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

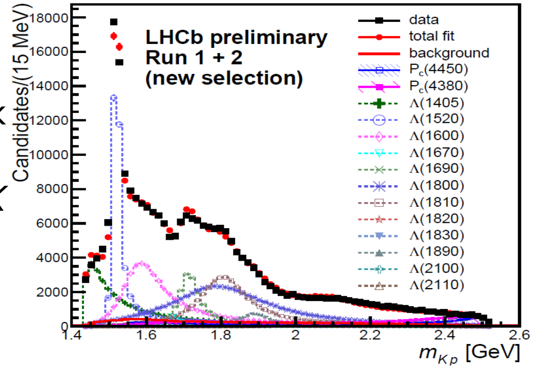
I. Yeletskikh
on behalf of the ATLAS Collaboration

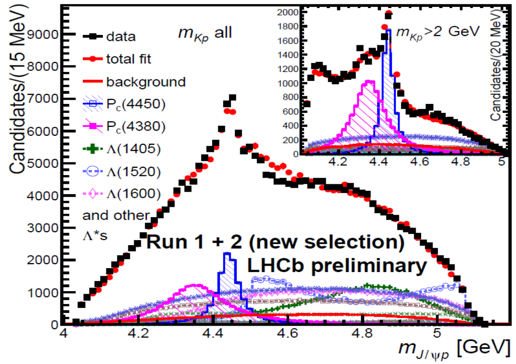
Contents

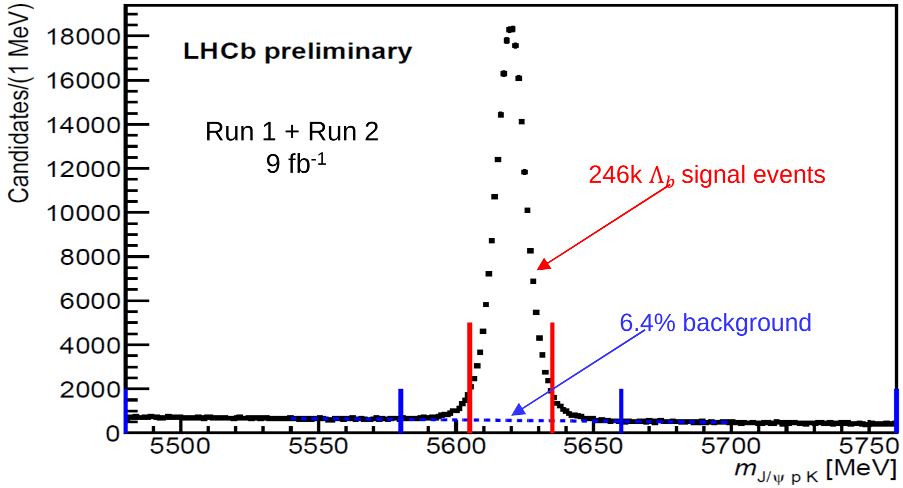
- Pentaquarks discovery and subsequent studies
- Λ_b candidate selection at ATLAS
- $H_b \to J/\psi hh$ decay models
- Fit procedure: event yields, control region description
- $\Lambda_b \to J/\psi pK$ Signal region analysis
  - Models with 2 and 4 pentaquarks
  - Models without pentaquarks
- Conclusions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

Pentaquark states discovery

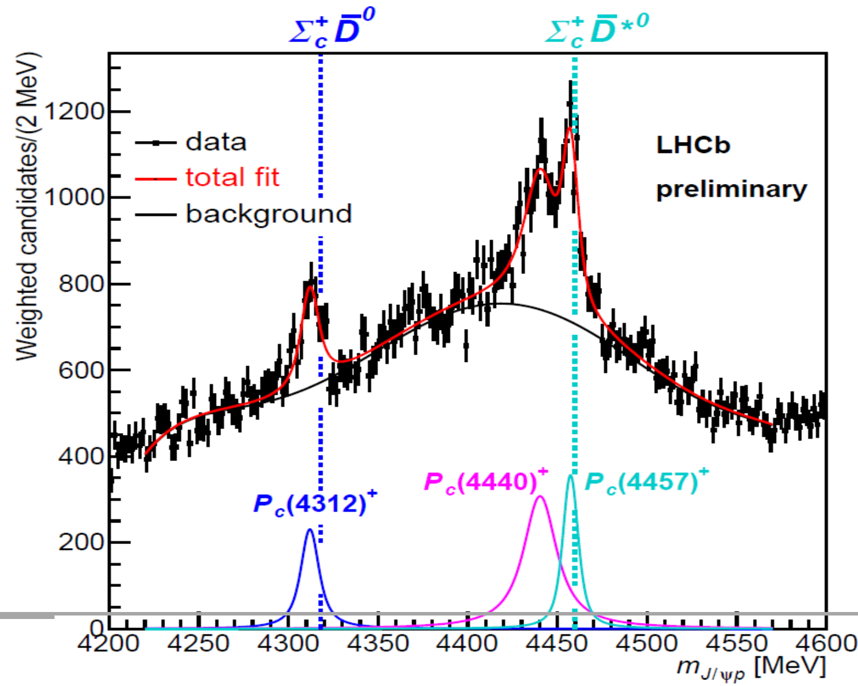
Two states $P_c(4380)$ and $P_c(4450)$ consistent with pentaquark hypothesis were discovered at LHCb in 2015.
With Run II data providing ~9x statistics of Run I for $\Lambda_b \to J/\psi pK$ decays (246K candidates) LHCb published new results:







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



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

Phys. Rev. Lett. 122 (2019) 222001

Reconstruction of $\Lambda_b \to J/\psi pK$ 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
   - $B^0 \to J/\psi, K, \pi$ via various K^* or exotic Z_c states
   - $B^0 \to J/\psi, \pi, \pi$
   - $B_s \to J/\psi, K, K$ via variuos f and φ states
   - $B_s \to J/\psi, \pi, \pi$

