Quarkonium: theory overview

Is bottomonium suppression in proton-nucleus and nucleus-nucleus collisions at LHC energies due to the same effects?

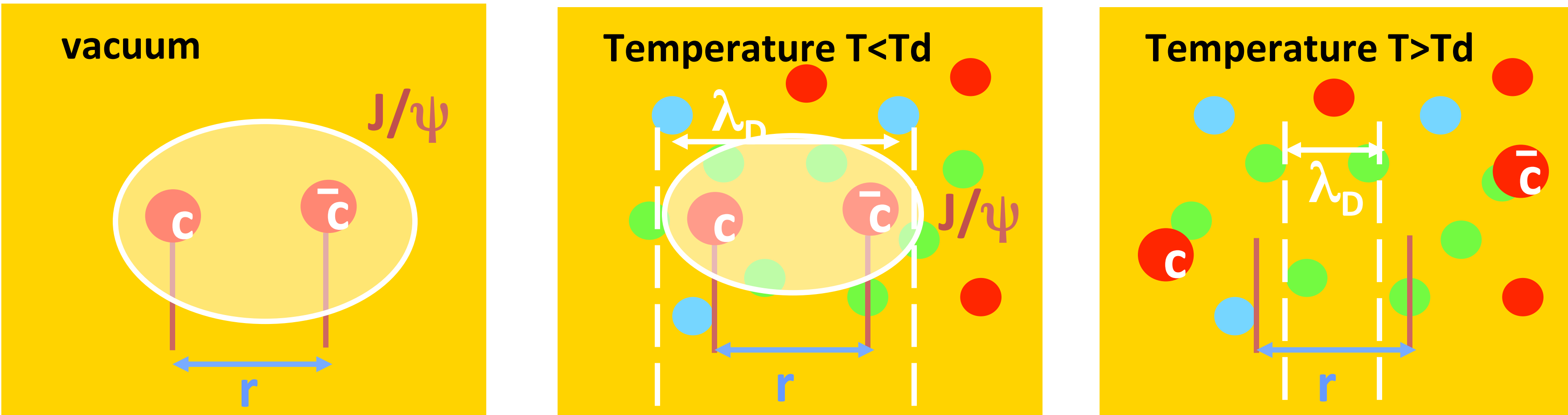
Elena G. Ferreiro

LLR, École polytechnique , France
IGFAE, Universidade de Santiago de Compostela, Spain

Why quarkonium?

The usual introduction: Debye screening $\lambda_D(T)$

Nice picture by Roberta Arnaldi



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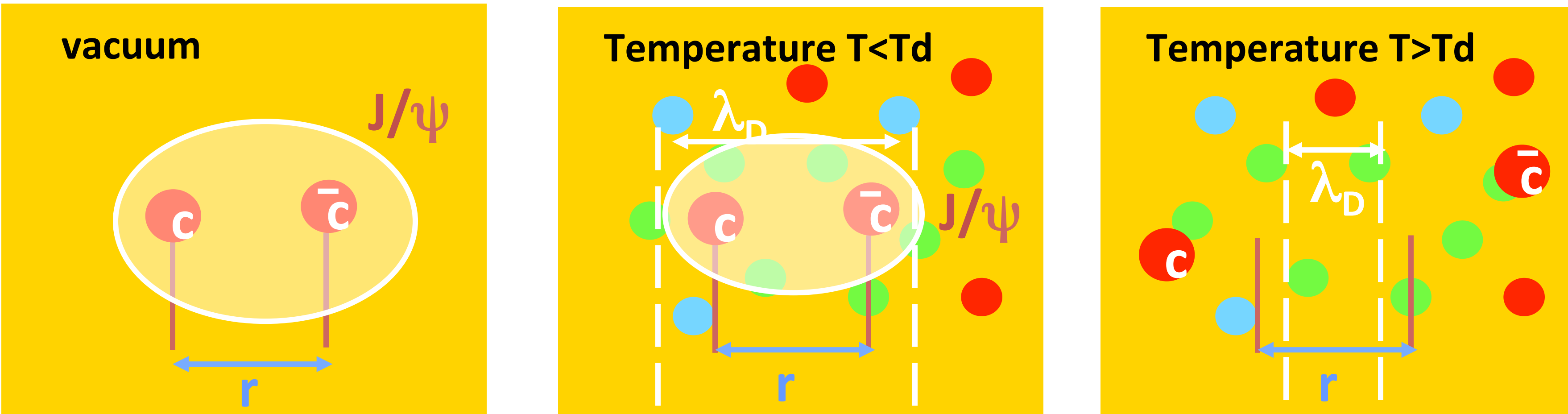
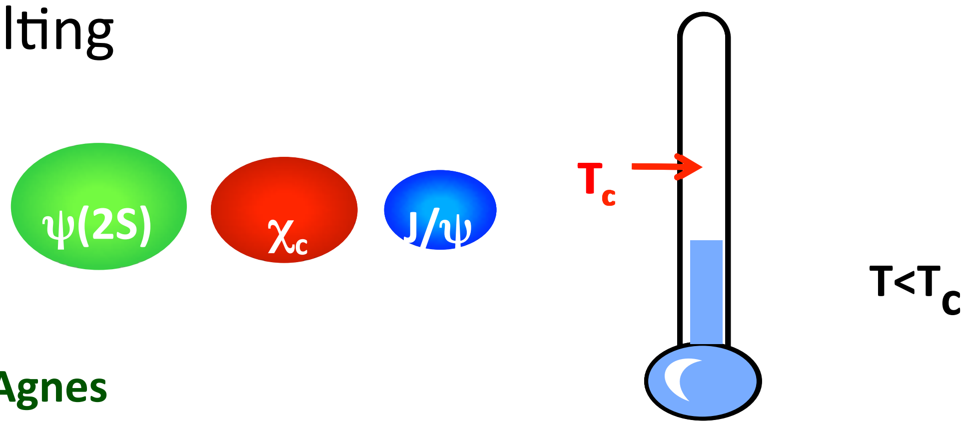


Sequential melting



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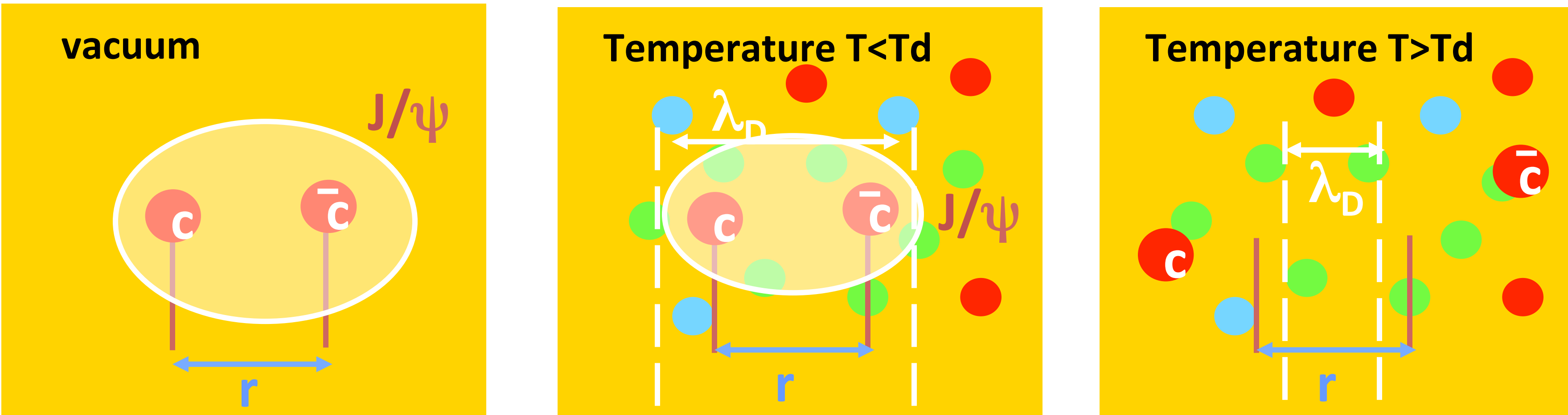

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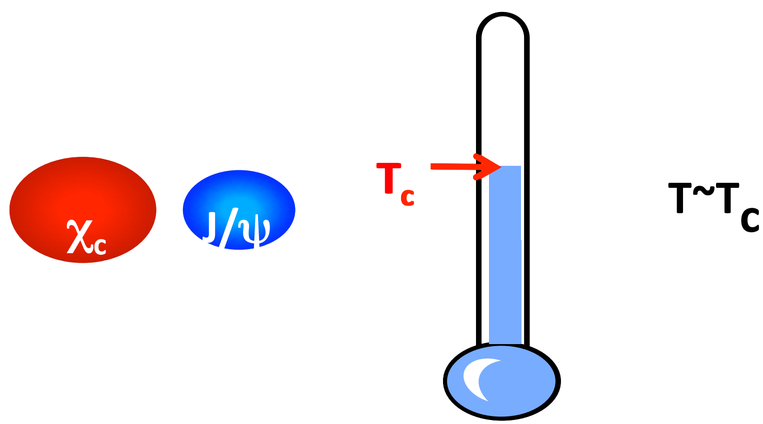

