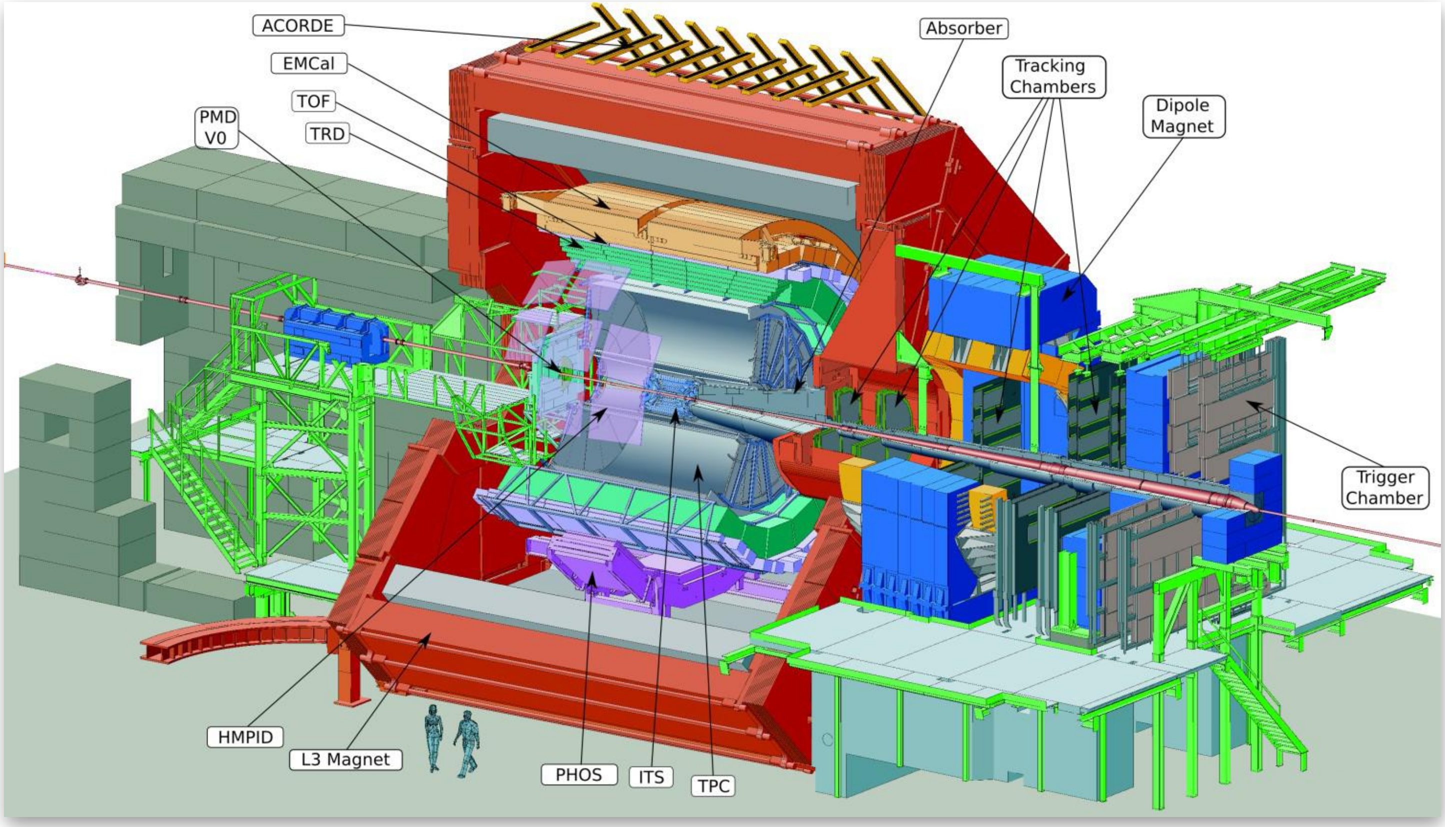
# Quarkonium production in pp collisions at the LHC, with ALICE

Hugo Pereira Da Costa, for the ALICE collaboration
CEA/IRFU
Quarkonium 2014 – Friday, November 14 2014

# Quarkonium measurements in ALICE




<u>Quarkonia are measured</u>

- at forward rapidity ($2.5<y_l<4$) in the $\mu^+\mu^-$ channel, using MTR, MCH and ITS
- at mid rapidity ($|y|<0.9$) in the $e^+e^-$ channel, using TPC and ITS
  possibility to separate prompt and non-prompt production

Trigger systems use VZERO, ITS and MTR

# Motivation

Leaving aside physics motivations…

At mid-rapidity ALICE is the only experiment that can measure charmonia (J/ψ) down to $p_T$ = 0 GeV/c

At forward rapidity ALICE measurements provide a unique and independent cross-check to LHCb measurements

pp measurements are also used to qualify the detector, reconstruction and analysis, as well as for reference to Heavy-Ion collisions.

# Data sets and outline

Datasets:

| | $\sqrt{s}$ | Integrated luminosity | |
|---|---|---|---|
| 2010 | 7 TeV | MB trigger (mid-rapidity) | ~5.6 $nb^{-1}$ |
| | | muon trigger (forward-rapidity) | ~7.7 to 100 $nb^{-1}$ |
| 2011 | 2.76 TeV | MB trigger (mid-rapidity) | ~1.1 $nb^{-1}$ |
| | | muon trigger (forward-rapidity) | ~19.9 $nb^{-1}$ |
| 2011 | 7 TeV | di-muon trigger (forward-rapidity) | ~1.4 $pb^{-1}$ |

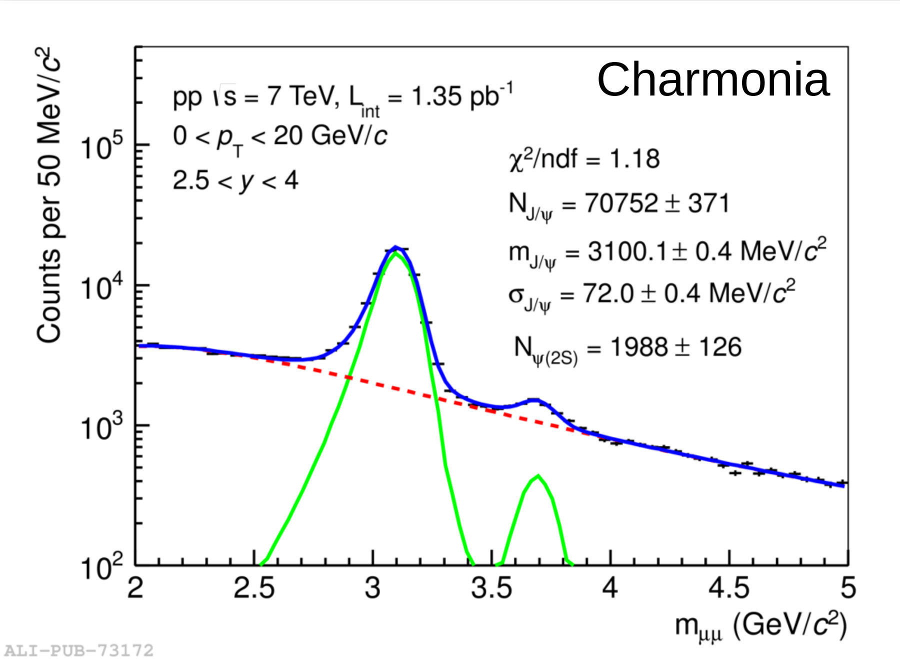
Measurements:

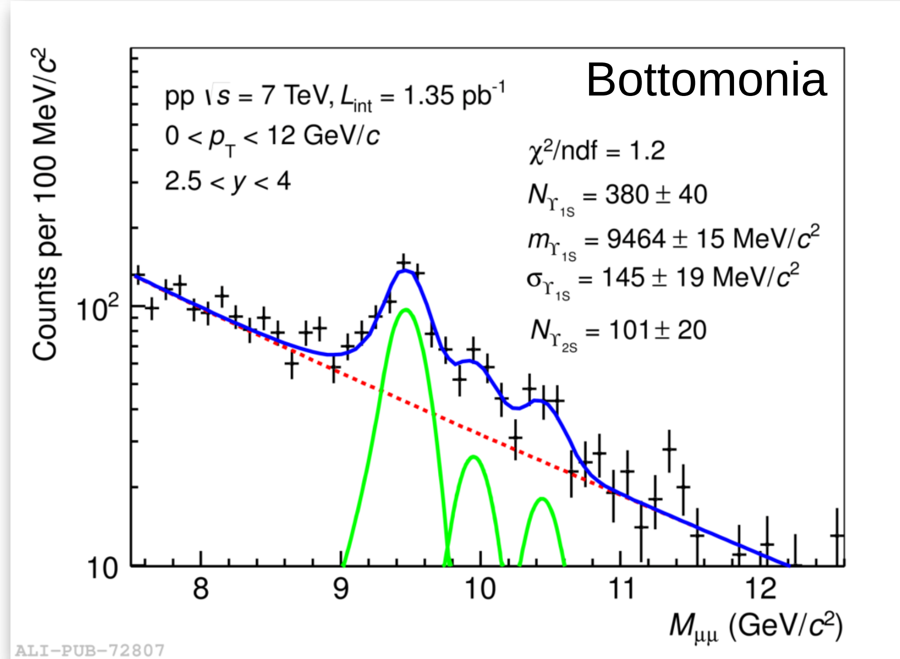
1. Inclusive J/ψ, ψ(2S) and Υ cross section and particle ratios at forward-rapidity (2.5<y<4)
   inclusive = contribution from higher mass resonances and from non-prompt production from b-mesons decay
2. Prompt and non-prompt J/ψ cross sections at mid-rapidity (|y|<0.9)
3. inclusive J/ψ polarization measurements at forward-rapidity
4. inclusive J/ψ production vs charged particle multiplicity (mid- and forward-rapidity)

# Inclusive production cross sections and particle ratios

EPJ. C 74 (2014) 2974

# Signal extraction



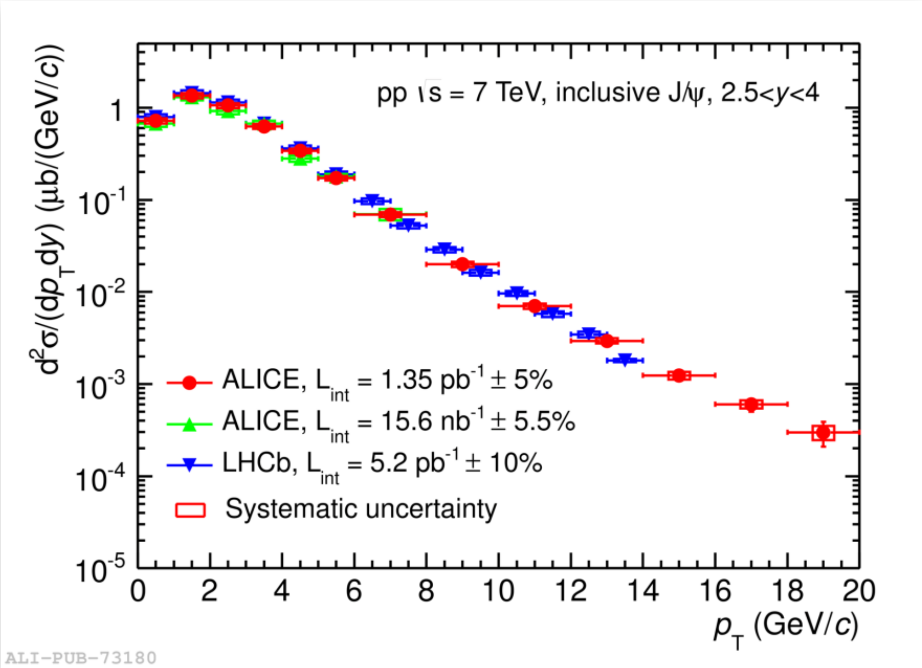

<u>Signal extraction uses</u>:

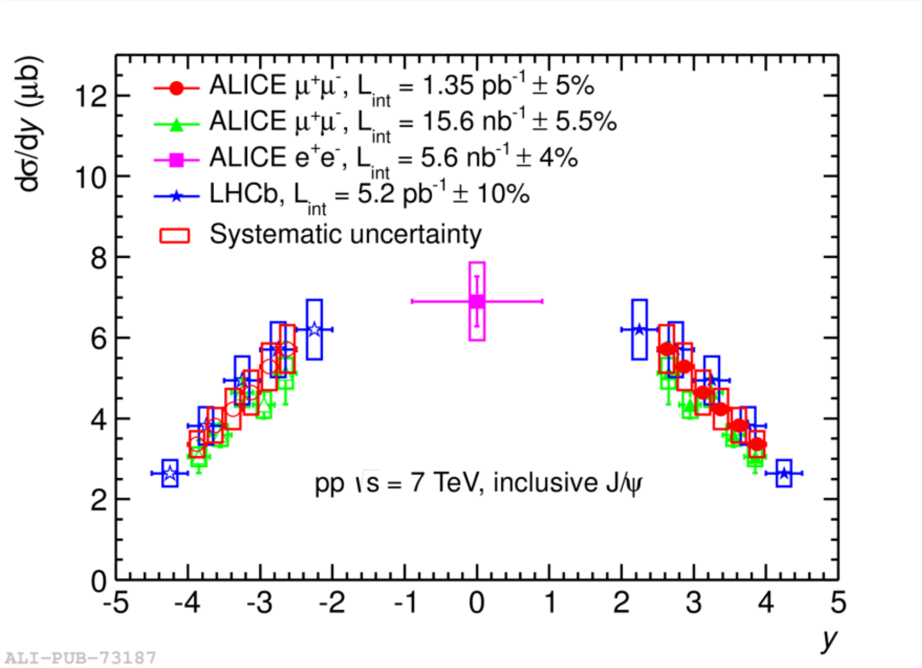
- Variable width Gaussian or polynomial x exponential for the background
- Crystal Ball or pseudo-Gaussian functions for the signal, with tails fixed to MC

<u>Systematic uncertainties include</u>:

- Acceptance x efficiency
- Signal extraction
- Luminosity
- Total pp inelastic cross section

# inclusive J/ψ cross section vs $p_T$ and rapidity

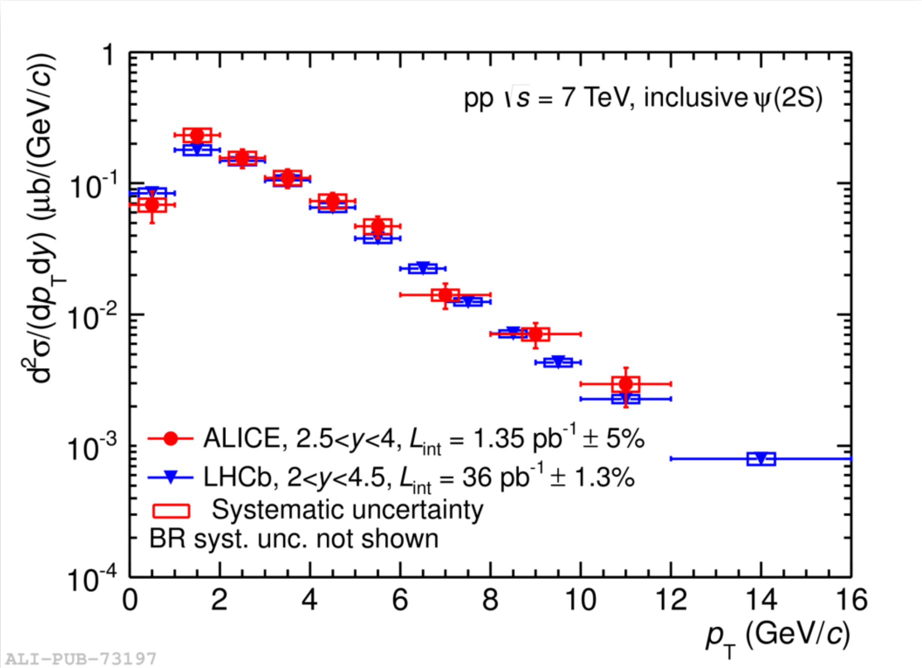


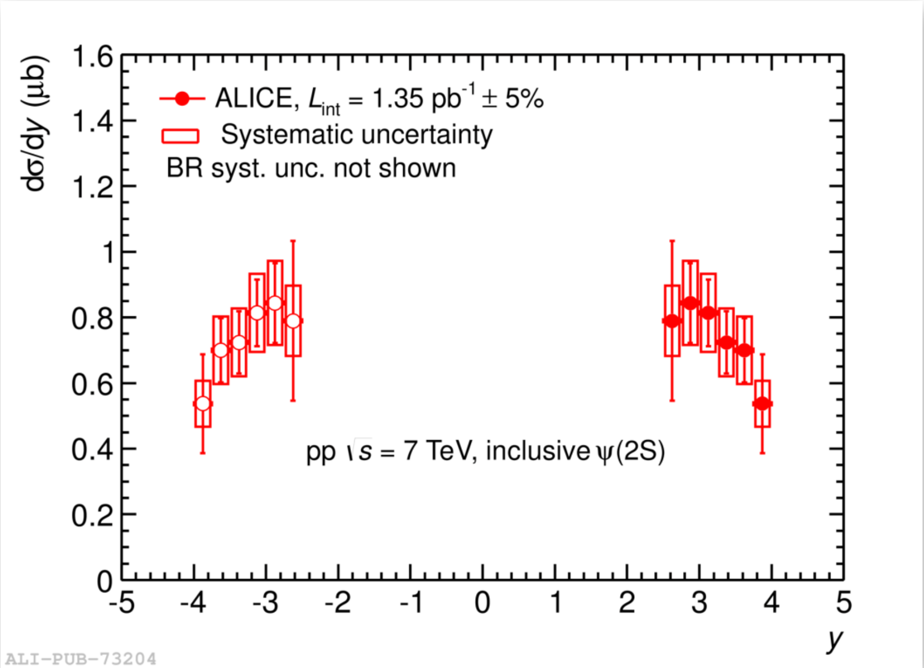




Left: J/ψ $p_T$ distribution, compared to LHCb (EPJ. C 71 (2011) 1645) and ALICE result using 2010 dataset (PLB 704 (2011) 442)

Right: J/ψ rapidity distribution, compared to LHCb (EPJ. C 71 (2011) 1645) and ALICE (2010) at mid- and forward-rapidity (PLB 704 (2011) 442)

# Inclusive ψ(2S) cross section vs $p_T$ and rapidity

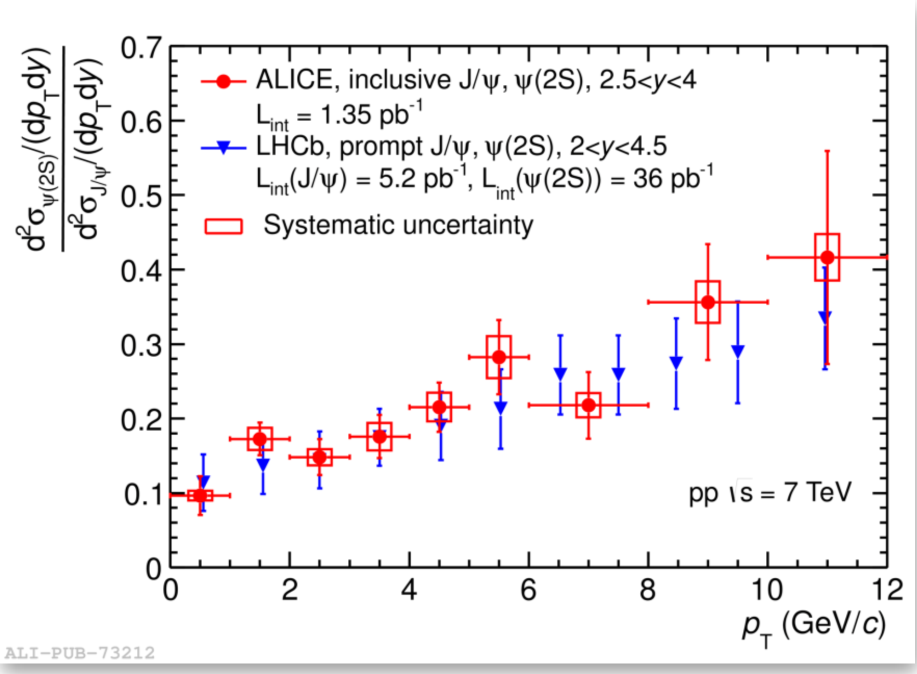


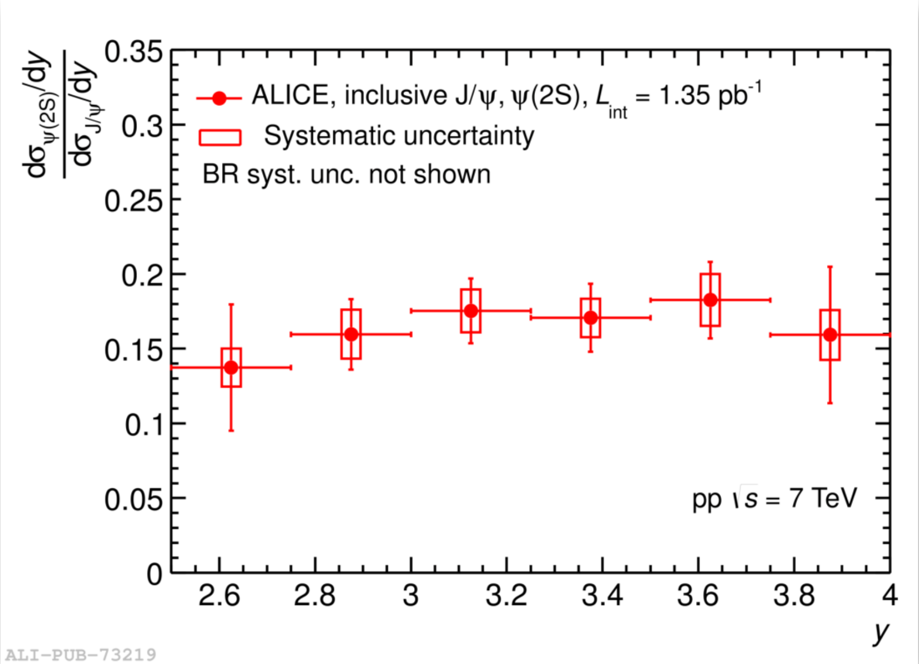




Left: ψ(2S) $p_T$ distribution, compared to LHCb (EPJ. C 72 (2012) 2100)

