

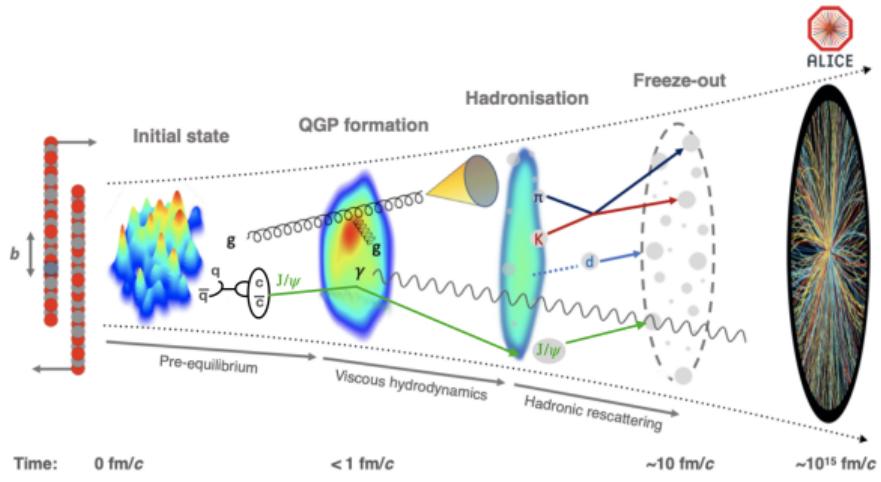
Recent quarkonium results in small systems with ALICE

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University of Bergen, Norway



The VII-th International Conference on the Initial Stages of High-Energy Nuclear Collisions
19 - 23 June 2023, Copenhagen

Quarkonium production in small systems



Quarkonium

- Bound state of a heavy quark pair
- **Production**
 - Hard scale: Creation of $q\bar{q}$ in initial hard scattering
 - Soft scale: Binding into colorless final state
 - Sensitive to gluon content of colliding hadrons
 - ⇒ Parton Distribution Functions of incoming partons or nuclei

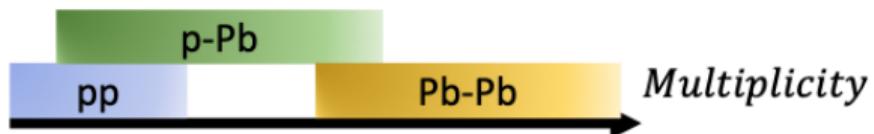
A meaningful interpretation of heavy-ion collisions relies on the study of small systems

- pp collisions: Reference system → understand basic production mechanism
- p–Pb collisions: Quantify cold nuclear matter effects

Quarkonium production in small systems

Hints of collective behaviours in small systems

- Study similarities in small systems and Pb–Pb collisions
- Use of observables directly linked to collectivity (flow)
- Multiplicity dependent analyses (behaviour across system size, indirect access to Multi Parton Interactions)
- Double quarkonium production (direct probe of MPIs)

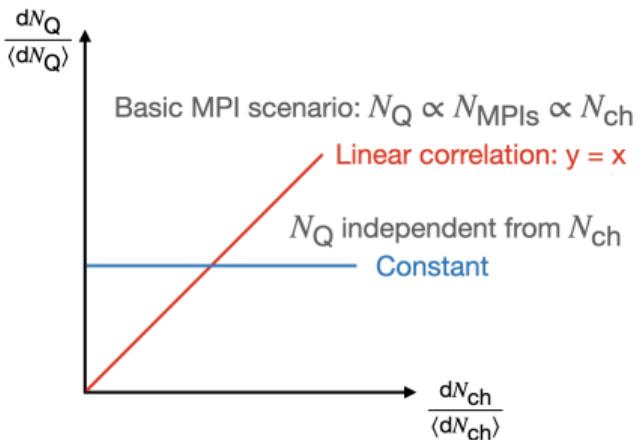


Multiplicity

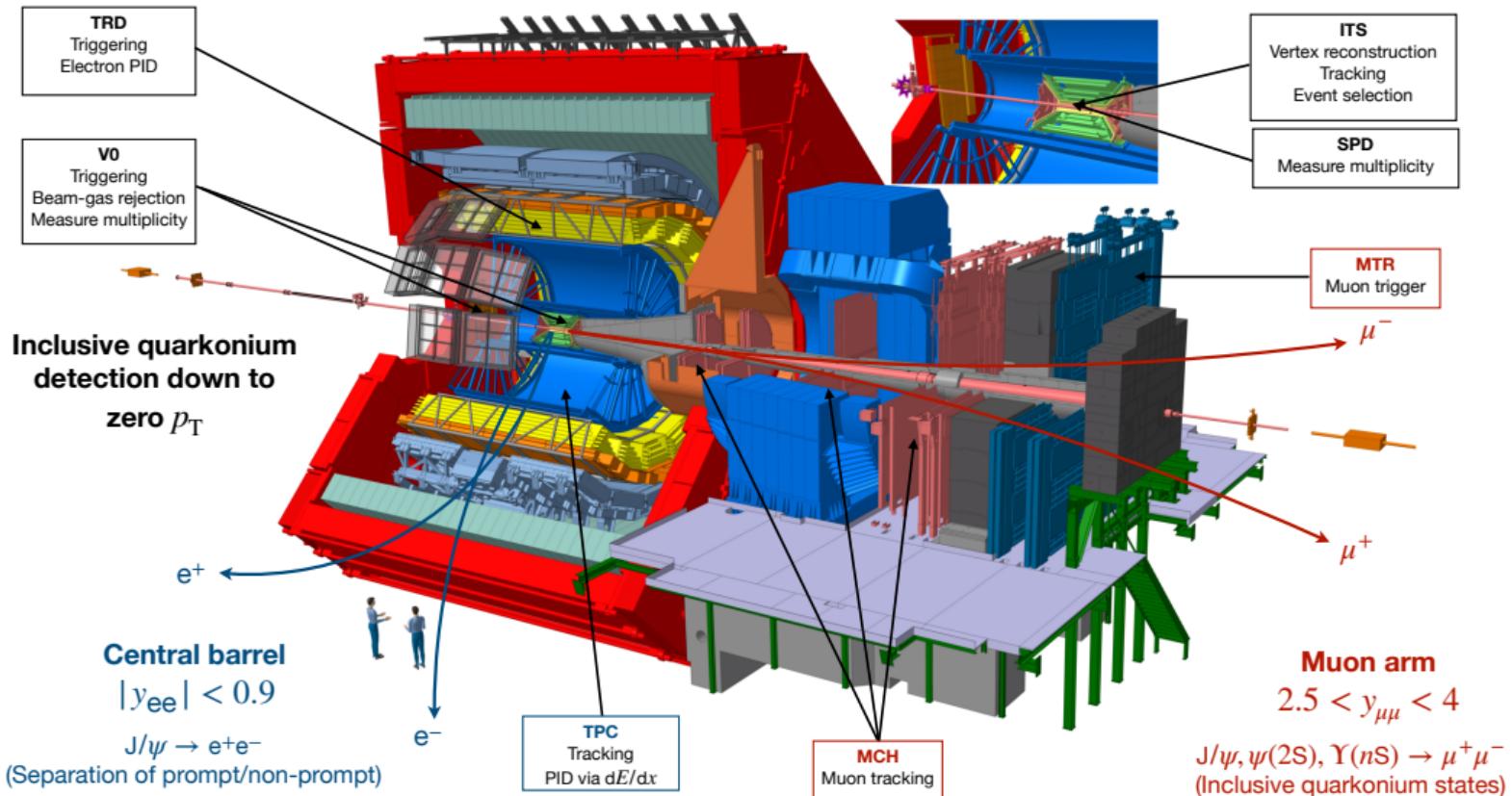
- Correlation between quarkonium production (N_Q) and underlying event (N_{ch}) in collision

