Quarkonia in heavy-ion (& proton-proton) collisions

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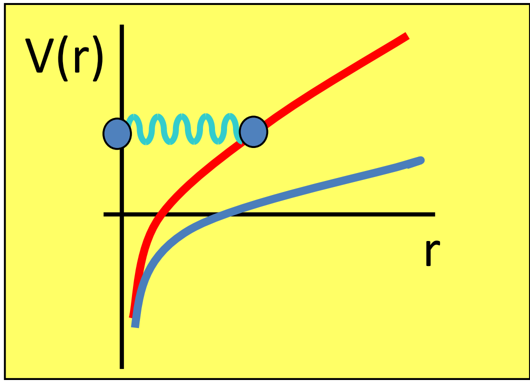
Motivation: J/ψ production as a signal of the QGP

Potential between q-anti-q pair grows linearly at large distances

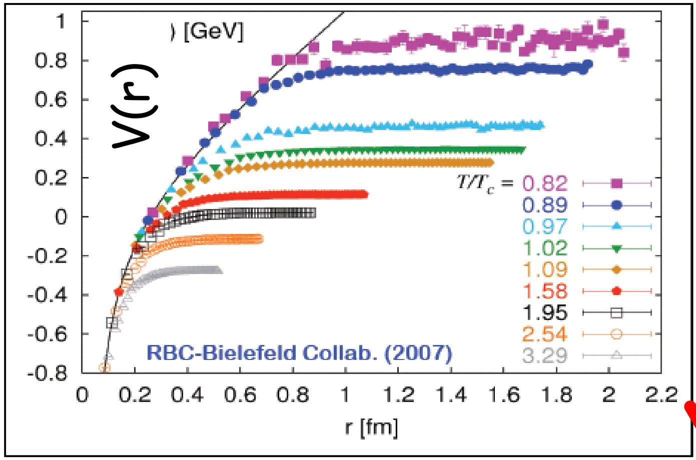
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



Screening of long range confining potential at high enough temperature or density.

$$V(r) = -\frac{\alpha}{r} + kr \longrightarrow V(r) = -\frac{\alpha}{r}e^{-r/\lambda_D}$$

Debye screening radius $\lambda_D(T)$ depends on temperature



What happens when the range of the binding force becomes smaller than the radius of the state?

$r > \lambda_D$

different states "melting" at different temperatures due to different binding energies.

Matsui and Satz 80's: J/ψ destruction in a QGP by Debye screening

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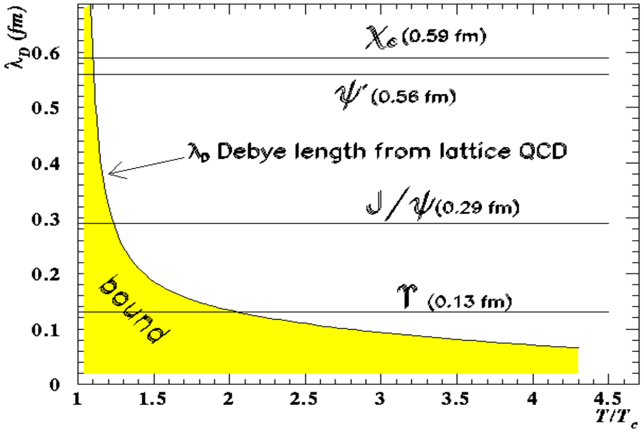
$\lambda_D(T)$ depends on temperature

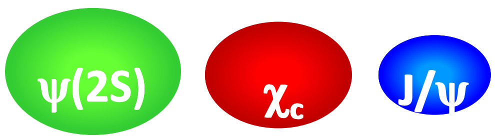


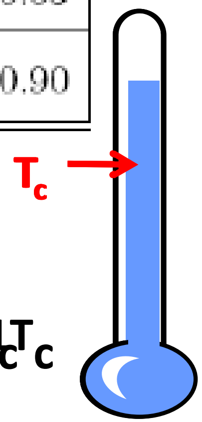
The quarkonium states are characterized by

- the binding energy
- radius

state	J/ψ	χ_c	ψ'
mass [GeV]	3.10	3.53	3.68
ΔE [GeV]	0.64	0.20	0.05
ΔM [GeV]	0.02	-0.03	0.03
r_0 [fm]	0.50	0.72	0.90

Debye screening condition **r > λ_D** will occur at different T for the different species

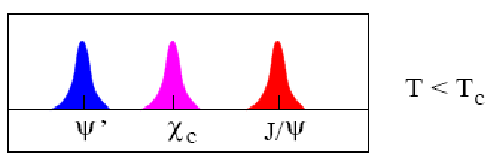


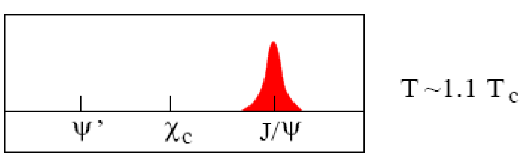


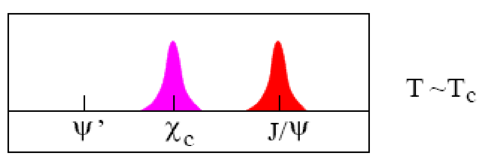
Quarkonium as a "thermometer" of the QGP

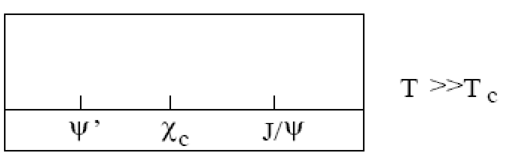
J/ψ suppression can be due to

- **the melting of the J/ψ itself**
- **the melting of excited states which feed down to J/ψ**









...but the story is not so simple

- Are there any other effects, not related to colour screening, that may induce a suppression of quarkonium states ?
- Can the melting temperature(s) and feed-downs be uniquely determined ?
- Are there effects that can induce an enhancement of quarkonium?
- Is it possible to define a “reference”(i.e. unsuppressed) process in order to properly define quarkonium suppression ?
- Do we understand charmonium production in elementary p+p collisions?

Let’s start by the end….

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- Do we understand **charmonium production in elementary p+p collisions?**

Let's start by the end....

Quarkonium production schemes: 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

Different approaches to hadronization

Production mechanism still not settled after more than 40 years!

Color singlet model (CSM): 1975 -

Einhorn, Ellis (1975), Chang [illegible] ger & Jone (1981), …

- Assume physical color singlet state, quantum nu [illegible] e conserved
- Only the pair with right quantum numbers [illegible]

Effectively no free parameter

Color evaporation model (CE [illegible] -

Fritsch (1977), Halzen (1977), …

- Does not distinguish [illegible] ith respect to their color and spin
- All pairs with [illegible] than open heavy flavor threshold

One parameter per quarkonium state

Nonre [illegible] tivistic QCD (NRQCD): 1986 -

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

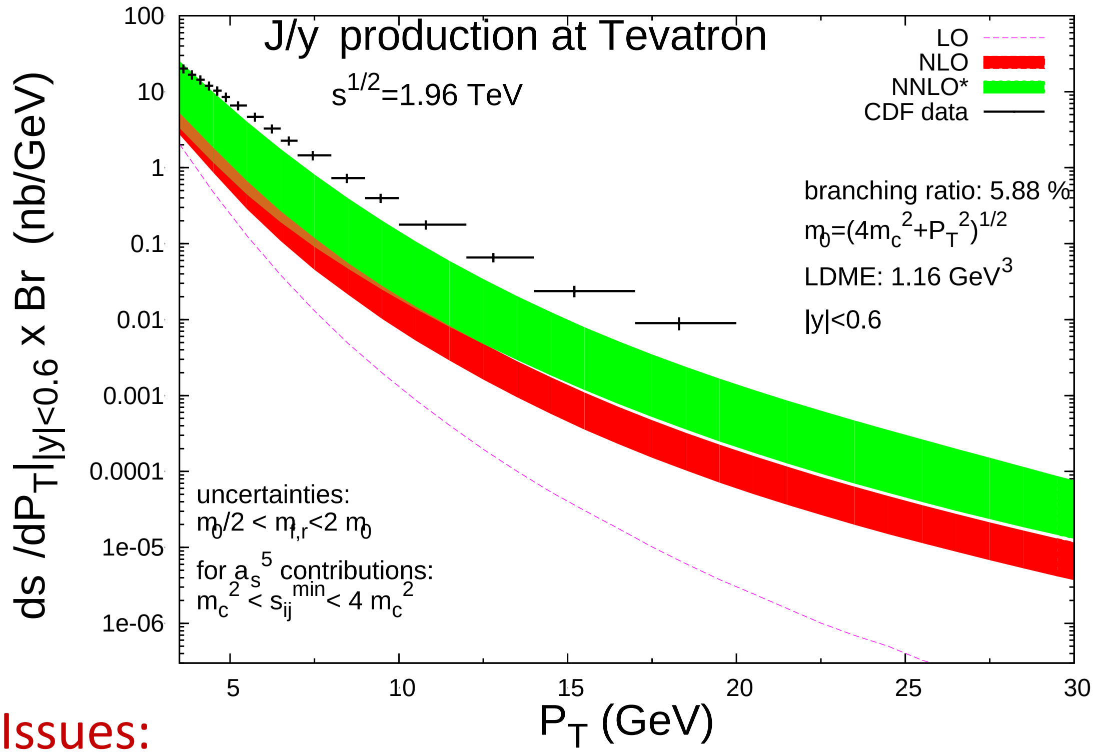
- Rigorous effective field theory based on factorization of soft and hard scales
- All pairs with various probabilities – NRQCD matrix elements

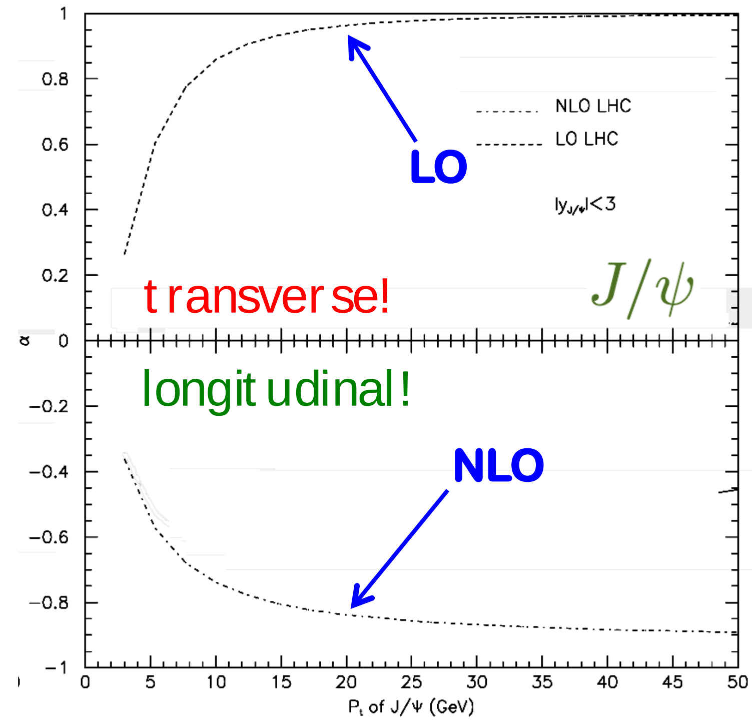
Infinite parameters – organized in powers of v and α_s

Color Singlet Model (CSM)

Effectively no parameter

Campbell, Maltoni, Tramontano (2007),
Artoisenet, Lansberg, Maltoni (2007),
Artoisenet, et al. (2008)





B. Gong et, al. PRL (2008)

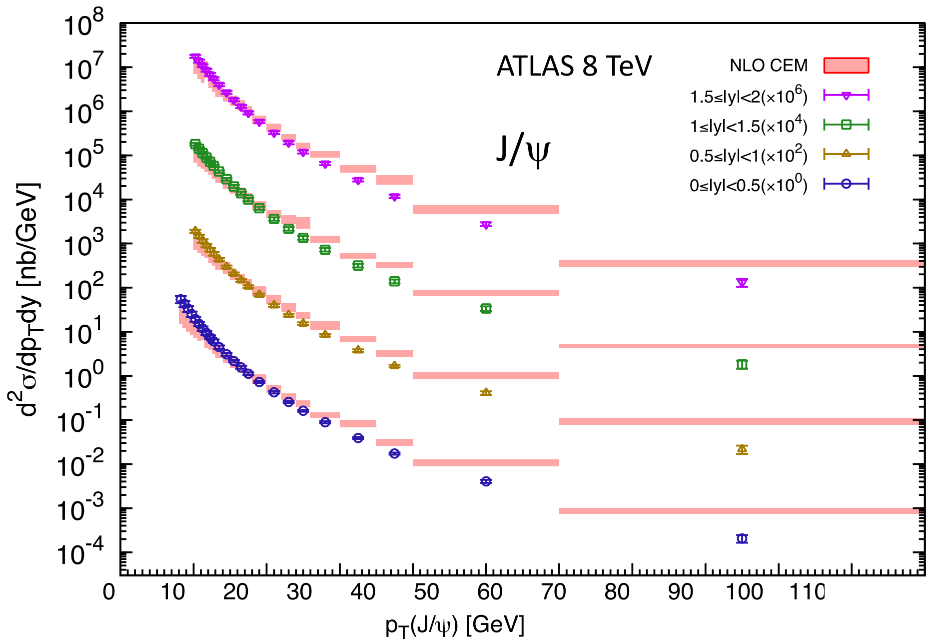
Issues:

- How reliable is the perturbative expansion?
  - S-wave: large corrections from high orders
  - P-wave: Infrared divergent – CSM is not complete
- Disagreement with p_T dependence:
  Including higher order terms makes significant improvement

