Search for exotic states in ATLAS: pentaquarks

I. Yeletskikh
on behalf of the ATLAS Collaboration

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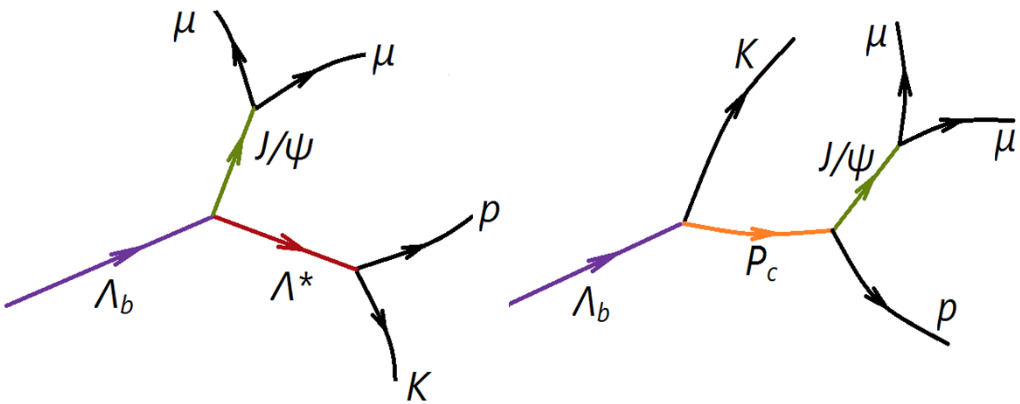
Hidden charm pentaquarks discovery

In 2015 LHCb reported observation of two exotic structures in the *J/ψ,p* invariant mass in $\Lambda_b \to J/\psi,p,K$ decays. Masses and widths measured:

m_1 = 4380 ± 8 ± 29 MeV, Γ_1 = 205 ± 18 ± 86 MeV,
m_2 = 4449.8 ± 1.7 ± 2.5 MeV, Γ_2 = 39 ± 5 ± 19 MeV.

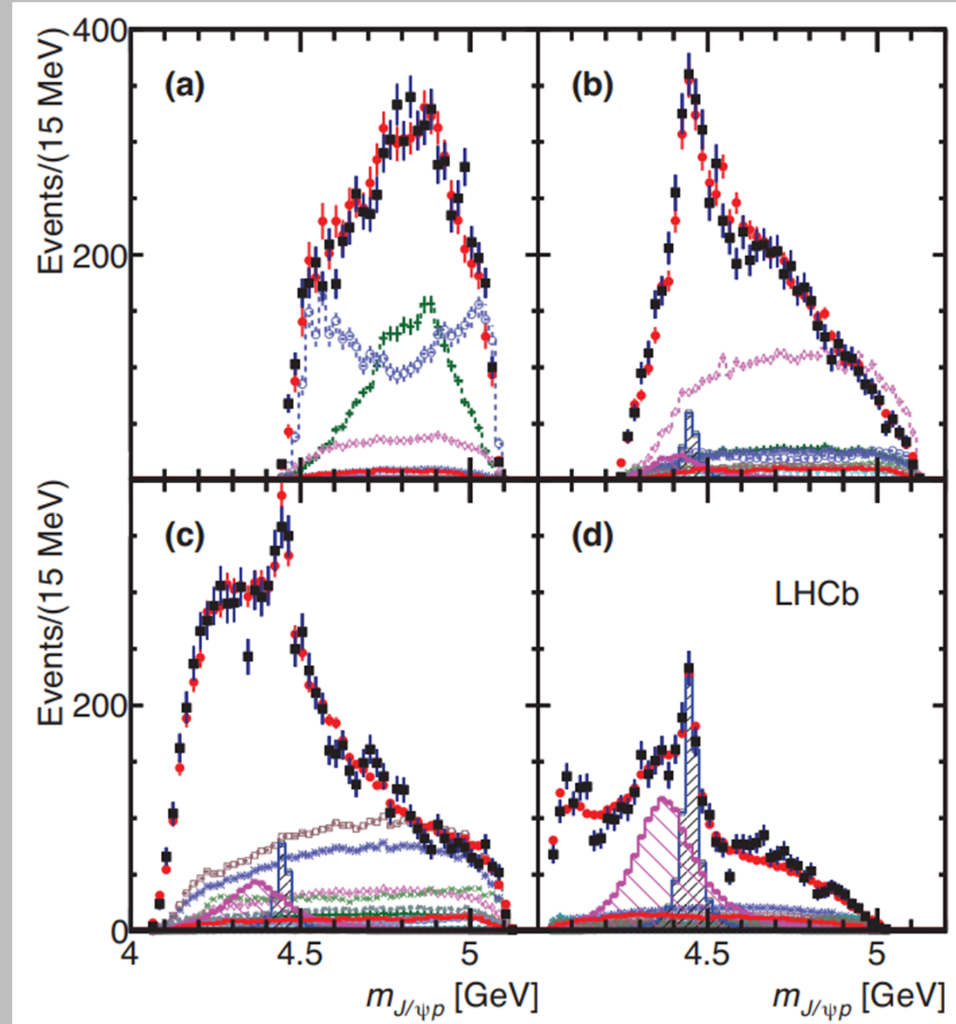


*Λ** (left) and *P_c* (right) decay chains

Measured spins of new states are J_1=3/2 and J_2=5/2, parities preferred are opposite.

P_c(4450) demonstrates well defined resonant behavior, while properties of *P_c*(4380) amplitude are less clear…

J/ψ,p invariant mass



Phys. Rev. Lett. 115 (2015) 072001
Phys. Rev. Lett. 117 (2016) 082002
Phys. Rev. Lett. 117 (2016) 082003

$\Lambda_b \to J/\psi, p, K$ candidates at ATLAS

1. Due to absence of hadron track identification, we select $J/\psi, h_1, h_2$ candidates, where h_1, h_2 are hadrons of unknown flavour: p, K, π;
2. We had to perform simultaneous analysis of kinematically close Λ_b, B_d and B_s decays:
   - $\Lambda_b \to J/\psi, p, K$ via variuos Λ^* or P_c states (ref. backup)
   - $B^0 \to J/\psi, K, \pi$ via various K^* or exotic Z_c states (ref. backup)
   - $B^0 \to J/\psi, \pi, \pi$
   - $B_s \to J/\psi, K, K$ via variuos f and φ states (ref. backup)
   - $B_s \to J/\psi, \pi, \pi$
3. Simulation of $\Lambda_b \to J/\psi, p, K$; $B^0 \to J/\psi, K, \pi$; $B_s \to J/\psi, K, K$ processes uses phase space decay events weighted by theoretically calculated matrix elements;
4. To suppress high backgrounds from light Λ^*, K^*, f, φ states as well as combinatorial background, only events with high $M(h,h)$ are selected: $M(K,\pi)$ and $M(\pi,K) > 1.55$ GeV $\to$ $M(p,K) \gtrsim 2$ GeV;

$\Lambda_b \to J/\psi, p, K$ candidates at ATLAS

5. Candidate events are analyzed in the Signal Region (SR: 5.59 < M($J/\psi,p,K$) < 5.65 GeV) as well as in two Control Regions (CR), dominated by *B*-meson backgrounds;
6. Due to complexity of the full decay model, subsequent fits are performed in the CR-s (to determine parameters of *B*-meson decays), SR (to determine parameters of Λ_b decays) and in 'global scope' (using all selected events – to determine signal and background yields):

Global fit

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

Information included:
2D: M($J/\psi,K,K$), M($J/\psi,\pi,\pi$)
2D: M($J/\psi,K,\pi$), M($J/\psi,\pi,K$);
2D: M($J/\psi,K$), M($J/\psi,\pi$) 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*

→

M($J/\psi,p,K$) fit

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

Information included:
2D: M($J/\psi,p,K$), M($J/\psi,\pi,\pi$);
2D: M($J/\psi,K,\pi$), M($J/\psi,\pi,K$);

→

Λ_b decays fit

Fit of Λ_b decay couplings;

Information included:
2D: M($J/\psi,p$), M($J/\psi,K$) in Λ_b *CR*
OR: *1D: M(p,K)* in Λ_b *CR*

