Charmonium production in pp collisions with ALICE at the LHC

Hugo Pereira Da Costa, CEA/IRFU
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

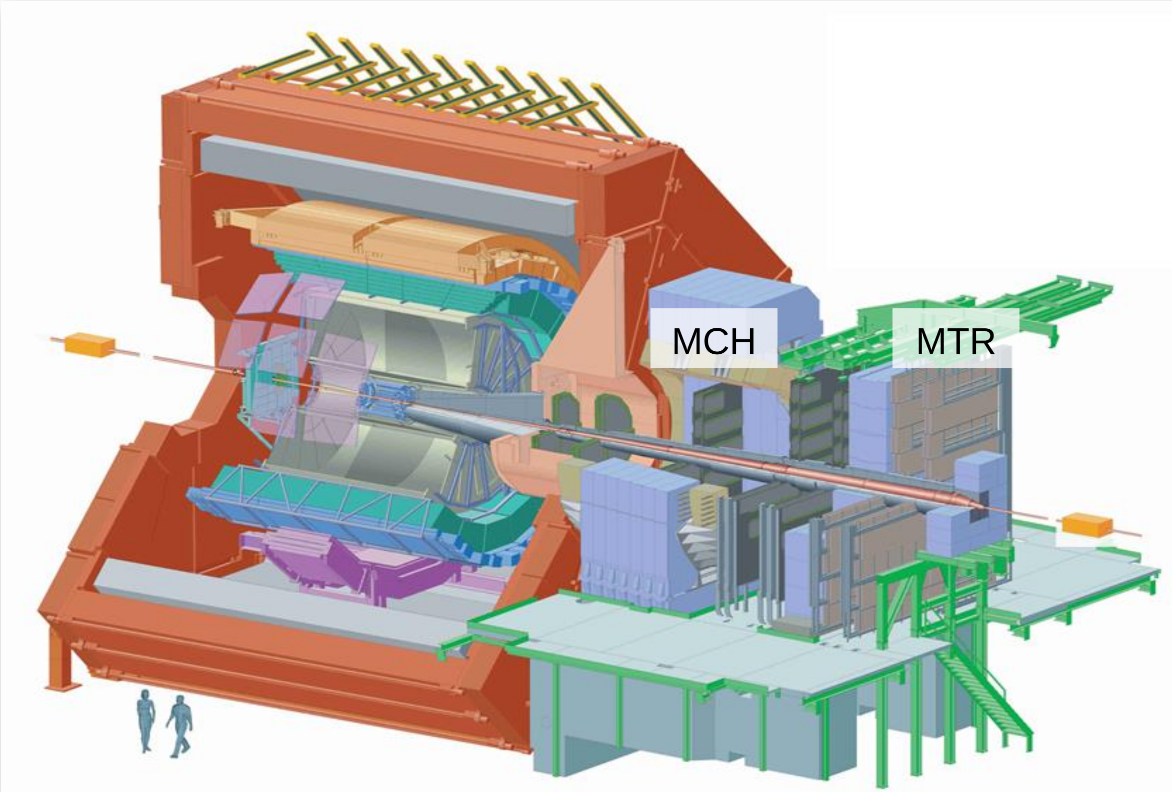
New results on forward-y J/ψ and ψ(2S) production in pp collisions at $\sqrt{s}$ = 13 TeV

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

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



<u>ALICE Muon system</u>:

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

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

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

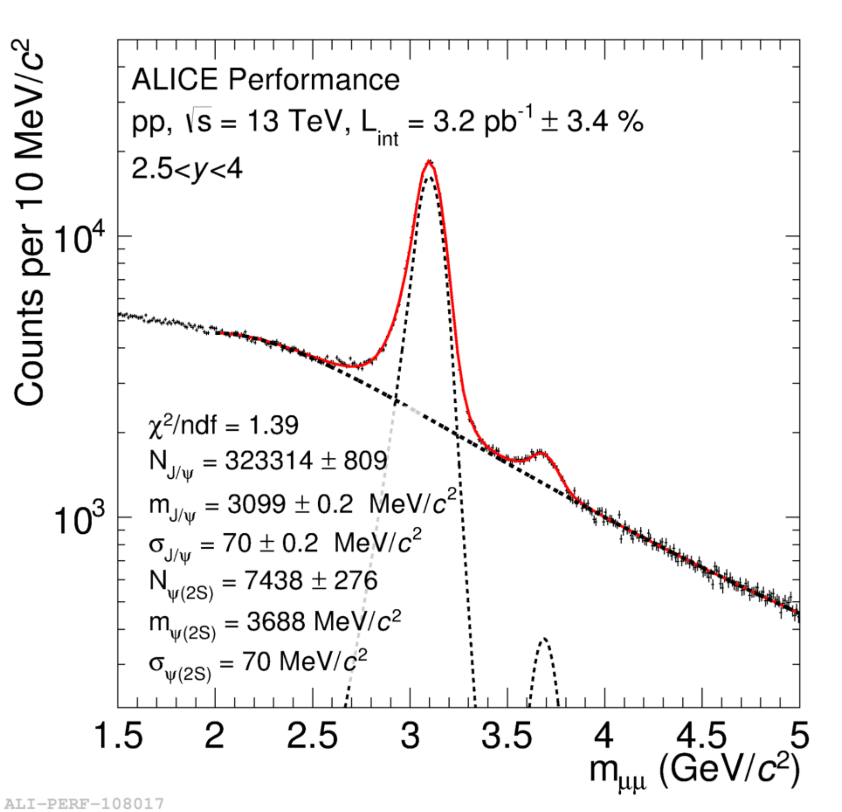
V0 detectors are also used for triggering (in coincidence with MTR)
T0 detectors for luminosity determination

