Recent heavy-flavour results from ATLAS

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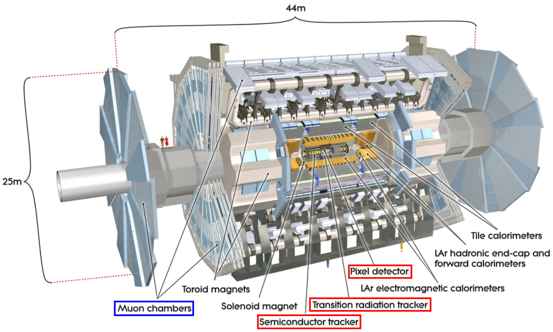
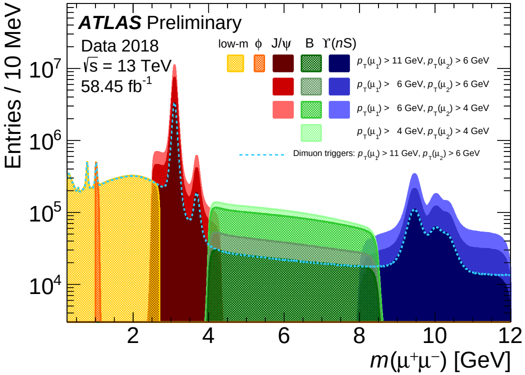
Outline

- ATLAS B-physics programme covers a wide range of studies:
  - Open heavy-flavour and heavy quarkonium production
  - Spectroscopy (including exotic states)
  - Decays (CPV, rare and semi-rare decays etc.)
- Competitive when (mostly) muon final states are involved

- **In this talk:**
  - Observation of structures in di-charmonium mass spectrum – EPJC 84 (2024) 169
  - Study of $\Upsilon + 2\mu$ mass spectrum – ATLAS-CONF-2023-041
  - Measurement of J/ψ and $\psi(2S)$ production at $\sqrt{s} = 13\,\text{TeV}$ – PRL 131 (2023) 151902
  - Measurement of $B_s^0 \to \mu^+\mu^-$ effective lifetime – JHEP 09 (2023) 199

ATLAS detector and trigger for B-physics

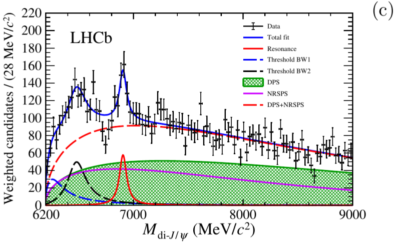


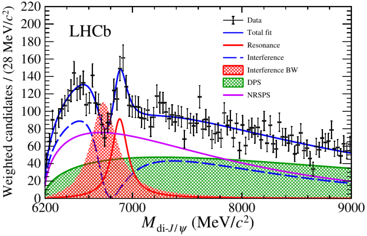


- Track reconstruction covers $|\eta| < 2.5$, $p_T > 500\,\text{MeV}$
- Muons reconstructed from $p_T > 2.5\,\text{GeV}$

- Two-level trigger system: hardware L1 and software HLT
- Di-muon triggers most relevant for B-physics
  - Typical p_T thresholds for two muons: 4–6 GeV

- LHCb claimed (arXiv:2006.16957) observation of a new *X(6900)* structure in $pp \to J/\psi J/\psi \to 4\mu$ mass spectrum
  - consistent with predictions for $T_{cc\bar{c}\bar{c}}$ tetraquarks
    - e.g. in diquark+antidiquark model (EPJC 80 (2020) 1004, PLB 811 (2020) 135952)
  - non-tetraquark interpretations also possible
    - e.g. in Pomeron exchanges in near-threshold $J/\psi - J/\psi$ scattering (PLB 824 (2022) 136794)
  - broad lower-mass structure can be e.g. a mixture of multiple $cc\bar{c}\bar{c}$ states or feed-down from their decays via heavier charmonia
- The observation then confirmed by ATLAS (PRL 131 (2023) 151902) and CMS (PRL 132 (2024) 111901)





Assuming no interference:

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV},$$

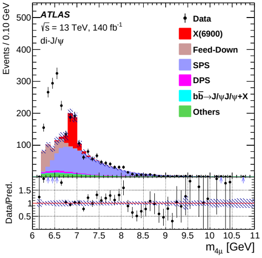
With NRSPS interference:

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}.$$

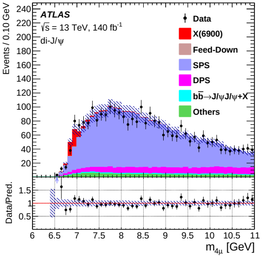
Low-mass 4-muon resonances

PRL 131 (2023) 151902

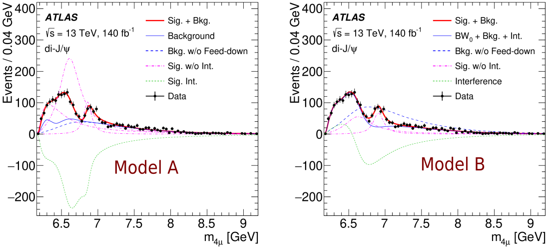
- Main background: SPS and DPS prompt charmonium pair production
  - From MC, corrected in control regions
- Other: $b\bar{b} \to J/\psi J/\psi X$, fake J/ψ, feed-down from TQ decaying to heavier charmonia



Signal region $\Delta R < 0.25$



Control region $\Delta R > 0.25$

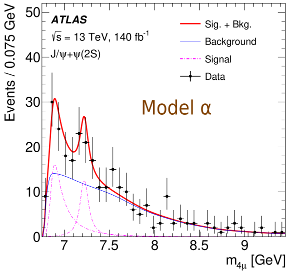


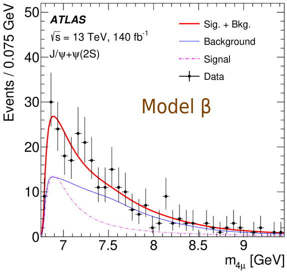
Two fit models similar to those used by LHCb:

- Model A: 3 *interfering* BW resonances
- Model B: 1 BW interfering with SPS background, 1 BW standalone
- Significance far exceeds 5σ

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

$J/\psi + \psi(2S)$ channel





- Model α: same 3 resonances decaying to $J/\psi + \psi(2S)$ and a 4th standalone BW resonance – 4.7σ
  - parameters fixed from di-J/ψ fit
- Model β: a single BW resonance – 4.3σ
- 3σ significance of the 7.2 GeV resonance in model α

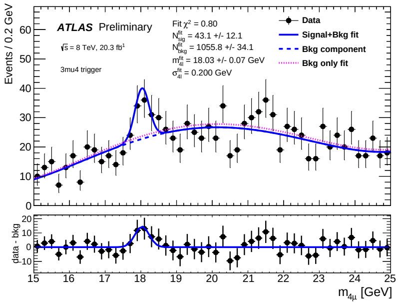
J/ψ+ψ(2S)	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

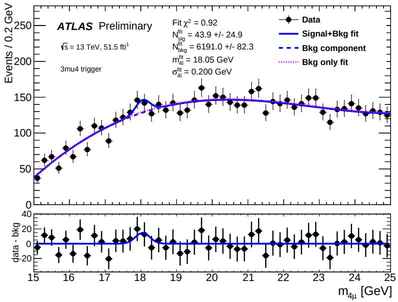
- $X(6900)$ reliably confirmed with consistent parameters and significance far above 5σ
  - CMS is also consistent
- Evidence for another resonance also hinted in LHCb results near 7.2–7.3 GeV in $J/\psi + \psi(2S)$ at level of 3–4σ
  - CMS reported an evidence in di-J/ψ channel
- The lowest-mass structure nature is less certain
  - Could also result from other effects, e.g. a more complicated mixture of states or feed-down from higher di-charmonium resonances

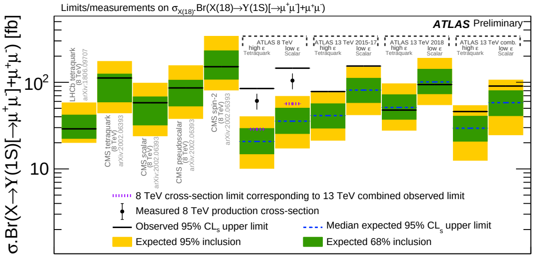
Search for $\Upsilon + 2\mu$ resonances in ATLAS

