22nd Particles and Nuclei International Conference

CP violation and HF production results from ATLAS and CMS

Federica Simone[1] on behalf of the CMS Collaboration

[1] Università & INFN Bari

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CP violation in B_s^0 decays

Measurement of the CP violating phase ϕ_s in the $B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$ channel

- Results from pp collisions at $\sqrt{s} = 13\,TeV$ ($\mathcal{L} = 96.4 fb^{-1}$) and combination with 8 TeV result at **CMS**: *Phys. Lett. B* **816** (2021) 136188
- Results from pp collisions at $\sqrt{s} = 13\,TeV$ ($\mathcal{L} = 80.5 fb^{-1}$) and combination with 8 TeV result at **ATLAS**: *Eur. Phys. J. C* **81,** 342 (2021)

Physics of B_c^+ mesons

- **CMS:** Relative cross sections of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states with respect to the B_c^+ [*Phys. Rev. D* **102**, 092007 (2020)]
- **CMS**: Observation of the B_c^+ meson in PbPb and pp collisions at $\sqrt{s} = 5.02$ TeV [CMS-PAS-HIN-20-004]
- **ATLAS:** Measurement of the relative $B_c^\pm/B^\pm$ production cross sections at $\sqrt{s} = 8\,TeV$ [*Phys. Rev. D* **104**, 012010]
- **ATLAS**: Study of the $B_c^+ \to J/\psi\, D_s^+$ and $B_c^+ \to J/\psi\, D_s^{*+}$ decays in pp collisions at $\sqrt{s} = 13\,TeV$ [ATLAS-CONF-2021-046]

More details in talk by S. Turchikhin

CP violation in B_s^0 decays

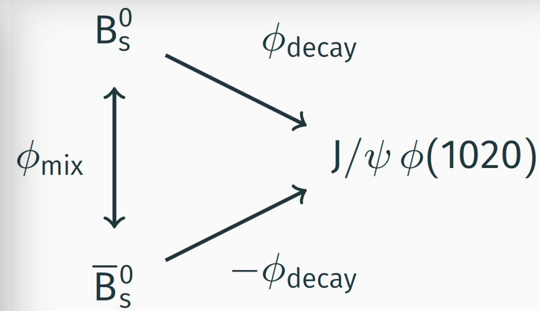
CP violating phase ϕ_s arises from the interference between direct decays to a CP final state and decays through mixing to the same final state ($B_s^0 - \bar{B}_s^0$)

SM prediction:

$$\phi_s \simeq -2\beta_s = -2arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.96^{+0.72}_{-0.84}\ \text{mrad}$$

New physics:

new particles contributing to the $B_s^0 - \bar{B}_s^0$ mixing can change the value of ϕ_s up to -10% [JHEP04(2010)031]



$$\phi_s = \phi_{mix} - 2\phi_{decay}$$

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$ is a good channel to measure ϕ_s phase:

- No direct CPV
- Only one CPV phase
- Easy to reconstruct with high S/B ratio

State-of-the-art: Agreement with SM, but exp. sensitivity ~ 25× theory

- 13 TeV results: LHCb [arXiv:1906.08356]
- Previous result at 8 TeV by CMS [*PLB 757 (2016), 424*] and ATLAS [*JHEP 08 (2016) 147*]

CMS $\sqrt{s} = 13\ TeV$ ($\mathcal{L} = 96.4 fb^{-1}$): *Phys. Lett. B* **816** (2021) 136188

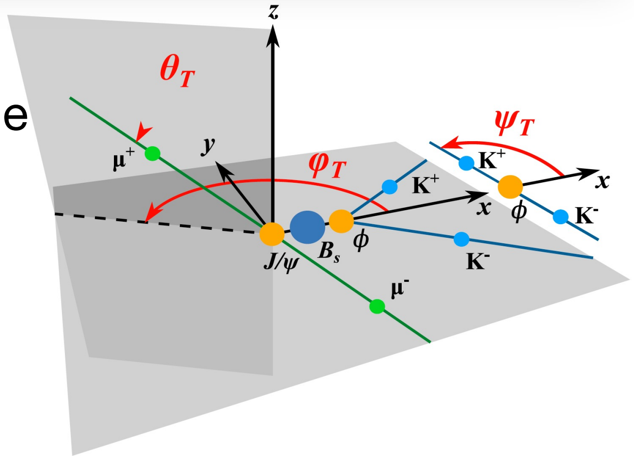
ATLAS $\sqrt{s} = 13\ TeV$ ($\mathcal{L} = 80.5 fb^{-1}$) *Eur. Phys. J. C* **81,** 342 (2021)

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: angular analysis

Final states are **mixtures of CP eigenstates** → require a **time-dependent angular analysis** to disentangle the CP-odd and CP-even components.

Analysis strategy:

An unbinned maximum-likelihood fit is performed on the combined data samples extracting parameters of interest:



- CPV phase ϕ_s
- $\Delta m_s(\Delta\Gamma_s)$ absolute mass (decay width) difference

between the B_S^H and B_S^L mass eigenstates, $\Gamma_s = \frac{\Gamma_L+\Gamma_H}{2}$

- The size of the CP-state amplitudes at t = 0: $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $|A_\perp(0)|^2$, $|A_S(0)|^2$ with $|A_0(0)|^2 + |A_\parallel(0)|^2 + |A_\perp(0)|^2 = 1$

ATLAS CMS

- The strong phases $\delta_\parallel$, $\delta_\perp$, $\delta_{S\perp} = \delta_S - \delta_\perp$

The likelihood function depends on:

- Base observable: ct (B_S^0 proper decay time), m, angular var. (ψ_T, θ_T, φ_T),
- Per-candidate quantities: resolutions, **flavor tagging** probability and method

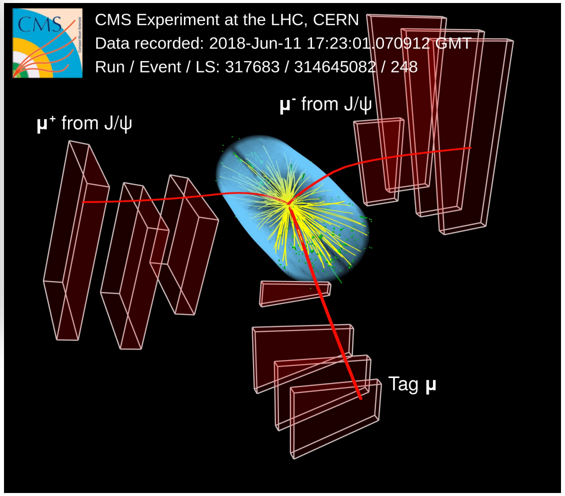
$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: event selection

Trigger strategy:

ATLAS: $J/\psi \to \mu^+\mu^-$ candidate

CMS: J/ψ + additional muon used to tag the B_s^0 flavour

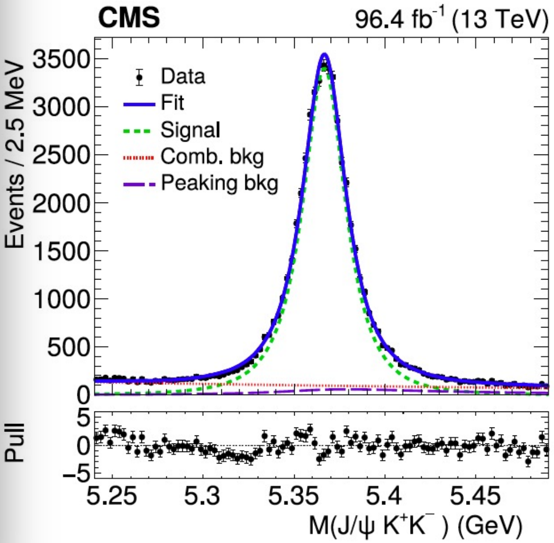
- allows for improved tagging efficiency at the cost of reduced number of signal events

