ATLAS results on exotic hadronic resonances

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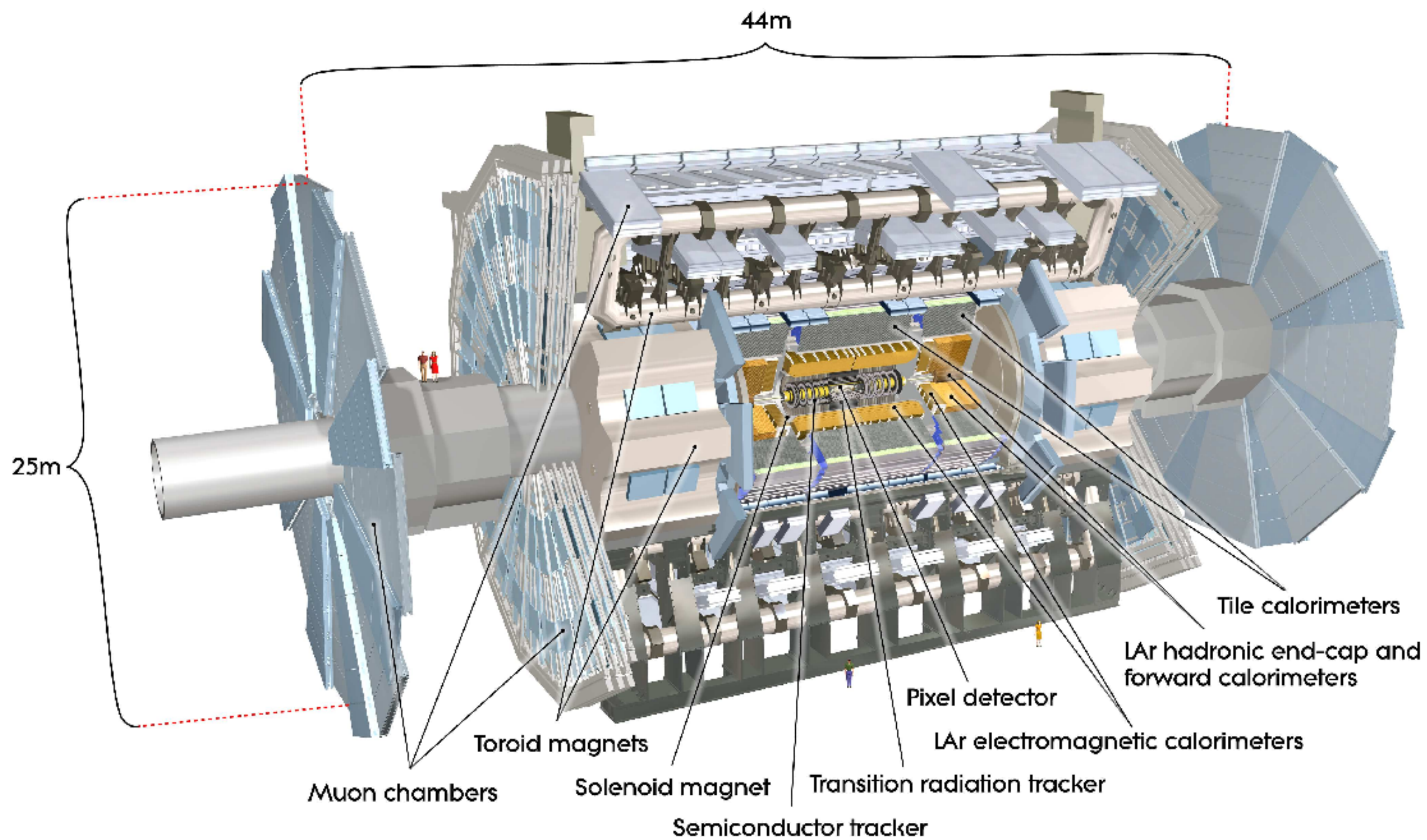
Outline

- ATLAS detector
- Study of $J/\psi p$ resonances in the $\Lambda_b^0 \to J/\psi p K^-$ decays in LHC pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector (2011-2012) ATLAS-CONF-2019-048
- Summary

ATLAS detector

- ATLAS (A Toroidal LHC ApparatuS) is one of the two general-purpose detectors at the Large Hadron Collider (LHC)
- It investigates a wide range of physics, from the Higgs boson to extra dimensions and particles that could make up dark matter.
- At 44 m long, 25 m high and 25 m wide, the 7000-tonne ATLAS detector is the largest volume particle detector ever constructed.



