Quarkonium production in dilute and dense systems with ALICE at the LHC

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EMMI

QCD Challenges from pp to AA

Outline

- Charmonia in heavy-ion collisions
  - Suppression vs enhancement
  - Nuclear modification and elliptic flow
- Charmonia in small systems
  - Reference for heavy-ion collisions at ‘moderate’ multiplicities
  - High-multiplicity environment
  - Collective behaviour

Quarkonia in heavy-ion collisions

$Q\bar{Q}$ potential

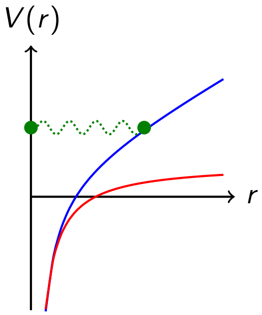
- At $T = 0$, vacuum

$$V(r) \propto -\frac{\alpha}{r} + \sigma r$$

$\rightarrow$ Coulomb-like
$\rightarrow$ String-like

- At $T \gtrsim T_c$, high colour density

$$V(r) \propto -\frac{\alpha}{r} \exp(-r/\lambda_D)$$

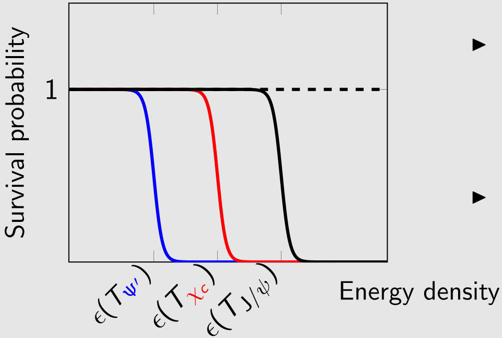


Matsui and Satz, PLB 178 (1986) 416

- No bound state, if $r_{Q\bar{Q}} > \lambda_D(T) \mathrel{\widehat{=}}$ screening length
- Quarkonium formation is prevented by a screening potential in hot medium

Quarkonium suppression

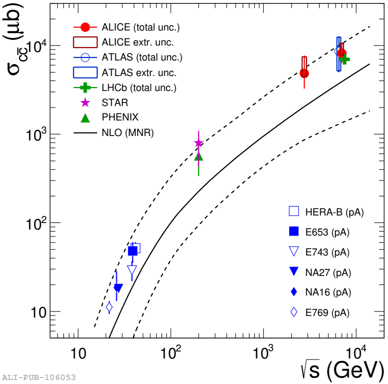
Sequential melting



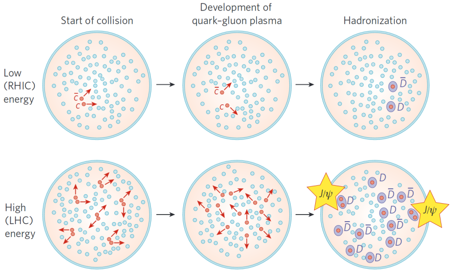
Karsch et al., PLB637 (2006) 75

- Differences in binding energy ϵ lead to a sequential suppression of $Q\bar{Q}$ states
- Charmonium an ideal thermometer for the QGP

Quarkonium 'enhancement' via recombination



ALICE, PRC94 (2016) 054908



Braun-Munzinger and Stachel, Nature 448 (2007) 302

$\left\{ \begin{array}{c} \text{Low} \\ \text{High} \end{array} \right\}$ energy: $\left\{ \begin{array}{c} \text{few} \\ \text{many} \end{array} \right\}$ c-quarks per collision

$\Rightarrow \left\{ \begin{array}{c} \text{suppression} \\ \text{enhancement} \end{array} \right\}$ of J/ψ dominating

Important observables in heavy-ion collisions

Nuclear modification factor

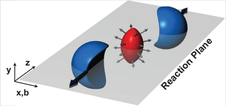
$$R_{AA} = \frac{N_{AA}}{\langle N_{\text{coll}} \rangle N_{pp}}$$

- Quantify medium effects by comparing AA to pp yield
- pp yield scaled by number of binary NN collisions
- 'Divide' by the vacuum contribution