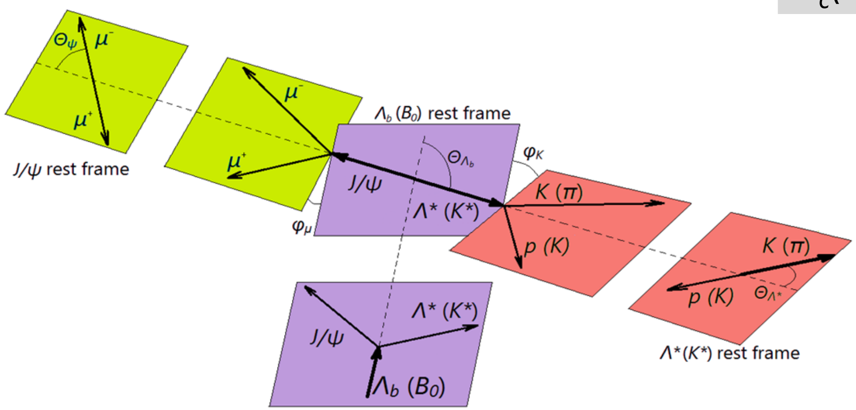
3. Simulation of $\Lambda_b \to J/\psi, p, K$; $B^0 \to J/\psi, K, \pi$; $B_s \to J/\psi, K, K$ processes uses phase space decay events weighted by theoretically calculated matrix elements;

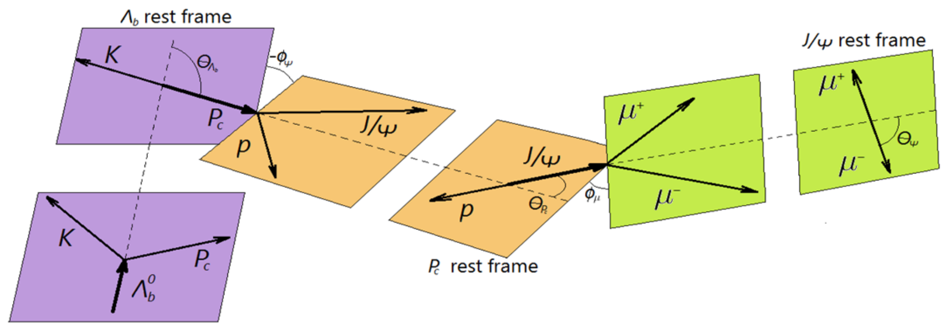
4. To suppress high backgrounds from light Λ^*, K^*, f, φ states as well as combinatorial background, only events with high M(h,h) are selected: M(K,π) and M(π,K)>1.55 GeV $\to$ M(p,K) $\gtrapprox$ 2 GeV;

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

- Helicity amplitudes are used to calculate weights to model differerent decay channels on top of the phase space MC
- Reduced model has only 1 complex coupling for each Λ^*; 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

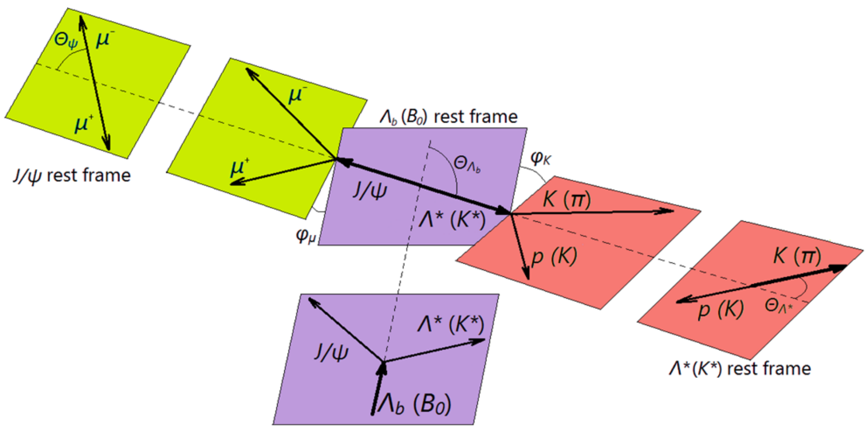


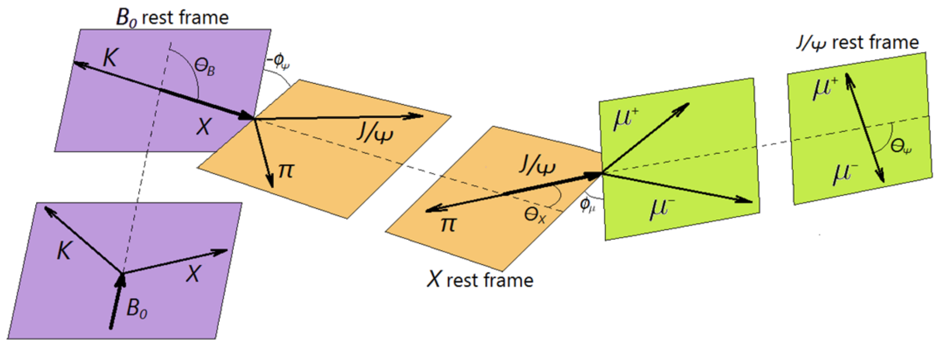


$B^0 \to J/\psi, K, \pi$; decays simulation

- 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 $B^0 \to J/\psi, K, \pi$ decays is used. The 'reduced' model is incapable in describing data
- Exotic $\boldsymbol{Z_c(4200)}$ state is included into B^0 decay model. **Its contribution is considered as systematic effect**

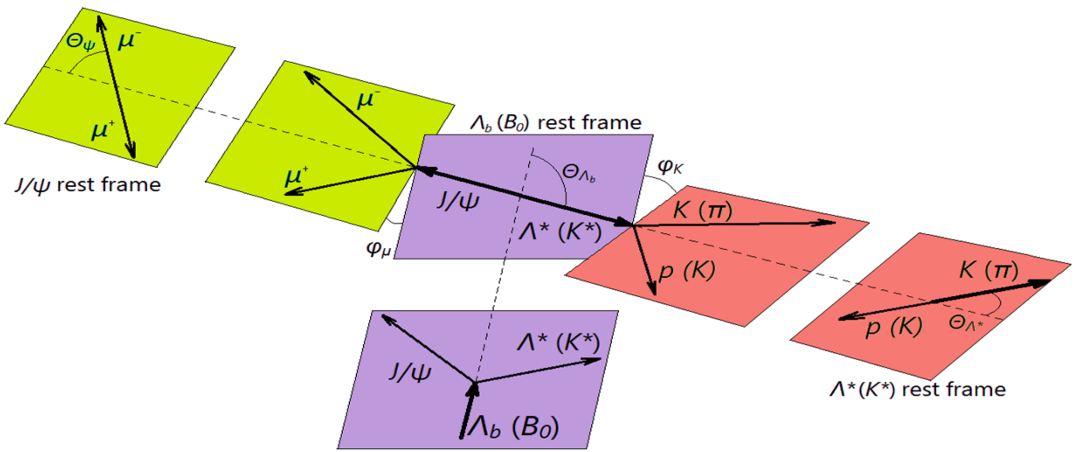
	Spin/parity	Number of couplings (extended)	Number of couplings (reduced)
$K^*(1410)$	1^-	3	1
$K^*(1430)$	0^+	1	1
$K^*(1430)$	2^+	3	1
$K^*(1680)$	1^+	3	1
$K^*(1780)$	3^-	3	1
$K^*(1950)$	0^+	1	1
$K^*(2045)$	4^+	1	1
$Z_c(4200)$	$1^+, 2^-, 3^+ \ldots$	2	2
$Z_c(4200)$	$0^-, 1^-, 2^+ \ldots$	1	1





