# Heavy flavour production at ATLAS

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Heavy-quark hadroproduction from collider to astroparticle physics
Mainz Institute for Theoretical Physics, Johannes Gutenberg University, Germany
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# Introduction

**B-physics at ATLAS**

- Possible to measure heavy flavour (HF) production at *highest possible energies*
- Much *higher HF yields* in *pp* environment compared to B-factories
- Possible to produce *all possible heavy states* $\rightarrow$ extended spectroscopy studies
- 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 heavy flavour production of few years
  - Impossible to cover all interesting studies at once + a bit untypical scope of the Workshop
  - $\rightarrow$ **Feel free to ask and discuss offline!**

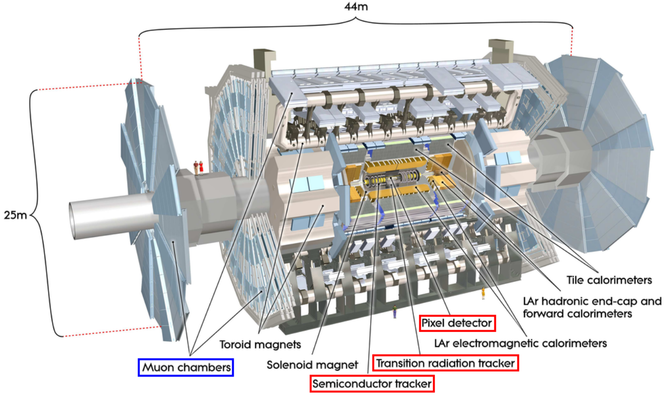
# Outline

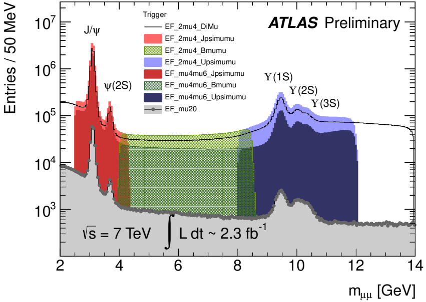
- ATLAS detector
- Open heavy flavour production
  - Charmed meson production at 7 TeV – Nucl. Phys. B 907 (2016) 717
  - $b$ hadron pair production measurement at 8 TeV– JHEP 11 (2017) 62
  - ★ Relative $B_c^+/B^+$ production measurement at 8 TeV – paper in preparation
- Hidden heavy flavour production
  - ★ High-$p_\mathrm{T}$ $J/\psi$ and $\psi(2S)$ production at 13 TeV paper in preparation
  - Heavy quarkonium production in $p$Pb (Eur. Phys. J. C 78 (2018) 171) and PbPb (Eur. Phys. J. C 78 (2018) 762)
  - ★ Search for pentaquarks in $J/\psi p$ system from $\Lambda_b \to J/\psi p K^+$ decays – preliminary conference note in preparation

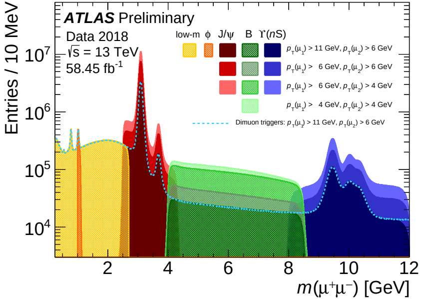
★ – brand-new results released just this week for Beauty conference!

# ATLAS detector and trigger for B-physics

- Inner Detector in solenoid field for reconstructing tracks and vertices
- Muon Spectrometer in toroid field for muon identification
- Trigger selection primarily bases on di-muon signature



### Motivation

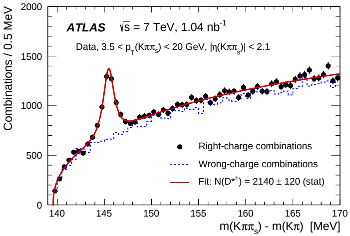
- Heavy quark production measurement at LHC → test of pQCD calculations at highest possible energies
  - Charmed mesons are produced in *charm hadronization* and *b hadron decays*
- Various theoretical approaches available
  - Fixed-order + next-to-leading-logarithm (FONLL) predictions
  - General-mass variable-flavour-number-scheme (GM-VFNS) calculations
  - NLO QCD calculations matched to LL parton-shower MC
    - MC@NLO matched to HERWIG
    - POWHEG matched to HERWIG or PYTHIA

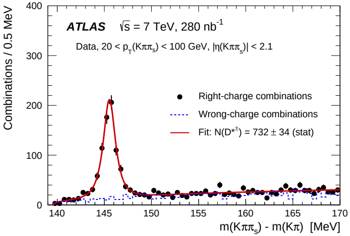
### Scope of the study

- Three $D$ mesons measured: $D^{*+}$, $D^{+}$, $D_s^{+}$
- Kinematic region of the x-section measurement:
  - $3.5 < p_{\mathrm{T}}(D) < 100\,\mathrm{GeV}$
  - $|\eta(D)| < 2.1$
- Data of 2010 at $\sqrt{s} = 7\,\mathrm{TeV}$ are used
  - $1.04\,\mathrm{nb}^{-1}$ collected with minimum-bias triggers used for $p_{\mathrm{T}} < 20\,\mathrm{GeV}$ range
  - $280\,\mathrm{nb}^{-1}$ with jet triggers for $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$ range

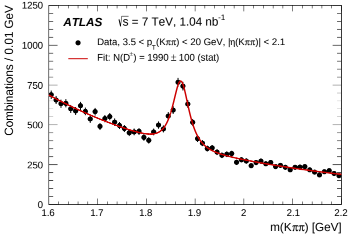
# $D$ meson reconstruction

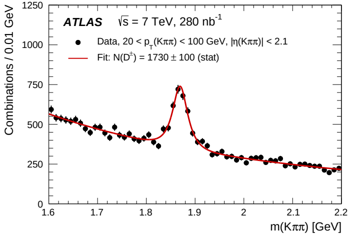
$D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+) \pi_s^+$



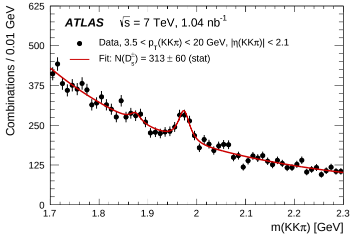



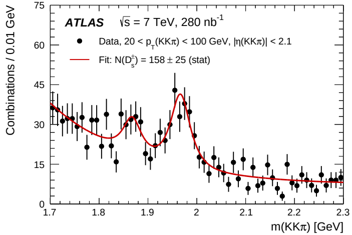

$D^+ \to K^- \pi^+ \pi^+$




$D_s^+ \to \phi \pi^+ \to (K^+ K^-) \pi^+$




$\pi_s^+$ – soft pion

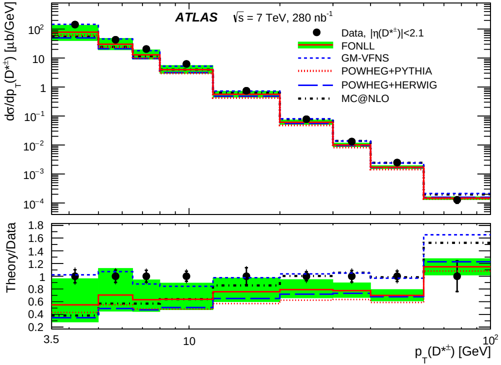
# Results: visible cross-sections

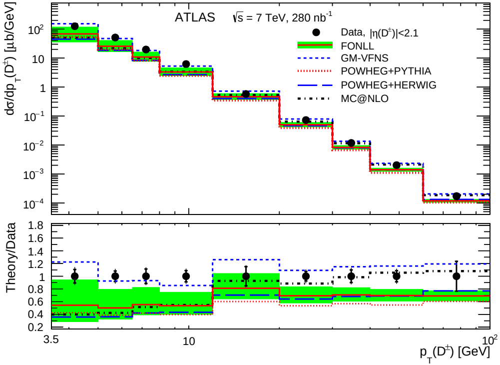
- Visible cross-sections measured:

| | $\sigma^{vis}(D^{*\pm})$ | | $\sigma^{vis}(D^{\pm})$ | | $\sigma^{vis}(D_s^{*\pm})$ | |
|---|---|---|---|---|---|---|
| Range [units] | low-$p_T$ [µb] | high-$p_T$ [nb] | low-$p_T$ [µb] | high-$p_T$ [nb] | low-$p_T$ [µb] | high-$p_T$ [nb] |
| ATLAS | $331 \pm 36$ | $988 \pm 100$ | $328 \pm 34$ | $888 \pm 97$ | $160 \pm 37$ | $512 \pm 104$ |
| GM-VFNS | $340^{+130}_{-150}$ | $1000^{+120}_{-150}$ | $350^{+150}_{-160}$ | $980^{+120}_{-150}$ | $147^{+54}_{-66}$ | $470^{+56}_{-69}$ |
| FONLL | $202^{+125}_{-79}$ | $753^{+123}_{-104}$ | $174^{+105}_{-66}$ | $617^{+103}_{-86}$ | - | - |
| POWHEG+PYTHIA | $158^{+179}_{-85}$ | $600^{+300}_{-180}$ | $134^{+148}_{-70}$ | $480^{+240}_{-130}$ | $62^{+64}_{-31}$ | $225^{+114}_{-69}$ |
| POWHEG+HERWIG | $137^{+147}_{-72}$ | $690^{+380}_{-160}$ | $121^{+129}_{-64}$ | $580^{+280}_{-140}$ | $51^{+50}_{-25}$ | $268^{+107}_{-62}$ |
| MC@NLO | $157^{+125}_{-72}$ | $980^{+460}_{-290}$ | $140^{+112}_{-65}$ | $810^{+390}_{-260}$ | $58^{+42}_{-25}$ | $345^{+175}_{-87}$ |

