Measurements of quarkonia production

L. Massacrier

Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

SQM2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Quarkonium related presentations at SQM 2024

❑ Quarkonium related experimental presentations:

- Recent results on heavy flavours and quarkonia from ALICE – F. Fionda – Mon. 11:05
- Observation of double J/ψ production in p-Pb with CMS – S. Leontsinis – Tues. 14:40
- Investigating the interplay between initial hard processes and final-state effects measuring (non)-prompt J/ψ with ALICE – M. Coquet – Tues. 15:00
- Detailed study of the production of ***Y*** mesons in Pb-Pb collisions with CMS – P. Ranjan Pujahari – Tues. 15:20
- Recent conventional and exotic charmonia results from LHCb – Y. Kang – Tues. 15:40
- Ultra-peripheral collisions at LHCb – L. Hengne – Tues. 17:10
- Forward rapidity elliptic flow measurements in PHENIX Au-Au collisions at 200 GeV – L. Bichon - Wed. 9:30
- J/ψ photoproduction and polarization in peripheral Pb-Pb collisions with ALICE – D. Mallick – Wed. 10:40
- Prospects for open-heavy flavour and quarkonium measurements with NA60+ - R. Arnaldi – Wed. 12:00

❑ Posters:

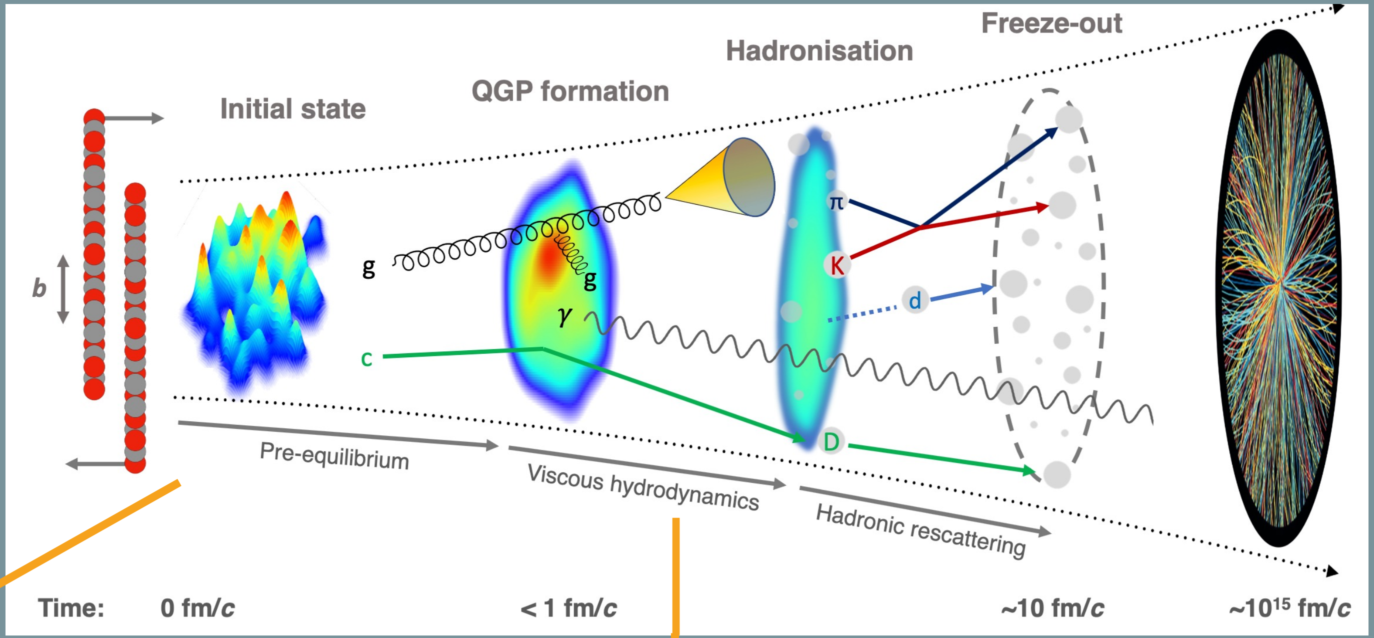
- Studying QCD production mechanisms and medium effects on quarkonia formation with ALICE – Z. Xiong
- Decoding charmonia polarization in pp collisions at LHC energies – S. Deb
- System size dependence of collective phenomena by means of quarkonia measurements with ALICE – S. Zhu
- Exploring ***Y*** production mechanisms using PYTHIA simulation in proton-proton collisions – O. Mezhenska
- The spin interference effect with photoproduced ρ^0 and J/ψ in UPC at STAR – A. Sheikh
- Multi-particle cumulant J/ψ v_2 measurement in Pb-Pb collisions – V. Valencia
- Prompt/Non-prompt J/ψ separation performances with ALICE - E. Barreau

This presentation will mainly focus on quarkonium hadronic production in pp/pA/AA
Usual disclaimer : personal biased selection of results, with focus on most recent results, in a more global context

Quarkonia as probe of the medium in AA collisions

- Quarkonia are bound states of a heavy quark (c,b) and its antiquark

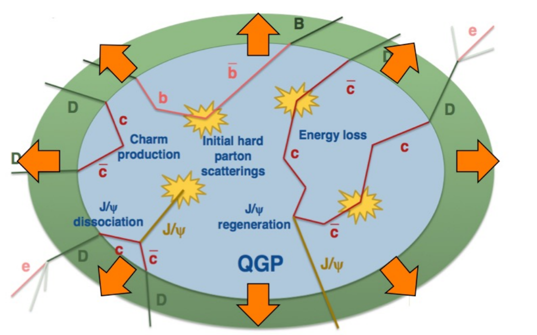
- Heavy quarks produce early in the collision and sensitive to full medium evolution



ALICE Coll., arXiv:2211.04384

- Sensitivity to:
  - Gluon distributions in nuclei
  - Initial magnetic field and vorticity in the QGP

thermalization



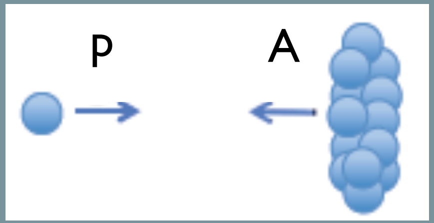
Parton energy loss

Sequential dissociation in medium depending on quarkonium binding energy

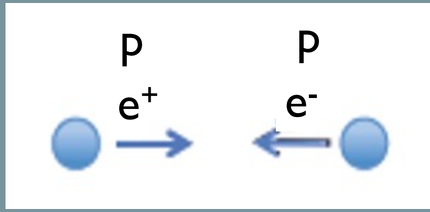
Regeneration in medium or at phase boundary

Quarkonia as tool in small systems

❑ Interpretation of medium effects on quarkonium production requires a good understanding of the probe in reference systems without QGP formation



Ideal system to study Cold Nuclear Matter effects : nPDFs, (coherent) energy loss, nuclear absorption, comovers…



Elementary collisions to understand the probe itself:

- Production mechanism: a two scales problem (perturbative initial $q\bar{q}$ production, non-perturbative binding into quarkonium). Several models on market: NRQCD, ICEM…
- Role of feed-down contributions
- But also a QCD tool: spectroscopy (rare decays, exotic quarkonium states/tetraquark), gluon distributions in proton

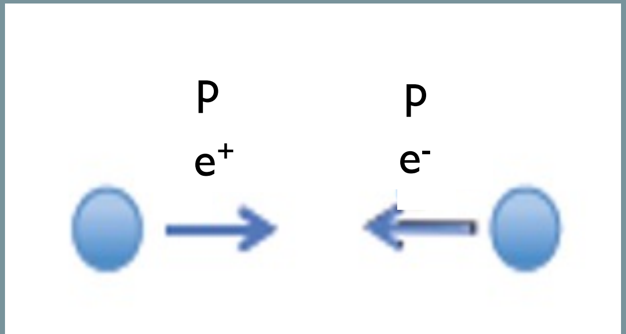
❑ The peculiarity of the high multiplicity regime in small systems: QGP-like features seen for several observables

- Role of initial/final state (MPI, comovers..) effects on quarkonium production
- Look for collectivity with heavy quarks

But quarkonium production in «min-bias» small system events remains a good baseline for AA studies…

Quarkonium production in « min-bias » pp/e$^+$e$^-$ collisions

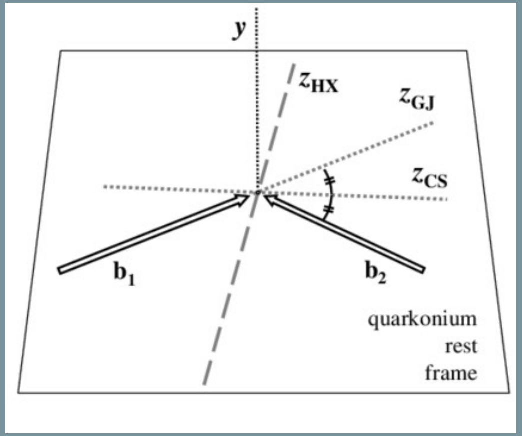
« Min-bias »



Spectroscopy

Production mechanisms*

Exotica

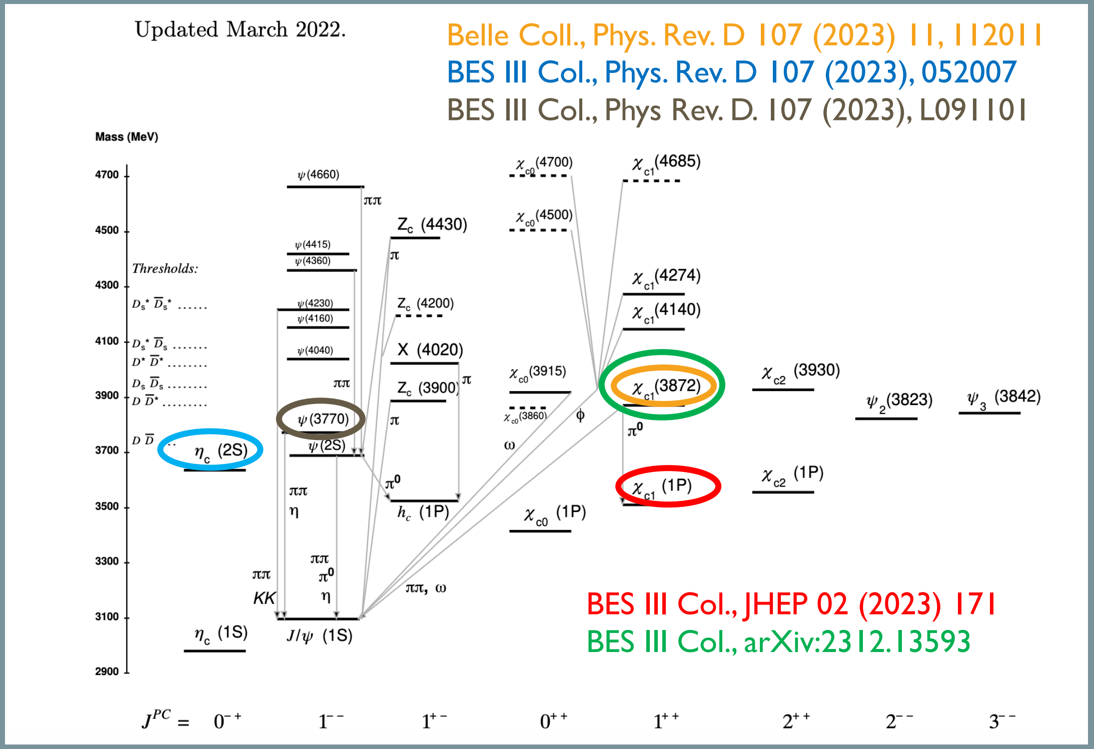


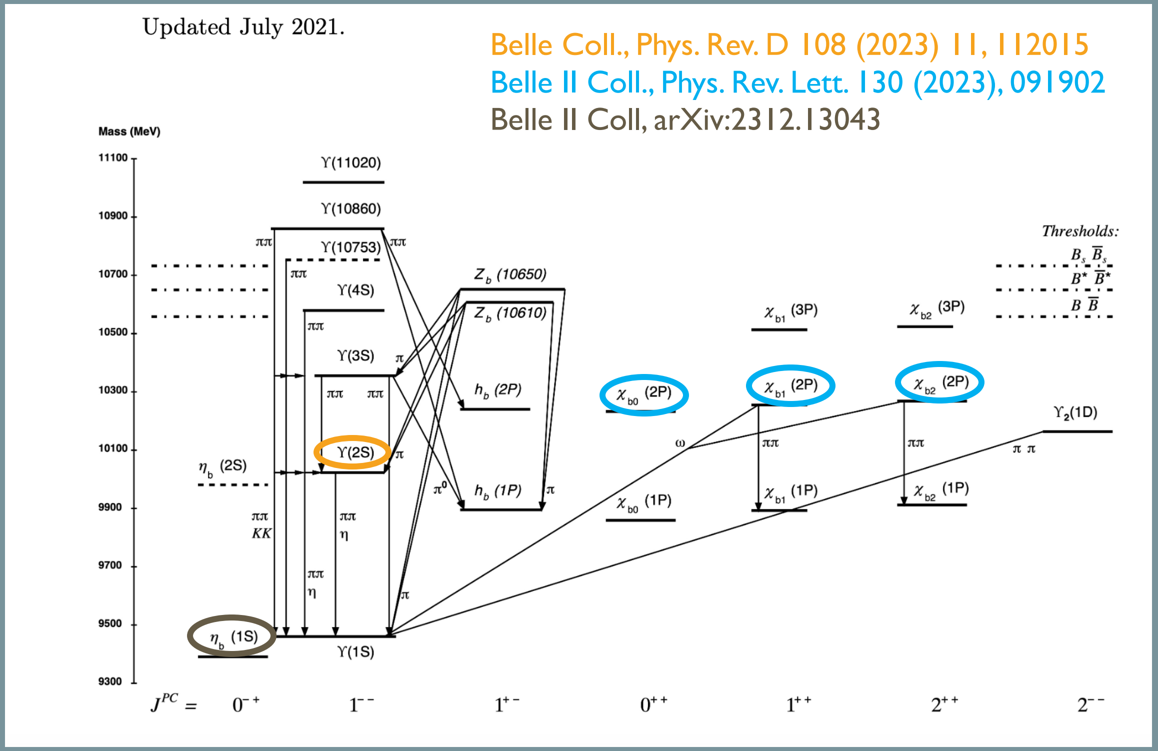
*Also quarkonium production in jets (not covered)

Quarkonium spectroscopy and exotica

Large variety of measurements to characterize all quarkonium family states (BES III, B-factories…), and their rare decays

S. Navas *et al.* (PDG), Phys. Rev. D 110, 030001 (2024)





And still discovery of new states

LHCb (2020) heavy tetraquark candidate X(6900)

Similar structure observation by ATLAS/CMS +

two more candidates X(6600) and X(7100)

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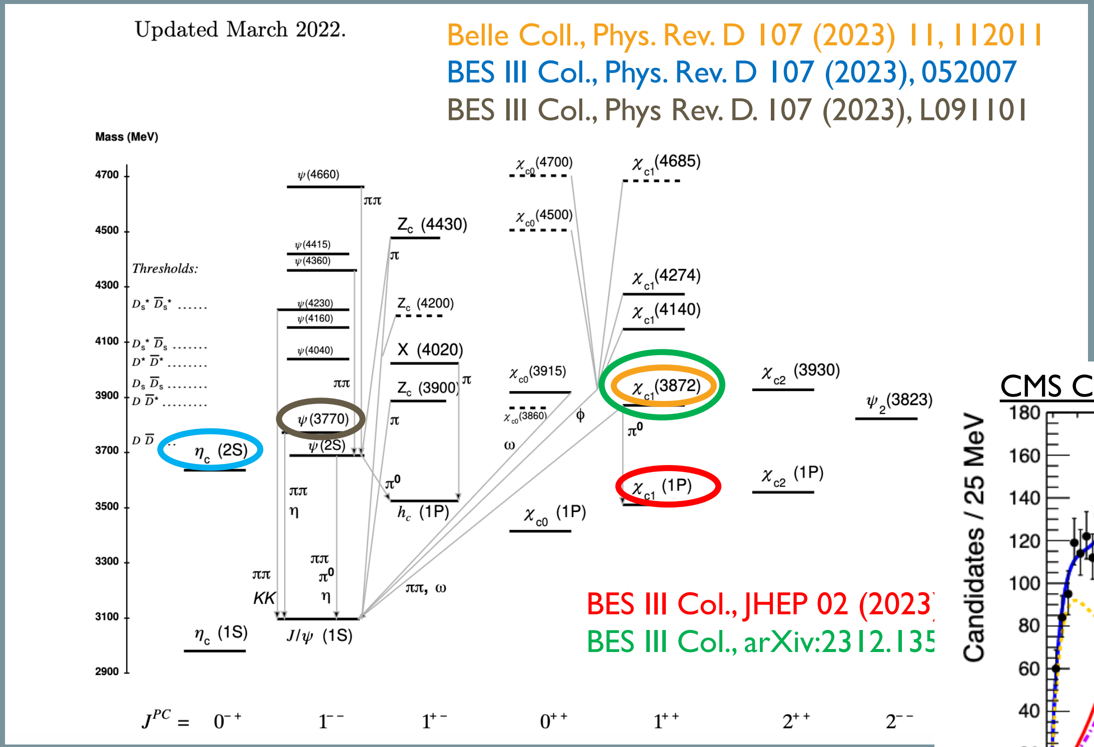

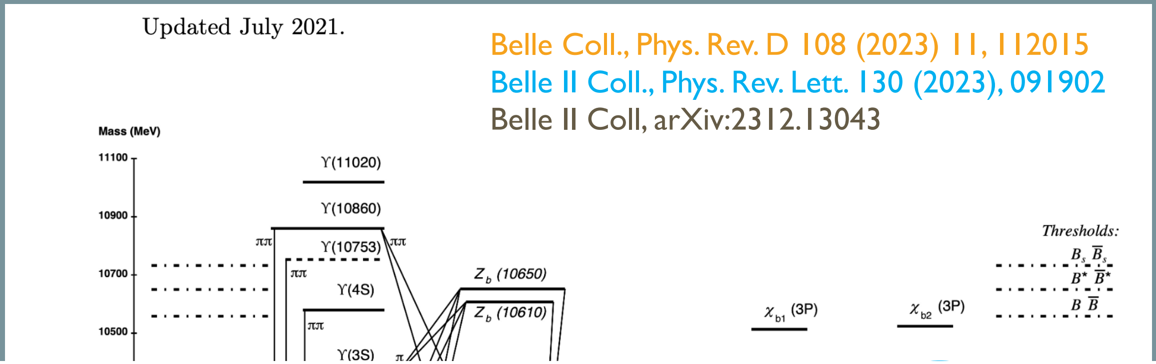

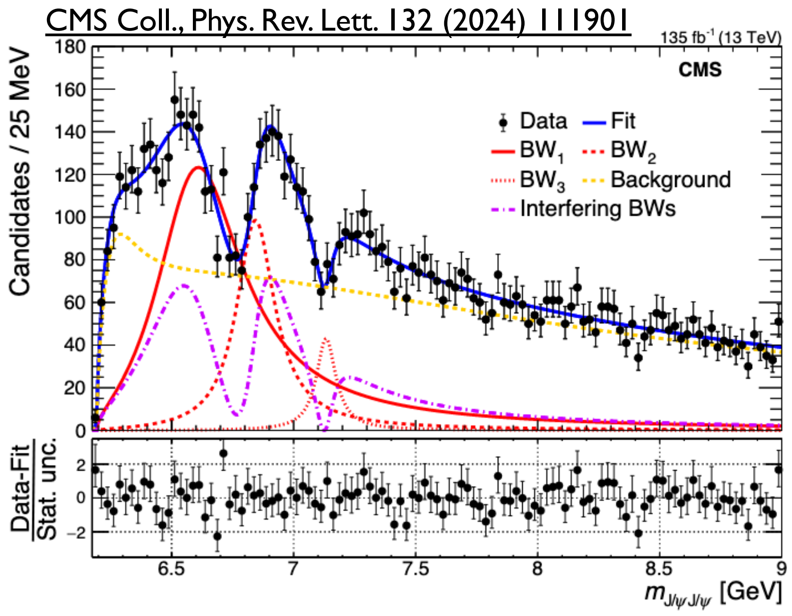

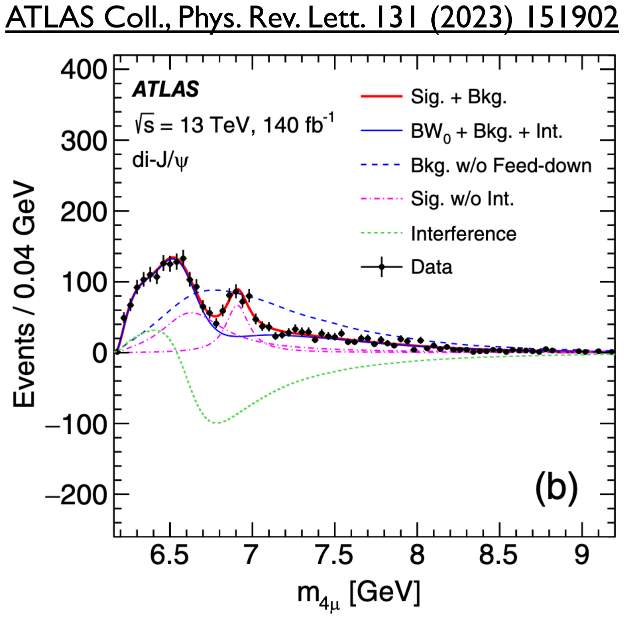

And still discovery of new states

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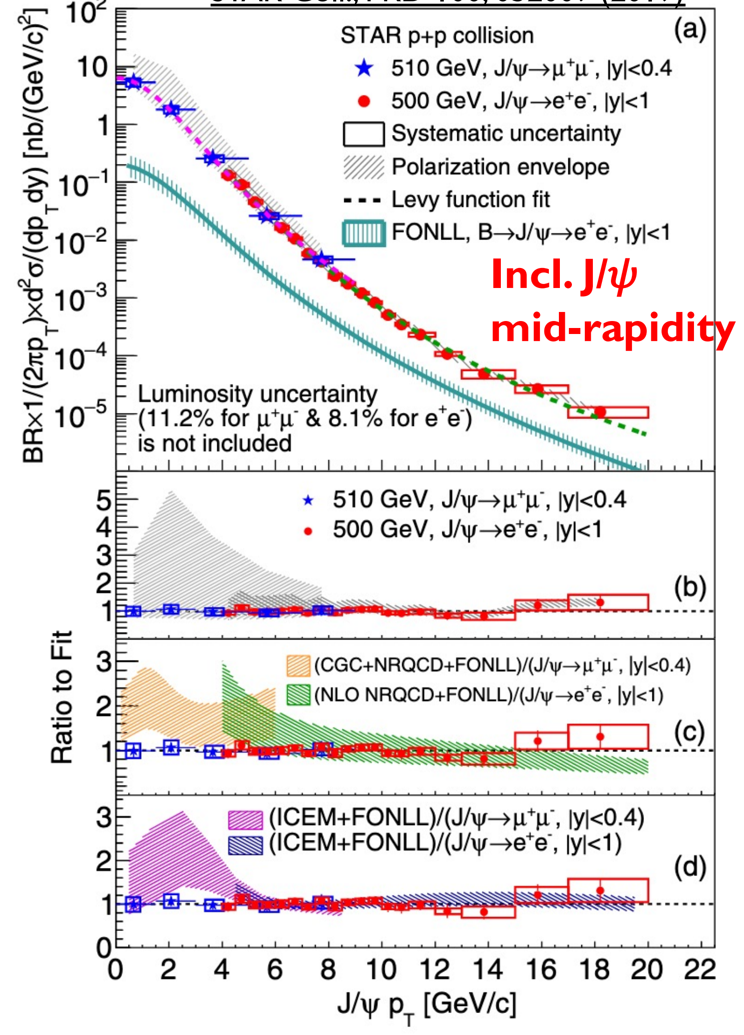
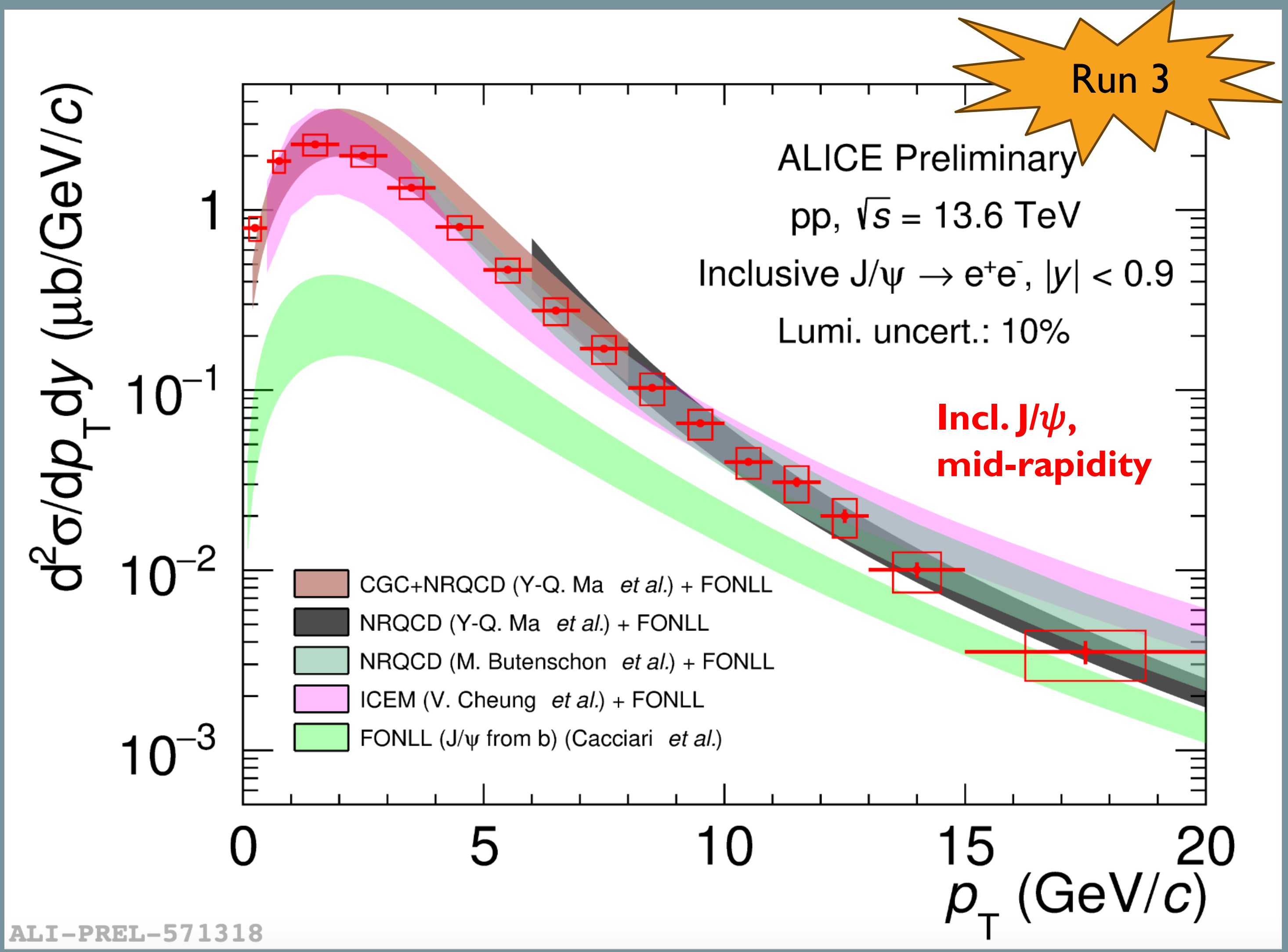
Similar structure observation by ATLAS/CMS + two more candidates X(6600) and X(7100)

