Quarkonium production in pp collisions with ALICE

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for the ALICE Collaboration

Quarkonia Working Group 2016
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OUTLINE

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- Physics motivations
- Quarkonium measurements with ALICE
- J/ψ production at $\sqrt{s}$ = 7 and 8 TeV
- ψ(2S) production at $\sqrt{s}$ = 7 and 8 TeV
- Υ production at $\sqrt{s}$ = 7 and 8 TeV
- New observable in quarkonium production: J/ψ yield vs. charged-particle multiplicity
- Conclusions and outlooks

ALICE

Physics Motivations

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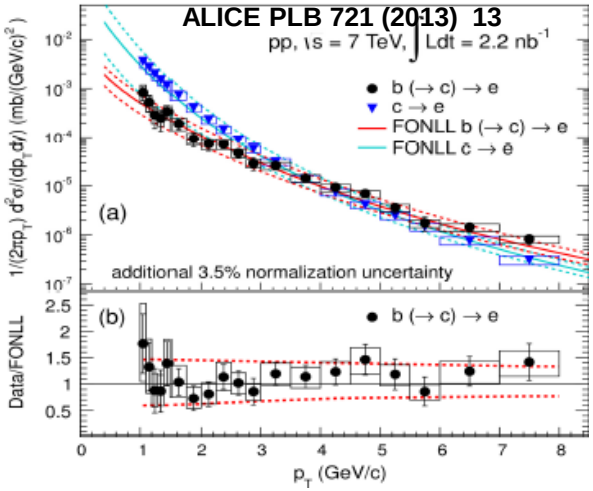
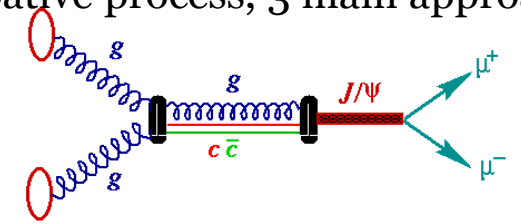
- Quarkonia
  - Charmonium bound state of $c\bar{c}$ pair (J/ψ, ψ(2S))
  - Bottomonium bound state of $b\bar{b}$ pair (Υ(1s), Υ(2s) and Υ(3s))



- Heavy-quark pair production relatively well understood by pQCD (FONLL)

- Binding into quarkonium state is a non perturbative process, 3 main approaches
  - Color Evaporation Model (CEM)
  - Color Singlet Model (CSM)
  - Non-Relativistic QCD (NRQCD)



Considerable theoretical progresses in recent years **[Eur. Phys. J. C 71 (2011) 1534]**
But no consensus on quarkonium production mechanism in hadronic collisions

- Complementary approach to understand quarkonium production mechanisms
[Eur.Phys.J. C76 (2016)]
  - Quarkonium associated production (light- or heavy- hadrons, quarkonia, vector bosons)
  - Quarkonium production as a function of the charged-particle multiplicity

Quarkonium measurements with ALICE

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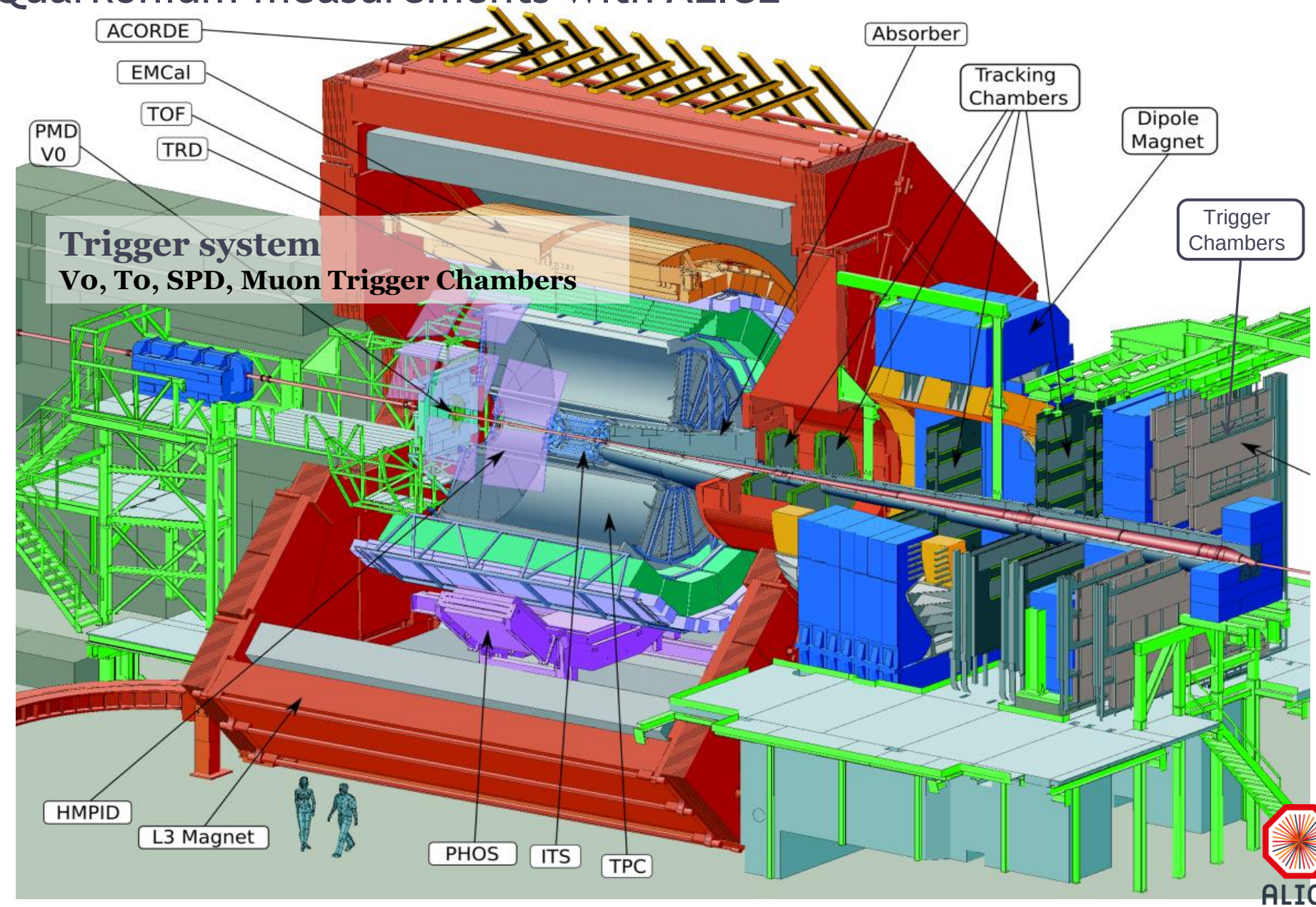

Trigger system

Vo, To, SPD, Muon Trigger Chambers

Quarkonium measurements with ALICE

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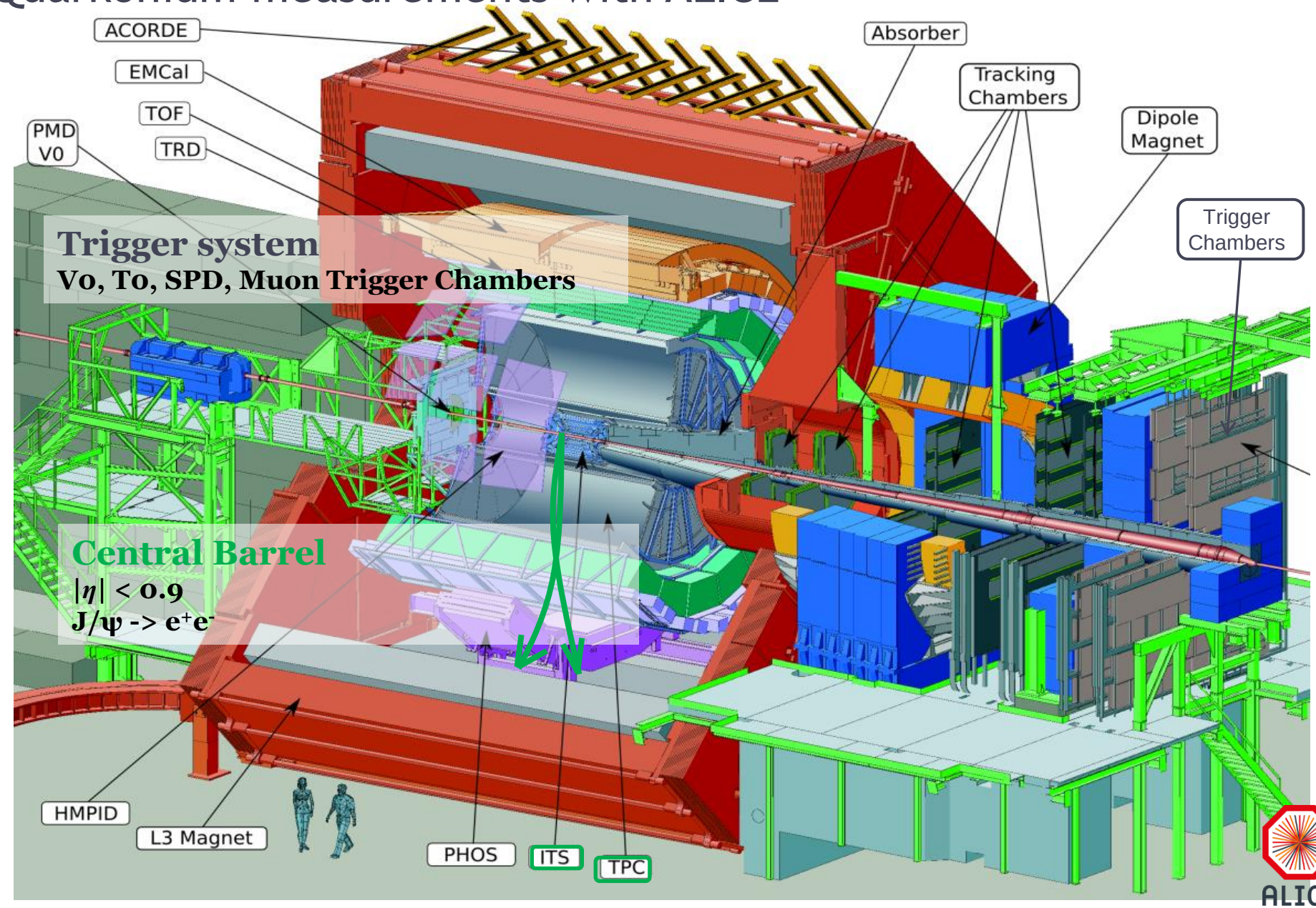

Quarkonium measurements with ALICE

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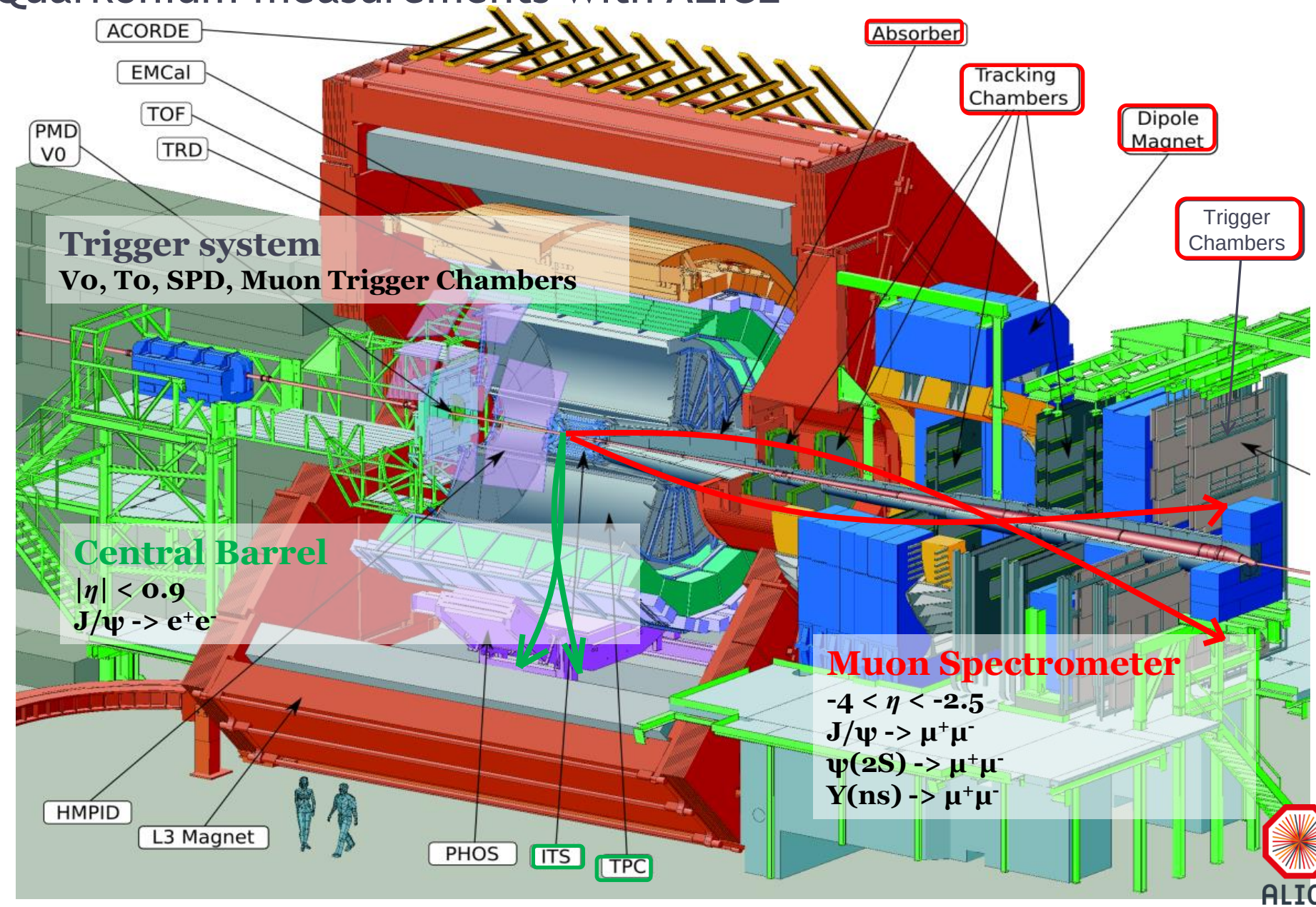

