ATLAS studies of spectroscopy and exotics

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Joint Institute for Nuclear Research

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Outline

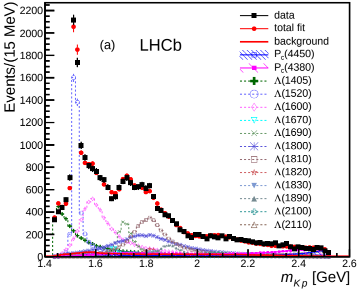
Presentation is devoted to the recent ATLAS result on study of the pentaquark resonances in $J/\psi p$ system in $\Lambda_b^0 \to J/\psi p K^-$ decays with the Run-1 dataset – ATLAS-CONF-2019-048

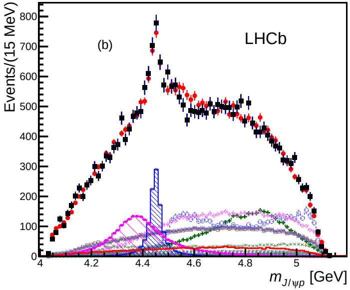
- Current experimental situation
- ATLAS analysis outline
  - fitting strategy
  - study of physics backgrounds from neutral B meson decays
  - study of the signal in Λ_b^0 decays
  - comparisons with LHCb results and null hypothesis
- Conclusions and plans

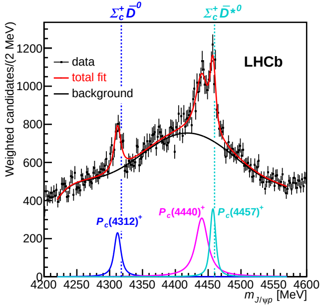
Pentaquarks with hidden charm: the story

- In 2015 (PRL 115 (2015) 072001) LHCb observed 2 structures in $J/\psi p$ mass spectrum of $\Lambda_b^0 \to J/\psi p K^-$ decay
  - Evidence in $\Lambda_b^0 \to J/\psi p \pi^-$ (PRL 117 (2016) 082003)
  - Preferred $J^P = 3/2^-, 5/2^+$
- Model-independent evidence came later (PRL 117 (2016) 082002)
- With Run-2 LHCb resolved $P_c(4450)^+$ into two states and discovered a new $P_c(4312)^+$ (PRL 122 (2019) 222001)
- Narrow states show well-defined resonant behaviour near $\Sigma_c \bar{D}^{(*)}$ threshold
  - Status of wide $P_c(4380)^+$ less clear
- Not observed in $\gamma p \to J/\psi p$ s-channel by GlueX (PRL 123 (2019) 072001)

Independent experimental confirmation much desirable



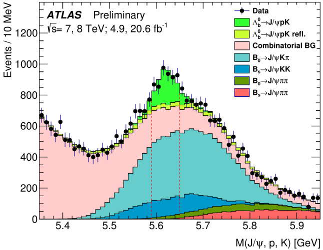




ATLAS analysis outline

- No particle-ID in ATLAS $\rightarrow$ considering all $H_b \rightarrow J/\psi h_1 h_2$ candidates
- Modelling these contributions with analytical matrix elements:
  - $\Lambda_b^0 \rightarrow J/\psi p K^-$ via intermediate Λ^*, P_c
  - $B^0 \rightarrow J/\psi K^+ \pi^-$ via intermediate K^*, Z_c
  - $B_s^0 \rightarrow J/\psi K^+ K^-$ via intermediate f, ϕ
- Without MEs (small contribution):
  - $B_{(s)}^0 \rightarrow J/\psi \pi^+ \pi^-$ via intermediate f, ρ
- Suppressing high background from Λ^*, K^*, f, ϕ in $h_1 h_2$ system:
  - Require $m(K\pi)$ and $m(\pi K) > 1.55$ GeV $\rightarrow m(pK) \gtrsim 2$ GeV
- Combinatorial background shapes:
  - events from $5.35 < m(J/\psi p K) < 5.45$ with scaled momenta
- Subtract same-sign $h_1 h_2$ combinations

