ATLAS results on charmonium production and B_c production and decays

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Joint Institute for Nuclear Research

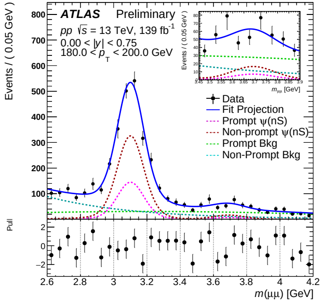
22nd Particles and Nuclei International Conference
5–10 September 2021

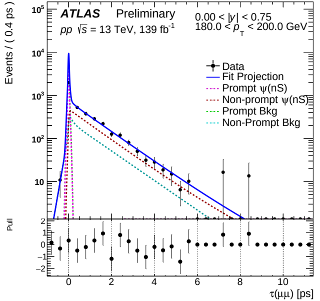
Outline

- Charmonium production
  - J/ψ and $\psi(2S)$ production measurement at $\sqrt{s} = 13\,\text{TeV}$ – ATLAS-CONF-2019-047
  - Associated prompt $J/\psi + W$ production measurement at $\sqrt{s} = 8\,\text{TeV}$ – JHEP 01 (2020) 095
- Physics of B_c meson
  - Measurement of relative B_c^+/B^+ production at $\sqrt{s} = 8\,\text{TeV}$ – PRD 104 (2021) 012010
  - Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays with $\sqrt{s} = 13\,\text{TeV}$ data – ATLAS-CONF-2021-046

High-p_T J/ψ and $\psi(2S)$ production measurement ATLAS-CONF-2019-047

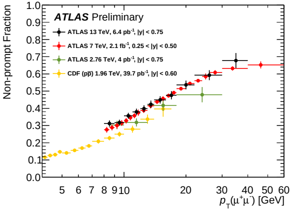
- Heavy quarkonium is a unique probe for our understanding of strong interactions
- Two production mechanisms:
  - *Prompt* in *pp* interaction or feed-down from heavier states
  - *Non-prompt* from *b* hadron decays
  - Distinguished by 2D fit of dimuon mass and pseudo-proper lifetime
- ATLAS Run 1 results (EPJC 76 (2016) 283) were well described by the conventionally used approaches: NRQCD (prompt) and FONLL (non-prompt, although slightly worse at highest p_T)
  - Used di-muon triggers, reaching only p_T ~100 GeV
- New analysis uses full Run 2 dataset, aims at high-p_T region
  - Use single-muon trigger with $p_T(\mu) > 50$ GeV