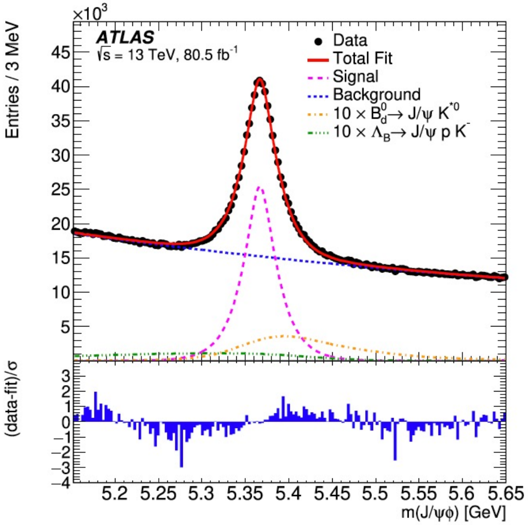


Offline selections:

CMS and ATLAS analyses have similar kinematic cuts

- J/ψ reconstructed from $\mu^+\mu^-$, good common vertex.
- ϕ formed from pairs of OS tracks with invariant mass compatible with $\phi(1020)$ meson mass (kaon mass assumed for both tracks)
- B_s from combination of J/ψ and $\phi(1020)$ candidates with refitted 2μ + 2tracks common vertex



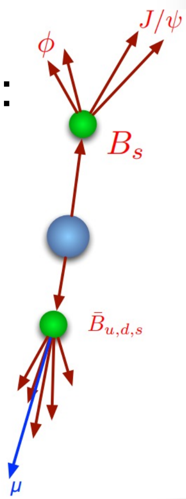


$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: flavour tagging

Identify the flavour of B_s^0 from $\bar{B}_s^0$: Opposite Side Tagging (OST)
tag the flavour of the opposite side b (in $b\bar{b}$ event) based on charge information

CMS:
Exploits the semileptonic $\mathrm{b} \to \mu + X$, the μ charge is the tagging variable

DNN trained on MC $B_s^0 \to J/\psi\phi$:
- to **define tag muons**
- to **evaluate per-event mistag probability**
- **calibrated in data** using $B^\pm \to J/\psi K^\pm$ self-tagging decays



Data sample	ε_{tag} (%)	ω_{tag} (%)	P_{tag} (%)
2017	45.7 ± 0.1	27.1 ± 0.1	9.6 ± 0.1
2018	50.9 ± 0.1	27.3 ± 0.1	10.5 ± 0.1

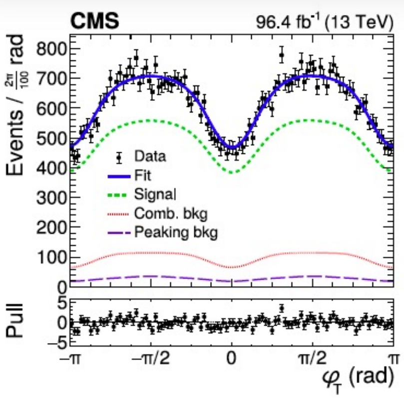
ATLAS:
Different OST methods used:
- Semileptonic
  - *b* → *l* transitions: clean tagging
  - *b* → *c* → *l* and neutral B-meson oscillations: dilute the tagging results
- Jet-Charge
  - Info from tracks in b-tagged jets
- **Calibration** using $B^\pm \to J/\psi K^\pm$ self-tagging decays

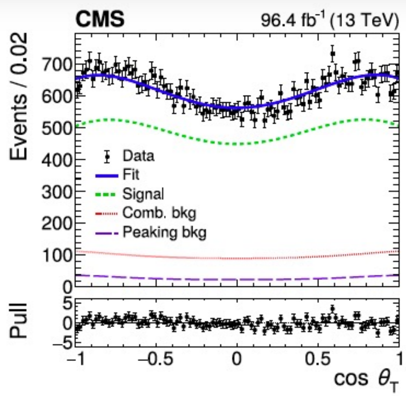
Tag method	ϵ_x (%)	D_x (%)	T_x (%)
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

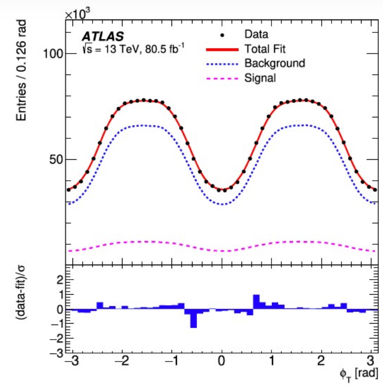
$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: fit

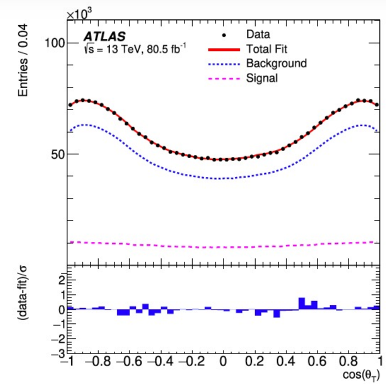
Unbinned maximum-likelihood fit:

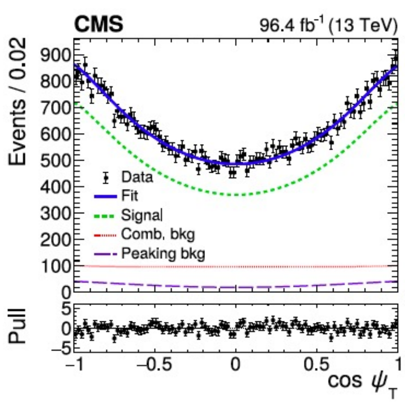
- Performed including the information on the B_s^0 inv. mass*, the three decay angles, the flavour tag decision, the mistag fraction, the proper decay length $ct(B_s^0)$ and its uncertainty.
- Likelihood function: components describing the sig. and bkg contributions (combinatorial and peaking bkg, dominated by $B^0 \to J/\psi K(892)^0 \to \mu^+\mu^-K^+\pi^-$)

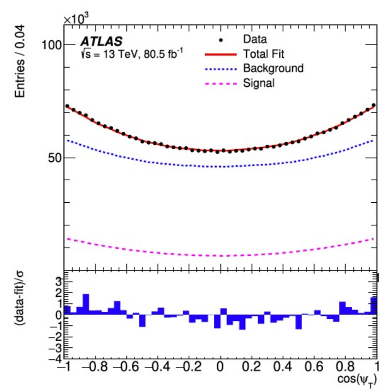












* [in ATLAS analysis] B_s^0 inv. mass uncertainty also used

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: results

CMS:

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0048
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0044
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.04
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

ATLAS:

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_\parallel(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	-0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

Systematic uncertainties

Extensive studies by both experiments, here the most relevant sources

CMS:

- Flavour tagging
- Fit bias
- Background angles model
- Best candidate selection
- Angular acceptance method

ATLAS:

- Model bias
- Angular efficiency
- Proper decay length resolution:
- Sig./bkg. ω_{tag} difference

Physics of B_c^+ mesons: motivations

The pseudoscalar $B_c^+(B_c^-)$ meson:

- ground state of the $\bar{b}c$ $(b\bar{c})$ system
- lightest particle containing two heavy quarks of different flavors
- unique laboratory to study heavy-quark dynamics
- much less explored compared to quarkonia due to the small production rate
- testing ground for effective models inspired by QCD

Excited B_c^+ states:

- decay to the ground state via the cascade emission of photons or pion pairs
- contribute significantly to heavy meson spectroscopy
- provide a rich source of information on the nonperturbative QCD

✓ **CMS:** Relative cross sections of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states with respect to the B_c^+ [*Phys. Rev. D* **102**, 092007 (2020)]

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✓ **ATLAS**: Study of the $B_c^+ \to J/\psi\, D_s^+$ and $B_c^+ \to J/\psi\, D_s^{*+}$ decays in pp collisions at $\sqrt{s} = 13\, TeV$ [ATLAS-CONF-2021-046]