- Statistical and systematics uncertainties generally of the same order
  - Tracking efficiency, luminosity and branching fractions are the main systematics sources
- GM-VFNS approach shows the best description of data
- FONLL and NLO+PS approaches are generally below data, but still consistent within uncertainties

# Results: differential cross-sections – $p_T$

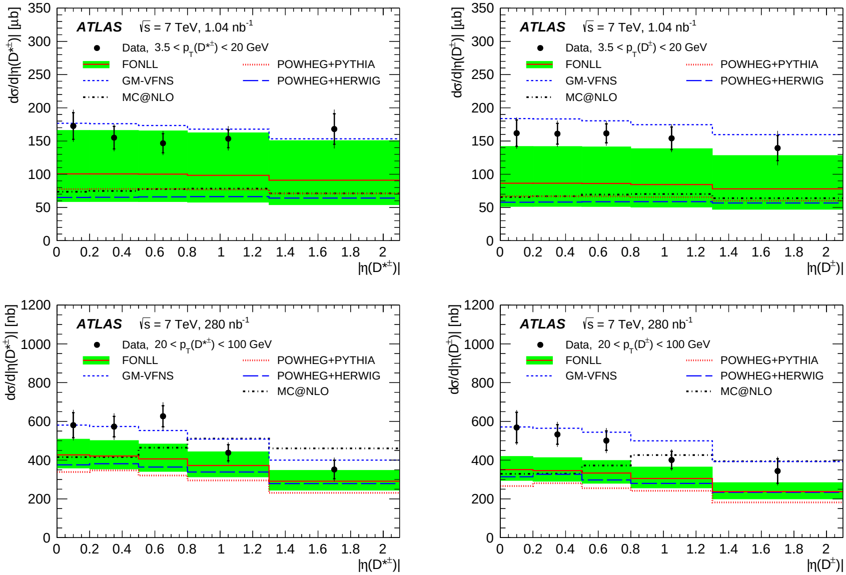



- GM-VFNS describes well both shape and normalization
- FONLL and NLO+PS are still consistent with data
- MC@NLO predicts harder $p_T$ spectrum than in data

# Results: differential cross-sections – $\eta$

- GM-VFNS shows again a better description
- MC@NLO predicts a different $\eta$ shape in the high-$p_T$ range



# Results: extrapolation

- For extrapolation to the full phase space, *FONLL* predictions are used (including subtraction of $b \to c$ contribution)
  - POWHEG+PYTHIA are used for extraction of fragmentation ratios
- Full $c\bar{c}$ production x-section:

$$\sigma_{c\bar{c}}^{\text{tot}} = 8.6 \pm 0.3\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.3\,(\text{lum}) \pm 0.2\,(\text{ff})^{+3.8}_{-3.4}\,(\text{extr})\,\text{mb}$$

  - Good agreement with ALICE measurement
- Charm fragmentation ratios:

$$\gamma_{s/d} = 0.26 \pm 0.05\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.02\,(\text{br}) \pm 0.01\,(\text{extr})\,,$$

$$P_{\text{v}}^{d} = 0.56 \pm 0.03\,(\text{stat}) \pm 0.01\,(\text{syst}) \pm 0.01\,(\text{br}) \pm 0.02\,(\text{extr})\,.$$

  - Good agreement with ALICE, HERA (*ep*) measurements and LEP averages
  - $P_{\text{v}}^{d}$ is smaller than expectation from naive spin-counting (0.75)
    - Questions the HQET assumption on charm fragmentation
  - Also slightly smaller than string fragmentation and thermodynamical approach predictions (2/3)

Overall uniquely advanced measurement for LHC general-purpose detectors!

# $b$ hadron pair production measurement JHEP 1711 (2017) 062

- A number of recent measurement of $b$ production highlighted certain disagreements between models and data
- Especially $b\bar{b}$ production at small open angles is *sensitive to the details of various calculations*, but only *loosely constrained experimentally*
- Studies of $H \to b\bar{b}$ much rely on modelling of $b\bar{b}$ production in this region

- Measure $b\bar{b}$ pair production
  - one $b$ is identified via $H_b \to J/\psi + X$ decay (including feed-downs of heavier charmonia)
  - the other via $H_b \to \mu + Y$ (including cascades)
- Differential cross-sections are measured in
  - $\Delta\phi(J/\psi, \mu)$,
  - $p_{\mathrm{T}}(J/\psi, \mu)$,
  - $\Delta R(J/\psi \mu)$ overall and in bins of $p_{\mathrm{T}}(J/\psi, \mu) < 20\,\mathrm{GeV}$ and $p_{\mathrm{T}}(J/\psi, \mu) > 20\,\mathrm{GeV}$,
  - $\Delta y(J/\psi, \mu)$,
  - average rapidity of $J/\psi$ and $\mu$, $y_{\mathrm{boost}}$,
  - $m(J/\psi, \mu)$
  - $p_{\mathrm{T}}(J/\psi, \mu)/m(J/\psi, \mu)$ and its inverse
- 11.5 $\mathrm{fb}^{-1}$ of $\sqrt{s} = 8\,\mathrm{TeV}$ are used

# Fiducial x-section

- Fiducial volume definition:
  - $p_T(\mu) > 6$ GeV for all three muons
  - $|\eta(\mu)| < 2.3$ for the $J/\psi$ muons and $< 2.5$ for the 3rd muon
- Full fiducial cross-section:

$$\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst})\ \text{nb}.$$

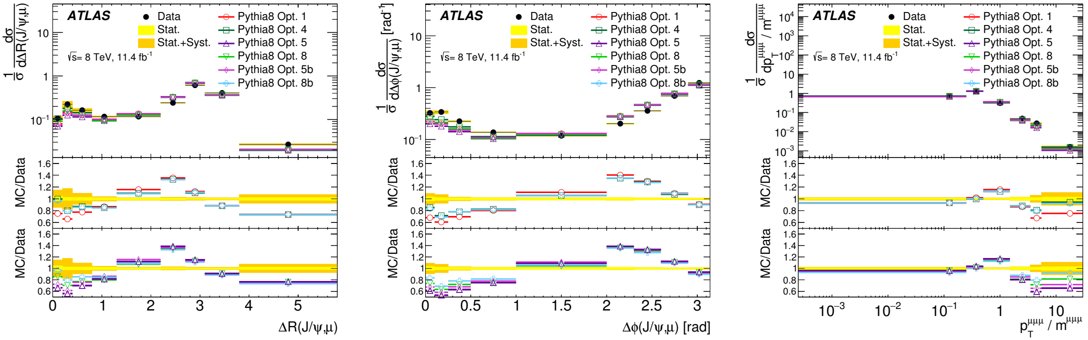
- Comparison with various models are performed:
  - Pythia 8
  - Herwig++
  - MadGraph_aMC@NLOv2.2.2 interfaced to Pythia 8 (CKKW-L merging scheme with 15 GeV merging scale)
    - 4-FNS and 5-FNS modelling in MadGraph
  - Sherpa 2.1.1 (5-FNS), merging with ME+PS@LO prescription

# Test PYTHIA 8 gluon splitting kernels

- Test gluon splitting description
  - Is the scale of $\alpha_s$ in splitting set by relative $p_T$ or by mass?
- 6 options for the splitting kernels in PYTHIA 8
- PYTHIA does not describe these shapes
  - $p_T$-based scale splitting kernels behave better for close-by $b\bar{b}$

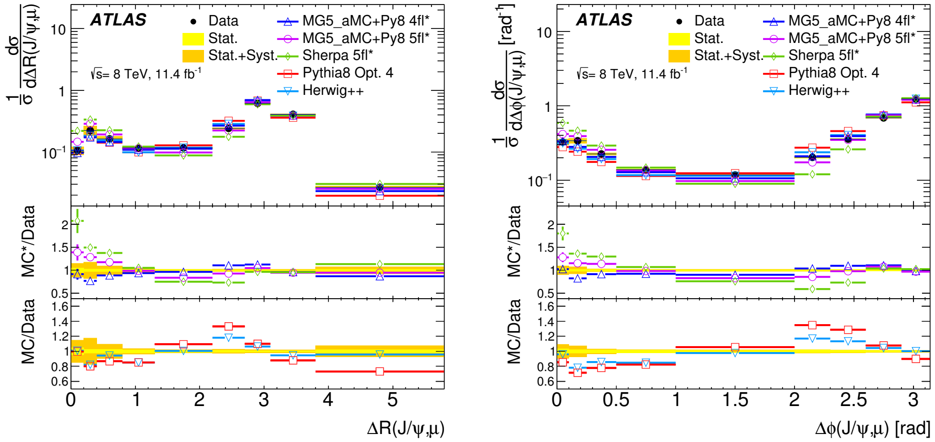
| Option label | Descriptions |
|---|---|
| Opt. 1 | The same splitting kernel, $(1/2)(z^2 + (1-z)^2)$, for massive as massless quarks, only with an extra $\beta$ phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [50] method. |
| Opt. 4 | A splitting kernel $z^2 + (1-z)^2 + 8r_q z(1-z)$, normalised so that the $z$-integrated rate is $(\beta/3)(1+r/2)$, and with an additional suppression factor $(1 - m_{qq}{}^2/m^2_{\text{dipole}})^3$, which reduces the rate of high-mass $q\bar{q}$ pairs. This is the default setting in PYTHIA8.2. |
| Opt. 5 | Same as Option 1, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_T)$, with $k = 1$. |
| Opt. 5b | Same as Option 5, but setting $k = 0.25$. |
| Opt. 8 | Same as Option 4, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_T)$, with $k = 1$. |
| Opt. 8b | Same as Option 8, but setting $k = 0.25$. |

Table 1: Description of PYTHIA8 options. Options 2, 3, 6 and 7 are less well physically motivated and not considered here. The notation used is as follows: $r_q = m^2_q/m^2_{qq}$, $\beta = \sqrt{1-4r_q}$, with $m_q$ the quark mass and $m_{qq}$ the $q\bar{q}$ pair invariant mass.