$\rightarrow$ $R_{AA} = 1$, no medium effects

$\rightarrow$ $R_{AA} \neq 1$, medium-induced effects

Elliptic flow

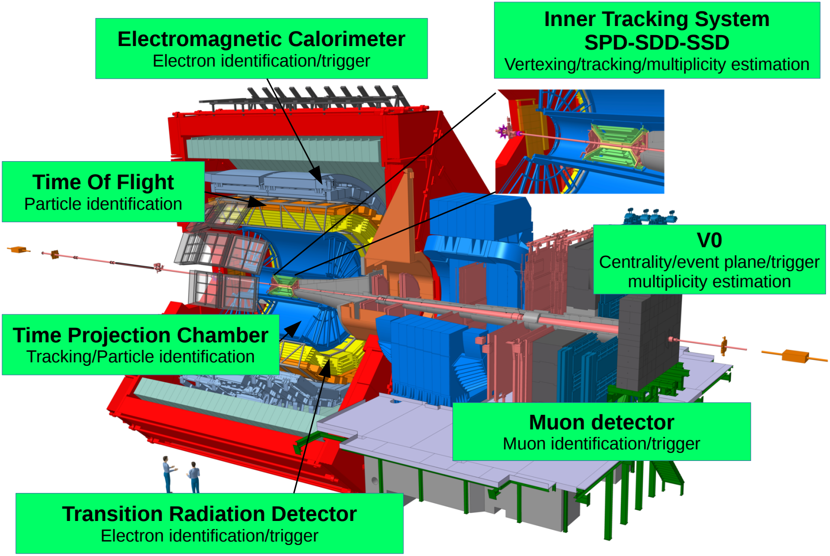


- Non-central collisions $\rightarrow$ anisotropic azimuthal distribution
- Second Fourier coefficient

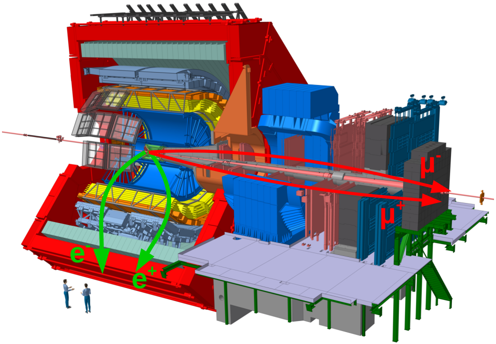
$$v_2(p_\text{T}, y) = \langle \cos[2(\varphi_{\mu\mu} - \varphi_\text{EP})] \rangle$$

- J/ψ could inherit flow of (thermalised) charm quarks $\rightarrow v_2^{\text{J}/\psi} > 0$

A Large Ion Collider Experiment



Quarkonium measurements in ALICE



$J/\psi \rightarrow e^+e^-$
▶ $\lvert y_{ee}\rvert < 0.9$
▶ $\Delta m/m \sim 1$ %

$J/\psi \rightarrow \mu^+\mu^-$
▶ $2.5 < y_{\mu\mu} < 4$
▶ $\Delta m/m \sim 2$ %

Run1 (2009-2013)

Pb-Pb (2.76 TeV)	$\mathcal{L}^{\mathrm{MB}} = 26\ \mu\mathrm{b}^{-1}$ $\mathcal{L}^{2\mu} = 69\ \mu\mathrm{b}^{-1}$
p-Pb (5.02 TeV)	$\mathcal{L}^{\mathrm{MB}} = 51\ \mu\mathrm{b}^{-1}$ $\mathcal{L}^{2\mu}_{\mathrm{Pbp}} = 5.8\ \mathrm{nb}^{-1}$ $\mathcal{L}^{2\mu}_{\mathrm{pPb}} = 5.0\ \mathrm{nb}^{-1}$
pp (0.9;2.76;7;8 TeV)	

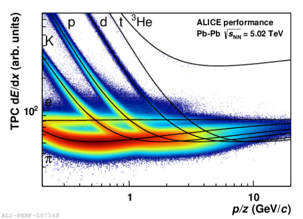
Run2 (2015-2017)

Pb-Pb (5.02 TeV)	$\mathcal{L}^{\mathrm{MB}} = 19\ \mu\mathrm{b}^{-1}$ $\mathcal{L}^{2\mu} = 225\ \mu\mathrm{b}^{-1}$
p-Pb (5.02 TeV)	$\mathcal{L}^{\mathrm{MB}} = 0.4\ \mathrm{nb}^{-1}$
p-Pb (8.16 TeV)	$\mathcal{L}^{2\mu}_{\mathrm{pPb}} = 8.7\ \mathrm{nb}^{-1}$ $\mathcal{L}^{2\mu}_{\mathrm{Pbp}} = 12.9\ \mathrm{nb}^{-1}$
pp (5.02;13 TeV)	