- Further data fits are done using following regions:
  - Λ_b^0 signal region (SR): $5.59 < m(J/\psi p K) < 5.65$ GeV
  - B^0 control region (CR): $5.25 < m(J/\psi K \pi) < 5.31$ GeV
  - B_s^0 control region (CR): $5.337 < m(J/\psi K K) < 5.397$ GeV
- Λ_b^0 signal contribution to CRs is small
- All regions dominated by B^0 decays



Fitting strategy

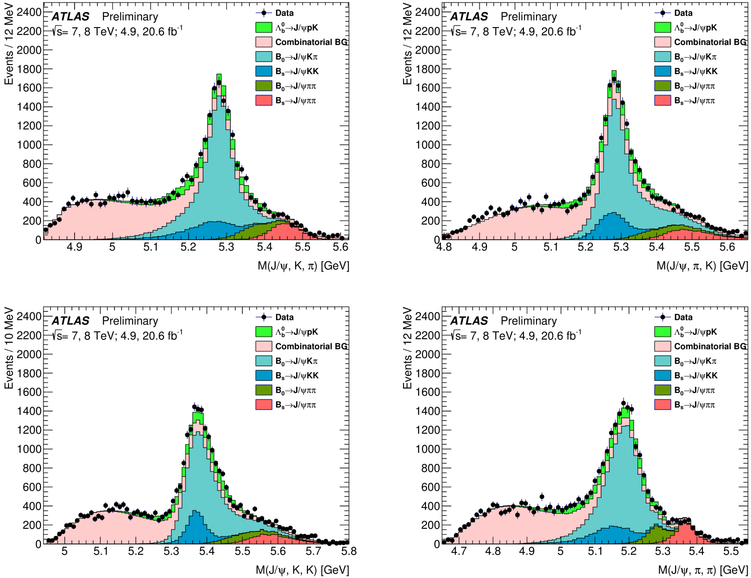
Iterative fit procedure due to complexity of the decay model – 4 steps at each iteration:

1. Global fit – extract the B^0 and B_s^0 coupling constants (Λ_b^0 couplings fixed)
   - Minimize sum of binned log-likelihoods of
     - 2D $M(J/\psi\pi K) \otimes M(J/\psi K\pi)$, 2D $M(J/\psi h_1 = K) \otimes M(J/\psi h_2 = \pi)$ (and swapped) in B^0 CR, $m(\pi K)$ and $m(K\pi)$ in B^0 CR
     - 2D $M(J/\psi KK) \otimes M(J/\psi\pi\pi)$, 2D $M(J/\psi h_1 = K) \otimes M(J/\psi h_2 = K)$ in B_s^0 CR, $m(KK)$in B_s^0 CR
2. $M(J/\psi pK)$ fit – extract the Λ_b^0, B^0, B_s^0 yields, and combinatorial background
   - χ^2 fit to $M(J/\psi pK)$
   - all couplings fixed
3. Λ_b^0 decays fit – obtain the Λ_b^0 decay constants
   - Minimize sum of binned log-likelihoods in the SR of
     - 2D $M(J/\psi h_1 = p) \otimes M(J/\psi h_2 = K)$ and $M(pK)$
4. $M(J/\psi p)$ fit – measure masses, widths, amplitudes and yields of the P_c signals
   - χ^2 fit to $M(J/\psi p)$ in SR

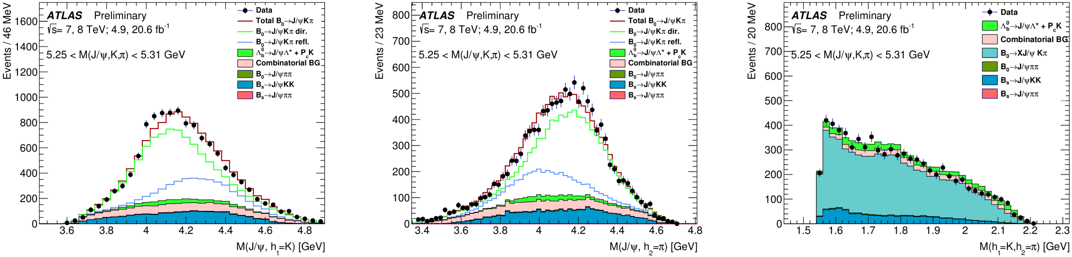
- Each iteration results used to fix parameters at corresponding steps of the next iteration
- Stop if no sizeable change in a next iteration – data fit converged after 4 iterations