→

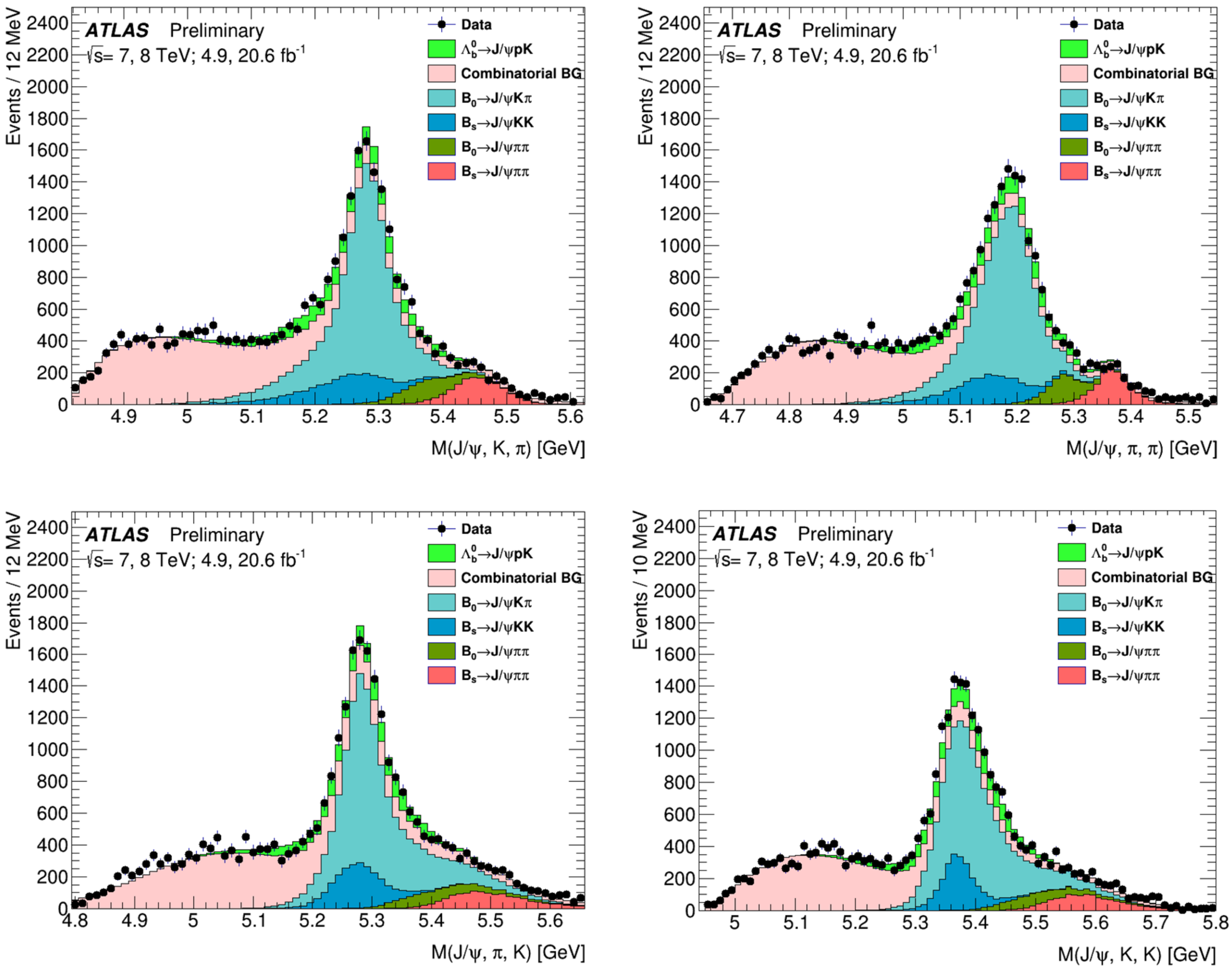
M($J/\psi,p$) fit

Fit of pentaquark signal parameters and yields.

Information included:
2D: M($J/\psi,p$), M($J/\psi,K$) in Λ_b *CR*
OR: *1D: M(p,K)* in Λ_b *CR*

7. Combinatorial background in SR and CR-s is estimated using data-driven technique;

Analysis of B-meson decays



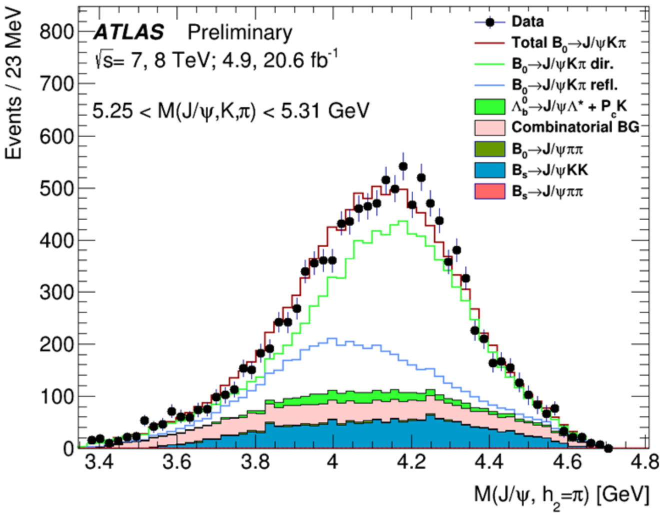
B-meson decays represent main physical background in the analysis.

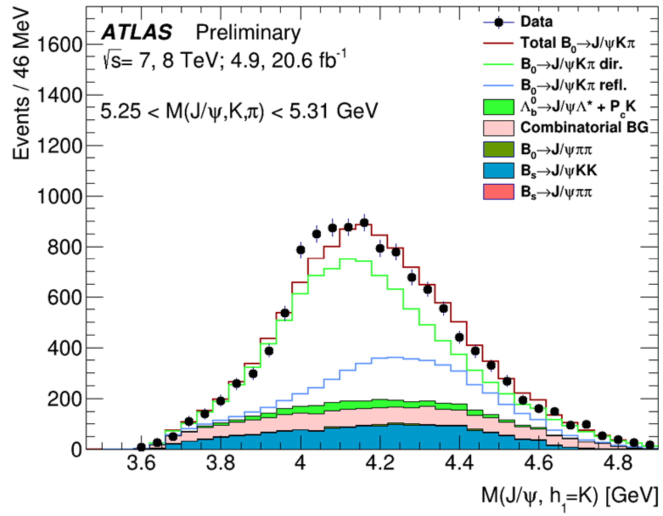
B-meson decay amplitudes are determined from simultaneous fit of $M(J/\psi,h_1,h_2)$ distributions in the 'global scope'…

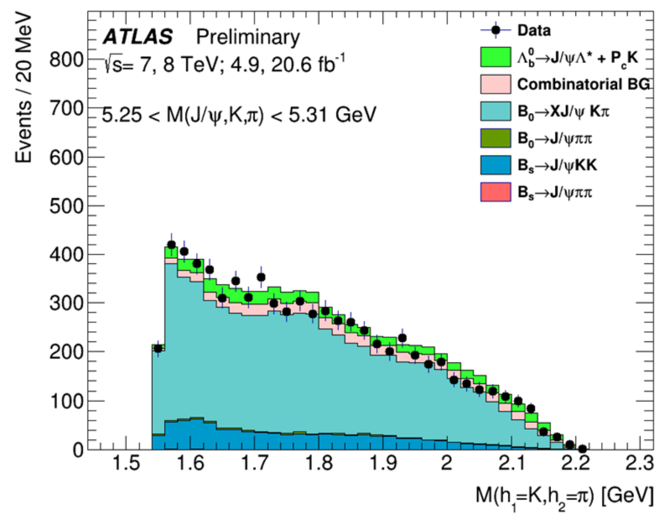
and $M(J/\psi,h)$, $M(h_1,h_2)$ distributions in CR-s (see next slide),

where $h_{1,2}$ is K or π.