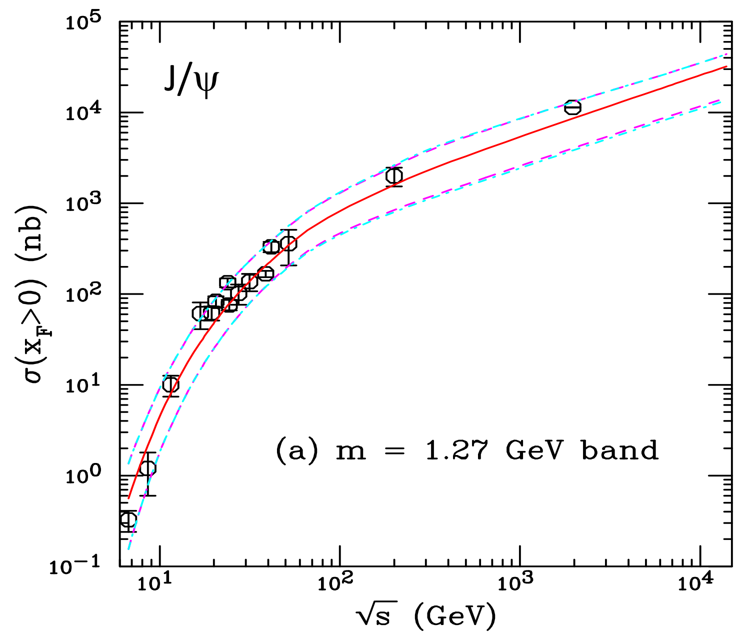
Color Evaporation Model (CEM)

One parameter per quarkonium state

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



Lansberg & Shao (2016)



Nelson & Vogt & Frawley (2013)

Issues:

- Discrepancies in some p_T spectra
- Absence of predictions for polarization observables

Color Evaporation Model (CEM)

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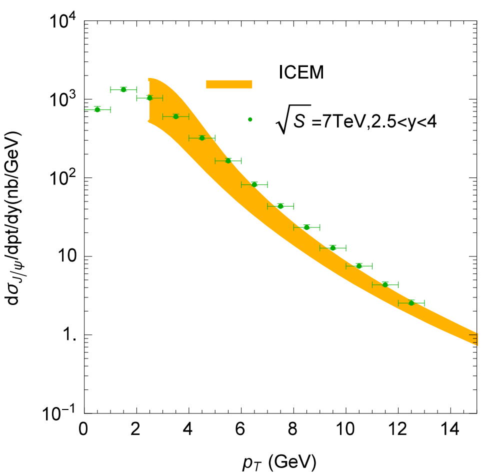
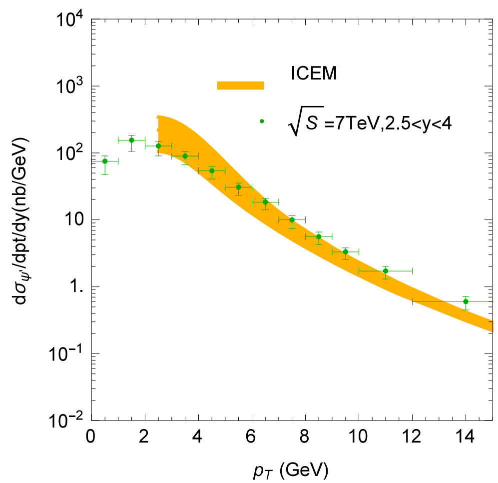
$$\sigma_Q^{(N)LO} = F_Q \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}^{(N)LO}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$

changes to M_ψ

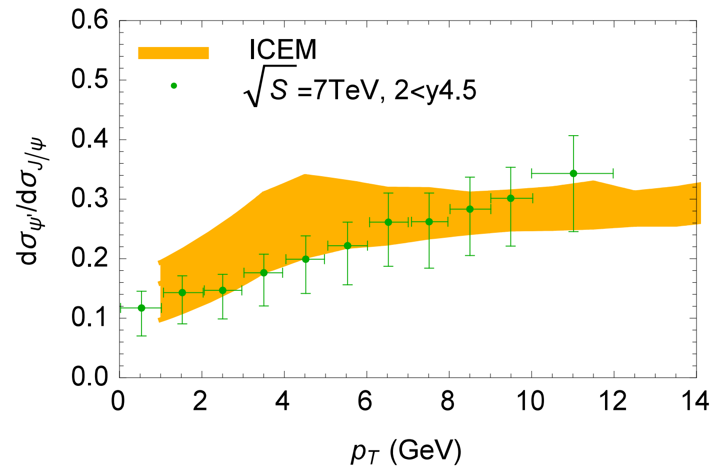
J/ψ



ψ’



ψ’/ψ ratio



Ma & Vogt (2016)

Issues:

- Discrepancies in some p_T spectra
- Absence of predictions for polarization observables (not bad if it is 0…)

ICEM: Relates the average final state ψ momentum, $\langle p_\psi \rangle$, to the cc pair momentum, p

Nonrelativistic QCD Approach (NRQCD)

NRQCD factorization: Sum over all Fock states, including color-octet states

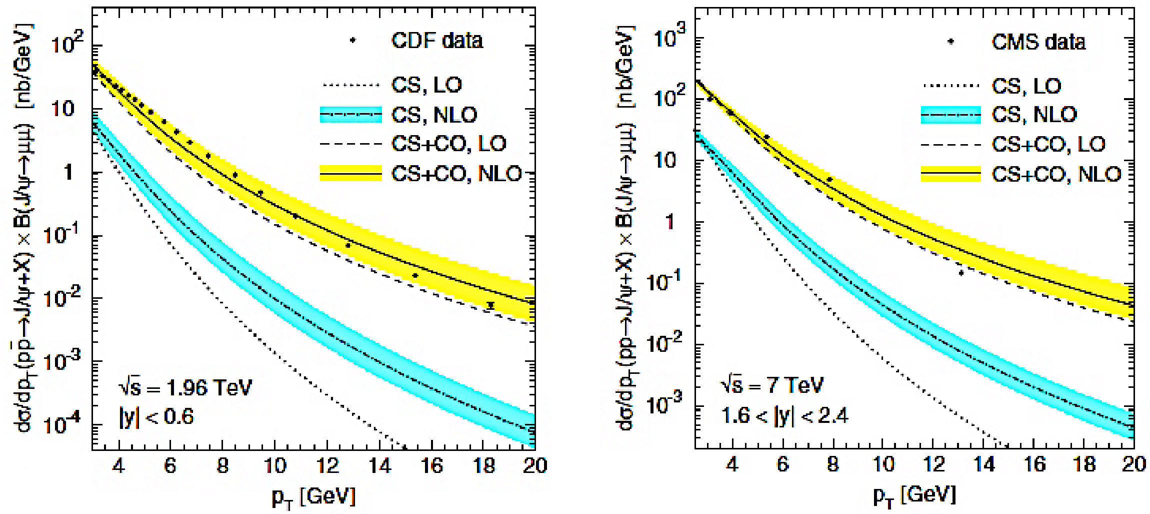
$\sigma^{J/\psi} = \Sigma_n \sigma_{cc[n]} \langle O^{J/\psi}[n] \rangle$

4 leading channels in v

$^3S_1^{[1]},\ ^1S_0^{[8]},\ ^3S_1^{[8]},\ ^3P_J^{[8]}$

Full NLO in α_s

Butenschön & Kniehl (2011)



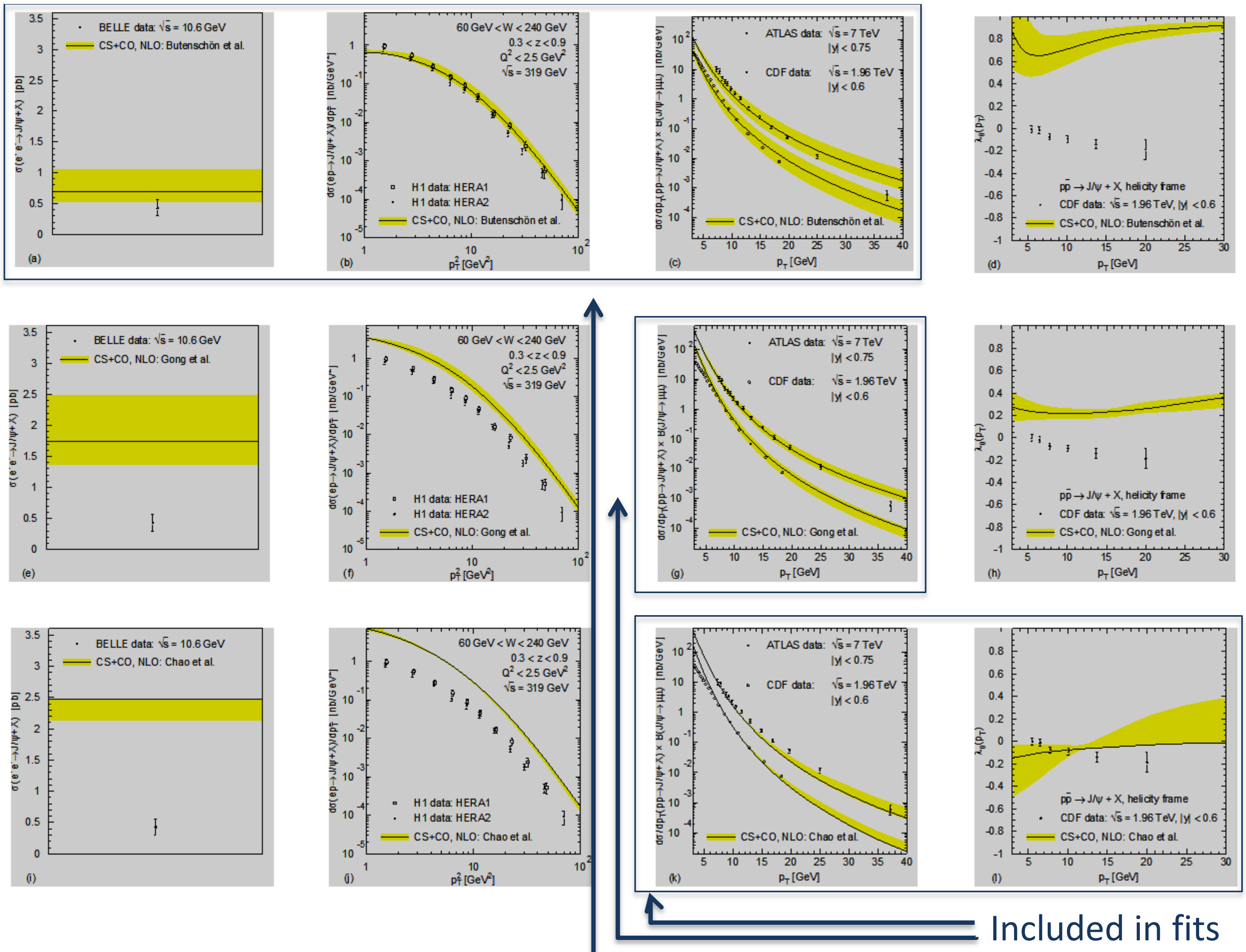
Issues:

- For some channels, NLO corrections are orders larger than LO:
  Are higher order contributions negligible? - extremely difficult to go beyond the NLO-
- Universality of NRQCD matrix elements – predictive power? The fit results depends on the energy scales of the process, the p_T scale and whether or not polarization is included
  - Polarization: Clear mismatch between theory predictions and data
  - Fits to p_T distributions do not describe the total cross section
  - LDMEs fitted to J/ψ results do not work for other states, e.g. η_c

Universality of NRQCD matrix elements – predictive power?

arXiv:1404.3723

	e+e-	ep	pp distribution	pp polarization
Butenschon & Kniel $p_T>3$ GeV	(a)	(b)	(c)	(d)
Gong et al. $p_T>5$ GeV	(e)	(f)	(g)	(h)
Chao et al. $p_T>7$ GeV	(i)	(j)	(k)	(l)



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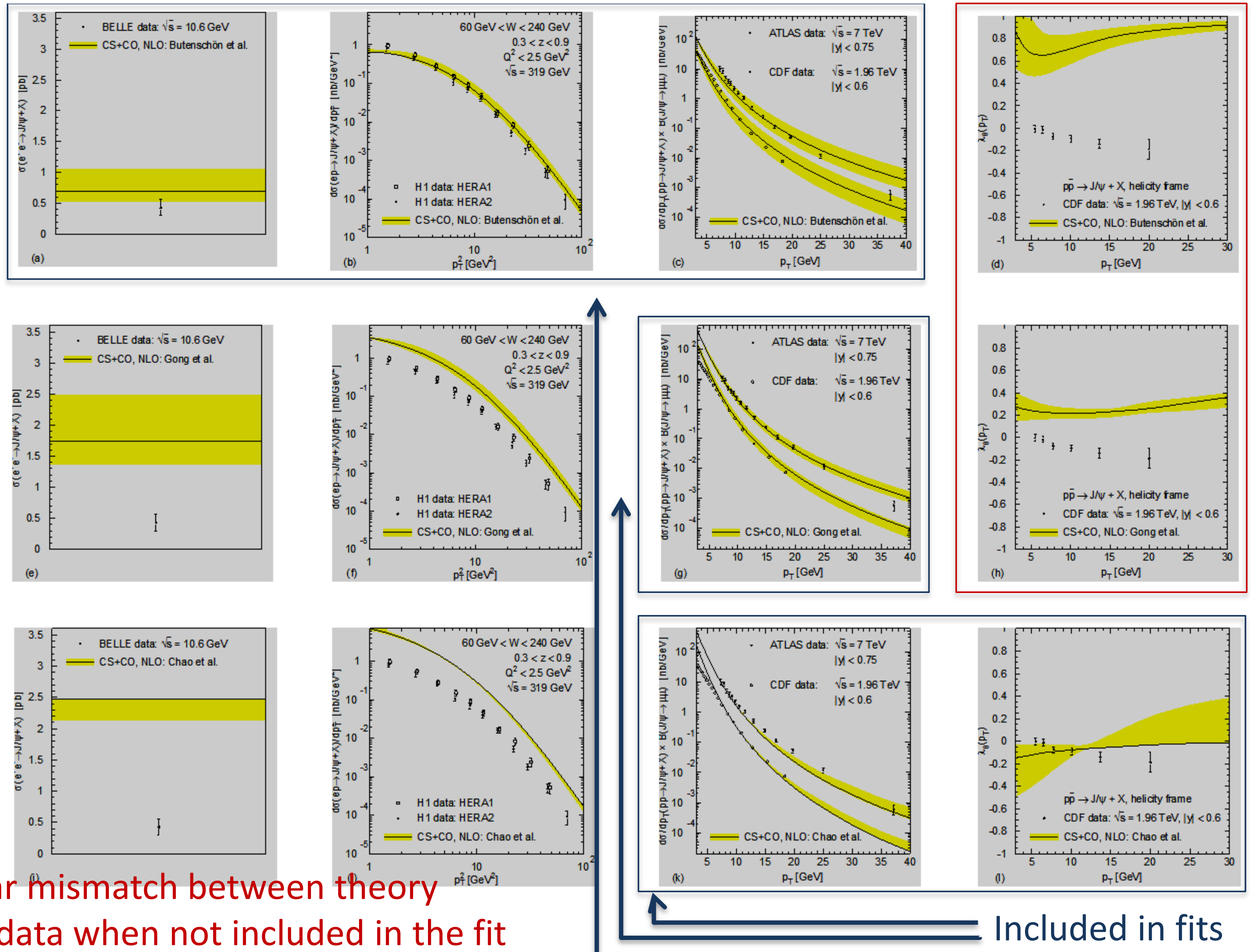

