# Charmonium production in pp collisions at the LHC

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# Motivation

Charmonia (J/ψ, ψ(2S), $\chi_c$) proceed from the production of a $c\bar{c}$ quark pair in a hard-scattering process.
This is followed by the evolution of the pair into a colorless bound state.

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

What can we learn from measuring charmonium production:

- pp: understand production mechanisms, probe PDFs, (particularly gluon's PDF's down to low *x: gluon saturation)* , provide a reference to p-Pb and Pb-Pb measurements
- p-Pb: probe cold nuclear matter effects (i.e. modification of the PDFs, saturation, Cronin enhancement...)
- Pb-Pb: probe the formation and properties of the QGP (color screening, dissociation, recombination..)

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$$d\sigma^{Q} = f_a(x_a).f_b(x_b)\times d\hat{\sigma}_{ab}^{q\bar{q}}\times\left\langle O_{q\bar{q}}^{Q}\right\rangle$$

Quarkonium production cross section has three components

- parton distribution functions: describe the partonic (quark/gluons) content of the proton (soft scale, measured in e.g. DIS experiments)
- partonic cross section: describe how to produce the heavy quark pair from two partons (hard scale, short distances, calculable with pQCD)
- evolution of the heavy quark pair into the quarkonium state Q (soft scale, large distances and model dependent)

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Applicable to direct production.

When we measure quarkonia we may have contributions from:

- decay from higher mass resonances (for J/ψ, they are the ψ(2S) and χc)
- decay from *b*-hadrons (non-prompt J/ψ, ψ(2S))

# Outline

Recent results at the LHC:

J/ψ and ψ(2S) production in pp collisions at $\sqrt{s}$ = 13 TeV central and forward rapidity.

- Non-prompt to inclusive fraction
- Prompt cross-sections (when available)
- Comparisons between experiments and to lower energies
- Comparisons to pQCD based models

J/ψ polarization and $\eta_c$

# LHC detectors

CMS:

Central rapidity

High $p_T$ coverage

Prompt-non prompt separation

ATLAS:

Central rapidity

High $p_T$ coverage

Prompt-non prompt separation

LHCb:

Forward rapidity

Down to $p_T = 0$

Prompt-non prompt separation

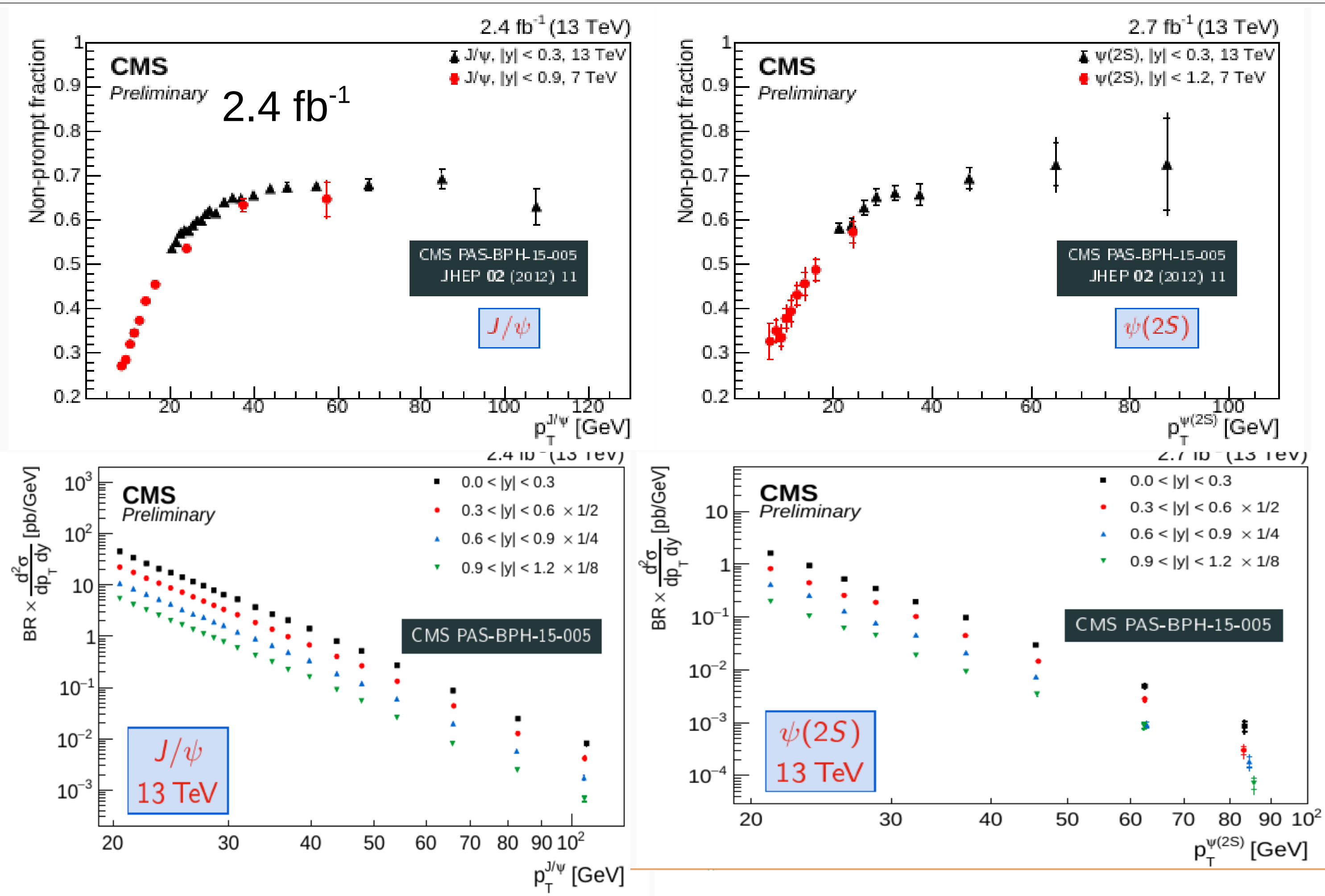
ALICE:

Central and forward rapidity

Down to $p_T = 0$

Inclusive measurements

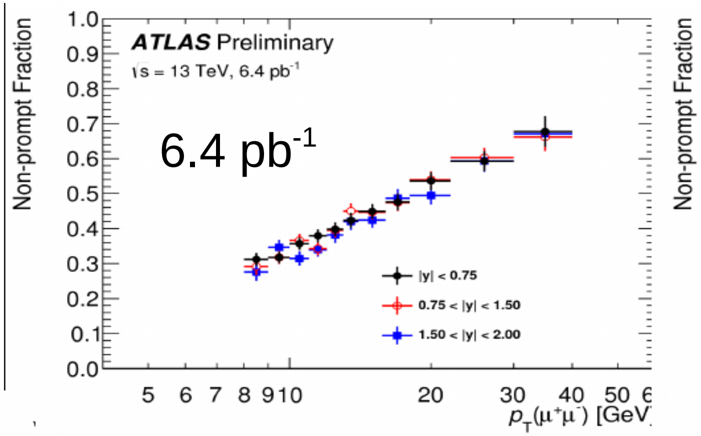
# J/ψ and ψ(2S) at 13 TeV at CMS

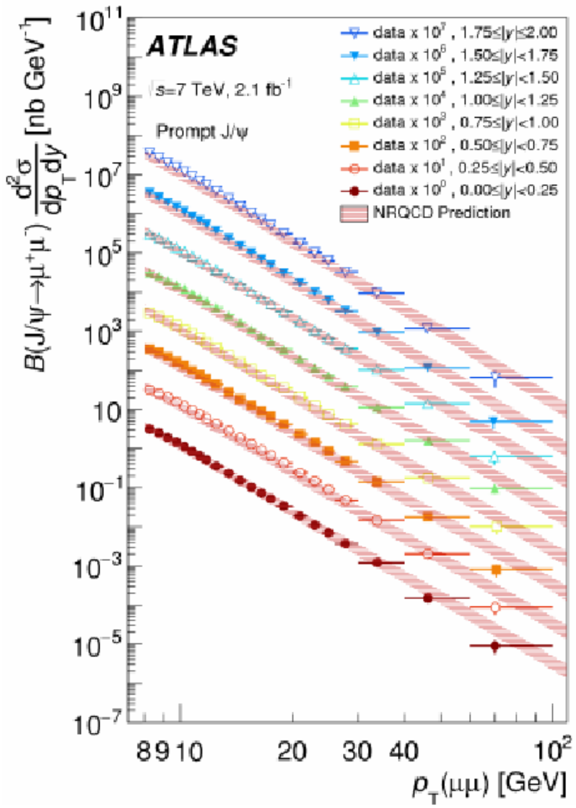


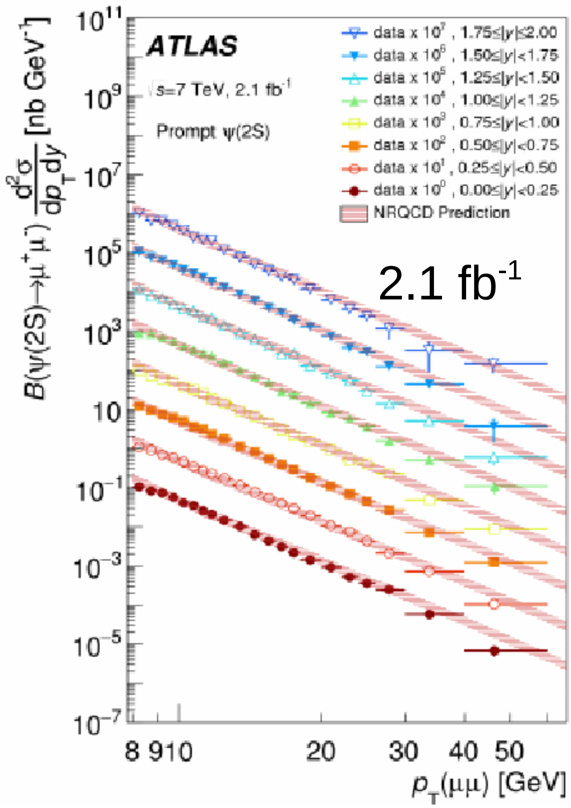

- Non-Prompt to inclusive fraction (7 and 13 TeV): Saturation at high $p_T$, identical $p_T$ slopes
- Four bins in rapidity in the range |y|< 1.2
- High $p_T$ coverage: 20-120 GeV/c, J/ψ; 20-100 GeV/c, ψ(2S)

# J/ψ and ψ(2S) at 7 TeV at ATLAS

- 13TeV : J/ψ non-prompt to inclusive fraction
- Two bins in rapidity in the range |y|< 2
- $p_T$ coverage: 8-35 GeV/c



