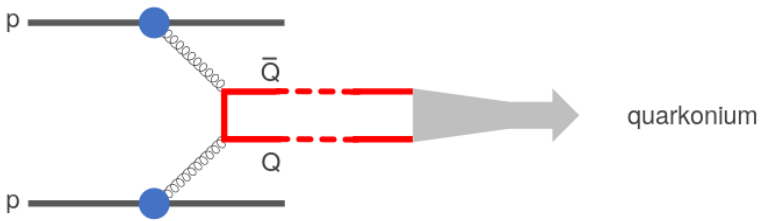
Quarkonium production and elliptic flow in small systems measured with ALICE

ICHEP2022, 6-13 July, Bologna

Maurice Coquet on behalf of the ALICE Collaboration, 9 July
CEA-Saclay/Irfu/DPhN

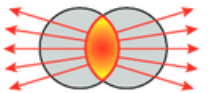
Quarkonium in small systems: testing QCD at its limits

- **Quarkonium production** involves different scales and processes:
  - hard-scales: heavy-quark production in initial hard scattering → test pQCD
  - soft-scales: binding of pairs into a colorless final state → probe non-perturbative physics



- Different models: e.g. Colour Evaporation Model (CEM), Non-Relativistic QCD (NRQCD), ...
  [Lansberg Phys.Rept. 889 (2020)]

- High-multiplicity events to probe collectivity
  - Striking similarities for a few observables between small systems (high-multiplicity pp, p–Pb) and Pb–Pb collisions
    [ALICE, PLB 719 29 (2013)] [ALICE, Nature Phys 13, 535–539 (2017)]
  - Study flow observables for heavy flavors: **J/ψ elliptic flow** in small systems



- Reference systems to study heavy-ion collisions and the quark-gluon plasma

See other ALICE quarkonium talks by

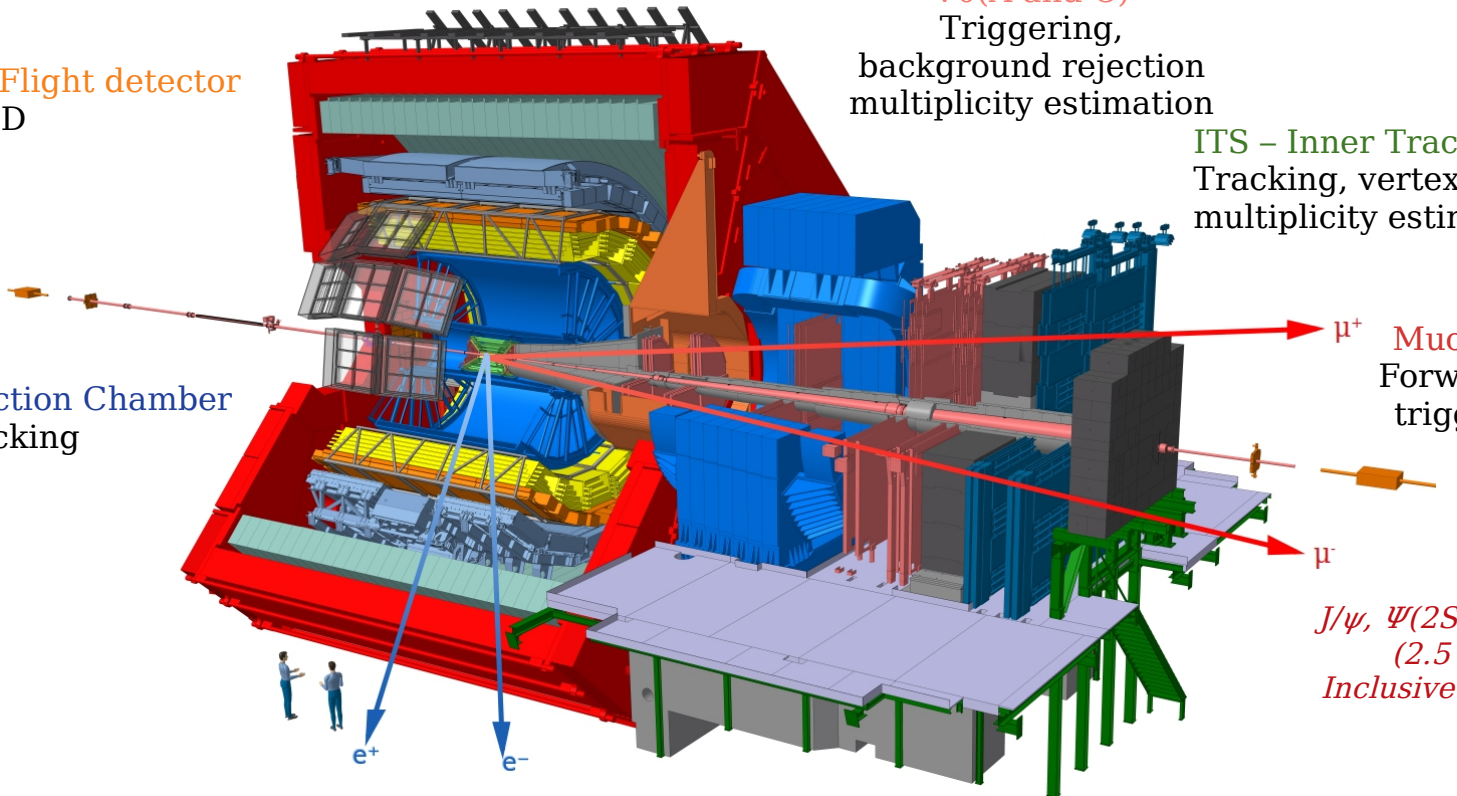
Raphaelle Bailhache (7 July -18:25)
Theera Tork (8 July - 18:35)
Biswarup Paul (9 July - 09:35)
Yanchun Ding (9 July – 10:10)
Himanshu Sharma (9 July - 12:05)

A Large Ion Collider Experiment

V0(A and C)
Triggering,
background rejection
multiplicity estimation

TOF – Time Of Flight detector
PID

ITS – Inner Tracking System
Tracking, vertex reconstruction,
multiplicity estimation



TPC – Time Projection Chamber
PID, tracking

Muon Spectrometer
Forward tracking and
triggering of muons

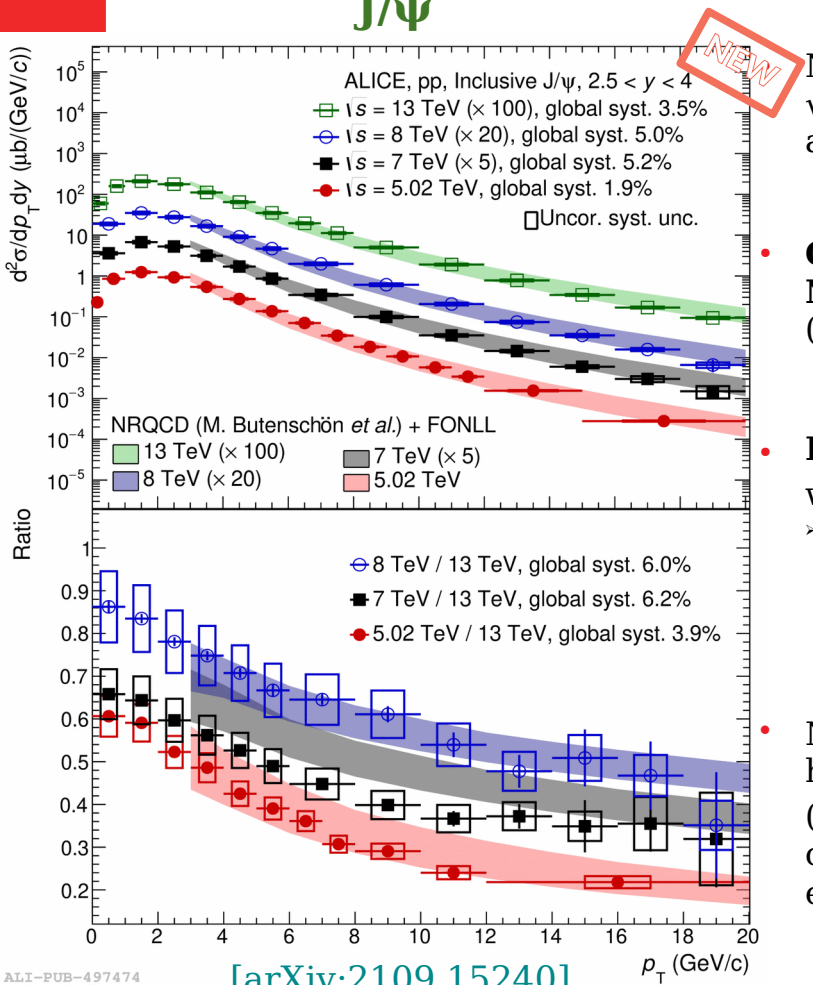
J/ψ, Ψ(2S), Υ(nS) → μ⁺ μ⁻
(2.5 < y < 4.0)
Inclusive measurements

