Recent results from ATLAS in beauty and charm physics

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On behalf of the ATLAS Collaboration

Lake Louise Winter Institute
10-15 February 2020

ATLAS EXPERIMENT

UKRI Science and Technology Facilities Council

ATLAS B-physics programme and trigger strategy

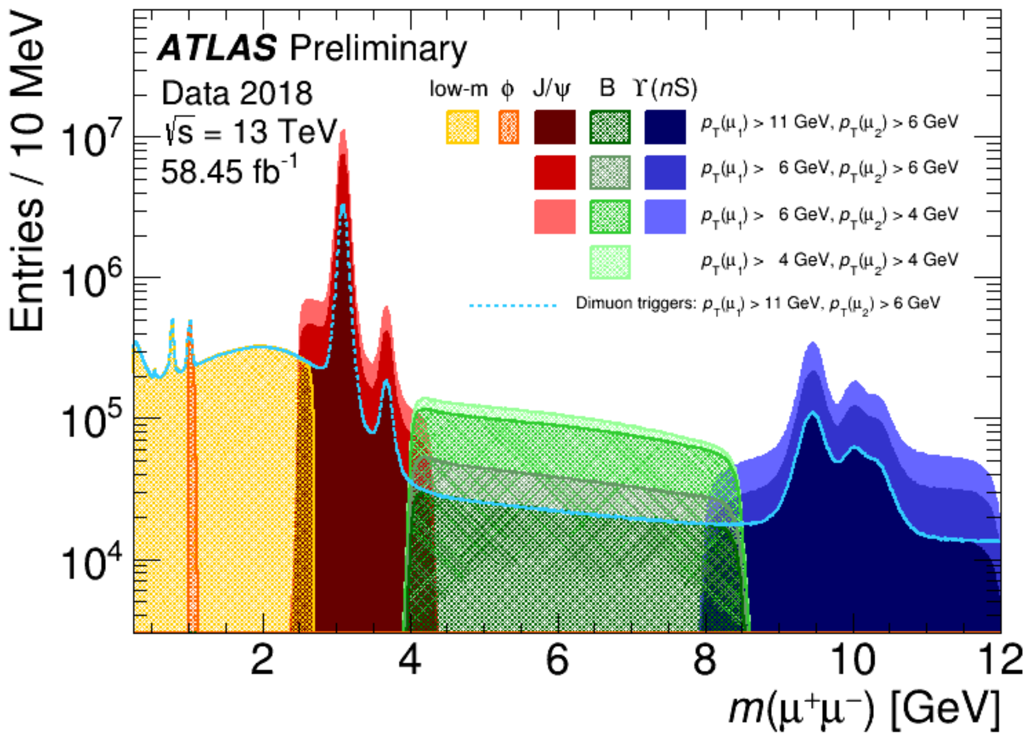
ATLAS is a general purpose detector – main focus is high-pT physics.

Still has a strong dedicated B-physics programme:

- Precise property measurements, including CPV ($B_s^0 \to J/\psi\phi$)
- Cross-section measurements, quarkonium and associated production
- Rare decay processes, e.g. $B_{s,d} \to \mu\mu, B_d^0 \to K^*\mu\mu$
- Spectroscopy, exotic states (e.g. pentaquarks)

Most analyses rely on low pT di-muon triggers:

I will concentrate on recent results



Data collected by triggers with different muon p_T thresholds and di-muon mass ranges

Quarkonium production at high p_T

ATLAS-CONF-2019-047

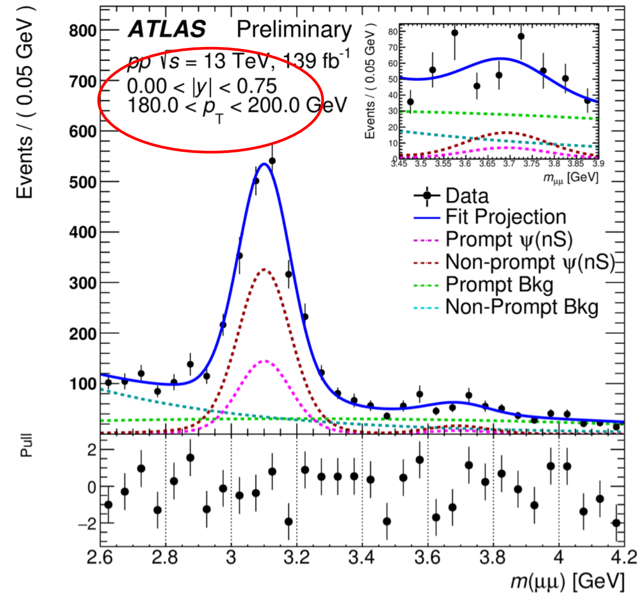
Heavy quarkonia provide insight into QCD near boundary between perturbative and non-perturbative regimes

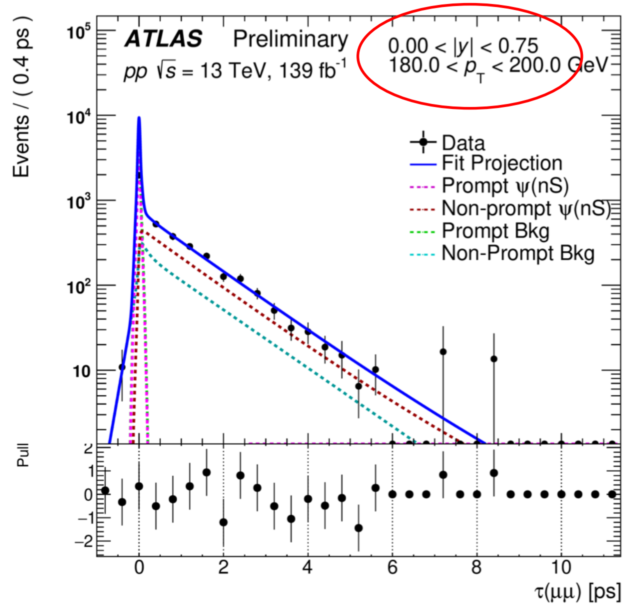
Measuring in a broader kinematical range may help differentiate between theoretical models (previous ATLAS measurement up to p_T~100 GeV)

Full Run2 data - measure double differential J/ψ and ψ(2S) cross-section for prompt and non-prompt production

Unbinned maximum likelihood fit to mass and pseudo-proper decay time, in bins of rapidity (*y*) and transverse momentum (p_T).

$$\tau = \frac{m}{p_T}\frac{L_{xy}}{c}$$





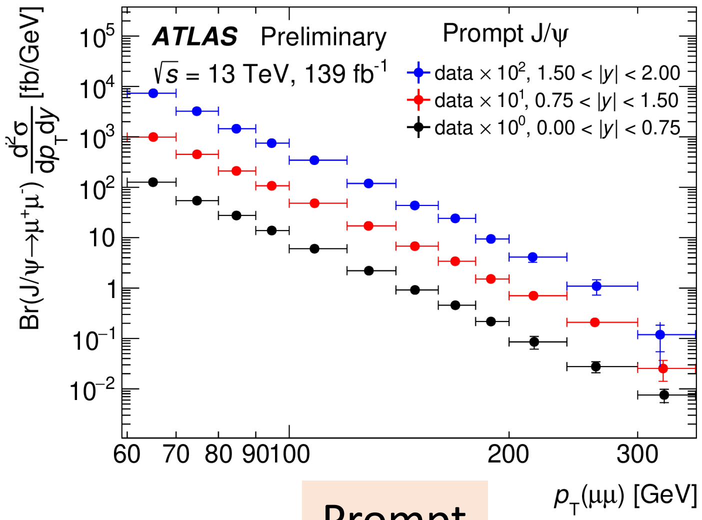
Quarkonium production at high p_T

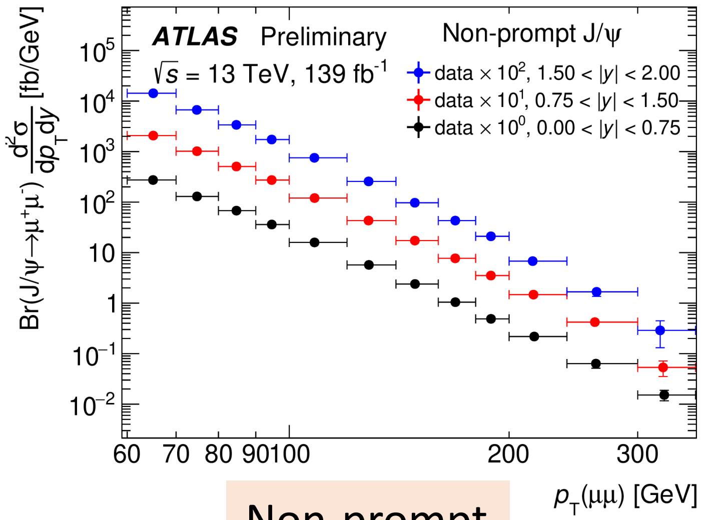
ATLAS-CONF-2019-047

Measurements of prompt and non-prompt production in the ranges:

J/ψ : 60-360 GeV
$\psi(2S)$: 60-140 GeV

Note: Scaling by 1,10,100 of different rapidity ranges for visual clarity

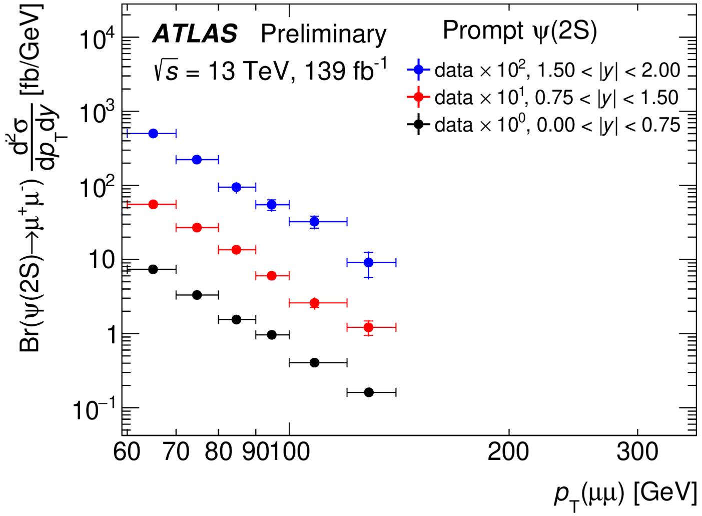




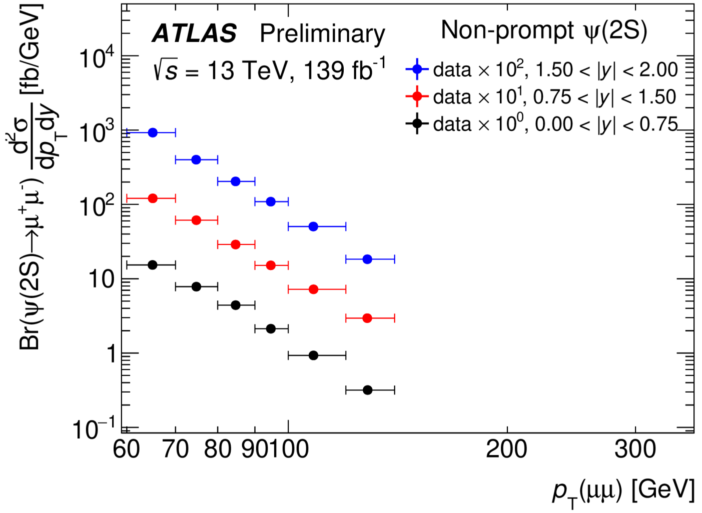
J/ψ

Prompt

Non-prompt



ψ(2S)



Quarkonium production at high p_T

ATLAS-CONF-2019-047

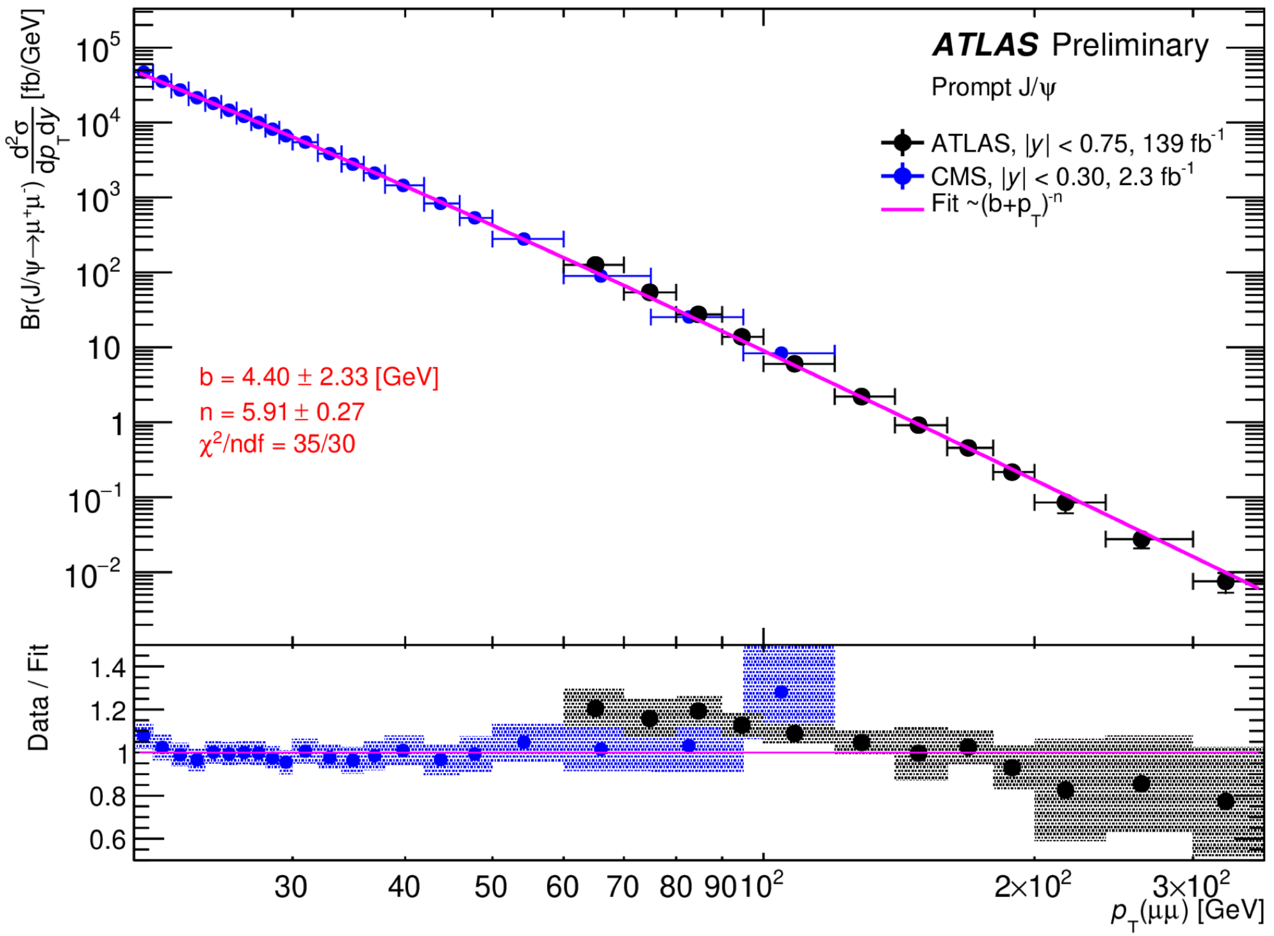
Prompt J/ψ cross-section

Fit CMS* and ATLAS results with simple parameterization

Good agreement in overlap region

(No predictions available yet)

*CMS Result: Phys Lett B 780 (2018) 251

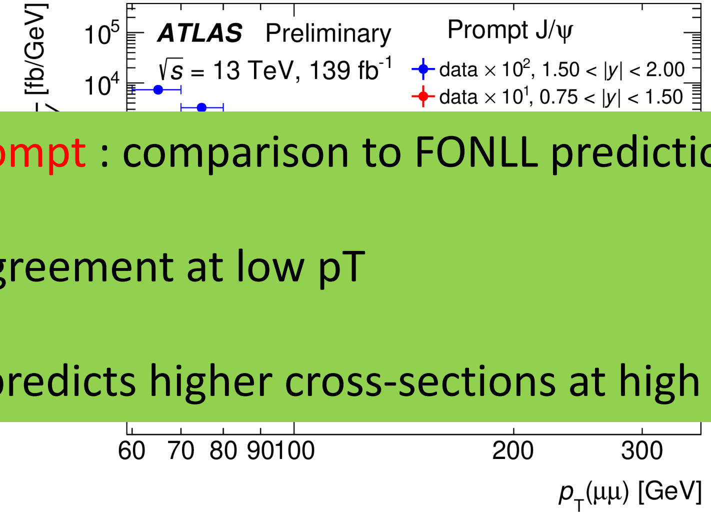


Quarkonium production at high p_T

ATLAS-CONF-2019-047

J/ψ prompt and non-prompt

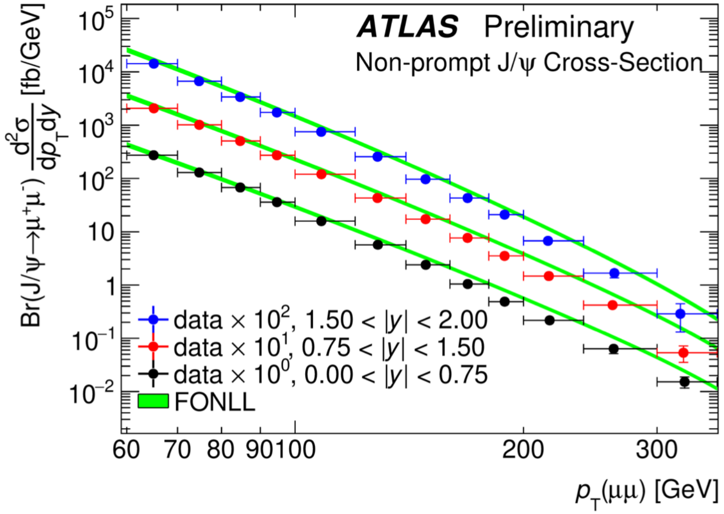
Note: Scaling by 1,10,100 of different rapidity ranges for visual clarity



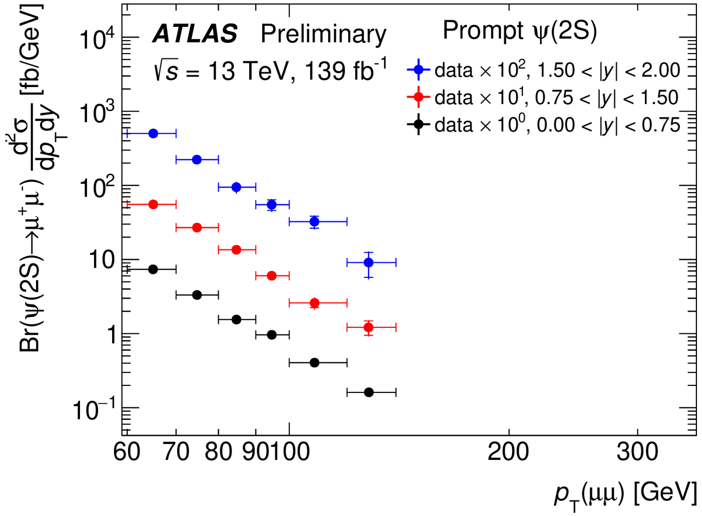
Non-prompt : comparison to FONLL predictions