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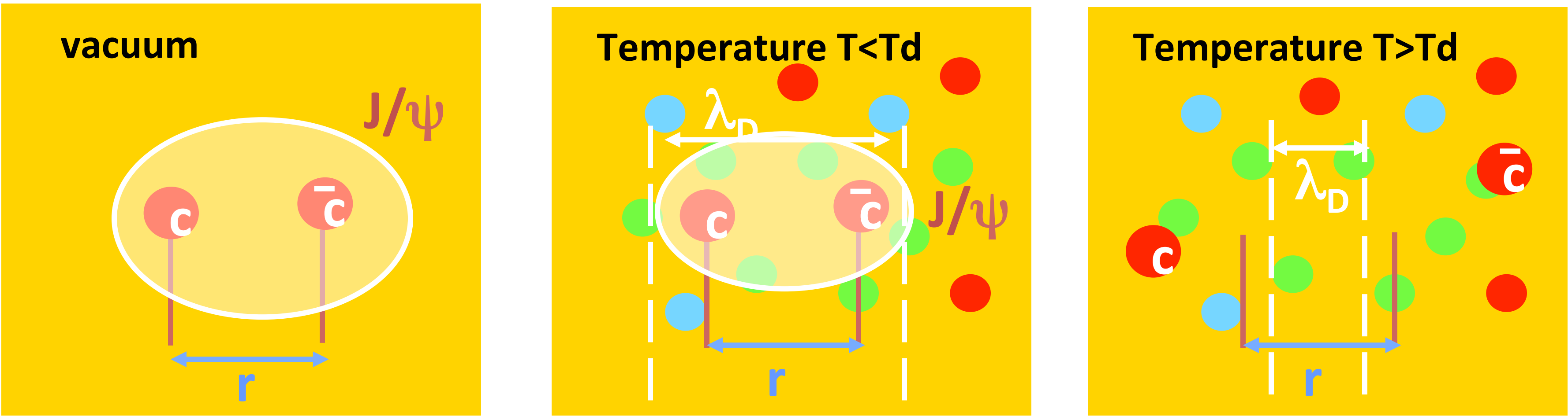

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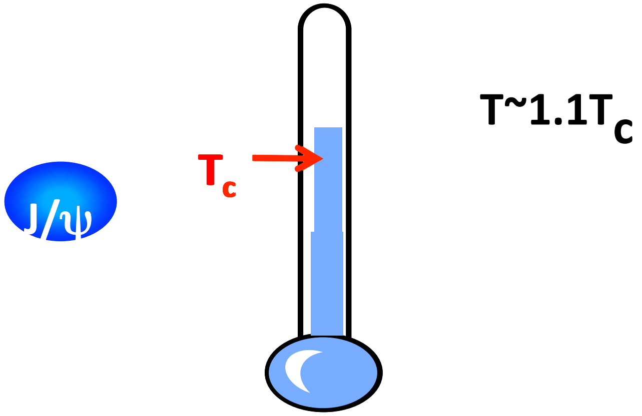

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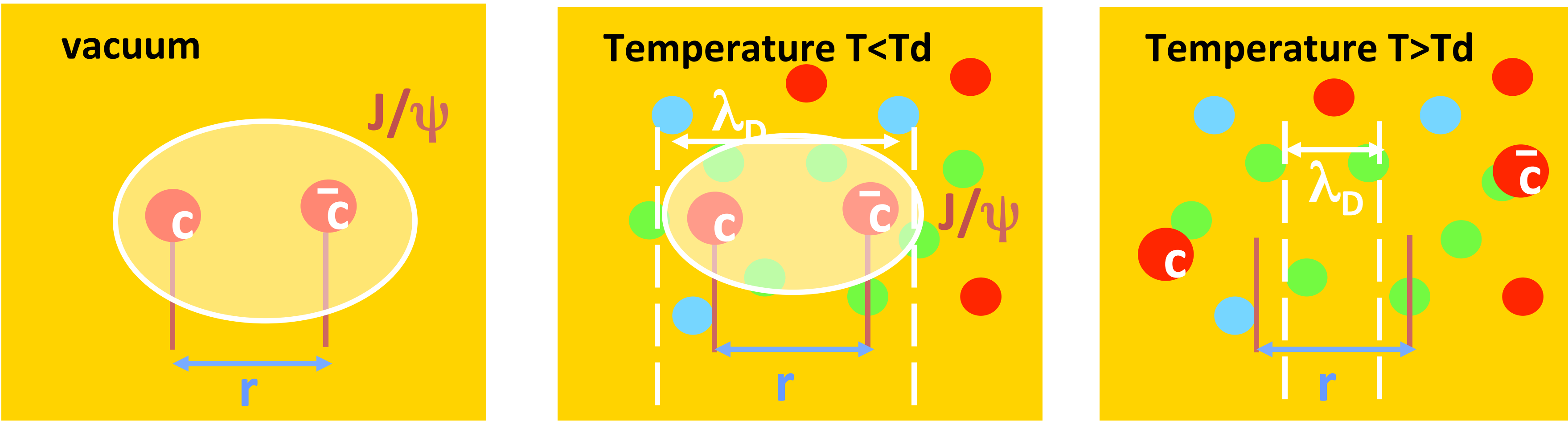

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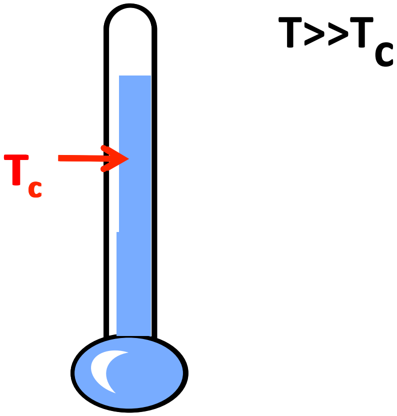

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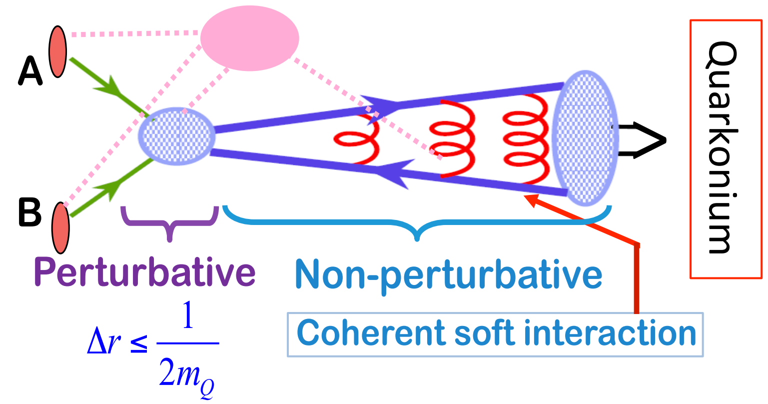
Sorry, but the nice picture is over…

Quarkonium production schemes in pp

Quarkonium production involves perturbative and non perturbative QCD

- Production of the heavy-quark pair, $Q\bar{Q}$: perturbative
- Evolution of the $Q\bar{Q}$ pair into the physical quarkonium state: non-perturbative



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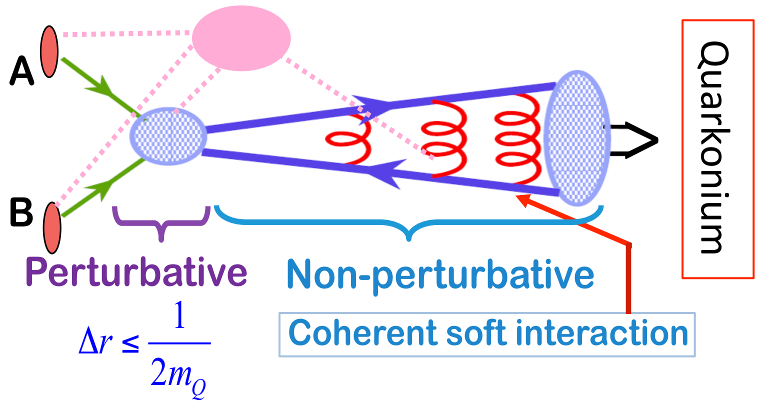

Different approaches to hadronization:

Color singlet model (CSM): 1975 -

Einhorn, Ellis (1975), Chang (1980), Berger & Jone (1981), …

- Assume physical color singlet state, quantum numbers are conserved
- Only the pair with right quantum numbers

Effectively no free parameter

Color evaporation model (CEM): 1977 -

Fritsch (1977), Halzen (1977), …

- Does not distinguish states with respect to their color and spin
- All pairs with mass less than open heavy flavor threshold

One parameter per quarkonium state

Nonrelativistic QCD (NRQCD): 1986 -

Caswell, Lapage (1986) Bodwin, Braaten, Lepage (1995), …

- Rigorous effective field theory based on factorization of soft and hard scales
- All pairs with various probabilities – NRQCD matrix elements

Infinite parameters – organized in powers of v and α_s

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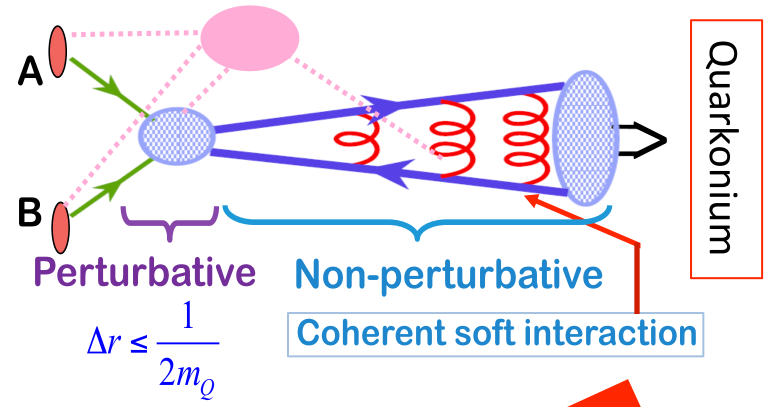

Different approaches to hadronization:

Production mechanism still not settled after more than 40 years!

