Charmonium production studies in nuclear collisions with ALICE

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Physics motivations for charmonium studies

ALICE

pp collisions : understand the charmonium production mechanisms at partonic level and reference for p–A, A–A
(high multiplicity regime : effect from Multiple Parton Interaction on charmonium yield)

Talk by F. Fionda on Thursday 18/03

Focus of today's presentation

p–Pb collisions : understand effects due to the presence of cold nuclear matter (CNM)
(high multiplicity regime : collective effects on heavy quarks)

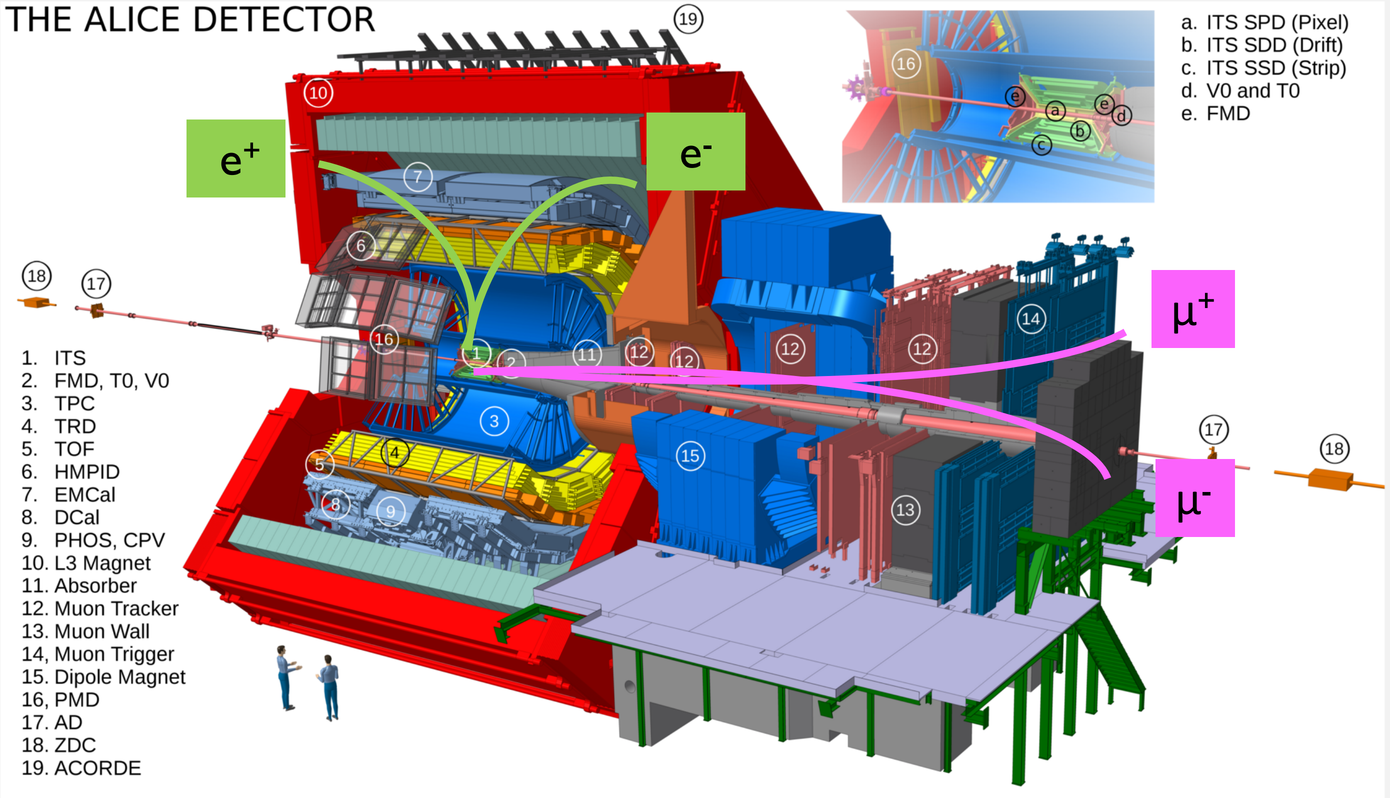
Observables : R_{pPb}, Q_{pPb}, v_2, self-normalized charmonium yield as a function of multiplicity

Pb–Pb collisions : A probe of deconfinement.
Understand the interplay between :
- charmonium suppression (dissociation, color screening) and charmonium regeneration → R_{AA} (low p_T) , polarization
- charmonium suppression (dissociation, color screening) and energy loss → R_{AA} (high p_T)

Study the collective behaviour of heavy quarks and their degree of thermalization → v_2, v_3
Study the initial stages of the heavy ion collisions:
- properties of the created medium (magnetic field, angular momentum) → polarization versus Event Plane
- gluon distribution in nuclei → photoproduction cross sections

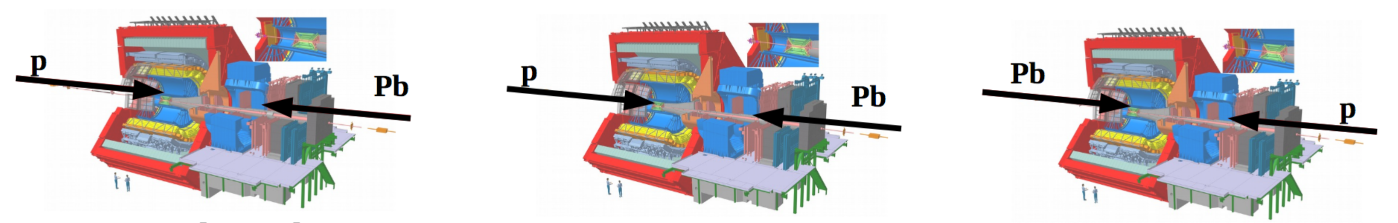
The ALICE apparatus and charmonium detection (Run 2)

Charmonium detection at mid-rapidity $|y| < 0.9$
$J/\psi \rightarrow e^+e^-$
Down to zero p_T
ITS+TPC : tracking and PID
SPD (ITS) : primary and secondary vertices
Separation of prompt and non-prompt J/ψ



Charmonium detection at forward rapidity
$2.5 < y < 4$
$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$
Down to zero p_T
MCH : tracking
MTR : trigger
SPD (ITS) : primary vertex
Inclusive J/ψ

p–Pb configurations



Forward rapidity $2.03 < y_{CMS} < 3.53$

Midrapidity $-1.37 < y_{CMS} < 0.43$

Backward rapidity $-4.46 < y_{CMS} < -2.96$

Centrality estimation : V0, ZDC
Multiplicity estimation : SPD, V0
Triggering : SPD, V0, MTR

Charmonium production in p–Pb collisions at forward rapidity

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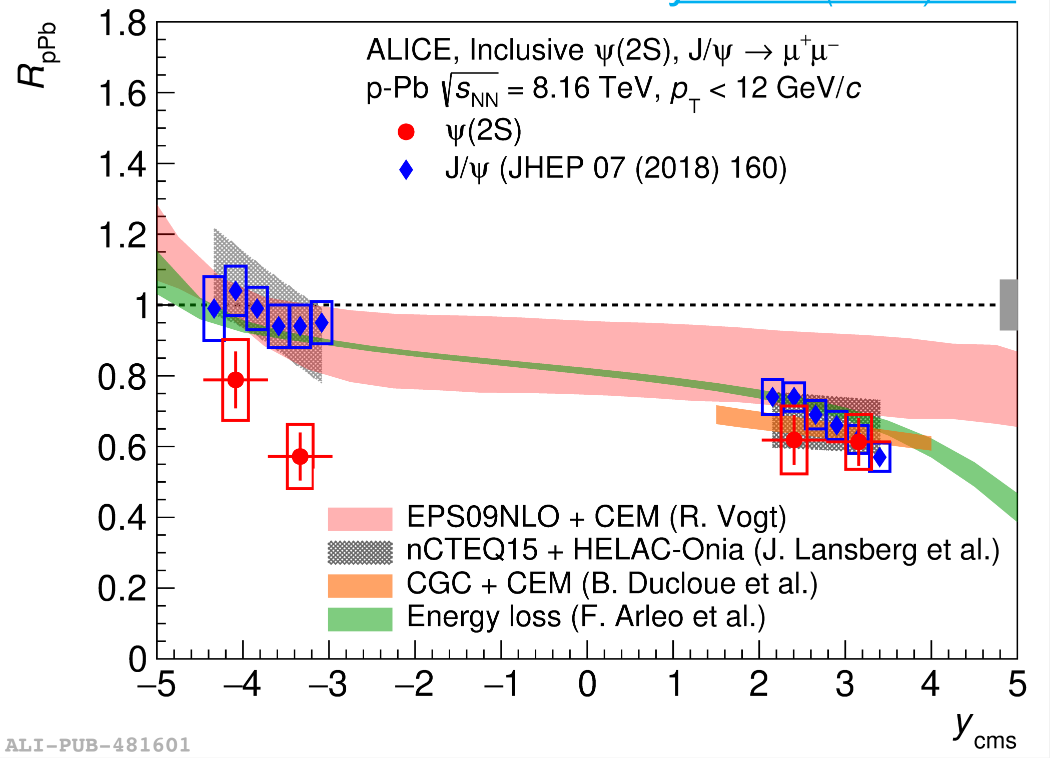
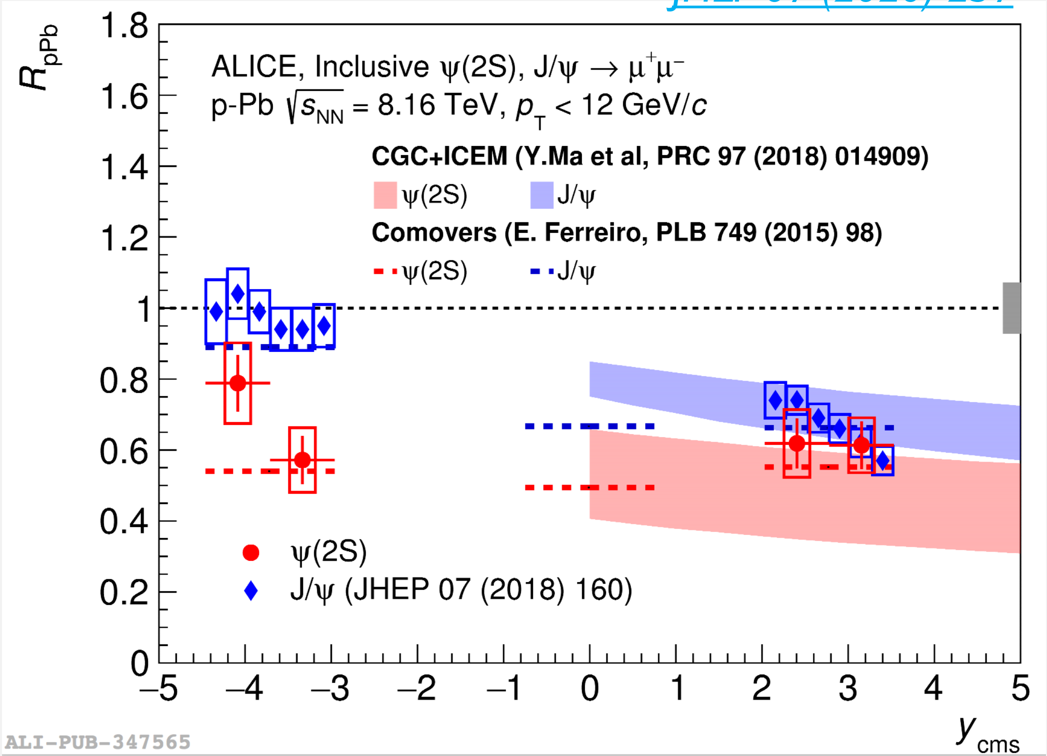
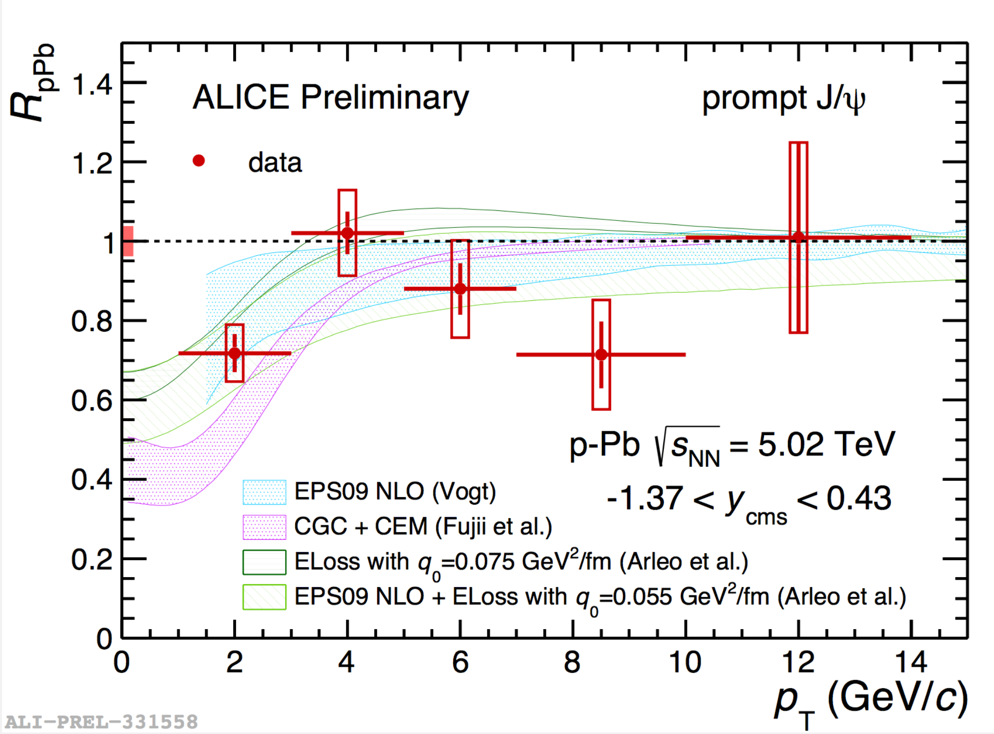


