Spectroscopy and exotic states in ATLAS

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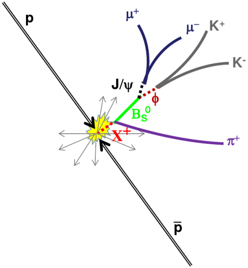
Outline

- 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 $B_c^\pm(2S)$

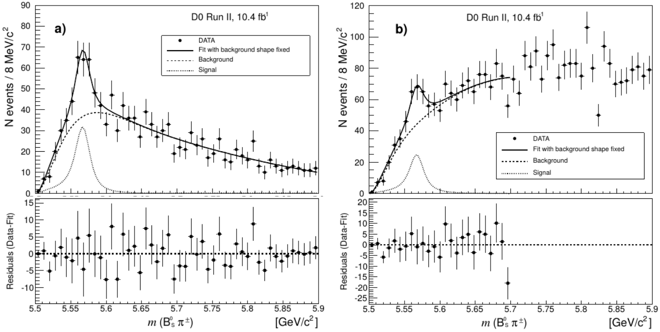
- In December 2016, DØ published the evidence for a narrow structure, $X(5568)$, in the decay sequence $X(5568) \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
  Phys. Rev. Lett. 117, 022003 (2016)
- $X(5568)$ is a tetraquark candidate, composed of two quarks and two antiquarks of four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



$B_s^0\pi^\pm$: D∅ Result

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

- Fixed background shape
- a) opening angle ($B_s^0 - \pi^\pm$) cut $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$:
  $m = 5567.8 \pm 2.9 \text{ (stat) } ^{+0.9}_{-1.9} \text{ (syst) MeV}/c^2$,
  $\Gamma = 21.9 \pm 6.4 \text{ (stat)}^{+5.0}_{-2.5} \text{ (syst) MeV}/c^2$,
  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



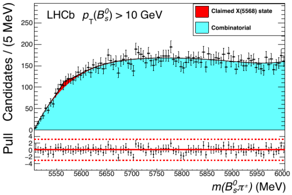
$B_s^0\pi^\pm$: Results from other experiments

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

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

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

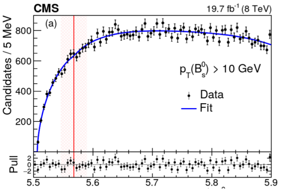
$$\rho_X^{\mathrm{LHC}b}(p_\mathrm{T}(B_s^0) > 15\ \mathrm{GeV}) < 0.020$$



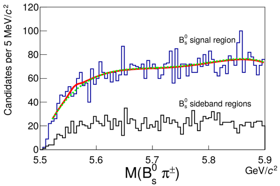
CMS:
(Phys. Rev. Lett. **120** (2018) no. 20, 202005)

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

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



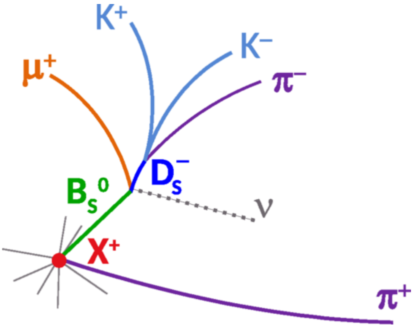
CDF:
(Phys. Rev. Lett. **120** (2018) no. 20, 202006) $f_{B_s^0/X(5568)} < 0.067$



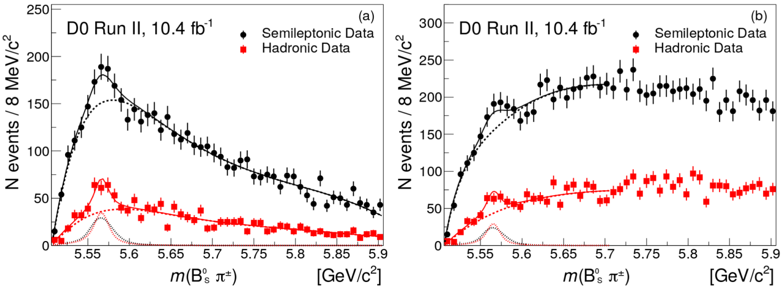
$B_s^0\pi^\pm$: DØ Semileptonic Result

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

- $p\bar{p}$ data 10.4 fb^{-1}
- $B_s^0 \to \mu^\pm D_s^\mp X$, $D_s^\pm \to \phi\pi^\pm$



- $p\bar{p}$ data 10.4 fb^{-1}
- $B_s^0 \rightarrow \mu^\pm D_s^\mp X$, $D_s^\pm \rightarrow \phi\pi^\pm$
- Significance including systematic uncertaint:
  - a) with cone cut $\sigma = 3.2$
  - b) without cone cut $\sigma = 3.4$