Quarkonium production in pp collisions

STAR Coll., PRD 100, 052009 (2019)



Quarkonium production in pp collisions



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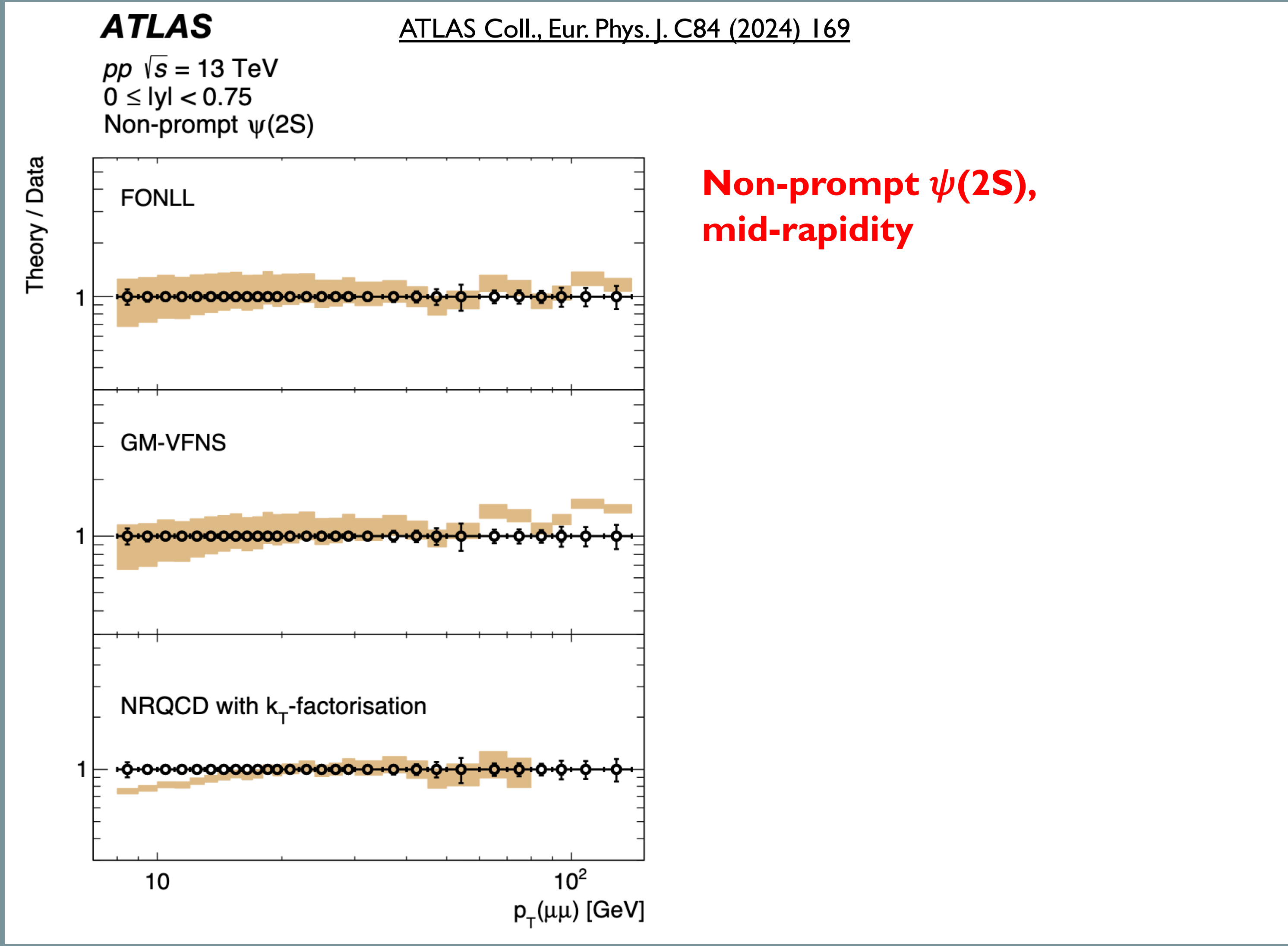
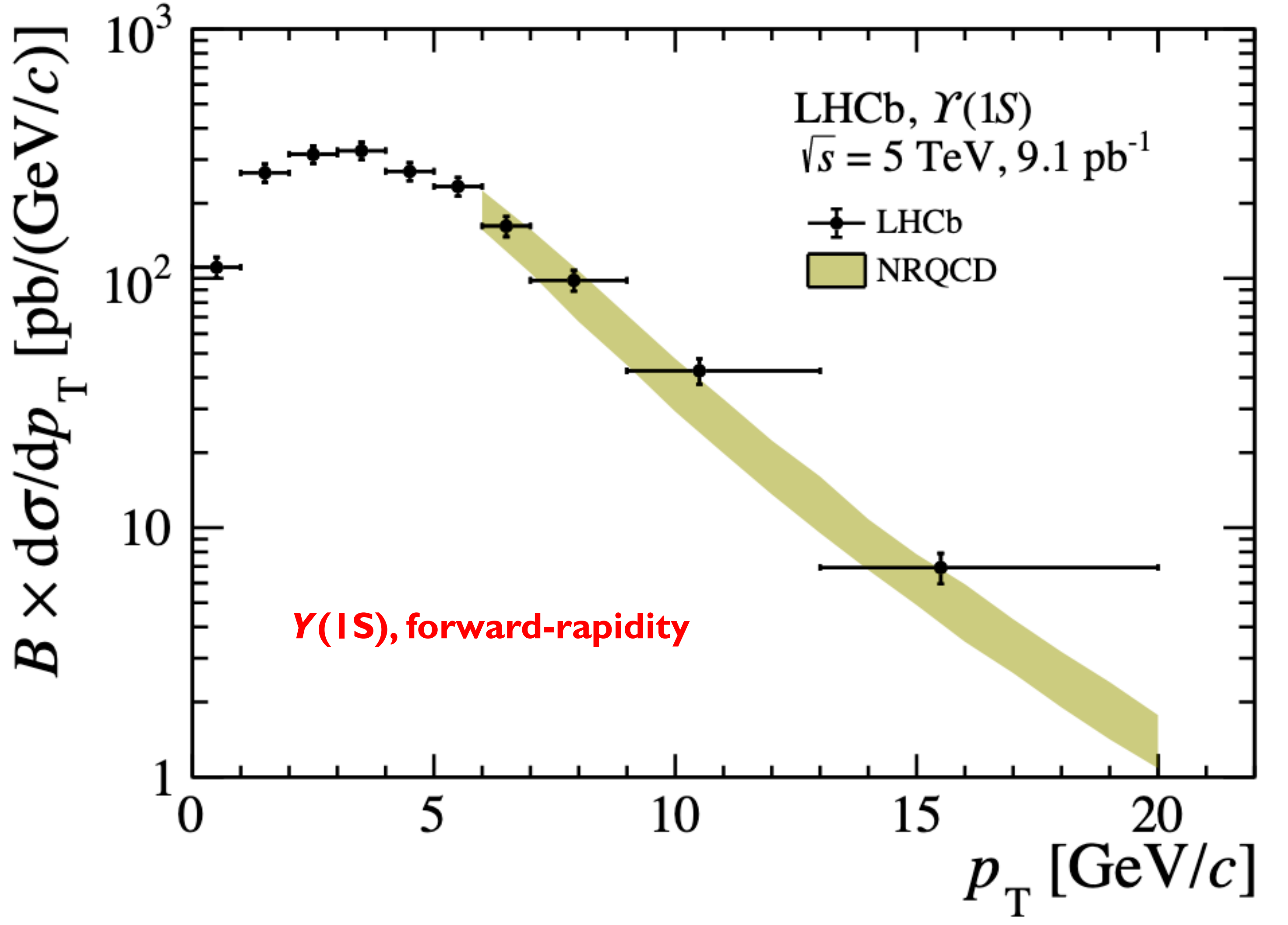


Non-prompt ψ(2S), mid-rapidity

Quarkonium production in pp collisions

LHCb Coll, JHEP 07 (2023) 069



- ❑ Various RHIC/LHC experiments complementary in kinematic coverages for quarkonium measurements
- ❑ Good description of prompt quarkonium cross sections over a wide range of energy/rapidity/p_T by NRQCD* (w/ or wo/ CGC) and ICEM*

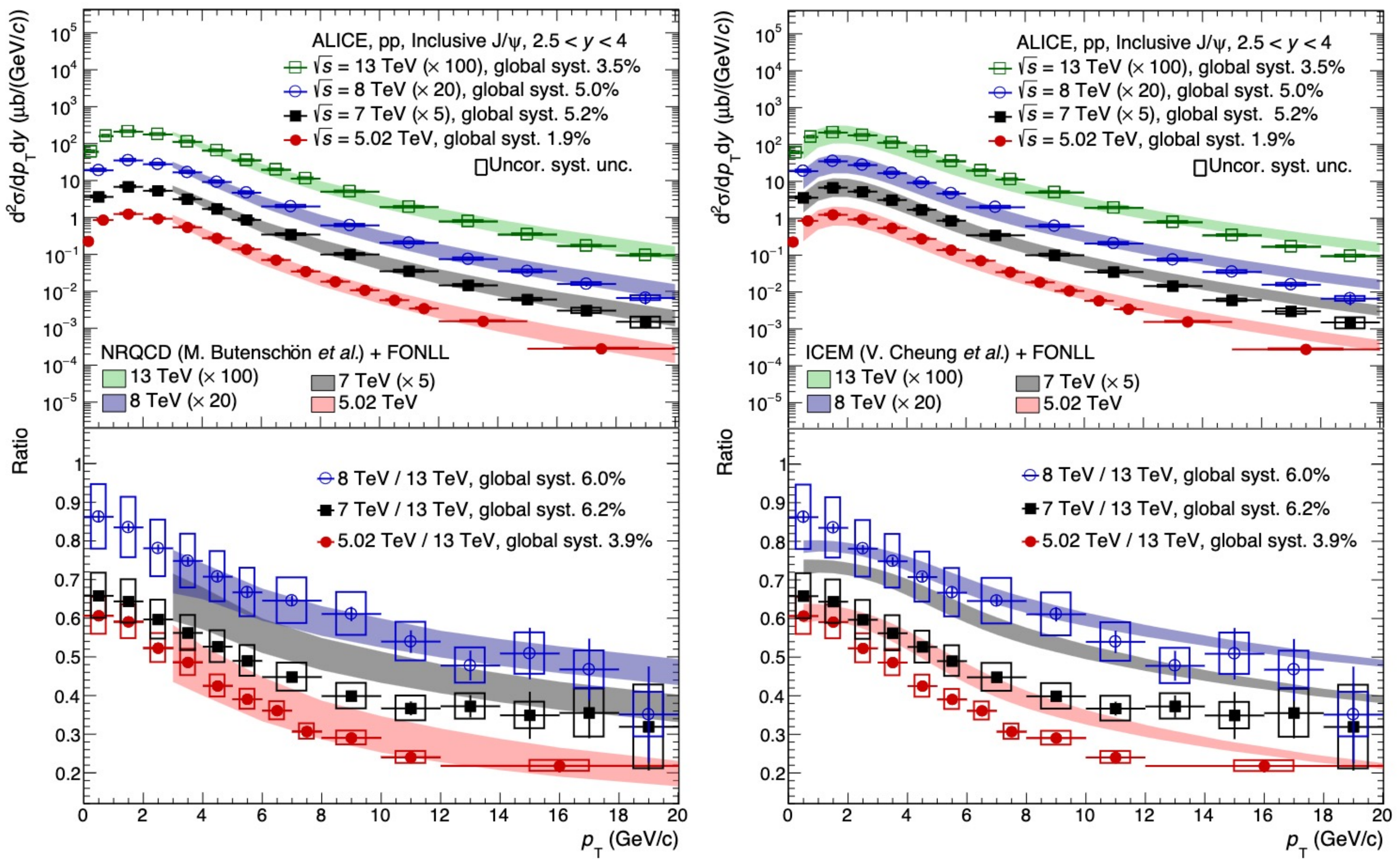
* small tension at low energy for low p_T (STAR, PHENIX)

- ❑ Non-prompt charmonium rather well described by FONLL, GM-VFNS
- ❑ Experimental data becoming more precise than theoretical model uncertainties

Quarkonium production in pp collisions

ALICE Coll, EPJC 83 (2023) 61

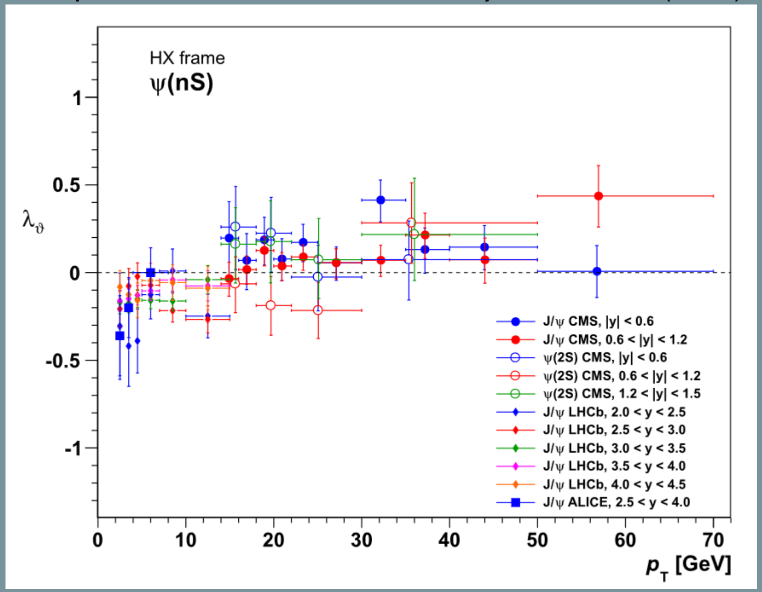
Incl. J/ψ, forward-rapidity

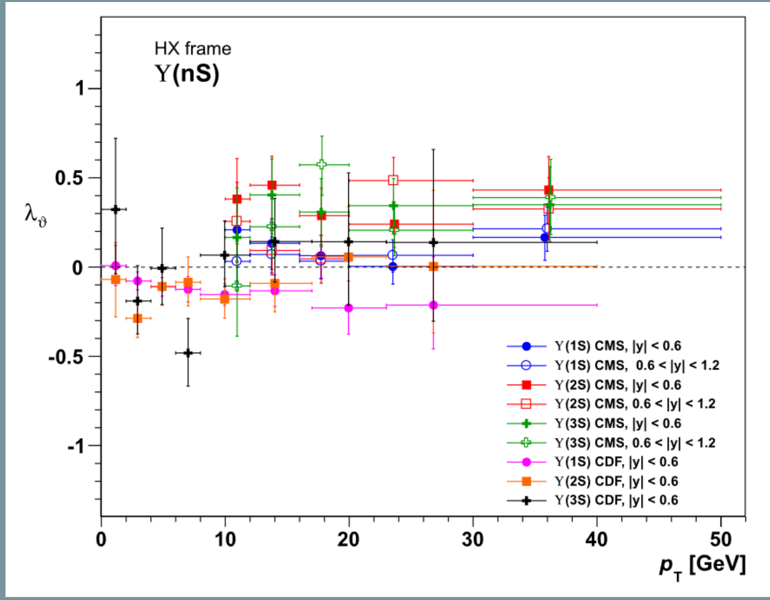


- ❑ Can data still further constrain models?
- ❑ LHC: large data sample for precise quarkonium production measurements at several c.m.s energies
- ❑ Cross section ratios among energies: benefit from partial cancellation of several theoretical uncertainties (renormalization scale, factorization scale…)
- ❑ Challenging for models to describe cross section ratios

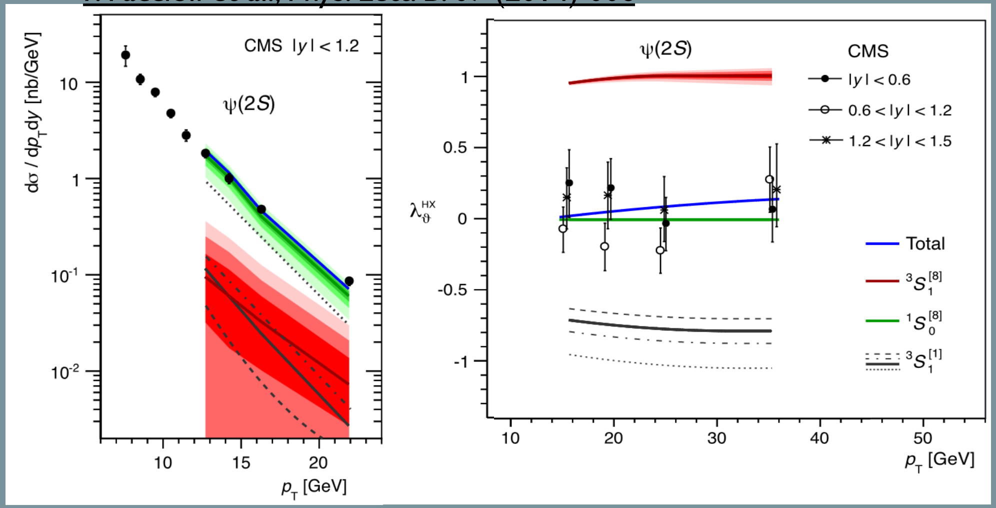
Quarkonium polarization in pp collisions

Compilation from P. Faccioli et al., Phys. Lett. B. 07 (2014) 006

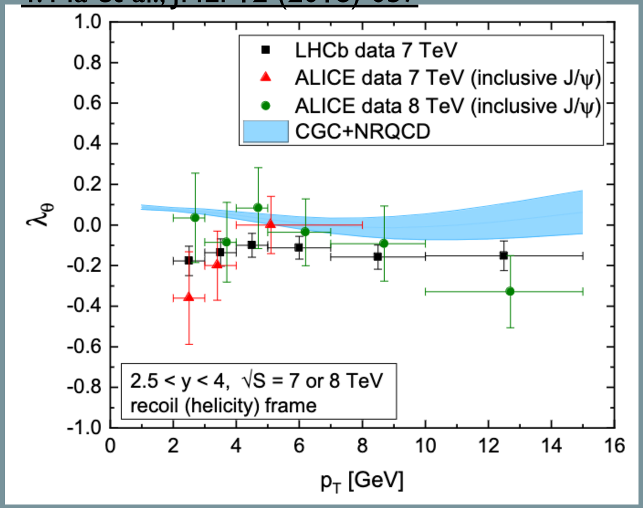




P. Faccioli et al., Phys. Lett. B. 07 (2014) 006



Y. Ma et al., JHEP12 (2018) 057



- Simultaneous description of quarkonium cross section and polarization observables: a long standing puzzle for models
- S-wave quarkonium produced almost unpolarized at LHC, long standing challenge for NRQCD
- χ_{c1} and χ_{c2} (P-wave) results from CMS favor a scenario where at least one of the two states is strongly polarized (HX), in agreement with NRQCD

CMS Collab., PRL 124, 162002 (2020)

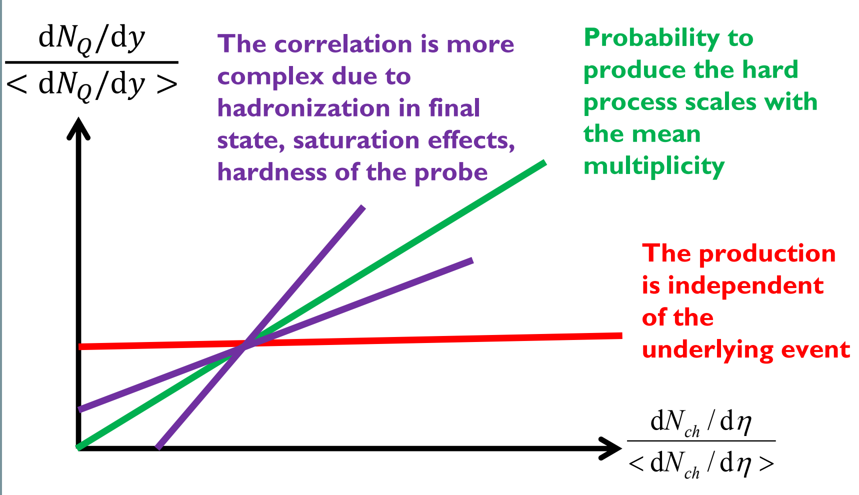
- Improvement of S-wave polarization description with NRQCD using global-fit analyses

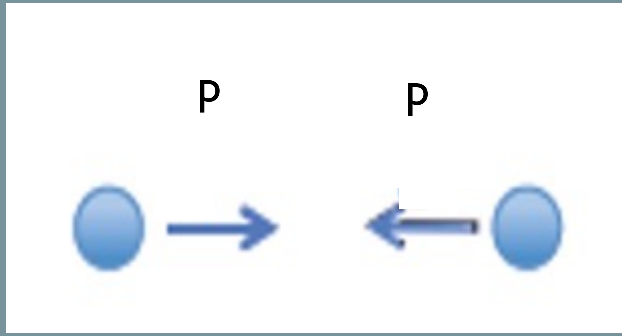
Quarkonium production in high multiplicity pp collisions and associated quarkonium production

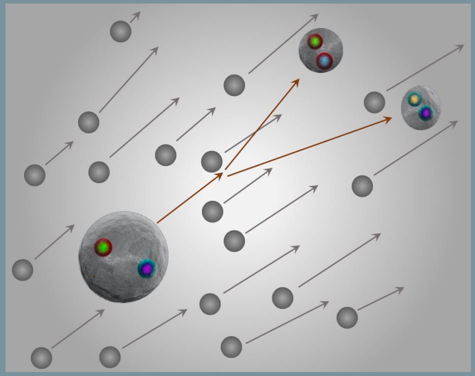
Initial state effects: Multiple parton interactions…

« High multiplicity » regime and associated quarkonium production

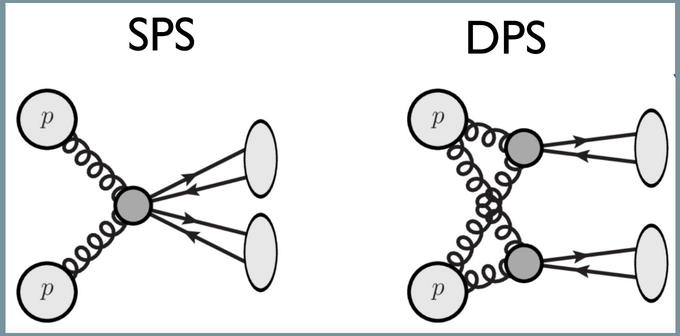
Final state effects: comovers…







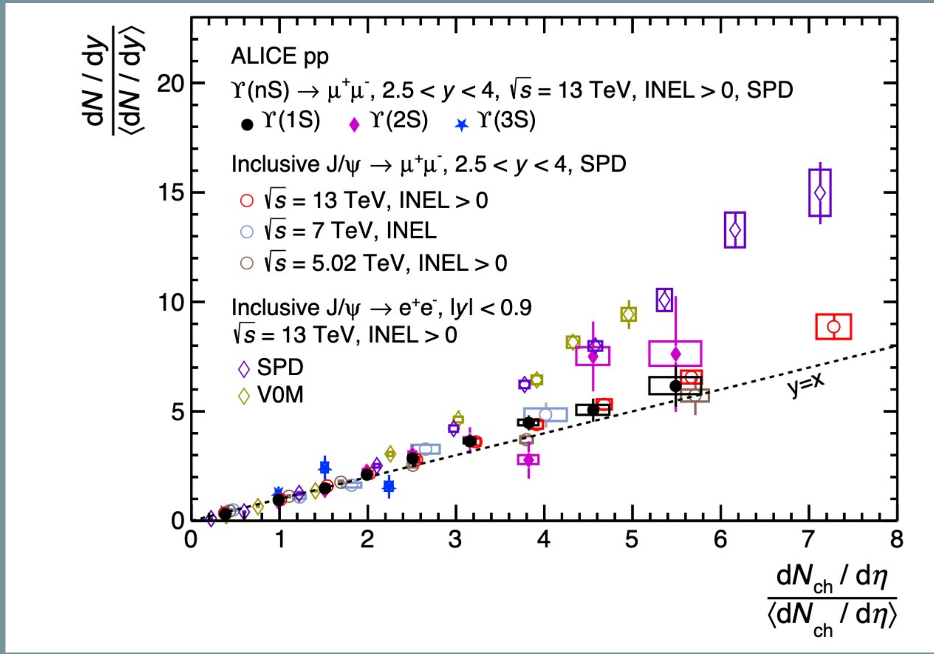
…and few related pPb results



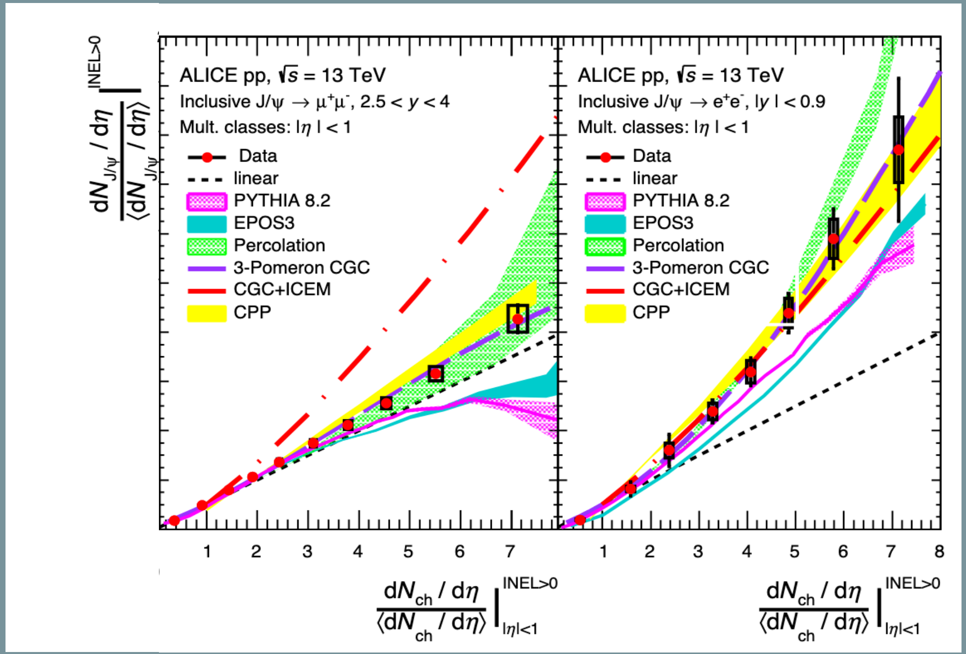
Collectivity

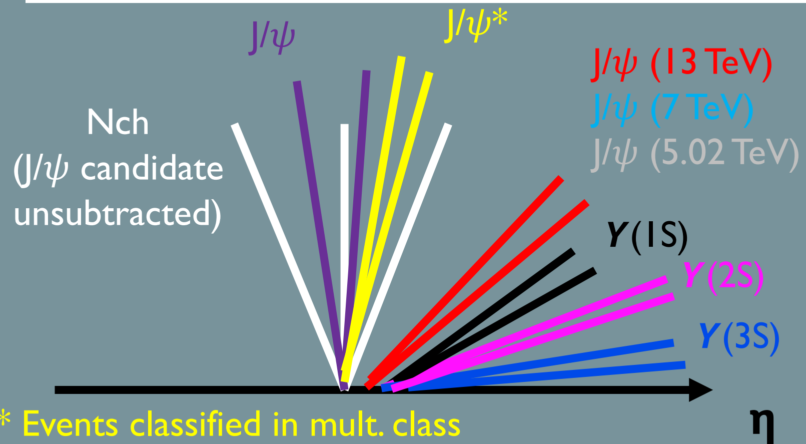
Quarkonium production versus multiplicity in pp collisions

