Heavy flavour production at ATLAS

Semen Turchikhin
on behalf of ATLAS Collaboration

Joint Institute for Nuclear Research

Heavy-quark hadroproduction from collider to astroparticle physics
Mainz Institute for Theoretical Physics, Johannes Gutenberg University, Germany
30 September – 11 October 2019

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!**

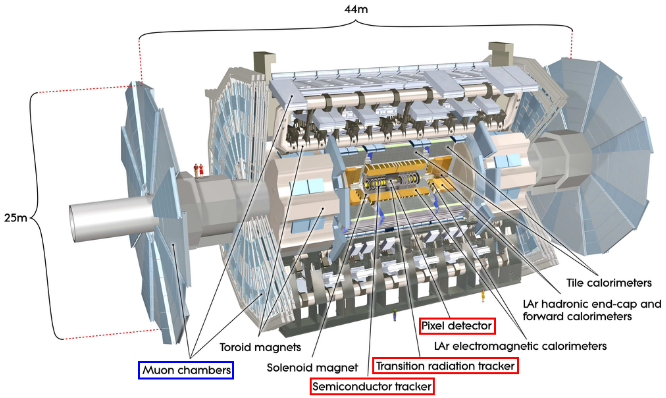
Outline

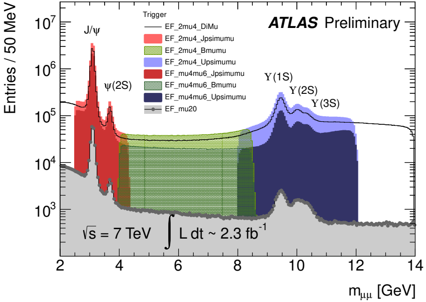
- ATLAS detector
- Open heavy flavour production
  - Charmed meson production at 7 TeV – Nucl. Phys. B 907 (2016) 717
  - b hadron pair production measurement at 8 TeV– JHEP 11 (2017) 62
  - ★ Relative B_c^+/B^+ production measurement at 8 TeV – paper in preparation
- Hidden heavy flavour production
  - ★ High-p_T J/ψ and $\psi(2S)$ production at 13 TeV paper in preparation
  - Heavy quarkonium production in pPb (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

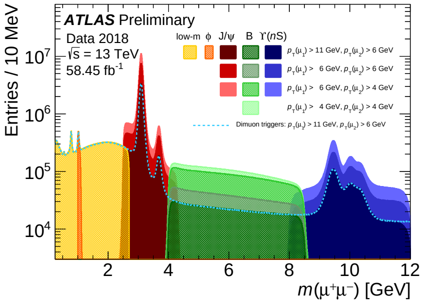
★ – brand-new results released just this week for Beauty conference!

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







D meson production cross-section measurement Nucl. Phys. B 907 (2016) 717

Motivation

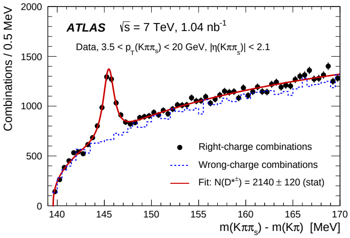
- Heavy quark production measurement at LHC $\rightarrow$ test of pQCD calculations at highest possible energies
  - Charmed mesons are produced in *charm hadronization* and *b hadron decays*
- Various theoretical approaches available
  - Fixed-order + next-to-leading-logarithm (FONLL) predictions
  - 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

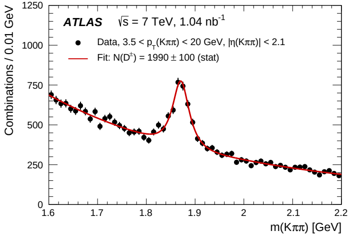
Scope of the study

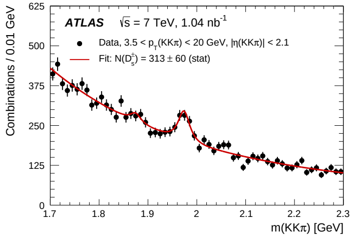
- Three D mesons measured: D^{*+}, D^{+}, D_s^{+}
- Kinematic region of the x-section measurement:
  - $3.5 < p_{\mathrm{T}}(D) < 100\,\mathrm{GeV}$
  - $|\eta(D)| < 2.1$
- Data of 2010 at $\sqrt{s} = 7\,\mathrm{TeV}$ are used
  - $1.04\,\mathrm{nb}^{-1}$ collected with minimum-bias triggers used for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

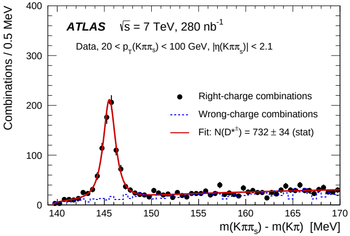
D meson reconstruction

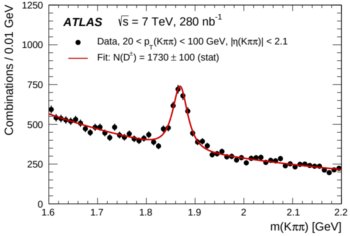
$D^{*+} \to D^0 \pi_s^+ \to (K^- \pi^+) \pi_s^+$ | $D^+ \to K^- \pi^+ \pi^+$ | $D_s^+ \to \phi \pi^+ \to (K^+ K^-) \pi^+$

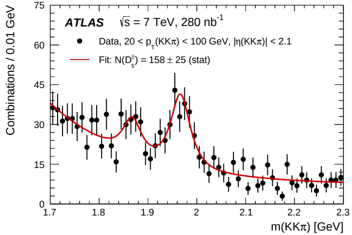












π_s^+ – soft pion

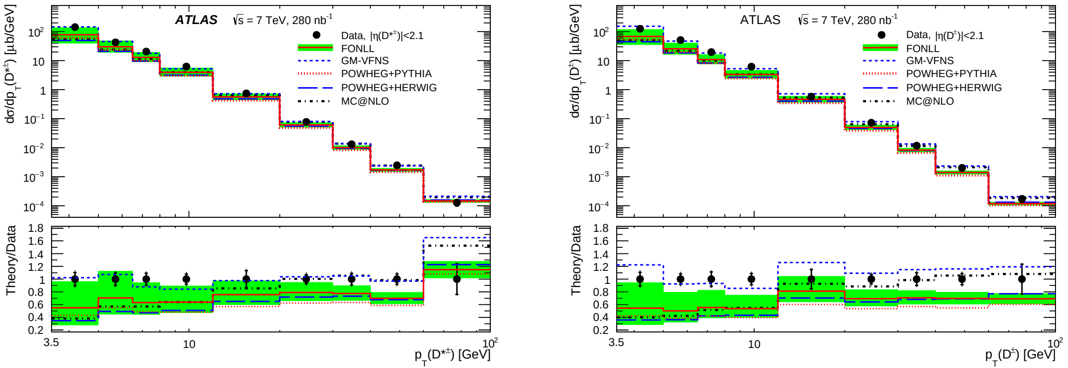
Results: visible cross-sections

- Visible cross-sections measured:

	$\sigma^{\text{vis}}(D^{*\pm})$		$\sigma^{\text{vis}}(D^{\pm})$		$\sigma^{\text{vis}}(D_s^{*\pm})$	
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 ± 36	988 ± 100	328 ± 34	888 ± 97	160 ± 37	512 ± 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}

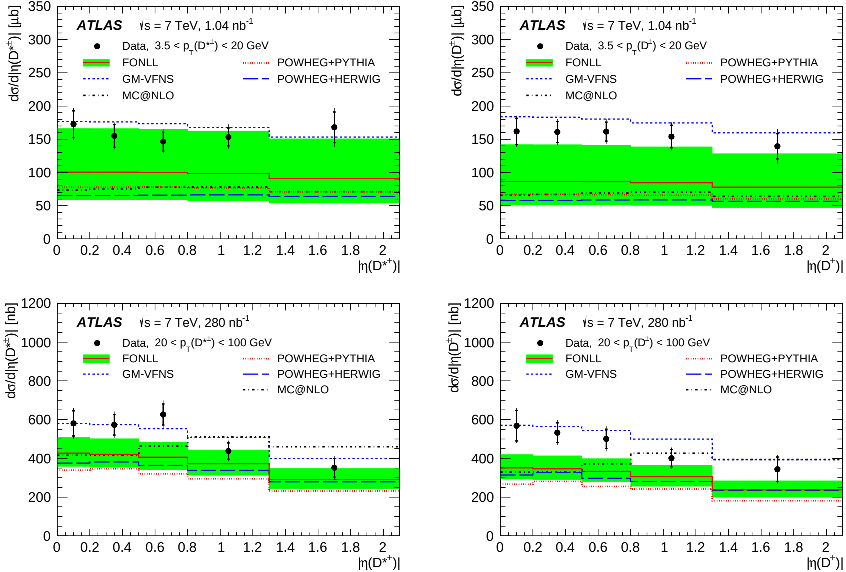
- Statistical and systematics uncertainties generally of the same order
  - Tracking efficiency, luminosity and branching fractions are the main systematics sources
- GM-VFNS approach shows the best description of data
- FONLL and NLO+PS approaches are generally below data, but still consistent within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

- GM-VFNS shows again a better description
- MC@NLO predicts a different η 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_{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/ψ and μ, y_{boost},
  - $m(J/\psi, \mu)$
  - $p_{\mathrm{T}}(J/\psi, \mu)/m(J/\psi, \mu)$ and its inverse
- 11.5 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/ψ muons and < 2.5 for the 3rd muon
- Full fiducial cross-section:

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

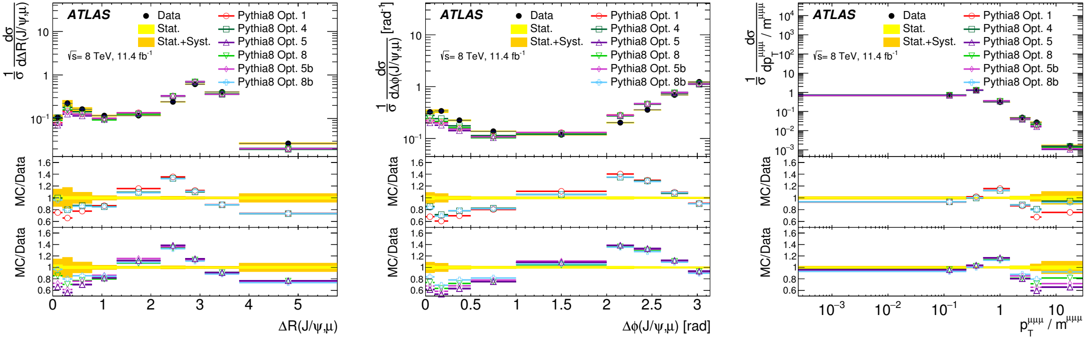
- Comparison with various models are performed:
  - Pythia 8
  - Herwig++
  - MadGraph_aMC@NLOv2.2.2 interfaced to Pythia 8 (CKKW-L merging scheme with 15 GeV merging scale)
    - 4-FNS and 5-FNS modelling in MadGraph
  - Sherpa 2.1.1 (5-FNS), merging with ME+PS@LO prescription

Test PYTHIA 8 gluon splitting kernels

- Test gluon splitting description
  - Is the scale of α_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 $b\bar{b}$

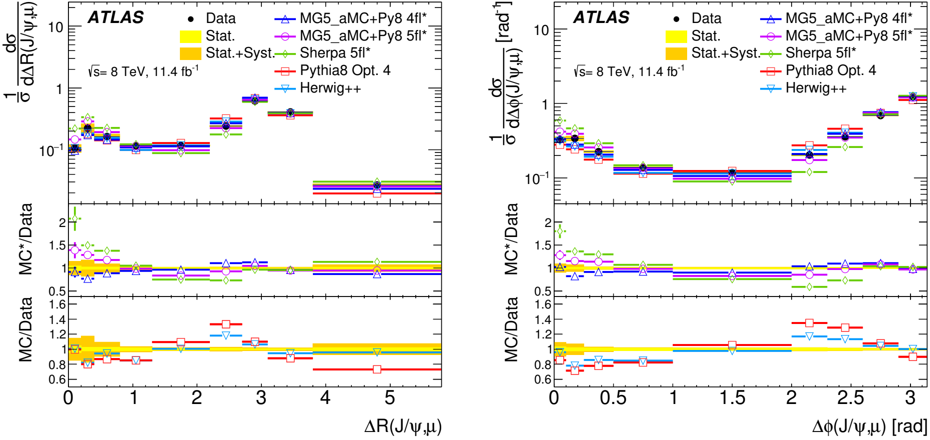
Option label	Descriptions
Opt. 1	The same splitting kernel, $(1/2)(z^2 + (1-z)^2)$, for massive as massless quarks, only with an extra β phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [50] method.
Opt. 4	A splitting kernel $z^2 + (1-z)^2 + 8r_q z(1-z)$, 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.



