Quarkonia in nuclear collisions

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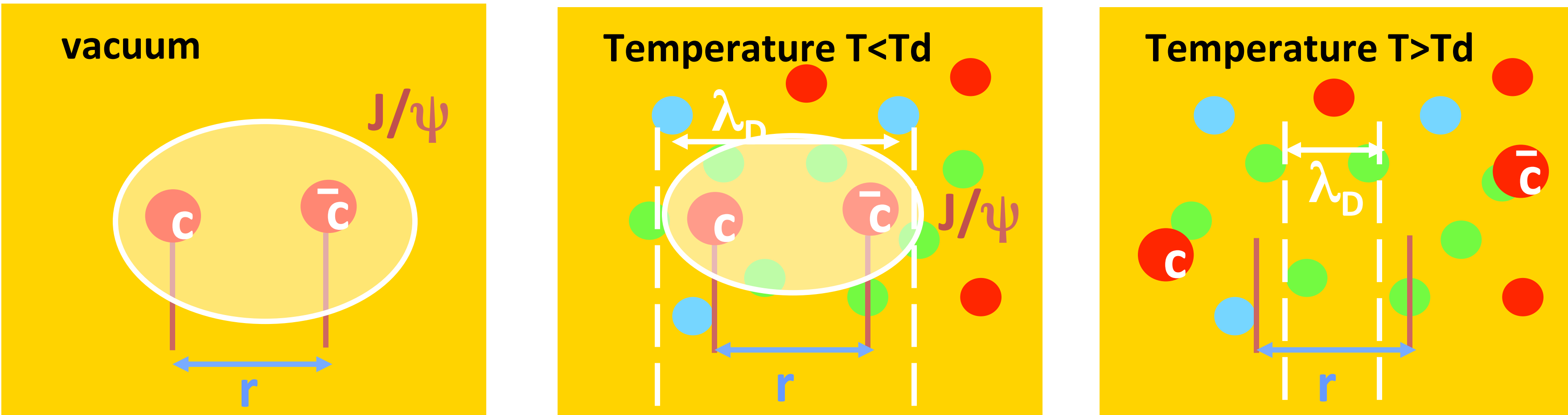
LLR, École polytechnique , France

Why quarkonium?

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



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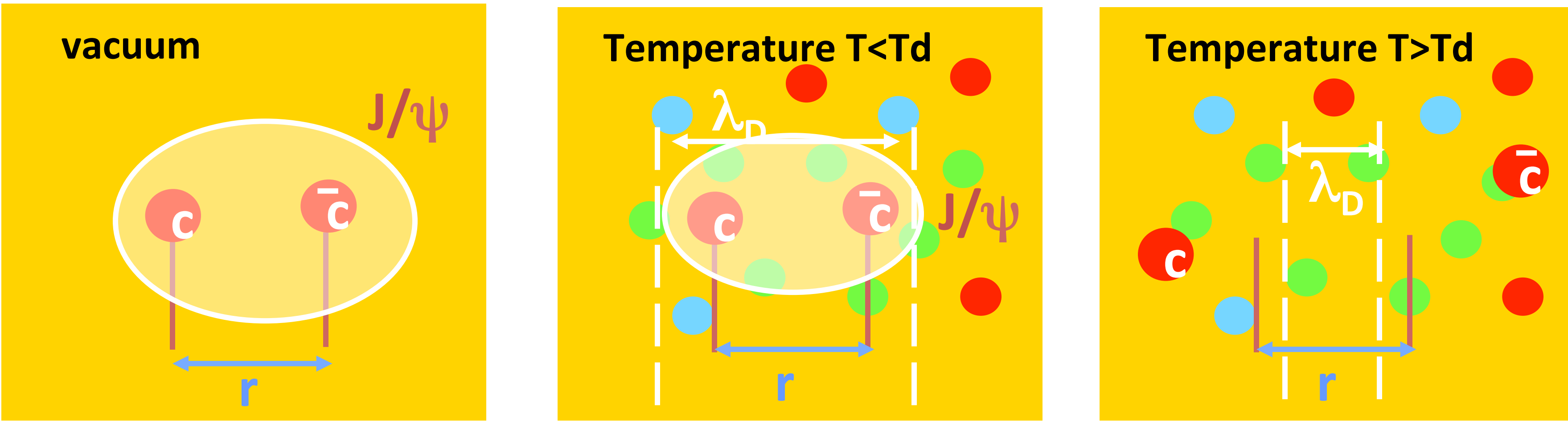
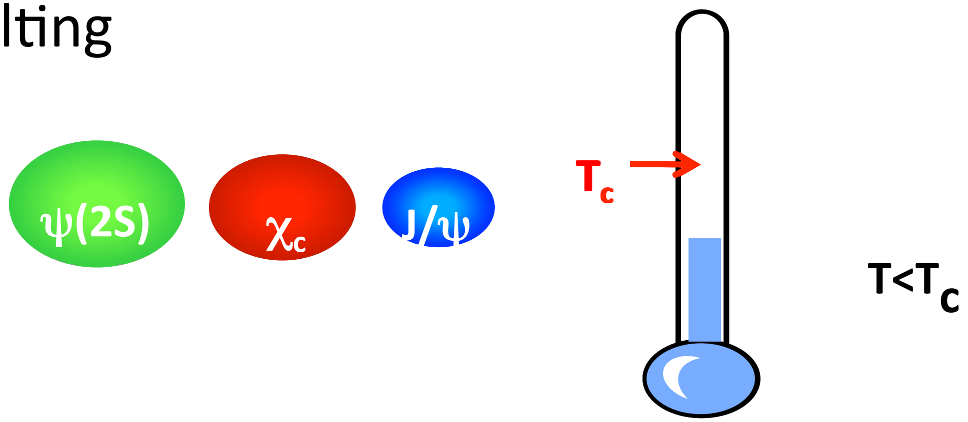


Sequential melting



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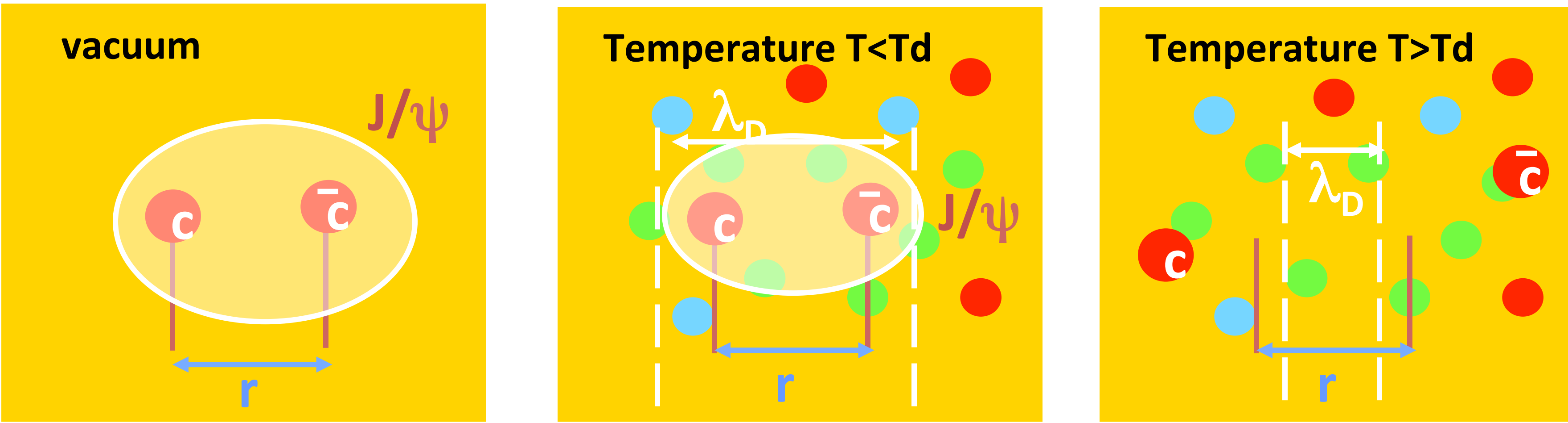

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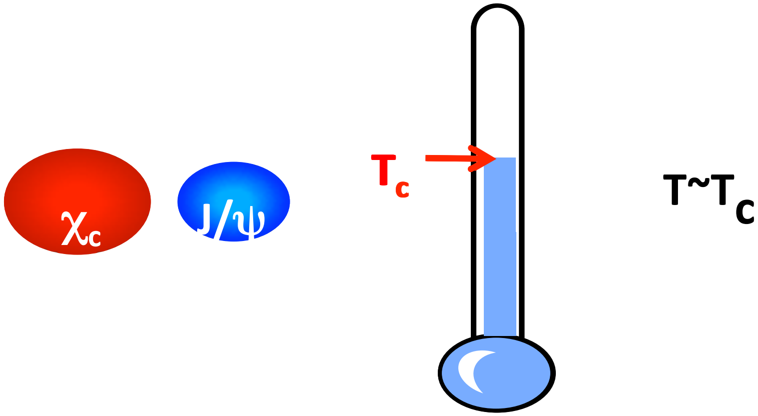

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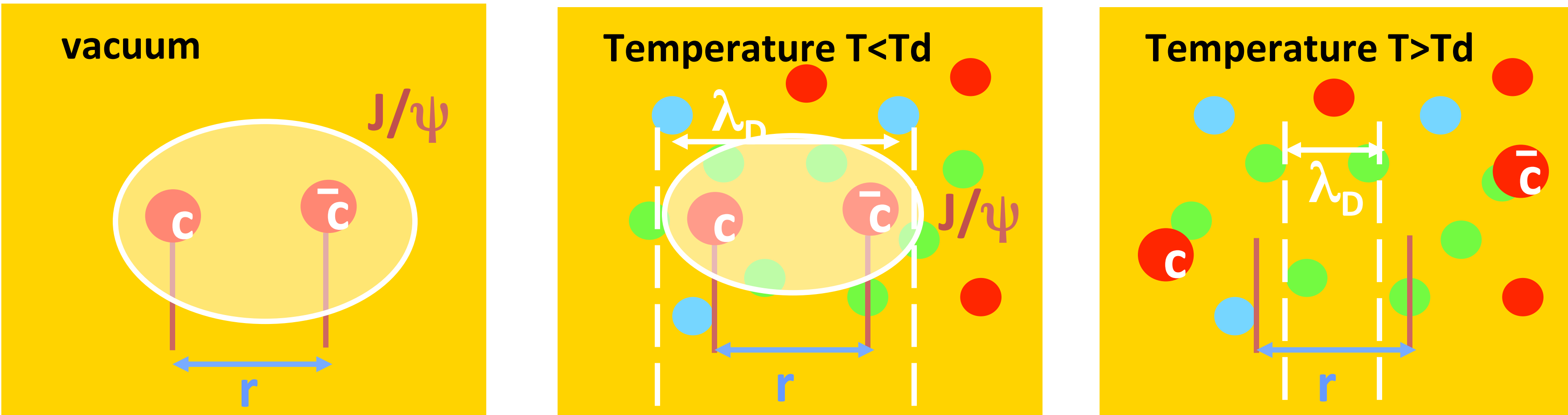

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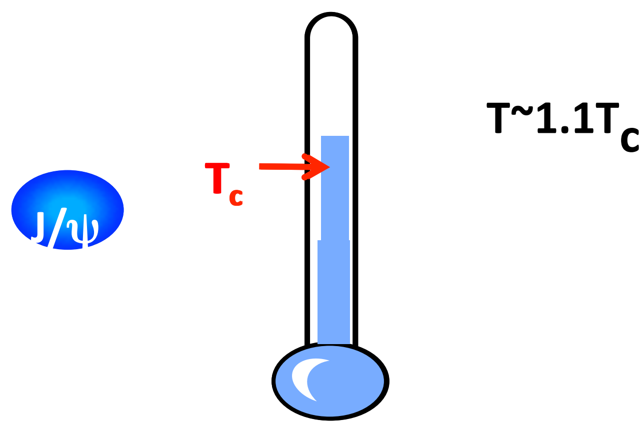

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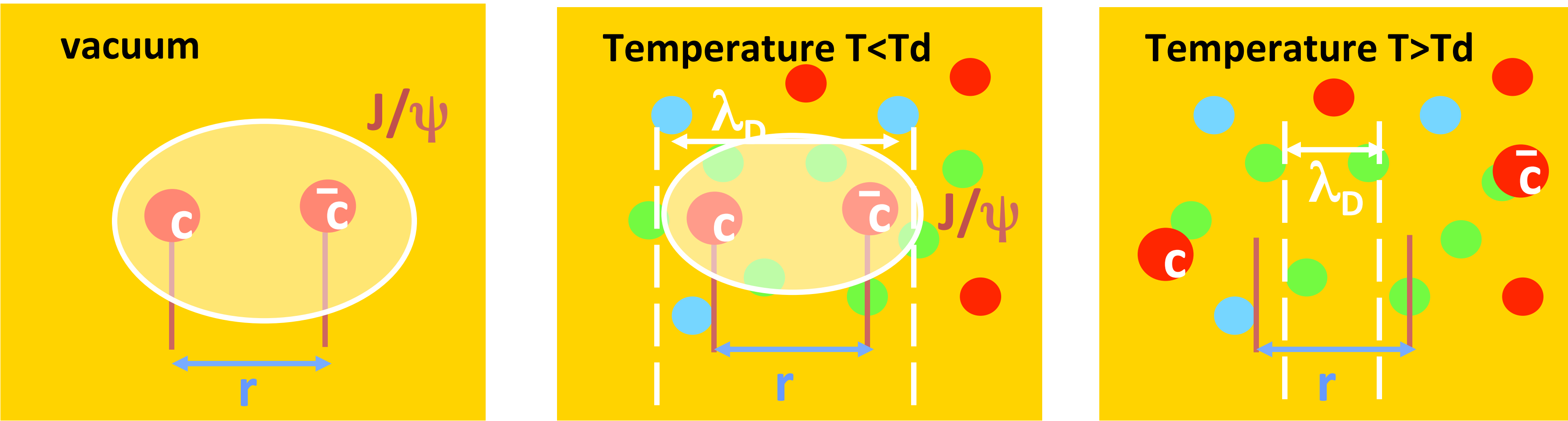

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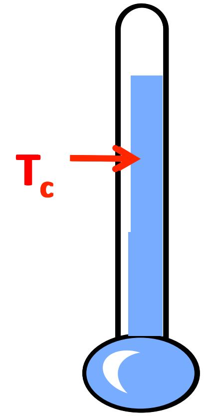
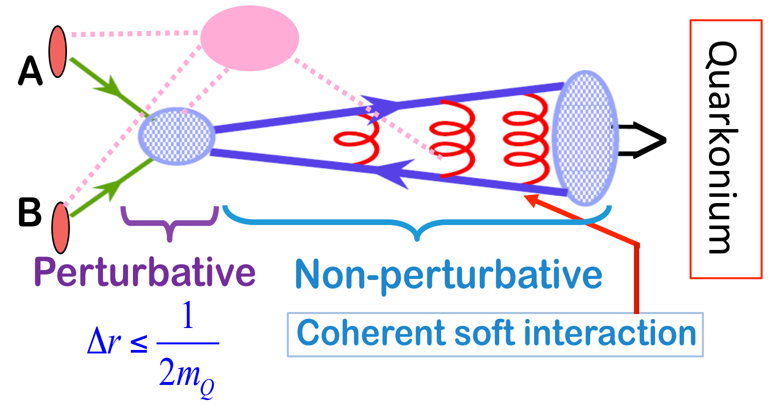


$T \gg T_c$

Quarkonium production schemes in pp: A long history

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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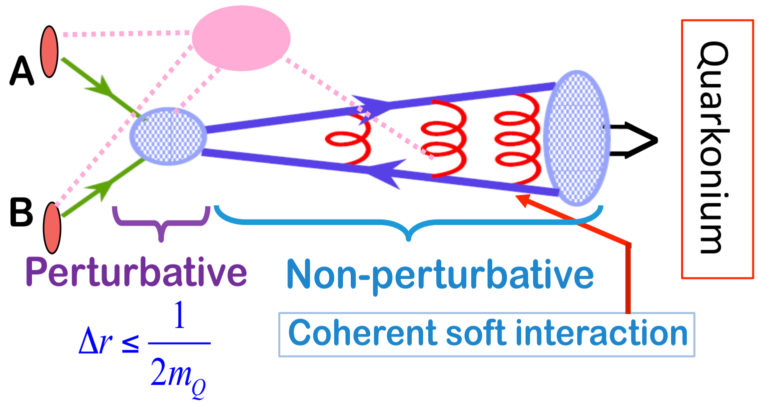