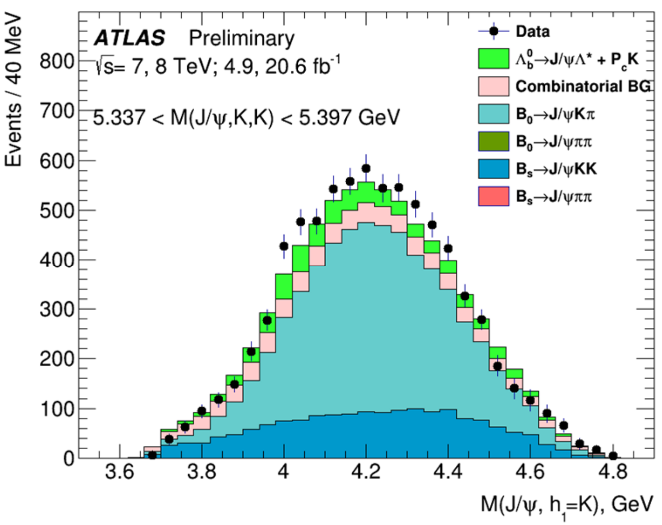
B^0-meson CR

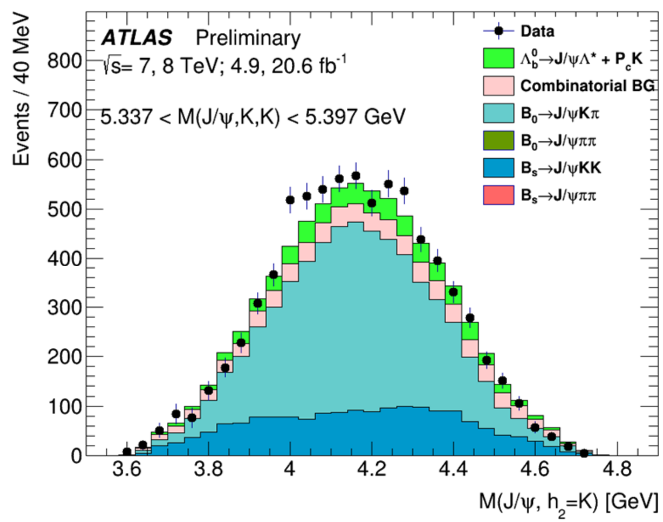


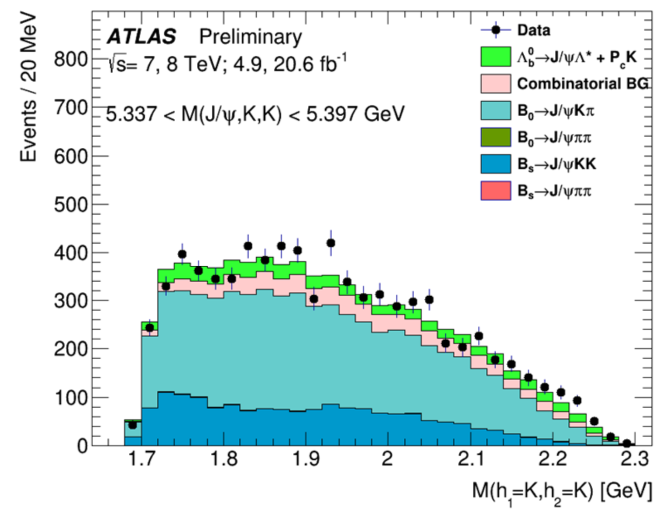


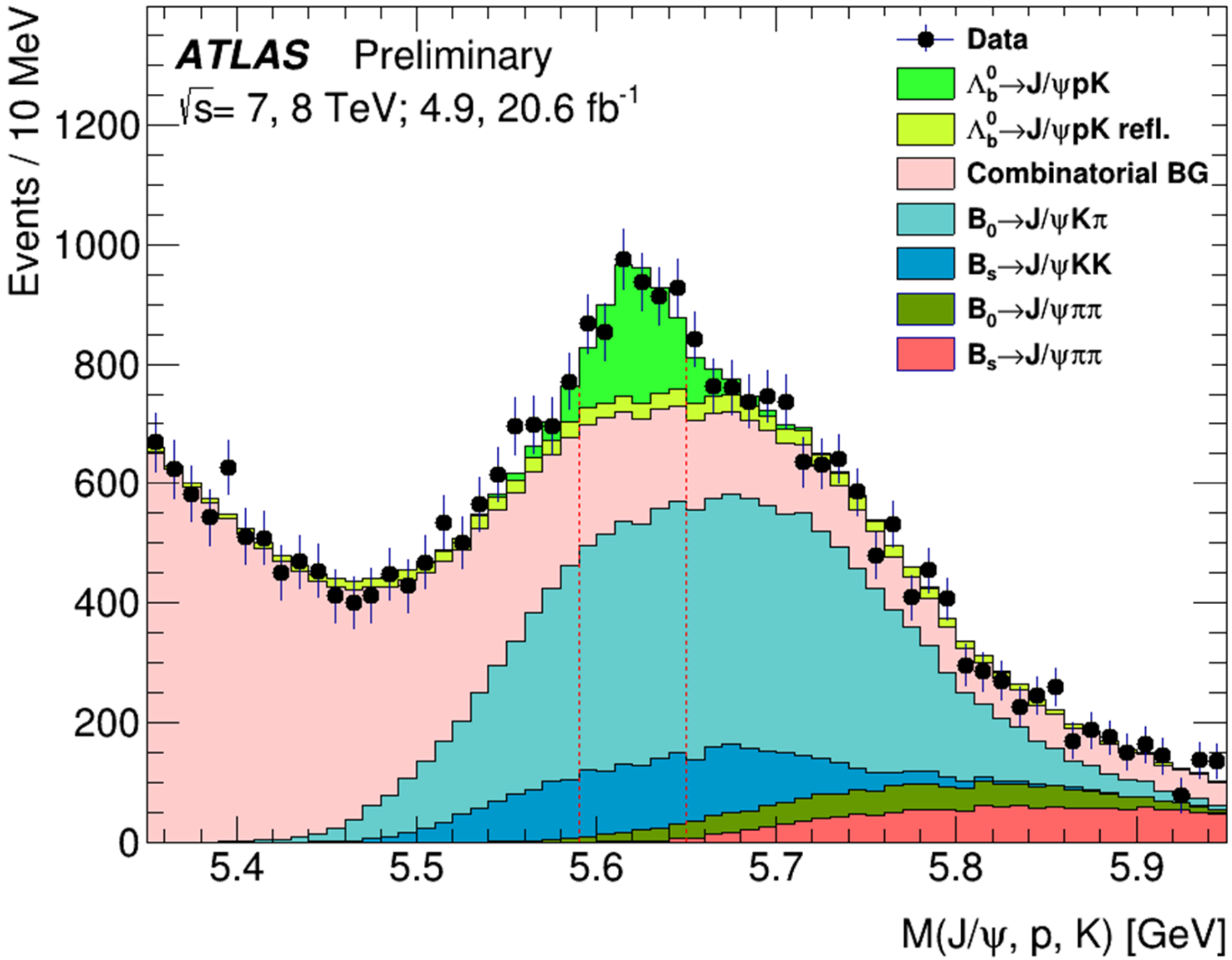


B_s-meson CR









After background parameters defined, we may start analyzing signal process…

Plot shows invariant mass distribution M($J/\psi,p,K$) for all selected Λ_b candidates

Red lines indicate Signal Region

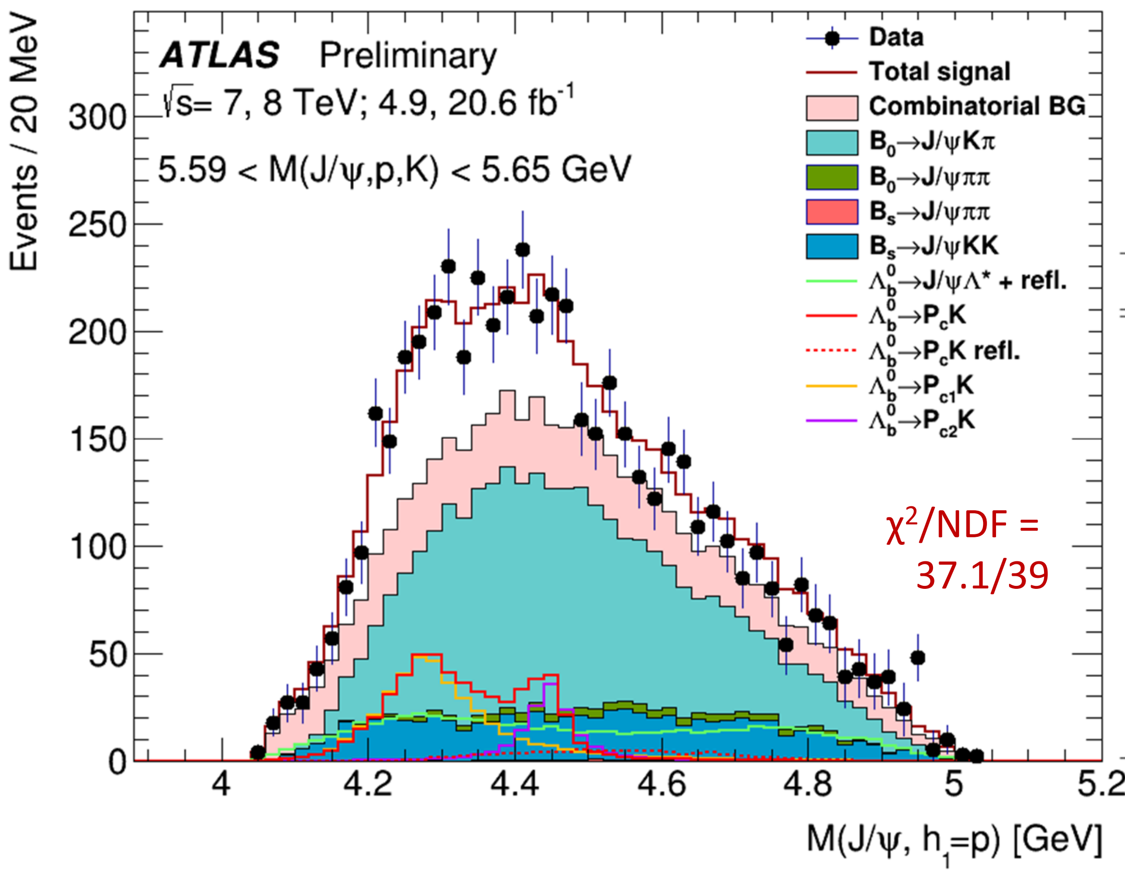
Event yields from fit:

N($\Lambda_b \to J/\psi,p,K$)=2270±300

N(Λ_b) direct in Signal region = 1010±140;
N(Λ_b) reflected in Signal region = 160±20;

N($B^0 \to J/\psi,K,\pi$) = 10770,
N($B_s \to J/\psi,K,K$) = 2290,
N($B^0 \to J/\psi,\pi,\pi$) = 1070,
N($B_s \to J/\psi,\pi,\pi$) = 1390;

