INT Program INT-17-1b

Precision spectroscopy of QGP properties with jets and heavy quarks

May 31st 2017

Quarkonium production in proton-nucleus collisions

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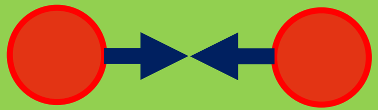
Quarkonium production in

- p-p (at LHC)
- p-A collisions (at both RHIC and LHC)

quarkonium in pp, pA, AA

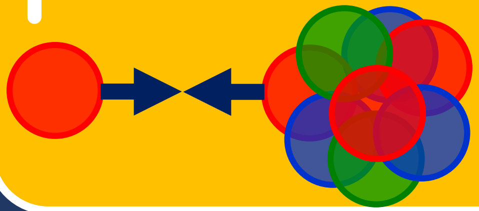
p-p

"vacuum" reference for AA, pA, genuine pp physics program



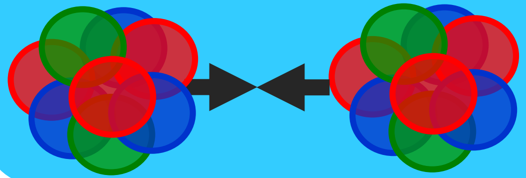
p-A

cold nuclear matter effects: shadowing/CGC, energy loss…



A-A

hot matter effects: regeneration vs suppression



Nuclear modification factor:

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA}\rangle \sigma_{pp}^{J/\psi}}$$

Medium effects quantified comparing AA (pA) quarkonium yield with the pp cross section, scaled by a geometrical factor (from Glauber model)

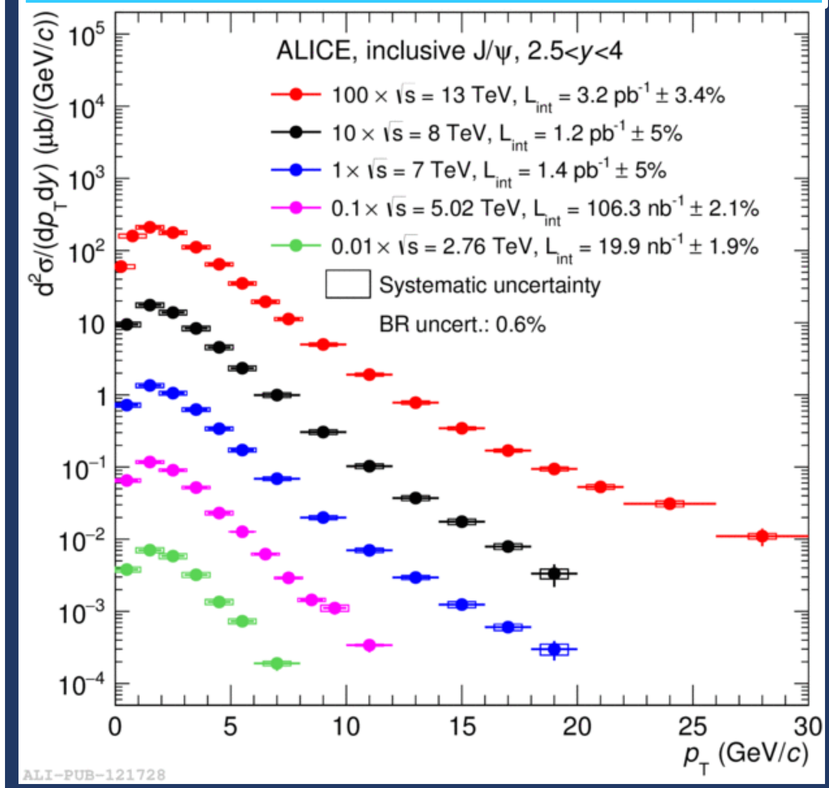
- no medium effects → $R_{AA} = 1$
- hot/cold matter effects → $R_{AA} \neq 1$

p-p collisions

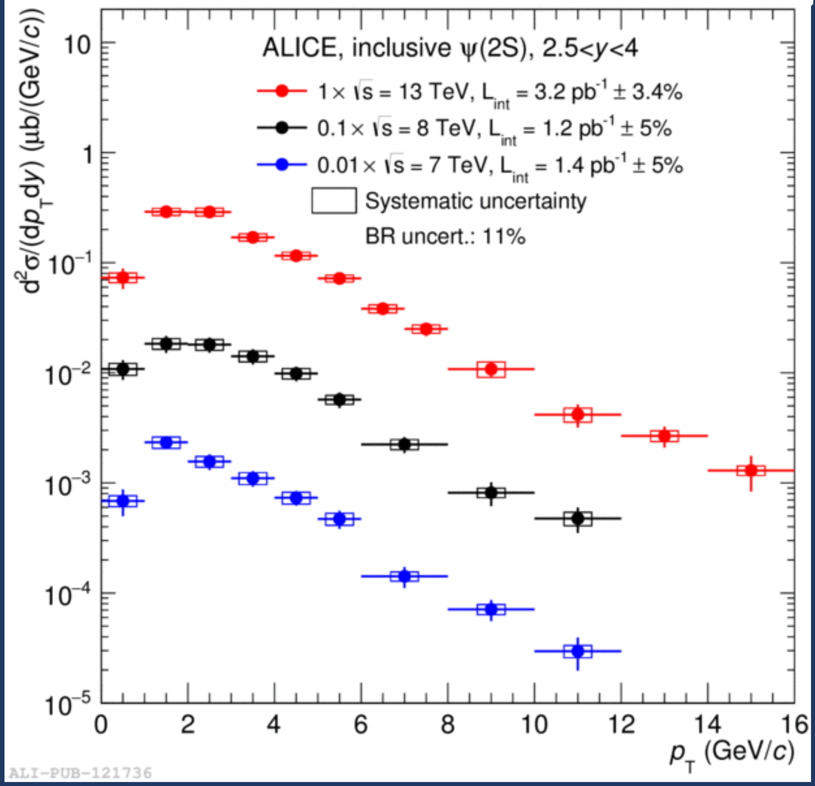
J/ψ production in pp collisions at LHC

➡ Focussing just on LHC results…RHIC covered in Zebo's talk!

J/ψ



ψ(2S)



➡ Quarkonium production now measured at LHC in many collision systems

√s(TeV)	2.76	5	7	8	13
pp	X	X	X	X	X

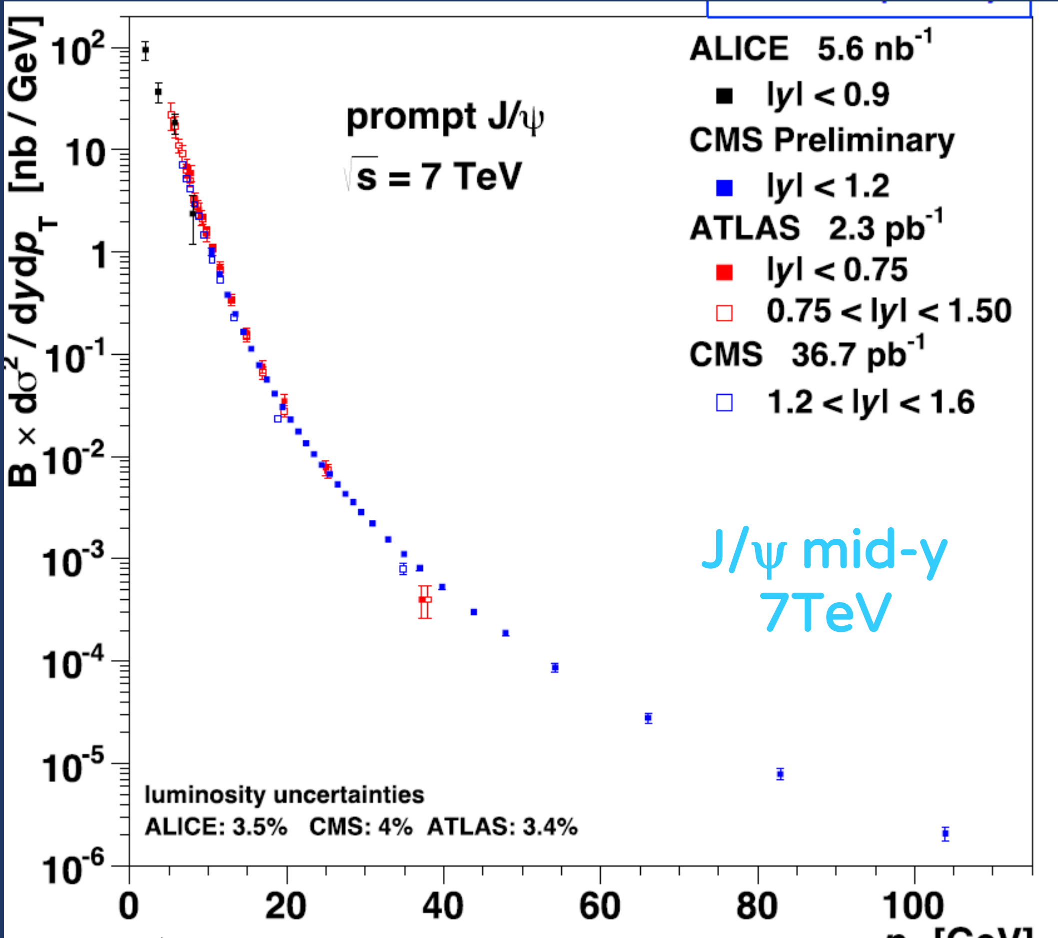
➡ not exhaustive selection of results on:

- y , p_T differential cross sections
- Double ratios
- Non prompt J/ψ fraction
- Self-normalized yields vs event multiplicity

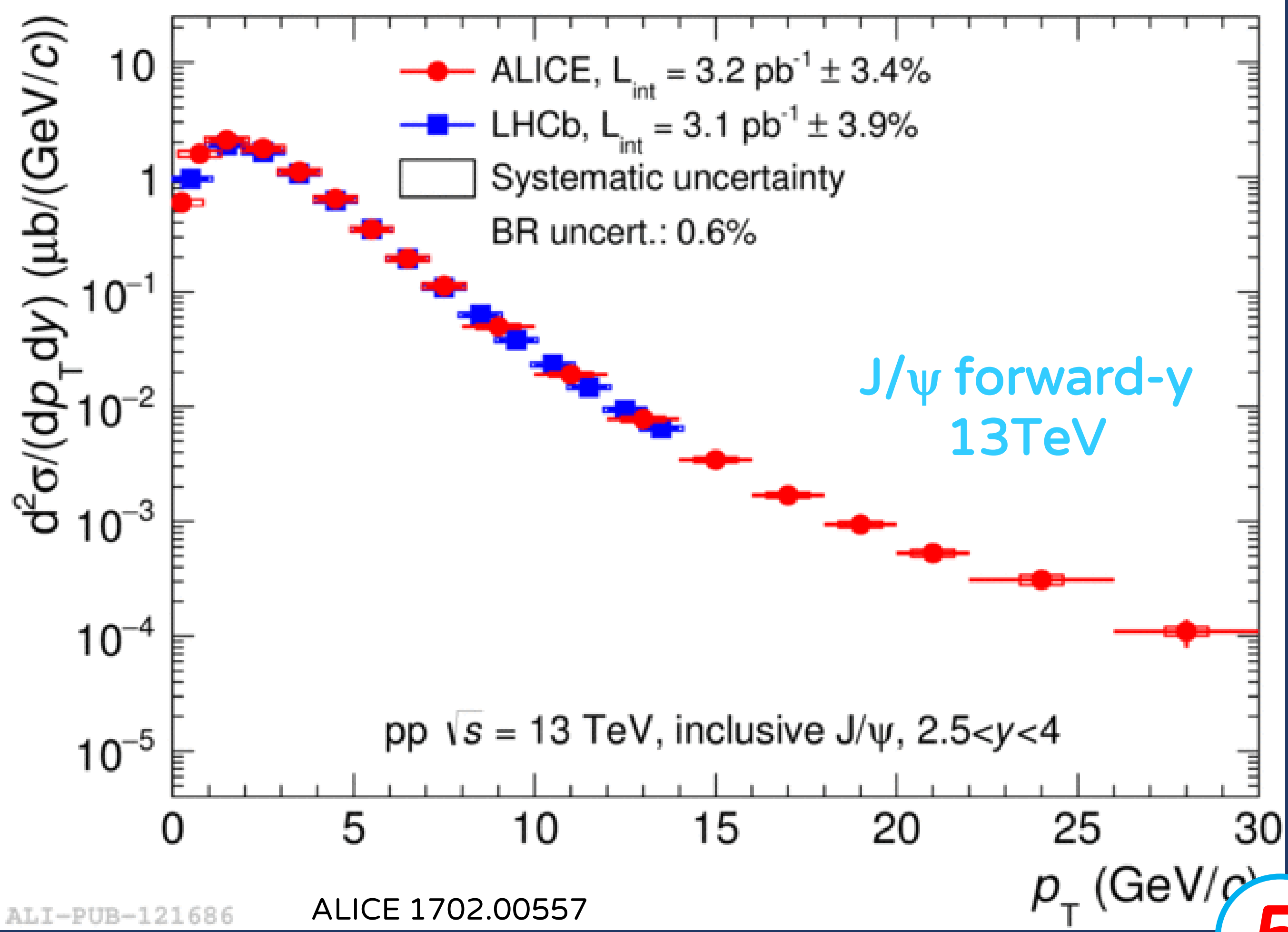
4

Comparison between experiments

➡ usually, good agreement between experiments in common kinematic regions
→ no hint for significant discrepancies



