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Recent Heavy Flavour results from ATLAS

Adam Barton,

On behalf of ATLAS experiment

Outline

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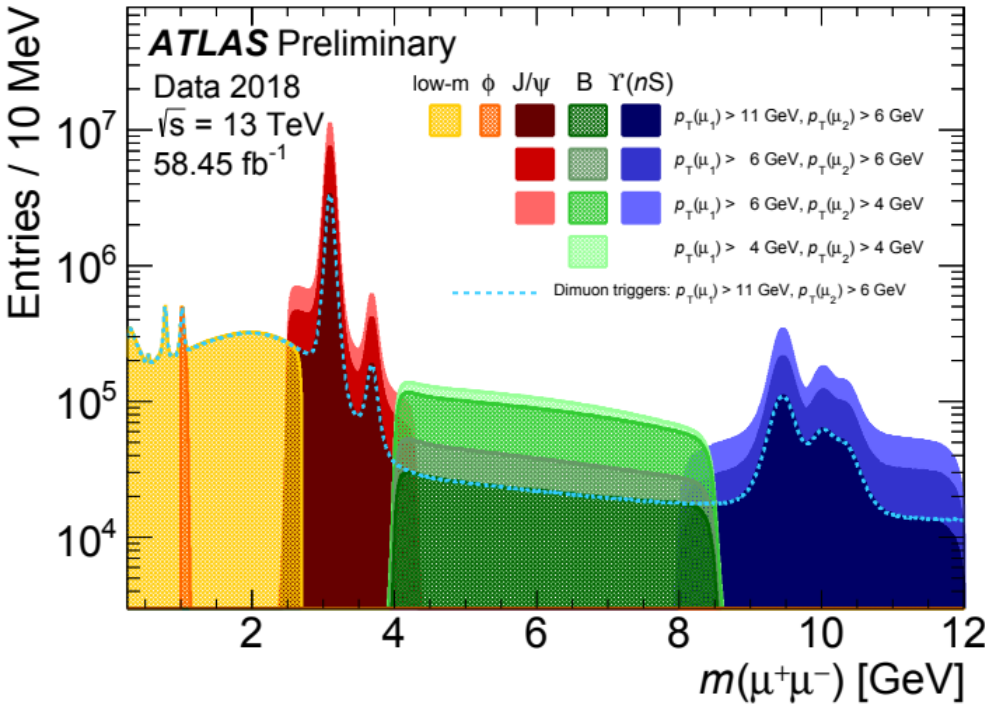
- Introduction
- J/ψ and ψ(2S) production at high p_T at 13 TeV [ATLAS-CONF-2019-047]
- J/ψ production associated with W ± [JHEP 01 (2020) 095]
- $B^{\pm}c$ / $B^{\pm}$ production cross-section [Phys. Rev. D 104 (2021) 012010]
- Pentaquark search in $\Lambda^0_b \rightarrow J/\psi p K^-$ [ATLAS-CONF-2019-048]
- CP-Violation in $B^0_s \rightarrow J/\psi$ (μ+ μ-) K + K - [Eur. Phys. J. C 81 (2021) 342]
- Study of the $B^+_c \rightarrow J/\psi D^+_s$ and $B^+_c \rightarrow J/\psi D^{*+}_s$ decays in pp collisions at √s=13 TeV with the ATLAS detector [ATLAS-CONF-2021-046]
- Combination of the ATLAS, CMS and LHCb results on the $B^0_s \rightarrow \mu^+\mu^-$ decays [ATLAS-CONF-2020-049]

Introduction

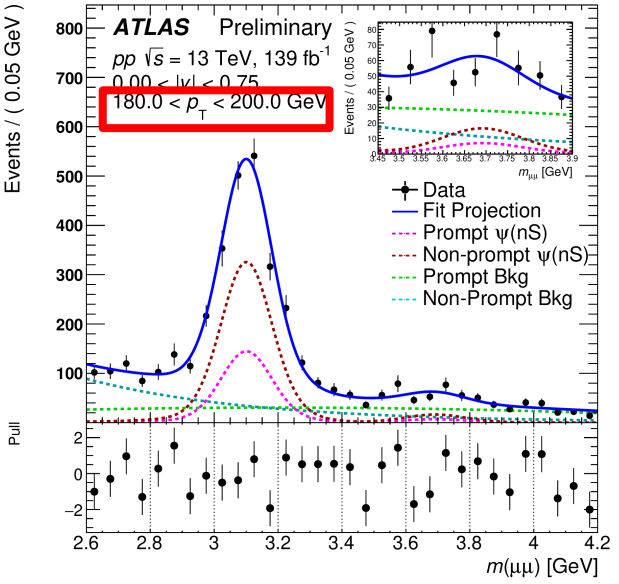
- ATLAS detects huge amount of B hadrons
- **Triggering** is a challenge as luminosity increases, most of B-physics data selected by low-pT dimuon triggers:
- **Resolution** in m(μμ) : ~50 MeV at J/ψ mass, ~150 MeV at Υ(nS) masses ~10 μm impact parameter resolution
- **Time resolution** ~60 fs after installation of IBL in Run 2 (30% improvement w.r.t. Run 1)

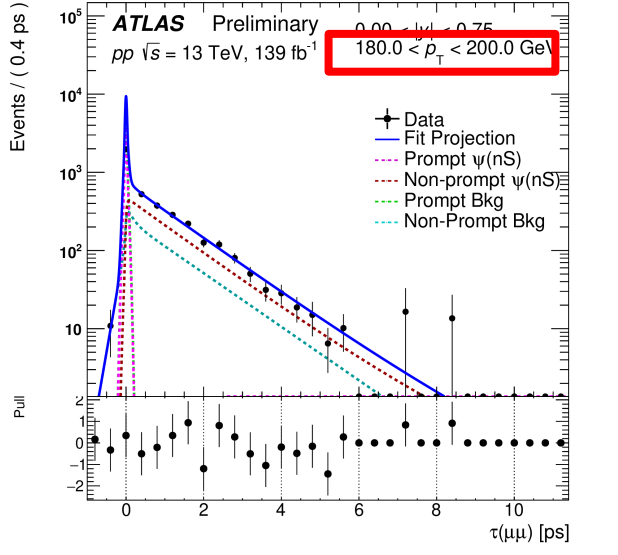


J/ψ and ψ(2S) production at high p_T

- Heavy quarkonia provide insight into QCD near the boundary of perturbative and non-perturbative regimes
- Inclusive cross section measurements are important for refining quarkonia production models
- Previous ATLAS measurements used low-threshold di-muon triggers, limiting p_T range to ~ 100 GeV → use single muon trigger with high threshold (50 GeV)
- We perform unbinned ML fit to mass and pseudo-proper decay time $\tau = m_{\mu\mu} L_{xy} /(p_T c)$, in bins of y and p_T.
- The double differential J/ψ and ψ(2S) cross-sections for prompt and non-prompt production is measured

	p_T range, GeV	y range
J/ψ	60<p T <360	|y|<2
ψ(2S)	60<p T <140	|y|<2





FONLL = (Fixed Order + Next-to-Leading Logarithms)

