Heavy-flavour spectroscopy results from ATLAS

Semen Turchikhin
on behalf of ATLAS collaboration

Istituto Nazionale di Fisica Nucleare, Sezione di Genova

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Paris, France
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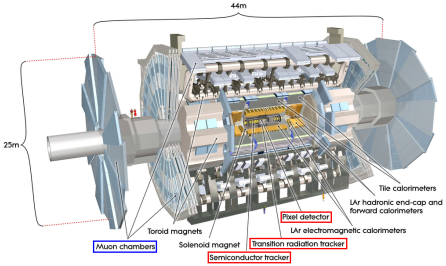
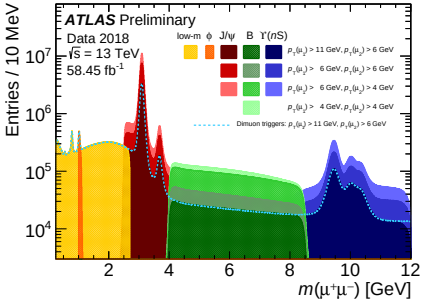
Outline

- ATLAS B-physics programme covers a wide range of studies:
  - Decays (CPV, rare and semi-rare decays etc.) – *Wed afternoon talk*
  - Open heavy-flavour and heavy quarkonium production – *Wed morning talk*
  - Spectroscopy of conventional and exotic states – *This talk*
- Competitive when muon final states are involved

- **In this talk:**
  - Observation of structures in $J/\psi + \psi(2S)$ mass spectrum – accepted to PRD
  - First observation of a B_c^{*+} meson – just off the press!



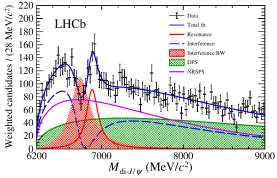


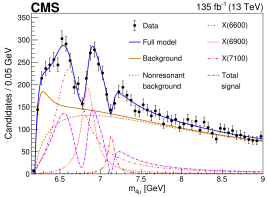
Structures in $J/\psi + \psi(2S)$ mass spectrum

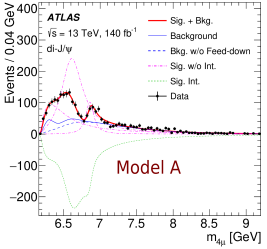
arXiv:2509.13101
accepted to PRD

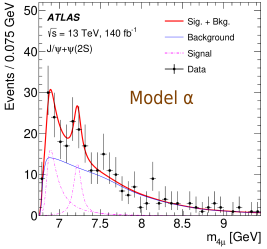
Structures in di-charmonium spectrum

- $X(6900)$ first observed by LHCb in $J/\psi J/\psi \to 4\mu$ final state
  - also broader structure lower near threshold
- Confirmed by ATLAS and CMS with the same final state
  - $X(7100)$ state seen by CMS
  - and hinted in ATLAS $J/\psi\psi(2S) \to 4\mu$
- CMS since then measured $J^{PC} = 2^{++}$ for all 3 states $\to$ *supports tightly bound tetraquark description*

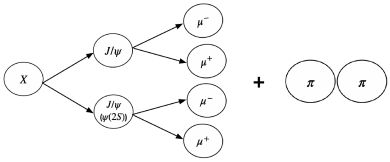








- New ATLAS analysis focuses on $J/\psi\psi(2S) \to 4\mu 2\pi$ channel

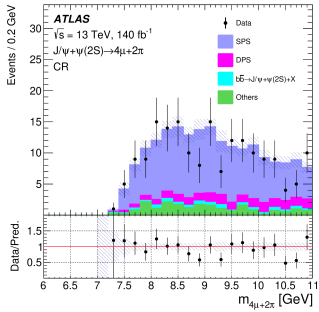


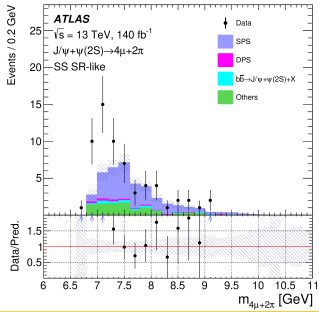
Study of $J/\psi\psi$(2S) mass spectrum: strategy

arXiv:2509.13101

- Backgrounds: SPS & DPS di-ψ production, Non-prompt ψ's, Other ($\geq 1\psi$ combinatorial)
  - In $4\mu + 2\pi$ channel: *feed-up from the $X \to J/\psi J/\psi \to 4\mu$ signal*
- Modelling corrected using dedicated *control regions*
  - Feed-up: use a CR with same-sign pions
- Simultaneous fit in 4μ and $4\mu + 2\pi$ SRs, CRs and SS CR
- Signal models:
  - Model A*: two interfering BW resonances from di-J/ψ channel
  - Model B*: two BW resonances from di-J/ψ channel, one interfering with SPS, other ($X(6900)$) standalone
  - Model C : independent resonance only in $J/\psi\psi$(2S) channel

