ATLAS results on quarkonia and heavy flavour production

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Introduction

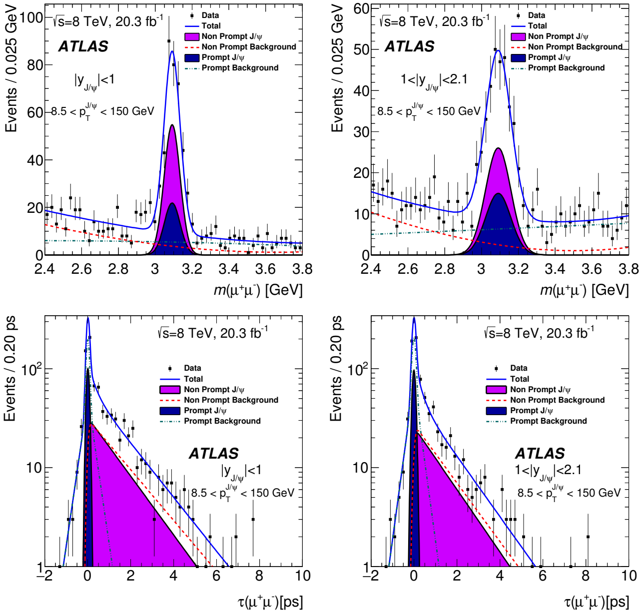
B-physics at ATLAS

- Possible to measure heavy flavour (HF) production at *high energy*
- Much *higher HF yields* in *pp* environment compared to B-factories
- Extended spectroscopy studies are possible
- ATLAS and CMS, although not specially optimized for B-physics, provide *complementary kinematic region to LHCb*
  - Benefit from *higher statistics* in certain analyses

- This talk covers a selection of ATLAS results on quarkonia and heavy flavour production
  - J/ψ production in association with a $W^{\pm}$ boson at $\sqrt{s} = 8$ TeV – JHEP 01 (2020) 095
  - High-p_{T} J/ψ and $\psi(2S)$ production at 13 TeV ATLAS-CONF-2019-047
  - Relative B_c/B^+ production measurement at 8 TeV – Submitted to PRD
  - Search for pentaquarks in $J/\psi p$ system from $\Lambda_b \to J/\psi p K^+$ decays – ATLAS-CONF-2019-048

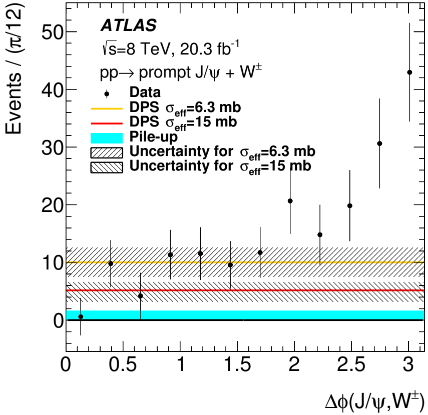
Associated production of $J/\psi + W^{\pm}$ at 8 TeV

- Production mechanism of charmonium in hadronic collisions is not fully understood;
- Relative contribution of Color Singlet (CS) and Color Octet (CO) is unknown
- In addition contributions of double parton scattering vs. single parton scattering processes unknown.
- A measurement of the production of prompt $J/\psi + W^{\pm}$ events in hadronic collisions;
  - Use 20.3 fb^{-1} @ 8 TeV data;
  - $J/\psi \to \mu^+\mu^-$ and $W^{\pm} \to \mu^{\pm}\nu_{\mu}$ – at least three identified muons;
- Prompt signal yields:
  - $93 \pm 14(stat)$ for $|y_{J/\psi}| < 1$ and $102 \pm 17(stat)$ for $1 < |y_{J/\psi}| < 2.1$



Associated production of $J/\psi + W^{\pm}$: double parton scattering

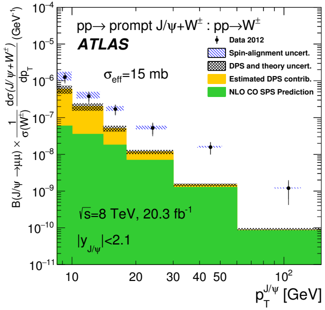
- Two principal possibilities to produce two objects in a *pp* collision:
  - Single Parton Scattering (*SPS*) – the two objects are produced via a subprocess in a single interaction of two partons.
  - Double Parton Scattering (*DPS*) – simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated.
- The probability is $P_{J/\psi|W^{\pm}} = \sigma_{J/\psi}/\sigma_{eff}$
  - Effective cross section σ_{eff} is unknown so choose two different values from previous ATLAS measurements:
    - $\sigma_{eff} = 15 \pm 3(stat.)^{+5}_{-3}(syst.)$ mb – from $W^{\pm} + 2$-jet
    - $\sigma_{eff} = 6.3 \pm 1.6(stat.) \pm 1.0(syst.)$ mb – from J/ψ pair production
  - The prompt J/ψ cross section from the ATLAS measurement
  - Between $(31^{+9}_{-12})\%$ $(\sigma_{eff} = 15$ mb$)$ and $(75 \pm 23)\%$ $(\sigma_{eff} = 6.3$ mb$)$ of the inclusive signal yield is due to *DPS* interactions.
- A uniform distribution in the azimuthal angle $\Delta\phi$ between the $W^{\pm}$ and J/ψ momenta is expected from DPS, under the assumption that the two interactions are independent.