Data analysis

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

pp@13 TeV data sample from 2015 run at LHC

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

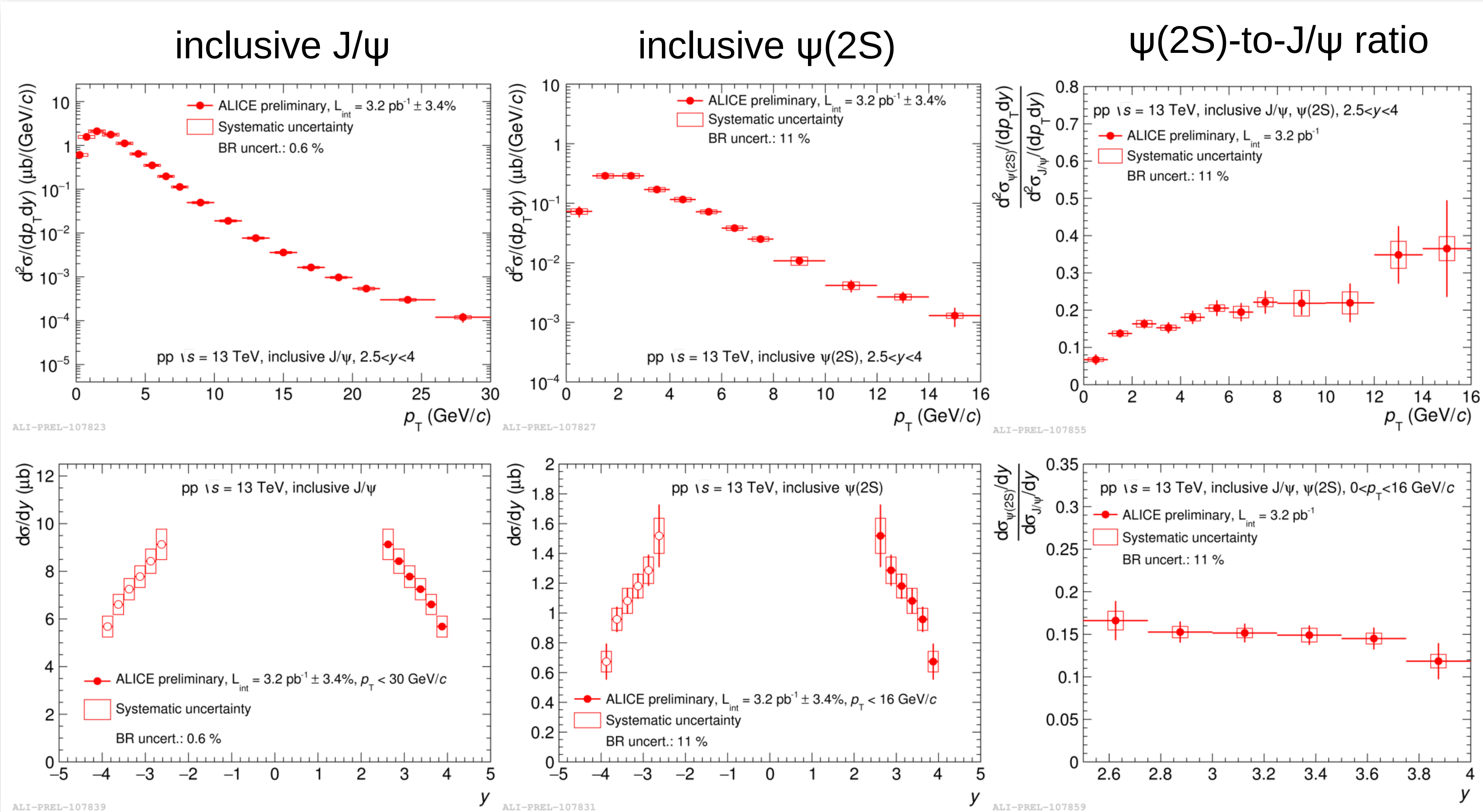


Corresponds to:

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

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



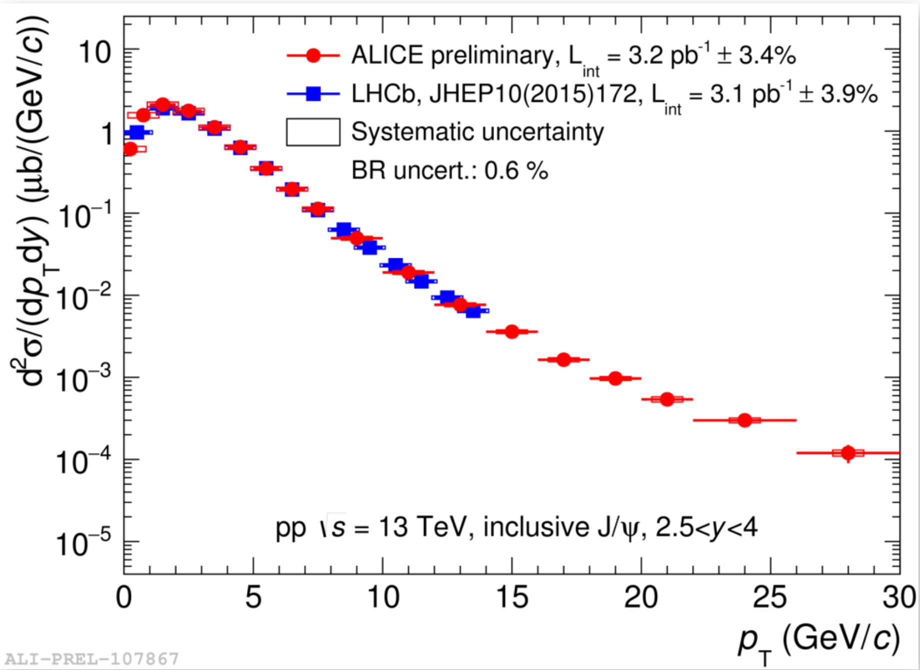
We reach $p_T = 30$ GeV/c for J/ψ, and 16 GeV/c for ψ(2S) as well as ψ(2S)-to-J/ψ ratio

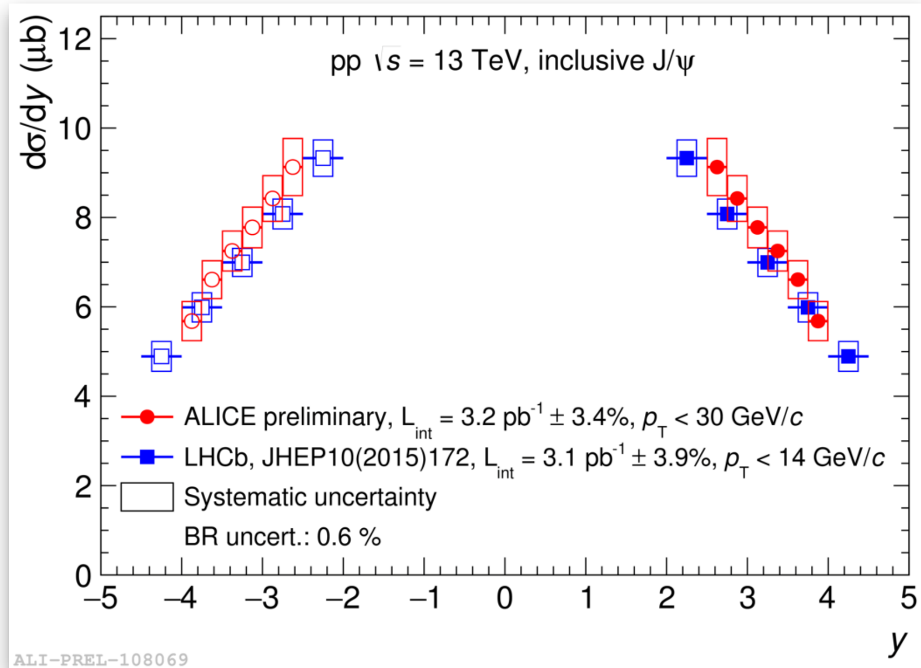
We measure 6 bins in y for 2.5<y<4

Comparison to LHCb

LHCb results from JHEP10 (2015) 172

Quoted values correspond to the sum of the prompt and non-prompt contributions, integrated over the same rapidity range as ALICE (2.5<y<4)