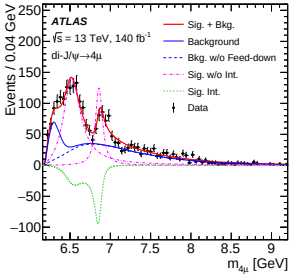
* assume $X(6900)$ decays to both di-J/ψ and $J/\psi\psi$(2S) channels

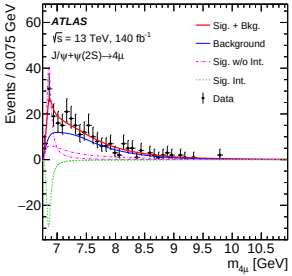


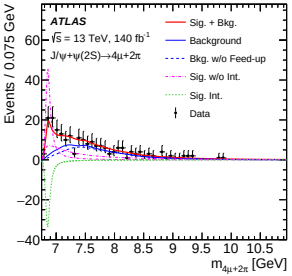


$J/\psi\psi$(2S) fit results

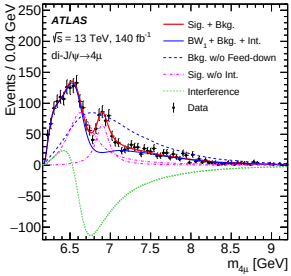
Model A

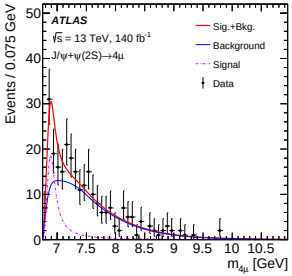


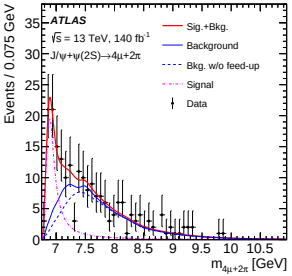




Model B







$J/\psi J/\psi \to 4\mu$ $J/\psi\psi(2S) \to 4\mu$ $J/\psi\psi(2S) \to 4\mu 2\pi$

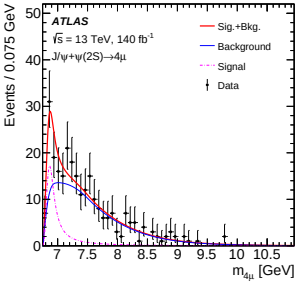
$J/\psi\psi$(2S) results

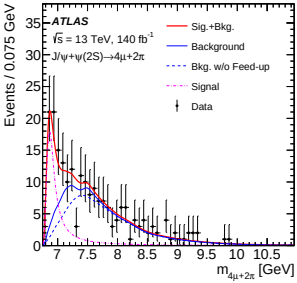
- $X(6900)$ resonance observed in $J/\psi + \psi(2S)$ channel with 8.9σ
- Existence of another state at 7.1–7.2 GeV not supported by data:
  - relative yield to $X(6900)$: 0.12 ± 0.11 with 95% C.L. upper limit of 0.41
- Measurements of mass, width and $R = \Gamma(X(6900) \to J/\psi\psi(2S))/\Gamma(X(6900) \to J/\psi J/\psi)$:

	model A	model B	model C
m / GeV	$6.860 \pm 0.023 \pm 0.010$	$6.902 \pm 0.008 \pm 0.010$	$6.884 \pm 0.017^{+0.058}_{-0.005}$
Γ / GeV	$0.082 \pm 0.032 \pm 0.015$	$0.183 \pm 0.025 \pm 0.007$	$0.178 \pm 0.054^{+0.176}_{-0.024}$
R	$1.08 \pm 0.20^{+0.40}_{-0.09}$	$0.93 \pm 0.17 \pm 0.11$	—

- Limited sensitivity of simple analyses → necessity of amplitude analysis + Run-3 data