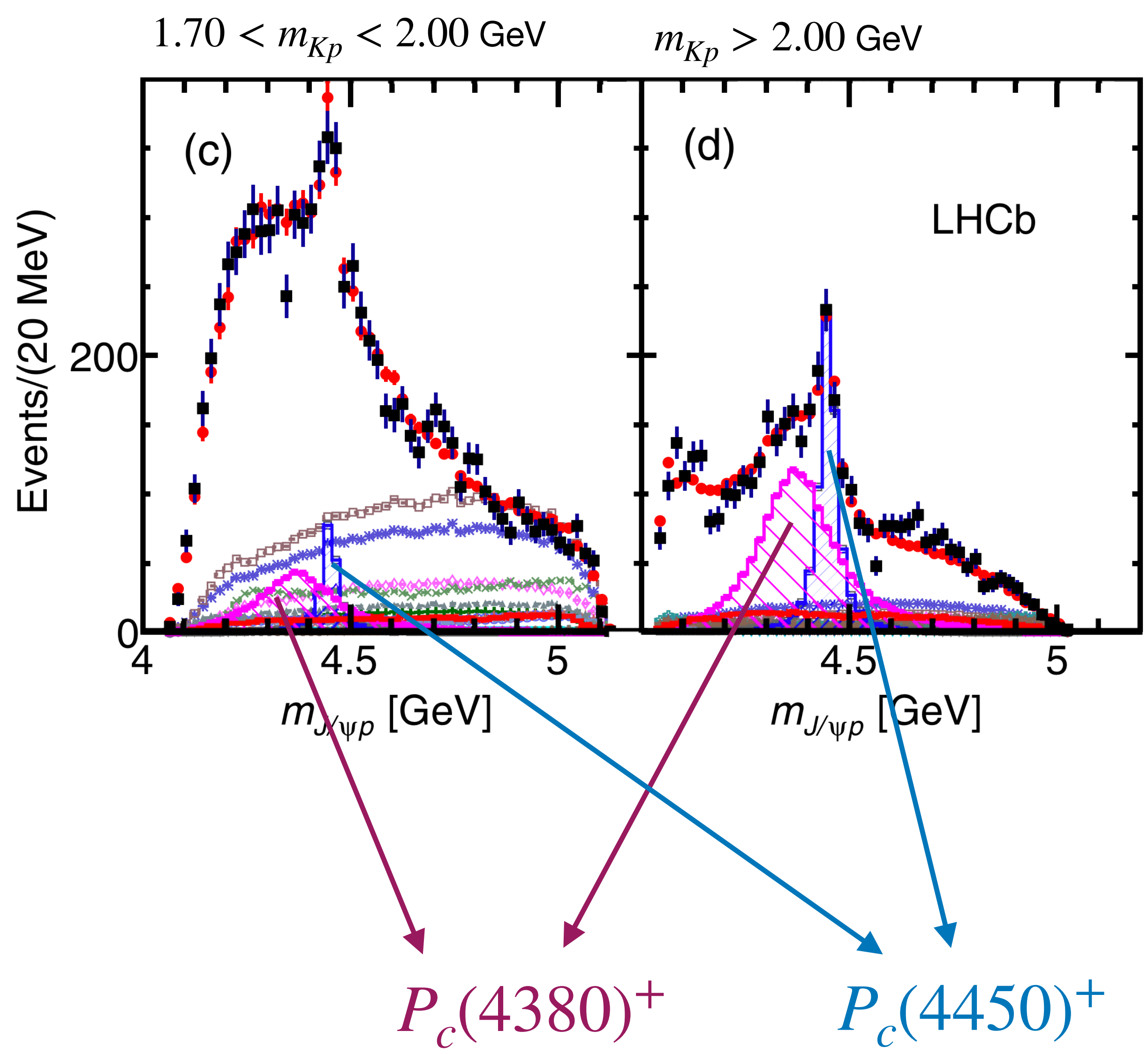
Motivation

- The experimental observation of pentaquark states has been controversial.

- In 2015, LHCb observed $J/\psi p$ resonant structures in the decay $\Lambda_b^0 \to J/\psi p K^-$ interpreted as $c\bar{c}uud$ pentaquark states (P_c) (Phys. Rev. Lett. 115 (2015) 072001, Chin. Phys. C 40 (2016) 011001):

