

# Quarkonium production in proton-nucleus (& proton-proton) collisions

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# 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

**Color singlet model (CSM): 1975** - Einhorn, Ellis (1975), Chang, Gross & Jone (1981), ...

- Assume physical color singlet state, quantum numbers are conserved
- Only the pair with right quantum numbers can hadronize. **Effectively no free parameter**

**Color evaporation model (CEM): 1977** - Fritsch (1977), Halzen (1977), ...

- Does not distinguish between pairs with respect to their color and spin
- All pairs with  $n < n_{\text{open}}$  than open heavy flavor threshold

**One parameter per quarkonium state**

**Nonrelativistic QCD (NRQCD): 1986** - Caswell, Lapage (1986) Bodwin, Braaten, Lepage (1995), ...

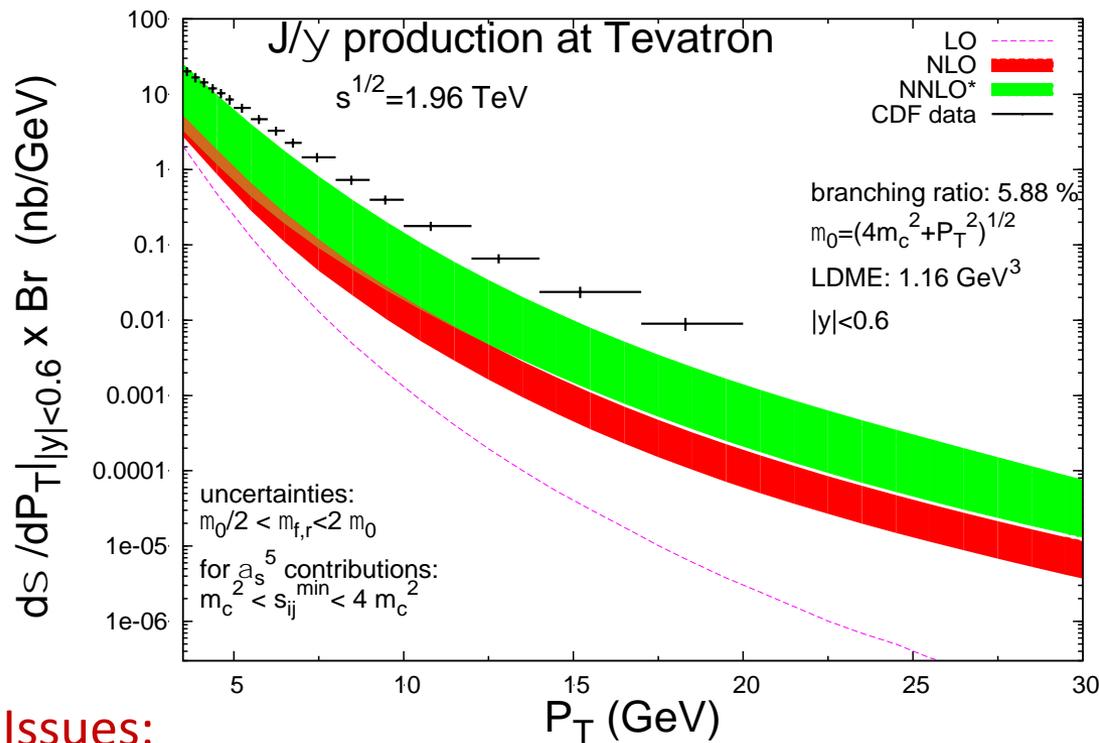
- Rigorous effective field theory based on factorization of soft and hard scales
- All pairs with various probabilities – NRQCD matrix elements

**Infinite parameters – organized in powers of  $v$  and  $\alpha_s$**

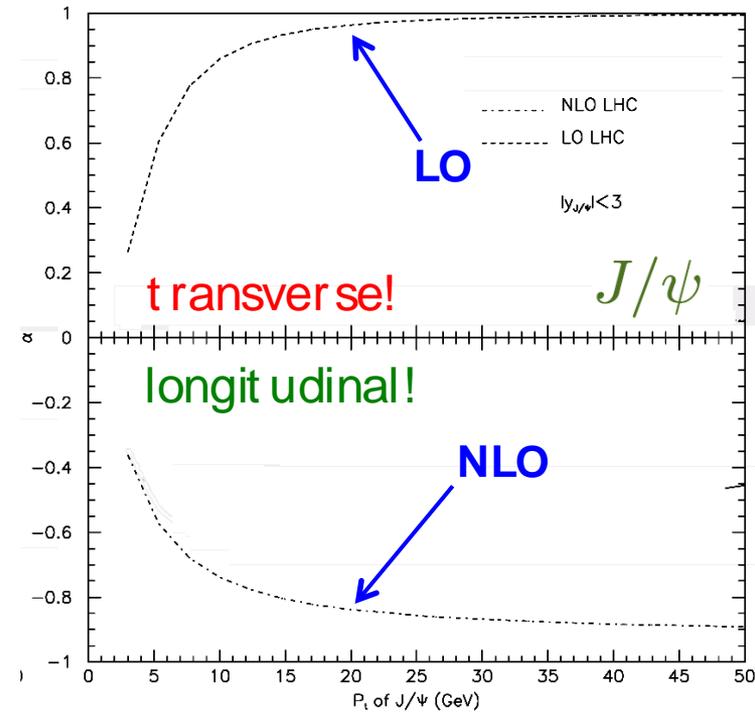
**Production mechanism still not settled after more than 40 years!**

# 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)

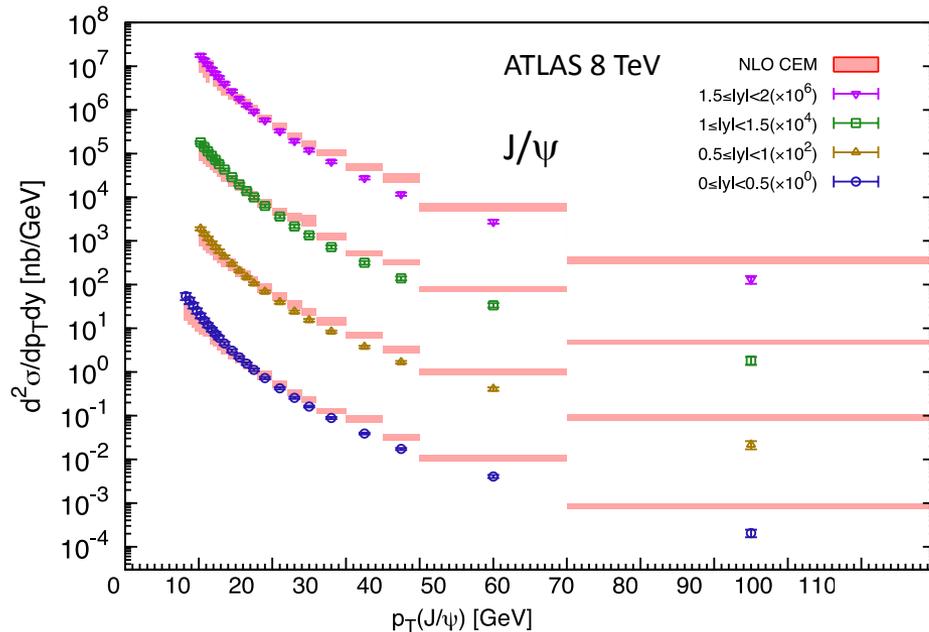
## Issues:

- 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

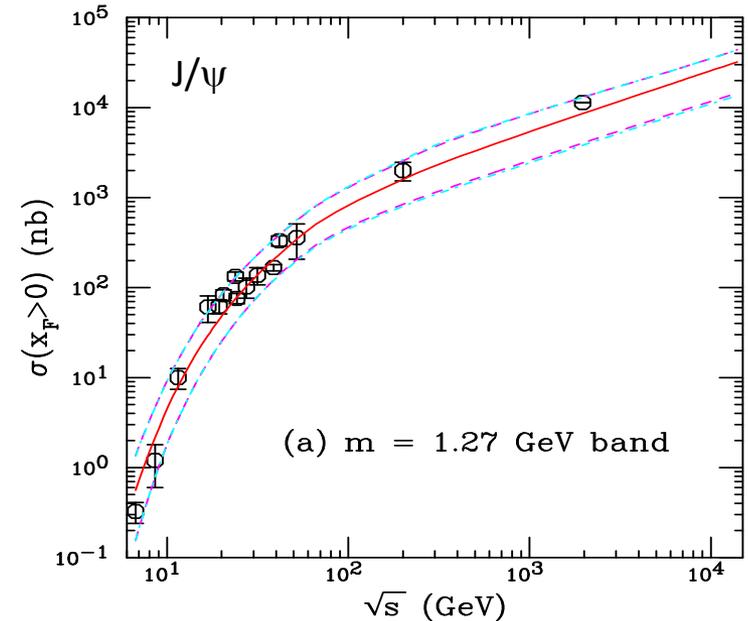
# Color Evaporation Model (CEM)

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

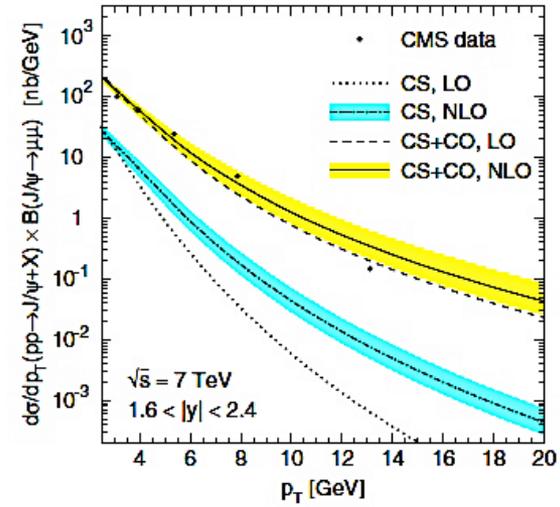
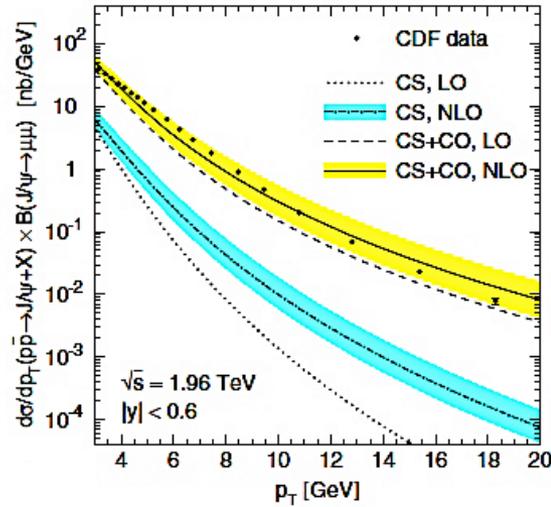
# Nonrelativistic QCD Approach (NRQCD)

