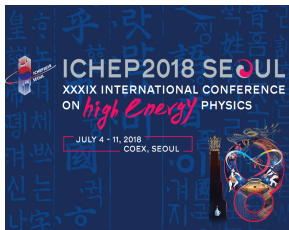# Charmonium production in pp collisions with ALICE at the LHC

Lucas Altenkamper*
for the ALICE Collaboration
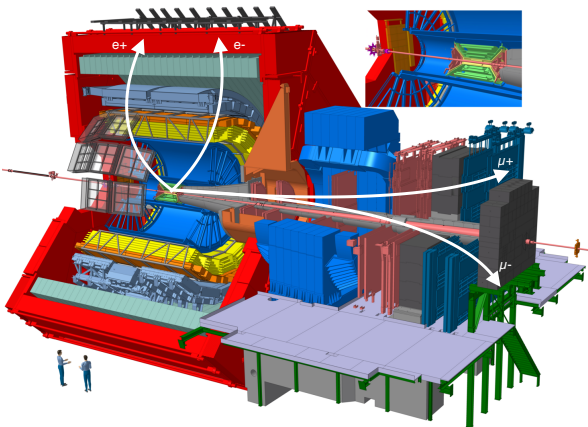
*University of Bergen, Norway

ICHEP 2018, Seoul
4-11 July 2018
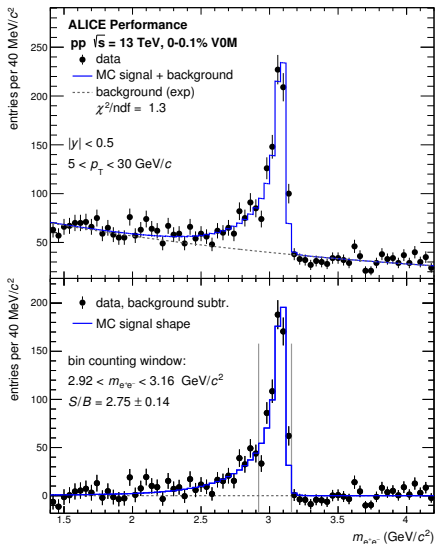
Charmonium production mechanisms

- charmonia typically separated into 2 groups according to origin:
  - *prompt* production, either direct or from excited charmonium states
  - *non-prompt* production, from b-hadron decays

- prompt charmonium production involves very different energy scales:
  - production of initial $c\bar{c}$ pair in hard scattering process, perturbative description applicable (pQCD)
    - gluon fusion dominant for $c\bar{c}$ production at LHC energies, sensitive to gluon PDFs
    - possible additional contribution from Multi Parton Interactions (MPI), semi-hard but still relevant for c and b quark production at LHC energies
  - non-perturbative evolution into color neutral bound state
    - not yet fully understood, models typically unable to describe all observables (e.g. cross section and polarization) simultaneously
  - $\rightarrow$ great testing grounds for QCD

Models for charmonium production mechanisms

- *Color Evaporation Model (CEM):* M. B. Einhorn, S. D. Ellis, Phys. Rev. D 12 (1975) 2007
  - every heavy q$\bar{\text{q}}$ pair evolves into quarkonium state if pair mass below threshold of open-flavor production
  - probability of bound state formation is energy and process independent

- *Color Singlet Model (CSM):* H. Fritzsch, Phys. Lett. B 67 (1977) 217
  - initial heavy q$\bar{\text{q}}$ pair in color-singlet state with same quantum numbers as final-state quarkonium
  - NLO (and NNLO) diagrams can introduce large corrections to CSM

- *Non-Relativistic QCD (NRQCD):* G. T. Bodwin et al., Phys. Rev. D 51 (1995) 1125
  - exploits non-relativistic momentum scale of quarkonium production by expanding matrix-elements in strong coupling and quark velocity
  - contains color-singlet and -octet contributions

Charmonium measurements in ALICE
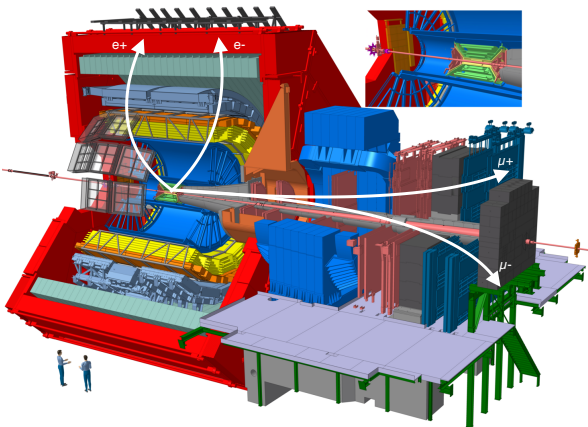

Central barrel ($J/\psi \to e^+e^-$)