J/ψ and ψ(2S) production at high p_T

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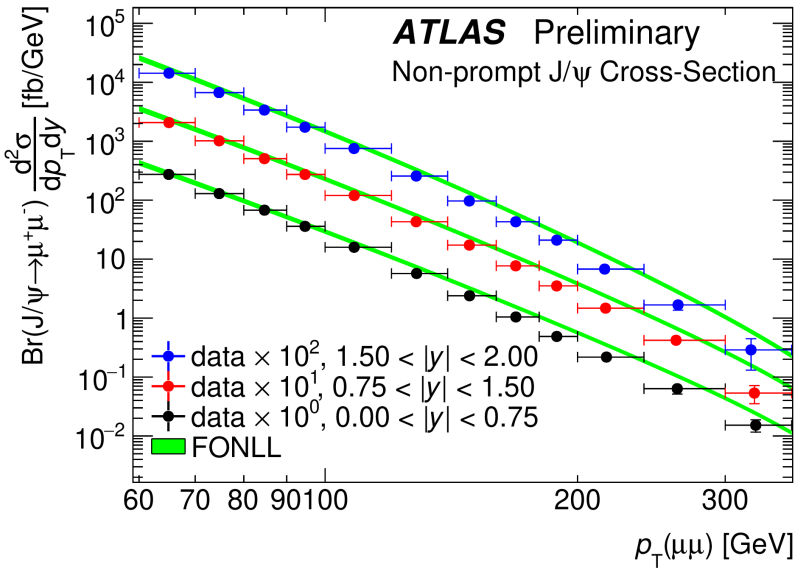
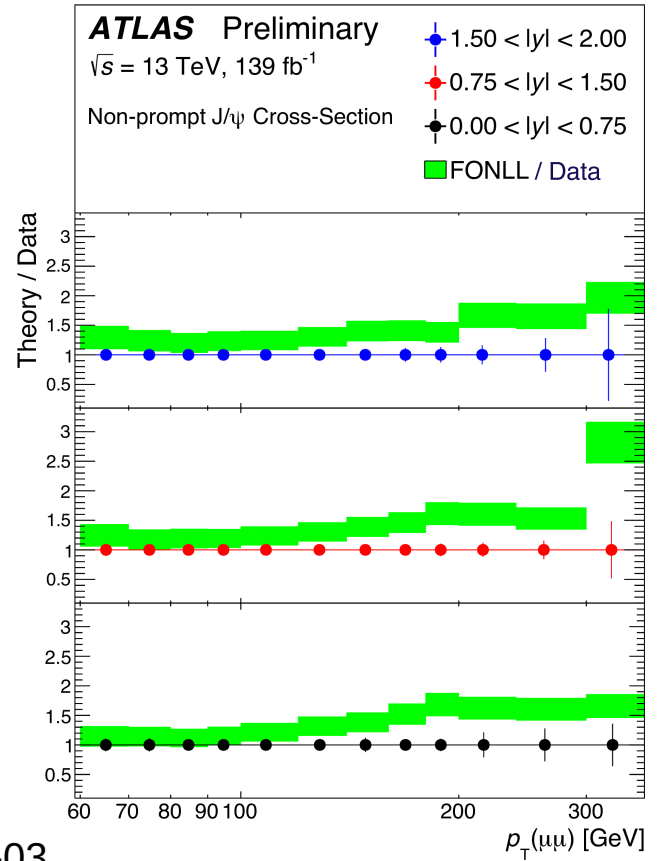
[ATLAS-CONF-2019-047]



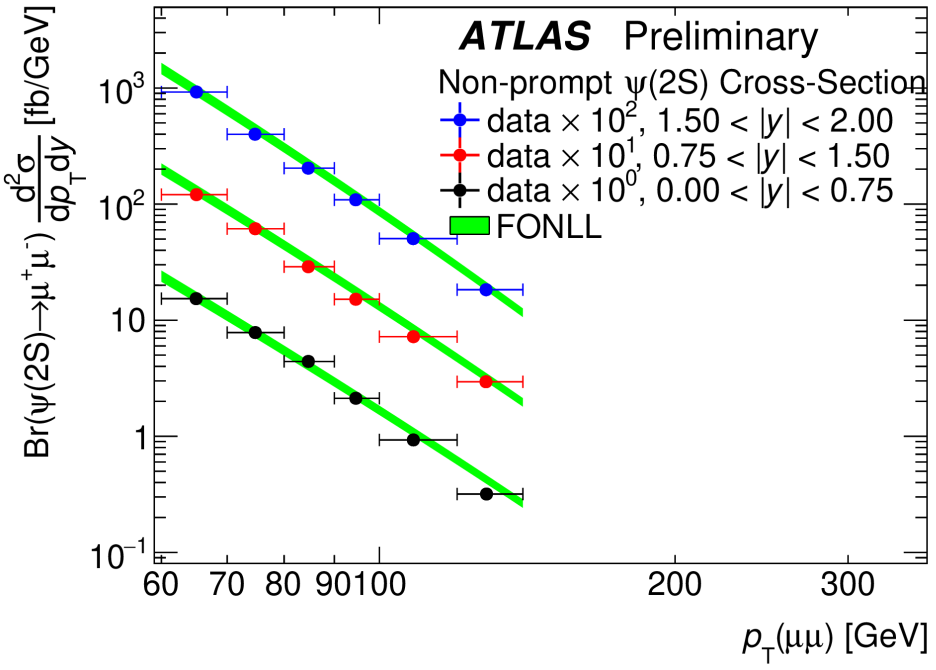


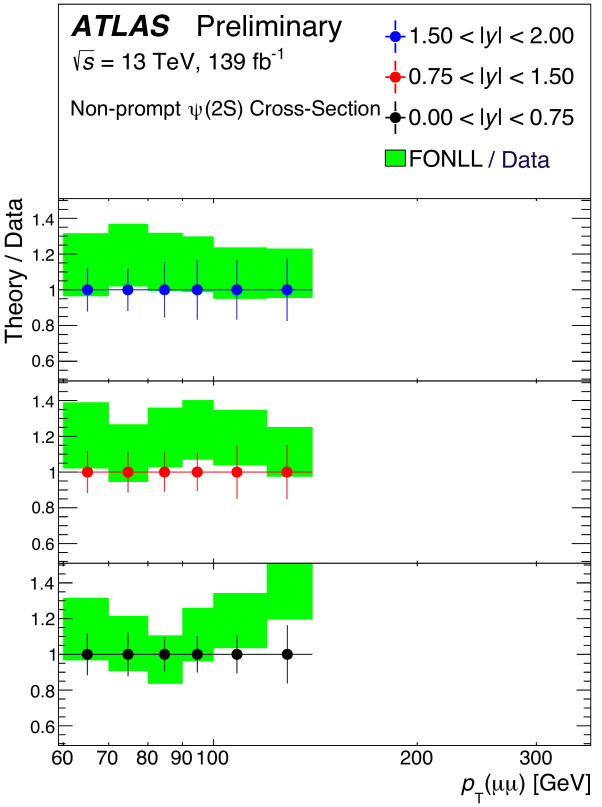
comparison to FONLL prediction*
good agreement at low p_T
at high p_T higher cross-sections are predicted

*FONLL Heavy Quark Production Matteo Cacciari, http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html, accessed: 2019-09-03

FONLL = (Fixed Order + Next-to-Leading Logarithms)

