Charmonium production in pp collisions with ALICE at the LHC

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for the ALICE Collaboration

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Motivation

Charmonia (J/ψ, ψ(2S), χ_c) are bound states of a *ccbar* quark pair
Their production is understood as the production of the *ccbar* pair in a hard-scattering process, followed by the evolution of this pair into a colorless bound state

The *c* quark mass should provide a high enough hard scale for pQCD to be applicable, but the evolution into a bound state is intrinsically non perturbative

Charmonium production measurements are interesting

- in pp, to understand production mechanism, probe Parton Distribution Functions (PDFs), especially for gluons, down to low *x* and as a reference to p-Pb and Pb-Pb
- in p-Pb, to probe so-called cold nuclear matter effects (modification of the PDFs, saturation, Cronin enhancement, etc.)
- in Pb-Pb, to probe the formation and properties of the Quark-Gluon Plasma (color screening, dissociation, recombination)

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Outline

Few words about the apparatus and analysis

New results on forward-y J/ψ and ψ(2S) production in pp collisions at $\sqrt{s}$ = 13 TeV

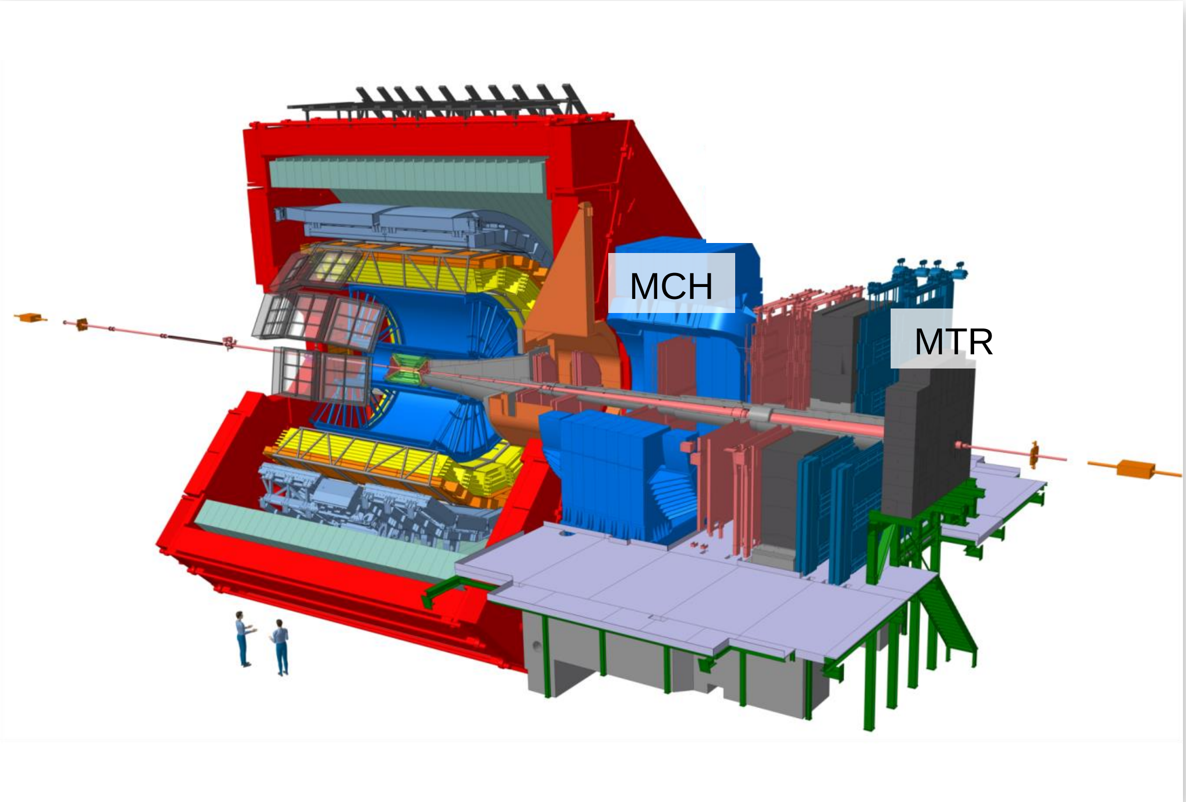
- comparison to other experiments
- comparison to lower energies
- comparison to models

All figures are from EPJ. C 77 (2017) 392

Inclusive measurements contain contributions from

- direct production
- decay from higher mass resonances (for J/ψ, they are ψ(2S) and χ_c)
- decay from *b*-hadrons (also called non-prompt J/ψ, ψ(2S))

Forward-y charmonium measurements in ALICE



ALICE measures quarkonia at both mid (|y|<1) and forward (2.5<y<4) rapidities. In this presentation we focus on forward measurements

<u>ALICE Muon system</u>:

- 5 stations of tracking chambers (2.5<η<4)
- 2 stations of trigger chambers
- dipole magnet
- absorbers

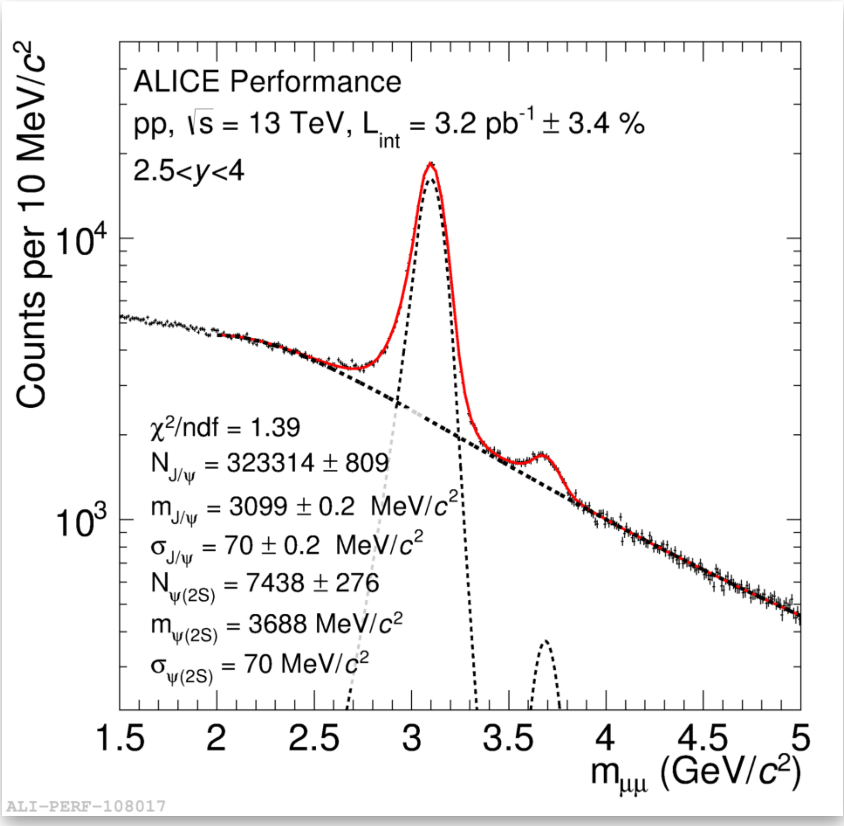
At forward rapidity (2.5<y<4) charmonia are measured in the $\mu^+\mu^-$ decay channel and down to $p_T = 0$ using

- ITS for vertex determination
- MTR for muon identification and triggering
- MCH for tracking

V0 detectors are also used for triggering (in coincidence with MTR)
T0 detectors for luminosity determination

Data analysis

Charmonia measured using fits to the invariant mass distribution of $\mu^+\mu^-$ pairs detected in the muon system



Muon track selection:

- Muon tracking-trigger matching
- $4 < \eta_\mu < 2.5$, $2.5 < y_{\mu\mu} < 4$
- $17.6 < R_{abs} < 89$ cm (R_{abs} = track radial position at the end of the front absorber)