- $|y_{lab}| < 0.9$
- tracking in ITS and TPC
- PID via dE/dx in TPC
- high p_T trigger using EMCal
- inclusive J/ψ, $p_T > 0$ GeV/c
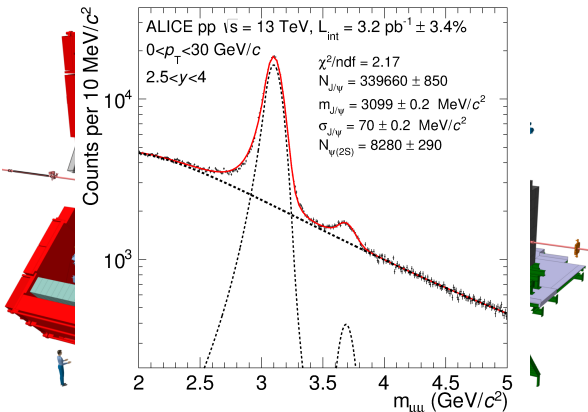- prompt/non-prompt J/ψ, $p_T > 1.3$ GeV/c

Charmonium measurements in ALICE

Central barrel ($J/\psi \rightarrow e^+e^-$)

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- prompt/non-prompt J/ψ, $p_T > 1.3$ GeV/c

Muon arm ($J/\psi \to \mu^+\mu^-$)

- $2.5 < y_{lab} < 4$
- trigger and tracking in muon spectrometer
- inclusive J/ψ and $\psi(2S)$, $p_T > 0$ GeV/c

Charmonium measurements in ALICE

ALI-PUB-122168

Central barrel (J/$\psi \to$ e$^+$e$^-$)

- $|y_{\text{lab}}| < 0.9$
- tracking in ITS and TPC
- PID via dE/dx in TPC
- high p_T trigger using EMCal
- inclusive J/ψ, $p_T > 0$ GeV/c
- prompt/non-prompt J/ψ, $p_T > 1.3$ GeV/c

Muon arm (J/$\psi \to \mu^+\mu^-$)

- $2.5 < y_{\text{lab}} < 4$
- trigger and tracking in muon spectrometer
- inclusive J/ψ and ψ(2S), $p_T > 0$ GeV/c

Outline

- inclusive J/ψ and $\psi(2S)$ cross sections at forward rapidity at 13 TeV
  (LHC Run-2 results)

- inclusive J/ψ polarization at forward rapidity at 8 TeV
  (LHC Run-1 results)

- multiplicity dependence of inclusive J/ψ at mid rapidity at 13 TeV
  (LHC Run-2 results)

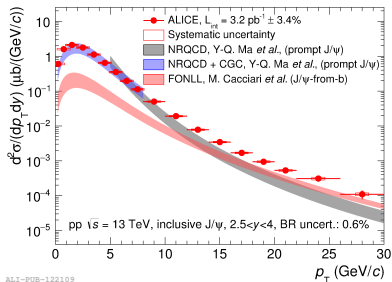- inclusive J/ψ-hadron correlations at mid rapidity at 13 TeV
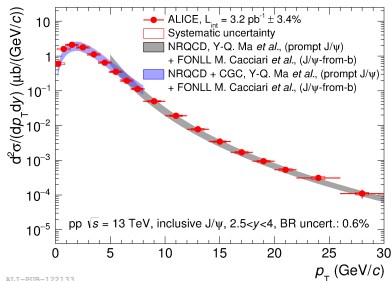 (LHC Run-2 results)