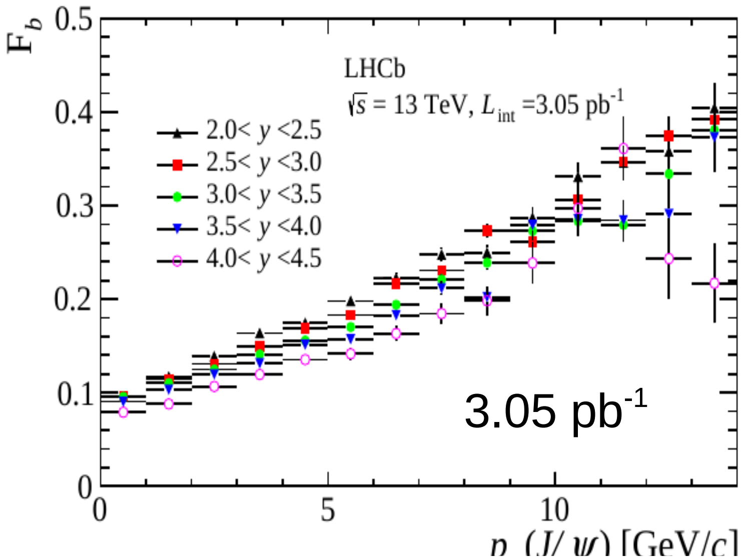




7 TeV:

- Prompt J/ψ and ψ(2S)
- Eight bins in rapidity
- $p_T$ coverage: 8-80 GeV/c, J/ψ and 8-45 GeV/c, ψ(2S)
- Comparisons to NLO NRQCD (to be discussed later)

Figures: Carlo Schiavi Moriond March 2016 La Thuile

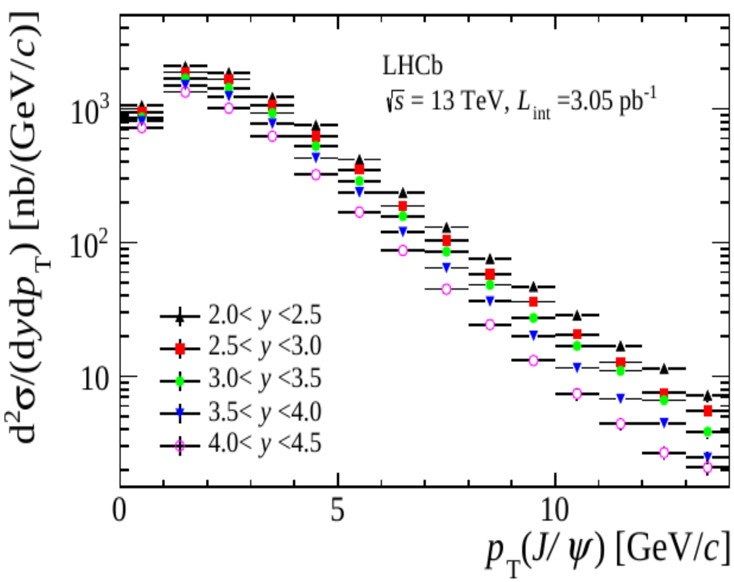
# J/ψ at 13 TeV LHCb

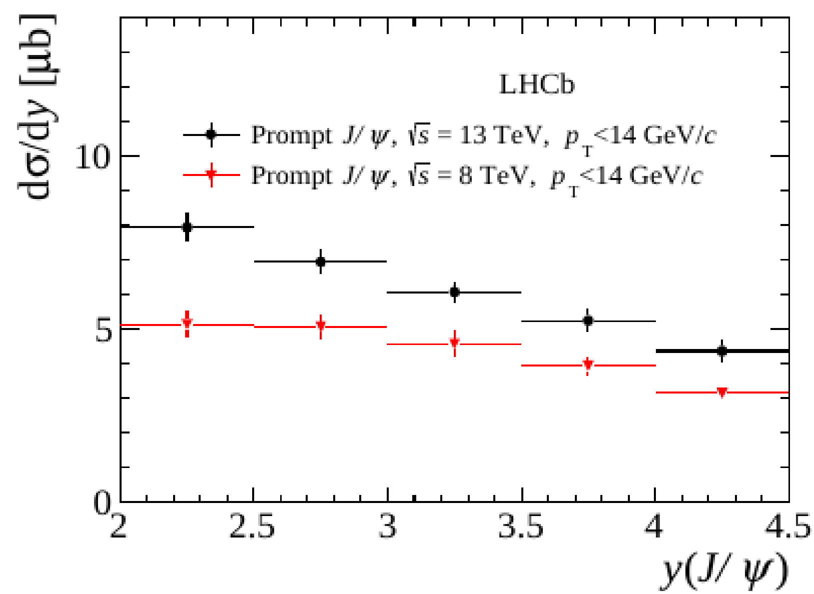



- J/ψ non-prompt to inclusive fraction

- J/ψ prompt-cross-sections as a function of pT
- J/ψ prompt-cross-sections as a function of Y for 13 TeV and 8 TeV