Right: ψ(2S) rapidity distribution

# inclusive ψ(2S)-to-J/ψ ratio vs $p_T$ and rapidity



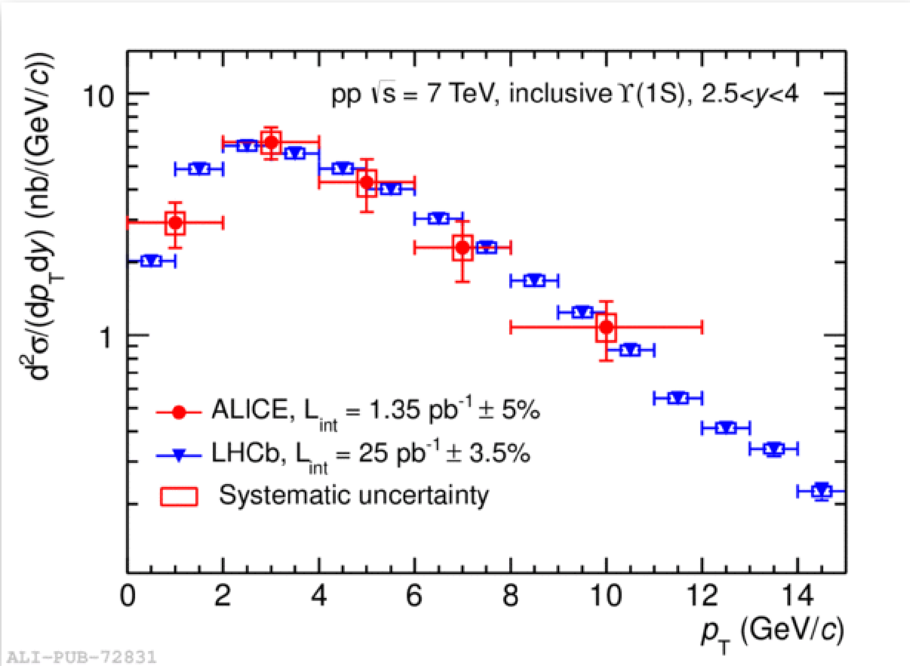

Left: inclusive ψ(2S)-to-J/ψ ratio vs $p_T$ distribution, compared to LHCb (prompt only) (EPJ. C 72 (2012) 2100). Steady increase is observed, a small fraction of which comes from the decay of higher mass resonances (see backups)

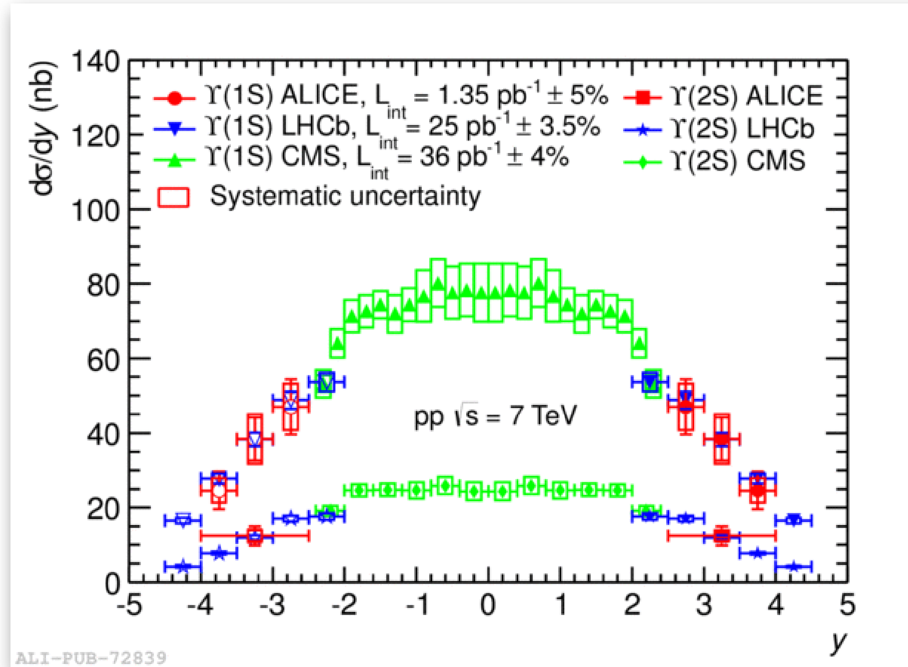
Right: inclusive ψ(2S)-to-J/ψ ratio vs rapidity. Consistent with flat.

Fraction of inclusive J/ψ that comes from ψ(2S) decay:

$$f_{\psi(2S)} = 0.103 \pm 0.007\ (\mathrm{stat}) \pm 0.008(\mathrm{syst})$$

# inclusive Υ(1S) and Υ(2S) vs $p_T$ and rapidity




Left: Υ(1S) $p_T$ distribution, compared to LHCb (EPJ. C 72 (2012) 2025)

Right: Υ(1S) and Υ(2S) rapidity distributions, compared to LHCb (EPJ. C 72 (2012) 2025) and CMS, at mid-rapidity (PRD 83 (2011) 112004, PLB 727 (2013) 101)

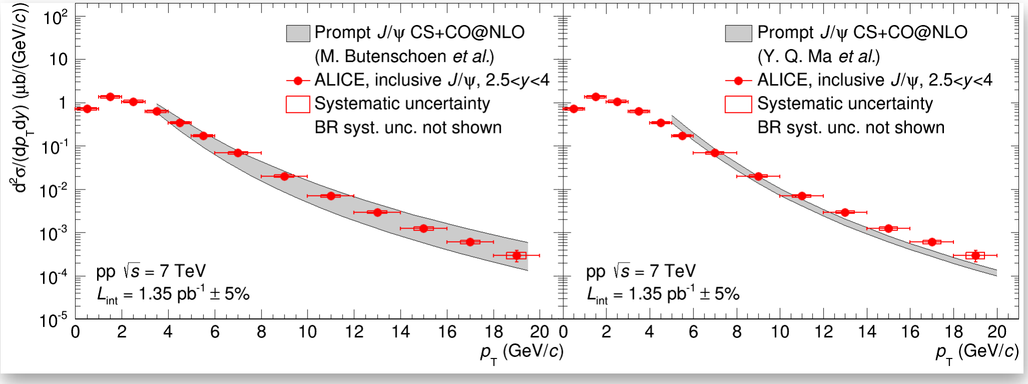
# Model Comparison (1) J/ψ, ψ(2S) NRQCD

Two NRQCD calculations at NLO compared to

Top: J/ψ cross section vs $p_T$

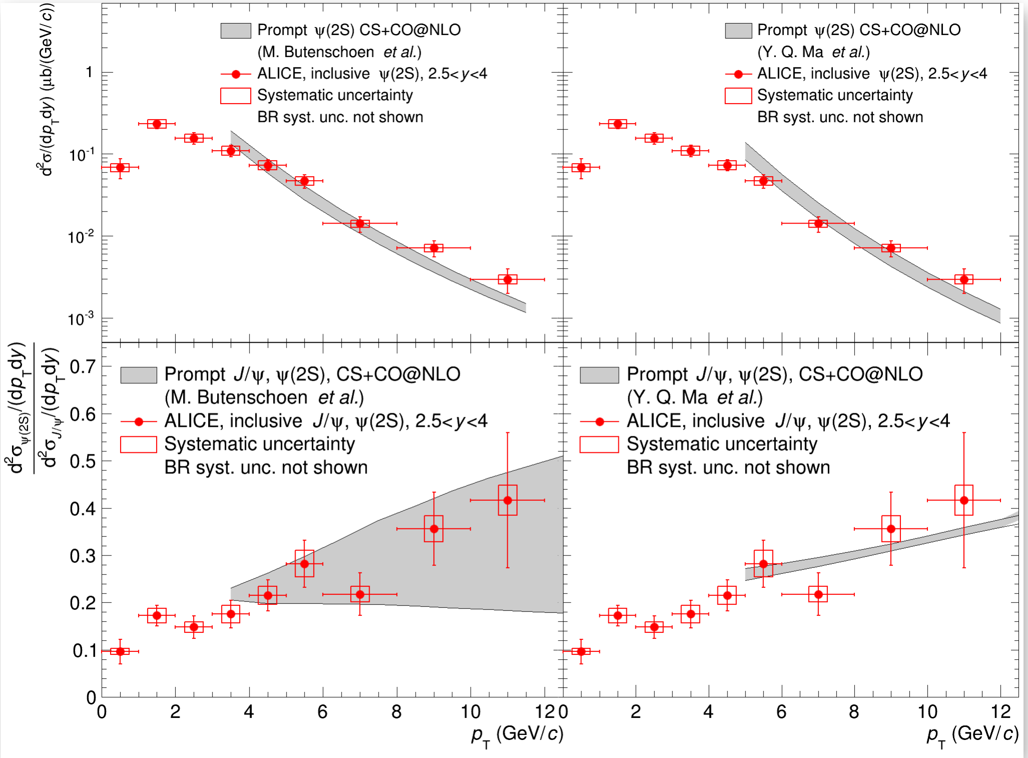
Middle: ψ(2S) cross section vs $p_T$

Bottom: ψ(2S)-to-J/ψ ratio vs $p_T$




The calculations differ by

- the data sets used for the fits
- the number of matrix elements fitted to data
- the $p_T$ range of the fit



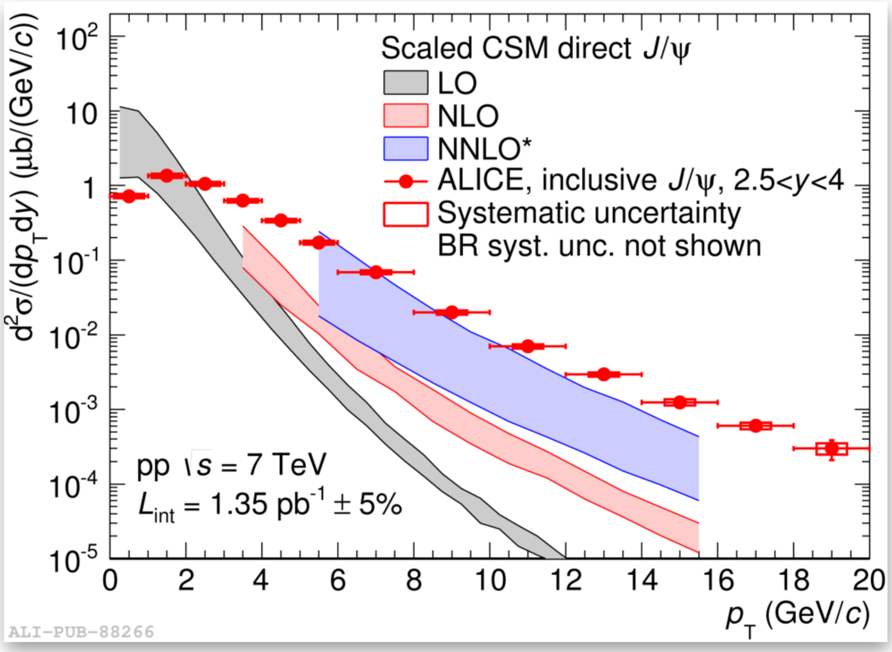

Both calculations account for feed-down corrections

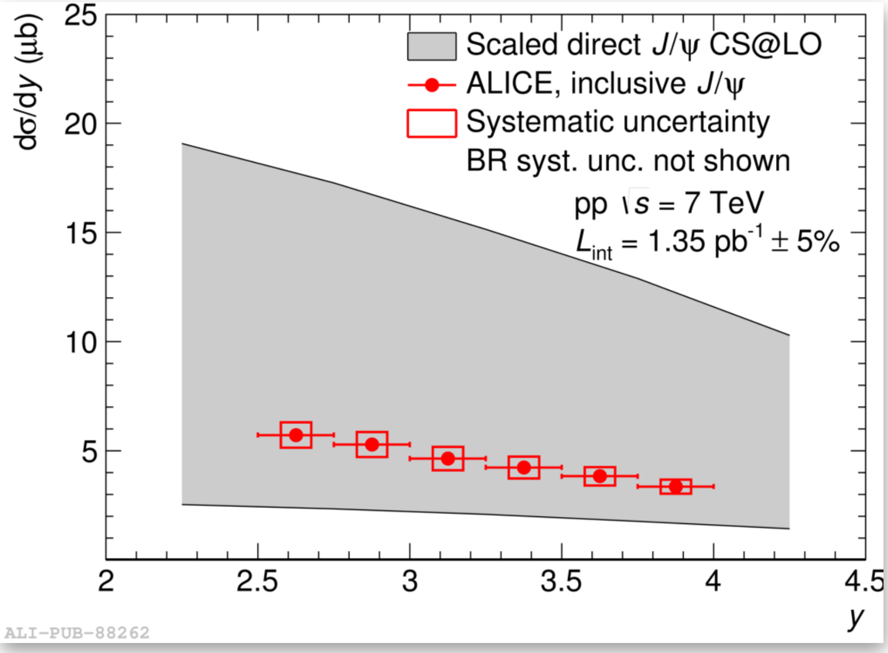
References:

Butenschoen *et al.* PRD 84 (2011) 051501

Ma *et al.* PRD 84 (2011) 114001

# Model Comparison (2) J/ψ CSM



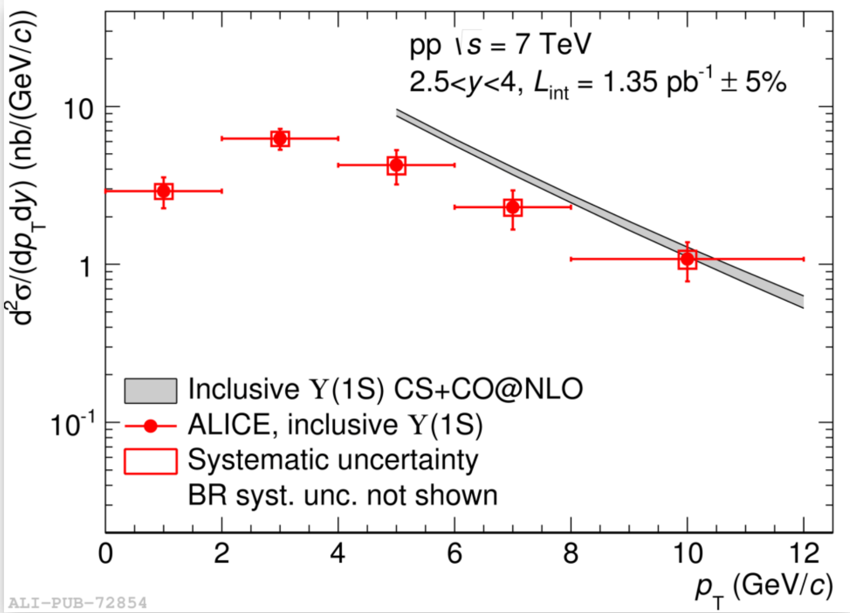



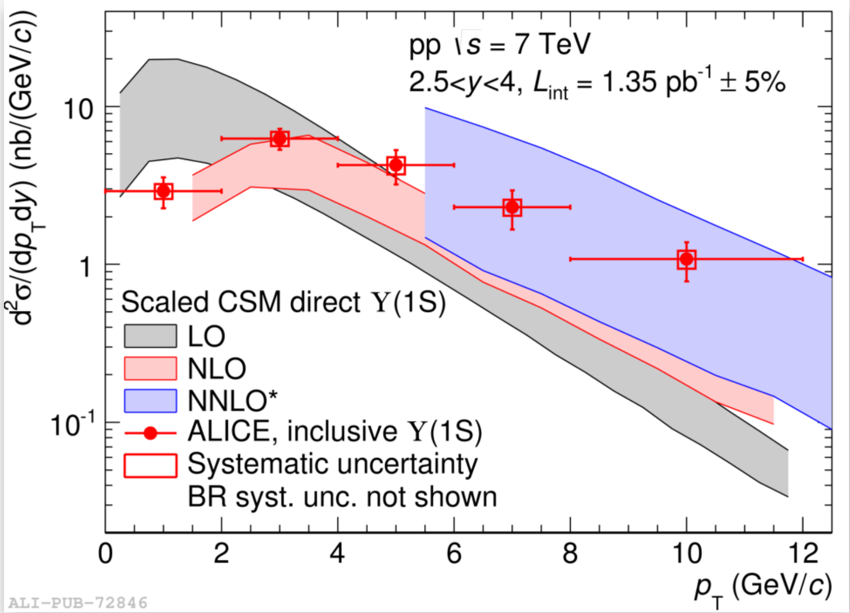

Left: J/ψ vs $p_T$ vs CSM at LO, NLO and NNLO* (Lansberg, JPG 38 (2011) 124110)

Right: J/ψ vs y vs CSM at LO (Lansberg, NP A 470 (2013) 910)

CSM calculations are scaled up by a constant factor of 1/0.6 to account for feed-down contributions (10% from ψ(2S), 20% from $\chi_c$ and 10% from b-mesons)

# Model Comparison (3) Upsilons

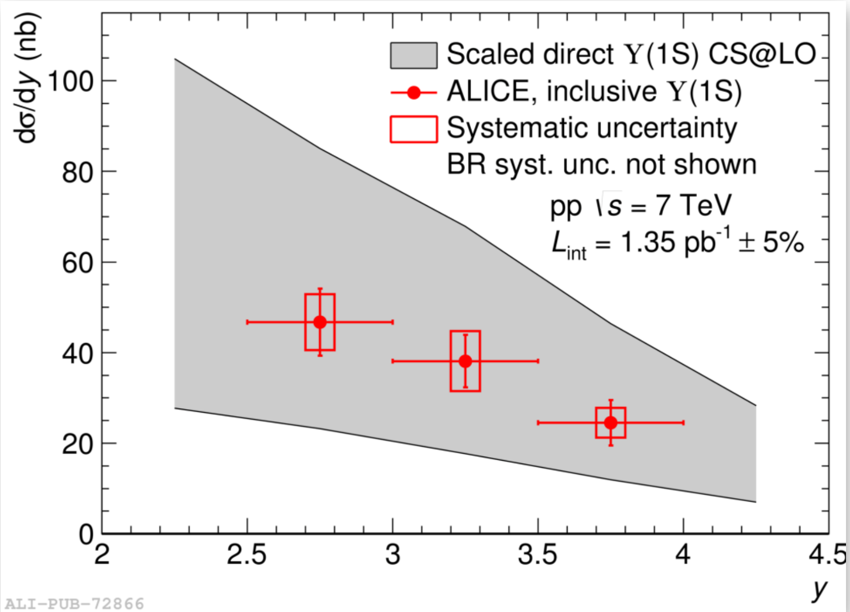



Top-left: Y(1S) vs $p_T$ vs NRQCD at NLO
(Ma *et al.*, PRD 84 (2011) 114001)

Top-right: Y(1S) vs $p_T$ vs scaled CSM at LO, NLO, NNLO*
(Lansberg, NP A 470 (2013) 910)

Bottom: Y(1S) vs y vs scaled CSM at LO
(Lansberg, NP A 470 (2013) 910)




CSM calculations are scaled up by 1/0.6: 9% from Y(2S), 1% from Y(3S), 20% from $\chi_b(1P)$ and 10% from $\chi_b(2P)$

# Prompt and non-prompt J/ψ separation

JHEP11(2012)065

# Motivation and principle

- Measuring prompt charmonia provides cleaner tests to production models
- Measuring non-prompt charmonia gives access to b-bbar production cross section

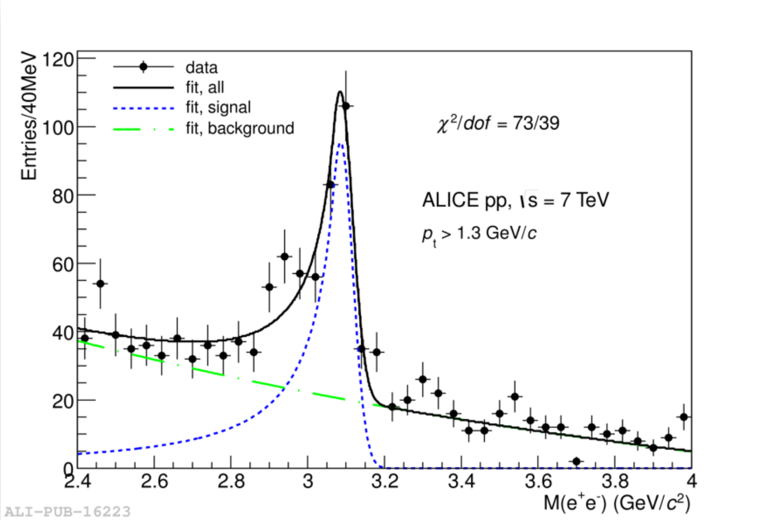
- Measurements performed at mid-rapidity (|y|<0.9) in the di-electron channel
- Signal extraction is performed using the di-electron invariant mass distribution
- Prompt and non-prompt separation is performed using the pseudo-proper decay length x:

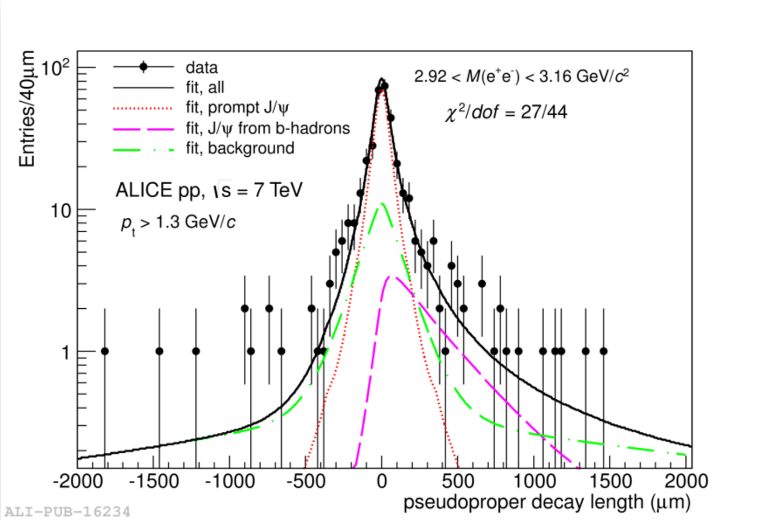
$$x = \frac{c.L_{xy}.m_{\mathrm{J}/\Psi}}{p_{\mathrm{T}}^{\mathrm{J}/\Psi}} \quad \text{with} \quad L_{xy} = \frac{\vec{L}\cdot\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}}$$

and L the vector from primary vertex to J/ψ decay vertex

- Both distributions (invariant mass and x) are fitted simultaneously, using a 2-dimensional unbinned log-likelihood maximization

