Spectroscopy and exotica of HF states in ATLAS

Radek Novotny
On behalf of the ATLAS collaboration

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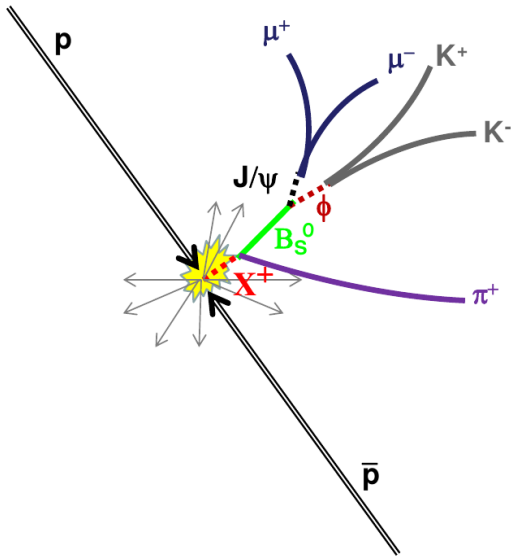
Outline

- Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum in the ATLAS
- Observation of an excited state of $B_c^\pm$ consistent with predictions for $B_c^\pm(2S)$

$B_s^0\pi^\pm$: Introduction

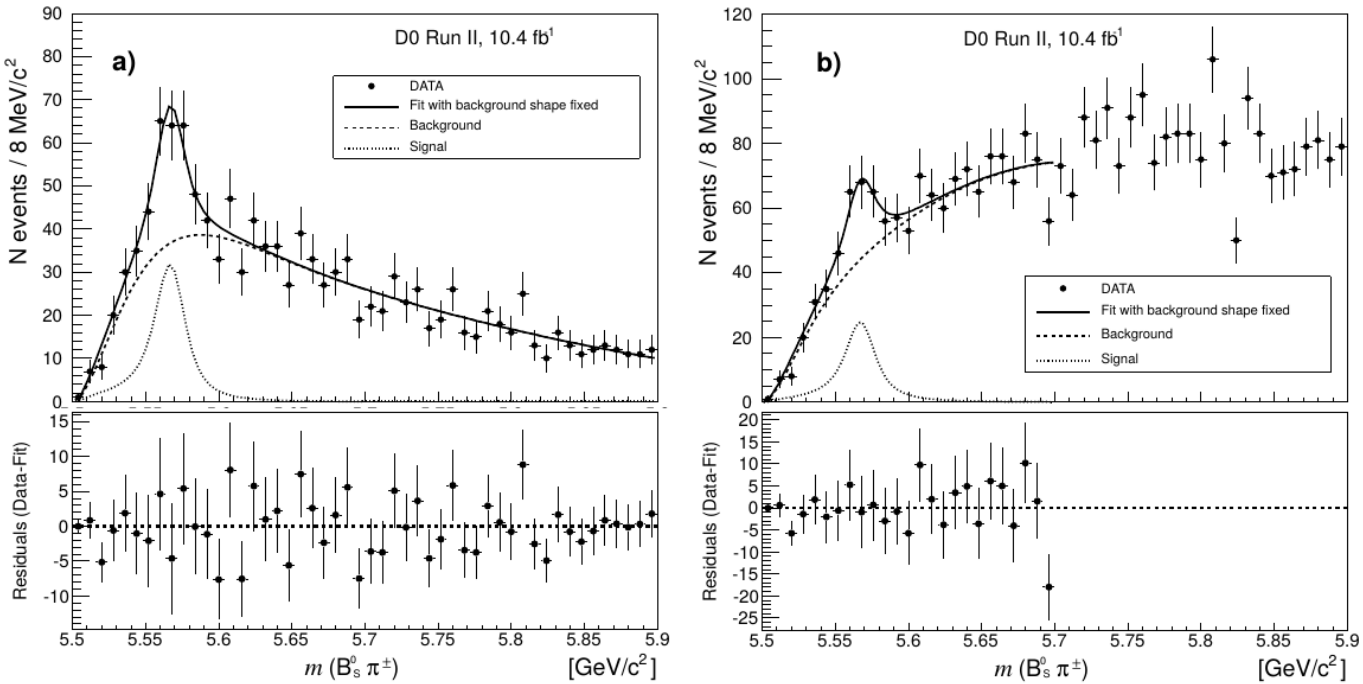
- In December 2016, DØ published the evidence for a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
  Phys. Rev. Lett. 117, 022003 (2016)
- $X(5568)$ is a tetraquark candidate, composed of two quarks and two antiquarks of four different flavors: b, s, u, d



