ATLAS results on exotic hadronic resonances

Evelina Bouhova-Thacker

(Lancaster University)

On behalf of the ATLAS Collaboration

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Introduction

Exotic hadrons composed of four ($qq\bar{q}\bar{q}$) or five quarks ($qqqq\bar{q}$) predicted by theory

They provide an unique environment to study the strong interaction and confinement

A series of states consistent with containing four quarks have been discovered

The existence of pentaquark states and their interpretation is not well established so far

In this talk:

Study of J/ψ p resonances in the $\Lambda_b^0 \to J/\psi\ \mathrm{pK^-}$ decays in $\mathrm{p\,p}$ collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS detector

ATLAS-CONF-2019-048

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

ATLAS-CONF-2022-040

NEW

Pentaquarks in the J/ψ pK state

In 2015 LHCb reported the observation of J/ψ p resonant structures in $\Lambda_b^0 \to J/\psi\ \mathrm{pK}^-$ decays

interpreted as $c\bar{c}uud$ pentaquark states [Phys. Rev. Lett. 115, 072001]

$$P_c(4380)^+ \qquad \mathrm{M} = 4380 \pm 8 \pm 29\ \mathrm{MeV}, \quad \mathrm{width} = 205 \pm 18 \pm 86\ \ \mathrm{MeV}, \quad J^P = 3/2^-$$
$$P_c(4450)^+ \qquad \mathrm{M} = 4449.8 \pm 1.7 \pm 2.5\ \mathrm{MeV}, \quad \mathrm{width} = 39 \pm 5 \pm 19\ \ \mathrm{MeV}, \quad J^P = 5/2^+$$

Later seen in $\Lambda_b^0 \to J/\psi\ \mathrm{p}\pi^-$ [Phys. Rev. Lett. 117, 082003]

Not observed by GlueX in $\gamma\mathrm{p} \to J/\psi\mathrm{p}$ [Phys. Rev. Lett. 123, 072001] (small BR)

Seen by D0 Collaboration (3σ): [arXiv:1910.11767]

In 2019 LHCb resolved the $P_c(4450)^+$ peak into 2 states

$P_c(4440)^+$ and $P_c(4457)^+$ $\quad 5.4\sigma$

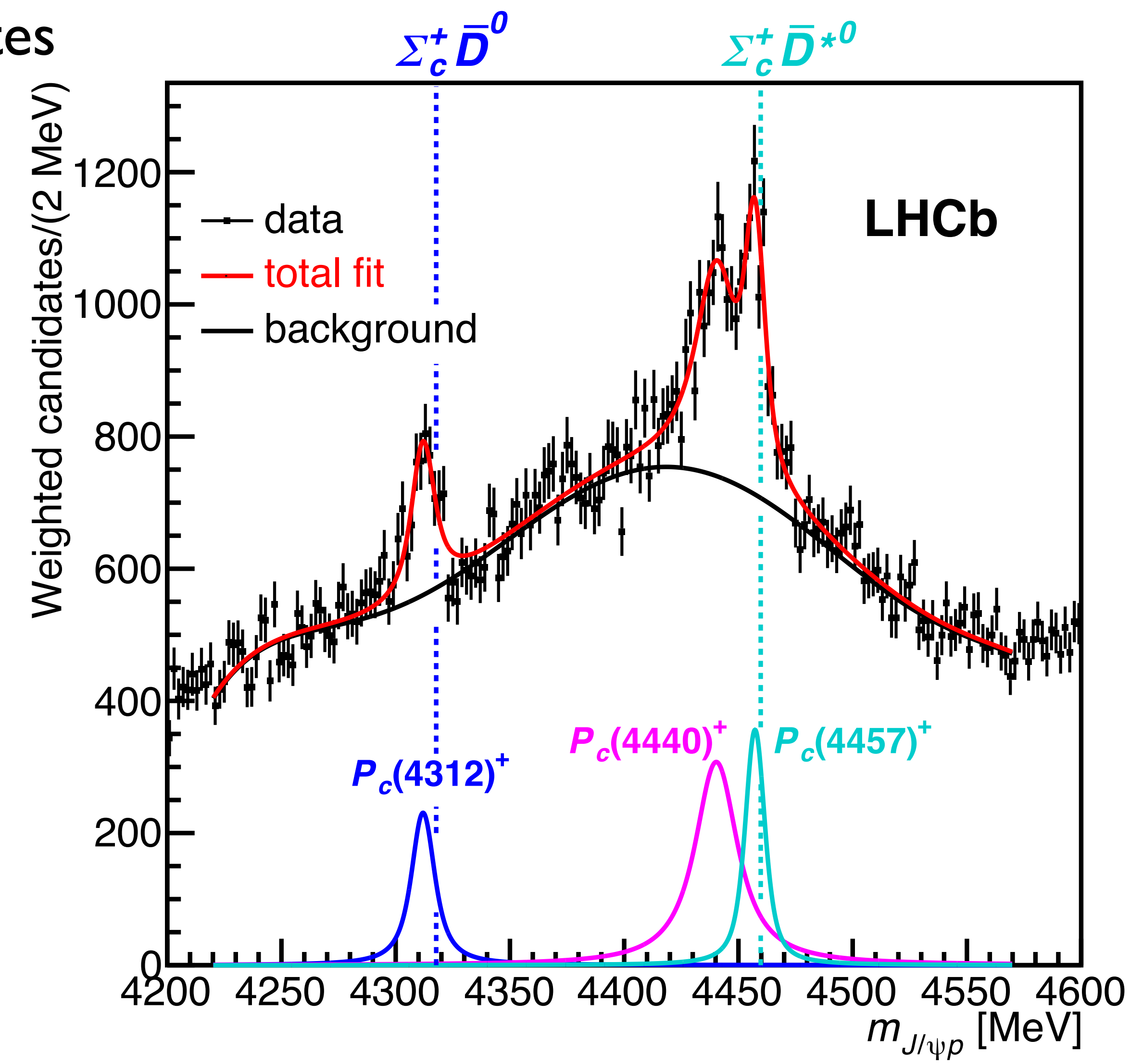
and reported an additional narrow state $P_c(4312)^+$ 7.3σ

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

narrow states below $\Sigma_c\bar{D}^{(*)}$ thresholds

alternative explanations not ruled out

[Phys. Rev. Lett. 122, 222001]

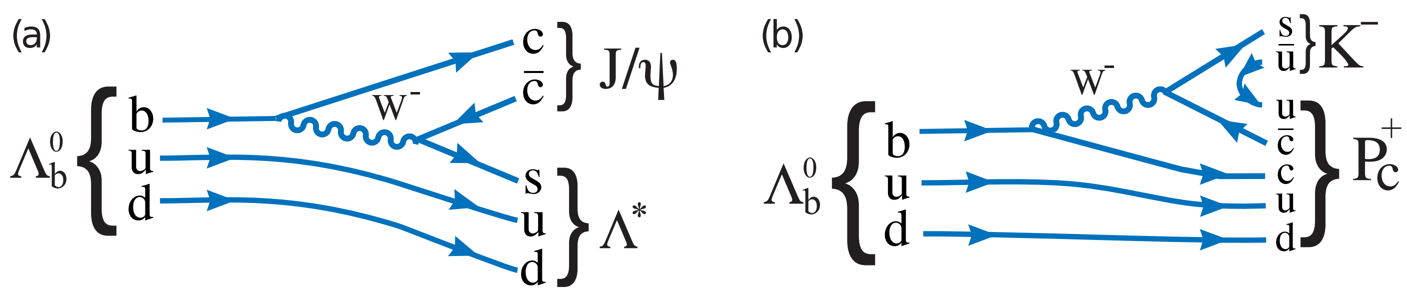


Study of $J/\psi\,\mathrm{p}$ resonances in the $\Lambda_b^0 \to J/\psi\,\mathrm{pK}^-$ decays in $\mathrm{p\,p}$ collisions at $\sqrt{s}=$ 7 and 8 TeV with the ATLAS detector

