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# ATLAS results on $J/\psi p$ resonances in the $\Lambda_b \rightarrow J/\psi p K$ decays

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I. Yeletsikh

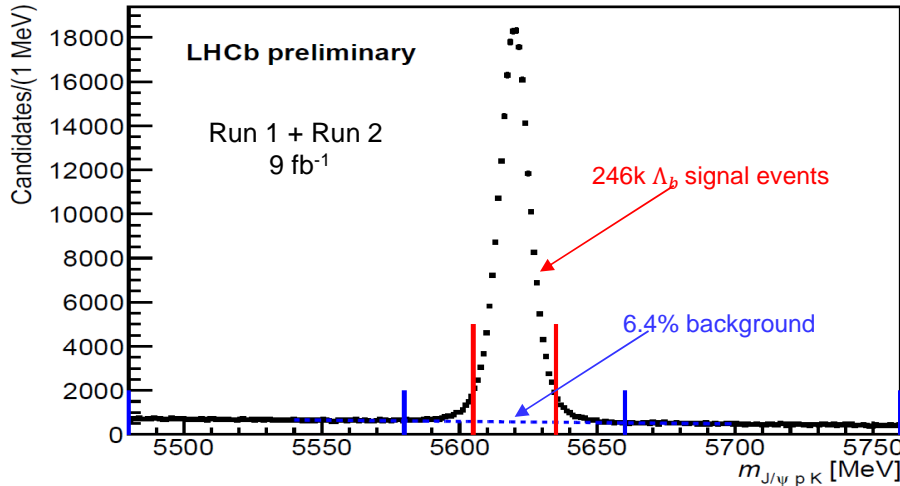
on behalf of the ATLAS Collaboration

- Pentaquarks discovery and subsequent studies
- $\Lambda_b$  candidate selection at ATLAS
- $H_b \rightarrow J/\psi hh$  decay models
- Fit procedure: event yields, control region description
- $\Lambda_b \rightarrow J/\psi pK$  Signal region analysis
  - Models with 2 and 4 pentaquarks
  - Models without pentaquarks
- Conclusions and Plans

# Pentaquark states discovery

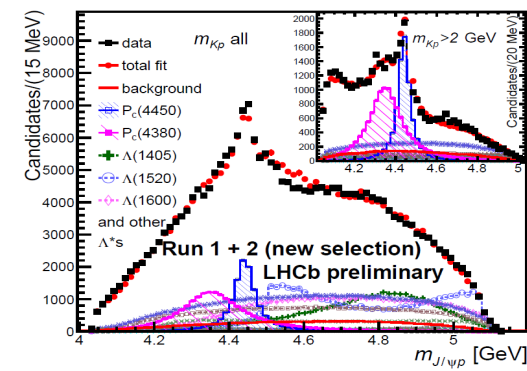
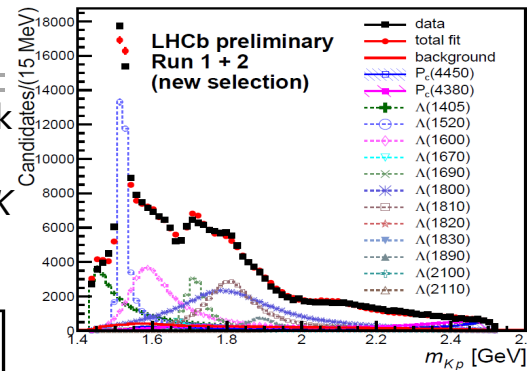
Two states  $P_c(4380)$  and  $P_c(4450)$  consistent with pentaquark hypothesis were discovered at LHCb in 2015.

With Run II data providing  $\sim 9x$  statistics of Run I for  $\Lambda_b \rightarrow J/\psi p K$  decays (246K candidates) LHCb published new results:

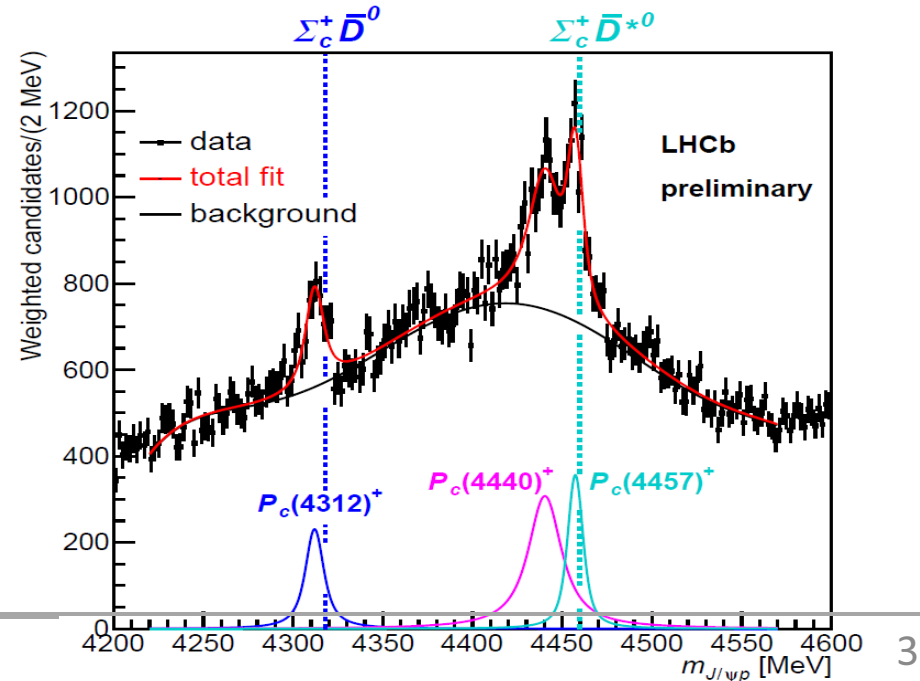


State  $P_c(4450)$  revealed its substructure: two states  $P_c(4457)$ ,  $P_c(4440)$  (widths 6.4 и 21 MeV respectively) and  $5.4\sigma$  significance w.r.t. to single state hypothesis;

Run II analysis methods **were not sensitive** to the wide  $P_c(4380)$  state.



New state  $P_c(4312)$  (width  $\sim 10$  MeV) and  $7.4\sigma$  significance has been discovered.



