



ATLAS results on exotic heavy hadrons

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on behalf of the ATLAS Collaboration

- Pentaquarks in ATLAS Run I data
- Hint on the $Z_c(4200)$ state
- Conclusions and Plans

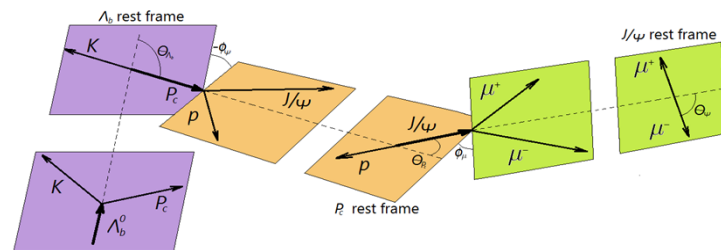
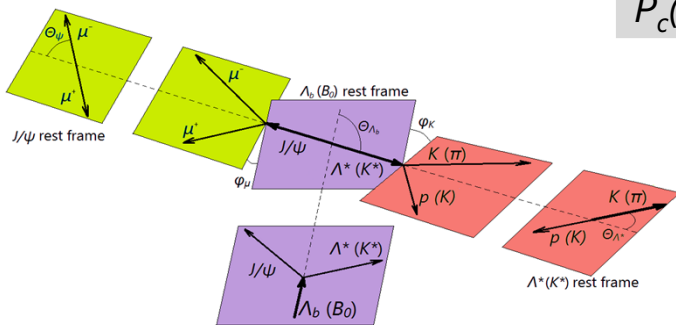
Reconstruction of $\Lambda_b \rightarrow J/\psi p K$ candidates at ATLAS

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:
 - $\Lambda_b \rightarrow J/\psi, p, K$ via various Λ^* or P_c states (ref. backup)
 - $B^0 \rightarrow J/\psi, K, \pi$ via various K^* or exotic Z_c states (ref. backup)
 - $B^0 \rightarrow J/\psi, \pi, \pi$
 - $B_s \rightarrow J/\psi, K, K$ via various f and φ states (ref. backup)
 - $B_s \rightarrow J/\psi, \pi, \pi$
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 $M(\pi, K) > 1.55$ GeV \rightarrow $M(p, K) \gtrsim 2$ GeV;

