B Physics Results at ATLAS

Iskander Ibragimov

UNIVERSITÄT SIEGEN

on behalf of the ATLAS Collaboration

Moriond QCD 2021
27.03.- 03.04.2021

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Center for Particle Physics Siegen

ErUM-FSP T02 ATLAS

ATLAS EXPERIMENT

Run: 333181
Event: 1942573294
2017-08-16 07:27:32 CEST

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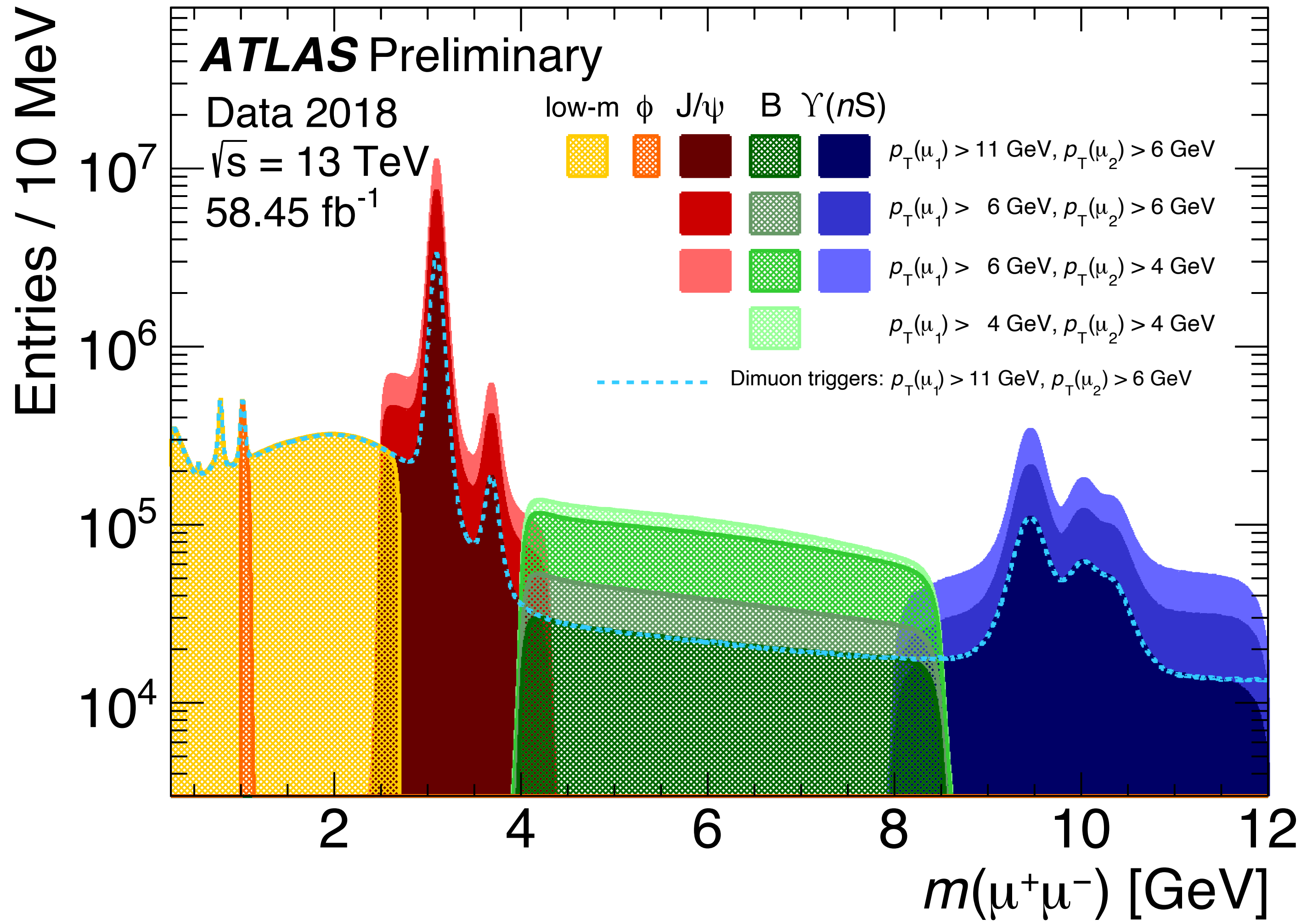
Outline

- Introduction
- J/ψ and ψ(2S) production at high p_T at 13 TeV [ATLAS-CONF-2019-047]
- J/ψ production associated with $W^{\pm}$ [JHEP 01 (2020) 095]
- $B^{\pm}_c$ / $B^{\pm}$ production cross-section [arXiv:1912.02672, submitted to PRD]
- Pentaquark search in $\Lambda^0_b \rightarrow J/\psi p K^-$ [ATLAS-CONF-2019-048]
- CP-Violation in $B^0_s \rightarrow J/\psi \phi \rightarrow \mu^+\mu^- K^+ K^-$ [arXiv:2001.07115, accepted by EPJC]
- Summary

Introduction

- ATLAS detects huge amount of B hadrons
- trigger is a challenge, most of B-physics data selected by low-pT dimuon triggers:



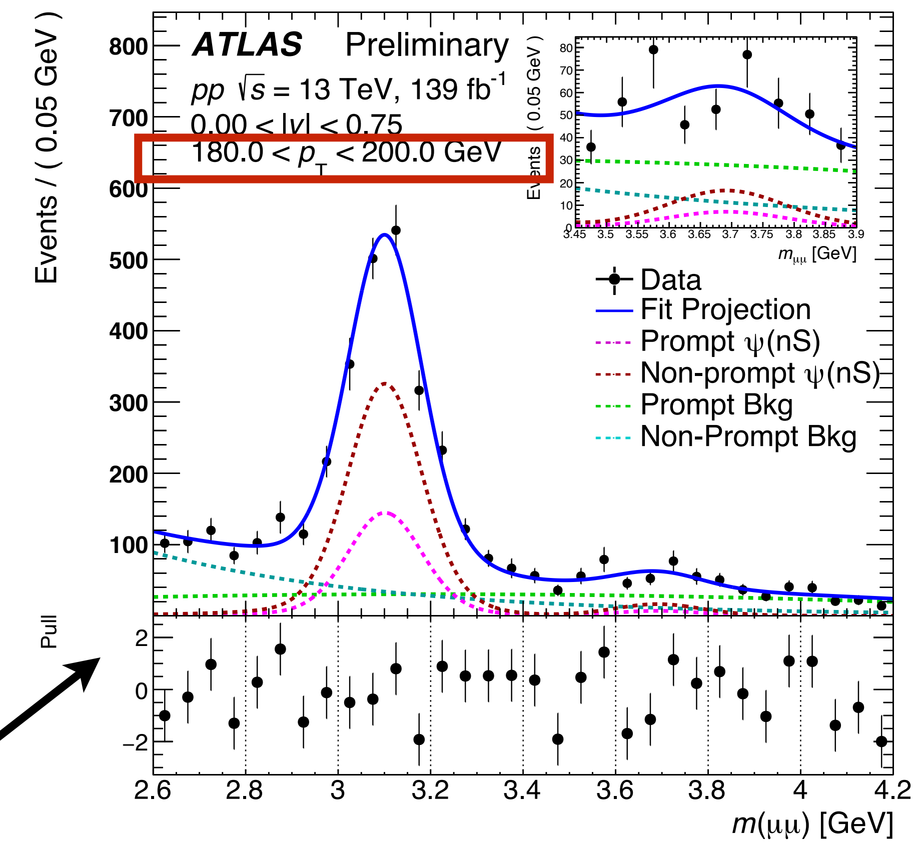
[ATL-COM-DAQ-2019-040]

- resolution in $m_{\mu\mu}$: ~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)

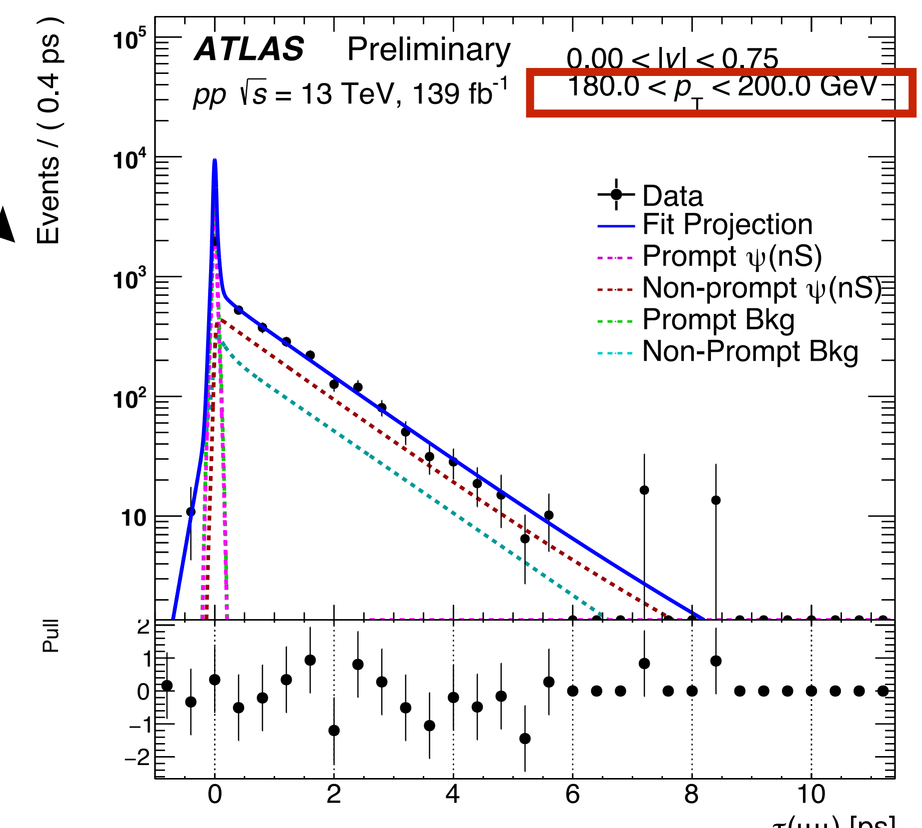
  [* from proper decay time measurements of b-hadrons]

J/ψ and ψ(2S) production at high p_T

- studies of heavy quarkonia provide insight into QCD near boundary of perturbative and non-perturbative regimes
- inclusive cross section 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)



- 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
- measure double differential J/ψ and ψ(2S) cross-sections for prompt and non-prompt production



	p_T range, GeV	y range
J/ψ	$60<p_T<360$	$\lvert y\rvert<2$
ψ(2S)	$60<p_T<140$	$\lvert y\rvert<2$

[ATLAS-CONF-2019-047]

