Quarkonium as a probe of the QGP and of the initial stages of the heavy-ion collision with ALICE

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Online Strangeness in Quark Matter Conference
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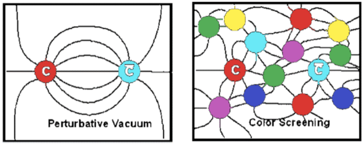
Quarkonium production in heavy-ion collisions

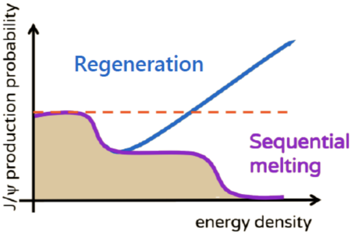
- **Heavy quarks (charm and beauty)**
  - Produced in initial hard partonic scattering
    $\rightarrow$ experience full evolution of heavy-ion collision
  - Natural probe to study the properties of the hot and dense medium



- **Quarkonium production**
  - Sensitive to medium produced in heavy-ion collisions

  $\rightarrow$ Suppression: color screening and medium-induced dissociation
  Matsui and Satz: PLB 178 (1986) 416-422
  A. Rothkopf: PR 858 (2020) 1-117

  $\rightarrow$ At LHC energies: (re)combination of uncorrelated heavy-quark pairs
  P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196
  Thews, Schroedter, Rafelski: PRC 63 (2001) 054905



Quarkonium production in heavy-ion collisions

- The medium effect is quantified using the **nuclear modification factor**:

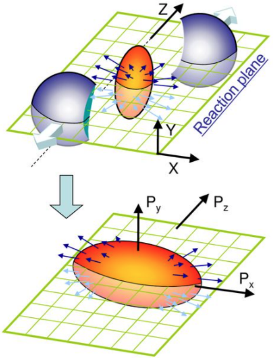
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

  - $R_{AA} \neq 1$ - means that there are cold or hot matter effects

- **Anisotropic flow:**
  - Look at the azimuthal dependence of particle production

$$\frac{dN}{d\phi} \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$$

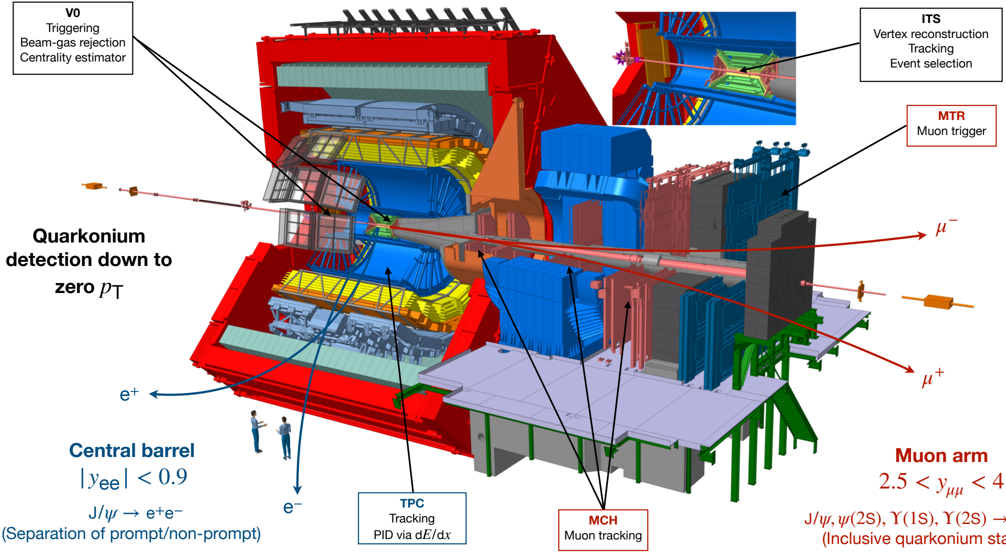
  - Initial spatial anisotropy → momentum-space anisotropy



- **Polarization**:
  - Measure anisotropies in the angular distribution of the decay products