- Five bins in rapidity spanning from  2<y< 4.5
- $p_T$ coverage: 0-14 GeV/c

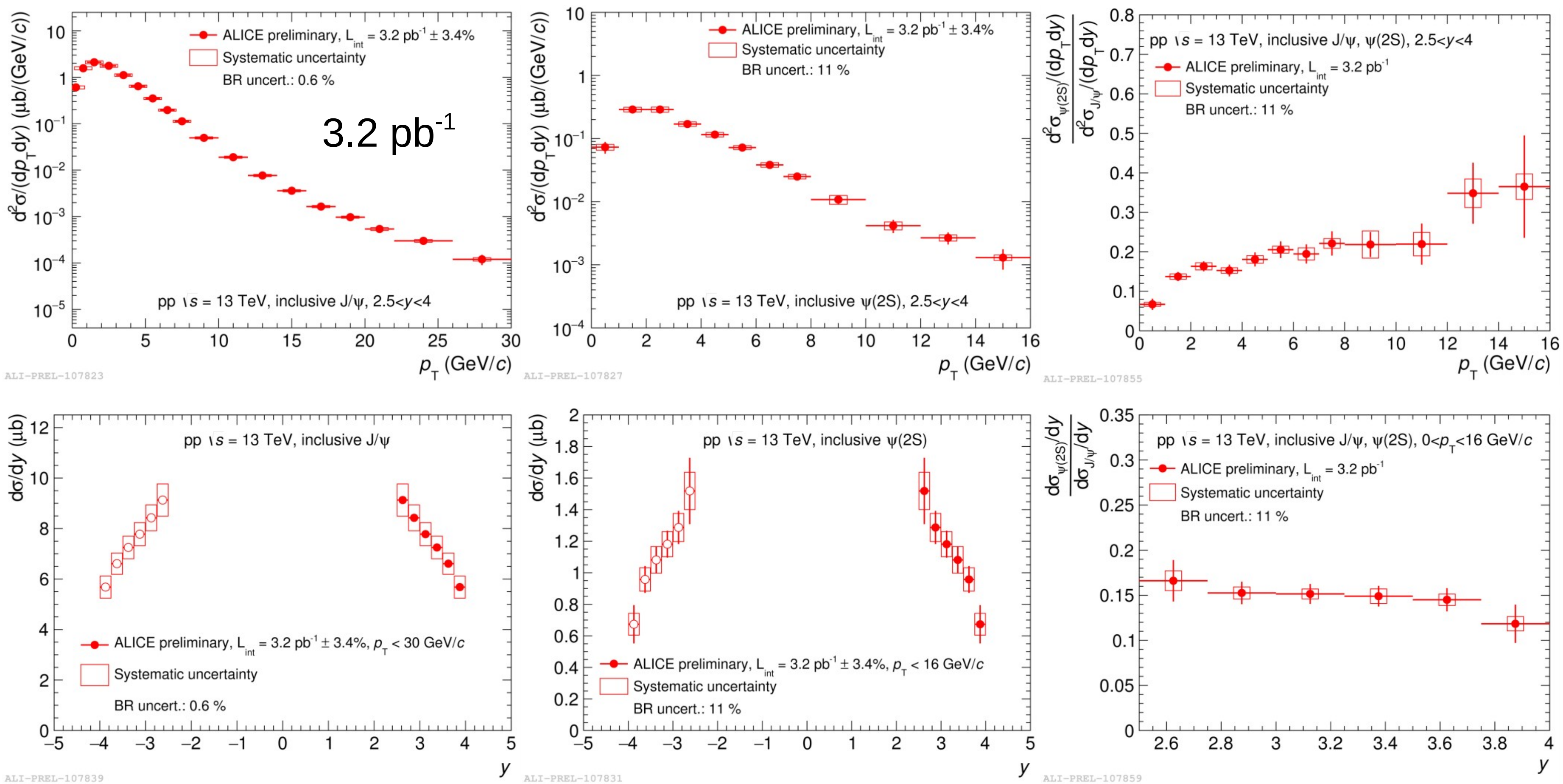



Figures:  JHEP 1510 (2015) 172

# Inclusive J/ψ and ψ(2S) at 13 TeV at ALICE

inclusive J/ψ | inclusive ψ(2S) | ψ(2S)-to-J/ψ ratio




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

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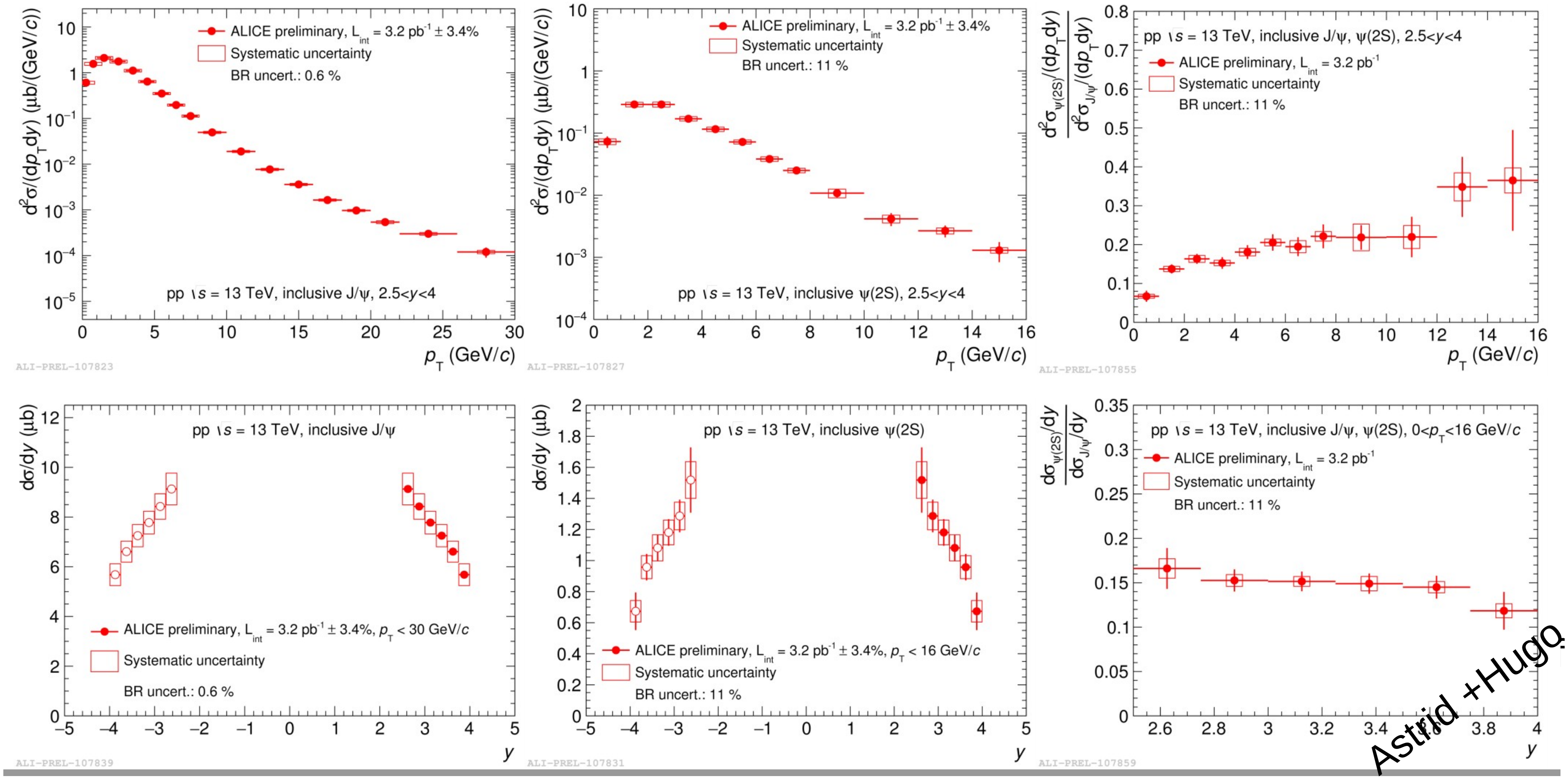


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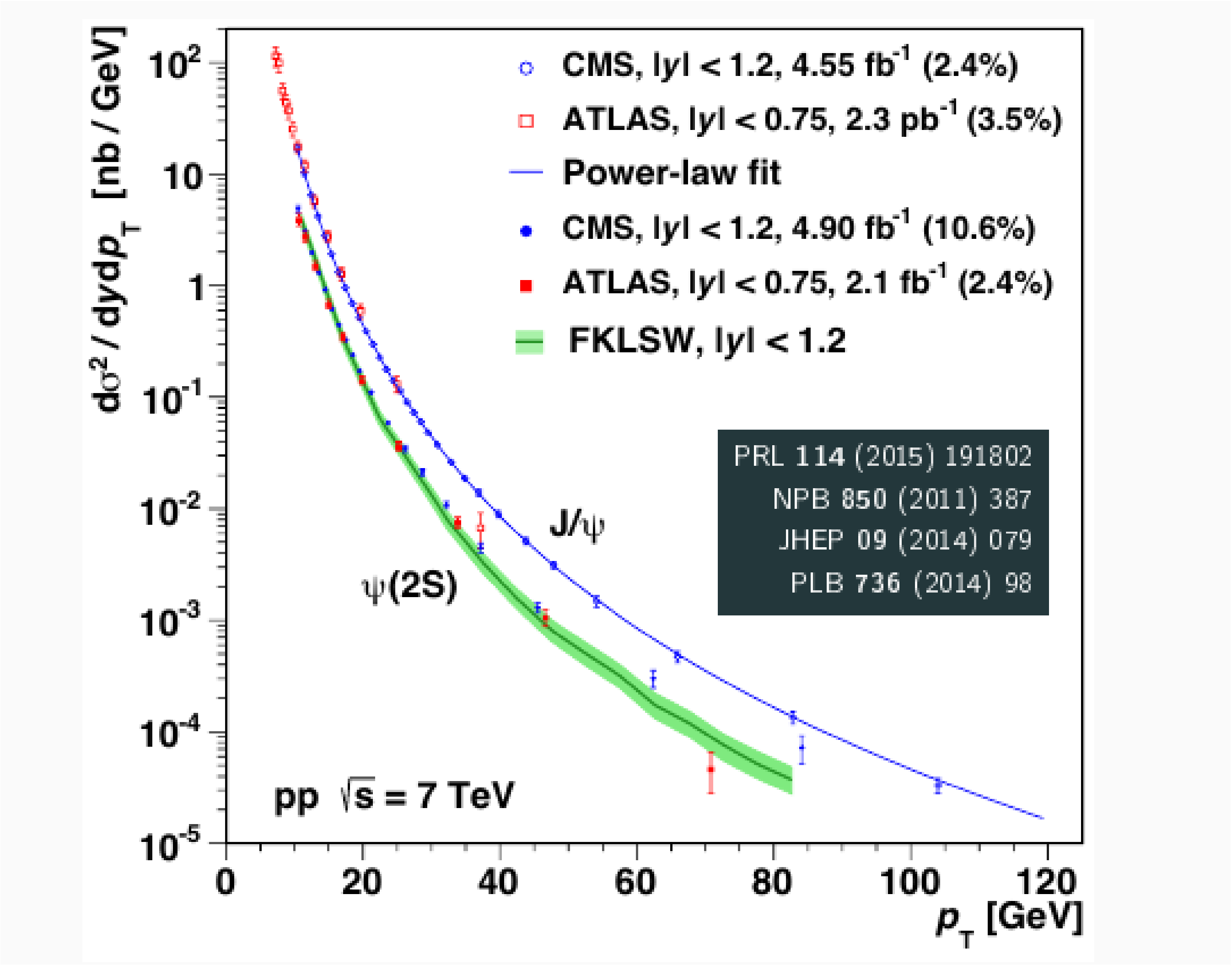
# Comparisons between experiments

# ATLAS & CMS comparison: central rapidity

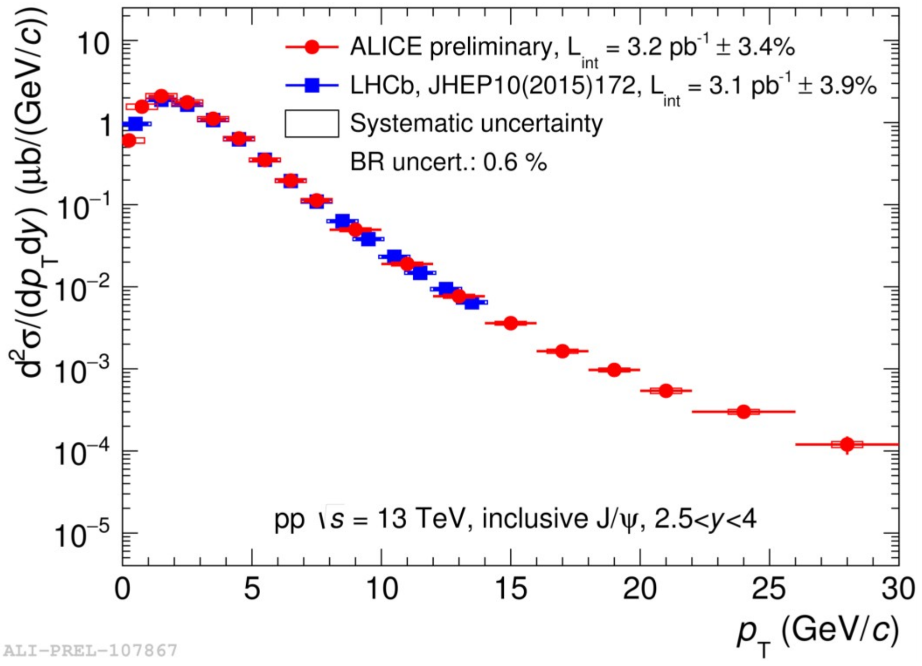


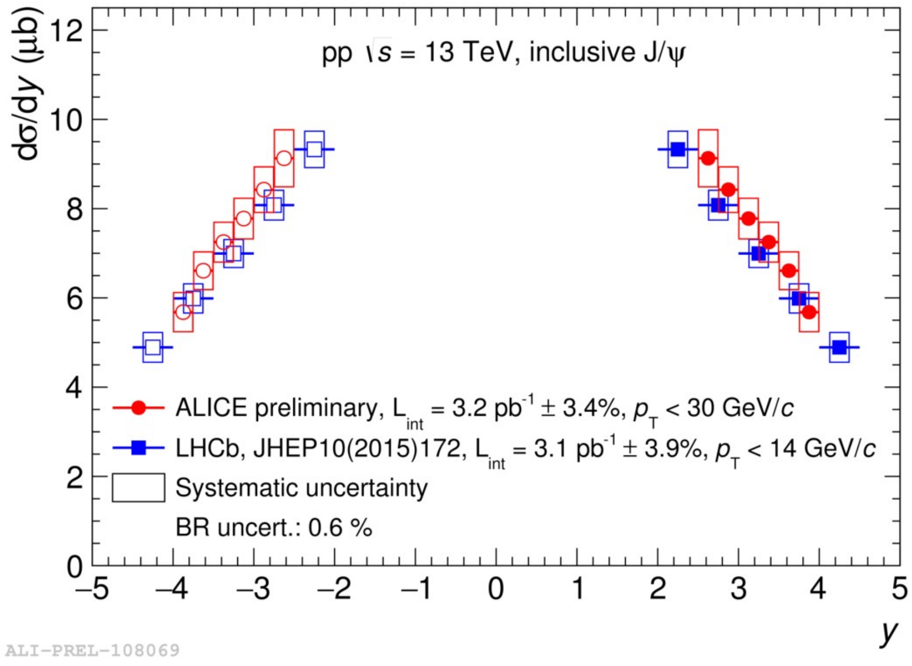

J/ψ and ψ(2S) at 7 TeV

# ALICE & LHCb Comparison: Forward rapidity

ALICE and LHCb results at 13 TeV (JHEP10 (2015) 172)

LHCb 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)