Polarization: Clear mismatch between theory predictions and data when not included in the fit

Universality of NRQCD matrix elements – predictive power?

arXiv:1404.3723 pp cross-section | pp distribution | pp distribution | pp

Butenschon & Kniel
p_T>3 GeV

Gong et al.
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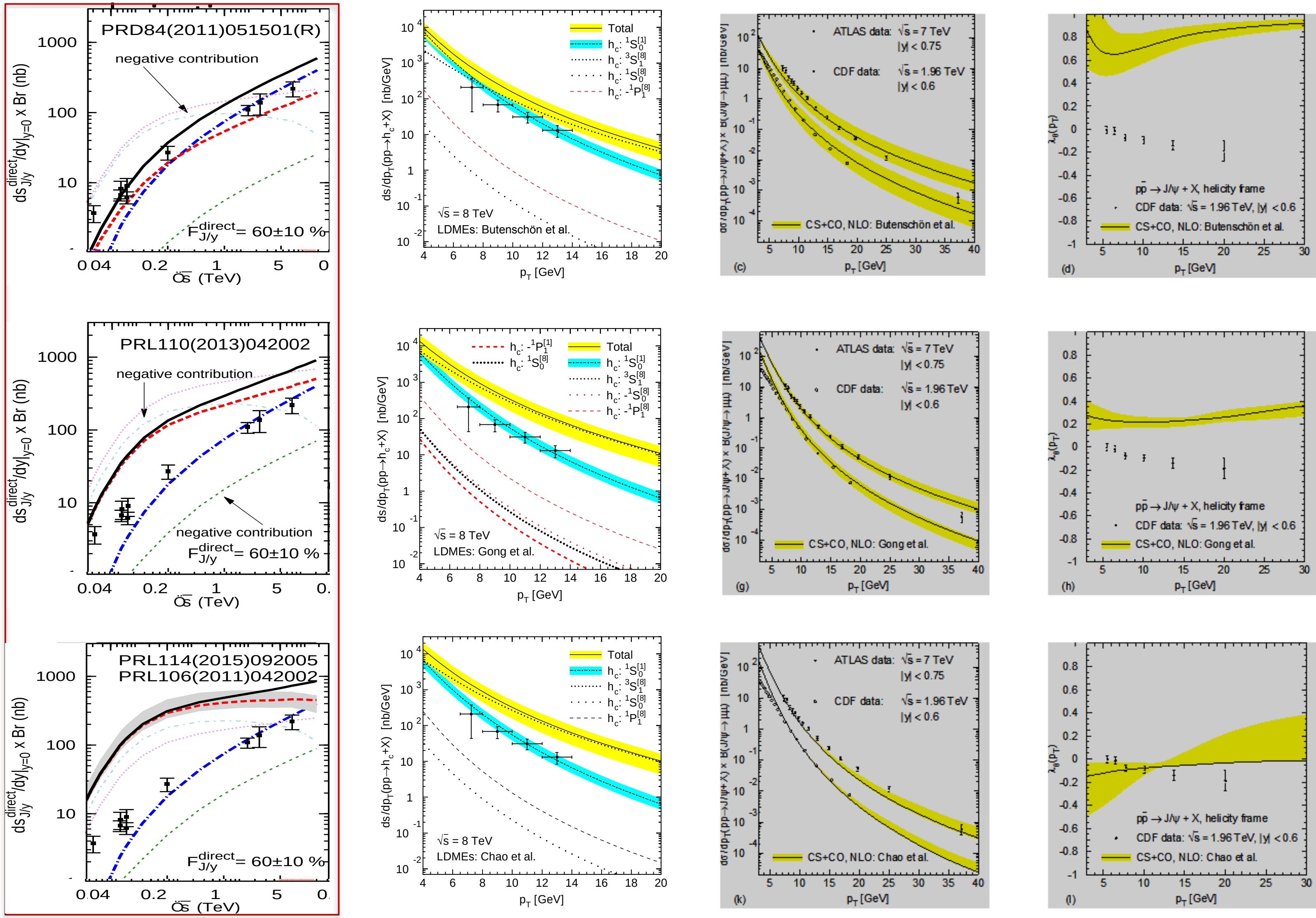
Feng, Lansberg Wang (2015)



LDMEs extracted from p_T distributions cannot describe the p_T integrated rate

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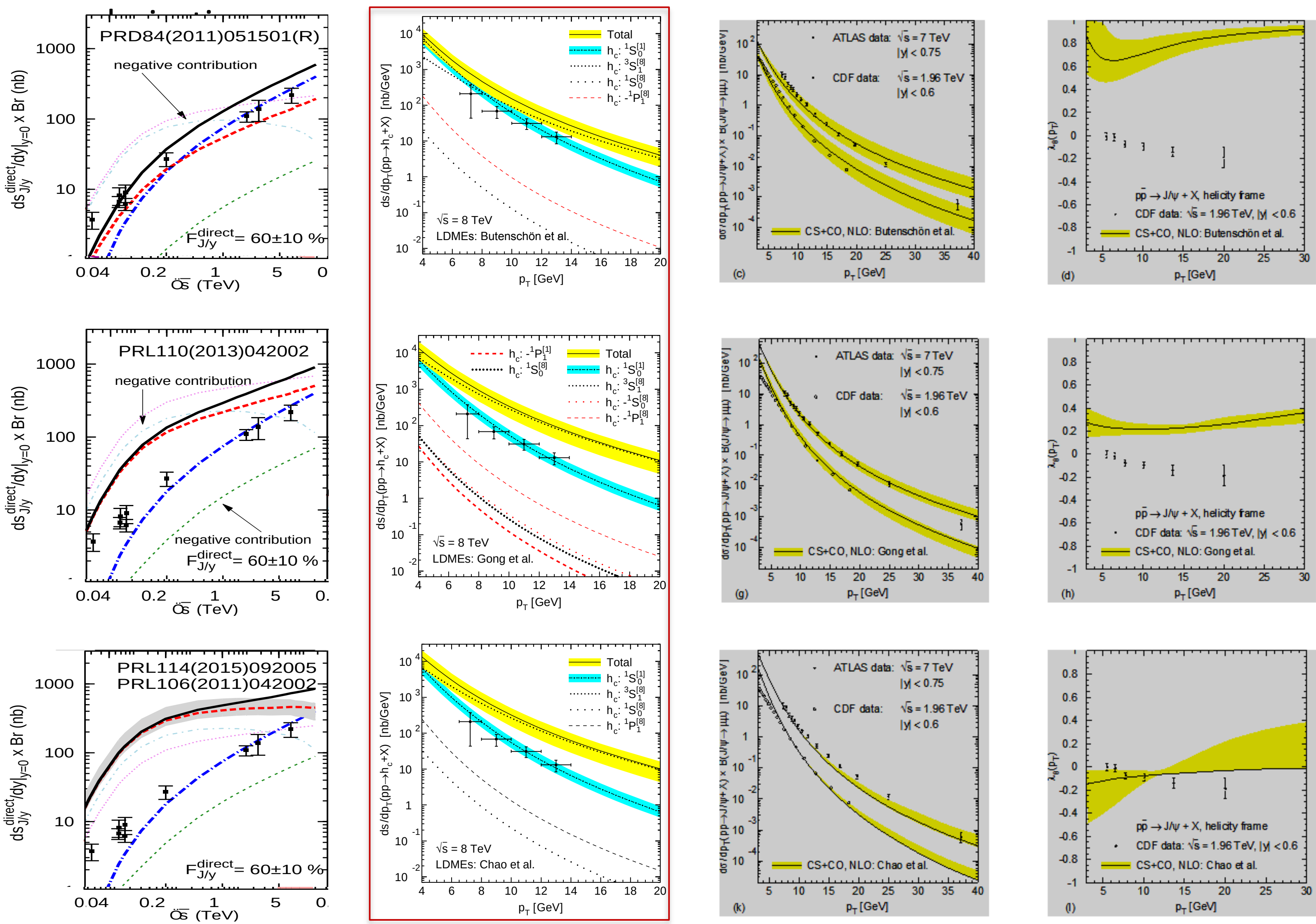
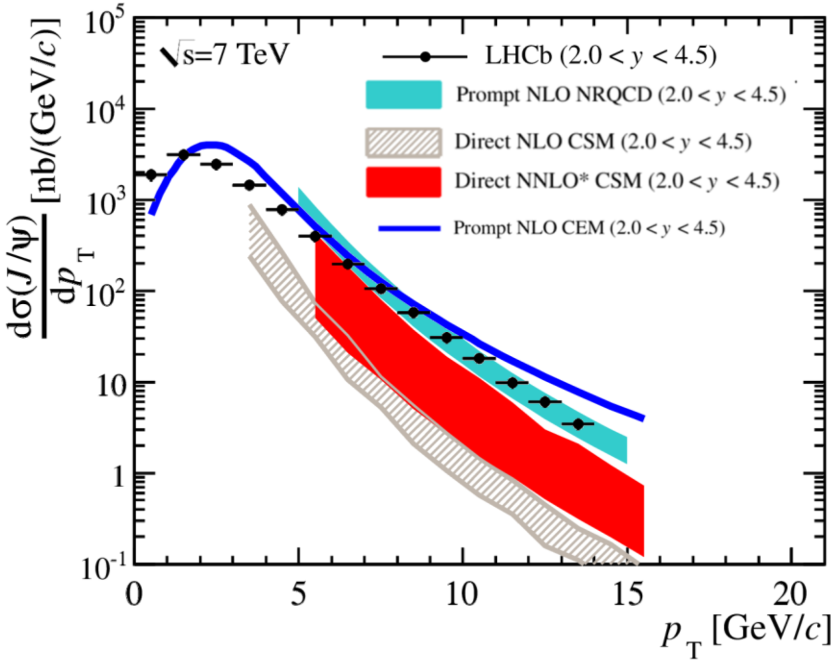
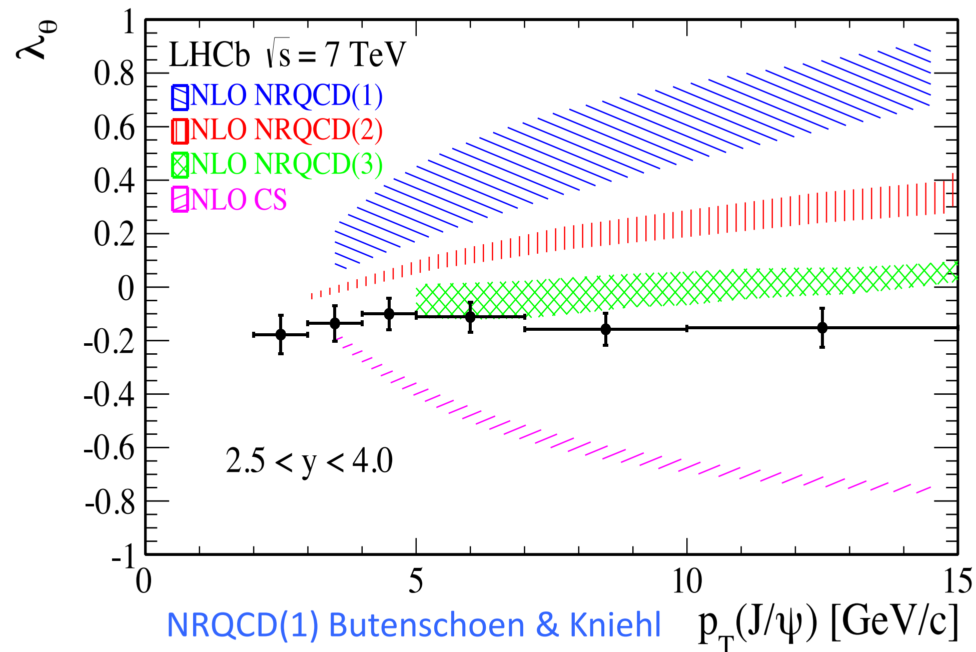


Taking heavy-quark spin symmetry LDMEs to apply to η_c production => overprediction LHCb η_c yields

State of the art for the J/ψ



Sapore Gravis Review arXiv:1506.03981

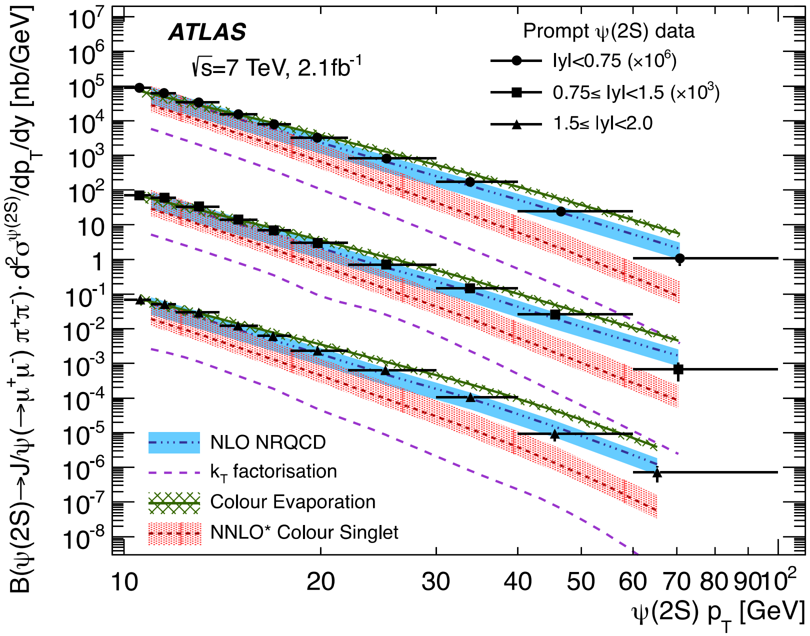


NRQCD(1) Butenschoen & Kniehl
NRQCD(2) Gong et al.
NRQCD(3) Chao et al.