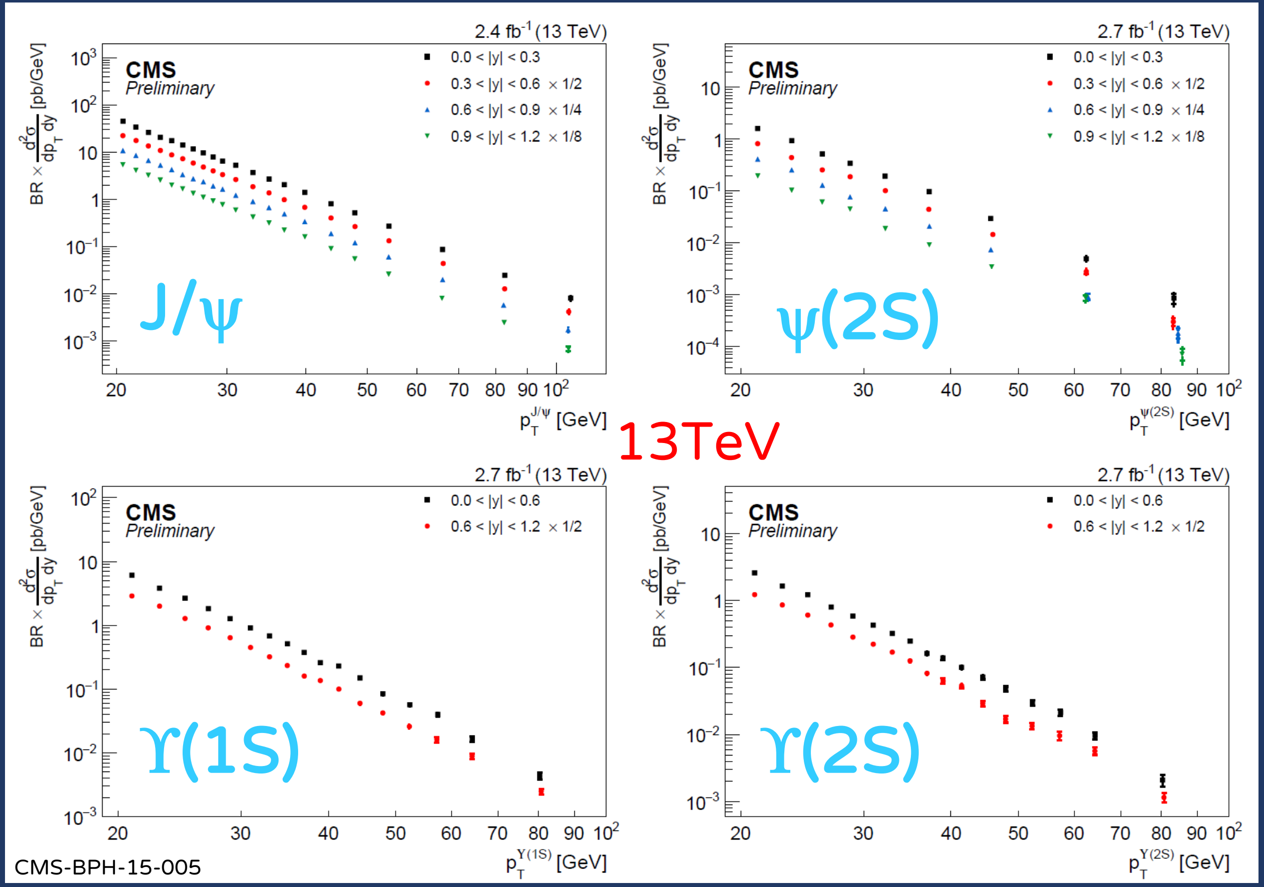
H. Woehri, QWG14

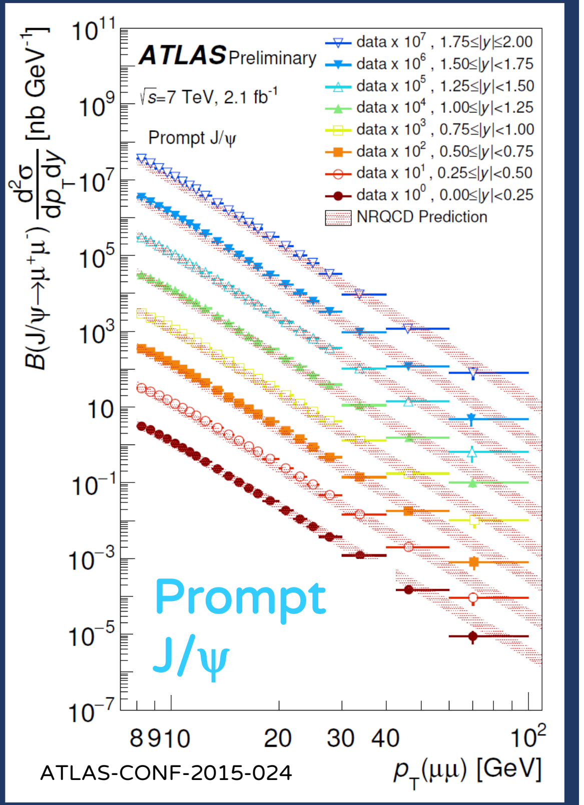


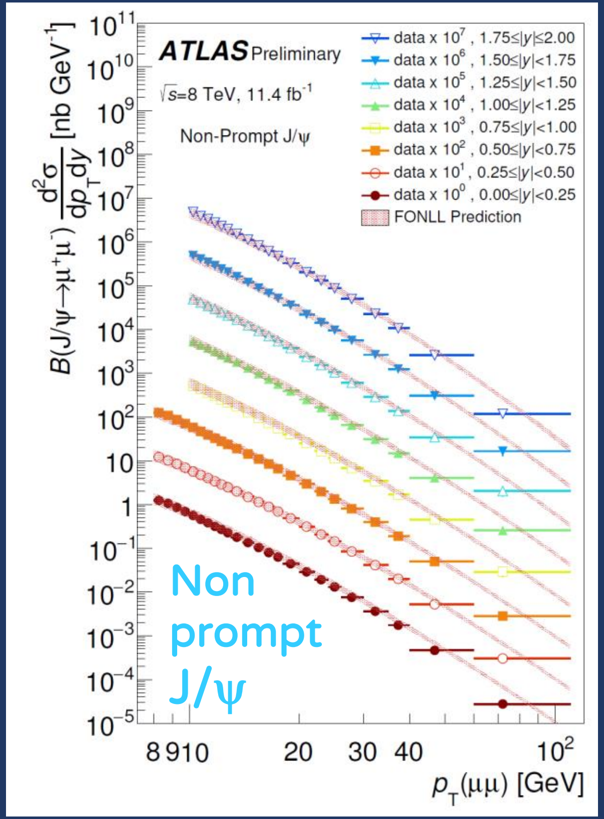
ALICE 1702.00557

Quarkonium p_T cross sections

➡ p_T range significantly extended by CMS and ATLAS measurements → up to 120 GeV!



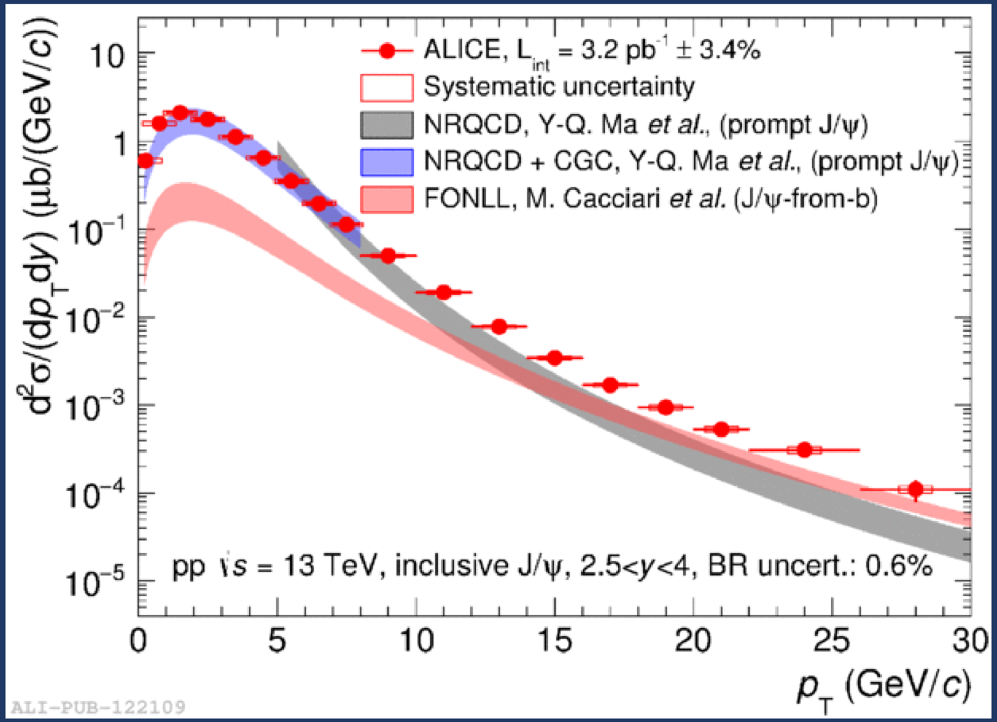


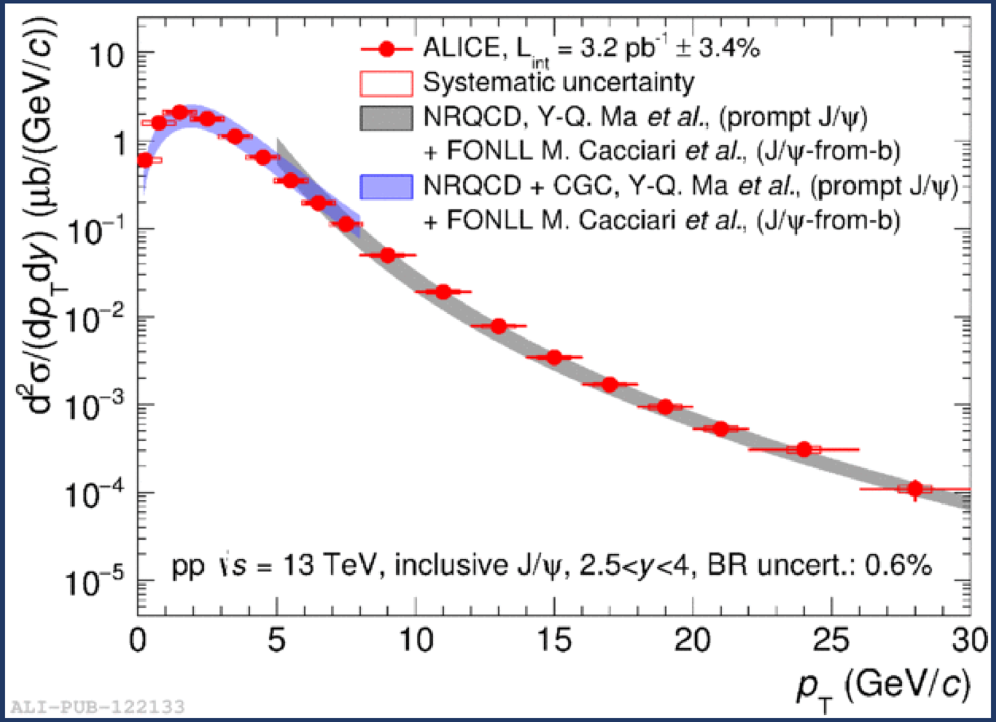


- NLO NRQCD describes prompt J/ψ production
- FONLL describes non-prompt contribution, but gives slightly harder p_T spectra

Inclusive J/ψ production

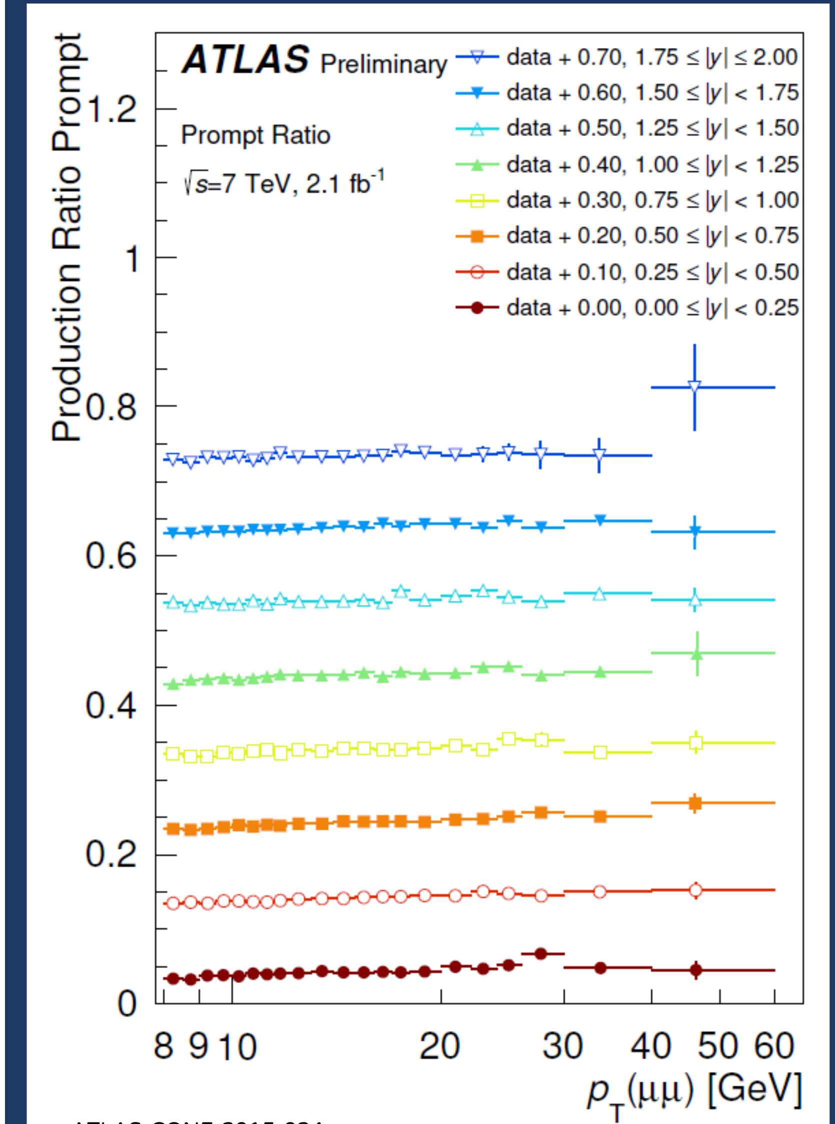
- ALICE inclusive J/ψ production is described, down to zero p_T, by a sum of:
  - (NLO) NRQCD for the prompt contribution at intermediate and high p_T
  - NRQCD + CGC for prompt J/ψ at low p_T
  - FONLL for J/ψ from B decay





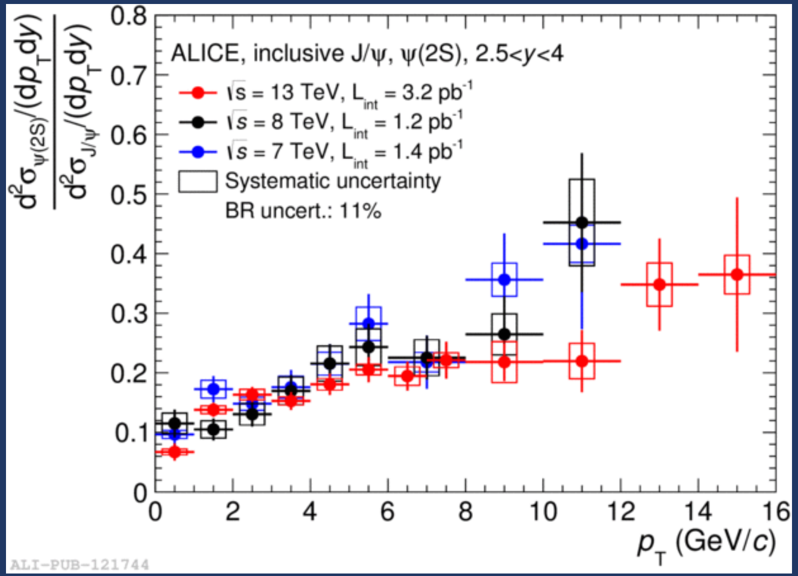
- Similar description holds for all the pp energies

$\psi(2S)/J/\psi$ in pp

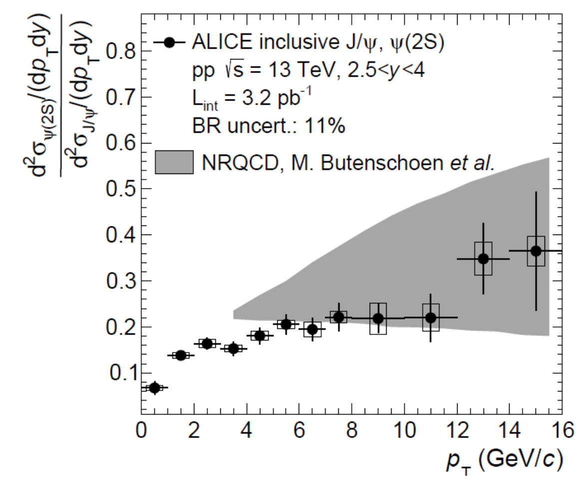


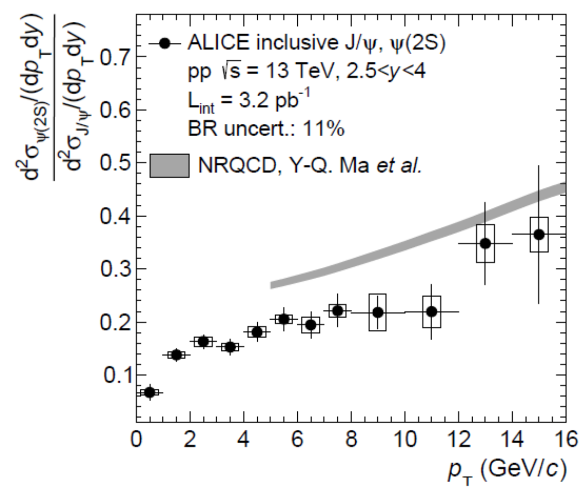
ATLAS-CONF-2015-024

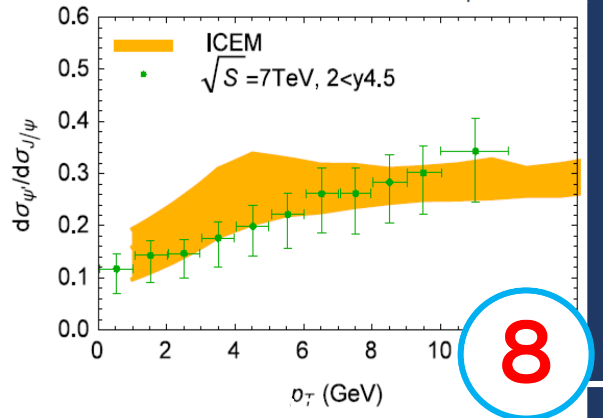
➡ Ratio $\psi(2S)/\psi$ shows an increase towards high p_T, with no energy and no y-dependence