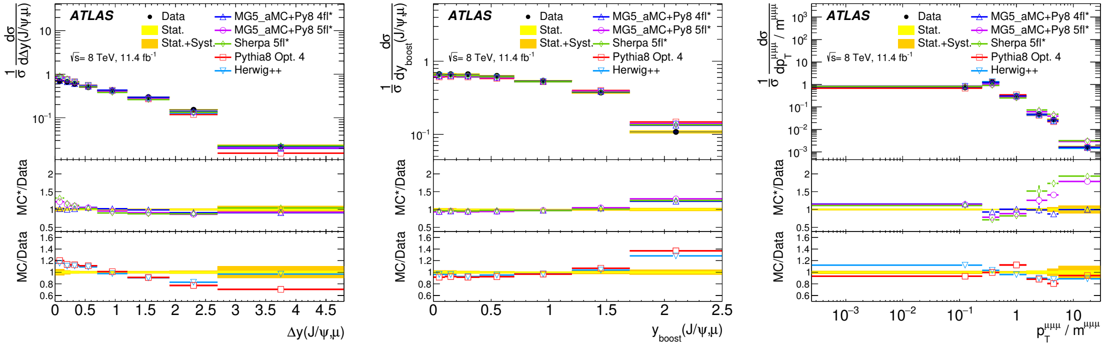
# Test various model predictions (1)

- HERWIG++ reproduces $\Delta R$ and $\Delta\phi$ best
- 4-FNS works better for $\Delta R$ and $\Delta\phi$ than 5-FNS (deviate to opposite sides from data)
- SHERPA is similar to 5-FNS MG, but the description is worse overall



# Test various model predictions (2)

- MG and SHERPA demonstrate better agreement in $\Delta y$, PYTHIA and HERWIG++ worse
- In $y_{\text{boost}}$, a comparable picture across the predictions (expected to be sensitive to PDF)
- 4-FNS describes the high $p_T/m$ region much better than 5-FNS; PYTHIA and HERWIG++ generally comparable

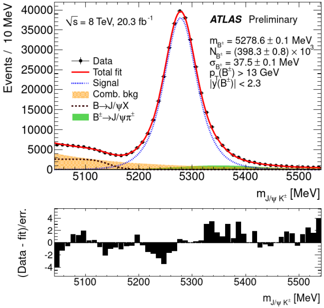


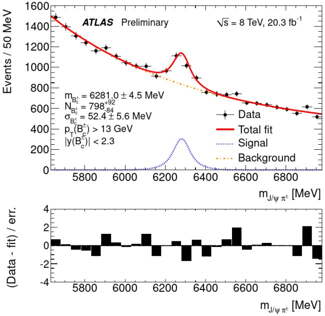
# $b$ hadron pair production: summary

- **Very comprehensive measurement** of differential cross-section of $b\bar{b}$ production performed
  - in 10 kinematic observables
- Particularly sensitive to close-by $b\bar{b}$ pairs down to zero open angle
- Various predictions compared to data
  - different ME, PS models, 4-/5-flavour treatment; $g$ splitting kernels
  - 4-FNS MadGraph_aMC@NLOv2.2.2 provides the best data description overall
  - Pythia and Herwig++ are comparable and further tuning may improve data description
  - theoretical uncertainties not evaluated in this study
- *New test of QCD, motivate the choice of calculations used to model b hadron production and their further tuning*

# Relative $B_c^+/B^+$ production measurement at 8 TeV (paper in preparation)

- $B_c^+$ is the only known weakly decaying particle made of two heavy quarks
  - Unique probe for heavy quark dynamics
- Production involves simultaneous producing $b\bar{b}$ and $c\bar{c}$
  - Expected to be dominated by $gg \to B_c^+ + b + \bar{c}$
  - x-section predicted at level 0.2 % of inclusive $b\bar{b}$ production
- 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:
  - $p_T(B) > 13\,\text{GeV}$, $|y(B)| < 2.3$
- Measure total production and differential in $p_T(B)$ and $|y(B)|$



# $B_c^+/B^+$ production: results

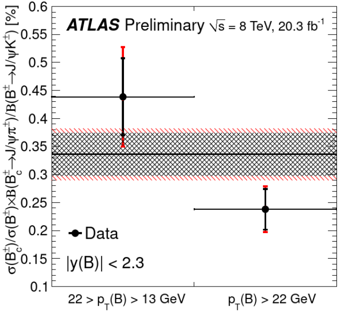
- Production ratio in the fiducial region

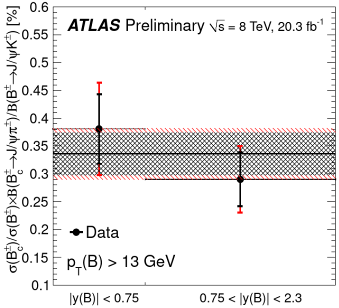
$$\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} =$$

$(0.34 \pm 0.04(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.01\ \text{lifetime})$

  - Lower than the LHCb result [1] for more forward and lower-$p_T$ fiducial volume
  - Fairly consistent with the CMS result [2] 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, $\lvert y(B)\rvert < 2.3$ | $(0.34 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$ |
| $22 > p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 2.3$ | $(0.44 \pm 0.07_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$ |
| $p_T(B) > 22$ GeV, $\lvert y(B)\rvert < 2.3$ | $(0.24 \pm 0.04_{\text{stat}} \pm 0.01_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$ |
| $p_T(B) > 13$ GeV, $\lvert y(B)\rvert < 0.75$ | $(0.38 \pm 0.06_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$ |
| $p_T(B) > 13$ GeV, $2.3 > \lvert y(B)\rvert > 0.75$ | $(0.29 \pm 0.05_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$ |



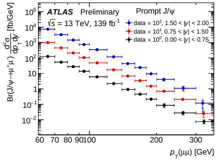



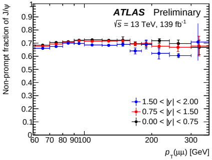
# High-$p_T$ $J/\psi$ and $\psi(2S)$ production measurement (paper in preparation)

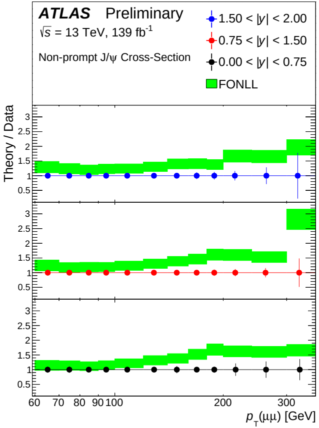
- Two different mechanisms for charmonium production:
  - *Prompt*: directly in *pp* interaction or via feed-down from heavier states
    - ~35% of $J/\psi$ comes from feed-down; $\psi(2S)$ is produced almost directly
    - Theory: Non-Relativistic QCD (NRQCD)
      introduces a number of phenomenological parameters (LDMEs) extracted from Tevatron data fits
    - fails to build a comprehensive description
  - *Non-prompt*: from decays of *b* hadrons
    - Can be distinguished by fitting the pseudo proper lifetime
    - Theory: Fixed Order Next-to-Leading Logarithm (FONLL)
      perturbative $b\bar{b}$ production, data-driven fragmentation and *b* hadron decay model
- ATLAS measured before $J/\psi$ and $\psi$(2S) differential x-sections at 7, 8 TeV– Eur. Phys. J. C 76 (2016) 283
  - Overall reasonable agreement for both approaches
- New measurement focuses on high-$p_T$ charmonia – paper in preparation
  - 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

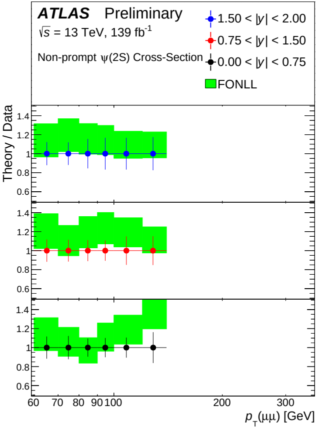
# High-$p_T$ $J/\psi$ and $\psi(2S)$ measurement: results

- Measured are
  - Prompt and non-prompt $J/\psi$ and $\psi(2S)$ x-sections
  - Non-prompt fraction for $J/\psi$ and $\psi(2S)$
  - $\psi(2S)/J/\psi$ production ratio for prompt and non-prompt
- $p_T$ ranges goes well beyond what was achieved so far
- FONLL consistent at low-$p_T$, over-estimates high-$p_T$ production

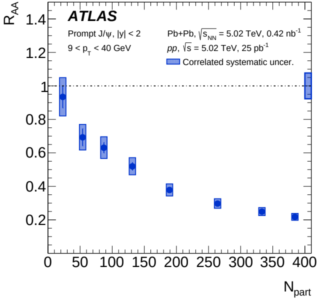


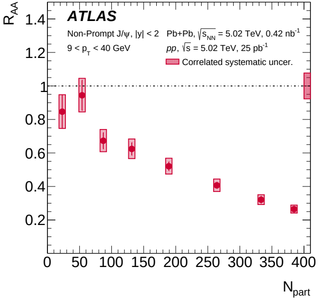



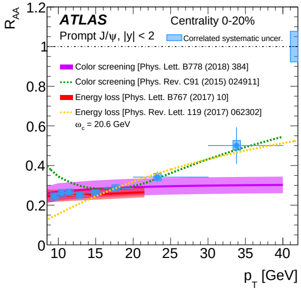



- Probe deconfined quark-gluon plasma in $A+A$ collisions
  - Suppression of *prompt* charmonia could provide info about temperature of deconfinement
  - Possible enhancement: new quarkonium formation mechanism ($c\bar{c}$ recombination in medium)
  - *Non-prompt* charmonia allows studying $b$ quark propagation through the medium
    - Possibly different mechanism (collisions, radiation) from $c\bar{c}$ suppression (colour screening)
- $J/\psi$ production strongly suppressed in central collisions
  - very similar for prompt and non-prompt
  - not quite expected, as the two cases have different origins
- $R_{AA}$ increases at high $p_T > 12$ GeV for prompt $J/\psi$, flat for non-prompt