$\Lambda_b \rightarrow J/\psi,p,K$ decays analysis: 2 pentaquark hypothesis



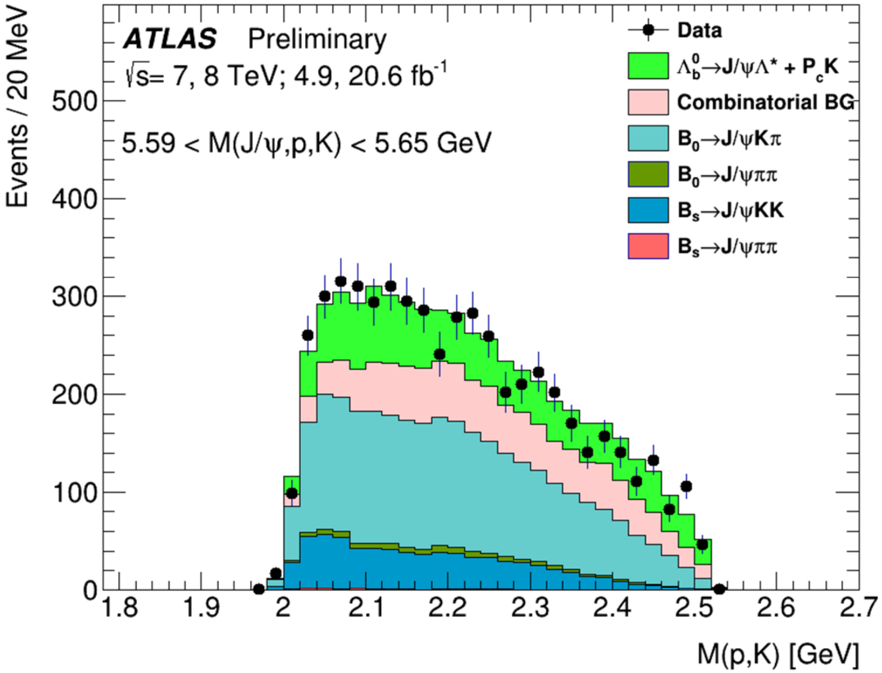
Plot shows invariant mass distribution $M(J/\psi,p)$ for selected Λ_b candidates in SR.

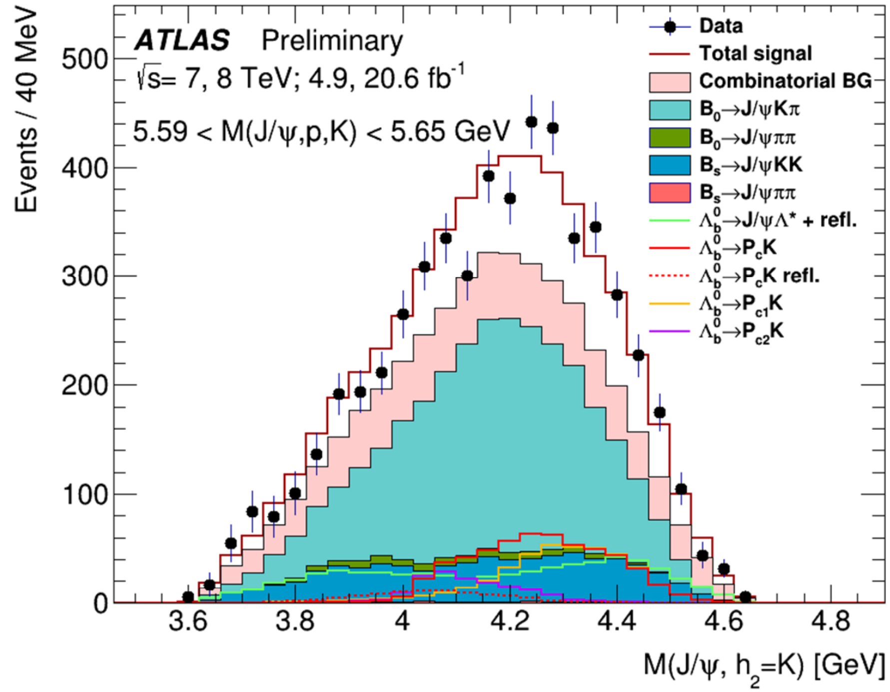
P_c signal parameters and yields from fit:

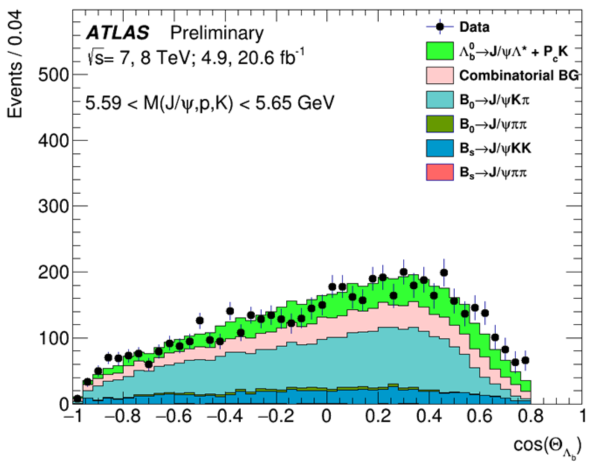
Parameter	Value	LHCb value
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$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

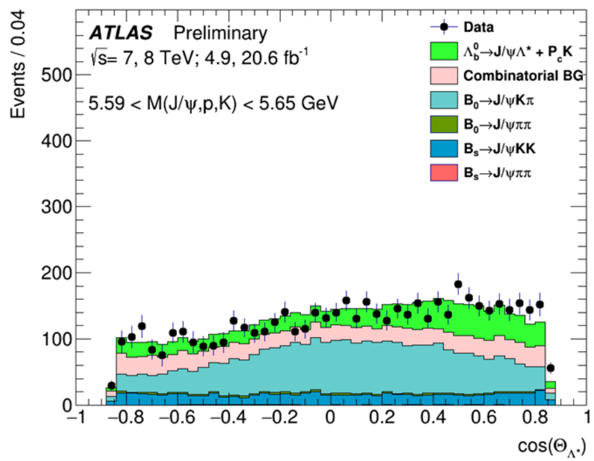
The fit with the two pentaquark masses and widths fixed to the LHCb values yields $\chi^2/N_{dof} = 49.0/43$ (p-value= 0.25);

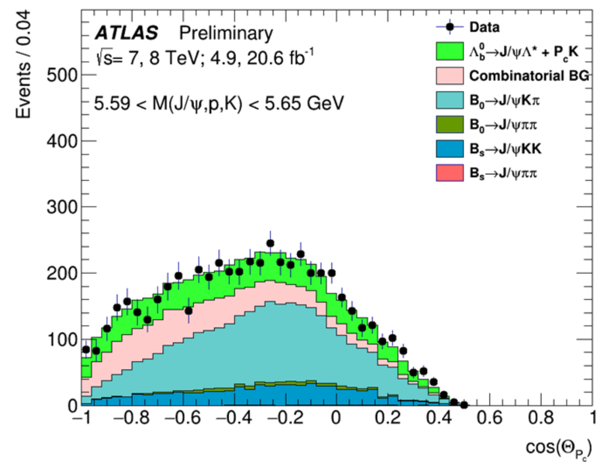
$\Lambda_b \to J/\psi, p, K$ decays analysis: 2 pentaquark hypothesis control plots