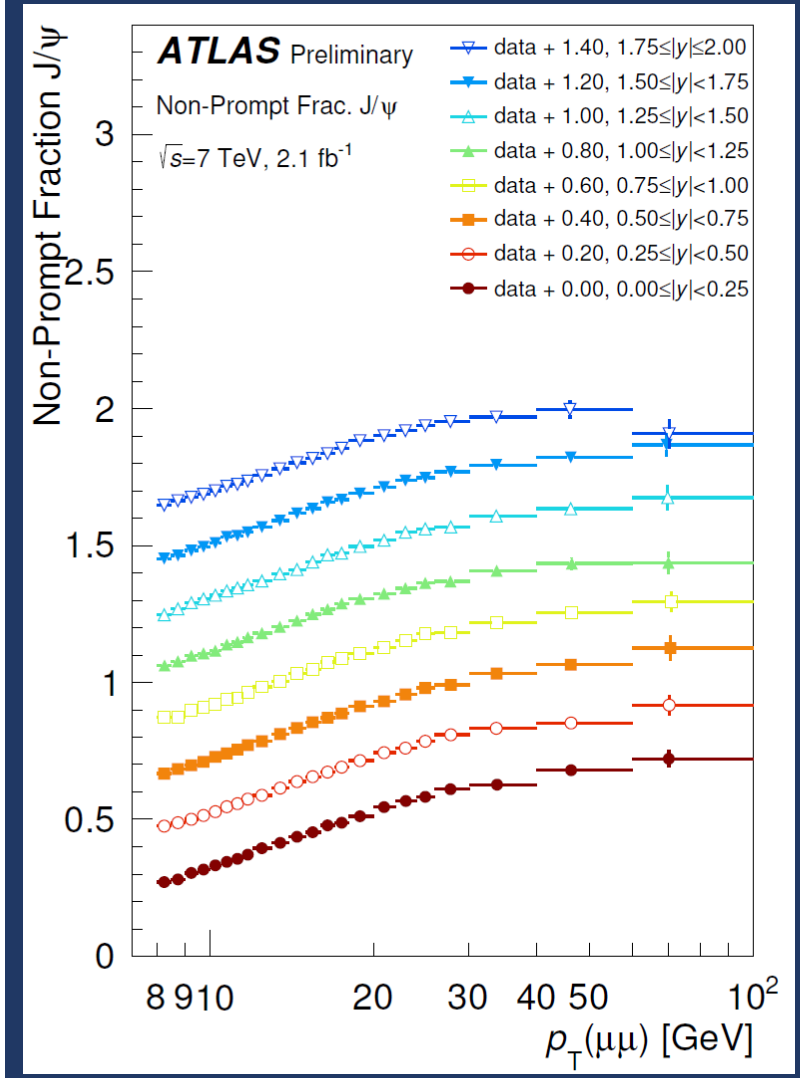
➡ $\psi(2S)/\psi$ is an interesting testing ground for models because of the error cancellation in both data and theory





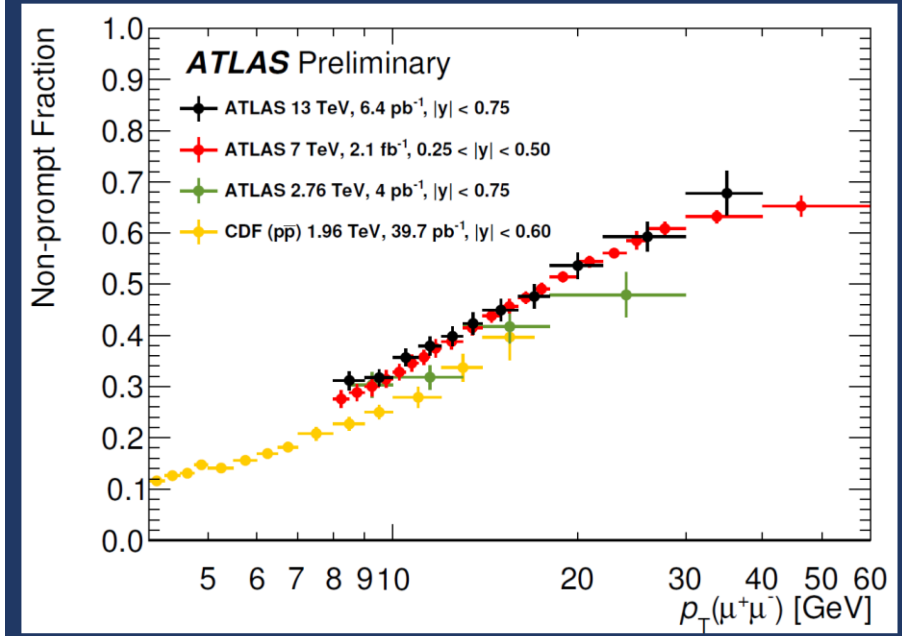


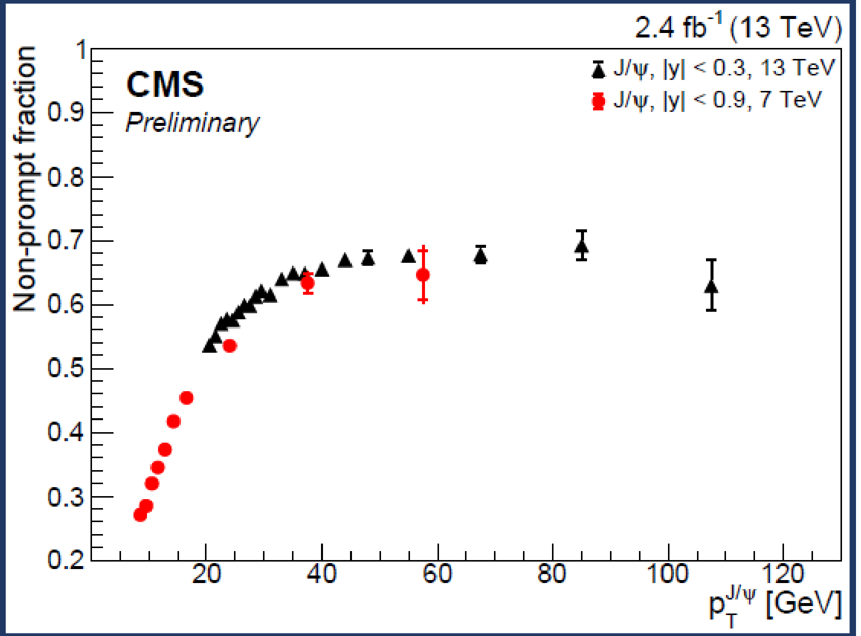
B feed down contribution



ATLAS-CONF-2015-030 ATLAS-CONF-2015-024

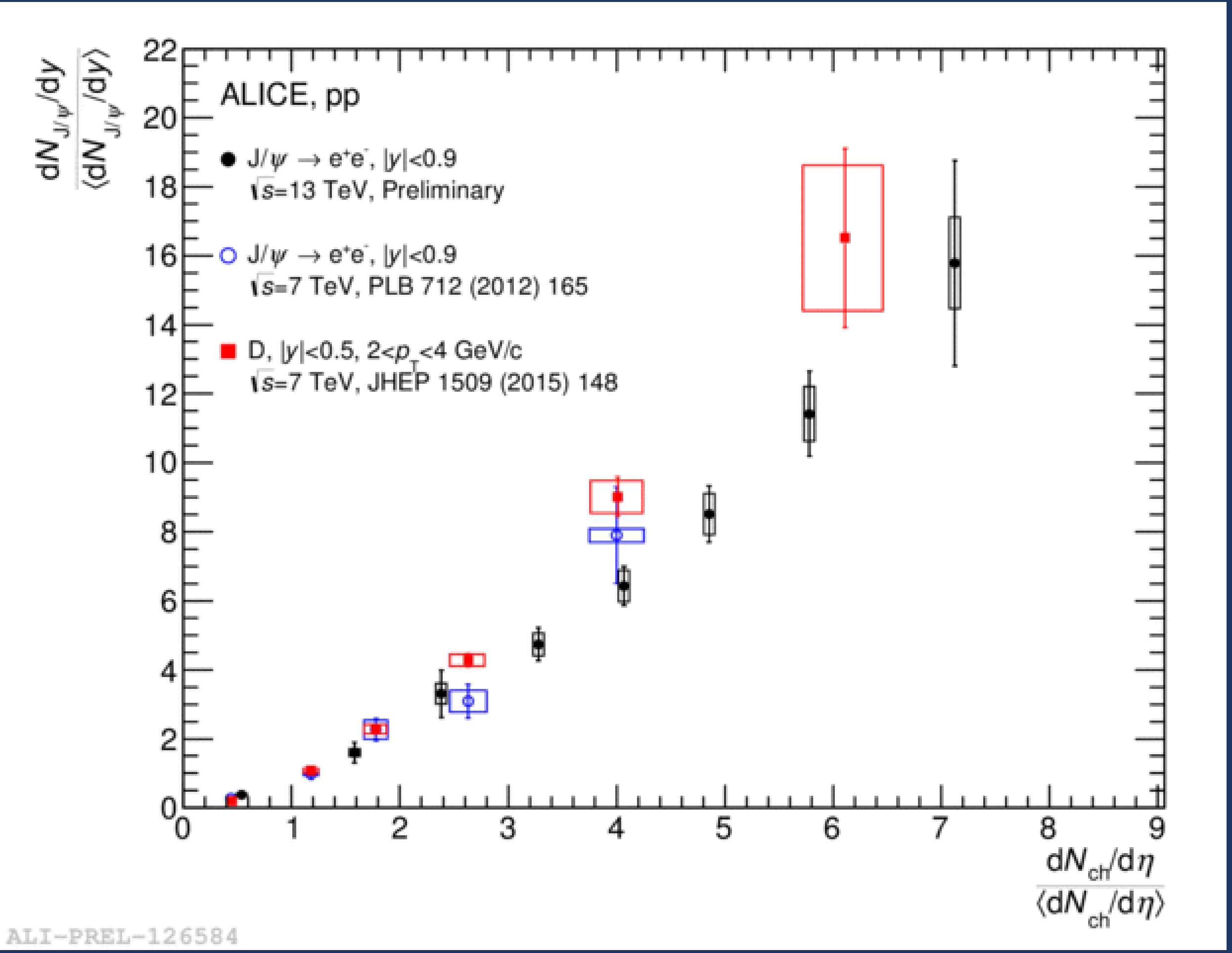
➡ Non-prompt fraction increases steadily, with p_T, from 10 to 60%, with no significant variation with y, and then saturates





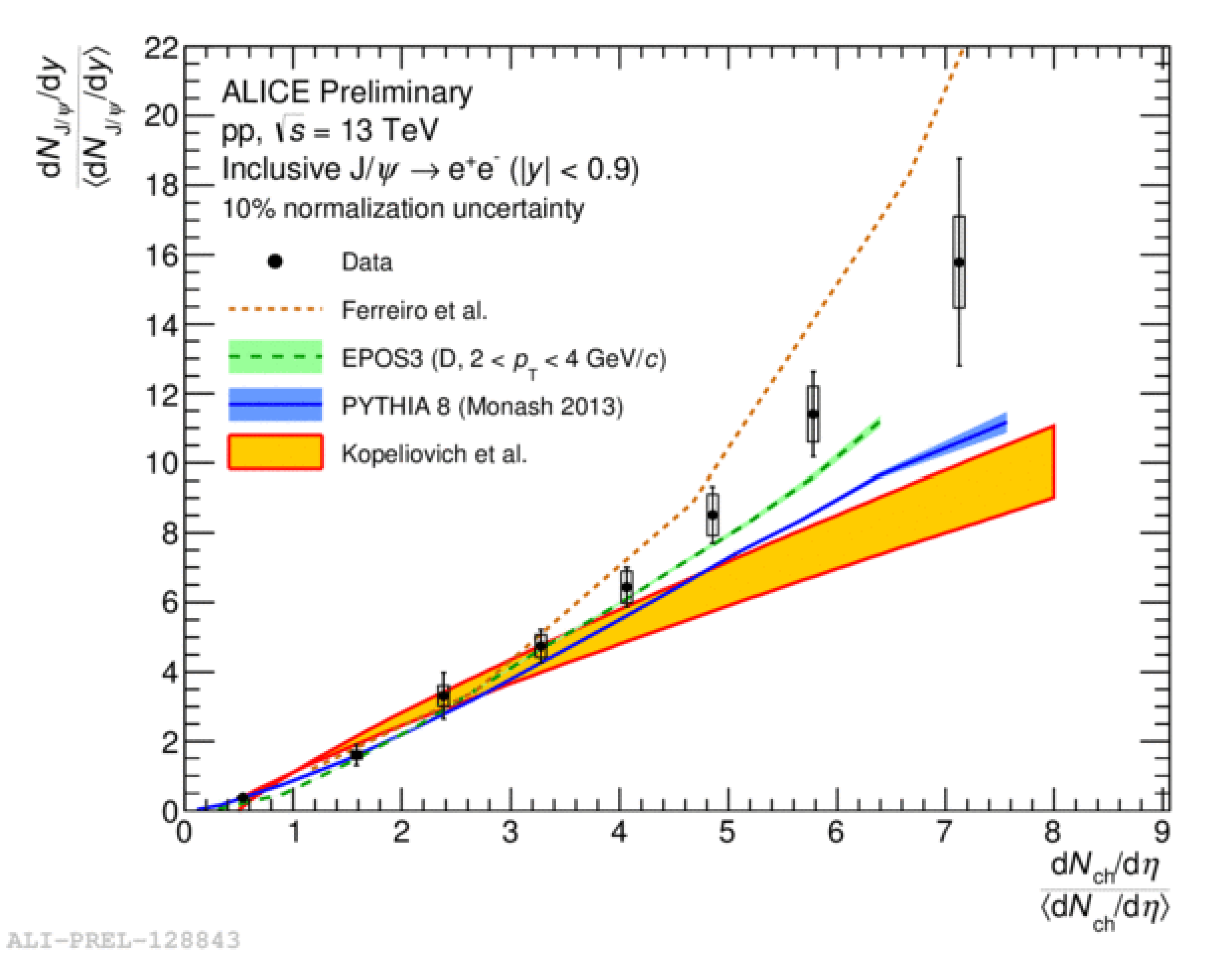
➡ No √s dependence is observed between 7 and 13TeV, while a difference is visible wrt lower energies

J/ψ production vs hadronic multiplicity



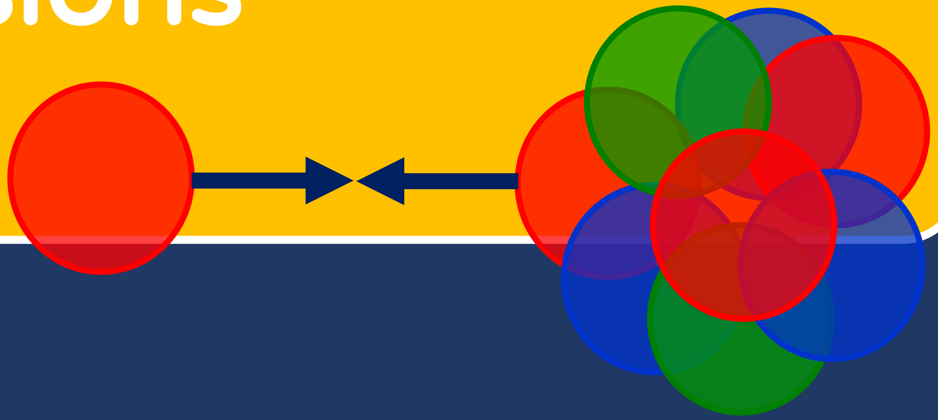
- Increase of J/ψ yield with event multiplicity observed at 7 and 13 TeV
- Stronger than linear increase, reaching up to 15 times the average J/ψ value, at a multiplicity of about 7 times the mean value
- No significant energy dependence
- Similar rise for open and closed charm (caveat: different p_T and y range)

J/ψ production vs hadronic multiplicity



- Models describe the lower multiplicity data, while they deviate at high multiplicity
- Models attribute the observed behavior to different underlying processes:
  - EPOS3 and PYTHIA: include MPI
  - Kopeliovich: high multiplicities reached via contribution of higher Fock states
  - Percolation: mimic MPI via interactions of colour sources with finite spatial extension

p-A collisions



Experimental pA landscape

Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	y_{cms} range	Data taking
SPS	NA50	p-Be,Al,Cu,Ag,W,Pb	27	-0.4<y<0.6	1996-2000
			29	-0.5<y<0.5	
	NA60	p-Be,Al,Cu,In,W,Pb,U	17	0.3<y<0.8	2004
			27	-0.1<y<0.3	
FNAL	E866	p-Be, Fe, W	39	-0.6<y<2.5*	~1996
HERA	HERA-B	p-C, Ti, W	42	-1.5<y<0.8	2002
RHIC	PHENIX, STAR	d-Au	200	-2.2<y<2.4	>2003
		p-Al, Au		1.2<|y|<2.2	2015
LHC	ALICE	p-Pb	5020 8016	-4.46<y<3.53	2013 2016
	ATLAS			-2.87<y<1.94	
	CMS			-2.87<y<1.93	
	LHCb			-5.0<y<-2.5 1.5<y<4.0	

➡ a large wealth of data has been collected in pA/dA collisions, in parallel with QGP studies in heavy-ion collisions

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Fixed target experiments:
Data collected on several A targets

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Collider experiments
- usually p vs a single beam specie
- forward and backward y range might be covered

How charmonium is studied in pA?