J/ψ → e⁺e⁻ (|y| < 0.9)
Distinction between J/ψ prompt (produced at primary vertex) and non-prompt (b-hadron decays)

Inclusive J/ψ measured down to p_T=0, for both midrapidity and forward rapidity

Inclusive charmonium production at forward rapidity in pp

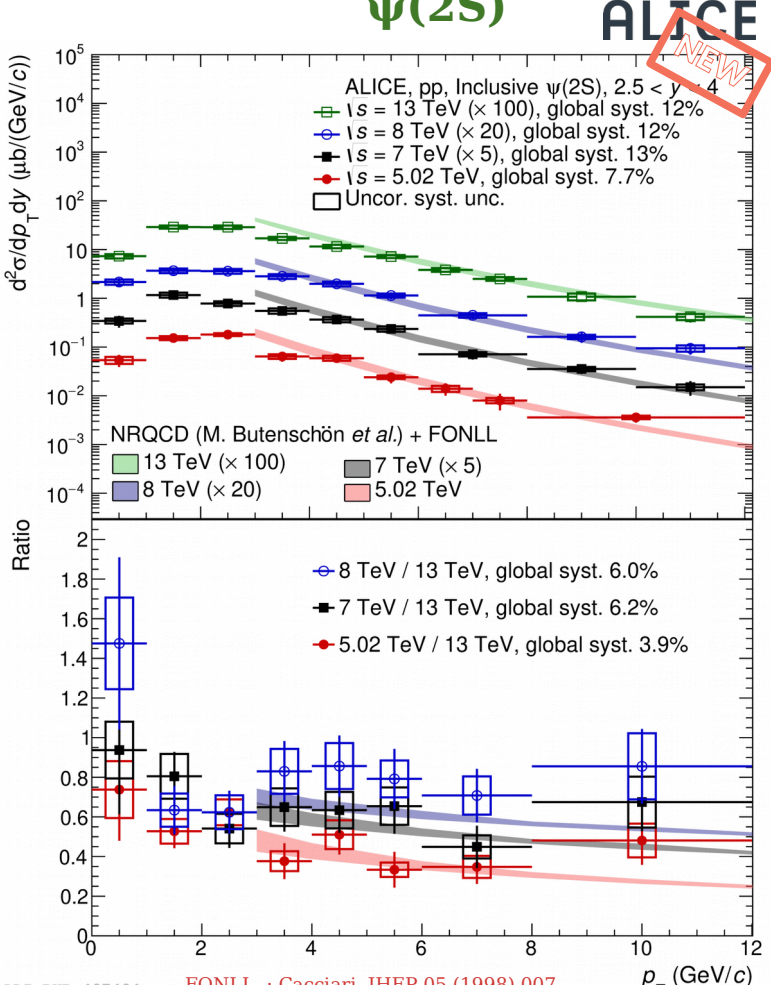
J/ψ



[arXiv:2109.15240]

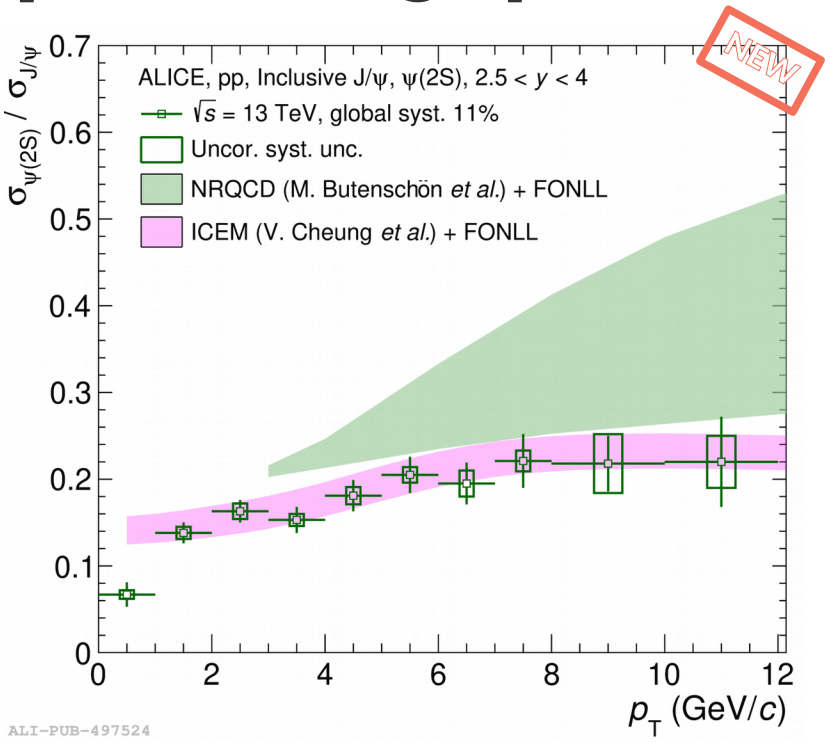
- New measurement done at √s=5 TeV (10 times the statistics available in earlier publication)
- **Cross sections described by NRQCD + FONLL** (for p_T > 3 GeV/c) at all energies
- **Hardening of J/ψ p_T spectrum** with collision energies:
  - Increase of prompt J/ψ mean p_T + Increase of non-prompt J/ψ fraction at high p_T
- NRQCD predicts a weaker hardening of ψ(2S) p_T spectrum (compared to J/ψ) → not observed in data, but large experimental uncertainties

ψ(2S)

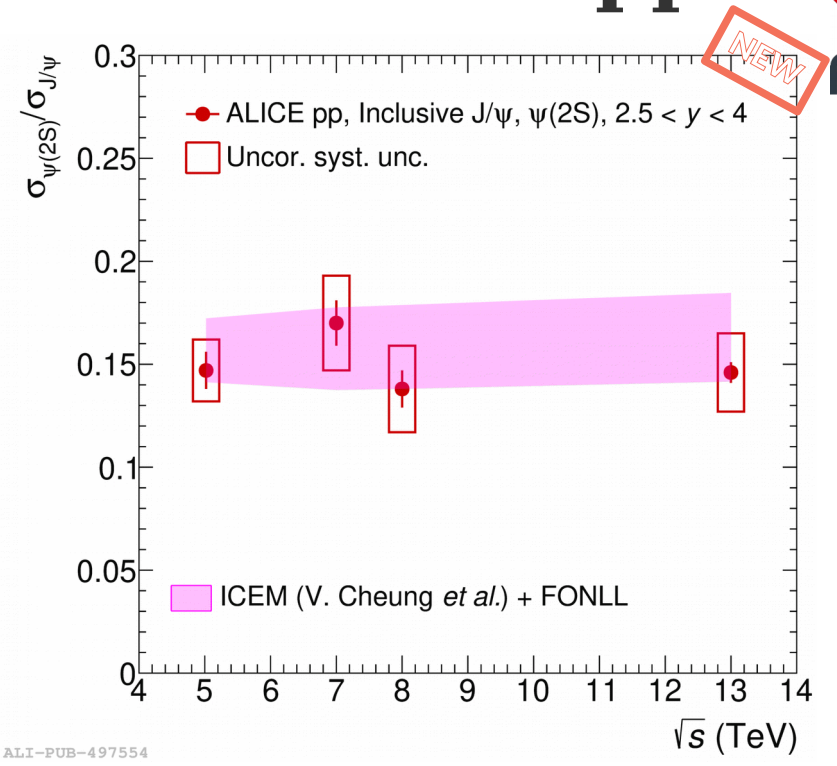


FONLL : Cacciari, JHEP 05 (1998) 007
NRQCD : Butenschoen, Phys. Rev. Lett. 106 (2011) 022003