# Signal extraction




<u>Invariant mass fit functions</u>

- signal: Crystal Ball
- background: exponential

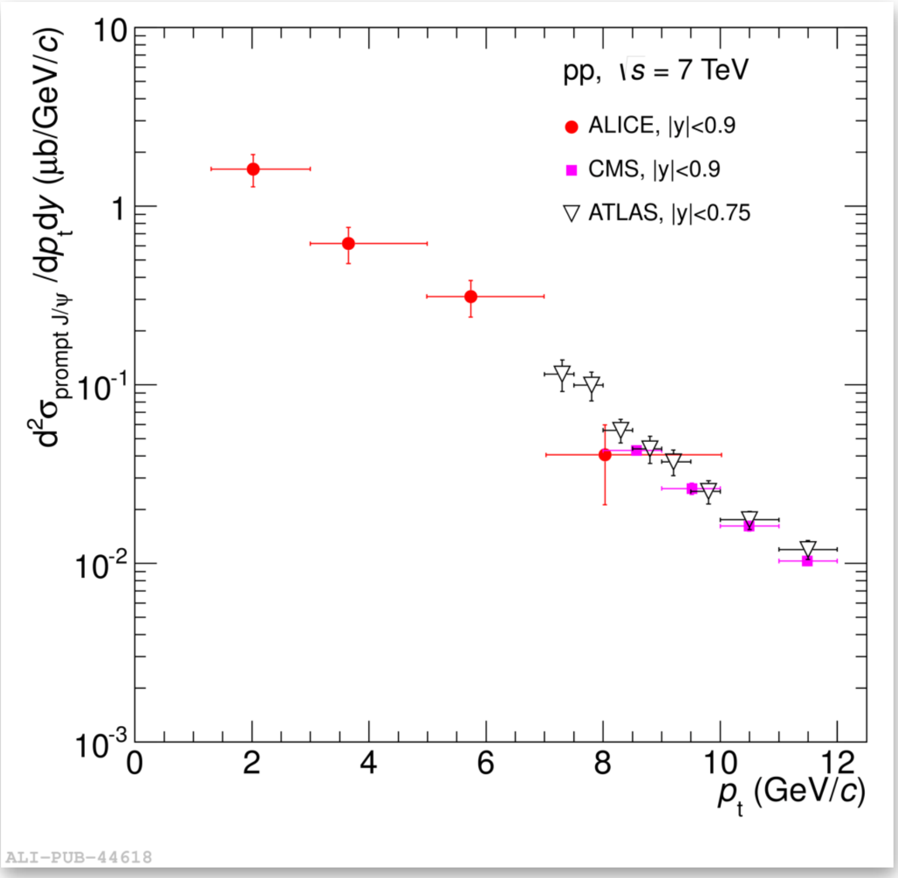
<u>Pseudo proper decay length x</u>

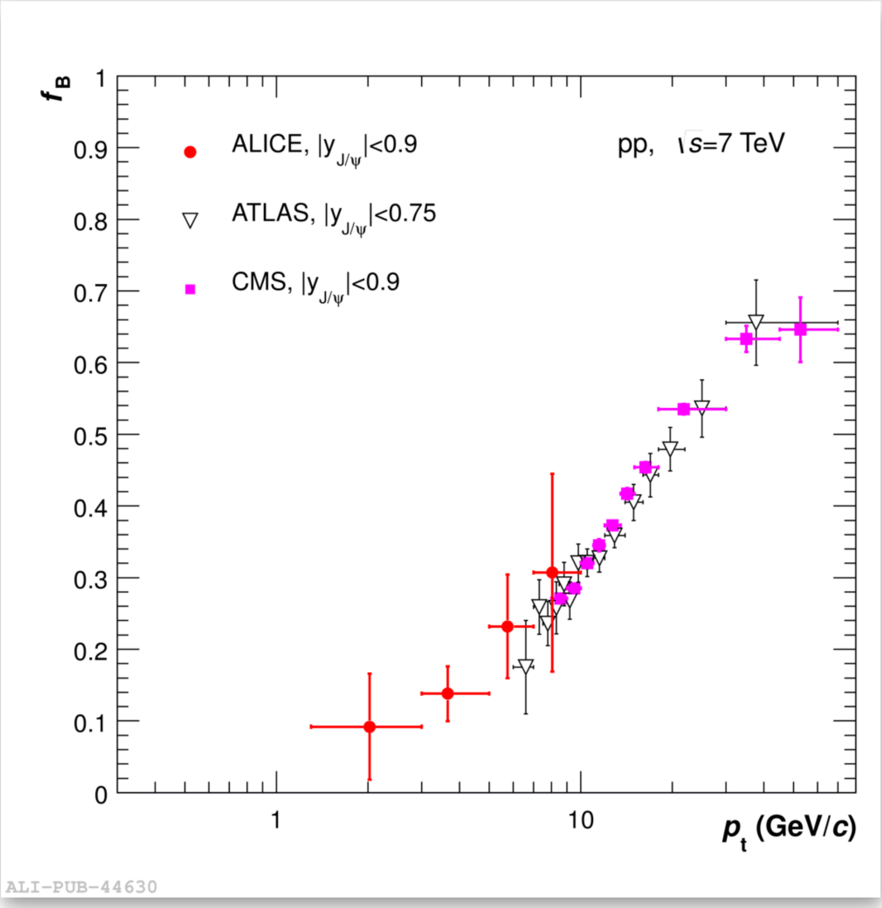
- non-prompt signal: from simulations
- background: CDF parametrization, fitted to the data (sidebands)

both smeared with a parametrization of the detector resolution, fitted to simulations

<u>Systematic uncertainties include</u>: resolution function, signal and background distributions (both mass and x), primary vertex determination, MC input $p_T$ spectrum

# Cross section and ratio vs $p_T$



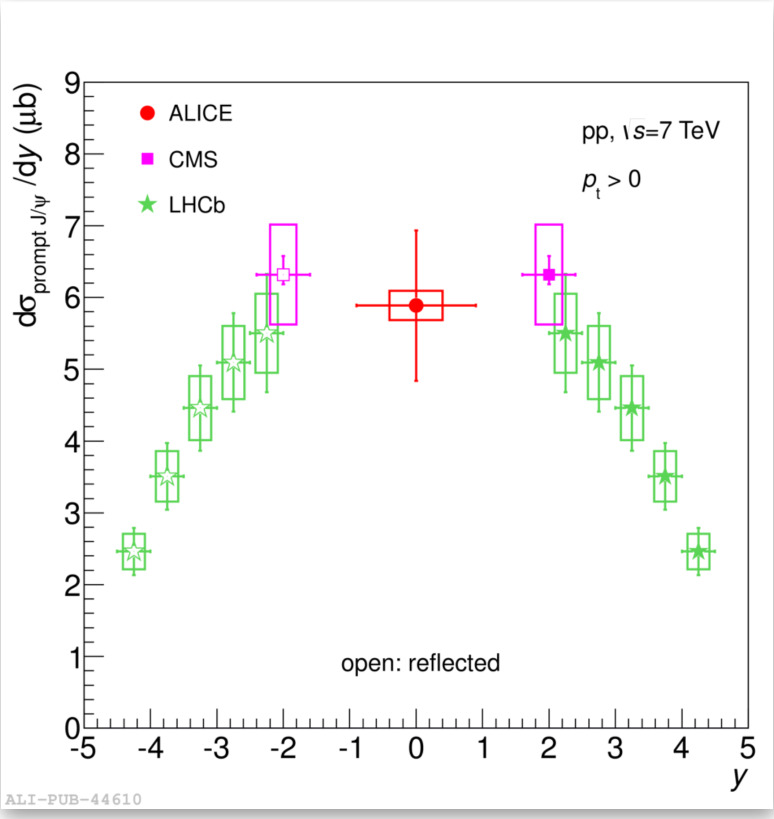



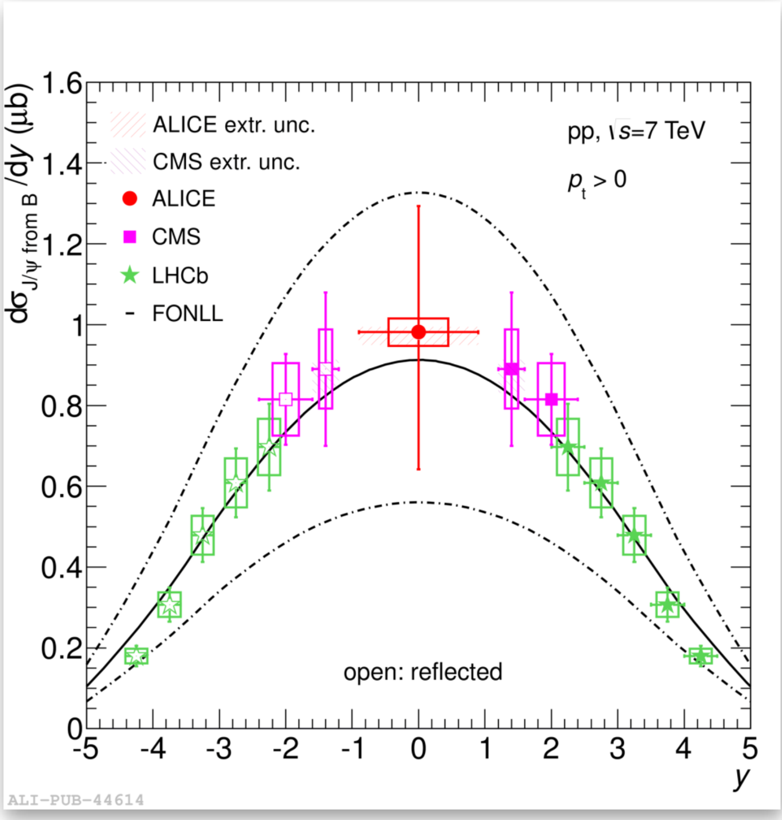

prompt cross section vs $p_T$

non-prompt/inclusive ratio vs $p_T$

ALICE measurement is consistent with results from ATLAS (NPB 850 (2011) 387) and CMS (JHEP 02 (2012) 011). It extends down to lower $p_T$ ($p_T$ > 1.3 GeV/c)

# Cross section vs rapidity




Left: prompt J/ψ vs y, compared to CMS (JHEP 02 (2012) 011) and LHCb (EPJ C 71 (2011) 1645), starting from $p_T$=0

Right: non-prompt J/ψ vs y, compared to CMS (EPJ C 71 (2011) 1575), LHCb (EPJ C 71 (2011) 1645) and FONLL (Cacciari *et al.*, JHEP 07 (2004) 033, JHEP 10 (2012) 137)