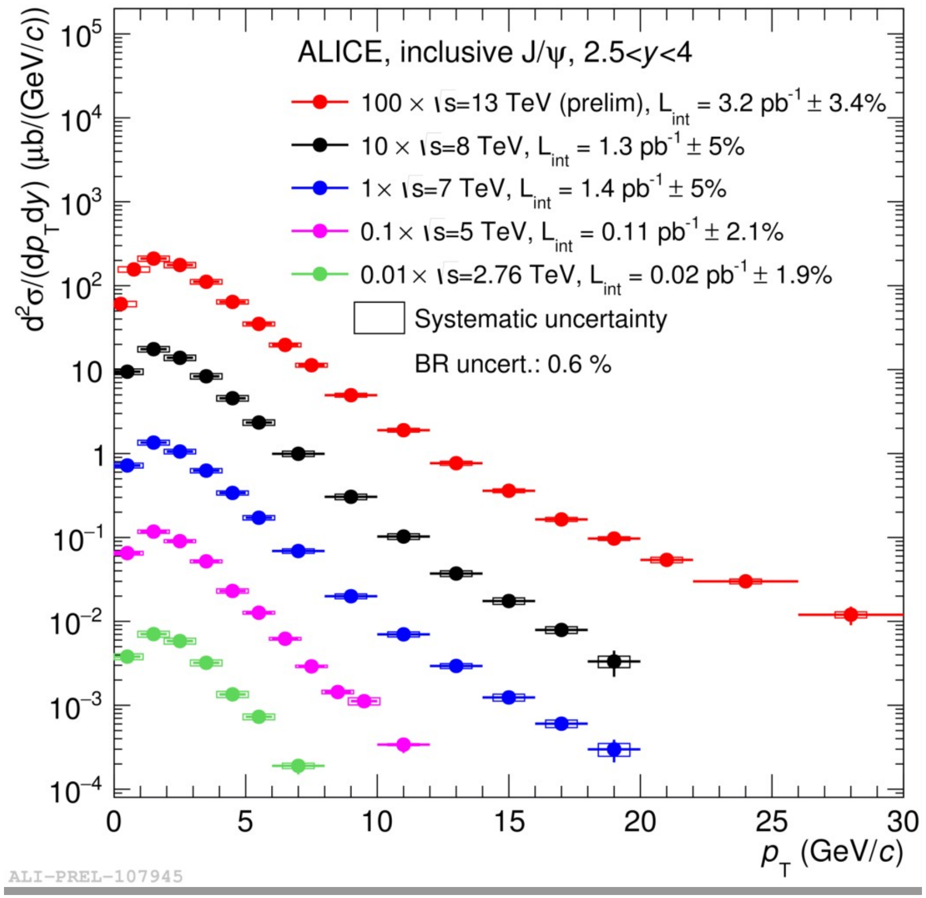



Excellent agreement between the two experiments

All points lie within 1 sigma (stat+syst) of each other

# Comparison to lower energy: J/ψ vs $p_T$




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

Steady increase of the luminosity and $p_T$ reach with increasing energy

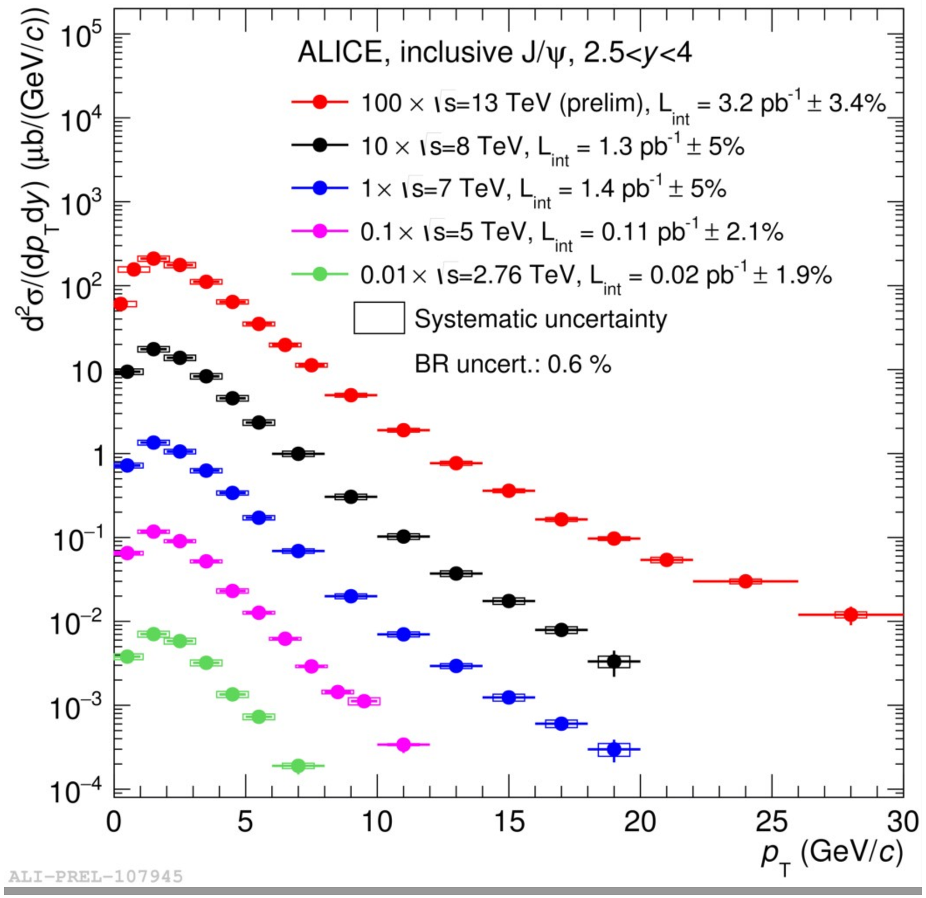
As expected, spectra becomes harder with increasing energy

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

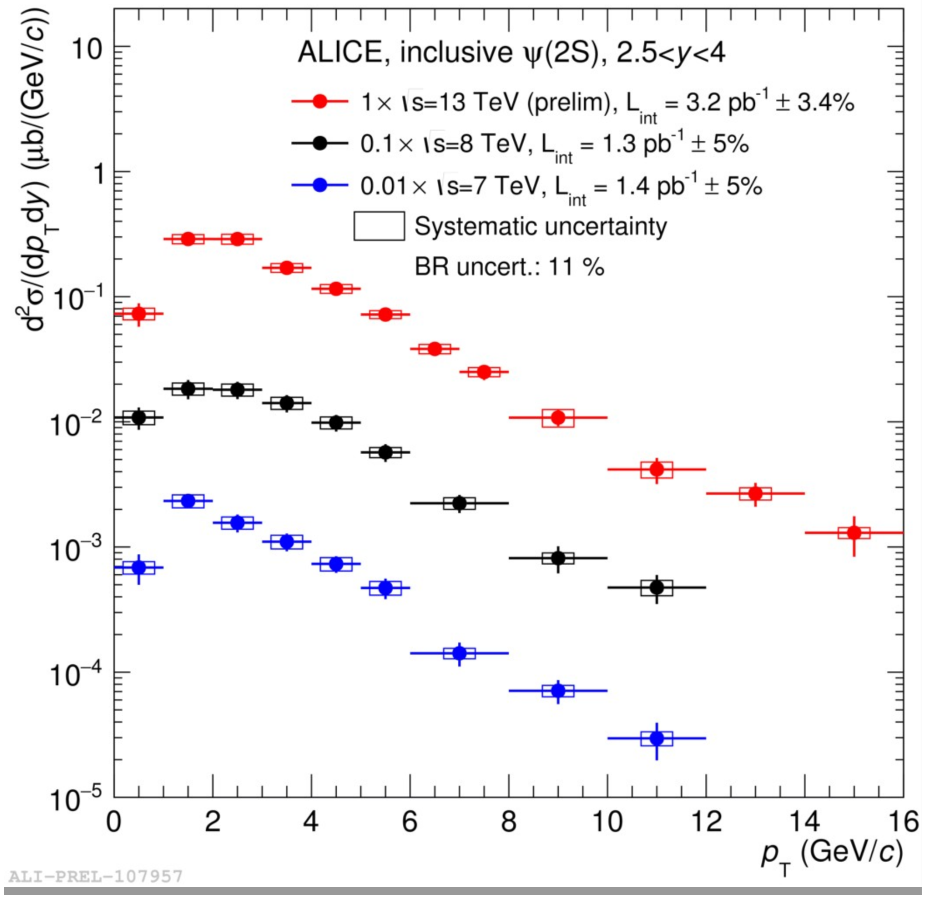
13 TeV Astrid+ Hugo
5 TeV Benjamin+Jana
8TeV Indra+Hugo

# Comparison to lower energy: ψ(2S) vs $p_T$

inclusive J/ψ




inclusive ψ(2S)




| | |
|---|---|
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| $\sqrt{s}$ = 7 TeV | EPJC 74 (2014) 2974 |
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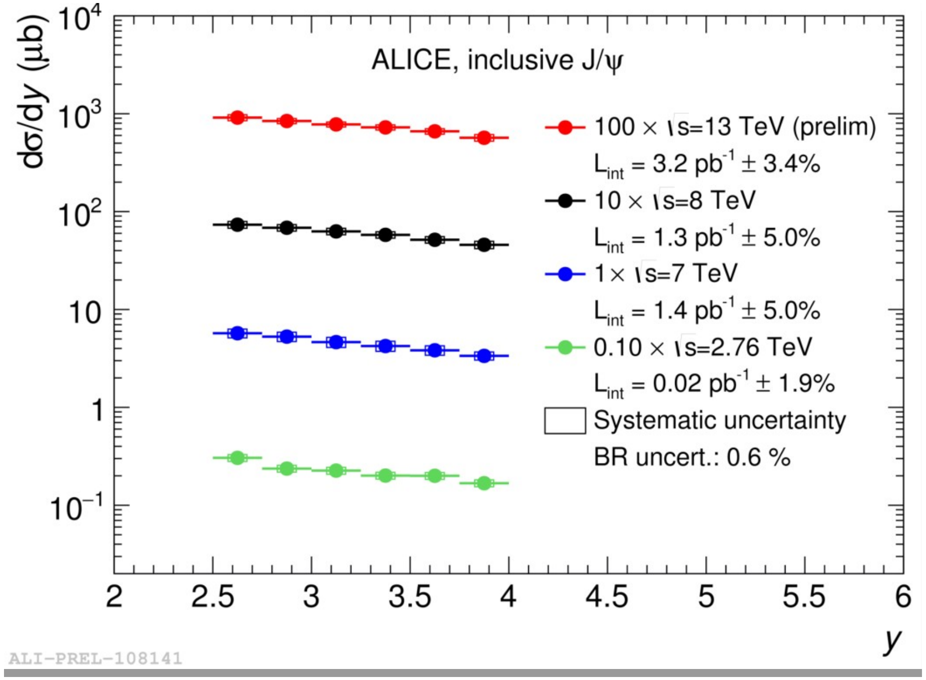
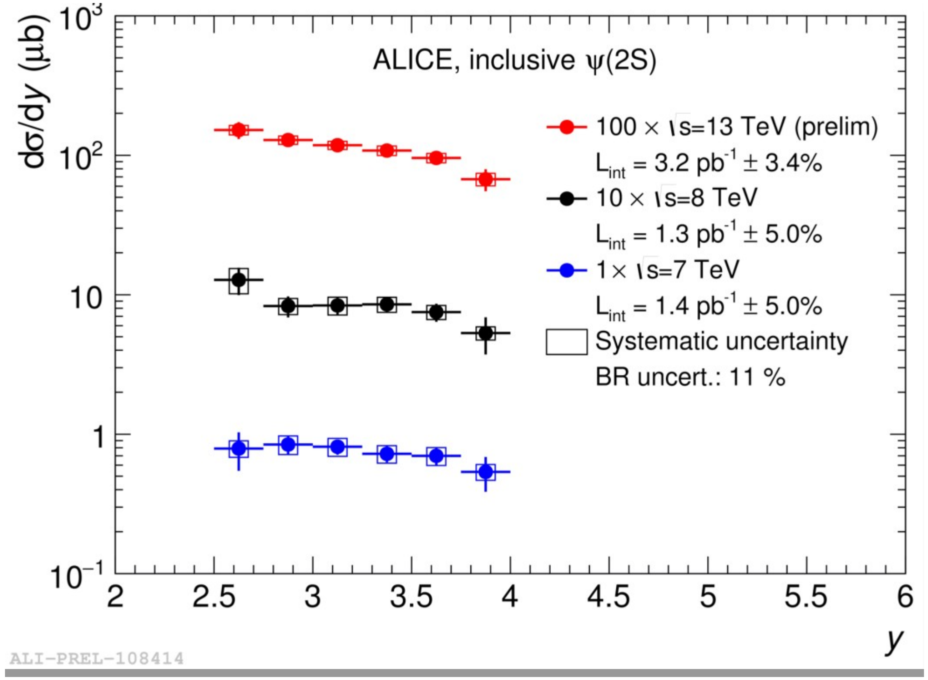
For ψ(2S) ALICE measurements available at $\sqrt{s}$ = 7, 8 and 13 TeV