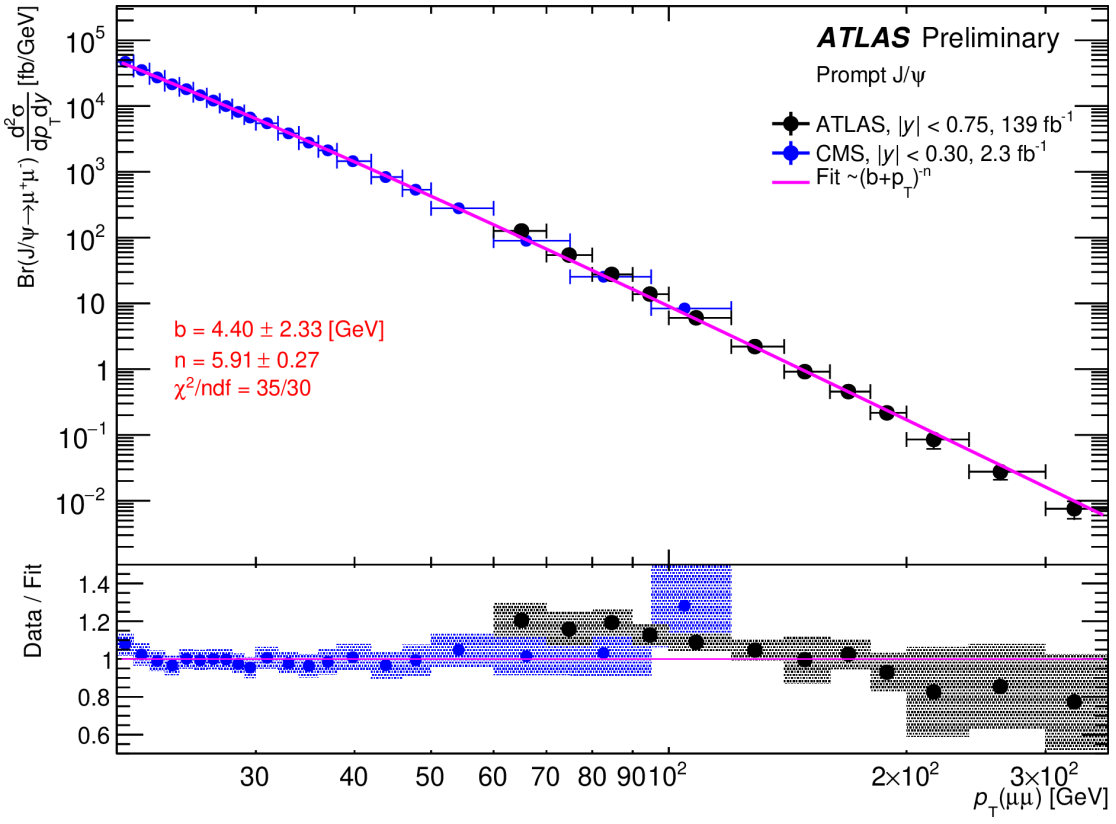
J/ψ and ψ(2S) production at high p_T





comparison to FONLL prediction*
good agreement though somewhat higher cross-sections are predicted

J/ψ and ψ(2S) production at high p_T



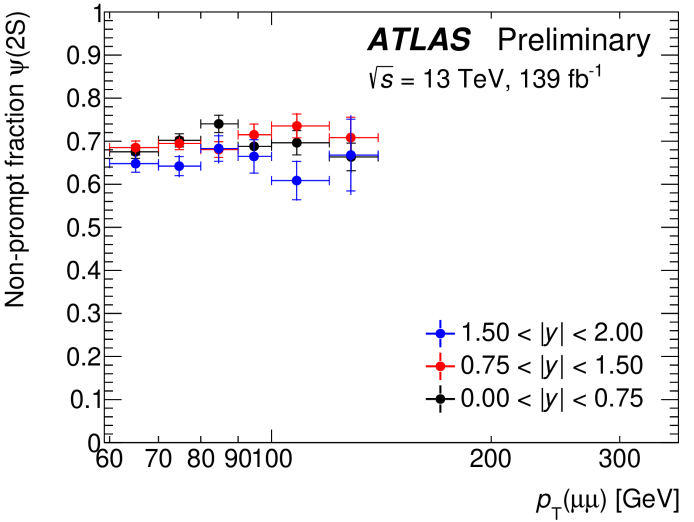
Prompt J/ψ cross-section at 13 TeV
fit CMS and ATLAS results with $\sim(b+p_T)^{-n}$
good agreement in the overlap region

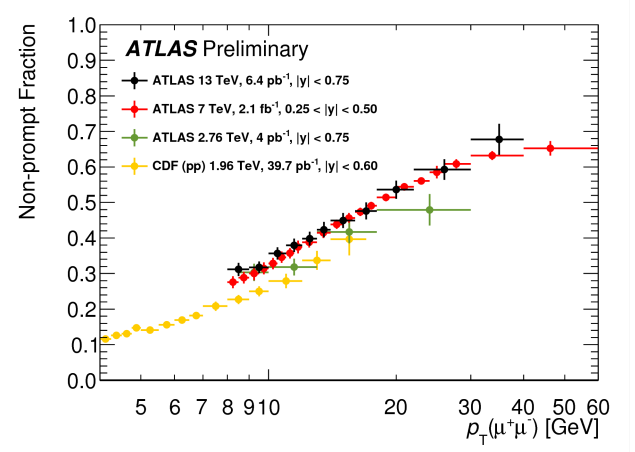
J/ψ and ψ(2S) production at high p_T

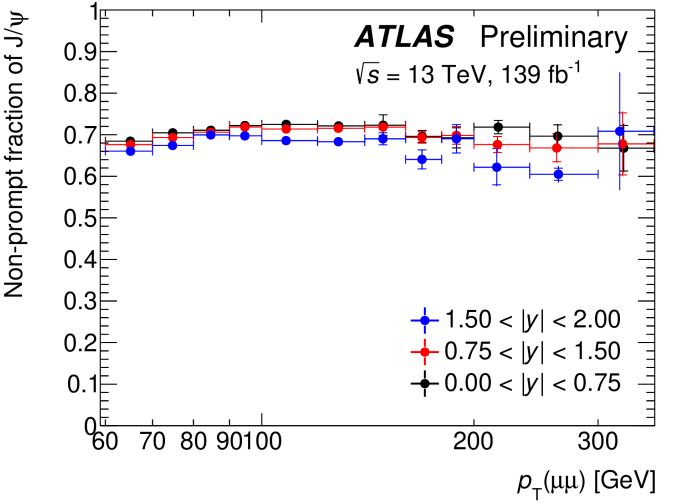
non-prompt production fractions:

$$F_{\psi}^{\mathrm{NP}}(p_{\mathrm{T}}, y) = \frac{N_{\psi}^{\mathrm{NP}}}{N_{\psi}^{\mathrm{P}} + N_{\psi}^{\mathrm{NP}}}$$

We simply see a plateau at 70% which was hinted at with previous measurements







[ATLAS-CONF-2015-030]

J/ψ production associated with W±

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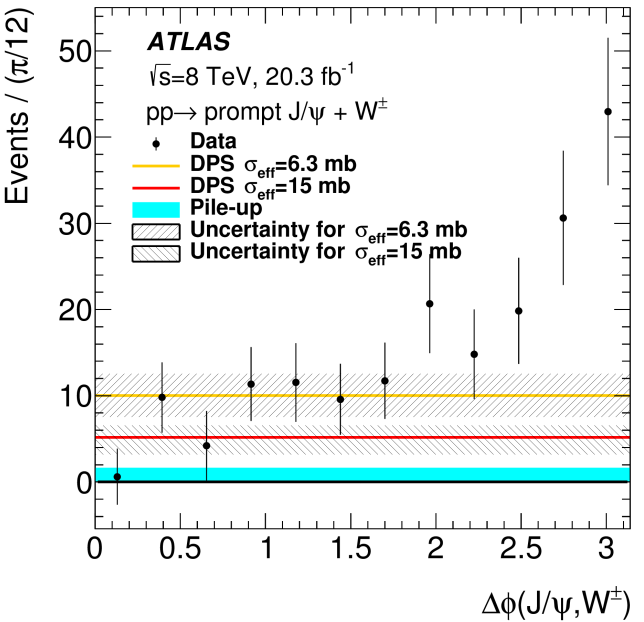
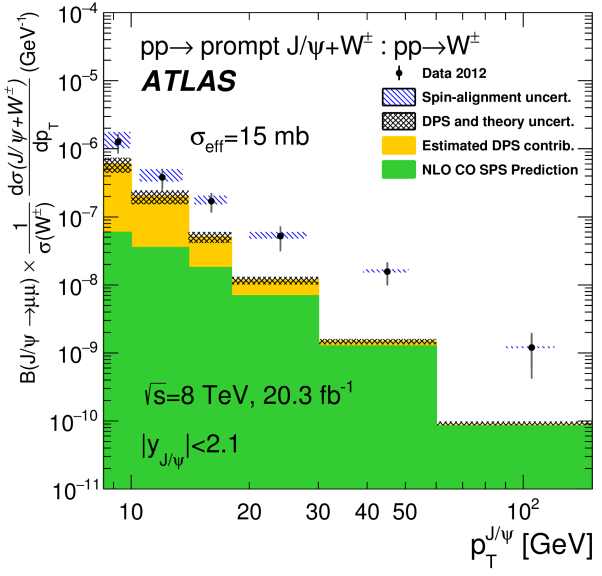
- For understanding charmonium production mechanism in hadronic collisions
  - The relative contribution of Color Singlet (CS) and Color Octet (CO)
  - contributions from Single (SPS) and Double Parton Scattering (DPS)
    - can be **probed using Δφ distribution** between J/ψ and W± - DPS should be flat, SPS peaks at ~π.
- The prompt-J/ψ signal is extracted from fit to J/ψ mass and pseudo-proper decay time
- Δφ measurement indicates presence of SPS
- in case of DPS, probability of producing J/ψ by second scatter: $P_{J/\psi|W\pm} = \sigma_{J/\psi}/\sigma_{eff}$
- σ_{eff} is unknown → two choices from previous ATLAS measurements:
  - σ_{eff} = 6.3 ± 1.6stat ± 1.0syst mb from prompt J/ψ pair production
  - σ_{eff} = 15 ± 3stat +5-3 syst mb from W± + 2jets
- We see both values consistent with data at low Δφ