Model C





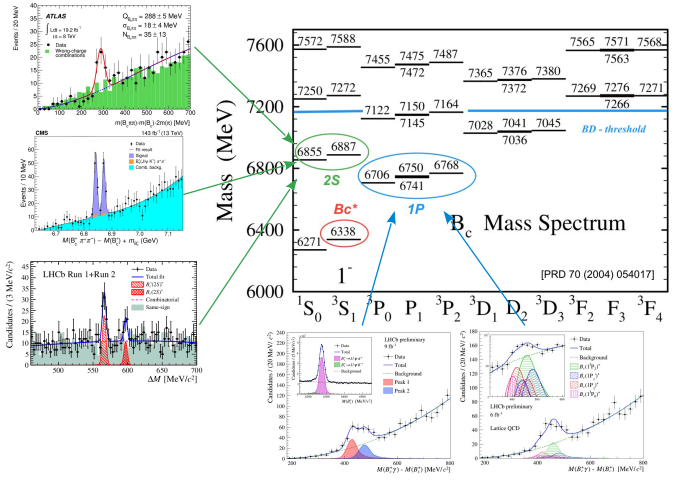
Observation of a B_c^{*+} meson

arXiv:2605.16228
submitted to PRL

Spectroscopy of $\bar{b}c$ system

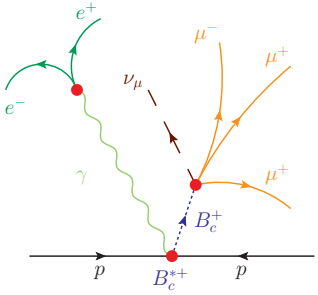
- Unique quarkonium-like system
- Numerous predictions for the excitation spectrum (lattice QCD, various potential models)
- Experimental knowledge limited:
  - $B_c^{(*)}(2S) \to B_c^{(*)}\pi^+\pi^-$: ATLAS, resolved by CMS, LHCb
  - $B_c(1P)$ in $B_c^+\gamma$: broad structure at LHCb compatible with four states
- Lowest spin excitation B_c^{*+} not seen so far:
  - Predictions for $\Delta m_{B_c^{*+}} = m(B_c^{*+}) - m(B_c^+)$ mostly about *50–70 MeV*

figure from PRD 70 (2004) 054017



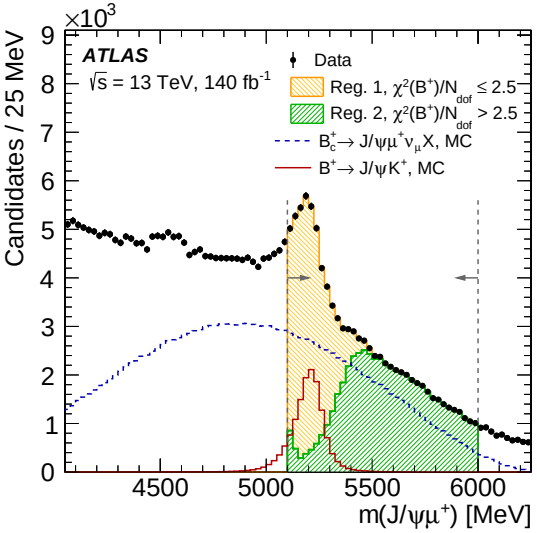
B_c^{*+} search: analysis strategy

- Use full Run-2 dataset, 140 fb^{-1}
- Search $B_c^{*+} \to B_c^+ \gamma$ radiative transition ($\mathcal{B} \approx 100\%$)
- Partially reconstructed $B_c^+ \to J/\psi \mu^+ \nu_\mu X$ final state
  - $\times 20$ larger $\mathcal{B}$ compared to e.g. $B_c^+ \to J/\psi \pi^+$
- Photons from conversions to e^+e^- in the tracker material
  - build from pairs of tracks down to $p_\text{T} = 100\,\text{MeV}$
  - run only *preselected events* with B_c^+ candidate
- Signal is identified in a distribution of $\Delta m = m(J/\psi \mu^+ e^+ e^-) - m(J/\psi \mu^+)$



B_c^+ reconstruction

- B_c^+ candidate = 3-muon vertex with J/ψ mass constraint for $\mu^+\mu^-$ pair
- Main selection criteria:
  - $\chi^2/N_{\text{dof}} < 2$ ($N_{\text{dof}} = 4$), 3rd track contribution < 4
  - $L_{xy} > 0$
  - $p_{\text{T}}(B_c^+)/\sum p_{\text{T}}(\text{track}) > 0.2$
  - $p_{\text{T}}(B_c^+) > 25$ GeV, $|\eta(B_c^+)| < 2.4$
- Below 5.1 GeV – large $B \to J/\psi X$ background (muon mis-id)
  - only $B^+ \to J/\psi K^+$ contributes above
- Two regions based on $\chi^2(B^+)/N_{\text{dof}}$:
  - Region 1: ≤ 2.5 – B^+-like events
  - Region 2: > 2.5 – almost free from B^+