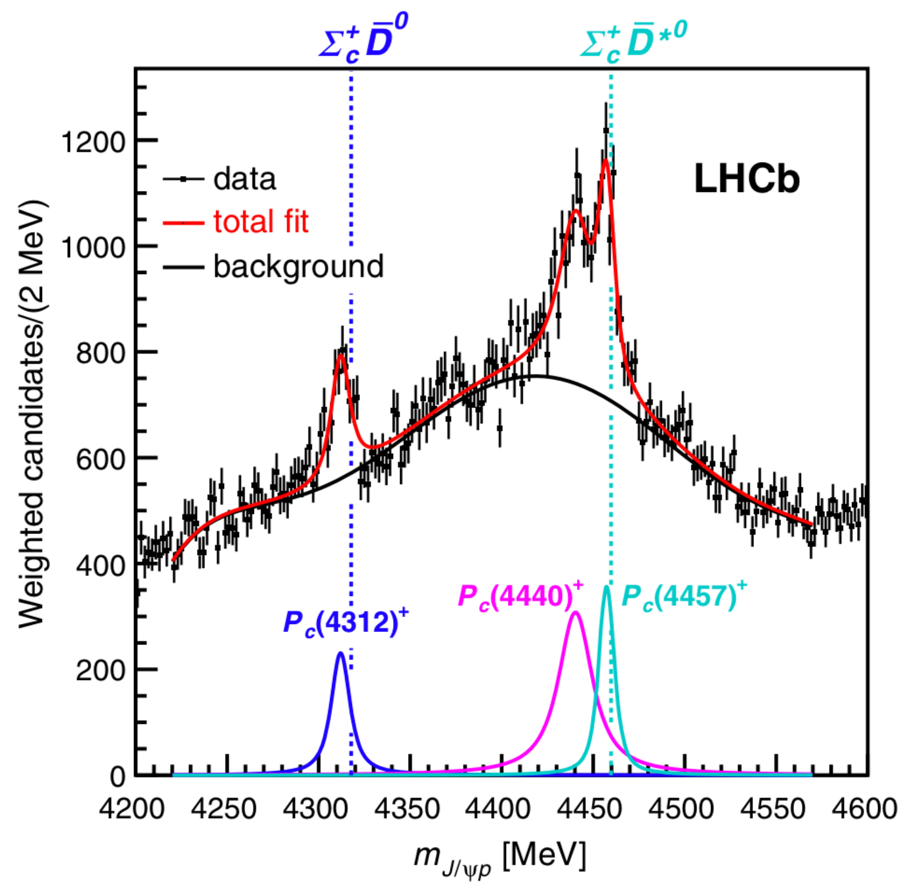
  - $P_c(4380)^+$ with $M = 4380 \pm 205$ MeV, $J^P = 3/2^-$, ~8% fractions

  - $P_c(4450)^+$ with $M = 4449.8 \pm 39$ MeV, $J^P = 5/2^+$, ~4% fractions



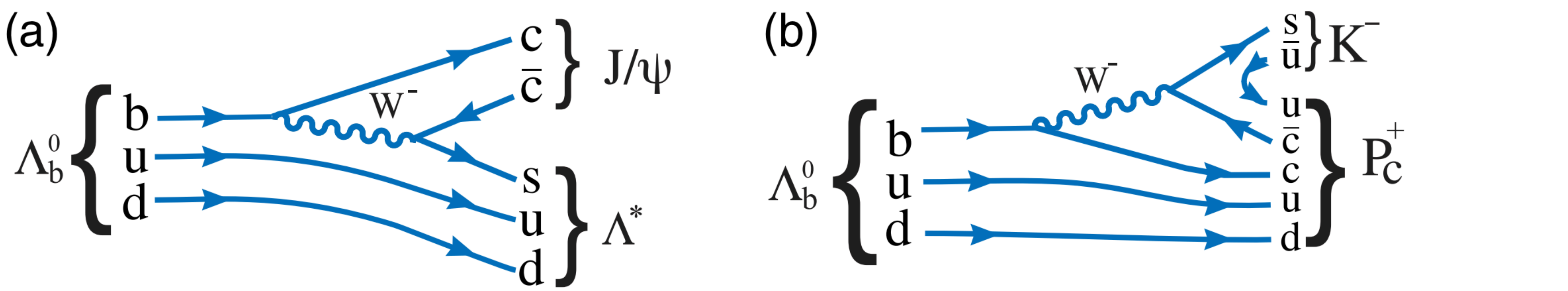
Motivation

- In 2019, LHCb reported $P_c(4450)^+$ may represent two narrower states $P_c(4440)^+$ and $P_c(4457)^+$, and there is another narrow resonance $P_c(4312)^+$ (Phys. Rev. Lett. 122 (2019) 222001).
- The confirmation from other experiments are needed.



Signal and Backgrounds

- $\Lambda_b^0 \to J/\psi p K^-$ process: contributions from **pentaquark states (signal)** and light Λ^* states are considered.
- $B^0 \to J/\psi K^+ \pi^-$ process:
  - Contributions from light K^* states are included.
  - The potential contribution from $B^0 \to Z_c(4200)^- K^+ \to J/\psi \pi^- K^+$ (Phys. Rev. D 90 (2014) 112009) is considered as systematics.
- $B_s^0 \to J/\psi K^+ K^-$ process: contributions from ϕ, f_2 states are included.
- Intermediate states and non-resonant decays are both considered for $B^0 \to J/\psi \pi^- \pi^+$ and $B_s^0 \to J/\psi \pi^- \pi^+$ processes.