ALICE Coll., arXiv:2209.04241



ALICE Coll., JHEP 06 (2022) 015



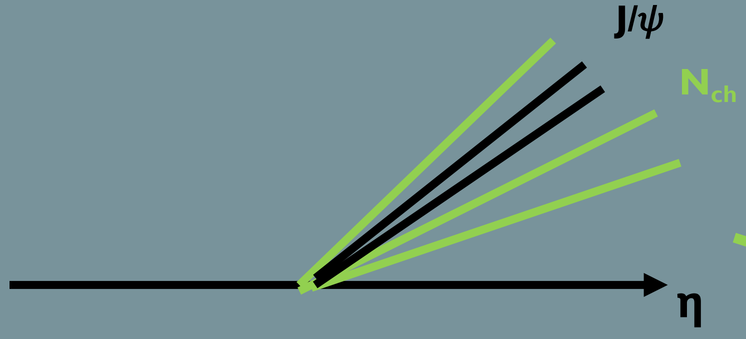


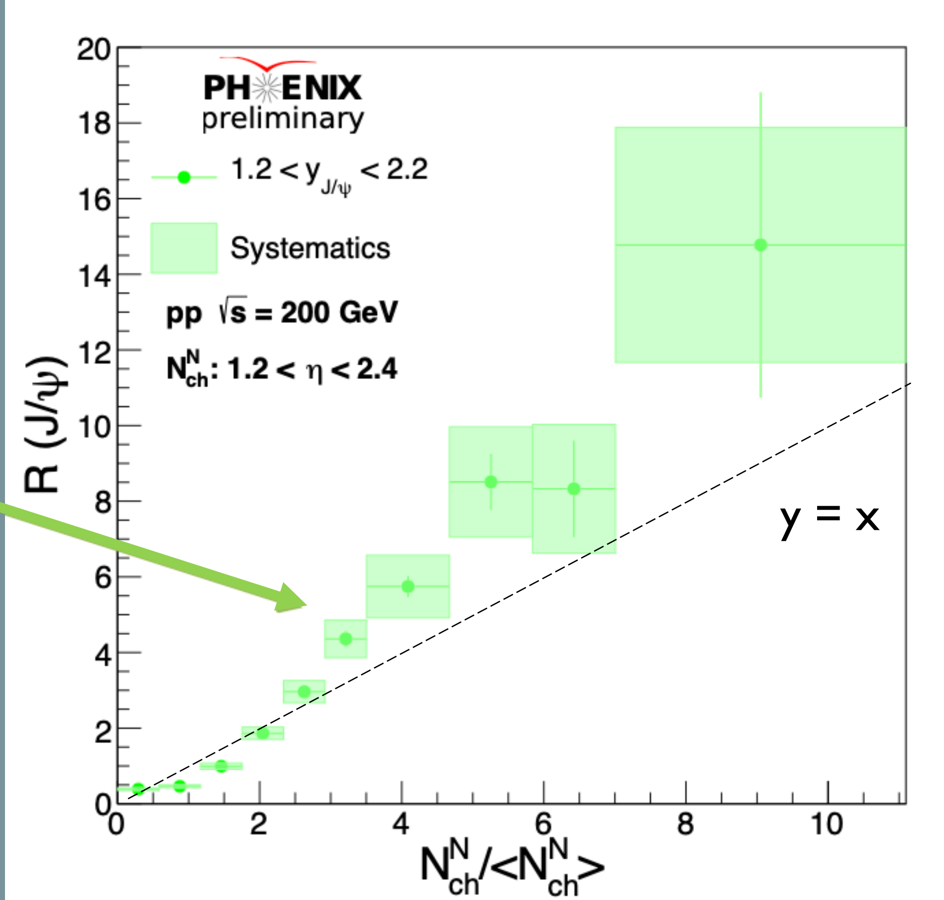
* Events classified in mult. class based on forward-y detector

- Study the correlation between soft and hard processes, role of MPI
- Stronger than linear increase for mid-y J/ψ, almost linear for forward J/ψ, Υ(ns)
- Different trend versus (midrapidity) multiplicity expected by most of the models for forward J/ψ and mid-y J/ψ, increase with mul. explained by different mechanisms (color reconnection, coherent particle production, 3-gluon fusion, saturation, or percolation) that might differ with rapidity. All models take into account MPI.

Quarkonium production versus multiplicity in pp collisions

- Different behaviour versus multiplicity could be related to the quarkonium rapidity, the charged particle rapidity, the Δy between the two (accounting for possible auto-correlations)…Need systematic scan of all quantities, and done recently by PHENIX





- Faster than linear increase when overlap in rapidity between N_{ch} and J/ψ

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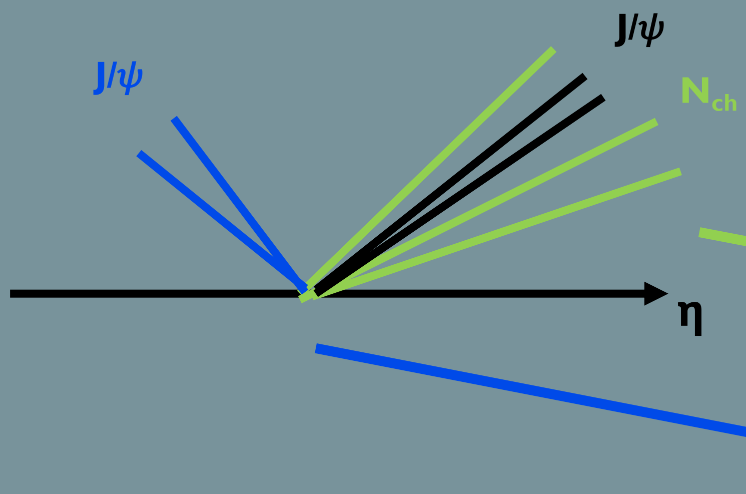

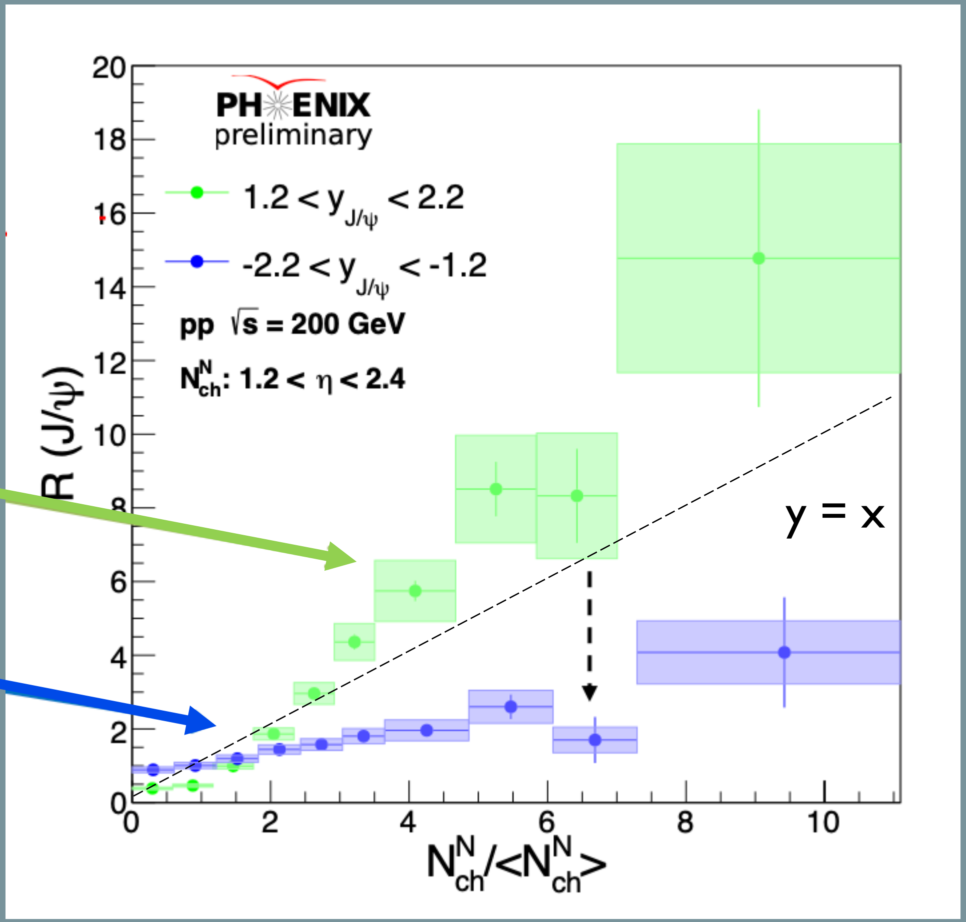

- Faster than linear increase when overlap in rapidity between N_{ch} and J/ψ
- Reduced increase with multiplicity for large Δy gap between N_{ch} and J/ψ

Quarkonium production versus multiplicity in pp collisions

SQM Strasbourg 2024

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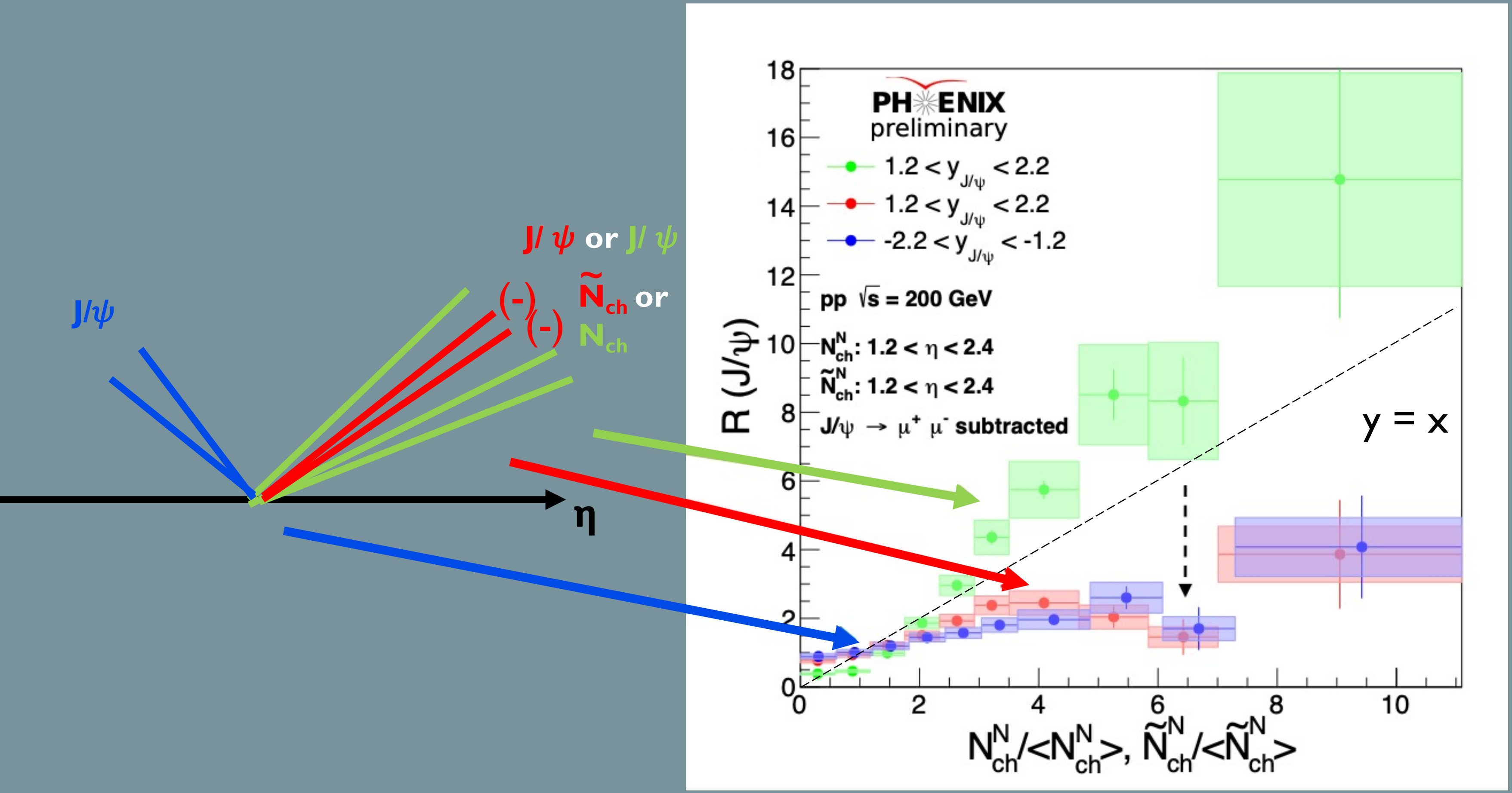

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- ❑ Reduced increase with multiplicity for large Δy gap between N_{ch} and J/ψ
- ❑ Strong reduction of the increase with mult. when J/ψ subtracted from the mult. evaluation (autocorrelations!)

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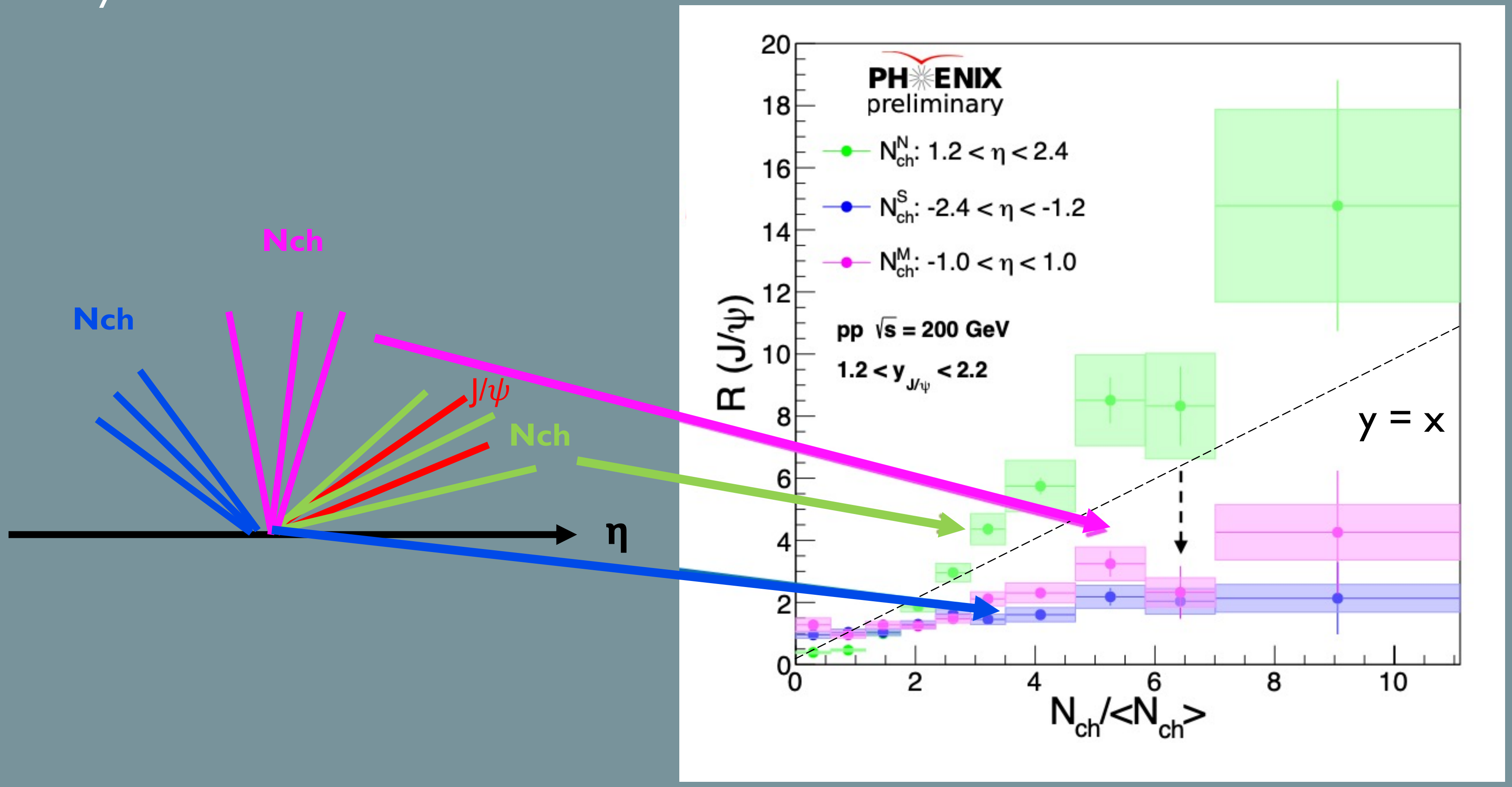

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- Reduced increase with multiplicity for large Δy gap between N_{ch} and J/ψ
- Strong reduction of the increase with mult. when J/ψ subtracted from the mult. evaluation (autocorrelations!)
- Less enhancement when large Δy gap between N_{ch} and J/ψ

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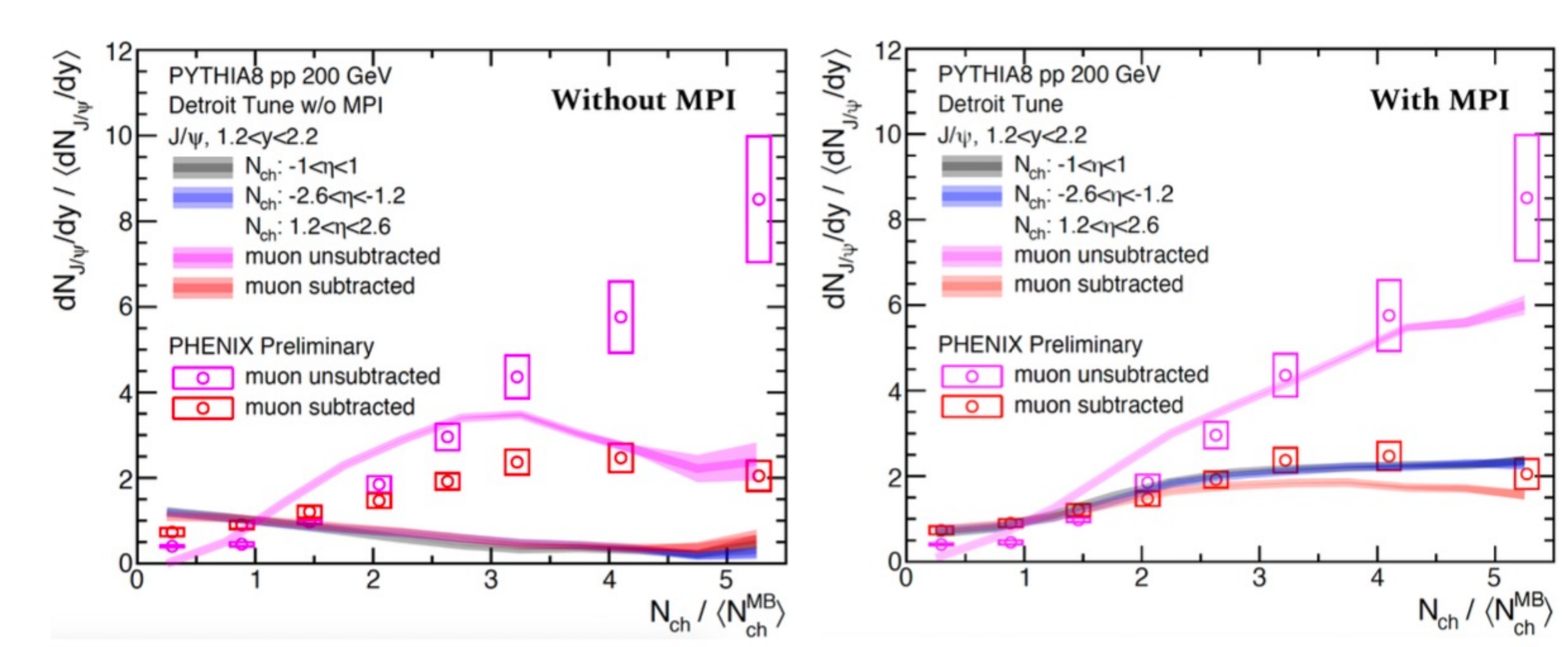

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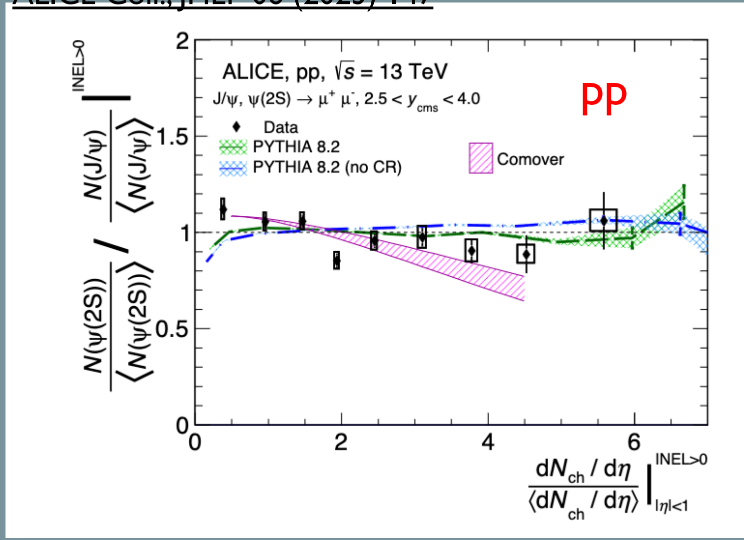
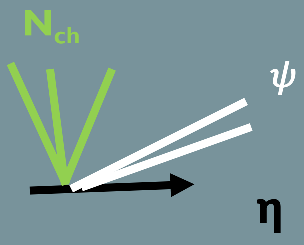
- Reduced increase with multiplicity for large Δy gap between N_{ch} and J/ψ
- Strong reduction of the increase with mult. when J/ψ subtracted from the mult. evaluation (autocorrelations!)
- Less enhancement when Δy gap between N_{ch} and J/ψ
- Results in between ALICE mid-y and forward-y
- MPI required to describe PHENIX data

Quarkonium excited to ground state ratio versus multiplicity

ALICE Coll., JHEP 06 (2023) 147



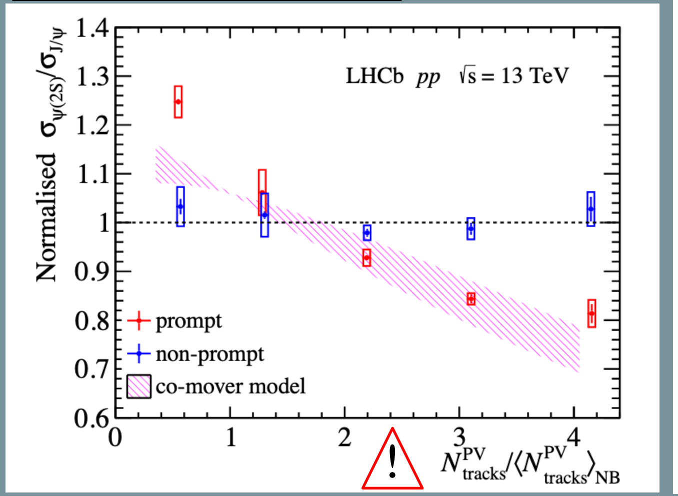


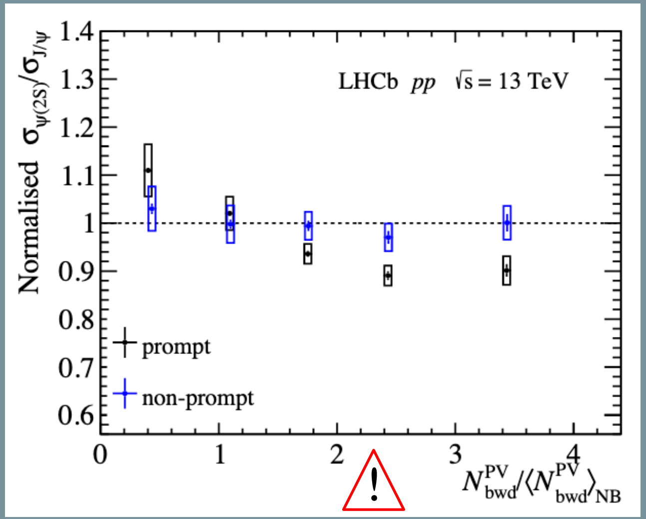
- Excited to ground state ratio to pin down final state effects on quarkonium production in high multiplicity events (eg. comovers)
- ALICE forward incl. ψ(2S)/J/ψ ratio vs mid-y mult. compatible with flat trend and comover scenario* within large unc. both in pp and pPb.

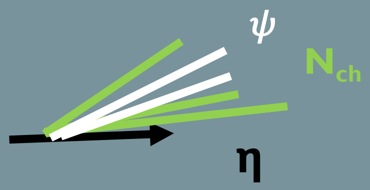
*for prompt production

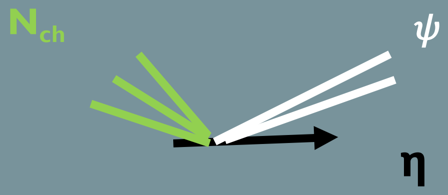
Quarkonium excited to ground state ratio versus multiplicity

LHCb Coll., arXiv:2312.15201









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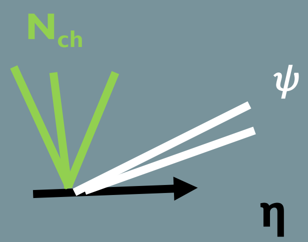
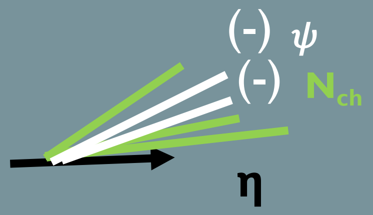
- ALICE forward incl. $\psi(2S)/J/\psi$ ratio vs mid-y mult. compatible with flat trend and comover scenario* within large unc. both in pp and pPb.

