Quarkonia phenomenology with ALICE

Guillaume Taillepied, for the ALICE Collaboration
GSI – Darmstadt

g.taillepied@cern.ch

QCD in Extreme Conditions
27-29 July 2022
Trondheim, Norway

Motivation: QCD studies with quarkonium measurements

Small systems

pp collisions:

- perturbative and non-perturbative QCD processes involved
- reference for measurements in p–Pb, Pb–Pb

p–Pb collisions:

- cold nuclear matter effects

High multiplicities:

- multiparton interactions
- collectivity in small systems

Pb–Pb collisions

Prompt J/ψ:

- heavy quarks experience the full evolution of the system
- sensitive to dissociation in the medium
- sensitive to (re)generation happening within the medium or at the phase boundary

Non-prompt J/ψ:

- access beauty quark energy loss

Bottomonia:

- thermalization(?) of b quarks
- sequential suppression

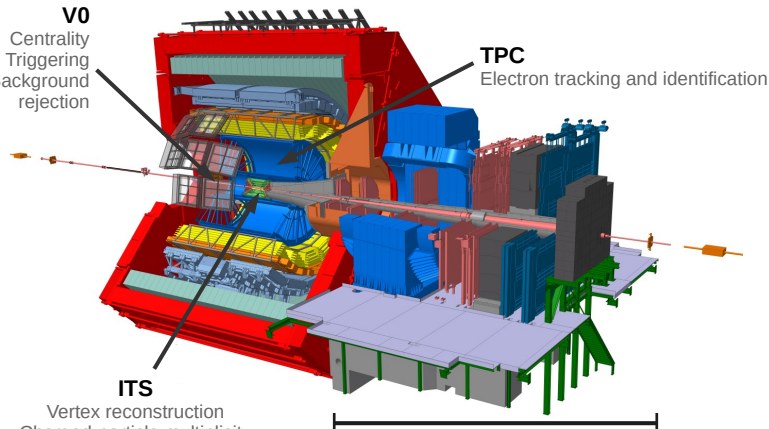
A Large Ion Collider Experiment

Central barrel:

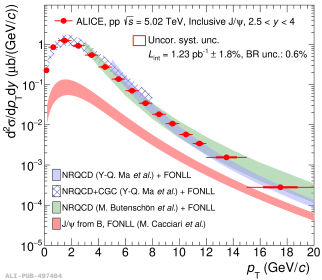
- $\mathrm{J}/\psi \to \mathrm{e}^+\mathrm{e}^-$
- Acceptance: $|y_{\mathrm{lab}}| < 0.9$
- Inclusive J/ψ down to $p_{\mathrm{T}} = 0$
- Prompt and non prompt separation at low p_{T}

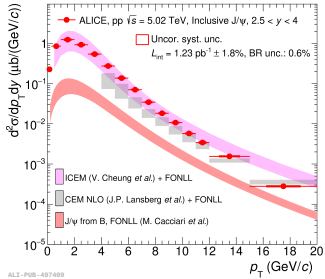
Muon spectrometer:

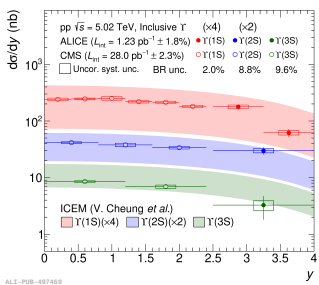
- J/ψ, $\psi(2\mathrm{S})$, $\Upsilon(\mathrm{nS})$
- Acceptance: $2.5 < y_{\mathrm{lab}} < 4.0$
- Inclusive measurements down to $p_{\mathrm{T}} = 0$



Inclusive quarkonia in pp collisions







pp at 5.02 TeV, $\Upsilon(\mathrm{nS}) \to \mu^+\mu^-$:

- ALICE measurement at large y shows a drop of the production described by ICEM

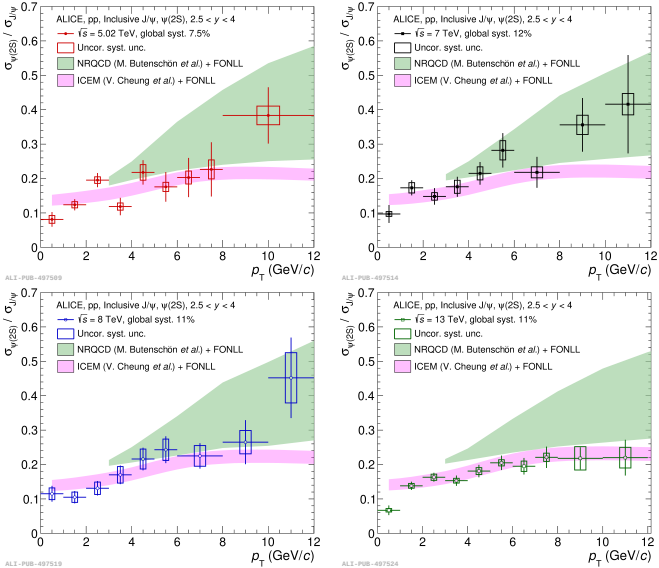
pp at 5.02 TeV, $J/\psi \to \mu^+\mu^-$: new results with 10 times more statistics than previous publication