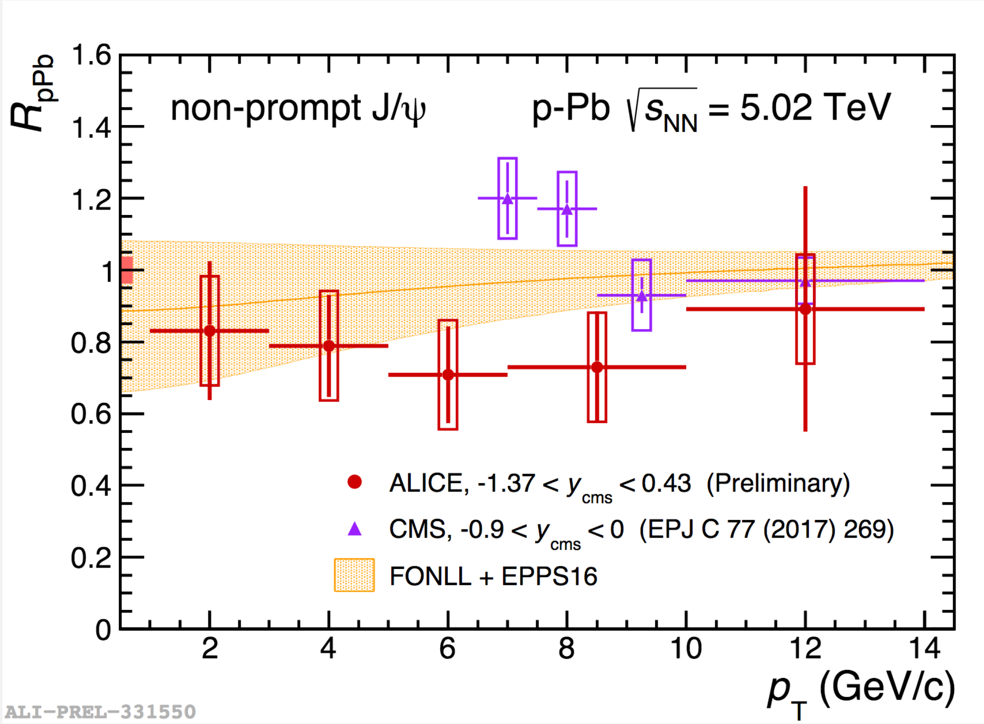
JHEP 07 (2020) 237



- Stronger suppression of the ψ(2S) w.r.t J/ψ at backward rapidity. Similar suppression at forward rapidity
- Theoretical calculations based only on initial state effects or coherent energy loss describe the J/ψ results but fail at describing the backward ψ(2S) suppression.
- Need to account for additional final state interactions (soft color exchanges, comovers)

Charmonium production in p–Pb collisions at midrapidity

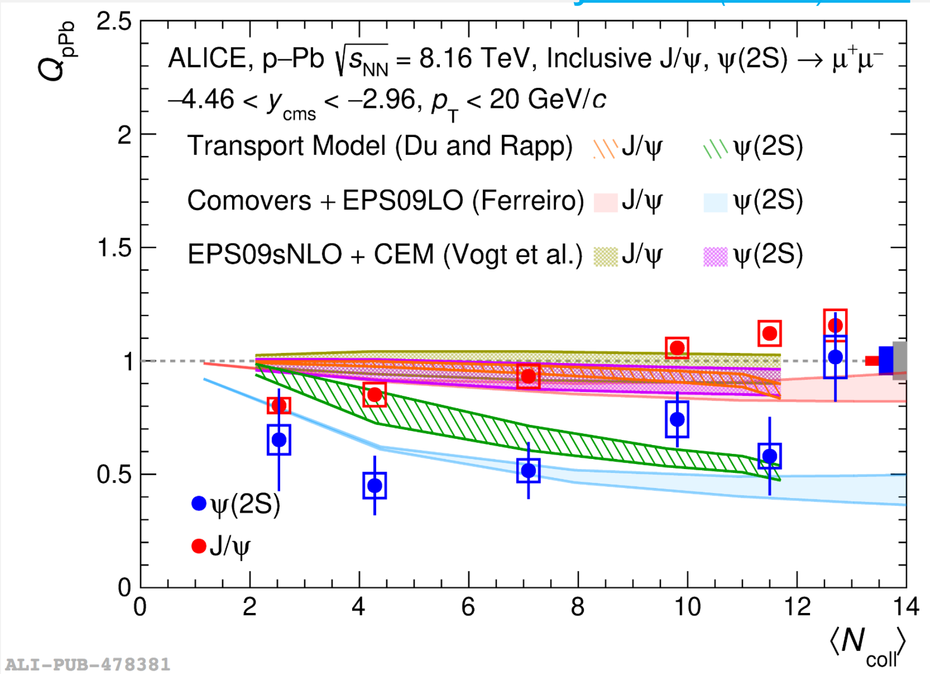




- Prompt J/ψ suppression at mid-rapidity for $p_T < 3$ GeV/c, reproduced by CNM models considering only initial state effects or coherent energy loss
- No significant suppression of J/ψ from B-hadron decays within uncertainties at mid-rapidity as a function of p_T. Fair agreement with the mild suppression predicted by FONLL + EPPS16 nPDFs

Charmonium production as a function of centrality in p–Pb collisions

JHEP02 (2021) 002



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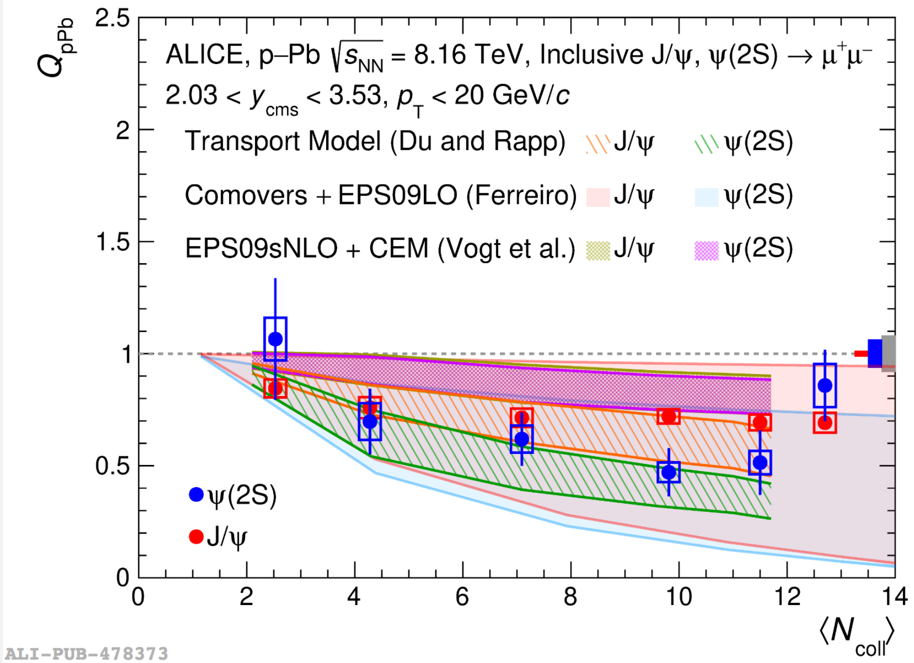

- Similar suppression for the J/ψ and the ψ(2S) as a function of centrality at forward rapidity
- Systematically stronger suppression for the ψ(2S) w.r.t J/ψ as a function of centrality at backward rapidity
- EPS09 + CEM describes the J/ψ Q_{pPb} at both rapidities within uncertainties but fails at describing the ψ(2S) Q_{pPb}
- Fair description by the Transport Model (TM) for both resonances at forward y. TM overestimates data at backward y in peripheral events
  - → stronger suppression of ψ(2S) in TM due to short QGP + hadron resonance gas

→ Comovers + EPS09 : fair description of the ψ(2S) suppression at backward y, no firm conclusion at forward y
  - → Larger density of comovers in the Pb-going direction

Charmonium production as a function of charged particle multiplicity in p–Pb collisions