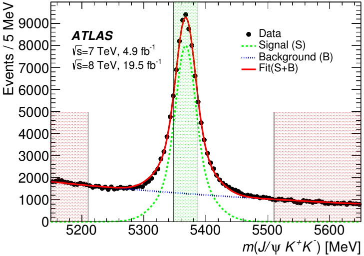
Data of *pp* collisions: 4.9 fb^{-1} (2011 7 TeV) + 19.5 fb^{-1} (2012 8 TeV)

B_s^0candidate selection:

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

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

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



Background Shape

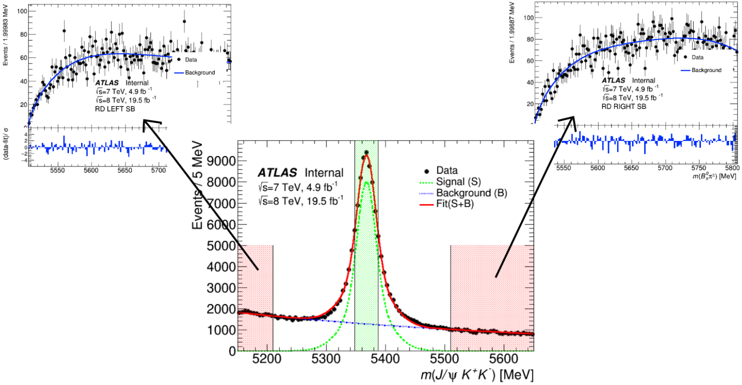
- $B_s^0\pi^\pm$ candidates are fitted using an unbinned maximum-likelihood fit
- Probability Density Function (PDF) for the background:

$$F_{\mathrm{bck}}(m) = \left(\frac{m - m_{\mathrm{thr}}}{n}\right)^a \cdot \exp\left(\sum_{i=1}^{4} p_i \cdot \left(\frac{m - m_{\mathrm{thr}}}{n}\right)^i\right), \qquad (1)$$

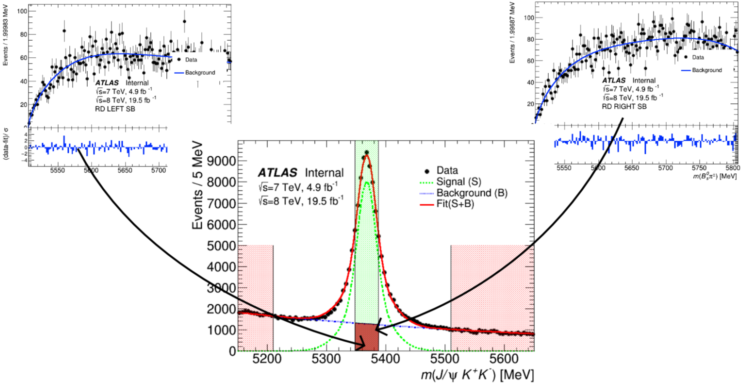
  where $m_{\mathrm{thr}} = m_{\mathrm{PDG}}(B_s^0) + m_{\mathrm{PDG}}(\pi^\pm)$ and n, a, p_i are free parameters

- Formula (1) was tested using events with no real $B_s^0\pi^\pm$ candidates:
  - a) events from the real data, where $B_s^0\pi^\pm$ candidates are formed using "fake" B_s^0 from the mass sidebands
  - b) events from B_s^0 MC sample ("true" B_s^0 is combined with an additional random pion in the given event)

Background Shape



Background Shape



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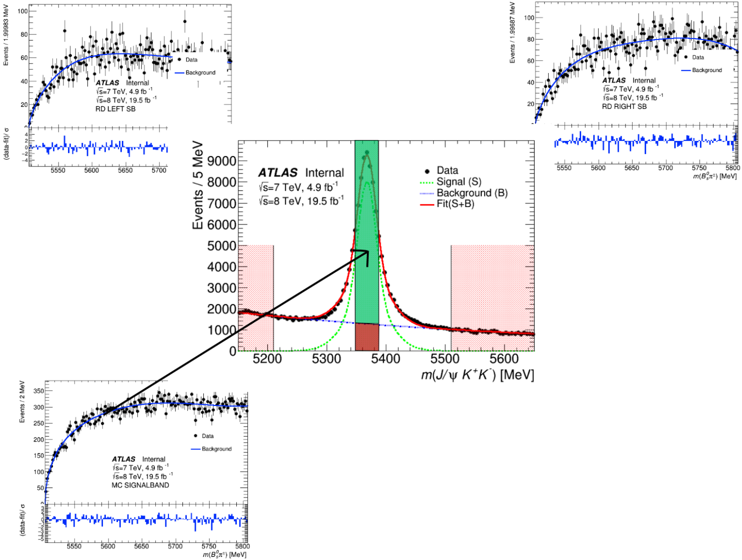