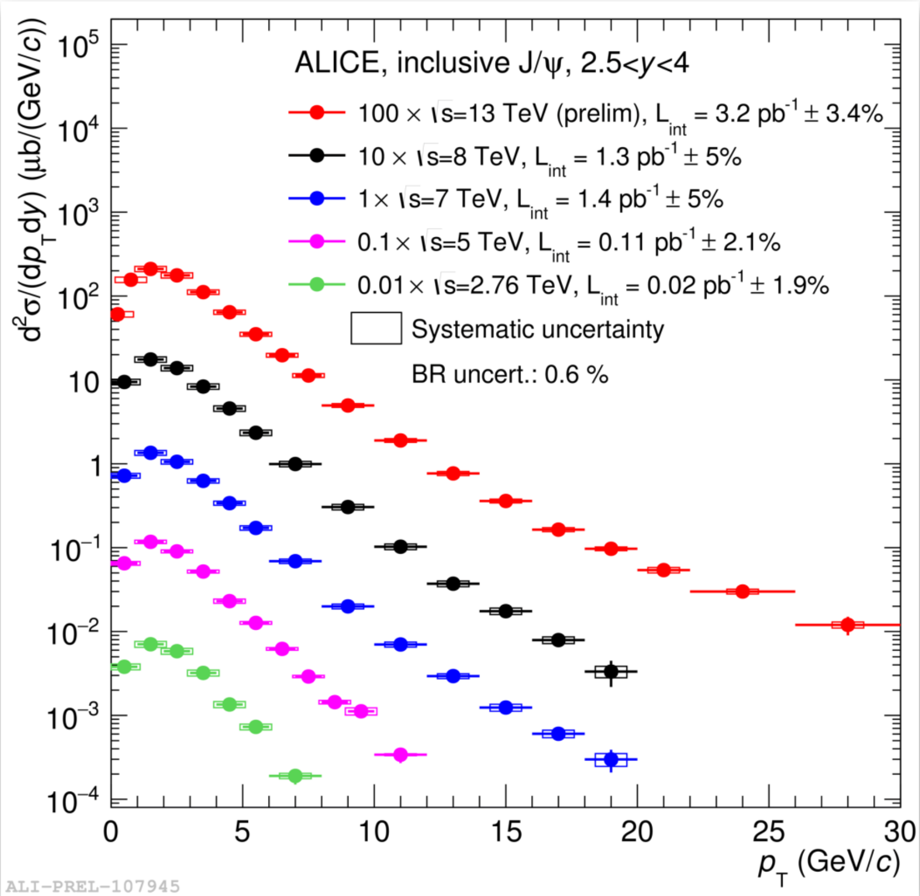




Excellent agreement between the two experiments

All points lie within 1 sigma (stat+syst) one with the other

Comparison to lower energy, J/ψ vs p_T



Comparison to ALICE measurements at $\sqrt{s}$ = 2.76, 5, 7 and 8 TeV

All results published except at 13 TeV

Steady increase of the luminosity and p_T reach with increasing energy

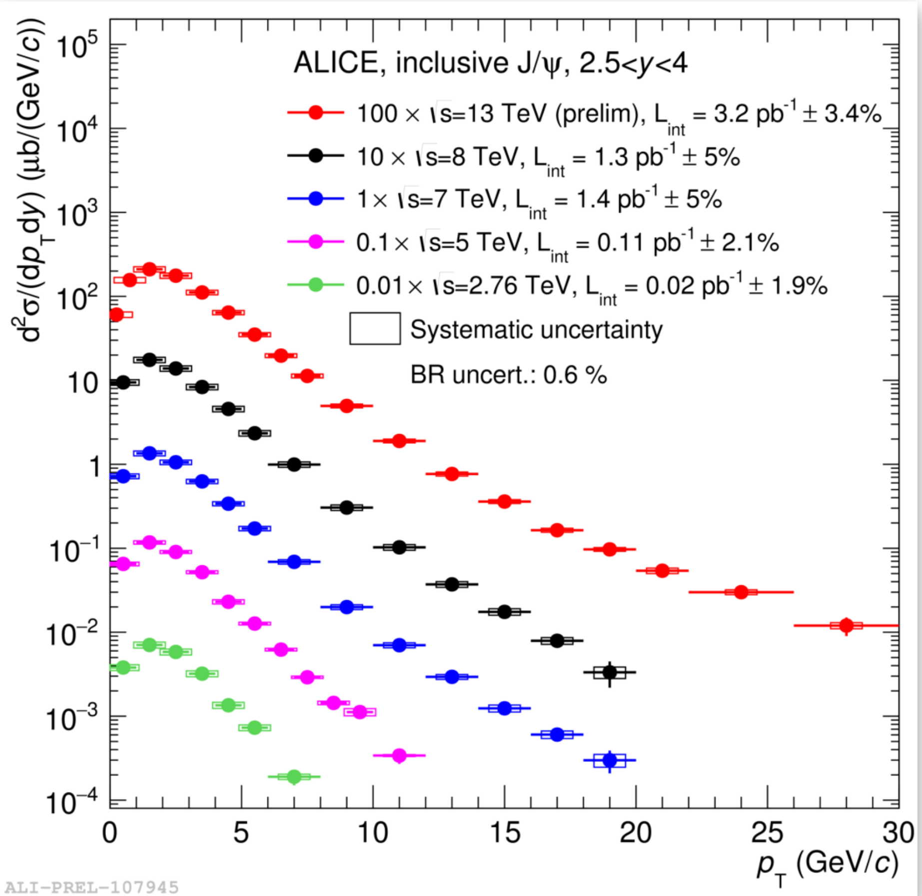
As expected, spectra becomes harder with increasing energy

Change of slope at high p_T and $\sqrt{s}$ = 13 TeV, attributed to the onset of the non-prompt J/ψ contribution

$\sqrt{s}$ = 2.76 TeV	PLB 718 (2012) 295
$\sqrt{s}$ = 5 TeV	ArXiv:1606.08197
$\sqrt{s}$ = 7 TeV	EPJC 74 (2014) 2974
$\sqrt{s}$ = 8 TeV	EPJC 76 (2016) 184