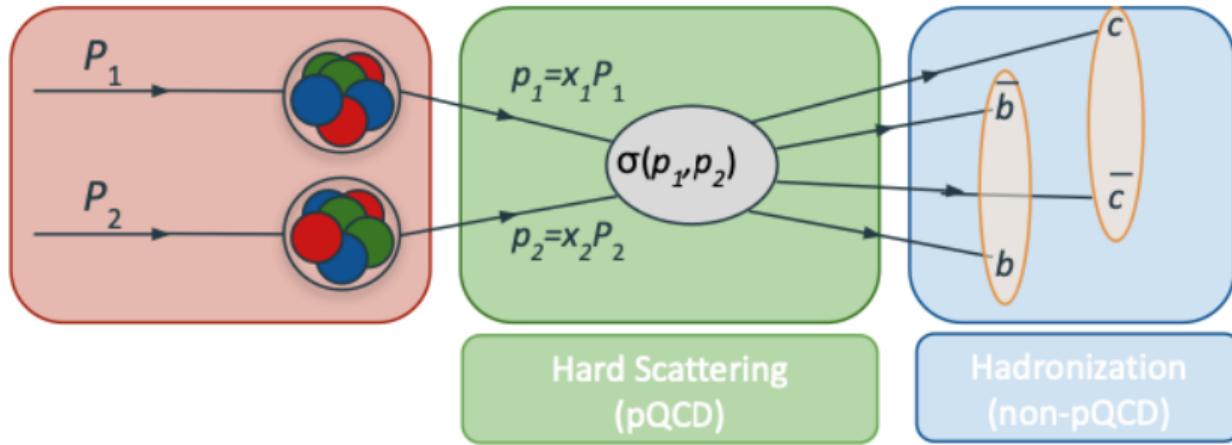
$$N_Q \propto N_{MPIs} \propto N_{ch}$$

⇒ Key observable to disentangle initial and final state effects



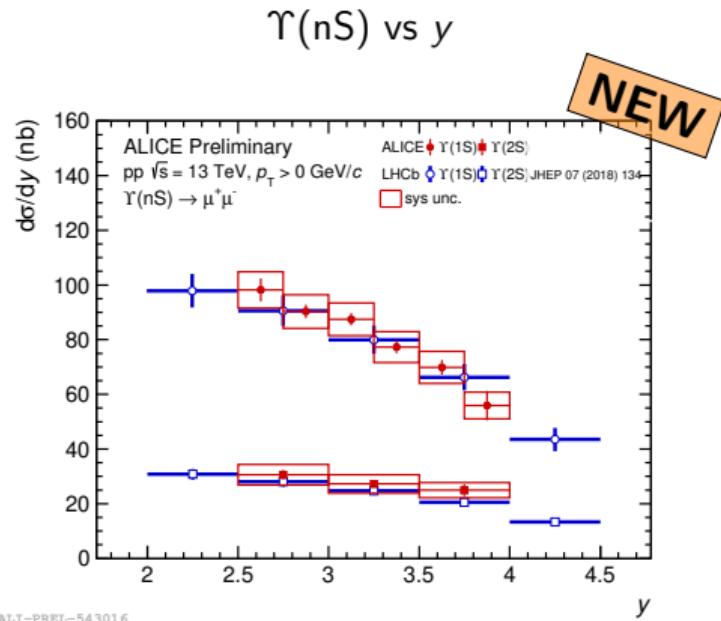
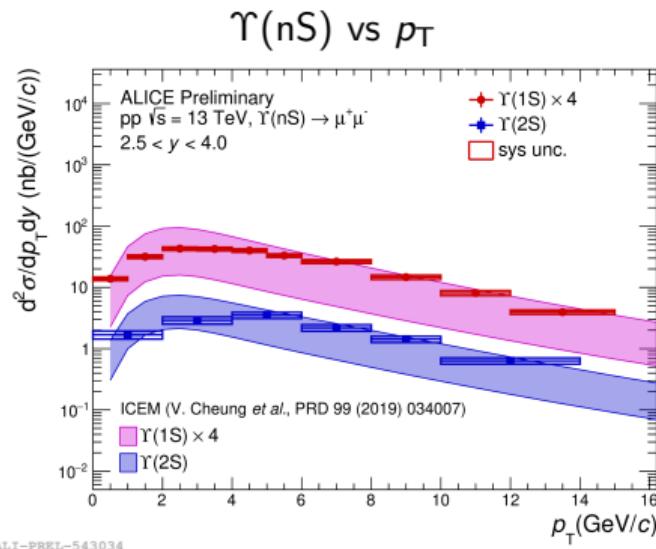
Quarkonium reconstruction in ALICE (Run 2)





Small systems - a way to study production mechanism

$\Upsilon(nS)$ production cross sections in pp collisions

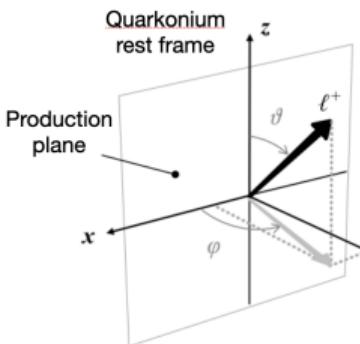
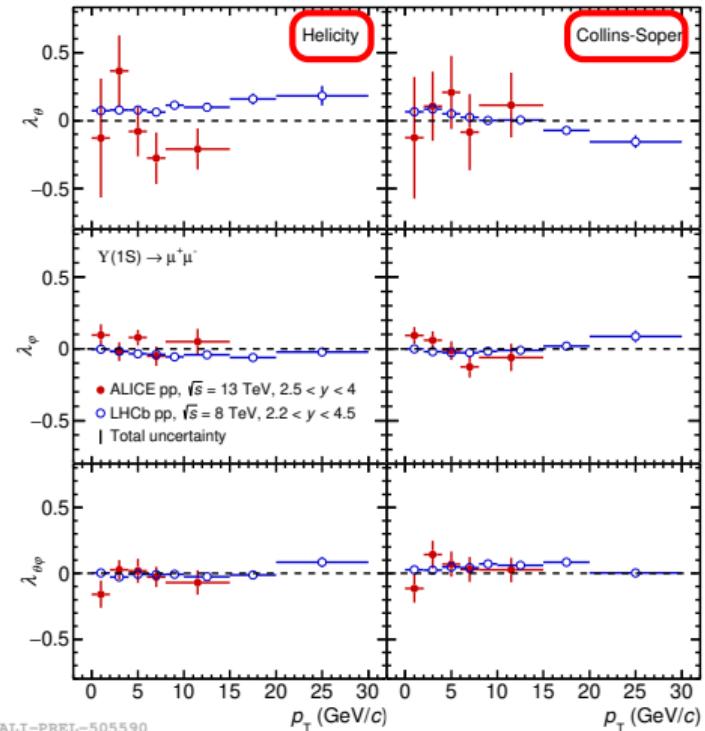