arXiv:2109.15240

- NRQCD(-based) models + FONLL provide a good description, significant overlaps among calculations prevent to discriminate between them
- ICEM+FONLL in good agreement with the data, while CEM NLO + FONLL shows some tensions.

NRQCD: Ma et al., PRL 106(2011)042002
NRQCD + CGC: Ma et al., PRL 113(2014)192301
NRQCD CS+CO: Butenschön et al., PRL 106(2011)022003
CEM: Lansberg et al., PLB 807(2020)135559
ICEM: Cheung et al., PRD 98(2018)114029
FONLL: Cacciari et al., JHEP 10(2012)137

Inclusive quarkonia in pp collisions



$\psi(2S)$ to J/ψ cross section ratio in pp collisions at several energies:

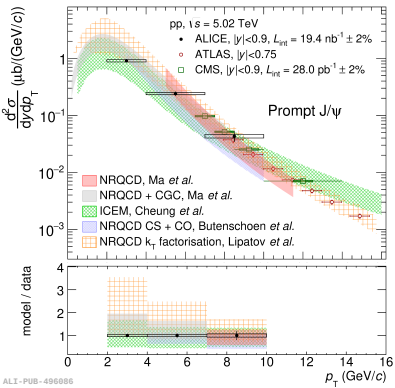
arXiv:2109.15240

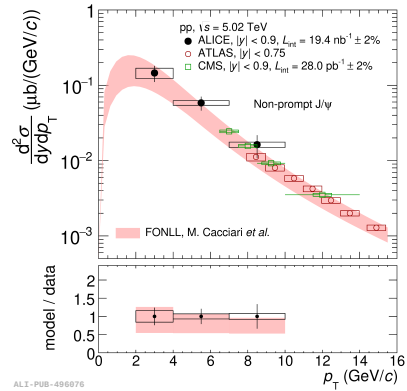
- at 5.02, 7 and 8 TeV: agreement within uncertainties with ICEM+FONLL at low p_T, NRQCD+FONLL at high p_T
- at 13 TeV, measurements are significantly more precise thanks to the higher luminosity
  ICEM+FONLL describes the ratio over the whole p_T range, NRQCD+FONLL overestimates it

Prompt and non-prompt J/ψ in pp collisions

pp at 5.02 TeV, $J/\psi \to e^+e^-$, non-prompt J/ψ disentangled through a fitting procedure using the pseudoproper decay length:

JHEP 03(2022)190





- Agreement between ALICE, ATLAS and CMS in the overlapping p_T range, unique ability of ALICE to probe the low-p_T region.
- Prompt J/ψ production described by NRQCD and ICEM models, non-prompt J/ψ by FONLL calculations.

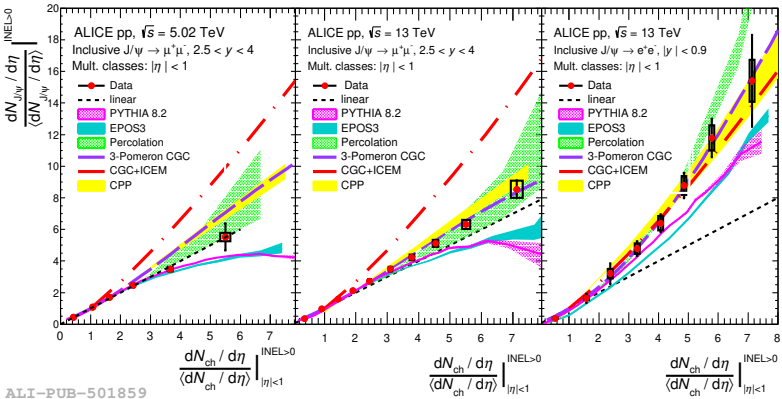
Model bands tend to overlap one another, preventing to discriminate between them. Same conclusion at 13 TeV (JHEP 03(2022)190).

NRQCD k_T factorisation: Lipatov et al., PRD 100(2019)114021.

Multiplicity-dependent J/ψ production in pp collisions

Inclusive J/ψ at mid- and forward rapidities, multiplicity measured at midrapidity.

