Quarkonia probes of QCD matter

Marzia Nardi

INFN Torino

Outline

Quarkonia (and heavy-flavour hadrons) are very importanti tools to study the properties of the matter produced in high-energy nuclear collisions.

- Create the probe, $Q\bar{Q}$ pairs ($Q = c, b$) are produced in hard interactions. They are studied in pp collisions: theoretical models are tested, free parameters are fitted to reproduce experimental data.
- Gauge the probe: once the $Q\bar{Q}$ pair is produced we must understand how it behaves in strongly interacting matter, pA collisions (cold nuclear matter, CNM)
- Use the probe: In AA collisions we have to separate CNM effects from QGP ones, to get the real signal.

Quarkonia in proton-proton collisions

$Q\bar{Q}$ production

Heavy-flavour production in pp collisions can be calculated with perturbative QCD (short distance, $q \sim m_Q$)

The binding of the heavy-quark pair into a quarkonium state is a non-perturbative process (long distances, $q \sim m_Q v, m_Q v^2$, $v \sim 0.3(c), 0.1(b)$).

In nearly all production models the idea of factorisation between short- and long-distance processes is assumed.

The comparison to experimental data provides an important testing ground for both perturbative and non-perturbative aspects of QCD calculations.

$Q\bar{Q}$ production: Color Evaporation Model (CEM)

The production cross section of quarkonia is connected to that to produce a $Q\bar{Q}$ pair in an invariant-mass region where its hadronisation into a quarkonium is possible, that is between the kinematical threshold to produce a quark pair, $2m_Q$, and that to create the lightest open-heavy-flavour hadron pair, $2m_H$.
The cross section to produce a given quarkonium state Ψ is assumed to be proportional by a phenomenological factor F_Ψ.
One assumes that a number of non-perturbative-gluon emissions occur once the $Q\overline{Q}$ pair is produced and the pair can change its quantum state (colour, spin).
Mathematically, one has

$$\sigma_\Psi^{(\mathrm{N})\mathrm{LO}} = F_\Psi \int_{2m_Q}^{2m_H} \frac{\mathrm{d}\sigma_{Q\overline{Q}}^{(\mathrm{N})\mathrm{LO}}}{\mathrm{d}m_{Q\overline{Q}}} \mathrm{d}m_{Q\overline{Q}} \tag{1}$$

No prediction for polarisation observables.

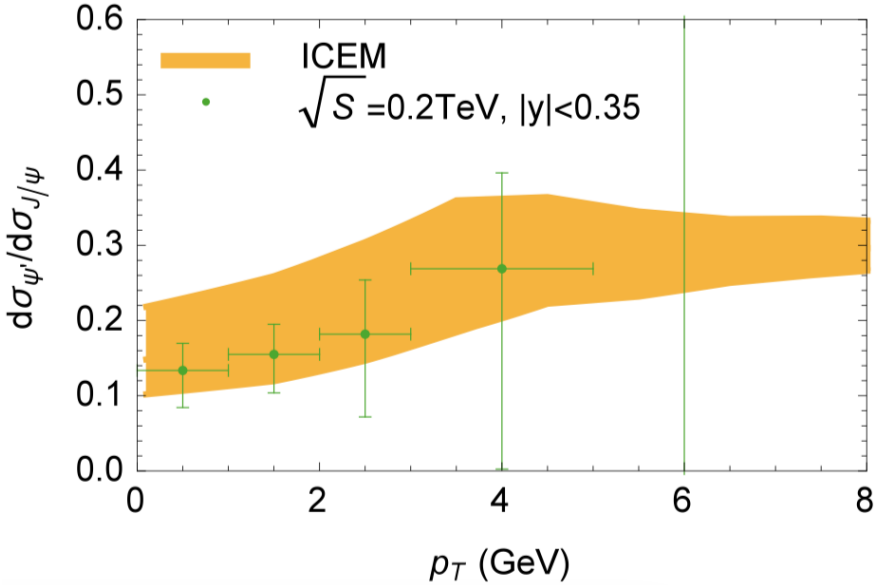
$Q\bar{Q}$ production: Improved Color Evaporation Model (ICEM)

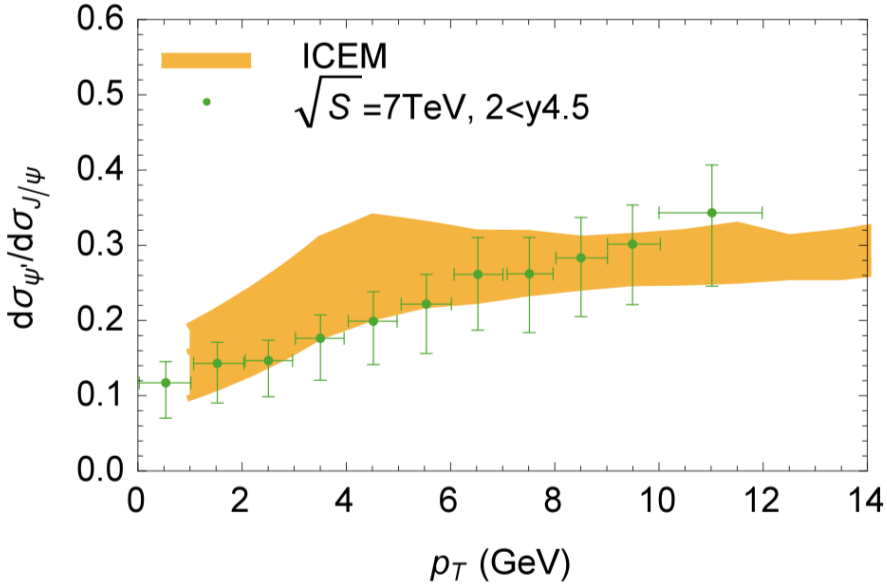
Ma & Vogt, PRD94 (2016) 114029

New constraint: invariant mass of the intermediate heavy quark-antiquark pair must be larger than the mass of produced quarkonium.

The momenta of the heavy quark-antiquark pair and of the quarkonium are correlated.

As a result, the $\psi'/(J/\psi)$ ratio is no longer constant!





Data: PHENIX (PRD 85, 092004) and LHCb (EPJC 72, 2100)

$Q\bar{Q}$ production: Color Singlet Model (CSM)

The $Q\bar{Q}$ pair is created in an octet state and emits a gluon to get into a colour-singlet state, after that it does not change its quantum numbers (spin, colour) in the hadronisation process.

It is assumes that the quarkonia are non-relativistic bound states with a highly peaked wave function in the momentum space.
No free parameters: very high predictive power.
Possibly due to its high predictive power, the CSM has faced several phenomenological issues although it accounts reasonably well for the bulk of hadroproduction in a wide range of energies, but it has some problem with p_T distributions.
NLO and approximate NNLO contributions improved the agreement[1]. A full NNLO computation ($\sim \alpha_s^5$) is needed.

