ATLAS results on exotic heavy hadrons

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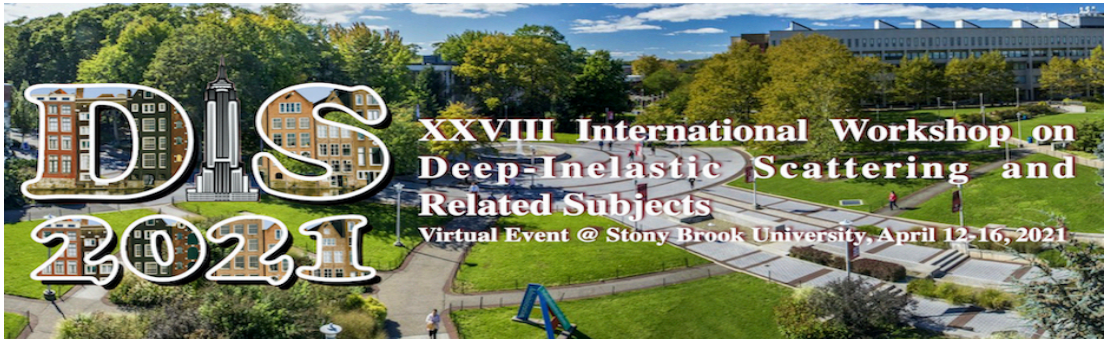
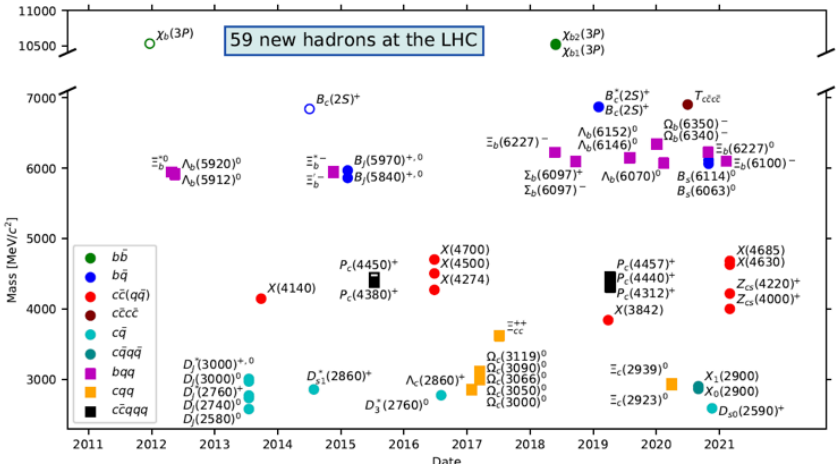
On behalf on the ATLAS Collaboration



Outline

- Selected results on tetra- and penta-quark state searches with heavy hadrons
- Pentaquark: Study of $\Lambda^0_b \rightarrow J/\psi p K^-$ (ATLAS-CONF-2019-048)
  - Experimental status
  - ATLAS analysis strategy
  - Results and comparison with LHCb results
- Tetraquark:
  - Search for $X^{\pm}(5568) \rightarrow B^0_s \pi^{\pm}$ resonance (Phys.Rev.Lett. 120(2018)202007)
  - Perspective for $Z_c^+(4200)$
- Conclusions