- J/ψ self-normalized yield at forward rapidity grows linearly with the event multiplicity, regardless of the collision energy. Not described by CGC+ICEM, Pythia 8.2 and EPOS3 generators.
- At midrapidity, faster-than-linear growth of the measured self-normalized yield, qualitatively described by available models.



JHEP 06(2022)015

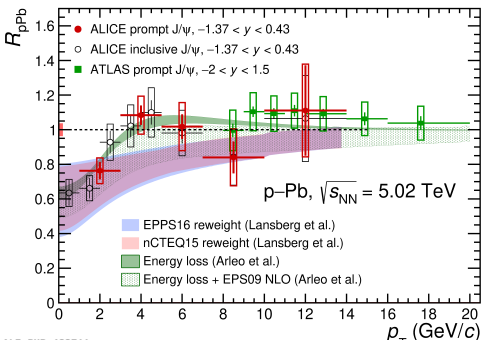
CPP: Kopeliovich et al., PRD 101(2020)054023
3-Pomeron CGC: Levin et al., EPJC 80(2020)560
Percolation: Ferreiro et al., PRC 86(2012)034903

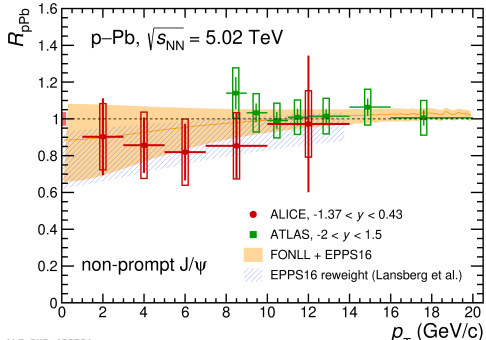
Pythia 8.2: Sjöstrand et al., Comp. Phys. Comm. 191(2015)159-177
EPOS3: Werner et al., PRC 89(2014)064903

Nuclear modification factor in p–Pb collisions

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}y}$$

Energy loss: Arleo et al., JHEP 05 (2013)155
nCTEQ15, EPPS15 rew.: Lansberg et al., PRL 121(2018)052004
EPPS16+FONLL: Eskola et al., EPJC 77(2017)163



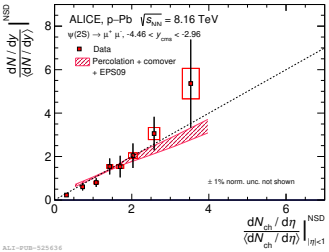


- Suppression of inclusive and prompt J/ψ for $p_{\mathrm{T}} < 3$ GeV/c, non-prompt J/ψ shows no p_{T} dependence and consistency with unity within uncertainties.
- Data reproduced, within uncertainties, by models using various nPDF models. Models with coherent energy loss also catches the trend at low p_{T} for prompt J/ψ.

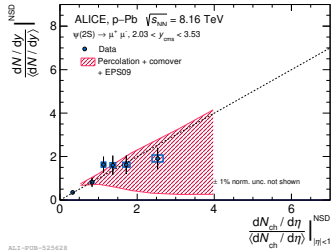
arXiv:2105.04957

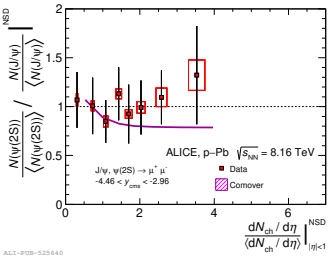
Multiplicity-dependent $\psi(2S)$ in p–Pb collisions

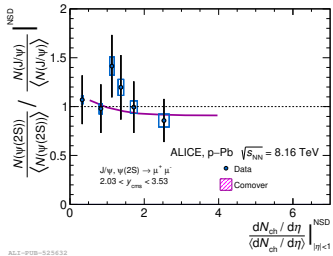
Pb–p, $-4.46 < y_{\rm cms} < -2.96$



p–Pb, $2.03 < y_{\rm cms} < 3.53$







Comover: Ferreiro, PLB 749(2015)98
EPS09: Eskola et al., JHEP 09(2009)065

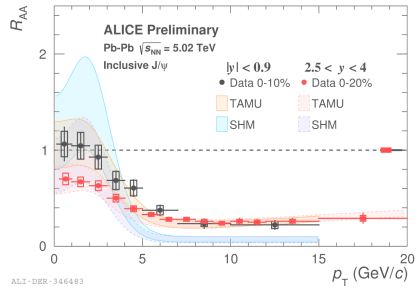
Self-normalized $\psi(2S)$ yield:

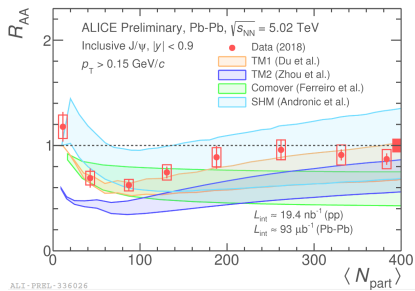
- Approximately linear trend, slope close to unity.
- Described by percolation + comover + EPS09, large uncertainty from nPDFs (EPS09).