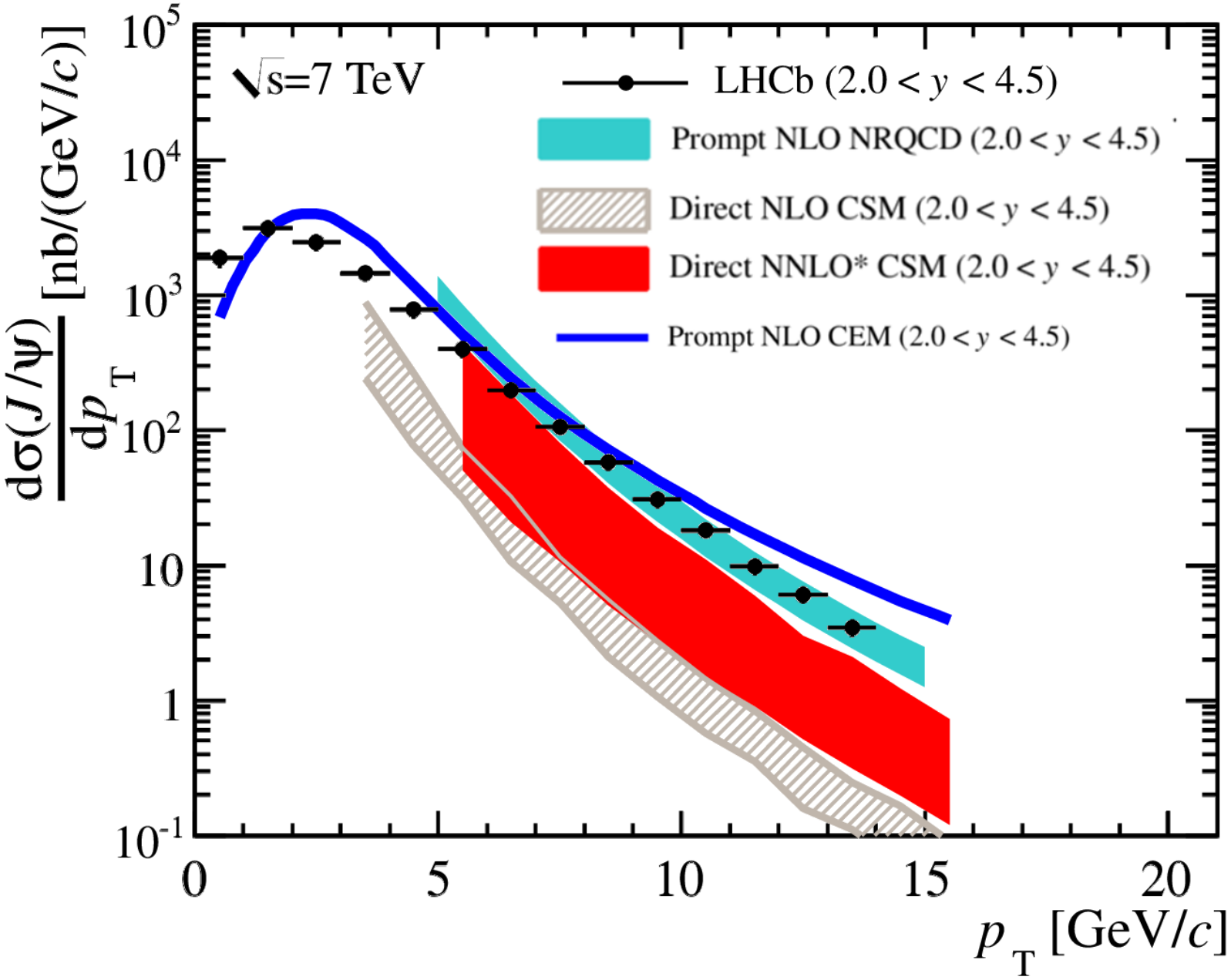
[1] Lansberg PLB 695 (2011) 149; JPG 38 (2011) 124110

$Q\bar{Q}$ production: Color Octet Model and nrQCD

Based on the effective theory NRQCD, assuming factorisation of soft and hard scales.
The hadronisation probability of a heavy-quark pair into a quarkonium is expressed in a rigorous way via long-distance matrix elements.

In addition to the usual expansion in powers of α_s, NRQCD further introduces an expansion in v.

It accounts for the effect of higher-Fock states where the $Q\bar{Q}$ pair is in an octet state with a different angular-momentum and spin states.
Non-perturbative transitions between these coloured states and the physical meson.
Many parameters: weaker predictive power



Sapore Gravis Review `arXiv:1506.03981`

Quarkonium polarization

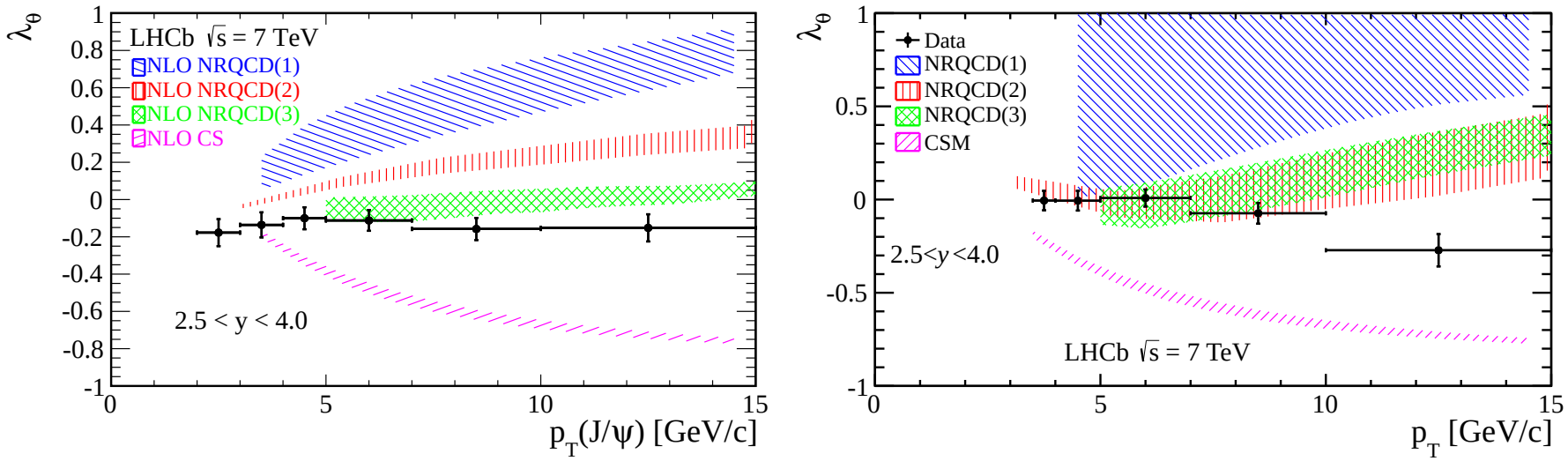
Polarization of a vector quarkonium state is analysed experimentally via the angular distribution of the leptons from the quarkonium dilepton decay:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}(\cos\theta)\mathrm{d}\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$

θ is the polar angle between the positive lepton in the quarkonium rest frame and the chosen polarization axis and ϕ angle is the corresponding azimuthal angle defined with respect to the plane of colliding hadrons.