Hadron spectroscopy boosted by LHC

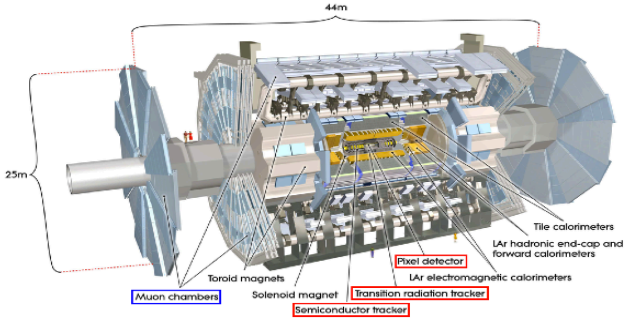


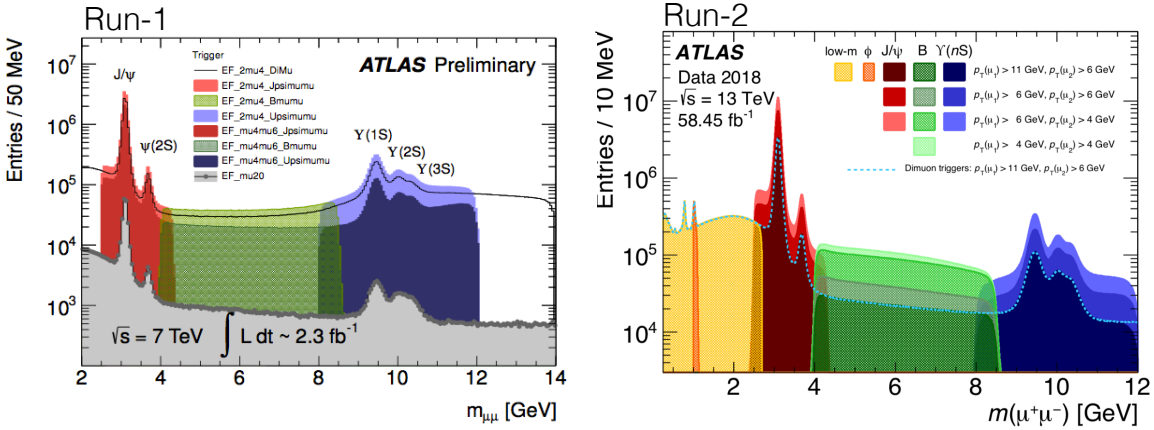
https://home.cern/news/news/physics/59-new-hadrons-and-counting

B-physics selected results among the many published by the Collaboration

Detector and trigger

- Trigger selection for heavy flavor studies mostly based on di-muon signature
  - Muon p_T threshold (4 or 6 GeV)
  - Di-muon vertex reconstruction
  - Invariant mass window
- No $\pi^{\pm}/K^{\pm}/p$ separation capability





Di-μ invariant mass spectrum

- Run-2 improvements
  - Trigger upgrade → maintain low muon threshold at high lumi
  - IBL (new vertex detector) → improves vertexing reconstruction
  - Increased statistics

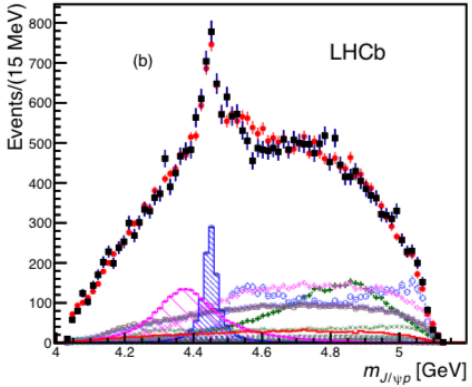
→ Great potential for new results in heavy flavor physics studies

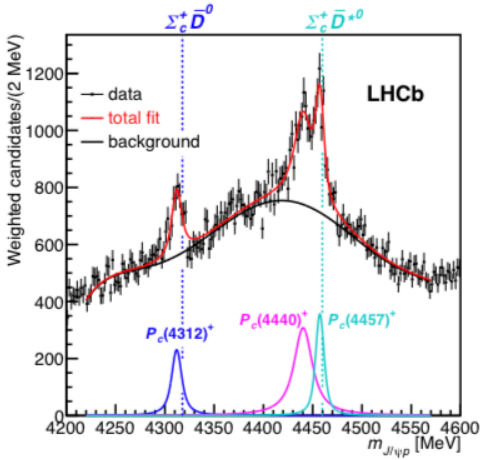
Study of $\Lambda^0_b \rightarrow J/\psi p K^-$