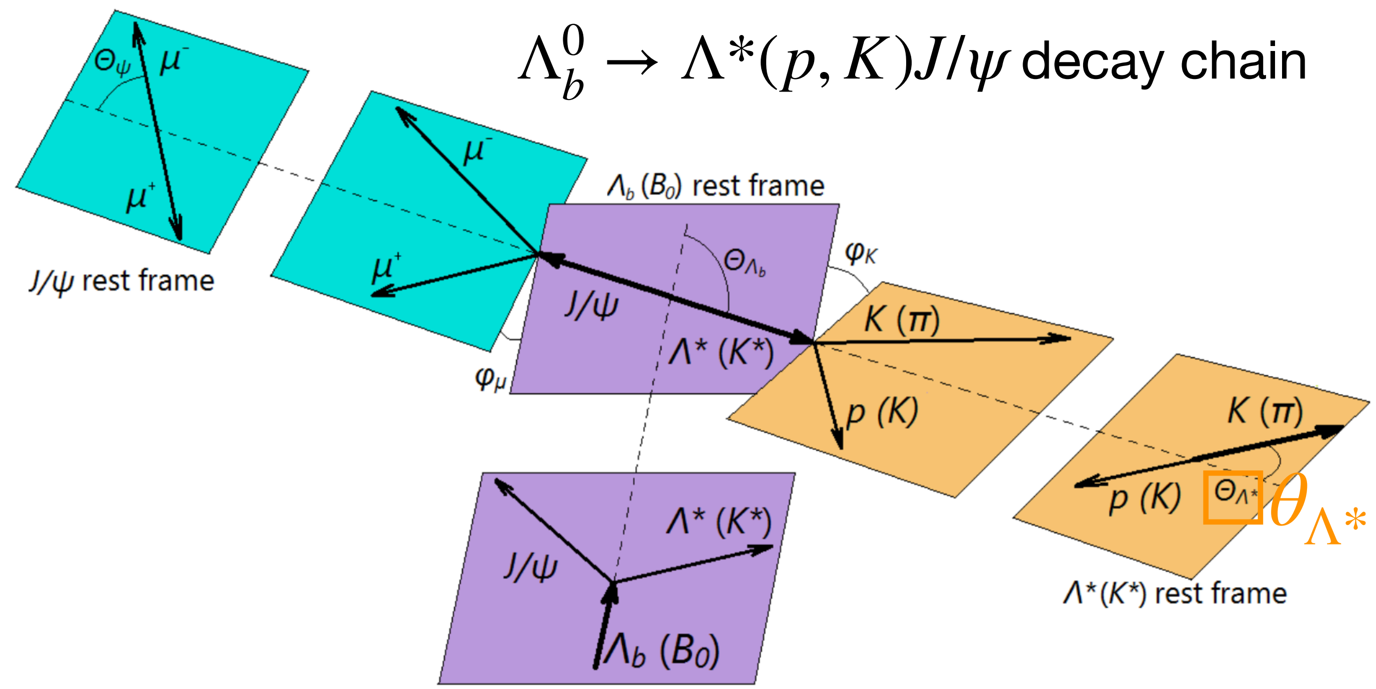
Phys. Rev. Lett. 115 (2015) 072001

Event selection and reconstruction

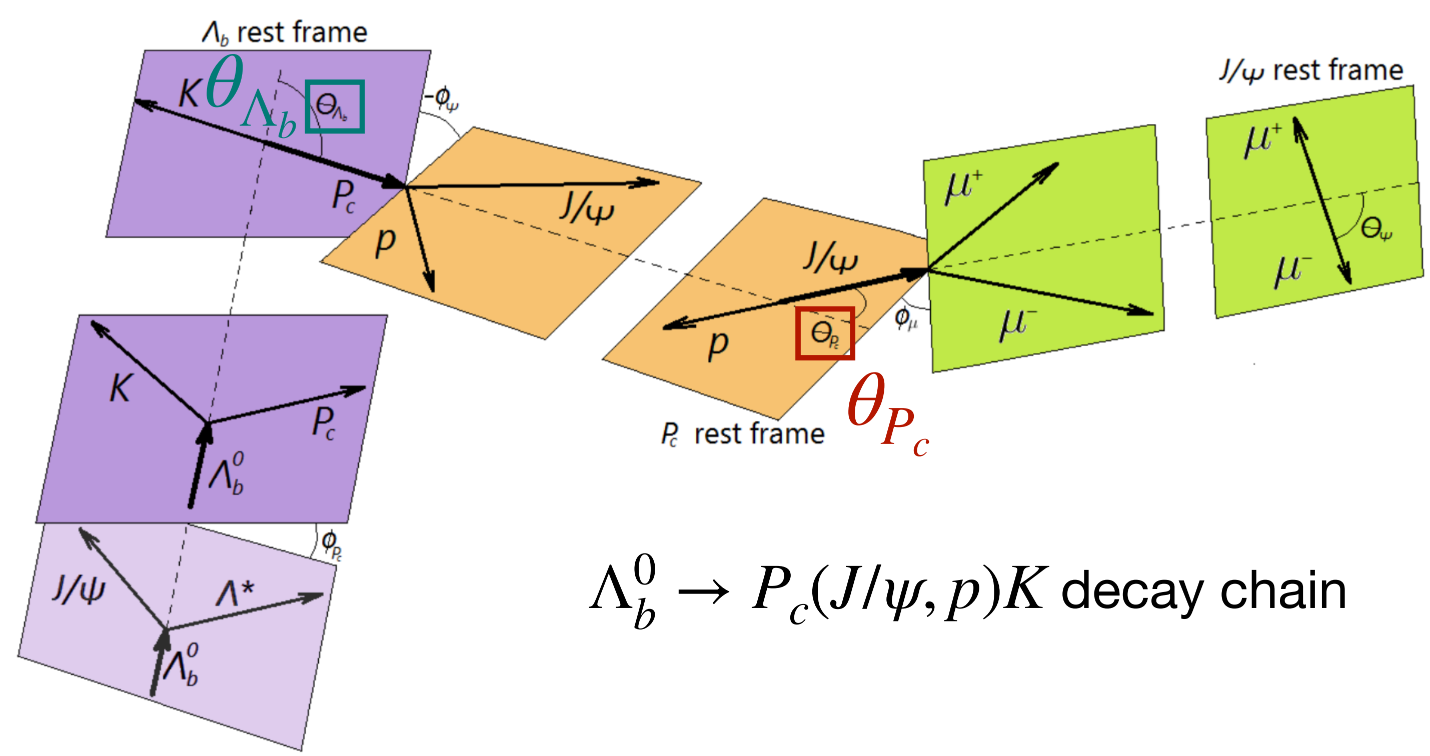
- J/ψ selection: $p_T(\mu^{\pm}) > 4$ GeV, $|\eta(\mu^{\pm})| < 2.3$, $2807 < m_{\mu^+\mu^-} < 3387$ MeV
- Due to the absence of particle identification, Λ_b^0 decays are reconstructed together with decays $B^0 \to J/\psi K^+\pi^-$, $B^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$
- B-hadron ($H_b = \Lambda_b$, B^0 or B_s) selection:
  - $\chi^2(H_b)/N_{dof} < 2$, $L_{xy}(H_b) > 0.7$ mm
  - $p_T(H_b)/\sum p_T(\text{track}) > 0.2$, $p_T(p) > 2.5$ GeV, $p_T(K^-) > 1.8$ GeV
  - $p_T(H_b) > 12$ GeV, $|\eta(H_b)| < 2.1$
  - Requirements on $cos\,\theta_{P_c,\ \Lambda_b,\ \Lambda^*}$
- $M(K\pi) > 1.55$ GeV: select candidates with $M(pK) > 2.0$ GeV.