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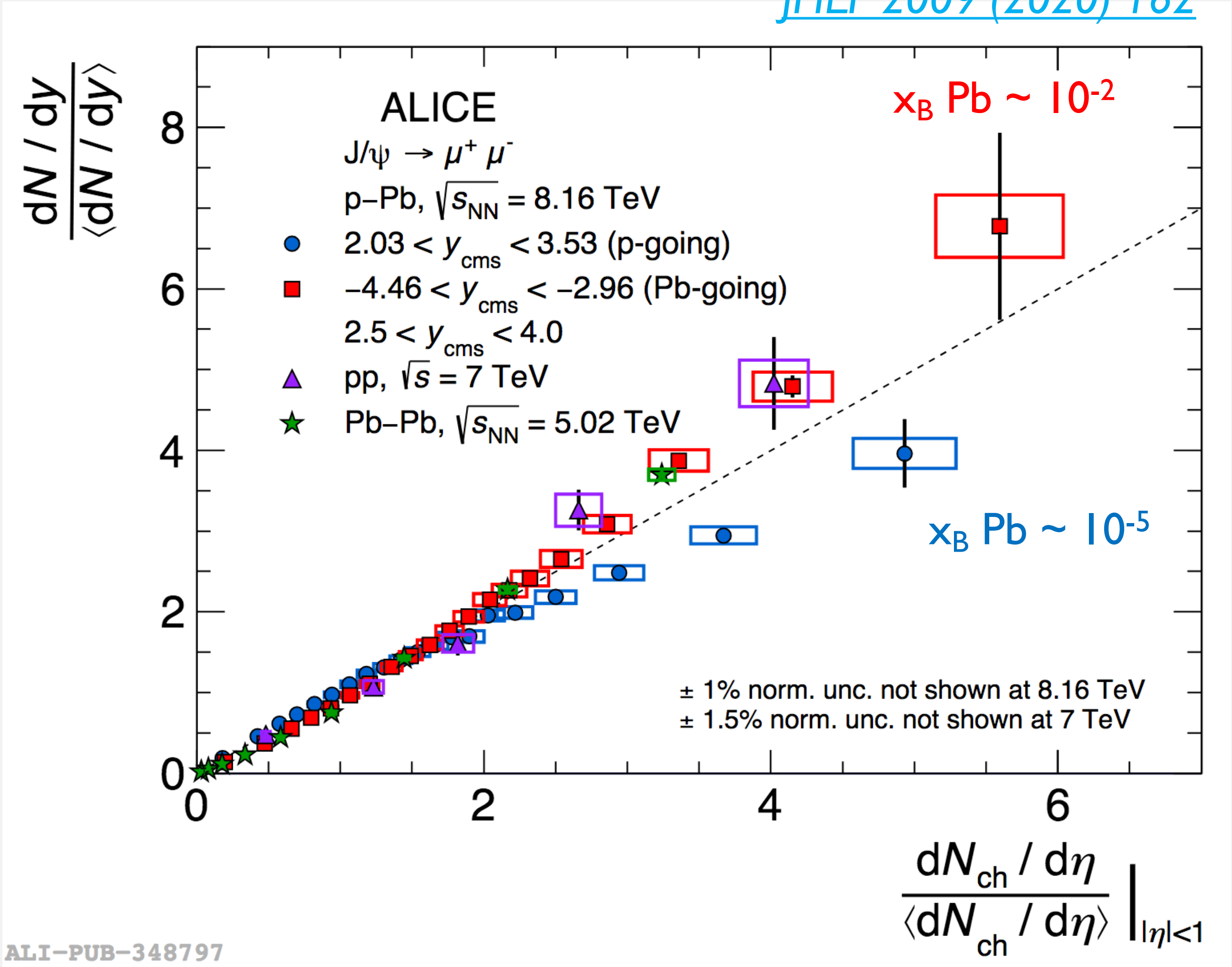
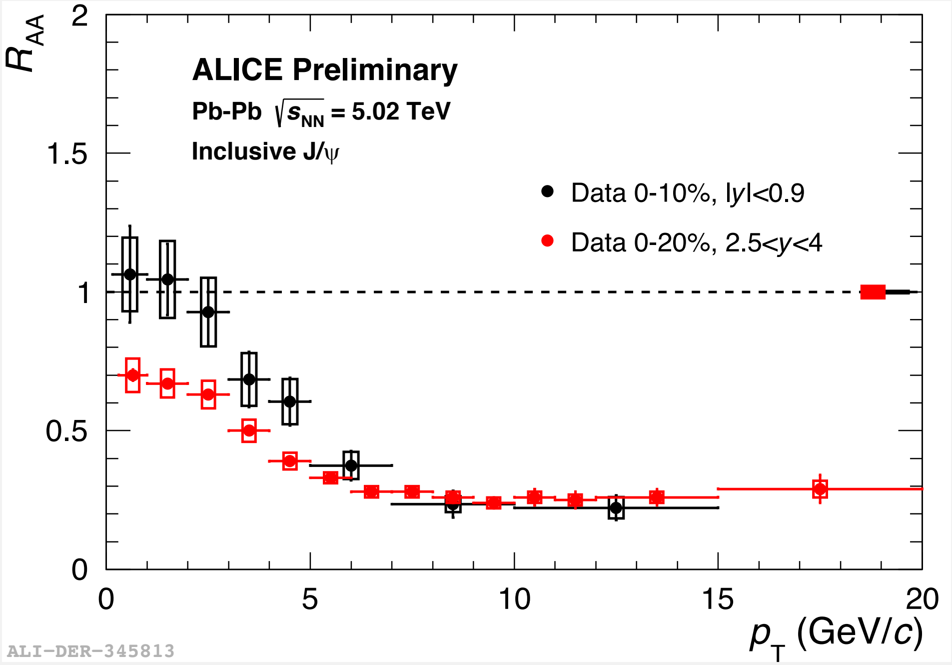
- Yield at backward rapidity (Pb-going) increases faster than at forward rapidity (p-going)
- Slower than linear increase at forward rapidity. Stronger CNM effects at forward rapidity (shadowing/saturation)
- Comparison with models (EPOS3, H. J. Drescher et al., *Phys. Rept. 350 (2001) 93-289*) suggests a J/ψ production from an incoherent superposition of parton-parton interaction
- Similar evolution of the J/ψ self-normalized yield with multiplicity for pp, p–Pb (backward) and Pb–Pb systems

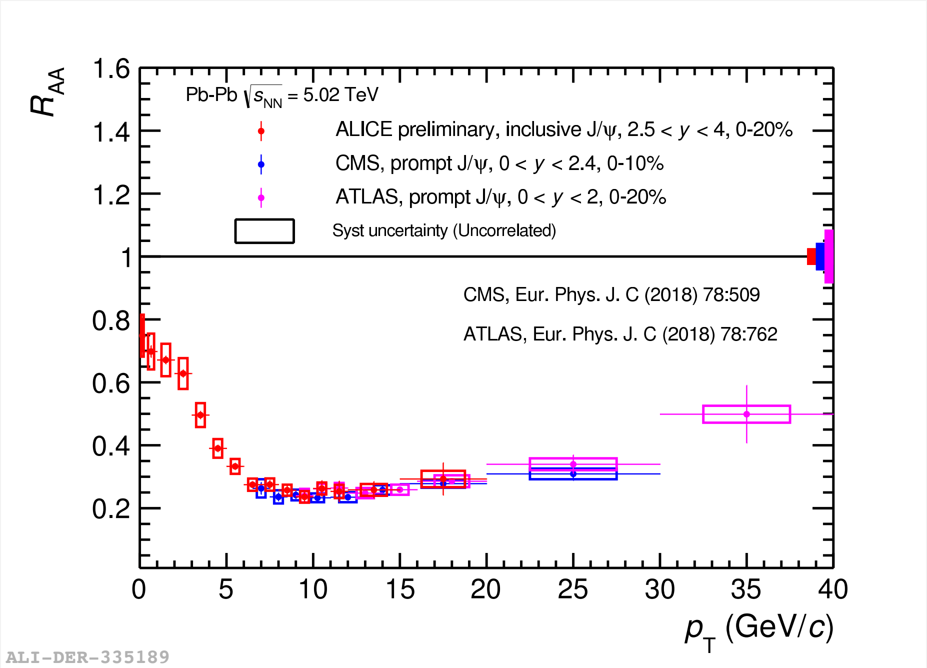
JHEP 2009 (2020) 162



Charmonium production in Pb–Pb collisions

Full Run 2 Pb–Pb data sample



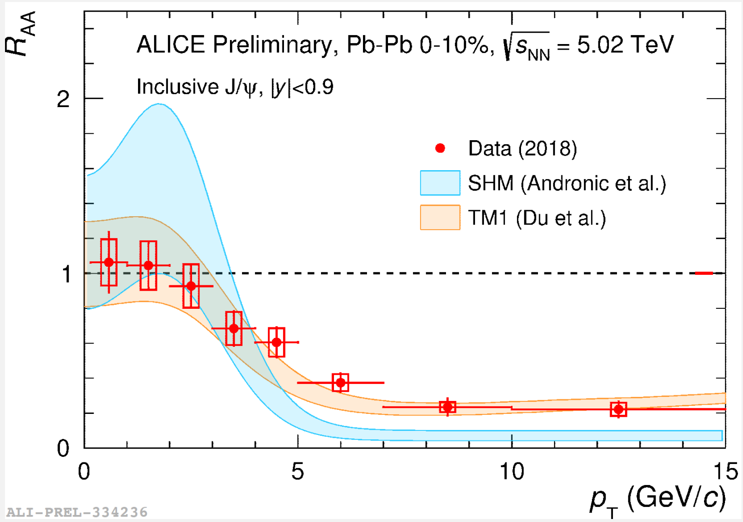


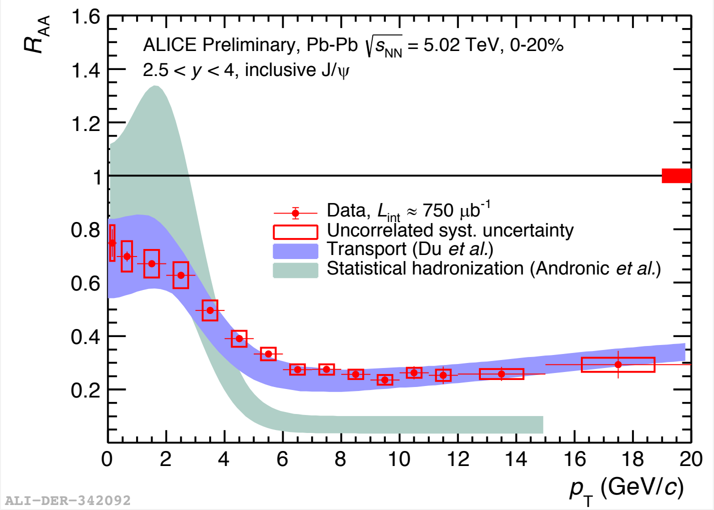
- Smaller suppression of J/ψ at low p_T than at high p_T in most central collisions both at forward and mid-rapidity
- At low p_T, stronger suppression at forward rapidity than at mid-rapidity, as expected from regeneration scenario
- Extension of the p_T reach of earlier measurements up to 20 GeV/*c* → can help to understand the interplay between color screening and in-medium energy loss
- Agreement of inclusive J/ψ ALICE measurement with prompt J/ψ measurements from CMS and ATLAS at high p_T

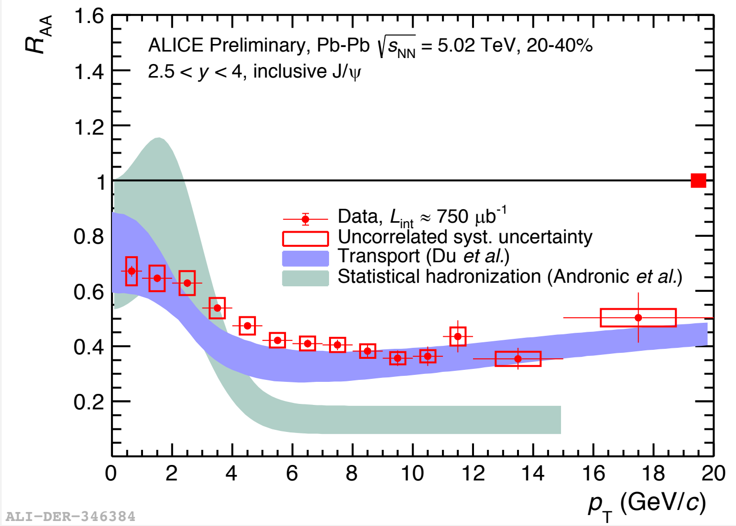
Charmonium production in Pb–Pb collisions at mid and forward rapidity

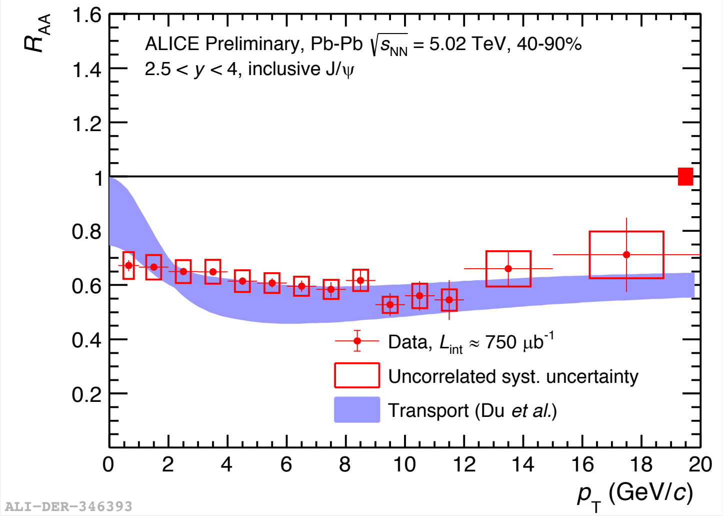
ALICE

Full Run 2 Pb–Pb data sample









SHM :

