ATLAS Results in Hadron Spectroscopy and Production

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For the ATLAS collaboration

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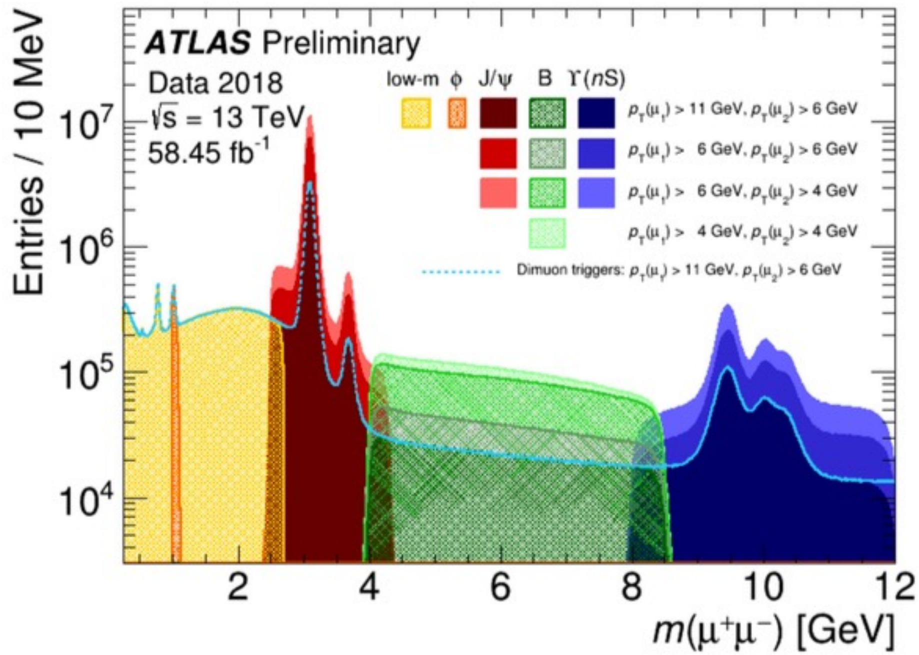
b/c physics at ATLAS

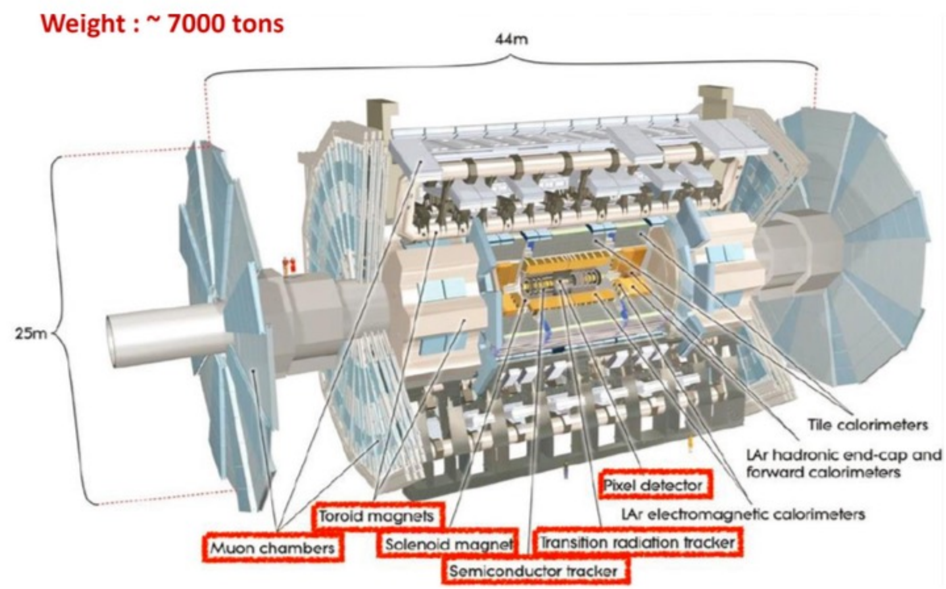
25 fb^{-1} in Run 1 and 139 fb^{-1} in Run 2

Analyses mostly focus on final states with muons

Typical trigger: dimuon with p_T thresholds at 4, 6 and 11 GeV

In 2018, a di-electron high-level trigger implemented and being analyzed now





Inner detector (Pixel+SCT+TRT)

p_T>0.4(0.1) GeV, |η|<2.5

Muon Spectrometer

Offline tracking: |η|<2.7

Triggering: |η|<2.4

In this talk

High-P_T J/ψ and $\psi(2S)$ production at 13 TeV ATLAS-CONF-2019-047

Study of J/ψ p resonances in $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays ATLAS-CONF-2019-048

Observation of di-charmonium excess in the four muon final state ATLAS-CONF-2022-040

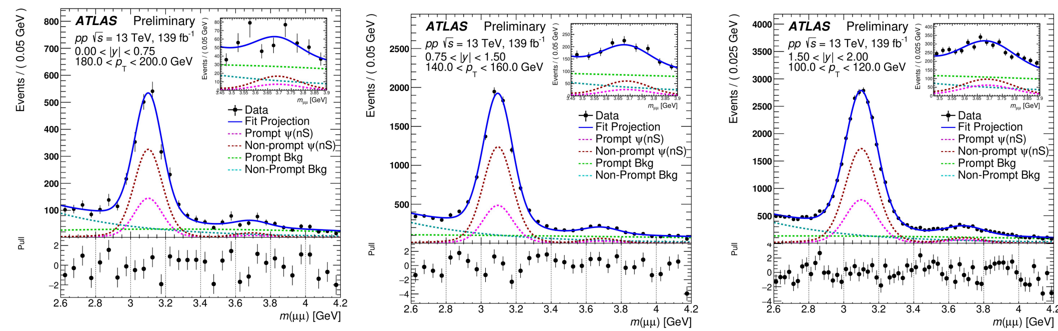
J/ψ and $\psi(2S)$ production

- Studies of heavy quarkonia provide insight into QCD near boundary of perturbative and non-perturbative regimes
- Important to measure cross sections to refine quarkonia production models
- ATLAS Run 1 result
  - p_T range limited to <100 GeV due to low-threshold dimuon triggers
- Run 2 (this result)
  - Use un-prescaled single muon triggers with 50 GeV threshold
  - Can now provide coverage at high-p_T < 300 GeV