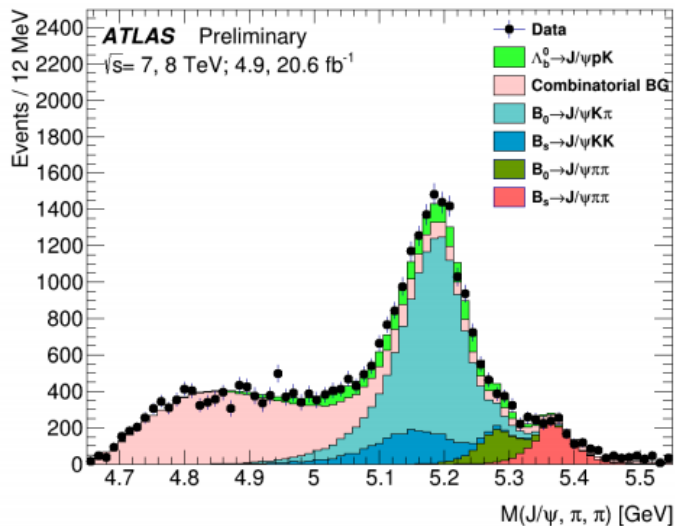
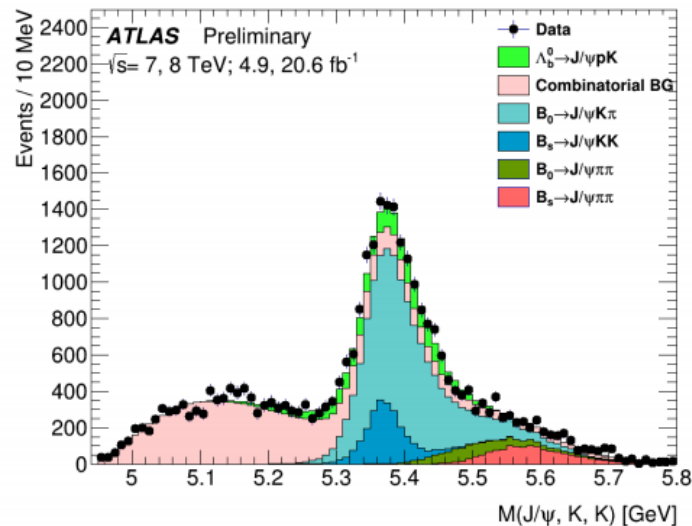
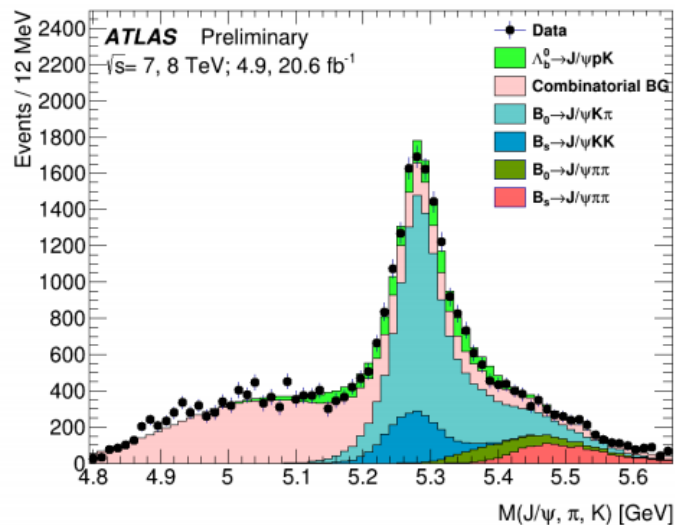
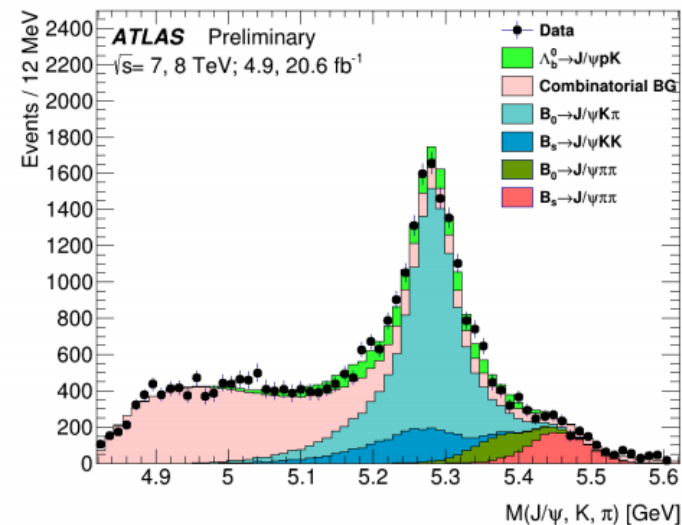
$\Lambda_b \rightarrow J/\psi, p, K$ decays simulation

1. Reduced 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 (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



1. Muon pairs for J/ψ candidates selected with muon triggers;
 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 $\chi^2/\text{NDF} < 16/8$;
 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. $p_T(\Lambda_b) / \sum p_T(\text{track}) > 0.2$, 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 πK mass hypotheses): $M(K\pi) > 1.55$ GeV and $M(\pi K) > 1.55$ GeV: to suppress decays via light intermediate K^* , Λ^* 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 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;



Description of selected candidates with different mass hypothesis for hadron tracks.

$$N(\Lambda_b \rightarrow J/\psi pK) = 2270 \pm 300$$

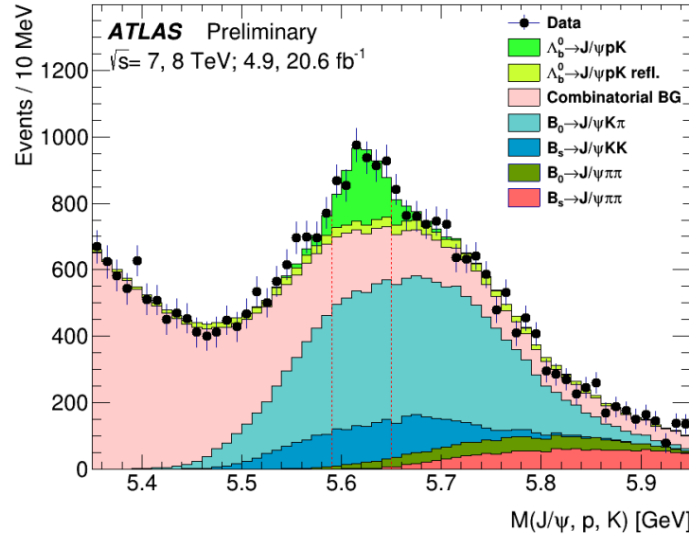
$$N(B^0 \rightarrow J/\psi K\pi) = 10770$$

