ATLAS results on charmonium production

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Hadronic production of charmonium

An important object of study in QCD at the large/small scale boundary

Study of production mechanisms helps develop QCD methods

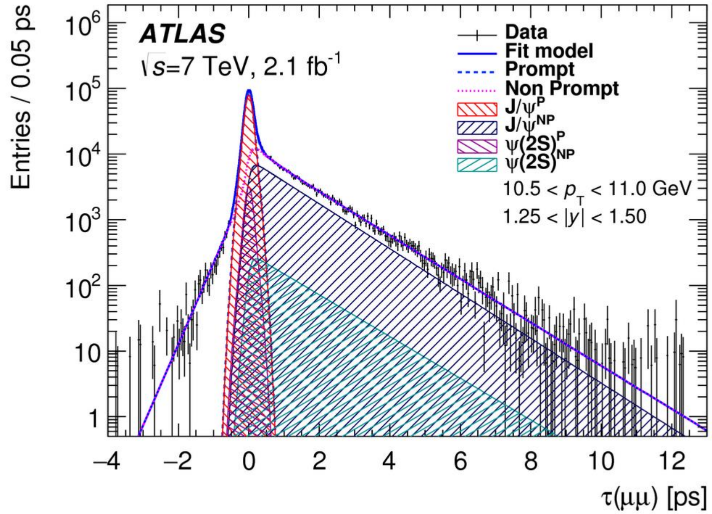
Various contributing sources can be separated experimentally

Recently used more and more as a tool for further studies:

- **Unique signature for quark-gluon plasma studies in heavy ion collisions**
- **Single/double-parton scattering separation**
- **Transverse-momentum-dependent (TMD) parton pdf studies**
- **…**

Prompt and non-prompt production

- **A large fraction of charmonium states produced in decays of B hadrons**
- **Due to long lifetime of parents, these have measurable decay length between the production and decay vertices**
- **In ATLAS, the "pseudo-proper" lifetime is used to separate prompt and non-prompt production**
- $$\tau = \frac{m\, L_{xy}}{c\, P_T}$$
- **This exploits the property of $B \to J/\psi\ X$ decays, where the J/ψ tends to carry a fixed fraction of parent's momentum**

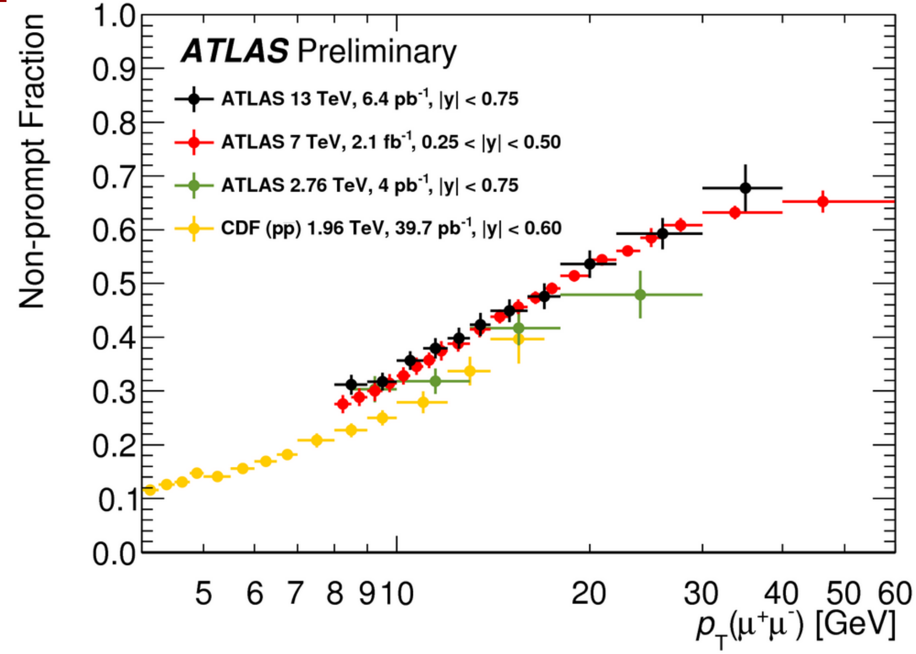


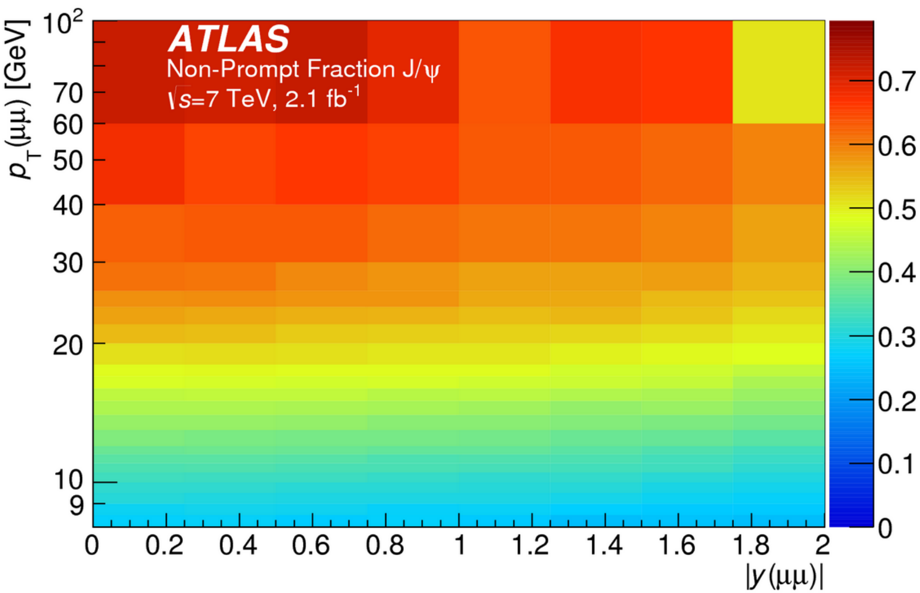
- **Promptly produced charmonium has τ consistent with zero within experimental resolution, while non-prompt events form a (quazi-) exponential tail**

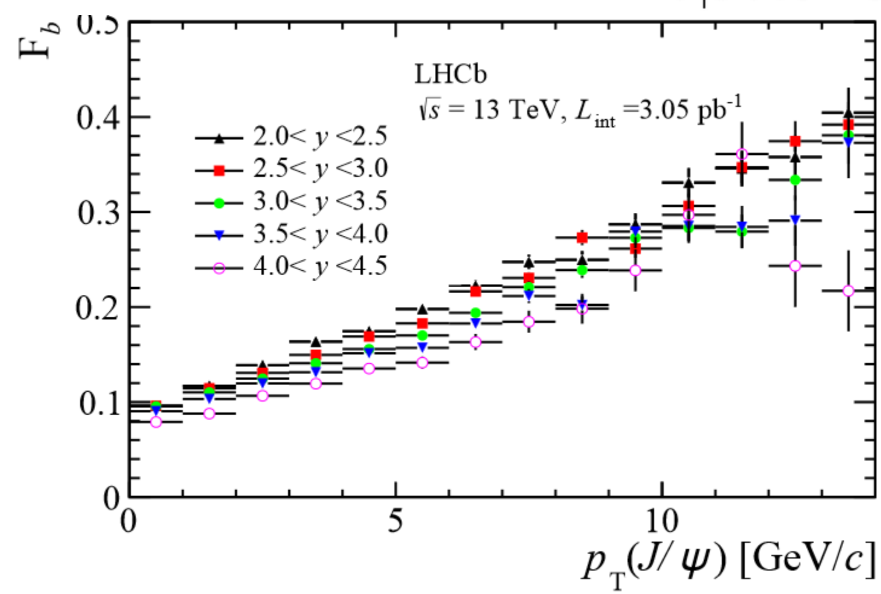
Non-prompt J/ψ fraction - overview

Non-prompt fraction can be measured in each analysis bin, by fitting the lifetime distribution with a superposition of a Gaussian resolution and an exponential tail

- **Strong pT dependence**
- **No dramatic evolution with energy**
- **Some dependence on rapidity forward (LHCb)**