- Varying the amount of nuclear matter crossed by cc pair
  e.g. studying J/ψ production vs. A or centrality
- Selecting the kinematics of quarkonium states
  e.g. selecting events where the resonance is formed inside or outside the nucleus
- Comparing the behavior of different resonances

1. $$\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi}\, A\, e^{-\langle \rho L \rangle \sigma_{abs}}$$

the larger σ_{abs}, the more important the CNM effects

2. $$\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi}\, A^{\alpha}$$

$\alpha = 1$
→ no nuclear effects
$\alpha \neq 1$
→ nuclear effects

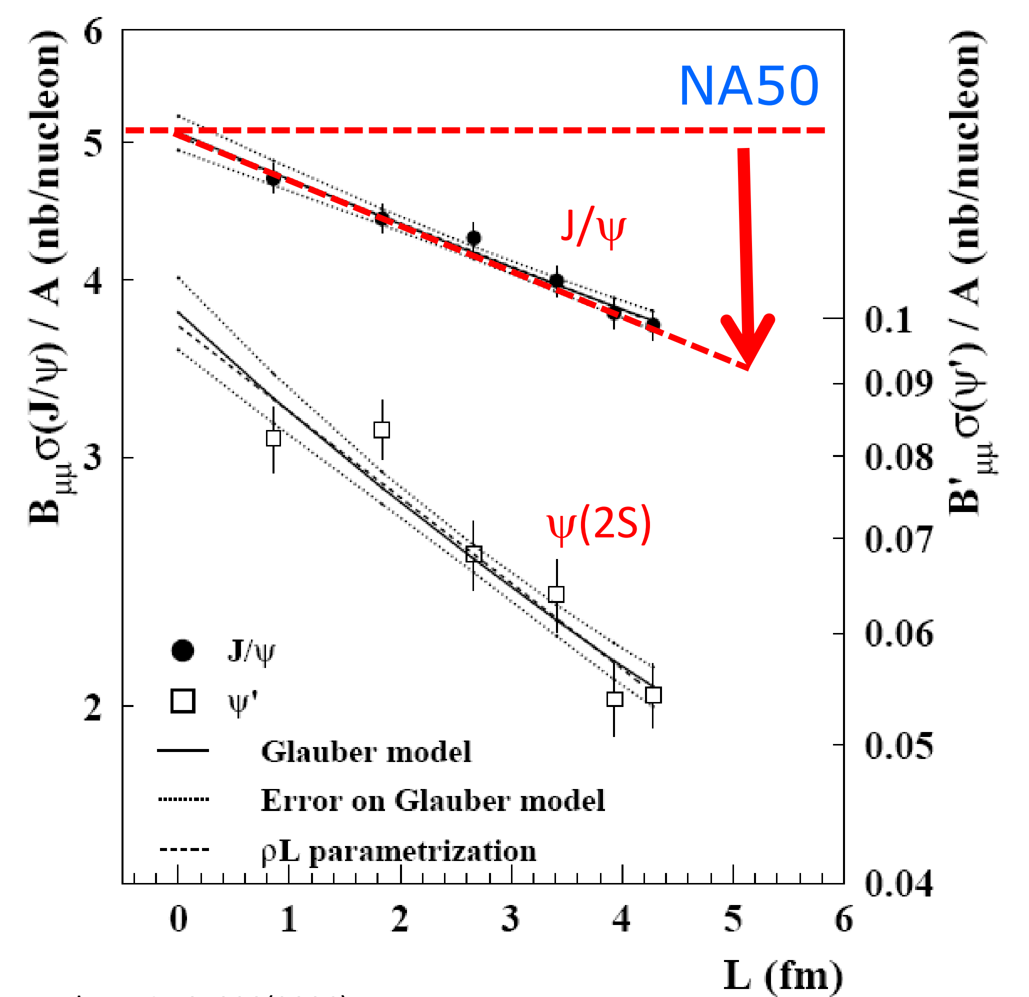
3. $$R^{pA}_{J/\psi} = \frac{\sigma^{pA}_{J/\psi}}{A\, \sigma^{pp}_{J/\psi}}$$

$R_{pA} = 1$
→ no nuclear effects
$R_{pA} \neq 1$
→ nuclear effects

- σ_{abs} and α are “effective” quantities which quantify the size of CNM effects

Results from SPS

A significant reduction of charmonium yields per NN collision is observed



Eur.Phys.J C 48, 329(2006)

- reduction interpreted as due to "nuclear absorption" of the cc pair in medium
- stronger absorption for the less bound state ψ(2S) at mid-*y*

Nucleus crossing time comparable or larger than charmonium formation time:
→ fully formed resonances traverse the nucleus

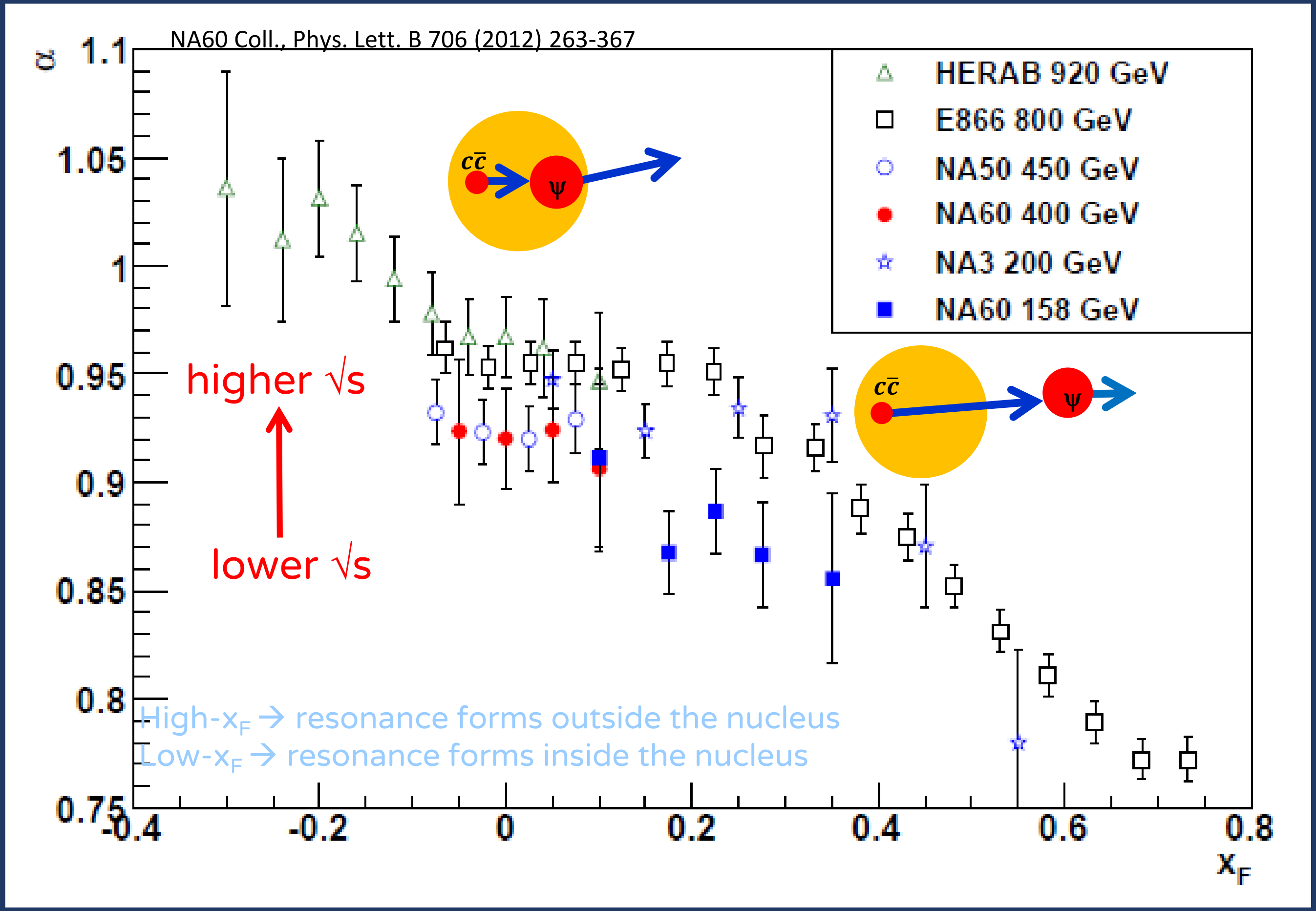
- Fitting with $\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A \cdot e^{-\langle\rho L\rangle\sigma_{abs}}$

σ_{abs} J/ψ = 4.5 ± 0.5 mb

σ_{abs} ψ(2S) = 8.3 ± 0.9 mb

J/ψ as a function of x_F

- Compilation of J/ψ results obtained in several fixed target experiments

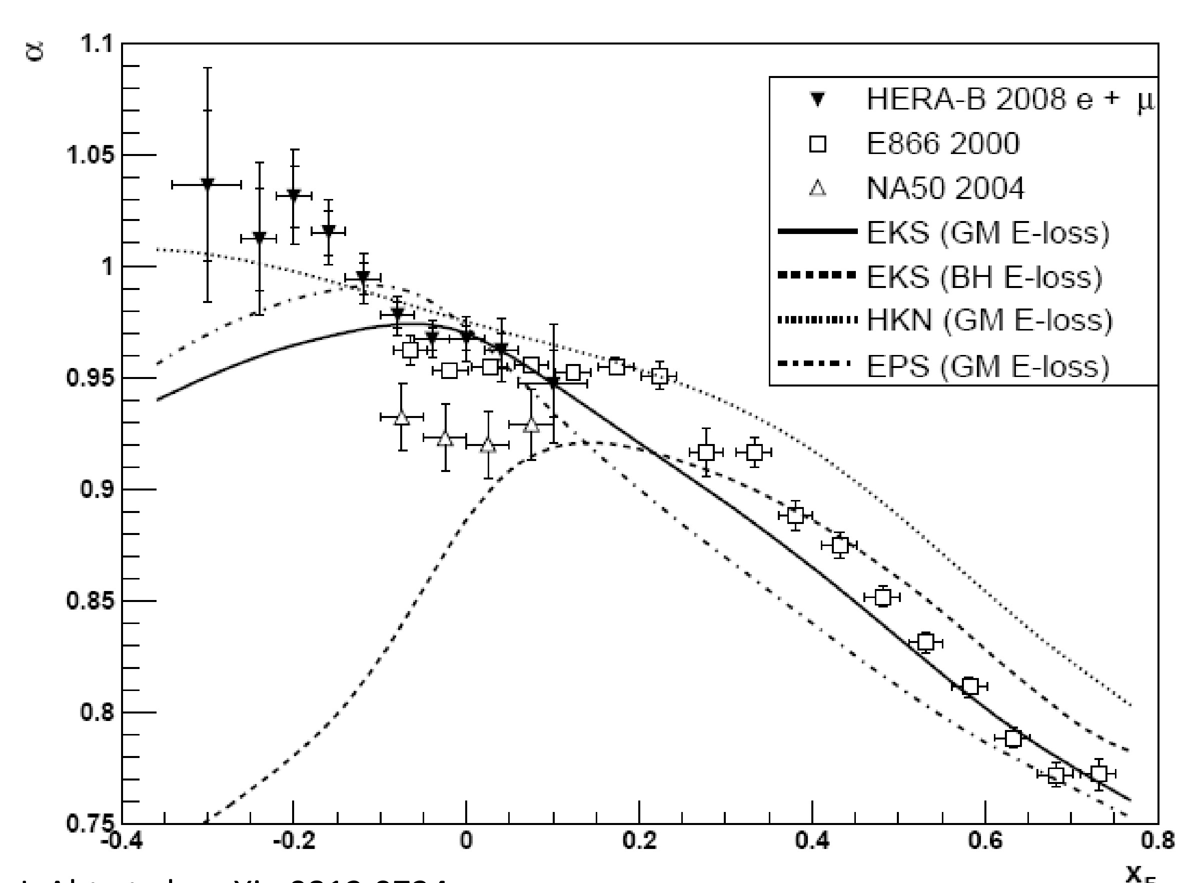


J/ψ yield in pA is modified with respect to pp collisions, with a strong kinematic dependence

- α strongly decreases with x_F
- for a fixed x_F, CNM are stronger at lower √s

J/ψ as a function of x_F

Compilation of J/ψ results obtained in several fixed target experiments



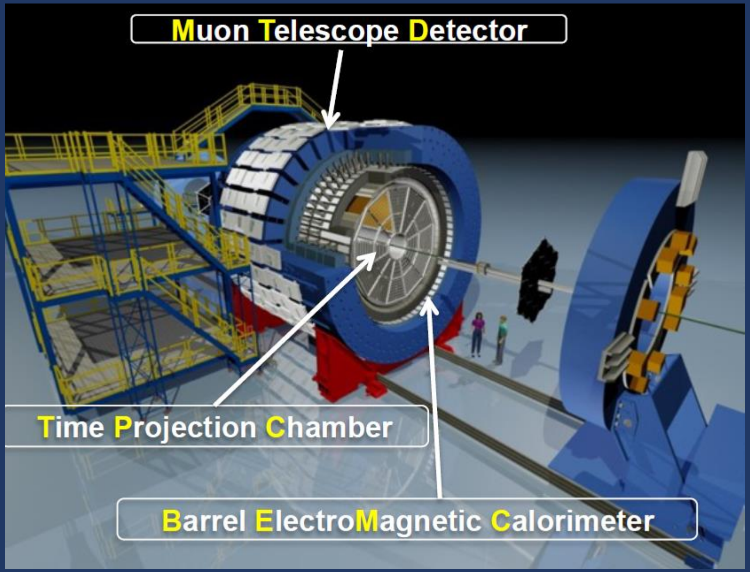
I. Abt et al., arXiv:0812.0734

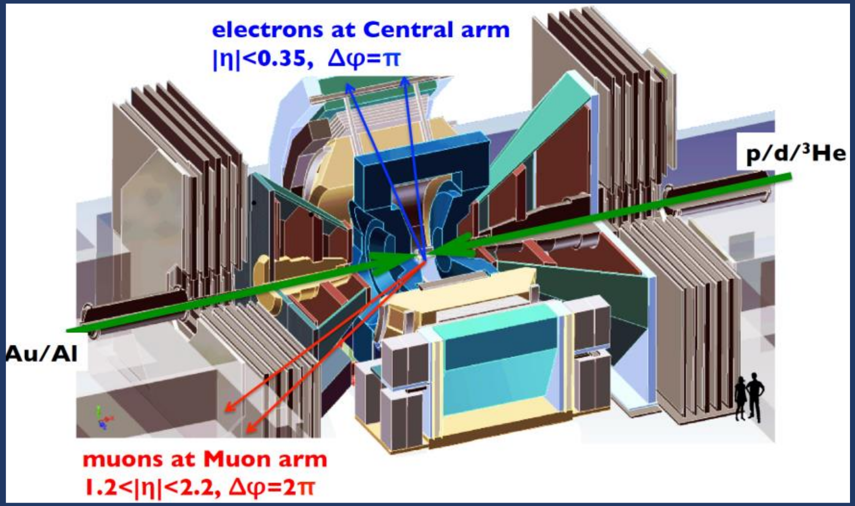
J/ψ yield in pA is modified with respect to pp collisions, with a strong kinematic dependence

- α strongly decreases with x_F
- for a fixed x_F, CNM are stronger at lower $\sqrt{s}$

Theoretical description over the full x_F range still difficult!