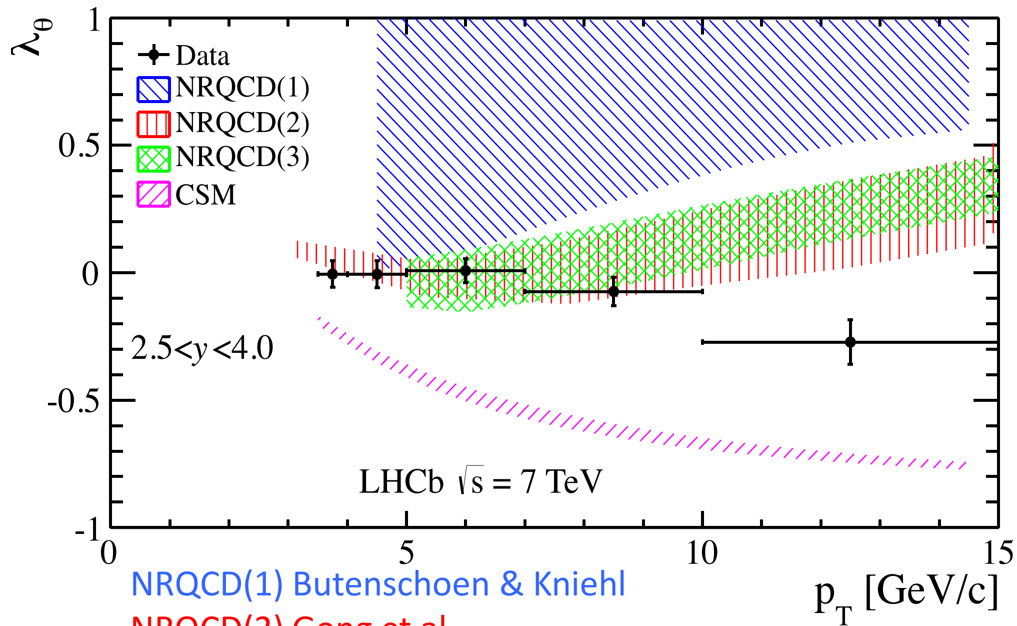
- CSM still in the game: Large NLO and NNLO; need a full NNLO
- NRQCD: COM helps in describing the p_T spectrum.
- CEM recent developments may be helpful

At low and mid p_T –which is the region where quarkonium heavy-ion studies are mainly carried out– none of the models can simply be ruled out owing to their theoretical uncertainties (scales, non-perturbative parameters, QCD corrections, ...).

State of the art for the ψ(2S)



Sapore Gravis Review arXiv:1506.03981



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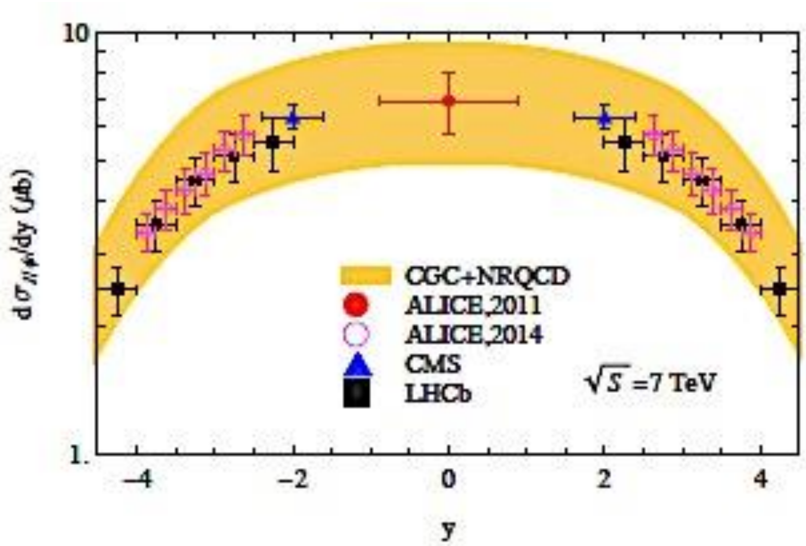
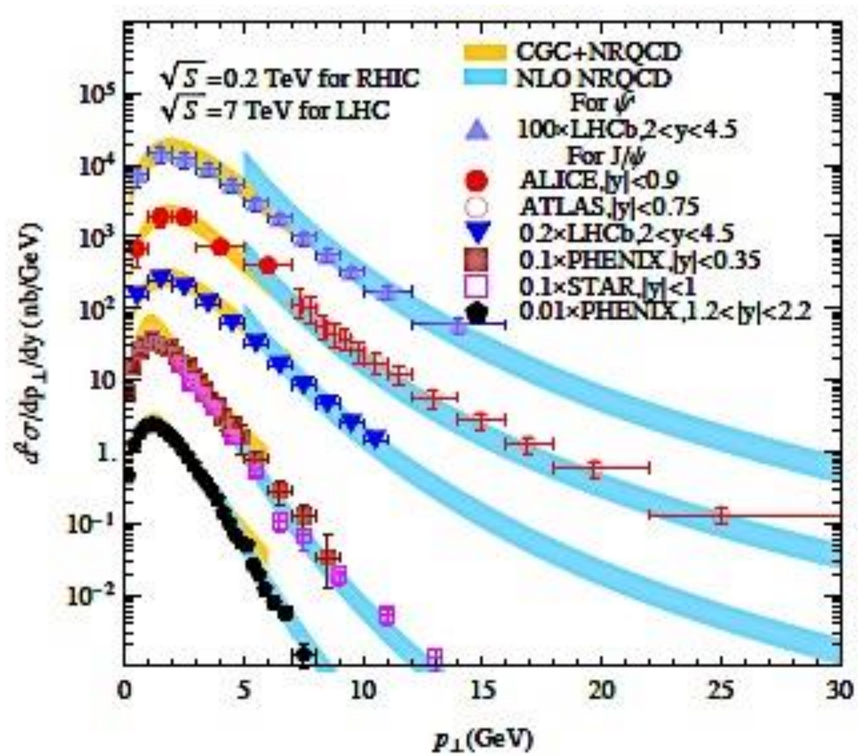
New developments: Color Glass Condensate and NRQCD

- Complementing NRQCD with CGC at low p_T allows for a good description of the total cross section:



Ma & Venugopalan (2014)



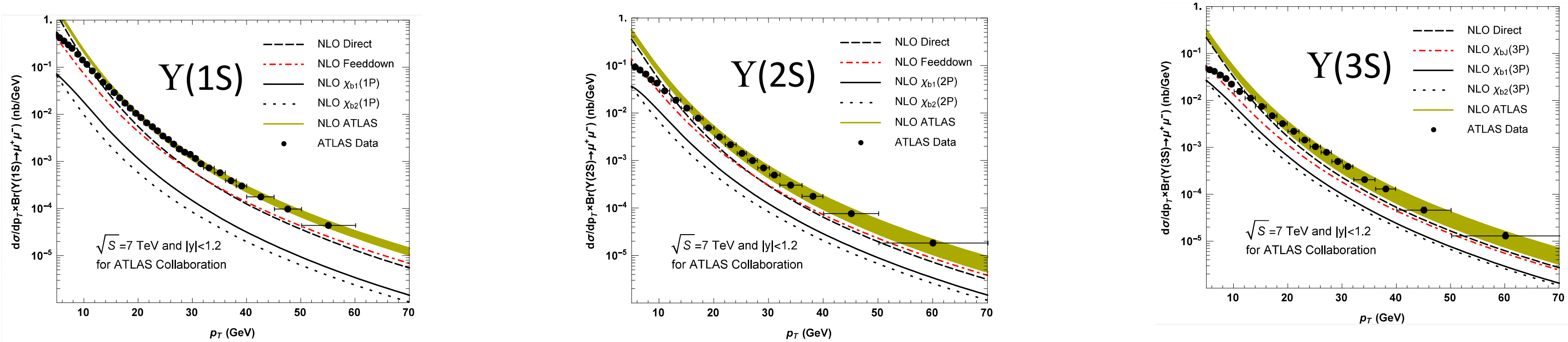
- Uses saturation model of gluon distributions in the proton with NLO NRQCD LDMEs
- Saturation physics at low p_T, normal collinear factorization at high p_T, matching at intermediate p_T

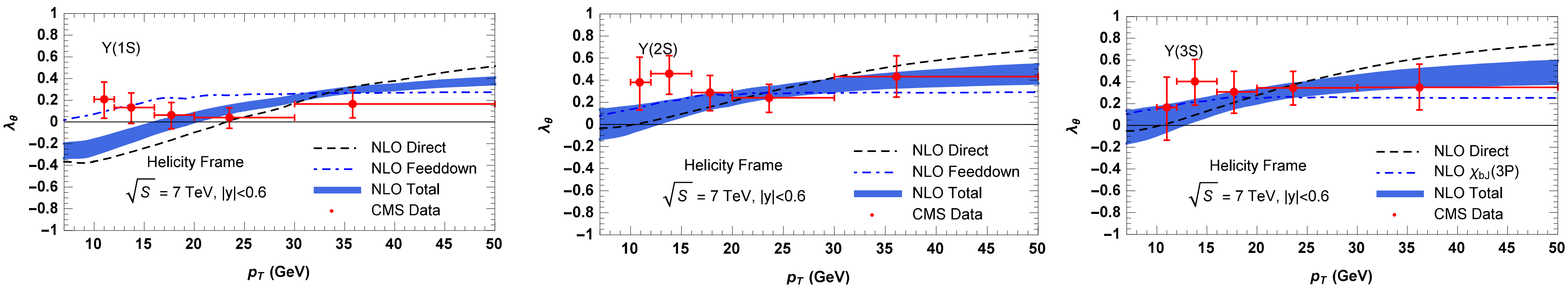
  Issues: Other observables sensitive to this effect? Heavy flavors?

What about bottomonium?

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

Hang et al.





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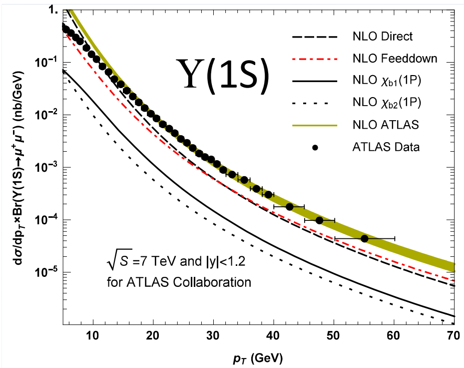
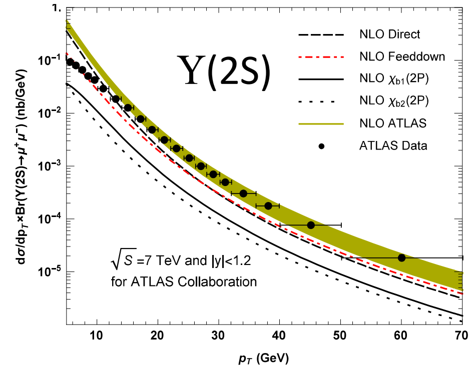
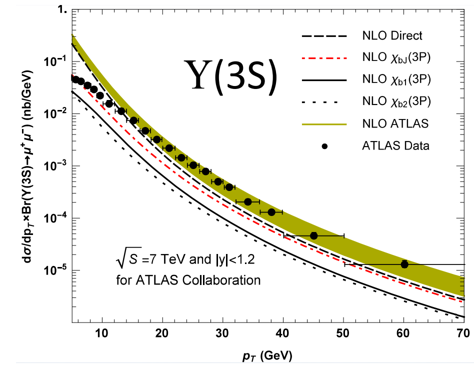
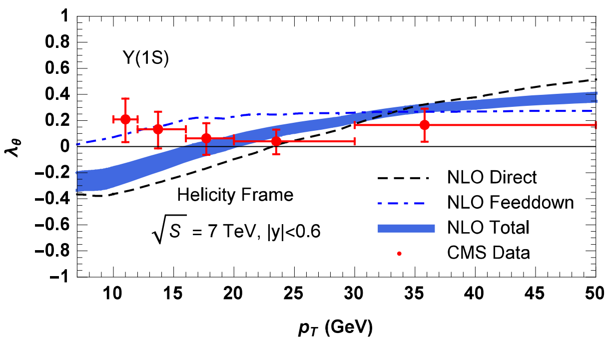
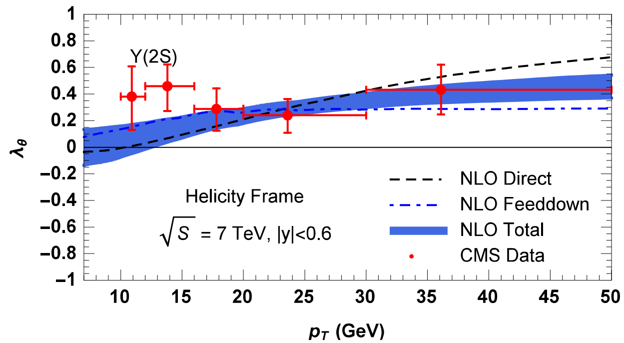
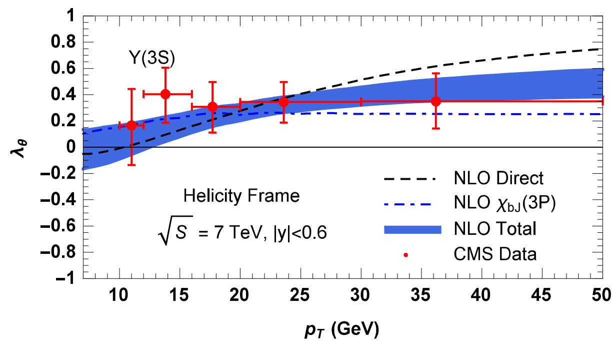




