Review on charmonium nuclear modification factors and flow coefficients in Pb-Pb and p-Pb collisions with ALICE

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On behalf of the ALICE Collaboration

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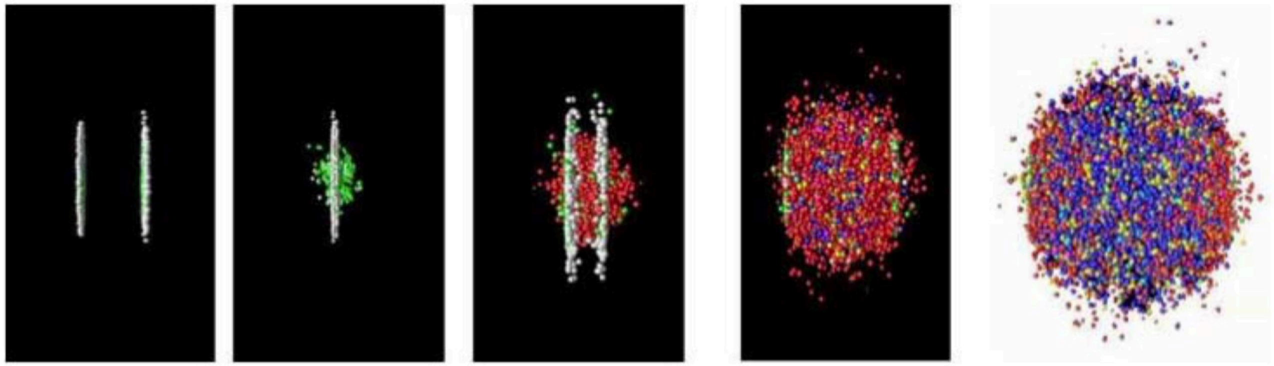
Charmonium as probe of the Quark-Gluon Plasma (QGP)

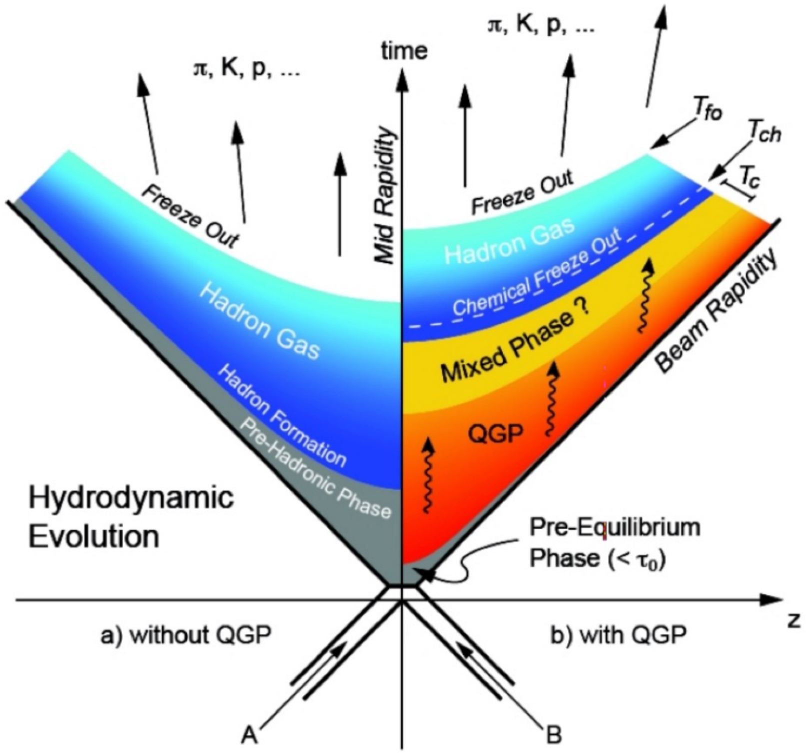
Study of Quark-Gluon Plasma (QGP)

- Deconfined state of matter
- Freely-roaming color charges



Formation through Heavy-ion collisions

Pb-Pb ⇒ Formation of QGP
p-Pb, pp ⇒ Reference, Cold Nuclear Matter (CNM) effects, but formation of a strongly interacting medium at LHC energy remains an open question

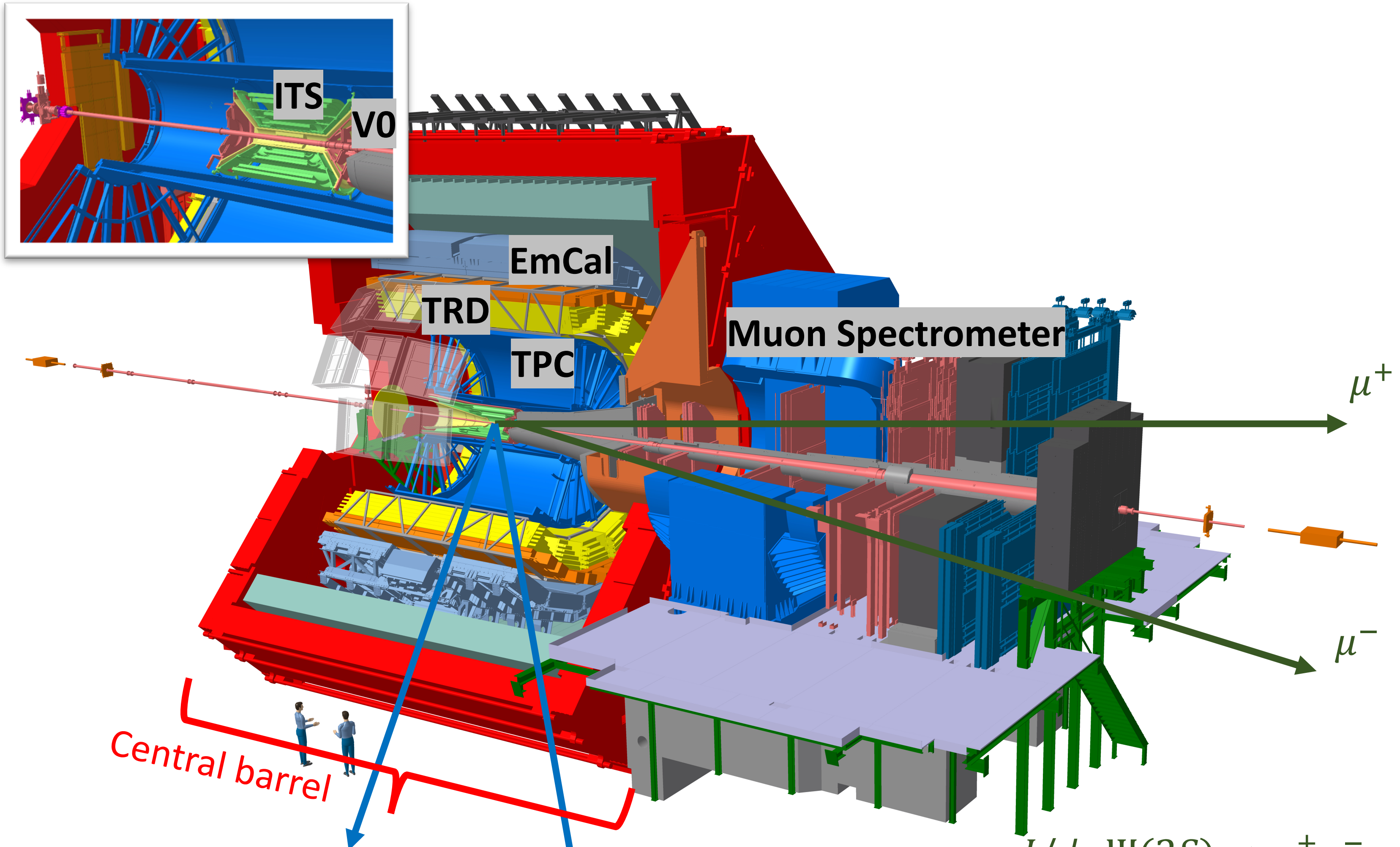


What probe can we use?

Focus on quarkonium ($Q\bar{Q}$)
Charmonium: $c\bar{c}$ (J/ψ, and excited $\Psi(2S)$)

Heavy quarks formed at early stages (hard scale)
Influenced by deconfined color charges
Insight on QGP properties

A Large Ion Collider Experiment



e^+ e^-

$J/\psi \rightarrow e^+e^-$ ($|y| < 0.9$)

Distinction J/ψ prompt (produced at primary vertex) / non-prompt (b-hadron decays)

$J/\psi, \Psi(2S) \rightarrow \mu^+\mu^-$

($2.5 < y < 4.0$)

Inclusive measurements

ITS – Inner Tracking System

Tracking, vertex reconstruction, multiplicity estimation

V0(A and C)

Triggering, Centrality estimation

TPC – Time Projection Chamber

PID, Tracking

EmCal – Electromagnetic Calorimeter

Triggering, PID

TRD – Transition Radiation Detector

Triggering, PID

Muon Spectrometer

Forward tracking and triggering of muons

Observable #1: Nuclear modification factor

Way to quantify hot and cold matter effects on particle production:

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} \text{ and } R_{\mathrm{pA}} = \frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{A.d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

The particle yield is compared to the one in pp scaled up to account for A and geometry changes

If $\boldsymbol{R_{\mathrm{AA}}}$ **= 1**, AA is equivalent to scaled-up pp: no apparent hot medium effects nor Cold Nuclear Matter (CNM) effects

If $\boldsymbol{R_{\mathrm{AA}}}$ **< 1**, hot medium effects or/and CNM effects lead to production decrease (energy loss, color screening, shadowing etc.)

