} at $\sqrt{s}$ = 13 TeV collected in 2017)

Decay $B_c^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\mu^+\nu_\mu$: **large branching fraction** (pro), **only partially reconstructed** (con)

Source of fake candidates:

- **fake J/ψ**: neither of the two opposite-sign muons comes from a J/ψ
- **B hadrons**: true J/ψ from B hadron (not B_c) and third muon (or mis-id hadron) from the same B-jet
- **J/ψ + random X**: true J/ψ + uncorrelated muon (or mis-id hadron)

Boosted Decision Tree (BDT) trained to recognize signal and backgrounds



$B_c^{\pm}$ production in PbPb collisions at CMS

Low BDT candidates discarded (0.1% of signal)

Yields from 3μ fit corrected by signal acceptance and efficiency of reconstruction, trigger and selection

Differential results in $p_T^{\mu\mu\mu}$ and $y^{\mu\mu\mu}$ bins

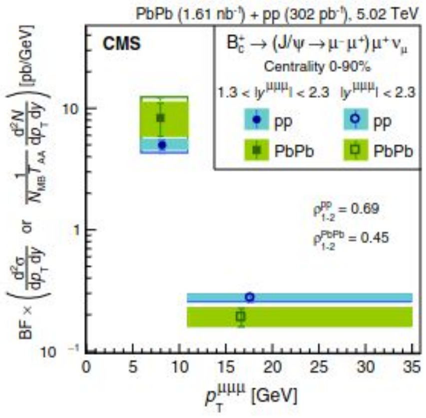
B_c significance >> 5σ; moderate suppression at high-$p_T^{\mu\mu\mu}$, but less relative suppression than in pp: *increased recombination?*

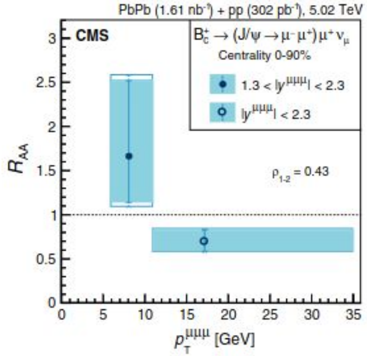
R_{AA} = f * yield(PbPb) / yield(pp), where f is defined so that R_{AA} = 1 implied no modification in the nuclear factor

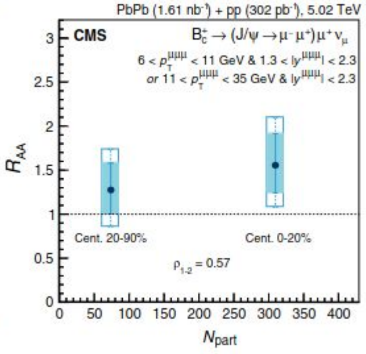
low-$p_T^{\mu\mu\mu}$ R_{AA} > 1 (1.2σ)   low-$p_T^{\mu\mu\mu}$ R_{AA} > high-$p_T^{\mu\mu\mu}$ R_{AA} (1.8σ)

No significant variation as a function of centrality

Other heavy mesons (except B^0_s) **show more suppression in similar p_T ranges** [discussed by G. Krintiras yesterday]

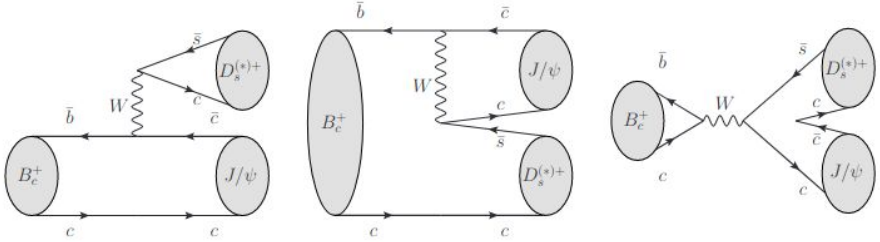






Study of $B_c \rightarrow J/\psi D_s^{(*)}$ decays at ATLAS

B_c meson can decay through **different mechanisms** (b decay, c decay, annihilation)



The **B_c decays** are reconstructed at **ATLAS** using 139 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV

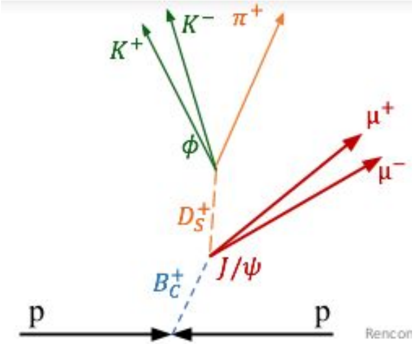
Previously observed in Run-1 by LHCb [PRD 87 (2013) 112012] and ATLAS [EPJC 76 (2016) 4]

A pseudoscalar meson decaying into two vector states is described with **three helicity amplitudes**: two transverse polarizations (**A_{++}, A_{--}**), and a longitudinal polarization (**A_{00}**)

The indices correspond to the helicities of the J/ψ and $D_s^{(*)+}$ mesons: the transverse polarizations are described by a single $A_{\pm\pm}$ component

