HADRON 2021:
ATLAS Results on Exotic Heavy Hadrons

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ATLAS Results on Exotic Heavy Hadrons

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Content:

- Tetraquarks in ATLAS Run I data:
    - Searches for the X(5568) state, [Phys. Rev. Lett. 120, 202007].
- Pentaquarks in ATLAS Run I data:
    - Searching for hidden charm in Λ_b decays, [ATLAS-CONF-2019-048].
- Perspective for extracting for $Z_c(4200)$ during Run 2.

Heavy Flavour Physics with ATLAS

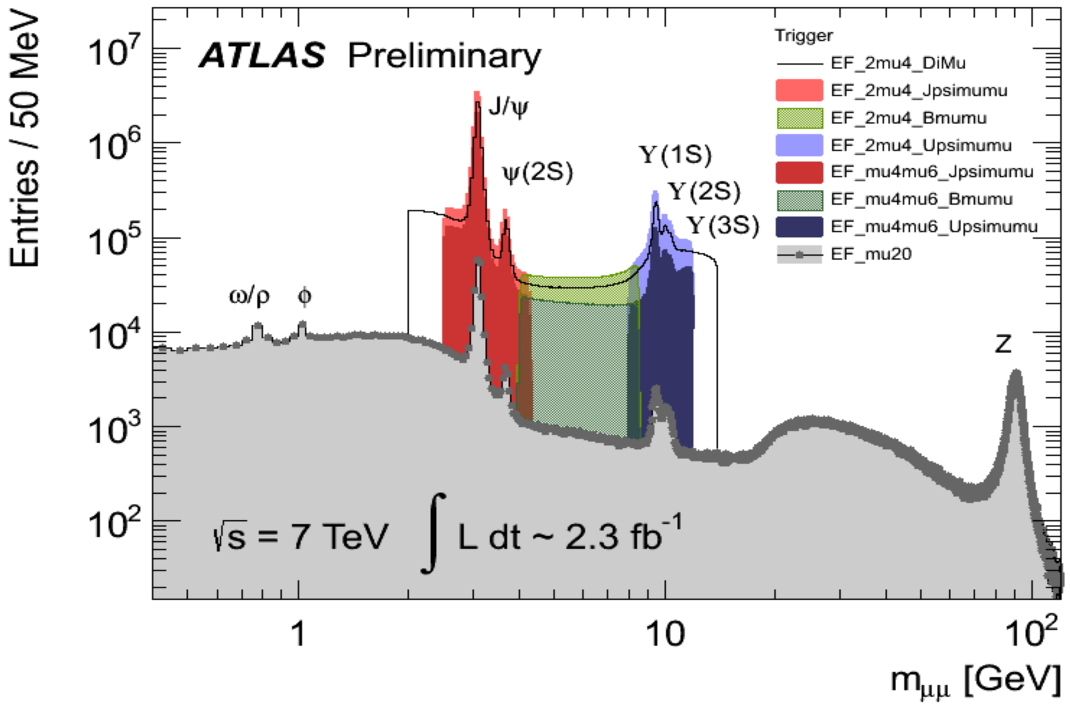
Mostly based on di-muon triggers:

- 4 or 6 GeV muon p_T threshold.
- Vertexing + di-muon mass cuts.

No π/K/p separation.

Run 2 upgrades included:

- IBL pixel detector.
- Trigger upgrades.



Searches for the X(5568)$^{\pm}$ State - 1

D0 evidence of a 4-quark X(5568):

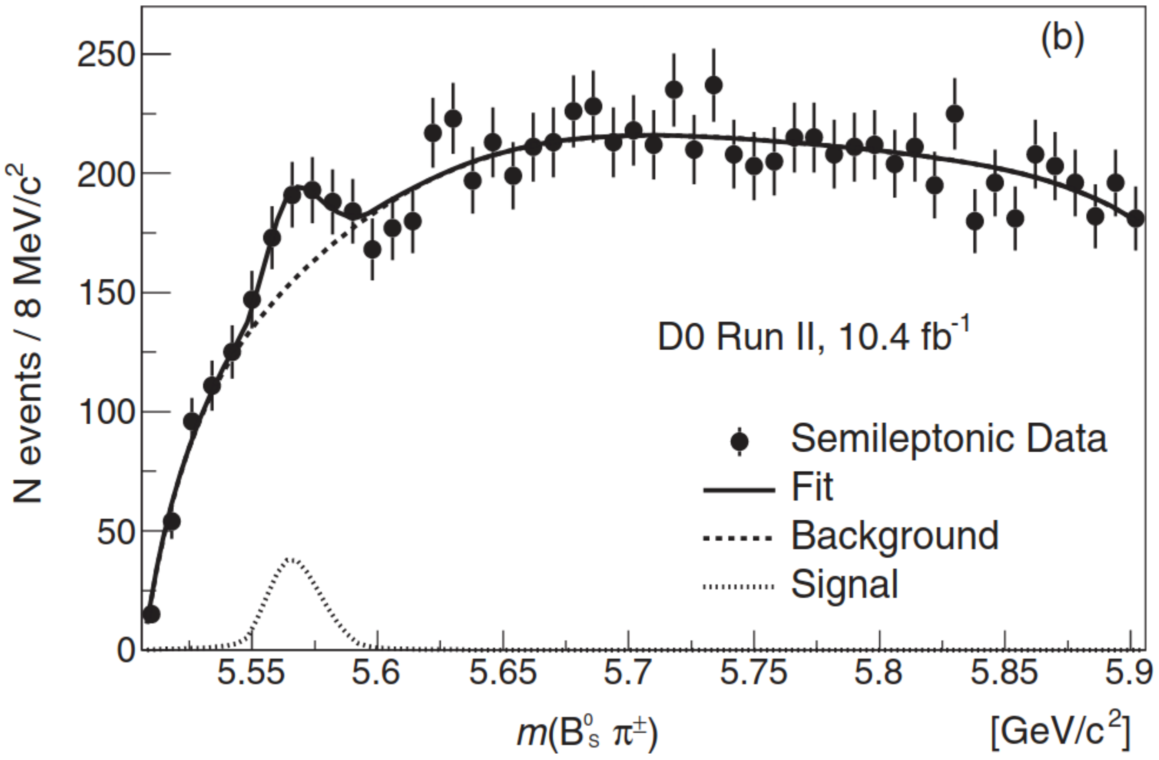
- $X(5568)^{\pm} \rightarrow B_s\, \pi^{\pm}$.
  - [Phys. Rev. Lett. 117, 022003]
  - [Phys. Rev. D 97, 092004]

Not observed at:

- CDF, [Phys. Rev. Lett. 120, 202006].
- LHCb, [Phys. Rev. Lett. 117, 152003].
- CMS, [Phys. Rev. Lett. 120, 202005].