Self-normalized $\psi(2S)$-to-J/ψ ratio:

- compatible with unity vs. charged-particle multiplicity
- described by comover model predictions within uncertainties

R_{AA} of inclusive J/ψ in Pb–Pb collisions





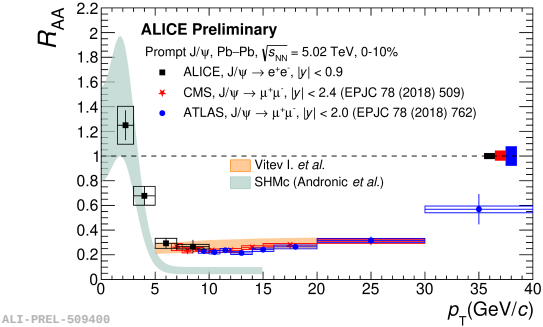
- Inclusive J/ψ R_{AA} rises towards low p_T, especially at $y = 0$ ⇒ strong signature of recombination mechanism.
- Statistical Hadronization (SHM) describes the data at low p_T, while transport model (TAMU) reproduces the full range.

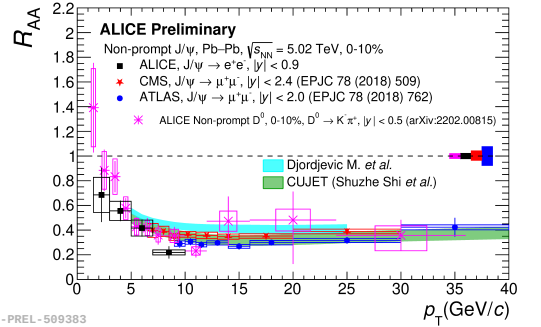
- Centrality dependence described by transport and SHM.
- Large model uncertainties, notably arising from the knowledge of the total charm cross section, lead to significant overlap between models.

TM1: Du, Rapp, NPA 943(2015)147, **TM2**: Zhou et al., PRC 89(2014)054911, **SHM**: Andronic et al., PLB 731(2014)57

Prompt and non-prompt J/ψ R_{AA}

Compared with results from other experiments and most recent models:



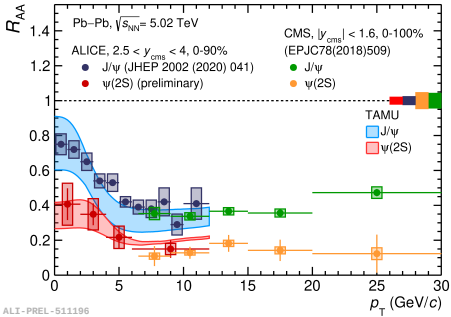


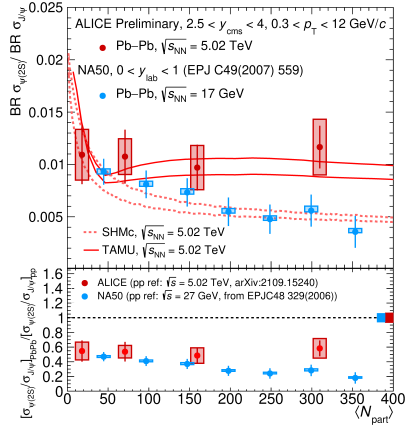
- Agreement among results from LHC experiments, ALICE extends the reach to very low p_T.
- Prompt component described by SHMc at low p_T, model by Vitev at al. at high p_T.
- Non-prompt J/ψ described by models including collisional and radiative energy loss above 5 GeV/c.