- Differential cross sections measured as a function of p_T and y
- Improved Color Evaporation Model calculations describe measured trend within uncertainties
- $\Upsilon(1S)$ and $\Upsilon(2S)$ differential production cross section compatible with LHCb measurements

ICEM: V. Cheung *et al.*, PRD 99 (2019) 034007
LHCb: JHEP 07 (2018) 134

$\Upsilon(1S)$ polarization in pp collisions

$\Upsilon(1S)$ polarization



$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0) \rightarrow$ No polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0) \rightarrow$ Pure longitudinal

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1,0,0) \rightarrow$ Pure transverse

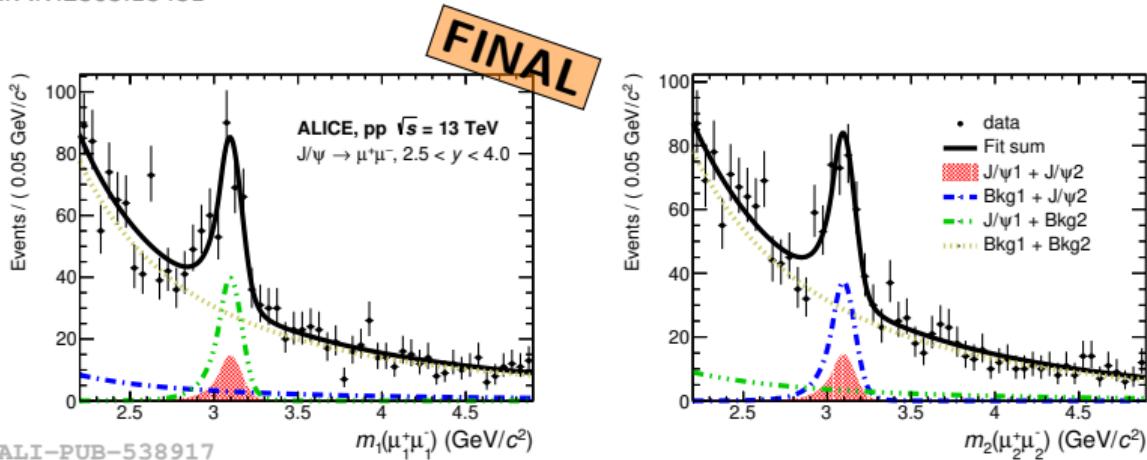
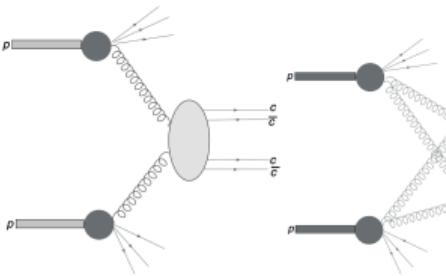
- First **ALICE** $\Upsilon(1S)$ polarization measurement in pp collisions
- Polarization parameters are consistent with zero within uncertainties in both reference frames
- Good agreement with **LHCb** results in similar rapidity range

LHCb: JHEP 12 (2017) 110

J/ψ pair production in pp collisions

arXiv:2303.13431

AIP Conf. Proc. 1523 (2013) 1

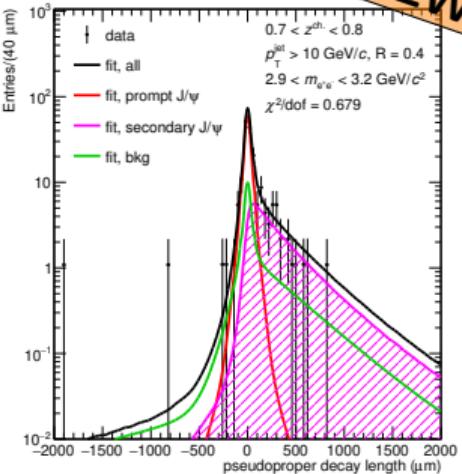
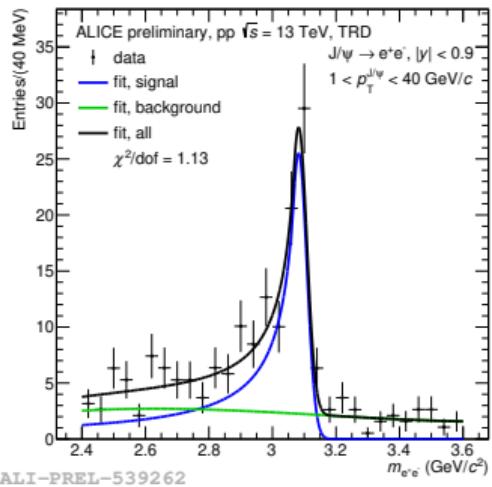


Cross sections (nb)	
ALICE	$10.3 \pm 2.3(\text{stat.}) \pm 1.3(\text{syst})$
LHCb	$15.2 \pm 1.0(\text{stat.}) \pm 0.9(\text{syst})$

LHCb: JHEP 06 (2017) 047

- Insight into double-parton scattering (DPS)
- Consistent with measured LHCb cross sections, with two caveats
 - Inclusive J/ψ measured in ALICE vs prompt J/ψ measured by LHCb
 - Slightly different rapidity intervals

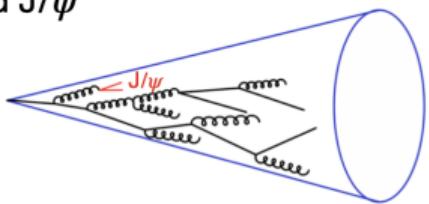
J/ψ fragmentation function in pp collisions