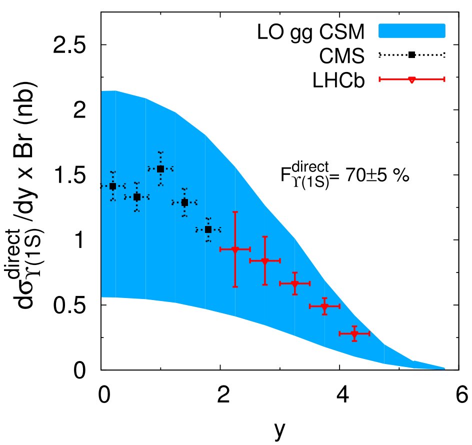


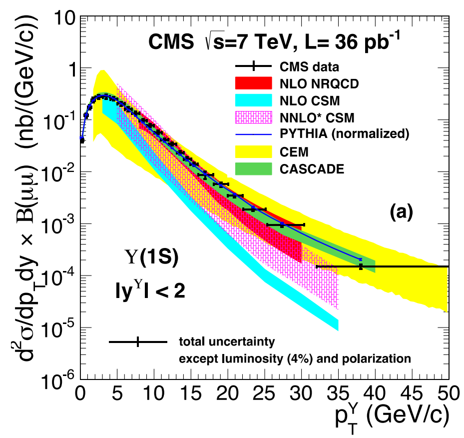






Lansberg

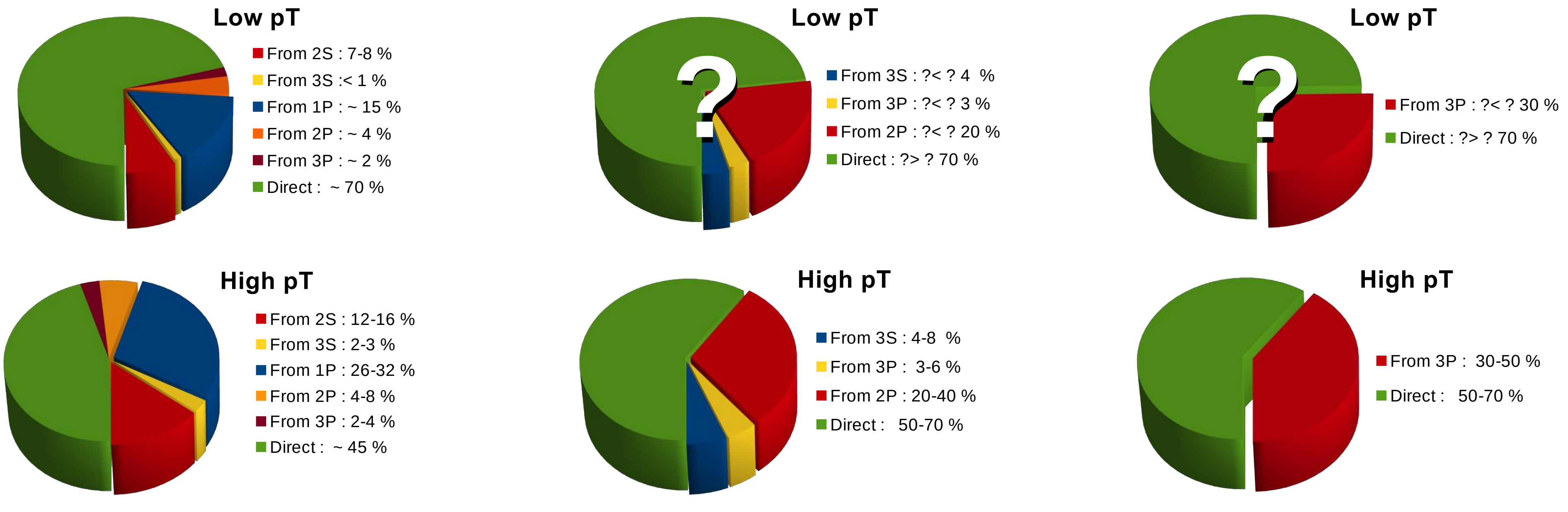




- None of the models can simply be ruled out due to their theoretical uncertainties
- Rapidity dependence of the Υ(1S) in line with the CS expectations -no evidence of CO contributions nor excluded-
- In general, LHC data are much more precise than theory

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) ⌥(1S) (b) ⌥(2S) (c) ⌥(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

Summary of proton-proton

Production mechanism still not settled after more than 40 years!

- CSM still in the game
  - Large NLO and NNLO correction to the p_T spectrum; but not perfect, need a full NNLO
  - It can be safely used for low p_T data

- NRQCD has long appeared promising but has many difficulties still remaining
  - COM helps in describing the p_T spectrum
  - Yet, the COM NLO fits differ a lot in their conclusions owing to their assumptions (data set, p_T cut, polarization fitted or not, etc.)

- k_T factorization and CGC can address low p_T, different mix of LDMEs

- New recent developments on CEM may be helpful

...but the story is not so simple

- Are there any other effects, not related to colour screening, that may induce a suppression of quarkonium states ? **Cold Nuclear Matter effects in pA**

- Can the melting temperature(s) and feed-downs be uniquely determined ?

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Let’s start by the end....

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* — Energy loss, Cronin
- Quarkonium-hadron interaction *final-state effect*
  - Break up in the nuclear matter — Nuclear absorption
  - Break up by comoving particles — Comover interaction
- QGP-like effects?

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

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

Baseline: nPDFs & nuclear absorption in a collinear pQCD framework

- Parton densities in nuclei are modified by the nuclear enviroment

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

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

PDFs in nuclei different from the superposition of PDFs of their nucleons

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:

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

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

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

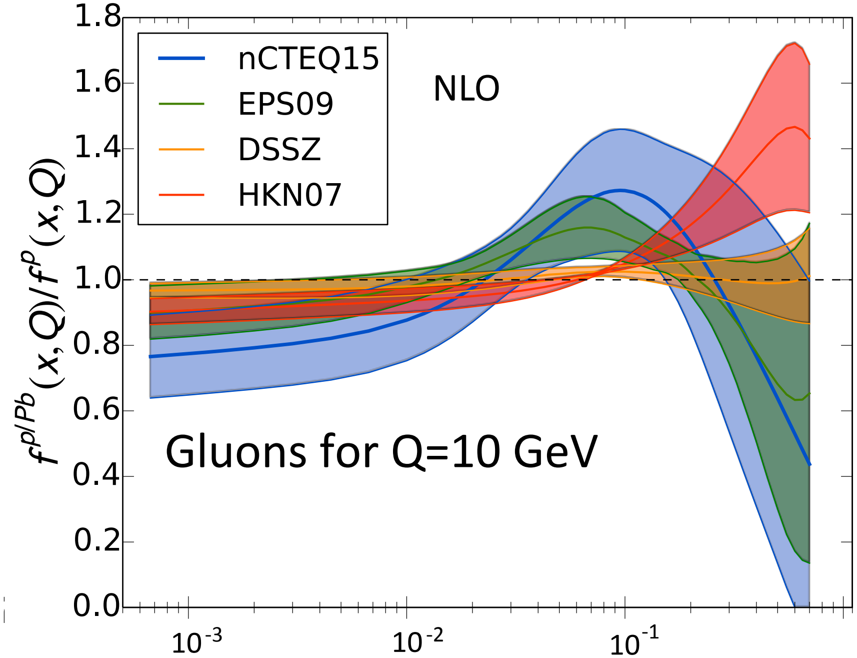
From any model (CSM, COM, CEM)

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

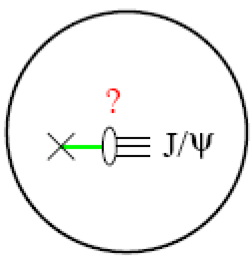
Nuclear absorption: Generalities on the break-up cross section

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

- 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÷0.4 fm
- t_f has to be considered in the rest frame of the target nucleus => $t_f = \gamma\, \tau_f$

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

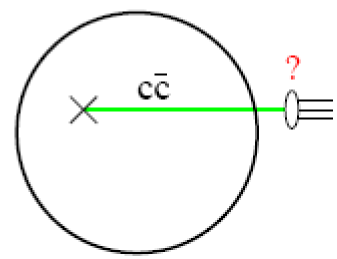
High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



Formation time depends on the boost

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

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



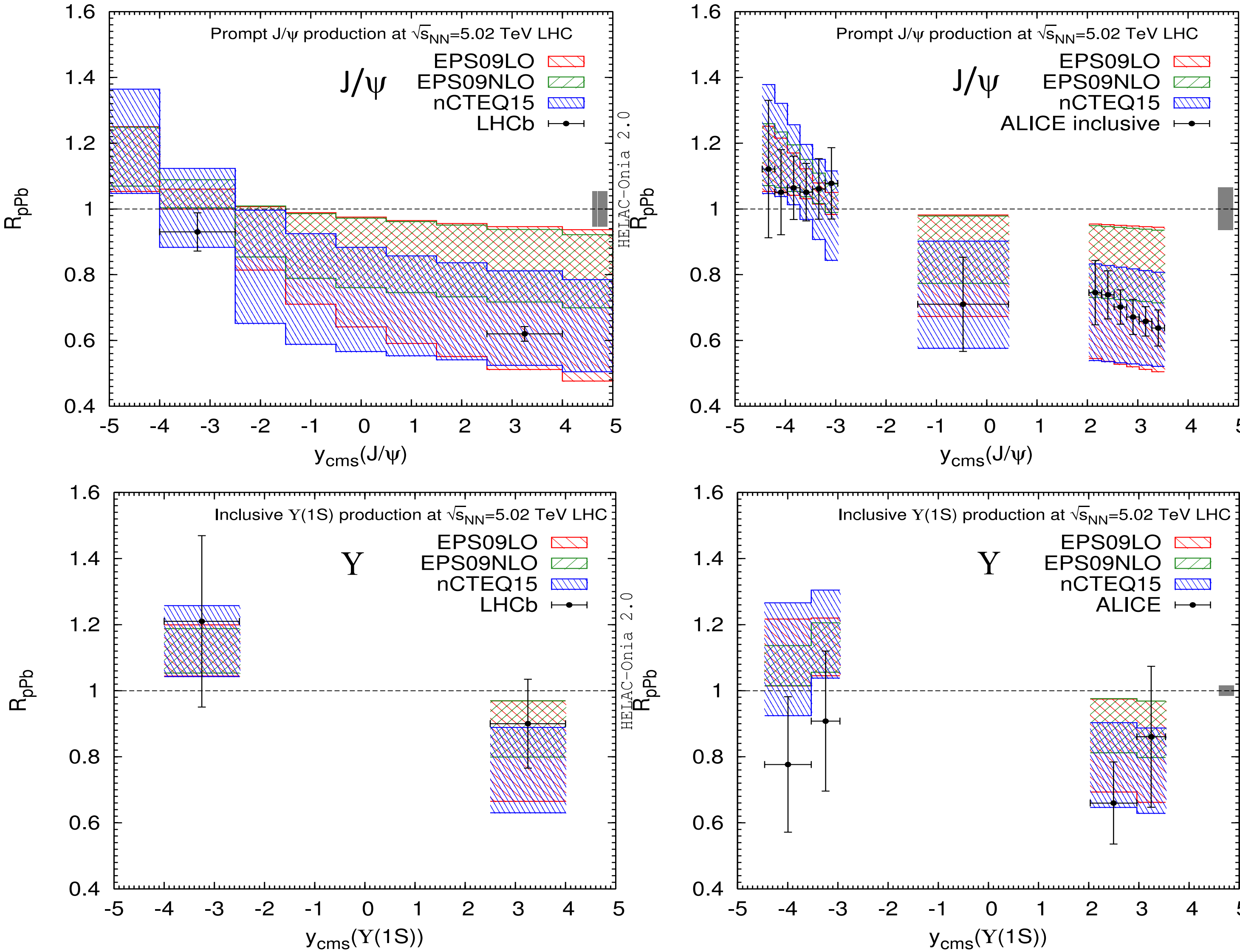
It takes t_f =30 fm/c at RHIC and t_f =800-1000 fm/c at LHC for a quarkonium to form and to become distinguishable from its excited states $t_f \gg R$

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

Comparison of nPDFs with LHC data

- **New** comparisons at LHC energies when the nuclear break-up is neglected

Lansberg & Shao (2016)

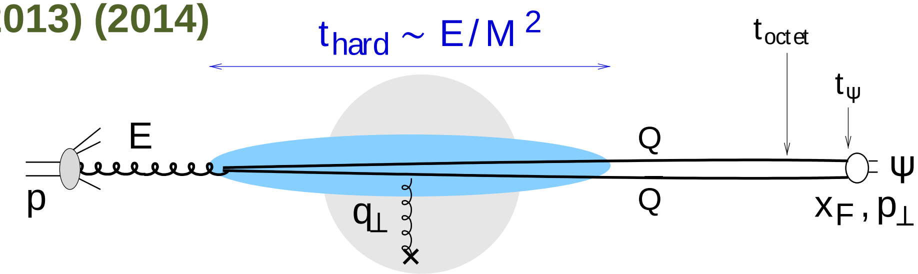


- Data is compatible with strong shadowing
- The precision of the current data is already much better than the nPDF uncertainties
- It may offer hints for constraining the gluon density in Pb

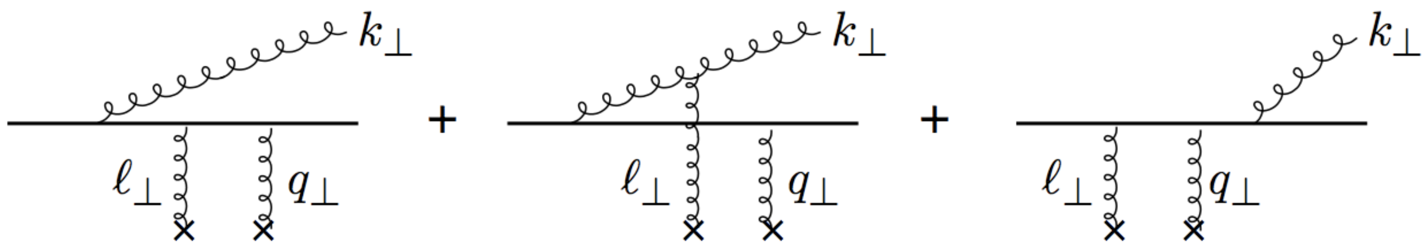
Going further: Coherent energy loss

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 $t_f \gg R$



IS and FS radiation cancels out in the induced spectrum

Interference terms does not cancel in the induced spectrum!