Vitev: Vitev et al., JHEP 10(2019)111
SHMc: Andronic et al., JHEP 07(2021)035

Djordevic: Djordevic et al., PRC 105(2022)L021901
CUJET: Shuzhe et al., CPC 43(2019)044101

$\psi(2S)$ R_{AA} and ratio to J/ψ in Pb–Pb collisions

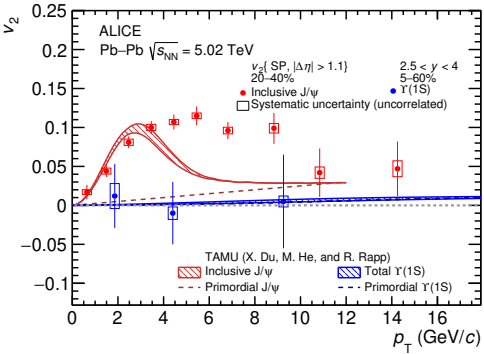


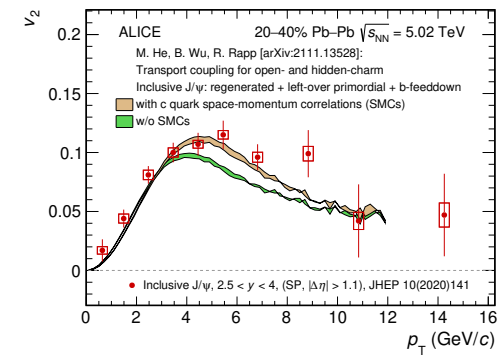


$\psi(2S)$ R_{AA} and $\psi(2S)$-to-J/ψ ratio at forward rapidities described by TAMU. Tension of SHMc with the ratio at large $\langle N_{part} \rangle$.

The $\psi(2S)$-to-J/ψ ratio removes the dependence to the total charm cross section, a significant source of uncertainty in the calculations!

Elliptic flow of J/ψ and $\Upsilon(1S)$ in Pb–Pb collisions

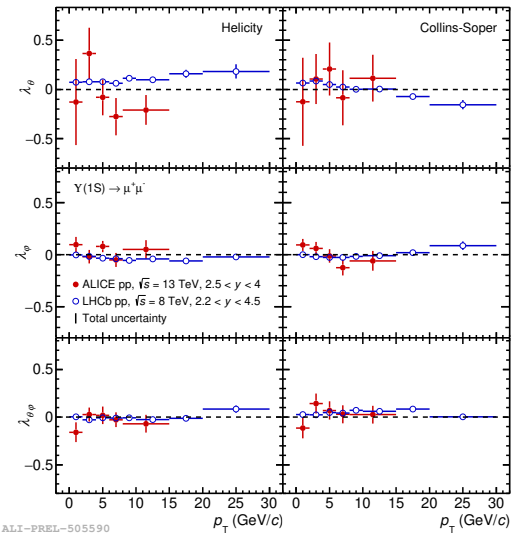




JHEP 2020(2020)141
PRL 123(2019)192301

- Large J/ψ v_2 at low p_T, suggesting charm thermalisation, while upsilon shows no flow within large uncertainty.
- TAMU model does not catch the trend for $p_T > 4$ GeV/c, recent improvements in the model lead to better agreement with the data, especially when including c-quark SMC.

Υ polarization in pp collisions

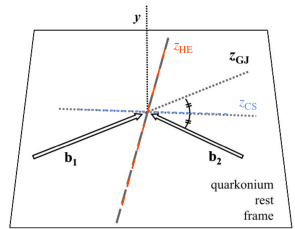


Polarization studied via the polar angle distribution of the dilepton:

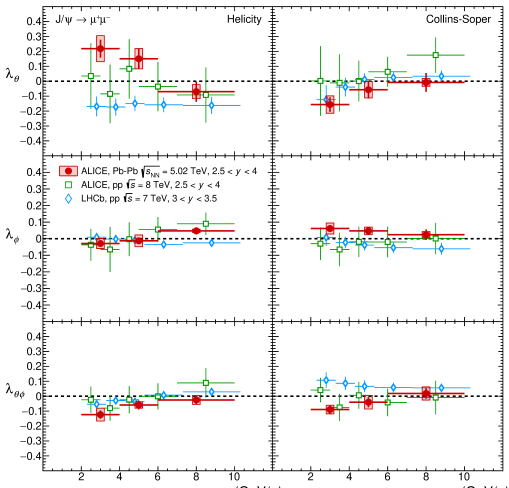
$$W(\theta) \propto \frac{1}{3+\lambda_\theta}(1 + \lambda_\theta \cos^2\theta + \lambda_\phi sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

First ALICE measurement of Υ(1S) polarization in pp.