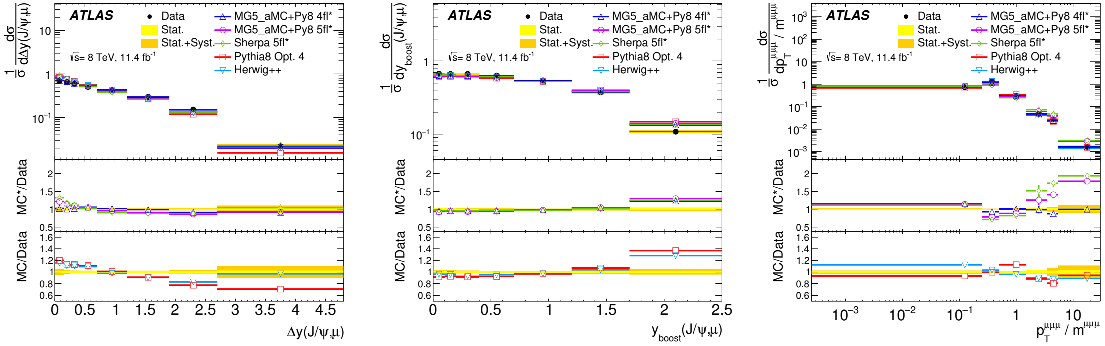
Test various model predictions (1)

- HERWIG++ reproduces ΔR and $\Delta\phi$ best
- 4-FNS works better for ΔR 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 Δy, PYTHIA and HERWIG++ worse
- In y_{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



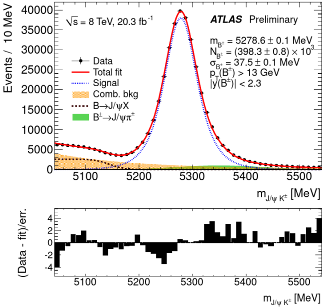
b hadron pair production: summary

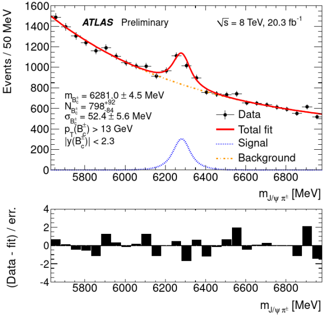
- **Very comprehensive measurement** of differential cross-section of $b\bar{b}$ production performed
  - in 10 kinematic observables
- Particularly sensitive to close-by $b\bar{b}$ pairs down to zero open angle
- Various predictions compared to data
  - different ME, PS models, 4-/5-flavour treatment; 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: $\dfrac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+ \to J/\psi K^+)}$
  - common systematic uncertainties mostly cancel
- Fiducial region of the measurement:
  - $p_{\mathrm{T}}(B) > 13\,\mathrm{GeV}$, $|y(B)| < 2.3$
- Measure total production and differential in $p_{\mathrm{T}}(B)$ and $|y(B)|$





B_c^+/B^+ production: results

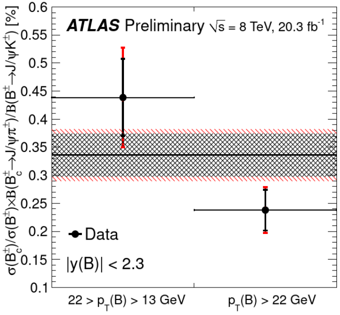
- Production ratio in the fiducial region

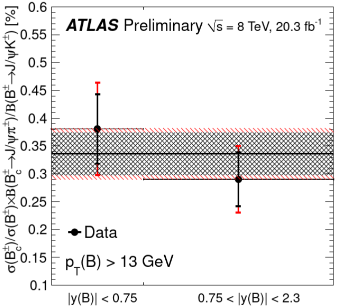
$$\frac{\sigma(B_c^+)\cdot\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\cdot\mathcal{B}(B^+\to J/\psi K^+)} =$$

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

  - 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, $2.3 > \lvert y(B)\rvert > 0.75$	$(0.29 \pm 0.05_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.01_{\text{lifetime}})\%$



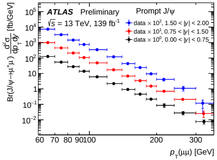


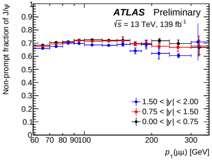
High-p_T J/ψ and $\psi(2S)$ production measurement (paper in preparation)

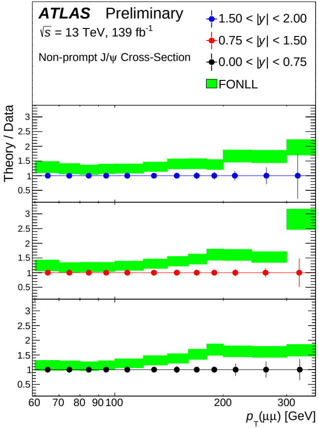
- Two different mechanisms for charmonium production:
  - *Prompt*: directly in *pp* interaction or via feed-down from heavier states
    - ~35% of J/ψ comes from feed-down; $\psi(2S)$ is produced almost directly
    - Theory: Non-Relativistic QCD (NRQCD)
      introduces a number of phenomenological 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/ψ and ψ(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

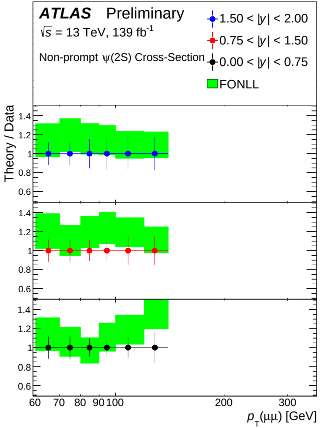
High-p_T J/ψ and $\psi(2S)$ measurement: results

- 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 goes well beyond what was achieved so far
- FONLL consistent at low-p_T, over-estimates high-p_T production

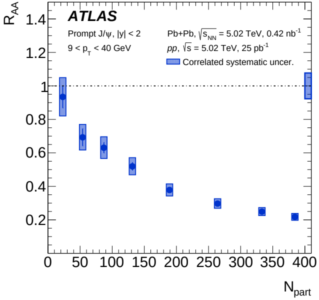


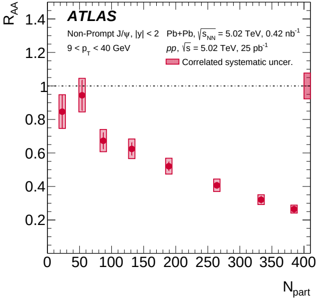


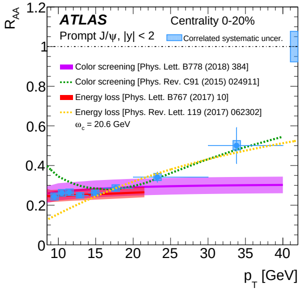




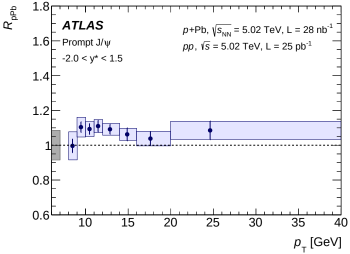
- Probe deconfined quark-gluon plasma in $A+A$ collisions
  - Suppression of *prompt* charmonia could provide info about temperature of deconfinement
  - Possible enhancement: new quarkonium formation mechanism ($c\bar{c}$ recombination in medium)
  - *Non-prompt* charmonia allows studying b quark propagation through the medium
    - Possibly different mechanism (collisions, radiation) from $c\bar{c}$ suppression (colour screening)
- J/ψ 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/ψ, flat for non-prompt