Different approaches to hadronization:

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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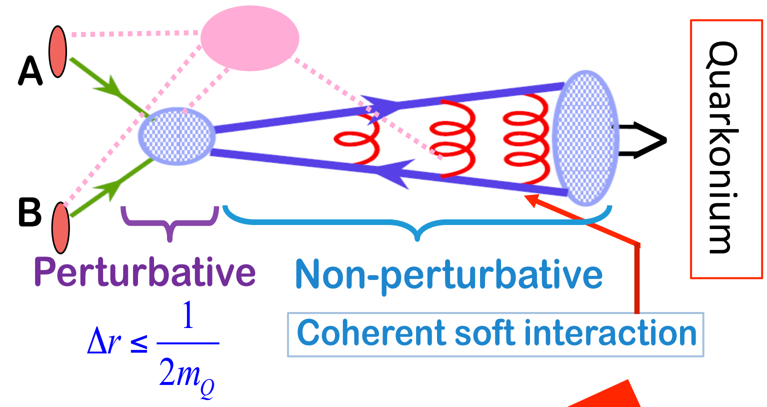

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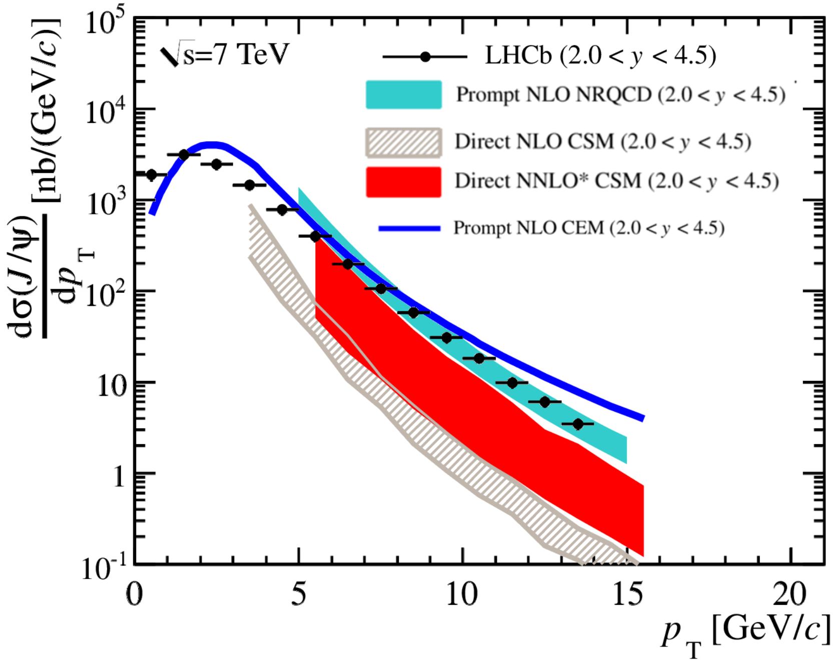
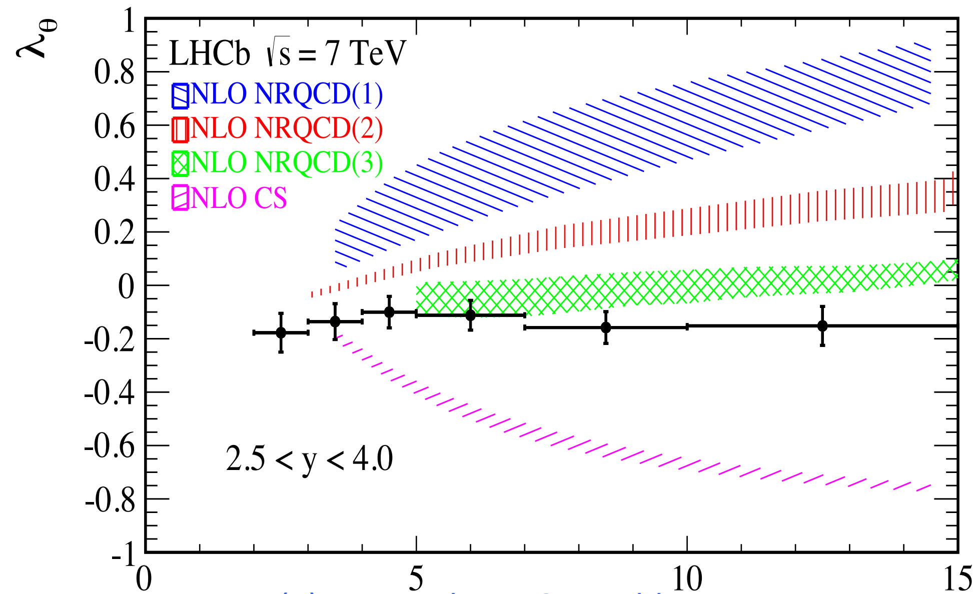
Production mechanism still not settled after more than 40 years!

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.

- CSM still in the game: Large NLO and NNLO* corrections in p_T; need a full NNLO
- NRQCD: COM helps in describing the p_T spectrum

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

Recent developments may be helpful

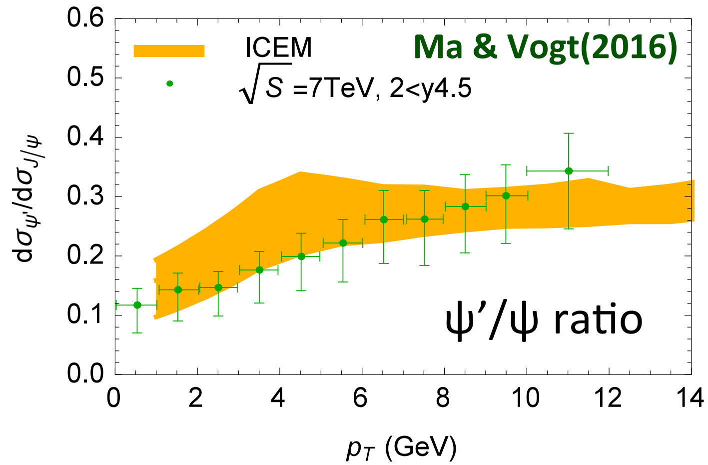
- Color Evaporation Model (CEM) Improved

$$\sigma_Q^{\rm (N)LO} = F_Q \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}^{\rm (N)LO}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$

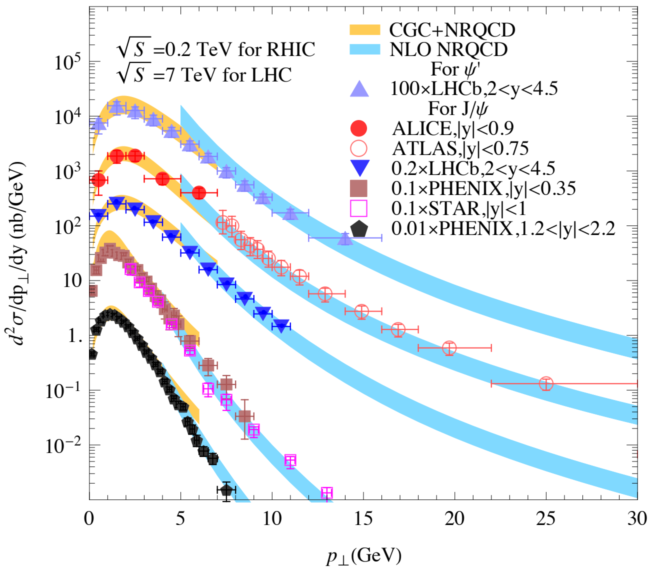
changes to M_ψ

- Explicit charmonium mass dependence
  => ψ'/ψ ratio no longer p_T independent
- Relates $\langle p_\psi \rangle$ to the $c\bar{c}$ pair momentum
  => explain the high p_T data better
- LO calculation of quarkonium polarization in the CEM, longitudinal polarized @ LHC

Cheung & Vogt(2017)



- Saturation meets NRQCD



- Uses Color Glass Condensate saturation model of gluon distributions in the proton with NLO NRQCD matrix elements
- Saturation physics at low p_T, normal collinear factorization at high p_T, matching at intermediate p_T

Ma, Venugopalan & Zhang (2015)

New observables can help

Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CS dominant) + DPS + gluon TMD
J/ψ+D	LHCb	LO	LO ?	LO	Prod. Mechanism (c to J/psi fragmentation) + DPS
J/ψ+ϒ	D0	(N)LO	LO ?	LO	Prod. Mechanism (CO dominant) + DPS
J/ψ+hadron	STAR	LO	--	LO	B feed-down; Singlet vs Octet radiation
J/ψ+Z	ATLAS	NLO	NLO	Partial NLO	Prod. Mechanism + DPS
J/ψ+W	ATLAS	LO	LO ?	Partial NLO	Prod. Mechanism (CO dominant) + DPS
J/ψ vs mult.	ALICE,CMS (+UA1)	--	--	--	Density effects (Saturation/Hydro)
J/ψ+b	-- (LHCb, D0, CMS ?)	--	--	LO	Prod. Mechanism (CO dominant) + DPS
ϒ+D	LHCb	LO	LO ?	LO	DPS
ϒ+γ	--	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CO LDME mix) + gluon TMD/PDF
ϒ vs mult.	CMS	--	--	--	Density effects (Saturation/Hydro)
ϒ+Z	--	NLO	LO ?	LO	Prod. Mechanism + DPS
ϒ+ϒ	CMS	NLO?	LO?	LO?	Prod. Mechanism + DPS + gluon TMD

Lansberg (2018)

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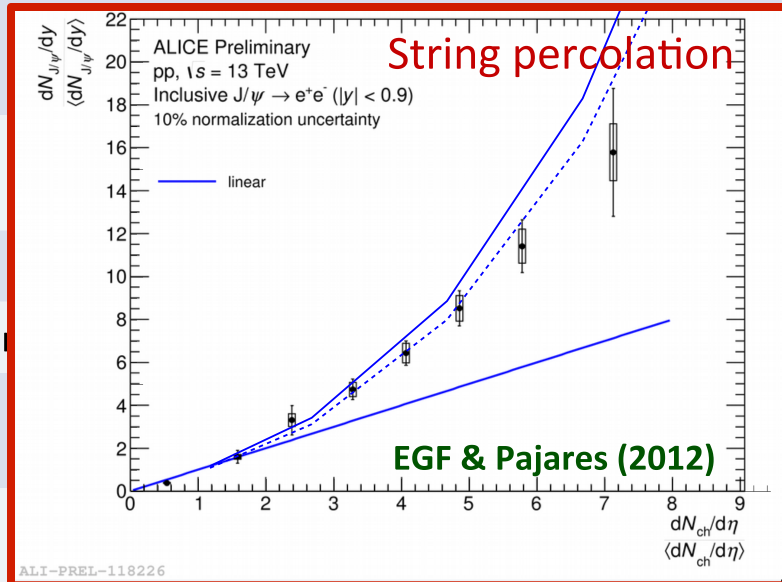
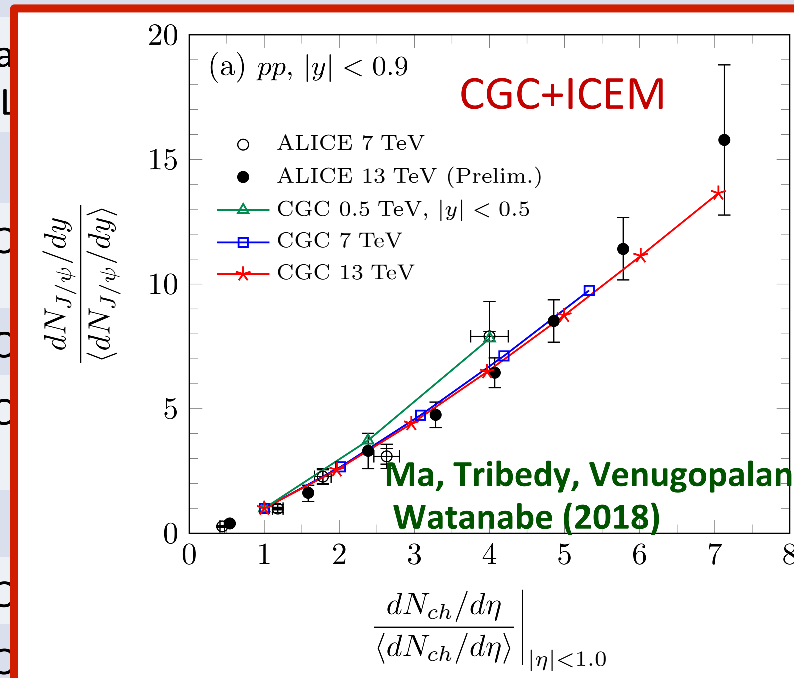
				LO	
				LO	
ϒ+Z	--	NLO	LO ?	LO	
ϒ+ϒ	CMS	NLO?	LO?	LO	





Events at different energies with the same $\rho_{strings}$ or Q_s are identical

Saturation in high multiplicity pp?

Lansberg (2018)

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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In addition of quantifying nuclear effects, quarkonium production in pA may be able to:

- Test QCD factorization in media
- Test the quarkonium production mechanisms: octet vs. singlet
- Test the dynamics of hadronization and time evolution of the $Q\bar{Q}$ pair

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- QGP-like effects?

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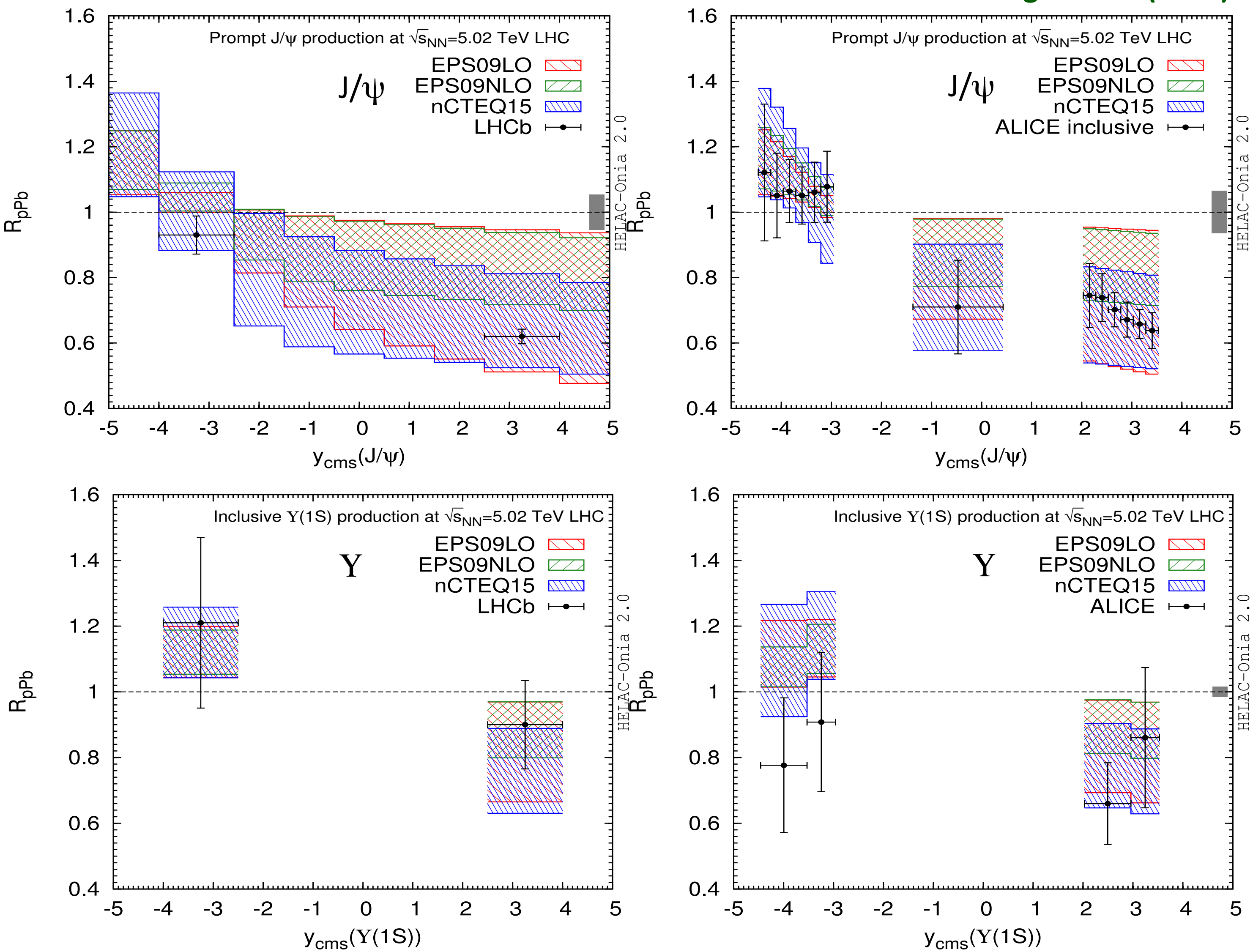
Obviously relevant if one wishes to use quarkonia as probes of the QGP => baseline