J/ψ and ψ(2S) Mass/Lifetime fits

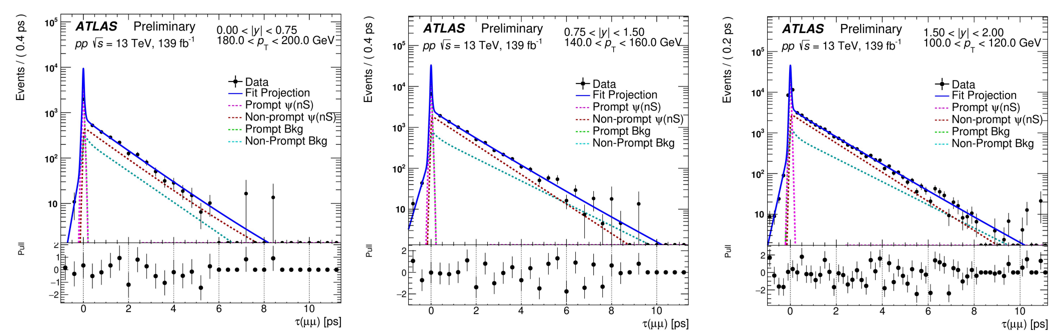
p_T range 60-360 GeV for J/ψ
60-140 GeV for ψ(2S)

Mass fits



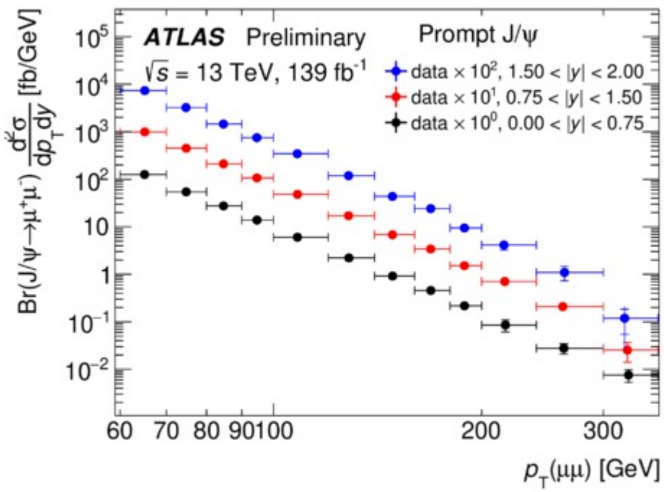
Measured in 3 bins of rapidity |y|< 2

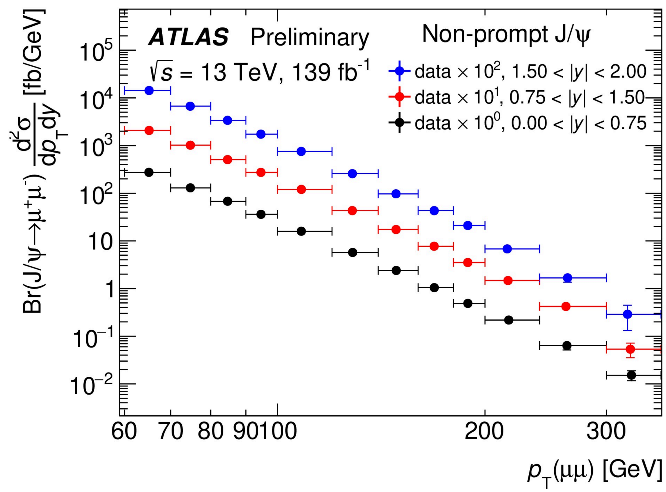
Lifetime fits $\tau = \frac{m}{p_T}\frac{L_{xy}}{c}$

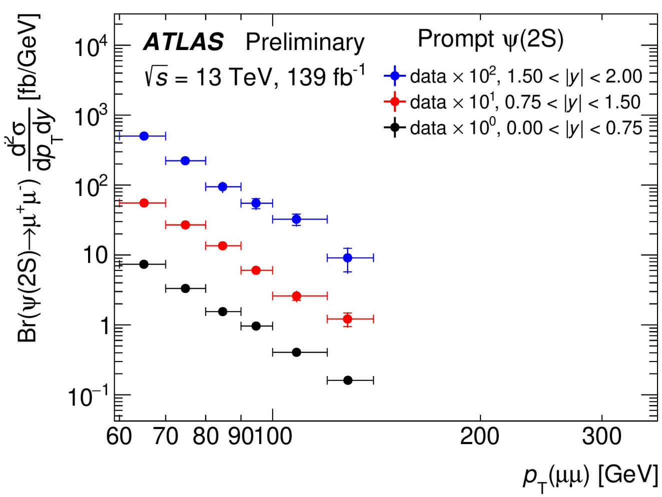


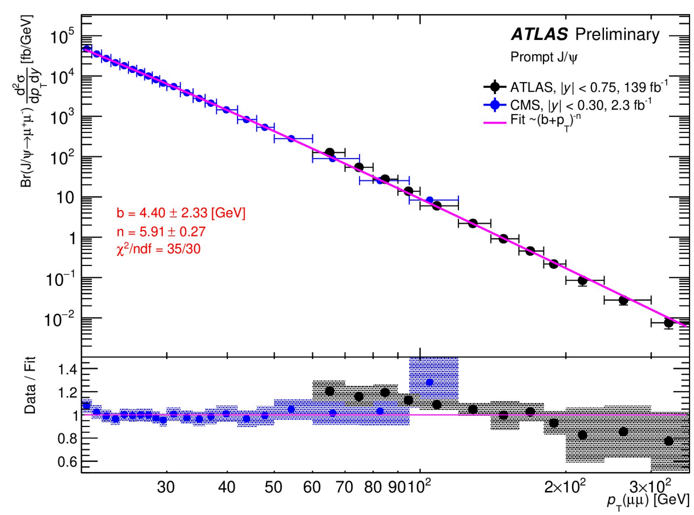
Simultaneous mass/lifetime fits provide J/ψ and ψ(2S) yields and prompt/non-prompt fractions