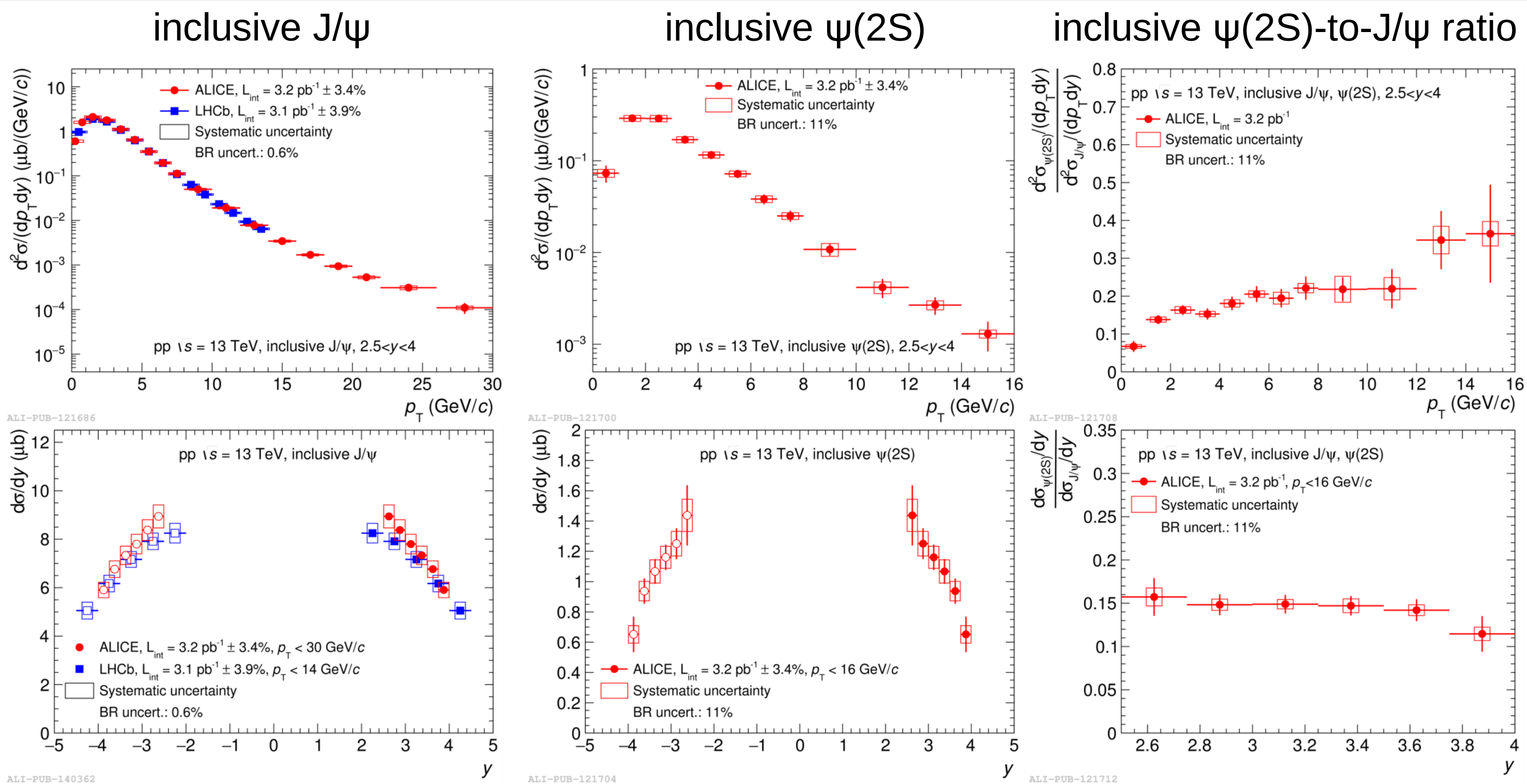
pp@13 TeV data sample from 2015 run at LHC

$$L_{int} = 3.2 \text{ pb}^{-1} \pm 3.4\%$$

Corresponds to: $N_{J/\psi} = 325$k
$N_{\psi(2S)} = 7.5$k

Systematic uncertainties on cross sections amount to ~7% for J/ψ and ~10% for ψ(2S). They include contributions from signal extraction, acceptance x efficiency corrections and luminosity

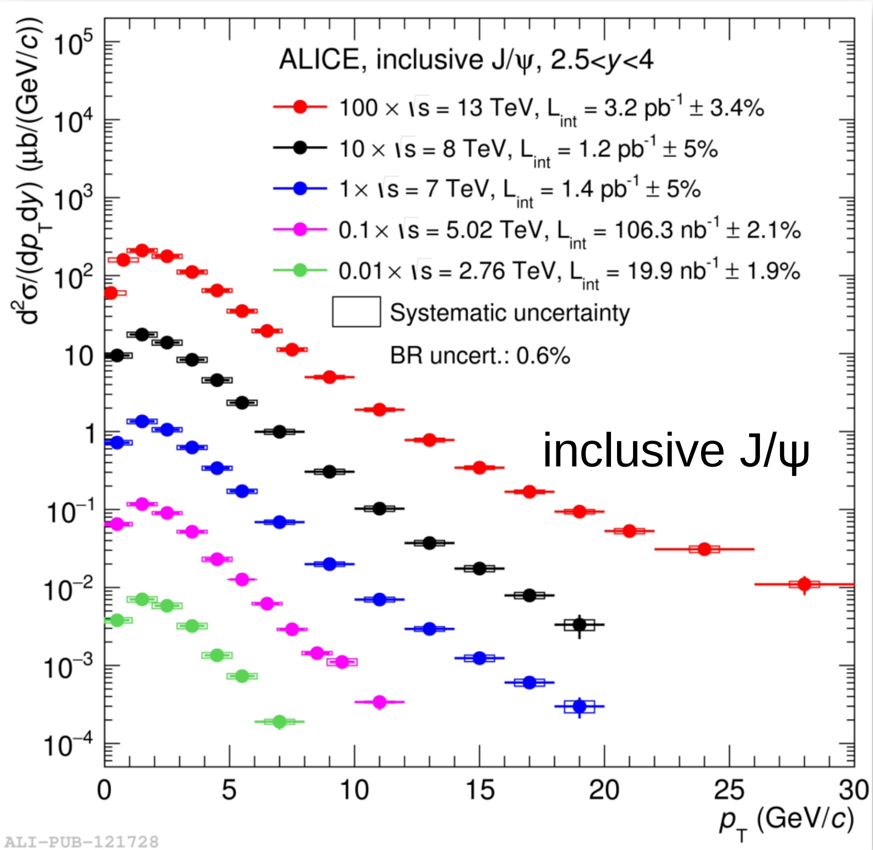
Cross sections and particle ratios in pp@13 TeV