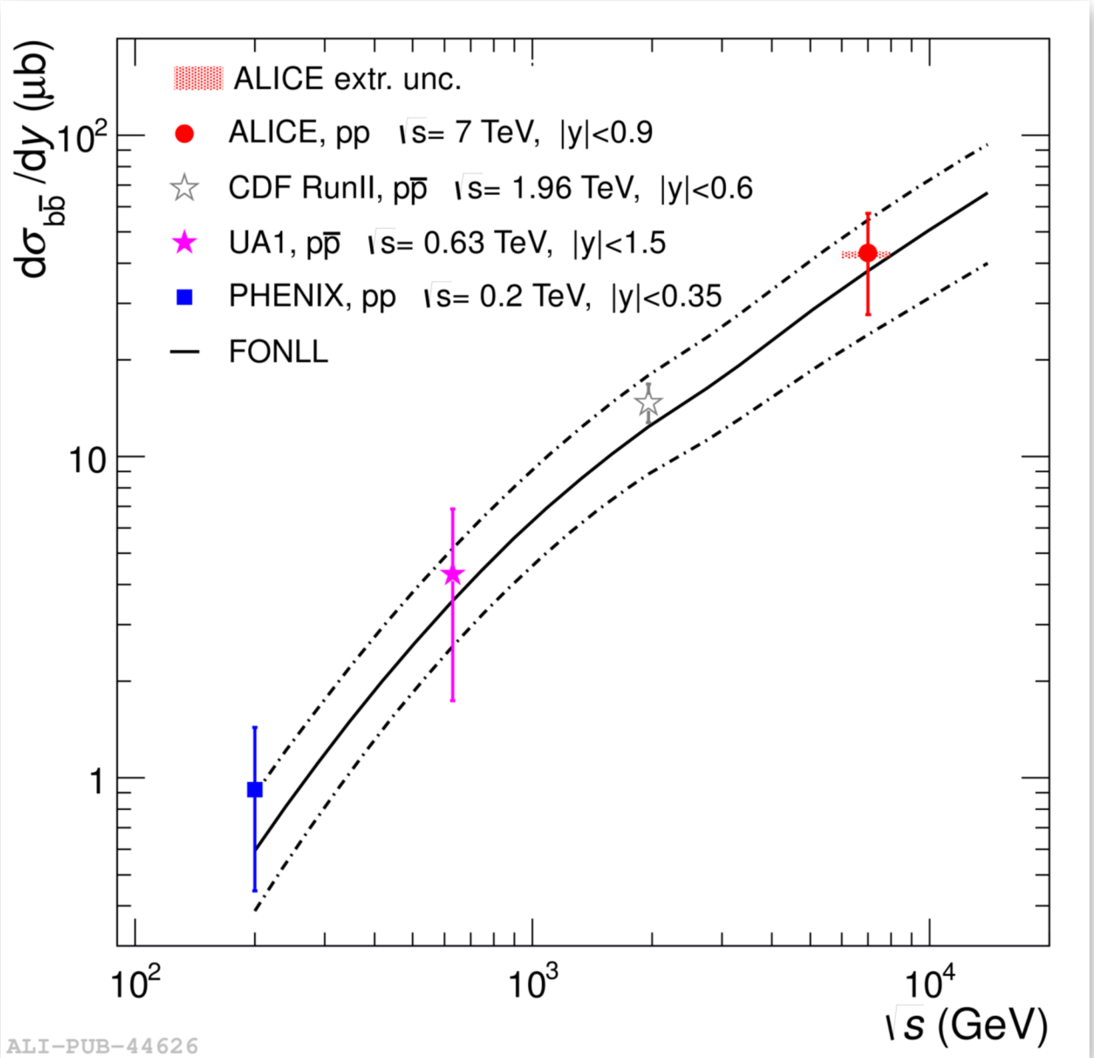
Non-prompt J/ψ extrapolation to $p_T$=0 uses FONLL. It is subtracted from inclusive J/ψ measurement to get the prompt component.

# b-bbar cross section at mid-rapidity vs √s

b-bbar cross section, dσ/dy at mid-rapidity is evaluated from non-prompt J/ψ cross section using FONLL.

It is compared to other experiments at lower energies and to FONLL.

Total ($p_T$ and rapidity integrated) b-bbar cross section is also consistent with similar measurements from LHCb (EPJ C 71 (2011) 1645, PLB 694 (2010) 209)





References:

PHENIX PRL 103 (2009) 082002

UA1 PLB 256 (1991) 121

CDF PRL 75 (1995) 1451

# J/ψ polarization

PRL108 (2012) 082001

# Motivation

J/ψ polarization (distribution of the decay products) provides additional constrains on production mechanism and has proven difficult to reproduce by models, simultaneously to cross-sections.

- NRQCD predicts a transverse polarization at high-enough $p_T$
- CSM predicts transverse polarization at LO and longitudinal at NLO
- CEM predicts no polarization

J/ψ polarization also enters calculation of the detector acceptance and therefore affects all cross-section measurements

# Principle

Distribution of the quarkonium decay products vs polar ($\theta$) and azimuthal ($\phi$) 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 $\phi$: $$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$$

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

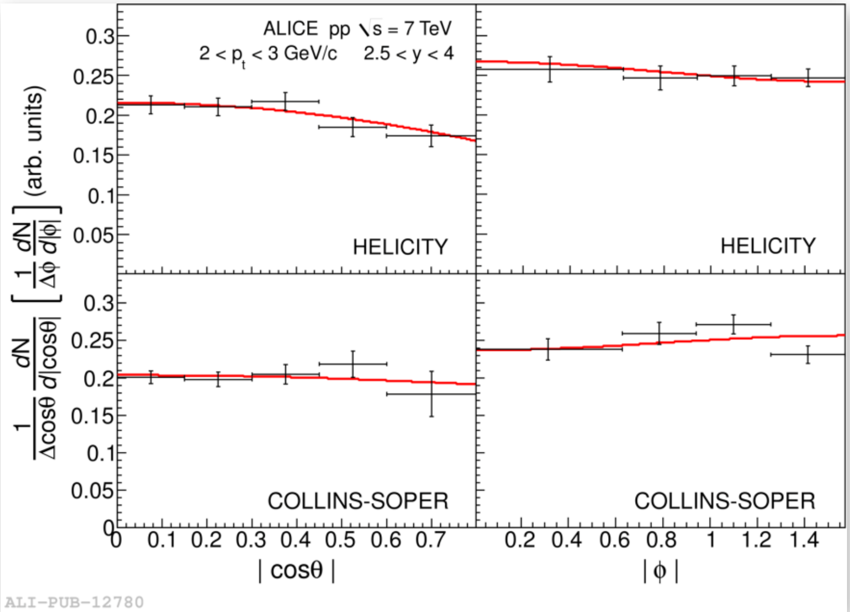
Measure quarkonium corrected yields in bins of $\cos\theta$, $\phi$ and $p_T$, perform a simultaneous fit using functions above to extract $\lambda_\theta$ and $\lambda_\phi$

Measurements are performed in two frames:

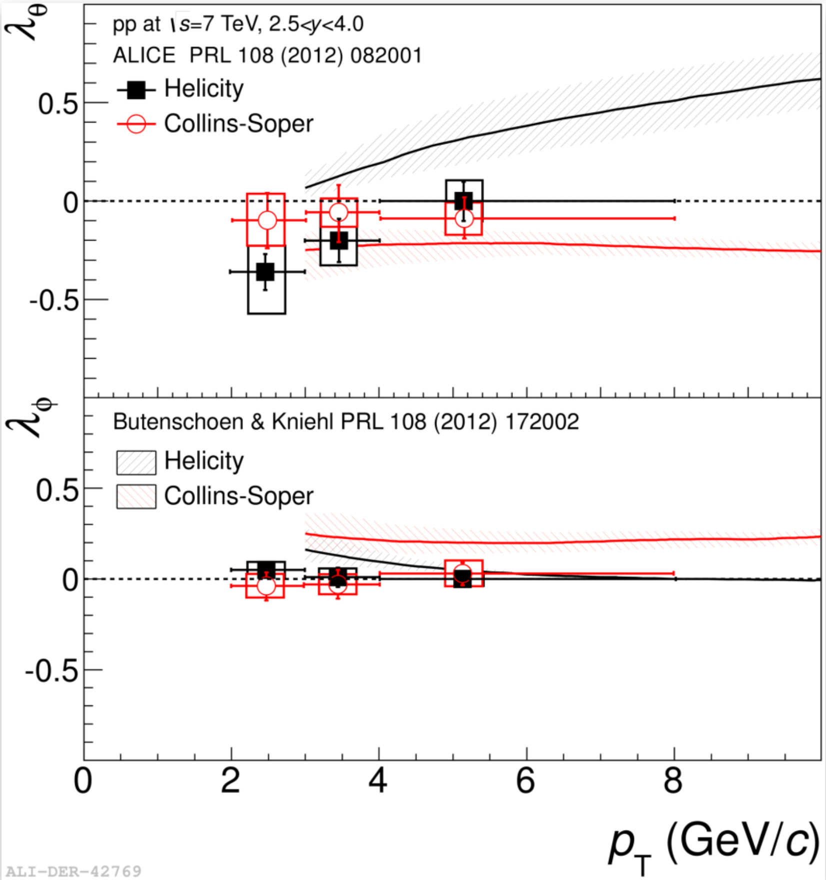
Top: Helicity frame

Bottom: Collins-Soper frame

<u>Systematic uncertainties include</u>: signal extraction, $p_T$ and y input distributions in MC, trigger efficiency



# Results




All measurements are compatible with zero within $2\sigma$.

$\lambda_\theta$ is negative (longitudinal polarization) at $1.6\sigma$ for low-$p_T$ J/ψs in the helicity frame

NRQCD calculation (Butenschoen et al., PRL 108 (2012) 082001) gives positive $\lambda_\theta$ (transverse polarization) in the helicity frame and is systematically above the data

Results are also compatible with measurements from LHCb (EPJ C 71 (2013) 11)

# J/ψ production vs multiplicity

PLB 712 (2012) 165-175

# Motivation and principle

Study the interplay between hard processes (J/ψ production) and soft processes from the underlying event, in pp collisions, in the context, for instance, of multi-parton interactions (MPI)

Study the possibility of collective behaviors in high multiplicity events (as high as in semi-central 200 GeV HI collisions) and their impact on J/ψ production

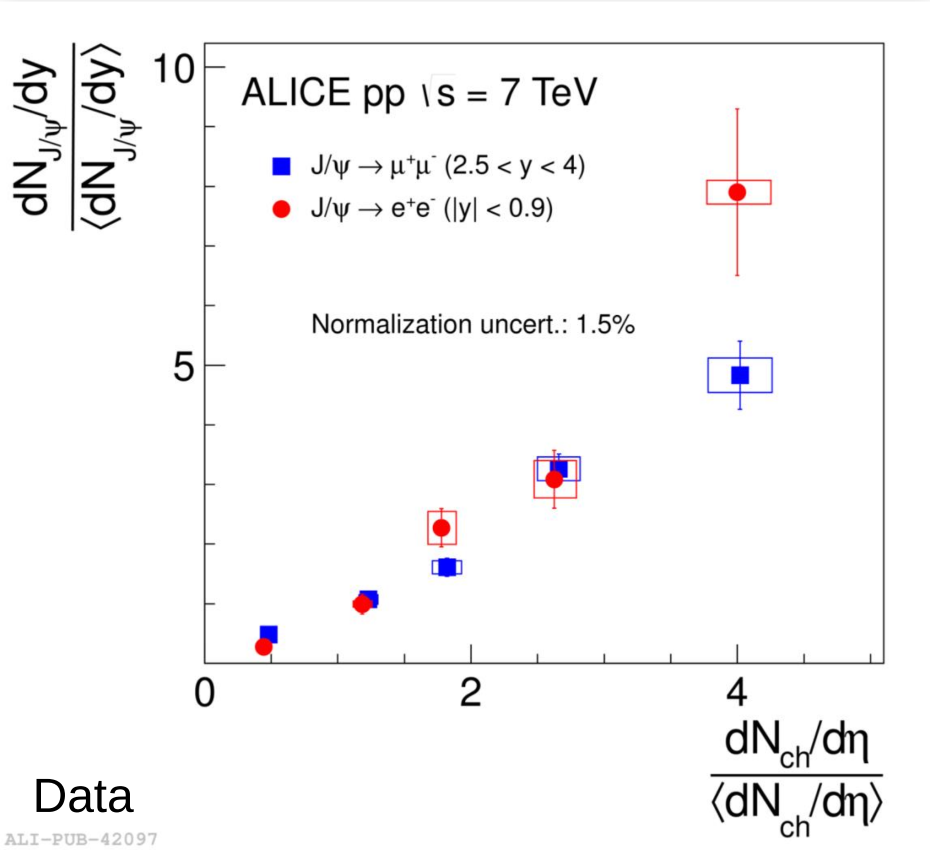
- Relative inclusive J/ψ yields, $(dN^{J/\psi}/dy)_i/\langle dN^{J/\psi}/dy\rangle$ are measured in bins of the relative charged tracks multiplicity $(dN_{ch}/d\eta)_i/\langle dN_{ch}/d\eta\rangle$, at both mid- and forward-rapidity. Acceptance x efficiency corrections cancel in the J/ψ yields ratio
- Charged track multiplicity ($dN_{ch}/d\eta$) measured using tracks in the SPD (the two innermost layers of the ITS)

