Prospects of Charm Physics at ATLAS

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The 9th International Workshop on Charm Physics
Novosibirsk, Russia
21–25 May 2018

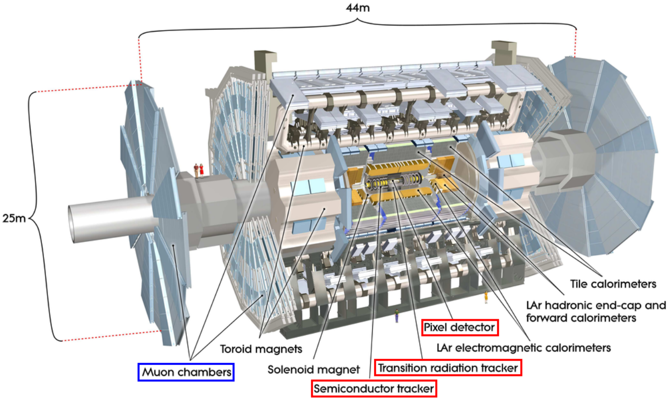
Introduction

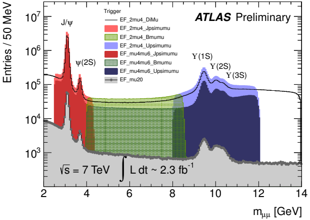
- ATLAS is a general purpose detector at LHC
- Unlike LHCb, not designed specially for B-physics studies, but
  - Benefits from $\sim \times 10$ higher statistics due to luminosity
    - Competitive in some statistically limited studies
  - Covers central rapidity region
    - Provides measurements complementary to those of LHCb

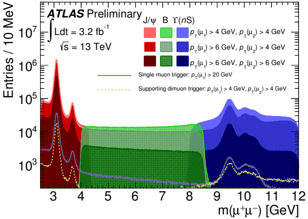
- In charm sector, covers wide area of studies:
  - Production
    - Open charm (e.g. D meson measurement Nucl. Phys. B 907 (2016) 717)
    - Charmonia, including exotics
    - Also in heavy ion collisions
    - Associated production with other objects, e.g. $J/\psi + W, Z$, di-J/ψ
  - Spectroscopy
    - Good opportunities for B_c meson studies
- In this talk, some recent studies of this program will be highlighted
  - Focus on those, not shown at previous editions of *Charm* conference series

ATLAS detector and trigger

- Inner Detector
  - used for track and vertex reconstruction
  - in 2T solenoid field
  - covers $|\eta| < 2.5$
    - Silicon pixels and strips
    - Straw tracker (TRT)
  - Insertable B-Layer added before Run-2, to improve lifetime resolution
- Muon Spectrometer
  - precision and trigger chambers
  - 0.5–2T toroid field
  - covers $|\eta| < 2.7$
- Two-level trigger system
  - Triggering on charmonia uses dimuon signature
  - Other triggers used for associated production

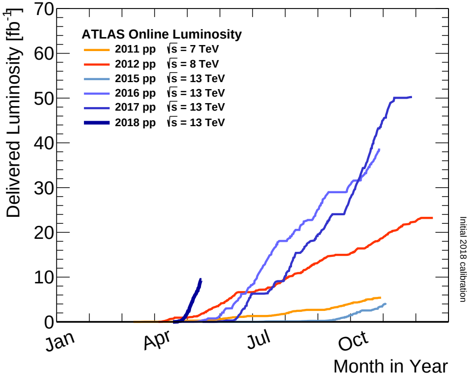


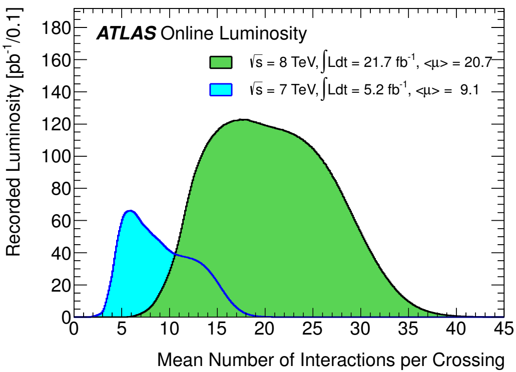




Data and LHC status

- Excellent LHC performance kept from Run-1 to Run-2
  - In 2018 exceeds $L = 2 \times 10^{34}$ cm^{-2} s^{-1} – twice projected value
- Data collected (similar for ATLAS and CMS):
  - 4.9 fb^{-1} @ 7 TeV (peak PU below ~15)
  - 20.3 fb^{-1} @ 8 TeV (peak PU below ~35)
  - (3.2 + 35.6 + 43.6 + 8.7) fb^{-1} @ 13 TeV (peak PU up to ~60)
  - Data also collected in *p*Pb and PbPb regimes





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

Eur. Phys. J. C 76 (2016) 283

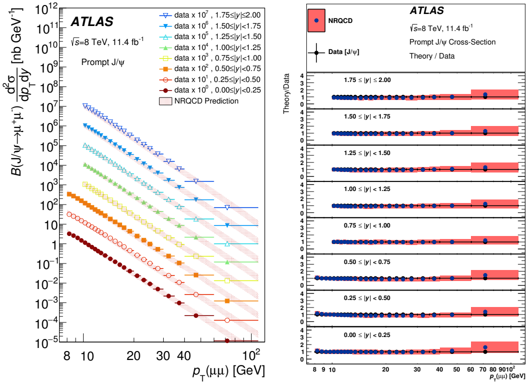
Heavy quarkonia production at LHC is a unique approach for understanding strong interactions

- Two different mechanisms for charmonium production:
  - *Prompt*: directly in *pp* interaction or via feed-down from heavier states
    - $\sim$35% of J/ψ comes from feed-down; $\psi(2S)$ is produced almost directly
    - Theory: Non-Relativistic QCD (NRQCD)
      pQCD $c\bar{c}$ production, CO contribution introduces a number of phenomenological parameters from Tevatron data fits
  - *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

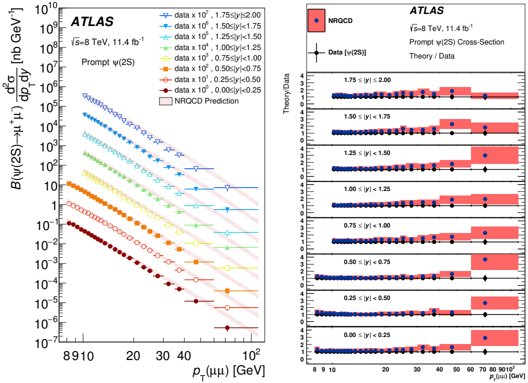
ATLAS analysis

- Use $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ modes
- 2.3 fb^{-1} @ 7 TeV + 11.4 fb^{-1} @ 8 TeV collected with dimuon triggers
- Charmonia kinematic region $8 < p_{\text{T}}(\psi) < 110$ GeV, $|y(\psi)| < 2.0$
- Muon $p_{\text{T}}(\mu_{1,2}) > 4$GeV, $|\eta(\mu_{1,2})| < 2.3$
- Prompt/Non-prompt contributions determined from 2D mass and lifetime fit