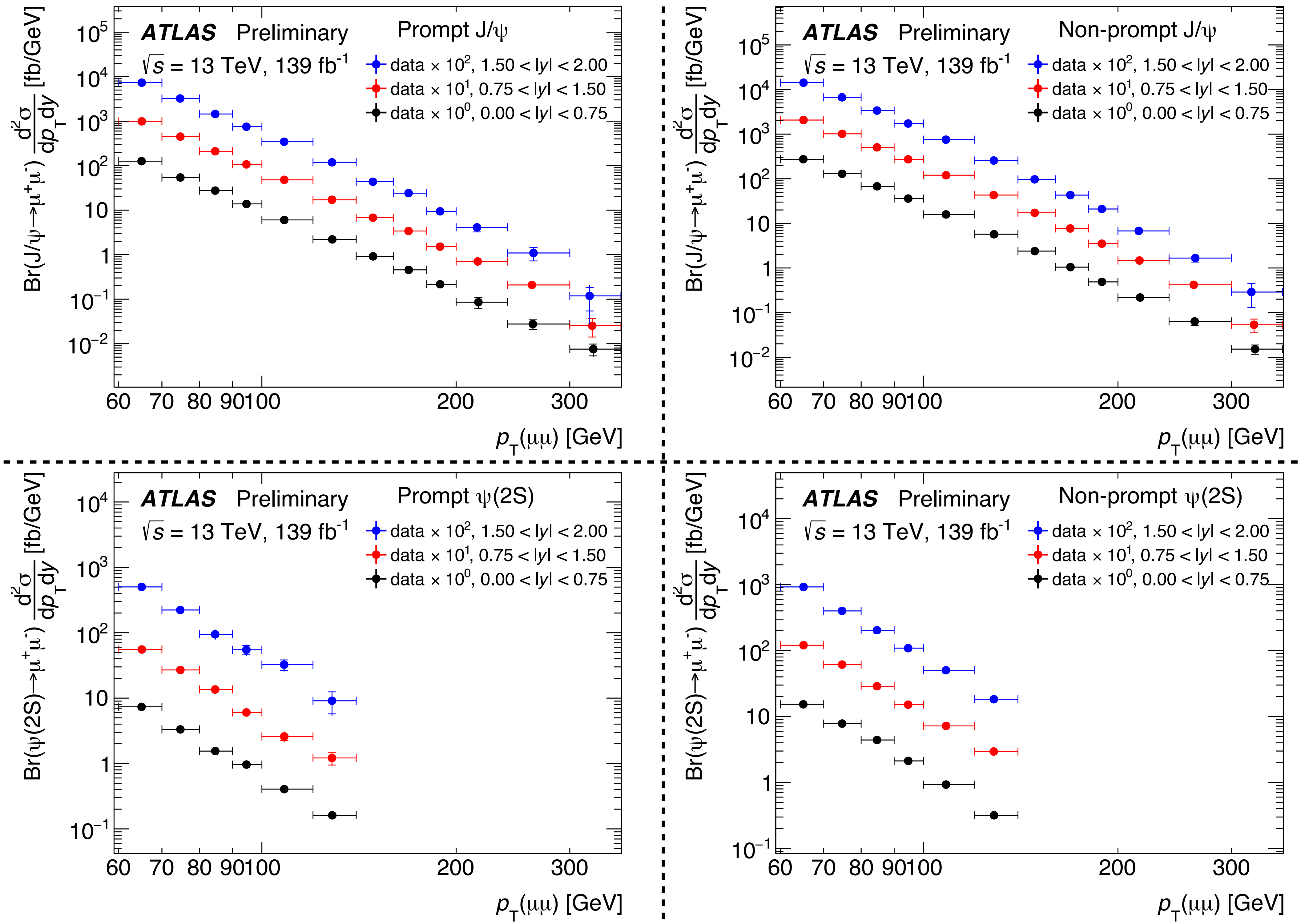
J/ψ and ψ(2S) production at high p_T

[ATLAS-CONF-2019-047]

Prompt | Non-prompt

J/ψ

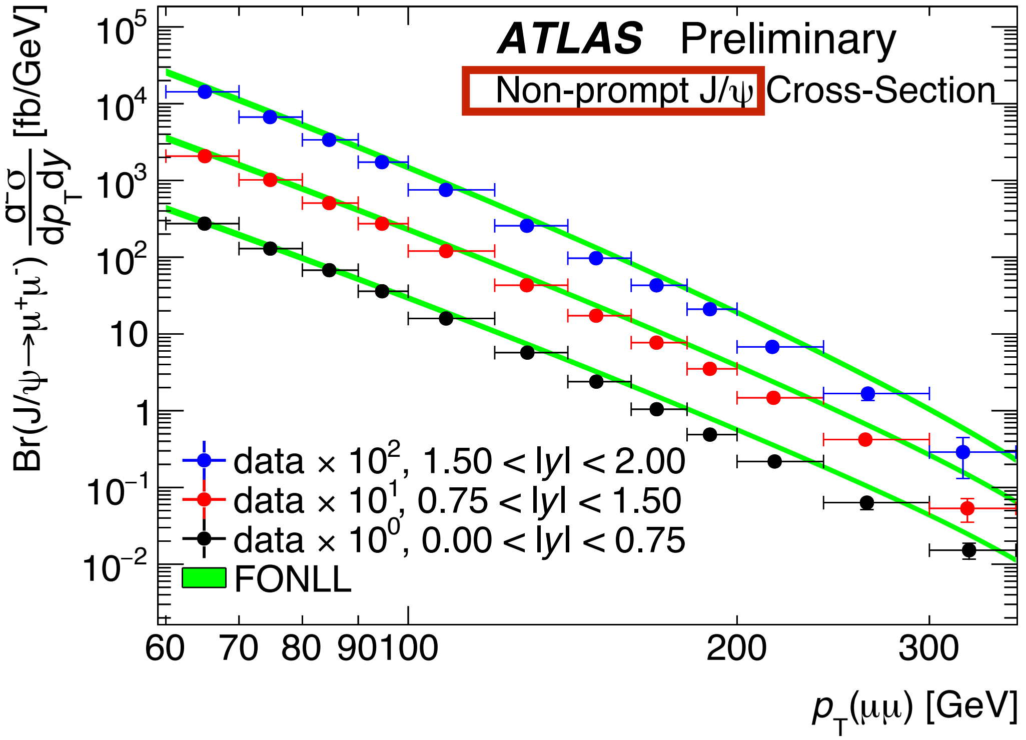
ψ(2S)



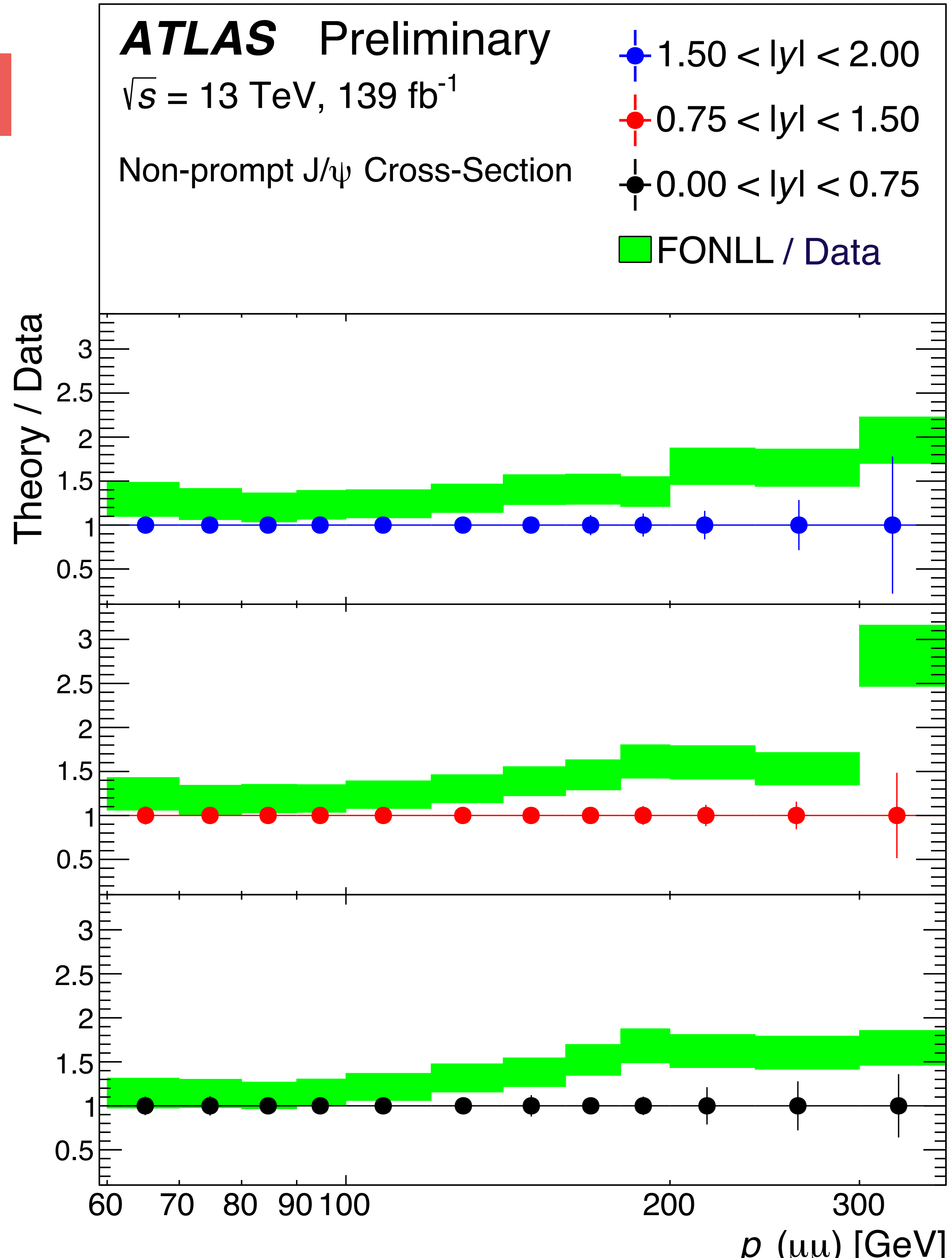
[x1, x10 and x100 scaling applied to different rapidity ranges for visual clarity]

J/ψ and ψ(2S) production at high p_T

[ATLAS-CONF-2019-047]