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

inclusive J/ψ




inclusive ψ(2S)

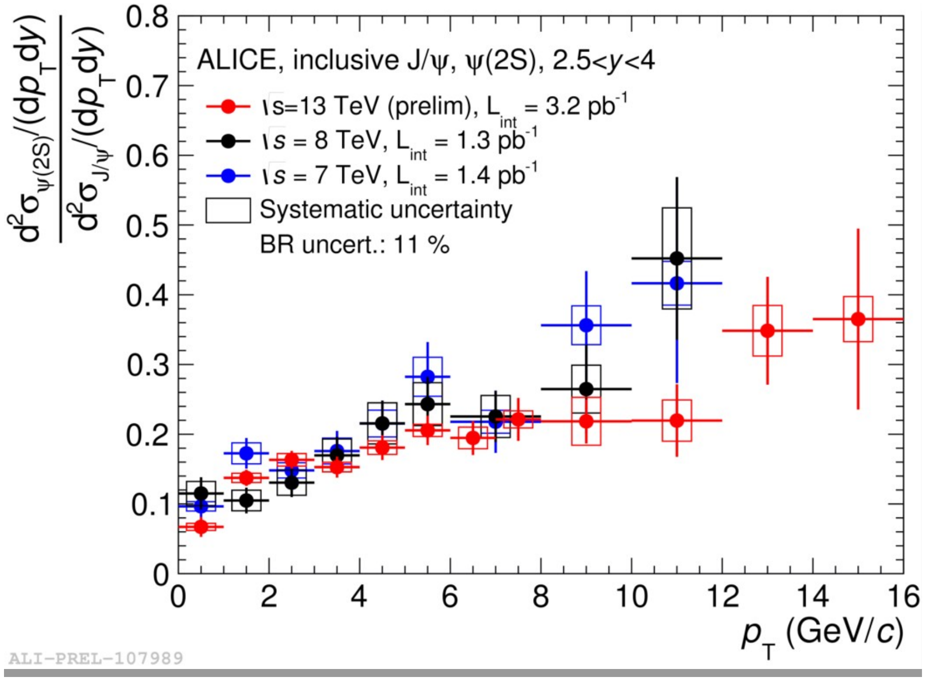


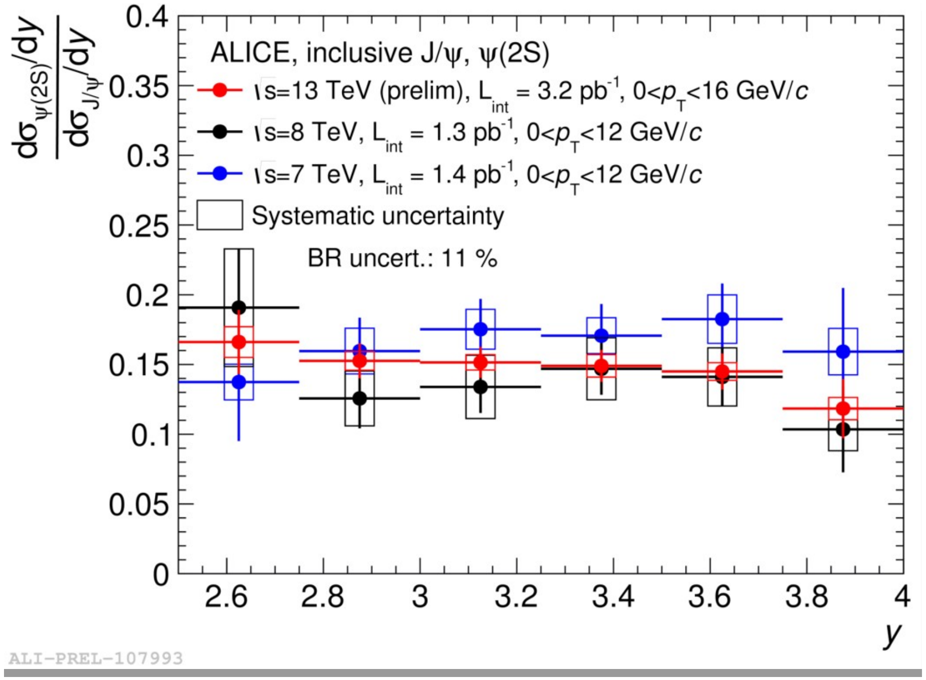

$\sqrt{s}$ = 2.76 TeV PLB 718 (2012) 295
$\sqrt{s}$ = 7 TeV EPJC 74 (2014) 2974
$\sqrt{s}$ = 8 TeV EPJC 76 (2016) 184

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

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

# ALICE's Particle ratios, energy dependence




No visible √*s* dependence of the $p_T$-differential ψ(2S)-to-J/ψ ratio

No clear trend either vs rapidity

# Comparisons with models

# Models

$$d\sigma^{Q} = f_a(x_a).f_b(x_b) \times d\hat{\sigma}_{ab}^{q\bar{q}} \times \left\langle O_{q\bar{q}}^{Q} \right\rangle$$

Three main approaches used to describe direct charmonium production in pp

- Color Evaporation Model (CEM):
  production cross section of a given charmonium is proportional to the $c\bar{c}$ 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 $c\bar{c}$ production with the same quantum numbers (CS) as the final-state meson.
- Non-Relativistic QCD (NRQCD):
  Based on factorization of soft and hard scales.
  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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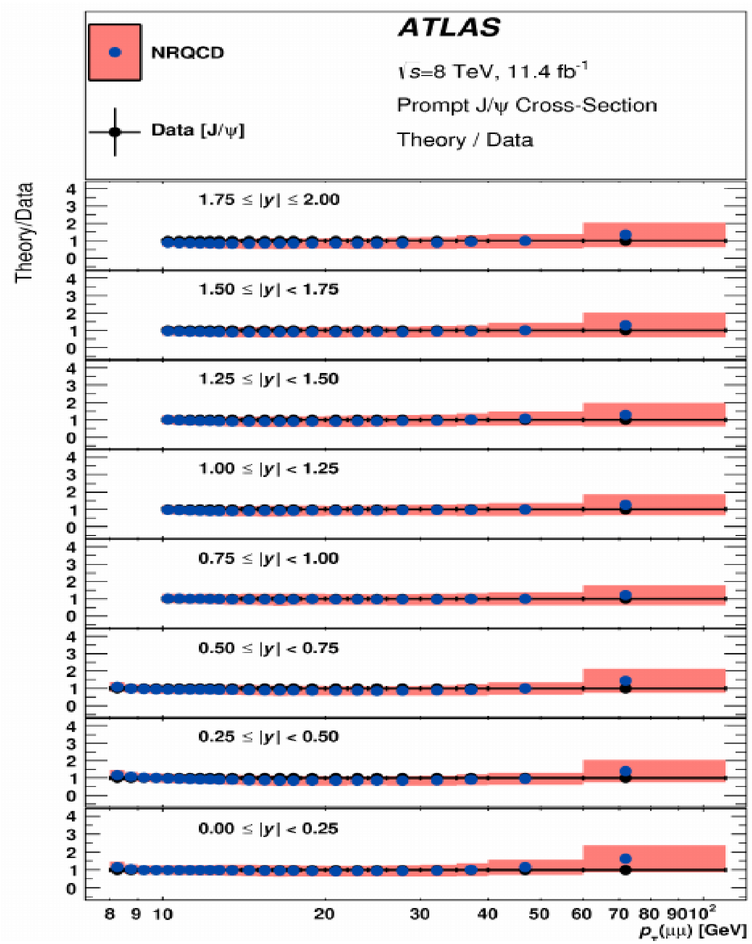
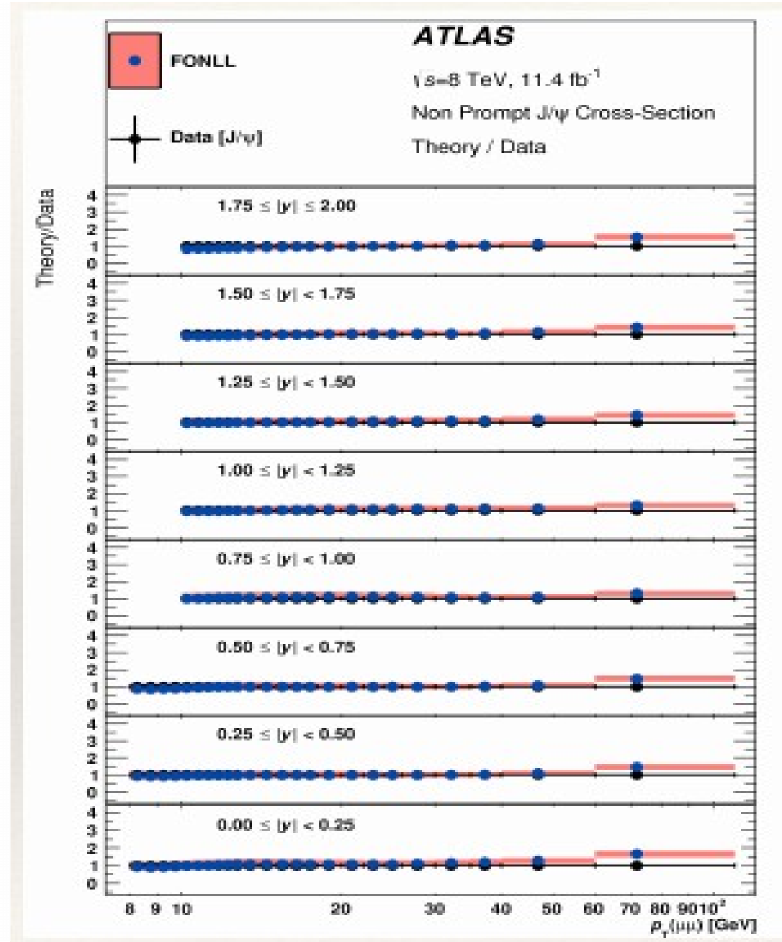
Non-prompt contribution corresponds to the production of *b*-hadrons. Can be calculated with pQCD, e.g. within FONLL