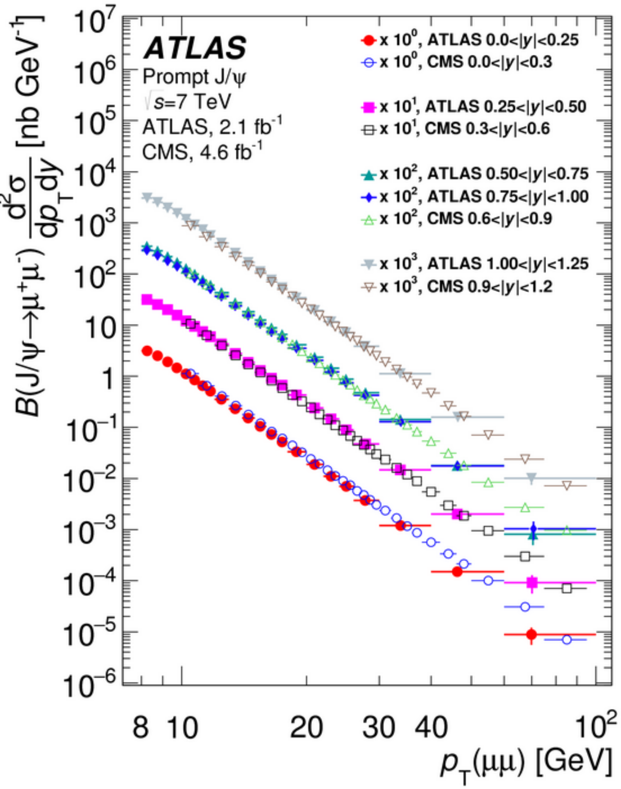
Prompt J/ψ with ATLAS in Run I

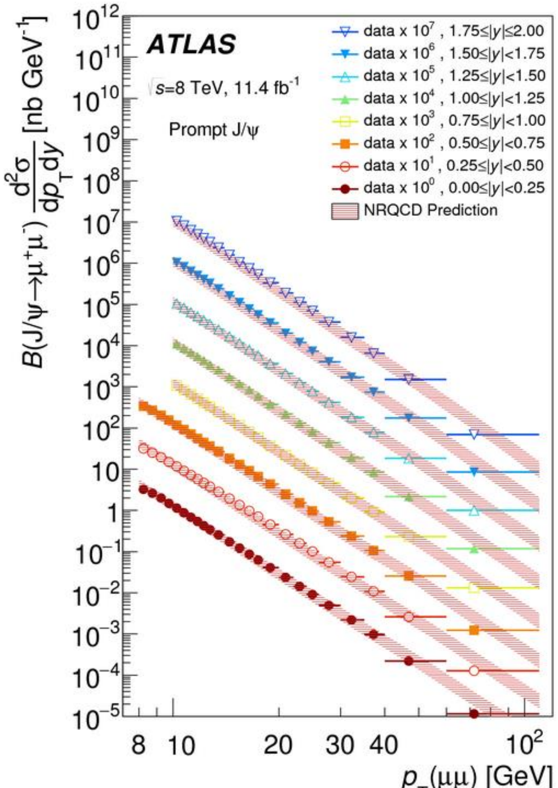
Using a dimuon trigger with 4 GeV threshold – low pT not accessible for ATLAS at high energy / luminosity

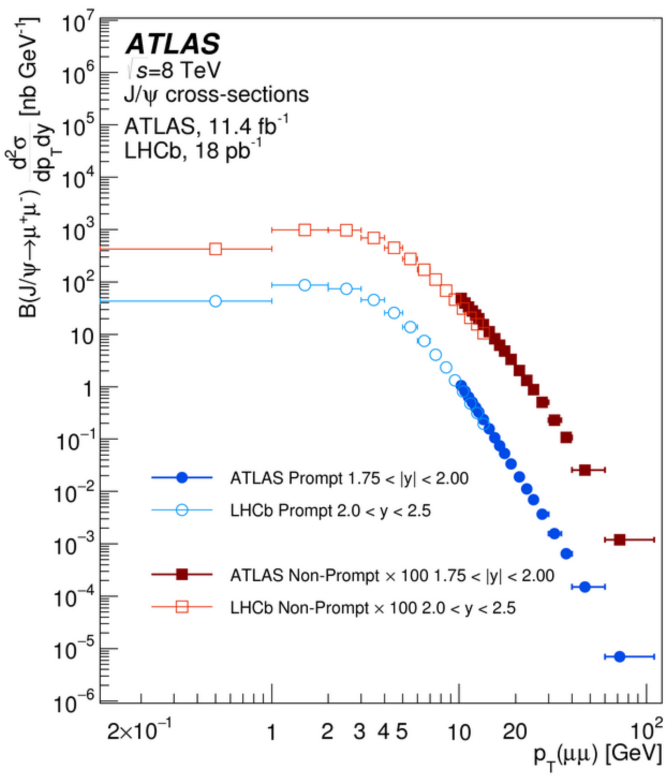
Yields at high pT drop dramatically after ~100 GeV, partly due to muon-muon correlations at trigger level

Good consistency and synergy between ATLAS, CMS and LHCb measurements

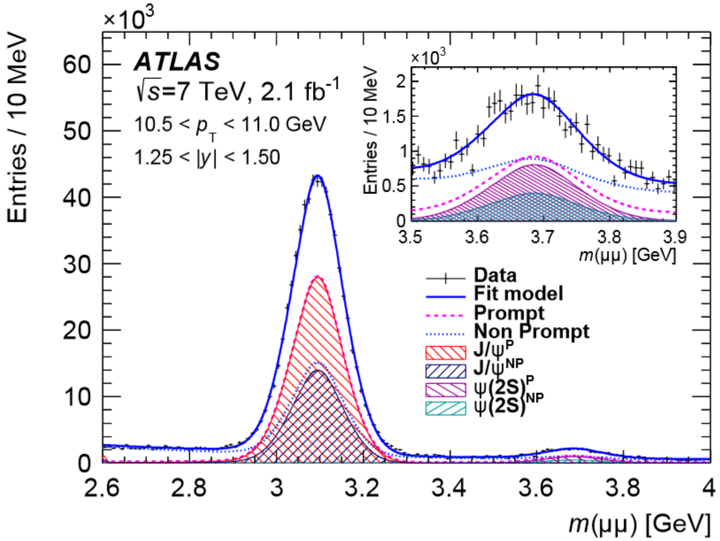
ATLAS Collab. Eur. Phys. J. C 76 (2016) 283







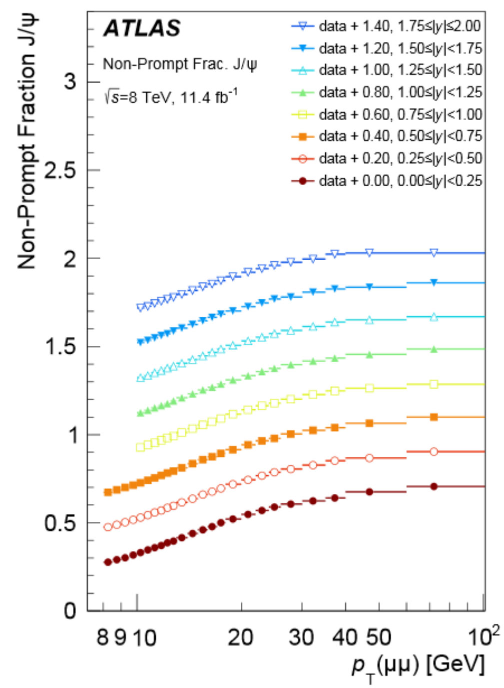
ψ(2S) production: general remarks

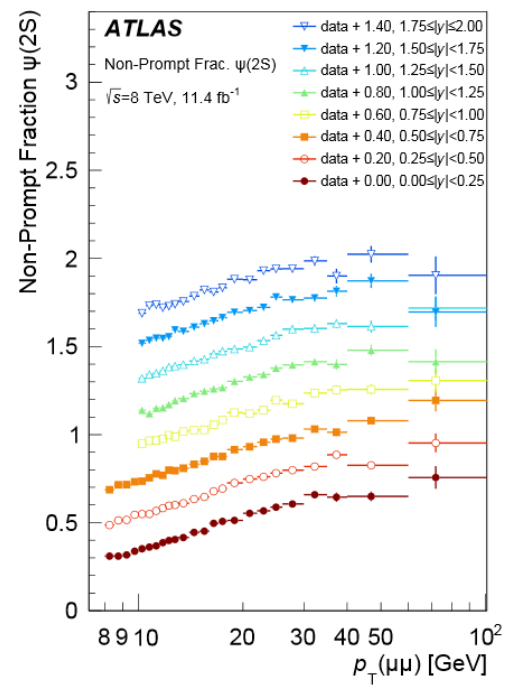


Experimentally, ψ(2S) more challenging:
much lower BR(μμ), hence lower stats, higher background