Using $\mathcal{L} = 4.9\ \mathrm{fb}^{-1}$ of 7 TeV (2011) and $\mathcal{L} = 20.6\ \mathrm{fb}^{-1}$ of 8 TeV (2012) ATLAS Run-1 data

No particle identification (for hadrons): $\Lambda_b^0 \to J/\psi\, pK^-$ decays (+ charge conjugate) reconstructed together with $B^0 \to J/\psi\, K^+\pi^-$, $B^0 \to J/\psi\, \pi^+\pi^-$, $B_s^0 \to J/\psi\, K^+K^-$ and $B_s^0 \to J/\psi\, \pi^+\pi^-$ decays

Signal and background processes generated with Pythia 8.1 (“phase space” model)



Phys. Rev. Lett. 122, 222001

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

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

Other exotic (Z_c) contributions not included

$\mathrm{M(K\pi)} > 1.55\ \mathrm{GeV}$ applied to both hypotheses combinations, leading to $\mathrm{M(pK)} > 2.0\ \mathrm{GeV}$

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

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

Study of $J/\psi\,\mathrm{p}$ resonances in the $\Lambda_b^0 \to J/\psi\,\mathrm{pK}^-$ decays in $\mathrm{p\,p}$ collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector

Signal and control regions and Fit Procedure

Fits performed after subtracting same-sign background contribution (both hadron tracks with 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:	$5.35\,\mathrm{GeV} < m(J/\psi, h_1 = p, h_2 = K) < 5.45\,\mathrm{GeV}$

Iterative fit procedure with 4 steps at each iteration:

Step 1: fit to $m(J/\psi\,hh)$, $m(J/\psi\,h)$, $m(hh)$ to obtain parameters of B^0 and B_s^0 backgrounds

Step 2: fit to $m(J/\psi\,h)$, $m(hh)$ to retrieve total number of Λ_b decays, number of combined B^0 and B_s^0 decays and combinatorial background parameters

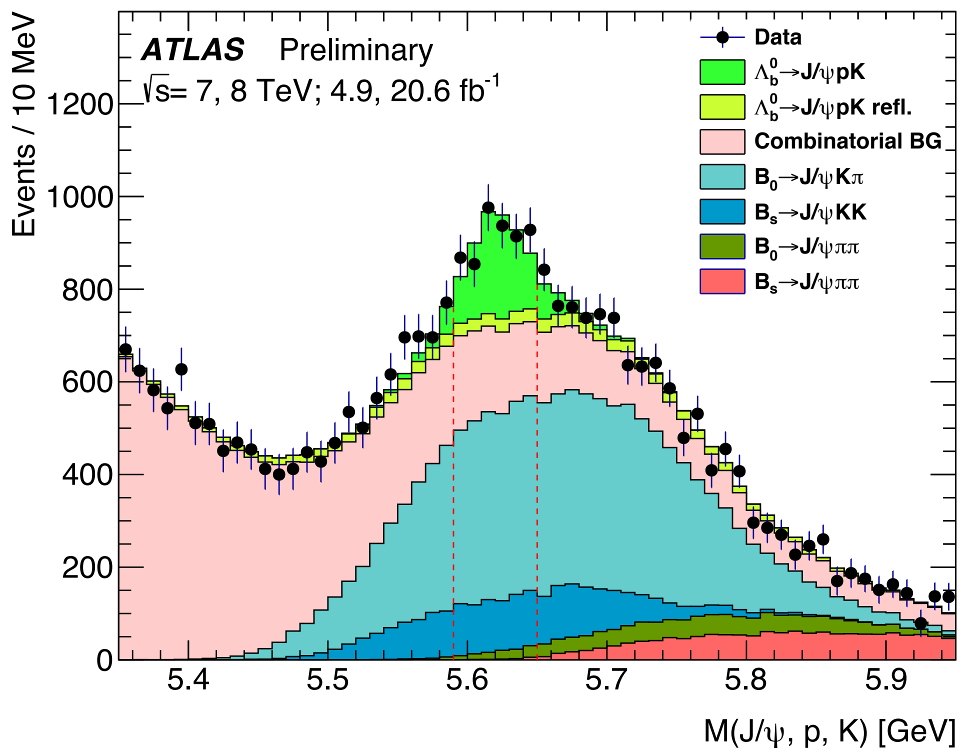
Step 3: fit $m(J/\psi, h_1 = p, h_2 = K)$ in SR to obtain the decay constants of the Λ_b decays

Step 4: fit $m(J/\psi, h_1 = p)$ in SR to obtain pentaquark masses, widths, amplitudes and the relative phase between the pentaquark amplitudes $\Delta\phi$

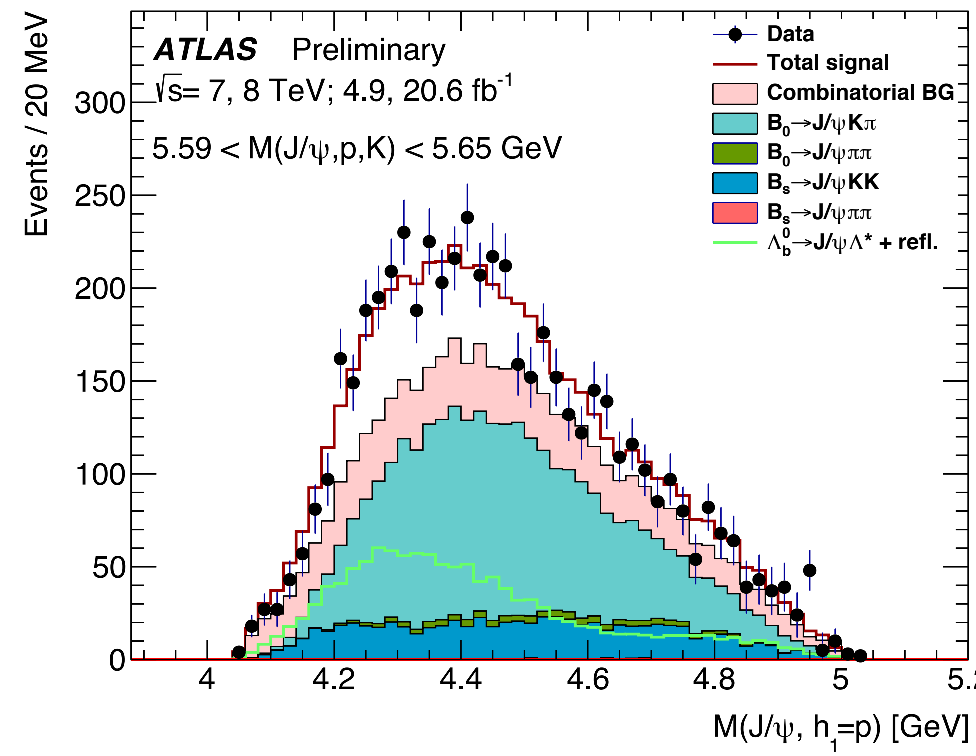
Study of $J/\psi\,\mathrm{p}$ resonances in the $\Lambda_b^0 \to J/\psi\,\mathrm{pK}^-$ decays in $\mathrm{p\,p}$ collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector

Results

Invariant mass for all selected Λ_b candidates



Fit without pentaquarks



Yields:

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

In SR:

$N(\Lambda_b^0 \to J/\psi\, pK^-) \approx 1010 \pm 140$ (correct mass assignment)

$N(\Lambda_b^0 \to J/\psi\, pK^-) \approx 160 \pm 20$ (swapped mass assignment)

Best result obtained using the extended $\Lambda_b^0 \to J/\psi\, \Lambda^{*0}$ decay model (no exotic states):

(clear region, corresponding to open green histogram)

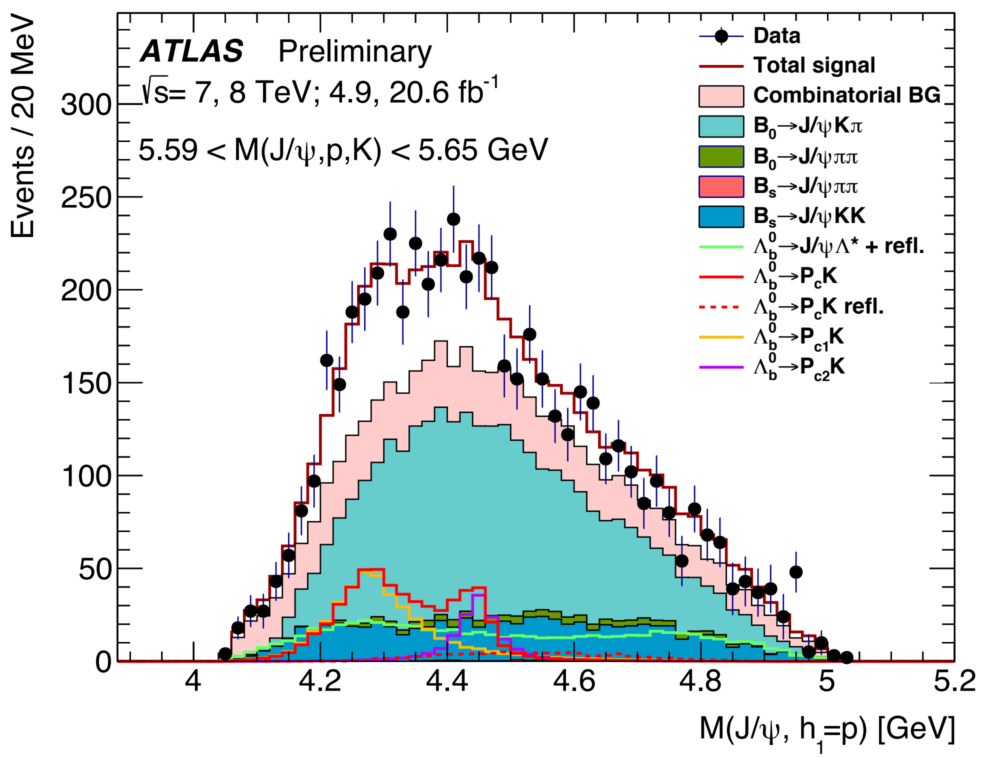
two lowest orbital momenta between the decay products of $\Lambda^*(1800)$, $\Lambda^*(1810)$ and $\Lambda^*(1890)$ and one lowest orbital momentum between the decay products of $\Lambda^*(2100)$ and $\Lambda^*(2110)$

$$\chi^2/N_{dof} = 42.0/23$$
$$(\text{p-value} = 9.1 \times 10^{-3})$$

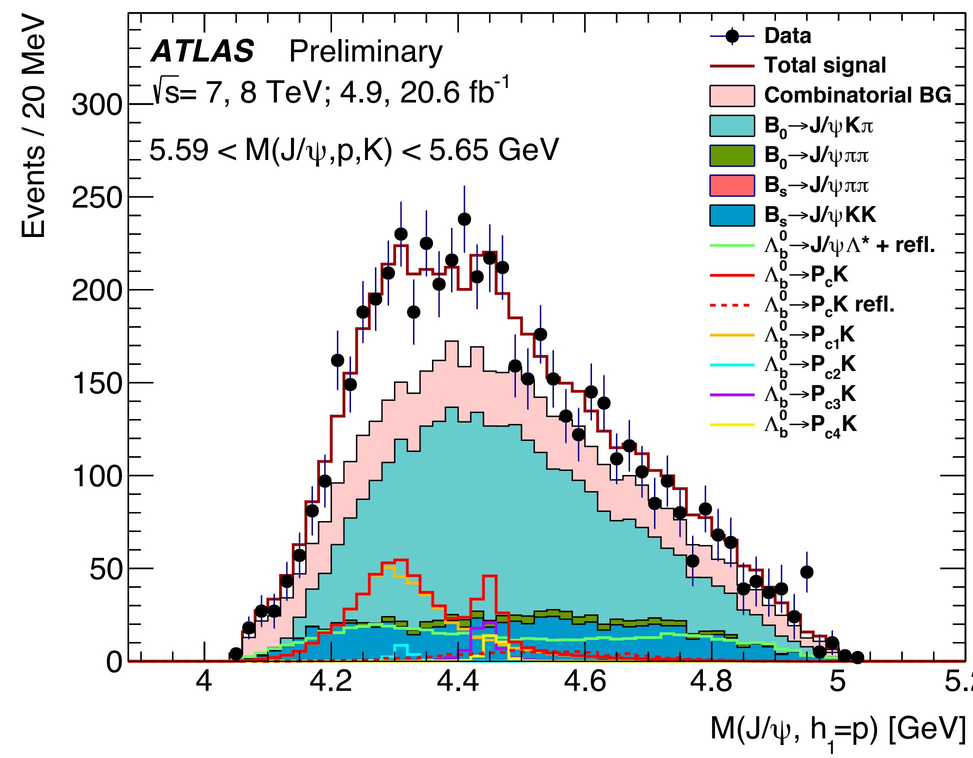
Study of J/ψ p resonances in the $\Lambda_b^0 \to J/\psi\, \mathrm{pK}^-$ decays in $\mathrm{p\,p}$ collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector

Results with pentaquarks

Fit with two pentaquarks, $J^P(3/2^-, 5/2^+)$



Fit with four pentaquarks (fixed to LHCb values)



	Parameter	Value	LHCb value [5]
no interference	$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
no interference	$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
	$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
	$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ 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