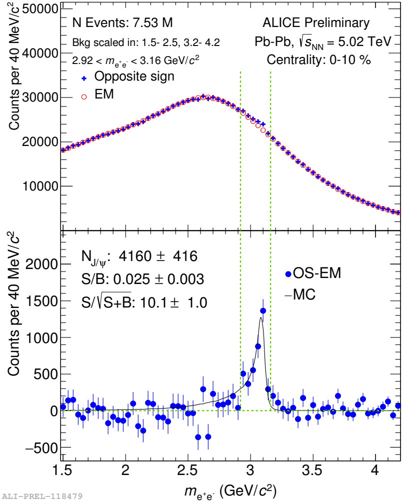
Mid-rapidity measurement

Data analysis of $J/\psi \rightarrow e^+e^-$

- Minimum-bias trigger
- Acceptance
  $|\eta_e| < 0.8$ & $p_T^e > 1$ GeV
- Particle identification
  $\rightarrow$ Energy-loss in the TPC



- Background description
  $\rightarrow$ Mixed-event technique

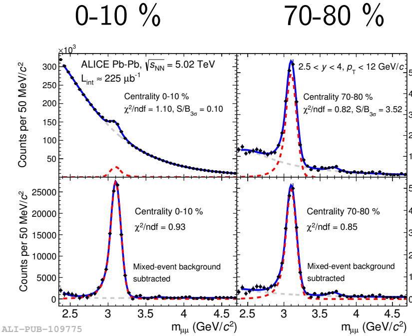


Forward rapidity measurement

ALICE, PLB 766 (2017) 212

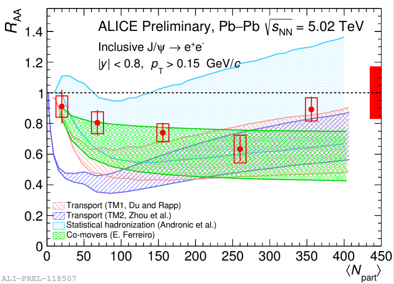
Data analysis of $J/\psi \to \mu^+\mu^-$

- Dimuon trigger
- Muon tracking-trigger matching
- Background description
  $\to$ Fitting dimuon invariant mass spectra with signal+background shapes
  $\to$ Also use mixed-events in Pb–Pb collisions



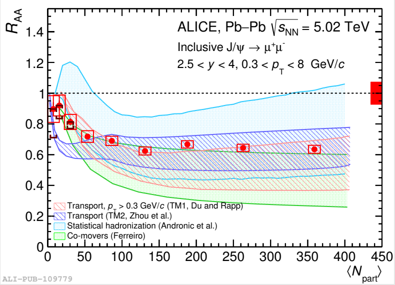
Nuclear modification vs centrality in Pb-Pb collisions

Mid-rapidity



Forward rapidity

ALICE, PLB 766 (2017) 212

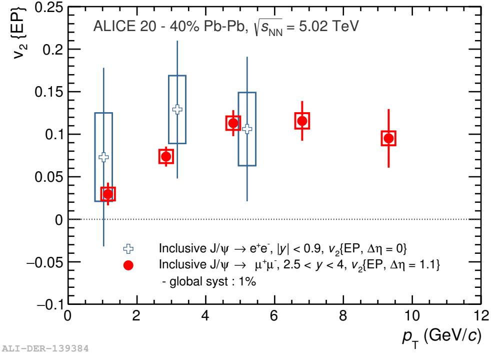


- In general, good description of the data by the models
- Large uncertainties from $\sigma_{c\bar{c}}^{\mathrm{PbPb}}$ and shadowing
- All models need to include a recombination component

Elliptic flow of J/ψ in Pb-Pb collisions

ALICE, arXiv:1709.05260 [nucl-ex]

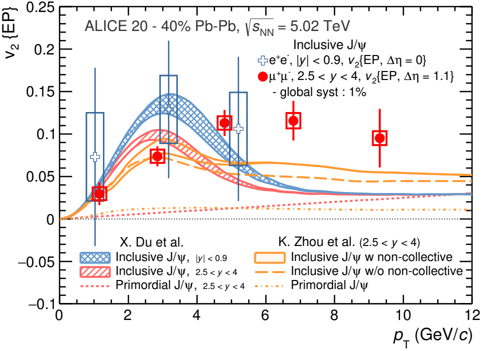
- From a hint (Run1) to evidence (Run2) $\rightarrow J/\psi$ flows



Elliptic flow of J/ψ in Pb-Pb collisions

ALICE, arXiv:1709.05260 [nucl-ex]

- From a hint (Run1) to evidence (Run2) $\rightarrow$ J/ψ flows
- Models have difficulties to describe the high p_T region

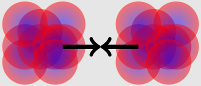


Contributions

1. Recombination of thermalised charm quarks (low p_T)
2. Primordial path-length dependent suppression in the medium (high p_T)

Heavy-ion collisions – Separating the components

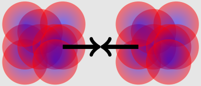
A-A collisions



- High energy densities and temperatures
- Hot nuclear matter effects (screening, recombination, ...)