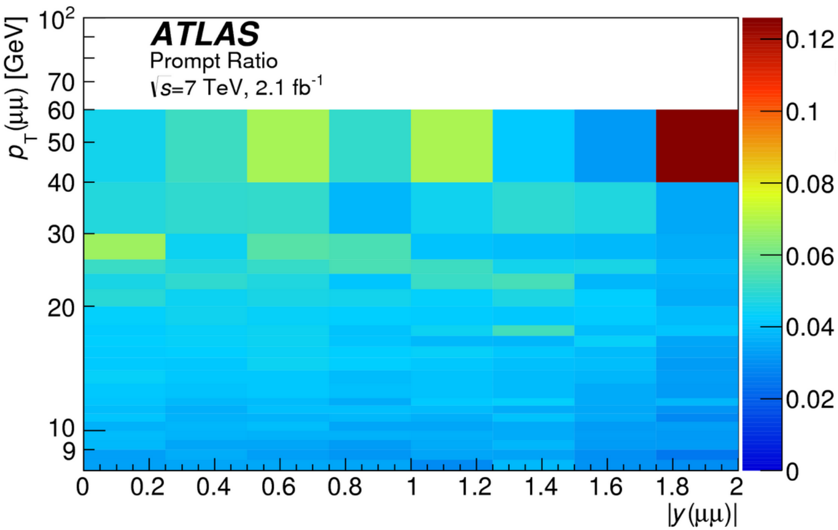
Production mechanism should be theoretically cleaner:
since the discovery of $\chi_b(3P)$ by ATLAS in 2011, ψ(2S) remains the only quarkonium state with no sizeable feeddown

Curiously, non-prompt fraction very similar for J/ψ and ψ(2S)





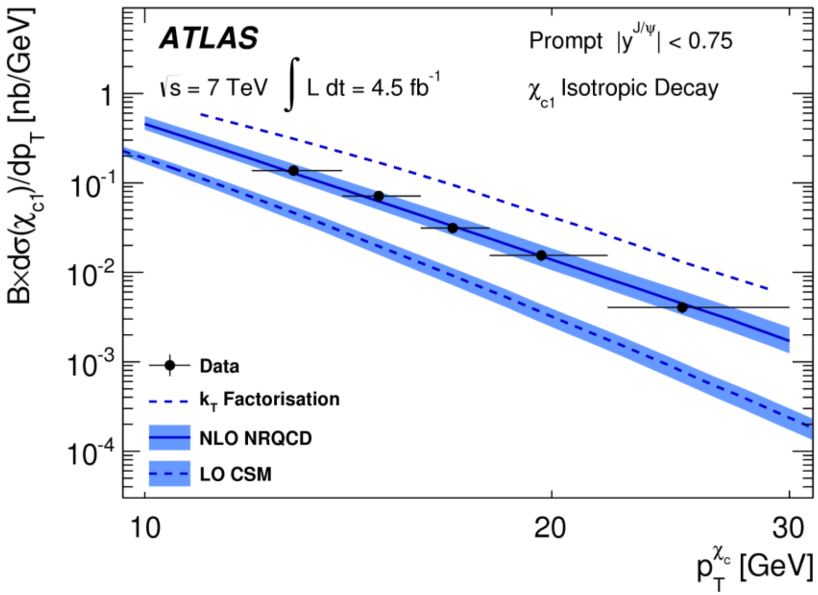
Prompt ψ(2S) / J/ψ ratio close to constant

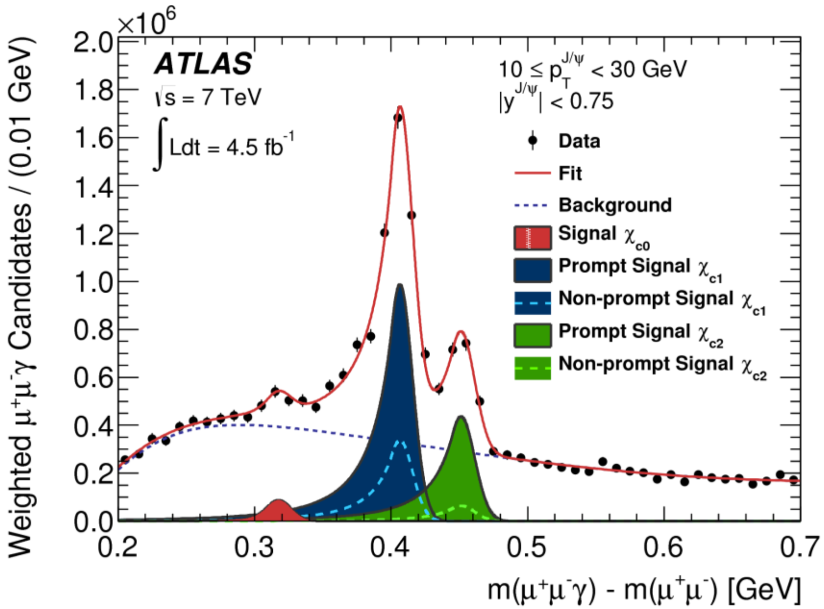


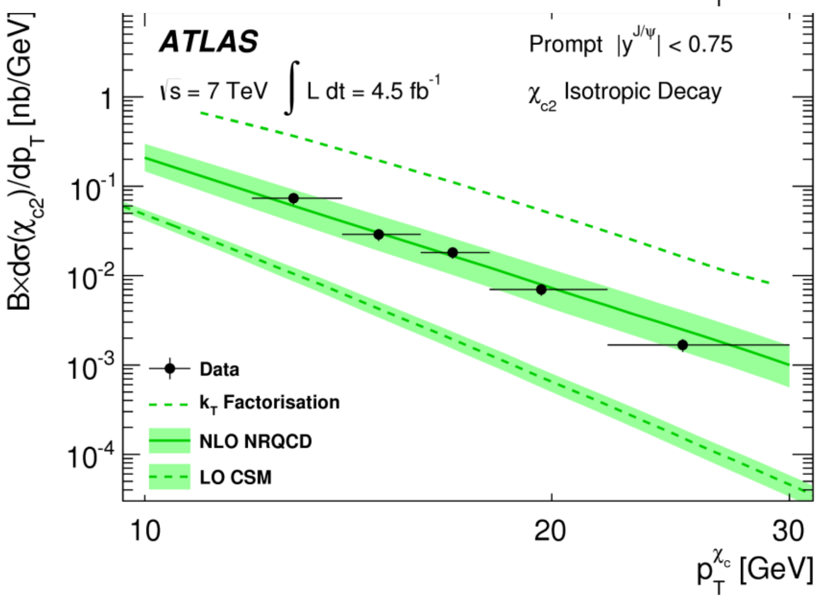
Feeddown from C-even charmonium states

- Two-gluon fusion into 1++ and 2++ states of quarkonium is a viable process
- Feeddown from these states is a significant source of J/ψ production, both prompt and non-prompt
- Measurement of differential spectra by ATLAS in J/ψ + γ decay mode