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

Two pentaquarks:

$$\chi^2/N_{dof} = 37.1/39$$

$$\text{p-value} = 55.7\%$$

(fixed to LHCb values: $\text{p-value} = 24.5\%$)

Four pentaquarks:

$$\chi^2/N_{dof} = 37.1/42$$

$$\text{p-value} = 68.6\%$$

Better fit achieved if pentaquark states are included, but non-pentaquark model still permitted

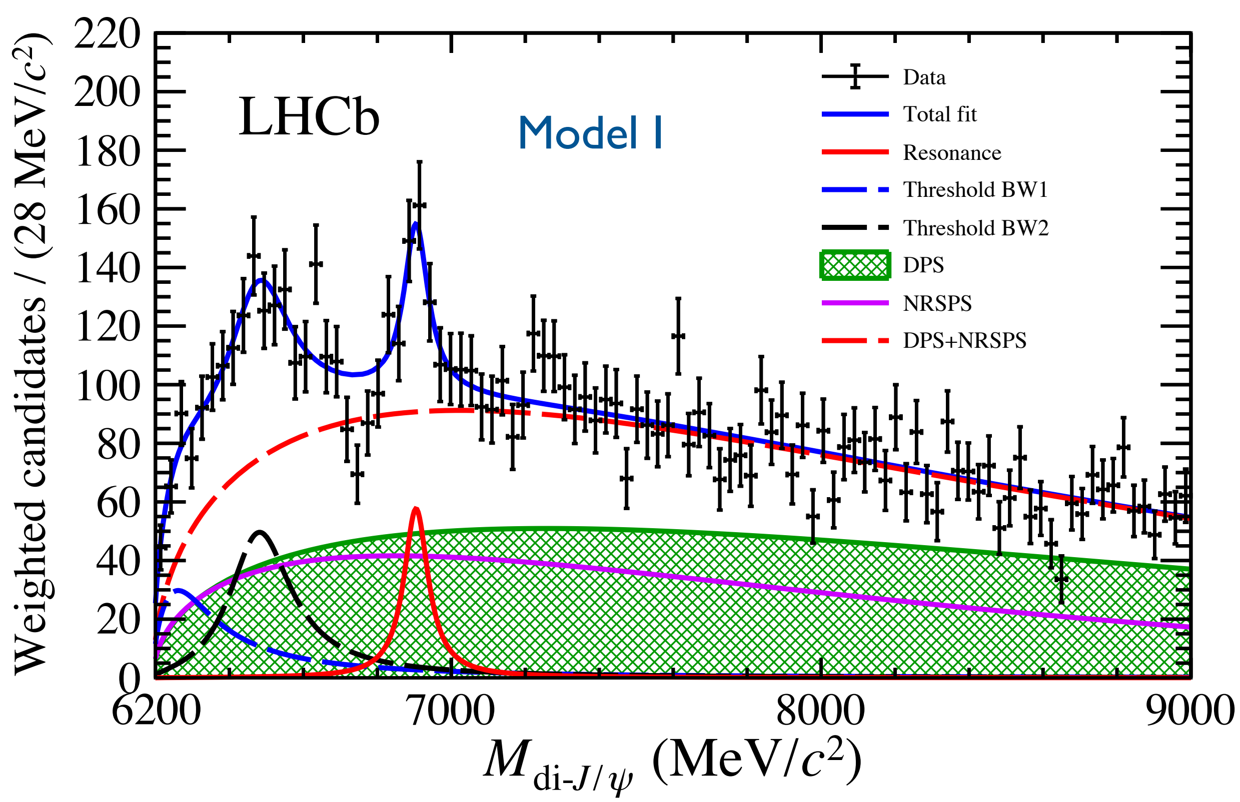
Tetraquarks in the four-muon final state

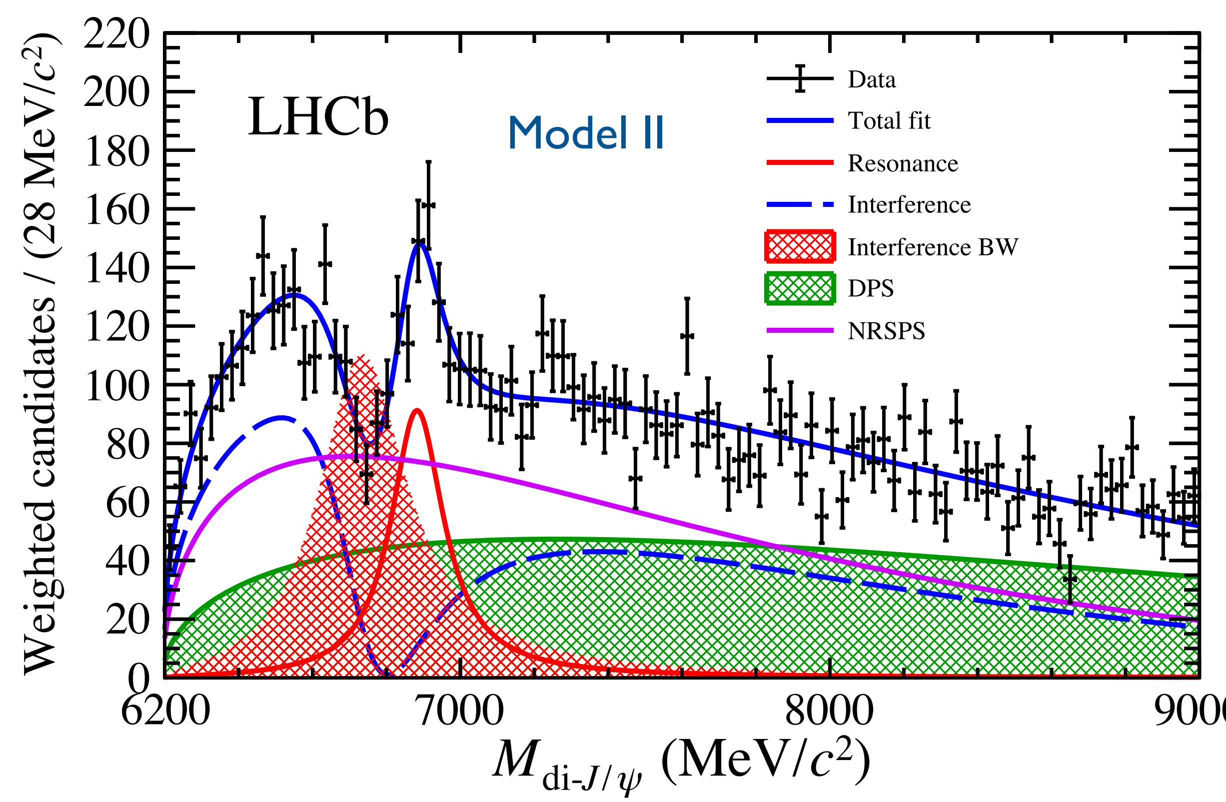
arXiv:2006.16957

Evidence for a narrow resonance at 6.9 GeV in the di-$J/\psi \to 4\mu$ mass spectrum in LHCb data

Can be interpreted as a tetra-quark with four charm quarks $T_{cc\bar{c}\bar{c}}$