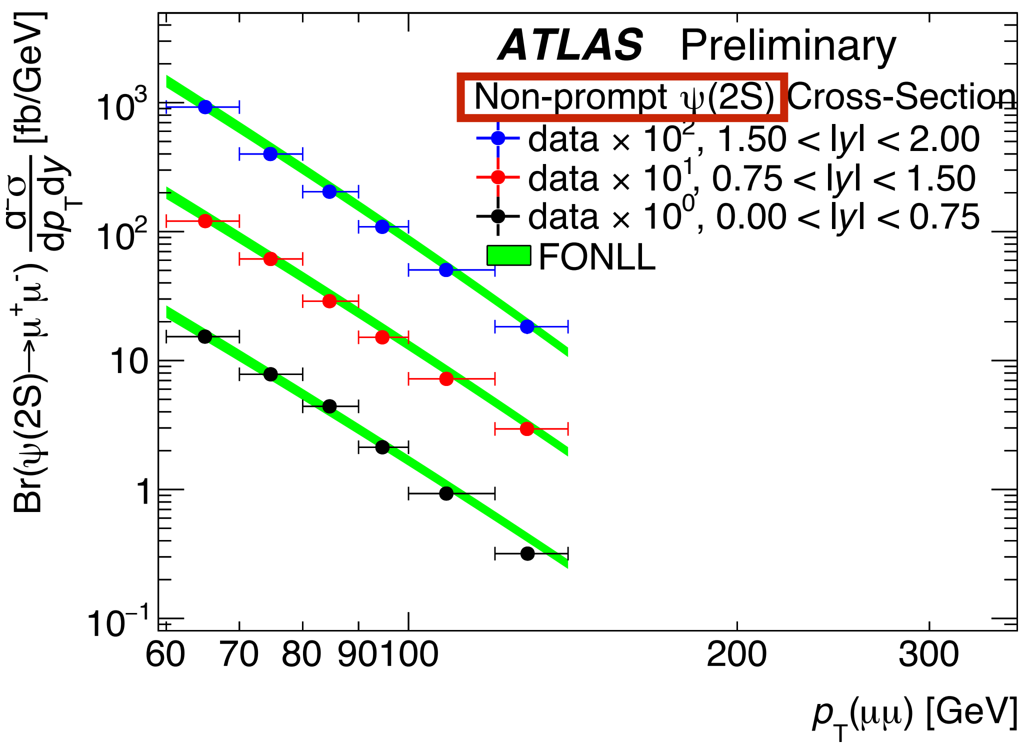
J/ψ



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

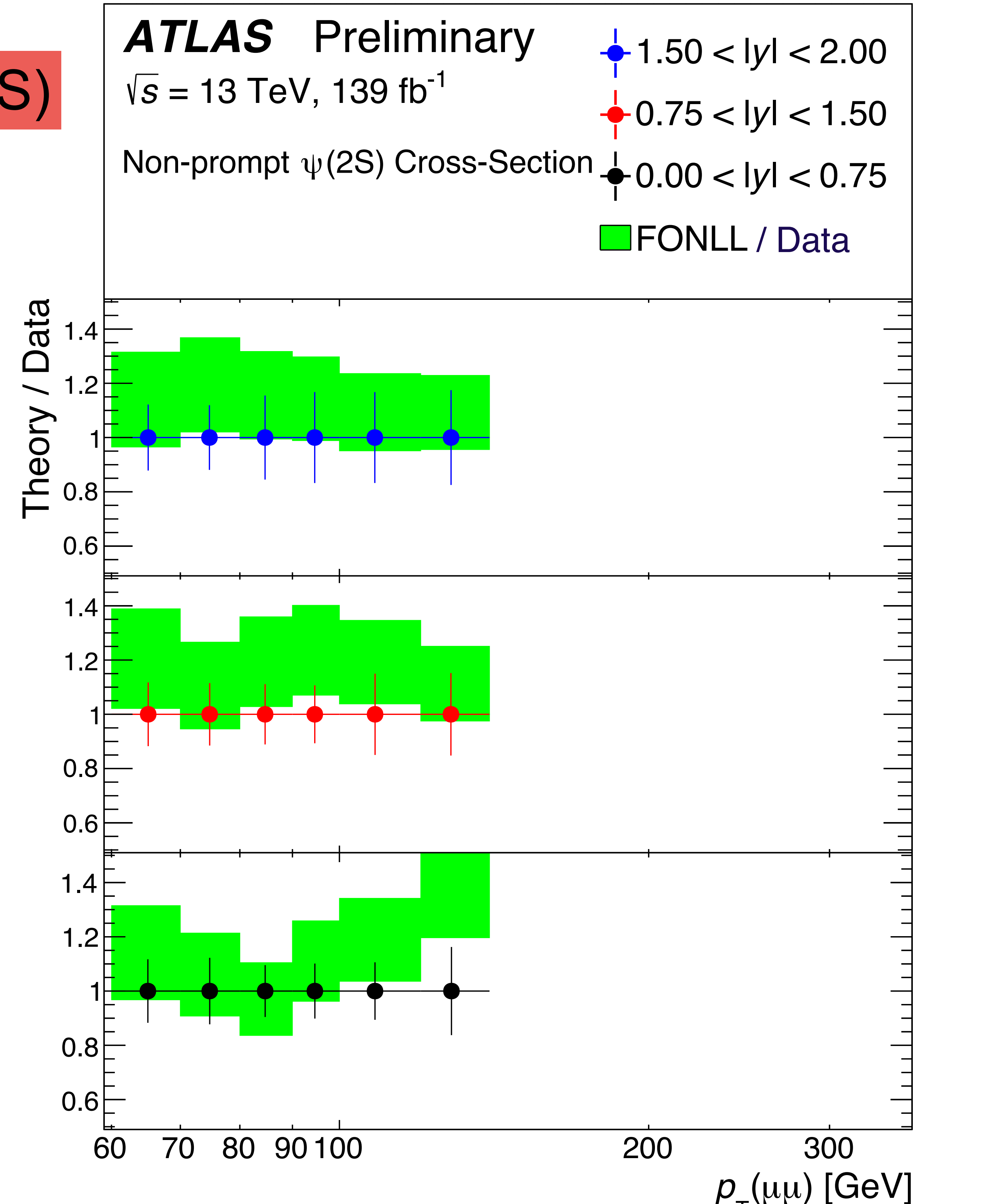
*FONLL Heavy Quark Production Matteo Cacciari, http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html, accessed: 2019-09-03

J/ψ and ψ(2S) production at high p_T



ψ(2S)

[ATLAS-CONF-2019-047]

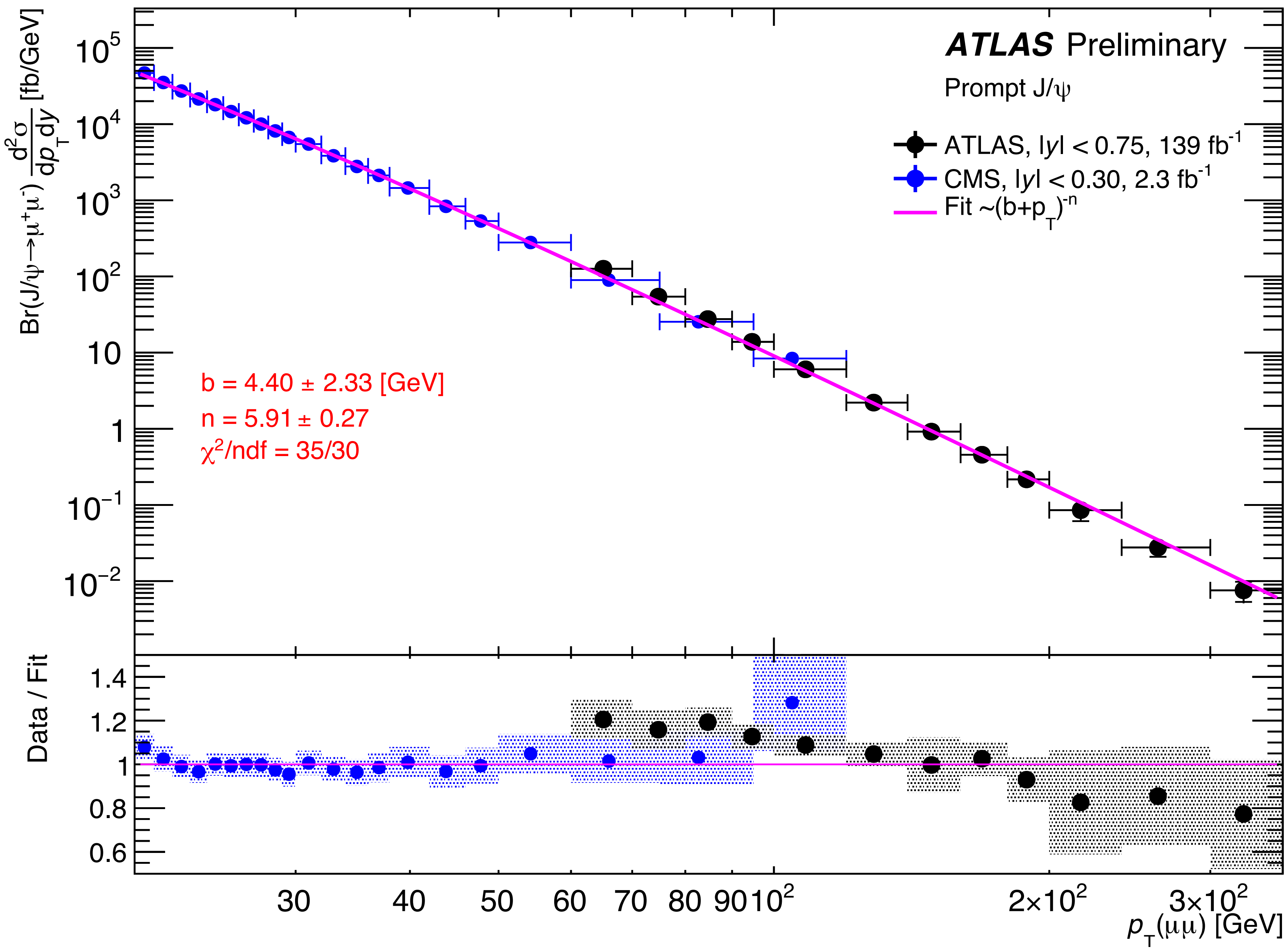


- comparison to FONLL prediction*
- good agreement though somewhat higher cross-sections are predicted

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

[ATLAS-CONF-2019-047]

J/ψ and ψ(2S) production at high p_T



[ATLAS-CONF-2019-047]
[CMS: PLB 780 (2018) 251]

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

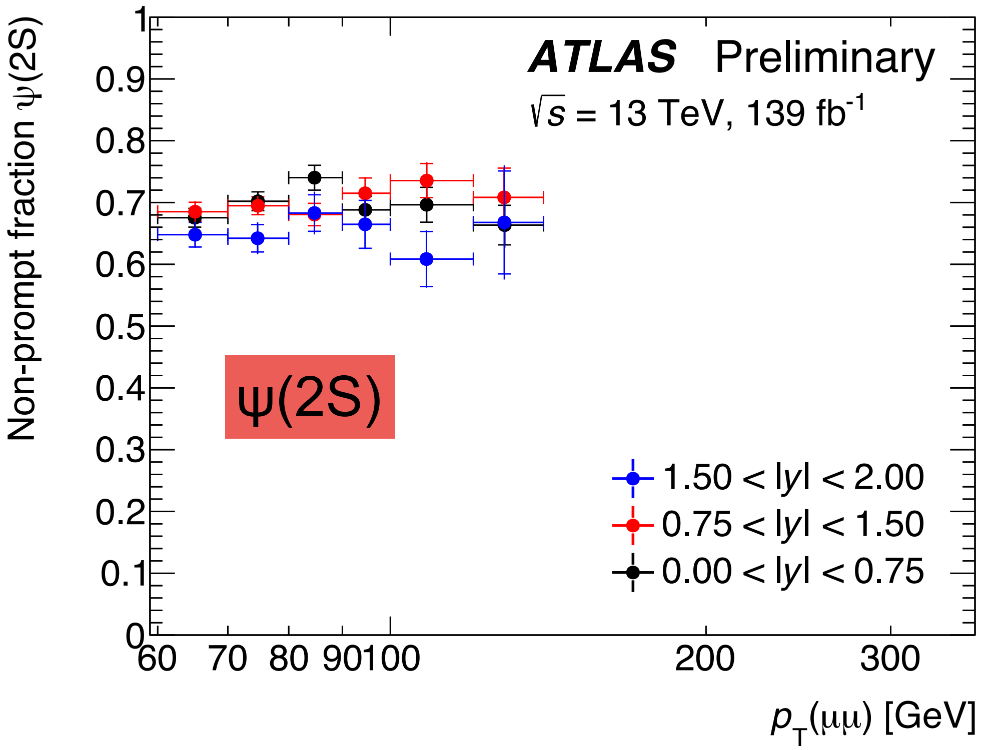
J/ψ and ψ(2S) production at high p_T

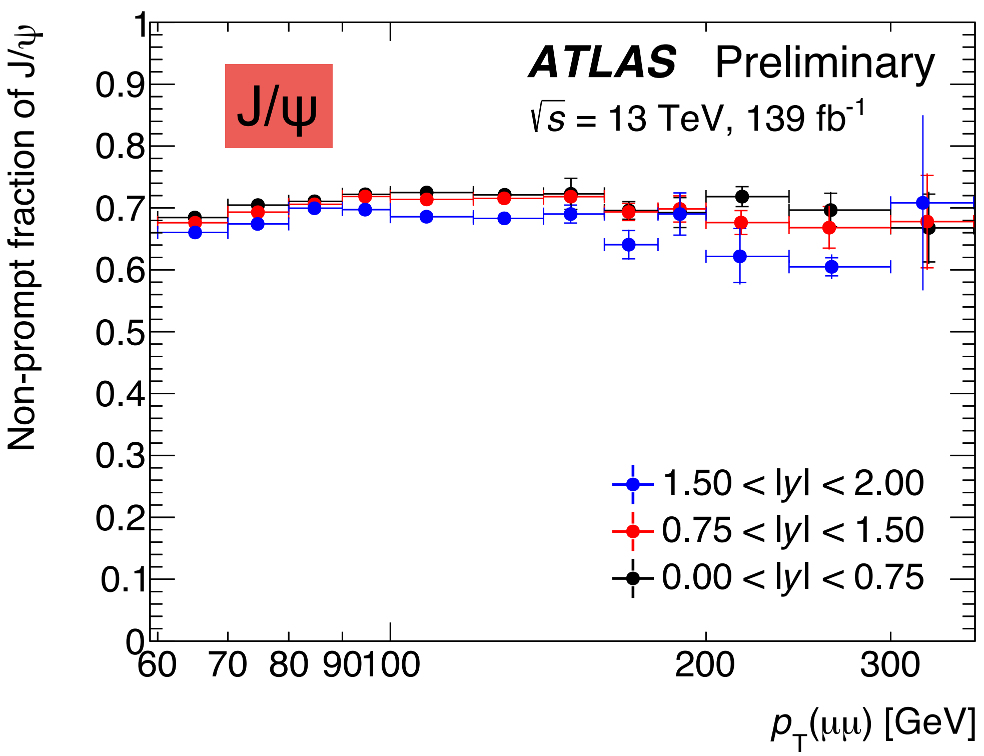
[ATLAS-CONF-2019-047]

- non-prompt production fractions:

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

- plateau at ~ 70%





J/ψ and ψ(2S) production at high p_T

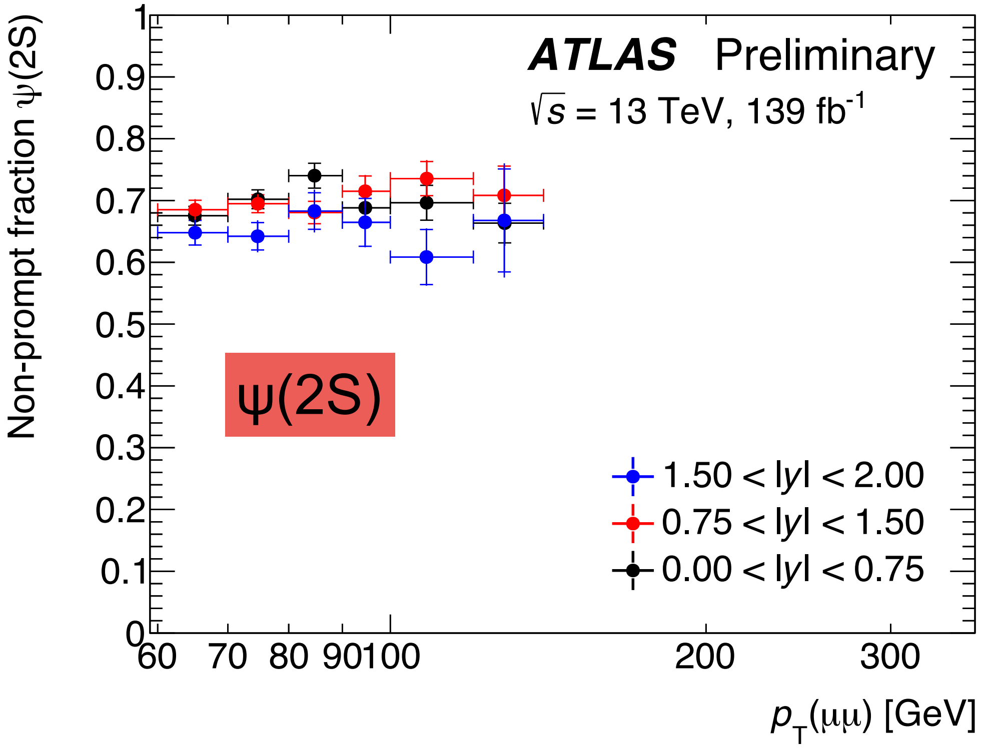
[ATLAS-CONF-2019-047]

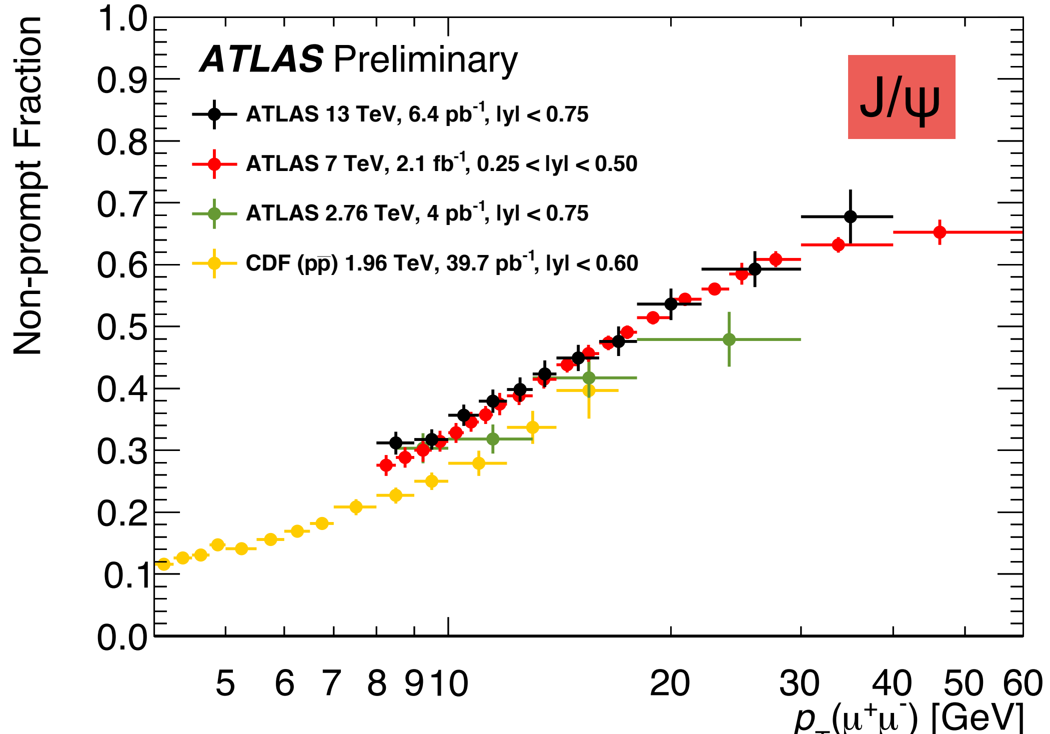
- non-prompt production fractions:

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

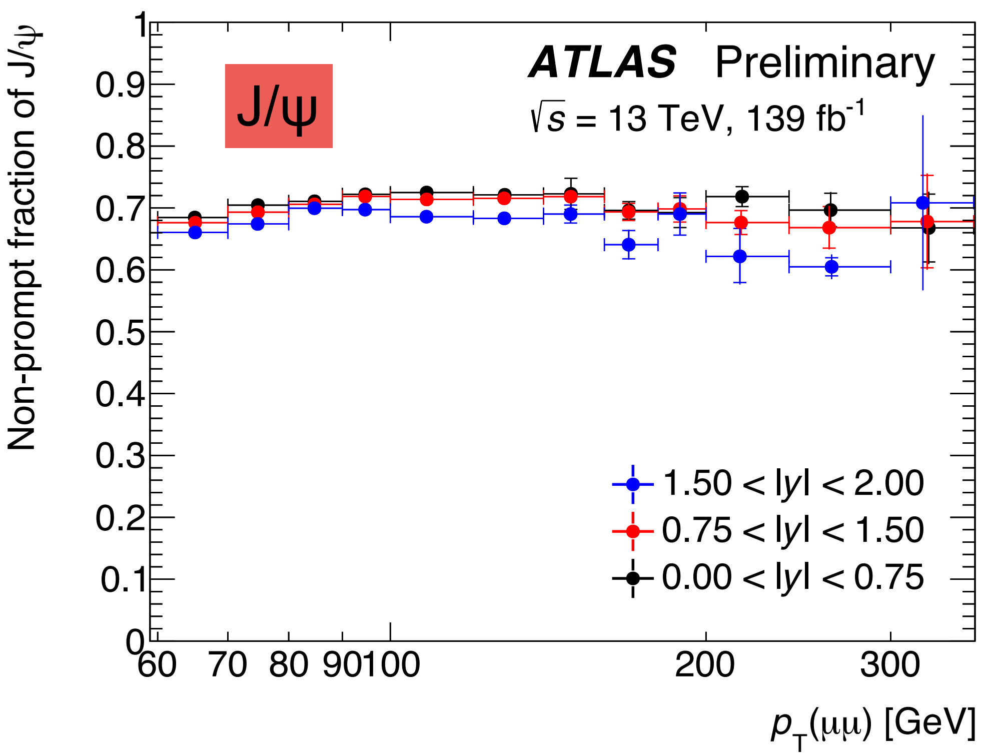
- plateau at ~ 70%

- complements previous measurements at low p_T:





[ATLAS-CONF-2015-030]



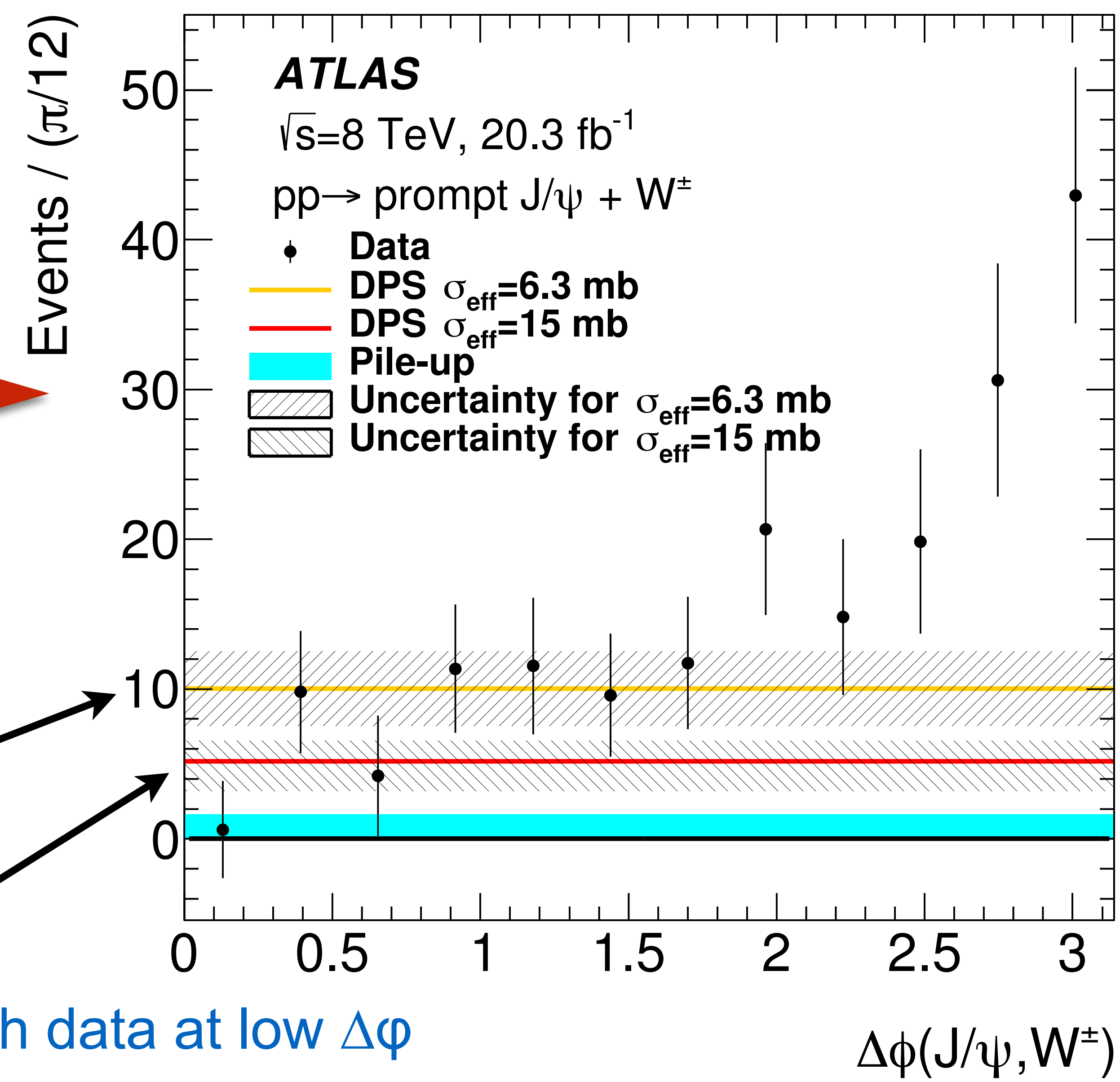
J/ψ production associated with $W^\pm$

[JHEP 01 (2020) 095]

- understand charmonium production mechanism in hadronic collisions
  - 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 $W^\pm$
      - expect DPS to be flat, SPS to peak at Δφ ~ π

- prompt-J/ψ signal 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:
  - $\sigma_{eff} = 6.3 \pm 1.6_{stat} \pm 1.0_{syst}$ mb from prompt J/ψ pair production
  - $\sigma_{eff} = 15 \pm 3_{stat}\,^{+5}_{-3}\,_{syst}$ mb from $W^\pm$ + 2jets