ATLAS search performed in Run 1 data.

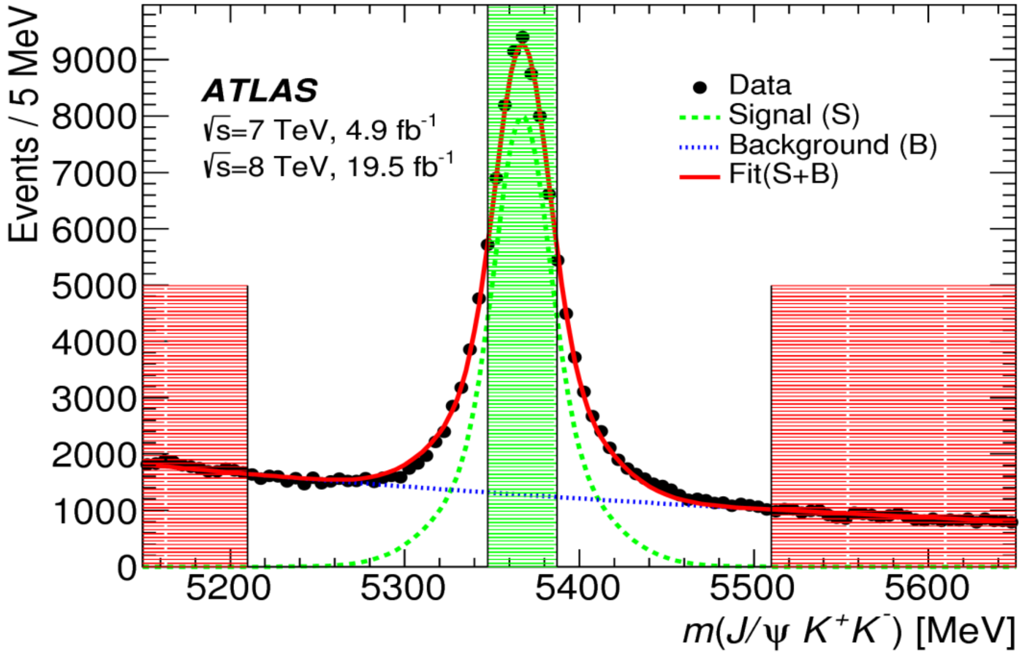
- $\sqrt{s}$=7 TeV (4.9 fb^{-1}), $\sqrt{s}$=8 TeV (19.5 fb^{-1}).



Searches for the X(5568)$^{\pm}$ State - 2

The ATLAS search:

- B_s candidates:
  - $p_T(\mu) > 4$ GeV, $p_T(K) > 1$ GeV.
  - Di-muon, di-kaon, and 4-track mass cuts.
  - Di-muon and 4-track vertex cuts.
  - $\tau(B_s) > 0.2$ ps.
- $B_s\pi$ reconstruction:
  - $p_T(\pi) > 500$ MeV + PV cut.
  - $5346.6 < m(B_s) < 5386.6$ GeV.



Set limits on:

- n_X, signal event count.
- ρ_X, B_s fraction from X(5568).

Searches for the $X(5568)^{\pm}$ State - 3

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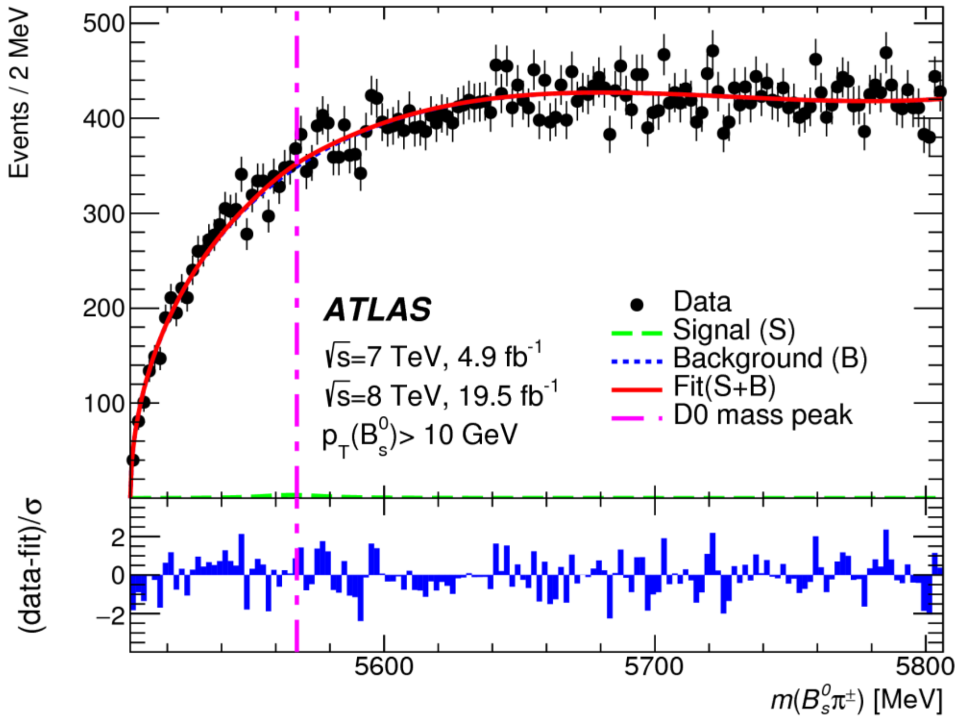
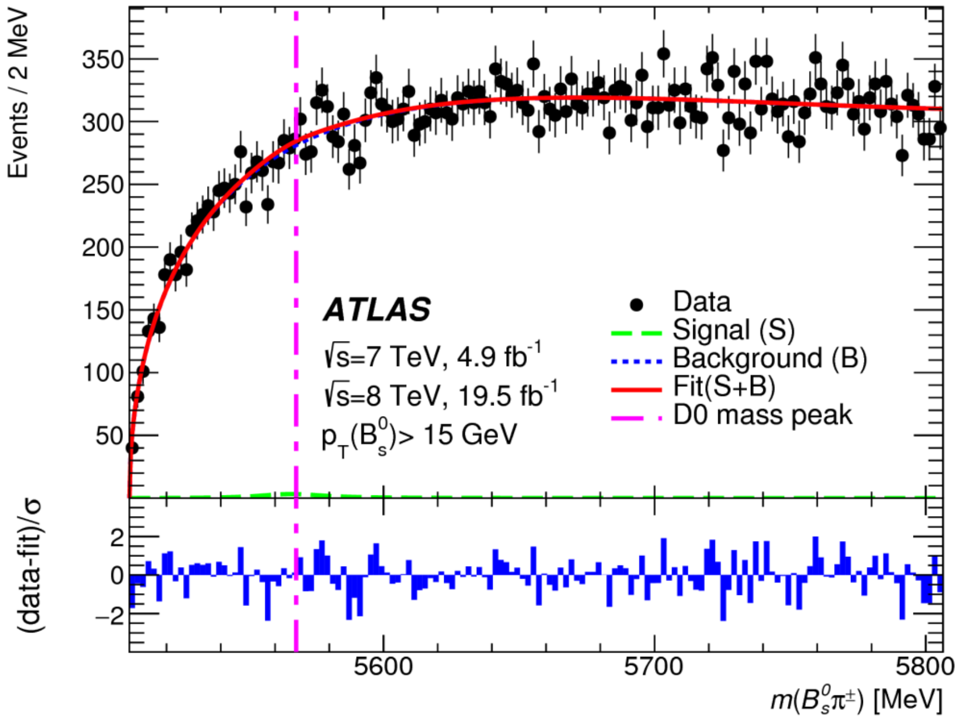
$p_T(B_s) > 10$ GeV