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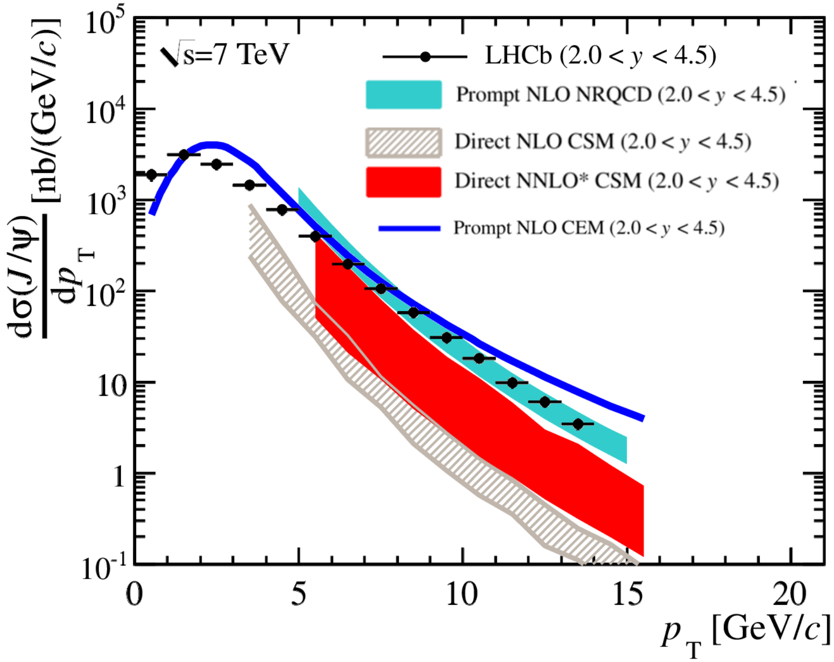
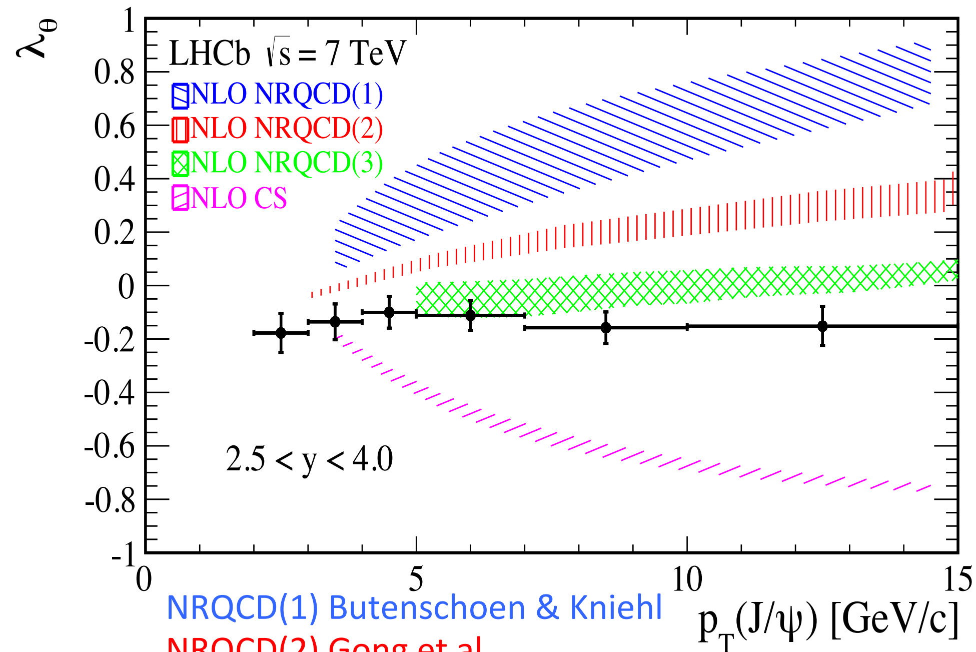
Production models: state of the art for the J/ψ



Sapore Gravis Review arXiv:1506.03981



NRQCD(1) Butenschoen & Kniehl
NRQCD(2) Gong et al.
NRQCD(3) Chao et al.

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Yet, fits differ in their conclusions owing to their assumptions (data set, p_T cut, polarization fitted or not)

At low and mid p_T –region where quarkonium heavy-ion studies are mainly carried out– none of the models can simply be ruled out due to theoretical uncertainties

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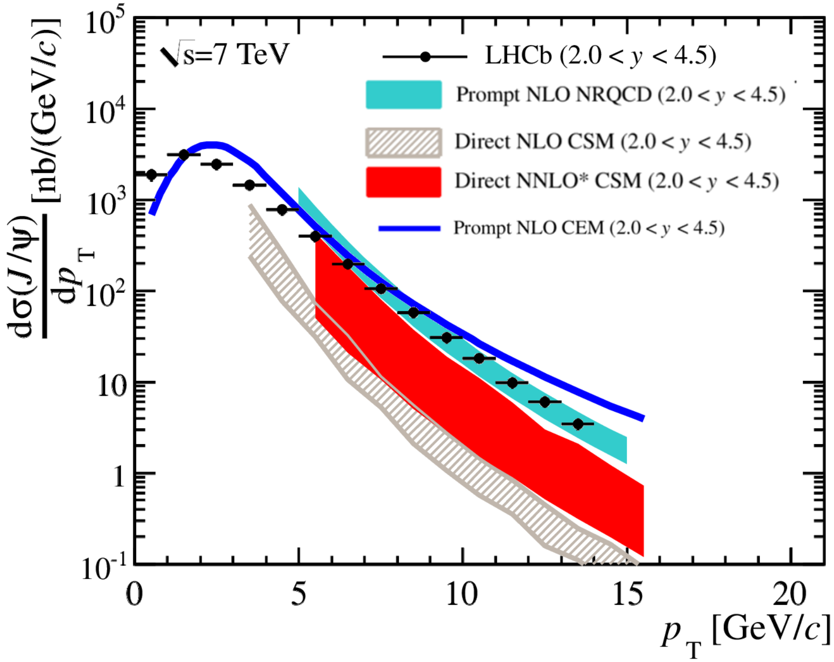

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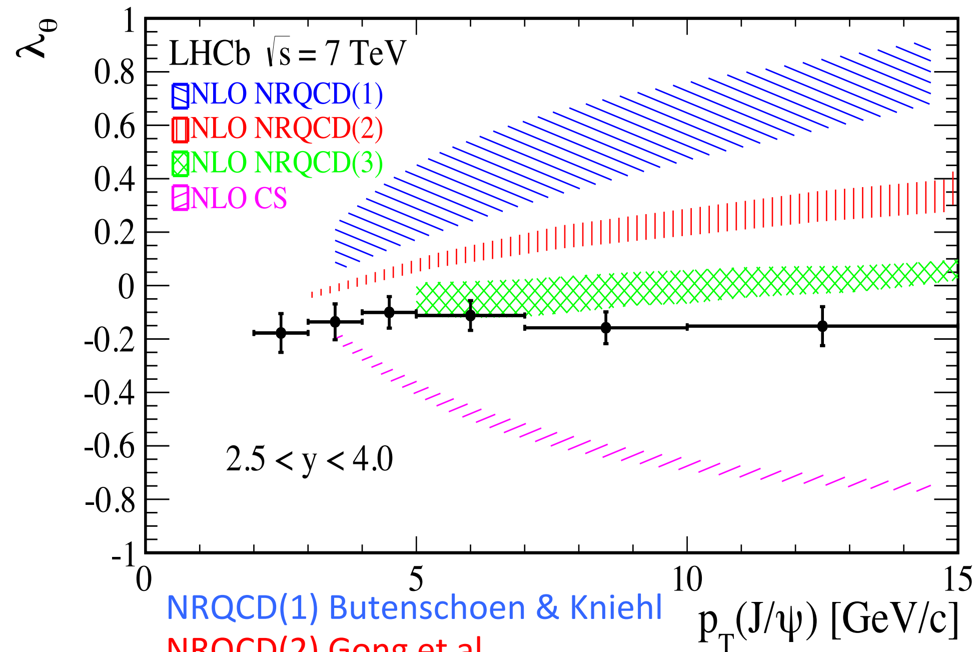

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In other words, all work

Quarkonium in proton-nucleus: Motivations and expected effects

In such reactions, many physics effects of specific interest are involved:

- Modification of the gluon flux *initial-state effect*
  - Modification of PDF in nuclei nPDF shadowing
  - Gluon saturation at low x CGC
- Parton propagation in medium *initial/final effect* Coherent energy loss
- Quarkonium-hadron interaction *final-state effect*
  - Break up in the nuclear matter Nuclear absorption
  - Break up by comoving particles Comover interaction

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- QGP-like effects?

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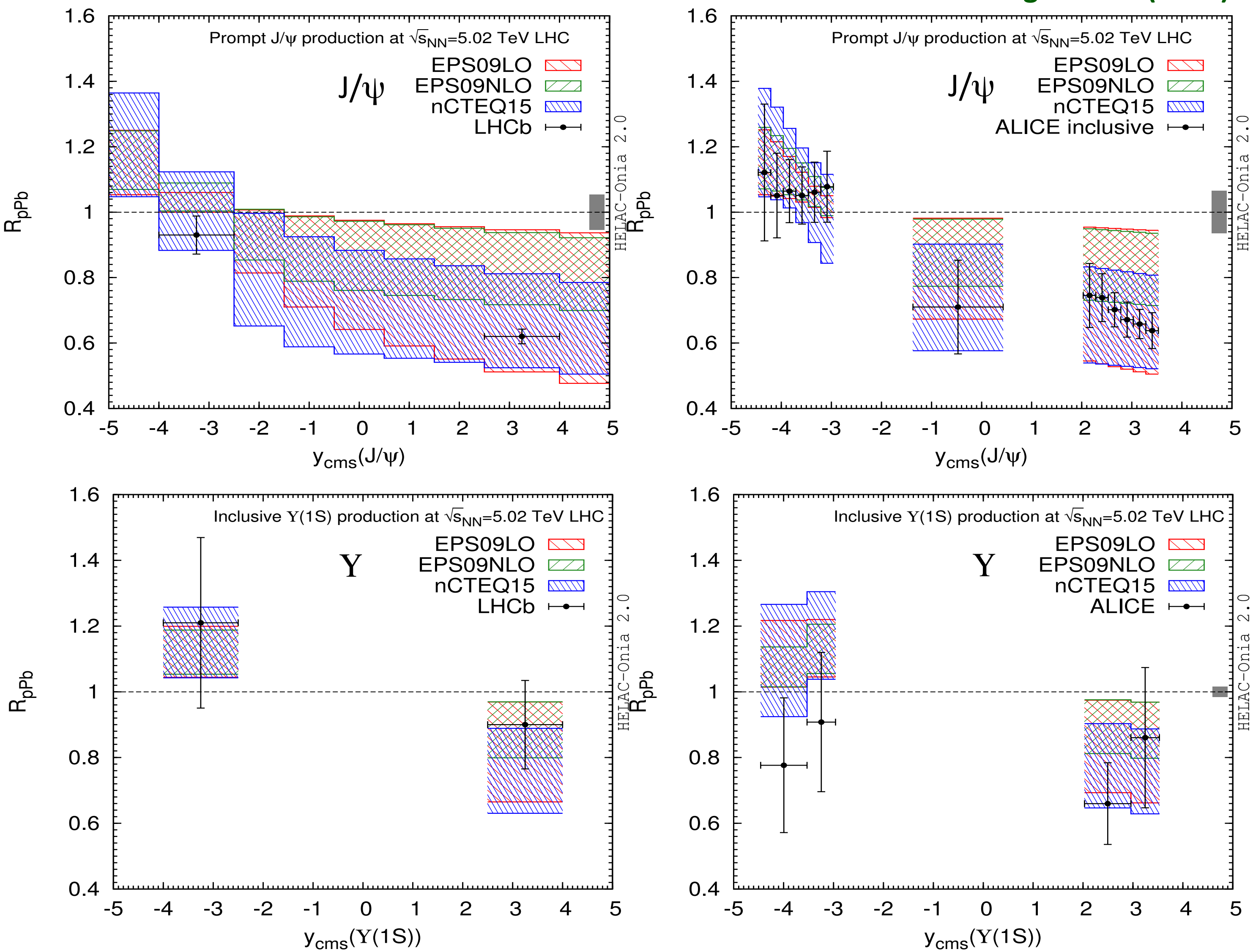
Obviously relevant if one wishes to use quarkonia as probes of the QGP => baseline