ATLAS Coll. JHEP07(2014)154





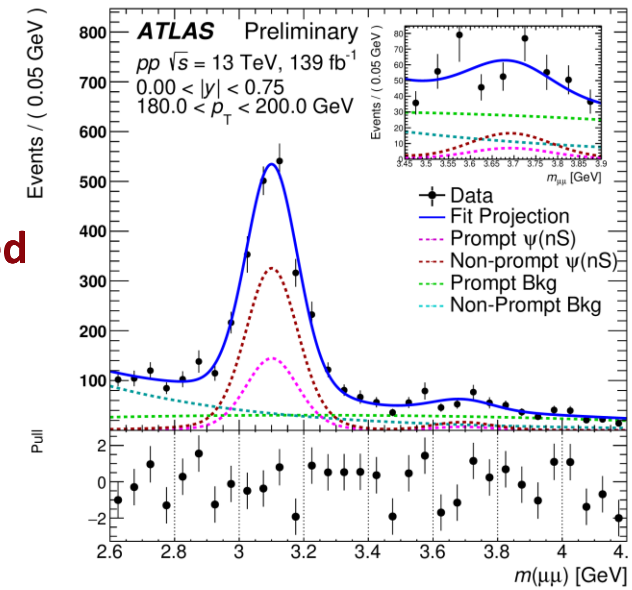


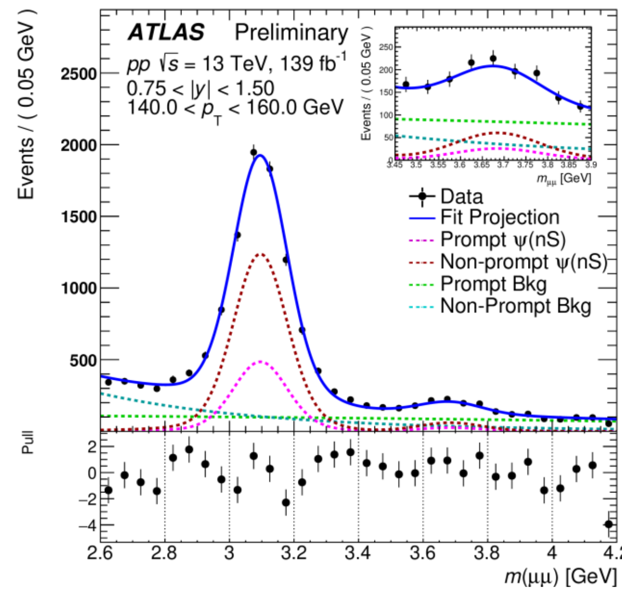
Charmonium production in Run II

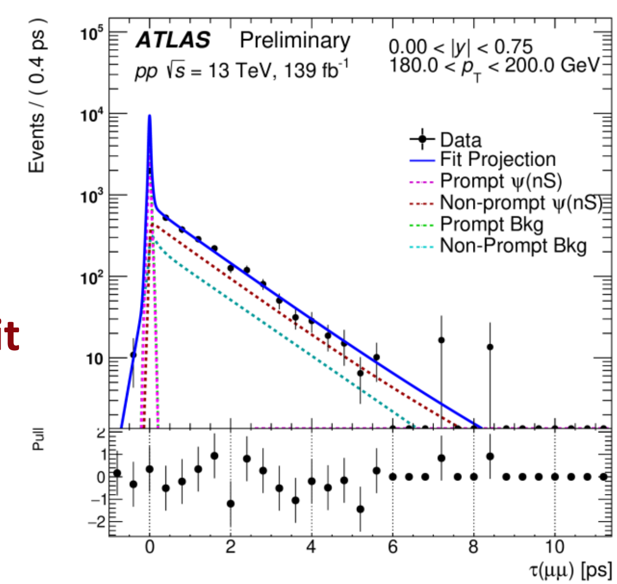
- **Higher energy – 13 TeV, much higher luminosity**
- **Inevitable sharp increase in muon trigger thresholds (or prescale)**
- **Preliminary results at high pT presented here (ATLAS-CONF-2019-047)**
- **Uses a single-muon trigger, with threshold at 50 GeV, un-prescaled for the full integrated luminosity of Run II, 139 / fb**
- **Provides coverage of the high-pT end of the distribution, well beyond previously achieved transverse momenta**
- **pT range covered: 60-360 GeV for J/ψ in 11 bins (60-140 GeV for ψ(2S))**
- **Rapidity range |y| < 2 covered in three bins**

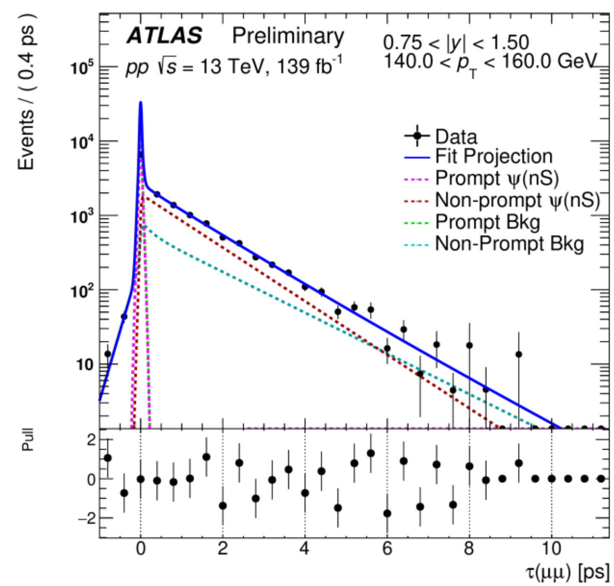
Mass and lifetime fits of 13 TeV data

- **Yields determined from an unbinned ML fit in 2D**
- **Fit function fairly complicated**
- **Corrected for acceptance, trigger and reconstruction efficiencies**
- **Projections shown here for some bins**
- **Yields for J/ψ and ψ(2S), as well as both non-prompt fractions and ψ(2S) to J/ψ ratios determined from the fit**
- **Most important systematic uncertainties assessed**



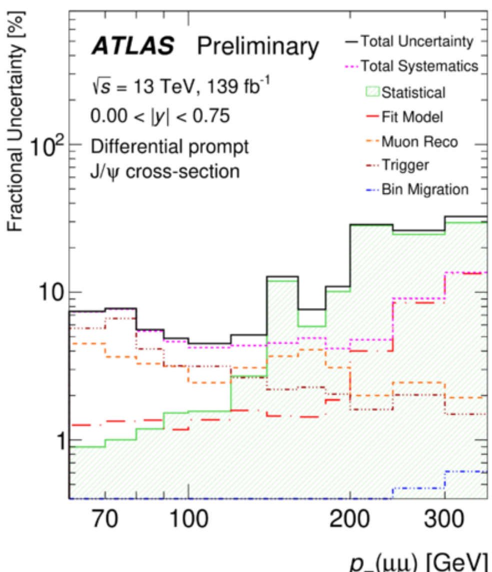


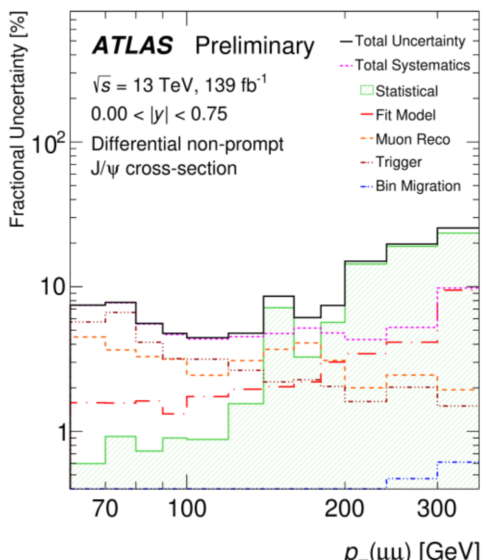


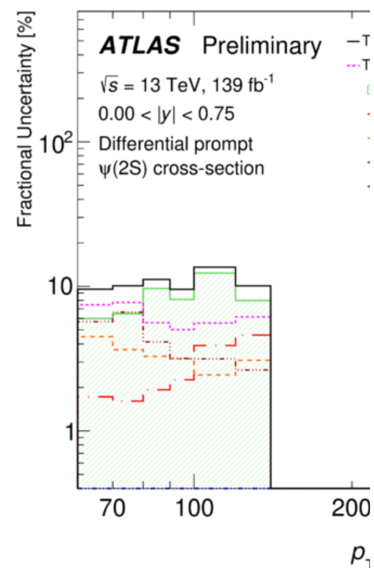


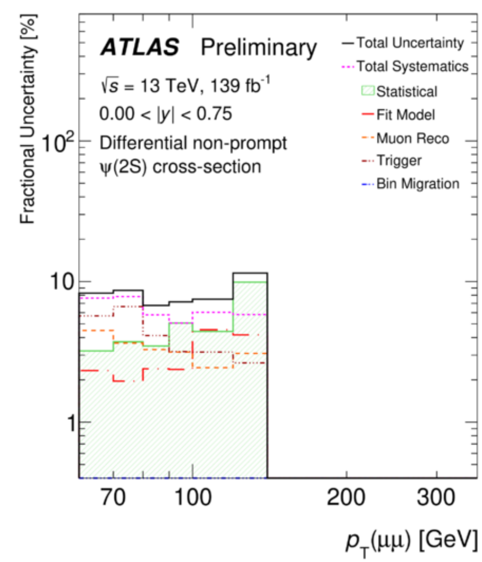
Systematic studies

- **Systematics due to fit model variation, muon and track reconstruction efficiency determination, trigger efficiency determination, and bin-to-bin migration have been studied**
- **Systematic uncertainties dominate for J/ψ up to pT of about 140 GeV**
- **At higher pT of J/ψ, and also for full range of pT for ψ(2S), statistical errors are dominant.**
- **Overall uncertainties for J/ψ start at the level of 5-7%, increasing at the highest pT to 30%**
- **For ψ(2S), uncertainties fairly stable at around 10%**