$$N(B_s \rightarrow J/\psi KK) = 2290$$

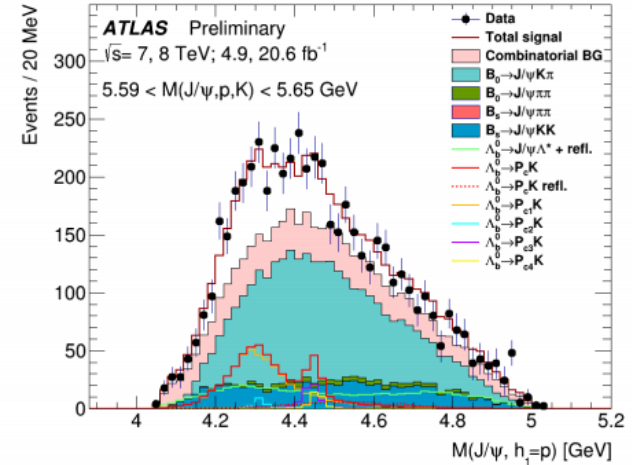
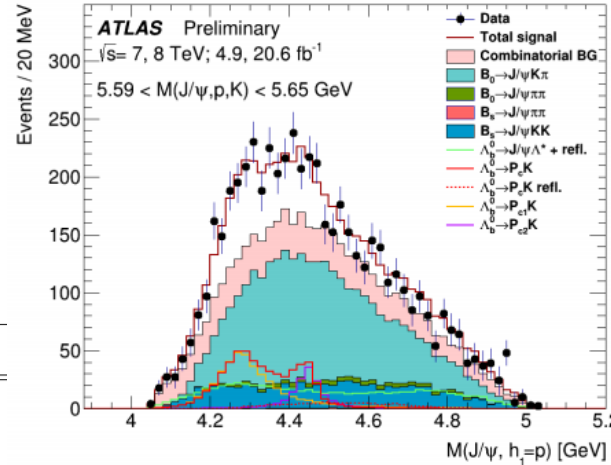
$$N(B^0 \rightarrow J/\psi \pi\pi\pi) = 1070$$

$$N(B_s \rightarrow J/\psi \pi\pi\pi) = 1390$$

In the signal region there are:
 $N(\Lambda_b \rightarrow J/\psi pK) = 1010 \pm 140$
 signal candidates with correct mass assignment



With ATLAS Run I data the amplitude analysis of $\sim 1\text{K}$ of $\Lambda_b \rightarrow J/\psi p K$ has been performed; signal area is contaminated by physical and combinatorial background