J/ψ and $\psi(2S)$ production: prompt



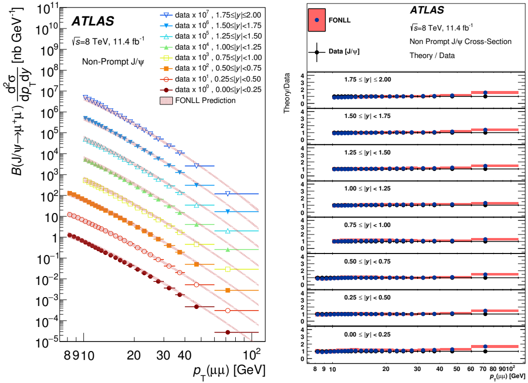
Prompt J/ψ



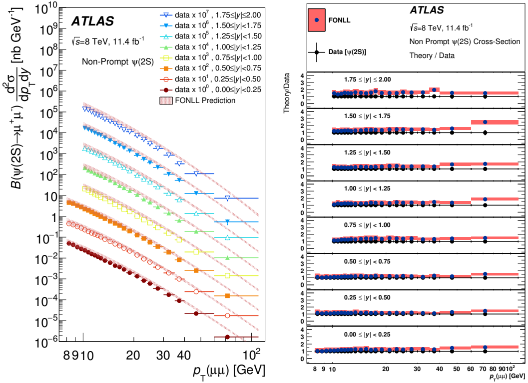
Prompt $\psi(2S)$

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

J/ψ and $\psi(2S)$ production: non-prompt

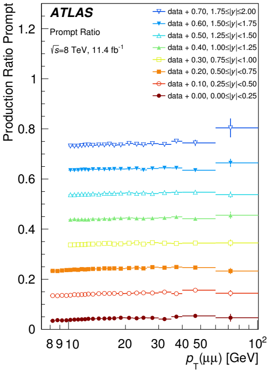


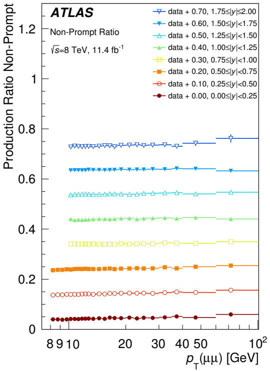
Non-prompt J/ψ

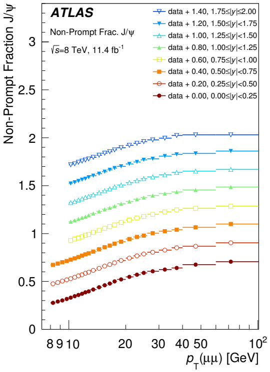


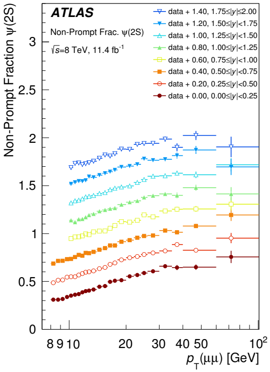
Non-prompt $\psi(2S)$

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









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

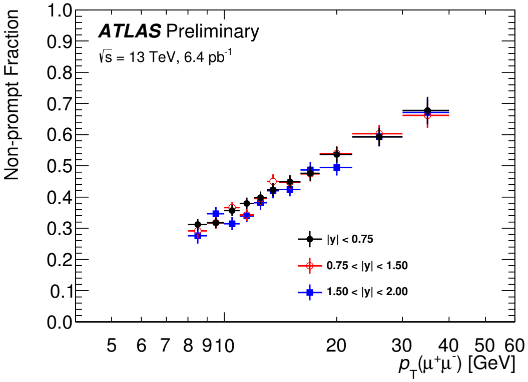
Non-prompt fraction for J/ψ and $\psi(2S)$

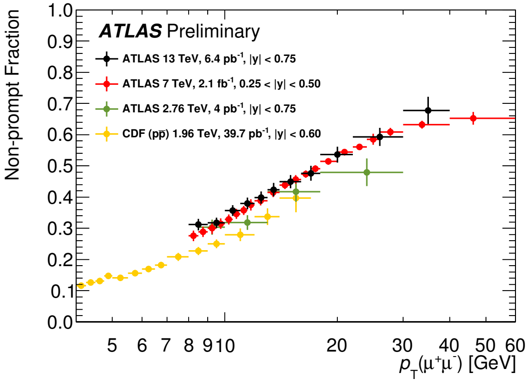
- Ratio of J/ψ to $\psi(2S)$ flat across the whole p_T range
- Prompt J/ψ ($\psi(2S)$) dominate over non-prompt at low p_T, but the non-prompt exceed after ∼20 GeV (∼30 GeV)

Non-prompt J/ψ fraction at $\sqrt{s} = 13$TeV

ATLAS-CONF-2015-030

- Analyse early sample of 6.4 pb^{-1} collected with di-muon triggers
- Very similar shape to $\sqrt{s} = 7$ TeV, but certain change compared to lower energies
  - The NP fraction grows steadily from 0.25 to 0.65 between 8 and 40 GeV
  - No sizeable dependence on rapidity