# Central rapidity results compared to models



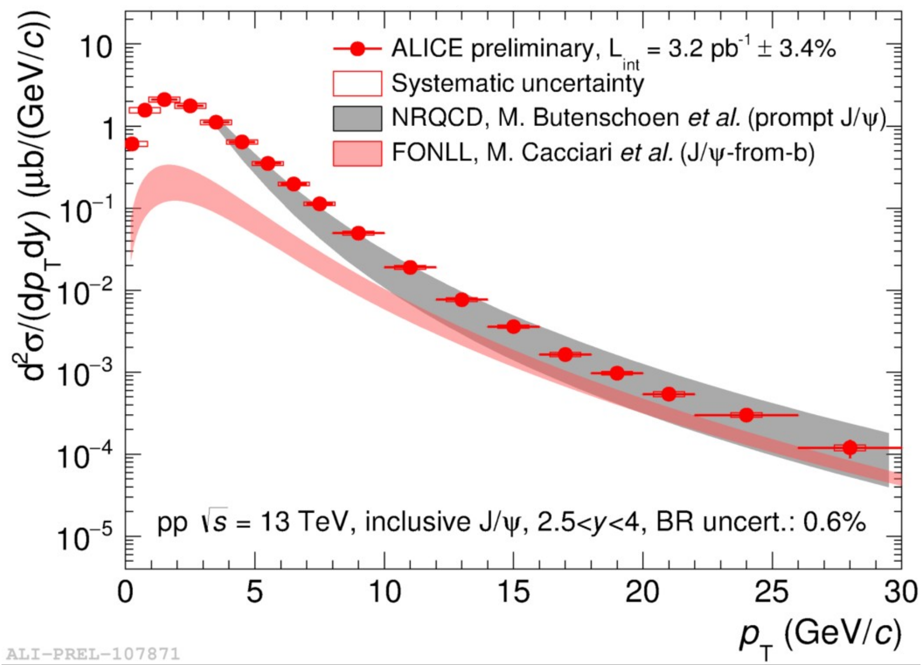



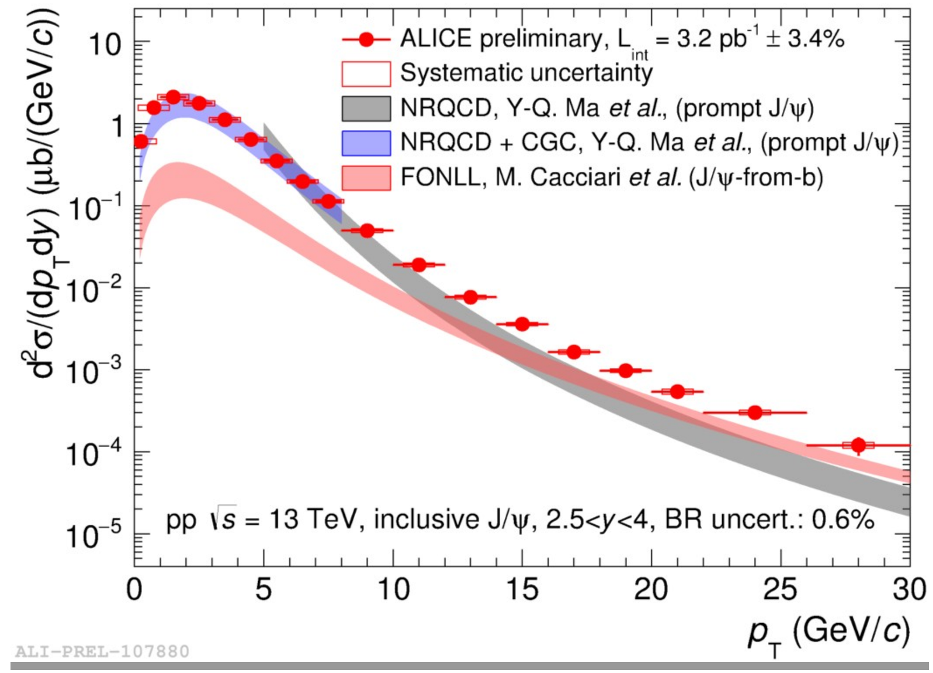

J/ψ vs $p_T$ : ratio of theory to ATLAS data at 8 TeV

Good agreement for both prompt (left) and non prompt(right) production

NRQCD Ma, Wang and Chao, PRL 106 (2011) 042002
FONLL (Cacciari *et al.*, JHEP 1210 (2012) 137 )

# ALICE's inclusive results compared to models




| | |
|---|---|
| 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 |

J/ψ vs $p_T$ @13 TeV

All models properly account for higher mass resonance decays

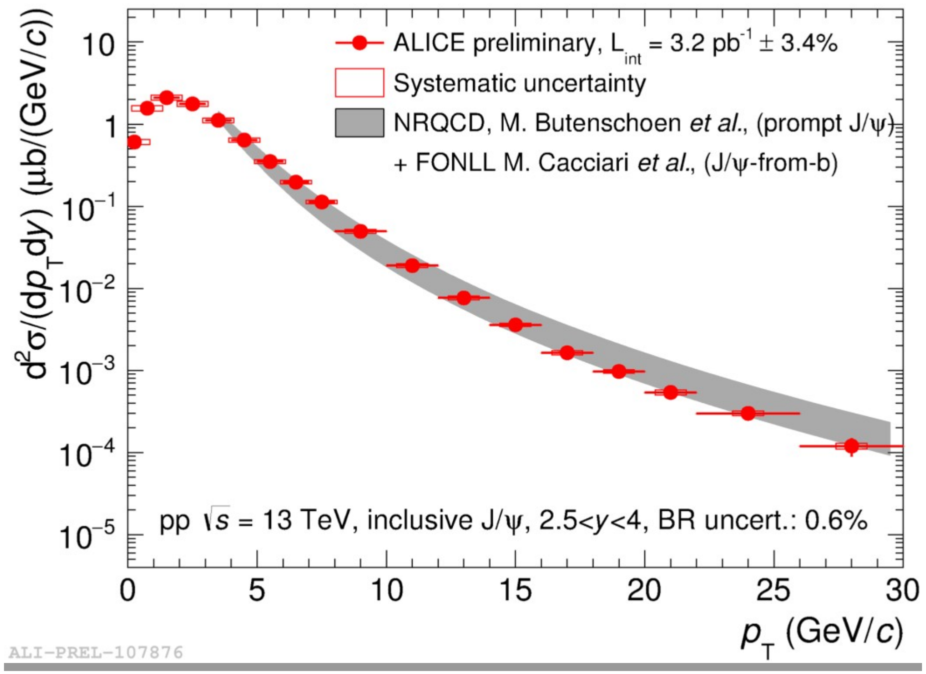
NRQCD models differ in the set of LRME that is used, the $p_T$ at which fits are performed and the datasets considered.

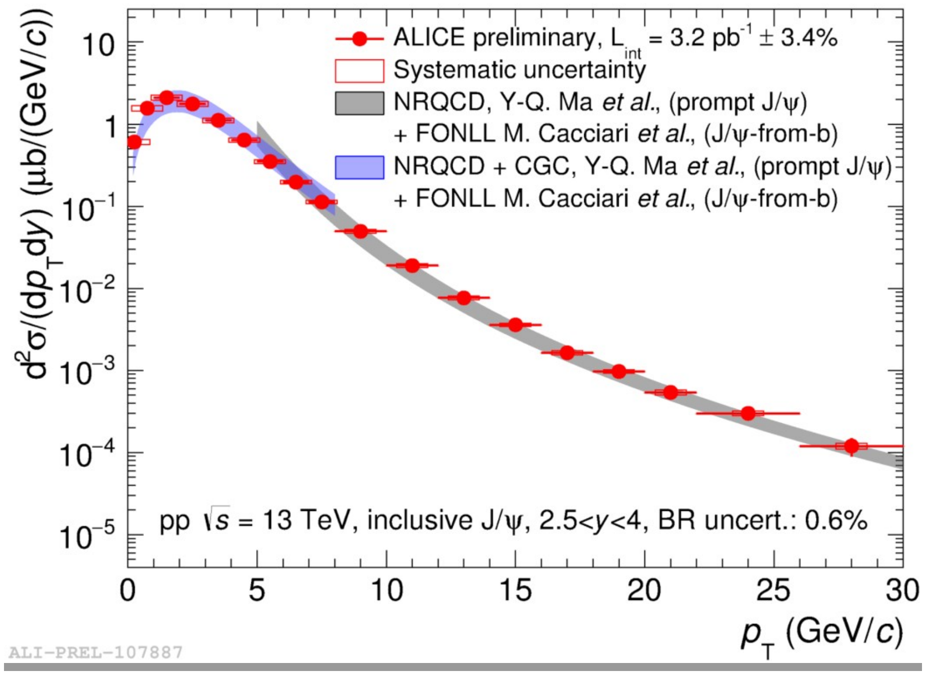
At low $p_T$ (right), NRQCD is coupled to a CGC description of the proton

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

# ALICE's inclusive results compared to models

Summed NRQCD and FONLL calculations assuming fully uncorrelated uncertainties.