- Regenerated J/ψ → low-p_T
- Initially produced J/ψ in nucleus corona → high-p_T

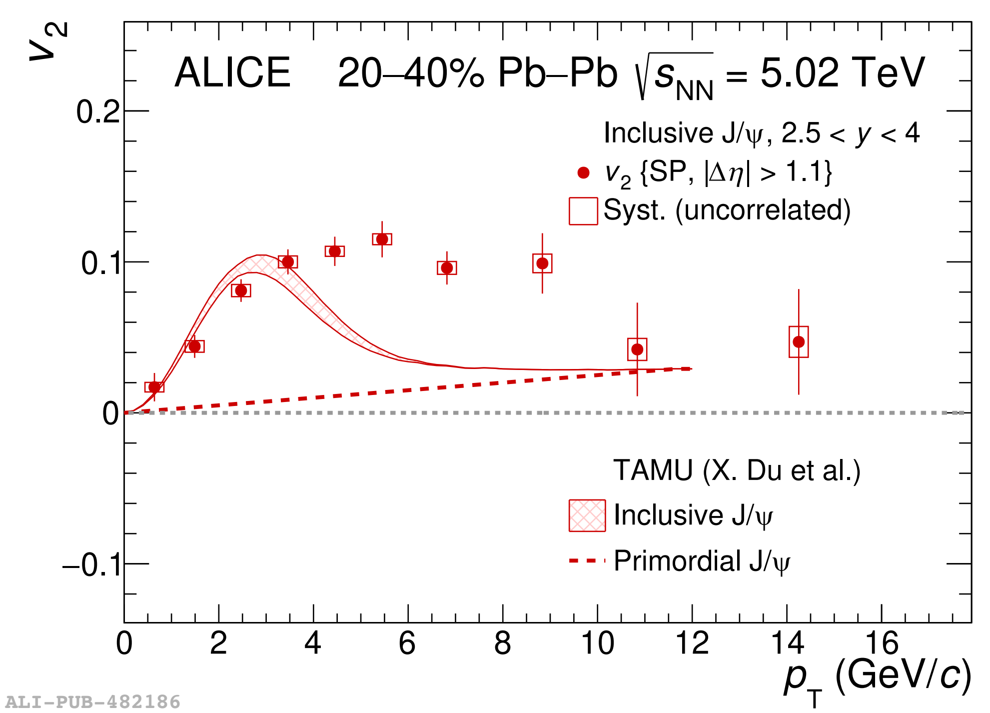
TM :

- Regenerated J/ψ → low-p_T
- Primordial J/ψ surviving in QGP → high-p_T

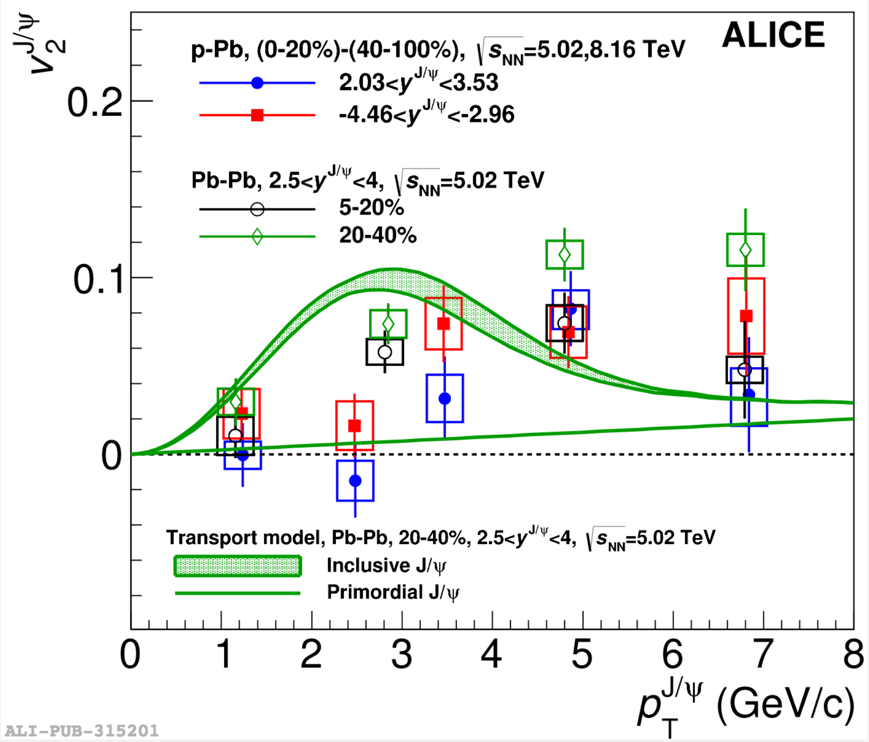
- ❑ At forward rapidity, significant variation of the p_T dependence of the suppression from central to peripheral events
- ❑ Data well described by TM in the whole p_T range and both at forward and mid-rapidity
- ❑ SHM reproduces well the data for p_T < 4 GeV/c, where the regeneration component is large, at both rapidities. SHM systematically overestimates the suppression at high p_T.

Charmonium elliptic flow in p–Pb and Pb–Pb collisions

Full Run 2 Pb–Pb data sample [JHEP 2020 (2020) 141]



[Phys. Lett. B. 780 (2018) 7-20]



- Significant positive J/ψ v_2 as a function of p_T in the 20-40% centrality range in Pb–Pb. TM can reproduce the magnitude of the v_2 for p_T < 4 GeV/c but fails at reproducing the intermediate p_T region.

- Positive J/ψ v_2 at forward rapidity with a significance of ~5σ for 3 < $p_T^{J/\psi}$ < 6 GeV/c in high-multiplicity p–Pb events. Similar magnitude as in Pb–Pb at high p_T could indicate a similar mechanism at play in both systems. A sign of collective behavior of heavy quarks in high multiplicity p–Pb collisions?

Charmonium elliptic flow in Pb–Pb collisions

ALICE

Full Run 2 Pb–Pb data sample

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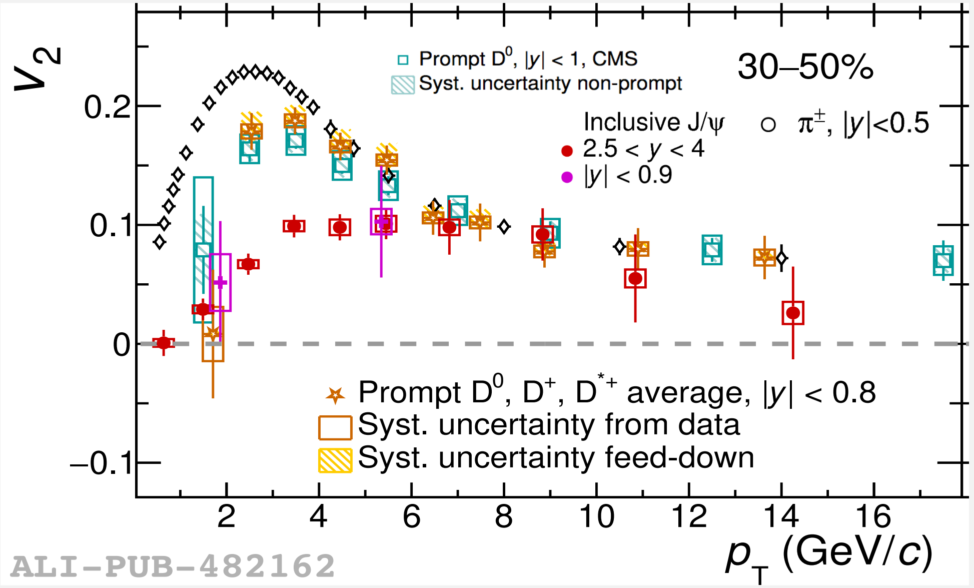

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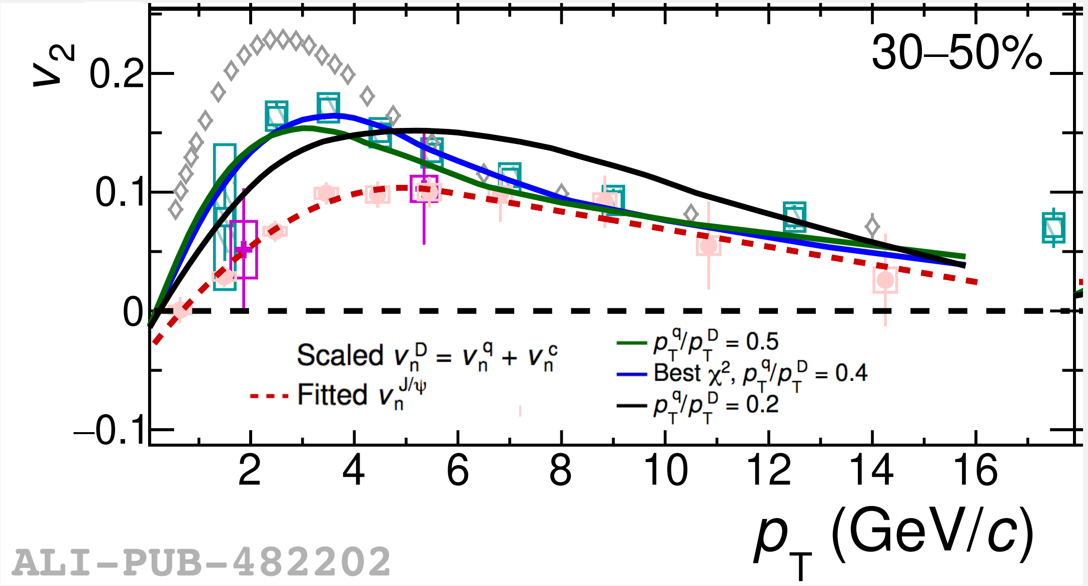


- ❑ First indication of positive J/ψ at mid-rapidity
- ❑ p_T coverage up to 15 GeV/c at forward rapidity
- ❑ Clear mass hierarchy at low-p_T: $v_2(\pi) > v_2(D) > v_2(J/\psi)$
- ❑ At high p_T, v_2 is similar for all species

