



# ALICE measurements on Quarkonium production in p-Pb and their impact on the understanding of Pb-Pb results



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de l'Univers

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**ALICE collaboration**

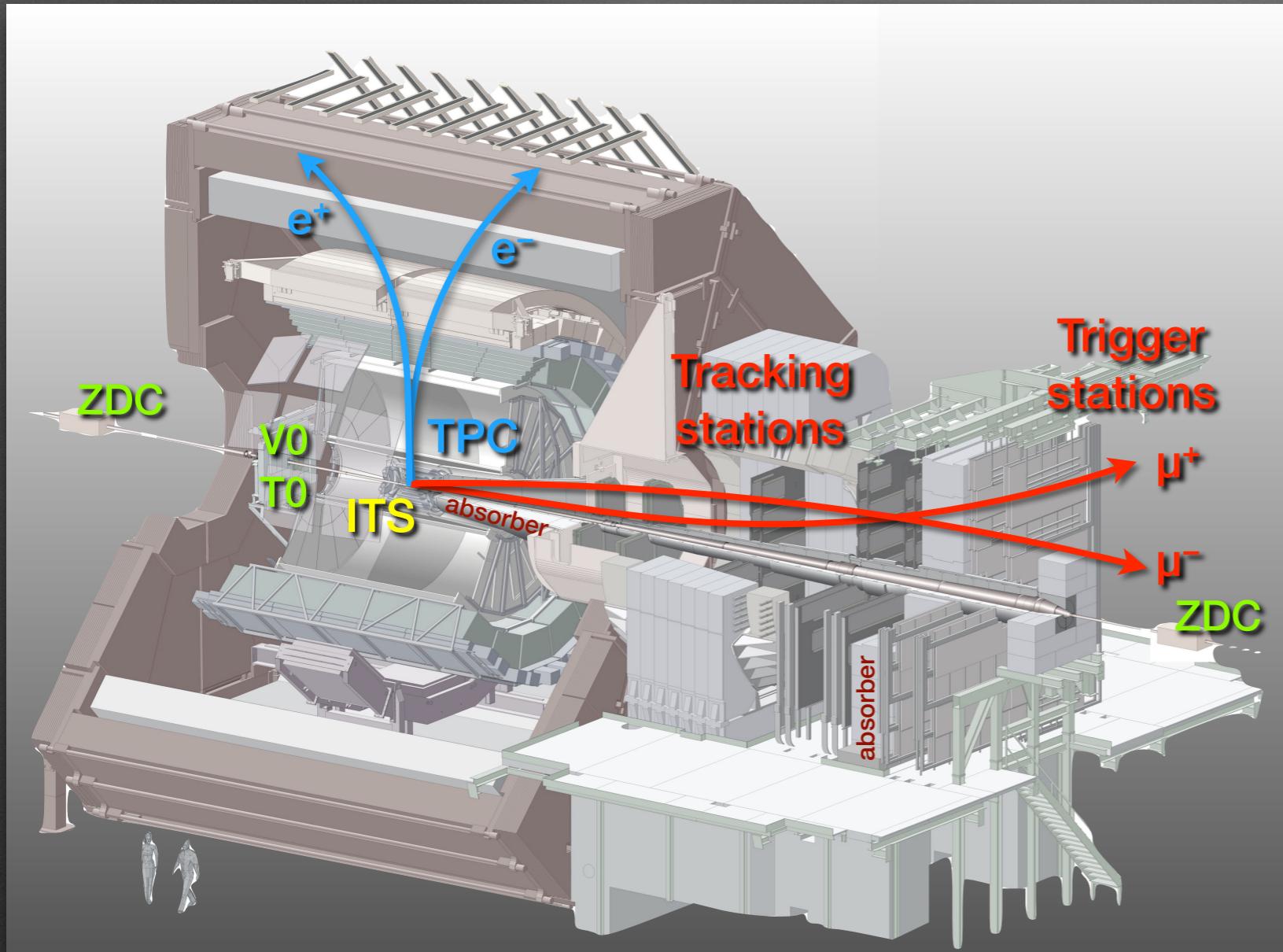
IS2016 Conference,  
May. 2016, Lisbon (Portugal)

# Motivations

- LHC Run 1 quarkonium measurements in p-Pb @ 5 TeV : probe Cold Nuclear Matter (CNM) effects at unprecedented high  $\sqrt{s_{NN}}$
- Explore  $x$  values of the initial gluons in a range where the nuclear modification of the PDF (shadowing) are loosely constrained (down to  $10^{-5}$ ), and could even be in the saturation regime (CGC models)
- Confront the data to recently revived coherent energy loss mechanism of the incoming parton or outgoing colored qqbar (pre-resonant) state
- Extrapolate to Pb-Pb, to go beyond CNM effects in search for a specific feature of the deconfined QCD matter reached at LHC energies

# Quarkonia in ALICE

Detected down to  $p_T \sim 0$  via their dilepton decay channels



ITS  
vertex  
tracking

V0, ZDC  
centrality estimation

V0, T0, ZDC, Muon  
Trigger stations  
triggering

in particular inclusive J/ $\psi$   
(i.e. prompt + non-prompt)

## Dielectrons

- $|n| < 0.9$
- TPC : full azimuth, tracking, PID via  $dE/dx$

## Dimuons

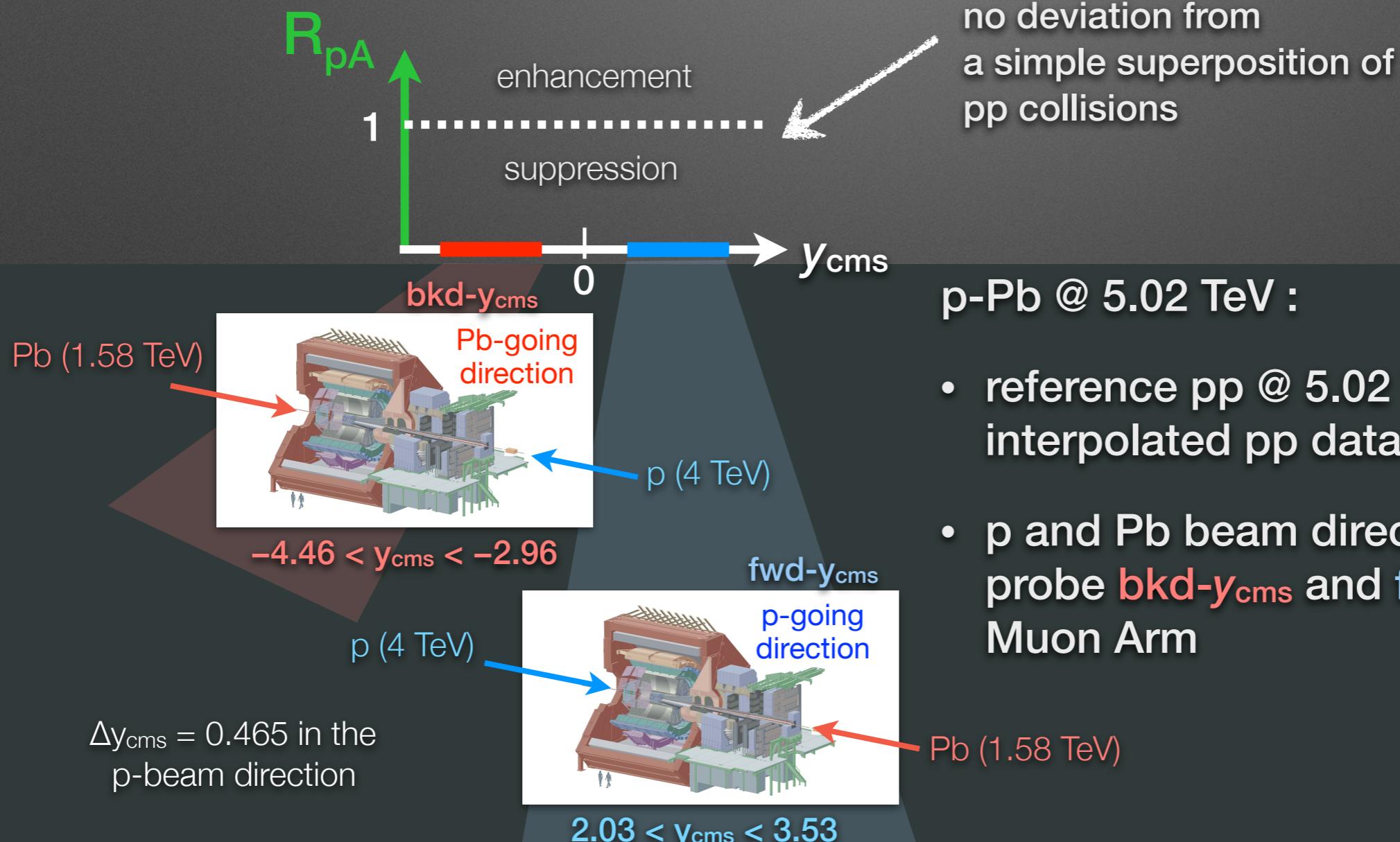
- $-4 < n < -2.5$
- Muon arm : matching tracker tracks to trigger tracklets

# Our favourite observable

Nuclear modification factor for a quarkonium in p-A collisions

$$R_{pA} = \frac{\text{yield}_{pA}^{Q\bar{Q}}}{\langle T_{pA} \rangle \times \sigma_{pp}^{Q\bar{Q}}} \quad \text{with } \langle T_{pA} \rangle : \text{nuclear overlap function}$$

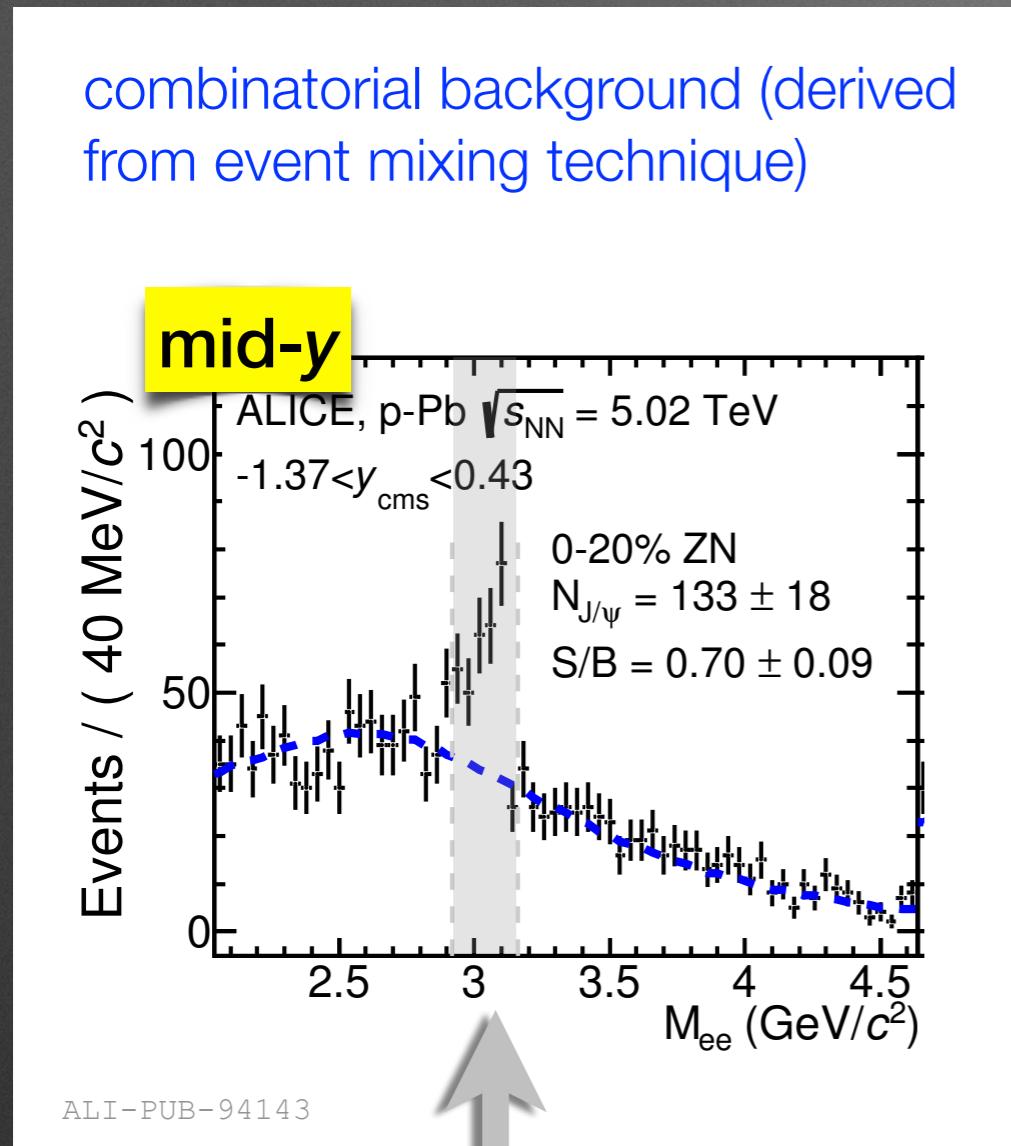
for e.g. vs rapidity (in c.m.s. frame) :



# Example of signal extraction : inclusive **J/ψ** in p-Pb @ 5.02 TeV

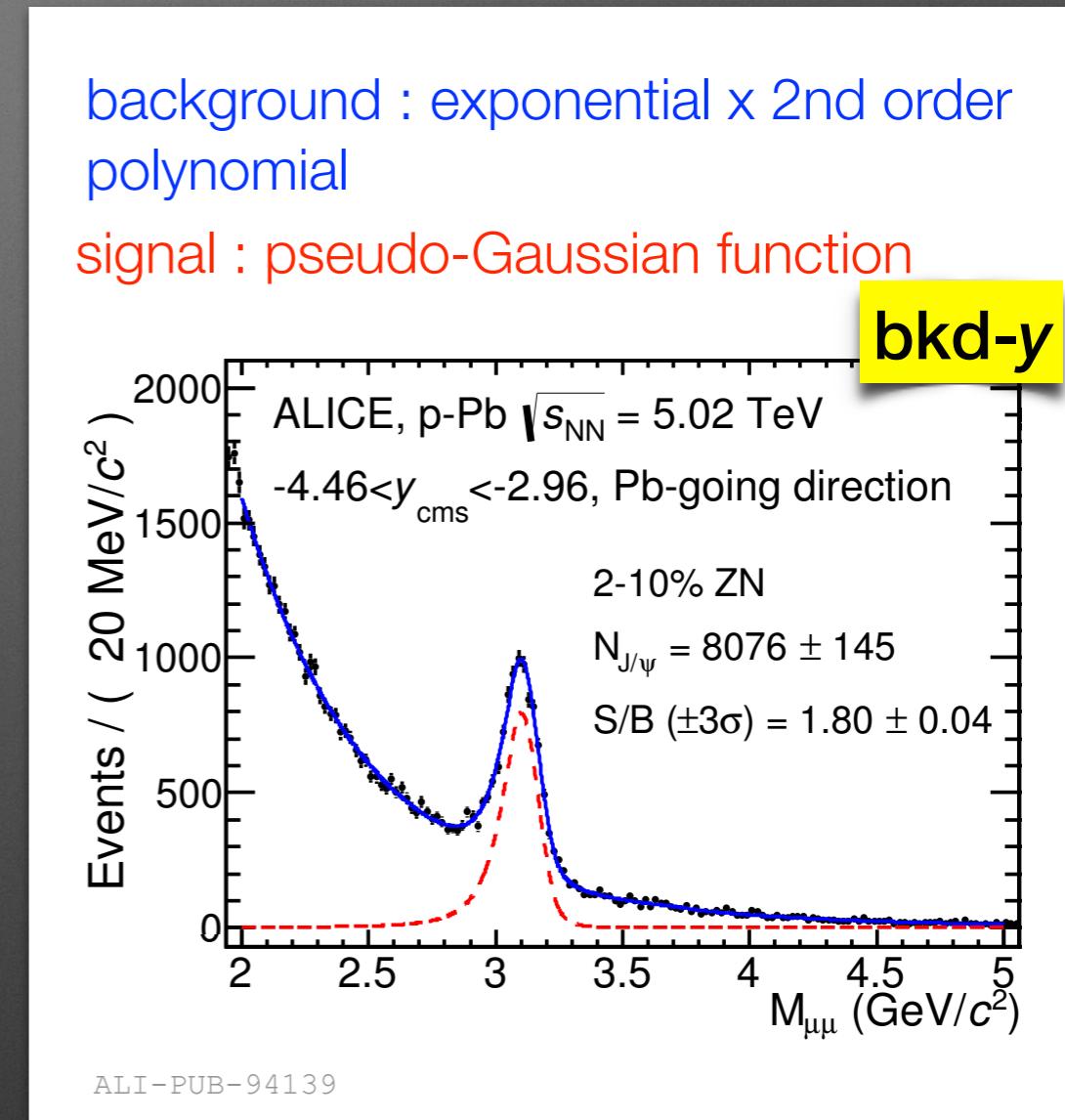
[ ALICE, JHEP 11 (2015) 127 ]

centrality 0-20%,  $p_T > 0$



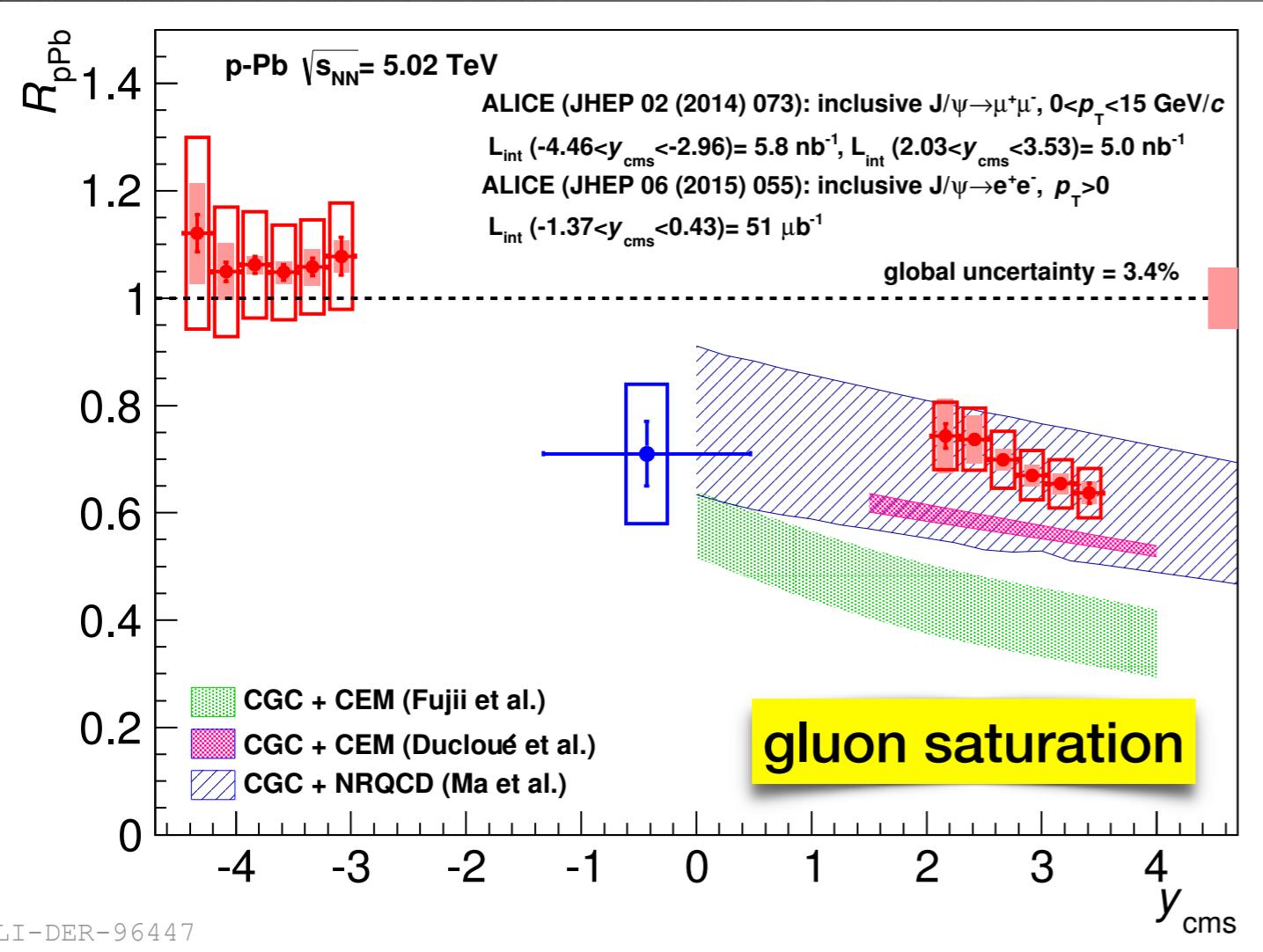
signal counting in this  
 $e^+e^-$  inv. mass range after  
background subtraction

centrality 2-10%,  $p_T < 15$  GeV/c



simultaneous fits of the  
background and the signal  
 $\mu^+\mu^-$  inv. mass distribution

# Inclusive J/ $\psi$ – $y$ dependence in p-Pb collisions



[ ALICE, JHEP 02 (2014) 073 ]

[ ALICE, JHEP 06 (2015) 055 ]

[ Fujii et al., NPA 915 (2013) 1 ]

[ Ducloué et al., PRD 91 (2015) 114005 ]

[ Ma et al., PRD 92 (2015) 071901 ]

Bar: stat. err.