Experimental status

- Driven by LHCb
  - 2015: 2 structures observed in (J/ψp) mass spectrum in $\Lambda^0_b \rightarrow J/\psi p K^-$ decay (PRL 115 (2015) 072001)
  - 2016: Evidence in $\Lambda^0_b \rightarrow J/\psi p \pi^-$ with preferred $J^p = 3/2^-$ and $5/2^+$
  - 2016: Model-independent evidence (PRL 117 (2016) 082003)
  - 2019 (Run2 data): $P_c(4450)^+$ resolved into 2 states (4440-4457); discovered $P_c(4312)^+$ and hint for a 4th broader state $P_c(4380)^+$ (PRL 122 (2019) 222001)
- Not observed by GLUEX in γp → J/ψp s-channel (PRL 123 (2019) 072001)
- Recent 3.1σ evidence reported by D0 at Moriond '21
  - Unresolved $P_c(4440)+P_c(4457)$ peak in inclusive $P_c \rightarrow J/\psi p$ channel (no reconstruction of Λ^0_b) (arXiv:1910.11767)

Confirmation from another experiment would be very welcome





Dataset & Event selection

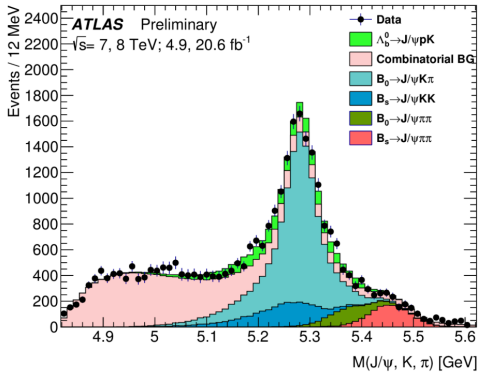
- Dataset: pp at $\sqrt{s}$ = 7 TeV (4.9 fb^{-1}) and 8 TeV (20.6 fb^{-1})

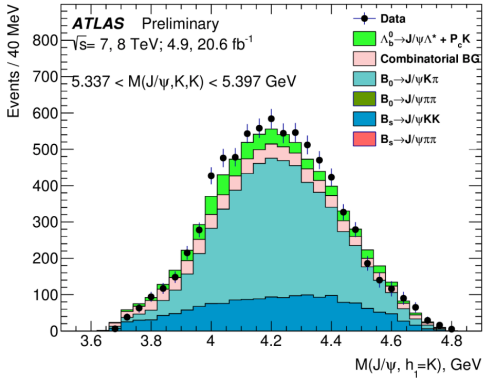
- No $\pi^{\pm}$/$K^{\pm}$/p separation → all H_b → $J/\psi h_1 h_2$ candidates considered
- J/ψ → $\mu^+\mu^-$ selection
  - $p_T(\mu^{\pm})$ > 4 GeV; $|\eta(\mu^{\pm})|$<2.3
  - $|M(J/\psi)_{WA} - m(\mu^+\mu^-)|$ < 290 MeV
- B-hadron (H_b = Λ_b, B^0, B_s) candidate selection
  - Di-muon (J/ψ) candidate + 2 charged particles with $|\eta|$<2.5
  - $p_T(H_b)$ > 12 GeV; $|\eta(H_b)|$<2.1
- Combinatorial bkg (modeled with analytical matrix elements)
  - Λ^0_b → $J/\psi\ \Lambda^*/P_c$ → $J/\psi\ pK^-$
  - B^0 → $J/\psi\ K^*/Z_c$ → $J/\psi\ K^+\pi^-$
  - B_s → $J/\psi\ f/\phi$ → $J/\psi\ K^+K^-$
  - Suppressed by requiring m(Kπ) >1.55 GeV (→ m(pK) > 2 GeV)
- Same-sign h_1h_2 combinations subtracted