ATLAS-CONF-2023-041

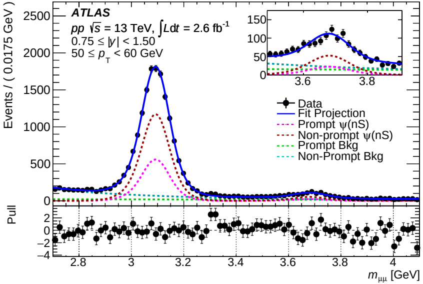
- Study $\Upsilon(\to \mu^+\mu^-) + \mu^+\mu^-$ mass spectrum
- 8 TeV data analysis: an excess at $m_{4\mu} = 18$ GeV
  - global significance 1.9–5.4σ depending on selection choice, survives extensive validation
- 13 TeV data: much less significant structure in 2015–17 data and no signal in 2018 (with tighter trigger)
  - MC and data-driven studies confirm reduction of sensitivity in Run-2 data
  - 13 TeV result is in tension with 8 TeV at 2.7σ level
- To be further studied with Run-3

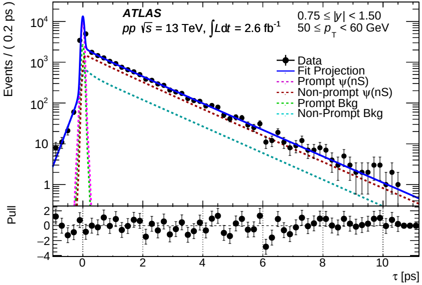






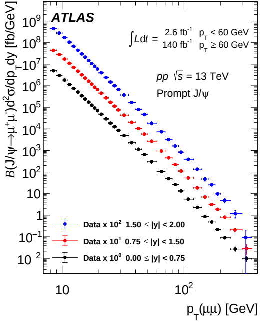
- Heavy quarkonium is a unique probe for our understanding of strong interactions
- Two production mechanisms:
  - *Prompt* in *pp* interaction or feed-down from heavier states
  - *Non-prompt* from *b* hadron decays
  - Distinguished by 2D fit of dimuon mass and pseudo-proper lifetime
- pQCD relatively successful for *non-prompt* production description, but not quite for *prompt*
- Full Run-2 analysis uses different trigger strategy for low and high p_{T}:
  - di-muon trigger for $8 < p_{\mathrm{T}}(J/\psi) < 60$ GeV (4 GeV muon threshold in 2015)
  - single-muon trigger for $p_{\mathrm{T}}(J/\psi) > 60$ GeV (50 GeV muon threshold)

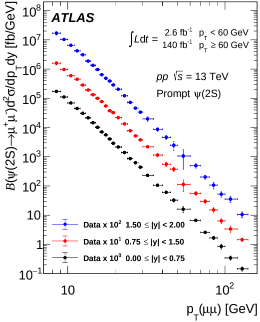


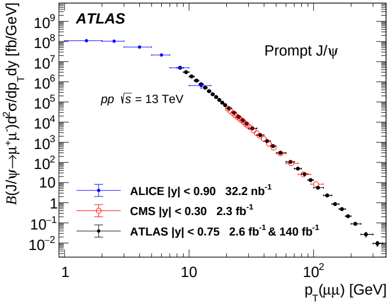


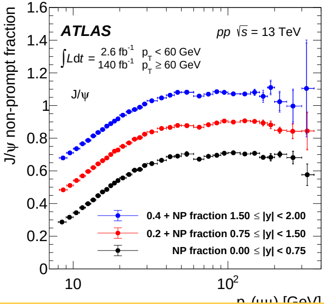
Results

- Widest p_T range achieved so far: 8–360 GeV for J/ψ (up to 140 GeV for $\psi(2S)$)
  - 9 (6) orders of magnitude variation of x-section for J/ψ ($\psi(2S)$)
- Non-prompt fraction increases at low p_T, plateau for higher
- Good agreement with other experiments withing overlapping kinematic ranges