B mesons make the principal physics backround for the analysis

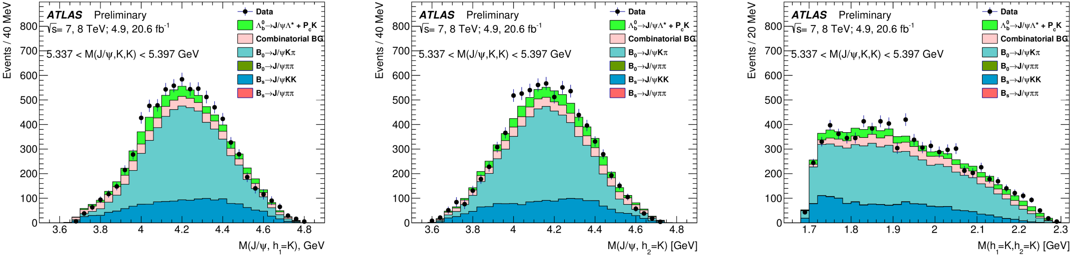
- The decay amplitudes determined from simulataneous $M(J/\psi h_1 h_2)$ fits in "global scope"...
- ...and $M(J/\psi h)$, $M(h_1 h_2)$ fits in corresponding CRs
- $h_1, h_2 = K, \pi$



$\boldsymbol{B}^0$ CR



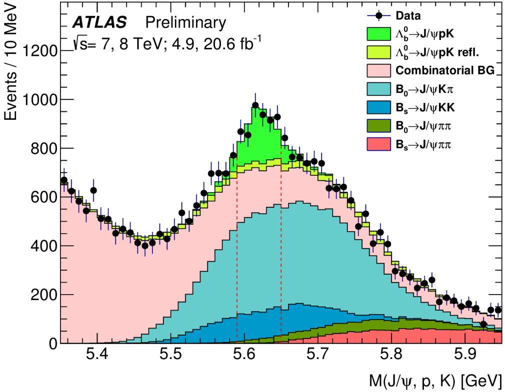
$\boldsymbol{B}_s^0$ CR



Decay yields (fit step 2)

Analyze signal process after the background decay parameters fixed at the step 1

- Fit the $M(J/\psi pK)$ distribution in the "global scope"
  - $N(\Lambda_b^0 \to J/\psi pK^-) = 2270 \pm 300$
  - $N(B^0 \to J/\psi K^+\pi^-) \approx 10770$
  - $N(B_s^0 \to J/\psi K^+K^-) \approx 2290$
  - $N(B^0 \to J/\psi \pi^+\pi^-) \approx 1070$
  - $N(B_s^0 \to J/\psi \pi^+\pi^-) \approx 1390$
- Further $\Lambda_b^0 \to J/\psi pK$ study is done in the SR (fit steps 3, 4)



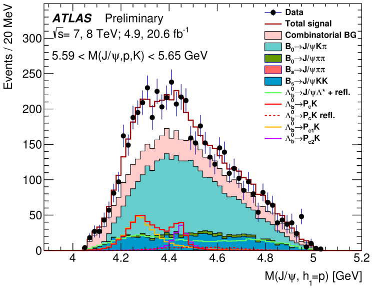
- $\Lambda_b^0 \to J/\psi pK$ yields in the SR:
  - 1010 ± 140 for right mass assignment
  - 160 ± 20 for wrong mass assignment