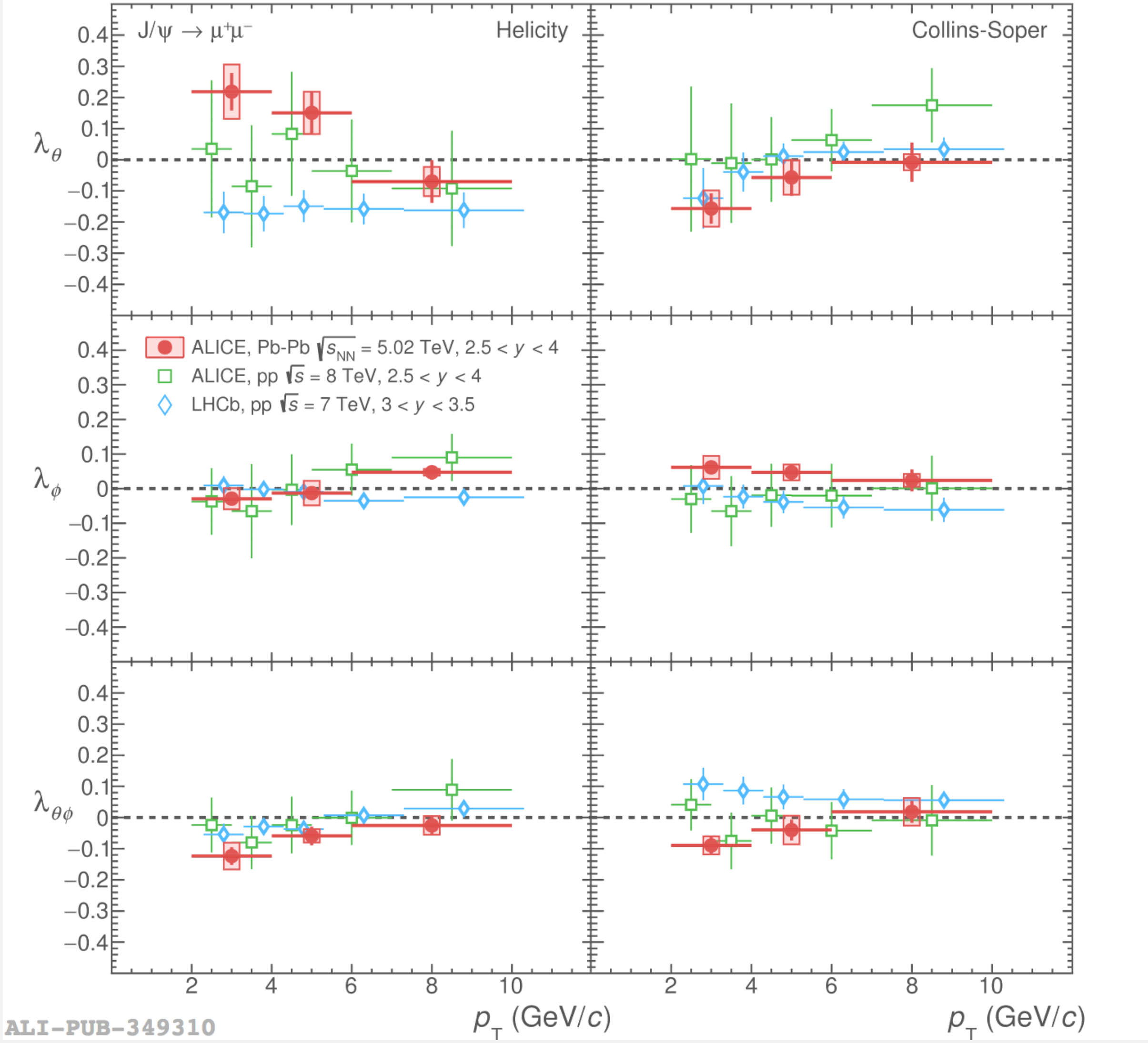
- ❑ Number of Consituent Quark Scaling (NCQ)
  $v_n^{J/\psi}\left(p_T^{J/\psi}\right) = 2v_n^c(p_T^{J/\psi}/2)$ and $v_n^{\pi}(p_T^{\pi}) = 2v_n^q(p_T^{\pi}/2)$
- ❑ D meson flow derived as : $v_n^D(p_T^D) = v_n^q\left(p_T^q\right) + v_n^c(p_T^c)$
- ❑ Need assumptions on the p_T sharing between the constituents quarks. Best fit obtained for p_T^q / p_T^D = 0.4

- ❑ Inclusive J/ψ v_3 also positive in most of the p_T and centrality intervals
- ❑ Finite v_2 and v_3 values may indicate that charm quarks are partially thermalized in the QGP

Charmonium polarization in Pb–Pb collisions

Full Run 2 Pb–Pb data sample

Phys. Lett. B 815 (2021) 136146



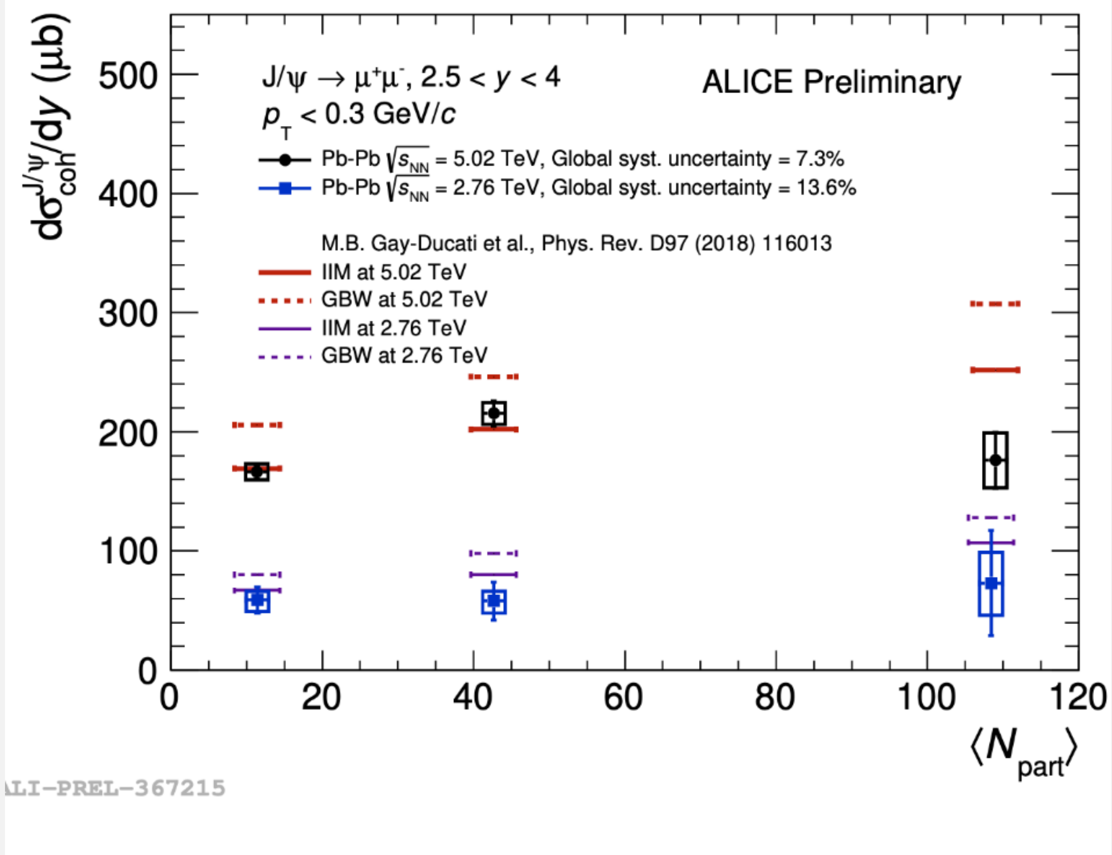
- First measurement of J/ψ polarization in A–A collisions
- λ_θ, λ_Φ, $\lambda_{\theta\Phi}$ close to zero in HE and CS frames:
  - → Maximum deviation of ~ 2σ in the low-p_T bin
  - → Indication of small transverse polarization in HE frame and small longitudinal polarization in CS frame for 2 < p_T < 4 GeV/c
- λ_θ, λ_Φ, $\lambda_{\theta\Phi}$ compatible within uncertainties with ALICE results at $\sqrt{s}$ = 8 TeV in pp collisions
- Significant difference for λ_θ at low p_T in HE frame with LHCb more precise data in pp collisions at $\sqrt{s}$ = 7 TeV
- No significant centrality dependence of the J/ψ polarization. Polarization studies as a function of the Event Plane are ongoing

Coherent J/ψ photoproduction in Pb–Pb collision with nuclear overlap

- J/ψ yield in Pb–Pb collisions, attributed to coherent photoproduction observed with a 5σ significance in semi-central events
- Theoretical challenges: survival of the coherence condition? Only spectator nucleons participating to the coherence?
- UPC-like models with modification of the photon flux reproduce peripheral data. In semi-central events need to account for the modification of the photonuclear cross section
- Coupled to UPC measurement, a potential novel way to measure $\sigma_{\gamma Pb}$ [J. G. Contreras, Phys. Rev. C96, 015203 (2017)]

- A potential new QGP probe in semi-central events?

Full Run 2 Pb–Pb data sample



Conclusions and prospects

ALICE

- ❑ Inclusive J/ψ at forward y and prompt low-p_T J/ψ at mid y strongly suppressed in Cold Nuclear Matter
- ❑ Stronger suppression of the ψ(2S) w.r.t J/ψ at backward y in p–Pb described by final state interactions
- ❑ Significant J/ψ v_2 in high multiplicity p–Pb collisions, collective behavior of heavy quarks?
- ❑ J/ψ R_{AA} in Pb–Pb supports suppression/regeneration mechanisms at low $p_{T,}$ and probes eloss at high p_T with full Run 2 stat
- ❑ J/ψ v_2, v_3 supporting a kinetic equilibration of the charm quark inside the QGP
- ❑ No significant deviation from zero polarization for the J/ψ in Pb–Pb
- ❑ First significant measurement of coherent J/ψ photoproduction in semi-central Pb–Pb collisions

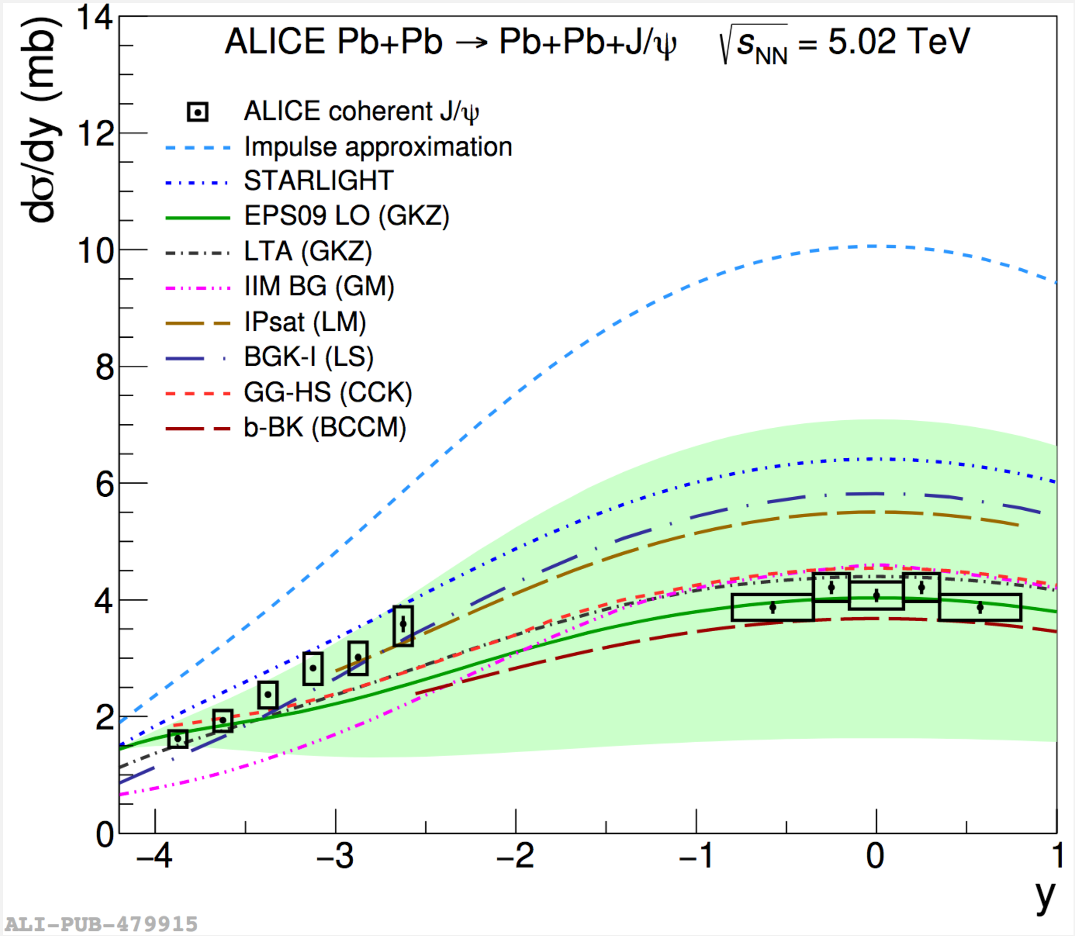
- ❑ Several opportunities for new and improved charmonium measurements in ALICE :
  - ALICE upgrade (LS2), Run 3 and beyond :
    - Continuous readout, 50 kHz int. rate (x100 stat. In central barrel, x10 in muon spectrometer)
    - Muon Forward Tracker at forward y (prompt/non-prompt charmonium separation, reduction of comb. background)
  - LS3, Run4 and beyond : QGP studies with quarkonium between SPS and RHIC top energies with ALICE fixed-target?
  - LS4, Run 5 and beyond : X,Y, Z charmonium-like states with ALICE3?