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

Quarkonium measurements in ALICE



Quarkonium detection down to zero p_T

Central barrel

$|y_{ee}| < 0.9$

$J/\psi \to e^+e^-$

(Separation of prompt/non-prompt)

Muon arm

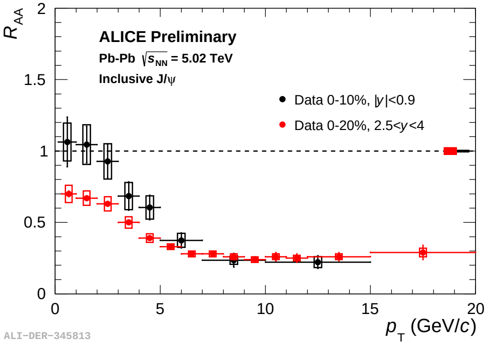
$2.5 < y_{\mu\mu} < 4$

$J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S) \to \mu^+\mu^-$

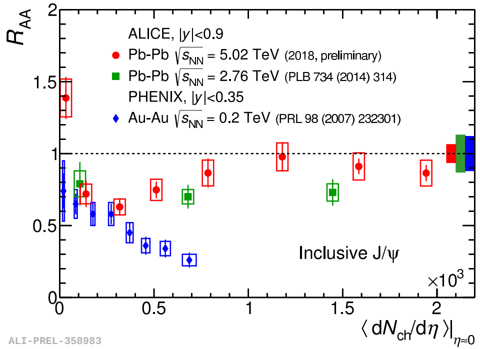
(Inclusive quarkonium states)

J/ψ nuclear modification factor, R_{AA}

Forward and midrapidity



Midrapidity

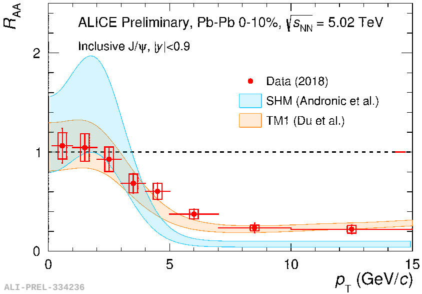


- Weaker suppression at lower p_T, especially at midrapidity
  → Consistent with J/ψ (re)generation scenario
- J/ψ R_{AA} larger at LHC than at RHIC despite much larger energy density
- Similar suppression observed at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV

Published results using 2015 data: PLB805 (2020) 135434, JHEP02 (2020) 041

Quarkonium nuclear modification factor

J/ψ R_{AA}, midrapidity

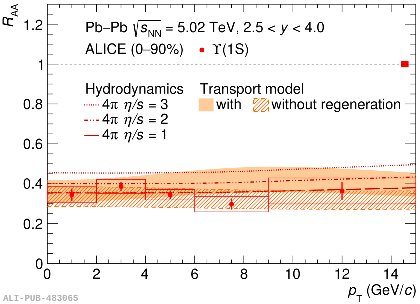


- J/ψ R_{AA} shows a strong p_T dependence
- $\Upsilon(1S)$ R_{AA} shows a flat p_T dependence
- Models describe trend within uncertainties
  $\rightarrow$ Unable to discriminate between (re)generation inside QGP or at phase boundary

Published results using 2015 data: PLB805 (2020) 135434

$\Upsilon(1S)$ R_{AA}, forward rapidity

arXiv:2011.05758



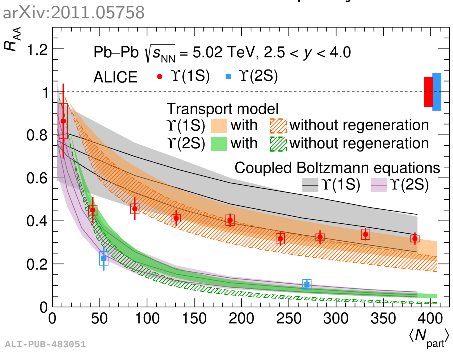
Statistical Hadronization Model PLB797 (2019) 134836
All charmed particles generated at chemical freeze-out