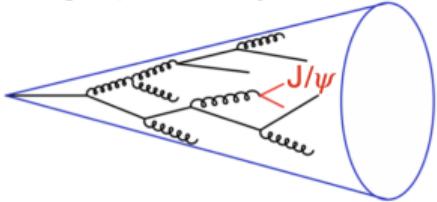
NEW

$$z^{\text{ch.}} = \frac{p_T^{J/\psi}}{p_T^{\text{jet, ch.}}}$$

Isolated J/ψ



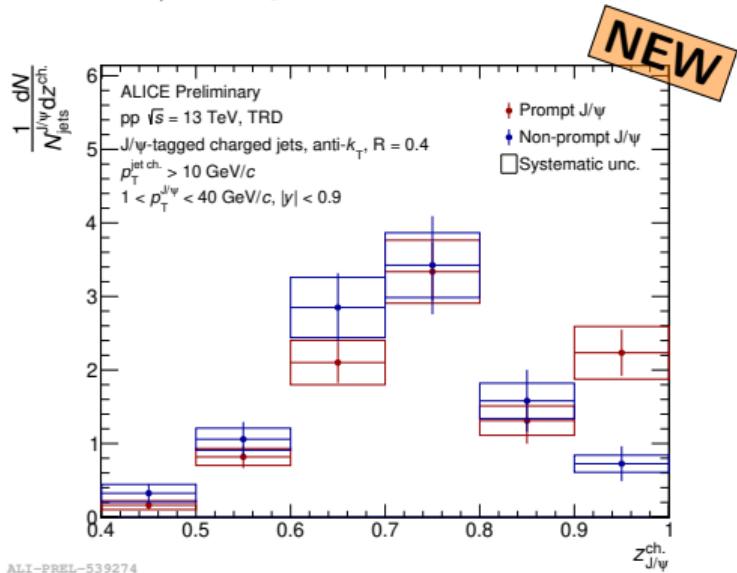
J/ψ with larger jet activity



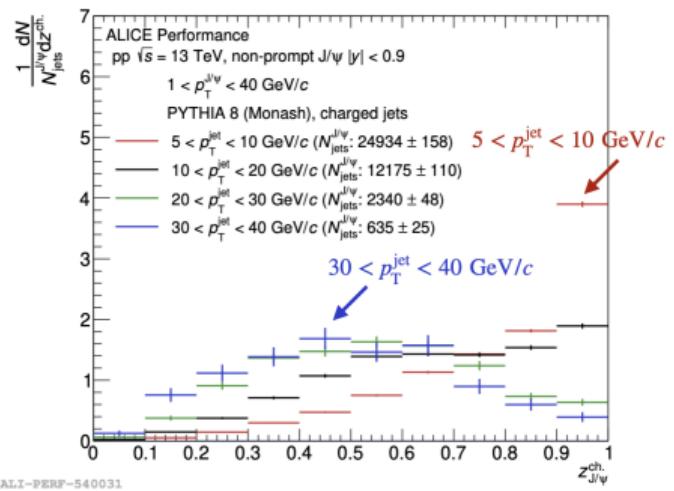
- Study interplay of J/ψ with the underlying event
- J/ψ production with larger jet activity may indicate production at later time scales

J/ψ fragmentation function in pp collisions

J/ψ fragmentation function



PYTHIA 8 studies

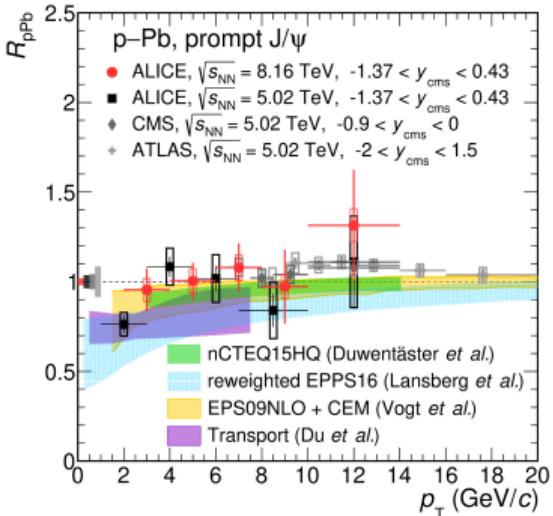


- Prompt and non-prompt J/ψ fragmentation function similar within uncertainties
- Comparison to models are needed
 → Ongoing Pythia 8 studies
 → Fragmentation function is particularly sensitive to the chosen jet p_T range

Nuclear modification factor, R_{pPb}

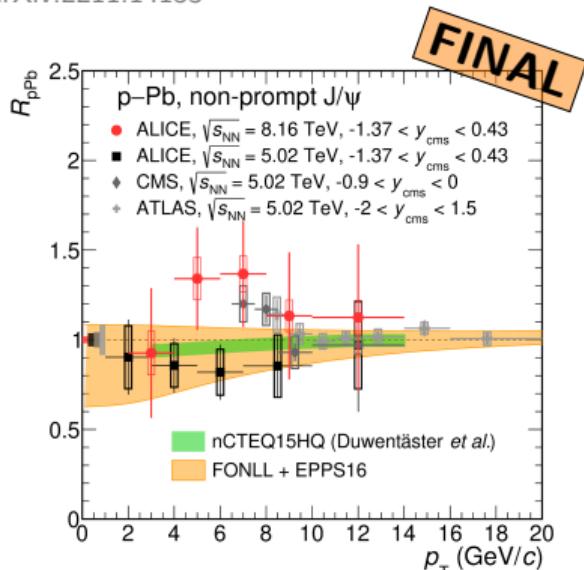
Prompt J/ψ

arXiv:2211.14153



Non-prompt J/ψ

arXiv:2211.14153



$$R_{\text{pPb}} = \frac{d^2\sigma_{\text{pPb}}/dydp_{\text{T}}}{A \times d^2\sigma_{\text{pp}}/dydp_{\text{T}}}$$

nCTEQ15HQ:
Dunwentäster *et al.*, PRD105 (2022) 114043

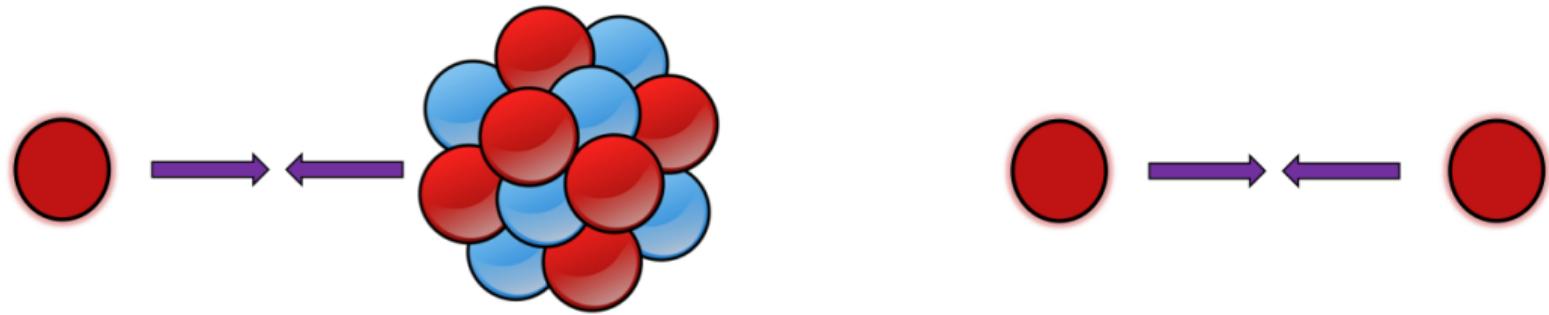
reweighted EPPS16:
Lansberg *et al.*, EPJC77 (2017) 1

EPS09NLO + CEM:
Vogt *et al.*, IJMPE22 (2013) 1330007

Transport:
Du *et al.*, JHEP03 (2019) 015

FONLL + EPPS16:
K.J. Eskola *et al.*, EPJC77 (2017) 163

- Prompt and non-prompt R_{pPb} at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ consistent with unity within uncertainties
 - Cold nuclear matter effects are modest in studied kinematic range
 - Contrary to forward rapidity where a strong suppression is observed at low p_{T} JHEP07 (2018) 160
- Results are reproduced within uncertainties by calculations including only modification of nuclear PDFs

