Results on exotic hadronic resonances with the ATLAS detector

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on behalf of the ATLAS collaboration

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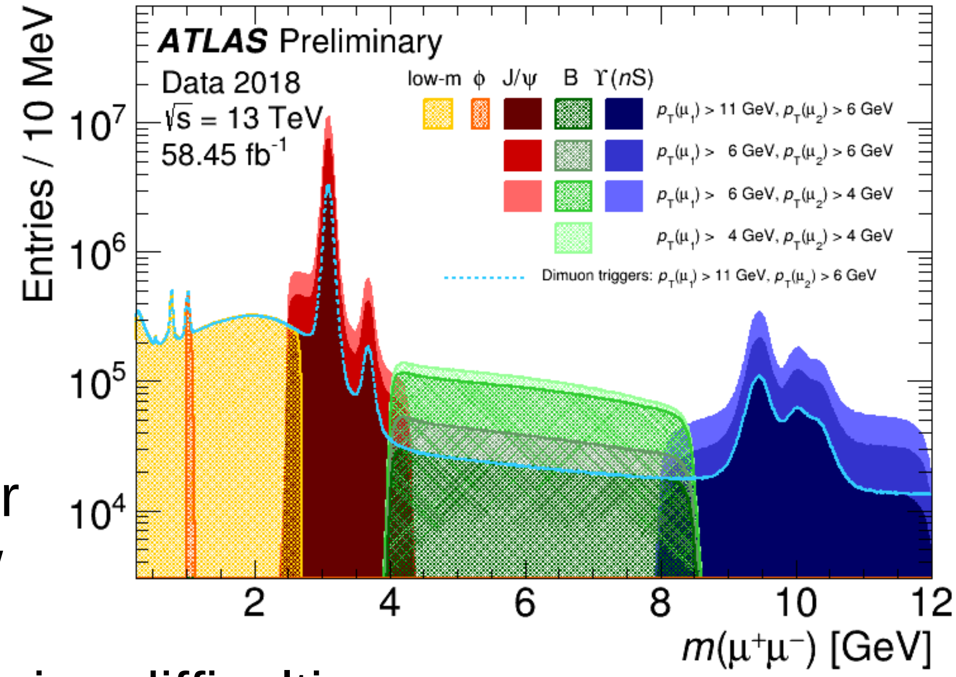
Low-p_T triggers in ATLAS

- 25 fb^{-1} in Run 1, and 139 fb^{-1} in Run 2
- B triggers focus mostly on final states with muons
  - typical trigger: di-muons with p_T thresholds at 4, 6 and 11 GeV
- In 2018, a di-electron high-level trigger implemented and being analysed now



- With higher luminosity we have increasing difficulties collecting low-p_T events within the bandwidth budget.
  - ~100 to 200 Hz trigger budget
  - ATLAS has topological triggers to keep lower thresholds and stay within the bandwidth budget.

Observation of an excess of di-charmonium events in the four-muon final state

Run-2 result:

arXiv: 2304.08962

Submitted to Phys. Rev. Lett.

di-charmonium events in four muons

arXiv: 2304.08962,
Submitted to PRL

- Motivated by LHCb discovery of resonant-like signal X(6900) in di-J/ψ spectrum [arXiv: 2006.16957].
  - See also CMS-PAS-BPH-21-003

- Strategy:
  - 139 fb^{-1} recorded by ATLAS Run 2 at 13TeV
  - 2- or 3-muon triggers with dimuon in mass range in 2.5-4.3 GeV
  - Trigger combinations with various prescaling to increase acceptance
  - X(6900) trigger efficiency is 72% relative to offline selection

di-charmonium events in four muons

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- Selection:
  - Events with 2 opposite-charge muon pairs and fit to common vertex
  - Then each vertex of the 2 pairs is refit with a J/ψ or ψ(2S) mass constraint
  - 0.33% $m_{4\mu}$ resolution for X(6900)
  - Different muon momenta (trigger-driven)
  - ΔR (between charmonia) and transverse decay lengths used to define signal and control regions

Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ 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 requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\lvert L^{\text{di-}\mu}_{xy}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi^2_{4\mu}/N > 6$, or $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	

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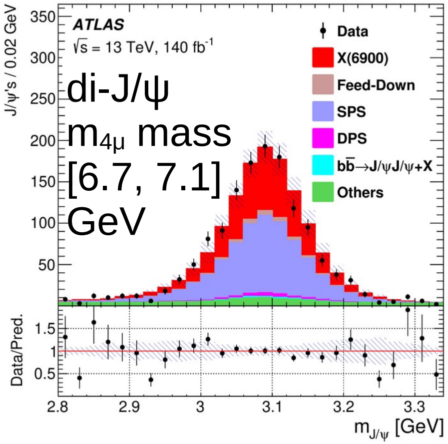
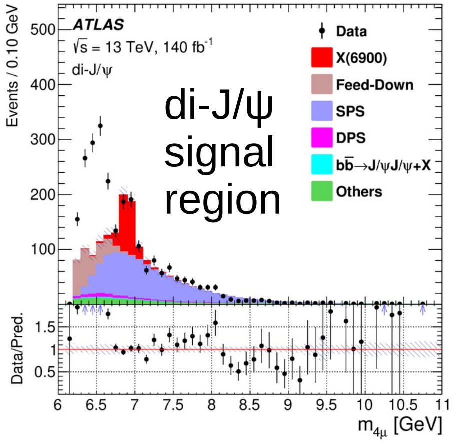
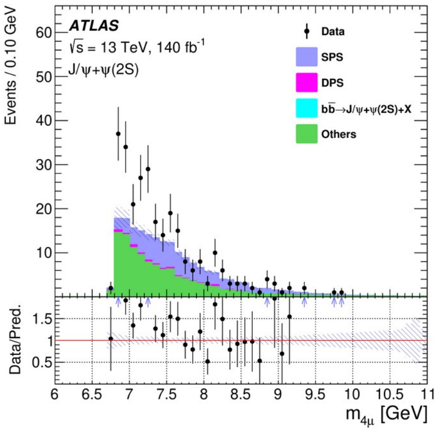
Backgrounds:

- Prompt J/ψ
  - Single parton scattering (SPS)
  - Double parton scattering (DPS)
- Non-prompt J/ψ
  - $b\bar{b} \rightarrow J/\psi\ J/\psi$
- ▶ From MC but kinematic scaling using data control regions
- Single J/ψ background
  - Prompt or non-prompt J/ψ plus fake muons from primary vertex
- Non-peaking background with no real J/ψ
- ▶ Single and non-peaking are 'others'
  - ▷ Data-driven modelling