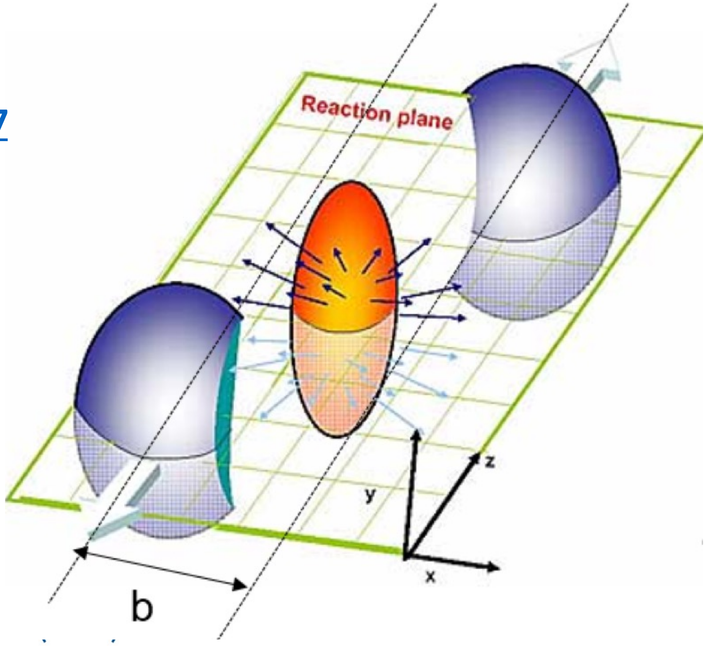
If $\boldsymbol{R_{\mathrm{AA}}}$ **> 1**, hot medium effects or/and CNM effects lead to production increase (antishadowing, heavy quark recombination, etc.)

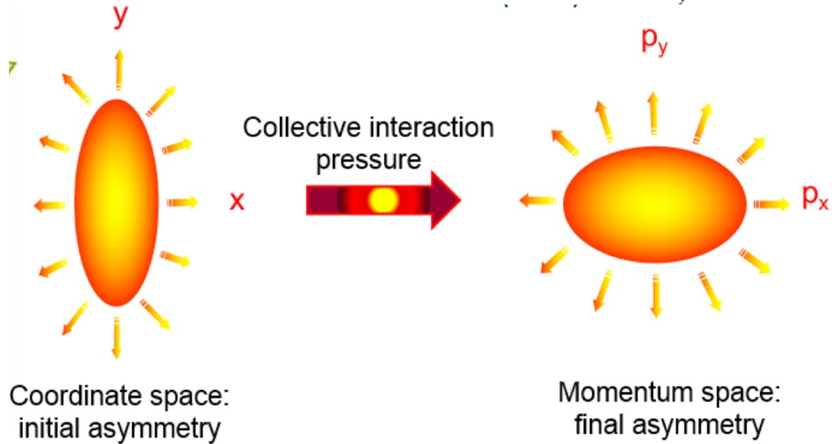
Observable #2: Flow

In Heavy-ion collisions, **anisotropic collision** region for b > 0

- **Anisotropies in momentum** distribution
- **Long-range correlations** of produced particles

Taken from Universe, 2017





Azimuthal correlations of particles quantified by Fourier coefficients in ϕ angle distribution (wrt event plane if large multiplicity), or 2-particle correlations (in smaller systems)

$$\frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left(1 + \sum 2v_n \cos[n(\phi - \Psi_n)] \right)$$

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

v_2 (elliptic) : sensitive to thermalization of the medium
v_3 (triangular) : sensitive to fluctuations of the initial state

Flow points to collective behaviours : signature of QGP

Constrains theoretical models

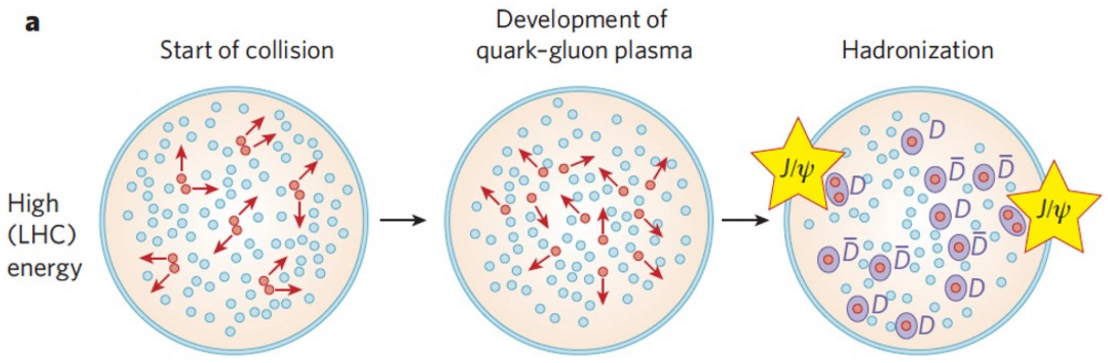
QGP effects on charmonium production

Suppression and recombination

Charmonia suppression: expected from interaction with color charges in QGP (color screening, dynamical dissociation, energy loss)

Charmonia recombination: charm and anti-charm quarks form quarkonia including combination from different hard scatterings

[*Nature* **448,** 302–309 (2007)]



Main theory approaches

Transport Model (TM) and Comovers:
Competition between suppression and recombination

Statistical Hadronization Model (SHM):
Production at freeze-out according to relative chemical equilibrium

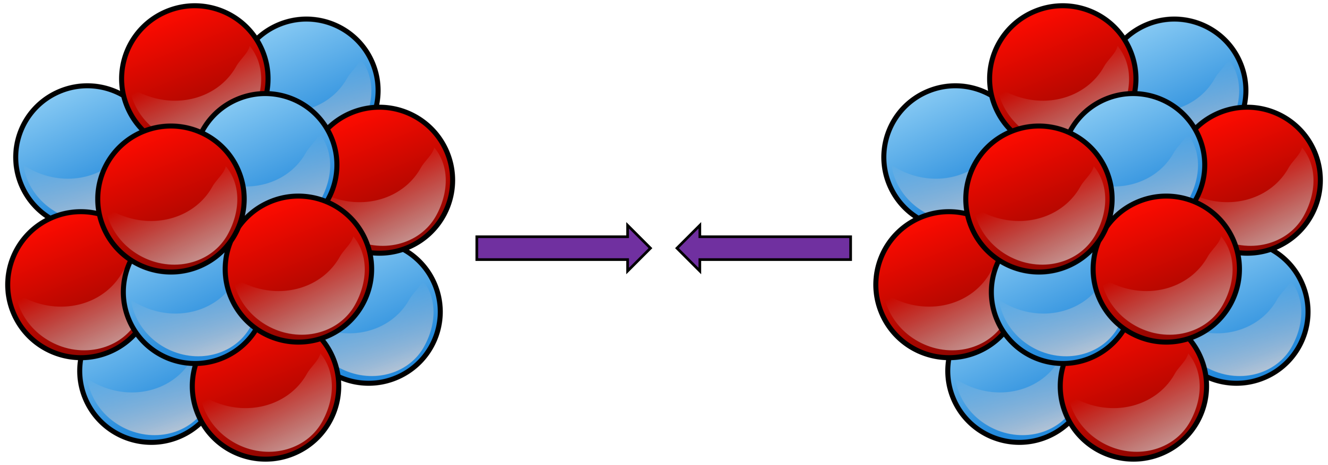
Nuclear modification factor expectation

R_{AA}: suppression leads to decrease with collision energy
R_{AA}: recombination leads to increase with collision energy

Flow expectation

Two sources:

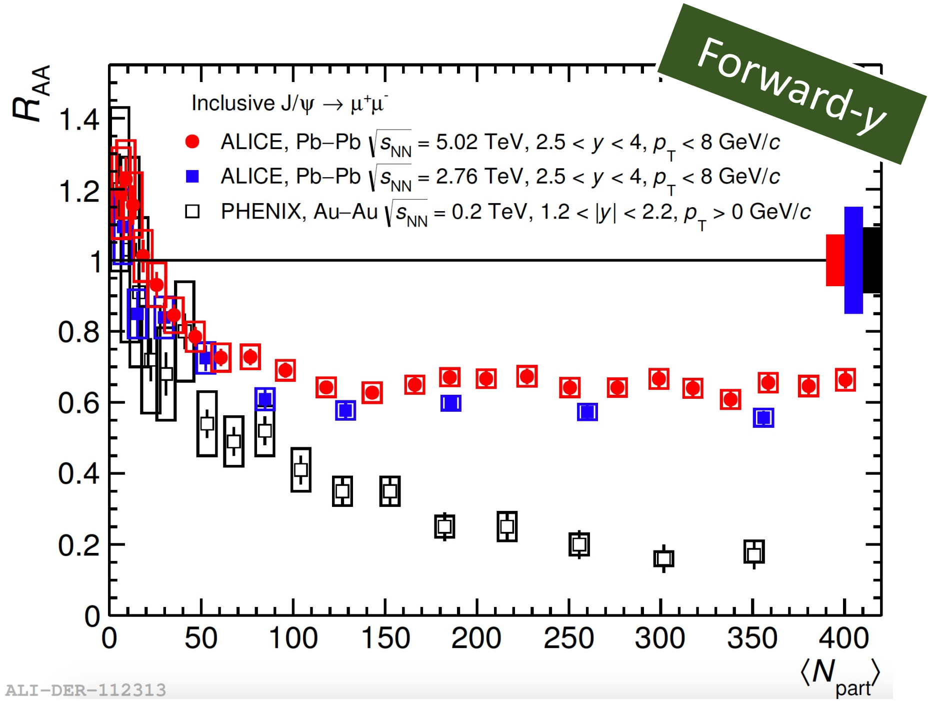
- Flow inheritance from charm quarks via recombination
  - At freeze-out (Statistical Hadronization Model SHM) [Phys.Lett. B490 (2000) 196-202]
  - Dynamically (Transport model TM - TAMU, X. Du et al., Comovers) [Thews et al. - Phys.Rev.C 63:054905 (2001)]
- Path-length dependent suppression