Open box: uncorr. sys. err.

Shaded box: partially corr. sys. err.

## Bkd-y data :

- compatible with no CNM effects

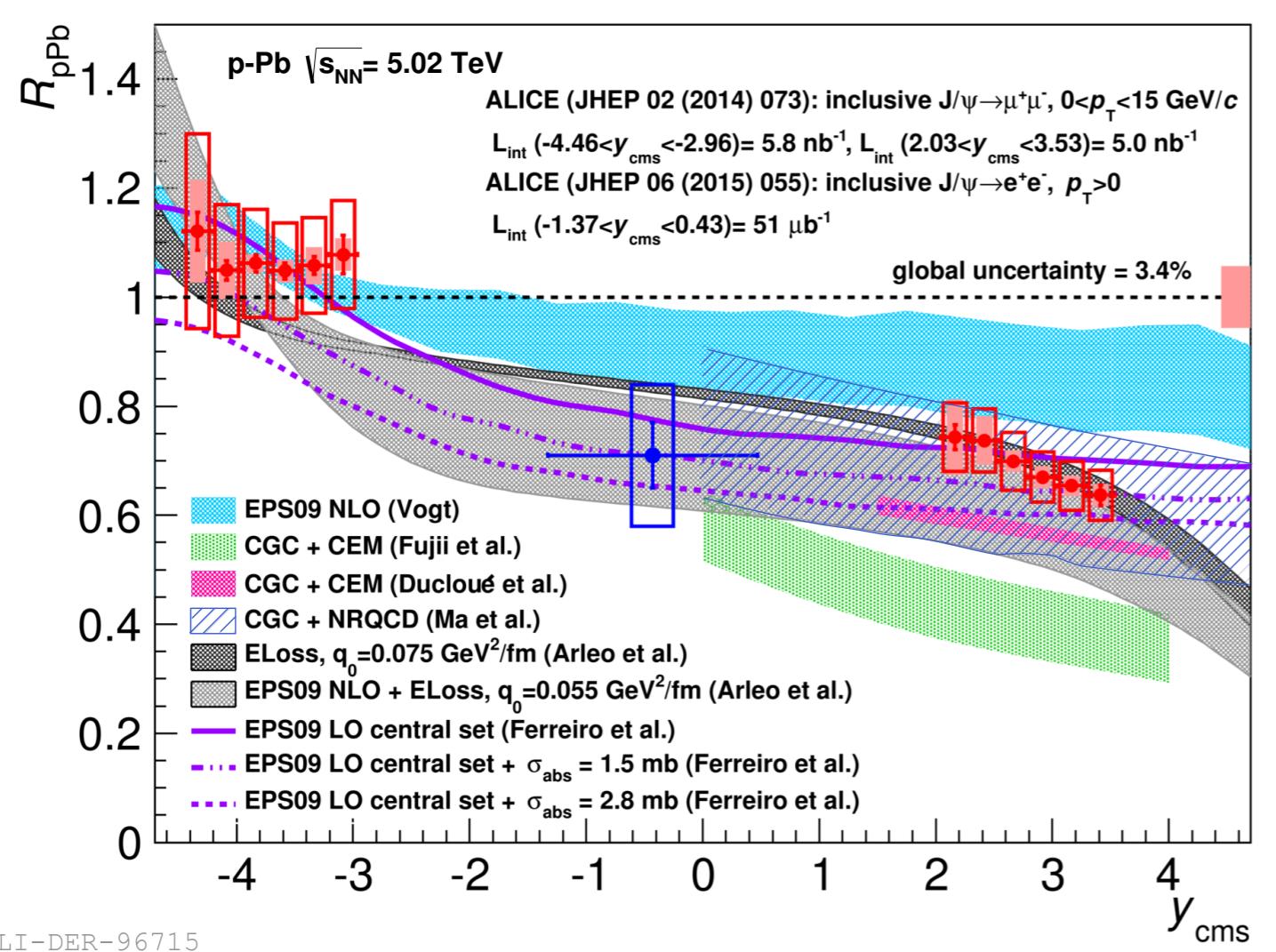
## Fwd-y data :

- sizeable CNM effects
- precision starts to be challenging for models

In particular, models with gluon saturation vs data :

- with NRQCD formalism, large theoretical uncertainties encompass the data [blue hatched]
- reduced discrepancy for the improved CGC + CEM [pink hatched]

# Inclusive J/ $\psi$ – $y$ dependence in p-Pb collisions



[ ALICE, JHEP 02 (2014) 073 ]

[ ALICE, JHEP 06 (2015) 055 ]

[ Vogt, PRC 92 (2015) 034909 ]

[ Arleo et al., JHEP 1303 (2013) 122 ]

[ Ferreiro et al., PRC 88 (2013) 047901 ]

**Full  $y$  dependence : hard to discriminate models with quite different mechanisms for CNM effets (mixed with different underlying  $J/\psi$  production processes)**

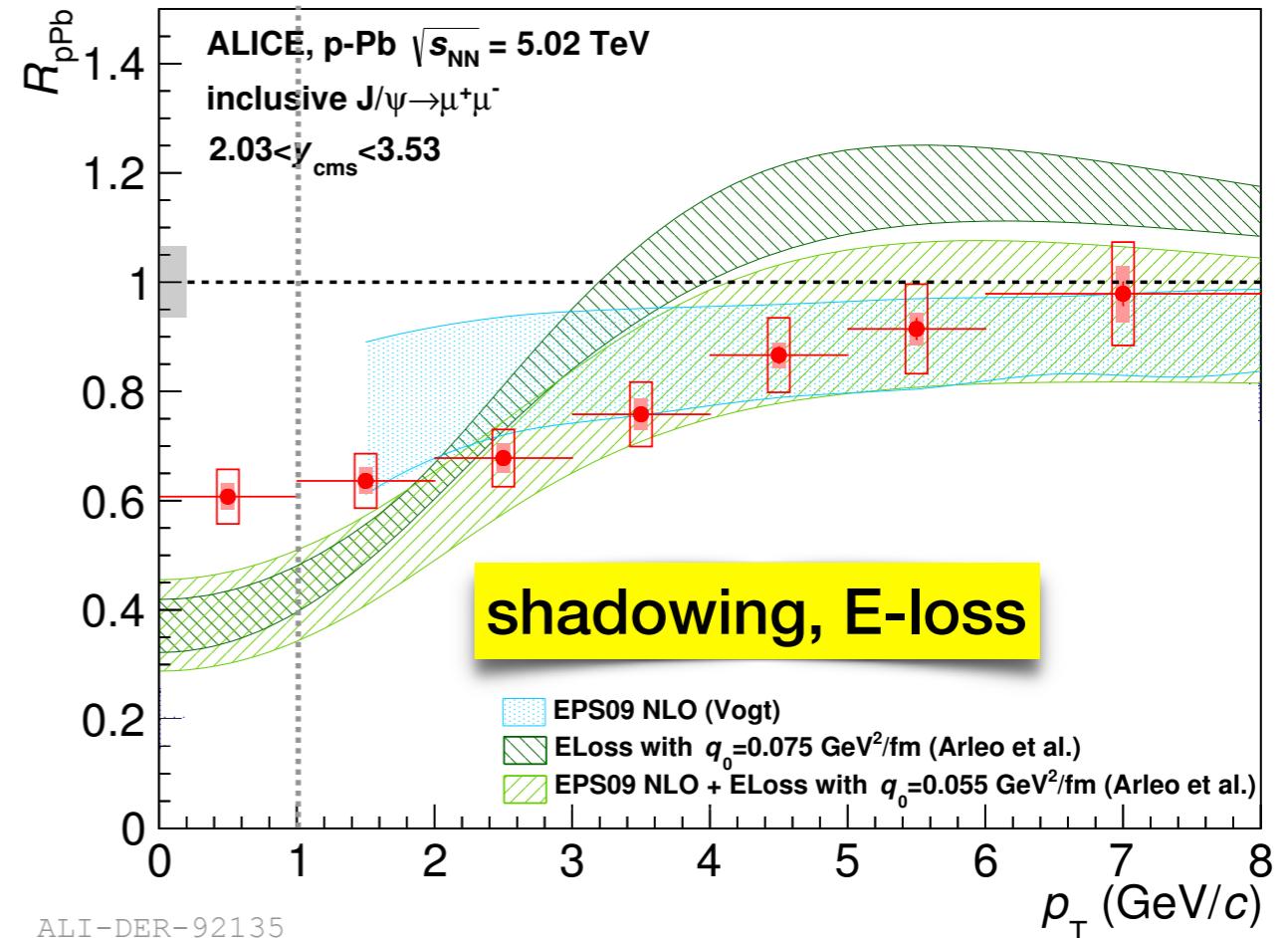
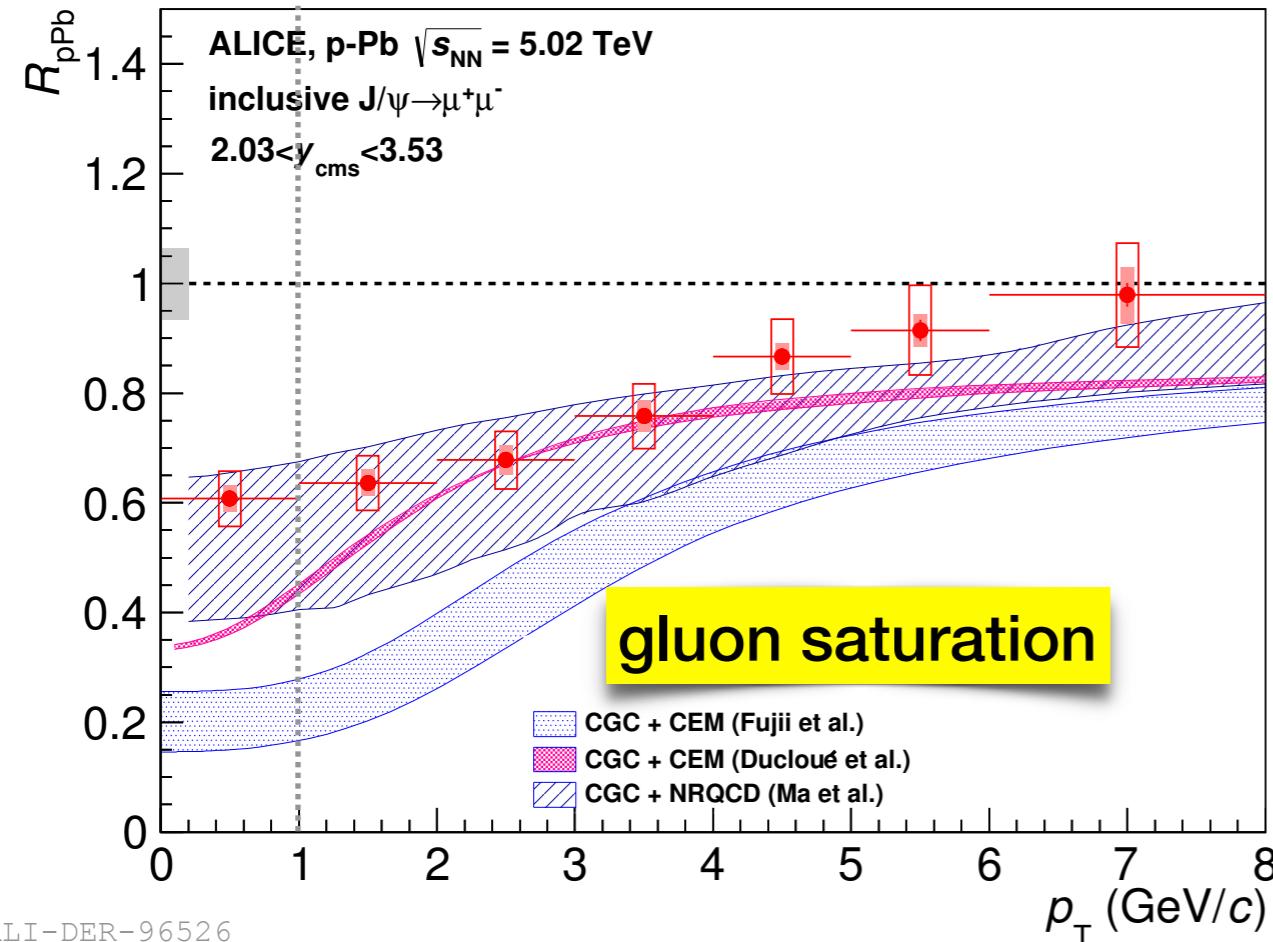
Different scenarios are plausible :

- dominant E-loss and negligible shadowing
- less E-loss and shadowing
- shadowing only or with a moderate final state nuclear absorption
- gluon saturation (at fwd-y)

# Inclusive $J/\psi - p_T$ dependence at fwd- $y$ in p-Pb collisions

no centrality selection

[ ALICE, JHEP 02 (2014) 073 ]

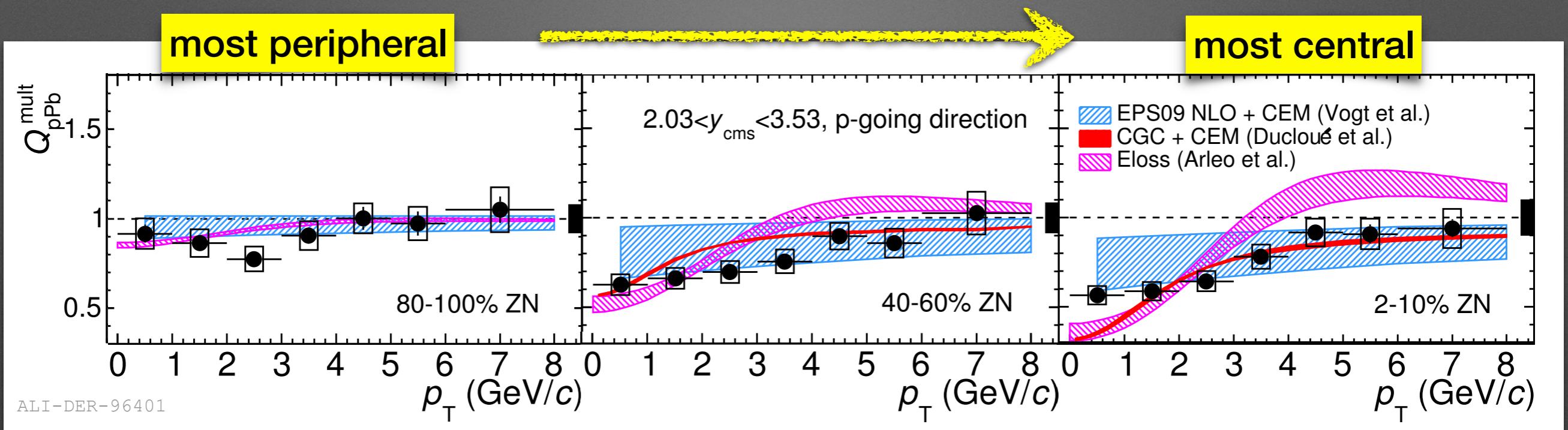


Explore the kinematical region with enhanced CNM effects :

- Models tend to undershoot the data at low  $p_T < 1$  GeV/c, except [CGC + NRQCD] i.e. the only one with an underlying  $J/\psi$  production process different from CEM.
- Fair agreement with the data at  $p_T > 1\text{-}2$  GeV/c, except for [CGC + CEM Fujii et al.] (which systematically undershoots the data) and pure E-loss (steeper  $p_T$  trend).

# Inclusive $J/\psi - p_T$ dependence at fwd- $y$ in p-Pb collisions

with centrality<sup>(\*)</sup> selection



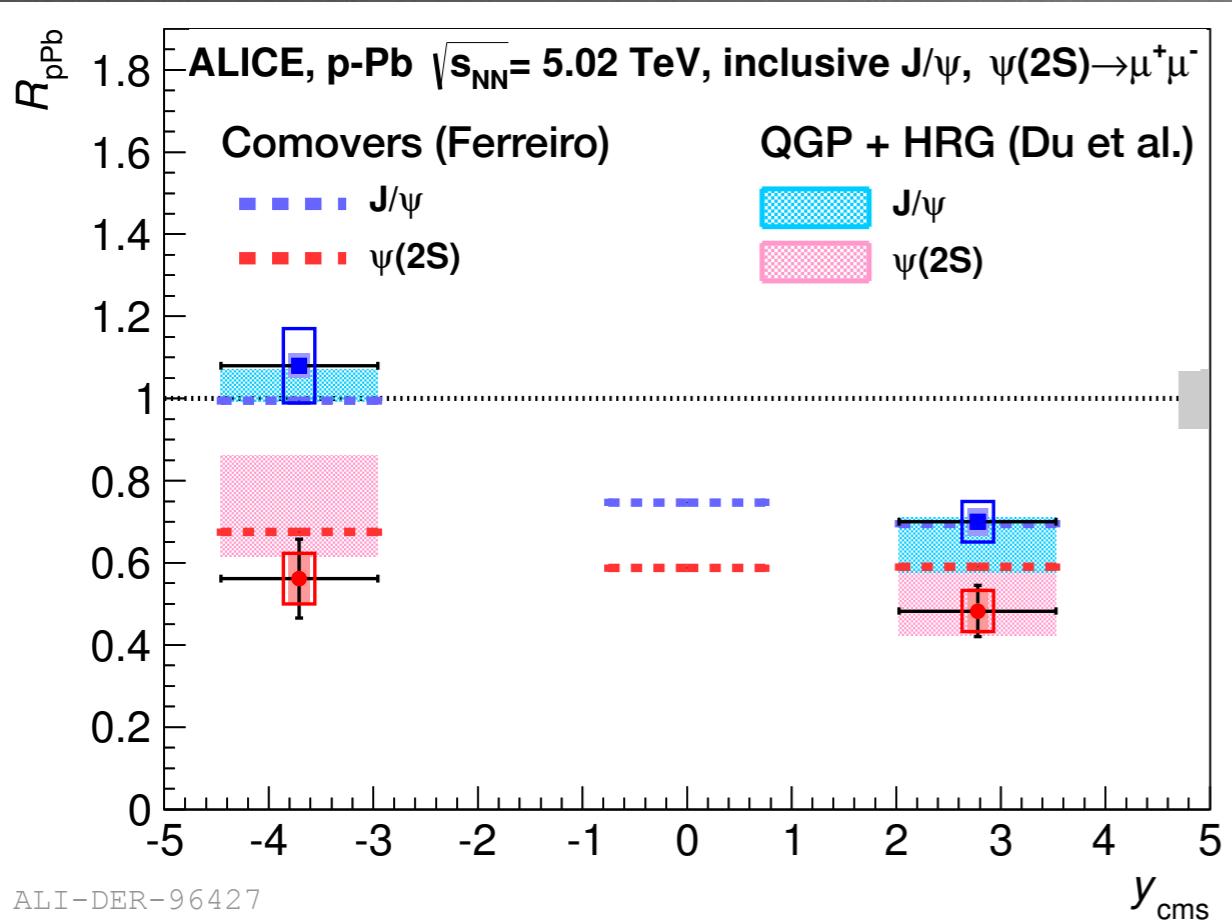
[ ALICE, JHEP 11 (2015) 127 ]

- Almost no CNM effects in peripheral collisions
- Clear enhancement of the CNM effects with collisions getting more and more central, also exhibited by the models
- Shadowing and improved CGC in agreement with the data
- Steeper  $p_T$  trend for pure E-loss model

(\*) The energy deposited by the « slow » neutrons emitted by the p and Pb-remnants in the fwd neutron calorimeters ZN, is used as centrality estimator [ ALICE, PRC 91 (2015) 064905 ]

# Production of different charmonium states in p-Pb collisions

$\Psi(2S)$  vs  $J/\psi$   
Rapidity



[ ALICE, JHEP 12 (2014) 073 ]

[ Ferreiro, PLB 749 (2015) 98 ]

[ Du et al., NPA 943 (2015) 147 ]