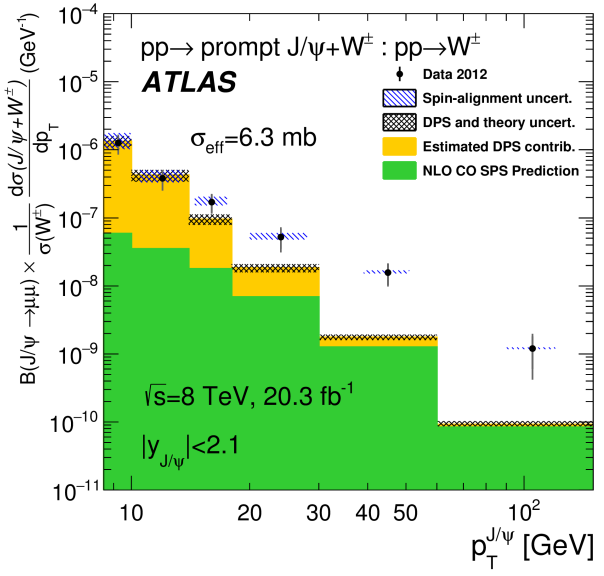


J/ψ production associated with W±

- We show the differential inclusive cross-section in 6 pT bins in the range: 8.5 < pT <150 GeV
- We compare to two theoretical predictions
  - differ in σ_{eff} values used for estimation of DPS
  - SPS contribution modelled by CO model for both

- comparison suggests smaller σ_{eff}, but both values don't describe pT dependence
- CS model not included





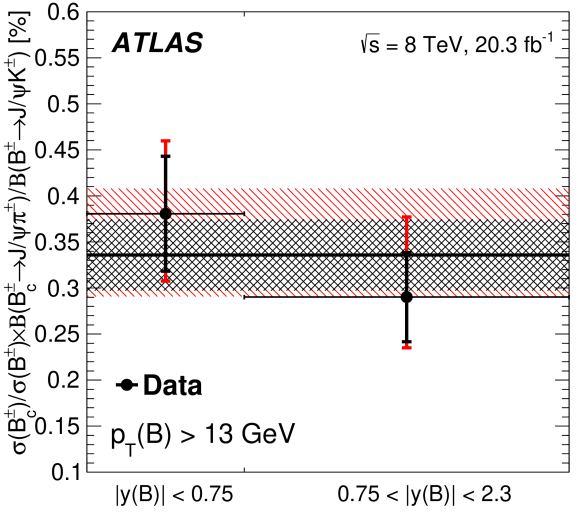
[arXiv:1912.02672, submitted to PRD]

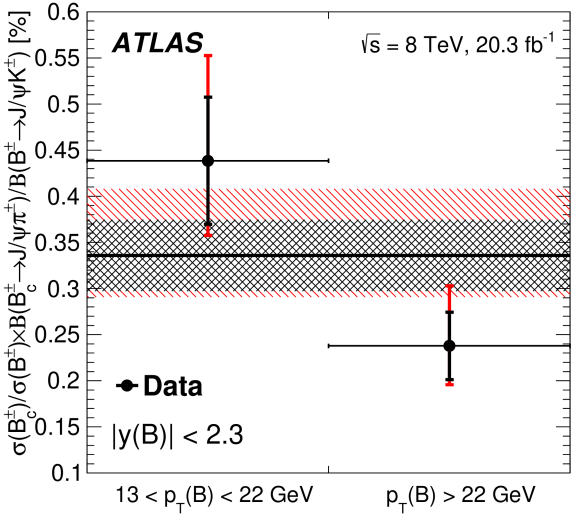
$B^{\pm}_c$ / $B^{\pm}$ production cross-section

- A unique probe for heavy quark dynamics
  - use similar decay mode for $B^{\pm}_c$ and $B^{\pm}$
- fiducial volume: p_T >13 GeV, |y|<2.3

$$\frac{\sigma(B_c^{\pm}) \cdot \mathcal{B}(B_c^{\pm} \to J/\psi\pi^{\pm}) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\sigma(B^{\pm}) \cdot \mathcal{B}(B^{\pm} \to J/\psi K^{\pm}) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)} = \frac{N^{\mathrm{reco}}(B_c^{\pm})}{N^{\mathrm{reco}}(B^{\pm})} \cdot \frac{\epsilon(B^{\pm})}{\epsilon(B_c^{\pm})}$$

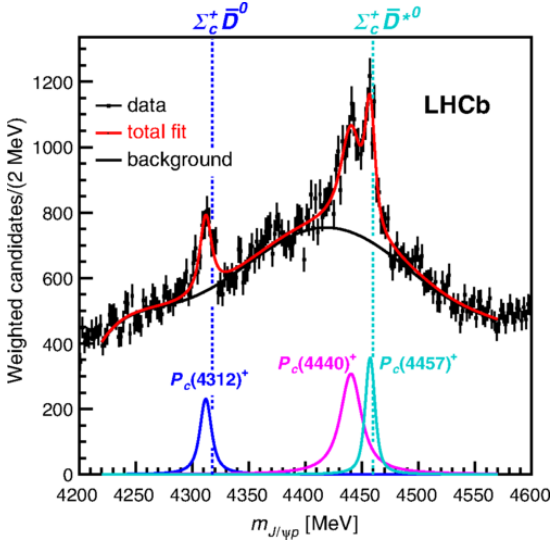
- double differential measurement in 2 bins of y and p_T
- The production ratio in fiducial region (horizontal line)
  - $(0.34 \pm 0.04_{\,\mathrm{stat}} \pm {}^{+0.06}_{-0.02\,\mathrm{syst}} \pm 0.01_{\,\mathrm{lifetime}})\%$
  - Complements LHCb and CMS
  - no evident rapidity dependence
  - $B^{\pm}_c$ cross-section decreases faster with p_T than $B^{\pm}$ cross-section