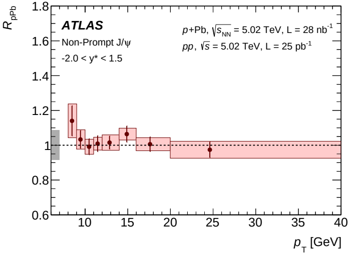


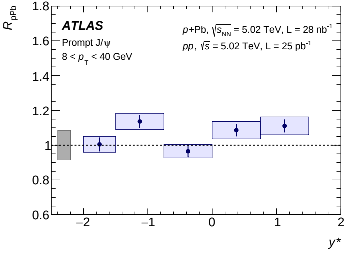


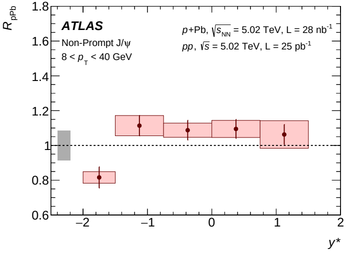


- $p+A$ collisions serve to disentangle cold nuclear matter effects (CNM)

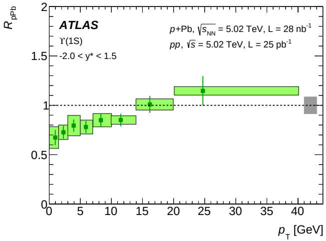






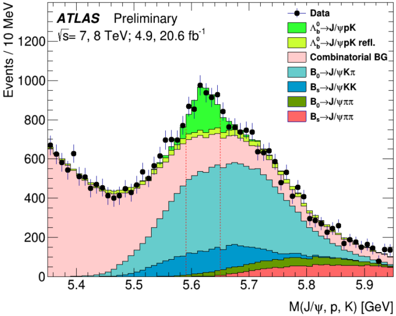


- R_{pPb} factors for prompt and non-prompt J/ψ consistent with unity
  - no p_{T} or y^* dependence
  - weak modification for J/ψ production due to CNM effects
- $R_{pPb} < 1$ for $\Upsilon(1S)$ below 15 GeV
  - stronger nPDF shadowing for small x?



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 ρ's)
  - $B_s^0 \to J/\psi K^+ K^-$ via intermediate f^0 and ϕ's
  - $B_s^0 \to J/\psi \pi^+ \pi^-$ (via intermediate f^0's and ρ's)
- Simulation uses phase-space decays weighted with theoretical MEs
- To suppress light $\Lambda^{\star 0}$'s, $K^{\star 0}$'s, f^0, ϕ's, remove events with $M(\pi K)$ or $M(K\pi) < 1.55\,\text{GeV}$



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.
Λ_b decay couplings are fixed

Information included:
2D: $M(J/\psi,K,K)$ $M(J/\psi,\pi,\pi)$
2D: $M(J/\psi,K,\pi)$ $M(J/\psi,\pi,K)$;
2D: $M(J/\psi,K)$ $M(J/\psi,\pi)$ in B_d CR
2D: $M(J/\psi,K_1)$ $M(J/\psi,K_2)$ in B_s CR
1D: $M(K,\pi)$ and $M(\pi,K)$ in B_d CR
1D: $M(K,\pi)$ in B_d CR
1D: $M(K,K)$ in B_s CR

→

χ^2 $M(J/\psi,p,K)$ fit

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

Information included:
1D: $M(J/\psi,p,K)$

→

Λ_b decays fit (likelihood)

Fit of Λ_b decay couplings;

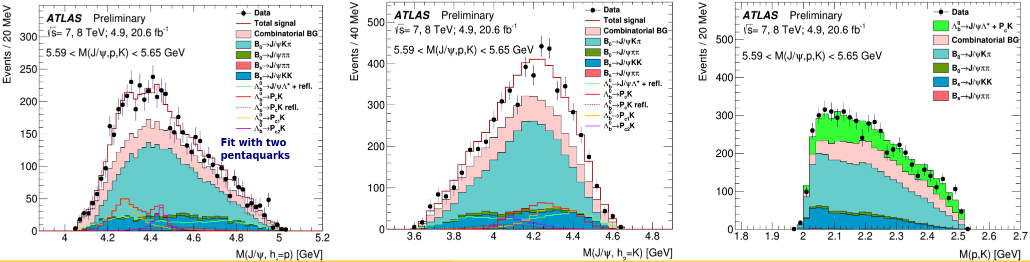
Information included:
2D: $M(J/\psi,p)$, $M(J/\psi,K)$ in Λ_b CR
1D: $M(p,K)$ in Λ_b CR

→

χ^2 $M(J/\psi,p)$ fit

Fit of pentaquark signal parameters and yields.

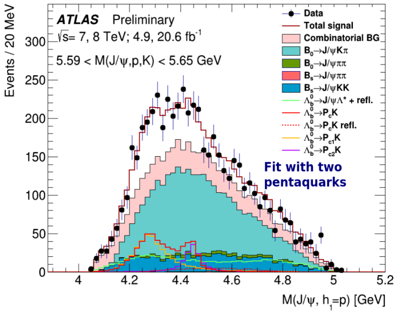
Information included:
1D: $M(J/\psi,p)$ in Λ_b CR

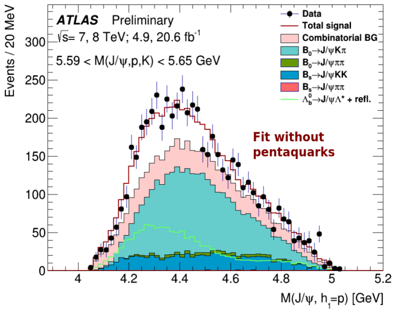


Search for pentaquarks: results

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

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

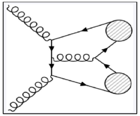
[5] CMS Collaboration, *Observation of Two Excited B_c^+ States and Measurement of the $B_c^+(2S)$ Mass in pp Collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. Lett. 122 (2019) 132001

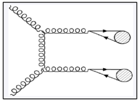
[6] LHCb Collaboration, *Observation of an excited B_c^+ state*, Phys. Rev. Lett. 122 (2019) 232001

Backup slides

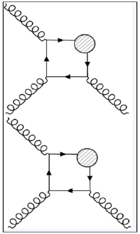
Prompt charmonium pair production

- Two principal possibilities to produce two objects in a *pp* collision:
- Single Parton Scattering (*SPS*)
- Double Parton Scattering (*DPS*)
  - effective cross-section σ_{eff} accounting for probability of the two processes to happen in a single *pp* collision: $\sigma_{\text{DPS}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\text{eff}}}$
  - σ_{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 σ_{eff}