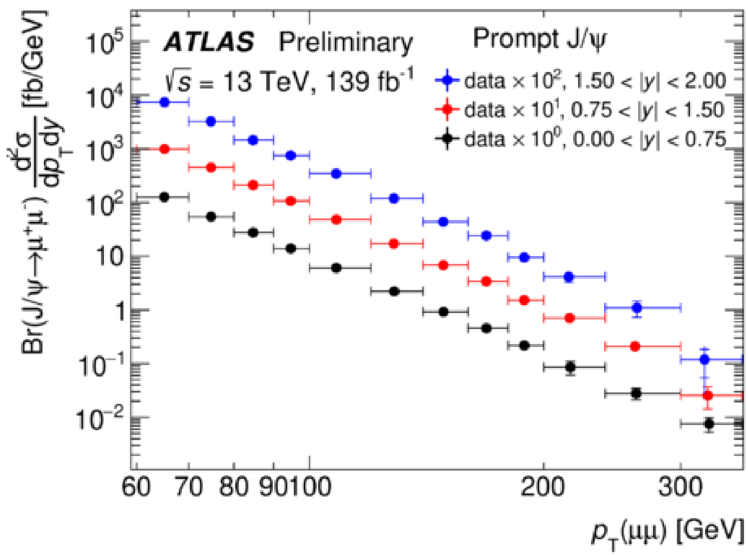


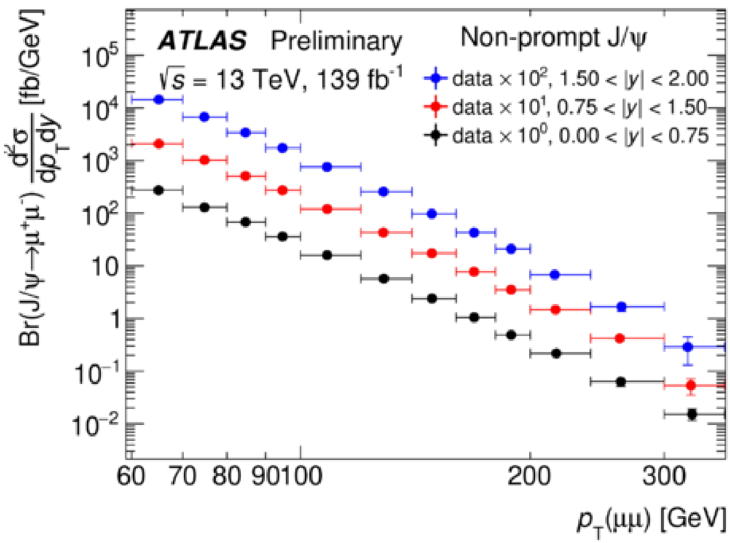


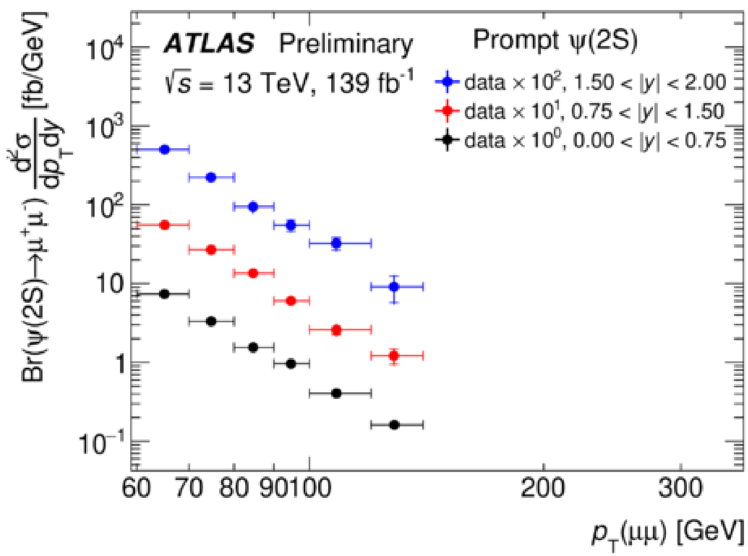


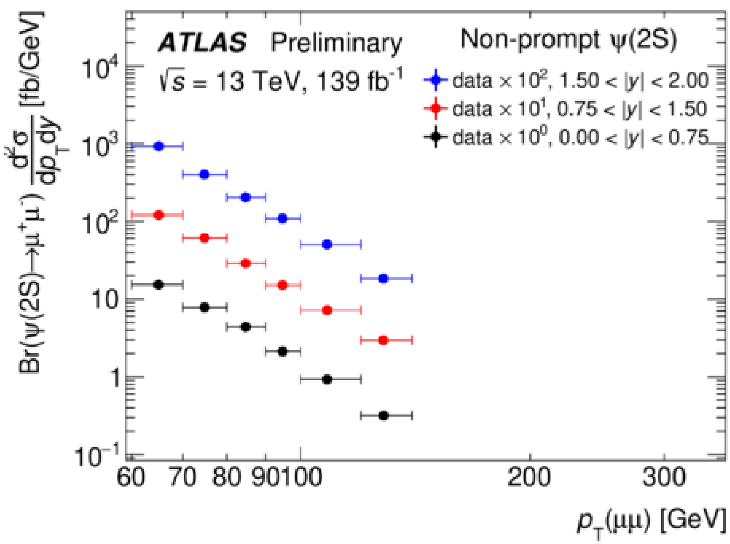


Differential cross sections



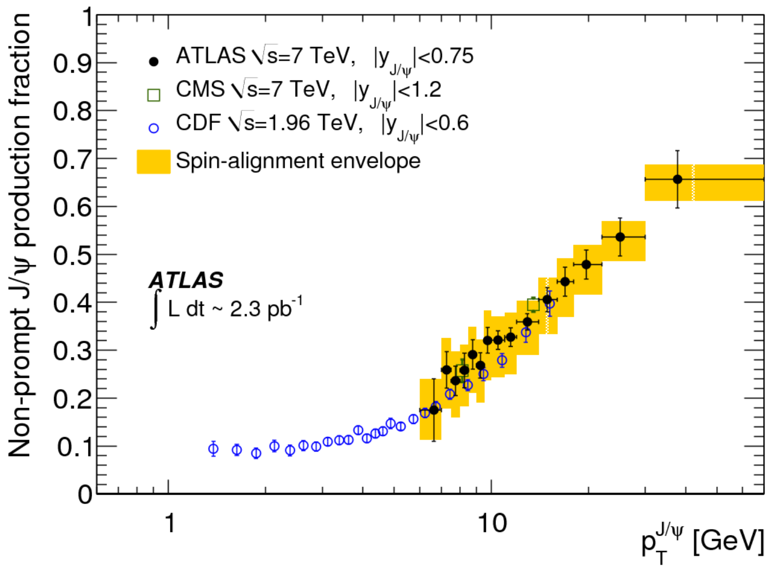


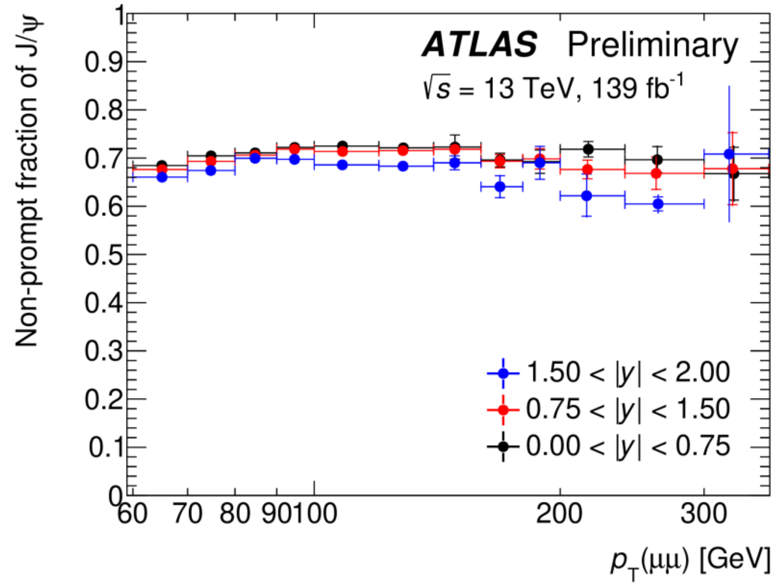




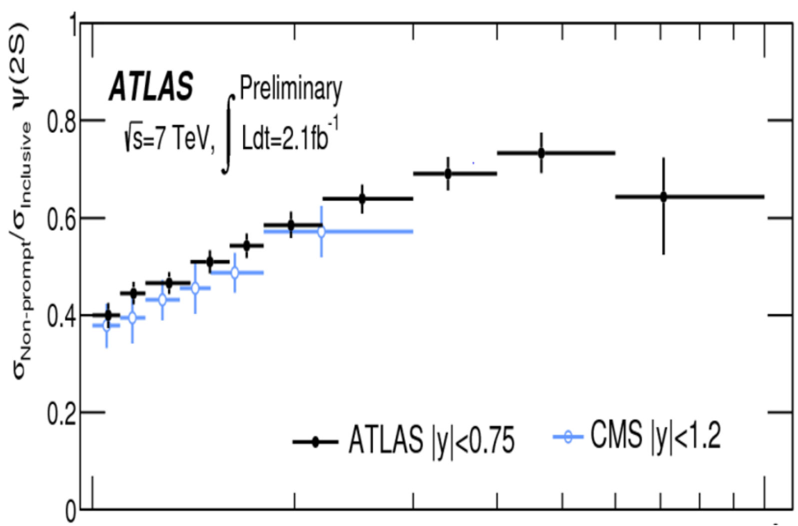
Non-prompt fractions

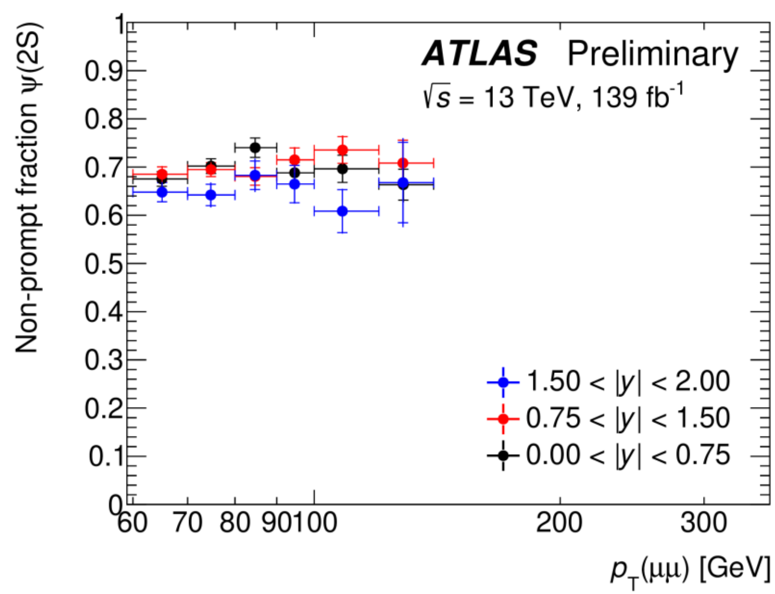
J/ψ