J/ψ production at $\sqrt{s}$ = 7 TeV

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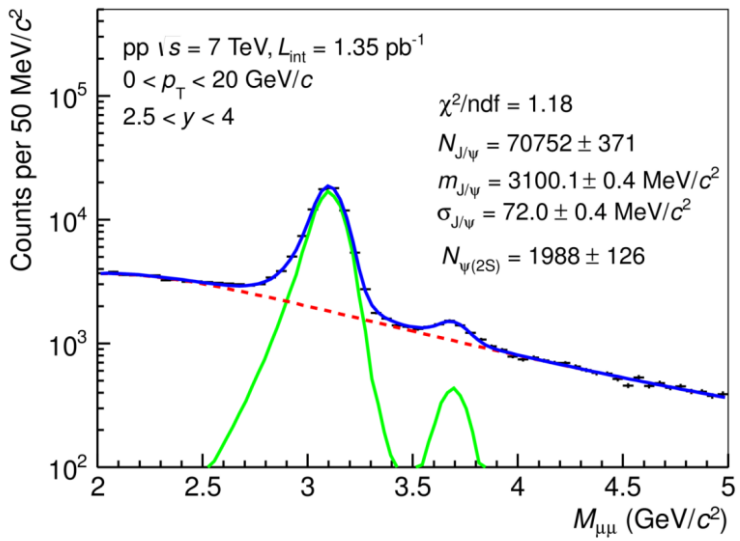

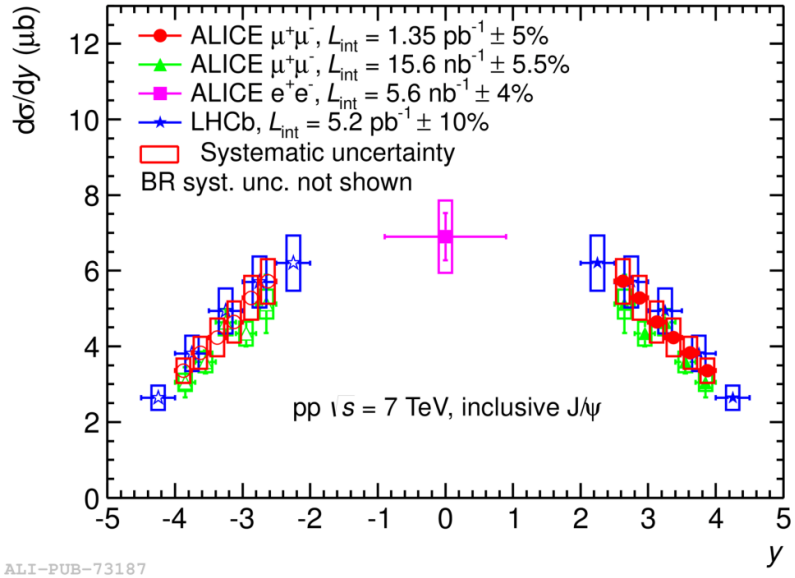

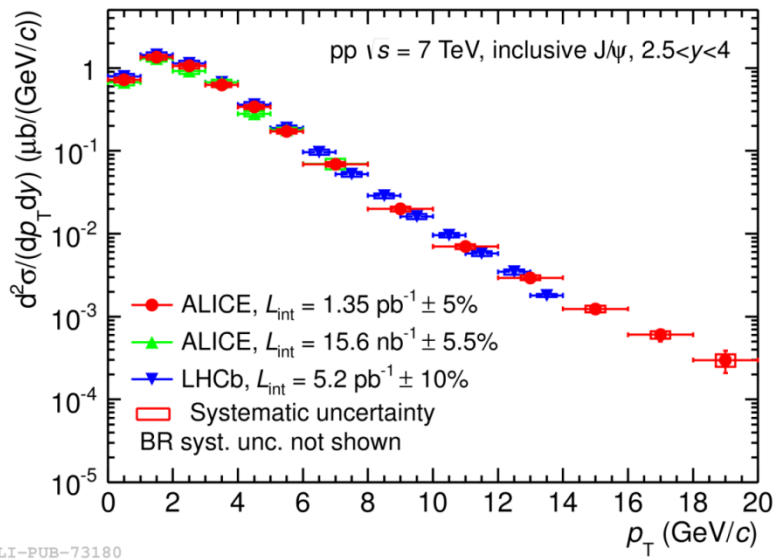

- <u>pp 7 TeV, di-muons (forward) and di-electrons (central)</u>

  Good agreement between ALICE and LHCb

  Extend previous ALICE measurement up to 20 GeV/c

  $\sigma_{J/\psi}$= 6.69 ±0.04 (stat.) ± 0.63 (syst.) μb

  $2.5 < y < 4$; $0 < p_T < 20$ GeV/c

  Eur. Phys. J. C74 (2014) 8, 2974

J/ψ production at $\sqrt{s}$ = 8 TeV

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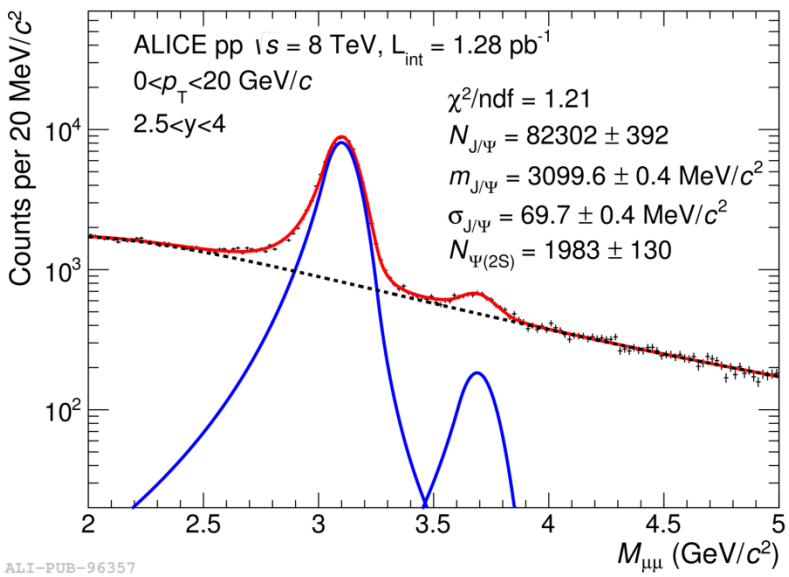

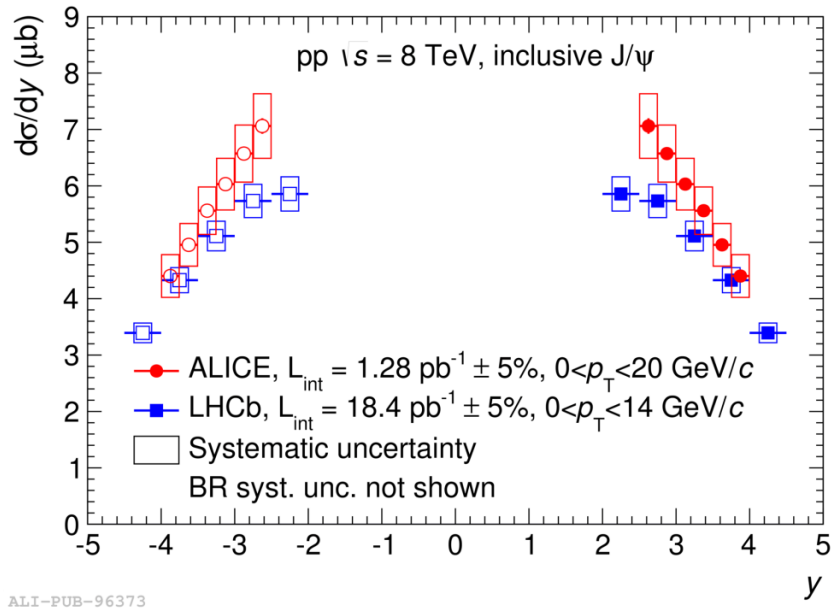

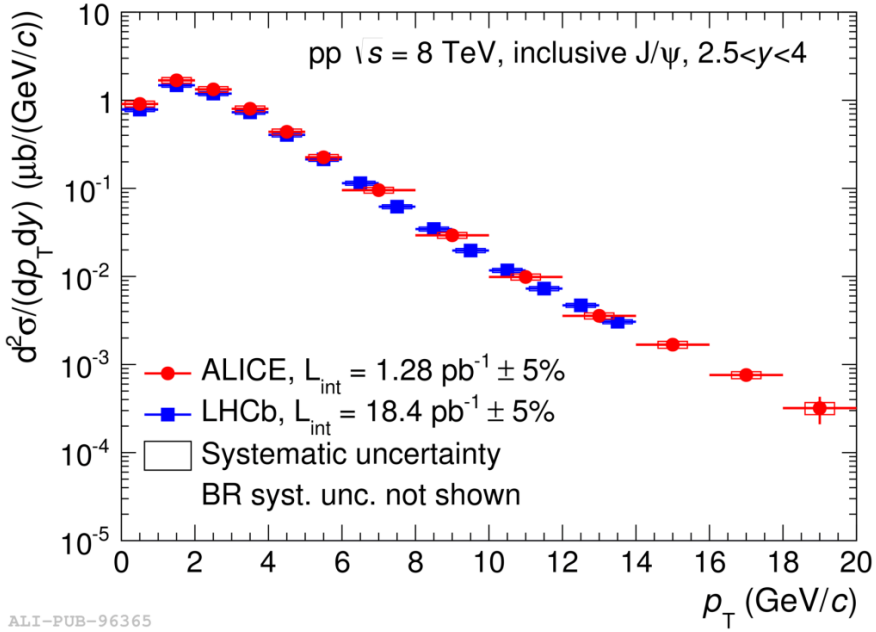

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- <u>pp 8 TeV, di-muons (forward)</u>

  Reasonable agreement between ALICE and LHCb

  Low-p_T and small-y: ALICE above LHCb (difference < 1.5 σ)

  $\sigma_{J/\psi}$ = 8.63 ±0.04 (stat.) ± 0.79 (syst.) μb

  $2.5 < y < 4$; $0 < p_T < 20$ GeV/c

  Eur. Phys. J. C76 (2016) 4, 184

J/ψ production vs. theory at $\sqrt{s}$ = 7 TeV

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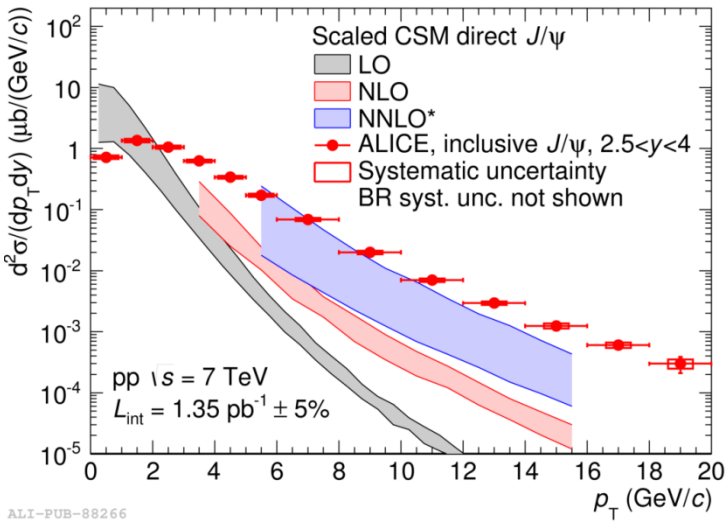
- Color Singlet Model (CSM) **J. Phys. G 38 (2011) 124110**

  Addition of the leading-p_T contribution of NNLO (NNLO*) further improves **data/theory agreement**



Eur. Phys. J. C74 (2014) 8, 2974

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- NRQCD (Color Singlet + Color Octet @ NLO)

  Two parametrizations of the Long-Range Matrix Elements for the CO contribution
  - Butenschoen: 3 matrix elements **Phys. Rev. D 84 (2011) 051501**
  - Ma: 2 linear combinations of the 3 matrix elements **Phys. Rev. D 84 (2011) 114001**