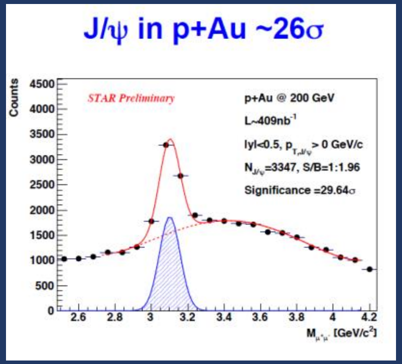
pA-dA data taking at RHIC

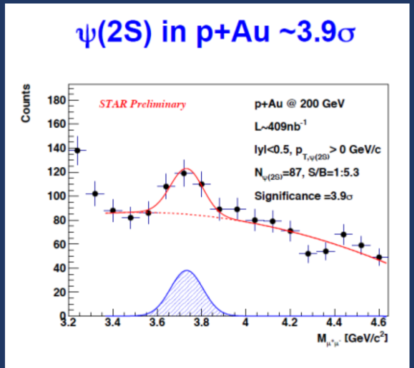




- Several collision systems and energy investigated at RHIC:

√s(GeV)	pp	p-Al	p-Au	d-Au	^{3}He-Au
510	X				
200	X	X	X	X	X
130				X	
62.4	X			X	
39				X	
27				X	
20				X	



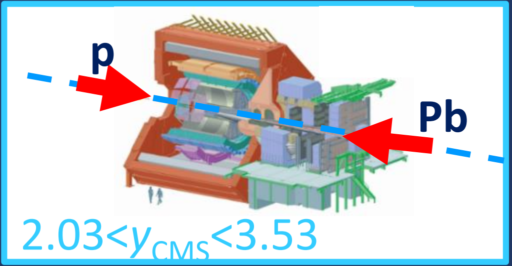


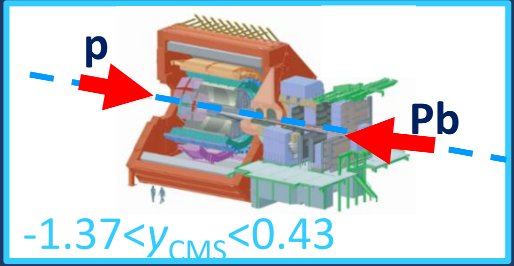
- Significant improvements:
  - STAR
    - → dimuon trigger with MTD, enhancing J/ψ and ϒ capabilities
  - PHENIX
    - → VTX and FVTX improving tracking and vertexing

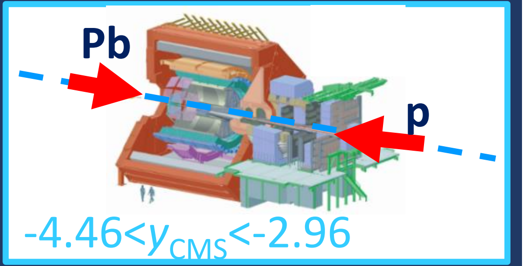
pA data taking at LHC

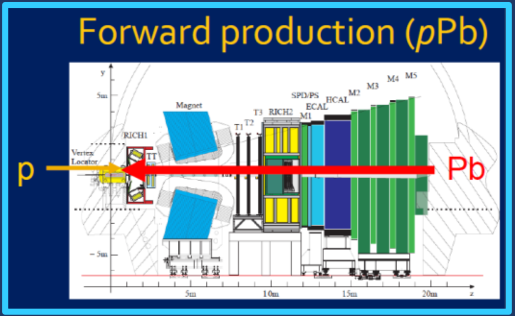
- pPb collisions at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV
- ALICE and LHCb data are collected with two beam configurations: p-Pb and Pb-p, with Δy = 0.465

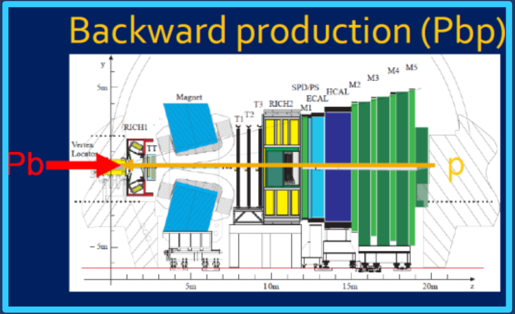
	$\sqrt{s_{NN}}$ (TeV)	fw-y	mid-y	bck-y
ALICE	5.02	5nb^{-1}	51μb^{-1}	6nb^{-1}
	8.16	9nb^{-1}	n.a.	13nb^{-1}
LHCb	5.02	1nb^{-1}		0.5nb^{-1}
	8.16	14nb^{-1}		21nb^{-1}
CMS	5.02		35nb^{-1}	
	8.16		n.a.	
ATLAS	5.02		28nb^{-1}	
	8.16		0.2pb^{-1}	











- Significant statistics increase between Run1 and Run2

pA results from RHIC and LHC

- All quarkonium states have been extensively studied in pA (dA) collisions

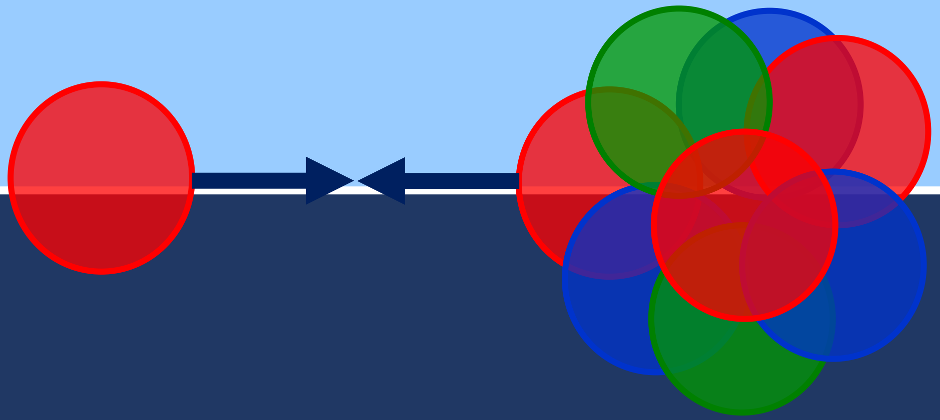
	J/ψ				ψ(2S)				Υ			
	pT	y	centrality	multip.	pT	y	centrality	multip.	pT	y	centrality	multip
	$\sqrt{s_{NN}}$ = 5.02 TeV											
ALICE	x	x	x	x	x	x	x		x	x		
ATLAS	x	x	x	x	x	x	x	x	x	x	x	x
CMS	x	x		x	x	x						x
LHCb	x	x			x	x			x	x		
	$\sqrt{s_{NN}}$ = 200 GeV											
PHENIX	x	x	x			x	x	x		x		
STAR	x	x	x							x		

pA results from RHIC and LHC

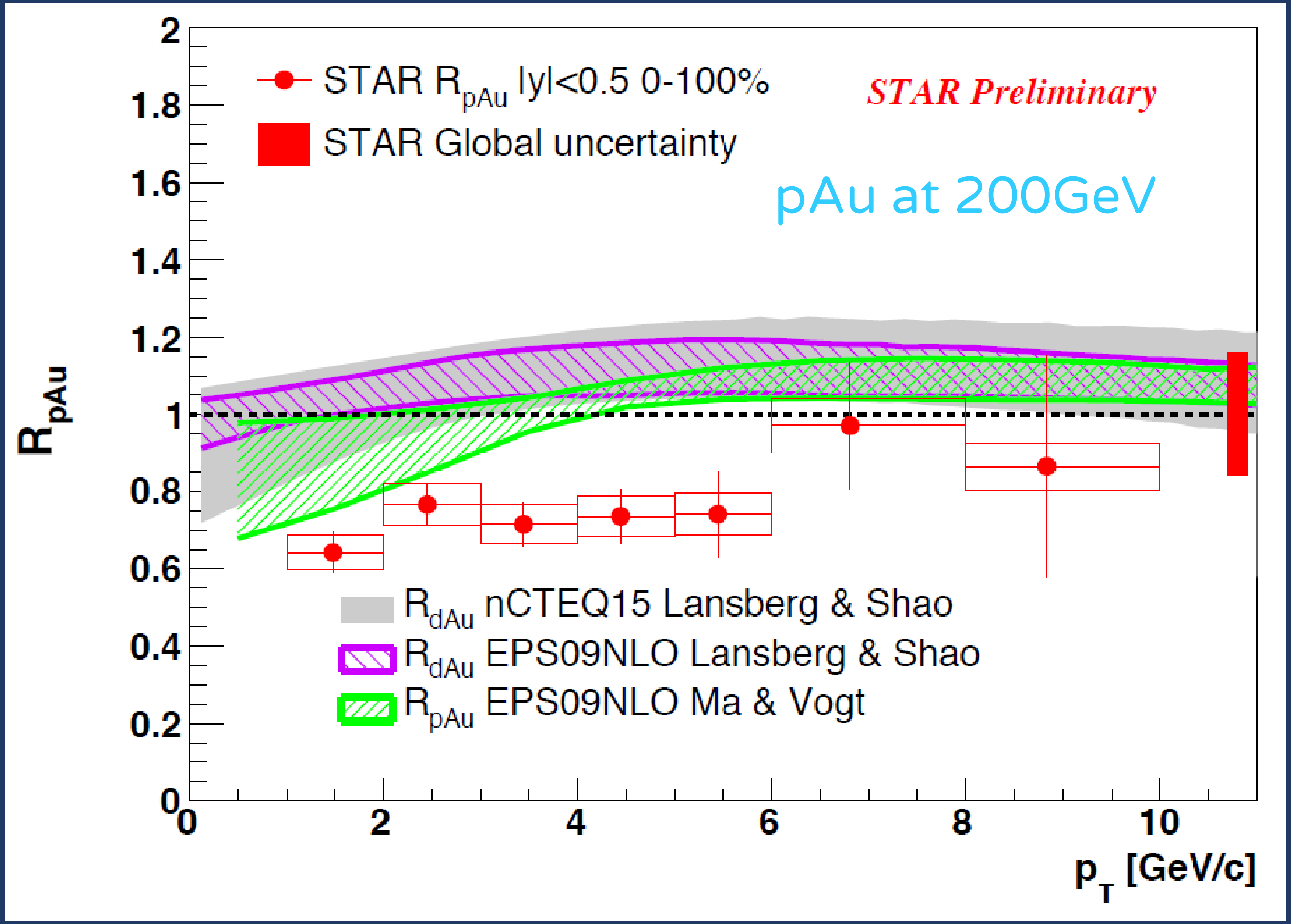
Analysis of the pA data at $\sqrt{s_{NN}}$ = 8.16TeV still at the beginning…

	J/ψ				ψ(2S)				Υ			
	pT	y	centrality	multip.	pT	y	centrality	multip.	pT	y	centrality	multip
	$\sqrt{s_{NN}}$ = 8.16 TeV											
ALICE	x	x										
ATLAS												
CMS												
LHCb	x	x										

p-A collisions:
J/ψ



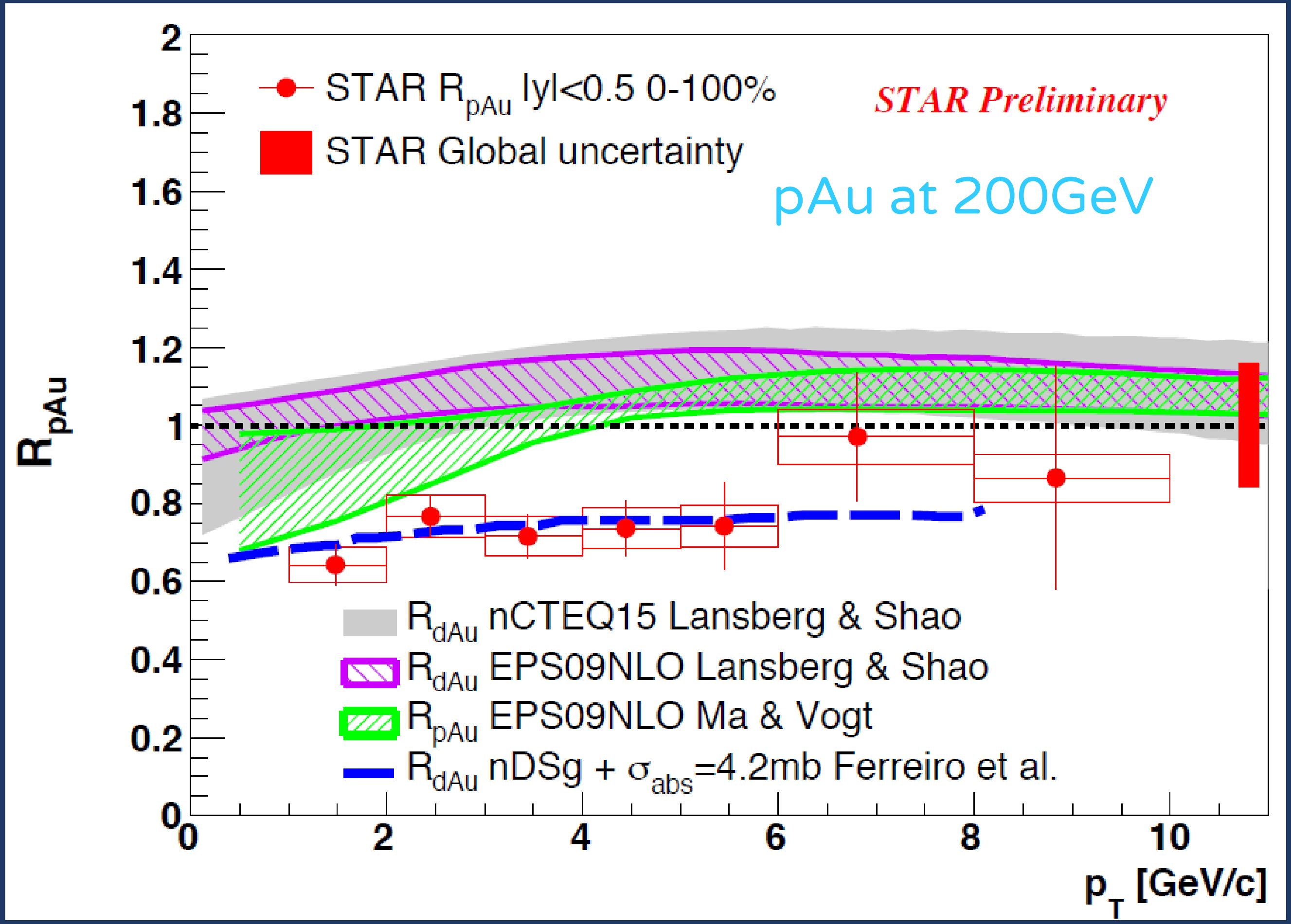
J/ψ R_{pA} at RHIC



- J/ψ R_{pA} shows a slightly increasing trend towards high p_T
- Shadowing models predicts R_{pA} slightly higher than unity

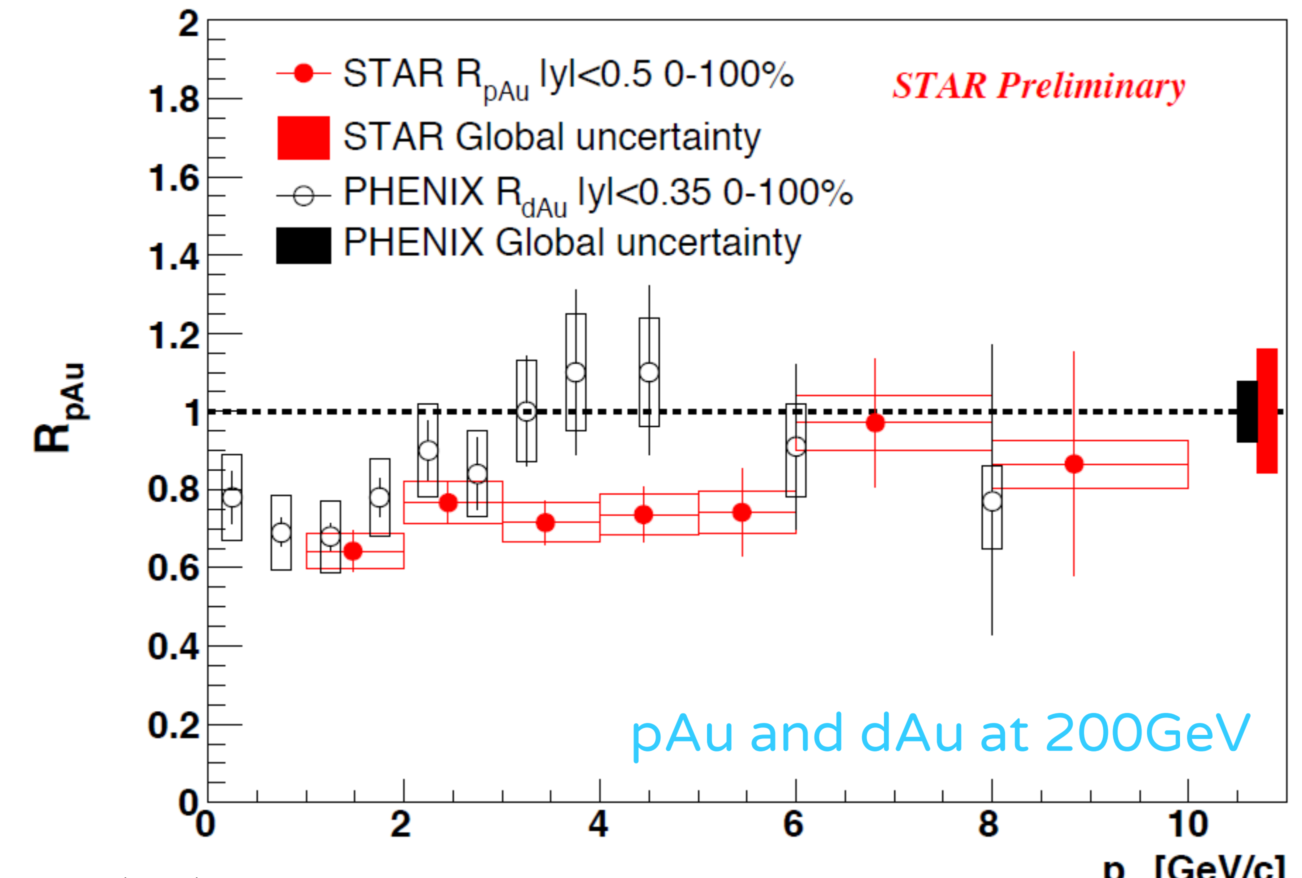
→ Is there room for other CNM effects on top of shadowing?