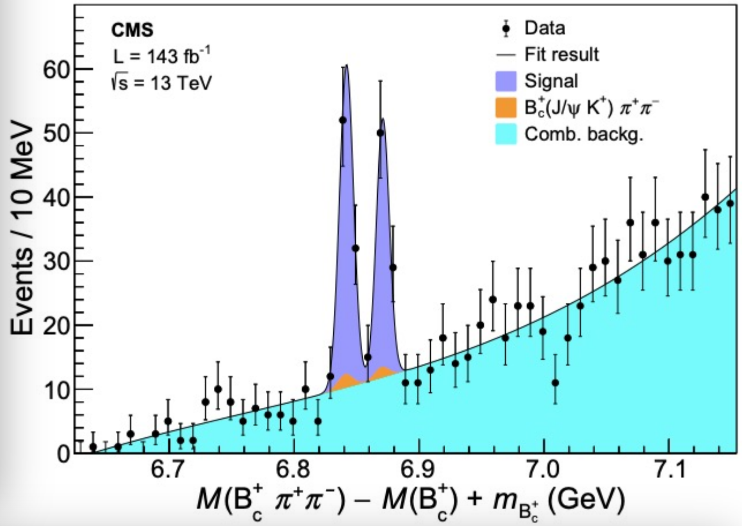
Cross section of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states at CMS

Observation of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states:

- $B_c^*(2S)^+ \rightarrow B_c^{*+}\pi^+\pi^-$ followed by $B_c^{*+} \rightarrow B_C\gamma_{lost}$, so observed decay is: $\boldsymbol{B_c^*(2S)^+ \rightarrow B_c^+\pi^+\pi^-}$ + ***missing energy***
- Same final state as $\boldsymbol{B_c(2S)^+ \rightarrow B_c^+\pi^+\pi^-}$

- Results recently published by CMS
- ATLAS observation at 8 TeV [Phys. Rev. Lett. 113, 212004 (2014)]

[Phys. Rev. Lett. 122 (2019) 132001]



Measurement of the relative cross sections:

- After $B_c(2S)^+$ and $B_c^*(2S)^+$ observations: further theoretical studies for understanding their properties [Phys.Rev. D99 (2019) 054025] [Mod.Phys.Lett. A34 (2019) 1950331]
- To test theoretical calculations:
  - relative production ratios of the two observed states
  - relative production ratio with respect to the base state

Results from pp collisions at $\sqrt{s} = 13\ TeV$ ($\mathcal{L}_{2015-18} = 143 fb^{-1}$) at CMS in the phase space $p_T(B_c^+) > 15 GeV$ and $|\eta| < 2.4$ [*Phys. Rev. D* **102**, 092007 (2020)]

Cross section of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states at CMS

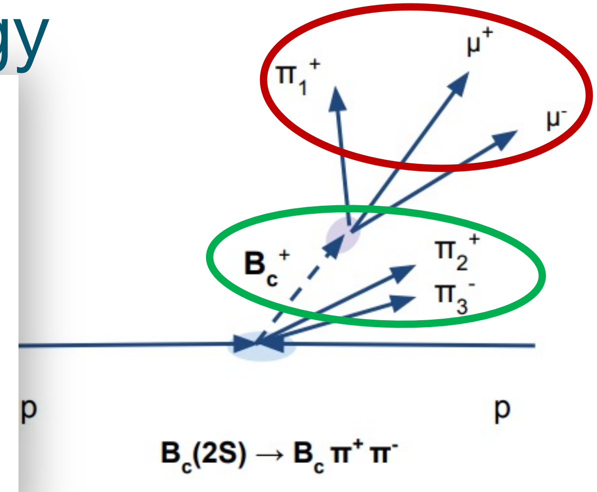
Reconstruction strategy

Reconstruction of B_c^+ candidates from $\mu\mu\pi$ final state:

- 2 OS muons with inv. mass within [2.9; 3.3] GeV and common displaced vertex
- B_c^+ candidate $p_T(B_c^+) > 15GeV$ and $|\eta| < 2.4$

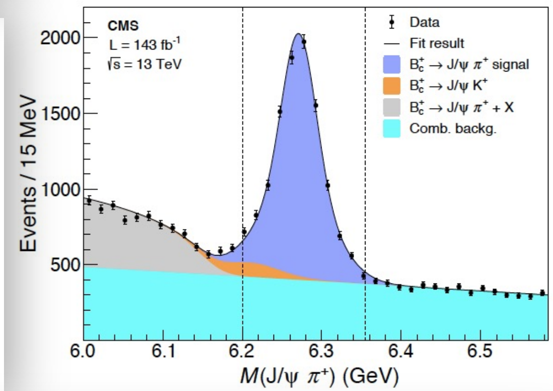
$B_c(2S)^+$ and $B_c^*(2S)^+$ states:

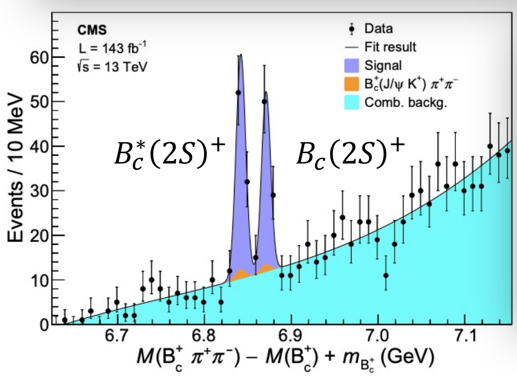
- combine 2 OS tracks with the B_c^+ candidate requiring common vertex
- $\boldsymbol{B_c^+\pi^+\pi^-}$ invariant mass within [6.2; 6.335] GeV
- If more than one candidate → highest p_T



B_c^+ signal yields from $\mu\mu\pi$ invariant mass spectrum:

- **signal**: double gaussian with common mean
- **background**: sum of 3 contributions
  - Uncorrelated J/ψ + track combination (first order polynomial)
  - Partially reconstructed $B_c^+ \to J/\psi\pi^+X$ (ARGUS function)
  - $B_c^+ \to J/\psi K^+$ contribution (shape from simulation and normalized to $B_c^+ \to J/\psi\pi^+$ signal yield, scaled by ratio of B.R. and reco efficiencies)





$B_c(2S)^+$ and $B_c^*(2S)^+$ signal yields from $B_c^+\pi^+\pi^-$:

- **signal**: two independent gaussians
- **background**: sum of 2 contributions
  - Continuum background (Chebyshev polynomial)
  - $B_c^+ \to J/\psi K^+$ contribution (shape from simulation)

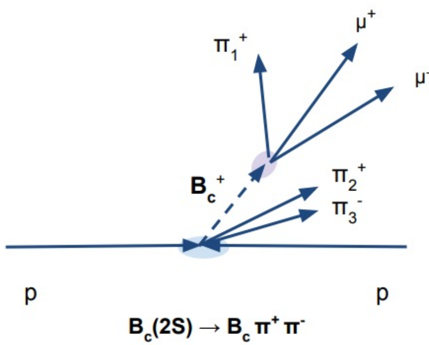
Cross section of the $\mathrm{B_c(2S)^+}$ and $\mathrm{B_c^*(2S)^+}$ states at CMS: results

Determination of the cross section ratios

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

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

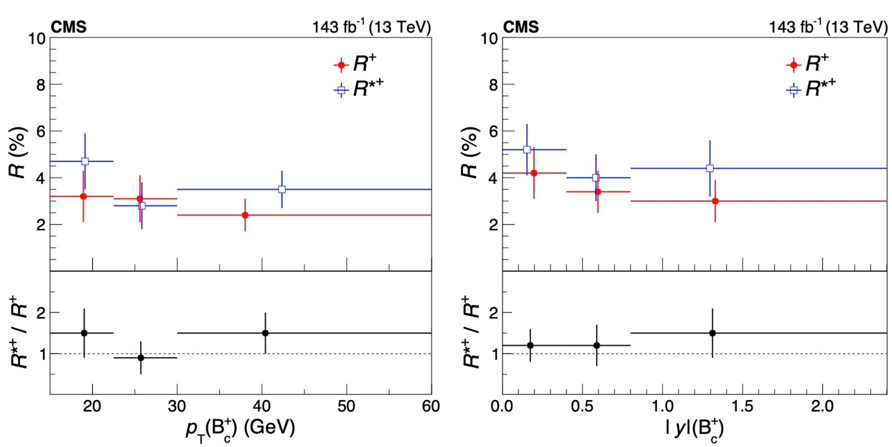
$$R^{*+}/R^+ = \frac{\sigma(\mathrm{B_c^*(2S)^+})}{\sigma(\mathrm{B_c(2S)^+})}\,\frac{\mathcal{B}(\mathrm{B_c^*(2S)^+} \to \mathrm{B_c^{*+}}\pi^+\pi^-)}{\mathcal{B}(\mathrm{B_c(2S)^+} \to \mathrm{B_c^+}\pi^+\pi^-)} = \frac{N(\mathrm{B_c^*(2S)^+})}{N(\mathrm{B_c(2S)^+})}\,\frac{\epsilon(\mathrm{B_c(2S)^+})}{\epsilon(\mathrm{B_c^*(2S)^+})}.$$