# Reconstruction of $\Lambda_b \rightarrow J/\psi p K$ candidates at ATLAS

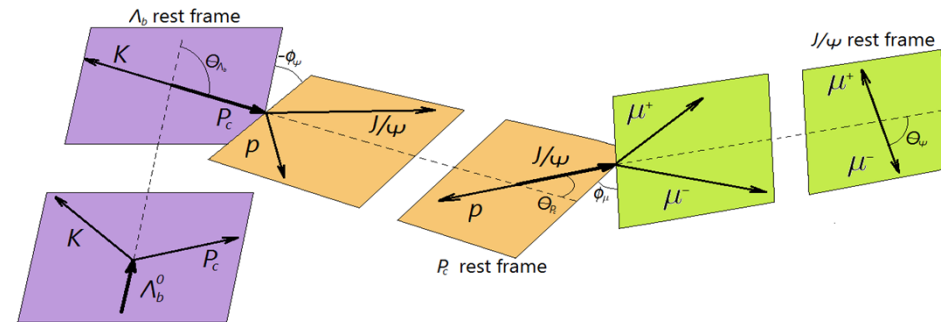
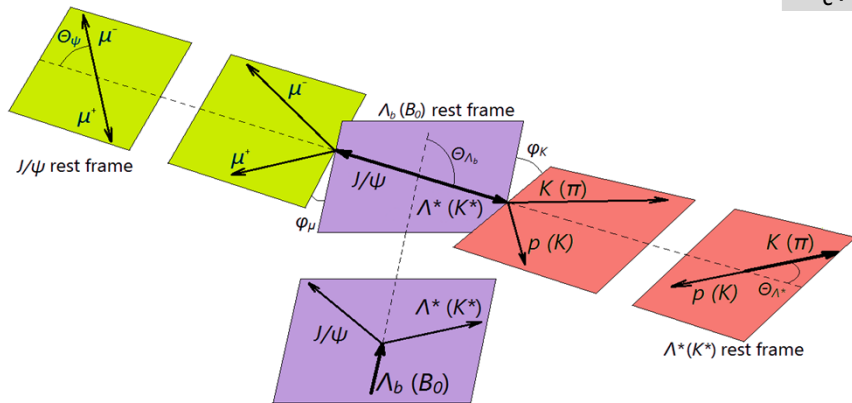
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1. Due to absence of hadron track identification, we select  $J/\psi, h_1, h_2$  candidates, where  $h_1, h_2$  are hadrons of unknown flavour:  $p, K, \pi$ ;
2. We had to perform simultaneous analysis of kinematically close  $\Lambda_b, B_d$  and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

# $\Lambda_b \rightarrow J/\psi, p, K$ decays simulation

- Helicity amplitudes are used to calculate weights to model different decay channels on top of the phase space MC
- Reduced model has only 1 complex coupling for each  $\Lambda^*$ ; while full matrix element for pentaquark signals (5 complex coupling constants each);
- Extended model (which coincides with LHCb "reduced" model) includes more terms for  $\Lambda^*(1800)$ ,  $\Lambda^*(1810)$ ,  $\Lambda^*(1890)$ ;

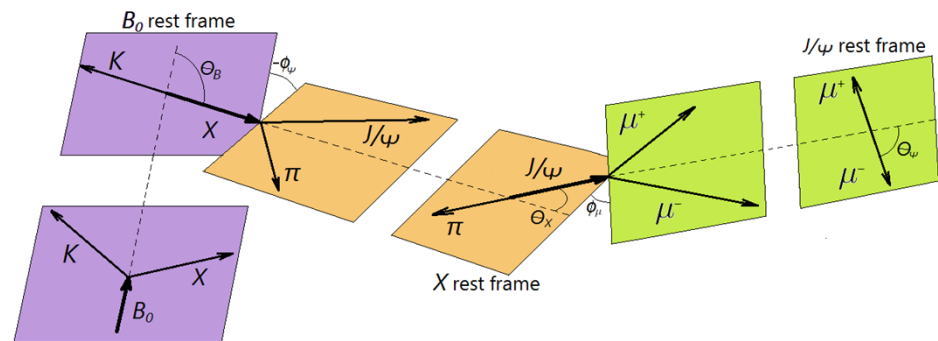
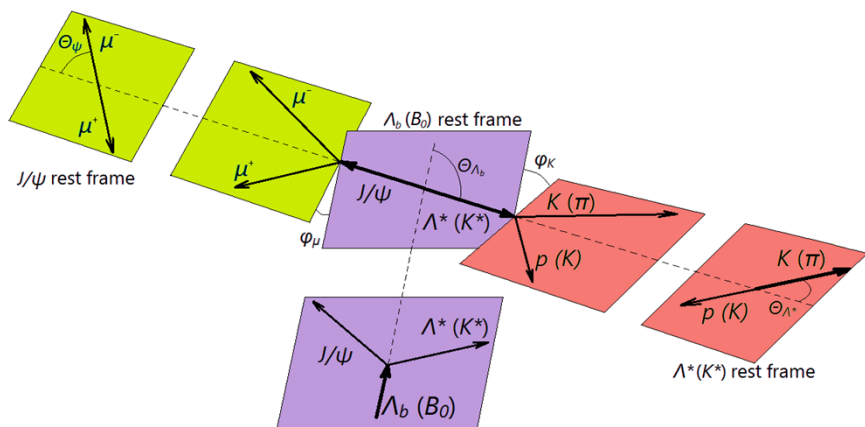
	Spin/parity	Number of couplings (extended)	Number of couplings (simplified)	Number of couplings (full model)
$\Lambda^*(1800)$	$1/2^-$	4	1	4
$\Lambda^*(1810)$	$1/2^+$	3	1	4
$\Lambda^*(1820)$	$5/2^+$	1	1	6
$\Lambda^*(1830)$	$5/2^-$	1	1	6
$\Lambda^*(1890)$	$3/2^+$	3	1	6
$\Lambda^*(2100)$	$7/2^-$	1	1	6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



# $B^0 \rightarrow J/\psi, K, \pi$ ; decays simulation

- Full theoretical model includes 3 complex couplings for each  $K^*$  with spin  $>0$ ;
- Reduced model has only 1 complex coupling for each  $K^*$
- Extended model for  $B^0 \rightarrow J/\psi, K, \pi$  decays is used. The 'reduced' model is incapable in describing data
- Exotic  $Z_c(4200)$  state is included into  $B^0$  decay model. **Its contribution is considered as systematic effect**

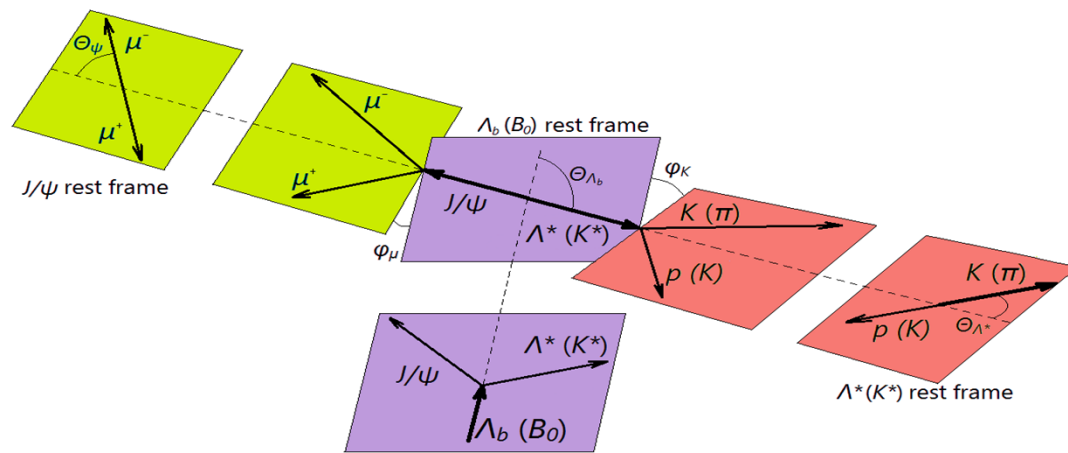
	Spin/parity	Number of couplings (extended)	Number of couplings (reduced)
$K^*(1410)$	$1^-$	3	1
$K^*(1430)$	$0^+$	1	1
$K^*(1430)$	$2^+$	3	1
$K^*(1680)$	$1^+$	3	1
$K^*(1780)$	$3^-$	3	1
$K^*(1950)$	$0^+$	1	1
$K^*(2045)$	$4^+$	1	1
$Z_c(4200)$	$1^+, 2^-, 3^+ \dots$	2	2
$Z_c(4200)$	$0^-, 1^-, 2^+ \dots$	1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