Requirements on angles

- B-hadron ($H_b = \Lambda_b$, B^0 or B_s) selection:
  - $cos\,\theta_{P_c} < 0.5$: θ_{P_c} is the angle between J/ψ momentum in the P_c rest frame and P_c momentum in the Λ_b rest frame
  - $cos\,\theta_{\Lambda_b} < 0.8$: θ_{Λ_b} is the angle between Λ_b momentum and P_c momentum in laboratory frame
  - $|cos\,\theta_{\Lambda^*}| < 0.85$: θ_{Λ^*} is the angle between kaon momentum in the $\Lambda^* \to pK$ rest frame and Λ^* momentum in the Λ_b rest frame



$\Lambda_b^0 \to \Lambda^*(p, K)J/\psi$ decay chain



$\Lambda_b^0 \to P_c(J/\psi, p)K$ decay chain

Kinematic regions

- Λ_b signal region (SR), B^0 and B_s^0 control regions (CR) are defined to extract pentaquark parameters (e.g. mass, width) in the fit.
- Contributions of Λ_b^0 decays in CRs are small.
- B^0 decays are the dominant background in all regions.

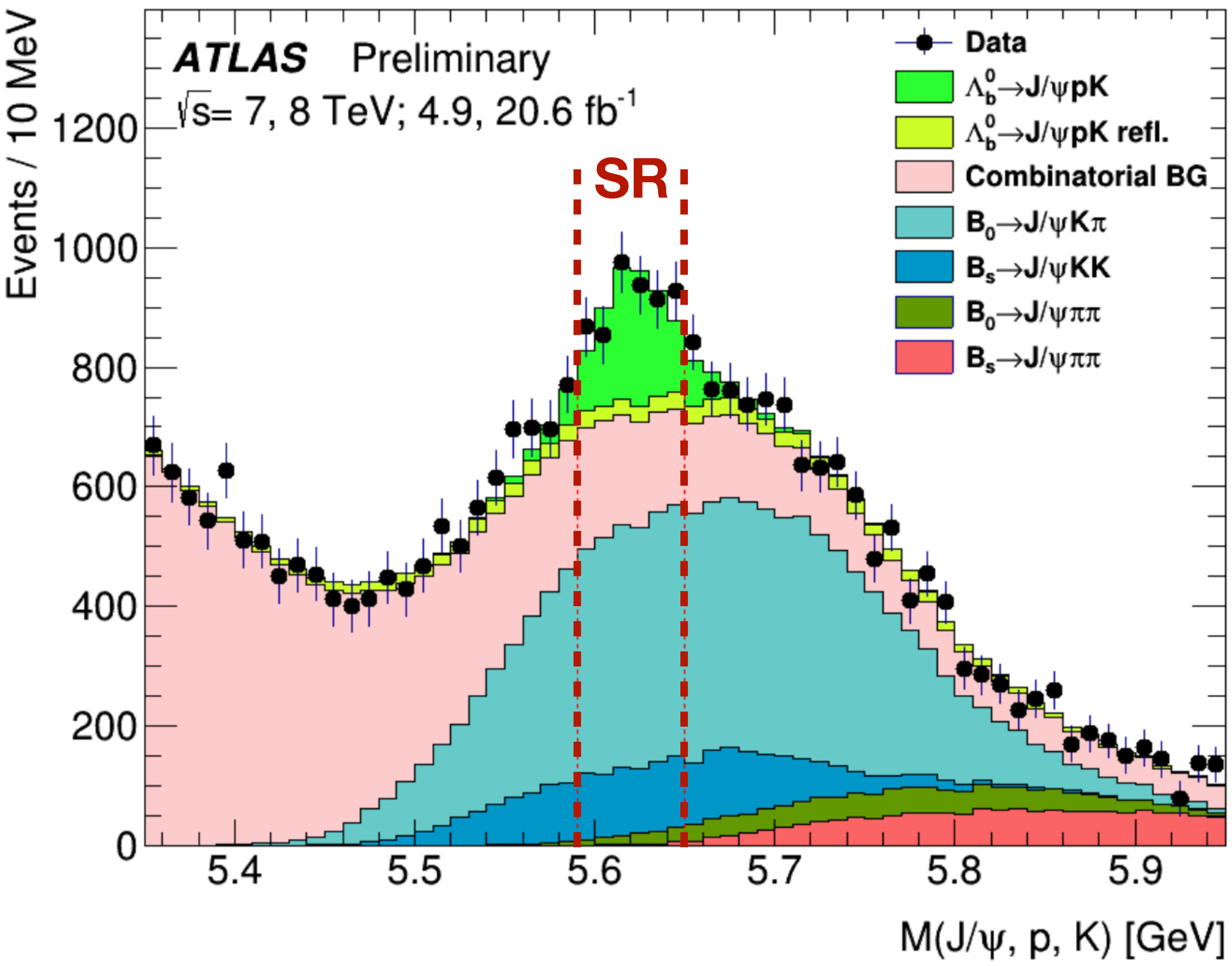
	Mass window
Λ_b **SR**	$5.59 < m(J/\psi, h_1 = p, h_2 = K) < 5.65$ GeV
B^0 **CR**	$5.25 < m(J/\psi, h_1 = K(\pi), h_2 = \pi(K)) < 5.31$ GeV