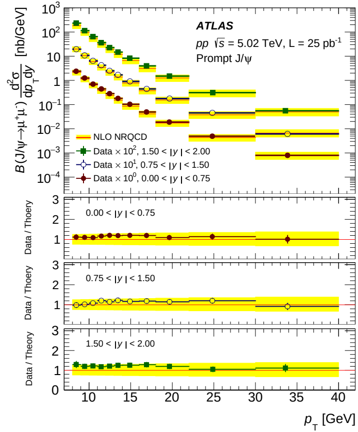


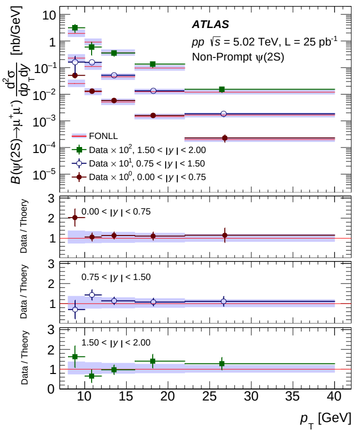
Charmonia production in Pb + Pb, p + Pb

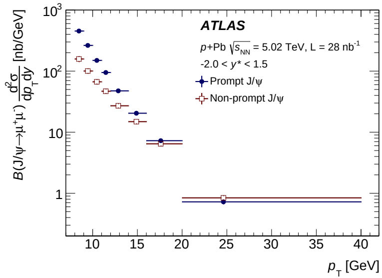
- Probe deconfined quark-gluon plasma in $A + A$ collisions
  - Suppression (melting) could provide info about temperature of deconfinement
  - Enhancement could also appear; at low-p_{T} $\rightarrow$ new quarkonium formation mechanism (recombination of $c\bar{c}$ from the medium)
  - Non-prompt charmonia allows studying b quark propagation through the medium
    - Possibly different mechanism (collisions, radiation) from $c\bar{c}$ suppression (colour screening)
  - ATLAS measurement for J/ψ and $\psi(2S)$ production in Pb + Pb with 0.42 nb^{-1} @ $\sqrt{s_{NN}} = 5.02$ TeV: arXiv:1805.04077
- Collisions of $p + A$ to disentangle cold nuclear matter effects (CNM)
  - Suppression of charmonia production versus pp collisions, $R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{O(nS)}_{\mathrm{pPb}}}{\sigma^{O(nS)}_{pp}}$
    - Seen in p + Pb at low p_{T} (ALICE) and high y (LHCb), but not at ATLAS or CMS
  - Suppression of relative production of the $1S$ and nS states in p + Pb vs. pp, $\rho^{O(nS)/O(1S)}_{\mathrm{pPb}} = \frac{R_{p\mathrm{Pb}}(O(nS))}{R_{p\mathrm{Pb}}(O(1S))}$
    - Seen at ALICE, PHOENIX for $\psi(2S)$ and J/ψ; at CMS for $\Upsilon(nS)$
    - Detector uncertainties mostly cancel
  - ATLAS measurement for J/ψ, $\psi(2S)$, and $\Upsilon(nS)$ production in p + Pb with 28 nb^{-1} @ $\sqrt{s} = 5.02$ TeV: Eur. Phys. J. C 78 (2018) 171, see below

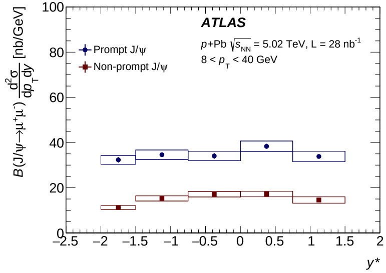
Charmonia in $p+\mathrm{Pb}$: cross-sections

- Prompt J/ψ and $\psi(2S)$ production compatible with NRQCD
- Non-prompt charmonia consistent with FONLL calculations



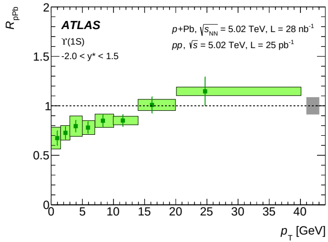


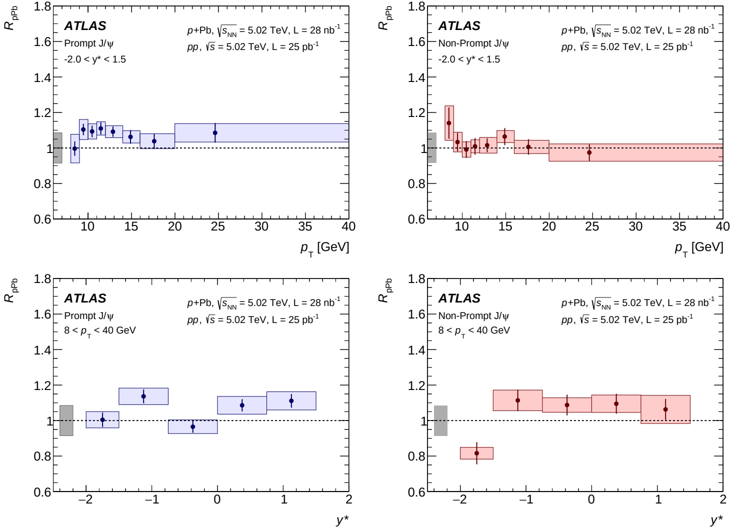




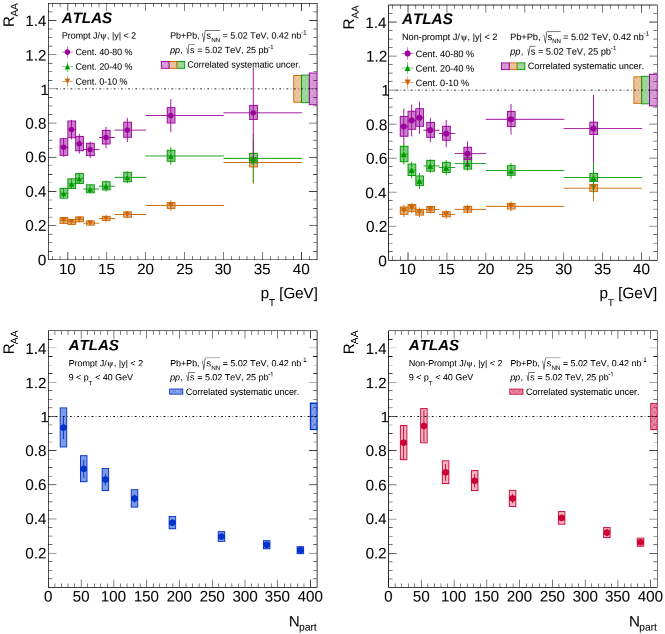
Charmonia in $p+\mathrm{Pb}$: R factors

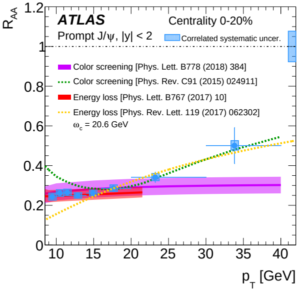
- R_{pPb} factors for prompt and non-prompt J/ψ consistent with unity
  - no p_T or y^* dependence
  - weak modification for J/ψ production due to CNM effects
- $R_{pPb} < 1$ for $\Upsilon(1S)$ below 15 GeV
  - stronger nPDF shadowing for small x?