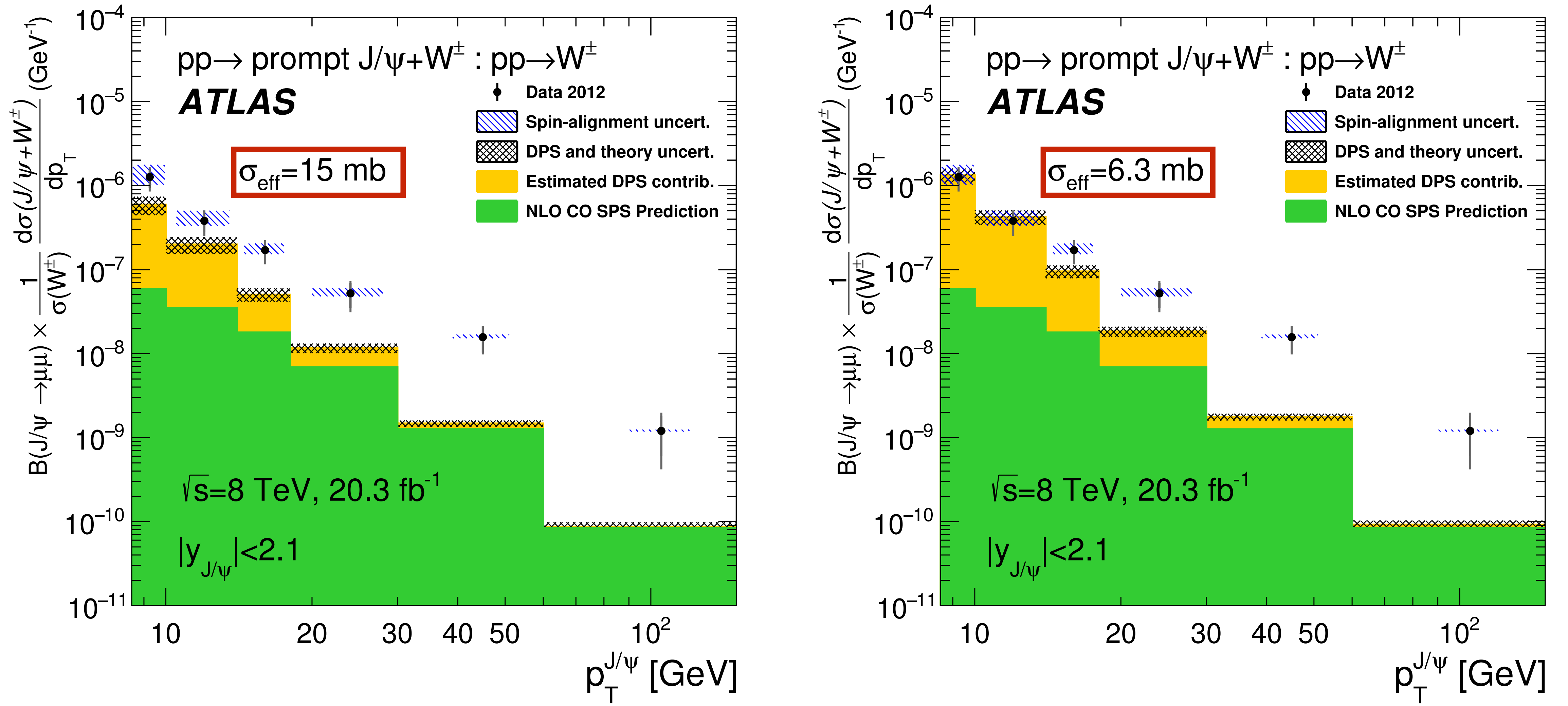
→ both values consistent with data at low Δφ



J/ψ production associated with W±

[JHEP 01 (2020) 095]

- differential inclusive cross-section in 6 p_T bins in the range: $8.5 < p_T < 150$ GeV
- 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
- possibly because CS model is not included

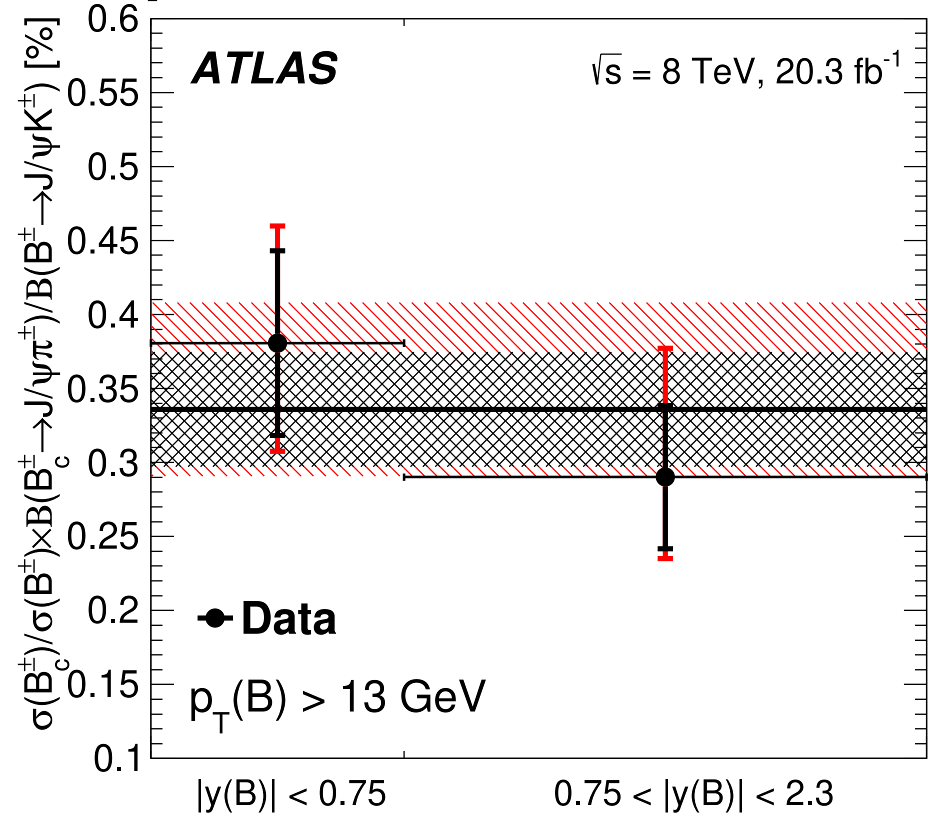
$B^\pm_c$ / $B^\pm$ production cross-section

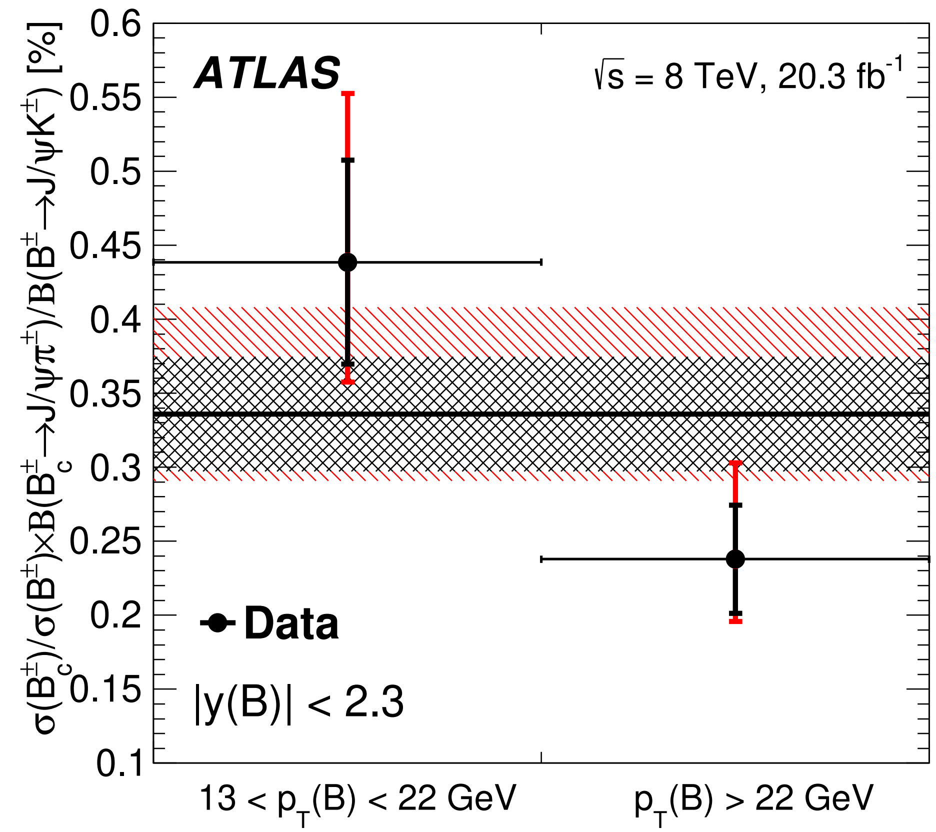
- unique probe for heavy quark dynamics
- use similar decay mode for $B^\pm_c$ and $B^\pm$:

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

- fiducial volume: p_T >13 GeV, |y|<2.3
- N($B^\pm_c$) ~ 800, N($B^\pm$) ~ 400k
- double differential measurement in 2 bins of *y* and p_T
- production ratio in fiducial region (horizontal line):
  - $(0.34 \pm 0.04_{\mathrm{stat}} \pm {}^{+0.06}_{-0.02\,\mathrm{syst}} \pm 0.01_{\mathrm{lifetime}})\%$
  - update w.r.t. preliminary result - additional systematic studies performed
  - complements CMS and LHCb results
- no evident rapidity dependence (upper plot)
- $B^\pm_c$ cross-section decreases faster with p_T than $B^\pm$ cross-section (lower plot)

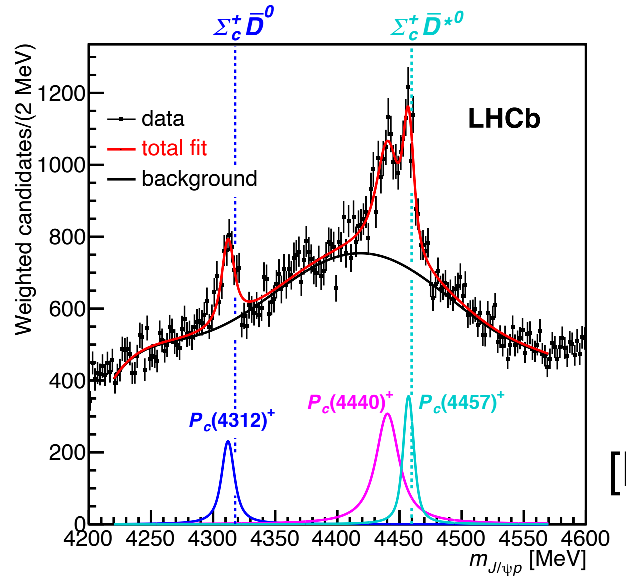
[arXiv:1912.02672, submitted to PRD]