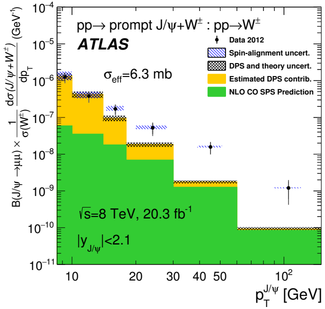


- Peak near π and a tail extending towards zero in data distribution $\Longrightarrow$ *SPS* and *DPS* events are present;
- Both values of σ_{eff} are consistent with the data at low $\Delta\phi$.

Associated production of $J/\psi + W^{\pm}$: cross-section ratios

- Cross-section ratios are presented for $8.5 < p_{\mathrm{T}}^{J/\psi} < 150$ GeV and $|y^{J/\psi}| < 2.1$
- Fiducial – production cross-section ratio in the J/ψ fiducial region
  $R^{fid}_{J/\psi} = (2.2 \pm 0.3 \pm 0.7) \times 10^{-6}$
- Inclusive – after correction for J/ψ acceptance
  $R^{incl}_{J/\psi} = (5.3 \pm 0.7 \pm 0.8^{+1.5}_{-0.7}) \times 10^{-6}$
- DPS-subtracted – after subtraction of the double parton scattering component
  $R^{DPS\ sub}_{J/\psi} = (3.6 \pm 0.7^{+1.1+1.5}_{-1.0-0.7}) \times 10^{-6}$, $[\sigma_{eff} = 15\text{ mb}]$
  $R^{DPS\ sub}_{J/\psi} = (1.3 \pm 0.7 \pm 1.5^{+1.5}_{-0.7}) \times 10^{-6}$, $[\sigma_{eff} = 6.3\text{ mb}]$
- neither value of σ_{eff} is able to correctly model the J/ψ p_{T} dependence



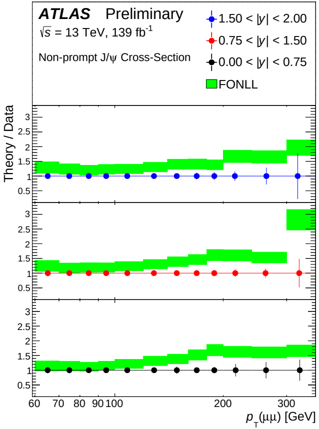


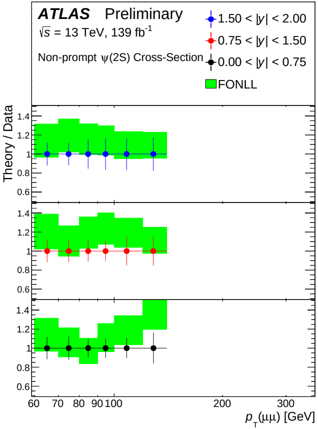
High-p_T J/ψ and $\psi(2S)$ production measurement

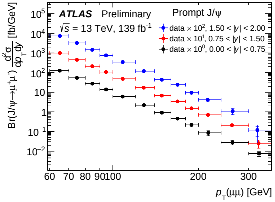
- Two different mechanisms for charmonium production:
  - *Prompt*: directly in pp interaction or via feed-down from heavier states
  - *Non-prompt*: from decays of b hadrons
- ATLAS measured before J/ψ and ψ(2S) differential x-sections at 7, 8 TeV– Eur. Phys. J. C 76 (2016) 283
  - Overall reasonable agreement with theoretical predictions for prompt and non-prompt production
  - Di-muon triggers with low thresholds – could not reach beyond p_T of $\sim$ 100 GeV
- New measurement focuses on high-p_T charmonia
  - Help to discriminate various theoretical models
  - Use *single-muon* triggers (50 GeV muon p_T thershold) to cover the range 60 – 360 GeV
  - Full Run-2 dataset, 139 fb^{-1} at 13 TeV
  - Double-differential x-section measurement

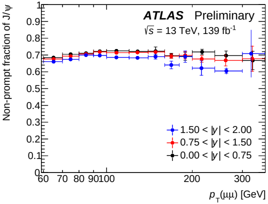
High-p_T J/ψ and $\psi(2S)$ measurement: results

