Production Measurements of Quarkonium and Heavy Flavour at ATLAS

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On behalf of the ATLAS Collaboration

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Overview

- Heavy Flavour Production
  - Studies of heavy flavour production of $b\bar{b}$ pairs
    JHEP 11 (2017) 62 Phys. Rev. D 99 (2019) 052004

- Spectroscopy
  - First observation of an excited B_c meson PRL 113 212004 (2014)

- Production of Quarkonium
  - Quarkonia in p-p and p-Pb collisions Eur. Phys. J. C 78 (2018) 171
  - di–J/ψ Production:
    - Prompt di–J/ψ production (8 TeV) Eur. Phys. J. C77 (2017) 76

Measurements of $b\bar{b}$ pair production

1) Measurement of b-hadron pair production with $J/\psi + \mu$ (8 TeV)

JHEP 11 (2017) 62

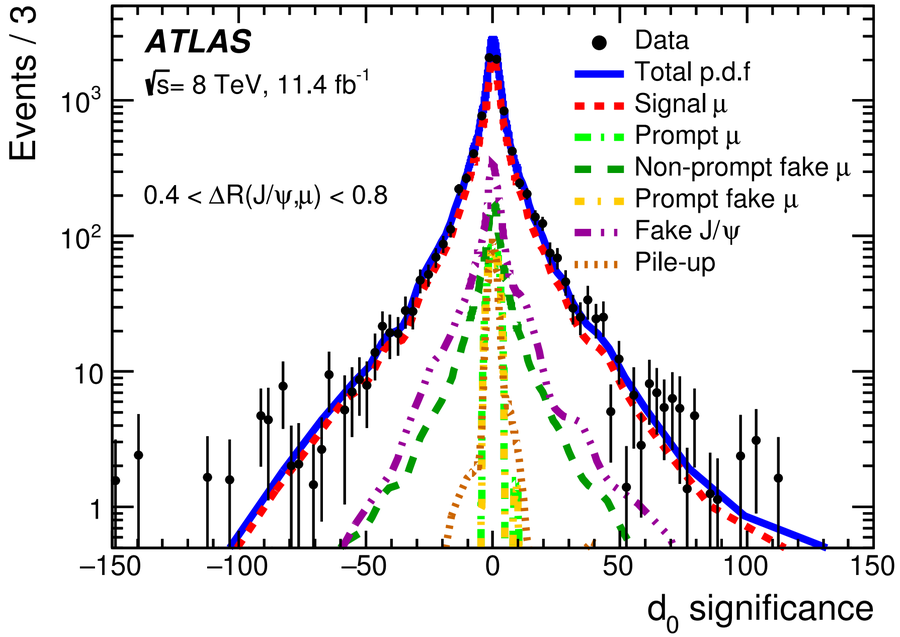
2) Properties of $g \to b\bar{b}$ at small opening angles (13 TeV)

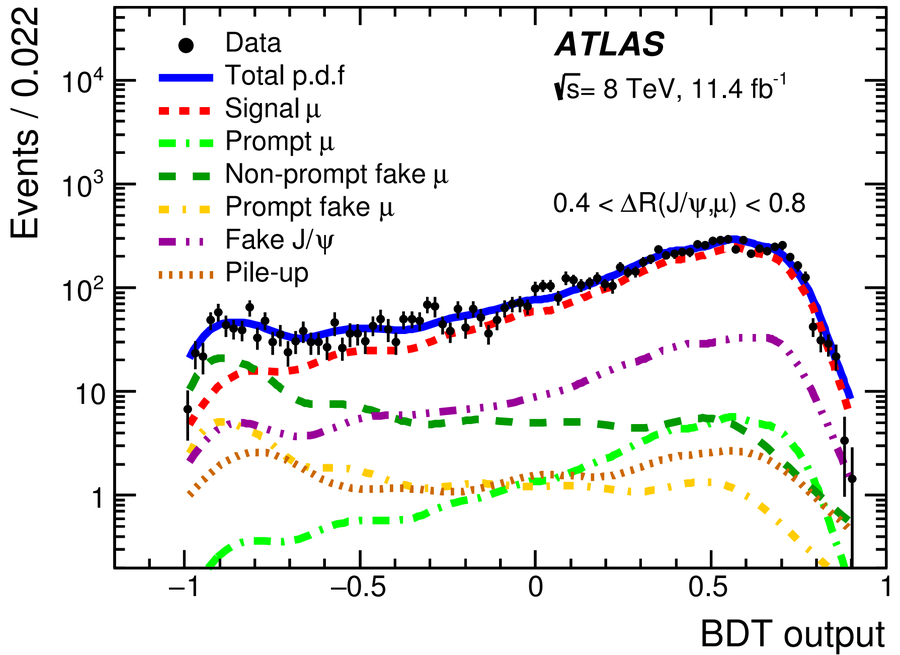
Phys. Rev. D 99 (2019) 052004

1) Production of *b*-hadron pairs

JHEP 11 (2017) 62

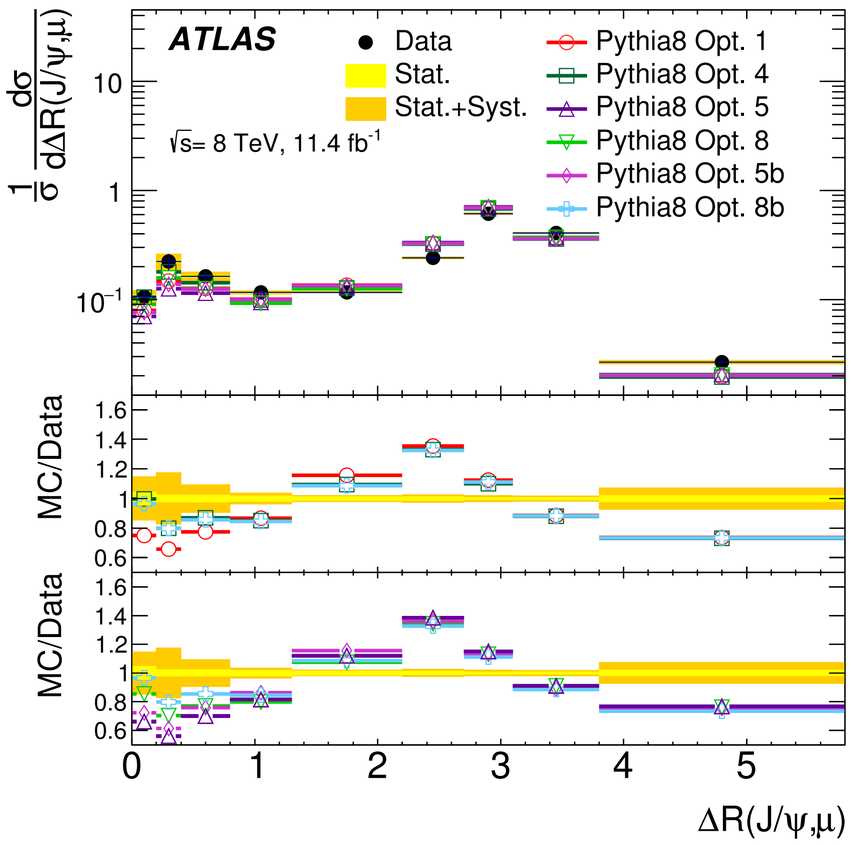
- Important background of processes such as V + Higgs($\rightarrow b\bar{b}$)
  - Small ΔR between *b*-hadrons
  - Access to this regime challenging from di-jet measurements
- Fiducial volume:
  - $pT(\mu) > 6$ GeV, $|\eta(\mu^{J/\psi})| < 2.3$, $|\eta(\mu)^3| < 2.5$;
- One b-hadron identified in $b \rightarrow J/\psi + X$
  - Non-prompt J/ψ yields from mass-lifetime fit;
- Other from a third muon: $b \rightarrow \mu + X$
  - Simultaneous fit to d_0 significance x BDT output to extract third-muon yields
- Irreducible backgrounds subtracted out, e.g. Bc → J/ψ + μ + X using simulation

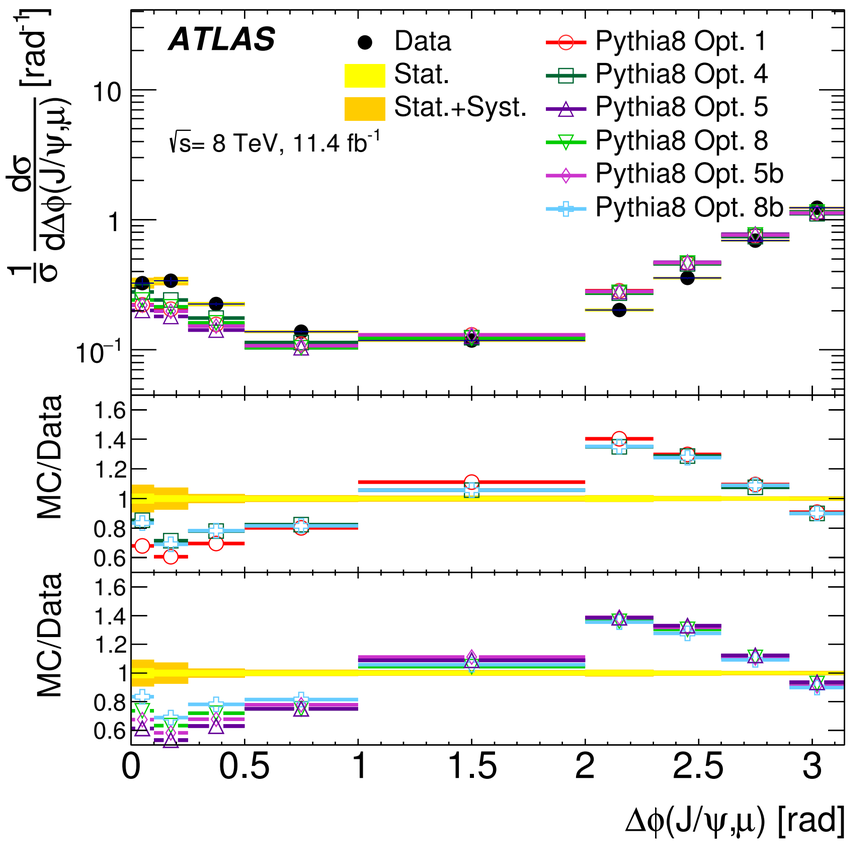




Total cross-section and comparison of Pythia splitting kernels

- Total fiducial cross-section: pT(μ) > 6GeV, |η (μ$^{J/\psi}$) | < 2.3, |η(μ)^3| <2.5;
- $\sigma(B \to J\psi(\mu\mu) + X, B \to \mu + X) = 17.7 \pm 0.1(\mathrm{stat}) \pm 2.0(\mathrm{syst})\ \mathrm{nb}$
- Differential cross-section provided as a function of 10 kinematic variables describing the $b\bar{b}$ system.
- Pythia8 tunes don't well describe the angular shapes
  - Pythia8 pT-splitting kernel (opt. 4) closest agreement.



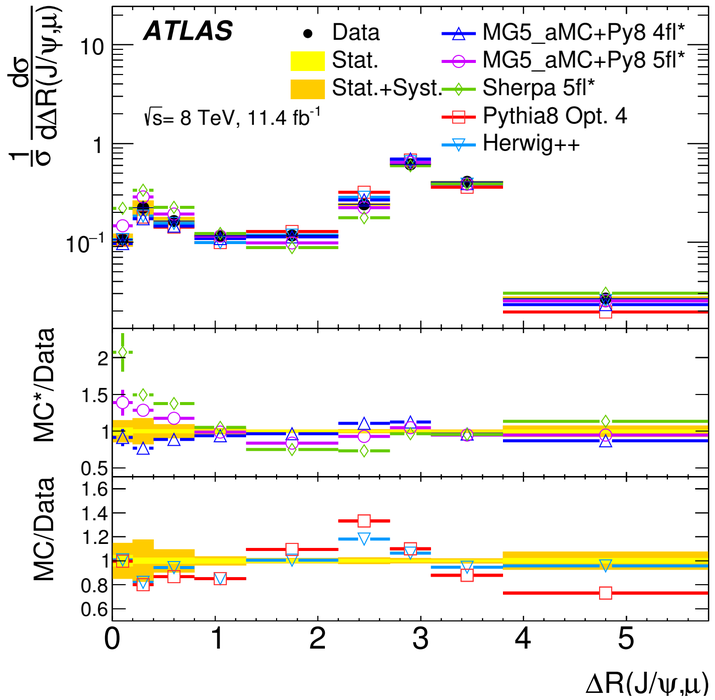


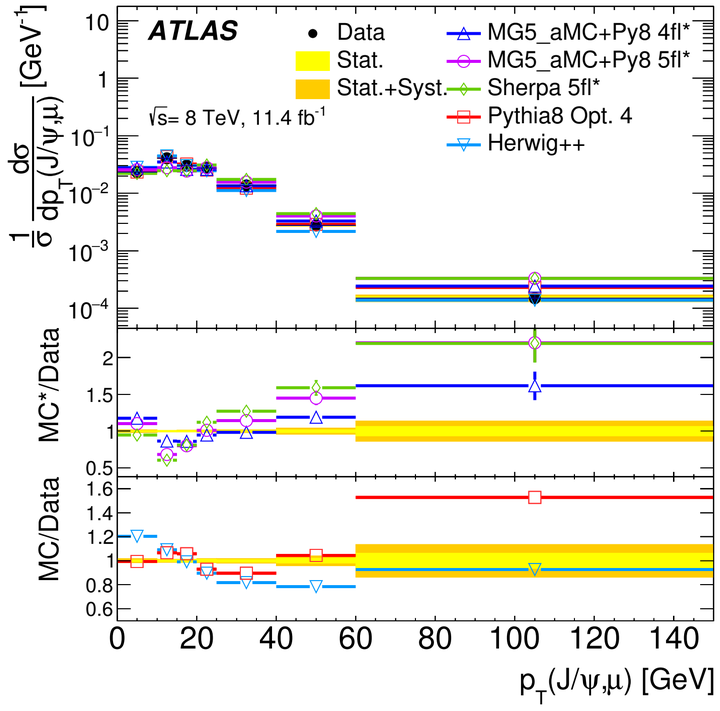
Generator comparisons

- $g \to b\bar{b}$ splitting kernel options tested for Pythia 8
  - Pythia8 pT-splitting kernel (and similarly Herwig++) gives closest agreement.

- In the comparisons of generators:
  - Four flavour MadGraph5_aMC@NLO+Pythia8 gives best performance overall.

– data collected (especially at small ΔR) useful in constraining future measurements.
  - Full results made available on HepData.