λ_θ, λ_ϕ and $\lambda_{\theta\phi}$, are the polarization parameters.

Unpolarised yield: $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0, 0, 0)$
fully transverse polarization: $(1, 0, 0)$
fully longitudinal polarization: $(-1, 0, 0)$



Polarization parameter λ_θ for prompt J/Ψ (a) and ψ'(b) from LHCb compared to different model predictions: direct NLO CSM and three NLO NRQCD calculations at $2.5 < y < 4.0$ in the helicity frame.

Sapore Gravis Review: arXiv:1506.03981

Quarkonia in proton(deuteron)-nucleus collisions

Proton-nucleus collisions are a suitable tool to study the behaviour of $Q\bar{Q}$ pairs in Cold Nuclear Matter (CNM).

The production of heavy quarks and of quarkonia in p-A (d-A) is modified with respect to p-p collisions: modification of parton distributions, multiple scattering (before and after the hard scattering), absorption of quarkonium states in the medium...

Cold Nuclear Matter effects take place in p-A and in A-A collisions,

A careful analysis of proton-nucleus collisions and different systems of nucleus-nucleus collisions (different A) is necessary to disentangle CNM from QGP effects.

Typical time-scales of heavy-quark hadron and quarkonium production processes in p-A collisions:

- Coherence time, or the time to produce a $Q\bar{Q}$ pair : $\tau_c \sim 1/m_{Q\bar{Q}} \lesssim 0.1\,\mathrm{fm}/c$ in the $Q\bar{Q}$ rest frame. In the rest frame of the target nucleus it is Lorentz dilated and it can be larger than the nuclear size: shadowing effects.
- formation time, needed by the $Q\bar{Q}$ pair to form the quarkonium wave function. As an estimate (uncertainty principle) : $\tau_\mathrm{f} \sim (m_{2S} - m_{1S})^{-1}$ ~0.3–0.4 fm/c. In the nucleus rest frame, t_f, becomes much larger than the nuclear size at the LHC. Consequently the quarkonium state is produced far outside the nucleus and should not be sensitive to nuclear absorption.
- time needed for the $Q\bar{Q}$ pair to turn into a colour singlet state.
  - In the CSM: emission of a perturbative gluon (τ_c).
  - In the NRQCD and CEM : soft process(τ_f).

The usual way to quantify CNM effects is through the nuclear modification factor

$$R_{pA}^{\mathcal{C}} = \frac{N_{pA}^{\mathcal{C}}}{\langle T_{pA} \rangle_{\mathcal{C}} \; \sigma_{pp}} \, .$$

Without a selection on centrality ($A =$ nuclear mass number):

$$R_{pA} = \frac{\sigma_{pA}}{A \; \sigma_{pp}} \, .$$

The nuclear dependence of a centrality-integrated hard cross section p-A is sometimes parametrised by α defined as

$$\sigma_{pA} = \sigma_{pp} \, A^{\alpha},$$

In the absence of CNM effects:

$$R_{pA} = 1 \qquad \text{and} \qquad \alpha = 1.$$

Modified Parton Distribution Functions

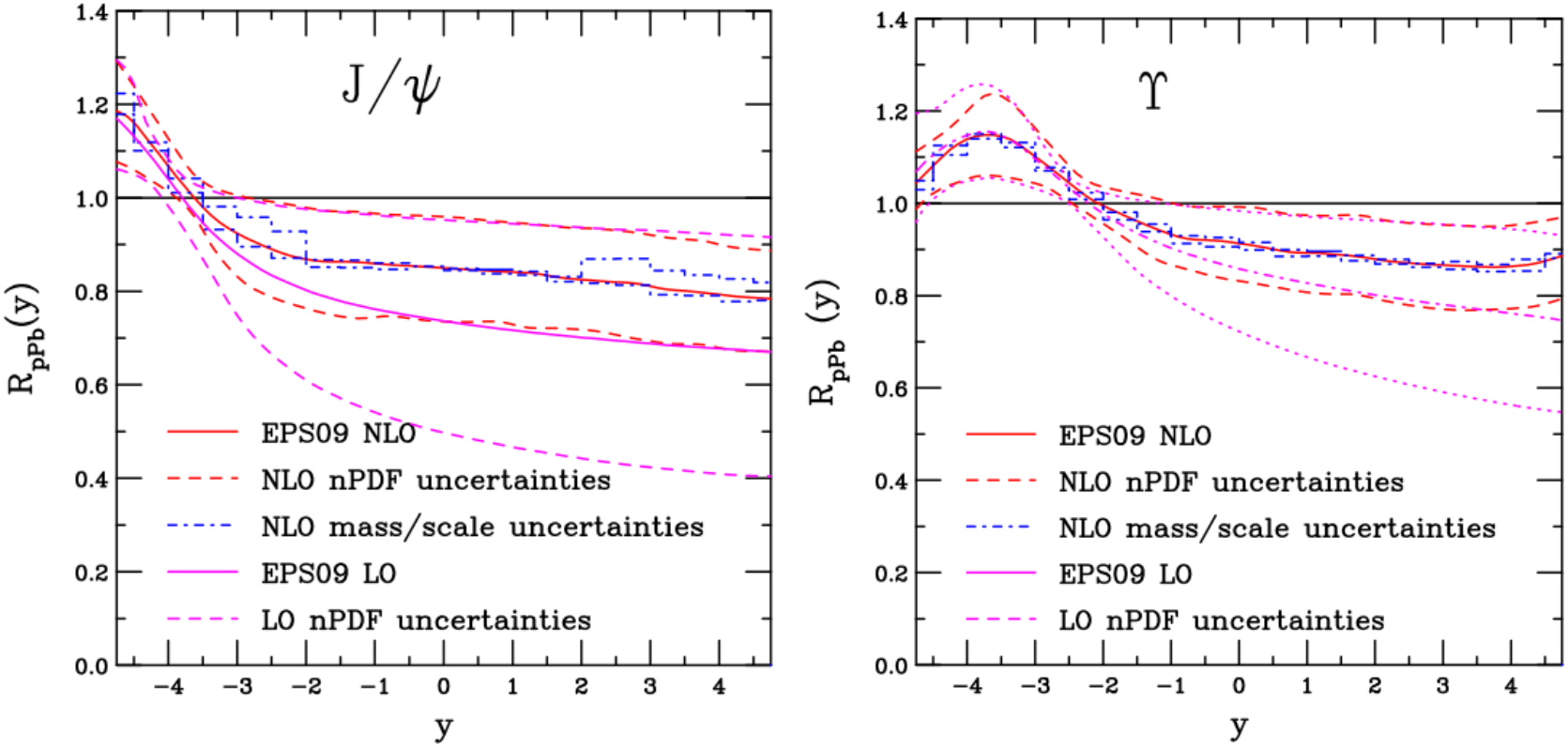
Modification of the effective partonic density in the nucleons of the colliding nuclei with respect to colliding protons, due to the different dynamics of partons.