$B_c \rightarrow J/\psi D_s^{(*)}$ decays reconstruction

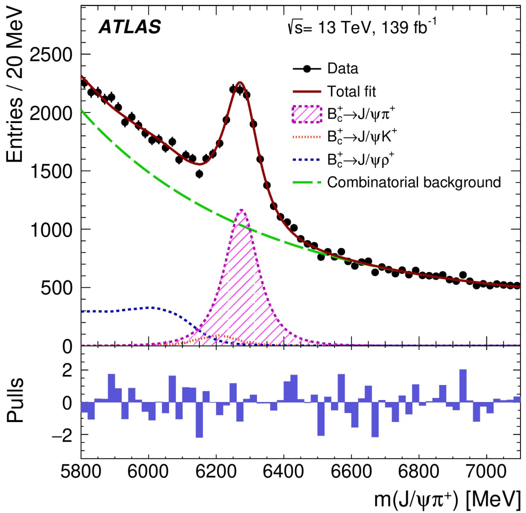
- **Decays' reconstruction:**
  - $J/\psi \rightarrow \mu^+\mu^-$
  - $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\,\pi^+$
  - $D_s^* \rightarrow D_s\pi^0/\gamma$ (soft, not reconstructed)
- **Fiducial region:**
  - $p_T(B_c) > 15$ GeV
  - $|\eta(B_c)| < 2.0$



$B_c^+ \rightarrow J/\psi\pi^+$ used as reference decay channel

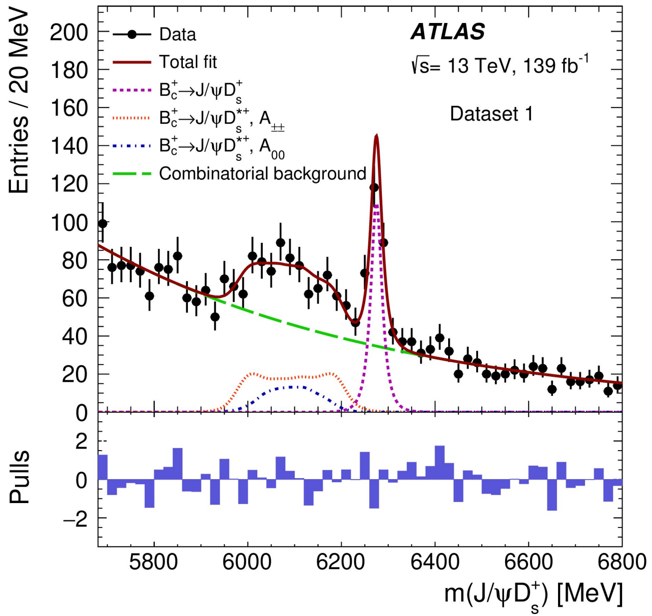
Signal yield for reference decay:

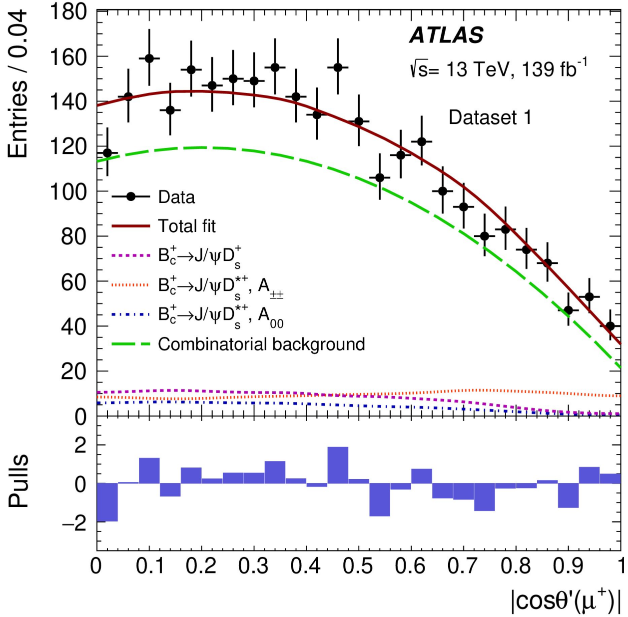
$$N(B_c^+ \rightarrow J/\psi\pi^+) = 8440^{+550}_{-470}$$



$B_c \rightarrow J/\psi D_s^{(*)}$ signal extraction

2D UML fit in $J/\psi D_s$ invariant mass $m(J/\psi D_s)$ and J/ψ helicity angle $\cos(\theta'(\mu^+))$





- $N(B_c \rightarrow J/\psi D_s^+) = 241 \pm 28$ (stat.)
- $N(B_c \rightarrow J/\psi D_s^*) = 424 \pm 46$ (stat.)

