SQM2022

Quarkonia production and elliptic flow in small systems measured with ALICE

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on behalf of the ALICE Collaboration

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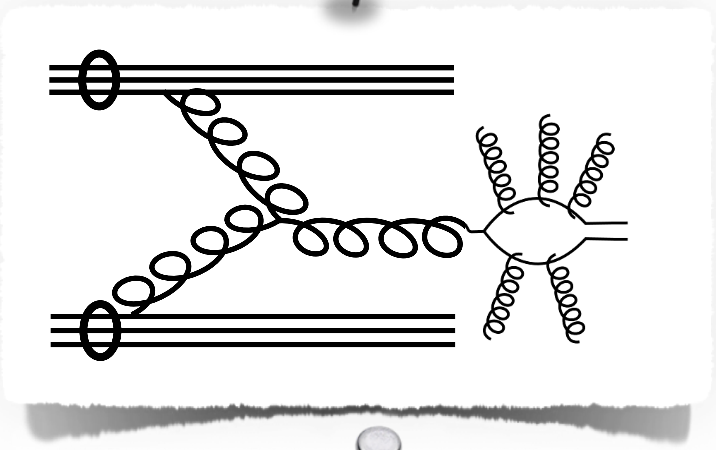
Outline

- Quarkonium production
- Multiplicity-dependent quarkonium production
- Elliptic flow
- J/ψ pair production

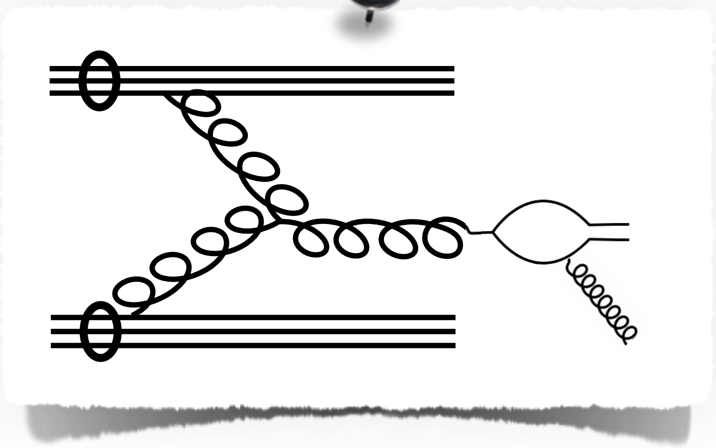
Why quarkonia in small systems?

Constrain theoretical models:



Color Evaporation Model [1]:

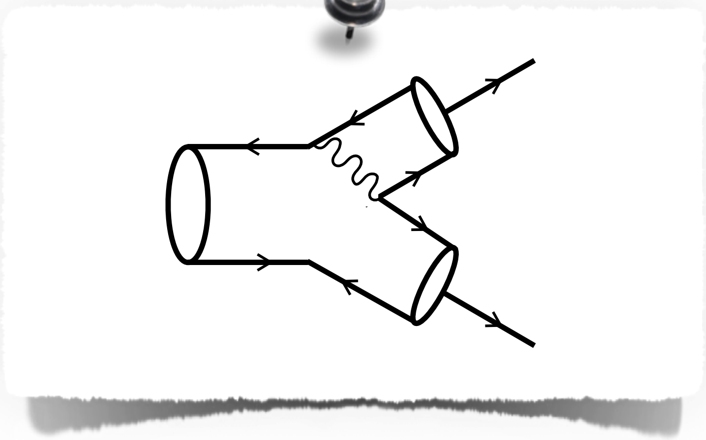
- pQCD Statistical approach
- Describes well quarkonia production
  No distinction between color singlet or octet mechanisms



NRQCD [2]:

- NRQCD formalism
- Predicts well cross sections

Beauty production via non-prompt charmonia:



Fixed Order Next-to-Leading- Logarithm [3]:

- pQCD for heavy quark production
- Used for non-prompt J/ψ (ψ(2S)) production, predicts well data

Shed light on Multiple Parton Interactions (MPI):

- Multiplicity dependent measurements
  → Quarkonia correlations with charged-particle multiplicity / flow
- Heavy quarks created in subsequent hard-scattering processes, in early stage of collision

Investigate collectivity in small systems

- Study of J/ψ elliptic flow at high collision energy and multiplicity

Reference for measurements in p—Pb and Pb—Pb collisions

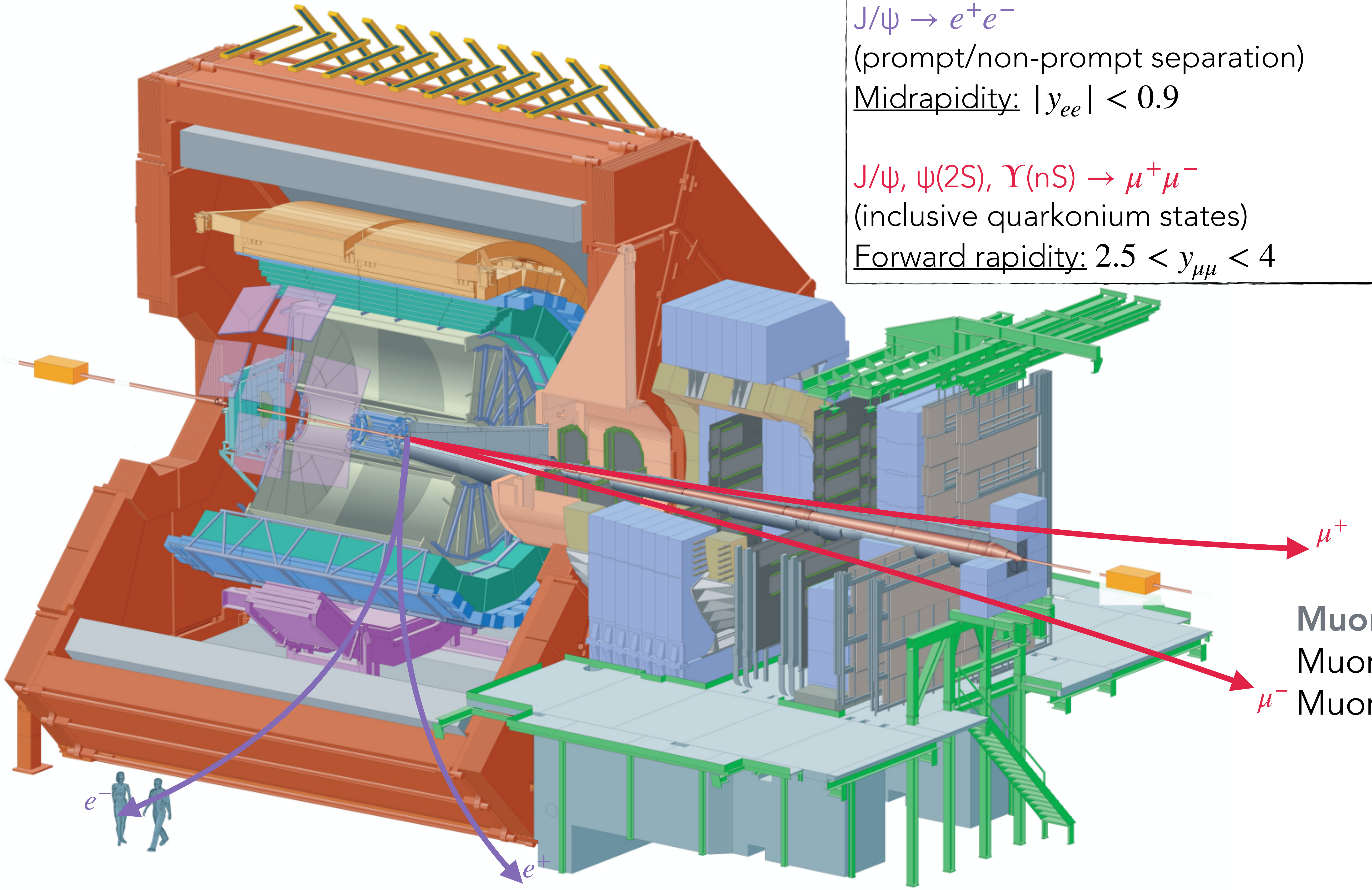
[1]: Phys. Lett. B, 67:217–221, 1977
[2]: Phys. Rev. D51:1125-1171,1995
[3]: JHEP 9805:007,1998

A Large Ion Collider Experiment

Time Projection Chamber:
Charged particle tracking
Particle identification

Inner Tracking System:
Particle tracking
Vertex reconstruction

V0:
Trigger detector
Event characterization
Background rejection



Inclusive quarkonia measurements down to p_T = 0 GeV/c:
J/ψ → e^+e^-
(prompt/non-prompt separation)
Midrapidity: $|y_{ee}| < 0.9$

J/ψ, ψ(2S), ϒ(nS) → $\mu^+\mu^-$
(inclusive quarkonium states)
Forward rapidity: $2.5 < y_{\mu\mu} < 4$

Muon Spectrometer:
Muon tracking
Muon trigger

J/ψ production at forward rapidity

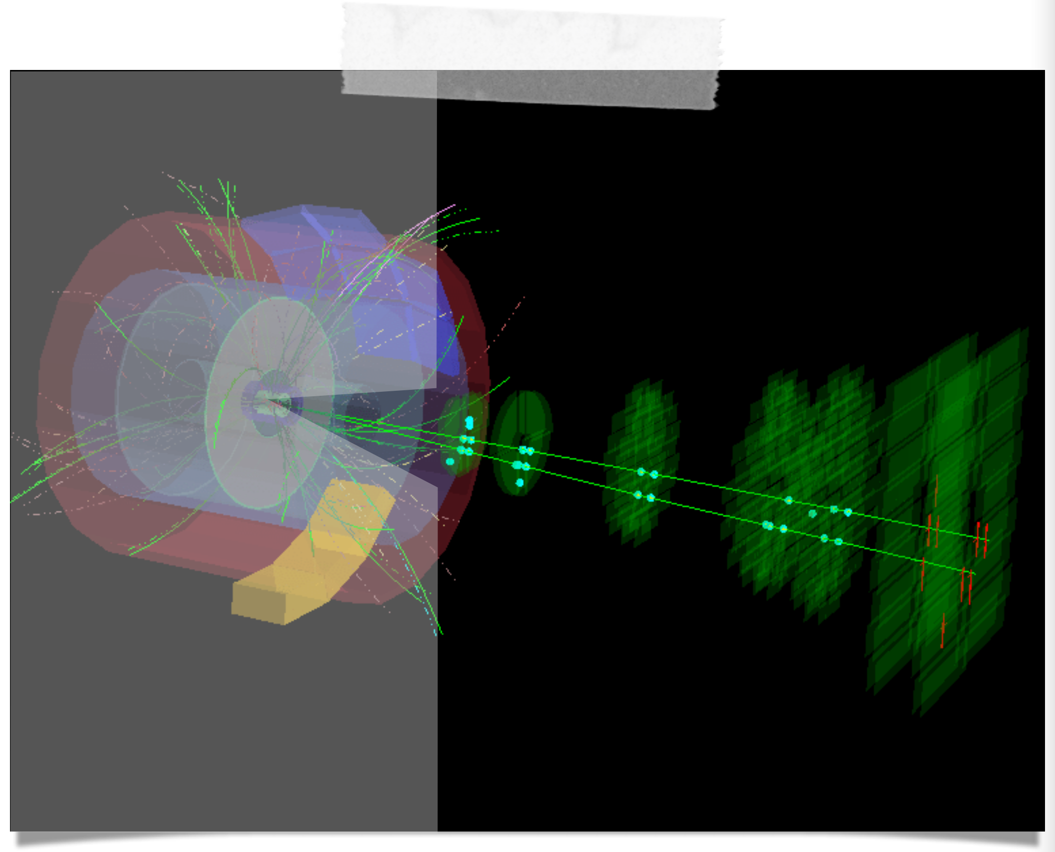
J/ψ production measurement in pp collisions:

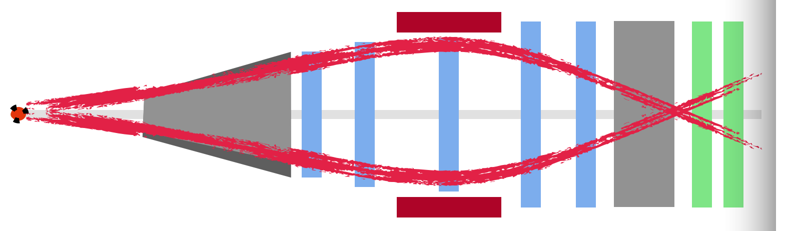
Muonic decay channel: J/ψ $\rightarrow \mu^{+}\mu^{-}$

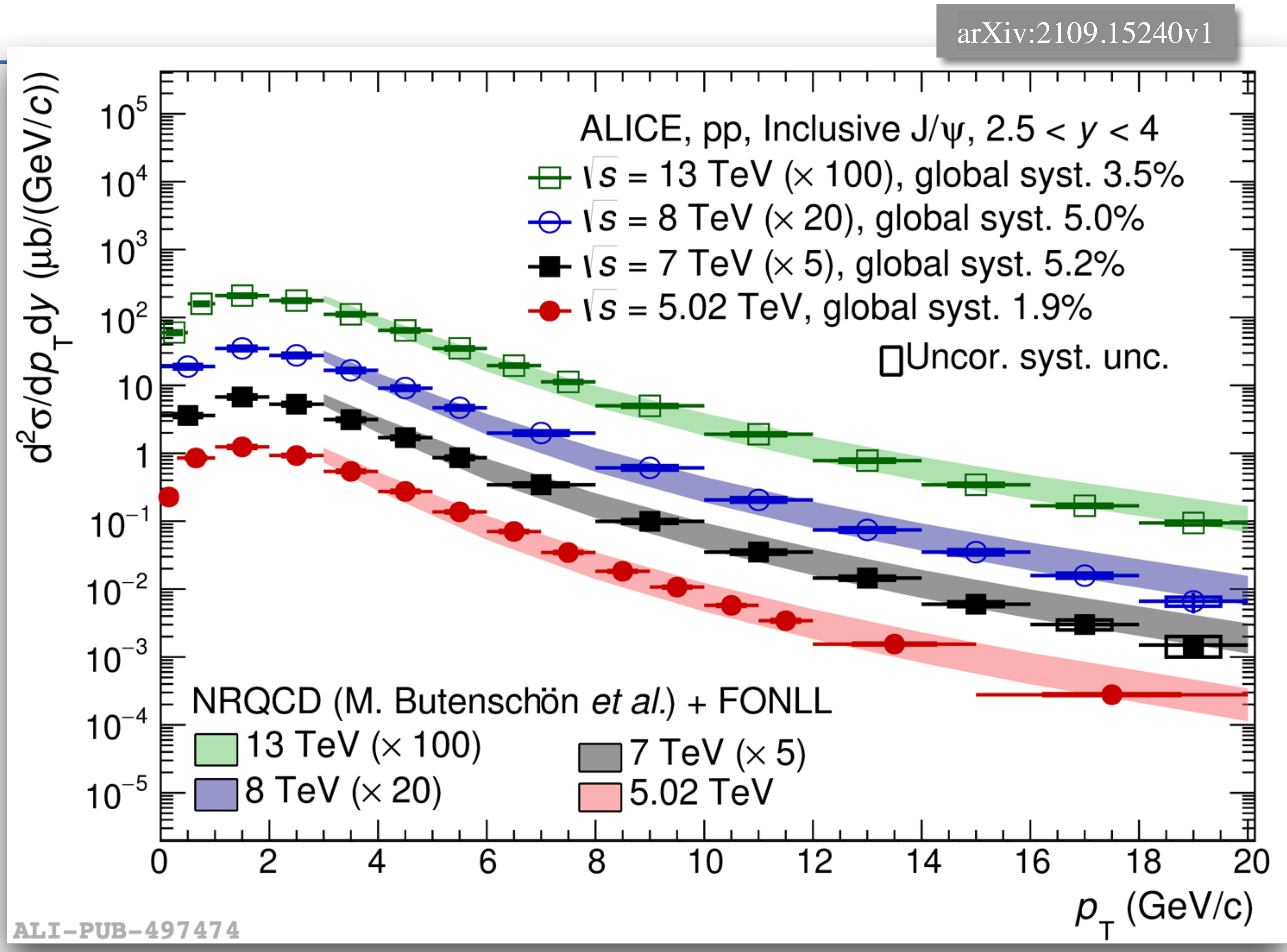
Forward rapidity: 2.5 < y < 4

Down to $p_{\mathrm{T}} = 0$ GeV/c

$\sqrt{s}$ = 5.02, 7, 8, and 13 TeV





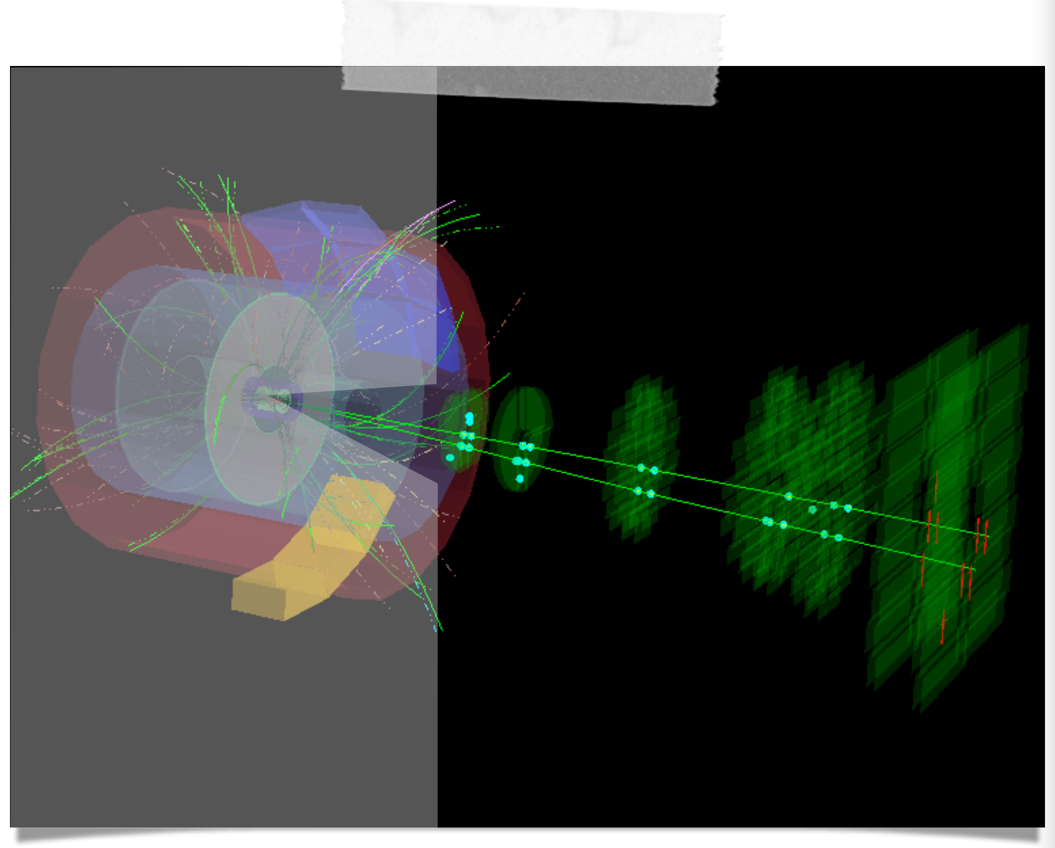


Cross section measurements vs p_{T}:

Agreement between data and NRQCD + FONLL model

Cross section increases with increasing collision energy

J/ψ production at forward rapidity



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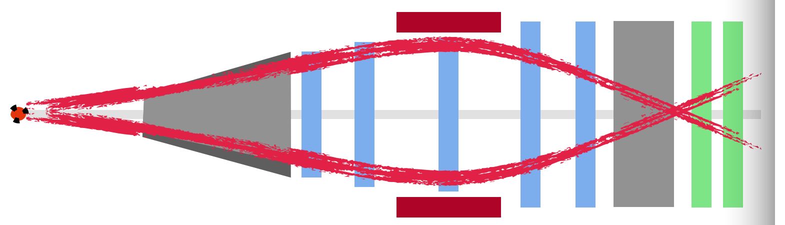


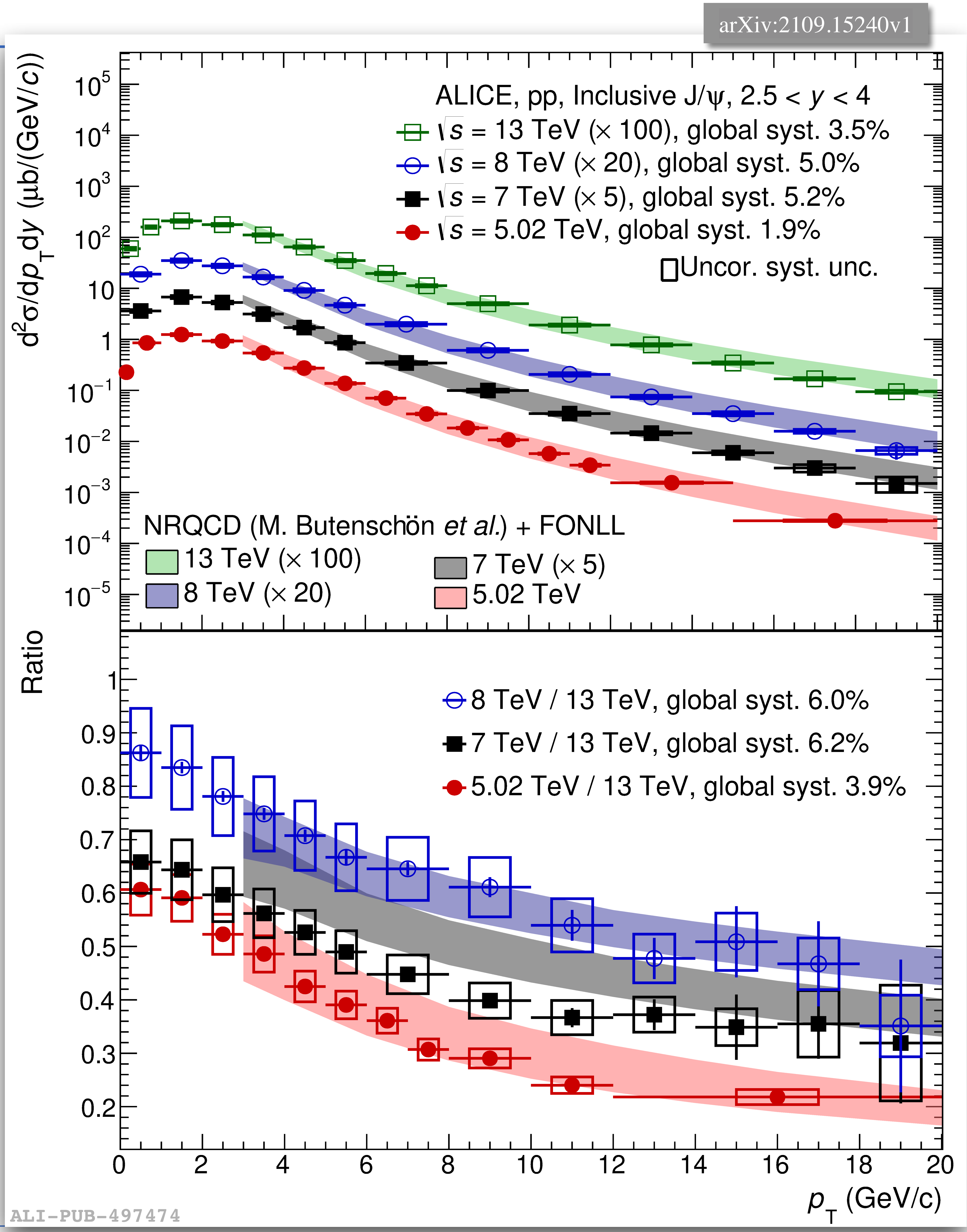
✱Cross section measurements vs p_T:

Agreement between data and NRQCD + FONLL model
Cross section increases with increasing collision energy

✱Ratio vs p_T:

Agreement for 8-to-13 TeV and 5-to-13 TeV ratios
7-to-13 TeV ratio slightly overestimated by model

Hardening of p_T spectra at 13 TeV compared to lower energies:
Predicted increase of prompt J/ψ mean p_T with energy
Increase of non-prompt J/ψ contribution at high p_T (FONLL predictions)



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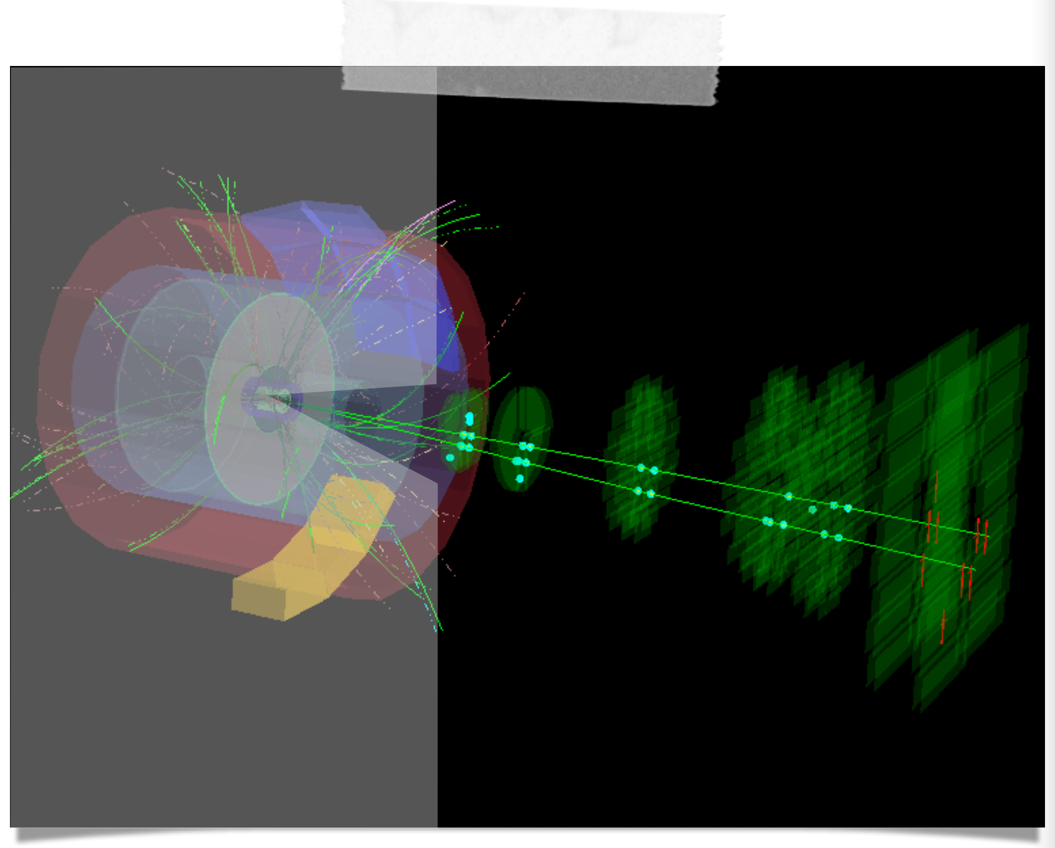

☑ J/ψ production measurement in pp collisions:

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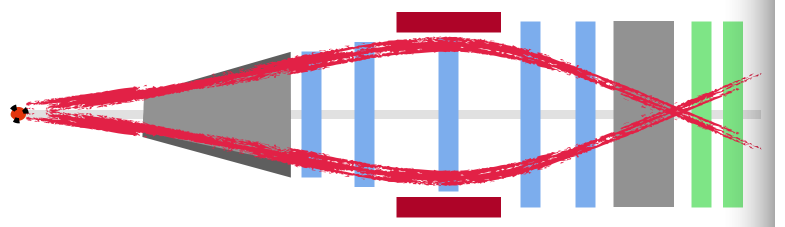

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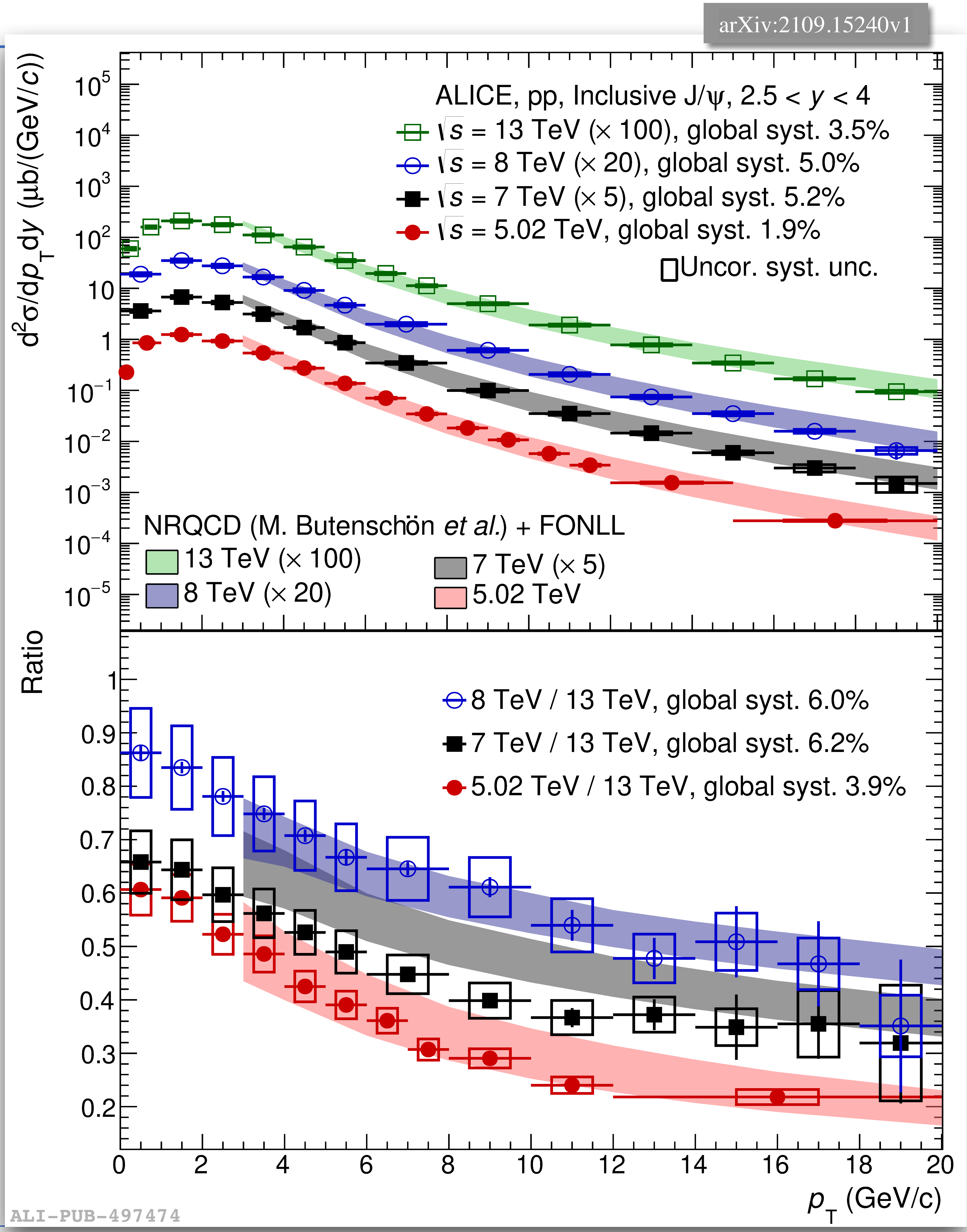


J/ψ production at midrapidity

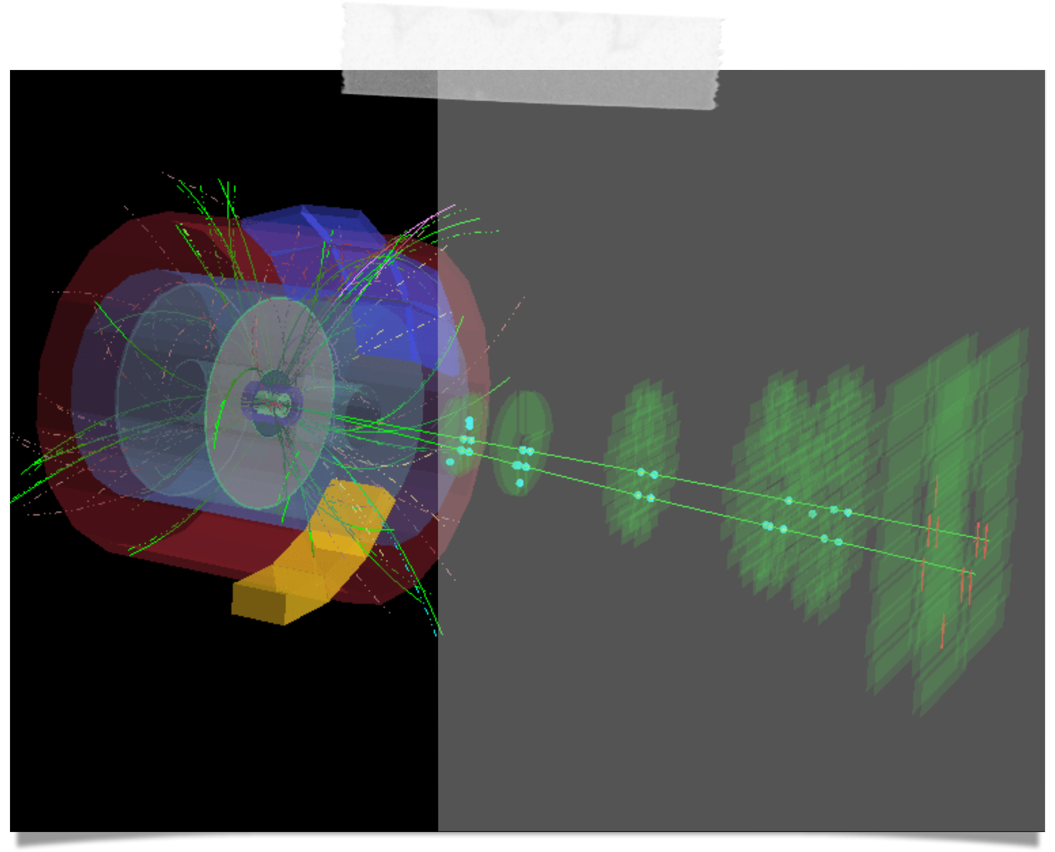
J/ψ production measurement in pp collisions:

Electron decay channel: J/ψ → $e^{+}e^{-}$

Midrapidity: $|y| < 0.9$

Down to p_{T} = 1 GeV/c for $\sqrt{s}$ = 13 TeV

Down to p_{T} = 2 GeV/c for $\sqrt{s}$ = 5.02 TeV

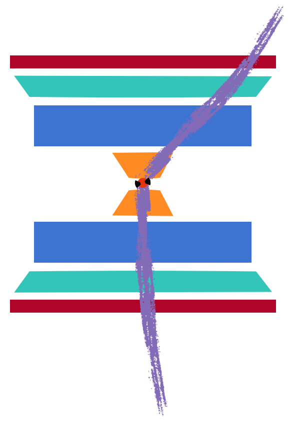


Cross section measurements vs p_{T}:

Prompt J/ψ:

ICEM + NRQCD based models: in agreement with data

NRQCD Lipatov calculations: slightly overestimate data at low p_{T}

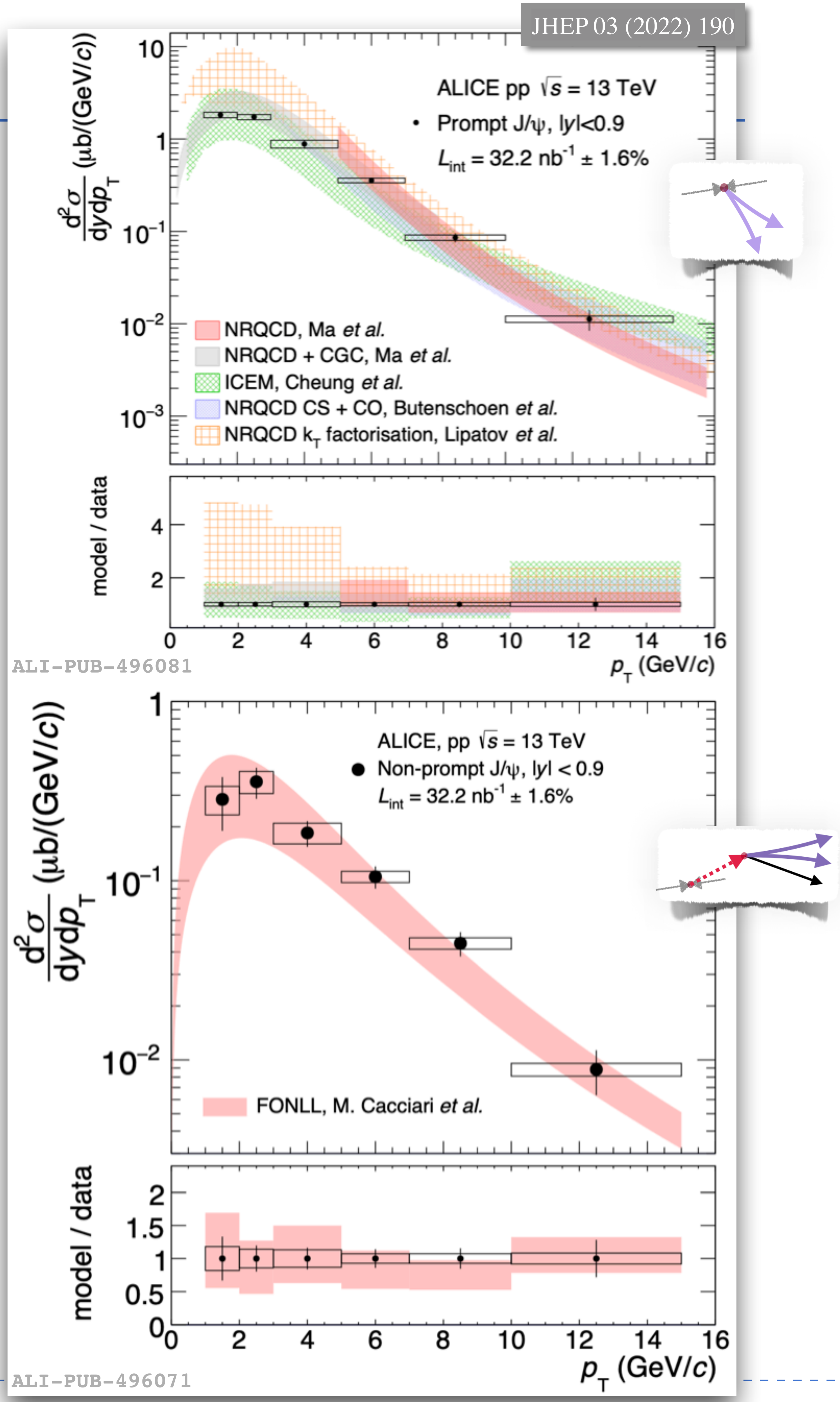


Non-prompt J/ψ:

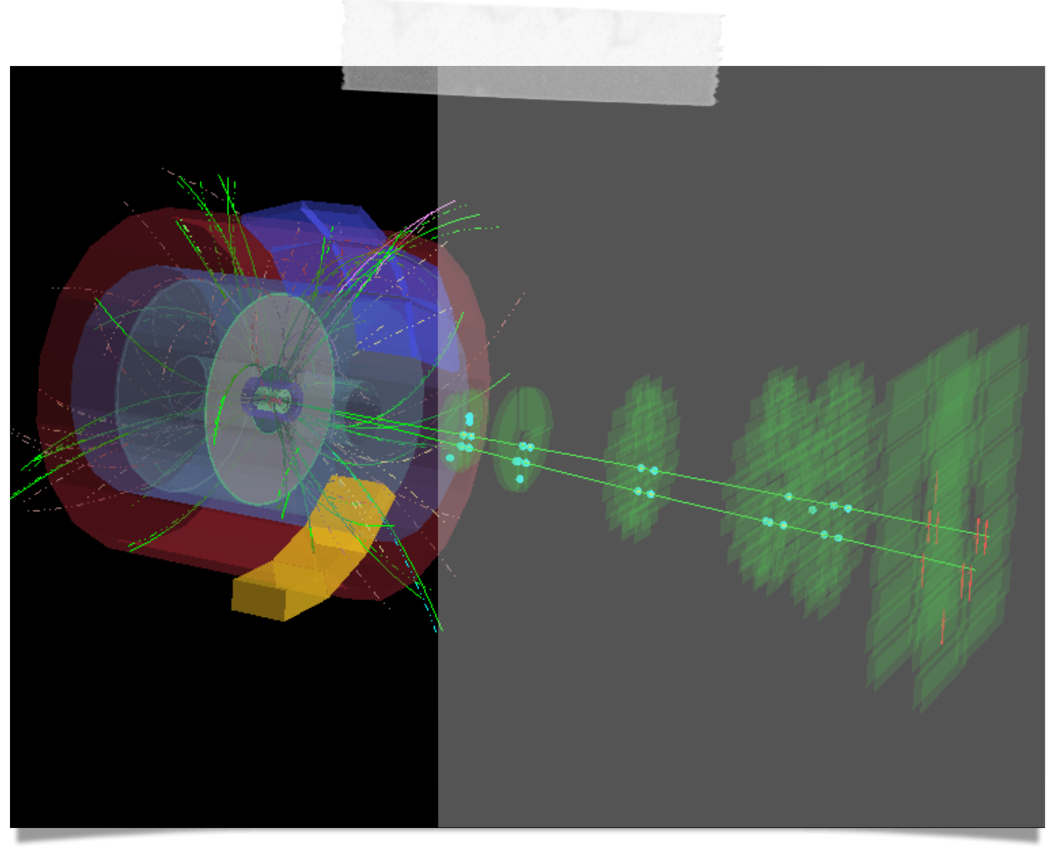
In agreement with FONLL model

Fraction of the non-prompt J/ψ:

$$f_B^{visible,\sqrt{s}=13\ \mathrm{TeV}}(p_{\mathrm{T}} > 1\mathrm{GeV}/c, |y| < 0.9) = 0.185 \pm 0.015(\mathrm{stat.}) \pm 0.014(\mathrm{syst.})$$



J/ψ production at midrapidity



J/ψ production measurement in pp collisions:

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Down to p_T = 1 GeV/c for $\sqrt{s}$ = 13 TeV
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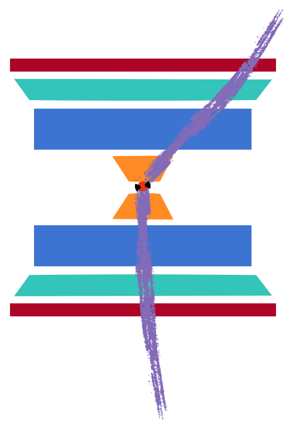
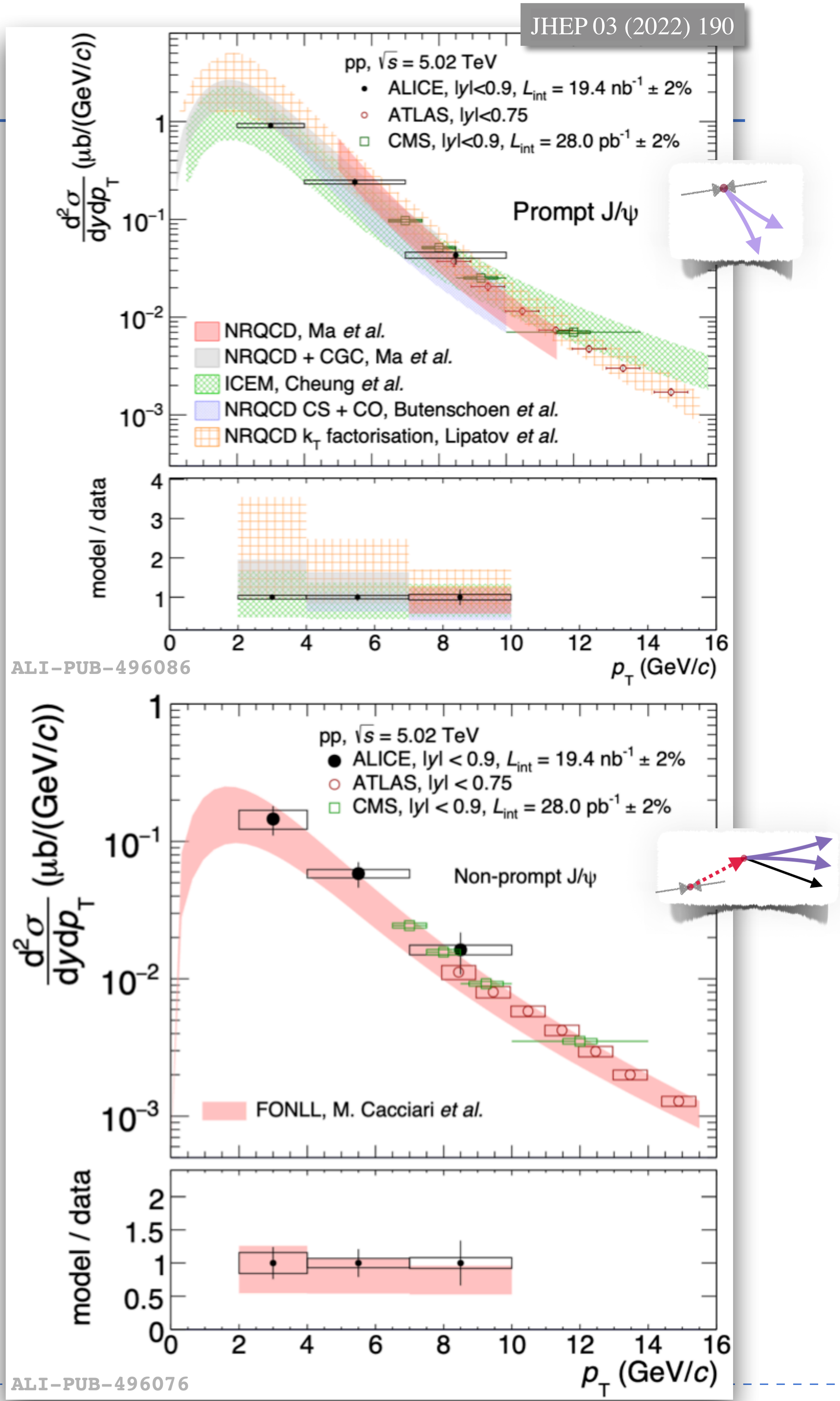


Non-prompt J/ψ:
In agreement with FONLL model

Fraction of the non-prompt J/ψ:

$$f_B^{visible,\sqrt{s}=5.02\ \mathrm{TeV}}(p_T > 2\mathrm{GeV}/c, |y| < 0.9) = 0.157 \pm 0.023(\mathrm{stat.}) \pm 0.016(\mathrm{syst.})$$

Comparison with CMS and ATLAS data, consistency is observed in the common p_T region



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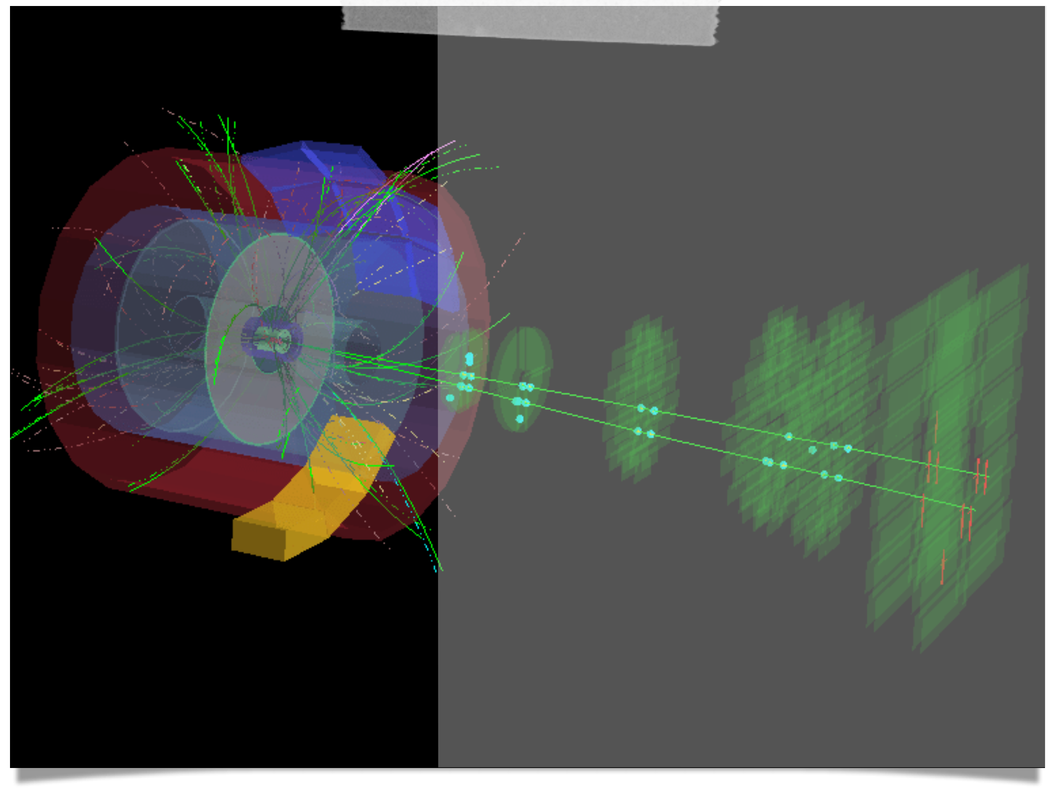

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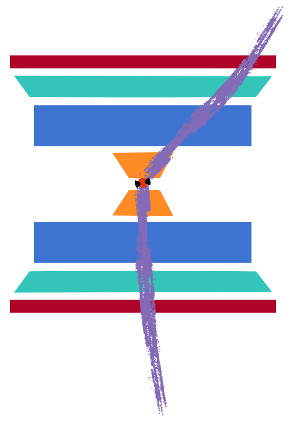

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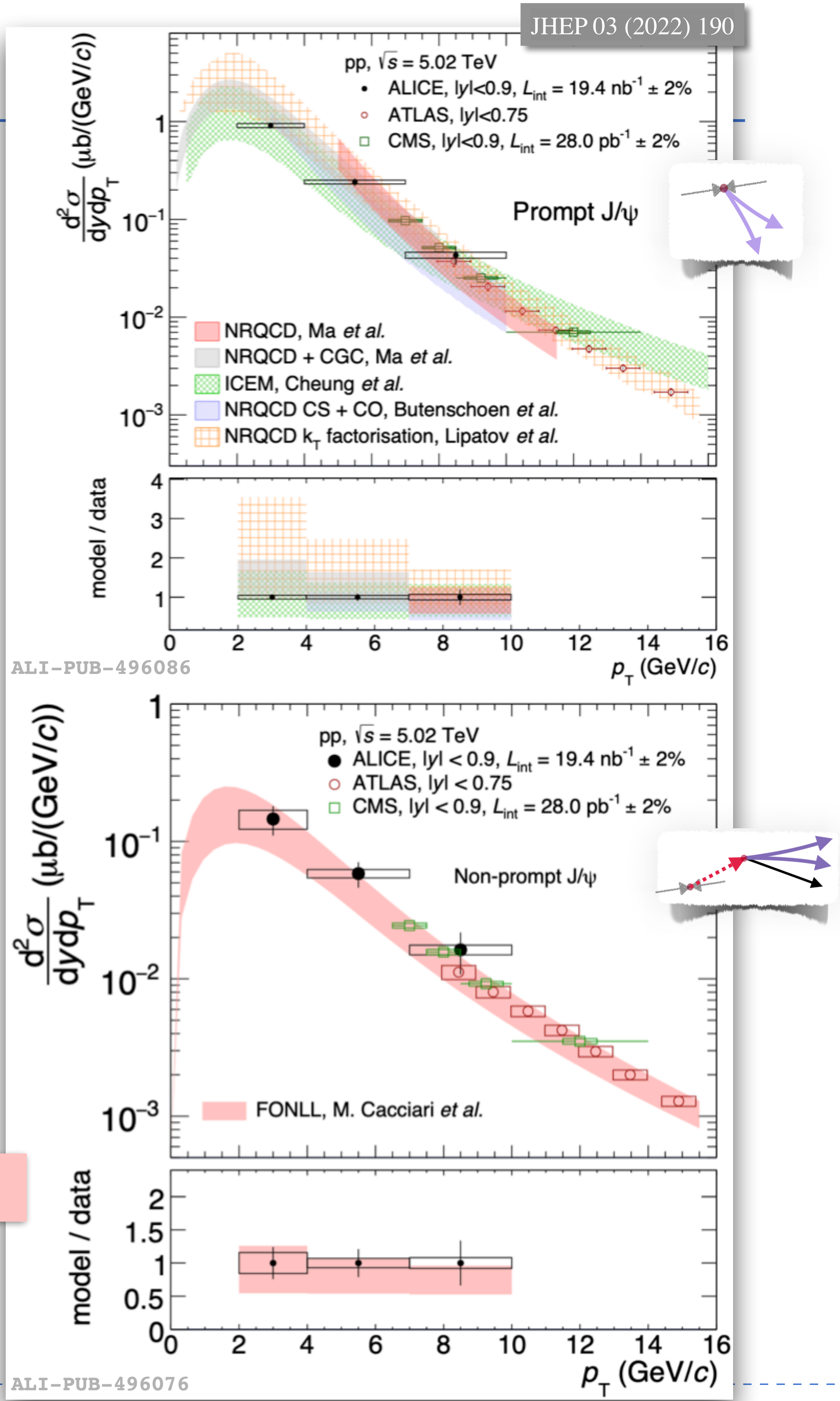
Indication of decrease of non-prompt fraction at lower collision energy

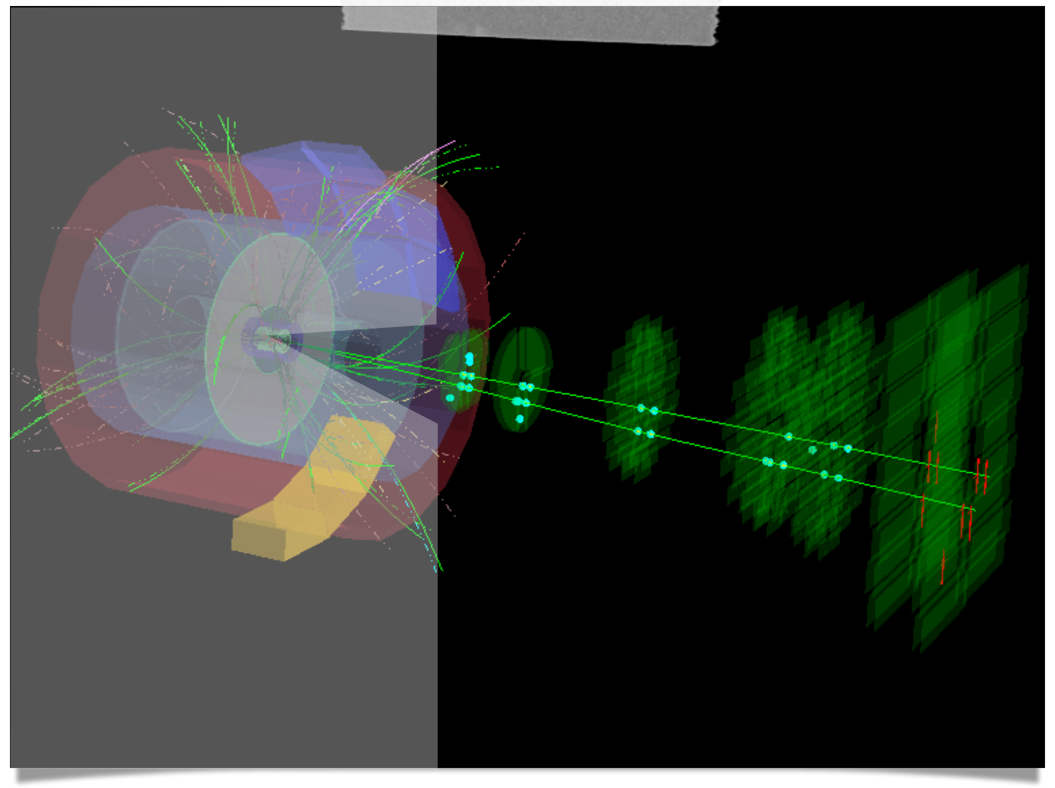
Comparison with CMS and ATLAS data, consistency is observed in the common p_T region