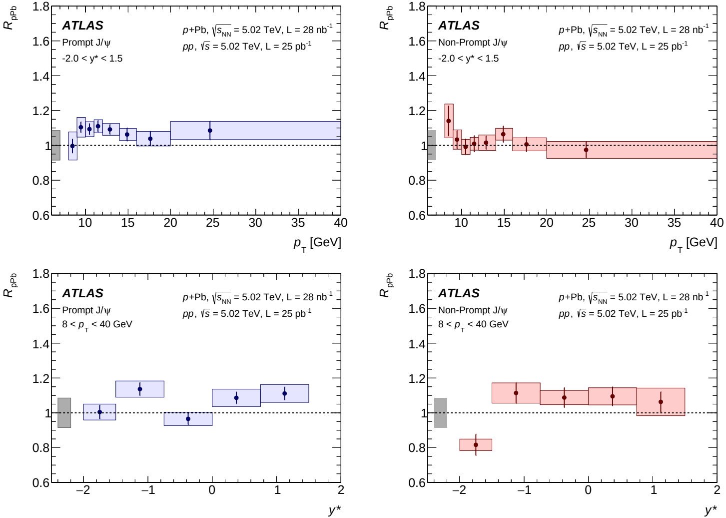


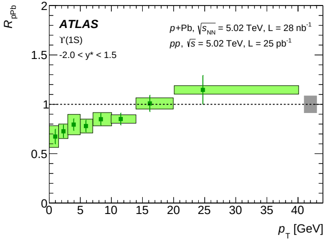



# Charmonia and bottomonia in $p+\text{Pb}$ Eur. Phys. J. C 78 (2018) 171

- $p+A$ collisions serve to disentangle cold nuclear matter effects (CNM)

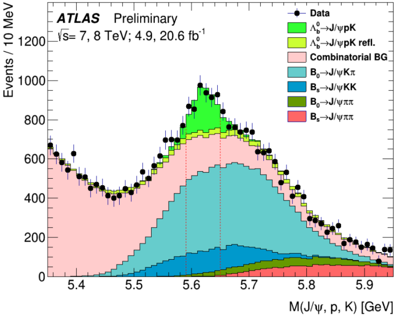



- $R_{pPb}$ factors for prompt and non-prompt $J/\psi$ consistent with unity
  - no $p_T$ or $y^*$ dependence
  - weak modification for $J/\psi$ production due to CNM effects
- $R_{pPb} < 1$ for $\Upsilon(1S)$ below 15 GeV
  - stronger nPDF shadowing for small $x$?



# Search for pentaquarks with Run 1 data (note in preparation)

- Motivated by LHCb discovery of new resonances in $J/\psi p$ system from $\Lambda_b \to J/\psi p K^-$ decay
- 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 $\Lambda^{\star 0}$'s and $P_c$'s
  - $B^0 \to J/\psi K^+ \pi^-$ via intermediate $K^{\star 0}$'s and $Z_c$'s
  - $B^0 \to J/\psi \pi^+ \pi^-$ (via intermediate $f^0$'s and $\rho$'s)
  - $B^0_s \to J/\psi K^+ K^-$ via intermediate $f^0$ and $\phi$'s
  - $B^0_s \to J/\psi \pi^+ \pi^-$ (via intermediate $f^0$'s and $\rho$'s)
- Simulation uses phase-space decays weighted with theoretical MEs
- To suppress light $\Lambda^{\star 0}$'s, $K^{\star 0}$'s, $f^0$, $\phi$'s, remove events with $M(\pi K)$ or $M(K\pi) < 1.55$ 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 (likelihood)**

Fitting decay coupling constants for B-meson decays.
$\Lambda_b$ 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,$K_1$) M(J/ψ,$K_2$) in $B_s$ CR
1D: M(K,π) and M(π,K) in $B_d$ CR
1D: M(K,π) in $B_d$ CR
1D: M(K,K) in $B_s$ CR

→

**$\chi^2$ M(J/ψ,p,K) fit**

Obtain yields of $\Lambda_b$, $B_d$, $B_s$ decays;
All decay coupling constants fixed;

Information included:
1D: M(J/ψ,p,K)

→

**$\Lambda_b$ decays fit (likelihood)**

Fit of $\Lambda_b$ decay couplings;

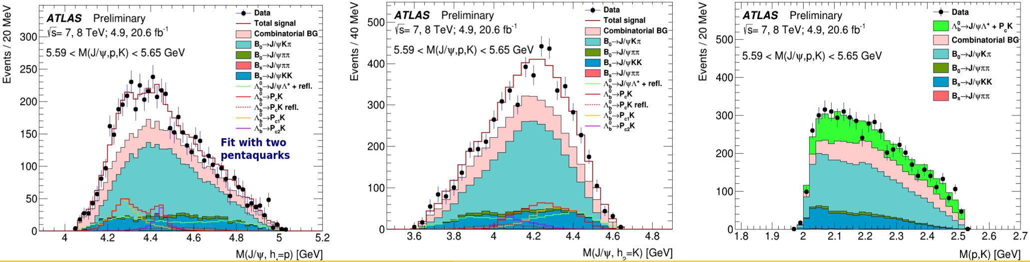
Information included:
2D: M(J/ψ,p), M(J/ψ,K) in $\Lambda_b$ CR
1D: M(p,K) in $\Lambda_b$ CR

→

**$\chi^2$ M(J/ψ,p) fit**

Fit of pentaquark signal parameters and yields.

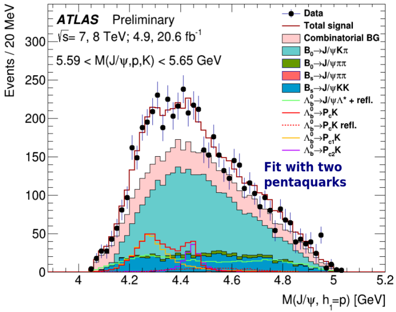
Information included:
1D: M(J/ψ,p) in $\Lambda_b$ CR

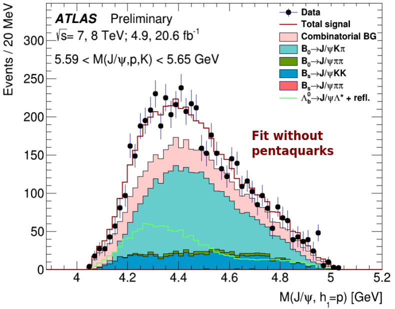


# Search for pentaquarks: results

- Data prefer the 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 [5] |
|---|---|---|
| $N(P_{c1})$ | $400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$ | – |
| $N(P_{c2})$ | $150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$ | – |
| $N(P_{c1}+P_{c2})$ | $540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$ | – |
| $\Delta\phi$ | $2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad | – |
| $m(P_{c1})$ | $4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV | $4380 \pm 8 \pm 29$ MeV |
| $\Gamma(P_{c1})$ | $140^{+77}_{-50}$ (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 |



# Summary

- A selection of ATLAS results on heavy flavour production was presented
  - Production of open charm and beauty
  - Physics of $B_c^+$ mesons
  - Conventional and exotic hidden charm states
  - *A few more interesting results on backup slides :-)*
  - **Do not hesitate to ask and discuss offline!**
- Many B-physics measurements are only based on Run-1 yet – the potential is nearly exhausted
- Full Run-2 dataset is still be be fully exploited – stay tuned for many new results!

# References


[1] LHCb Collaboration, *Measurement of $B_c^+$ Production in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV*, Phys. Rev. Lett. 114 (2015) 132001

[2] CMS Collaboration, *Measurement of the ratio of the production cross sections times branching fractions of $B_c^\pm \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$ and $B(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)/B(B_c^\pm \to J/\psi\pi^\pm)$ at $\sqrt{s} = 7$ TeV*, JHEP 01 (2015) 063

[3] ATLAS Collaboration , *Observation of an Excited $B_c^\pm$ Meson State with the ATLAS Detector*, Phys. Rev. Lett. 113 (2014) 212004

[4] LHCb Collaboration, *Search for excited $B_c^+$ states*, JHEP 01 (2018) 138

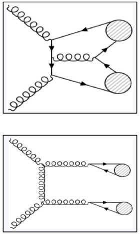
[5] CMS Collaboration, *Observation of Two Excited $B_c^+$ States and Measurement of the $B_c^+(2S)$ Mass in pp Collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. Lett. 122 (2019) 132001

[6] LHCb Collaboration, *Observation of an excited $B_c^+$ state*, Phys. Rev. Lett. 122 (2019) 232001

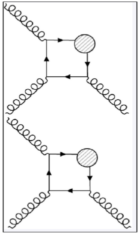
# Backup slides

# Prompt charmonium pair production

- Two principal possibilities to produce two objects in a *pp* collision:
- Single Parton Scattering (*SPS*)
- Double Parton Scattering (*DPS*)
  - effective cross-section $\sigma_{\text{eff}}$ accounting for probability of the two processes to happen in a single *pp* collision: $\sigma_{\text{DPS}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\text{eff}}}$
  - $\sigma_{\text{eff}}$ is assumed to be universal across processes and energy scales
  - 12–20 mb values obtained earlier; however, indication of lower values from pair charmonia/bottommonia production questions the universality of $\sigma_{\text{eff}}$



