AMHME 2019

Overview on exotica production at ATLAS

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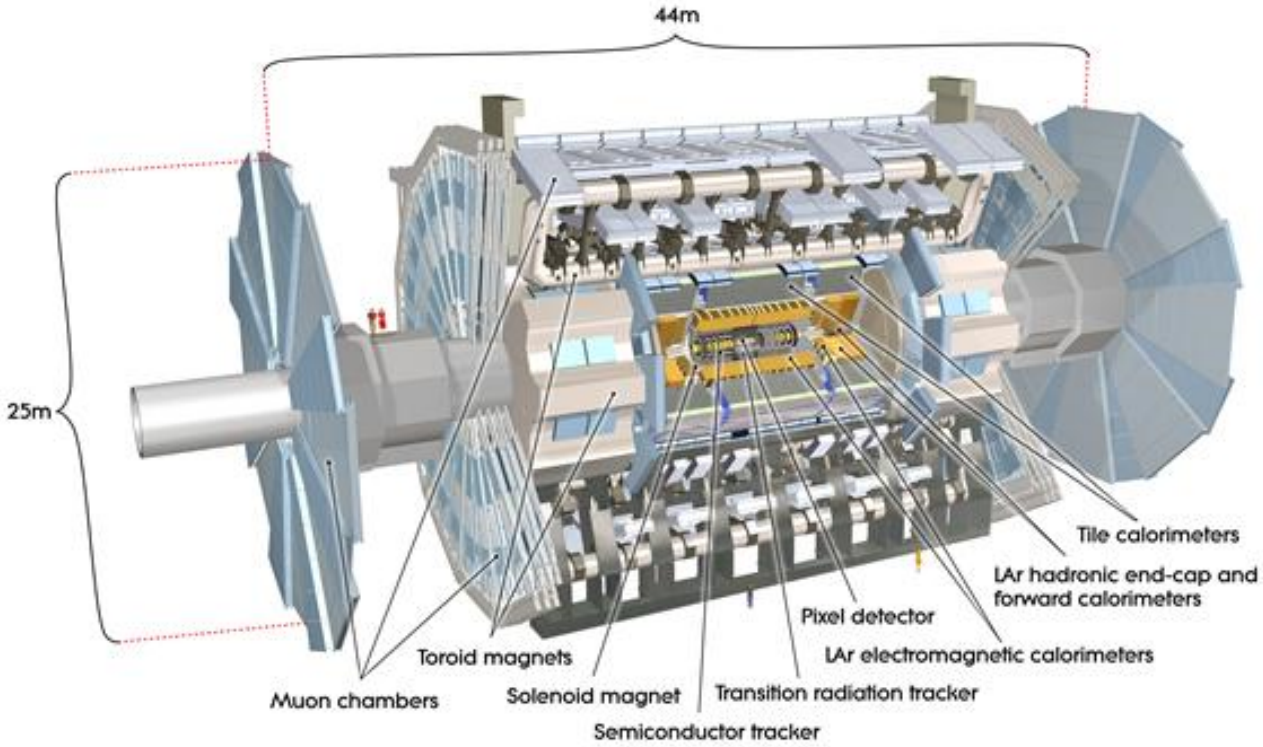
Summary

Introduction

- Exotic hadrons: everything beyond qq-meson and qqq-baryon scheme
  - First predicted in 1964 the original papers by M. Gell-Mann and G. Zweig
  - First seen by Belle in 2003 [PRL 91, 262001 (2003)]
    $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$ [aka $\chi_{c1}(3872)$]
- Exotic Charminium-like states
  - X: neutral, positive parity, first seen in B decays
  - Y: neutral, negative parity, first seen in e^+e^- annihilation with ISR
  - Z: charged (and their isospin partners)
  - P: pentaquarks, first seen by LHCb in $J/\psi p$ system from $\Lambda_b \to J/\psi p K^-$ decays [PRL 115, 072001 (2015)]
- Lots of predictions within different theoretical models
  - Tetraquarks, diquark-onium, molecules, etc.