ψ(2S)-to-J/ψ cross section ratio in pp



[arXiv:2109.15240]



- **ICEM + FONLL describes well the ratio of ψ(2S)-to-J/ψ** cross sections

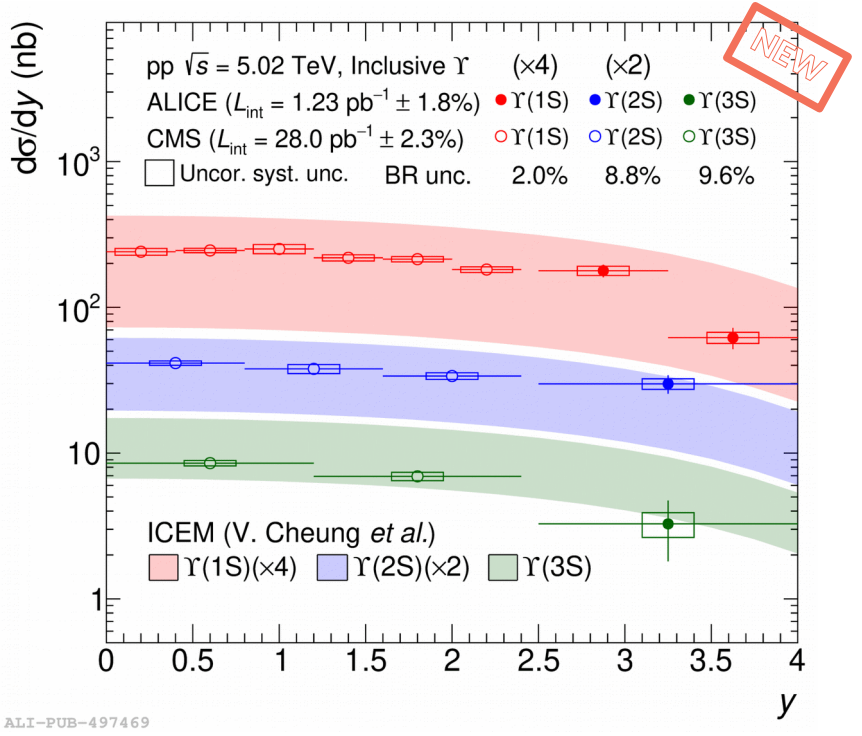
  → Ratio increases with p_T

  → NRQCD calculation by Butenschön *et al.* overpredicts it at 13 TeV

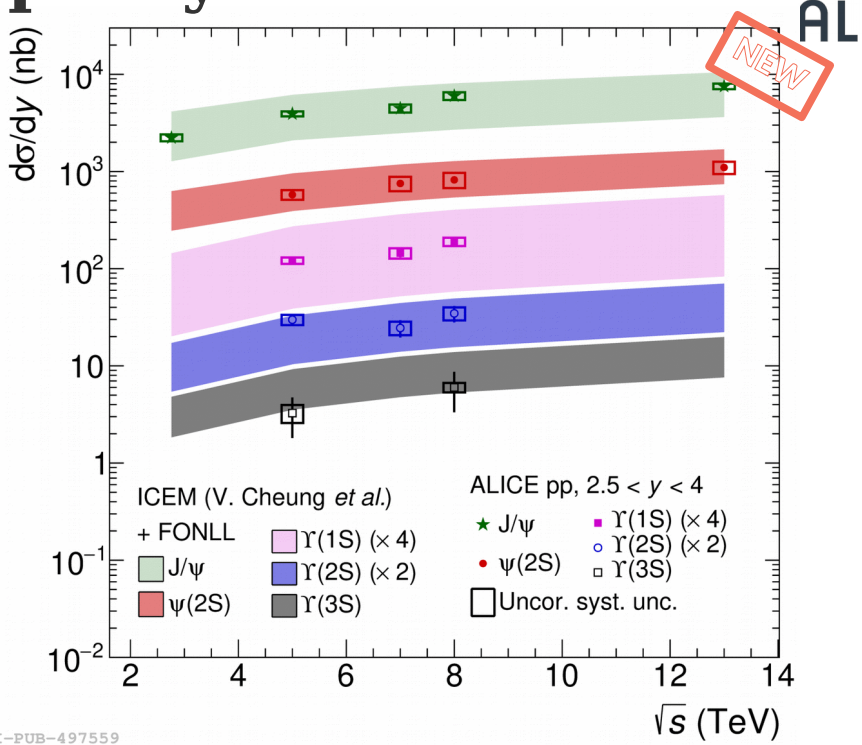
- No dependence on collision energy seen in data, in agreement with ICEM+FONLL

FONLL : Cacciari, JHEP 05 (1998) 007
NRQCD : Butenschoen, Phys. Rev. Lett. 106 (2011) 022003
ICEM : Cheung, Phys. Rev. D 98 no. 11, (2018) 114029

Inclusive quarkonium production in pp at forward rapidity



[arXiv:2109.15240]



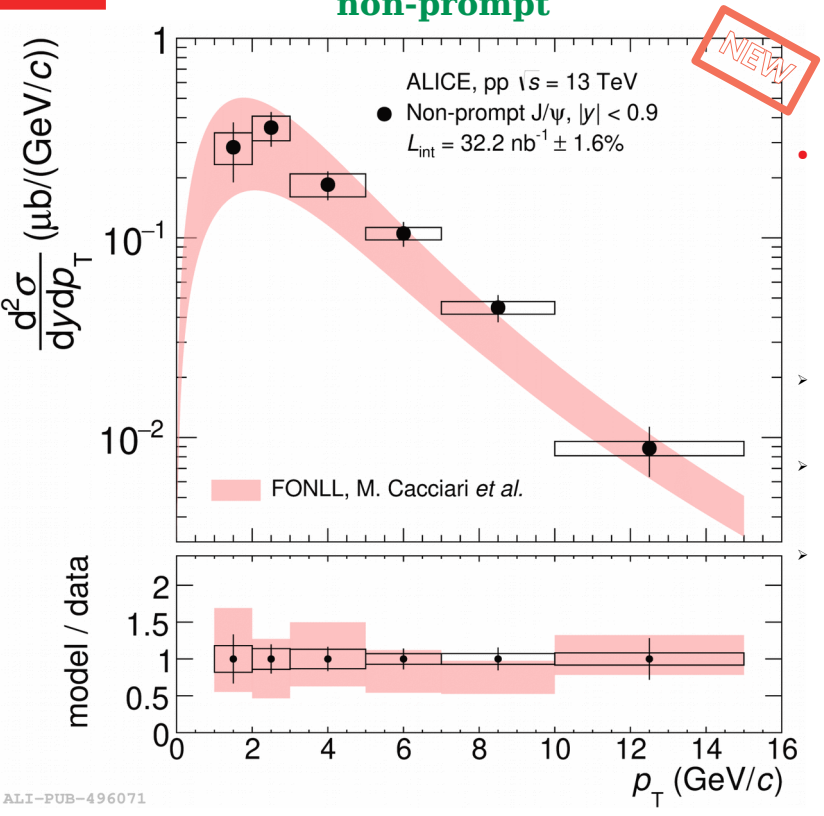
- **ICEM describes well ϒ(ns) cross sections as a function of rapidity**, ALICE and CMS data cover wide rapidity region 0<y<4 [CMS coll. Phys.Lett.B 790 (2019) 270-293]
- Decrease at most forward rapidity
- Cross section rises with collision energy for different quarkonium species, well described by ICEM