J/ψ+ψ(2S)
signal region

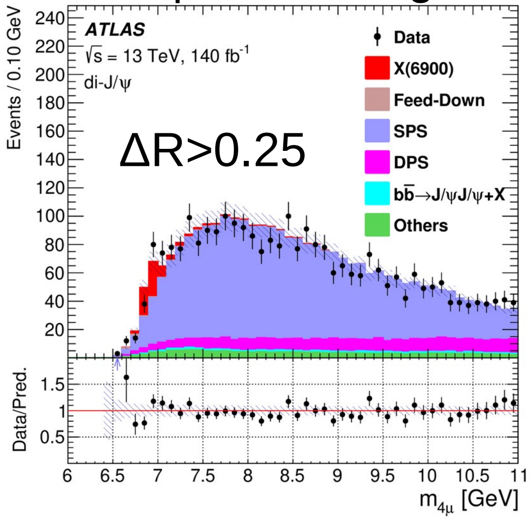
di-charmonium events in four muons

arXiv: 2304.08962, Submitted to PRL

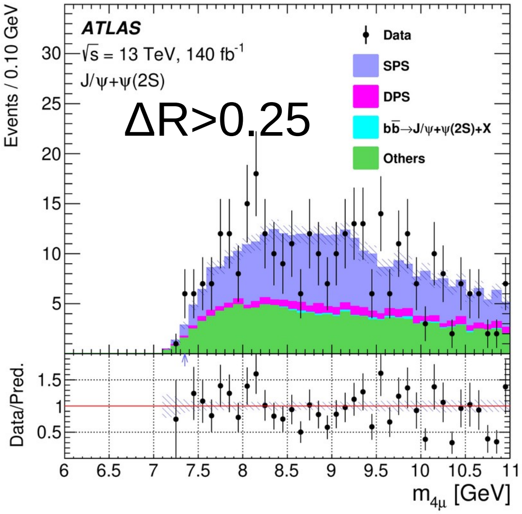
Backgrounds:

- Control regions
  - Low & high 4-muon mass sidebands for SPS and DPS studies
  - $\Delta R > 0.25$ to study SPS mass spectrum
- Reweighting between data and MC in di-J/ψ p_T, $\Delta\varphi$, $\Delta\eta$ between charmonia and lower-p_T muons
- Poor 4μ vertex or very long proper lifetime to select non-prompt control region
- Feed-down from J/ψ+ψ(2S) included in di-J/ψ

di-J/ψ control region



J/ψ+ψ(2S) control region



di-charmonium events in four muons

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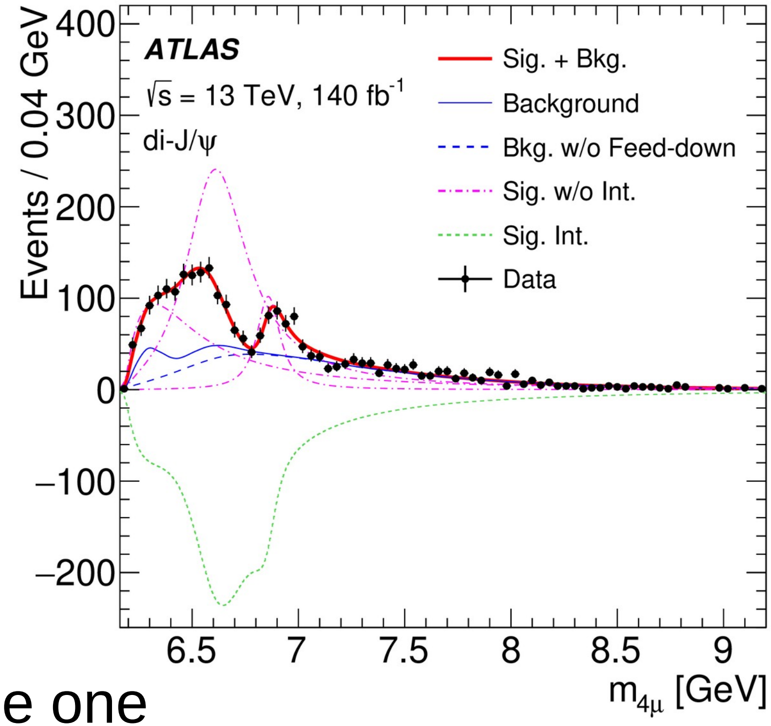
- Fit models:
  - di-J/ψ: could have two resonances but interference may be important
    - Model A has 3 resonances interfering with each other
    - Model B has 2 resonances, of which only one interferes with SPS
      - *Two-res. with interference and three-res. without interferences also tried and excluded >95%*
  - J/ψ+ψ(2S)
    - Model α has the same resonances as in model A plus an additional standalone one
    - Model β has a single resonance



di-charmonium events in four muons

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Systematics:

- SPS: PYTHIA uncertainty on suppression of the soft double charmonia production (tuned on data)
- Bkg: shape uncertainty for di-charmonium p_T mismodelling
- Fit biases in the resonance parameters.
- The P&D-wave BW functions for systematic on orbital angular momentum assumptions
- Systematic shape variations in the X(6900) and in the second resonance in J/ψ+ψ(2S)
- 4th resonance around 7.2 GeV (LHCb hint)
- The feed-down background normalizations varied
- J/ψ+ψ(2S): uncertainties on transfer factor between signal and control regions, and on “Others” shape from the non-prompt region
- J/ψ+ψ(2S): interference between the 4th resonance and the others

Systematic Uncertainties (MeV)	di-J/ψ m_2	Γ_2	J/ψ+$\psi(2S)$ m_3	Γ_3
Muon calibration	±6	±7	<1	±1
SPS model parameter	±7	±7	<1	
SPS di-charmonium p_T	±7	±8	<1	
Background MC sample size	±7	±8	±1	<1
Mass resolution	±4	−3	−1	$^{+2}_{-4}$
Fit bias	−13	+10	$^{+9}_{-10}$	$^{+50}_{-16}$
Shape inconsistency	<1		±4	±6
Transfer factor	—		±5	±23
Presence of 4th resonance	<1		—	
Feed-down	$^{+4}_{1}$	$^{+6}_{2}$	—	
Interference of 4th resonance	—		−32	−11
P and D-wave BW	+9	+19	<1	±1
ΔR and muon p_T requirements	$^{+3}_{-2}$	$^{+6}_{-4}$	$^{+1}_{-2}$	−2

di-charmonium events in four muons

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- Observation of the X(6900) structure is confirmed.
- Evidence for a broad lower mass structure
  - In both channels, details of the lower-mass structure cannot be extracted directly from the data.
  - More data are required to better characterise the excesses observed in both channels.