The enhancement seen near the di-J/ψ mass threshold could be due to a mixture of multiple four-charm quark states or have contributions from feed-down decays of four-charm states through heavier quarkonia or could be the result of re-scattering of charmonium final states





assuming no interference with the NRSPS continuum

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

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

assuming interference with the NRSPS continuum

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

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

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

NEW

Using $\mathcal{L} = 139\ \mathrm{fb}^{-1}$ of 13 TeV of ATLAS Run-2 data collected in 2015 to 2018

Search in the 4μ final state through the di-J/ψ and $J/\psi + \psi(2\mathrm{S})$ channels

di-$\psi(2\mathrm{S}) \rightarrow 4\mu$ statistically not accessible with Run-2 data

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

Background processes (simulated with Pythia8):

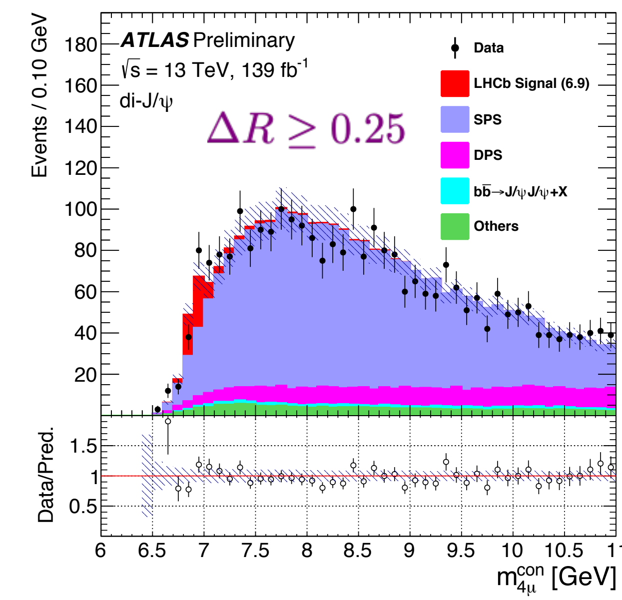
prompt di-J/ψ : Single Parton Scattering (SPS) and Double Parton Scattering (DPS)

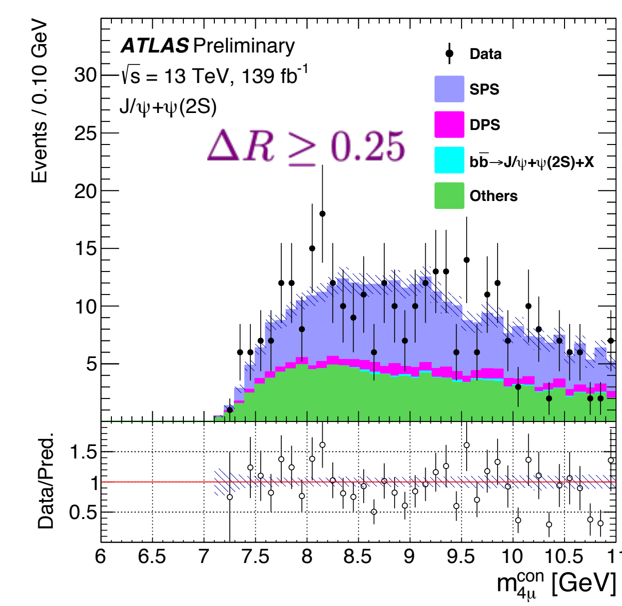
non prompt di-J/ψ : $b\bar{b} \rightarrow J/\psi J/\psi$

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

(CRs defined in sidebands and by requiring one charmonium containing a non muon track)

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





Event selection and signal and control regions:

	Signal region	SPS/DPS control region	non-prompt region
	Di-muon or tri-muon triggers, Opposite charged muons from the same J/ψ or $\psi(2S)$ vertex, Loose muon ID, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in \{2.94, 3.25\}$ GeV, or $m_{\psi(2S)} \in \{3.56, 3.80\}$ GeV, Loose vertex cuts $\chi^2_{4\mu}/N < 40$ and $\chi^2_{\text{di-}\mu}/N < 100$,		
N = 5; w.r.t primary vertex closest in z	Vertex $\chi^2_{4\mu}/N < 3$, $L_{xy}^{4\mu} < 0.2$ mm, $\lvert L_{xy}^{\text{di-}\mu}\rvert < 0.3$ mm,		Vertex $\chi^2_{4\mu}/N > 6$, $\lvert L_{xy}^{\text{di-}\mu}\rvert > 0.4$ mm
	$m_{4\mu} < 7.5$ GeV, $\Delta R < 0.25$ between charmonia	$7.5\ \text{GeV} < m_{4\mu} < 12.0$ GeV (SPS) $14.0\ \text{GeV} < m_{4\mu} < 25.0$ GeV (DPS)	

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

Fit Models

Unbinned maximum likelihood fits on the four-muon mass spectra < 11 GeV, no ΔR cut

fit signal region $\Delta R < 0.25$, fit control region $\Delta R \geq 0.25$, with transfer factors for background yields from MC or data driven methods

The signal probability density function (PDF) 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 the amplitudes

z_1 fixed to unity with zero phase

no interference with NRSPS (LHCb model)

di-J/ψ channel:

models with different numbers of resonances (2 or 3) are compared in terms of χ^2 or toy MC distributions

$J/\psi + \psi(2\mathrm{S})$ channel:

Model A: same resonances as in di-J/ψ, plus a 4th standalone resonance

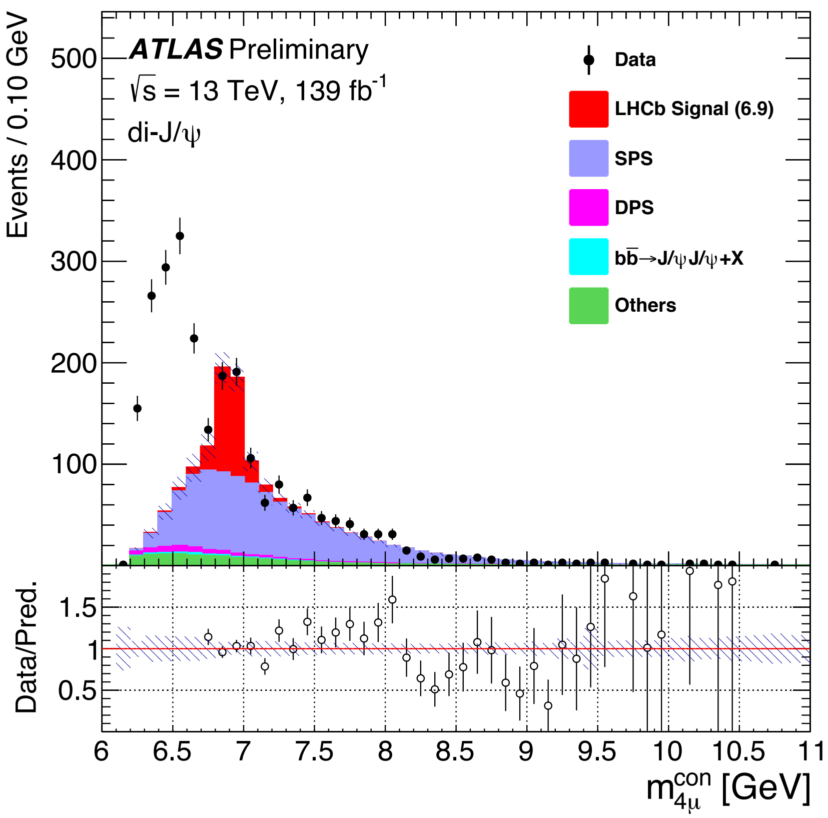
$$f_s(x) = \left(\left| \sum_{i=0}^{2} \frac{z_i}{x^2 - m_i^2 + i m_i \Gamma_i} \right|^2 + \left| \frac{z_3}{x^2 - m_3^2 + i m_3 \Gamma_3} \right|^2 \right) \sqrt{1 - \left(\frac{m_{J/\psi} + m_{\psi(2S)}}{x} \right)^2} \otimes R(\alpha)$$