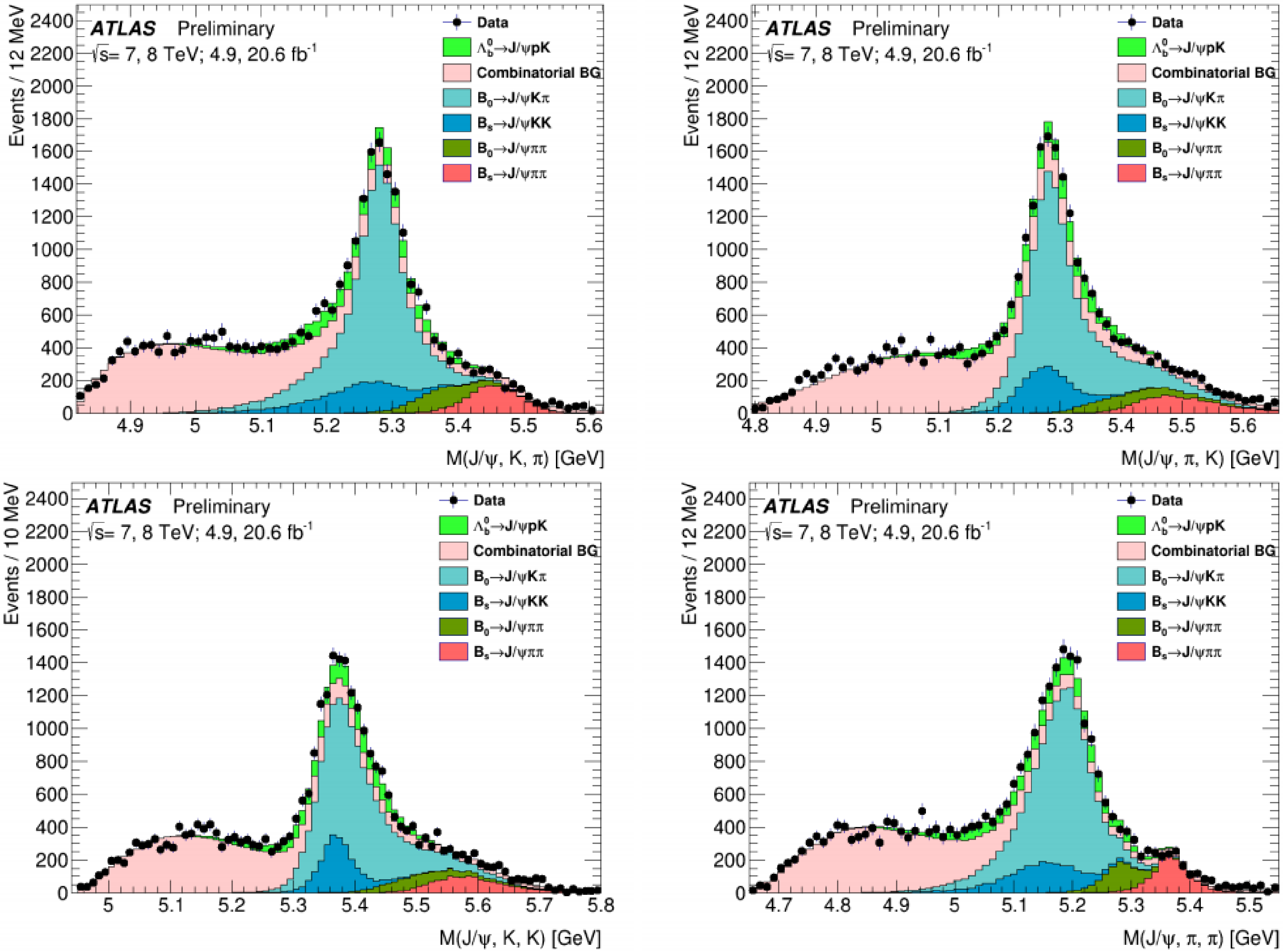
1. Full theoretical model includes 3 complex couplings for each ***φ*** or ***f*** state with spin >0;
2. Reduced model has only 1 complex coupling for each resonance;
3. We use **extended model** to describe data in B_s CR.

	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



Reconstruction of $H_b \to J/\psi hh$ candidates

ATLAS-CONF-2019-048



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:

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

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

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

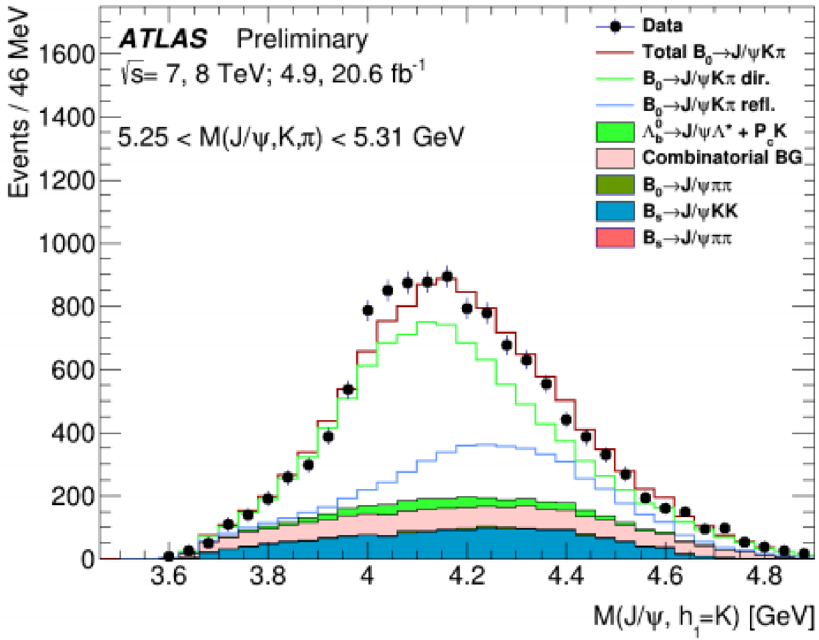
$N(B^0 \to J/\psi \pi\pi) = 1070$

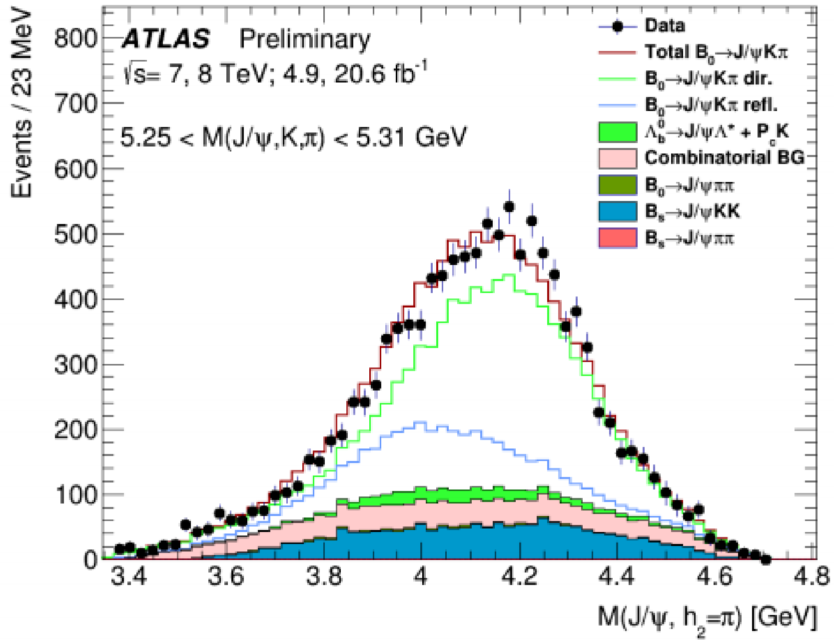
$N(B_s \to J/\psi \pi\pi) = 1390$

B-meson control region

ATLAS-CONF-2019-048

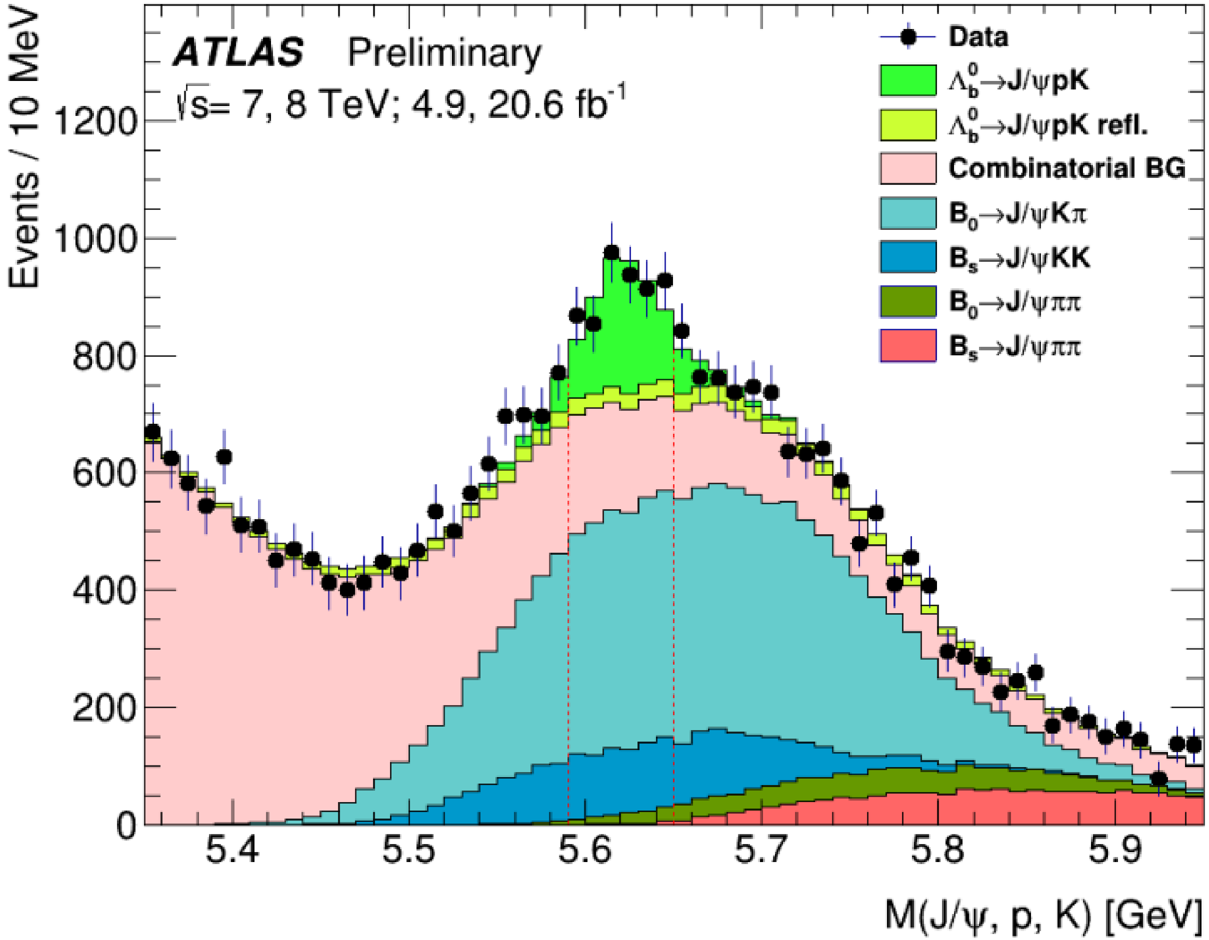
We analyzed ~10K $B^0 \to J/\psi K\pi$ decays with Run I data w.r.t. properties of intermediate states. Data description without exotic contributions is not perfect (right plot) and demonstrates hints on $Z_c^+(4200)$ contributions.