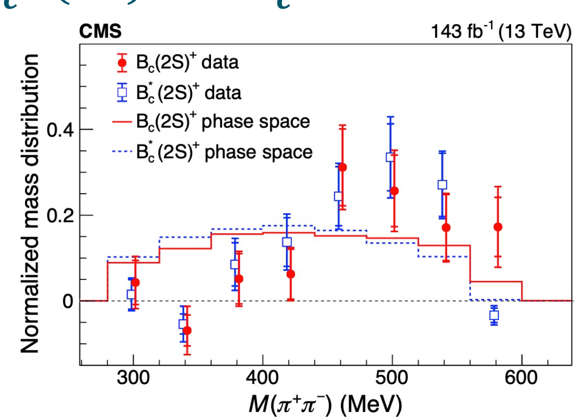
- The decay $B_c^{*+} \to B_c^+\gamma$ has not been measured yet because the photon is too soft to be detected (branching fraction assumed to be 100%)
- Yield ratios corrected by the corresponding recontruction efficiencies ratios

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

Dependence on the B_c^+ kinematics:



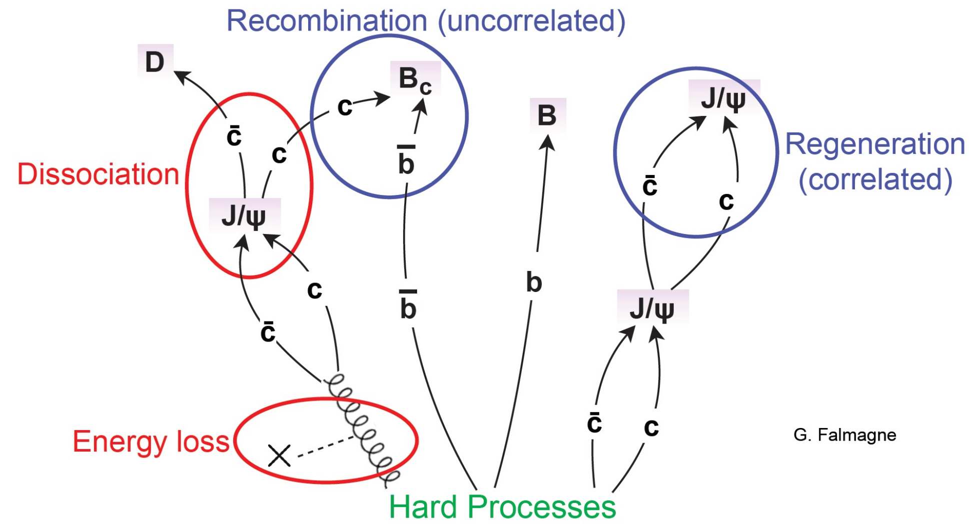
Dipion invariant mass from $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays



CMS: First observation of the B_c^+ meson in PbPb collisions

- Dissociation: binding energy between that of J/ψ and $\Upsilon(1S)$
- Recombination of b with uncorrelated c quark? Small $\sigma_{pp}^{B_c}$ → enhancement at $p_T < m_{B_c}$ could be dramatic !
- Partonic energy loss: Mass and color-charge dependence?

B_c = bridge between $c\bar{c}$ and $b\bar{b}$ and between open charm and open beauty



The B_c^+ was first observed in pp collisions in the $B_c^+ \to J/\psi \ell^+ \nu_\ell$ channel at the Tevatron, then at the LHC by ATLAS, LHCb and CMS

[NEW] First observation of the B_c^+ meson in heavy ions collisions

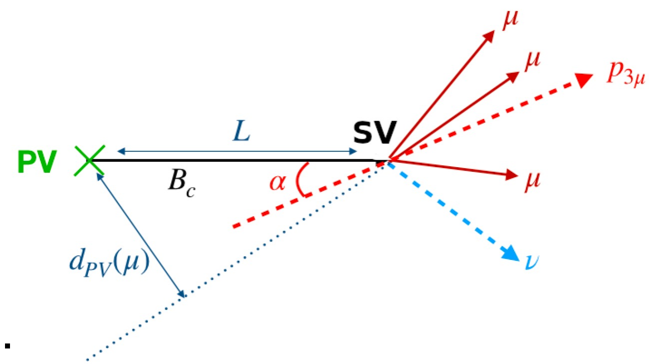
[CMS-PAS-HIN-20-004]

- $\sqrt{s} = 5.02$ TeV, integrated luminosity of 302 pb^{-1} (pp coll.) and 1.61 nb–1 (PbPb)
- partially reconstructed $B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+ \, \nu_\mu$ decay channel
- results in two p_T(μμμ), y(μμμ) bins:
  - $6 < p_T^{\mu\mu\mu} < 11 \; GeV \; and \; 1.3 < |y^{\mu\mu\mu}| < 2.3$
  - $11 < p_T^{\mu\mu\mu} < 35 \; GeV \; and \; |y^{\mu\mu\mu}| < 2.3$

CMS: First observation of the B_c^+ meson in PbPb collisions

Selection

- Dimuon trigger
- 3 μ from displaced vertex, OS(μμ) to reconstruct J/ψ
- m(μμμ) corrected by $p_T(\nu_\mu)$



Sources of background:

1. *Fake J/ψ*: estimated from data in μμ mass sidebands.
2. *J/ψ from B decays* + muon (misid. hadron) from same vtx: estimated via simulation
3. True J/ψ + random muon: estimated from data by rotating J/ψ candidates before associating them with the third muon candidates.

BDT training: kinematic variables, signal MC vs 3 background categories → **signal and background template fits**