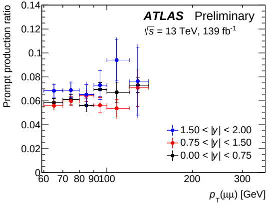
- Measured are
  - Prompt and non-prompt J/ψ and $\psi(2S)$ x-sections
  - Non-prompt fraction for J/ψ and $\psi(2S)$
  - $\psi(2S)/J/\psi$ production ratio for prompt and non-prompt
- p_T ranges extends significantly
- FONLL consistent at low-p_T, over-estimates high-p_T production





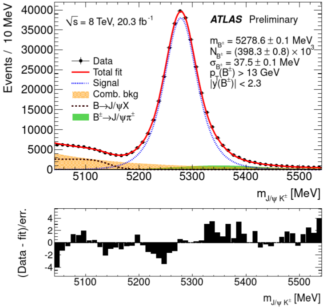


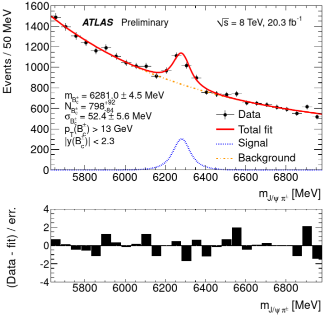




Relative B_c/B^+ production measurement at 8 TeV

- B_c^+ is the only known weakly decaying particle made of two heavy quarks
  - Unique probe for heavy quark dynamics
  - The first observation of radial excitation was done by ATLAS and confirmed by LHCb and CMS
  - Spin splitting for $Bc(2S)$ wasn't observed in ATLAS $\Longrightarrow$ further study underway
- 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 mostly cancel
- Fiducial region of the measurement:
  - $p_{\mathrm{T}}(B) > 13\,\mathrm{GeV}$, $|y(B)| < 2.3$





B_c/B^+ production: results

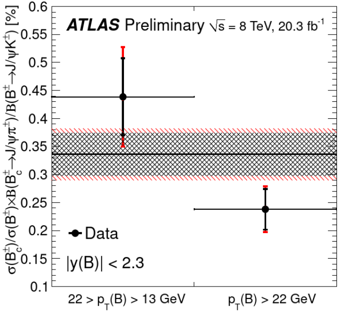
- Production ratio in the fiducial region

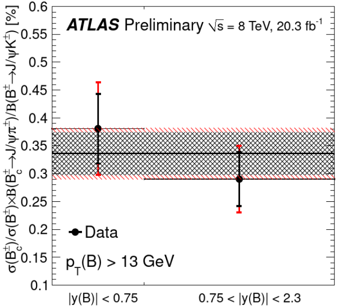
$$\frac{\sigma(B_c)\cdot\mathcal{B}(B_c\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} =$$

$$(0.34\pm0.04(\text{stat.})\pm0.02(\text{syst.})\pm0.01(\text{lifetime}))\%$$

  - Lower than the LHCb result for more forward and lower-p_T fiducial volume
  - Fairly consistent with the CMS result in a similar (but not identical) volume
- B_c production decreases faster with p_T than that for B^+
- No evident rapidity dependence

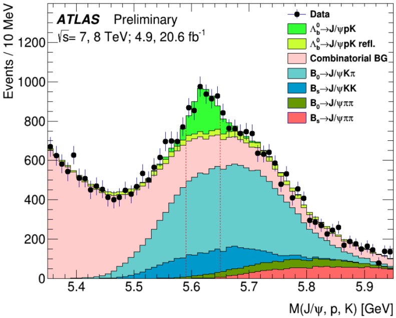
Analysis bin	$\sigma(B_c^\pm)/\sigma(B^\pm)\times\mathcal{B}(B_c^\pm\to J/\psi\pi^\pm)/\mathcal{B}(B^\pm\to J/\psi K^\pm)$
$p_T(B)>13$ GeV, $\lvert y(B)\rvert<2.3$	$(0.34\pm0.04_{\text{stat}}\pm0.02_{\text{syst}}\pm0.01_{\text{lifetime}})\%$
$22>p_T(B)>13$ GeV, $\lvert y(B)\rvert<2.3$	$(0.44\pm0.07_{\text{stat}}\pm0.04_{\text{syst}}\pm0.01_{\text{lifetime}})\%$
$p_T(B)>22$ GeV, $\lvert y(B)\rvert<2.3$	$(0.24\pm0.04_{\text{stat}}\pm0.01_{\text{syst}}\pm0.01_{\text{lifetime}})\%$
$p_T(B)>13$ GeV, $\lvert y(B)\rvert<0.75$	$(0.38\pm0.06_{\text{stat}}\pm0.04_{\text{syst}}\pm0.01_{\text{lifetime}})\%$
$p_T(B)>13$ GeV, $2.3>\lvert y(B)\rvert>0.75$	$(0.29\pm0.05_{\text{stat}}\pm0.02_{\text{syst}}\pm0.01_{\text{lifetime}})\%$