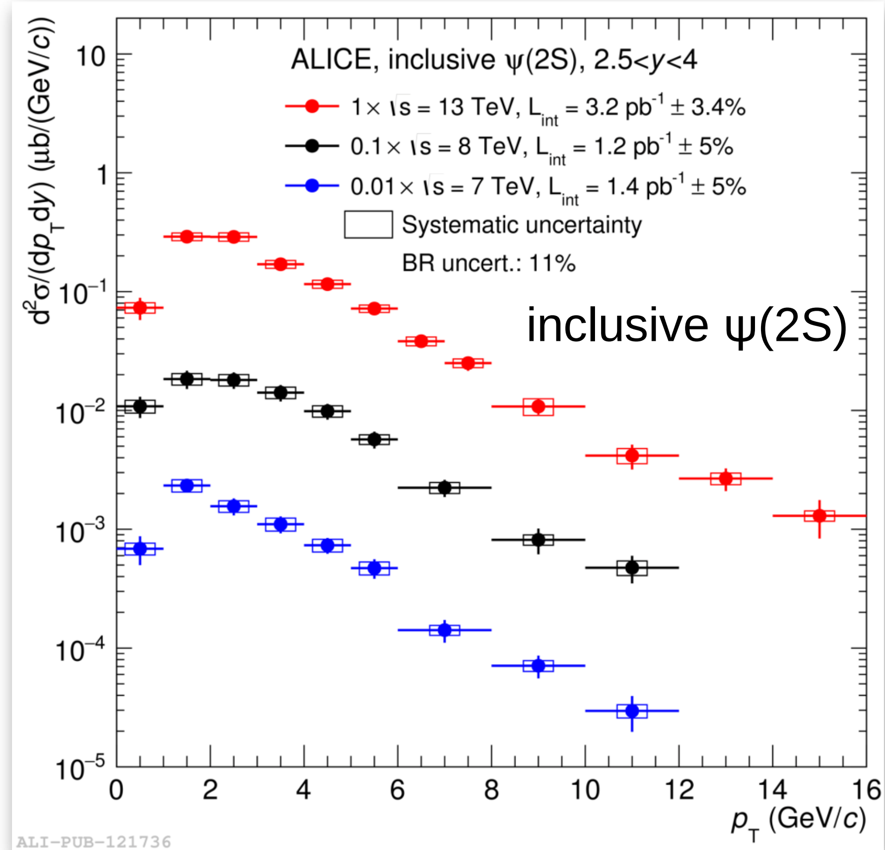


For J/ψ, good agreement with LHCb (JHEP10 (2015) 172 and erratum)

For ψ(2S), only measurement in this rapidity range

Comparison to lower energy, J/ψ and ψ(2S) vs p_T





Comparison to ALICE measurements at $\sqrt{s}$ = 2.76, 5.02, 7 and 8 TeV

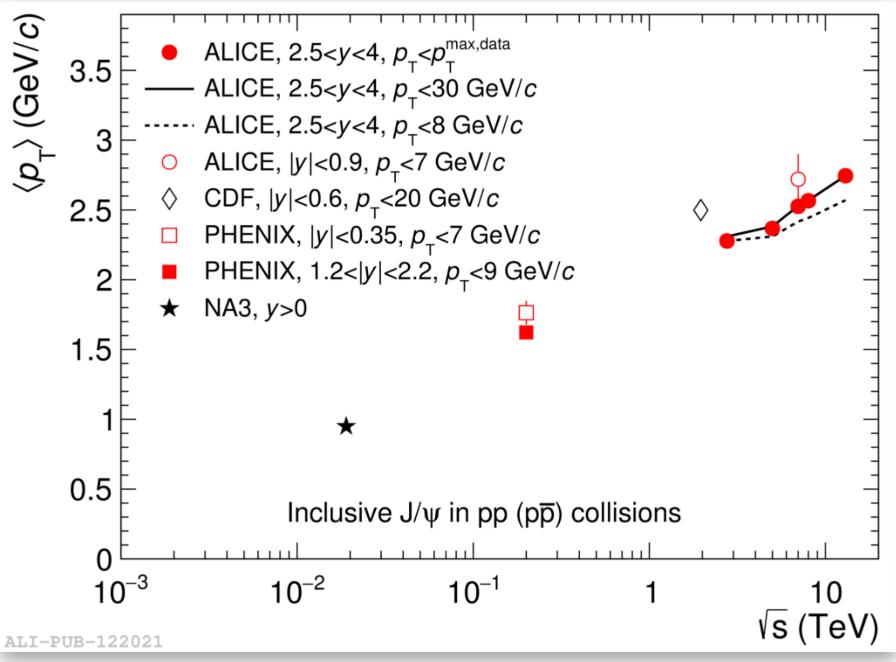
$\sqrt{s}$ = 2.76 TeV	PLB 718 (2012) 295
$\sqrt{s}$ = 5.02 TeV	PLB 766 (2017) 212
$\sqrt{s}$ = 7 TeV	EPJC 74 (2014) 2974
$\sqrt{s}$ = 8 TeV	EPJC 76 (2016) 184

Steady increase of the luminosity and p_T reach with increasing energy
As expected, spectra becomes harder with increasing energy

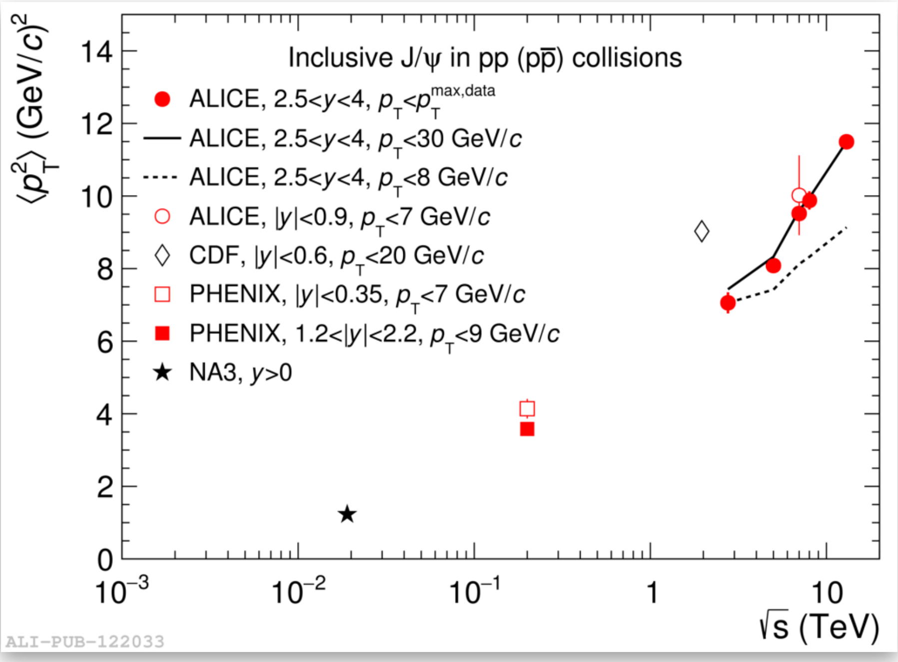
To quantify this we look at $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ vs energy

J/ψ ⟨p_T⟩ and ⟨p_T^2⟩ square vs energy

J/ψ ⟨p_T⟩ vs $\sqrt{s}$



J/ψ ⟨p_T^2⟩ vs $\sqrt{s}$



Circles are ALICE data

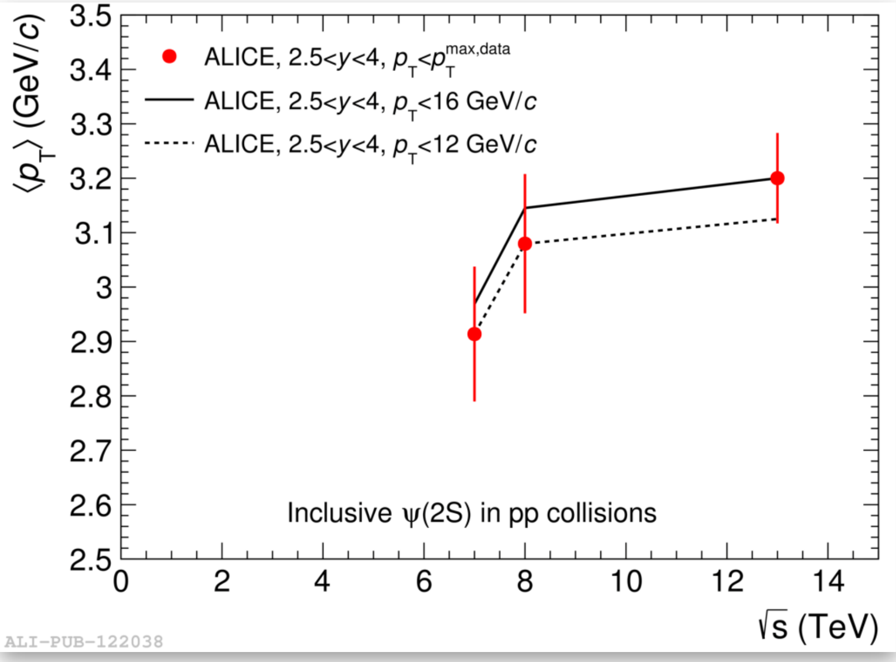
Open symbols are for mid-rapidity measurements