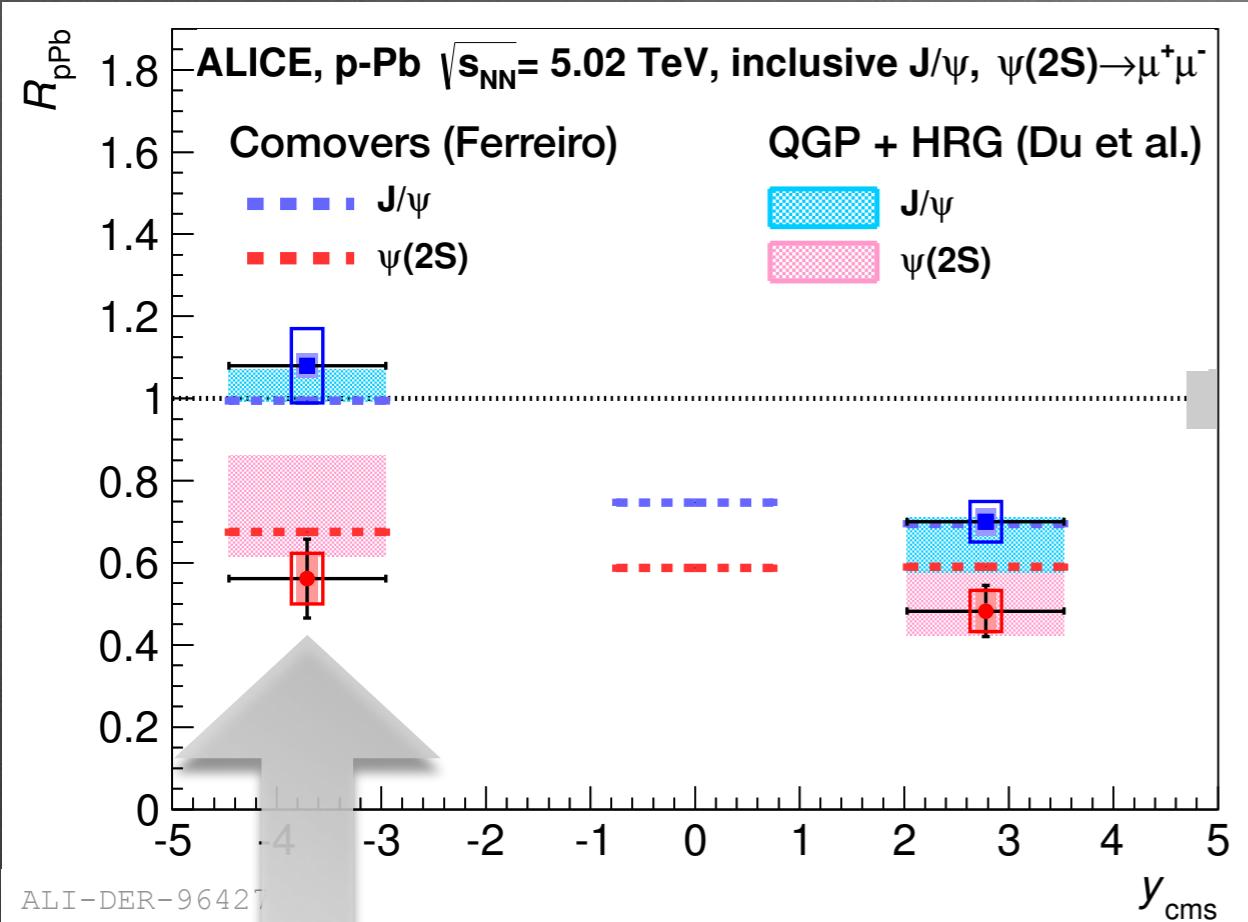
Excited state more suppressed. Unexpected from initial-state effects (gluon saturation, shadowing) and E-loss effects.

=> Due to a **final-state interaction** ? with hadronic medium only ? or with (hot) partonic medium as well (in p-Pb collisions) ?

# Production of different charmonium states in p-Pb collisions

Rapidity

$\Psi(2S)$  vs  $J/\psi$



[ ALICE, JHEP 12 (2014) 073 ]

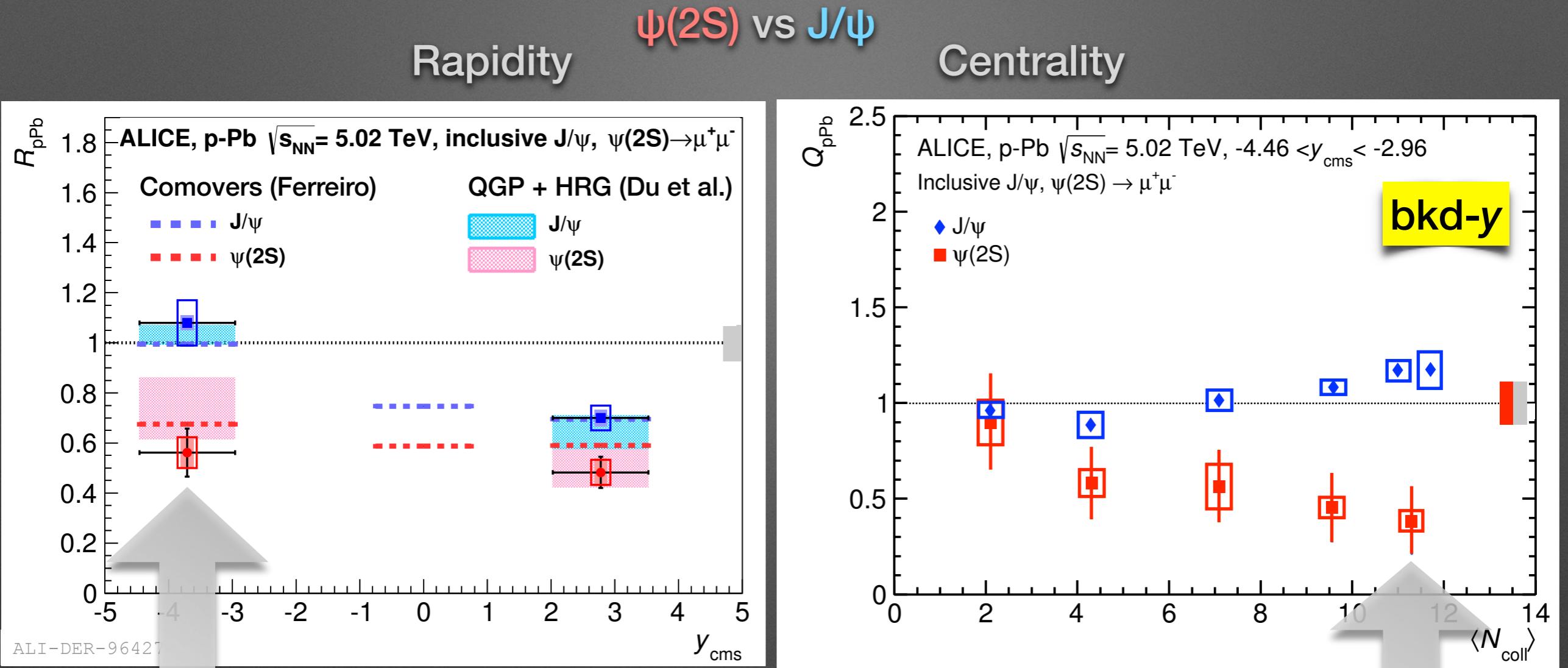
[ Ferreiro, PLB 749 (2015) 98 ]

[ Du et al., NPA 943 (2015) 147 ]

The difference

is more pronounced at bkd-y (Pb-going direction)

# Production of different charmonium states in p-Pb collisions



[ ALICE, JHEP 12 (2014) 073 ]

[ Ferreiro, PLB 749 (2015) 98 ]

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[ ALICE, arXiv:1603.02816 ]

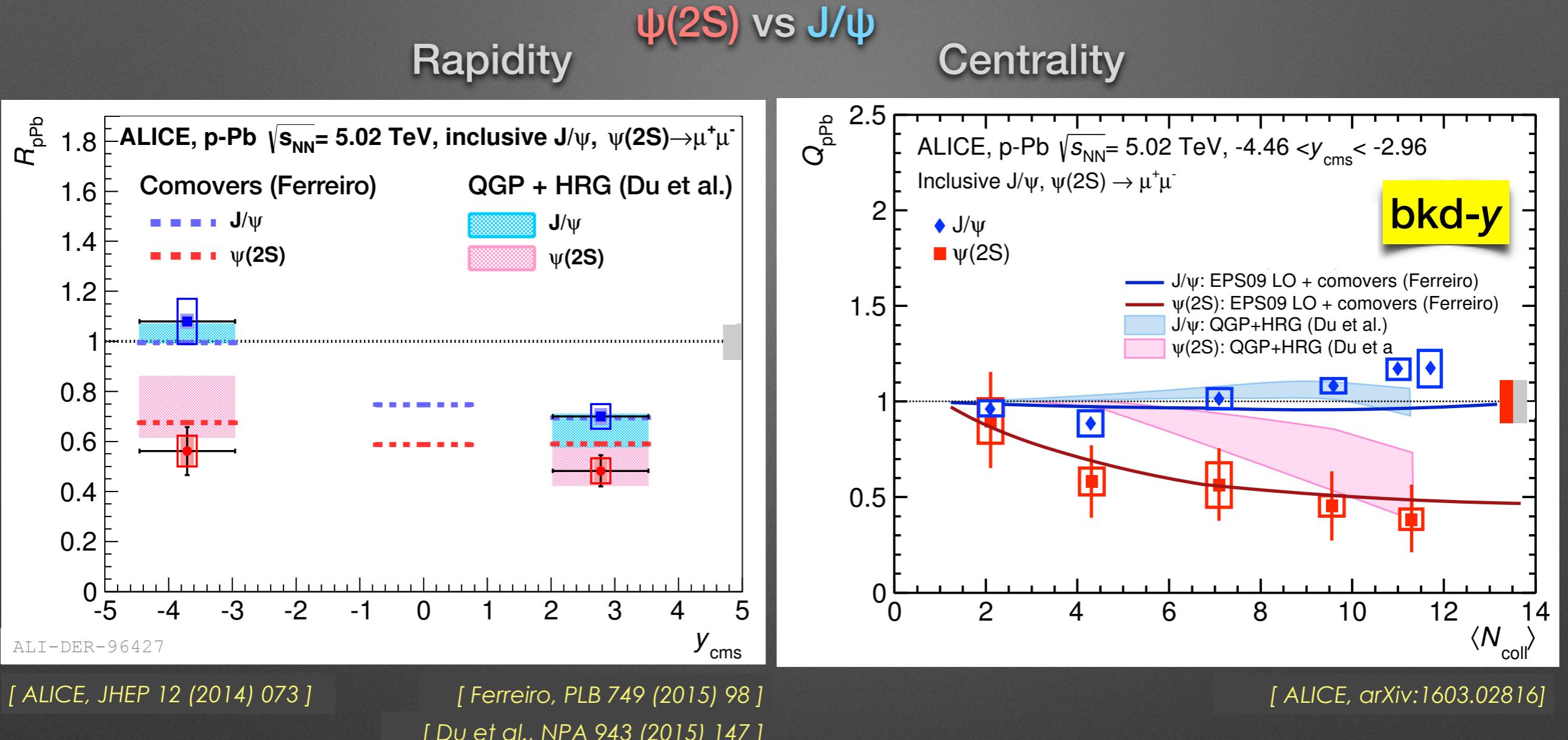
The difference

is more pronounced at bkd-y (Pb-going direction)

and gets enhanced in more central collisions

as expected with increasing density of comovers/hadron gas.

# Production of different charmonium states in p-Pb collisions

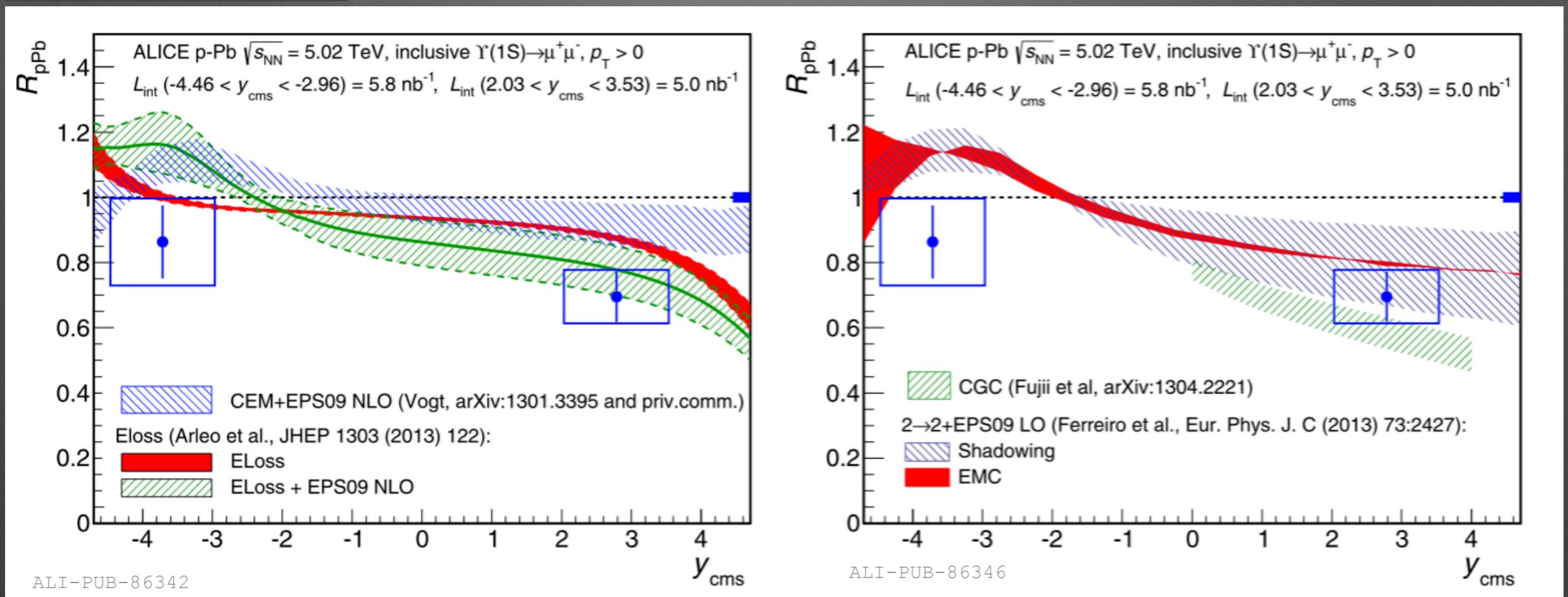


Comover and [QGP + Hadron Gas] models vs data :

- a good description for both rapidity and centrality dependence at once ?
- could be discriminated with higher precision measurements of  $\Psi(2S)$  suppression at intermediate centralities

# Inclusive $\Upsilon(1S)$ – $y$ dependence in p-Pb collisions

[ ALICE, PLB 740 (2015) 105 ]



Models including EPS09 parametrization of the gluon PDF nuclear modification tend to overshoot the data at bkd-y.

=> less gluon anti-shadowing as in DSSZ parametrization ?

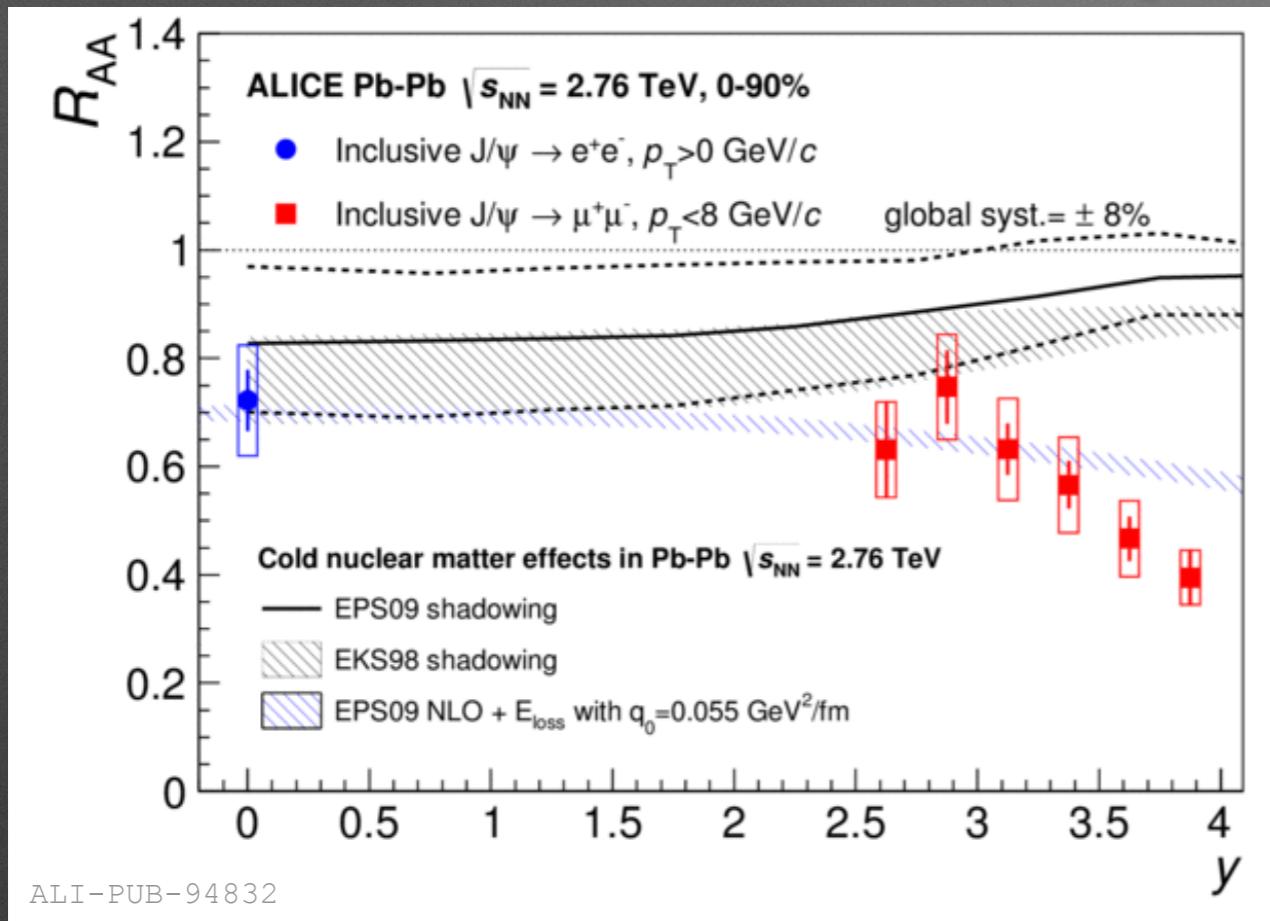
[ de Florian et al., PRD 85 (2012) 074028 ]

No strong conclusion

=> higher precision data needed to further discriminate the models

# Going further than the cold effects (1/2)

inclusive  $\text{J}/\psi$  in Pb-Pb collisions vs  $y$



Models tested in p-Pb collisions are extrapolated to Pb-Pb collisions : sizeable CNM effects in Pb-Pb !

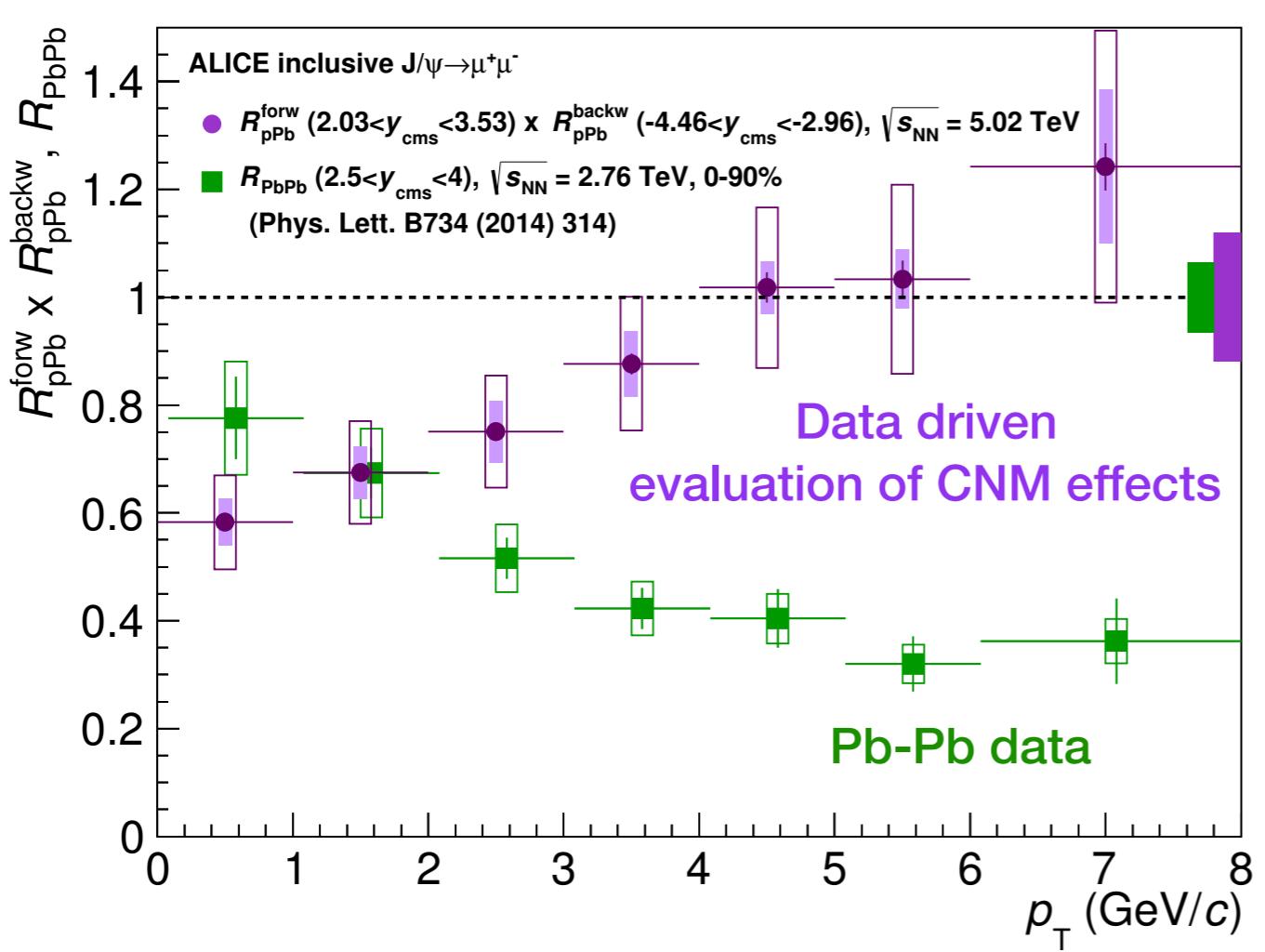
[ ALICE, arXiv:1506.08804, accepted in JHEP ]

Resulting  $R_{AA}$  ( $\text{J}/\psi$ ) = CNM effects  $\downarrow$  + color screening  $\downarrow$  + regeneration  $\uparrow$

CNM effects : a crucial « ingredient » at play in A-A collisions in order to properly evaluate/understand the hot medium effects at LHC energies.