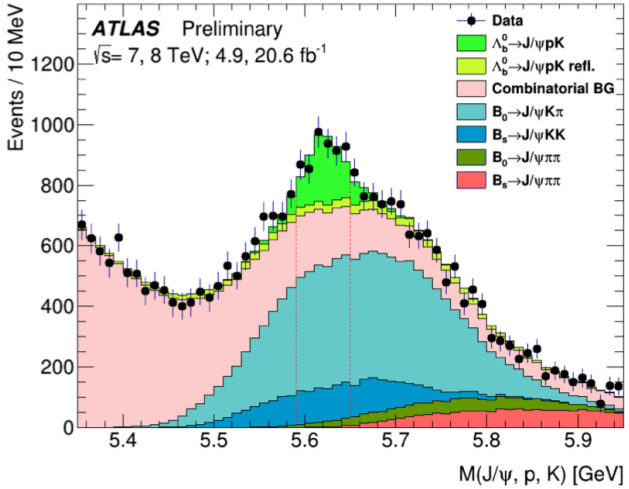
Region definition	Mass interval (GeV)
Λ^0_b Signal Region	5.59 < m(J/ψpK) < 5.65
B^0 Control Region	5.25 < m($J/\psi K\pi$) < 5.31
B_s Control Region	5.337 < m(J/ψKK) < 5.397
Comb. bkg shape	5.35 < m(J/ψpK) < 5.45

Fit procedure

- Fit to all kinematic distributions
  - M(J/ψ Kπ)
  - M(J/ψ πK)
  - M(J/ψ KK)
  - M(J/ψ ππ)
  - M(J/ψ h) & M(h_1h_2) in B^0 CR
  - M(J/ψ h) & M(h_1h_2) in B_s CR







Fitted Yields

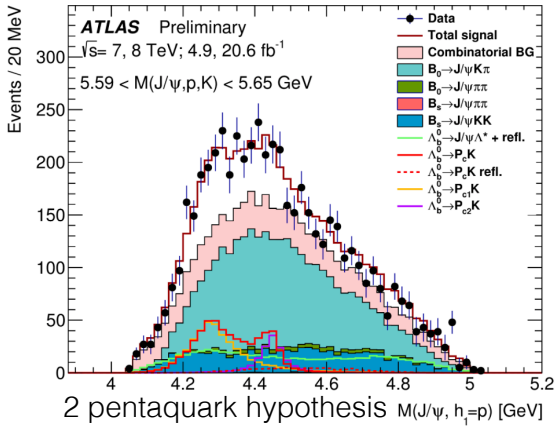
$$N(\Lambda_b^0 \to J/\psi p K^-) = 2270 \pm 300$$
$$N(B^0 \to J/\psi K^+\pi^-) \approx 10770$$
$$N(B_s^0 \to J/\psi K^+K^-) \approx 2290$$
$$N(B^0 \to J/\psi \pi^+\pi^-) \approx 1070$$
$$N(B_s^0 \to J/\psi \pi^+\pi^-) \approx 1390$$

Λ^0_b → J/ψ pK yields in Signal Region:
1010±140 for right mass assignment
160±20 for wrong mass assignment

Fit results

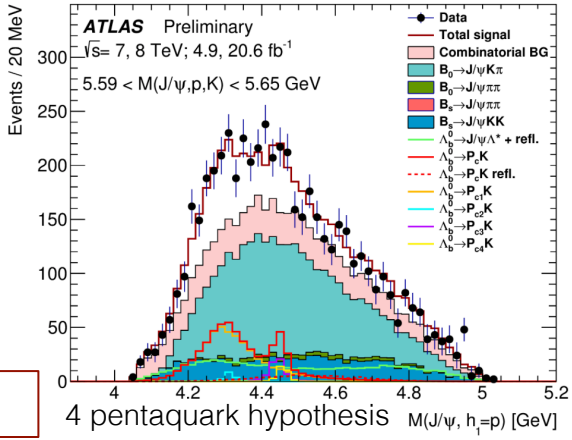
- Fit results for 2 pentaquarks ($3/2^-$, $5/2^+$)

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} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV



- Good description of data: χ^2/ndf = 37.1/39 (p = 55.7%)

- 4-pentaquark hypothesis
  - can't be distinguished because of low mass resolution and limited stat
  - Tested by fixing parameters to LHCb ones
  - χ^2/ndf = 37.1/42 (p = 68.6%)



2- and 4-pentaquark models both consistent with data

Systematics

- Four main source of systematics affecting signal yields, relative phase, masses and widths

Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1}+P_{c2})$	$\Delta\phi$	$m(P_{c1})$	$\Gamma(P_{c1})$	$m(P_{c2})$	$\Gamma(P_{c2})$
Number of $\Lambda_b^0 \to J/\psi p K^-$ decays	$^{+1.8}_{-0.6}\%$	$^{+6.6}_{-9.2}\%$	$^{+1.6}_{-0.8}\%$	$^{+0.3}_{-0.0}\%$	$^{+0.06}_{-0.03}\%$	$^{+3.5}_{-2.5}\%$	$^{+0.07}_{-0.04}\%$	$^{+7}_{-13}\%$
Pentaquark modelling	$^{+21}_{-0}\%$	$^{+1}_{-22}\%$	$^{+8.7}_{-4.4}\%$	$^{+1.6}_{-0.0}\%$	$^{+0.6}_{-0.0}\%$	$^{+18}_{-0}\%$	$^{+0.2}_{-0.0}\%$	$^{+0}_{-33}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling	$^{+14}_{-2}\%$	$^{+5}_{-44}\%$	$^{+9.2}_{-9.1}\%$	$^{+3.6}_{-1.6}\%$	$^{+0.23}_{-0.05}\%$	$^{+9.2}_{-1.2}\%$	$^{+0.24}_{-0.02}\%$	$^{+2}_{-62}\%$
Combinatorial background	$^{+0.7}_{-4.0}\%$	$^{+18}_{-5}\%$	$^{+4.2}_{-4.8}\%$	$^{+3.2}_{-0.0}\%$	$^{+0.03}_{-0.15}\%$	$^{+0}_{-11}\%$	$^{+0.01}_{-0.17}\%$	$^{+22}_{-4}\%$
B meson decays modelling	$^{+13}_{-25}\%$	$^{+28}_{-35}\%$	$^{+1.6}_{-9.3}\%$	$^{+0.5}_{-2.1}\%$	$^{+0.24}_{-0.00}\%$	$^{+21}_{-21}\%$	$^{+0.27}_{-0.14}\%$	$^{+17}_{-57}\%$
Total systematic uncertainty	$^{+28}_{-25}\%$	$^{+35}_{-61}\%$	$^{+14}_{-15}\%$	$^{+5.1}_{-2.7}\%$	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

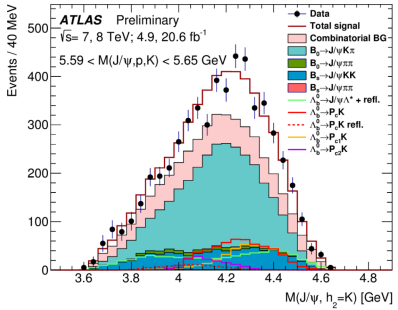
- Pentaquark modeling includes:
  - alternative J^p hypotheses for 2 pentaquarks,
  - P_c decay models with all possible orbital momentum between their decay products
  - model with 4 pentaquark
- Non-pentaquark $\Lambda^0_b \to J/\psi pK$ modeling includes the extended $\Lambda^0_b \to J/\psi \Lambda^{*0}$ decay model
- B meson decay modeling includes:
  - Contribution from $Z_c(4200)$ intermediate state

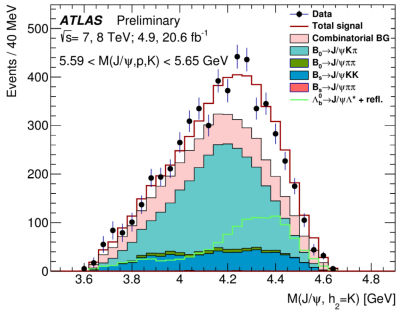
Systematic uncertainties comparable to statistical ones:
$N(P_{c1}+P_{c2}) = 540^{+80}_{-70}(stat)^{+70}_{-80}(syst)$