*SPS*

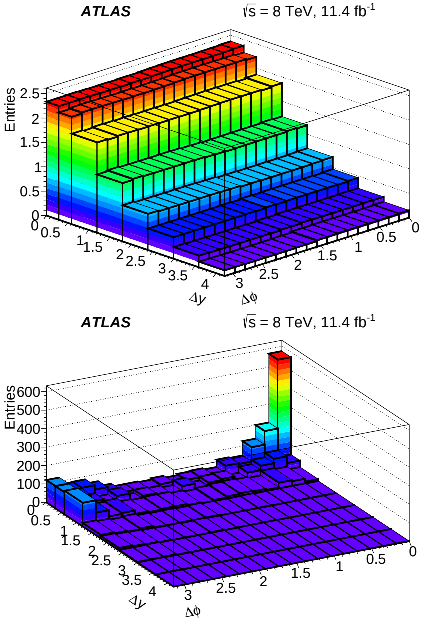


*DPS*

# Prompt $J/\psi$ pair production – Eur. Phys. J. C 77 (2017) 76

- Measure production of prompt $J/\psi$ pairs
- Use $11.4\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$
- Kinematic range: $p_\mathrm{T}(J/\psi) > 8.5\,\mathrm{GeV}$, $|\eta(J/\psi)| < 2.1$
- Per-event corrections
  - Efficiency of trigger and reconstruction
  - Muon acceptance
- Backgrounds
  - Non-$J/\psi$ background separated by 2D mass fits
  - Non-prompt $J/\psi$ contribution separated by 2D $L_\mathrm{xy}$ fits
    - per-event weights as a function of $L_\mathrm{xy}$
  - (Small) pile-up background separated by 1D fit to $d_z$ vertex distance
- Due to different resolution, the measurement is done separately in central ($|y(J/\psi)| < 1.05$) and forward ($1.05 < |y(J/\psi)| < 2$) regions
- DPS and SPS contributions are distinguished with a data-driven approach

- Templates for DPS and SPS contribution in $\Delta\phi(J/\psi J/\psi) \times \Delta y(J/\psi J/\psi)$
- DPS template – event mixing
  - combine $J/\psi$'s from random different events, assuming their independent kinematics
  - normalize to $\Delta y > 1.8$, $\Delta\phi > \pi/2$ region
- SPS contribution
  - obtained by subtracting the DPS from data
- Per-event weights $w_{\text{DPS}}(\Delta\phi, \Delta y)$, $w_{\text{SPS}}(\Delta\phi, \Delta y)$ assigned to study the DPS/SPS spectra



# Results: cross-sections (1)

- Fiducial cross-section in $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, $p_T(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$, $p_T(\mu) > 4$ GeV for two trigger muons

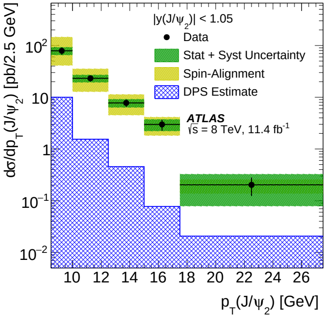
  $15.6 \pm 1.3\,\text{(stat)} \pm 1.2\,\text{(syst)} \pm 0.2\,\text{(BF)} \pm 0.3\,\text{(lumi)}$ pb, for $|y| < 1.05$,
  $13.5 \pm 1.3\,\text{(stat)} \pm 1.1\,\text{(syst)} \pm 0.2\,\text{(BF)} \pm 0.3\,\text{(lumi)}$ pb, for $1.05 \leq |y| < 2.1$

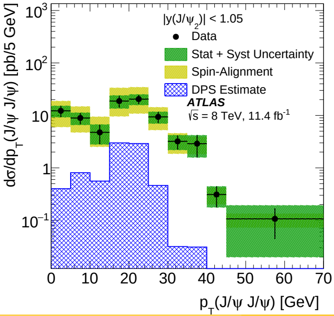
- Total cross-section in the $J/\psi$ kinematic volume

  $82.2 \pm 8.3\,\text{(stat)} \pm 6.3\,\text{(syst)} \pm 0.9\,\text{(BF)} \pm 1.6\,\text{(lumi)}$ pb, for $|y| < 1.05$,
  $78.3 \pm 9.2\,\text{(stat)} \pm 6.6\,\text{(syst)} \pm 0.9\,\text{(BF)} \pm 1.5\,\text{(lumi)}$ pb, for $1.05 \leq |y| < 2.1$

  - assume unpolarized production

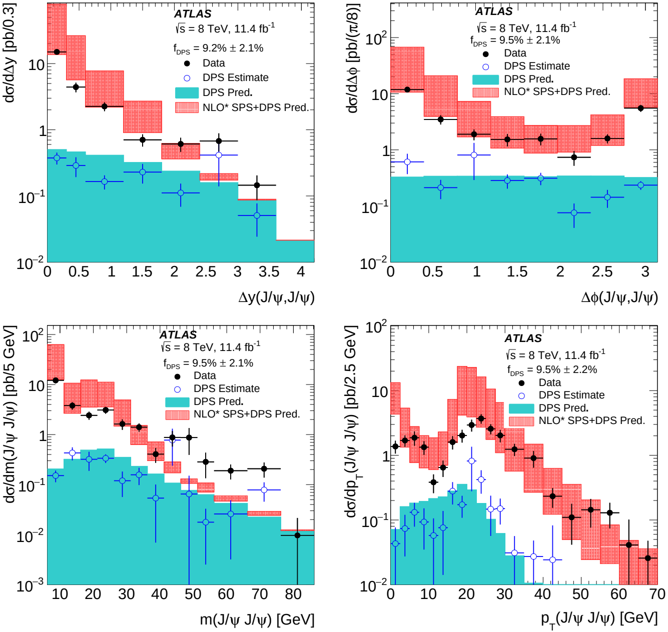
- Two peaks in $p_T(J/\psi J/\psi)$
  - near zero – away topology, back-to-back
  - near higher $p_T$ – towards topology
    - back-to-back to another gluon
    - NLO effect



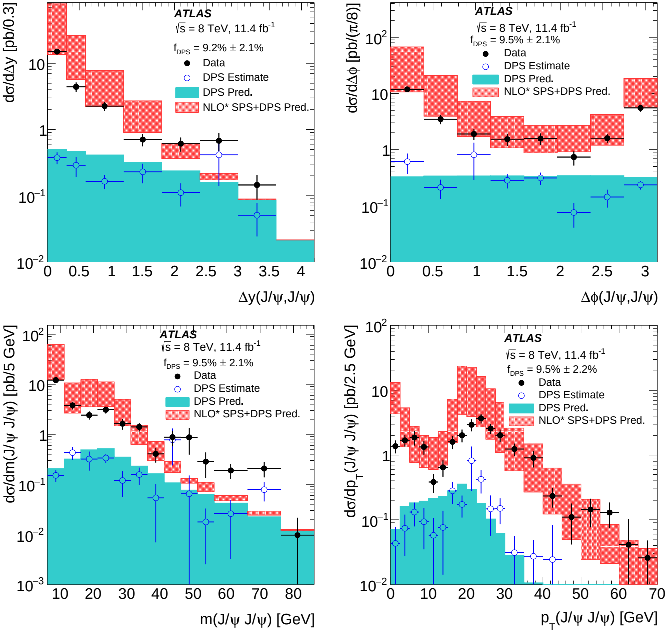



# Results: cross-sections (2)

- Differential SPS/DPS cross-sections measured in the muon fiducial volume
- DPS: scaled to measured $f_{DPS}$ – only shape comparison
  - LO predictions based on Phys. Rev. D 95 (2017) 034029
- SPS
  - Colour-Singlet NRQCD w/o loops (NLO*) Phys. Lett. B 751 (2015) 479, Phys. Rev. Lett. 111 (2013) 122001
  - Scaled by $\times 1.85$ to allow for feed-down



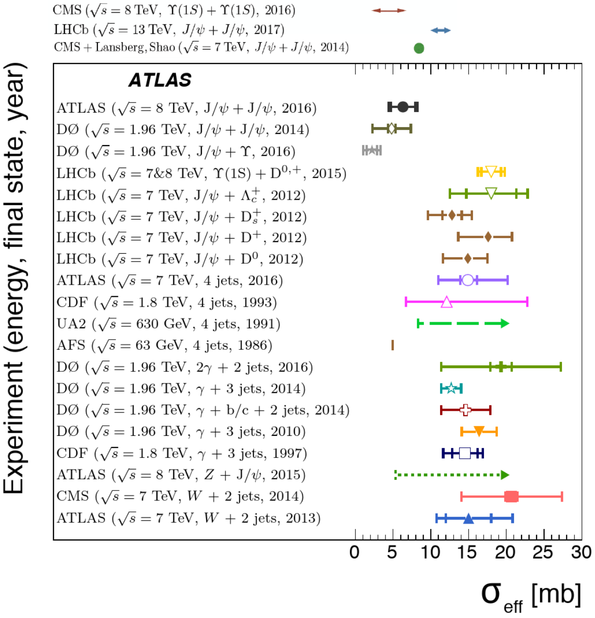
# Results: cross-sections (2)



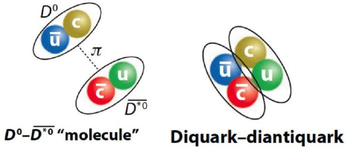

- Overall good agreement for DPS contribution
- Some discrepancies in total cross-section for away topology
- Significant fraction of events with towards topology → LO predictions alone not enough to describe it