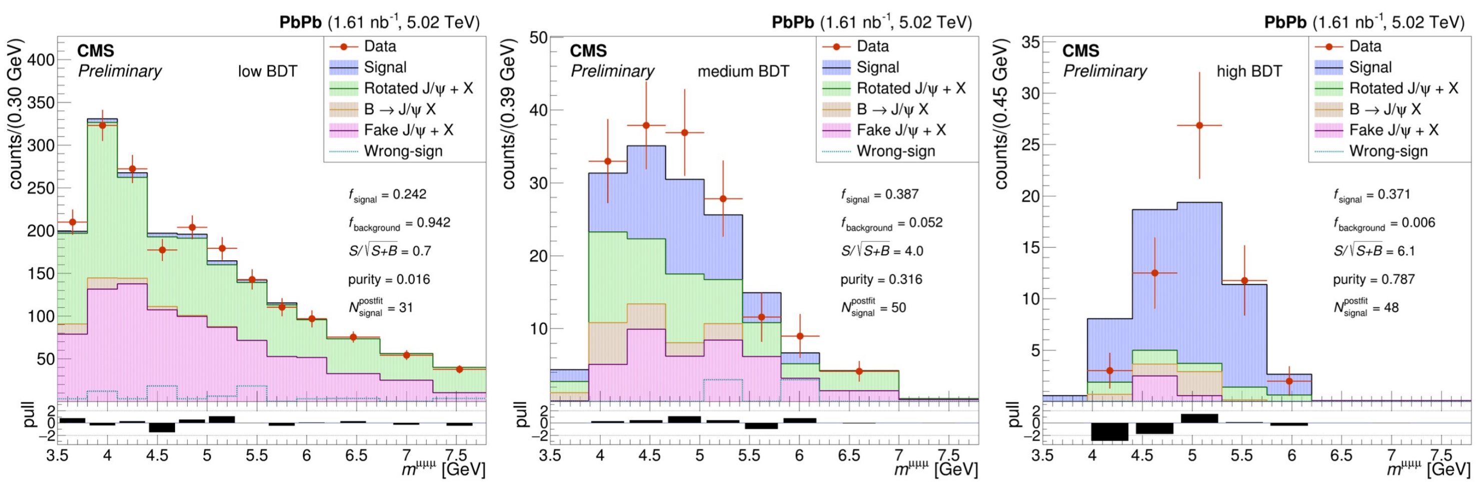


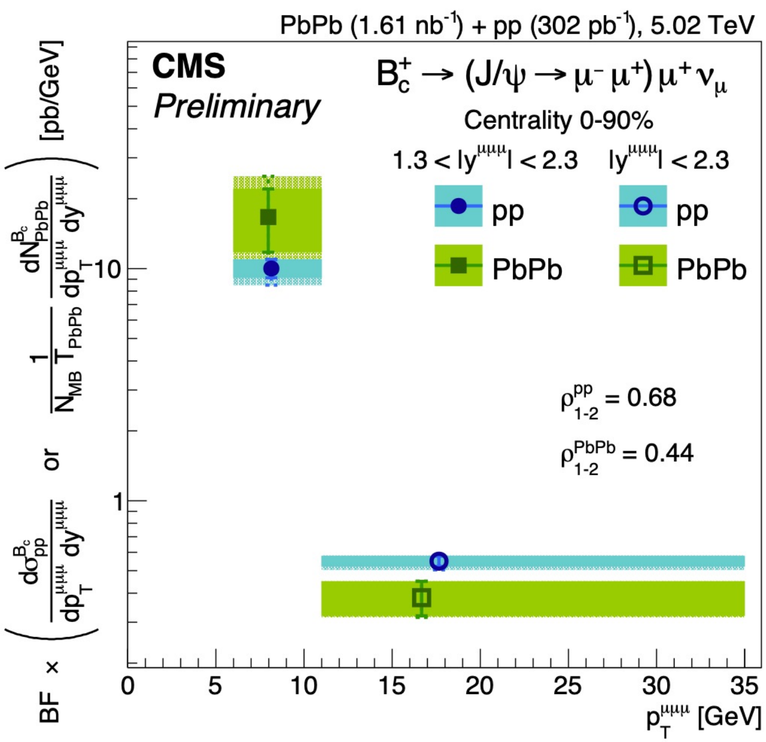
Figure 2: Template fit of the trimuon mass distributions in the three BDT bins, for the PbPb data sample integrated over the two studied kinematic regions. The lower panels show the pull between data and the fitted distributions.

CMS: First observation of the B_c^+ meson in PbPb collisions

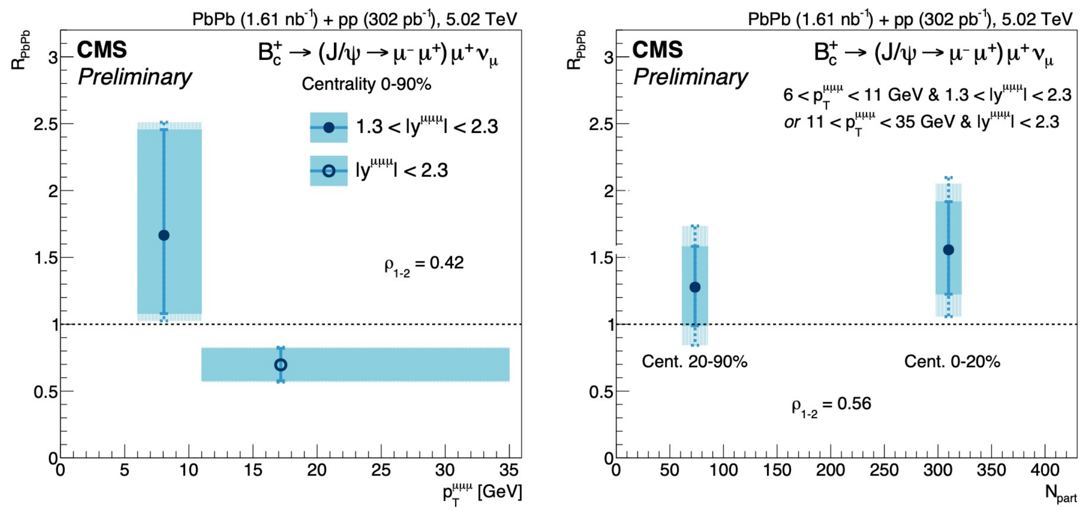
Yields correction and uncertainties:

- Signal yield corrected for acceptance and efficiencies (reco., trigger, selection)
- Single-μ id and trigger eff. from tag-and-probe
- Main sources of uncertainties: *statistical*, *background* (shapes and normalizations), choice of the *fit method*, *muon efficiency*, B_c^+ *kinematics* (acceptance and efficiency), *contamination* from other B_c^+ decays, and overall *normalization*.

Results



B_c^+ meson $p_{\mu\mu\mu}$-differential pp-equivalent cross sections in pp and PbPb collisions



B_c^+ nuclear modification factor, R_{PbPb}, *i.e.* the ratio of the (pp-equivalent) PbPb to the pp cross sections

Relative $B_c^{\pm}/B^{\pm}$ production cross sections at ATLAS (1)

B_c^+ is the only known weakly decaying particle made of two heavy quarks
- test of the QCD prediction;
- important input for heavy quark production models;

Complements CMS [J. HEP 01 (2015) 063] and LHCb [Phys. Rev. Lett. 114, 132001] measurements

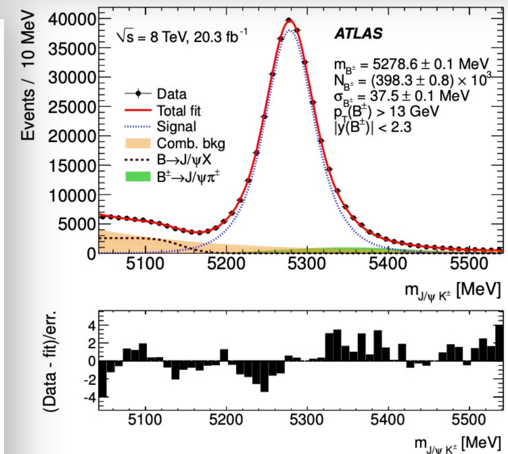
More details in talk by S. Turchikhin

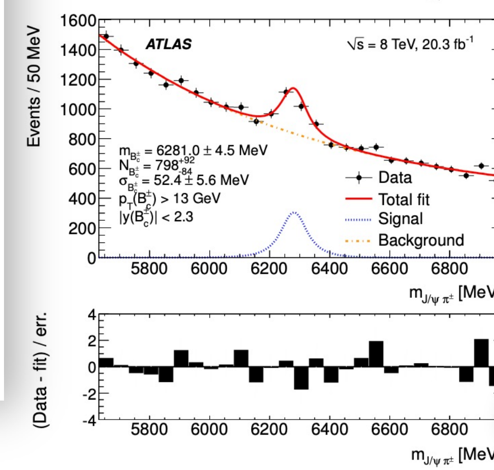
ATLAS: Data from pp collisions at $\sqrt{s} = 8\,TeV$ ($\mathcal{L}_{2012} = 20.3 fb^{-1}$)
Phys. Rev. D **104**, 012010

Measure the ratio:

$$R = \frac{\sigma(B_c^+) * \mathcal{B}(B_c^+ \to J/\psi\,\pi^+) * \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\sigma(B^+) * \mathcal{B}(B^+ \to J/\psi\,K^+) * \mathcal{B}(J/\psi \to \mu^+\mu^-)}$$

- Common systematic uncertainties mostly cancel
- Fiducial region of the measurement:
  - $p_T(B) > 13$ GeV, $|y(B)| < 2.3$
  - two bins in p_T ($13 < p_T(B) < 22$ GeV and $p_T > 22$ GeV)
  - two bins in rapidity ($|y| < 0.75$ and $0.75 < |y| < 2.3$)