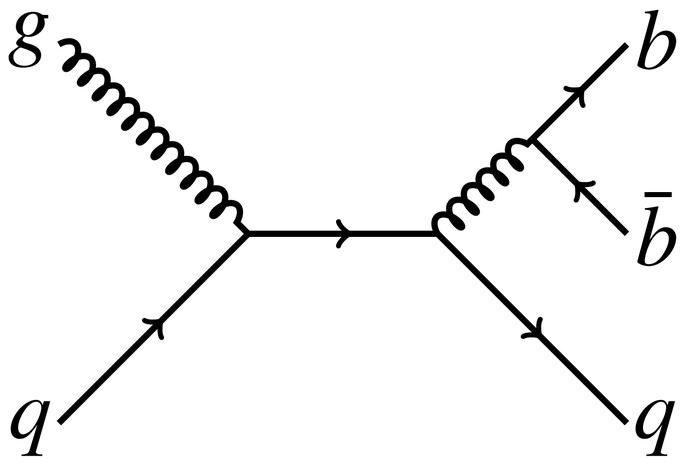




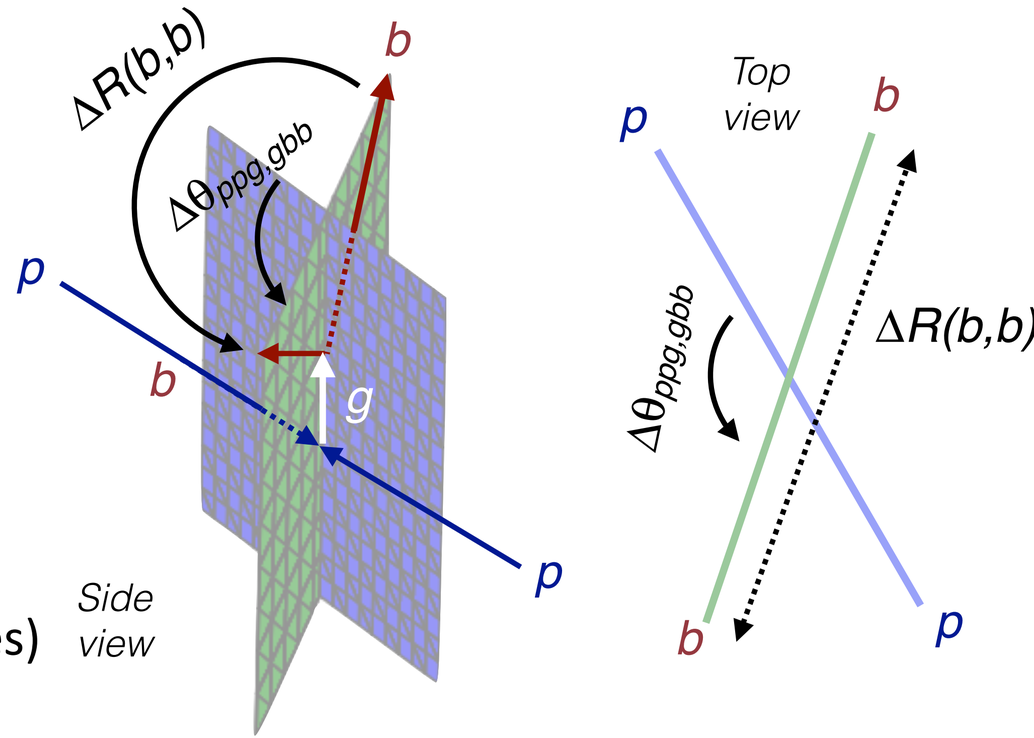
2) Properties of $g \to b\bar{b}$ at small opening angles

Phys. Rev. D 99 (2019) 052004

- Study of modelling of fragmentation of $g \to b\bar{b}$ using high-pT jets with 33fb^{-1} of 13 TeV data



- R=1.0 anti-kT jet, pT>450 GeV from calibrated topological calorimeter-cell clusters
- Two R=0.2 track-based jets (anti-kT) pT>10 GeV associated to the large-R jet required.
  - Leading jet with b-tag requirement (MV2c10) at 60% nominal efficiency working point.
- Differential distributions presented for
  - $\Delta R(b,b) = \sqrt{\Delta\phi(b,b)^2 + \Delta\eta(b,b)^2}$
  - $z(p_{\mathrm{T}}) = p_{\mathrm{T},2}/(p_{\mathrm{T},1} + p_{\mathrm{T},2})$
  - $\Delta\theta_{\mathrm{ppg,gbb}}$ (sensitive to orientation of gluon splitting)
  - $\log(m_{bb}/p_{\mathrm{T}})$ (m_{bb} important observable in high-mass searches)

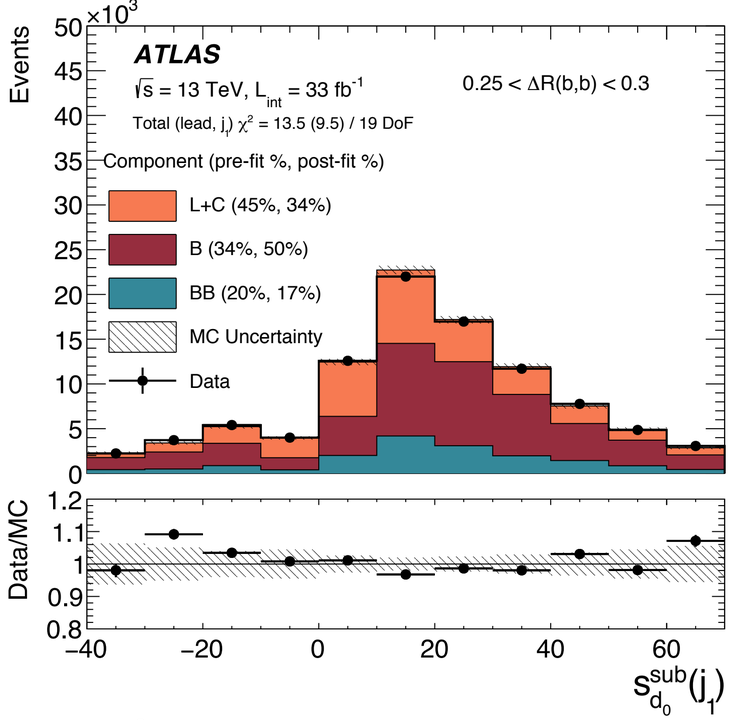


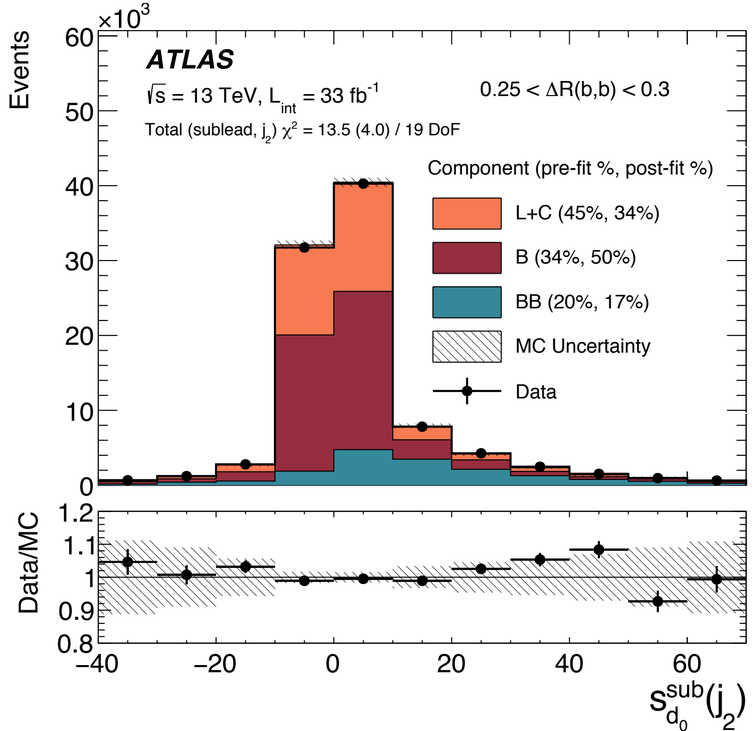
Signal and background estimation

- MC templates normalised to data:
  - signed transverse impact parameter significance (**s_{d0}**) distributions plotted in each differential bin.
  - For each jet, the sub-leading track (ordered by **$|s_{d0}|$**) is used
- Signal (BB), single b-hadron (B) and other backgrounds (L+C) plotted and simultaneous fit ($s_{d0}(j_1)$ *x* $s_{d0}(j_2)$) performed
  - Fractions of the contributions extracted from the fit
- Data are unfolded using Iterative Bayes procedure (RooUnfold), back to the particle level

Results systematics limited; dominated uncertainty from theory modelling.

	$\Delta R(b,b)$	$\Delta\theta_{\mathrm{ppg,gbb}}$	$z(p_{\mathrm{T}})$	$\log(m_{bb}/p_{\mathrm{T}})$
Calorimeter jet energy	2–3%	2–3%	2–6%	2–4%
Flavor tagging	<1%	<1%	<1%	<1%
Tracking	1–2%	1–2%	2–4%	1–2%
Background fit	1%	1%	1–2%	2%
Unfolding method	2–3%	2%	2–4%	2–5%
Theoretical modeling	3–10%	2–13%	3–10%	4–11%
Statistical	1%	1%	2%	1%
Total	3–10%	3–10%	3–14%	4–12%

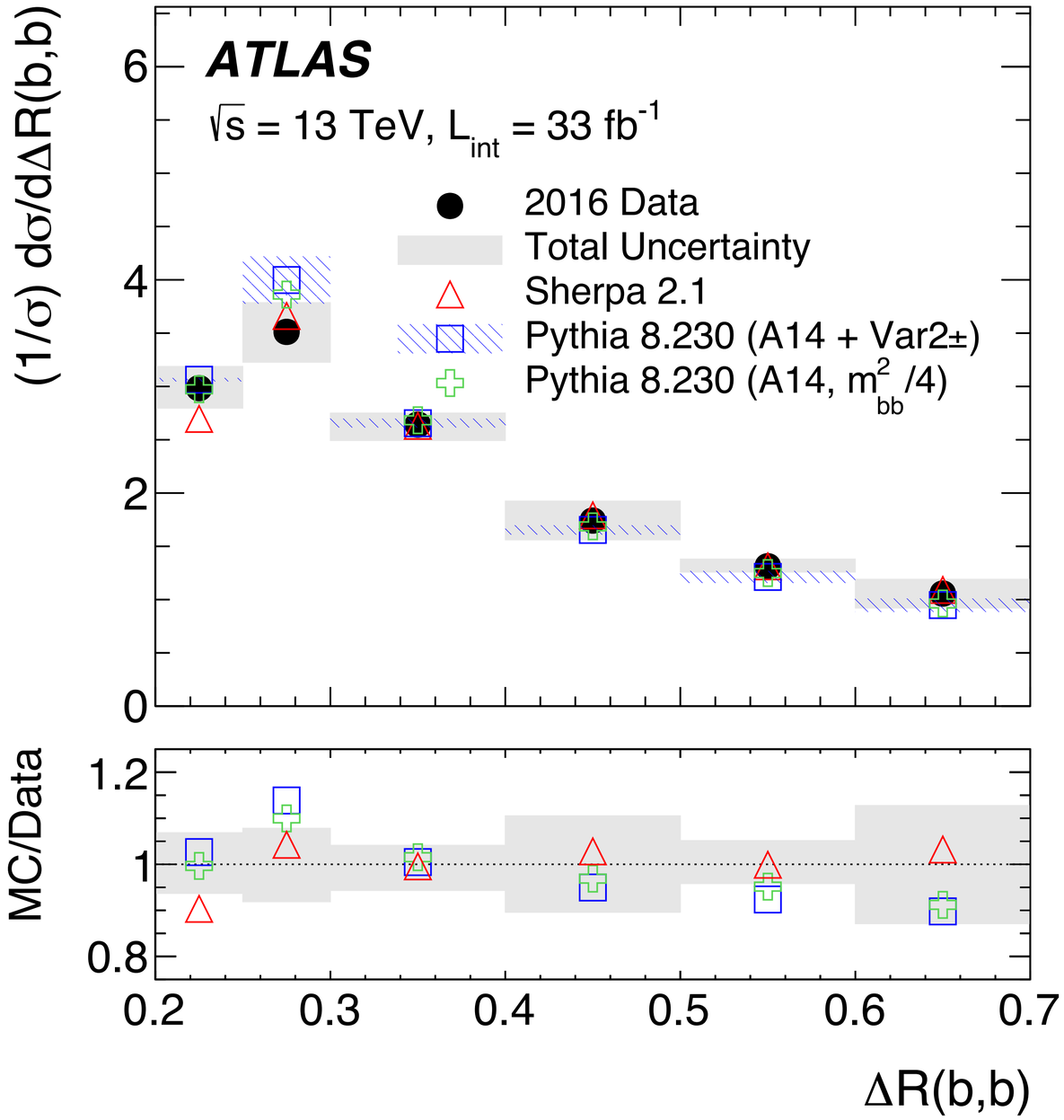




Results and comparisons

- Unfolded differential distributions
  - Compared to Sherpa 2.1 and Pythia 8 (under two different fragmentation variations: $m^2_{bb}/4$ splitting kernel (cf pT^2_{bb}) and Var2+A14 variation ($\alpha_s(M_z) = 0.139$) *A14 tunes*

- Sherpa generally in better agreement
- Deviations at low z(pT), low masses and all $\Delta\theta_{ppg,gbb}$.
- Future measurements with $\Delta\theta_{ppg,gbb}$ may help to constrain properties of gluon polarisation in unpolarised hadrons



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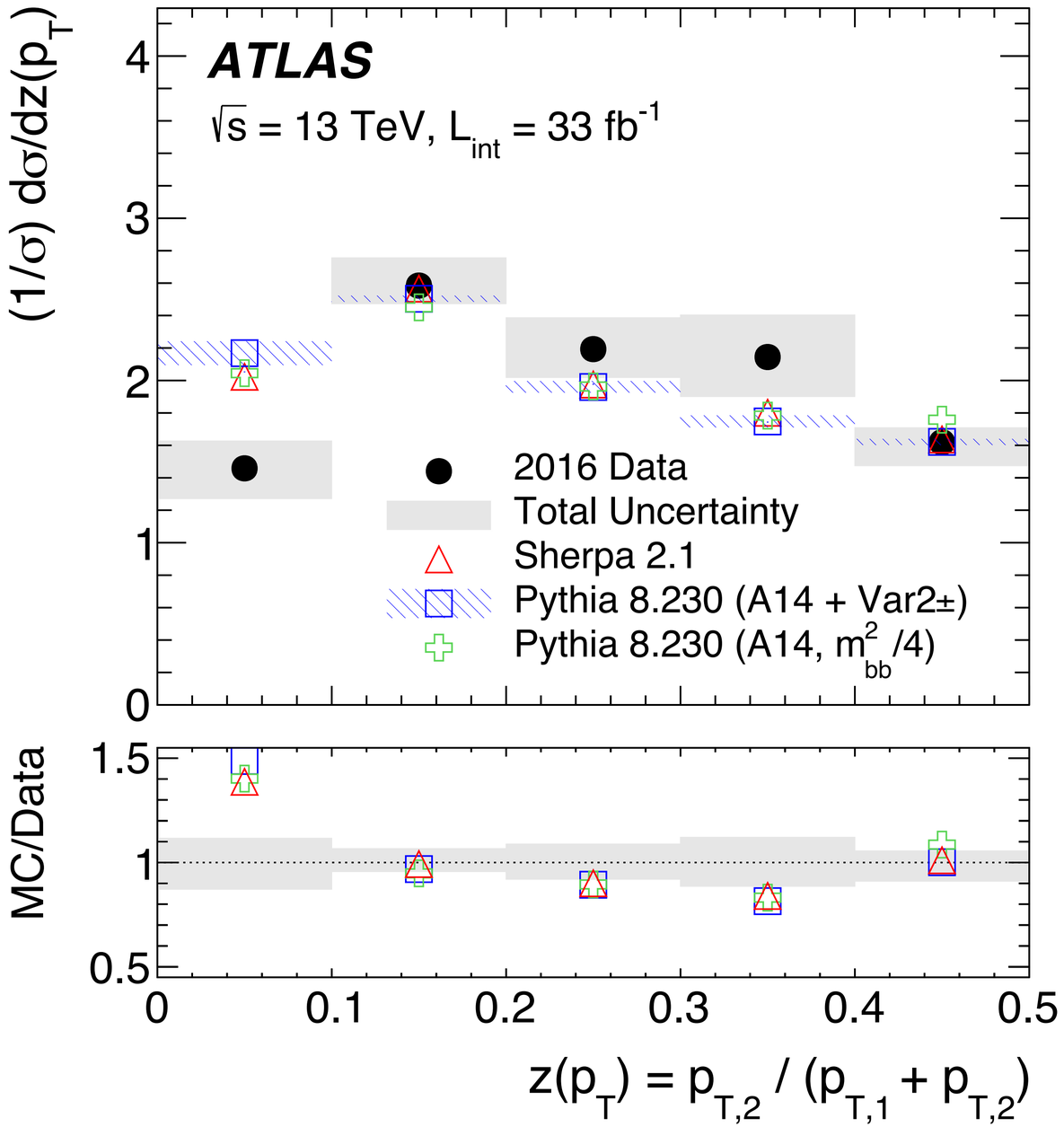