Search for pentaquarks with Run 1 data

- Motivated by LHCb discovery of new resonances $P_c(\bar{c}cuud)$ in $J/\psi p$ system from $\Lambda_b \to J/\psi p K^-$ decay
- $P_c(4380)^+$, $P_c(4450)^+$
  - LHCb has reported that the $P_c(4450)^+$ signal may represent two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$, and that there is another narrow resonance, $P_c(4312)^+$
- No particle-ID in ATLAS – select $J/\psi h_1 h_2$ candidates where $h_{1,2}$ can be p, $K^\pm$, $\pi^\pm$
  - $\Lambda_b \to J/\psi p K^-$ via intermediate Λ^{*0}'s and P_c's
  - $B^0 \to J/\psi K^+\pi^-$ via intermediate K^{*0}'s and Z_c's[1]
  - $B_s^0 \to J/\psi K^+ K^-$ via intermediate f^0 and ϕ's
  - $B^0 \to J/\psi \pi^+\pi^-$ (via intermediate f^0's and ρ's)
  - $B_s^0 \to J/\psi \pi^+\pi^-$ (via intermediate f^0's and ρ's)
- Simulation uses phase-space decays weighted with with the analytically derived decay matrix elements
- Same-sign $h_1 h_2$ background is subtracted
- To suppress light Λ^{*0}'s, K^{*0}'s, f^0, ϕ's, remove events with $M(\pi K)$ or $M(K\pi) < 1.55$ GeV

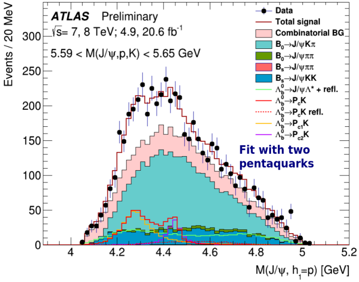


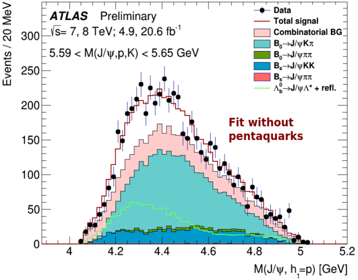
1010 ± 140 Λ_b candidates in the signal region

[1] $Z_c(4200)(\bar{c}c\bar{d}u)$

- Data prefer the model with two or more pentaquark states:
  - Model with two pentaquarks:
    $\chi^2/\text{n.d.f.} = 37.1/39, p = 55.7\%$
  - Equally fine with four-pentquarks hypothesis
  - Model w/o pentaquarks still not excluded:
    $\chi^2/\text{n.d.f.} = 42.0/23, p = 9.1 \cdot 10^{-3}$
- P_{c1} mass slightly lower than LHCb result
  - Fit with all masses and widths fixed to LHCb gives
    $\chi^2/\text{n.d.f.} = 49.0/43, p = 24.5\%$

Parameter	Value	LHCb value
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	$140^{+77}_{-50}(\text{stat})^{+41}_{-33}(\text{syst})$ MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	$4449^{+20}_{-29}(\text{stat})^{+18}_{-10}(\text{syst})$ MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	$51^{+59}_{-48}(\text{stat})^{+14}_{-46}(\text{syst})$ MeV	$39 \pm 5 \pm 19$ MeV



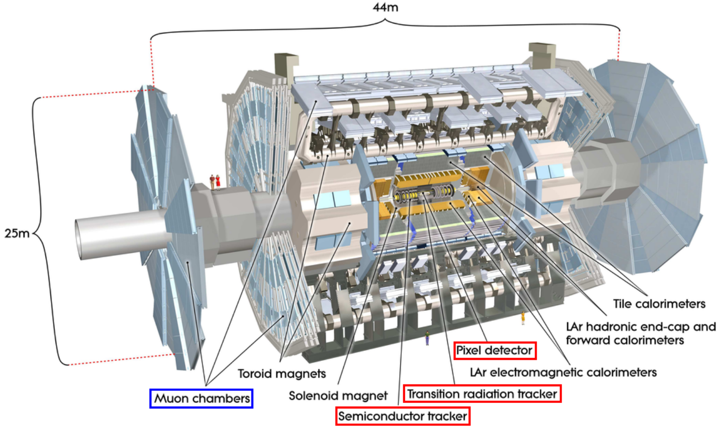


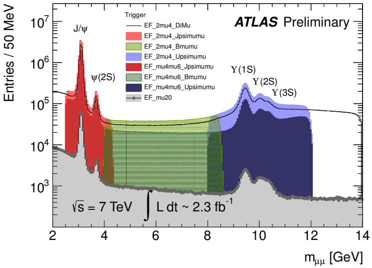
Summary

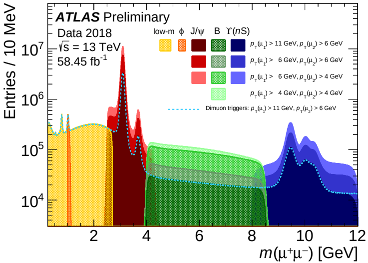
- A selection of ATLAS results on heavy flavour production was presented
  - Associated production of $J/\psi + W$
  - Production of open charm
  - Physics of B_c mesons
  - Conventional and exotic hidden charm states
- More can be found here:
  - ATLAS B-physics public results page
- Many interesting results are still to come!