Pb-Pb Collisions

Results in Pb-Pb – Nuclear modification factor

Energy dependence and Centrality dependence



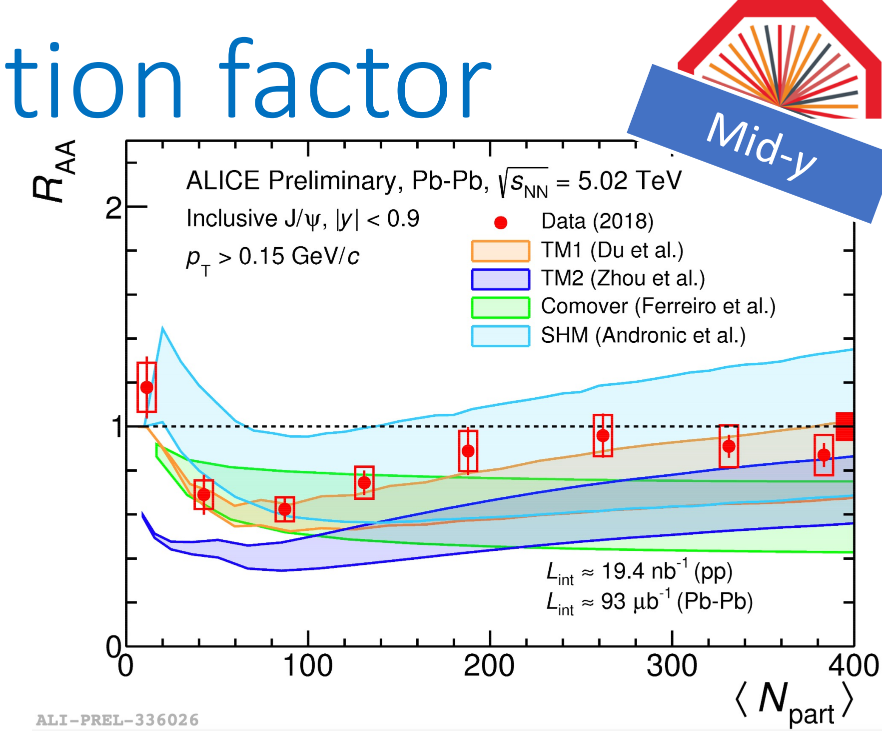
Energy dependence of R_{AA}:

Less suppression as energy increases

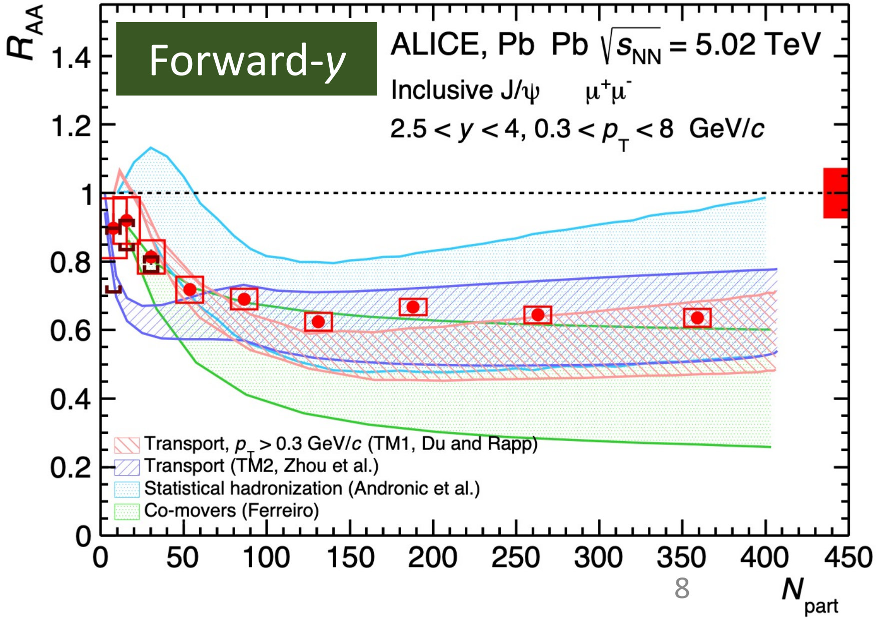
(Interpreted as regeneration)

Model comparisons:

Good agreement with models including **charmonium regeneration** from charm quarks

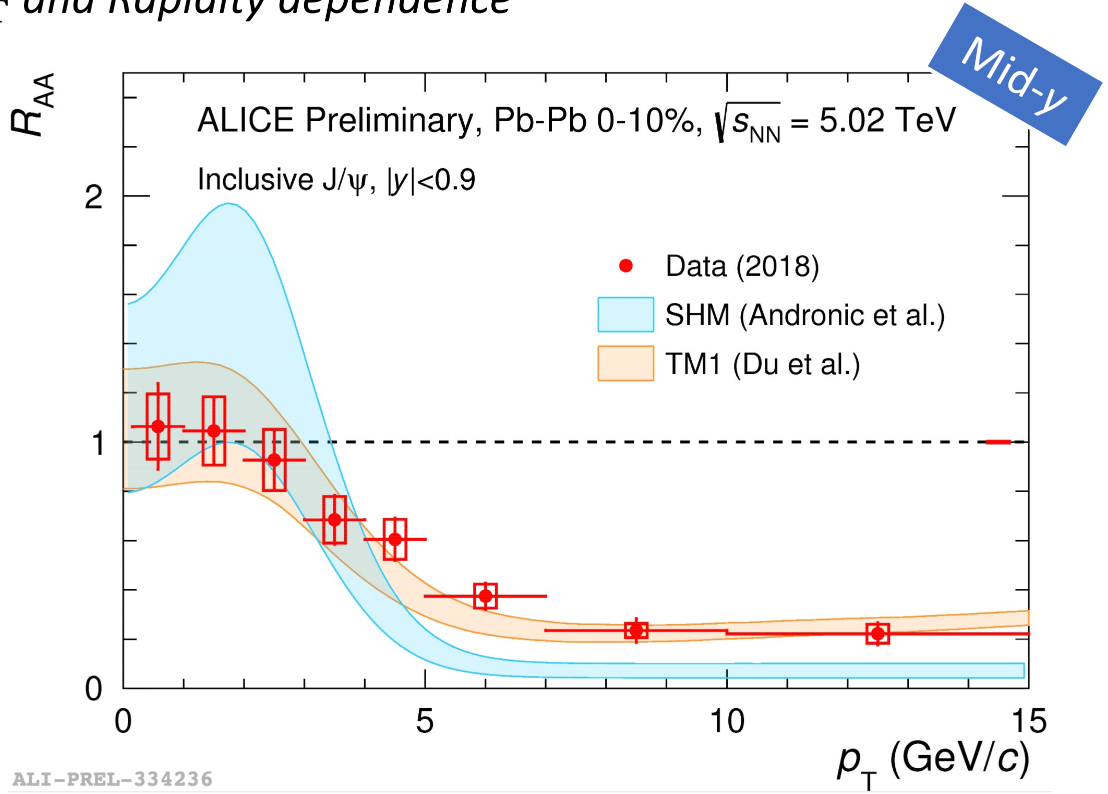


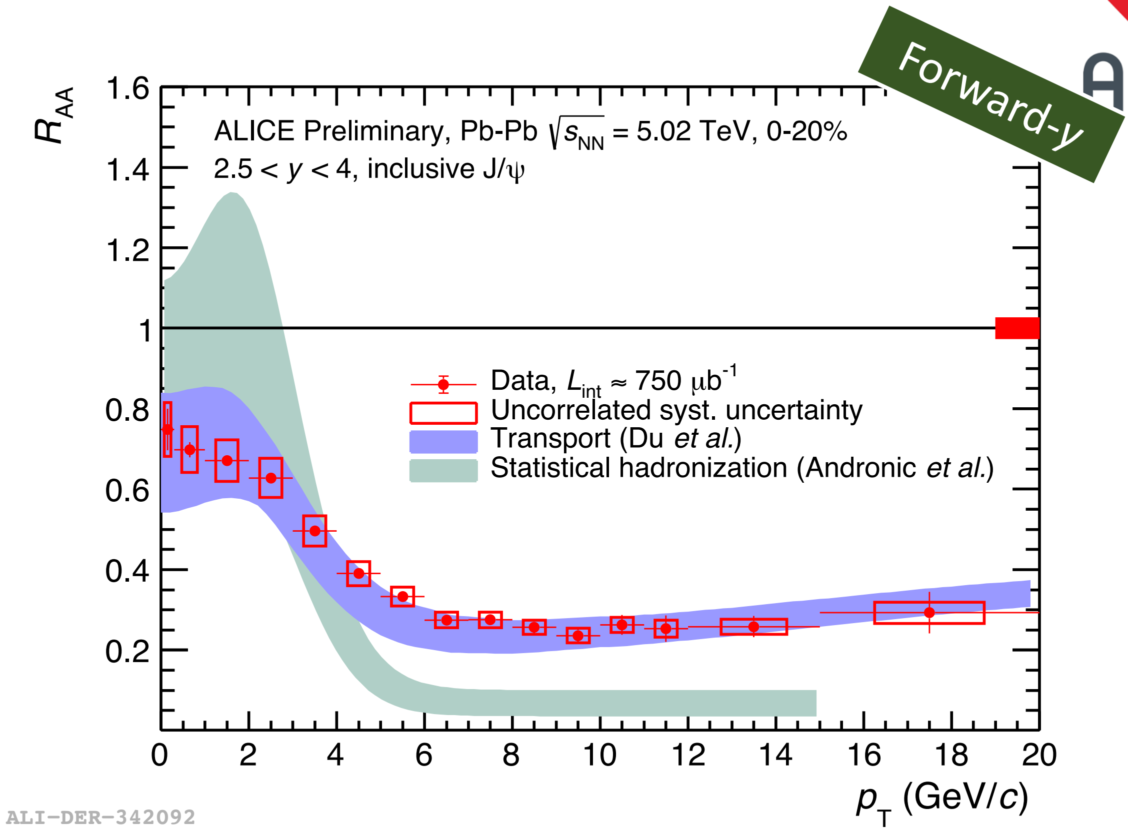
[PLB 766 (2017) 212]