Comparison of nPDFs with LHC data

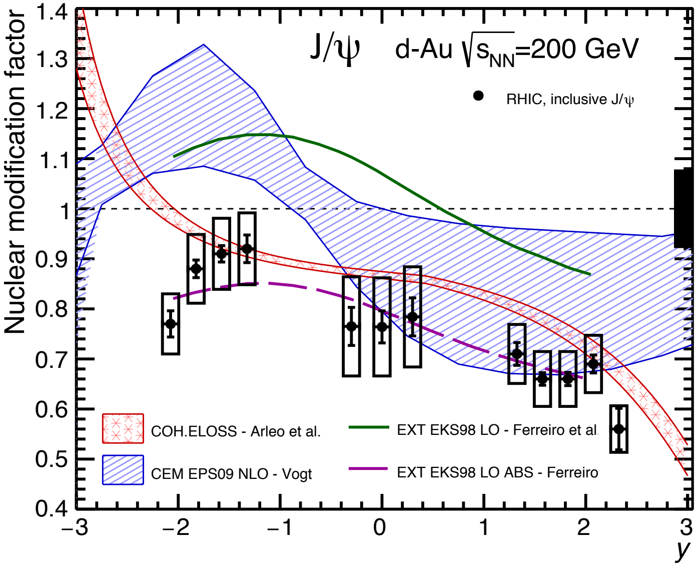
- Several nPDF sets available (using various data, LO/NLO, etc)
- Nuclear break-up neglected at LHC energies

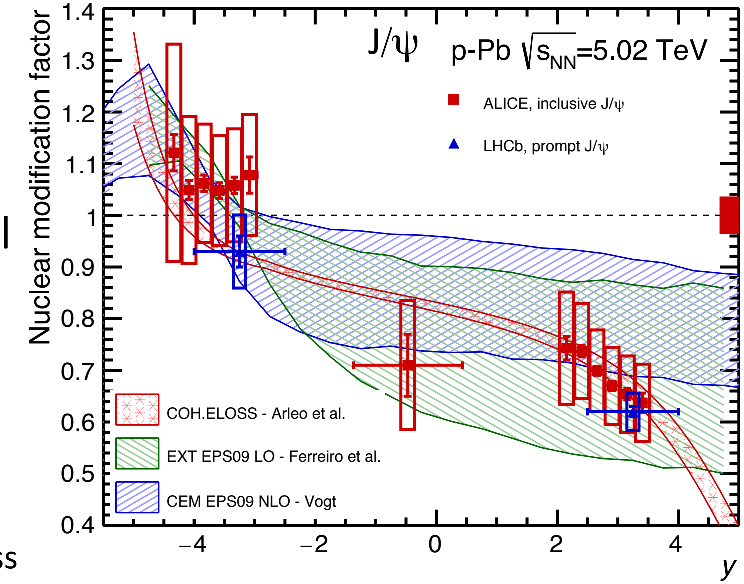
Lansberg & Shao (2016)



- 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}

$\Delta E \propto E$

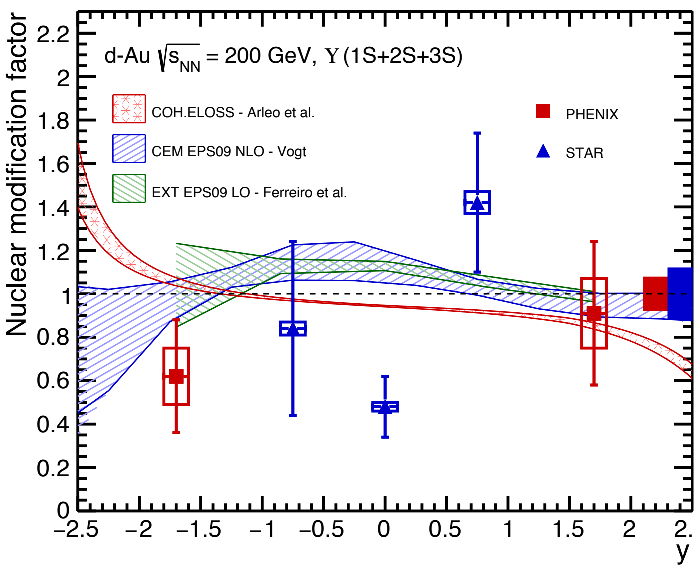
Interference terms initial/final state for $t_f >> R$

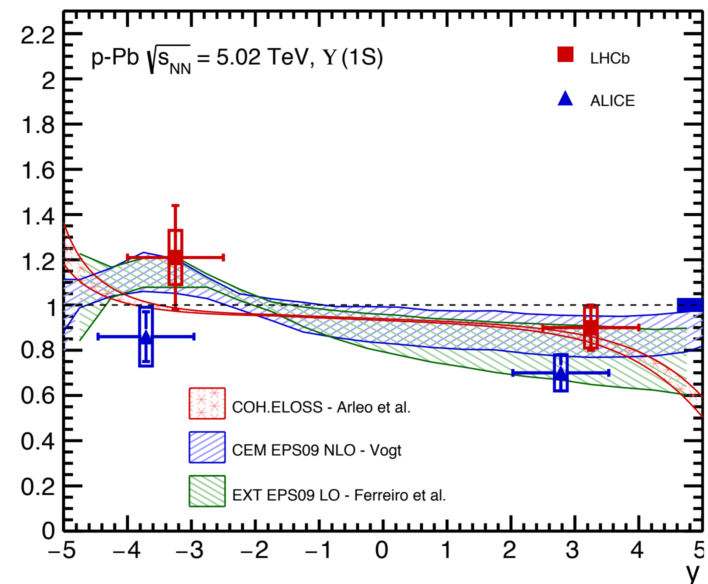
Arleo *et al.* (2014)

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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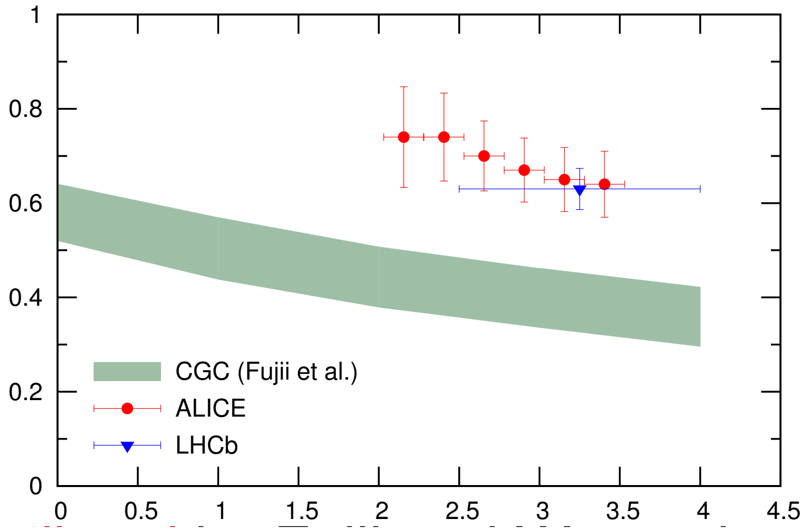

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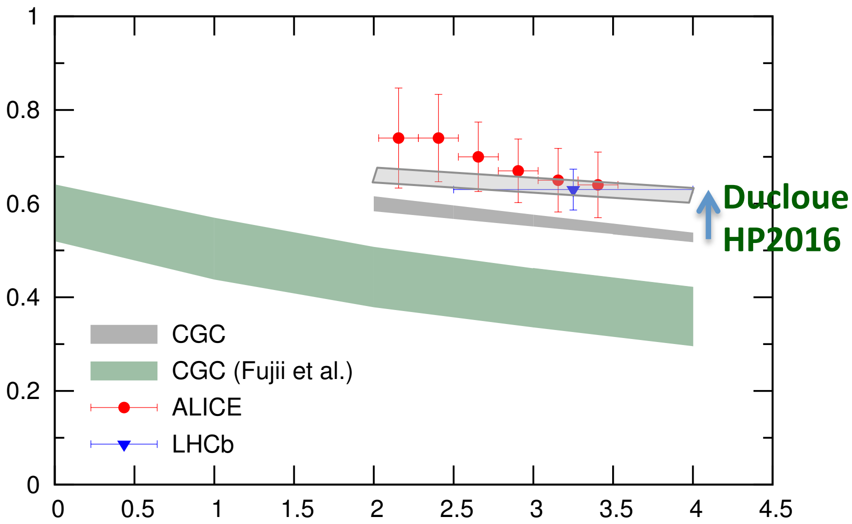

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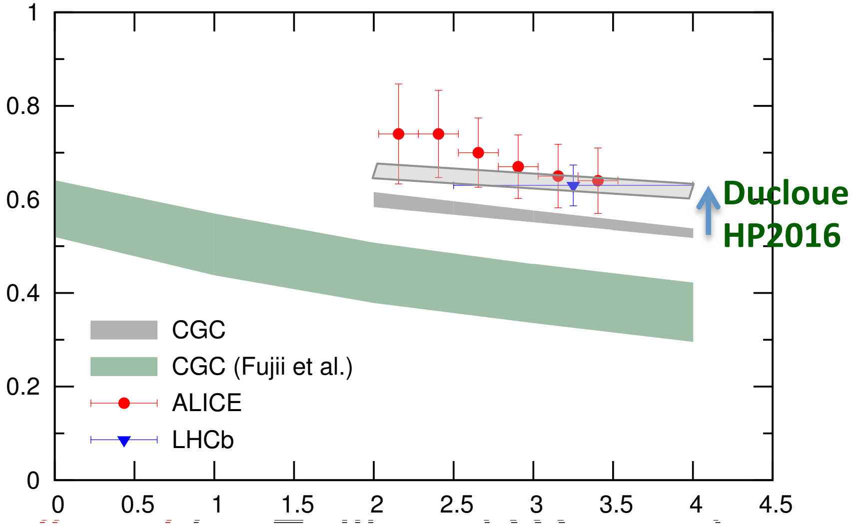

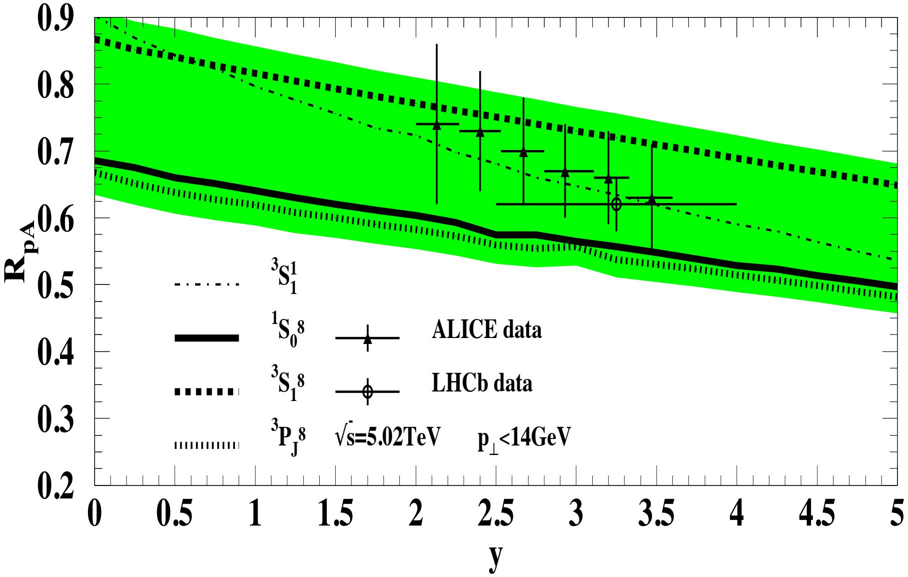

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    contribution of CS channel relatively small 10% in pp, 15-20% in pA at low p_T

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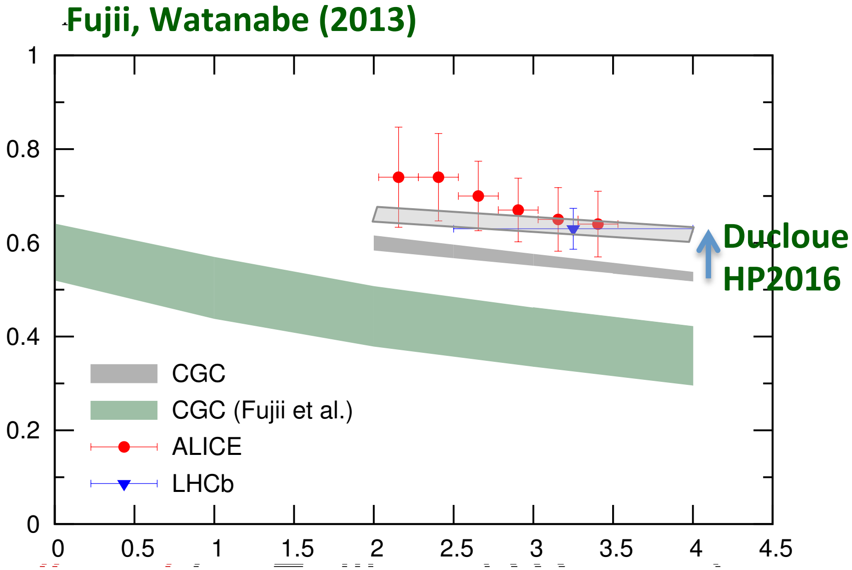

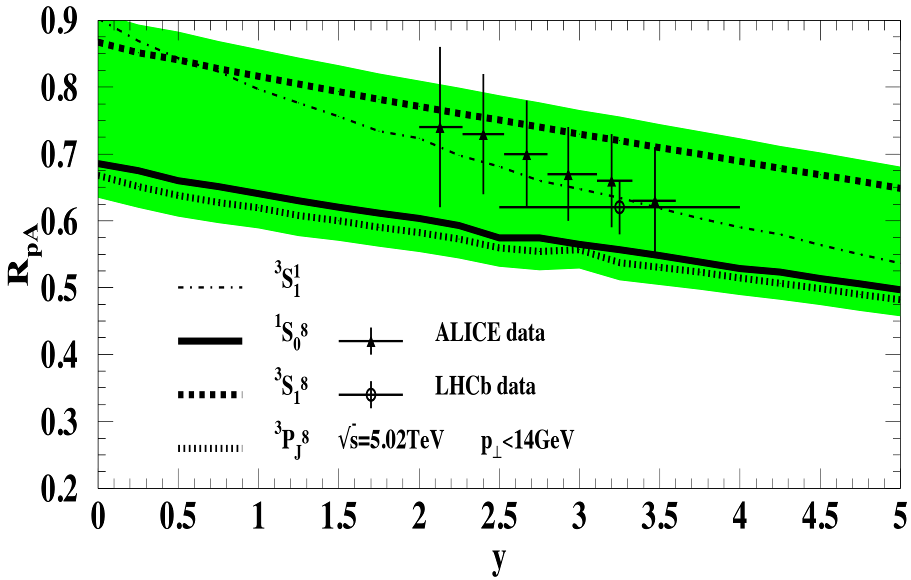

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- Issue: CGC results very much widespread (as those from nPDFs)
- Note: CGC on J/ψ suppression applies at forward y (not backward)

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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  $\sigma_{breakup} \alpha\, r^2_{meson}$

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

  the quantum state does not matter!