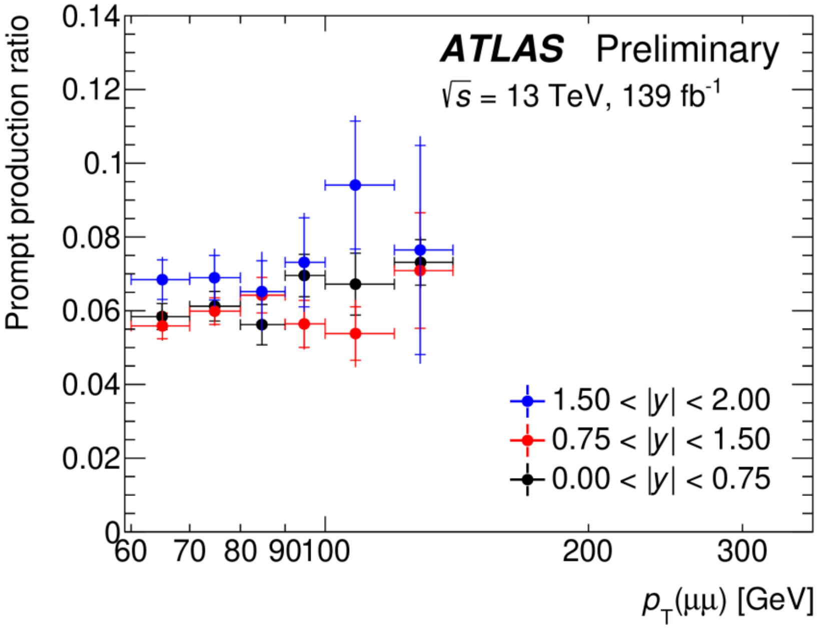


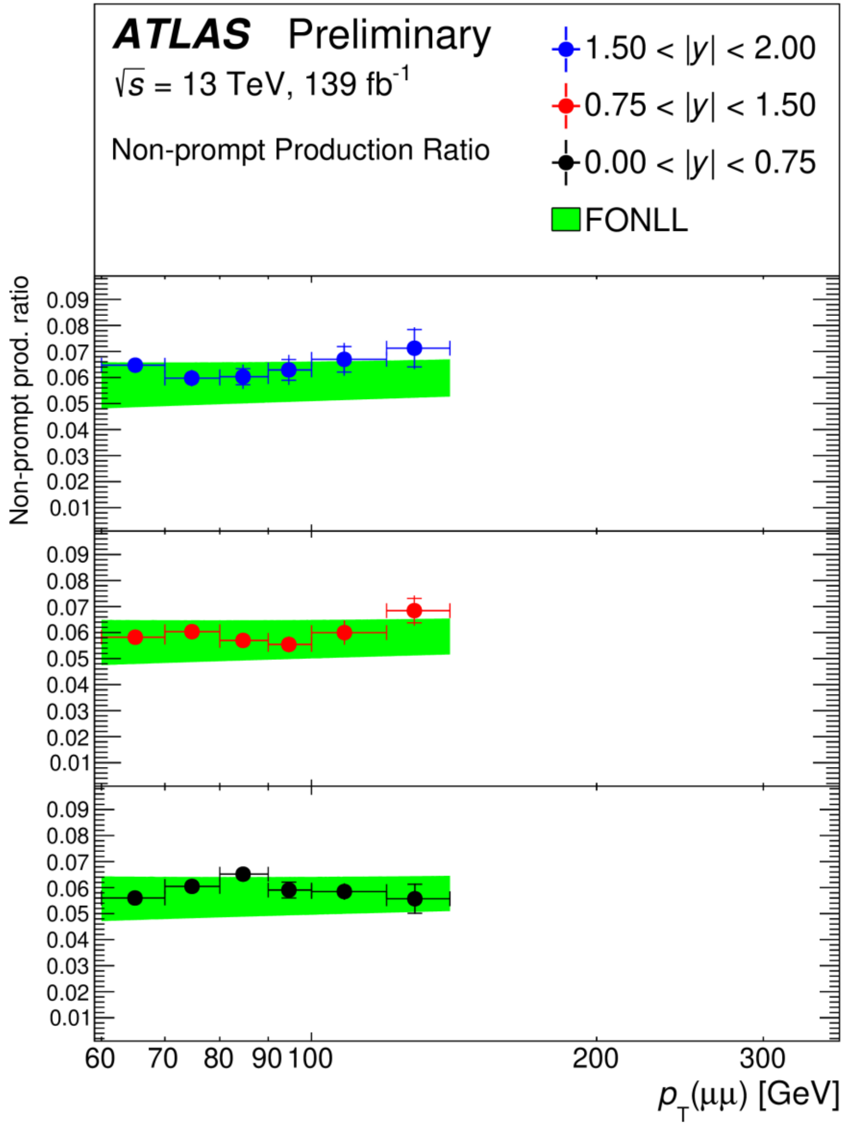
ψ(2S)





Prompt and non-prompt ψ(2S) / J/ψ ratios

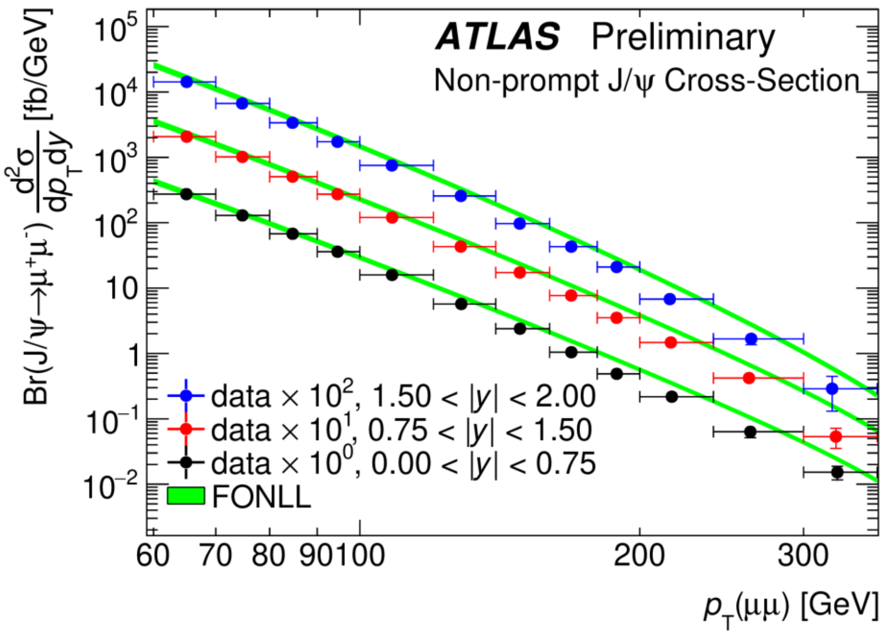


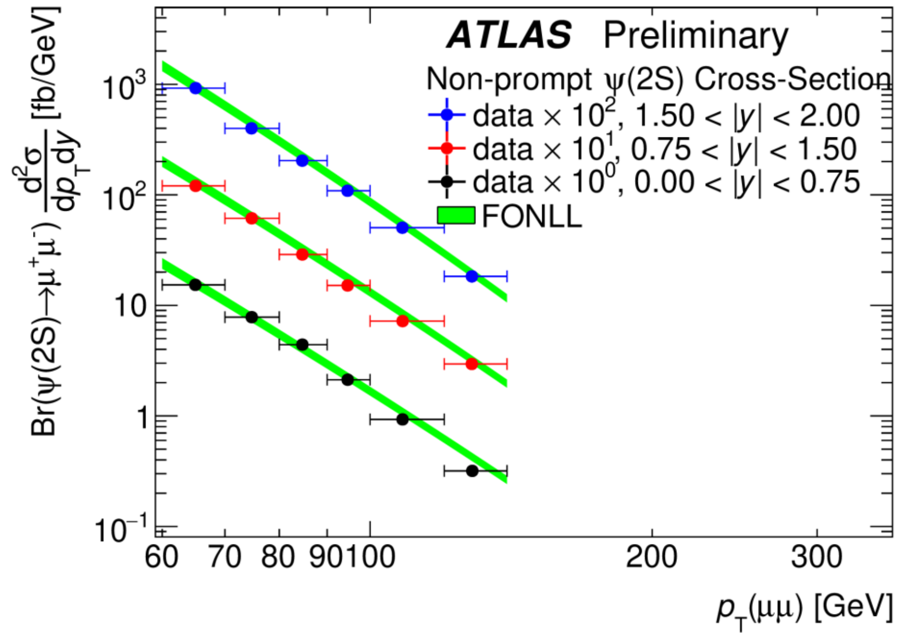


- Ratios not corrected for BR(μμ)
- Naïve estimate ~BR*Γ_{ee} is 5.6%
- Both production ratios roughly constant over the range
- Prompt is more susceptible to stat fluctuations
- FONLL prediction largely holds