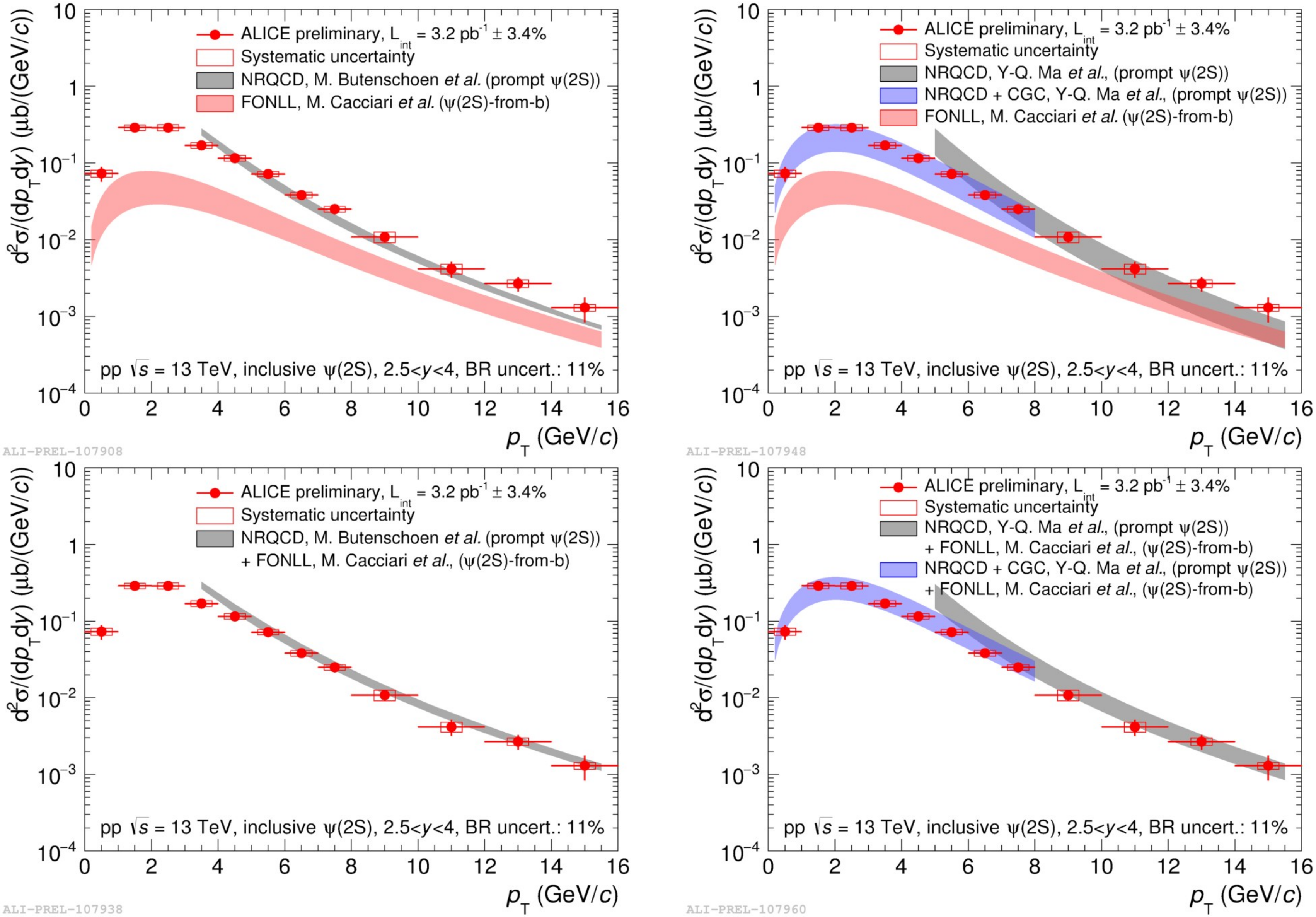



Agreement to the data is much improved, already at intermediate $p_T$ and especially for the calculation from Ma *et al.*

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

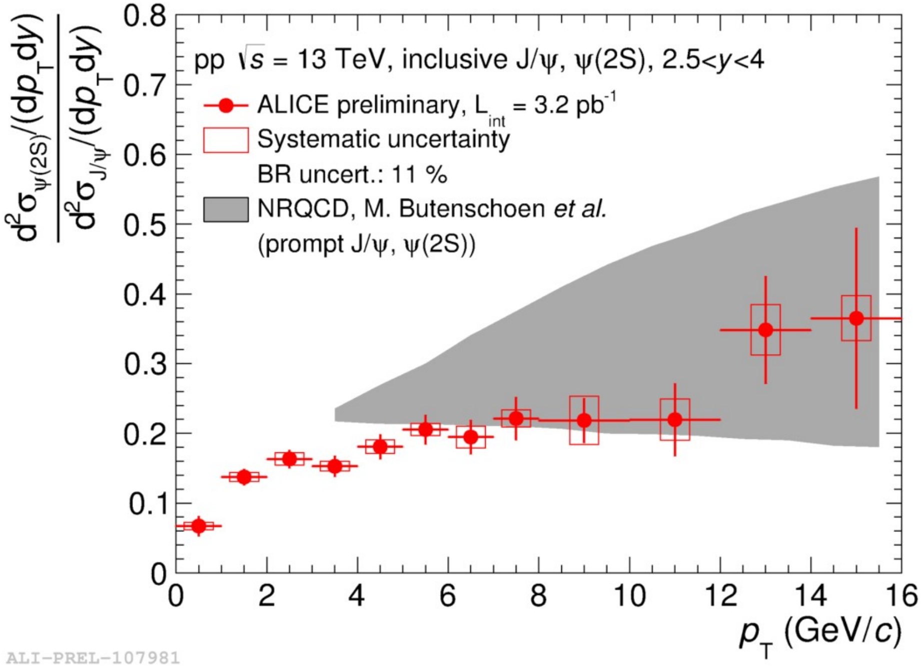
# Comparison to models: ALICE's ψ(2S) vs $p_T$

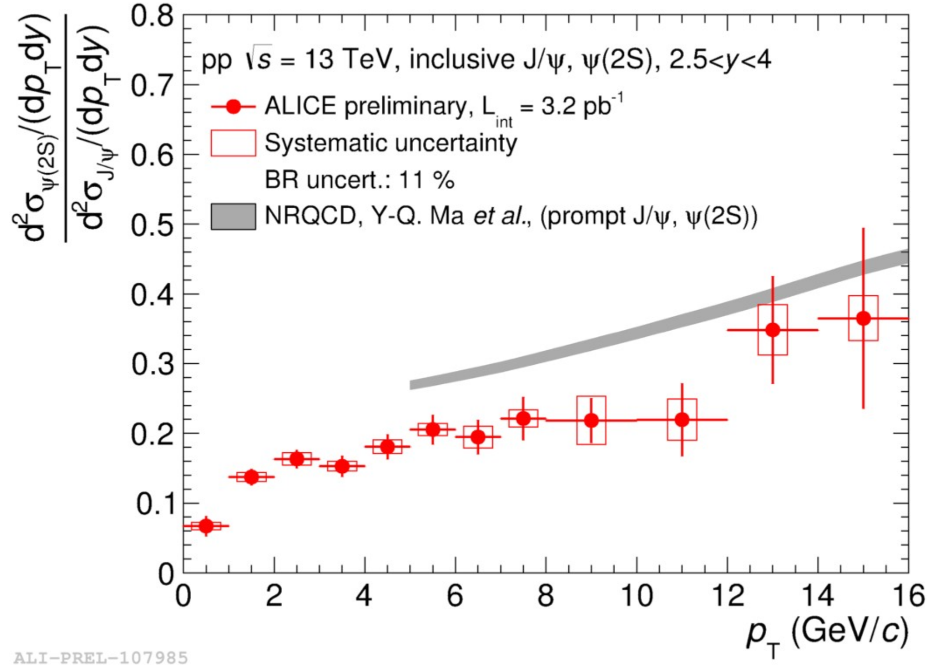



Same conclusions as for the J/ψ case

# ALICE's 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

# J/ψ polarization and $\eta_c$

# J/ψ polarization

J/ψ (spin 1) alignment analyzed via the angular distribution of the decay products vs polar (θ) and azimuthal (ϕ) angles:

$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right)$$

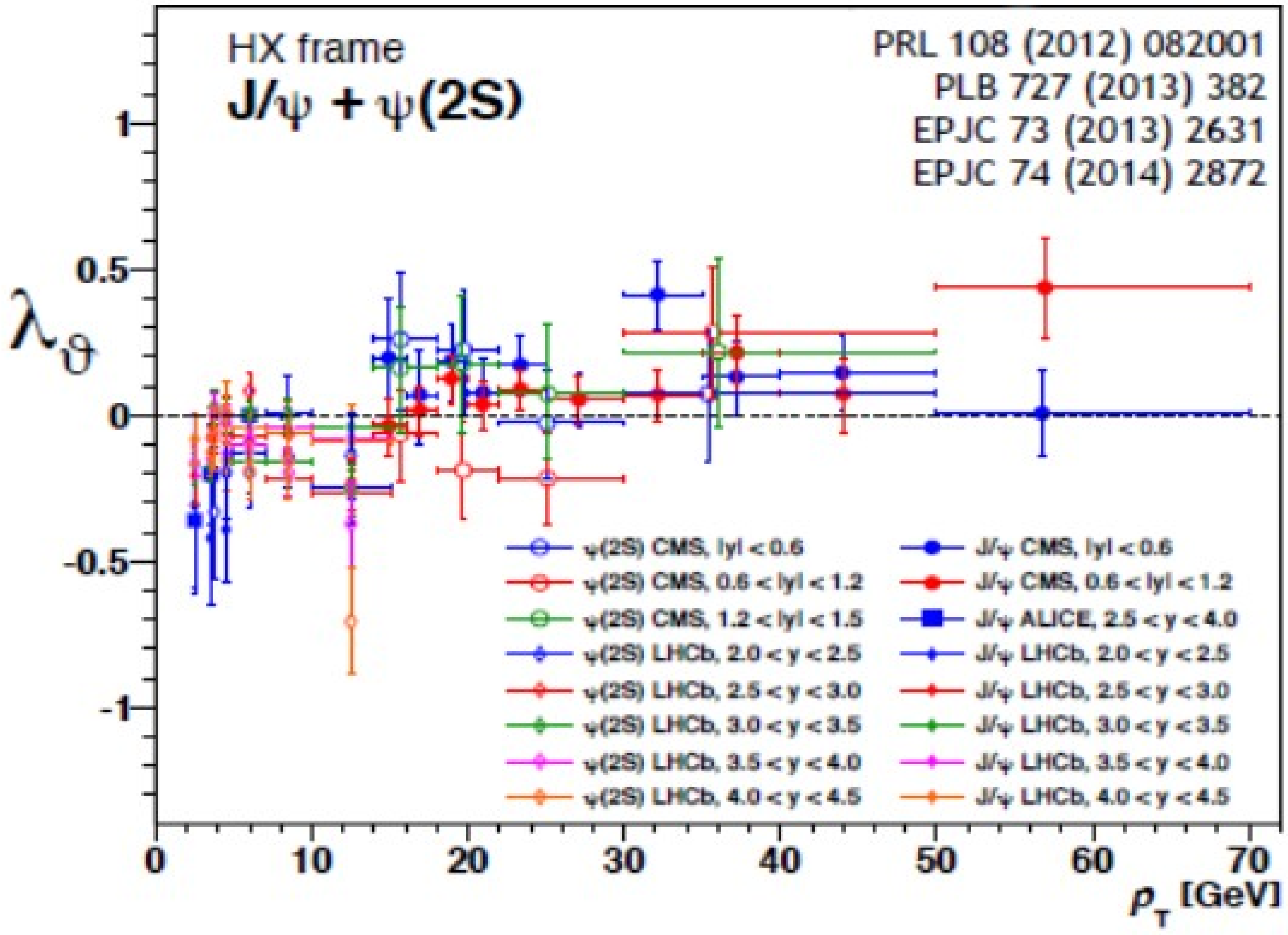
Integrating over ϕ: $$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$$