- No polarization measured within uncertainties
- In agreement with LHCb results (JHEP 12(2017)110)



J/ψ polarization in pp and Pb–Pb collisions



ALI-PUB-490215

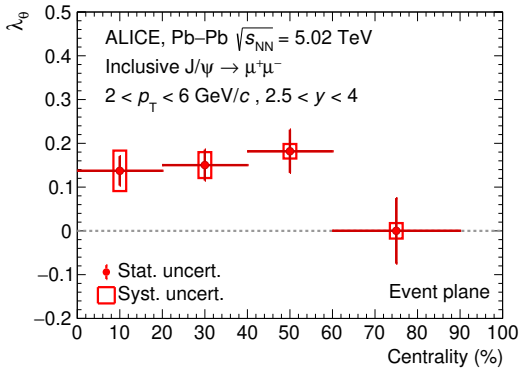
J/ψ polarization in Pb–Pb collisions:

- λ_θ deviates by up to 2σ w.r.t. zero in both frames in $2 < p_T < 4$ GeV/c.
- Compatible with ALICE measurement in pp collisions within uncertainties (EPJC 78(2018)562).
- 3σ difference between ALICE results in Pb–Pb and LHCb measurements (EPJC 73(2013)2631) in pp collisions in HE frame.

PLB 815(2021)136146

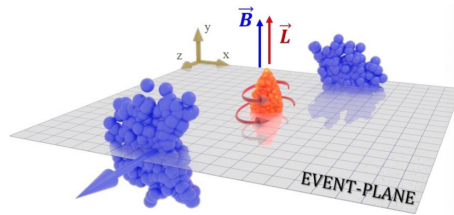
Polarization of J/ψ in Pb–Pb collisions w.r.t. the event plane

J/ψ polarization in Pb–Pb collisions measured using another reference frame. arXiv:2204.10171



ALI-PUB-521052

Event plane: normal to $\vec{B}$ and $\vec{L}$.



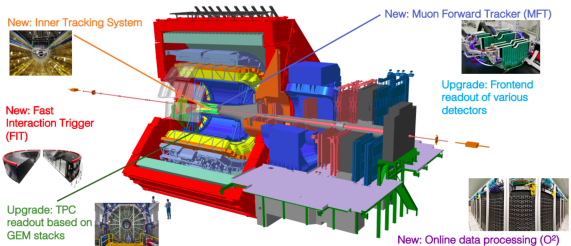
First measurement of J/ψ polarization w.r.t. the event plane.

Significant centrality dependence, significant polarization (3.5σ) for λ_θ in the 40-60% centrality interval.

Theoretical models are needed to describe this measurement!

Prospects for Run 3

Update of the LHC and ALICE during Long Shutdown 2 (2018-2022):



- move to continuous readout, improving the available statistics ($\mathcal{L}_{\rm int} = 10$ nb^{-1} in Pb–Pb, 200 pb^{-1} in pp)
- improved vertexing capabilities: new ITS, MFT at forward rapidities for separation of prompt and non-prompt charmonium

New and improved measurements of quarkonia in small and large systems:

- all Run 1 & 2 measurements will benefit from the increased statistics, and new methodologies (e.g. ML)
- new observables accessible: prompt/non-prompt charmonium elliptic flow, improved precision on ψ(2S) in Pb–Pb, measurement of χ_c and X(3872), double J/ψ production, correlations between mid and forward rapidities...

Conclusion

Selection of measurements presented, much more available!

Phenomenology outcomes of the presentation:

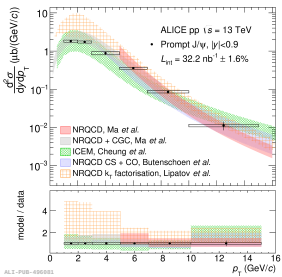
- in pp collisions:
  - quarkonia cross sections are well described by NRQCD- and ICEM-based (+FONLL) models
  - multiplicity-dependent production and ψ(2S)-to-J/ψ ratio provide important constraints to QCD at high energy
- in p–Pb collisions: measurements reproduced by models including PDF nuclear modifications and coherent energy loss
- in Pb–Pb collisions:
  - significant inputs for the description of the quarkonia (re)generation mechanisms, with transport models showing a good agreement with J/ψ and ψ(2S) measurements at high p_{T} and $\langle N_{\mathrm{part}} \rangle$
  - J/ψ polarization w.r.t. the event plane: new observable that requires a theoretical description

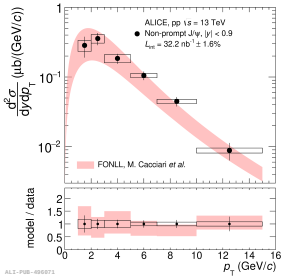
Run 3 & 4 will provide measurements of unprecedented precisions, a crucial step for the confrontation of data and theory. Stay tuned!

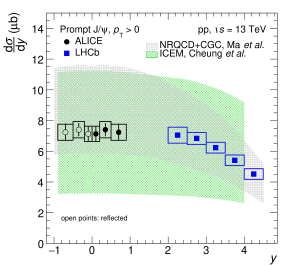
Thank you!