Excited charmonia: ψ(2S) production

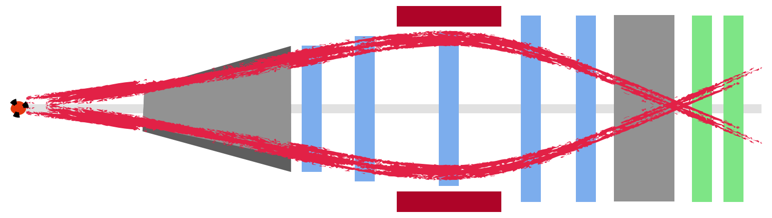
ψ(2S) production measurement in pp collisions:

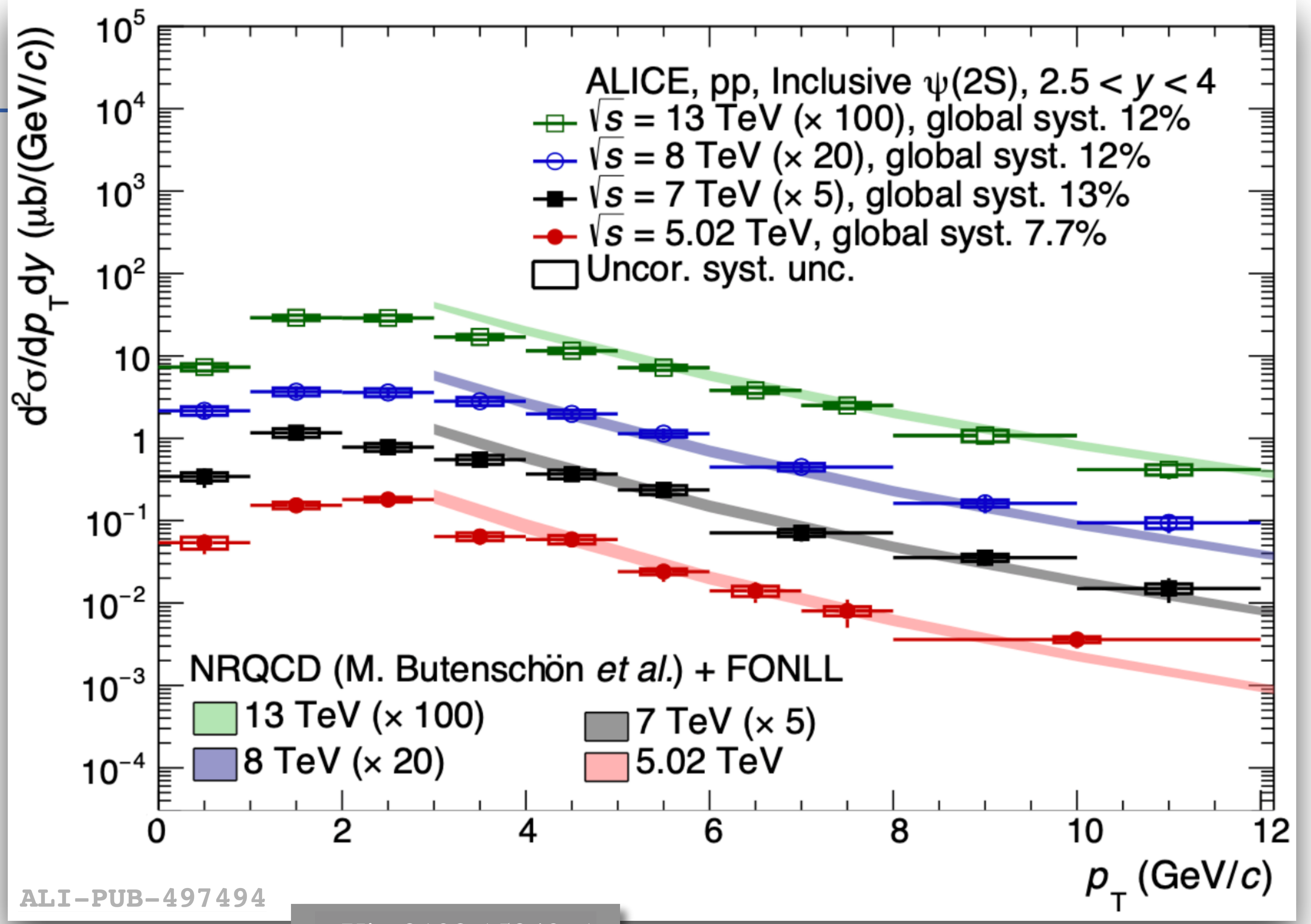
- Muonic decay channel: ψ(2S) → $\mu^+\mu^-$
- Forward rapidity: $2.5 < y < 4$
- Down to $p_T = 0$ GeV/c
- $\sqrt{s}$ = 5.02, 7, 8, and 13 TeV



Cross section measurements vs p_T:

- Agreement between data and NRQCD + FONLL model
- Increase of ψ(2S) cross section with increasing collision energy





arXiv:2109.15240v1

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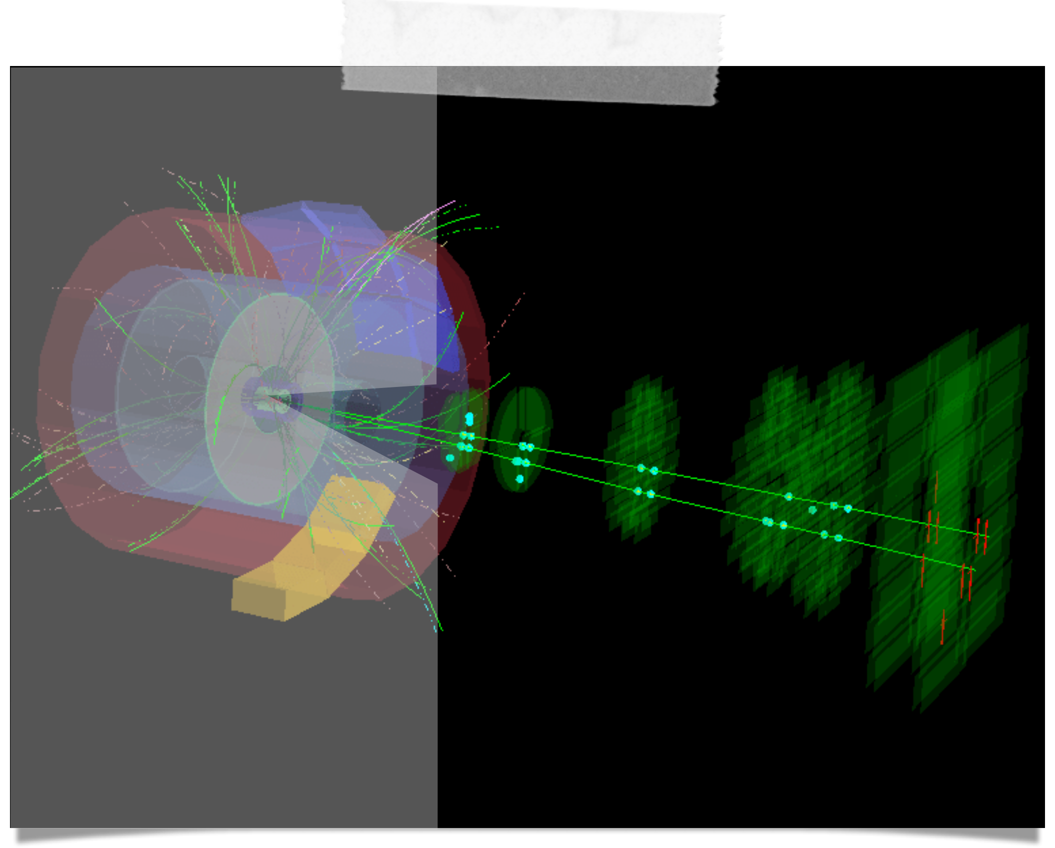

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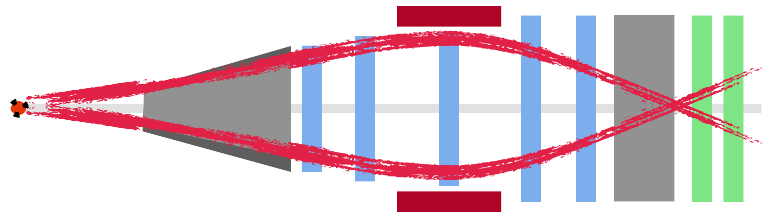


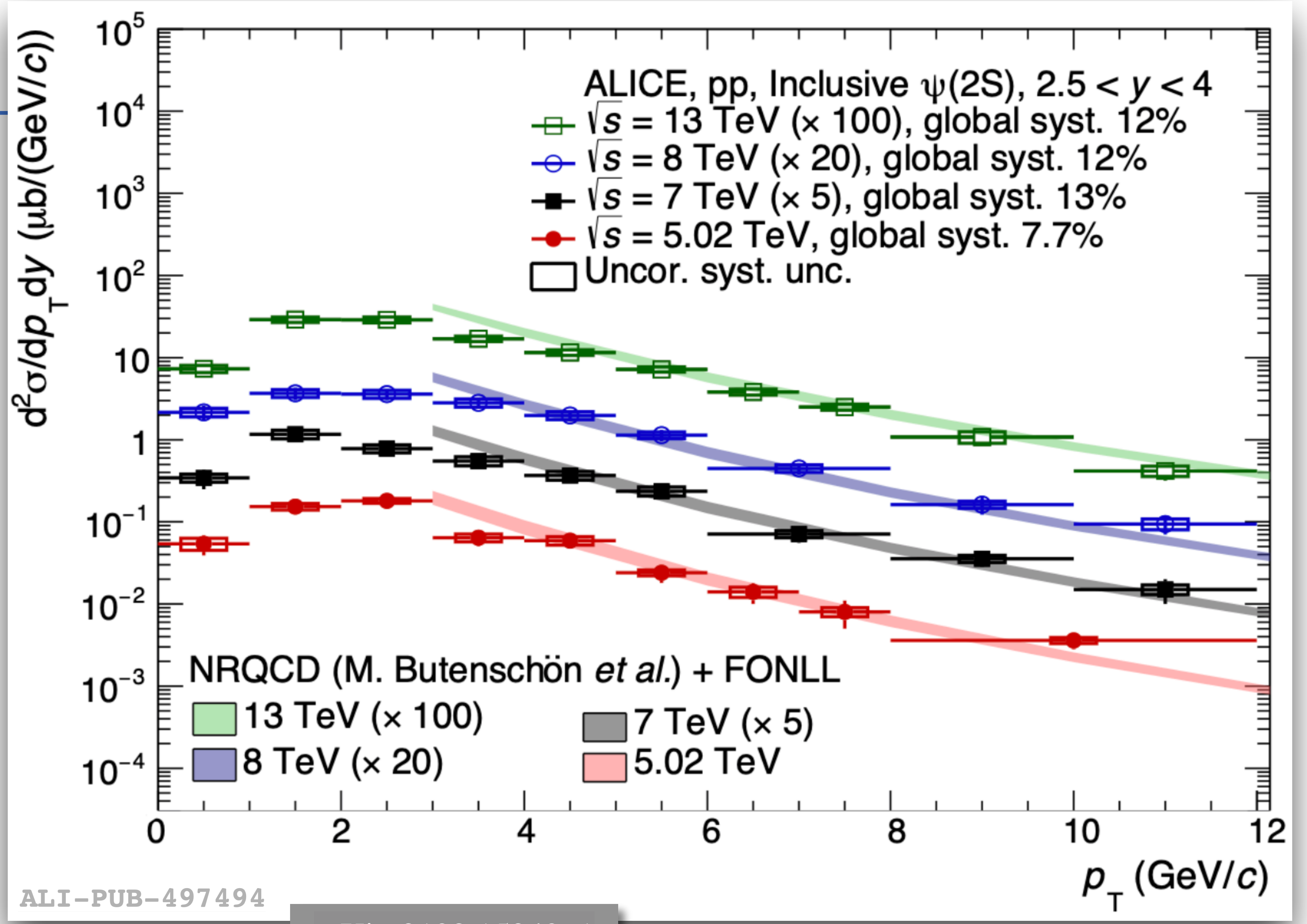
Cross section measurements vs p_{T}:

Agreement between data and NRQCD + FONLL model

Increase of ψ(2S) cross section with increasing collision energy

Cross section ratio of ψ(2S)-to-J/ψ vs p_{T}:

Ratio increases with increasing p_{T}, no energy dependence



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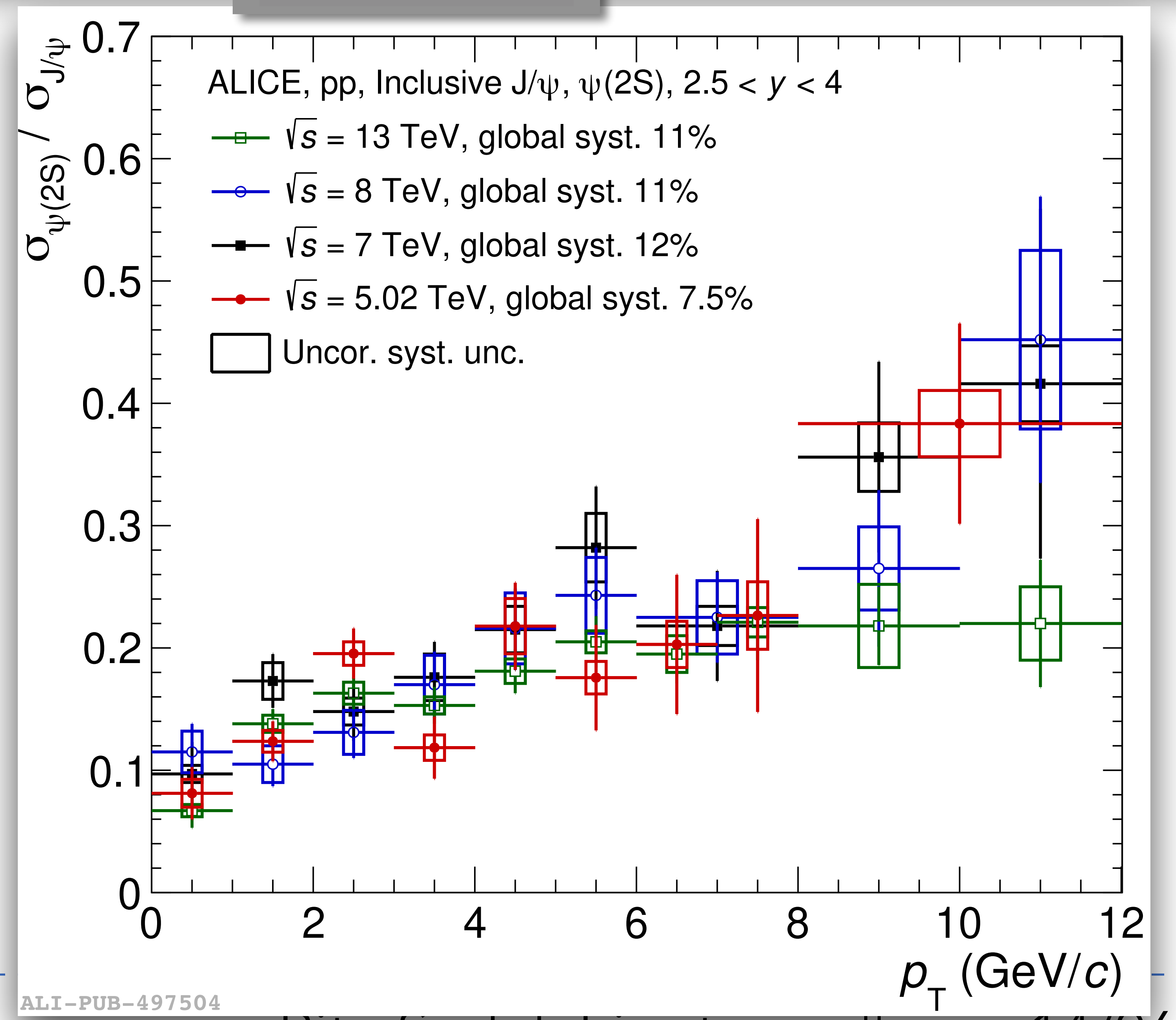

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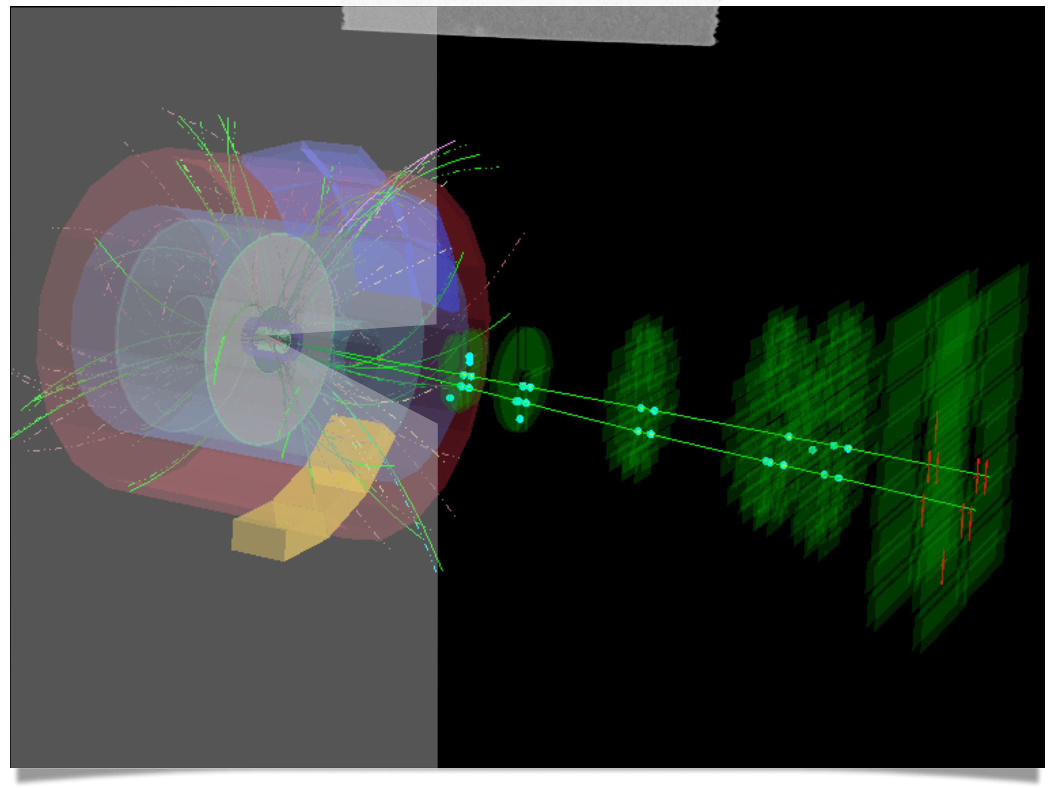

