In collaboration with E. G. Ferreiro,
F. Fleuret, J. P. Lansberg & N. Matagne

Nuclear effects on Quarkonia and Heavy Quarks

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sur les lois fondamentales
de l'Univers

IS 2013, Sept. 12th, Illa da Toxa – Galicia (Spain)

A ride into the cold lands ...

A ride into the ~~cold~~ windy lands ...

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- necessary to unravel hot (QGP) from cold effects

A ride into the ~~cold~~ windy lands ...

- [ ] necessary to unravel hot (QGP) from cold effects
- [x] interesting on its own !
- [x] complex features, challenging for theories/models
  - hidden vs open charm/beauty
  - ground state vs excited state
  - hadronised or pre-resonant state
  - initial (shadowing ...) or final-state effect (absorption ?)

Workflow : from pp to pA

- Quarkonia in pp

$2 \longrightarrow 2$ process

partonic production
process used as an input

- Quarkonia in pA

estimate
CNM effects + uncertainties

p+p

p+p

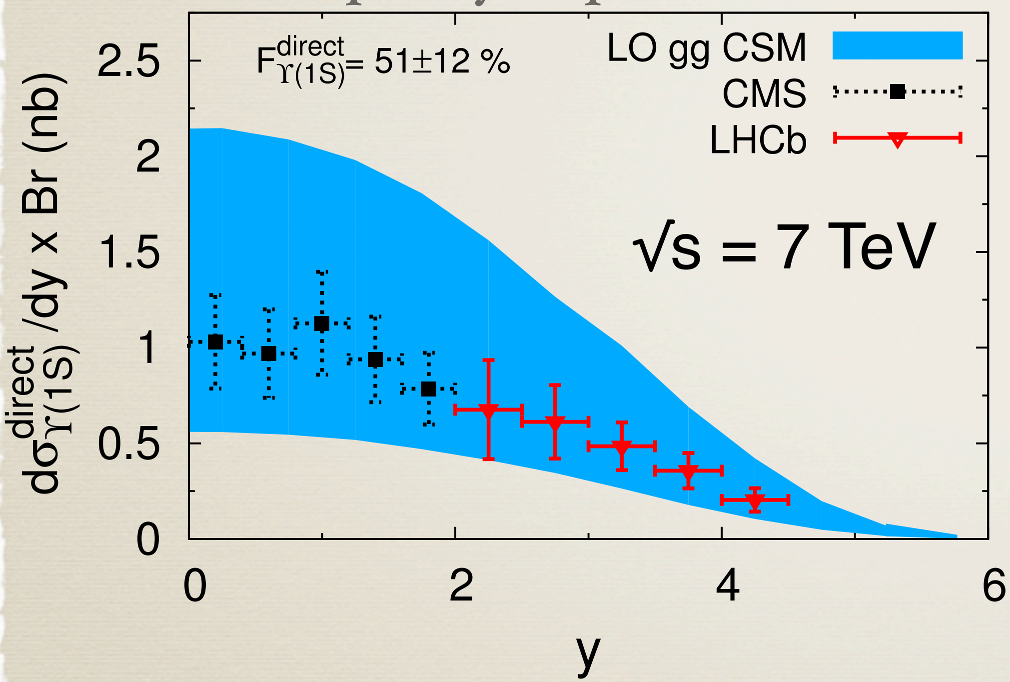
$\Upsilon(1S)$

CSM @ LO

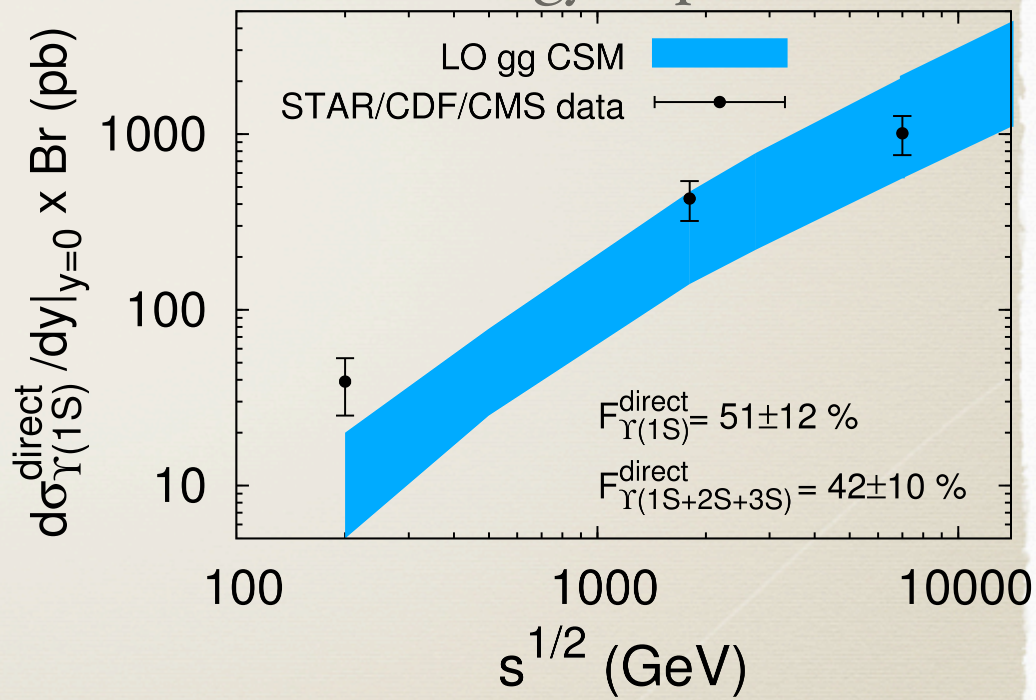
$$g + g \rightarrow \Upsilon + g$$

CSM LO sufficient to describe p_T integrated data

rapidity dependence



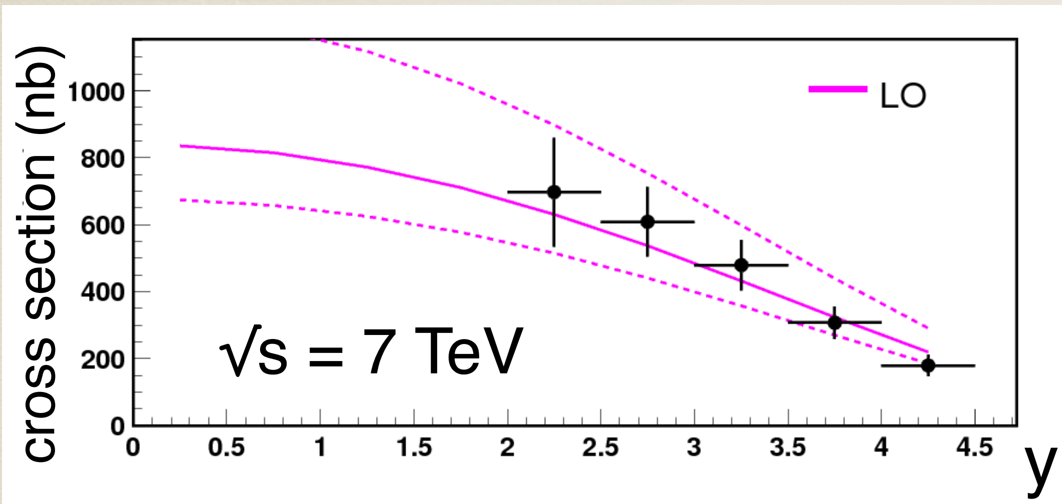
energy dependence



J.P. Lansberg, Nucl. Phys. A 910-911 (2013) 470

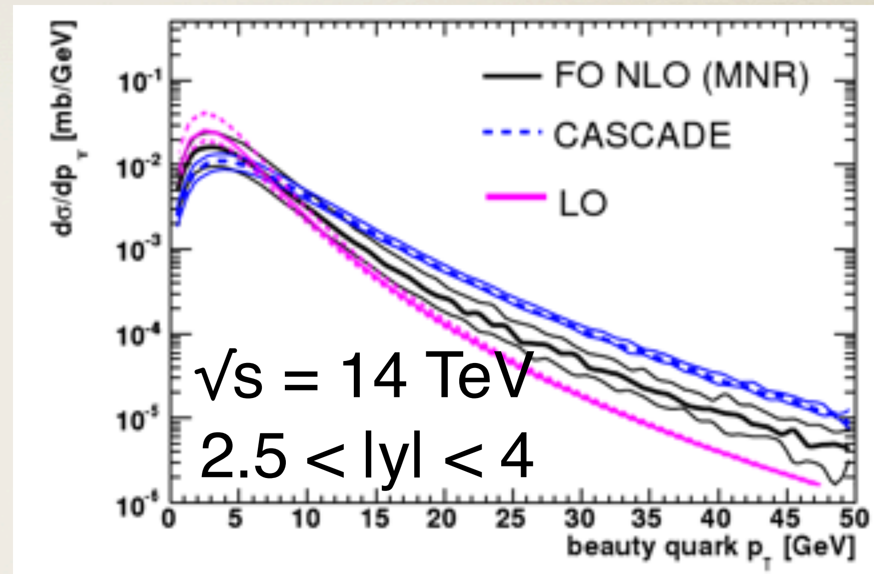
p+p LO $g + g \to b + \bar{b}$ for b-quark production

J/ψ from b @ LHC



data: LHCb Collaboration, Eur. Phys. J. C 71 (2011) 1645

b-quarks prod. @ LHC



E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
in preparation

good agreement with :

- ☑ data vs y
- ☑ other approaches at low p_T of the b quark

$p+A$

Nuclear modification of g(x)

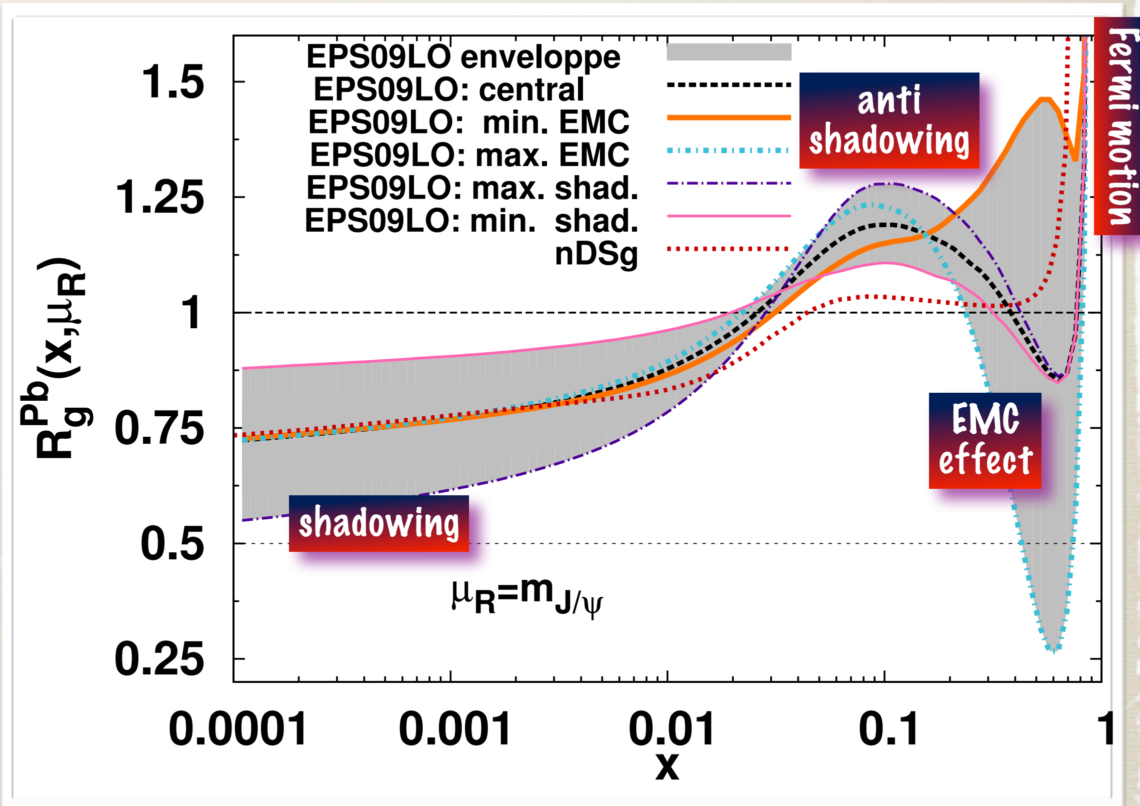
p+A

Large uncertainties for gluons :

- « **qualitative** » i.e. shape of the nPDF
  - antishadowing ?
  - EMC effect / Fermi motion ?
- « **quantitative** »
  - strength of the shadowing ?
  - strength of the EMC effect

Ratio of nuclear struct. f. per nucleon :

$$R_g^A = \frac{\text{g PDF} \in \textbf{bound} \text{ nucleon}}{\text{g PDF} \in \textbf{free} \text{ nucleon}}$$



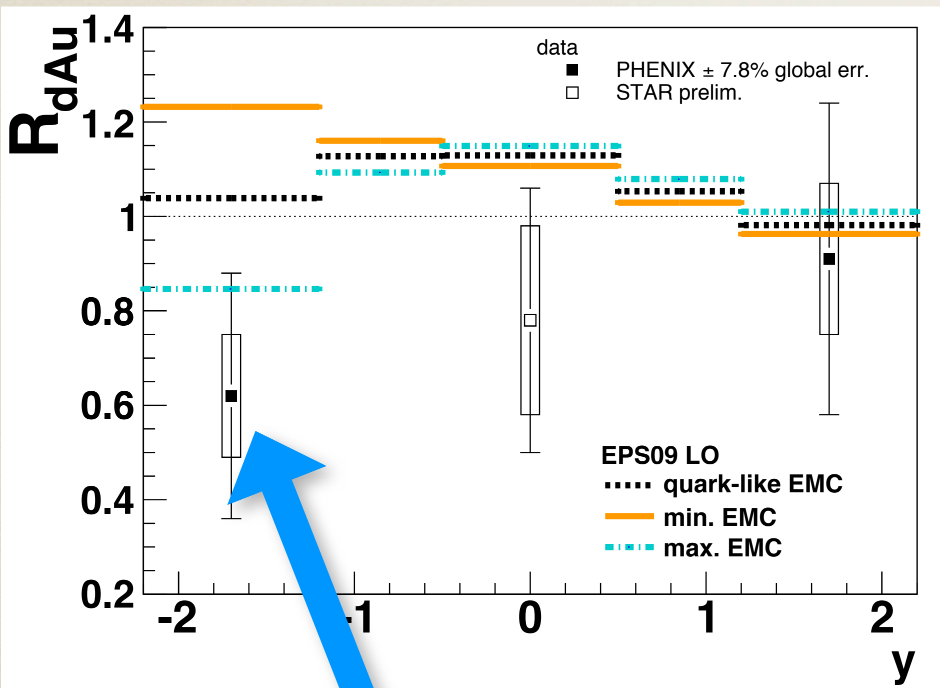
initial-state effect measured in p(d)+A

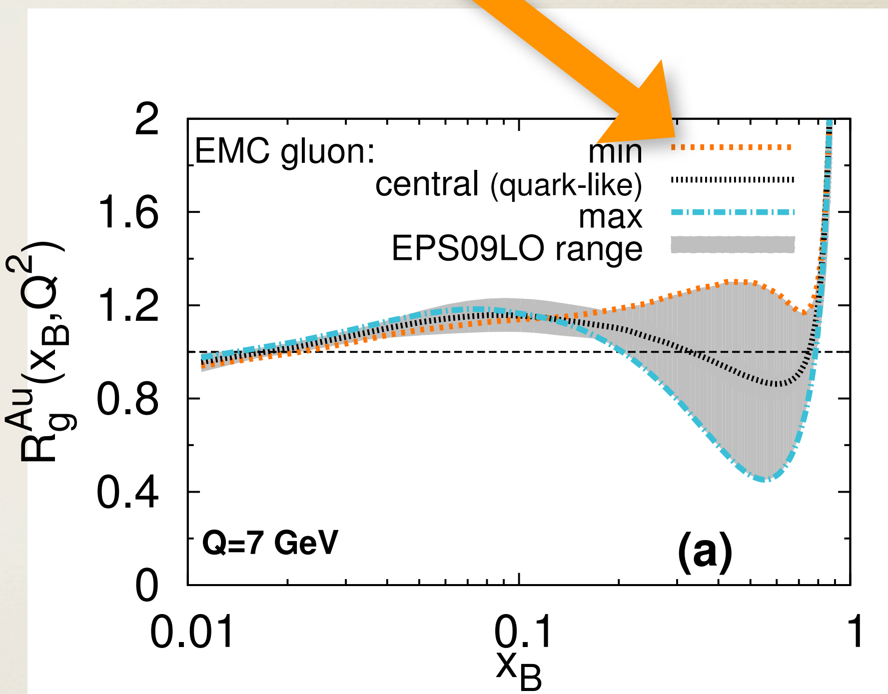
Υ in dAu @ RHIC : gluon EMC effect

Let us focus in the **EMC region** and pick the EPS09 sets that are the limiting cases in this region :

$$R_{pA} = \sigma_{pA}/\langle N_{\rm coll}\rangle \sigma_{pp}$$

min. disfavoured





EMC effect stronger for g than for q ?