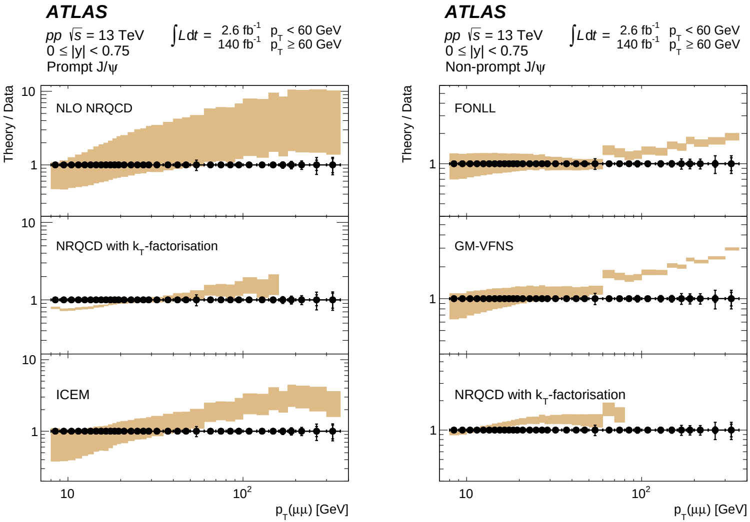






Comparison to predictions

- *Prompt:* much harder spectra predicted, room for improvement in all models
- *Non-prompt:* generally better description, although still tend to over-estimate high p_T



$B_s^0 \to \mu^+\mu^-$ effective lifetime measurement

JHEP 09 (2023) 199

- Rare decay, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.01 \pm 0.35) \times 10^{-9}$
- In SM, only CP-odd $B^0_{s,H}$ state contributes to $B_s^0 \to \mu^+\mu^-$ decay ($A_{\mu\mu} = +1$)
- Certain BSM scenarios allow CP-even $B^0_{s,L}$ contribution ($A_{\mu\mu} \in [-1, +1]$)

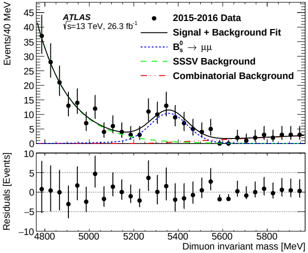
$$\tau_{\mu\mu}^{\text{eff}} = \frac{\tau_{B_s^0}}{1-y^2}\left[\frac{1+2yA_{\mu\mu}+y^2}{1+yA_{\mu\mu}}\right], \qquad y = \frac{\Gamma_{s,L}-\Gamma_{s,H}}{\Gamma_s}, \qquad A_{\mu\mu} = \frac{\Gamma(B^0_{s,H}\to\mu^+\mu^-)-\Gamma(B^0_{s,L}\to\mu^+\mu^-)}{\Gamma(B^0_{s,H}\to\mu^+\mu^-)+\Gamma(B^0_{s,L}\to\mu^+\mu^-)}$$

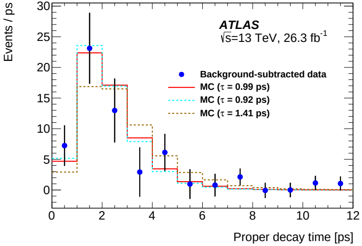
- Large lifetime difference $\tau_{B^0_{s,H}} - \tau_{B^0_{s,L}} = 1.624 - 1.431 = 0.193\, ps$ allows sensitivity to $B^0_{s,L}$ contribution
- Complementary observable to $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ – different set of effective operators
- First measurement in ATLAS done with 2015–2016 data

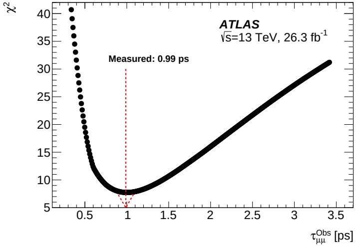
Analysis strategy

1. Unbinned ML fit to $m(\mu^+\mu^-)$ distribution
   - Main backgrounds: continuum di-muons, partially reconstructed B decays
   - Signal yield: 58 ± 13 *events*
2. Extraction of the signal proper decay time distribution with *sPlot*
3. χ^2 fit of that distribution with MC templates for $\tau_{\mu\mu}$