Transport Model NPA943 (2015) 147, PRC96 (2017) 054901
Interplay of dissociation and regeneration inside QGP

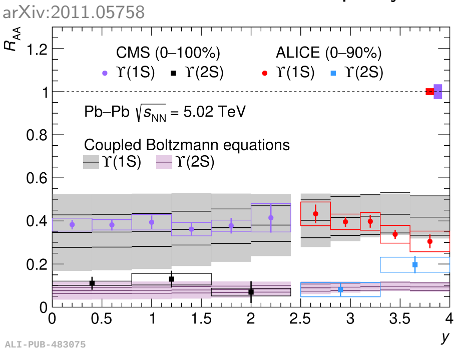
Hydrodynamics Universe (2016) 2(3) 16
Thermal modification of heavy-quark potential inside anisotropic plasma

$\Upsilon(1S)$, $\Upsilon(2S)$ nuclear modification factor

Forward rapidity



Forward and midrapidity



- Stronger suppression towards more central collisions
  → Models reproduce observed trend within uncertainties
- Hint of decreasing $\Upsilon(1S)$ R_{AA} at forward rapidity
  → Coupled Boltzmann eq. predict a slight increase (hydrodynamics model shows similar issue vs y)

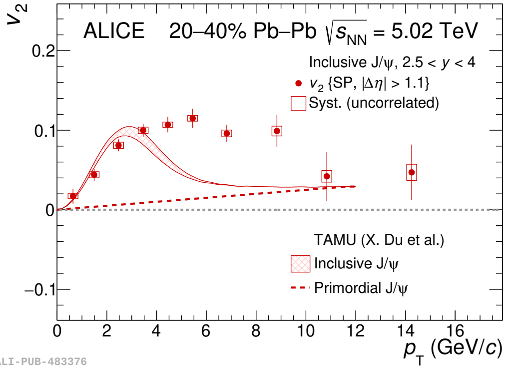
Transport Model PRC96 (2017) 054901
Interplay of dissociation and regeneration inside QGP

Coupled Boltzmann equations JHEP01 (2021) 046
Regeneration dominated by real-time recombination of correlated heavy-quark pairs

J/ψ and Υ(1S) elliptic flow (v_2)

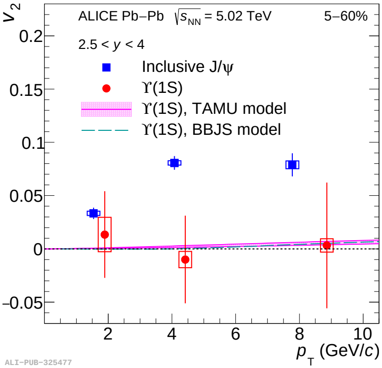
J/ψ v_2, forward rapidity

JHEP10 (2020) 141



Forward rapidity

PRL123 (2019) 192301



- Positive J/ψ v_2 up to high-p_T $\rightarrow$ underestimated by transport model above 4 GeV/c
  - Described by spatial-momentum correlations?
- Υ(1S) v_2 compatible with 0 with large uncertainties
  $\rightarrow$ significantly lower than inclusive J/ψ v_2
  $\rightarrow$ consistent with models predicting little or no (re)generation

TAMU PRC96 (2017) 054901

BBJS PRC 100 (2019) 051901

J/ψ elliptic flow (v_2)

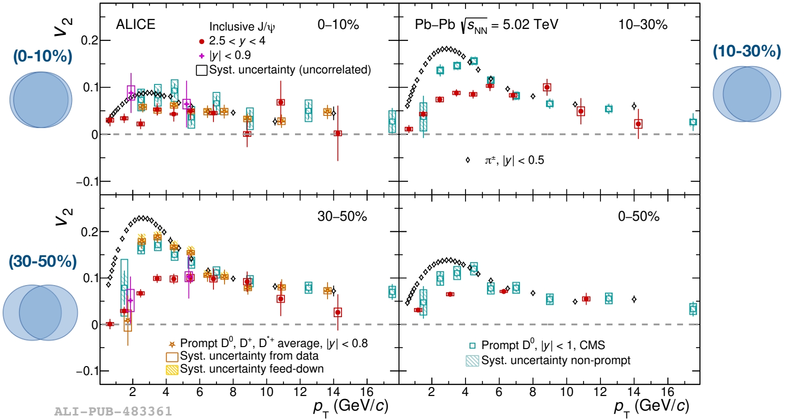
J/ψ - forward rapidity
J/ψ - midrapidity
π - midrapidity
D - midrapidity
D - midrapidity, CMS