Lines correspond to different p_T integration ranges

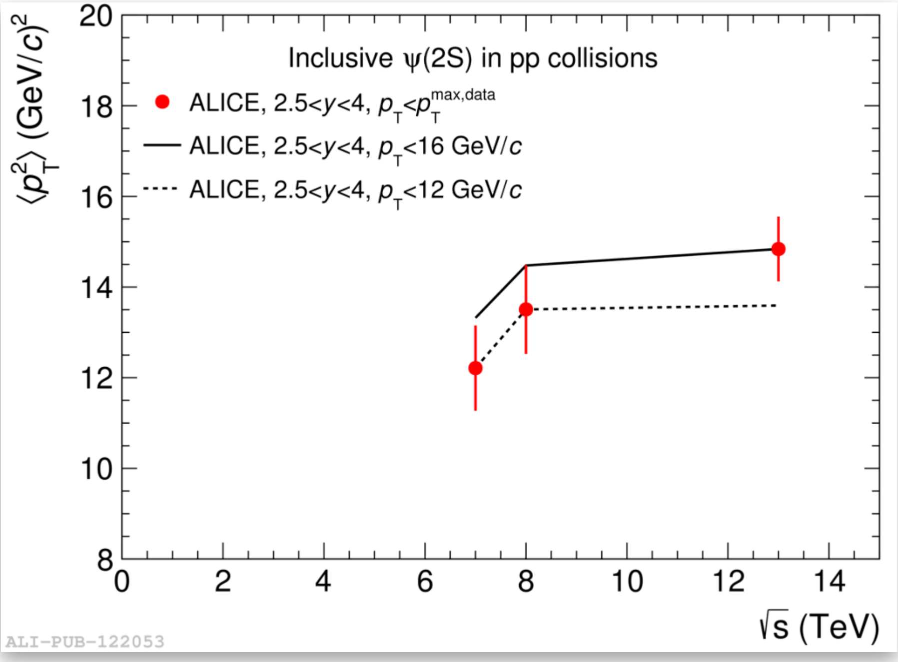
Contribution from b-hadron decays is not subtracted. Might ‘bias’ the measurement at high p_T

ψ(2S) ⟨p_T⟩ and ⟨p_T^2⟩ square vs energy

ψ(2S) ⟨p_T⟩ vs $\sqrt{s}$



ψ(2S) ⟨p_T^2⟩ vs $\sqrt{s}$

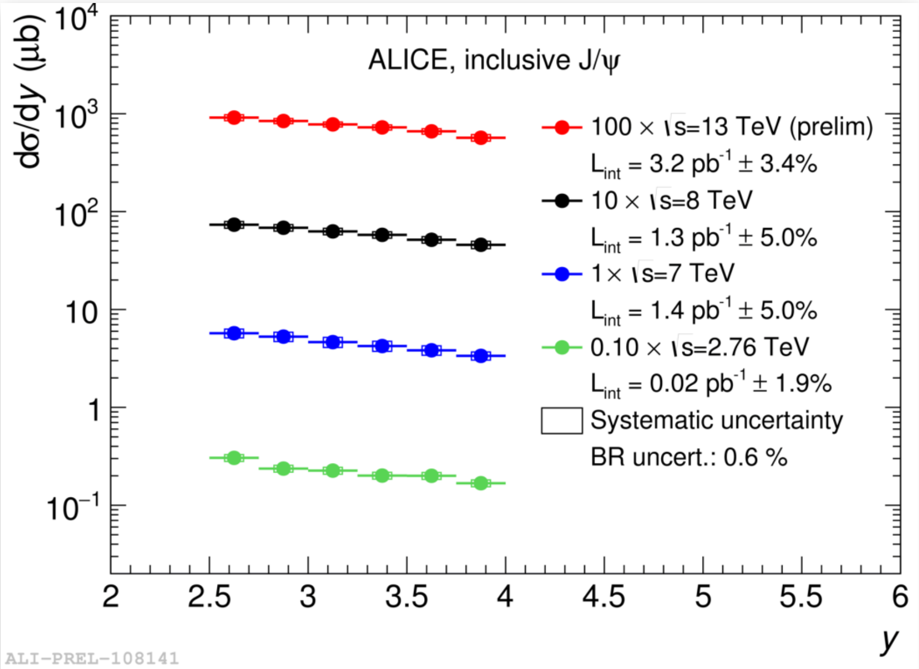


$\sqrt{s}$ = 7 TeV EPJC 74 (2014) 2974
$\sqrt{s}$ = 8 TeV EPJC 76 (2016) 184

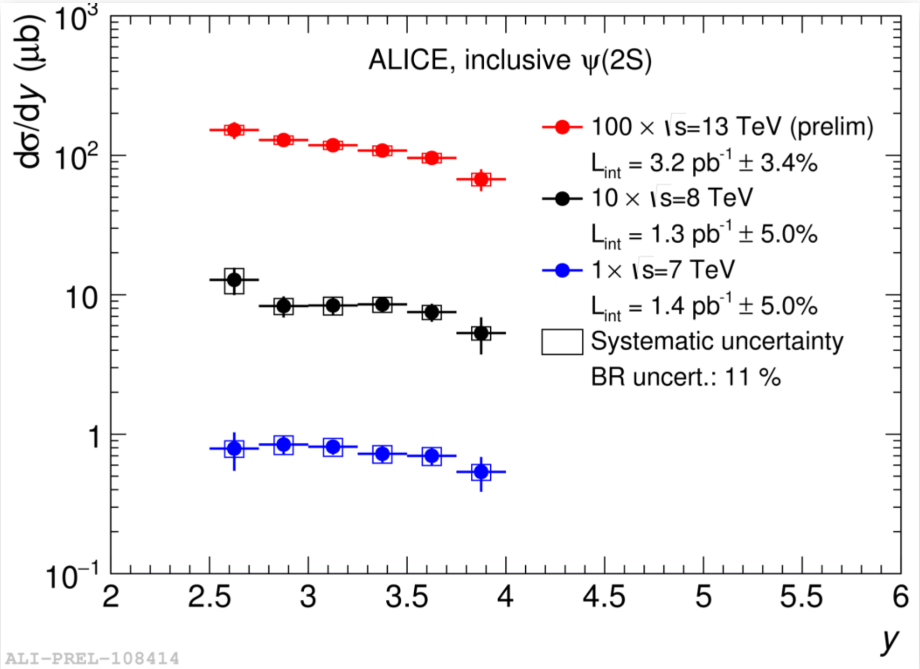
Same trend observed for the ψ(2S) though larger uncertainties and less measurements available (in ALICE and elsewhere)

Comparison to lower energy, J/ψ and ψ(2S) vs *y*

inclusive J/ψ



inclusive ψ(2S)