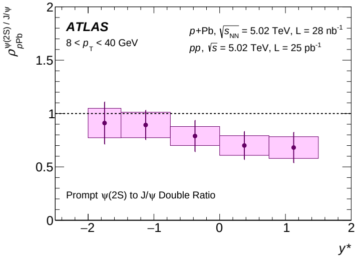
- J/ψ production strongly suppressed in central collisions
  - very similar for prompt and non-prompt
  - not quite expected, as the two cases have different origins
- R_{AA} increases at high $p_T > 12$ GeV for prompt J/ψ, flat for non-prompt

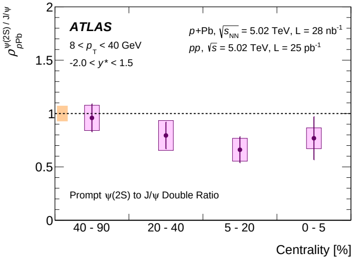


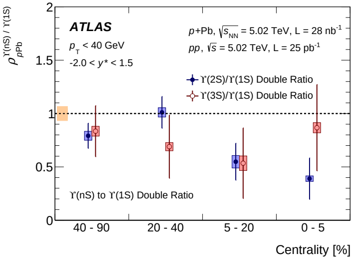


Charmonia in $p+\mathrm{Pb}$: (nS) suppression

- 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
  - $\Upsilon(nS)$ suppression by 2σ in the full $p_{\mathrm{T}} < 40$ GeV and $-2 < y^* < 1.5$ region
  - Both more suppressed with more central collisions

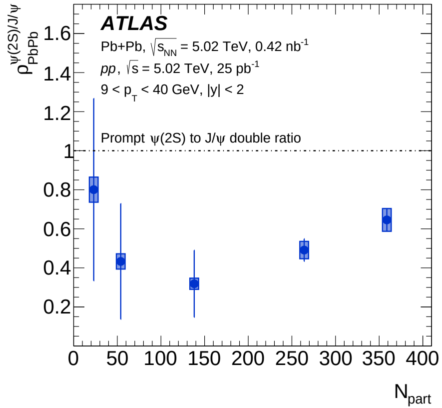


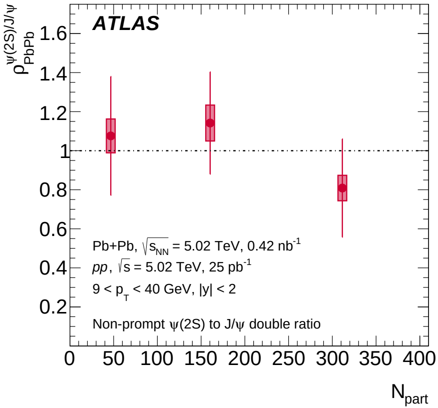




Charmonia in Pb + Pb: (nS) suppression

- Expect $\rho_{pPb}^{O(nS)/O(1S)} = 1$ 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 survites in the hot and dense medium with higher probability than more loosely bound $\psi(2S)$





Studying charmonia associated production

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

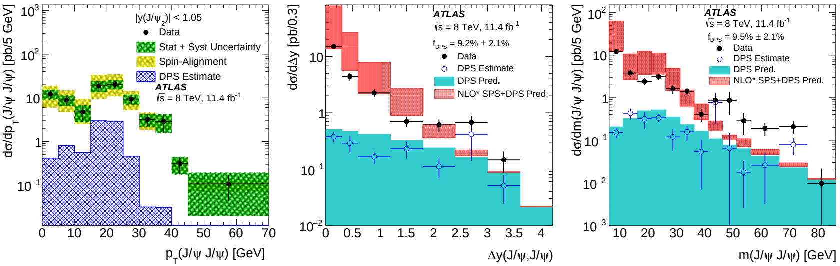
$$\sigma_{AB} = \sigma_{AB}^{\mathrm{SPS}} + \sigma_{AB}^{\mathrm{DPS}} = \sigma_{AB}^{\mathrm{SPS}} + \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} \times \frac{1}{1 + \delta_{AB}}$$

- ATLAS performed a few relevant measurements
  - $J/\psi + W$ production @ 7 TeV JHEP 04 (2014) 172
  - $J/\psi + Z$ production @ 8 TeV Eur. Phys. J. C 75 (2015) 229
  - J/ψ prompt pairs production @ 8 TeV Eur. Phys. J. C 77 (2017) 76, see below, more details in the talk on Wednesday

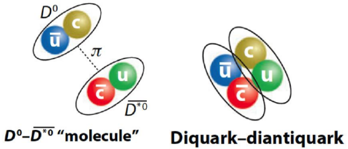
J/ψ pair production measurement

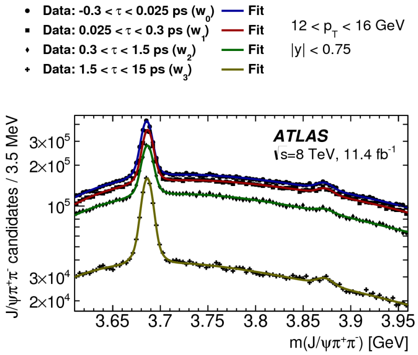
Eur. Phys. J. C 77 (2017) 76

- Use 11.4 fb^{-1} @ 8 TeV data
  - di-muon triggers with $p_T(\mu_{1,2}) > 4$ GeV, lower-p_T J/ψ with $p_T(\mu_{1,2}) > 2.5$ GeV
- DPS measurement:
  - $f_{DPS} = (9.2 \pm 2.1(\text{stat.}) \pm 0.5(\text{syst.}))\%$
  - $\sigma_{eff} = 6.3 \pm 1.6(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.1(\text{BF}) \pm 0.1(\text{lumi.})$ mb
    - consistent with LHCb, D0 measurements with quarkonia
    - smaller than many other measurements
- Reasonable agreement with data (SPS@NLO + DPS@LO)
  - larger deviations for *back-to-back topology*



- $X(3872)$ was observed by Belle in 2003, later confirmed by others
- No clear theoretical picture yet
  - Loosely bound $D^0\bar{D}^{*0}$ molecule
  - Excited charmonium 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

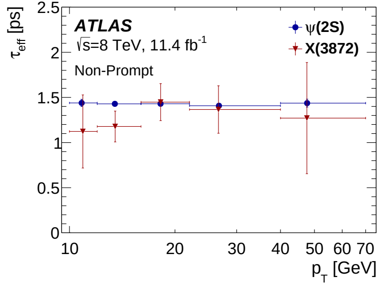


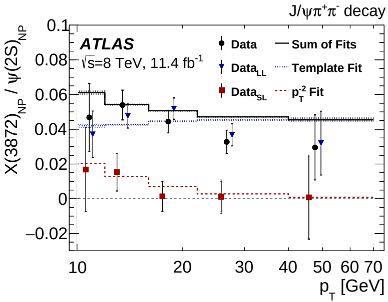


$X(3872)$ lifetime hypotheses

- 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
  - 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