*for prompt production

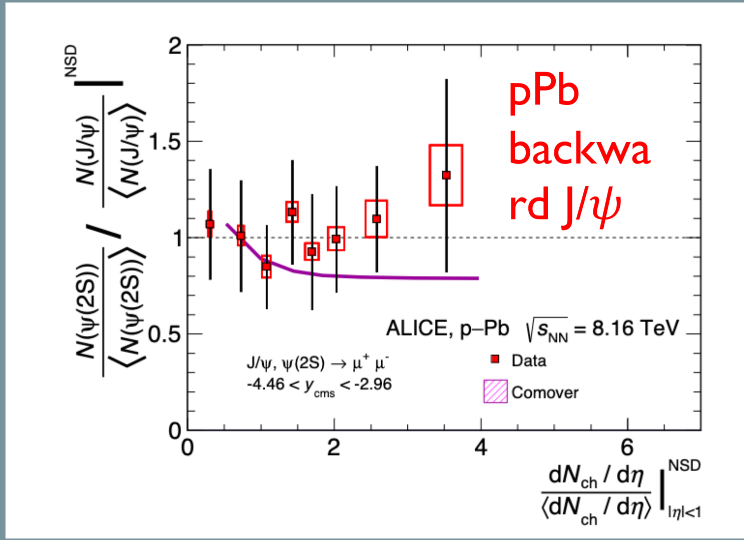
- New (precise) LHCb measurement separating prompt/non-prompt charmonium. Significant decreasing trend with multiplicity, compatible with comovers when probe and N_{ch} in the same rapidity interval (caveat: autocorrelation, x-axis not fully corrected)

Quarkonium excited to ground state ratio versus multiplicity

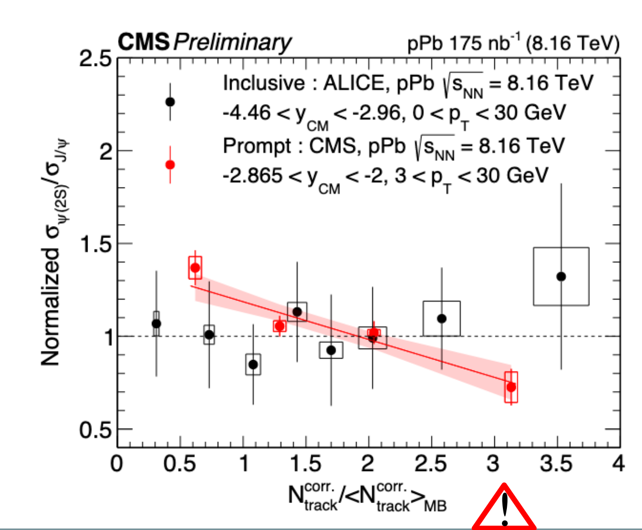




ALICE Coll., JHEP 06 (2023) 147



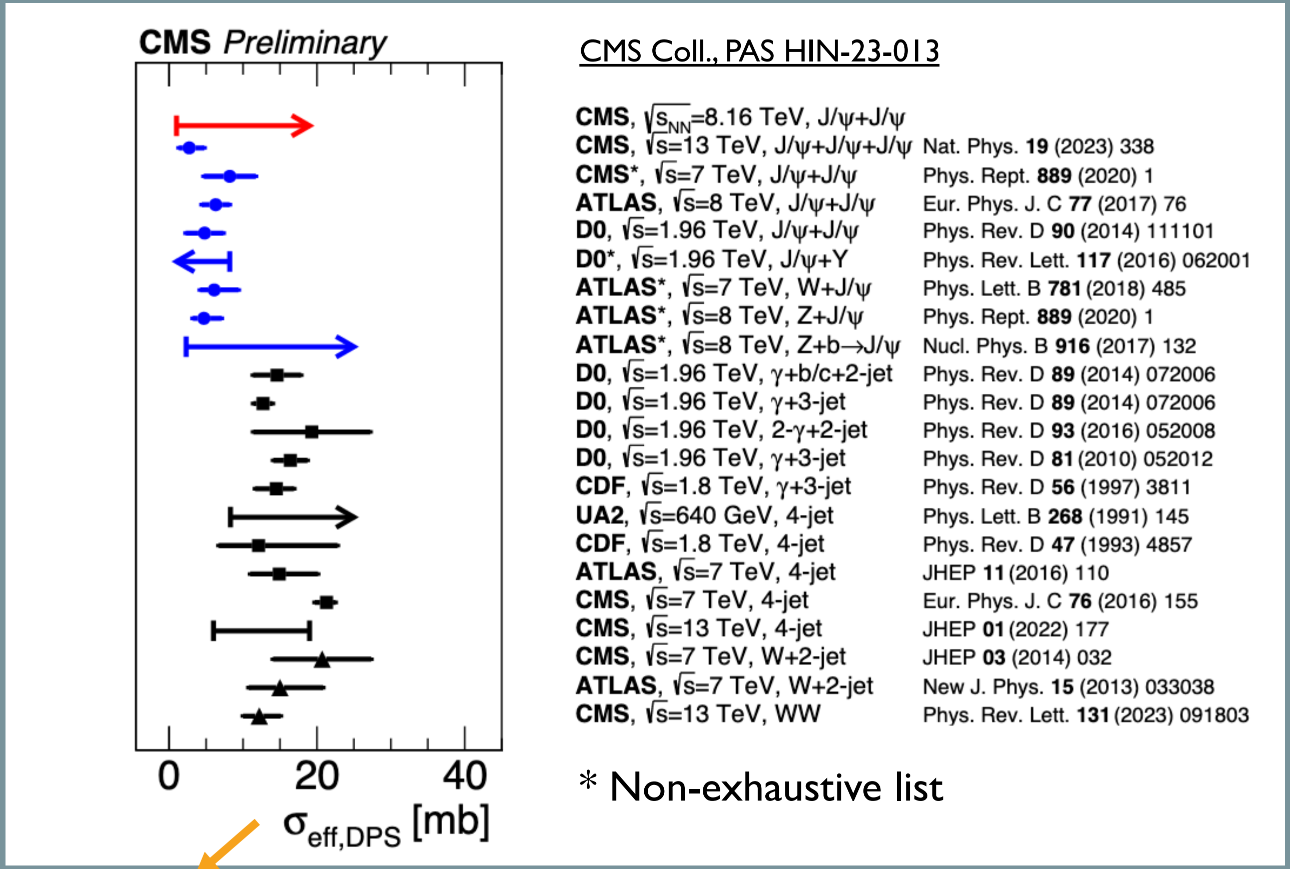
CMS Coll., CMS-PAS-HIN-24-001



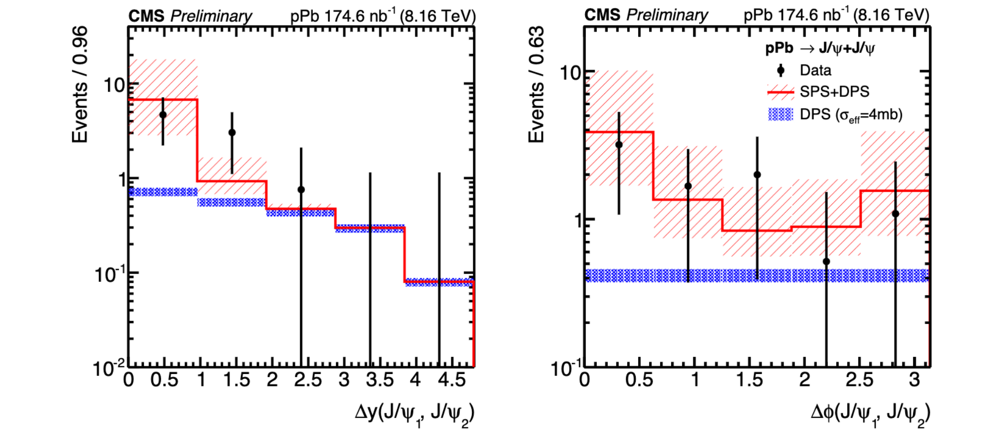
- ❑ Excited to ground state ratio to pin down final state effects in high multiplicity events
- ❑ ALICE forward incl. ψ(2S)/J/ψ ratio vs mid-y mult. compatible with flat trend and comover scenario within large unc. in pp
- ❑ New (precise) LHCb measurement (for prompt ψ(2S)/J/ψ) in pPb tends to favor comover scenario but several caveats for comparison to ALICE and models (x-axis corrections, $\Delta\eta$ between the probe and N_{ch})
- ❑ ALICE forward incl. ψ(2S)/J/ψ ratio vs mid-y mult. compatible with flat trend and comover scenario within large unc. in pPb
- ❑ New precise CMS measurement for prompt ψ(2S)/J/ψ ratio tends to favor comovers (also caveats in comparison to ALICE and models)

Associated quarkonium production in pp/pPb collisions

- Associated quarkonium production → Direct probe for MPI
- Pioneering measurements by CMS: triple J/ψ production in pp, double J/ψ production in pPb
- In pPb, benefit from the fact that large transverse parton density of the nucleus enhances DPS contribution w.r.t pp



- Use Δy and $\Delta\phi$ variables to disentangle SPS and DPS contribution to the di-J/ψ cross section



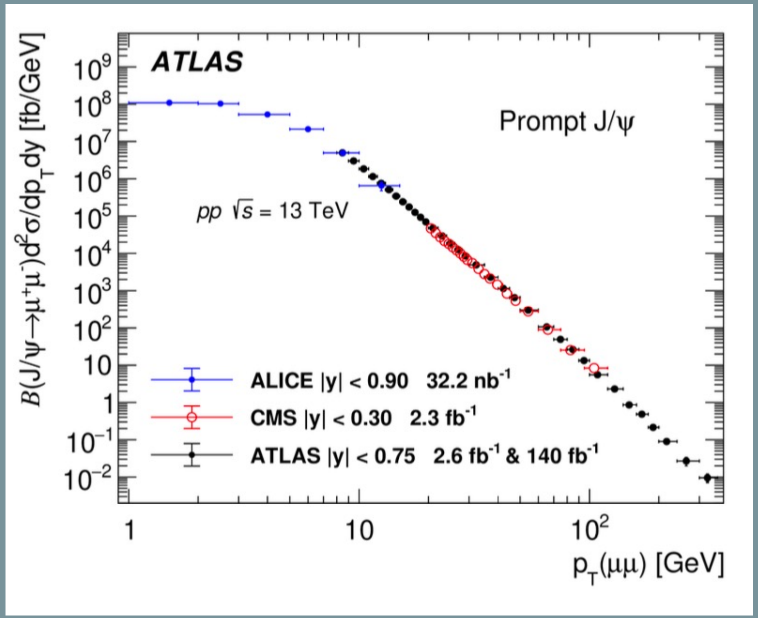
- Non universality of σ_{eff} → depends on parton species and x fraction probed

Characterizes the area occupied by the interacting partons in the transverse space

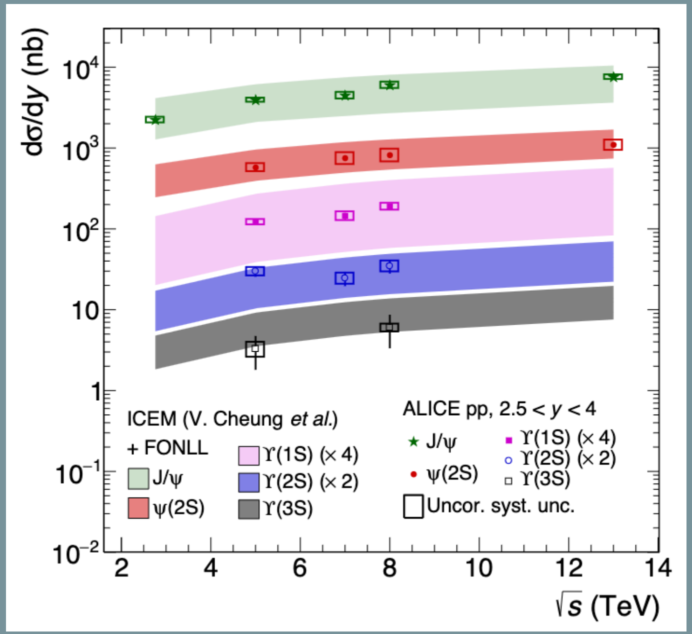
Take home message: quarkonium in pp collisions

- Large variety of precise quarkonium cross section measurements (over wide kinematic and energy ranges thanks to complementary experiments), together with polarization
- Improvement in the simulatenous description of both quantities by NRQCD and ICEM models
- Associated quarkonium production and quarkonium production versus multiplicity powerful to probe MPI and comovers but require for the latter : large statistics, common description of axis by experiments (and compatible with theory outputs), systematic scans with rapidity of the probe and of the multiplicity (accounting for autocorrelations when any)

ALICE Coll., JHEP 03 (2022) 190
ATLAS Coll., EPJC 78 (2018) 171
LHCb Coll., EPJC 77 (2017) 269



ALICE Coll, EPJC 83 (2023) 61

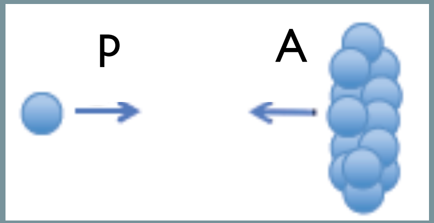


Quarkonium production in pA collisions

Cold nuclear matter effects

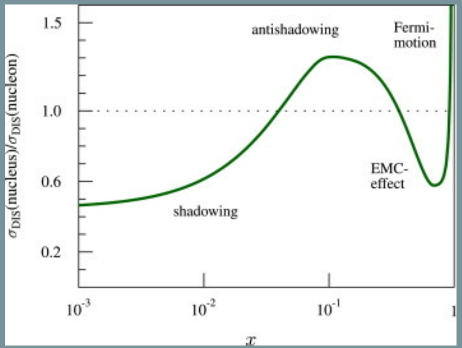
Collectivity

$$R_{\mathrm{pPb}}(y_{\mathrm{cms}}, p_{\mathrm{T}}) = \frac{\mathrm{d}^2\sigma^{\mathrm{J}/\psi}_{\mathrm{pPb}}/\mathrm{d}y_{\mathrm{cms}}\mathrm{d}p_{\mathrm{T}}}{A_{\mathrm{Pb}} \cdot \mathrm{d}^2\sigma^{\mathrm{J}/\psi}_{\mathrm{pp}}/\mathrm{d}y_{\mathrm{cms}}\mathrm{d}p_{\mathrm{T}}}$$

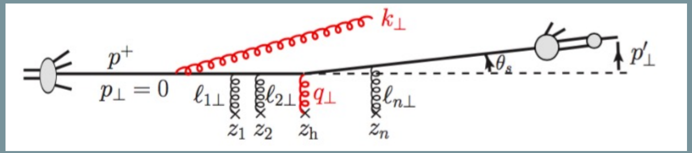


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2\mathrm{v}_n \cos\left(n\left(\phi - \Psi_{RP}\right)\right)\right)$$

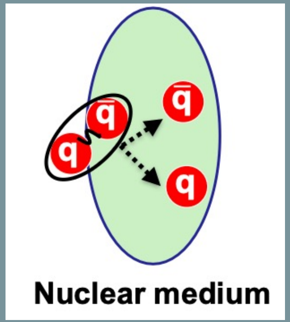
nPDF



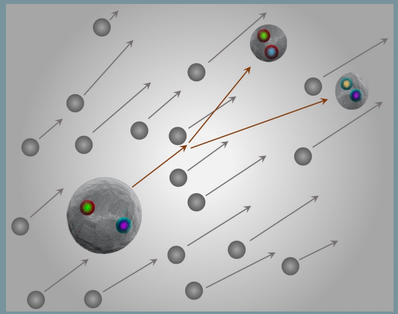
coherent energy loss



nuclear absorption



comovers

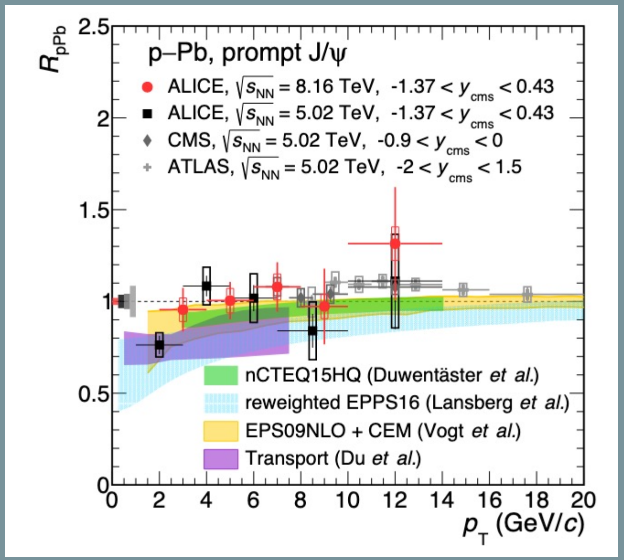


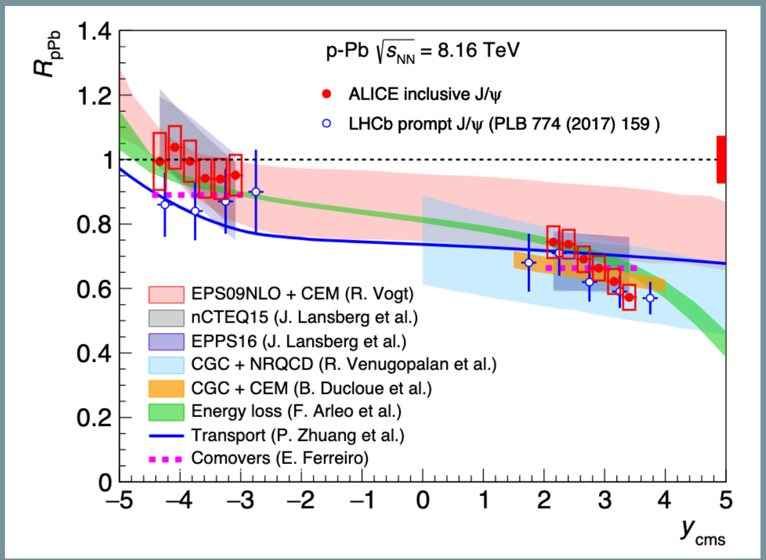
Cold nuclear matter effects on J/ψ production in pPb/pAu

Strasbourg 2024

ALICE Coll., JHEP 1807 (2018) 160, LHCb Coll., Phys. Lett. B 774 (2017) 159

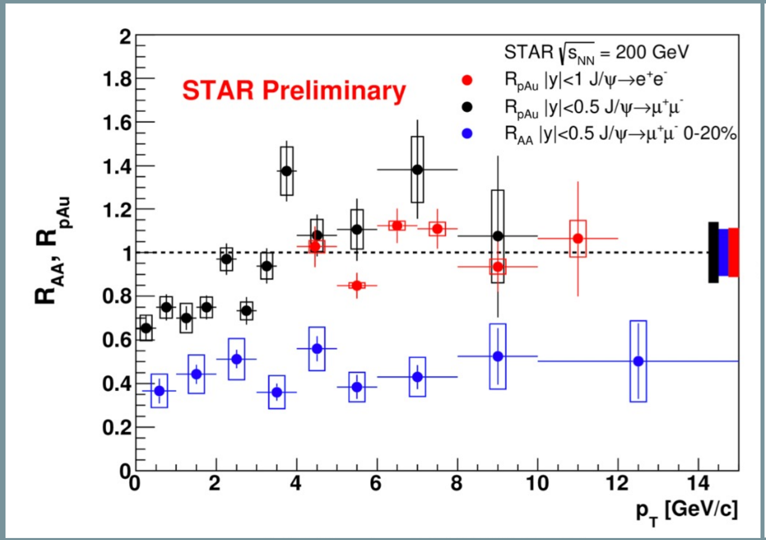
ALICE Coll., JHEP 07 (2023) 137
ALICE Coll., JHEP 06 (2022) 011
ATLAS Coll. Phys.. Rev. C 92 (2015) 034904
CMS Coll., Eur. Phys. J. C 77 (2017) 269

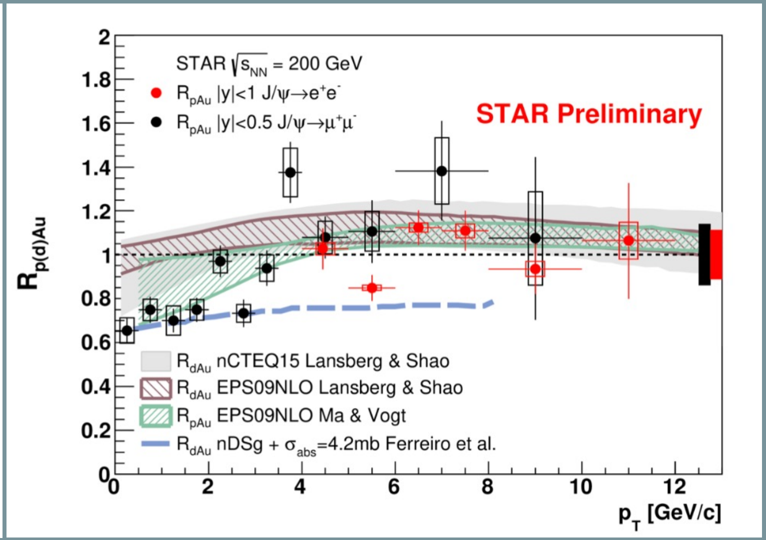




- LHC energies:
  - Moderate CNM on prompt J/ψ at mid-rapidity (mainly low p_T), modeled by nPDF
  - Stronger suppression at forward-y (p-going) describe by several models (nPDFs, coherent energy loss…)

STAR Coll., Phys. Lett. B 825 (2022) 136865
STAR Coll., Phys. Lett. B 797 (2019) 134917



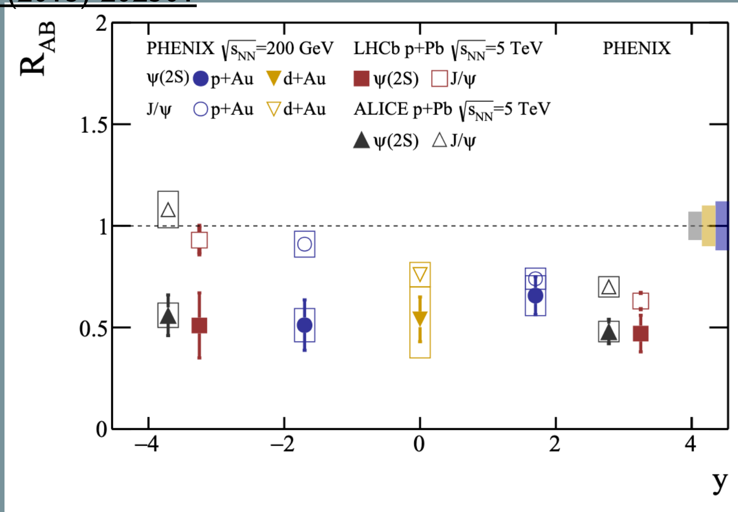


- RHIC energies:
  - Suppression due to CNM also concentrated at low p_T for midrapidity and described by nPDFs

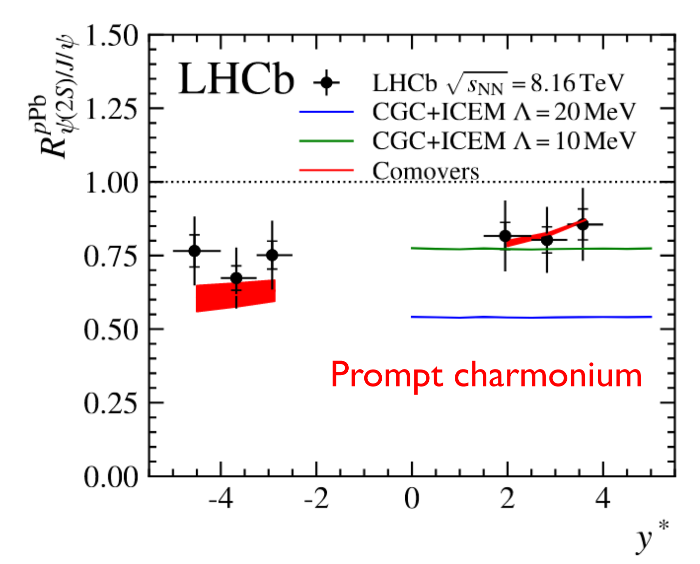
- What about excited charmonia?

Cold nuclear matter effects on $\psi(2S)$ production in pPb/pAu

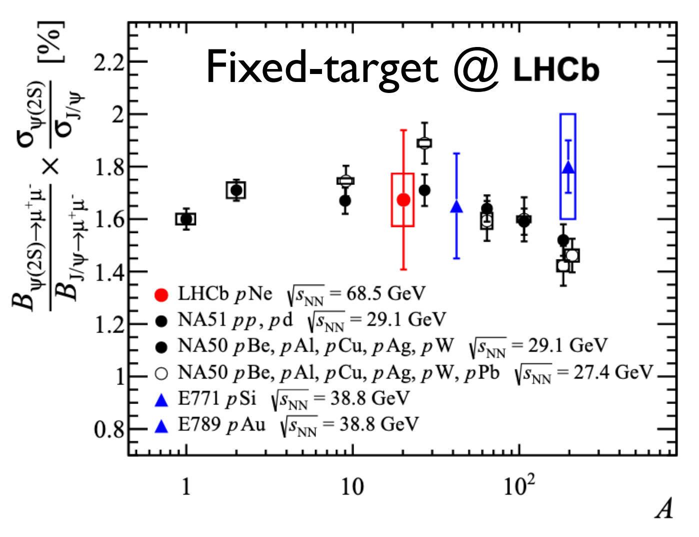
PHENIX Coll., Phys. Rev C. 105 (2022) 064912 and ref therein
PHENIX Coll., Phys. Rev Lett. 111 (2013) 202301



LHCb Coll., arXiv:2401.11342



LHCb Coll., EPJC 83 (2023) 625 and ref therein

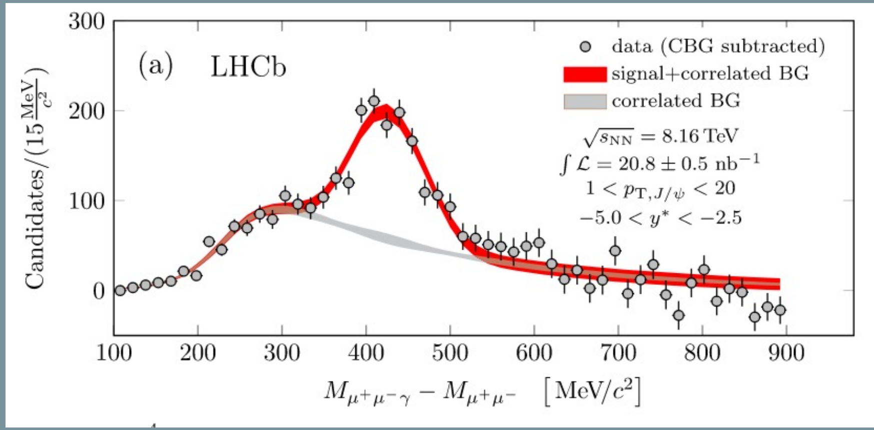


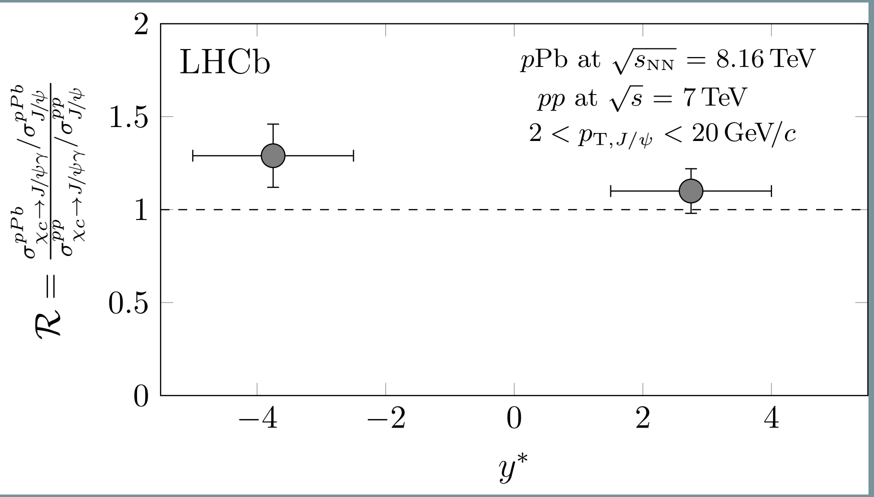
- Similar R_{pPb} evolution for J/ψ and $\psi(2S)$ at LHC and RHIC in pPb/pAu despite different c.m.s energies
- Stronger suppression for $\psi(2S)$ w.r.t J/ψ at backward rapidity, suggesting final state effects at play (and of similar strength at both energies)
- Recent prompt $\psi(2S)/J/\psi$ measurement from LHCb, described by comover models both at forward and backward rapidities
- LHCb SMOG pNe measurement in agreement with other $\psi(2S)/J/\psi$ ratio measurements at low energy