  (+ different data sets, minimum p_T and χ_c contribution)

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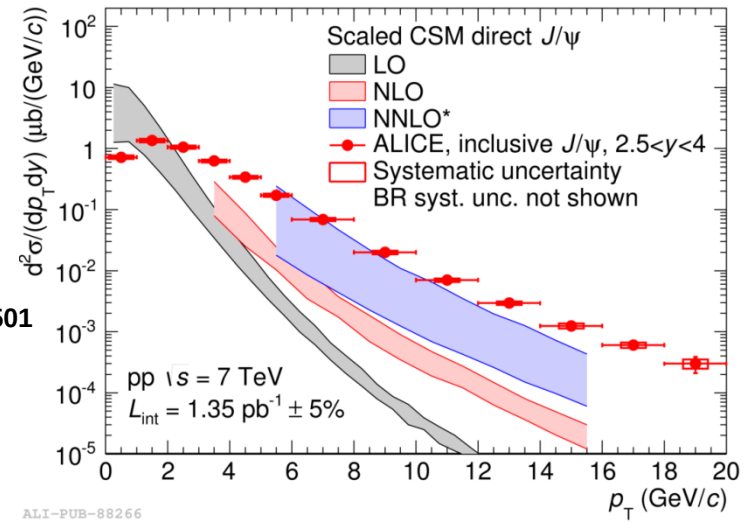

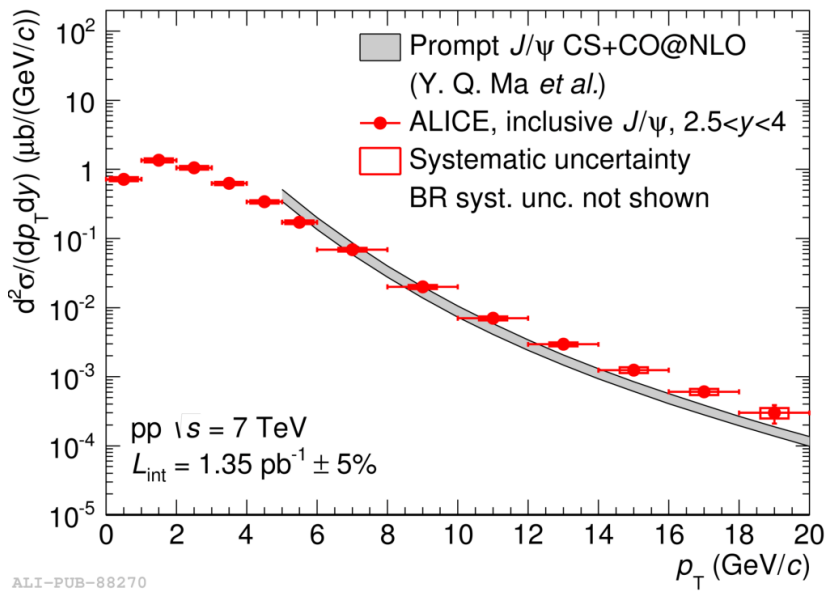

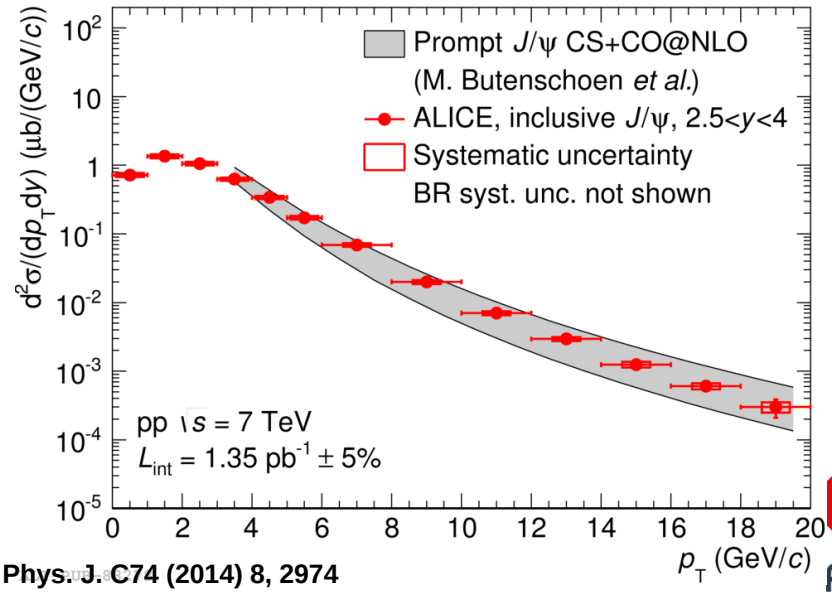

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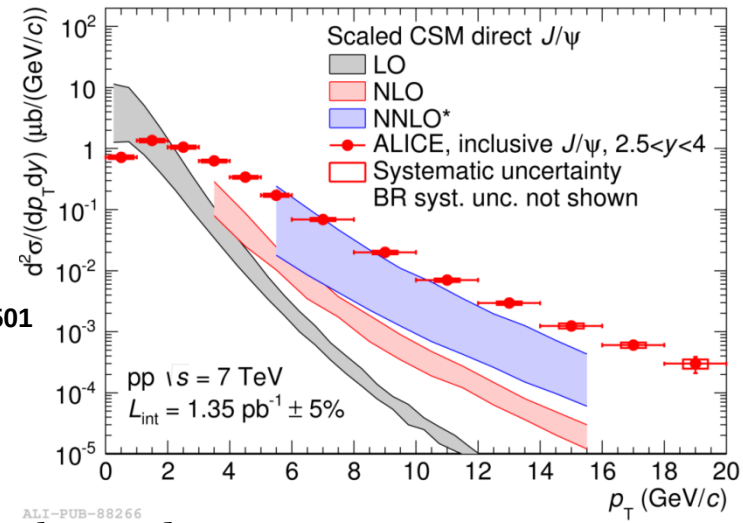
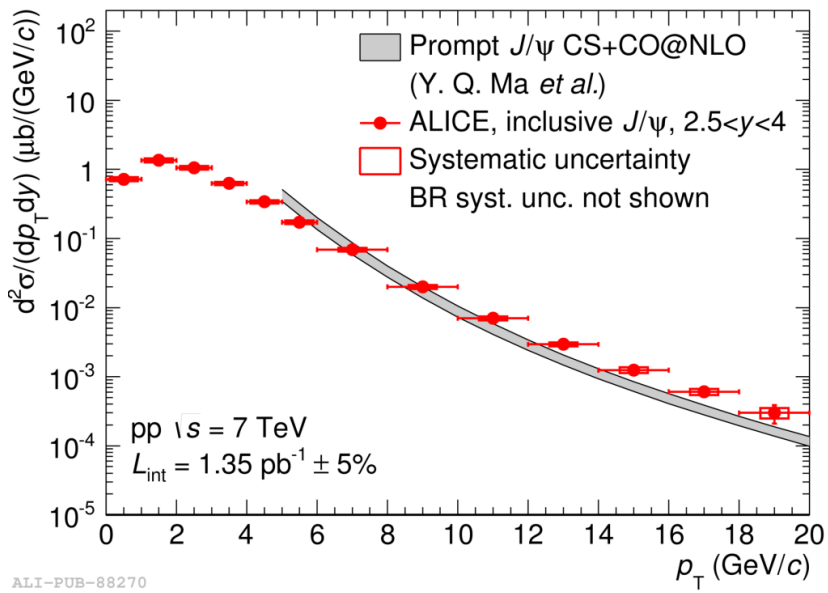
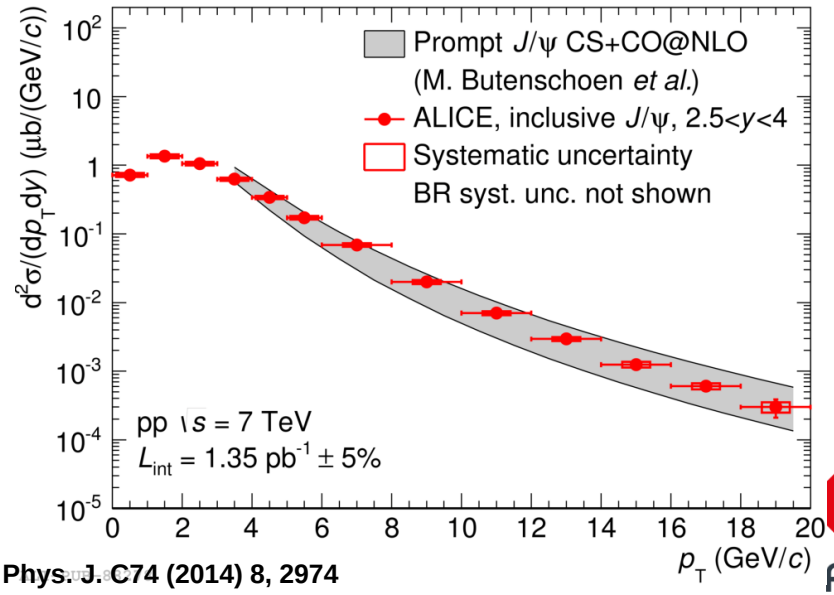


! Measurement = inclusive J/ψ, B-hadron decay contribution not subtracted





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Separation of prompt/non-prompt J/ψ

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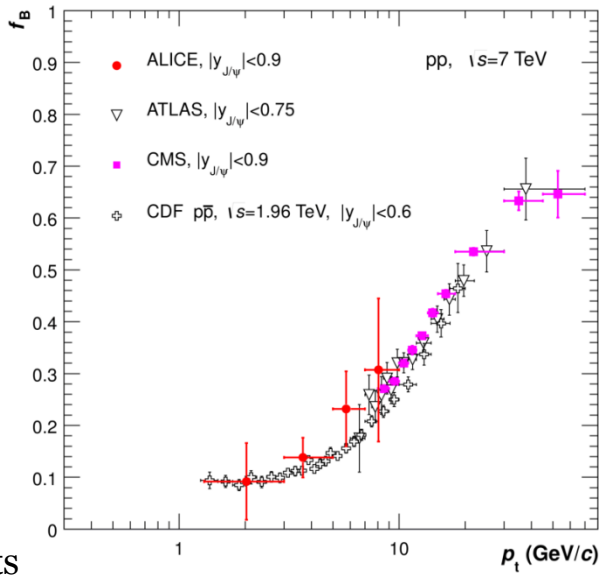
In the di-electron channel $|y|<0.9$,
discrimination by the pseudo-proper decay length

f_B: fraction of non-prompt J/ψ (from B-hadron decays)



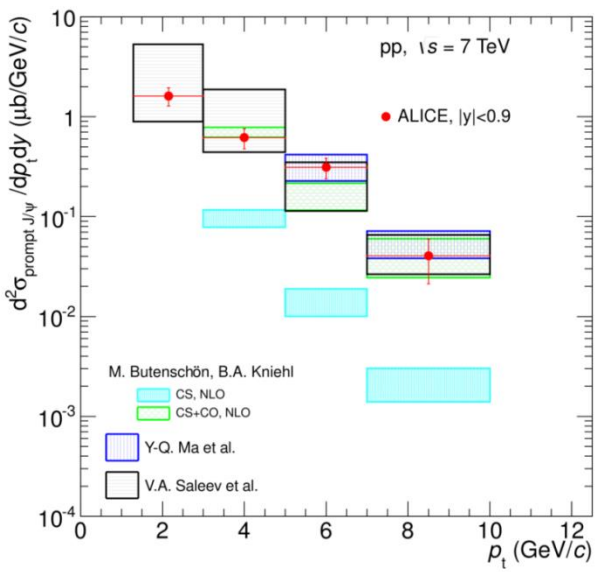
- Prompt J/ψ
  $\sigma_{\text{prompt J/}\psi} = 8.3 \pm 0.8\ (\text{stat.}) \pm 1.1\ (\text{syst.})^{+1.5}_{-1.4}\ (\text{syst. pol.})\ \mu\text{b}$
  $|y| < 0.9,\ p_T > 1.3$ GeV/c

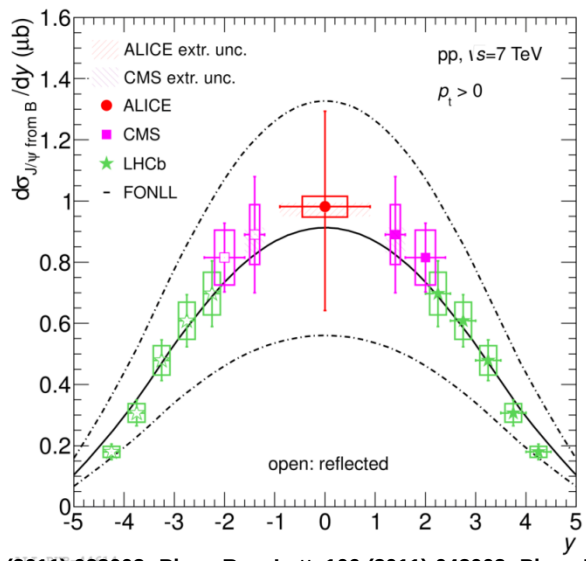
  Direct comparison with models => **good data/theory agreement** with 3 NRQCD (CS+CO @ NLO) implementations