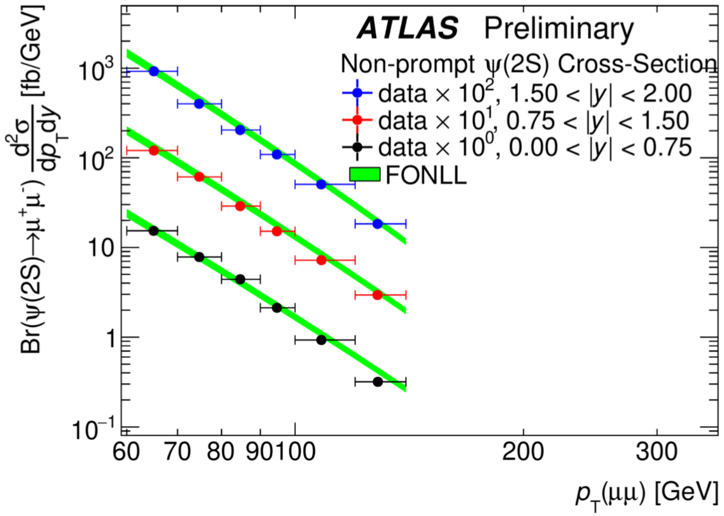
Good agreement at low pT

FONLL predicts higher cross-sections at high pT



ψ(2S) prompt and non-prompt



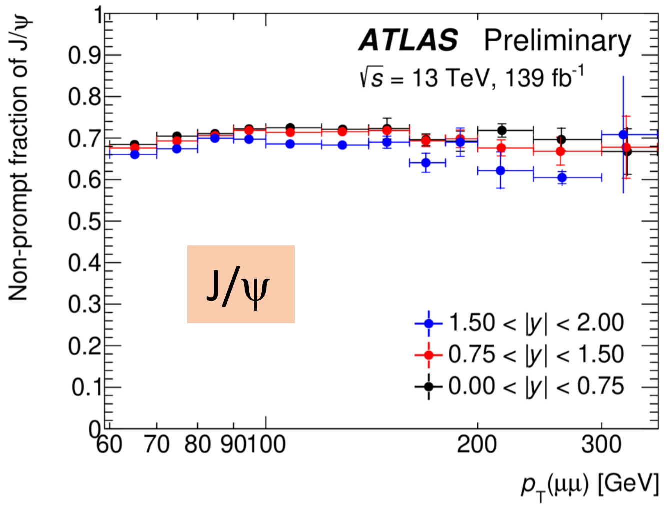


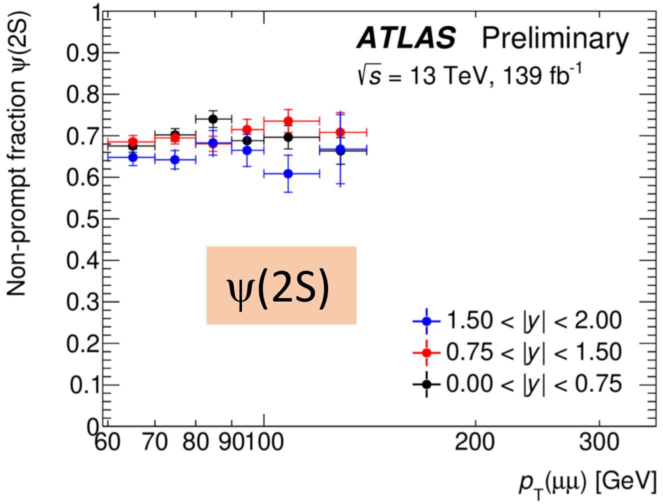
Quarkonium production at high p_T

ATLAS-CONF-2019-047

Non-prompt production fractions

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



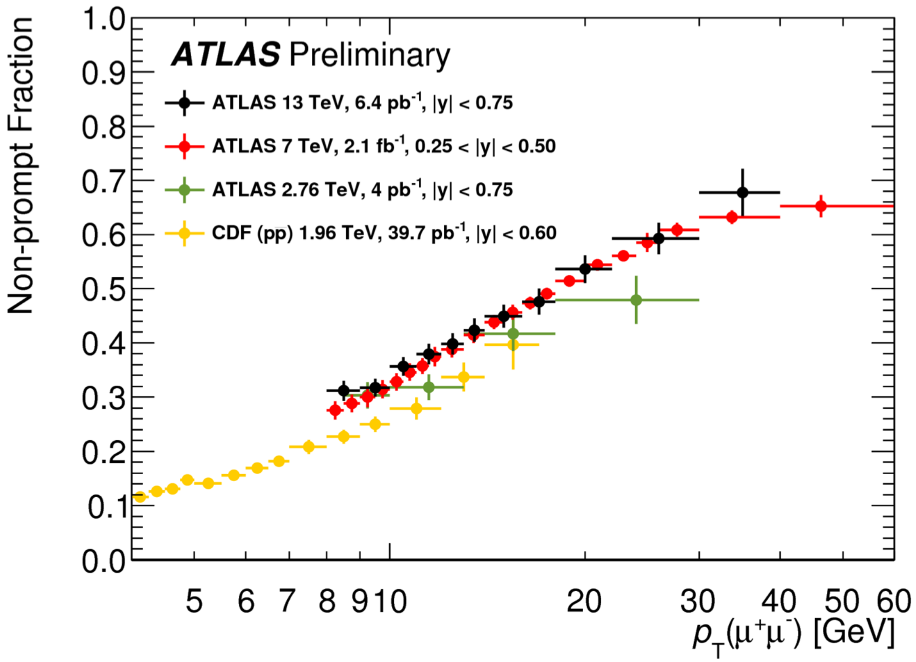


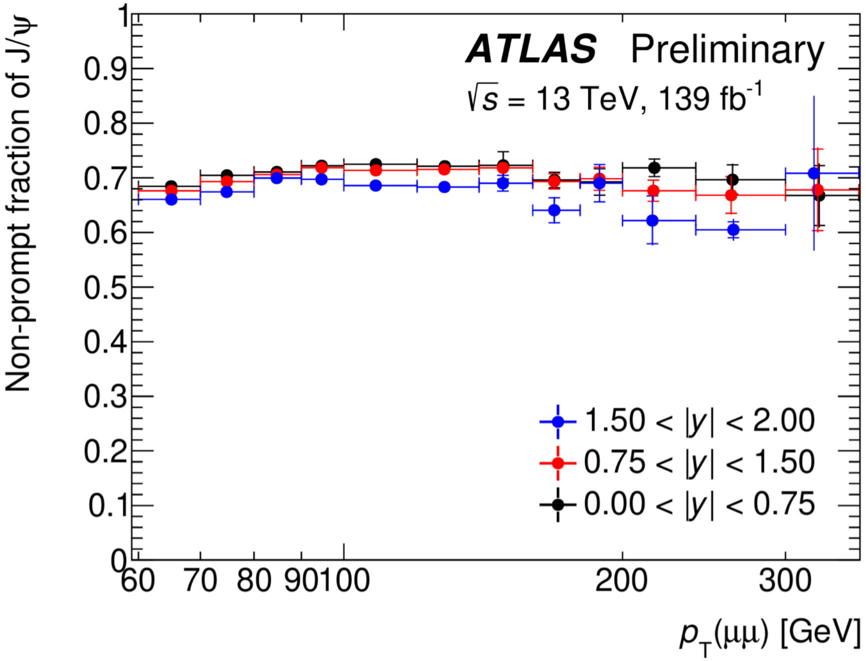
Quarkonium production at high p_T

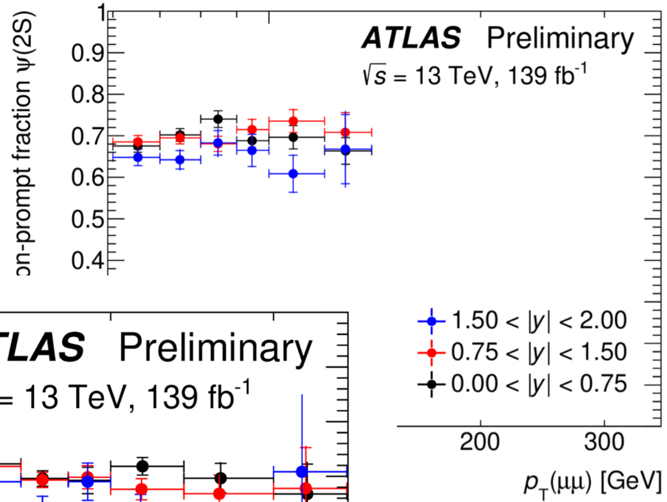
ATLAS-CONF-2019-047

Non-prompt production fractions

Complements previous low pT J/ψ measurements. Plateau around ~70%



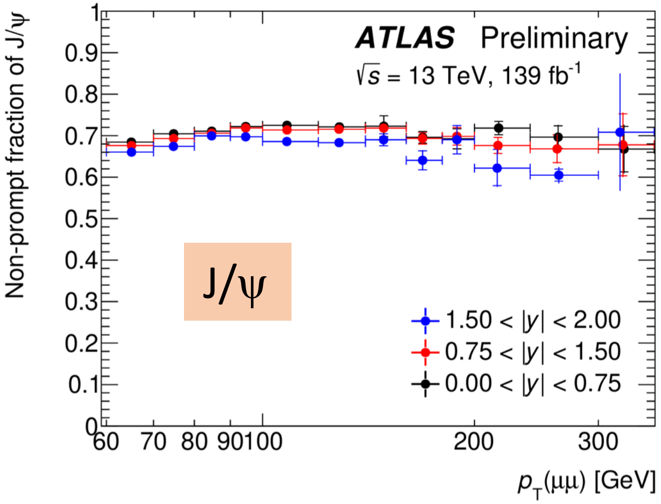


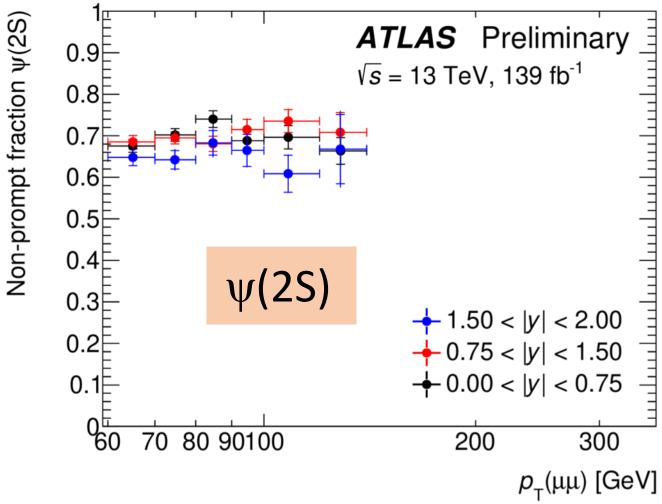


Quarkonium production at high p_T

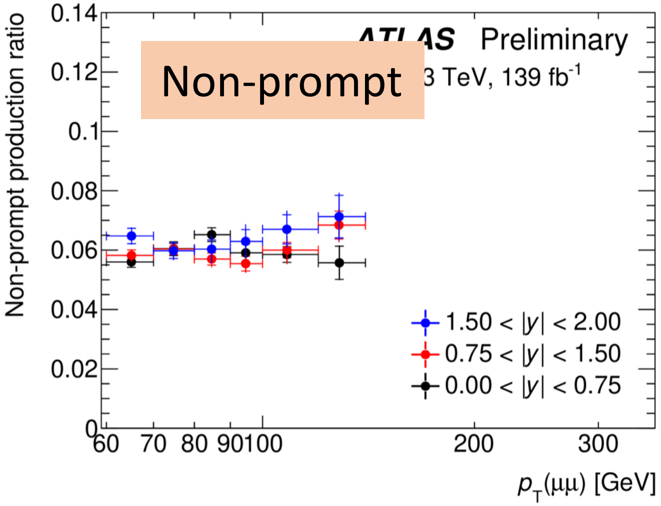
ATLAS-CONF-2019-047

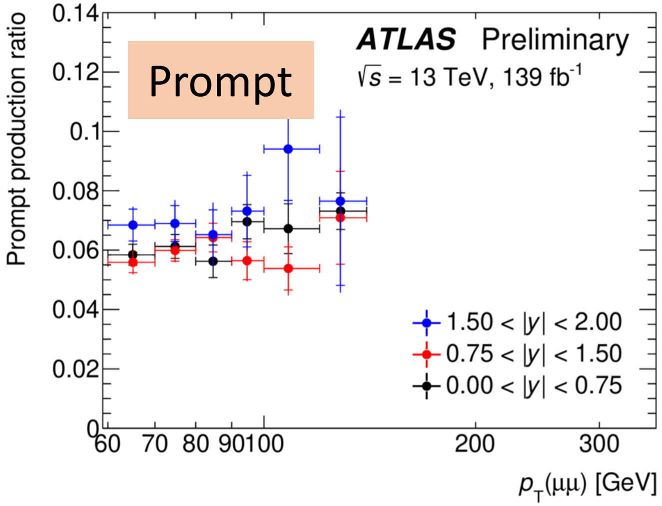
Non-prompt production fractions





Ratio of $\psi(2S)$ to J/ψ

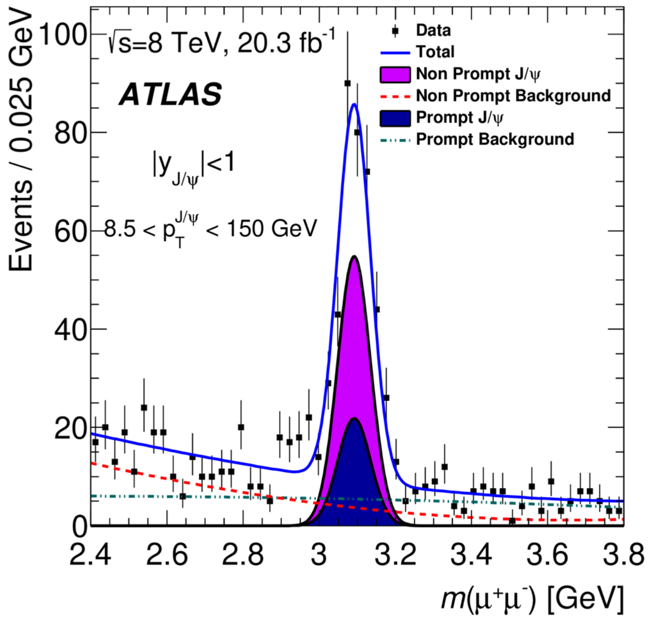


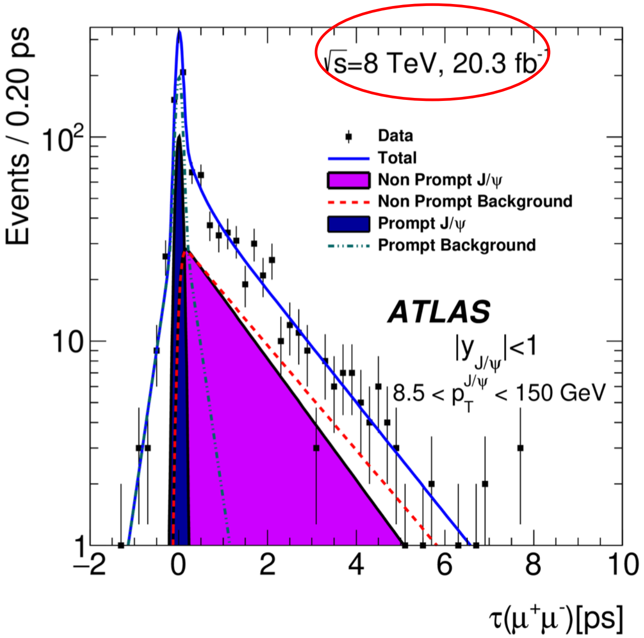


Associated production: W + J/ψ