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

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

4 leading channels in  $v$   
 $3S_1^{[1]}, 1S_0^{[8]}, 3S_1^{[8]}, 3P_J^{[8]}$   
 Full NLO in  $\alpha_s$

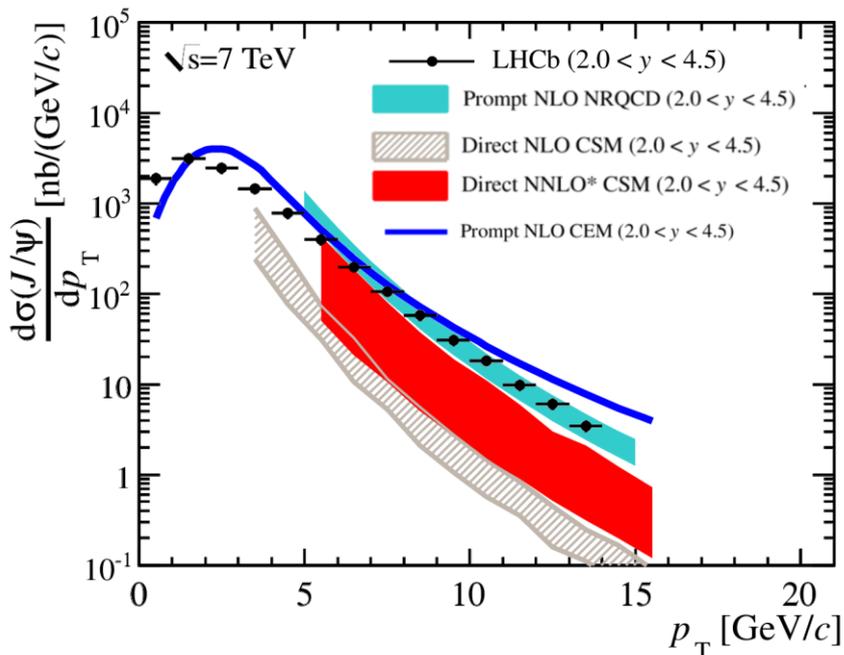
Butenschön & Kniehl (2011)



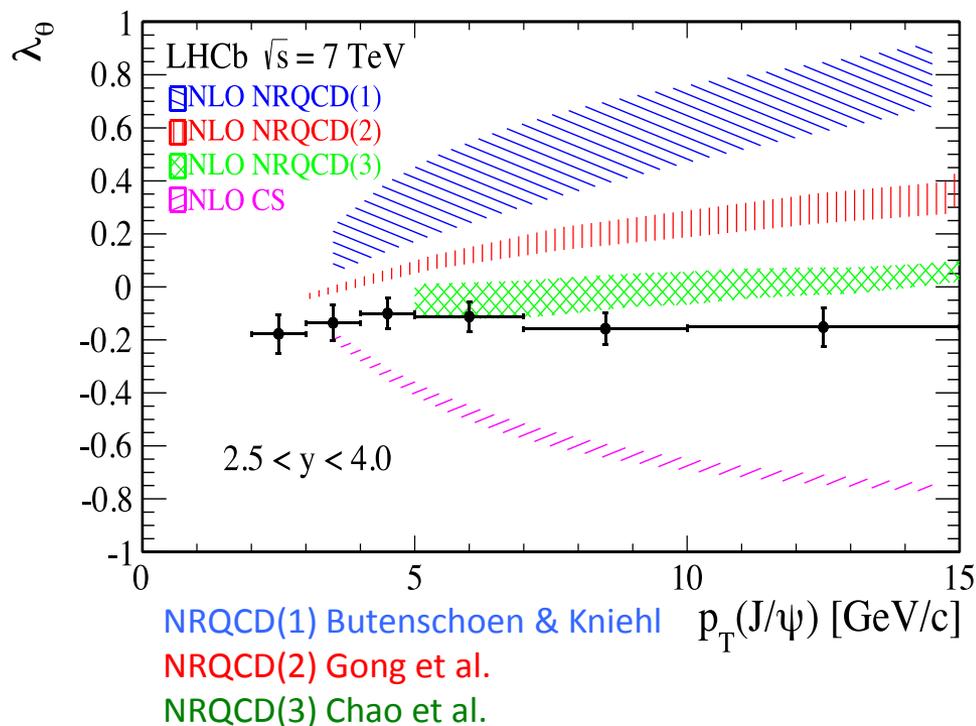
## Issues:

- 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  $J/\psi$  results do not work for other states, e.g.  $\eta_c$

# State of the art for the $J/\Psi$



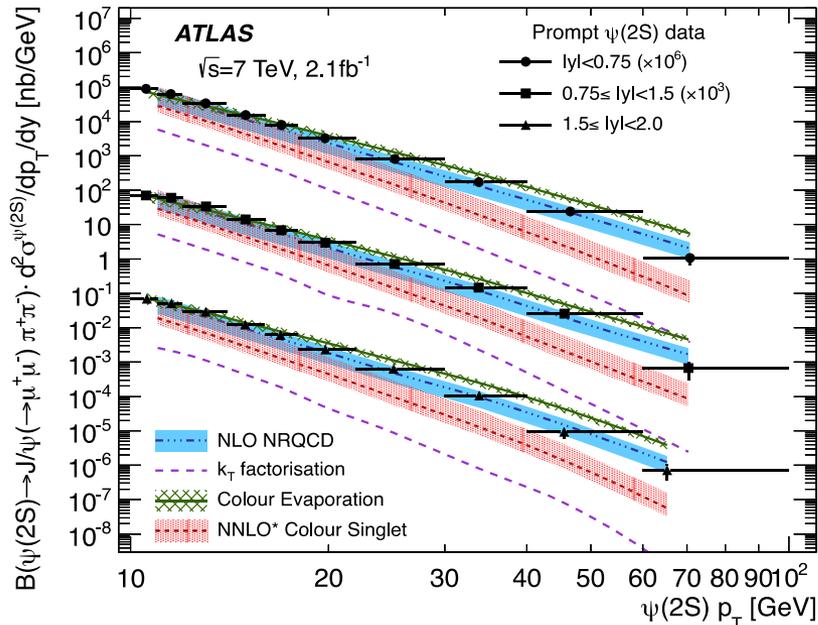
Sapore Gravis Review arXiv:1506.03981



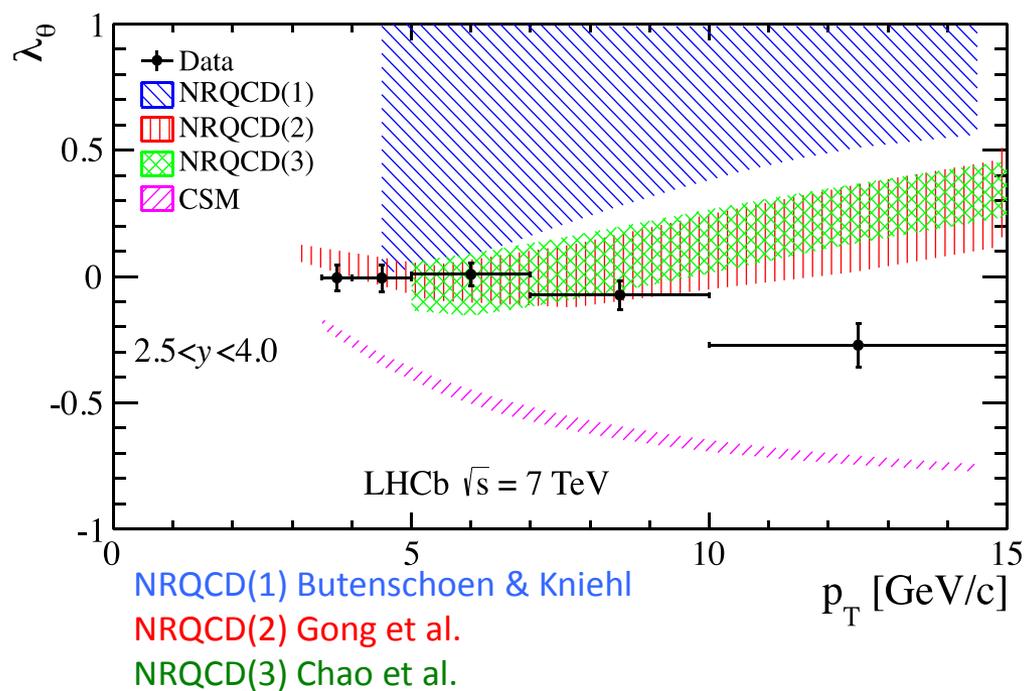
- **CSM** still in the game: Large NLO and NNLO; need a full NNLO
- **NRQCD**: COM helps in describing the  $p_T$  spectrum.
- **CEM** recent developments may be helpful

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 $\Psi(2S)$



Sapore Gravis Review arXiv:1506.03981



NRQCD(1) Butenschoen & Kniehl

NRQCD(2) Gong et al.

NRQCD(3) Chao et al.