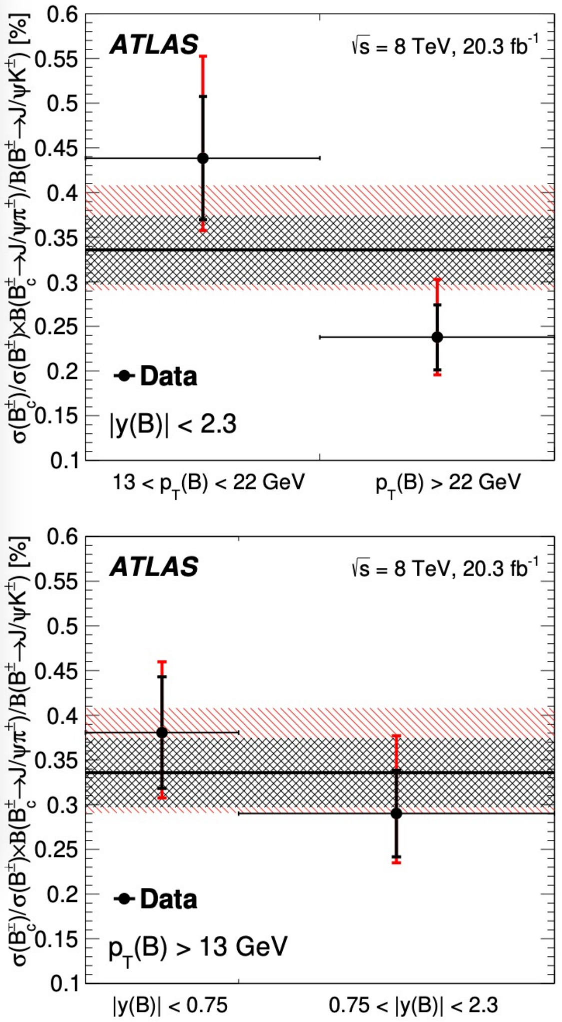
Relative $B_c^{\pm}/B^{\pm}$ production cross sections at ATLAS (2)

$$R = \frac{\sigma(B_c^+) * \mathcal{B}(B_c^+ \to J/\psi\,\pi^+) * \mathcal{B}(J/\psi \to \mu^+\,\mu^-)}{\sigma(B^+) * \mathcal{B}(B^+ \to J/\psi\,K^+) * \mathcal{B}(J/\psi \to \mu^+\,\mu^-)}$$

$= (0.34 \pm 0.04(\text{stat.})^{+0.06}_{-02.02}(\text{syst.}) \pm 0.01(\text{lifetime}))\%$

- Lower than the LHCb result for more forward and lower-p_T fiducial volume:
  - (0.683 ± 0.018 ± 0.009)%
  - 0<pT(B)<20 GeV, 2<y(B)<4.5
- Fairly consistent with the CMS result in a similar fiducial volume:
  - (0.48 ± 0.05(stat.) ± 0.03(syst.) ± 0.05(lifetime))%
  - p_T(B) > 15 GeV, |y(B)| < 1.6

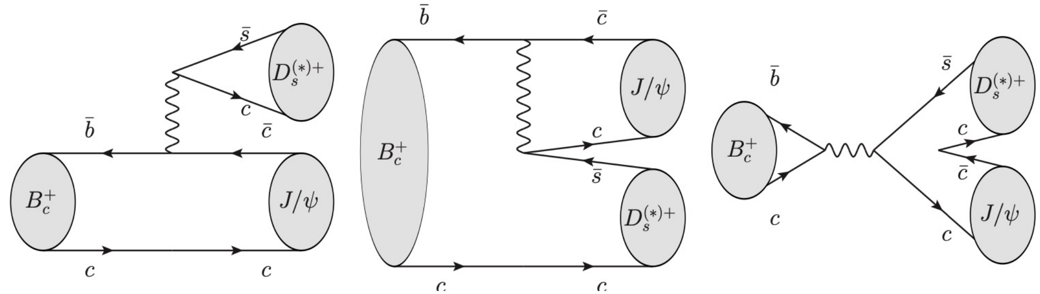
B_c^+ production decreases faster with p_T than that for B^+
No evident rapidity dependence



Analysis bin	$\sigma(B_c^{\pm})/\sigma(B^{\pm}) \times \mathcal{B}(B_c^{\pm} \to J/\psi\pi^{\pm})/\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})$
$p_T(B) > 13$ GeV, $\|y(B)\| < 2.3$	$(0.34 \pm 0.04_{\text{stat}}\ {}^{+0.06}_{-0.02\ \text{syst}} \pm 0.01_{\text{lifetime}})\%$
$13 < p_T(B) < 22$ GeV, $\|y(B)\| < 2.3$	$(0.44 \pm 0.07_{\text{stat}}\ {}^{+0.09}_{-0.04\ \text{syst}} \pm 0.01_{\text{lifetime}})\%$
$p_T(B) > 22$ GeV, $\|y(B)\| < 2.3$	$(0.24 \pm 0.04_{\text{stat}}\ {}^{+0.05}_{-0.01\ \text{syst}} \pm 0.01_{\text{lifetime}})\%$
$p_T(B) > 13$ GeV, $\|y(B)\| < 0.75$	$(0.38 \pm 0.06_{\text{stat}}\ {}^{+0.05}_{-0.04\ \text{syst}} \pm 0.01_{\text{lifetime}})\%$
$p_T(B) > 13$ GeV, $0.75 < \|y(B)\| < 2.3$	$(0.29 \pm 0.05_{\text{stat}}\ {}^{+0.07}_{-0.02\ \text{syst}} \pm 0.01_{\text{lifetime}})\%$

ATLAS: Study of the $B_c^+ \to J/\psi\, D_s^{(*)+}$ decays (1)

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



Test for various predictions: perturbative QCD calculation, relativistic potential models, sum rules calculations etc

Observed by LHCb [PRD 87 (2013) 112012] and ATLAS [EPJC 76 (2016) 4]

New: analysis aimed at more precise measurement of $B_c^+ \to J/\psi\, D_s^{(*)+}$ branching fraction and polarization with **full Run-2 data** [ATLAS-CONF-2021-046]

Strategy:

- Decays of interest:
  - $B_c^+ \to J/\psi(\mu\mu)\, D_s^+(\to \phi(K^+K^-)\pi^+)$
  - $B_c^+ \to J/\psi(\mu\mu)\, D_s^{*+}(\to D_s^+\, \gamma/\pi^0)$
    - Same reconstructed final state, soft neutral particle escapes detection
- fiducial region: $p_T(B_c^+) > 15\ GeV, |\eta(B_c^+)| < 2.0$
- $B_c^+ \to J/\psi\pi^+$ as reference channel for BR measurement

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ATLAS: Study of the $B_c^+ \to J/\psi\, D_s^{(*)+}$ decays (2)