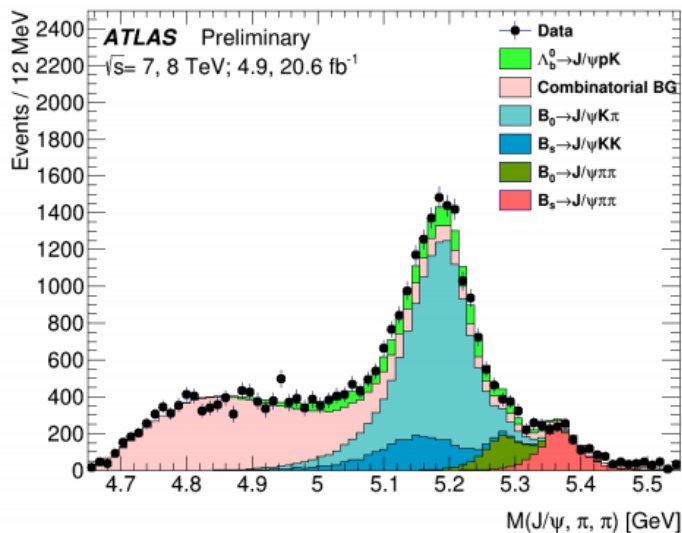
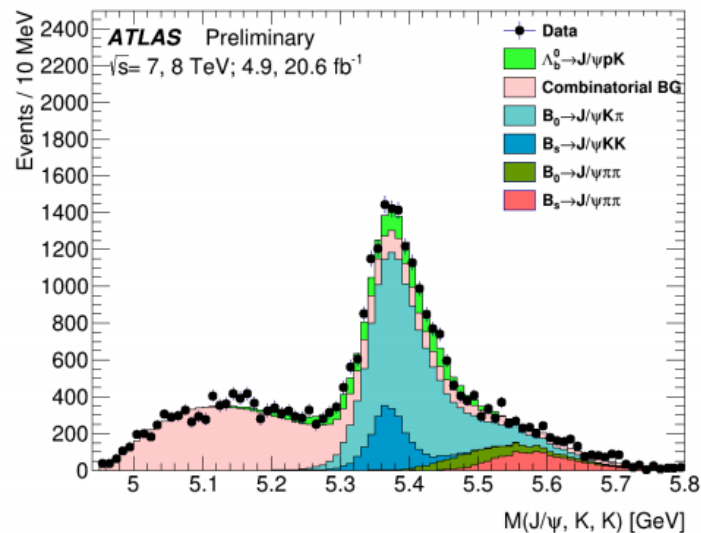
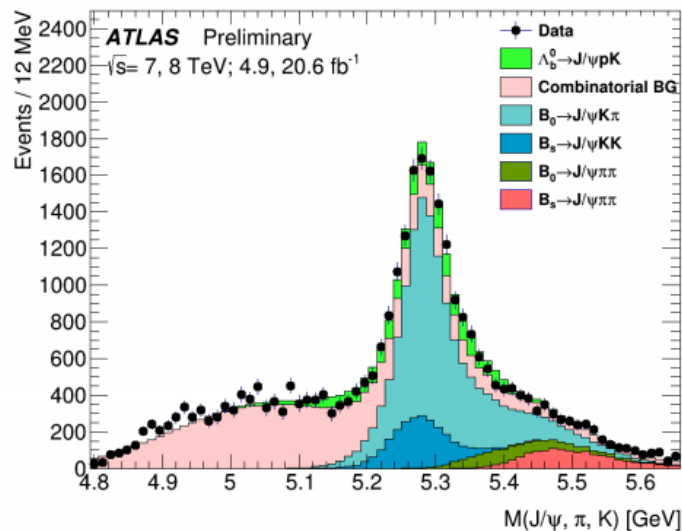
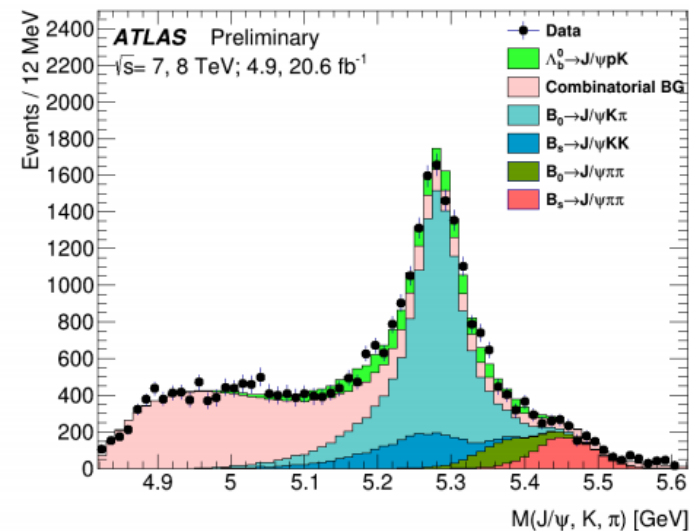


$B_s \rightarrow J/\psi, K, K$ ; decays simulation

1. Full theoretical model includes 3 complex couplings for each  $\boldsymbol{\varphi}$  or  $\boldsymbol{f}$  state with spin  $>0$ ;
2. Reduced model has only 1 complex coupling for each resonance;
3. We use **extended model** to describe data in  $B_s$  CR.

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





Selected events are analyzed simultaneously with different hadrons mass assignments.

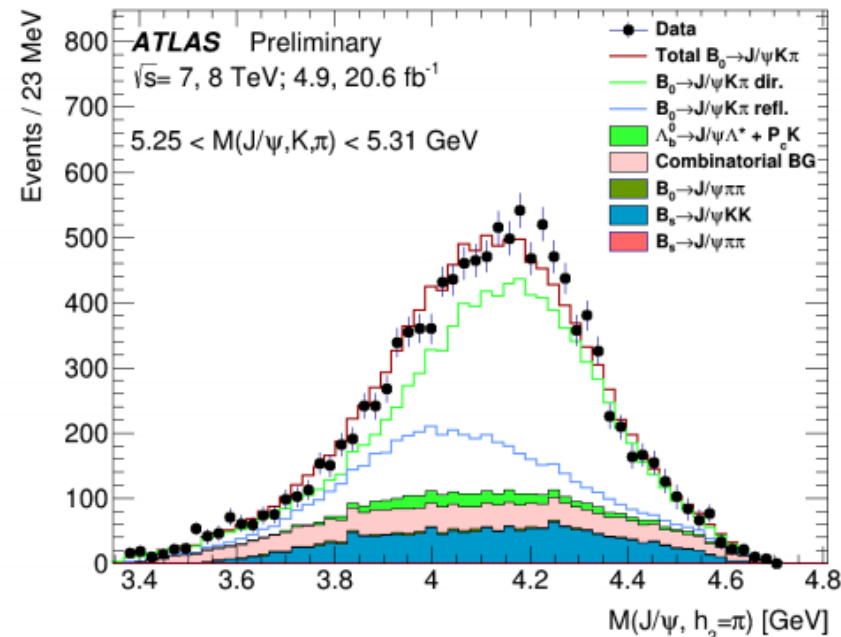
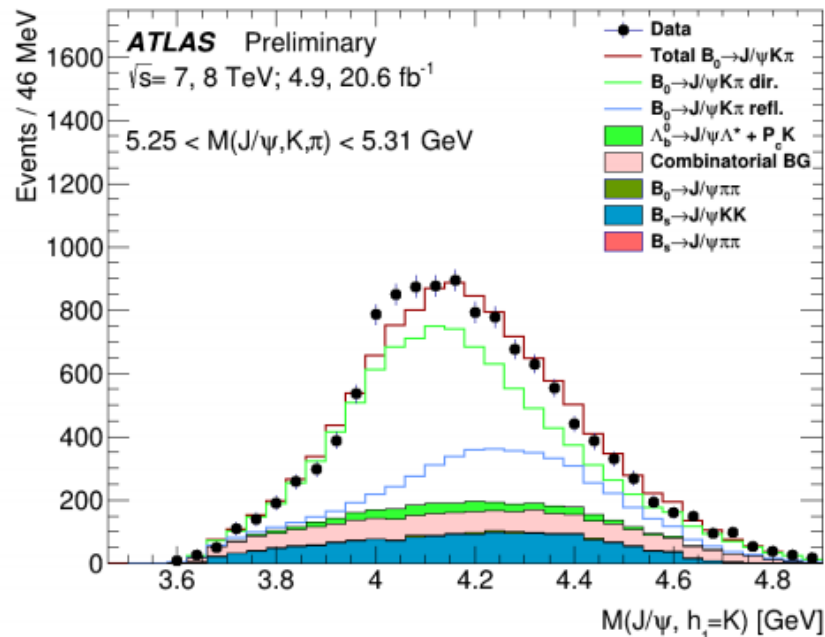
This provides sensitivity to all processes contributing to our kinematic region...