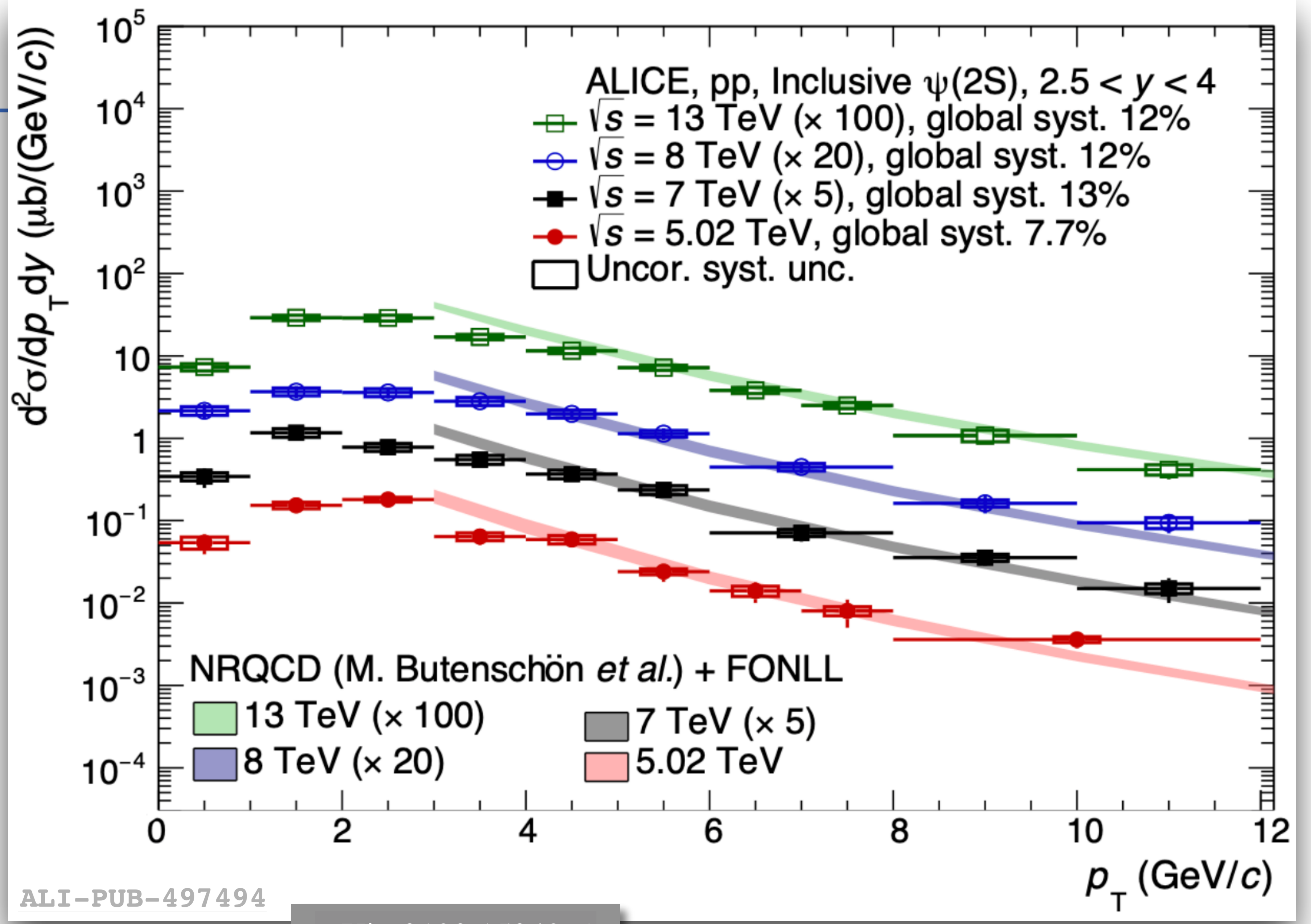

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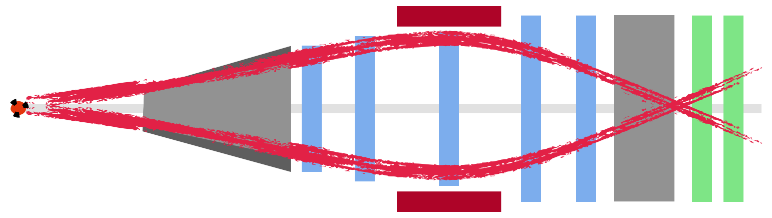
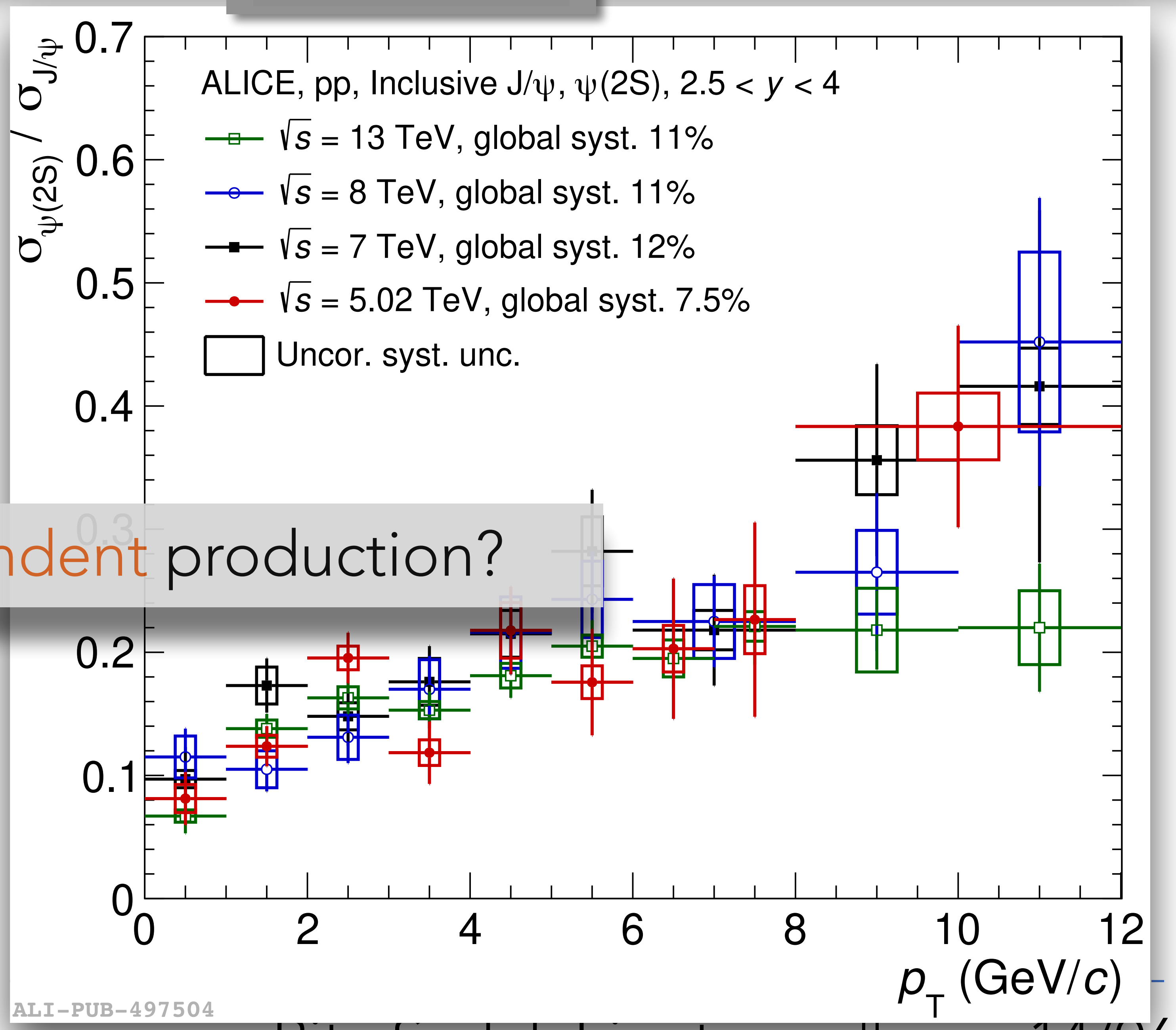


Agreement between data and NRQCD + FONLL model
Increase of ψ(2S) cross section with increasing collision energy

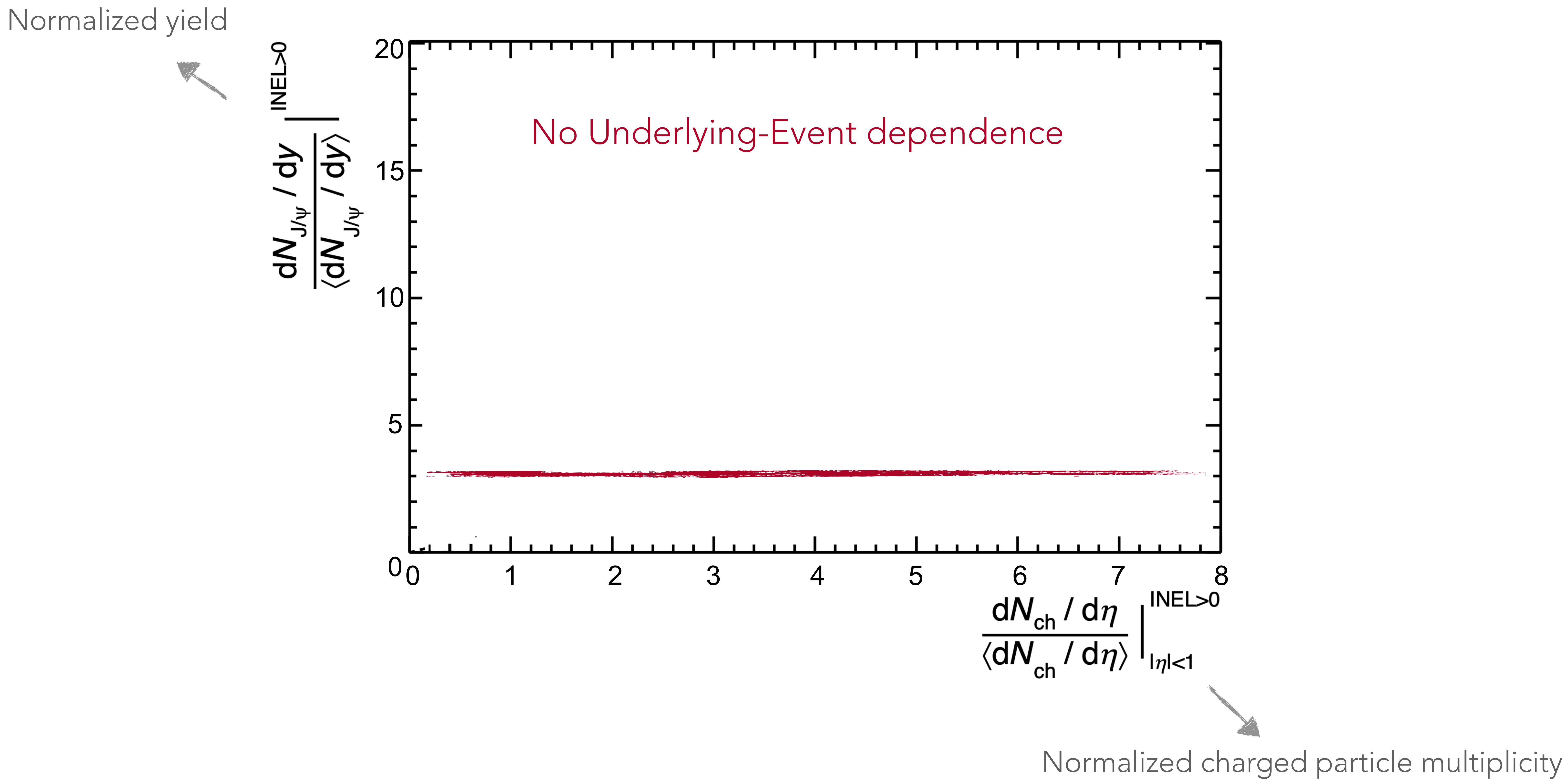
✱Cross section ratio of ψ(2S)-to-J/ψ vs p_T:

Ratio increases with increasing p_T, no energy dependence



ψ(2S) production, as J/ψ, increases with collision energy - what about multiplicity-dependent production?

Multiplicity-dependent quarkonium production



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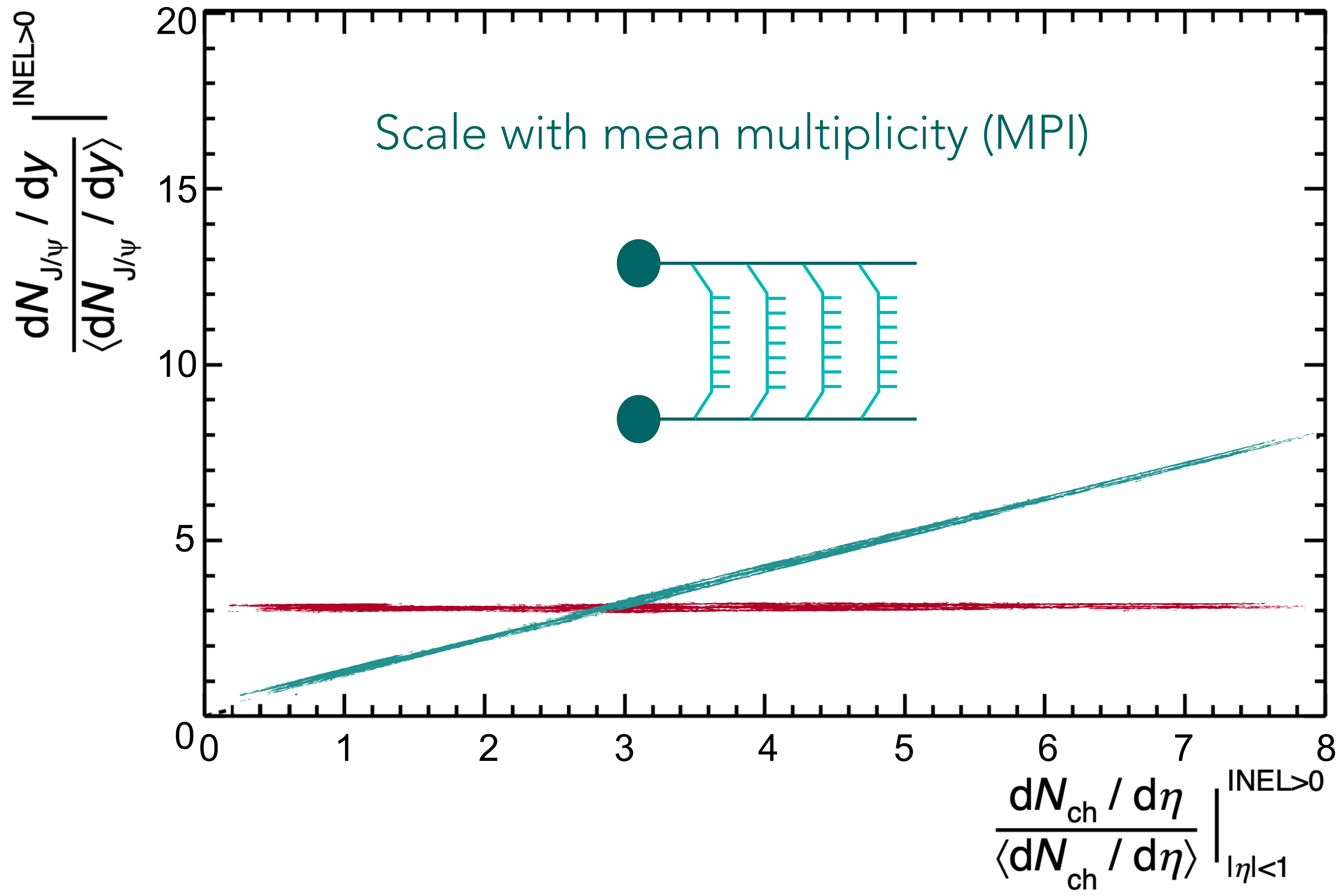