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

inclusive J/ψ



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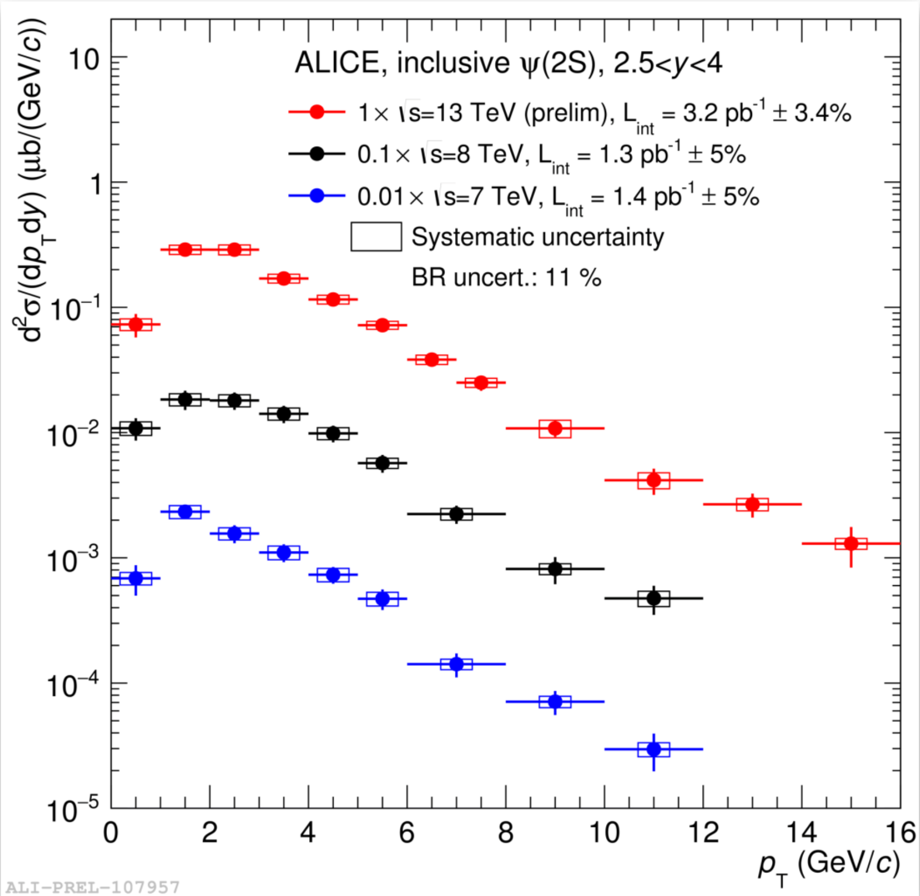

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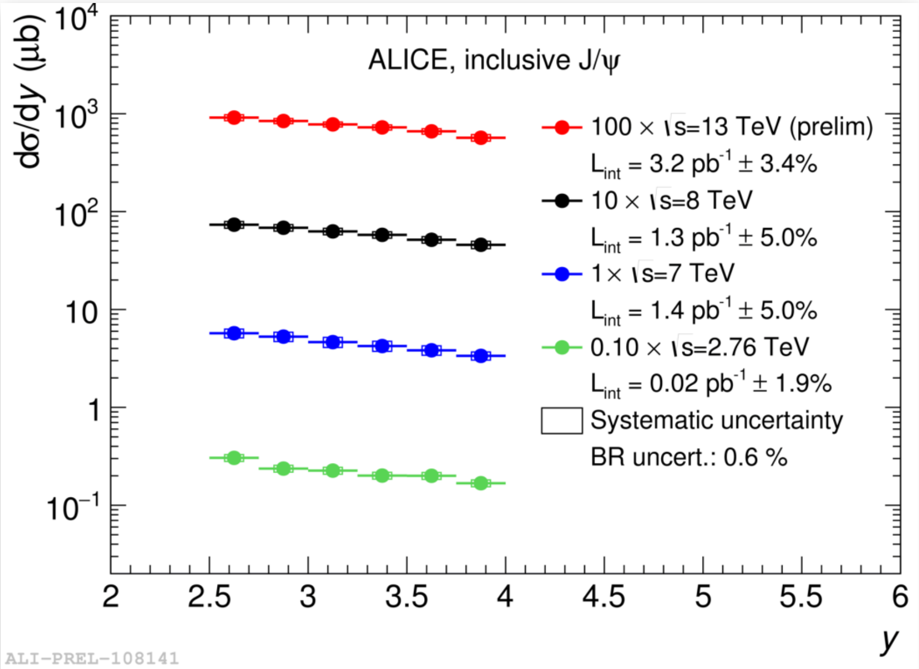
For ψ(2S) we have measurements at $\sqrt{s}$ = 7, 8 and 13 TeV

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

inclusive J/ψ



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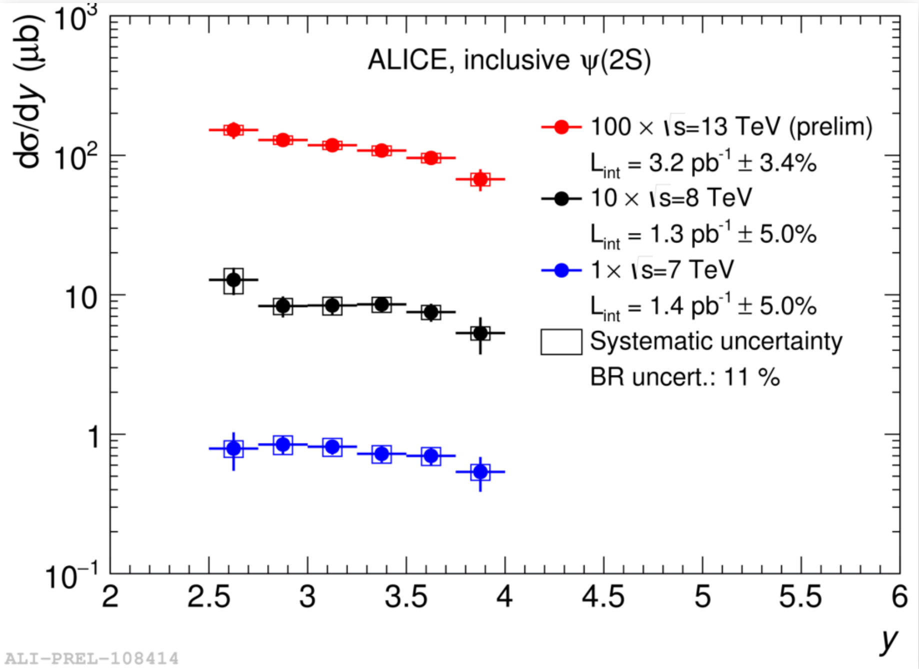