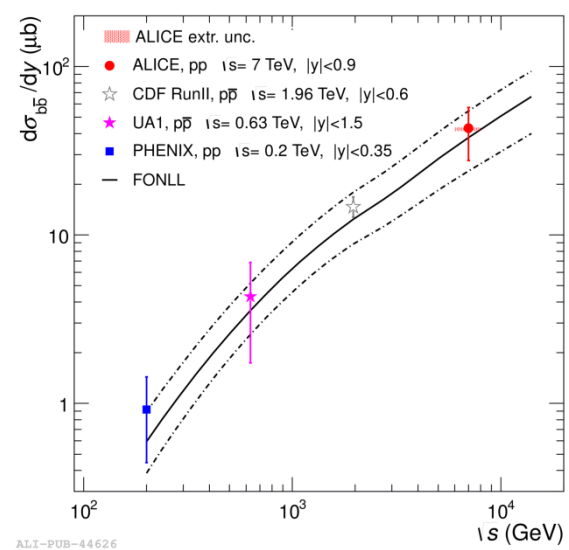
- Non-prompt J/ψ
  $\sigma_{\text{J/}\psi\ <\text{-hB}} = 1.46 \pm 0.38\ (\text{stat.})\ ^{+0.26}_{-0.32}\ (\text{syst.})\ \mu\text{b}$
  $|y| < 0.9,\ p_T > 1.3$ GeV/c

ALICE measurements at central rapidity complement LHC measurements

FONLL describes y-distribution and energy dependence of the beauty cross section at central rapidity







JHEP 1211 (2012) 065; Phys. Rev. Lett. 106 (2011) 022003; Phys. Rev. Lett. 106 (2011) 042002; Phys. Rev. D 85 (2012) 074013; JHEP 07 (2004) 33

J/ψ polarization at $\sqrt{s}$ = 7 TeV

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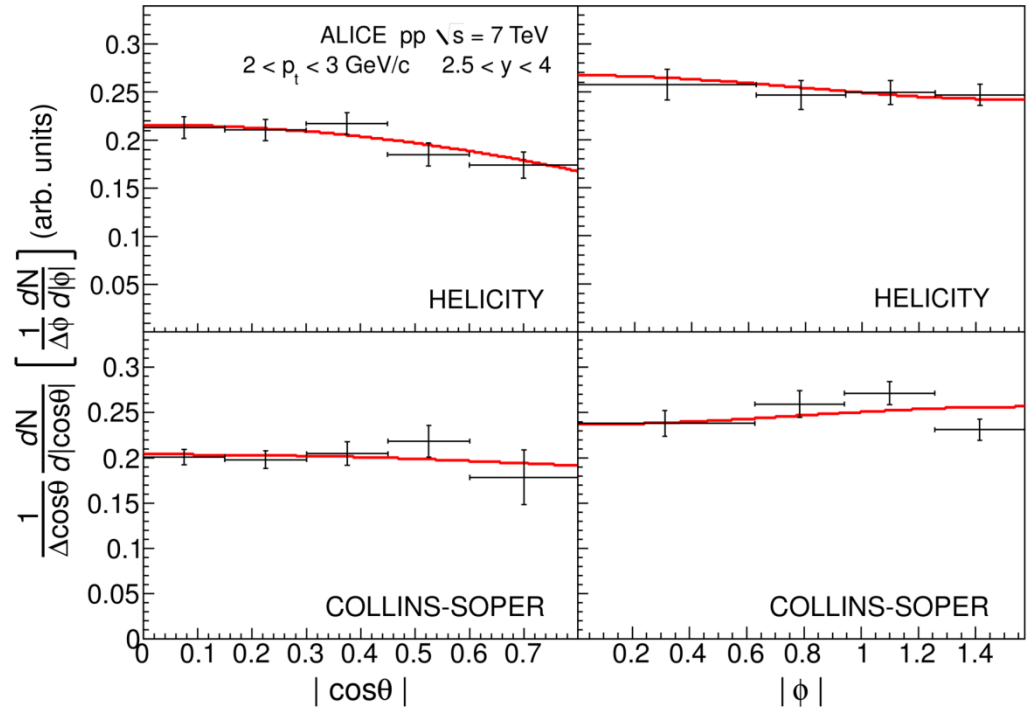
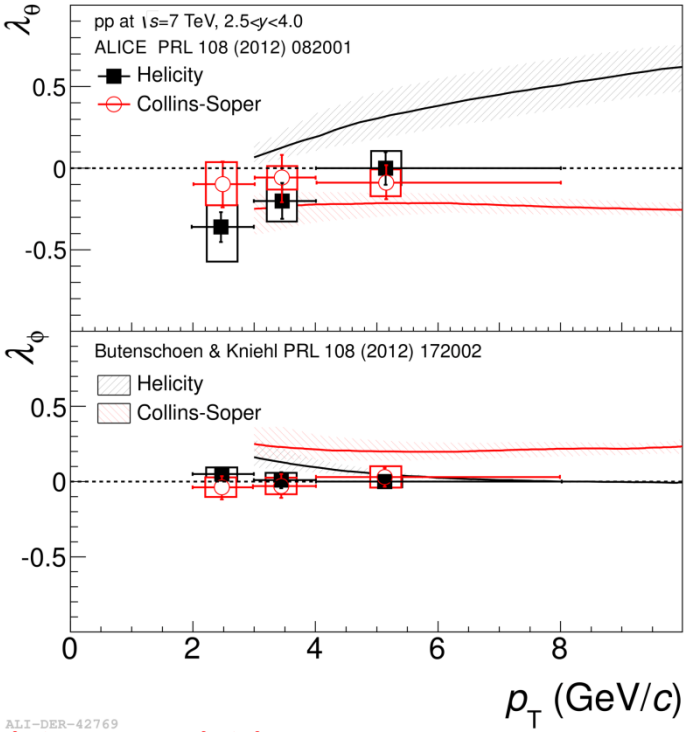
- Theoretical challenge to reproduce differential cross sections and polarization
  - CEM: no polarization
  - CSM: transverse at LO and longitudinal at NLO
  - NRQCD: transverse at high-p_T
- Detector acceptance dependent of J/ψ polarization





All measurements compatible with zero within 2σ

$\lambda_\theta < 0$ (longitudinal) for low-p_T J/ψ in the helicity frame
Results compatible with LHCb (EPJC 47 (213) 11)

Phys. Rev. Lett. 108 (2012) 082001

Ψ(2S) production at √s = 7 TeV

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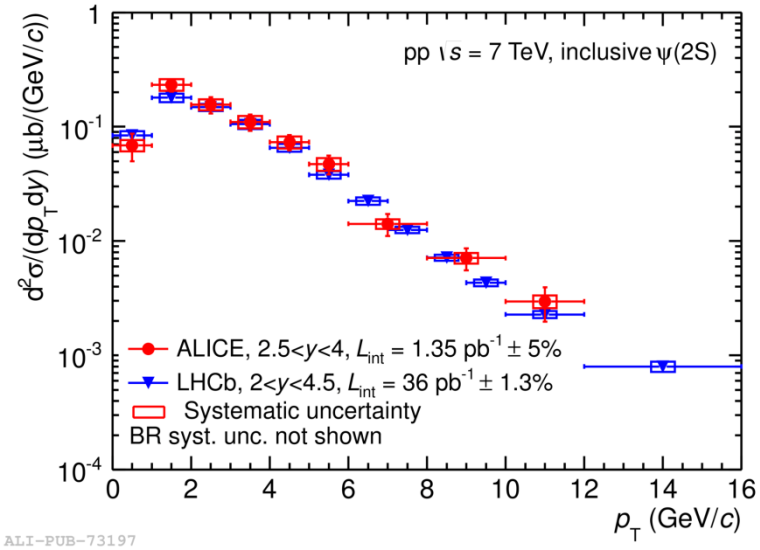
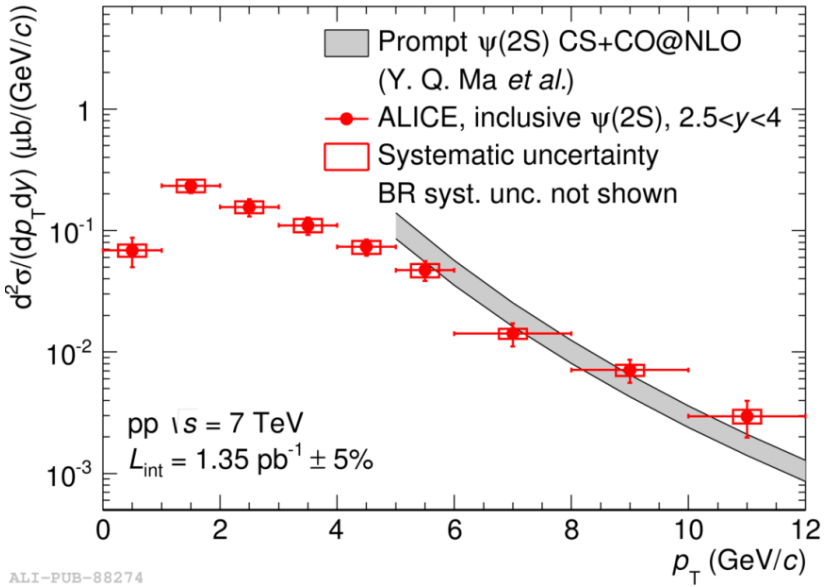
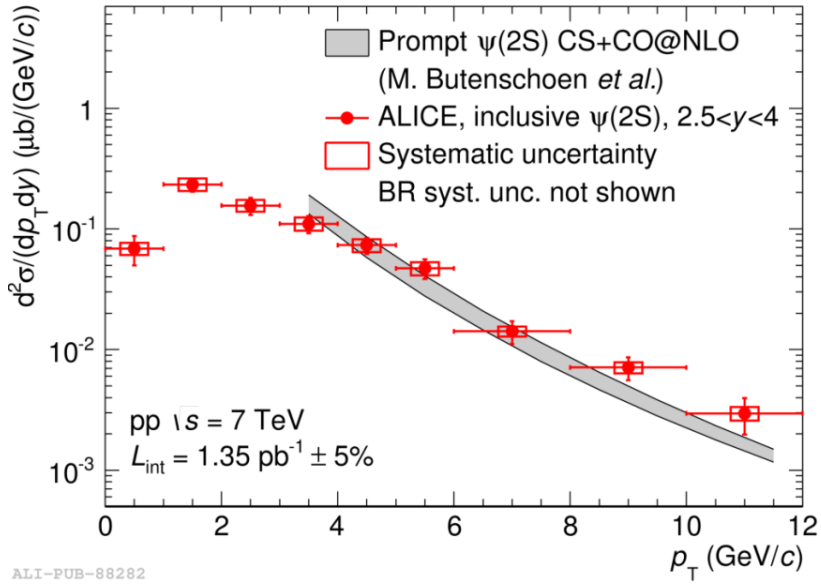


- pp 7 TeV, di-muon (forward)
  - Agreement between ALICE and LHCb within systematic uncertainties
    $\sigma_{\psi(2S)} = 1.13 \pm 0.07\ (\text{stat.}) \pm 0.19\ (\text{syst.})\ \mu b$
    $2.5 < y < 4;\ 0 < p_T < 12\ \text{GeV}/c$
  - Data compared to two NRQCD implementations of CS+CO@NLO (Butenschoen and Ma)

Reasonable **data/theory agreement**

Data: Eur. Phys. J. C74 (2014) 8, 2974; Theory: Phys. Rev. D 84 (2011) 114001; Phys. Rev. D 84 (2011) 051501





Ψ(2S) production at √s = 8 TeV

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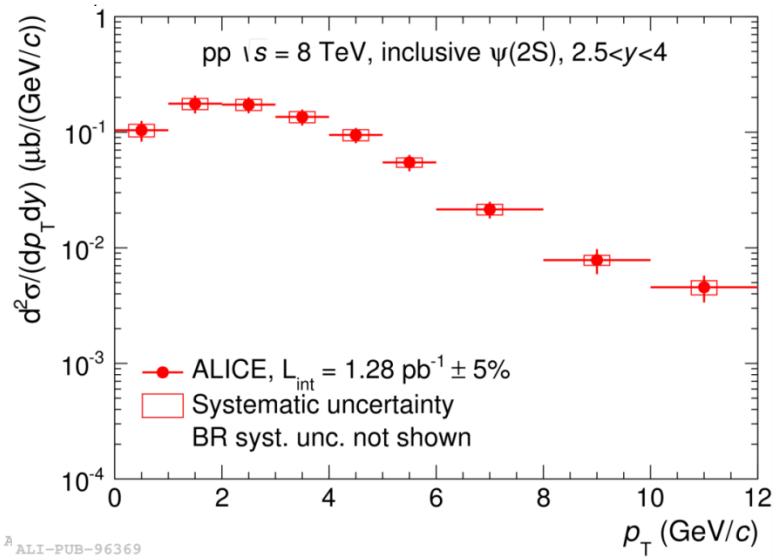

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- pp 8 TeV, di-muon (forward)