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

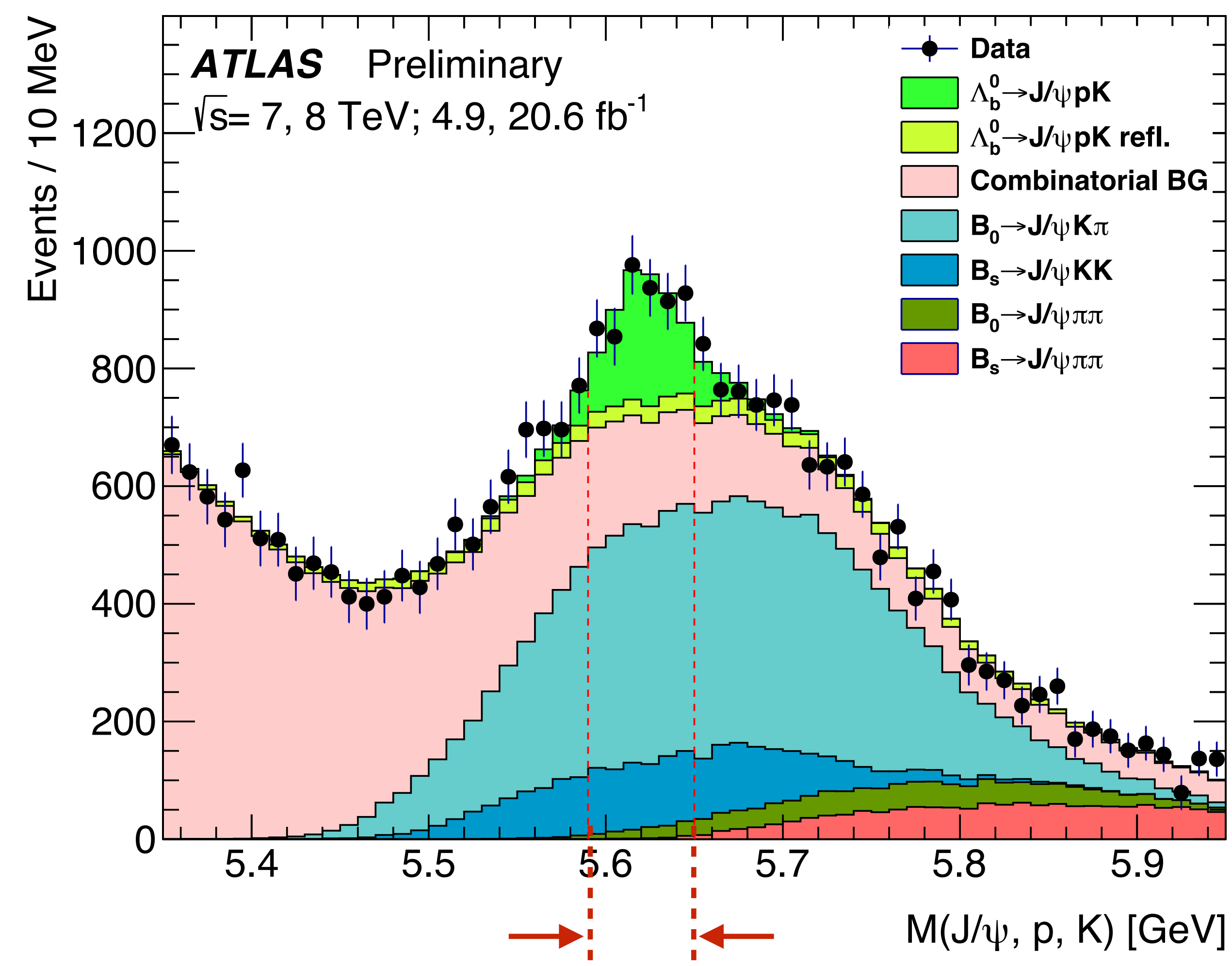
[ATLAS-CONF-2019-048]



[PRL 122 (2019)]

- in total 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 $H_b \rightarrow J/\psi h_1 h_2$ ($h_{1,2}$ = 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

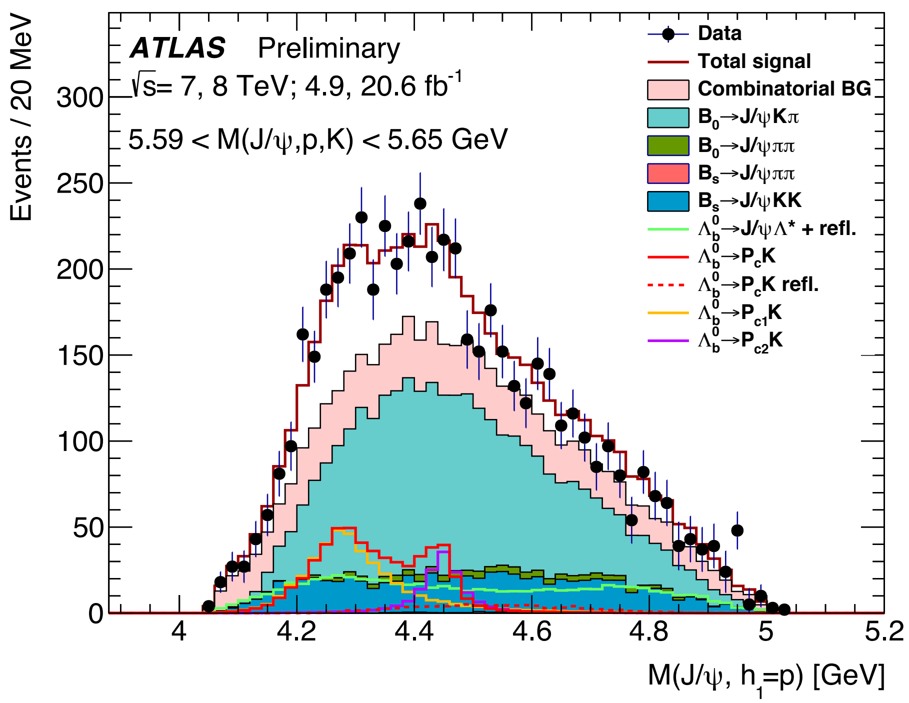


signal region: (5.59, 5.65) GeV

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

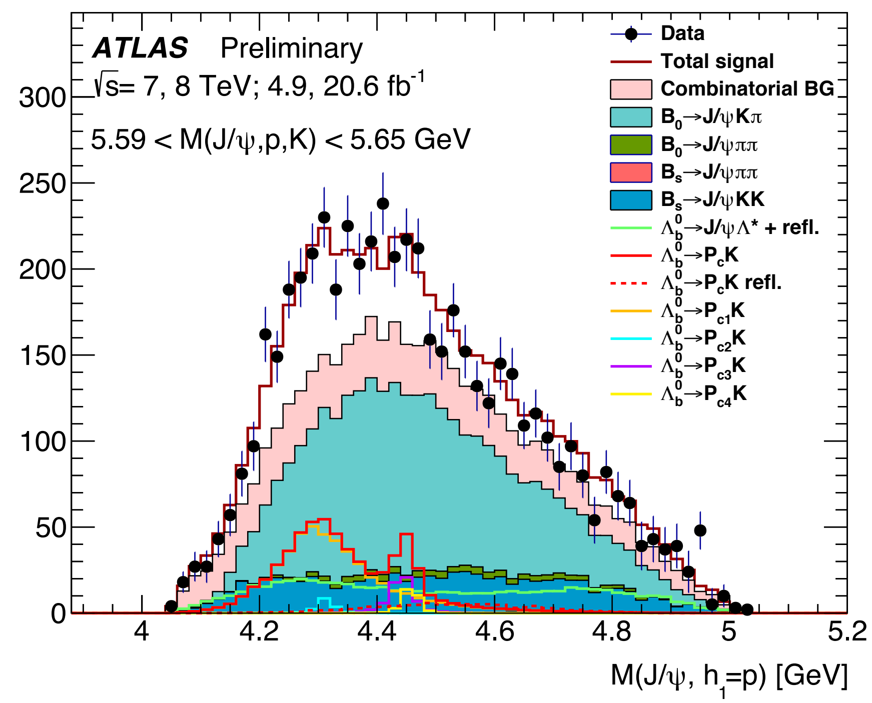
[ATLAS-CONF-2019-048]

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



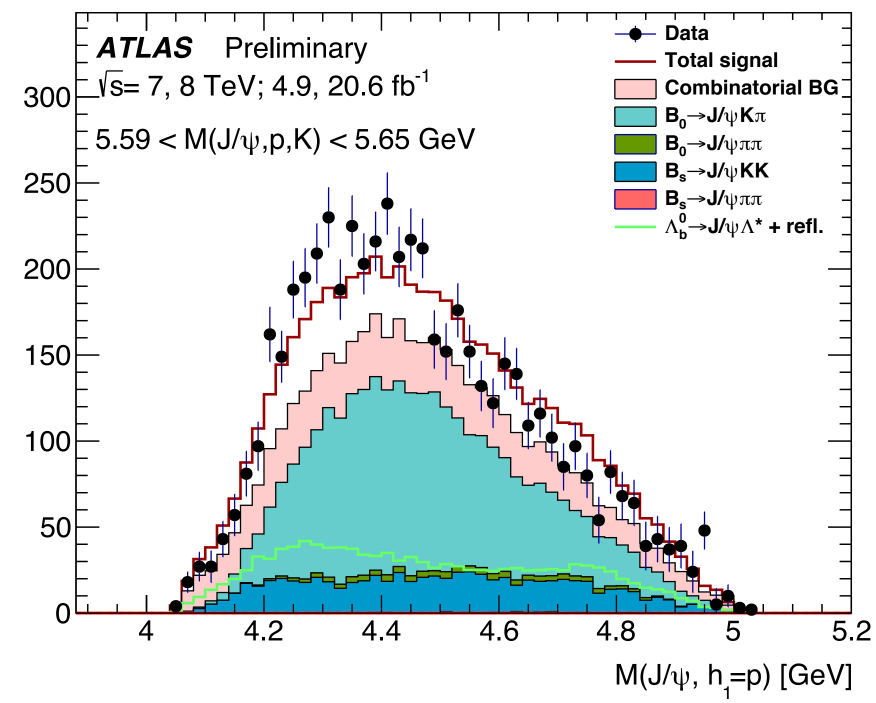
χ^2/n.d.f = 37.1/39

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

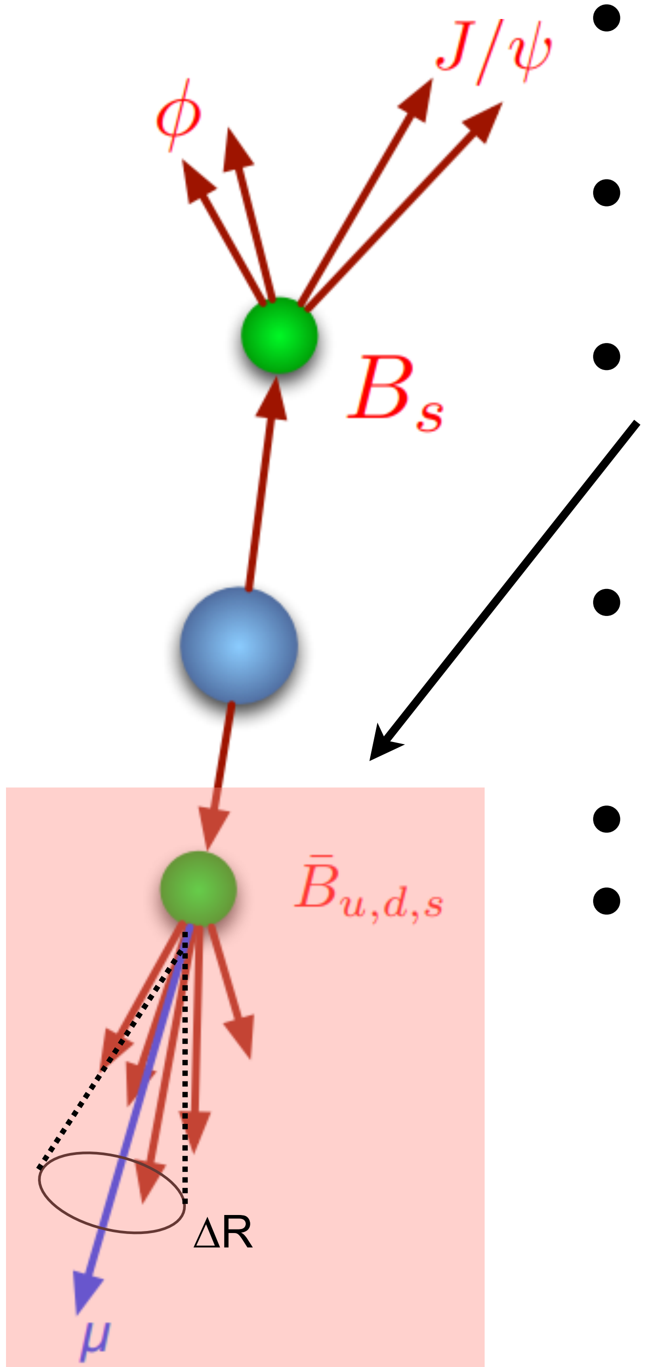
fit without pentaquarks



χ^2/n.d.f = 69.2/37

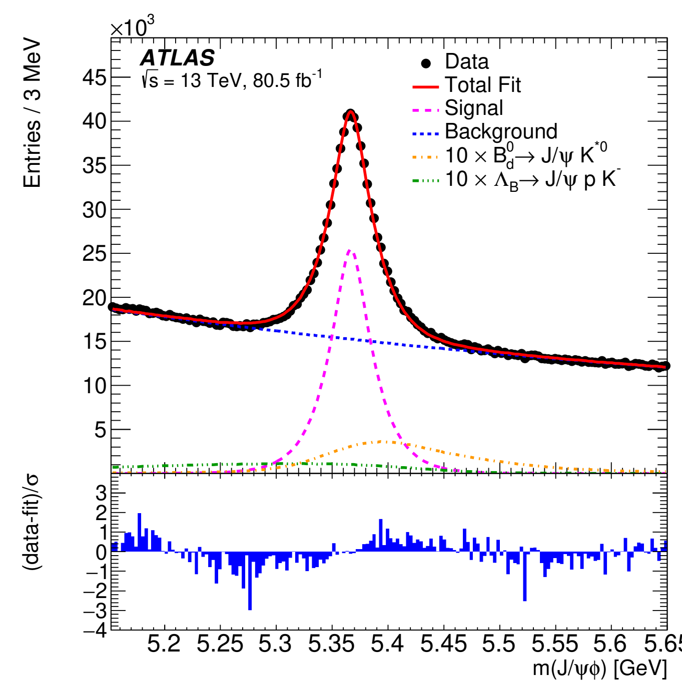
- hypotheses with 2 and 4 pentaquarks consistent with data
- hypothesis without pentaquarks cannot be excluded