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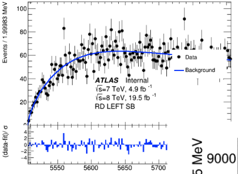
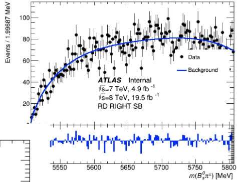
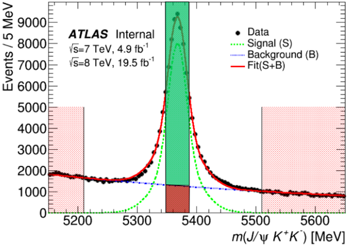
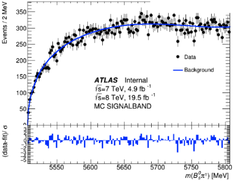
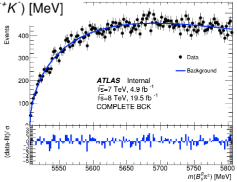










Signal Shape

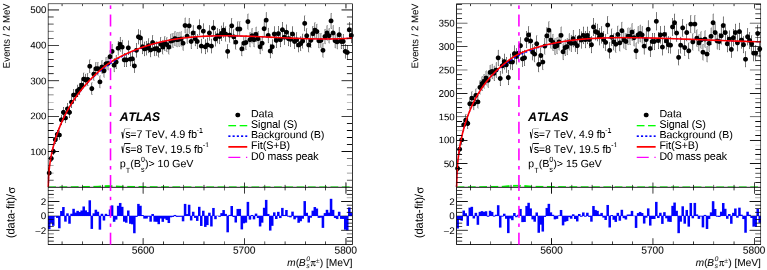
- PDF of an S-wave Breit-Wigner:

$$BW(m, M_X, \Gamma_X) = \frac{m \cdot M_X \cdot \Gamma(m)}{(M_X^2 - m^2)^2 + M_X^2 \cdot \Gamma^2(m)}, \quad (2)$$

  where the mass-dependent width $\Gamma(m) = \Gamma_X \cdot (q_1/q_0)$ is proportional to the natural width Γ_X, where q_1 and q_0 are three-vector momenta of the B_s^0 meson in the rest frame of the $B_s^0\pi^\pm$ system at the invariant mass equal to $m(B_s^0\pi^\pm)$ and M_X, respectively
- The signal PDF (F_{sig}) is defined as a convolution of an S-wave Breit-Wigner PDF and the detector resolution
- In the mass fit there are two usual approaches to represent mass resolution: 1. per-candidate errors - representing each event by individual Gauss function or 2. fitting the whole signal by few gauss functions, that are tested on MC signal, then applied to data. These functions are obviously convoluting the Physics BW width. Per-candidate is more data-based while the 3 Gauss is more MC based. So the second approach is a naturally used as a systematic test.

$B_s^0\pi^\pm$: 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 DØ collaboration, i.e. $M_X = 5567.8$ MeV and $\Gamma_X = 21.9$ MeV
- The fits are performed for two subsets of the $B_s^0\pi^\pm$ candidates $p_\mathrm{T}(B_s^0) > 10$ GeV(left) and $p_\mathrm{T}(B_s^0) > 15$ GeV(right)
- No significant signal corresponding to the properties of the DØ resonance is observed



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

- No significant signal corresponding to the properties of the D∅ 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∅ parameters

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

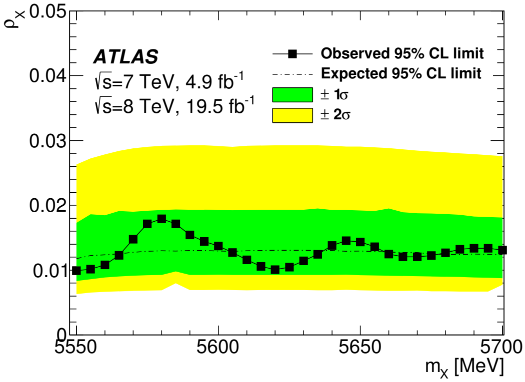
- The upper limit for $\rho_{\rm X}$ is established in the same way as for $N(X)$ including in addition the systematic effects from determination of number of B_s^0 signal events and of the relative efficiency $\epsilon^{\rm rel}$ as gaussian constraints.
- The highest upper limits are extracted by including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

	$\rm p_T(B_s^0)$>10 GeV	$\rm p_T(B_s^0)$>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