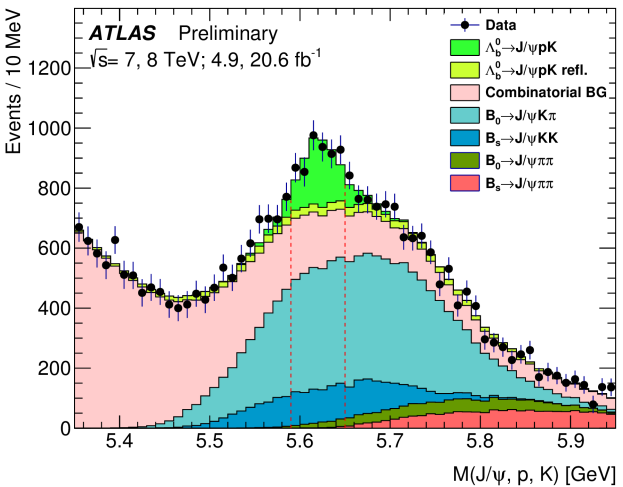




Pentaquark search in $\Lambda^0_b \to J/\psi p K^-$

- 4 structures observed in J/ψp mass spectrum by LHCb.
  - interpreted as pentaquark states $P_c(4312)^+$, $P_c(4380)^+$, $P_c(4440)^+$ and $P_c(4457)^+$.
- ATLAS search uses 4.9 fb^{-1} (7 TeV) and 20.9 fb^{-1} (8 TeV) data.
  - no PID → consider all $H_b \to J/\psi h_1 h_2$ ($h_{1,2}$ = p, K, π) candidates
  - modelling these contributions with analytical matrix elements
  - suppressing background from Λ*, K*, f, φ → m(Kπ) > 1.55 GeV
  - performing sequence of iterative fits in Λ^0_b signal region, B^0 ($J/\psi\pi K$) and B^0_s ($J/\psi KK$) control regions and in full range of selected dataset





signal region: (5.59, 5.65) GeV

Pentaquark search in $\Lambda^0_b \to J/\psi p K^-$

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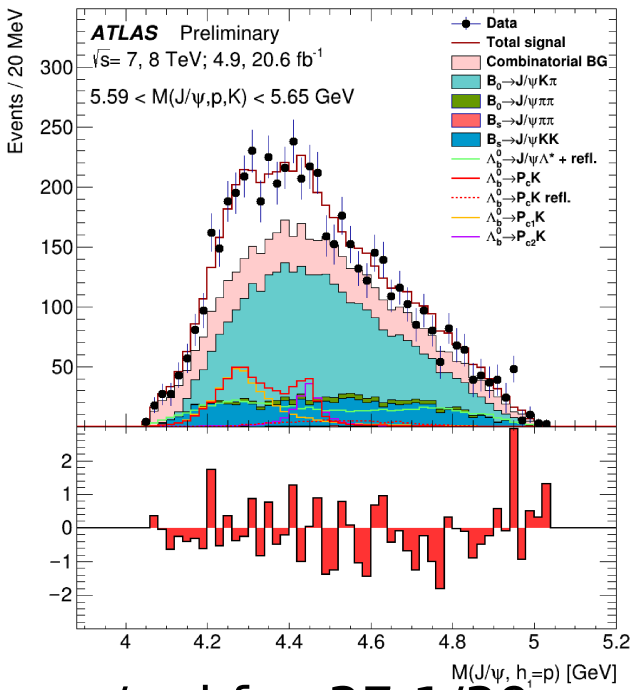
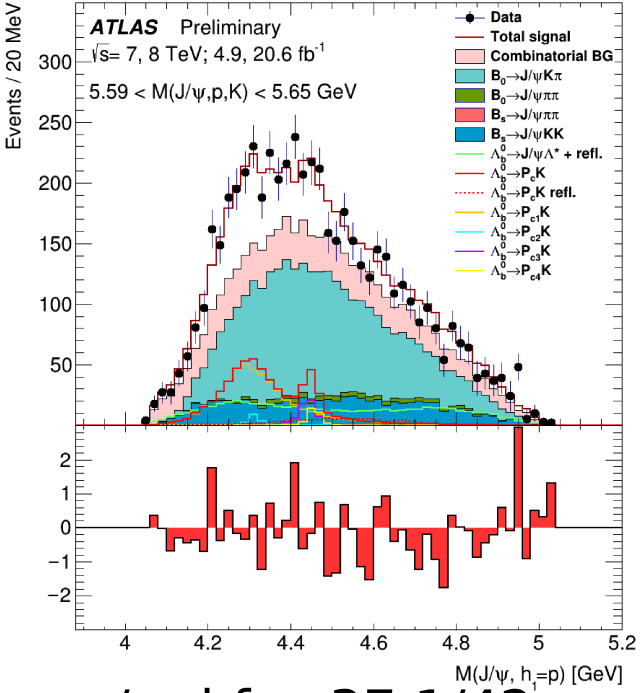
fit with 2 pentaquark hypothesis with spin parity of 3/2- (light) and 5/2+ (heavy)



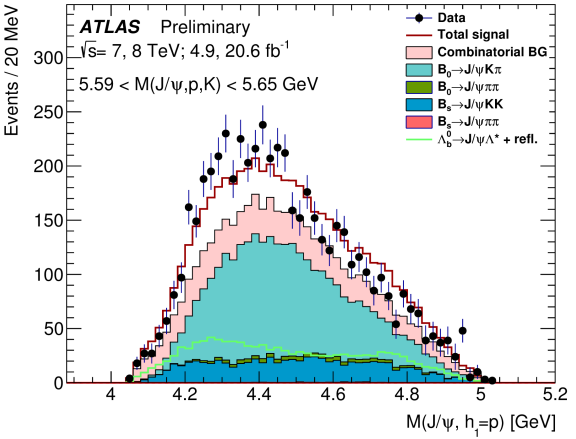
χ^2/n.d.f = 37.1/39

fit with 4 pentaquark hypothesis: masses, widths and relative yields of narrow states fixed to LHCb values



χ^2/n.d.f = 37.1/42

fit without pentaquarks



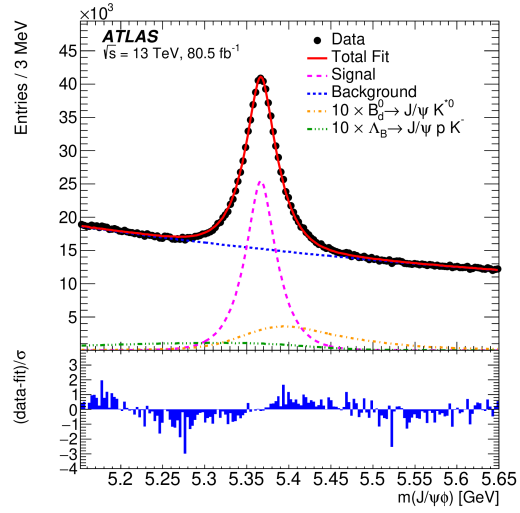
χ^2/n.d.f = 69.2/37

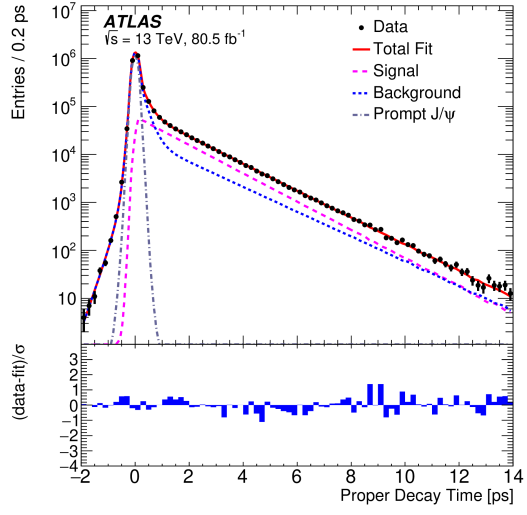
Conclusions

- hypotheses with 2 and 4 pentaquarks consistent with data
- hypothesis without pentaquarks cannot be excluded