J/ψ R_{pA} at RHIC



- J/ψ R_{pA} shows a slightly increasing trend towards high p_T
- Shadowing models predicts R_{pA} slightly higher than unity
- Data seems to allow the inclusion of an additional contribution, as the cc break up in medium, on top of shadowing

J/ψ R_{pA} at RHIC: pAu vs dAu



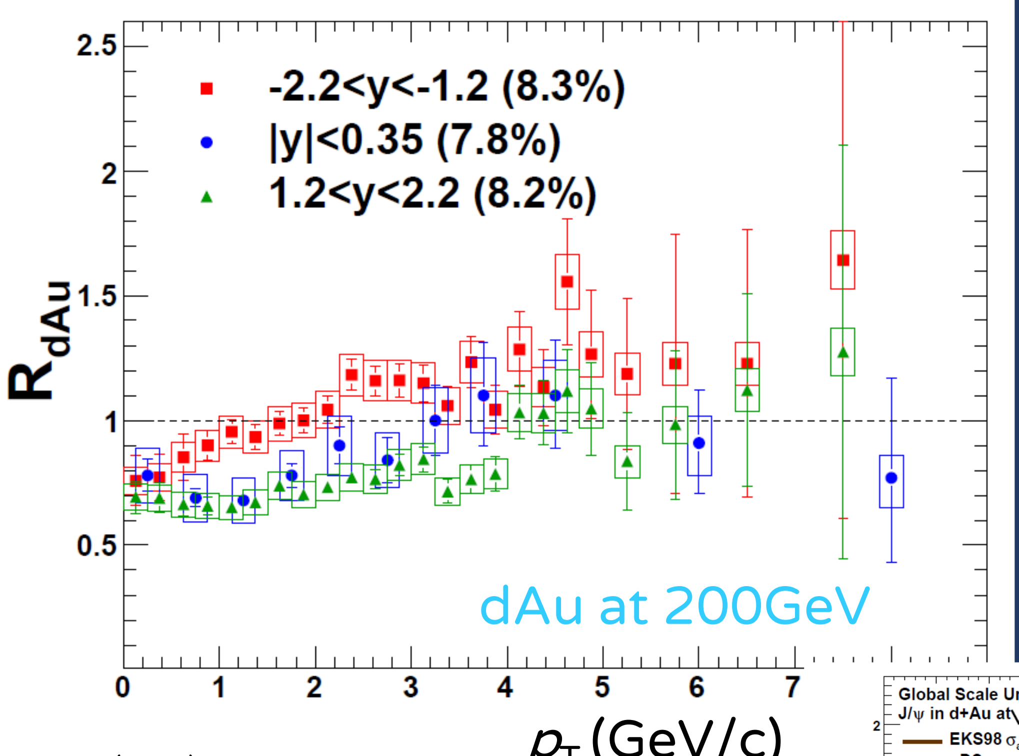
PRC 87 (2012) 034903

- R_{dAu} pattern is consistent, within uncertainties, with R_{pAu} at the same energy

  → (rather) similar CNM effects in pAu and dAu

  → …but R_{dA} may be increasing faster with p_T (at p_T ~ 3.5-5GeV, significance is 1.4σ)

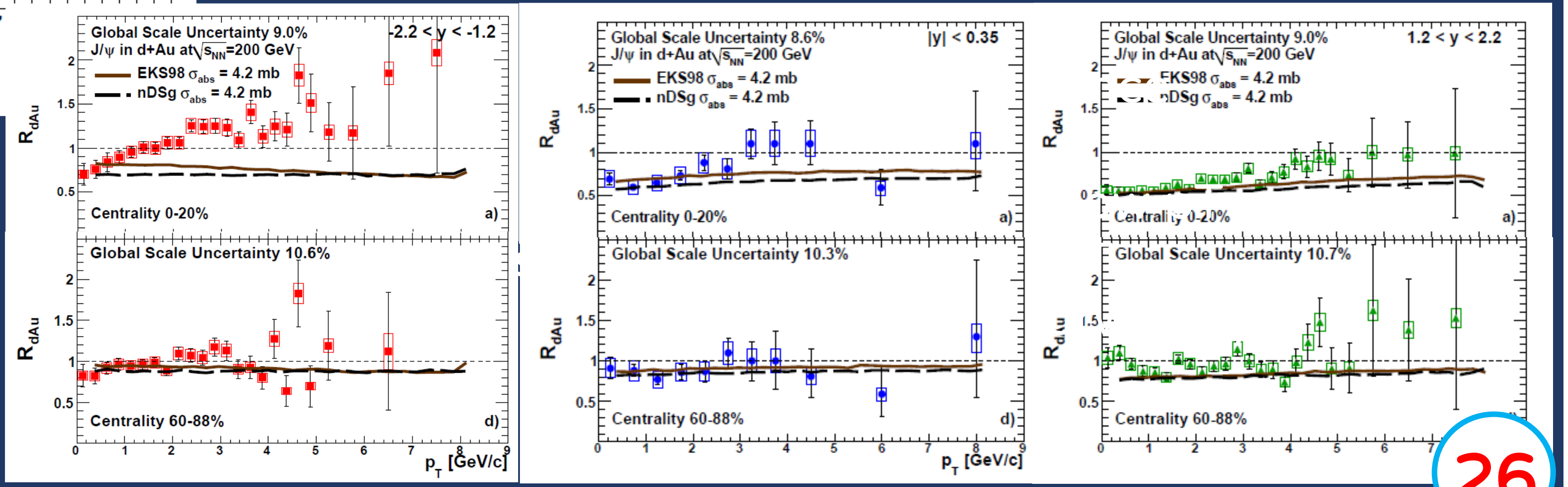
J/ψ R_{dAu} at RHIC



PRC 87 (2012) 034903

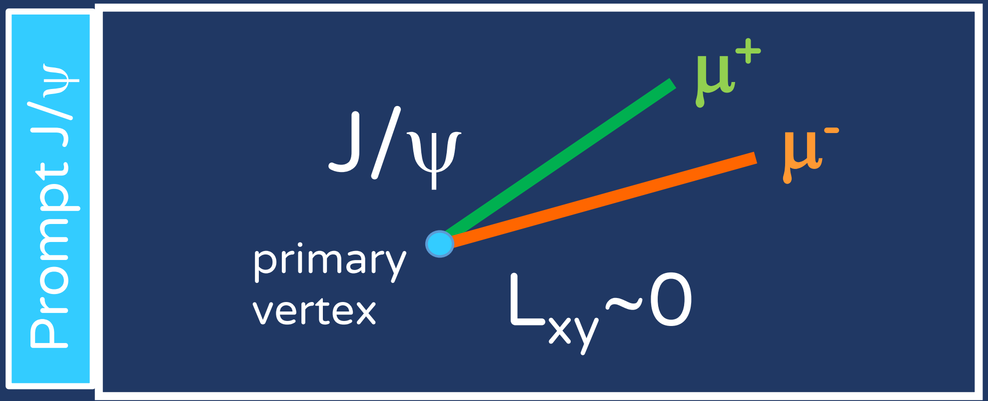
- R_{dAu} shows a p_T and y dependent trend:
  - CNM effects are stronger at low p_T
  - R_{dAu} approaches unity at high p_T
  - CNM effect are more sizeable at forward-y

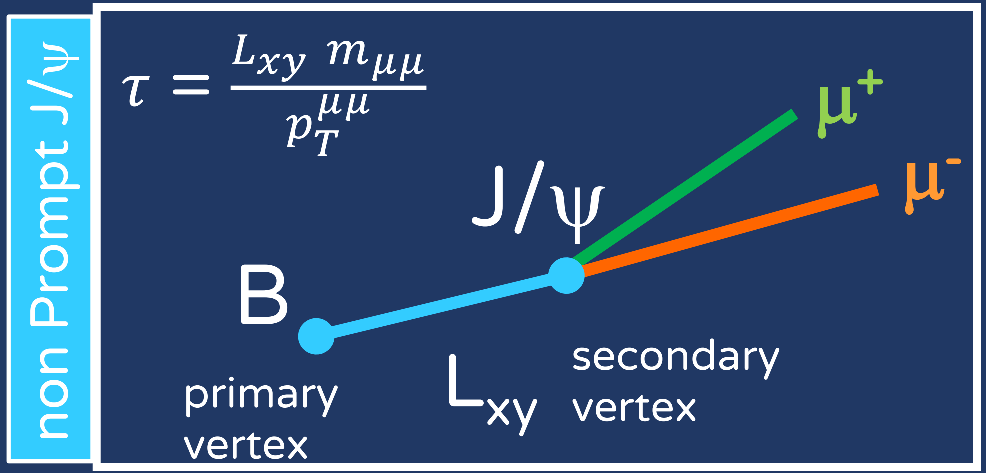
- Models based on shadowing + ccbar breakup describe R_{dAu}, except for central collisions and negative y

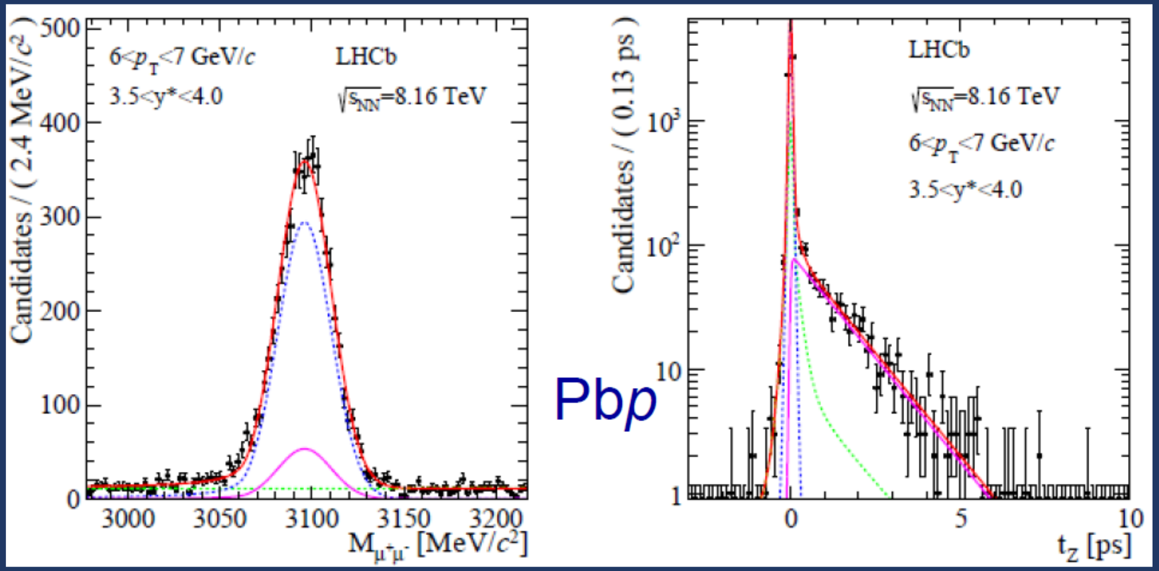


prompt and non-prompt J/ψ at LHC

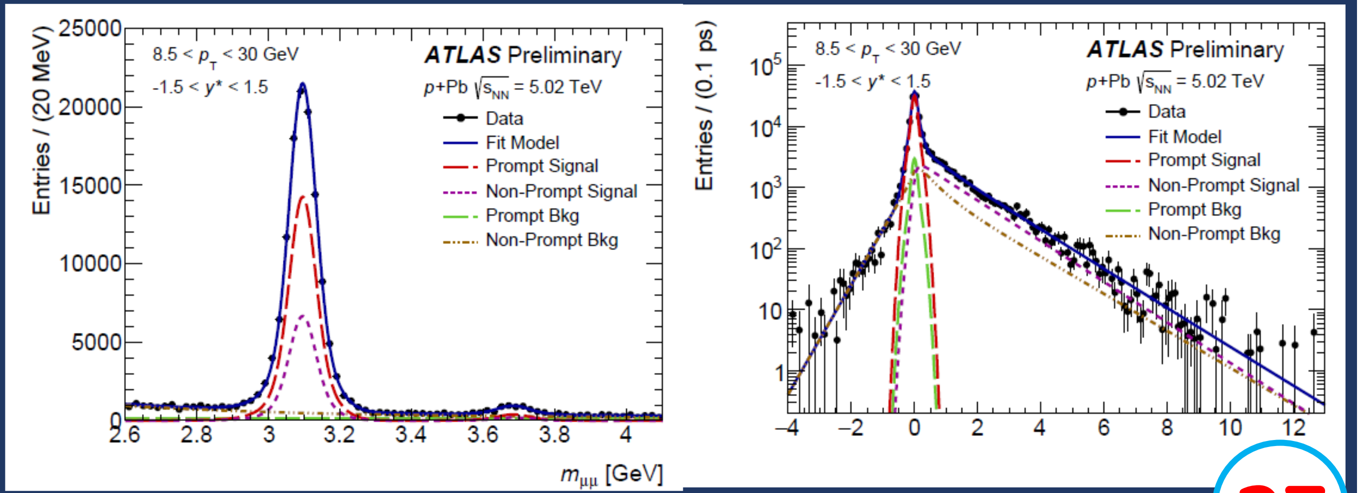
- prompt and non-prompt J/ψ are separated through 2D fit to mass and pseudo-proper decay time







LHCb-PAPER-2017-014

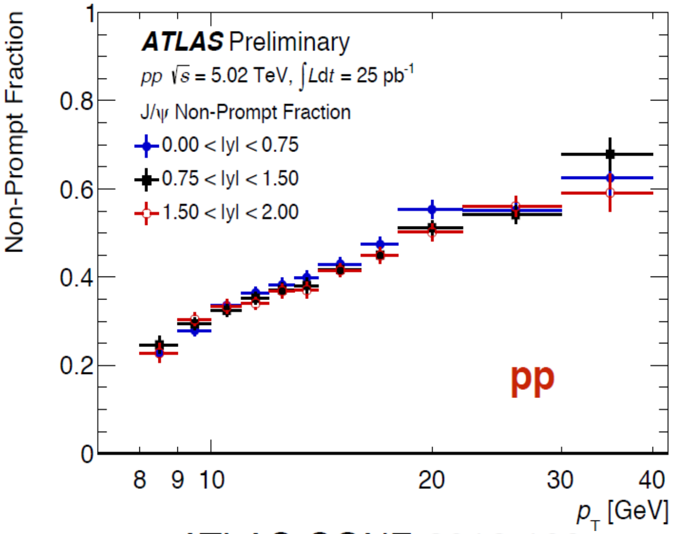


Fraction of J/ψ from B

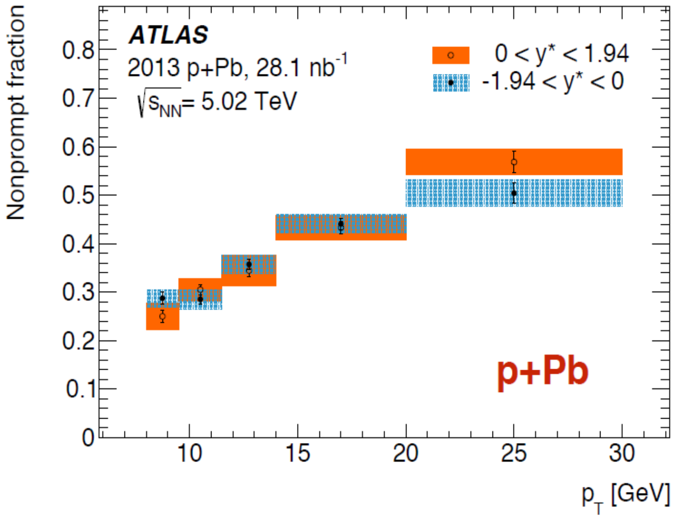
- Fraction of J/ψ from B can be evaluated as

$$F_B = \frac{\sigma_{non\ prompt\ J/\psi}}{\sigma_{prompt\ J/\psi} + \sigma_{non\ prompt\ J/\psi}}$$