Signal channels

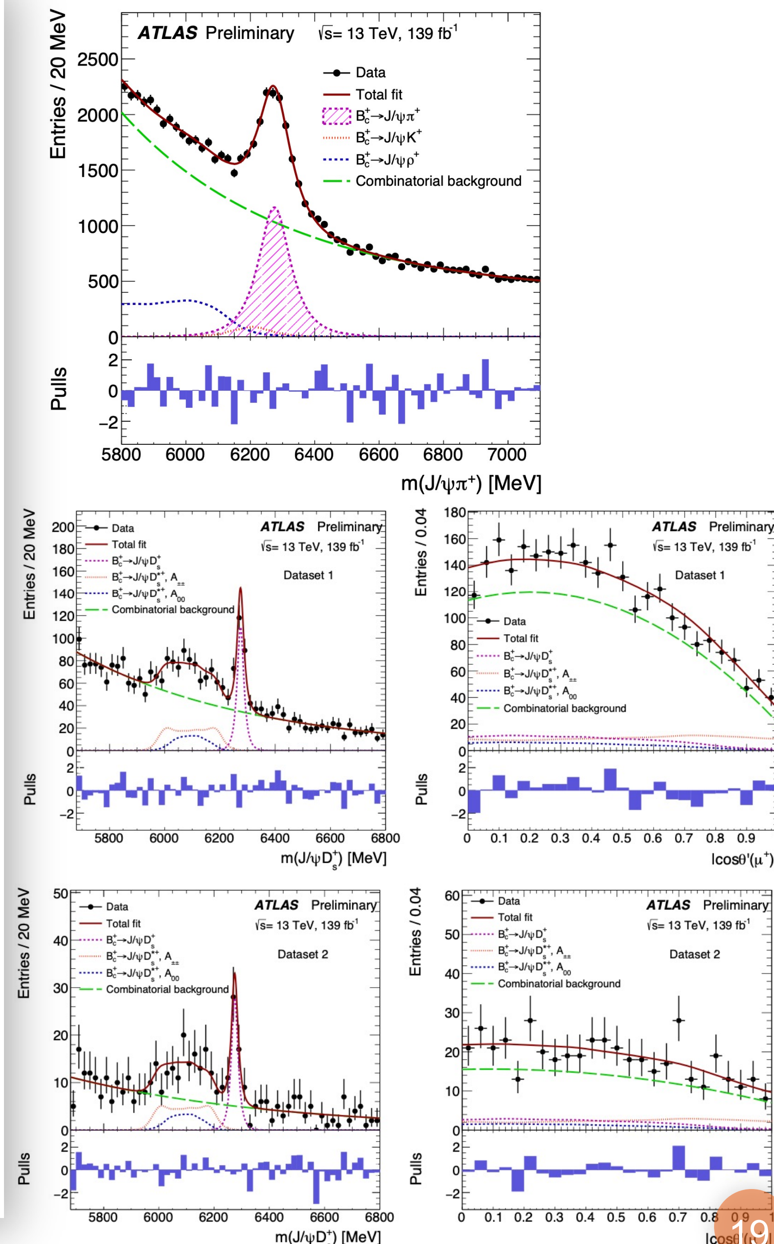
- $B_c^+ \to J/\psi(\mu\mu)\, D_s^+(\to \phi(K^+K^-)\pi^+)$
- $B_c^+ \to J/\psi(\mu\mu)\, D_s^{*+}(\to D_s^+\,\gamma/\pi^0)$

Measured quantities:

- $\boldsymbol{R}(\boldsymbol{D_s^{(*)+}}/\boldsymbol{\pi^+})$ ratios of B.R. signal channels wrt ref. channel $B_c^+ \to J/\psi\pi^+$
- $\boldsymbol{R}(\boldsymbol{D_s^{*+}}/\boldsymbol{D_s^+})$ ratios of B.R. between the two signal channels
- $\boldsymbol{\Gamma_{\pm}\Gamma_{\pm}/\Gamma}$ transverse polarisation fractions for the $B_c^+ \to J/\psi\, D_s^+$ channel

Two different datasets:

1. collected by 2-mu and 3-mu triggers
2. exclusive contribution of dedicated $B_s^0 \to \mu\mu\phi$ trigger: enhanced sensitivity to $R(D_s^{*+}/D_s^+)$ and $\Gamma_{\pm}\Gamma_{\pm}/\Gamma$



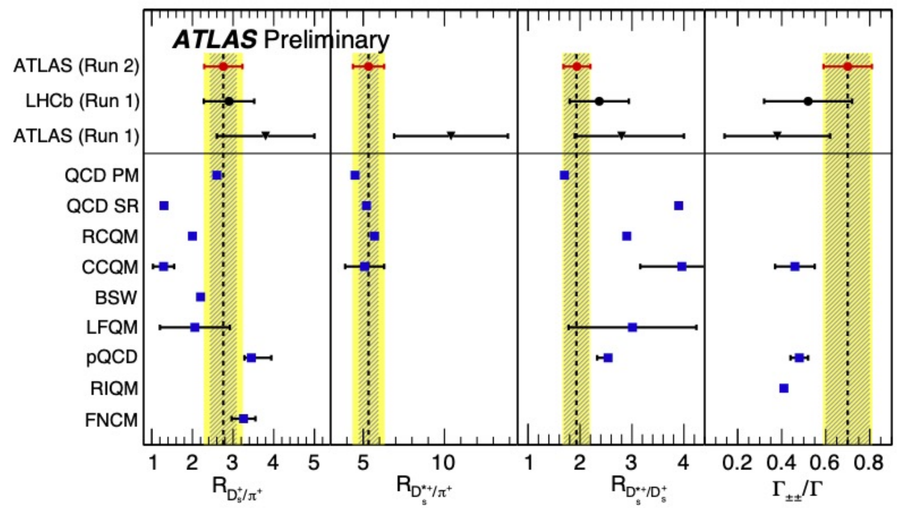
ATLAS: Study of the $B_c^+ \to J/\psi\, D_s^{(*)+}$ decays (3)

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

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

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

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



Results are consistent with previous measurements by LHCb and ATLAS, with improved precision.

$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Ref.
2.76 ± 0.47	5.33 ± 0.96	1.93 ± 0.26	0.70 ± 0.11	ATLAS Run 2
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb Run 1
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS Run 1
2.6	4.5	1.7	–	QCD potential model
1.3	5.2	3.9	–	QCD sum rules
2.0	5.7	2.9	–	RCQM
1.29 ± 0.26	5.09 ± 1.02	3.96 ± 0.80	0.46 ± 0.09	CCQM
2.2	–	–	–	BSW
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	pQCD
–	–	–	0.410	RIQM
3.257 ± 0.293	–	–	–	FNCM

Conclusions:

CP violation in B_s^0 decays:

- The CPV phase ϕ_s and the decay with difference $\Delta\Gamma_s$ measured using the $B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$ channel
- Results obtained by ATLAS and CMS ($\sqrt{s} = 13\ TeV$), combined with $\sqrt{s} = 8\ TeV$
- Consistent with the SM prediction

Physics of B_c^+ mesons

CMS:

- Relative production ratios of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states and relative production ratio w.r.t. the base state measured using Run-II pp collisions
  - No significant dependences on the B_c^+ kinematics
- First observation of the B_c^+ meson in heavy ion collisions

ATLAS:

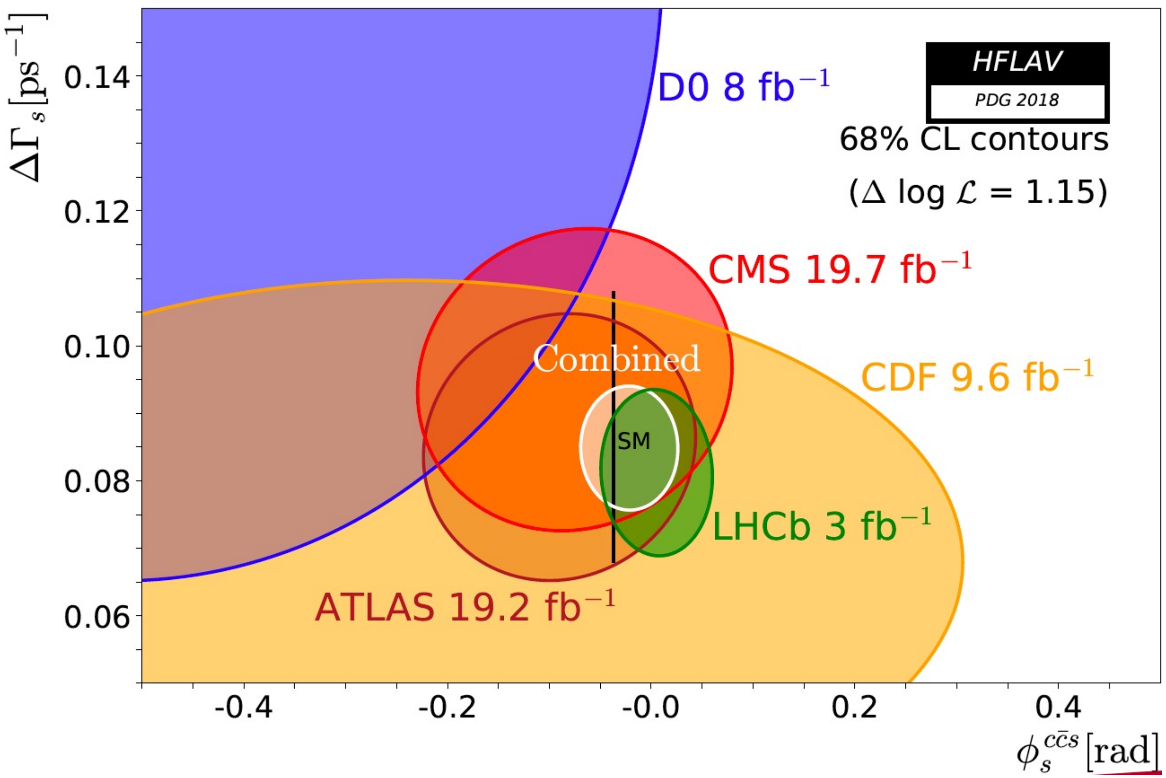
- Measurement of the relative $B_c^\pm/B^\pm$ production cross sections at $\sqrt{s} = 8\ TeV$
- Study of the $B_c^+ \to J/\psi\ D_s^+$ and $B_c^+ \to J/\psi\ D_s^{*+}$ decays in pp coll. at $\sqrt{s} = 13\ TeV$
  - Results consistent with other experiments
  - Improved precision using Run 2 data