SPS



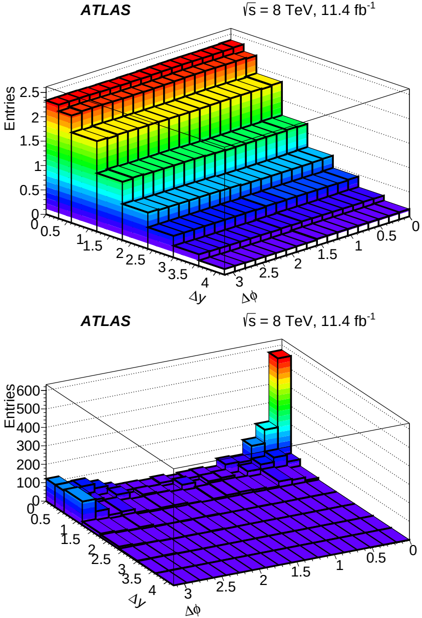
DPS

Prompt J/ψ pair production – Eur. Phys. J. C 77 (2017) 76

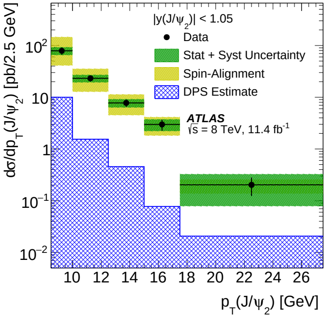
- Measure production of prompt J/ψ pairs
- Use $11.4\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$
- Kinematic range: $p_{\text{T}}(J/\psi) > 8.5\,\text{GeV}$, $|\eta(J/\psi)| < 2.1$
- Per-event corrections
  - Efficiency of trigger and reconstruction
  - Muon acceptance
- Backgrounds
  - Non-J/ψ background separated by 2D mass fits
  - Non-prompt J/ψ contribution separated by 2D L_{xy} fits
    - per-event weights as a function of L_{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

Data-driven extraction of DPS contribution

- 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/ψ'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)



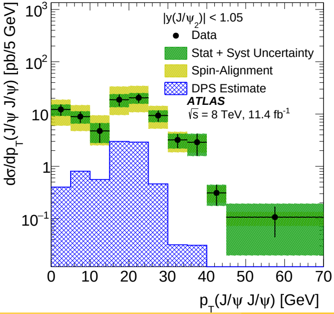
- Fiducial cross-section in $p_T(J/\psi) > 8.5$ GeV, $|y(J/\psi)| < 2.1$, $p_T(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$, $p_T(\mu) > 4$ GeV for two trigger muons

  $15.6 \pm 1.3\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 0.2\,(\text{BF}) \pm 0.3\,(\text{lumi})$ 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/ψ kinematic volume

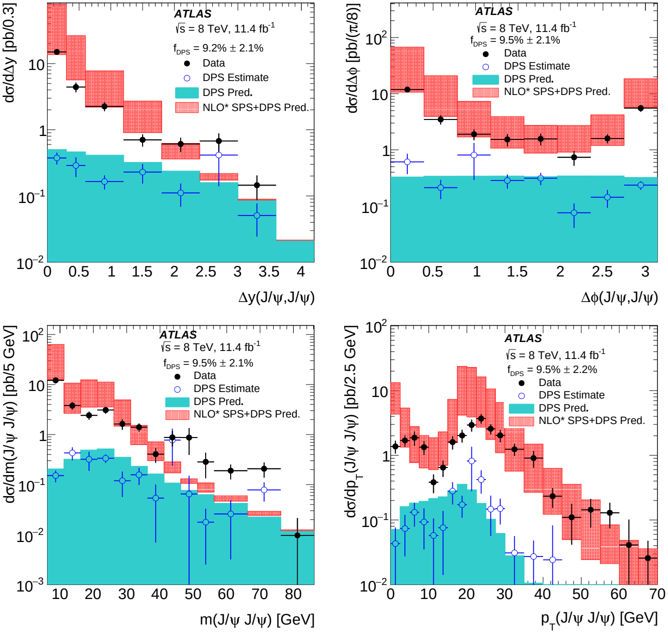
  $82.2 \pm 8.3\,(\text{stat}) \pm 6.3\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.6\,(\text{lumi})$ pb, for $|y| < 1.05$,
  $78.3 \pm 9.2\,(\text{stat}) \pm 6.6\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.5\,(\text{lumi})$ pb, for $1.05 \leq |y| < 2.1$

  - 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



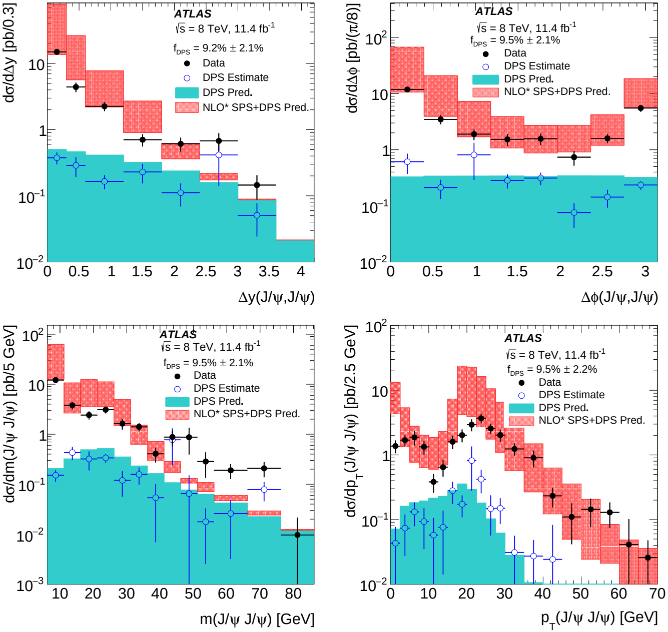
Results: cross-sections (2)

- 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



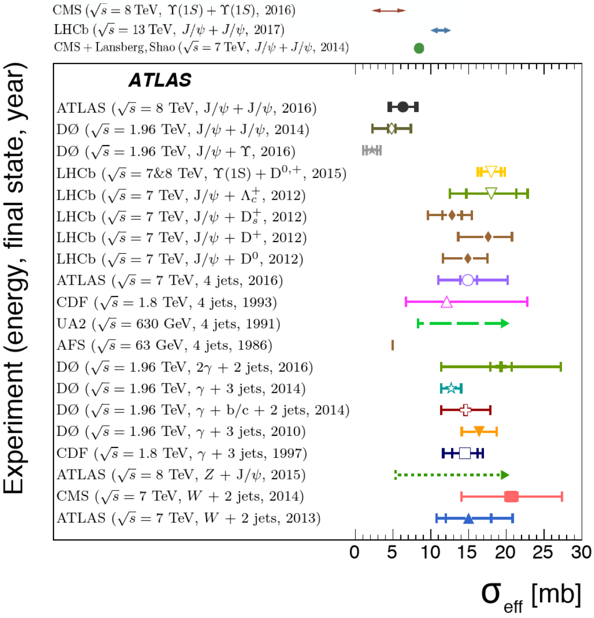
Results: cross-sections (2)

- 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

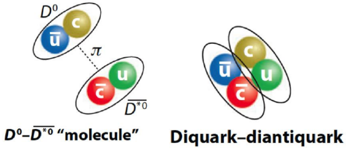
- σ_{eff} can be measured as
  $\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{f_{\text{DPS}} \times \sigma(J/\psi J/\psi)}$
  - $\sigma(J/\psi)$ from the ATLAS measurement Eur. Phys. J. C 76 (2016) 283
- $f_{\text{DPS}} = (9.2 \pm 2.1(\text{stat.}) \pm 0.5(\text{syst.}))\%$
- $\sigma_{\text{DPS}} = 14.8 \pm 3.5(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.2(\text{BF}) \pm 0.3(\text{lumi.})$ 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 σ_{eff} universality
  - di-J/ψ, J/ψ–Υ, 4-jet processes are dominated by gg interactions $\rightarrow$ probe gluon distributions in proton