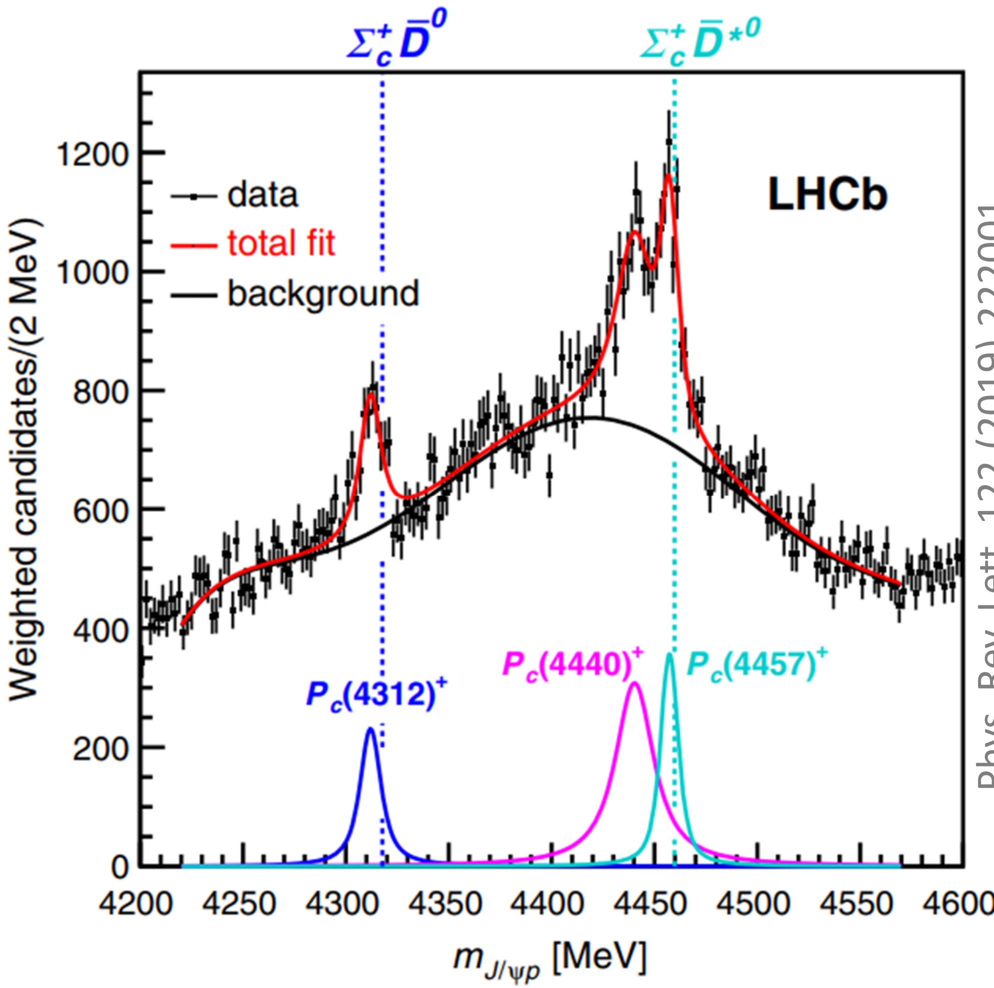


Summary of systematic uncertainties

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 (δ_1)	$^{+1.8}_{-0.6}\%$	$^{+6.6}_{-9.2}\%$	$^{+1.6}_{-0.8}\%$	$^{+0.3}_{-0.0}\%$
Pentaquark modelling (δ_2)	$^{+21}_{-0}\%$	$^{+1}_{-22}\%$	$^{+8.7}_{-4.4}\%$	$^{+1.6}_{-0.0}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling (δ_3)	$^{+14}_{-2}\%$	$^{+5}_{-44}\%$	$^{+9.2}_{-9.1}\%$	$^{+3.6}_{-1.6}\%$
Combinatorial background (δ_4)	$^{+0.7}_{-4.0}\%$	$^{+18}_{-5}\%$	$^{+4.2}_{-4.8}\%$	$^{+3.2}_{-0.0}\%$
B meson decays modelling (δ_5)	$^{+13}_{-25}\%$	$^{+28}_{-35}\%$	$^{+1.6}_{-9.3}\%$	$^{+0.5}_{-2.1}\%$
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 (δ_1)	$^{+0.06}_{-0.03}\%$	$^{+3.5}_{-2.5}\%$	$^{+0.07}_{-0.04}\%$	$^{+7}_{-13}\%$
Pentaquark modelling (δ_2)	$^{+0.6}_{-0.0}\%$	$^{+18}_{-0}\%$	$^{+0.2}_{-0.0}\%$	$^{+0}_{-33}\%$
Non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ modelling (δ_3)	$^{+0.23}_{-0.05}\%$	$^{+9.2}_{-1.2}\%$	$^{+0.24}_{-0.02}\%$	$^{+2}_{-62}\%$
Combinatorial background (δ_4)	$^{+0.03}_{-0.15}\%$	$^{+0}_{-11}\%$	$^{+0.01}_{-0.17}\%$	$^{+22}_{-4}\%$
B meson decays modelling (δ_5)	$^{+0.24}_{-0.00}\%$	$^{+21}_{-21}\%$	$^{+0.27}_{-0.14}\%$	$^{+17}_{-57}\%$
Total systematic uncertainty	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

$\Lambda_b \to J/\psi, p, K$ decays analysis: 4 pentaquark hypothesis



Phys. Rev. Lett. 122 (2019) 222001

LHCb selected 9 times more Λ_b candidates in Run II compared to Run I.

The $J/\psi p$ mass resolution is 2.3-2.7 MeV (RMS) in 4.3-4.6 GeV region.

New data showed evidence for a new narrow state: $P_c(4312)$.

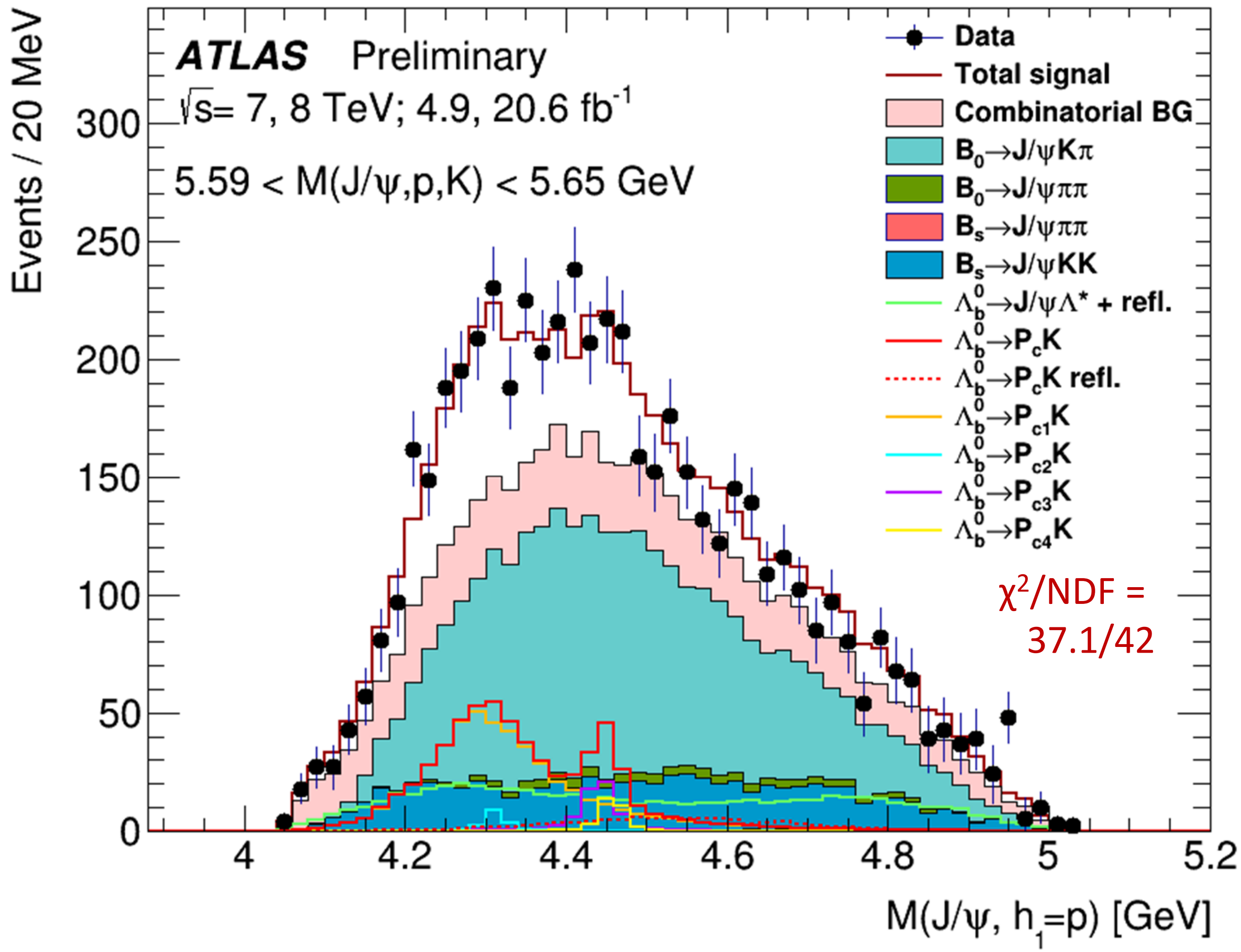
Moreover, the former $P_c(4450)$ state revealed substructure: 2 narrow states $P_c(4440)$ and $P_c(4457)$ have been observed.

Signal parameters are obtained using non-coherent sum of Breit-Wigner amplitude.

Presence of the broad state $P_c(4380)$ is not confirmed…

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

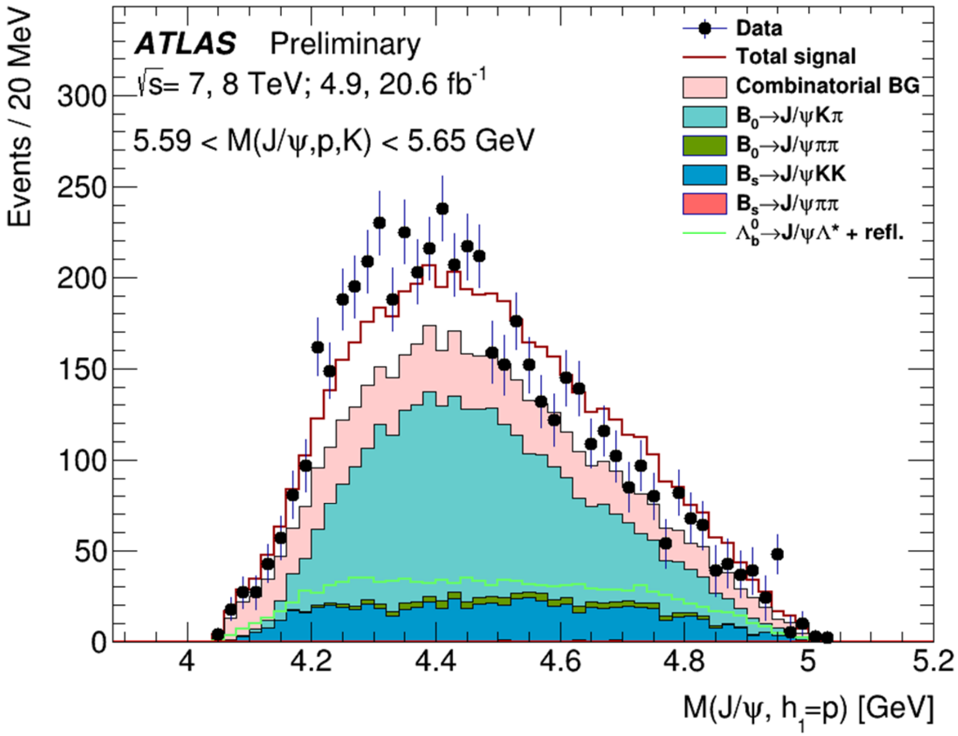
$\Lambda_b \to J/\psi,p,K$ decays analysis: 4 pentaquark hypothesis