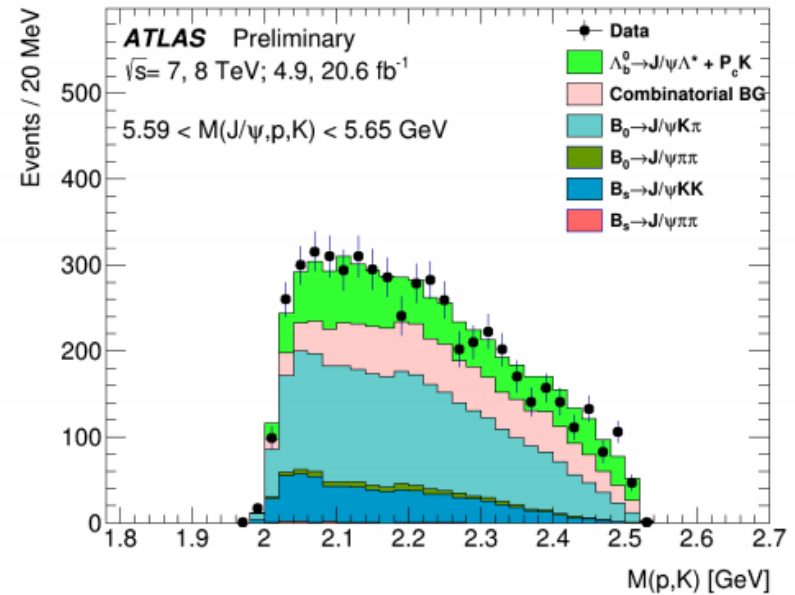
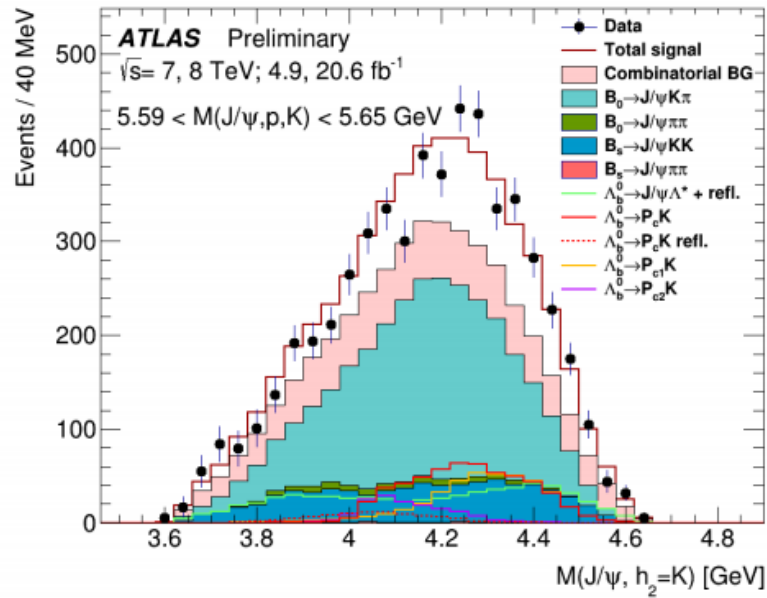


Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	—
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	—
$N(P_{c1} + P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	—
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst}) \text{ rad}$	—
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst}) \text{ MeV}$	$4380 \pm 8 \pm 29 \text{ MeV}$
$\Gamma(P_{c1})$	$140^{+77}_{-50}(\text{stat})^{+41}_{-33}(\text{syst}) \text{ MeV}$	$205 \pm 18 \pm 86 \text{ MeV}$
$m(P_{c2})$	$4449^{+20}_{-29}(\text{stat})^{+18}_{-10}(\text{syst}) \text{ MeV}$	$4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$
$\Gamma(P_{c2})$	$51^{+59}_{-48}(\text{stat})^{+14}_{-46}(\text{syst}) \text{ MeV}$	$39 \pm 5 \pm 19 \text{ MeV}$