PRL 120 (2018) 202301

- v_2 grows from central to semicentral collisions
- Clear mass hierarchy at low p_T: $v_2(\pi) > v_2(D) > v_2(J/\psi)$

Forward and midrapidity

JHEP02 (2020) 041



- Species independent v_2 at high p_T $\rightarrow$ suggests path-length dependent energy-loss effects

J/ψ triangular flow (v_3)

- J/ψ - forward rapidity
- π - midrapidity
- D - midrapidity
- D - midrapidity, CMS

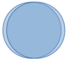
PRL 120 (2018) 202301

- Little centrality dependence
- Positive v_3 $\rightarrow$ initial state energy-density fluctuations reflected in charm quark flow

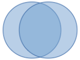
Forward rapidity

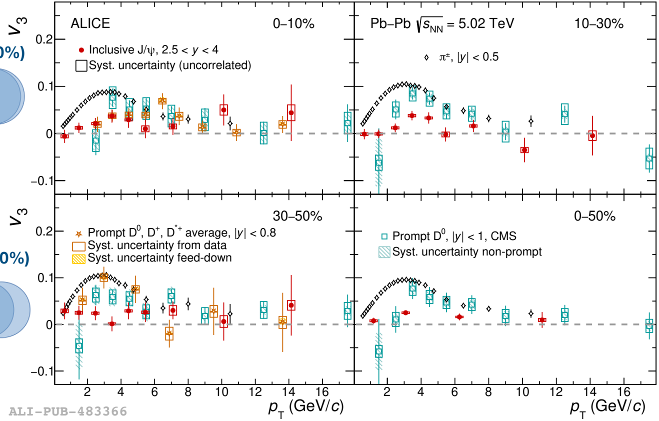
JHEP10 (2020) 141

(0-10%)

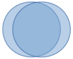


(30-50%)





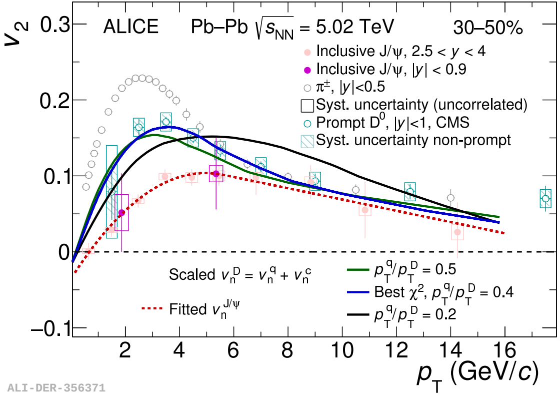
(10-30%)



- Observed mass hierarchy for v_2 and v_3
  $\rightarrow$ supports hypothesis of charm quarks being kinetically equilibrated in QGP medium

Constituent-quark scaling

JHEP10 (2020) 141



- Flow of light and strange particles scale approximatly with number of constituent quarks (NCQ)
- Extend NCQ scaling to D mesons:
  → Assume $v_2(p_T)$ derived by NCQ scaling

$$v_2^c(p_T^c) = v_2^{J/\psi}(2p_T^c)/2$$
$$v_2^q(p_T^q) = v_2^{\pi}(2p_T^q)/2$$
$$\Downarrow$$
$$v_2^D(p_T^D) = v_2^q(p_T^q) + v_2^c(p_T^c)$$