B_s^0 **CR**	$5.337 < m(J/\psi, h_1 = K, h_2 = K) < 5.397$ GeV

Fit model

- The fit procedure is iterative with four steps in each iteration. Parameters obtained in previous step are used in the current step.
  - Step 1: fit $m(J/\psi hh)$, $m(J/\psi h)$, $m(hh)$ spectra to obtain parameters of B_0 and B_s backgrounds.
  - Step 2: fit $m(J/\psi, h_1 = p, h_2 = K)$ spectrum to retrieve total number of Λ_b decays, number of combined B^0 and B_s^0 decays.
  - Step 3: fit $m(J/\psi h)$, $m(hh)$ spectra in SR to get decay constants of Λ_b decays.
  - Step 4: fit $m(J/\psi, h_1 = p)$ spectrum in SR to obtain pentaquark masses, widths, amplitudes and relative phase between pentaquark amplitudes ($\Delta\phi$)

Fit results

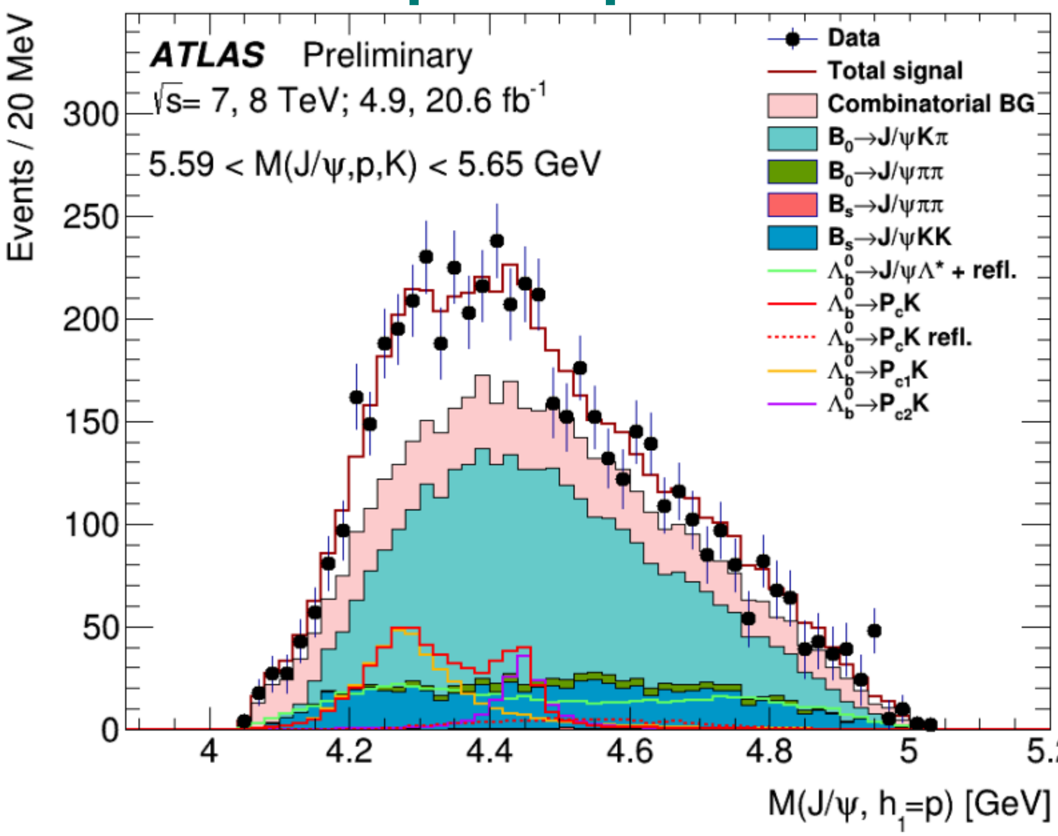
- $m(J/\psi p K^-)$ spectrum for all selected Λ_b candidates.
- Processes displayed with their correct hadron mass assignment are called '**direct signals**', while processes shown with the wrong mass assignment are '**reflected signals**'