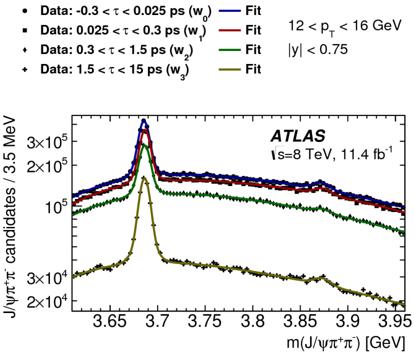


$\psi(2S)$ and $X(3872)$ production

JHEP 01 (2017) 117

- $X(3872)$ 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_{T} bins
  - Use 4 bins of pseudo proper lifetime to extract prompt/non-prompt components

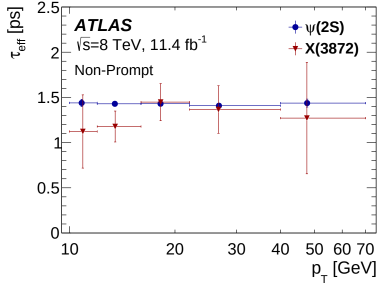




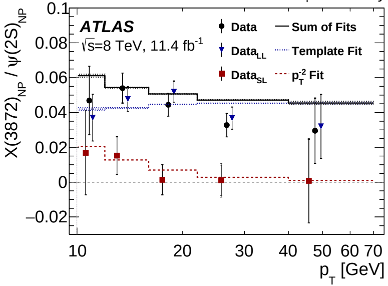
$X(3872)$ lifetime hypotheses

- 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_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_T bins
    - Possible B_c^+ contribution?
- Double lifetime hypothesis: long-lived (LL) and short-lived (SL) components
  - τ_{LL} determined from $\psi(2S)$ fits, allowing for some SL contribution
  - τ_{SL} from simulation, varying B_c^+ lifetime
  - Calculate $X(3872)$ fraction from B_c^+

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

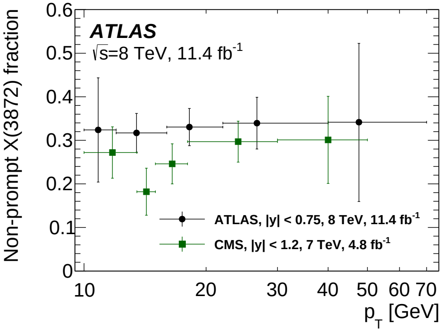


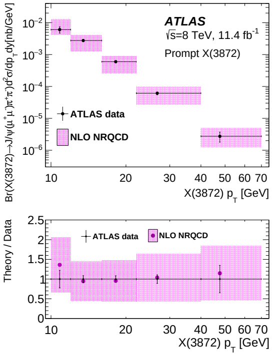
J/ψπ+π- decay

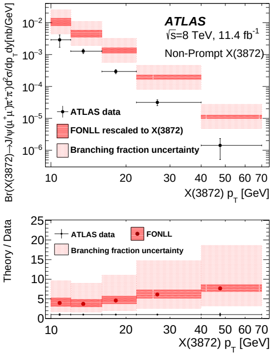


$X(3872)$ production cross-section

- 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



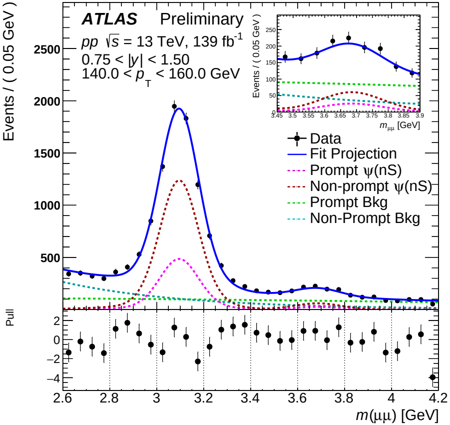


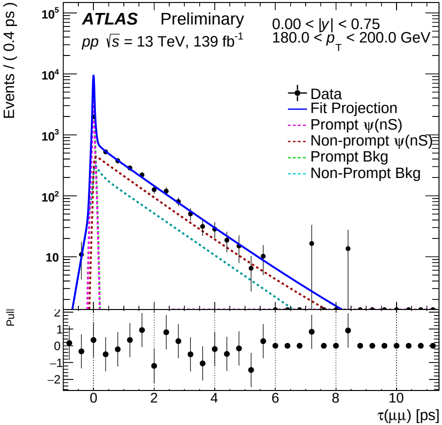


J/ψ and $\psi(2S)$ fits

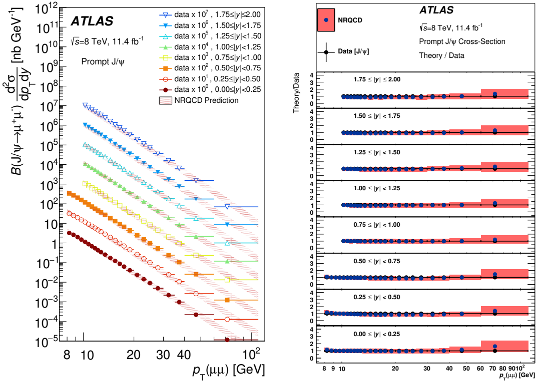
i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega G_1(m) + (1-\omega) CB_1(m)$	$\delta(\tau)$
2	J/ψ	NP	$\omega G_1(m) + (1-\omega) CB_1(m)$	$E_1(\tau)$
3	$\psi(2S)$	P	$\omega G_2(m) + (1-\omega) CB_2(m)$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega G_2(m) + (1-\omega) CB_2(m)$	$E_2(\tau)$
5	Bkg	P	B	$\delta(\tau)$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