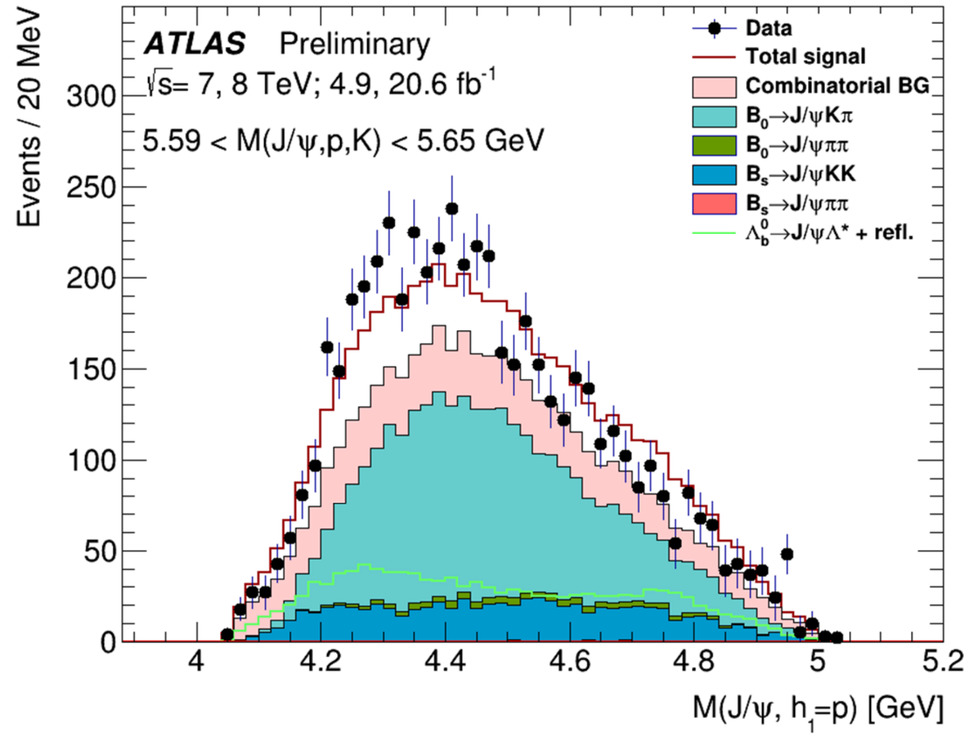


Similar fits (no interference, Breit-Wigner amplitudes) has been performed on our data with masses, widths and relative yields of narrow states fixed to LHCb values. Parameters of $P_c(4380)$ kept free.

ATLAS data is consistent with LHCb Run II results.

No pentaquark fits: default Λ^* decay model

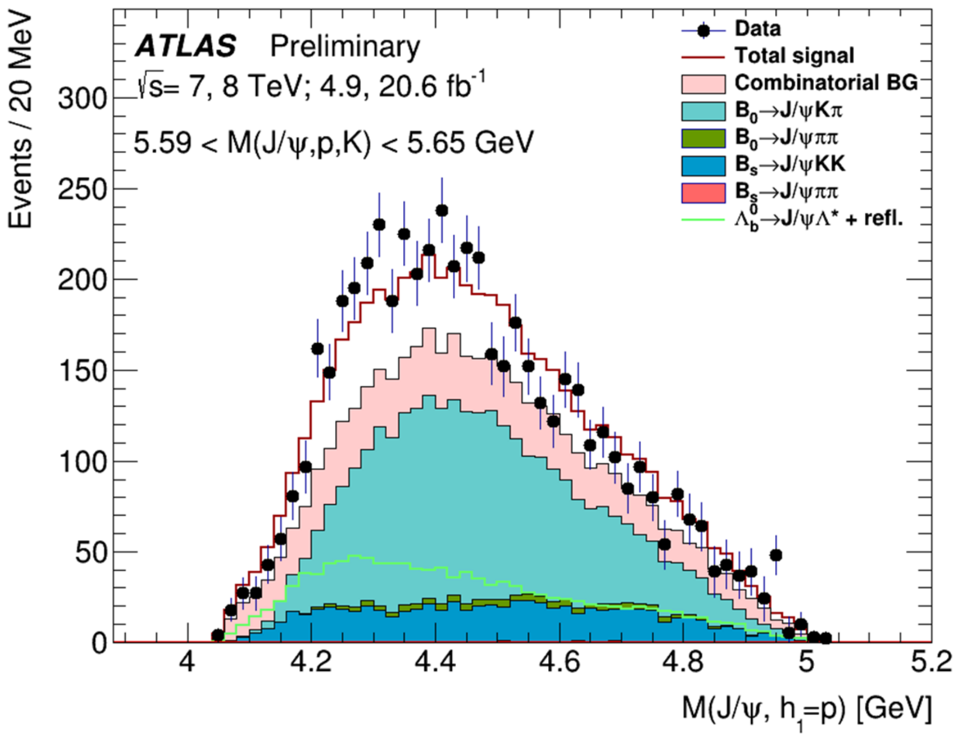


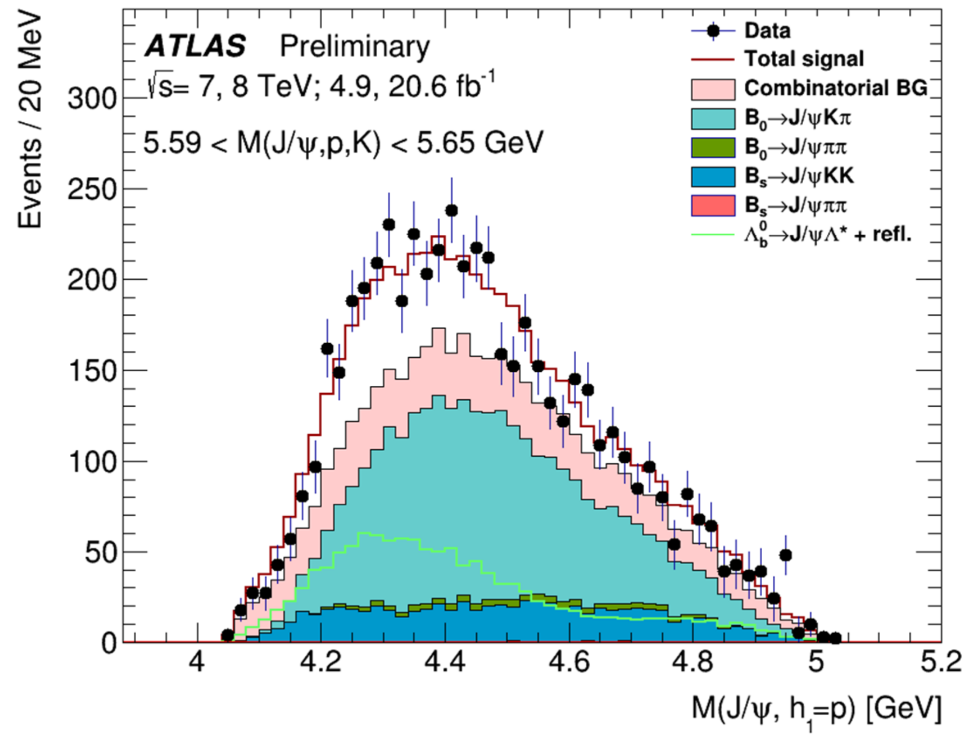


Projection of 2D M($J/\psi,p$) vs. M($J/\psi,K$) + 1D M(p,K) fit without pentaquarks, operating default Λ^* decay model (left)

Result of the 1D χ^2 M($J/\psi,p$) fit with the same model (right):
χ^2/NDF = 69.2/37, p-value=1.0e-3