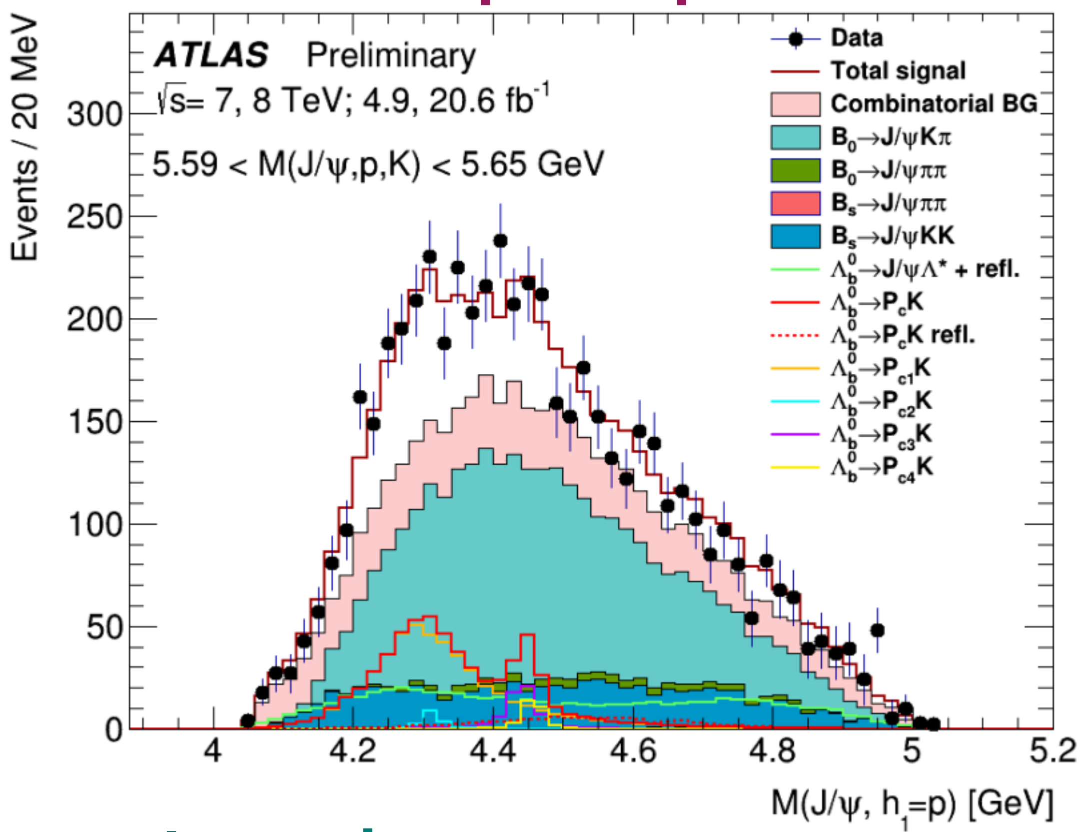
- $N(\Lambda_b^0 \to J/\psi p K^-) = 2270 \pm 300$
- $N(B^0 \to J/\psi K^+ \pi^-) = 10770$
- $N(B_s^0 \to J/\psi K^+ K^-) = 2290$
- $N(B^0 \to J/\psi \pi^+ \pi^-) = 1070$
- $N(B_s^0 \to J/\psi \pi^+ \pi^-) = 1390$
- In **SR**, $N(\Lambda_b^0 \to J/\psi p K^-)$ ~ 1200