Different decays yields obtained from fits to data:

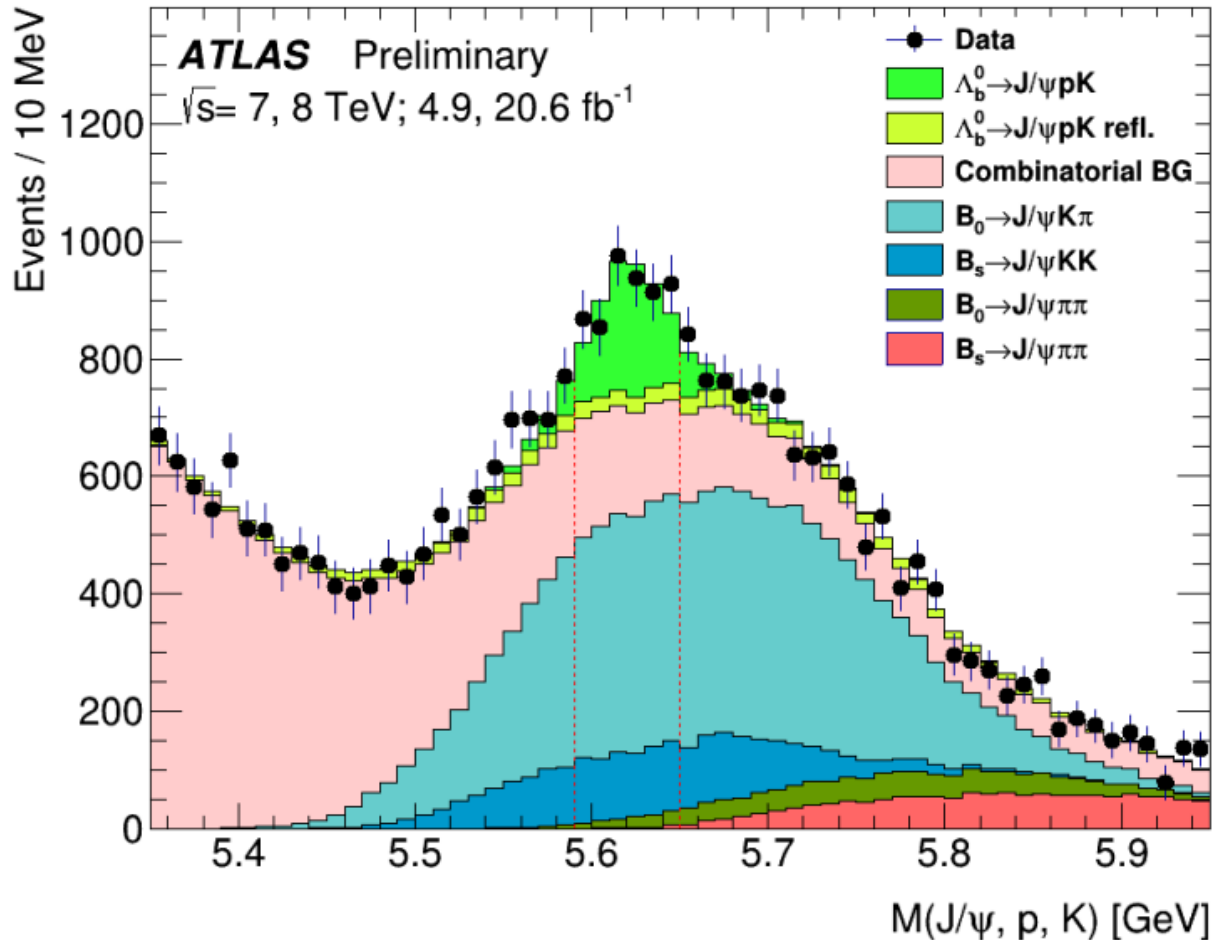
- $N(\Lambda_b^0 \rightarrow J/\psi p K) = 2270 \pm 300$
- $N(B^0 \rightarrow J/\psi K \pi) = 10770$
- $N(B_s \rightarrow J/\psi K K) = 2290$
- $N(B^0 \rightarrow J/\psi \pi \pi) = 1070$
- $N(B_s \rightarrow J/\psi \pi \pi) = 1390$



We analyzed  $\sim 10\text{K } B^0 \rightarrow J/\psi K\pi$  decays with Run I data w.r.t. properties of intermediate states. Data description without exotic contributions is not perfect (right plot) and demonstrates hints on  $Z_c^+(4200)$  contributions.



- Plots show  $M(J/\psi K)$ ,  $M(J/\psi\pi)$  distributions in the  $B^0$ -meson signal region;
- $Z_c(4200)$  is discovered by BELLE collaborationn 2014, its one of the exotic candidates with large ( $\sim 300\text{-}400\text{MeV}$ ) decay width, implying specific internal structure of this state; properties of this state are known with poor accuracy;
- $Z_c(4200)$  contribution is considered as systematics w.r.t. pentaquark parameters measured;
- With Run II data  $\sim 5$  times more signal candidates are expected with smaller systematic from other processes parameters; also, angular information to be included to gain sensitivity to the spin-parity; **Run II analysis is ongoing...**



Total number of  $\Lambda_b \rightarrow J/\psi p K$  candidates selected is **2270±300**

**Green** histogram shows  $\Lambda_b$  signal with correct mass assignment;  
**Yellow** histogram shows  $\Lambda_b$  signal with wrong mass assignment;

Signal region include events with:  
 $5.59 \text{ GeV} < M(J/\psi p K) < 5.65 \text{ GeV}$  OR  
 $5.59 \text{ GeV} < M(J/\psi K p) < 5.65 \text{ GeV}$

In the signal region there are:

**$N(\Lambda_b \rightarrow J/\psi p K) = 1010 \pm 140$**

signal candidates with correct mass assignment

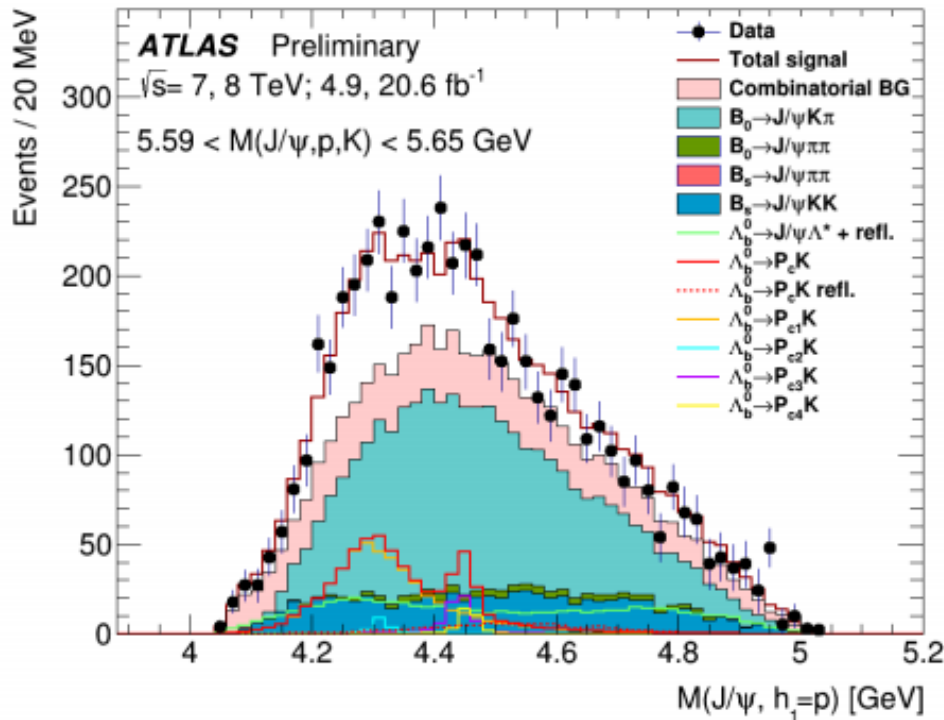
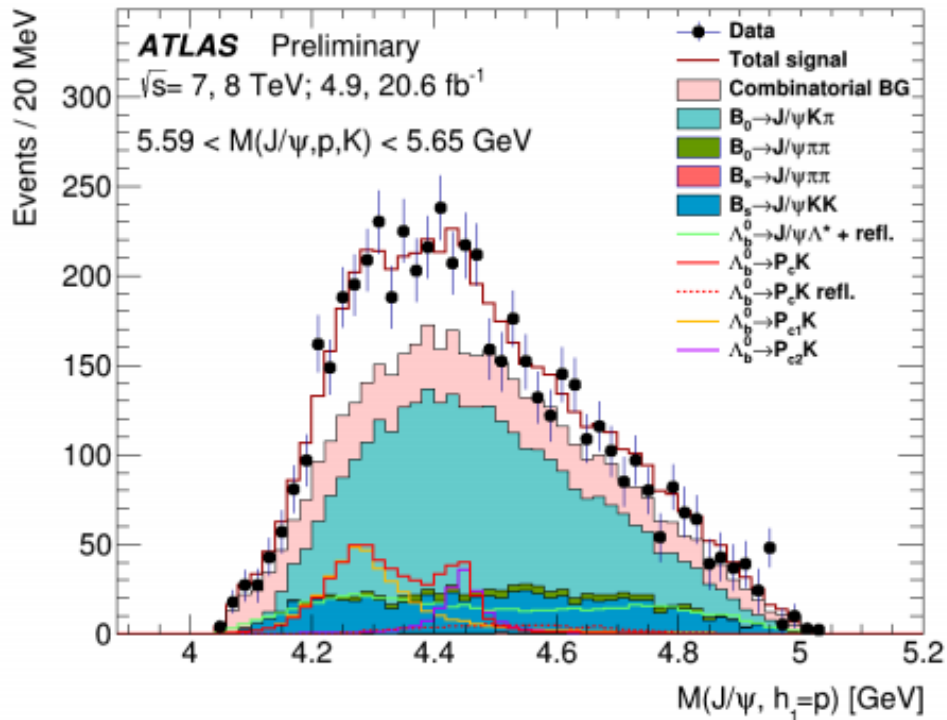
# Pentaquark studies at ATLAS experiment

In the **2 pentaquark** hypothesis (left plot), parameters of 2 pentaquarks are consistent with those measured by LHCb in 2015. **4 pentaquark** hypothesis (following LHCb 2019 result, right plot) is also consistent with ATLAS data;

**$P_c(4380)$  state is questioned...**

4  $P_c$  model result is included into systematics for  $P_c(4380)$

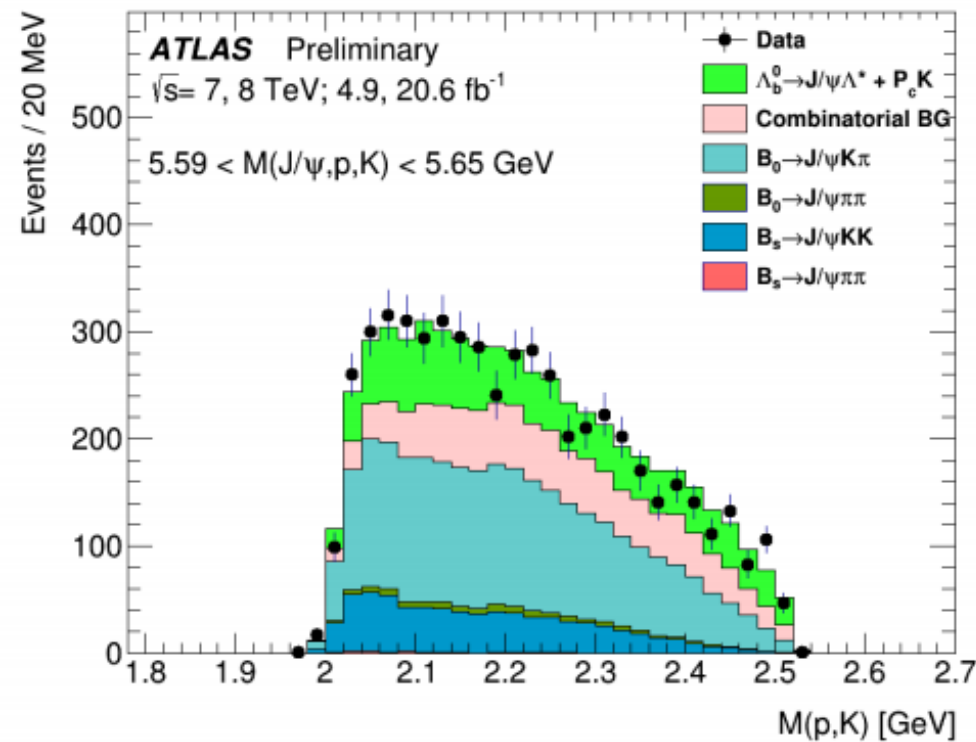
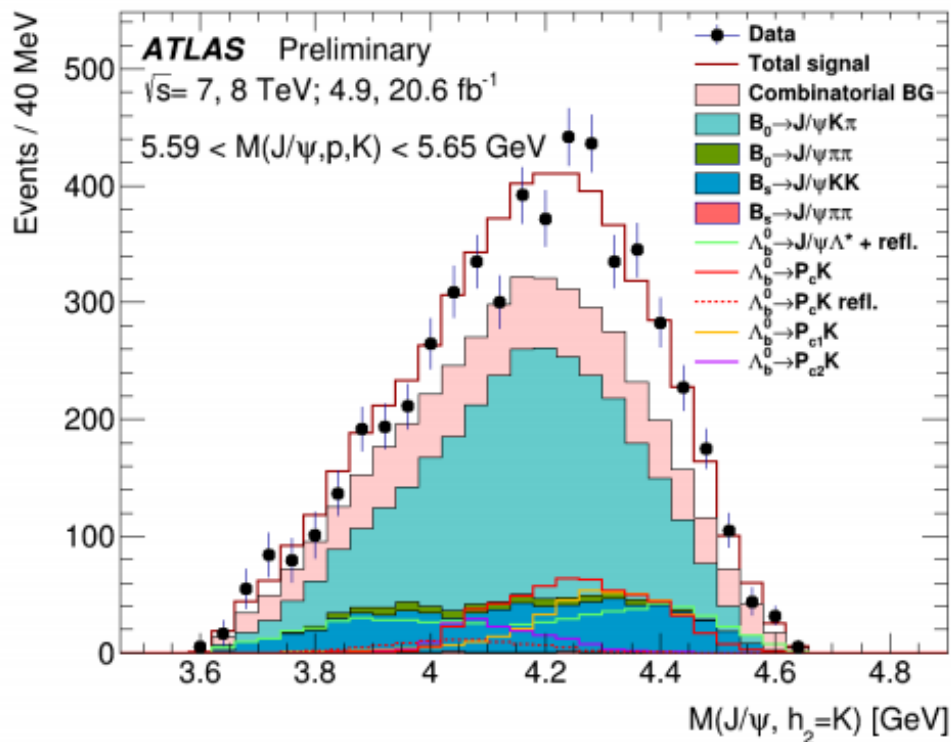
Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1} + P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ 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