JHEP 01 (2020) 095
arXiv:1909.13626

- Production mechanism for charmonium in hadronic collisions is not fully understood
- Relative contribution of Colour Singlet (CS) and Colour Octet (CO) is unknown (including both gives better agreement between theory and experiment)
- Contributions from Single Parton Scattering (SPS) and Double Parton Scattering (DPS) are unknown.
- Can be probed using $\Delta\varphi$ distribution between J/ψ and W





Standard muonic W selection (p_T>25GeV, |η|<2.4)

Extract prompt signal from fit to J/ψ mass and pseudo-proper decay time

Associated production: W + J/ψ

JHEP 01 (2020) 095
arXiv:1909.13626

Expect DPS to be flat, SPS to peak at high Δφ

Data indicate presence of SPS at high Δφ

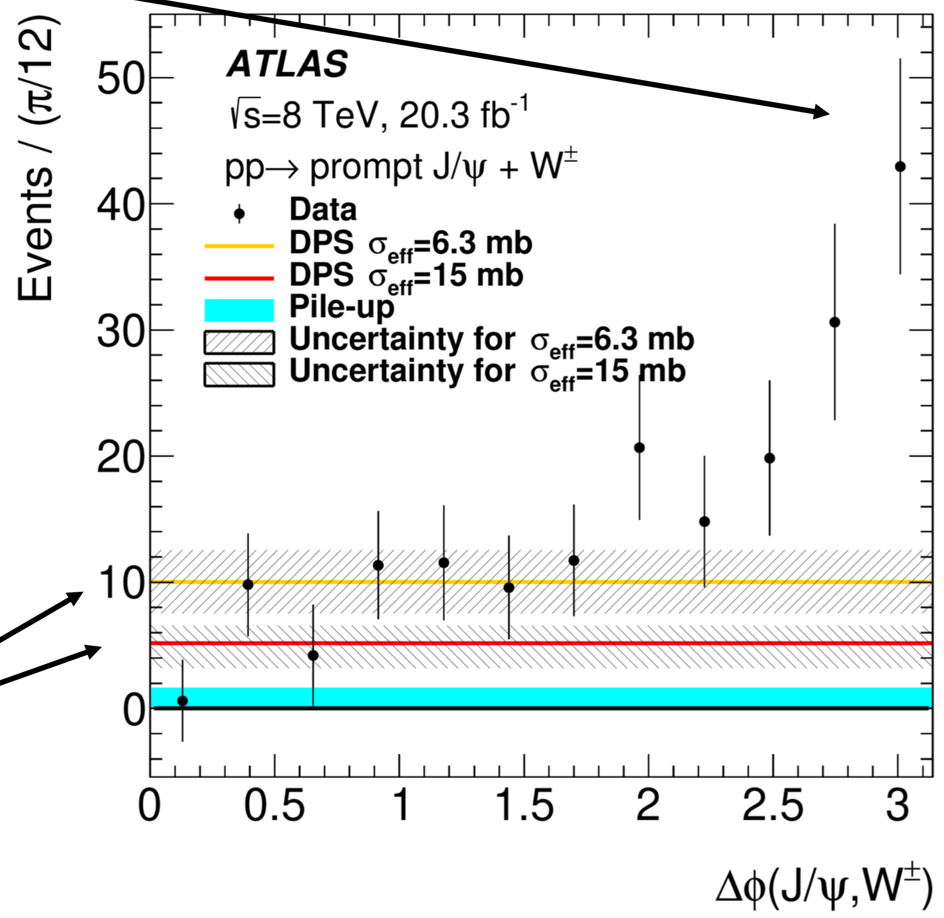
Double Parton Scattering

Probability of producing J/ψ in second hard scatter :

$$p^{ij}_{J/\psi} = \frac{\sigma^{ij}_{J/\psi}}{\sigma_{eff}}$$

Effective cross-section (σ_{eff}) unknown – choose 2 different values from previous ATLAS measurements (W+2jets, prompt J/ψ pair production)