$B_s^0\pi^\pm$: DØ Result

Phys. Rev. Lett. **117** (2016) no.2, 022003

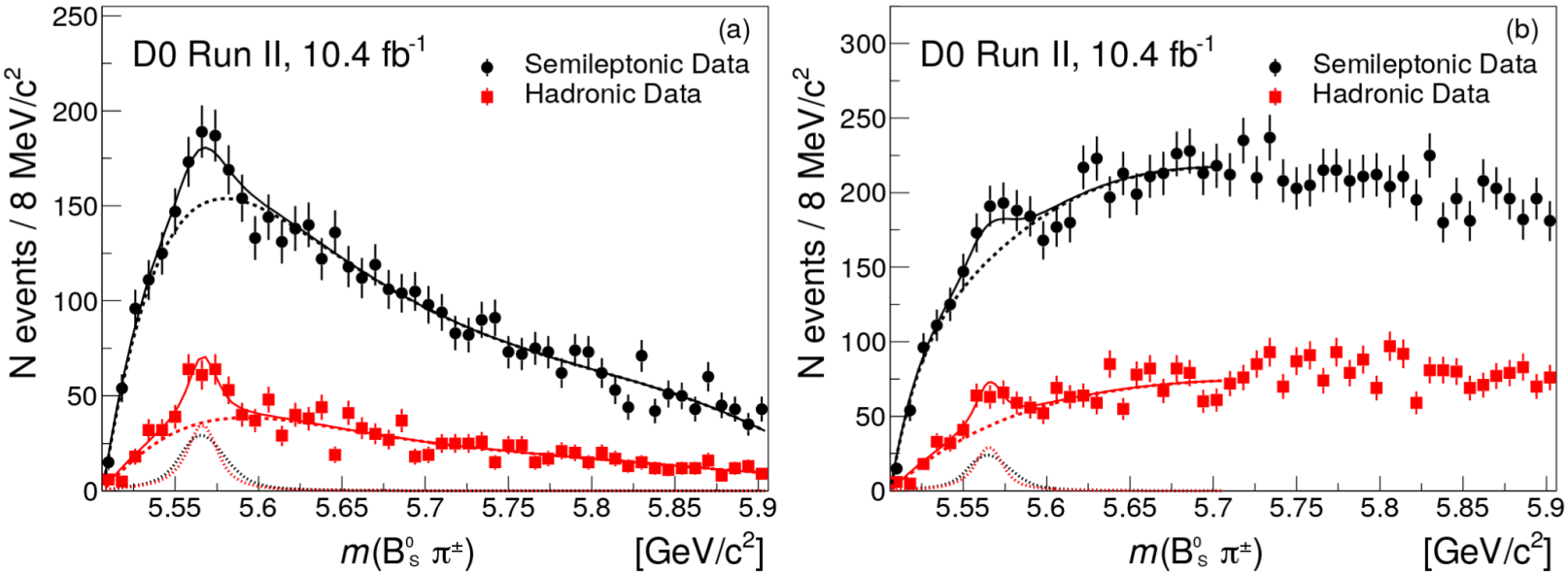
- Fixed background shape
- a) opening angle $(B_s^0 - \pi^\pm)$ cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$:
  $m = 5567.8 \pm 2.9$ (stat) $^{+0.9}_{-1.9}$ (syst) MeV/c^2,
  $\Gamma = 21.9 \pm 6.4$ (stat)$^{+5.0}_{-2.5}$ (syst) MeV/c^2,
  significance 5.1σ, and number of signal events $N = 133 \pm 31$
- b) without ΔR cut (but with the mass, natural width, and background shape fixed to default values): $N = 106 \pm 23$, significance 3.9σ



$B_s^0\pi^\pm$: DØ Semileptonic Result

Phys. Rev. D **97** no 9 (2018), 092004

- $p\bar{p}$ data 10.4 fb^{-1}
- Significance including systematic uncertaint:
  - a) with cone cut $\sigma = 3.2$
  - b) without cone cut $\sigma = 3.4$