  $\sigma_{\psi(2S)}$ = 1.18 ±0.08 (stat.) ± 0.21 (syst.) μb
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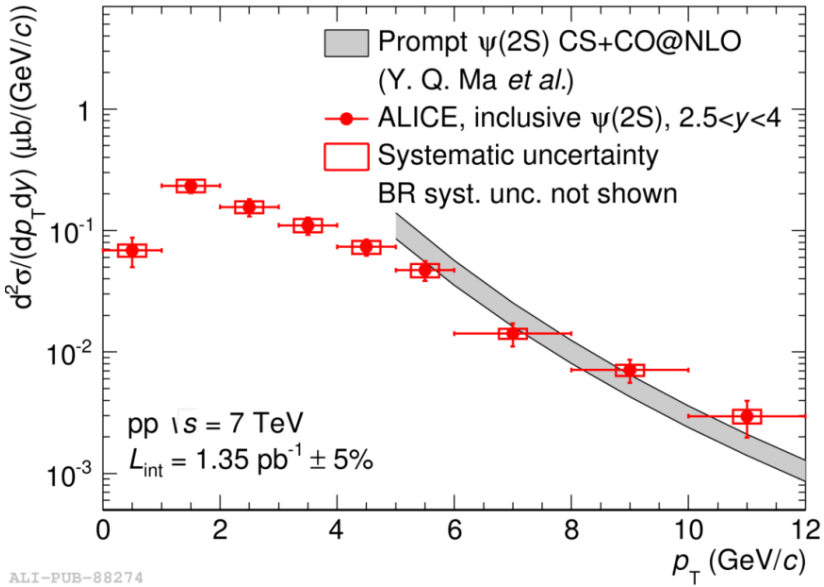

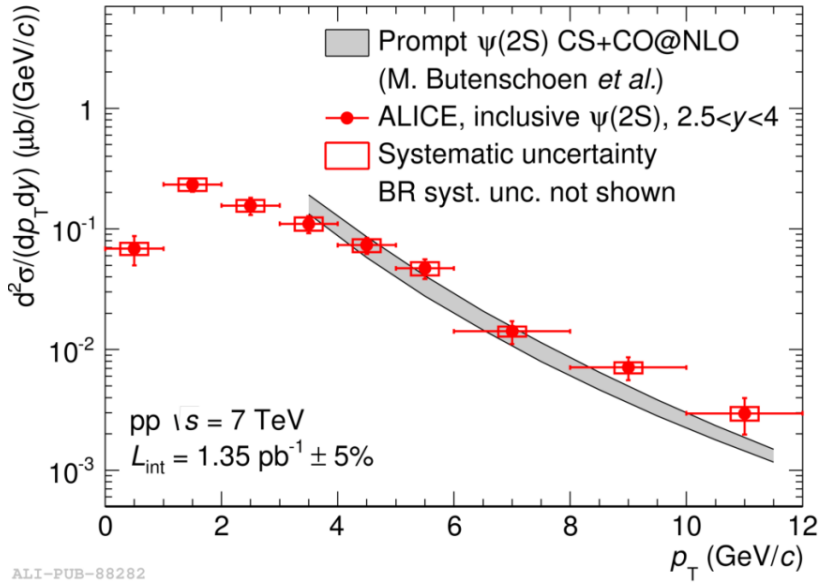

Charmonium ratio ψ(2S)-to-J/ψ

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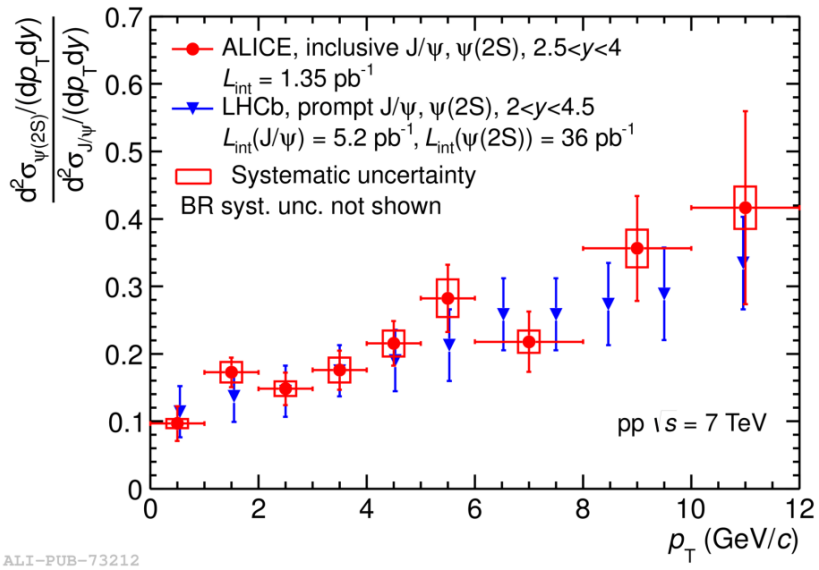
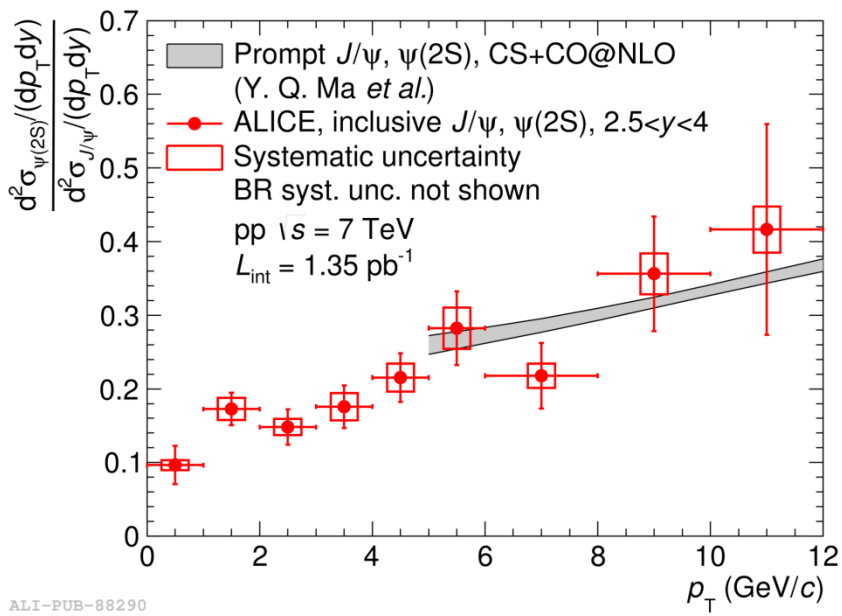
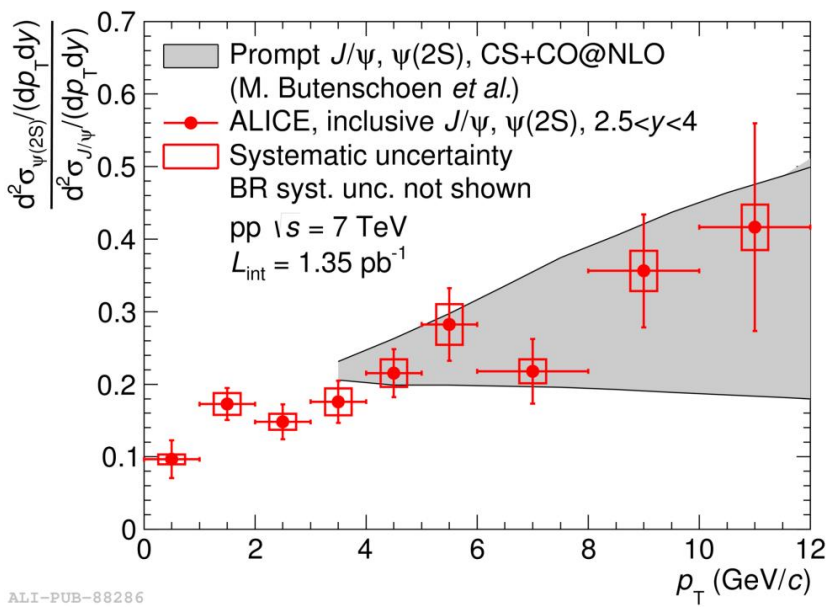


- ➢ <u>pp 7 TeV, di-muon (forward)</u> **Eur. Phys. J. C74 (2014) 8, 2974**
  - independent of y
  - increase with p_T,
    in agreement with LHCb measurement for prompt charmonium
    Increase cannot be accounted only by decay of higher mass resonances
  - CSM predicts $\psi(2S)_{direct}/J/\psi_{direct}$=0.42, independent of p_T and y
  - **Octet contributions** (NRQCD implementations) are sufficient to **reproduce the observed trend**





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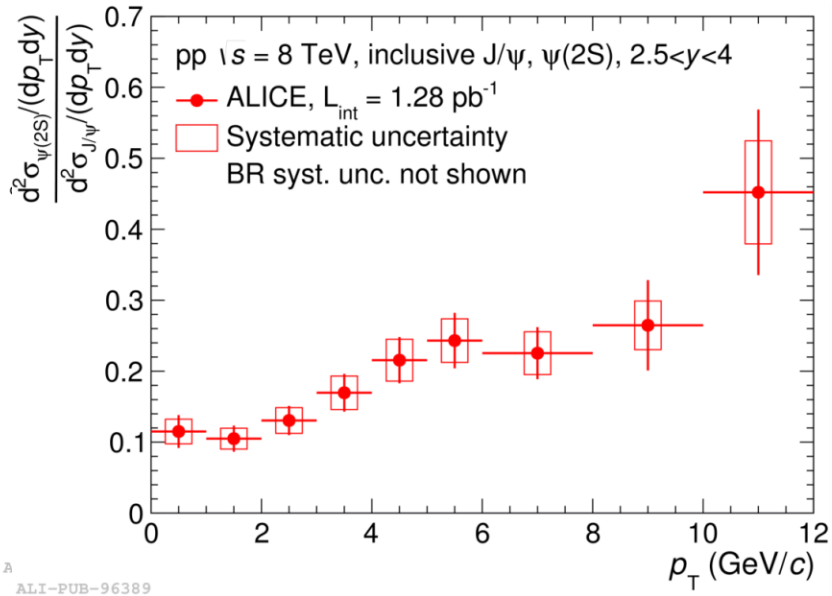

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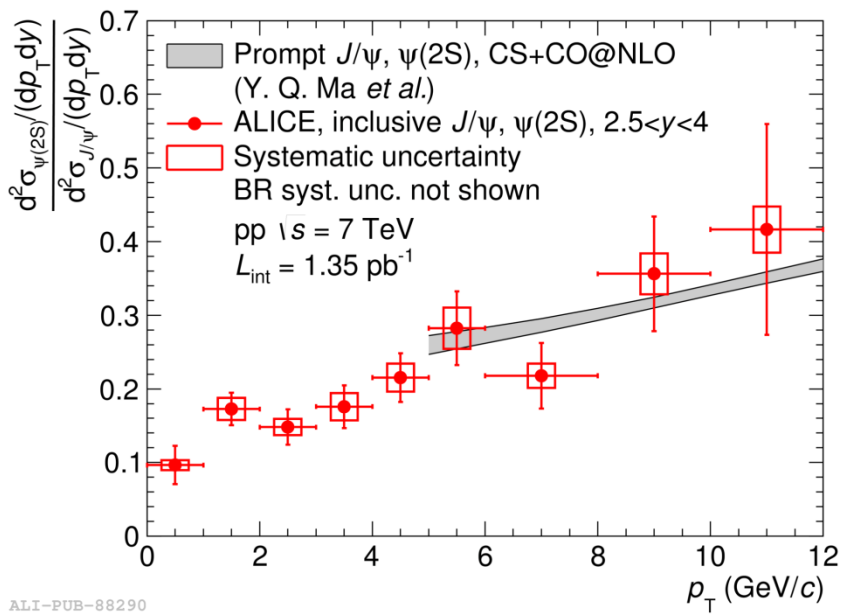
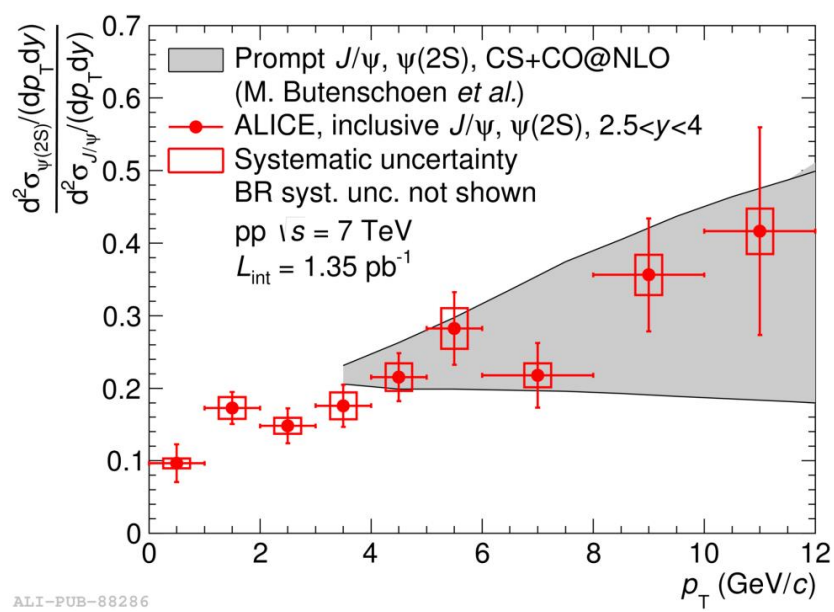
➢ pp 8 TeV, di-muon (forward) **Eur. Phys. J. C76 (2016) 4, 184**