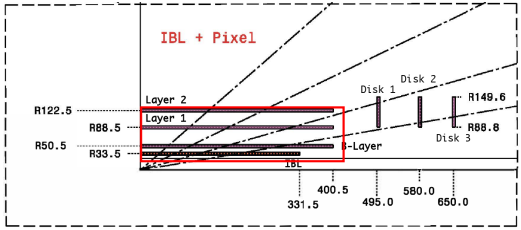
Acceptance cuts:
$p_{\text{T}}(\mu_{1,2,3}) > 4, 4, 3$ GeV,
$|\eta(\mu_{1,2,3})| < 2.4, 2.4, 2.5$

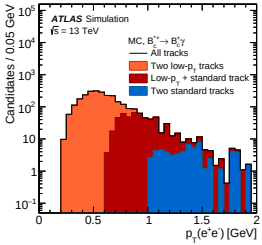
Photon conversion reconstruction

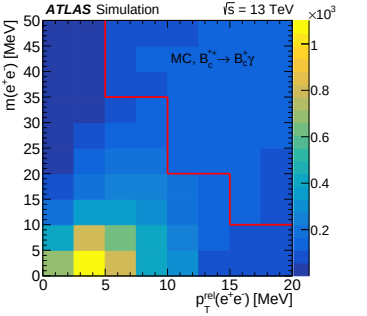
- 2-track vertices within *beampipe + barrel Pixel layer* volume
- Special low-p_T tracking on preselected B_c^+ candidate events
  - $p_T > 100\,\text{MeV}$, vertex $\chi^2 < 3$
  - further selection based on $m(e^+e^-)$ and p_T^{rel}

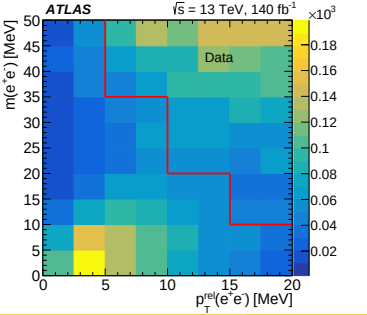
Combined with B_c^+ to form B_c^{*+} candidates

- $m(J/\psi K^+ e^+ e^-) < 6050\,\text{MeV}$ (K^+ mass for 3rd muon)
  - to suppress fully reconstructed $B_c^+ \to J/\psi\pi^+/K^+$ decays + FSR photons



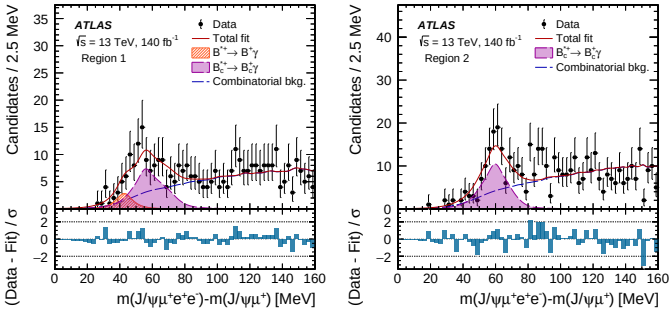






B_c^{*+} signal fit

- Unbinned ML fit to Δm
- Simultaneously in Region 1 and 2
- Signal model:
  - MC templates
  - scaled proportionally to $\Delta m_{B_c^{*+}}$ which is a floating parameter
  - (validated with MC produced for different $\Delta m_{B_c^{*+}}$)
  - $N^{R1}_{B_c^{*+}} / N^{R2}_{B_c^{*+}}$ fixed to MC
- $B^{*+} \to B^+\gamma$ background:
  - present only in Region 1
  - modified Gaussian shape fixed to MC (true $\Delta m_{B^{*+}} \approx 45$ MeV)
- Combinatorial background:
  - event mixing: B_c^+ and γ from different events
  - further corrections of $p_T(\gamma)$ bias