$B_s^0\pi^\pm$: Results from other experiments

LHCb:
(Phys. Rev. Lett. **117** (2016) no.15, 152003)

$$\rho_X^{\mathrm{LHC}b}(p_{\mathrm{T}}(B_s^0) > 5\ \mathrm{GeV}) < 0.012,$$

$$\rho_X^{\mathrm{LHC}b}(p_{\mathrm{T}}(B_s^0) > 10\ \mathrm{GeV}) < 0.024,$$

$$\rho_X^{\mathrm{LHC}b}(p_{\mathrm{T}}(B_s^0) > 15\ \mathrm{GeV}) < 0.020$$

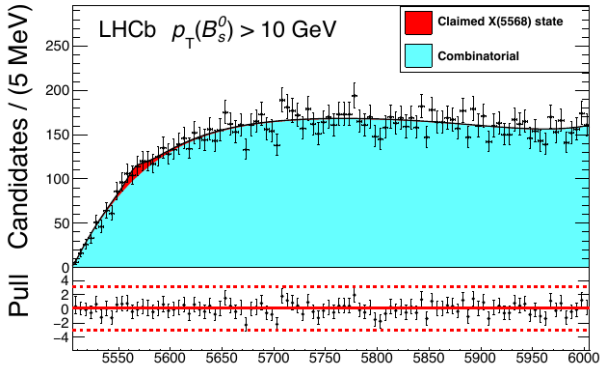
CMS:
(Phys. Rev. Lett. **120** (2018) no. 20, 202005)

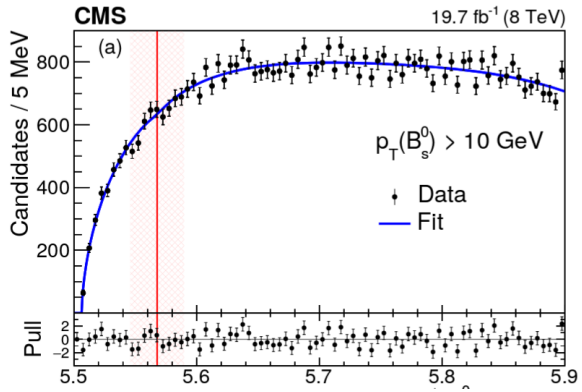
$$\rho_X^{\mathrm{CMS}}(p_{\mathrm{T}}(B_s^0) > 10\ \mathrm{GeV}) < 0.011$$

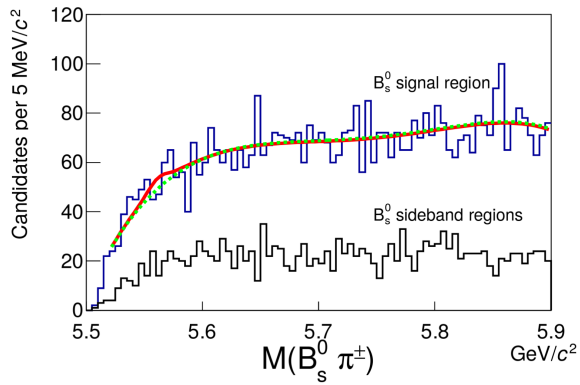
$$\rho_X^{\mathrm{CMS}}(p_{\mathrm{T}}(B_s^0) > 15\ \mathrm{GeV}) < 0.010$$

CDF:
(Phys. Rev. Lett. **120** (2018) no. 20, 202006)

$$f_{B_s^0/X(5568)} < 0.067$$







$B_s^0\pi^\pm$: Data and Selection

B_s^0 candidate

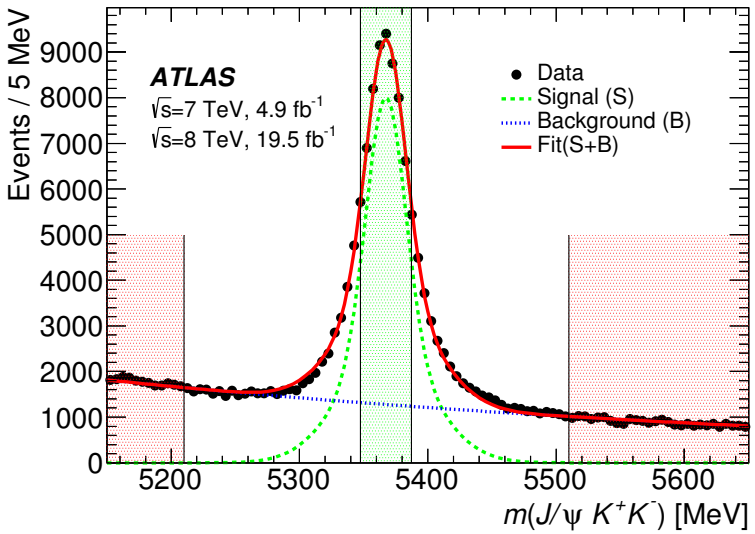
Data of pp collisions: 4.9 fb^{-1} (2011 7 TeV) + 19.5 fb^{-1} (2012 8 TeV)

B_s^0candidate selection:

- Jpsi has been reconstructed by fitting muon pairs into common vertex
- $m(KK) \in 1008.5\,\text{MeV} - 1030.5\,\text{MeV}$
- $p_\text{T}(K) > 1\,\text{GeV}$
- Only using the best χ^2/NDF candidate from each event
- $p_\text{T}(B_s) > 10\,\text{GeV}$
- $\tau(B_s) > 0.2\,\text{ps}$

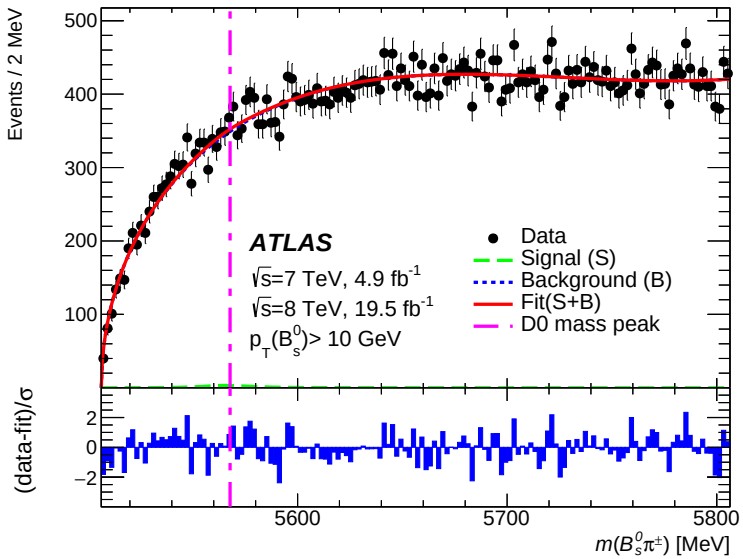
$B_s^0\pi^\pm$ candidate selection:

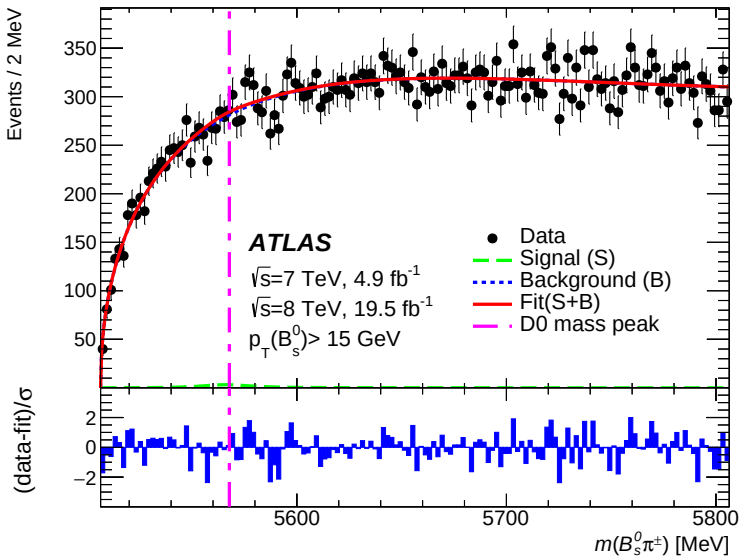
- $m(B_s) \in 5346.6\,\text{MeV} - 5386.6\,\text{MeV}$
- $p_\text{T}(\pi^\pm) > 500\,\text{MeV}$
- $m(B_s^0\pi^\pm) < 5900\,\text{MeV}$
- All $B_s^0\pi^\pm$ candidates in the event are taken



$B_s^0\pi^\pm$: Fit to the Data

- $B_s^0\pi^\pm$ candidates from RUN1 data with combined integrated luminosty of 24.3 fb^{-1} are fitted using an unbinned maximum-likelihood fit
- The signal mass and Breit-Wigner width (BW) are fixed according to the central values obtained by the D$\emptyset$ collaboration, i.e. $M_X = 5567.8\ \mathrm{MeV}$ and $\Gamma_X = 21.9\ \mathrm{MeV}$
- The fits are performed for two subsets of the $B_s^0\pi^\pm$ candidates $p_\mathrm{T}(B_s^0) > 10\ \mathrm{GeV}$(left) and $p_\mathrm{T}(B_s^0) > 15\ \mathrm{GeV}$(right)
- No significant signal corresponding to the properties of the D$\emptyset$ resonance is observed





$B_s^0\pi^\pm$: Upper Limits

- No significant signal corresponding to the properties of the D$\emptyset$ resonance is observed
- CLs formalism is used to establish the upper limits for the number of expected $B_s^0\pi^\pm$ signals $N(X)$ and for the relative production rate ρ_X at 95 % CL