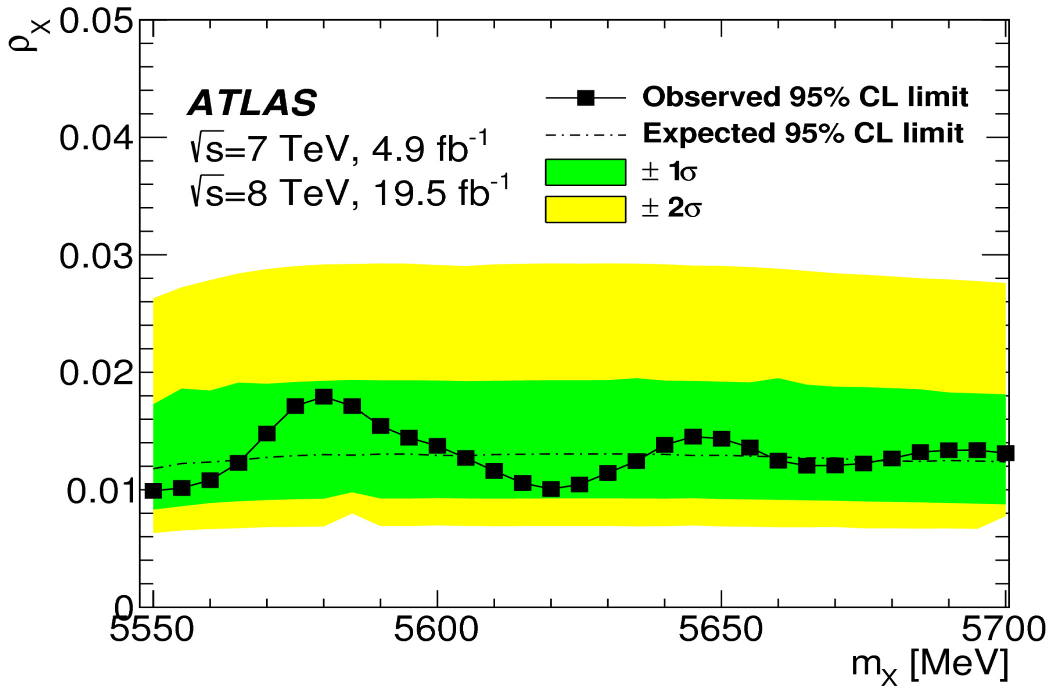
$p_T(B_s) > 15$ GeV



Searches for the X(5568)$^{\pm}$ State - 4

The ATLAS results:

- n_X:
  - $n_X = 60 \pm 140$, with $p_T(B_s) > 10$ GeV.
  - $n_X = 30 \pm 150$, with $p_T(B_s) > 15$ GeV.
  - No evidence of signal events.
- ρ_X @ 95% CL:
  - $\rho_X < 1.5\%$, with $p_T(B_s) > 10$ GeV.
  - $\rho_X < 1.6\%$, with $p_T(B_s) > 15$ GeV.
  - Limits compatible with LHCb & CMS.



Alternate candidate masses?

- No evidence in CLs scan.

Pentaquarks in the J/ψ p K^- State - 1

Overview of LHCb results:

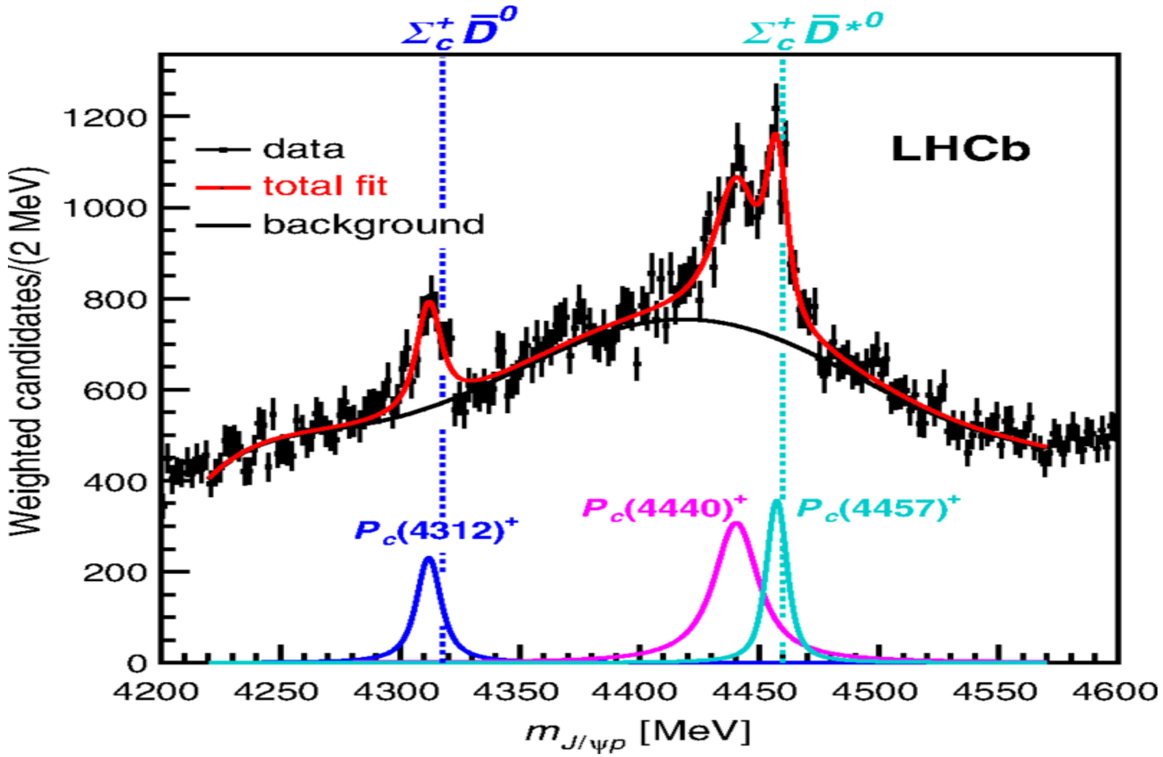
- 2 pentaquark in $\Lambda_b \rightarrow J/\psi\ p\ K^-$.
  - [Phys. Rev. Lett. 115, 072001]
- Later seen in $\Lambda_b \rightarrow J/\psi\ p\ \pi^-$.
  - [Phys. Rev. Lett. 117, 082003]
- 2 additional states seen in Run 2.
  - [Phys. Rev. Lett. 122, 222001]