# Going further than the cold effects (2/2)

inclusive  $\text{J}/\psi$  in Pb-Pb collisions vs  $p_{\text{T}}$



[ ALICE, JHEP 06 (2015) 055 ]

Bar: stat. err.

Open box: uncorr. sys. err.

Shaded box: partially corr.  
sys. err.

Use p-Pb 5 TeV data to evaluate CNM effects in Pb-Pb 2.76 TeV

Assumptions :

- $2 \rightarrow 1$  kinematics for  $\text{J}/\psi$  production  
 $\Rightarrow$  similar  $x$  ranges in p-Pb and Pb-Pb dimuon data
- CNM effects dominated by shadowing, which can be factorized as  $R_{\text{pPb}}(y) \times R_{\text{pPb}}(-y)$

In Pb-Pb collisions, high  $p_{\text{T}}$   $\text{J}/\psi$  are suppressed much beyond CNM effects.

Enhancement at low  $p_{\text{T}}$  ? as expected from a sizable fraction of regenerated  $\text{J}/\psi$  at LHC energies ?

# Summary

- LHC Run 1 quarkonium measurements in p-Pb collisions : probe CNM effects at unprecedented high  $\sqrt{s_{NN}}$   $\Leftrightarrow$  low  $x$  values of the initial gluons for charmonium states
- p-Pb data reasonably described by models with quite different mechanisms of CNM effects
  - They imply sizable CNM effects on  $J/\psi$  production in Pb-Pb collisions, that should be properly addressed in order to evaluate hot medium effects esp. the regeneration component.
- The precision achieved for the  $J/\psi$  measurement in p-Pb collisions at  $2.03 < y_{cms} < 3.53$  starts to be challenging for the models.
- Final state effects could explain the additional suppression suffered in p-Pb collisions by the  $\Psi(2S)$  relative to the  $J/\psi$ . Part of these effects could be hot medium effects.

LHC Run 2

Stay tuned: p-Pb data to be taken in late 2016 !

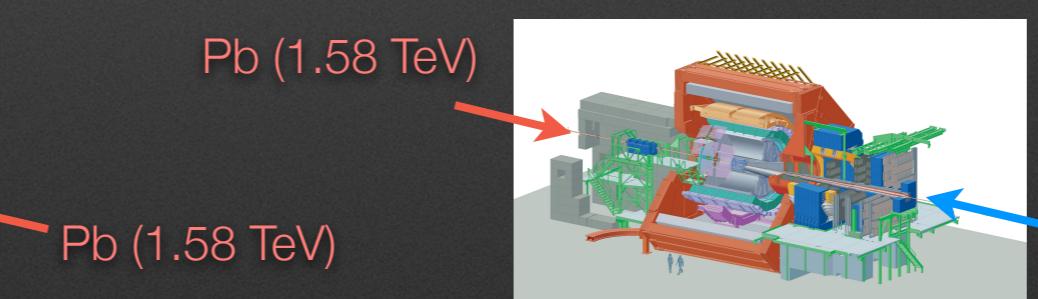
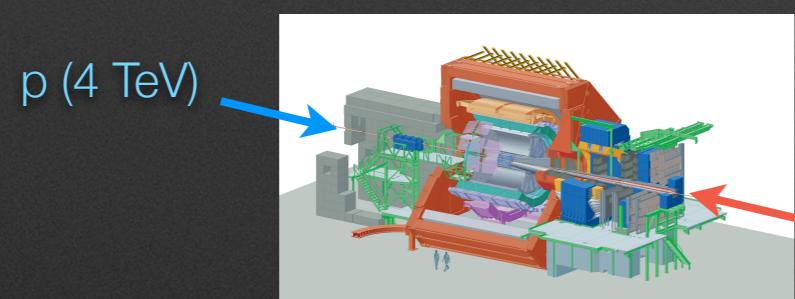


# Spare Slides

# LHC Run 1 : ALICE data taking (focus on heavy ion)

year	system	$\sqrt{s_{\text{NN}}} \text{ (TeV)}$	$L_{\text{int}}$
2010	Pb-Pb	2.76	$\sim 10 \mu\text{b}^{-1}$
2011	pp	2.76	$\sim 250 \text{ nb}^{-1}$
2011	Pb-Pb	2.76	$\sim 150 \mu\text{b}^{-1}$
2013	p-Pb	5.02	$\sim 30 \text{ nb}^{-1}$
2013	pp	2.76	$\sim 5 \text{ pb}^{-1}$

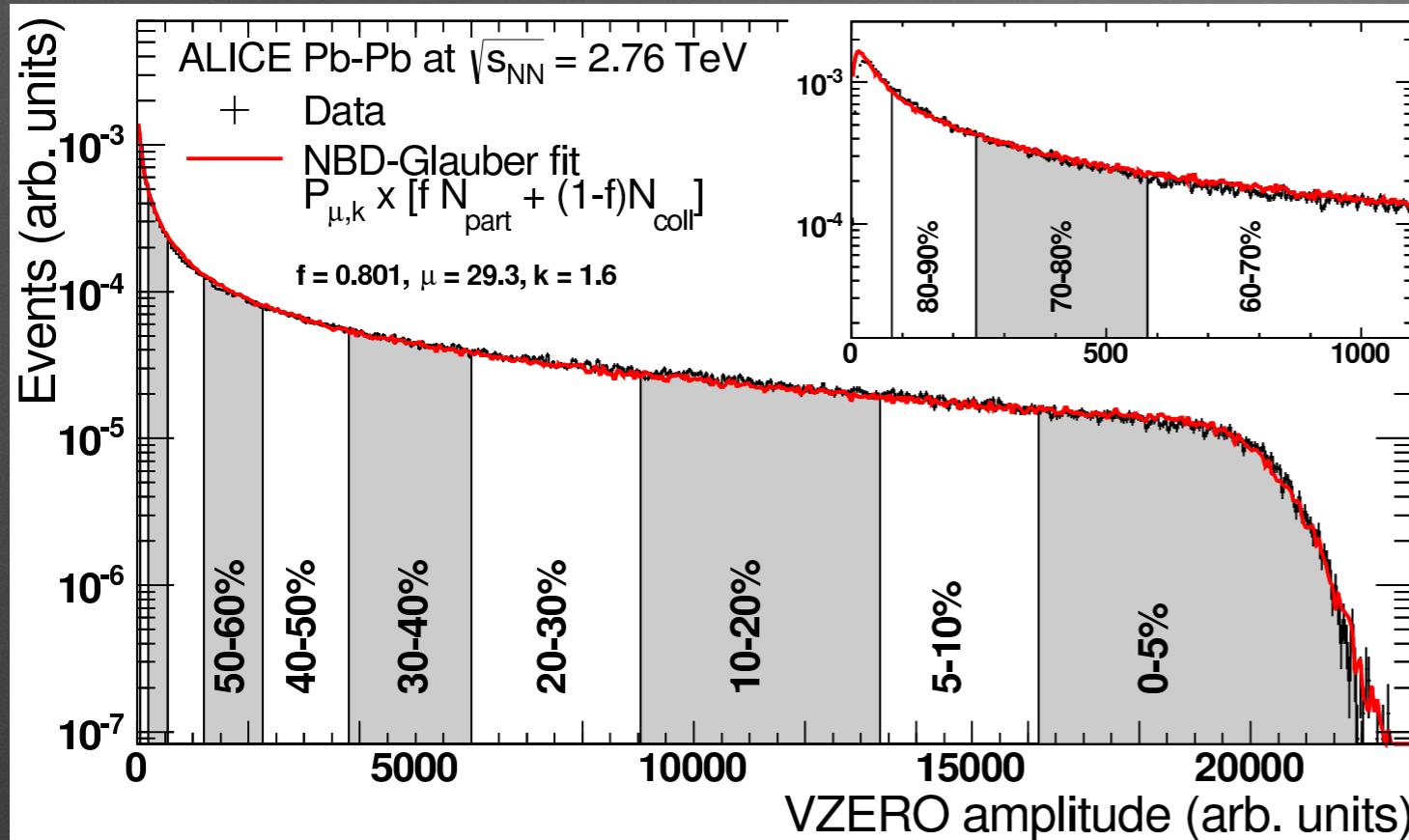
Two configurations in 2013



$\Delta y_{\text{cms}} = 0.465$  in the p-beam direction

# Multiplicity based centrality estimator (Pb-Pb)

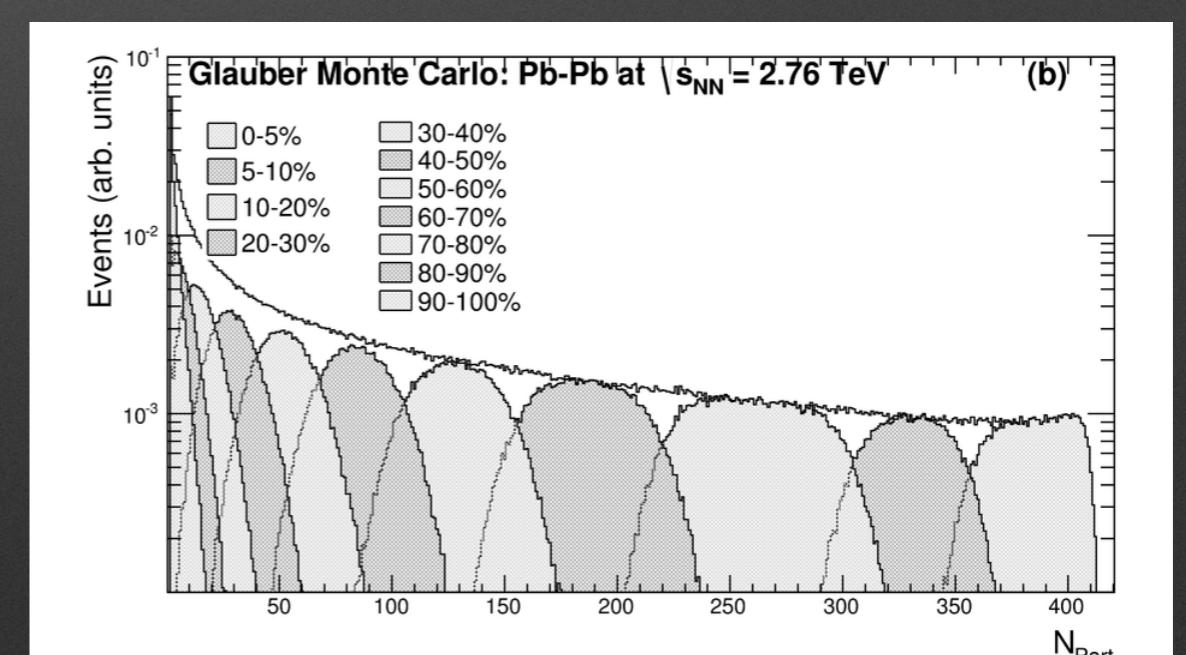
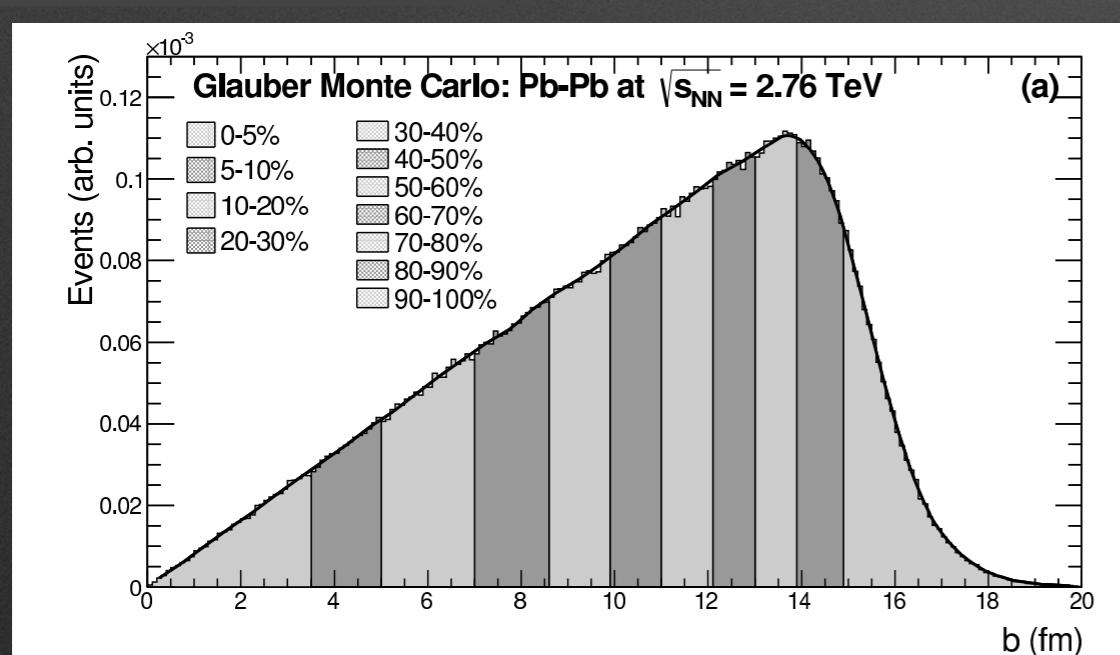
centrality = slices of percentiles of the hadronic cross-section



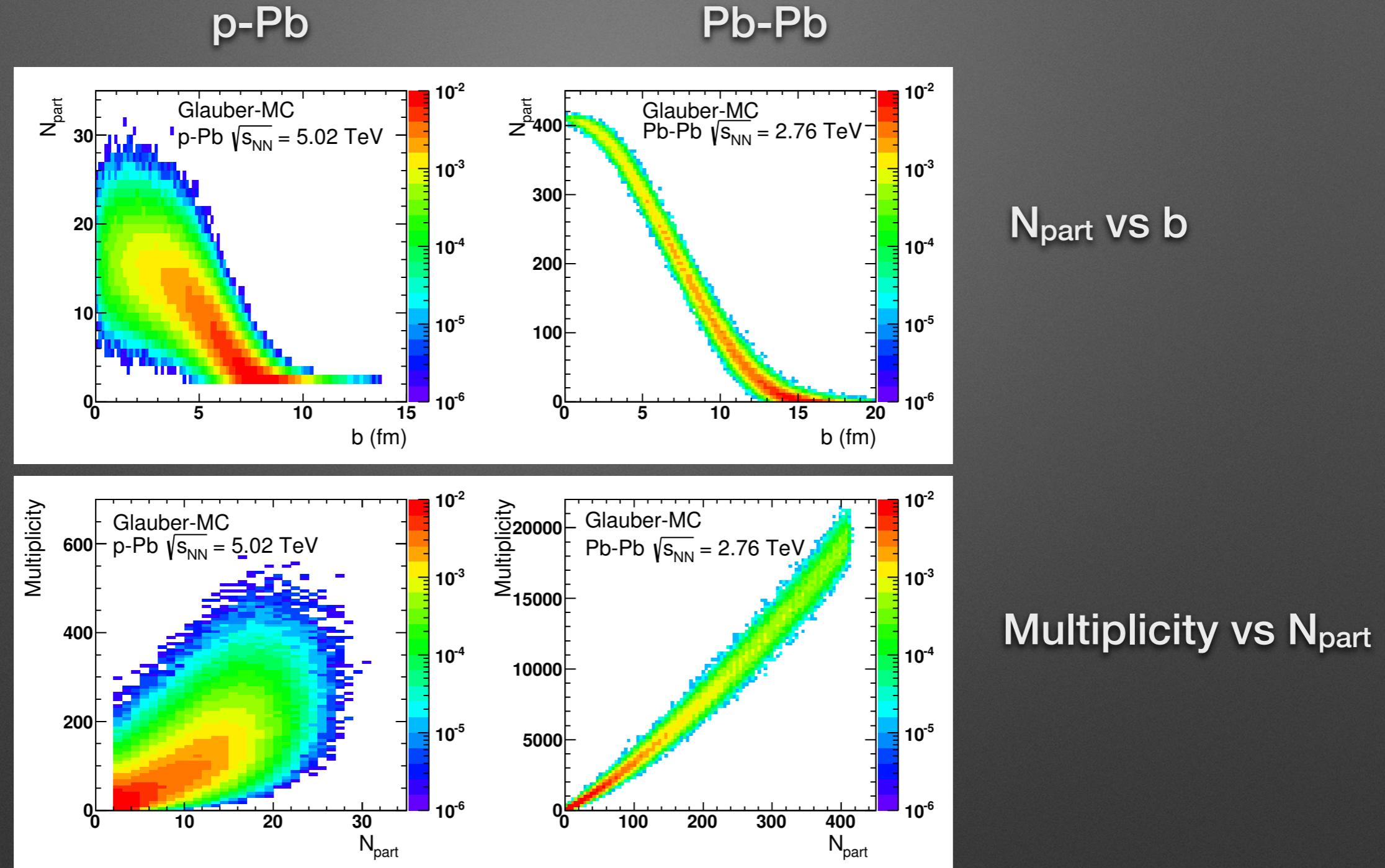
For a given  $b$ , Glauber model (Woods-Saxon function) predicts :

- $N_{\text{part}}$  (nb. participants)
- $N_{\text{coll}}$  (nb. binary collisions)

Monte-Carlo Glauber model  
 ↓  
 each collision has  $N_{\text{ancestors}} = f.N_{\text{part}} + (1-f).N_{\text{coll}}$   
 ↓  
 Each ancestor contributes to a Negative Binomial distribution of hits (fluctuations of the multiplicity at a given  $N_{\text{ancestors}}$ )  
 ↓  
 Fit VZERO amplitude distribution

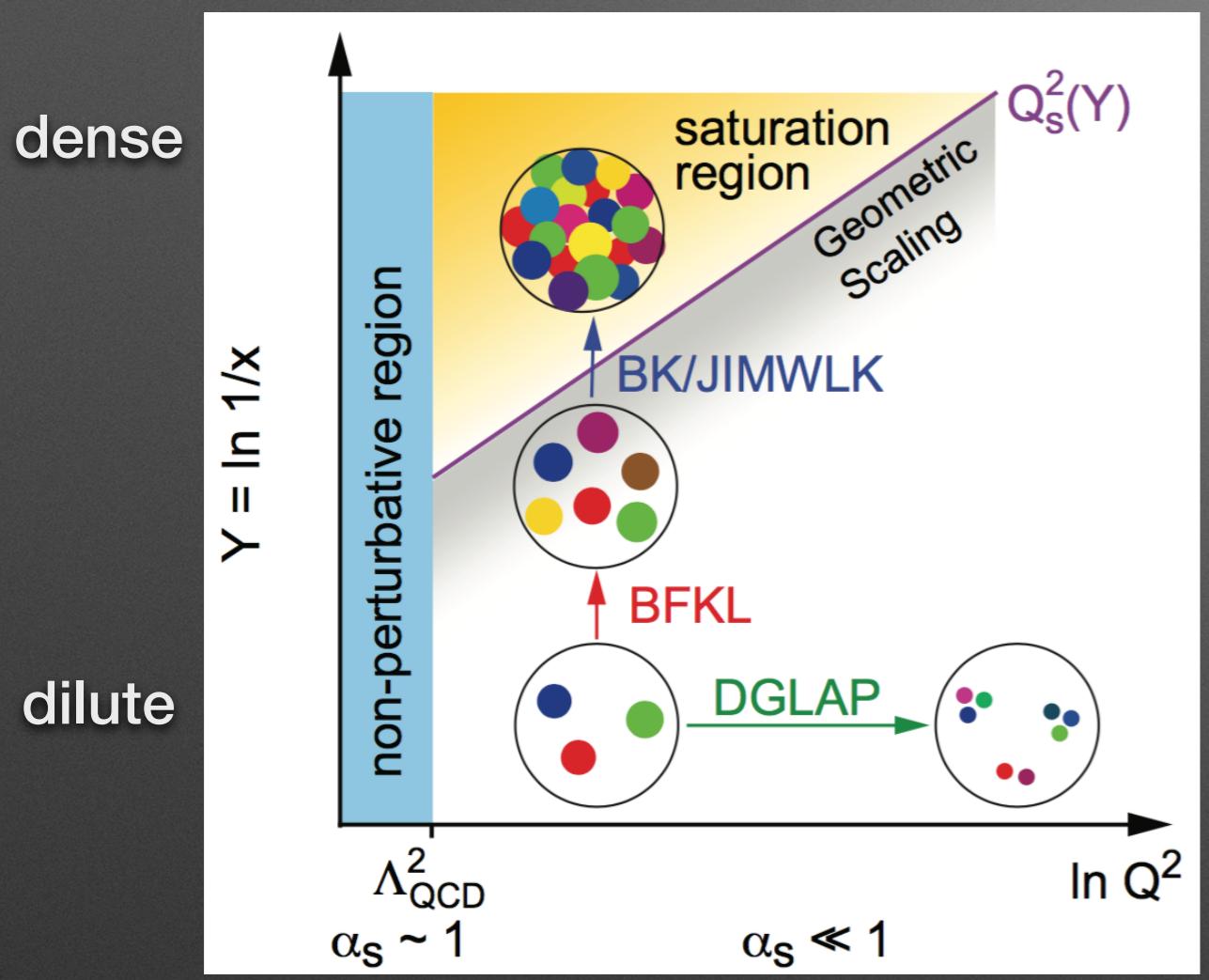


# Correlation of impact parameter, $N_{\text{part}}$ and multiplicity



Loose correlation in p-Pb degrades the quality of the centrality estimator based on the charge particle multiplicity.