E. G. Ferreiro, F. Fleuret, J. P. Lansberg, N. Matagne and A. R.
EPJ C (2013) 73:2427

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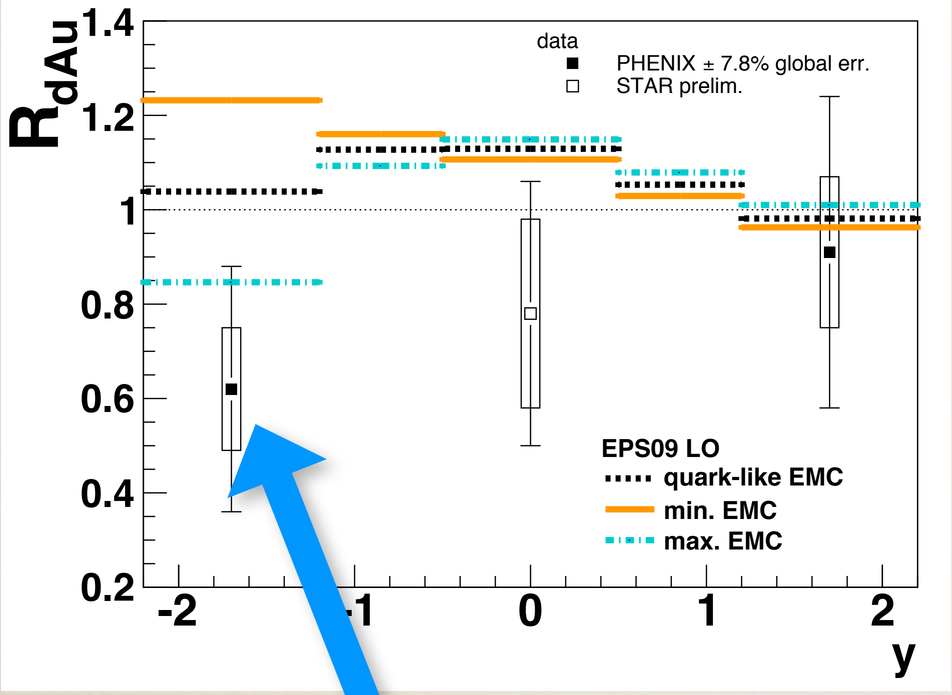

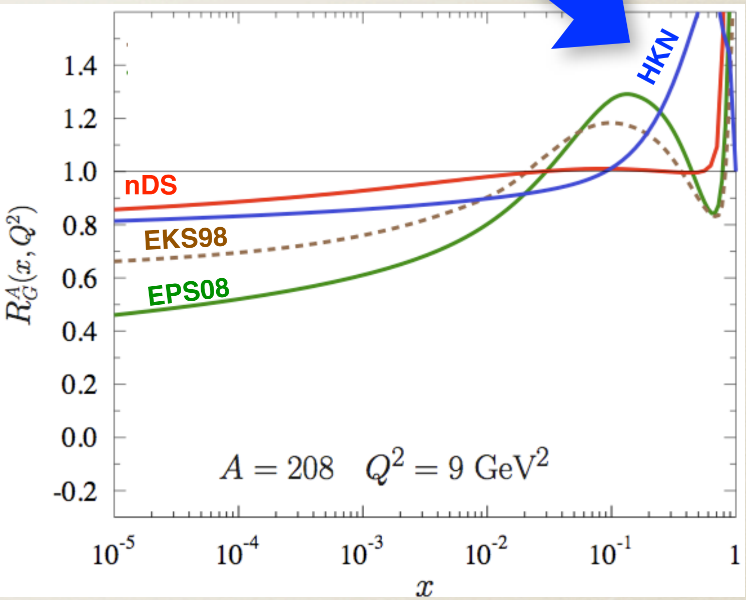

EMC effect stronger for *g* than for *q* ?

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Υ in dAu @ RHIC : shadowing

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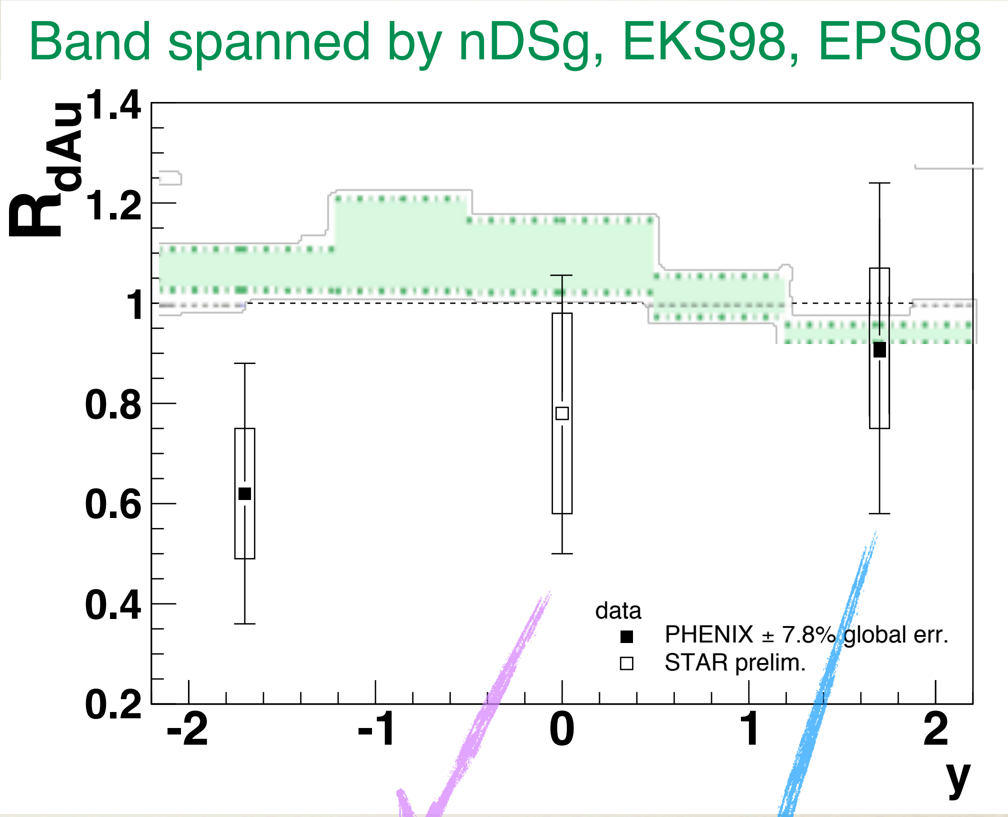
Υ could be a nice tool to **check antishadowing** (still under debate)

$\Rightarrow$ need much more precise data (AFTER@LHC ? see talk by J.P. Lansberg)



absence of antishadowing ?

entering shadowing

Data:
STAR Preliminary, Nucl. Phys. A855 (2011) 440, PRD 82 (2010) 012004.
PHENIX Preliminary, PoS DIS2010 (2010) 077.

The pPb run @ LHC

pPb $\sqrt{s_{NN}}$ = 5.02 TeV

☹ No pp reference at the same $\sqrt{s}$

⇒ naively, we thought that it would be a source of a sizeable systematic error for R_{pPb}

(apparently, it is not the case, why ?)

⇒ we propose to use in priority :

forward / backward $$R_{FB}\left(|y_{c.m.}|\right) \equiv \frac{R_{pPb}(y_{c.m.})}{R_{pPb}(-y_{c.m.})}$$

central / peripheral $$R_{CP} \equiv \frac{R_{pPb}^{0-20\%}}{R_{pPb}^{60-90\%}}$$

Υ in pPb @ LHC

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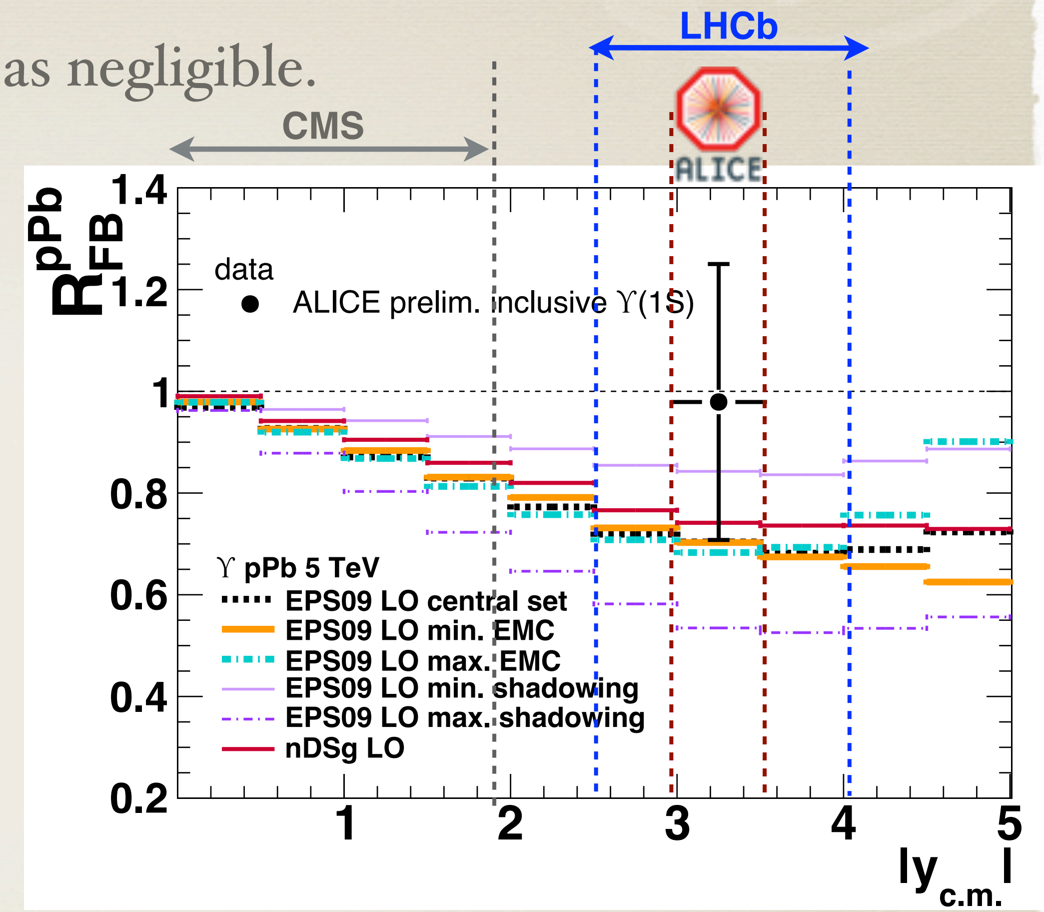
Absorption can safely be considered as negligible.
Focus on shadowing effects :



- Experiments probe the shadowing and antishadowing regions. The interesting **EMC region** will be **out of reach**.

Υ in pPb @ LHC

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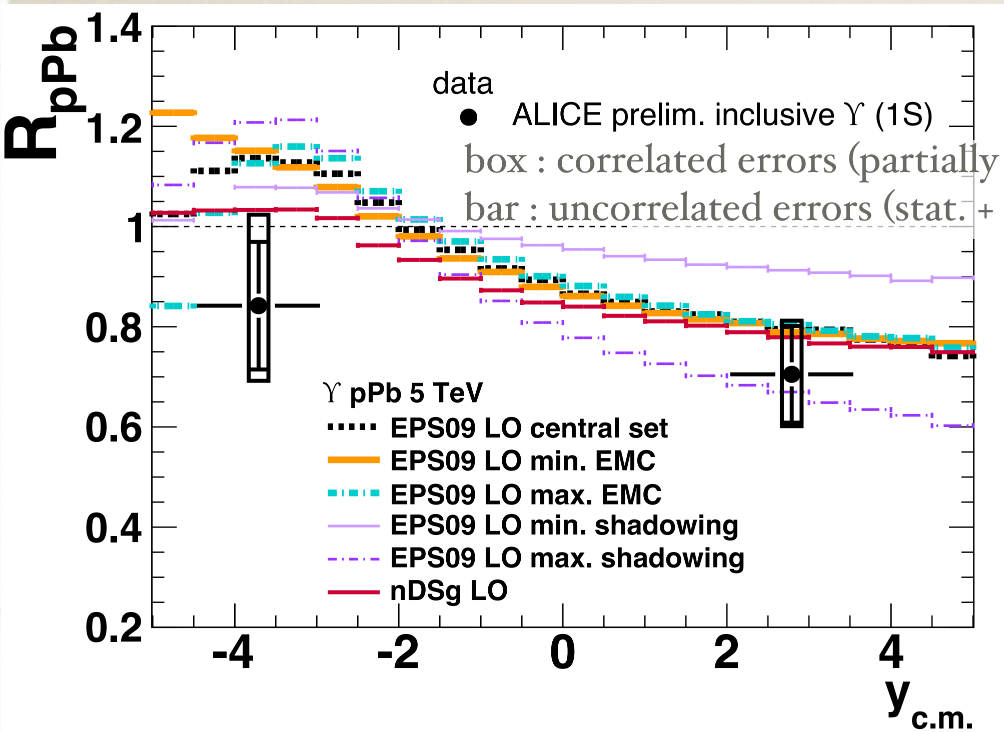

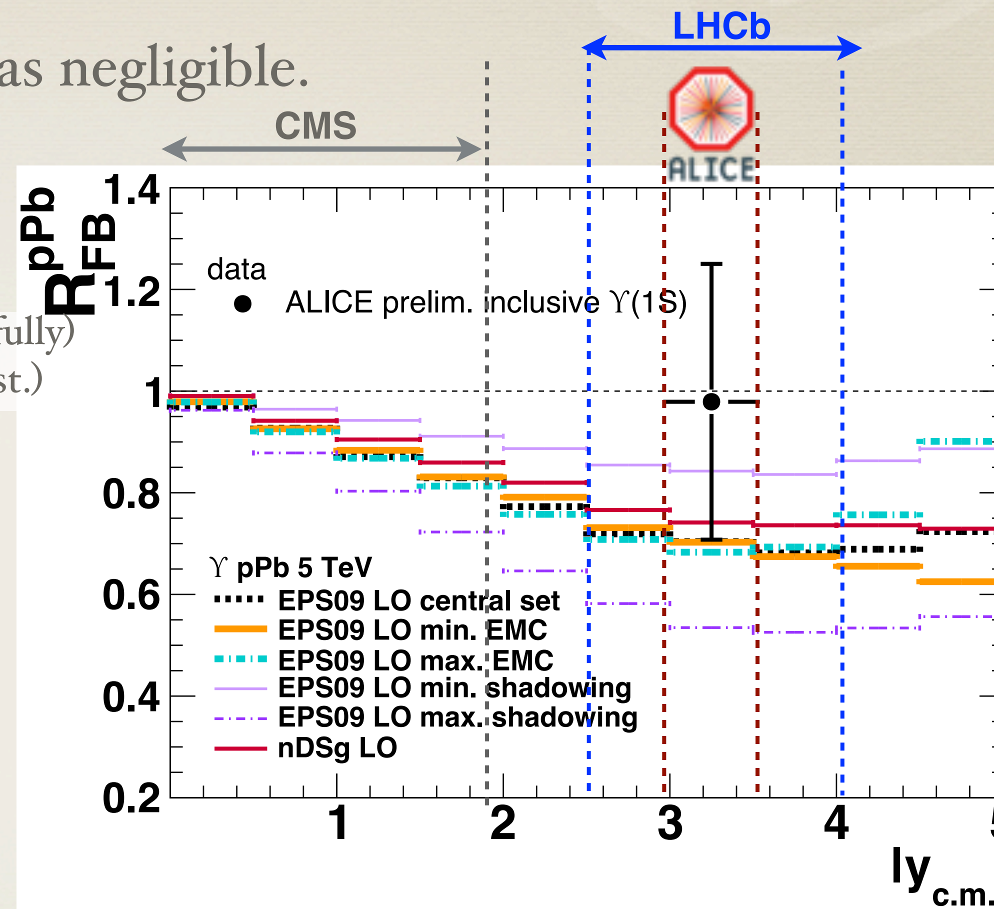

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- More precision needed at backward-y to conclude about antishadowing.