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
$J/\psi+\psi(2S)$	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

di-charmonium events in four muons

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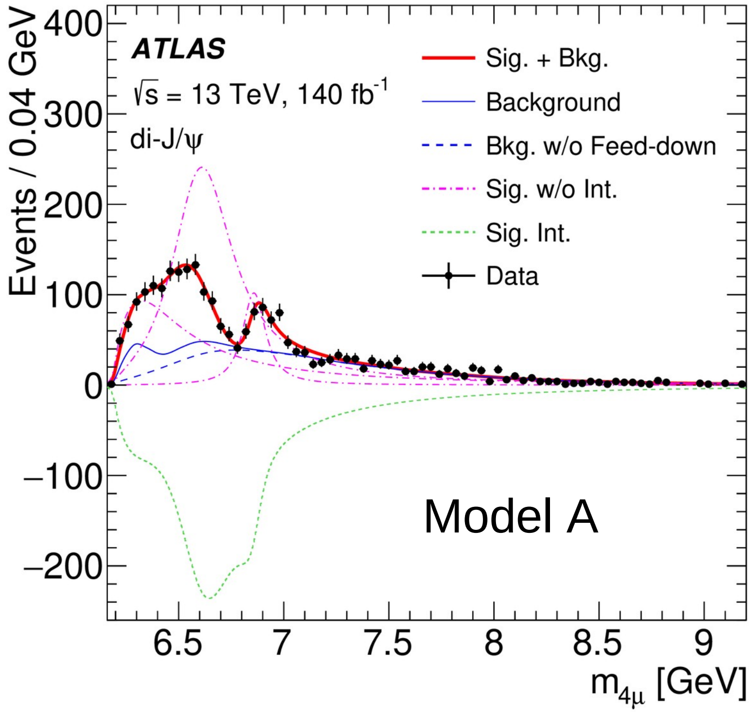
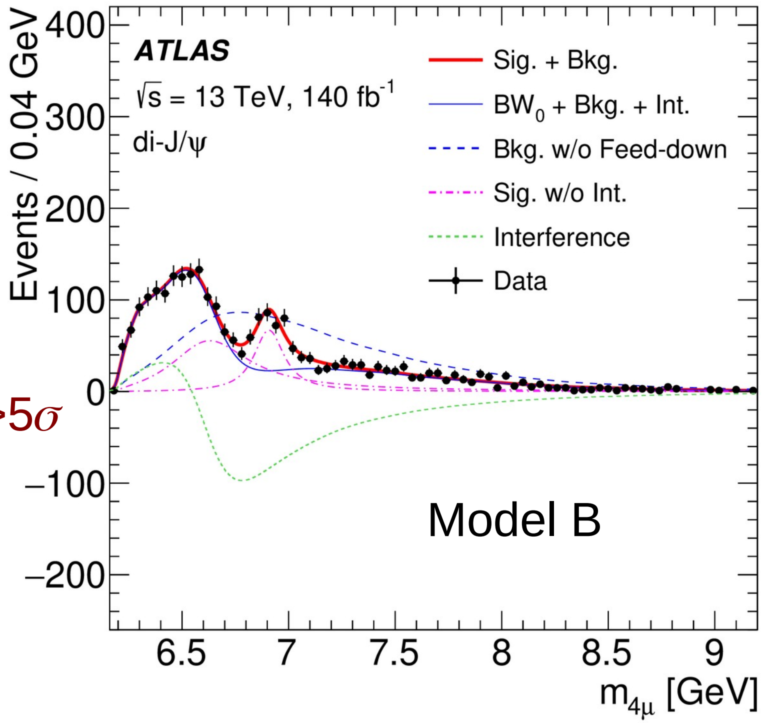
- Evidence for a broad lower mass structure



All >5σ



Both models A and B describe the data well.

di-charmonium events in four muons

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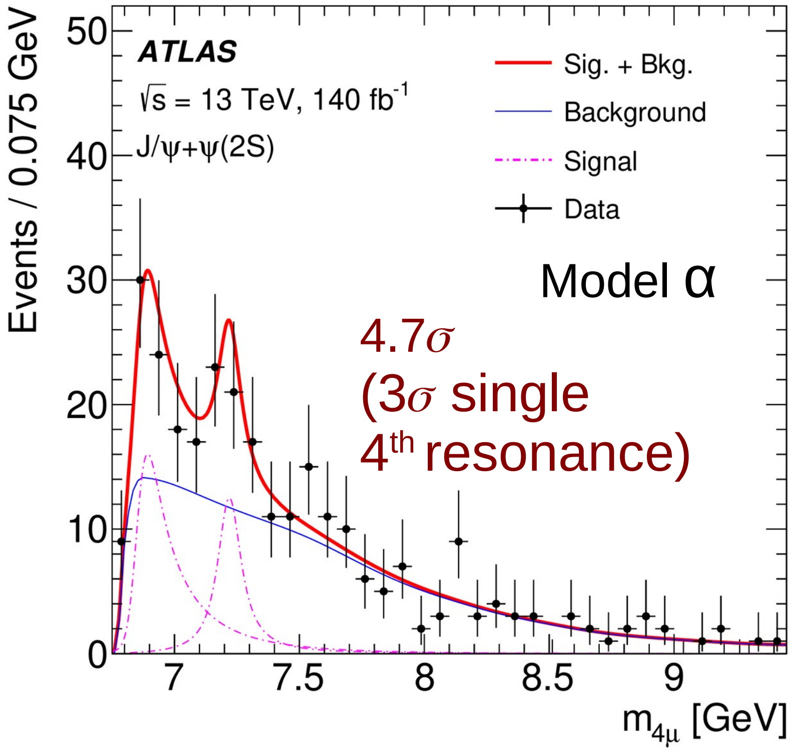
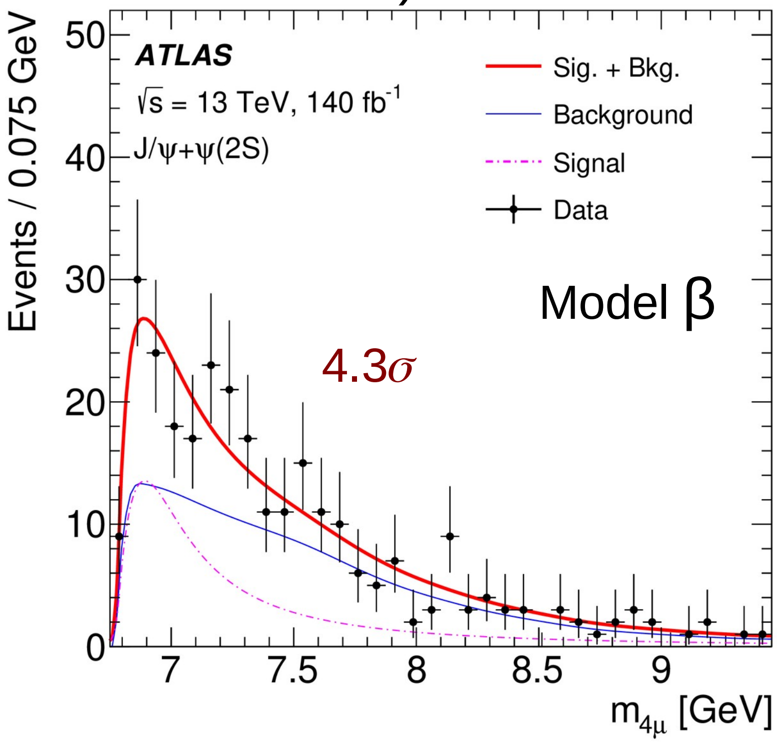
- 4.7σ excess with two resonances, one near 6.9 GeV threshold.
- Low-mass structure not clear: other interpretations (e.g. multiple non-interfering resonances, reflection effects and threshold enhancements) not excluded