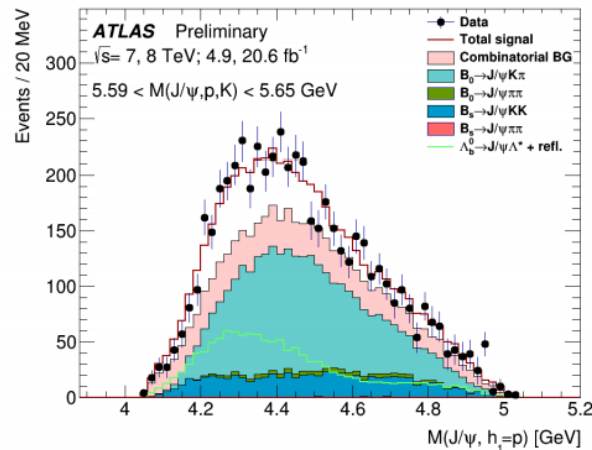
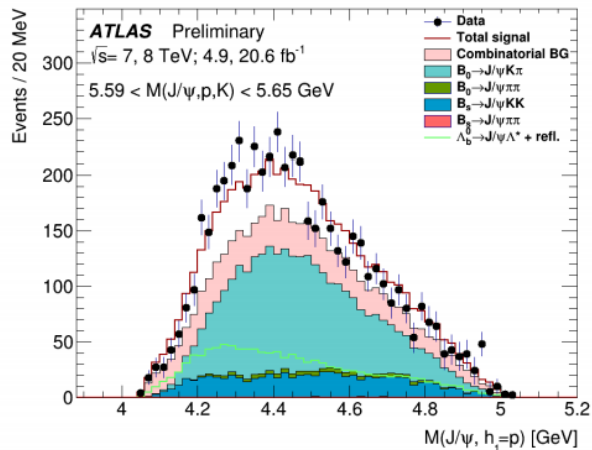
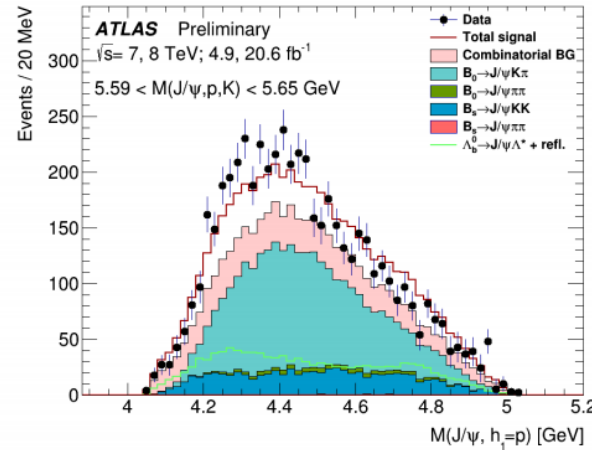
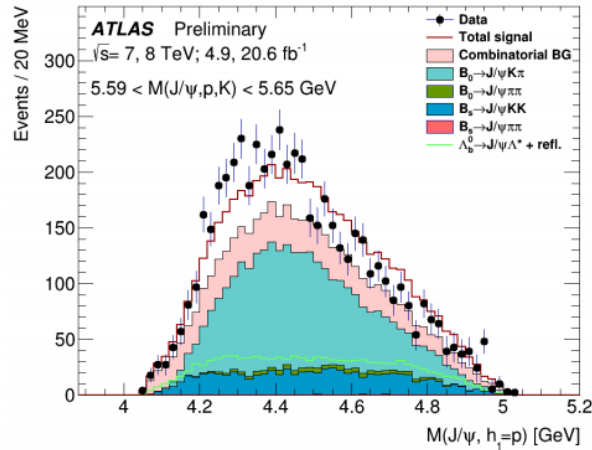
Accounting for systematics uncertainties the no- P_c hypothesis is characterized by $p\text{-value} = 9.1 \cdot 10^{-3}$.
 Parameters of 2 pentaquarks are consistent with those measured by LHCb;
 4 P_c hypothesis is also consistent with ATLAS data;
 Run II studies are ongoing;

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 show description of $M(J/\psi K)$ and $M(pK)$ in the signal region.



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.