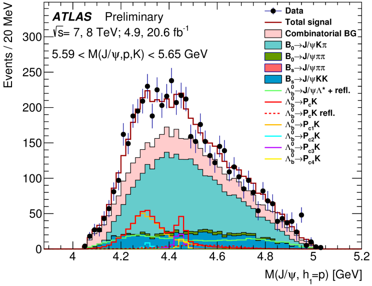
Final pentaquark fits

- Fit under 2 pentaquarks hypothesis yields

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	$140^{+77}_{-50}(\text{stat})^{+41}_{-33}(\text{syst})$ MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	$4449^{+20}_{-29}(\text{stat})^{+18}_{-10}(\text{syst})$ MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	$51^{+59}_{-48}(\text{stat})^{+14}_{-46}(\text{syst})$ MeV	$39 \pm 5 \pm 19$ MeV

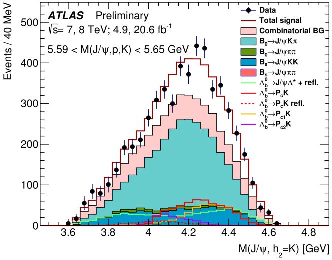
  - $\chi^2/\text{n.d.f.} = 31.7/39$ ($p = 55.7\%$)
  - Fixing M and Γ of the two P_c to LHCb values yields $\chi^2/\text{n.d.f.} = 49.0/43$ ($p = 24.5\%$)
- The new narrow P_c states cannot be distinguished by ATLAS due to a worse mass resolution and low stats
- Check the hypothesis by fixing their parameters to the LHCb results
  - $\chi^2/\text{n.d.f.} = 31.7/42$

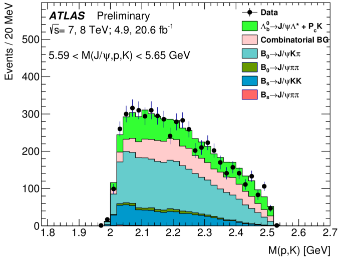


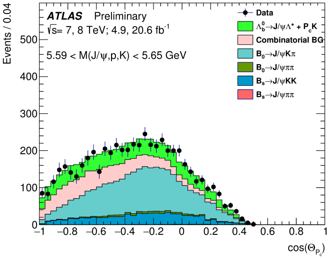


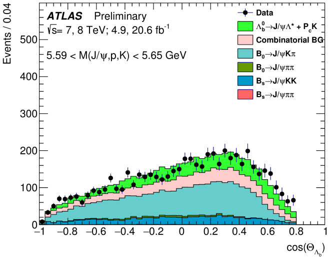
Control plots with 2 pentaquarks

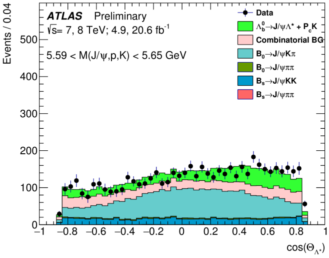
- Fit step 3 projections on $M(J/\psi K)$ and $M(pK)$ also show good agreement with data
- So do the angular variables distributions











Systematics sources

- *Non-pentaquark Λ_b^0 decay modelling* includes an extended Λ^* decay model allowing two lowest orbital momenta of certain Λ^* decay products
- *B meson decays modelling* allows for $Z_c(4200)^+$ intermediate state

Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1}+P_{c2})$	$\Delta\phi$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays	$^{+1.8}_{-0.6}\%$	$^{+6.6}_{-9.2}\%$	$^{+1.6}_{-0.8}\%$	$^{+0.3}_{-0.0}\%$
Pentaquark modelling	$^{+21}_{-0}\%$	$^{+1}_{-22}\%$	$^{+8.7}_{-4.4}\%$	$^{+1.6}_{-0.0}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling	$^{+14}_{-2}\%$	$^{+5}_{-44}\%$	$^{+9.2}_{-9.1}\%$	$^{+3.6}_{-1.6}\%$
Combinatorial background	$^{+0.7}_{-4.0}\%$	$^{+18}_{-5}\%$	$^{+4.2}_{-4.8}\%$	$^{+3.2}_{-0.0}\%$
B meson decays modelling	$^{+13}_{-25}\%$	$^{+28}_{-35}\%$	$^{+1.6}_{-9.3}\%$	$^{+0.5}_{-2.1}\%$
Total systematic uncertainty	$^{+28}_{-25}\%$	$^{+35}_{-61}\%$	$^{+14}_{-15}\%$	$^{+5.1}_{-2.7}\%$