Backup slides

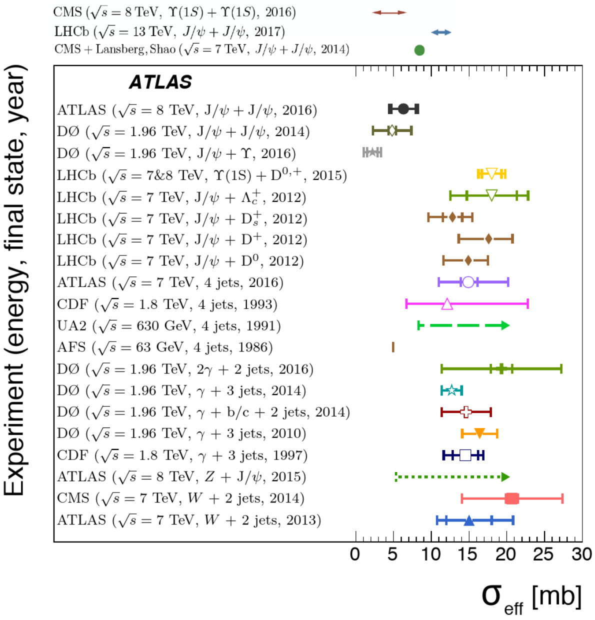
ATLAS detector and trigger







Measurement overview – Eur. Phys. J. C 77 (2017) 76



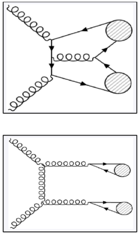
Studying associated production

- Multiple possibilities to produce two objects A, B in a pp collision
  - Single Parton Scattering (*SPS*)
    - described by specific process cross-section σ_{AB}^{SPS} – higher-order *"real"* associated production
  - Double Parton Scattering (*DPS*)
    - individual process cross-sections σ_A, σ_B
    - effective cross-section σ_{eff} accounting for probability of the two processes to happen in a single *pp* collision

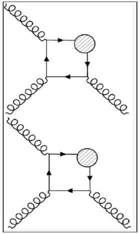
$$\sigma_{AB} = \sigma_{AB}^{\text{SPS}} + \sigma_{AB}^{\text{DPS}} = \sigma_{AB}^{\text{SPS}} + \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}}$$

- DPS/SPS separation is intrinsically uncertain
  - Limited knowledge of σ_{eff}
  - Higher-order SPS contributions can undermine assumptions
  - Experimentally one can measure N_A, N_B, and N_{AB}, with different efficiencies, lumi etc

$$f_{\text{DPS}} = \frac{\sigma_{AB}^{\text{DPS}}}{\sigma_{AB}} = \frac{\sigma_A \sigma_B}{\sigma_{AB}\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}} \sim \frac{1}{\sigma_{\text{eff}}} \times \frac{N_A N_B}{N_{AB}} \times \frac{1}{1+\delta_{AB}}$$



SPS



DPS

Definitions & backgrounds

$W^{\pm}$ boson selection
At least one isolated muon that originates < 1 mm from primary vertex along z-axis
p_{T} (trigger muon) $> 25\,\mathrm{GeV}$
$\lvert\eta^{\mu}\rvert < 2.4$
Missing transverse momentum $> 20\,\mathrm{GeV}$
$m_{\mathrm{T}}(W^{\pm}) > 40\,\mathrm{GeV}$
$\lvert d_0\rvert/\sigma_{d_0} < 3$

J/ψ selection
$2.4 < m(\mu^+\mu^-) < 3.8$ GeV
$8.5 < p_{\mathrm{T}}^{J/\psi} < 150$ GeV, $\lvert y_{J/\psi}\rvert < 2.1$
$p_{\mathrm{T}}^{\mu_1} > 4$ GeV, $\lvert\eta^{\mu_1}\rvert < 2.5$
$\left\{ \begin{array}{ll} \text{either } p_{\mathrm{T}}^{\mu_2} > 2.5 \text{ GeV}, & 1.3 \le \lvert\eta^{\mu_2}\rvert < 2.5 \\ \text{or } p_{\mathrm{T}}^{\mu_2} > 3.5 \text{ GeV}, & \lvert\eta^{\mu_2}\rvert < 1.3 \end{array} \right\}$