- 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 (~300-400MeV) 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 ~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…**

ATLAS-CONF-2019-048



Total number of $\Lambda_b \to J/\psi pK$ candidates selected is **2270±300**

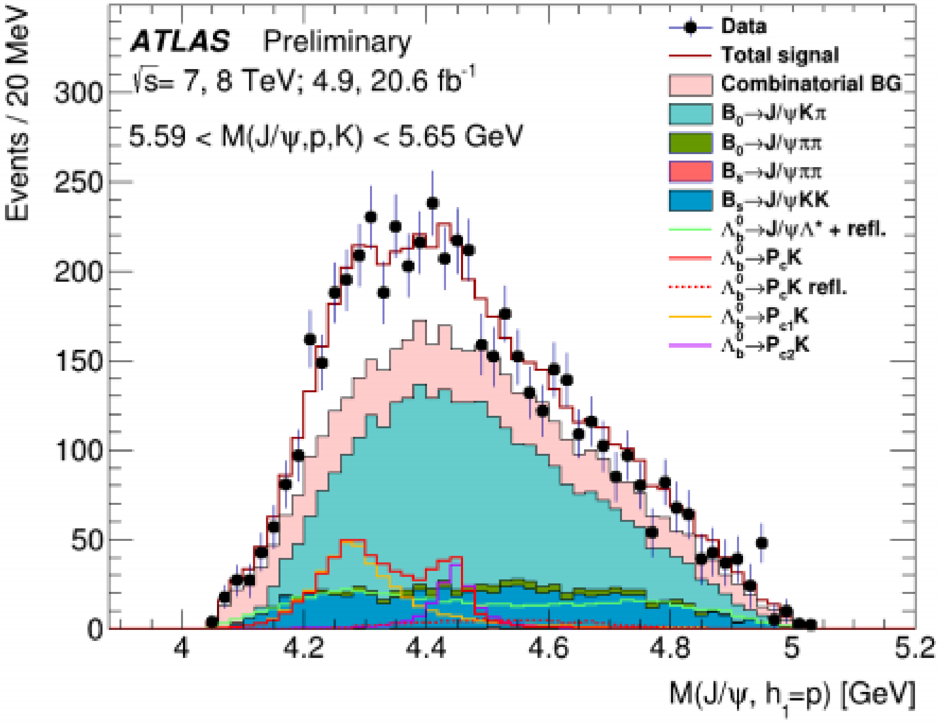
Green histogram shows Λ_b signal with correct mass assignment;
Yellow histogram shows Λ_b signal with wrong mass assignment;

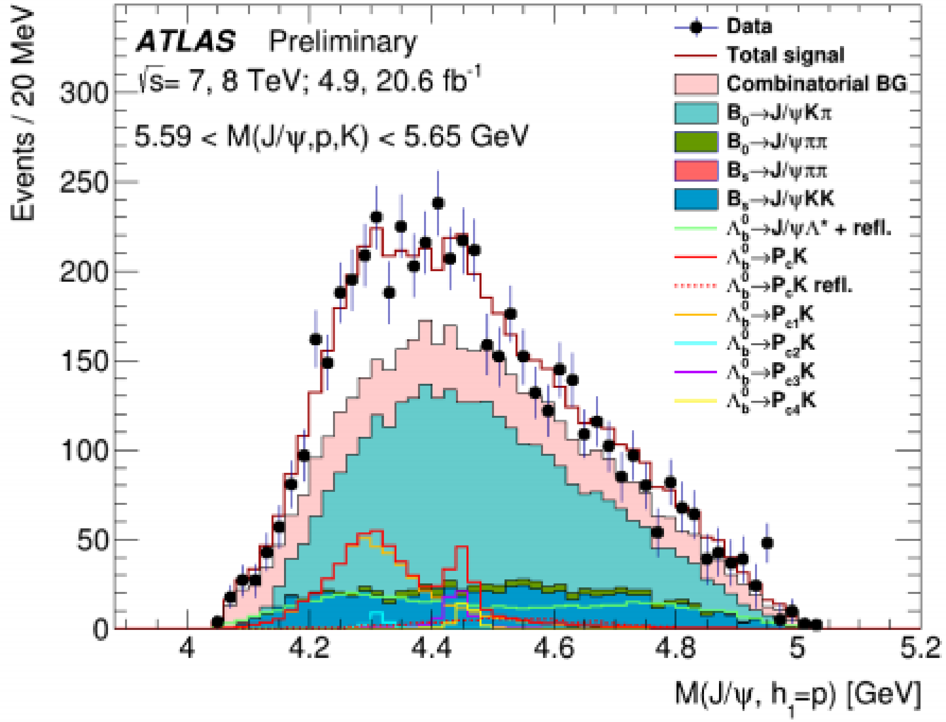
Signal region include events with:
5.59GeV < M($J/\psi pK$) < 5.65GeV OR
5.59GeV < M($J/\psi Kp$) < 5.65GeV

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

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}(stat)$^{+110}_{-100}$(syst)	–
$N(P_{c2})$	150^{+170}_{-100}(stat)$^{+50}_{-90}$(syst)	–
$N(P_{c1}+P_{c2})$	540^{+80}_{-70}(stat)$^{+70}_{-80}$(syst)	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}$(stat)$^{+0.2}_{-0.1}$(syst) rad	–
$m(P_{c1})$	4282^{+33}_{-26}(stat)$^{+28}_{-7}$(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