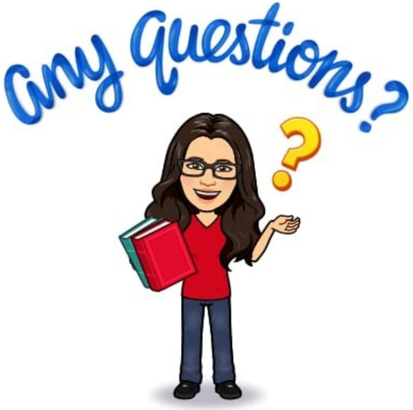


Both models α and β describe the data well.

Conclusions

- ATLAS is competitive in B physics, b quarks and low-p_T studies
  - Thanks to accumulated statistical samples
  - Thanks to some detector performance (tracking)

- **Stay tuned for on-going work towards more Run-2 analyses, while taking Run 3 data**



back-up slides

Properties of b-quark fragmentation to $B^{\pm} \rightarrow J/\psi K^{\pm}$

Run-2 result:

arXiv:2108.11650, JHEP 12 (2021) 131

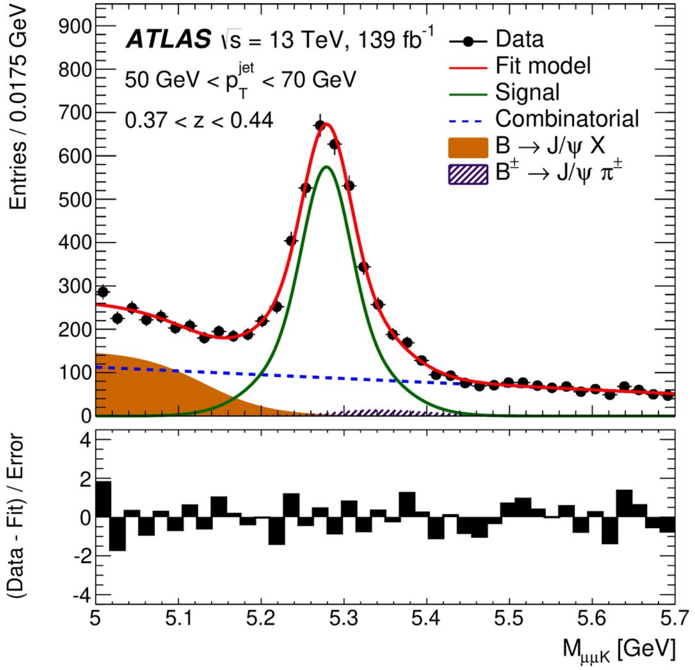
Properties of b-quark fragmentation

arXiv:2108.11650
JHEP 12 (2021) 131

- 139 fb^{-1} of Run-2 data
- b-fragmentation functions provide:
  - Test of QCD at LHC energy; MC tunes
  - $H \to b\bar{b}$ and many other channels with b-jet signatures - dominant uncertainty
- We measure longitudinal (z) and transverse (p_T^{rel}) of the $B^\pm$ momentum to jet axis.

$$z = \frac{\vec{p}_J \cdot \vec{p}_B}{\left|\vec{p}_J\right|^2}; \qquad p_T^{\mathrm{rel}} = \frac{\left|\vec{p}_J \times \vec{p}_B\right|}{\left|\vec{p}_J\right|}$$

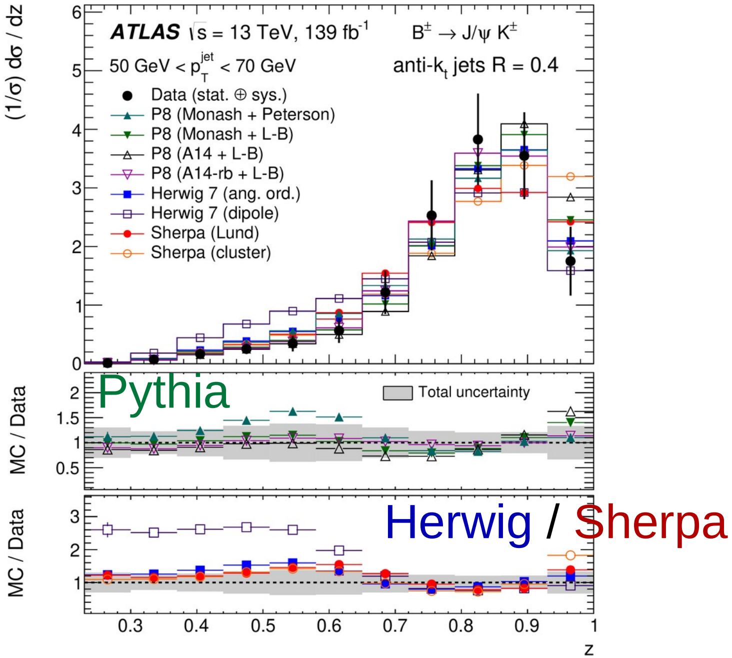
- $B^\pm$ mesons are associated to jets if they are within $\Delta R = 0.4$ from jet axis.
- $B^\pm$ invariant mass is used to extract differential cross section in each z or p_T^{rel} bins, for jet momentum bins:
  - 50 GeV < p_T < 70 GeV, 70 GeV < p_T < 100 GeV and p_T > 100 GeV.