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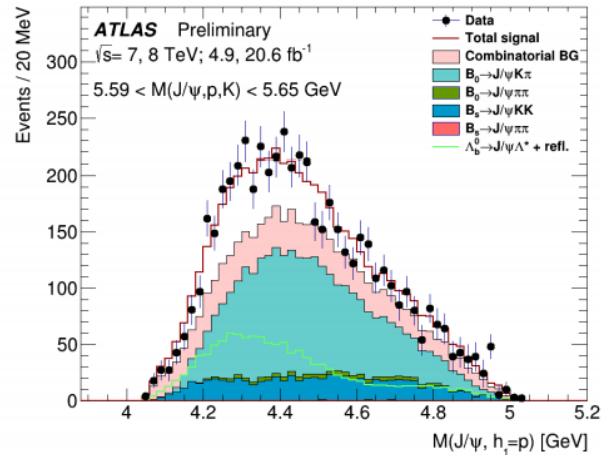
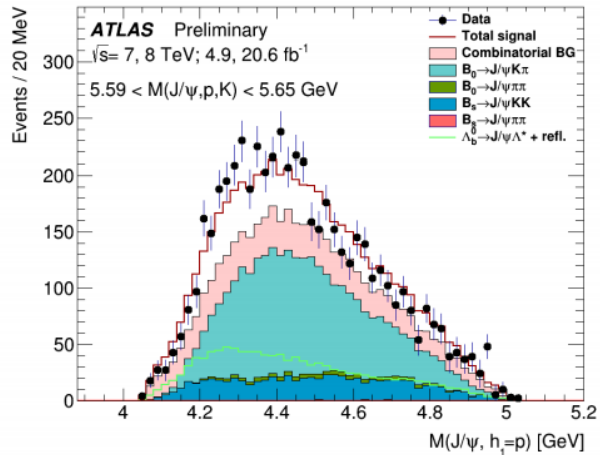
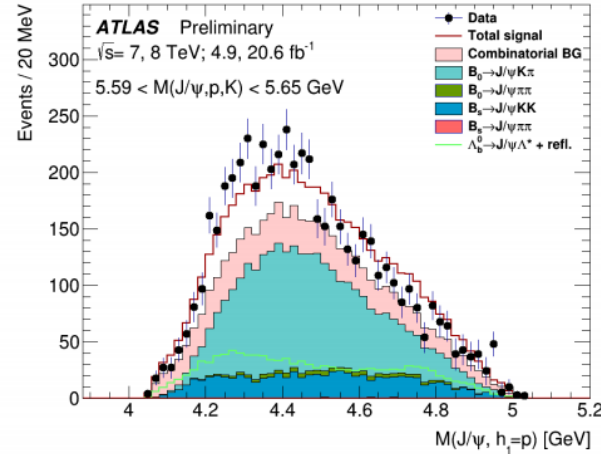
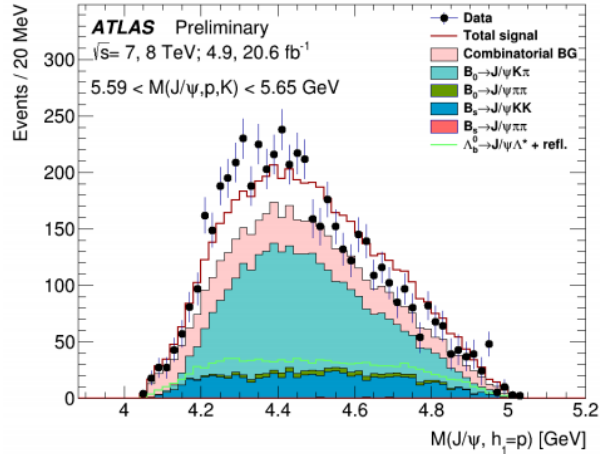
Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1} + P_{c2})$	$\Delta\phi$
Number of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays	+1.8% -0.6%	+6.6% -9.2%	+1.6% -0.8%	+0.3% -0.0%
Pentaquark modelling	+21% -0%	+1% -22%	+8.7% -4.4%	+1.6% -0.0%
Non-pentaquark $\Lambda_b^0 \rightarrow J/\psi p K^-$ modelling	+14% -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 $\Lambda_b^0 \rightarrow J/\psi p K^-$ 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 $\Lambda_b^0 \rightarrow J/\psi p K^-$ 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%



Control plots (2 pentaquark hypothesis) show good description of  $M(J/\psi K)$  and  $M(pK)$  in the signal region.

Angular variables do not take part in fits due to complexity of background (esp. combinatorics) behavior.



Plots show different models without exotic contribution.

Top left: fit of  $M(J/\psi p)$ ,  $M(J/\psi K)$ ,  $M(p, K)$  with minimal  $\Lambda_b \rightarrow J/\psi \Lambda^*$  decay model.

Bottom left: fit of  $M(J/\psi p)$ ,  $M(J/\psi K)$ ,  $M(p, K)$  with extended  $\Lambda_b \rightarrow J/\psi \Lambda^*$  decay model.

Top right: fit of  $M(J/\psi p)$  with minimal  $\Lambda_b \rightarrow J/\psi \Lambda^*$  decay model.

Bottom right: fit of  $M(J/\psi p)$  with extended  $\Lambda_b \rightarrow J/\psi \Lambda^*$  decay model.