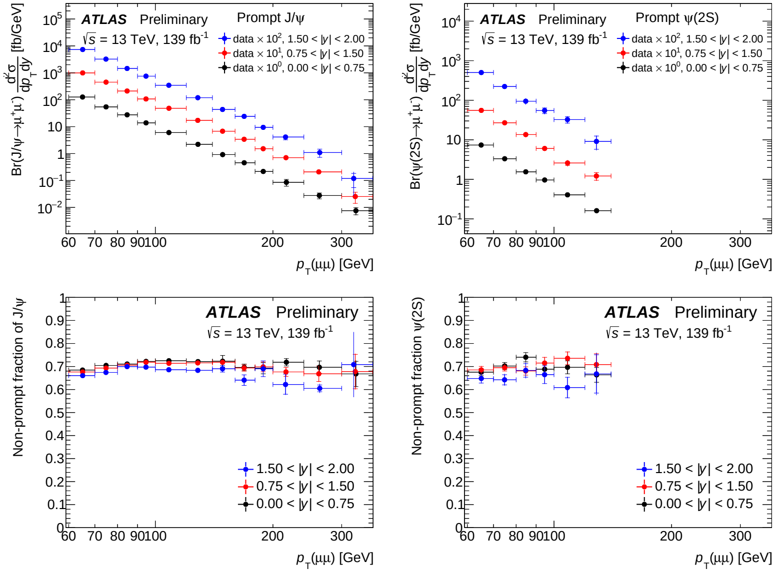




Prompt production results

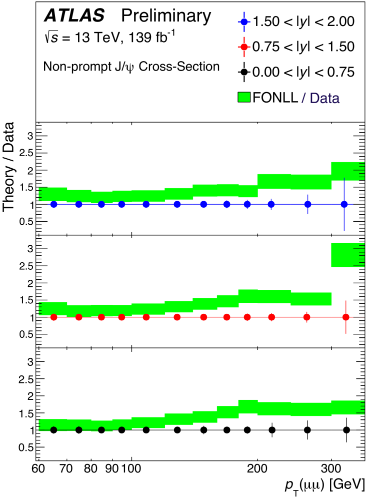
- p_T range goes up to 360 GeV – much beyond what was achieved before
- Non-prompt fraction has little dependence on p_T above 60 GeV
  - cf. growth from $\sim$0.3 to $\sim$0.7 between 8 and 40 GeV observed in ATLAS-CONF-2015-030

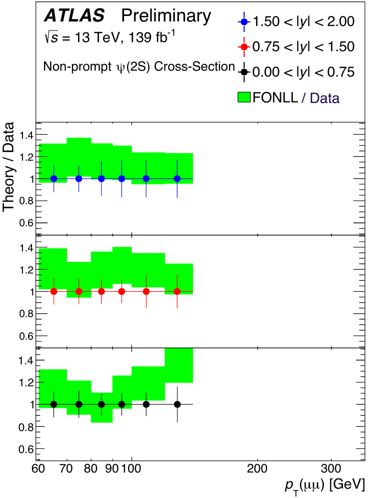




Non-prompt production results

- FONLL agrees with data at low p_T within theory uncertainty
- Overestimates them above 150 GeV for J/ψ
  - not enough statistics for $\psi(2S)$

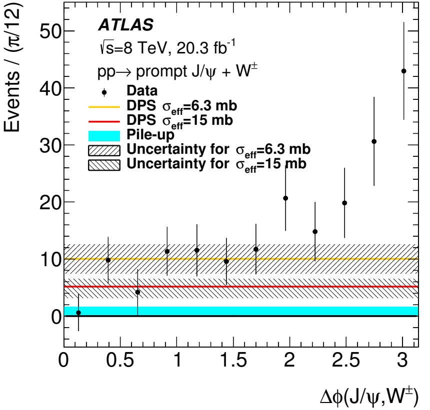




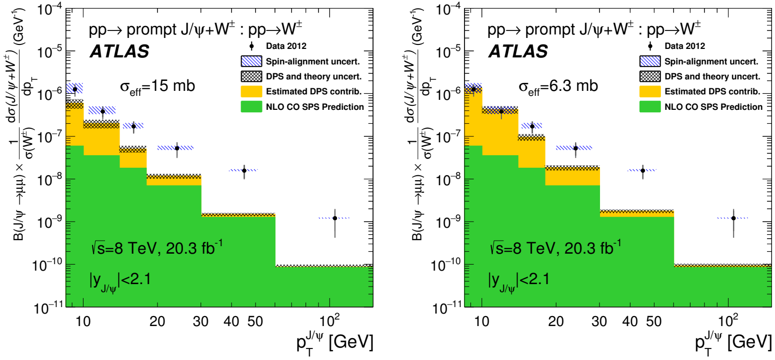
$J/\psi + W$ production measurement (1)