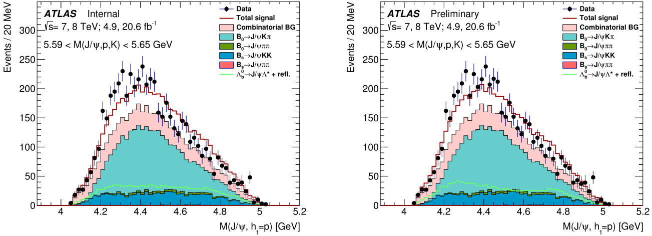
Source	$m(P_{c1})$	$\Gamma(P_{c1})$	$m(P_{c2})$	$\Gamma(P_{c2})$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays	$^{+0.06}_{-0.03}\%$	$^{+3.5}_{-2.5}\%$	$^{+0.07}_{-0.04}\%$	$^{+7}_{-13}\%$
Pentaquark modelling	$^{+0.6}_{-0.0}\%$	$^{+18}_{-0}\%$	$^{+0.2}_{-0.0}\%$	$^{+0}_{-33}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling	$^{+0.23}_{-0.05}\%$	$^{+9.2}_{-1.2}\%$	$^{+0.24}_{-0.02}\%$	$^{+2}_{-62}\%$
Combinatorial background	$^{+0.03}_{-0.15}\%$	$^{+0}_{-11}\%$	$^{+0.01}_{-0.17}\%$	$^{+22}_{-4}\%$
B meson decays modelling	$^{+0.24}_{-0.00}\%$	$^{+21}_{-21}\%$	$^{+0.27}_{-0.14}\%$	$^{+17}_{-57}\%$
Total systematic uncertainty	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

No-pentaquark hypothesis results

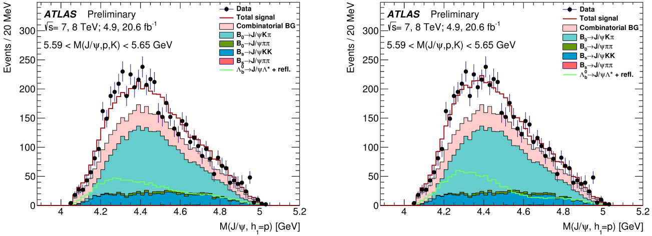
Fit procedure repeated using the Λ_b^0 decay model w/o pentaquarks

- Fit step 3 projection and a separate χ^2 fit of $M(J/\psi p)$ distribution show
- Nominal Λ_b^0 decay modelling yields
  - $\chi^2/\text{n.d.f.} = 69.2/37$, $p = 1.0 \times 10^{-3}$
- Test against all systematic variations
- Extended $\Lambda_b^0 \to J/\psi\Lambda^{*0}$ decay model yields the best agreement with data
  - $\chi^2/\text{n.d.f.} = 42.0/23$, $p = 9.1 \times 10^{-3}$

Nominal model w/o pentaquarks

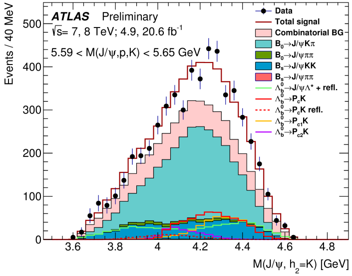


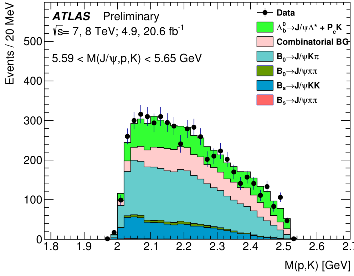
Extended Λ^* decay model w/o pentaquarks