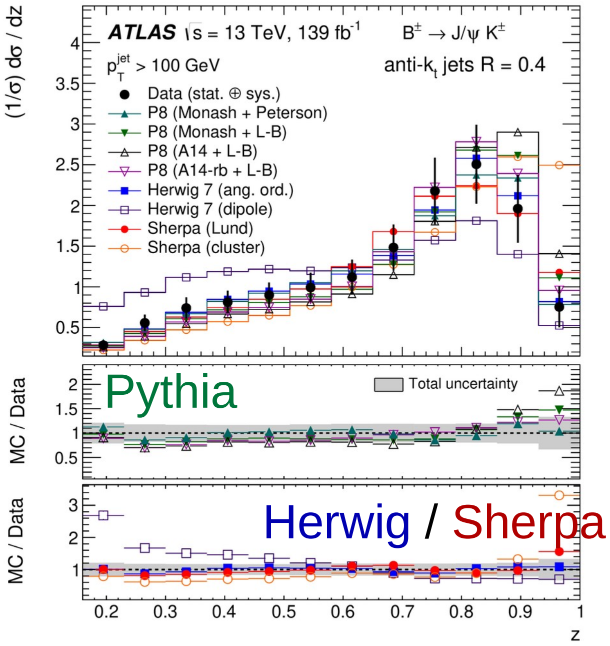


Properties of b-quark fragmentation

arXiv:2108.11650
JHEP 12 (2021) 131

- Results for z distributions for the lowest and highest jet p_T bins: 50 GeV < p_T < 70 GeV and p_T > 100 GeV



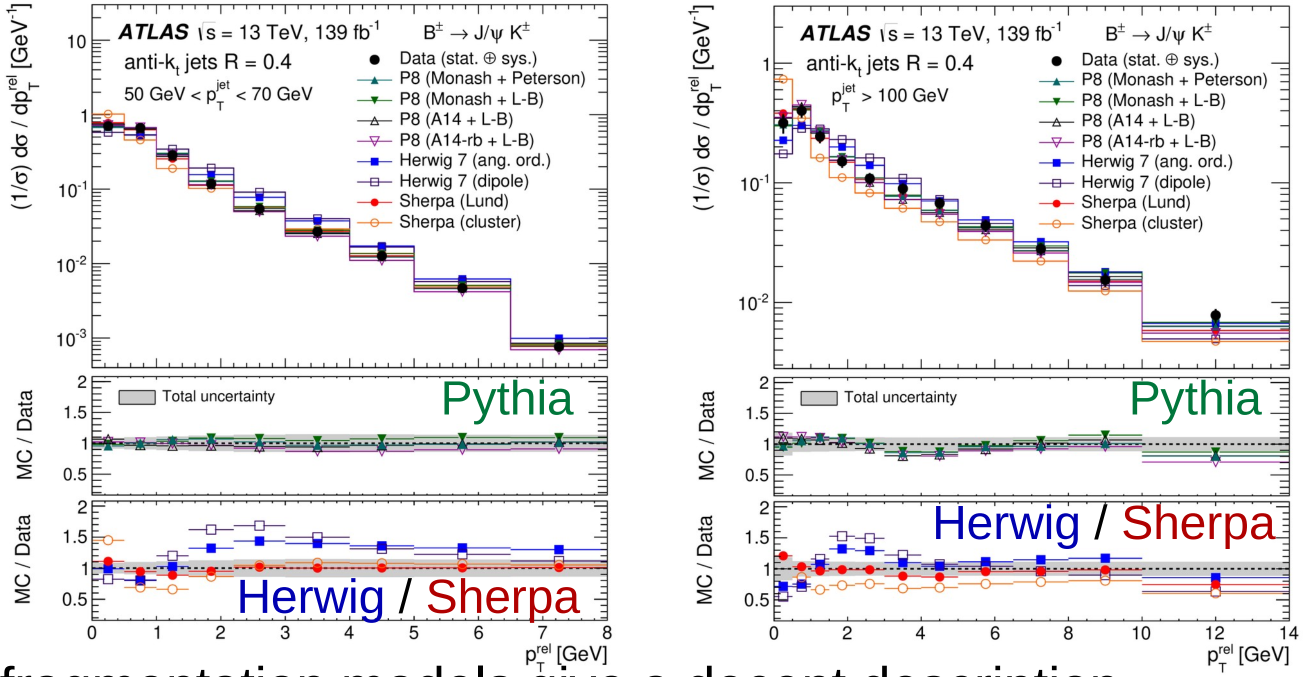


- lower tails of z distributions contain larger fraction of data at high p_T
  - gluon splitting → larger probability at higher p_T values → b quarks in the same jet and B meson from fragmentation of one b → smaller z and higher p_T^{rel}

Properties of b-quark fragmentation

arXiv:2108.11650
JHEP 12 (2021) 131

- Results for p_T^{rel} distributions for the lowest and highest jet p_T bins:
  50 GeV < p_T < 70 GeV and p_T > 100 GeV