FONLL : Cacciari, JHEP 05 (1998) 007
ICEM : Cheung, Phys. Rev. D 98 no. 11, (2018) 114029

Prompt & non-prompt J/ψ at midrapidity in pp

[JHEP 03 (2022) 190]

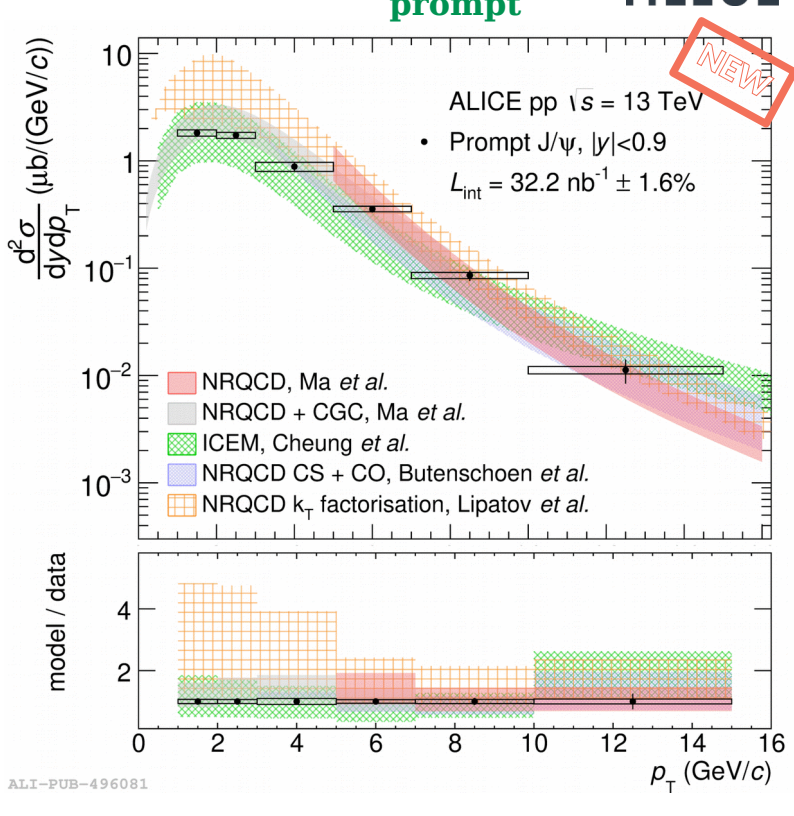
non-prompt



- **Models describe well the prompt** (NRQCD,ICEM) **and non-prompt** J/ψ (FONLL) differential cross sections at midrapidity, at **√s=13 TeV**.

- NRQCD+CGC: good agreement down to low p_T
- ICEM: good at low p_T, slightly overshoots at high p_T
- NRQCD + k_T factorization: slightly overestimates data at low p_T

prompt



Fraction of the non-prompt J/ψ:
$f_B^{visible}$ (√s=13 TeV, |y| < 0.9, p_T > 1 GeV/c) = 0.185 ± 0.015(stat.) ± 0.014(syst.)

FONLL : Cacciari, JHEP 05 (1998) 007
NRQCD CS+CO : Butenschoen, Phys. Rev. Lett. 106 (2011) 022003
NRQCD : Ma, Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC : Ma, Phys. Rev. Lett. 113 no. 19 (2014) 192301
ICEM : Cheung, Phys. Rev. D 98 no. 11, (2018) 114029
NRQCD+k_T fact. : Lipatov, Phys. Rev. D 100 no. 11, (2019) 114021

Prompt & non-prompt J/ψ at midrapidity in pp

[JHEP 03 (2022) 190]

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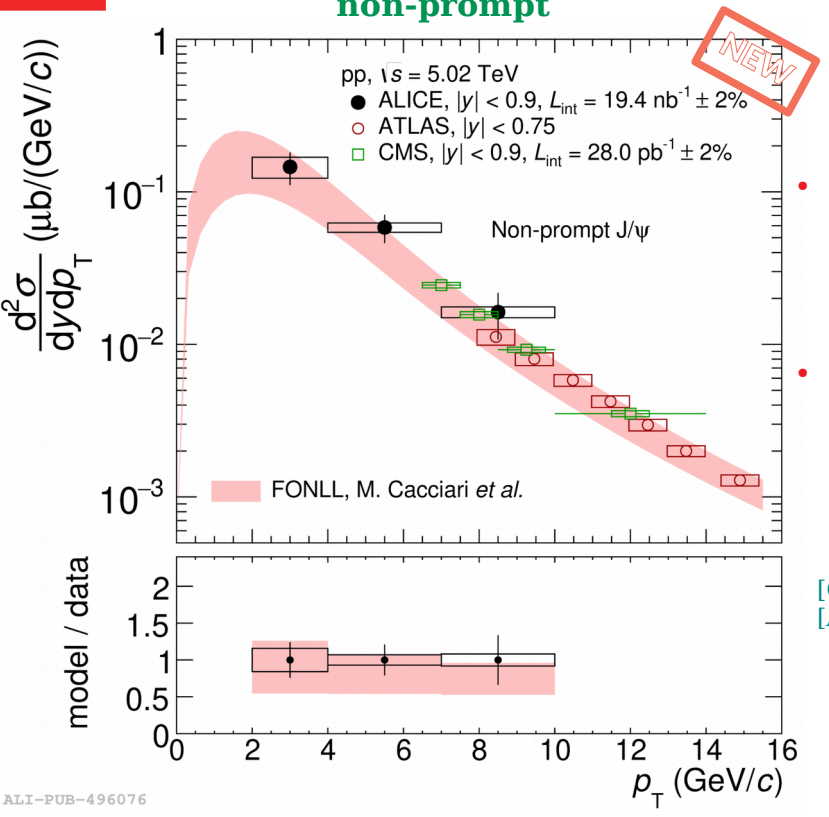
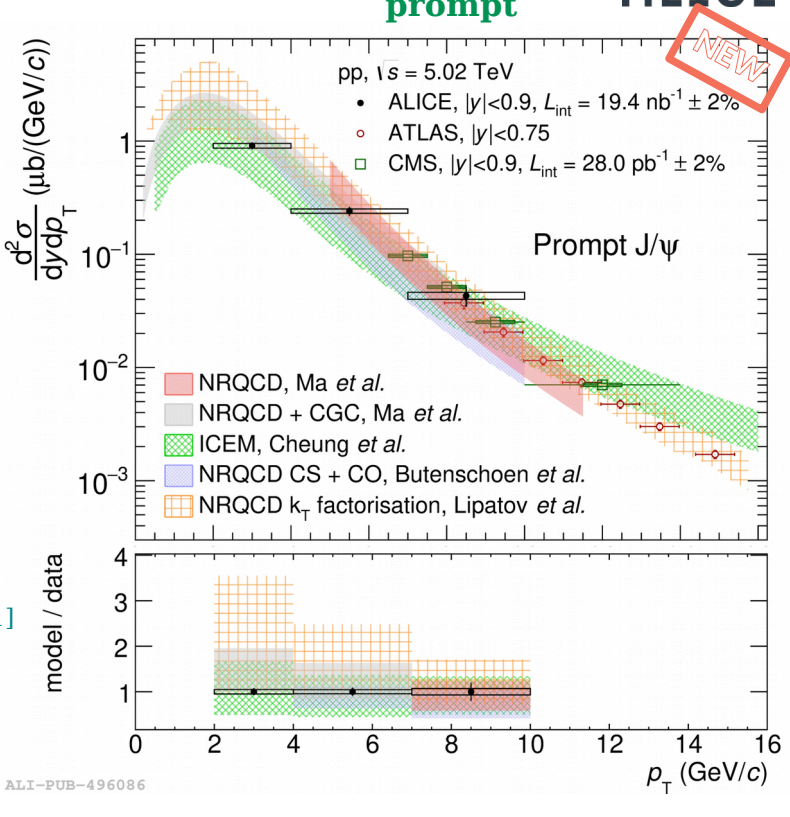


- Similar conclusions for data-model comparison for **<u>√s=5.02 TeV</u>** data.
- Good agreement with corresponding measurements from ATLAS and CMS in the overlapping p_T range

[CMS coll. Eur.Phys.J.C 77 (2017) 4, 269]
[ATLAS coll. Eur.Phys.J.C 78 (2018) 3, 171]

prompt



Fraction of the non-prompt J/ψ:
$f_B^{visible}$ (√s=5.02 TeV,|y| < 0.9, p_T > 2 GeV/c) = 0.157 ± 0.023(stat.) ± 0.016(syst.)