- Dominant systematics: signal MC modelling
  - evaluated using $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ reference channel data/MC comparison



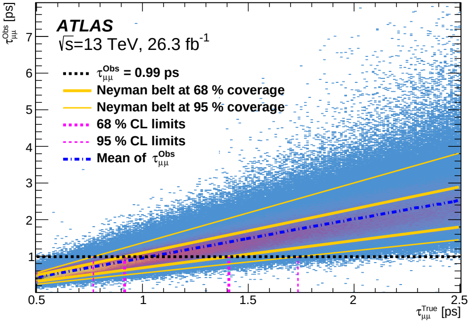


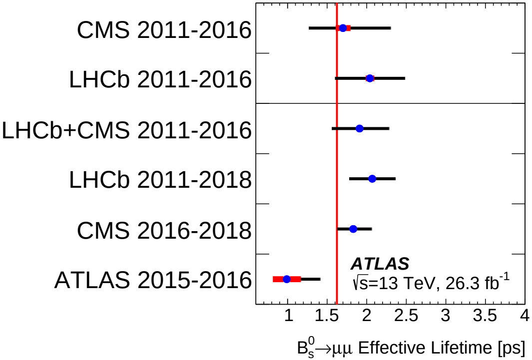


- Stat. uncertainty evaluated with Neyman construction using toy MC fits
- Measured value:

$$\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}(\text{stat.}) \pm 0.17(\text{syst.})\text{ ps}$$

- Consistent with SM $\tau_{B^0_{s,H}} = 1.624 \pm 0.009$ ps





- Consistent with other experiments
  - Competitive precision for the similar-size dataset
- Full Run-2 dataset analysis underway

Summary

ATLAS has released a set of competitive results in various areas of B-physics

- Study of the exotics in 4-muon final states
- The most comprehensive measurement of charmonium production so far
- $B_s^0 \to \mu^+\mu^-$ rare decay lifetime measurement

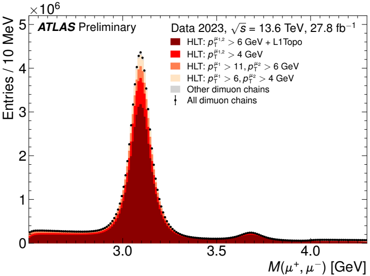
Stay tuned for further results!

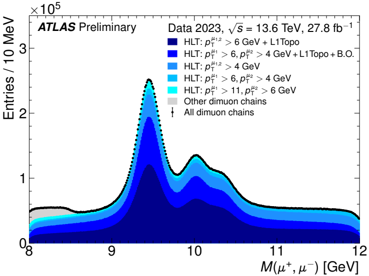
ATLAS B-physics public result page:

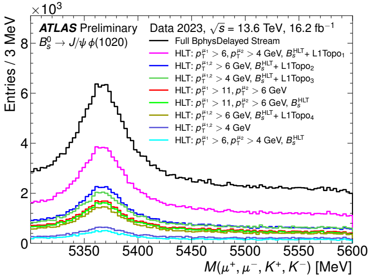
- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