$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon^{\text{rel}}(X)},$$

- Systematics for $N(X)$
  - alternative Background PDF Chebyshev of 7th order - replacing default PDF
  - P-wave BW for Signal replacing the default S-wave
  - Tripple-Gaus for detector Bspi mass resolution determined by MC - replacing the per-candidate resolution model of the default fit.
  - Uncertainty on D$\emptyset$ parameters

$B_s^0\pi^\pm$: Upper Limits

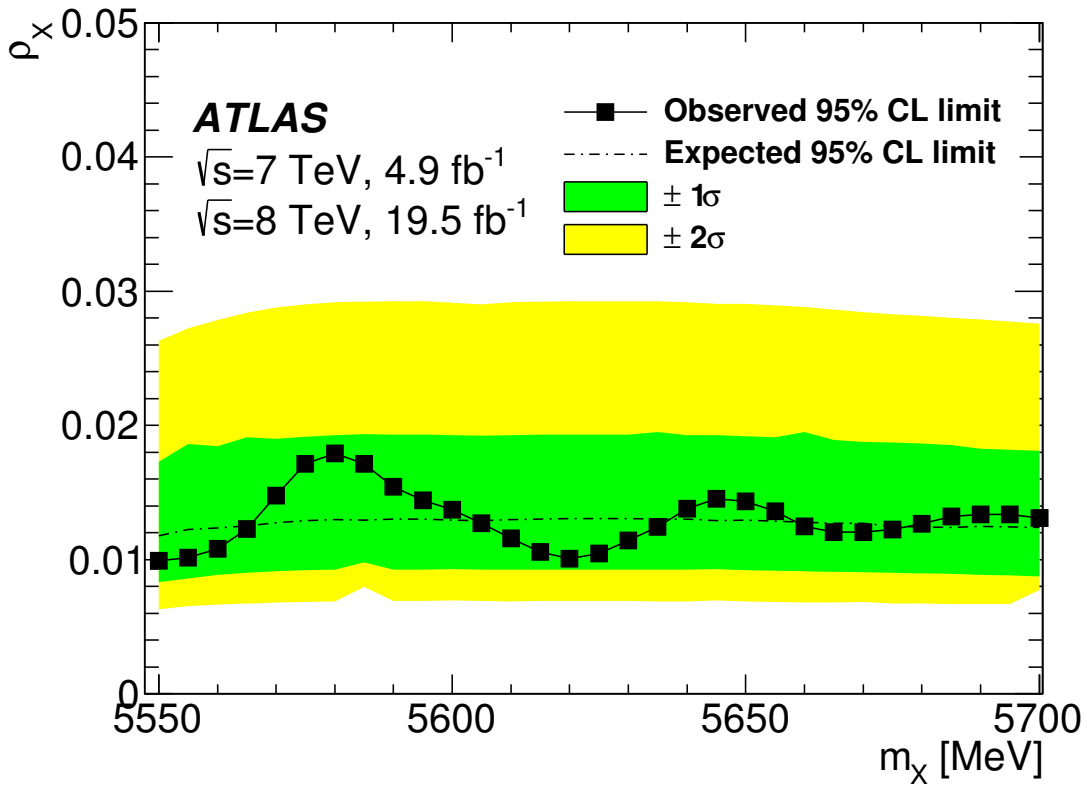
- The upper limit for ρ_X is established in the same way as for $N(X)$ including in addition the systematic effects from determination of number of B_s^0 signal events and of the relative efficiency ϵ^{rel} as gaussian constraints.
- The highest upper limits are extracted by including all systematics and give