Cold nuclear matter effects on χ_c production in pPb

SQM Strasbourg 2024

LHCb Coll., PRL132 (2024) 102302, LHCb-PAPER-2023-028



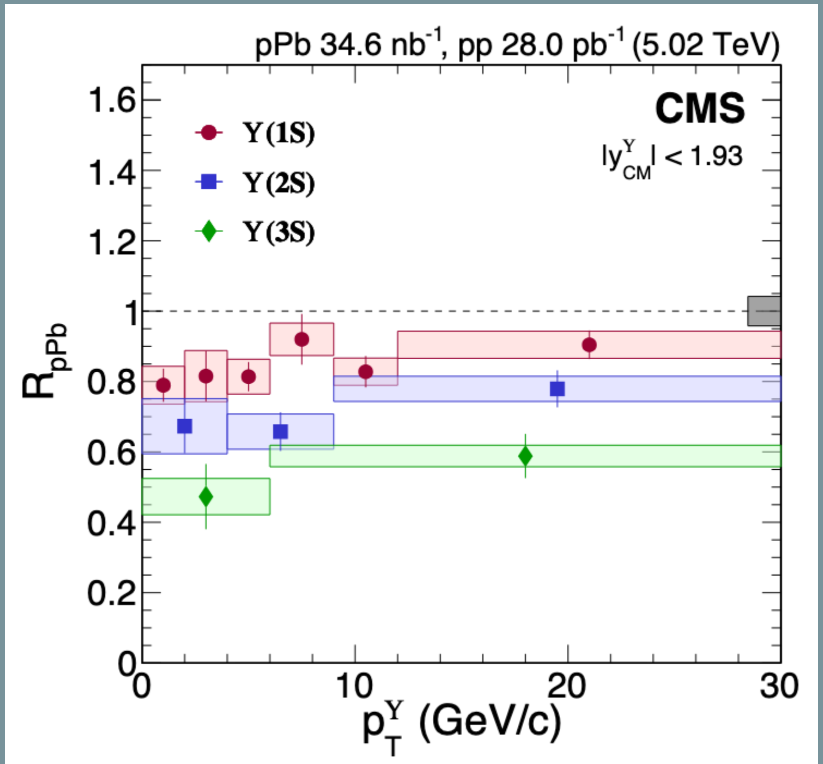


- New measurement by LHCb of $\chi_{c1} + \chi_{c2}$ via $J/\psi+\gamma$ decay
- χ_c / J/ψ fraction in pPb consistent with pp data at forward y
- Ratio larger than unity at backward y could be related to $\psi(2S)$ suppression at backward y (and therefore affecting prompt J/ψ production via feed-down)
- No final state dissociation of χ_c observed in pPb collisions

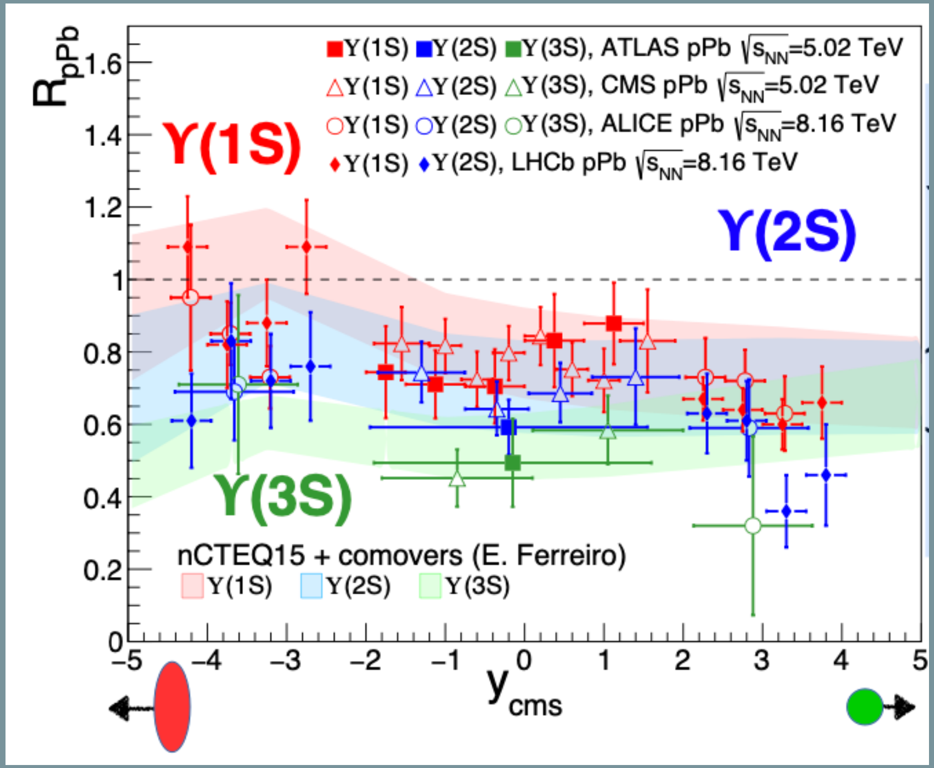
Reminder : prompt J/ψ :
- Direct J/ψ
- J/ψ from χ_c decay
- J/ψ from $\psi(2S)$ decay

Cold nuclear matter effects on Υ production in pPb

CMS Coll., Phys. Lett. B 835 (2022) 137397



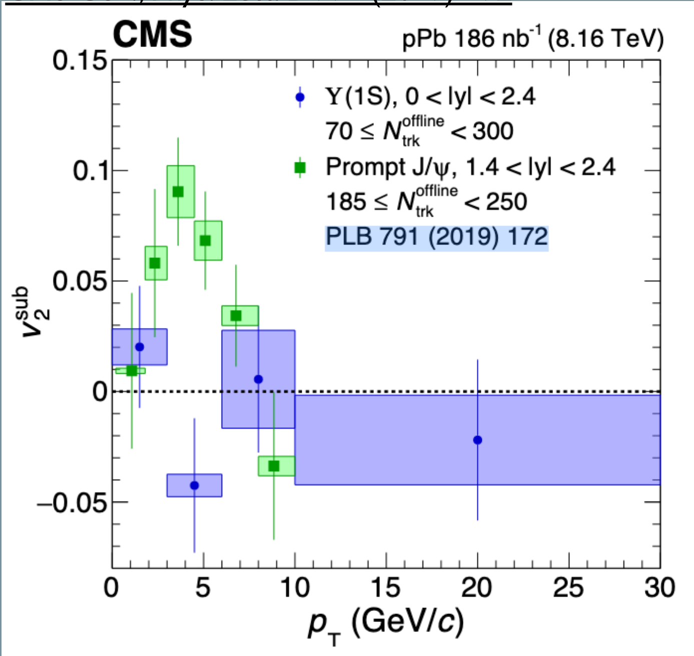
LHCb Coll., JHEP 11 (2018) 194
ATLAS, EPJC 78 (2018) 3, 171
ALICE, PLB 806 (2020) 135486



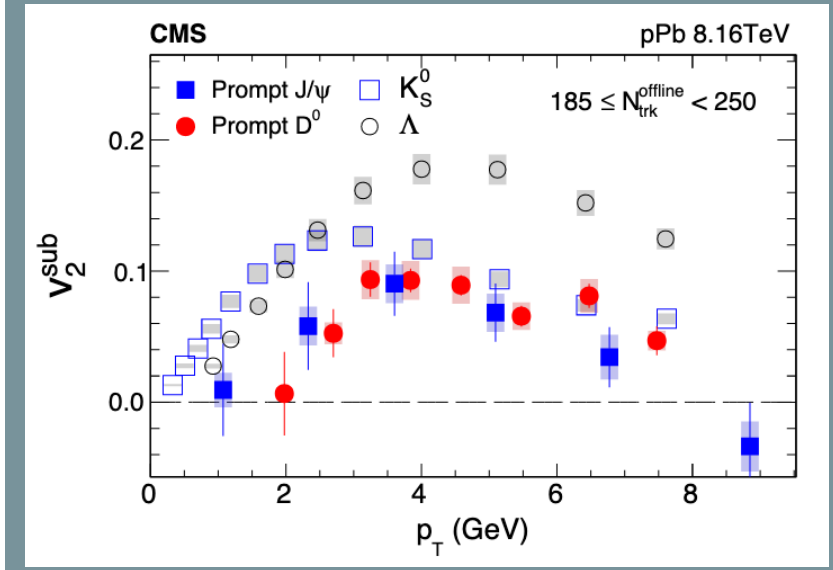
- CMS at mid-rapidity: Indication of suppression for Υ(nS) states, stronger suppression for excited states (following order of binding energies), $R_{pPb}(\Upsilon(1S)) > R_{pPb}(\Upsilon(2S)) > R_{pPb}(\Upsilon(3S))$
- Final state effects required to describe the stronger suppression for excited states. nPDFs+comovers describe the rapidity trend of the Υ(nS) RpPb (caveat large experimental uncertainties for excited states in some of the y bins)

Quarkonium elliptic flow in pPb

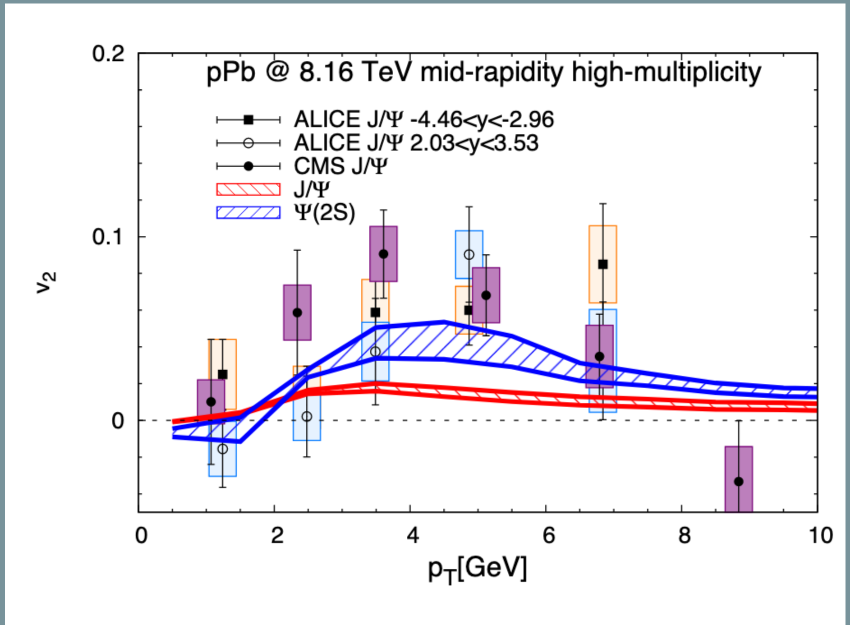
CMS Coll., Phys. Lett. B 850 (2024) 138518
CMS Coll., Phys. Lett. B 791 (2019) 172



CMS Coll., PLB 791 (2019) 172 and ref therein



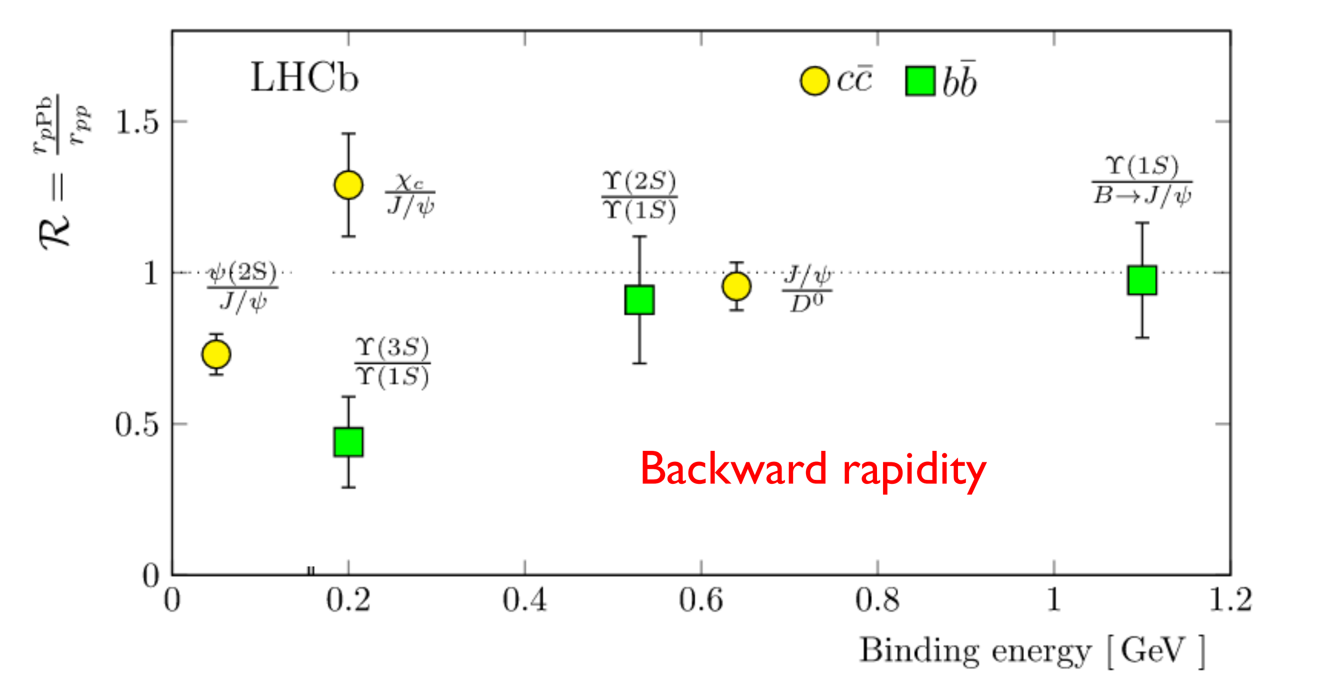
X. Du et al, High Energy Phys. (2019) 2019:15 and ref therein



- Evidence for non-zero prompt J/ψ v_2 in high multiplicity pPb collisions (evidence for heavy quark collectivity, weaker collectivity for heavy quarks than light quarks)
- Υ(1S) v_2 consistent with zero, smaller than J/ψ v_2
- Transport model underestimates J/ψ v_2 (negligible path length dependent effects and regeneration in pPb). Similar v_2 at forward and backward rapidity (although different event multiplicities) suggest that observed v_2 cannot originate from final-state interactions alone

Take home message: quarkonium in pA collisions

LHCb Coll., PRL132 (2024) 102302, LHCb-PAPER-2023-028

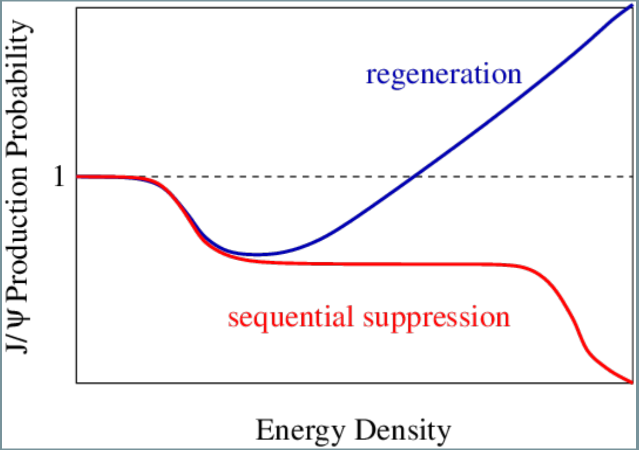


- Systematic studies of charmonia (including χ_c!) and bottomonia states in pA collisions done at LHC. Important to understand feed-down effects
- Weakly bound resonances (ψ(2S),Υ(3S)) seem suppressed with respect to their ground state at backward rapidity (except for χ_c)
- Significance of the deviation w.r.t unity still not so large → improved precision would help

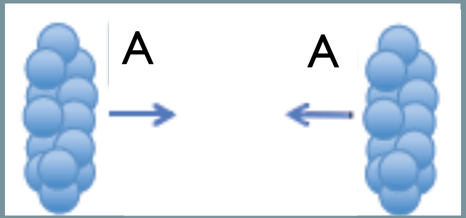
Quarkonium production in AA collisions

Hot nuclear matter effects

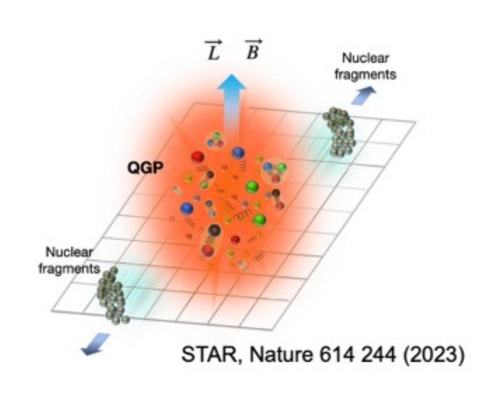
$$R_{AA} = \frac{d^2N/(dy\,dp_T)}{\langle T_{AA}\rangle\, d^2\sigma_{pp}/(dy\,dp_T)}$$



+ energy loss



Initial stages



$$\lambda_\theta = \frac{(1-3\rho_{00})}{(1+\rho_{00})}$$

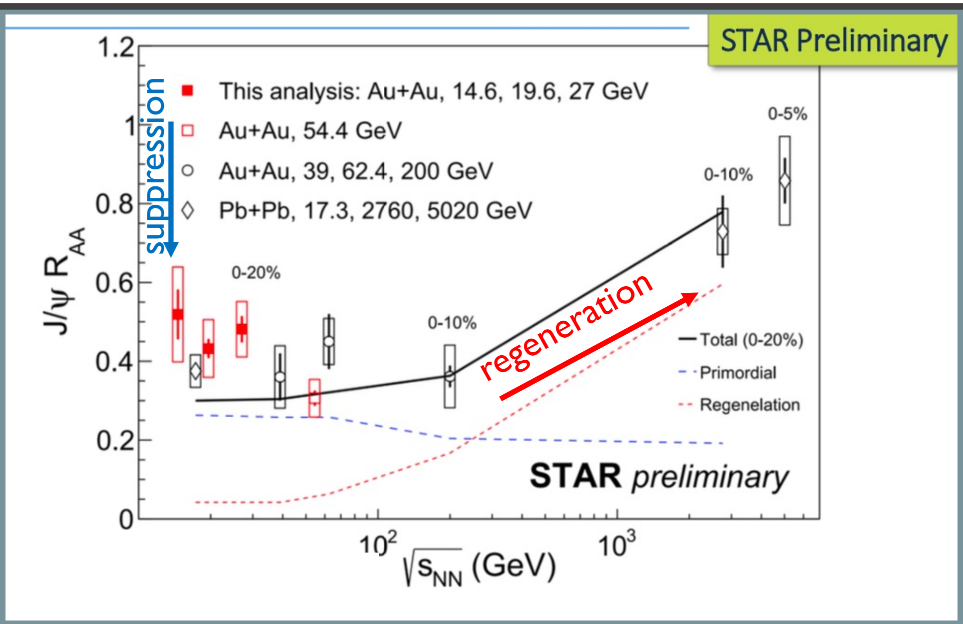
Collectivity

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_{RP}\right)\right)\right)$$

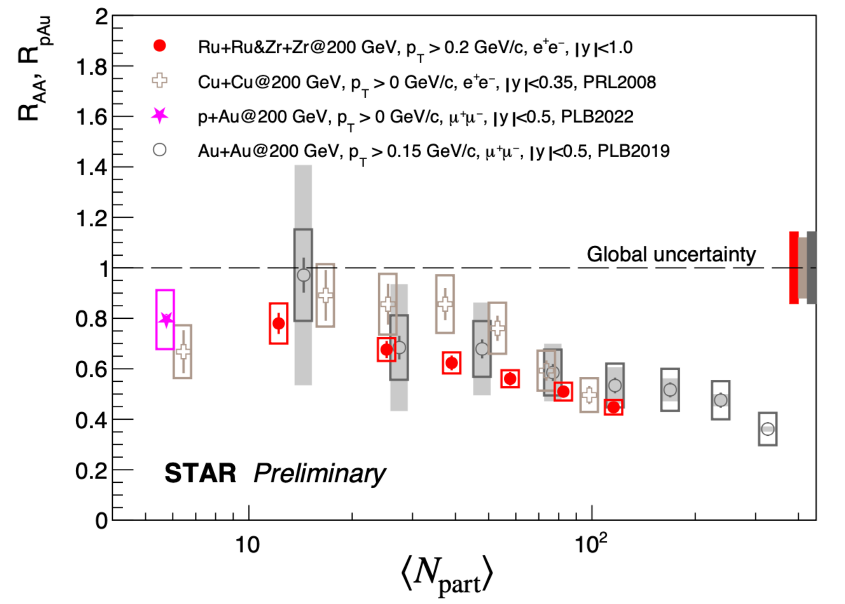
Cold nuclear matter effects

*B_c, X(3872) not covered

Energy and system size dependence of J/ψ R_{AA}



STAR Coll., PLB 771 (2017) 13
STAR Coll. PLB 797 (2019) 134917
ALICE Coll., NPA1005 (2021) 121769
ALICE Coll., PLB 734 (2014) 314
NA50 Coll., PLB 477 (2000) 28

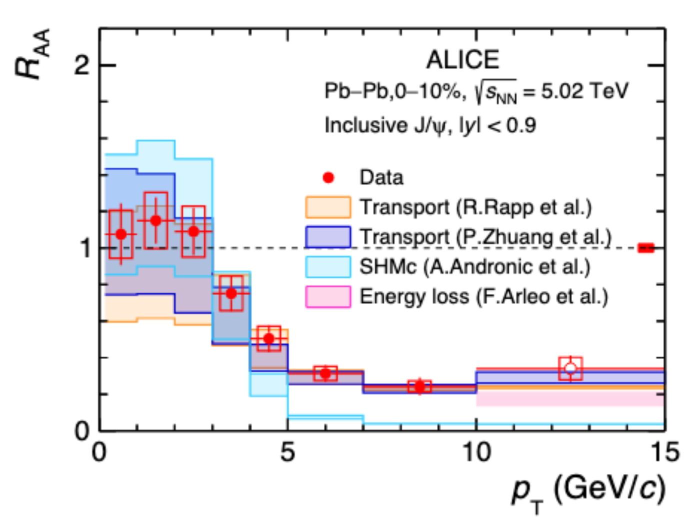


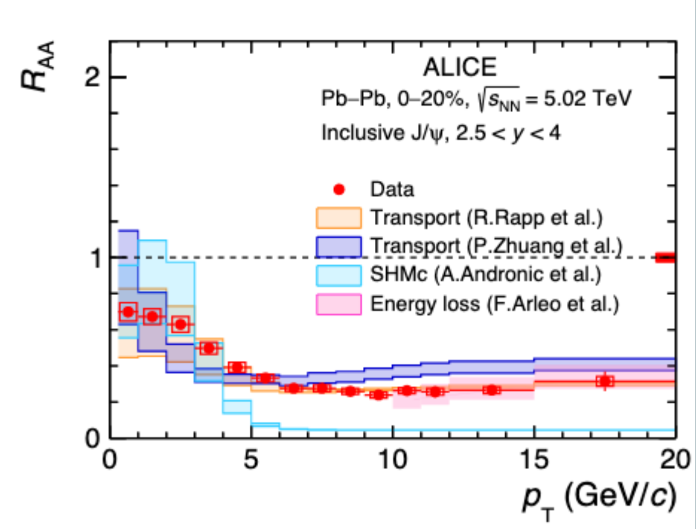
- ❑ Strong rise of the J/ψ R_{AA} from RHIC to LHC energies → evidence for charmonium regeneration at LHC

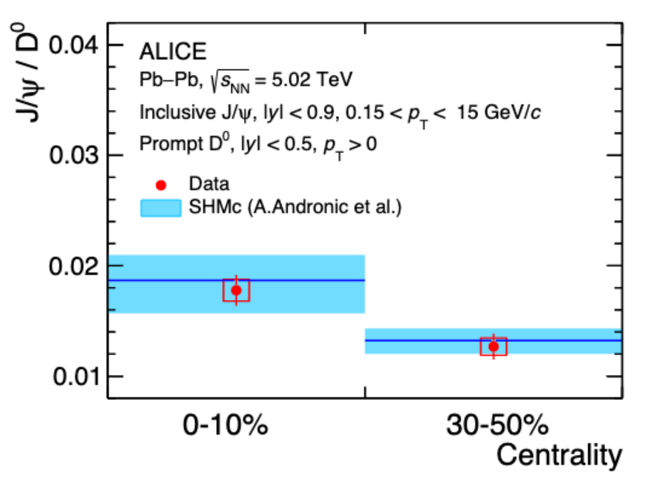
- ❑ STAR: No strong collision system size dependence of the J/ψ R_{AA}
- ❑ Amont of suppression at $\sqrt{s_{NN}}$ = 200 GeV in Au-Au beyond expectation from CNM

More on J/ψ R_{AA} at LHC

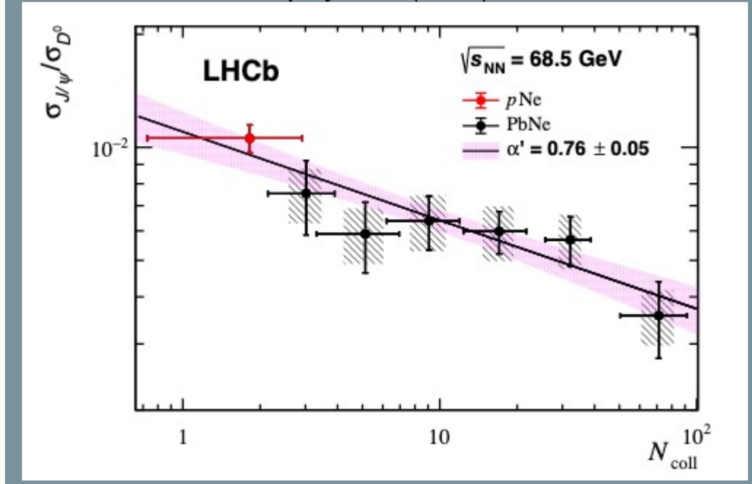
ALICE Coll., Phys. Lett. B 849 (2024) 138451







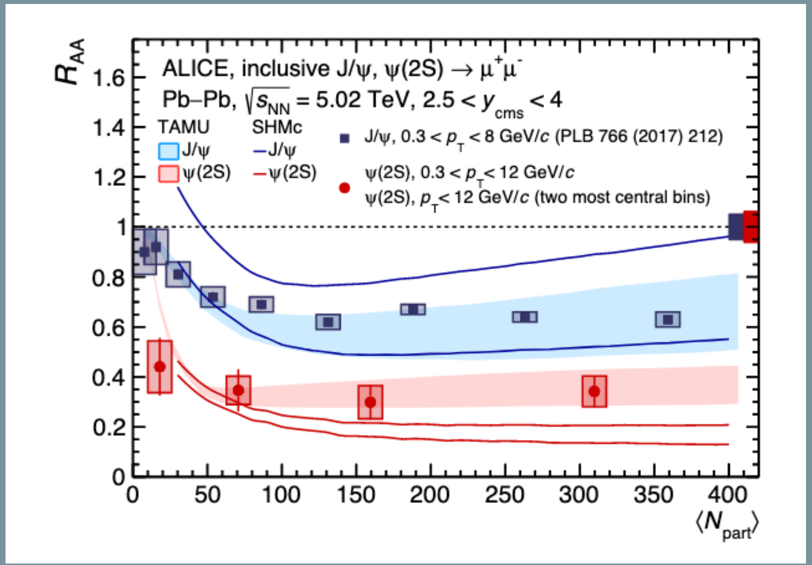
LHCb Coll., Eur. Phys. J C83 (2023) 658



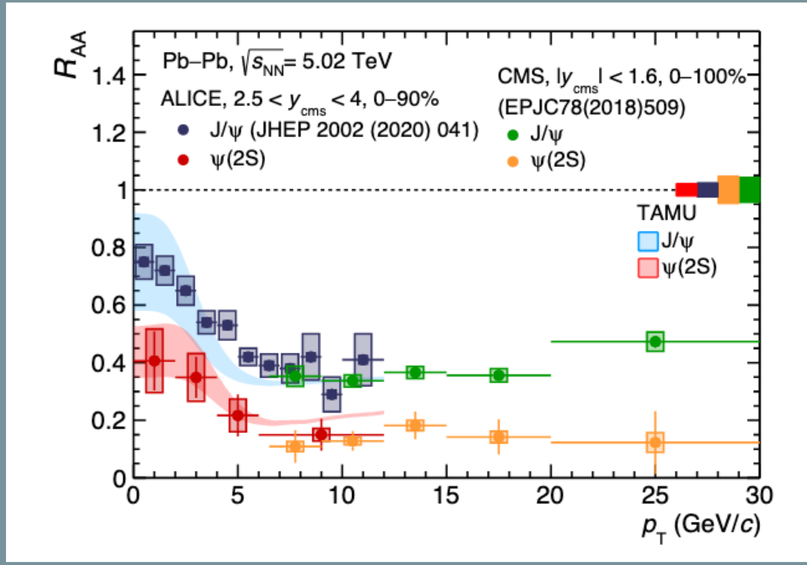
- ❑ J/ψ production in central Pb-Pb collisions described by an interplay between dissociation, regeneration and energy loss
- ❑ Stronger regeneration at midrapidity w.r.t forward rapidity
- ❑ $J/\psi/D^0$ ratio interesting to further contrain models (similar initial state). Increasing ratio with centrality well described by SHMc at $\sqrt{s_{NN}}$ = 5.02 TeV (ratio related to charm fugacity)
- ❑ Fixed Target@LHC: No evidence for anomalous J/ψ suppression in central Pb-Ne collisions at $\sqrt{s_{NN}}$ = 68.5 GeV