Results on the $B_c \to J/\psi D_s^{(*)}$ branching fraction ratios

The signal yields enter the ratios R after being corrected by an overall efficiency (from MC)

$$R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{N^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^{(*)+}}}{N_{B_c^+ \to J/\psi \pi^+}} \times \frac{\epsilon_{B_c^+ \to J/\psi \pi^+}}{\epsilon^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^{(*)+}}} \times \frac{1}{\mathcal{B}(D_s^+ \to \phi(K^+K^-)\pi^+)},$$

$$R_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} = \frac{N^{\mathrm{DS1\ 2}}_{B_c^+ \to J/\psi D_s^{*+}}}{N^{\mathrm{DS1\ 2}}_{B_c^+ \to J/\psi D_s^+}} \times \frac{\epsilon^{\mathrm{DS1\ 2}}_{B_c^+ \to J/\psi D_s^+}}{\epsilon^{\mathrm{DS1\ 2}}_{B_c^+ \to J/\psi D_s^{*+}}} = r_{D_s^{*+}/D_s^+} \times \frac{\epsilon^{\mathrm{DS1\ 2}}_{B_c^+ \to J/\psi D_s^+}}{\epsilon^{\mathrm{DS1\ 2}}_{B_c^+ \to J/\psi D_s^{*+}}}.$$

$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33 \pm 0.29 \pm 0.16$$

$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32,$$

$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24 \pm 0.09.$$

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10 \pm 0.04.$$

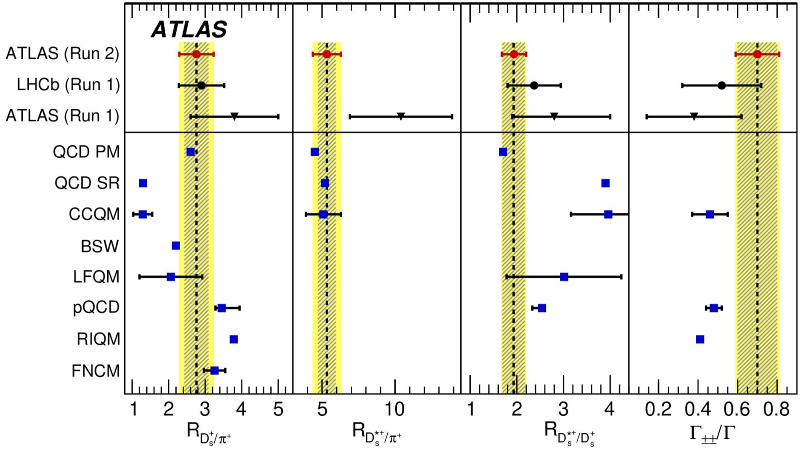
The branching fractions $R(D_s^{*+}/\pi)$, $R(D_s^{+}/\pi)$, $R(D_s^{*+}/D_s^{+})$ and the transverse polarization fraction $\Gamma_{\pm\pm}/\Gamma_{00}$ are measured

Measurements in agreement with previous ones, with improved precision

$R(D_s^{*+}/\pi)$ well described by predictions

Other predictions consistently deviate from data

$\Gamma_{\pm\pm}/(\Gamma_{00}+\Gamma_{\pm\pm})$ in agreement with naive ⅔ spin counting



Two B_c excited states at CMS

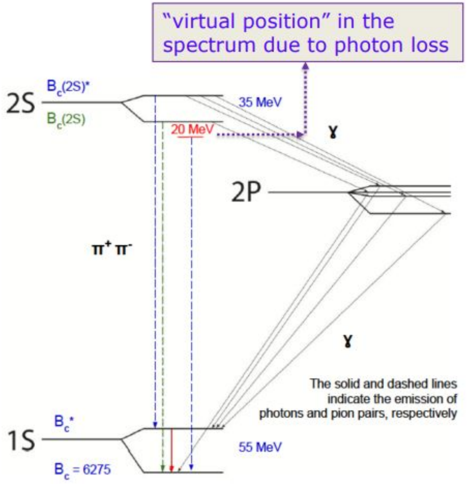
$B_c(2S)^+$ and $B_c^*(2S)^+$ states are observed at **CMS** using 143 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV (full Run-2)

They appear as **two well-resolved peaks** in the $B_c\pi^+\pi^-$ invariant mass

Previously observed as a single peak by ATLAS [PRL 113, 212004 (2014)]

$B_c^*(2S) \rightarrow B_c^*\pi^+\pi^-$ is followed by $B_c^* \rightarrow B_c + \gamma_{lost}$ (BF of 100% is assumed)

$E(\gamma) \simeq$ 55MeV (from NRQCD predictions): too soft to be detected



The (relative) **differential production cross sections** are measured in p_T and rapidity bins

Kinematical range: $p_T(B_c^+)$ > 15 GeV and $|y(B_c^+)|$ < 2.4

R^{*+}: relative cross section of $B_c^*(2S)^+$ to B_c^+
R^+: relative cross section of $B_c(2S)^+$ to B_c^+
R^{*+}/R^+: relative cross section of $B_c^*(2S)^+$ to $B_c(2S)^+$

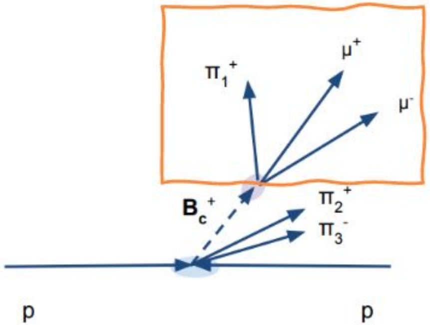
$$R^+ \equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)}\mathcal{B}(B_c(2S)^+ \rightarrow B_c^+\pi^+\pi^-) = \frac{N(B_c(2S)^+)}{N(B_c^+)}\frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)},$$

$$R^{*+} \equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)}\mathcal{B}(B_c^*(2S)^+ \rightarrow B_c^{*+}\pi^+\pi^-) = \frac{N(B_c^*(2S)^+)}{N(B_c^+)}\frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)},$$