Maximal  $p$ -value found for the no- $P_c$  models is  $9.1 \cdot 10^{-3}$

- Analyses of exotic states are ongoing with ATLAS Run II data;
- For pentaquark analysis – signal candidates statistics, detector mass resolution and precision of background modeling are critical;
- Amplitude analysis is needed to confirm/disclaim  $P_c(4380)$  state;
- Pentaquarks with strangeness (discovered in 2020) and naturally expected from QCD neutral pentaquarks can be searched in ATLAS data;
- Its also interesting to test D0 results for inclusive production of pentaquarks;
  
- Study of the  $Z_c(4200)$  state is ongoing with ATLAS Run II data; plans are to improve precision for the parameters of this state compared to other experiments, measure helicity couplings to provide further information for theoretical interpretations;
- With Run II data  $\sim 5x$  statistics of  $B^0 \rightarrow J/\psi K\pi$  candidates is available;
- Several  $B$ -hadron decays may also include contributions from  $Z_{cs}(4000)$ ,  $Z_{cs}(4220)$  states, neutral  $X$ -states discovered by LHCb in 2016-2021;
- Other exotic states can be studied, e.g., di- $J/\psi$  resonances, neutral states in  $B^+ \rightarrow J/\psi K^+ \varphi$  decays.

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**Thanks for your attention!**

**BACKUP**



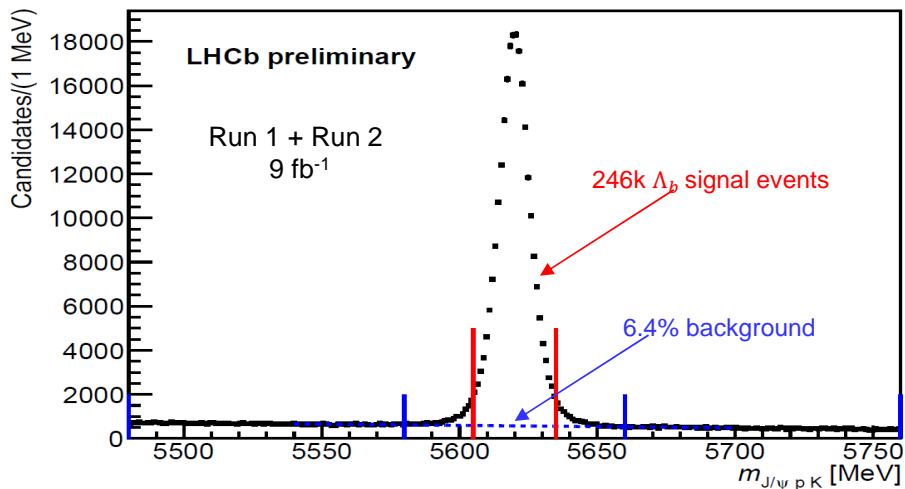


1. Muon pairs for  $J/\psi$  candidates selected with muon triggers;
2. 2 muons passing MCP selection rules, coming from  $J/\psi$  decay ( $3097 \pm 290$  GeV);
3. 2 muon tracks + 2 hadron tracks simultaneously fit to common vertex (dimuon mass constrained to  $J/\psi$  mass) and  $\Lambda_b$  candidate track to primary vertex with  $\chi^2/\text{NDF} < 16/8$ ;
4. 2 hadron tracks, (each of them can be assigned different mass hypotheses (proton, kaon, pion));
5.  $p_T > 2.5$  GeV for proton candidate and  $p_T > 1.8$  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 for 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  $\pi K$  mass hypotheses):  $M(K\pi) > 1.55$  GeV and  $M(\pi K) > 1.55$  GeV: to suppress decays via light intermediate  $K^*$ ,  $\Lambda^*$  and other 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  $\Lambda_b$  candidate in  $\Lambda_b$  candidate rest frame  $> -0.8$ ;
12.  $|\cos\theta^*|$  between kaon and  $\Lambda^*$  in  $\Lambda^*$  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;

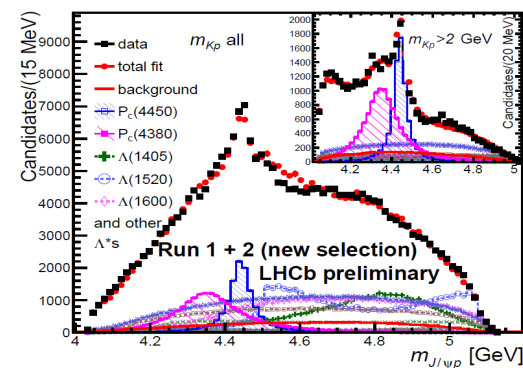
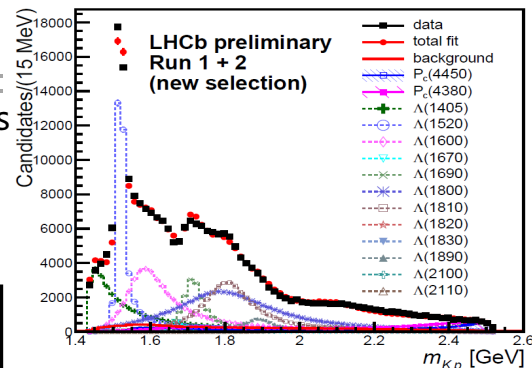
# LHCb pentaquarks in Run II data

Run II provides  $\sim 9\times$  statistics of Run I for  $\Lambda_b \rightarrow J/\psi p K$  decays (246K candidates).

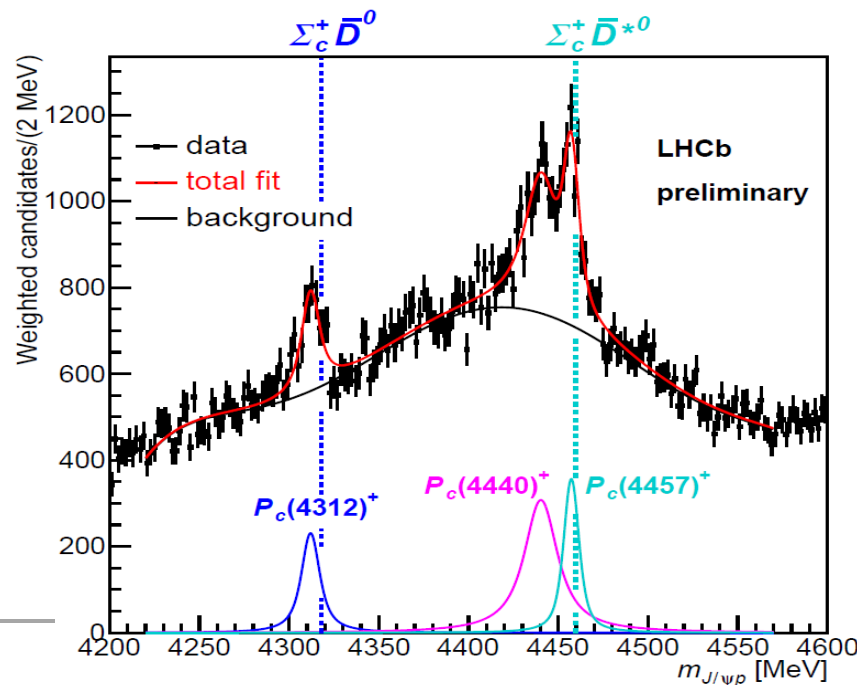
Phys. Rev. Lett. 122 (2019) 222001



State  $P_c(4450)$  revealed its substructure: two states  $P_c(4457)$ ,  $P_c(4440)$  (widths 6.4 и 21 MeV respectively) and  $5.4\sigma$  significance w.r.t. to single state hypothesis; Analysis methods were not sensitive to the wide  $P_c(4380)$  state.