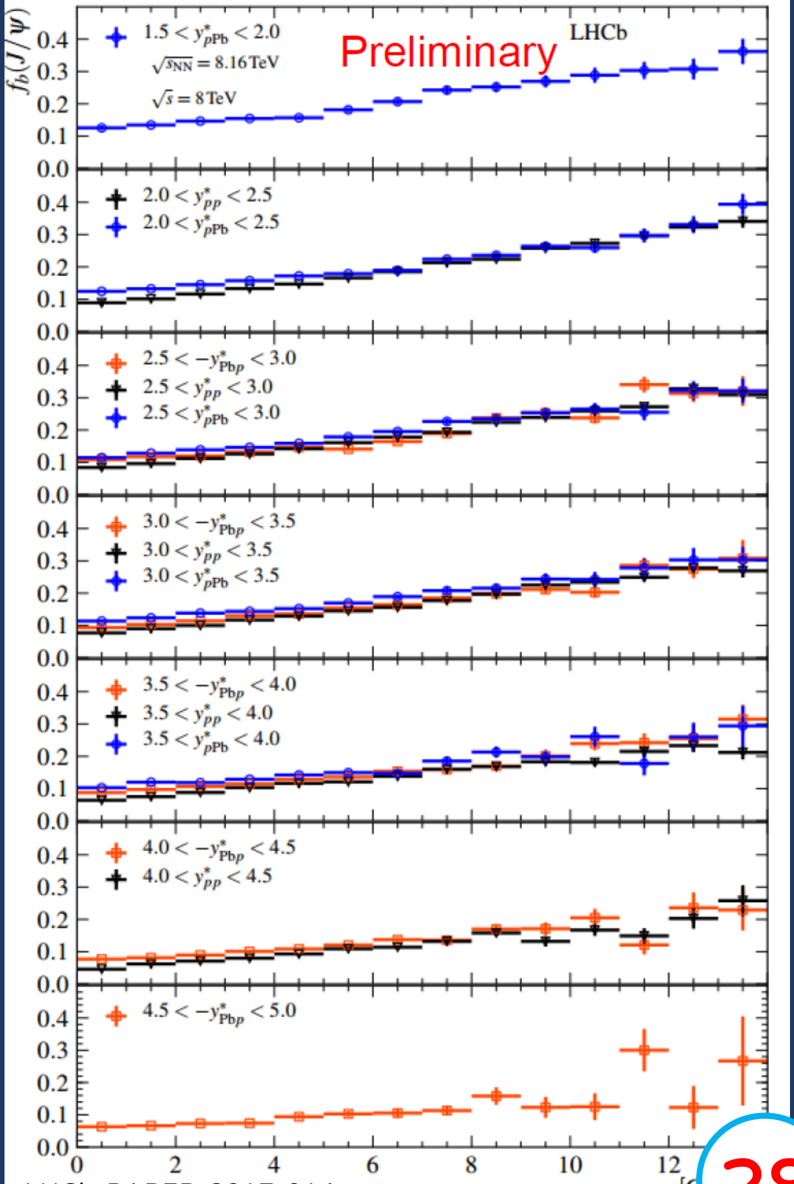
- Similar p_T dependence in pp, pPb and Pbp



ATLAS-CONF-2016-109



Phys. Rev. C 92, 034904

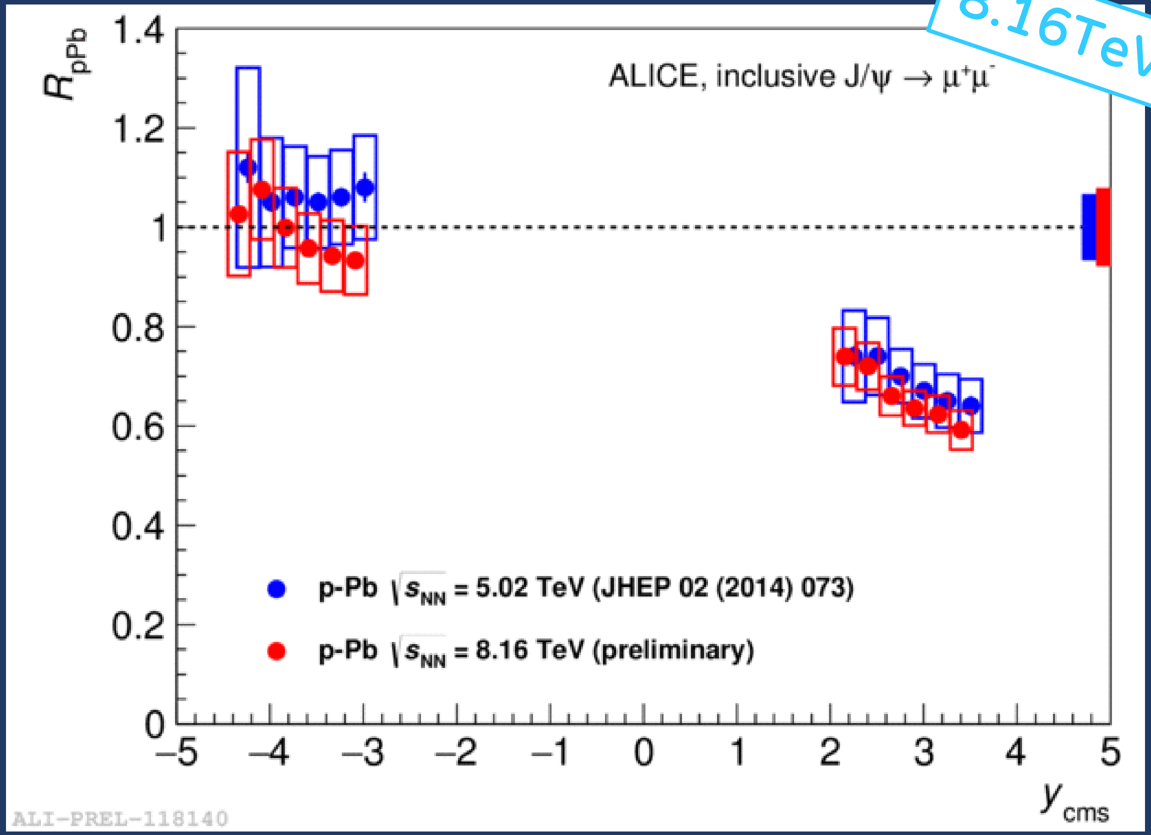


LHCb-PAPER-2017-014

- F_B increases from 10% at low p_T up to 40-60% at high p_T, with a weak y dependence

J/ψ R_{pA} at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV

8.16TeV



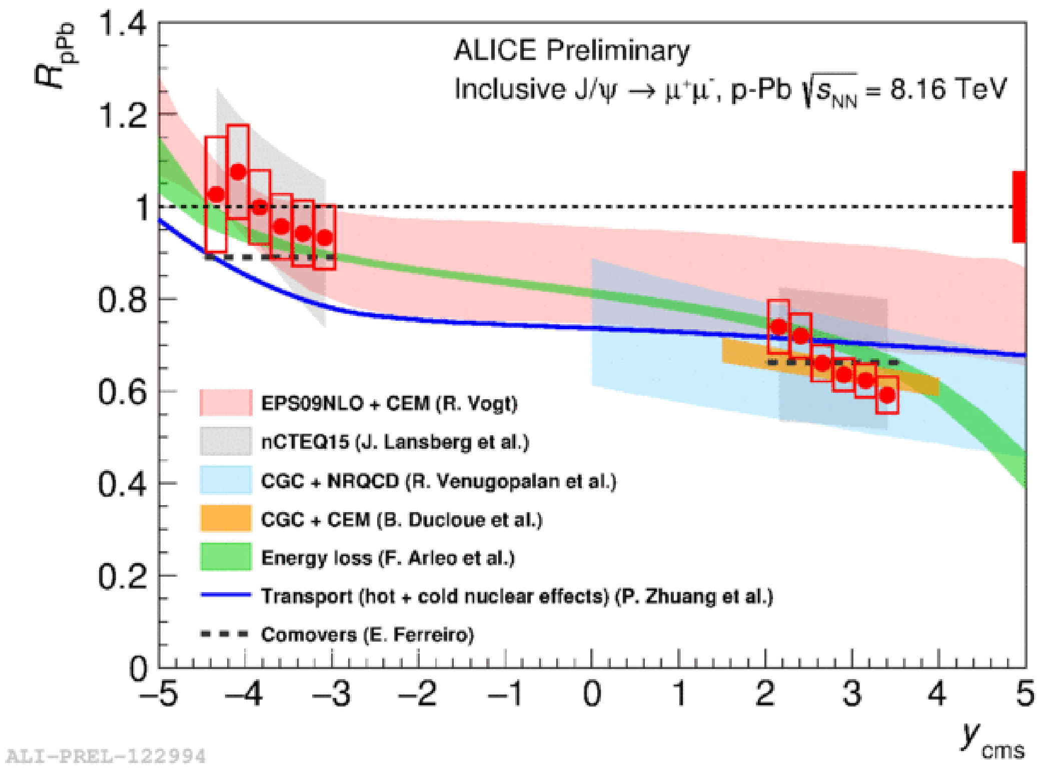
CERN-ALICE-PUBLIC-2017-001

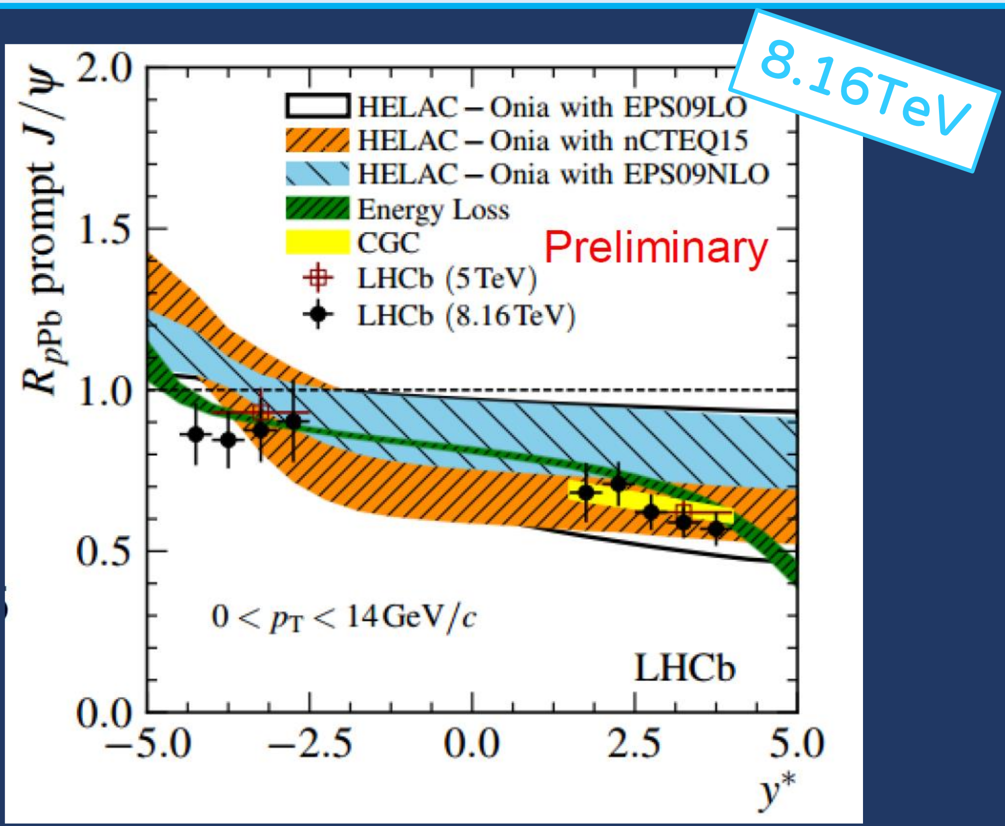
- Clear J/ψ suppression at forward-*y*, while R_{pA} is compatible with unity at backward-*y*
- R_{pA} compatible at $\sqrt{s_{NN}}$ = 5.02 and 8.16TeV, even if *x* coverage is slightly different

	$\sqrt{s_{NN}}$ = 8.16TeV, $p_T^{J/\psi}$= 0	$\sqrt{s_{NN}}$ = 5.02TeV, $p_T^{J/\psi}$= 0
p-going	$1.1\ 10^{-5} < x < 5\ 10^{-5}$	$2\ 10^{-5} < x < 8\ 10^{-5}$
Pb-going	$7.3\ 10^{-3} < x < 3.3\ 10^{-2}$	$1\ 10^{-2} < x < 5\ 10^{-2}$

2→1 kinematics, p_T=0

J/ψ R_{pA} vs rapidity: theory comparison



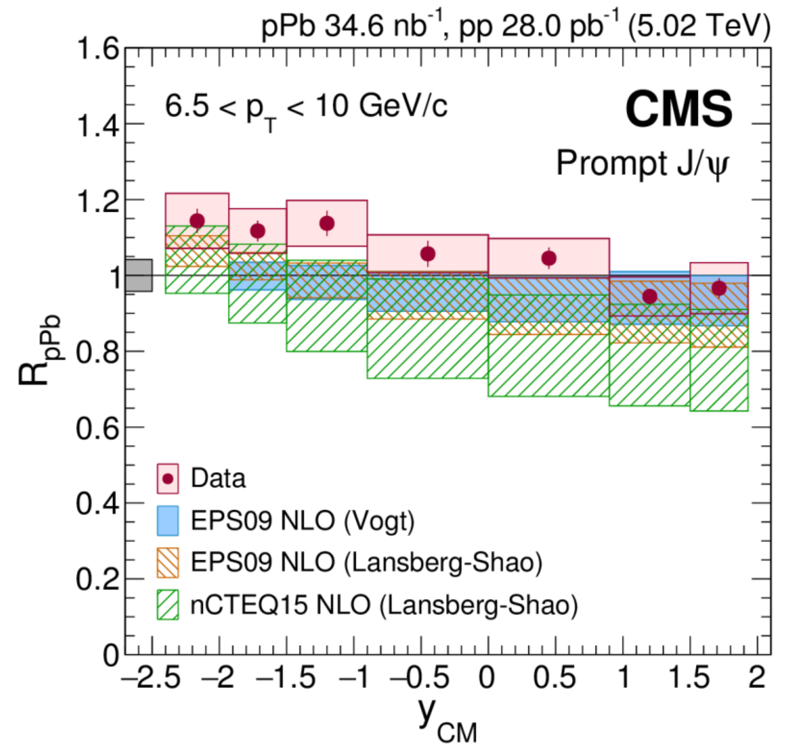


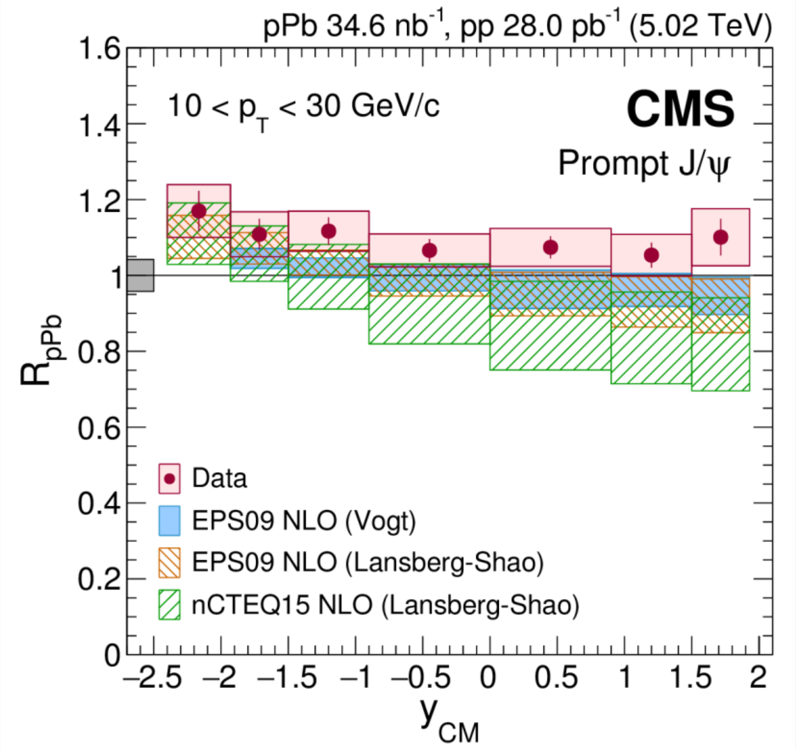
- Good agreement between ALICE and LHCb data
- Results described by models based on shadowing and/or energy loss

Size of theory uncertainties (mainly shadowing) still limits a more quantitative comparison