Not observed by GLUEX:

- See [Phys. Rev. Lett. 123, 072001].
- Limits set on model independent production.

D0 observe a 3 σ evidence in J/ψ p events:

- See [arXiv:1910.11767].



Pentaquarks in the $J/\psi\ p\ K^-$ State - 2

No hadronic identification in ATLAS.

- Lots of states to consider!

$J/\psi \rightarrow \mu^+\mu^-$:

- $pT(\mu) > 4$ GeV, $|\eta\ (\mu)| < 2.3$.
- $|m(J/\psi_{PDG}) - m(\mu^+\mu^-)| < 290$ MeV.

B-hadron reconstruction:

- $|\eta\ (h_x)| < 2.5$.
- 4-track vertex cuts on (μ^+, μ^-, h_1, h_2).
- $pT(H_b) > 12$ GeV, $|\eta\ (H_b)| < 2.1$.
- $m(H_b)$ cuts dependent on mass of h_x.
- L_{xy} decay length and helicity cuts.

Region Definition	Mass Range (GeV)
Λ_b Signal Region	$5.59 < m(J/\psi\ p\ K^-) < 5.65$
B_d Control Region	$5.25 < m(J/\psi\ K^+\ \pi^-) < 5.31$
B_s Control Region	$5.337 < m(J/\psi\ K^+\ K^-) < 5.397$
Background Shape	$5.35 < m(J/\psi\ p\ K^-) < 5.45$

Pentaquarks in the $J/\psi\ p\ K^-$ State - 3

Fits of:

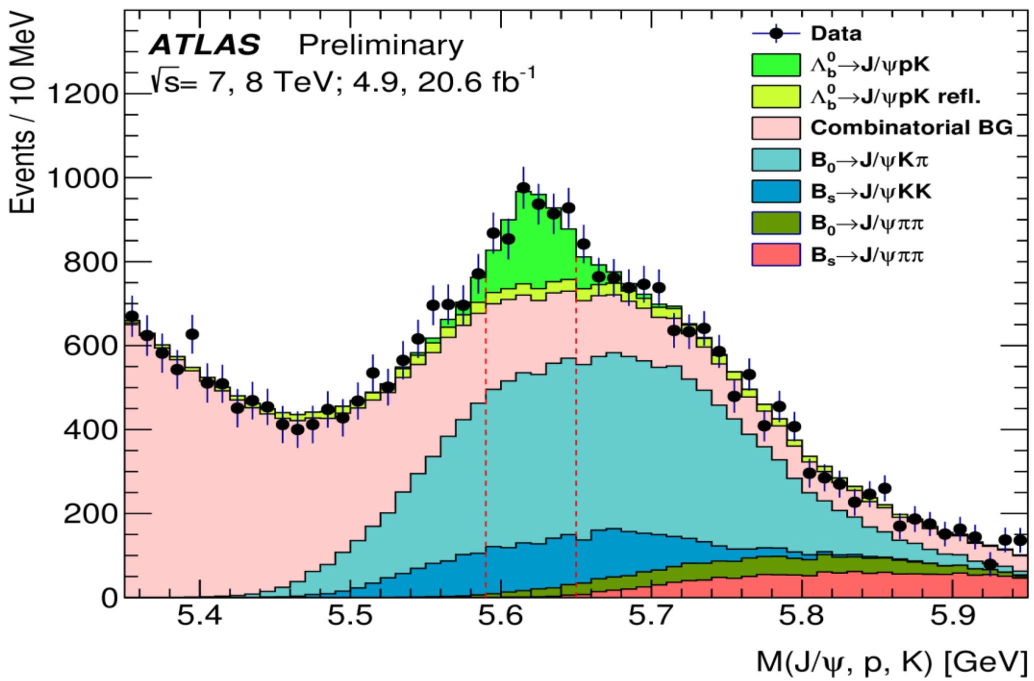
- $\Lambda_b \to J/\psi\ \Lambda^*$ or $P_c^+\ K^- \to J/\psi\ p\ K^-$.
- $B_d \to J/\psi\ K^*$ or $Z_c^-\ K^+ \to J/\psi\ K^+\ \pi^-$.
- $B_s \to J/\psi$ f or $J/\psi\ \phi \to J/\psi\ K^+\ K^-$.

Background suppression via:

- Same-sign subtraction.
- $m(\pi\ K)$ and $m(K\ \pi) > 1.55$ GeV.

B-hadron reconstruction:

- $m(J/\psi\ p\ K)$.
- $m(J/\psi\ \pi\ K)$.
- $m(J/\psi\ K^+\ K^-)$.
- $m(J/\psi\ \pi^+\ \pi^-)$.
- $m(J/\psi\ h_x)$ & $m(h_1\ h_2)$ in a B_d CR.
- $m(J/\psi\ h_x)$ & $m(h_1\ h_2)$ in a B_s CR.