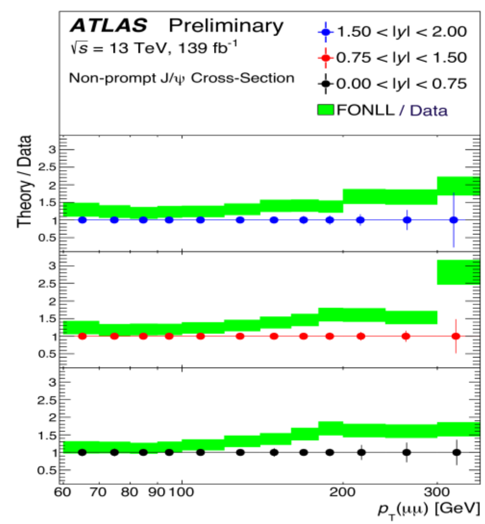
http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html

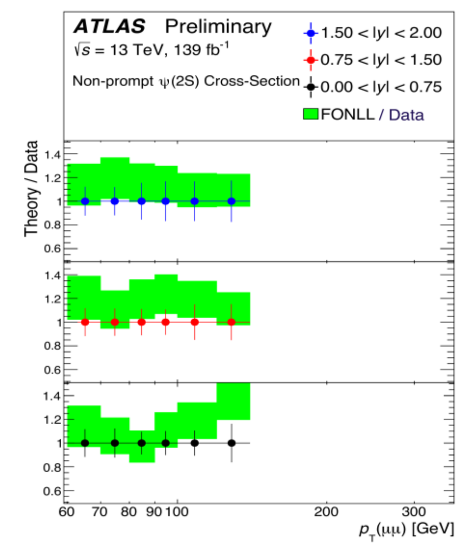
Non-prompt cross sections vs FONLL





- **FONLL predictions seem to work reasonably well**
- **Deviation of ~2 over 5 orders of magnitude**
- **Is it possible to correct high-pT behavior within FONLL framework?**

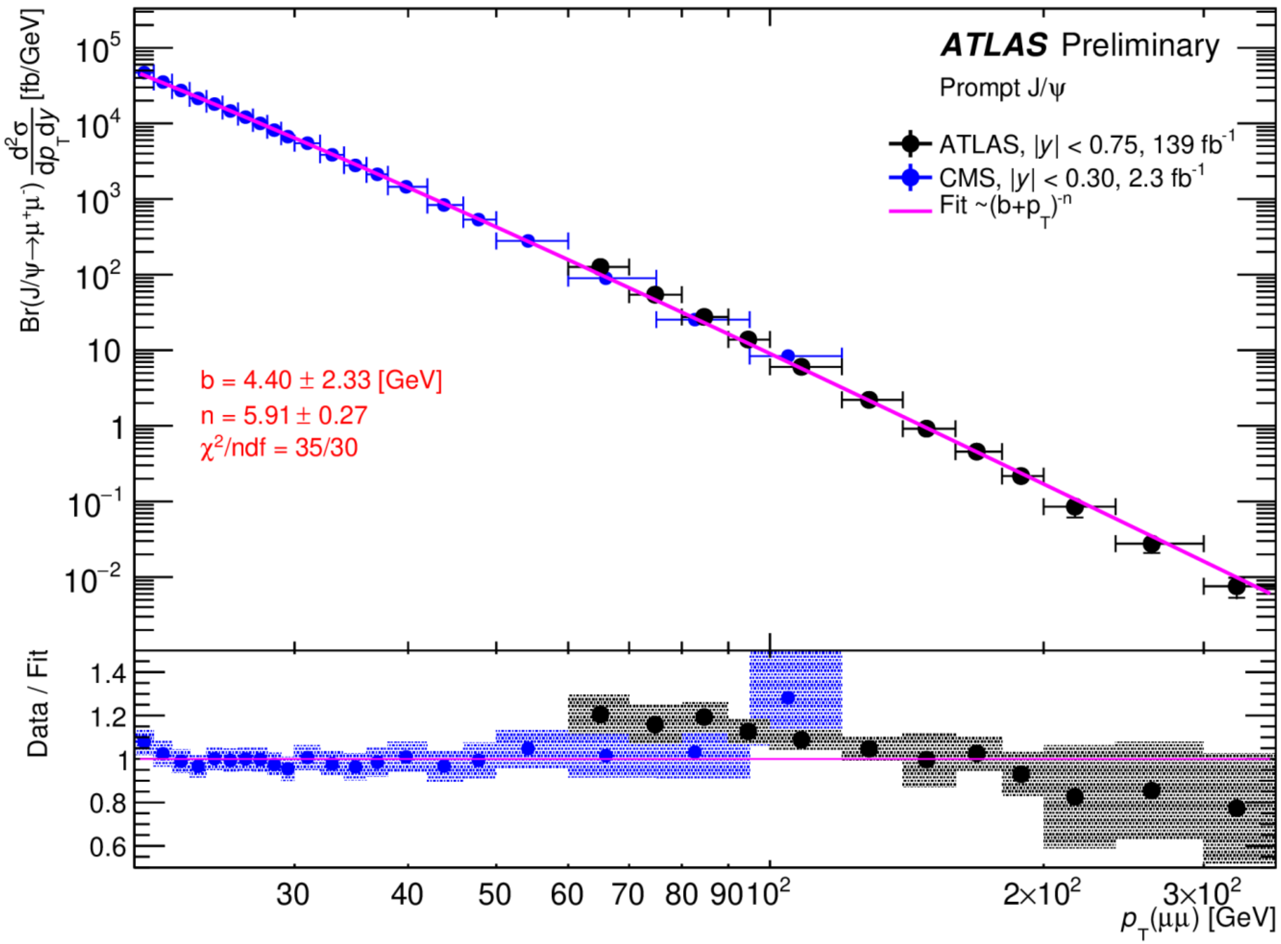




Prompt cross section comparison

CMS early measurement covers pT range from 20 up to 120-150 GeV

Phys. Lett. B780(2018) 251



Together smoothly cover 20-360 GeV

Simple parameterisation

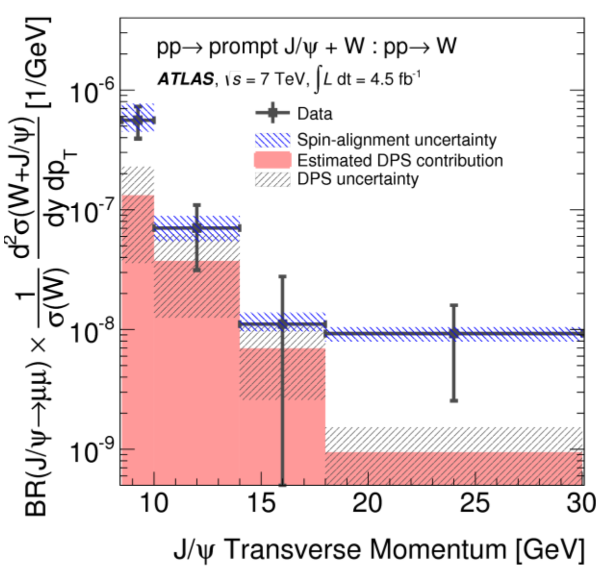
$\sim(b+pT)^{-n}$

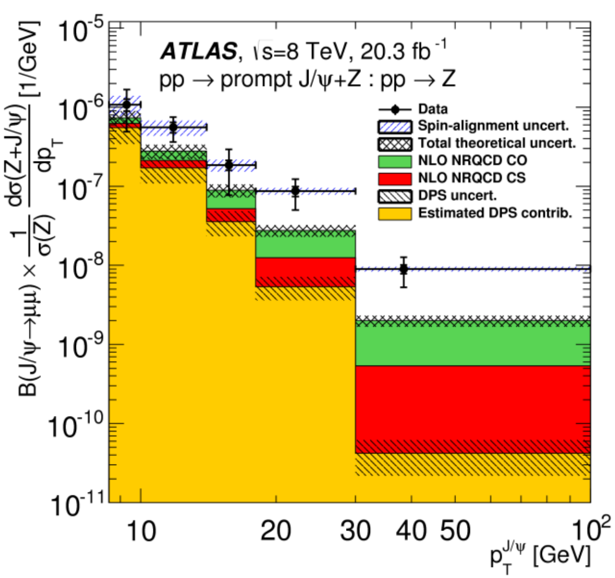
describes data well, over 7 orders of magnitude, with b=4.4 and n=6