Backup

Rapidity dependence of coherent J/ψ photoproduction in Pb–Pb

arXiv:2101.04577

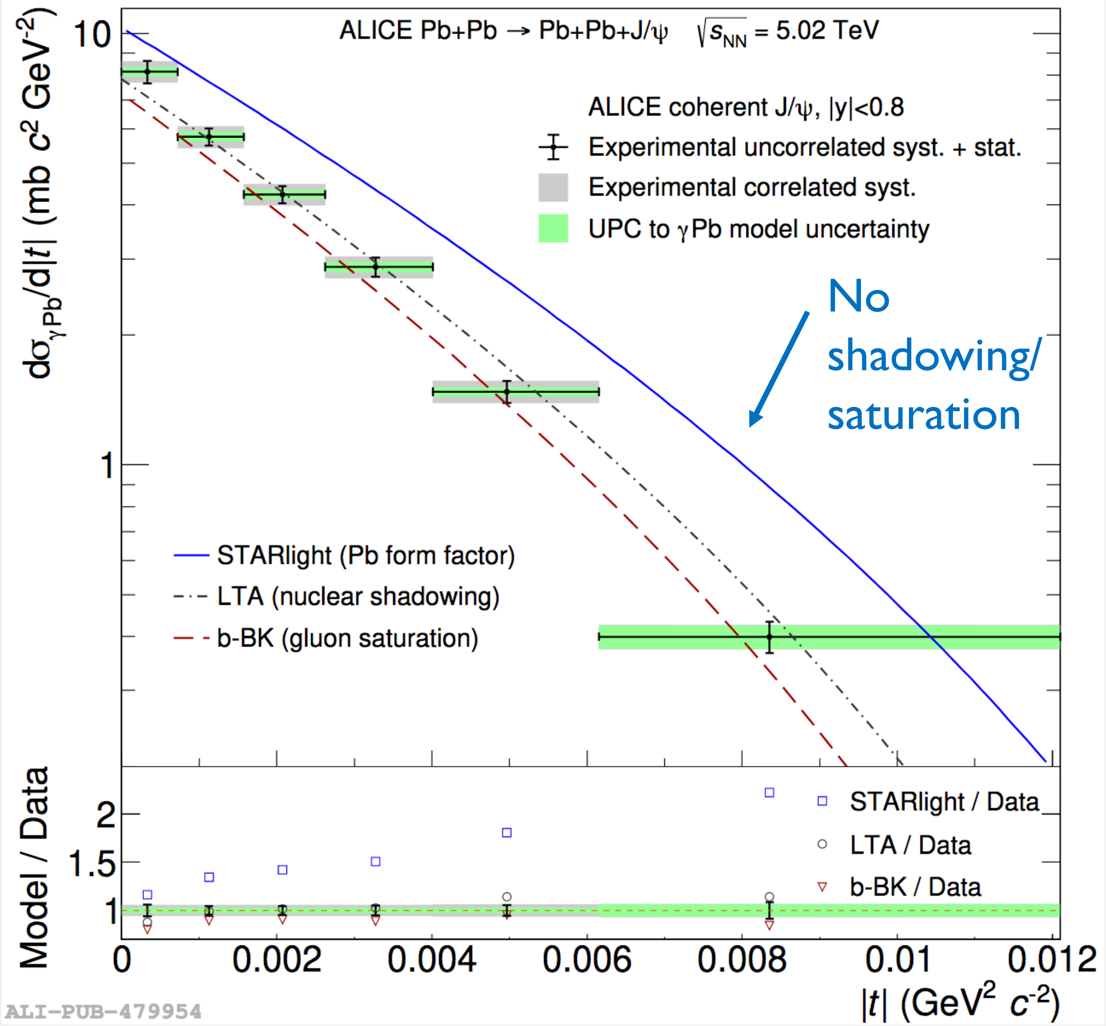
- Inclusion of new midrapidity data
- Comparison of data to impulse approximation (no nuclear effects) leads to a nuclear suppression factor $S_{Pb}(x \sim 10^{-3}) \sim 0.65 \pm 0.03$
- STARLIGHT model (no gluon shadowing) overpredicts the data
- GKZ with EPS09 shadowing and the GG-HS (colour-dipole model with hot spots and including saturation) agree with data at forward and midrapidity, but not at semi-forward rapidity (2.5 < y < 3.5). The data might be better explained with a model where shadowing has a smaller effect in this Bjorken-x region.



$|t|$ dependence of coherent J/ψ photoproduction in Pb–Pb

arXiv:2101.04623

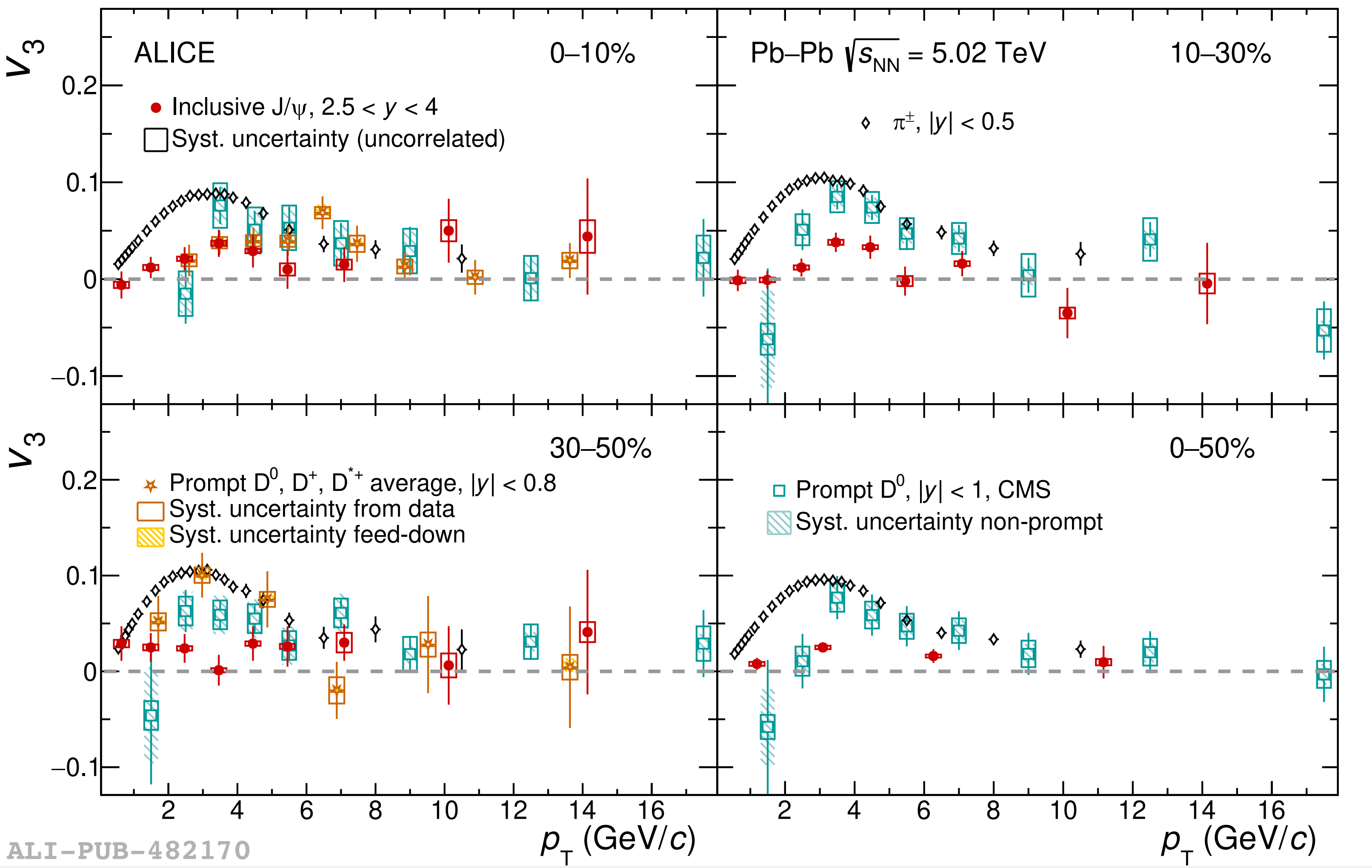
- The first measurement ever of the |t|-dependence of the J/ψ photonuclear production cross section
- |t| obtained from J/ψ p_T^2 measurement + unfolding
- Access to the distribution of gluons in the impact-parameter plane
- STARLIGHT calculation (Pb form factor) without shadowing/saturation overpredicts the data → existence of QCD dynamical effects
- Models incorporating nuclear shadowing (LTA) or gluon saturation (b-BK) describe well the data



Charmonium triangular flow in Pb–Pb collisions

Full Run 2 Pb–Pb data sample

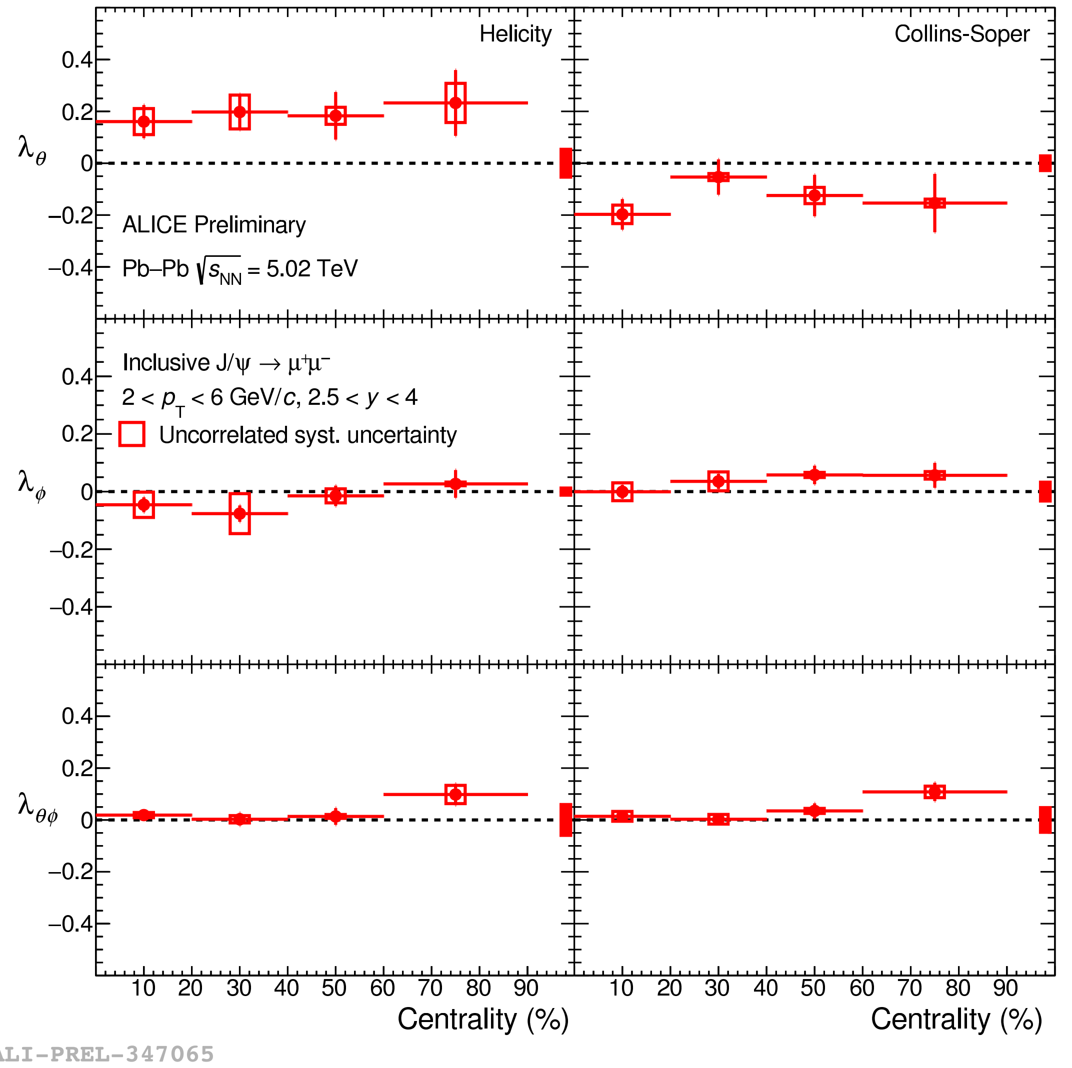
JHEP 2020 (2020) 141



- Triangular flow v_3 is sensitive to initial state energy-density fluctuations
- Inclusive J/ψ v_3 positive in most of the p_T and centrality intervals
  → 5.1σ in 0-50%, for 2 < p_T < 5 GeV/c
- Same mass hierarchy as for v_2 :
  $v_3(\pi) > v_3(D) > v_3(J/\psi)$
- Together with v_2 measurements in favor of the hypothesis that charm quark are at least partially kinetically equilibrated in the QGP