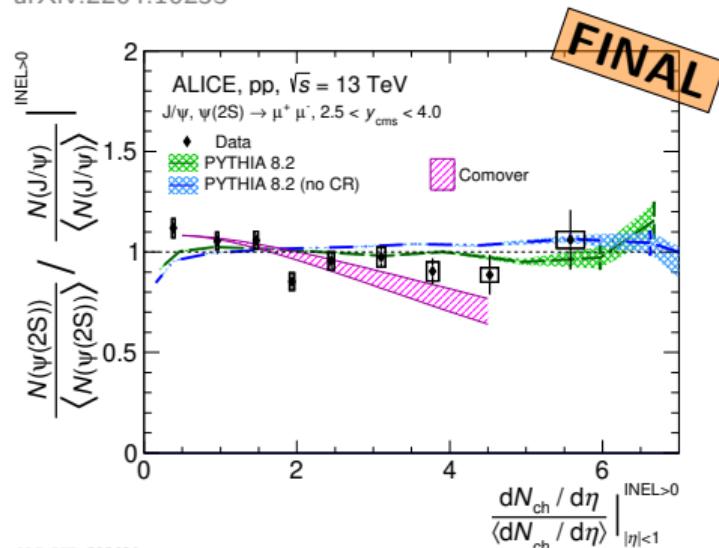
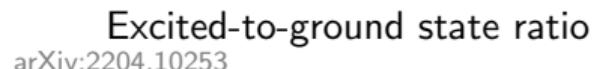
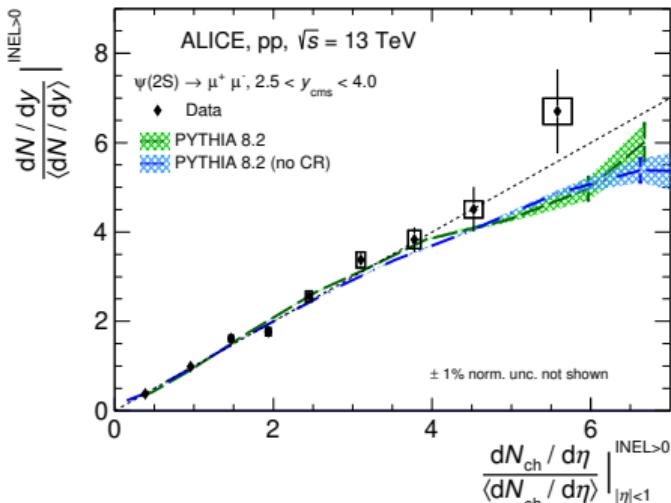


Small systems - a way to study MPI and collective effects

$\psi(2S)$ vs. multiplicity in pp collisions

$\psi(2S)$ vs. multiplicity

arXiv:2204.10253



PYTHIA 8.2:
T. Sjöstrand *et al.*,
JHEP08 (2015) 003

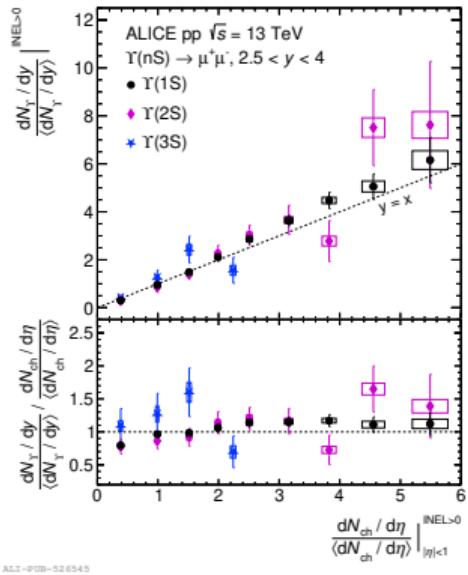
Comover:
E.G. Ferrieiro, PBL 749
(2015) 98

- Linear correlation between self-normalized $\psi(2S)$ yield and charged particle multiplicity
- Excited-to-ground state ratio consistent with unity within uncertainty
- Qualitatively good description provided by PYTHIA 8.2 with and without color-reconnection
- Ratio in fair agreement with comover model

$\Upsilon(nS)$ vs multiplicity in pp collisions

 $\Upsilon(nS)$

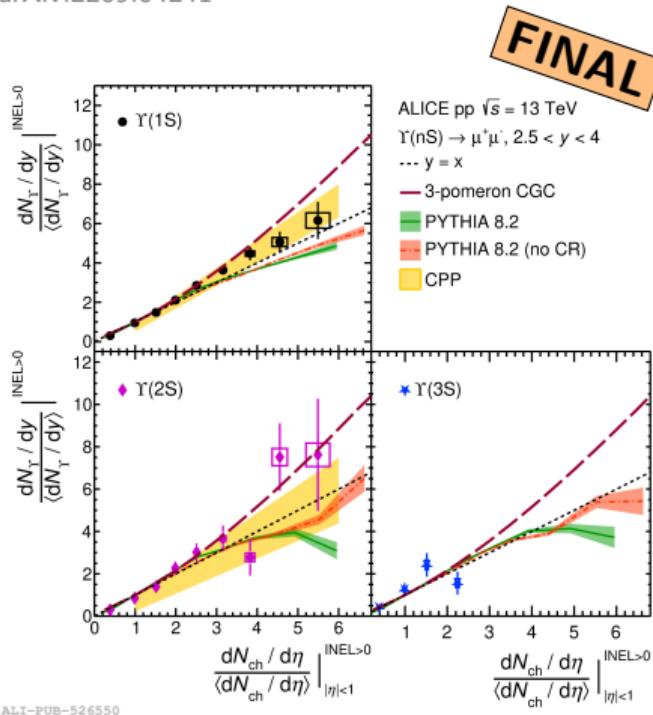
arXiv:2209.04241



- Linear trend for $\Upsilon(nS)$ states vs. multiplicity
- Coherent Particle Production provides a fair description within uncertainties of $\Upsilon(1S)$ and $\Upsilon(2S)$
- 3-pomeron CGC overestimates $\Upsilon(1S)$ at high multiplicity while PYTHIA underestimates data

 $\Upsilon(nS)$

arXiv:2209.04241



3-pomeron CGC:
E. Levin *et al.*,
EPJC80 (2020) 560

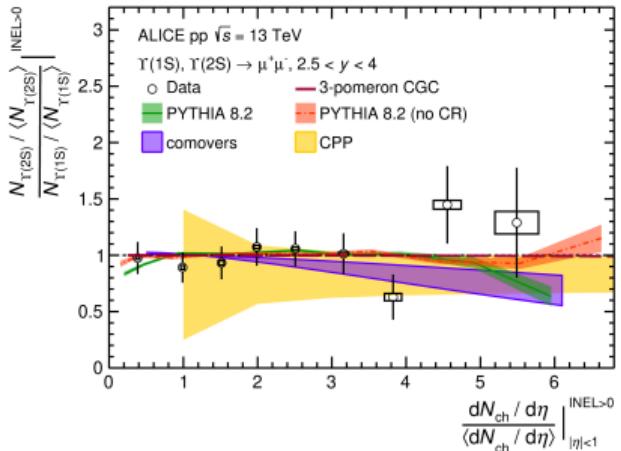
PYTHIA 8.2:
T. Sjöstrand *et al.*,
JHEP08 (2015) 003

CPP:
B.Z. Kopeliovich *et al.*, PRD101 (2020)
054023

Exited-to-ground state ratio in pp collisions

$\Upsilon(2S)/\Upsilon(1S)$

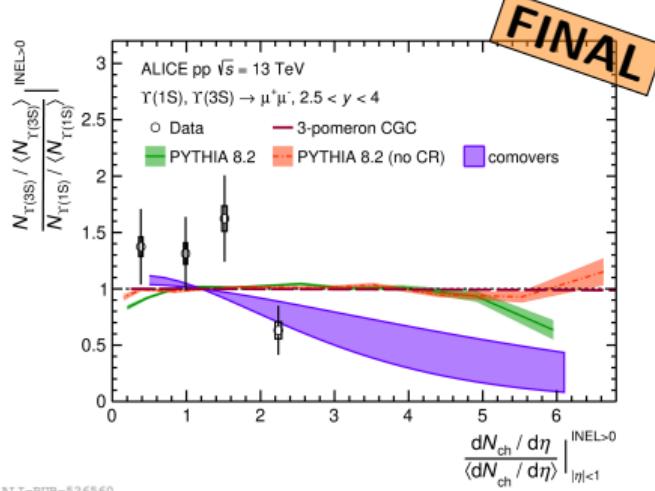
arXiv:2209.04241



ALI-PUB-526555

$\Upsilon(3S)/\Upsilon(1S)$

arXiv:2209.04241



3-pomeron CGC:

E. Levin *et al.*, EPJC80 (2020) 560

PYTHIA 8.2:

T. Sjöstrand *et al.*, JHEP08 (2015) 003

CPP:

B.Z. Kopeliovich *et al.*, PRD101 (2020) 054023

Comover:

E.G. Ferreiro, PBL 749 (2015) 98

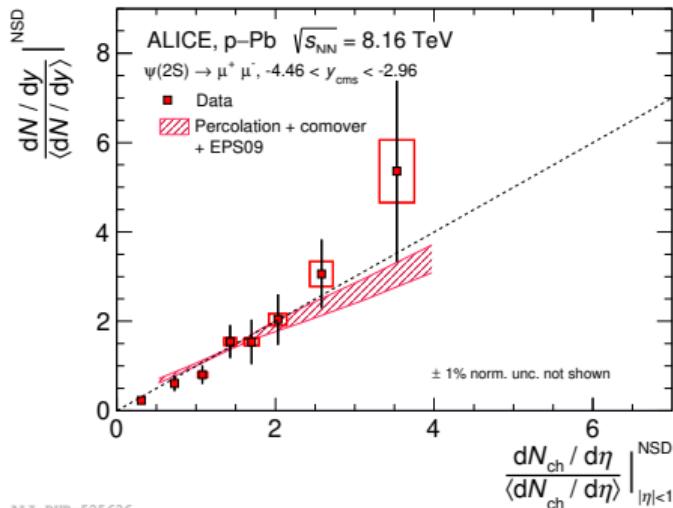
A. Esposito *et al.*, JHEP 10 (2018) 094

- Excited-to-ground state ratios consistent with unity within uncertainties
→ None or weak dependence of measured correlation with the binding energy of the state
- Models describe the observed trend within uncertainties
→ Not possible to disentangle any final state effects with current uncertainties

$\psi(2S)$ vs. multiplicity in p-Pb collisions

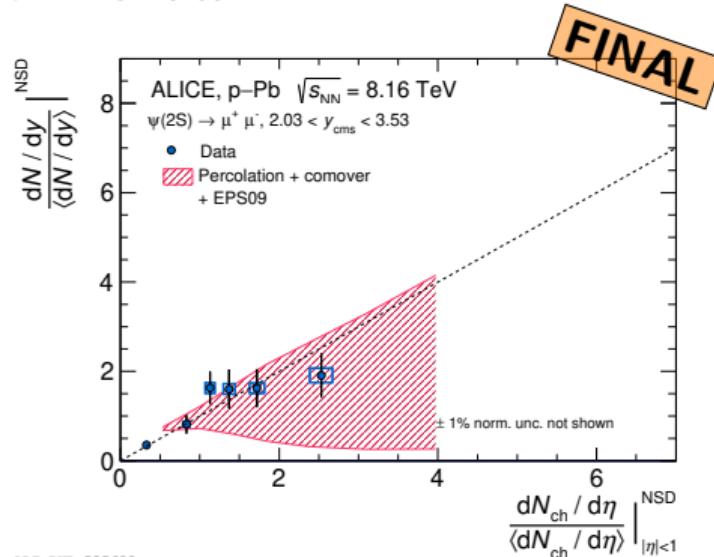
backward rapidity

arXiv:2204.10253



forward rapidity

arXiv:2204.10253



Percolation:
N. Armesto *et al.*, PRL 77 (1996) 3736

Comover:
E.G. Ferreiro, PLB 749 (2015) 98

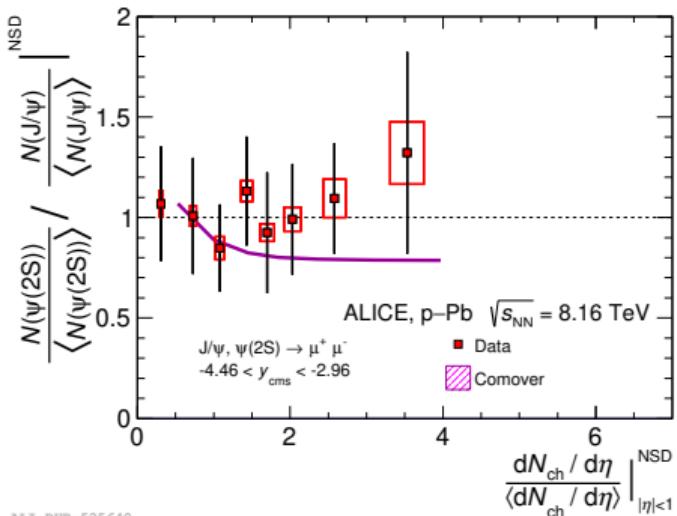
EPS09:
K-J. Eskola *et al.*, JHEP 04 (2009) 065

- Nearly linear increase of $\psi(2S)$ self-normalized yield with multiplicity
- Calculations by EPS09 coupled with Percolation and Comovers models describe the measured trends within uncertainties