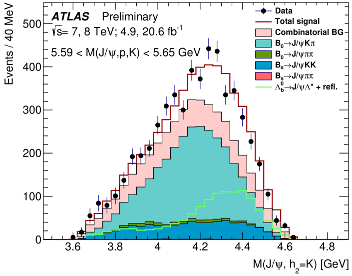
Control distributions for 2 pentaquarks and no pentaquarks

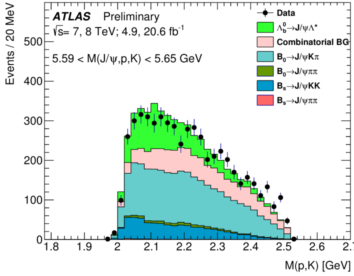
Fit step 3 projections for 2 pentaquarks hypothesis. . .





. . . and for no pentaquarks hypothesis with extended Λ^* decay model





Conclusions and plans

- Study of $J/\psi p$ resonances in $\Lambda_b^0 \to J/\psi p K^-$ performed with the full Run-1 dataset at $\sqrt{s} = 7, 8\,\text{TeV}$ analysed
  - *Model with 2 pentaquarks* yields 540 P_c events in total, with their parameter consistent with the LHCb results
  - *4 pentaquarks model* equally consistent with data
    - independent measurement too challenging yet
  - The *no pentaquarks model* describe data poorly, but still cannot be excluded ($p = 9.1 \times 10^{-3}$)
- Serious challenges have been overcome in the Run-1 analysis
  - Run-2 analysis will improve the result due to higher statistics, better resolution and the anticipated procedure improvements

- Just one study presented at this conference, but more spectroscopy&exotics results to come soon – stay tuned!

Backup slides

Event selection

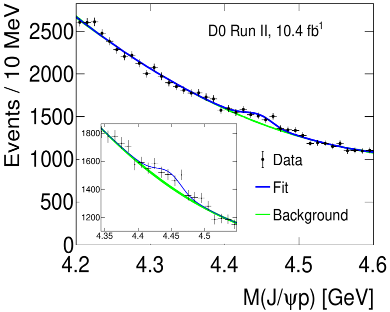
- Inclusive set of 2-muon, 3-muon and single-muon triggers
- Di-muon candidate vertex fit with $\chi^2 < 10$
  - $p_\mathrm{T}(\mu) > 4\,\mathrm{GeV}$, $|\eta(\mu) < 2.3|$
  - $m(\mu^+\mu^-)$ within $\pm 290\,\mathrm{MeV}$ of the J/ψ mass
- Fit the dimuon and two additional tracks to an H_b decay vertex, mass constraint on J/ψ and pointing to the PV
  - $\chi^2/\mathrm{n.d.f.} < 2$ $(\mathrm{n.d.f.} = 8)$
  - $L_{xy}(H_b) > 0.7\,\mathrm{mm}$
  - $p_\mathrm{T}(H_b)/\sum p_\mathrm{T}(\mathrm{trk}) > 0.2$
  - $p_\mathrm{T}(p) > 2.5\,\mathrm{GeV}$, $p_\mathrm{T}(K) > 2.5\,\mathrm{GeV}$, $|\eta(p, K)| < 2.5$
  - $\cos\theta_{P_c} < 0.5$
  - $\cos\theta_{\Lambda_b} < 0.8$
  - $|\cos\theta_{\Lambda^*}| < 0.85$
  - $p_\mathrm{T}(H_b) > 12\,\mathrm{GeV}$, $|\eta(H_b)| < 2.1$
  - $M(K\pi) > 1.55\,\mathrm{GeV}$ for both mass hypotheses