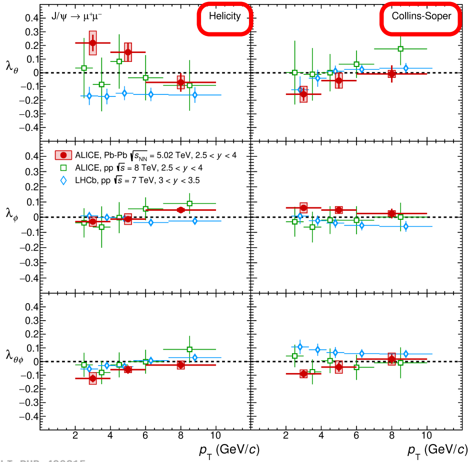
- Scaling depends on the assumed p_T fraction carried by each constituent
  → Best agreement with measured D-meson flow for equal or nearly equal p_T fraction

First measurement of J/ψ polarization in Pb–Pb collisions

ALICE

Forward rapidity

PLB 815 (2021) 136146



ALI-PUB-490215

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

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

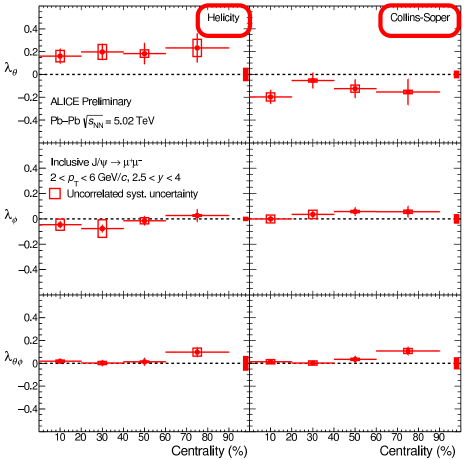
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1, 0, 0) \rightarrow$ Pure transverse

- Polarization parameters are close to zero
- λ_θ shows a maximum 2σ deviation w.r.t zero in both reference frames for $2 < p_T < 4$ GeV/c
- Compatible with ALICE pp results
- 3σ difference with LHCb pp results in Helicity $\rightarrow$ reflect different production and suppression mechanisms Pb–Pb w.r.t pp collisions?

First measurement of J/ψ polarization in Pb–Pb collisions

ALICE

Forward rapidity



ALI-PREL-347065

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

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

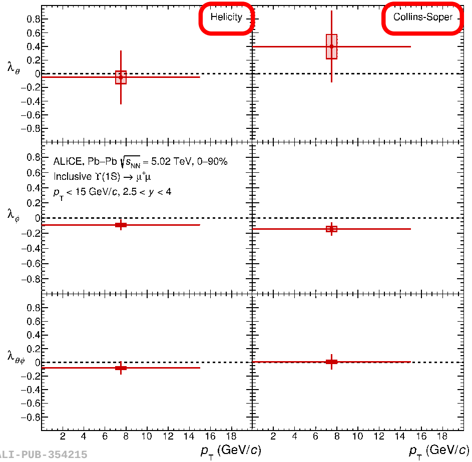
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1, 0, 0) \rightarrow$ Pure transverse

- Flat trend for all polarization parameters as a function of centrality
- Non-zero λ_θ observed in both reference frames
- Polarization measurement w.r.t. event plane underway $\rightarrow$ study effects related to the large angular momentum of the two colliding ions and the intense magnetic field produced in heavy-ion collisions

First measurement of $\Upsilon(1S)$ polarization in Pb–Pb collisions

Forward rapidity

PLB 815 (2021) 136146



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

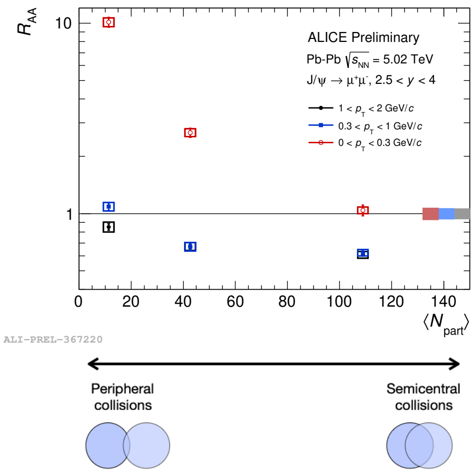
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1, 0, 0) \rightarrow$ Pure longitudinal