ψ(2S) R_{AA} and ψ(2S)/J/ψ (double) ratio

ALICE Coll., PRL 132 (2024) 042301

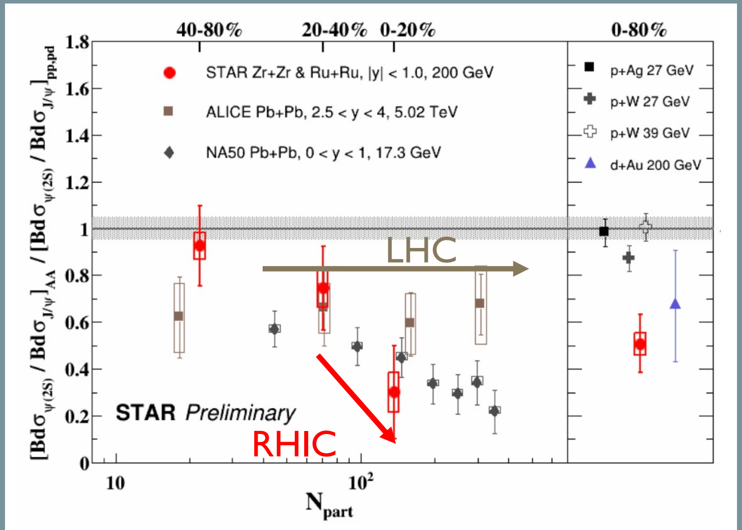


ALICE Coll., PRL 132 (2024) 042301, ALICE Coll., JHEP 2002 (2020) 041, CMS Coll., EPJC 78 (2018) 509



- A golden probe at low p_T to disentangle among regeneration models
- First hint of ψ(2S) regeneration at LHC energies (still statistically limited in Run 2)
- Transport model better reproduces the ψ(2S) R_{AA} in central Pb-Pb events

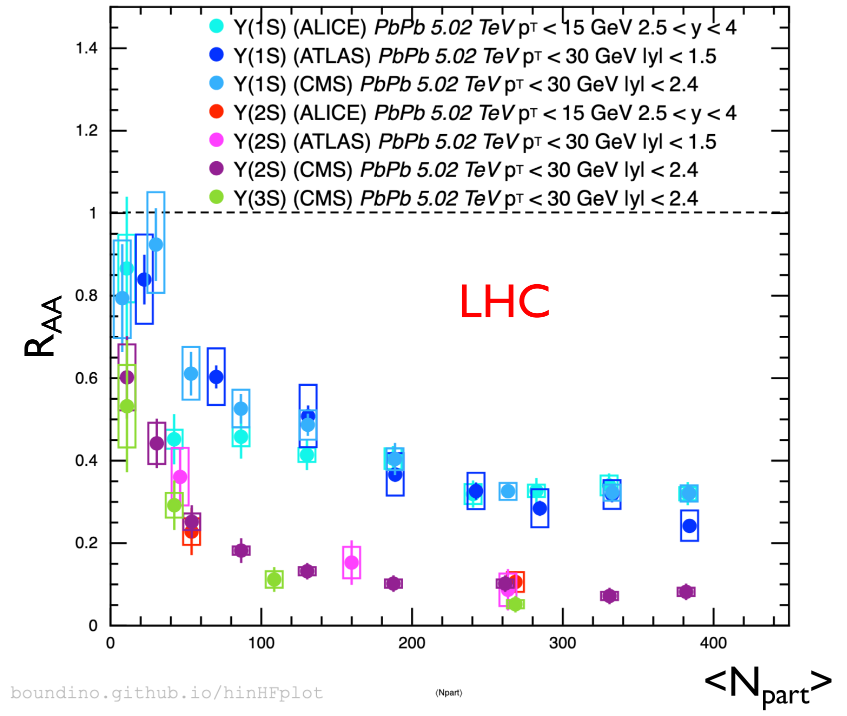
ALICE Coll., PRL 132 (2024) 042301
NA50 Coll., EPJC 49 (2007) 559

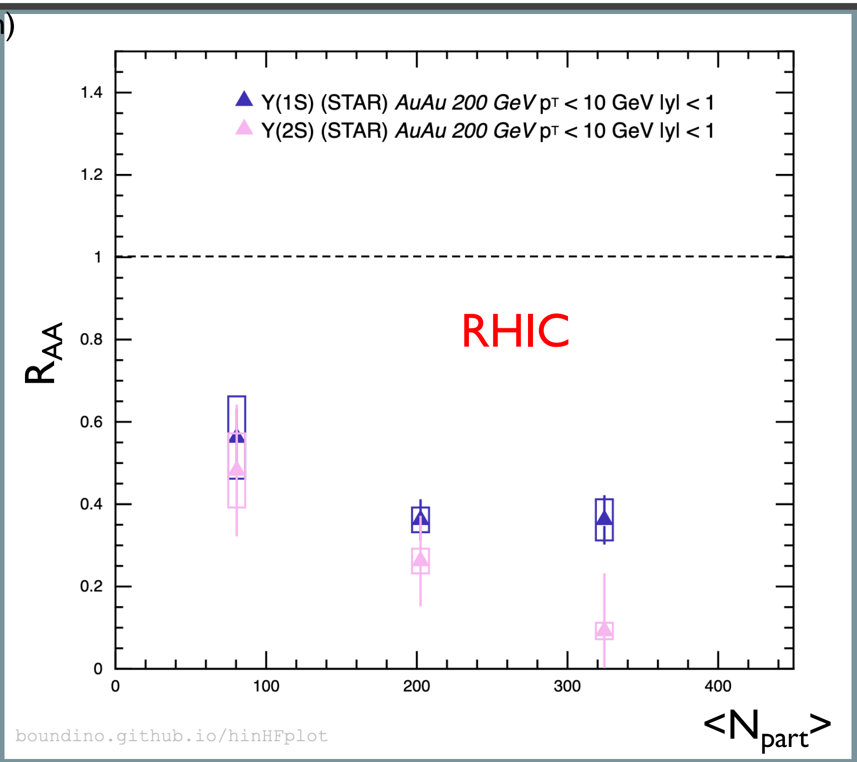


- Sequential suppression of charmonia at RHIC in AA, ψ(2S)/J/ψ double ratio in AA significantly lower than in pA

Υ(nS) R_{AA}

Generated from https://boundino.github.io/hinHFplot/ (ref therein)

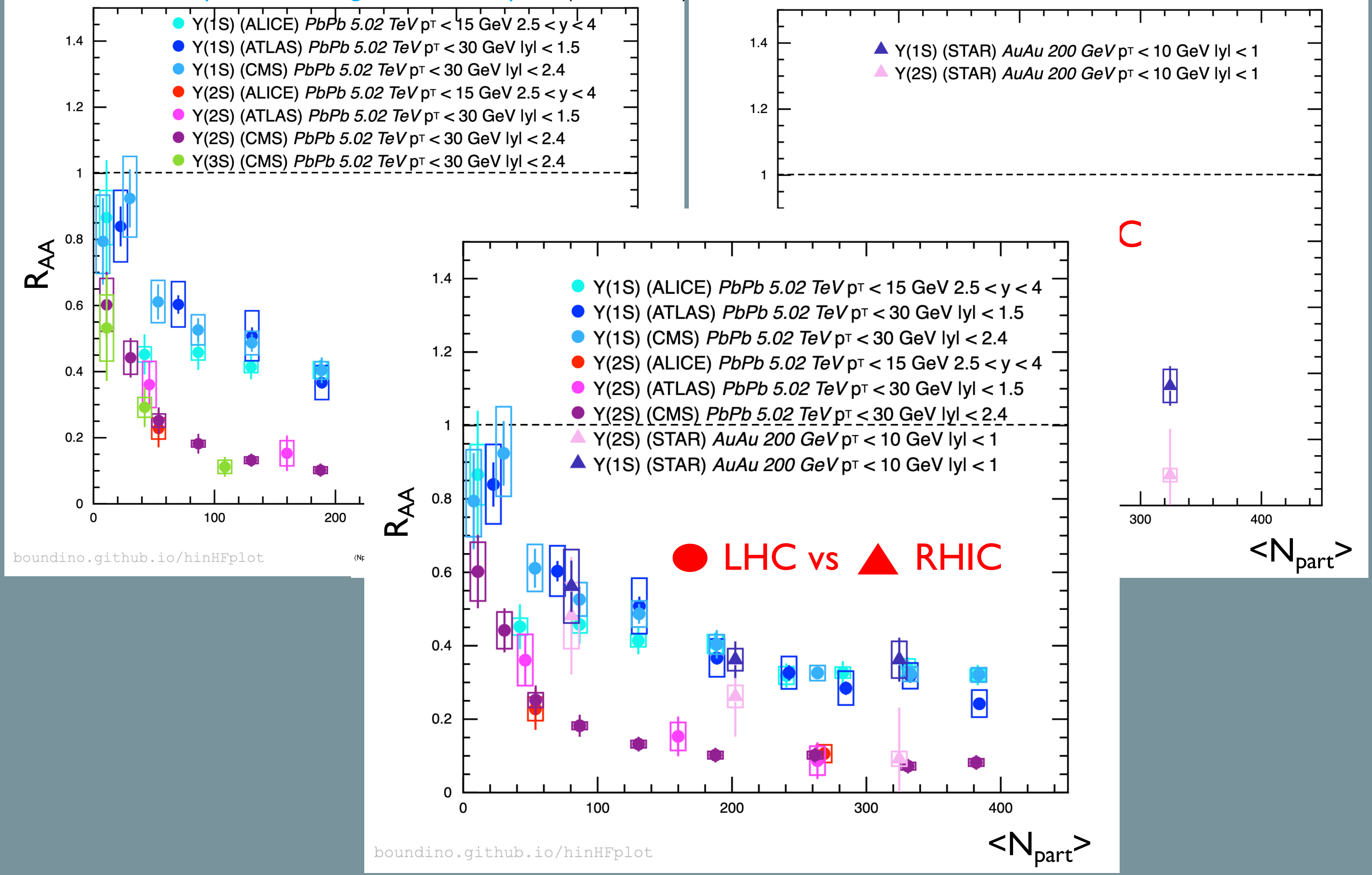




- Obervation of Υ(3S) by CMS in Pb-Pb collisions
- Sequential suppression of Υ(nS) states at LHC energy, and also at RHIC

Υ(nS) R_{AA}

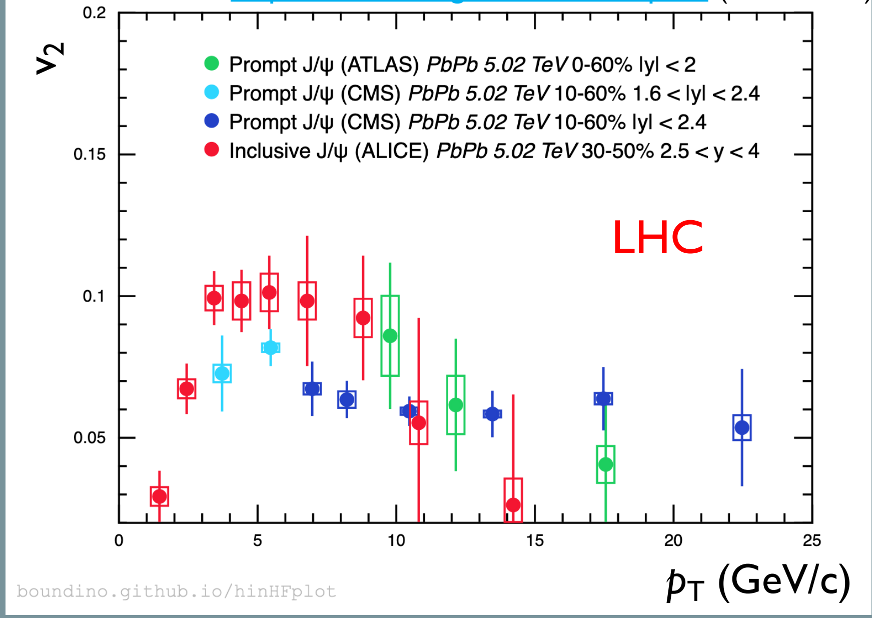
Generated from https://boundino.github.io/hinHFplot/ (ref therein)

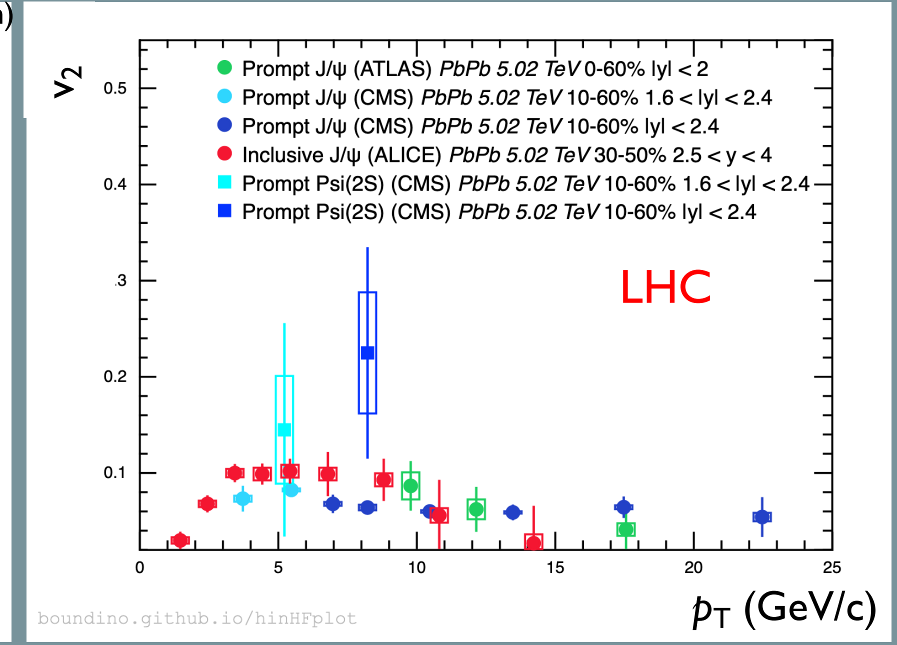


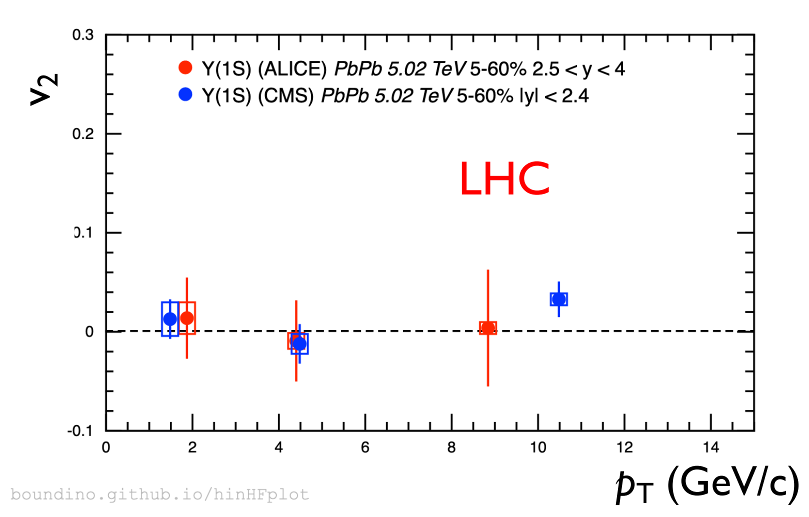
- Obervation of Υ(3S) by CMS in Pb-Pb collisions
- Sequential suppression of Υ(nS) states at LHC energy, and also at RHIC
- Similar suppression at RHIC and LHC for Υ(1S) despite factor 25 in $\sqrt{s}$: in favor of a negligible melting of direct Υ(1S) Suppression of excited states only + CNM effects
- Hint that Υ(2S) might be less suppressed at RHIC in peripheral events than at LHC

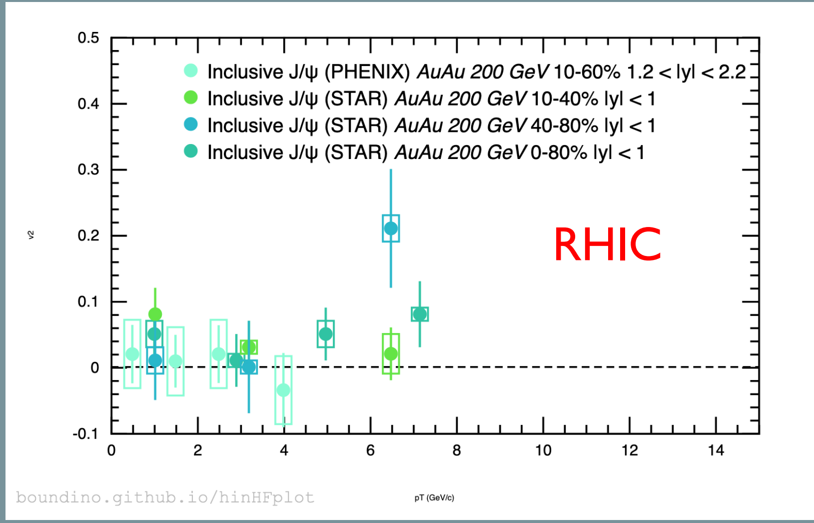
Quarkonium collectivity in AA collisions

Generated from https://boundino.github.io/hinHFplot/ (ref therein)





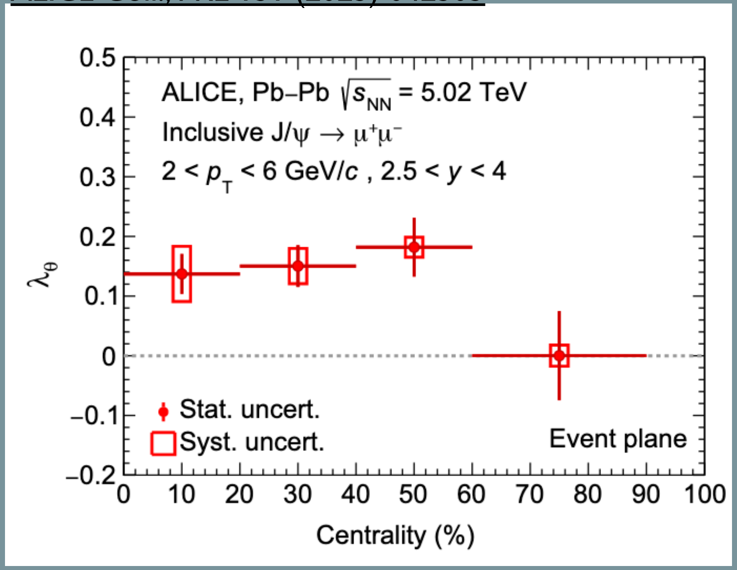


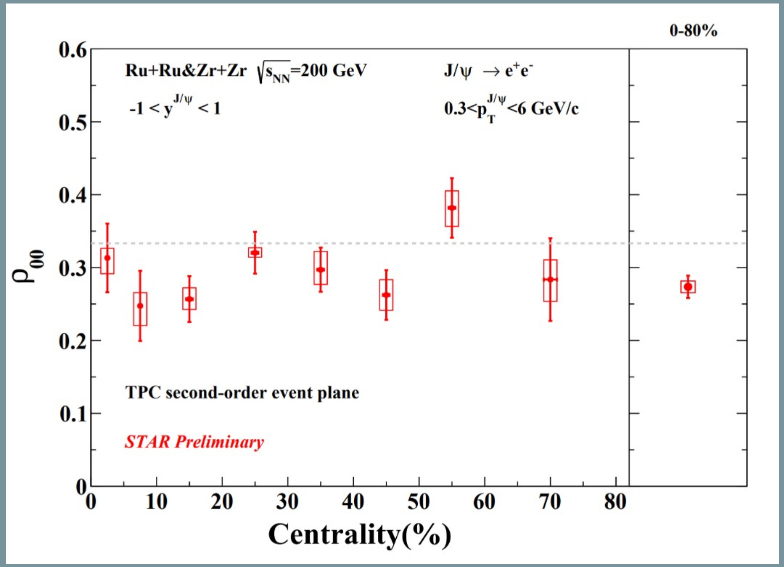


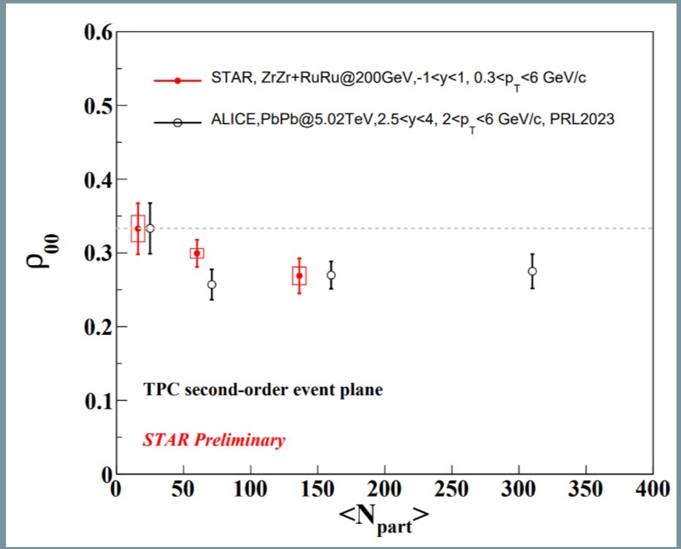
- ❑ Significant J/ψ v_2 at low p_T and LHC energies (and stronger than pPb/pp) : sign of regeneration and thermalization of charm quarks in medium
- ❑ Hint for ψ(2S) v_2 larger than J/ψ v_2 for p_T > 6.5 GeV/c. Larger contribution from recombination for ψ(2S)? Interesting to extend with Run 3 and down to lower p_T
- ❑ Υ(1S) v_2 compatible with zero, no evidence for regeneration within current uncertainties. Would be interesting to look at v_2 of excited states if doable
- ❑ J/ψ v_2 compatible with zero at RHIC

Quarkonium polarization in AA collisions

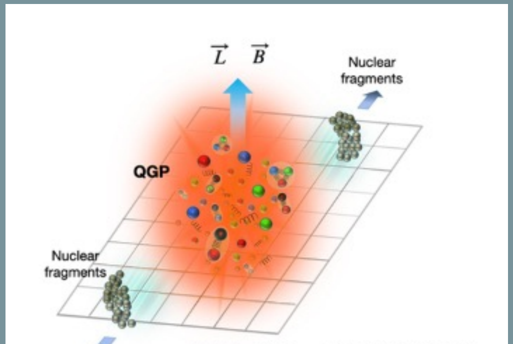
ALICE Coll., PRL 131 (2023) 042303







- Polarization measurement w.r.t event plane can probe the initial magnetic field and angular momentum of the formed medium



STAR, Nature 614 244 (2023)

$$\lambda_\theta = \frac{(1-3\rho_{00})}{(1+\rho_{00})}$$

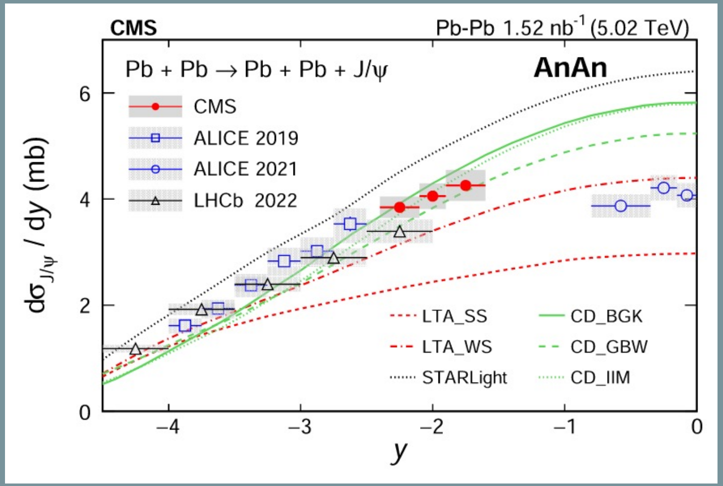
ρ_{00} = 1/3 → absence of spin alignment

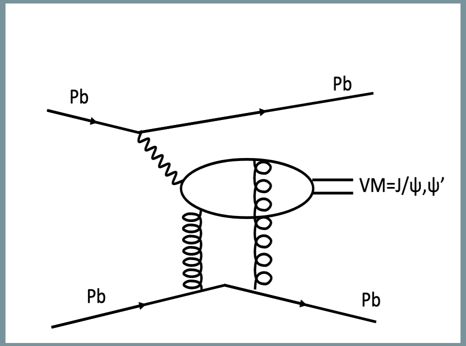
- Hint for spin alignment of J/ψ both at RHIC and ALICE with similar pattern, despite different initial magnetic field, regeneration effects, rapidities… Theoretical guidance needed

Quarkonium photoproduction in AA collisions

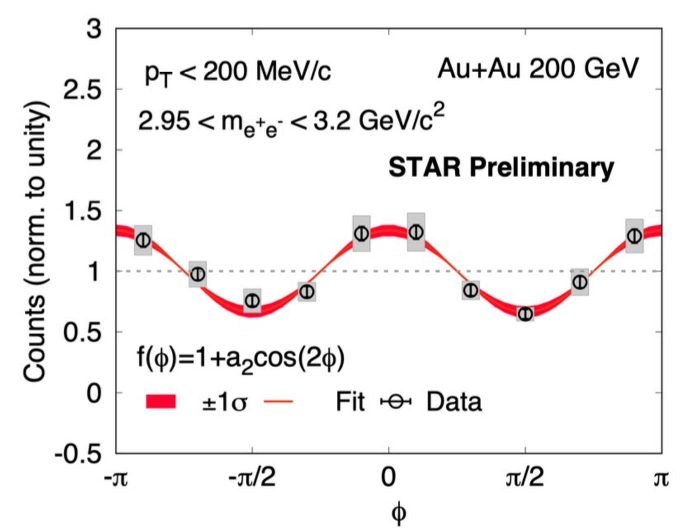
Probe small Bjorken-x nuclear gluonic structure