JHEP 01 (2020) 095

- W+*prompt* J/ψ production is supposed to be a signature of colour-octet (CO) J/ψ production
  - although theorists argue that higher-order colour-singlet (CS) processes may dominate
- ATLAS analysis uses Run 1 $\sqrt{s} = 8\,\text{TeV}$ data
- Ratio of $J/\psi + W$ to inclusive W production cross-section
  - $8.5\,\text{GeV} < p_{\text{T}}(J/\psi) < 150\,\text{GeV}$, $|y(J/\psi)| < 2.1$
  - $R^{\text{incl}}_{J/\psi} = \frac{\sigma_{\text{incl}}(pp\to J/\psi+W^{\pm})}{\sigma(pp\to W^{\pm})} \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.3 \pm 0.7(\text{stat.}) \pm 0.8(\text{syst.})^{+1.5}_{-0.7}\,(\text{spin})) \cdot 10^{-6}$
- Subtraction of the DPS contribution done under two assumptions on σ_{eff}
  - $R^{\text{DPSsub}}_{J/\psi} = (3.6 \pm 0.7^{+1.1}_{-1.0}{}^{+1.5}_{-0.7}) \cdot 10^{-6}$, $\sigma_{\text{eff}} = 15.0^{+5.8}_{-4.2}\,\text{mb}$
  - $R^{\text{DPSsub}}_{J/\psi} = (1.3 \pm 0.7 \pm 1.5^{+1.5}_{-0.7}) \cdot 10^{-6}$, $\sigma_{\text{eff}} = 6.3 \pm 1.9\,\text{mb}$
- Theory predictions using CO LDME (from fits of Tevatron data) gives $(0.428 \pm 0.017) \cdot 10^{-6}$



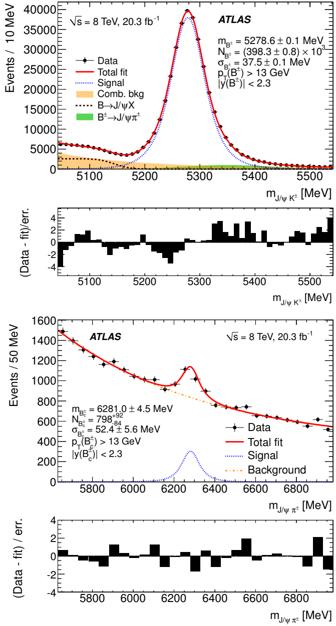
- Excess of SPS production is more visible in differential $J/\psi + W$ production rate at high $p_{\mathrm{T}}(J/\psi)$



- May be an indication of significant contribution of CS mechanism not accounted for in the predictions

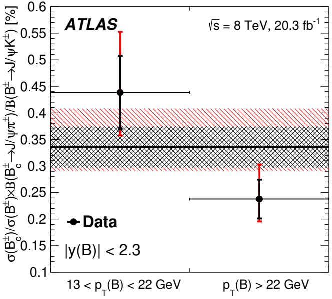
B_c^+/B^+ production measurement

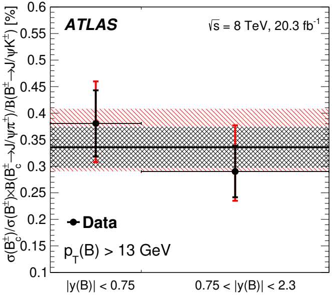
- B_c^+ production involves producing $b\bar{b}$ and $c\bar{c}$ simultaneously
  - x-section predicted at $\sim$0.2% of inclusive $b\bar{b}$ production
  - dominated by $gg \to B_c^+ + b + \bar{c}$
- Measure the ratio: $\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)}$
  - common systematic uncertainties largely cancel
- Use Run 1 data at $\sqrt{s} = 8\,\text{TeV}$
- Total x-section in fiducial range
  - $p_\text{T}(B) > 13\,\text{GeV}$, $|y(B)| < 2.3$
- and differentially, in two bins of $p_\text{T}(B)$ and $|y(B)|$