Model B: a single resonance

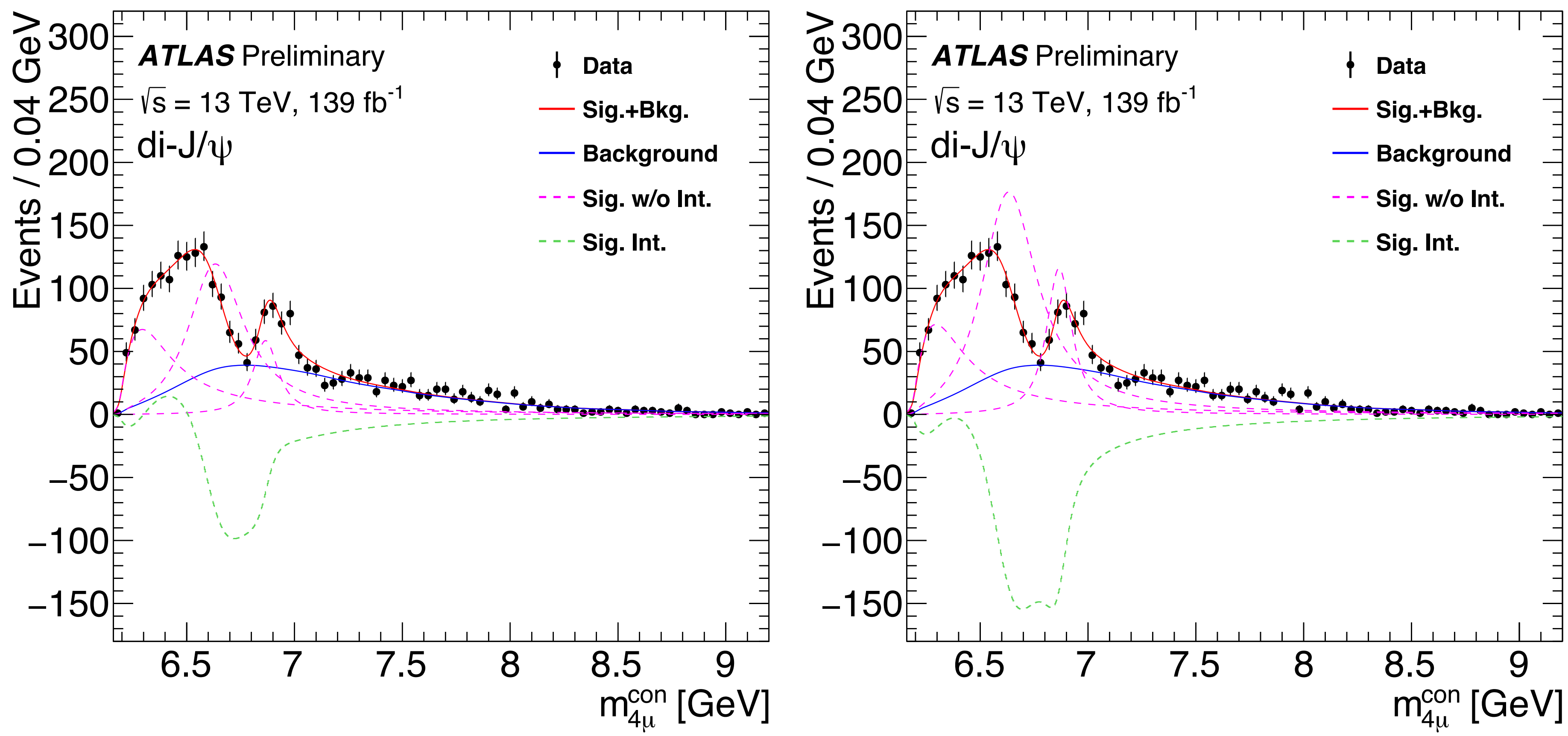
Observation of di-charmonium excess in the four-muon final state with the ATLAS detector

Results in di-J/ψ channel

4μ mass distribution from data and background predictions before fit



fitted mass in SR, 3-resonance fit (2 out of 4 degenerate solutions for z_i)



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

significance of third resonance: 10σ

using LHCb Model I values for 3rd resonance gives similar results

LHCb Model II fit (interference with NRSPS) disfavoured based on fit quality

70% worse fit quality for 2-resonance fit

Fitted masses and widths

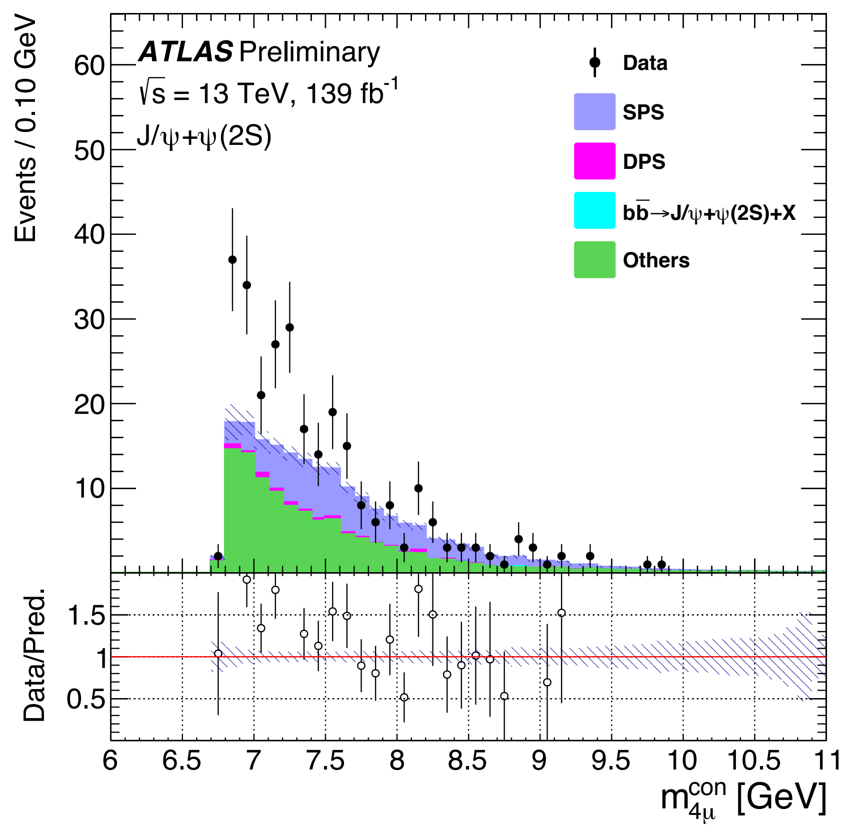
(GeV)	m_0	Γ_0	m_1	Γ_1
di-J/ψ	$6.22 \pm 0.05^{+0.04}_{-0.05}$	$0.31 \pm 0.12^{+0.07}_{-0.08}$	$6.62 \pm 0.03^{+0.02}_{-0.01}$	$0.31 \pm 0.09^{+0.06}_{-0.11}$
	m_2	Γ_2	—	
consistent with LHCb	$6.87 \pm 0.03^{+0.06}_{-0.01}$	$0.12 \pm 0.04^{+0.03}_{-0.01}$	—	