CMS Coll., PRL 131 (2023) 262301

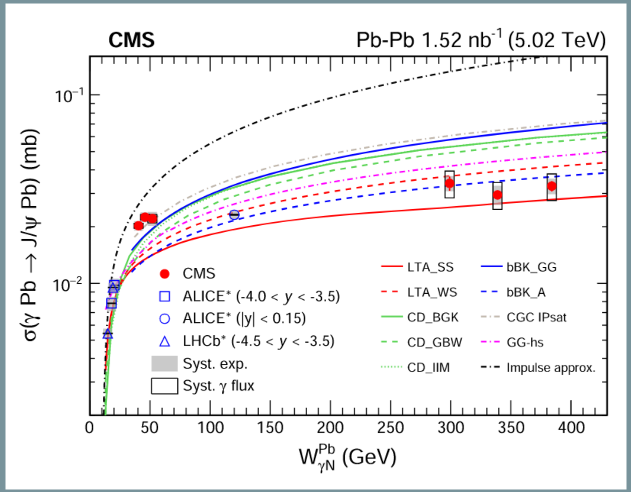


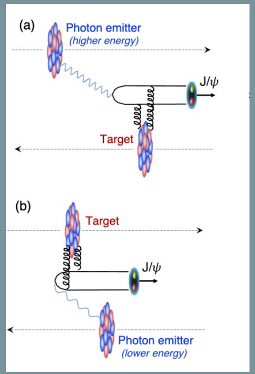


Spin interference of J/ψ



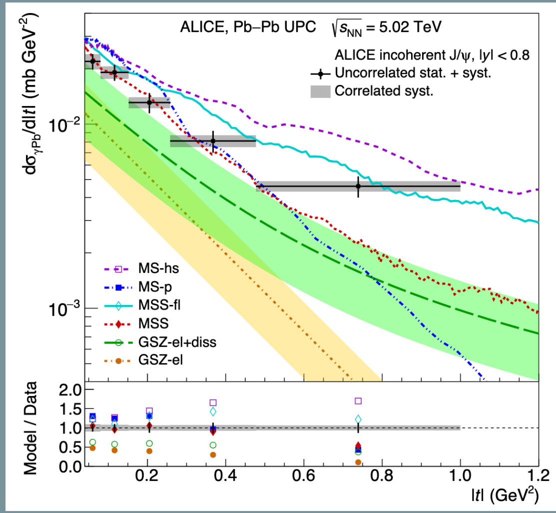
Study ambiguity in nuclei photon emitter



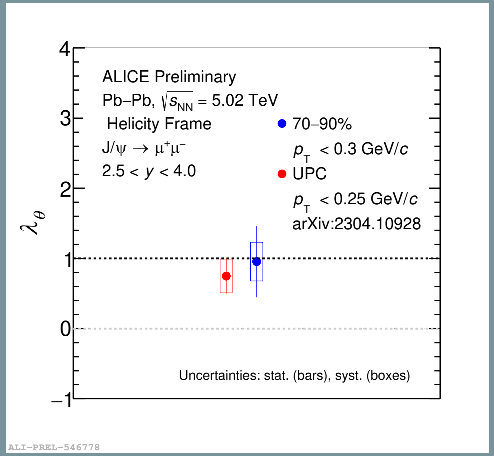


Probe quantum fluctuations of the gluon density

Phys. Rev. Lett 132 (2024) 162302

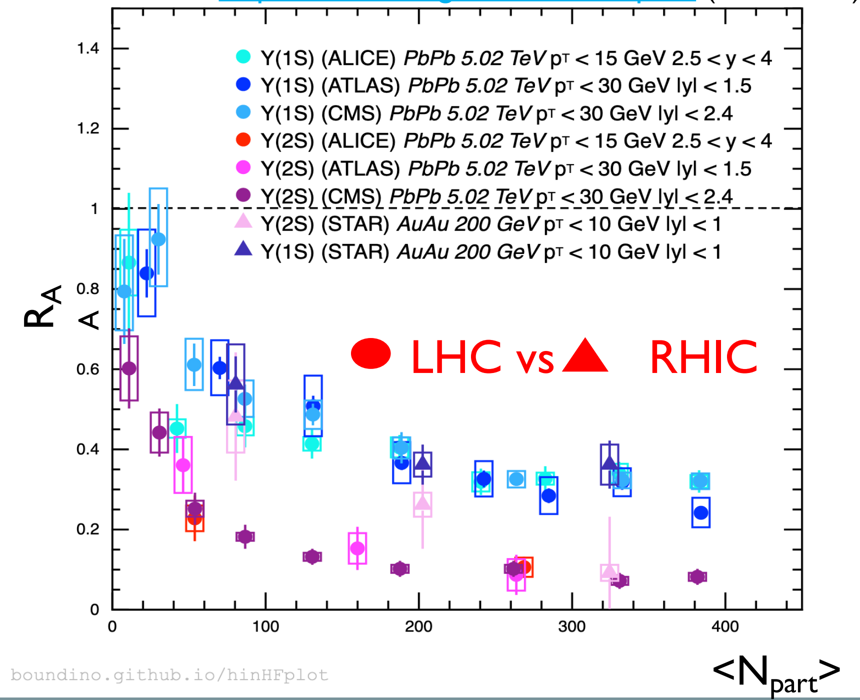


Transverse polarization of photoproduced J/ψ in Pb-Pb collisions with nuclear overlap

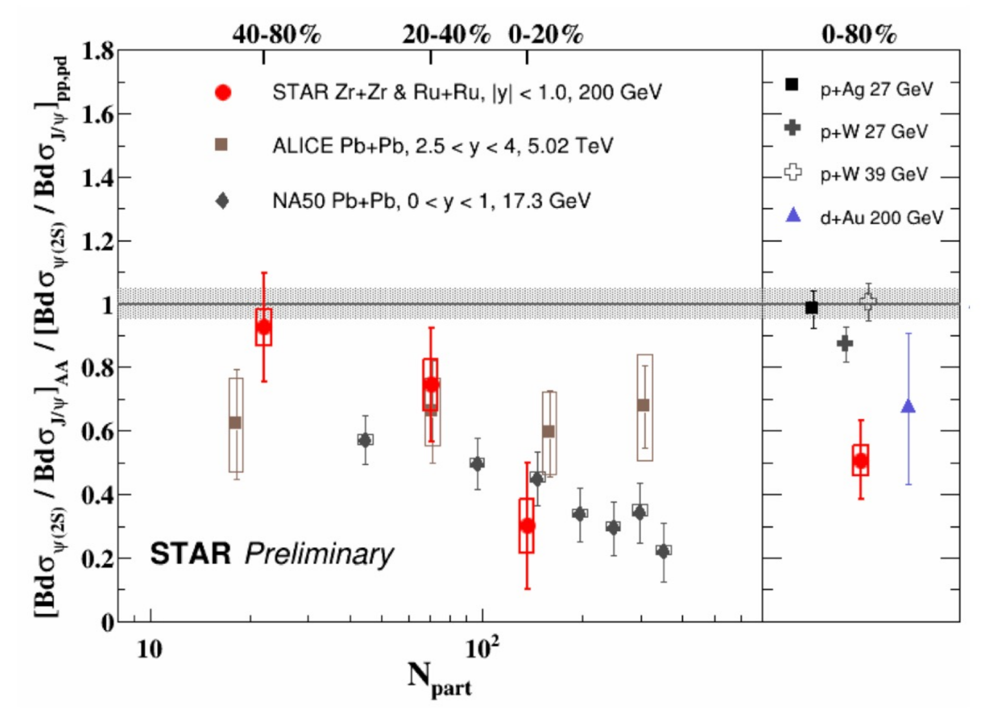


Take home message AA

Generated from https://boundino.github.io/hinHFplot/ (ref therein)



ALICE Coll., PRL 132 (2024) 042301
NA50 Coll., EPJC 49 (2007) 559



- ❑ Sequential dissociation of Υ(nS) states in medium at RHIC and LHC with similar pattern → important to understand feed-down contributions
- ❑ Sequential suppression of charmonia at RHIC, interplay between dissociation and regeneration of charmonia at LHC (looking forward improved precision for ψ(2S) measurements)
- ❑ Thermalization of charm quarks in medium at LHC

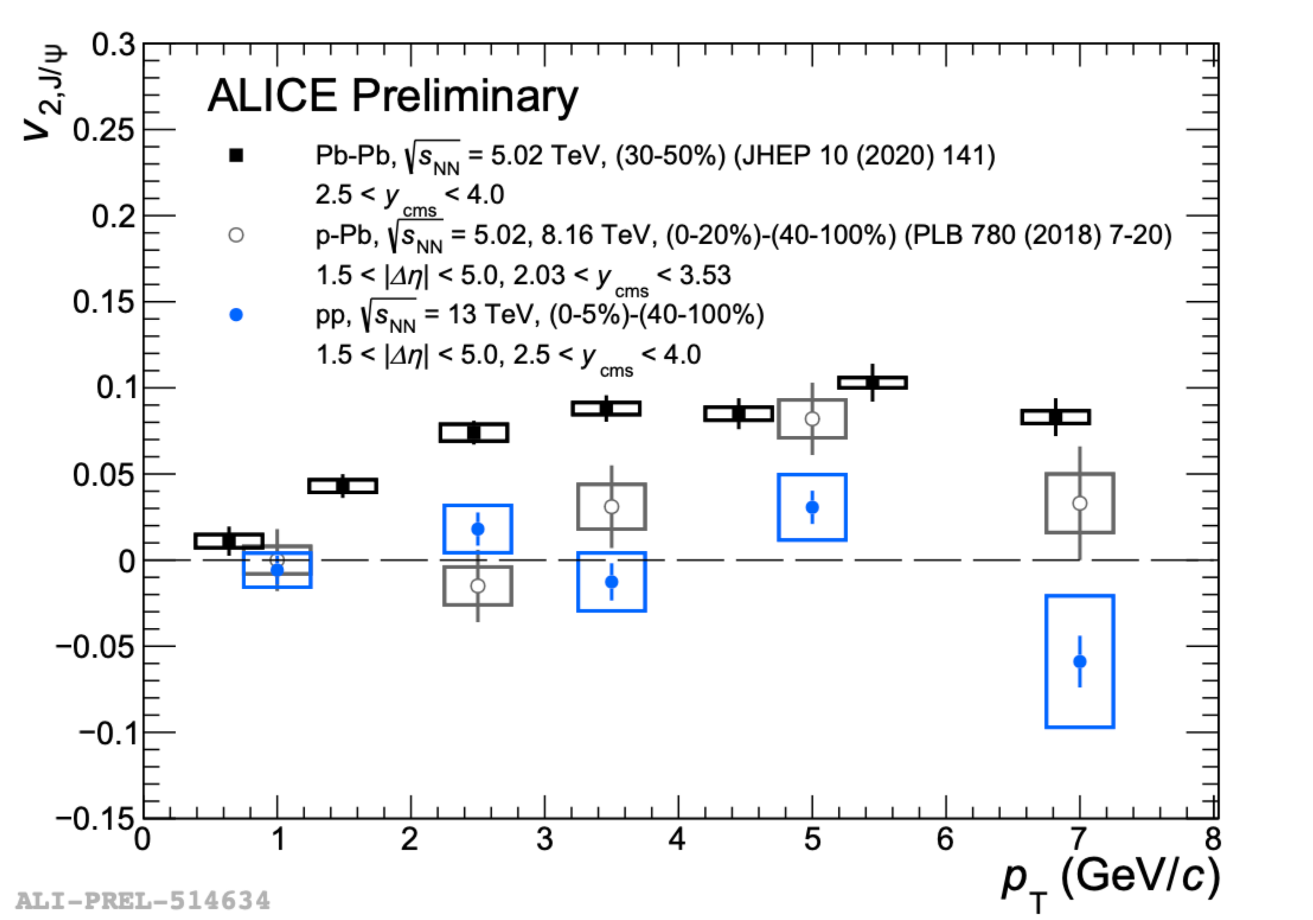
Prospects

- First Run 3 quarkonium results starting to be released

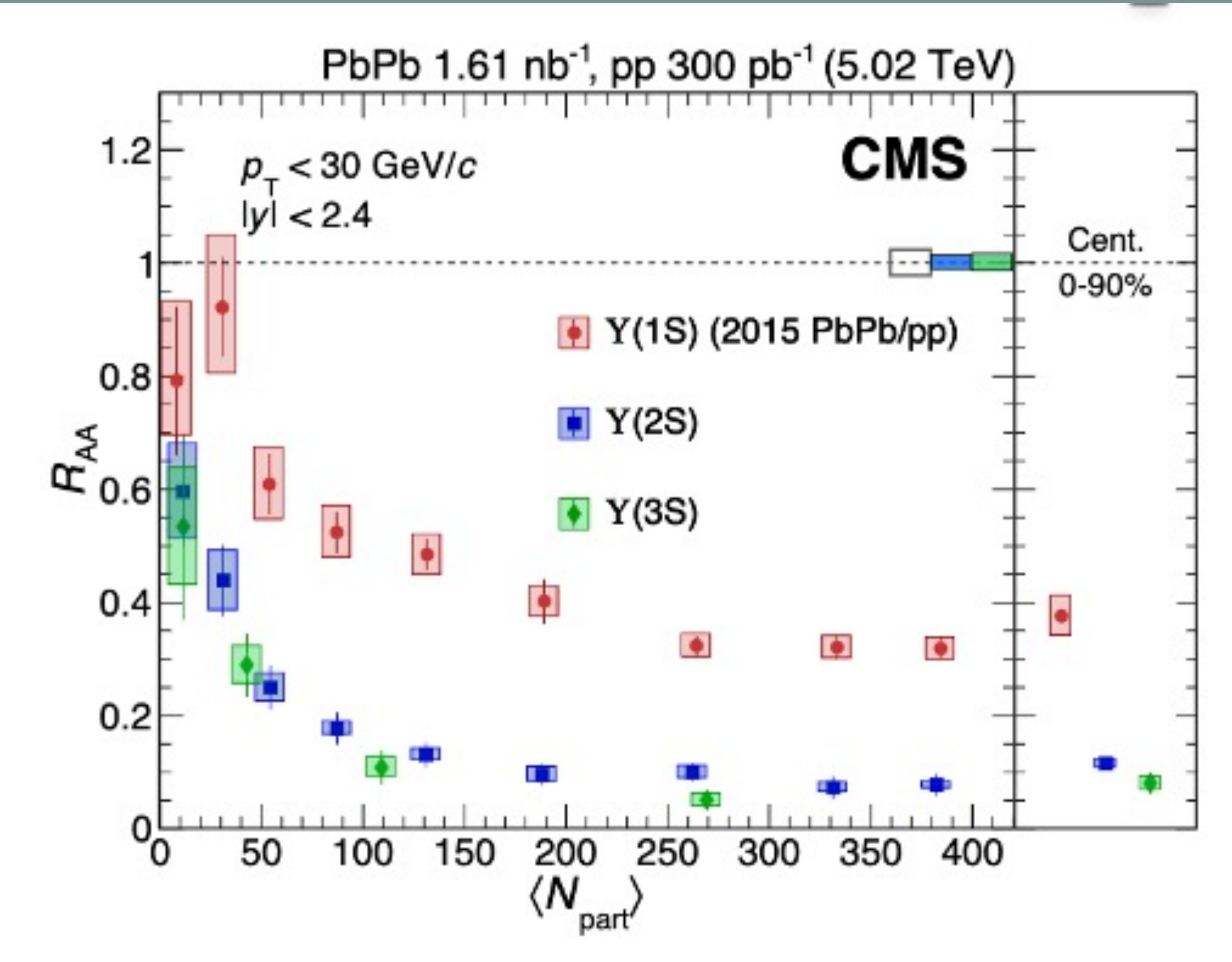
- Several LHC upgrades highly relevant for quarkonium physics:
  - ALICE mid-rapidity: access to Υ states, prompt/non-prompt charmonium separation down to lower p_T
  - ALICE forward rapidity: prompt/non-prompt charmonium separation
  - LHCb: quarkonium measurements down to centrality 30% in Pb-Pb, access to all centralities in Pb-Ar
  - CMS: analysis of minbias data could improve the low p_T reach for quarkonia

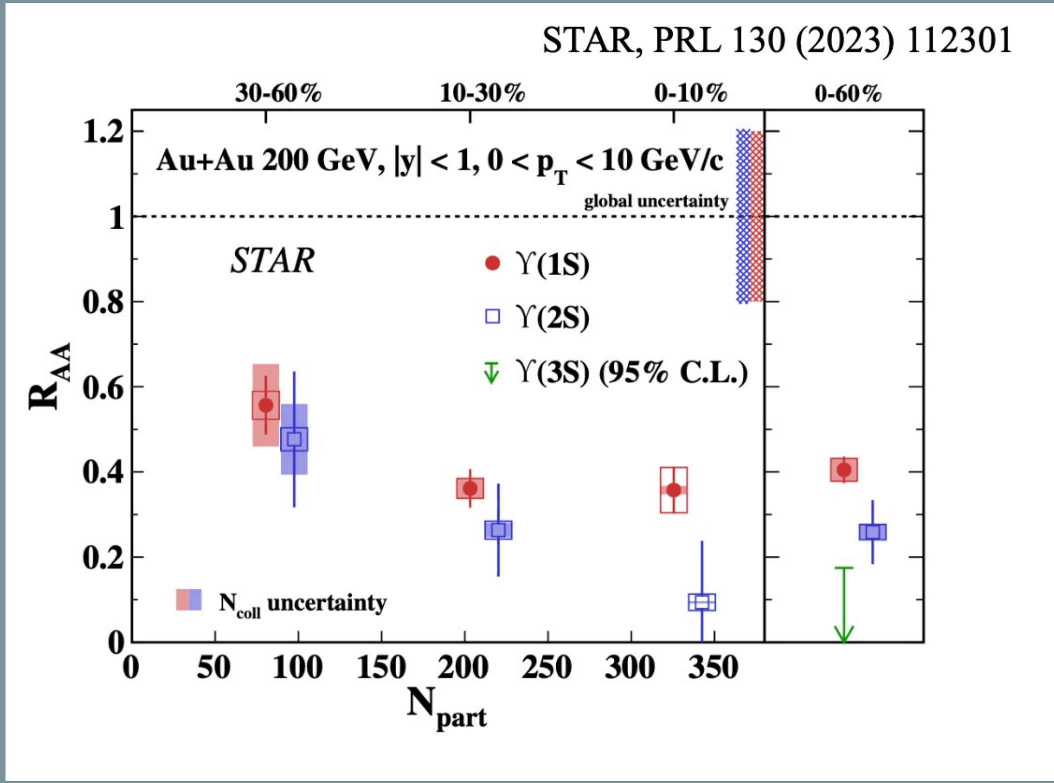
Stay tuned and thanks for your attention!

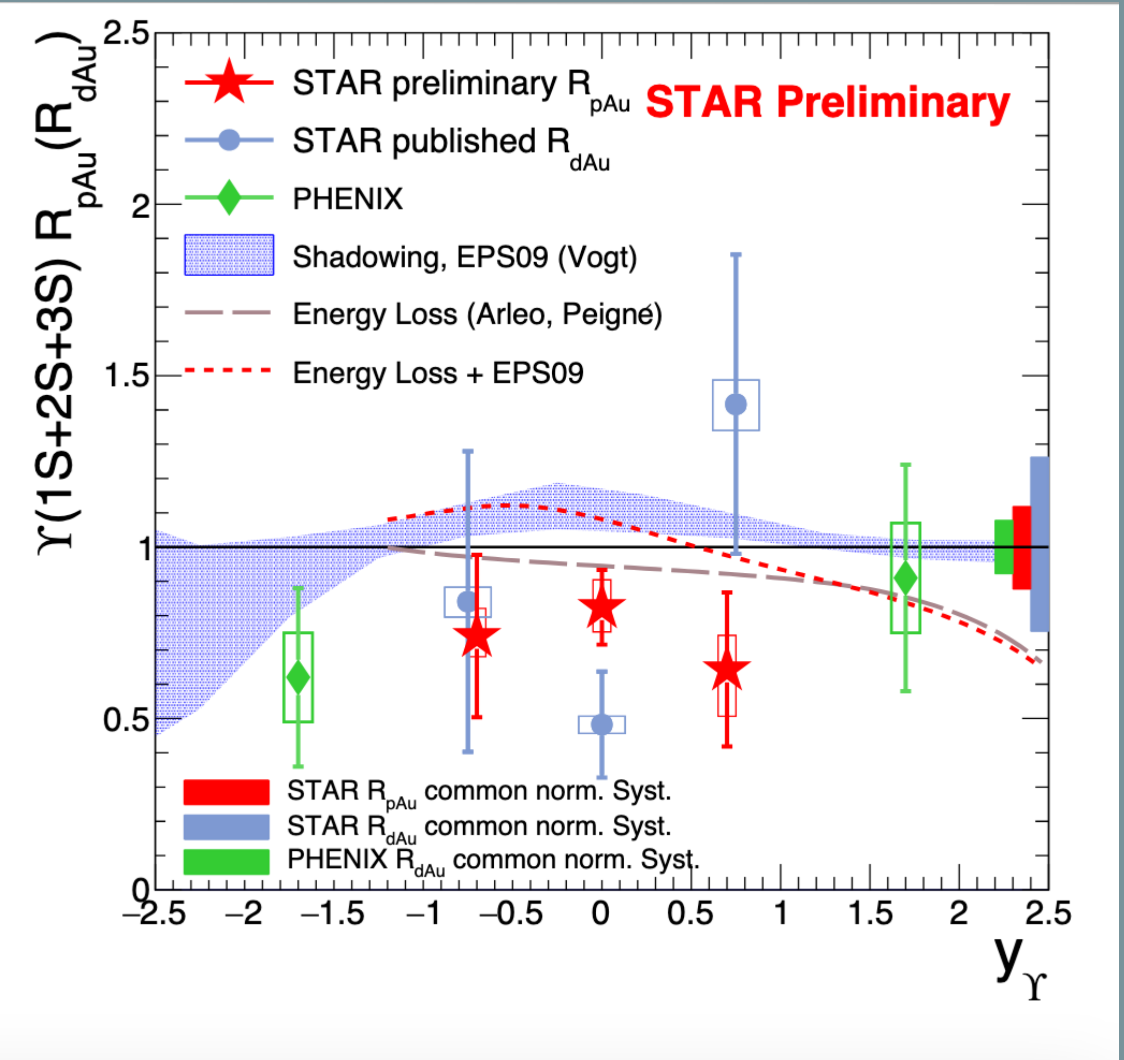
Back up

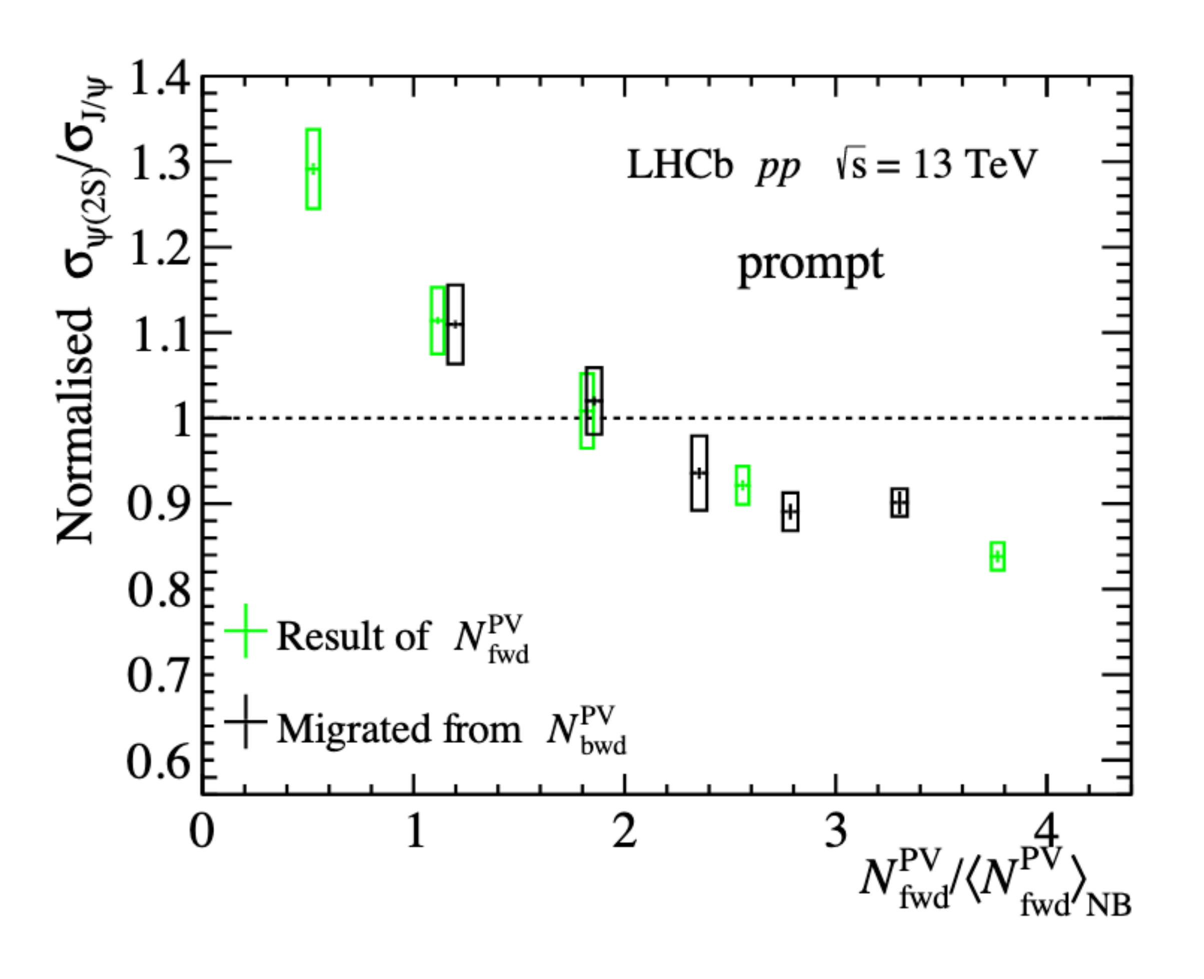


ALICE Preliminary
Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, (30-50%) (JHEP 10 (2020) 141)
2.5 < y_{cms} < 4.0
p-Pb, $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV, (0-20%)-(40-100%) (PLB 780 (2018) 7-20)
1.5 < $|\Delta\eta|$ < 5.0, 2.03 < y_{cms} < 3.53
pp, $\sqrt{s_{NN}}$ = 13 TeV, (0-5%)-(40-100%)
1.5 < $|\Delta\eta|$ < 5.0, 2.5 < y_{cms} < 4.0
$v_{2,J/\psi}$
p_T (GeV/c)
ALI-PREL-514634