# Gluon saturation



Saturation criterion : when it becomes more « efficient » to recombine gluons (non-linear effect) than to increase the gluon surface density

[ Gribov, Levin, Ryskin (1983) ]

$$\underbrace{\alpha_s Q^{-2}}_{\sigma_{gg \rightarrow g}} \times \underbrace{A^{-2/3} x G(x, Q^2)}_{\text{surface density}} \geq 1$$

$\sigma_{gg \rightarrow g}$       surface density

$$Q^2 \leq Q_s^2 \equiv \underbrace{\frac{\alpha_s x G(x, Q^2)}{A^{2/3}}}_{\text{saturation scale}} \sim A^{1/3} x^{-0.3}$$

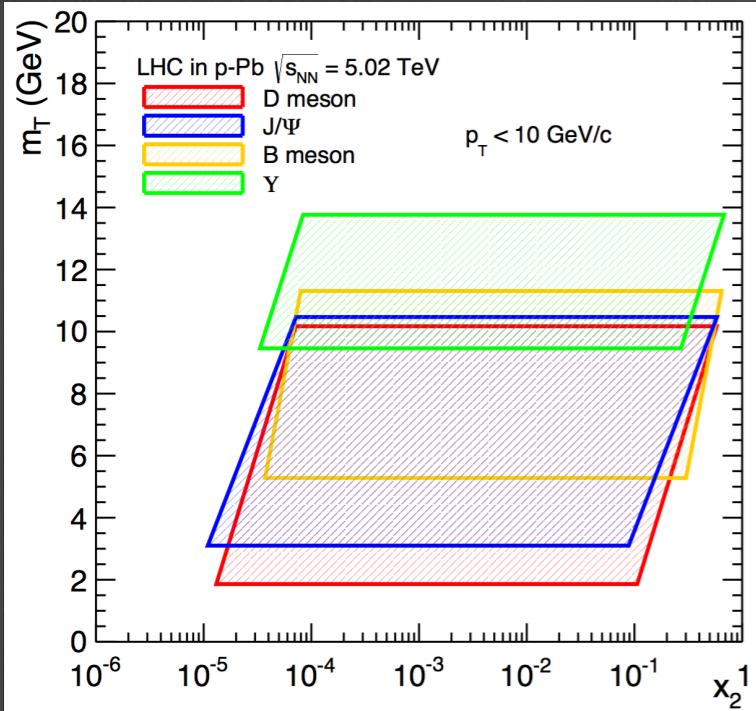
# Nuclear modif. of the gluon PDF in Pb nucleus

Ratio of nuclear struct. f. per nucleon :

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

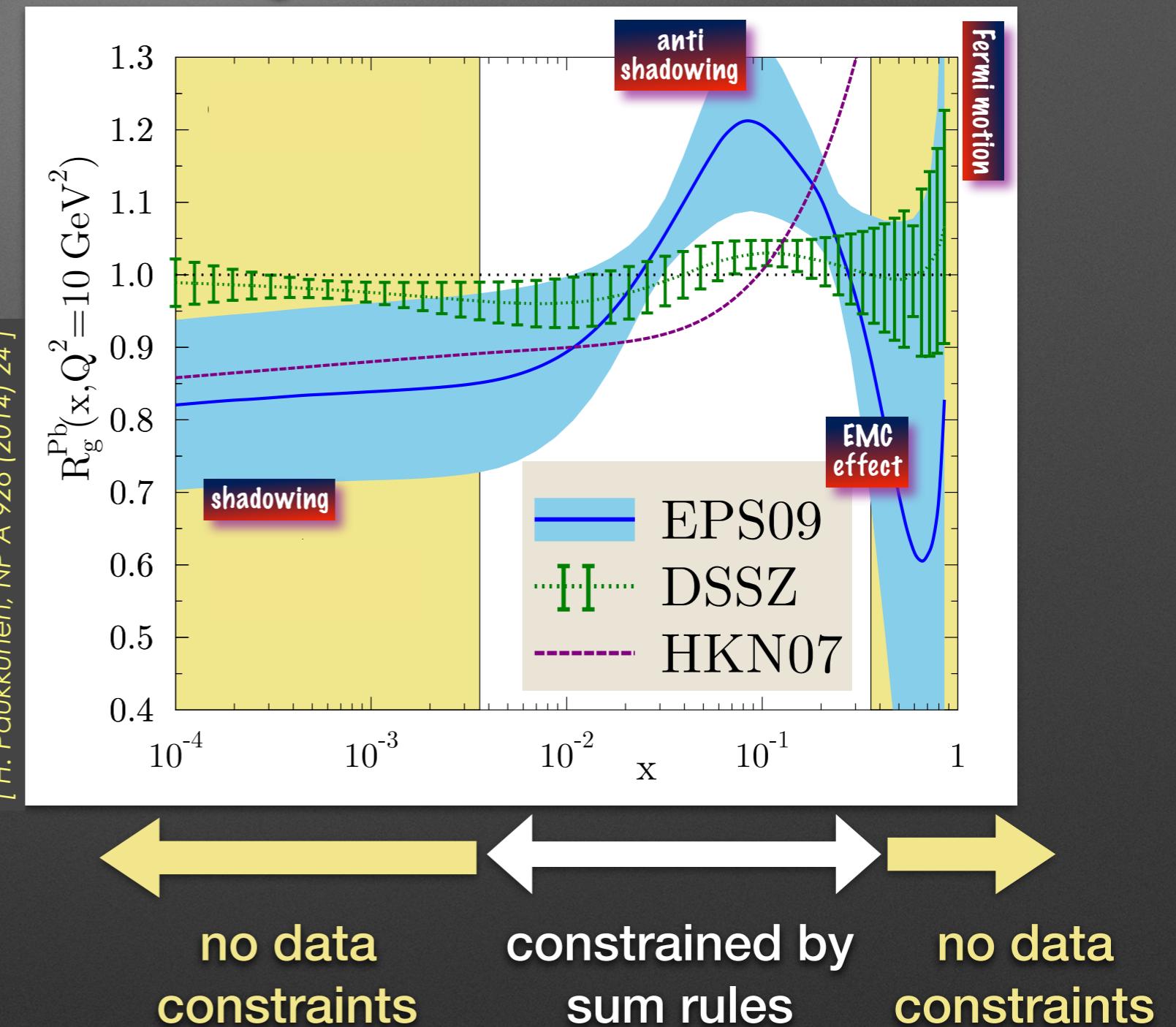
If  $g + g \rightarrow c\bar{c} (b\bar{b})$  then :

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



I SaporiGravis network, EPJ C76  
(2016) no.3, 107

At high scale, i.e.  $Q^2 = 10$  GeV $^2$

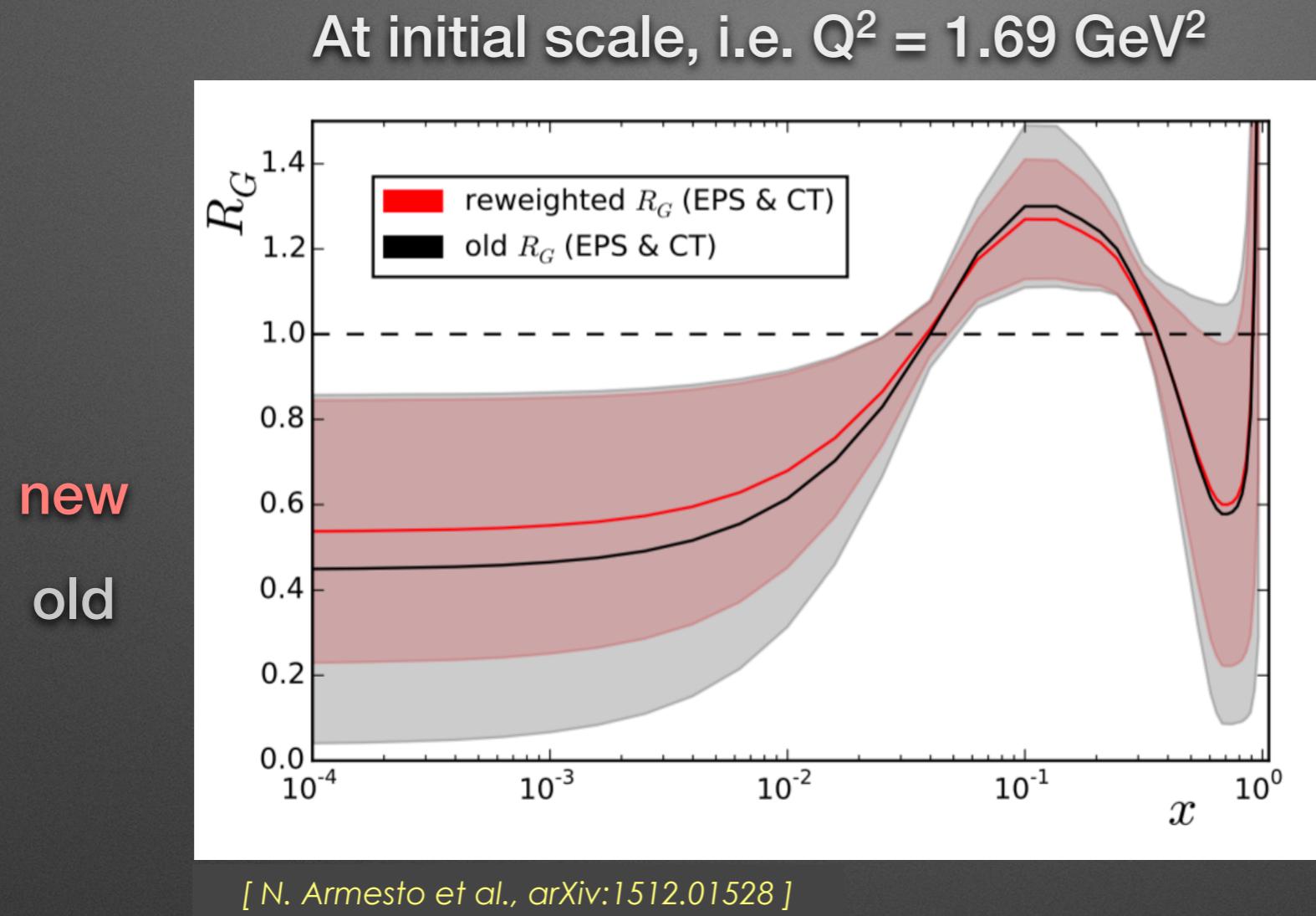


# Key characteristics of the nPDF fits

	HKN07	EPS09	DSSZ	NCTEQ
Order in $\alpha_s$	LO & NLO	LO & NLO	NLO	NLO
Neutral current DIS I+A/I+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p		✓	✓	
Neutrino-nucleus DIS			✓	
$Q^2$ cut in DIS	1 GeV	1.3 GeV	1 GeV	2 GeV
Datapoints	1241	929	1579	708
Free parameters	12	15	25	17
Error analysis	✓	✓	✓	✓
Error tolerance $\Delta\chi^2$	13,7	50	30	35
Free proton baseline PDFs	MRST98	CTEQ6.1	MSTW2008	CTEQ6M-like
Heavy quark treatment	ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS

all assuming that isospin symmetry holds for bound protons and neutrons,  
i.e.  $u^p = d^n$  and  $d^p = u^n$

# Impact of LHC Run 1 data on the gluon nPDF EPS09 in Pb nucleus

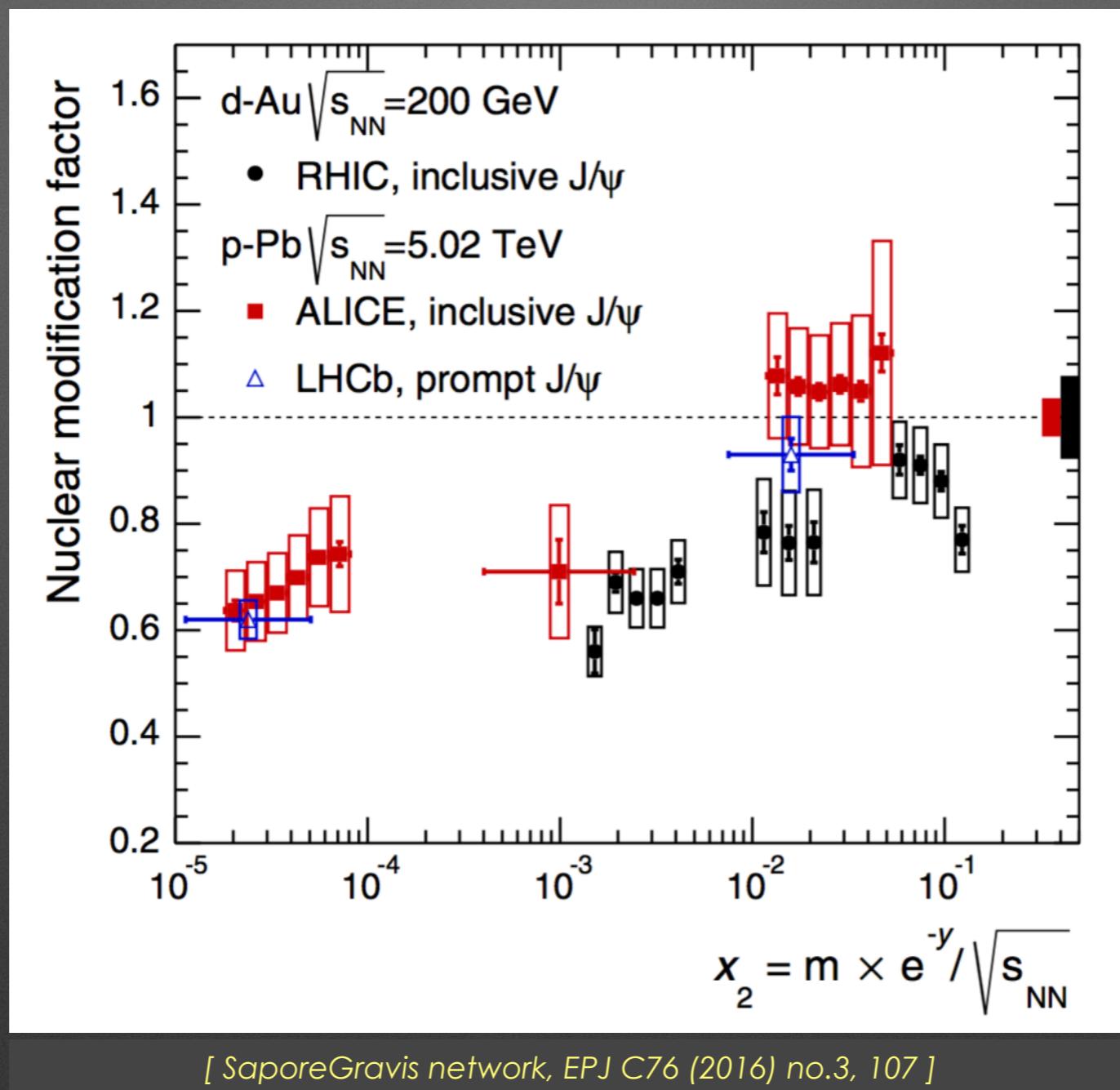


According to the authors, this « study should be seen [...] as a preparatory work towards nPDFs analyses including LHC data ».

Updated gluon nPDF : most effective new constraints from CMS dijet p-Pb data

[ CMS, EPJ C 74 (2014) 7, 2951 ]