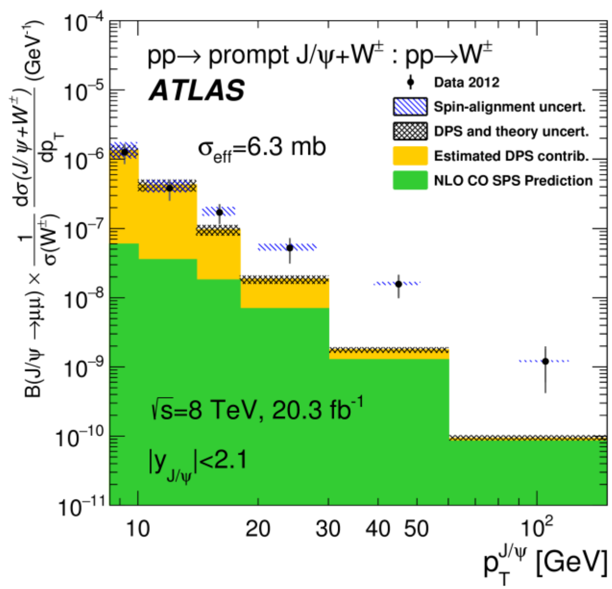
It would be interesting to see how NRQCD-based model calculations compare with the data, especially at the high pT end

Related: Associated production of J/ψ

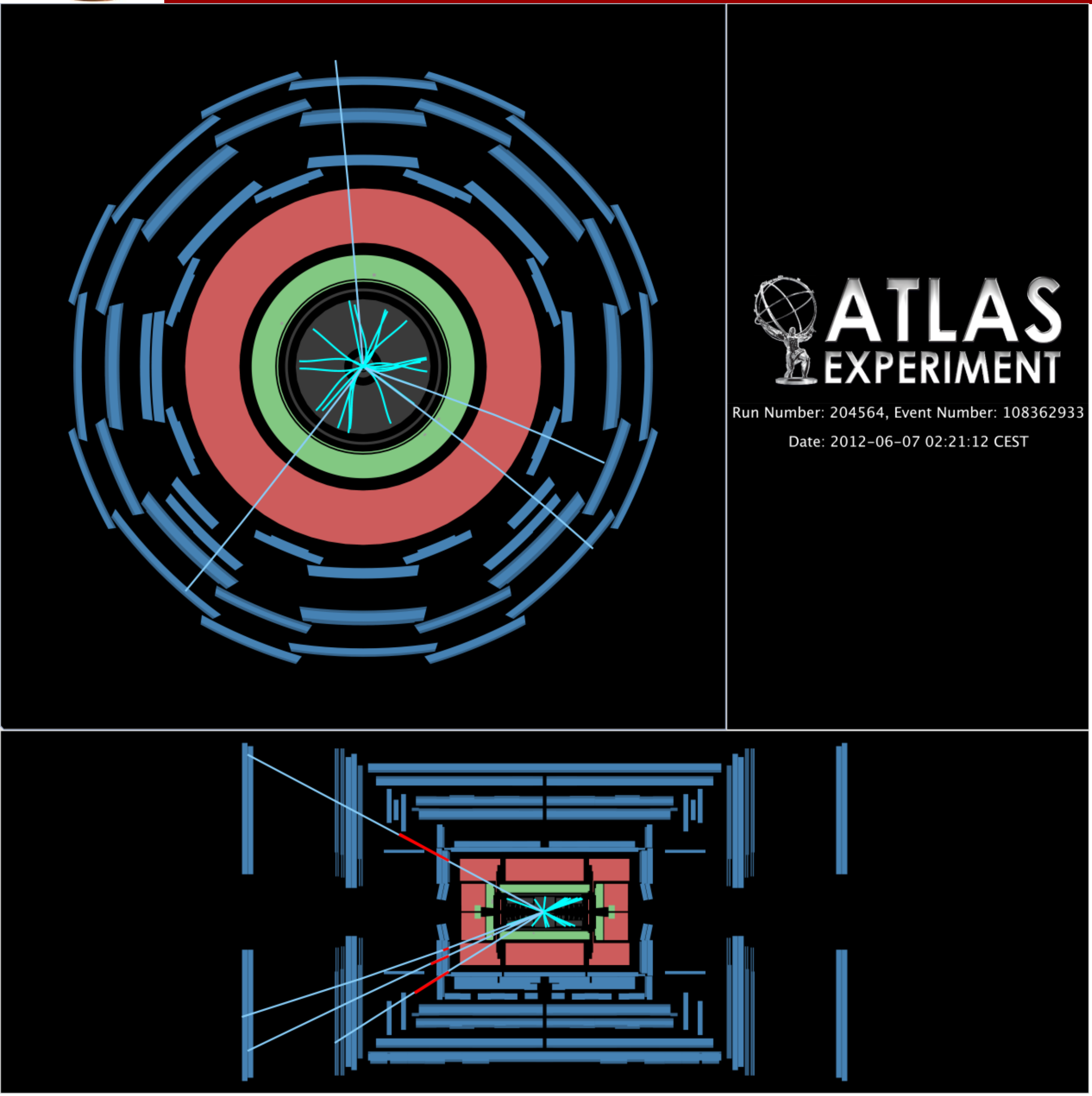
- **Several measurements by ATLAS of such processes**
  - **W+J/ψ at 7 TeV** **JHEP 04 (2014) 172** **(prompt only)**
  - **Z +J/ψ at 8 TeV** **EPJ C75 (2015) 229** **(prompt, non-prompt)**
  - **J/ψ+J/ψ at 8 TeV** **EPJ C77 (2017) 76** **(prompt only)**
  - **W+J/ψ at 8 TeV** **JHEP 01 (2020) 095** **(prompt, non-prompt)**
- **Difficult to obtain fully corrected distributions, mainly concentrating on ratios like (J/ψ + V) / $V_{inclusive}$ differentially in J/ψ parameters, with SPS-DPS separation**
- **Large excess over NRQCD predictions, especially at higher pT, even with smaller-than-usual σ_{eff}**







J/ψ + Z^0 : event candidate



Thank you for your attention!

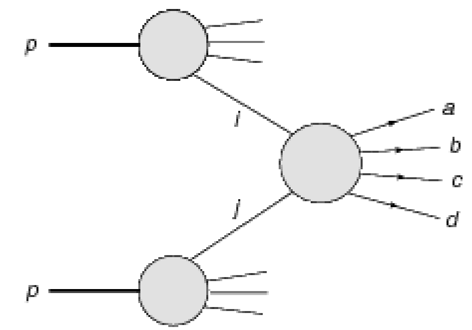
BACKUP SLIDES

Associated production: DPS and SPS

The production of two objects in the same pp collision can be due to

Single-Parton Scattering (SPS):

- **the two objects are produced via a subprocess in a single interaction of two partons**
- **can be treated in the usual way, once the subprocess cross section is calculated**
- **expected to be "back-to-back" in transverse plane**

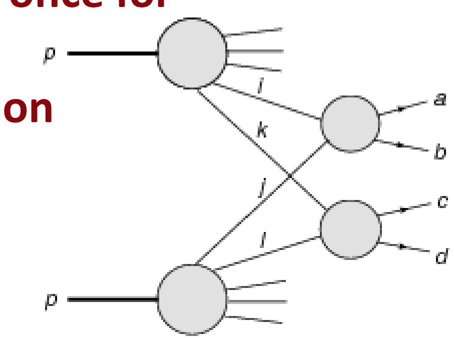


Double-Parton Scattering (DPS):

- **simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated**
- **one can apply the usual parton model / QCD formalism TWICE, once for subprocess A and once for subprocess B**
- **Dimensional factor σ_{eff} determines the scale of the cross section**

$$\sigma^{\text{DPS}}_{A+B} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

- **assumed (hoped?) to be independent of process and energy**



E. Berger et al. Phys.Rev. D84 (2011) 074021 arXiv:1107.3150 [hep-ph]