	$p_T(B_s^0)>10$ GeV	$p_T(B_s^0)>15$ GeV
$N(X)$	382	356
ρ_X	0.015	0.016

- These results are consistent with LHCb and CMS measurements

$B_s^0\pi^\pm$: Mass scan

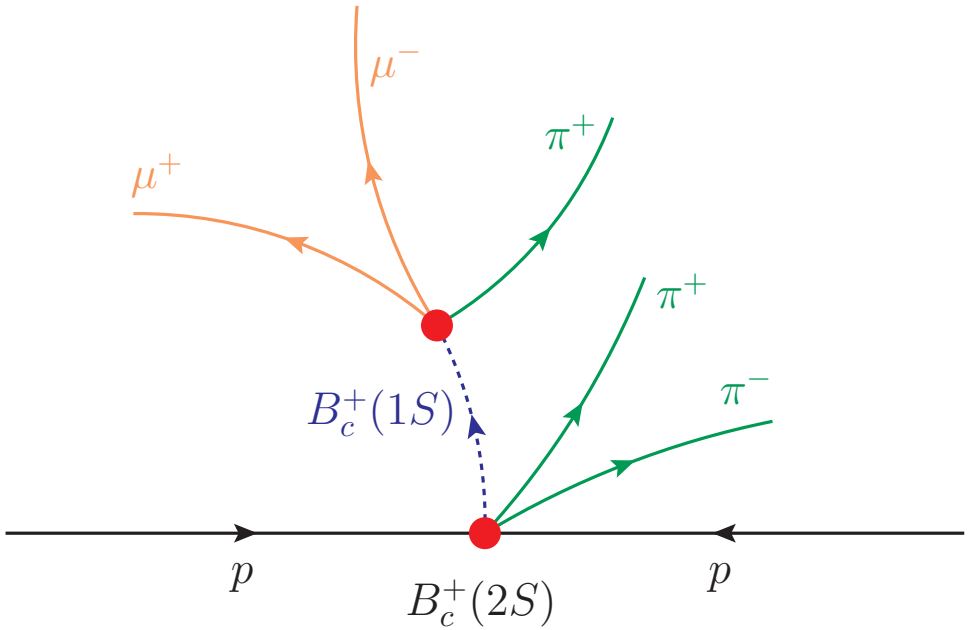
- BW width fixed to DØ value + uncertainty on DØ value
- Scanning with the mean resonance masses from 5550 MeV to 5700 MeV, in steps of 5 MeV using 10 GeV p_T cut
- All systematics are included



$B_s^0\pi^\pm$: Conclusions

- A search for a new state $X(5568)$ decaying to $B_s^0\pi^\pm$ was performed by ATLAS, using RUN1 pp data
- No significant signal has been found
- The upper limit on the production rate of the $X(5568)$ decaying to $B_s^0\pi^\pm$ state relative to B_s^0 mesons produced in ATLAS volume has been determined at 95 % CL
- ATLAS results are published at Phys. Rev. Lett. **120** (2018) 202007 and are consistent with CMS and LHCb measurements

- The $B_c^{\pm}(1S)$ meson was first observed by the CDF experiment in the semileptonic decay mode
- The spectrum and properties of $B_c^{\pm}$ family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations
- The search for first excited state $B_c^{\pm}(2S)$ was performed in the decay sequence $B_c^{\pm}(2S) \to B_c^{\pm}(1S)\pi^+\pi^-$



- The analysis uses *7 TeV and 8 TeV pp collisions data*
  - 4.9 $fb^{-1}$and 19.2 fb^{-1}, respectively
- Selection optimised using MC
  - Optimization performed separately for 7 TeV and 8 TeV data