J/ψ and ψ(2S) cross sections







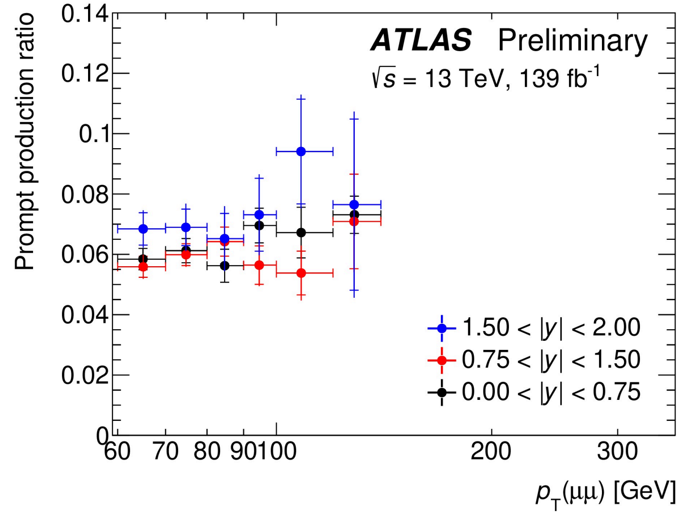


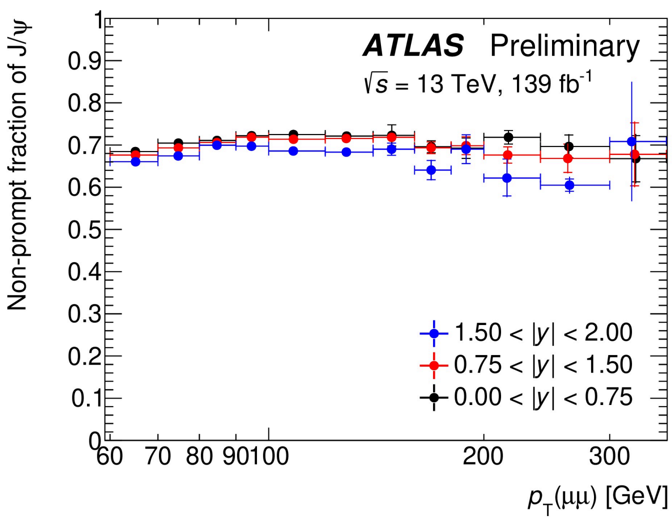
Good agreement between ATLAS and CMS in overlap region

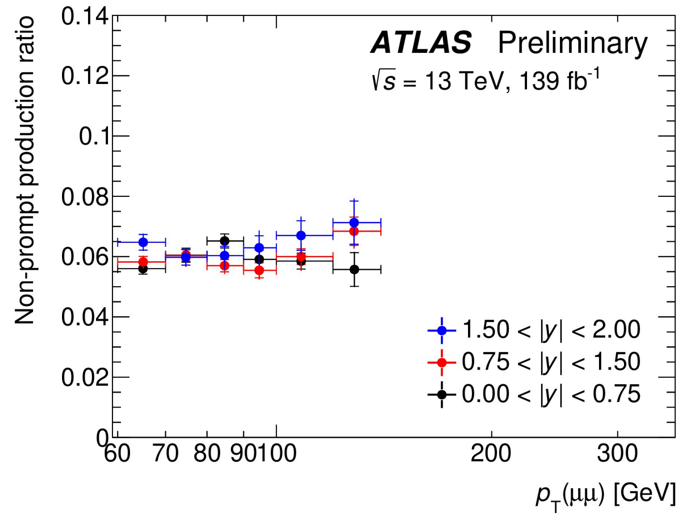
J/ψ and ψ(2S) prompt fractions

Non-prompt fraction ~ flat for all rapidities

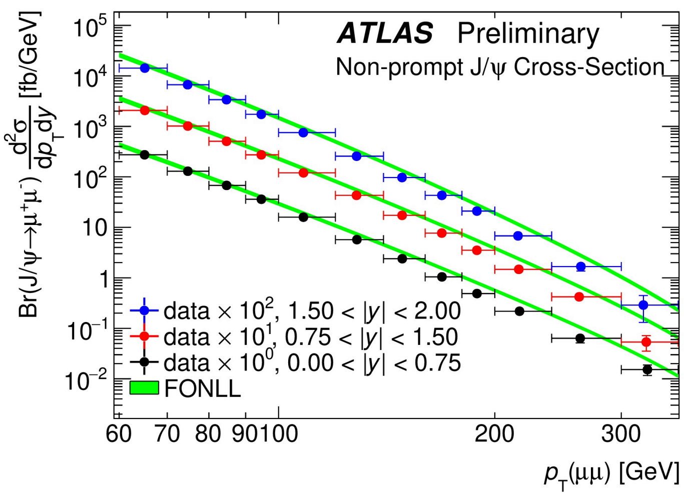
Similar for J/ψ and ψ(2S)