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For J/ψ, no visible change in the *y* distribution

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

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 range matrix elements (LRME), fitted to a subset of the data (e.g. Tevatron)

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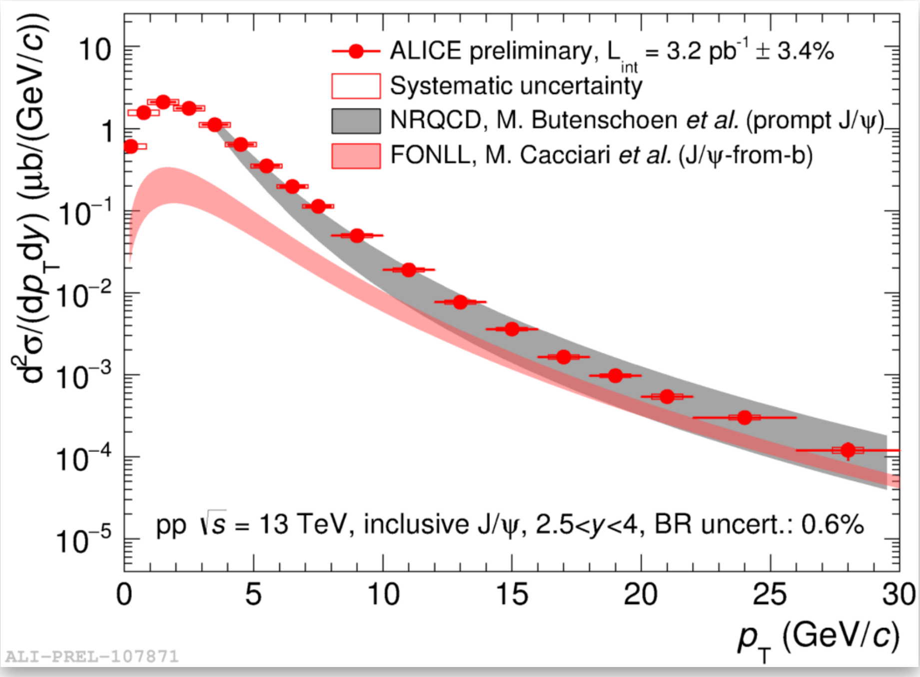
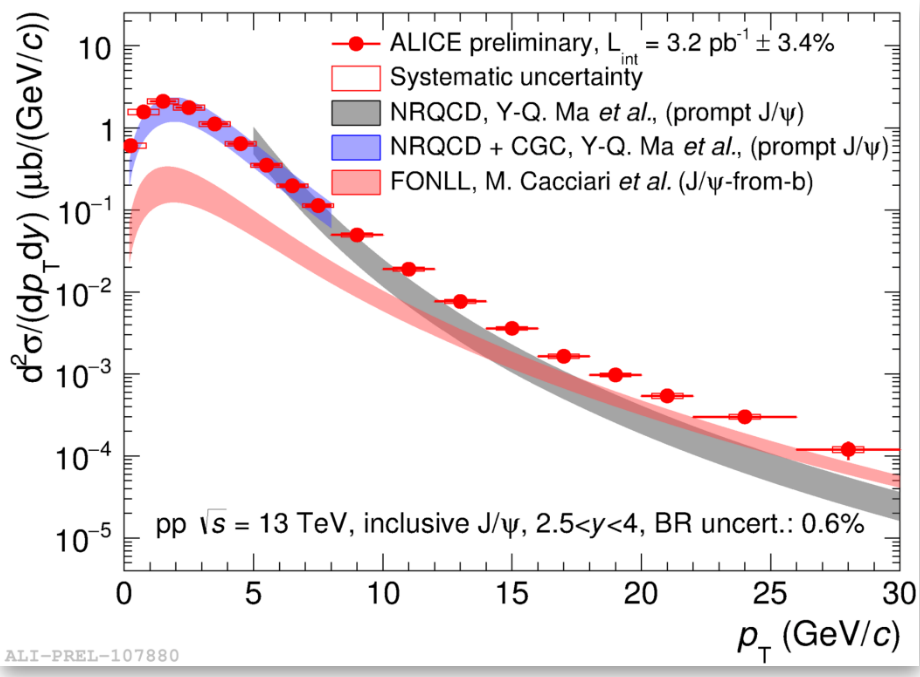
Non-prompt contribution corresponds to the production of *b*-hadrons. Can be calculated with pQCD, e.g. within FONLL

Comparison to models, J/ψ vs p_T





NRQCD (left)	Butenschon and Kniel, PRL 106 (2011) 022003
NRQCD (right)	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

All models properly account for higher mass resonance decays

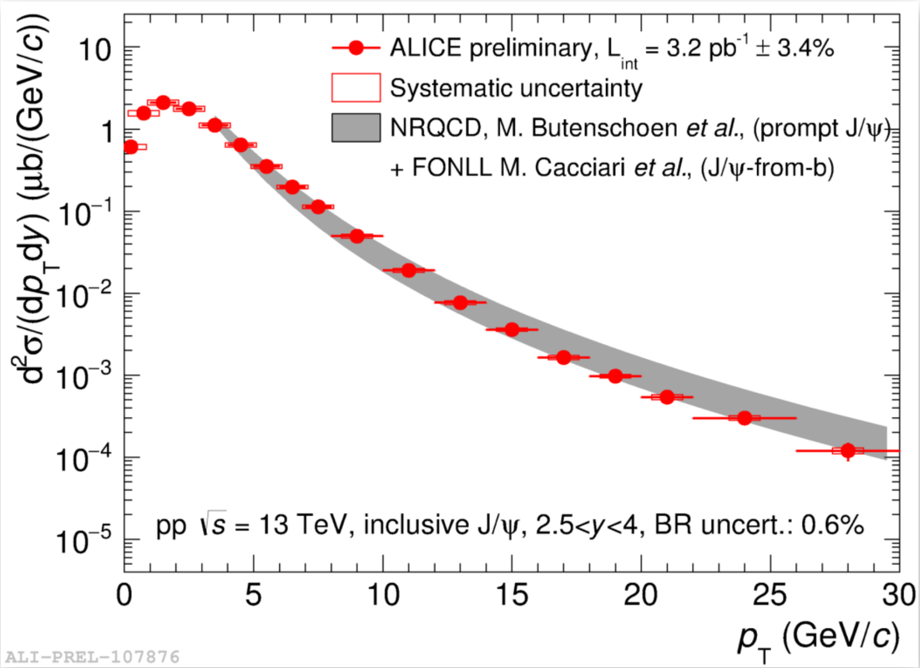
NRQCD models differ in the set of LRME that is used, the p_T at which fits are performed and the datasets considered.