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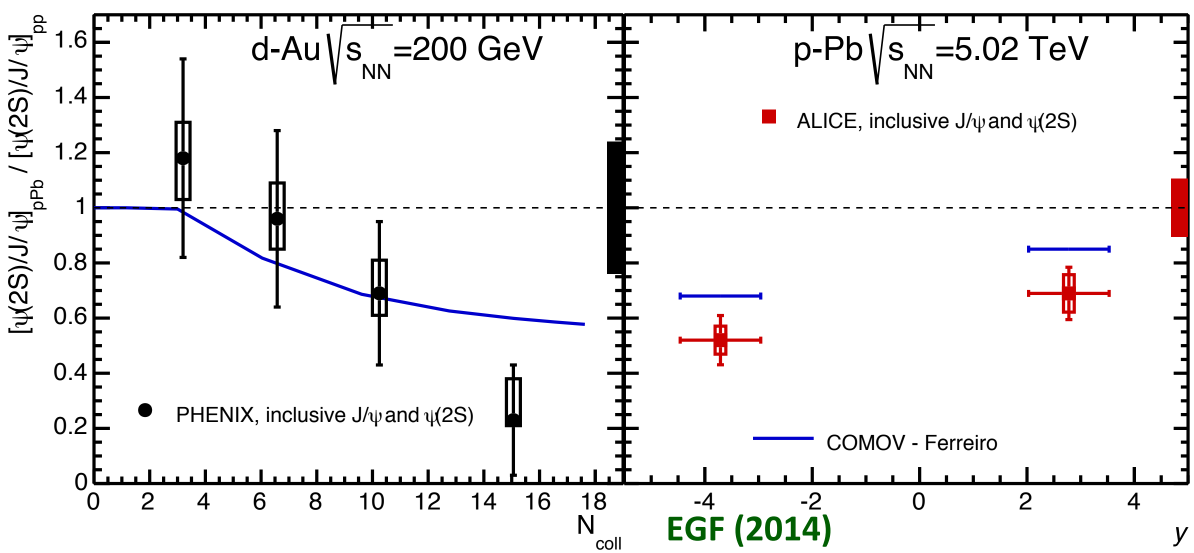
A natural explanation would be a final-state effect acting over sufficiently long time
=> **interaction with a comoving medium?**

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



EGF (2014)

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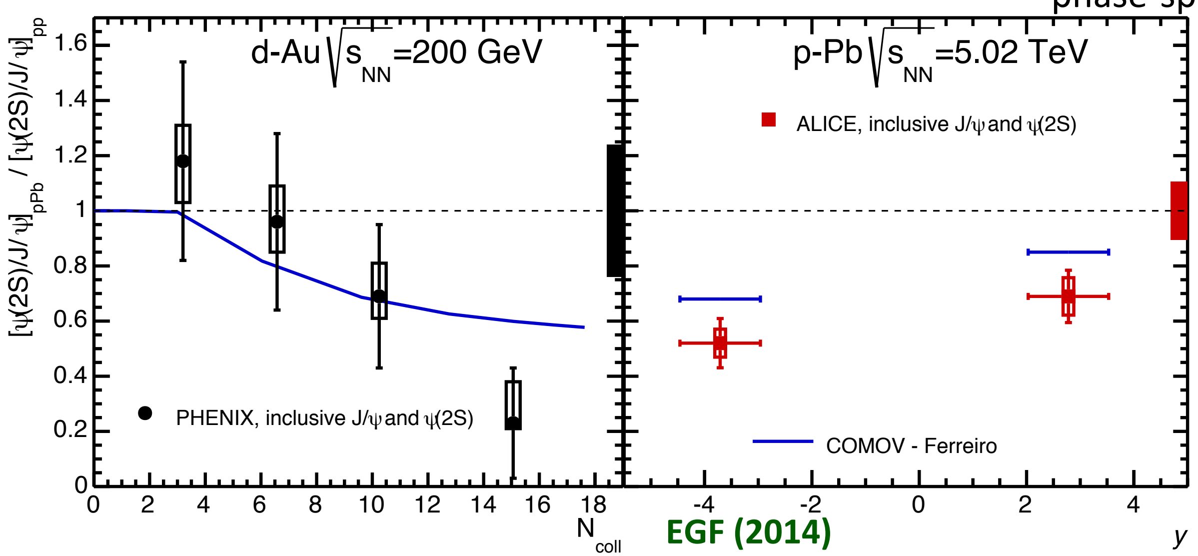
$\sigma^{co-\psi}$ originally fitted from SPS data

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

- 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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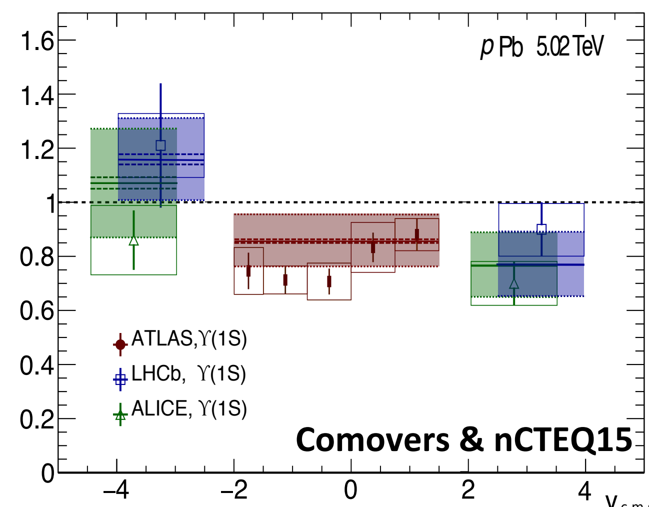
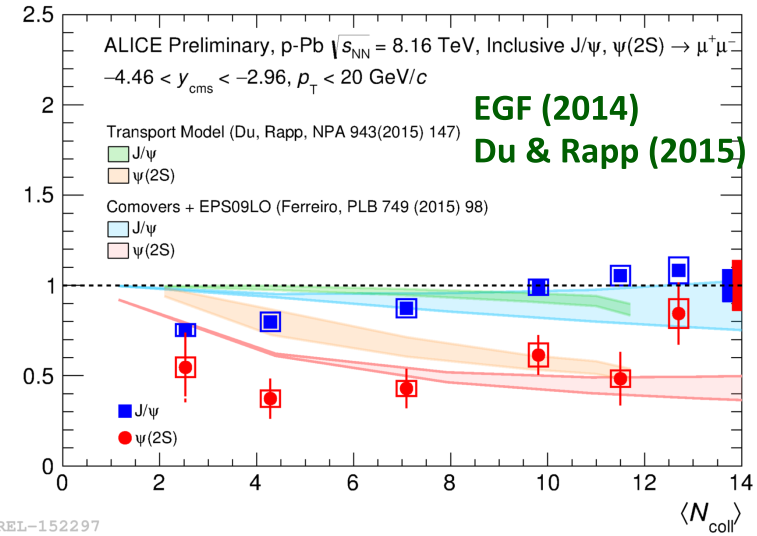


EGF & Lansberg (2018)

Excited states: Comover interaction

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

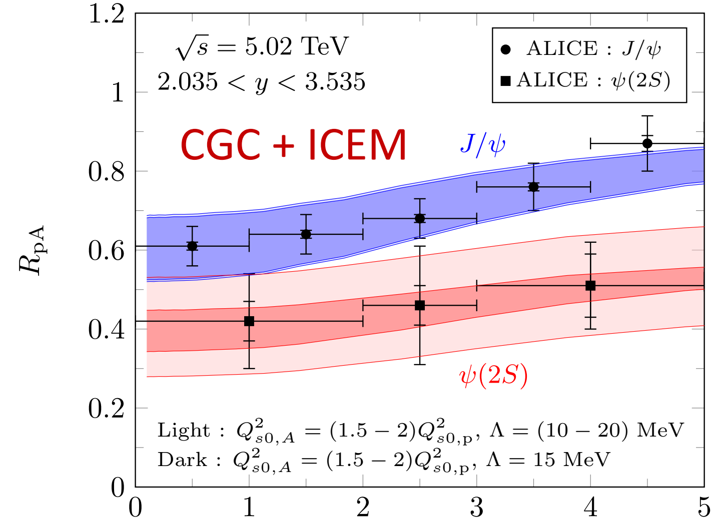
Soft color exchanges between cc & co-movers at later stage => effect on ψ(2S)



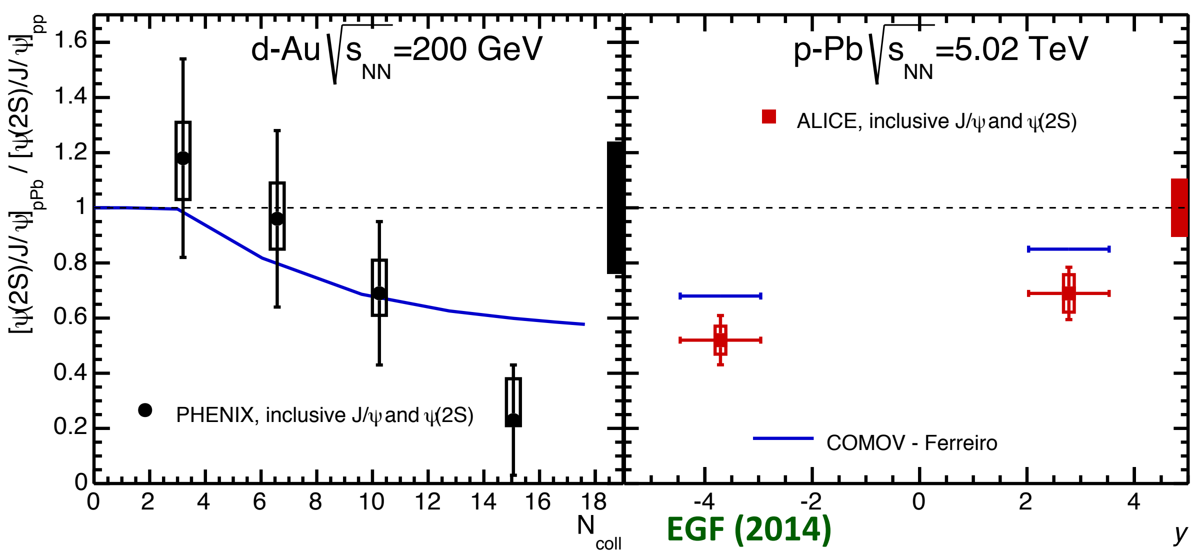
→New results on ψ(2S) confirm stronger suppression w.r.t. to J/ψ in the Pb-going direction.

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

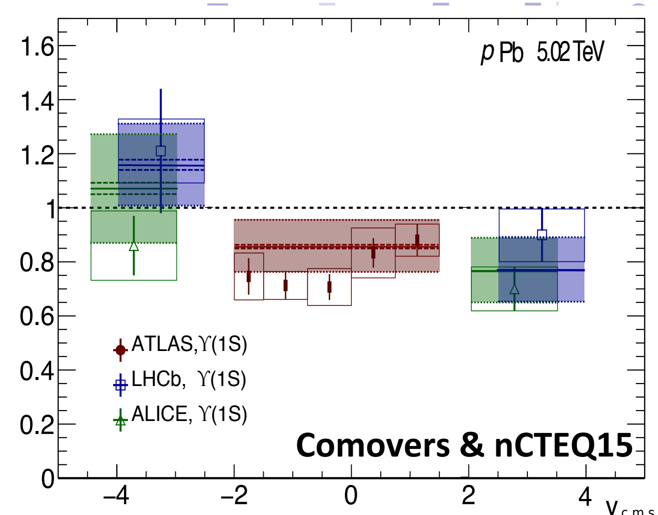
→Still problems for a quantitative description of the data.



Ma, Venugopalan, Zhang, Watanabe (2018)



EGF (2014)

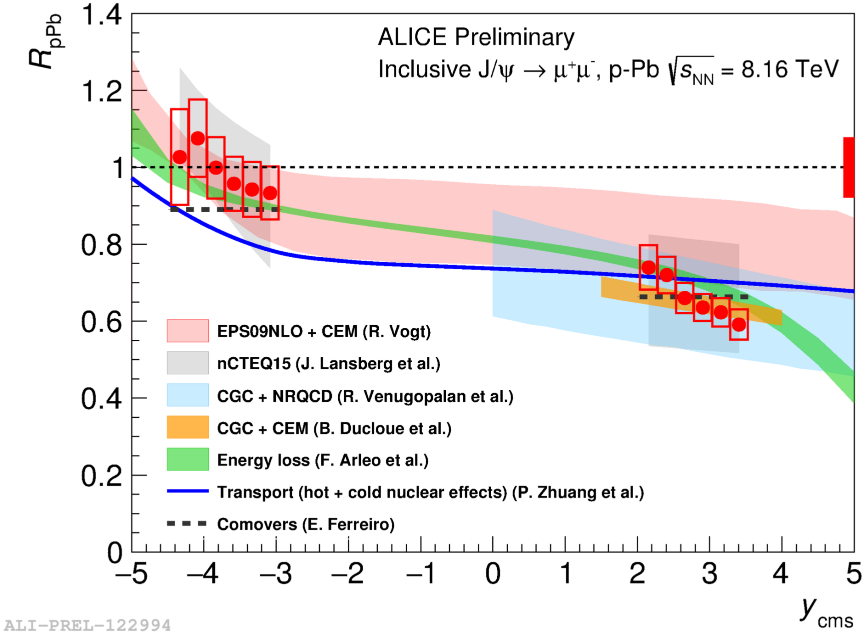


EGF & Lansberg (2018)

Some comments on proton-nucleus collisions

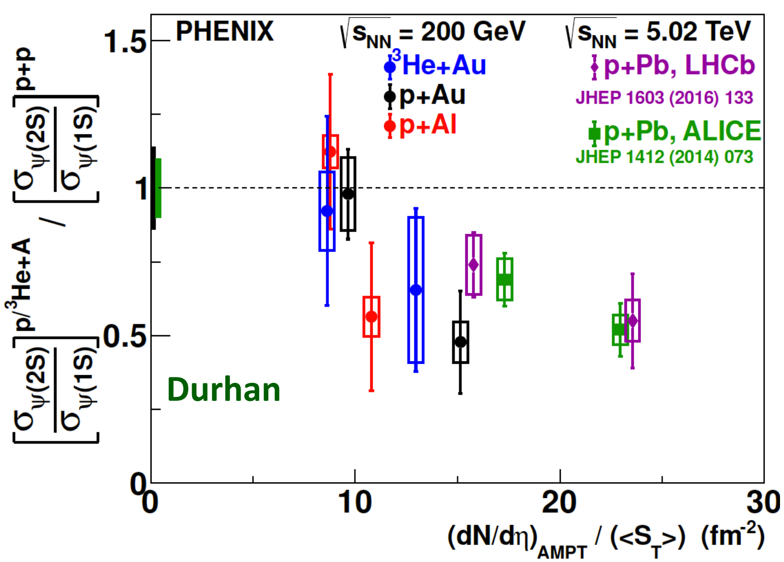
- **Initial-state effects** are required to explain pA data from RHIC and LHC
=> Modification of the gluon flux, either by modified nPDF **or** CGC, needs to be taken into account

  Issues:
  - Huge incertainty of nPDFS
  - Widespread CGC results



- Coherent Eloss mechanism can also reproduce **ground state** data

Direct comparison with LHC data as function of comoving particle density



- Final-state effects as comover interaction, are good candidates to reproduce **excited to ground state** data

EGF & Lansberg (2018)

*p*Pb 5.02 TeV	Comover model	CMS data $-1.93 < y < 1.93$
	$-1.93 < y < 1.93$	CMS data
$\Upsilon(2S)/\Upsilon(1S)$	0.91 ± 0.03	0.83 ± 0.05 (stat.) ± 0.05 (syst.)
$\Upsilon(3S)/\Upsilon(1S)$	0.72 ± 0.02	0.71 ± 0.08 (stat.) ± 0.09 (syst.)