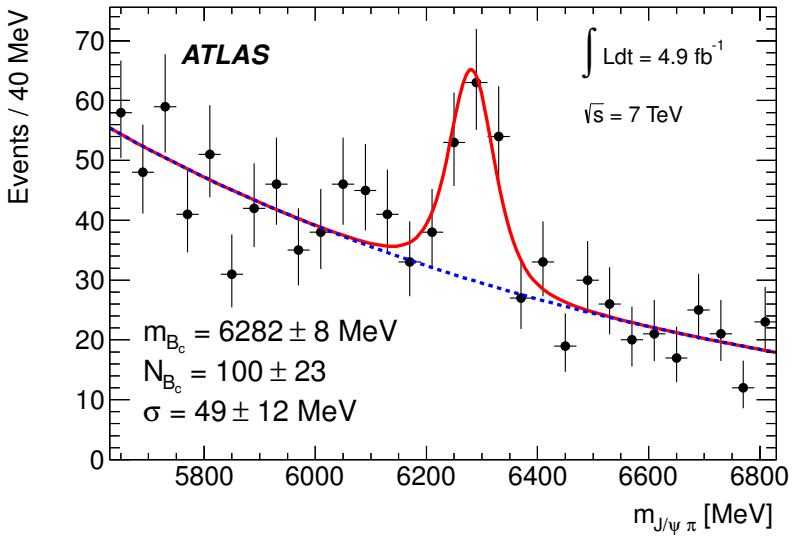
$B_c^{\pm}(1S)$ selection and fit

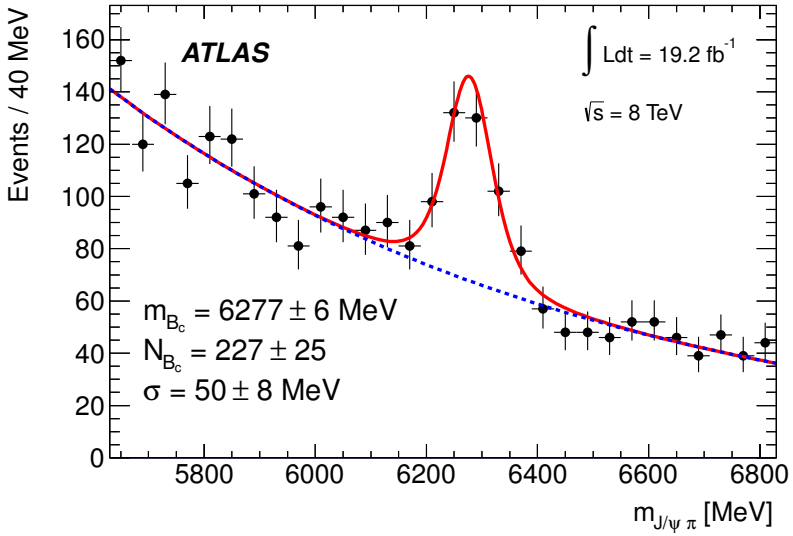
$B_c^{\pm}$(1S) selection for 2011 (2012) data

- $p_T(\mu_1, \mu_2) > 4,6$ GeV
- $\chi^2/n.d.f.(J/\psi) < 15$
- $m(J/\psi)$ within $\pm 3\sigma$ of the nominal (σ depending on the rapidity range)
- $\chi^2/n.d.f.(B_c^{\pm}) < 2.0$ (1.5)
- $p_T(B_c^{\pm}) > 15$ GeV (18 GeV)
- $\frac{d_{xy}^0}{\sigma(d_{xy}^0)}(\pi^+) > 5$ (4.5)

Extended unbinned fit of the mass distribution

- *Signal*: Gaussian with per-candidate errors
- *Background*: exponential





$B_c^{\pm}(2S)$ selection and fit

Selection of $B_c^{\pm}(2S) \to B_c^{\pm}(1S)\pi^+\pi^-$ candidates

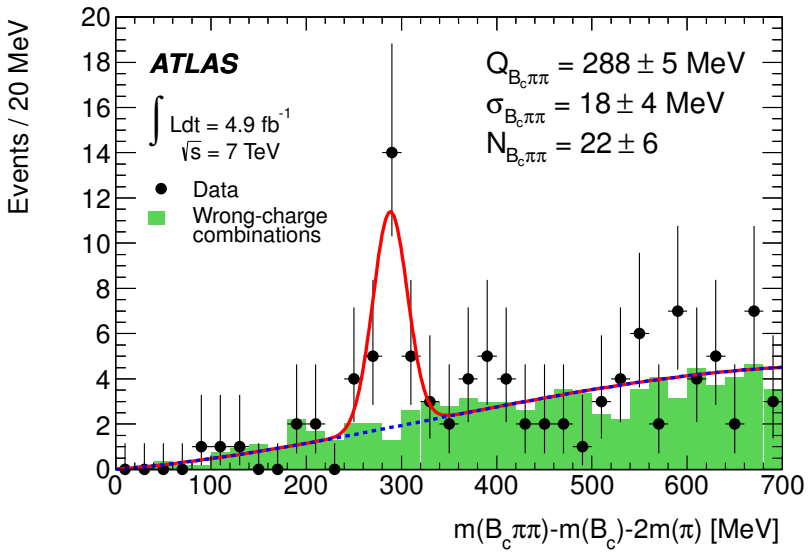
- $B_c^{\pm}(1S)$ candidates within $\pm 3\sigma$ of the fitted mass
- $p_{\mathrm{T}}(\pi^+, \pi^-) > 400$ MeV
- for several candidates in event, the one with the best cascade fit χ^2 is kept

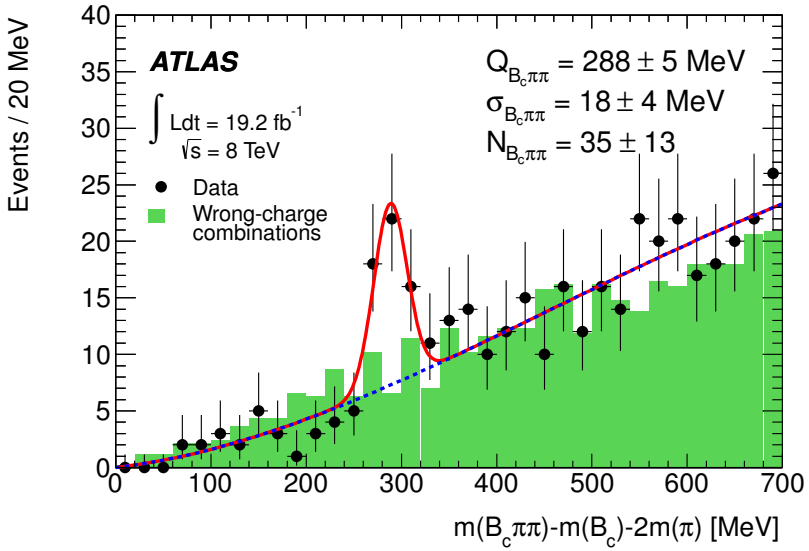
Extended unbinned fit of Q-value distribution