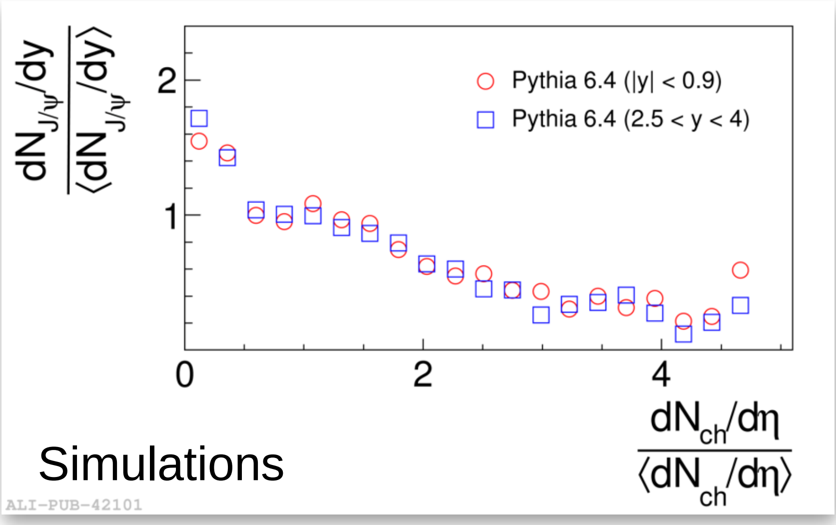
Current statistics allow to measure events for which the charged track multiplicity is up to x4 the average multiplicity

<u>Systematic uncertainties include</u>:

- signal extraction
- possible dependence of the $p_T$ distribution on the event multiplicity
- conversion from number of SPD tracks to charged particle multiplicity
- minimum bias trigger efficiency and pile-up corrections

# Result




PYTHIA 6.4.24, Perugia 2011 tune
hard scattering production only

Steady increase of the relative J/ψ yield with respect to relative charged particle multiplicity, compatible with linear

Similar trend observed for open heavy flavor (see backups)

No consensus on the interpretation of the result

Some simulations (right figure) produce the opposite trend

# Summary and outlook

ALICE has performed extensive measurements of quarkonium production in pp collisions at both mid- and forward-rapidity. This includes:

- inclusive production cross-section of J/ψ, ψ(2S), Υ(1S) and Υ(2S) at forward-rapidity
- separation between prompt and non-prompt J/ψ at mid-rapidity down to low $p_T$
- inclusive J/ψ polarization parameters $\lambda_\theta$ and $\lambda_\phi$ at forward-rapidity
- inclusive J/ψ production vs charged particle multiplicity

All measurements are compatible with/complementary to similar results from other LHC experiments

Cross sections and particle ratios are in reasonable agreement with NRQCD calculations for both inclusive and prompt quarkonia

Non-prompt J/ψ cross-section and b-bbar cross-sections are consistent with FONLL

No visible polarization of inclusive J/ψ has been observed, within uncertainties

Inclusive J/ψ production increases steadily with event multiplicity at both mid- and forward-rapidity, with no consensus yet on the interpretation

Future measurements include: analysis of 2012 8 TeV data, and of course LHC Run2, starting this year

# Backups

# Quarkonium production models

Color Evaporation Model (CEM) (PLB 67 (1977) 217, PLB 390 (1997) 323)

Quarkonium cross section is proportional to the open heavy flavor cross section, integrated from the lightest meson mass (x2) to the quarkonium mass.

Proportionality factor depends on the quarkonium type but not its $p_T$ or rapidity.

It is fitted to the data

Color Singlet Model (CSM) (PLB 102, (1981) 364)

Heavy quark pair must be produced with the same quantum number as the quarkonium (color-singlet), before hadronization. Calculation available at LO, NLO and NLO* (with only dominant NNLO contributions calculated).

Non-relativistic QCD (NRQCR) (PRD 51 (1995) 1125)

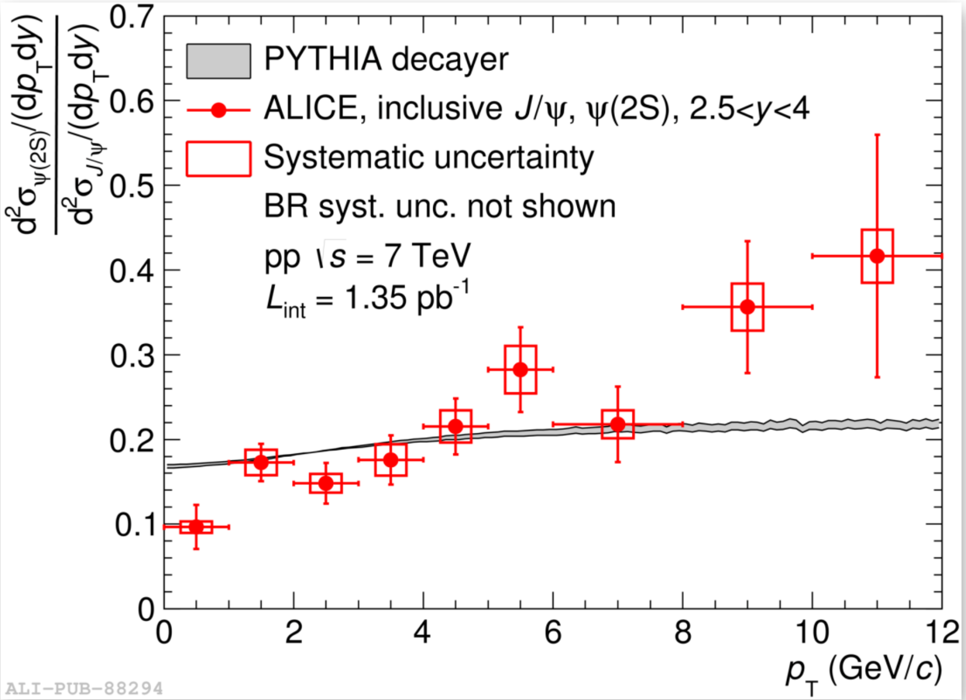
Quark pairs produced in a color-octet state are also considered.

Neutralization is non-perturbative, expanded in powers of the relative velocity between the two quarks.

The parameters of the expansion are fitted to the data.

# Inclusive ψ(2S)-to-J/ψ at forward rapidity

EPJ. C 74 (2014) 2974

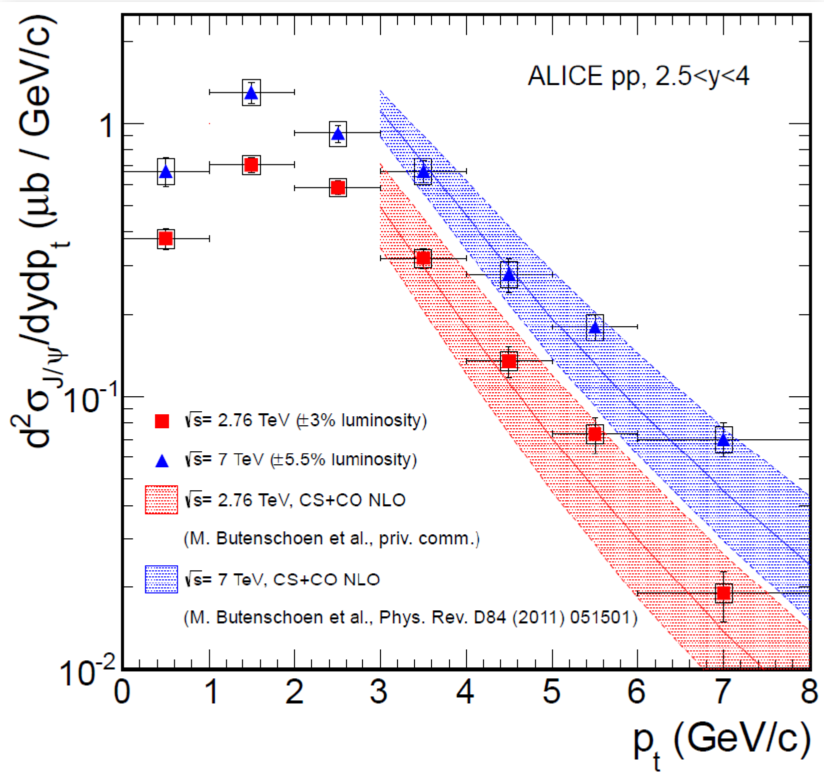


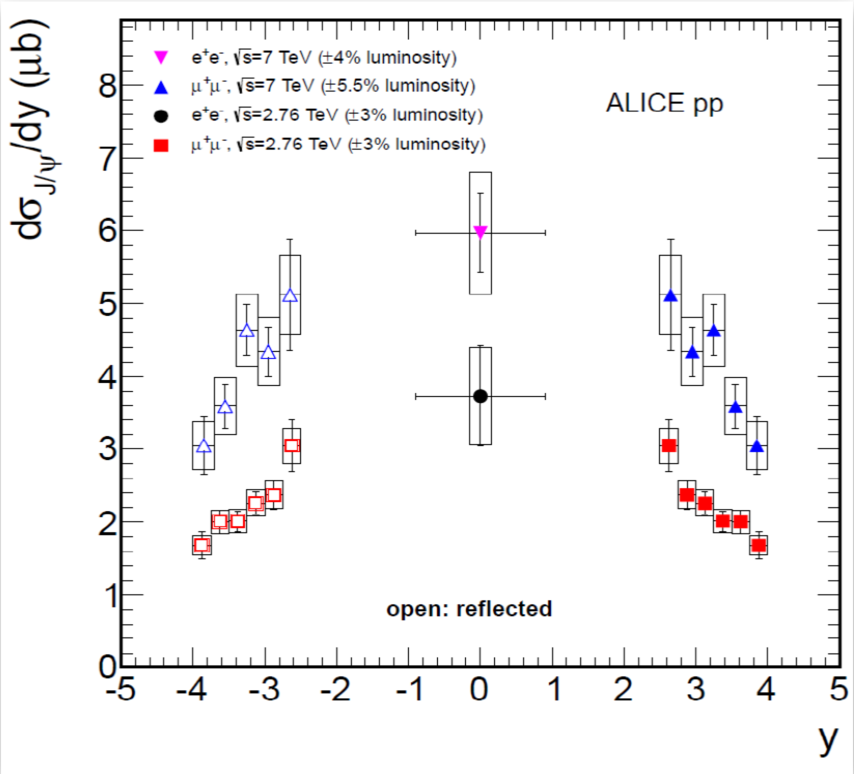

inclusive ψ(2S)-to-J/ψ vs $p_T$ at forward rapidity

Greyed region corresponds to kinematics-only effect from higher mass resonances decay, estimated assuming that the $p_T$ spectra of ψ(2S) and $\chi_c$ are the same as the one for J/ψ, and using Pythia to decay these particles into a J/ψ