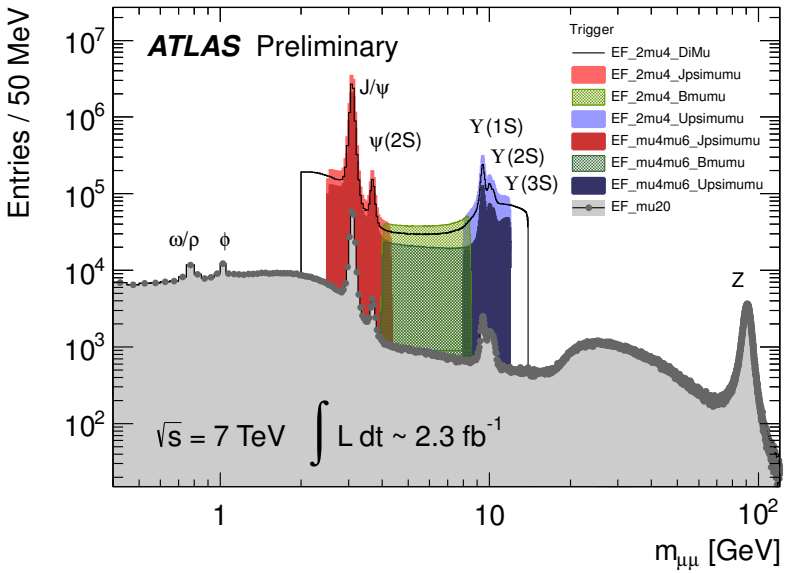
The ATLAS detector

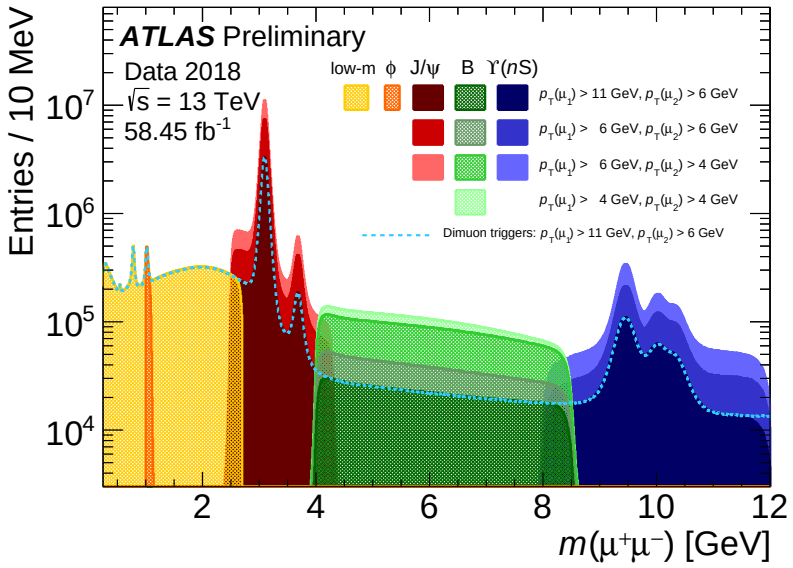


- Subsystems most relevant to *B*-physics:
  - Inner Detector (PIX, SCT and TRT): tracking, momentum and vertexing, $|\eta| < 2.5$
  - Muon Spectrometer: trigger and muon identification, $|\eta| < 2.7$

Trigger system

- For Run-1, events were collected with mixture of triggers based on identification a $J/\psi \to \mu^+\mu^-$ decay, with muon pT thresholds of either 4 GeV or 6 GeV (vary over run periods).
- No lifetime or impact parameter cut at HLT level.