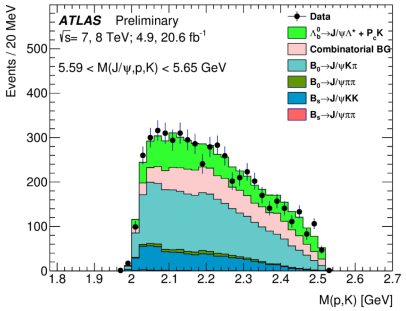
No-pentaquark test hypothesis

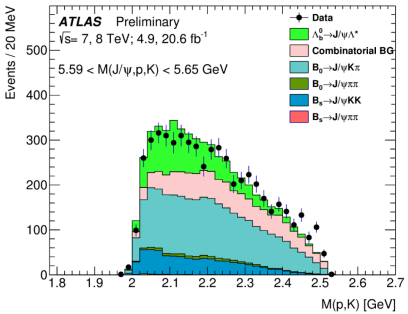
- Iterative fit procedure repeated using the $\Lambda^0_b \rightarrow J/\psi pK$ decay model w/o pentaquarks
  - $\chi^2/ndf = 69.2/37$ ($p = 1.0 \times 10^{-3}$)
  - $\chi^2/ndf = 42.0/23$ ($p = 9.1 \times 10^{-3}$) including the extended $\Lambda^0_b \rightarrow J/\psi \Lambda^{*0}$ decay model

- Control distributions for 2- and 0- pentaquark hypotheses:

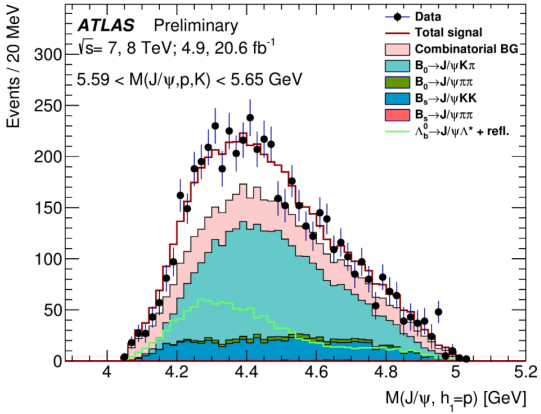








Model without pentaquark strongly disfavored but can't be excluded yet



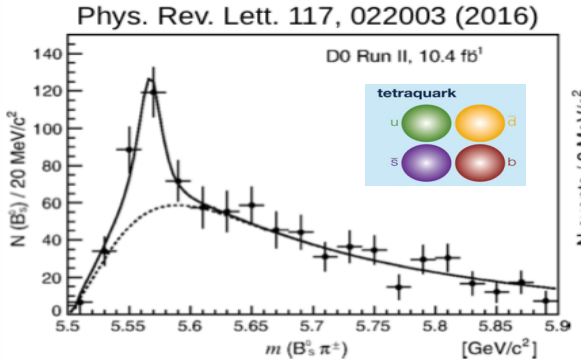
χ^2 fit of the m(J/ψp) distribution in the signal region for the hypothesis without pentaquarks with the extended $\Lambda^0_b \rightarrow J/\psi \Lambda^{*0}$ decay model

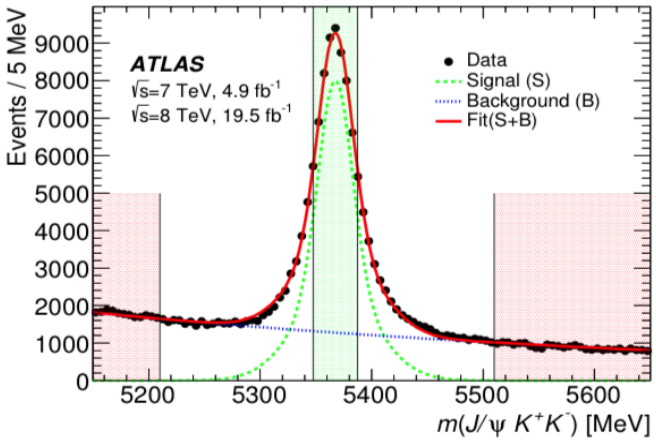
Ongoing analysis with Run-2 data
~5x more Λ^0_b candidate statistic and improved mass resolution