$$Q_{B_c^{\pm}\pi\pi} = m(B_c^{\pm}\pi^+\pi^-) - m(B_c^{\pm}) - 2m(\pi^+)$$

- *Signal*: Gaussian
- *Background*: 3rd order polynomial

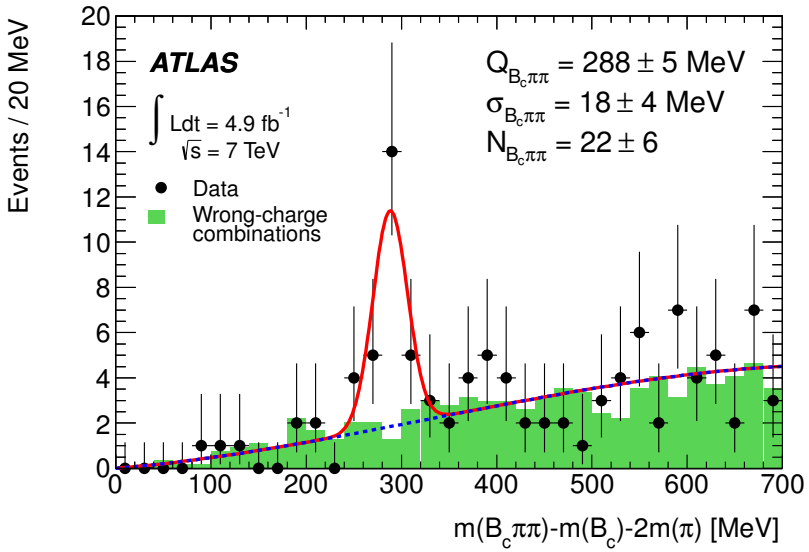
Wrong charge combination (same-sign π) used for background control

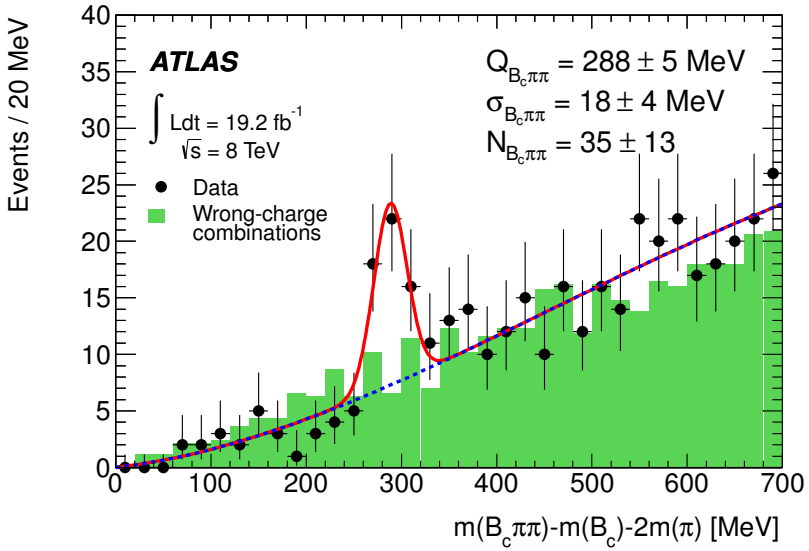




$B_c^{\pm}(2S)$: Observation

- Significance of the observed signal calculated with toy studies accounting for a *"look elsewhere effect"*
  - 3.7σ in 7 TeV data
  - 4.5σ in 8 TeV data
  - Combined significance is 5.2σ
  - (local significance is 5.4σ)
- A new state observed at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV (error-weighted mean of 7 and 8 TeV values)
- Corresponds to a mass $6842 \pm 4 \pm 5$ MeV, that is consistent with the predicted mass of $B_c^{\pm}(2S)$ with no B_c*(2S) hypothesis





$B_c^{\pm}(2S)$: Conclusions

- $B_c^{\pm}(2S)$ Highlights:
- First and so far the only observation of an excited state of B_c
  - LHCb published upper limits on the observation of this state (J. High Energ. Phys. (2018) 2018: 138) and awaiting results from CMS.
- ATLAS is continuing $B_c^{\pm}$ program in RUN2 with special attention to $B_c^{\pm}(2S)$

Stay tuned.