Pentaquarks in the J/ψ p K^- State - 4

Fitted yields:

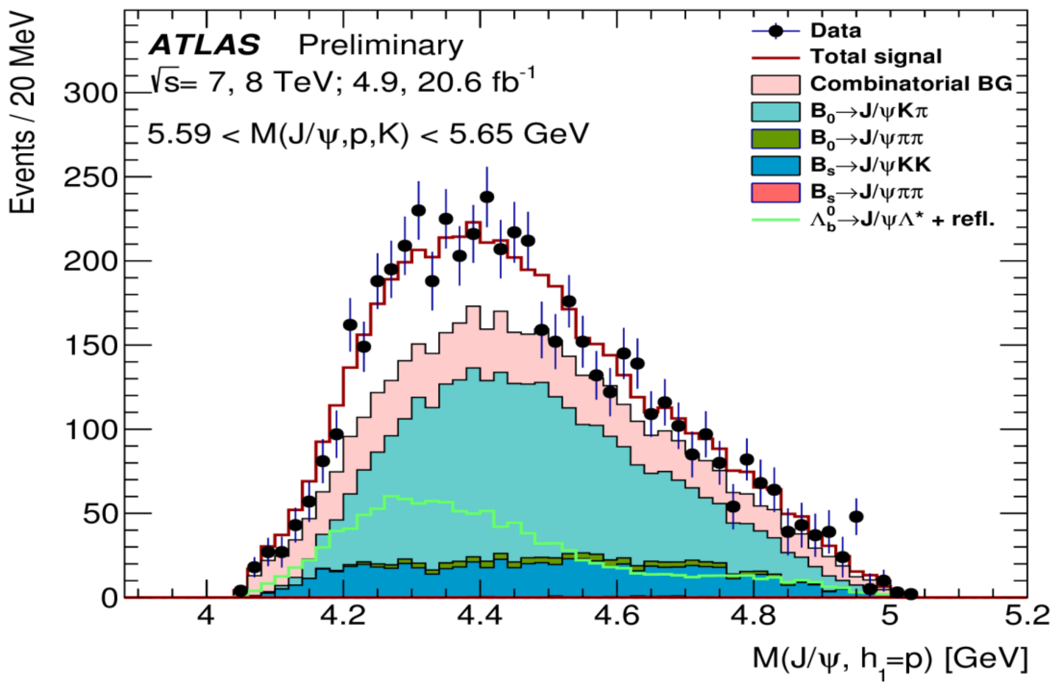
- $\Lambda_b \rightarrow J/\psi\ p\ K^- = 2270 \pm 300$.
- $B_d \rightarrow J/\psi\ K^+ \pi^- \sim 10770$.
- $B_s \rightarrow J/\psi\ K^+ K^- \sim 2290$.
- $B_d \rightarrow J/\psi\ \pi^+ \pi^- \sim 1070$.
- $B_s \rightarrow J/\psi\ \pi^+ K^- \sim 1390$.

P_c signal regions fits:

- $\Lambda_{b(\text{Right})} \rightarrow J/\psi\ p\ K^- = 1010 \pm 140$.
- $\Lambda_{b(\text{Wrong})} \rightarrow J/\psi\ p\ K^- = 160 \pm 20$.

No P_c-state hypothesis:

- P-value = 9.1 * 10^{-3}.



Pentaquarks in the $J/\psi\ p\ K^-$ State - 5

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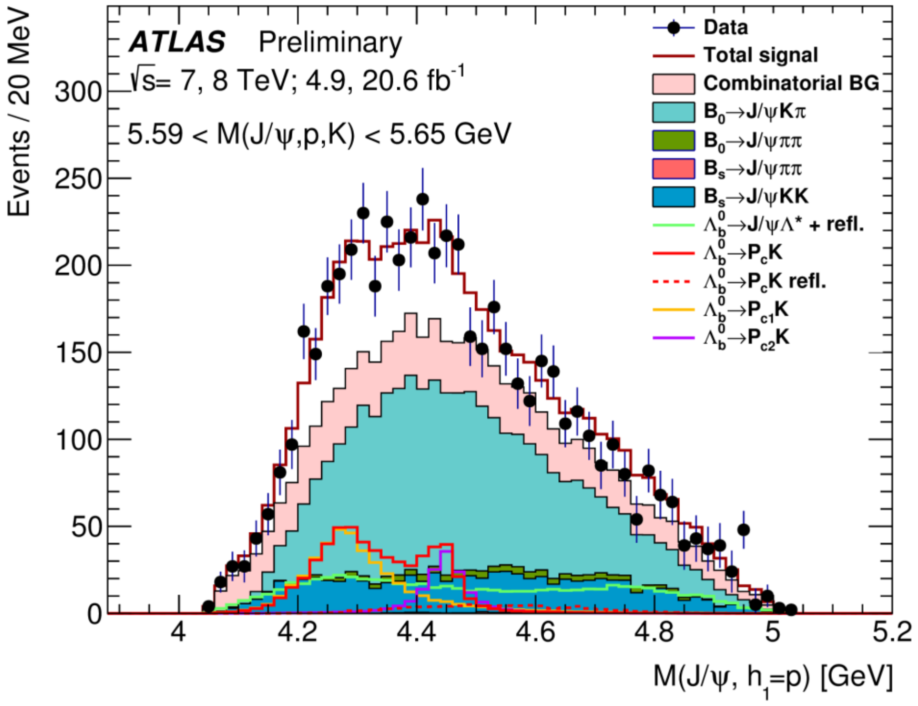
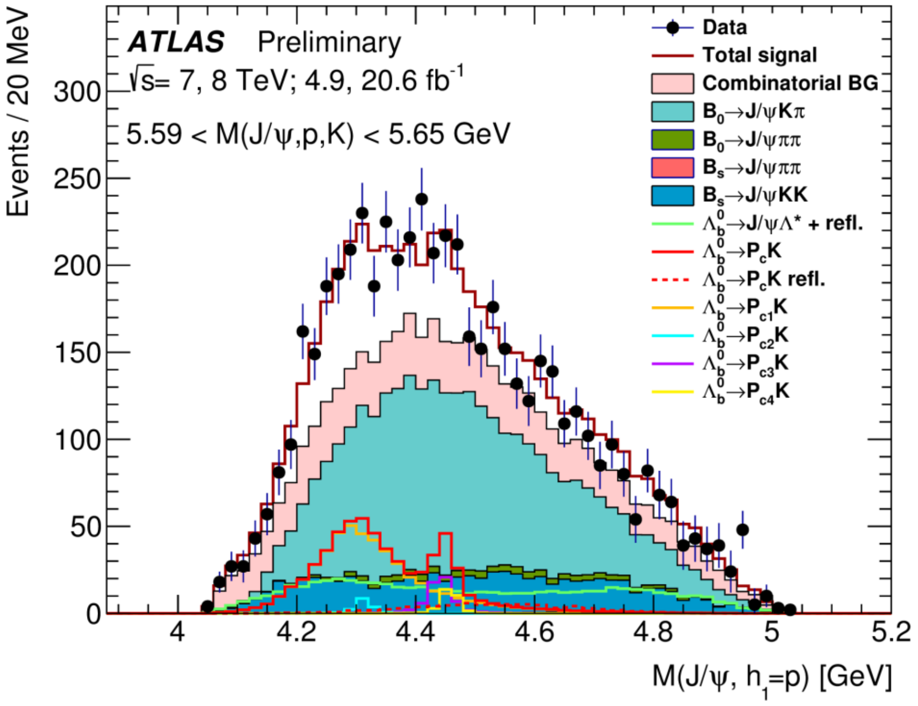
2 P_c-state hypothesis: P-value = 55.7%.