B_c^+/B^+ production measurement results

- Total x-section ratio:
  - $\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} =$
    $(0.34 \pm 0.04(\text{stat.})^{+0.06}_{-0.02}(\text{syst.}) \pm 0.01\ (\text{lifetime}))\%$
  - Lower than LHCb result in forward and softer kinematics
    - $2.0 < y(B) < 4.5$, $p_T(B) < 20$ GeV:
    - $(0.683 \pm 0.018 \pm 0.009)\%$
  - c.f. ATLAS results in the p_T bins:
    - $(0.44 \pm 0.07 \pm^{+0.09}_{-0.04} \pm 0.01)\%$ for $13 < p_T(B) < 22$ GeV
    - $(0.24 \pm 0.04 \pm^{+0.05}_{-0.01} \pm 0.01)\%$ for $p_T(B) > 22$ GeV
  - Fairly consistent with CMS result at $\sqrt{s} = 7$ TeV in a similar kinematics
    - $|y(B)| < 1.6$, $p_T(B) > 15$ GeV:
    - $(0.48 \pm 0.05 \pm 0.03 \pm 0.05)\%$
- With $p_T(B)$, the B_c^+ production decreases faster than B^+
- No significant dependence on $|y(B)|$ found

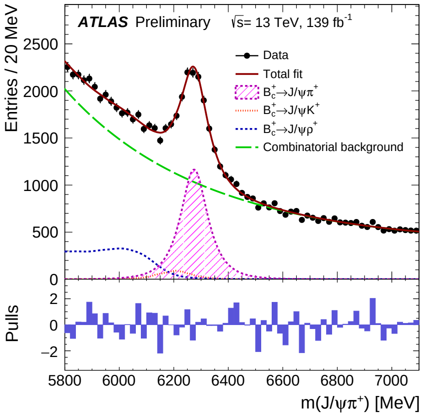




Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays

ATLAS-CONF-2021-046

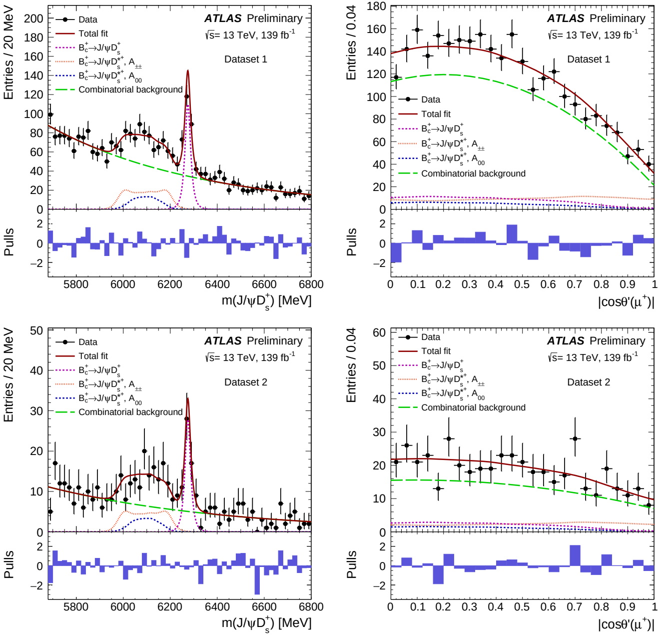
- Observed earlier by LHCb (PRD 87 (2013) 112012) and ATLAS (EPJC 76 (2016) 4) in Run 1.
- Aiming at more precise measurement of $\mathcal{B}$'s and polarization with full Run 2 dataset
  - Test various approaches used for their predictions, e.g. pQCD calculation, relativistic potential models, sum rules calculations etc.
- Signal channel uses $D_s^+ \to \phi(K^+K^-)\pi^+$ reconstruction, and $D_s^{*+} \to D_s^+\pi^0/\gamma$ with incomplete reconstruction
- Use $B_c^+ \to J/\psi\pi^+$ *reference channel* for $\mathcal{B}$ measurement
- Fiducial range: $p_T(B_c^+) > 15\,\text{GeV}$, $|\eta(B_c^+)| < 2.0$