Charmonium polarization in Pb–Pb collisions

Full Run 2 Pb–Pb data sample

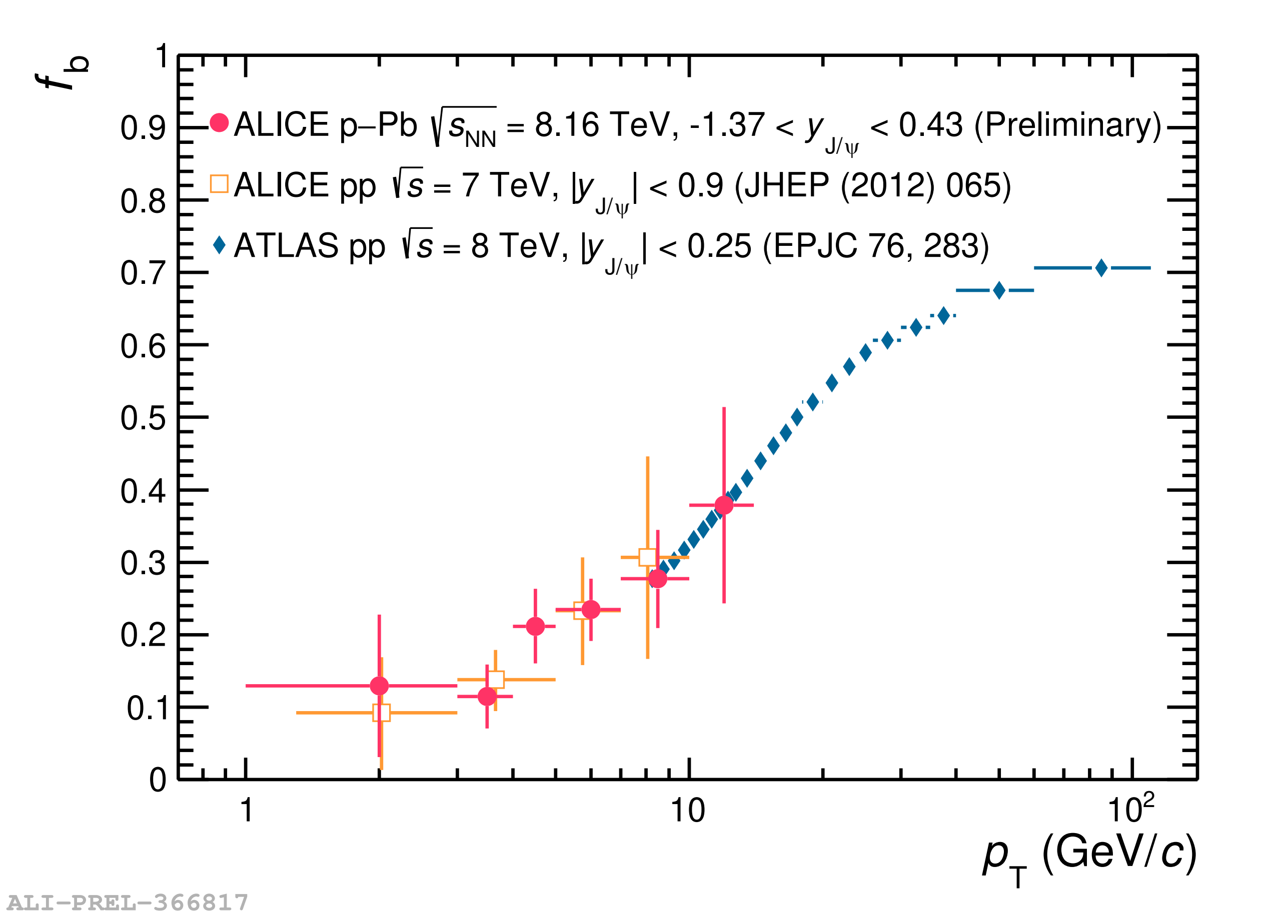


- ❑ Flat trend of all the polarization parameters as a function of centrality

→ No significant centrality dependence of the J/ψ polarization

- ❑ Polarization studies as a function of the Event Plane are ongoing

Charmonium production in p–Pb collisions at midrapidity



Charmonium production in p–Pb collisions at forward rapidity

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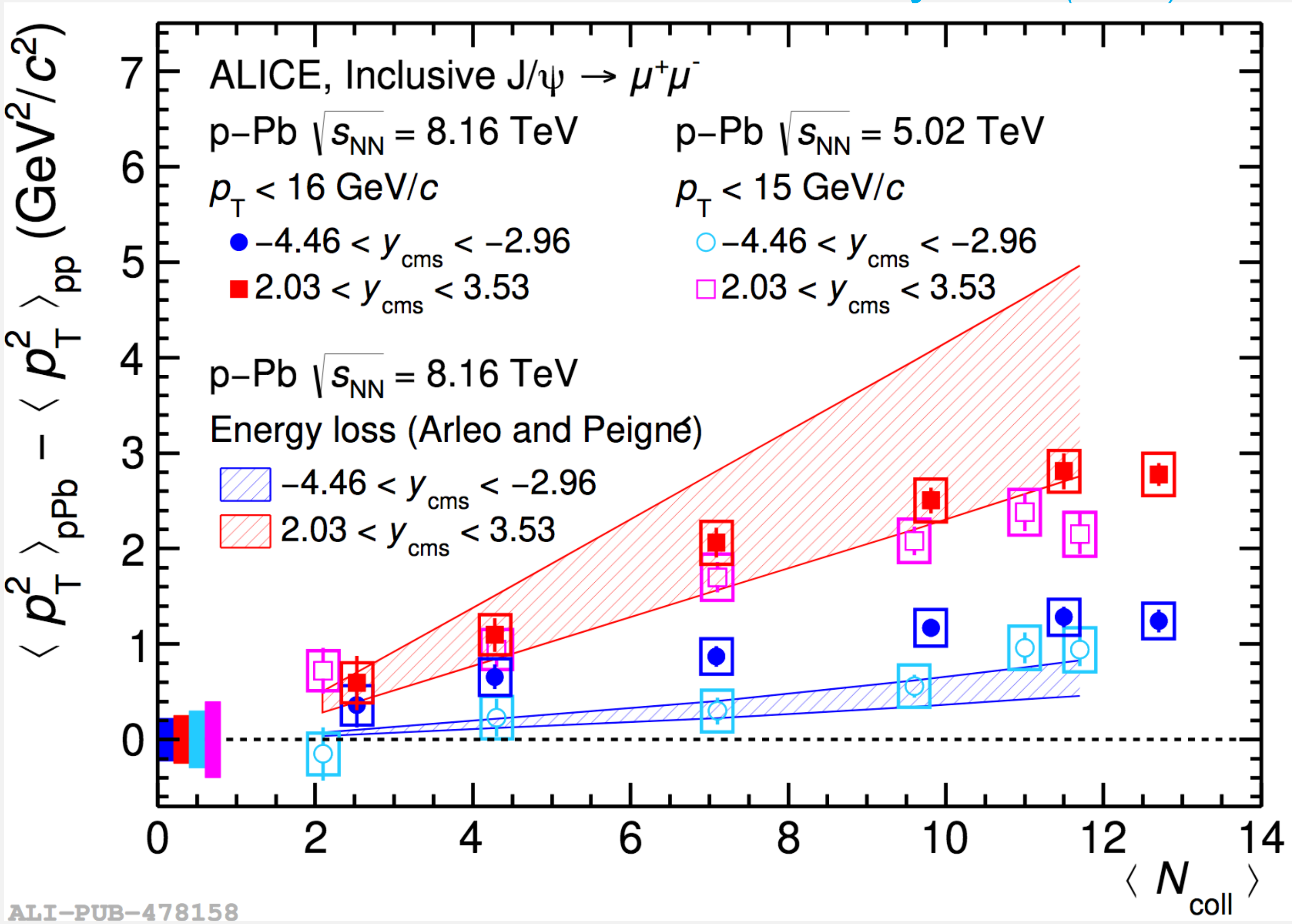
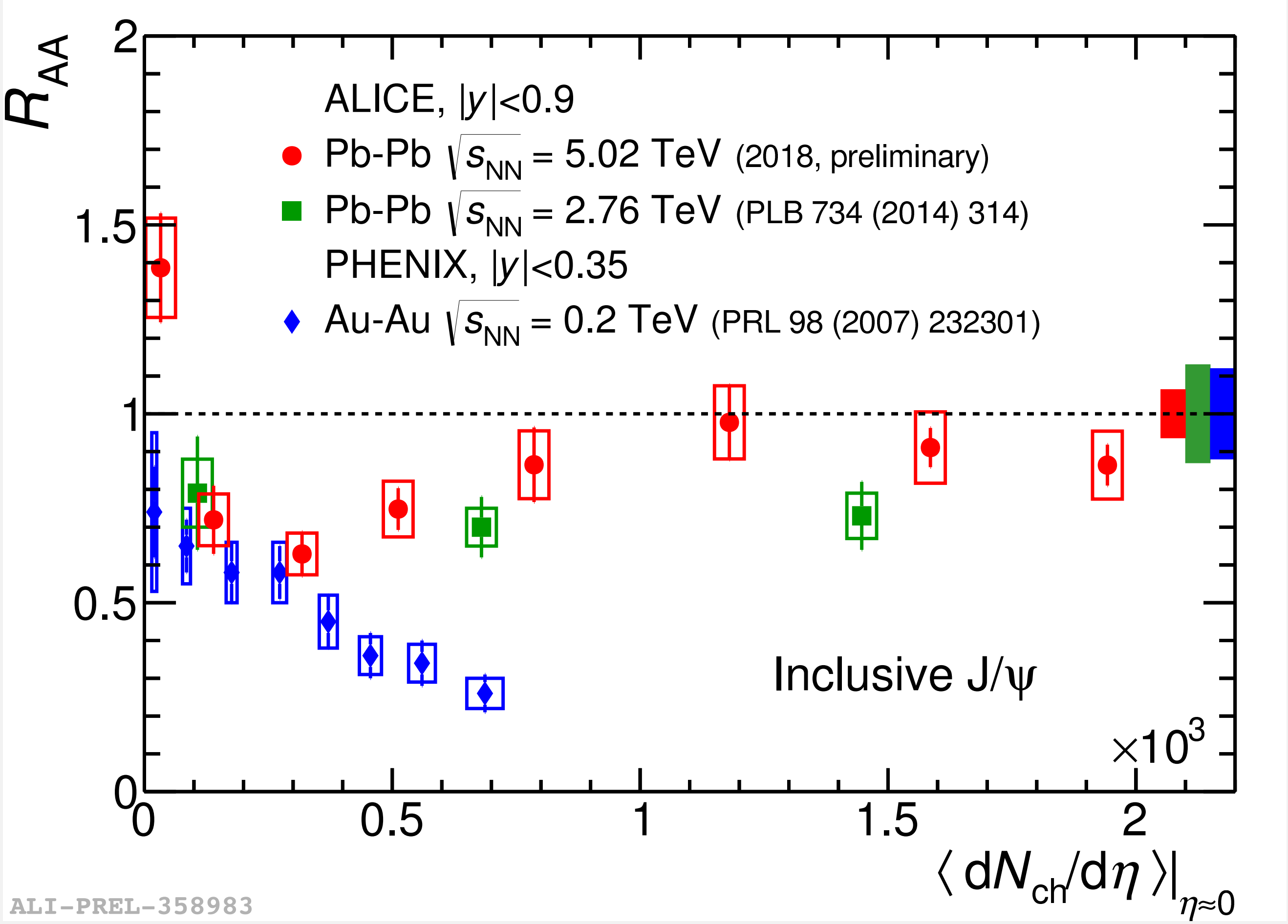
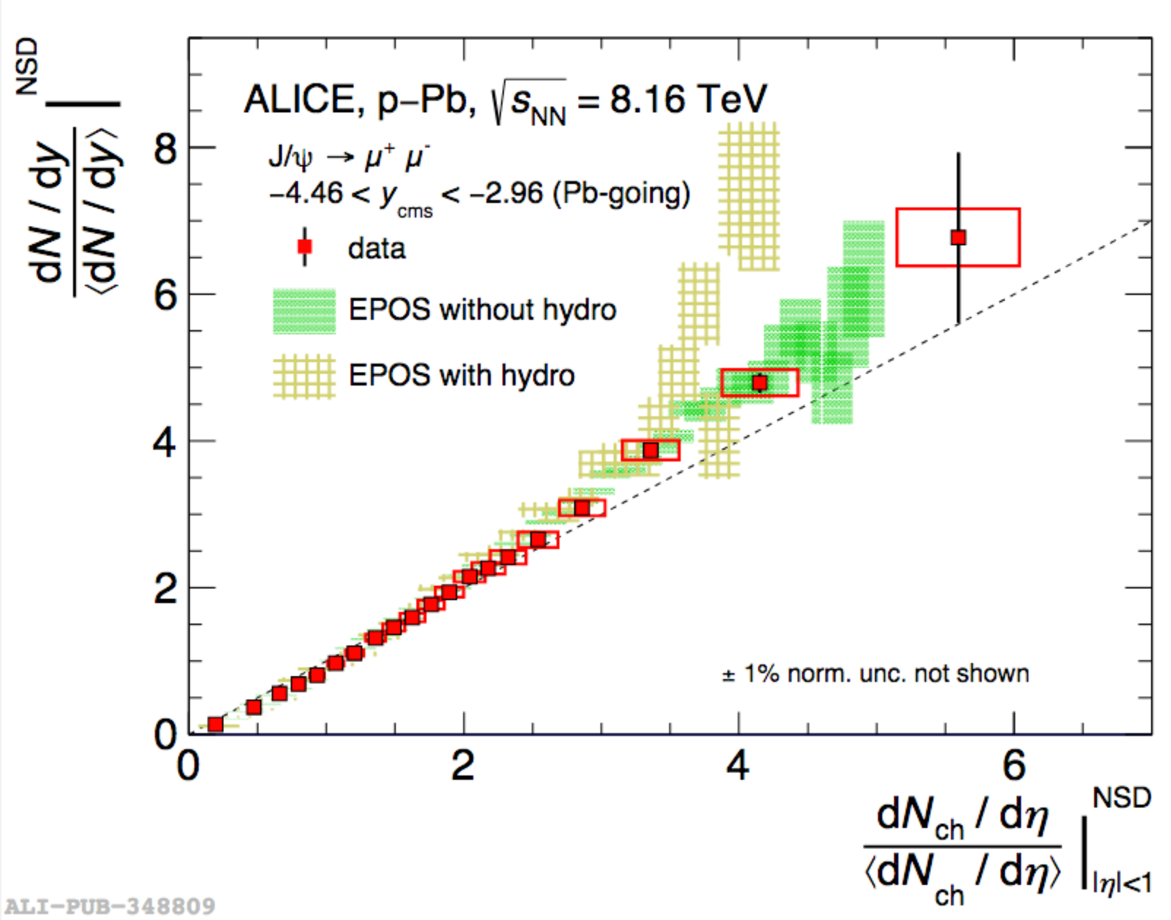
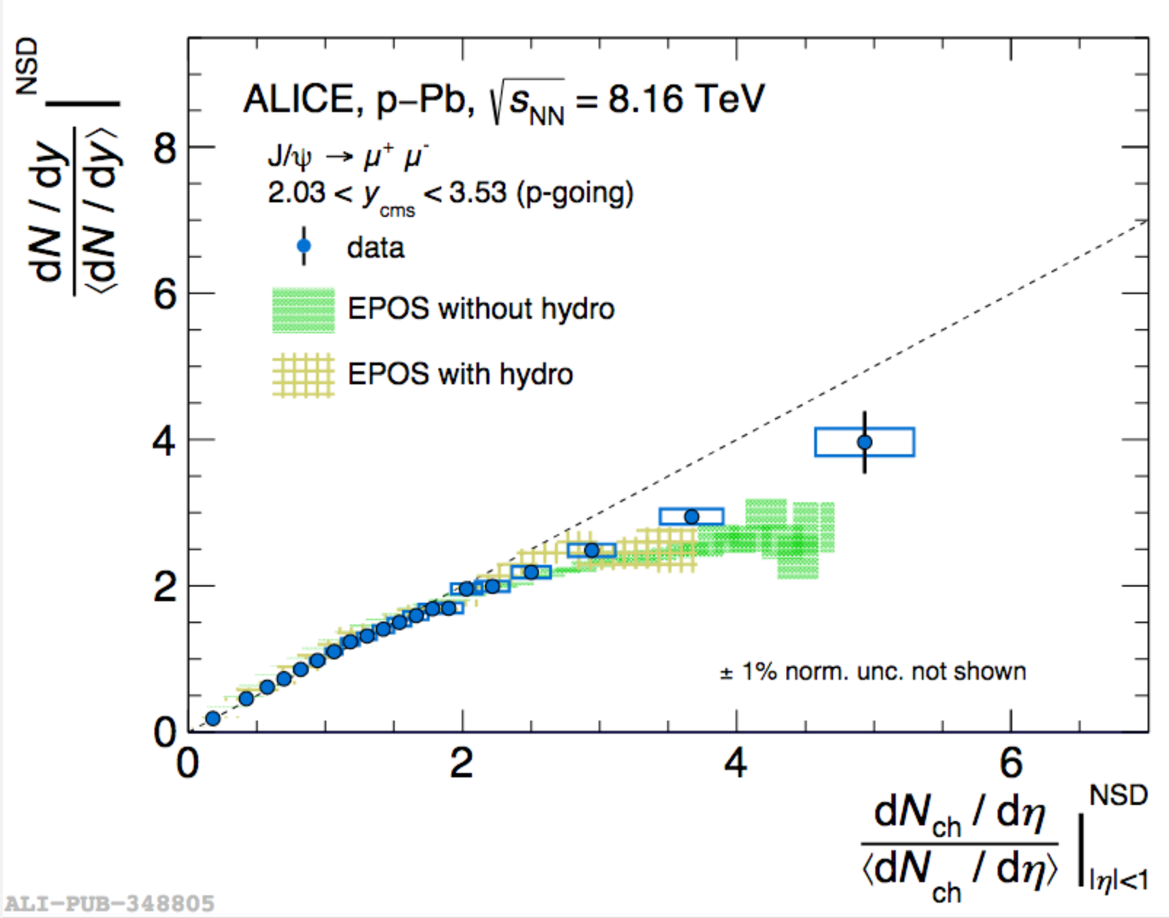