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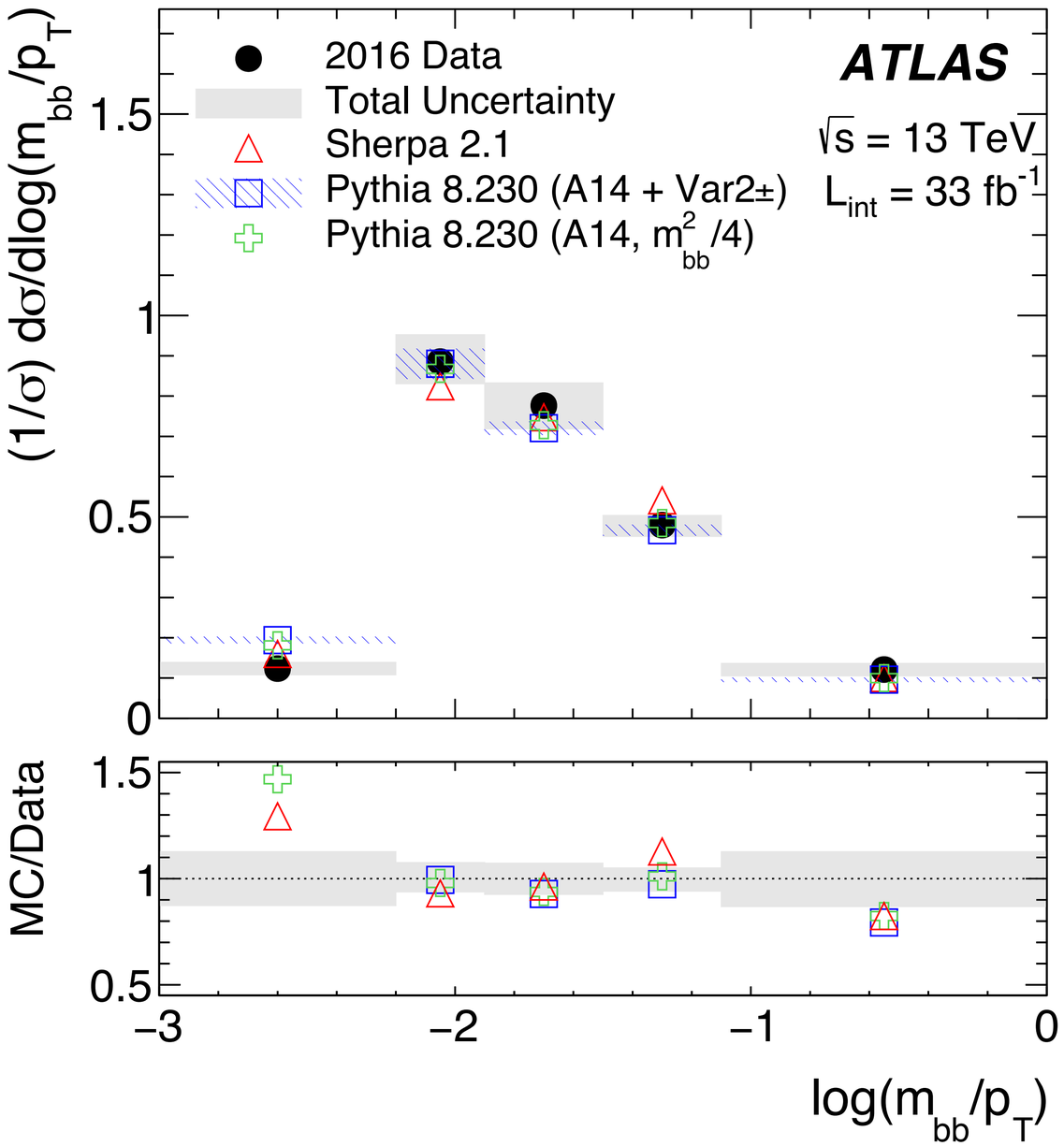

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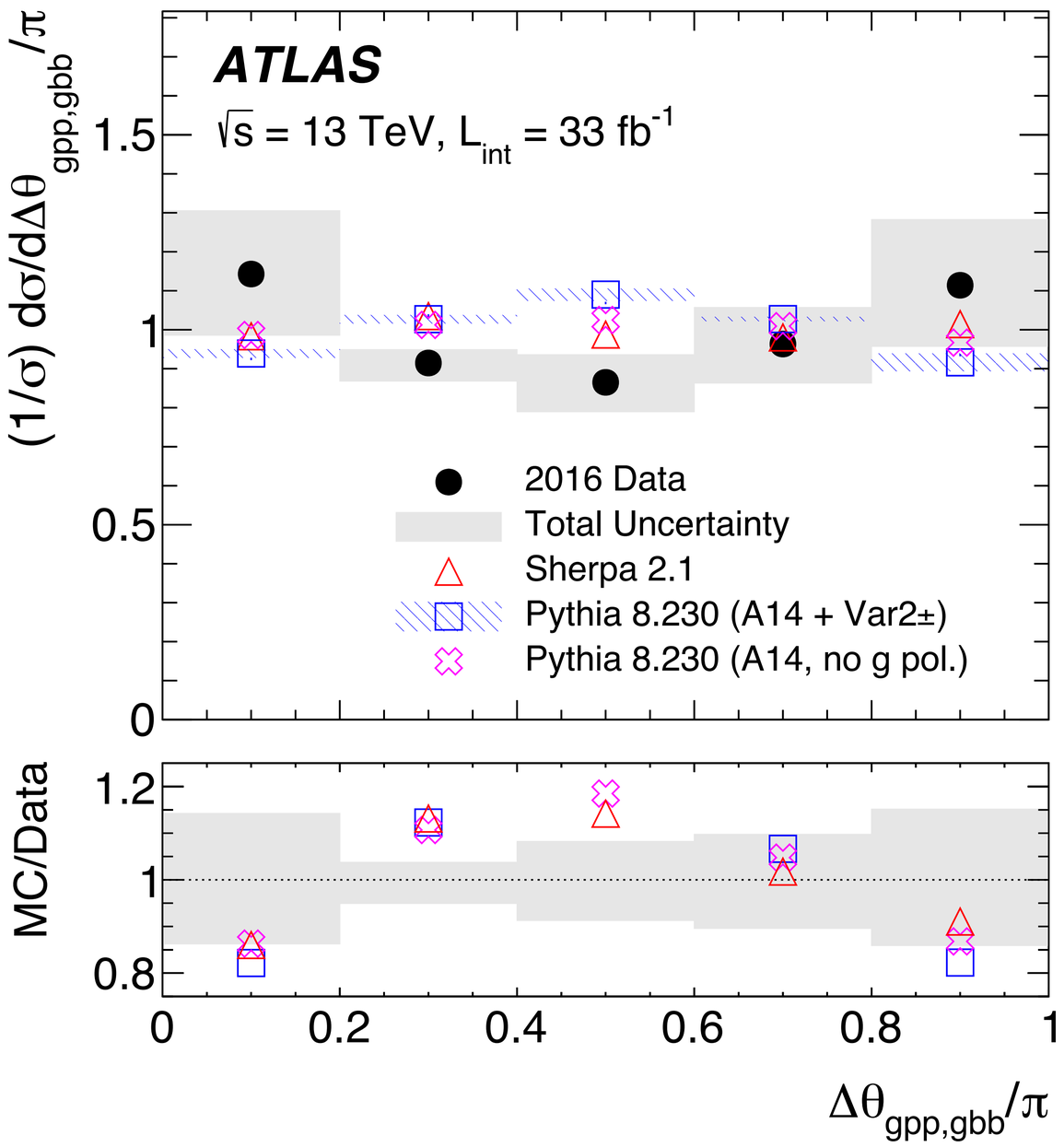


Observation of an excited $B_c(2S)$ state

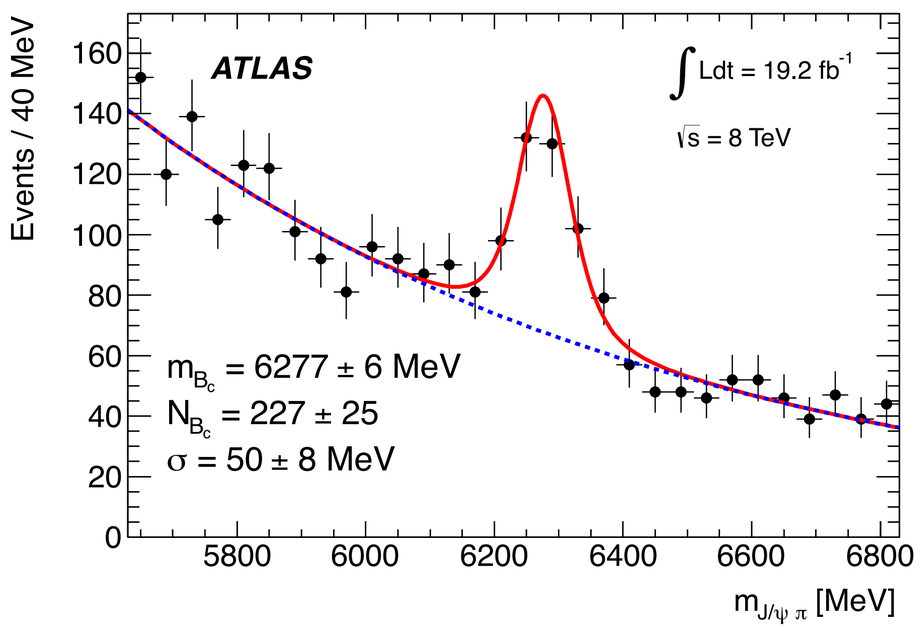
PRL 113 212004 (2014)

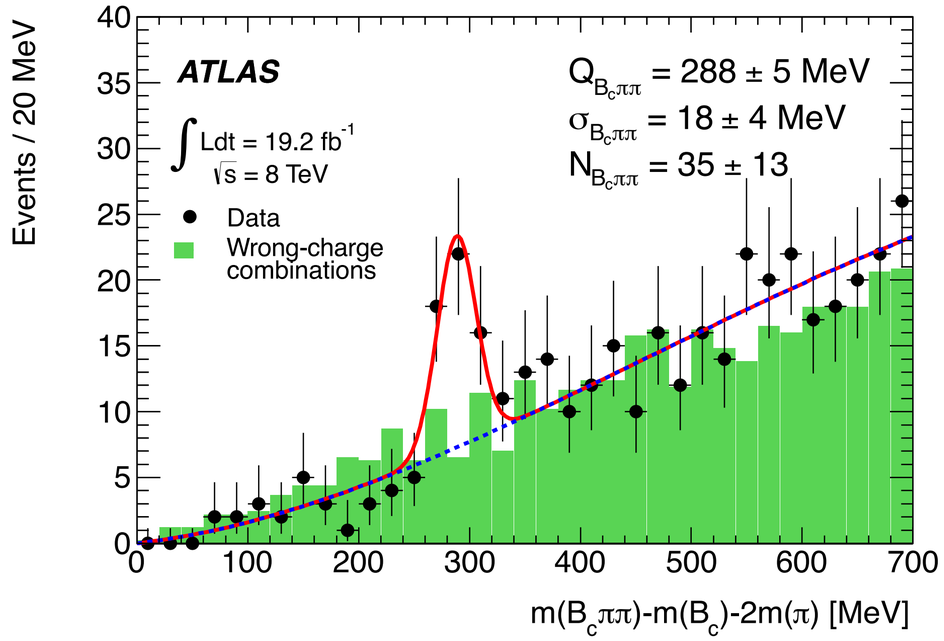
Bc(2S) production

- First observation of excited production of B_c meson
- Combined run-1 4.9fb^{-1} (7 TeV), 19.2fb^{-1} (8 TeV)
  - Separate optimisation for each dataset;
- Ground state $Bc^+ \to J/\psi(\mu\mu)\,\pi^+$:

Data	Signal events	Peak mean [MeV]	Peak width [MeV]
7 TeV	100±23	6282±8	49±12
8 TeV	227±25	6277±6	50±8

- Excited state observed through decay with 2 additional pions from primary vertex: $Bc(2S) \to Bc\,\pi^+\pi^-$
- Constrain resolution effects with $Q = m(Bc\pi\pi) - m(J/\psi\pi) - 2m(\pi)$
  - Structure observed:
  - $Q = 288.3 \pm 3.5 \pm 4.1$ MeV (from weighted average of the two datasets)
- Mass of 6842 ± 4 ± 5 MeV.





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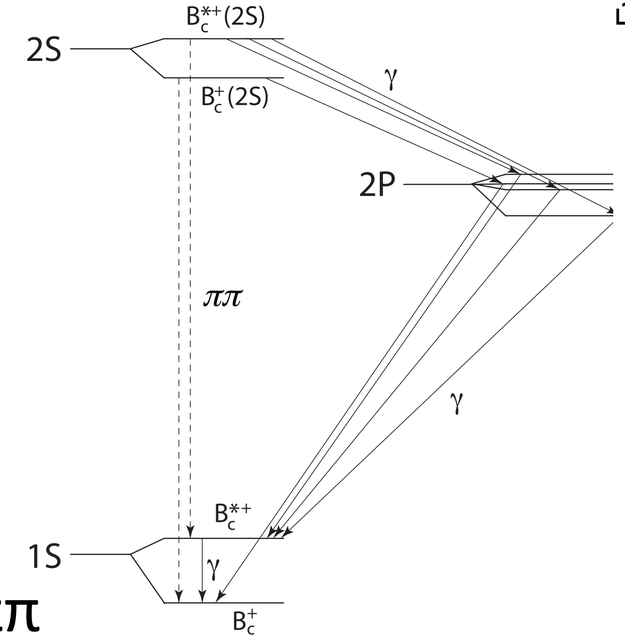
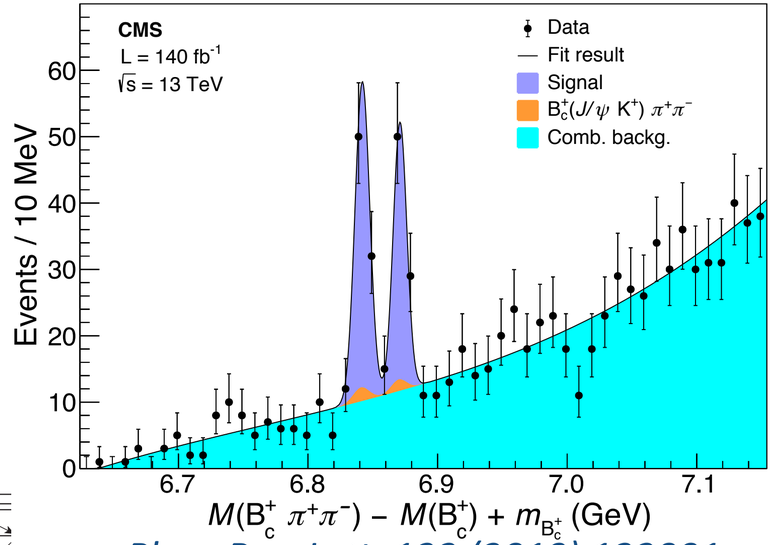
- Excited state observed through decay with 2 additional pions, $Bc(2S) \to Bc\,\pi^+\pi^-$



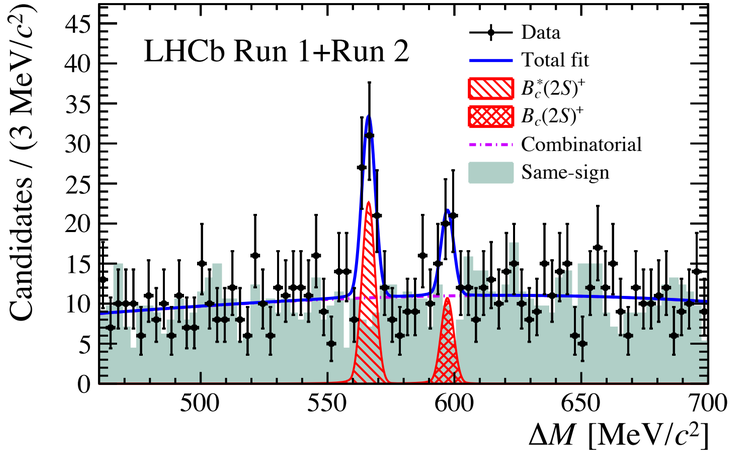


Phys. Rev. Lett. 122 (2019) 132001

Now confirmed by CMS and LHCb to actually be a superposition of two states: Bc(2S) and $Bc^*(2S) \to Bc^*\pi\pi$ (Photon from Bc* not reconstructed).