Excited-to-ground state ratio in p-Pb collisions

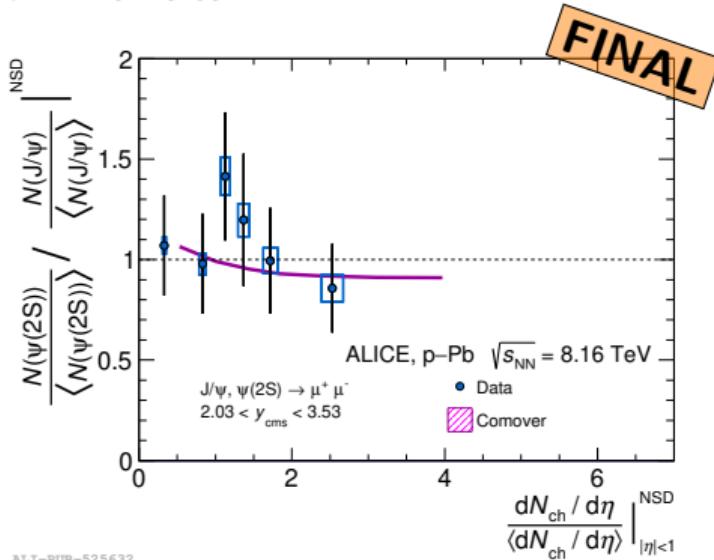
backward rapidity

arXiv:2204.10253



forward rapidity

arXiv:2204.10253

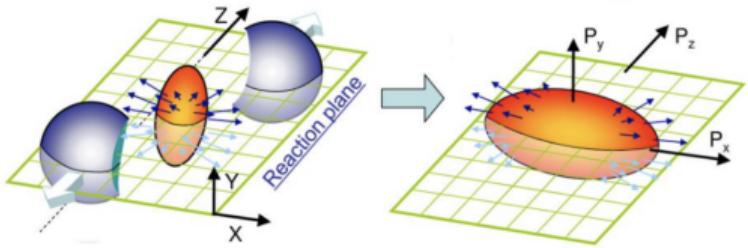
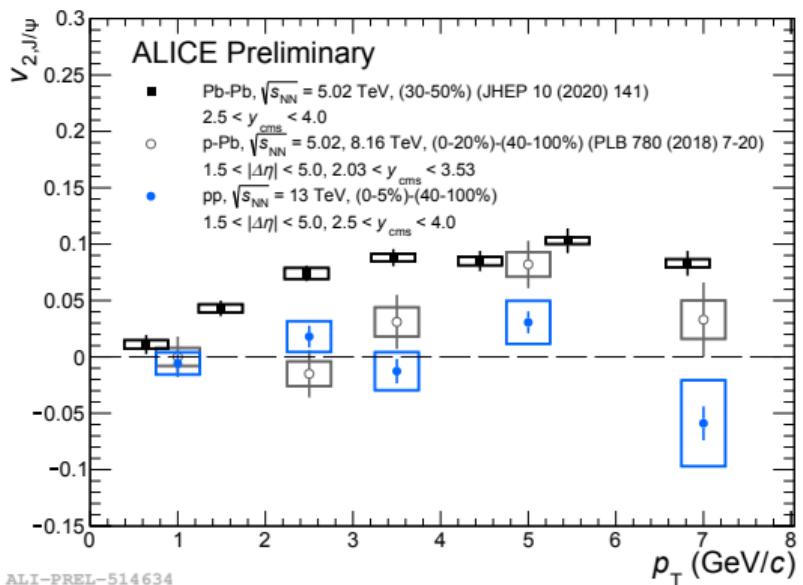


Comover:
E.G. Ferreiro, PLB 749
(2015) 98

- Excited-to-ground state ratio is compatible with unity within current uncertainties
→ Similar dependence on multiplicity for $\psi(2S)$ and J/ψ

J/ψ elliptic flow in small systems

$J/\psi v_2$ in pp, p-Pb and Pb-Pb



- Study collectivity in small systems
- $J/\psi v_2$ in pp compatible with 0 (within 1σ), contrary to larger systems
 - p-Pb: $v_2 > 0$ for $p_T > 4$ GeV/c
 - Pb-Pb: $v_2 > 0$ for $p_T > 1$ GeV/c

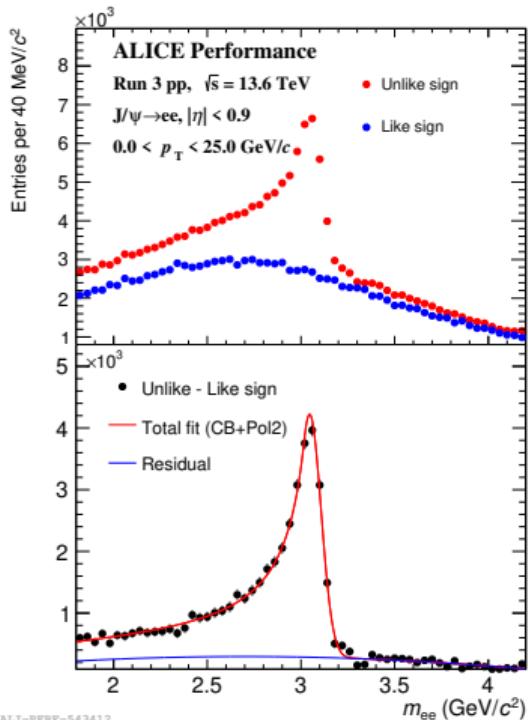
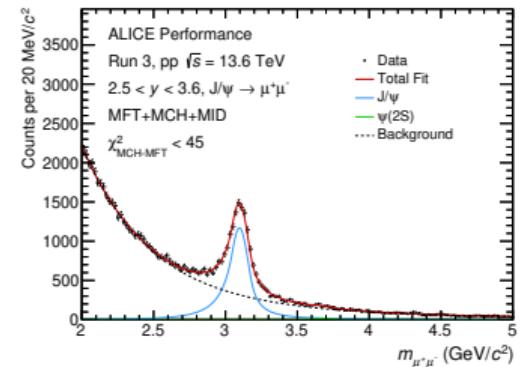
Conclusions



- **Small collision systems as a way to study production mechanism**
 - Little or no polarization observed for $\Upsilon(1S)$
 - Similar J/ψ fragmentation functions for prompt and non-prompt J/ψ
 - Prompt and non-prompt $J/\psi R_{pPb}$ above 2 GeV/c show modest dependence on cold nuclear matter effects at 8.16 TeV at mid-rapidity
- **Small collision systems as a way to study MPI and collectivity**
 - J/ψ pair production provides important insight into MPI
 - Results in agreement with LHCb
 - Multiplicity dependent quarkonium production shows a weak dependence on the system size or excited states
 - Not possible to disentangle initial and final state effects with current uncertainties
 - J/ψ in pp collisions does not show collective flow effects within uncertainties
 - J/ψ collective flow in p-Pb still to be understood

Run 3 upgrades and expectations

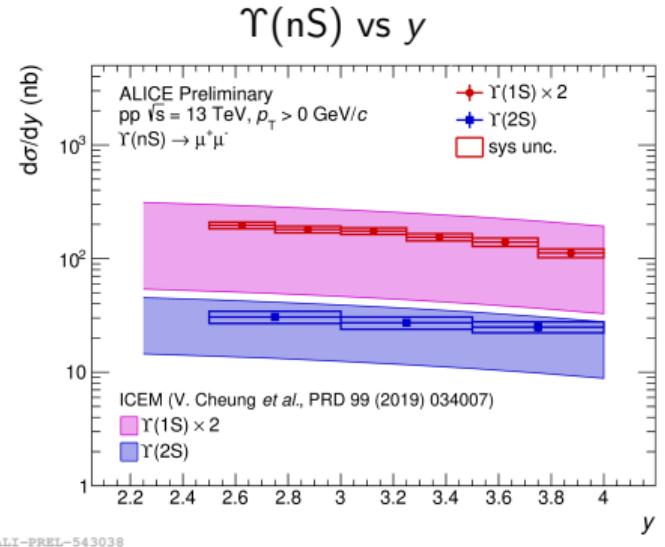
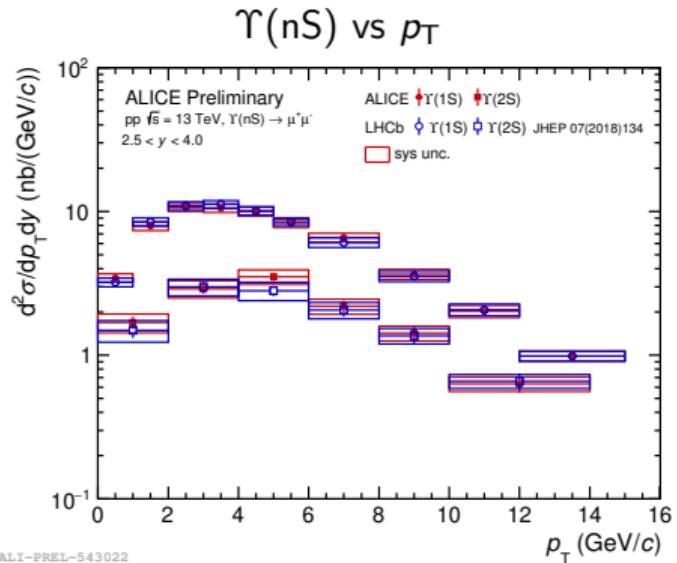
- ALICE - ITS upgrade will provide more precise measurements at midrapidity
- The new ALICE-MFT will allow for separation of prompt and non-prompt charmonium at forward rapidity
- Larger multiplicity may be reached with increased luminosity collected thanks to continuous readout
- Physics based software triggers will provide increased quarkonium data sample



Thank you for your attention!