4 P_c-state hypothesis: P-value = 68.6%.



Pentaquarks in the J/ψ p K$^-$ State - 6

Good agreement with LHCb.

- Some tension in P_{c1} properties.

Alternative fit:

- 2 P_c-states - fixed to LHCb values.
- P-value = 24.5%

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} (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

Run 2 Searches for the $Z_c(4200)$

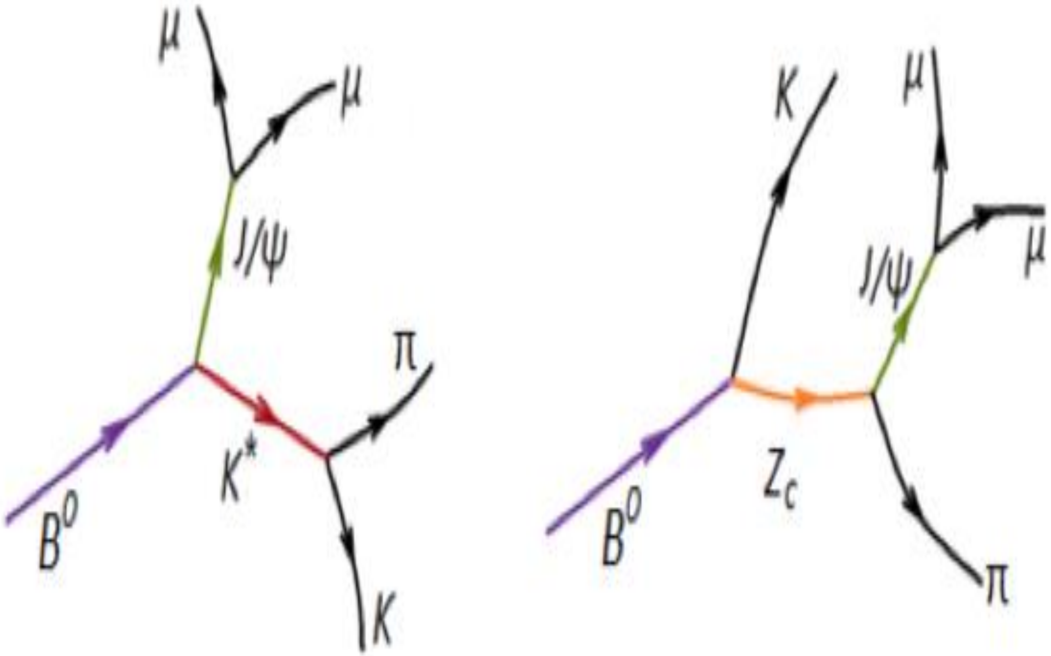
Run 2 searches for exotic Z_c states.

Belle observes $Z_c(4200)^+ \rightarrow J/\psi\, \pi^+$.

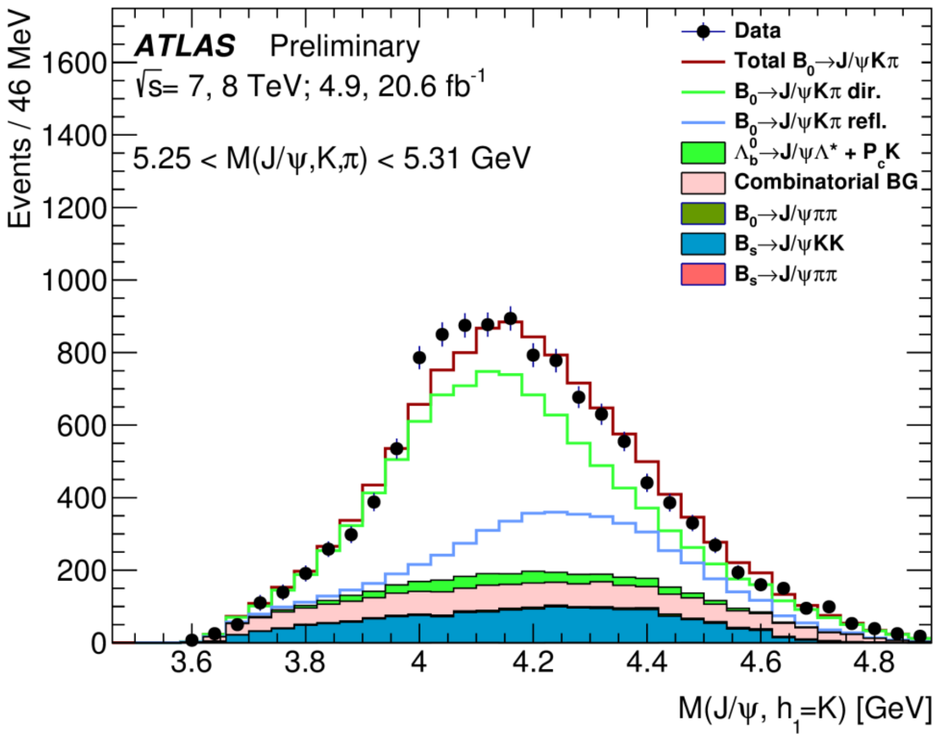
- See [Phys. Rev. D 90, 112009].