# J/ $\psi$ production at RHIC and LHC



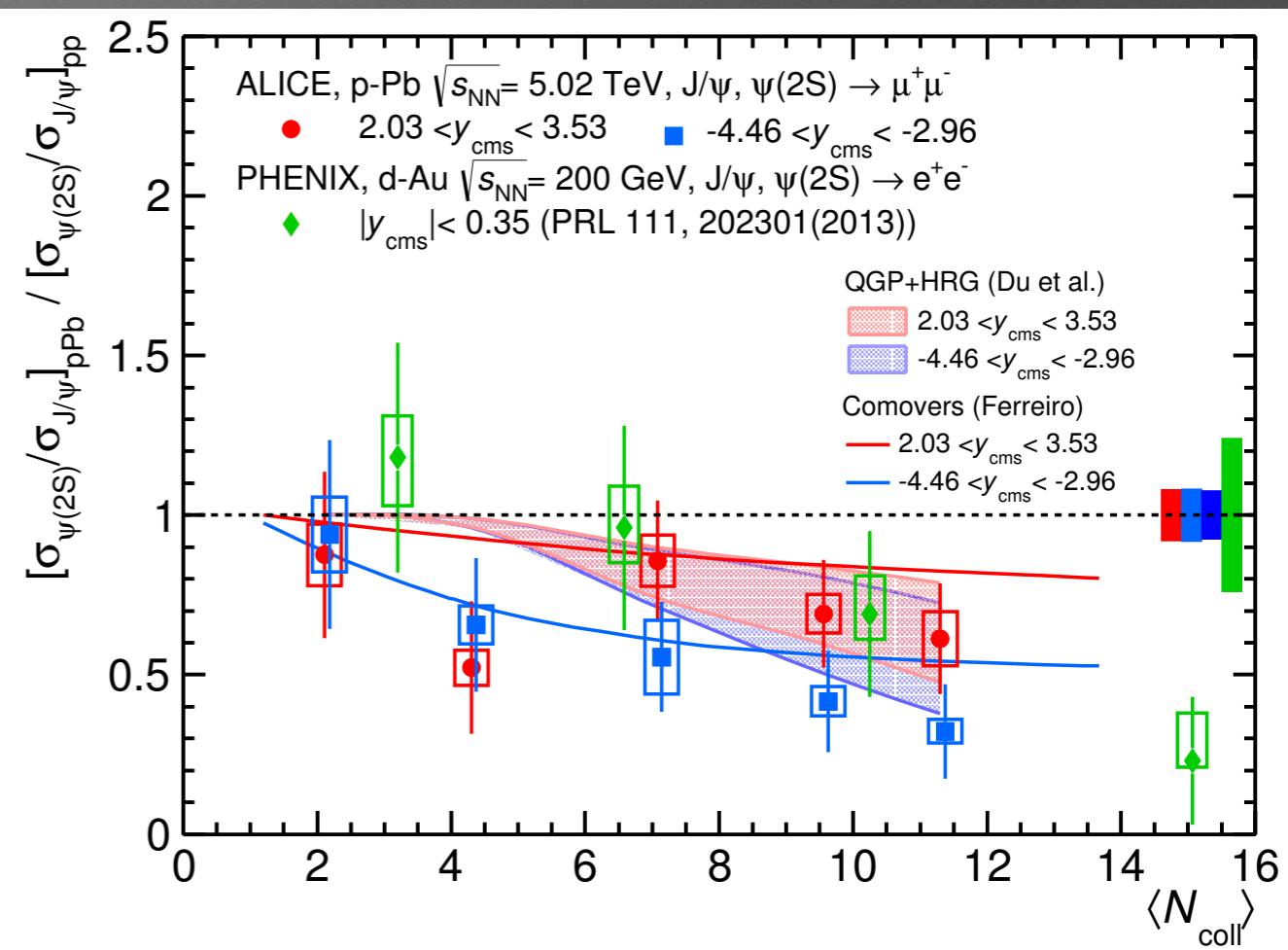
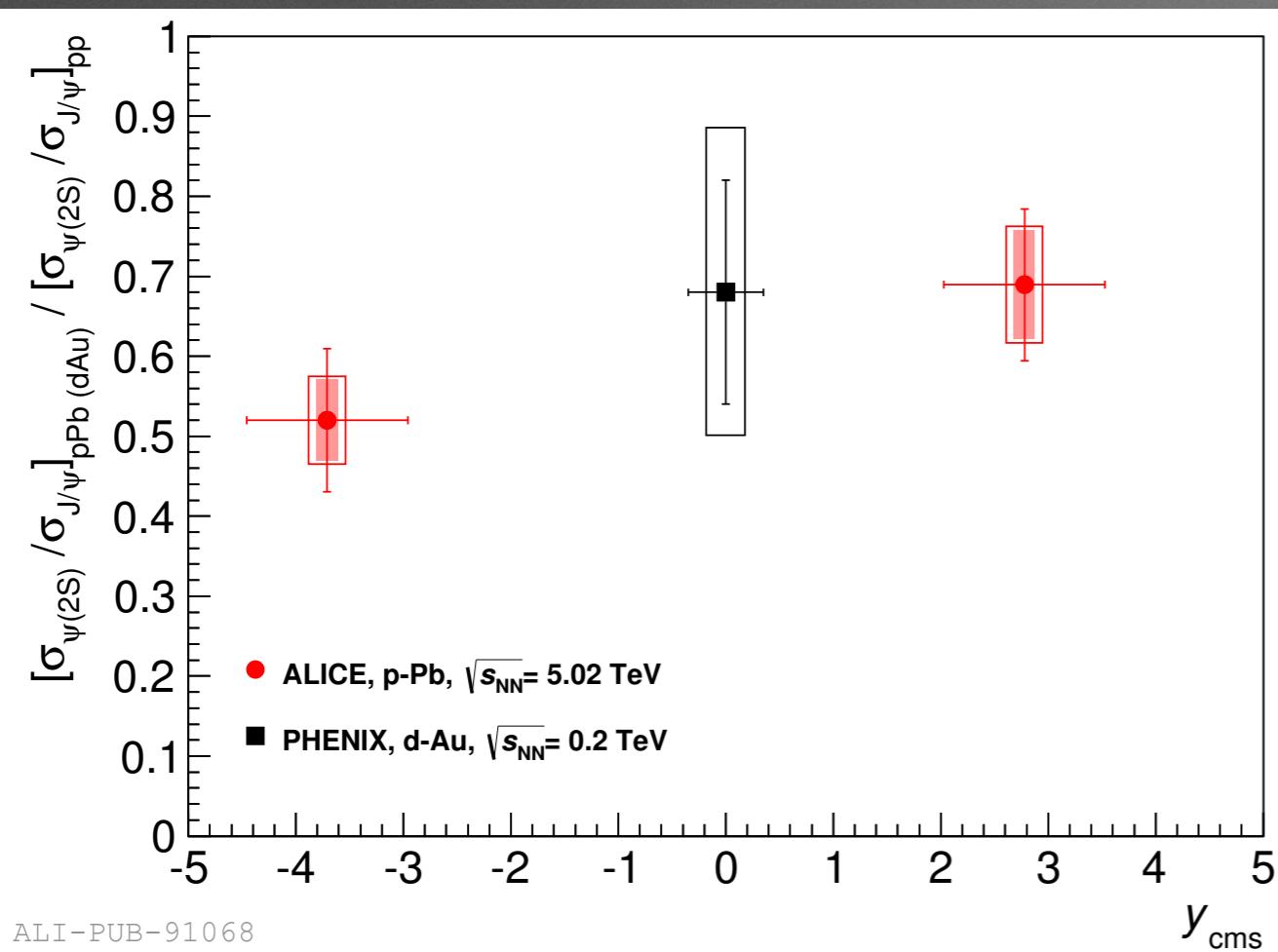
Summary plot with a juxtaposition of RHIC and LHC data using their resp. estimated x-coverage

# $\Psi(2S)$ production at RHIC and LHC

Double ratio pA/pp

Rapidity

Centrality



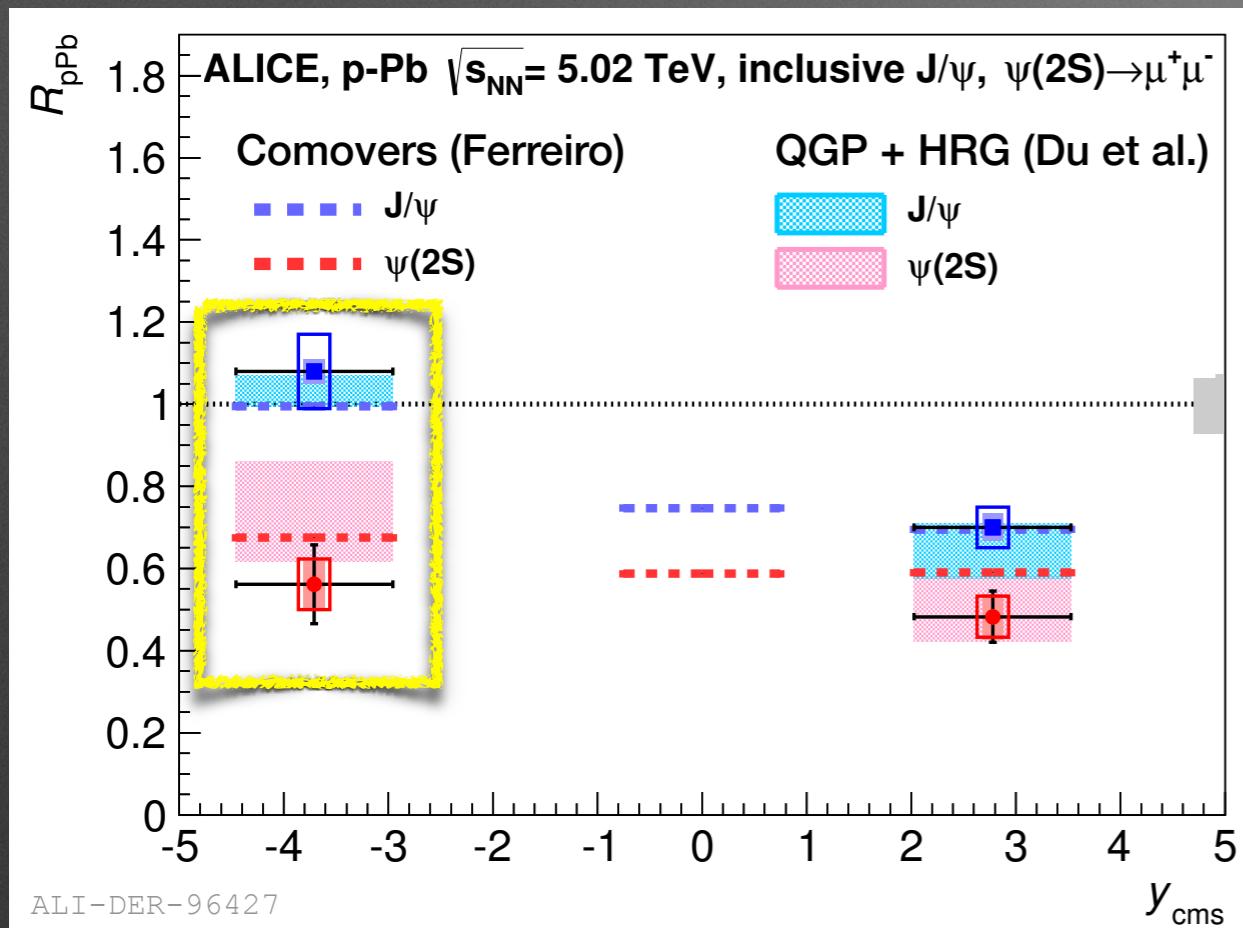
[ ALICE, JHEP 12 (2014) 073 ]

[ ALICE, arXiv:1603.02816 ]

# Production of different charmonium states in p-Pb collisions

$\Psi(2S)$  vs  $J/\psi$

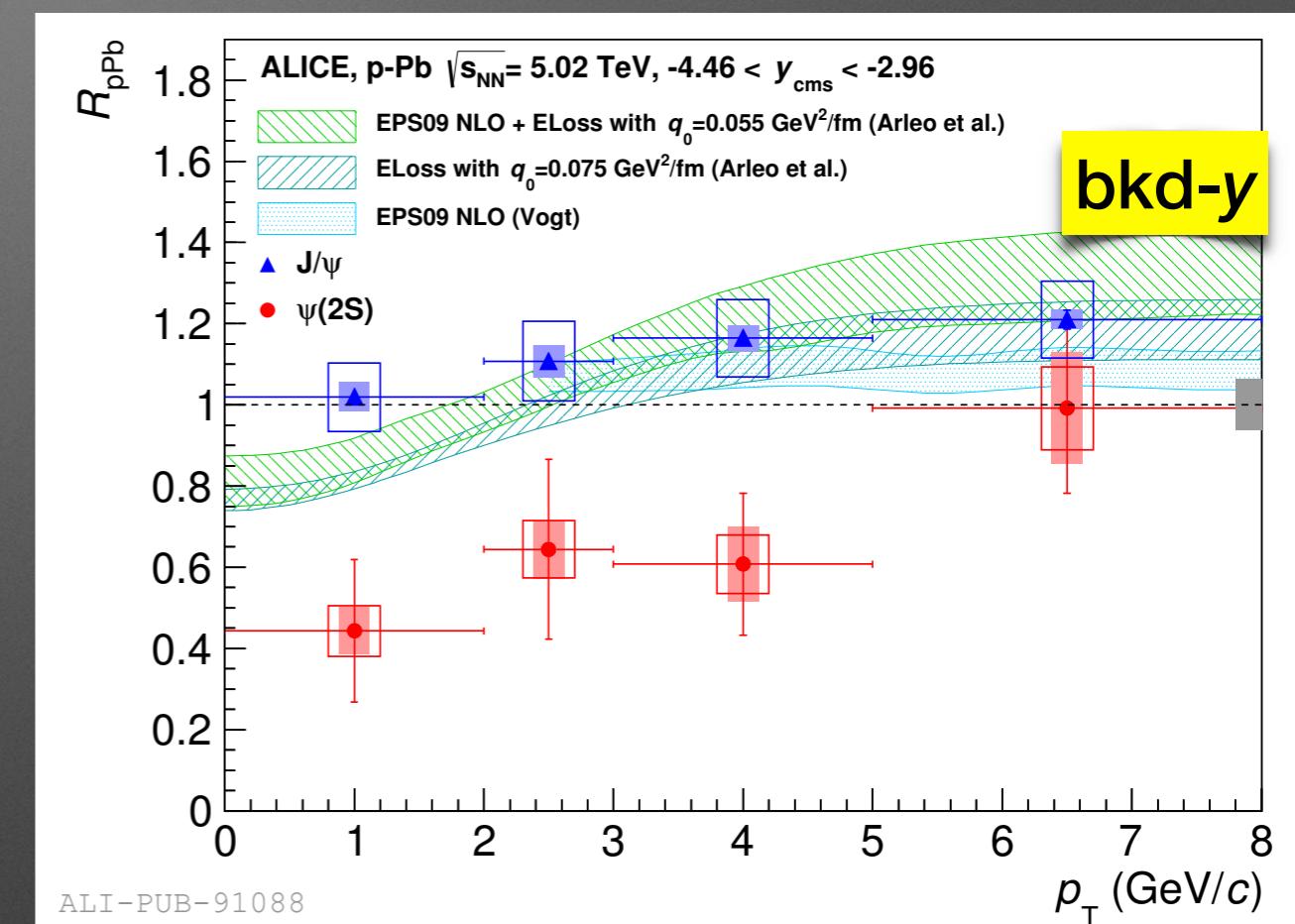
Rapidity



[ Ferreiro, PLB 749 (2015) 98 ]

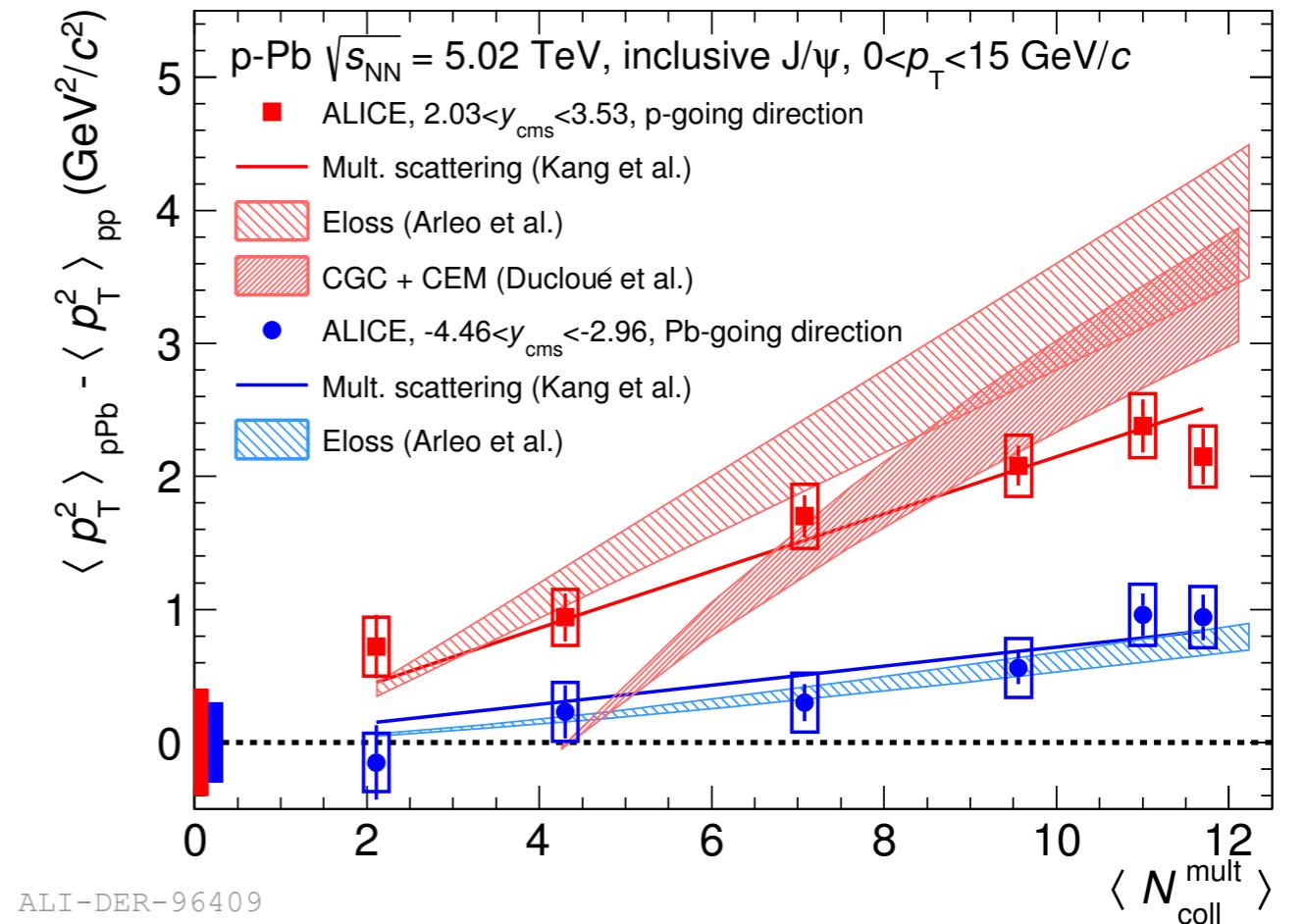
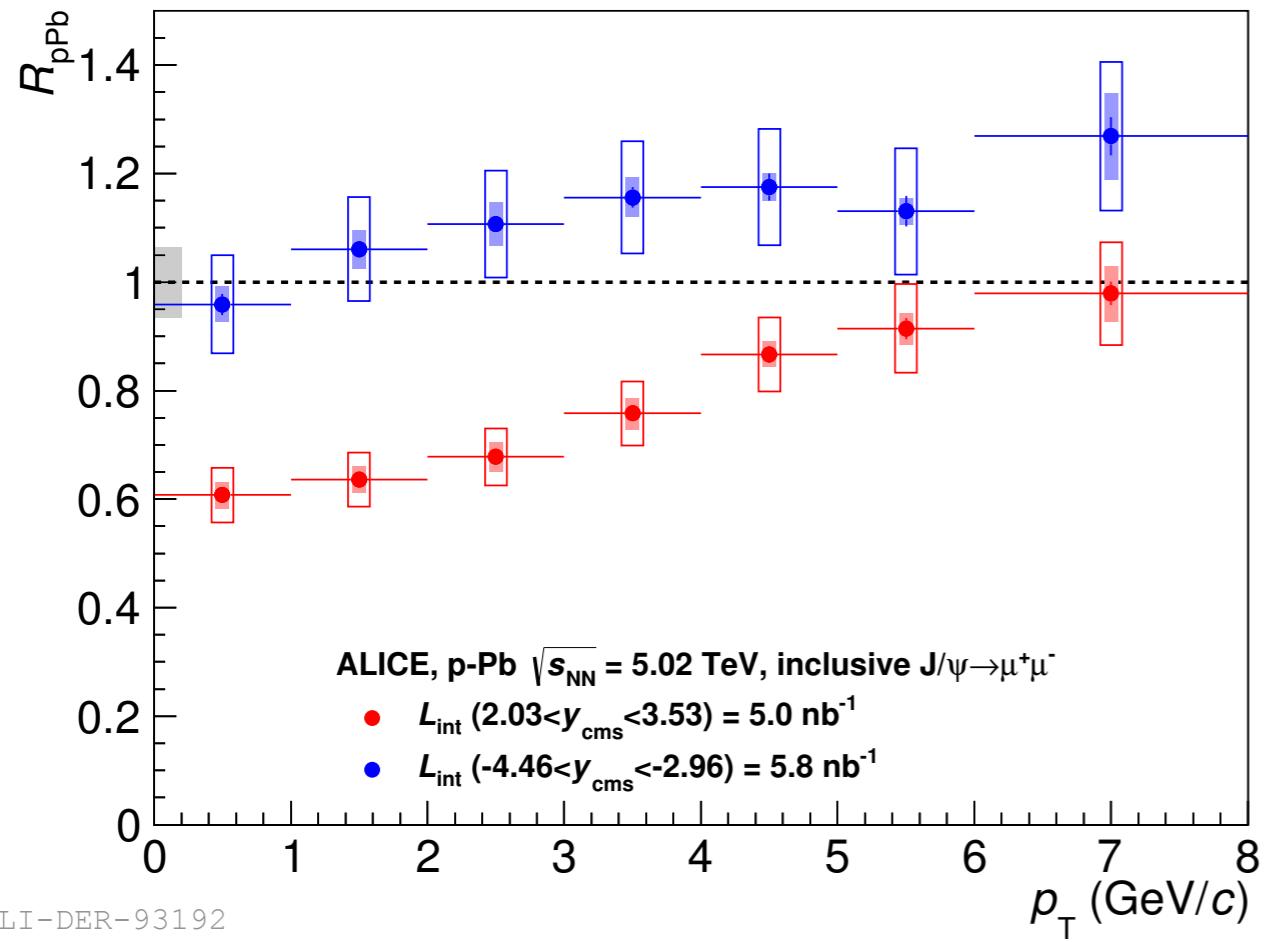
[ Du et al., NPA 943 (2015) 147 ]

Transverse momentum



[ ALICE, JHEP 12 (2014) 073 ]