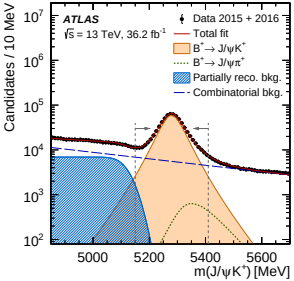


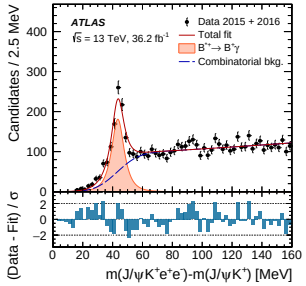
Parameter	Value
$\Delta m_{B_c^{*+}}$ [MeV]	64.5 ± 1.4
$N_{B_c^{*+}}$	163 ± 19
$N_{B^{*+}}$	17 ± 8

Systematics on $\Delta m_{B_c^{*+}}$ (1)

Source	Uncertainty [MeV]
Material, γ momentum scale & resolution	$^{+0.44}_{-1.13}$
B_c^+ production modelling	± 0.19
$B_c^+ \to J/\psi \mu^+ \nu_\mu X$ decay modelling	± 0.05
$N^{\mathrm{R1}}_{B_c^{*+}} / N^{\mathrm{R2}}_{B_c^{*+}}$ ratio	± 0.12
Muon reconstruction and trigger	± 0.16
Background shape modelling	± 0.79
Total	$^{+0.95}_{-1.41}$

- Varying material distribution in the tracker volume in MC
- Photon momentum scale & resolution studied using $B^{*+} \to B^+(\to J/\psi K^+)\gamma$ control channel
  - identical reconstruction procedure
  - systematics based on data-MC discrepancy
- Correlated effects $\to$ take an envelope

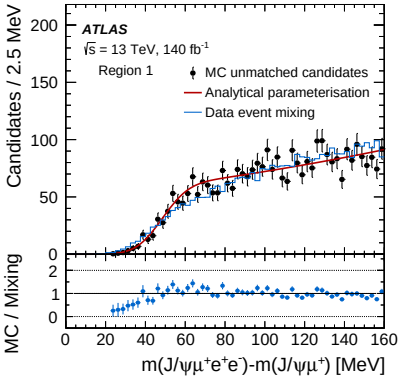




Systematics on $\Delta m_{B_c^{*+}}$ (2)

Source	Uncertainty [MeV]
Material, γ momentum scale & resolution	$^{+0.44}_{-1.13}$
B_c^+ production modelling	± 0.19
$B_c^+ \to J/\psi\mu^+\nu_\mu X$ decay modelling	± 0.05
$N^{\mathrm{R1}}_{B_c^{*+}}/N^{\mathrm{R2}}_{B_c^{*+}}$ ratio	± 0.12
Muon reconstruction and trigger	± 0.16
Background shape modelling	± 0.79
Total	$^{+0.95}_{-1.41}$

- Varying the mixing procedure
  - keeping $p_z(\gamma)$ from the B_c^+ event
  - alternative $p_{\mathrm{T}}(\gamma)$ reweighting
- Use the shape from MC truth-unmatched B_c^{*+} candidates



B_c^{*+} results

- *A new state decaying to B_c^+ and a photon* observed in ATLAS Run-2 data
  - Signal significance **exceeds 8σ** (across all systematic variations)
- Measured mass difference:

$$\Delta m_{B_c^{*+}} = 64.5 \pm 1.4(\text{stat.})^{+1.0}_{-1.4}(\text{syst.})\,\text{MeV}$$

- With the B_c^+ mass from PDG corresponds to

$$m(B_c^{*+}) = 6339.0 \pm 1.4(\text{stat.})^{+1.0}_{-1.4}(\text{syst.}) \pm 0.3(m_{B_c^+})\,\text{MeV}$$

- Agrees with expectations for the lowest $\bar{b}c$ excited state, the B_c^{*+} meson, which are *mostly within 50–70 MeV*
- Measured $\Delta m_{B_c^{*+}}$ a bit above the recent precise lattice QCD predictions *below 60 MeV*
  - HPQCD: PRL 104 (2010) 022001, PRD 86 (2012) 094510
  - Mathur et al. PRL 121 (2018) 202002
- The discovery made possible thanks to
  - innovative use of $B_c^+ \to J/\psi\mu^+\nu_\mu X$ mode for $\bar{b}c$ spectroscopy studies
  - low-p_T tracking for soft photon conversion reconstruction on a preselected sample

Summary

Two new ATLAS results on *exotic* and *conventional* heavy-flavour hadron spectroscopy:

- Study of the resonant structures in $J/\psi + \psi(2S)$ system
  - More data and full amplitude analysis crucial to verify the picture proposed by the latest CMS studies
- Discovery of B_c^{*+}, the lowest excitation of $\bar{b}c$ system
  - Type of analysis ATLAS is perfectly suited for

Stay tuned for further results!