Comparison of nPDFs with LHC data

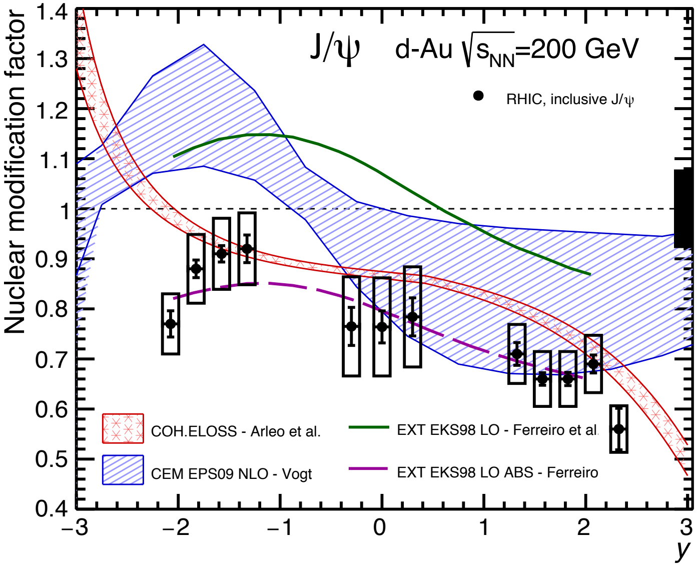
- Several nPDF sets available (using various data, LO/NLO, etc)
- Nuclear break-up neglected at LHC energies

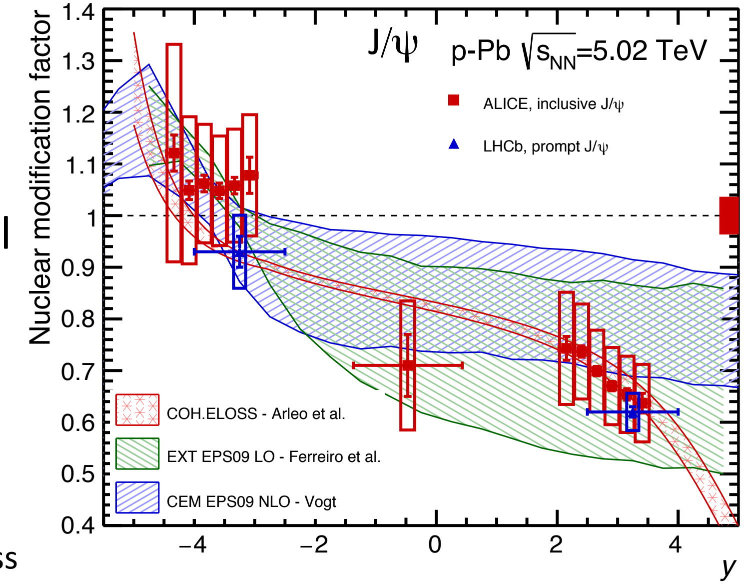
Lansberg & Shao (2016)



- Data is compatible with strong shadowing
- The precision of the current data is already much better than the nPDF uncertainties
- It may offer hints for constraining the gluon density in Pb

Comparison of nPDFs & E_{loss} with RHIC & LHC d/p+A data





Coherent E_{loss}

$\Delta E \propto E$

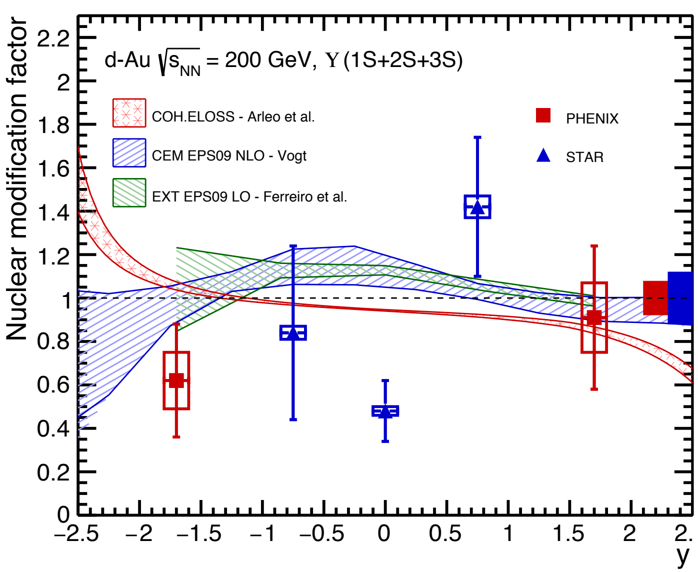
Interference terms initial/final state for $t_f >> R$

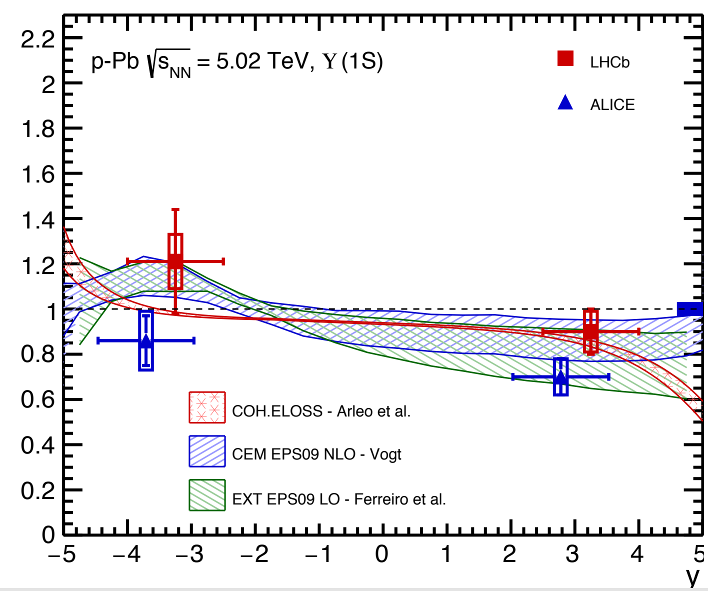
Arleo *et al.* (2014)

nPDF modification &/or E_{loss} fairly agree with data

Do data show energy increase of suppression?

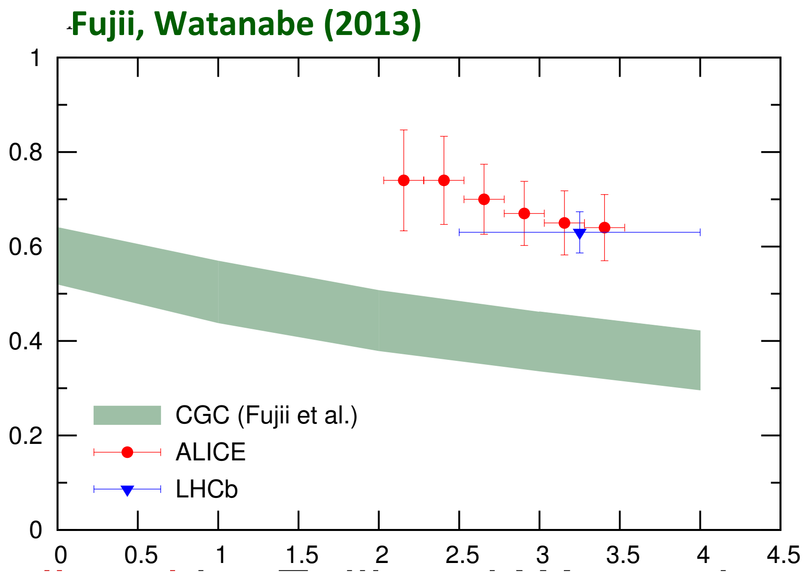
More precise data needed





CGC computations: not just gluon saturation

- J/ψ suppression predicted by Fujii and Watanabe within CEM significantly below the data:



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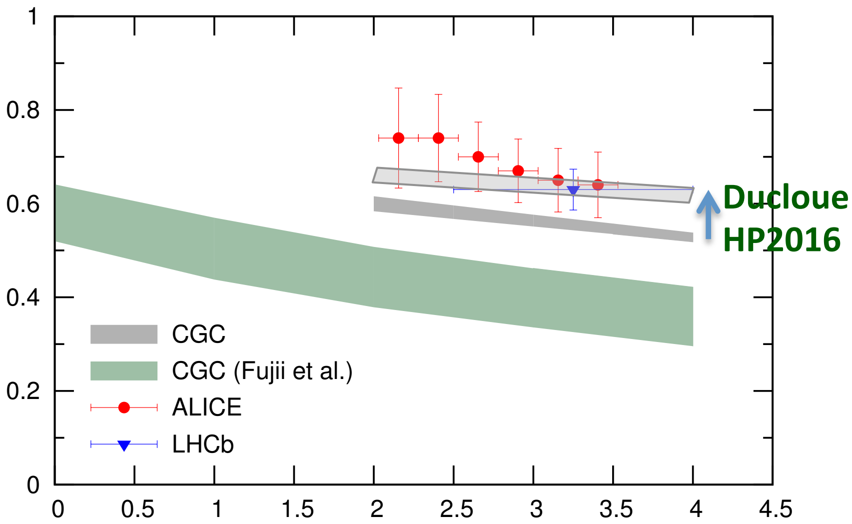