$$N_{B_c^+ \to J/\psi\pi^+} = 8440^{+550}_{-470}$$

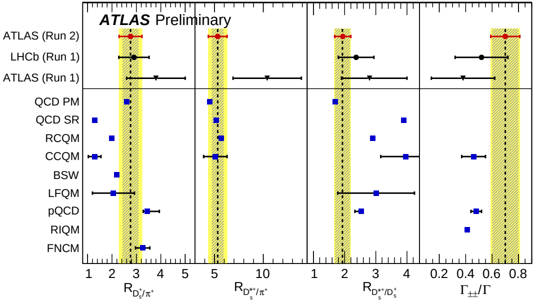
$B_c^+ \to J/\psi D_s^{(*)+}$ fit

- 2D fit to extract the signal parameters
  - $m(J/\psi D_s^+)$ and the J/ψ helicity angle
- Both sensitive to polarization $B_c^+ \to J/\psi D_s^{*+}$
- Two datasets defined based on triggers
  - (dedicated $J/\psi\phi$ triggers inefficient for the reference channel but contribute much to signal)
- Total yields
  - $N_{B_c^+ \to J/\psi D_s^+} = 241 \pm 28$
  - $N_{B_c^+ \to J/\psi D_s^{*+}} = 424 \pm 46$



$B_c^+ \to J/\psi D_s^{(*)+}$ results

- $R_{D_s^+/\pi^+} = 2.76 \pm 0.33(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.16(\text{BF})$
- $R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61(\text{stat.}) \pm 0.67(\text{syst.}) \pm 0.32(\text{BF})$
- $R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24(\text{stat.}) \pm 0.10(\text{syst.})$
- $\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$



- Generally agree with the earlier measurements
- $R_{D_s^{*+}/D_s^+}$ 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) perfectly agreeing
- $\Gamma_{\pm\pm}/\Gamma$ agrees with naive spin-counting estimate of $2/3$ and larger than the dedicated predictions

- The most precise measurement of these decay parameters to date

Summary

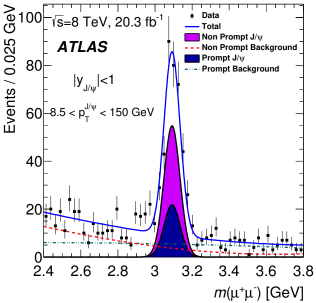
- Charmonium precise measurements provide important input for both theory and experimental studies
- ATLAS provides wide opportunities here, still room for many other measurements with Run 2

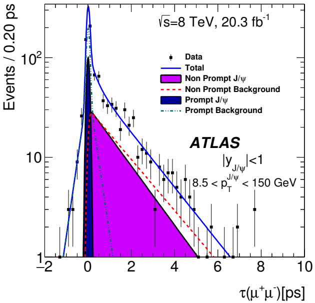
- For B_c^+ physics, Run 2 provides more than order-of-magnitude higher yields
- Lots of further possible measurements on production, decays, and spectroscopy of B_c mesons

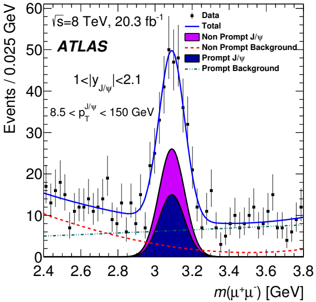
Stay tuned for further results!

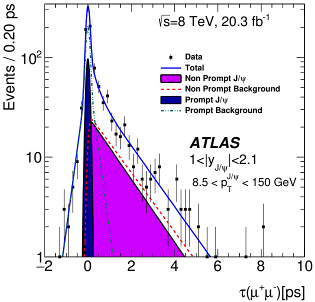
Backup slides

J/ψ mass–lifetime fits









ATLAS detector and trigger for B-physics

- Inner Detector in solenoid field for reconstructing tracks and vertices ($|\eta| < 2.5$)
- Muon Spectrometer in toroid field for muon identification ($|\eta| < 2.7$)
- Trigger selection primarily bases on di-muon signature