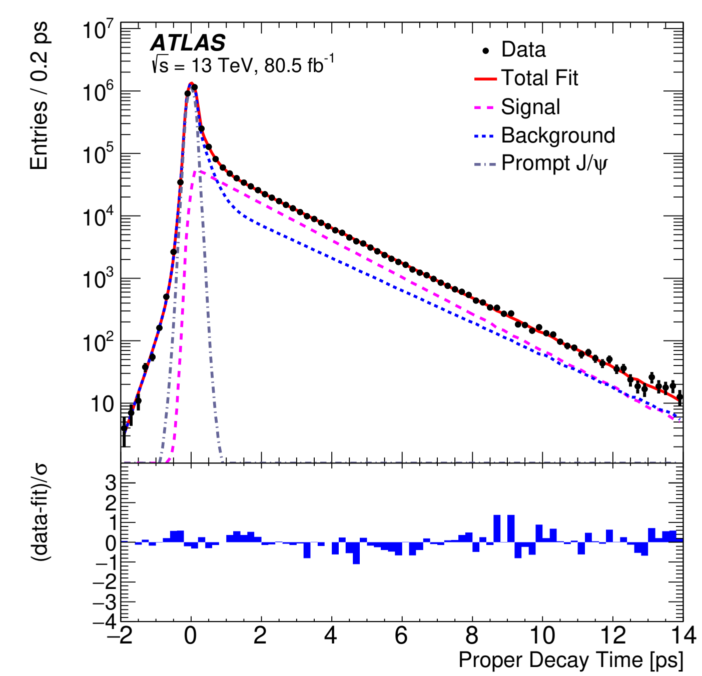
CP-Violation in $B^0_s \to J/\psi\phi \to \mu^+\mu^-K^+K^-$



- measure CP-violating phase ϕ_s sensitive to New Physics processes
- in SM, ϕ_s is related to the CKM matrix elements:
  - $\phi_s \approx -2\beta_s = -2\arg[-V_{ts}V^*_{tb}/V_{cs}V^*_{cb}] = -0.03696^{+0.00072}_{-0.00082}$ rad [CKMfitter]
- other $\bar{B}^0_s$-B^0_s mixing quantities: width difference between B^0_s 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 $\bar{b}$ 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
  - distinguishable 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





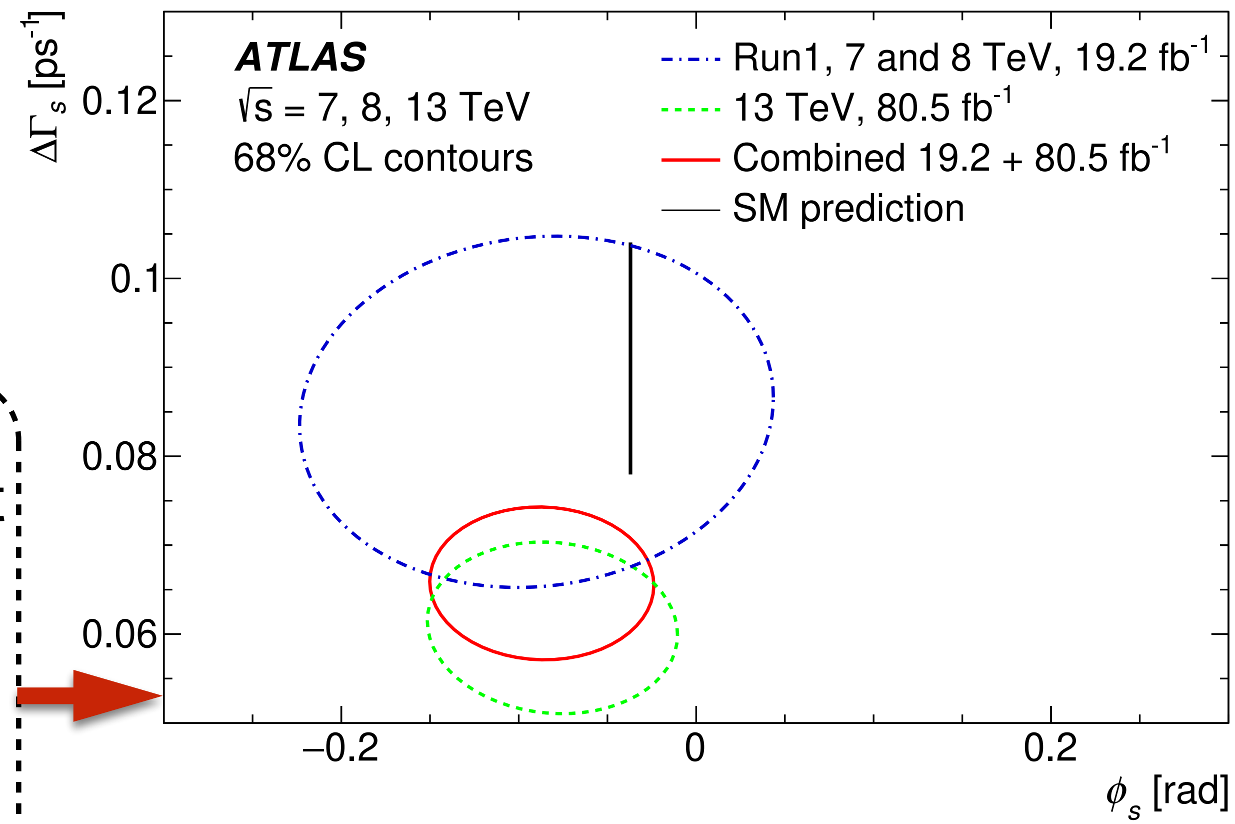
[arXiv:2001.07115, accepted by EPJC]

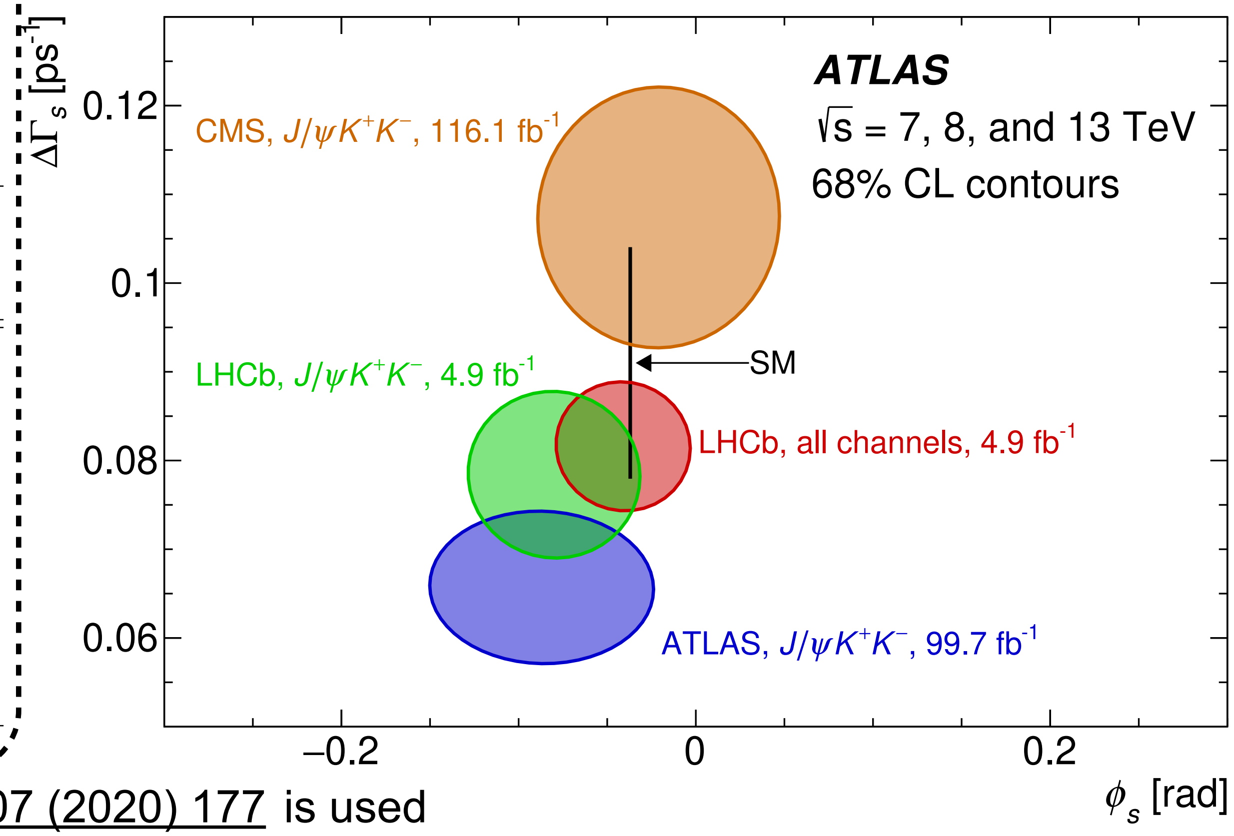
CP-Violation in $B^0_s \to J/\psi\phi \to \mu^+\mu^-K^+K^-$

[arXiv:2001.07115, accepted by EPJC]

- LH fit returned two well-separated solutions for strong phases $\delta_{\|}$ and $\delta_{\perp}$ of CP-even and CP-odd final state configurations
  - difference in LH maxima is small → minor impact on parameter values
- NEW w.r.t. preliminary result: additional systematic studies performed and included to fit
  - affected $\sigma_{syst}(\Delta\Gamma_s)$
- combination with previous Run 1 result updated
  - made separately for both solutions
- ϕ_s and $\Delta\Gamma_s$ results consistent with updated SM(*)
- ~ 3σ tension in Γ_s with current world average [PDG2020]

Parameter	Solution (a) Value	Solution (a) Statistical uncertainty	Solution (a) Systematic uncertainty	Solution (b) Value	Solution (b) Statistical uncertainty	Solution (b) Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018	0.6704	0.0014	0.0018
$\|A_{\|}(0)\|^2$	0.2220	0.0017	0.0021	0.2218	0.0017	0.0021
$\|A_0(0)\|^2$	0.5152	0.0012	0.0034	0.5152	0.0012	0.0034
$\|A_S\|^2$	0.0343	0.0031	0.0045	0.0348	0.0031	0.0045
$\delta_{\perp}$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_{\|}$ [rad]	3.36	0.05	0.09	2.95	0.05	0.09
$\delta_{\perp} - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04





(*) for $\Delta\Gamma_s$ prediction from A. Lenz and G. Tetlalmatzi-Xolocotzi, JHEP 07 (2020) 177 is used

Summary

- ATLAS has a rich B-Physics program
- selection of results has been presented:
  - J/ψ and $\psi(2S)$ production at high p_T
  - J/ψ + W associated production
  - $B^{\pm}_{c}$ / $B^{\pm}$ production cross-section
  - Pentaquark search
  - CP-Violation
- statistical precision of many analyses can still be improved (data available)
- more analyses in the pipeline
- stay tuned for the new results!