Results in Pb-Pb – Nuclear modification factor

p_{T} and Rapidity dependence





Less suppression of low-p_T J/ψ, in line with regeneration from charm quarks

At low-p_{T}, J/ψ is **more suppressed at forward** rapidity
At high-p_{T}, **equivalent suppression** regardless of rapidity

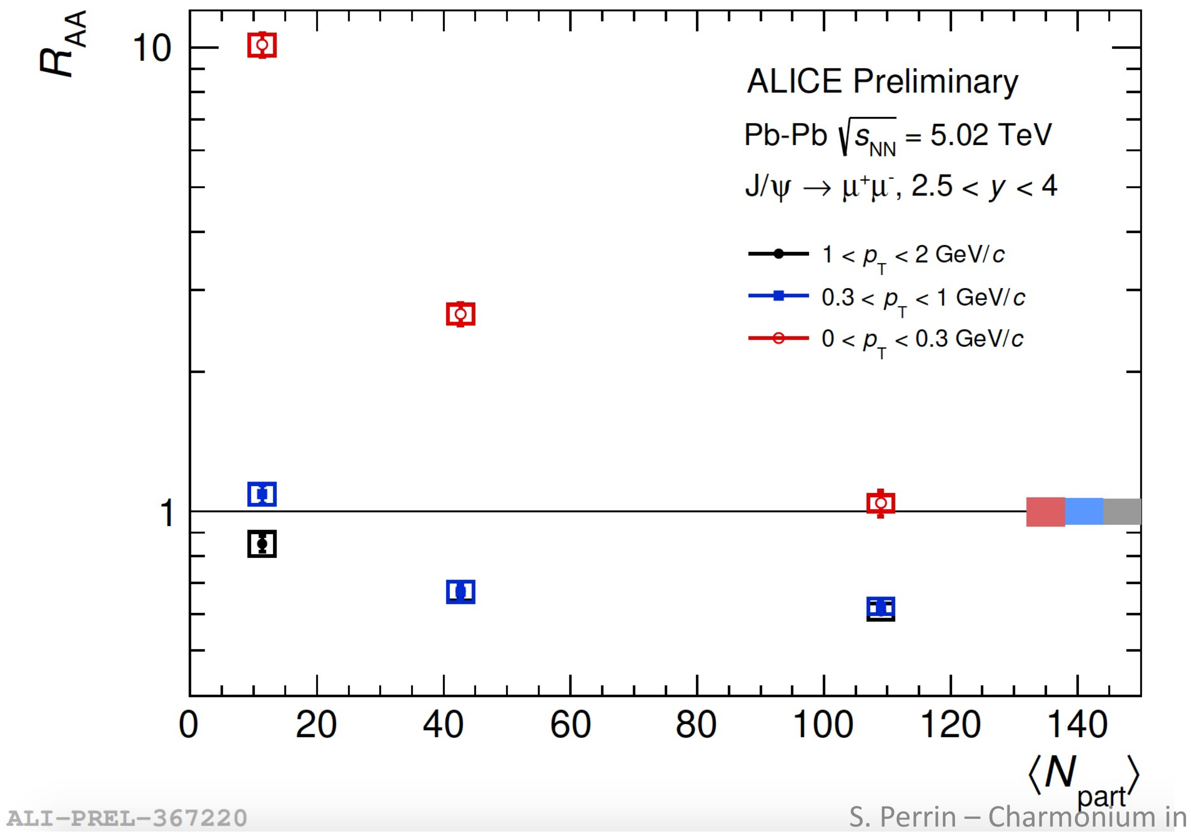
Similar R_{AA} profiles in both rapidity ranges in which data are well reproduced by TM over all the p_{T} interval, and by SHM up to p_{T} around 3-4 GeV/c

Results in Pb-Pb – Nuclear modification factor

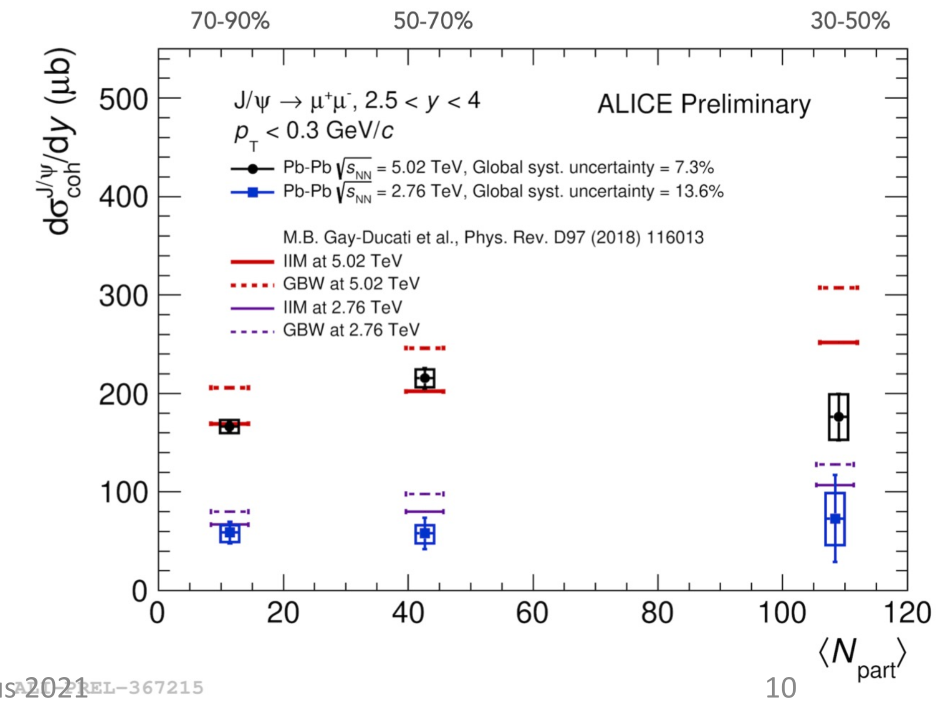
Dependence on production mechanism

Excess of produced J/ψ in **peripheral collisions at very low p_T**

- Suggested origin: photoproduction of J/ψ



Models describing the production cross section with photon/pomeron flux in Ultra-peripheral collisions (UPC) show good agreement with data from very peripheral collisions.
Such models start to fail as collisions become more central.



Results in Pb-Pb – Flow

Regeneration of the J/ψ

Comparison to Transport Model (which reproduces nicely R_{AA} behaviour)