- Leads to a behaviour $\Delta E \propto E$

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

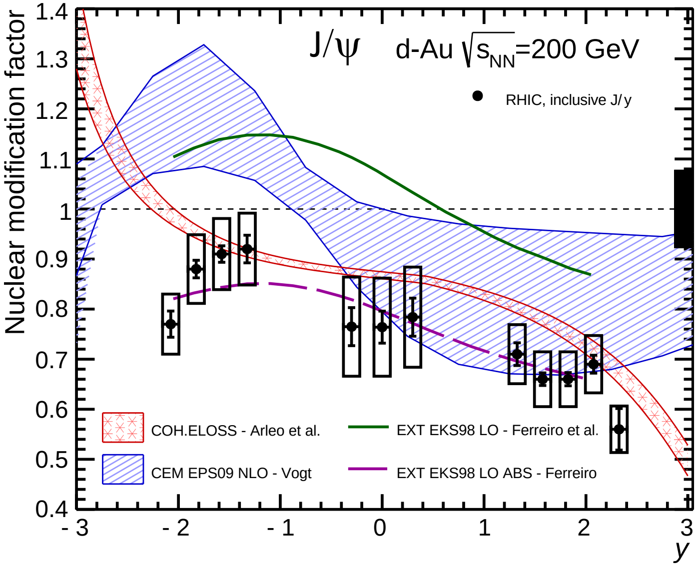
- $\sqrt{\Delta q_{\perp}^2}$ related to the transport coeficient $\hat{q}$

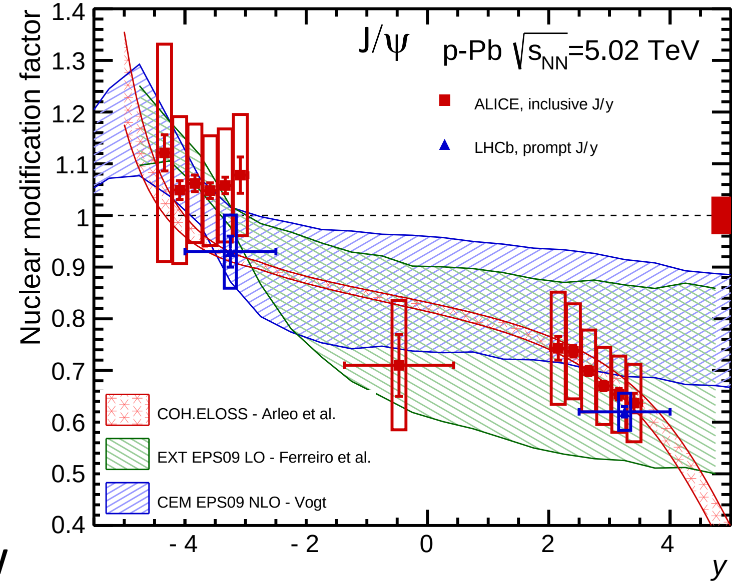
$$\hat{q}(x) \simeq \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

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

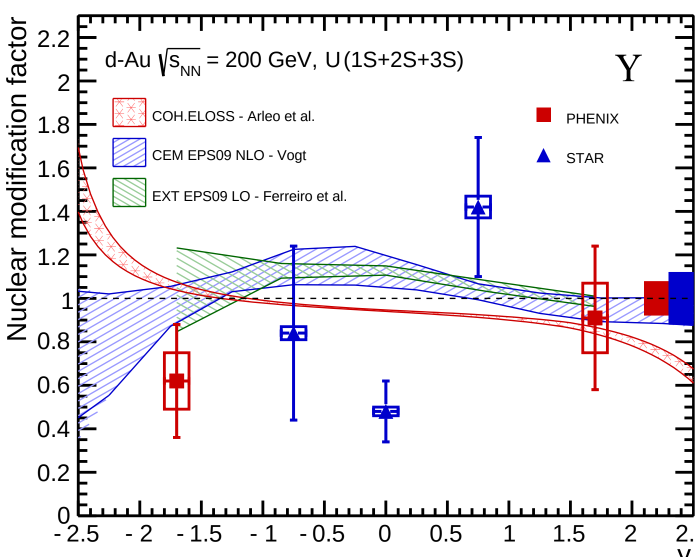
$\hat{q}_0$ is the only fitted parameter of the approach+the option to switch on/off the shadowing

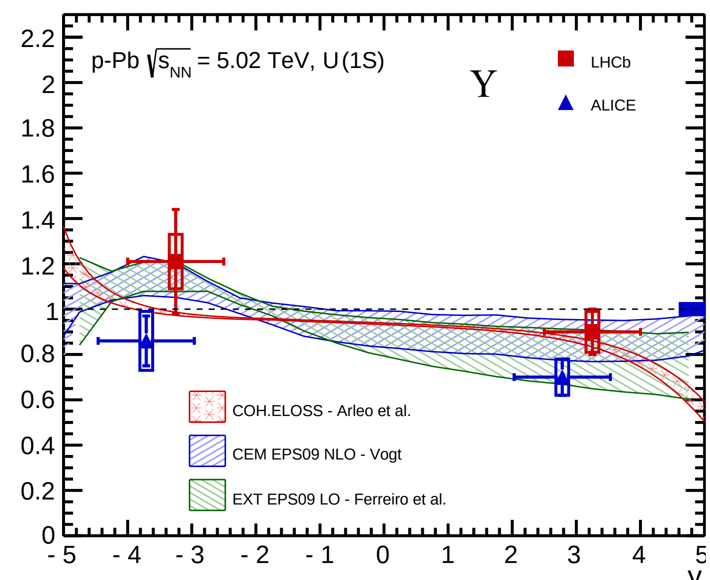
Comparison of nPDFs & Eloss with RHIC & LHC d/p+A data





- nPDF modification and/or coherent energy loss fairly agree with data
- Do data show energy increase of suppression?
- More data and more precise ones are needed

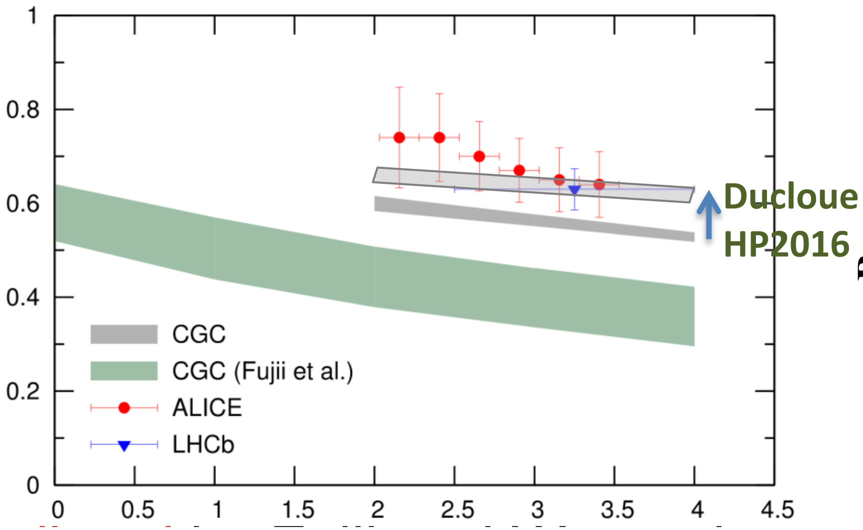


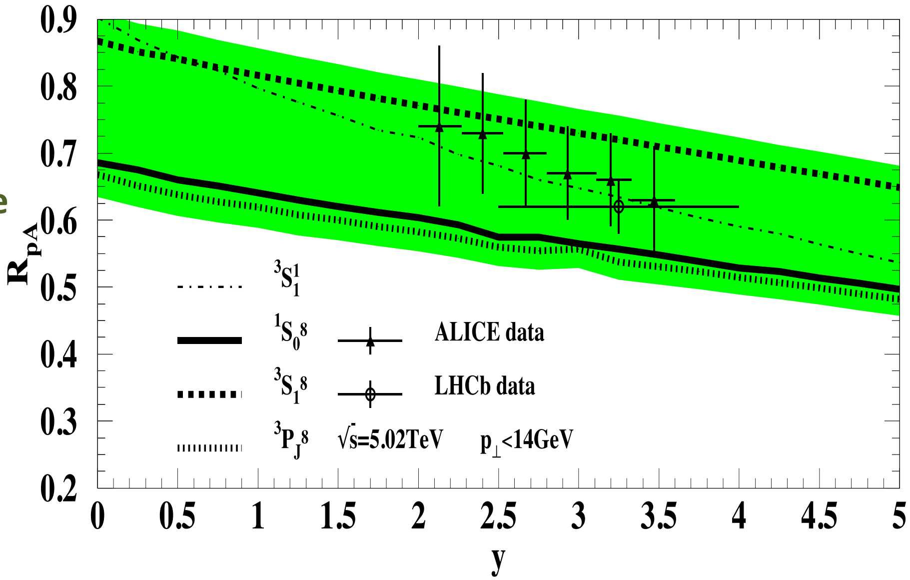


CGC computations: not just gluon saturation

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

Fujii, K. Watanabe (2013)





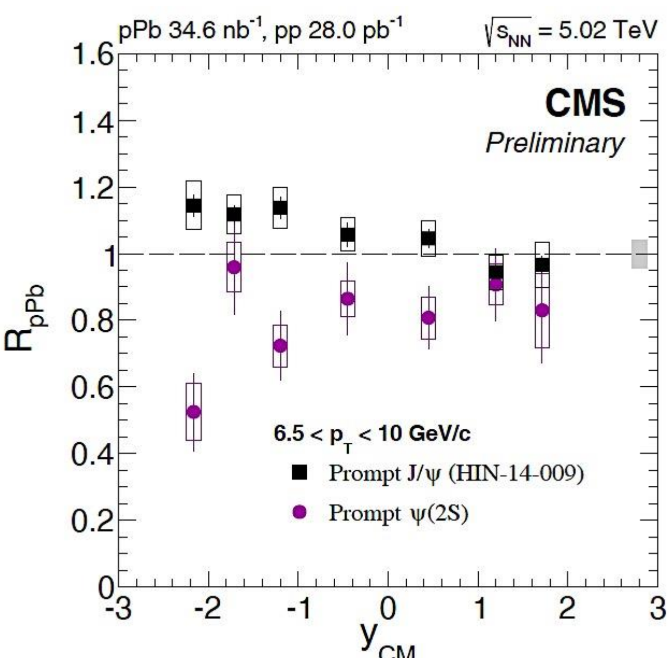
- Improved postdictions:
  - CEM with improved geometry Ducloue, Lappi, Mäntysaari (2015)
  - NRQCD : results depend on the CO channel mix Ma, Venugopalan, Zhang (2015)

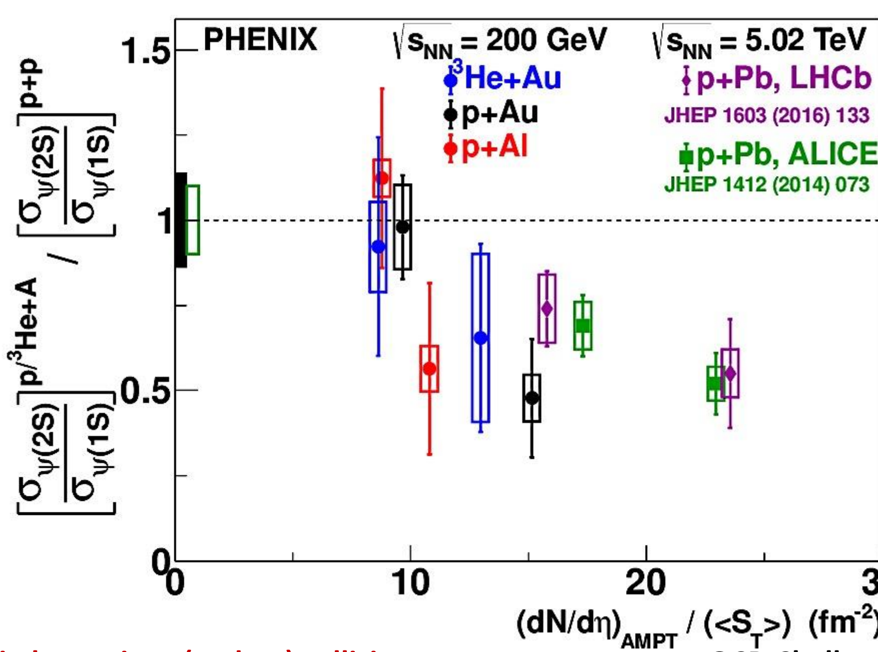
- CGC results very much widespread (as those from nPDFs): J/ψ suppression at forward y in pA collisions at the LHC is not the expected CGC smoking gun signal

Excited states: An intriguing relative suppression

- ALICE&CMS found out a relative ψ(2S)/J/ψ suppression in pPb collisions at 5.02 TeV
- Another hint came from PHENIX with a relative ψ(2S)/J/ψ suppression in dAu collisions at 200 GeV increasing with centrality
- Moreover, an unexpected relative suppression of Υ(2S,3S) w.r.t. Υ(1S) has been found by CMS in pPb collisions at 5 TeV

$\frac{[\Upsilon(nS)/\Upsilon(1S)]_{ij}}{[\Upsilon(nS)/\Upsilon(1S)]_{pp}}$	$2S$	$3S$
PbPb	$0.21 \pm 0.07\,(\text{stat.}) \pm 0.02\,(\text{syst.})$	$0.06 \pm 0.06\,(\text{stat.}) \pm 0.06\,(\text{syst.})$
pPb	$0.83 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	$0.71 \pm 0.08\,(\text{stat.}) \pm 0.09\,(\text{syst.})$





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- Moreover, an unexpected relative suppression of $\Upsilon(2S,3S)$ w.r.t. $\Upsilon(1S)$ has been found by CMS in pPb collisions at 5 TeV
- **At low energies**, the relative suppression pattern $\psi(2S)/J/\psi$ could easily be explained by the nuclear absorption $\sigma_{\mathrm{break-up}} \propto r^2_{\mathrm{meson}}$ $t_f \leq R$
- **At high energies** this is irrelevant: too long formation times $t_f = \gamma\, \tau_f$ => the quantum state should not matter
- Moreover, **initial**-state effects –modification of nPDFs/ parton E loss- are **identical**
- A natural explanation would be a **final**-state effect acting over sufficiently long time in order to impact different states with a different magnitude=>

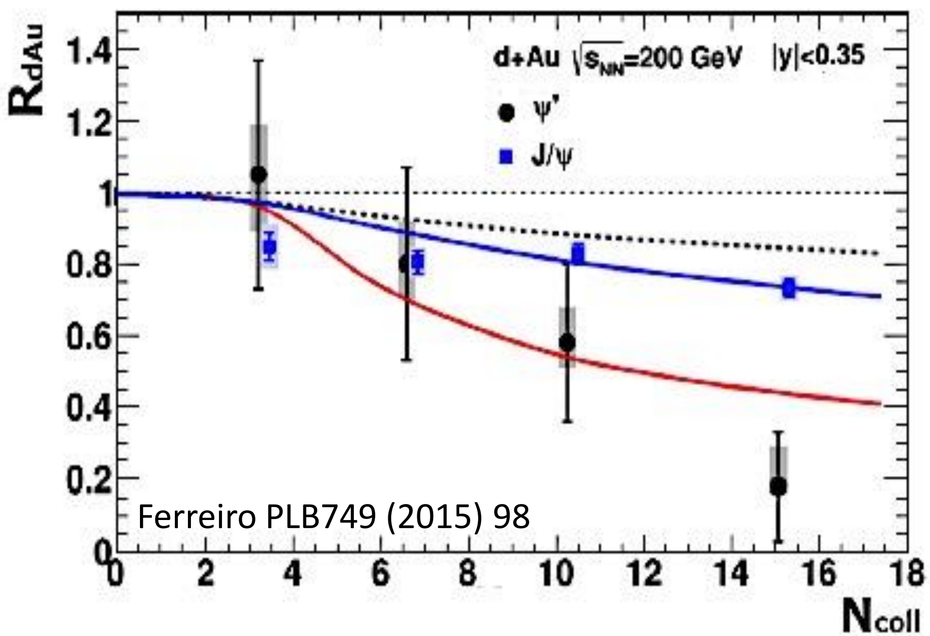
  comover interaction model?