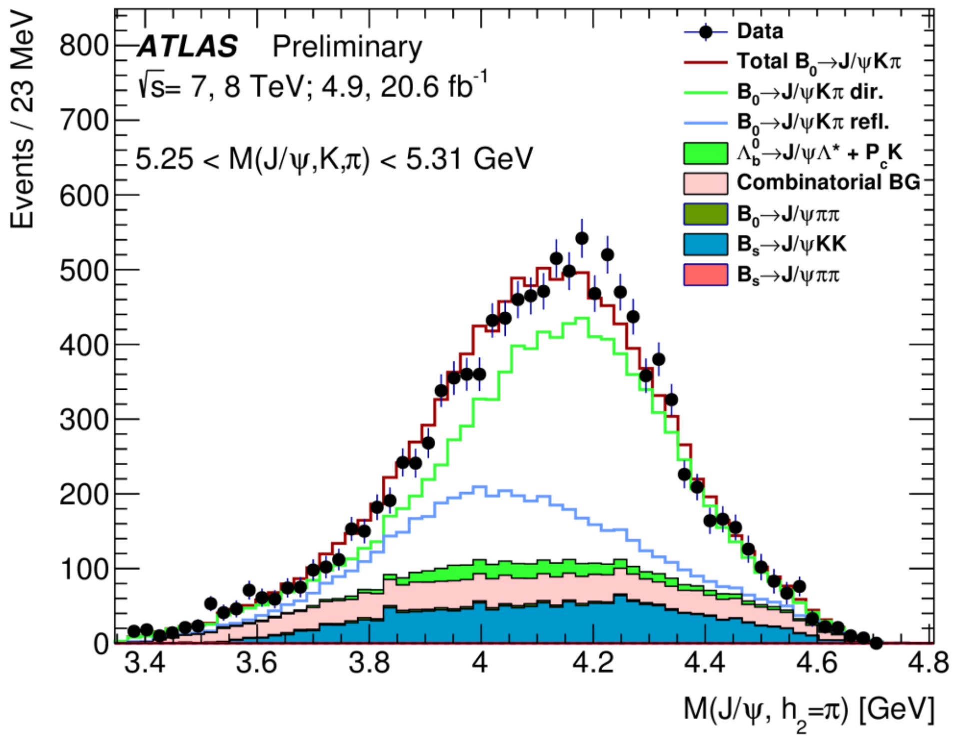
Seen in $B_d \rightarrow J/\psi\, K^+ \pi^-$ decays.

- Large m(K π).



$Z_c(4200)$ Hints in the Run 1 Analysis





ATLAS Results on Exotic Heavy Hadrons

Summary:

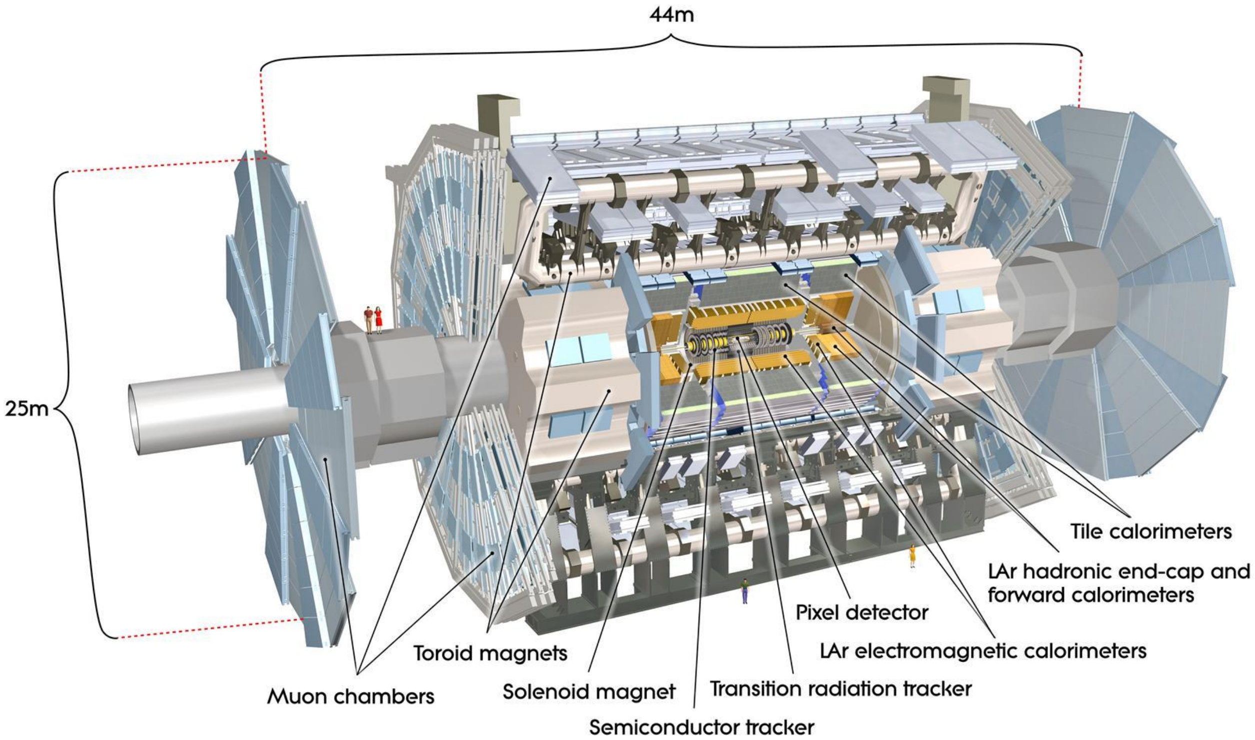
- Search for a X(5568) resonance:
  - No evidence of the state claimed by D0.
  - Strong limits on production set from Run 1 data.

- Pentaquarks with $\Lambda_b \rightarrow J/\psi\ p\ K^-$:
  - 0-pentaquark model strongly disfavoured (not excluded) by data.
    - Run 2 statistics required.
  - 2-pentaquark model consistent with data and LHCb.
  - 4-pentaquark model also consistent with data (with parameters fixed from LHCb).
    - Poor mass resolution limits analysis.
  - Run 2 analysis offers better statistics, better resolution…
    - Underway - expect results soon!

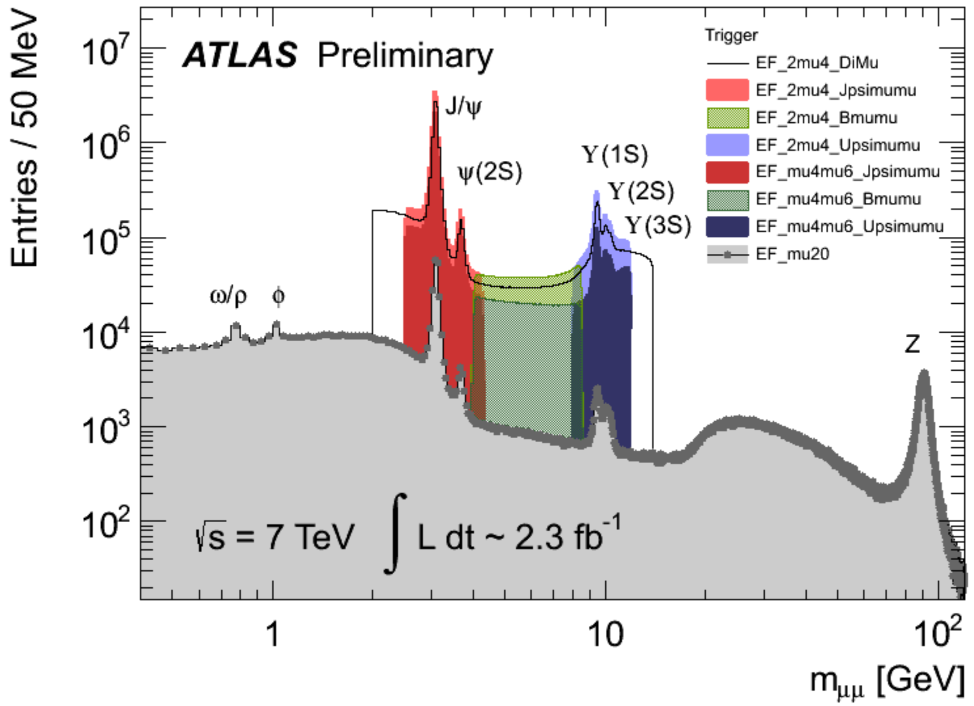
- Z_c(4200) searches in Run 2:
  - Running in parallel with the Run 2 pentaquark analysis.