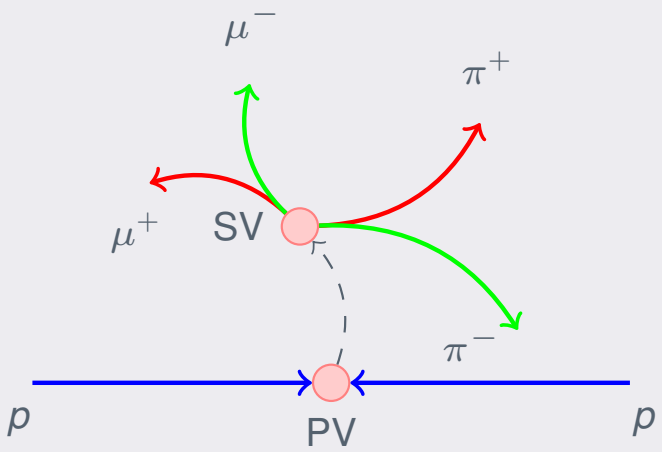


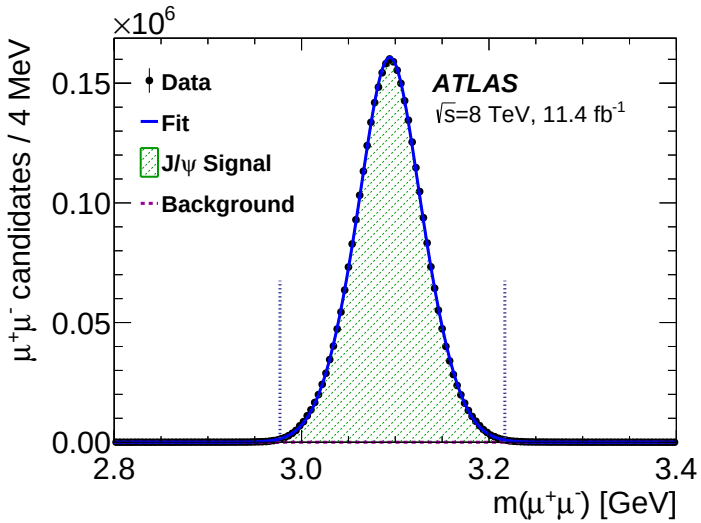
$X(3872)$ production at 8 TeV

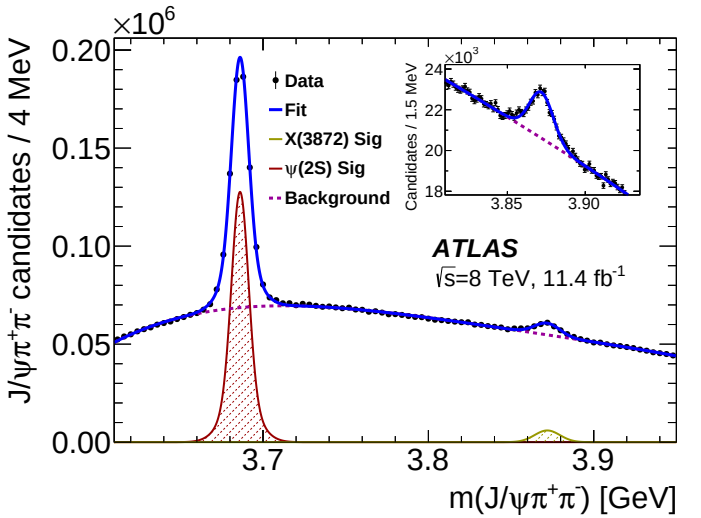
JHEP 01 (2017) 117

Analysis overview

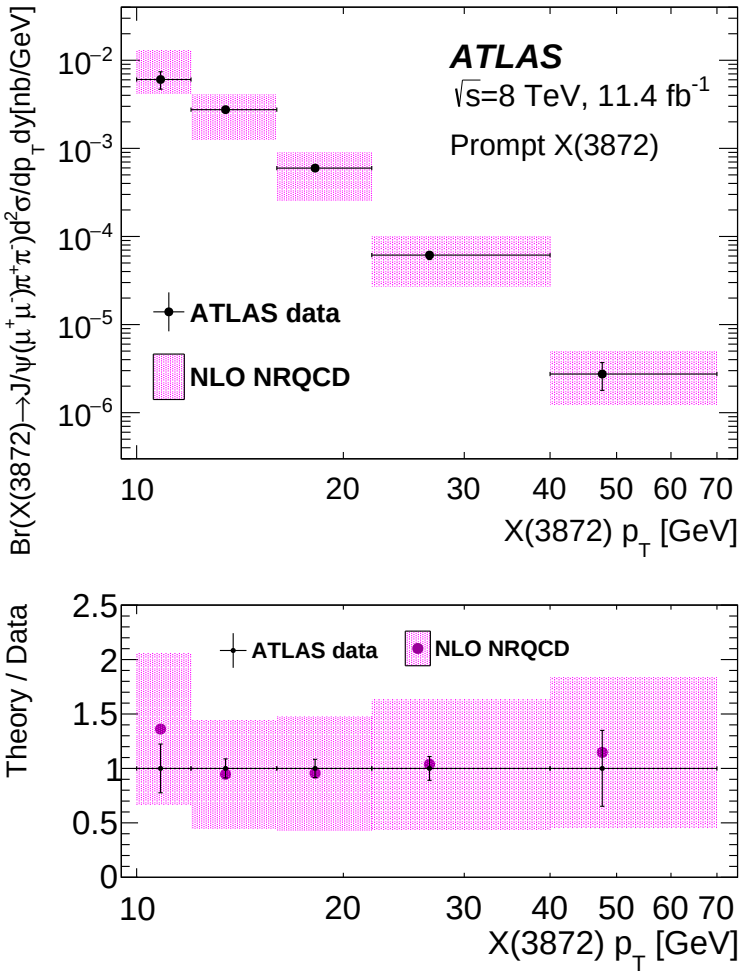
- 11.4 fb^{-1} of pp collision data at 8 TeV
- J/ψ candidates formed by fitting a muon pair to a common vertex
- Combine a J/ψ candidate with another 2 tracks assumed as pions
- Di-muon mass is constrained to the J/ψ mass in a 4-prong vertex fit

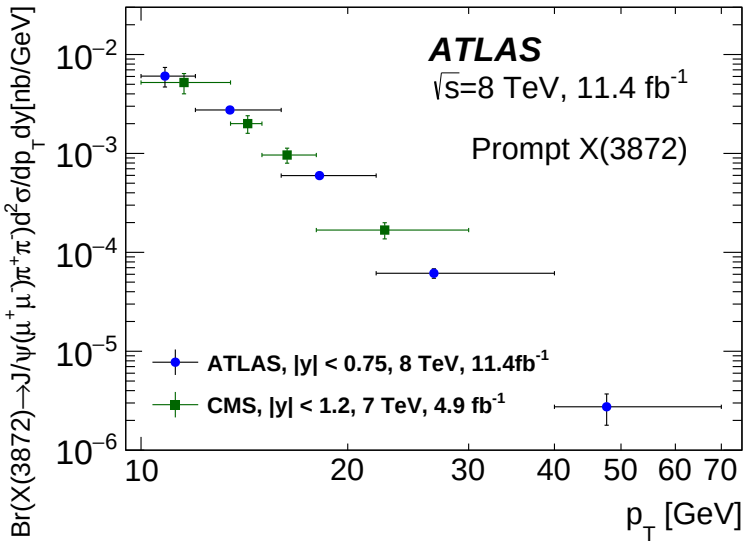






Measured cross sections

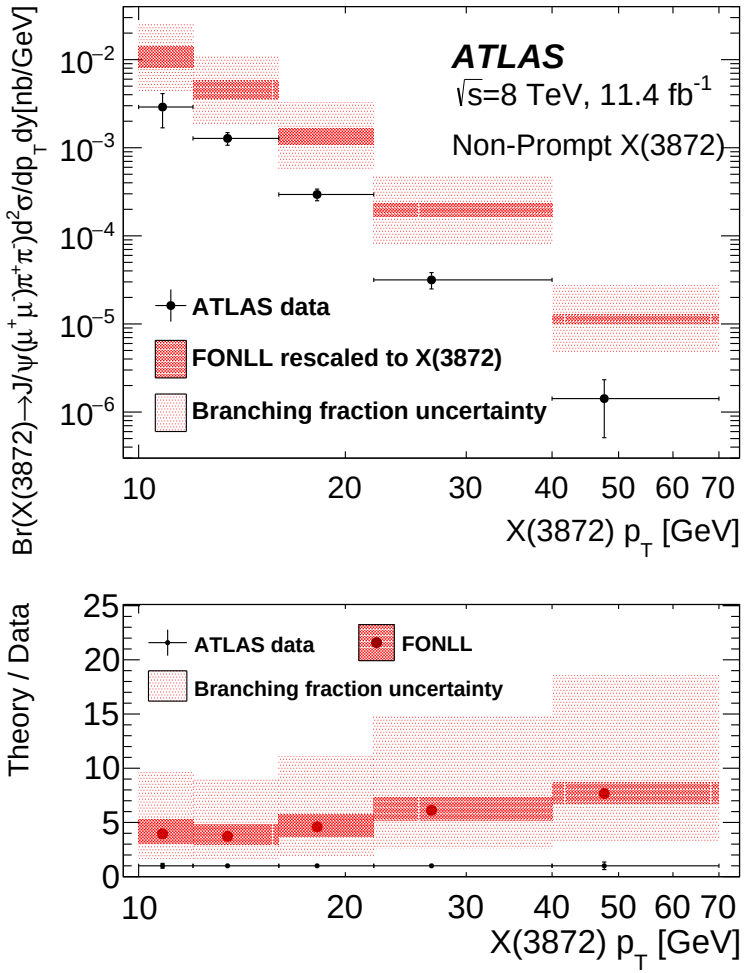


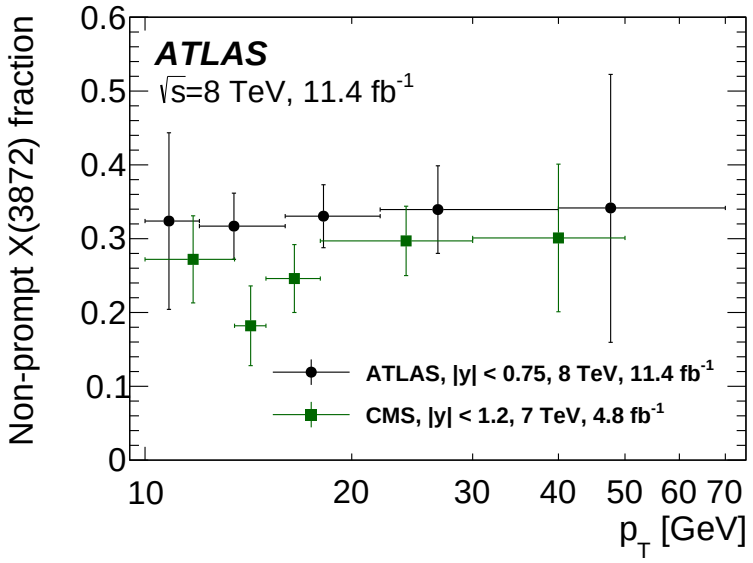


- The prompt $X(3872)$ cross-section measurement shows good agreement with NLO NRQCD prediction, which considers $X(3872)$ to be a mixture of $\chi_{c1}(2P)$ and a $D^0\bar{D}^{*0}$ molecular state.