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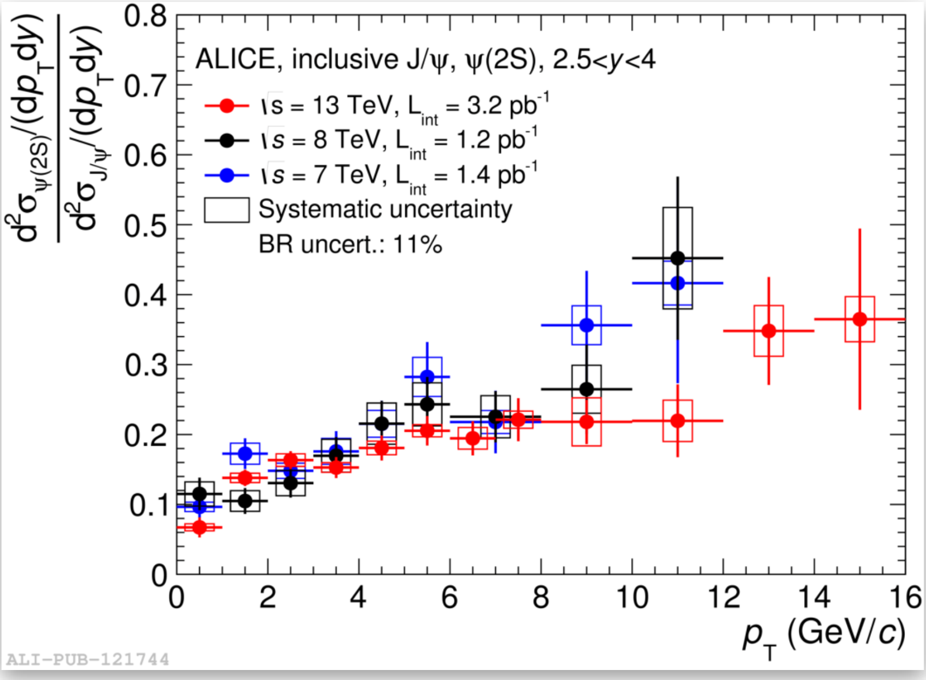
For J/ψ, no visible change in the *y* distribution

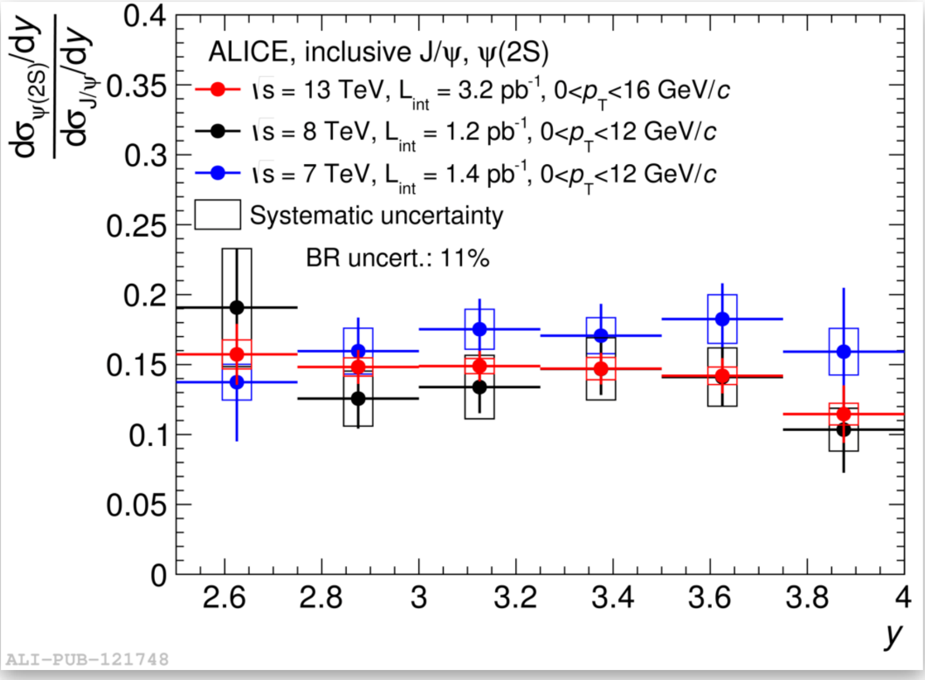
For ψ(2S), large uncertainties prevent firm conclusions

Comparison to lower energy, J/ψ-to-ψ(2S) ratio

Inclusive J/ψ-to-ψ(2S) ratio vs p_T



Inclusive J/ψ-to-ψ(2S) ratio vs y



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No dependence on energy observed within uncertainties

A few words about models

Mainly three approaches used to describe direct charmonium production in pp

- Color Evaporation Model (CEM):
  production cross section of a given charmonium is proportional to the *ccbar* cross section, integrated between the mass of the charmonium and twice the mass of the D meson. Proportionality factor is independent of y, p_T and $\sqrt{s}$

- Color Singlet model (CSM):
  pQCD is used to describe the *ccbar* production with the same quantum numbers (CS) as the final-state meson.

- Non-Relativistic QCD (NRQCD):
  both CS and CO state of the *ccbar* pairs are considered. The relative contribution of the states is parametrized using a finite set of universal long distance matrix elements (LDME), fitted to a subset of the data (e.g. Tevatron)

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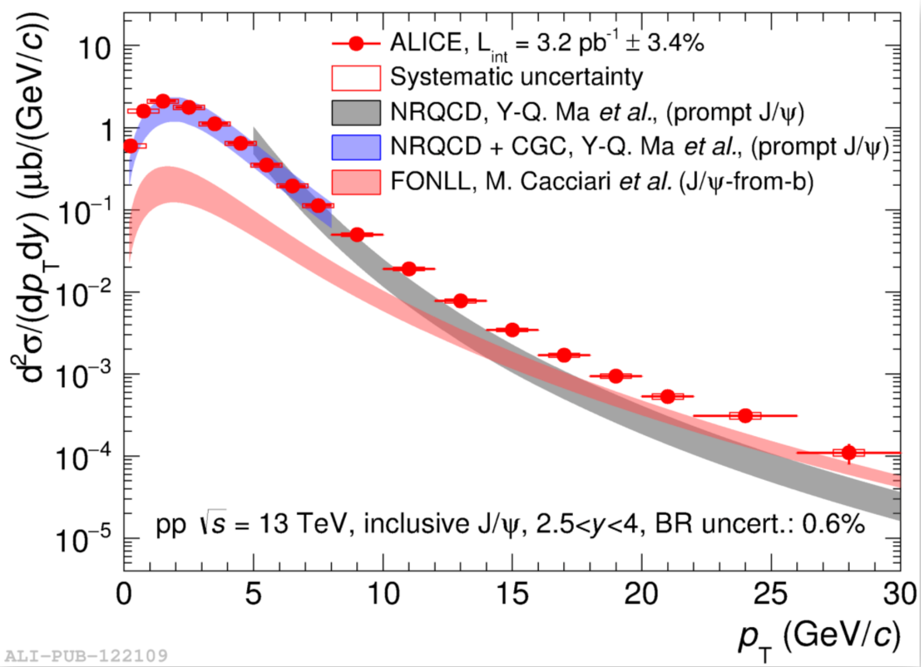
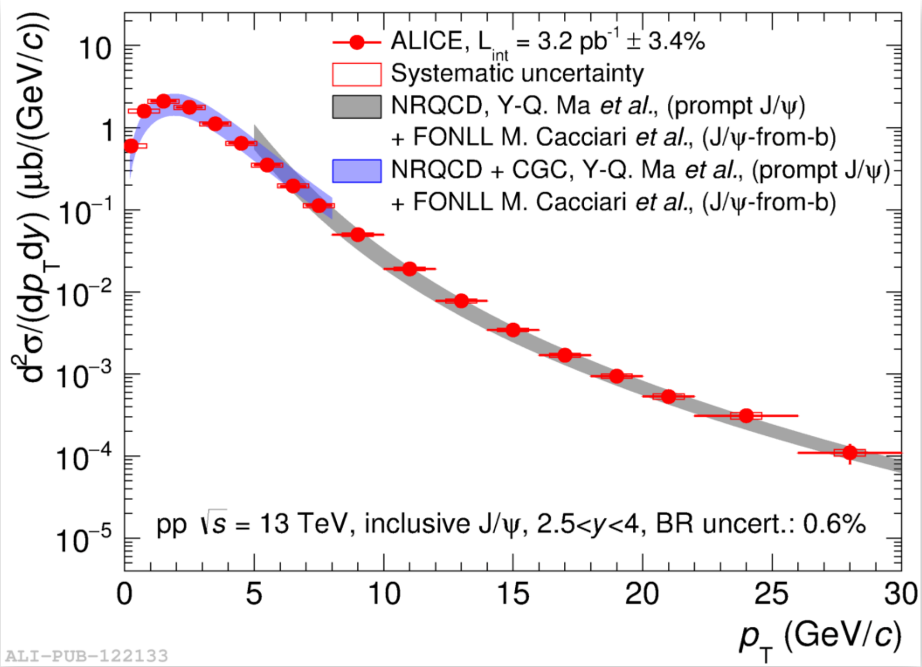
Non-prompt contribution corresponds to the production of *b*-hadrons. Can be calculated with pQCD, e.g. within FONLL