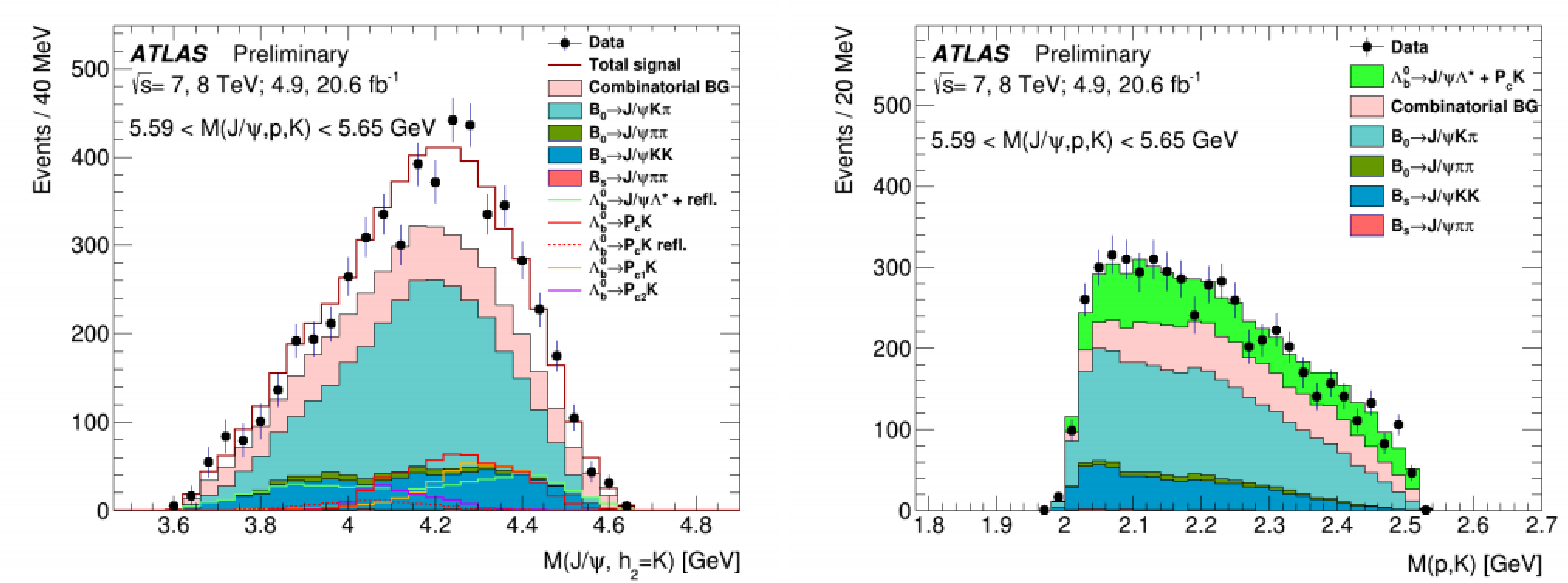
ATLAS-CONF-2019-048

Pentaquark studies: summary of systematic uncertainties

Source	$N(P_{c1})$	$N(P_{c2})$	$N(P_{c1}+P_{c2})$	$\Delta\phi$
Number of $\Lambda_b^0 \to J/\psi pK^-$ 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 $\Lambda_b^0 \to J/\psi pK^-$ 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 $\Lambda_b^0 \to J/\psi pK^-$ 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 $\Lambda_b^0 \to J/\psi pK^-$ 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	$^{+0.7}_{-0.2}\%$	$^{+30}_{-24}\%$	$^{+0.4}_{-0.2}\%$	$^{+28}_{-91}\%$

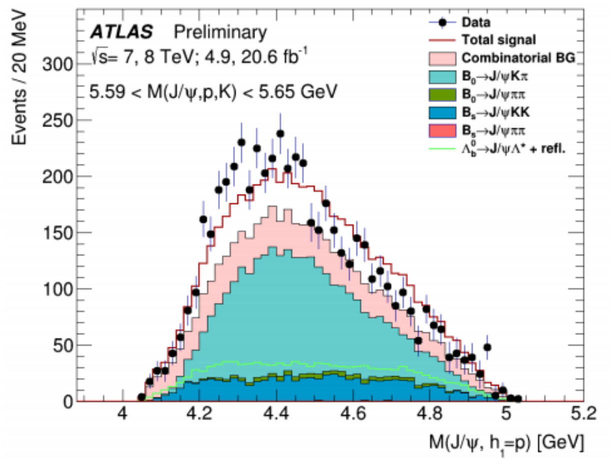
ATLAS-CONF-2019-048

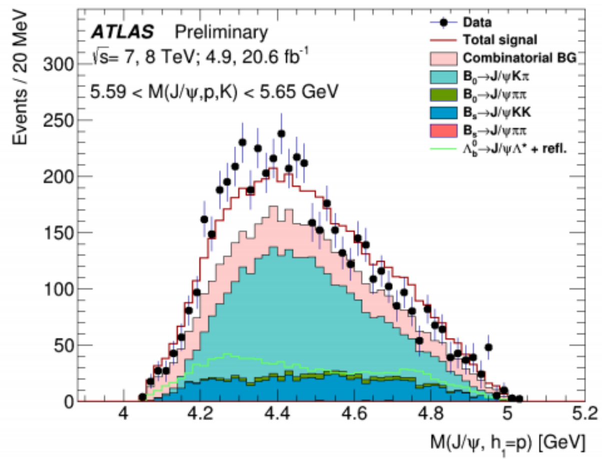


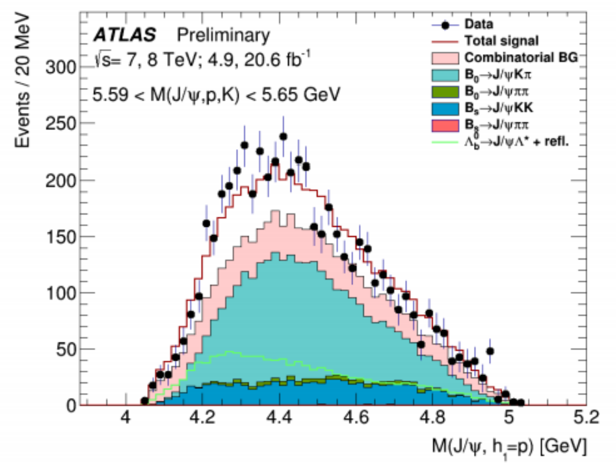
Control plots (2 pentaquark hypothesis) show good description of M($J/\psi K$) and M(pK) in the signal region.