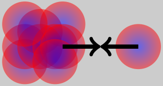
Heavy-ion collisions – Separating the components

A-A collisions



- High energy densities and temperatures

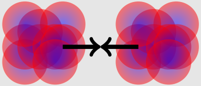
p-A collisions



- Sensitivity to cold nuclear matter effects
- Modifications of PDF: (anti-)shadowing, saturation, ...
- Medium energy-loss, Cronin-effect, ...

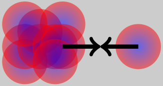
Heavy-ion collisions – Separating the components

A-A collisions



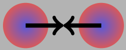
- High energy densities and temperatures

p-A collisions



- Sensitivity to cold nuclear matter effects

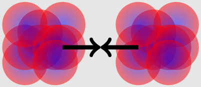
pp collisions



- Vacuum production (singlet, octet, evaporation, ...)

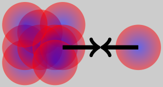
Heavy-ion collisions – Separating the components

A-A collisions



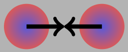
- High energy densities and temperatures

p-A collisions



- Sensitivity to cold nuclear matter effects

pp collisions

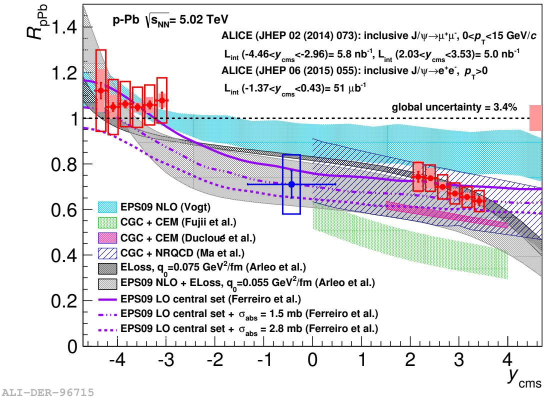


- Vacuum production (singlet, octet, evaporation, ...)

- Superposition of various effects and production mechanisms

Nuclear modification vs rapidity in p-Pb collisions

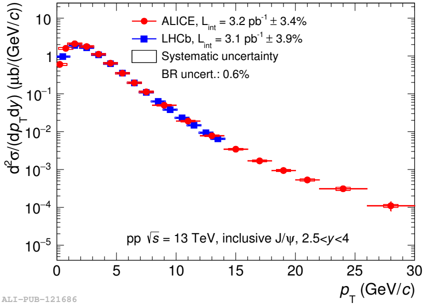
ALICE, JHEP 06 (2015) 55

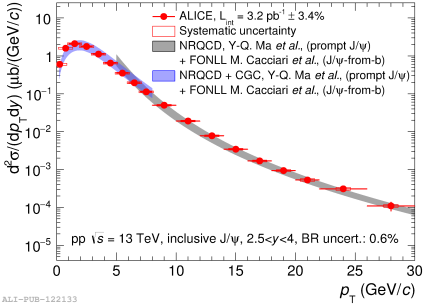


- Centrality and p_T integrated data fairly well described by different models

J/ψ production in pp collisions

ALICE: Eur.Phys.J. C 77 (2017) 392 and LHCb:JHEP 10 (2015) 172



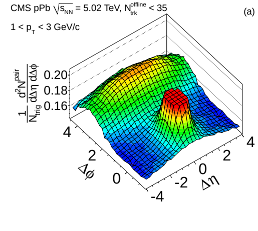


At 'moderate' multiplicities

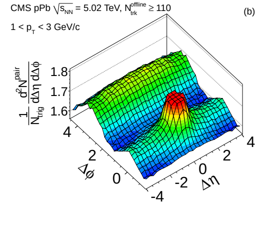
- Good agreement between experiments
- NRQCD (+ FONLL for $b \to J/\psi$) decribe data well at high p_T
- For low p_T, CGC-based approach needed

Particle production vs multiplicity

- Different collision systems allow for the disentanglement of processes of different physical origin
- But: Small collision systems show collective and nuclear effects, reminiscent of those observed in heavy-ion collisions



Increase $\Longrightarrow$ multiplicity



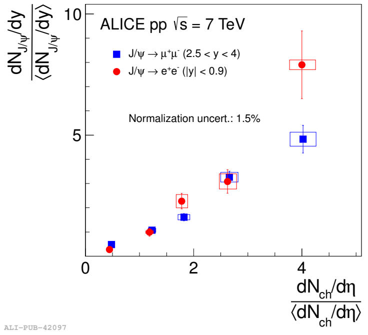
CMS, PLB 718 (2013) 795

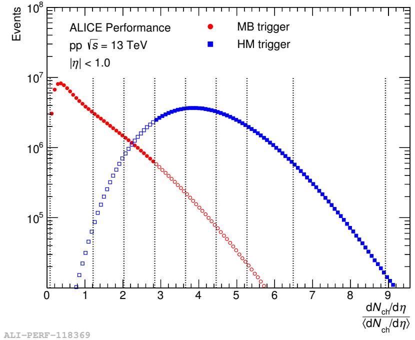
- J/ψ provides the perspective from the initial hard scattering