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

- Polarization parameters compatible with zero
- Significantly limited by available statistics

Low p_T J/ψ excess

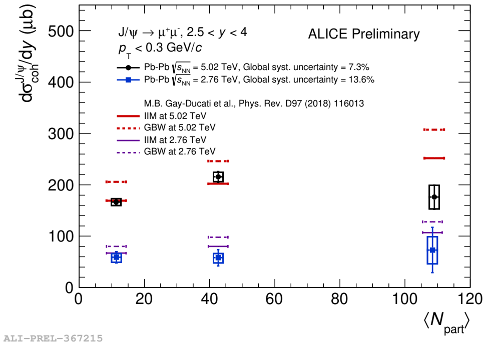
Forward rapidity



- Preliminary measurement of J/ψ R_{AA} at very low p_T
- Increasing R_{AA} in peripheral collisions for $p_T < 0.3$ GeV/c
  $\rightarrow$ Systematically larger than the hadronic R_{AA} in the p_T reference interval $1-2$ GeV/c
- Coherent J/ψ photoproduction suggested as underlying physics mechanism
  $\rightarrow$ photonuclear cross section probes the gluon density at very low Bjorken-x (LHC energies: $x \sim 10^{-5} - 10^{-2}$)

Coherent J/ψ photoproduction cross section

Forward rapidity



- Increase in cross section with increasing collision energy
- Models implementing modification of photon flux (purely electromagnetic) w.r.t. ultra-peripheral collisions (UPC)
- Qualitative agreement in peripheral collisions
- Deviations in semicentral events $\rightarrow$ insufficient model description?

Conclusions

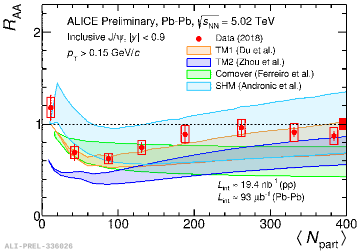
Quarkonium as a probe of the QGP and initial stages of heavy-ion collisions

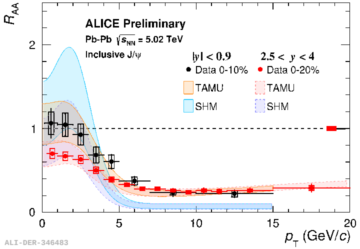
- **Nuclear modification factor**
  - J/ψ R_{AA} consistent with significant contribution from (re)generation
  - Υ(1S), Υ(2S) show strong suppression
- **Elliptic and triangular flow**
  - Υ(1S) v_2 significantly lower than J/ψ v_2
  - Clear mass hierarchy observed for J/ψ v_2 and v_3 w.r.t. D mesons at low p_{T}
    $\rightarrow$ supports hypothesis of charm quark thermalization within the medium
- **Polarization**
  - First measurement of J/ψ and Υ(1S) polarization in Pb–Pb collisions
  - J/ψ exhibits a maximum 2σ deviation w.r.t. zero for λ_θ
- **Coherent photoproduction**
  - Preliminary measurements of coherent J/ψ photoproduction
  - Qualitatively reproduced by UPC-based models in peripheral collisions
  - Deviations in semicentral collisions

Thank you for your attention!

Backup

Nuclear modification factor models - charmonium





Statistical Hadronization Model PBL797 (20199 134836

- Heavy quarks produced during initial hard partonic interactions followed by thermalization in QGP
- Subsequent formation of bound states at phase boundary according to thermal weights

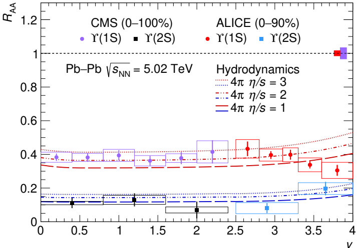
Transport models NPA943 (2015) 147, PRC89 (2014) 054911

- Continuous generation, dissociation and regeneration inside QGP
- Governed by a set of rate equations