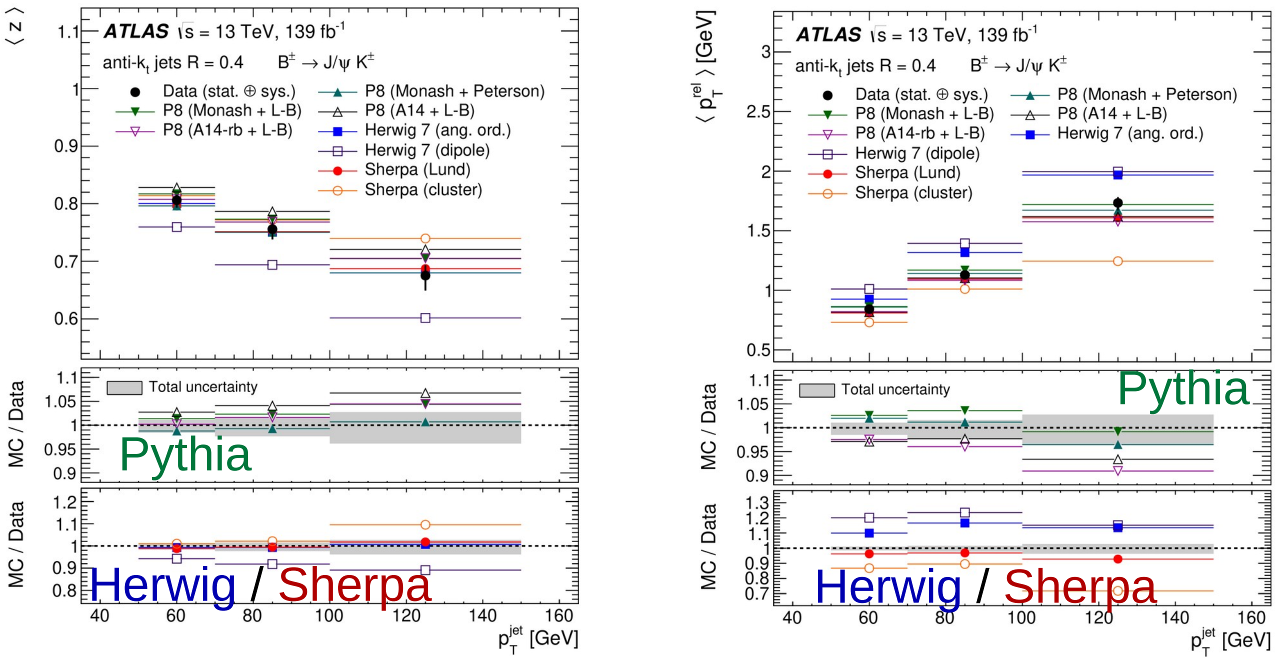


- All Pythia fragmentation models give a decent description.
- Herwig7 with dipole PS overestimates for p_T^{rel} in [1.5, 4.0] GeV at low p_T
- Sherpa (mainly cluster HM) discrepant for low p_T^{rel}, gets worse for higher jet p_T.

Properties of b-quark fragmentation

arXiv:2108.11650
JHEP 12 (2021) 131

- test of scale dependence: average values of the longitudinal profile <z> and of the transverse profile $\langle p_T^{rel} \rangle$ as a function of the jet p_T



- Pythia (A14*) predicts slightly larger <z> and slightly lower $\langle p_T^{rel} \rangle$
- Both Herwig7 discrepant at 15-20% level in $\langle p_T^{rel} \rangle$ profile
- Sherpa (cluster) disagreeing at 10% to 25% for $\langle p_T^{rel} \rangle$

Study of $B_c^+ \rightarrow J/\psi D_s^{(*)}$ decays

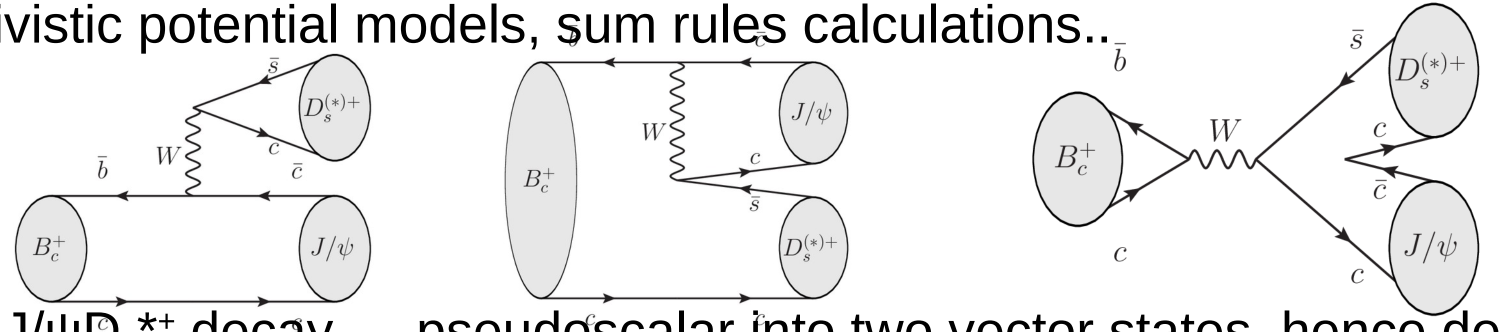
Run-2 result:

arXiv:2203.01808, CERN-EP-2022-025

Study of $B_c^+ \rightarrow J/\psi D_s^{(*)}$ decays

arXiv:2203.01808
CERN-EP-2022-025

- Observed earlier by LHCb (PRD 87 (2013) 112012) and ATLAS (EPJC 76 (2016) 1) in Run 1.
- Using entire Run 2 dataset: aiming at more precise measurement of branching fractions and the final state polarisation
  - Testing predictions of various theory models, e.g. pQCD calculation, relativistic potential models, sum rules calculations...



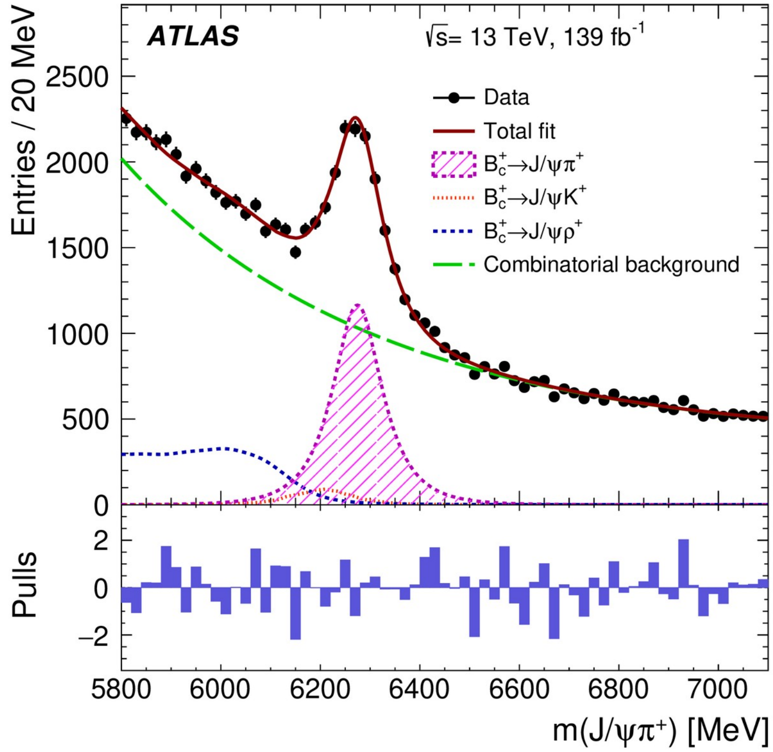
- $B_c^+ \rightarrow J/\psi D_s^{*+}$ decay $\rightarrow$ pseudoscalar into two vector states, hence described in terms of three helicity amplitudes: A_{++}, A_{00} and A_{--},
  - the indices correspond to the helicities of the J/ψ and D_s^{*+} mesons
  - A_{++} and A_{--} amplitudes are the $A_{\pm\pm}$ component and correspond to the J/ψ and D_s^{*+} transverse polarization.
  - The fraction, $\Gamma_{\pm\pm} / \Gamma$ is also measured.