Comparison to models, J/ψ vs p_T



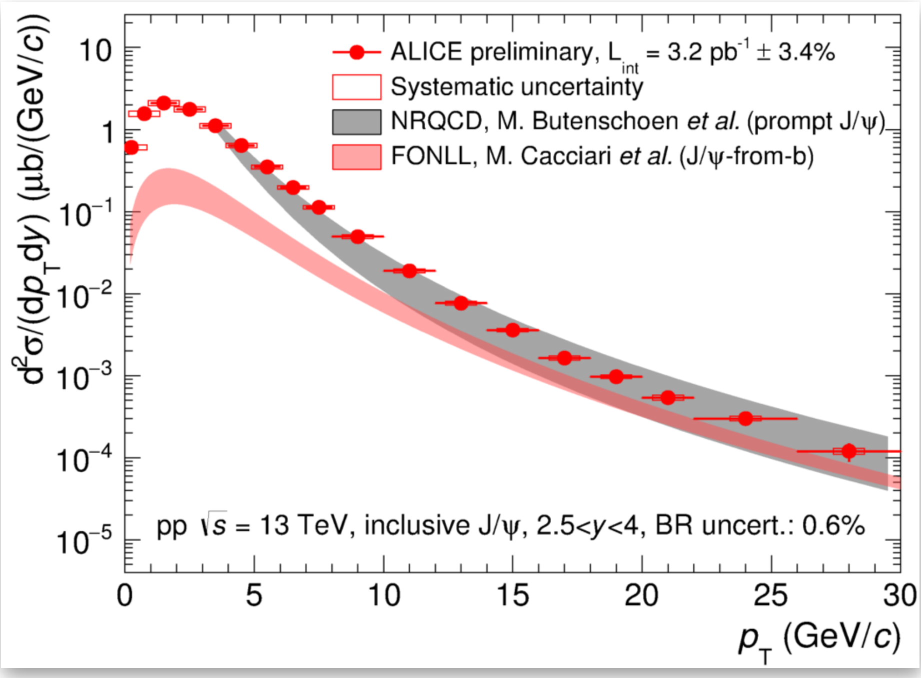


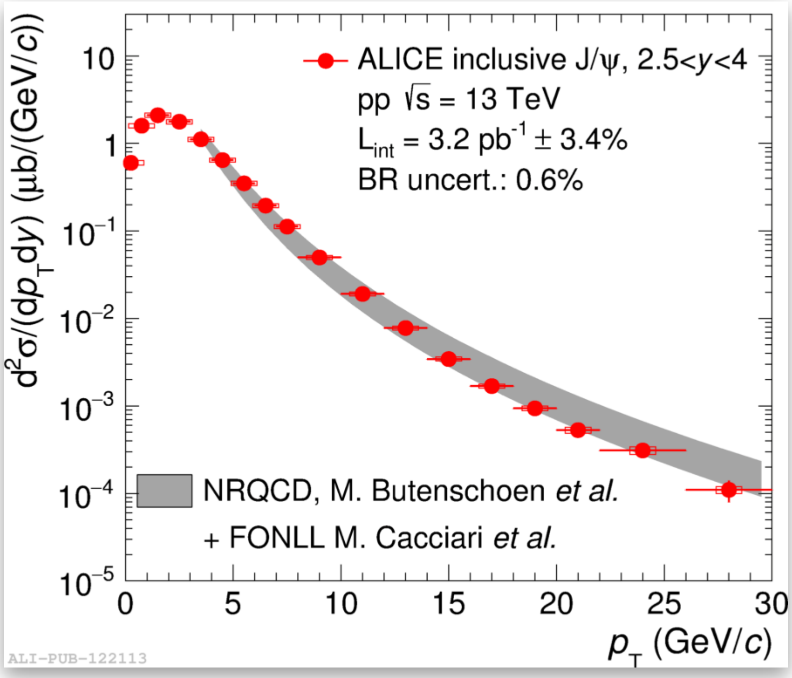
NRQCD	Ma, Wang and Chao, PRL 106 (2011) 042002
NRQCD+CGC	Ma and Venugopalan, PRL 113 (2014) 192301
FONLL	Cacciari *et al.*, JHEP 1210 (2012) 137

Left: NRQCD calculation at high p_T for prompt J/ψ
CGC+NRQCD calculation at low p_T for prompt J/ψ
FONLL calculation for non-prompt J/ψ
Both NRQCD calculations account for contributions from higher mass decay

Right: NRQCD and FONLL calculations are summed, to get a prediction for inclusive J/ψ. Agreement to the data is much improved over the full p_T range

Comparison to models, J/ψ vs p_T (cont'd)