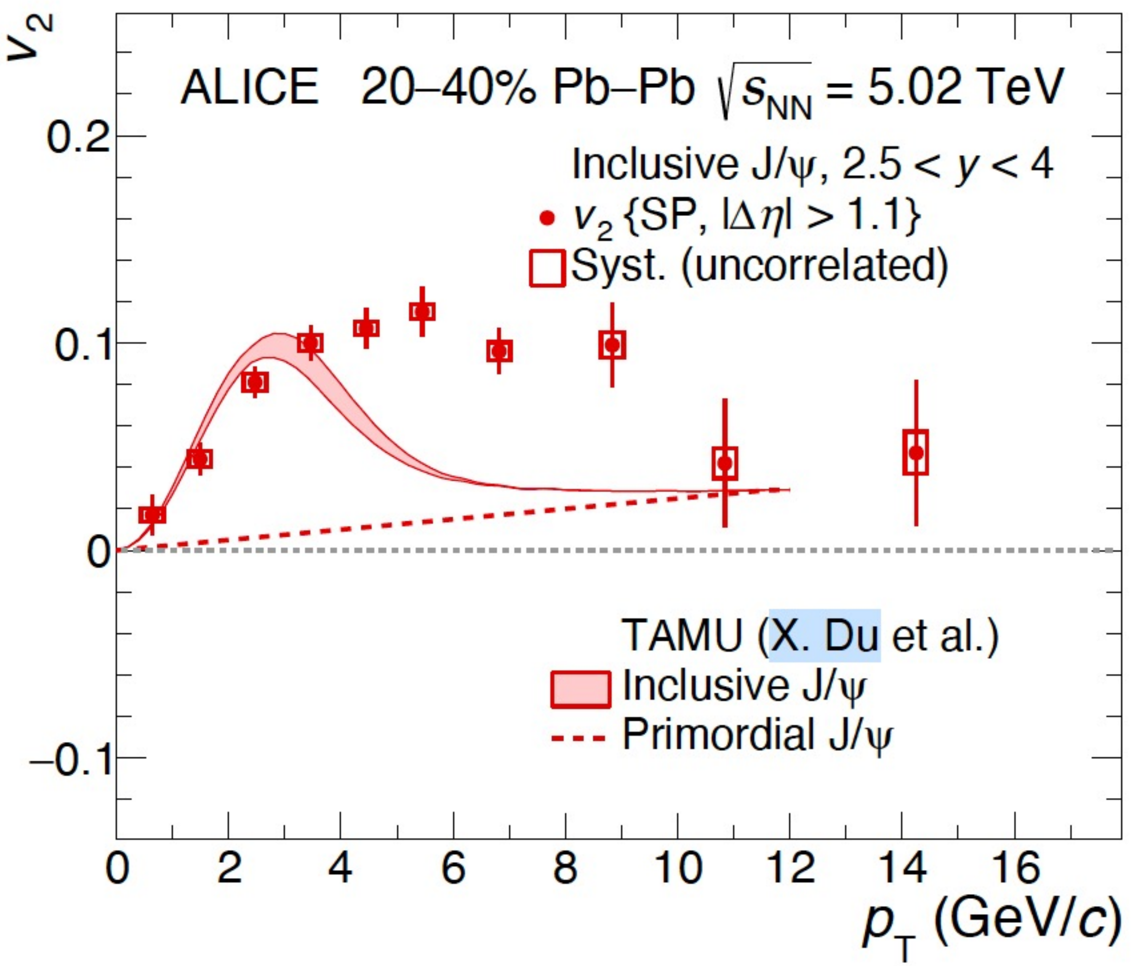
Overall behaviour pattern understood:

- Increase at low p_{T} (recombined c quarks)
- Decrease at high p_{T} (less recombination)
- $v_2 > 0$ also at high p_{T}, likely due to a path-length dependence for primordial J/ψ production

Data and model agreement at low p_{T} shows that J/ψ regenerates

Worse description at intermediate p_{T}, still in need of explanation

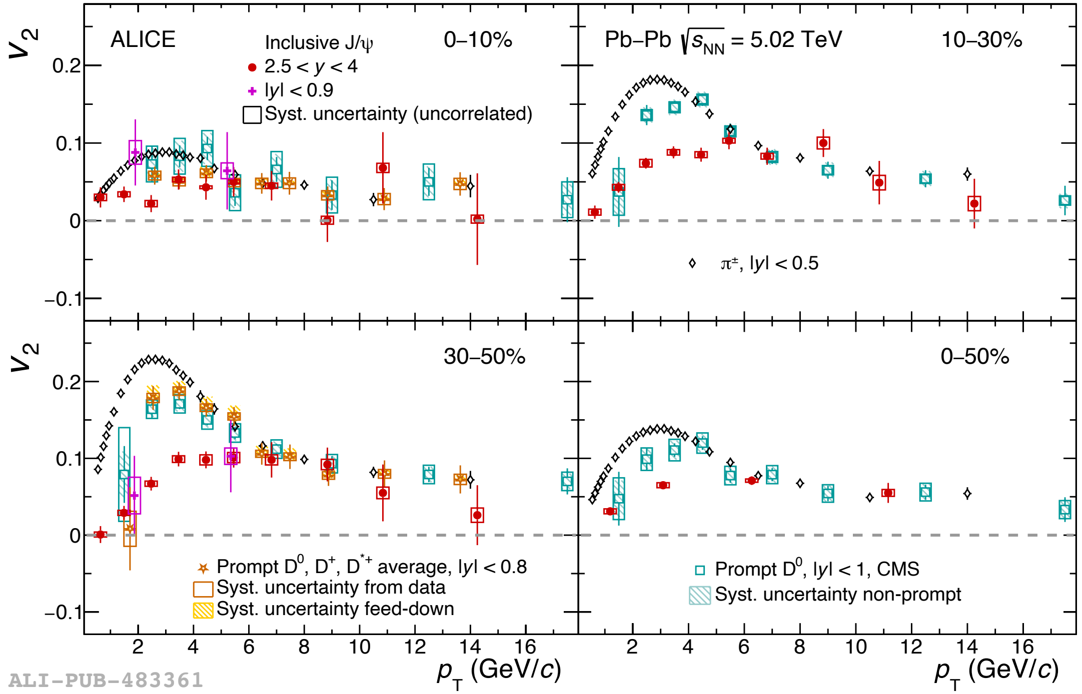
[JHEP 10 (2020) 141]

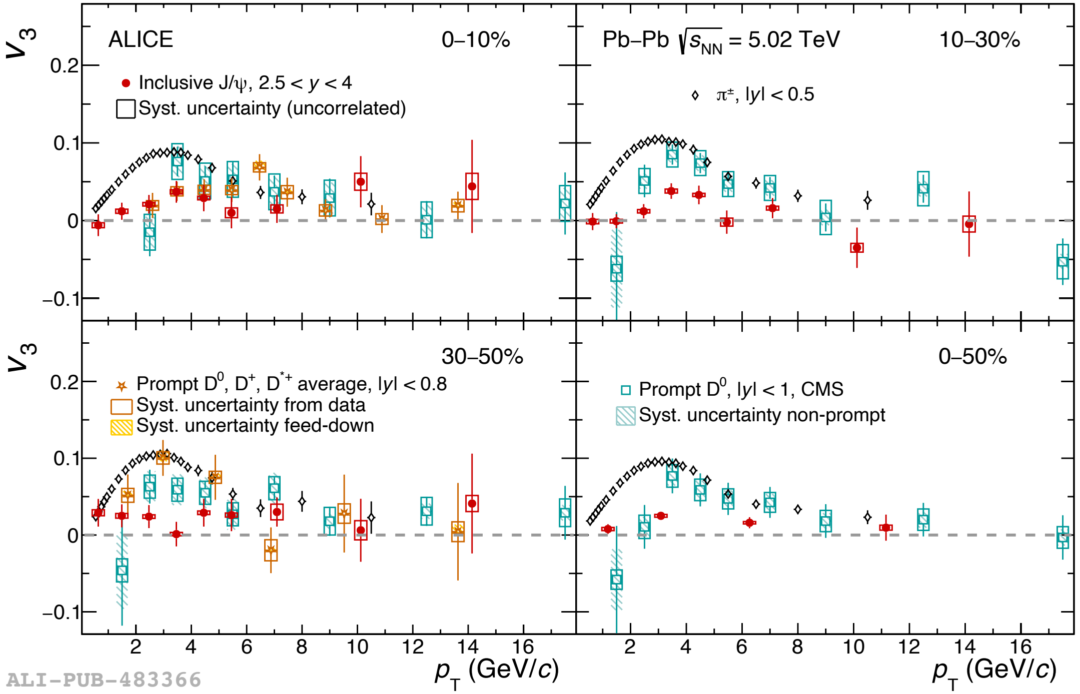


Results in Pb-Pb – Flow

Species dependence of the flow

[JHEP 10 (2020) 141]





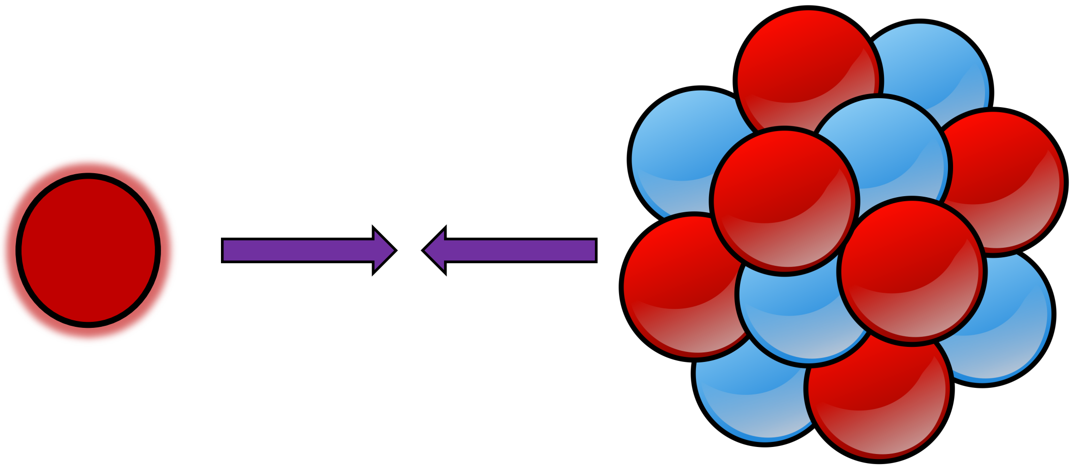
Intermediate p_{T}: $v_{2,J/\psi} > 0$

High p_{T}: compatible v_2 for all species, pointing to a common mechanism

- Mass hierarchy of v_2 and v_3 at intermediate p_{T} : consistent with hydrodynamics
- Similar v_2 magnitudes between species: at least partial charm quark thermalisation

$v_{3,J/\psi} > 0$ ($> 5\sigma$ between 2 and 5 GeV/c in 0-50%)

Charm quarks are sensitive to initial fluctuations quantified by the v_3 coefficient.