– Bc*(2S) observed at lower Δm, due to missing photon

Phys. Rev. Lett. 122 (2019) 232001



Quarkonium production in *pp* and *pPb* collisions at √s=5.02 TeV

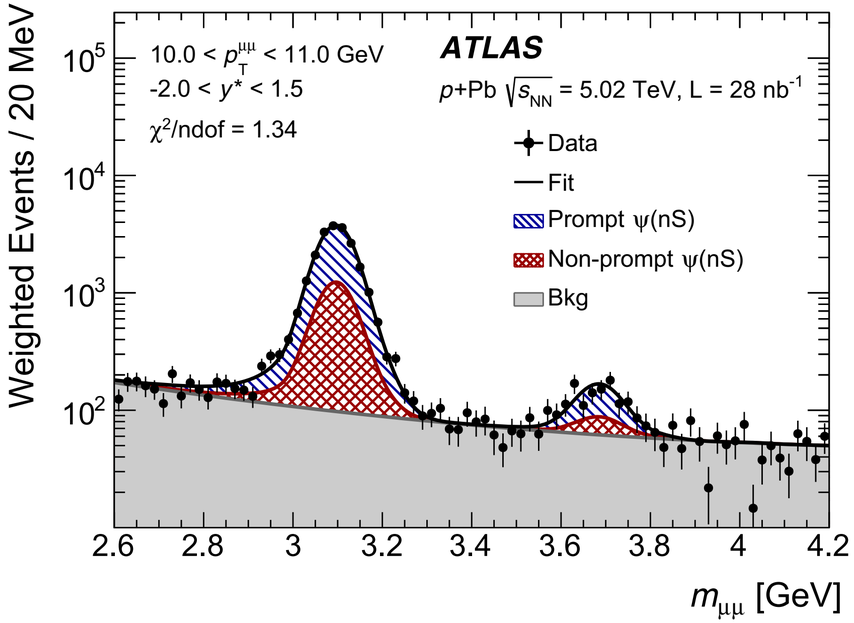
Quarkonium production *Eur. Phys. J. C 78 (2018) 171*

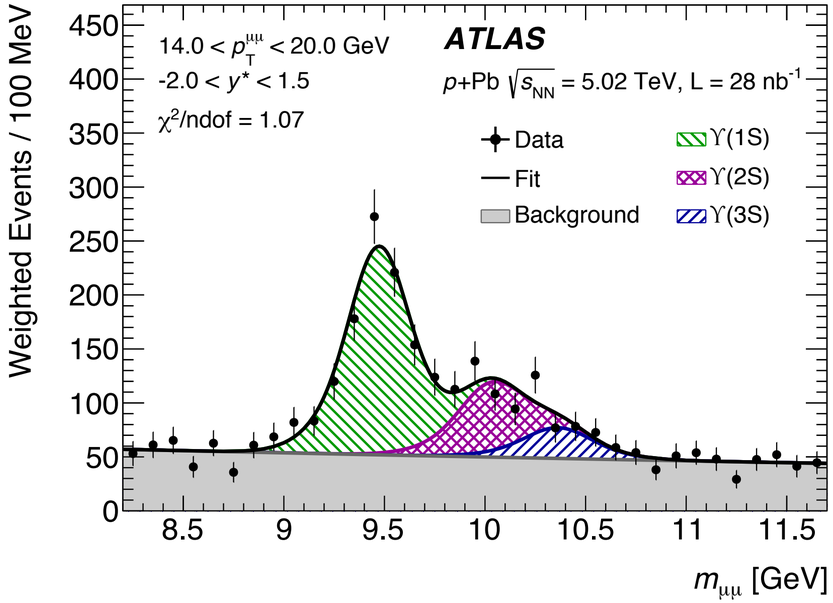
Charmonium production in Pb-Pb: *Eur. Phys. J. C 78 (2018) 762*

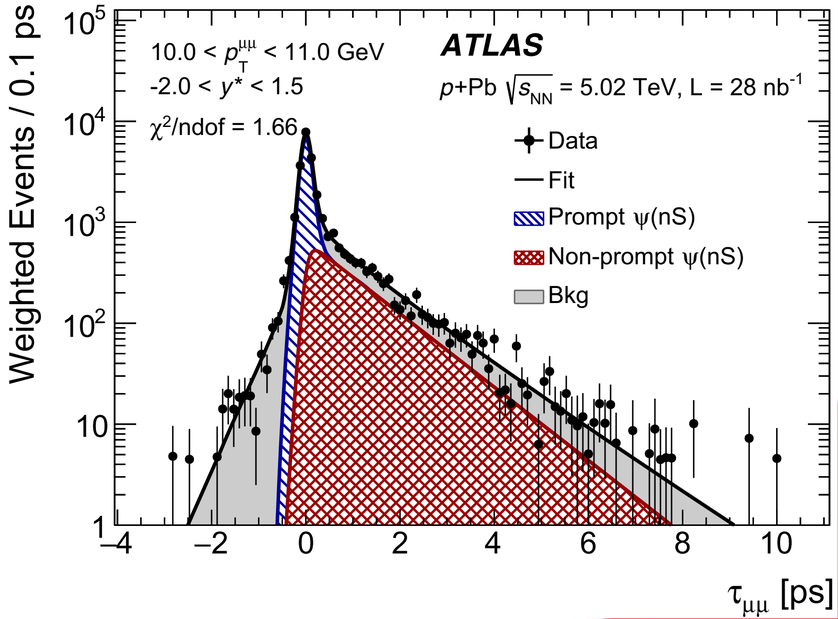
Quarkonium production in pp and pPb

- Study of suppression of Charmonium in pp and p-Pb (Pb-Pb studies not shown here).
- Mass – pseudo-proper decay time simultaneous fit to separate Bkgd. & (non-)prompt Signal.
- Fits performed in bins of pT, y (and centrality)
- Similar approach and mass fits in the Bottomonium system
- Events weighted for acceptance and efficiencies:

$$w_{\text{total}}^{-1} = \mathcal{A}(\mathcal{O}(n\mathrm{S})) \cdot \varepsilon_{\text{reco}} \cdot \varepsilon_{\text{trig}}$$



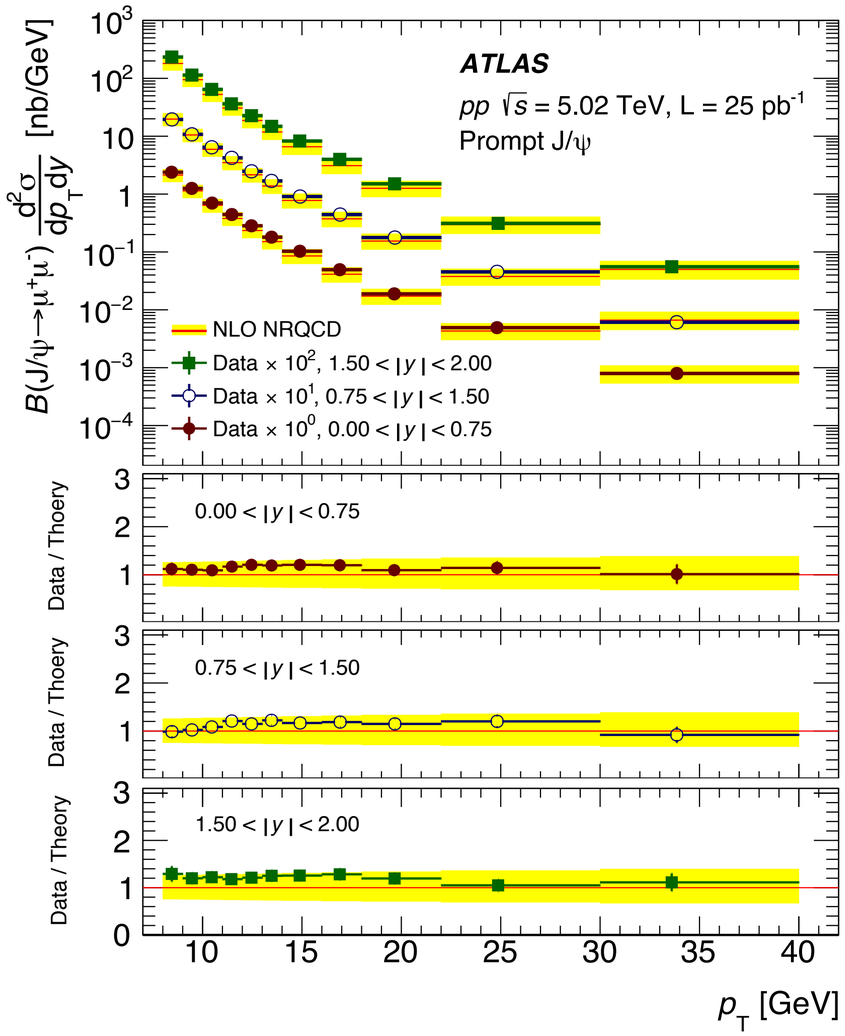


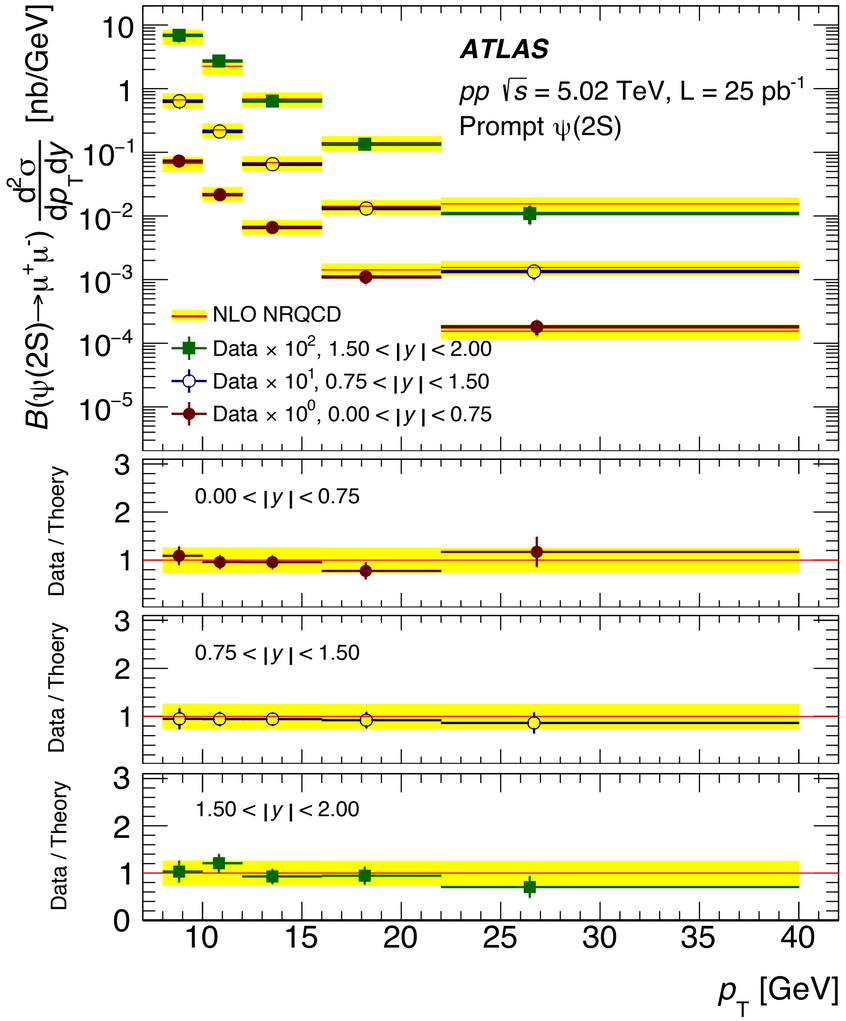


Differential pp results

- $$\frac{d^2\sigma_{\mathcal{O}(n\mathrm{S})}}{dp_T dy^*} \times B(\mathcal{O}(n\mathrm{S}) \to \mu^+\mu^-) = \frac{N_{\mathcal{O}(n\mathrm{S})}}{\Delta p_T \times \Delta y \times L}$$

- In pp collisions:
  - **Charmonium**
    - Good agreement observed between data and: NRQCD; prompt