- However, $\chi_{c1}(2P)$ contribution is dominant and enough to describe the prompt $X(3872)$ production.

Measured cross sections



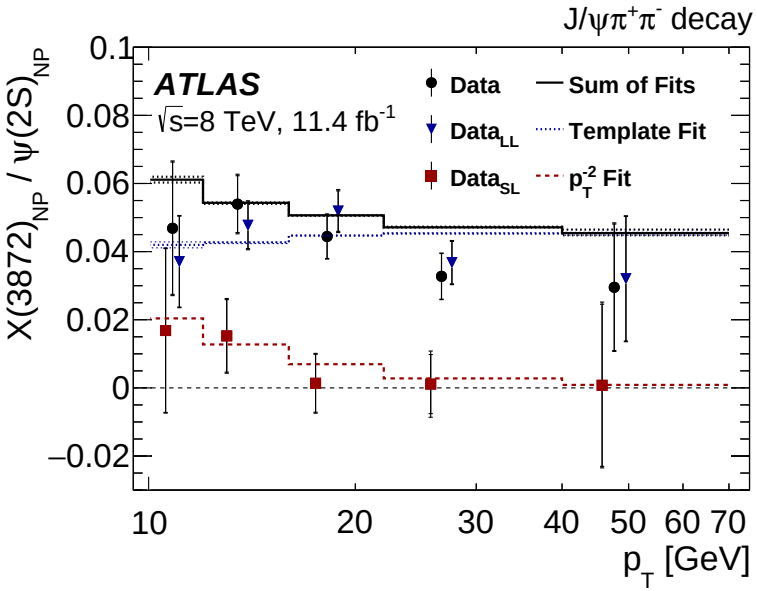


- The non-prompt fraction of $X(3872)$ shows no sizeable dependence on pT
- Agrees within errors with the CMS result at 7 TeV [JHEP 04 (2013) 154]

Ratio of non-prompt $X(3872)$ to $\psi(2S)$

- Long-lived part (fitted with MC kinematic template)

$$R_B^{2L} = \frac{\mathcal{B}(B \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any})\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.57 \pm 0.33_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-2}$$



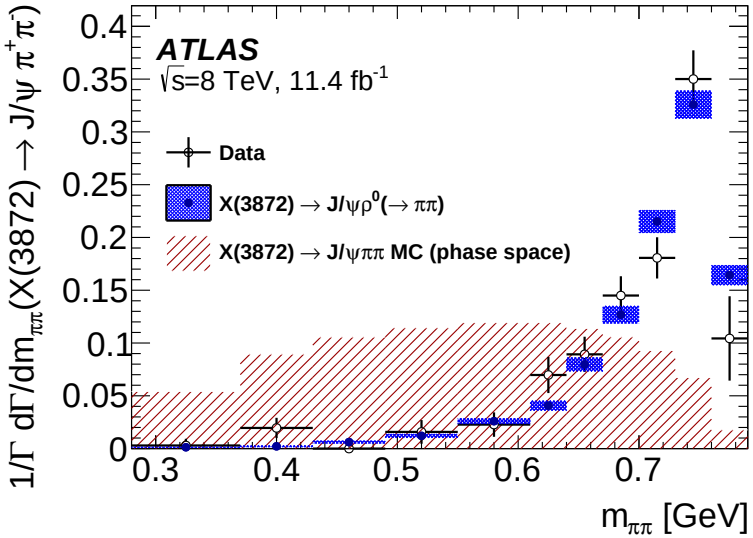
- Short-lived part
  - Assume non-fragmentation process dominated at low pT
  - Fit with a/p_T^2 relative to the fragmentation contribution
  - Integrate over pT range ($>$ 10 GeV) to determine the fraction of non-prompt $X(3872)$ from short-lived sources

$$\frac{\sigma(pp \to B_c)\mathcal{B}(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt})X(3872)} = (25 \pm 13_{\text{stat}} \pm 2_{\text{syst}} \pm 5_{\text{spin}})\%$$

- B_c small fraction of b hadron prodcution at LHC
  $\Longrightarrow$ Suggestion of $X(3872)$ production enhanced in B_c decays

Invariant mass of the dipion system

- The invariant mass distributions of the dipion system in $X(3872) \to J/\psi\pi^+\pi^-$ decays is measured.



- The result disfavors a phase-space distribution, and point strongly to the dominance of $X(3872) \to J/\psi\rho^0$ mode.

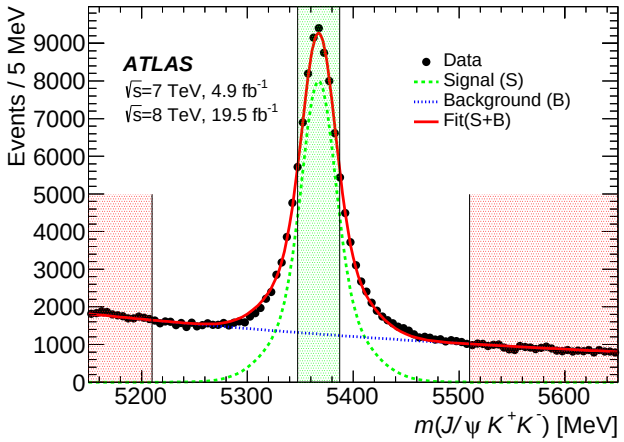
Search for $X(5568)$ in $B_s^0\pi^+$ state

Phys. Rev. Lett. 120, 202007 (2018)