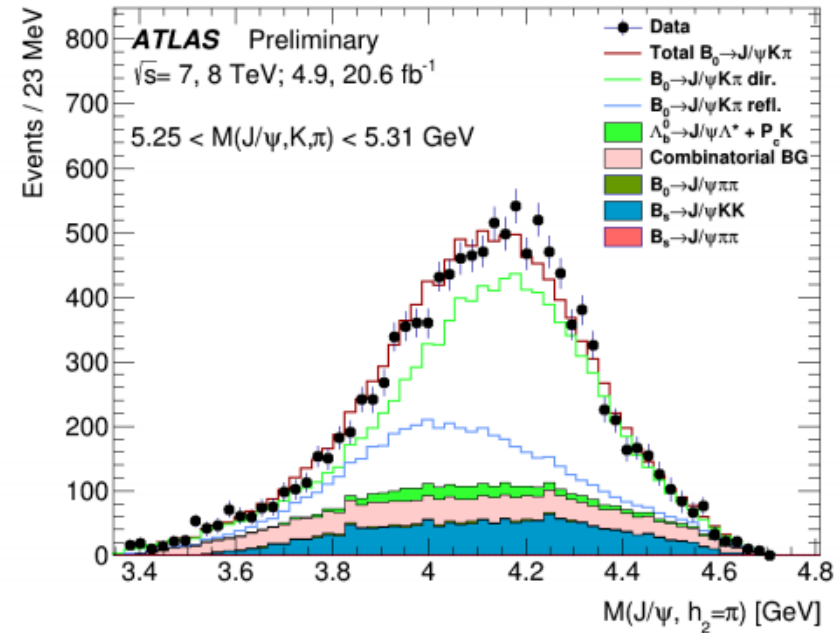
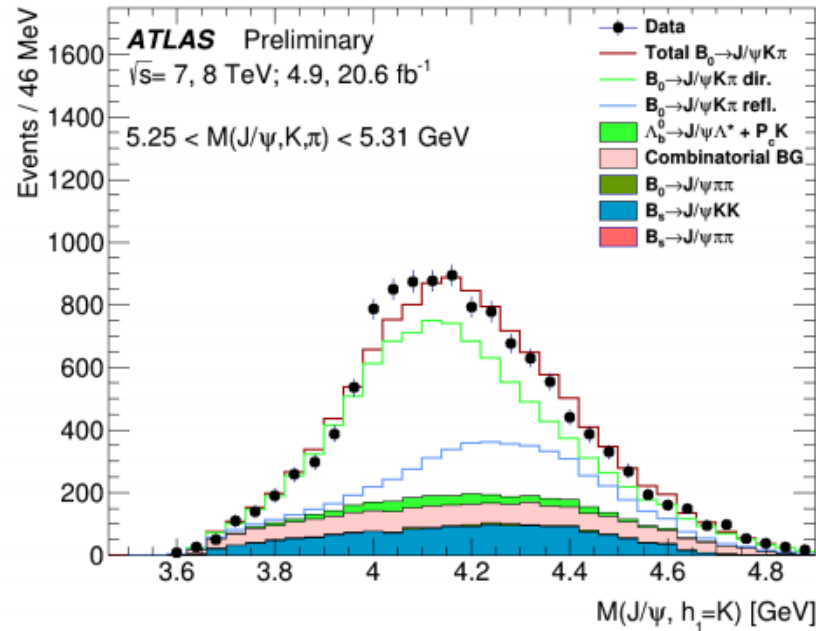
Bottom left: fit of $M(J/\psi p)$, $M(J/\psi K)$, $M(p, K)$ with extended $\Lambda_b \rightarrow J/\psi \Lambda^*$ decay model.

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 $9.1 \cdot 10^{-3}$

ATLAS 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 $Z_c^+(4200)$ and/or $Z_{cs}^+(4000)$ 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 collaboration 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;
- With Run II data ~ 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;

- 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/ψ resonances, neutral states in $B^+ \rightarrow J/\psi K^+ \varphi$ decays.

Thanks for your attention!