Think bigger: 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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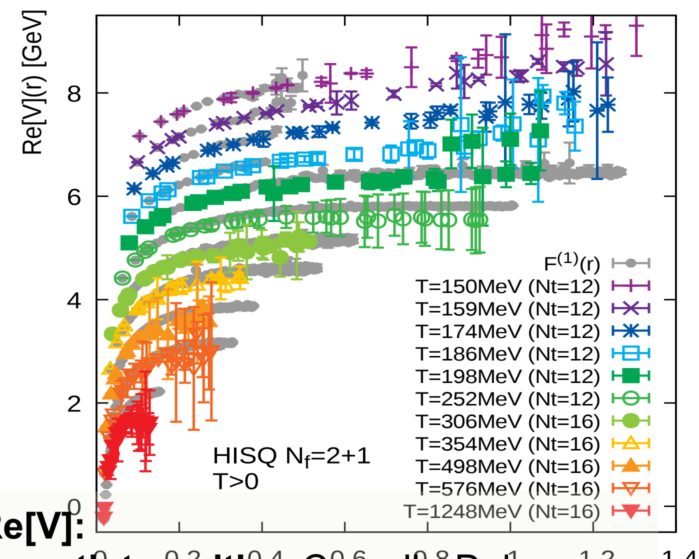
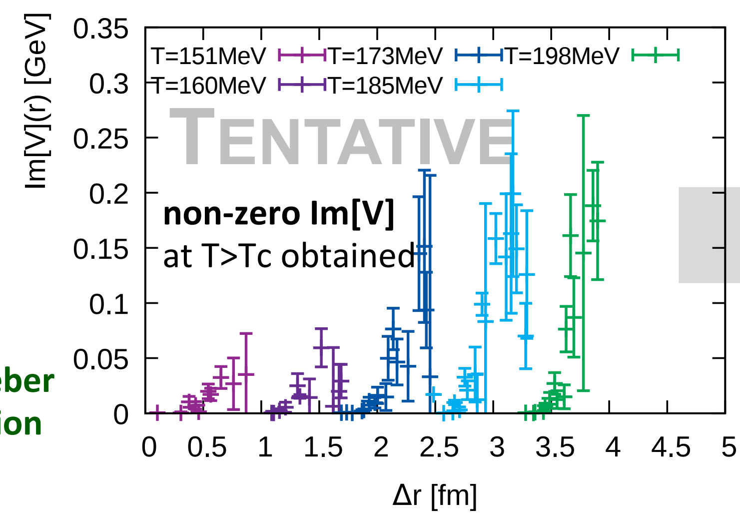


Re[V]:
smooth transition Cornell➡Debye
agrees with $F^{(1)}$ within uncertainty

Current efforts:

- lattice QCD calculation of complex in-medium HQ potential

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



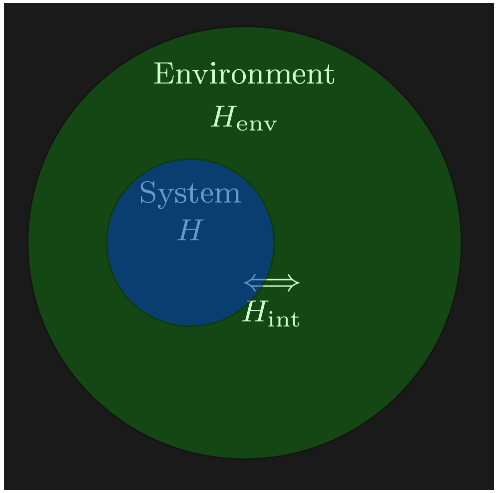
- understand the origin and physics implications of Im[V]

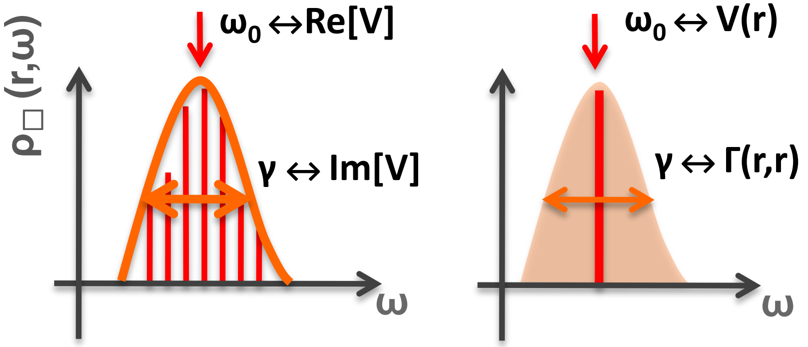
Thinking big: quarkonium in nucleus-nucleus collisions

- 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





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

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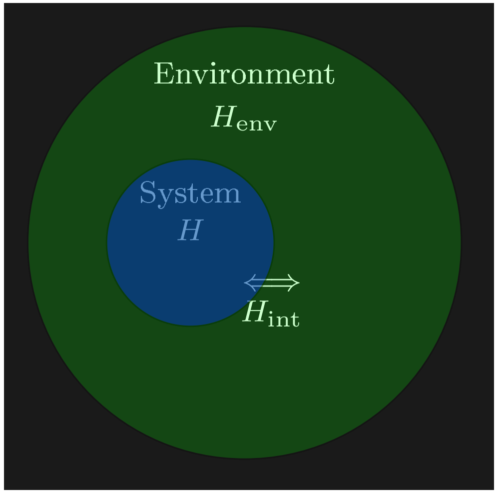

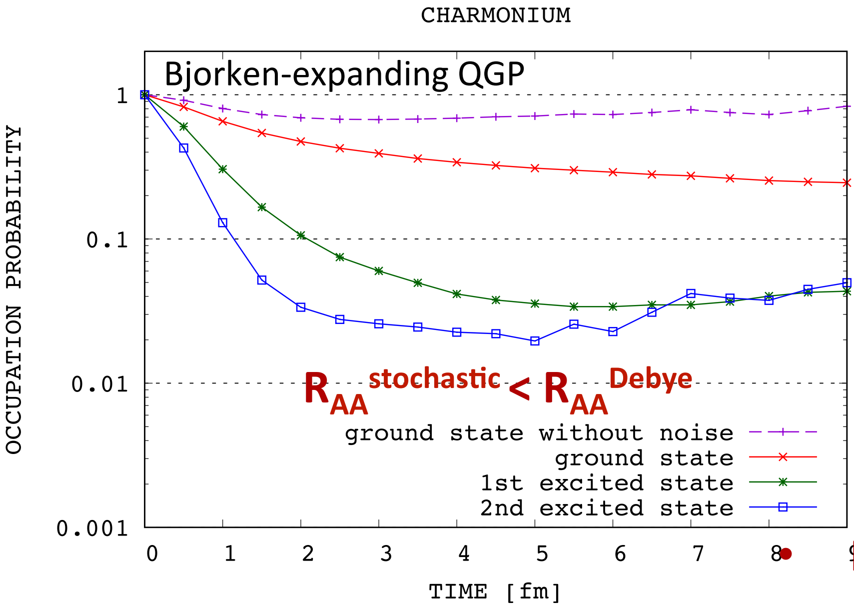

Kajimoto, Akamatsu, Asakawa, Rothkopf (2018)

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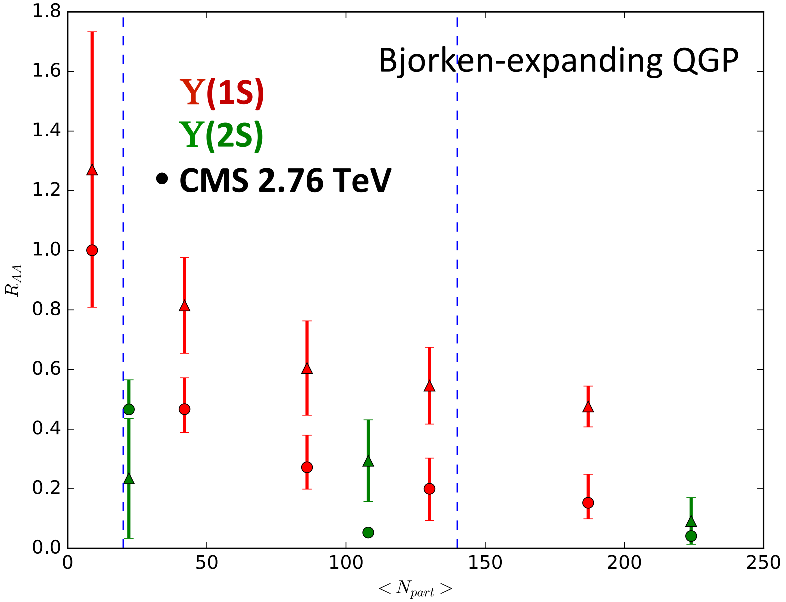
Noise provides an dynamical dissociation mechanism

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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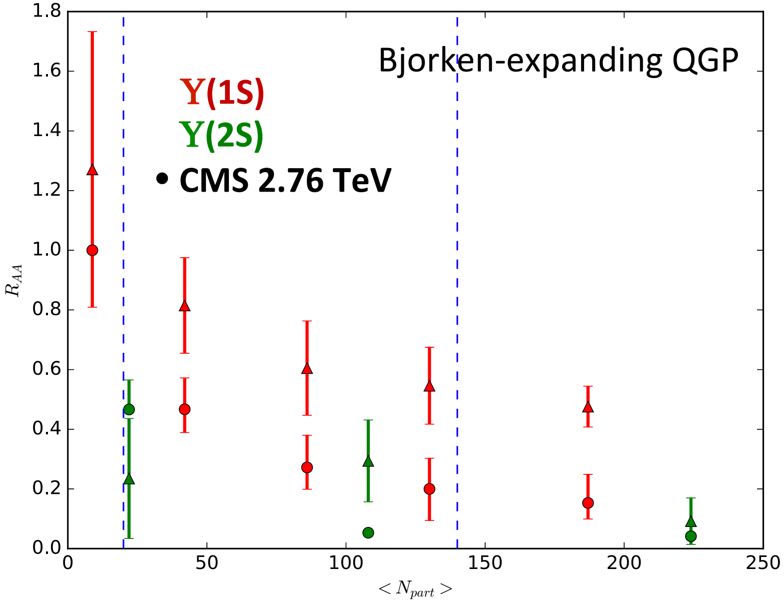

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Brambilla ... Soto & Vairo (2017)

Master equation with time evolution of the HQ states

In the same line: equations for the time ev... the HQ reduced-density matrix in a non-Abelian QGP

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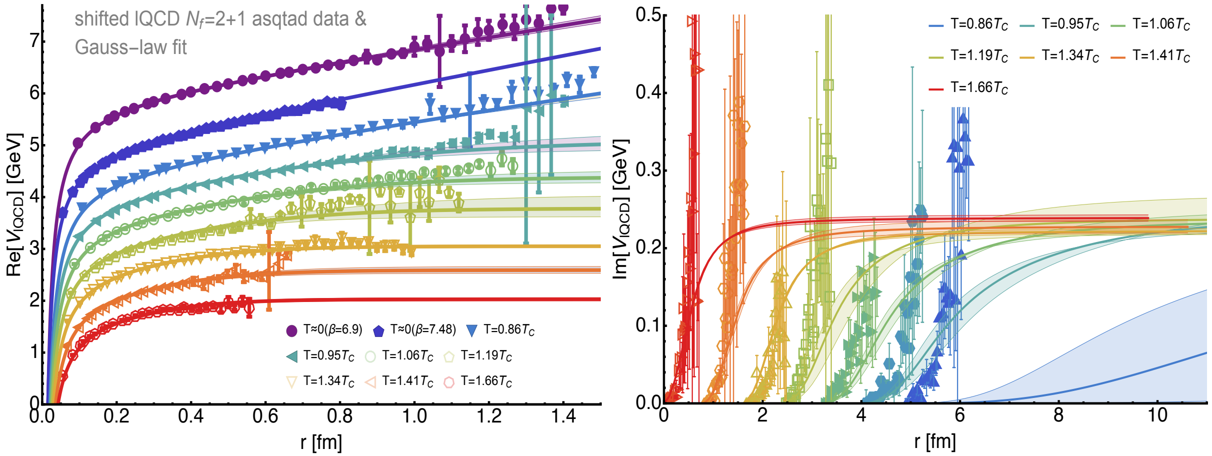
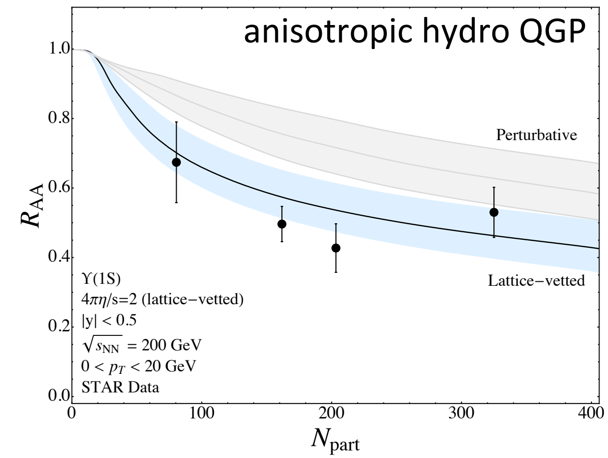
Recent developments on phenomenology for quarkonia

Anisotropic QGP with lattice potential

- lattice QCD vetted HQ potential: complex values at high T
- Υ states more easily dissociated

Kroupa, Strickland, Rothkopf (2018)

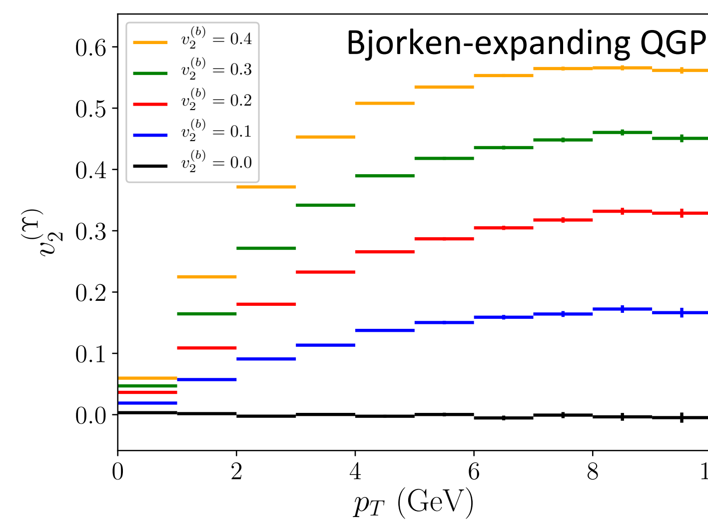




Dynamical in-medium transport model:

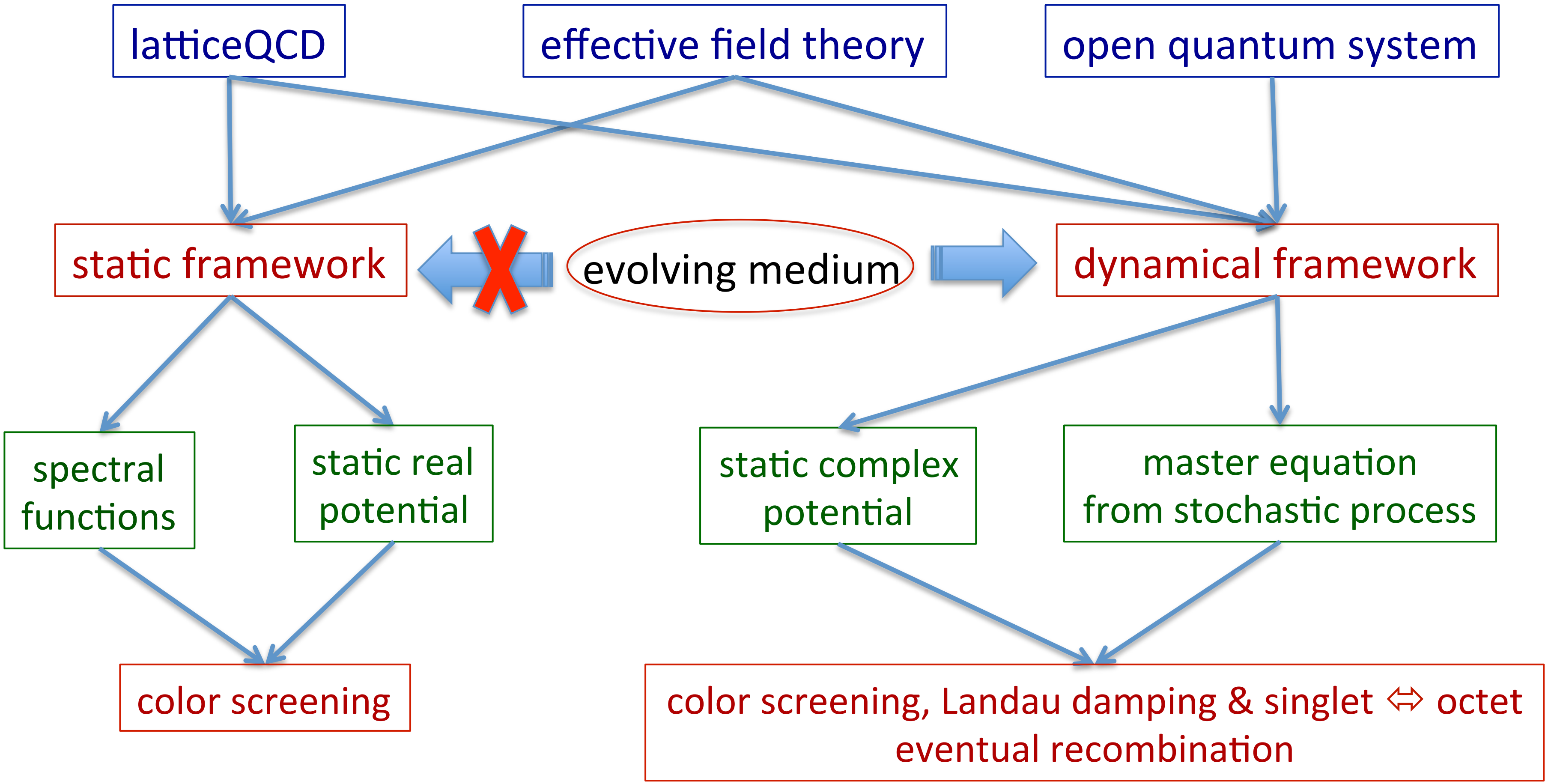
Yao & Muller (2018)