No pentaquark fits: extended Λ^* decay model



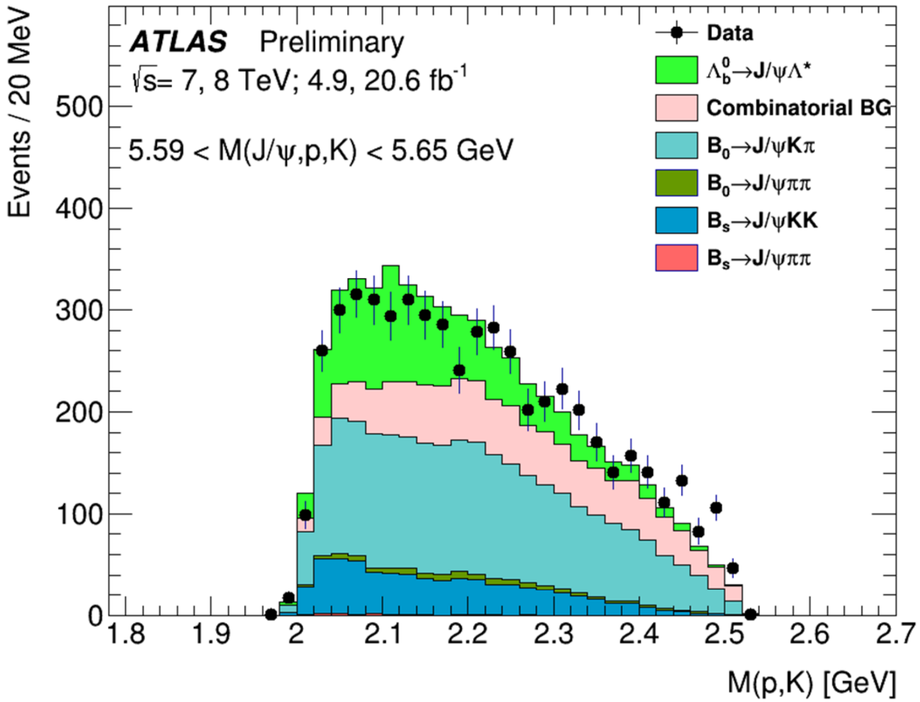


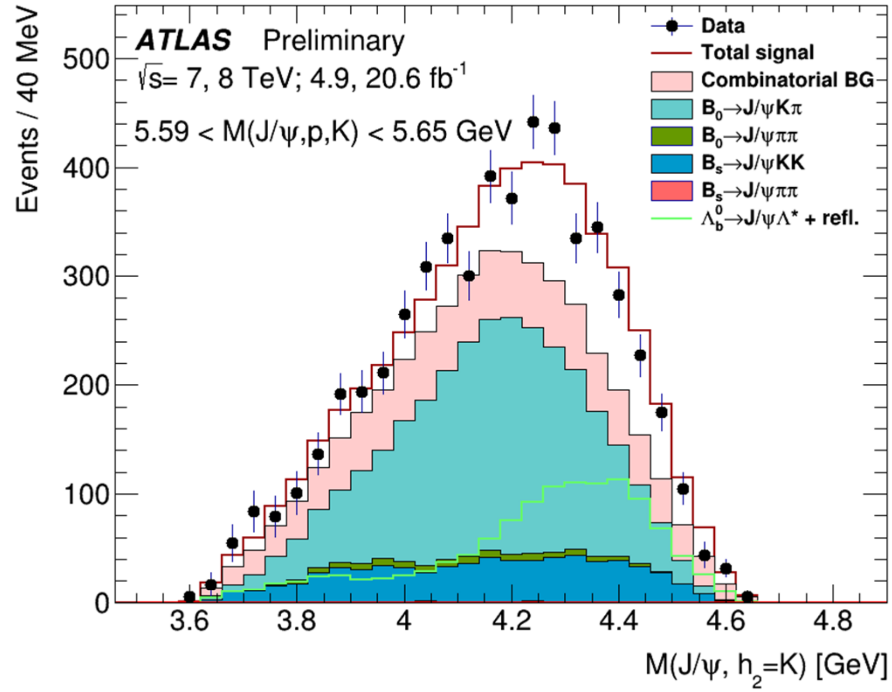
Projection of 2D M($J/\psi,p$) vs. M($J/\psi,K$) + 1D M(p,K) fit without pentaquarks, operating extended Λ^* decay model (left).

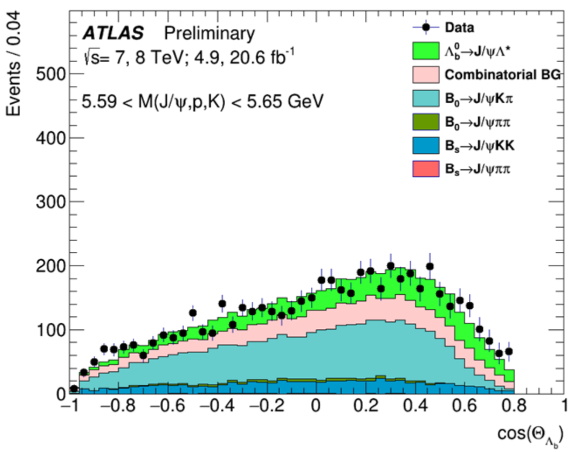
Result of the 1D χ^2 M($J/\psi,p$) fit with the same model (right):
χ^2/NDF = 42.0/23, p-value=9.1e-3

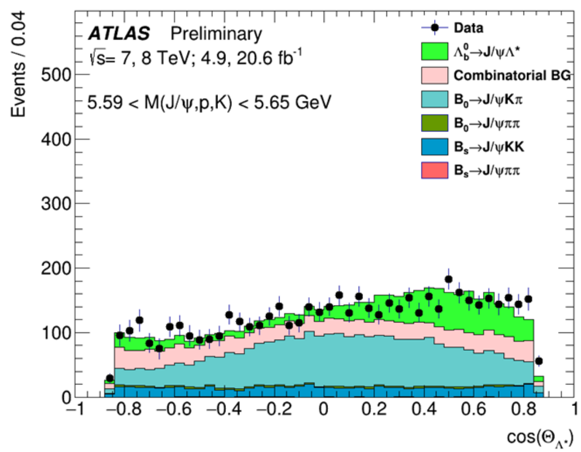
This model shows a 'border-line agreement' with data.

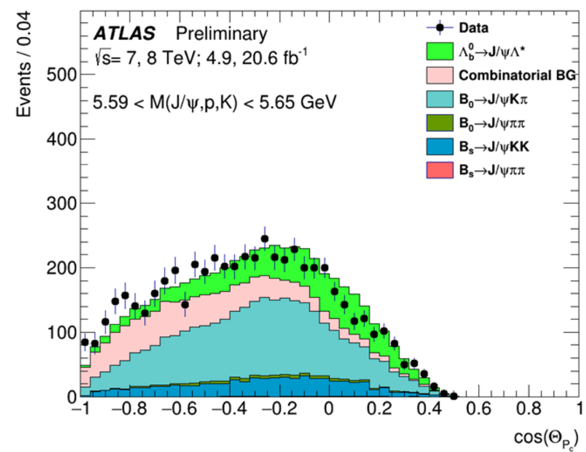
No pentaquark M(J/ψ,p) χ^2 fits (extended Λ* model) control plots











1. 1010±140 direct $\Lambda_b \to J/\psi, p, K$ candidates are analyzed in the kinematic region with high invariant mass of proton-kaon system;

2. Parameters of two pentaquark signals (540 events in total) are measured being consistent with LHCb results;

3. Four pentaquark hypothesis is also consistent with ATLAS data;

4. In the No-pentaquark hypothesis, data description is poor, though this hypothesis cannot be completely statistically excluded (p-value = $9.1 \cdot 10^{-3}$);

5. Most of the difficulties we faced in Run I (physical backgrounds analysis, fitting techniques, combinatorial background estimation, etc.) are overcome. Analysis on Run II data featuring more statistics and higher resolution is planned to be performed using established approaches…

Thank you!

Backup slides

Λ_b candidates selection criteria

1. Muon triggers (see backup);
2. 2 muons passing MCP selection rules, coming from J/Ψ decay (3097 ± 290 GeV);
3. 2 muon tracks + 2 hadron tracks simultaneously fit to common vertex (dimuon mass constrained to J/ψ mass) and Λ_b candidate track to primary vertex with $\chi^2/NDF<16/8$;
4. 2 hadron tracks, with each of them to be assigned different mass hypothesis (proton or kaon);
5. Pt>2.5 GeV for proton candidate and Pt>1.8 GeV for kaon candidate, having at least 2 hits in Pixel and 6 hits in SCT;
6. Transverse decay length $L_{xy}(\Lambda_b)>0.7$mm;
7. $p_T(\Lambda_b)/\Sigma p_T(\text{track}) > 0.2$, where sum is taken over all tracks originating from PV;
8. $p_T(\mu^{\pm}) > 4$GeV, $|\eta(\mu^{\pm})|<2.3$, $p_T(\Lambda_b) > 12$GeV, $|\eta(\Lambda_b)|<2.1$;

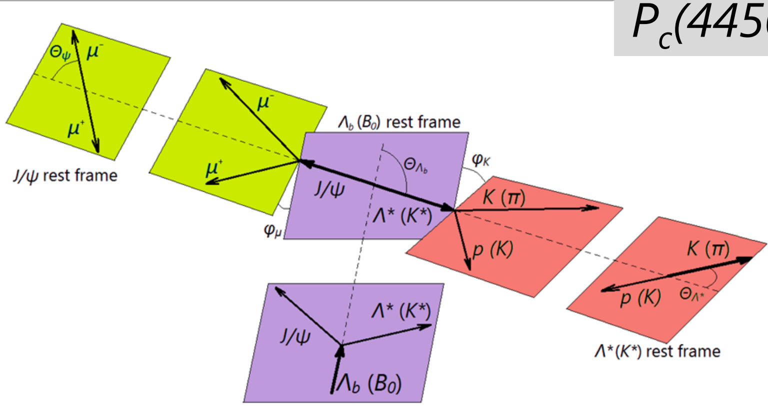
9. Inv. mass of hadron tracks (in $K\pi$ and πK mass hypotheses): $M(K\pi) > 1.55$ GeV and $M(\pi K) > 1.55$ GeV: to suppress decays via light intermediate resonances;
10. $\cos\theta^*$ between proton and $J/\Psi\ p$ system in $J/\Psi\ p$ rest frame > -0.5;
11. $\cos\theta^*$ between kaon and Λ_b candidate in Λ_b candidate rest frame > -0.8;
12. $|\cos\theta^*|$ between kaon and Λ^* in Λ^* rest system less than *0.85*;
13. Events for $J/\Psi p$ signal search are taken in window $M(J/\Psi\ p\ K) = 5620 \pm 30$ MeV;
14. Subtraction of distributions with two same sign hadron tracks is applied;