Study of $B_c^+ \to J/\psi D_s^{(*)}$ decays

arXiv:2203.01808
CERN-EP-2022-025

- D_s^+ and D_s^{*+} are reconstructed from their decays:
  - $D_s^+ \to \varphi(K^+K^-)\pi^+$
  - $D_s^{*+} \to D_s^+ \pi^0/\gamma$ (soft, not reco)
- Use $B_c^+ \to J/\psi\pi^+$ reference channel for BR measurement
- Fiducial range: $p_T(B_c^+) > 15$ GeV, $|\eta(B_c^+)| < 2.0$

Reference channel with signal statistics
$N(B^+ \to J/\psi\pi^+) = 8440\ ^{+550}_{-470}$

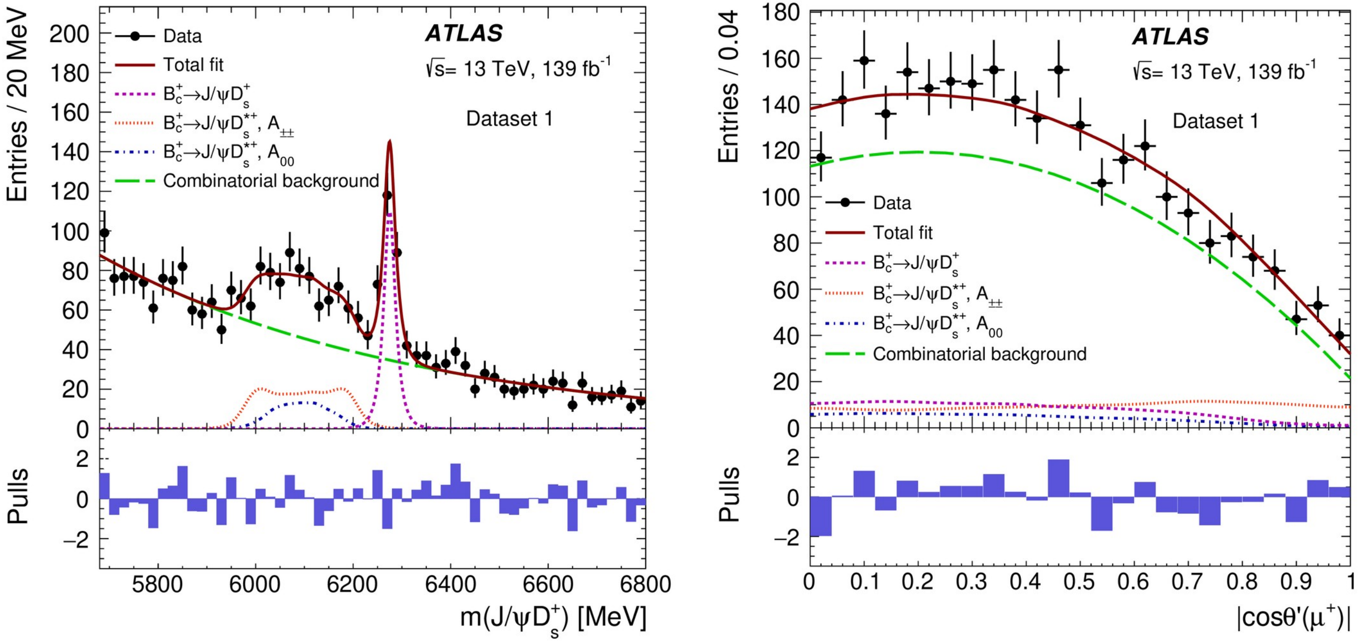


- 2D fit to extract the signal parameters
  - $m(J/\psi D_s^+)$ and the J/ψ helicity angle
- Both sensitive to polarisation of the final state particles J/ψ and D_s^+ in $B_c^+ \to J/\psi D_s^{*+}$ decay.

Study of $B_c^+ \to J/\psi D_s^{(*)}$ decays

arXiv:2203.01808
CERN-EP-2022-025

- Total yields
  - $N(B_c^+ \to J/\psi D_s^+) = 241 \pm 28$ (stat)
  - $N(B_c^+ \to J/\psi D_s^{*+}) = 424 \pm 46$ (stat)



Left: fit to inv. mass $m(J/\psi D_s^+)$. Right: fit to $|\cos\theta'(\mu^+)|$, where $\theta'(\mu^+)$ is the helicity angle between μ^+ and D_s^+ momenta, in J/ψ rest frame.

Study of $B_c^+ \rightarrow J/\psi D_s^{(*)}$ decays

arXiv:2203.01808
CERN-EP-2022-025

- Results on the ratios of branching fractions and on the fraction of transverse polarization of the $B_c^+ \rightarrow J/\psi D_s^*$ decay:

Uncertainties:
(Stat) (syst) (BF)

$$R_{D_s^+/\pi^+} \equiv \mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) = 2.76 \pm 0.33 \pm 0.30 \pm 0.16$$

$$R_{D_s^{*+}/\pi^+} \equiv \mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) = 5.33 \pm 0.61 \pm 0.67 \pm 0.32$$

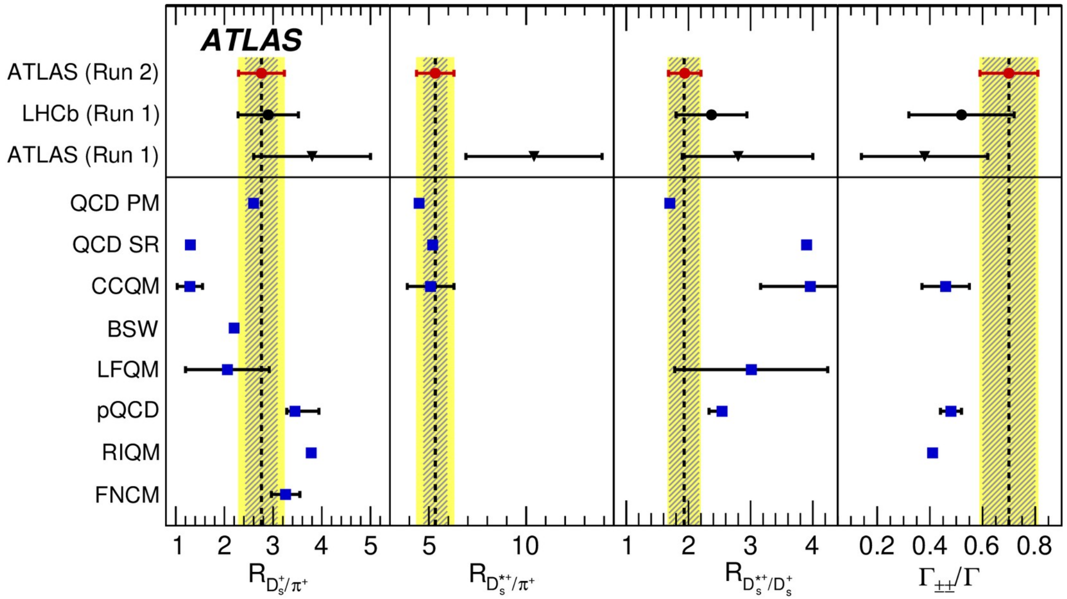
$$R_{D_s^{*+}/D_s^+} \equiv \mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+) = 1.93 \pm 0.24 \pm 0.10$$

$$\Gamma_{\pm\pm}/\Gamma(B_c^+ \rightarrow J/\psi D_s^{*+}) = 0.70 \pm 0.10 \pm 0.04$$