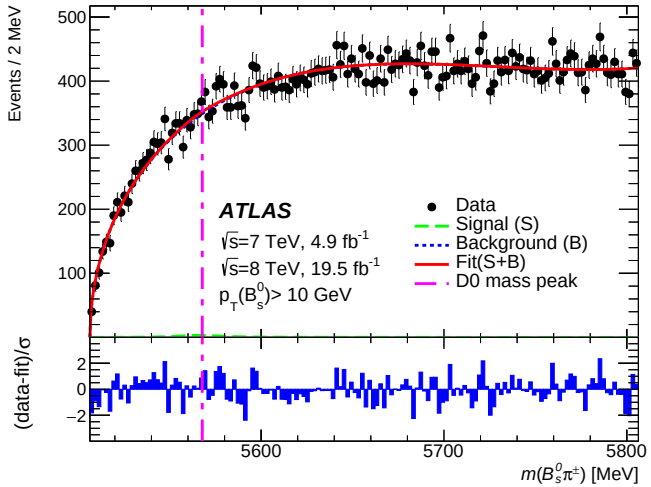
Analysis overview

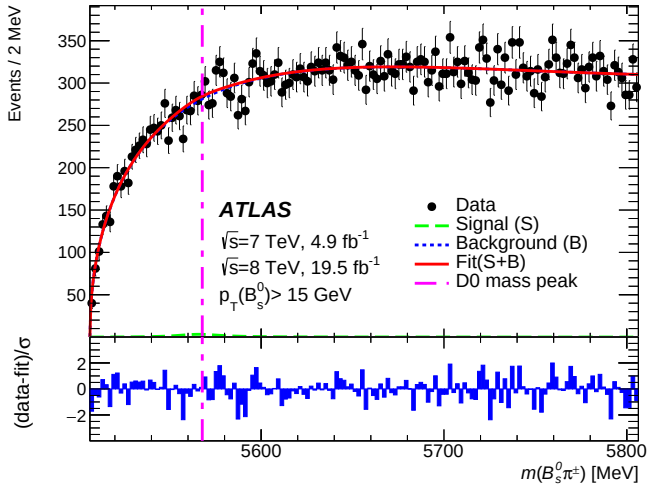
D0 reported evidence of a narrow structure, $X(5568)$, which was interpreted as a tetraquark with four different quark flavors: b, s, u, d. [PRL 117, 022003 (2016)]

- 4.9 fb^{-1} of pp collision data at 7 TeV and 19.5 fb^{-1} at 8 TeV
- Reconstruct B_s^0 mesons in their decays to $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$



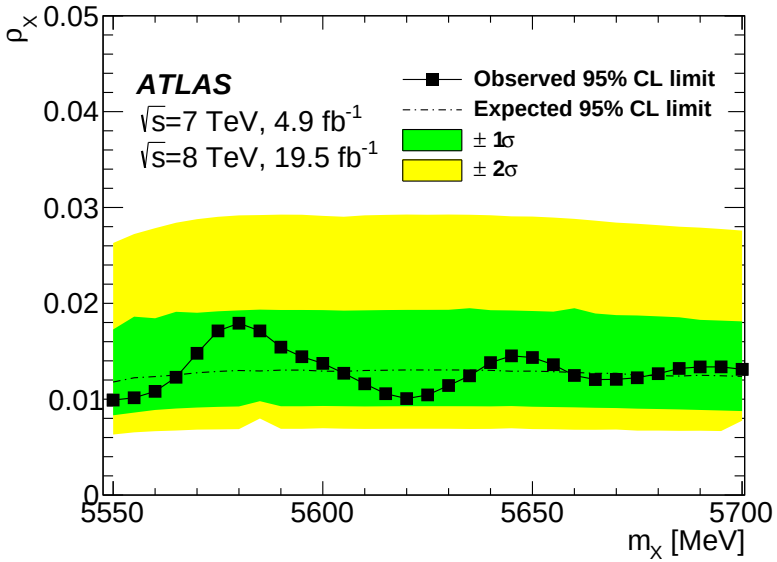
- Combine each of the tracks forming the selected PV with the selected B_s^0 candidate





Upper limits on X production relative to B_s^0

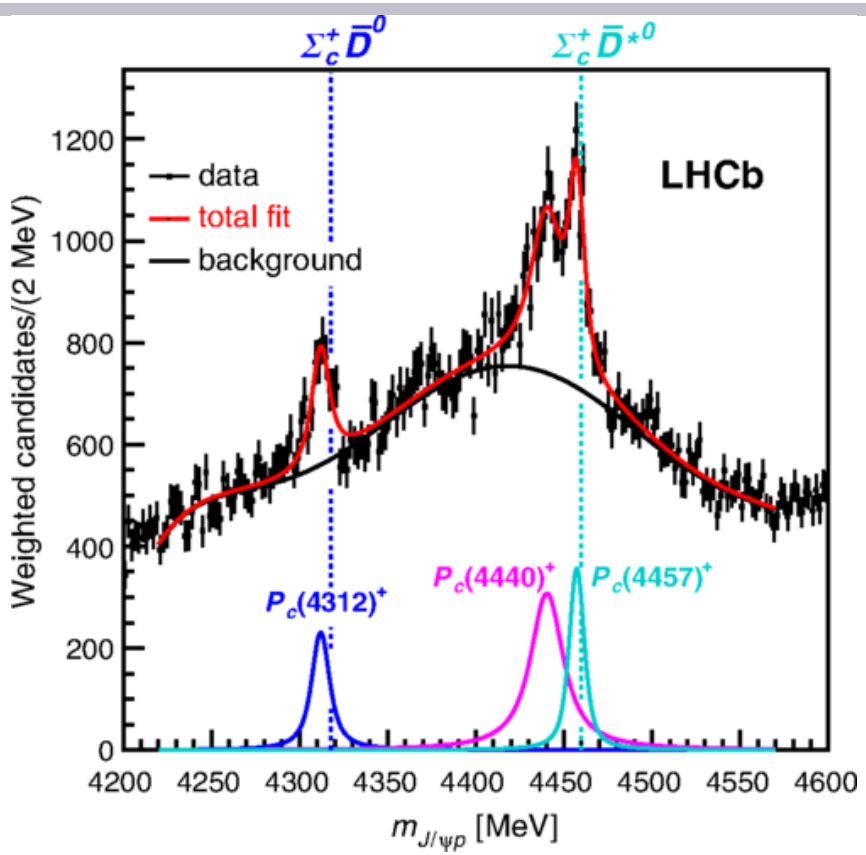
- No significant signal was found, agrees with LHCb and CMS results which also revealed no signal.
- $\rho_X \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$



- The upper limit set on ρ_X at 95% C.L. varies between 0.010 and 0.018, and does not exceed the $\pm 1\sigma$ error band from the expected limit.