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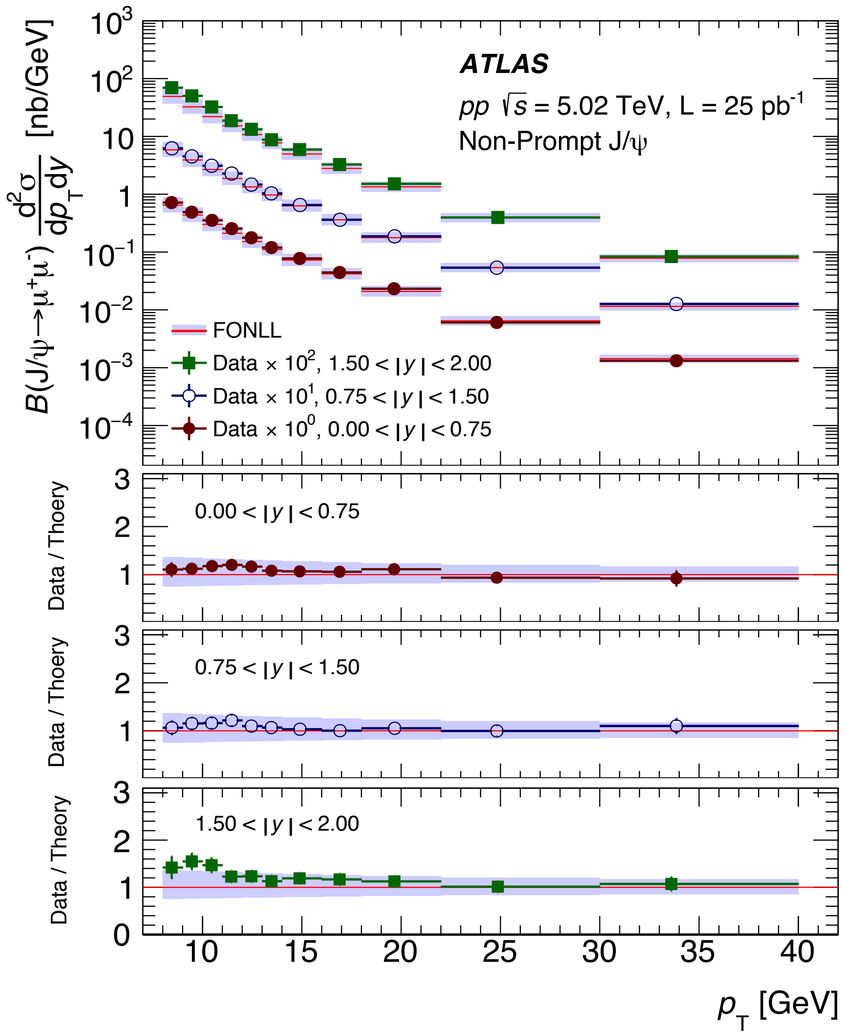
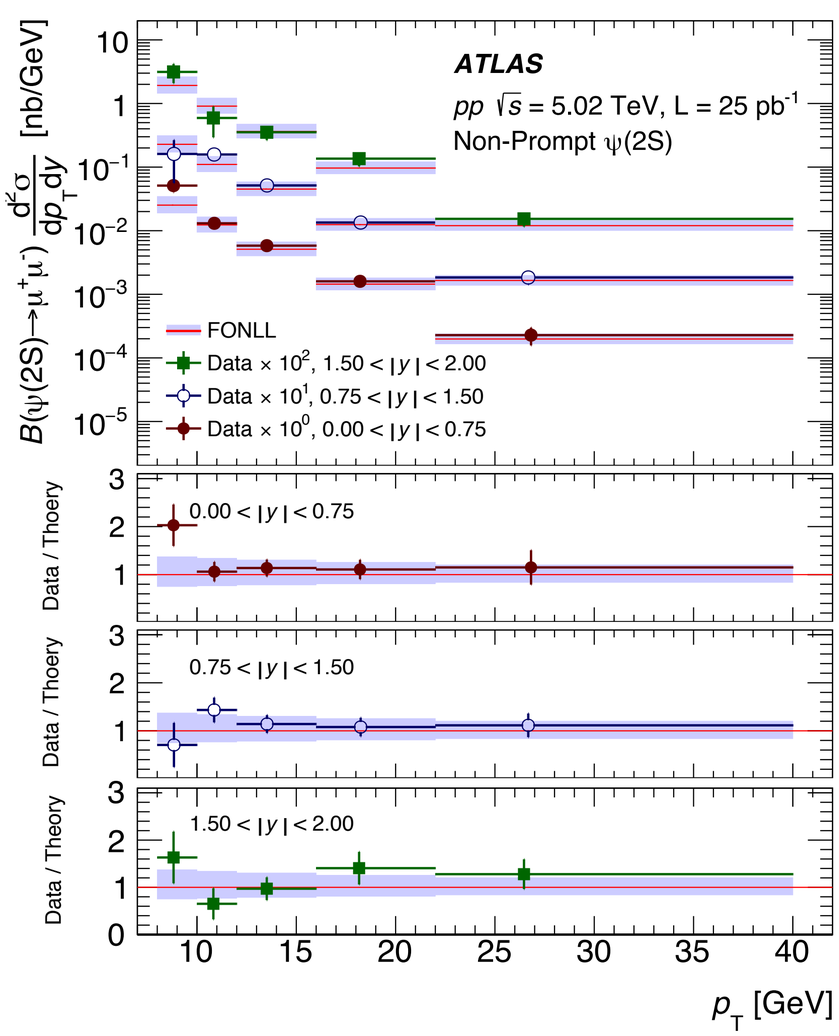
- In pp collisions:
  - **Charmonium**
    - Good agreement observed between data and: FONLL (non-prompt)

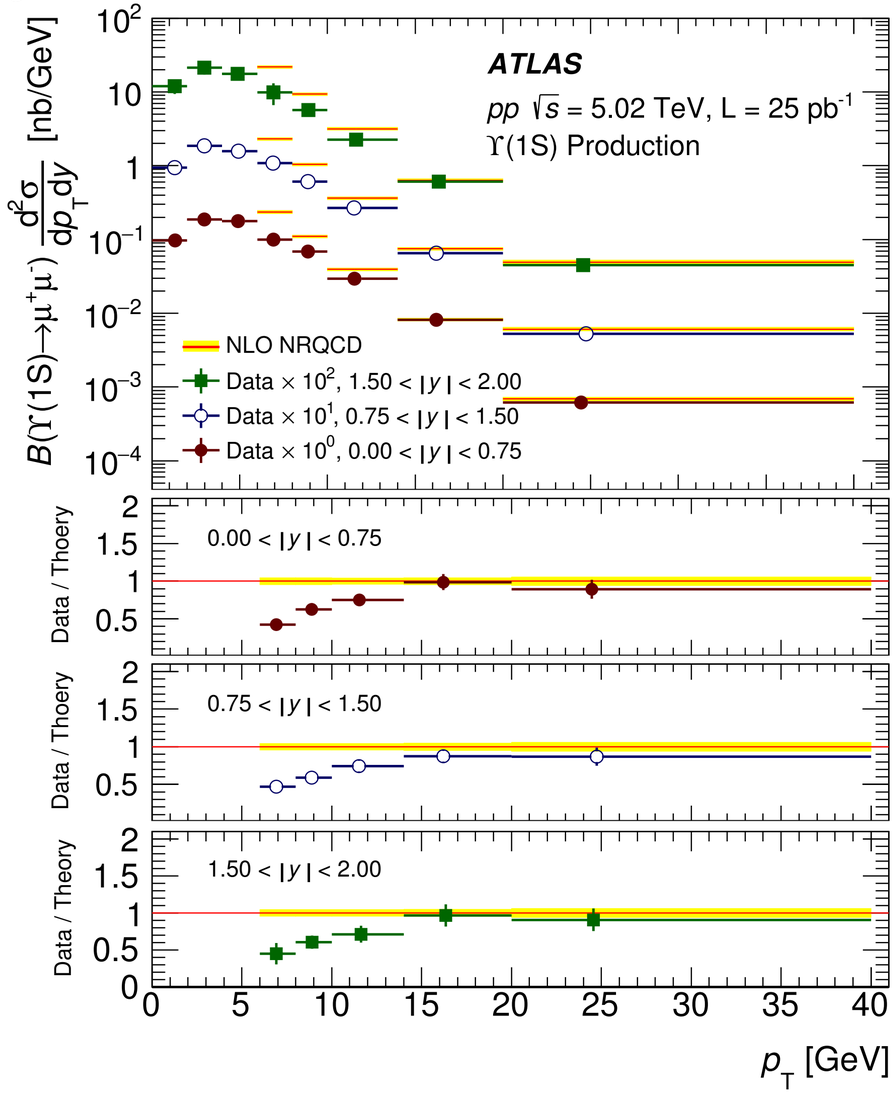


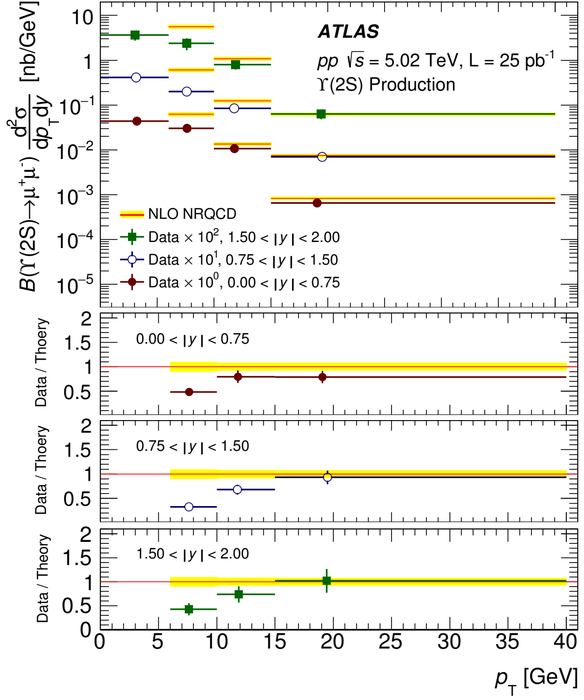


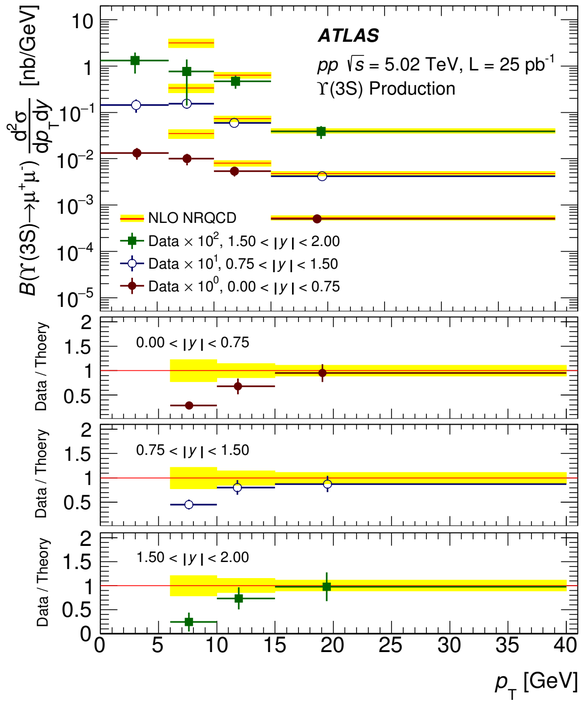
Differential pp results

- $$\frac{d^2\sigma_{O(nS)}}{dp_T dy^*} \times B(O(nS) \to \mu^+\mu^-) = \frac{N_{O(nS)}}{\Delta p_T \times \Delta y \times L}$$

- In pp collisions:
  - Charmonium:
    - Good agreement observed between data and FONLL (non-prompt), NRQCD (prompt)
  - **Bottomonium:**
    - NRQCD in agreement for pT > 15 GeV

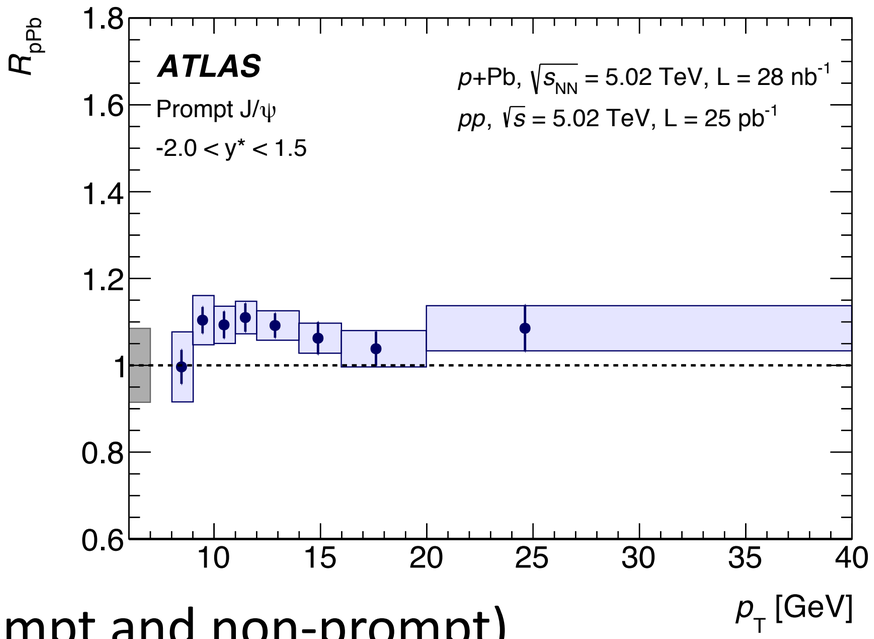


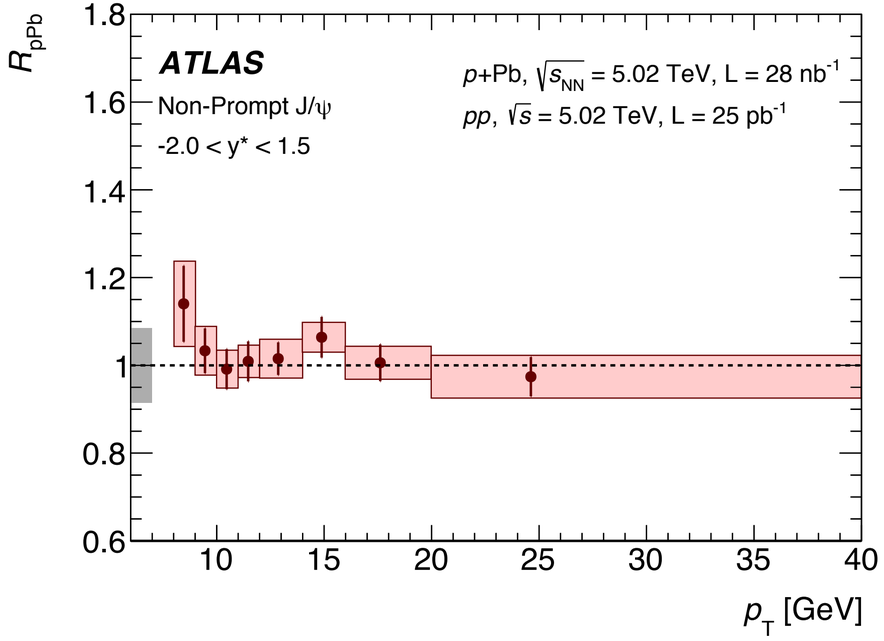




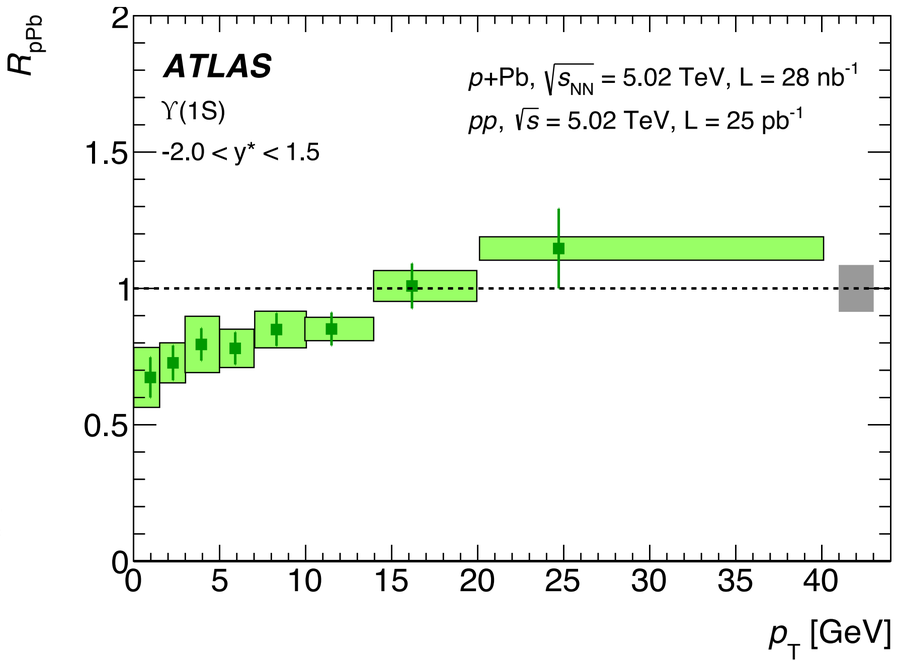
Nuclear modification factors

$$R_{p\mathrm{Pb}} = \frac{1}{208}\frac{\sigma^{\mathcal{O}(n\mathrm{S})}_{p+\mathrm{Pb}}}{\sigma^{\mathcal{O}(n\mathrm{S})}_{pp}}$$





- Normalised ratio of cross-sections R_{pPb}
- Reasonably consistent with unity in J/ψ (both prompt and non-prompt) (and also across rapidities)