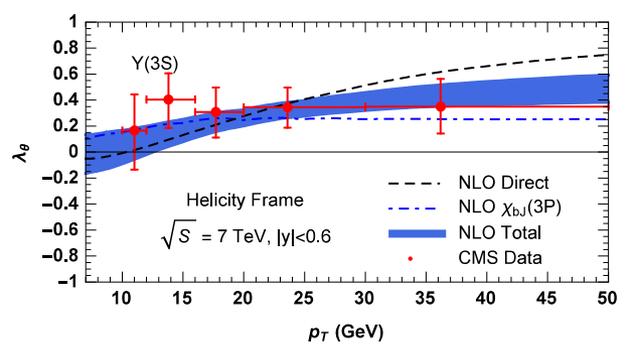
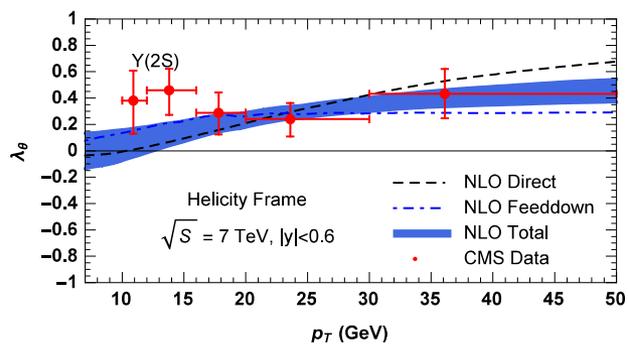
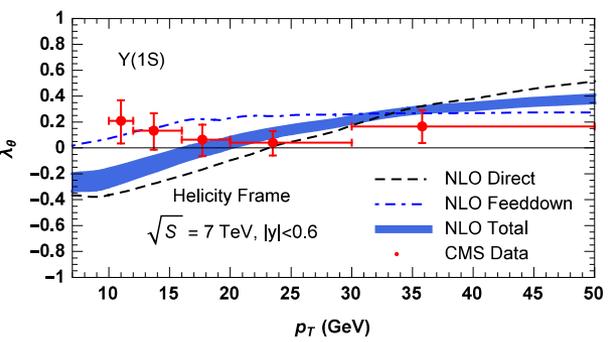
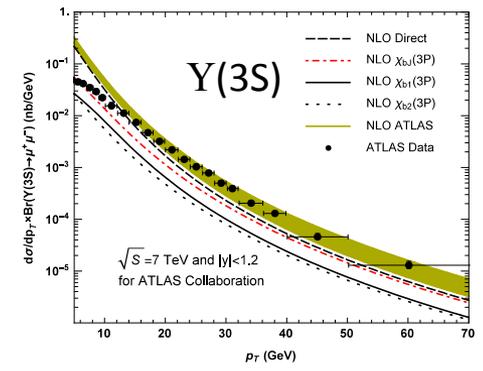
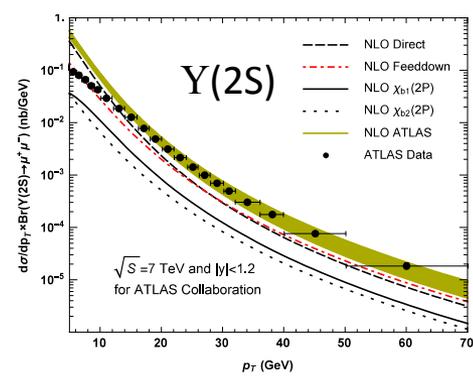
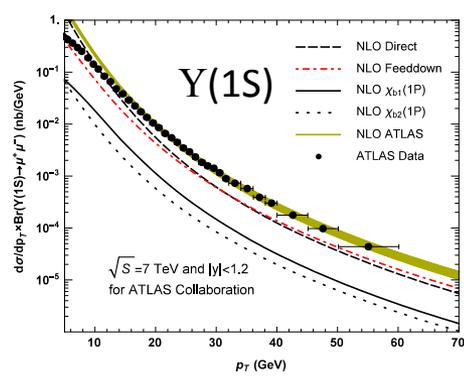
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# What about bottomonium?

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

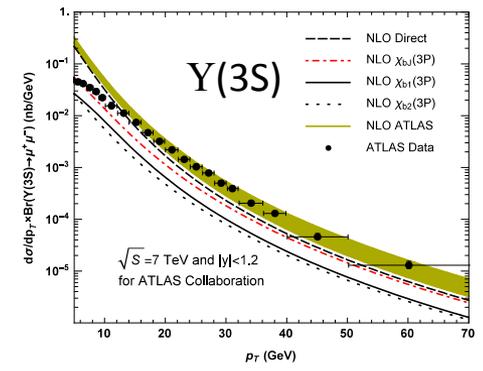
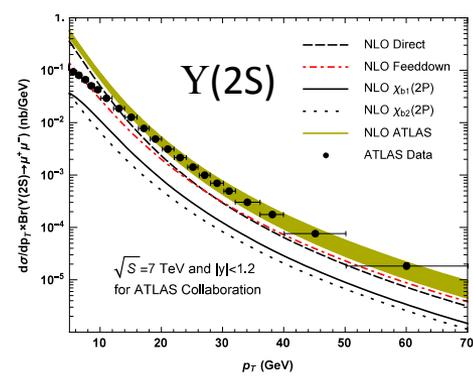
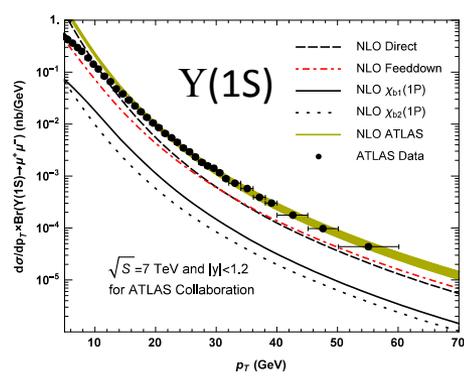
Hang et al.



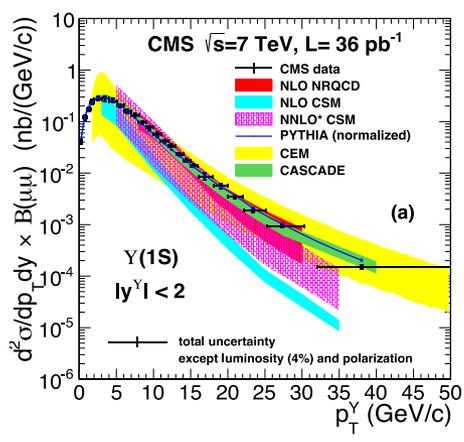
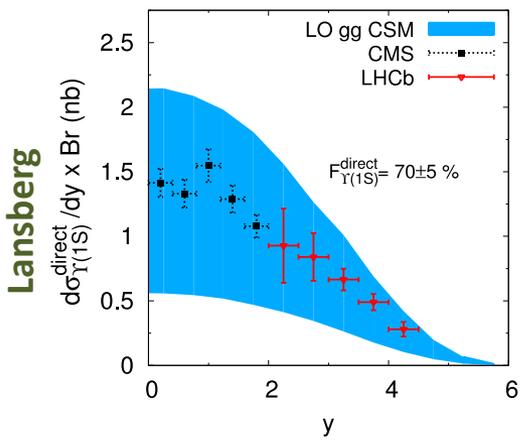
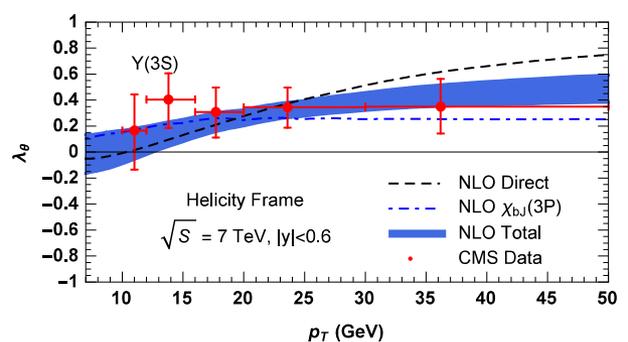
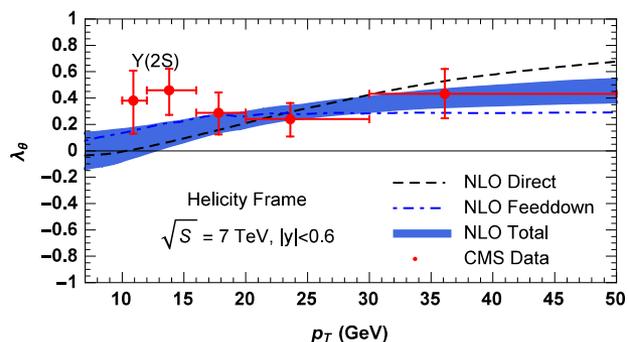
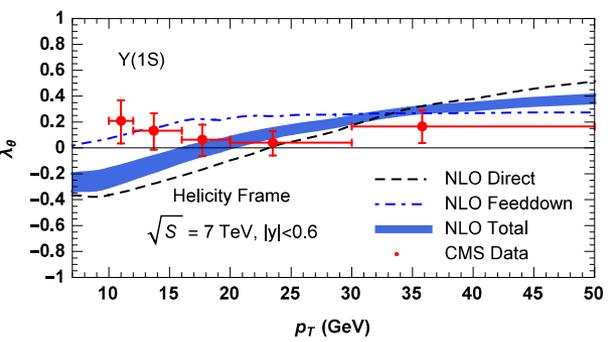
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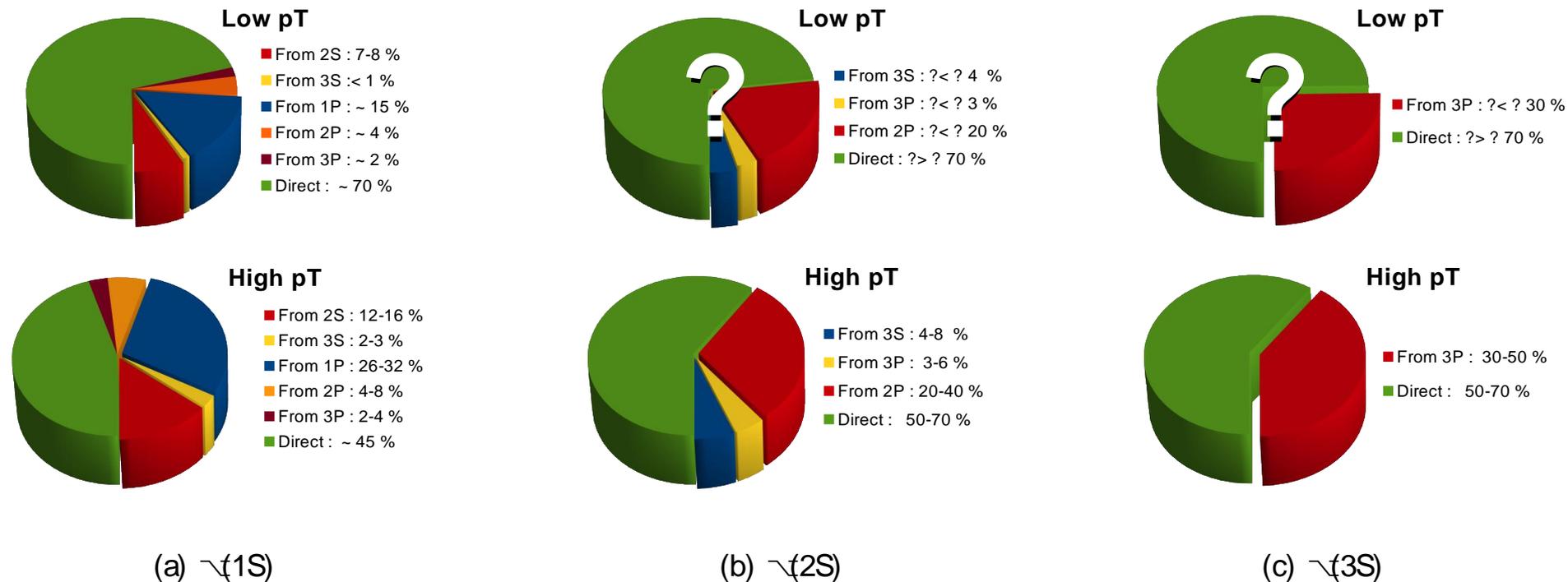
Lansberg