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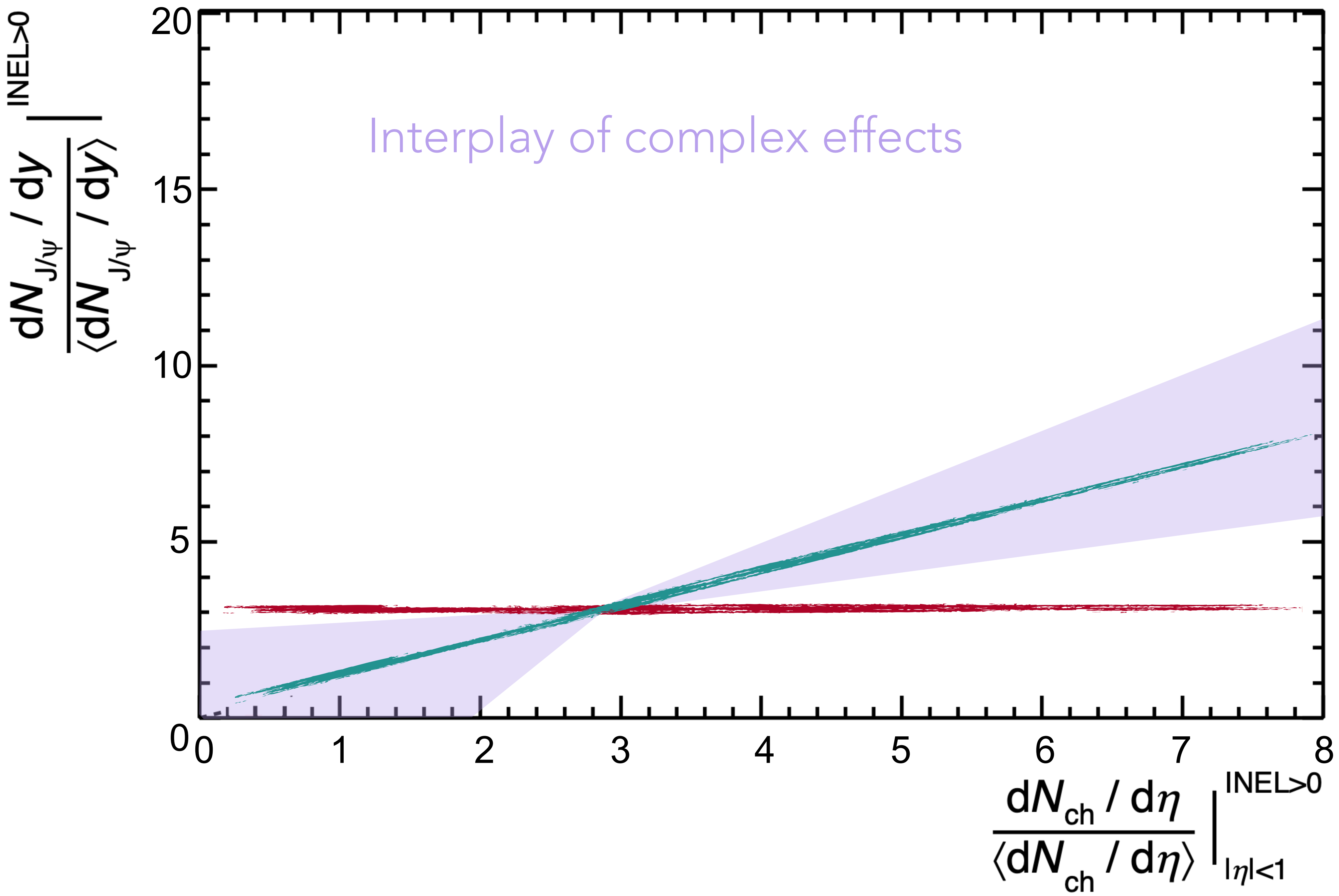
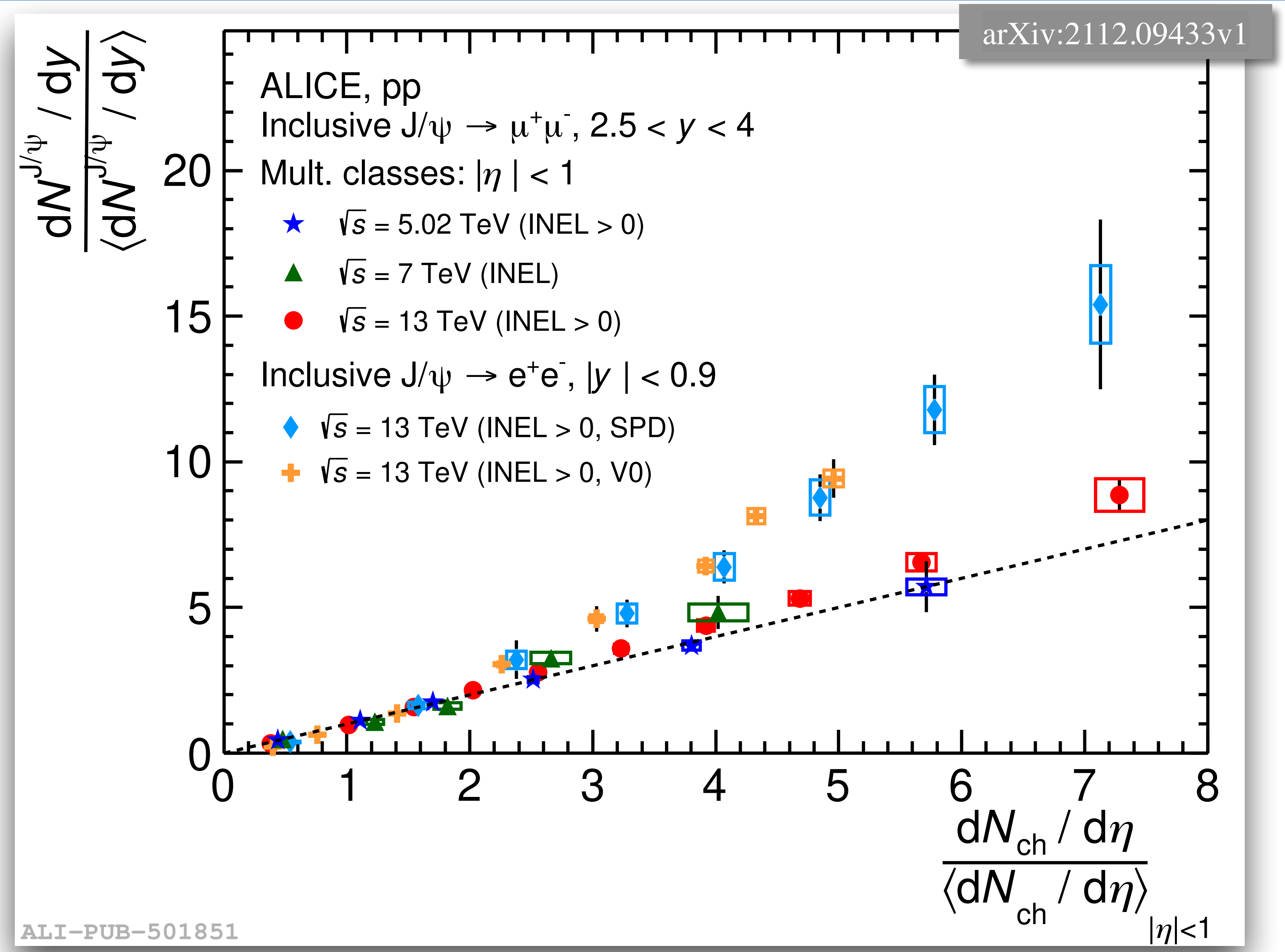


Multiplicity-dependent quarkonium production

J/ψ production measurement:

Electron decay channel: J/ψ → e^+e^-
Midrapidity: $|y| < 0.9$
Muonic decay channel: J/ψ → $\mu^+\mu^-$
Forward rapidity: $2.5 < y < 4$
With $\sqrt{s}$ = 5.02 TeV, and 13 TeV



Production measurement vs charged particle multiplicity:

Midrapidity region: stronger than linear increase of the yield with the multiplicity
Forward rapidity region: trend compatible with linear dependence on multiplicity, independent of the center-of-mass energy

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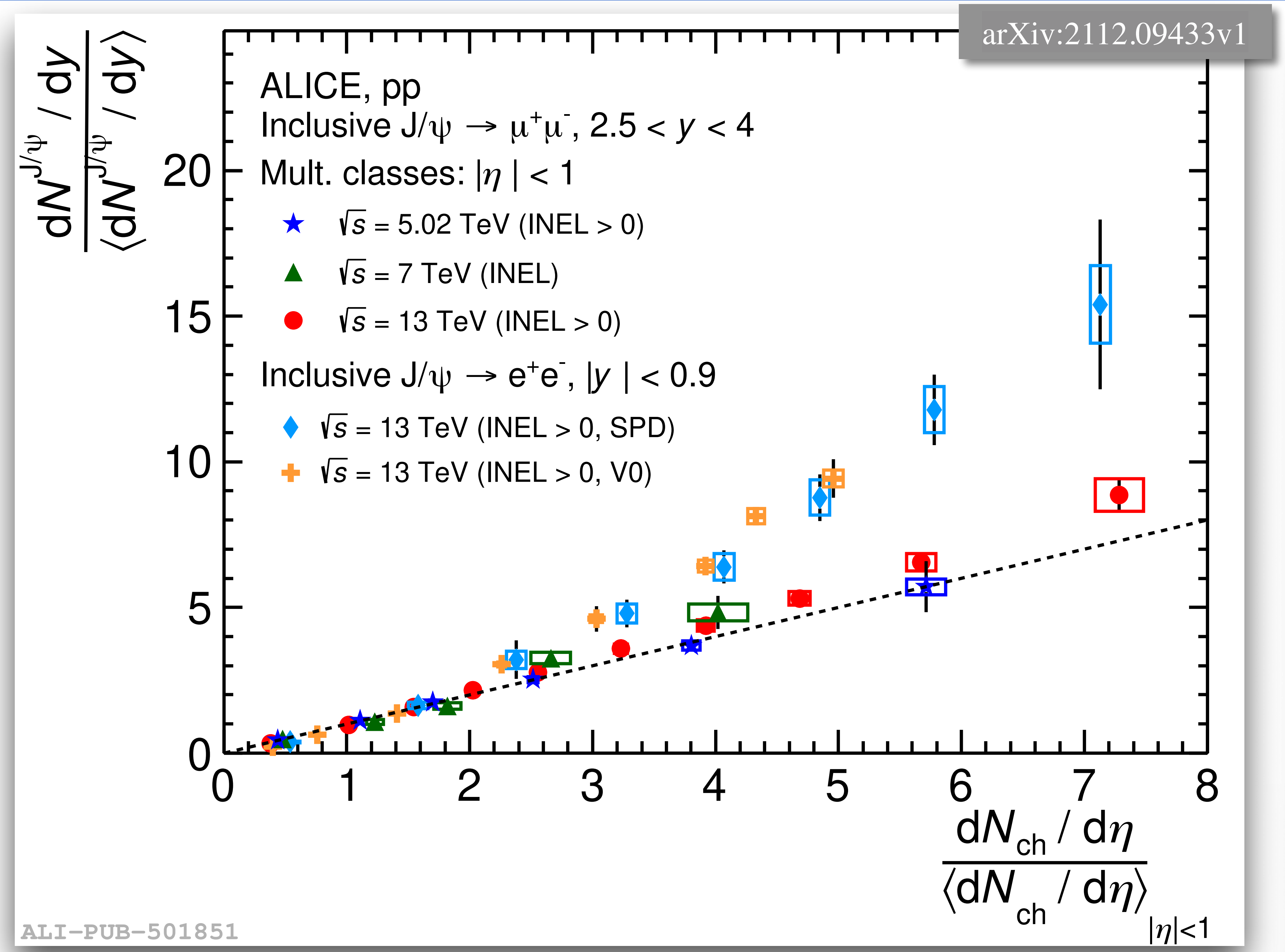

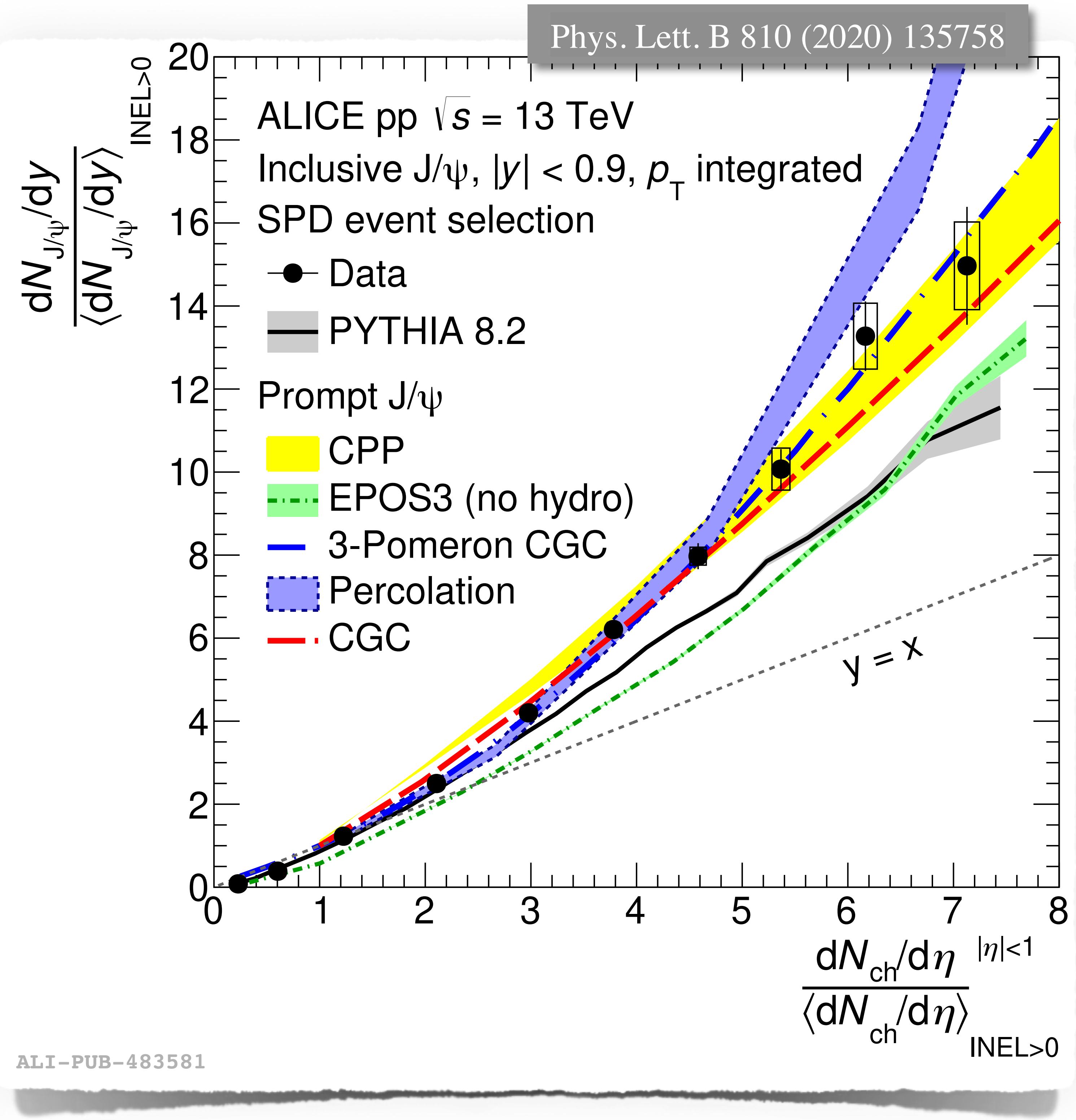

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✱Comparison with models:

CPP, CGC, and 3-Pomeron models in agreement with the inclusive midrapidity data

<u>Faster-than-linear increase predicted by different models due to different mechanisms:</u>

Color string reconnection, gluon saturation, coherent particle production, 3-gluon fusion in gluon ladders/Pomerons

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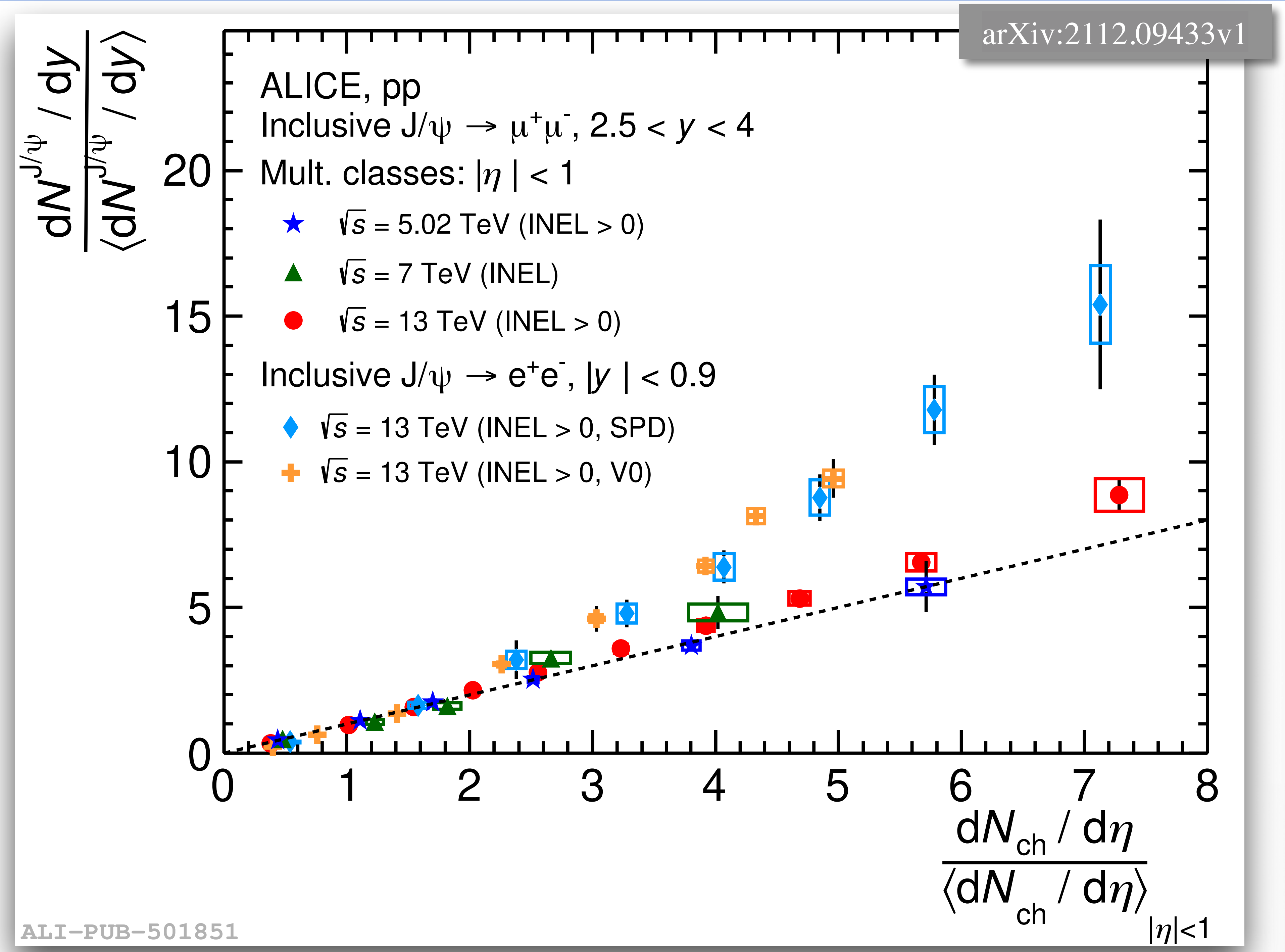