Fit results

Two pentaquarks



Four pentaquarks



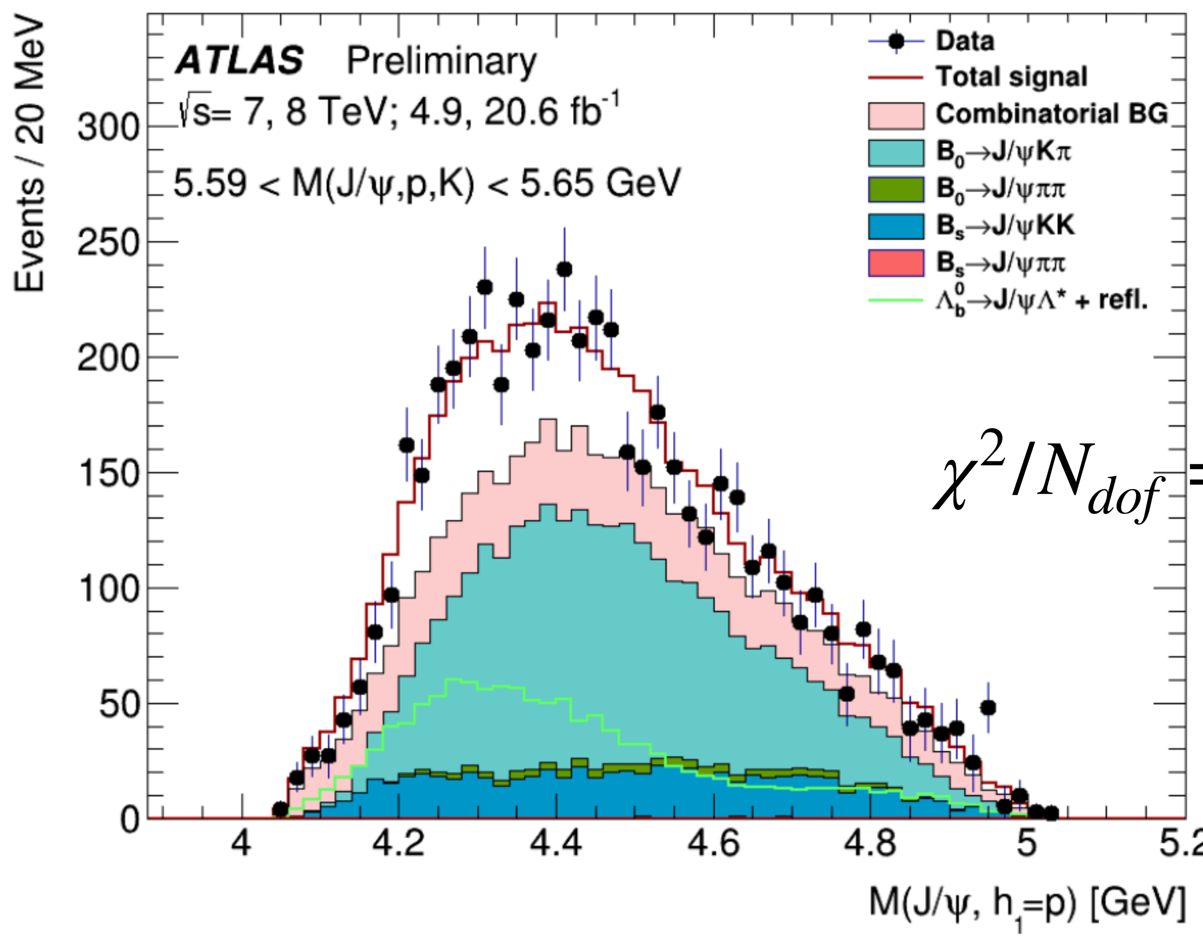
- Two hypotheses are tested:
- Two pentaquarks:
  - $\chi^2/N_{dof} = 37.1/39$
  - The pentaquark masses and widths are consistent with the LHCb results.
- Four pentaquarks:
  - $\chi^2/N_{dof} = 37.1/42$
  - use pentaquark properties from LHCb.

Two pentaquarks

Parameter	Value	LHCb value
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	Phys. Rev. Lett. 115 (2015) 072001
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ 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

Model without pentaquarks

- The fit procedure is repeated using $\Lambda_b^0 \to J/\psi p K^-$ decay without pentaquarks.
- The extended $\Lambda_b^0 \to J/\psi p K^-$ decay model with two lowest orbital momenta between the decay products of $\Lambda^*(1800)$, $\Lambda^*(1810)$ and $\Lambda^*(1890)$ give the best result.
- The fit quality is worse than the models with pentaquarks.



$\chi^2/N_{dof} = 42.0/23$

Systematics

- Systematic uncertainties for extracted yields and relative phase

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	$^{+28}_{-25}\%$	$^{+35}_{-61}\%$	$^{+14}_{-15}\%$	$^{+5.1}_{-2.7}\%$

- Systematic uncertainties for pentaquark masses and natural widths

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	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

Summary

- Analysis of $\Lambda_b^0 \to J/\psi p K^-$ decays is performed with $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV pp collision data collected by ATLAS detector.

- Obtained pentaquark masses and widths with hypothesis of two pentaquarks are consistent with LHCb results.

- Data prefer model with two or more pentaquarks, but model without pentaquark is not excluded.

- More studies are on-going with Run 2 data.

Stay tuned!

Thanks