- Same trend as at 7 TeV observed





Υ production at √s = 7 TeV

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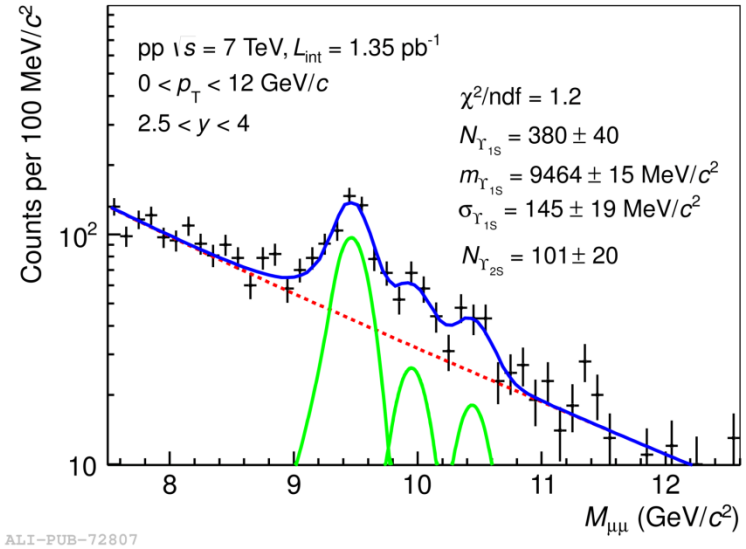

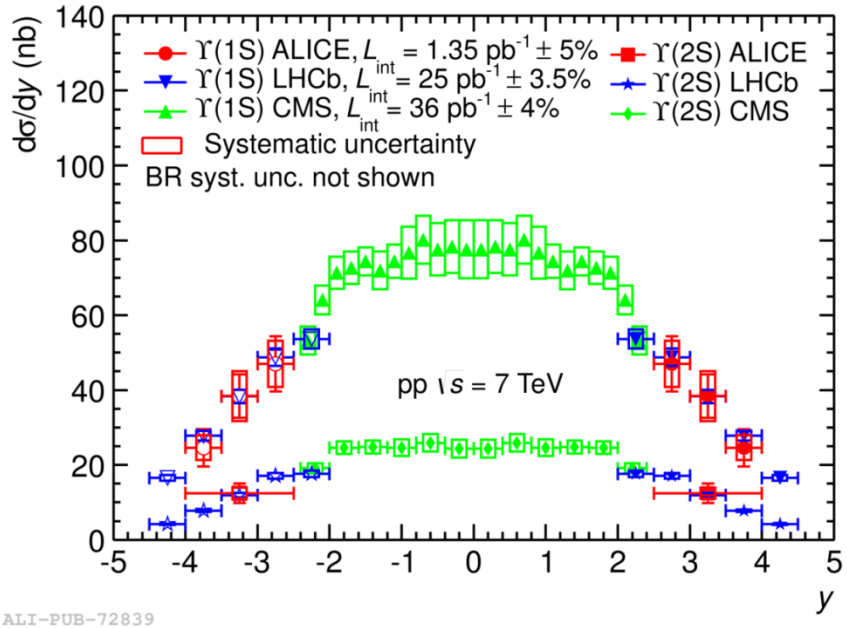

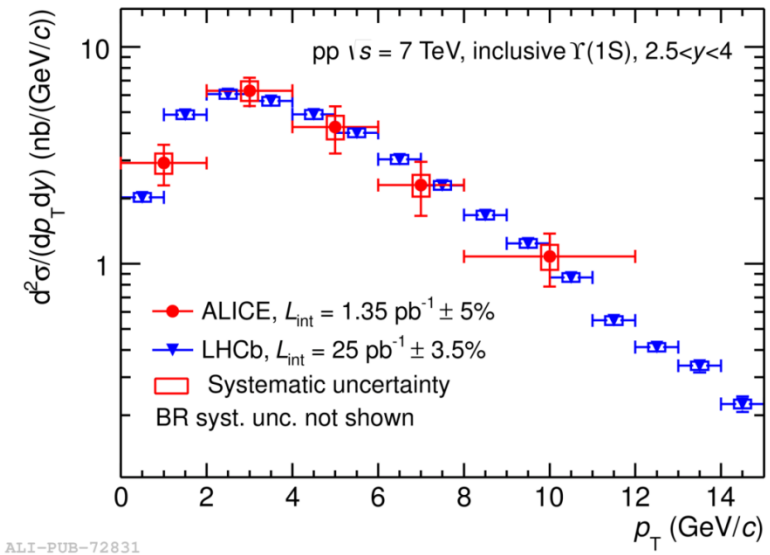

- pp 7 TeV, di-muon (forward): Υ(1s) and Υ(2s)

Good agreement between ALICE and LHCb for both states

Extend CMS measurement

$\sigma_{\Upsilon(1s)}$= 54.2 ± 5.0 (stat.) ± 6.7 (syst.) nb

$\sigma_{\Upsilon(2s)}$= 18.4 ± 3.7 (stat.) ± 2.9 (syst.) nb

$2.5 < y < 4$; $0 < p_T < 12$ GeV/c

Data: Eur. Phys. J. C74 (2014) 8, 2974, Eur. Phys. J. C76 (2016) 4, 184

Υ production at √s = 8 TeV

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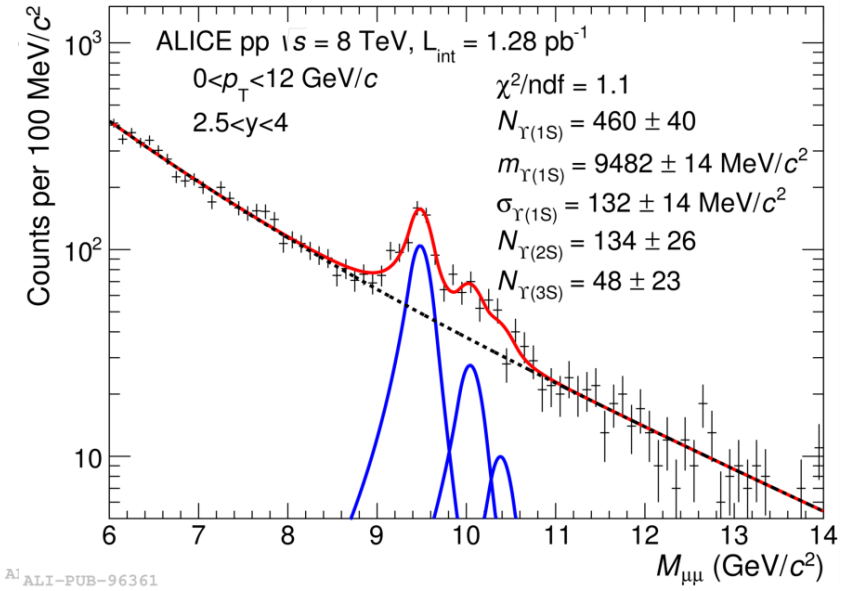

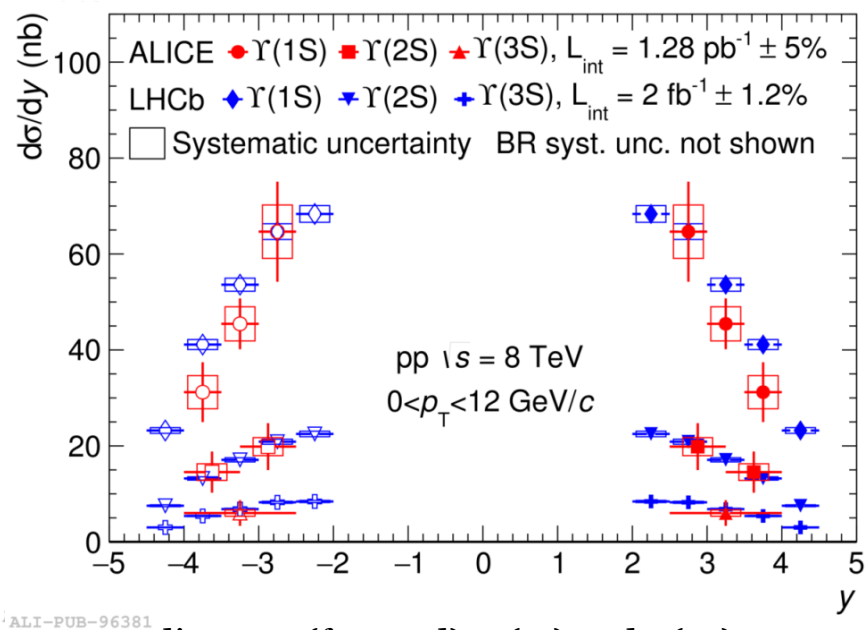

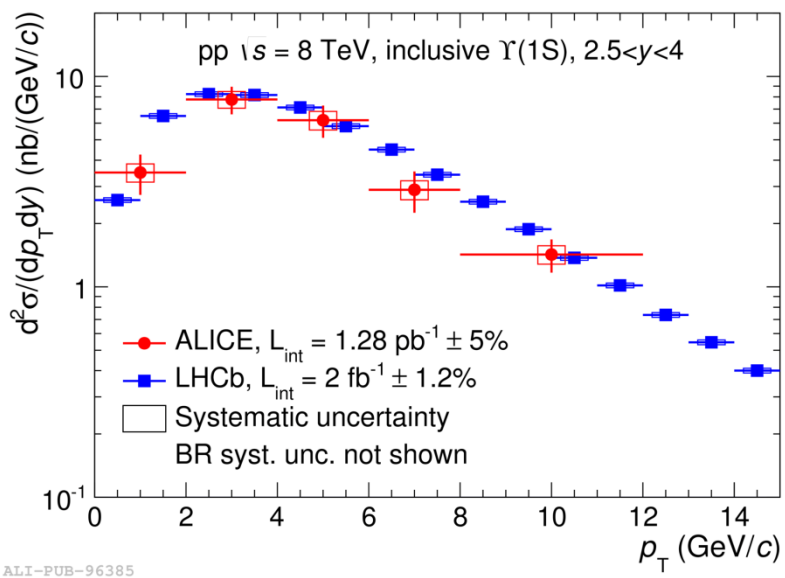

- pp 7 TeV, di-muon (forward): Υ(1s) and Υ(2s)

  Good agreement between ALICE and LHCb for both states
  Extend CMS measurement
  $\sigma_{\Upsilon(1s)}$= 54.2 ± 5.0 (stat.) ± 6.7 (syst.) nb
  $\sigma_{\Upsilon(2s)}$= 18.4 ± 3.7 (stat.) ± 2.9 (syst.) nb
  $2.5 < y < 4$; $0 < p_T < 12$ GeV/c

- pp 8 TeV, di-muon (forward): Υ(1s), Υ(2s) and Υ(3s)

  Reasonable agreement between ALICE and LHCb
  For Υ(1s): ALICE lower than LHCb (difference < 1.5 σ)
  $\sigma_{\Upsilon(1s)}$= 68 ± 6 (stat.) ± 7 (syst.) nb
  $\sigma_{\Upsilon(2s)}$= 25 ± 5 (stat.) ± 4 (syst.) nb
  $\sigma_{\Upsilon(3s)}$= 9 ± 4 (stat.) ± 1 (syst.) nb
  $2.5 < y < 4$, $0 < p_T < 12$ GeV/c