- None of the models can simply be ruled out due to their theoretical uncertainties
- Rapidity dependence of the  $Y(1S)$  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



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

# 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**

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:

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

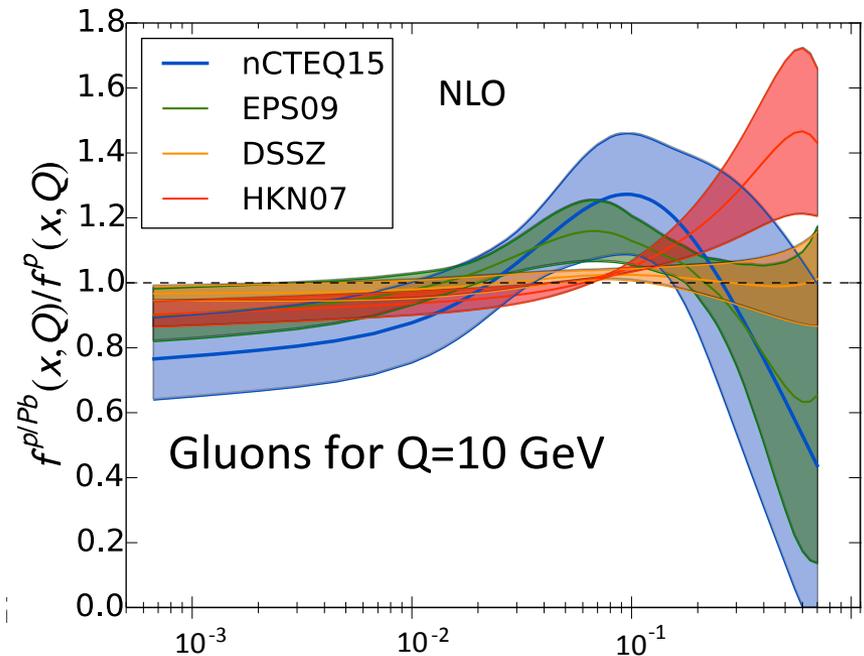
From any model (CSM, COM, CEM)

# 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 expects

$$\sigma_{\text{break-up}} \propto r_{\text{meson}}^2$$

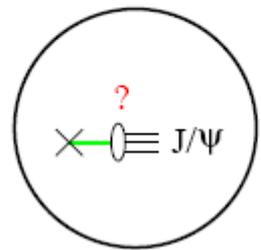
• In order to interact with nuclear matter =>  $t_f \leq R$

• In the meson rest frame:  $\tau_f = \frac{2M_{c\bar{c}}}{(M_{2S}^2 - M_{1S}^2)} \approx 0.3 \div 0.4 \text{ fm}$

•  $t_f$  has to be considered in the rest frame of the target nucleus =>  $t_f = \gamma \tau_f$

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

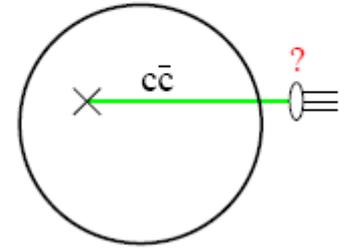
High energy:  $t_f = \gamma(x_2) \tau_f \gg R$



**Formation time depends on the boost**

$$\gamma = \cosh(y - y_{\text{beam}}^A) \Rightarrow \text{At } y=0:$$

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



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

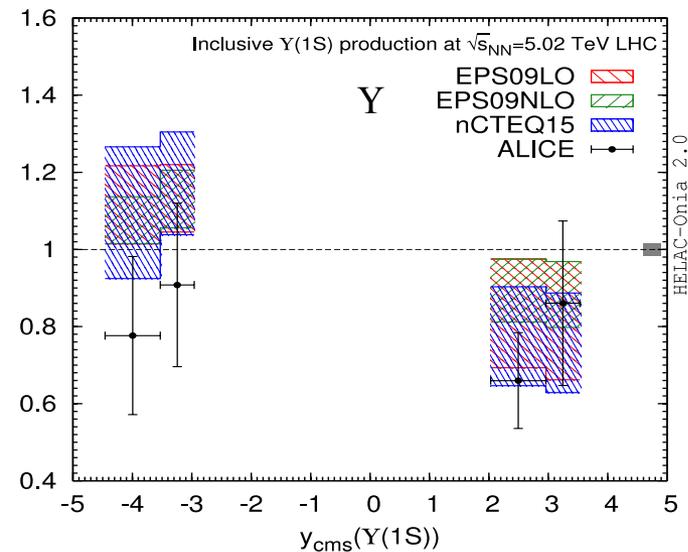
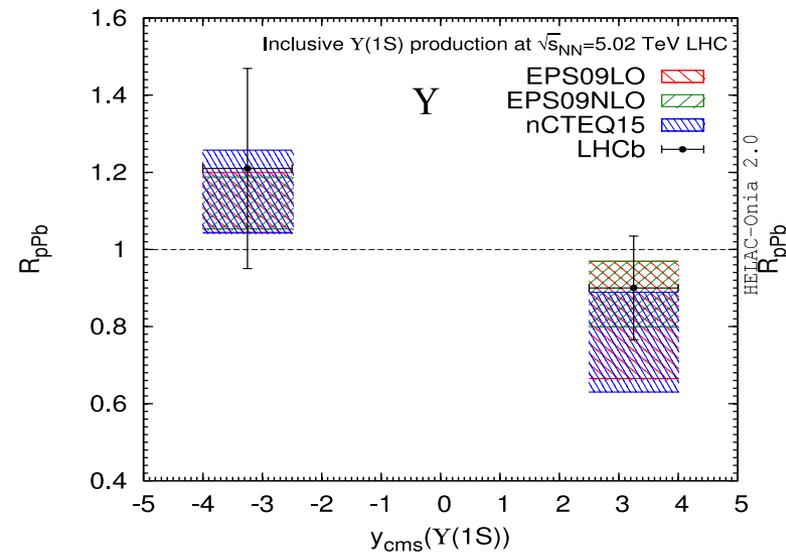
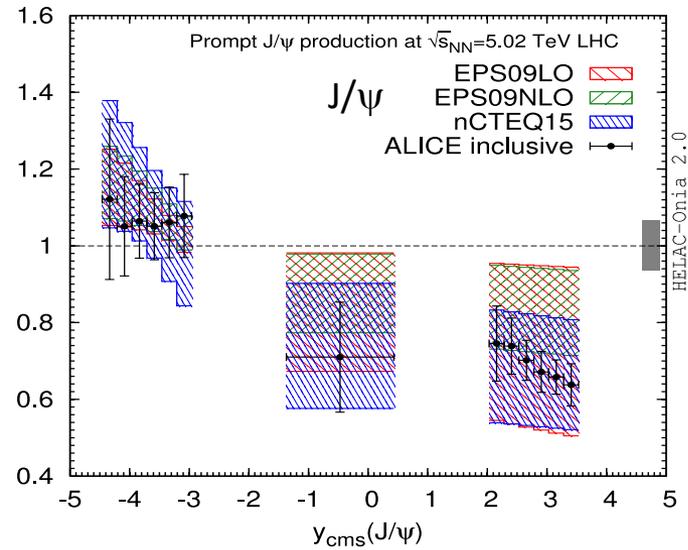
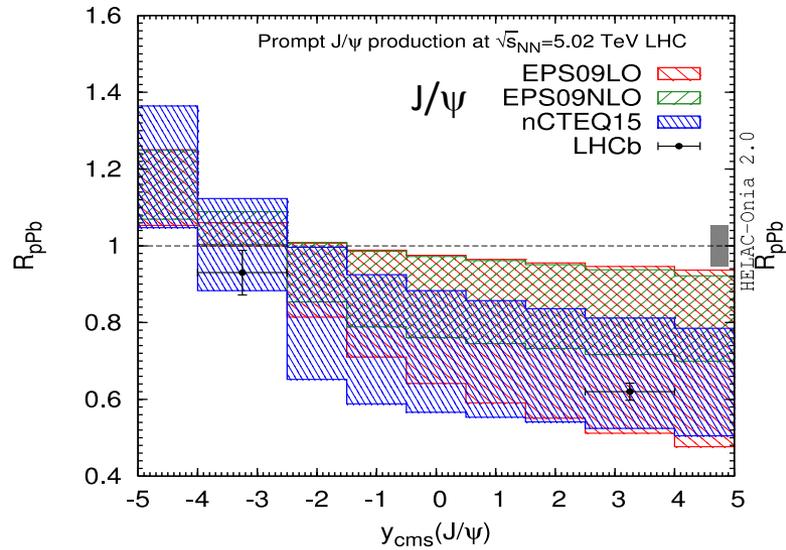
$$t_f \gg R$$

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)

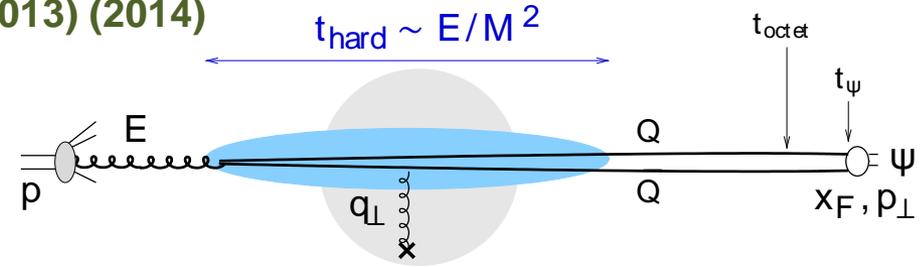


- Data is compatible with strong shadowing
- The precision of the current data is already much better than the nPDF uncertainties
- It may offer hints for constraining the gluon density in Pb