# Inclusive $\text{J}/\psi$ – $p_{\text{T}}$ dependence in p-Pb collisions



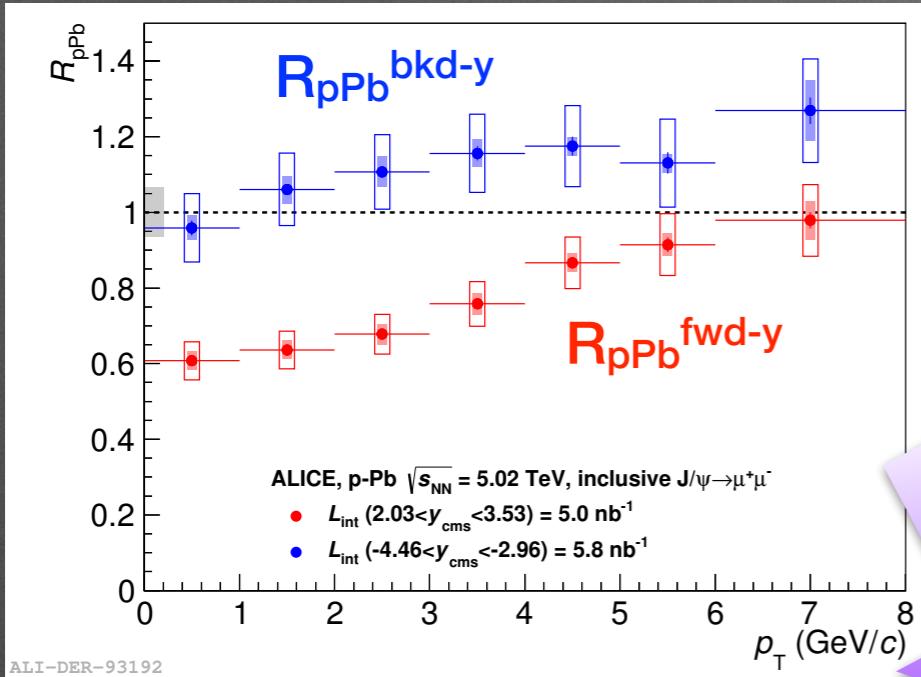
[ ALICE, JHEP 06 (2015) 055 ]

[ Arleo et al., JHEP 1303 (2013) 122 ]

[ Ducloué et al., PRD 91 (2015) 114005 ]

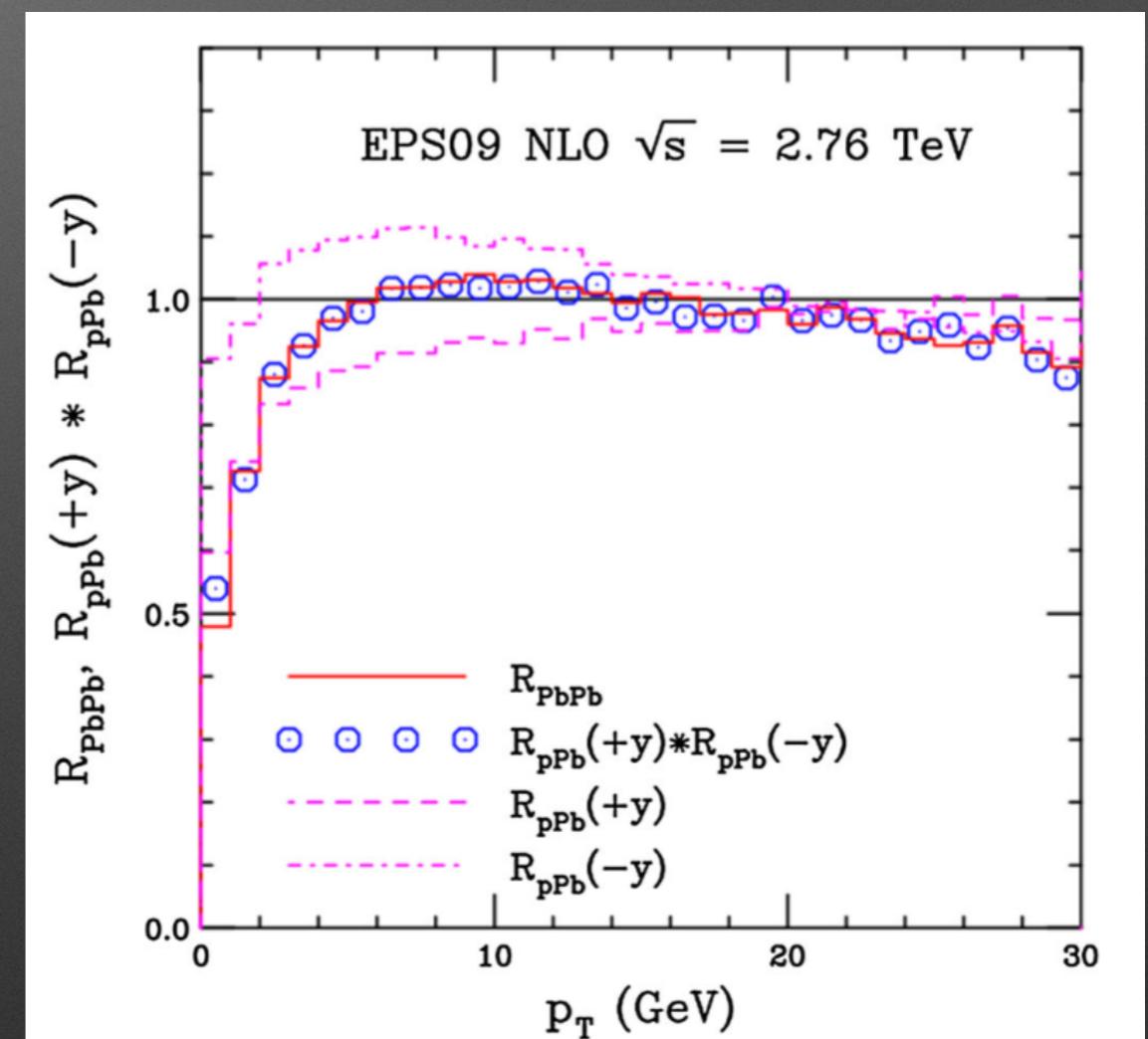
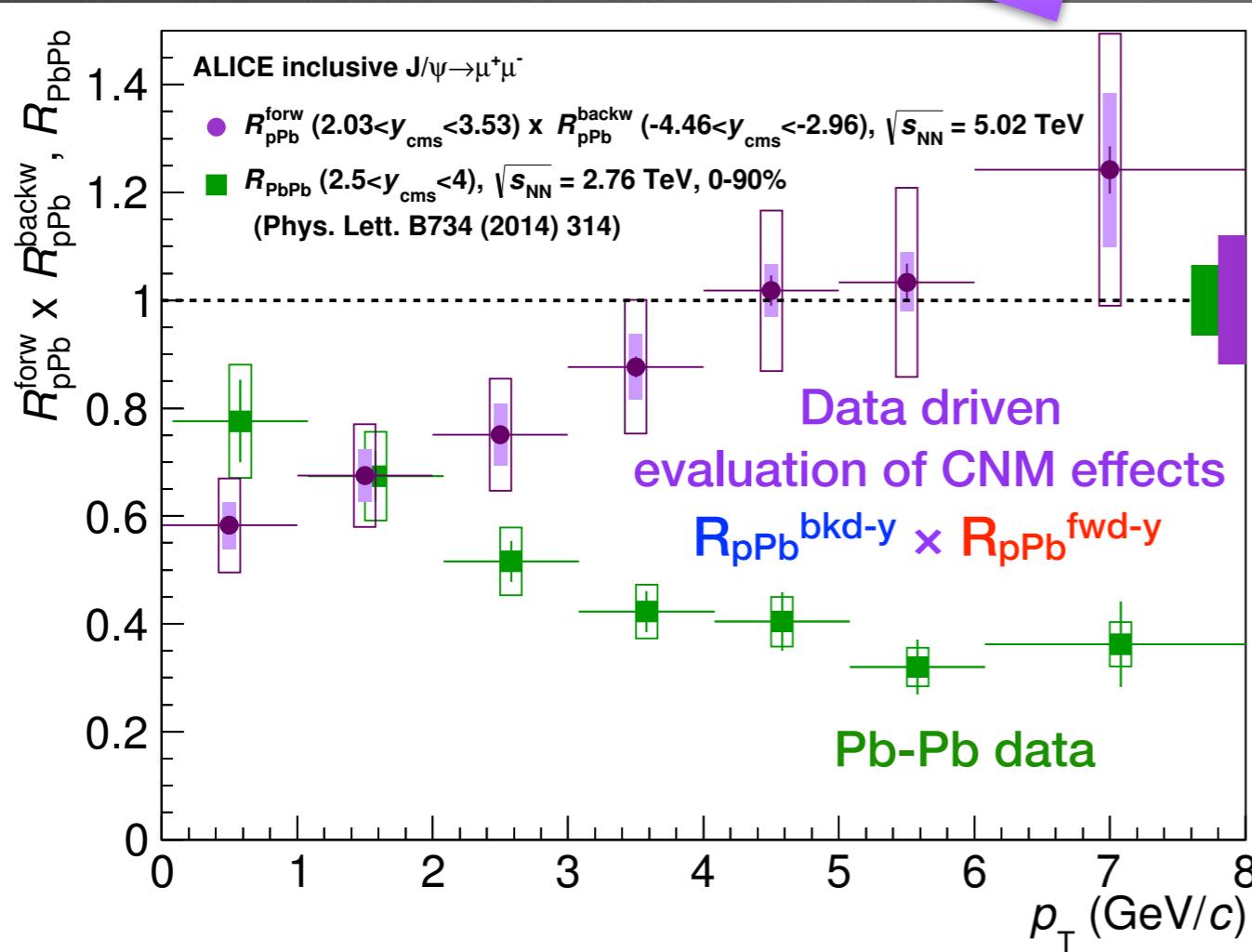
[ Kang et al., JHEP 1303 (2013) 122 ]

# Using $R_{pA}$ to infer $R_{AA}$



data

model

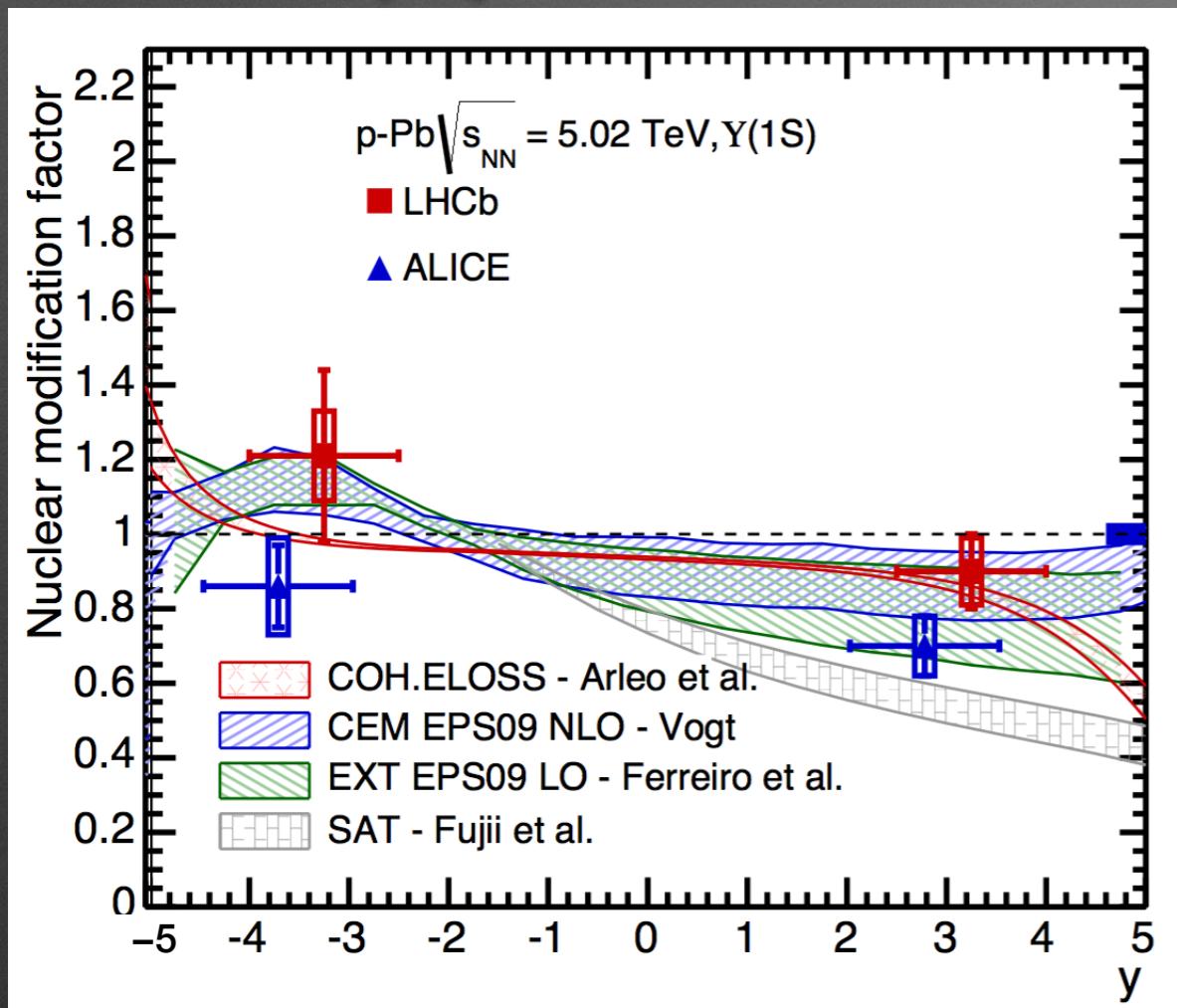


[ ALICE, JHEP 06 (2015) 055 ]

[ Vogt, PRC 92 (2015) 034909 ]

# $\Upsilon$ production in p-Pb @ 5 TeV

$\Upsilon(1S)$  ALICE vs LHCb

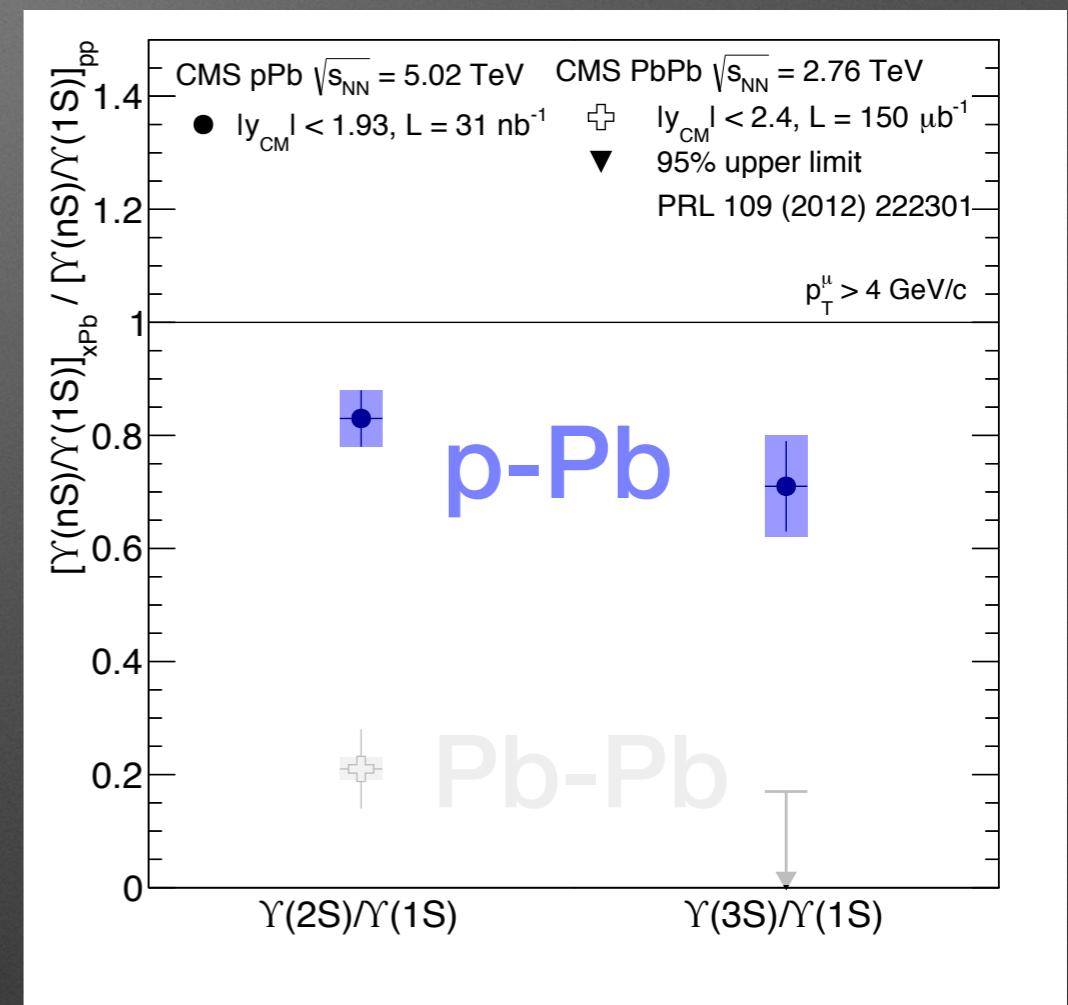


[ SaporeGravis network, EPJ C76 (2016) no.3, 107 ]

[ LHCb, JHEP 07 (2014) 084 ]

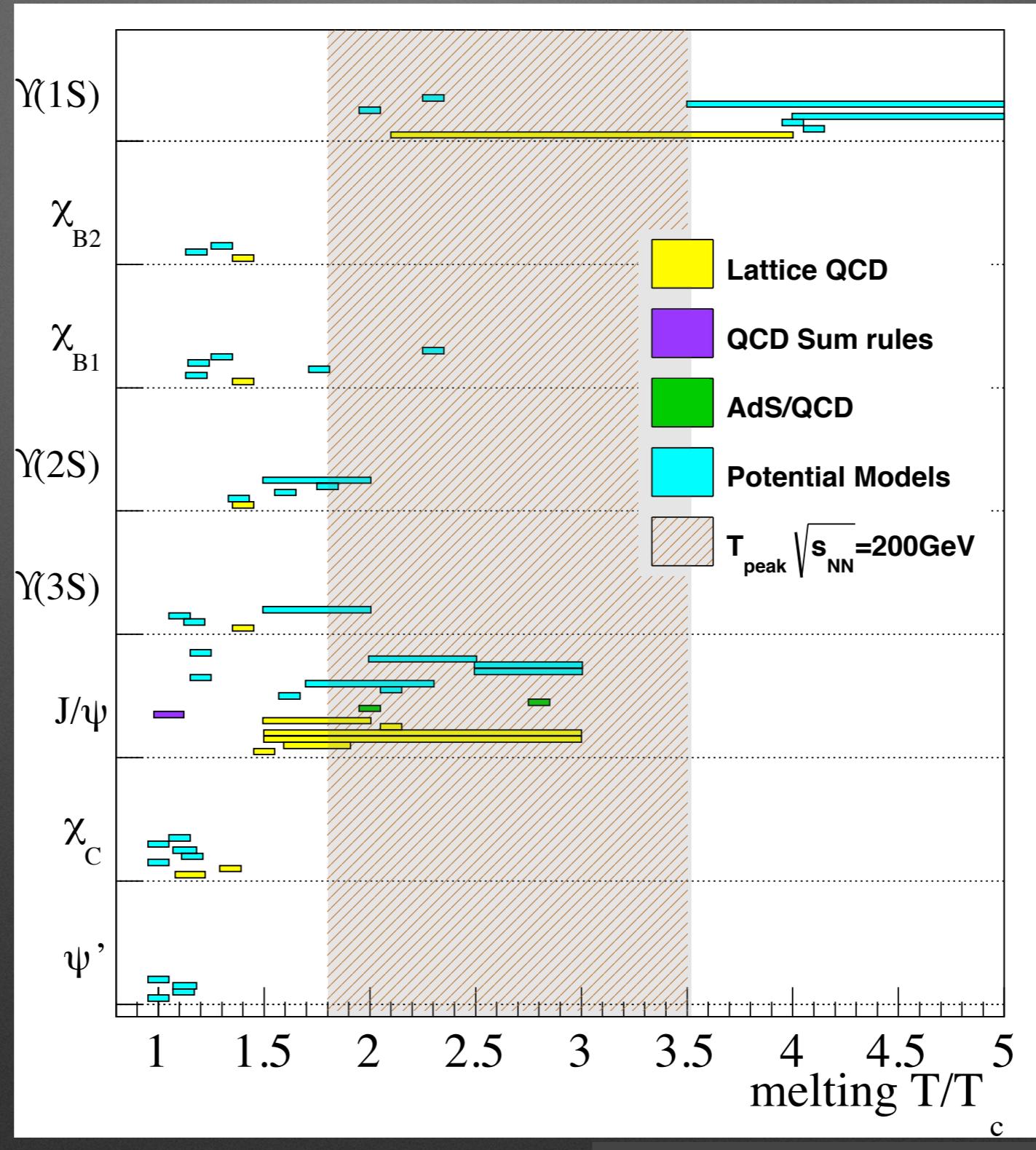
[ ALICE, PL B 740 (2015) 105 ]