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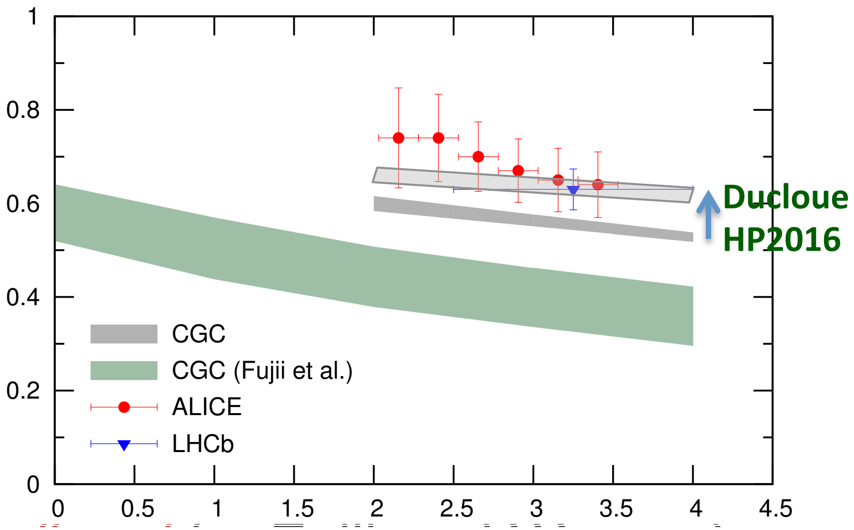

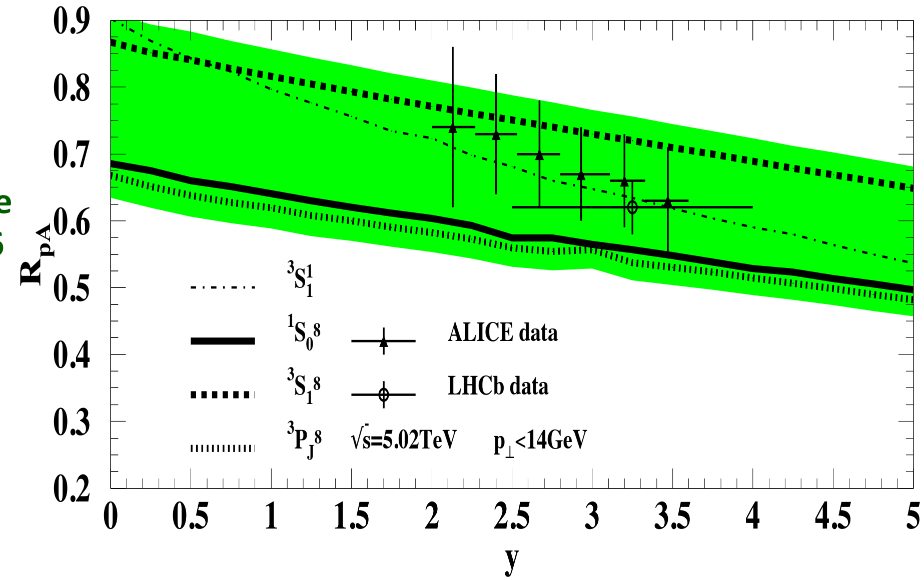

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    contribution of CS channel relatively small 10% in pp, 15-20% in pA at low p_T

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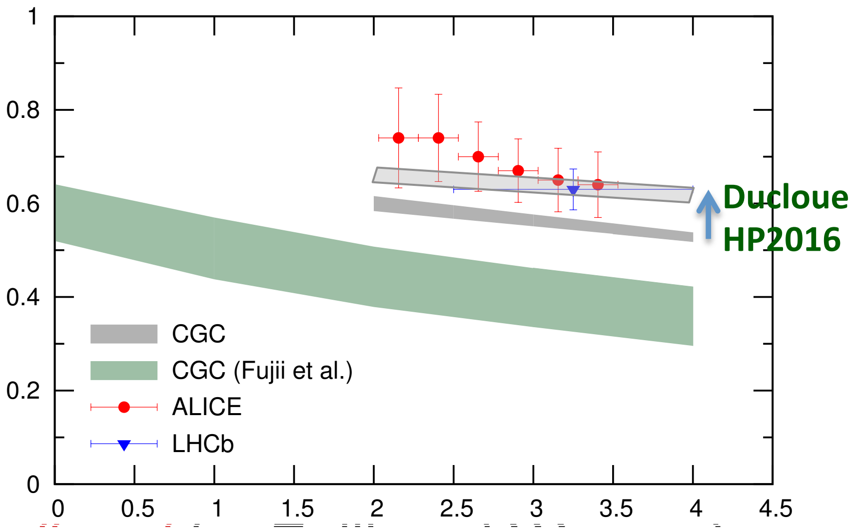

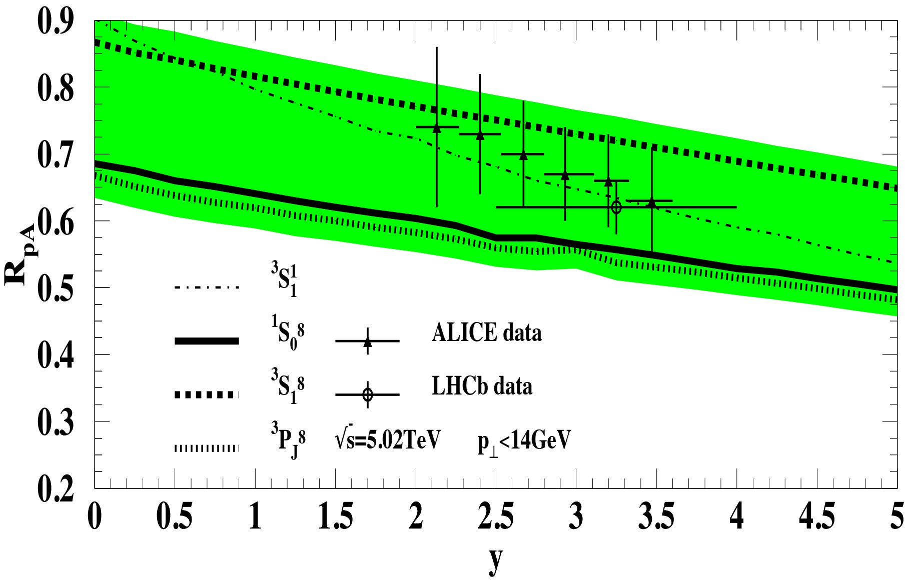

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- Issue: CGC results very much widespread (as those from nPDFs)
- Note: CGC on J/ψ suppression applies at forward y (not backward)

Excited states: An intriguing relative suppression in pA

The facts: **data from RHIC & LHC**

- PHENIX: relative ψ(2S)/J/ψ suppression in dAu collisions @ 200 GeV
- ALICE & LHCb: relative ψ(2S)/J/ψ suppression in pPb collisions @ 5 & 8 TeV
- CMS & ATLAS: relative ψ(2S)/J/ψ suppression in pPb collisions @ 5 TeV
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  $\sigma_{breakup} \propto r^2_{meson}$

  At high E: too long formation times $t_f = \gamma\, \tau_f >> R$ =>

  the quantum state does not matter!

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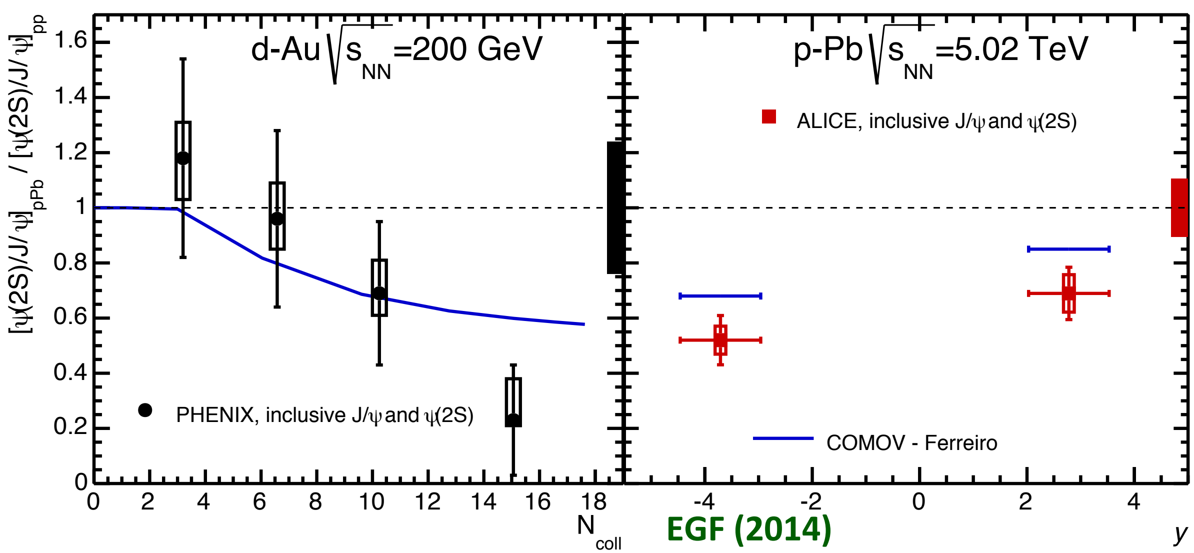
A natural explanation would be a final-state effect acting over sufficiently long time
=> **interaction with a comoving medium?**

Excited states: Comover interaction

- In a comover model: suppression from scatterings of the nascent ψ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, EGF, Tywoniuk…**
- Stronger comover suppression where the comover densities are larger. For asymmetric collisions as proton-nucleus, stronger in the nucleus-going direction
- Rate equation governing the charmonium density:

$$\tau \frac{\mathrm{d}\rho^{\psi}}{\mathrm{d}\tau}\,(b,s,y) \;=\; -\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\rho^{\psi}(b,s,y)$$