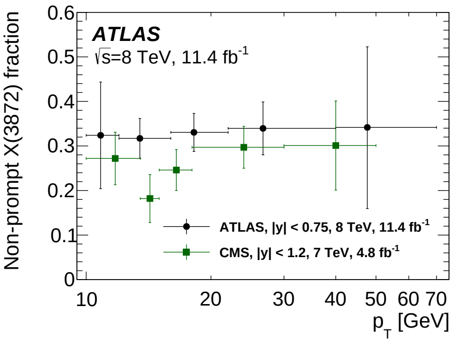
$$\frac{\sigma(pp \to B_c + \text{any})\mathcal{B}(B_c \to X(3872) + \text{any})}{\sigma(pp \to \text{non-prompt } X(3872) + \text{any})} = (25 \pm 13(\text{stat.}) \pm 2(\text{syst.}) \pm 5(\text{spin}))\%$$

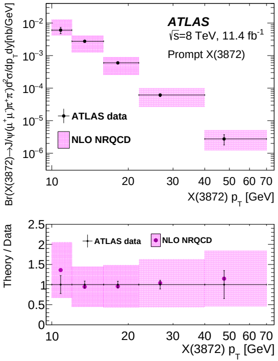


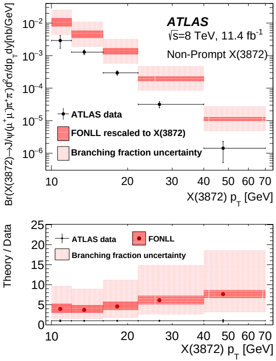


$X(3872)$ production cross-section

- 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

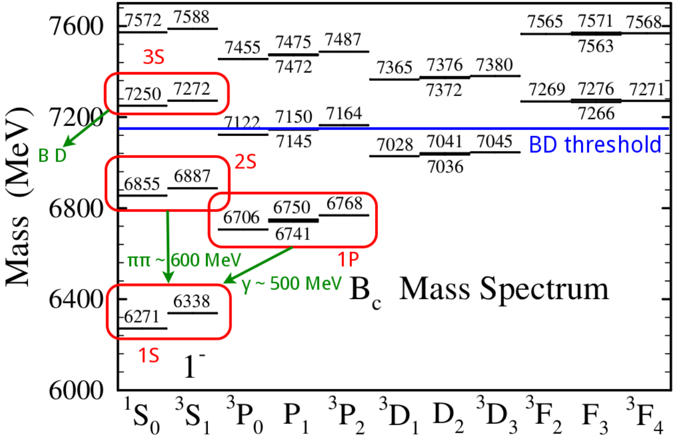






B_c excited states

- No excited states of B_c reported previously
- The spectrum and properties of B_c family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations
- Measurements of the ground and excited states $\rightarrow$ test of these predictions
  - 2S states are experimentally easy to search
  - Both 1S and 2S have pseudoscalar and vector components

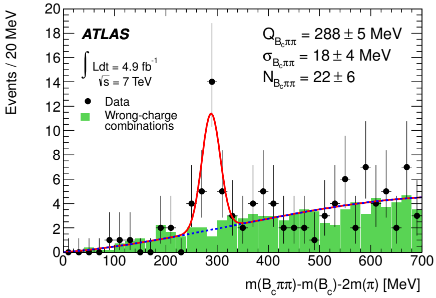


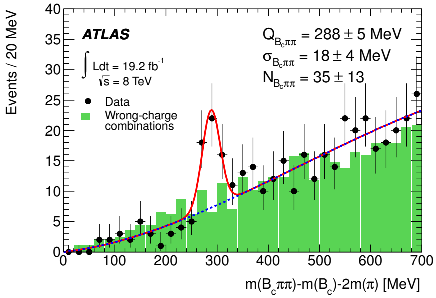
Phys. Rev. D 70 (2004) 054017

$B_c(2S)$ observation

Phys. Rev. Lett. 113 (2014) 212004

- Search in $B_c\pi^+\pi^-$ final state, B_c in $J/\psi\pi^+$ mode
  - Study the spectrum of $Q = m(B_c\pi^+\pi^-) - m(B_c) - 2m(\pi^+)$
- A new state observed at $Q = 288.3 \pm 3.5(\text{stat.}) \pm 4.1(\text{syst.})$ MeV (error-weighted mean of 7 and 8 TeV values)
  - Corresponds to a mass $6842 \pm 4(\text{stat.}) \pm 5(\text{syst.})$ MeV, consistent with the predicted mass of $B_c(2S)$
  - Combined significance is 5.2σ
- Possible interpretations:
  - $B_c[2^3S_1] \to B_c^*(1S)(\to B_c\gamma)\pi^+\pi^-$
  - $B_c[2^1S_0] \to B_c(1S)\pi^+\pi^-$
- Similar analysis recently reported by LHCb (arXiv:1712.04094,JHEP 1801 (2018) 138)
  - no evidence, upper limits set
- Further study underway

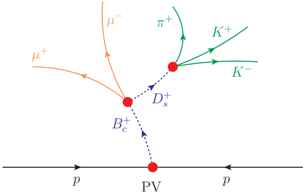


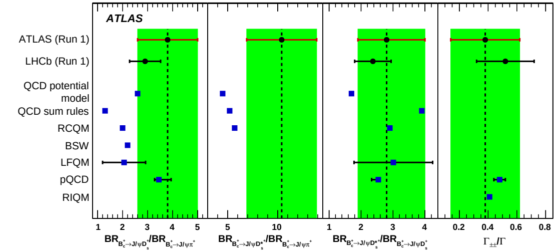


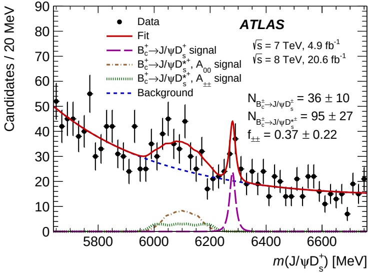
$B_c^+ \to J/\psi D_s^{(*)+}$ decay measurement