Multiplicity reach of J/ψ production in pp collisions

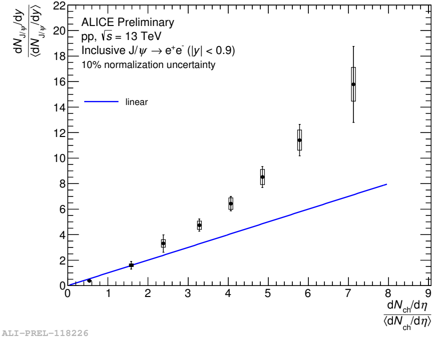
ALICE, PLB 712 (2012) 165

- Stronger than linear increase first observed at $\sqrt{s} = 7$ TeV
- Multiplicity reach almost doubled in 13 TeV data with dedicated high-multiplicity trigger



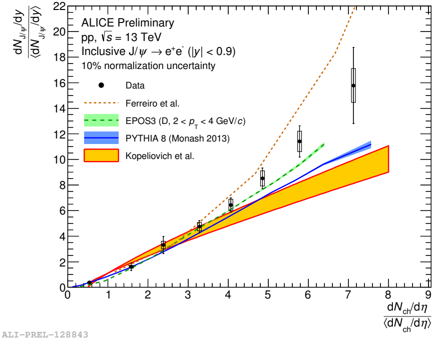


J/ψ production vs event multiplicity in pp collisions



- Stronger than linear increase more pronounced

J/ψ production vs event multiplicity in pp collisions



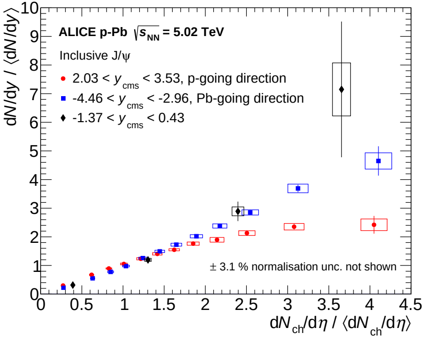
- Stronger than linear increase more pronounced
- Quantitative description of data by several models
  - Percolation
  - EPOS3
  - PYTHIA8.2
  - Higher Fock states

Ferreiro et al., PRC86 (2012) 034903
Werner et al., PRC89 (2014) 064903
Sjöstrand et al.,Comp. Phys. Comm. 191 (2015) 159
Kopeliovich et al.,PRD88 (2013) 116002

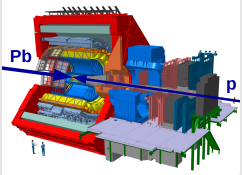
Multiplicity dependence vs rapidity in p-Pb collisions

ALICE, arXiv:1704.00274 [nucl-ex]

- Increase of J/ψ production at all rapidities with $dN_{ch}/dy/\langle dN_{ch}/dy \rangle$
- For $dN_{ch}/dy/\langle dN_{ch}/dy \rangle \gtrsim 2$, the trends start to differ

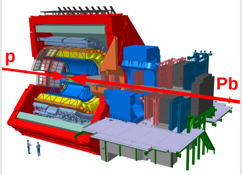


Pb-going side



- Similar to mid-rapidity

p-going side

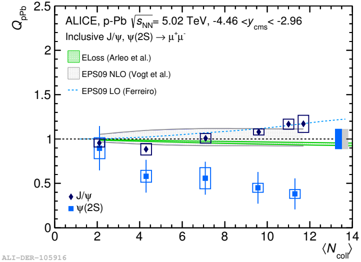


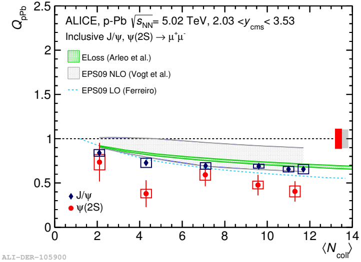
- Shadowing/saturation

$\Psi(2S)$ and J/ψ production in p-Pb collisions

ALICE, JHEP 06 (2016) 50

- Initial-state effects act nearly identical on ground and excited state
- $\Psi(2S)$ stronger suppressed than J/ψ
- J/ψ can be described by only shadowing or coherent energy-loss, while $\Psi(2S)$ cannot be described