Searches for tetraquark states

Search for $X^{\pm} \rightarrow B^0_s \pi^{\pm}$ resonance

- D0 published evidence of a (tetraquark) state X(5568) in the $B_s \pi^{\pm}$ spectrum via $B_s^0 \rightarrow J/\psi\, \phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$
- Also seen in semi-leptonic decays: $X^{\pm}(5568) \rightarrow B^0_s \pi^{\pm}$ where $B^0_s \rightarrow \mu^{\pm} D^{\pm}_s X$, $D^{\pm}_s \rightarrow \phi\pi^{\pm}$
- Not seen by LHCb, nor CDF, nor CMS
- LHC experiments have enough statistic to observe a signal or set precise limits on production cross-section



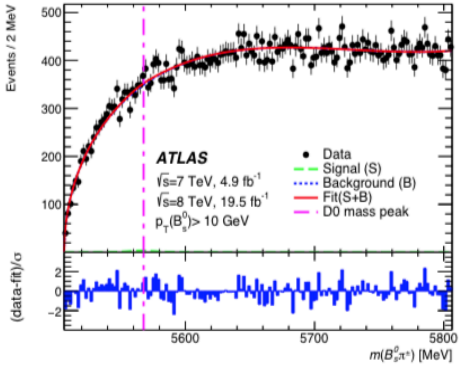


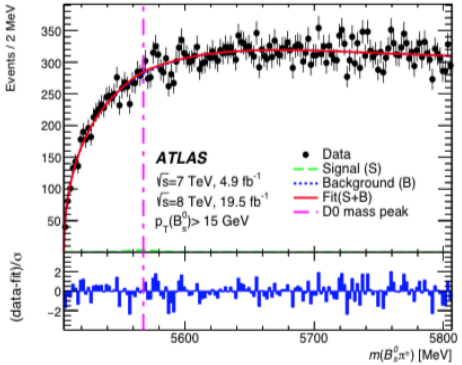
B^0_s yield from fit: $N(B^0_s) = 52750 \pm 280$

ATLAS uses 4.9 fb^{-1} at 7 TeV + 19.5 fb^{-1} at 8 TeV data

- $B^0_s \pi^{\pm}$ candidates selected by requiring a charged track, with p_T>500 MeV + track quality cuts, from the same PV as the B^0_s
- Analysis repeated for $p_T(B^0_s)$>10 GeV and for $p_T(B^0_s)$>15 GeV

Search for $X^{\pm} \rightarrow B^0_s \pi^{\pm}$ resonance



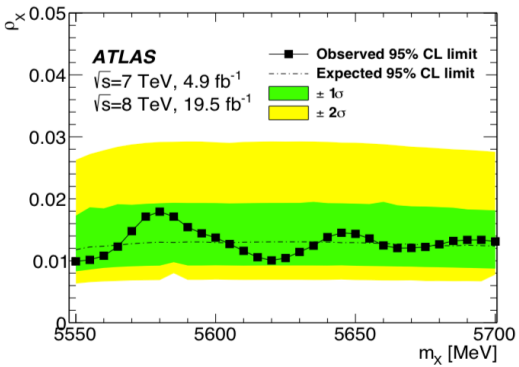


Number of $X^{\pm}$ candidates from unbinned max-likelihood fit

$N(X)\ p_T(B^0_s)>10$ GeV	$N(X)\ p_T(B^0_s)>15$ GeV
60±140	30±150

- No signal evidence → set upper limits set on cross-section ratio of X(5568) to B^0_s

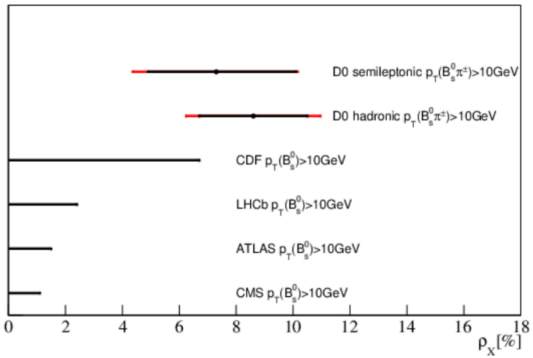
$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything})\,\mathcal{B}(X \to B^0_s \pi^{\pm})}{\sigma(pp \to B^0_s + \text{anything})} = \frac{N_X}{\epsilon_{rel} N_{B^0_s}}$$