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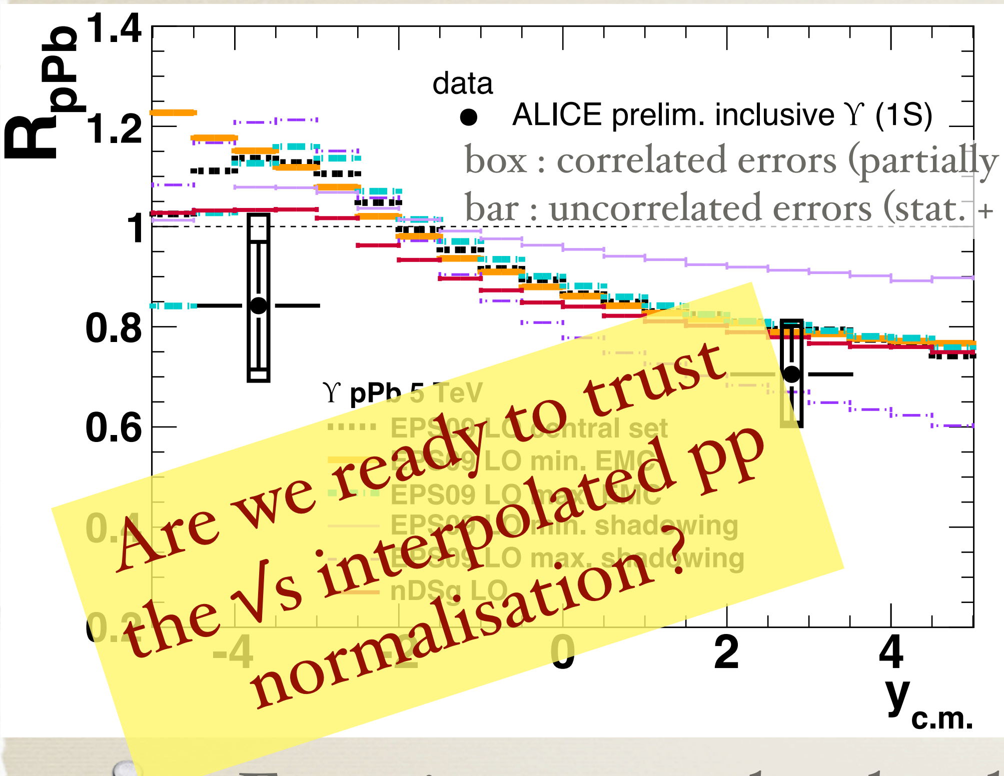

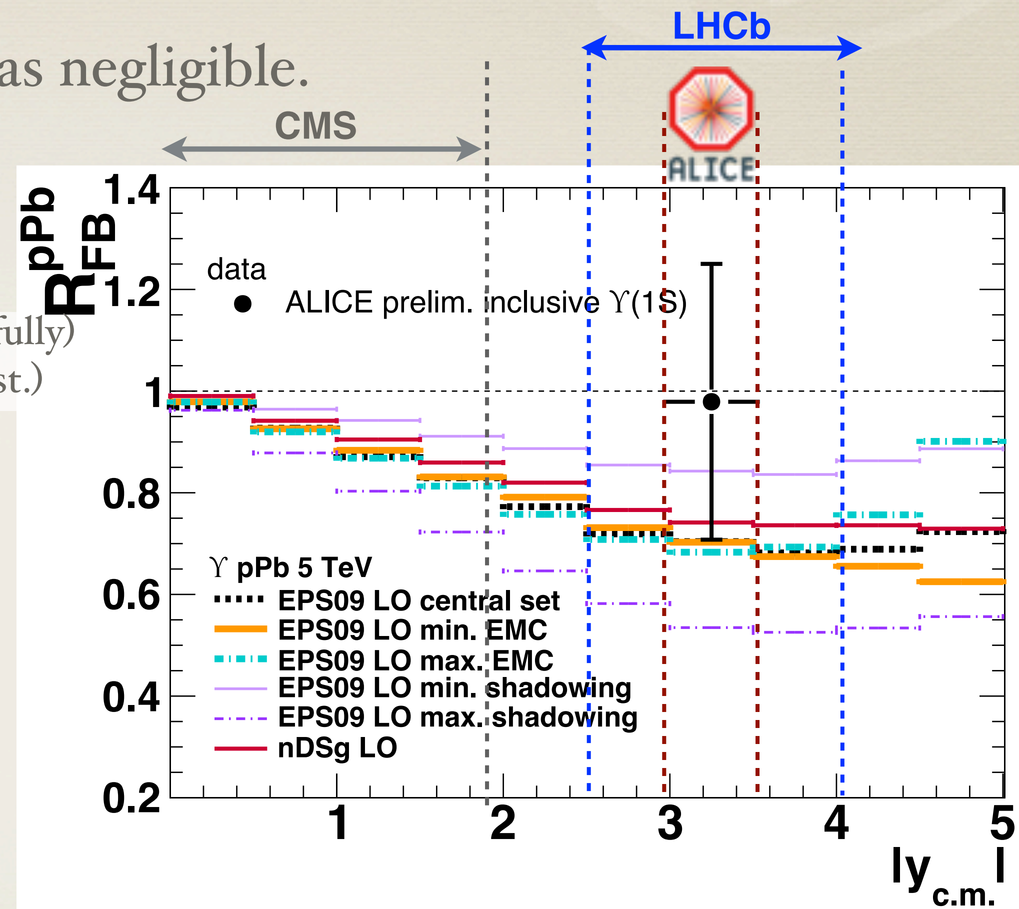

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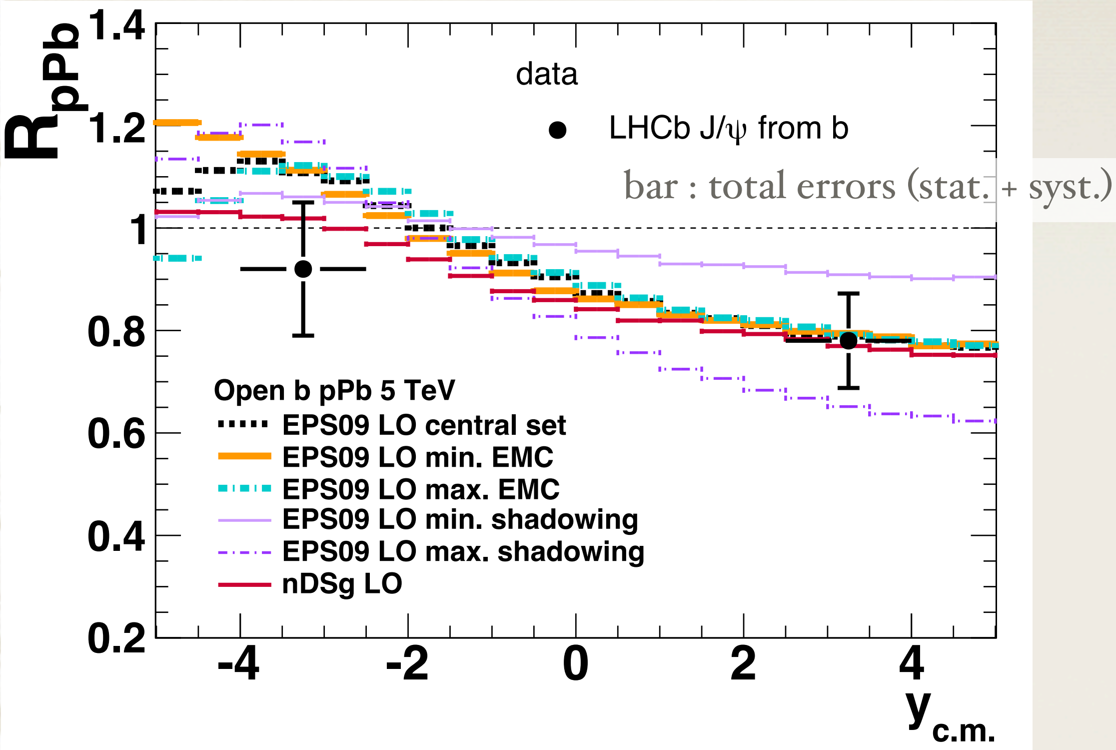
b-quarks in pPb @ LHC

E. G. Ferreiro, F. Fleuret,
J. P. Lansberg and A. R.
in preparation



data : LHCb non-prompt J/Ψ, arXiv:1308.6729

- **For the first time,** measurement of *b*-quarks production at LHC in pA, using non-prompt J/ψ down to $p_T = 0$.

b-quarks in pPb @ LHC

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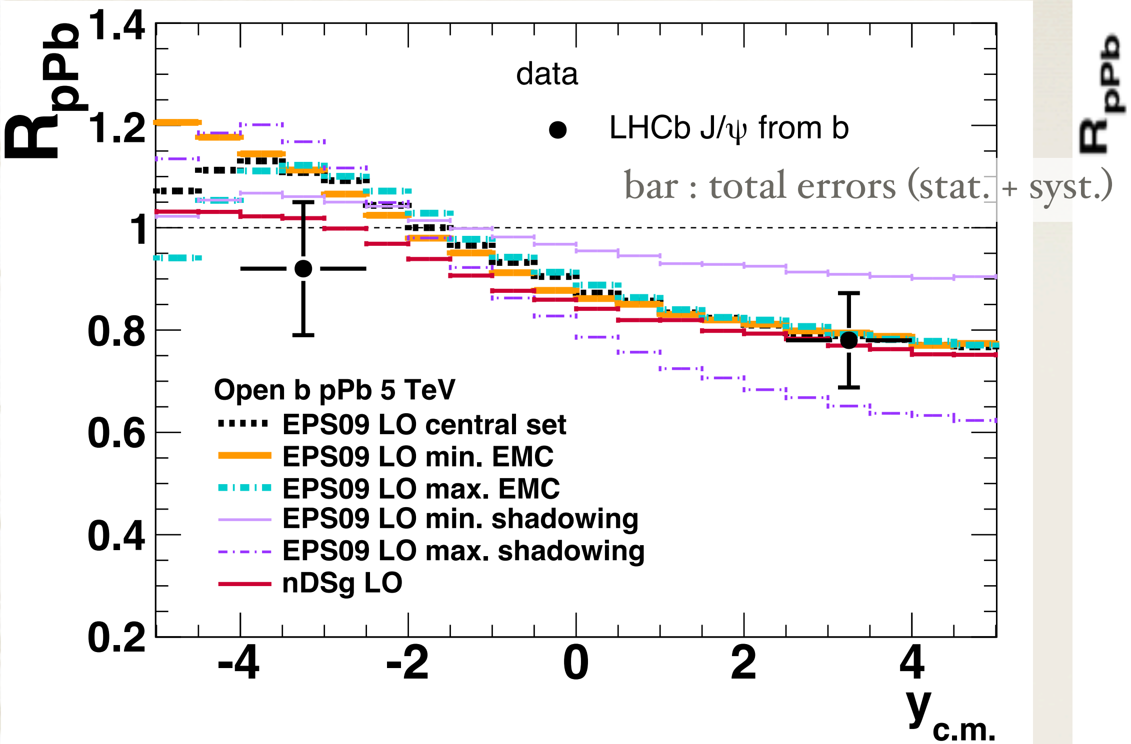

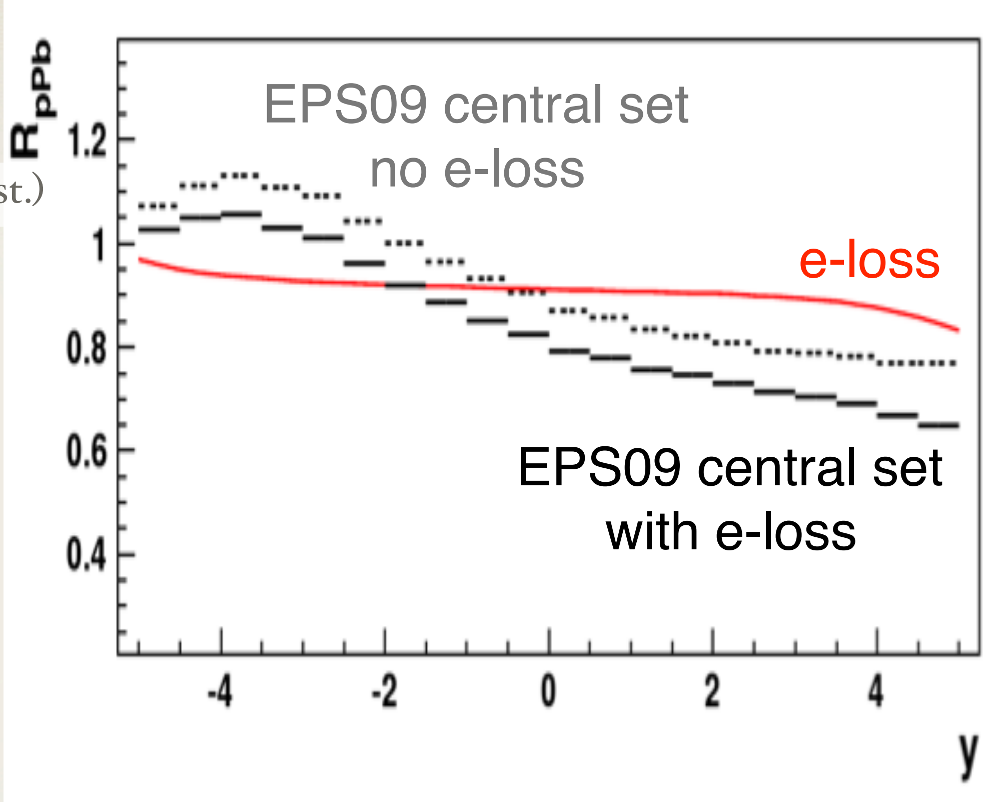

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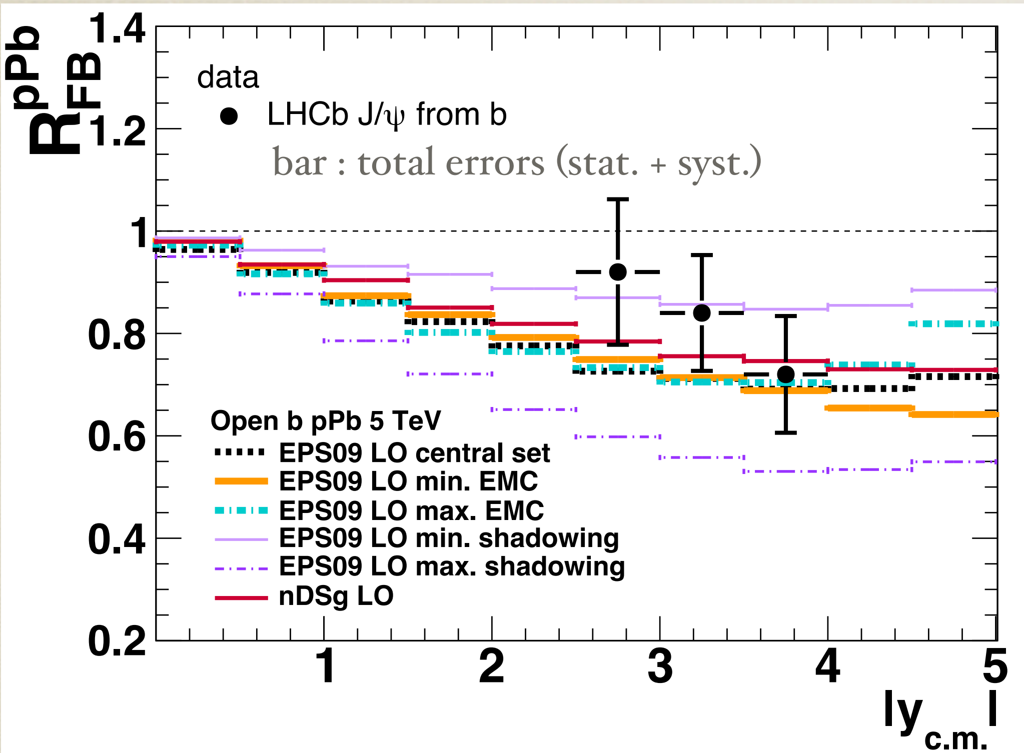
- **For the first time,** measurement of *b*-quarks production at LHC in pA, using non-prompt *J/ψ* down to $p_T = 0$.
- The *b*-quark is a **colored** object. Arléo *et al.* : there should be a coherent energy loss.