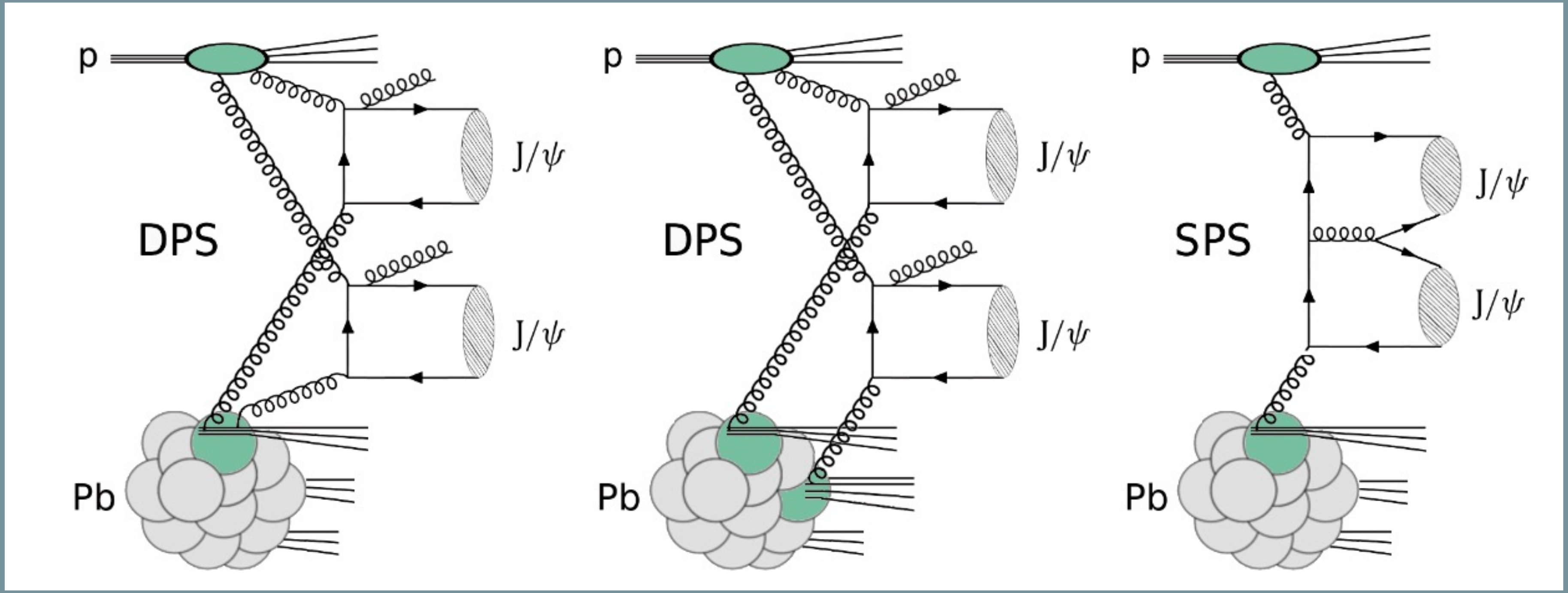

PbPb 1.61 nb⁻¹, pp 300 pb⁻¹ (5.02 TeV)
CMS
p_T < 30 GeV/c
|y| < 2.4
Cent.
0-90%
Υ(1S) (2015 PbPb/pp)
Υ(2S)
Υ(3S)
R_{AA}
⟨N_{part}⟩


STAR, PRL 130 (2023) 112301
30-60%
10-30%
0-10%
0-60%
Au+Au 200 GeV, |y| < 1, 0 < p_T < 10 GeV/c
global uncertainty
STAR
Υ(1S)
Υ(2S)
Υ(3S) (95% C.L.)
N_{coll} uncertainty
R_{AA}
N_{part}

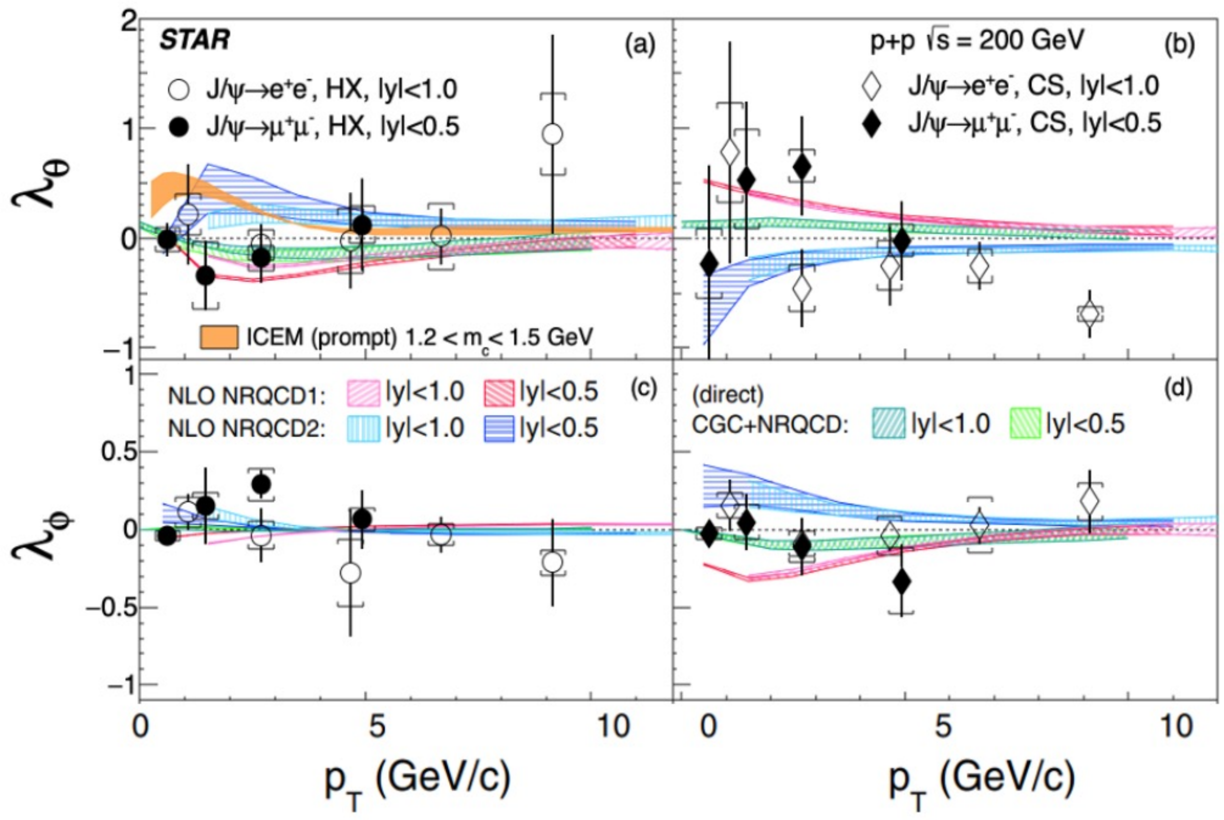

STAR preliminary R_{pAu}
STAR Preliminary
STAR published R_{dAu}
PHENIX
Shadowing, EPS09 (Vogt)
Energy Loss (Arleo, Peigné)
Energy Loss + EPS09
STAR R_{pAu} common norm. Syst.
STAR R_{dAu} common norm. Syst.
PHENIX R_{dAu} common norm. Syst.
Υ(1S+2S+3S) R_{pAu}(R_{dAu})
y_{Υ}



LHCb pp $\sqrt{s} = 13$ TeV
prompt
Normalised $\sigma_{\psi(2S)}/\sigma_{J/\psi}$
$N^{PV}_{fwd}/\langle N^{PV}_{fwd}\rangle_{NB}$
Result of N^{PV}_{fwd}
Migrated from N^{PV}_{bwd}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0
1
2
3
4

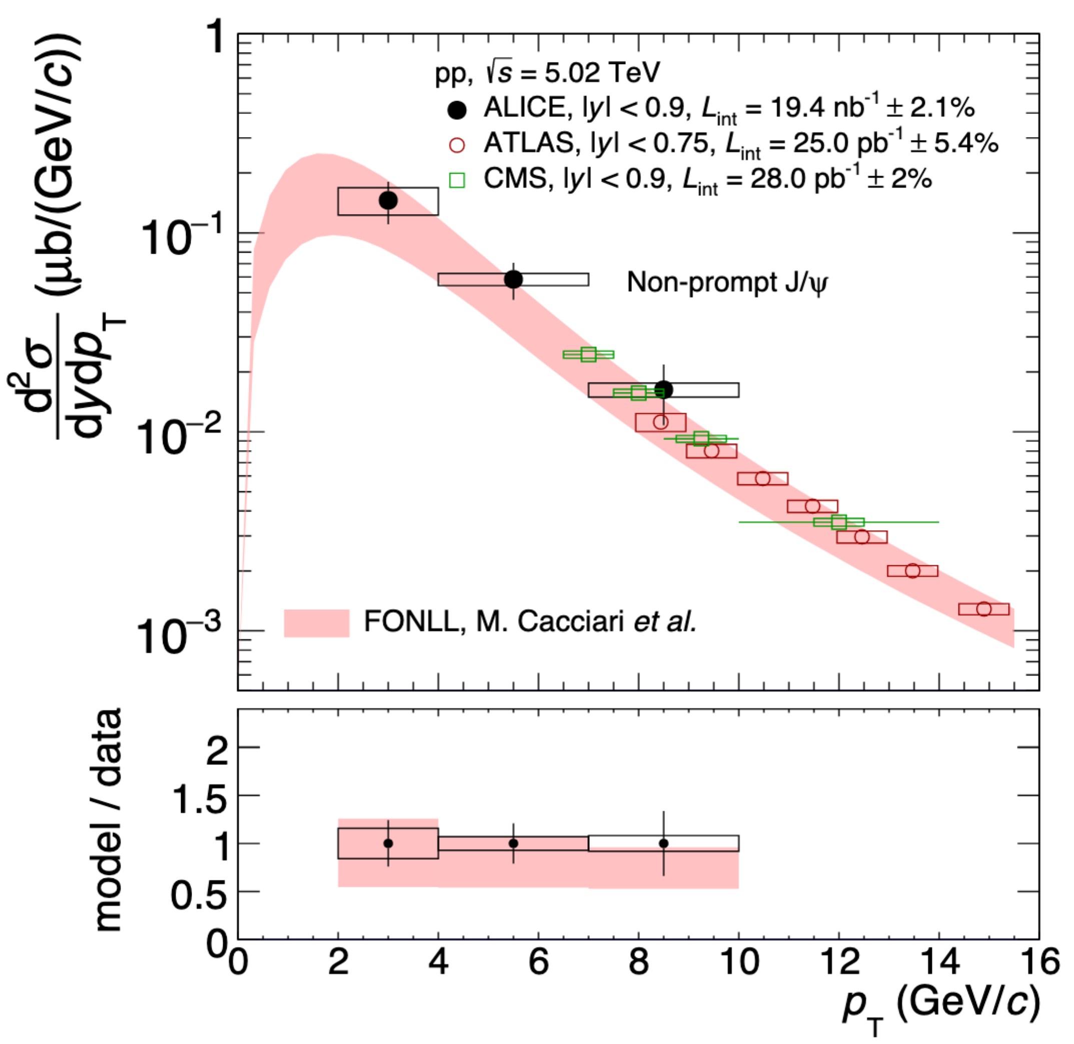

p
DPS
J/ψ
J/ψ
Pb
p
DPS
J/ψ
J/ψ
Pb
p
SPS
J/ψ
J/ψ
Pb

STAR PRD 102,092009 (2020)



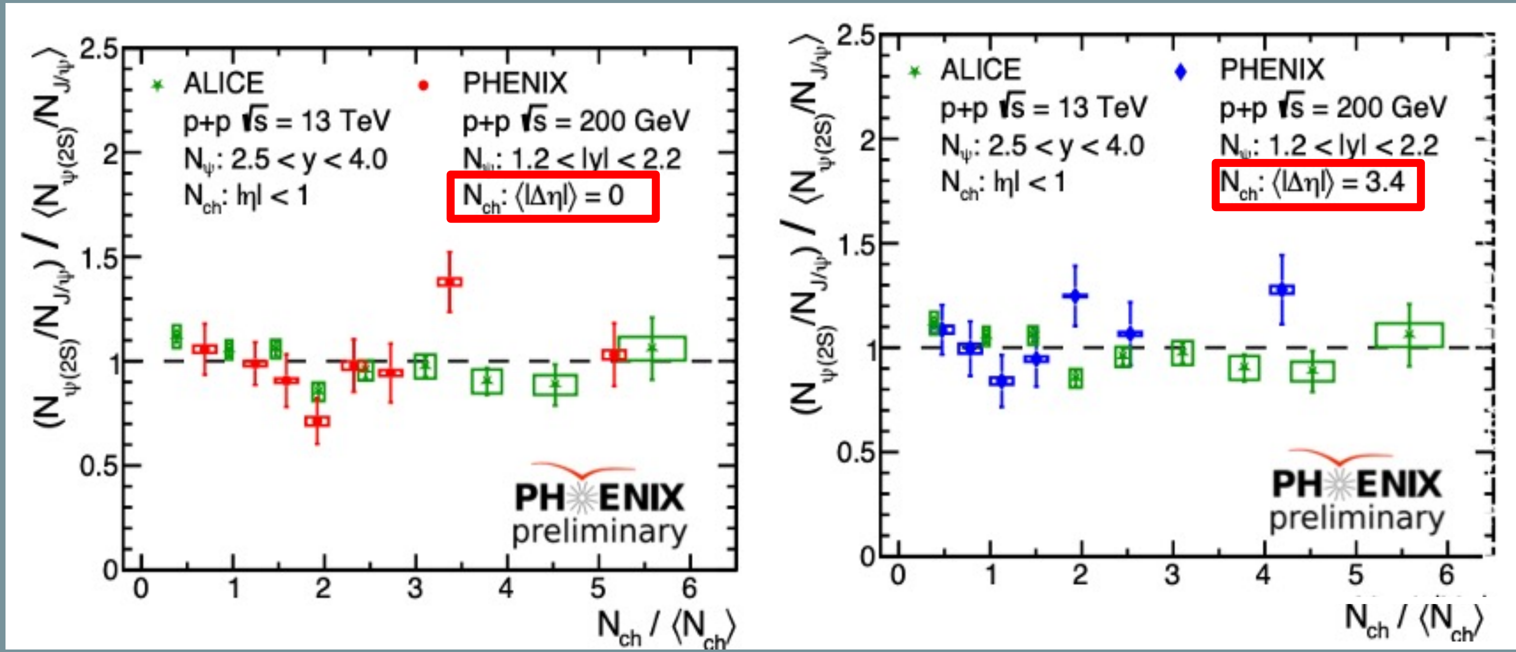
Quarkonium production in pp collisions

ALICE Coll., JHEP (2022) 190, CMS Coll. Eur. Phys. J. C77 (2017) 269, ATLAS Coll., Eur. Phys. J. C78 (2018) 171

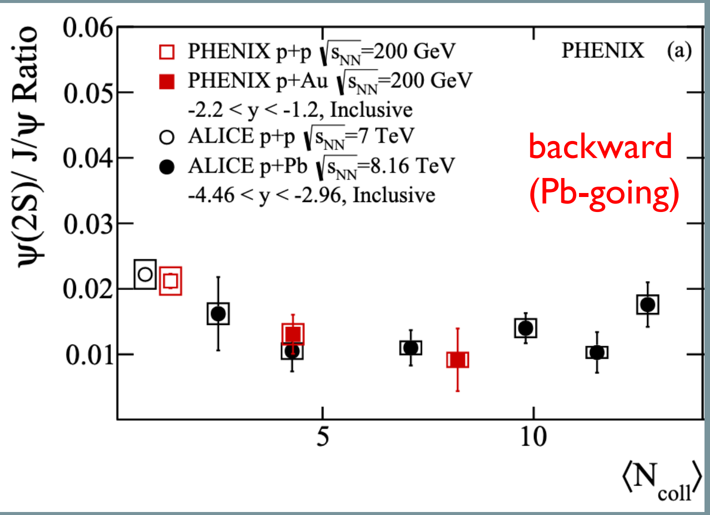


Non-prompt J/ψ, mid-rapidity

Quarkonium excited to ground state ratio versus multiplicity



- Excited to ground state ratio to pin down final state effects in high multiplicity events
- ALICE forward incl. ψ(2S)/J/ψ ratio vs mid-y mult. Compatible with flat trend and comover scenario within large unc. both in pp and pPb.
- New (precise) CMS measurement in pPb tends to favor comover scenario but several caveats for comparison to ALICE and models (x-axis corrections, $\Delta\eta$ between the probe and N_{ch})
- Trend of PHENIX data compatible with ALICE in pp independently of the $\Delta\eta$ gap

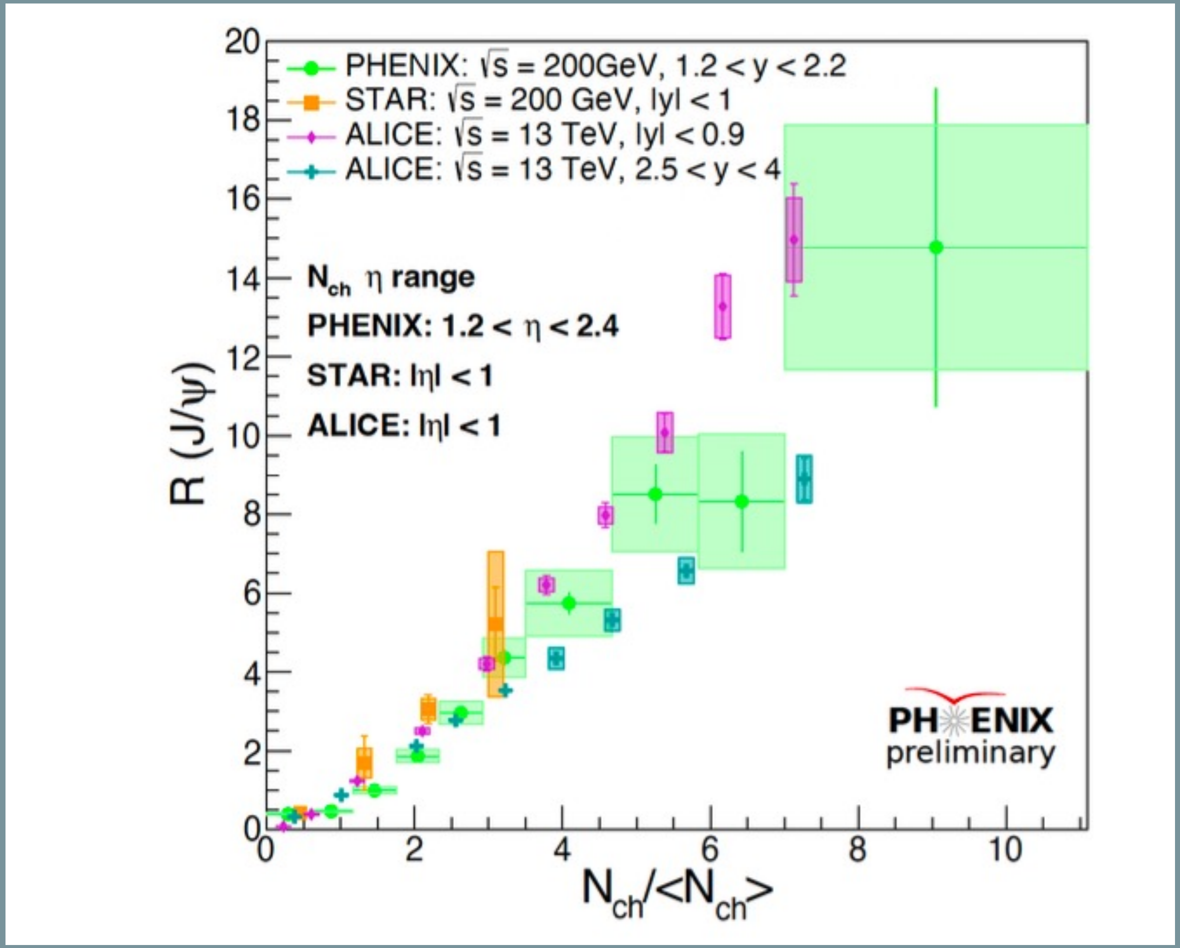


ALICE Coll., JHEP 02 (2021) 002

PHENIX Coll., Phys. Rev C. 105 (2022) 064912

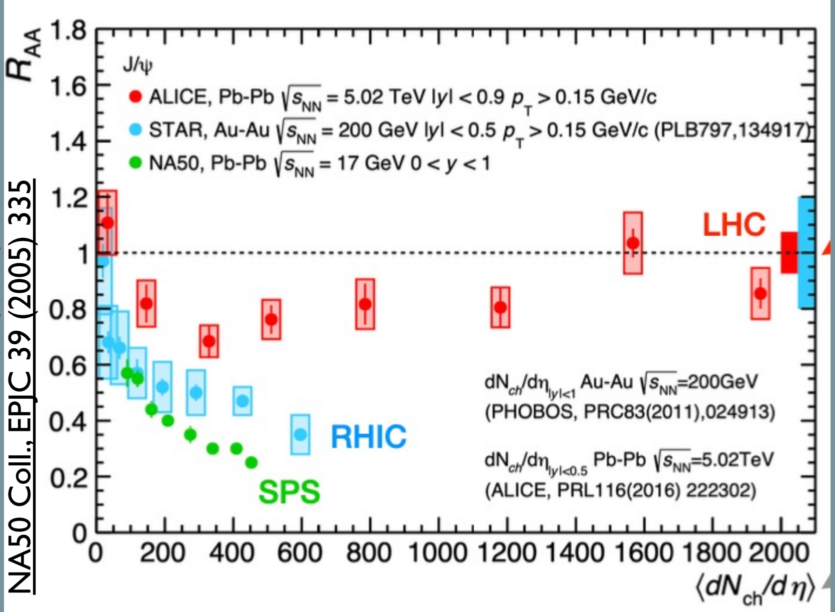
Quarkonium production versus multiplicity in pp collisions

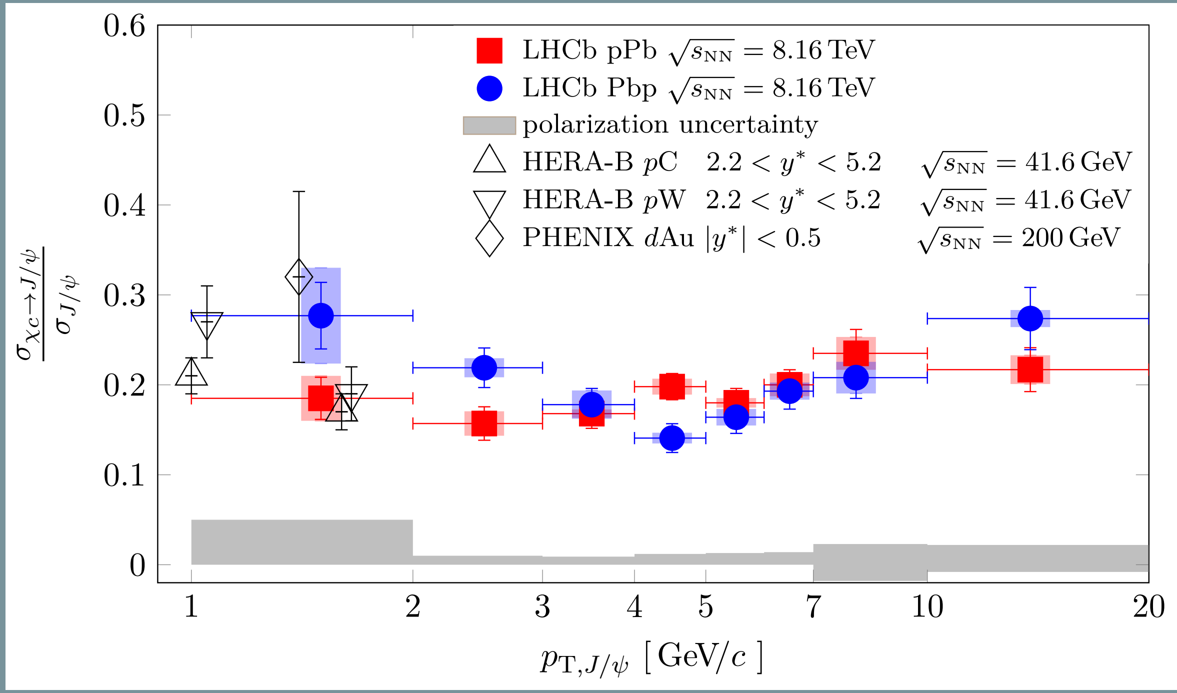
- Different behaviour versus multiplicity could be related to the quarkonium rapidity, the charged particle rapidity, the Δy between the two (accounting for possible auto-correlations)…Need systematic scan of all quantities, and done recently by PHENIX



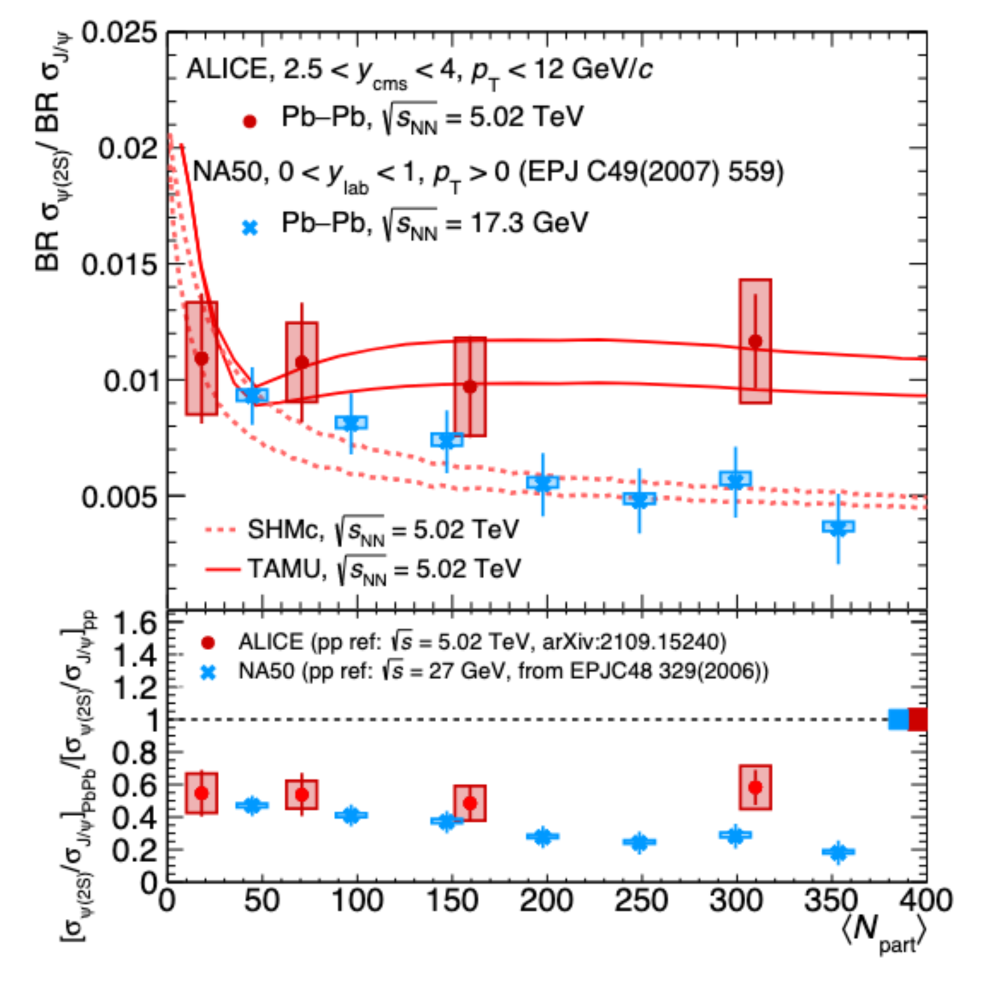
- Faster than linear increase when overlap in rapidity between N_{ch} and J/ψ
- Reduced increase with multiplicity for large Δy gap between N_{ch} and J/ψ
- Strong reduction of the increase with mult. when J/ψ subtracted from the mult. evaluation (autocorrelations!)
- Less enhancement when Δy gap between N_{ch} and J/ψ
- Results in between ALICE mid-y and forward-y

ALICE Coll., PLB 849 (2024) 138451
STAR Coll., PLB 797 (2019) 134917
NA50 Coll., EPJC 39 (2005) 335





LHCb pPb $\sqrt{s_{NN}} = 8.16$ TeV
LHCb Pbp $\sqrt{s_{NN}} = 8.16$ TeV
polarization uncertainty
HERA-B pC $2.2 < y^* < 5.2$ $\sqrt{s_{NN}} = 41.6$ GeV
HERA-B pW $2.2 < y^* < 5.2$ $\sqrt{s_{NN}} = 41.6$ GeV
PHENIX dAu $|y^*| < 0.5$ $\sqrt{s_{NN}} = 200$ GeV
$\frac{\sigma_{\chi_c \to J/\psi}}{\sigma_{J/\psi}}$
$p_{T,J/\psi}$ [GeV/c]



ALICE Coll., PRL 132 (2024) 042301
NA50 Coll., EPJC 49 (2007) 559