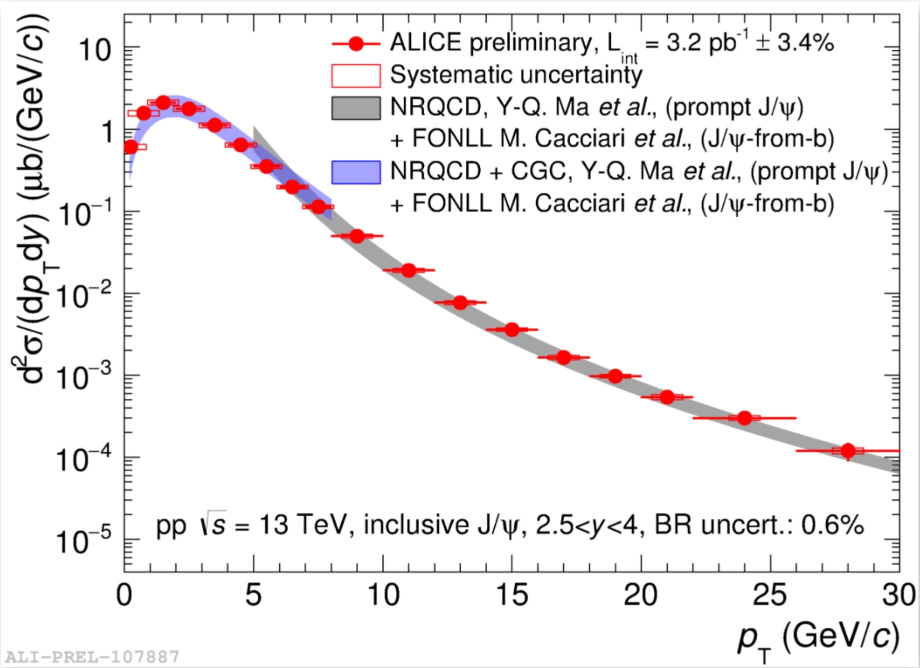
At low p_T (right), NRQCD is coupled to a CGC description of the proton

Predictions are quite different at high p_T, but in both cases, non-prompt J/ψ constitute a sizable contribution to the inclusive cross section

Comparison to models, J/ψ vs p_T

As an exercise, we summed NRQCD and FONLL calculations assuming fully uncorrelated uncertainties.

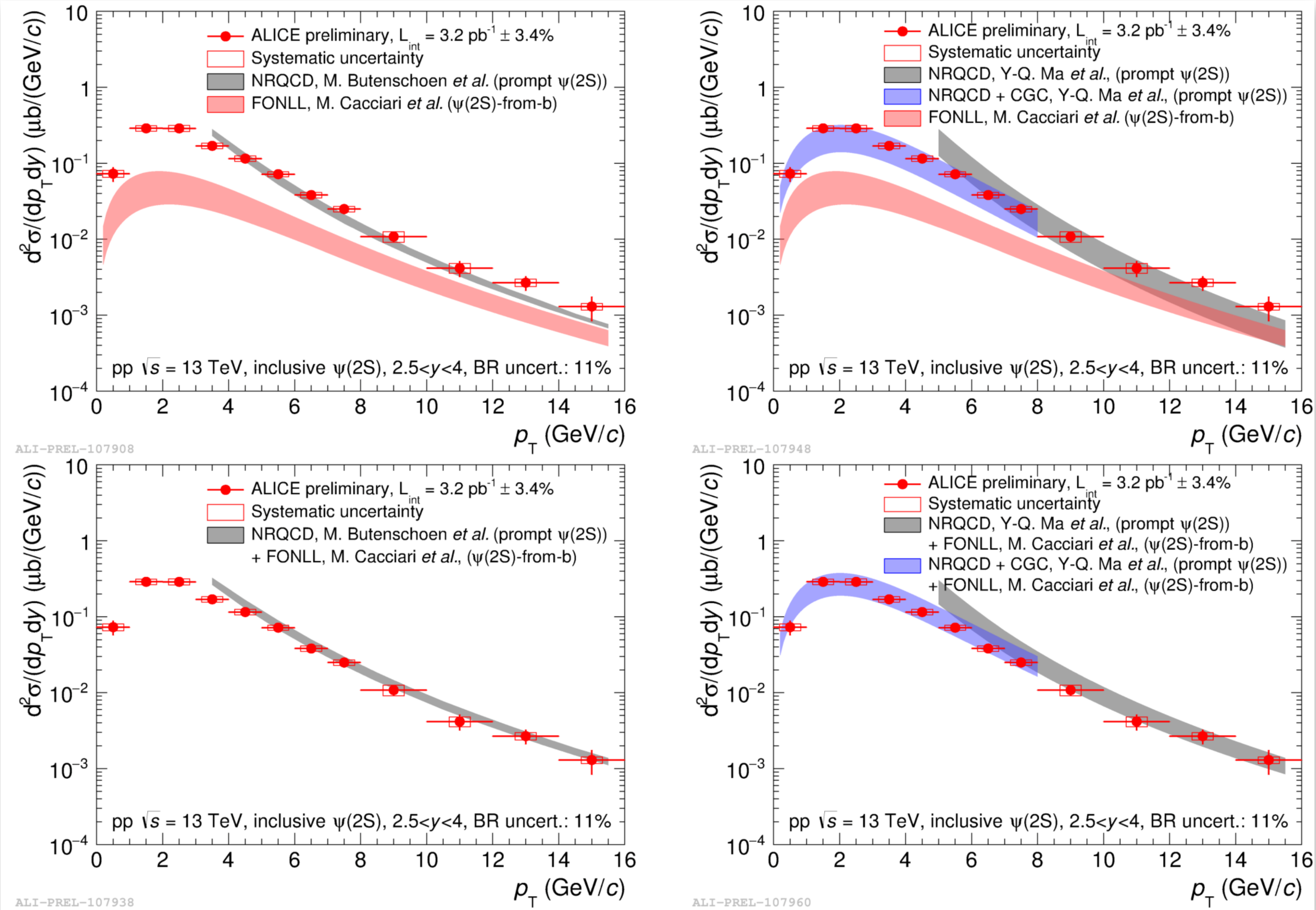




Agreement to the data is much improved, already at intermediate p_T and especially for the calculation from Ma *et al.*

Note that the calculations are completely independent, and that there was no data at this energy and at such high p_T before