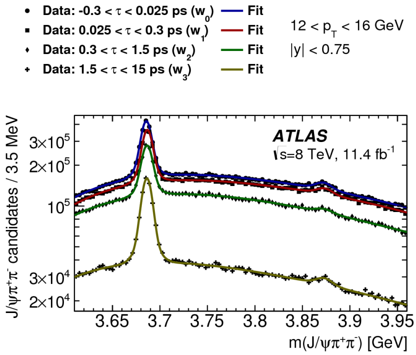
# Results: DPS measurements

- $\sigma_{\text{eff}}$ can be measured as $\sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma(J/\psi)^2}{f_{\text{DPS}} \times \sigma(J/\psi J/\psi)}$
  - $\sigma(J/\psi)$ from the ATLAS measurement Eur. Phys. J. C 76 (2016) 283
- $f_{\text{DPS}} = (9.2 \pm 2.1(\text{stat.}) \pm 0.5(\text{syst.}))\%$
- $\sigma_{\text{DPS}} = 14.8 \pm 3.5(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.2(\text{BF}) \pm 0.3(\text{lumi.})$ pb
- $\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.1(\text{BF}) \pm 0.1(\text{lumi.})$ mb
- LHC results with quarkonia are close to each other and to those of D0, but *lower than measurements with other probes*
  - Questions the assumption of $\sigma_{\text{eff}}$ universality
  - di-$J/\psi$, $J/\psi$–$\Upsilon$, 4-jet processes are dominated by $gg$ interactions $\rightarrow$ probe gluon distributions in proton



- $X(3872)$ was observed by Belle in 2003, later confirmed by others, $J^{PC} = 1^{++}$
- No clear theoretical picture yet
  - Loosely bound $D^0 \bar{D}^{*0}$ molecule
  - $\chi_{c1}(2P)$ state, or the mixture with $D^0 \bar{D}^{*0}$
  - Tetraquark (diquark + diquark)
- ATLAS measurement can help to answer some of the questions
  - Measure in $J/\psi\pi^+\pi^-$ mode, together with well known $\psi(2S)$ state
    - helps to reduce systematics in ratios
  - Use 11.4 fb$^{-1}$ @ 8 TeV data
    - Limit to $|y| < 0.75$ for the best mass resolution
  - Measure differential cross-sections over 5 $p_{\mathrm{T}}$ bins
  - Use 4 bins of pseudo proper lifetime to extract prompt/non-prompt components

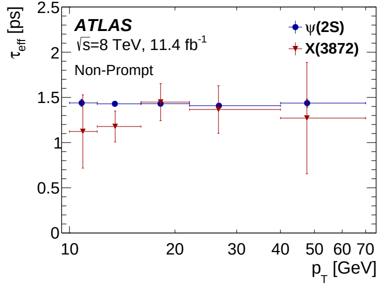


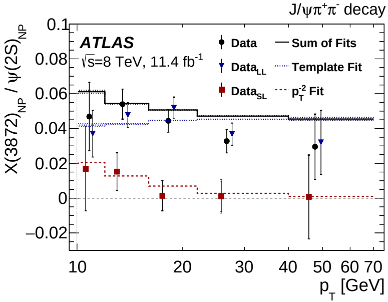



# $X(3872)$ lifetime hypotheses

- Measure the $X(3872)/\psi(2S)$ ratio
  $R_B = \frac{\mathcal{B}(B\to X(3872)+\text{any})\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)}{\mathcal{B}(B\to\psi(2S)+\text{any})\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-)}$
- Single lifetime hypothesis
  - Assume non-prompt $\psi(2S)$ and $X(3872)$ produced from the same mix of parent $b$ hadrons
  - same lifetime for $\psi(2S)$ and $X(3872)$ in each $p_{\mathrm{T}}$ bin
    $R_B^{1L} = (3.95 \pm 0.32(\text{stat.}) \pm 0.08(\text{syst.})) \times 10^{-2}$
  - $X(3872)$ lifetime shorter in low-$p_{\mathrm{T}}$ bins
    - Possible $B_c^+$ contribution?
- Double lifetime hypothesis: long-lived (LL) and short-lived (SL) components
  - $\tau_{LL}$ determined from $\psi(2S)$ fits, allowing for some SL contribution
  - $\tau_{SL}$ from simulation, varying $B_c^+$ lifetime
  - Calculate $X(3872)$ fraction from $B_c^+$

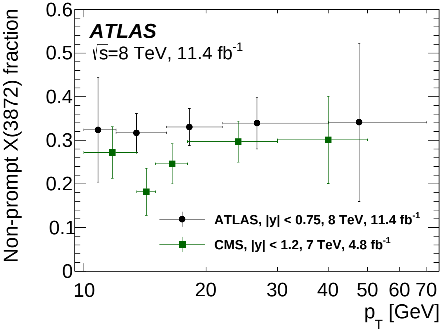
$$\frac{\sigma(pp \to B_c^+ + \text{any})\mathcal{B}(B_c^+ \to X(3872) + \text{any})}{\sigma(pp \to \text{non-prompt } X(3872) + \text{any})} = (25 \pm 13(\text{stat.}) \pm 2(\text{syst.}) \pm 5(\text{spin}))\%$$

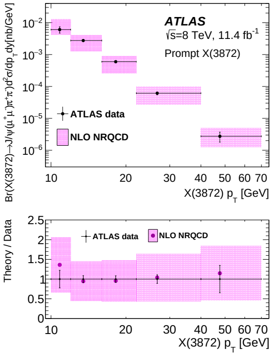


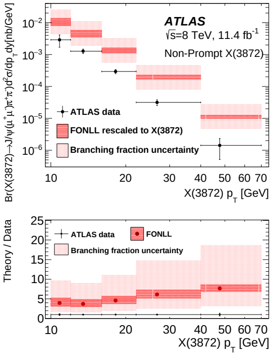



# $X(3872)$ production cross-section

- Prompt production described well by NRQCD
  - $X(3872)$ considered as a mixture of $\chi_c(2P)$ and $D^0\bar{D}^{*0}$ molecule
- Non-prompt compared to FONLL calculations
  - Predictions for $\psi(2S)$ recalculated using kinematic template of $X(3872)/\psi(2S)$
  - $\mathcal{B}$s estimated from CDF data
  - Factor 4–8 above the data, larger discrepancy at high $p_T$
- Non-prompt production fraction: no $p_T$ dependence, agreement with CMS data



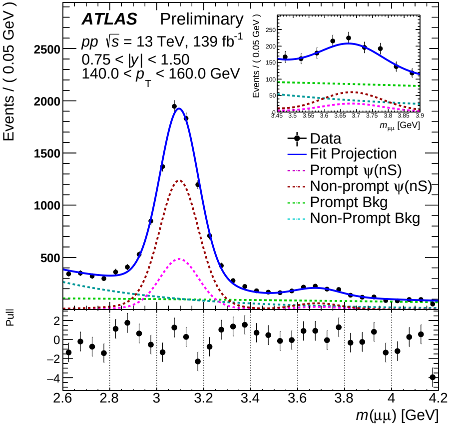



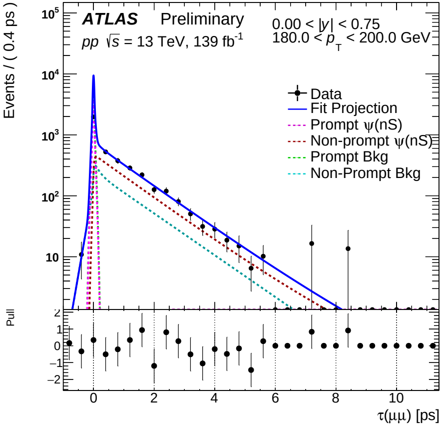



# $J/\psi$ and $\psi(2S)$ fits

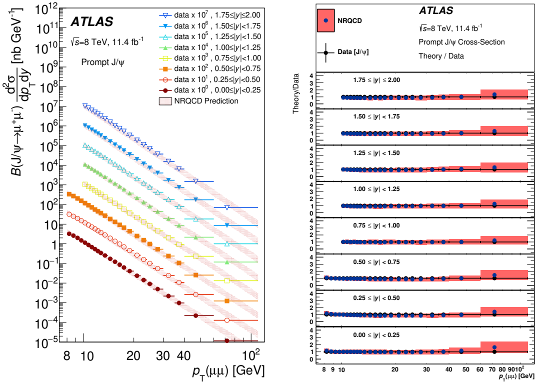
| i | Type | P/NP | $f_i(m)$ | $h_i(\tau)$ |
|---|---|---|---|---|
| 1 | $J/\psi$ | P | $\omega G_1(m) + (1-\omega)CB_1(m)$ | $\delta(\tau)$ |
| 2 | $J/\psi$ | NP | $\omega G_1(m) + (1-\omega)CB_1(m)$ | $E_1(\tau)$ |
| 3 | $\psi(2S)$ | P | $\omega G_2(m) + (1-\omega)CB_2(m)$ | $\delta(\tau)$ |
| 4 | $\psi(2S)$ | 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 |