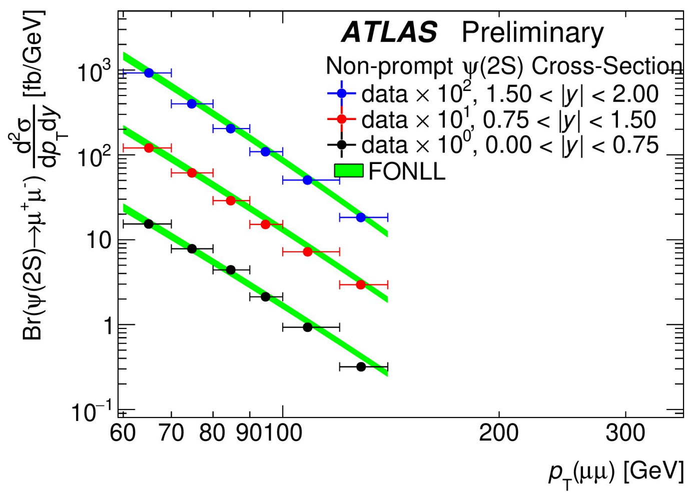




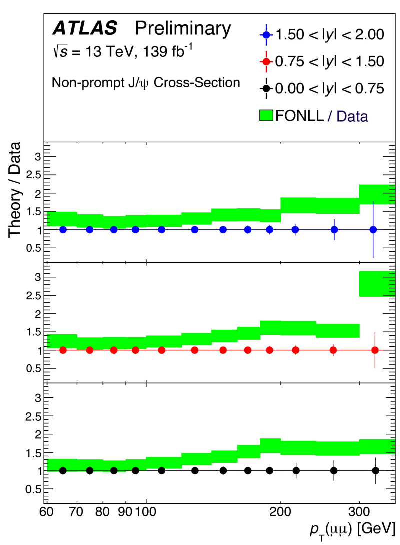


J/ψ and ψ(2S) comparison to FONLL



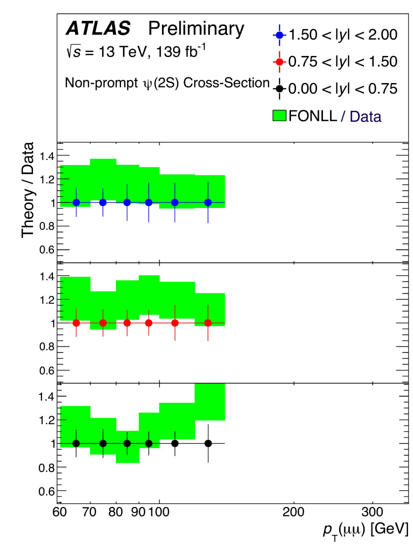


FONLL predictions agree reasonably well over 5 orders of magnitude



Factor of 2 deviation at high p_T

Will be interesting to see NRQCD predictions, especially at high p_T



Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$

In 2015 LHCb reported observation of J/ψ p resonant structure in $\Lambda_b^0 \to J/\psi p K^-$ (PRL 115,072001)

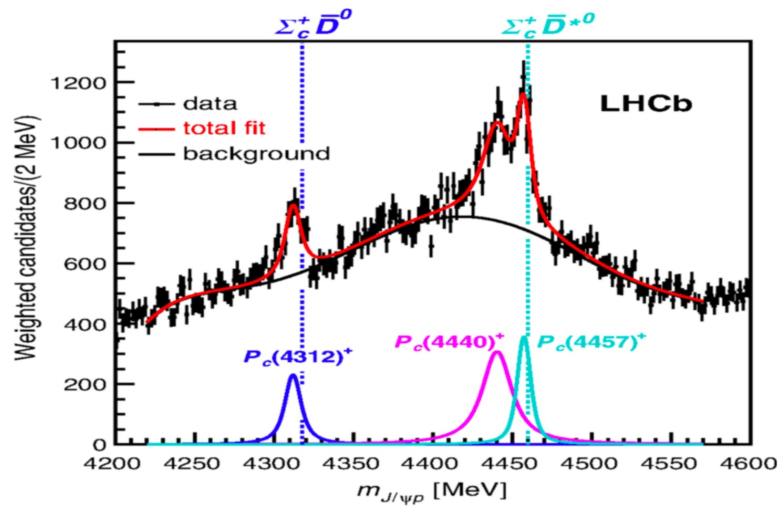
$P_c(4380)^+$ M = 4380 ± 8 ± 29 MeV, width = 205 ± 18 ± 86 MeV, $J^P = 3/2^-$

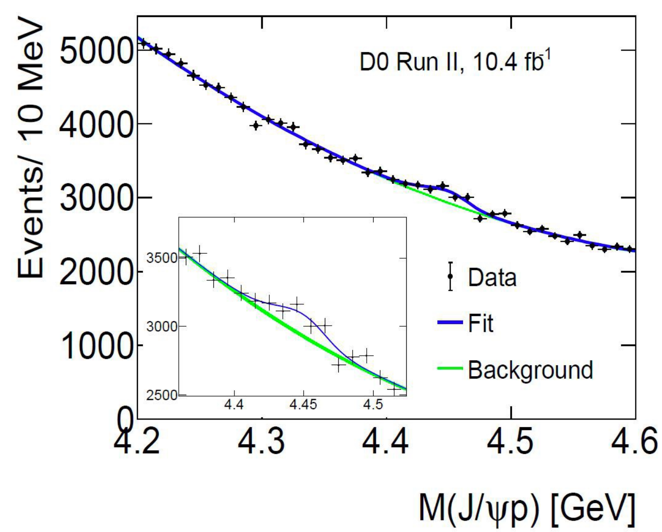
$P_c(4450)^+$ M = 4449.8 ± 1.7 ± 2.5 MeV, width = 39 ± 5 ± 19 MeV, $J^P = 5/2^+$

Later $\Lambda_b^0 \to J/\psi p \pi^-$ decays consistent with $\Lambda_b^0 \to J/\psi p K^-$ results (PRL 117,082003)

In 2019 with a larger data set of $\Lambda_b^0 \to J/\psi p K^-$ LHC b resolved $P_c(4450)^+$ into 2 states $P_c(4440)^+$, $P_c(4457)^+$ 5.4 σ and reported an additional narrow state $P_c(4312)^+$ 7.3 σ (PRL 112,222001)

State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$





Not observed by GlueX Collaboration: PRL 123, 072001 Small(BR)

D0 observed 3 σ evidence in J/ψ p events (arXiV:1910.11767)

Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$

Data set: 4.9 fb^{-1} of 7 TeV and 20.6 fb^{-1} of 8 TeV ATLAS Run-1 data

No hadron identification in ATLAS so need to consider numerous states.

$J/\psi \to \mu^+\mu^-$

$p_T(\mu) > 4$ GeV ; $|\eta(\mu)| < 2.3$

$|m(J/\psi_{pdg}) - m(\mu^+\mu^-)| < 290$ MeV

B-hadron reconstruction

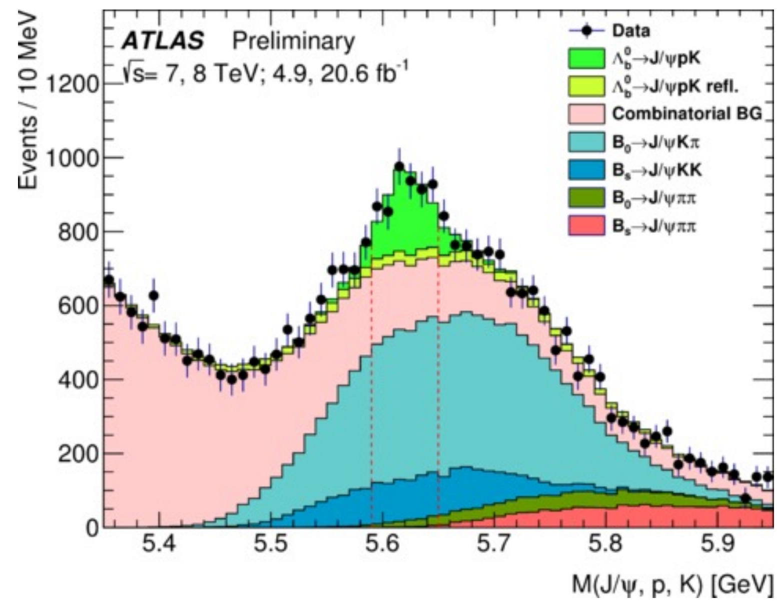
$|\eta(h_x)| < 2.5$

4-track vertex cuts on (μ^+, μ^-, h_1, h_2)