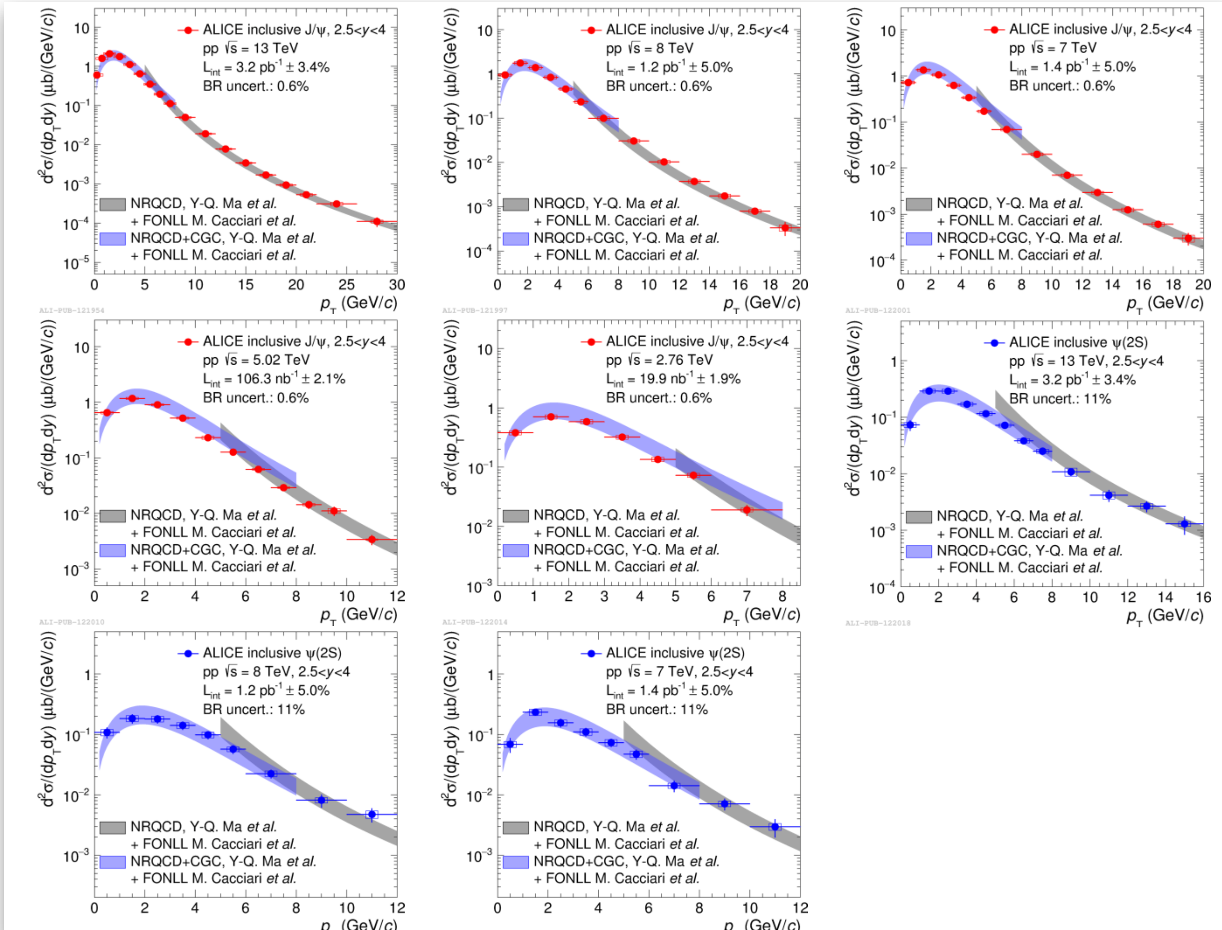


NRQCD Butenschon and Kniel, PRL 106 (2011) 022003
FONLL Cacciari *et al.*, JHEP 1210 (2012) 137

Similar exercise using NRQCD calculation from Butenschoen and Kniel with qualitatively the same conclusion

The two NRQCD calculations differ in the set of LDME that is used, the p_T at which fits are performed and the datasets considered for the fit

Comparison to lower energy results



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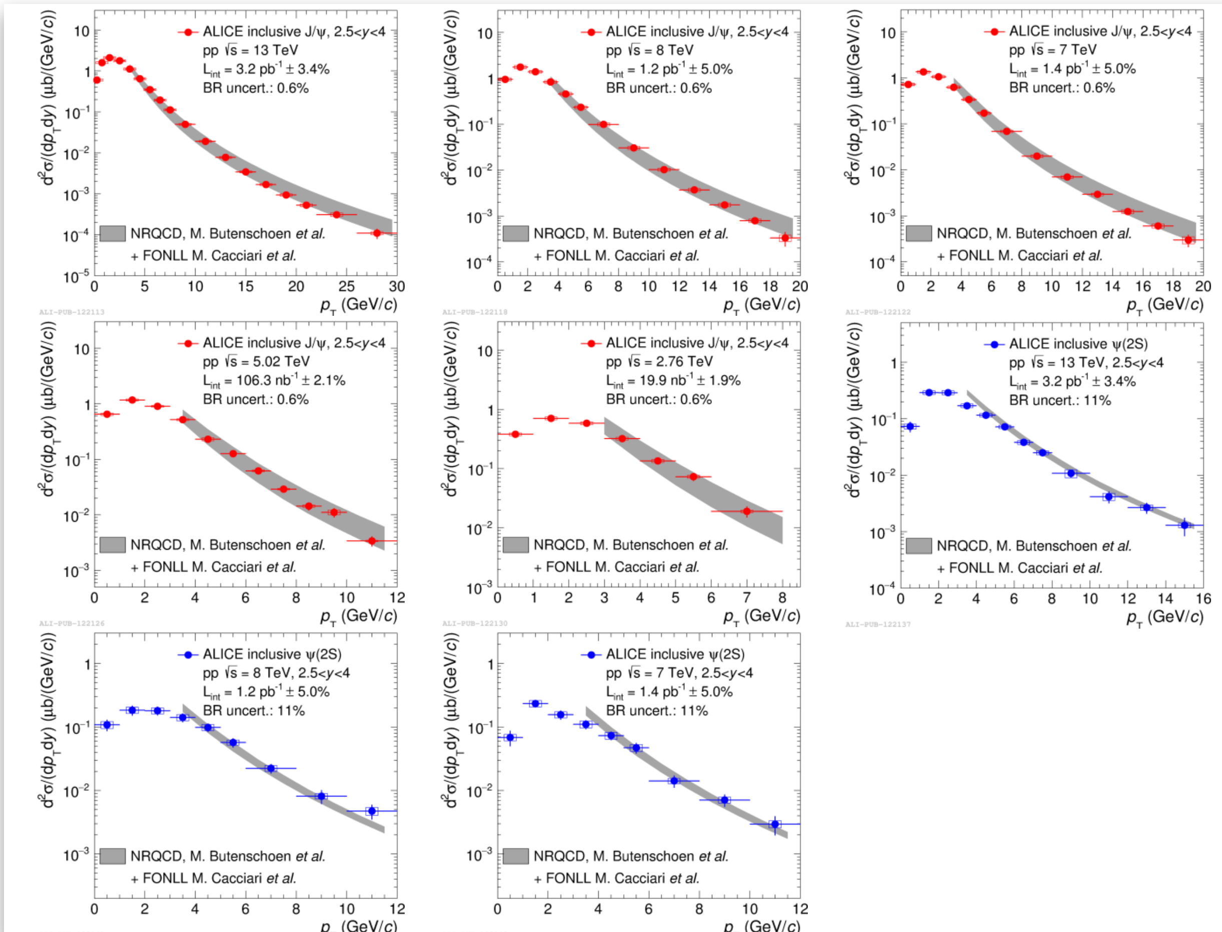
Same exercise performed for the other energies for which ALICE has data, and for the ψ(2S), here for the calculations of Ma *et al.*

Comparison to lower energy results (cont'd)