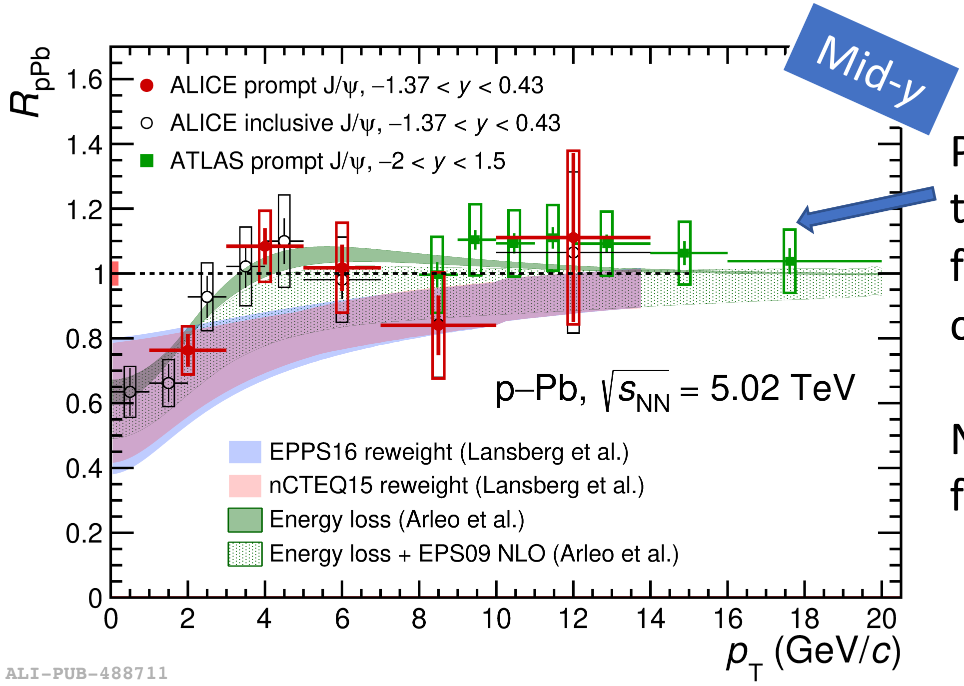


p-Pb Collisions

Results in p-Pb – Nuclear modification factor

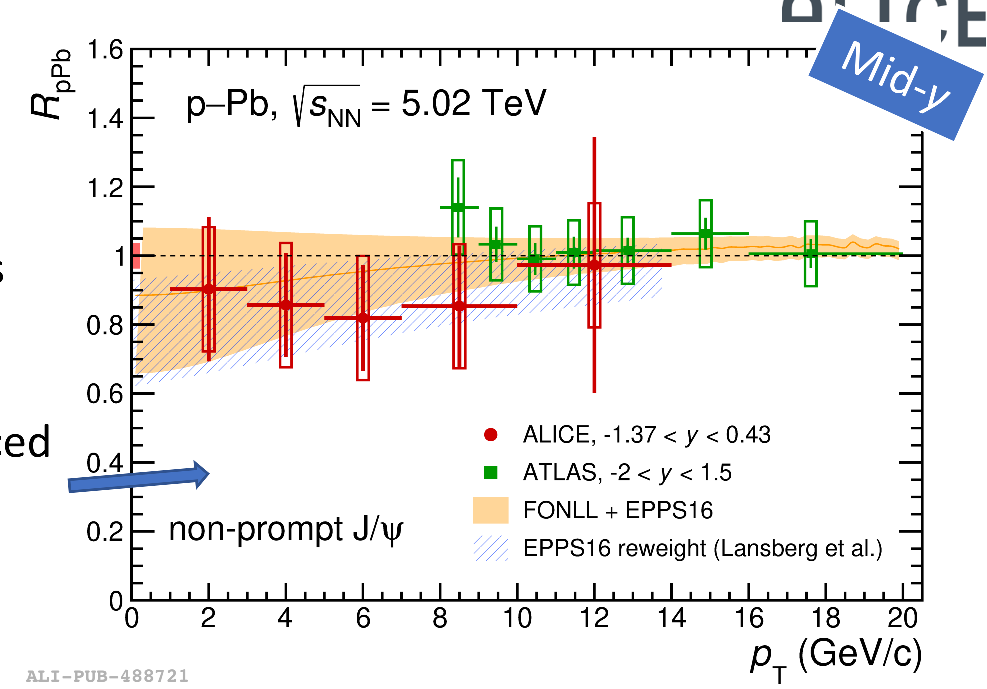
p_T dependence – Central Barrel → Prompt/Non-prompt

[arXiv:2105.04957]



Prompt J/ψ: J/ψ produced at the primary vertex (direct) or from the decay of higher-mass charmonium states

Non-prompt J/ψ: J/ψ produced from the decay of a b-hadron



Stronger suppression of prompt J/ψ at low-p_T compared to high-p_T

Agreement with ATLAS results at mid-p_T and with calculations of energy-loss models

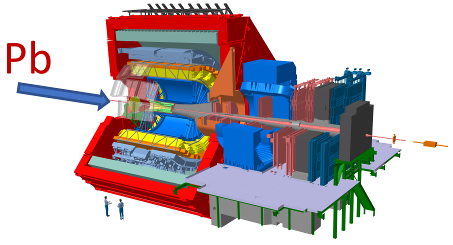
Large uncertainties at low p_T, at intermediate p_T results are compatible with no suppression

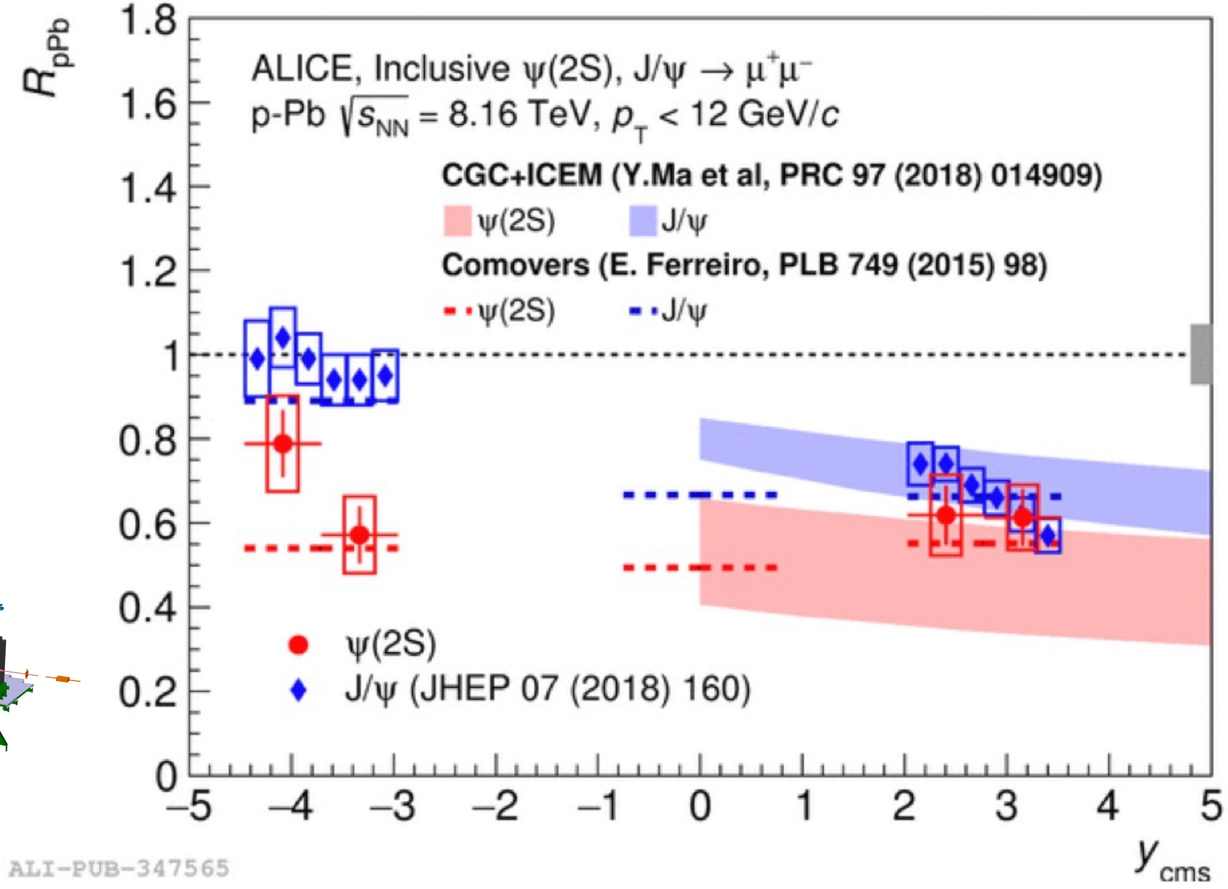
Agreement with ATLAS results at mid-p_T and with calculations

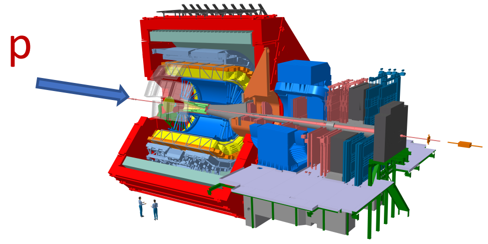
Results in p-Pb – Nuclear modification factor

Rapidity dependence

[JHEP07 (2020) 237]