- Asymptotic CLs method

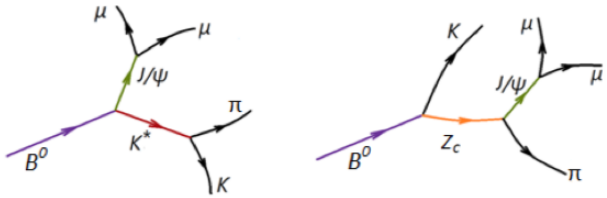
$$\rho_X < 1.5\% \text{ at } 95\% \text{ CL for } p_T(B^0_s) > 10 \text{ GeV}$$
$$\rho_X < 1.6\% \text{ at } 95\% \text{ CL for } p_T(B^0_s) > 15 \text{ GeV}$$

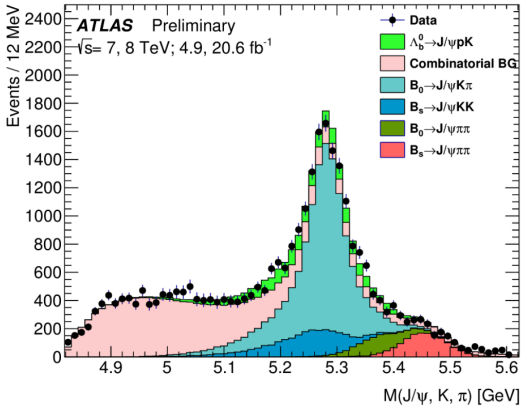
Comparison of X(5568) searches from Tevatron and LHC experiments (arXiv:2010.00676) for p_T>10 GeV bin. Combination of LHC results gives ρ_X<1% for both p_T bins



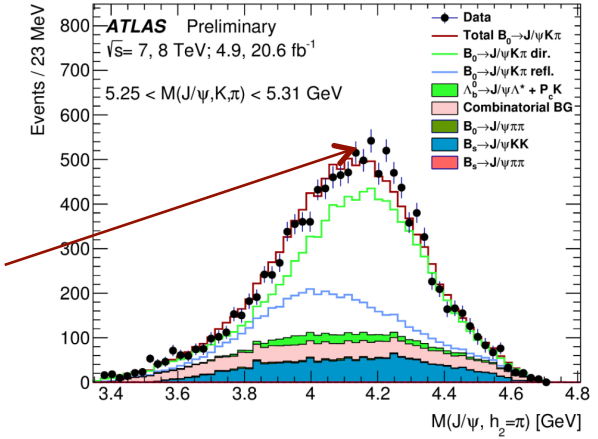
Perspective on $Z_c(4200)$

- Study of $Z_c(4200)$ exotic state with ATLAS Run2 data is ongoing
- Purity of B^0 → J/ψ Kπ sample >70%
- ~30-40k events in high m(p,K) mass region for ~140 fb^{-1} at √s=13 TeV
- Promising for exotic states searches





- Hint on $Z_c(4200)$ contribution from B^0 control region of Run-1 pentaquark analysis



Summary

- ATLAS has a rich physics program for studies of exotic heavy hadrons
- Here presented selected results on

- Pentaquark: Study of $\Lambda^0_b \rightarrow J/\psi p K^-$ (ATLAS-CONF-2019-048) with Run-1 data
  - Model with 2 pentaquarks $P_c \rightarrow J/\psi p$ consistent with data (and with LHCb results) with 540 candidate events found
  - Model with 4 pentaquarks consistent with data too, but can't be resolved
  - Model with 0 pentaquark strongly disfavored but can't be totally excluded → more stat needed
  - Analysis of Run-2 data ongoing. Large improvement expected from larger statistics and better resolution
- Search for $X^{\pm}(5568) \rightarrow B^0_s \pi^{\pm}$ resonance (Phys.Rev.Lett. 120(2018)202007)
  - No evidence; strong limits set on cross-section
- Searches of Z_c state with Run-2 data ongoing
  - Results to come soon

More studies ongoing; more results to come in the next months

Thank you!