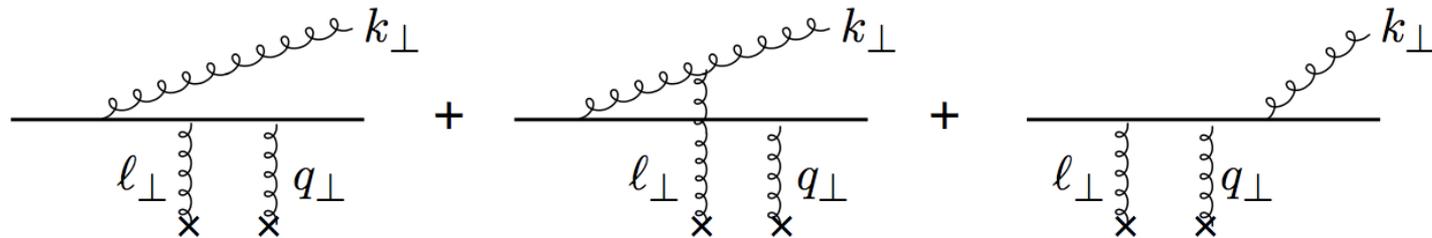
# Going further: Coherent energy loss

Arleo, Kolevatov, Peigné, Rostamova (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**  $\Delta E \propto E$

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

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

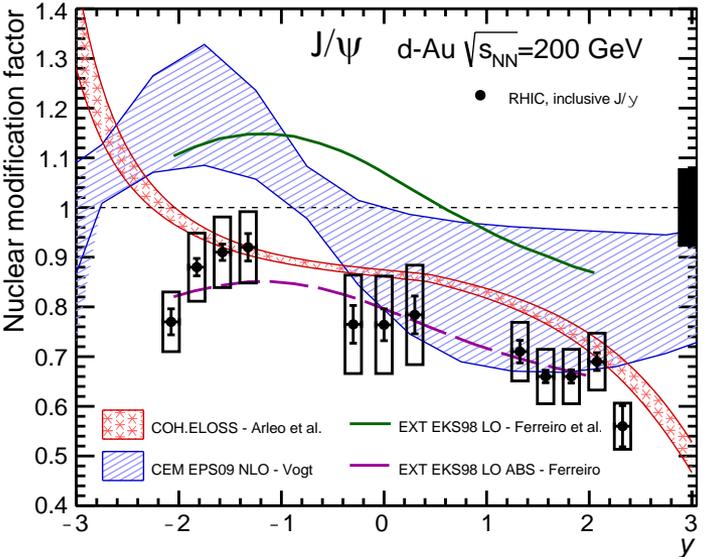
$$\hat{q}(x) \sim \hat{q}_0 \frac{10^{-2}}{x} \blacklozenge^{0.3}$$

- $\hat{q}$  related to the **saturation scale** by

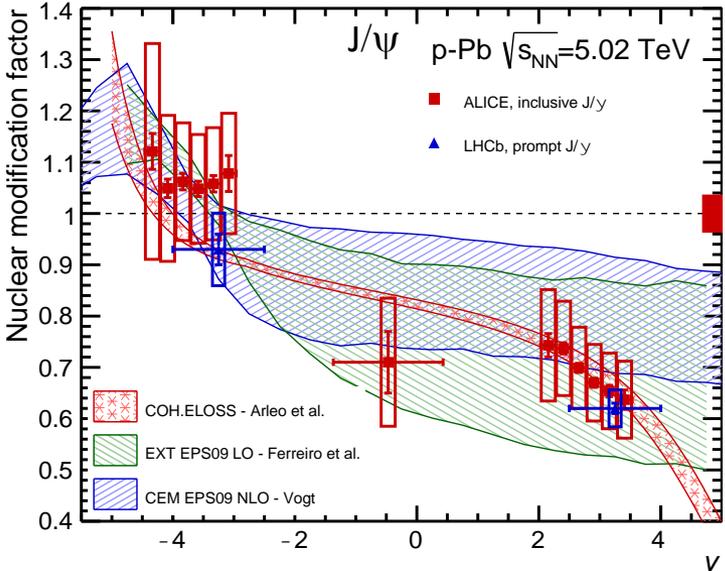
$$Q_s^2(x, L) = \hat{q}(x) L$$

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

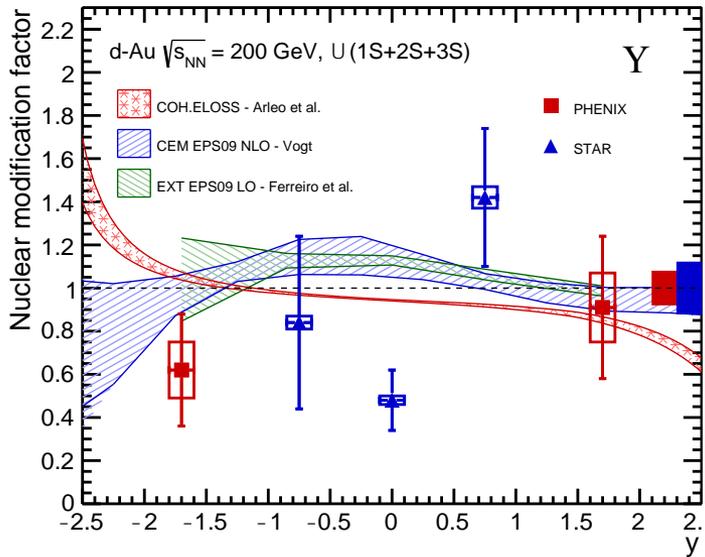
# Comparison of nPDFs & Eloss with RHIC & LHC d/p+A data



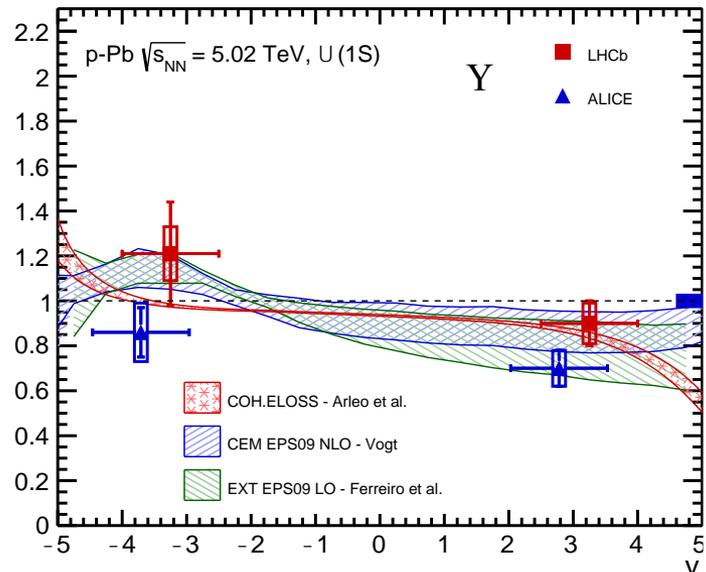
- nPDF modification and/or coherent energy loss fairly agree with data



- Do data show energy increase of suppression?



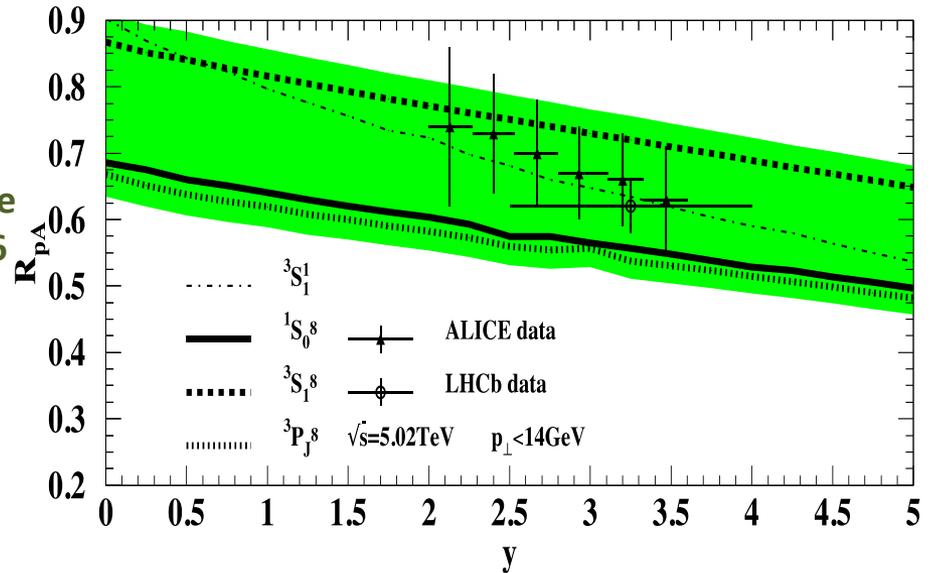
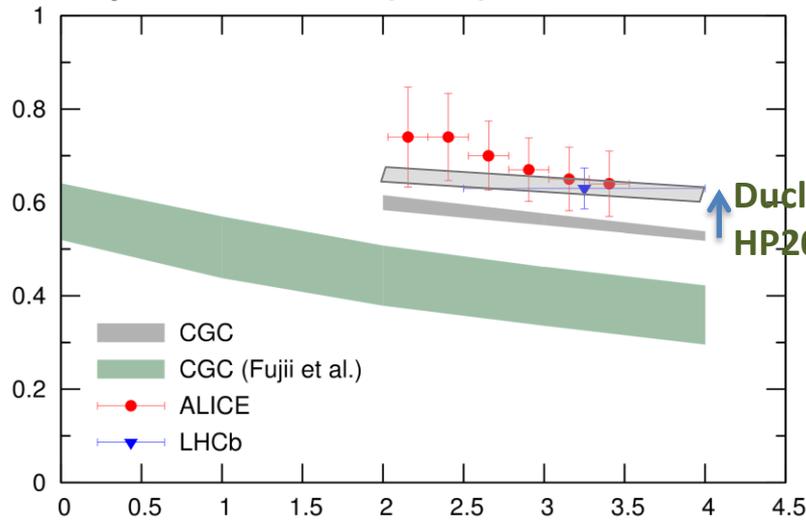
- More data and more precise ones are needed



# CGC computations: not just gluon saturation

- $J/\psi$  suppression **predicted** by Fujii and Watanabe within CEM significantly below the data:

Fujii, K. Watanabe (2013)