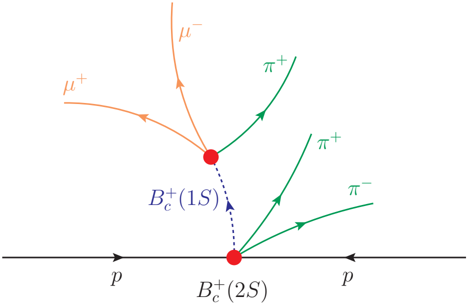
- BW width fixed to DØ value + uncertainty on DØ value
- Scanning with the mean resonance masses from 5550 MeV to 5700 MeV, in steps of 5 MeV using 10 GeV p_T cut
- All systematics are included



$B_s^0\pi^\pm$: 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 LHC*b* 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 $B_c^{\pm}(2S) \to B_c^{\pm}(1S)\pi^+\pi^-$



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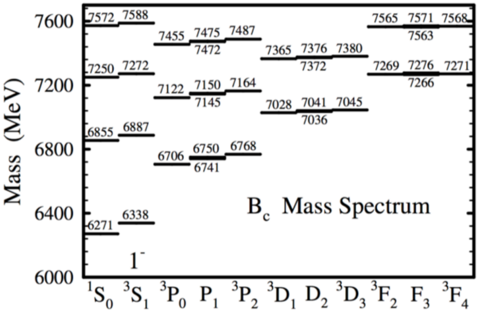
Phys.Rev.D70:054017,2004



- 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

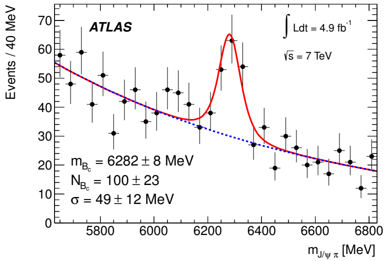
$B_c^{\pm}(1S)$ selection for 2011 (2012) data

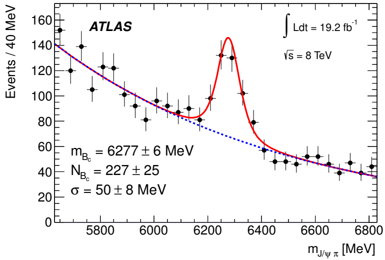
- $p_T(\mu_1, \mu_2) > 4, 6$ GeV
- $\chi^2/n.d.f.(J/\psi) < 15$
- $m(J/\psi)$ within $\pm 3\sigma$ of the nominal (σ depending on the rapidity range)

- $\chi^2/n.d.f.(B_c^{\pm}) < 2.0$ (1.5)
- $p_T(B_c^{\pm}) > 15$ GeV (18 GeV)
- $\frac{d^0_{xy}}{\sigma(d^0_{xy})}(\pi^+) > 5$ (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

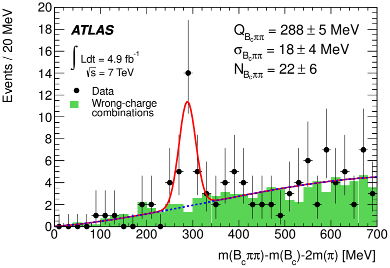
- $B_c^{\pm}(1S)$ candidates within $\pm 3\sigma$ of the fitted mass
- $p_T(\pi^+, \pi^-) > 400$ MeV
- for several candidates in event, the one with the best cascade fit χ^2 is kept

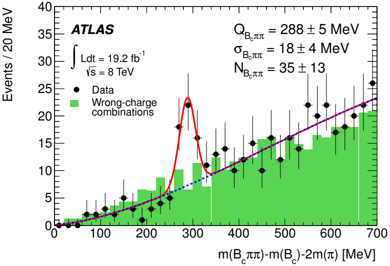
Extended unbinned fit of Q-value distribution

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

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

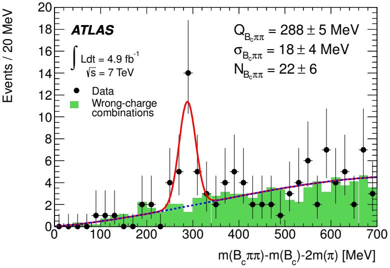
Wrong charge combination (same-sign π) used for background control

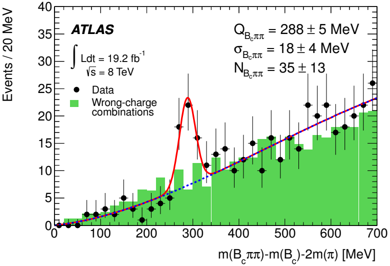




$B_c^{\pm}(2S)$: Observation

- 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.