$\Upsilon(2S)$  and  $\Upsilon(3S)$  compared to  $\Upsilon(1S)$

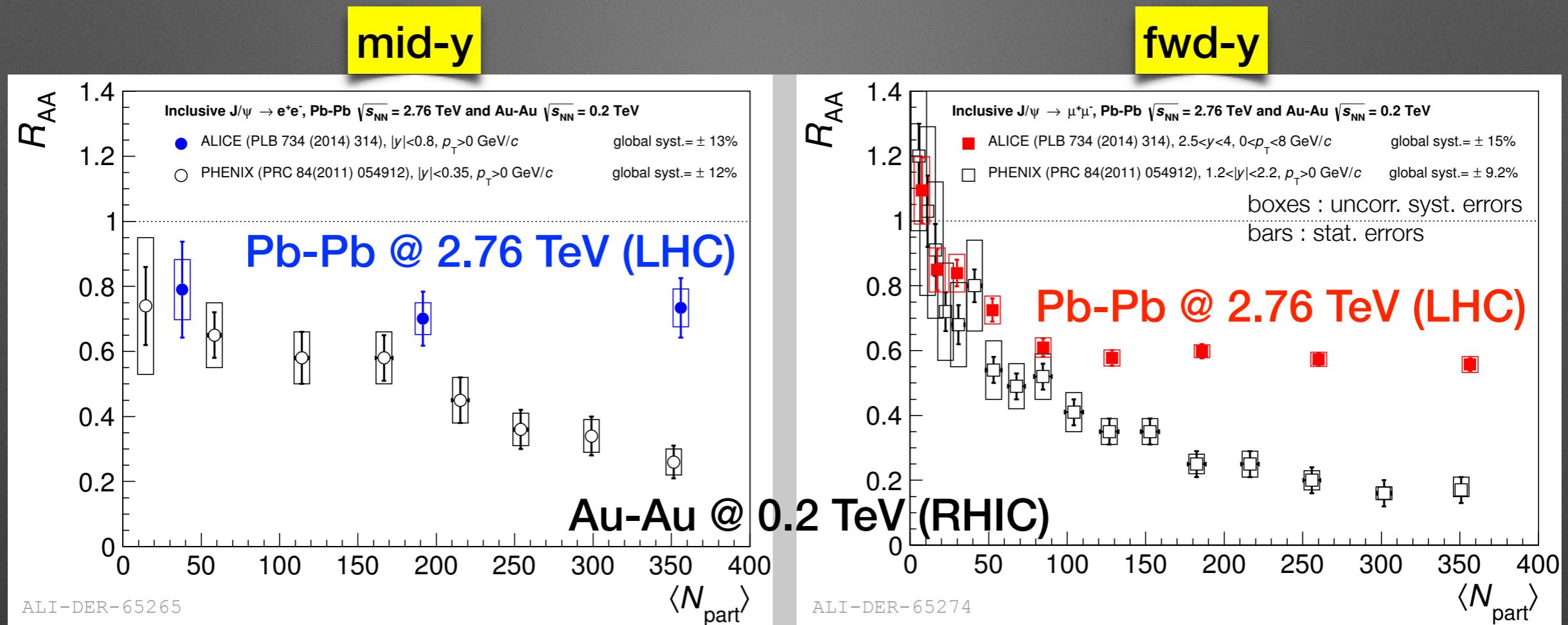


[ CMS, JHEP 04 (2014) 103 ]

# Uncertainties on the dissociation temperature

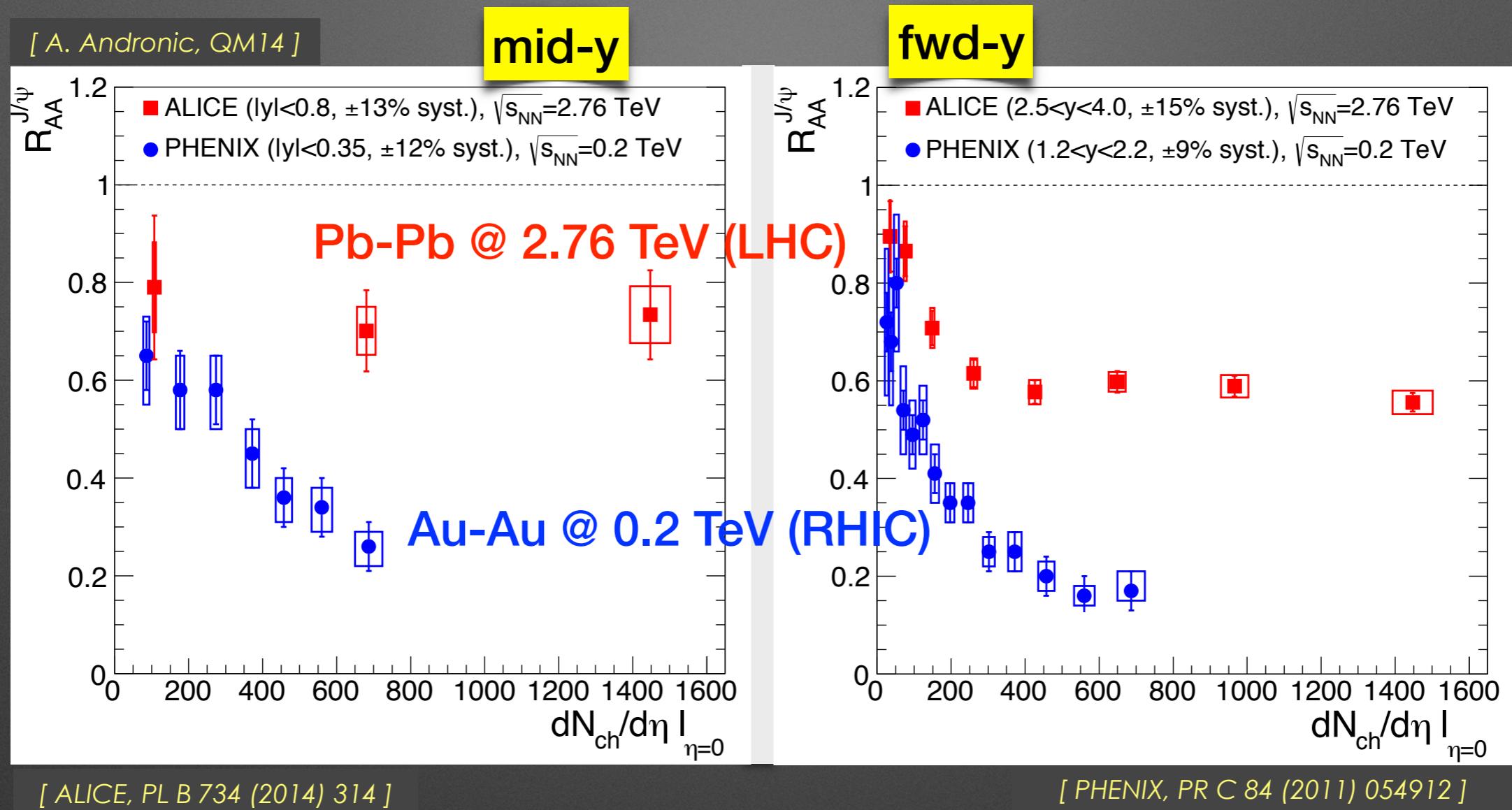


# At LHC : higher $\epsilon$ , but less suppression of inclusive J/ $\psi$



- > Max  $\langle N_{\text{part}} \rangle$  is ~ same at LHC and RHIC
- ⇒ probably not the most meaningful variable for LHC/RHIC comparison
- > At LHC, the (presumably) larger suppression from color screening at higher  $\epsilon$  is compensated by a sizeable regeneration ?

# LHC vs RHIC : highlighting the difference in $\epsilon$



- $R_{AA}$  of inclusive  $J/\psi$  vs the measured  $dN_{ch}/d\eta$  in each centrality bin
- $dN_{ch}/d\eta$  better reflects the reach in  $\epsilon$

# Going further to test the J/ $\psi$ regeneration

fwd-y

Transport Models (mainly differ in the rate equation)

TM1 : all J/ $\psi$

TM2 : all J/ $\psi$

TM2 : Regenerated J/ $\psi$

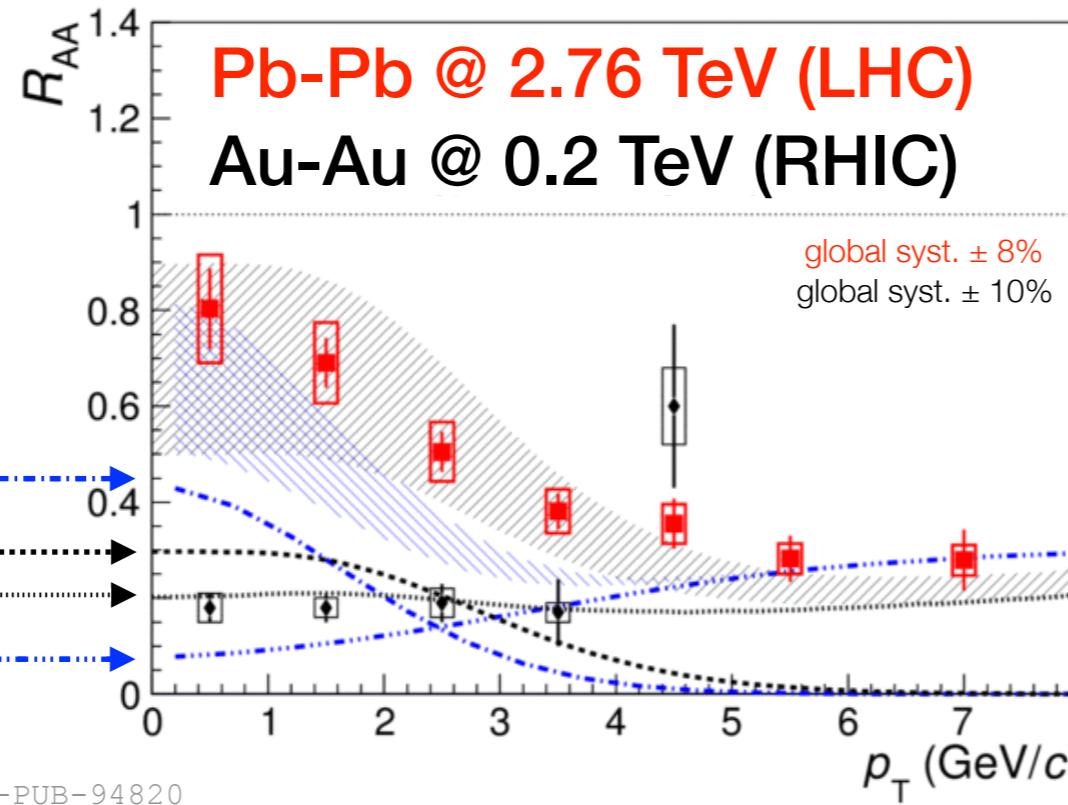
TM1 : Regenerated J/ $\psi$

TM1 : Primordial J/ $\psi$

TM2 : Primordial J/ $\psi$

centrality 0-20%

centrality 40-90%

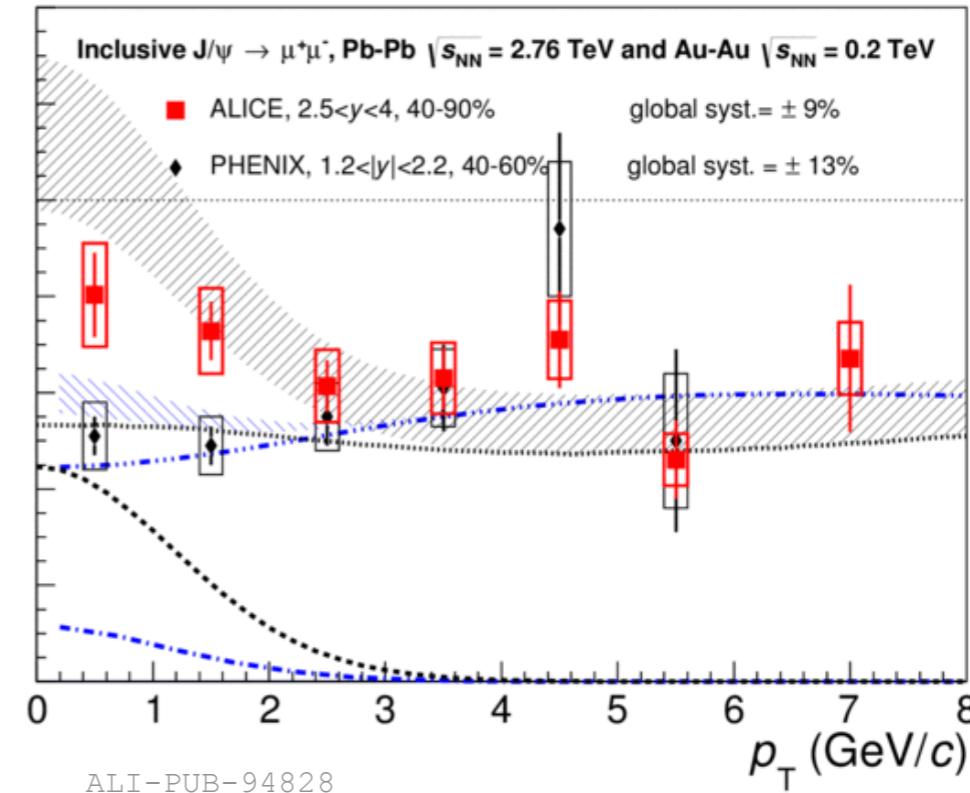


[ TM1 : X. Zhao and R. Rapp, NP A 859 (2011) 114 ]

[ TM2 : K. Zhou et al., PR C 89 (2014) 054911 ]

[ ALICE, arXiv:1506.08804 ]

[ PHENIX, PR C 84 (2011) 054912 ]



When going to more central collisions, the  $p_T$  dependence seen at LHC energy clearly differs from the one measured at lower energy.

Most central collisions at LHC :  $R_{AA}$  increases with decreasing  $p_T$ , which could be explained by the growing # of regenerated J/ $\psi$  with centrality, essentially produced at low  $p_T$ .

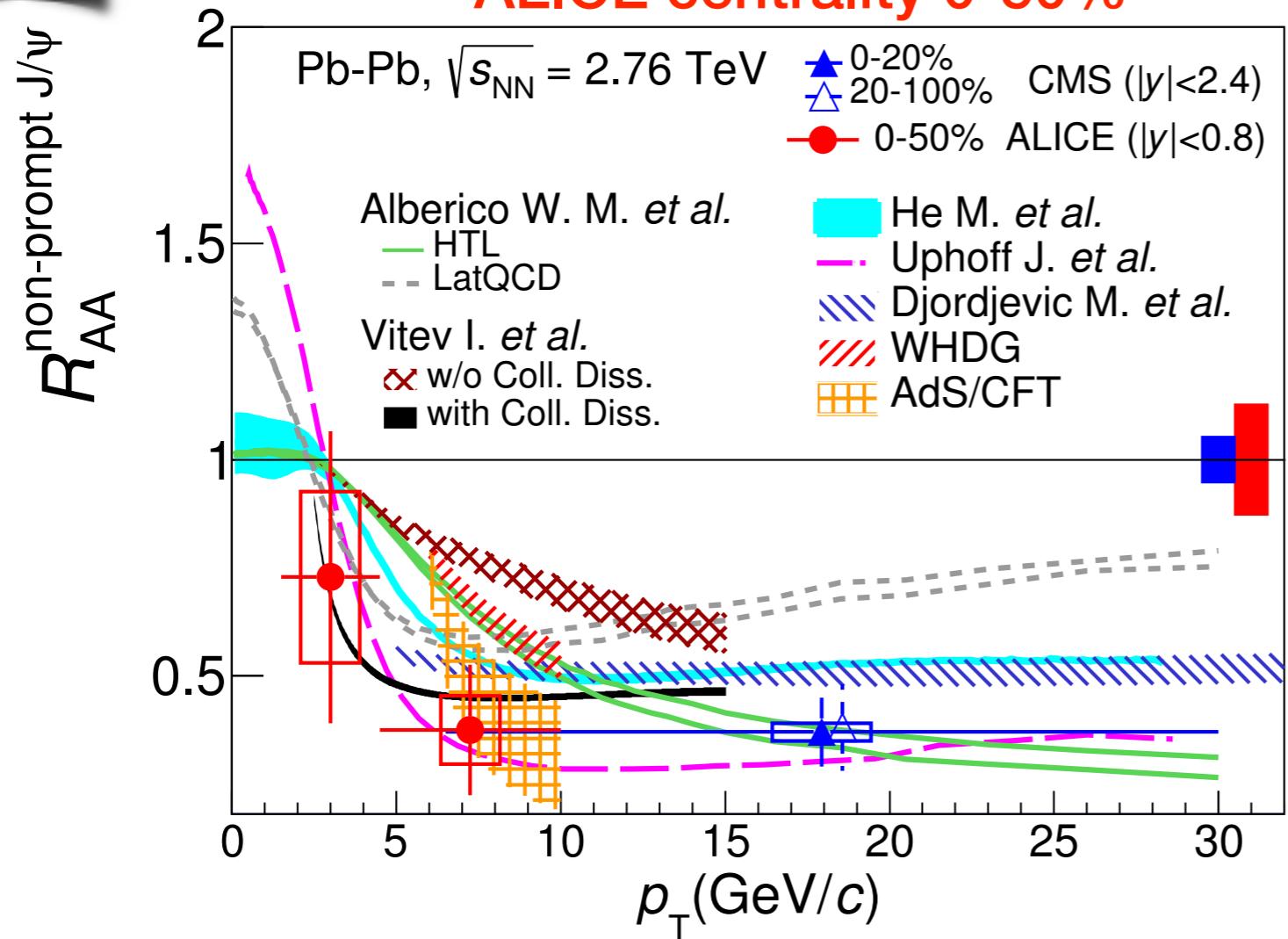
According to the models, high  $p_T$  J/ $\psi$  should be dominated by primordial J/ $\psi$ .

# Non-prompt J/ $\psi$ measurement in ALICE

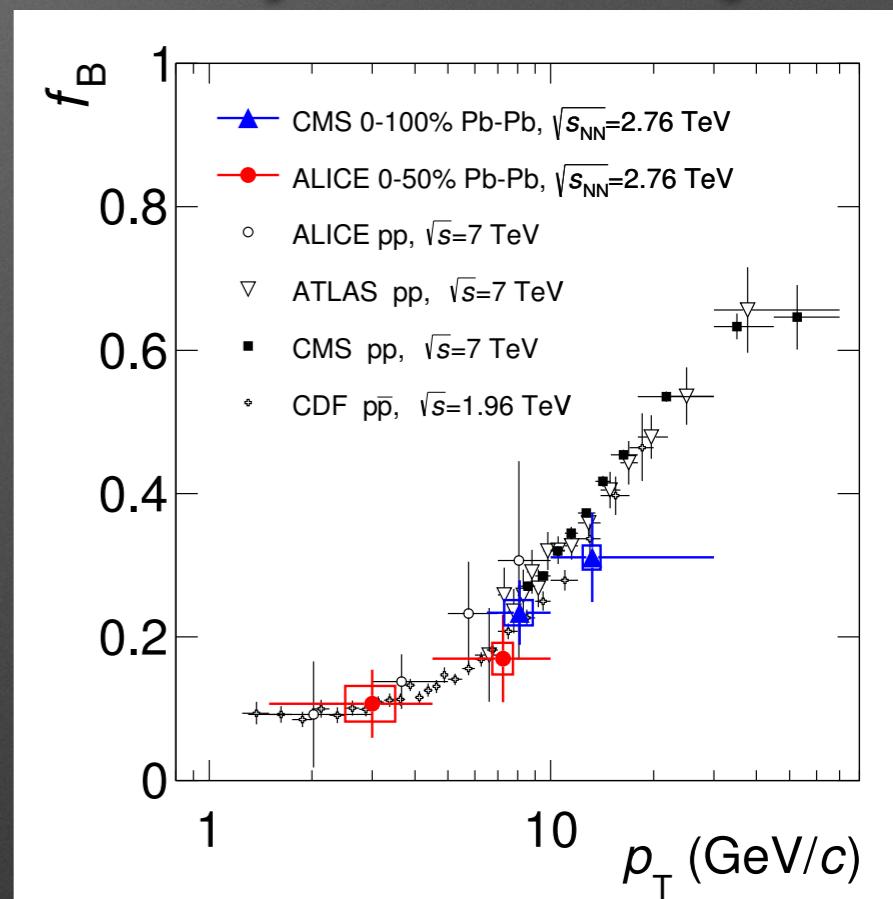
Pb-Pb @ 2.76 TeV : J/ $\psi$   $\longleftrightarrow$  B

mid-y

ALICE centrality 0-50%



Fraction of J/ $\psi$  from beauty hadron decays



[ ALICE, JHEP 07 (2015) 051 ]

Access to the b-quark energy loss in the hot medium, before hadronisation into J/ $\psi$