Charmonium production in Pb–Pb collisions



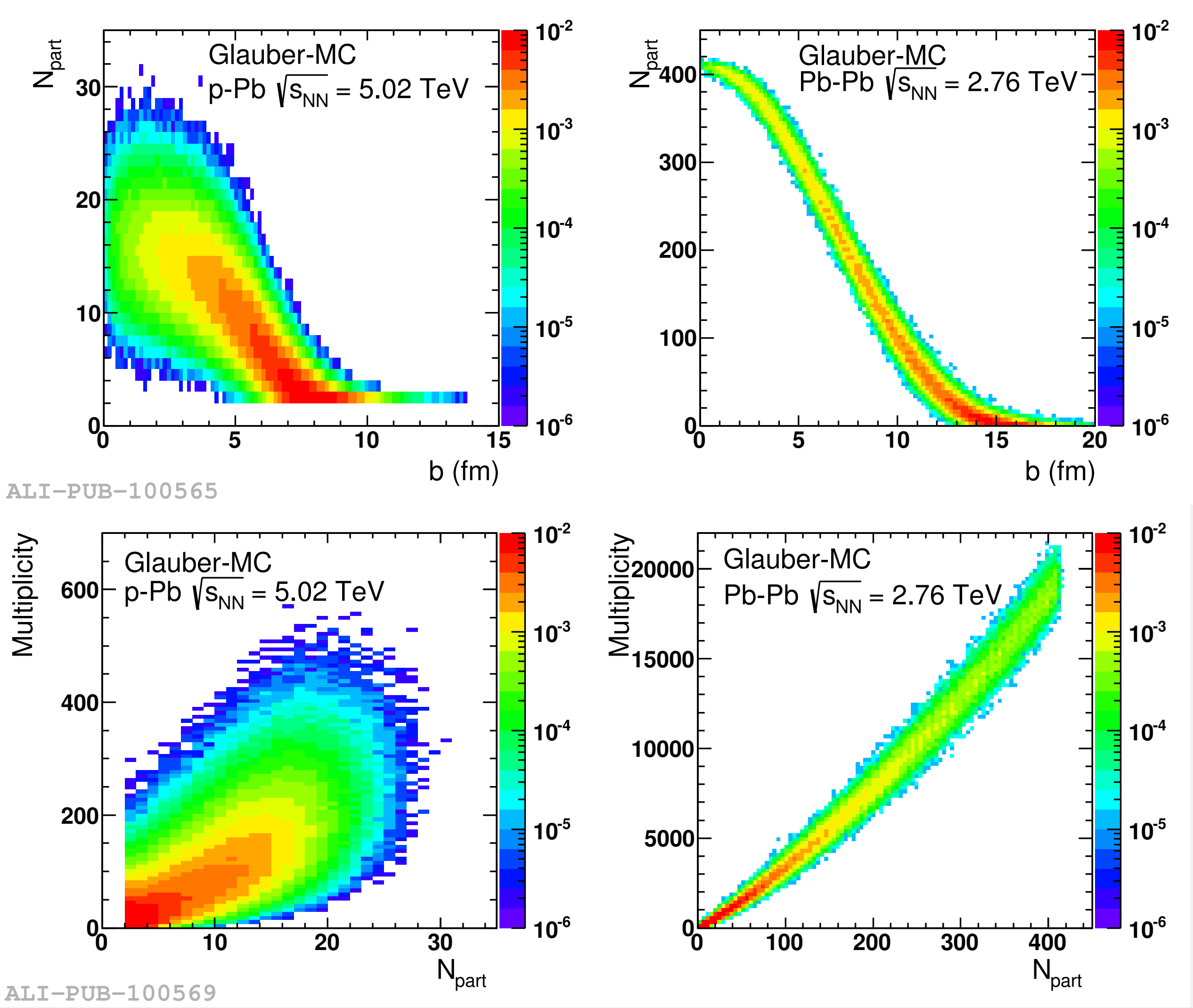
Charmonium production as a function of charged particle multiplicity in p–Pb collisions (model comparison)





Centrality determination in p–Pb collisions : origin of the bias

Phys. Rev. C 91 (2015) 064905



- In p–Pb, looser correlation between N_{part} and b, multiplicity and N_{part}, different multiplicity estimators
- Fluctuations at the origin of physical bias
- Centrality selection based on the multiplicity of the event can be strongly biased in p-Pb
- Energy deposited at zero degrees by slow nucleons in the ZDC expected to be insensitive to a multiplicity bias