Backup slides

ATLAS B-physics trigger in Run-3

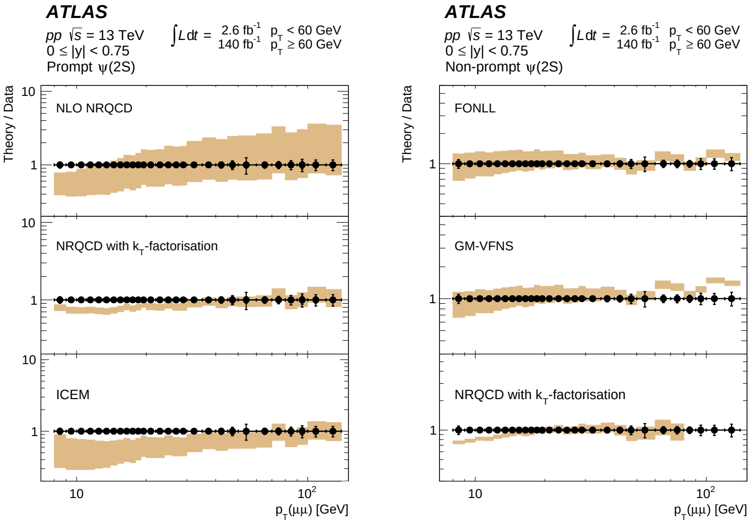




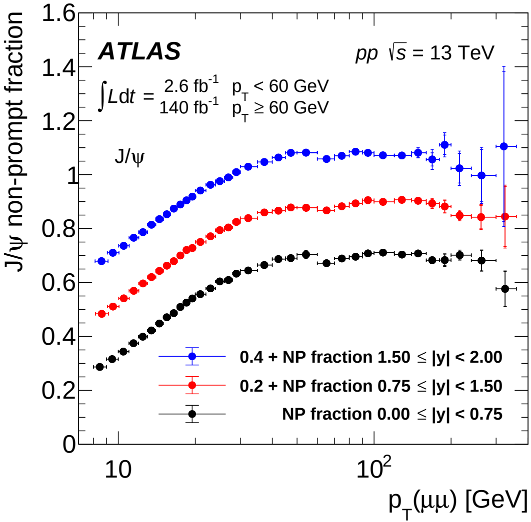


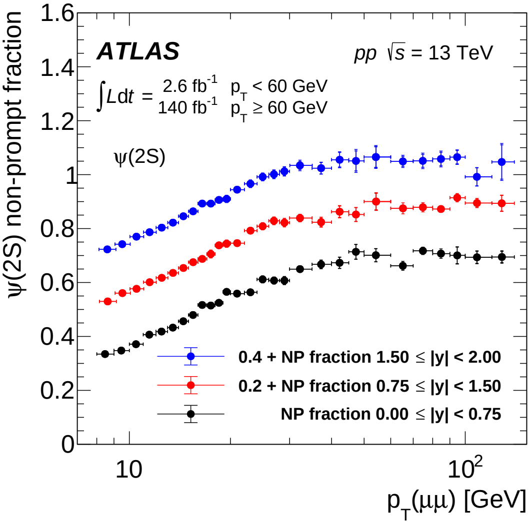
Comparison to predictions $\psi(2S)$

- NLO NRQCD with k_T-factorisation: based on PEGAUS generator (EPJC 80 (2020) 330)
- ICEM: Improved Colour Evaporation Model

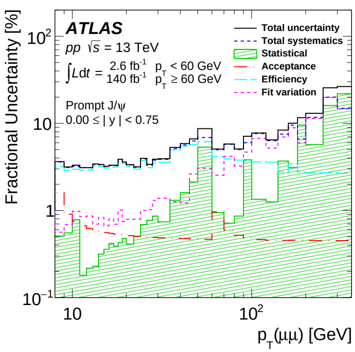


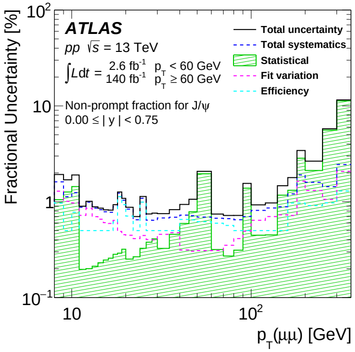
Non-prompt fraction

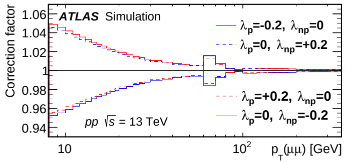




Charmonium production systematics







$B_s^0 \to \mu^+\mu^-$ lifetime systematics

Uncertainty source	$\Delta\tau_{\mu\mu}^{\mathbf{Obs}}$ [fs]
Data - MC discrepancies	134
SSSV lifetime model	60
Combinatorial lifetime model	56
B kinematic reweighting	55
B isolation reweighting	32
SSSV mass model	22
B_d background	16
Fit bias lifetime dependency and B_s^0 eigenstates admixture	15
Combinatorial mass model	14
Pileup reweighting	13
B_c background	10
Muon Δ_η correction	6
$B \to hh'$ background	3
Muon reconstruction SF reweighting	2
Semileptonic background	2
Trigger reweighting	1
Total	174