Study of $J/\psi p$ resonances in $\Lambda_b \to J/\psi p K^-$

ATLAS-CONF-2019-048



- In 2015, LHCb observed two $J/\psi p$ resonant structures in $\Lambda_b \to J/\psi p K^-$ decay and interpreted the resonances as $c\bar{c}uud$ pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$. [PRL 115, 072001 (2015)]

State	M [MeV]	Γ [MeV]
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$
$P_c(4450)^+$	$4450 \pm 2 \pm 3$	$39 \pm 5 \pm 19$

- Later LHCb provided model-independent evidence for $J/\psi p$ resonance contribution to $\Lambda_b \to J/\psi p K^-$ decays. [PRL 117, 082002 (2016)]
- Recently LHCb showed that $P_c(4450)^+$ may represent two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$, and there's a new narrow state, $P_c(4312)^+$. [PRL 122, 222001 (2019)]

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

- A confirmation of the LHCb observation by other experiments is therefore needed.

Study of $J/\psi p$ resonances in $\Lambda_b \to J/\psi p K^-$

ATLAS-CONF-2019-048

- 4.9 fb^{-1} of pp collision data at 7 TeV and 20.6 fb^{-1} at 8 TeV
- Due to absence of hadron identification, select $J/\psi h_1 h_2$ candidates, where $h_1(h_2) = p, K, \pi$
- Perform simultaneous analysis of kinematically close Λ_b, B^0, B_s^0 decays
  1. $\Lambda_b \to J/\psi p K$ via various Λ^* or P_c states
  2. $B^0 \to J/\psi K \pi$ via various K^* or Z_c states
  3. $B_s^0 \to J/\psi K K$ via various f and ϕ states
  4. $B^0_{(s)} \to J/\psi \pi \pi$
- Simulation uses phase space events weighted by theoretically calculated matrix elements
- To suppress backgrounds from Λ^*, $K*$, f, ϕ states, select events with $M(K\pi) > 1.55$ GeV
- Subsequent fits are performed in the CR-s (to determinine parameters of B-meson decays), SR (to determine parameters of Λ_b decays) and in global scope

Fitting decay coupling constants for B-meson decays. Λ_b decay couplings are fixed

Information included:
2D: M(J/ψ,K,K), M(J/ψ,π,π)
2D: M(J/ψ,K,π), M(J/ψ,π,K);
2D: M(J/ψ,K), M(J/ψ,π) in B_d CR
2D: M(J/ψ,1K), M(J/ψ,2K) in B_s CR
1D: M(K,π) and M(π,K) separately in B_d CR
1D: M(K,π) in B_d CR

Obtain yields of Λ_b, B_d, B_s decays; All decay coupling constants fixed;

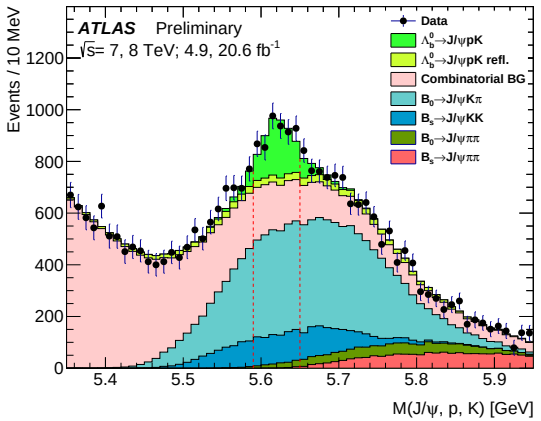
Information included:
2D: M(J/ψ,p,K), M(J/ψ,π,π);
2D: M(J/ψ,K,π), M(J/ψ,π,K);

Fit of Λ_b decay couplings;

Information included:
2D: M(J/ψ,p), M(J/ψ,K) in Λ_b CR
OR: 1D: M(p,K) in Λ_b CR

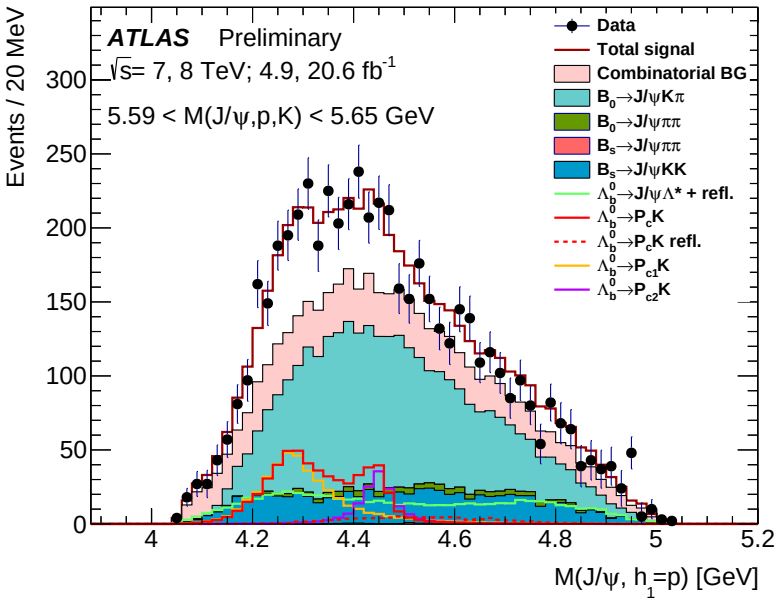
Fit of pentaquark signal parameters and yields.