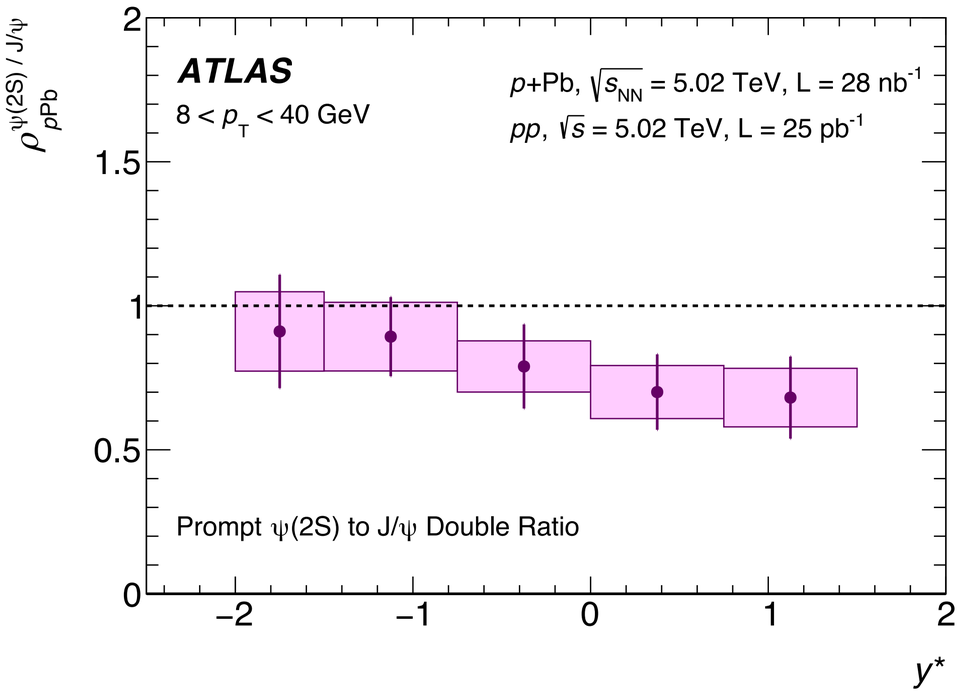


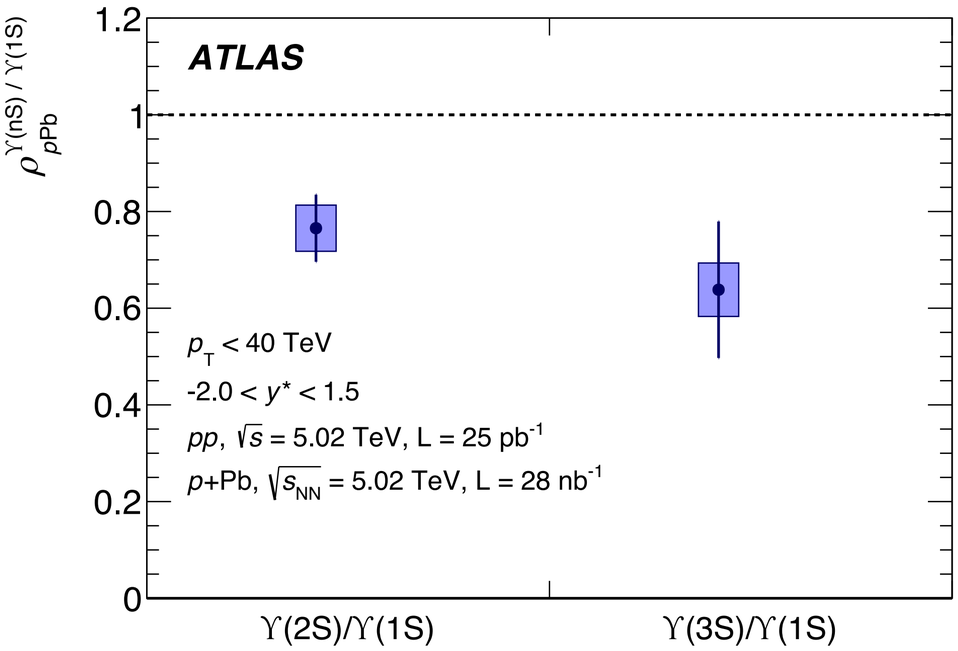
- In Bottomonium sector Y(1S) shows significant discrepancy with unity at low-pT.
- Low pT Y(1S) can probe smaller Bjorken-x region compared to J/ψ measured in 8 < pT < 40 GeV
  - observed suppression of Y(1S) come from the reduction of hard-scattering cross sections due to stronger nPDF shadowing at smaller Bjorken-x

Double production ratio

$$\rho_{p\mathrm{Pb}}^{O(n\mathrm{S})/O(1\mathrm{S})} = \frac{R_{p\mathrm{Pb}}(O(n\mathrm{S}))}{R_{p\mathrm{Pb}}(O(1\mathrm{S}))} = \frac{\sigma_{p+\mathrm{Pb}}^{O(n\mathrm{S})}}{\sigma_{p+\mathrm{Pb}}^{O(1\mathrm{S})}} \Big/ \frac{\sigma_{pp}^{O(n\mathrm{S})}}{\sigma_{pp}^{O(1\mathrm{S})}}$$

- Double ratio ρ of O(nS) to O(1S) production between p-Pb and pp collisions
- Suppression of Υ(3S) and O(2S) states wrt. O(1S) between 1–2σ



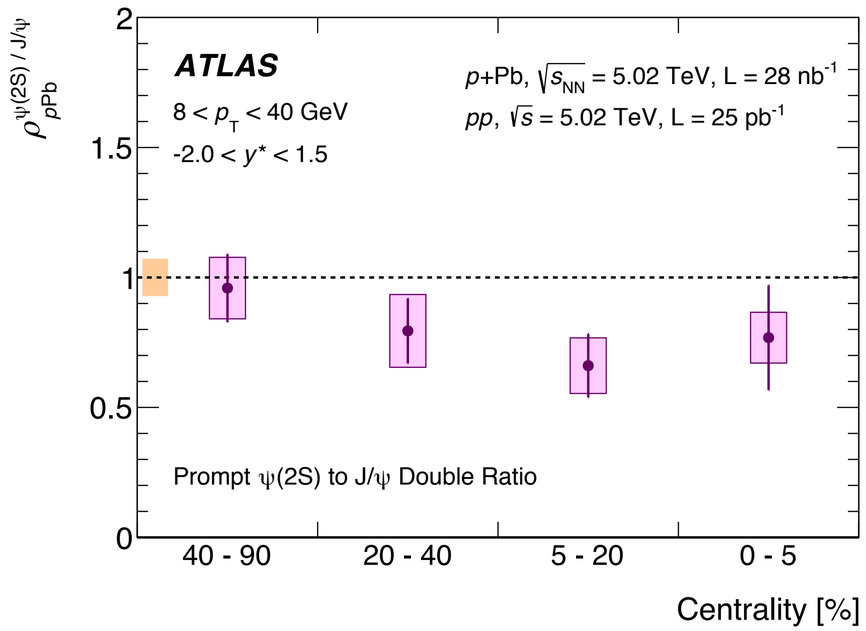


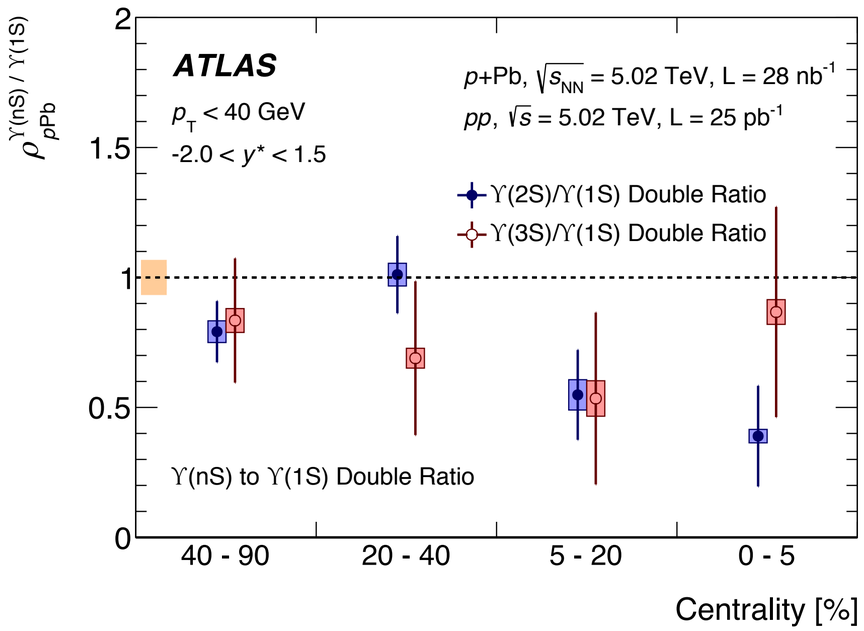
y^* shift of Δy=0.465 wrt. y in lab frame

*proton direction defined as +ve y**

Double production ratio

$$\rho_{p\mathrm{Pb}}^{\mathcal{O}(n\mathrm{S})/\mathcal{O}(1\mathrm{S})} = \frac{R_{p\mathrm{Pb}}(\mathcal{O}(n\mathrm{S}))}{R_{p\mathrm{Pb}}(\mathcal{O}(1\mathrm{S}))} = \frac{\sigma_{p+\mathrm{Pb}}^{\mathcal{O}(n\mathrm{S})}}{\sigma_{p+\mathrm{Pb}}^{\mathcal{O}(1\mathrm{S})}} \Big/ \frac{\sigma_{pp}^{\mathcal{O}(n\mathrm{S})}}{\sigma_{pp}^{\mathcal{O}(1\mathrm{S})}}$$

- Double ratio ρ of $\mathcal{O}$(nS) to O(1S) production between p-Pb and pp collisions
- Suppression effect decreases between peripheral to central collisions
- Stronger cold nuclear matter effect observed in excited quarkonium states compared to that in ground states
- 



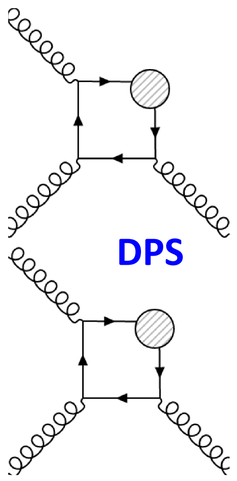
Measurement of prompt J/ψ pair-production cross-section

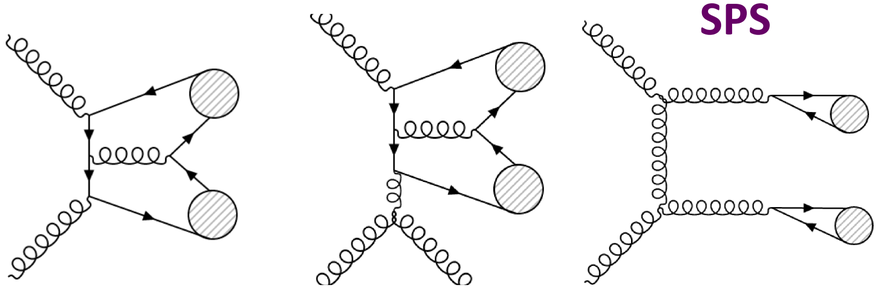
Eur. Phys. J. C77 (2017) 76

Prompt J/ψ pair production

Eur. Phys. J. C77 (2017) 76

- Wide range of quarkonium studies in ATLAS of Charmonium, Bottomonium and associated production (W,Z + J/ψ).
  - Prompt production J/ψ – J/ψ, gluon-dominated; sensitive to higher order QCD corrections, and tests of non-perturbative regime.
- Expected to be dominated by single parton scattering (SPS); double parton scattering (DPS) also present;
  - DPS becoming increasingly significant at higher CM energies



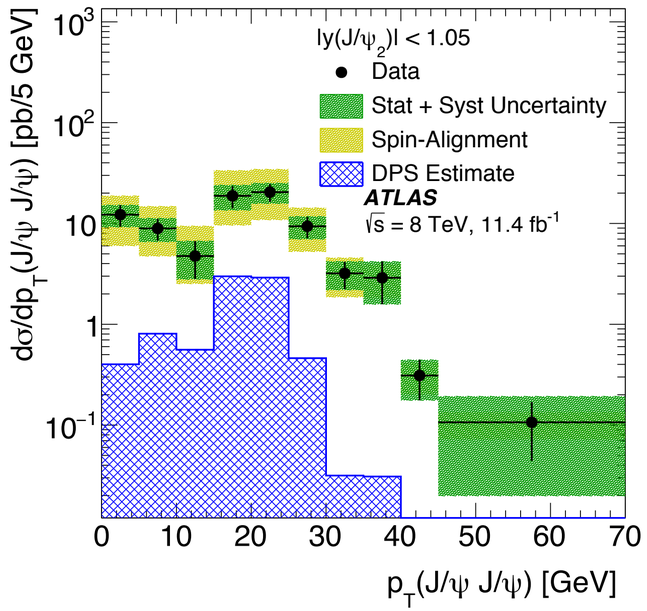


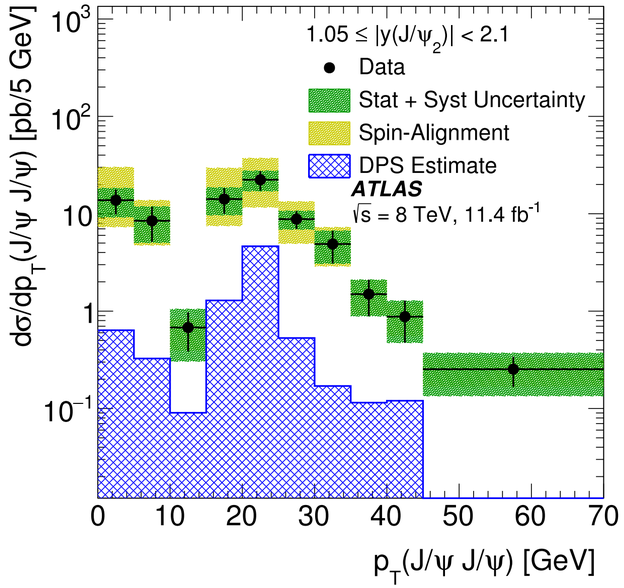
J/ψ($\mu\mu$) decay mode; 8 TeV, 11.4fb^{-1}

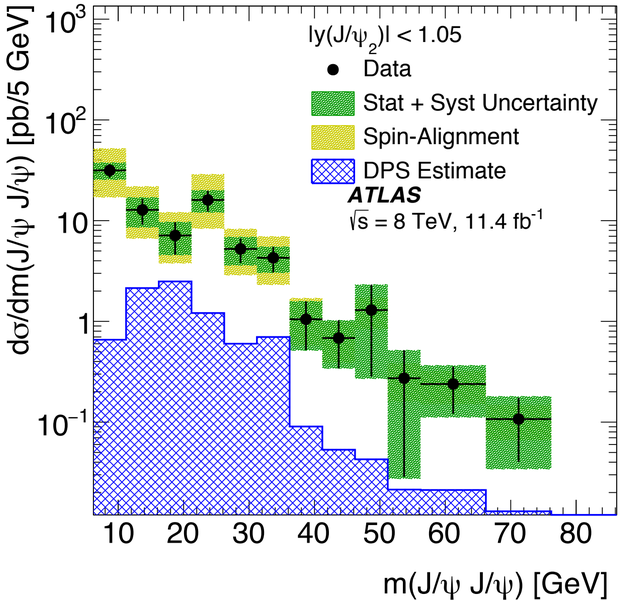
- Extraction of f_{DPS} and σ_{eff}.
- Differential cross-section measurement in variety of kinematic observables:
  - Function of pT(J/ψ_2), pT(J/ψ+J/ψ), m(J/ψ+J/ψ).
  - Isotropic assumption for nominal results; extremal variations considered.