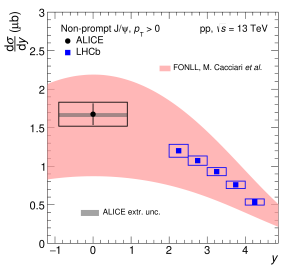
Back-up

Prompt and non-prompt J/ψ in pp collisions









pp 13 TeV, $J/\psi \rightarrow e^+e^-$: arXiv:2108.02523

- Prompt J/ψ production well described by NRQCD-based and ICEM calculations
- FONLL calculations in agreement with measurement of non-prompt J/ψ

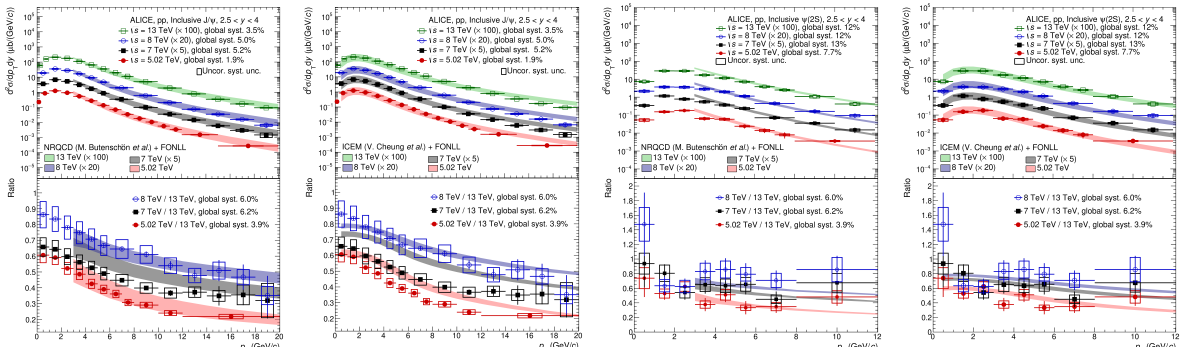
ALICE measurement at midrapidity compared with LHCb measurement at forward rapidity (JHEP 10(2015)172):

- Good agreement between the two experiments
- Measurements from both experiments described by CGC+NRQCD and ICEM (prompt J/ψ), FONLL (non-prompt J/ψ)
- y-dependent model calculations have large uncertainties

J/ψ and $\psi(2S)$ in pp collisions

Ratio of 5.02, 7 and 8 TeV to 13 TeV, compared with NRQCD+FONLL and ICEM+FONLL

arXiv:2109.15224



- Partial cancellation of uncertainties in the energy ratios (charm and bottom masses, factorization and renormalization scales...)

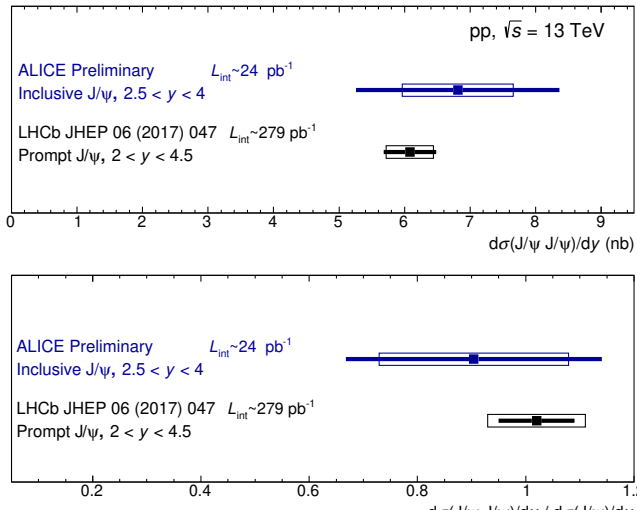
Double J/ψ production in pp collisions

pp at 13 TeV, double J/ψ production:

- Good agreement between ALICE and LHCb on the double J/ψ cross section and double-to-single-J/ψ cross section ratio.

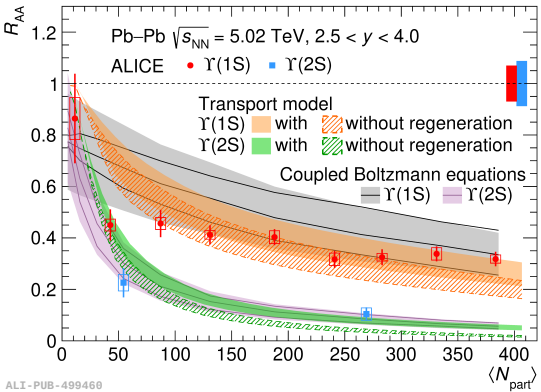
To be noted:

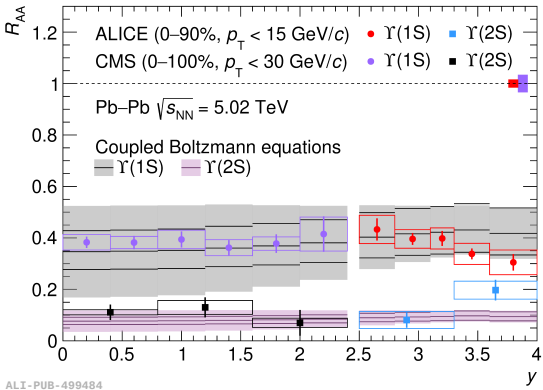
- Different rapidity ranges
- ALICE measurement is inclusive J/ψ, LHCb measured prompt J/ψ



ALI-PREL-505385

R_{AA} of Υ(1S) and Υ(2S)



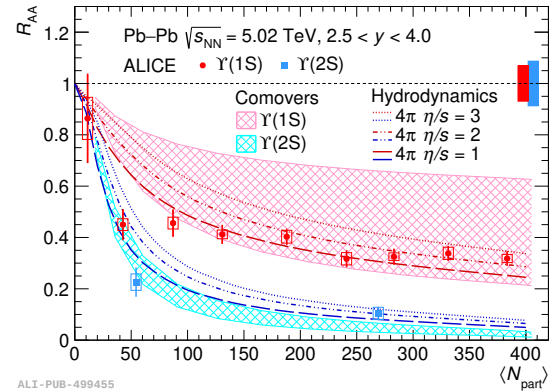


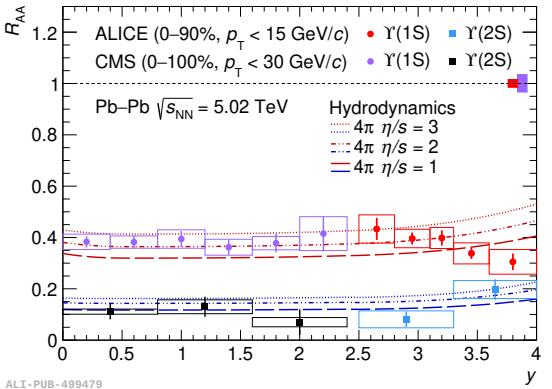
PLB 822(2021)136579

Transport model: PRC 96(2017)054901
Coupled Boltzmann equations: JHEP 01(2021)046

- Suppression of Υ(2S) stronger than that of Υ(1S), both R_{AA} show small centrality dependence. Hint of decrease of the Υ(1S) R_{AA} at very large rapidity
- Model calculations in good agreement with the data, also when regeneration is not included, consistency between ALICE and CMS.

R_{AA} of Υ(1S) and Υ(2S)





PLB 822(2021)136579

Comovers: Ferreiro, Landsberg, JHEP 10(2018)094
Hydro: Krouppa, Strickland, Universe 2(2016)16

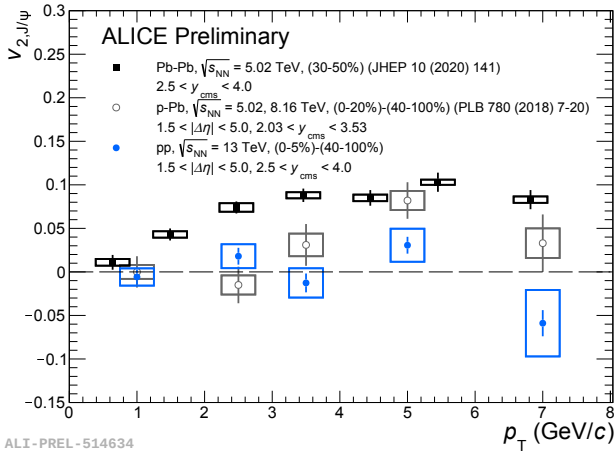
- Υ(1S) and Υ(2S) also well described by comovers and hydrodynamics calculations.

J/ψ v_2 in pp, p–Pb and Pb–Pb collisions

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

Looking for collective effects of HF in small systems.
$\Rightarrow$ first measurement of J/ψ elliptic flow in pp collisions at the LHC.

- no collective behaviour observed for J/ψ in high-multiplicity pp collisions within uncertainties
- similar flow in p–Pb and Pb–Pb above 4 GeV/c, p–Pb not described by transport models



Ordering with system size: $v_2^{J/\psi}(\text{pp}) < v_2^{J/\psi}(\text{p-Pb}) < v_2^{J/\psi}(\text{Pb-Pb})$