CP-Violation in $B^0_s \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$

- The CP-violating phase ϕ_s is sensitive to New Physics processes
- In SM, ϕ_s is related to the CKM matrix elements:
  - Estimated precisely as −0.03696 rad with small uncertainty.
- other B0s-B0s mixing quantities: width difference between B0s mass eigenstates $\Delta\Gamma_s = \Gamma_s^H - \Gamma_s^L$, average decay width $\Gamma s = (\Gamma_s^H + \Gamma_s^L)/2$.
- tag whether B meson contains b or b quark at time of production using opposite side tagging (by computing weighted sum of charge of tracks in cone ΔR around direction of either μ, e or b-tagged jet)
- Final state is admixture of CP-even(L=0,2) and CP-odd(L=1) states distinguished through time-dependent angular analysis
- 80.5 fb-1 (13 TeV) partial Run 2 data (2015-2017)
  - unbinned maximum likelihood (LH) fit to extract signal and S-wave parameters

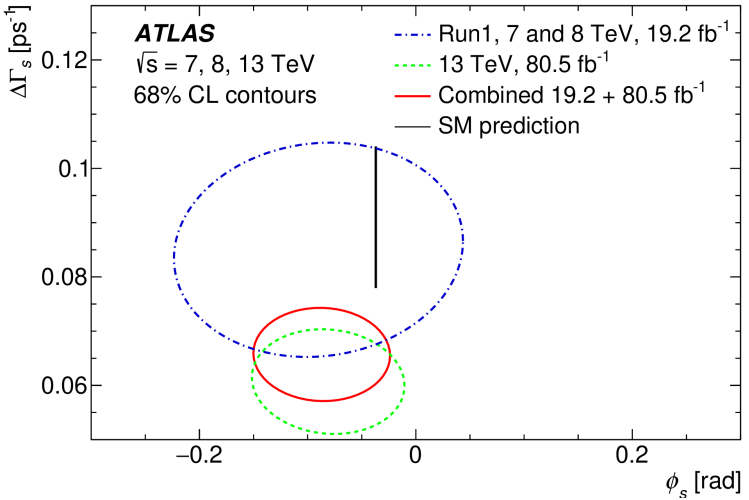


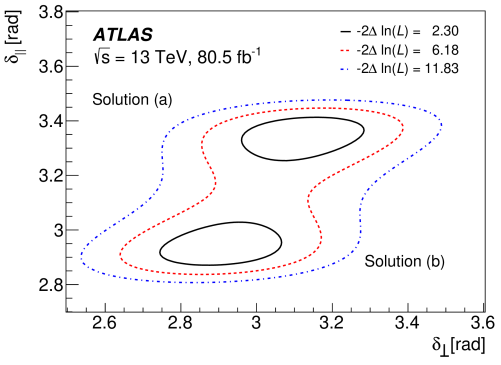


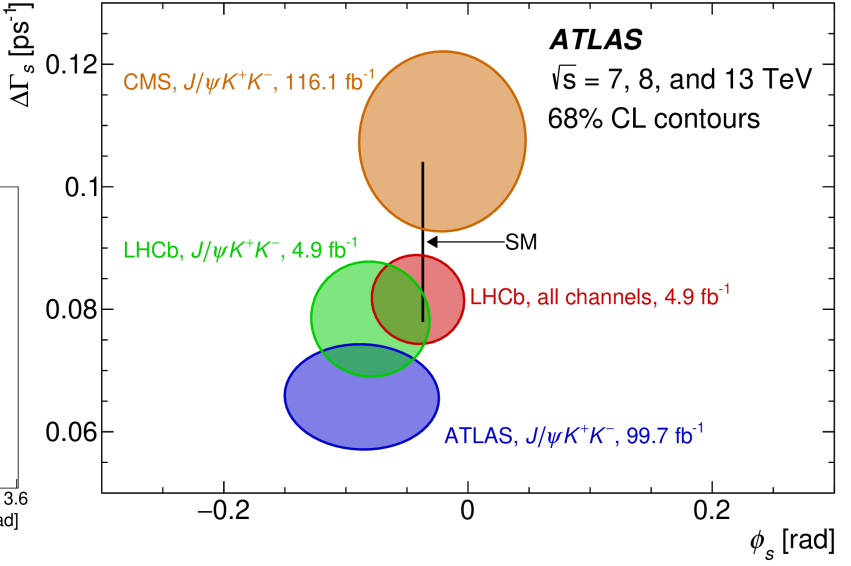
CP-Violation in $B^0_s \to J/\psi\phi \to \mu^+\mu^- K^+K^-$

- fit returned two well-separated solutions for strong phases of CP-even and CP-odd final state configurations
  - Main parameters are identical in both solutions
- ϕ_s and $\Delta\Gamma_s$ results consistent with updated SM
- ~ 3σ tension in Γ_s with current world average [PDG2020]
- A full run-2 paper is in progress

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_\parallel(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09





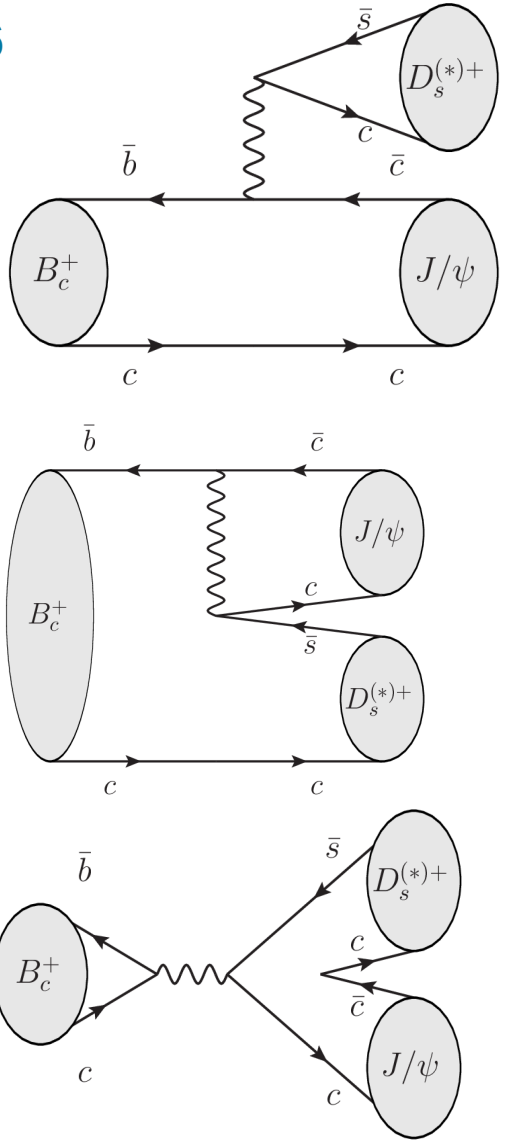


Eur. Phys. J. C 81 (2021) 342

ATLAS-CONF-2021-046

New: Study of the $B^+_c \rightarrow J/\psi\, D_s^{(*)+}$

- Decays $B^+_c \rightarrow J/\psi\, D^{*+}_s$ can occur through b decay with c as spectator, or through annihilation diagram.
- The analysis seeks a more precise measurement of the branching fractions and polarization using full Run-2 data.
- Dataset 1: candidates in the events collected by the standard dimuon or three-muon triggers without requirements on additional ID track.
- Dataset 2: candidates collected only by the dedicated $B^0_s \rightarrow J/\psi\, \varphi$ triggers but excluding the ones used in dataset 1.