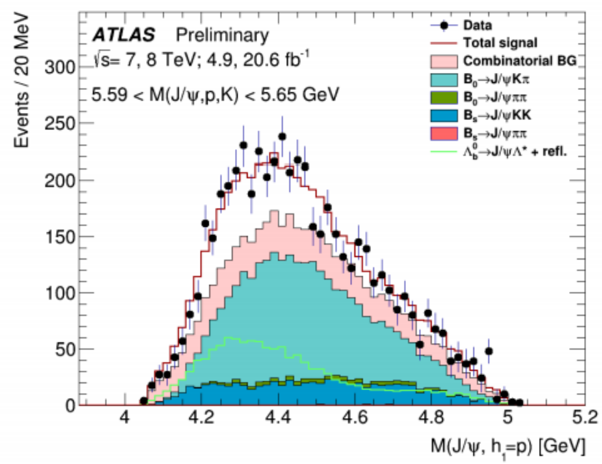
Angular variables do not take part in fits due to complexity of background (esp. combinatorics) behavior.

Testing models without P_c states









Plots show different models without exotic contribution.

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

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

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

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

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

Conclusions and plans

- 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 ~5x statistics of $B^0 \to J/\psi K\pi$ 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 $B^+ \to J/\psi K^+\varphi$ decays.

Thanks for your attention!

BACKUP

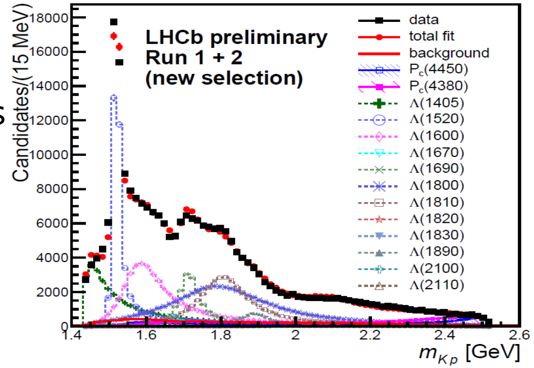
$\Lambda_b \to J/\psi, p, K$ candidate selection at ATLAS

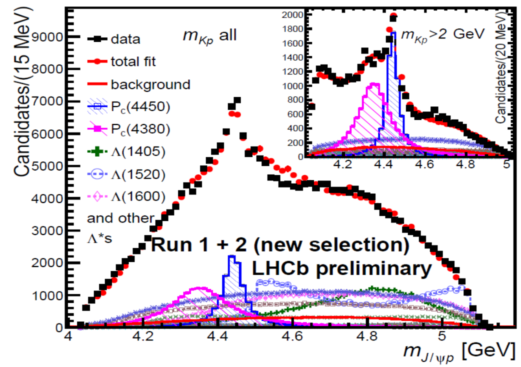
1. Muon pairs for J/ψ candidates selected with muon triggers;
2. 2 muons passing MCP selection rules, coming from J/ψ decay (3097 ± 290 GeV);
3. 2 muon tracks + 2 hadron tracks simultaneously fit to common vertex (dimuon mass constrained to J/ψ mass) and Λ_b candidate track to primary vertex with χ^2/NDF<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 $L_{xy}(\Lambda_b)$>0.7mm;
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, $|\eta(\Lambda_b)| < 2.1$;

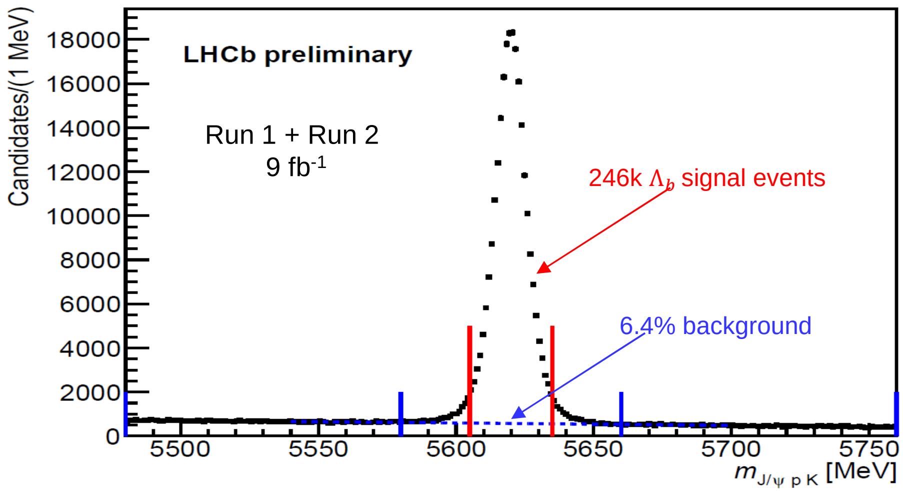
9. Inv. mass of hadron tracks (in $K\pi$ and πK mass hypotheses): $M(K\pi) > 1.55$ GeV and $M(\pi K) > 1.55$ GeV: to suppress decays via light intermediate K^*, Λ^* and other resonances;
10. $\cos\theta^*$ between proton and $J/\Psi\ p$ system in $J/\Psi\ p$ rest frame > -0.5;
11. $\cos\theta^*$ between 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 $M(J/\psi pK) = 5620 \pm 30$ MeV;
14. Subtraction of distributions with two same sign hadron tracks is applied;

LHCb pentaquarks in Run II data

Run II provides ~9x statistics of Run I for $\Lambda_b \to J/\psi p K$ decays (246K candidates).