ATLAS B-physics public result page:

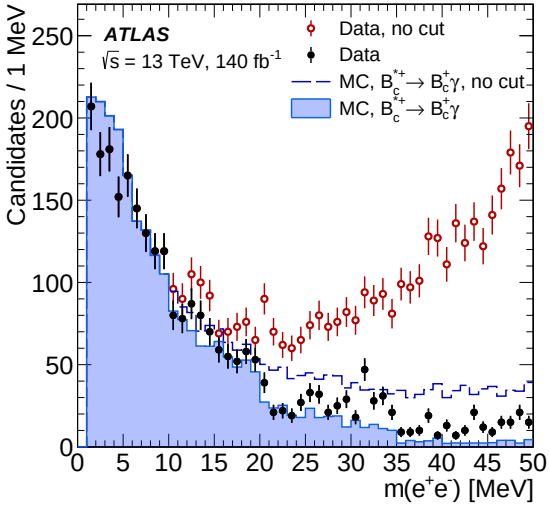
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

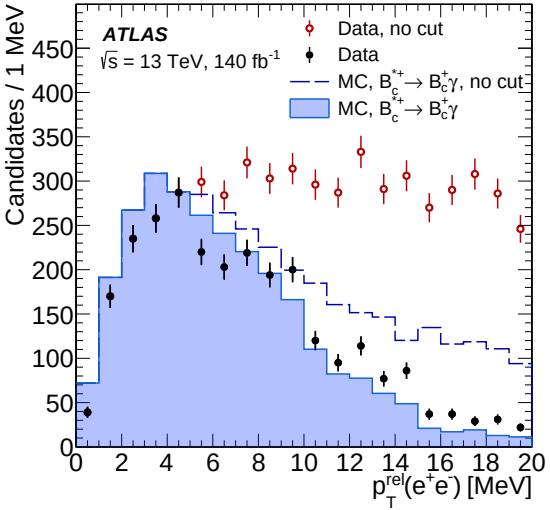
Other ATLAS talks in this section:

- *Davide Malito*: Measurements of heavy flavor production at ATLAS – Wednesday morning
- *Pavel Řezníček*: Rare decays at ATLAS – Wednesday afternoon

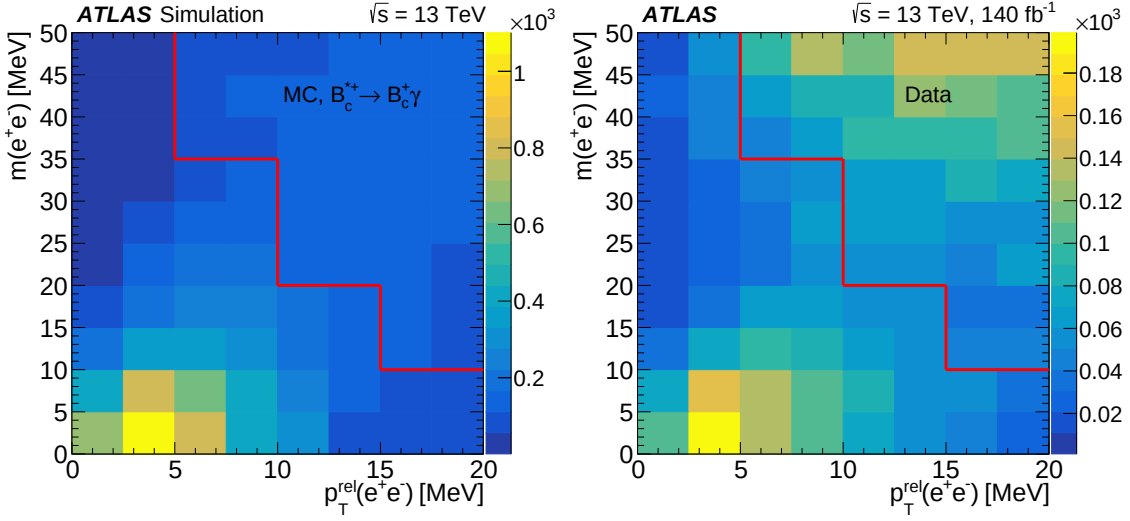
Backup slides

B_c^{*+} photon selection (1)