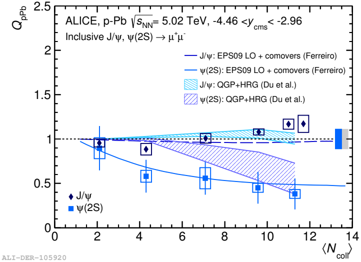


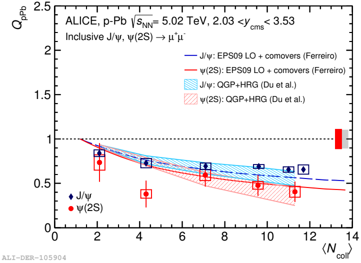


Ψ(2S) and J/ψ production in p-Pb collisions

ALICE, JHEP 06 (2016) 50

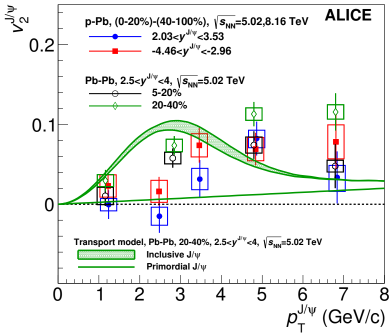
- Initial-state effects act nearly identical on ground and excited state
- Ψ(2S) stronger suppressed than J/ψ
- J/ψ can be described by only shadowing or coherent energy-loss, while Ψ(2S) cannot be described
- Additional mechanism needed to describe Ψ(2S)
- Models including final-state effects can describe the suppression





Collectivity in small vs large systems

ALICE, arXiv:1709.06807 [nucl-ex]



- In Pb–Pb collisions models could not describe high p_T flow
- For $p_T < 3$ GeV$/c$, p–Pb collisions show zero flow
- For $p_T > 3$ GeV$/c$, correlated component similar to Pb–Pb

- Common origin of high-p_T collective effects in small collision systems at high-multiplicity and heavy-ion collisions?

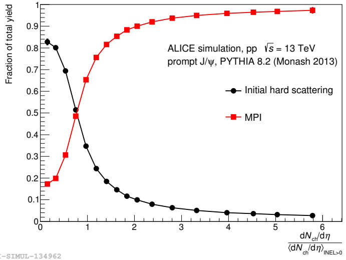
Summary

- We presented recent ALICE results on quarkonia production in pp, p–Pb and Pb–Pb collisions
- Quantitative description of data by models
  - Strong evidence for recombination in Pb–Pb collisions
  - In small collision systems strong increase of J/ψ production vs multiplicity
  - Unexpected suppression observed for Ψ(2S) in p–Pb collisions, which can be interpreted as final-state effects
- High-multiplicity pp or p–Pb collisions can help to answer open questions in heavy-ion collisions

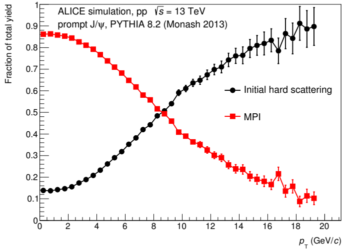
Backup

Monte Carlo studies

Pythia 8.2: Comput. Phys. Commun. 191 (2015) 159
Monash 2013: J. Eur. Phys. J. C (2014) 74: 3024



ALI-SIMUL-134962

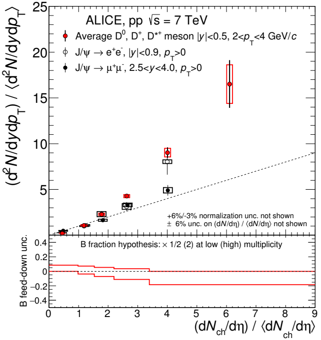


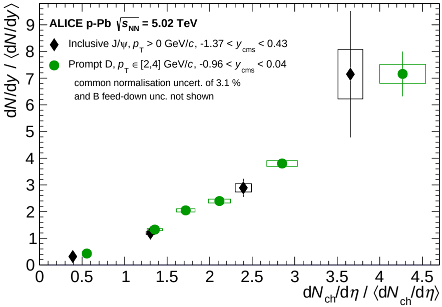
ALI-SIMUL-134966

- Contributions from initial hard scatterings dominate at low multiplicities and $p_T > 8$ GeV/c
- Multi-Parton Interactions dominate the high multiplicity regime

Open compared to hidden charm

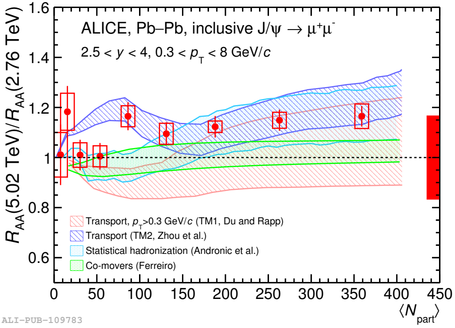
ALICE, JHEP 09 (2015) 148; arXiv:1704.00274 [nucl-ex]