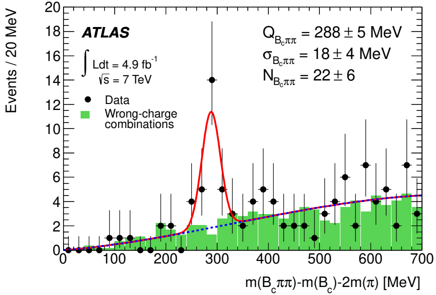
- The backgrounds $W^{\pm} \to \tau\nu$, $Z \to \mu\mu$, $Z \to \tau\tau$, diboson, $t\bar{t}$ and single top were also modelled with MC simulations.
- Production of $W^{\pm}$ bosons in association with b quarks, subsequent b-hadron decay to J/ψ rejected using the fit;
- Decays of $B_c \to J/\psi\mu\nu_{\mu}X$ – negligible background;
- Multi-jet production – a standard data-driven technique is used

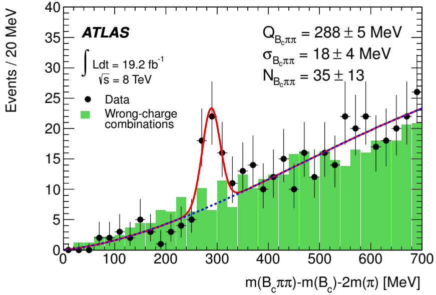
$$R_{J/\psi}^{\mathrm{fid}} = \frac{\sigma_{\mathrm{fid}}(pp \to J/\psi + W^{\pm})}{\sigma(pp \to W^{\pm})} \cdot \mathcal{B}(J/\psi \to \mu\mu) = \frac{1}{N(W^{\pm})} \sum_{p_{\mathrm{T}}\,\mathrm{bins}} [N^{\mathrm{eff}}(J/\psi + W^{\pm}) - N_{\text{pile-up}}^{\mathrm{fid}}],$$

$$R_{J/\psi}^{\mathrm{incl}} = \frac{\sigma_{\mathrm{incl}}(pp \to J/\psi + W^{\pm})}{\sigma(pp \to W^{\pm})} \cdot \mathcal{B}(J/\psi \to \mu\mu) = \frac{1}{N(W^{\pm})} \sum_{p_{\mathrm{T}}\,\mathrm{bins}} [N^{\mathrm{eff+acc}}(J/\psi + W^{\pm}) - N_{\text{pile-up}}]$$

$B_c(2S)$ observation

- Search in $B_c\pi^+\pi^-$ final state, B_c in $J/\psi\pi^+$ mode
  - Study the spectrum of $Q = m(B_c\pi^+\pi^-) - m(B_c) - 2m(\pi^+)$
- A new state observed at $Q = 288.3 \pm 3.5(\text{stat.}) \pm 4.1(\text{syst.})$ MeV (error-weighted mean of 7 and 8 TeV values)
  - Corresponds to a mass $6842 \pm 4(\text{stat.}) \pm 5(\text{syst.})$ MeV, consistent with the predicted mass of $B_c(2S)$
  - Combined significance is 5.2σ
- Possible interpretations:
  - $B_c[2^3S_1] \to B_c^*(1S)(\to B_c\gamma)\pi^+\pi^-$
  - $B_c[2^1S_0] \to B_c(1S)\pi^+\pi^-$
- Similar analysis recently reported by LHCb and CMS
  - State splitting was observed in both
- Further study underway in ATLAS