b-quarks in pPb @ LHC

E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
in preparation

forward / backward



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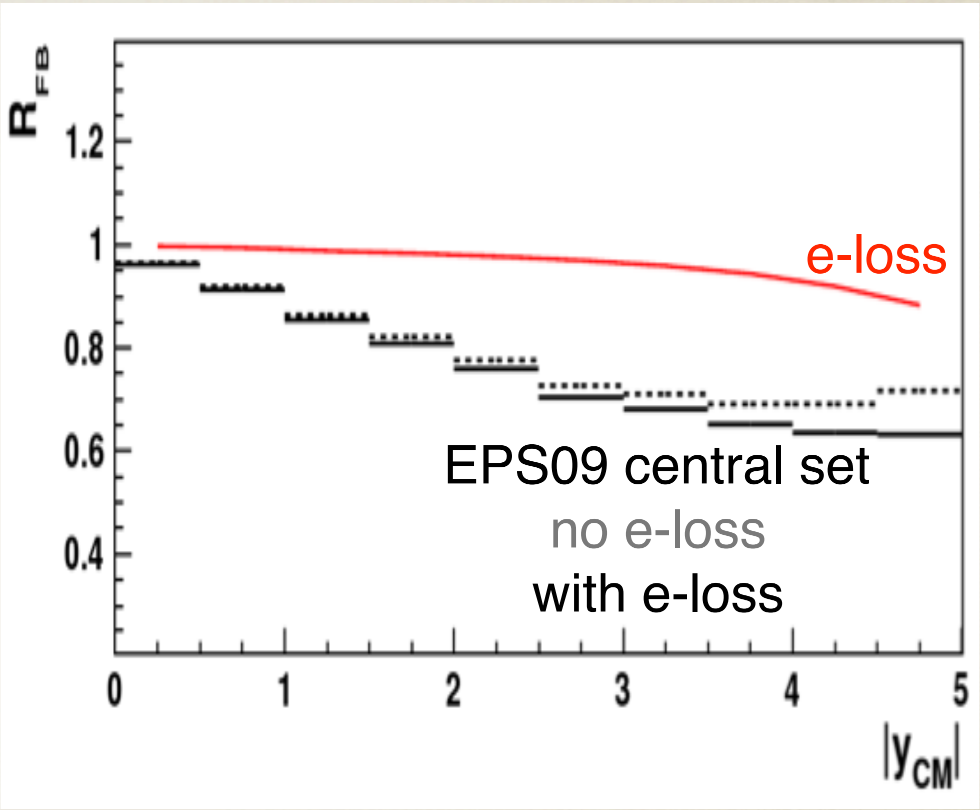
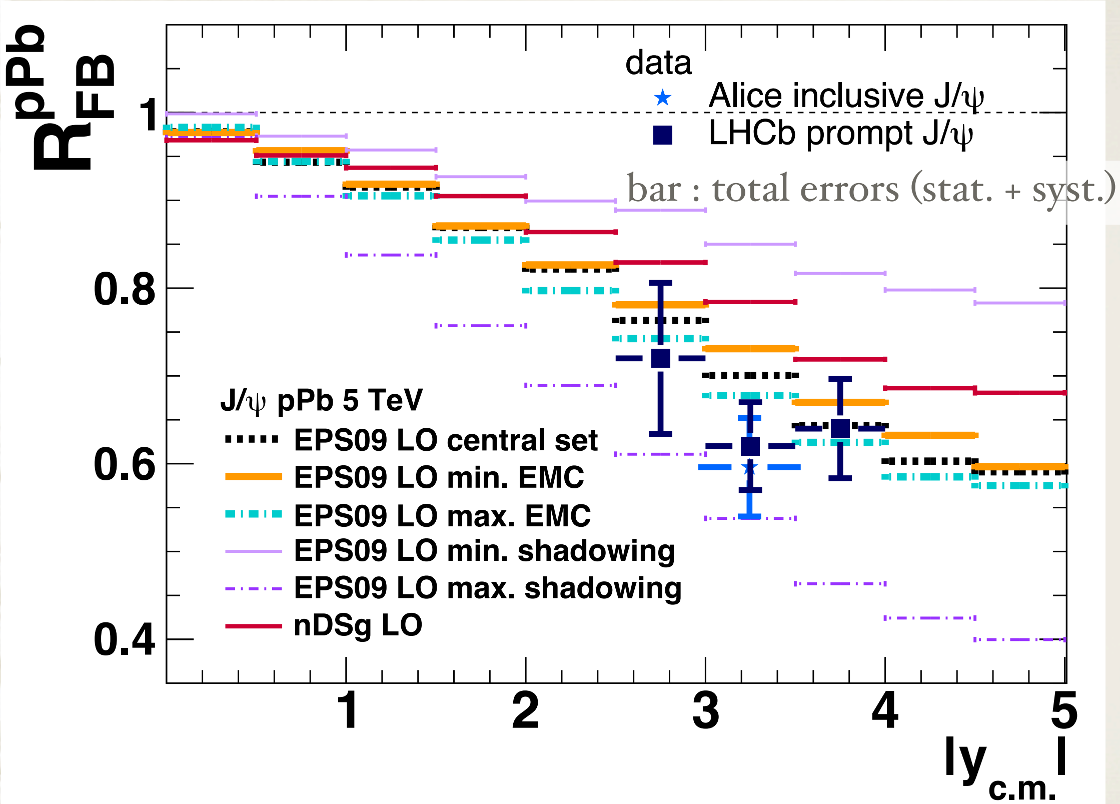


- The effect of the energy loss nearly cancels out in the forward / backward ratio.

J/ψ in pPb @ LHC

E. G. Ferreiro, F. Fleuret,
J. P. Lansberg and A. R.
arXiv:1305.4569

Forward / backward



data : ALICE inclusive J/Ψ, arXiv:1308.6726
LHCb prompt J/Ψ, arXiv:1308.6729

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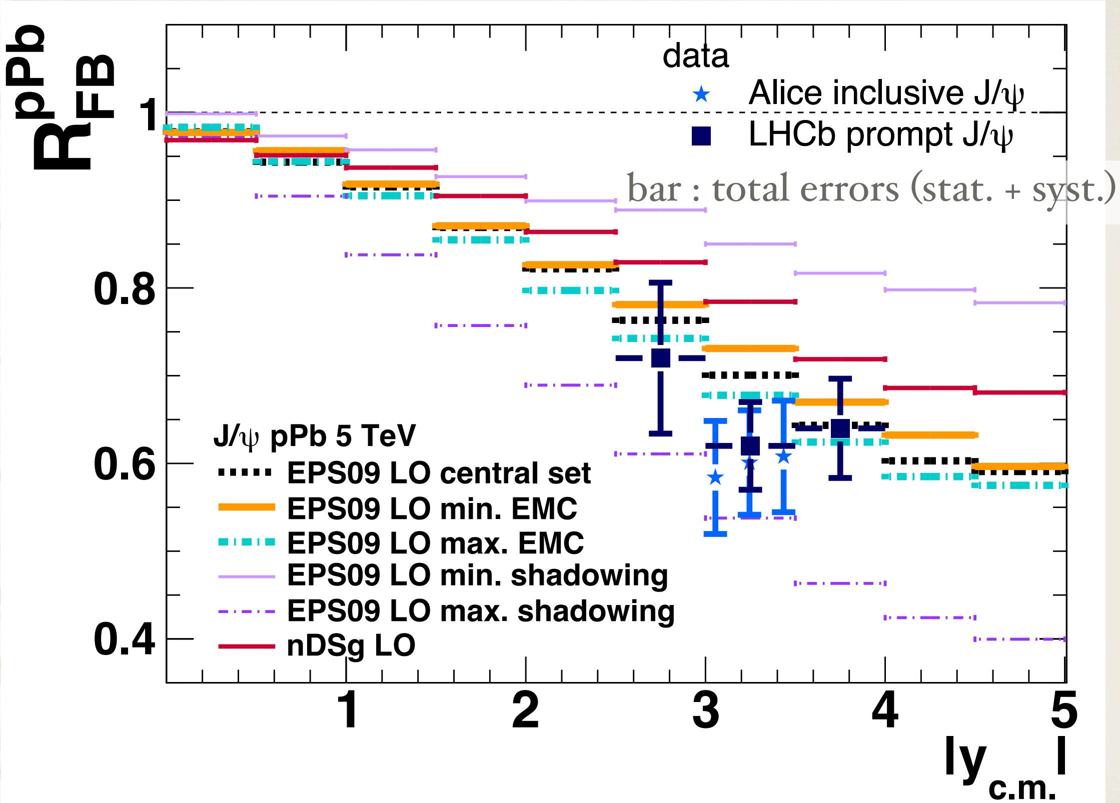

bar : total errors (stat. + syst.)

data : ALICE inclusive J/Ψ, arXiv:1308.6726
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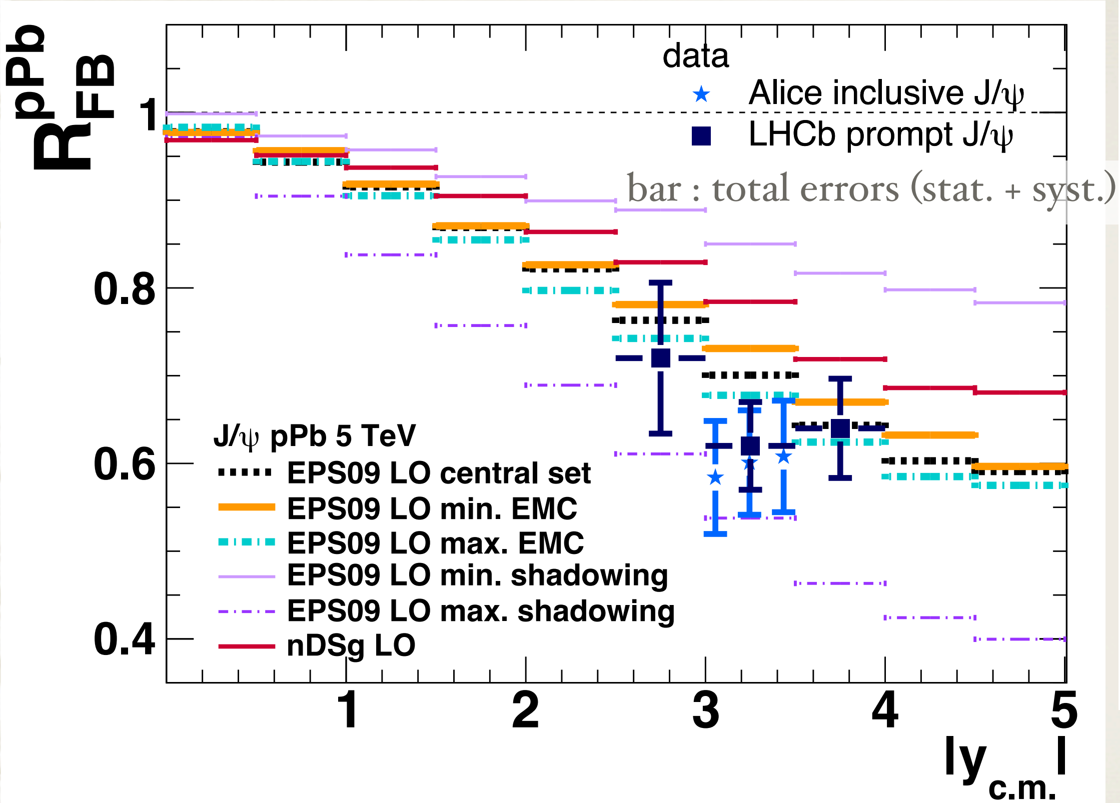

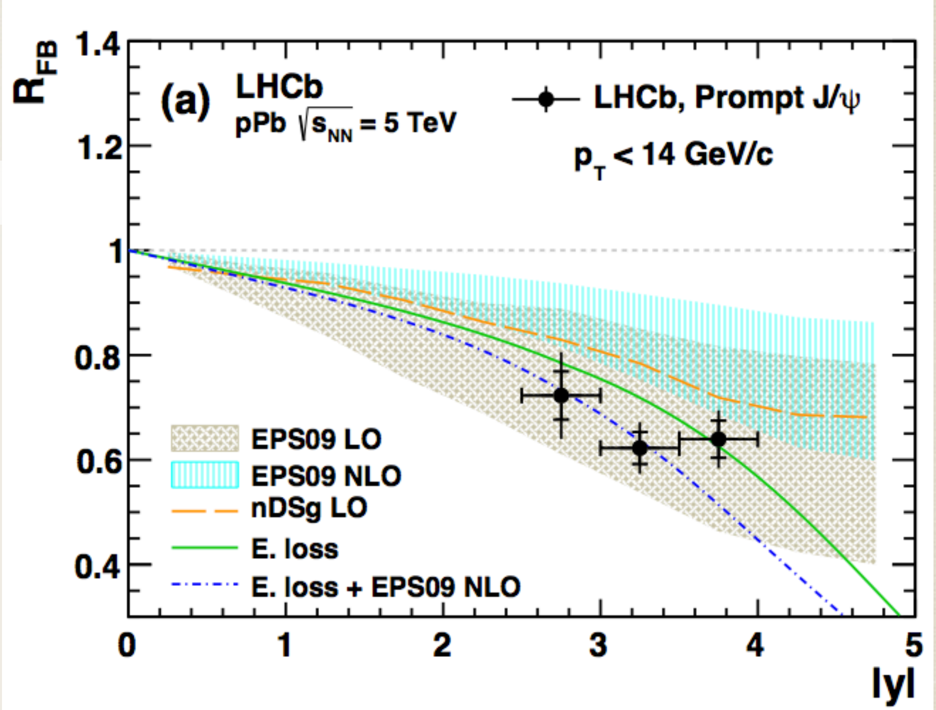

data : ALICE inclusive J/Ψ, arXiv:1308.6726
LHCb prompt J/Ψ, arXiv:1308.6729
E. loss : F. Arleo et al., PRD 83 (2011) 114036

Our model : fair agreement with data.

E-loss : need more observables (open heavy flavor ?) to determine the size of the effect

J/ψ in pPb @ LHC

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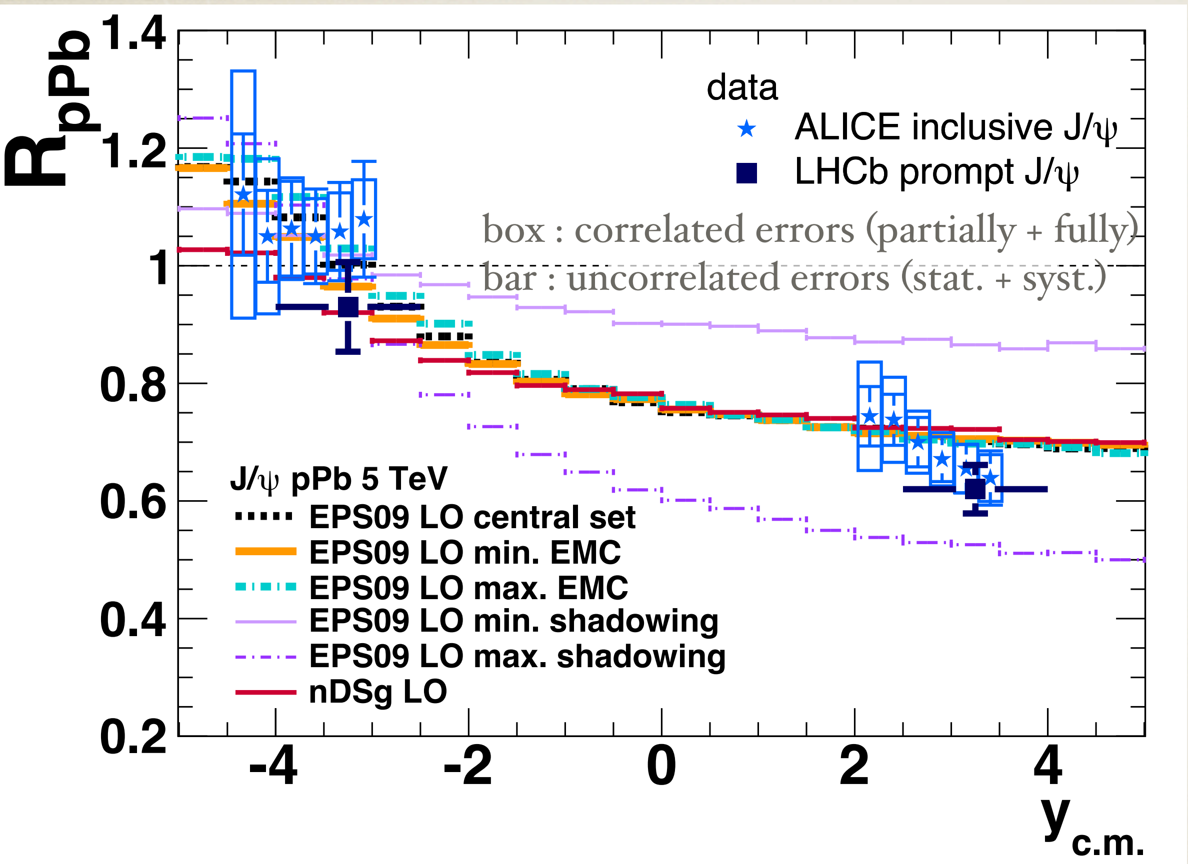
arXiv:1305.4569



Fair agreement with the data

Alice

- box : correlated errors (partially + fully)
- bar : uncorrelated errors (stat. + syst.)