FONLL : Cacciari, JHEP 05 (1998) 007
NRQCD CS+CO : Butenschoen, Phys. Rev. Lett. 106 (2011) 022003
NRQCD : Ma, Phys. Rev. Lett. 106 (2011) 042002
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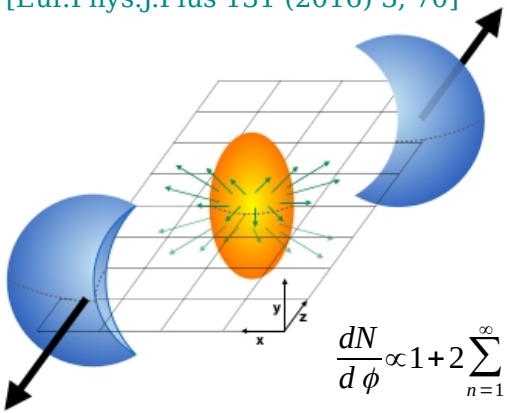
NRQCD+k_T fact. : Lipatov, Phys. Rev. D 100 no. 11, (2019) 114021

J/ψ elliptic flow in small systems

[Eur.Phys.J.Plus 131 (2016) 3, 70]

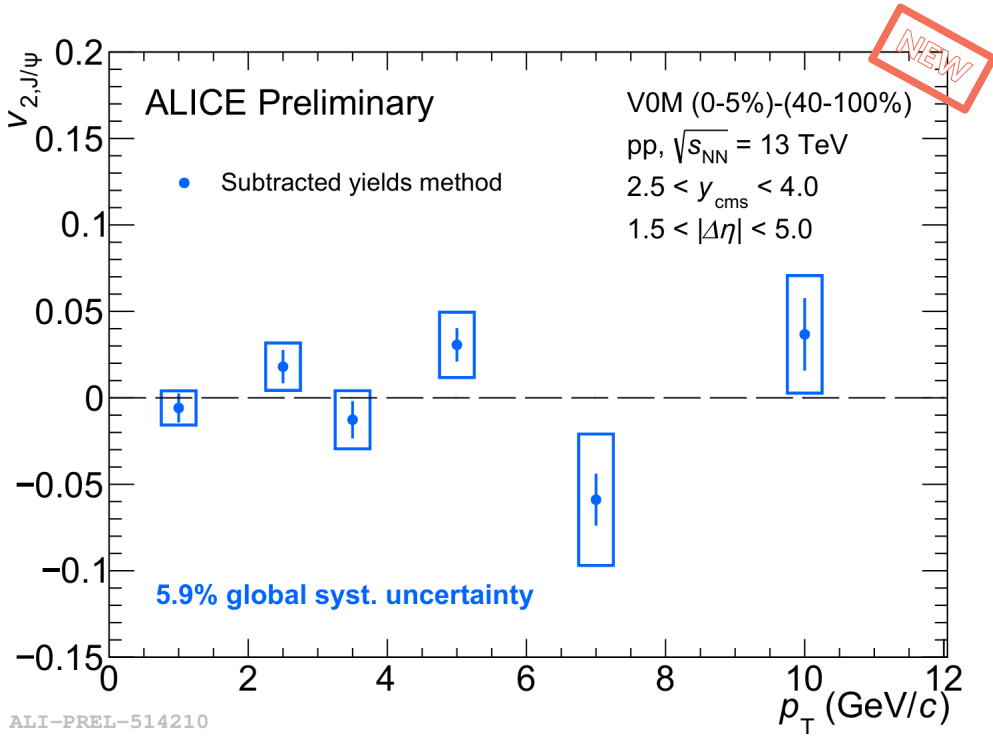


$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n(\phi - \psi_n)\right)$$

- Collective effects for heavy flavors in small systems ?

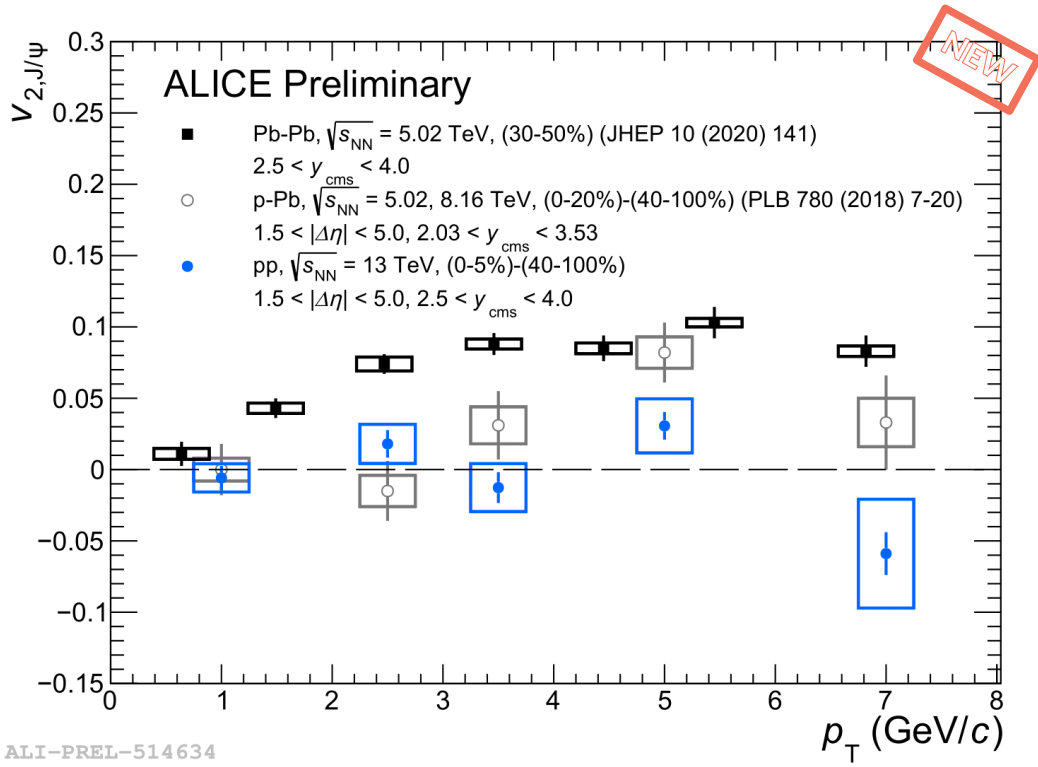
  → can be accessed by studying flow observables, e.g. elliptic flow coefficient v_2 (which quantifies response to initial collision geometry)

- First J/ψ elliptic flow measurement in pp collisions at LHC
  - **No collective behavior observed for the J/ψ in high multiplicity pp collisions at the LHC, within current uncertainties**



J/ψ elliptic flow in small systems

- Non-flow effects (e.g. jets) suppressed by subtracting low-multiplicity yields from high-multiplicity yields
- p–Pb: [PLB 780 (2018) 7-20]
  - Similar flow as in Pb–Pb for p_T > 4 GeV/c
    → common mechanism at play ?
  - Transport model, which describes v_2 in Pb–Pb collisions, does not reproduce the p–Pb data
    [X.Du Nucl.Phys.A 943 (2015) 147-158]
  - Other possible explanations for correlations among produced particles: e.g. CGC ?
    [Zhang et al. Phys.Rev.D 102 (2020) 3, 034010]
- Ordering of J/ψ elliptic flow with system size:
  $v_2^{J/\psi}$(pp) < $v_2^{J/\psi}$(pPb) < $v_2^{J/\psi}$(PbPb)