Both values consistent with data at low Δφ



Associated production: W + J/ψ

JHEP 01 (2020) 095
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Measure ratio of cross-sections, $R_{J/\psi}$:

$$R_{J/\psi} = \frac{\sigma_{W+J/\psi}}{\sigma_W}$$

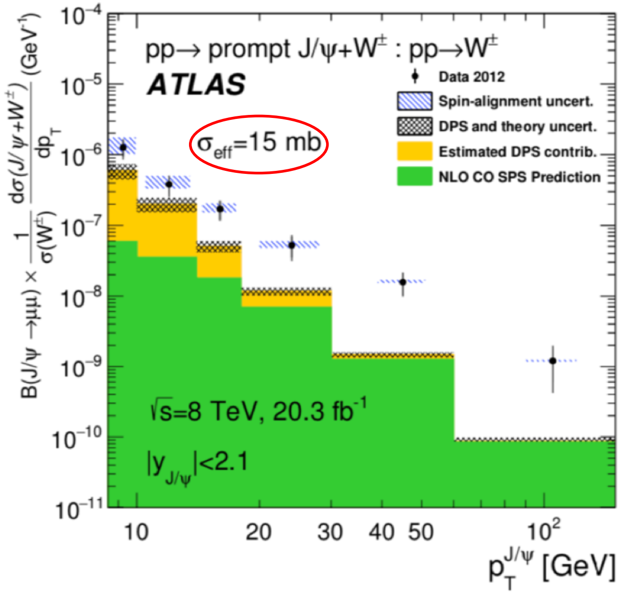
Almost all systematic uncertainties cancel in ratio

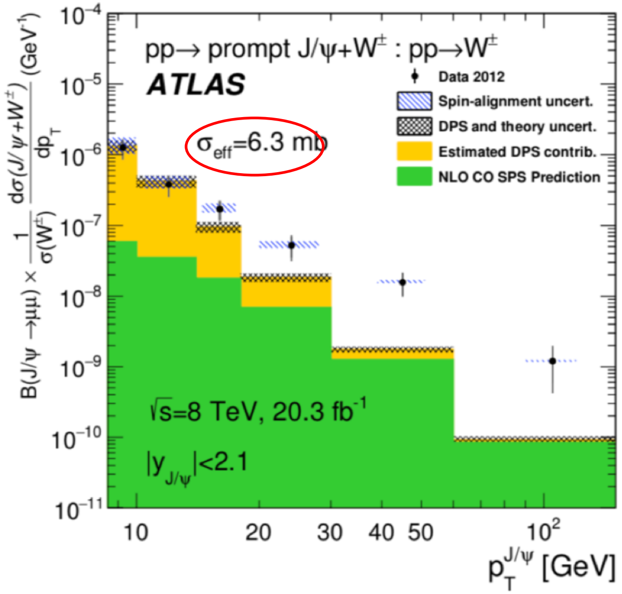
NLO CO SPS prediction: $(0.428 \pm 0.017)\text{x}10^{-6}$

$$R_{J/\psi}^{\text{DPSsub}} = (3.6 \pm 0.7^{+1.1}_{-1.0}{}^{+1.5}_{-0.7}) \times 10^{-6}\,, \quad [\sigma_{\text{eff}} = 15^{+5.8}_{-4.2}\text{ mb}]$$

$$R_{J/\psi}^{\text{DPSsub}} = (1.3 \pm 0.7 \pm 1.5^{+1.5}_{-0.7}) \times 10^{-6}\,, \quad [\sigma_{\text{eff}} = 6.3 \pm 1.9\text{ mb}]$$

DPS contribution subtracted





Differential inclusive cross-section in 6 bins of J/ψ p_T

SPS contribution modelled by CO model

DPS contribution estimated using both values of σ_{eff}

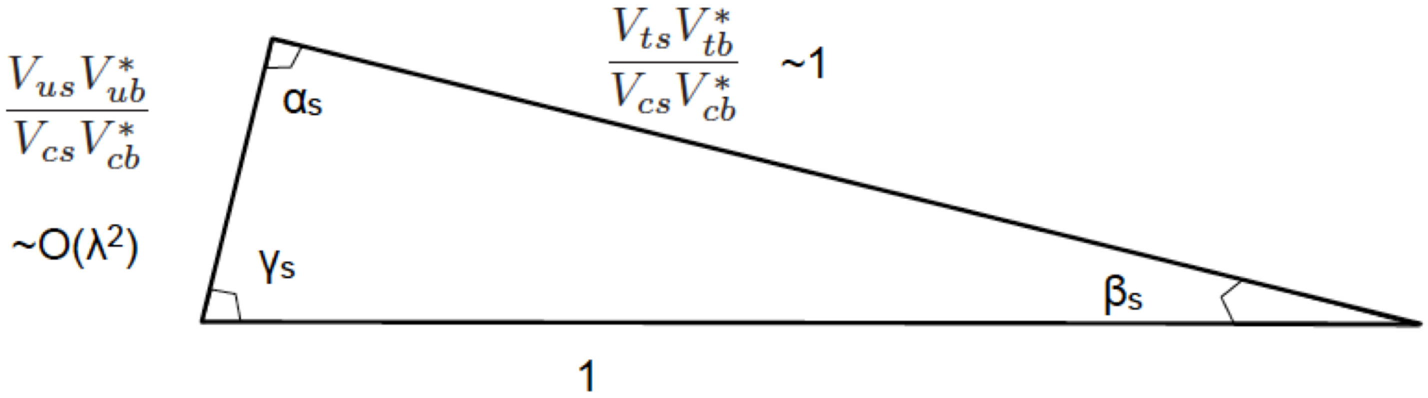
In both cases, prediction underestimates the measurement

CP violation in $B_s^0 \to J/\psi\phi \to \mu\mu K^+ K$

Submitted to EPJC
arXiv:2001.07115

B_s unitarity triangle

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



$\varphi_s = -2\beta_s$

CP violation in $B_s^0 \to J/\psi\phi \to \mu\mu K^+K$

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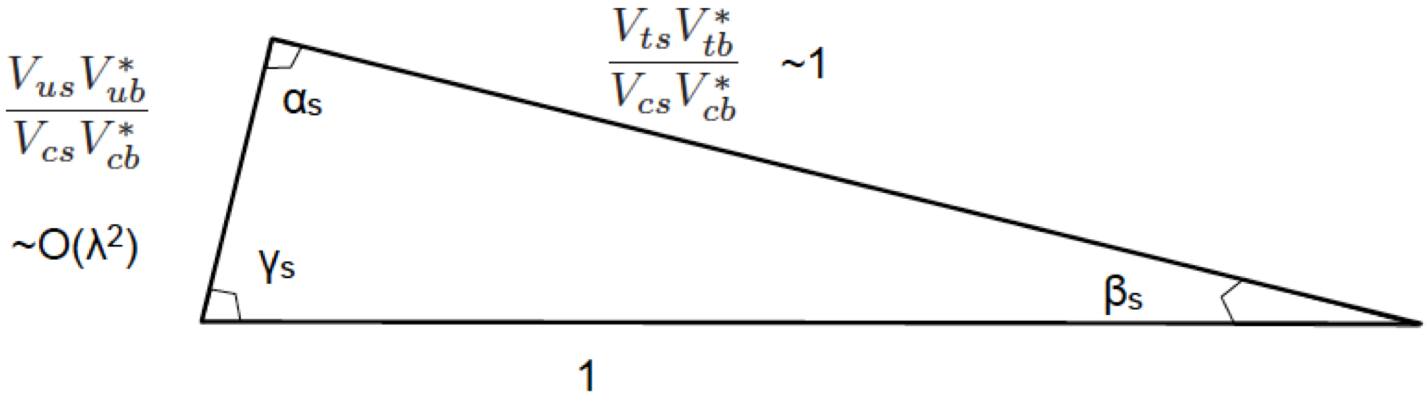
B_s unitarity triangle

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

CP violating phase ϕ_s - small in SM

New Physics can increase ϕ_s



SM value:
$$\varphi_s = -2\beta_s = -0.0365\ \pm^{0.0013}_{0.0012}$$

CP violation in $B_s^0 \to J/\psi\phi \to \mu\mu K^+K$

Submitted to EPJC
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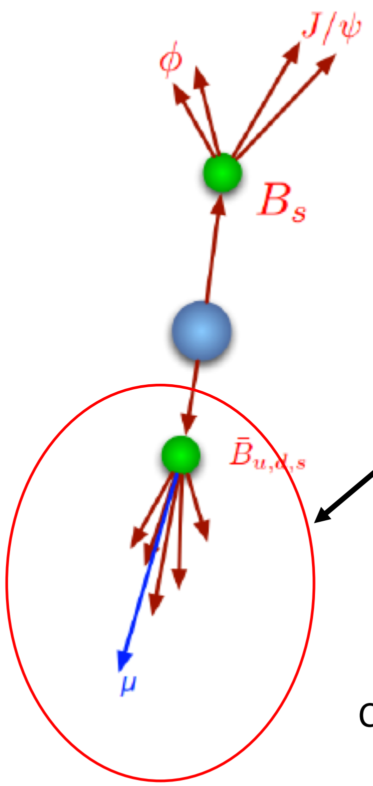


Tag flavour of neutral B meson at production using Opposite Side Tagging:

- Muons
- Electrons
- Secondary vertex

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\mathrm{T}i})^\kappa}{\sum_i^{N \text{ tracks}} (p_{\mathrm{T}i})^\kappa},$$

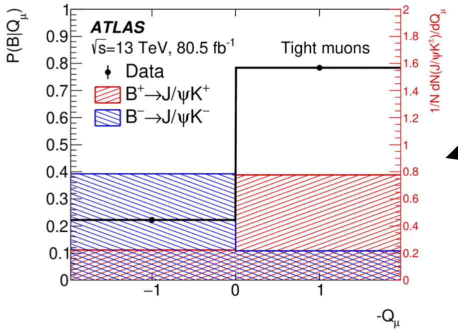
Cone charge used to tag flavour

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

Tagging efficiency

Dilution

Tagging Power



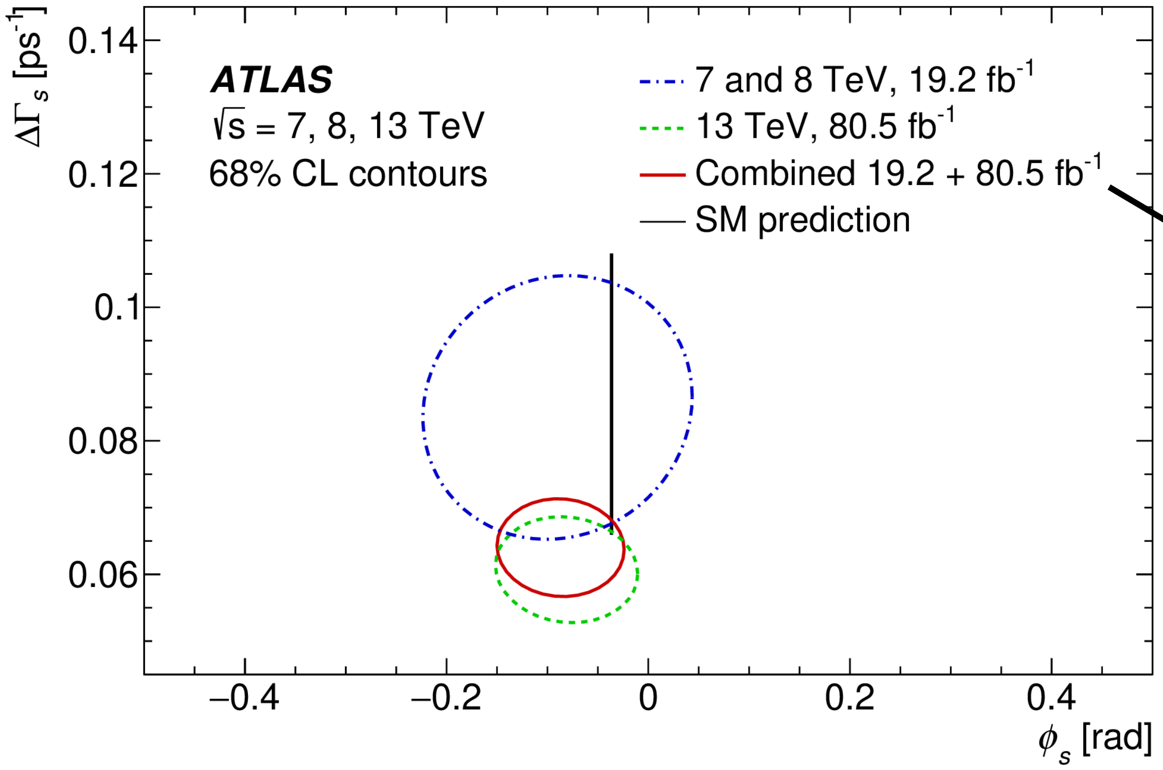
Use $B^\pm \to J/\psi K^\pm$ as calibration channel

CP violation in $B_s^0 \to J/\psi\phi \to \mu\mu K^+K$

Submitted to EPJC
arXiv:2001.07115

Unbinned maximum likelihood fit simultaneously for B_s^0 mass, decay time, tagging probability and decay angles

Run 2 result from 80.5 fb^{-1} (2015-17) - combined with previous Run1 result
(Have another 60 fb^{-1} recorded)



Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.037	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0640	0.0042	0.0024
Γ_s [ps^{-1}]	0.6698	0.0014	0.0015
$\|A_{\|\|}(0)\|^2$	0.2221	0.0018	0.0022
$\|A_0(0)\|^2$	0.5149	0.0012	0.0031
$\|A_S\|^2$	0.0343	0.0032	0.0044
$\delta_\perp$ [rad]	3.21	0.10	0.05
$\delta_{\|\|}$ [rad]	3.36	0.05	0.08
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.02

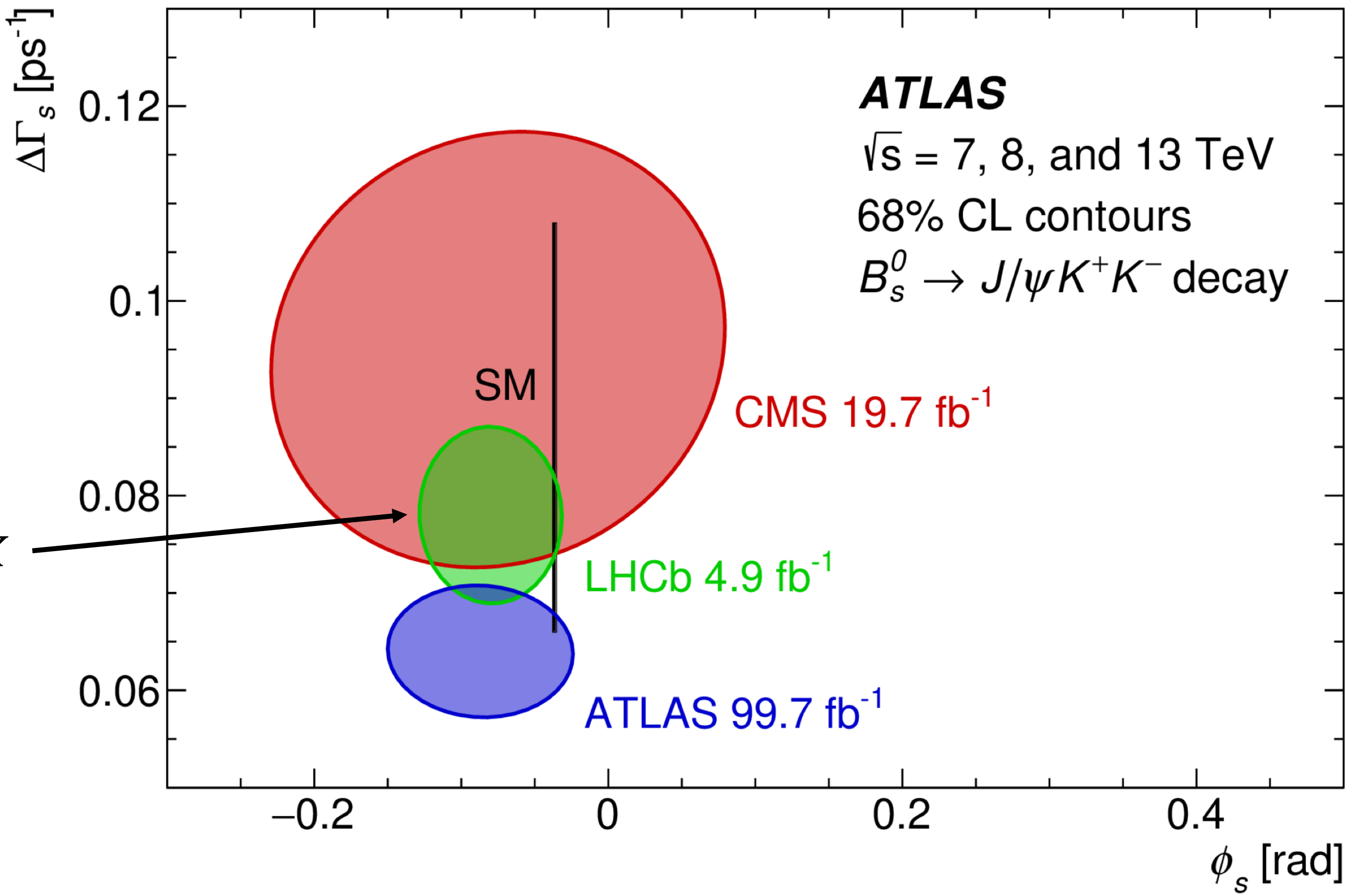
CP violation in $B_s^0 \to J/\psi\phi \to \mu\mu K^+ K$

Submitted to EPJC
arXiv:2001.07115

Comparison to other experiments

CMS: Phys. Lett. B 757 (2016) 97
LHCb: Eur. Phys. J. C79 (2019) 706

LHCb result using only $B_s^0 \to J/\psi\phi \to \mu\mu K^+ K$



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

Submitted to PRD
arXiv:1912.02672

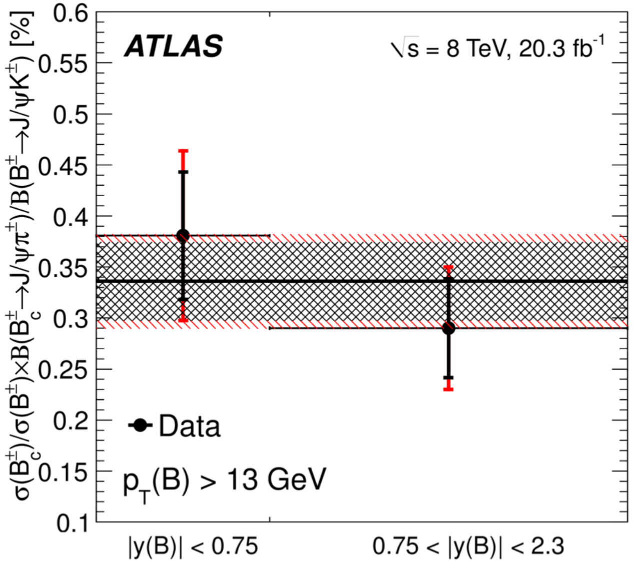
20.3 fb^{-1} data at $\sqrt{s}$ = 8 TeV

$B^{\pm} \to J/\psi(\mu^+\mu^-)\ K^{\pm}$ $\qquad$ $B_c^{\pm} \to J/\psi(\mu^+\mu^-)\ \pi^{\pm}$