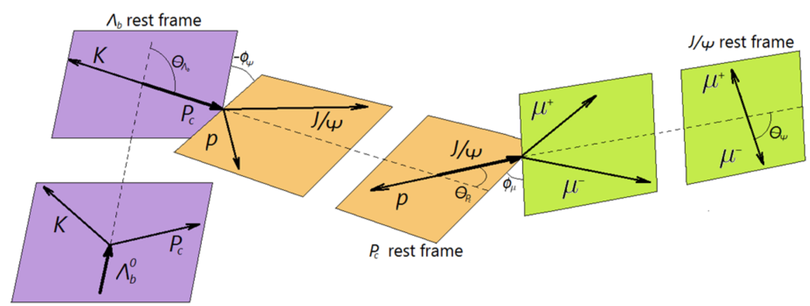
$\Lambda_b \to J/\psi, p, K$ decays simulation

1. 'Default' model has only 1 complex coupling for each Λ^*; while full matrix element for pentaquark signals (5 complex coupling constants each);

2. Extended model (which coincides with LHCb "reduced" model) includes more terms for $\Lambda^*(1800)$, $\Lambda^*(1810)$, $\Lambda^*(1890)$;

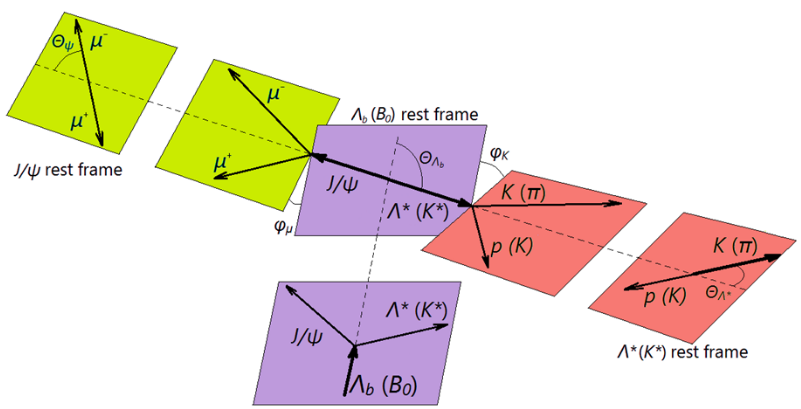
	Spin/parity	Number of couplings (extended)	Number of couplings (default)	Number of couplings (full model)
$\Lambda^*(1800)$	$1/2^-$	4	1	4
$\Lambda^*(1810)$	$1/2^+$	3	1	4
$\Lambda^*(1820)$	$5/2^+$	1	1	6
$\Lambda^*(1830)$	$5/2^-$	1	1	6
$\Lambda^*(1890)$	$3/2^+$	3	1	6
$\Lambda^*(2100)$	$7/2^-$	1	1	6
$\Lambda^*(2110)$	$5/2^+$	1	1	6
$P_c(4380)$	$3/2^-$	5	1	5
$P_c(4450)$	$5/2^+$	5	1	5

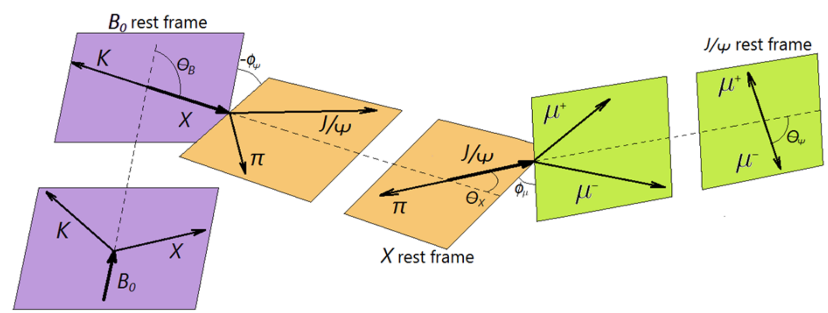




1. Full theoretical model includes 3 complex couplings for each K^* with spin >0;
2. Reduced model has only 1 complex coupling for each K^*;
3. For $Z_c(4200)$, the $\boldsymbol{0^+}$ spin/parity is forbidden; for $\boldsymbol{1^+, 2^-, 3^+}$ spin/parity there are 2 couplings, whereas for $\boldsymbol{0^-, 1^-, 2^+, 3^-}$... there is only 1 complex coupling constant;
4. For the analysis central result we use **default model without $\boldsymbol{Z_c}$.**

	Spin/parity	Number of couplings (default)	Number of couplings (reduced)
$K^*(1410)$	1^-	3	1
$K^*(1430)$	0^+	1	1
$K^*(1430)$	2^+	3	1
$K^*(1680)$	1^+	3	1
$K^*(1780)$	3^-	3	1
$K^*(1950)$	0^+	1	1
$K^*(2045)$	4^+	1	1
$Z_c(4200)$	$1^+,2^-,3^+$...	2	2
$Z_c(4200)$	$0^-,1^-,2^+$...	1	1

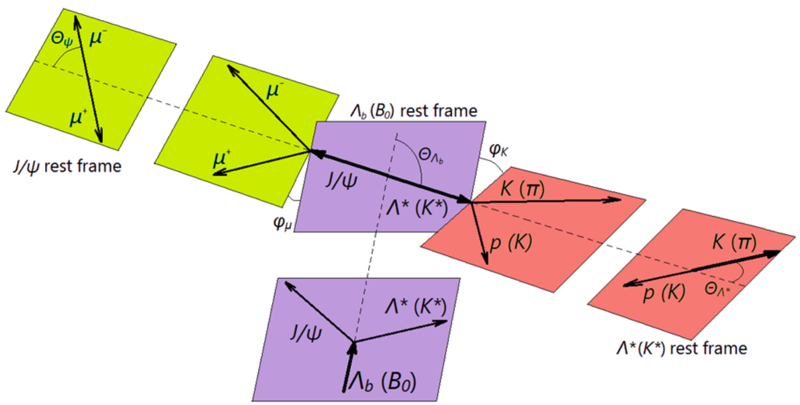




$B_s \rightarrow J/\psi,K,K;$ decays simulation

Full theoretical model includes 3 complex couplings for each φ or f state with spin >0 and is used for the central result of the analysis;

	Spin/parity	Number of couplings (default)
$\varphi(1680)$	1^-	3
$f_2(1525)$	2^+	3
$f_2(1640)$	2^+	3
$f_2(1750)$	2^+	3
$f_2(1950)$	2^+	3



Summary of systematic uncertainties

The following groups of systematic uncertainty sources are considered:

- The uncertainty due to that in the number of the $\Lambda_b^0 \to J/\psi p K^-$ decays in SR. This is calculated by adding in quadrature the statistical uncertainty of the number (Section 6) and its systematic uncertainty, obtained by variations of the functional form, Eq. (3), used for the combinatorial background description and by changing the $m(J/\psi p K^-)$ mass range used in the fit at step 2.
- The uncertainty of the pentaquark modelling. This is determined by comparing the results of the central analysis with those obtained using the following modifications:
  - using alternative spin-parity hypotheses, $(3/2^-, 5/2^+)$ and $(5/2^+, 3/2^-)$, for two pentaquarks [5];
  - using the P_c decay model with all possible orbital momenta between their decay products;
  - using the model with four pentaquarks [9].
- The uncertainty of the non-pentaquark $\Lambda_b^0 \to J/\psi p K^-$ decay modelling. This is estimated by comparing the results of the central analysis with those obtained using the following modifications:
  - using the extended $\Lambda_b^0 \to J/\psi \Lambda^{*0}$ decay model with two lowest orbital momenta between the decay products of $\Lambda^*(1800)$, $\Lambda^*(1810)$ and $\Lambda^*(1890)$;
  - including the $\Lambda^*(2350)$ contribution to the model;
  - adding the non-resonant component to the $\Lambda_b^0 \to J/\psi p K^-$ decay model either as a wide resonance [5] or as a phase-space decay contribution;
  - varying the Λ^{*0} masses and widths by their uncertainties [23].

Summary of systematic uncertainties

- The uncertainty of the combinatorial background description for distributions in the Λ_b^0 SR. It is determined by varying the maximal allowed momentum corrections and by using different corrections for the proton and kaon momenta.
- The uncertainty of the B meson background description. This is estimated by comparing the results of the central analysis with those obtained using the following modifications:
  - using the model including $Z_c(4200)$ state. The model including $Z_c(4200)$ state and with only the lowest orbital momenta between the B^0 and B_s^0 decay products is also considered as it describes the data satisfactorily;
  - adding the non-resonant components either as wide resonances or as phase-space decay contributions;
  - changing the combinatorial background description for the 2D $m(J/\psi, h_1 = K, h_2 = \pi) - m(J/\psi, h_1 = \pi, h_2 = K)$ distribution from the functional form of Eq. (1) to the form of Eq. (2);
  - changing the combinatorial background descriptions for distributions in the B^0 and B_s^0 CRs. It is determined by varying the maximal allowed momentum corrections and by using different corrections for two hadron tracks.