$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)}\frac{\mathcal{B}(B_c^*(2S)^+ \rightarrow B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \rightarrow B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)}\frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

B_c Candidates' reconstruction

B_c (ground state) reconstructed in $B_c^+ \to J/\psi(\to \mu^+\mu^-)\pi^+$ (+ c.c), with the dimuon invariant mass kinematically constrained to the J/ψ mass (kinematic vertex fit)



$B_c(2S) \to B_c \pi^+ \pi^-$

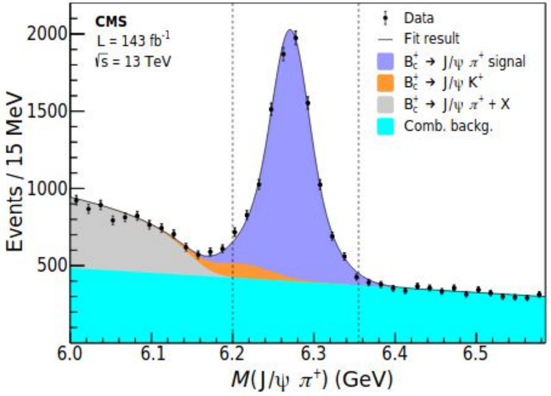
Details on event reconstruction in backup

B_c signal yield extracted with 1D UML fit

- **Signal**: weighted sum of two Gaussians with same mean
  - $w = 0.47$
  - $\sigma_1 = 21$ MeV
  - $\sigma_2 = 42$ MeV

$$\boxed{wG(\mu,\sigma_1) + (1-w)G(\mu,\sigma_2),}$$

- **Background**:
  - Combinatorial: Chebyshev polynomial
  - $J/\psi K^+$: shape from simulation
  - $J/\psi\pi^+ + X$: ARGUS function



$N(B_c) = 7629 \pm 225$ events

Selected mass window: 6.2 GeV < $m(B_c)$ < 6.355 GeV

$B_c(2S)$ and $B_c^*(2S)$ signal yields

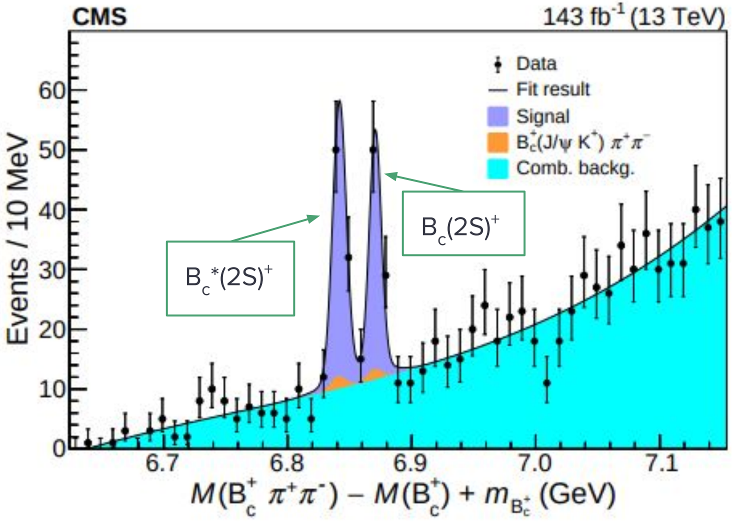
Two opposite-sign high-purity tracks (assumed to be pions) are combined with the reconstructed B_c candidate

UML fit on $B_c\pi^+\pi^-$ invariant mass distribution:

- **Signal**:
  - sum of two Gaussians
- **Background**:
  - Combinatorial: 3rd-order Chebyshev polynomial
  - $B_c^+ \to J/\psi K^+$ contribution: two Gaussians

$N(B_c^*(2S)^+)$ = 67 ± 10 events
$N(B_c(2S)^+)$ = 52 ± 9 events
ΔM = 28.9 ± 1.5 MeV

Yields enter the ratios once corrected by relative efficiencies (derived from MC studies)



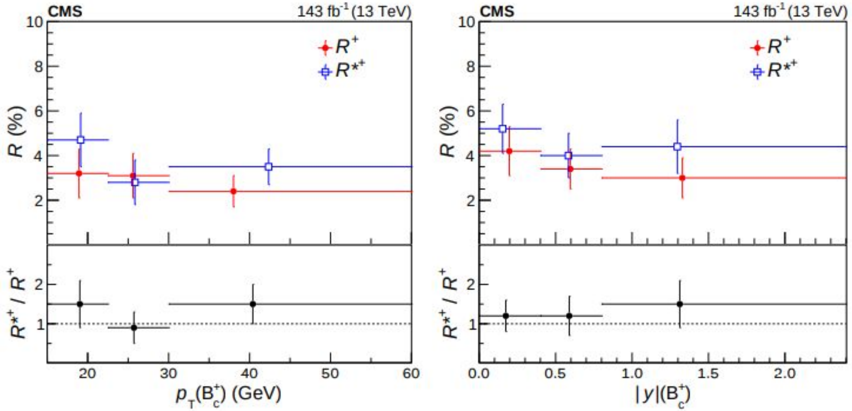
$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$
$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$