- Similar trends observed for pp and p–Pb collisions for D mesons and J/ψ

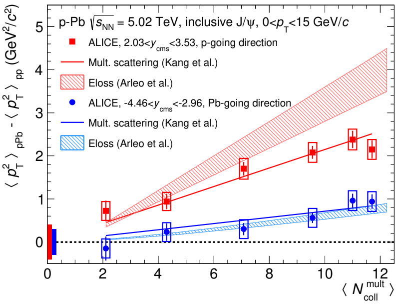
Charm cross sections used by different models

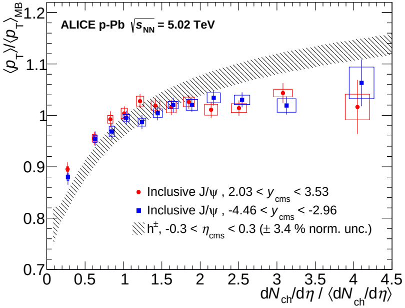


Model	$\sigma_{c\bar{c}}$ (mb)	Shadowing	Reference
SHM	0.45 ± 0.17	EPS09 NLO	NPA 789 (2007) 334
TM1	0.72 ± 0.13	EPS09 NLO	NPA 859 (2011) 114
TM2	0.86 ± 0.09	EPS09 NLO	PRC 89 (2014) 054911
Co-mover	0.56 ± 0.11	Glauber-Gribov	PLB 731 (2014) 57

Transverse momentum of J/ψ vs multiplicity

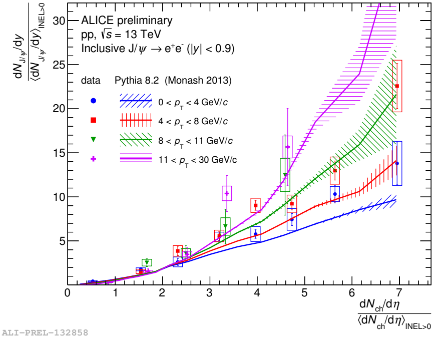
ALICE, JHEP 11 (2015) 127; arXiv:1704.00274 [nucl-ex]





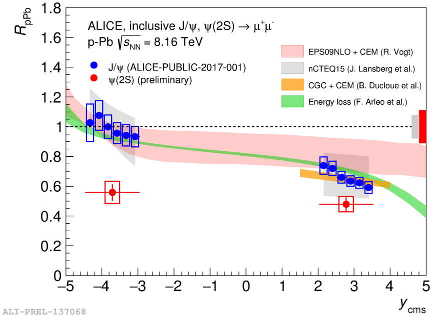
- p_T broadening in p-going and Pb-going side described by initial and final state multiple scattering
- Saturation of $\langle p_T \rangle$ sets in for $dN_{ch}/dy / \langle dN_{ch}/dy \rangle \gtrsim 2$, which corresponds to the maximum in the left plot

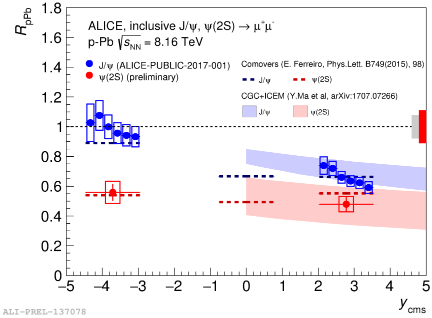
Multiplicity dependence for different p_T



- Increase p_T reach with calorimeter triggered events
- Indication for increased average J/ψ production with increasing p_T
- Qualitative behaviour described by Pythia8.2

J/ψ and $\Psi(2S)$ in p-Pb collisions at 8 TeV





Statistical Hadronisation Model

Andronic et al., NPA 789 (2007) 334

- Full screening before T_c
- Rapid hadronisation of (light or heavy) quarks at phase boundary

Transport Models

Zhao and Rapp, NPA 859 (2011) 114; Zhou et al., PRC89 (2014) 054911

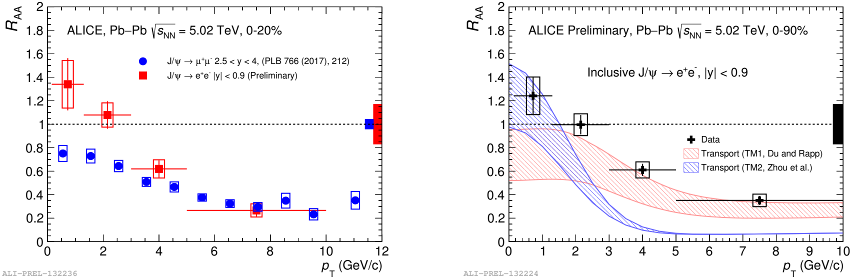
- Kinetic rate-equation approach in an evolving QGP
- Continous production and dissociation of Ψ already before T_c