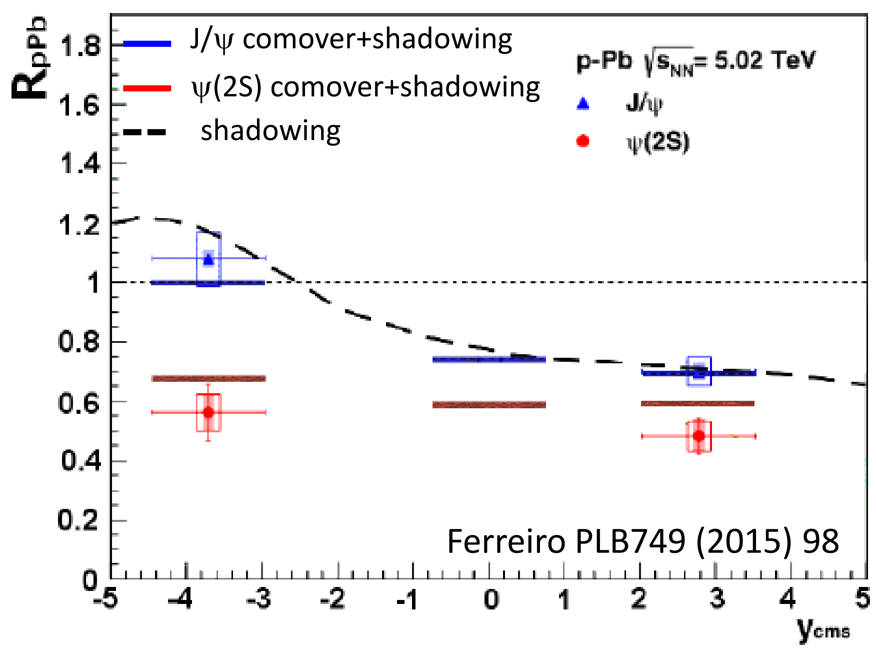
Excited states: Comover interaction model

- In a comover model: suppression from scatterings of the nascent ψ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)**
- 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:

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

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





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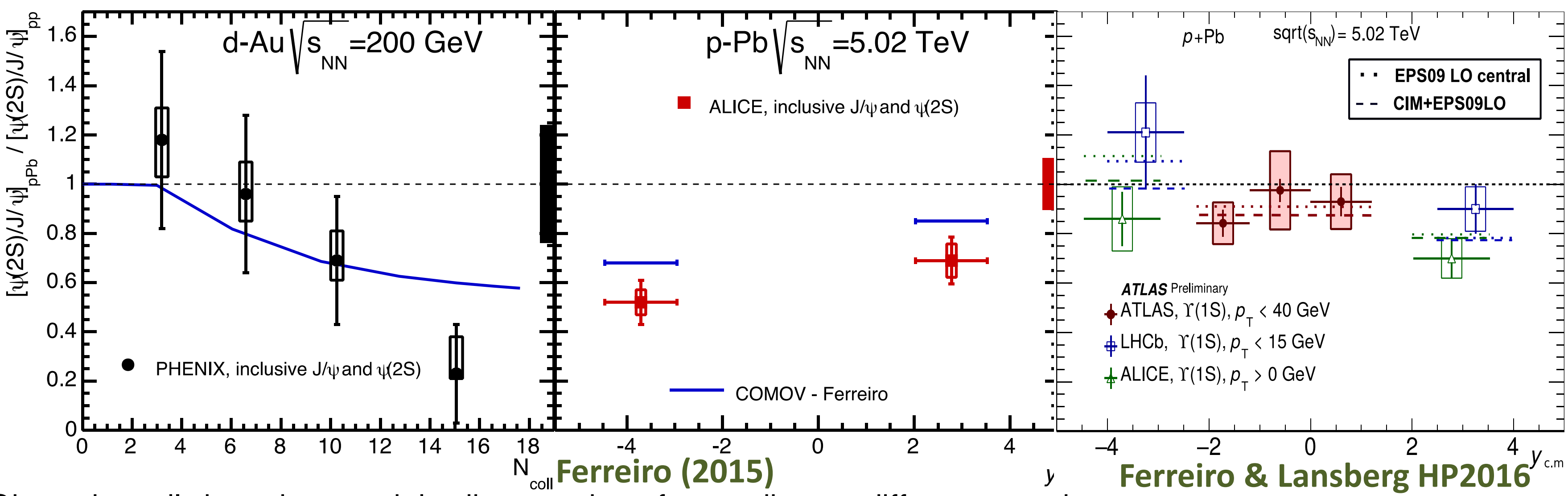
- New: $\sigma^{co-\psi}$ can be parametrized

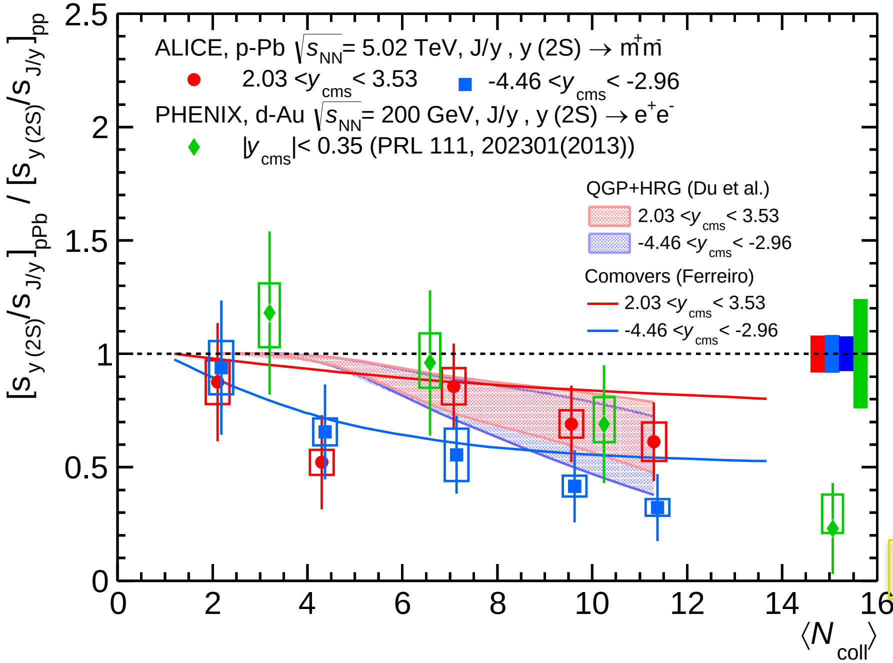
$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\mathrm{geom}}\left(1 - \frac{E_{\mathrm{Binding}}}{\langle E_{co}\rangle}\right)^{n}$$



Ferreiro (2015) **Ferreiro & Lansberg HP2016**

QGP-like effects in pA? … in fact not quite

ALICE 1603.02816 Prediction: Ferreiro arxiv:1411.0549 Postdiction: Du & Rapp, private communication



Du & Rapp 1504.00670

In the present work, we have investigated the production systematics of ψ' mesons in URHICs. We first revisited the problem of hadronic ψ' dissociation and found that a more complete inclusion of hadronic states in a resonance gas suggests a marked increase of its inelastic reaction rates. When implementing these rates into an expanding fireball for d-Au collisions at RHIC, we found a much improved description of the rather strong suppression of ψ' mesons observed in these reactions. This is similar in spirit to, and thus supports, the recently suggested comover suppression effects [16] in dA and pA reactions at RHIC and LHC.

- The transport model (QGP+HRG) is based on a thermal-rate equation framework which also implements the dissociation of charmonia in a hadron resonance gas
- The fireball evolution includes the transition from a short QGP phase into the hadron resonance gas, through a mixed phase
- Most of the effect in pA collisions comes from hadronic final-state interactions=> Similar in spirit to the comover suppression effects

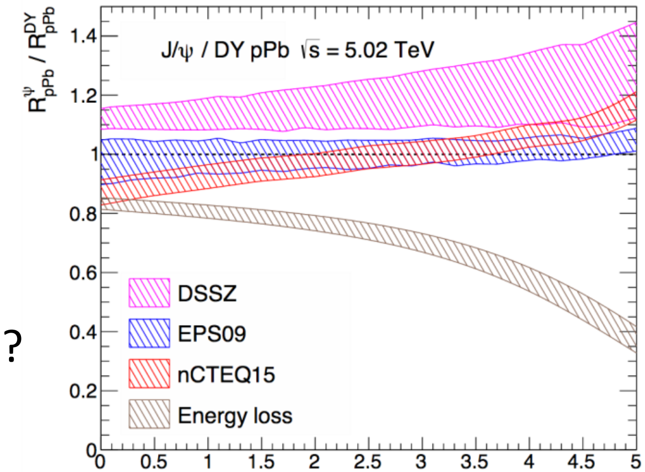
Summarizing on proton-nucleus collisions:

- 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

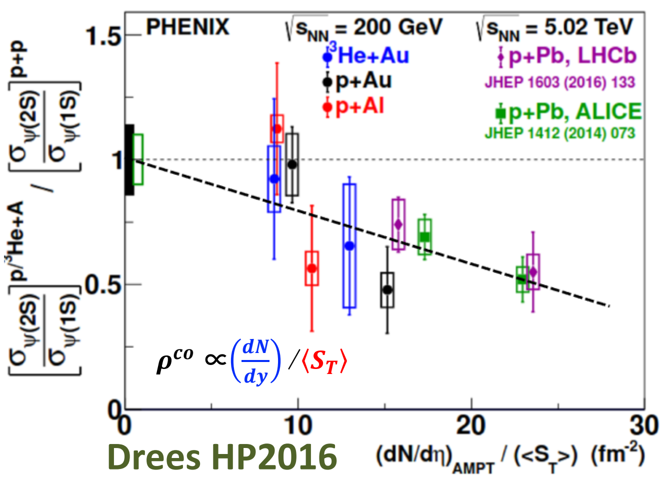
Possibility to distinguish bewteen them?



Arleo (2016)

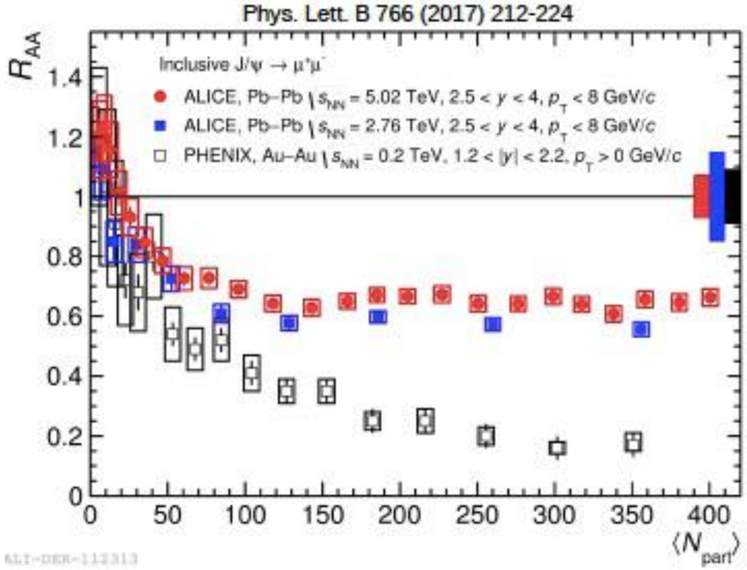
- Coherent Eloss mechanism can also reproduce **ground state** data

- Final-state effects as comover interaction, are good candidates to reproduce **excited to ground state** data.
  Comover interaction similar to **transport model**



Drees HP2016

A glimpse on nucleus-nucleus collisions: J/ψ state of the art

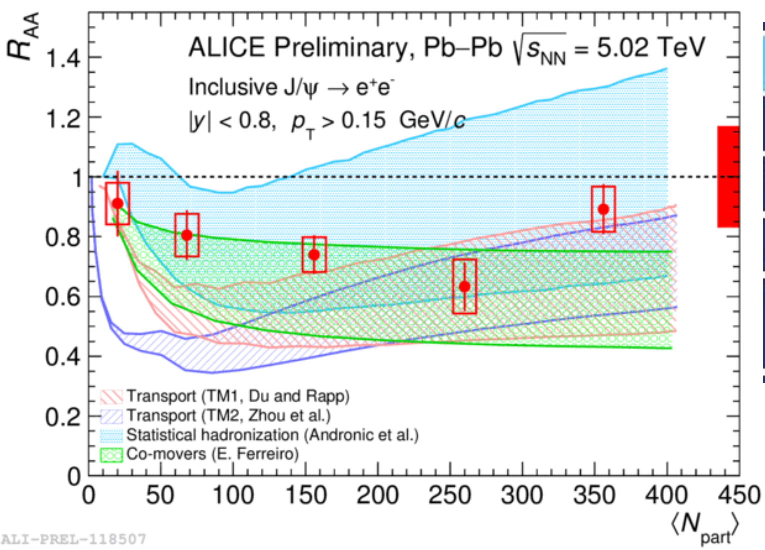


- Experimentally:

  Stronger suppression at RHIC than at LHC
  => ***Regeneration***

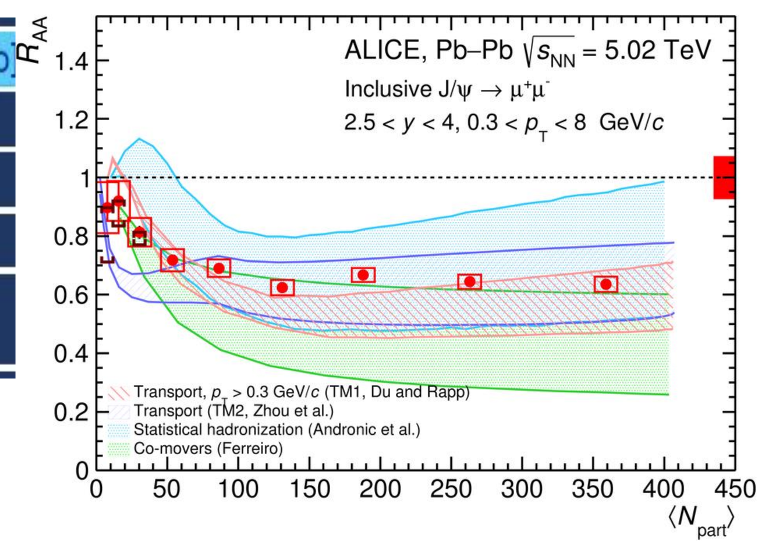
- Statistical hadronization, transport model & comovers can describe J/ψ data taking into account *regeneration*

- Problems: indetermination of σ_{cc} ^{2} thermalization?