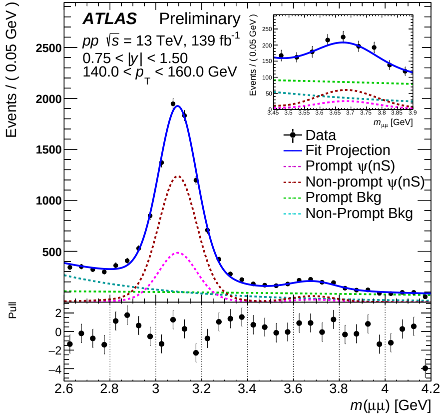


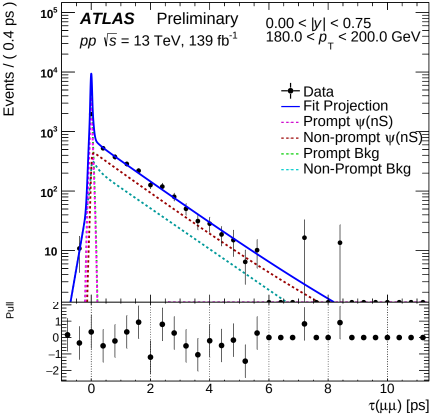


J/ψ and $\psi(2S)$ fits

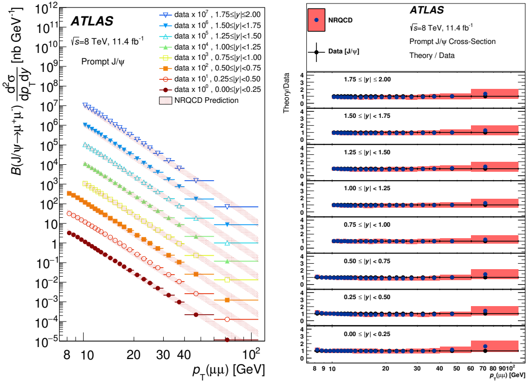
i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega G_1(m) + (1-\omega)CB_1(m)$	$\delta(\tau)$
2	J/ψ	NP	$\omega G_1(m) + (1-\omega)CB_1(m)$	$E_1(\tau)$
3	$\psi(2S)$	P	$\omega G_2(m) + (1-\omega)CB_2(m)$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega G_2(m) + (1-\omega)CB_2(m)$	$E_2(\tau)$
5	Bkg	P	B	$\delta(\tau)$
6	Bkg	NP	$E_4(m)$	$E_5(\tau)$
7	Bkg	NP	$E_6(m)$	$E_7(\|\tau\|)$

Notation	Function
G	Gaussian
CB	Crystal Ball
E	Exponential
B	Bernstein polynomials

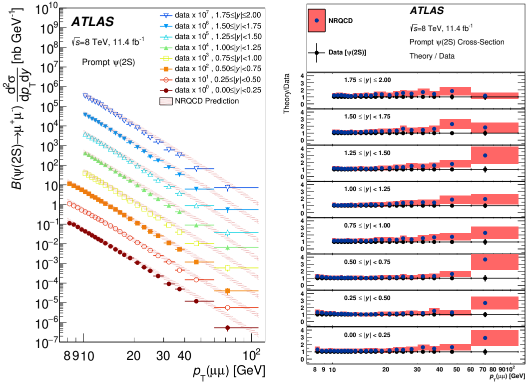




J/ψ and $\psi(2S)$ production @ 8 TeV(Eur. Phys. J. C 76 (2016) 283): prompt



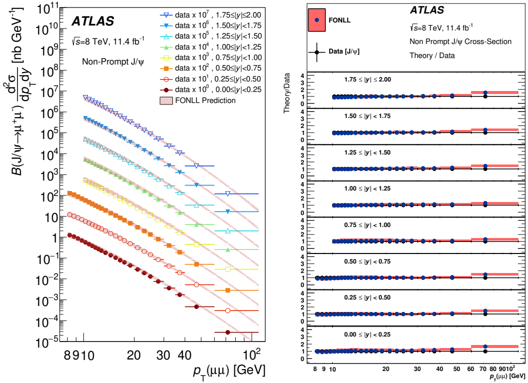
Prompt J/ψ



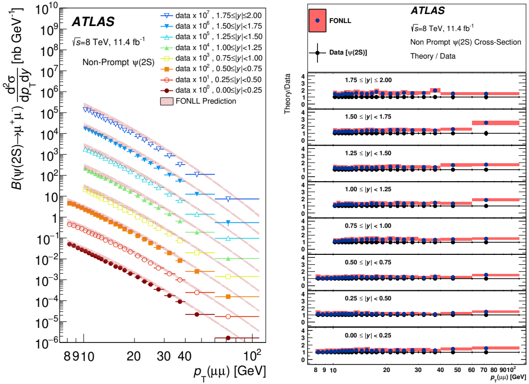
Prompt $\psi(2S)$

- J/ψ: good description by NRQCD across range of p_{T}, no y dependence
- $\psi(2S)$ (no significant feed-down): NRQCD mostly well describes data
  - some deterioration at high p_{T}