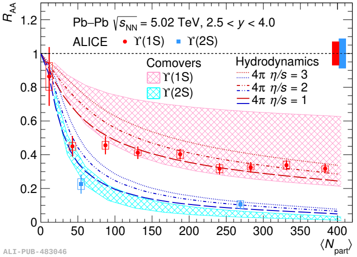
Comover model PBL 731 (2014) 57, JHEP 10 (2018) 094

- Dissociation by scattering of comoving partons and hadrons
- Includes a (re)generation component depending on the primordial charm quark cross section

Nuclear modification factor models - bottomonium



ALI-PUB-483070



ALI-PUB-483046

Transport models PRC96 (2017) 054901

- Continuous generation, dissociation and regeneration inside QGP
- Band width: modification of the PDF modelled by effective scale factor of initial number of $b\bar{b}$ pairs

Comover model JHEP 10 (2018) 094, JHEP 03 (2019) 063

- Dissociation via interaction with surrounding particles in final state
- Uncertainties from nCTEQ15 shadowing

Hydrodynamics Universe (2016) 2(3) 16

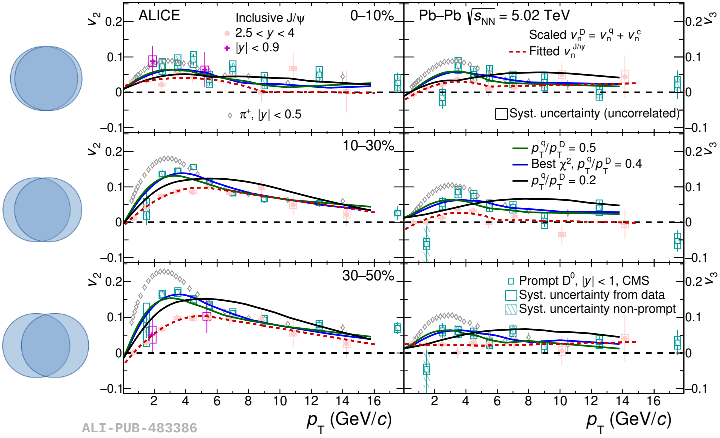
- Thermal modification of complex heavy-quark potential inside anisotropic plasma
- Survival probability evaluated based on the local energy density
- Does not include any modification of nuclear PDFs or regeneration phenomenon

Coupled Boltzmann equations JHEP 01 (2021) 046

- Regeneration dominated by recombination of correlated heavy-quark pairs
- Derived from open quantum system
- Theoretical bands due to nPDF uncertainties

NCQ scaling

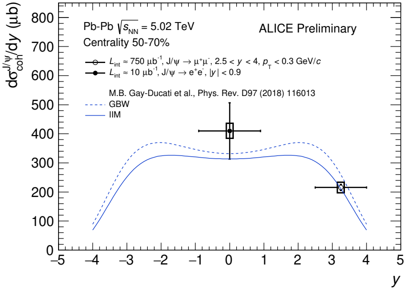
v_2 v_3



- Scaling works well for both v_2 and v_3
- Based on simplified underlying physics assumptions

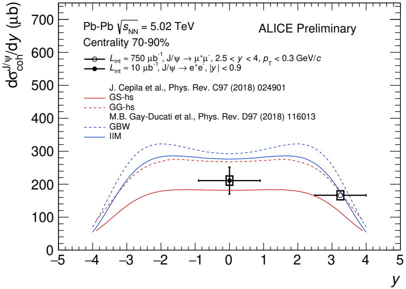
Coherent J/ψ photoproduction cross section

centrality 50 - 70%



ALI-PREL-367204

centrality 70 - 90%



ALI-PREL-367210

- Models with effective description of the photon flux w.r.t. ultra peripheral collisions (UPC):

Energy dependent hot-spot model

PRC97 (2018) 024901

  - GG-hs: Glauber Gribov formalism
  - GS-hs: Geometric scaling

Dipole model

PRD97 (2018) 116013

  - GBW: Ligth cone color dipole formalism
  - IIM: Color Glass Condensate approach

- Qualitative agreement with models within uncertainties