BACKUP

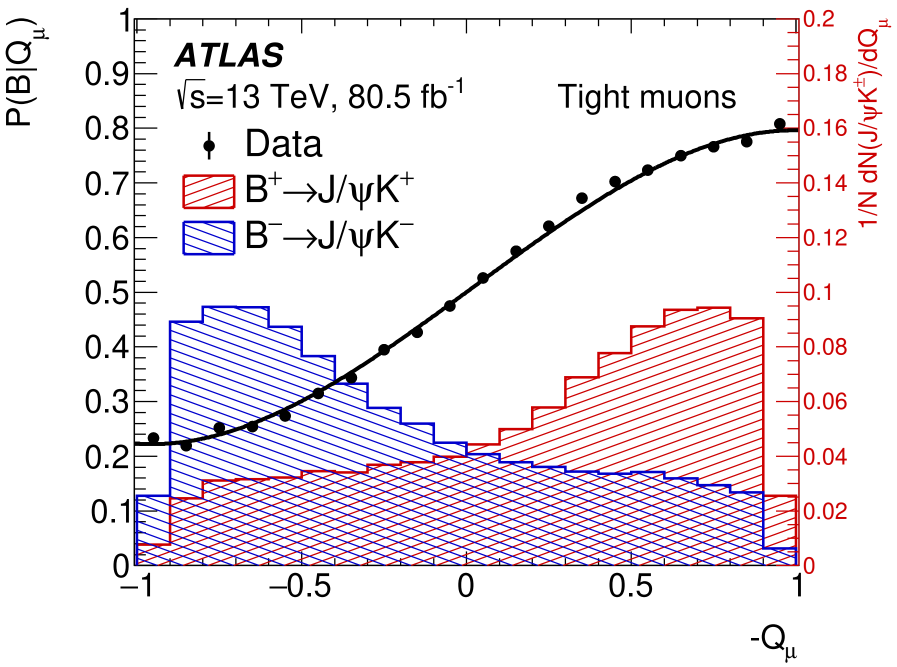
CP-Violation in $B^0_s \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$

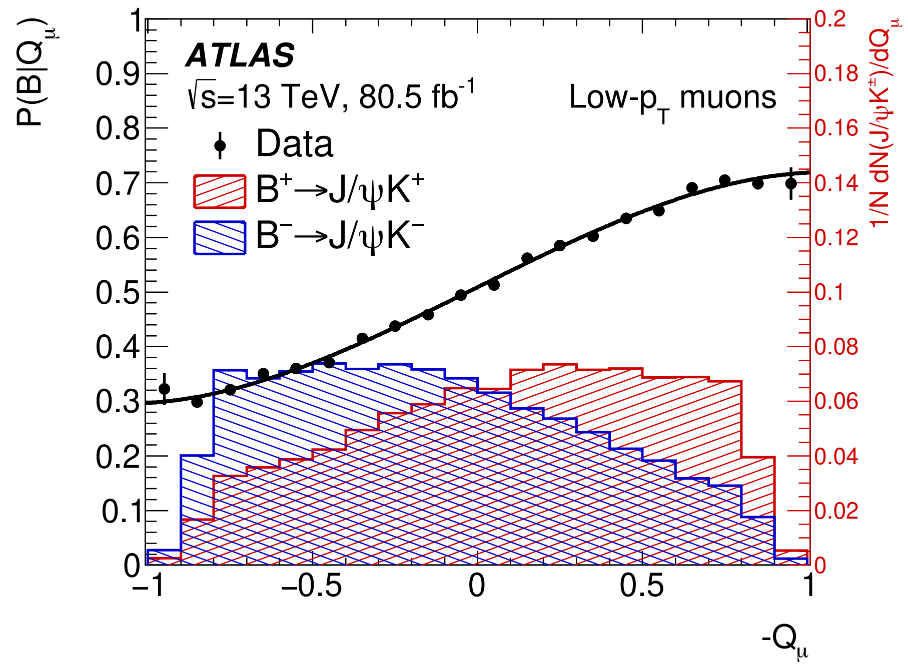
[arXiv:2001.07115, accepted by EPJC]

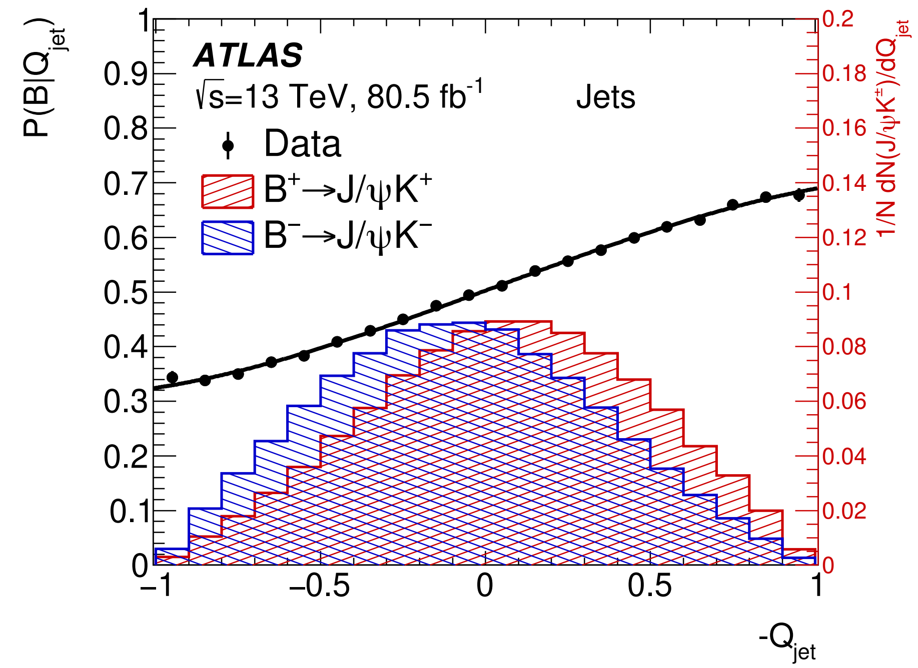
	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\|A_{\|\|}(0)\|^2$ [10^{-3}]	$\|A_0(0)\|^2$ [10^{-3}]	$\|A_S(0)\|^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_{\|\|}$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Acceptance	0.5	0.3	< 0.1	1.0	0.9	2.9	37	64	8.6
Time efficiency	0.2	0.2	0.5	< 0.1	< 0.1	0.1	3.0	5.7	0.5
Best candidate selection	0.4	1.6	1.3	0.1	1.0	0.5	2.3	7.0	7.4
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_T bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass window	9.3	3.3	< 0.1	0.4	0.8	0.4	17	8.6	1.8
Choice of sidebands intervals	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B^0_d	2.6	1.1	< 0.1	0.2	3.1	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Alternate Δm_s	1.0	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	15	4.0	< 0.1
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_T bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.3	< 0.1	< 0.1	< 0.1	< 0.1	0.2	8.0	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	22	4.3	2.2	2.3	3.8	4.6	55	88	39

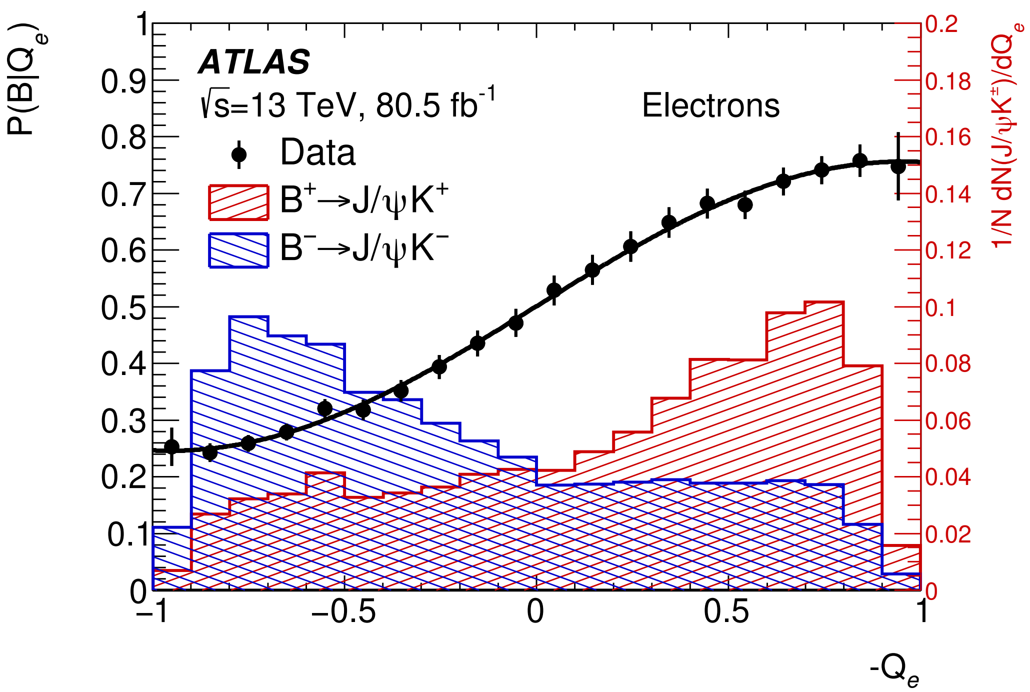
CP-Violation in $B^0_s \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$

[arXiv:2001.07115, accepted by EPJC]







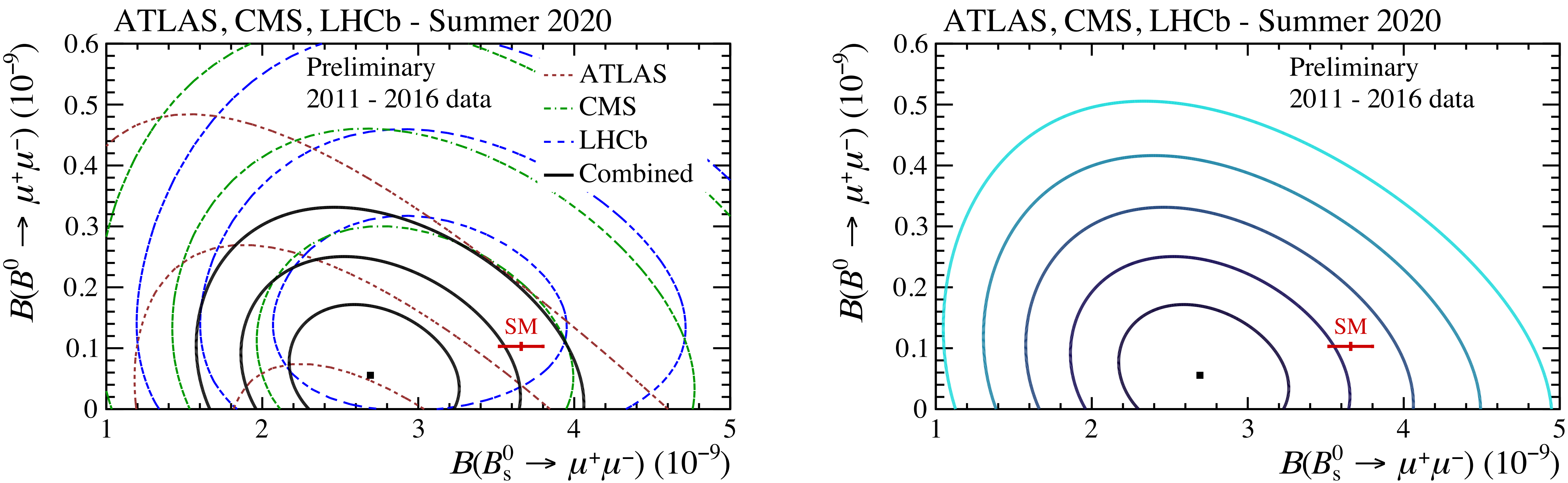


Tag method	ϵ_x [%]	D_x [%]	T_x [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

$B^0_{(s)} \to \mu^+\mu^-$ LHC Combination 2011-2016

[CMS-PAS-BPH-20-003 ; LHCb-CONF-2020-002 ; ATLAS-CONF-2020-049]

- data collected by each LHC experiment during LHC Run 1 (2011-2012) and first part of LHC Run 2 (2015-2016)
- using the binned two-dimensional profile likelihoods obtained by each experiment
  - fitted by analytical function (variable-width Gaussian) and summed up



ATLAS, CMS, LHCb and combination: likelihood contours correspond to the values of -2ΔlnL = 2.3, 6.2, 11.8

Combination: likelihood contours correspond to the values of -2ΔlnL = 2.3, 6.2, 11.8, 19.3, and 30.2

- $BR(B^0_s \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35})\text{x}10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) < 1.9\ \text{x}10^{-10}$ at 95% CL
- compatible with SM at ~2.1σ