Study of $B_c^+ \rightarrow J/\psi D_s^{(*)}$ decays

arXiv:2203.01808
CERN-EP-2022-025

- New results consistent with earlier measurements
- $R(D_s^{*+}/\pi^+)$ described well by the predictions



- $R(D_s^+/\pi^+)$ and $R(D_s^{*+}/D_s^+)$ predictions consistently deviate from data
  - except QCD PM (PRD 61 (2000) 034012)
- $\Gamma_{\pm\pm}/\Gamma$ agrees with a naive spin-counting estimate of 2/3 and larger than predictions
- Hatched areas → stat uncertainties; yellow bands → total uncertainties.

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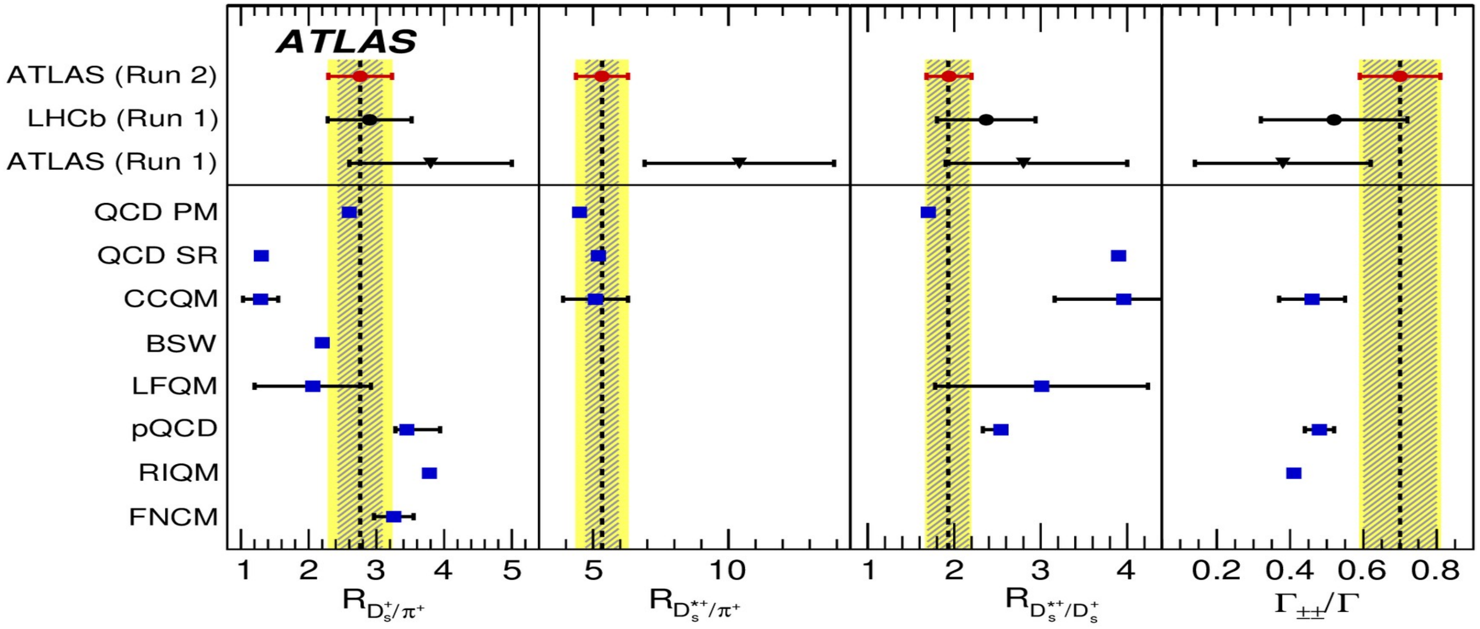

QCD PM: QCD relativistic potential model [arXiv:hep-ph/9909423, Phys. Rev. D 61, 034012 (2000)]
QCD SR: QCD sum rules [arXiv:hep-ph/0211021]
CCQM: covariant confined quark mode [arXiv:1708.09607 [hep-ph], Phys. Rev. D 96, 076017 (2017)]
BSW: Bauer-Stech-Wirbel relativistic quark model [arXiv:0810.4284 [hep-ph], Phys. Rev. D 79, 034004 (2009)]
LFQM: light-front quark mode [arXiv:1307.5925 [hep-ph], Phys. Rev. D 89, 017501 (2014)]
pQCD: perturbative QCD [arXiv:1407.5550 [hep-ph], Phys. Rev. D 90, 114030 (2014)]
RIQM: relativistic independent quark model [Phys. Rev. D 88, 094014 (2013) / arXiv:2202.01167 [hep-ph]]
FNCM: calculations in the QCD factorization approach [Int. J. Mod. Phys. A 33, 1850044 (2018), erratum 1892003]

arXiv:2203.01808
CERN-EP-2022-025

Parameter	Value
$m_{B_c^+}$ [MeV]	6274.5 ± 1.5
$\sigma_{B_c^+}$ [MeV]	47.5 ± 2.5
$N_{B_c^+ \to J/\psi \pi^+}$	8440^{+550}_{-470}

Parameter	Value
$m_{B_c^+}$ [MeV]	6274.8 ± 1.4
$\sigma_{B_c^+}$ [MeV]	11.5 ± 1.5
$r_{D_s^{*+}/D_s^+}$	1.76 ± 0.22
$f_{\pm\pm}$	0.70 ± 0.10
$N^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^+}$	193 ± 20
$N^{\mathrm{DS2}}_{B_c^+ \to J/\psi D_s^+}$	49 ± 10
$N^{\mathrm{DS1}}_{B_c^+ \to J/\psi D_s^{*+}}$	338 ± 32
$N^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^+}$	241 ± 28
$N^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi D_s^{*+}}$	424 ± 46

arXiv:2108.11650
JHEP 12 (2021) 131