- pNRQCD in a thermal QGP
- Stochastic Boltzmann equations
- HQ diffusion in the medium: necessary for the system to reach equilibrium



Summarizing: theory elements on quarkonia in a QGP

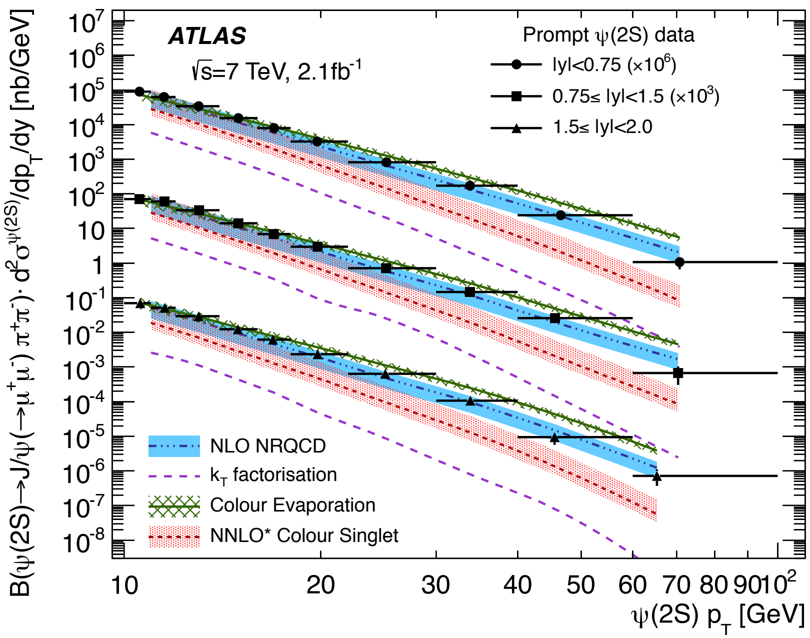
Caveat I: we need firm theoretical understanding of quarkonium production in pp collisions



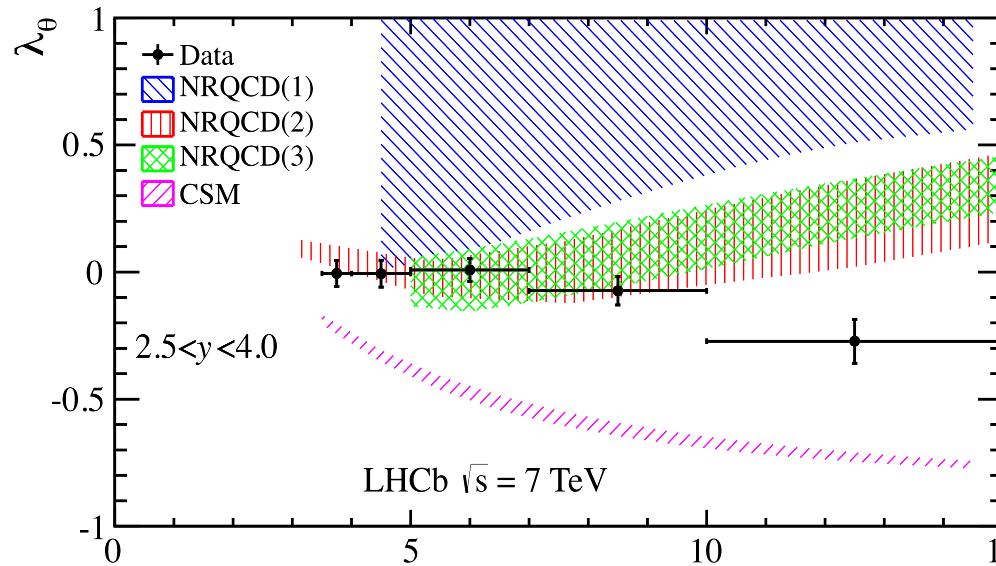
Caveat II: how to extrapolate pA effects –initial & final- to AA? Factorization?
If yes… nature of the medium in pA?

BACKUP PROTON-PROTON

Production model: state of the art for the ψ(2S)



Sapore Gravis Review arXiv:1506.03981



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

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 (heavy-quark mass, scales, non-perturbative parameters, unknown QCD and relativistic corrections, ...)

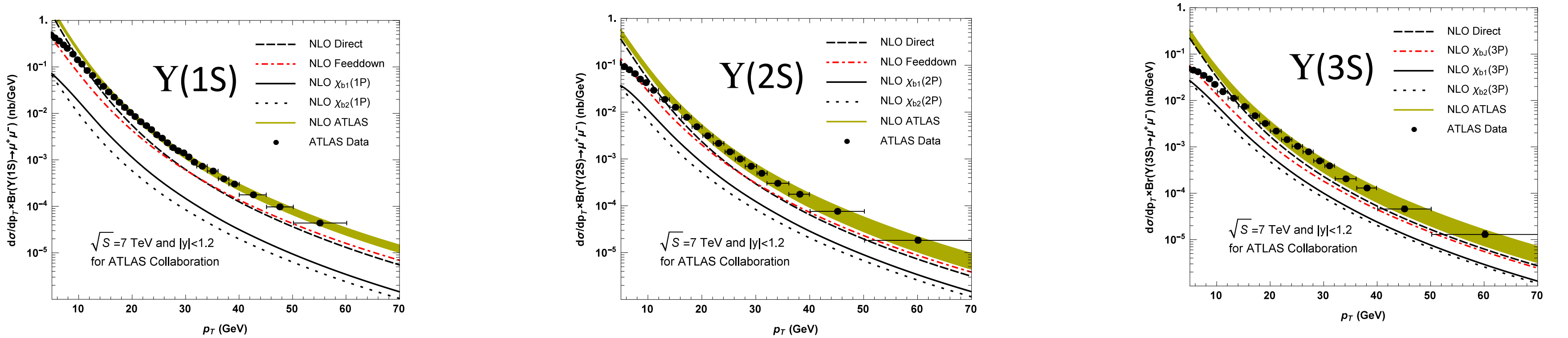
New recent developments on may be helpful:

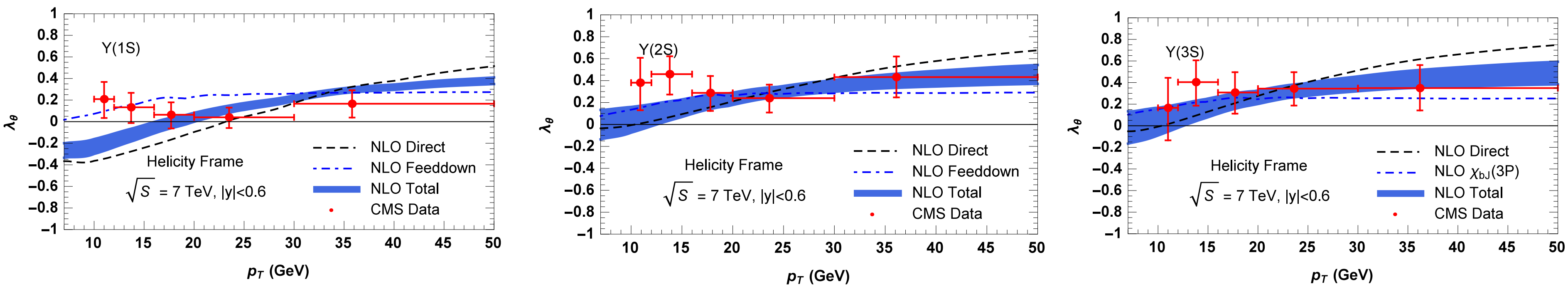
- CEM improved
- CGC meets NRQCD

Production model: state of the art for the Υ

- Larger mass, higher scale and slower velocity could make Υ a better candidate for NRQCD

Hang et al.





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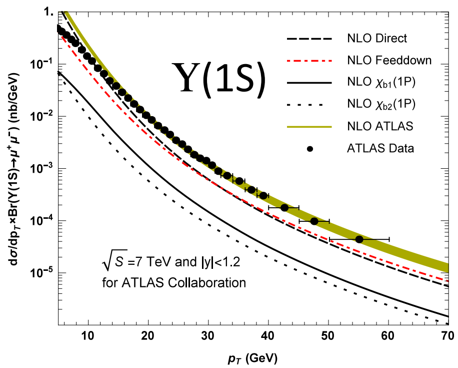
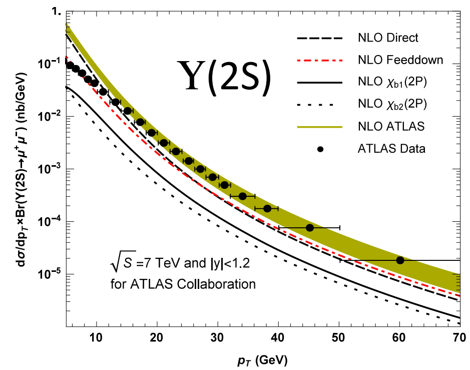
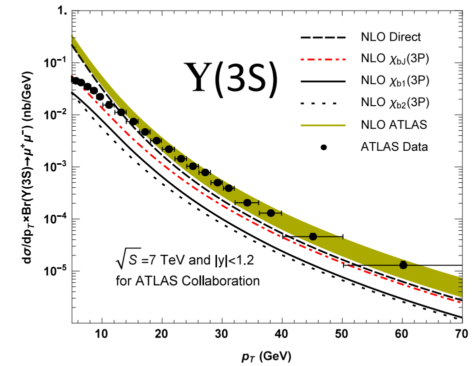
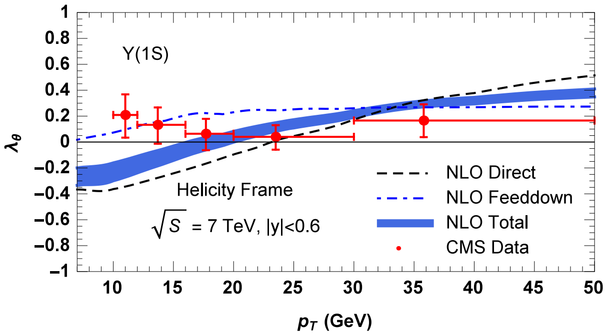
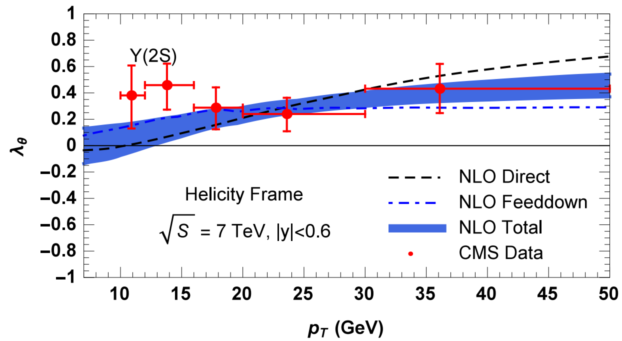
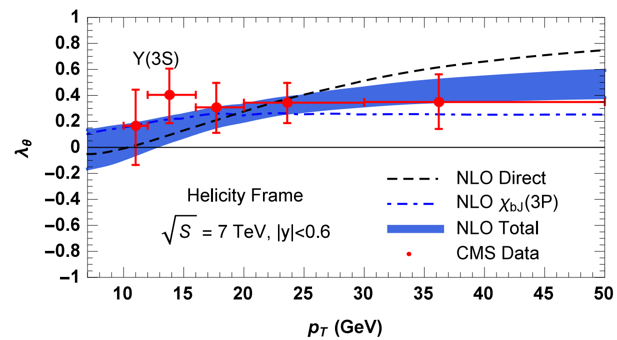




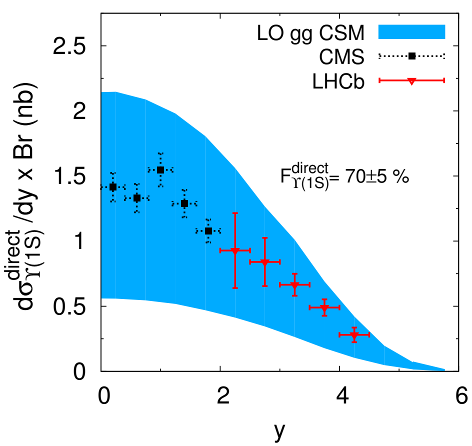


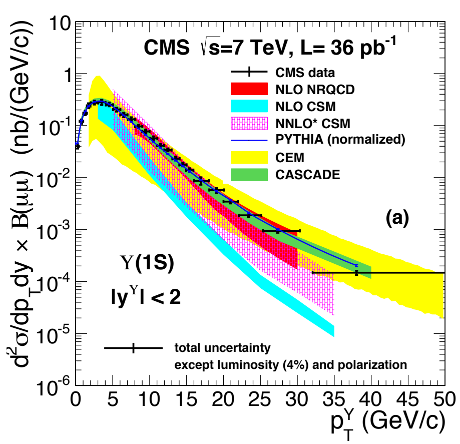






Lansberg

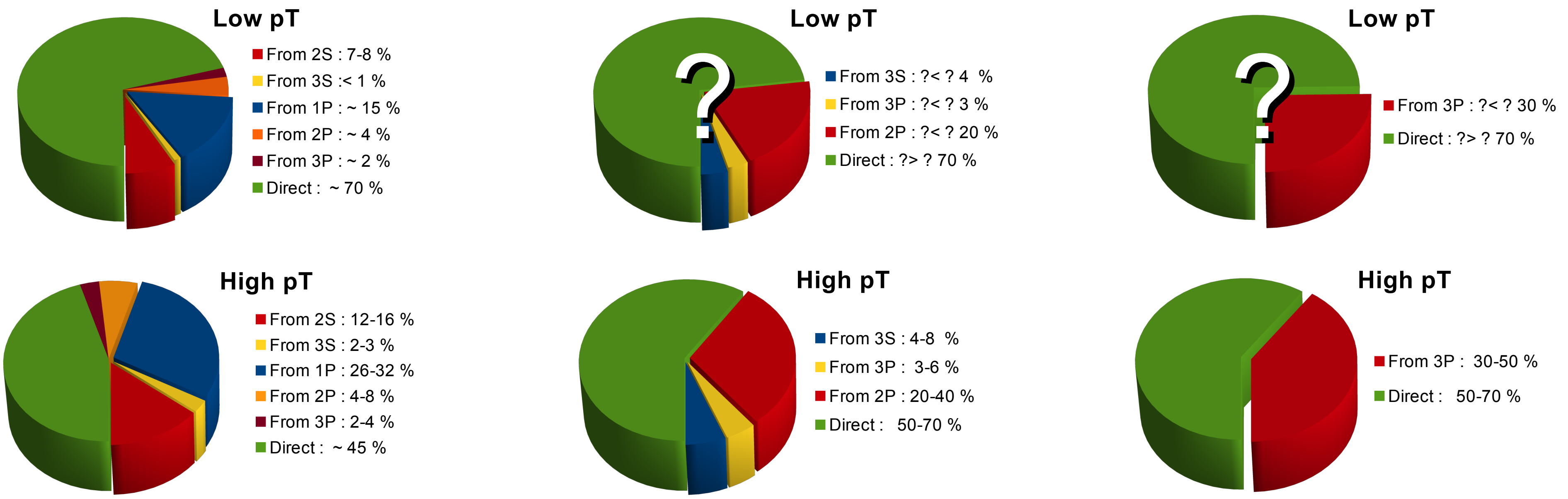




- None of the models can simply be ruled out due to their theoretical uncertainties
- In general, LHC data are much more precise than theory
- Caveat: Important feeddown contributions -6 states- to be taken into account for interpretations of their possible sequential suppression