Important information to improve theoretical understanding of the bc heavy quarkonium states and their production

Backup

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: Run 1

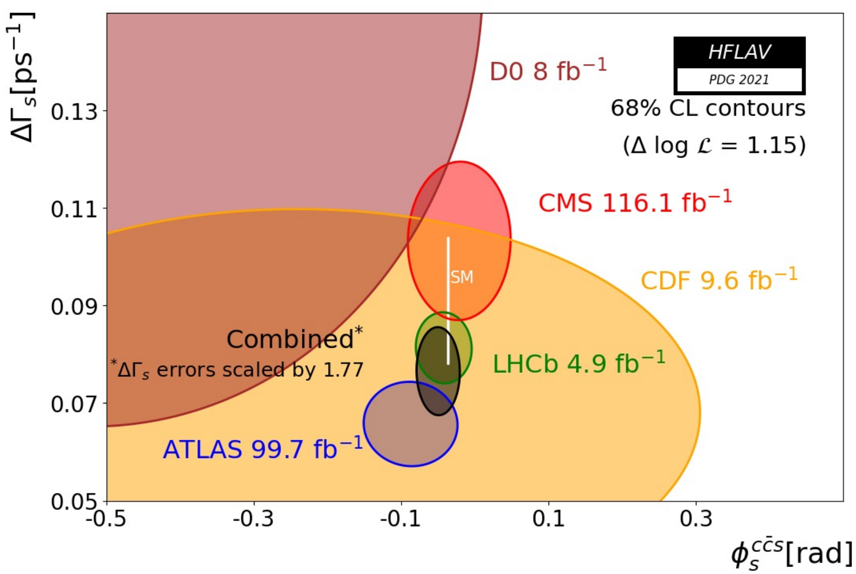
- The CP-violation measurement in the $B_s^0 \to J/\psi\phi$ channel was previously performed at the LHC in Run1 and at the Tevatron CDF and $D\emptyset$ experiments.
- The results were consistent with the SM prediction within measured uncertainties.
- Although large new physics enhancements of the mixing amplitude have been excluded by the precise measurement of the oscillation frequency, there is still room for improvements and discoveries

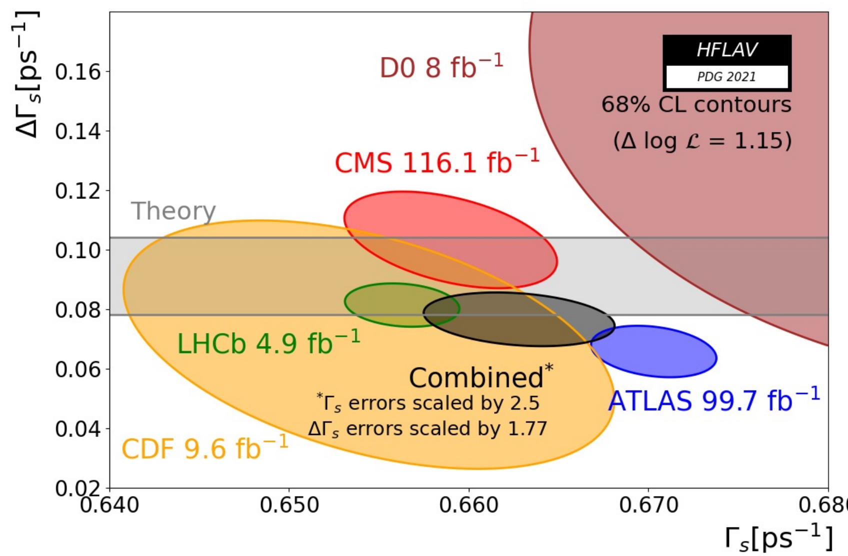


HFLAV Collaboration

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: state-of-the-art

Individual 68% confidence-level contours of ATLAS, CMS, CDF, D0 and LHCb, their combined contour (black solid line and shaded area), and the Standard Model prediction





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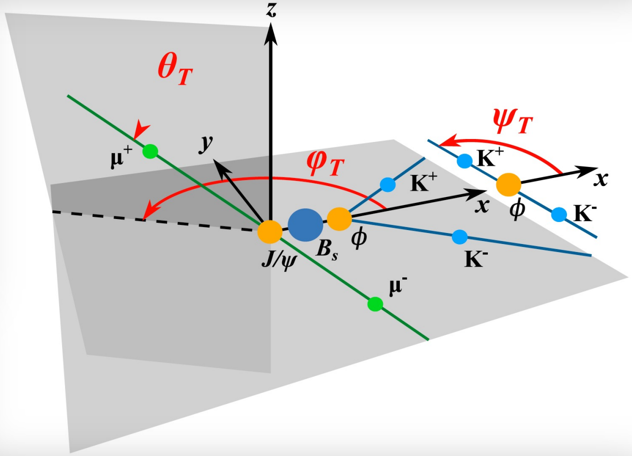
$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: angular analysis

Final states are **mixtures of CP eigenstates** → require a **time-dependent angular analysis** to disentangle the CP-odd and CP-even components.

Angular variables:

- ψ_T: helicity angle of K^+ in the ϕ rest frame w.r.t. the negative J/ψ meson flight direction
- θ_T: polar angle of μ^+ in the J/ψ rest frame
- φ_T: azimuthal angle of μ^+ in the J/ψ rest frame



Decay rate model:

$$\frac{d^4\Gamma(B_S^0)}{d\Theta d(ct)} = f(\Theta, ct, \alpha) \propto \sum_{i=1}^{10} O_i(ct, \alpha)\ g_i(\Theta)$$

- O_i time-dependent functions (ct = proper decay time of the B_S^0 candidate)
- g_i angular functions
- α set of physics parameters*

* $\Delta m_s(\Delta\Gamma_s)$ absolute mass (decay width) difference between the B_S^H and B_S^L mass eigenstates

* $\lambda = (q/p)(A_f/\bar{A}_f)$ where A_f ($\bar{A}_f$) is the decay amplitude of B_S^0 ($\bar{B}_S^0$) to the final state f and the p and q relate the mass and flavour eigenstates ($B_S^{H,L} = p|B_s\rangle \mp |\bar{B}_s\rangle q$

Accurate flavour tagging

- Needed to infer the initial flavour of the B_S^0 meson
- The most sensitive terms to ϕ_s in the decay rate depend on this information

$B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$: fit and results

Systematic uncertainties

CMS:

- **Flavour tagging**: calibration, MC difference and dependencies on the pile-up distribution
- **Fit bias**: fit stability is validated by the pseudoexperiments with default fit results
- **Background angles model**: varying the bin boundaries, invariant mass window and sideband definition
- **Best candidate selection**: statistically equivalent sample is created where all candidates in the event are retained
- **Angular acceptance method**: different acceptance functions are calculated using different numbers of pT bins as well as different widths and central values of the bins

ATLAS:

- **Model bias**: pseudo experiments, each statistically equivalent to the data samples, from the fitted model in data
- **Angular efficiency**: systematic uncertainty related to the limited MC event count used to estimate the angular efficiency function is evaluated by regenerating the efficiency histograms
- **Proper decay length resolution**: varying the correction factor κ by 10%, as estimated from a data-to-simulation comparison
- **Sig./bkg. ω difference**: differences in the mistag probabilities between signal and background studied on the sideband and signal range