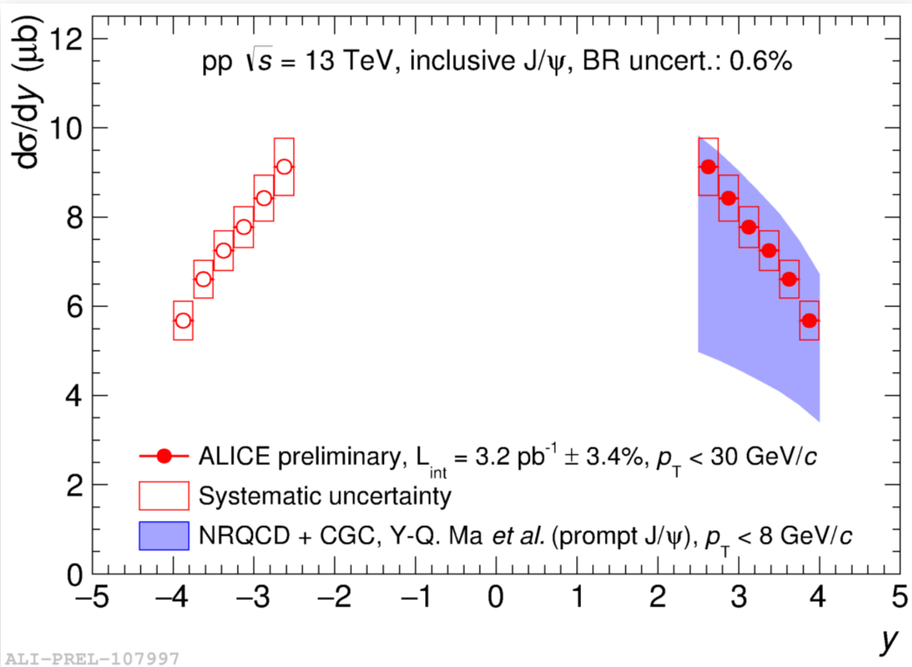
Comparison to models, ψ(2S) vs p_T



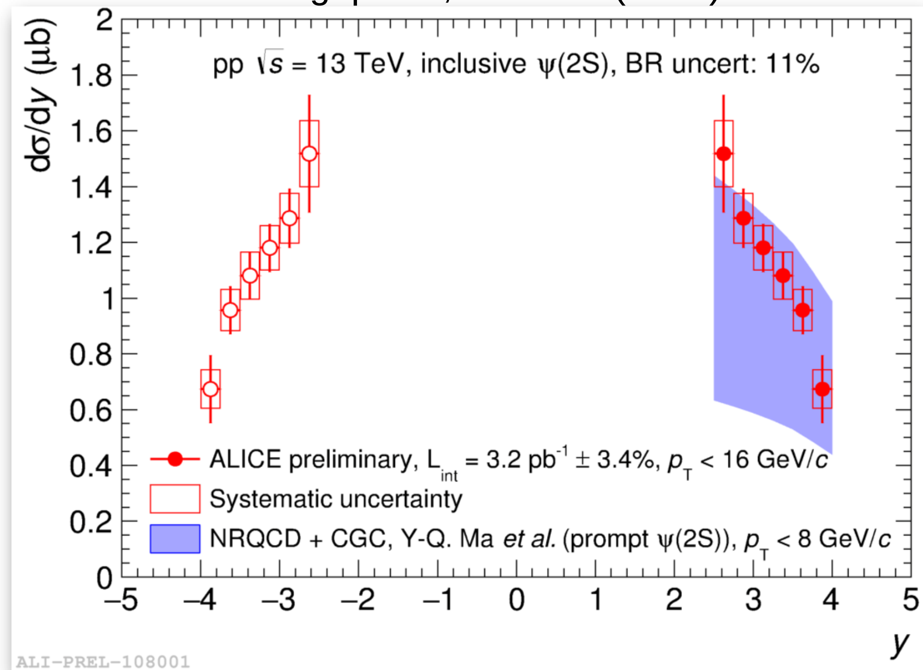
Same conclusions as for the J/ψ case

Rapidity distributions

Since the NRQCD+CGC calculation goes down to p_T = 0, it can be compared to our p_T-integrated data vs rapidity