Co-Mover Model

Ferreiro, PLB 731 (2014) 57

- Does not assume thermal equilibrium
- Interaction with comoving (hadronic or partonic) particles

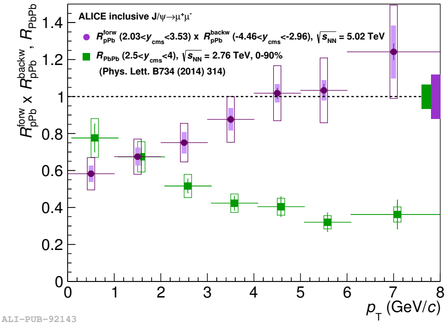
Nuclear modification vs transverse momentum



- Increase at mid-rapidity for low p_T supports recombination picture
- Transport models describe general behaviour, however show deviations at low or high p_T

Can cold nuclear matter effects describe the R_{AA}?

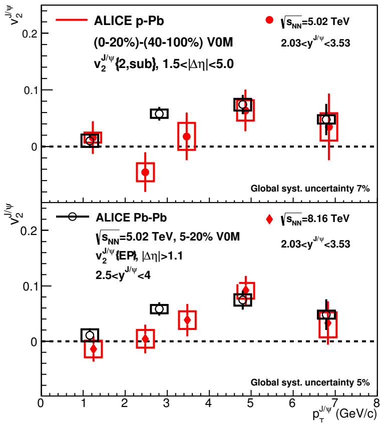
ALICE, JHEP 06 (2015) 55



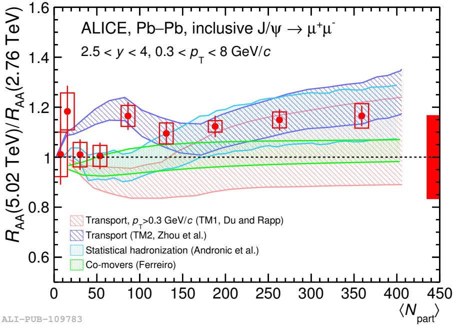
- CNM contribution $R_{AA}^{CNM} = R_{pA}(-y) \times R_{pA}(y)$
- CNM effects cannot explain the suppression at high p_T
- CNM alone would lead to a stronger suppression at low p_T
- This is consistent with a recombination picture

J/ψ v_2 in p–Pb and Pb–Pb collisions

ALICE, arXiv:1709.06807 [nucl-ex]



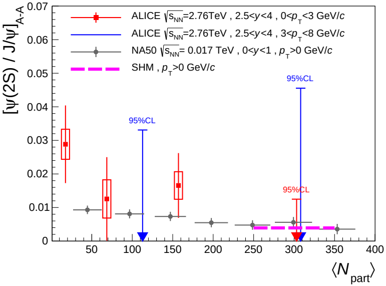
Ratio of R_{AA} at different collision energy

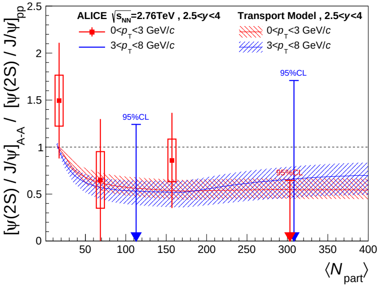


- Quantitatively a good description of the energy dependence
- Increase of R_{AA} with collision energy is strong evidence for recombination

$\Psi(2S)$ to J/ψ ratio in Pb-Pb collisions

ALICE, JHEP 05 (2016) 179



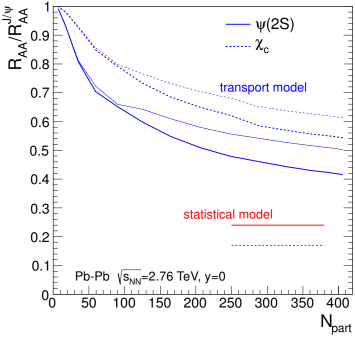


- Statistical hadronisation and transport models reproduce measured ratio
- Increased statistics from Run2 and Run3 will help to discriminate between the models

How to discriminate between the models?

Statistical model: Andronic et al., PLB 678 (2009) 350

Transport model: Zhao and Rapp, NPA 859 (2011) 114



- Excited charmonium states, e.g. $\psi(2S)$ and χ_c, can be used to discriminate between statistical and transport models
- Crucial to understand whether colourless bound states exist in the QGP