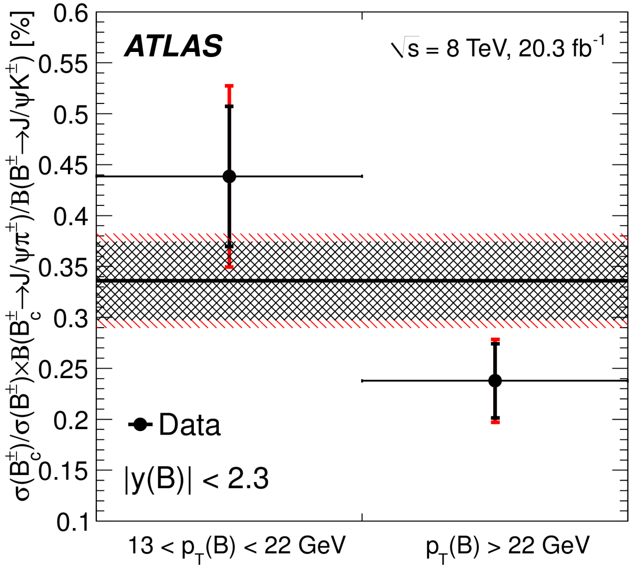
Extended unbinned maximum likelihood fits to B invariant mass distributions.
Full region plus 2 bins in p_T and 2 bins in rapidity (*y*)

Yield : ~400k $B^{\pm}$ and ~800 $B_c^{\pm}$

Measure relative cross-section
- First double differential measurement in central rapidity
- Complements CMS and LHCb measurements

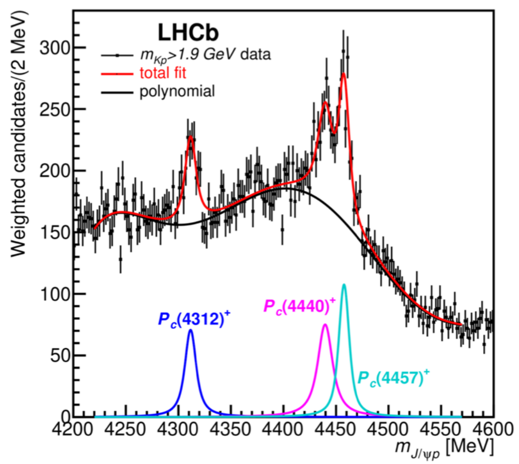


$B_c^{\pm}$ cross-section decreases faster with p_T than $B^{\pm}$ cross-section



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

ATLAS-CONF-2019-048



Observation by LHCb in $J/\psi p$ invariant mass in $\Lambda_b^0 \to J/\psi p K^-$

ATLAS search uses 7 TeV (4.9 fb^{-1}) and 8 TeV (20.9 fb^{-1}) data

No hadron ID : select $J/\psi h_1 h_2$ ($h_{1,2} = p, K, \pi$)

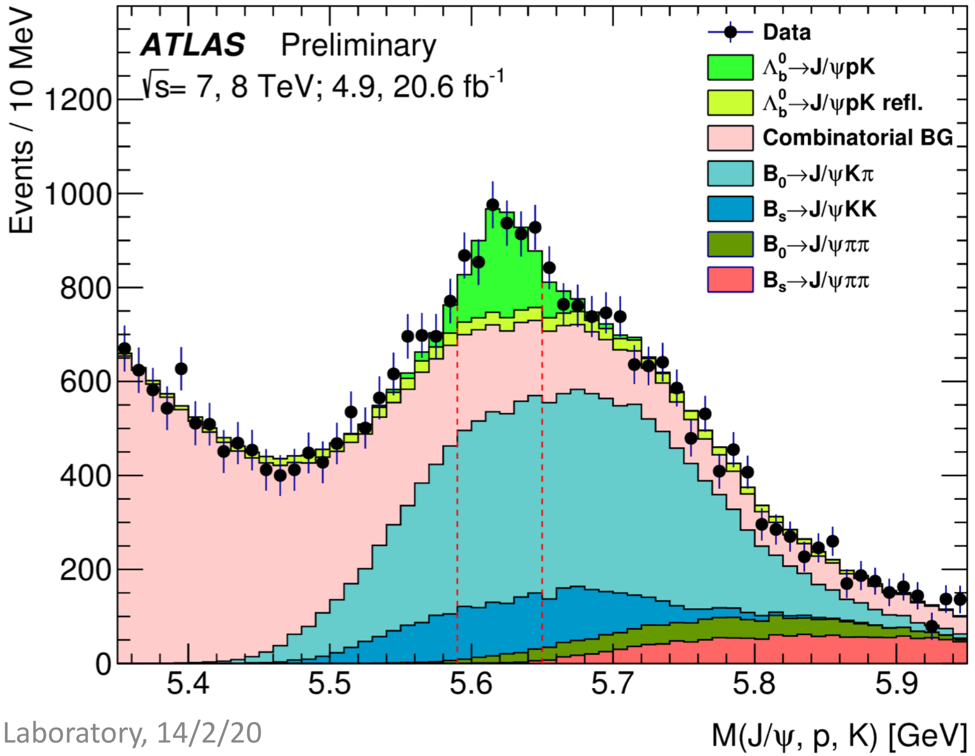
Perform simultaneous analysis of kinematically close:

- $\Lambda_b^0 \to J/\psi p K^-$ via various Λ^* or P_c states
- $B^0 \to J/\psi K\pi$ via various K^* or Z_c states
- $B_s^0 \to J/\psi KK$ via various f or ϕ states
- $B_{(s)} \to J/\psi\pi\pi$

Simulated events use phase space events weighted by theoretically calculated matrix elements

Suppress background with $M(K\pi) > 1.55$ GeV

Sequence of fits in Control Region, Signal Region and global scope

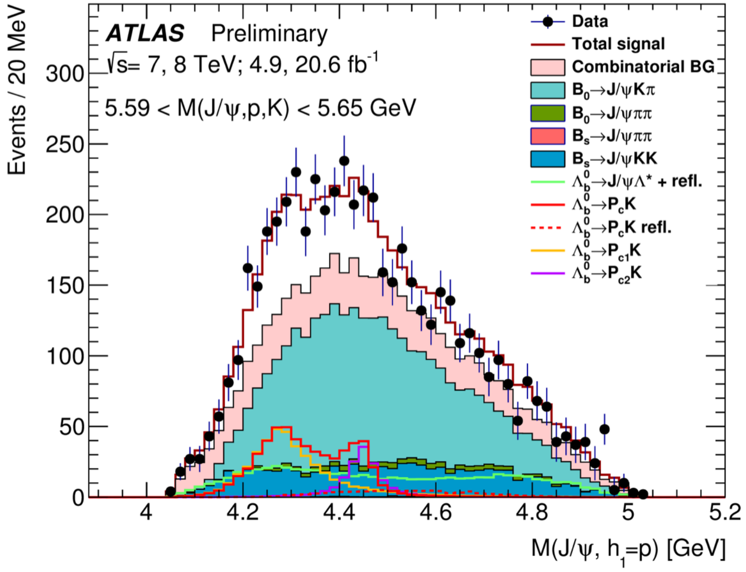


Pentaquark search in $\Lambda_b^0 \rightarrow J/\psi p K^-$

ATLAS-CONF-2019-048

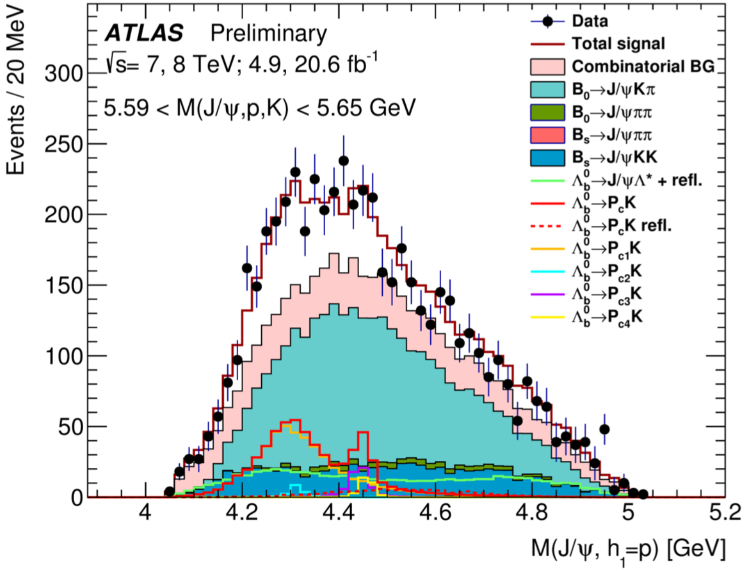
Fit with 2 pentaquark hypothesis
(spin parity 3/2$^-$ (light) and 5/2$^+$ (heavy)

χ^2/N_{dof} = 37.1/39 (p-value = 55.7%)