LHCb
only an overall syst. error was published

- bar : stat. + syst

data : ALICE inclusive J/Ψ, arXiv:1308.6726
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J/ψ in pPb @ LHC

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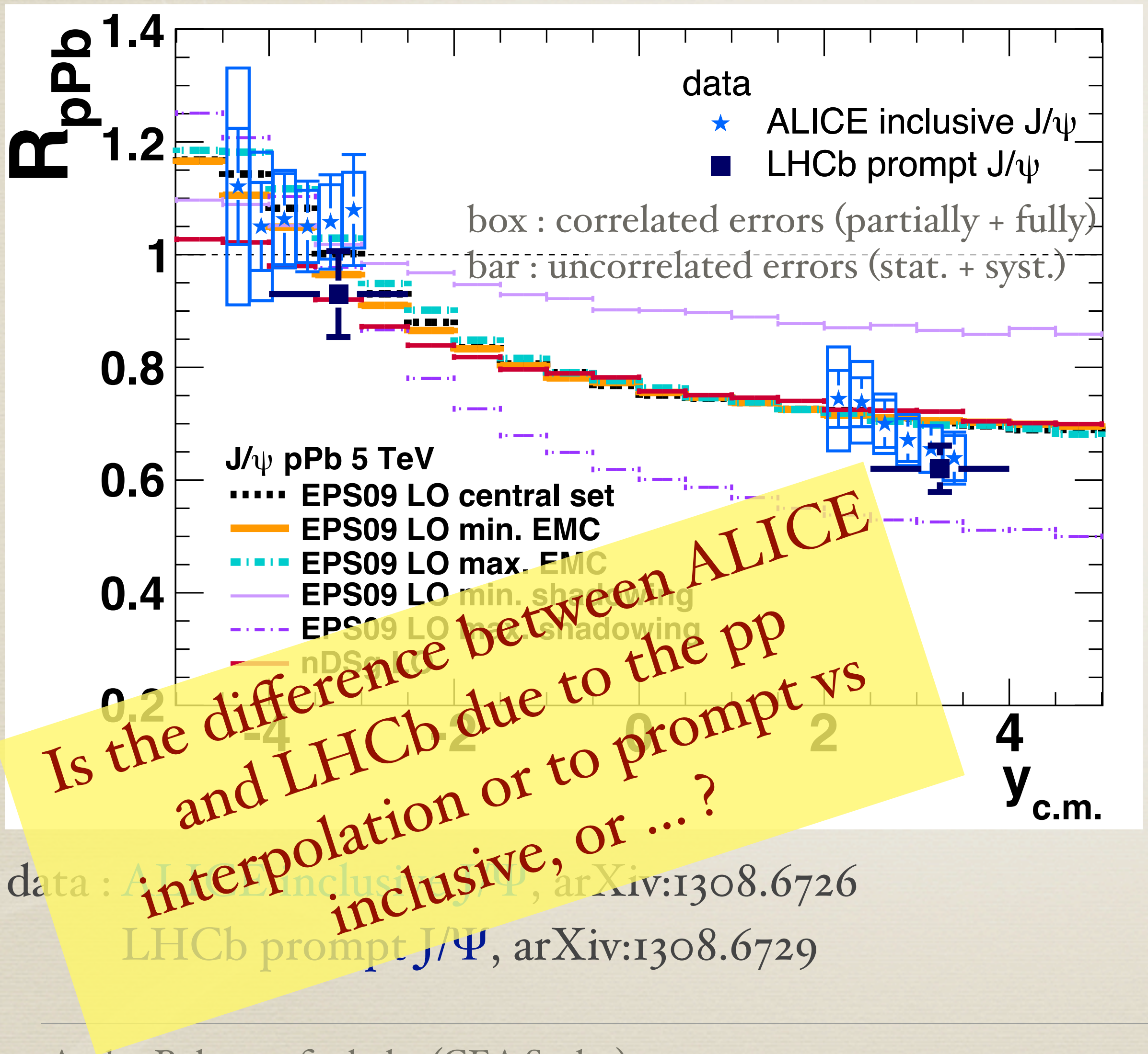

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only an overall syst. error was published
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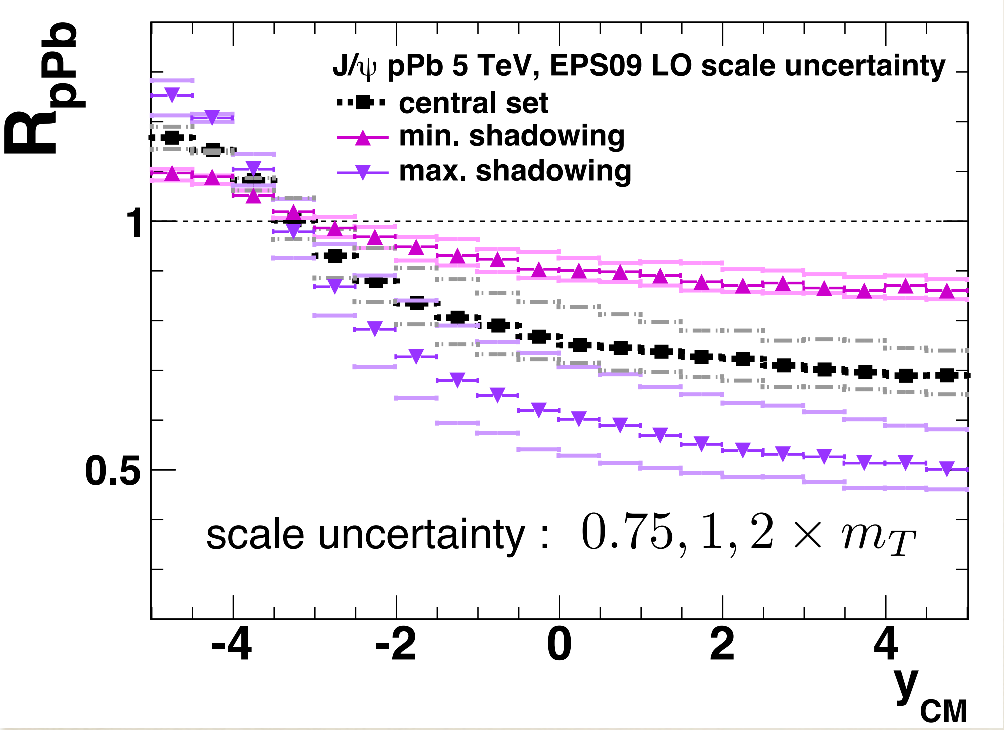
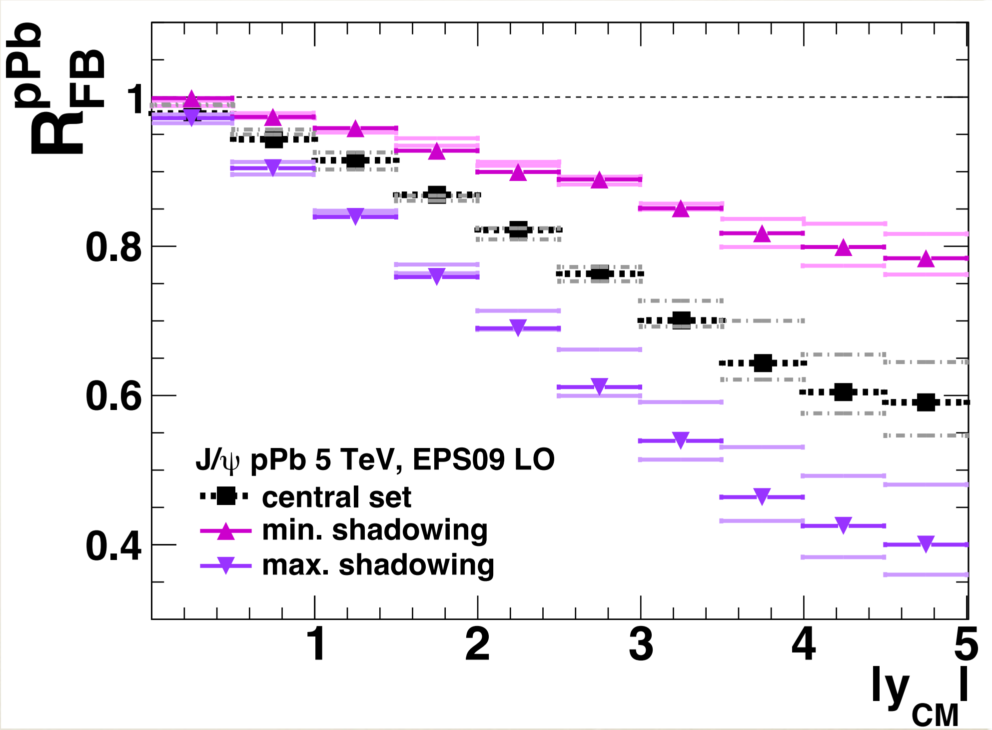
Scale uncertainty

- What enters the evaluation is $R_g^A(x, \mu_F)$
- What value to take for μ_F ?
- In DIS, $\mu_F \leftrightarrow Q$ (Q is measured).
- For quarkonia ? $\mu_F = M$, m_c , m_T ?

E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R. arXiv:1305.4569



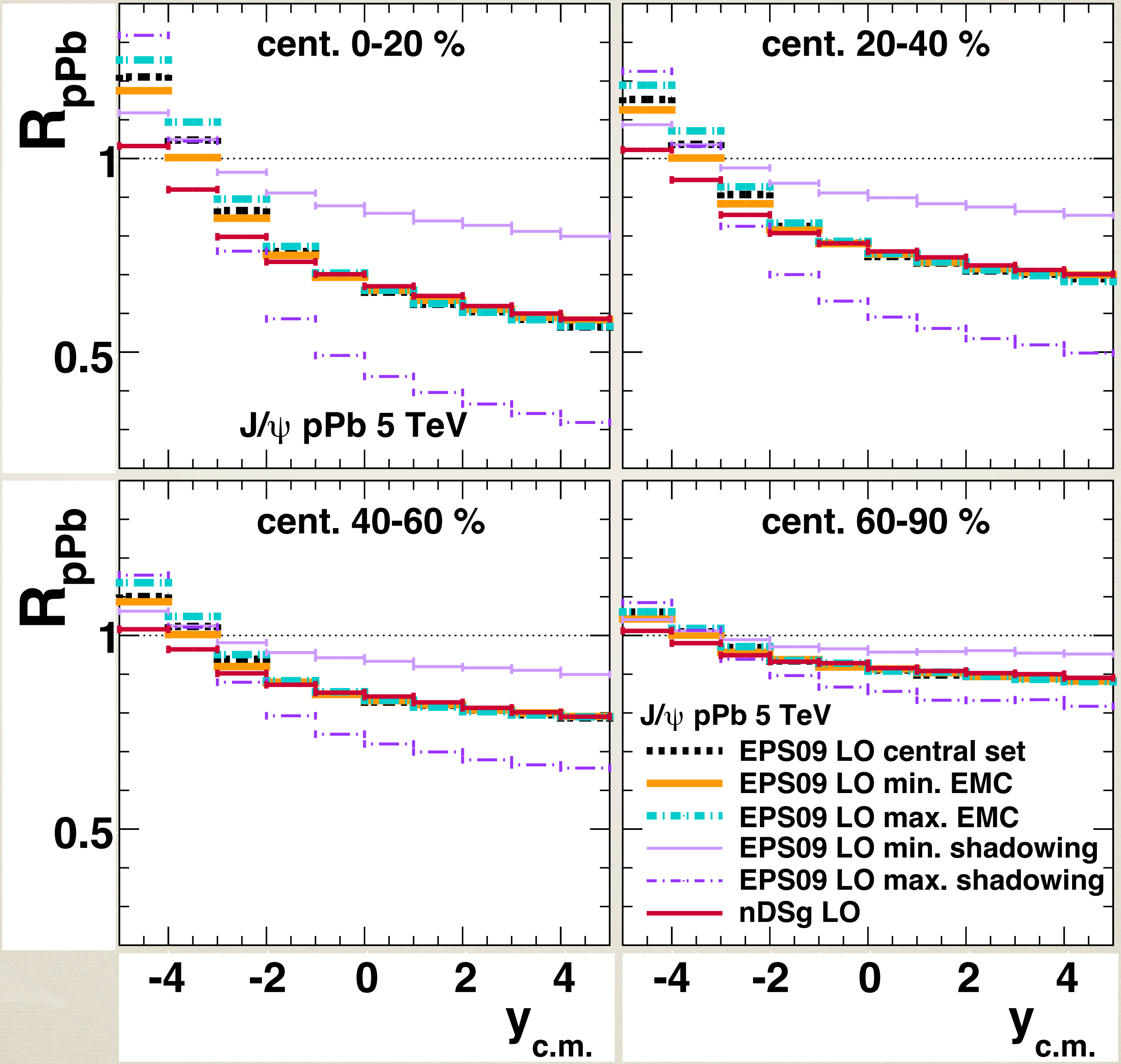


The scale uncertainty must be added on top the EPS09 error evaluation.

J/ψ in pPb @ LHC

E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R.
arXiv:1305.4569

centrality dependence



J/ψ in pPb @ LHC

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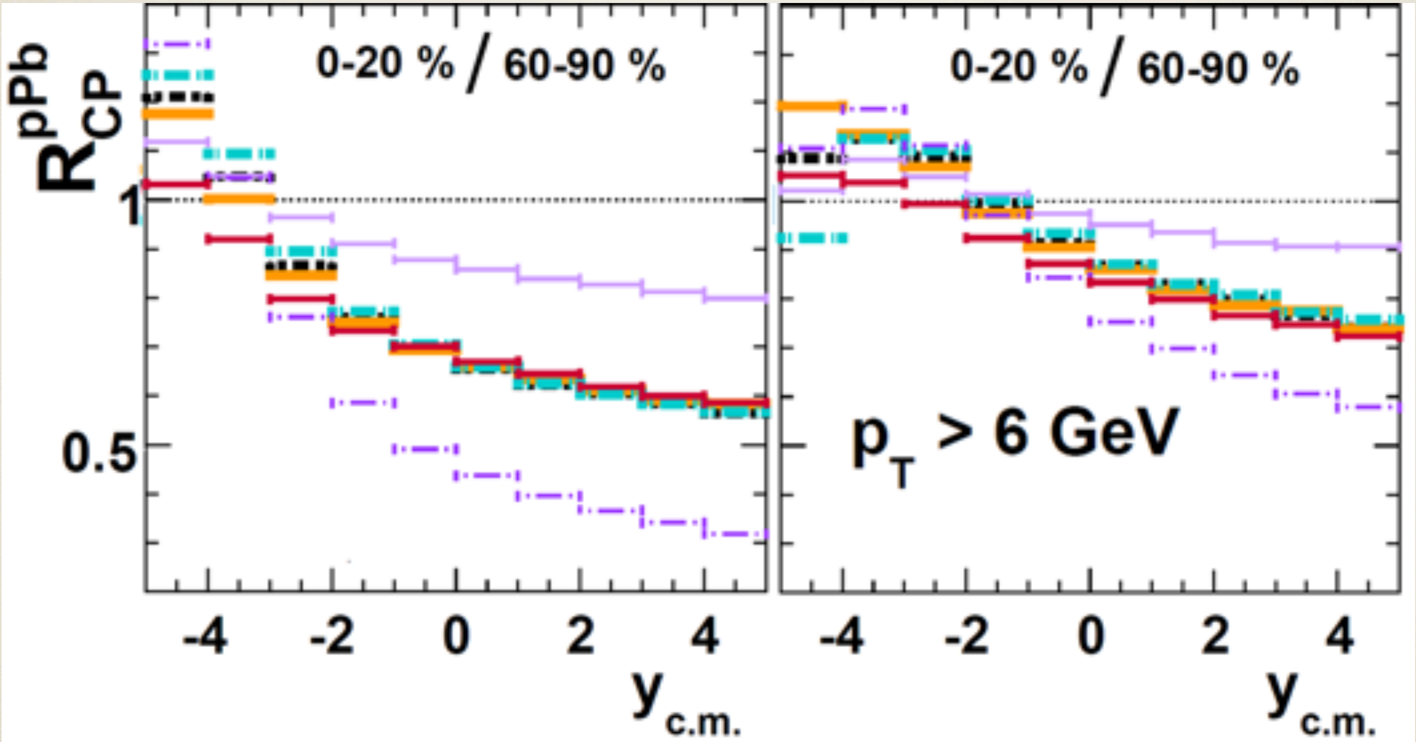
central / peripheral



Summary

<u>At RHIC energies :</u>

- Backward-y Υ data favours the presence of a gluon EMC effect (maybe stronger than the quark one)

<u>At LHC energies :</u>

- For J/ψ, nPDF fits reproduce the data. No need for saturation ?
- Scale uncertainty : large. To be added to the uncertainties of the nPDFs.
- Backward-y Υ and non-prompt J/ψ can be used to constrain the gluon antishadowing. More data is needed.
- Grain of salt : no pp cross section measured @ 5 TeV!