Integrating over cosθ: $$W(\phi) \propto 1+\frac{2\lambda_\phi}{3+\lambda_\theta}\cos 2\phi$$

Typically: measure quarkonium corrected yields in bins of cosθ, ϕ and $p_T$, perform a simultaneous fit using functions above to extract $\lambda_\theta$ and $\lambda_\phi$

# J/ψ polarization

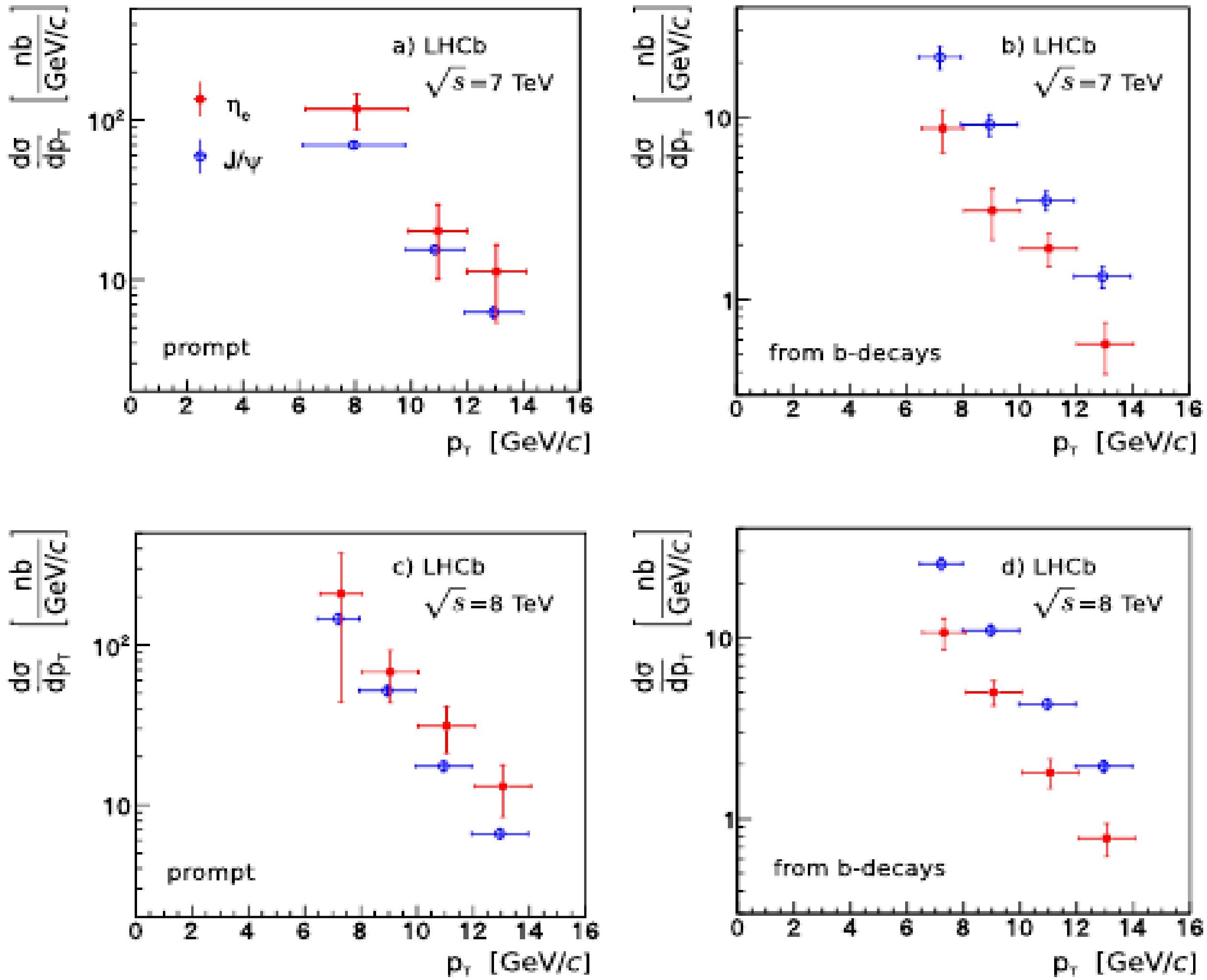
J/ψ spin alignment analyzed via the angular distribution of the decay products in the helicity frame




Agreement between CMS, LHCb and ALICE, consistent with zero polarization within the (large) experimental uncertainties

# LHCb's $\eta_c$ measurements

$\eta_c(1S)$ mesons reconstructed via the ppbar final decay channel.




Eur.Phys.J. C75 (2015)

# What about model comparisons?

**pp yield:** **pp polarization:** **ηc production:**

**Butenschön, Kniehl:**

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.0497\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.0022\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3P_0)\rangle = -0.0161\ \mathrm{GeV}^5$

**Gong, Wan, J.-X. Wang, H.-F. Zhang:**

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.097\ \mathrm{GeV}^3$ $\langle O_8^{\psi'}(^1S_0)\rangle = -0.0001\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3S_1)\rangle = -0.0046\ \mathrm{GeV}^3$ $\langle O_8^{\psi'}(^3S_1)\rangle = 0.0034\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3P_0)\rangle = -0.0214\ \mathrm{GeV}^5$ $\langle O_8^{\psi'}(^3P_0)\rangle = 0.0085\ \mathrm{GeV}^5$
$\langle O_1^{\psi'}(^3S_1)\rangle = 0.0022\ \mathrm{GeV}^3$

**Chao, Ma, Shao, K. Wang, Y.-J. Zhang:**

$\langle O_8^{J/\psi}(^1S_0)\rangle = 0.089\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003\ \mathrm{GeV}^3$
$\langle O_8^{J/\psi}(^3P_0)\rangle = 0.0126\ \mathrm{GeV}^5$

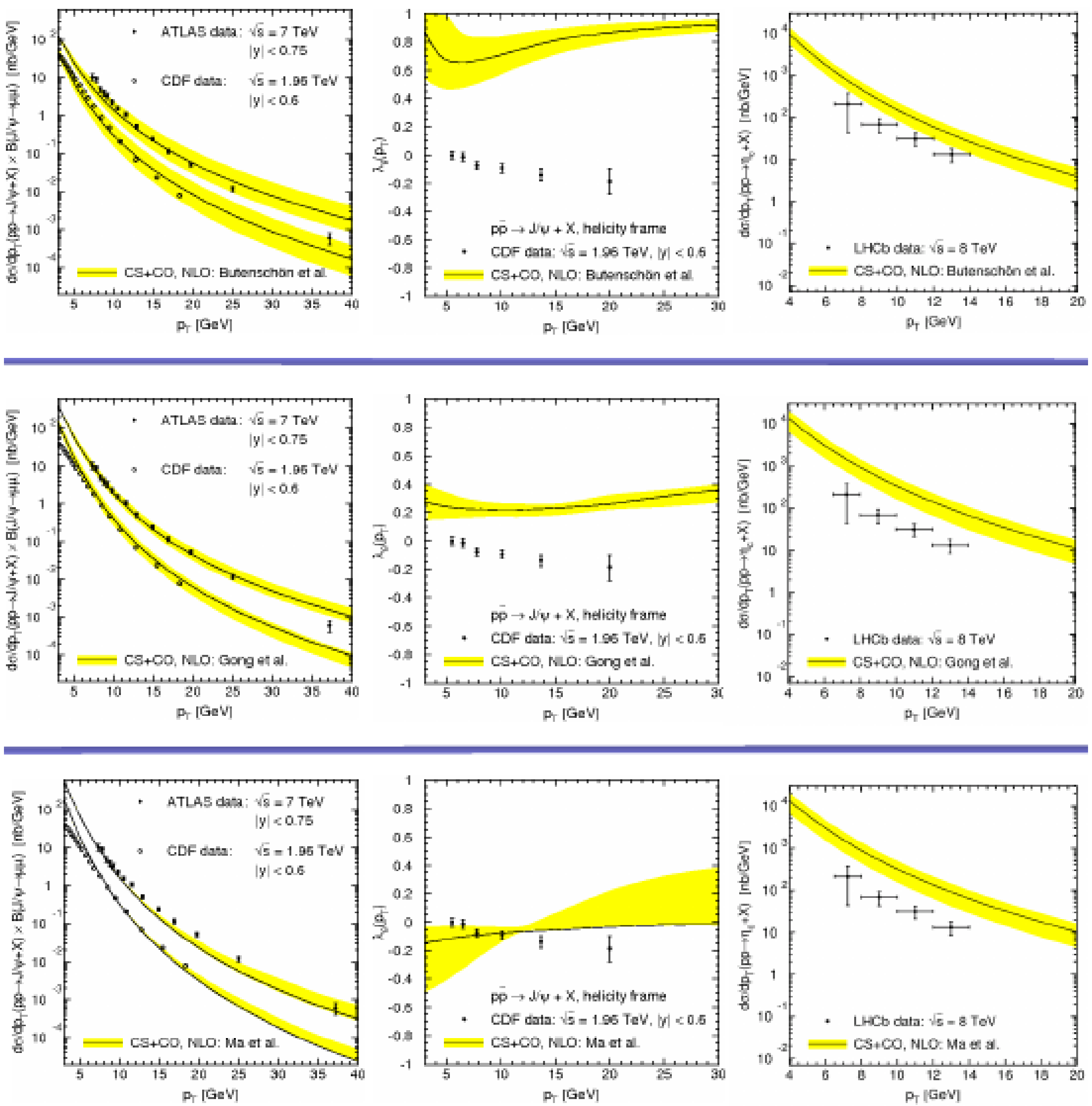



Figure from **KNIEHL B.** Quarkonium 2016 VA, USA

# Summary

Inclusive J/ψ and ψ(2S) production at forward-and central-*y* in pp collisions at several $\sqrt{s}$

J/ψ: the results are consistent between the LHC experiments.

ψ(2S): ALICE is the only measurement available at $\sqrt{s}$ *=13 TeV* down to $p_T$ =0 GeV/*c*

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 (and FONLL for the non-prompt contributions)

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

J/ψ polarization is consistent among all LHC experiments and with zero polarization.

For the $\eta_{c,}$ LHCb is the only measurement available at the LHC

J/ψ polarization and $\eta_c$ challenge factorized NRQCD