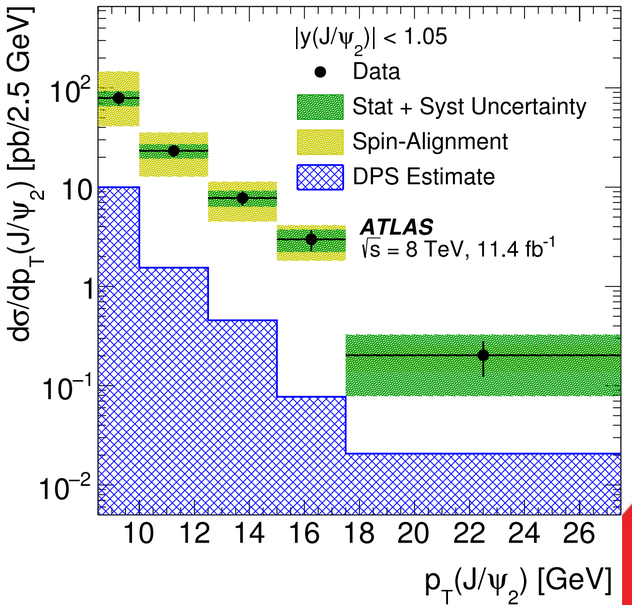
Prompt J/ψ pair production

- Differential cross-section:
  - Corrected for muon acceptance
  - pT of J/ψ pair,
  - mass of J/ψ pair,
    - pT(J/ψ) > 8.5 GeV
    - |y(J/ψ_2)|<1.05, 1.05<|y(J/ψ_2)|<2.1.
  - also for pT(J/ψ_2)
- Low-pT region – *away topology*:
  - J/ψs produced back-to-back
- High-pT region – *towards topology*
  - J/ψs produced together
  - (modelled only in NLO calculation)



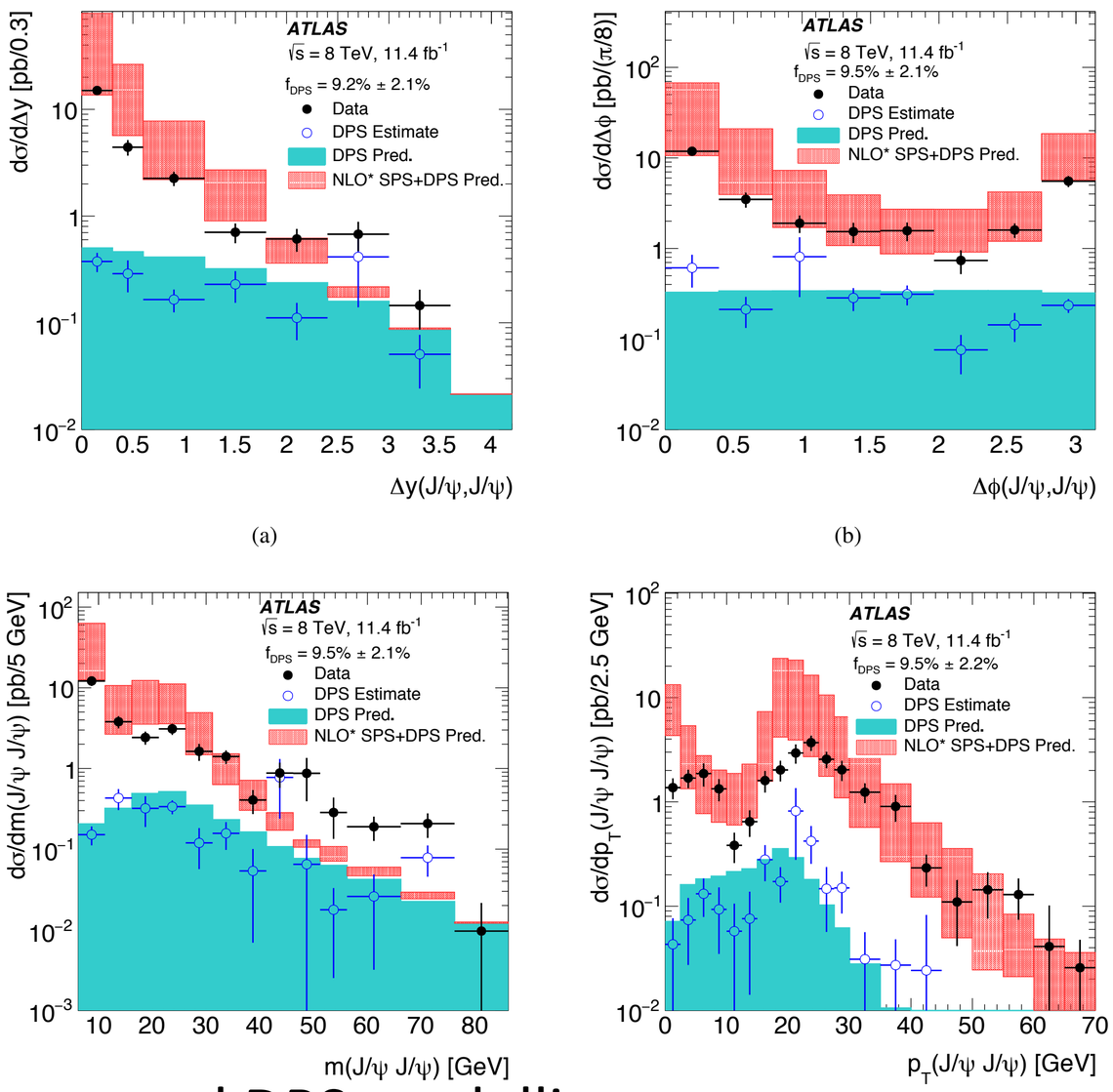






Prompt J/ψ pair production

- For extraction of of DPS:
  - Calculated in muon fiducial volume
    - DPS LO prediction normalised to measured f_{DPS}.
      - QCD factorisation; input from data.
    - SPS NLO* correction factor 1.85 applied to account for feed-down.
      - HELAC-Onia, no CO contributions
- DPS prediction in broad agreement with data-derived estimate.
  - Discrepancies in *away topology* between data and theory,
    - May suggest some non-constant feed down factor from higher mass states.
- Dominant systematics from trigger efficiency. and DPS modelling.



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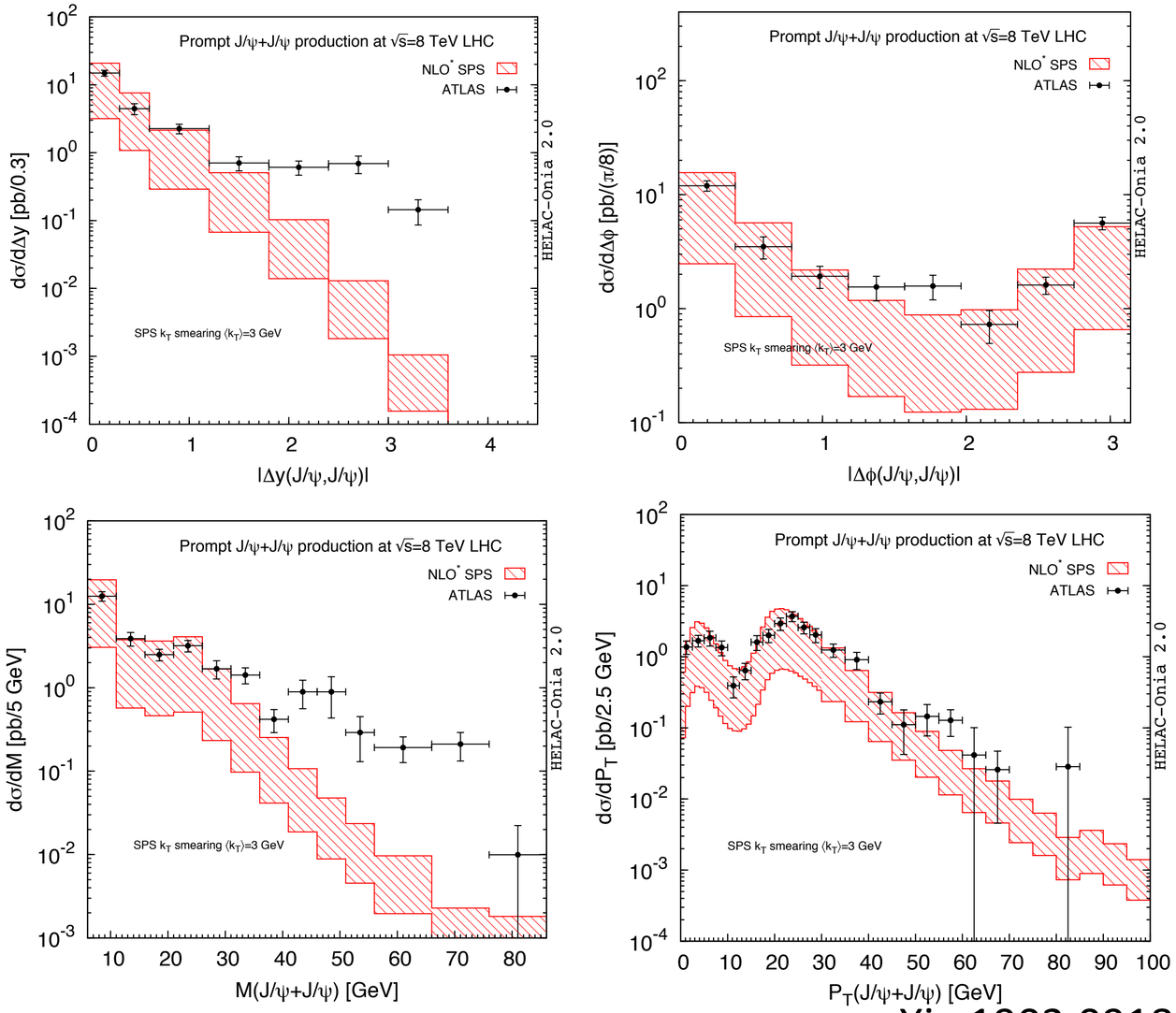


arXiv:1903.09185

- J–P Lansberg

Prompt J/ψ pair production

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\text{DPS}}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{f_{\text{DPS}} \times \sigma_{J/\psi J/\psi}}$$

- DPS cross-section corrected for muon acceptance

$$\sigma^{J/\psi,J/\psi}_{\text{DPS}} = 14.8 \pm 3.5\ (\text{stat}) \pm 1.5\ (\text{syst}) \pm 0.2\ (\text{BF}) \pm 0.3\ (\text{lumi})\ \text{pb}.$$

arXiv:1512.03657

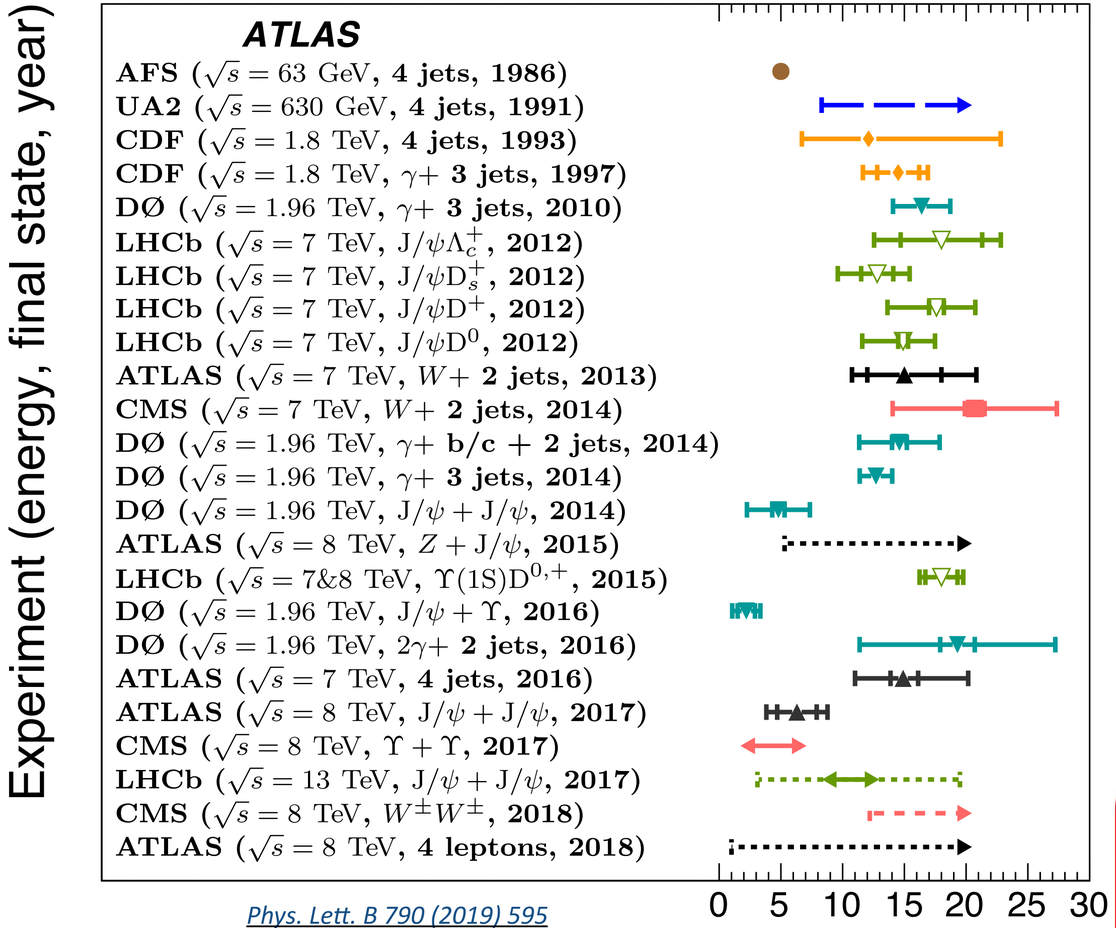
$\sigma_{J/\psi} = 429.8 \pm 0.1\ (\text{stat}) \pm 38.6\ (\text{syst})$ nb.

- Fraction of DPS in muon fiducial volume

$$f_{\text{DPS}} = (9.2 \pm 2.1\ (\text{stat}) \pm 0.5\ (\text{syst}))\%.$$

$$\sigma_{\text{eff}} = 6.3 \pm 1.6\ (\text{stat}) \pm 1.0\ (\text{syst}) \pm 0.1\ (\text{BF}) \pm 0.1\ (\text{lumi})\ \text{mb}.$$

- σ_{eff} ~ 5–20 mb from other experiments and measurements
- Di-Quarkonium results suggests non-universal σ_{eff}.
  - Further studies at higher √s needed.