News from feed-down

Feed-down structure at low p_T -where quarkonium heavy-ion measurements are mostly carried out- is quite different than that commonly accepted ten years ago based on the CDF measurement, with a p_T>8 GeV



(a) $\Upsilon(1S)$ (b) $\Upsilon(2S)$ (c) $\Upsilon(3S)$

Sapore Gravis Review arXiv:1506.03981 from LHCb data

This information is fundamental to use bottomonia as probes of QGP, especially for the interpretation of their possible sequential suppression

BACKUP PROTON-NUCLEUS

Baseline: nPDFs & nuclear absorption in a collinear pQCD framework

- Parton densities in nuclei are modified

Nuclear PDF assumed to be factorizable in terms of the nucleon PDFs :

$$\mathcal{F}_g^A(x_1, \mu_f) = g(x_1; \mu_f) \times R_g^A(x, \mu_f)$$

In presence of nuclear effects: $R_g^A(x, \mu_f) \neq 1$

- Mesons may scatter inelastically with nucleons in the nuclear matter

Survival probability for a $Q\bar{Q}$ to pass through the target unscathed:

$$S_A(\vec{r}_A, z_A) = \exp\left(-A\,\sigma_{\text{break-up}} \int_{z_A}^{\infty} d\tilde{z}\, \rho_A(\vec{r}_A, \tilde{z})\right)$$

- Any differential cross section can then be obtained from the partonic one:

$$\frac{d\sigma_{pA\to\mathcal{Q}X}}{dy\, dP_T\, d\vec{b}} = \int dx_1 dx_2 g(x_1, \mu_f) \int dz_A \mathcal{F}_g^A(x_2, \vec{b}, z_B, \mu_f) \mathcal{J} \frac{d\sigma_{gg\to\mathcal{Q}+g}}{d\hat{t}} S_A(\vec{b}, z_A)$$

From any model (CSM, COM, CEM)

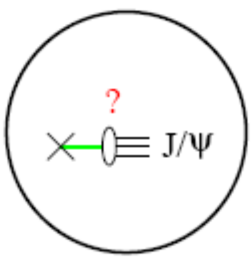
Nuclear absorption: Generalities on the break-up cross section

The bound states may be destroyed by inelastic scatterings with nucleons if they are formed in the nuclear medium. One expect $\sigma_{\mathrm{break-up}} \propto r^2_{\mathrm{meson}}$

- In order to interact with nuclear matter => $t_f \leq R$
- In the meson rest frame: $\tau_f = \frac{2M_{c\bar{c}}}{(M^2_{2S} - M^2_{1S})} \approx 0.3 \div 0.4$ fm
- t_f has to be considered in the rest frame of the target nucleus => $t_f = \gamma\, \tau_f$

Low energy: $t_f = \gamma(x_2)\,\tau_f \ll R$

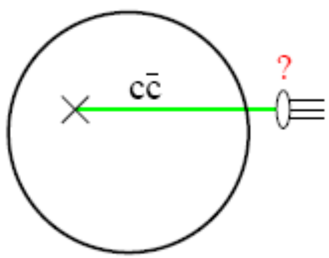
High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



Formation time depends on the boost

$\gamma = \cosh(y - y^A_{\mathrm{beam}})$ => At y=0:

$\gamma_{\mathrm{RHIC}}=107$ and $\gamma_{\mathrm{LHC}}=2660$



It takes t_f =30 fm/c at RHIC and t_f =800-1000 fm/c at LHC for a quarkonium to form and to become distinguishable from its excited states $t_f \gg R$

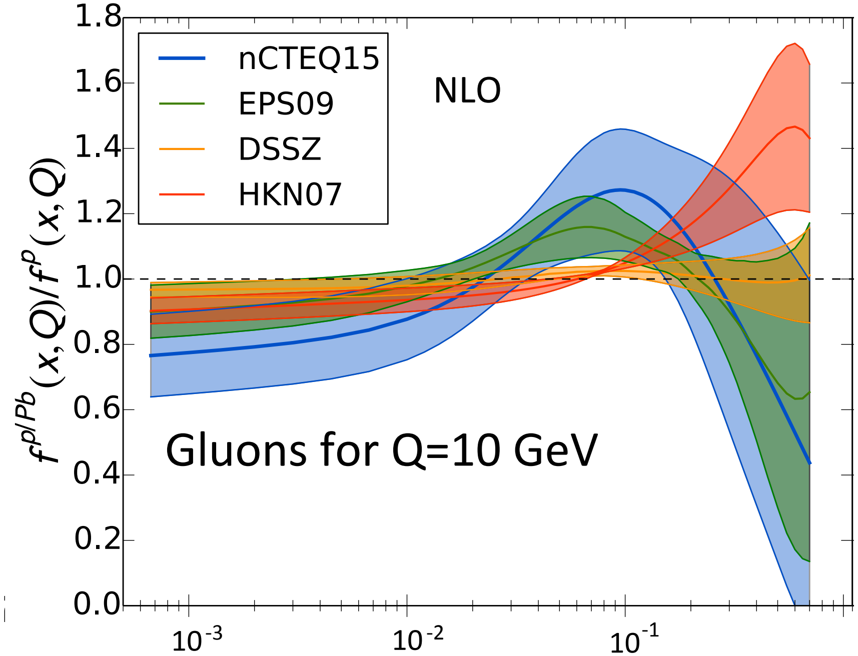
Consensus: $\sigma_{\mathrm{break-up}}$ is getting small at high energies and may be the same for ground and excited states

Typical gluon nuclear PDFs

There are several nPDF sets available (using various data, LO/NLO, etc)

Typical gluon nPDFs: 4 regions

- $x \leq 10^{-2}$: shadowing
- $x \approx 10^{-1}$: anti-shadowing
- $0.3 \leq x \leq 0.7$: EMC effect
- $x \geq 0.7$: Fermi motion

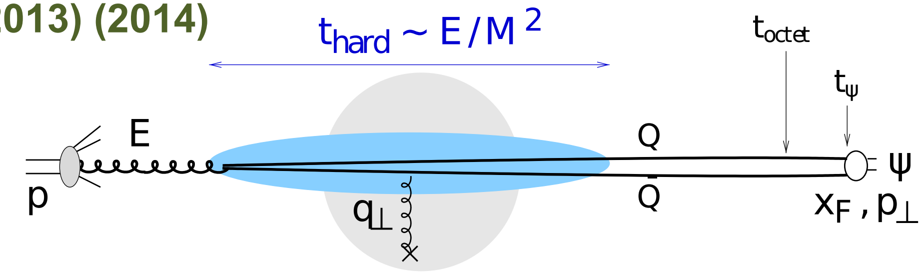


- For the gluons, only the shadowing depletion is established although its magnitude is still discussed
- The gluon antishadowing not yet observed although used in many studies; absent in some nPDF fits
- The gluon EMC effect is even less known, hence the uncertainty there

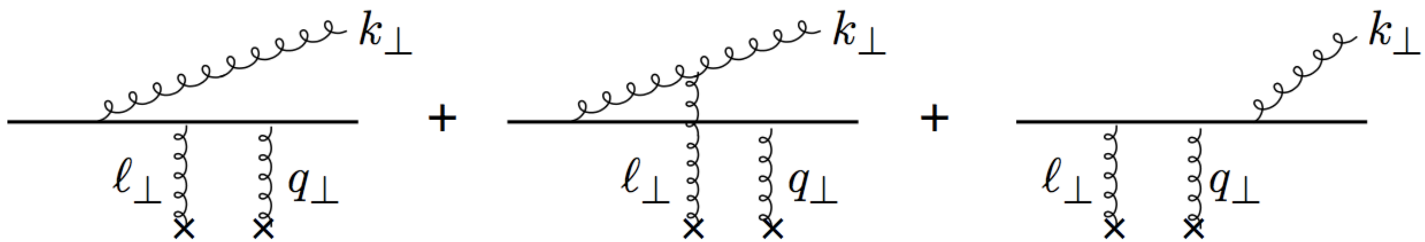
Going further: Coherent energy loss

Arleo, Kolevatov, Peigné, Rustamova (2012) (2013) (2014)

This approach is based on the fact that for large formation times all scattering centers in the medium act coherently.



- Coherent radiation (interference) in the initial/final state crucial for $t_f >> R$



IS and FS radiation cancels out in the induced spectrum
Interference terms does not cancel in the induced spectrum!

- Leads to a behaviour $\Delta E \,\alpha\, E$

$$\Delta E = \int d\omega\, \omega \left.\frac{dI}{d\omega}\right|_{\text{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{m_T} E$$

- $\sqrt{\Delta q_\perp^2}$ related to the transport coeficient $\hat{q}$

$$\hat{q}(x) \simeq \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

- $\hat{q}$ related to the saturation scale by $Q_s^2(x, L) = \hat{q}(x) L$

- $\hat{q}_0$ is the only fitted parameter of the approach+the option to switch on/off the shadowing

BACKUP NUCLEUS-NUCLEUS

In-medium Quarkonium properties from first principles

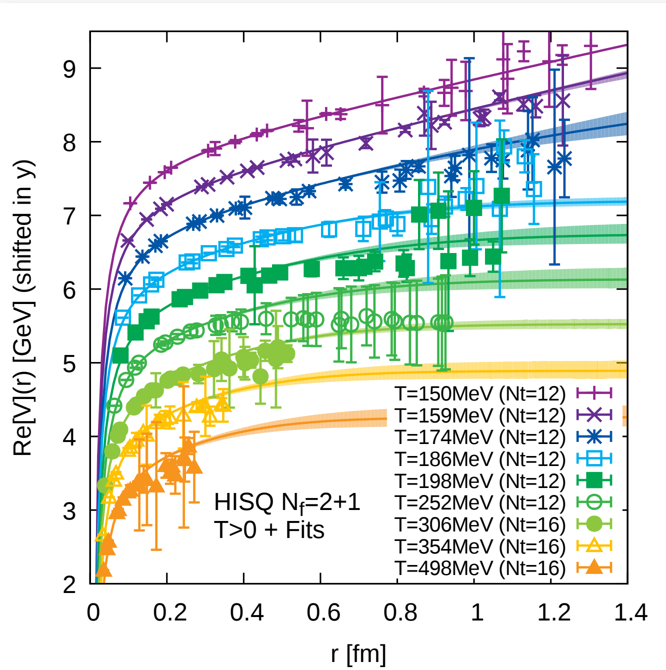
Realistic **lattice QCD** calculation of the complex in-medium **heavy quark potential**

In-medium quarkonium **spectral properties** from a lattice **effective field theory** (NRQCD)

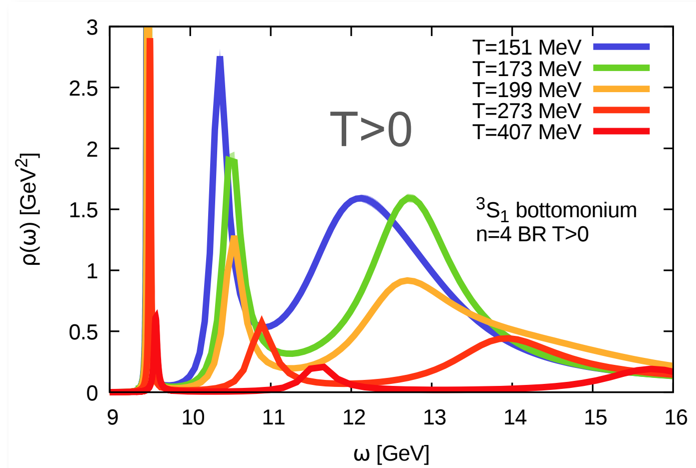
Improved spectral function extraction **algorithm**, **higher statistics**, **larger temperature** range

P. Petreczky, A. Rothkopf, J. Weber
[TUM-QCD] in preparation

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



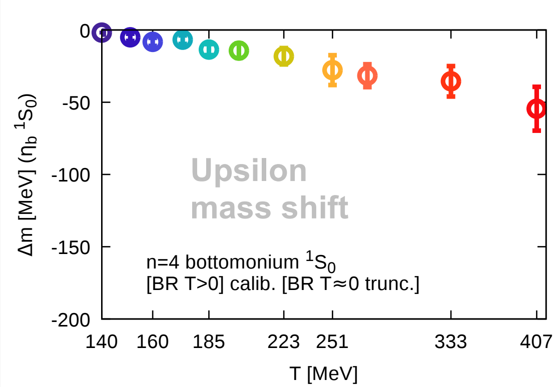
non-zero Im[V] at T>Tc obtained

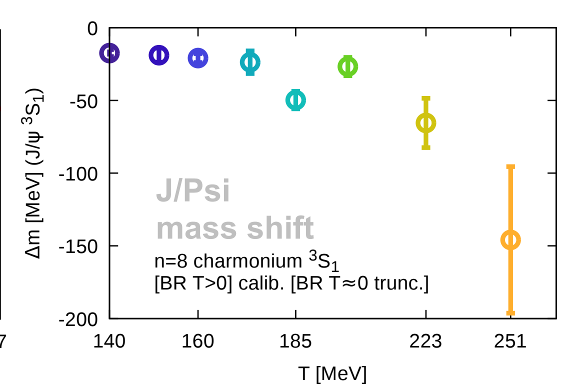


S.Kim, P. Petreczky, A. Rothkopf, in preparation

more accurate **melting temperatures**

Heavy $Q\bar{Q}$ becomes **lighter** before melting



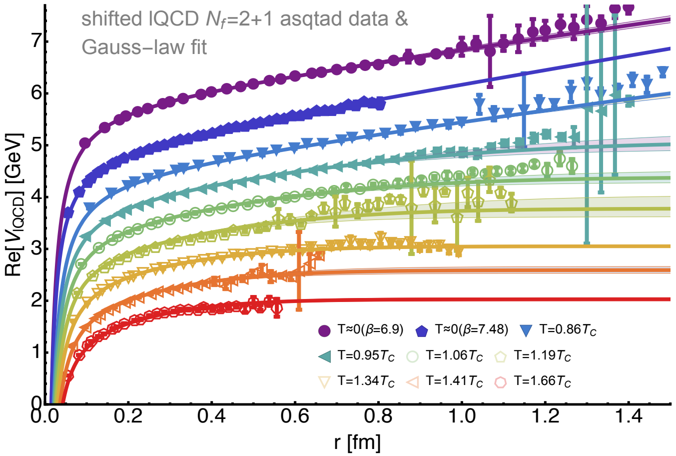


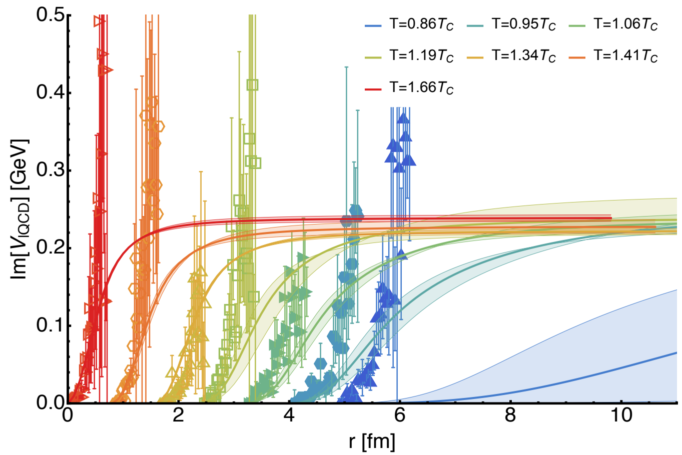
Δm<0 consistent with potential based results