New: Study of the $B^+_c \to J/\psi\, D_s^{(*)+}$: Result

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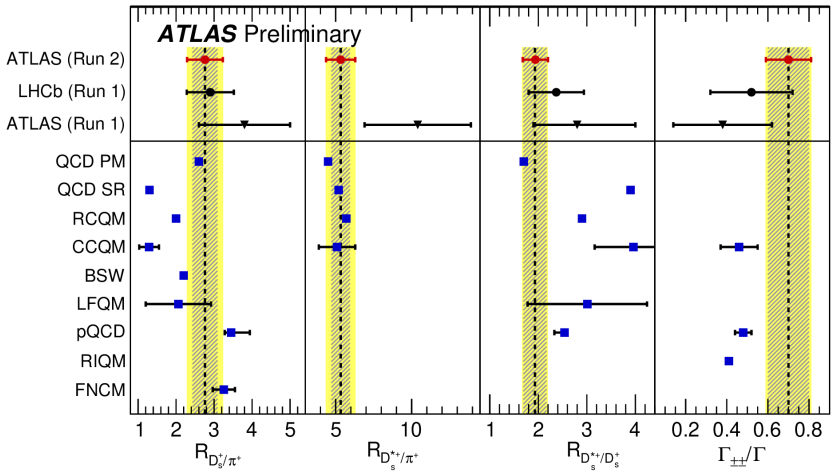
$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33(\text{stat.}) \pm 0.29(\text{syst.}) \pm 0.16(\text{br.f.})$$
$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61(\text{stat.}) \pm 0.67(\text{syst.}) \pm 0.32(\text{br.f.})$$
$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24(\text{stat.}) \pm 0.10(\text{syst.})$$
$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

- Measurements are consistent with LHCb.
- The precision of this measurement exceeds that of all previous studies.



$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Ref.
2.76 ± 0.47	5.33 ± 0.96	1.93 ± 0.26	0.70 ± 0.11	ATLAS Run 2
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb Run 1 [1]
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS Run 1 [2]
2.6	4.5	1.7	–	QCD potential model [3]
1.3	5.2	3.9	–	QCD sum rules [4]
2.0	5.7	2.9	–	RCQM [5]
1.29 ± 0.26	5.09 ± 1.02	3.96 ± 0.80	0.46 ± 0.09	CCQM [6]
2.2	–	–	–	BSW [7]
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM [8]
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	pQCD [9]
–	–	–	0.410	RIQM [10]
3.257 ± 0.293	–	–	–	FNCM [11]

ATLAS-CONF-2020-049

Combination of the ATLAS, CMS and LHCb results on the $B^0_s \to \mu^+\mu^-$ decays

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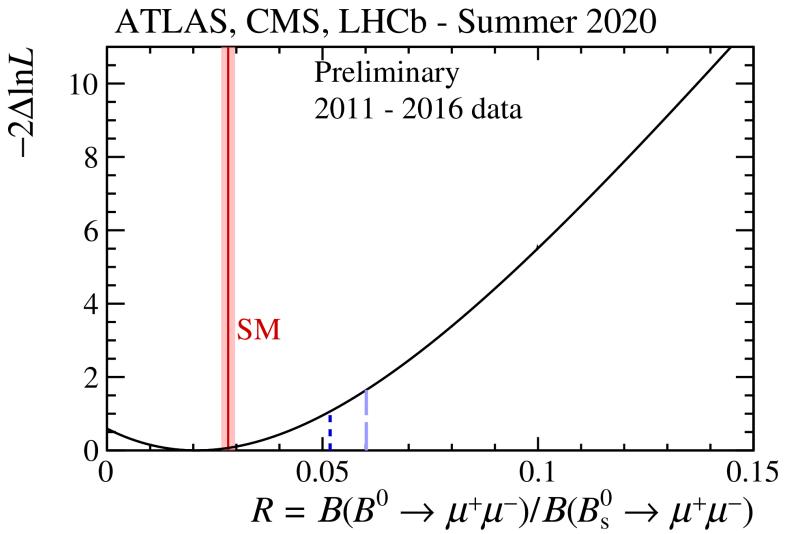
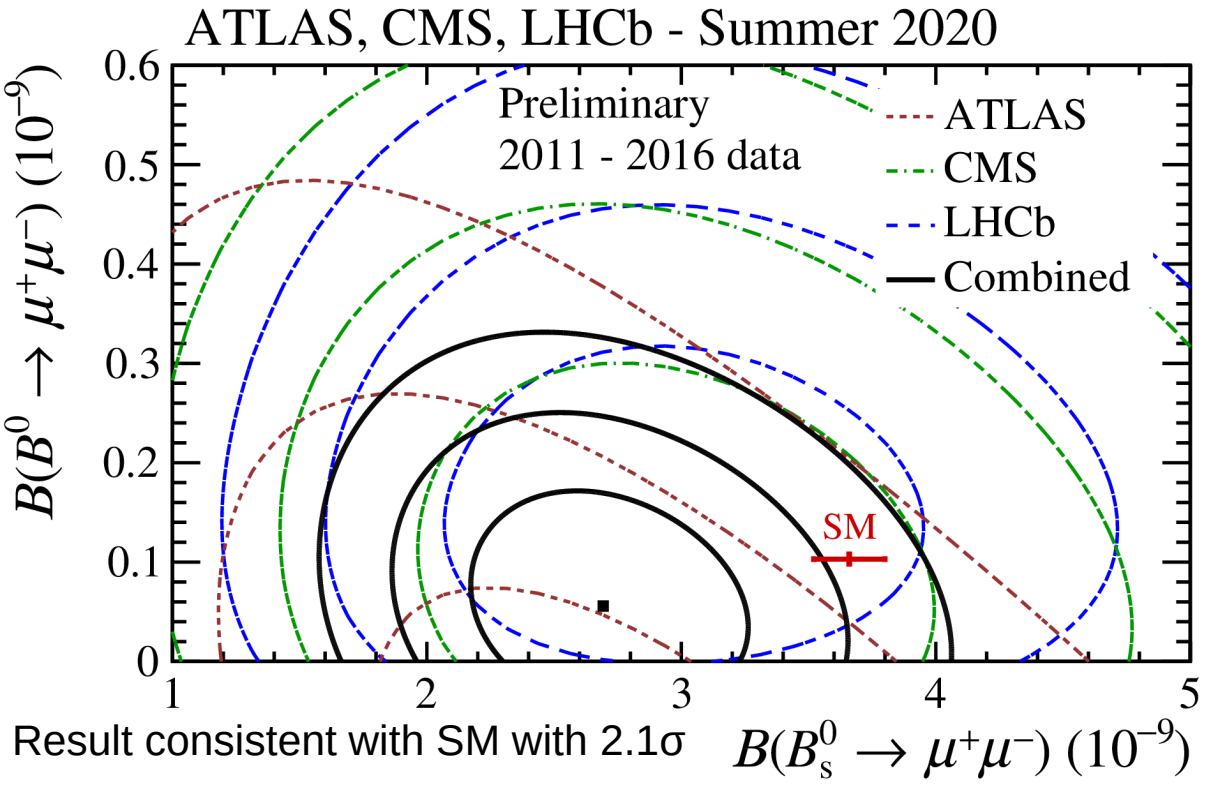
A combination of results on the rare $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays from the ATLAS, CMS, and LHCb experiments using data collected at the Large Hadron Collider between 2011 and 2016





Result consistent with SM with 2.1σ

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.6 \times 10^{-10}$ at 90% CL, and
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ at 95% CL.