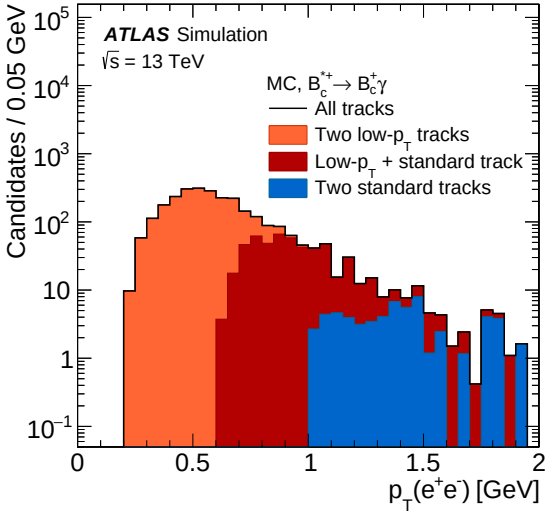


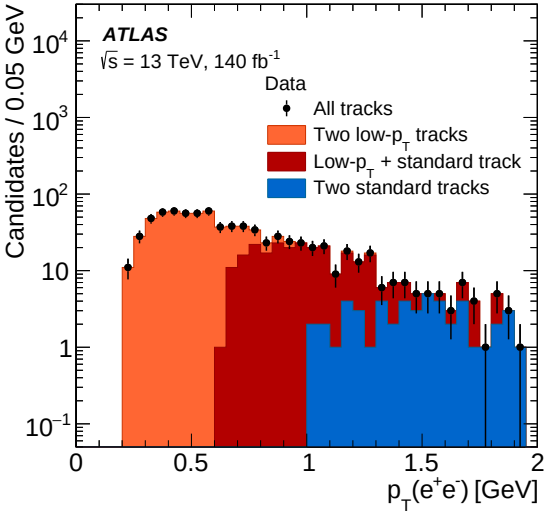


B_c^{*+} photon selection (2)