Data: Eur. Phys. J. C74 (2014) 8, 2974, Eur. Phys. J. C76 (2016) 4, 184

Υ(1s) production vs. theory at √s = 7 TeV

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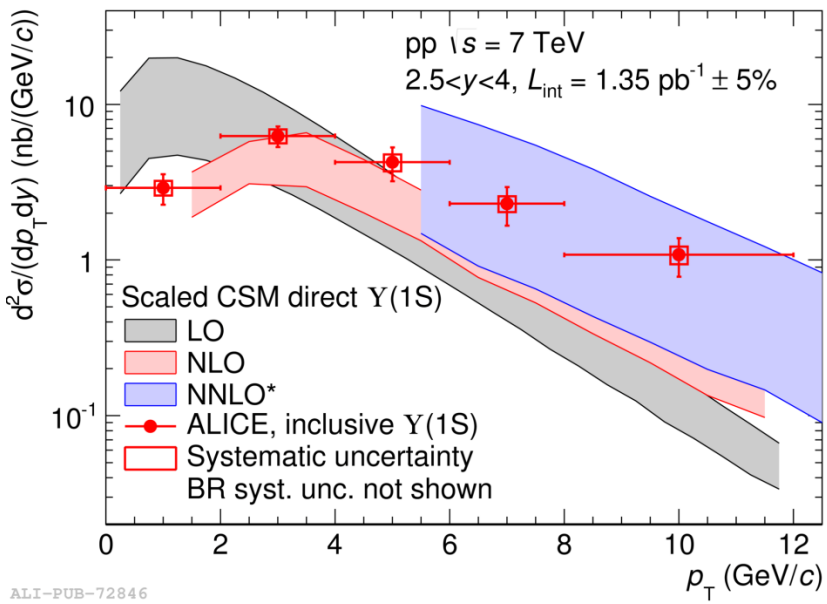
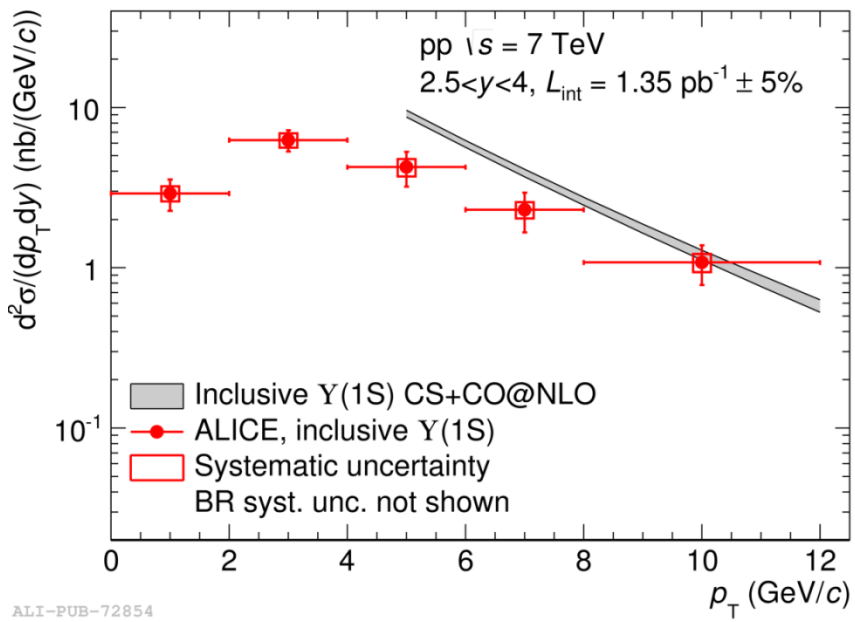
- Color Singlet Model (CSM) **Nucl. Phys. A 470 (2013) 910**
  Same implementation as for J/ψ
  Implementation of the leading-p_T contribution of NNLO further improves **data/theory agreement**
  Data/theory comparison shows qualitatively the same features as for J/ψ

- NRQCD (Color Singlet + Color Octet @ NLO)
  Implementation of Ma *et al.* **Phys. Rev. D 85 (2012) 114003**
  Include feed-down contributions from Υ(2s), Υ(3s) and χ_b
  Theory overestimates data, disagreement smaller at high-p_T (as for LHCb)





Data: Eur. Phys. J. C74 (2014) 8, 2974

New observable in quarkonium production

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Relative J/ψ yield as a function of relative charged-particle multiplicity

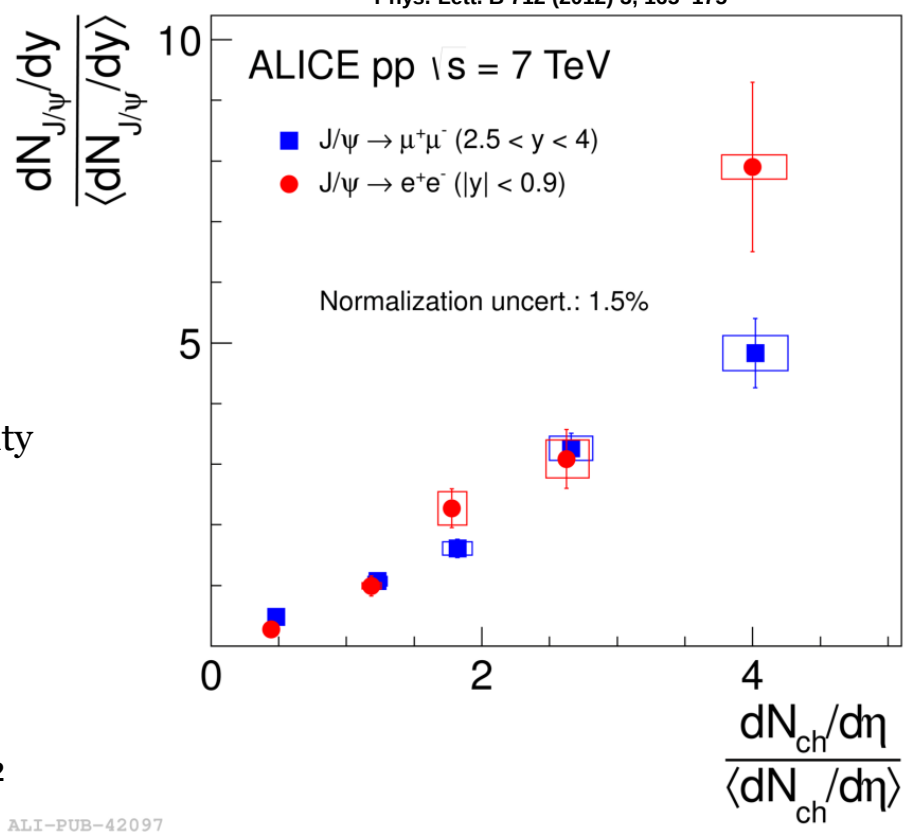
- Approximate linear increase of J/ψ yield as a function of charged-particle multiplicity

- Same trend in 2 rapidity regions
(apart from the highest multiplicity bin)
Correlation extends over three rapidity units
Correlation extends up to four times the mean multiplicity

- possible interpretations:
- Hadronic activity accompanying J/ψ production
- Multi-parton interactions
- Impact of hydro evolution at high multiplicities

PYTHIA **JHEP 0625 (2006) 026 / Comput.Phys.Commun. 178 (2008) 852**
Percolation Model **Phys.Rev. C86 (2012) 034903;**
EPOS **Phys.Rept. 350 (2001) 93 / Phys.Rev. C89809 (2014) 064903**

Phys. Lett. B 712 (2012) 3, 165–175



Conclusions

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- ALICE measured quarkonium production at 2,76 (not shown in this talk), 7 and 8 TeV in central and forward rapidity regions
- ALICE measurements in agreement with LHCb (similar rapidity range), tension at 8 TeV
- CSM NNLO* calculation compatible with J/ψ and Υ(1s) differential cross sections at high-p_T
- NRQCD (CS+CO @ NLO) calculations describe differential cross sections for inclusive J/ψ, prompt J/ψ, and ψ(2S) as well as ψ(2S)-to-J/ψ ratio
- No polarization of inclusive J/ψ in the helicity and Collins-Soper frame
- Approximate linear increase of J/ψ yield as a function of charged-particle multiplicity at forward and mid rapidity

ALICE

Conclusions

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Stay tuned for ALICE Quarkonia measurements at √s = 13 TeV !

More on quarkonia from ALICE in C. Blume's talk

ALICE

Data Taking during the LHC Run 2

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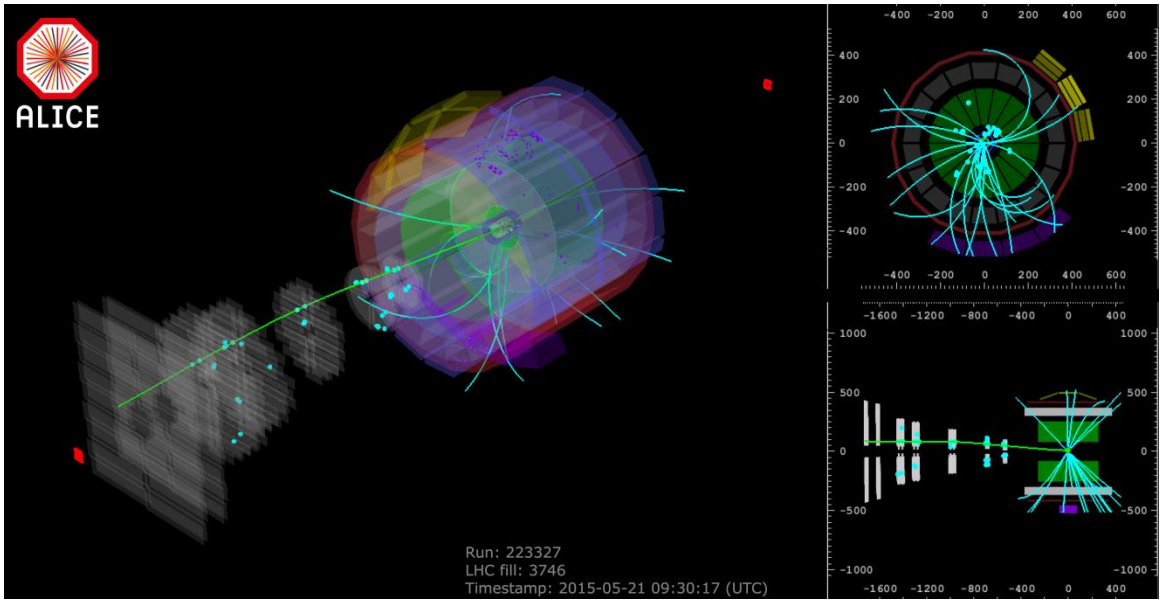
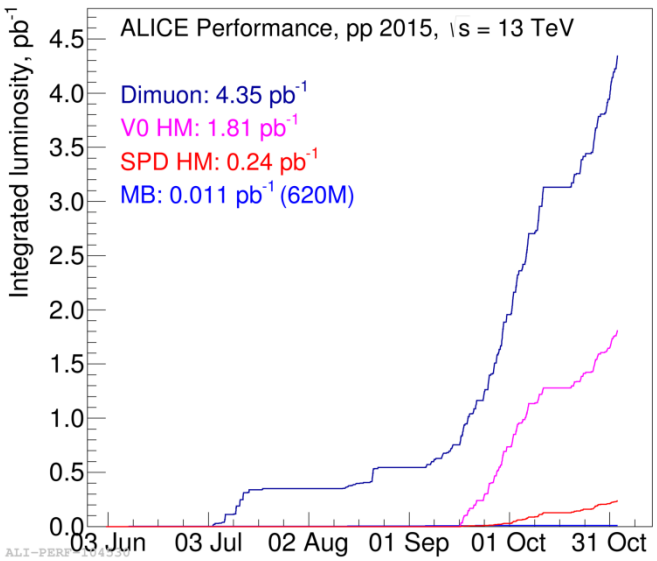
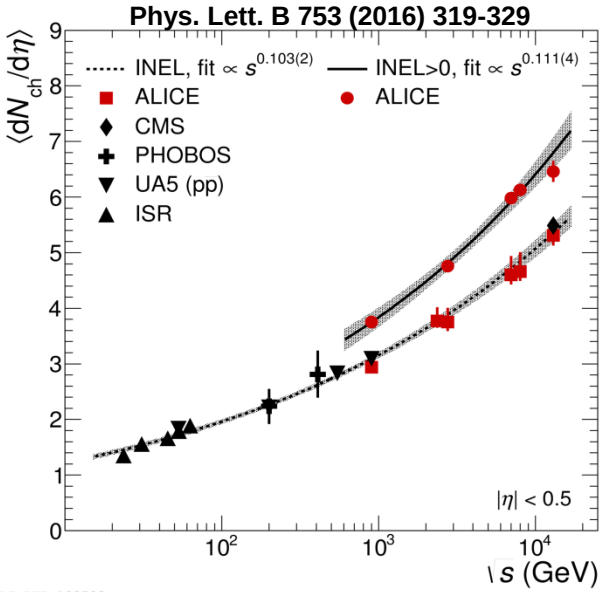




- 2015: new energy record => pp at $\sqrt{s}$ = 13 TeV
  - $L_{int}^{di\text{-}\mu}$=4.35 pb^{-1}
  - No quarkonium published results yet, analysis ongoing [stay tuned]
- 2015: reference measurement pp at $\sqrt{s}$ = 5 TeV
- 2016 pp at $\sqrt{s}$ = 13 TeV
  Data taking started in April 2016



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BACKUP

J/Ψ production at 2,76 TeV

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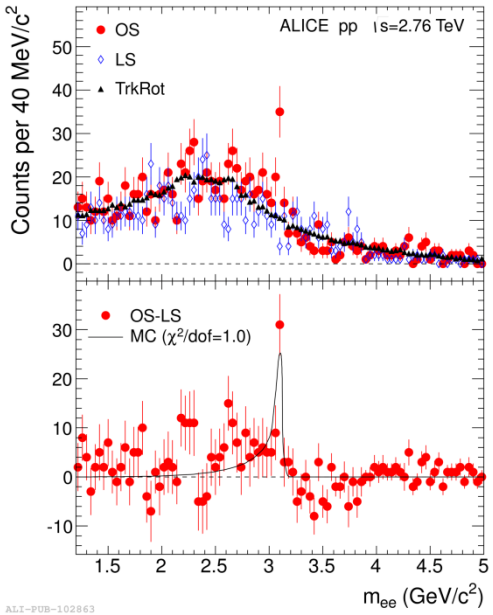