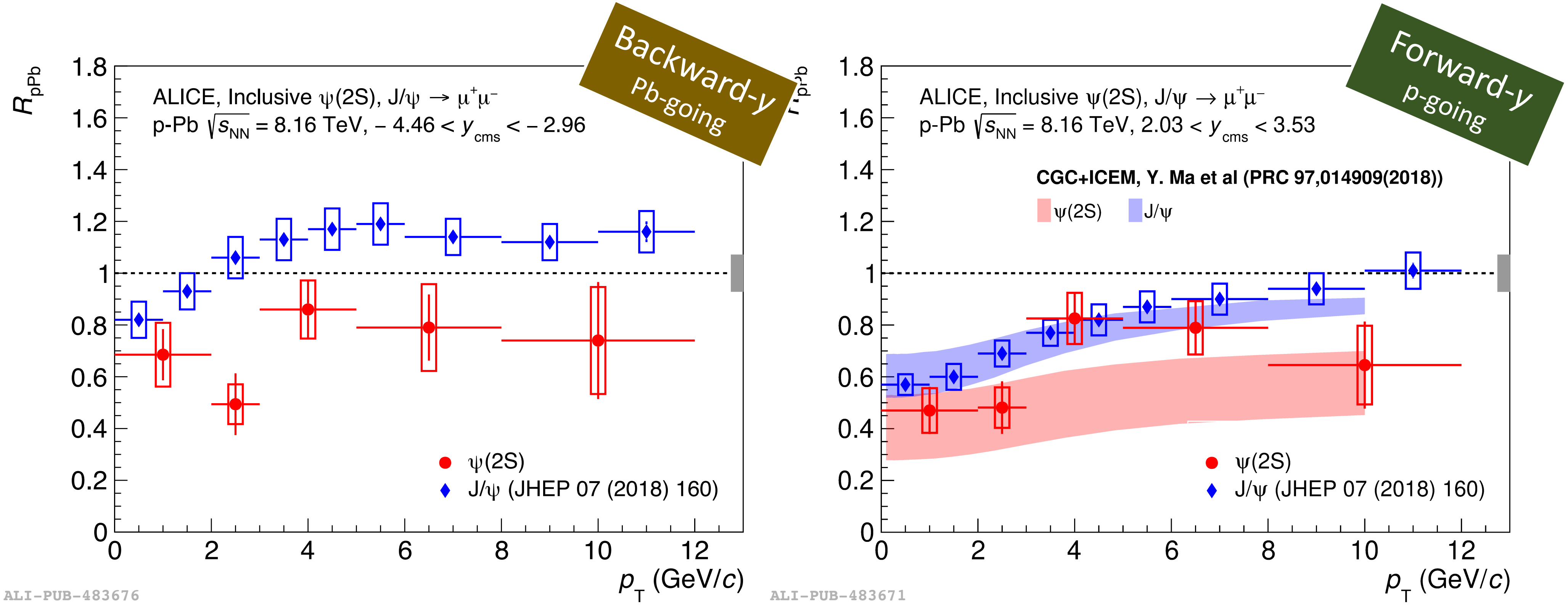


Forward: Equally large suppression for J/ψ and $\Psi(2S)$, **Backward:** Stronger suppression of $\Psi(2S)$
Well reproduced by models implementing final state interactions

Results in p-Pb – Nuclear modification factor

p_T dependence – Muon spectrometer

[JHEP07 (2020) 237]

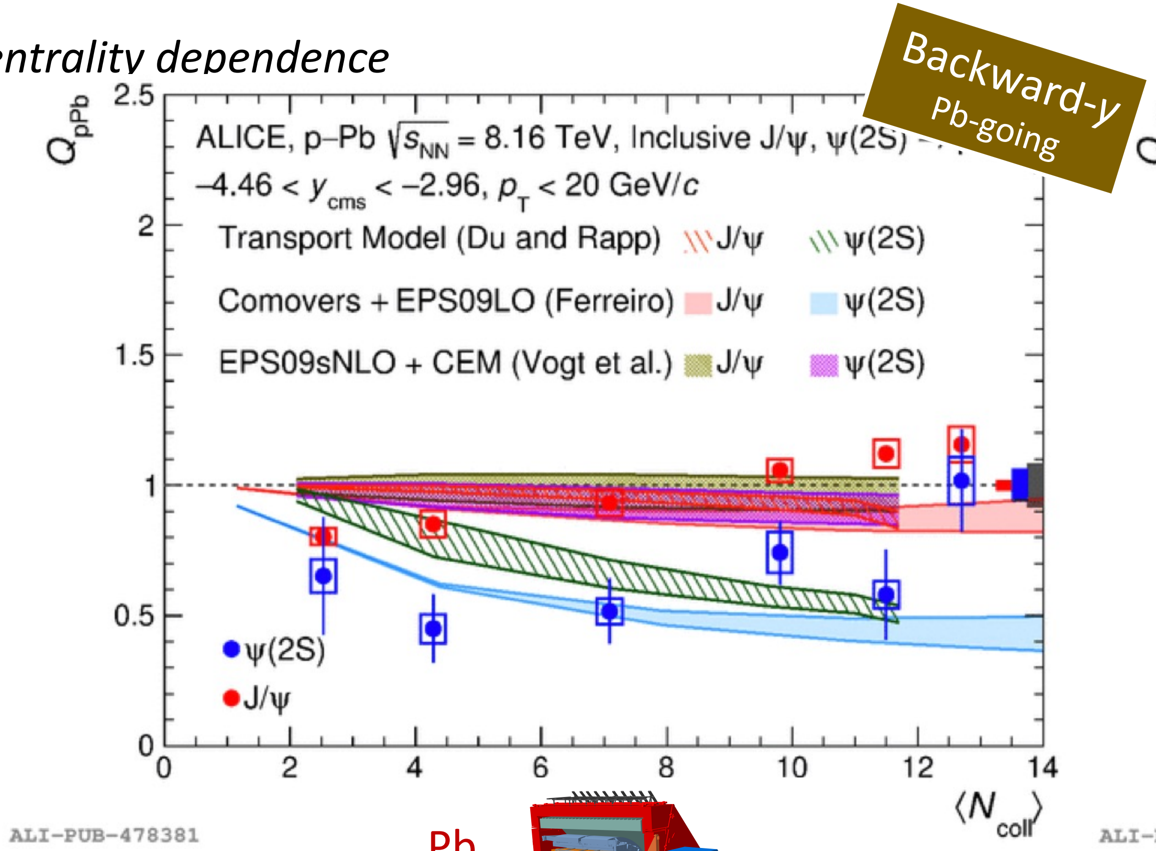


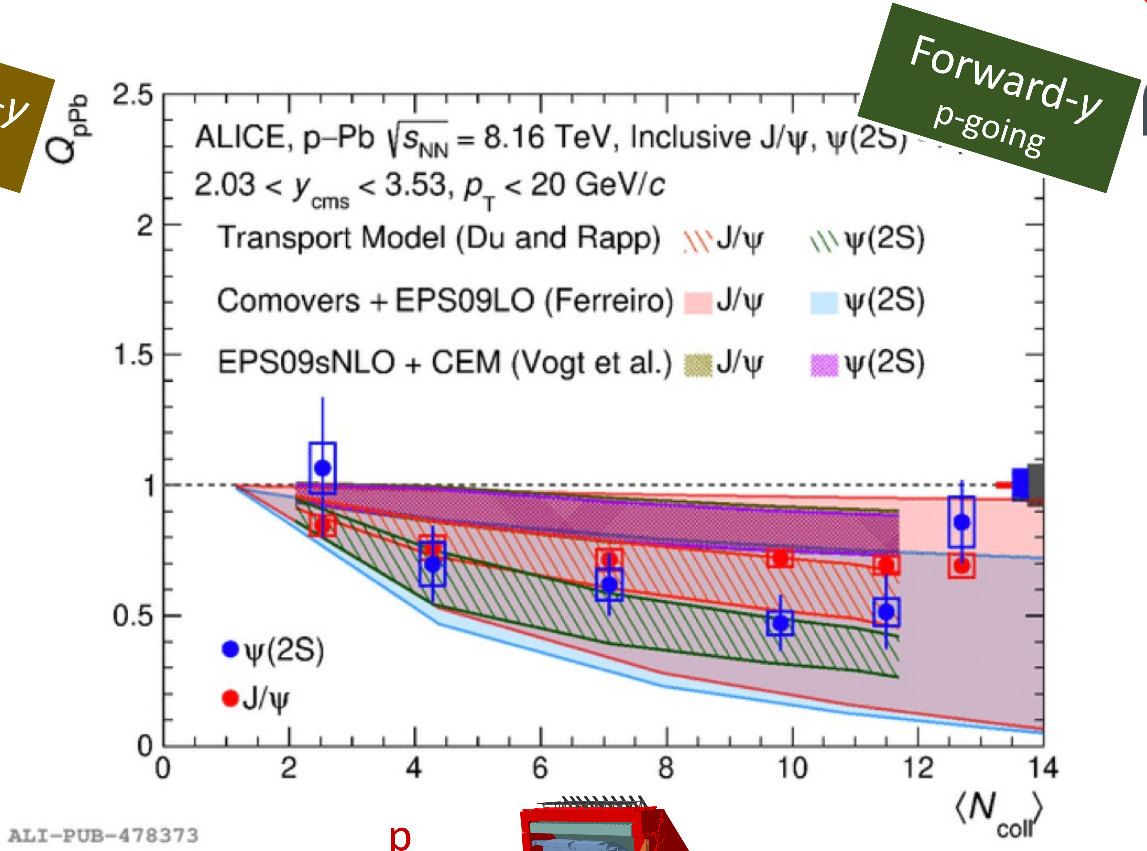
Backward: Significantly stronger suppression of $\Psi(2S)$ wrt J/ψ