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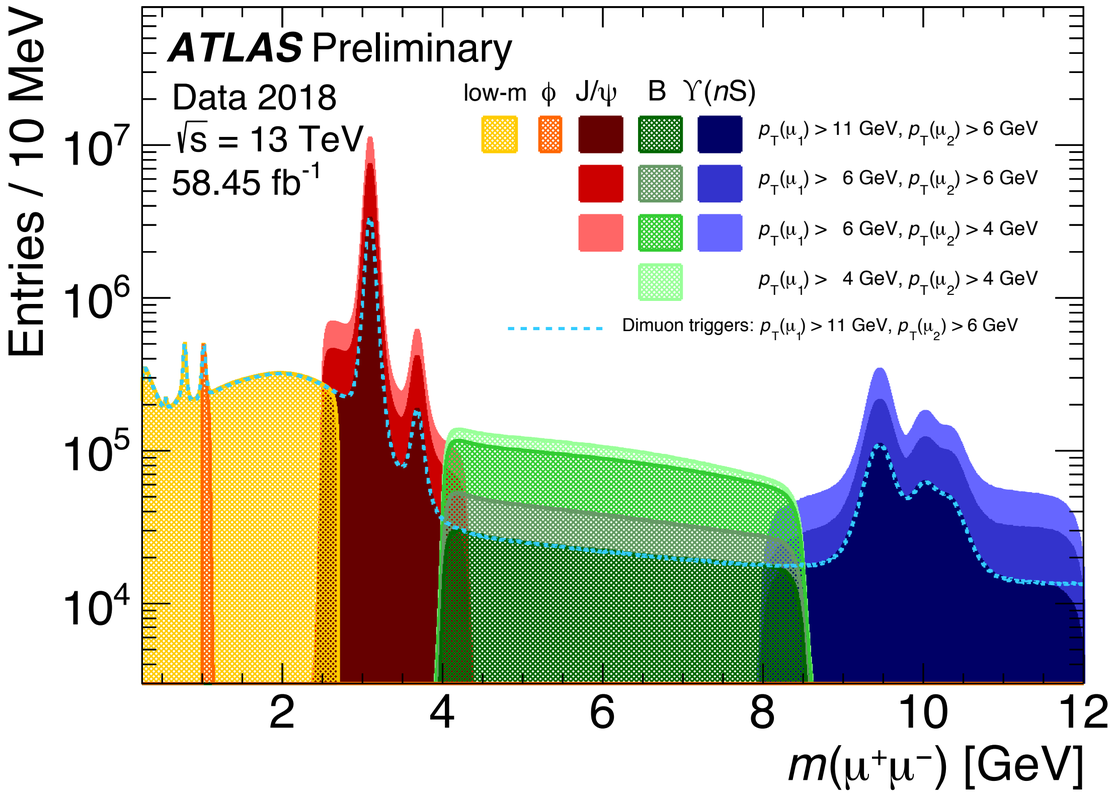
Summary

- Selected measurements from ATLAS in heavy flavour production shown.

- Quarkonia allowing probes of QCD at the pertubative / non-perturbative boundary and in studying effects of Cold Nuclear Matter

- Detailed studies of angular correlations in b b-bar production help to constrain theoretical inputs and improved understanding of certain background modelling

- Significant dataset from run-2 still to be exploited:
  - New results coming soon.
  - BPhysPublicResults



Additional Material

b-hadron pair production

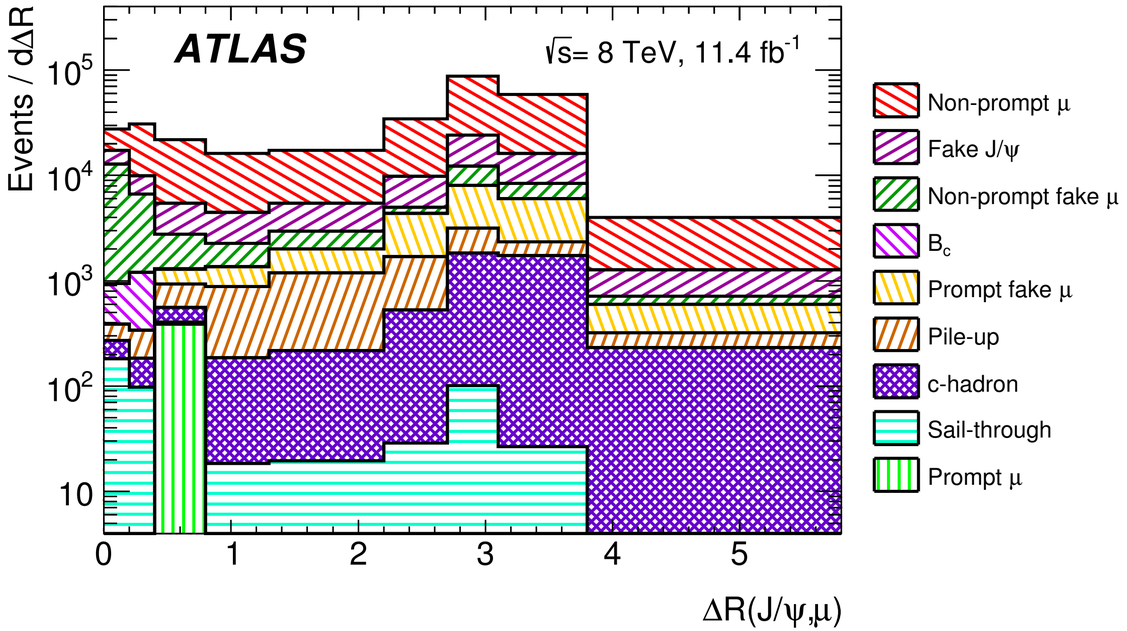
- Splitting schemes for Pythia8

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 $\alpha_s(p^2_T)$, 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 $k = 0.25$.

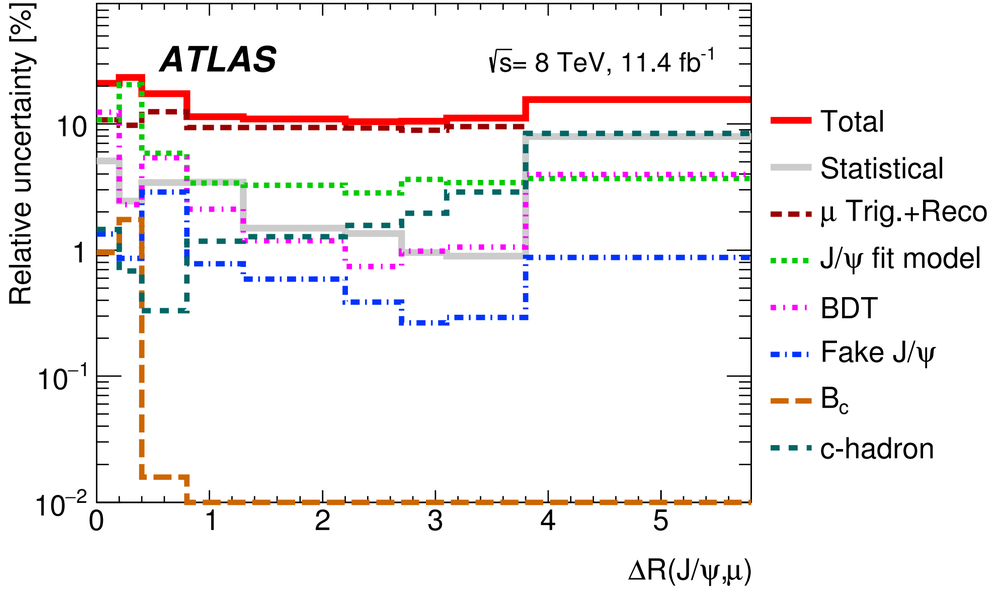
Table 1: Description of PYTHIA8 options. Options 2, 3, 6 and 7 are less well physically motivated and not considered here. The notation used is as follows: $r_q = m^2_q/m^2_{qq}$, $\beta = \sqrt{1-4r_q}$, with m_q the quark mass and m_{qq} the $q\bar{q}$ pair invariant mass.

bb-bar: Backgrounds and Systematics

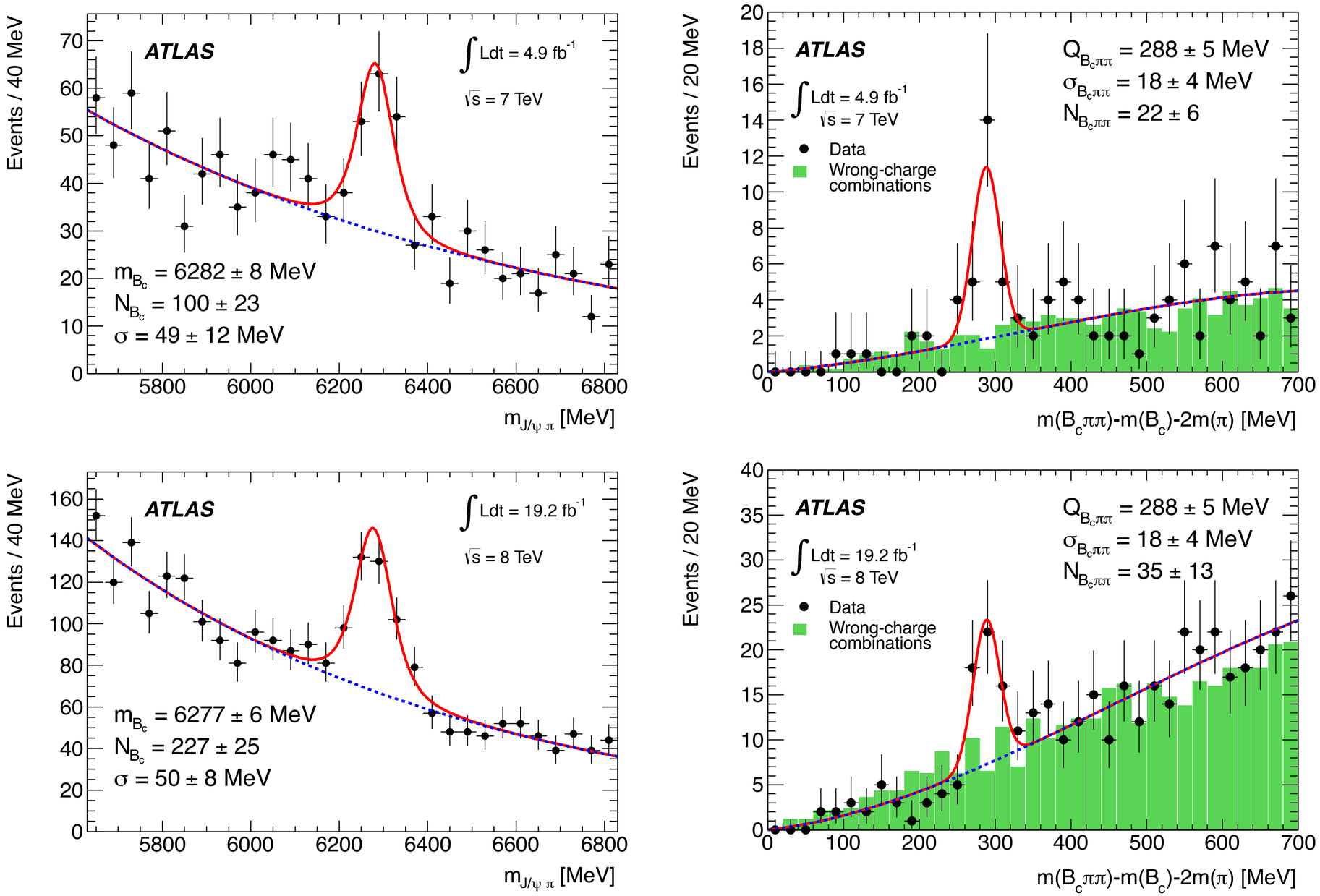
- Irreducible Backgrounds



- Systematic uncertainties
-



Bc(2S)


ATLAS
∫Ldt = 4.9 fb⁻¹
√s = 7 TeV
m_Bc = 6282 ± 8 MeV
N_Bc = 100 ± 23
σ = 49 ± 12 MeV
Events / 40 MeV
m_J/ψ π [MeV]
ATLAS
∫Ldt = 4.9 fb⁻¹
√s = 7 TeV
Data
Wrong-charge combinations
Q_Bcππ = 288 ± 5 MeV
σ_Bcππ = 18 ± 4 MeV
N_Bcππ = 22 ± 6
Events / 20 MeV
m(Bcππ)-m(Bc)-2m(π) [MeV]
ATLAS
∫Ldt = 19.2 fb⁻¹
√s = 8 TeV
m_Bc = 6277 ± 6 MeV
N_Bc = 227 ± 25
σ = 50 ± 8 MeV
Events / 40 MeV
m_J/ψ π [MeV]
ATLAS
∫Ldt = 19.2 fb⁻¹
√s = 8 TeV
Data
Wrong-charge combinations
Q_Bcππ = 288 ± 5 MeV
σ_Bcππ = 18 ± 4 MeV
N_Bcππ = 35 ± 13
Events / 20 MeV
m(Bcππ)-m(Bc)-2m(π) [MeV]

- J–P Lansberg

https://arxiv.org/abs/1903.09185

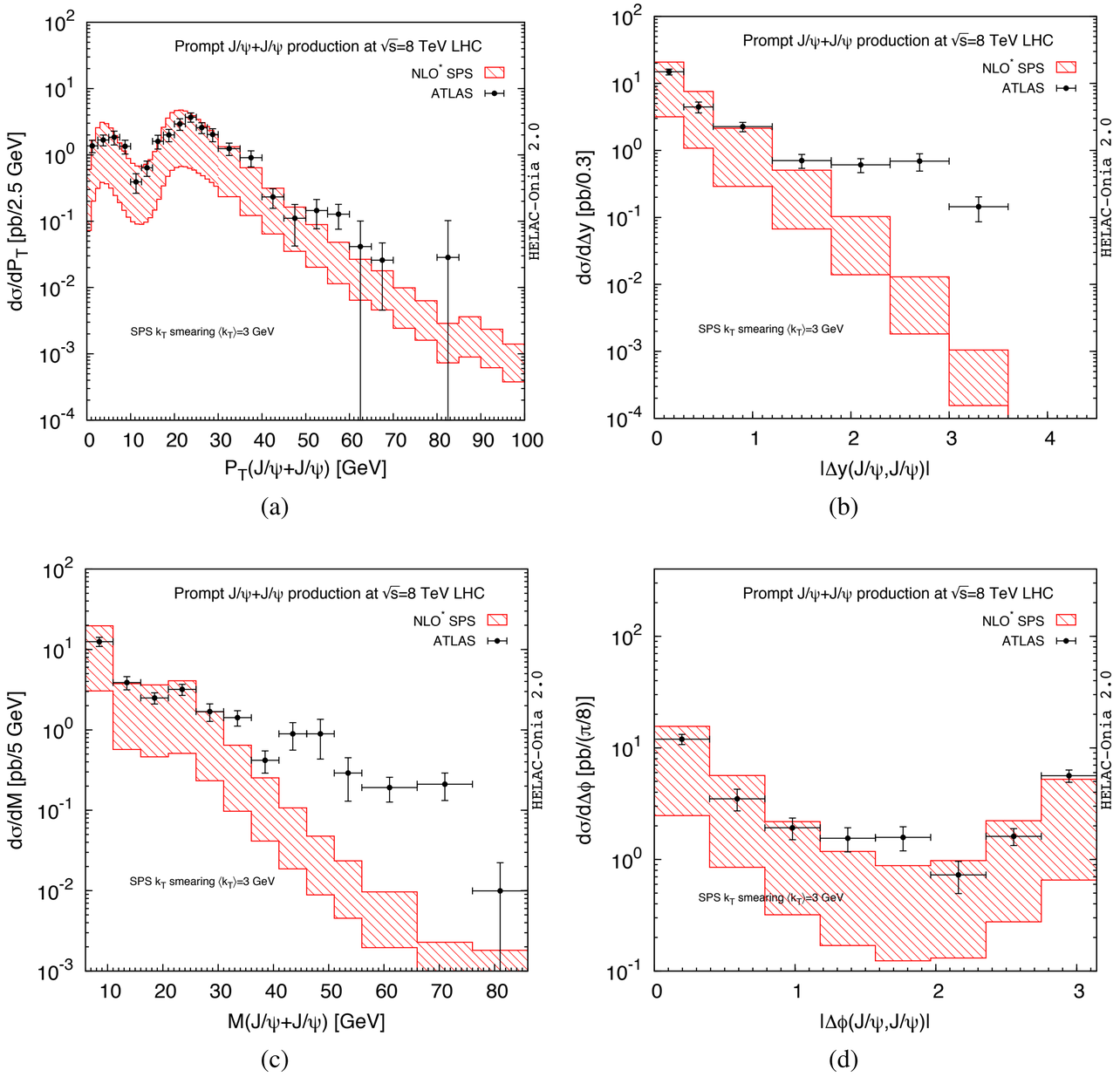


Figure 40: Comparison of the NLO* CSM theoretical predictions with the ATLAS measurement as a function of the (a) pair transverse momentum; (b) absolute-rapidity difference ; (c) pair invariant mass; (d) azimuthal separation.