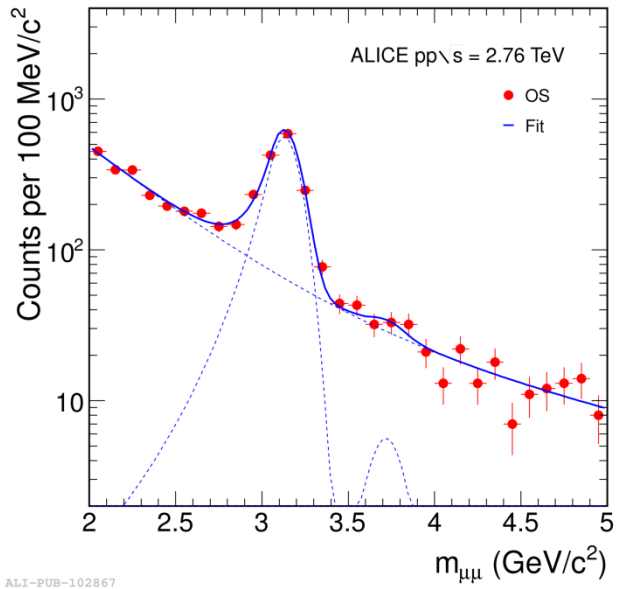

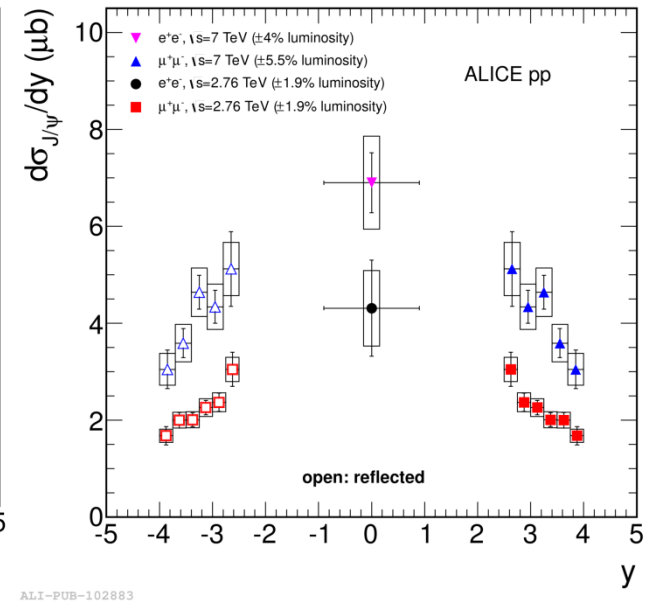

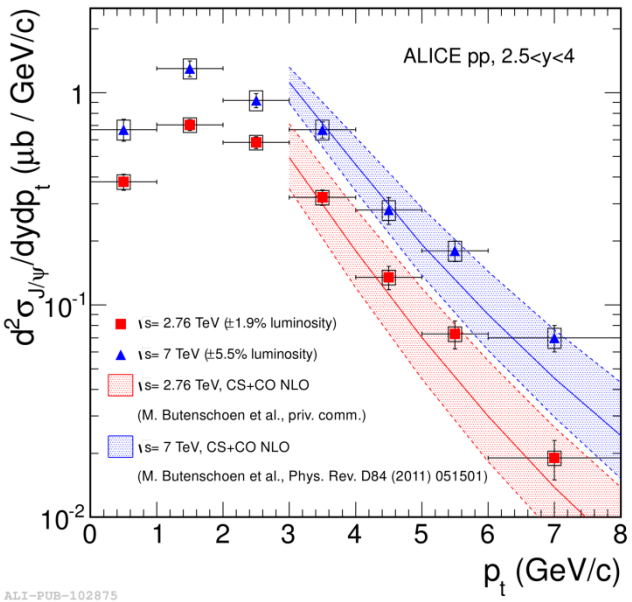

- <u>pp 2,76 TeV, di-muons (forward) and di-electrons (central)</u>

$\sigma_{J/\psi}$ = 3.34 ± 0.13 (stat.) ± 0.27 (syst.)$^{+0,53}_{-1,07}$ (syst. pol.) μb

2,5< y < 4; p_T>0

$\sigma_{J/\psi}$ = 7.75 ± 1.78 (stat.) ± 1.39 (syst.)$^{+1.16}_{-1.63}$ (syst. pol.) μb

$|y|$ < 0,9; p_T>0

Phys. Lett. B718 (2012) 295; Err Phys. Lett. B748 (2015) 472

New observables in quarkonium production

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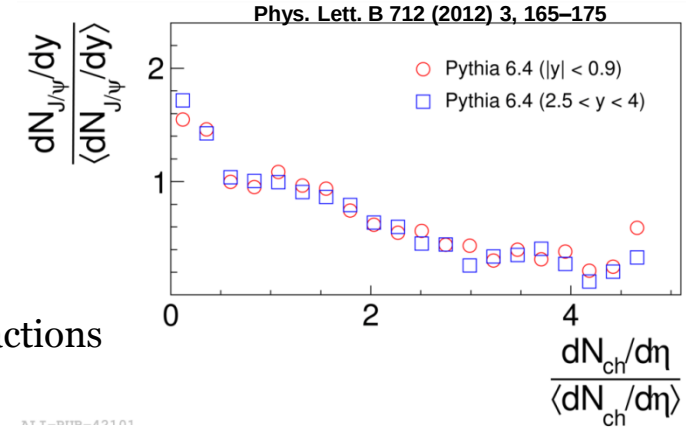
Relative charm production yield as a function of relative charged multiplicity

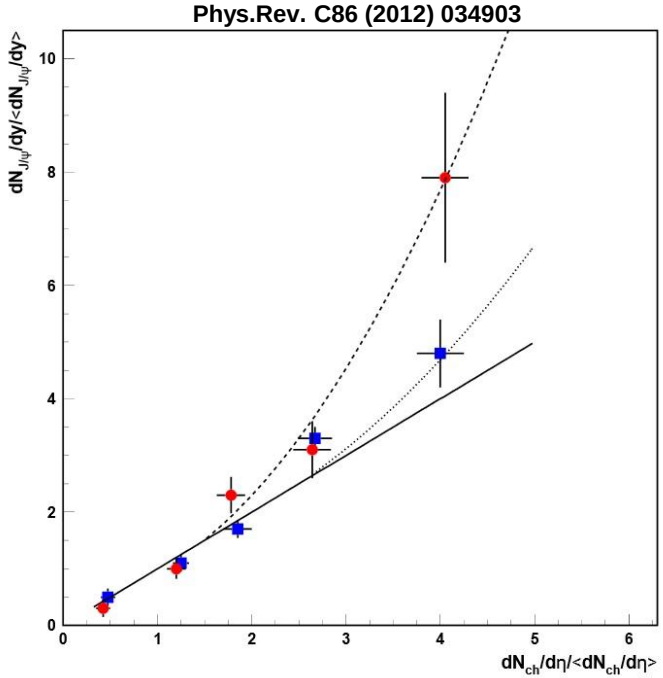
- Trend not reproduced by PYTHIA 6,4 (PERUGIA 2011, direct J/ψ only)
- Trend reproduced by the string percolation model

Number of J/ψ proportional to elementary initial parton-parton interactions
Reduction of the number of charged particles due to percolation

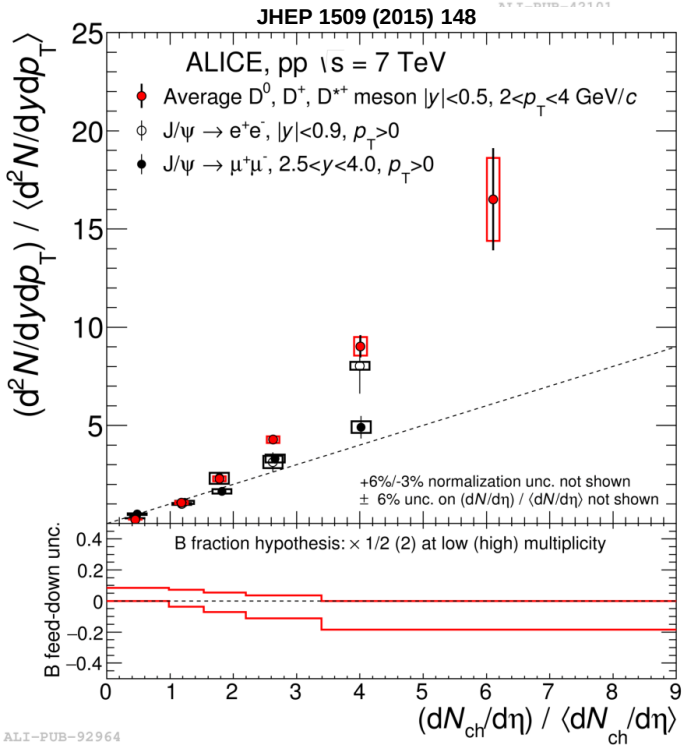
Phys. Lett. B 712 (2012) 3, 165–175



Phys.Rev. C86 (2012) 034903



JHEP 1509 (2015) 148



- More than linear increase observed for central D-mesons up to 6 times de mean multiplicity

ALI-PUB-92964

New observables in quarkonium production

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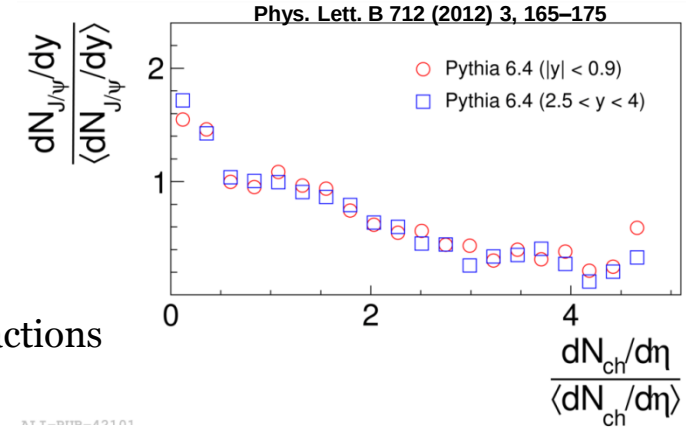

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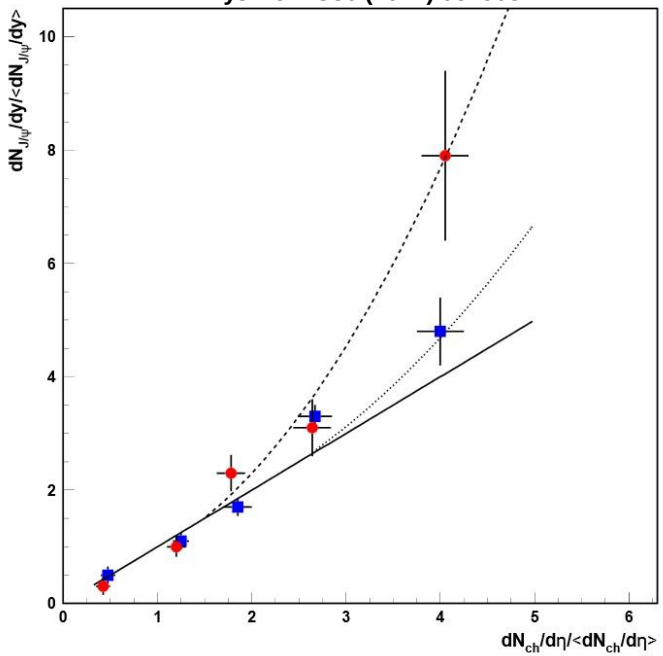
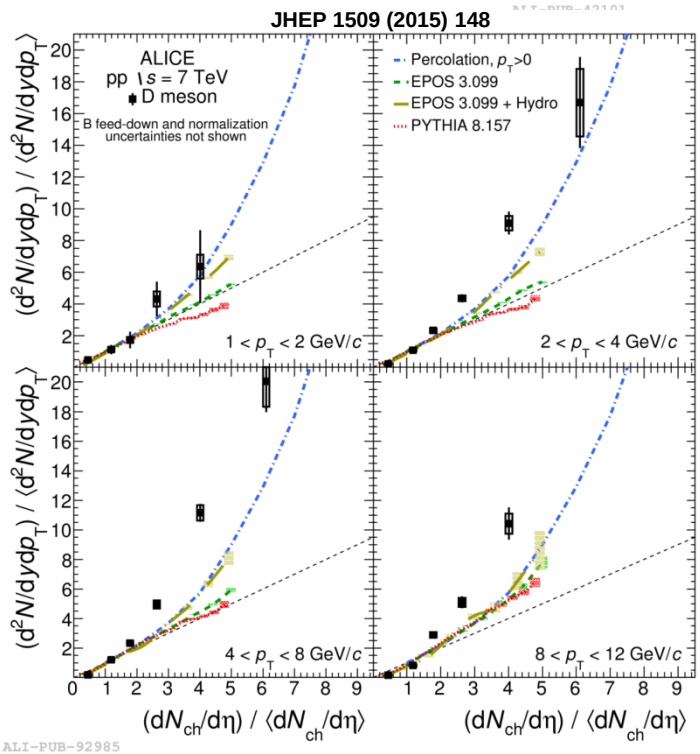


JHEP 1509 (2015) 148



- More than linear increase observed for central D-mesons up to 6 times de mean multiplicity
- MPI in PYTHIA 8 not enough to reproduce D-meson data
- Can be interpreted in term a reduction of charged particle (percolation or hydro in EPOS)