Details on systematics in backup

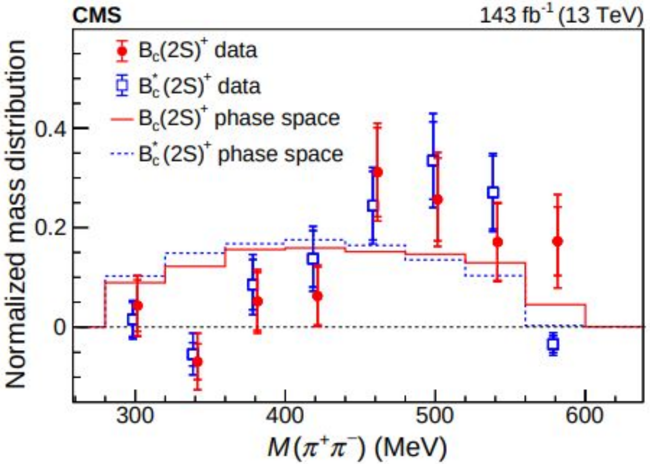
Differential cross section and dipion mass distribution

Different models [1] [2] bring to different predictions on the production ratios and the dipion system

No significant dependence of the cross section on transverse momentum and rapidity observed



Observed shapes for the invariant mass of the dipion system (with background subtraction) are consistent with each other and different from phase space, but the difference is not fully significant at the available level of statistics and uncertainties



[1] [Berezhnoy, A. V. et al. Mod. Phys. Lett. A34 (2019) 1950331]
[2] [E. Eichten, C. Quigg, PRD 99 (2019) 054025]

Conclusions

- **LHC provides high luminosity: heavy flavor production cross section several order of magnitudes greater than at e-e colliders**

- **The CMS and ATLAS experiments at the LHC, together with LHCb, are able to investigate different aspects of the B_c meson: B_c production, B_c decays and B_c spectroscopy**

- **Precise measurements of Physics parameters with larger statistics and in different collision environments (pp, PbPb, pPb) can rule out theoretical models and lead to further understanding of the Quantum Chromo-Dynamics and Heavy Flavour Physics**

THANKS FOR YOUR ATTENTION

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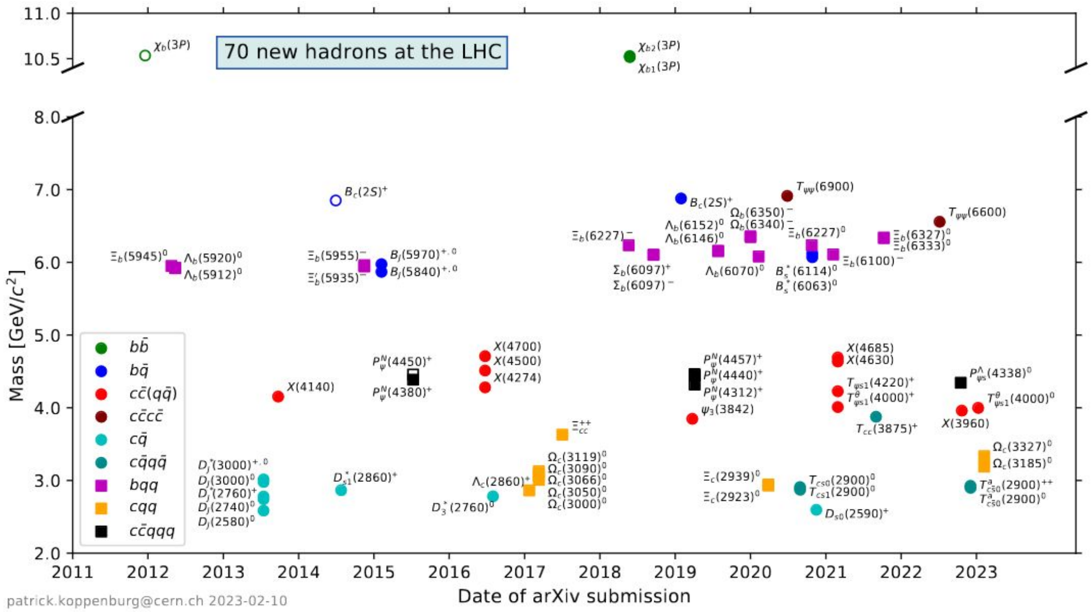
LHC provides high luminosity for heavy flavour physics processes

Heavy flavor production cross section several order of magnitudes greater than at e-e colliders,

but the hadron collisions environment is characterized by **complex initial state and high background**