New state  $P_c(4312)$  (width  $\sim 10$  MeV) and  $7.4\sigma$  significance has been discovered.



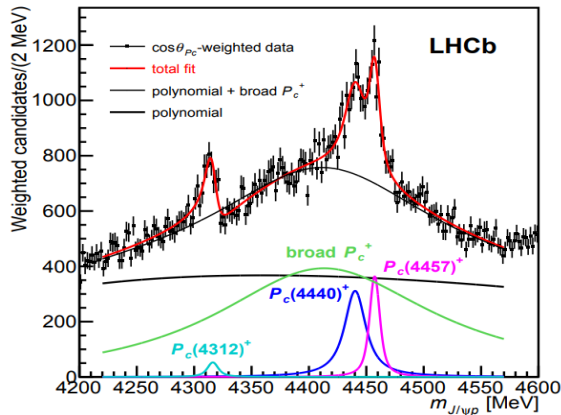
# Pentaquark structure

$P_c(4312)^+$  and  $P_c(4457)^+$  are perfect candidates for the  $\Sigma_c^+ D_0$  and  $\Sigma_c^+ D_0^*$  bound states coupled mainly via  $\pi$ ,  $\rho$  meson exchange.

$P_c(4440)^+$  with bound energy of  $\sim 20\text{MeV}$  is possibly another spin state of  $\Sigma_c^+ D_0^*$  molecule.

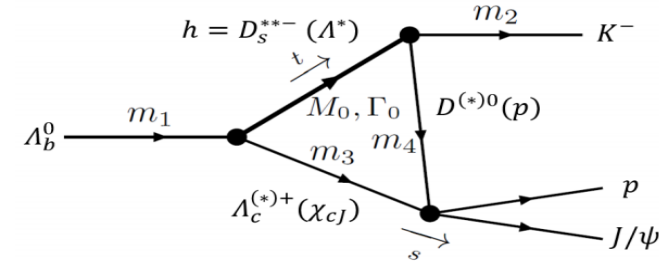
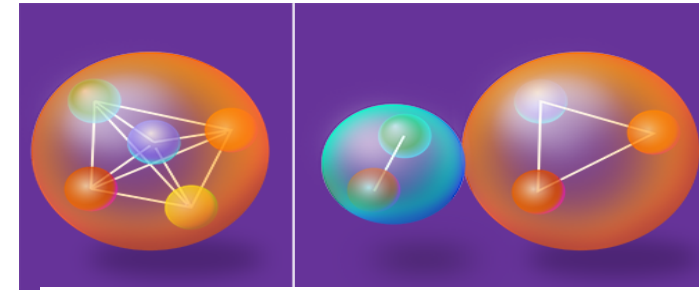
Existence of  $P_c(4380)^+$  is under question. In case confirmed by amplitude analysis, it is not going to be described by molecular model and maybe interpreted as compact 5q state.

LHCb tried to include it into their background model (left plot).



Another possible interpretation for narrow structures in  $J/\psi p$  final states is triangular (rescattering) diagrams. However, it works well only for  $P_c(4457)$ . Still to be considered...

Natural predictions from QCD for new states are neutral pentaquarks (masses close to 4.3-4.4), strange pentaquarks, doubly strange pentaquarks, etc.



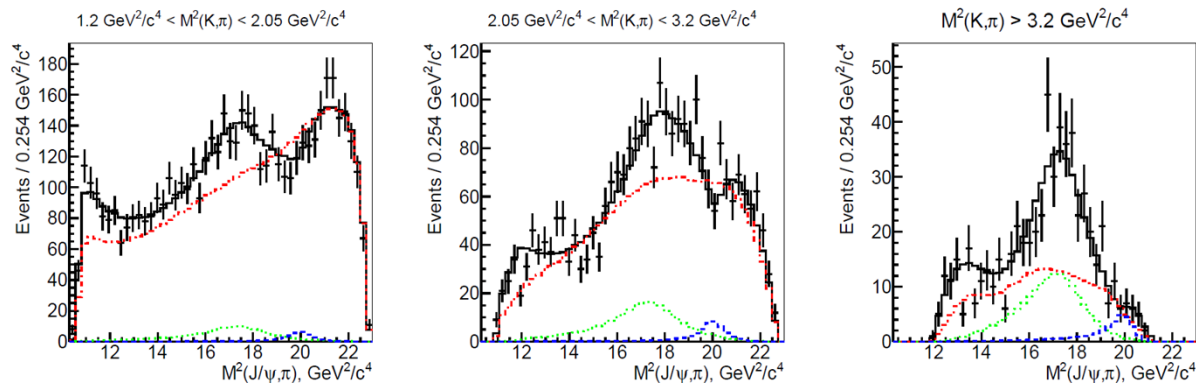
# Exotic states in $J/\psi\pi^+$ spectrum: $Z_c$ states

$Z_c(4200)$  was discovered by BELLE collaboration with a significance of  $6.2\sigma$  in 2014. An amplitude analysis was performed to determine the parameters of this state:

$J^P$	$0^-$	$1^-$	$1^+$	$2^-$	$2^+$
Mass, $\text{MeV}/c^2$	$4318 \pm 48$	$4315 \pm 40$	$4196^{+31}_{-29}$	$4209 \pm 14$	$4203 \pm 24$
Width, MeV	$720 \pm 254$	$220 \pm 80$	$370 \pm 70$	$64 \pm 18$	$121 \pm 53$
Significance (Wilks)	$3.9\sigma$	$2.3\sigma$	$8.2\sigma$	$3.9\sigma$	$1.9\sigma$

$$M = 4196^{+31+17}_{-29-13} \text{ MeV}$$

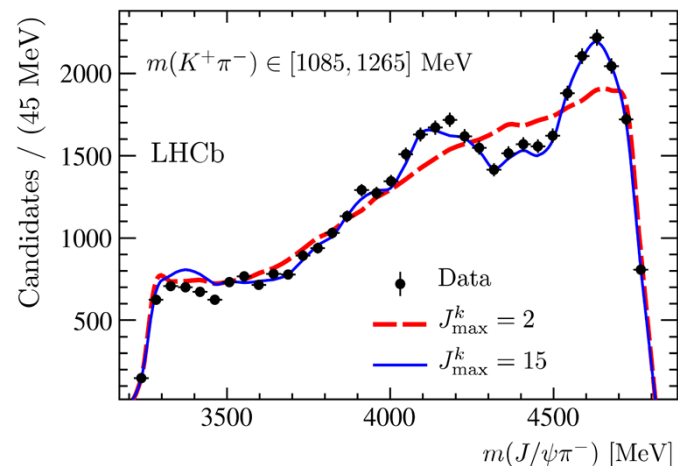
$$\Gamma = 370^{+70+70}_{-70-132} \text{ MeV}$$



10.1103/PhysRevD.90.112009

In 2008 BaBar collaboration performed model independent analysis of  $B^0 \rightarrow J/\psi K\pi$  decays to study  $Z_c(4430)$  state. No evidence of  $Z_c(4200)$  existence was found; ATLAS Run I studies gave hint on presence of  $Z_c$  contribution to B-meson decays;

In 2019 LHCb collaboration performed model independent analysis of  $B^0 \rightarrow J/\psi K\pi$  decays. They discovered an exotic structure near the mass  $m(J/\psi\pi) = 4200$  MeV.



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