EXTRA SLIDES

J/ψ in pPb @ LHC

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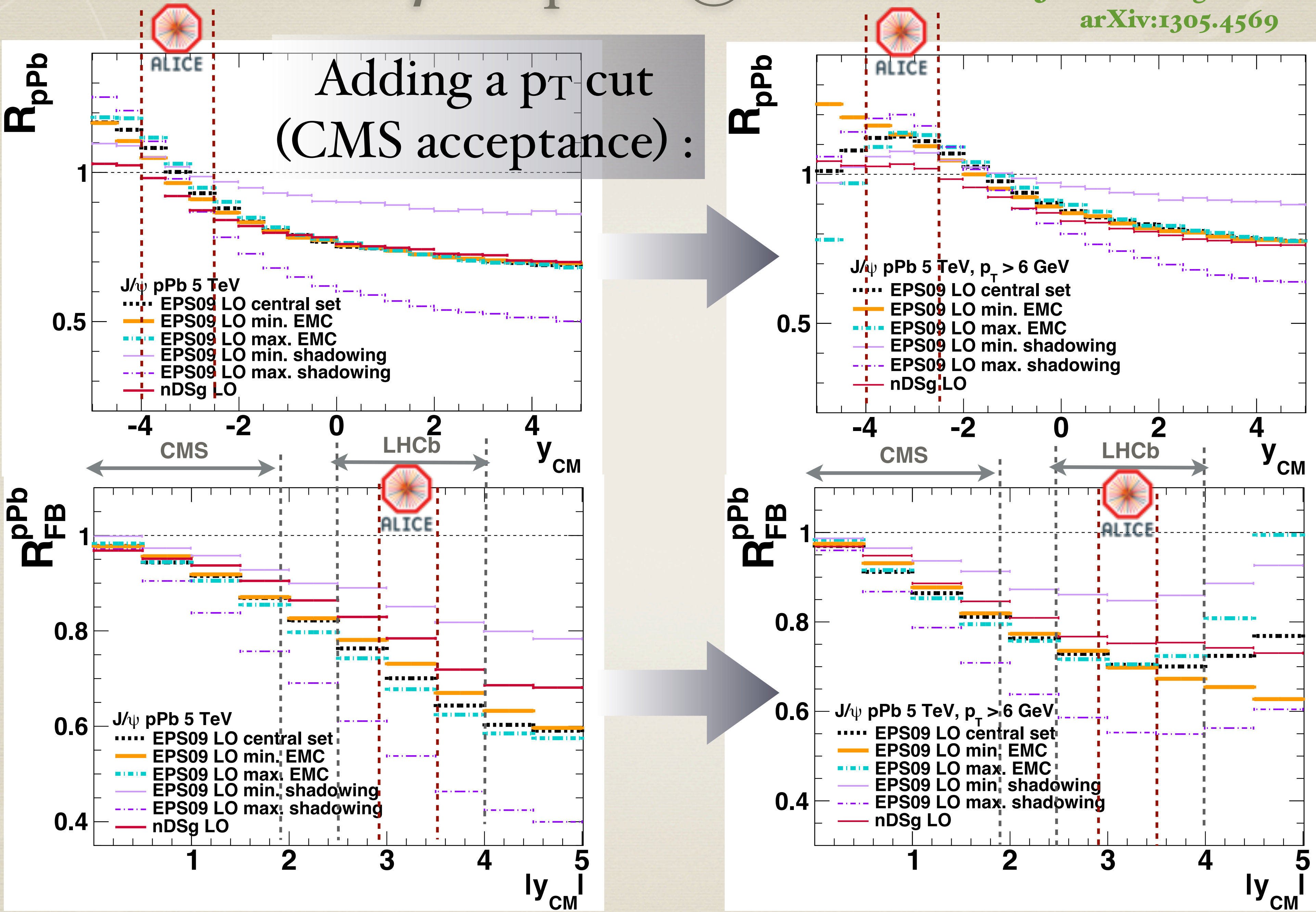
arXiv:1305.4569

Adding a p_T cut (CMS acceptance) :



J/ψ in pPb @ LHC

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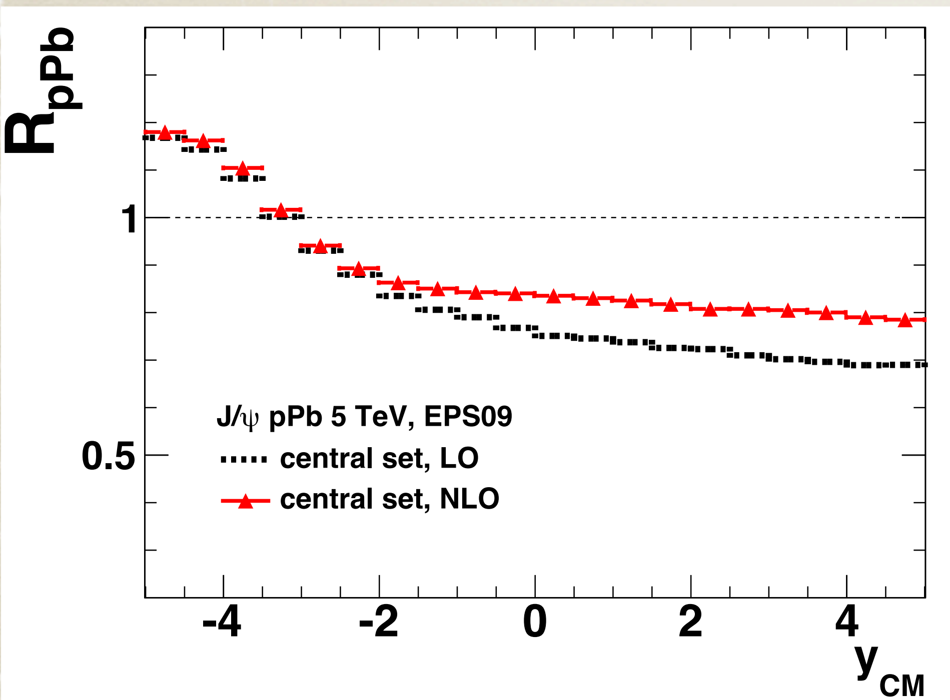
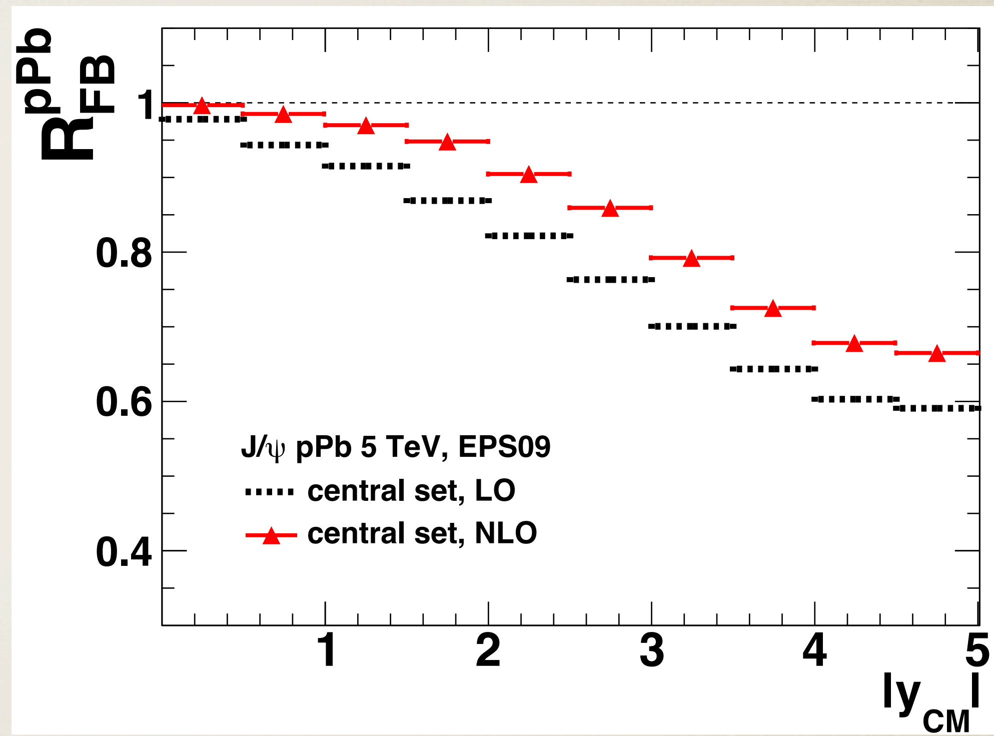
LO vs NLO EPS09 :





J/ψ in pPb @ LHC

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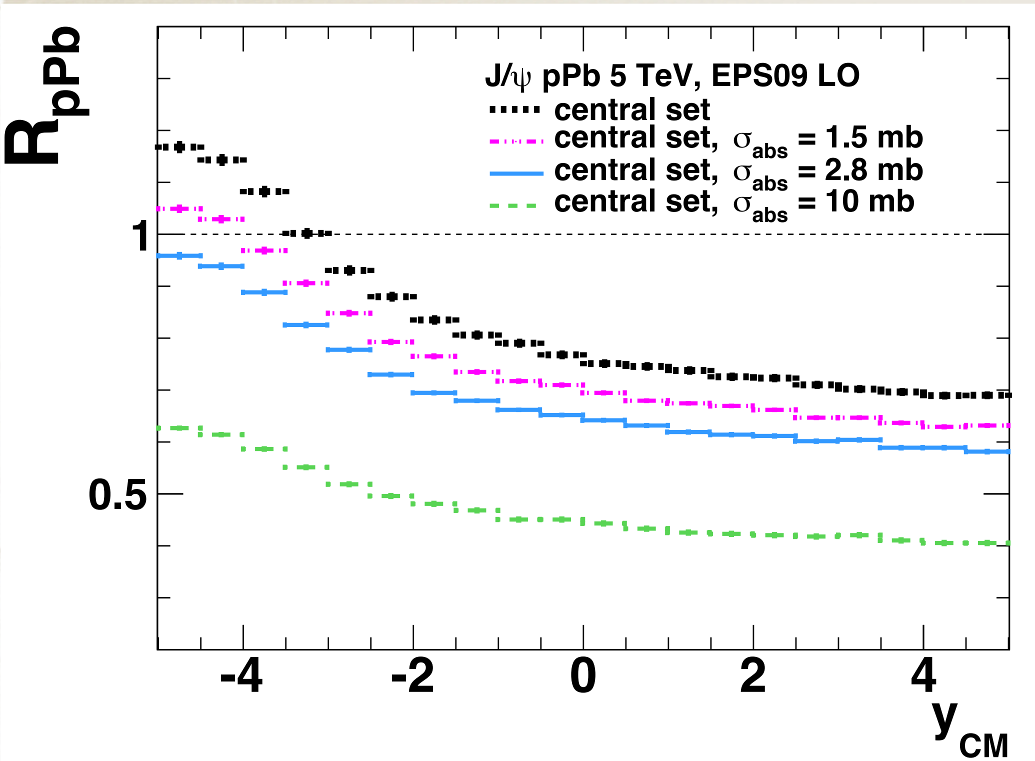
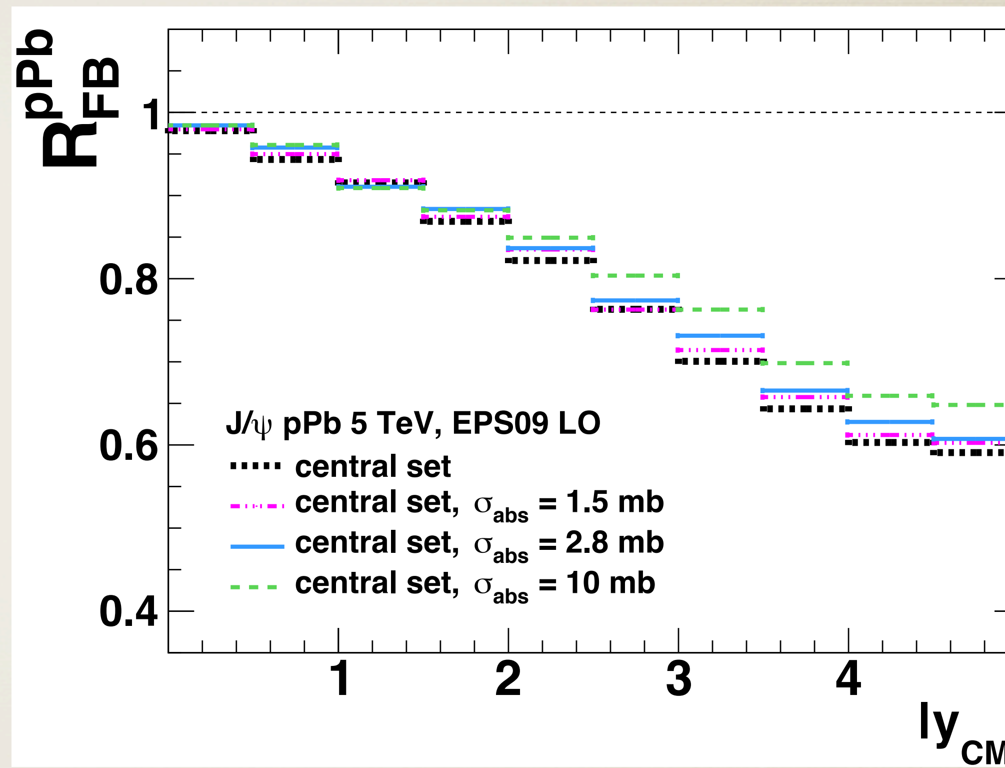
Adding absorption :





The forward/backward ratio is much less sensitive to the absorption effect.

Shadowing computation

- in pA: quarkonia production cross-section e.g. modified by a **shadowing correction factor** :

$$R_g^A(x_2, Q^2)$$

- **4-mom conservation relates** (x_1, x_2) **to quarkonia** (y, p_T)
- models (CEM, NRQCD, CSM ...) in p+p explain quarkonium prod. via **various mechanisms, each with:**
  - **a given phase-space in** (x_1, x_2, y, p_T)
  - a given differential cross-section (weight) for each point in this phase-space

☑ different production models a priori results in different shadowings

- extrinsic scheme
  $2 \longrightarrow 2$ process

How prod. models can differ ?

intrinsic scheme
$2 \longrightarrow 1$ process

$$g + g \longrightarrow c\bar{c} \text{ or } b\bar{b}$$

$$x_{1,2} = \frac{m}{\sqrt{s_{NN}}} e^{\pm y}$$

- Handy : unequivocal correspondence

$$(x_1, x_2) \Leftrightarrow (y, p_T)$$

- Quarkonia p_T comes from initial partons
- e.g. CEM LO

extrinsic scheme
$2 \longrightarrow 2$ process

$$g + g \longrightarrow \{J/\psi, \Upsilon\} + g$$

more degrees of freedom in the kinematics :

- several $(x_1, x_2) \Leftarrow (y, p_T)$

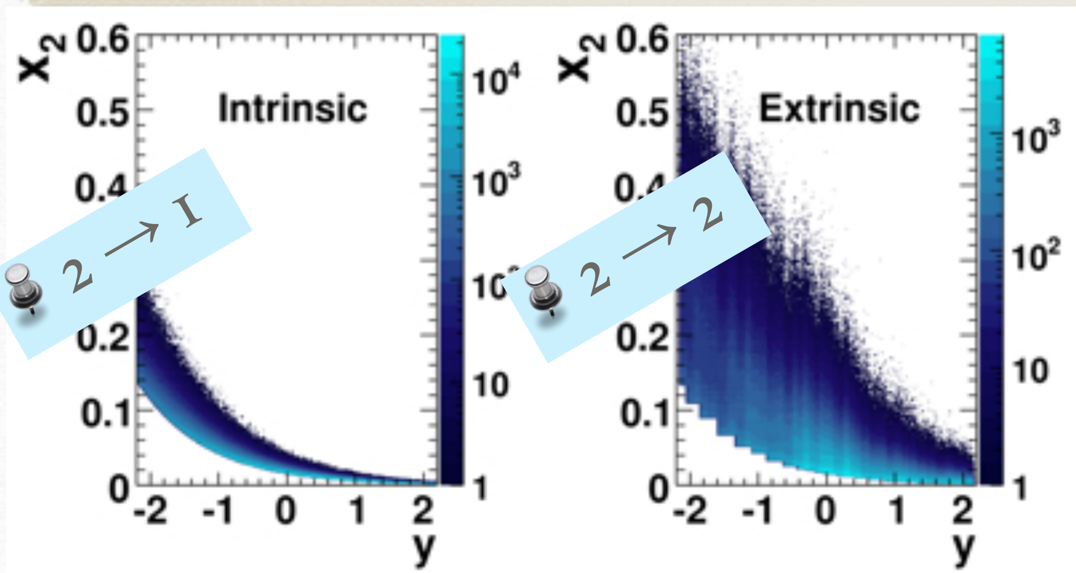
$$y, p_T, x_1 \Longrightarrow x_2 = \frac{x_1 m_T \sqrt{s} e^{-y} - M^2}{\sqrt{s}\,(\sqrt{s} x_1 - m_T e^{y})}$$