70 new hadrons discovered at LHC since its start!
23 new exotics hadrons

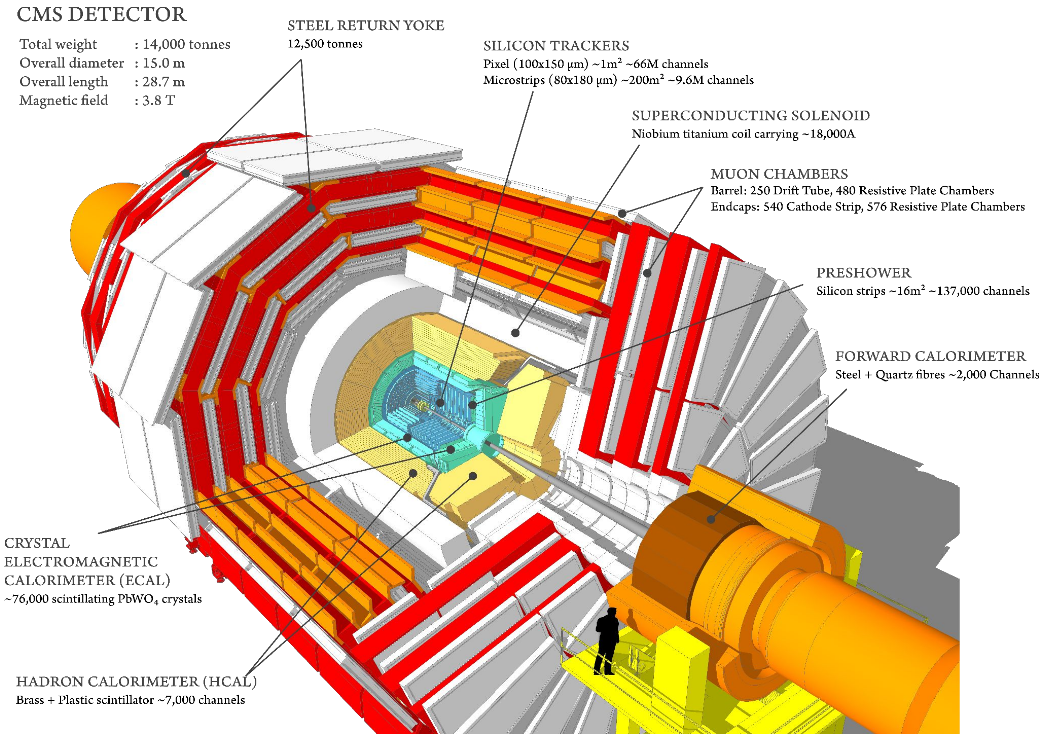
LHCb-FIGURE-2021-001, 2023 updated

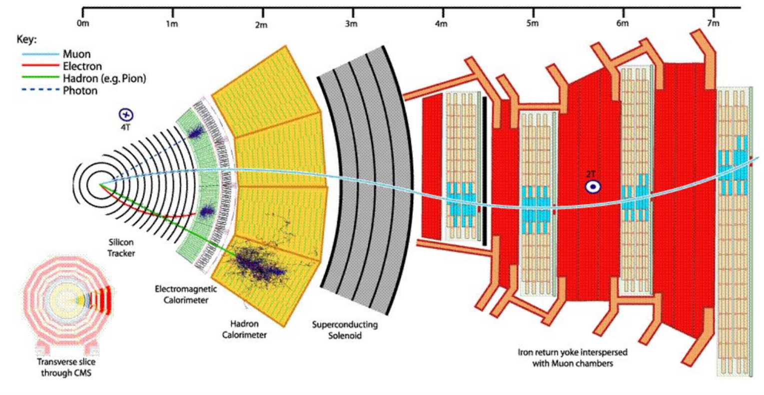
new naming scheme to navigate through this growing hadronic particle zoo proposed by PDG

PDG 2022

The CMS detector at the Large Hadron Collider

General purpose detector with **cylindrical symmetry** and (almost) **full coverage of the solid angle**





Strengths:

- muon reconstruction and identification
- large muons' acceptance
- high-performance tracking & vertexing

BDT results:

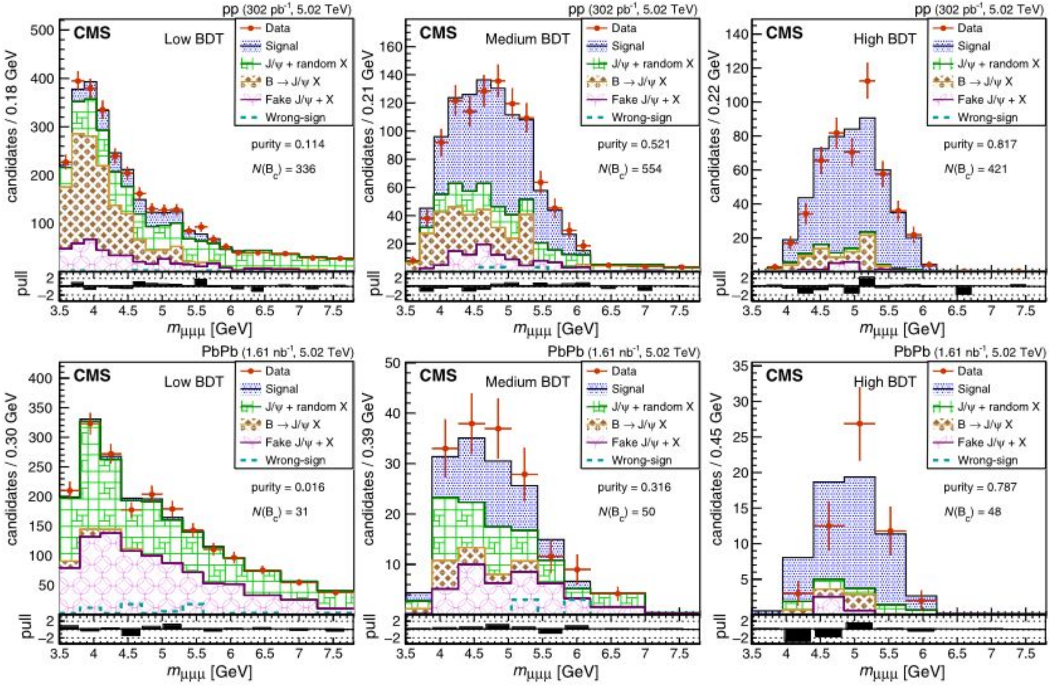


FIG. 1. Template fit of the trimuon mass distributions in the three BDT bins, for the pp (top row) and Pb-Pb (bottom row) data samples integrated over the two studied kinematic regions. The lower panels show the pull between the data and the fitted distributions.

$B_c^{\pm}$ production in PbPb collisions at CMS

R_{AA} for different heavy mesons

From MC: B_c visible p_T 15% smaller than total p_T

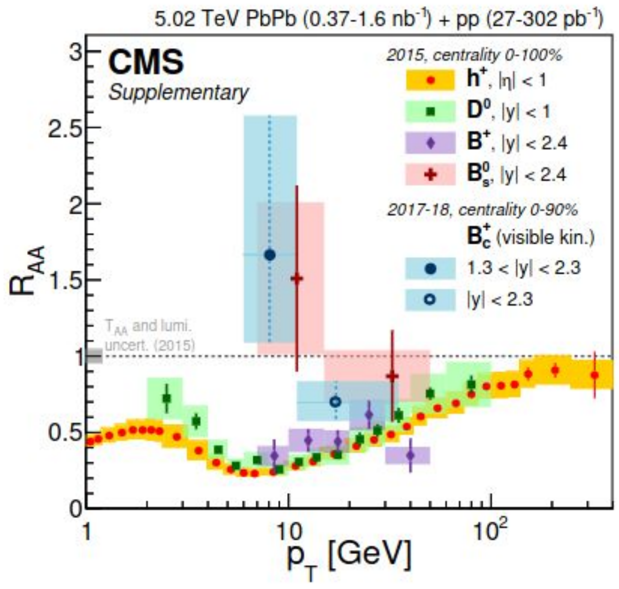


FIG. 1. Nuclear modification factor of the B_c^+ meson compared to that of light charged hadrons, and B^+, B_s and D^0 mesons, as a function of the measured transverse momentum. The total uncertainty is shown for the B_c^+ meson, whereas the statistical (bars) and systematic (filled rectangles) uncertainties are shown for the other hadrons.

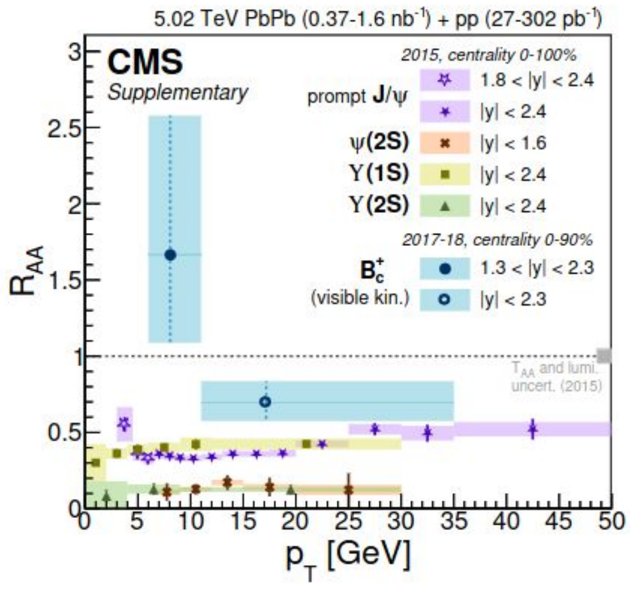


FIG. 2. Nuclear modification factor of the B_c^+ meson compared to that of the ground and first excited states of charmonia and bottomonia, as a function of the measured transverse momentum. The total uncertainty is shown for the B_c^+ meson, whereas the statistical (bars) and systematic (filled rectangles) uncertainties are shown for the other hadrons.

$B_c(2S)$: hyperfine structure

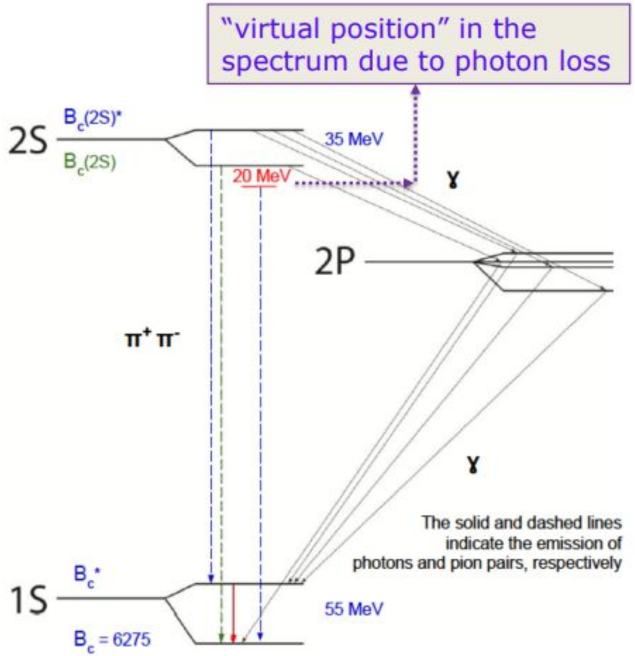
$B_c^*(2S) \rightarrow B_c^* \pi^+ \pi^-$ followed by **$B_c^* \rightarrow B_c \gamma_{lost}$**