$p_T(H_b) > 12$ GeV, $|\eta(H_b)| < 2.1$

Mass, L_{xy} decay length and helicity cuts

$m(K\pi)$ and $m(\pi K) > 1.55$ GeV



Signal and backgrounds generated with Pythia 8.1 ("phase-space" model)

$\Lambda_b^0 \to J/\psi\ pK^-$: contributions from light Λ^* states considered

$B^0 \to J/\psi\ K^+\pi^-$: contributions from light K* states included, potential contribution from $B^0 \to Z_c(4200)^- K^+ \to J/\psi\pi^- K^+$ (considered as systematic effect)

$B_s^0 \to J/\psi K^+K^-$: contributions from ϕ and f_2 states included

$B^0 \to J/\psi\ \pi^+\pi^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$: intermediate and non-resonance phase space decays considered

Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$

Signal/control regions and fit procedure

Fits performed after subtracting contribution where both hadron tracks have same charge

Multi-dimensional (different hadron mass assignments) binned maximum likelihood fits

Λ_b signal region (SR): $5.59\,\mathrm{GeV} < m(J/\psi, h_1 = p, h_2 = K) < 5.65\,\mathrm{GeV}$

B^0 control region (CR): $5.25\,\mathrm{GeV} < m(J/\psi, h_1 = K, h_2 = \pi) < 5.31\,\mathrm{GeV}$

B_s^0 control region: $5.337\,\mathrm{GeV} < m(J/\psi, h_1 = K, h_2 = K) < 5.397\,\mathrm{GeV}$

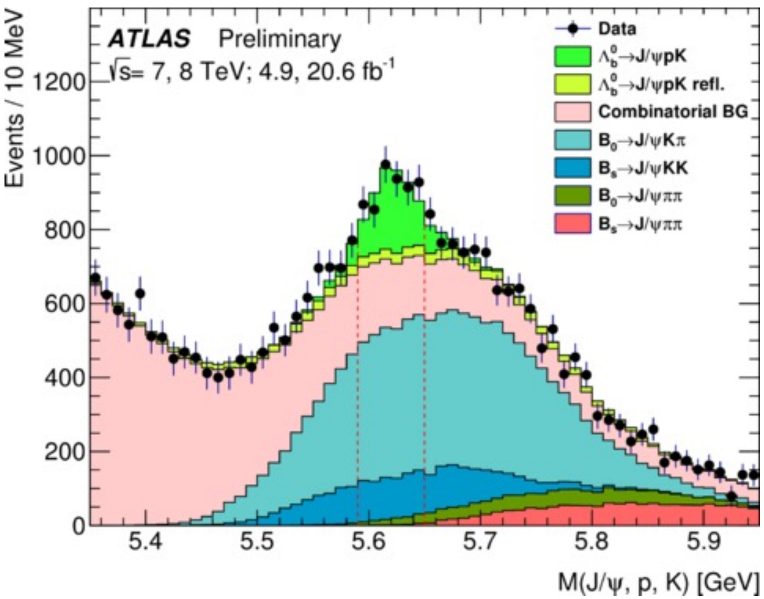
Background shape CR: $5.35\,\mathrm{GeV} < m(J/\psi, h_1 = p, h_2 = K) < 5.45\,\mathrm{GeV}$

Iterate 4 step procedure

1) Fit to m(J/ψ hh), m(J/ψ h), m(hh) to obtain parameters for B^0 and B_s^0 backgrounds
2) Fit to m(J/ψ h), m(hh) to determine number of Λ_b decays, combined B^0 and B_s^0 decays and combinatorial background parameters
3) Fit m(J/ψ, h_1=p,h_2=K) in SR to obtain decay constants of Λ_b
4) Fit m(J/ψ, h1=p) in SR to obtain pentaquark, mass, width , amplitudes and relative phase between pentaquark amplitudes $\Delta\phi$

Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p K^-$

Results



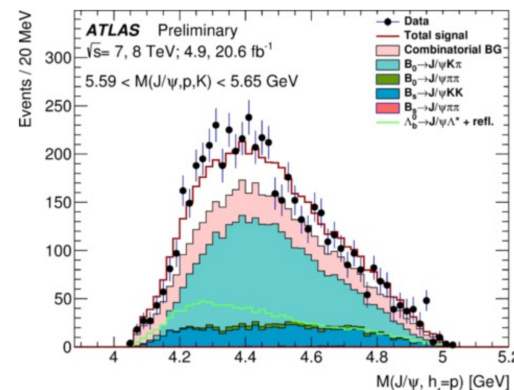
Yields:

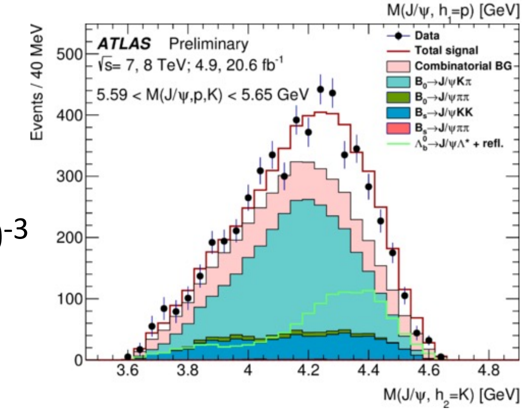
$$N(\Lambda_b^0 \rightarrow J/\psi\, pK^-) \approx 2270 \pm 300$$
$$N(B^0 \rightarrow J/\psi\, K^+\pi^-) \approx 10770$$
$$N(B_s^0 \rightarrow J/\psi\, K^+K^-) \approx 2290$$
$$N(B^0 \rightarrow J/\psi\, \pi^+\pi^-) \approx 1070$$
$$N(B_s^0 \rightarrow J/\psi\, \pi^+\pi^-) \approx 1390$$