Pheno: Υ suppression in anisotropic QGP with lattice potential

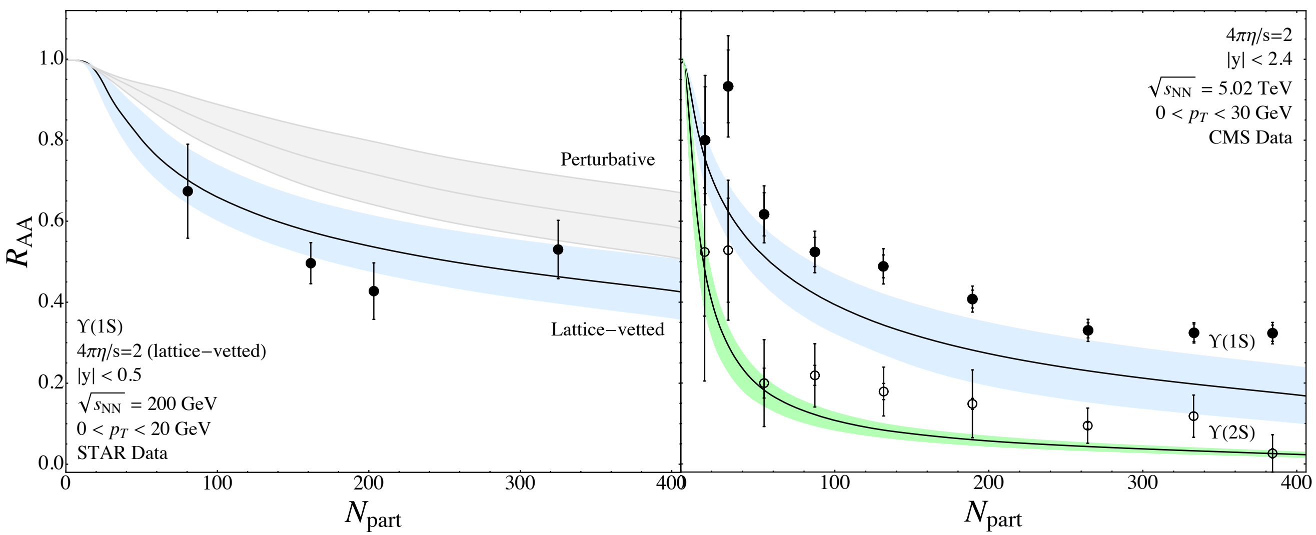
- lattice QCD vetted in-medium heavy-quark potential with anisotropic hydro QGP
- in-medium potential: complex values at high temperatures
- discrete values of the potential obtained from lattice QCD

Krouppa, Strickland, Rothkopf (2018)





- a single T-dependent parameter remains, the Debye mass m_D

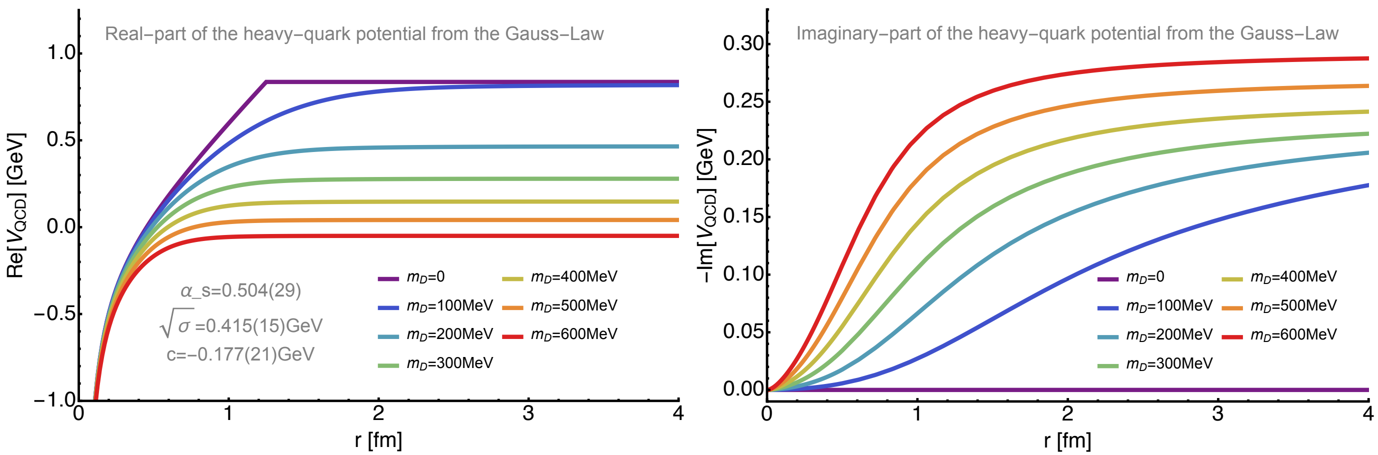


- feed down taken into account
- stronger imaginary part present in the lattice-vetted potential => Υ states more easily dissociated
- space for recombination?

Pheno: Υ suppression in anisotropic QGP with lattice potential

- lattice QCD vetted in-medium heavy-quark potential with anisotropic hydro QGP
- in-medium potential: complex values at high temperatures
- discrete values of the potential obtained from lattice QCD

Krouppa, Strickland, Rothkopf (2018)



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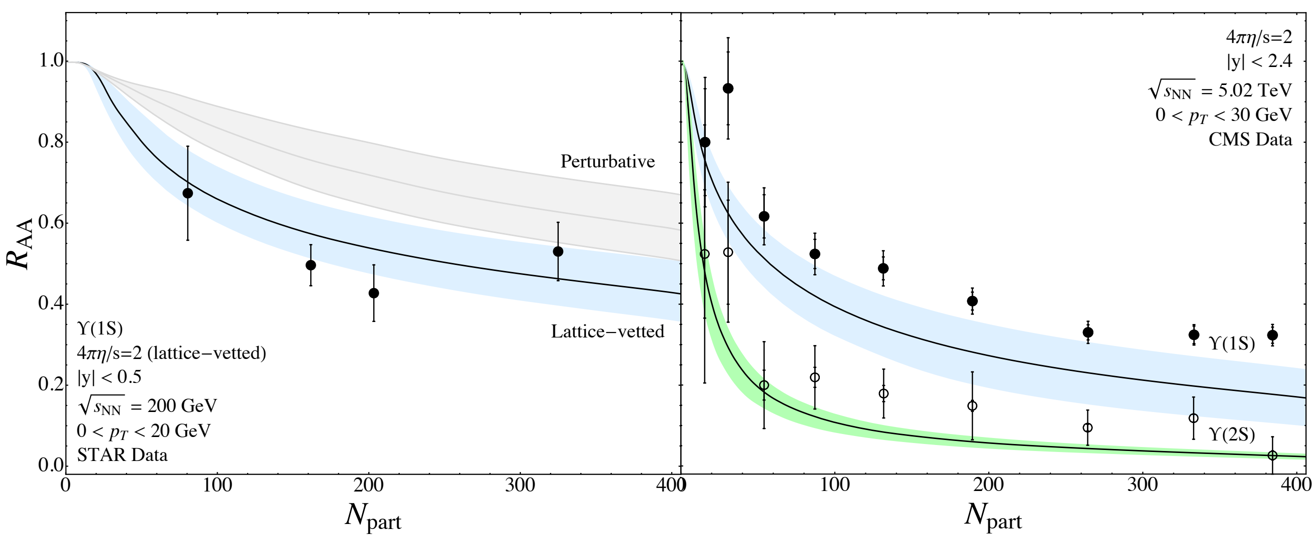

- feed down taken into account
- stronger imaginary part present in the lattice-vetted potential => Υ states more easily dissociated
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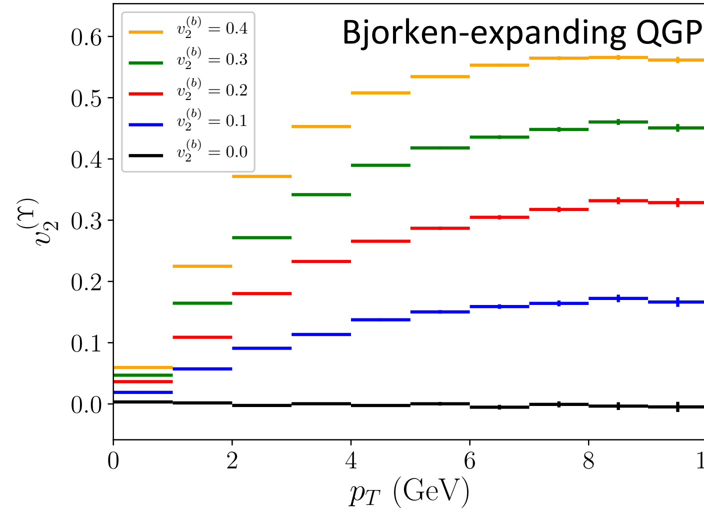
Phenomenology: recent developments

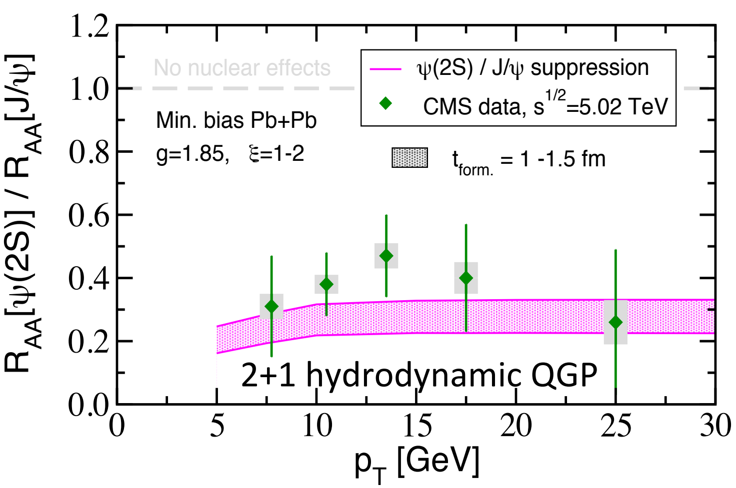
Dynamical in-medium transport model:

- pNRQCD in a thermal QGP
- Stochastic Boltzmann equations
- HQ diffusion in the medium:
  necessary for the system to reach equilibrium
- Predicts v_2 from recombination **Yao & Muller (2018)**



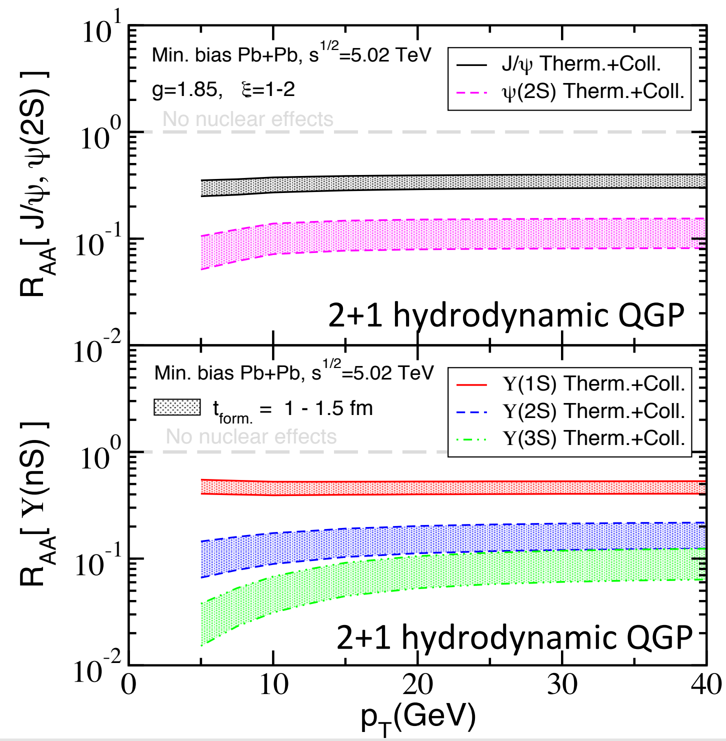
Collisional and thermal dissociation at high p_T:

- Collisional dissociation by p_T broadening
- Debye screening, no Im[V] **Vitev & Sharma (2017)**



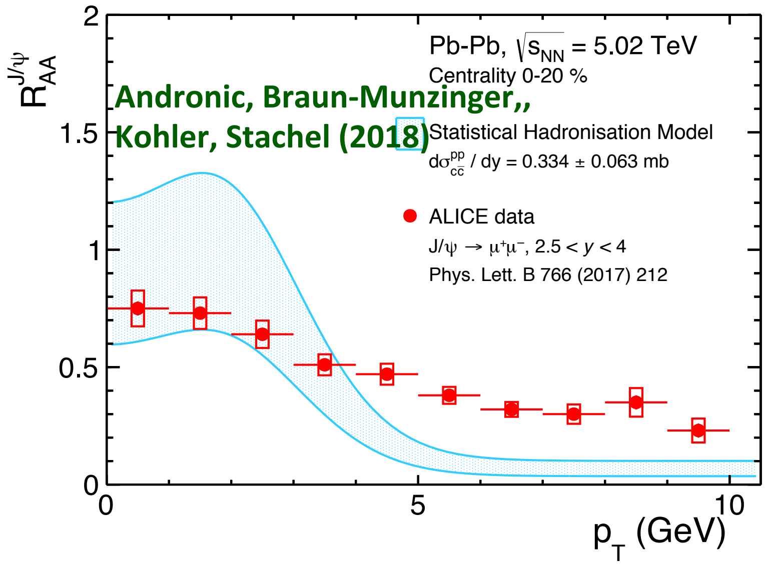
Quarkonium formation time ~1 fm

NRQCD for nucleon-nucleon baseline

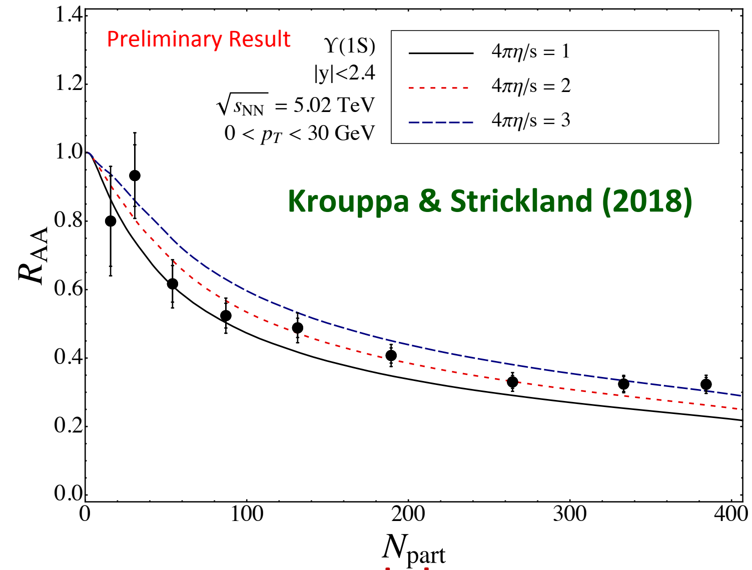


Recent results from some long-lasting phenomenology models

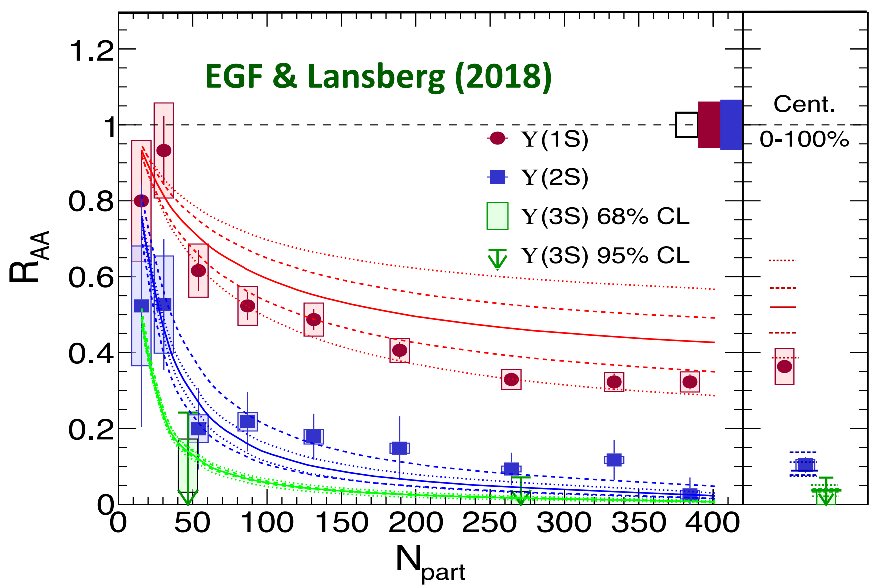
Statistical hadronisation model



a-hydro model



Comover model



Transport model