Conclusion

- Testing production mechanisms

  → **Quarkonium production in pp collisions well described by models** (small tensions when considering cross section ratios)

  → Hardening of J/ψ p_{T} spectrum with collision energy

  → ψ(2S)-to-J/ψ ratio: increases with p_{T}, independent of collision energy

- Collectivity in small systems

  → First elliptic flow measurement for J/ψ in high multiplicity pp collisions:
  No evidence for positive J/ψ elliptic flow within uncertainties

  → J/ψ collective flow mechanism in p-Pb still to be understood

  → Ordering of J/ψ elliptic flow with system size

Perspectives for Run 3:

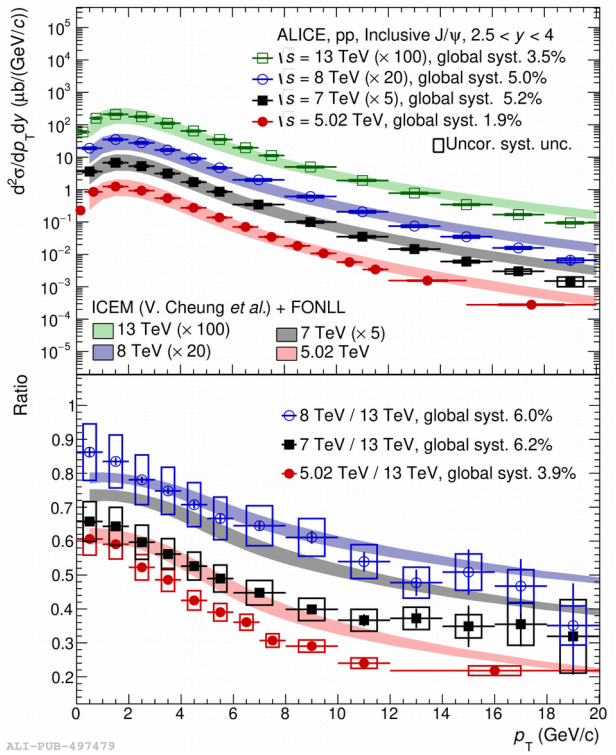
- Increased statistics

  → larger multiplicities can be achieved

  → precise measurements expected in small systems, also for bottomonia

- Separation of prompt and non-prompt charmonia at forward rapidity with the Muon Forward Tracker (MFT)

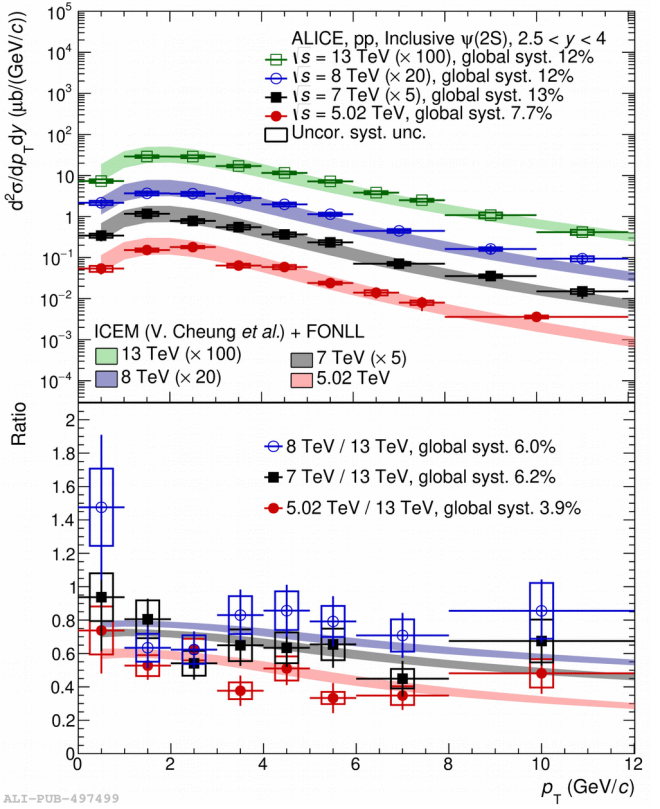
Inclusive charmonia production cross sections at forward rapidity in pp



J/ψ, ψ(2S) → μ⁺ μ⁻ ($2.5 < y < 4$)
Down to p_T=0 GeV/c,
√s = 5.02, 7, 8, and 13 TeV

[arXiv:2109.15240]

- New measurement done at 5 TeV (10 times the statistics available in earlier publication)
- **Cross sections described by ICEM + FONLL** (for $p_T > 3$ GeV/c) at all energies
- **Hardening of J/ψ p_T spectrum at 13 TeV** compared to lower energies:
  - Increase of prompt J/ψ mean p_T + Increase of non-prompt J/ψ fraction at high p_T (FONLL)



Multiplicity-dependent J/ψ production in pp

See talk by Theera Tork (8 july 2022 at 18:35)

J/ψ production measurement in two rapidity ranges:

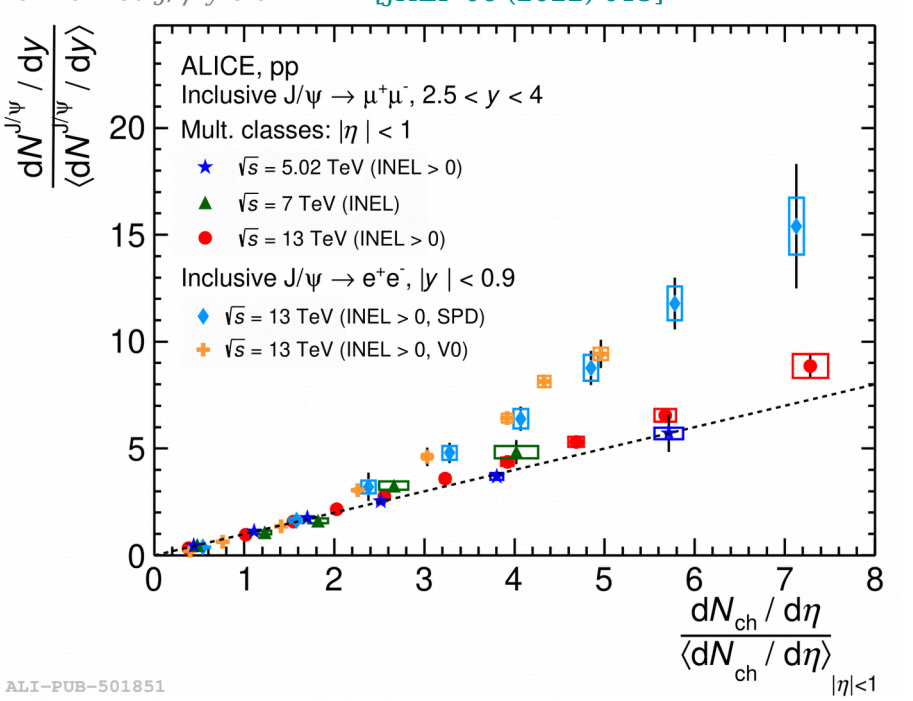
Electron decay channel: J/ψ→ $e^+ e^-$ ($|y| < 0.9$)

Muonic decay channel: J/ψ→$\mu^+ \mu^-$ ($2.5 < y < 4$)
With √s= 5.02 TeV, 7 and 13 TeV

- Forward rapidity region:
  - Compatible with **linear dependence** of J/ψ self-normalized yield on multiplicity
  - Three collision energies give compatible results

- Midrapidity region:
  - **Faster-than-linear increase** of J/ψ self-normalized yield with the multiplicity
  - Results using multiplicity selection based on the SPD and V0 detectors are compatible within the uncertainties

Self-normalized J/ψ yield [JHEP 06 (2022) 015]