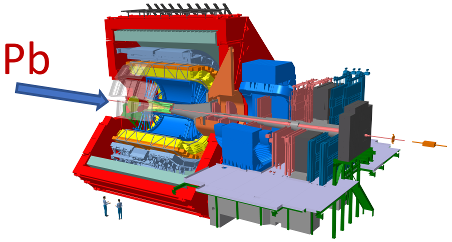
Forward: Equivalent suppression of $\Psi(2S)$ wrt J/ψ. Good agreement with CGC (Color Glass Condensate) framework calculations

Results in p-Pb – Nuclear modification factor

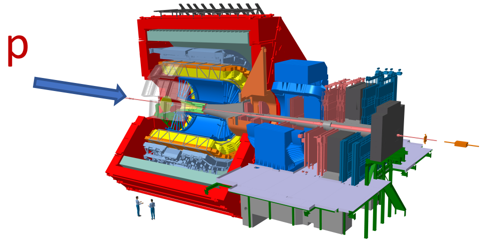
Centrality dependence







[JHEP02 (2021) 002]



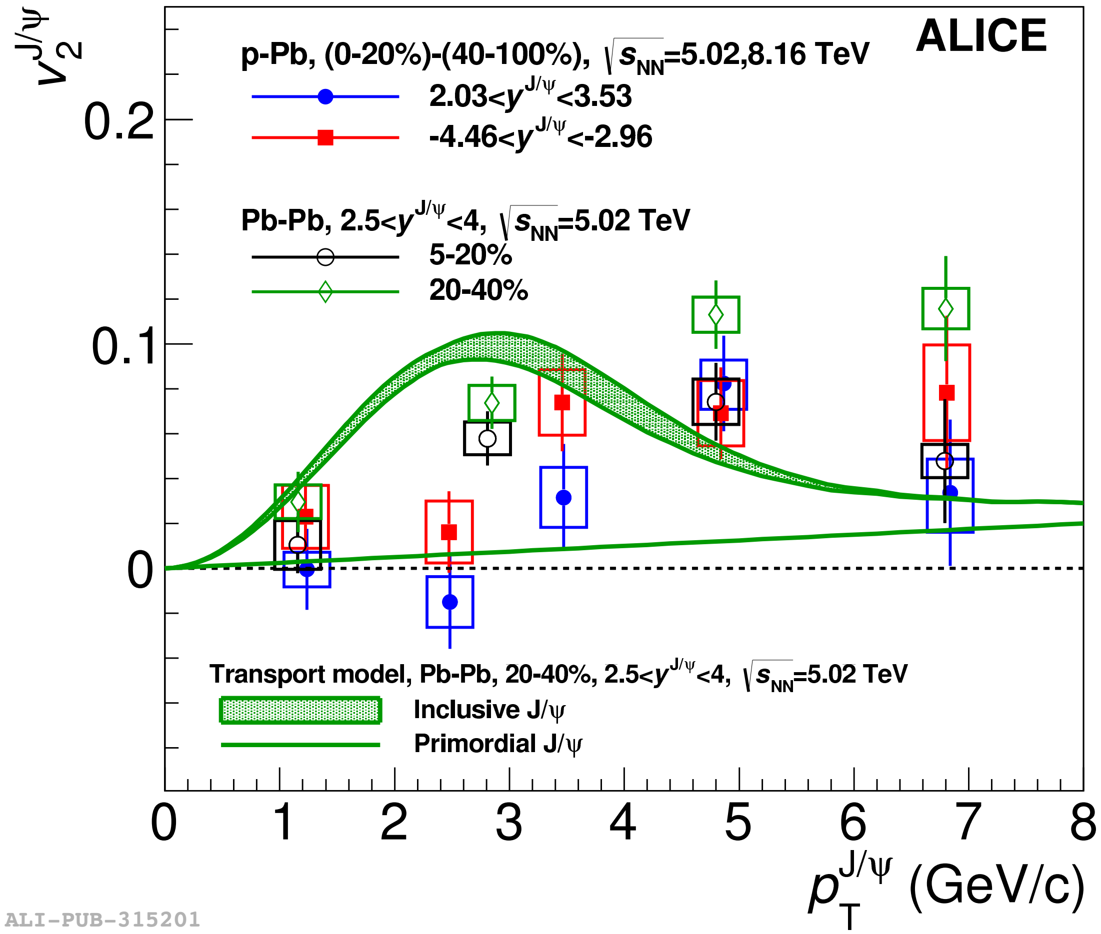
Forward: Similar suppression of J/ψ and $\Psi(2S)$, **Backward:** $\Psi(2S)$ more suppressed than J/ψ
Main features understood by models implementing final state interactions. (NLO and CEM calculation fails for the $\Psi(2S)$, but works within uncertainties for the J/ψ)

Results in p-Pb – Flow

A positive elliptic flow for the J/ψ

[PLB 780 (2018) 7-20]

- $v_{2,J/\psi} > 0$ ($> 5\sigma$) for $3 < p_{\mathrm{T}} < 6$ GeV/c
- Values in p-Pb close to Pb-Pb, suggests common mechanism
- Low-p_{T} v_2 compatible with 0 : barely any recombination expected in p-Pb
- No sizeable v_2 expected from path-length dependence at high p_{T}



Intriguing result, that TM calculations fail to reproduce as they underestimate the data [*Energ. Phys.* **2019,** 15 (2019)]

On the other hand, CGC calculations appear to reproduce p-Pb data well ([Phys. Rev. Lett. 122, 172302 (2019)]).

Could the J/ψ flow in an even smaller system, namely pp ?

Conclusions

Charmonium is a key probe of the QGP

Two observables presented: Nuclear modification factor, Flow

Pb-Pb collisions

R_{PbPb}

- Demonstrates charm quark recombination
- Photoproduction of J/ψ at low p_{T}

$v_{2,3}$

- Confirms the role of charm recombination at low p_{T}, with some remaining tension with models at intermediate p_{T}
- Sizeable collective effects for heavy quarks

p-Pb collisions

$R_{\mathrm{pP}b}$

- Agreement with variety of models :
  - Suppression of ground state described either by gluon depletion (nPDF or CGC) or by coherent energy loss
  - $\Psi(2S)$ exhibits a further suppression: final state effects suggested as explanation

v_2

- Collective effects despite relatively small system size
- Flow magnitude comparable to Pb-Pb: similar flow sources ?
- Motivation to look at smaller hadronic systems (pp)

Thank you for your attention !

Backup

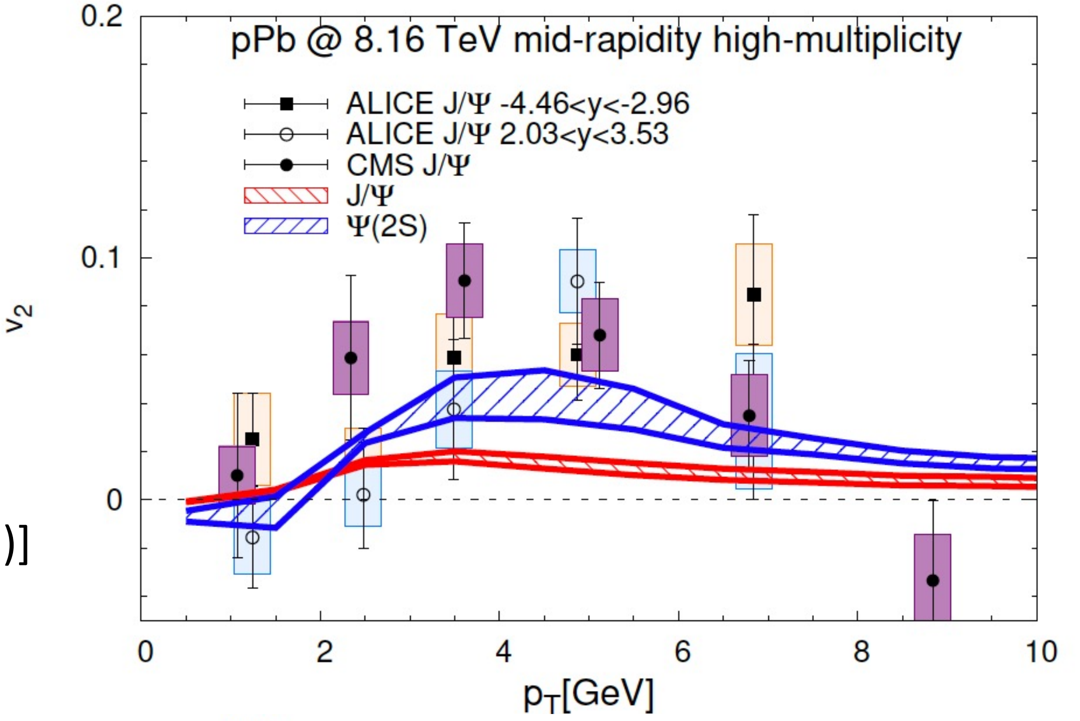
p-Pb, theories of flow

- Transport model (TAMU, X. Du et al.)

Model way below the experimental data

Missing mechanism

[*Energ. Phys.* **2019,** 15 (2019)]



- Initial state effects – CGC (C. Zhang et al.)

Idea: Flow is **here from the start**

- Long-range correlations come from initial momentum/color correlations (CGC framework)

Nice agreement with both ALICE and CMS data

[Phys. Rev. Lett. 122, 172302 (2019)]