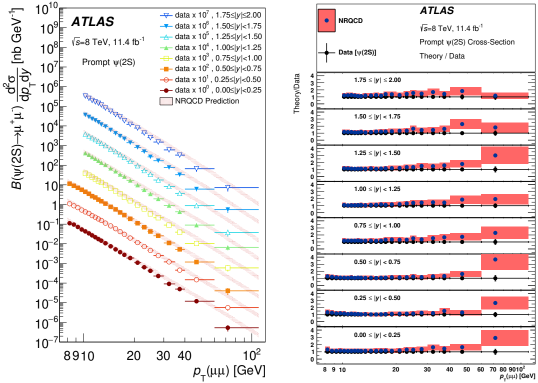




J/ψ and $\psi(2S)$ production @ 8 TeV (Eur. Phys. J. C 76 (2016) 283): prompt

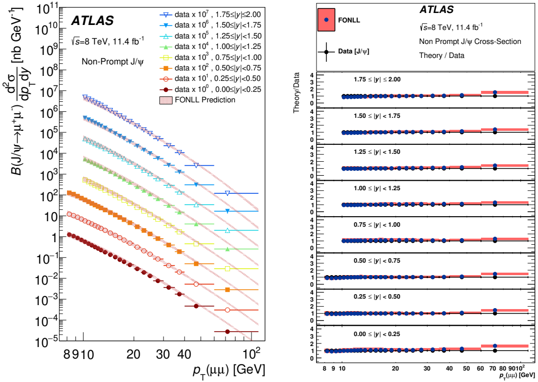


Prompt J/ψ

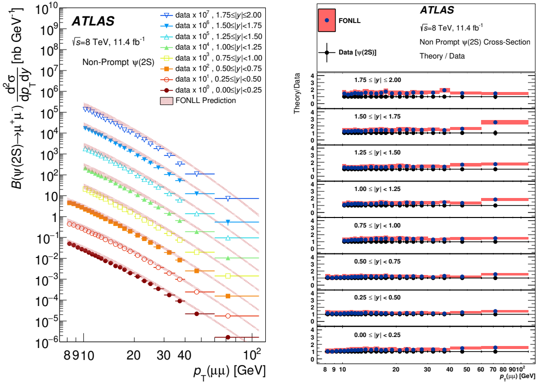


Prompt $\psi(2S)$

- 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

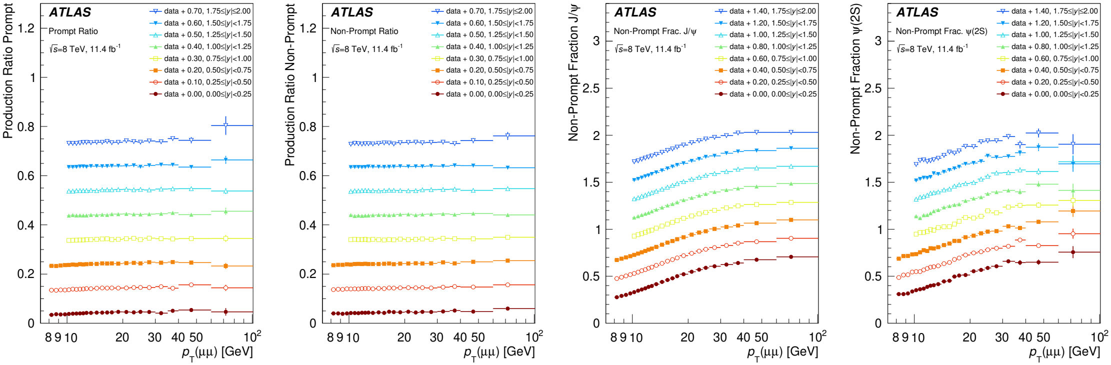


Non-prompt J/ψ



Non-prompt $\psi(2S)$

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



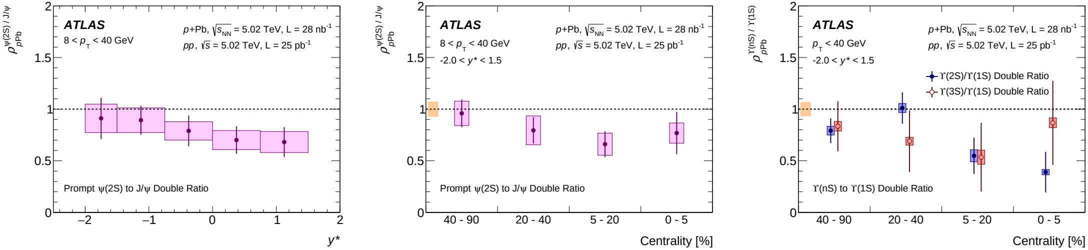
$\psi(2S)$ to J/ψ ratio for prompt/non-prompt

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 $\sim$20 GeV ($\sim$30 GeV)

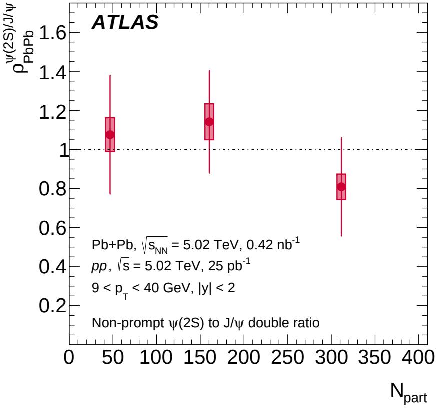
Charmonia in $p+\mathrm{Pb}$: (nS) suppression

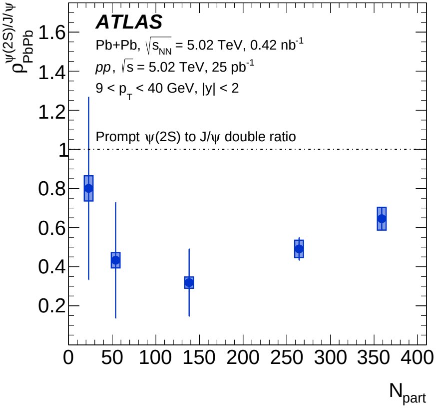
- Double ratios $\rho_{p\mathrm{Pb}}^{O(nS)/O(1S)}$ in $p+\mathrm{Pb}$
  - Relative $\psi(2S)$ suppression increases with centre-of-mass rapidity, 1σ significance trend
  - Both $\Upsilon(2,3S)$ suppressed by 2σ in the full $p_\mathrm{T} < 40$ GeV and $-2 < y^* < 1.5$ region
  - $\rho^{\psi(2S)/\psi(1S)}$ 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



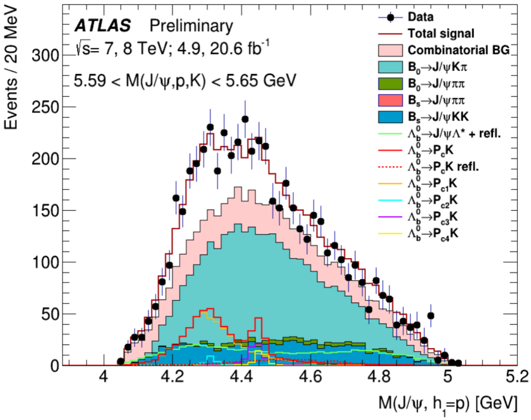
Charmonia in Pb + Pb: (nS) suppression

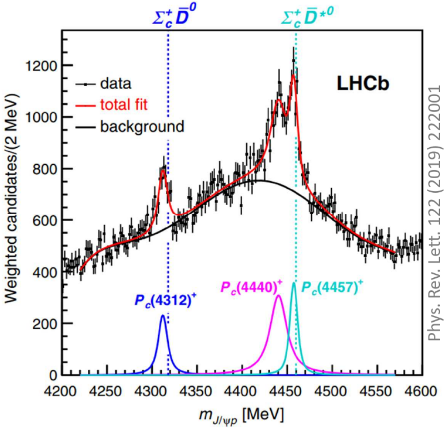
- Expect $\rho_{\mathrm{PbPb}}^{O(nS)/O(1S)} = 1$ for non-prompt charmonia
  - originate from b quark loosing energy in the medium and hadronizing outside
- The double ratio indeed consistent with unity for non-prompt, and < 1 for prompt
  - consistent with the interpretation that the tighter bound J/ψ 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]	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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Pentaquarks: event selection