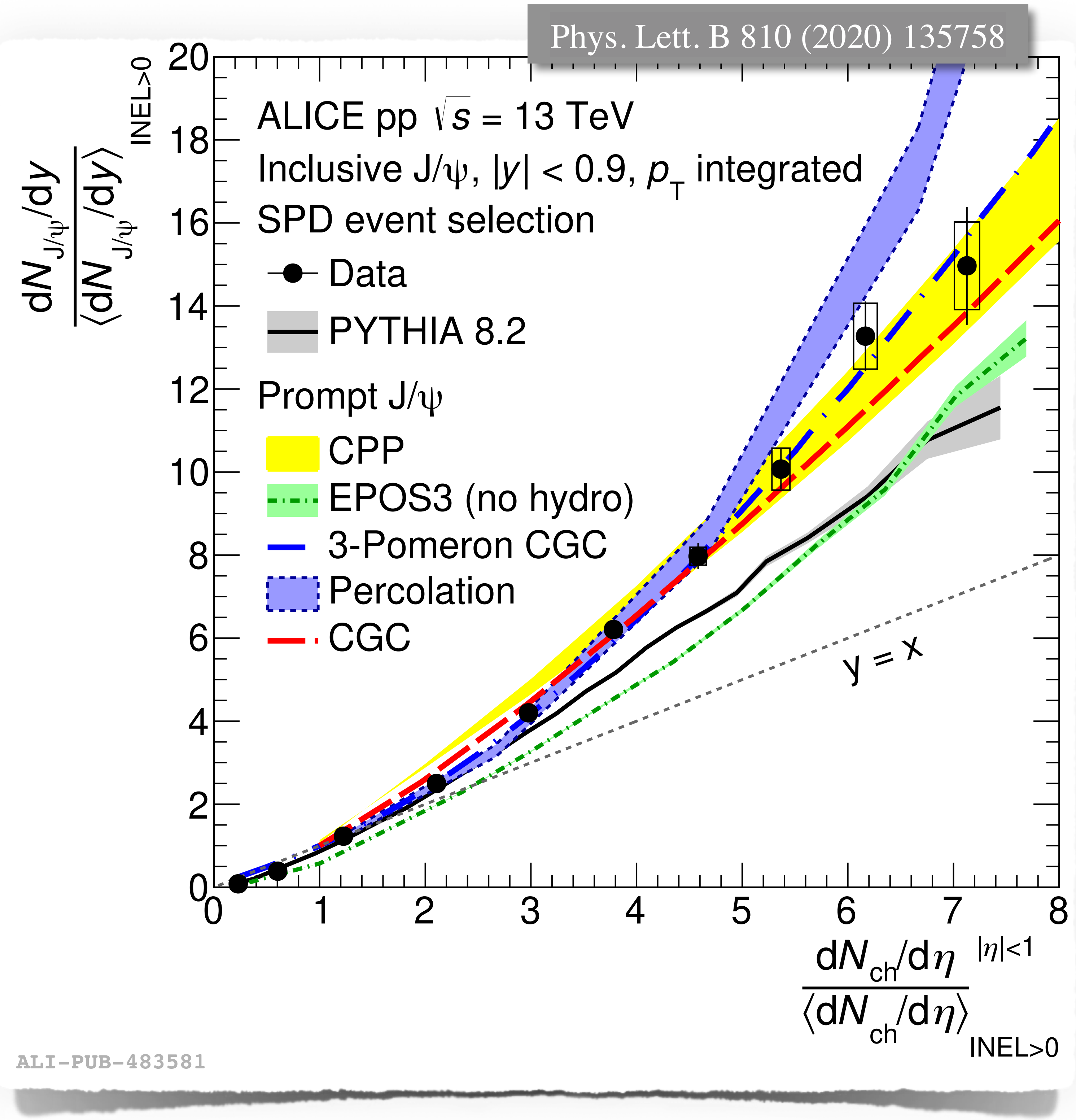

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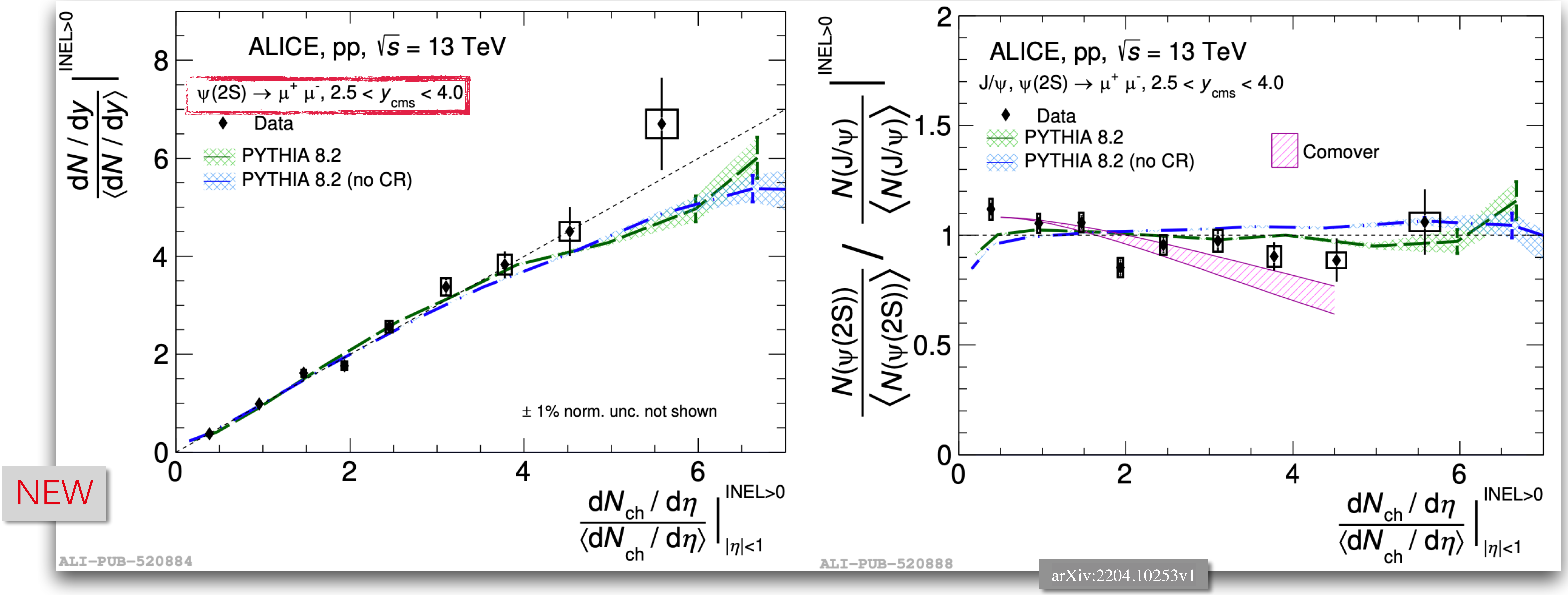
What about the excited charmonium states?

Relative ψ(2S)-to-J/ψ production vs multiplicity



✱**ψ(2S) production measurement at forward *y* as a function of charged particle multiplicity (mid-*y*) in pp:**

Linear correlation of ψ(2S) production with charged particle multiplicity, self-normalized ψ(2S)/J/ψ compatible with unity

<u>Conclusion:</u> production at forward rapidity independent of the charmonium state + collision energy

ψ(2S) yield: PYTHIA, with/without color reconnections, in agreement with data at low multiplicity, tension at high multiplicity

ψ(2S)-to-J/ψ ratio: tension at low multiplicity between data and PYTHIA → different event activity bias to explain the discrepancy?

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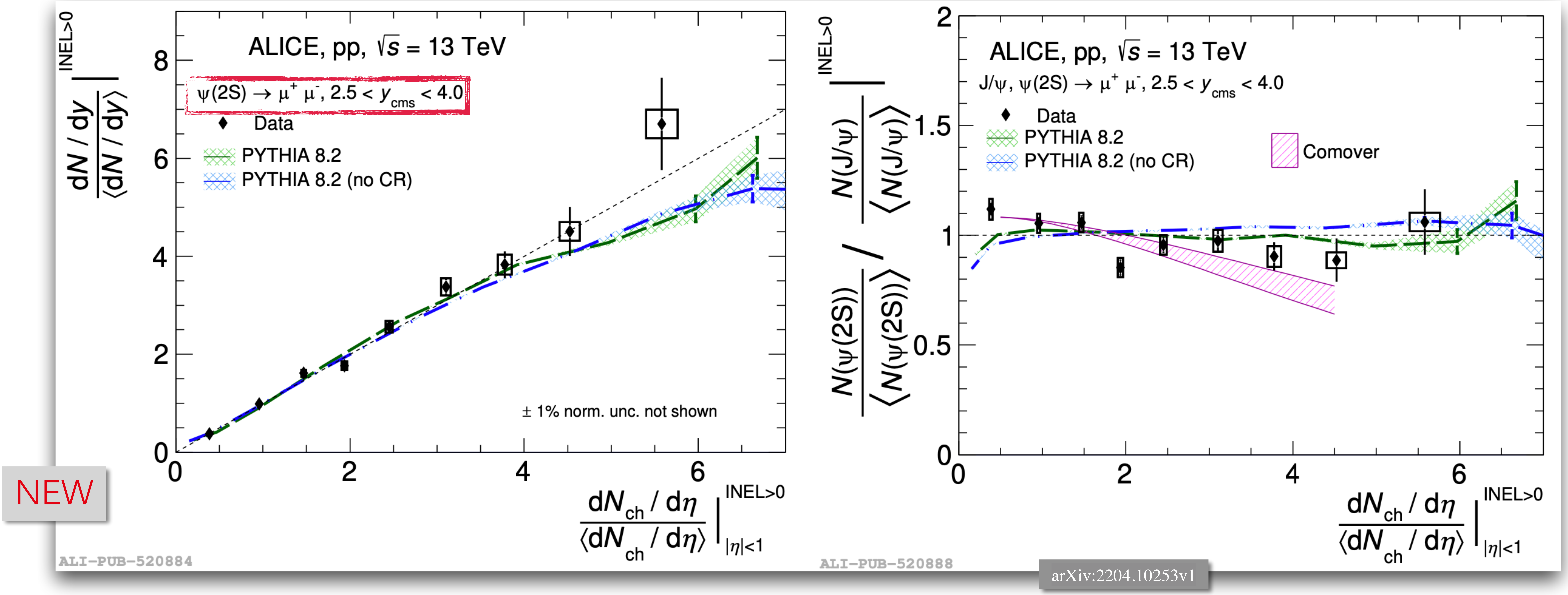

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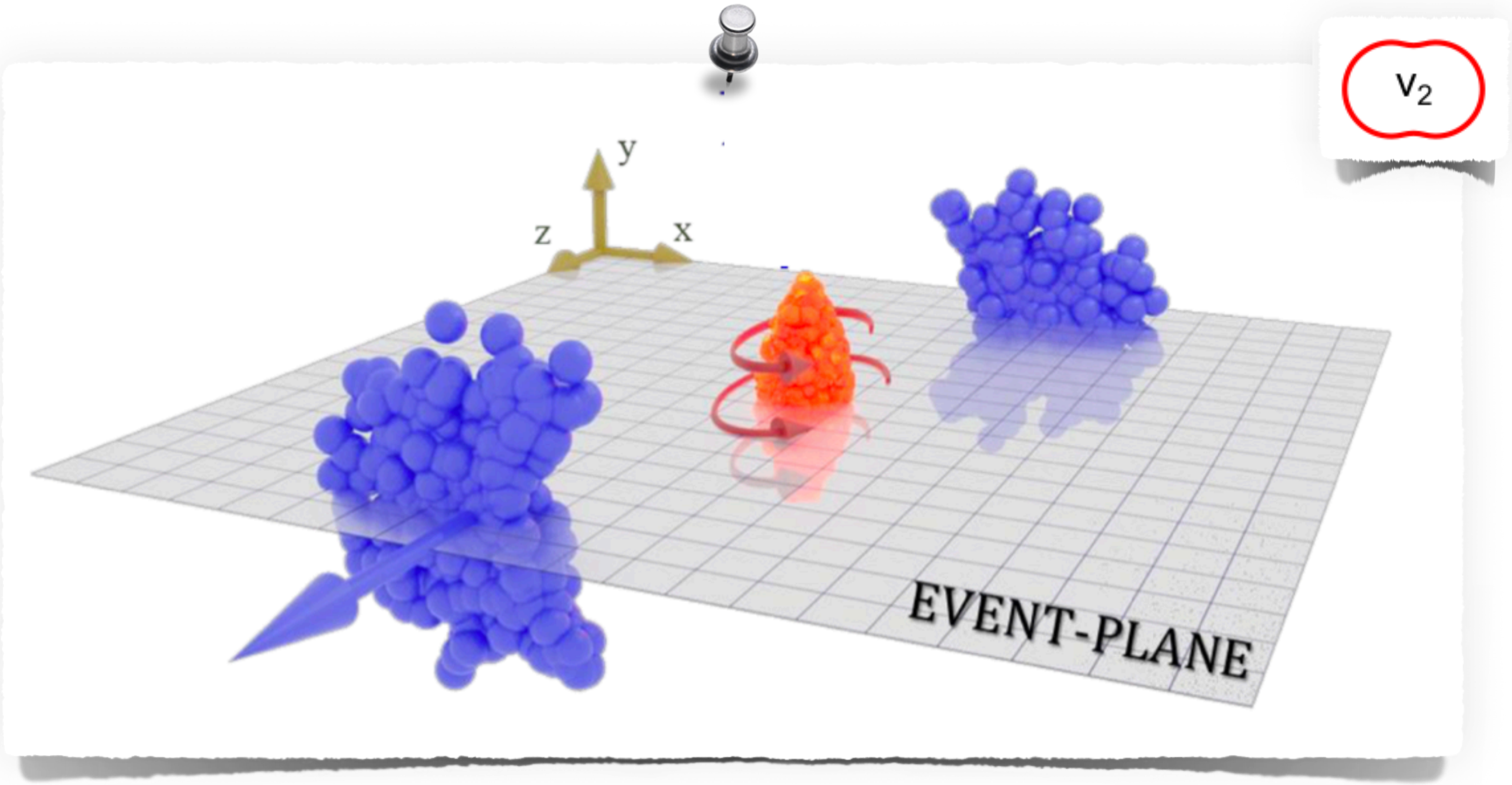
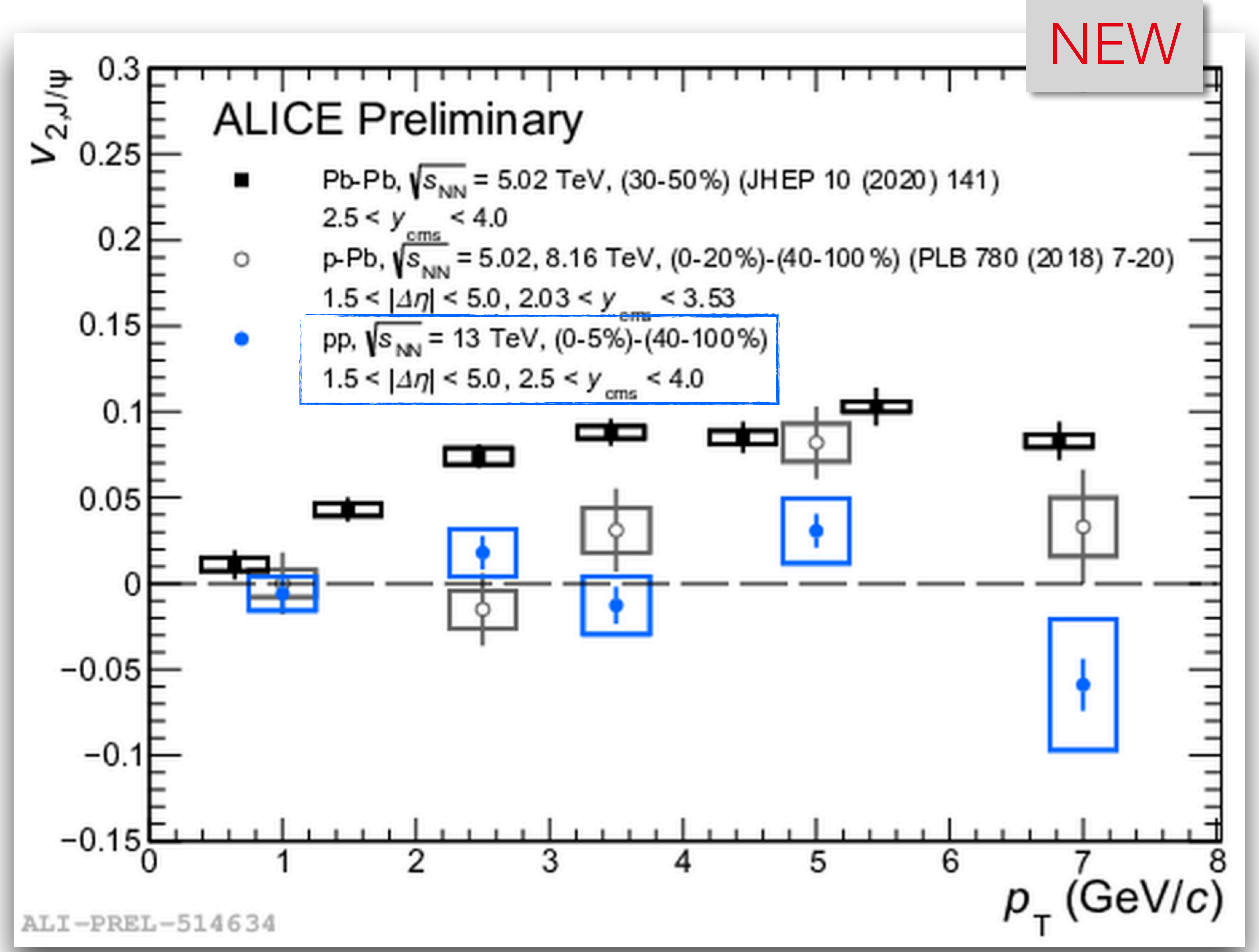
Collectivity at high multiplicity in small system?