Soft photon (55 MeV in the rest frame) not detected, we end up seeing
$B_c^*(2S) \rightarrow B_c \pi^+ \pi^-$ plus "missing energy"
Same final state as $B_c(2S) \rightarrow B_c \pi^+ \pi^-$

A two-peak structure in the Bc $\pi^+ \pi^-$ mass distribution is expected,
with the $B_c(2S)^*$ peak at a mass shifted by
$\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c^*(2S)) - M(B_c(2S)]$
which is predicted to be around 20 MeV.

The two-peak can be appreciated only if ΔM value is larger than experimental resolution!

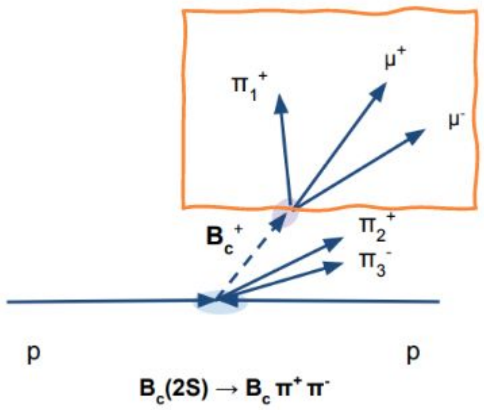
Predictions indicate:
$[M(B_c^*(1S)) - M(B_c(1S))] > [M(B_c^*(2S)) - M(B_c(2S)]$
that would imply that the
$B_c^*(2S)$ peak is the lower peak!



B_c(2S): event selection

HLT Requirements (DoubleMu4_JpsiTrk_displaced):

- OS muon pair in [2.9, 3.3] GeV
- dimuon vertex χ^2 probability > 10%
- distance of closest approach between muons < 0.5 cm
- significance(flight distance) > 3
- $p_T(\mu) > 4$ GeV && $|\eta(\mu)| < 2.5$
- cos(dimuon_transverse_pointing_angle) > 0.9 (*)
- third track (from $\mu\mu$-vtx, $p_T > 1.2$ GeV, $\eta < 2.5$, sip > 2)



Offline requirements:

- Muons matching trigger muons
- High quality muons
- $|\eta(\mu)| < 2.4$ and cos(dimuon_transverse_pointing_angle) > 0.98 (*)
- muons close in angular space: $(\Delta\eta)^2 + (\Delta\phi)^2 < 1.2^2$

Integrated Luminosity per year: 2.8, 36.1, 42.1, 61.6 fb^{-1}

(*) cosine of the angle formed by the flight direction and the momentum in the transverse plane

B_c reconstruction

B_c candidates fit

$$wG(\mu,\sigma_1) + (1-w)G(\mu,\sigma_2),$$

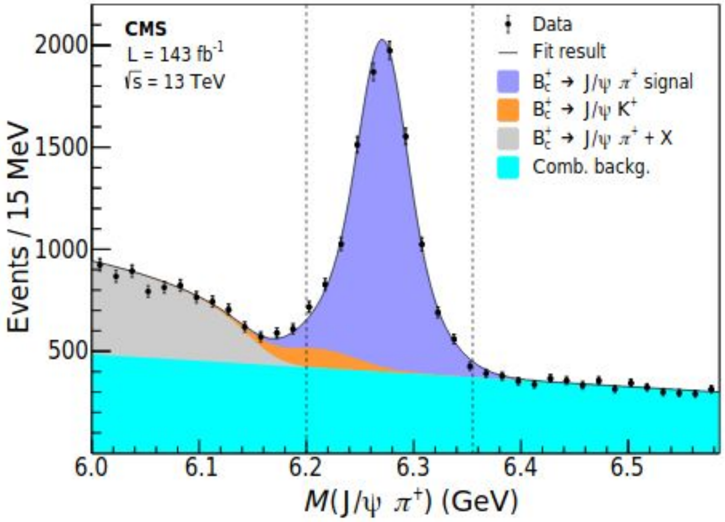
Signal: weighted sum of two gaussians with same mean

$w = 0.47$ $\sigma_1 = 21$ MeV $\sigma_2 = 42$ MeV

Background:

- Combinatorial: Chebychev polynomial
- $J/\psi K$: shape from simulation
- $J/\psi\pi + X$: ARGUS function

$N(B_c) = 7629 +/- 225$ events



$B_c(2S)$ cross section ratios

Reconstruction efficiencies (MC studies):
- statistical: finite size of simulated events
- dispersion: average over four years
- pions: π reconstruction efficiency

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

Systematic uncertainties:
- from signal yield
  (evaluated with different fit models)
- from efficiency
- from correlations in di-pion kinematics

	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

Results:

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