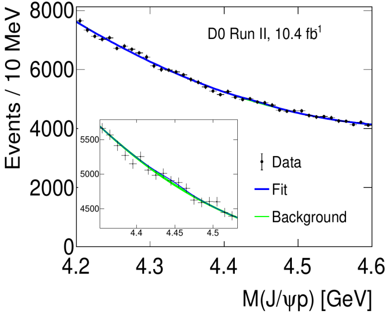
Angular variables

- $\cos\theta_{P_c} < 0.5$, where θ_{P_c} is the angle between J/ψ momentum in the P_c candidate rest frame and P_c candidate momentum in Λ_b candidate rest frame;
- $\cos\theta_{\Lambda_b} < 0.8$, where θ_{Λ_b} is the angle between P_c candidate momentum and Λ_b candidate momentum in laboratory frame;
- $|\cos\theta_{\Lambda^*}| < 0.85$,
  where θ_{Λ^*} is the angle between kaon momentum in $\Lambda^* \to pK$ candidate rest frame and Λ^* candidate momentum in Λ_b candidate rest frame.

D0 evidence for the pentaquarks

- D0 pentaquarks search in inclusive $J/\psi p$ sample: arXiv:1910.11767
  - Sum of $P_c(4440)+$ and $P_c(4457)^+$: 523 ± 145 non-prompt, 188 ± 263 prompt
  - $P_c(4312)^+$: 42 ± 132 non-prompt
- $P_c(4440)^+$ and $P_c(4457)^+$ non-prompt production siginficance 3.0σ
  - $N_{\text{prompt}}/N_{\text{non-prompt}} = 0.05 \pm 0.39$, < 0.8 @ 95% C.L.
  - Relative yield to $B^+ \to J/\psi K^+$: 0.03 ± 0.01
- No evidence for $P_c(4312)^+$
  - Relative rate < 0.6 @ 95% C.L. $\to$ consistent with LHCb

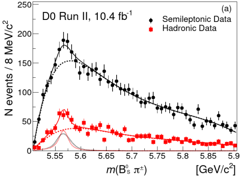




$B_s^0\pi^\pm$ mass structure search

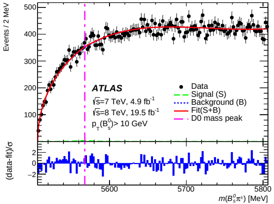
PRL 120 (2018) 202007

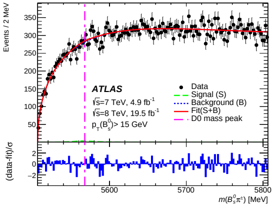
- A narrow structure $X(5568)$ was observed in $B_s^0\pi^\pm$ system by D0 (PRL 117 (2016) 022003, PRD 97 (2018) 092004): $\rho = (8.4 \pm 1.9 \pm 1.4)\%$

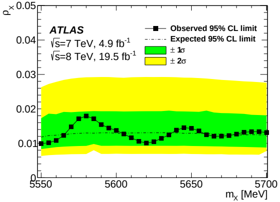


- Non-confirmations shortly published by LHCb (PRL 117 (2016) 152003), CMS (PRL 120 (2018) 202005) and CDF (PRL 120 (2018) 202006): 95% C.L. upper limits on ρ between 1.1 and 6.4%

- No signal found in ATLAS; for the D0 kinematics and mass, $\rho < 1.5\%$ @ 95% C.L.







- Search in $B_c^+\pi^+\pi^-$ final state, B_c^+ in $J/\psi\pi^+$ mode
  - Study the spectrum of $Q = m(B_c^+\pi^+\pi^-) - m(B_c^+) - 2m(\pi^+)$
- A new state observed at $Q = 288.3 \pm 3.5(\text{stat.}) \pm 4.1(\text{syst.})$ MeV
  - Corresponds to a mass $6842 \pm 4(\text{stat.}) \pm 5(\text{syst.})$ MeV, consistent with the predicted mass of $B_c^+(2S)$
  - Combined significance is 5.2σ
- Possible interpretation: one or both of
  - $B_c^+[2^3S_1] \to B_c^{+*}(1S)(\to B_c^+\gamma)\pi^+\pi^-$
  - $B_c^+[2^1S_0] \to B_c^+(1S)\pi^+\pi^-$
- CMS observed two separate states, measured the production rate (CMS-PAS-BPH-19-001)
  - LHCb also sees two signals (PRL 122 (2019) 232001)
- Further study in ATLAS underway