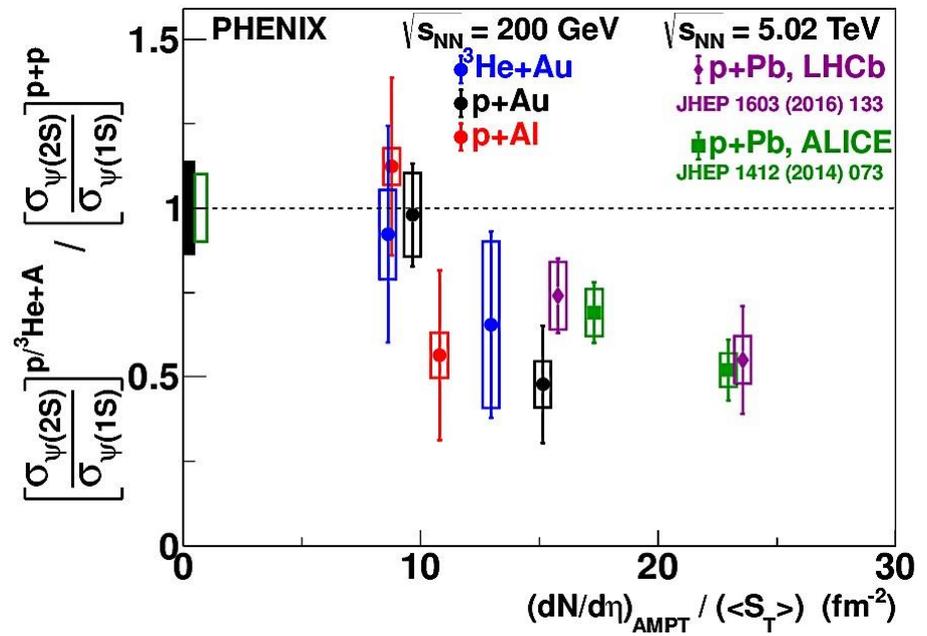
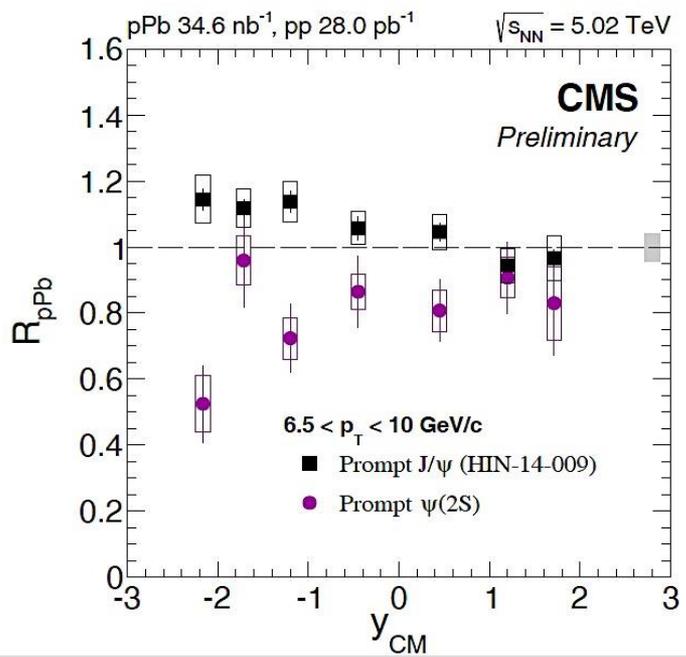


- Improved **postdictions**:
  - ◆ CEM with improved geometry **Ducloue, Lappi, Mäntysaari (2015)**
  - ◆ NRQCD : results depend on the CO channel mix **Ma, Venugopalan, Zhang (2015)**
- CGC results very much widespread (as those from nPDFs):  $J/\psi$  suppression at forward  $y$  in pA collisions at the LHC is not the expected CGC smoking gun signal

# Excited states: An intriguing relative suppression

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

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



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- **At low energies**, the **relative suppression pattern  $\psi(2S)/J/\psi$**  could easily be explained by the **nuclear absorption**  $\sigma_{\text{break-up}} \propto r_{\text{meson}}^2$   $t_f \leq R$
- **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?**

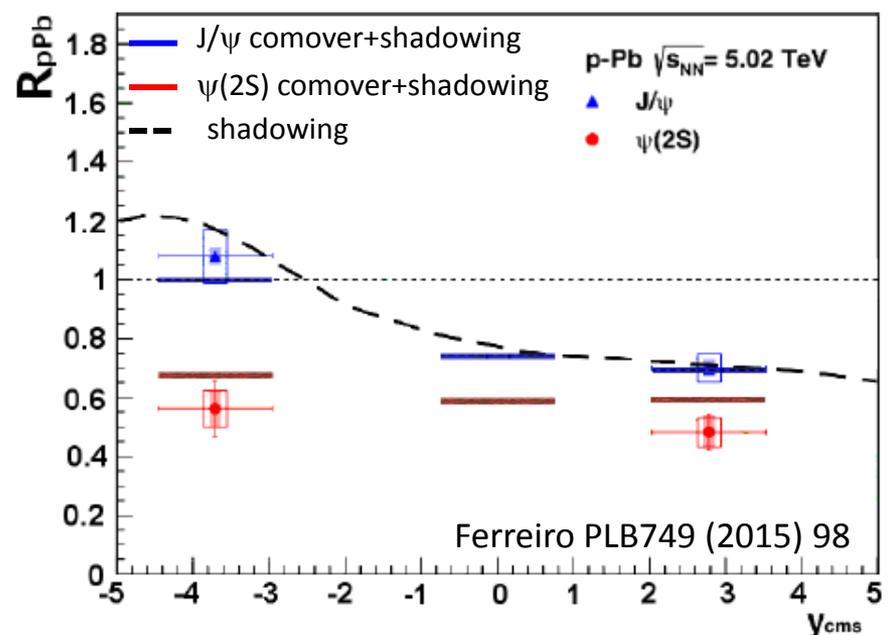
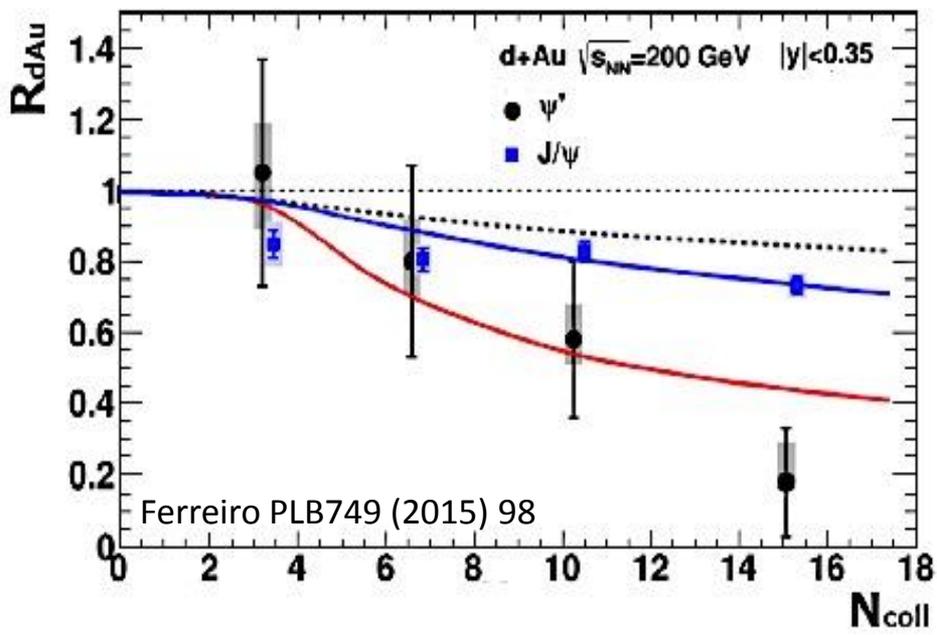
# Excited states: Comover interaction model

- In a comover model: suppression from scatterings of the nascent  $\psi$  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



# Excited states: Comover interaction model

- In a comover model: suppression from scatterings of the nascent  $\psi$  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**

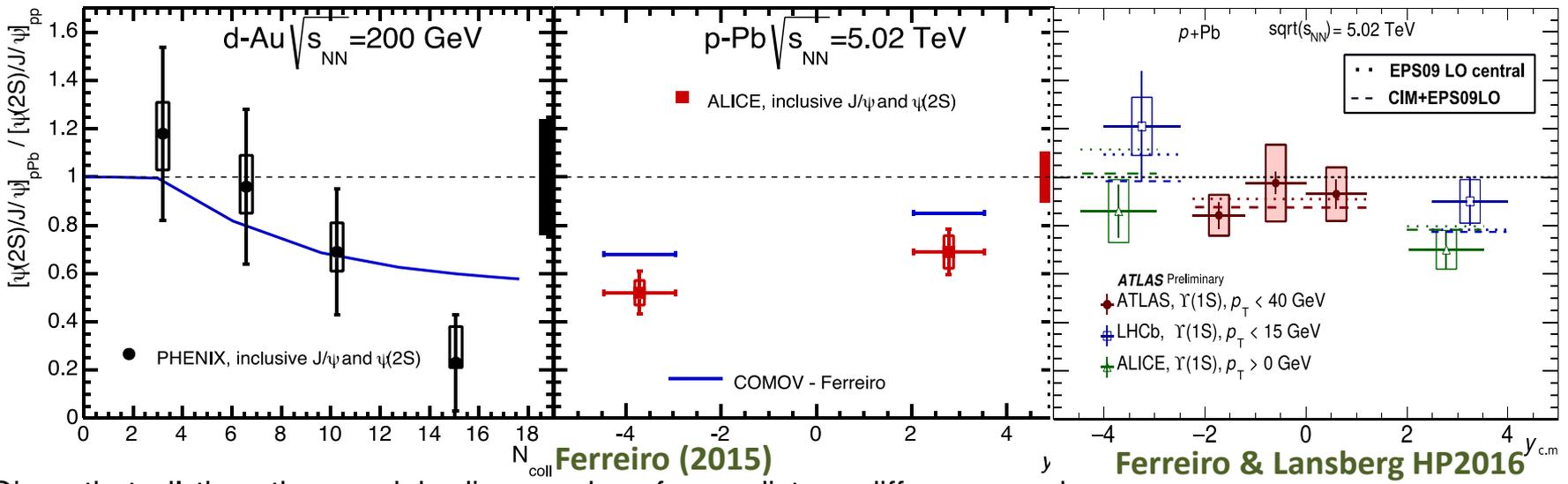
- Rate equation governing the charmonium density:

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

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

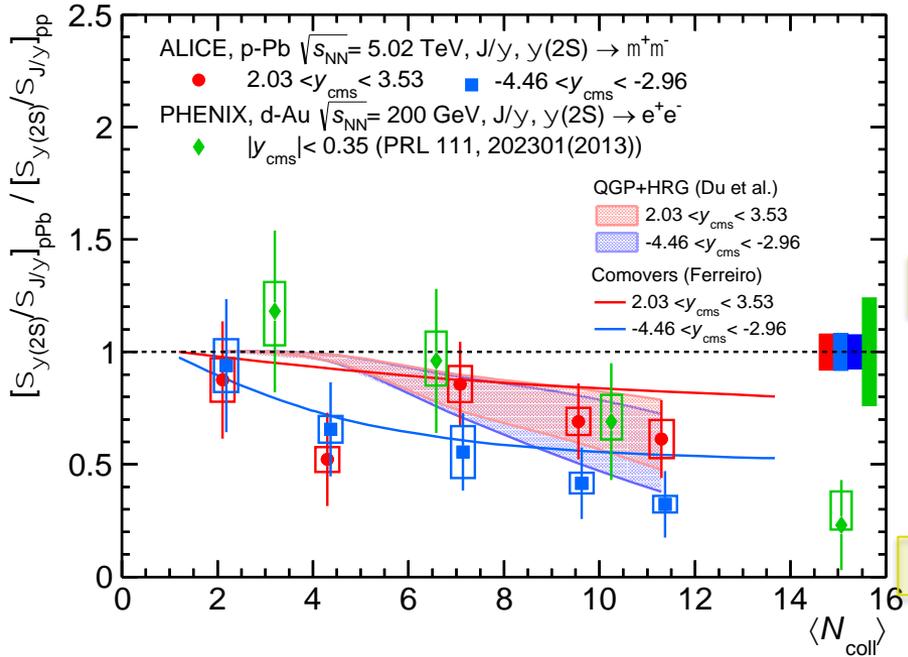
$$\sigma^{co-Q_{bb}} = \sigma_{geom} \left(1 - \frac{E_{Binding}}{\langle E_{co} \rangle}\right) n$$

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



# 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  $\psi'$  mesons in URHICs. We first revisited the problem of hadronic  $\psi'$  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  $\psi'$  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:

- 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:

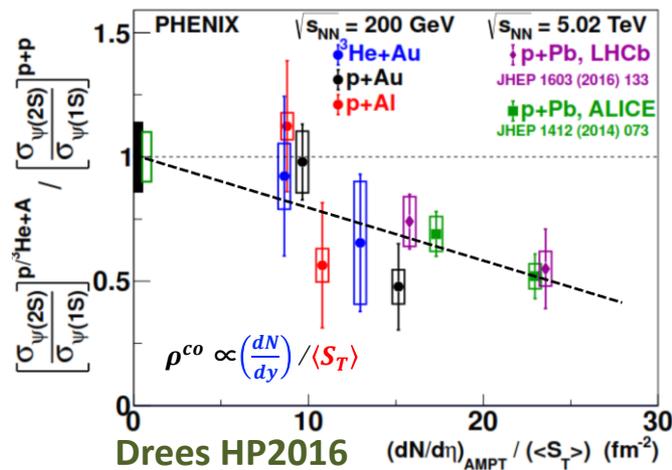
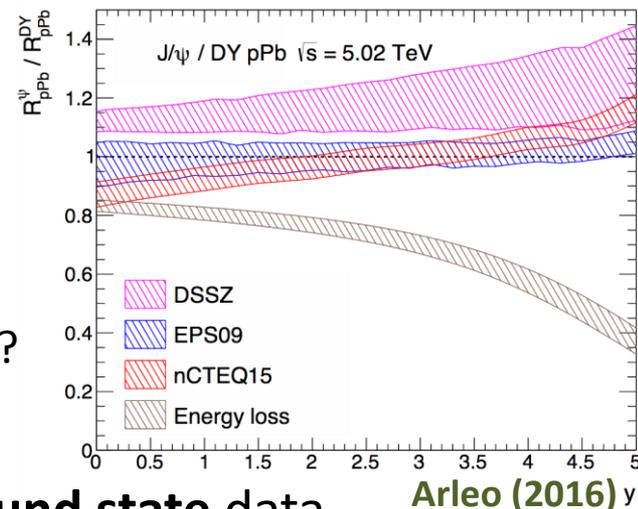
- Huge uncertainty of nPDFS
- Widespread CGC results

Possibility to distinguish between them?

- 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



BACKUP

# Universality of NRQCD matrix elements – predictive power?

arXiv:1404.3723

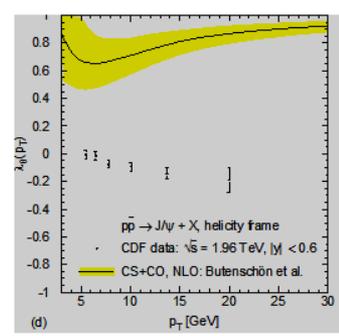
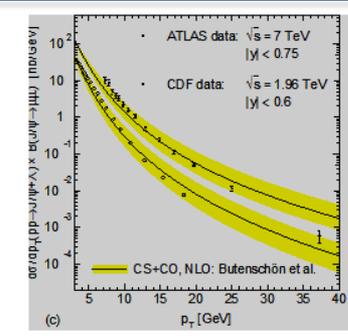
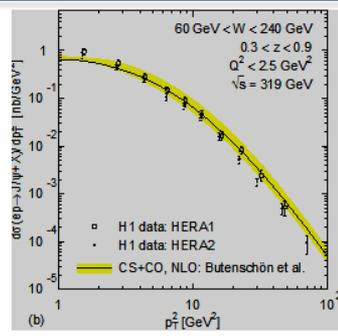
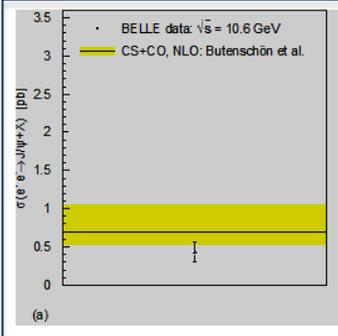
e+e-

ep

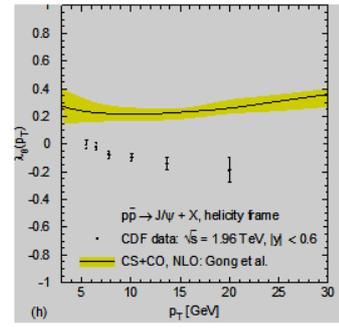
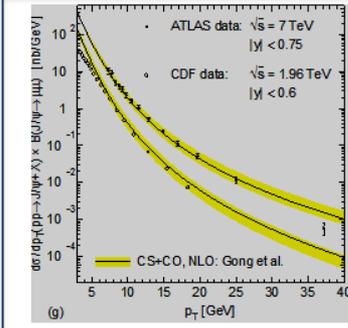
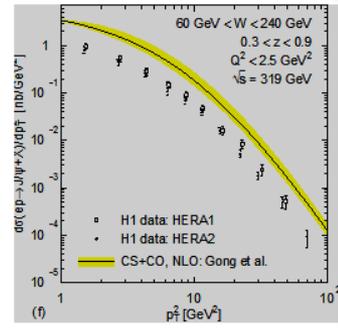
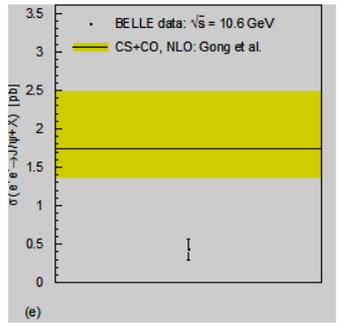
pp distribution

pp polarization

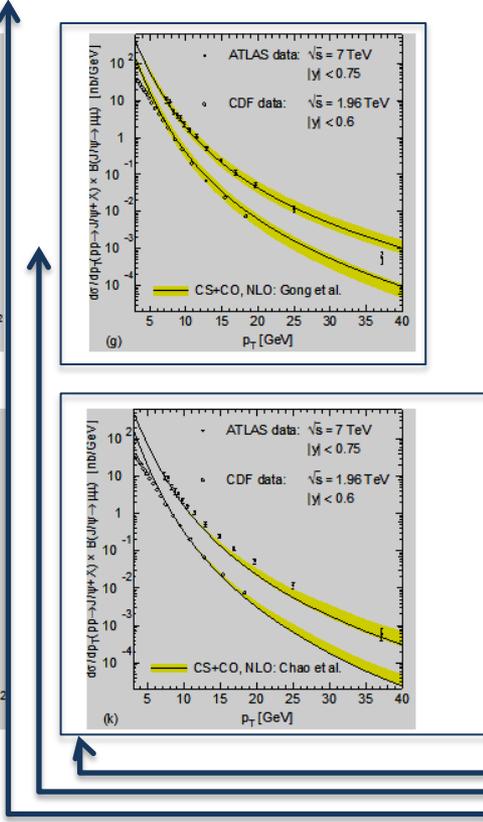
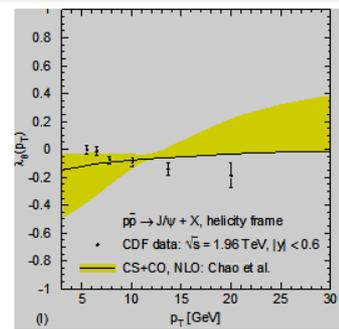
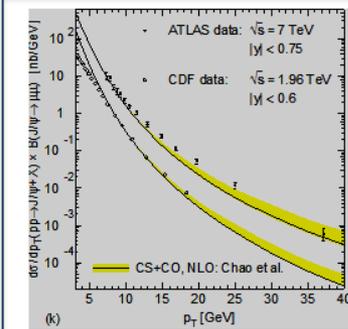
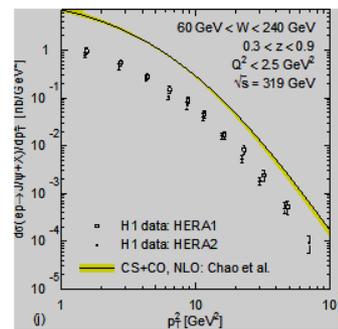
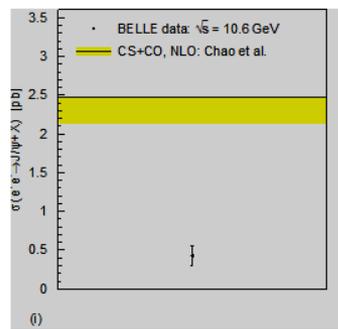
Butenschon  
& Kniel  
 $p_T > 3$  GeV