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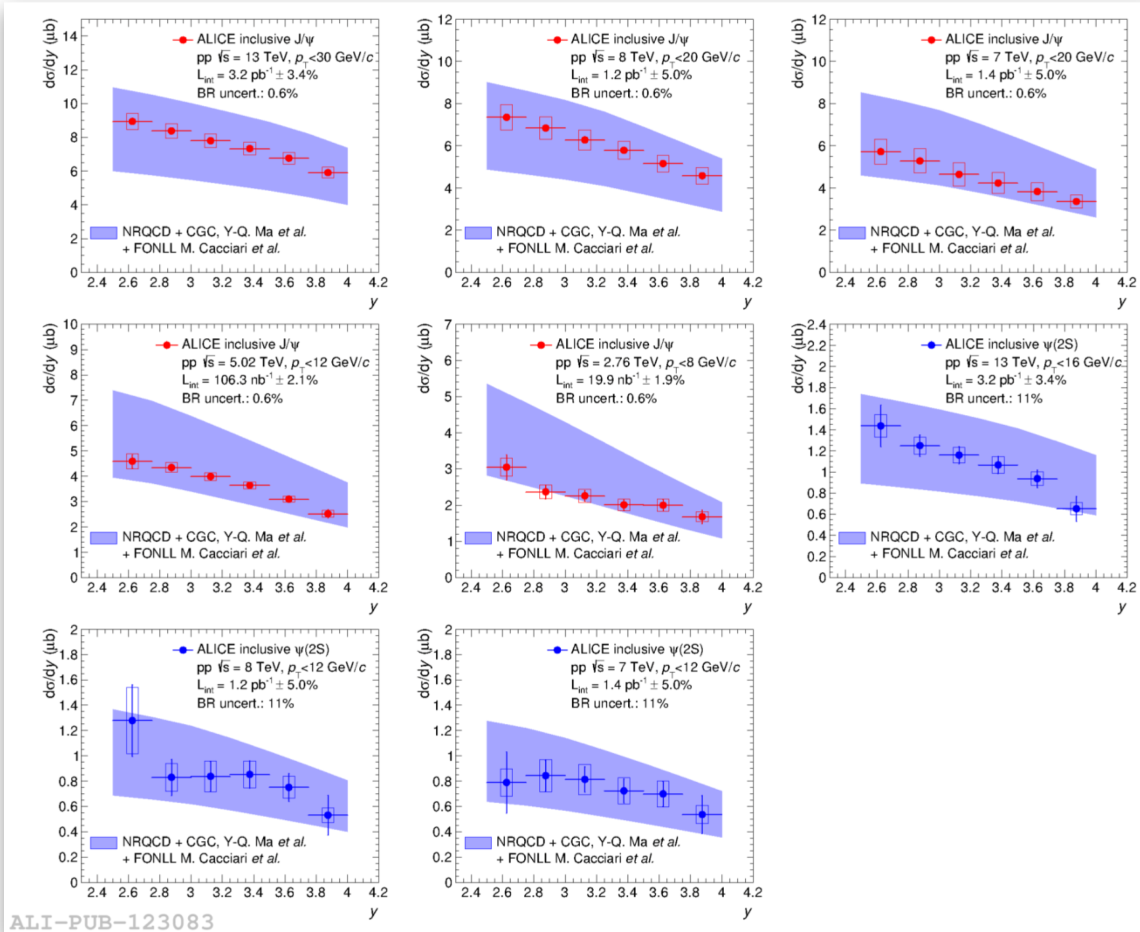
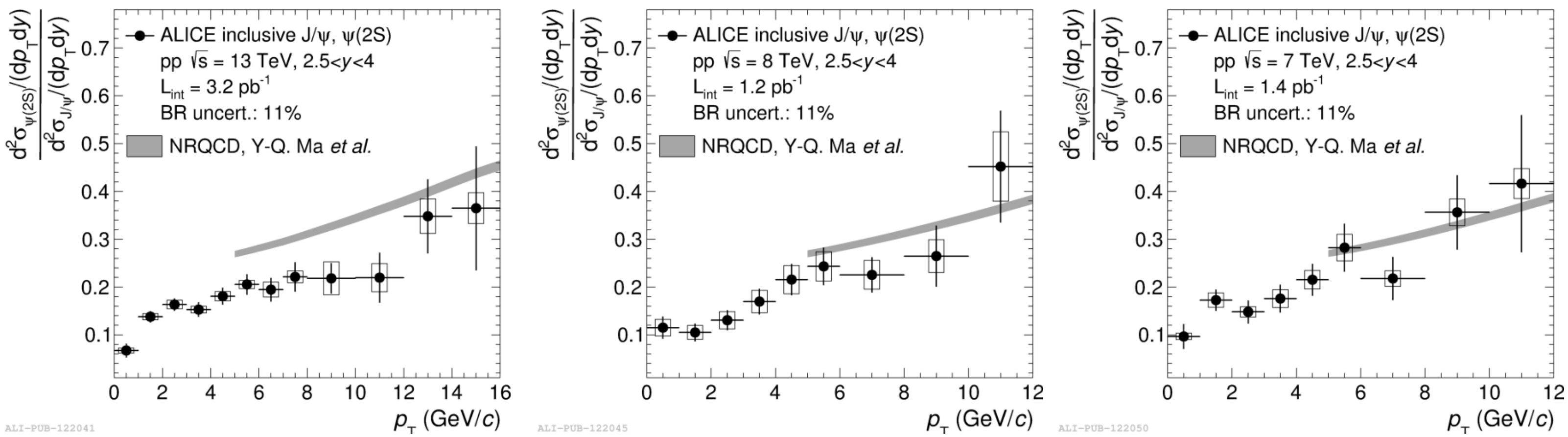


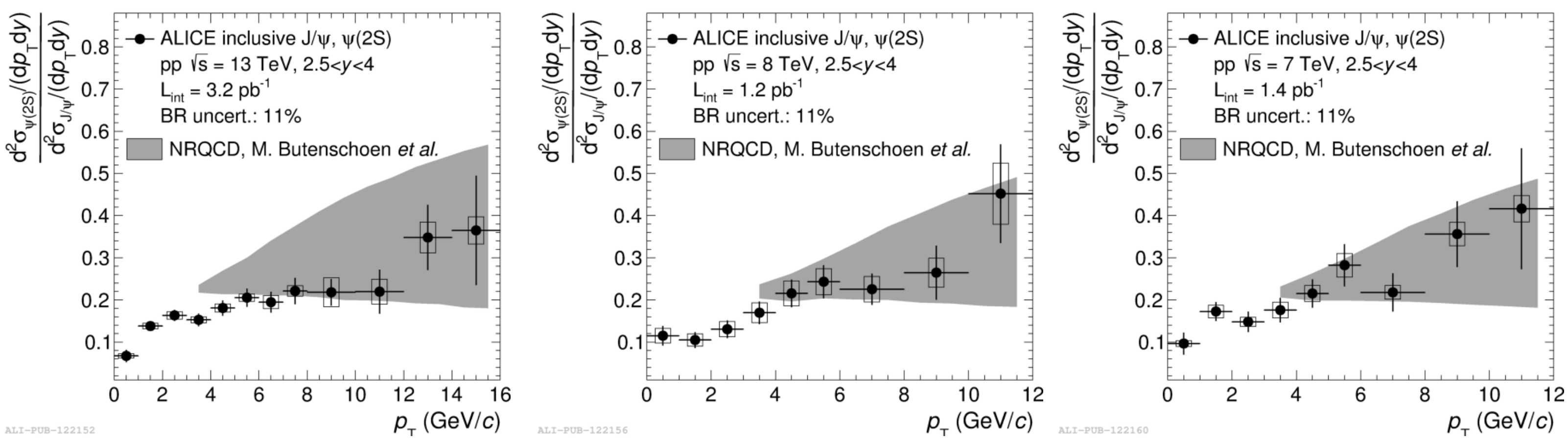
NRQCD+CGC Ma and Venugopalan, PRL 113 (2014) 192301
FONLL Cacciari *et al.*, JHEP 1210 (2012) 137

Since the calculation from Ma and Venugopalan extends down to $p_T = 0$ it can be integrated over p_T and compared to ALICE y-differential cross sections

Comparison to lower energy results (cont'd)



Ma, Wang and Chao, PRL 106 (2011) 042002



Butenschon and Kniel, PRL 106 (2011) 022003

Calculations from Ma *et al.* (top) and Butenschoen and Kniel (bottom) compared to ALICE ψ(2S)-to-J/ψ ratio. Many uncertainties cancel when forming the ratio. Differences are visible between the two calculations. Some tension for the first calc.

Summary

ALICE has measured inclusive J/ψ and ψ(2S) production at forward-y in pp collisions at $\sqrt{s}$ = 13 TeV

For J/ψ, our result is consistent with LHCb and extends the p_T reach up to 30 GeV/c

For ψ(2S), this is the only measurement available at this energy

Data can be well reproduced

- at low p_T by a model that couple a CGC description of the proton to NRQCD
- at intermediate and high-p_T by NRQCD calculations

provided that the non-prompt contribution is properly accounted for (e.g. with FONLL)

Rapidity distribution is also well reproduced by CGC+NRQCD calculation

ψ(2S)-to-J/ψ ratio is slightly overestimated by models, and shows no dependence on the collision energy

Outlook:

Starting from 2021, the addition of the MFT will allow to properly separate prompt and non-prompt forward-y charmonia in pp, p-Pb and Pb-Pb