- 2 muons from J/ψ decay with mass $3097 \pm 290\,\mathrm{GeV}$
- 2 muon tracks + 2 hadron tracks vertex fit: dimuon mass constrained to J/ψ mass, Λ_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); $p_\mathrm{T} > 2.5\,\mathrm{GeV}$ for proton candidate and $p_\mathrm{T} > 1.8\,\mathrm{GeV}$ for kaon candidate
- Transverse decay length $L_{xy}(\Lambda_b^0) > 0.7\,\mathrm{mm}$;
- $p_\mathrm{T}(\Lambda_b^0)/\sum p_\mathrm{T}(\mathrm{tracks}) > 0.2$, where sum is taken over all tracks originating from PV;
- $p_\mathrm{T}(\mu^\pm) > 4\,\mathrm{GeV}$, $|\eta(\mu^\pm)| < 2.3$, $p_\mathrm{T}(\Lambda_b^0) > 12\,\mathrm{GeV}$, $|\eta(\Lambda_b^0)| < 2.1$;
- Inv. mass of hadron tracks (in $K\pi$ and πK mass hypotheses): $M(K\pi) > 1.55\,\mathrm{GeV}$ and $M(\pi K) > 1.55\,\mathrm{GeV}$, 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 Λ_b^0 candidate in Λ_b^0 candidate rest frame > -0.8;
- $|\cos\theta^\star|$ between kaon and Λ^{*0} in Λ^{*0} rest system < 0.85;
- Events for $J/\psi p$ signal search are taken in window $M(J/\psi pK) \in 5620 \pm 30\,\mathrm{MeV}$;
- 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 (δ_1)	-	${}^{+0.9}_{-1.0}\%$	-	${}^{+0.9}_{-1.0}\%$	-	${}^{+0.9}_{-1.0}\%$
Tracking (δ_2)	$\pm 7.8\%$	$\pm 7.4\%$	$\pm 7.7\%$	$\pm 7.4\%$	$\pm 7.6\%$	$\pm 7.4\%$
D selection (δ_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 (δ_4)	$\pm 1.3\%$	$\pm 0.9\%$	$\pm 1.3\%$	$\pm 1.5\%$	$\pm 6.4\%$	$\pm 5.3\%$
Modelling (δ_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 (δ_6)	$\pm 0.6\%$	$\pm 0.9\%$	$\pm 0.8\%$	$\pm 0.8\%$	$\pm 2.9\%$	$\pm 3.1\%$
Luminosity (δ_7)	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$	$\pm 3.5\%$
Branching fraction (δ_8)	$\pm 1.5\%$	$\pm 1.5\%$	$\pm 2.1\%$	$\pm 2.1\%$	$\pm 5.9\%$	$\pm 5.9\%$

LEP average fragmentation fractions

Eur. Phys. J. C 75 (2015) 19

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

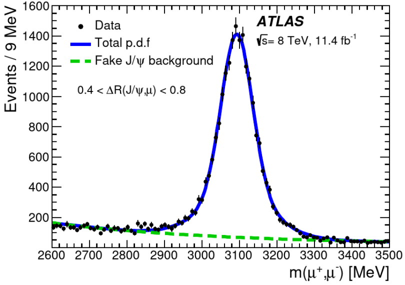
Gluon splitting kernels in PYTHIA

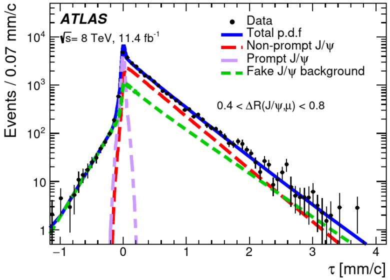
Option label	Descriptions
Opt. 1	The same splitting kernel, $(1/2)(z^2 + (1-z)^2)$, for massive as massless quarks, only with an extra β phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [50] method.
Opt. 4	A splitting kernel $z^2 + (1-z)^2 + 8r_q z(1-z)$, 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: $r_q = m_q^2/m_{qq}^2$, $\beta = \sqrt{1-4r_q}$, with m_q the quark mass and m_{qq} the $q\bar{q}$ pair invariant mass.

$b\bar{b}$ production measurement details

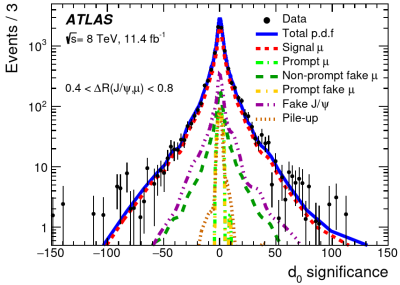
- Fiducial volume definition:
  - $p_T(\mu) > 6\,\text{GeV}$ for all three muons
  - $|\eta(\mu)| < 2.3$ for the J/ψ muons and < 2.5 for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to J/ψ mass and pseudo-proper lifetime to extract the yield of J/ψ from b

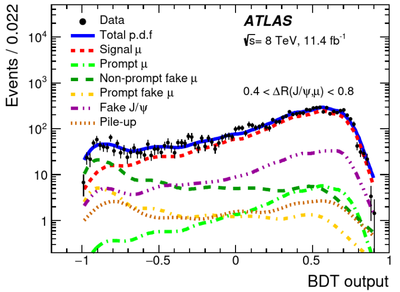




$b\bar{b}$ production measurement details

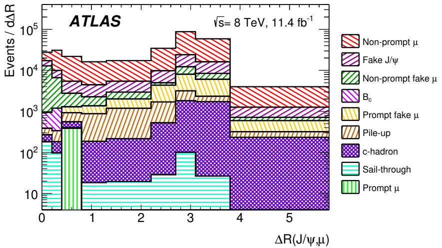
- Fiducial volume definition:
  - $p_T(\mu) > 6\,\text{GeV}$ for all three muons
  - $|\eta(\mu)| < 2.3$ for the J/ψ muons and < 2.5 for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to J/ψ mass and pseudo-proper lifetime to extract the yield of J/ψ from b
  - Yield of 3rd muon from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

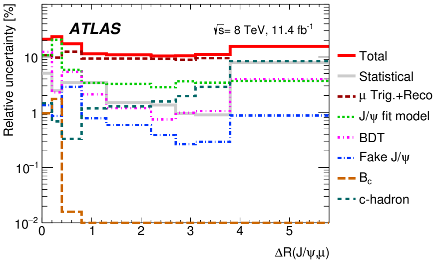




$b\bar{b}$ production measurement details

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





$b\bar{b}$ production measurement details

- Fiducial volume definition:
  - $p_T(\mu) > 6\,\text{GeV}$ for all three muons
  - $|\eta(\mu)| < 2.3$ for the J/ψ muons and < 2.5 for the 3rd muon
- Signal extraction, in each bin
  - Simultaneous fit to J/ψ mass and pseudo-proper lifetime to extract the yield of J/ψ 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 τ range
  - Correct for detector resolution effects