$\sigma^{co-\psi}$ originally fitted from SPS data



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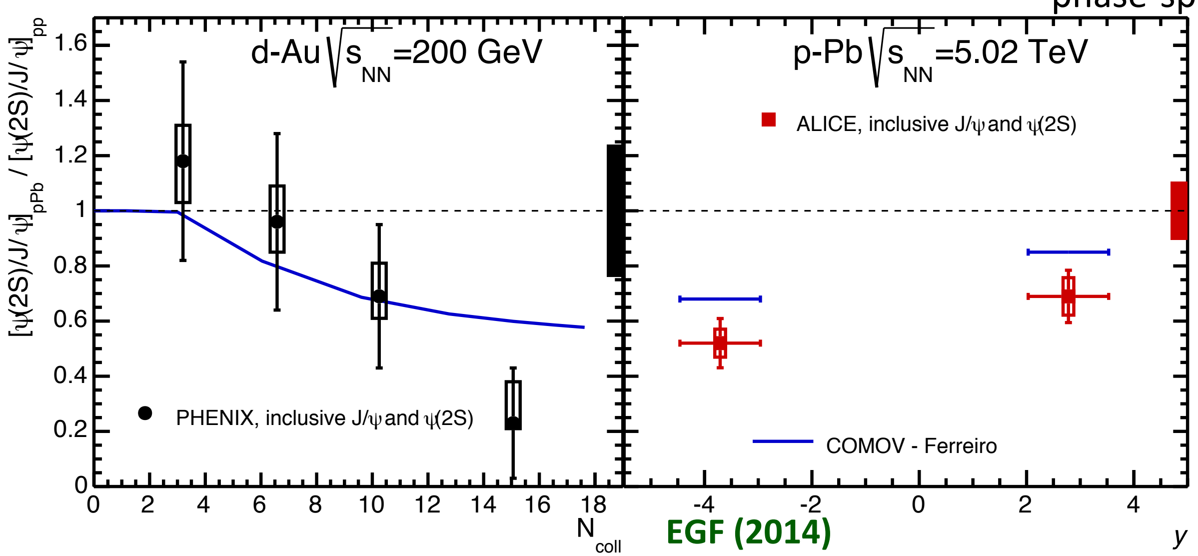
$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\mathrm{geom}}\left(1 - \frac{E_{\mathrm{Binding}}}{\langle E_{co}\rangle}\right)^{n}$$

- New: $\sigma^{co-\psi}$ can be parametrized: n & T_{eff}

averaged over comover phase-space distribution $1/(e^{E^{co}/T_{eff}} - 1)$



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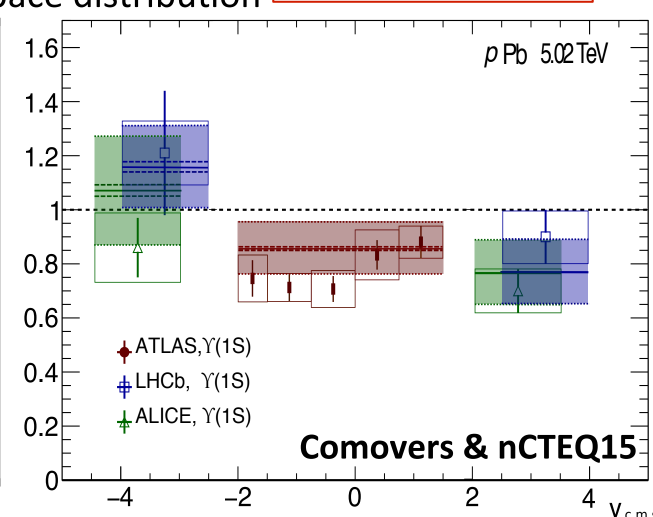
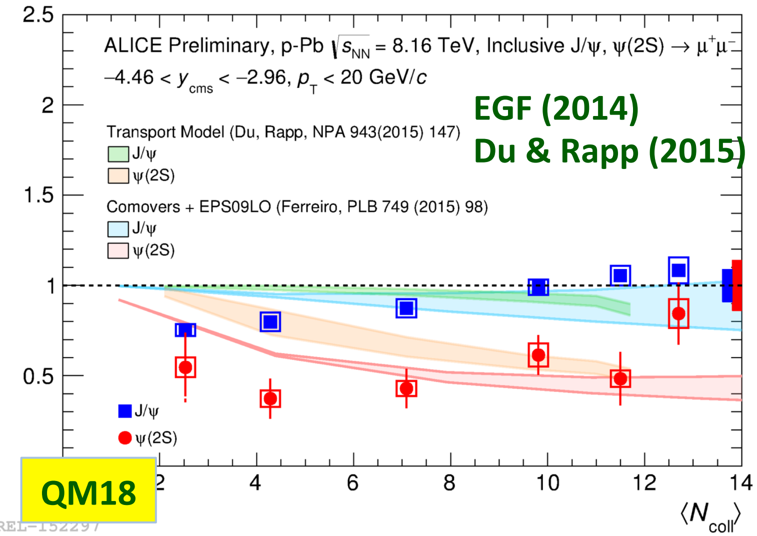


EGF & Lansberg (2018)

Excited states: Comover interaction

Transport model with final interactions
"similar in spirit to comover suppression"

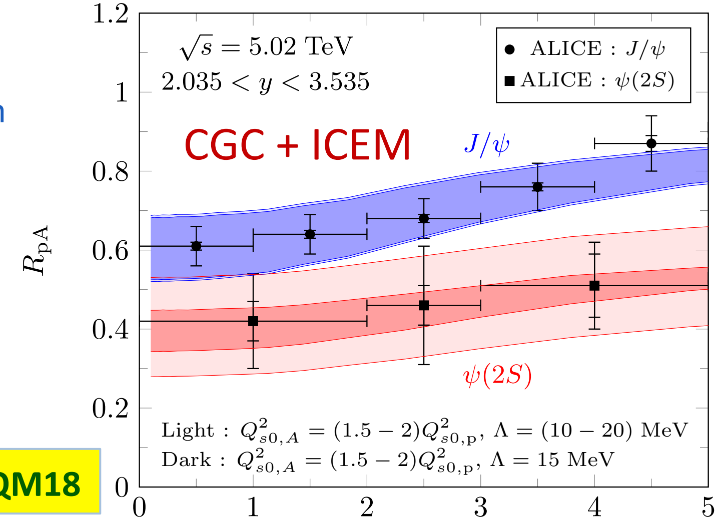
Soft color exchanges between cc & co-movers at later stage => effect on ψ(2S)



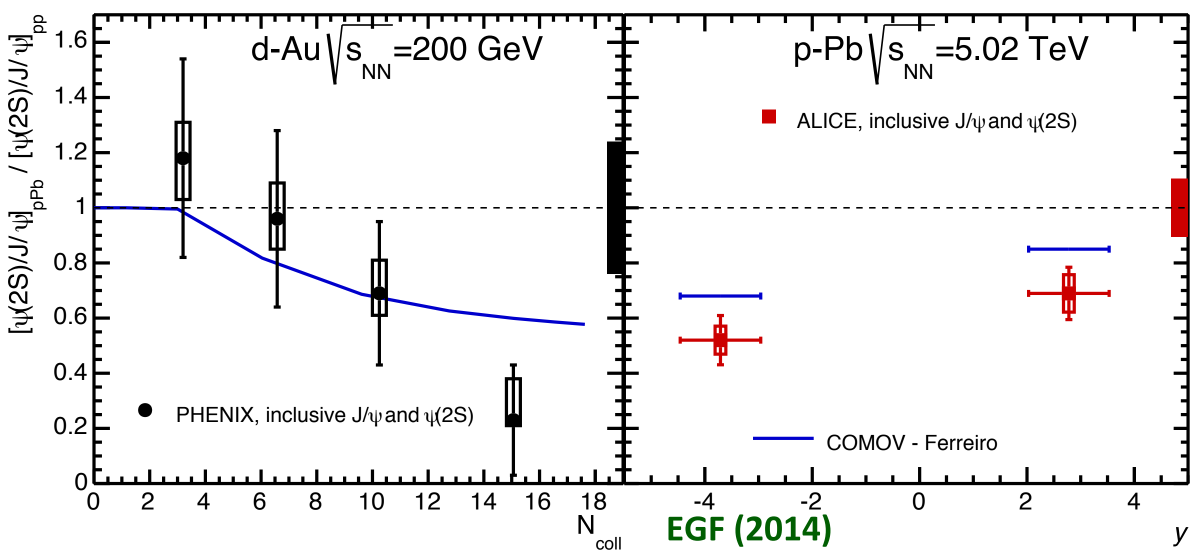
→New results on ψ(2S) confirm stronger suppression w.r.t. to J/ψ in the Pb-going direction.

→Final state effects are needed to reproduce the ψ(2S) suppression.

→Still problems for a quantitative description of the data.