Information included:
2D: M(J/ψ,p), M(J/ψ,K) in Λ_b CR
OR: 1D: M(p,K) in Λ_b CR



Two pentaquark hypothesis

- Fit with the hypothesis of two pentaquarks (with spin-parity $3/2^-$ and $5/2^+$ for lighter and heavier pentaquark candidates, respectively) yields $\chi^2/N_{\rm dof} = 37.1/39$ (p-value = 55.7%).



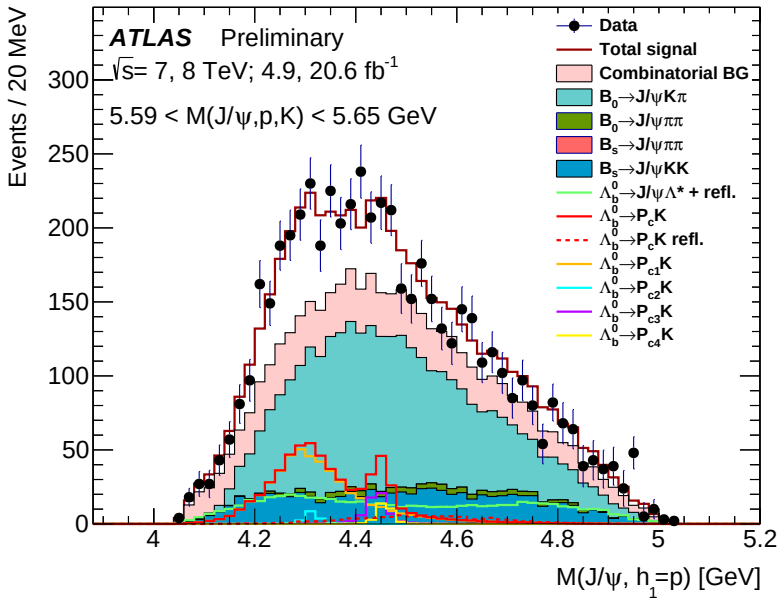
P_c signal parameters and yields from fit:

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

- The pentaquark masses and widths obtained are consistent with the LHCb results within uncertainties.
- The fit with the two pentaquark masses and widths fixed to the LHCb values yields $\chi^2/N_{\rm dof} = 49.0/43$ (p-value = 24.5%).

Four pentaquark hypothesis

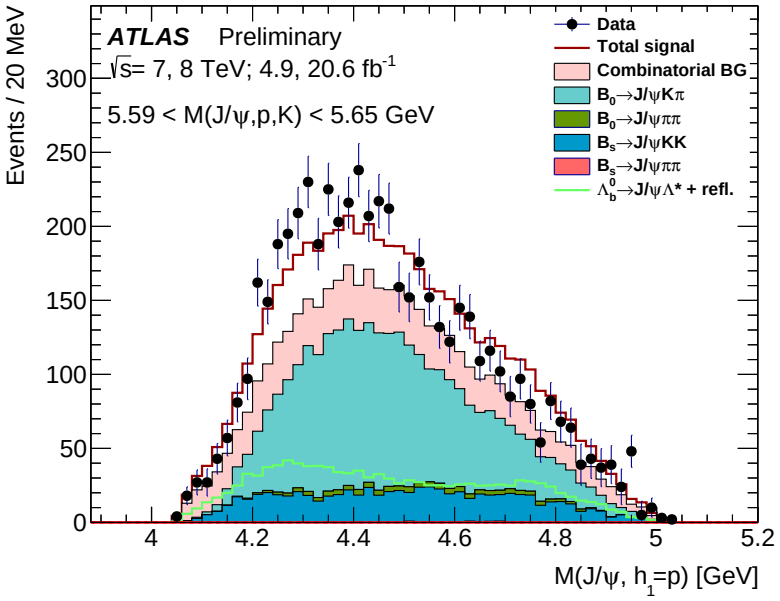
- Fit with the hypothesis of four pentaquarks with masses, widths and relative yields of narrow states fixed to LHCb values.



- The data description by this fit is also good ($\chi^2/N_{\mathrm{dof}} = 37.1/42$).
- ATLAS data is consistent with LHCb results.

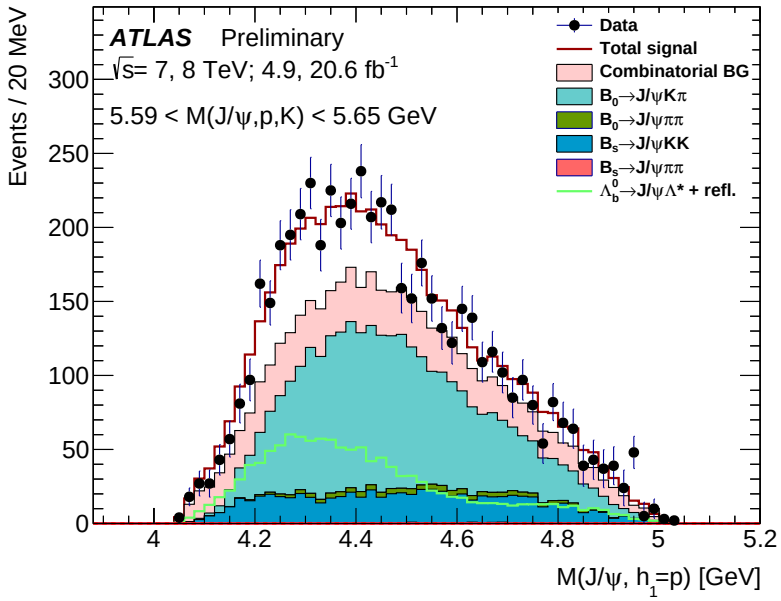
No pentaquark fits

1. Fit with default $\Lambda_b^0 \to J/\psi\Lambda^{*0}$ decay model



$\chi^2/N_{\mathrm{dof}} = 69.2/37$
(p-value = 1.0×10^{-3})

2. Fit with extended $\Lambda_b^0 \to J/\psi\Lambda^{*0}$ decay model



$\chi^2/N_{\mathrm{dof}} = 42.0/23$
(p-value = 9.1×10^{-3})

- The data description with model without pentaquarks is worse in comparison to models with pentaquarks.
- Model without pentaquarks is still not statitically excluded.