Inclusive J/ψ and ψ(2S)
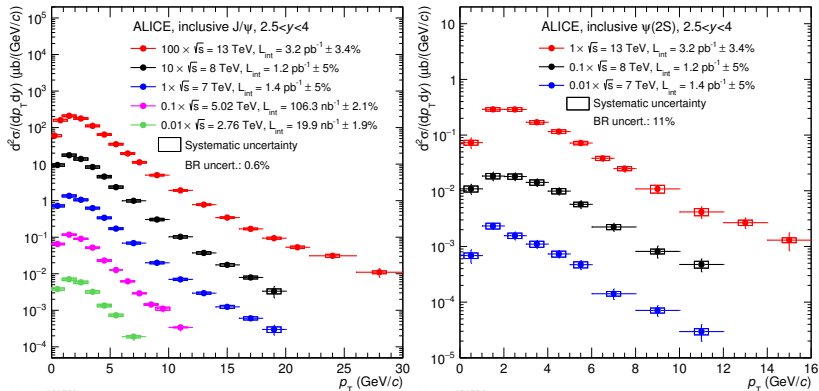
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- J/ψ and ψ(2S) measured at several collision energies at forward rapidity
- hardening of spectra with $\sqrt{s}$ for J/ψ and ψ(2S)

Inclusive J/ψ and ψ(2S) and models

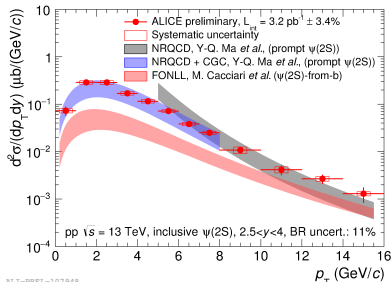
pp √s = 13 TeV, inclusive J/ψ, 2.5<y<4, BR uncert.: 0.6%

ALI-PUB-122109

ALI-PUB-122133

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- prompt J/ψ at high (low) p_T described by NRQCD (CGC+NRQCD), contains contributions from higher mass decays

- non-prompt J/ψ contribution, coming from b-hadron decays, described by FONLL

- non-prompt J/ψ fraction rises to (and exceeds) 50% at $p_T \sim 15$ GeV/c

- inclusive cross section agrees with summed prompt and non-prompt calculations (lower plot)

NRQCD	Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC	Phys. Rev. Lett. 113 (2014) 192301
FONLL	J. High Energ. Phys. 1210 (2012) 137

Inclusive J/ψ and ψ(2S) and models

pp √s = 13 TeV, inclusive ψ(2S), 2.5<y<4, BR uncert.: 11%

ALI-PREL-107948

pp √s = 13 TeV, inclusive ψ(2S), 2.5<y<4, BR uncert.: 11%
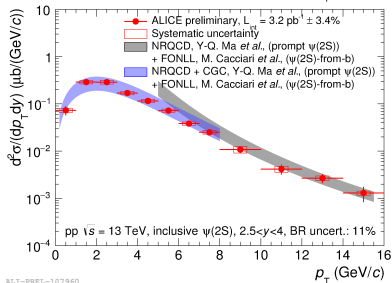
ALI-PREL-107960

Eur. Phys. J. C 77 (2017) 392

- prompt J/ψ at high (low) p_T described by NRQCD (CGC+NRQCD), contains contributions from higher mass decays

- non-prompt J/ψ contribution, coming from b-hadron decays, described by FONLL

- non-prompt J/ψ fraction rises to (and exceeds) 50% at $p_T \sim 15$ GeV/c

- inclusive cross section agrees with summed prompt and non-prompt calculations (lower plot)

- agreement also observed for ψ(2S)

NRQCD   Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC   Phys. Rev. Lett. 113 (2014) 192301
FONLL   J. High Energ. Phys. 1210 (2012) 137

Inclusive J/ψ polarization at forward rapidity
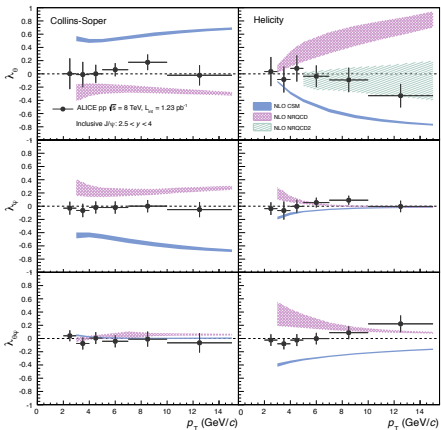

New results! (arXiv:1805.04374)

NLO CSM	Phys. Rev. Lett. 108 (2012) 172002
NLO NRQCD	Phys. Rev. Lett. 108 (2012) 172002
NLO NRQCD2	Phys. Rev. Lett. 108 (2012) 242004

- inclusive J/ψ reconstructed from di-muon decay channel at 8 TeV, polarization in Collins-Soper and Helicity frames