# Inclusive J/ψ production at √s = 2.76 TeV

PLB 718 (2012) 295



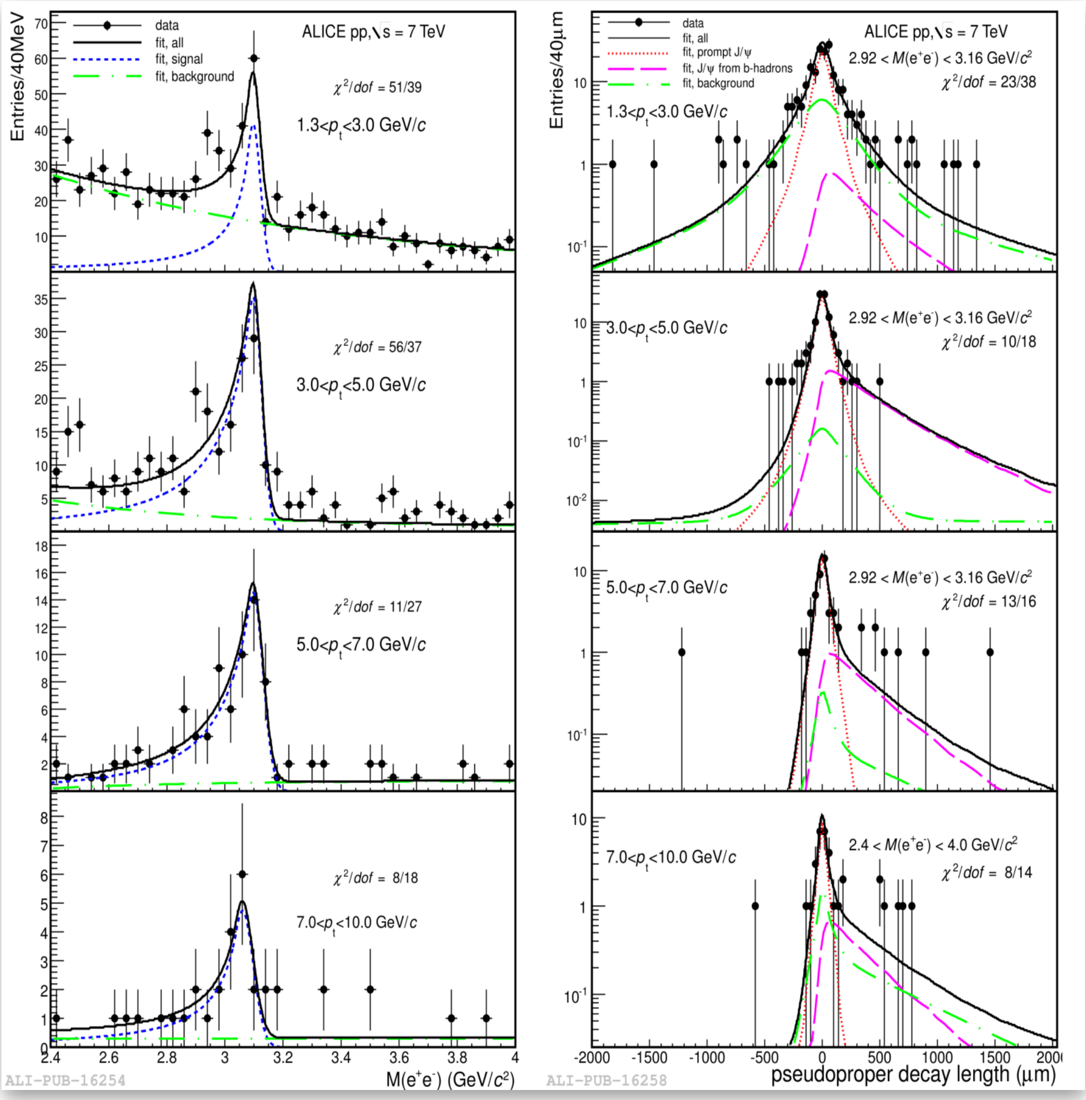




Left: J/ψ vs $p_T$ vs NRQCD, at both 2.76 and 7 TeV

Right: J/ψ vs y, at both 2.76 and 7 TeV

# Prompt and non-prompt J/ψ separation

JHEP11(2012)065

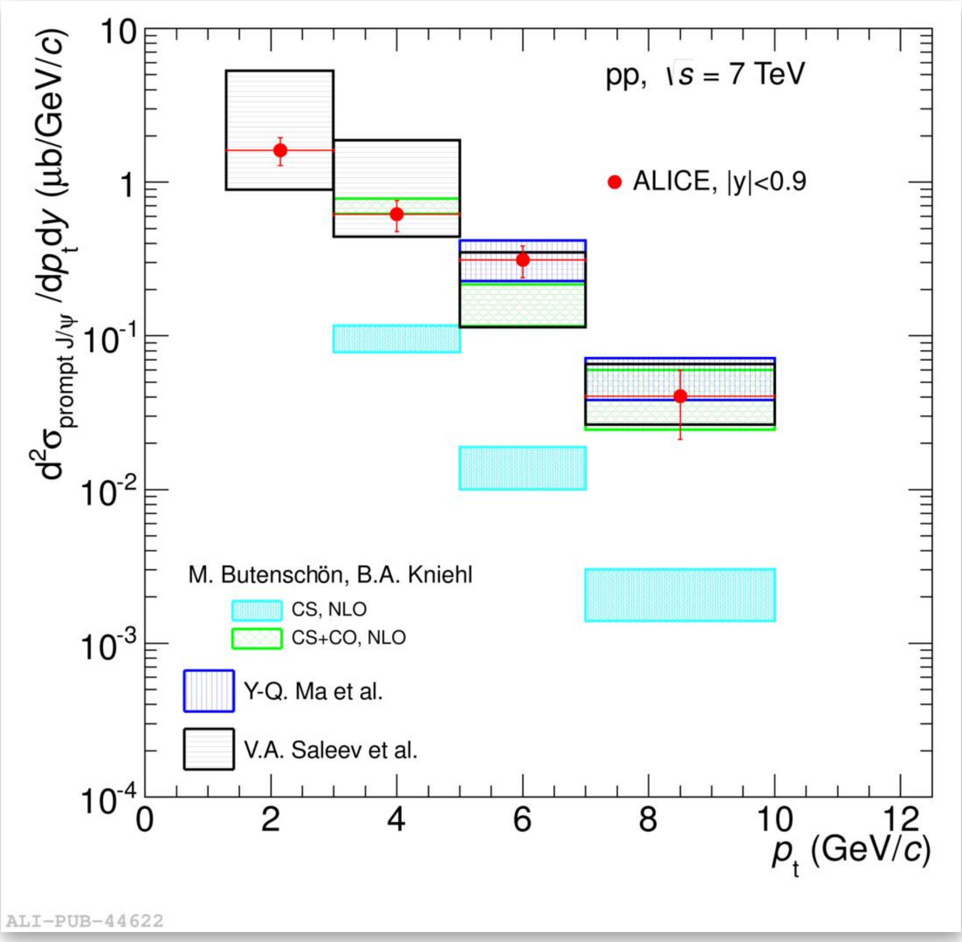


# Prompt J/ψ production vs $p_T$ vs models

JHEP11(2012)065

Models:

- two NRQCD calculations
- one NRQCD + parton sub-processes



# Reference frames for polarization measurements

Helicity frame:

z axis is given by the quarkonium momentum in the lab frame

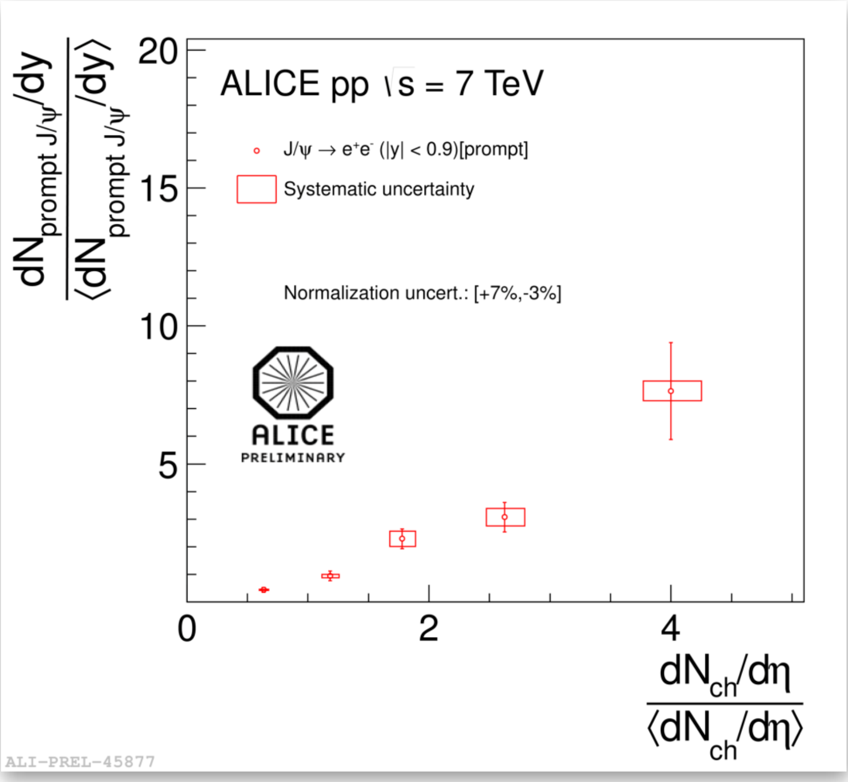
Collins-Soper frame:

z axis given by the bisector between one bin and the opposite of the other beam, in quarkonium rest frame

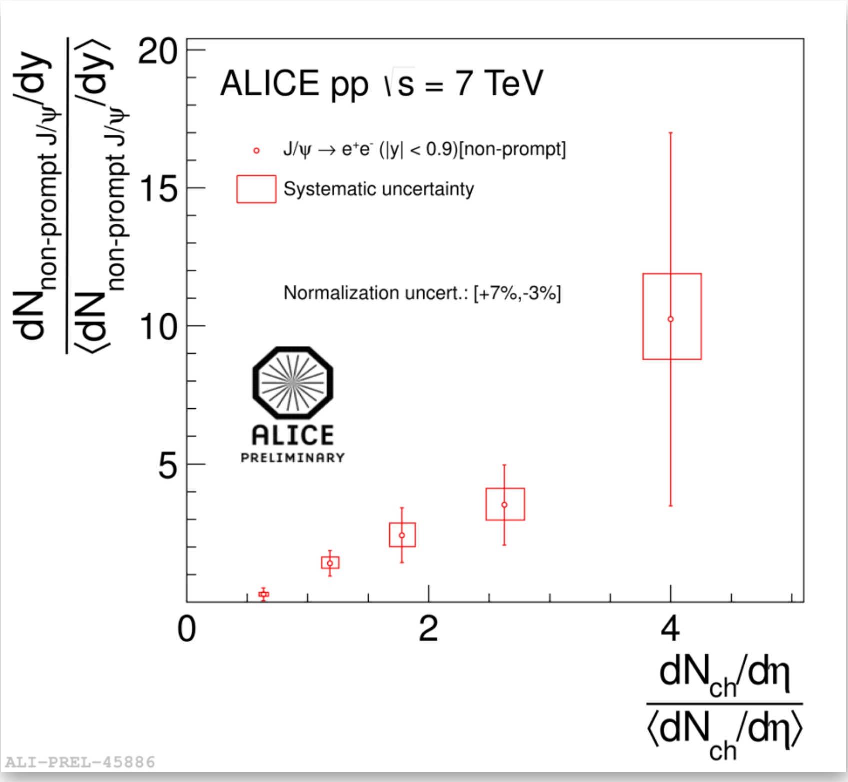
For both, $\theta$ and $\phi$ are measured in the quarkonium rest frame.

The plane at $\phi = 0$ is the one that contains the two beams.

# Prompt and non-prompt J/ψ vs multiplicity




Prompt J/ψ




Non-prompt J/ψ

Steady increase wrt charged particle multiplicity is also observed for non-prompt J/ψ ( = b hadrons). The slope is similar to the one from prompt J/ψ.

# J/ψ and $D^0$ mesons vs multiplicity