- Quarkonia p_T is balanced by the outgoing gluon
- e.g. CSM LO, COM LO

Use reasonably good models in p+p to compute CNM effects in p+A, A+A

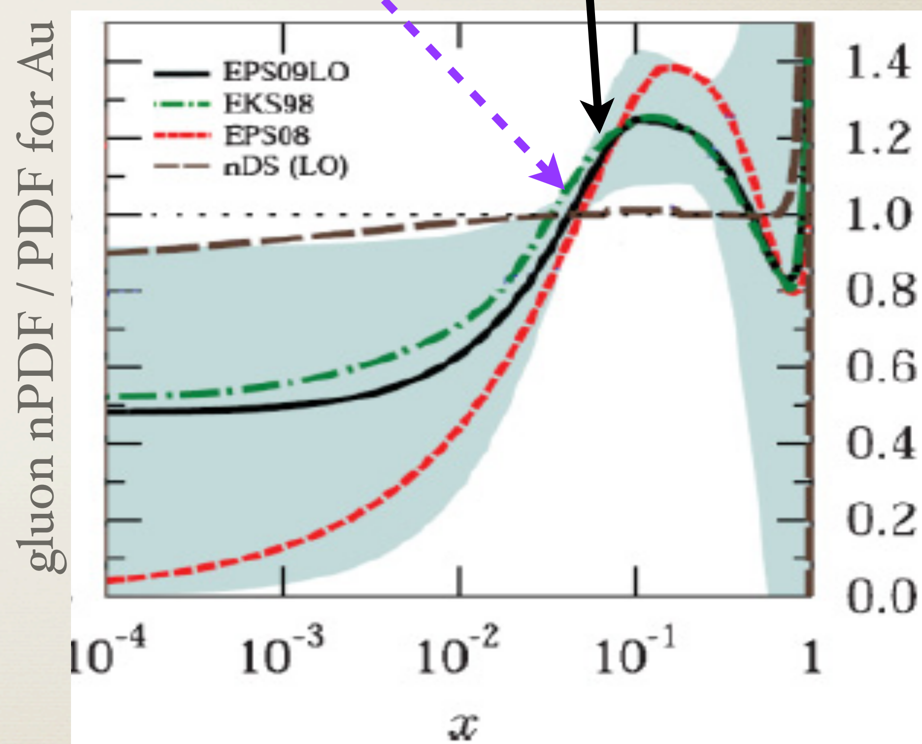
CNM effects at RHIC : J/ψ in dAu

$g + g \to c\bar{c}$ $g + g \to J/\psi + g$



x for a given y

2 → 1 2 → 2



- for a given y, <x> is larger in the 2 → 2 process

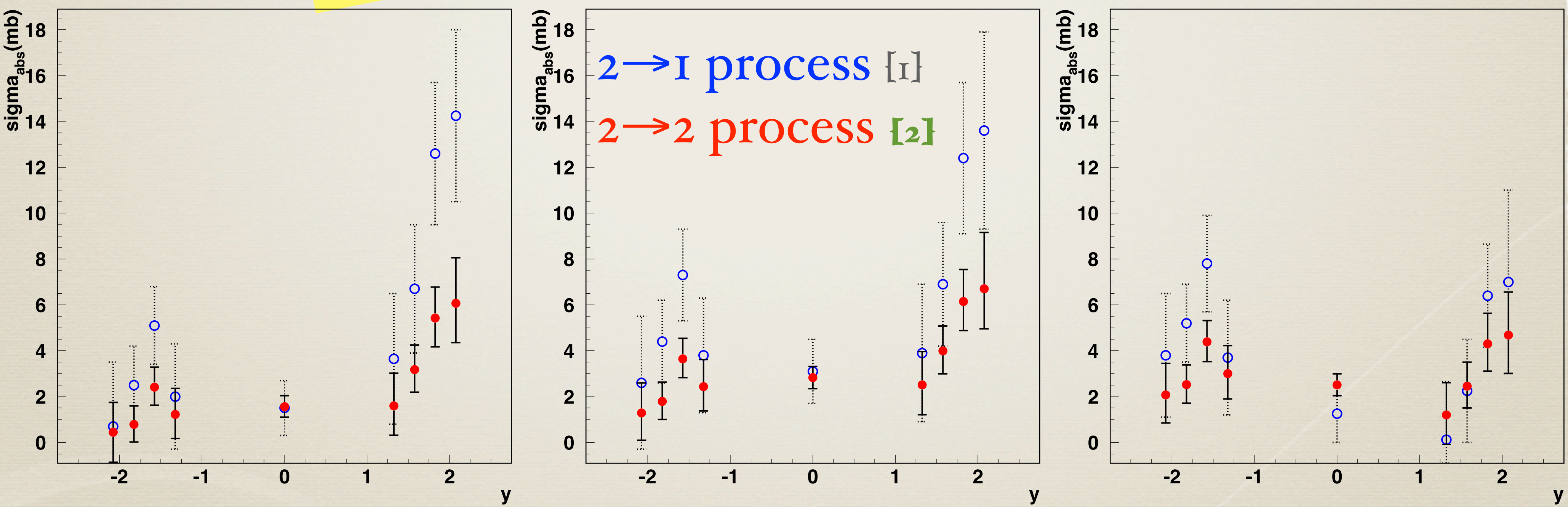
$2\rightarrow1$ vs $2\rightarrow2$ prod. models :

$\sigma_{abs}(y)$ from Rcp in dAu @ 200 GeV

$\sigma_{abs}(y)$ much flatter for the $2\rightarrow2$ process

[1] A. D. Frawley, INT, Seattle USA, June 2009

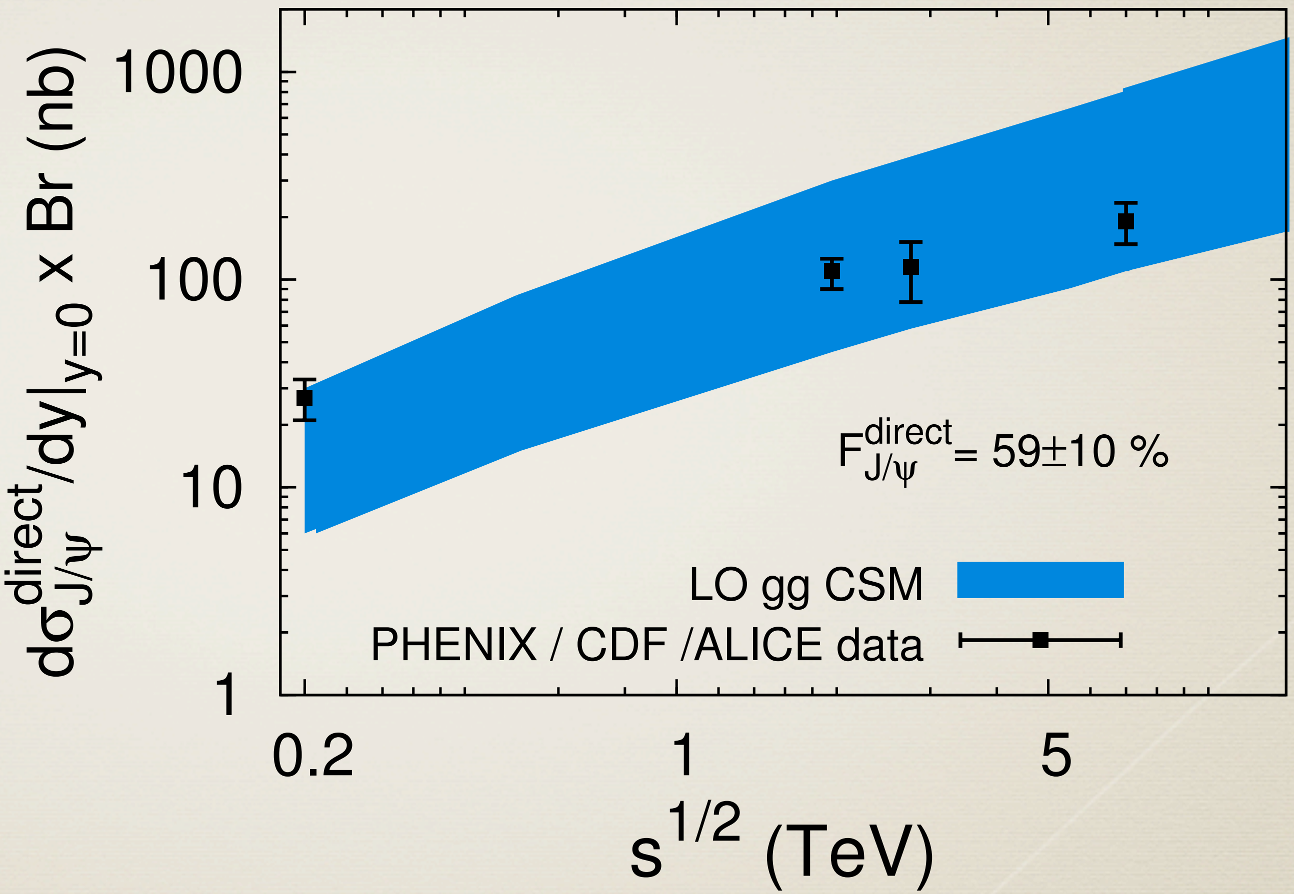
[2] E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R., PRC 81 (2010) 064911



nDSg EKS98 EPS08

CSM LO
integrated cross section

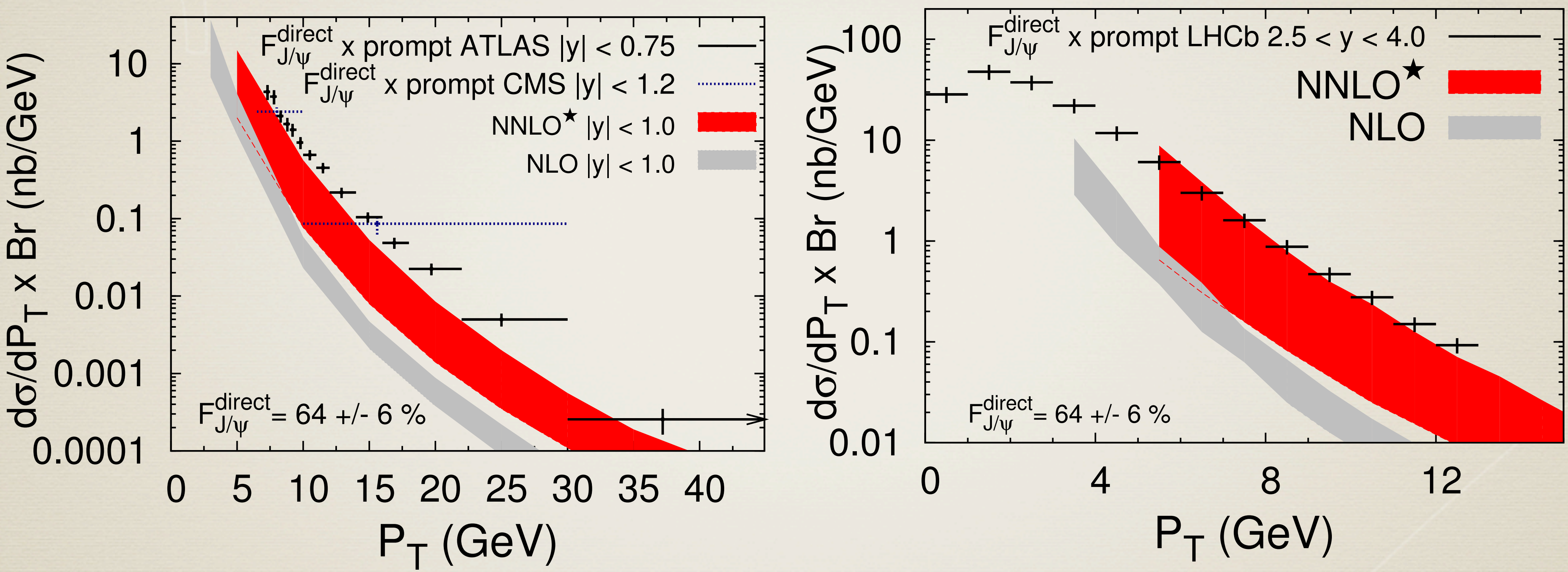
direct J/ψ



J. P. Lansberg, PoS ICHEP 2010 (2010) 206

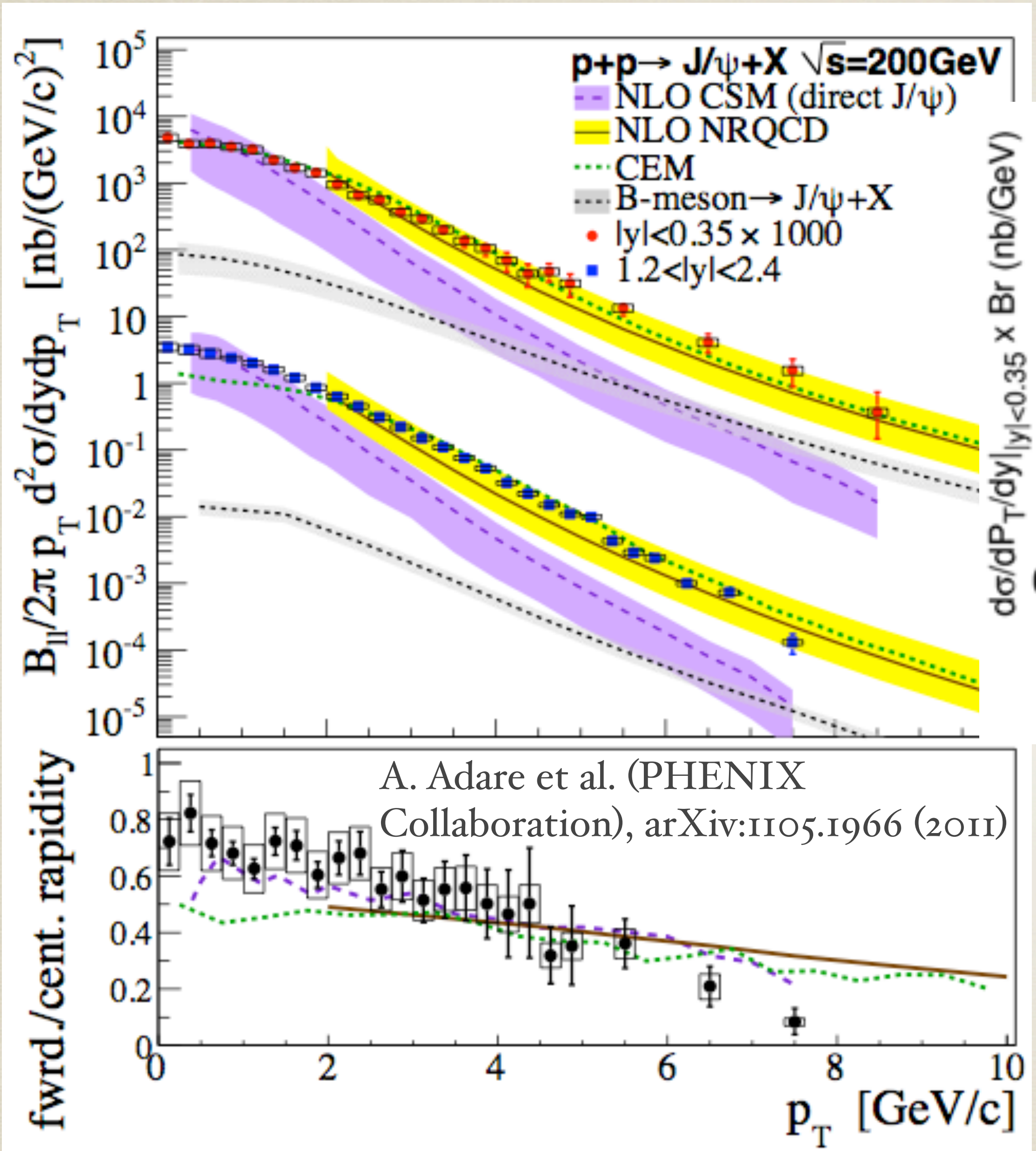
CSM vs LHC data

direct J/ψ

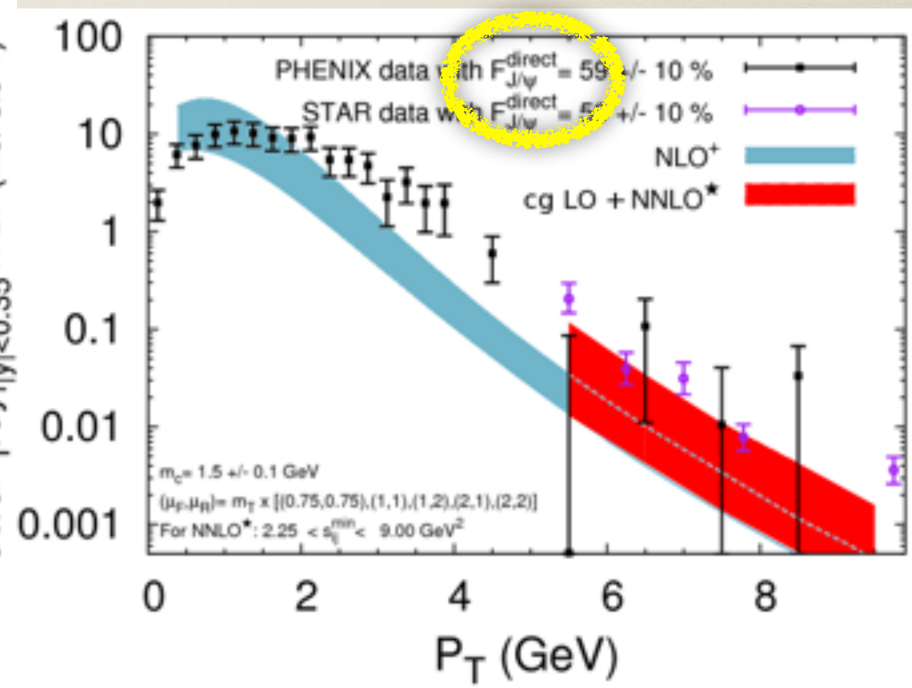


J. P. Lansberg, J. Phys. G 38 (2011) 124110

The pT spectra in p+p at RHIC



A. Adare et al. (PHENIX Collaboration), arXiv:1105.1966 (2011)



Brodsky, Lansberg, PRD 81:051502 (R) (2010)