Eur. Phys. J. C 76 (2016) 4

- Measurement of $B_c^+ \to J/\psi D_s^{(*)+}$ decay rates and polarization done with full Run 1 dataset
  - $\frac{\mathcal{B}_{B_c^+\to J/\psi D_s^+}}{\mathcal{B}_{B_c^+\to J/\psi \pi^+}} = 3.8 \pm 1.1(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.2(\text{BF})$
  - $\frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi \pi^+}} = 10.4 \pm 3.1(\text{stat.}) \pm 1.5(\text{syst.}) \pm 0.6(\text{BF})$
  - $\frac{\mathcal{B}_{B_c^+\to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+\to J/\psi D_s^+}} = 2.8^{+1.2}_{-0.8}(\text{stat.}) \pm 0.3(\text{syst.})$
  - $\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23(\text{stat.}) \pm 0.07(\text{syst.})$
- Comparable precision to LHCb due to more accurate fit for the polarization







Summary

- ATLAS has a wide and active *B-physics* program
- Despite the B, includes a lot of *charm* related studies
  - Biased towards charmonia, due to trigger limitation
- Most of presented studies are based on Run 1 data
  - Many measurements statistically limited – expect improvements with Run 2
  - Also improvements in the detector (IBL) and trigger
- Stay tuned for many new results!

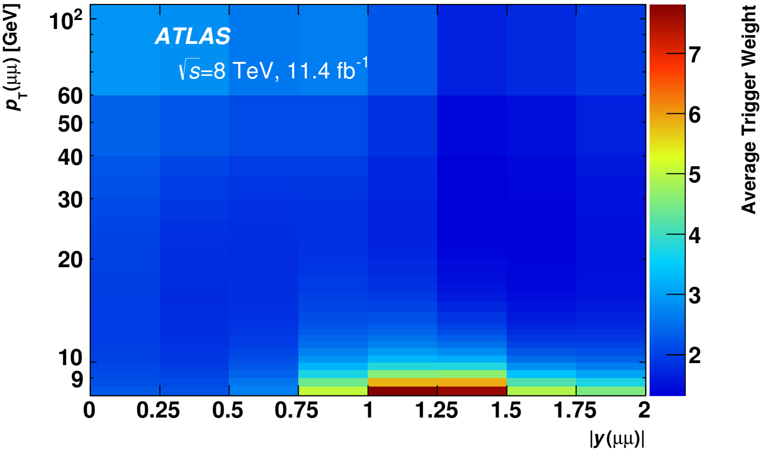
Backup slides

ATLAS Upgrage

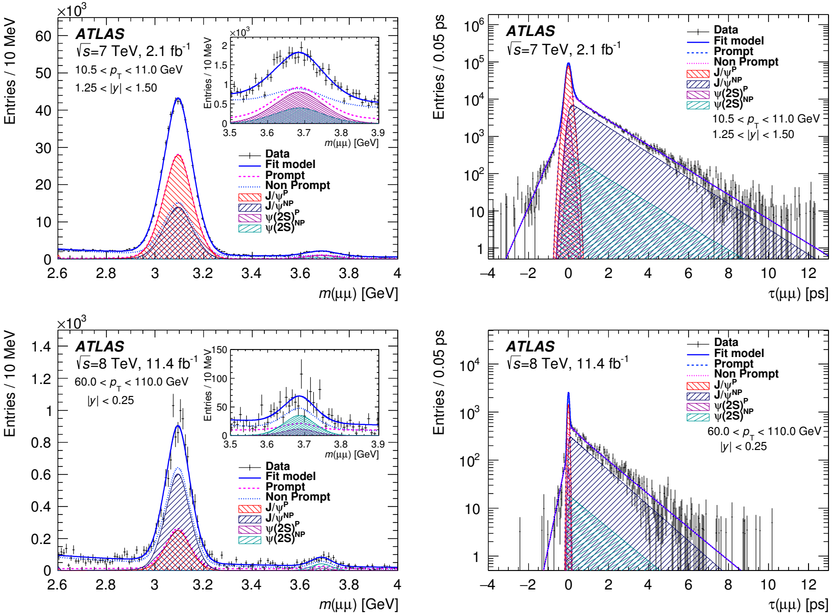
system	phase0 / run 2	phase 1 / run 3	phase 2 / run 4
Pixel	IBL at R=34 mm, new cooling, new services		replaced by ITk pixel
SCT			replaced by ITk strips
TRT			decommissioned
LAr	all new power supplies	new L1 trigger electronics	new readout electronics (input to L0Calo), 40 MHz streaming, High Granularity Timing Detector (HGTD)
Tile	new low voltage power supplies		readout electronics, 40 MHz streaming, improved drawer mechanics, new HV power supplies
RPC	gas leak repairs	BMG (sMDT) in acceptance gaps, BIS78 chambers between barrel and end-caps	new chambers in inner barrel
TGC		New Small Wheel (sTGC + MicroMegas)	new front-end electronics, forward tagger (option)
MDT			replace all front-end electronics
Trigger	new L1Topo, upgraded CTP, partial FTK L2 + EF → HLT	new FEX, full FTK, new muon-CTP interface HLT: multi-threading, offline-like algorithms	L0 (Calo, Muons) 1 MHz, 10 µs latency optional: L1 (L0 at 4 MHz, L1Track) 800 kHz, 35 µs latency
DAQ	custom hard-/firmware	FELIX for some systems	FELIX for all systems

- Phase 0: 2013–2015
  - Run 2: 2015–2018
  - **We are here**
- Phase 1: 2019-2020
  - Run 3: 2021–2023
- Phase 2: 2024–2025+
  - Run 4+: ∼2026+