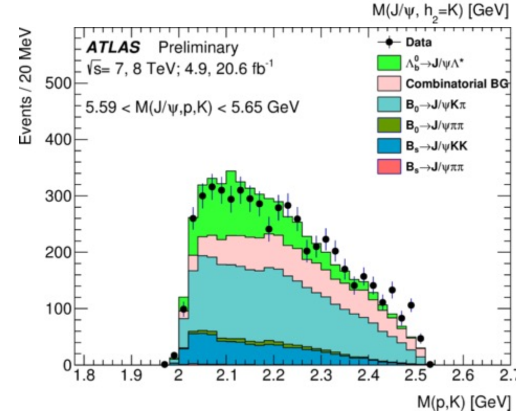
No pentaquarks in fit

χ^2/N_{dof}=42.0/23

p-value=9.1 x 10^{-3}





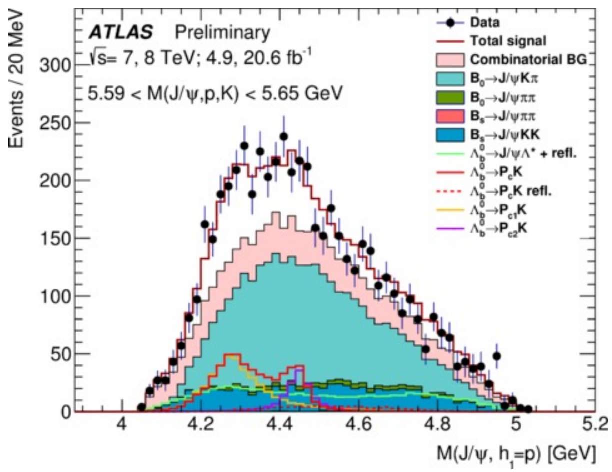


Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$

χ^2/N_{dof}=37.1/39
p-value=55.7%

If fixed to LHCb values
p-value=24.5%

m(J/ψ p)

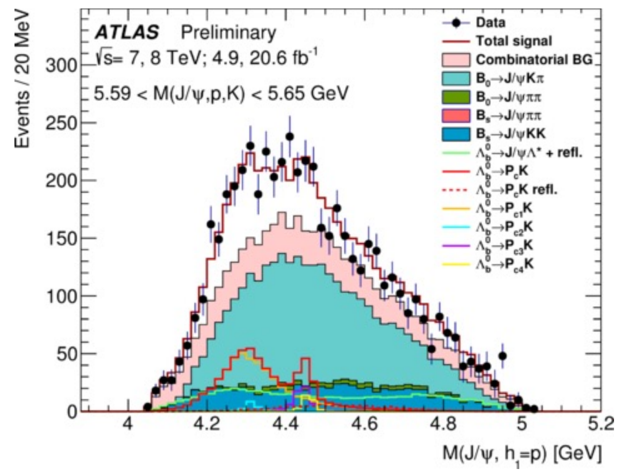


Hypothesis with two pentaquarks P_{c1} and P_{c2} with spin parity $3/2^-$ (lighter) and $5/2^+$ (heavier)

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

χ^2/N_{dof}=37.1/42
p-value=68.6%

Masses, widths, relative yields of narrow pentaquarks fixed to LHCb values



Hypothesis with four pentaquarks P_{c1},P_{c2},P_{c3},P_{c4}

Good agreement with LHCb (slight tension in P_{c1}

Better fit if pentaquarks included but non-pentaquark model cannot be excluded

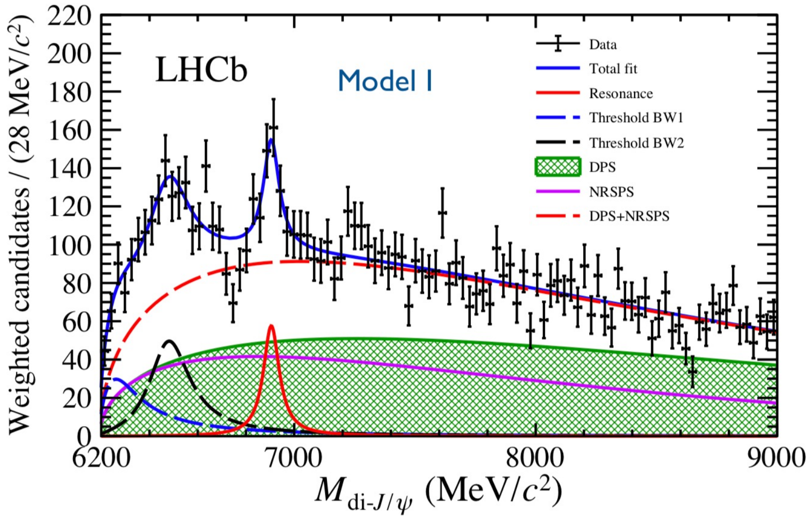
Tetraquarks in four muon final state

LHCb reported evidence of a narrow resonance at 6.9 GeV in di-J/ψ → 4μ arXiv:2006.16957

Can be interpreted as a tetraquark consisting of four charm quarks

Enhancement near di-J/ψ threshold could be due to:

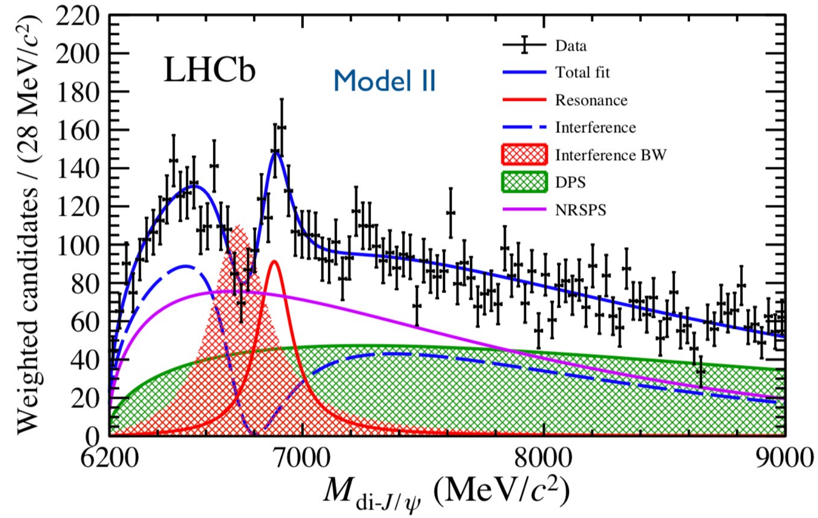
- mixture of multiple four-charm quark states
- contributions from feed down decays of four charm quark states through heavier quarkonia
- rescattering of charmonium final state