Ma, Venugopalan, Zhang, Watanabe (2018)



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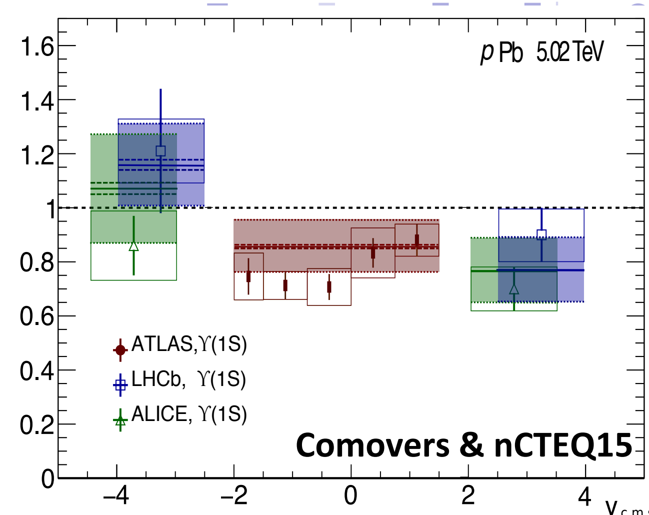

EGF & Lansberg (2018)

Think big: quarkonium in nucleus-nucleus collisions

- Matsui and Satz: suppression of quarkonium as a signature of the QGP

  Debye screened potential above the deconfinement temperature

- Time-independent notion of the melting process, purely real model potentials

  Popular candidates: free energies $F^1(r)$ &/or internal energies $U^1(r)$ **Static**

- An essential step: heavy quark potential not only shows Debye screening but also features an imaginary part **Laine *et al.* (2007)**

  Intuitive idea: Re[V] captures the screened $Q\bar{Q}$ interaction **Dynamic**

  Im[V] captures dissociation by Landau damping & singlet ⇔ octet

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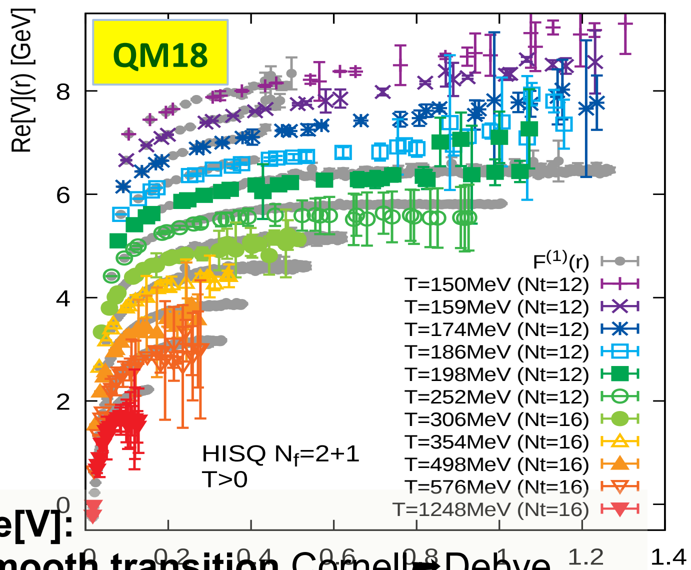
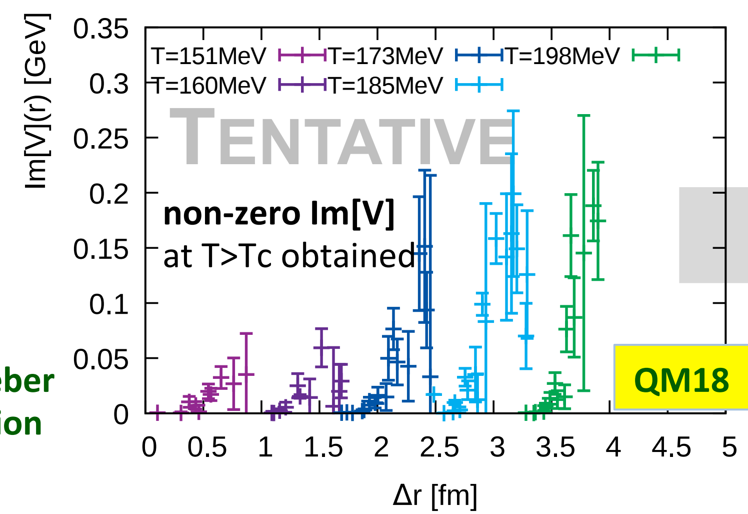


Re[V]:
smooth transition Cornell➡Debye
agrees with $F^{(1)}$ within uncertainty

Current efforts:

- lattice QCD calculation of complex in-medium HQ potential

Petreczky, Rothkopf, Weber [TUM-QCD] in preparation



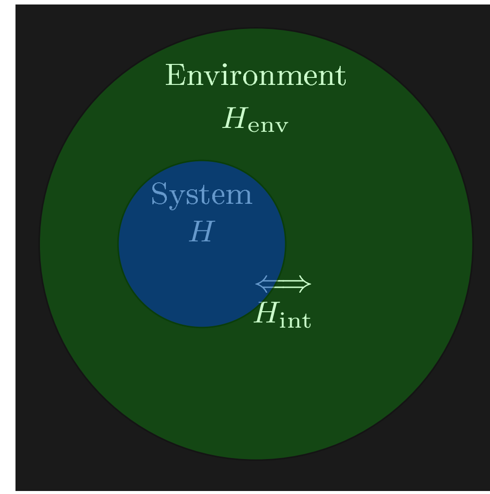
- understand the origin and physics implications of Im[V]

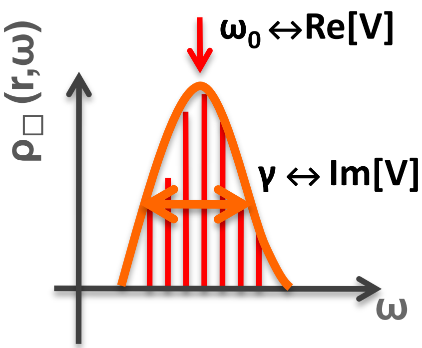
Think big: quarkonium in nucleus-nucleus collisions

- To formalize the idea of decoherence in the language of QM and to see how the imaginary part arises from the thermal fluctuations in the medium:

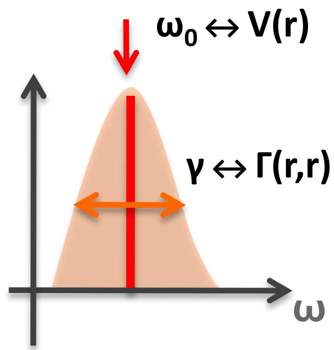
Theory of open quantum systems:

- solution of a stochastic Schrodinger equation
  Asakawa& Rothkopf; Katz & Gossiaux,
  Kajimoto, Akamatsu, Asakawa, Rothkopf
- computation of the evolution of the density matrix
  Borghini, Dutta, Gombeaud;
  Brambilla, Escobedo, Soto, Vairo;
  Blaizot; De Boni





Effective Field Theory

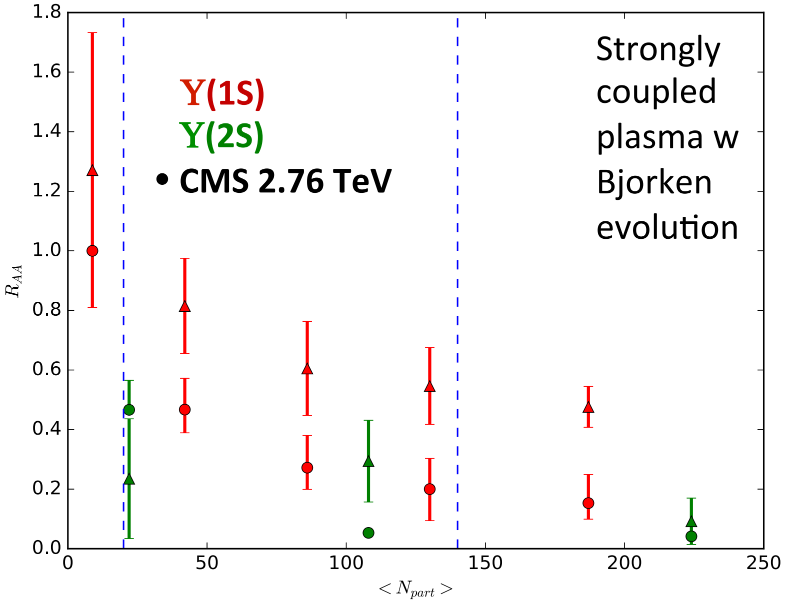


Open Quantum System

The real and imaginay parts of the in-medium HQ potential can be related to the stochastic evolution of the in-medium wave function which is perturbed by the thermal medium:

- Stochastic term = thermal noise
- Im[V] related to the strenght of the thermal noise

Recent developments on open quantum systems for quarkonia



Time evolution of HQ states in an expanding hot QCD medium by implementing EFT –pNRQCD- in the framework of open quantum systems
=> Lindblad equation

- non-Abelian nature of QCD: color transitions
- conserves the total number of heavy quarks
- avoids classical approximations

Brambilla, Escobedo, Soto & Vairo (2017)

In the same line: equations for the time evolution of the HQ reduced-density matrix in a non-Abelian QGP **Blaizot & Escobedo (2017)**

- treat the relative motion of the heavy quarks semi-classically
- take into account the color transitions within 2 strategies:
  - instantaneusly, perturbation theory => Langevin equation, analogous to QED
  - as collisions => Botzman equation **De Boni (2017)**

Also: Schrödinger-Langevin equation **Gossiaux & Katz (2016)**

- interesting framework but not derived from first QCD principles
- QCD features enter in the parameters (similarly to Langevin dynamics in HF physics)

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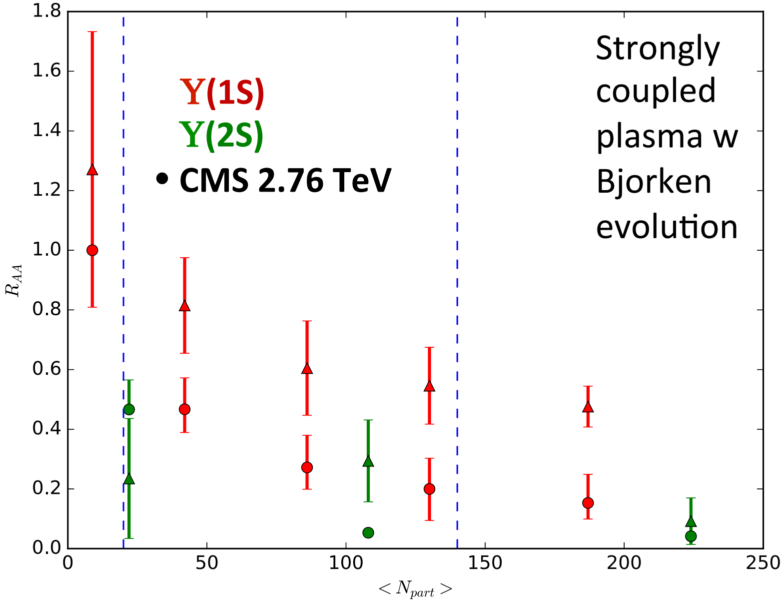