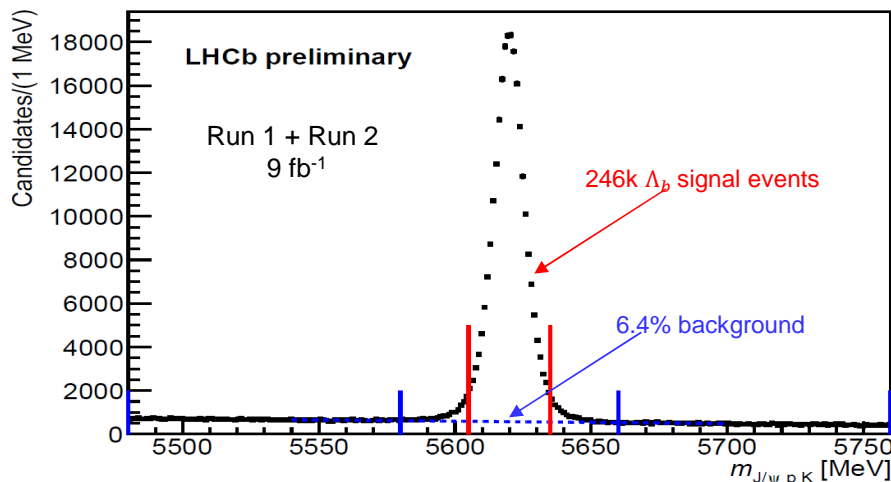
BACKUP



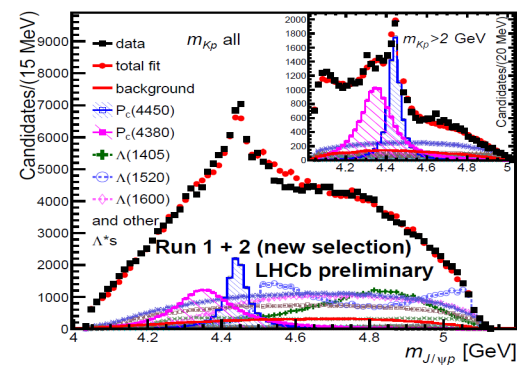
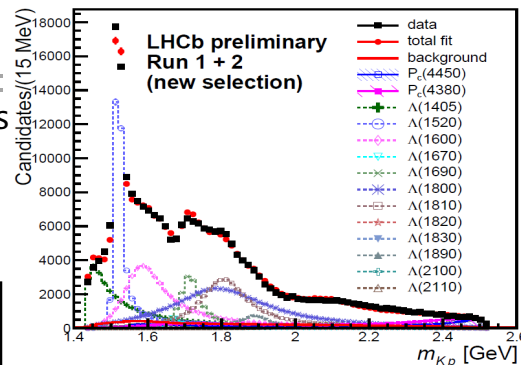
LHCb pentaquarks in Run II data

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

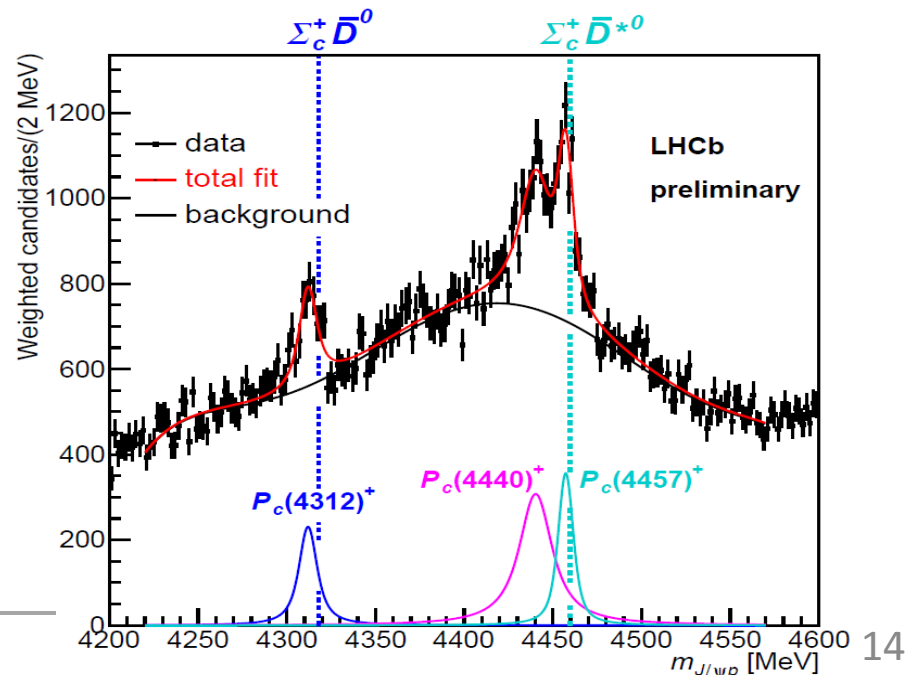
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State $P_c(4450)$ revealed its substructure: two states $P_c(4457)$, $P_c(4440)$ (widths 6.4 и 21 MeV respectively) and 5.4 σ significance w.r.t. to single state hypothesis; Analysis methods were not sensitive to the wide $P_c(4380)$ state.



New state $P_c(4312)$ (width ~ 10 MeV) and 7.4 σ significance has been discovered.