6.9 GeV resonance confirmed, best fit with 3 interfering resonances, other explanations possible

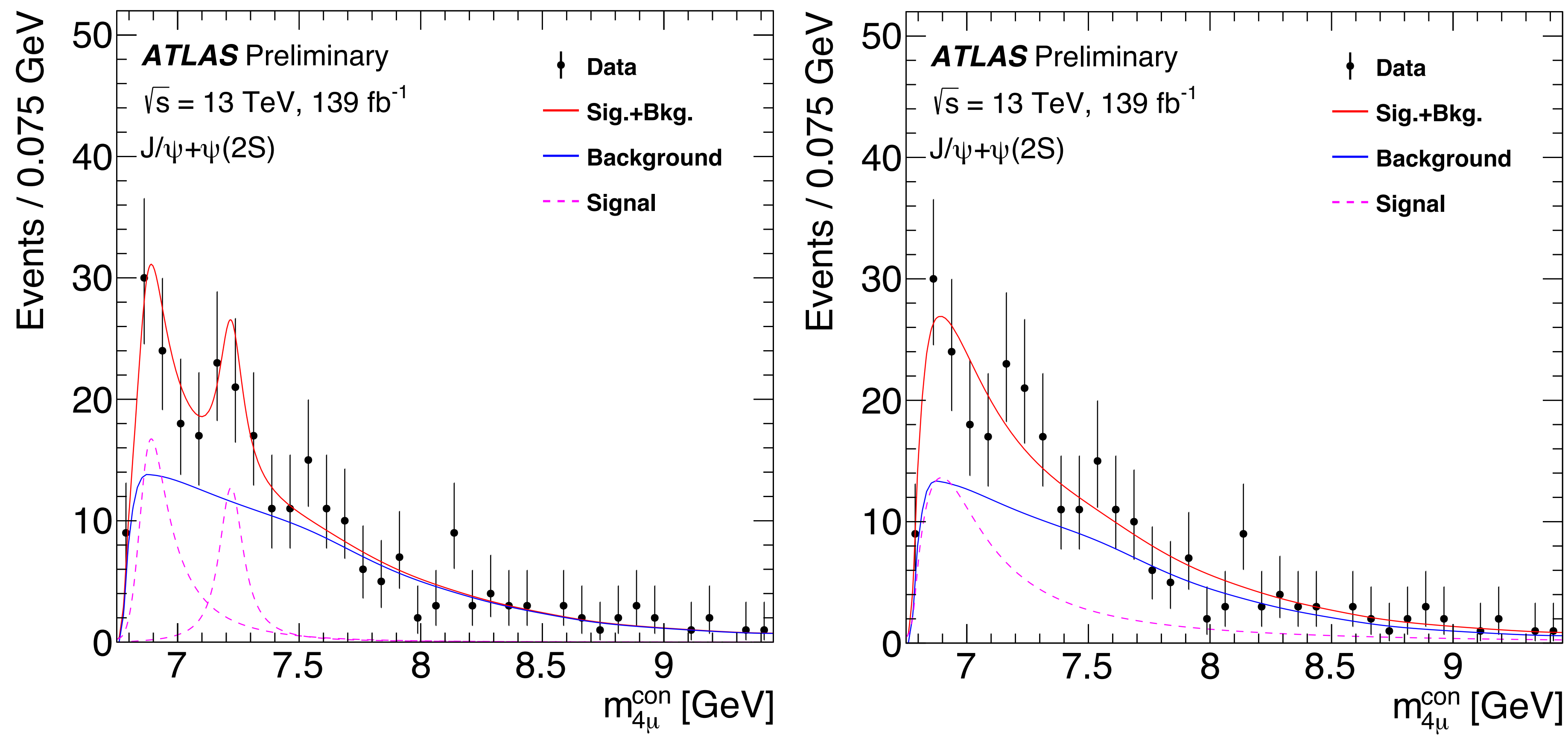
Observation of di-charmonium excess in the four-muon final state with the ATLAS detector

Results in $J/\psi + \psi(2S)$ channel

4μ mass distribution from data and background predictions before fit



fitted mass in SR (Model A and Model B)



significance Model A: 4.6σ

second resonance (7.2 GeV): 3.2σ

(hint for a 7.2 GeV resonance in LHCb data)

significance Model B: 4.3σ

Fitted masses and widths

(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 for an enhancement at 6.9 GeV and a resonance at 7.2 GeV, other explanations possible

Conclusions

Analysis of ATLAS of 7 and 8 TeV data containing $\Lambda_b^0 \to J/\psi\, pK^-$ decays with large $m(\mathrm{p}K^-)$:

shows evidence for the existence of pentaquark states, consistent with the LHCb results

data does not allow independent measurements of pentaquark parameters

model without pentaquark states not excluded

Di-charmonium resonance search in the four-muon final state with ATLAS 13 TeV data:

significant excess observed in the di-J/ψ channel

a broad structure at lower mass and a resonance around 6.9 GeV

consistent with LHCb results

best description given by a 3-resonance model with interference

other interpretations not ruled out

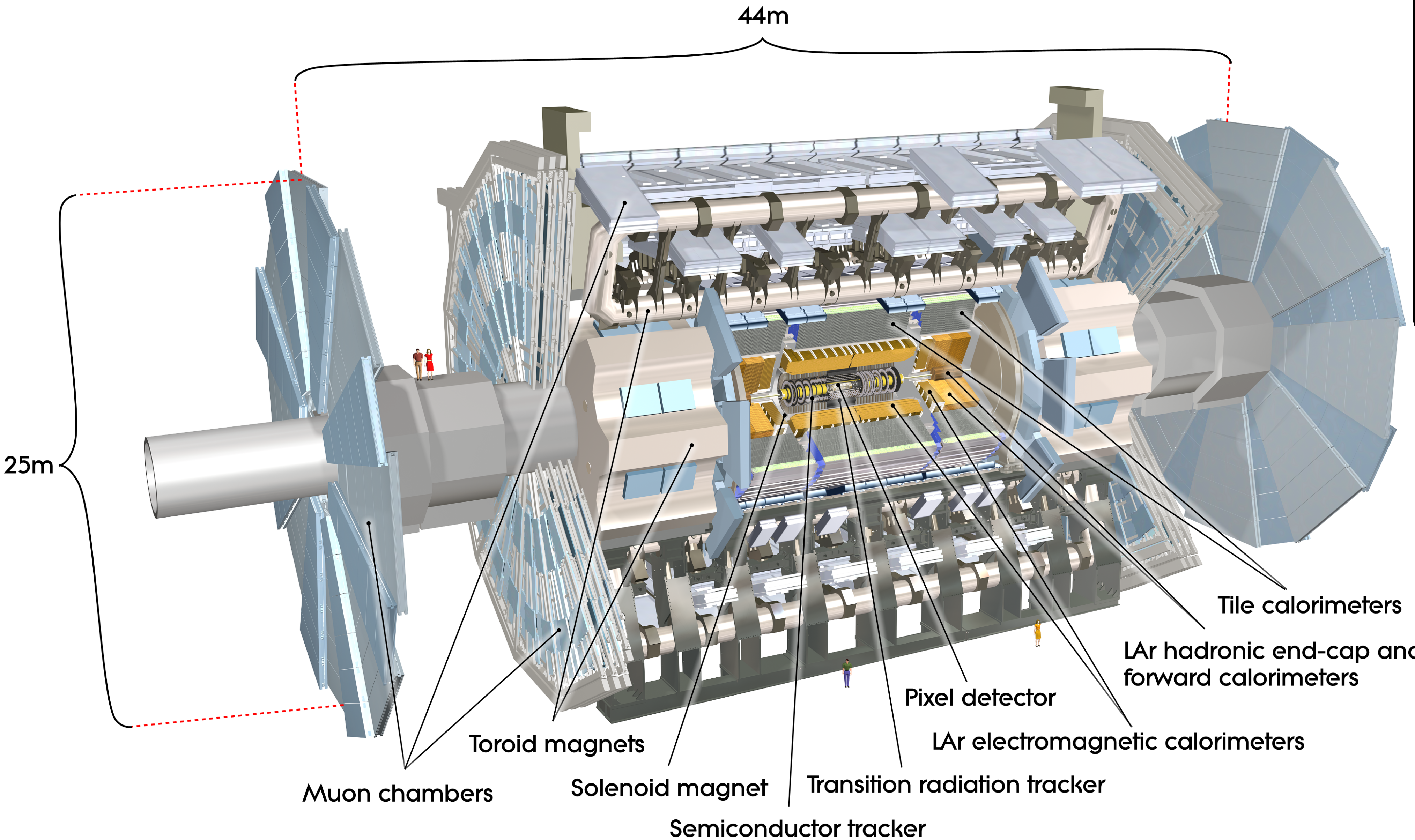
(multiple peaks without interference, reflections, threshold enhancement)

excess observed in the $J/\psi + \psi(2S)$ channel at 6.9 and 7.2 GeV

more data needed to characterise the excesses in both channels

Backup slides

The ATLAS Detector



Muon Spectrometer:
$|\eta| < 2.7$
air core toroids(average 0.5T)
gas-based muon chambers
Muon trigger and reconstruction
Momentum resolution < 10%
$up\ to\ E(\mu) \sim 1\ TeV$

3-level trigger, reducing the rate from 40 MHz to ~200 Hz

EM Calorimeter:
Pb-LAr accordion
e/γ trigger, identification and measurement
Resolution:
$\sigma/E \sim 10\%/\sqrt{E}$

Inner Detector:
Si Pixels, Si Strips, TRT straws
Precise tracking and vertexing
pT resolution:
$\sigma/p_T \sim 3.8 \times 10^{-4}\ p_T(GeV) \oplus 0.015$
$|\eta| < 2.5,\ B = 2T$

HAD Calorimetry:
$|\eta| < 5$
Fe/scintillator tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and MET
Resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Study of $J/\psi\,\mathrm{p}$ resonances in the $\Lambda_b^0 \to J/\psi\,\mathrm{pK}^-$ decays in $\mathrm{p\,p}$ collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector

Event selection

J/ψ selection: $p_T(\mu^\pm) > 4\,\mathrm{GeV}$ $\quad |\eta(\mu^\pm)| < 2.3 \quad 2807 < m_{\mu^+\mu^-} < 3387\,\mathrm{MeV}$

B-hadron $(H_b = \Lambda_b, B^0 \text{ or } B_s)$ selection:

$\chi^2(H_b)/N_{dof} < 2,\ N_{dof} = 8$ fit with a J/ψ mass constraint

$L_{xy}(H_b) < 0.7\,\mathrm{mm}$ w.r.t primary vertex closest in 3D

$p_T(p) > 2.5\,\mathrm{GeV},\ p_T(K) > 1.8\,\mathrm{GeV},\ p_T(H_b)/\Sigma p_T(\mathrm{track})$

$\cos\theta_{P_c} < 0.5$ θ_{P_c}: angle between J/ψ momentum in the P_c rest frame and P_c momentum in the Λ_b rest frame

$\cos\theta_{\Lambda_b} < 0.8$ θ_{Λ_b}: angle between P_c momentum and Λ_b momentum in the laboratory frame

$|\cos\theta_{\Lambda^*}| < 0.85$ θ_{Λ^*}: angle between kaon momentum in the $\Lambda^* \to pK$ rest frame and Λ^* momentum in the Λ_b rest frame

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

Selected events dominated by combinatorial background and B-hadron decays to J/ψ and light neutral mesons

$M(K\pi) > 1.55$ GeV applied to both hypotheses combinations, leading to $M(pK) > 2.0$ GeV.

Study of J/ψ p resonances in the $\Lambda_b^0 \to J/\psi\, \mathrm{pK}^-$ decays in p p collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector

Systematic uncertainties

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

Systematic uncertainties for measurements of the pentaquark yields under assumption of no interference effects, the yield of a sum of two pentaquarks and the relative phase between pentaquark amplitudes.

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

Systematic uncertainties for measurements of the pentaquark masses and natural widths.

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

Systematic uncertainties

Normalisations are free-floating

Uncertainties affecting signal and background shapes:

- muon momenta
- J/ψ mass resolution
- MC simulation statistics
- parameter **pT0timesMPI**
- background transfer factor
- non-closure

Systematic Uncertainties (MeV)	di-J/ψ m_0	Γ_0	m_1	Γ_1	m_2	Γ_2	J/ψ+$\psi(2S)$ m_3	Γ_3
SPS theory	7	15	4	20	5	6	<1	
SPS di-charmonium p_T	<1	8	4	14	5	7	<1	
Background MC statistics	<1	8	4	14	5	7	<1	
Mass resolution	19	34	3	21	4	9	<1	4
Fit bias	43	58	10	56	11	16	13	41
Nonclosure	<1						<1	
Transfer factor	—						<1	16
Presence of fourth resonance	29	49	11	108	60	18	—	
Interference of fourth resonance	—						29	11
Data statistics	50	119	34	88	30	39	28	130

Systematic and statistical uncertainties on the masses and natural widths (in MeV) of the interfering resonances from different sources in the di-J/ψ and J/ψ+ψ(2S) channels. The errors shown in the J/ψ+ψ(2S) channel are for model A. In the case of an asymmetric uncertainty, only the larger direction is shown.