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Master equation with time evolution of the HQ states

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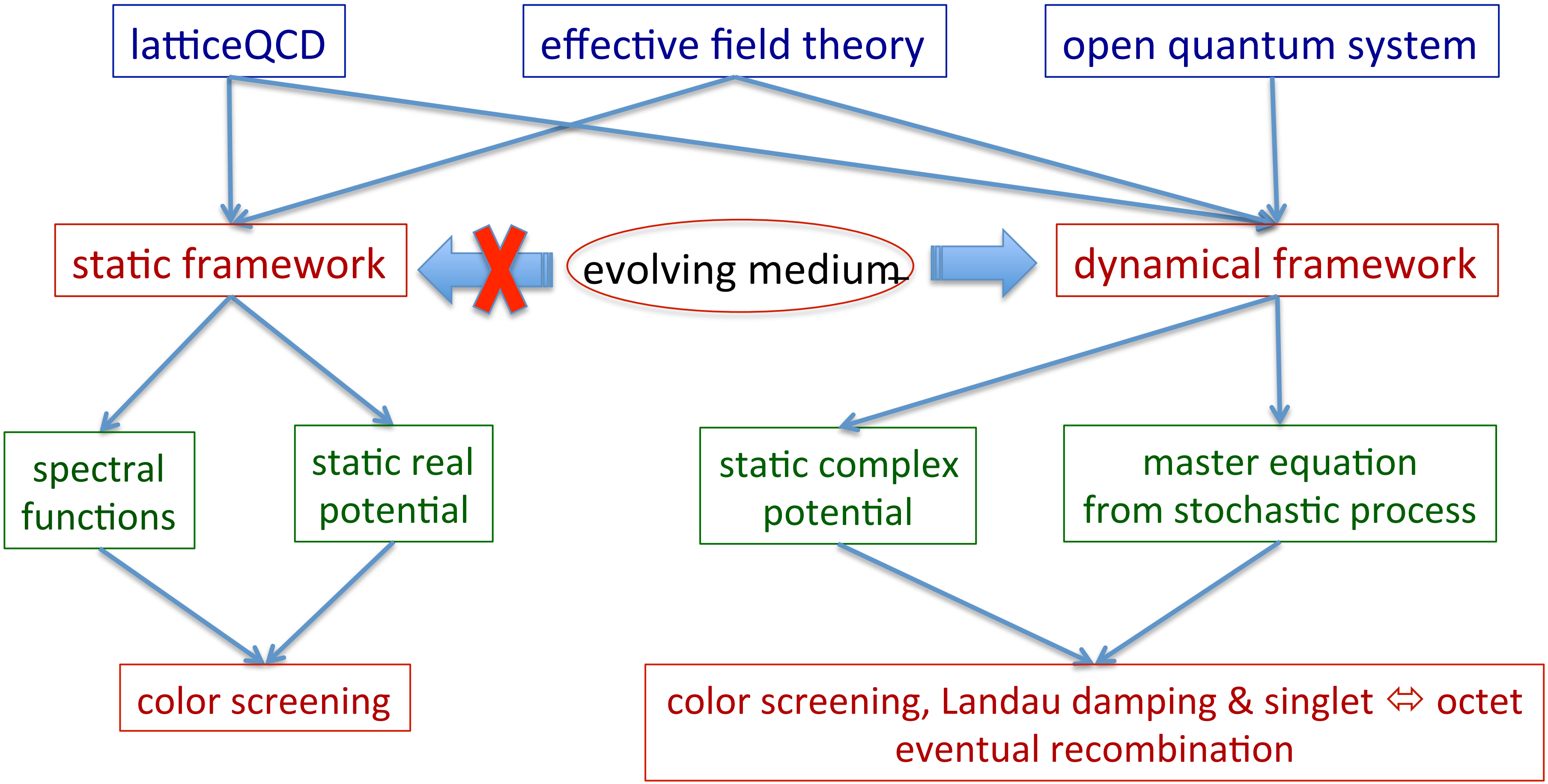
Be aware: theory elements on quarkonia in a QGP

Caveat I: we need firm theoretical understanding of quarkonium production in pp collisions



Caveat II: how to extrapolate pA effects –initial & final- to AA? Factorization?
If yes… nature of the medium in pA?

An example: apply comover model to pPb **and** PbPb

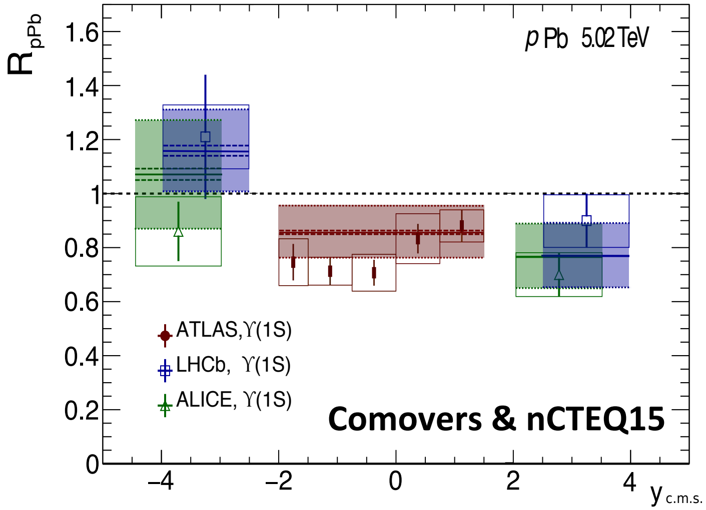
- We take:

$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\text{geom}}\left(1 - \frac{E_{\text{Binding}}}{\langle E_{co}\rangle}\right)^n$$

averaged over comover phase-space distribution $1/(e^{E^{co}/T_{eff}} - 1)$

- Using pPb CMS and ATLAS data on relative Υ(nS)/Υ(1S) at 5.02 TeV –only comovers at play- we fit T_{eff} & *n: n=1, T=250 ± 50* MeV

- We check consistency with $R_{pPb}^{\Upsilon(1S)}$



EGF & Lansberg arXiv:1804.04474

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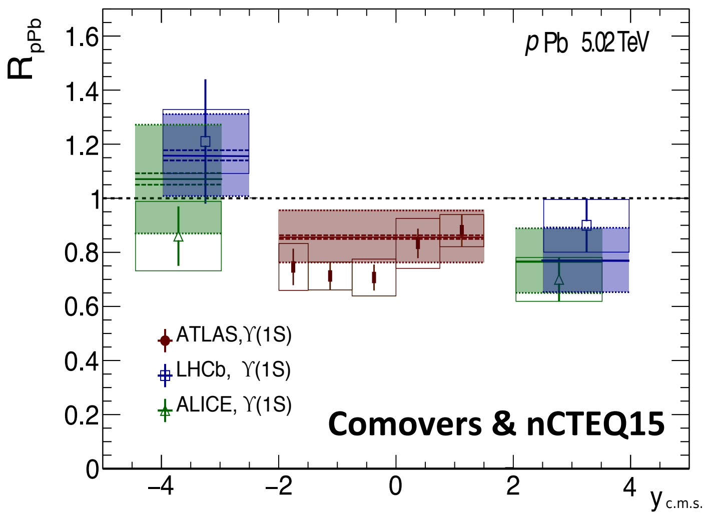

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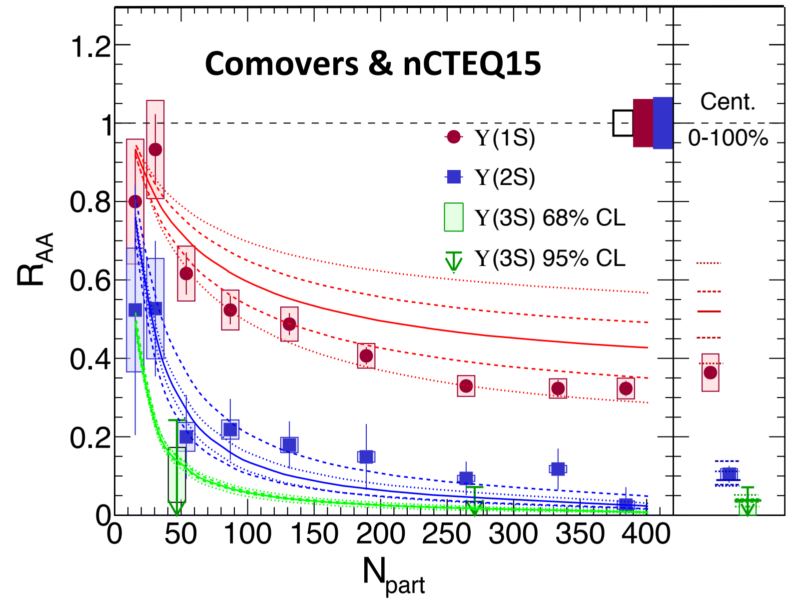
- We calculate R_{PbPb} for Υ(1S), Υ(2S) and Υ(3S) @ 5.02 TeV



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- The magnitude of suppression in PbPb -is well reproduced without the need to invoke any other phenomena

Physical interpretation: what the nature of the comovers is

- Case I: The medium is hadronic in pPb collisions, while it is gluonic in PbPb
  - The most common expectation: The relevant d.o.f. are hadrons in pPb collisions where the QGP is not produced whereas the gluons become relevant in the hotter PbPb environment with the presence of QGP

- Case II: Both in pPb and PbPb collisions, the medium is made of hadrons, i.e. the comovers can be identified with pions
  - Both in pA and AA collisions, Υ not affected by the hot (deconfined) medium
  - Possible interpretation: melting temperature of the Υ(1S) and Υ(2S) is too high to be observed and the Υ(3S) is fragile enough to be entirely broken by hadrons. Bottomonia unaffected by the presence of a possible QGP

- Case III: Both in pPb and PbPb collisions, the medium is made of partons, i.e. the comovers can be identified with gluons
  - Comovers are to be considered as partons in a (deconfined?) medium
  - A QGP-like medium is formed following pPb collisions at LHC energies
  - CIM: effective modelling of bottomonium dissociation in the QGP