Summary

- A selection of ATLAS results on exotica production was presented

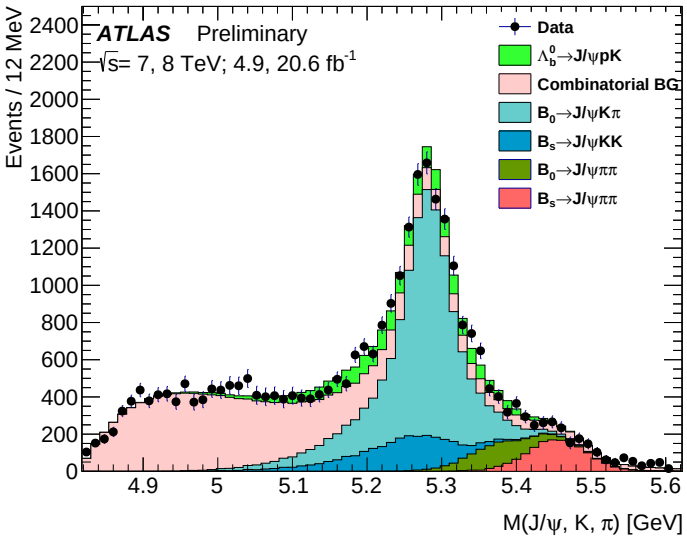
  1. Measurement of the differential cross sections for the production of $X(3872)$ state in the decay channel $J/\psi\pi^+\pi^-$
  2. Search for $X(5568)$ decaying into $B_s^0\pi^\pm$ with properties as reported by D0
     - No significant signal was found
  3. Study of $J/\psi p$ resonances in $\Lambda_b^0 \to J/\psi p K^-$ decays
     - Parameters of two pentaquark signals (540 events in total) are measured being consistent with LHCb results;
     - Four pentaquark hypothesis is also consistent with ATLAS data;
     - In the No-pentaquark hypothesis, data description is poor, though this hypothesis cannot be completely statistically excluded.

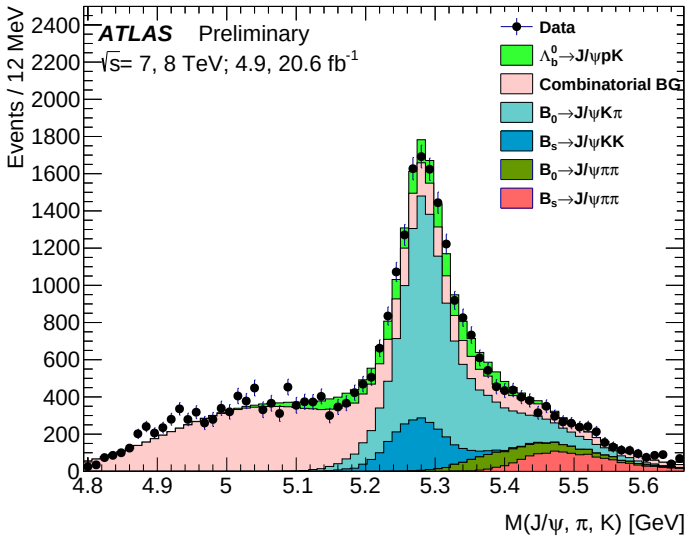
- Many *B*-physics measurements are only based on Run-1 dataset yet.
  - See more public results here: BPhysPublicResults
- Full Run-2 dataset is still to be fully exploited.

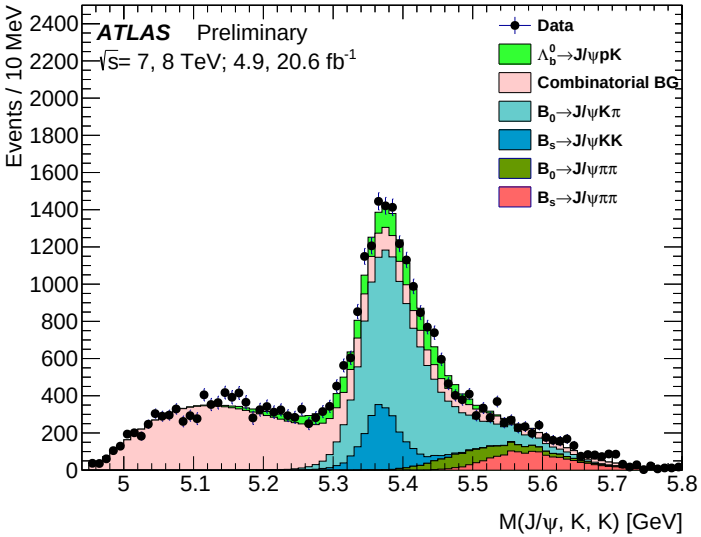
Thank you!

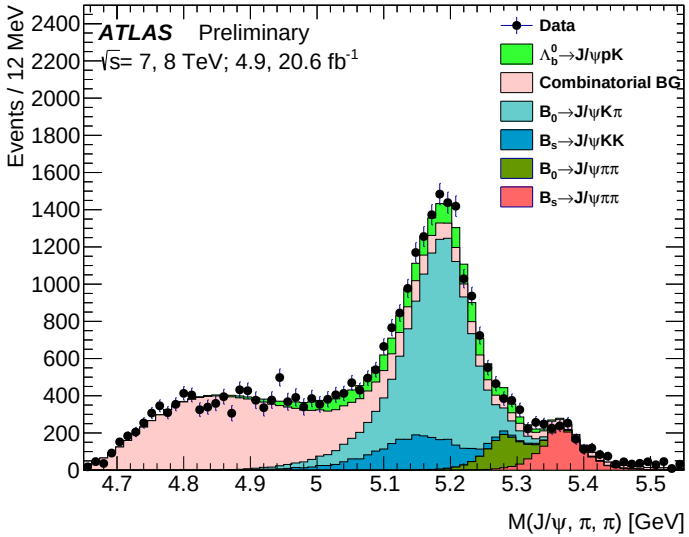
Search for P_c in $\Lambda_b \to J/\psi p K^-$ decays

Analysis of B-meson decays









Search for P_c in $\Lambda_b \to J/\psi p K^-$ decays

Analysis of *B*-meson decays in CR-s