J/ψ elliptic flow in pp collisions





☑ <u>The elliptic flow coefficient for small system:</u>

$v_2(p_T, y) = < \cos(2\Delta\phi) >$

✱J/ψ elliptic flow measurement vs p_T:

First results in pp down to 0 GeV/c

No significant deviation of J/ψ v_2 from zero

→ No collective behavior observed in pp collisions at high multiplicity for the J/ψ

Comparison between pp, p—Pb, and Pb—Pb collisions: for the latter, presence of collective behavior, with a clear difference w.r.t pp data ($v_{2,J/\psi}^{pp} < v_{2,J/\psi}^{pPb} < v_{2,J/\psi}^{PbPb}$)

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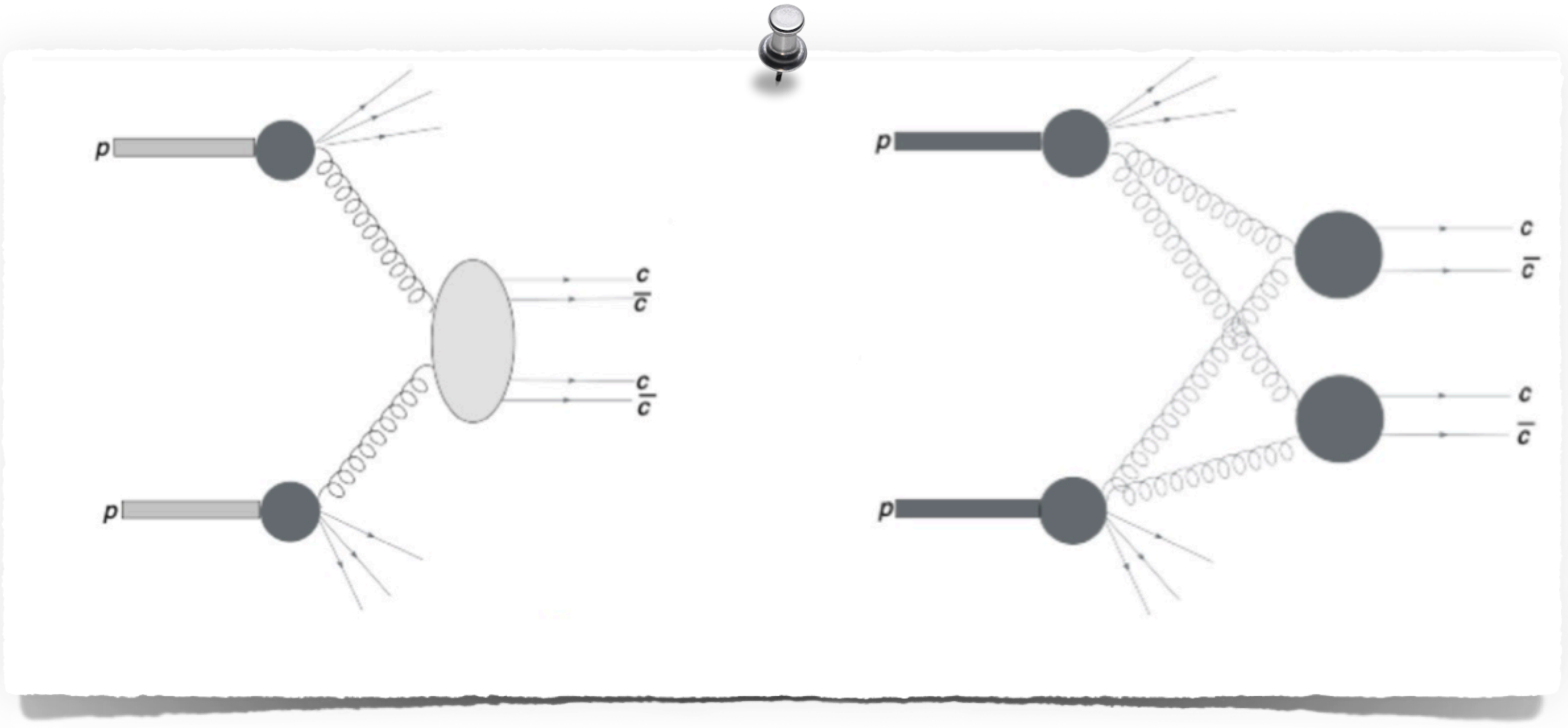
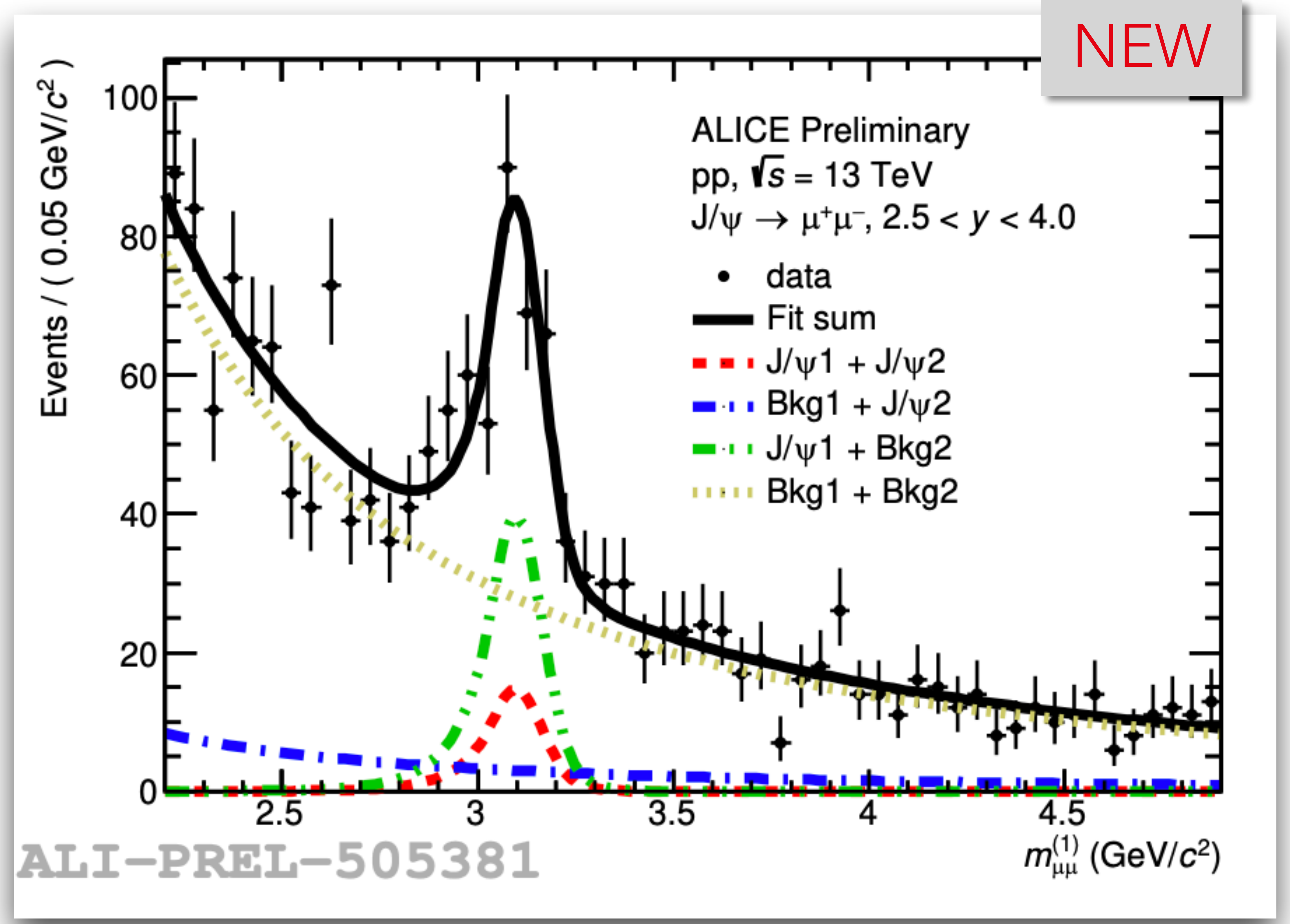
J/ψ pair production





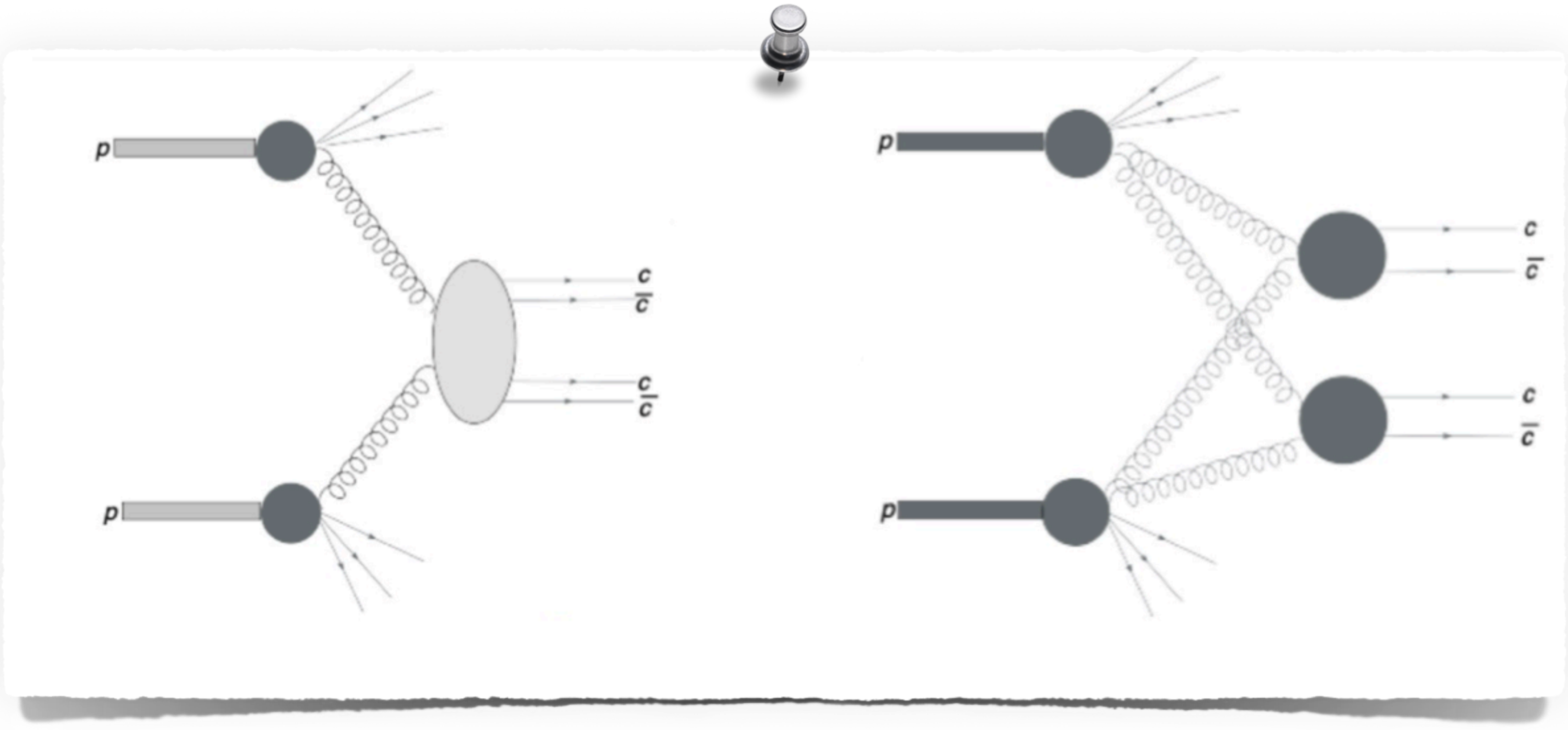
✱J/ψ pair production measurements at 13 TeV:

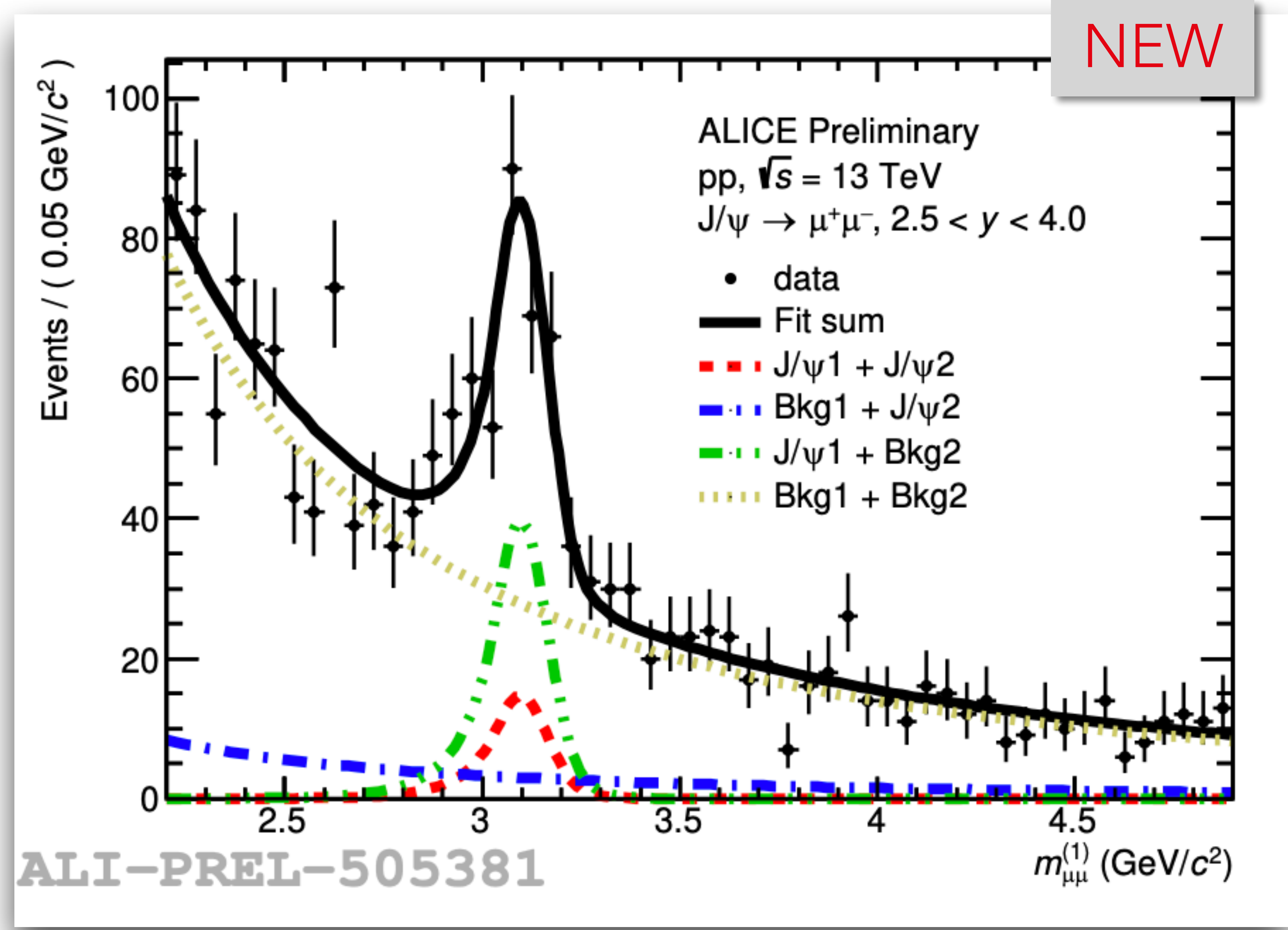
Disentangle mechanisms for J/ψ production

Constraints on CS and COM models

Insights on double parton scattering

J/ψ pair production





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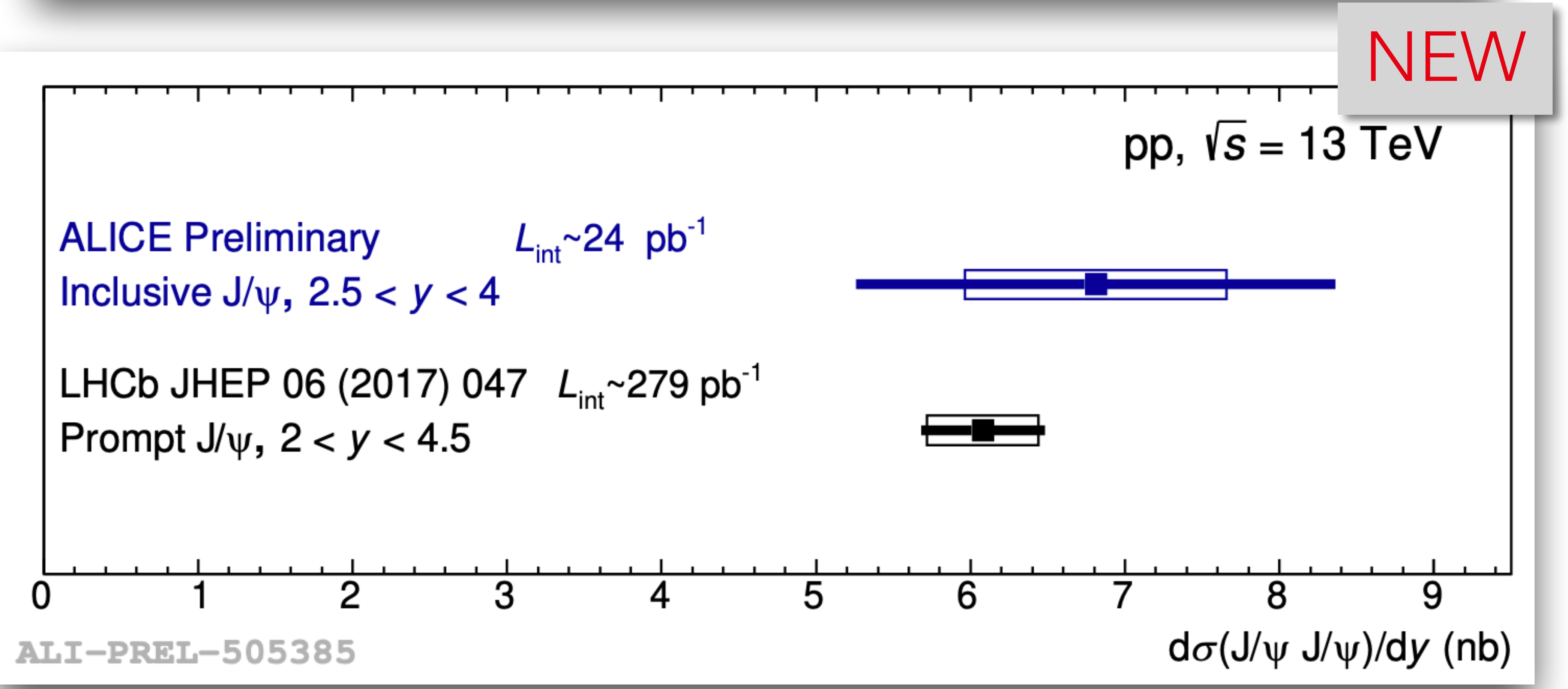

✱di-J/ψ production cross section:

Consistency with LHCb cross section measurement observed

(!) Prompt J/ψ measured in LHCb, inclusive J/ψ in ALICE
(!) Slightly different rapidity ranges

Conclusion

* **Quarkonium production in pp collisions:**
  Well described by models
  J/ψ and ψ(2S) cross section increases with energy
  ψ(2S)-to-J/ψ ratio: increases with increasing p_{T} + independent of energy

* **Measurements of multiplicity dependent charmonium production in pp collisions:**
  Different behavior versus charged particle multiplicity for the J/ψ produced at mid and forward rapidity
  Same trend versus multiplicity for the J/ψ and ψ(2S) at forward rapidity

* **First elliptic flow measurements for J/ψ in pp collisions at 13 TeV:**
  No evidence for positive J/ψ elliptic flow in high multiplicity events

* **First J/ψ pair production measurements in pp collisions:**
  First results of double J/ψ cross section: in agreement with LHCb

Perspective for Run 3:

Larger multiplicity can be achieved with increased statistics
Better S/B for quarkonium measurements
Separation of the prompt and non-prompt J/ψ at forward rapidity thanks to the Muon Forward Tracker
Improved spatial resolution at midrapidity thanks to the upgraded ITS

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Thank you for your attention!