Assuming no interference with NRSPS continuum

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\mathrm{MeV}$$



Assuming interference with NRSPS continuum

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\mathrm{MeV}/c^2$$

$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\mathrm{MeV}$$

Observation of di-charmonium excess in the four muon final state with the ATLAS detector

ATLAS-CONF-2022-040

Dataset: 139 fb^{-1} of 13 TeV Run-2 data collected in 2015-2018

Search in 4-μ final state in di-J/ψ and $J/\psi+\psi(2S)$ channels. (di-$\psi(2S) \rightarrow 4\mu$ statistically not accessible)

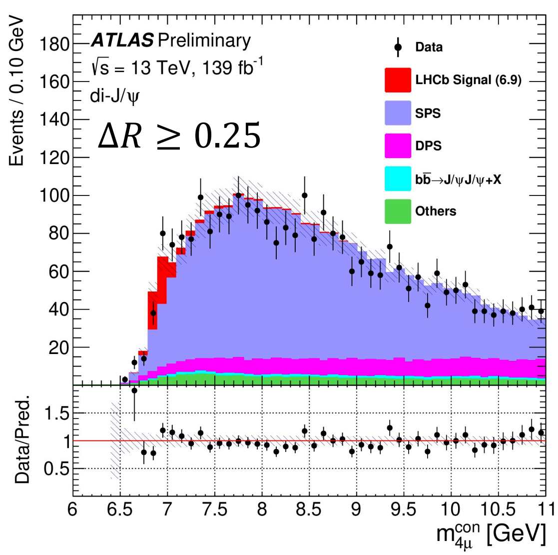
Backgrounds simulated with Pythia 8 with data driven corrections

Prompt di-J/ψ: Single Parton Scattering (SPS) and Double Parton Scattering (DPS)

Non-prompt di-J/ψ: $bb \rightarrow J/\psi J/\psi$

"Others" background: single (prompt or non-prompt) charmonium plus fake muons, non-peaking background containing no real charmonium candidates

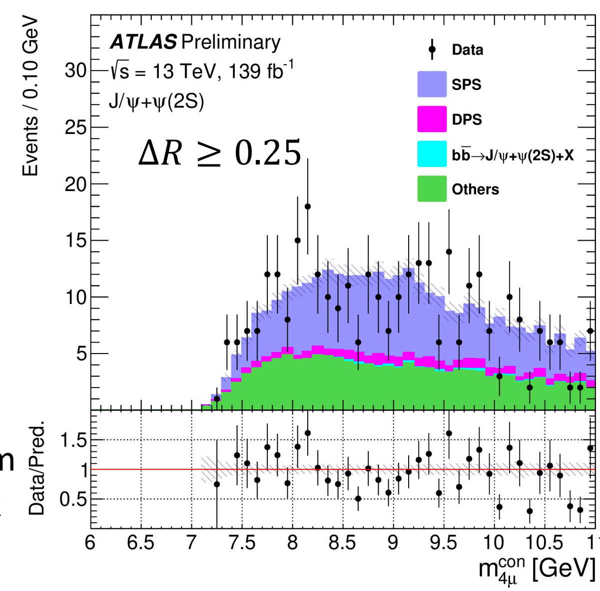
Signal simulated using JHU generator : TQ mass=6.9 GeV, width 0.1 GeV, spin=0



SPS mass shape validated using $\Delta R \geq 0.25$

ΔR defined between onia candidates

CR defined in sidebands and by requiring one charmonium containing a non-muon track



Observation of di-charmonium excess in the four muon final state with the ATLAS detector

Fitting

Unbinned maximum likelihood fits on the four muon mass spectra < 11 GeV
signal region $\Delta R < 0.25$, control region $\Delta R \geq 0.25$, with transfer factors for background yields from MC or data driven techniques

Signal consists of several interfering S-wave Breit-Wigner resonances convoluted with a mass resolution function $R(\alpha)$

$$f_s(x) = \left| \sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i} \right|^2 \sqrt{1 - \frac{4m_{J/\psi}^2}{x^2}} \otimes R(\alpha)$$

z_i: complex numbers representing amplitudes

z_1 fixed to unity with zero phase

No interference with NRSPS

Di-J/ψ: models with 2 or 3 resonances compared using χ^2 or toy MC

J/ψ+ψ(2S):

Model A: same resonances as di-J/ψ+ 4th standalone resonance

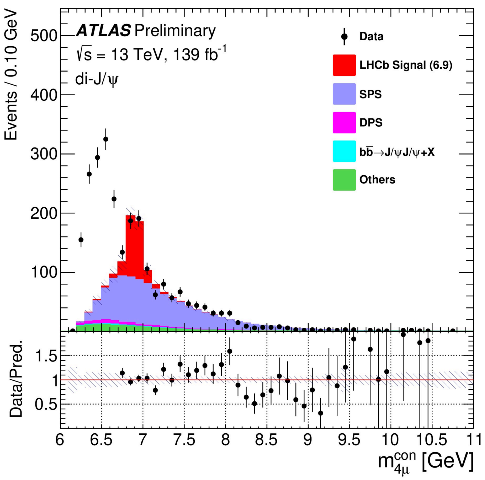
$$f_s(x) = \left(\left| \sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i} \right|^2 + \left| \frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3} \right|^2 \right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x} \right)^2} \otimes R(\alpha)$$

Model B: single resonance

Observation of di-charmonium excess in the four muon final state with the ATLAS detector