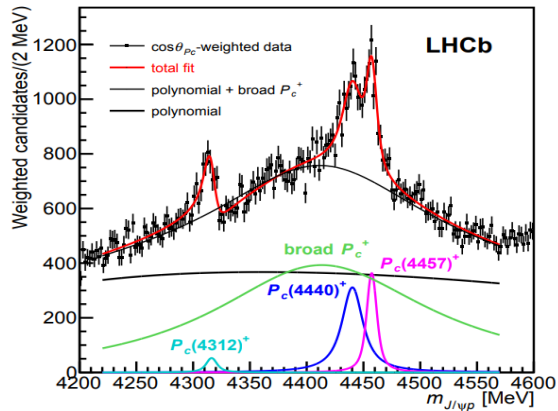
Pentaquark structure

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

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

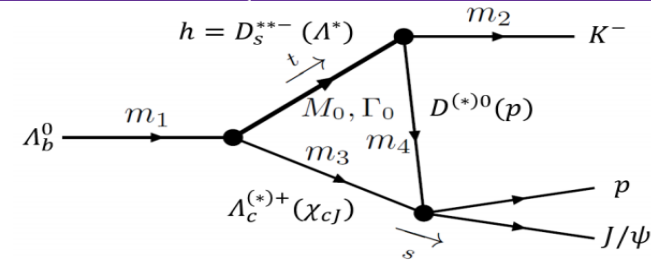
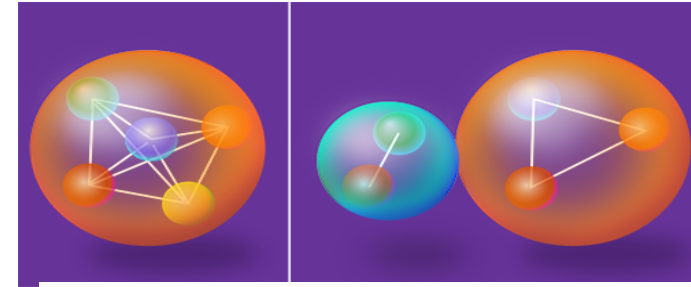
Existence of $P_c(4380)^+$ is under question. In case confirmed by amplitude analysis, it is not going to be described by molecular model and maybe interpreted as compact 5q state.

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.



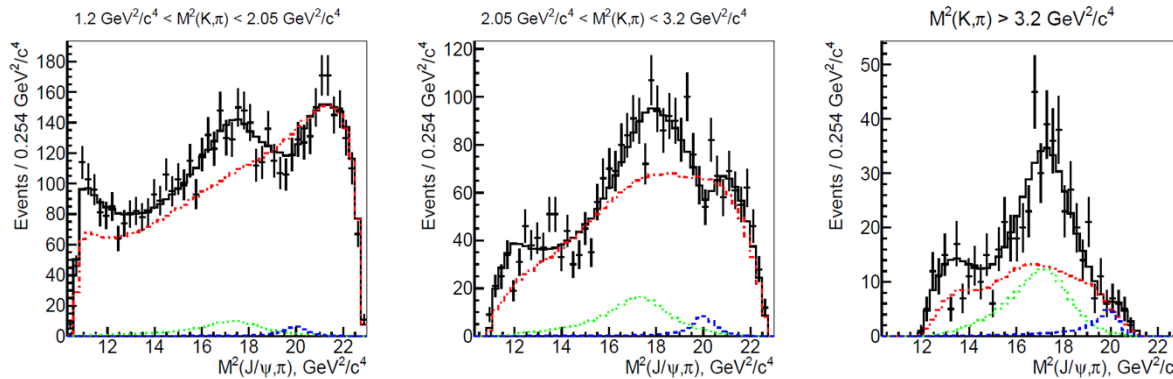
Exotic states in $J/\psi\pi^+$ spectrum: Z_c states

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

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

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

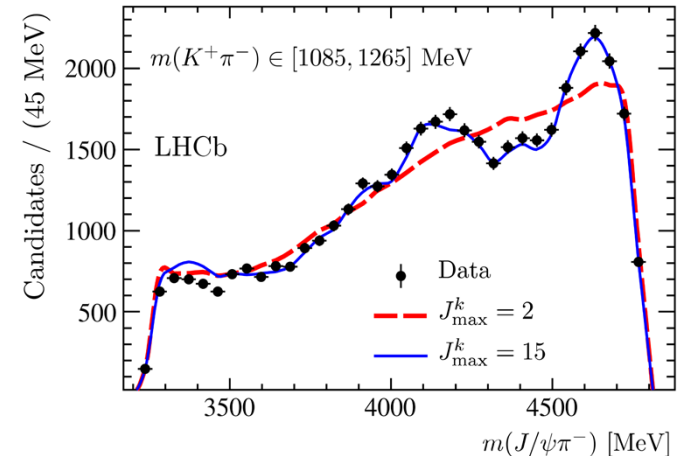
$$\Gamma = 370^{+70+70}_{-70-132} \text{ MeV}$$



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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