Model	$d\sigma_{cc}/dy$ [mb]
Transport, TM1	0.57
Transport, TM2	0.82
Stat. Hadroniz.	0.45
Comovers	0.45-0.7

Different **shadowing** considerations



Theoretical models

Statistical hadronization model

Braun-Munzinger, Stachel, PLB 490 (2000) 196; NPA 789 (2006) 334, PLB 652 (2007) 259

all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq 0.1$ fm/c)
thermalized in QGP (thermal, but not chemical equilibrium)
charmed hadrons are formed at chemical freeze-out together with all hadrons ("generation") . ..
no J/ψ survival in QGP (full screening)

if supported by data, J/ψ looses status as "thermometer" of QGP

Transport models Ralf Rapp et al

implement screening picture with space-time evolution of the fireball (hydro-like)

continuous destruction and "(re)generation" ("recombination")

Thews et al., PRC 63 (2001) 054905 ...
"TAMU", PLB 664 (2008) 253, NPA 859 (2011) 114, EPJA 48
"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, arXiv:14

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c N_{\bar{c}} [V(\tau)]^{-1} - \lambda_D N_{J/\psi} \rho_g$$

Comover model

Capella et al., PLB 393 (1997) 431; PLB 430 (1998) 23; PRC 59 (1999) 395;
PRL 85 (2000) 2080; EPJC 42 (2005) 419; EPJC 61 (2009) 865; PLB 731 (2014) 57

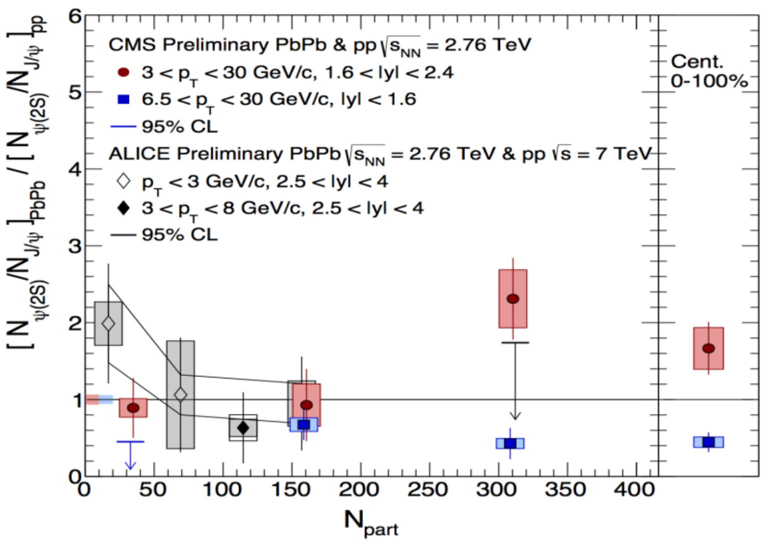
Similar gain and loss diferential eqs.

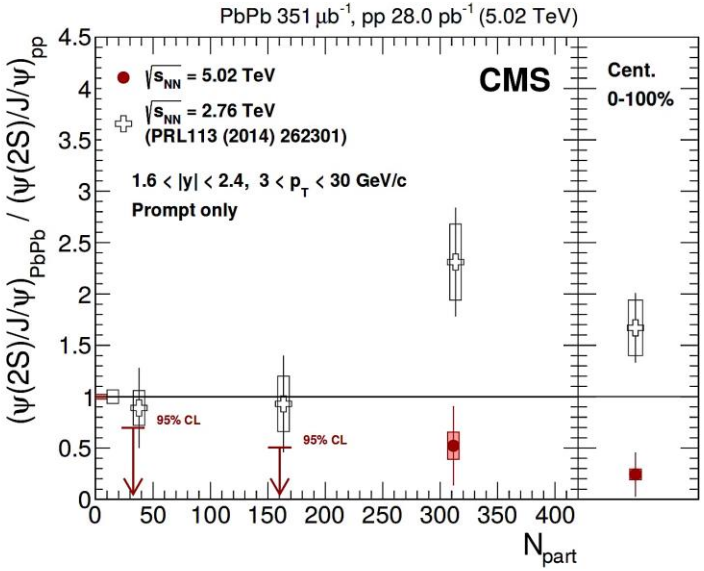
Similar to transport model
Hadronic and partonic comovers contribute
to suppression and recombination
No thermalization

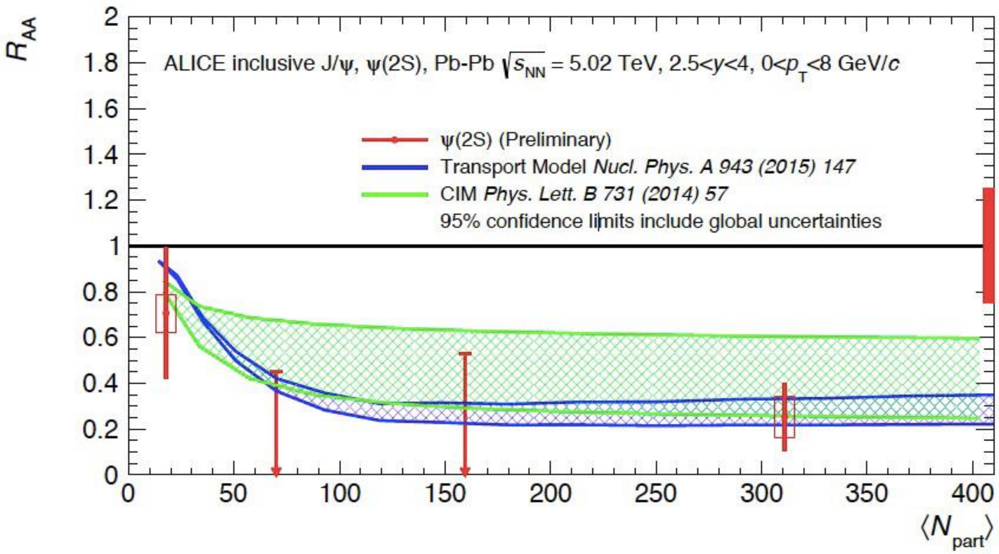
$$\tau \frac{dN^{J/\psi}}{d\tau}(b, s, y) = -\sigma \{ N_{J/\psi} N^{co} - N_D N_{\bar{D}} \}$$

A glimpse on nucleus-nucleus collisions: ψ(2S) state of the art

- The situation is far from clear for ψ(2S)

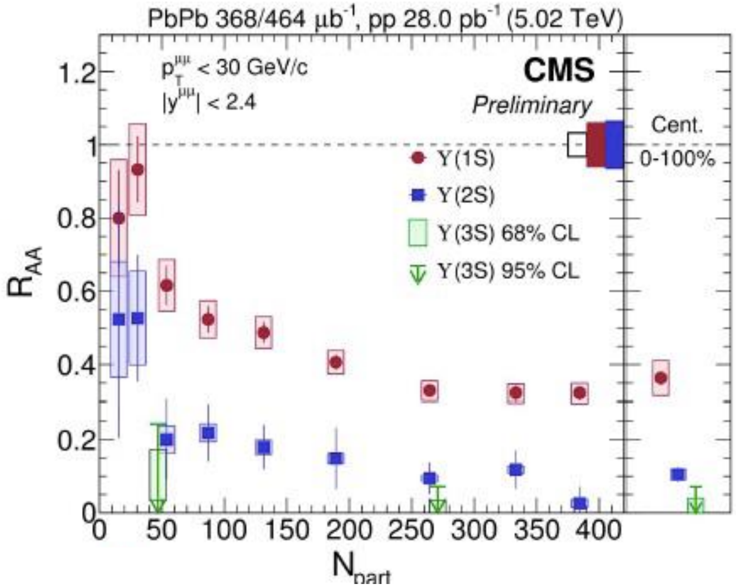






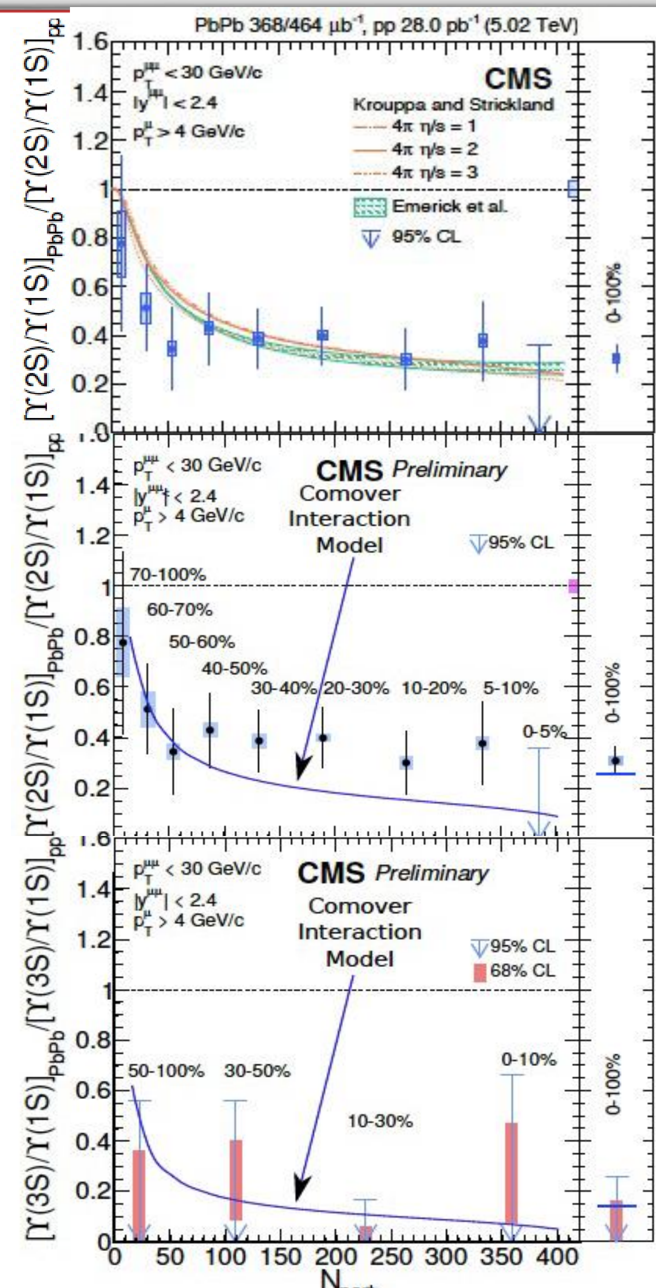
- Transport model & comovers can describe ψ(2S) data taking into account *regeneration*

A glimpse on nucleus-nucleus collisions: Υ state of the art



- Hydro model, transport model and comovers overlaid

- No signal of regeneration



Concerning Υ:

- All 3 states are suppressed with increasing centrality

R_{AA}[Υ(1S)] > R_{AA}[Υ(2S)] > RAA[Υ(3S)]

=> Sequential melting

Summarizing: Quarkonium=puzzle of many pieces

Strickland QM2017

pp reference

Experimental measurements rely on R_{AA} which is **defined relative to the pp cross section**; therefore, we need reliable pp reference data and a firm theoretical understanding of open- and closed-charm production in pp collisions

Cold nuclear matter effects

Quarkonia production is also affected by **nuclear-modified PDFs, Cronin effect, and co-movers** which can result in enhancement or suppression of quarkonia production depending on the kinematic window.

Regeneration

If the population of open- and closed-charm states is high, then it is possible for quarkonia to be regenerated through **recombination of open heavy flavor with a liberated heavy flavor**. There can also be local recombination of an individual bound state due to medium interactions.

Viscous QGP modeling

Quarkonia are sensitive to the full spatio-temporal evolution of the QGP. Need to compute dynamical processes including non-equilibrium corrections. **Should use codes that reproduce experimental data for bulk observables** such as particle spectra and azimuthal flow.

What have we learnt from quarkonia production @ LHC?

J/ψ production seems at least **qualitatively understood**

- **Initial cold nuclear matter** effects can be described with shadowing/energy loss
- Production in HI collisions is described by a combination of

suppression (either color screening, or in-medium dissociation)
recombination (either in-medium or at phase boundary)

Challenge will be to discriminate between these possible scenarios

What is the **state of the art for ψ(2S)?**

- **Initial cold nuclear matter effects** (shadowing/ energy loss) are considered to be the same for than for the J/ψ
- **In-medium effects** depending on density (comovers) are able to distinguish between J/ψ and ψ(2S)

ϒ(nS): Sequential suppression of the three states in order of their binding energy

- Color screening, or in-medium dissociation?
- Small room for recombination, some shadowing effects
- **In-medium effects** (comovers) able to distinguish between states