These effects depend on x and on the scale of the parton–parton interaction Q^2 .

In collinearly-factorised pQCD calculations the nuclear effects on the parton dynamics are described in terms of nuclear-modified PDFs (nPDF).

Shadowing: $x \lesssim 10^{-2}$
Anti-shadowing: $10^{-2} \lesssim x \lesssim 10^{-1}$
EMC effect: $x \gtrsim 10^{-1}$

The physics of *parton saturation* at small x can be also described within the Colour Glass Condensate (CGC) theoretical framework. Unlike the nPDF approach, which uses DGLAP linear evolution equations, the CGC framework is based on the Balitsky-Kovchegov or JIMWLK non-linear evolution equations.



Sapore Gravis Review: arXiv:1506.03981

CGC and CEM

Ducloué, Lappi, Mäntysaari, Nucl.Part.Phys.Proc. 289-290 (2017) 309

Nuclear modification of forward J/Ψ (and D meson) production in high energy proton-nucleus collisions at the LHC in the CGC formalism.
For the hadronization the CEM is assumed.

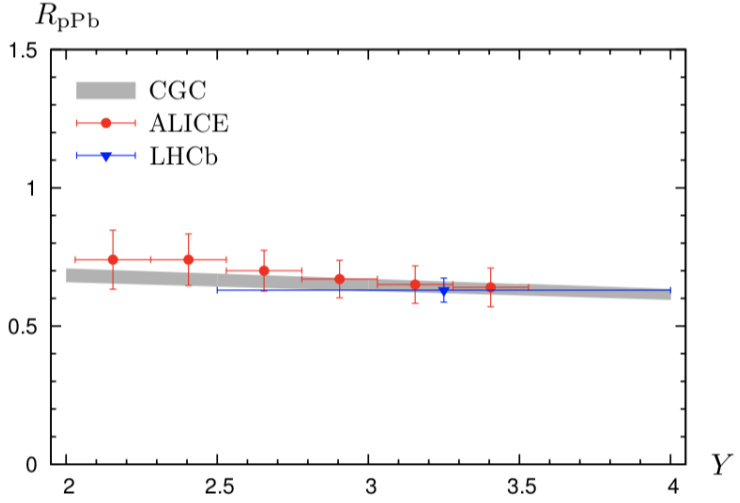


Figure 1: Nuclear modification factor for J/ψ production as a function of Y. Data from Refs. [19, 20].

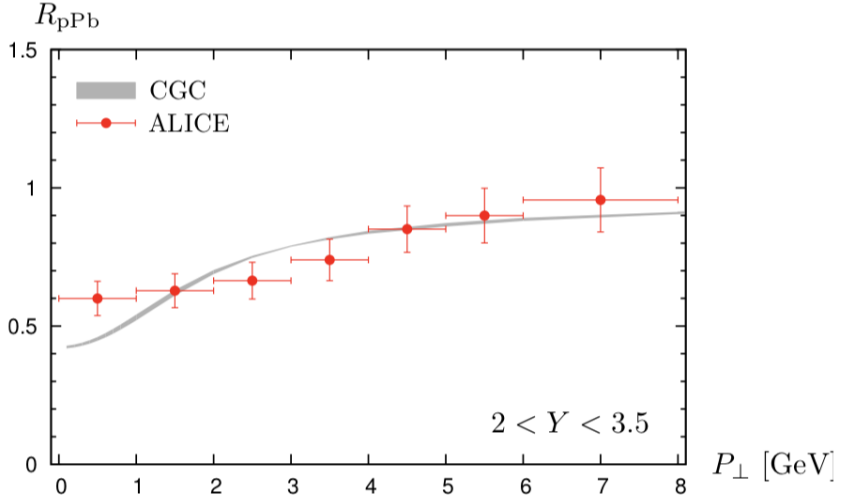


Figure 2: Nuclear modification factor for J/ψ production as a function of $P_\perp$ ($2 < Y < 3.5$). Data from Ref. [19].

Energy Loss

The partons suffers multiple scattering in the nucleus (before and after the hard collision), loosing some energy, causing a reduction of the quarkonium production at large longitudinal momenta; the transverse momentum increases (Cronin effect).
These effects are studied by several groups:

- Kopeliovich et al. , PRC 83 (2011)014912; NPA 864 (2011) 203
- Vitev et al, PRD 74 (2006) 054010

Nuclear absorption

The quarkonium nuclear absorption is characterized by an effective cross-section σ_{abs}.

In an extensive analysis of p-A data on J/ψ production[2], with several nPDF parametrizations, σ^{ψ}_{abs} (at $x_F \simeq 0$) is found to depend on $\sqrt{s_{NN}}$, but it is almost independent of the chosen nPDF.

Away from mid-rapidity, the extracted σ^{ψ}_{abs} grows with x_F up to unrealistically large values.
Comover absorption?

One expects nuclear absorption effects to become negligible at the LHC since the quarkonium formation time becomes significantly larger than the nuclear size at all values of the rapidity.

[2] C.Lourenco et al, JHEP 0902 (2009) 014

Quarkonium in nucleus-nucleus collisions

Suppression...

In nucleus–nucleus collisions, quarkonium production is expected to be suppressed as a consequence of the colour screening of the force that binds the $c\bar{c}$ or $b\bar{b}$ pair.

This suppression should occur sequentially, according to the binding energy of each state of the $c\bar{c}$ or $b\bar{b}$ families.

The in-medium dissociation probability of these states are expected to provide an estimate of the initial temperature reached in the collisions.

The sequential suppression pattern is complicated by several factors.
Feed-down decays of higher-mass resonances, and of b-hadrons in the case of charmonium, contribute to the observed yield of quarkonium states.

Furthermore, other hot and cold matter effects can play a role, competing with the suppression mechanism.

...and regeneration

At high energies, as at the LHC, the abundance of c and $\overline{c}$ quarks might lead to a new charmonium production source: the recombination of these quarks throughout the collision evolution[3] or at the hadronisation stage[4].

This mechanism is negligible for $b\bar{b}$ states, even at LHC energies.

$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos2\phi + \ldots$$

The second coefficient of the Fourier expansion of the azimuthal distribution, v_2, is called elliptic flow.
J/Ψ produced through a recombination mechanism, should inherit the elliptic flow of the charm quarks in the QGP, acquiring a positive v_2.

[3] R.Thews et al., PRC63 (2001) 054905
[4] P.Braun-Munzinger et al., PLB490 (2000) 196

Quarkonium production in A-A collisions is also affected by several effects related to cold matter, already discussed in p-A collsions:

- nPDF
- gluon saturation (CGC)
- parton energy loss
- nuclear absorption

The in-medium modification of quarkonium production is usually quantified through the nuclear modification factor

$$R_{AA} = \frac{N_{AA}^{Q\bar{Q}}}{\langle T_{AA} \rangle \cdot \sigma_{pp}^{Q\bar{Q}}}$$

R_{AA} is expected to equal unity if the AA collision behaves as a superposition of incoherent nucleon–nucleon interactions (direct γ, W, and Z) .
Such a scaling is assumed to approximately hold for the total charm cross section.
A value of R_{AA} different from unity implies that the quarkonium production in AA is modified with respect to a binary nucleon-nucleon scaling.
The nuclear modification factor is usually investigated in its rapidity and transverse momentum dependence, and in different centrality classes of the AA collisions.