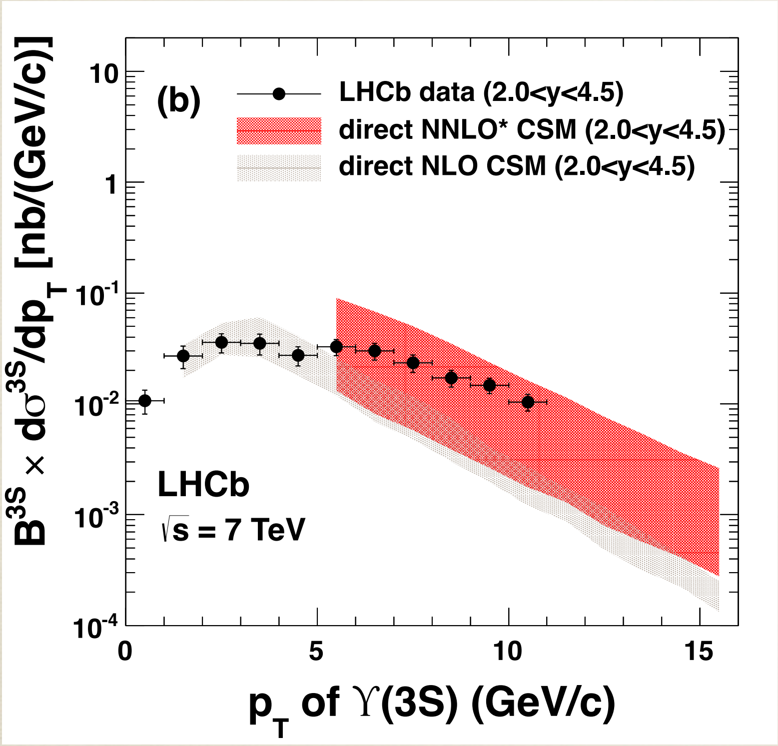
J/ψ

CSM @ LO and higher orders

p+p

$\Upsilon(3S)$

LHC (7 TeV):
CSM in good agreement with data vs p_T



J.P. Lansberg, EPJ C 61 (2009) 693.
LHCb Collaboration, arXiv 1202.6579.

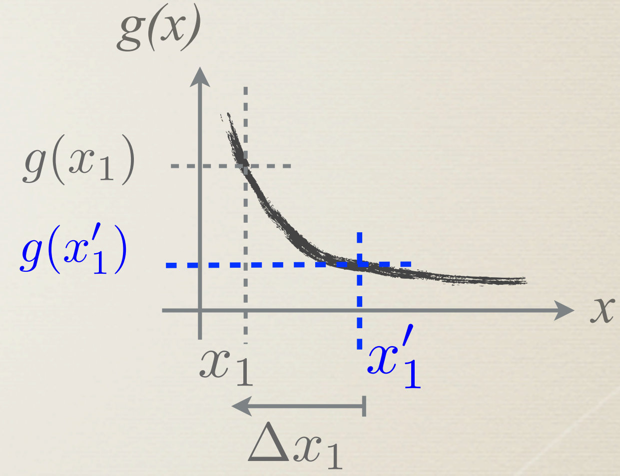
CSM provides a **good description** of the **direct** production of both **Υ(1S)** and **Υ(3S)** states at low p_T.

Coherent energy loss

[F. Arleo, S. Peigné, T. Sami, PRD 83 (2011) 114036]

$$t_f^{\text{gluon}} \gg r_{Au} \qquad \Delta E/E = \Delta x_1/x_1 \simeq N_c \alpha_s \sqrt{\Delta\langle p_T^2\rangle}/M_T$$

radiation off the incoming parton and outgoing colored object is coherent (small scattering angle in the rest frame of the nucleus)



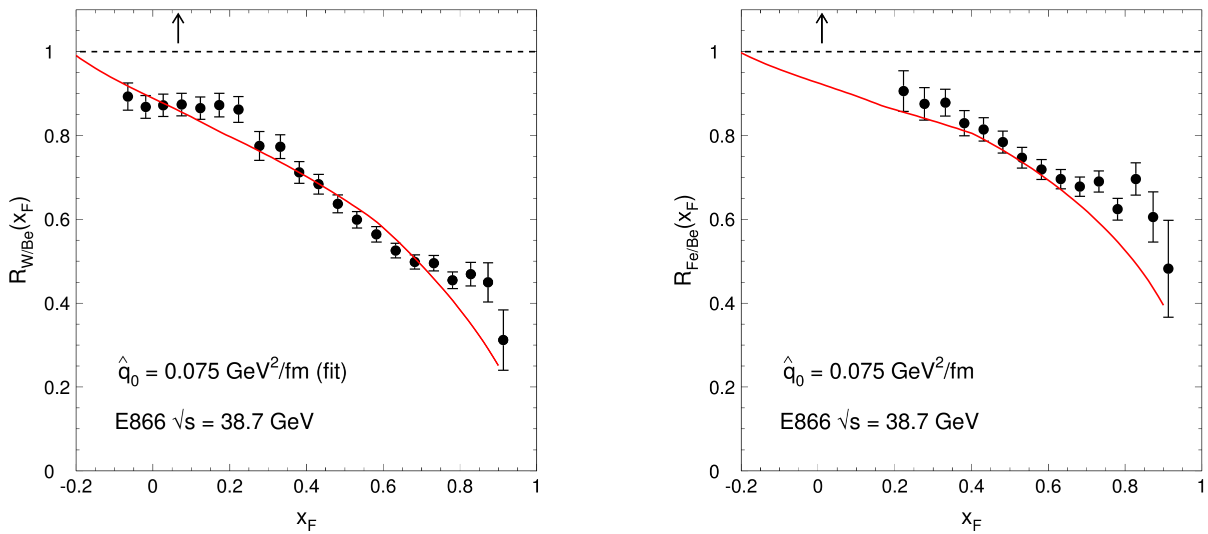
Different E loss for CSM vs COM ?
Max. E loss for **octet**.

$$R_{\text{loss}}(x_1, Q^2) = \frac{g(x_1', Q^2)}{g(x_1, Q^2)}$$

Coherent energy loss

Procedure

1. Fit $\hat{q}_0$ from J/ψ E866 data in p W collisions:
   $\hat{q}_0 = 0.075\ \mathrm{GeV}^2/\mathrm{fm}$
2. Predict J/ψ and Υ suppression for all nuclei and c.m. energies



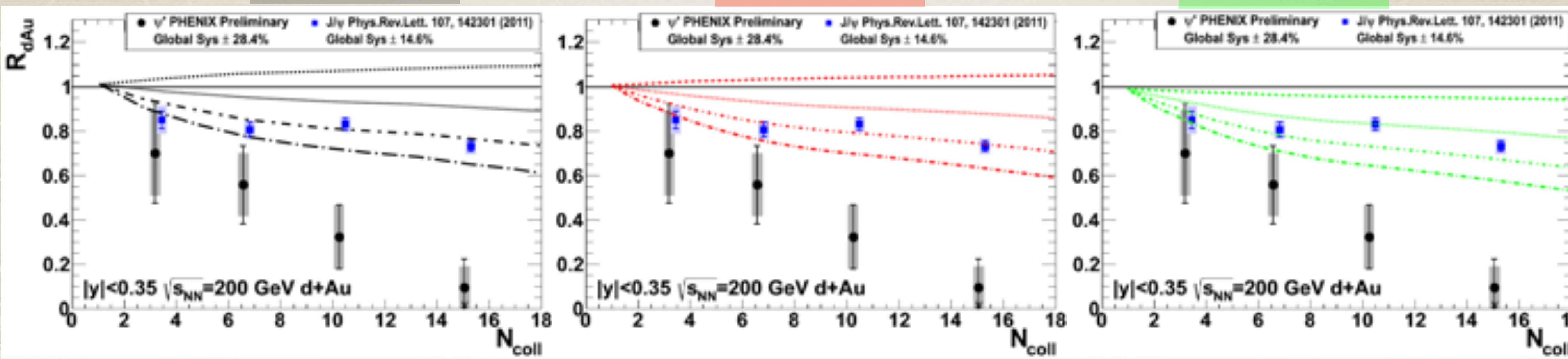
- Fe/Be ratio well described, supporting the L dependence of the model

[F. Arleo, R. Kolevatov, S. Peigné, M. Rustamova, ECT* Trento, May 2013]

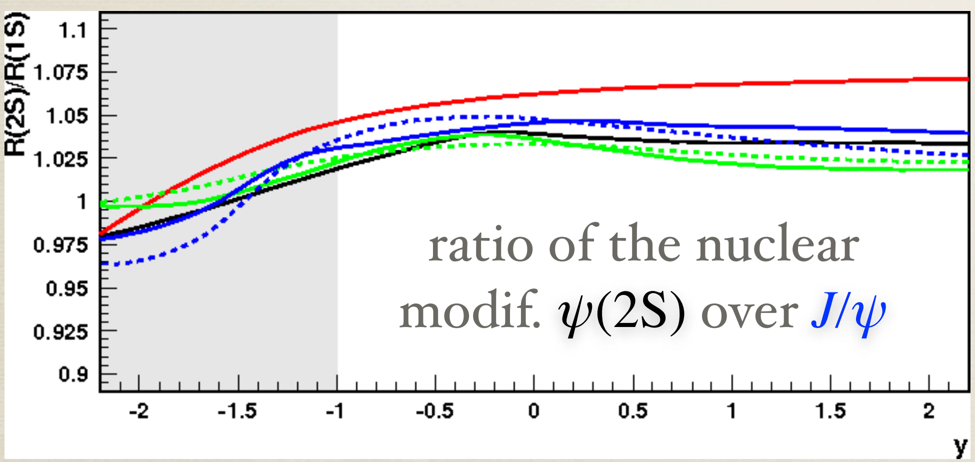
J/ψ vs in $\psi(2S)$ @ RHIC

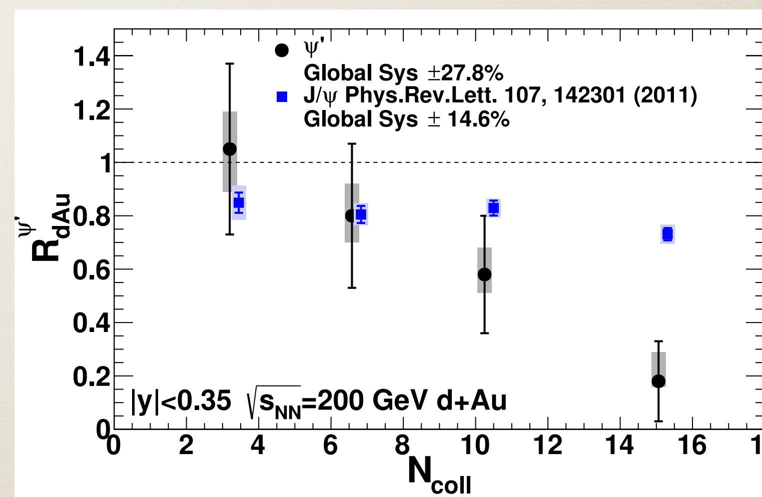
E. G. Ferreiro, F. Fleuret,
J. P. Lansberg and A. R.
J. Phys.(2013) Conf. Ser. 422 012018

EKS98 EPS08 nDSg



$\psi(2S)$ PHENIX preliminary data in dAu





$t_f \sim r_{dAu}$ $t_f >> r_{dAu}$

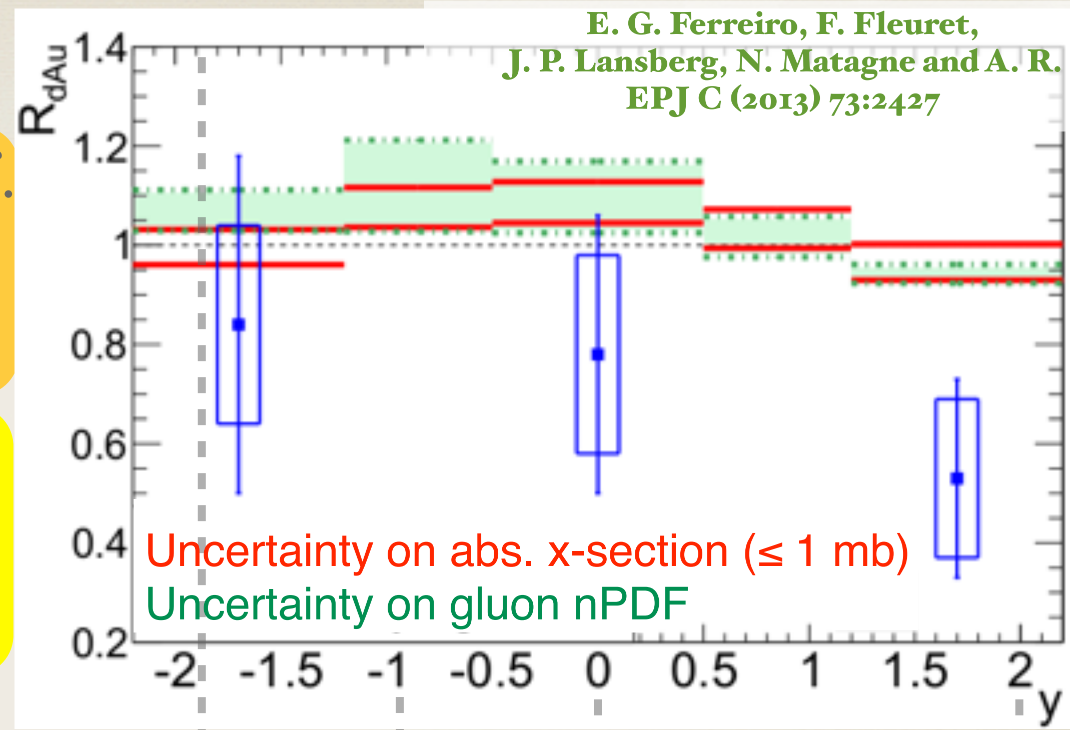
$\psi(2S)$ final data : arXiv:1305.5516

Υ in dAu @ RHIC : abs. **effective** x-section

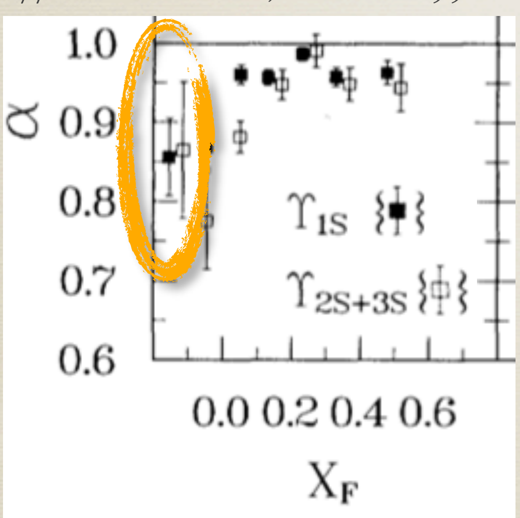
σ_{abs} **should be small :**

- at bkwd-y, $t_f < r_{Au}$, fully formed Υ. But no diff. exp. seen between Υ(1S) and Υ(2S+3S) σ_{abs}.
- at y>0, $t_f > r_{Au}$, same small-size pre-resonance for all Υ states

$$\sigma_{\Upsilon} \sim 0.1\, \sigma_{J/\psi}\ ?$$



E772 collaboration, PRL 66 (1991) 2285.



increasing t_f in the Au rest frame: r_{Au}, $2.r_{Au}$, $7.r_{Au}$, $52.r_{Au}$

propagating in Au : fully formed Υ | pre-resonant state $\sigma_{\Upsilon} \sim \left(\frac{m_c}{m_b}\right)^2 \sigma_{J/\psi}$

$x_F = 0$ $\quad$ $x_F \simeq 0.28$