Ma and Venugopalan, PRL 113 (2014) 192301

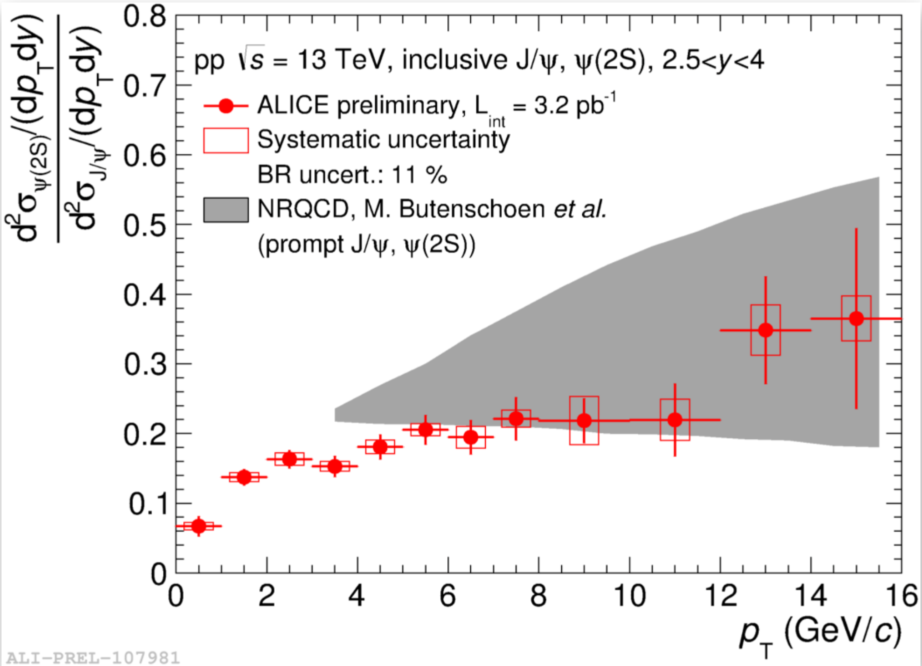


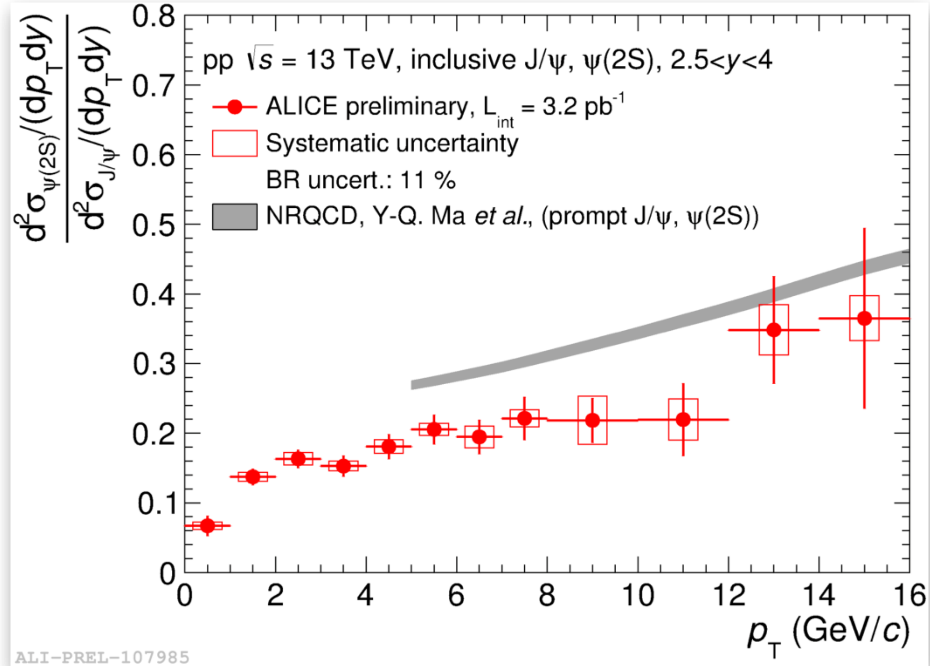
Agreement to the data is reasonable, and would be improved when adding the contribution from non-prompt J/ψ and ψ(2S) (10-15%)

The only other calculation that provides p_T-integrated rapidity distributions is CSM@LO, with significantly larger uncertainties (see ALICE (7TeV) EPJC 74 (2014) 2974)

Particle ratio, comparison to models

Many systematic uncertainties cancel in the particle ratio, for both data and theory





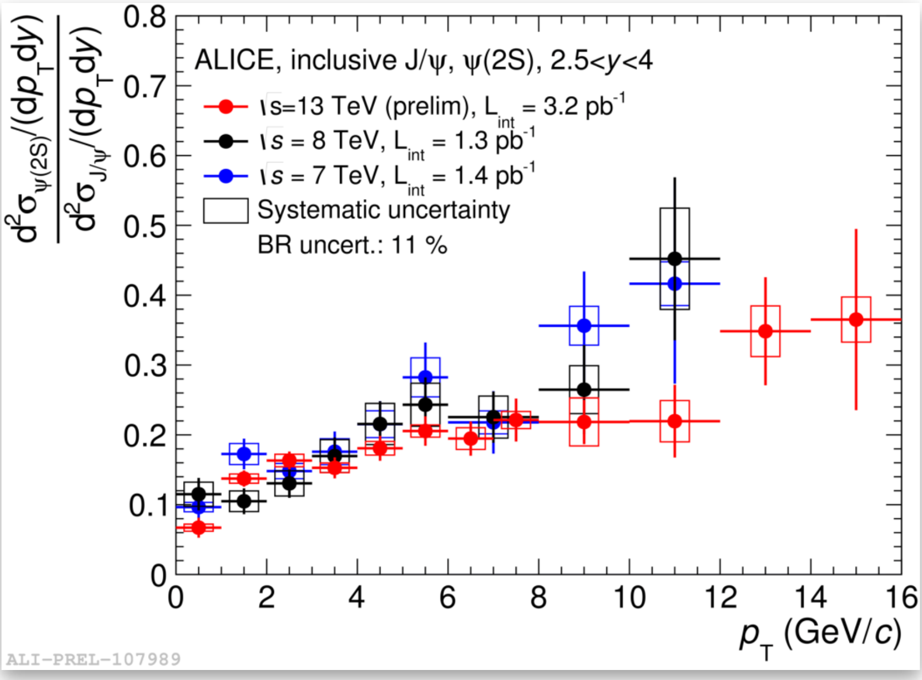
NRQCD (left) Butenschon and Kniel, PRL 106 (2011) 022003
NRQCD (right) Ma, Wang and Chao, PRL 106 (2011) 042002

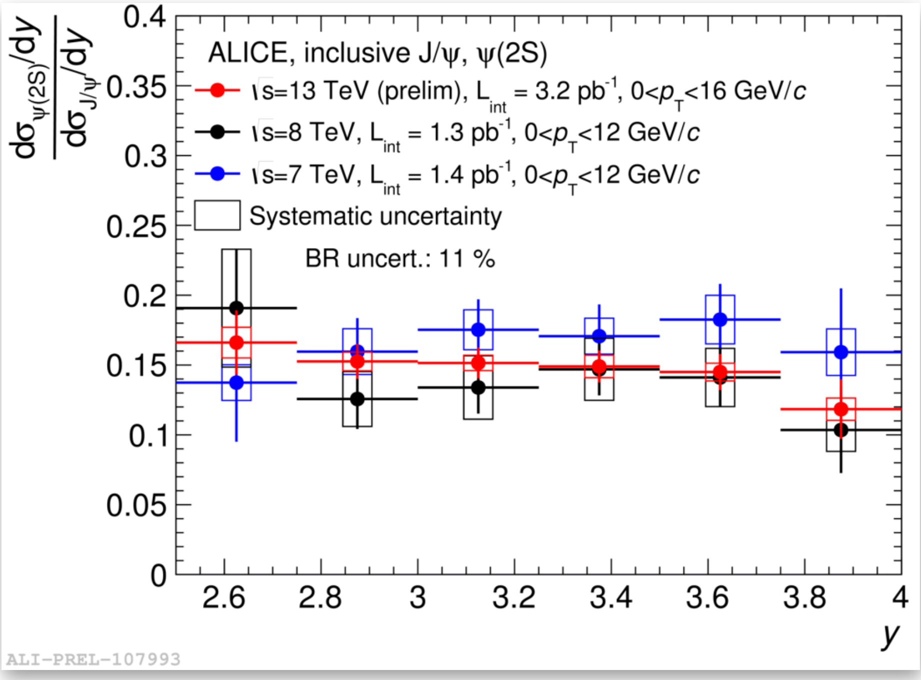
Both calculations follow the same trend but with very different uncertainties. This was already the case at $\sqrt{s}$ = 7 TeV (see ALICE EPJC 74 (2014) 2974)

Calculation from Y-Q Ma *et al.* tends to overestimate the ψ(2S)-to-J/ψ ratio

Contributions from non-prompt J/ψ and ψ(2S) have little impact here because they enter both the numerator and denominator, with a similar (small) magnitude

Particle ratio, energy dependence





No visible dependence of the p_T-differential ψ(2S)-to-J/ψ ratio on $\sqrt{s}$

No clear trend either vs rapidity

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