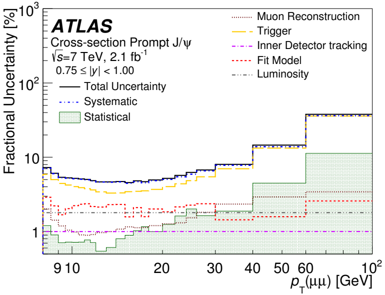
Dimuon trigger efficiency map

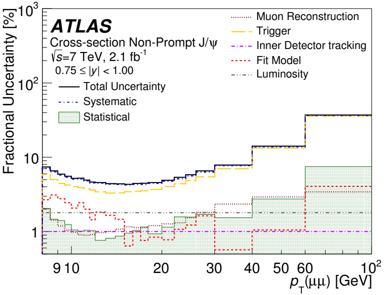


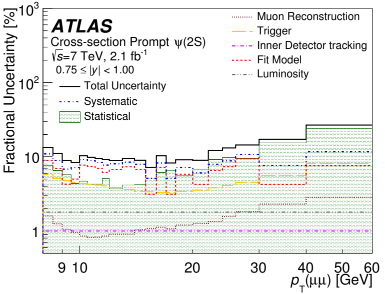
Charmonia production fit examples

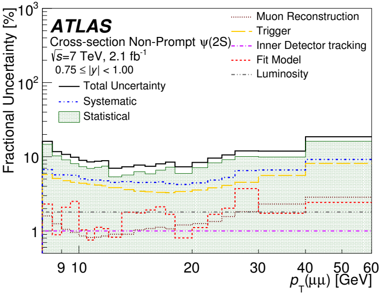


Charmonia production systematics breakdown

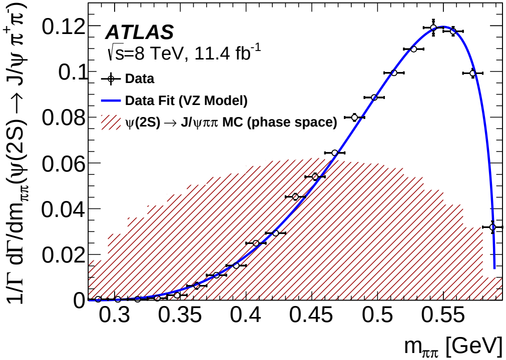


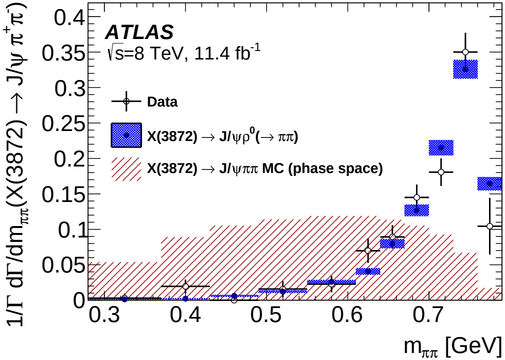






$m(\pi^+\pi^-)$ shape in $\psi(2S)$ and $X(3872)$





- $m(\pi^+\pi^-)$ spectrum disfavours the phase space distribution, preferring higher masses

D meson production measurement: 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

Analysis overview

- Data of 2010 at $\sqrt{s} = 7\,\text{TeV}$ are used
  - $1.04\,\text{nb}^{-1}$ collected with minimum-bias triggers used for $p_{\text{T}} < 20\,\text{GeV}$ range
  - $280\,\text{nb}^{-1}$ with jet triggers for $20 < p_{\text{T}} < 100\,\text{GeV}$ range
- Measurement kinematic range:
  - $3.5 < p_{\text{T}}(D) < 100\,\text{GeV}$
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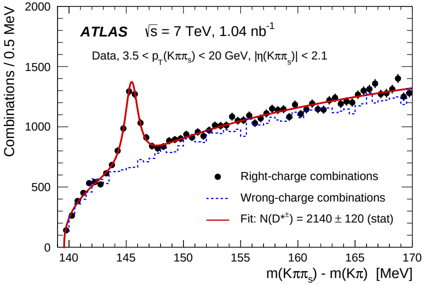

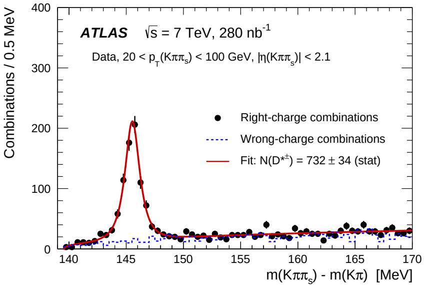

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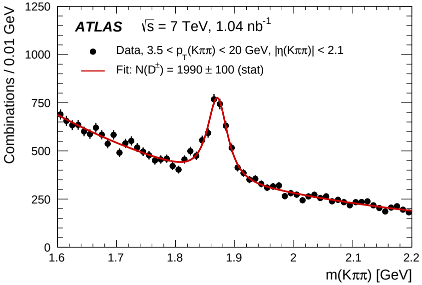

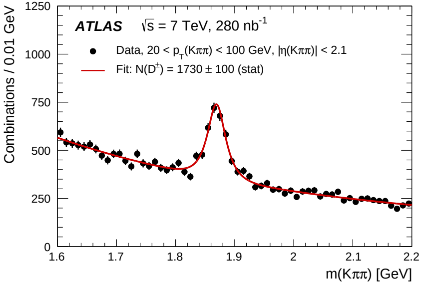

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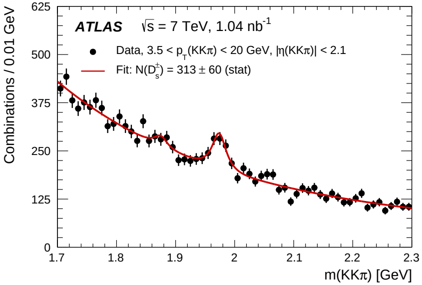
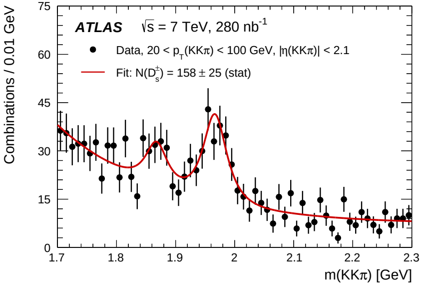
  - $D_s^+ \to \phi\pi^+ \to (K^+K^-)\pi^+$





Results: visible cross-sections

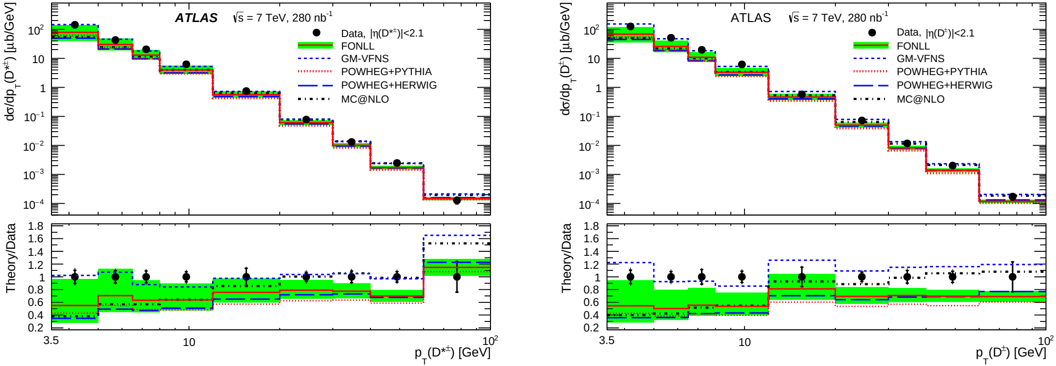
- Visible cross-sections measured:

	$\sigma^{\text{vis}}(D^{*\pm})$		$\sigma^{\text{vis}}(D^{\pm})$		$\sigma^{\text{vis}}(D_s^{*\pm})$	
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 $\mathcal{B}$ are the main systematics sources

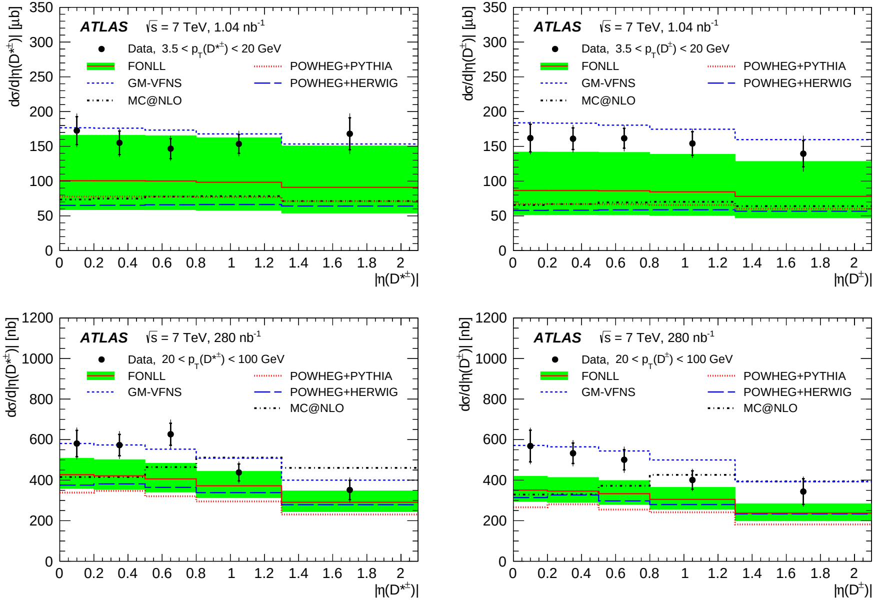
- GM-VFNS approach shows the best description of data
- FONLL and NLO+PS approaches are generally below data, but still consistent within uncertainties

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 – η



Results: extrapolation

- For extrapolation to the full phase space, *FONLL* predictions are used (including subtraction of b 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 HQET (0.75), string fragmentation and thermodynamical approach (2/3)

Overall uniquely advanced measurement for LHC general-purpose detectors!

Studying charmonia associated production

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

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

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

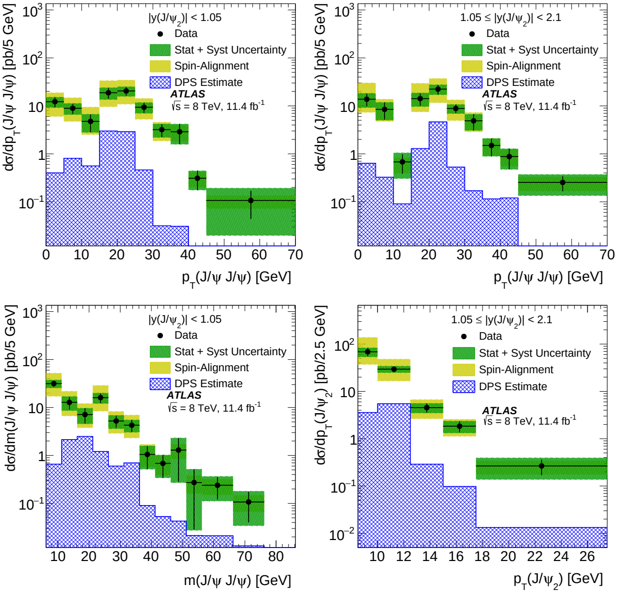
$$f_{\text{DPS}} = \frac{\sigma_{AB}^{\text{DPS}}}{\sigma_{AB}} = \frac{\sigma_A \sigma_B}{\sigma_{AB}\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}} \sim \frac{1}{\sigma_{\text{eff}}} \times \frac{N_A N_B}{N_{AB}} \times \frac{1}{1+\delta_{AB}}$$

- ATLAS performed a few relevant measurements
  - $J/\psi + W$ production @ 7 TeV JHEP 04 (2014) 172
  - $J/\psi + Z$ production @ 8 TeV Eur. Phys. J. C 75 (2015) 229
  - J/ψ prompt pairs production @ 8 TeV Eur. Phys. J. C 77 (2017) 76, see below

J/ψ pair production measurement: cross-sections

Eur. Phys. J. C 77 (2017) 76

- Use 11.4 fb^{-1} @ 8 TeV data
  - di-muon triggers with $p_T(\mu_{1,2}) > 4$ GeV
  - lower J/ψ with $p_T(\mu_{1,2}) > 2.5$ GeV
- $\sim$1200 candidates with $p_T(J/\psi) > 8.5$ GeV, $|\eta(J/\psi)| < 2.1$
- Corrected (for muon acceptance) cross-section:
  - $82.2 \pm 8.3(\text{stat.}) \pm 6.3(\text{syst.}) \pm 0.9(\text{BF}) \pm 1.6(\text{lumi.})$ 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 $1.05 < |y| < 2.1$
- Measure cumulative and DPS-only spectra of $p_T(J/\psi_2)$, $p_T(J/\psi J/\psi)$, $m(J/\psi J/\psi)$



J/ψ pair production measurement: DPS estimates

- Data-driven DPS model
  - overlay of J/ψ from different events
  - normalized to DPS-enriched region $\Delta y > 1.8,\ \Delta\phi < \pi/2$
- DPS measurement:
  - $f_{\mathrm{DPS}} = (9.2 \pm 2.1(\mathrm{stat.}) \pm 0.5(\mathrm{syst.}))\%$
  - $\sigma_{\mathrm{DPS}}^{J/\psi,J/\psi} = 14.8 \pm 3.5(\mathrm{stat.}) \pm 1.5(\mathrm{syst.}) \pm 0.2(\mathrm{BF}) \pm 0.3(\mathrm{lumi.})$ pb
  - $\sigma_{\mathrm{eff}} = 6.3 \pm 1.6(\mathrm{stat.}) \pm 1.0(\mathrm{syst.}) \pm 0.1(\mathrm{BF}) \pm 0.1(\mathrm{lumi.})$ mb
- Reasonable agreement with data (SPS@NLO + DPS@LO)
  - larger deviations for *back-to-back topology*
- Predictions are a limitation factor