The information from R_{AA} can be complemented by the study of the quarkonium azimuthal distribution with respect to the reaction plane, defined by the beam axis and the impact parameter vector of the colliding nuclei.

Sequential suppression

The QGP consists of deconfined colour charges, so that the binding of a $Q\bar{Q}$ pair is subject to the effect of colour screening which limits the range of strong interactions.
if $r_D \gg r_Q$, the medium does not really affect the heavy quark binding.
Once $r_D \ll r_Q$, however, the two heavy quarks separate.
It is therefore expected that (strongly bound) quarkonia will survive in a QGP through some range of temperatures above T_c, and then dissociate once T becomes large enough.

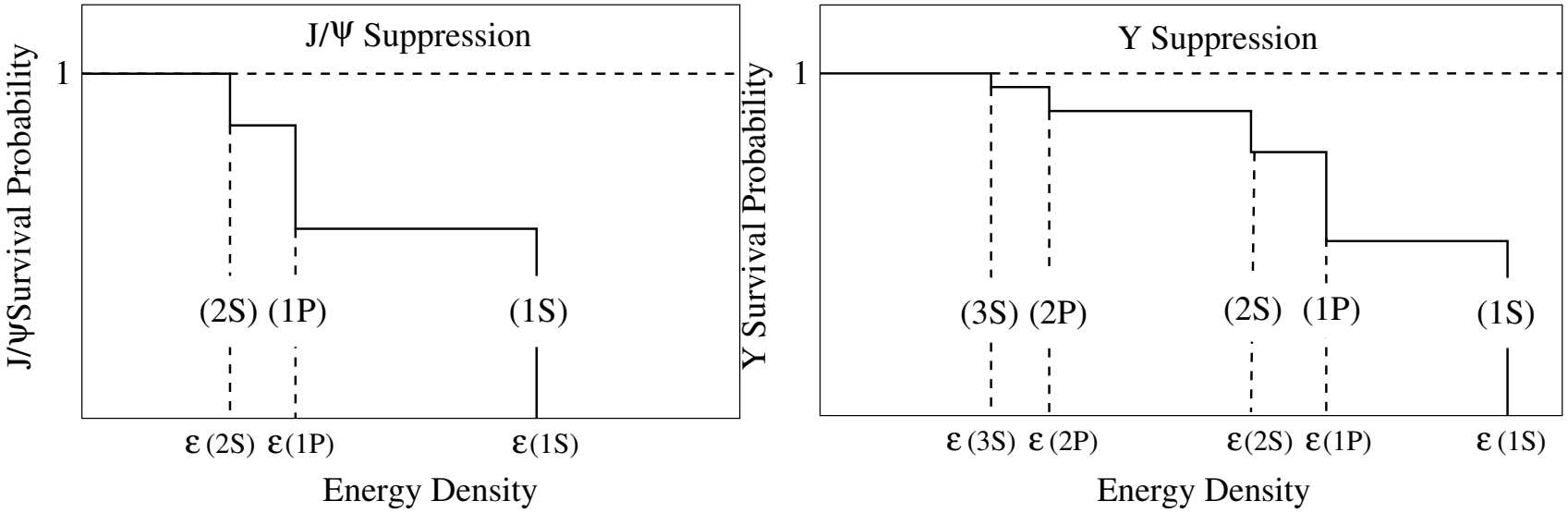
Finite-temperature lattice studies on quarkonium mostly consist of calculations of spectral functions for temperatures in the range explored by the experiments.
The spectral function $\rho(\omega)$ is the basic quantity encoding the equilibrium properties of a quarkonium state.
Bound or resonance states manifest themselves as peaks with well defined mass and spectral width.
The spectral functions appear in the (zero-momentum) Euclidean propagator:

$$G(\tau) = \int_0^\infty \rho(\omega) \frac{\mathrm{d}\omega}{2\pi} K(\tau, \omega) \quad \text{with} \quad K(\tau, \omega) = \frac{\left(e^{-\omega\tau} + e^{-\omega(1/T-\tau)}\right)}{1 - e^{-\omega/T}}$$

The calculation of $\rho(\omega)$ has been mostly performed by using the Maximum Entropy Method (MEM).

Sequential melting

The survival probability for a given quarkonium state depends on its size and binding energy, therefore the excited states will be dissolved at a lower initial temperature than the more tightly-bound ground states.
In the case of the J/Ψ however, only a fraction (about 60%) of the observed J/Ψ is a directly produced (1S) state, the remainder is due to the feed-down of excited states, with about 30% from χ_c(1P) and 10% from ψ' decays. A similar decay pattern arises for ϒ production.



[F. Karsch et al.,Phys. Lett. B637 (2006) 75 , hep-ph/0512239]

Statistical regeneration models

Heavy quarks are not produced thermally but only in initial hard scattering processes.
One can assume that charm quarks, formed in a high energy nuclear collision in initial hard scattering, find themselves colour-screened, therefore deconfined in a QGP, and hadronize with light quarks and gluons at the phase transition.[5]. At hadronisation open charm hadrons as well as charmonia are formed according to their statistical weights and the mass spectrum of charmed hadrons.

Since for each beam energy the values of T and μ_b are already fixed by the measured light hadron yields, the only additional input needed is the initial charm production cross section per unit rapidity in the appropriate rapidity interval. The conservation of the number of charm quarks is introduced in the statistical model via a fugacity g_c.
The statistical model reproduces the significant increase observed, for central collisions, in the J/Ψ R_{AA} from RHIC to the LHC.
The statistical hadronisation picture is a low p_T phenomenon.