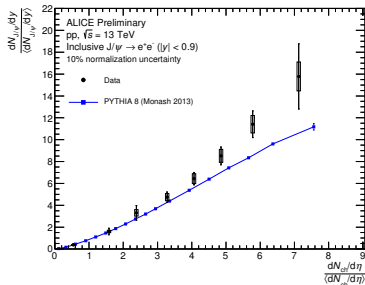- polarization determined from angular distribution of muons:

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

- transverse: $\lambda_\theta = 1$, longitudinal: $\lambda_\theta = -1$

- inclusive J/ψ shows **no polarization within current uncertainties**

  - caveat: still containing non-prompt contributions

- tensions between CSM and NRQCD models and experimental data

Multiplicity dependence of inclusive J/ψ
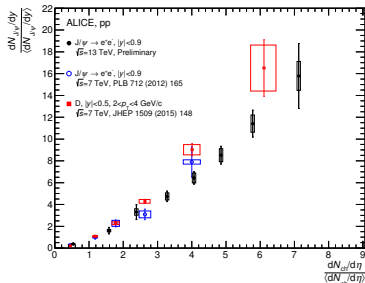
- MPI initially thought to be relevant mainly for soft-particle production

- *Run-1 observation*: incl. J/ψ and D-meson yields grow stronger than linear with event multiplicity
  - same observation for $e^{\pm}$, $\mu^{\pm}$ from c, b decays (backup)

- dedicated high mult. trigger in *Run-2* increases mult. range of incl. J/ψ (black points)
  - reinforces Run-1 observation

- Pythia 8 (containing MPI) qualitatively reproduces data

- $\rightarrow$ MPI might play a role in hard processes at LHC energies

Multiplicity dependence of inclusive J/ψ

ALI-PREL-128843
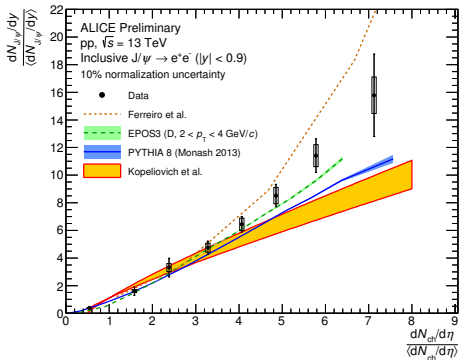
multiplicity dependence qualitatively described by different models:

- *Ferreiro et al.:*
  saturation of soft-particle production via percolation
  (Phys. Rev. C 86 (2012) 034903)

- *Kopeliovich et al.:*
  contributions of higher Fock states
  (Phys. Rev. D 88 (2013) 116002)

- *Pythia 8:*
  MPI and saturation of soft-particle production via color reconnection
  (Comput. Phys. Commun. 178 (2008) 852-867)

- *EPOS3:*
  MPI and hydrodynamic evolution of the system
  (Phys. Rept. 350 (2001) 93-289)

Multiplicity dependence of inclusive J/ψ
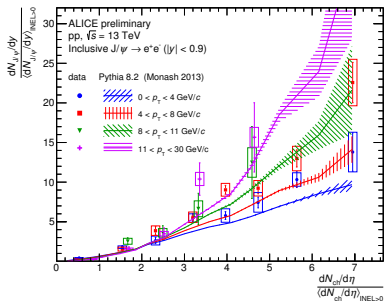
ALI-PREL-132858
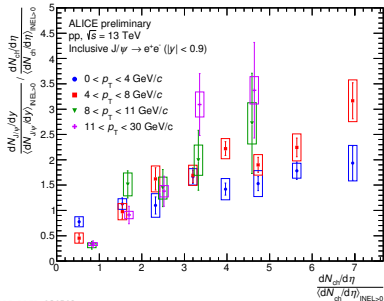
ALI-PREL-134549

- multiplicity dependence in p_T bins at 13 TeV (Run-2)

- p_T range for incl. J/ψ at mid rapidity extended up to 30 GeV/c by using EMCal trigger

- data qualitatively reproduced by Pythia with J/ψ production included in MPI
  - hint for steeper slope at higher p_T in data

- p_T-integrated results reinforced by analysis in p_T bins
  - faster-than-linear increase with multiplicity for all p_T