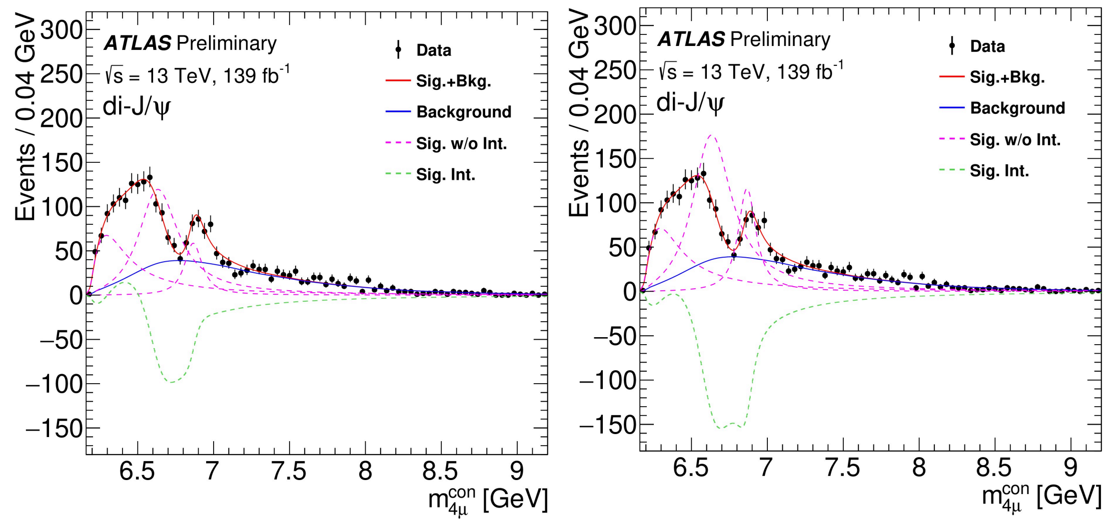
Results for di-J/ψ

4μ mass before fit



Feed-down from $J/\psi+\psi(2S)$ or higher di-charmonium resonances not included

SR 3 resonance fit, 2 of 4 degenerate solutions



Significance of third resonance: 10 σ

LHCb model I values for 3rd resonance gives similar results

LHCb model II (interference with NRSPS) disfavored based on fit quality

70% worse χ^2/dof using 2-resonances

Fitted mass and widths

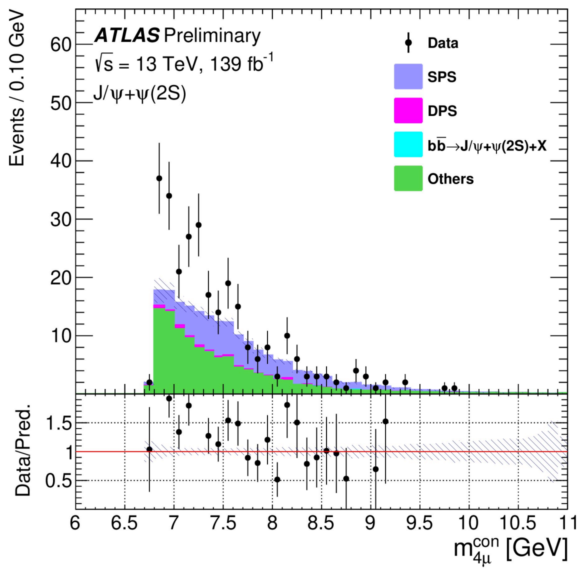
(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

6.9 GeV resonance confirmed
Best fit with 3 interfering resonances.
Other explanations possible

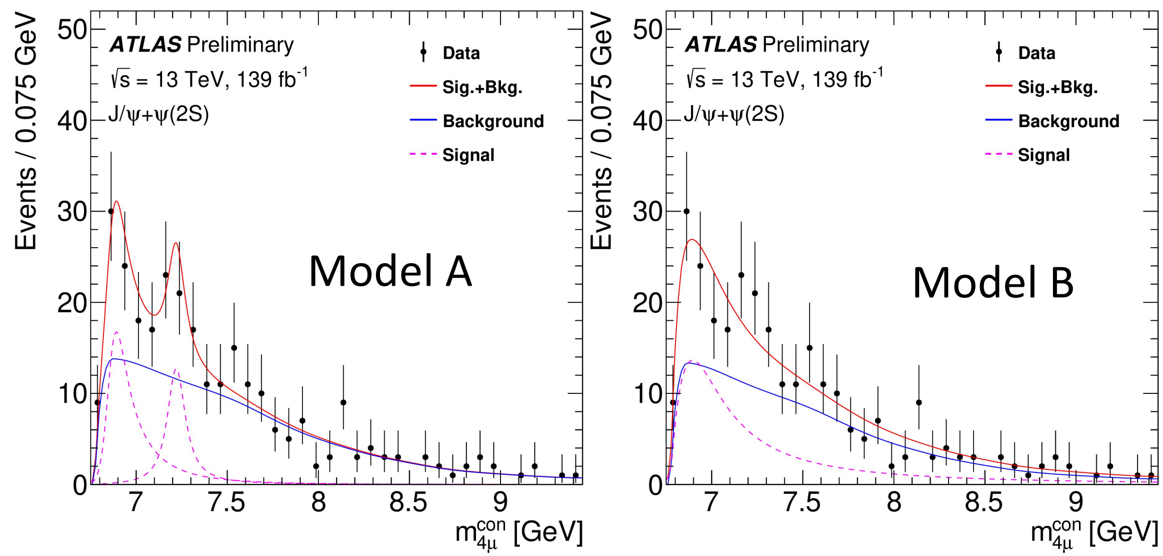
Observation of di-charmonium excess in the four muon final state with the ATLAS detector

Results for J/ψ+ψ(2S)

4μ mass before fit



Fitted mass in SR for Model A and Model B



Significance for Model A: 4.6 σ
second resonance at 7.2 GeV : 3.2 σ

Significance for Model B: 4.3 σ

Fitted mass and width

(GeV)		m_3	Γ_3
$J/\psi+\psi(2S)$	model A	$7.22 \pm 0.03^{+0.02}_{-0.03}$	$0.10^{+0.13+0.06}_{-0.07-0.05}$
	model B	$6.78 \pm 0.36^{+0.35}_{-0.54}$	$0.39 \pm 0.11^{+0.11}_{-0.07}$

Evidence of enhancement at 6.9 GeV and a resonance at 7.2 GeV.
Other explanations possible

Conclusions

J/ψ and $\psi(2S)$ cross sections at high p_T

Non-prompt fraction ~0.7 for both J/ψ and $\psi(2S)$
Predictions from FONLL tend to be higher than data at high p_T

Study of J/ψ p resonances in $\Lambda_b^0 \to J/\psi\ pK^-$ decays

Evidence for existence of pentaquark states consistent with LHCb results
Data does not allow independent measurements of pentaquark parameters
Model without pentaquarks states not excluded

Di-charmonium search in 4μ final state

Significance excess found in di-J/ψ channel
Resonance near 6.9 GeV and a broad structure at lower mass
Consistent with LHCb results
3-resonance model with interference is best description of the models considered
Other interpretations not ruled out

- multiple peaks without interference
- reflections
- threshold enhancement

Excess observed in $J/\psi+\psi(2S)$ channel at 6.9 GeV and 7.2 GeV
More data needed to characterize excesses in both channels