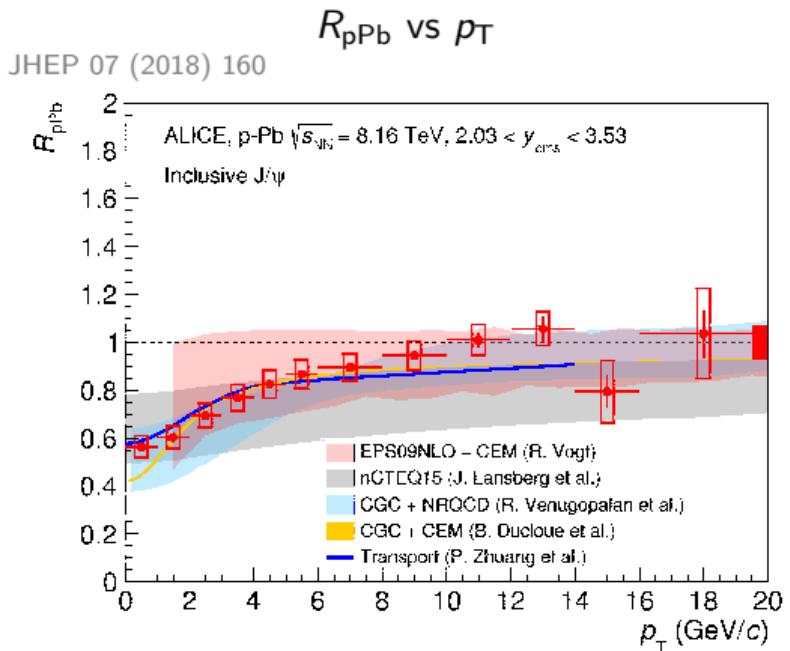
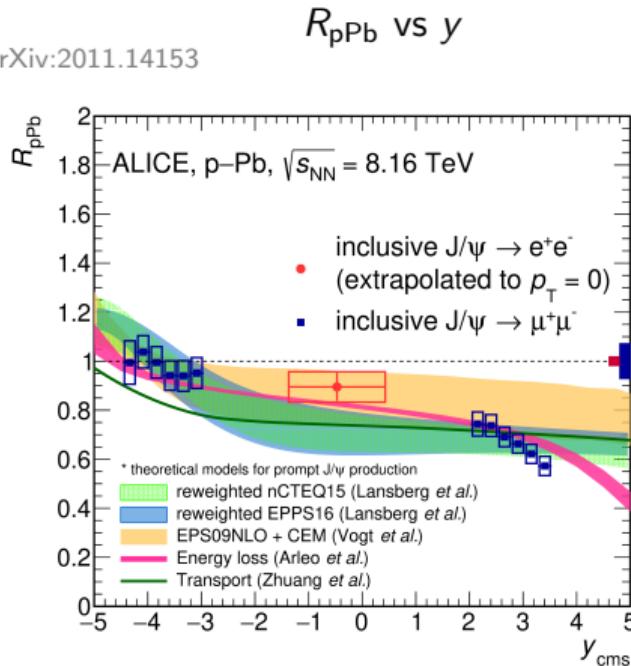
Backup

$\Upsilon(nS)$ production cross sections in pp collisions



Nuclear modification factor, R_{pPb}

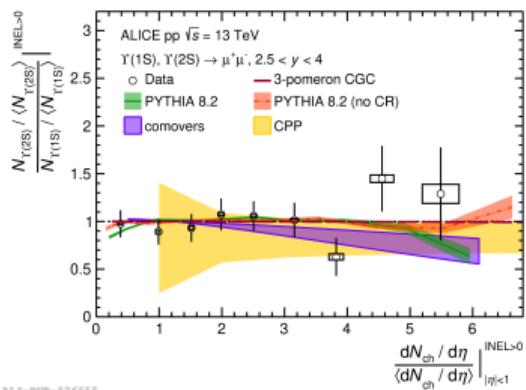
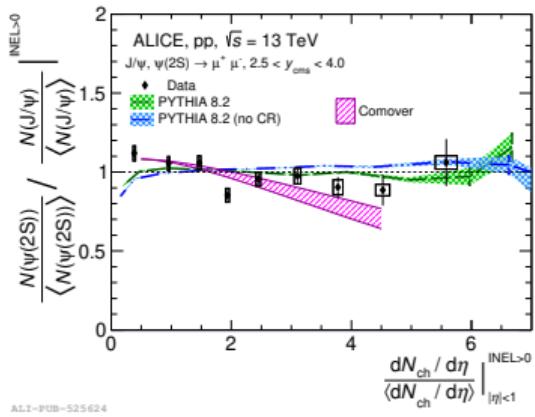
arXiv:2011.14153



ALI-PUB-529535

- At forward rapidity there is a strong suppression observed at small p_T

Quarkonium vs multiplicity: models



PYTHIA 8.2 with Color Reconnection JHEP08 (2015)003

- Combination of *initial* and *final* state effects
- Final state effect at play with MPI where strings are merged based on a QCD full color flow calculation with a loose modeling of dynamical effect via a global saturation

Coherent particle production (CPP) PRD101 (2020) 054023

- Includes nuclear-like effects and gluon saturation in the *initial* stage

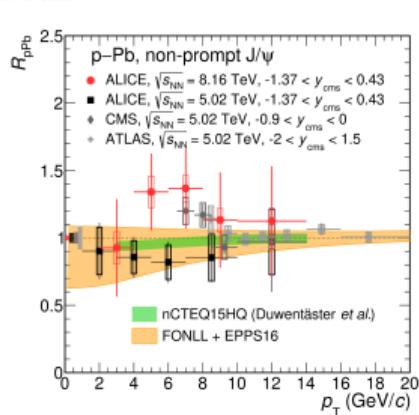
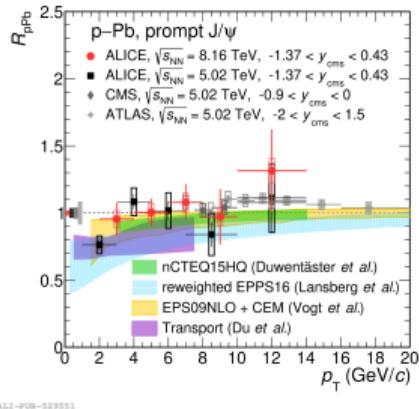
3-pomeron CGC EPJC80 (2020) 560

- Initial* state effects
- Increased quarkonium production probability from multi-pomeron mechanism

Comover model PBL 731 (2014) 57, JHEP 10 (2018) 094

- Quarkonia dissociated in *final* state by interactions with comoving particles

Nuclear modification factor: models



nCTEQ15HQ PRD105 (2022) 114043

- Based on CEM and EPS09 nPDFs and NLO calculations

EPS09NLO + CEM IJMPE22 (2013) 1330007

- Pure shadowing scenario employing the NLO CEM
- Shadowing effects parametrized via EPS09 nPDFs

Reweighted EPPS16 EPJC77 (2017) 1

- Based on NRQCD factorization with EPPS16 nPDF sets
- Reweighted to include RICH and LHC results

Transport model JHEP03 (2019) 015

- Based on kinetic rate-equation approach within a fireball model

FONLL + EPPS16 EPJC77 (2017) 163

- FONLL calculations using EPPS16 nPDFs