Inclusive J/ψ-hadron correlations
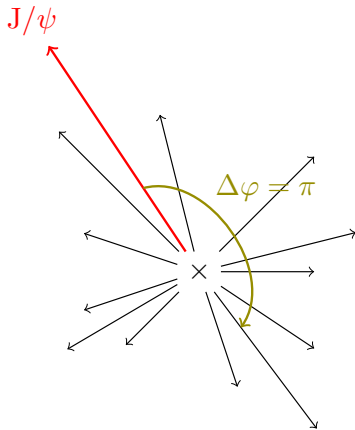
- theoretical models have troubles to describe J/ψ cross section and polarization simultaneously

$\rightarrow$ new experimental observables can help constraining models

- J/ψ-hadron correlations to quantify hadronic activity w.r.t. to J/ψ direction

- near-side: $\Delta\varphi \sim 0$, away-side: $\Delta\varphi \sim \pi$

- e.g. near-side correlation expected for non-prompt J/ψ from additional decay products

Inclusive J/ψ-hadron correlations
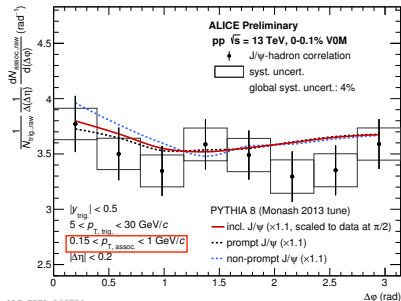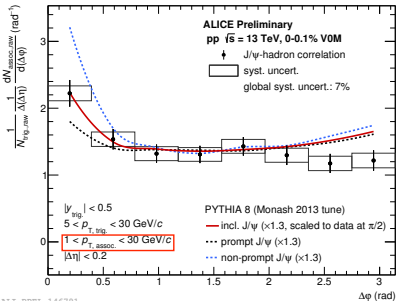
- inclusive J/ψ ($p_T > 5$ GeV/c) correlated with unidentified charged hadrons at mid rapidity at 13 TeV

- no significant correlation observed for hadrons with $p_T < 1$ GeV/c, near-side peak for hadrons with $p_T > 1$ GeV/c

- sharp $\Delta\eta$ cut to enhance near-side, suppresses possible away-side correlation

- qualitative agreement with Pythia 8, near-side dominated by non-prompt contributions

Summary and conclusions

- ALICE has studied charmonium states intensively at various LHC energies

- fair agreement between inclusive J/ψ and $\psi(2S)$ cross sections and models

- no polarization of inclusive J/ψ observed at 8 TeV,
  tension between models and data

- models including MPI describe multiplicity dependence of J/ψ production

- inclusive J/ψ-hadron correlations at 13 TeV agree qualitatively with
  Pythia 8, near-side correlation dominated by non-prompt contribution

More Run-2 pp results at mid rapidity can be expected soon!
(e.g. J/ψ cross section, non-prompt fraction and J/ψ-hadron correlations)

Thank you very much for your attention!

Backup

THE ALICE DETECTOR

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

Charmonium measurements in ALICE

mid rapidity:

forward rapidity:

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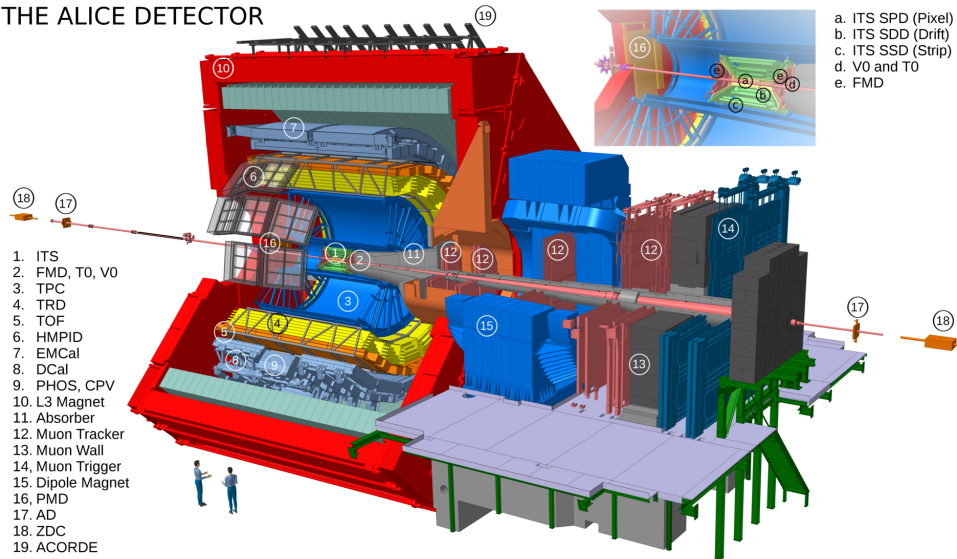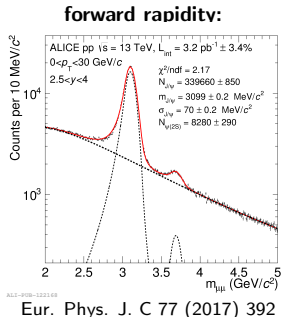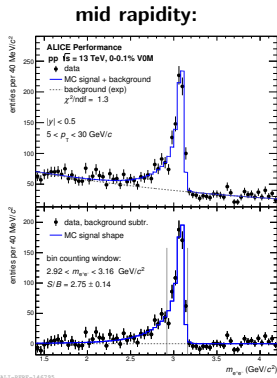
- reconstruction through di-electron decay channel
- background determined from fit (MC signal shape + background)
- yield extracted after background subtraction by bin counting