J/ψ and $\psi(2S)$ production @ 8 TeV(Eur. Phys. J. C 76 (2016) 283): non-prompt



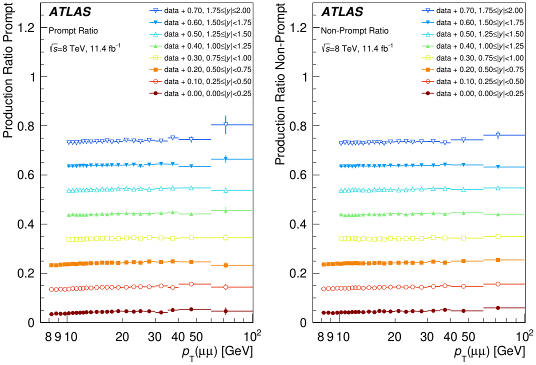
Non-prompt J/ψ



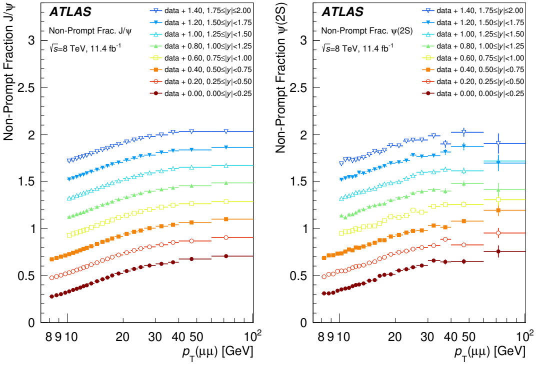
Non-prompt $\psi(2S)$

- FONLL predicts slightly harder p_T spectra for both J/ψ and $\psi(2S)$

J/ψ and $\psi(2S)$ production @ 8 TeV (Eur. Phys. J. C 76 (2016) 283): ratios



$\psi(2S)$ to J/ψ ratio for prompt/non-prompt



Non-prompt fraction for J/ψ and $\psi(2S)$

- Ratio of J/ψ to $\psi(2S)$ flat across the whole p_T range
- Prompt J/ψ ($\psi(2S)$) dominate over non-prompt at low p_T, but the non-prompt exceed after ~20 GeV (~30 GeV)

Search for pentaquarks: fit

Fit uses signal region ($5.59 < m(J/\psi p K^-) < 5.65$ GeV) and two control regions for B^0 and B^0_s

Global fit

Fitting decay coupling constants for B-meson decays. Λ_b decay couplings are fixed

Information included:
- 2D: M(J/ψ,K,K), M(J/ψ,π,π)
- 2D: M(J/ψ,K,π), M(J/ψ,π,K);
- 2D: M(J/ψ,K), M(J/ψ,π) in B_d CR
- 2D: M(J/ψ,1K), M(J/ψ,2K) in B_s CR
- 1D: M(K,π) and M(π,K) separately in B_d CR
- 1D: M(K,π) in B_d CR

→

M(J/ψ,p,K) fit

Obtain yields of Λ_b, B_d, B_s decays; All decay coupling constants fixed;

Information included:
- 2D: M(J/ψ,p,K), M(J/ψ,π,π);
- 2D: M(J/ψ,K,π), M(J/ψ,π,K);

→

Λ_b decays fit

Fit of Λ_b decay couplings;

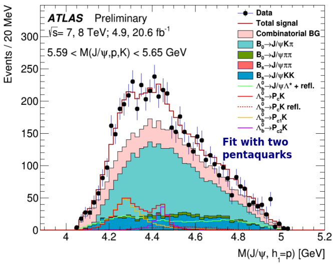
Information included:
- 2D: M(J/ψ,p), M(J/ψ,K) in Λ_b CR
- OR: 1D: M(p,K) in Λ_b CR

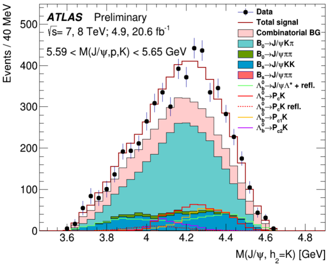
→

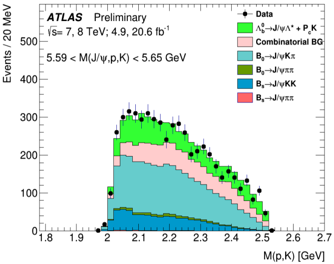
M(J/ψ,p) fit

Fit of pentaquark signal parameters and yields.

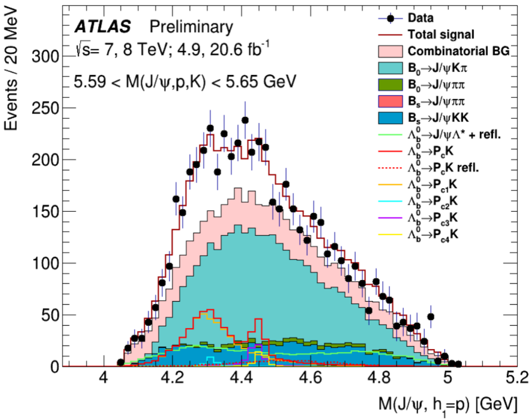
Information included:
- 2D: M(J/ψ,p), M(J/ψ,K) in Λ_b CR
- OR: 1D: M(p,K) in Λ_b CR

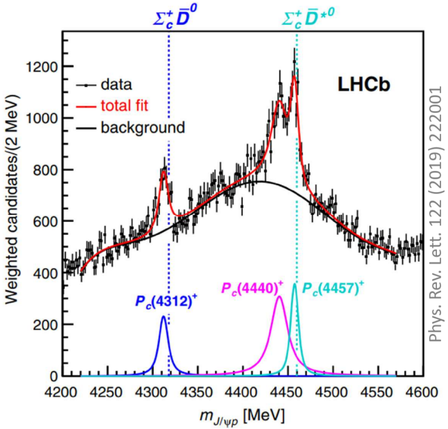






Pentaquark fit with four pentaquarks hypothesis





State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$