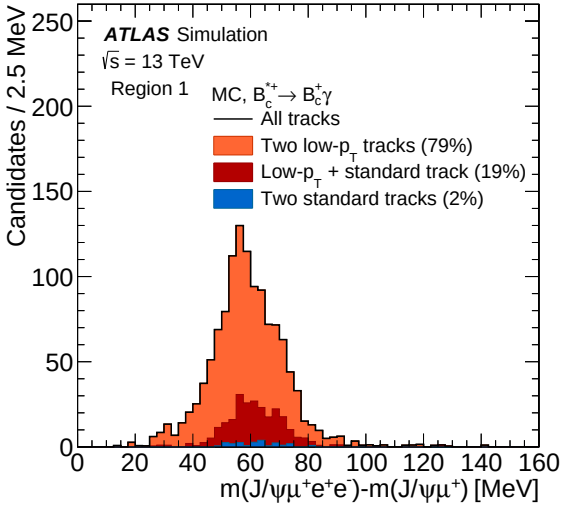


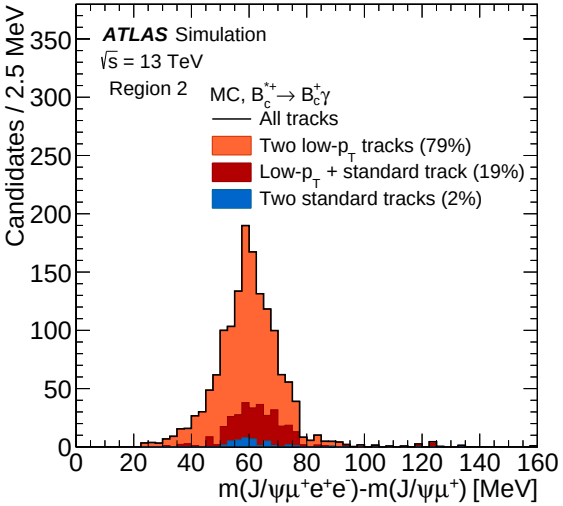
B_c^{*+} photon p_T distributions



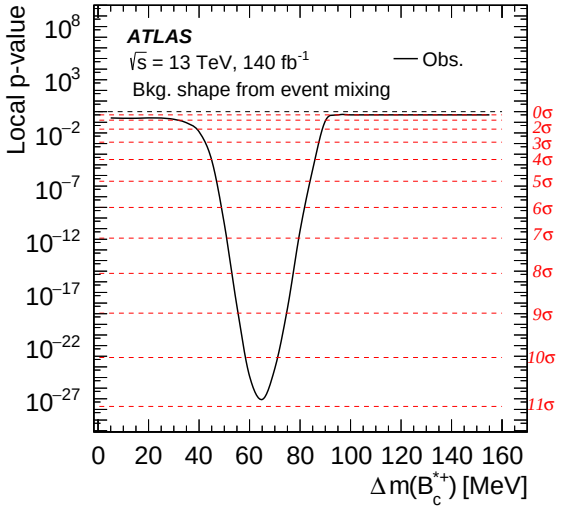


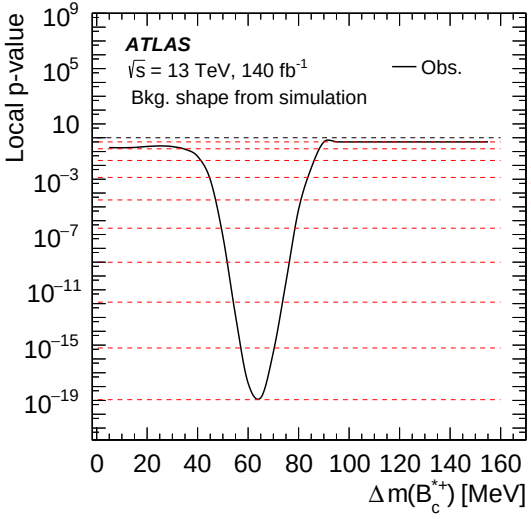
B_c^{*+} signal Δm shapes





B_c^{*+} profile LL scans





Di-charmonium selection regions

4μ channel		$4\mu + 2\pi$ channel	
SR	CR	SR	CR
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *Loose* muons, $p_{\mathrm{T}1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, $m_{\psi(2S)} \in [3.56, 3.80]$ GeV			
—		Two *loose* OS ID tracks with $p_{\mathrm{T}} > 0.5$ GeV for pions, BDT requirement	
$\chi^2_{4\mu}/N < 3$, $\lvert L_{xy}^{4\mu}\rvert < 0.2$ mm, $\lvert L_{xy}^{\mathrm{charm}}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV		$\chi^2_{4\mu+2\pi}/N < 3$, $\lvert L_{xy}^{4\mu+2\pi}\rvert < 0.2$ mm, $\lvert L_{xy}^{\mathrm{charm}}\rvert < 0.3$ mm, $m_{4\mu+2\pi} < 11$ GeV	
$\Delta R(J/\psi, \psi(2S)) < 0.25$	$\Delta R(J/\psi, \psi(2S)) \geq 0.25$	$\Delta R(J/\psi, \psi(2S)) < 0.25$	$\Delta R(J/\psi, \psi(2S)) \geq 0.25$

"others"	non-prompt	DPS	SPS
$m_{J/\psi} \in [2.60, 2.76]$ GeV or $m_{J/\psi} \in [3.34, 3.50]$ GeV for either J/ψ; $m_{\psi(2S)} \in [3.35, 3.48]$ GeV or $m_{\psi(2S)} \in [3.88, 4.10]$ GeV for $\psi(2S)$	$L_{xy}^{\mathrm{charm}} > 0.3$ mm for either charmonium, $\chi^2_{4\mu(+2\pi)}/N < 15$, $m_{4\mu(+2\pi)} < 25$ GeV	No ΔR or BDT requirements, $m_{4\mu(+2\pi)} \in [14, 25]$ GeV	No ΔR or BDT requirements, $m_{4\mu(+2\pi)} \in [8, 12]$ GeV

Di-charmonium systematics

Sources	Model A			Model B			Model C	
	m	Γ	R	m	Γ	R	m	Γ
Statistical uncertainties	±23	±32	±0.20	±8.1	±25	±0.17	±17	±54
Di-J/ψ bkg. modeling	±5.4	±7.7	±0.041	±1.4	—	—	—	—
J/ψ+ψ(2S) bkg. modeling	±4.1	±6.7	±0.038	—	—	—	±2.6	±8.6
Signal ratios	—	—	±0.069	—	—	±0.054	—	—
Mass resolution	±6.8	±8.6	±0.033	±1.3	±2.2	±0.002	±0.3	±4.4
Feed-up bkg.	—	—	±0.002	—	—	±0.002	±0.3	±0.6
P or D-wave BW	±3.2	±5.4	+0.39	±9.9	±2.9	±0.094	+58	+170
Fit bias	±0.2	±2.1	±0.007	±0.2	±4.7	±0.010	±0.4	±11
Inclusion of $X(7200)$	±1.0	±1.2	—	±0.1	±3.8	±0.001	±4.2	±19