Normalized charged particle multiplicity

Multiplicity-dependent J/ψ production in pp

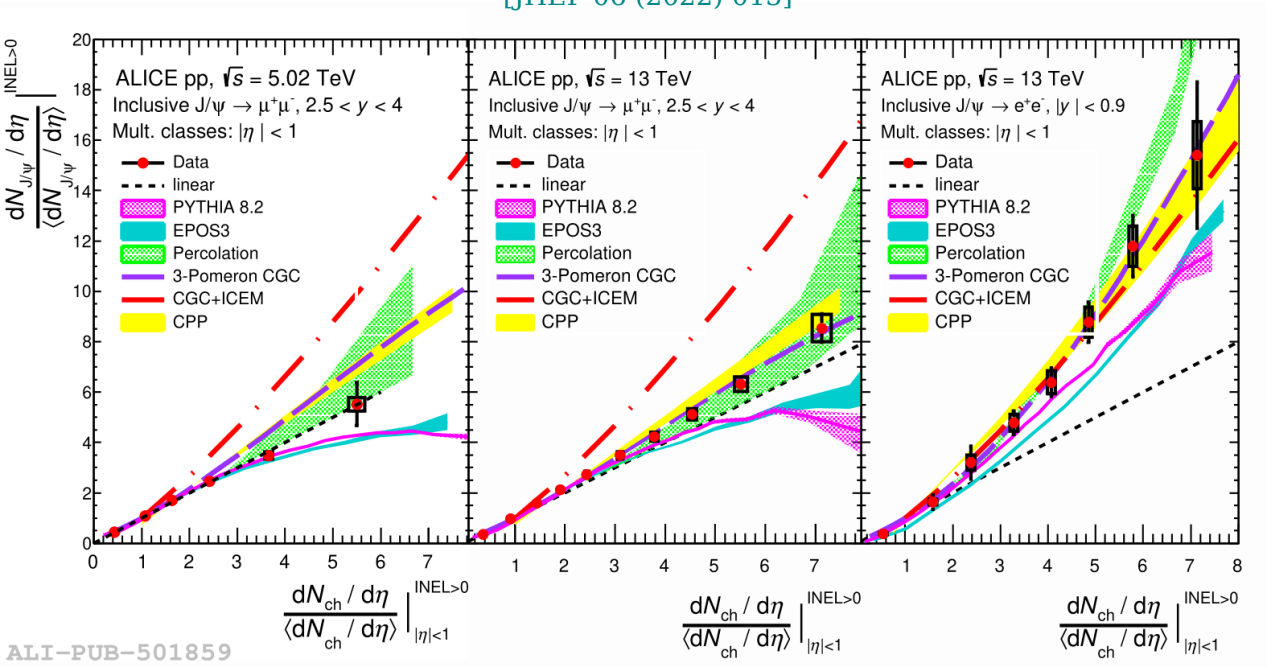
See talk by Theera Tork (8 july 2022 at 18:35)

[JHEP 06 (2022) 015]

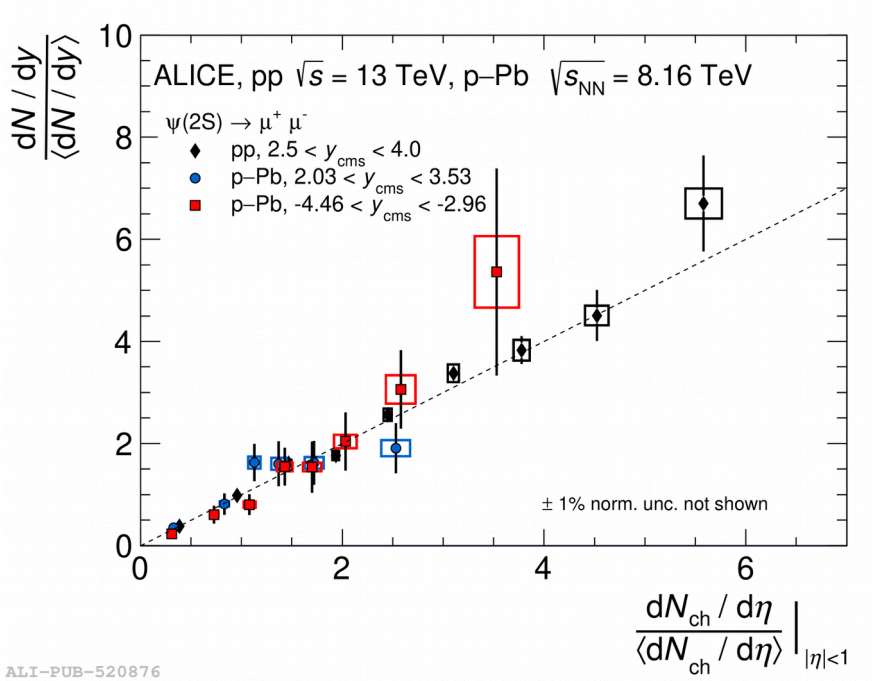
Comparaison with theoretical calculations

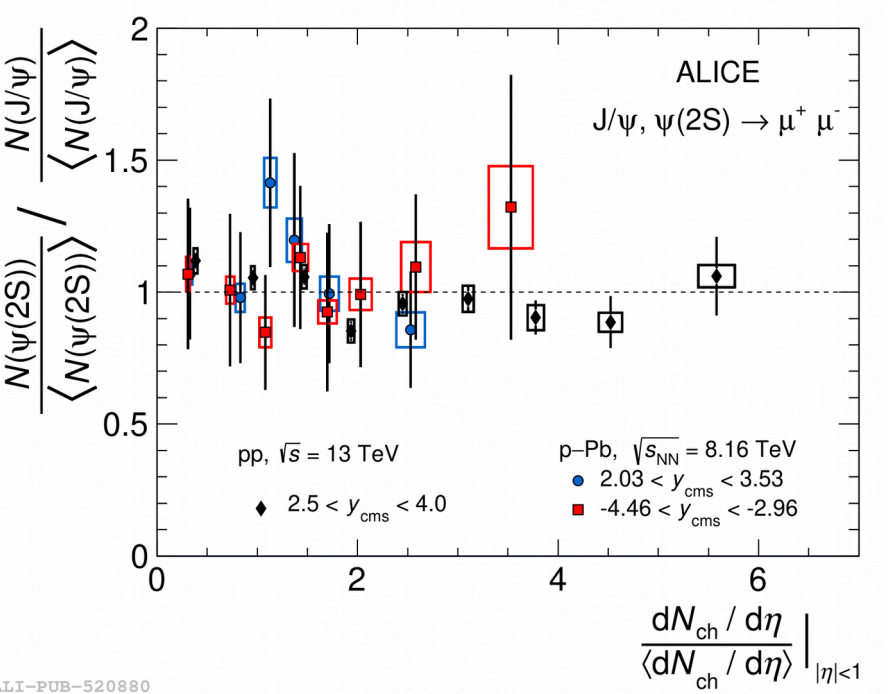
- Forward rapidity (left and middle) :
  - CPP, 3-Pomeron and percolation models in good agreement with linear increase
  - CGC+ICEM overpredicts results

- Midrapidity (right) :
  - Faster-than-linear increase predicted in models by Color string reconnection, gluon saturation, … → **different mechanisms predict similar behavior**