- reconstruction through di-muon decay channel
- J/ψ and $\psi(2S)$ visible
- combined signal + background fit, including J/ψ and $\psi(2S)$ contribution
- yield extracted by integrating signal part of combined fit

Inclusive J/ψ comparison to LHCb measurement
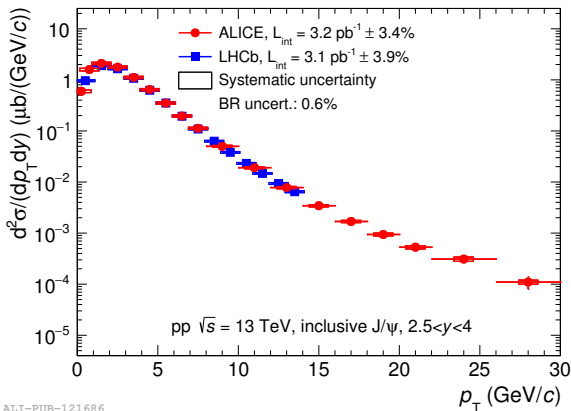
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- inclusive J/ψ cross section measured at forward rapidity agrees with LHCb result (J. High Energ. Phys. 1705 (2017) 063 and erratum J. High Energ. Phys. 1705 (2017) 063)

Inclusive J/ψ, ψ(2S) and models continued
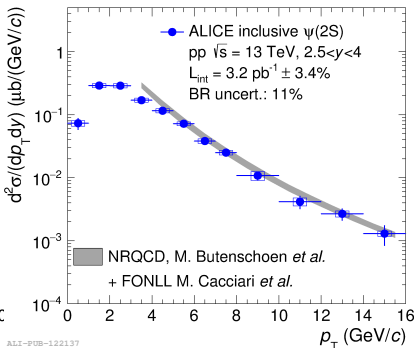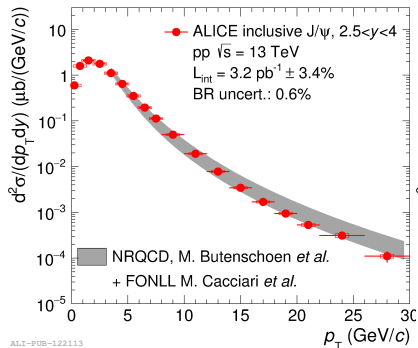
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- prompt J/ψ and ψ(2S) described by NRQCD (Phys. Rev. Lett. 106 (2011) 022003)
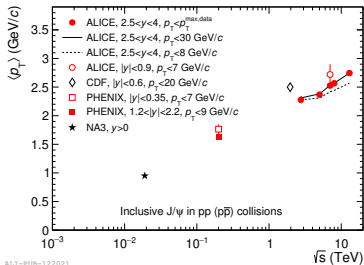
- non-prompt contribution described by FONLL