Gong et al.  
 $p_T > 5$  GeV



Chao et al.  
 $p_T > 7$  GeV



Included in fits

# Universality of NRQCD matrix elements – predictive power?

arXiv:1404.3723

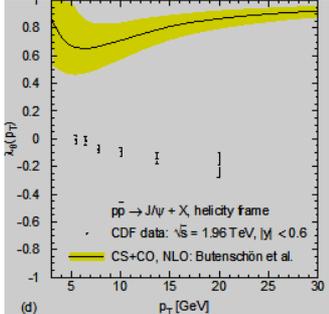
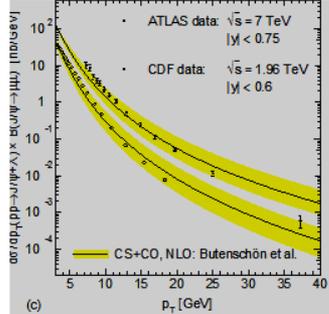
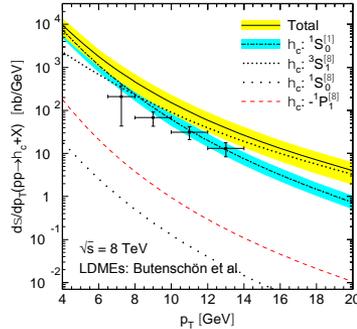
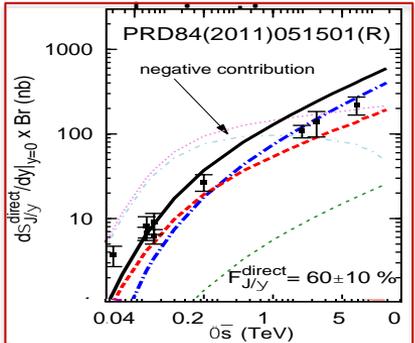
pp cross-section

pp distribution

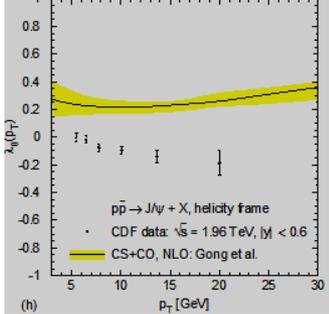
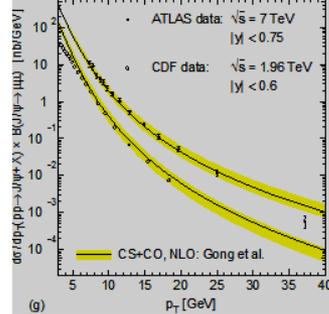
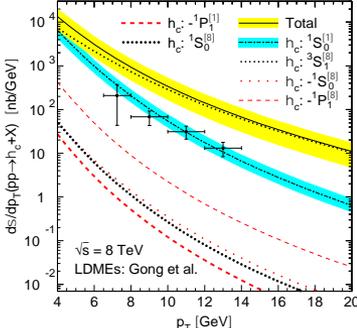
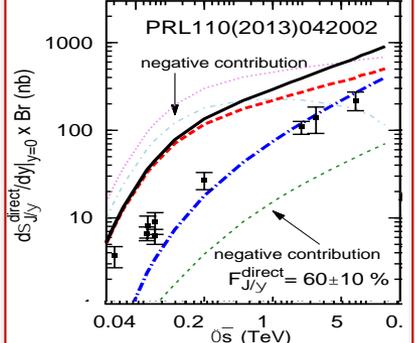
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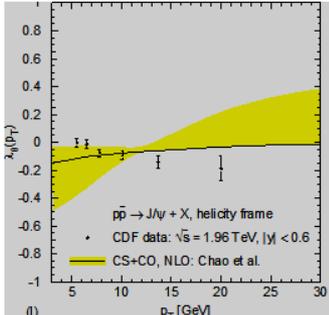
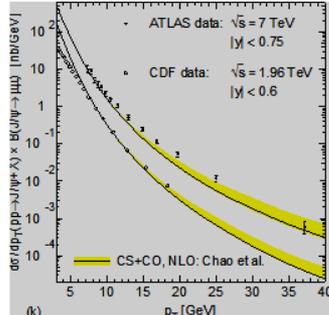
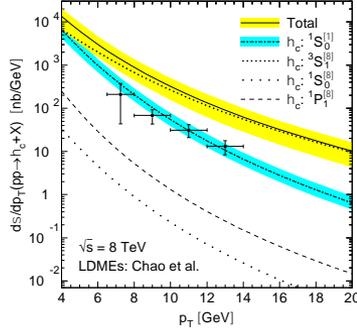
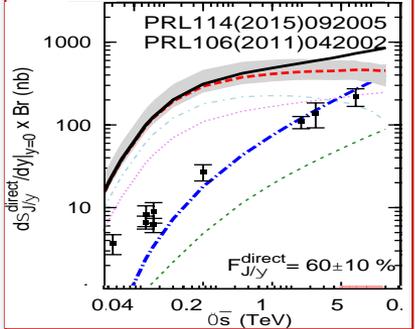
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Feng, Lansberg  
Wang (2015)

LDMEs extracted from  $p_T$  distributions cannot describe the  $p_T$  integrated rate

# Universality of NRQCD matrix elements – predictive power?

arXiv:1404.3723

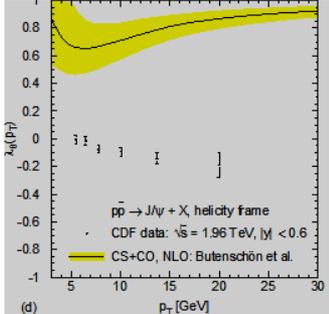
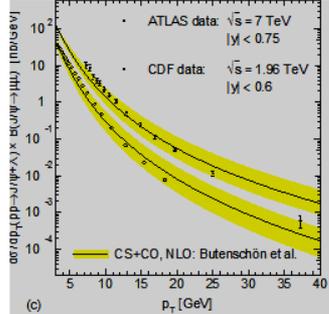
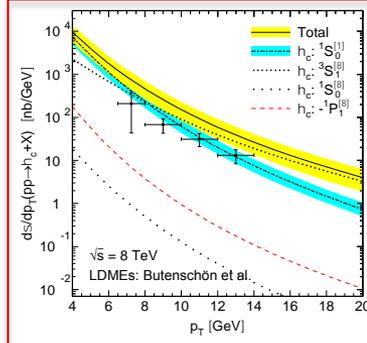
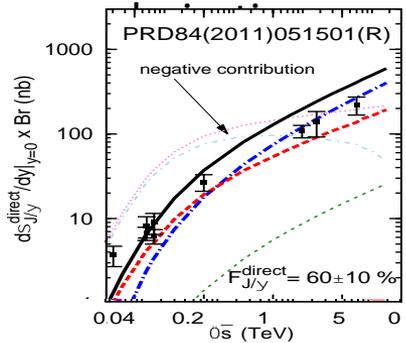
pp cross-section

pp distribution

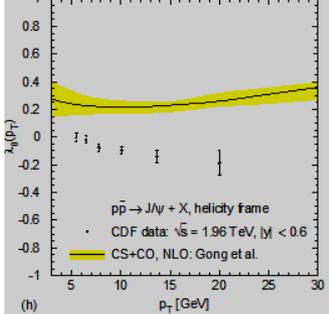
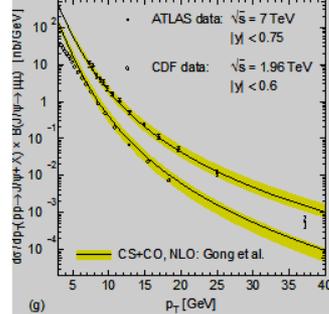
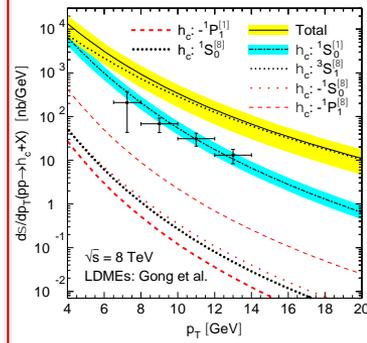
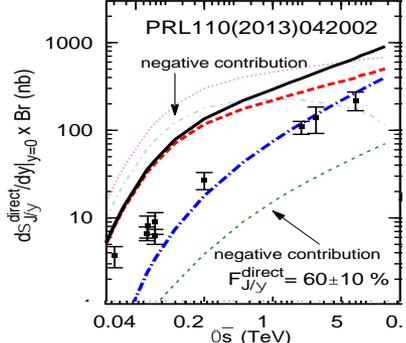
pp distribution

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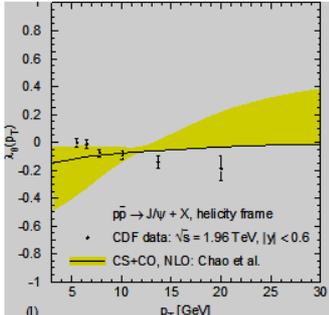
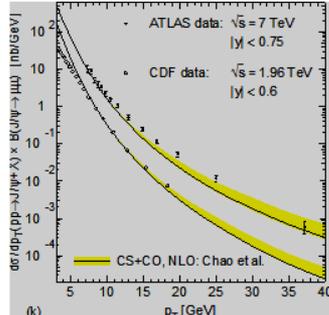
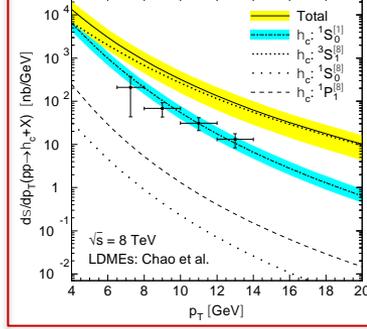
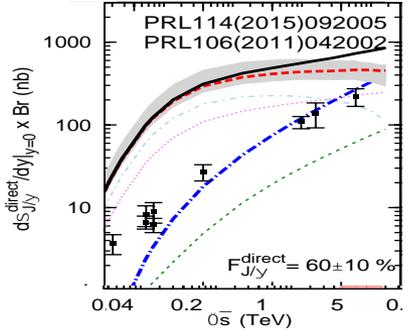
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Taking heavy-quark spin symmetry LDMEs to apply to  $\eta_c$  production => overprediction LHCb  $\eta_c$  yields