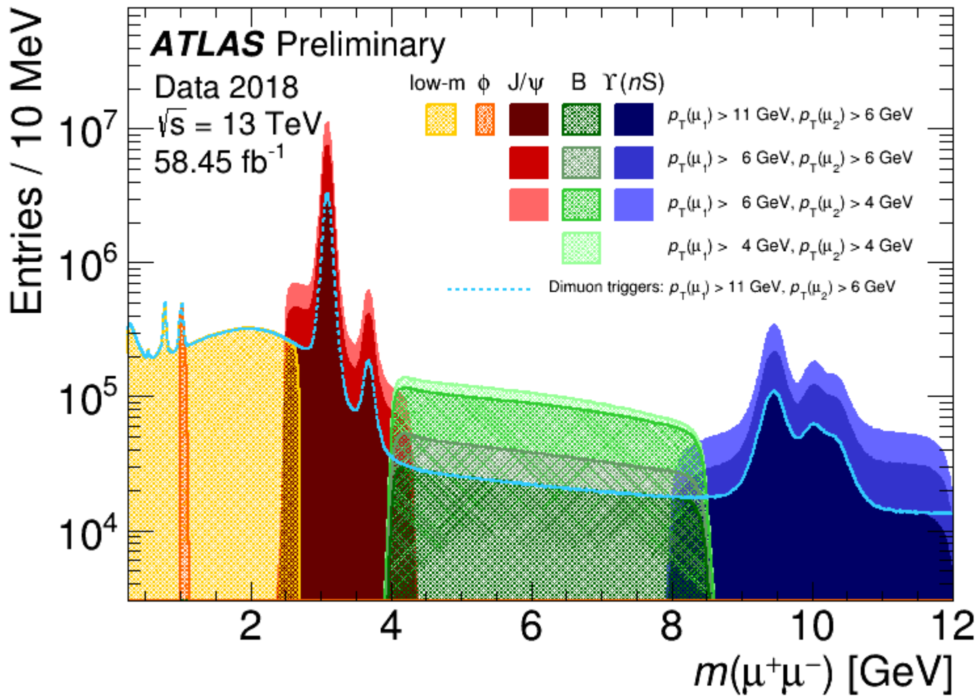
Backup

ATLAS:
The Detector



B-Physics Triggers: Run 1 and Run 2





Pentaquarks in the $J/\psi\ p\ K^-$ State: 2 Pc State Fits

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
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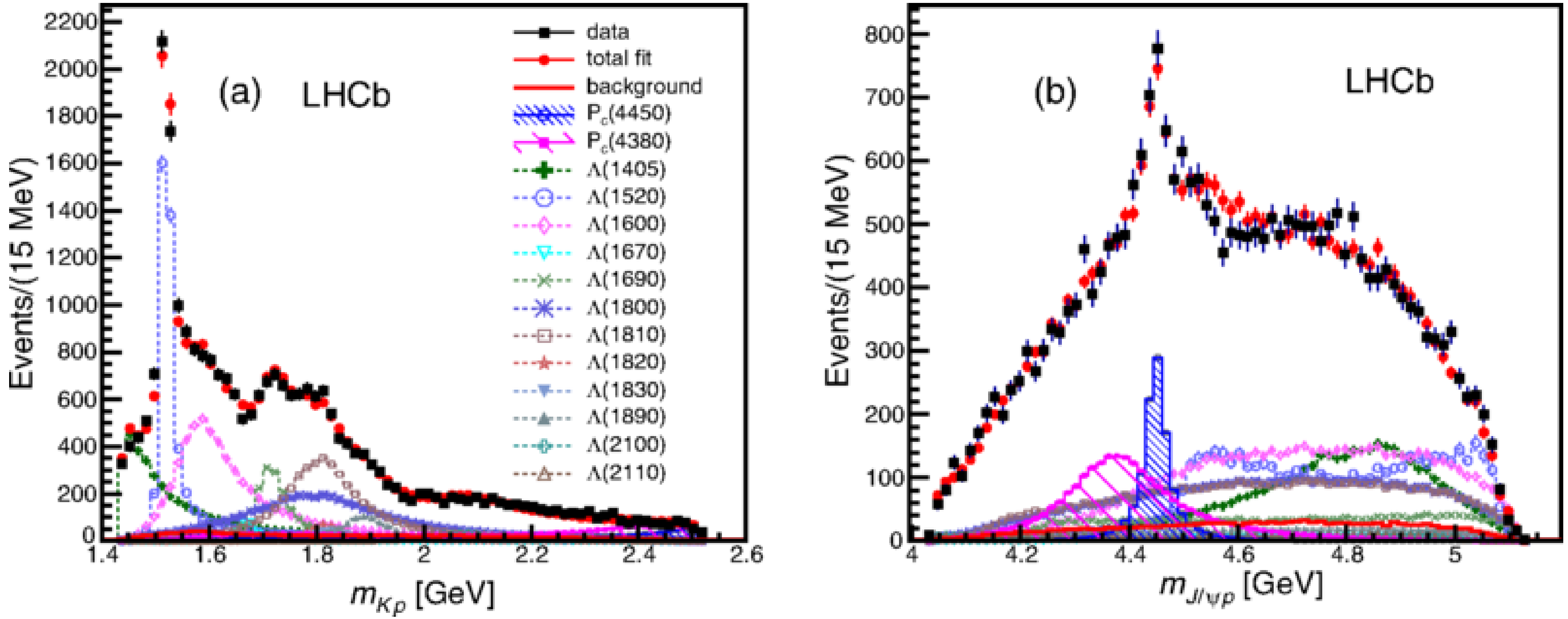
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

Pentaquarks in the J/ψ p K⁻ State: Initial LHCb Results



Pentaquarks in the J/ψ p K⁻ State: Systematics

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

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