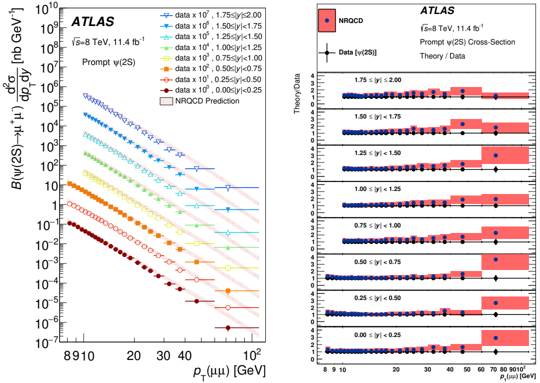


# $J/\psi$ and $\psi(2S)$ production @ 8 TeV (Eur. Phys. J. C 76 (2016) 283): prompt



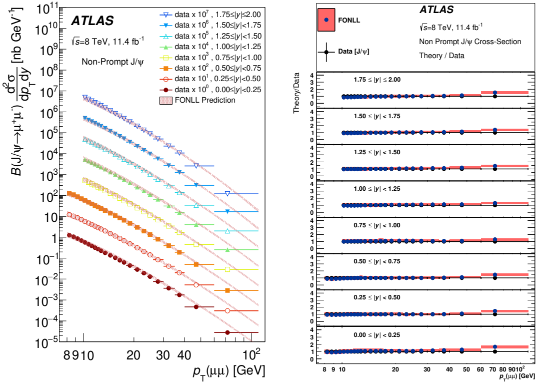

*Prompt $J/\psi$*



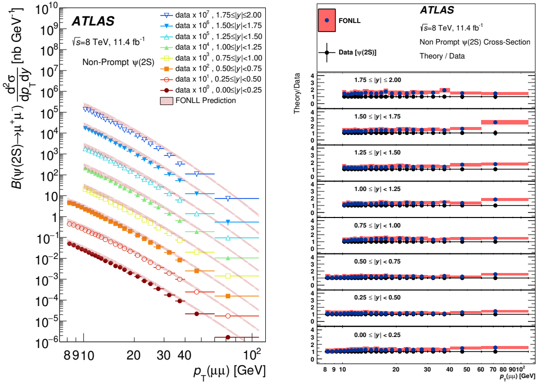

*Prompt $\psi(2S)$*

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

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



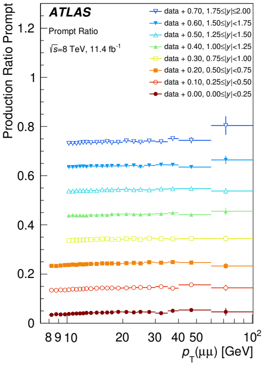

*Non-prompt $J/\psi$*



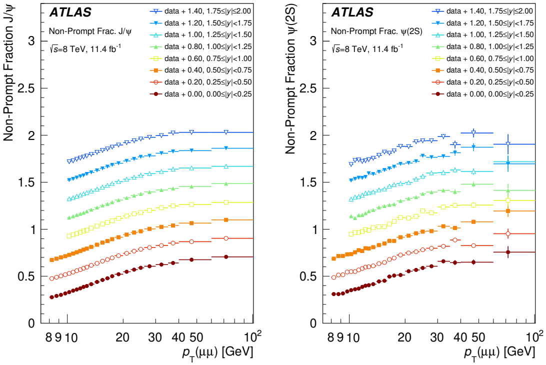

*Non-prompt $\psi(2S)$*

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

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




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

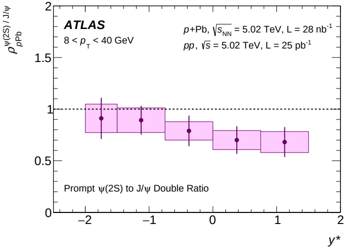


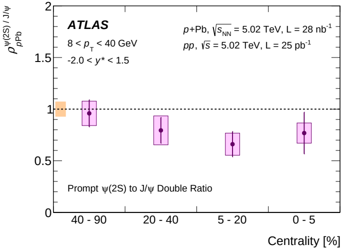

*Non-prompt fraction for $J/\psi$ and $\psi(2S)$*

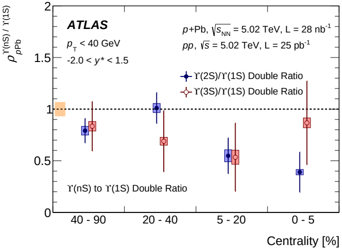
- Ratio of $J/\psi$ to $\psi(2S)$ flat across the whole $p_T$ range
- Prompt $J/\psi$ ($\psi(2S)$) dominate over non-prompt at low $p_T$, but the non-prompt exceed after ∼20 GeV (∼30 GeV)

# Charmonia in $p+\text{Pb}$: $(nS)$ suppression

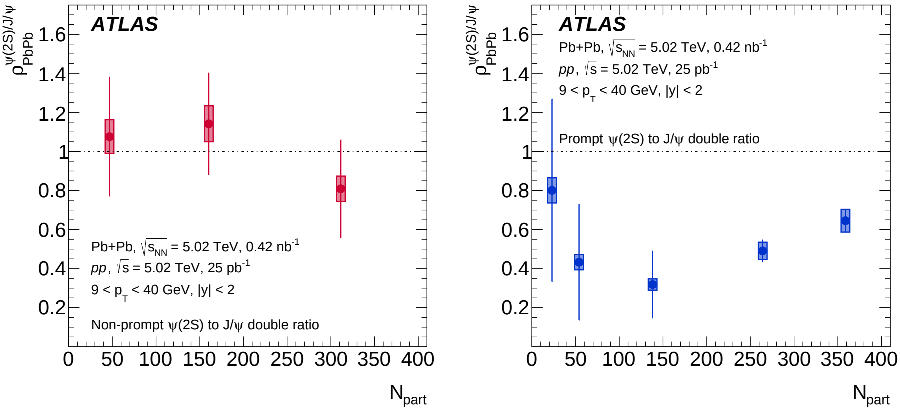
- Double ratios $\rho_{p\text{Pb}}^{O(nS)/O(1S)}$ in $p+\text{Pb}$
  - Relative $\psi(2S)$ suppression increases with centre-of-mass rapidity, $1\sigma$ significance trend
  - Both $\Upsilon(2,3S)$ suppressed by $2\sigma$ in the full $p_{\text{T}} < 40$ GeV and $-2 < y^* < 1.5$ region
  - $\rho^{\psi(2S)/\psi(1S)}$ and $\rho^{\Upsilon(2S)/\Upsilon(1S)}$ decreases towards more central collisions; $\rho^{\Upsilon(3S)/\Upsilon(1S)}$ statistically limited
  - Stronger effect of CNM in the excited states production compared to ground state



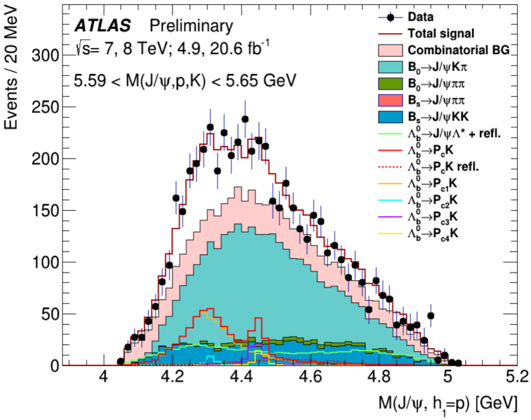



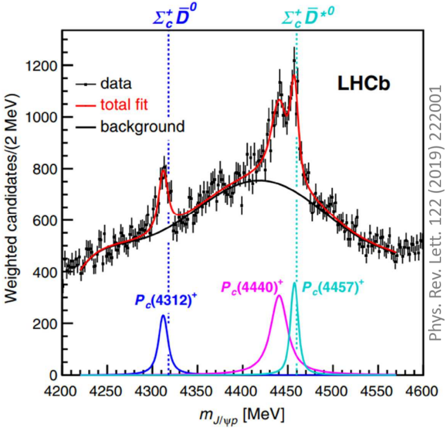



- Expect $\rho_{\text{PbPb}}^{O(nS)/O(1S)} = 1$ for non-prompt charmonia
  - originate from $b$ quark loosing energy in the medium and hadronizing outside
- The double ratio indeed consistent with unity for non-prompt, and $< 1$ for prompt
  - consistent with the interpretation that the tighter bound $J/\psi$ survives in the hot and dense medium with higher probability than more loosely bound $\psi(2S)$
  - also consistent with radiative energy loss scenario (Phys. Lett. B 767 (2017) 10)



# Pentaquark fit with four pentaquarks hypothesis




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

# Pentaquarks: event selection

- 2 muons from $J/\psi$ decay with mass $3097 \pm 290$ GeV
- 2 muon tracks + 2 hadron tracks vertex fit: dimuon mass constrained to $J/\psi$ mass, $\Lambda_b^0$ to point to primary vertex, $\chi^2/\mathrm{n.d.f.} < 16/8$;
- 2 hadron tracks, with each of them to be assigned different mass hypothesis (proton or kaon); $p_\mathrm{T} > 2.5$ GeV for proton candidate and $p_\mathrm{T} > 1.8$ GeV for kaon candidate
- Transverse decay length $L_{xy}(\Lambda_b^0) > 0.7$ mm;
- $p_\mathrm{T}(\Lambda_b^0)/\sum p_\mathrm{T}(\text{tracks}) > 0.2$, where sum is taken over all tracks originating from PV;
- $p_\mathrm{T}(\mu^\pm) > 4$ GeV, $|\eta(\mu^\pm)| < 2.3$, $p_\mathrm{T}(\Lambda_b^0) > 12$ GeV, $|\eta(\Lambda_b^0)| < 2.1$;
- Inv. mass of hadron tracks (in $K\pi$ and $\pi K$ mass hypotheses): $M(K\pi) > 1.55$ GeV and $M(\pi K) > 1.55$ GeV, to suppress decays via light intermediate resonances;
- $\cos\theta^\star$ between proton and $J/\psi p$ system in $J/\psi p$ rest frame $> -0.5$;
- $\cos\theta^\star$ between kaon and $\Lambda_b^0$ candidate in $\Lambda_b^0$ candidate rest frame $> -0.8$;
- $|\cos\theta^\star|$ between kaon and $\Lambda^{*0}$ in $\Lambda^{*0}$ rest system $< 0.85$;
- Events for $J/\psi p$ signal search are taken in window $M(J/\psi pK) \in 5620 \pm 30$ MeV;
- Subtraction of distributions with two same sign hadron tracks is applied before fits to data;