[5] P. Braun-Munzinger et al., PLB490 (2000) 196; NPA 690 (2001) 119

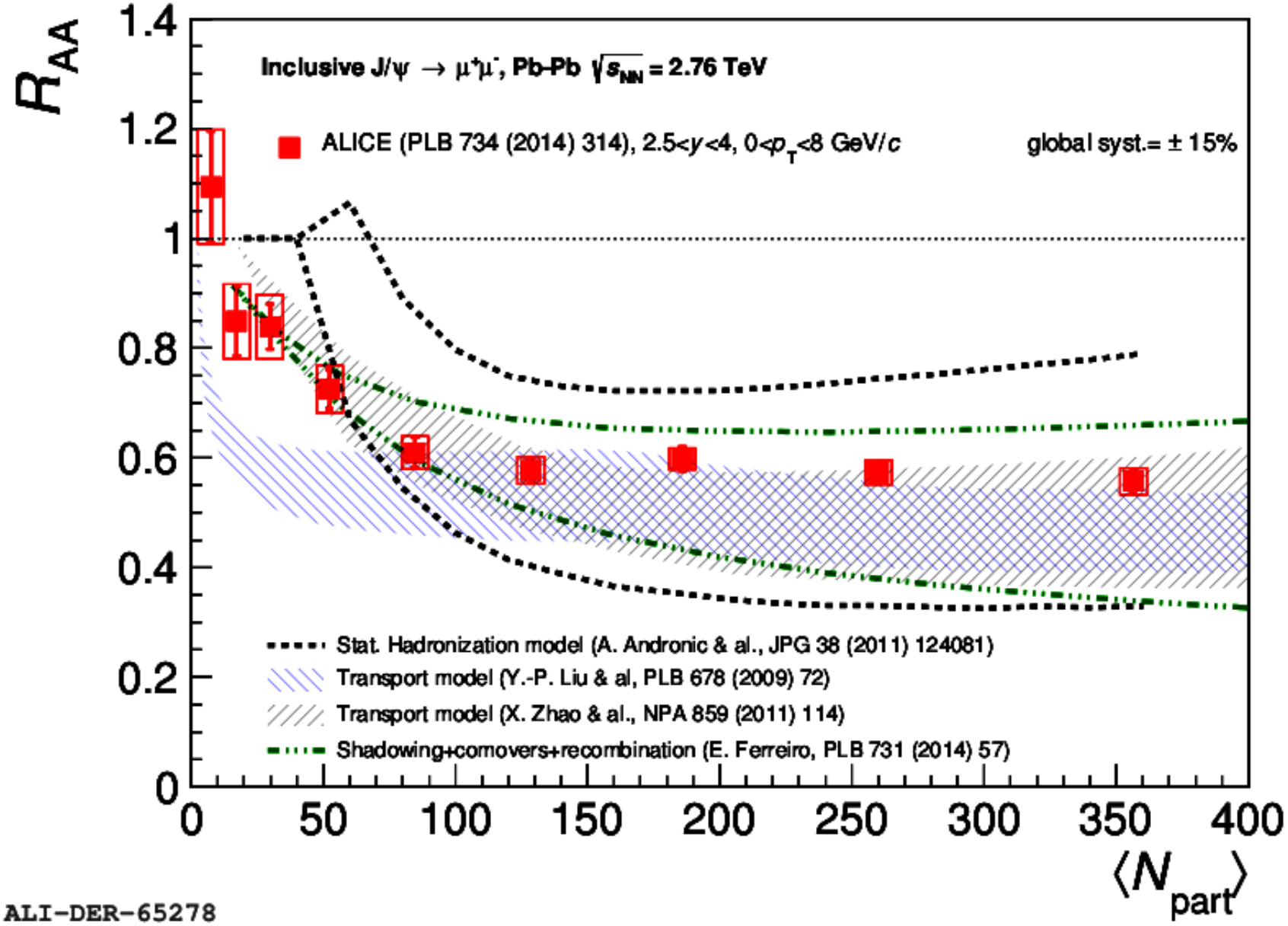
Transport approach for in-medium quarkonia

In the transport models, there is continuous dissociation and regeneration of quarkonia over the entire lifetime of the deconfined stage. The space-time evolution of the phase-space distribution, $f_{\mathcal{Q}}$, of a quarkonium state in hot and dense matter may be described by the relativistic Boltzmann equation.,

$$p^{\mu}\partial_{\mu} f_{\mathcal{Q}}(\vec{r},\tau;\vec{p}) = -E_p\ \Gamma_{\mathcal{Q}}(\vec{r},\tau;\vec{p})\ f_{\mathcal{Q}}(\vec{r},\tau;\vec{p}) + E_p\ \beta_{\mathcal{Q}}(\vec{r},\tau;\vec{p})$$

where $p_0 = E_p = (\vec{p}^2 + m_{\mathcal{Q}}^2)^{1/2}$, τ is the proper time, and $\vec{r}$ is the spatial coordinate. $\Gamma_{\mathcal{Q}}$ denotes the dissociation rate and the gain term, $\beta_{\mathcal{Q}}$, depends on the phase-space distribution of the individual heavy (anti-)quarks, $Q = c$, b in the QGP (or D, $\overline{\mathrm{D}}$ mesons in hadronic matter).
The key ingredients to the rate equation are the *transport coefficients*: the inelastic reaction rate, $\Gamma_{\mathcal{Q}}$, for both dissociation and formation, and the quarkonium equilibrium limit, $N_{\mathcal{Q}}^{\mathrm{eq}}(T)$.

Forward rapidity:



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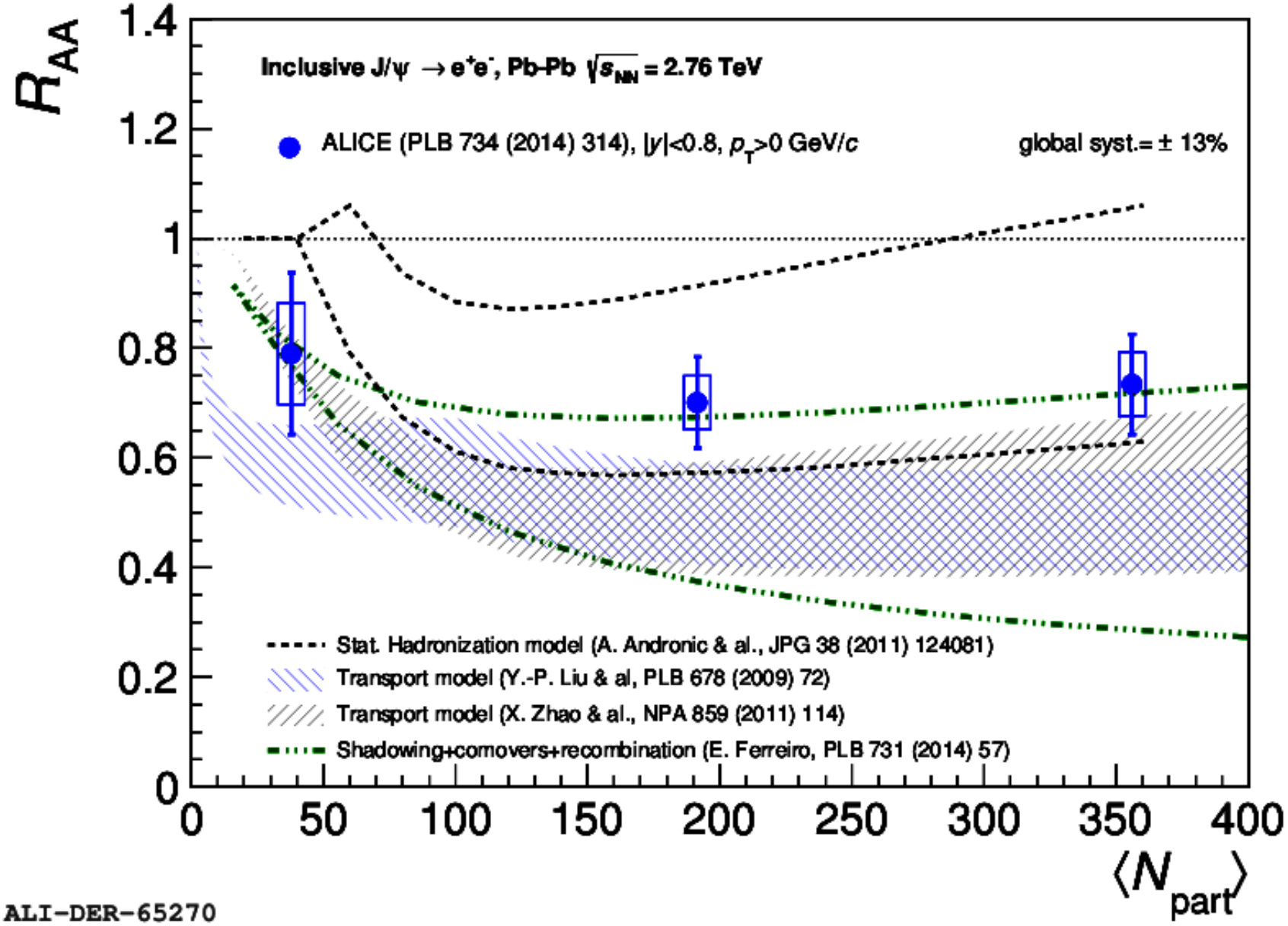
Central rapidity:



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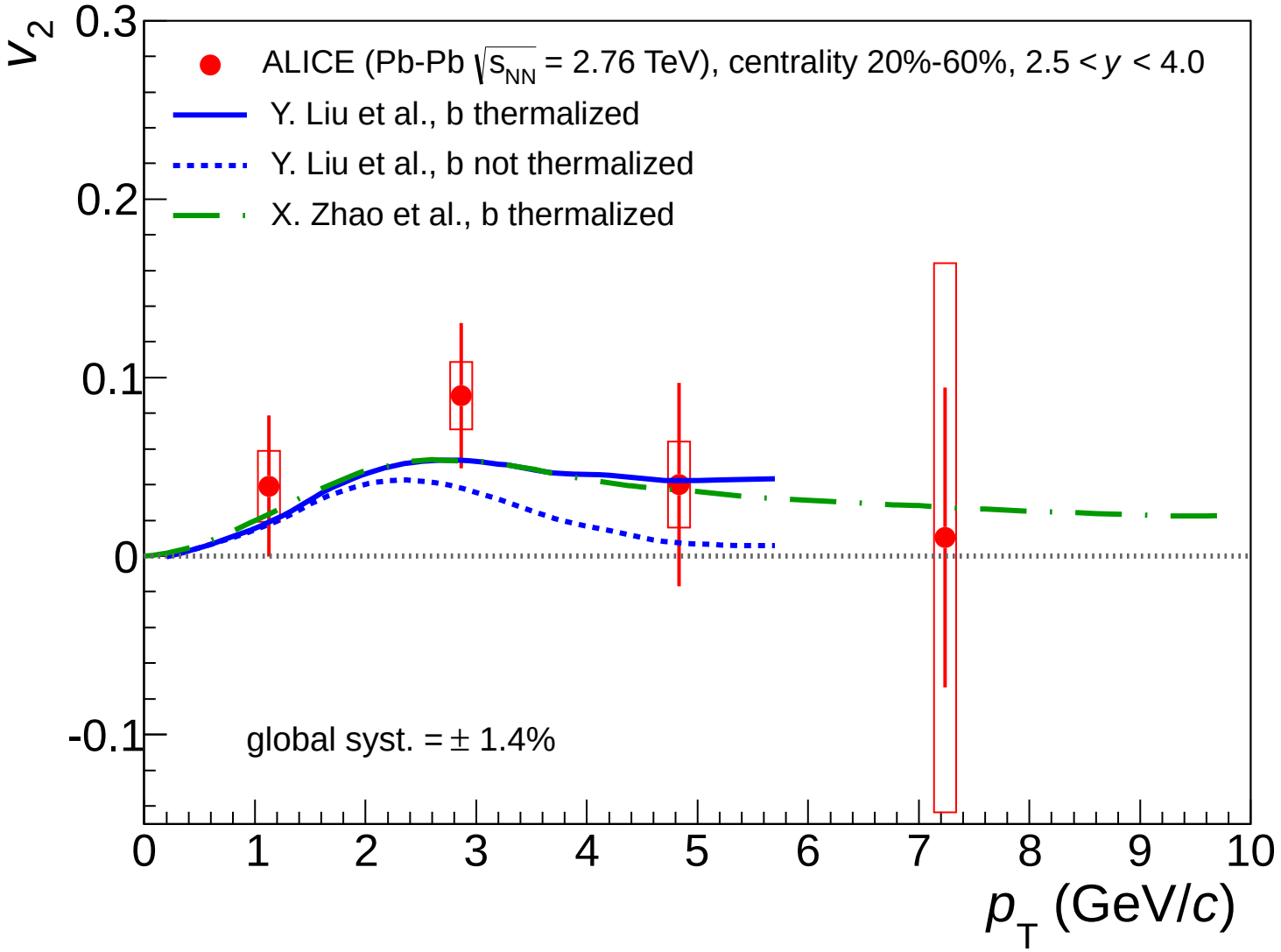
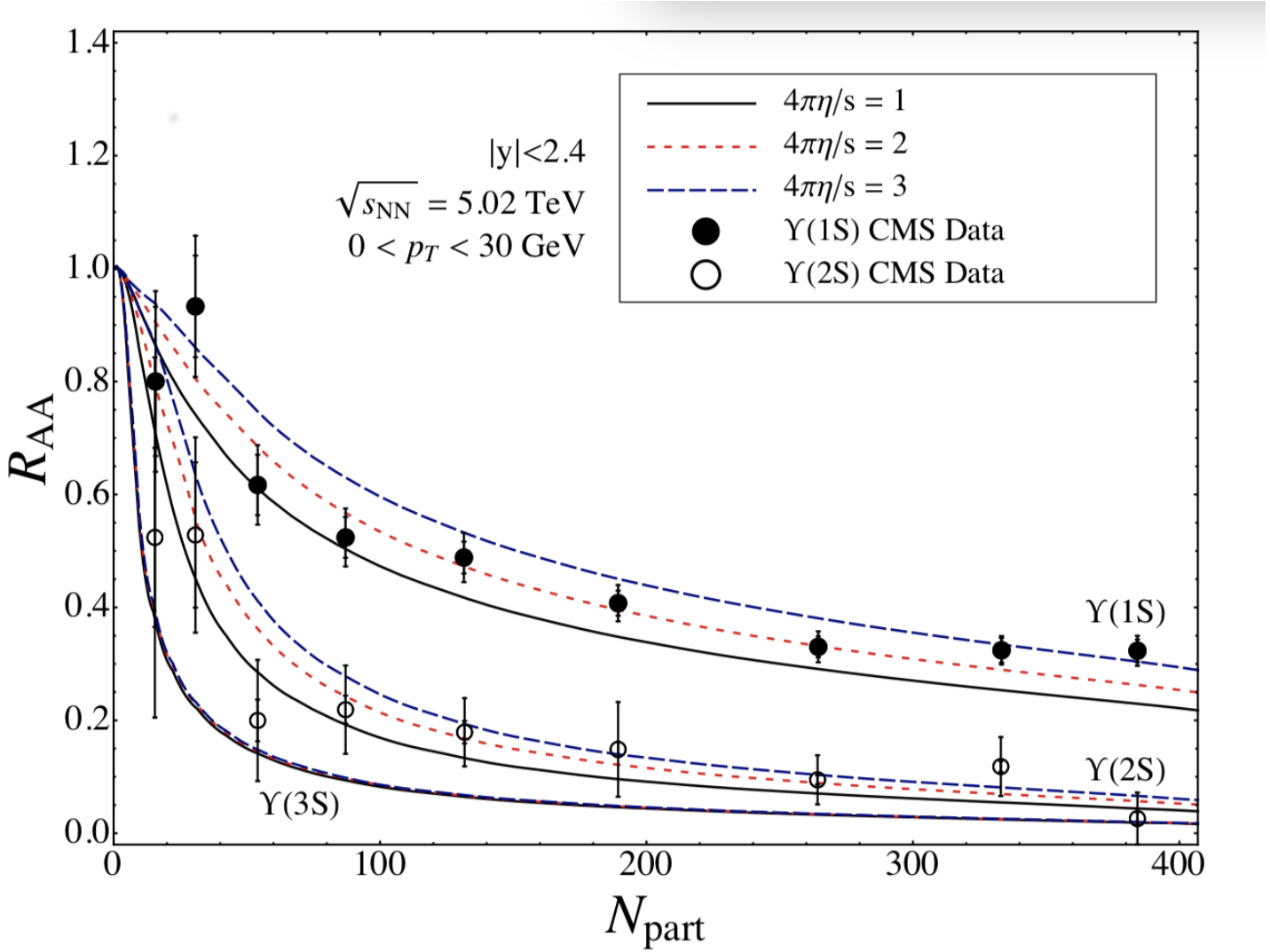
Elliptic flow:



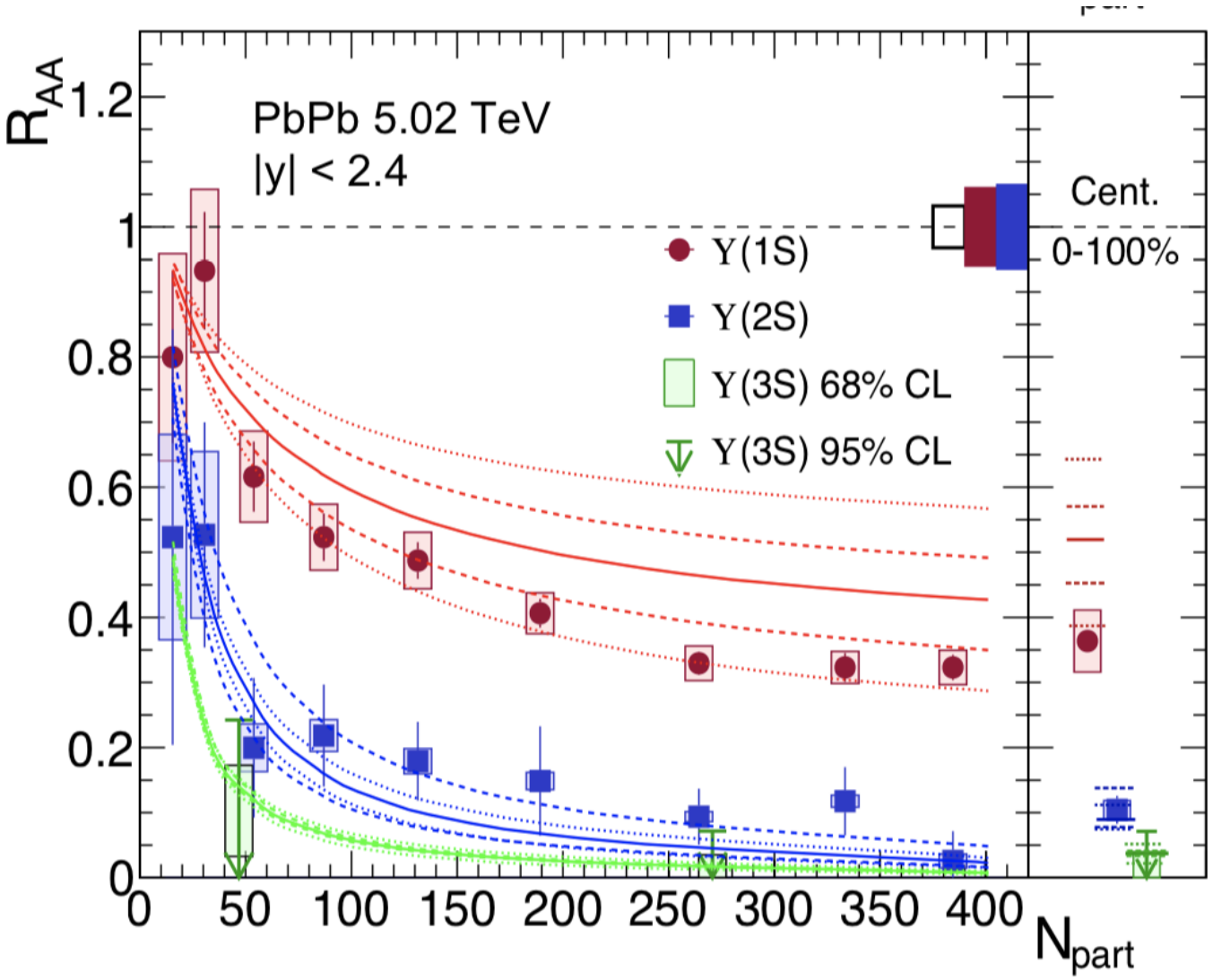
Recent results on Bottomonium[6]



Transport model with 3+1 d viscous hydrodynamical evolution.

[6] Krouppa et al., arXiv:1807.07452

Comover model[7]



[7] Ferreiro & Lansberg, arXiv:1804.04474

Conclusions

- On the p-p side, the quarkonium formation mechanism is not yet well under control.
  The usual models are partially successful, none of them is fully satisfactory.
  In particular the polarization issue has to be studied.
- For the p-A, we know the most imprtant CNM effects, but we need to work to separate their effects.
  More data with different nuclear beams and/or different energies.
- On the A-A, there is evidence for some extra effect w.r.t. p-A, i.e. final state suppression and regeneration.
  The J/Ψ elliptic flow indicates some degree of thermalization with the medium.
  Need to extend the available models and try to apply them to all observables.

There have been many improvements recently,
but a lot of work is still needed.