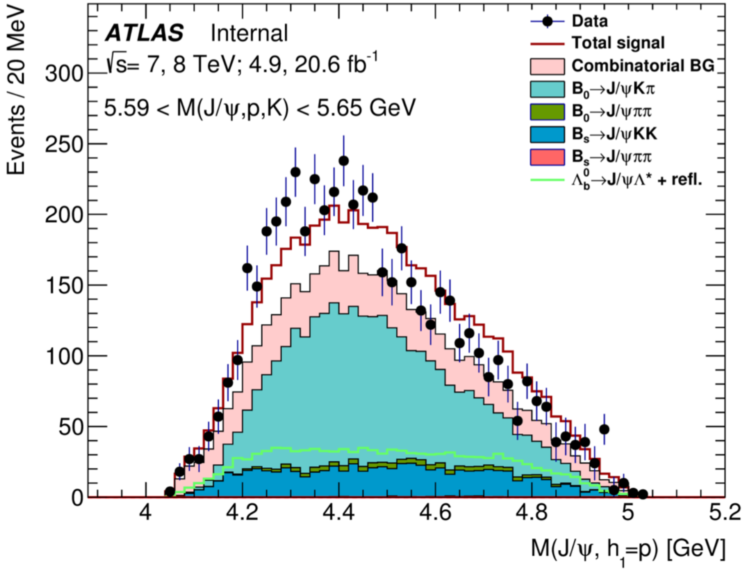
Fit with 4 pentaquark hypothesis
Properties of narrow states fixed to LHCb values

χ^2/N_{dof} = 37.1/42



Fit with no pentaquarks

χ^2/N_{dof} = 69.2/37



Two and four pentaquark hypotheses consistent with data. No pentaquark hypothesis cannot be excluded

Summary

ATLAS has an active and varied B-physics programme

Recent results presented on

- Quarkonium production
- W + J/ψ associated production
- CP violation
- $B_c^{\pm}/B^{\pm}$ production cross-section
- Pentaquark search

All public results available here :
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

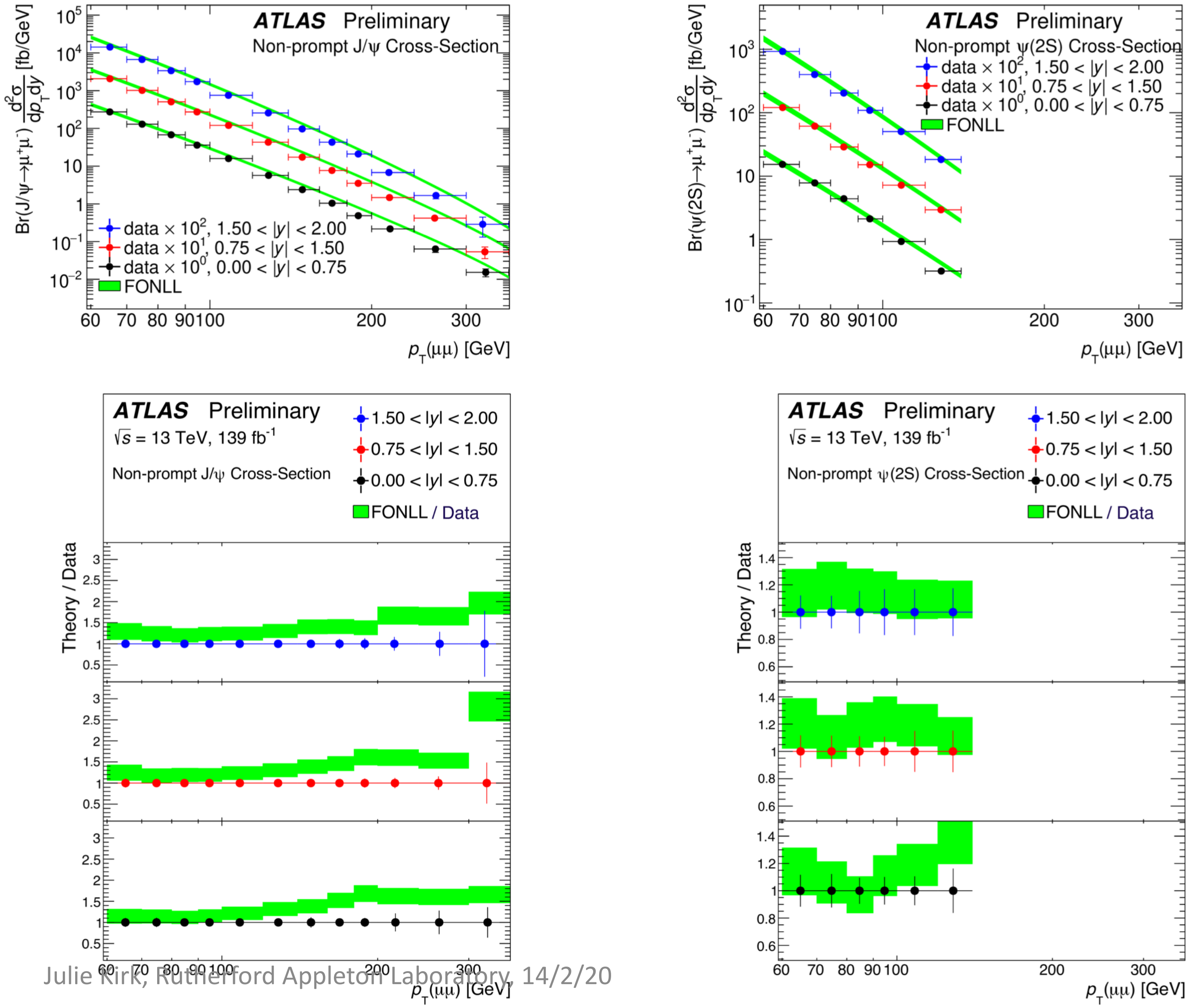
Backup

Quarkonium production at high p_T

ATLAS-CONF-2019-047

Comparison to FONLL predictions

Good agreement at low pT
FONLL predicts higher cross-sections at high pT



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CP violation in $B_s^0 \to J/\psi\phi \to \mu\mu K^+K$

Unbinned maximum likelihood fit input:

- ➢ B_s^o properties: m_i, σ_{mi}, t_i, σ_{ti}, p_{Ti}, $p_i(B|Q_x)$
- ➢ Traversity angles: $\Omega_i(\theta_{Ti}, \phi_{Ti}, \psi_{Ti})$

- ➢ Parameters: ϕ_s, $\Delta\Gamma_s$, Γ_s, $|A_{||}(0)|^2$, $|A_o(0)|^2$, $|A_s(0)|^2$, $\delta_\perp$, δ_s, $\delta_\perp - \delta_s$

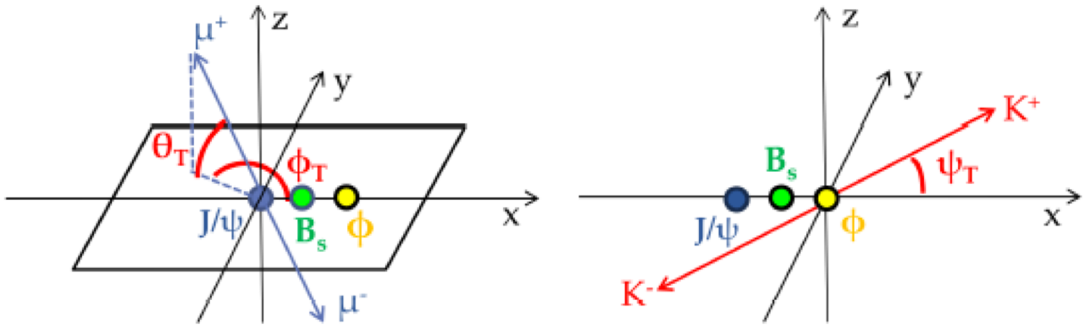
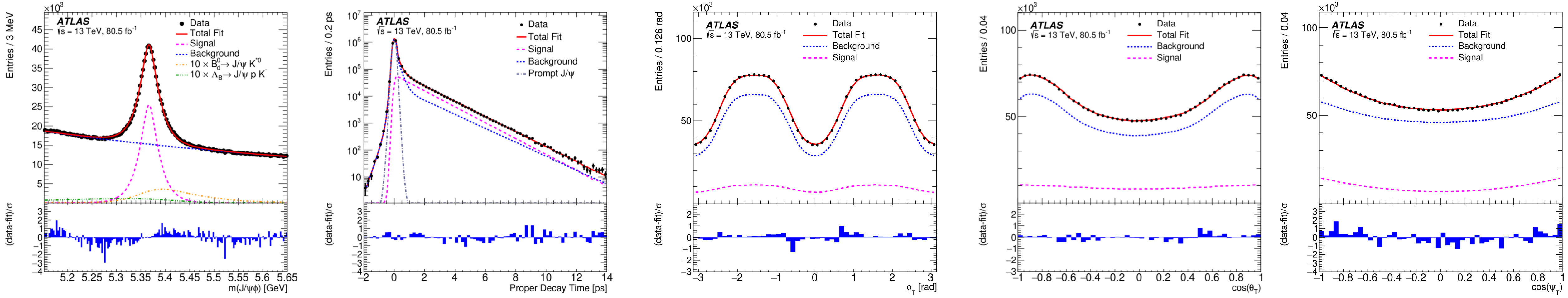


Figure: Angles between final state particles in transversity basis.



CP violation in $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu\mu K^+ K$

Tagging : weighted sum of charge in a cone

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\mathrm{T}i})^\kappa}{\sum_i^{N \text{ tracks}} (p_{\mathrm{T}i})^\kappa},$$

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

Tagging efficiency (ϵ_x): $\epsilon_x = \frac{N_{sig}^{tagged}}{N_{sig}^{total}}$

Dilution: $\mathcal{D}(Q_x) = 2P(B|Q_x) - 1$

Tagging power (T_x): $T_x = \Sigma_i \epsilon_{xi} . \mathcal{D}(Q_{xi})$

Effective Dilution: $D_x = \sqrt{(\frac{T_x}{\epsilon_x})}$