# Systematics in the $D$ meson measurement

| Source | $\sigma^{\text{vis}}(D^{*\pm})$ | | $\sigma^{\text{vis}}(D^{\pm})$ | | $\sigma^{\text{vis}}(D_s^{\pm})$ | |
|---|---|---|---|---|---|---|
| | Low-$p_T$ | High-$p_T$ | Low-$p_T$ | High-$p_T$ | Low-$p_T$ | High-$p_T$ |
| Trigger ($\delta_1$) | - | ${}^{+0.9}_{-1.0}\%$ | - | ${}^{+0.9}_{-1.0}\%$ | - | ${}^{+0.9}_{-1.0}\%$ |
| Tracking ($\delta_2$) | $\pm 7.8\%$ | $\pm 7.4\%$ | $\pm 7.7\%$ | $\pm 7.4\%$ | $\pm 7.6\%$ | $\pm 7.4\%$ |
| $D$ selection ($\delta_3$) | ${}^{+2.8}_{-1.6}\%$ | ${}^{+1.7}_{-1.4}\%$ | ${}^{+1.6}_{-1.0}\%$ | ${}^{+0.9}_{-0.6}\%$ | ${}^{+2.6}_{-1.6}\%$ | ${}^{+1.1}_{-0.9}\%$ |
| Signal fit ($\delta_4$) | $\pm 1.3\%$ | $\pm 0.9\%$ | $\pm 1.3\%$ | $\pm 1.5\%$ | $\pm 6.4\%$ | $\pm 5.3\%$ |
| Modelling ($\delta_5$) | ${}^{+1.0}_{-1.7}\%$ | ${}^{+2.7}_{-2.3}\%$ | ${}^{+2.3}_{-2.6}\%$ | ${}^{+2.9}_{-2.4}\%$ | ${}^{+1.7}_{-2.4}\%$ | ${}^{+2.8}_{-2.4}\%$ |
| Size of MC sample ($\delta_6$) | $\pm 0.6\%$ | $\pm 0.9\%$ | $\pm 0.8\%$ | $\pm 0.8\%$ | $\pm 2.9\%$ | $\pm 3.1\%$ |
| Luminosity ($\delta_7$) | $\pm 3.5\%$ | $\pm 3.5\%$ | $\pm 3.5\%$ | $\pm 3.5\%$ | $\pm 3.5\%$ | $\pm 3.5\%$ |
| Branching fraction ($\delta_8$) | $\pm 1.5\%$ | $\pm 1.5\%$ | $\pm 2.1\%$ | $\pm 2.1\%$ | $\pm 5.9\%$ | $\pm 5.9\%$ |

# LEP average fragmentation fractions

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| | LEP data |
|---|---|
| $f(c \to D^{*+})$ | $0.236 \pm 0.006 \pm 0.003$ |
| $f(c \to D^{+})$ | $0.225 \pm 0.010 \pm 0.005$ |
| $f(c \to D_s^{+})$ | $0.092 \pm 0.008 \pm 0.005$ |
| $f(b \to D^{*\pm})$ | $0.221 \pm 0.009 \pm 0.003$ |
| $f(b \to D^{\pm})$ | $0.223 \pm 0.011 \pm 0.005$ |
| $f(b \to D_s^{\pm})$ | $0.138 \pm 0.009 \pm 0.006$ |

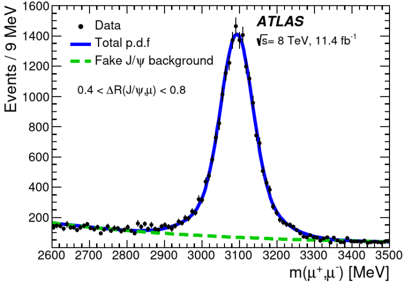
# Gluon splitting kernels in PYTHIA

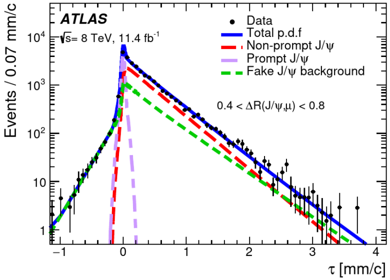
| Option label | Descriptions |
|---|---|
| Opt. 1 | The same splitting kernel, $(1/2)(z^2 + (1 - z)^2)$, for massive as massless quarks, only with an extra $\beta$ phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [50] method. |
| Opt. 4 | A splitting kernel $z^2 + (1 - z)^2 + 8r_q z(1 - z)$, normalised so that the $z$-integrated rate is $(\beta/3)(1 + r/2)$, and with an additional suppression factor $(1 - m_{qq}{}^2/m^2_{\mathrm{dipole}})^3$, which reduces the rate of high-mass $q\bar{q}$ pairs. This is the default setting in PYTHIA8.2. |
| Opt. 5 | Same as Option 1, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_{\mathrm{T}})$, with $k = 1$. |
| Opt. 5b | Same as Option 5, but setting $k = 0.25$. |
| Opt. 8 | Same as Option 4, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_{\mathrm{T}})$, with $k = 1$. |
| Opt. 8b | Same as Option 8, but setting $k = 0.25$. |

Table 1: Description of PYTHIA8 options. Options 2, 3, 6 and 7 are less well physically motivated and not considered here. The notation used is as follows: $r_q = m^2_q/m^2_{qq}$, $\beta = \sqrt{1 - 4r_q}$, with $m_q$ the quark mass and $m_{qq}$ the $q\bar{q}$ pair invariant mass.

# $b\bar{b}$ production measurement details

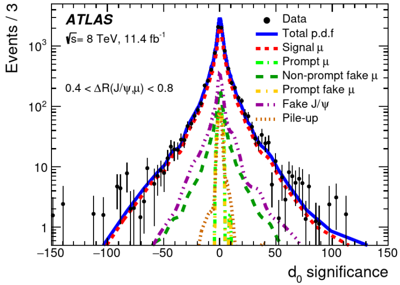
- Fiducial volume definition:
  - $p_T(\mu) > 6$ GeV for all three muons
  - $|\eta(\mu)| < 2.3$ for the $J/\psi$ muons and $< 2.5$ for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to $J/\psi$ mass and pseudo-proper lifetime to extract the yield of $J/\psi$ from $b$

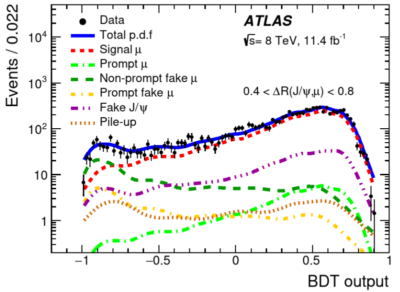


# $b\bar{b}$ production measurement details

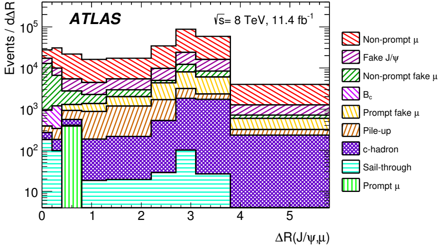
- Fiducial volume definition:
  - $p_T(\mu) > 6$ GeV for all three muons
  - $|\eta(\mu)| < 2.3$ for the $J/\psi$ muons and $< 2.5$ for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to $J/\psi$ mass and pseudo-proper lifetime to extract the yield of $J/\psi$ from $b$
  - Yield of 3rd muon from $b$ determined by fit to $d_0/\sigma(d_0)$ and BDT output
    - in signal-enriched region of $\tau > 0.25$ mm$/c$

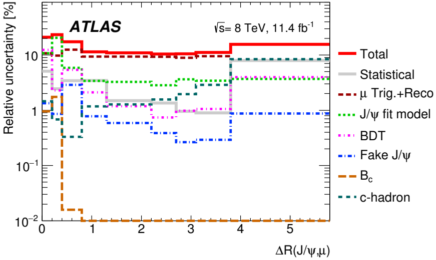


# $b\bar{b}$ production measurement details

- Fiducial volume definition:
  - $p_T(\mu) > 6$ GeV for all three muons
  - $|\eta(\mu)| < 2.3$ for the $J/\psi$ muons and $< 2.5$ for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to $J/\psi$ mass and pseudo-proper lifetime to extract the yield of $J/\psi$ from $b$
  - Yield of 3rd muon from $b$ determined by fit to $d_0/\sigma(d_0)$ and BDT output
    - in signal-enriched region of $\tau > 0.25$ mm$/c$
  - Subtract irreducible backgrounds
    - $B_c^+ \to J/\psi\mu^+X$, prompt charm, fake muons



# $b\bar{b}$ production measurement details

- Fiducial volume definition:
  - $p_T(\mu) > 6\,\text{GeV}$ for all three muons
  - $|\eta(\mu)| < 2.3$ for the $J/\psi$ muons and $< 2.5$ for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to $J/\psi$ mass and pseudo-proper lifetime to extract the yield of $J/\psi$ from $b$
  - Yield of 3rd muon from $b$ determined by fit to $d_0/\sigma(d_0)$ and BDT output
    - in signal-enriched region of $\tau > 0.25\,\text{mm}/c$
  - Subtract irreducible backgrounds
    - $B_c^+ \to J/\psi\mu^+X$, prompt charm, fake muons
  - Extrapolate to full $\tau$ range
  - Correct for detector resolution effects