Inclusive J/ψ to $\psi(2S)$ ratio
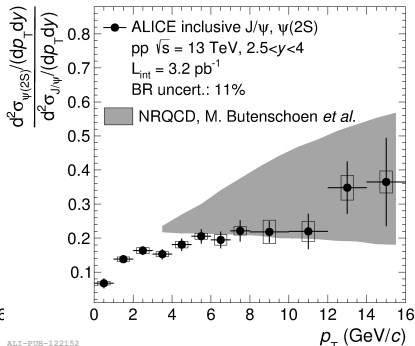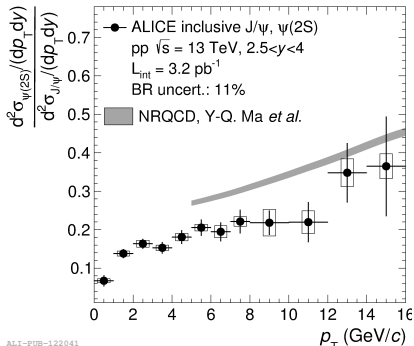
Eur. Phys. J. C 77 (2017) 392

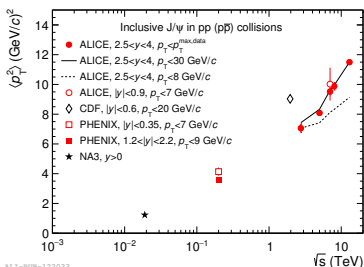# $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ for inclusive J/ψ and ψ(2S)
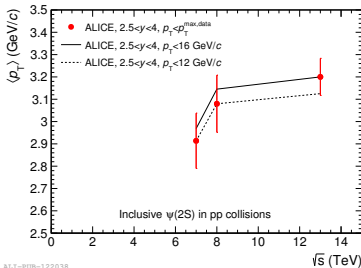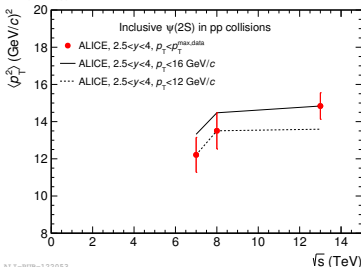

$$J/\psi$$

$$\psi(2S)$$

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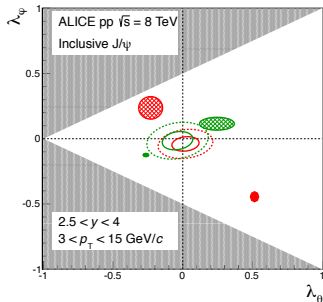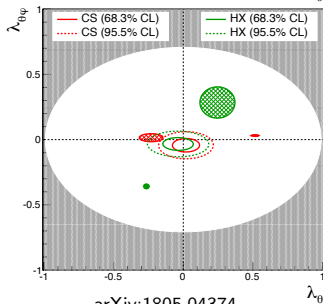
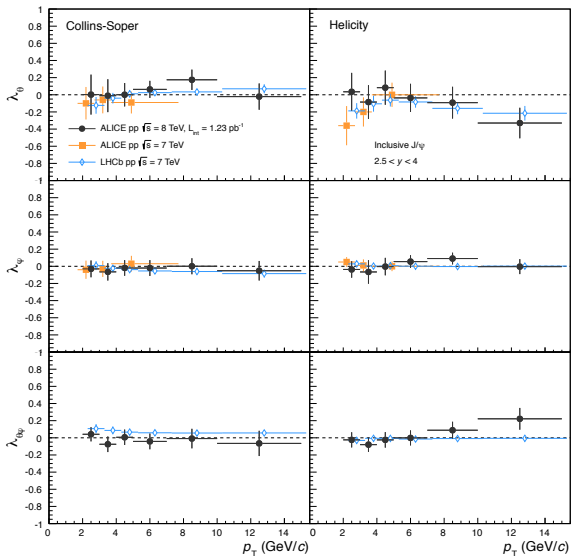# Inclusive J/ψ polarization parameter space
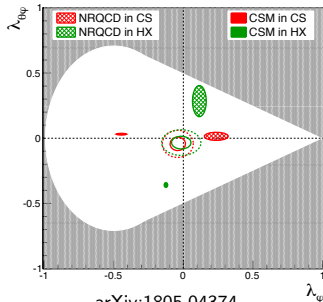
arXiv:1805.04374

arXiv:1805.04374

- average p_T integrated polarization parameters in $3 < p_T < 15$ GeV/c
- 1σ (2σ) contours shown as full (dashed) ellipses in both frames
- model predictions from CSM (NRQCD) shown as filled (shaded) contours
- data not reproduced by models, discrepancy larger for CSM

Inclusive J/ψ polarization

arXiv:1805.04374

$e^{\pm}$ and $\mu^{\pm}$ from HF decays