Summary

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- ATLAS has a rich B-Physics program
- The statistical precision of many analyses can still be improved (data available)
- More papers coming
- ATLAS B-physics team is well prepared for Run3

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Backups

J/ψ and ψ(2S) production at high p_T

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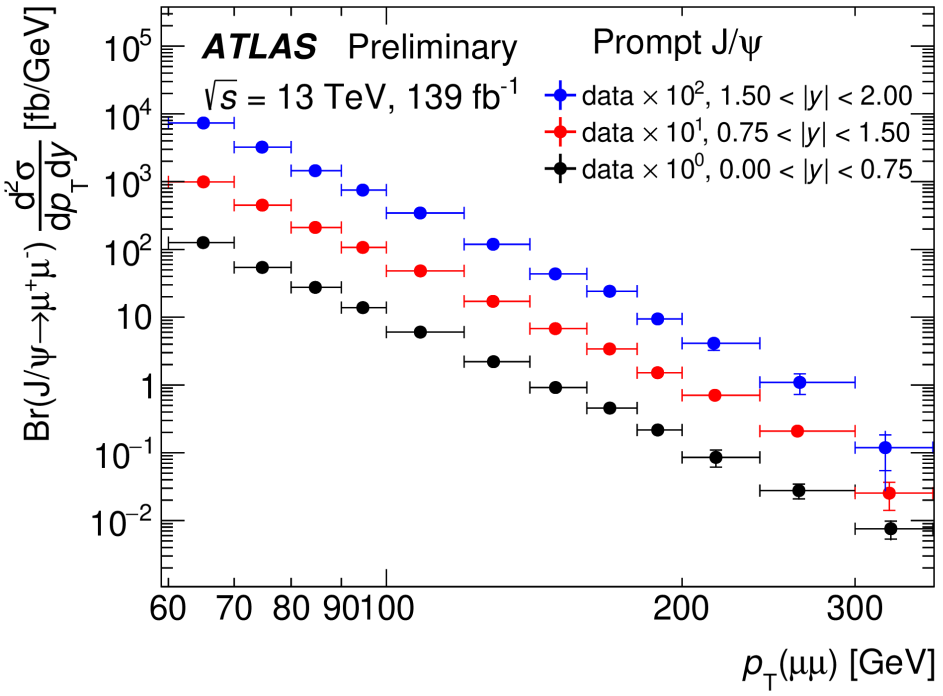
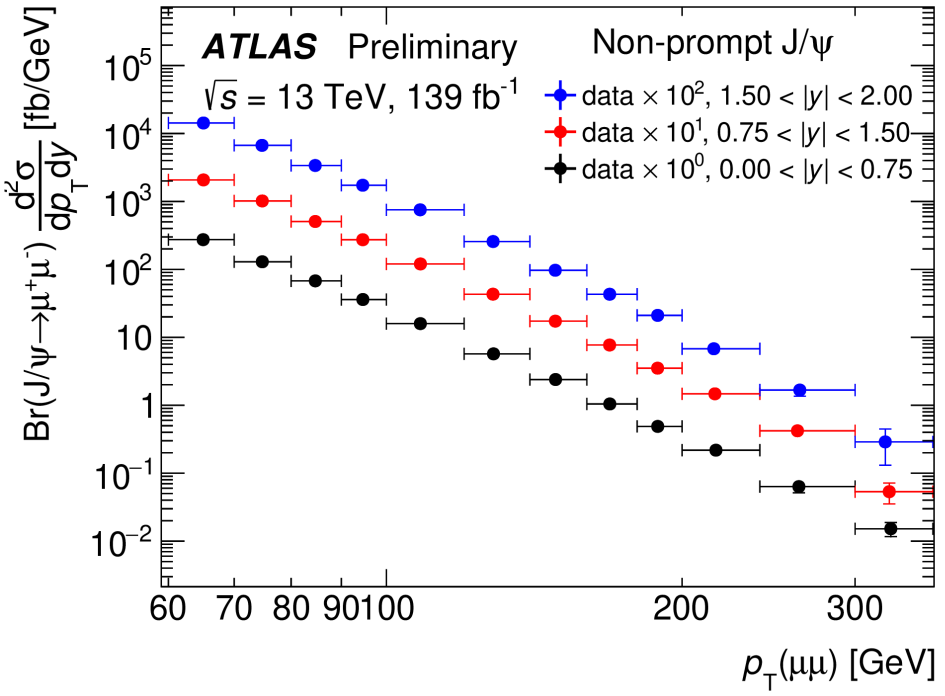
Prompt



Non-prompt



[x1, x10 and x100 scaling applied to different rapidity ranges for visual clarity]

J/ψ and ψ(2S) production at high p_T

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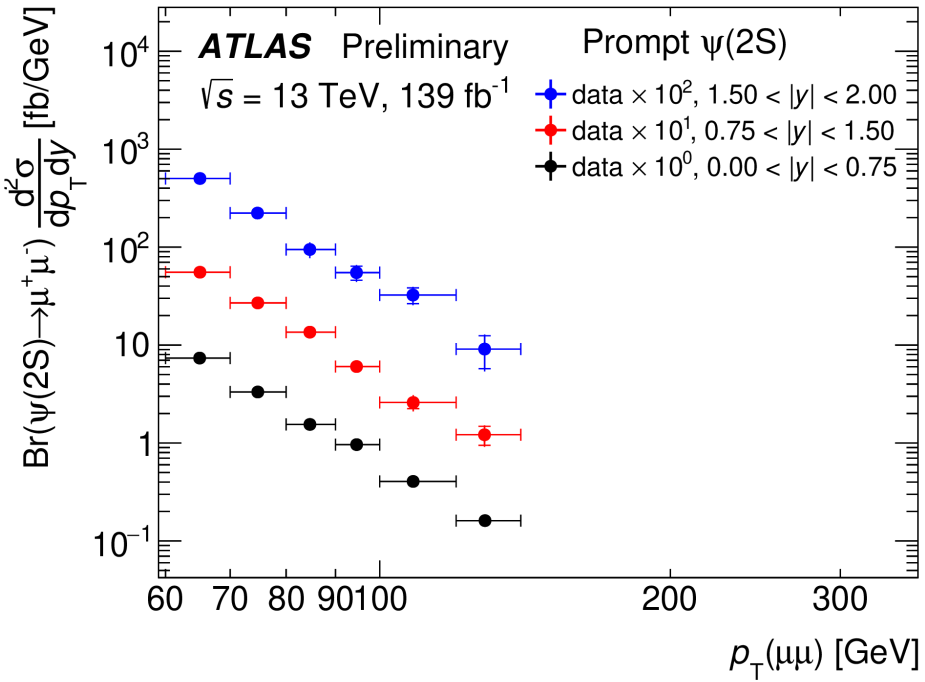
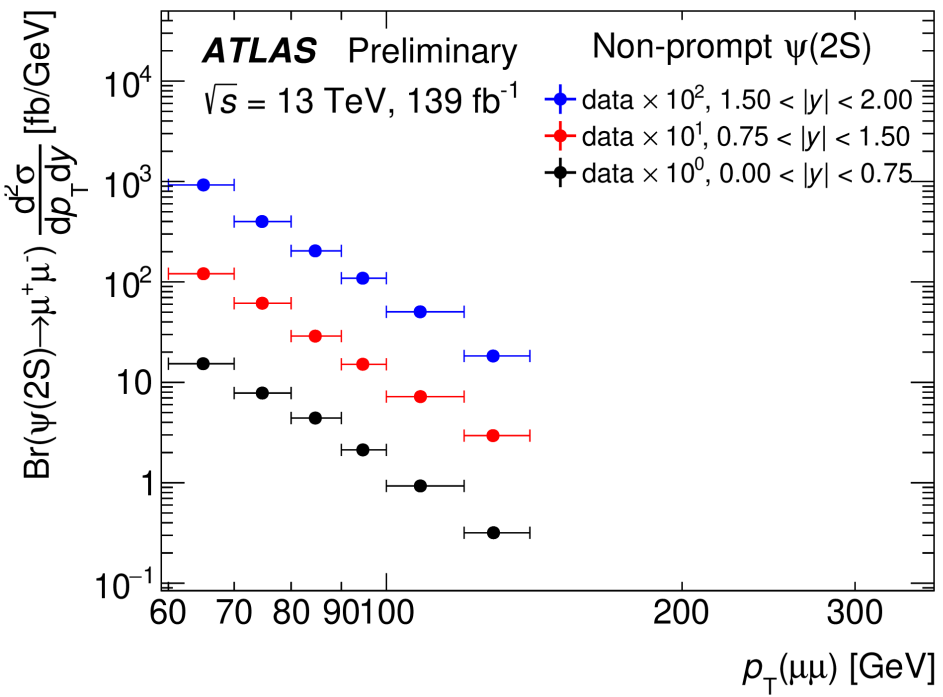
Prompt



Non-prompt



[x1, x10 and x100 scaling applied to different rapidity ranges for visual clarity]