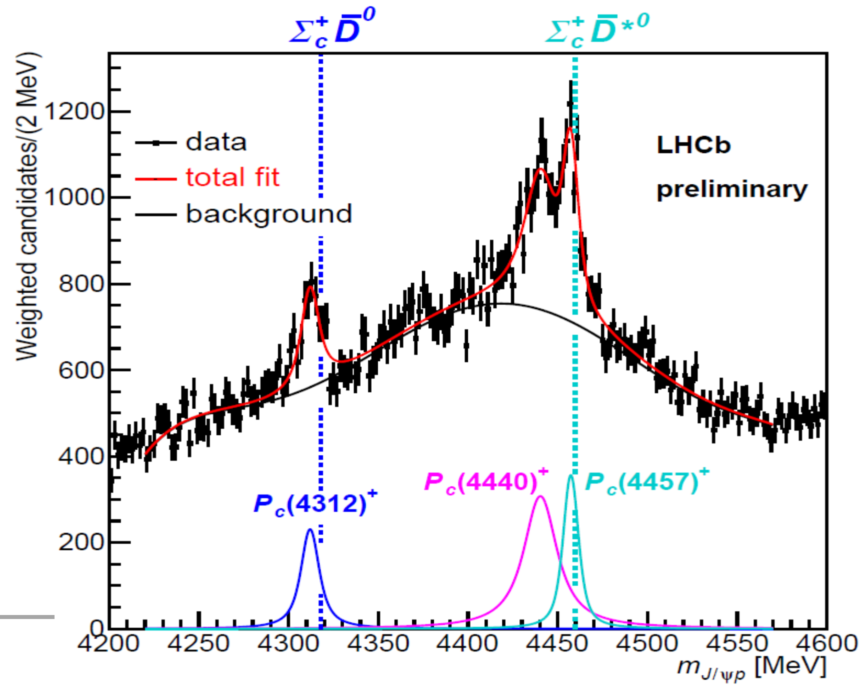






Phys. Rev. Lett. 122 (2019) 222001

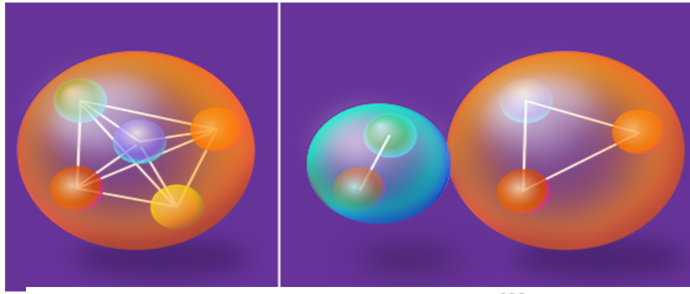
New state $P_c(4312)$ (width ~10 MeV) and 7.4σ significance has been discovered.



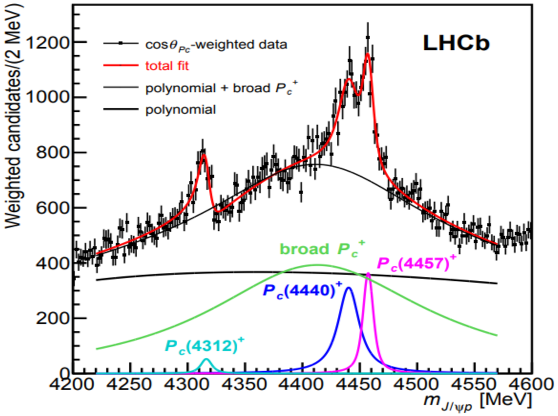
State $P_c(4450)$ revealed its substructure: two states $P_c(4457)$, $P_c(4440)$ (widths 6.4 и 21 MeV respectively) and 5.4σ significance w.r.t. to single state hypothesis;
Analysis methods were not sensitive to the wide $P_c(4380)$ state.

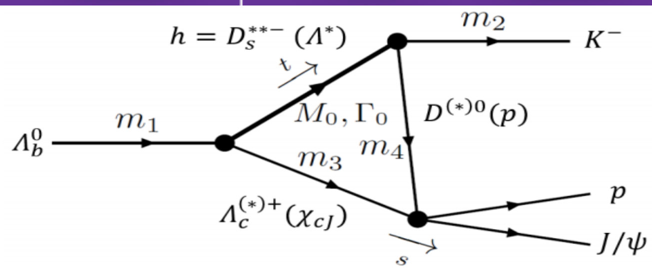
Pentaquark structure

$P_c(4312)^+$ 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 ~20MeV 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).





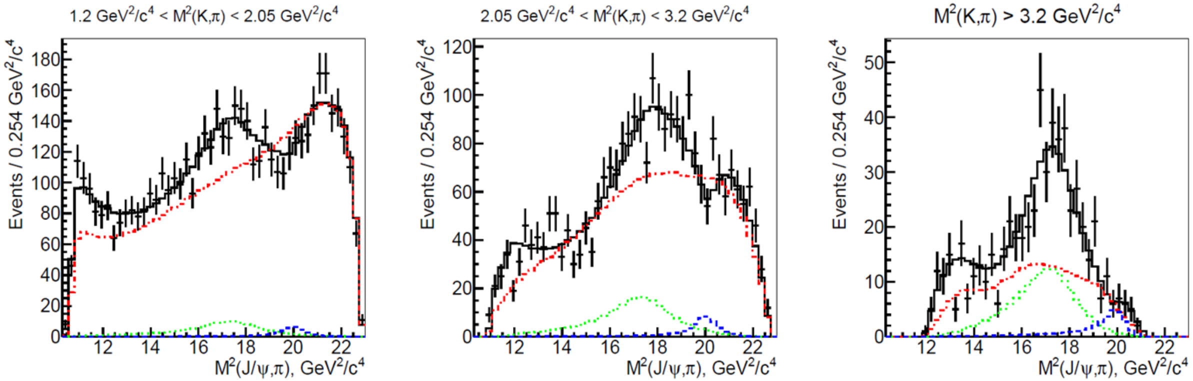
Another possible interpretation for narrow structures in J/ψp final states is triangular (rescattering) diagrams. However, it works well only for $P_c(4457)$. Still to be considered…

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

Z_c(4200) was discovered by BELLE collaboration with a significanceof 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

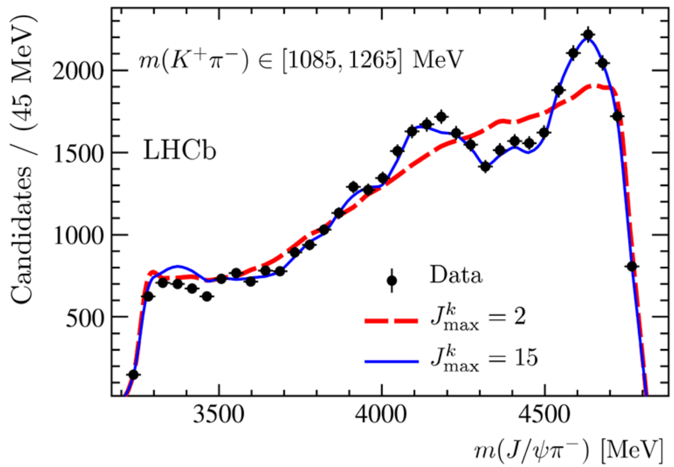
$$M = 4196^{+31+17}_{-29-13}\text{ MeV}$$
$$\Gamma = 370^{+70+70}_{-70-132}\text{MeV}$$



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/ψπ) = 4200 MeV.



Phys. Rev. Lett. 122, 152002 (2019)