ψ(2S) multiplicity dependent production in small systems

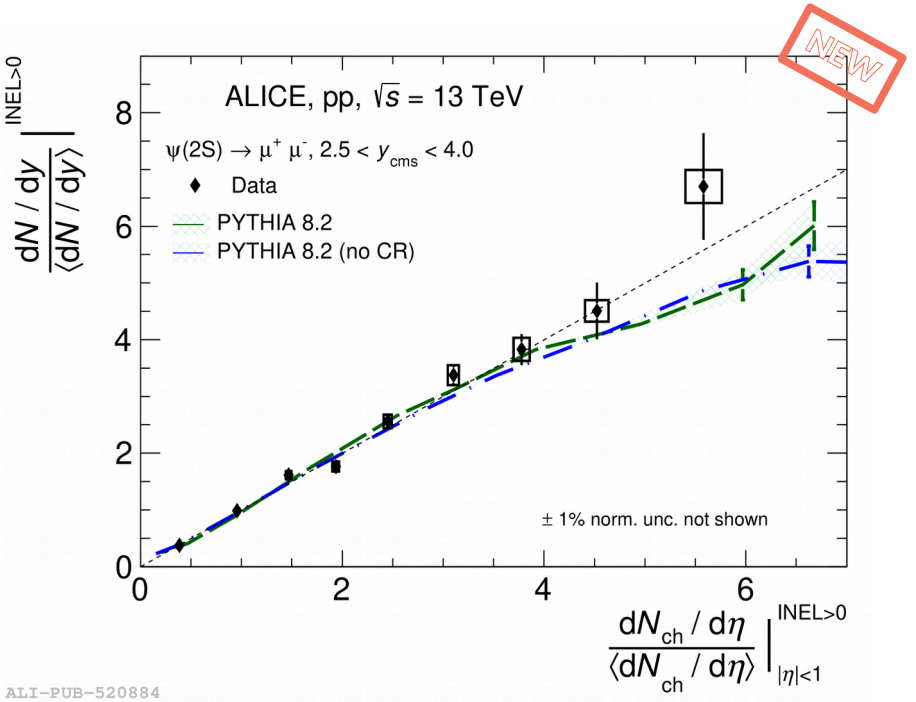


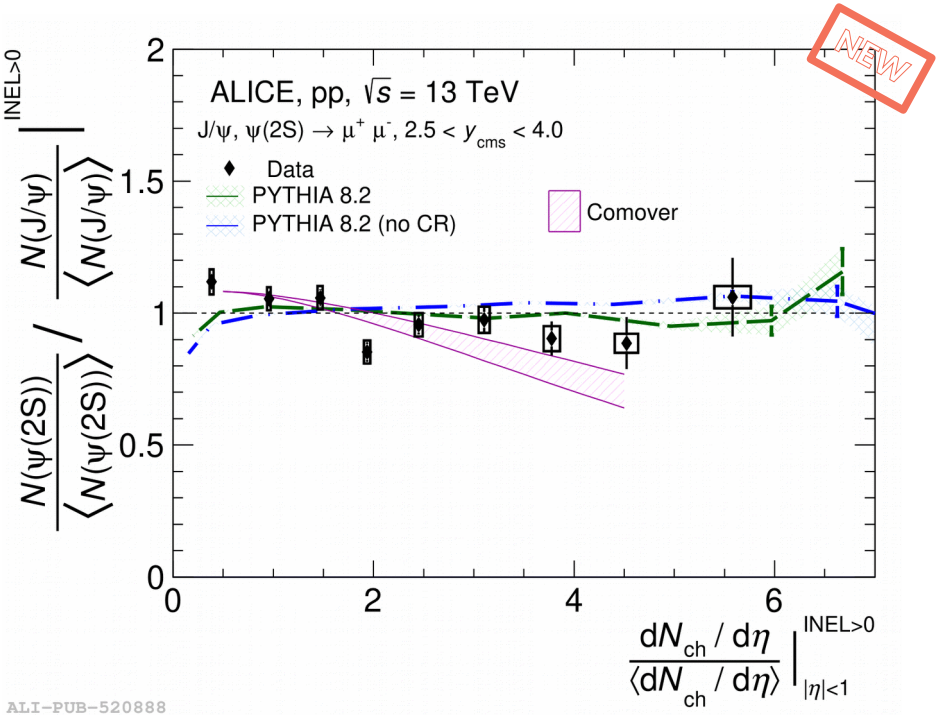


- ψ(2S) production measurement at fwd-*y*, charged particle multiplicity at mid-*y* in pp:
  → Linear rise of ψ(2S) production, self-normalized ψ(2S)/J/ψ compatible with unity
  → production at forward rapidity independent of the charmonium state + collision energy

ψ(2S) multiplicity dependent production in small systems

See talk by Theera Tork

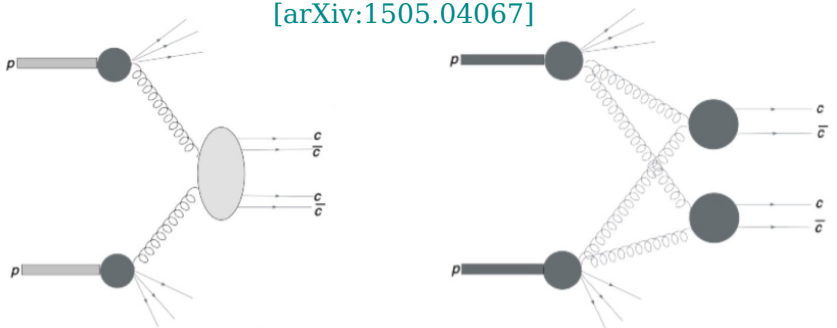


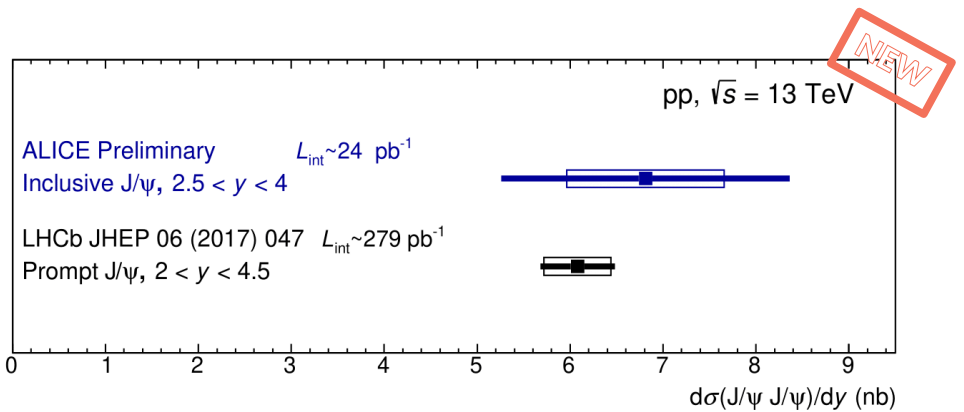


- ψ(2S) production measurement at fwd-*y*, charged particle multiplicity at mid-*y* in pp:
  - → Linear rise of ψ(2S) production, self-normalized ψ(2S)/J/ψ compatible with unity
  - → production at forward rapidity independent of the charmonium state + collision energy
- PYTHIA models with/without color reconnections in agreement with data at low multiplicity, underestimates at high multiplicity

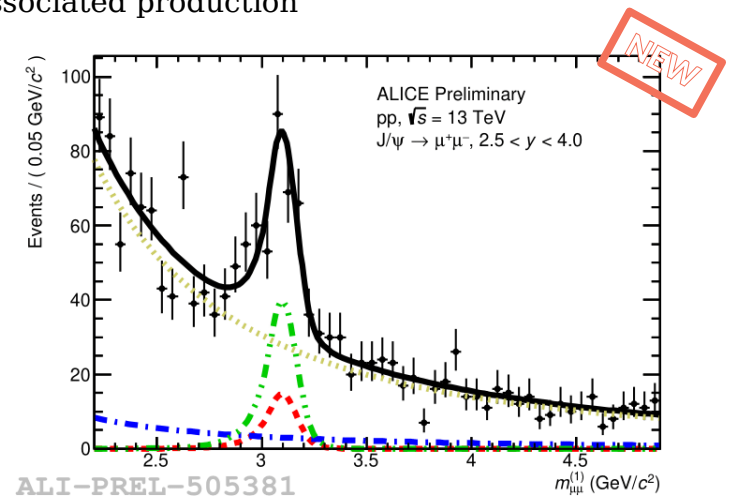
J/ψ pair production in pp at 13 TeV

[arXiv:1505.04067]





- Constrain long-distance matrix elements of NRQCD models
- Different sensitivity to feeddown from excited stated then single J/ψ production
- Insights on double parton scattering (DPS) and associated production



Consistency with LHCb cross section measurement observed, with two caveats :

- Prompt J/ψ measured in LHCb, inclusive J/ψ in ALICE
- Slightly different rapidity ranges