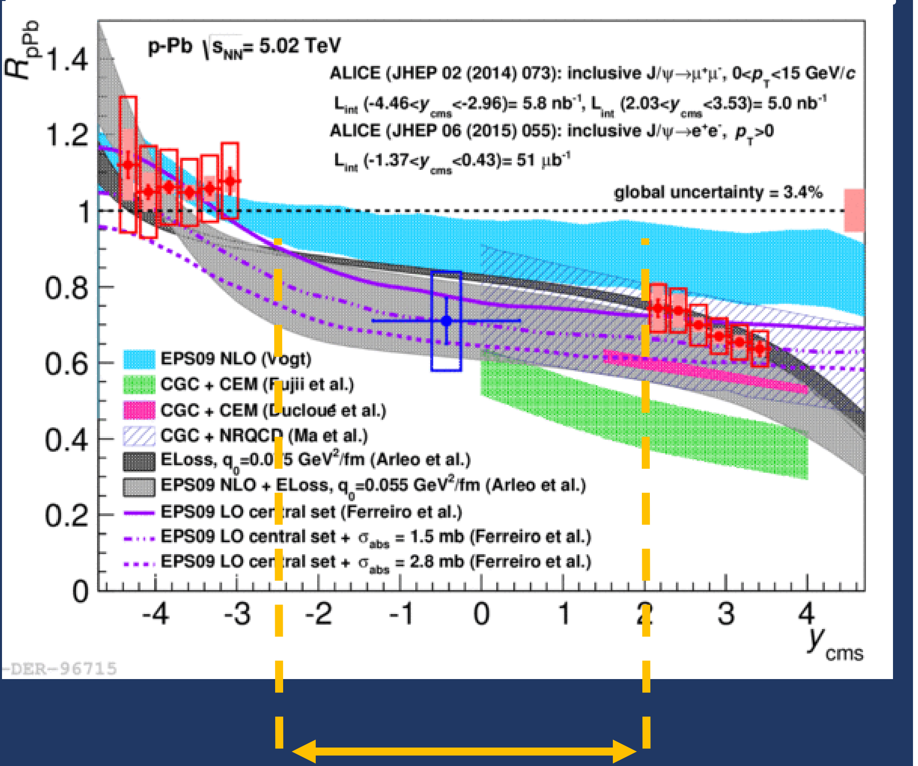
Rapidity dependence of J/ψ R_{pA}

CMS: high p_T





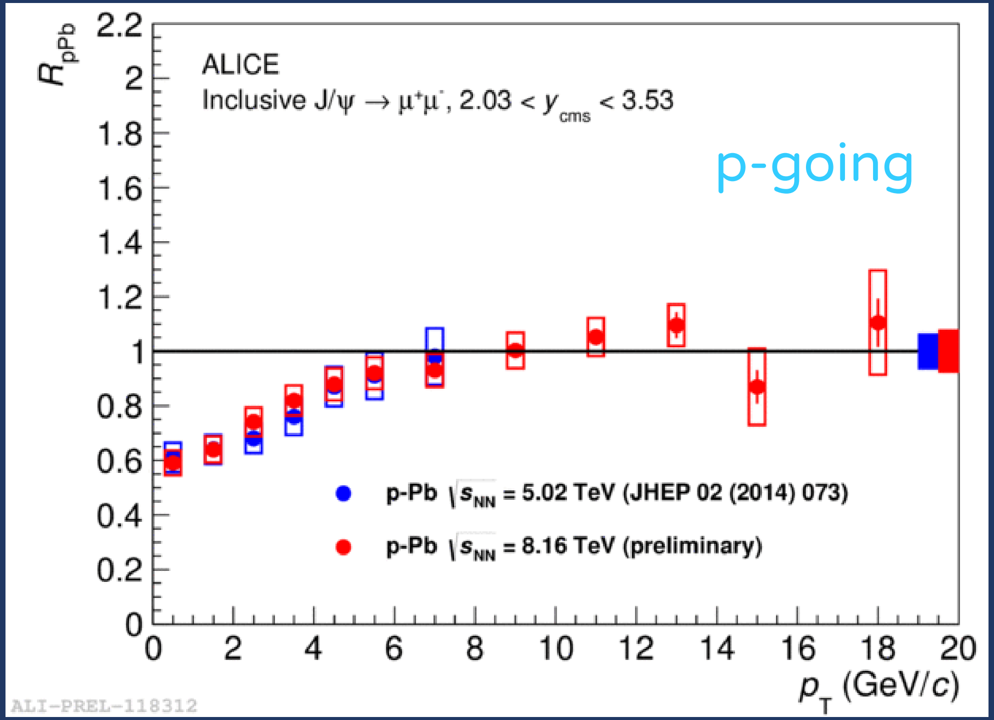
ALICE: low p_T

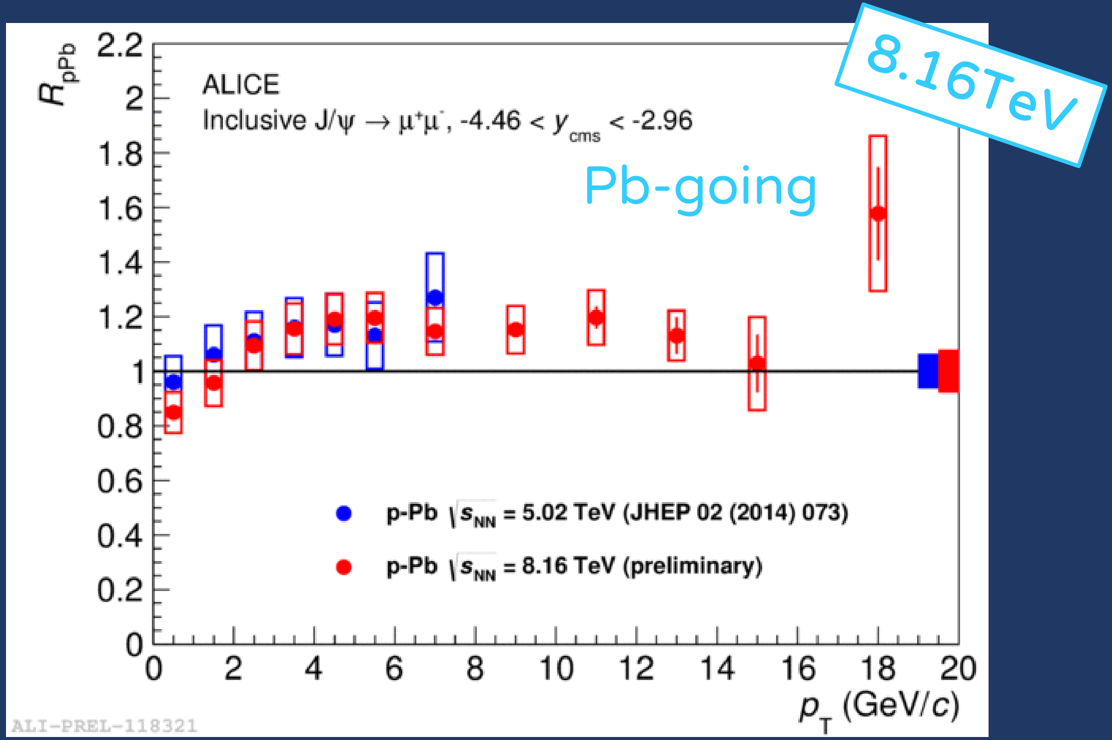


- Mid-y R_{pA} for high p_T J/ψ is slightly higher than unity
- Shadowing implementations tend to underestimate the size of CNM effects

ALICE maximum p_T reach at mid y is 10GeV/c → R_{pA}, significantly smaller than the CMS one, reflects the p_T coverage

p_T dependence of J/ψ R_{pA}



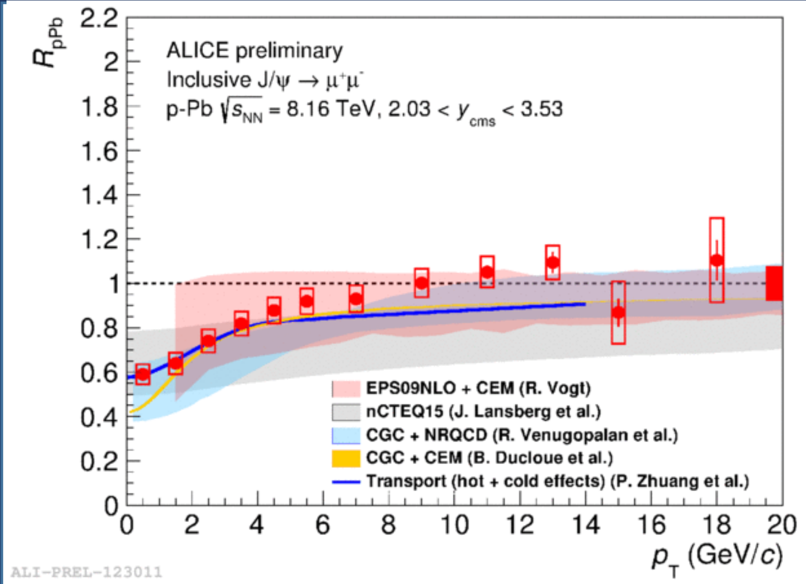


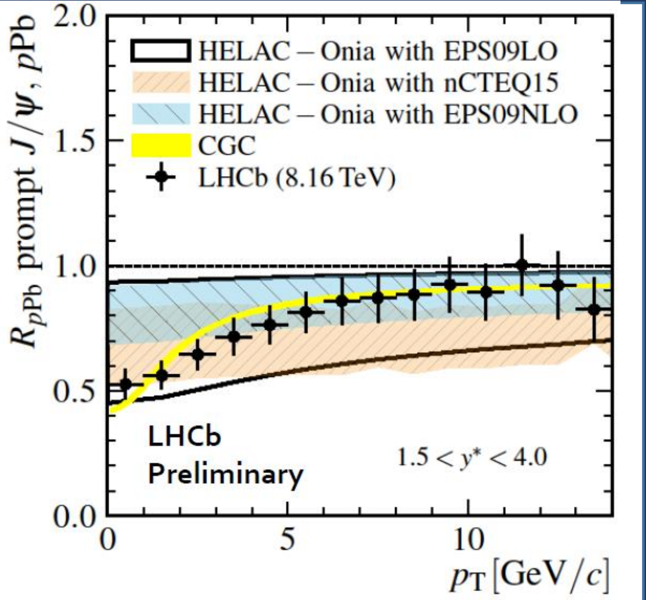
➡ p_T coverage extended up to 20 GeV/c in Run2

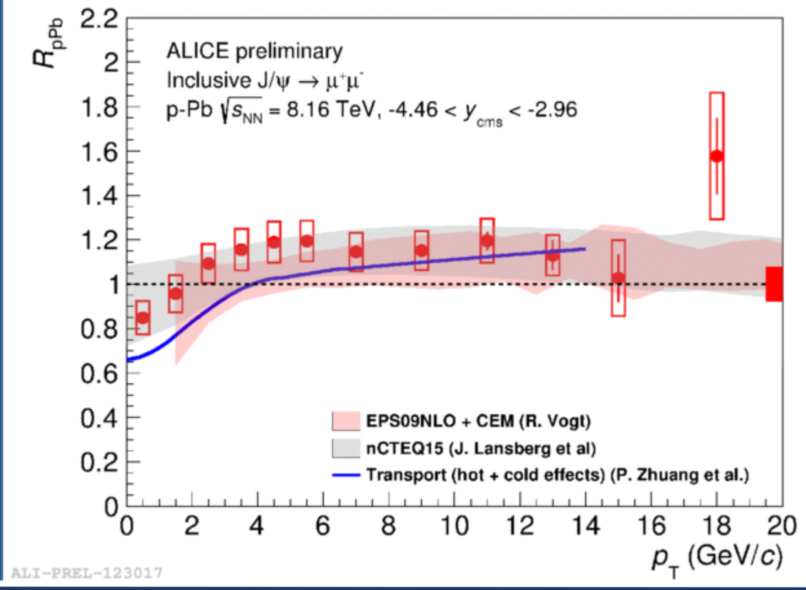
- p-going: R_{pA} increases with p_T
- Pb-going : R_{pA} rather constant

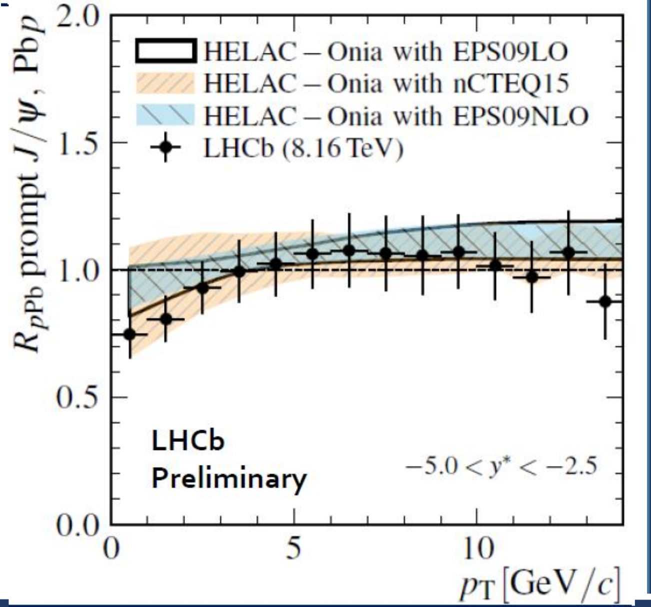
➡ The strong J/ψ suppression observed in Pb-Pb data at high p_T cannot be due to CNM effects

p_T dependence of J/ψ R_{pA}: theory comparison



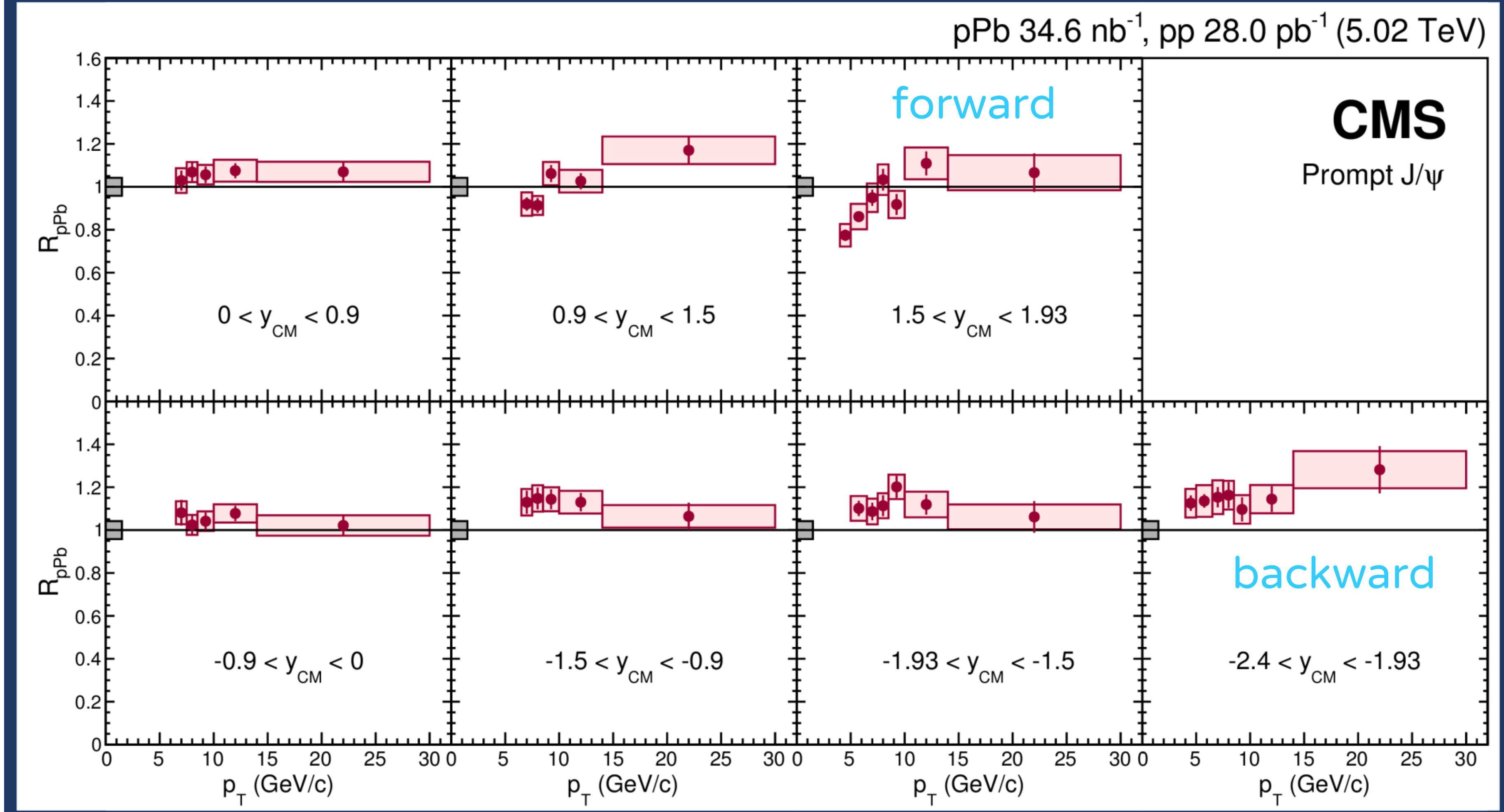






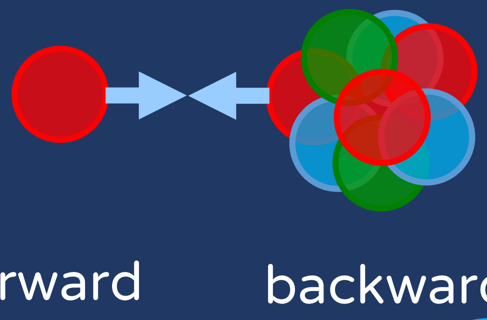
- Slightly different y coverage in ALICE and LHCb, but rather similar p_T dependences
- Shadowing and energy loss models describe the R_{pA} trend vs p_T

J/ψ R_{pA} at high p_T

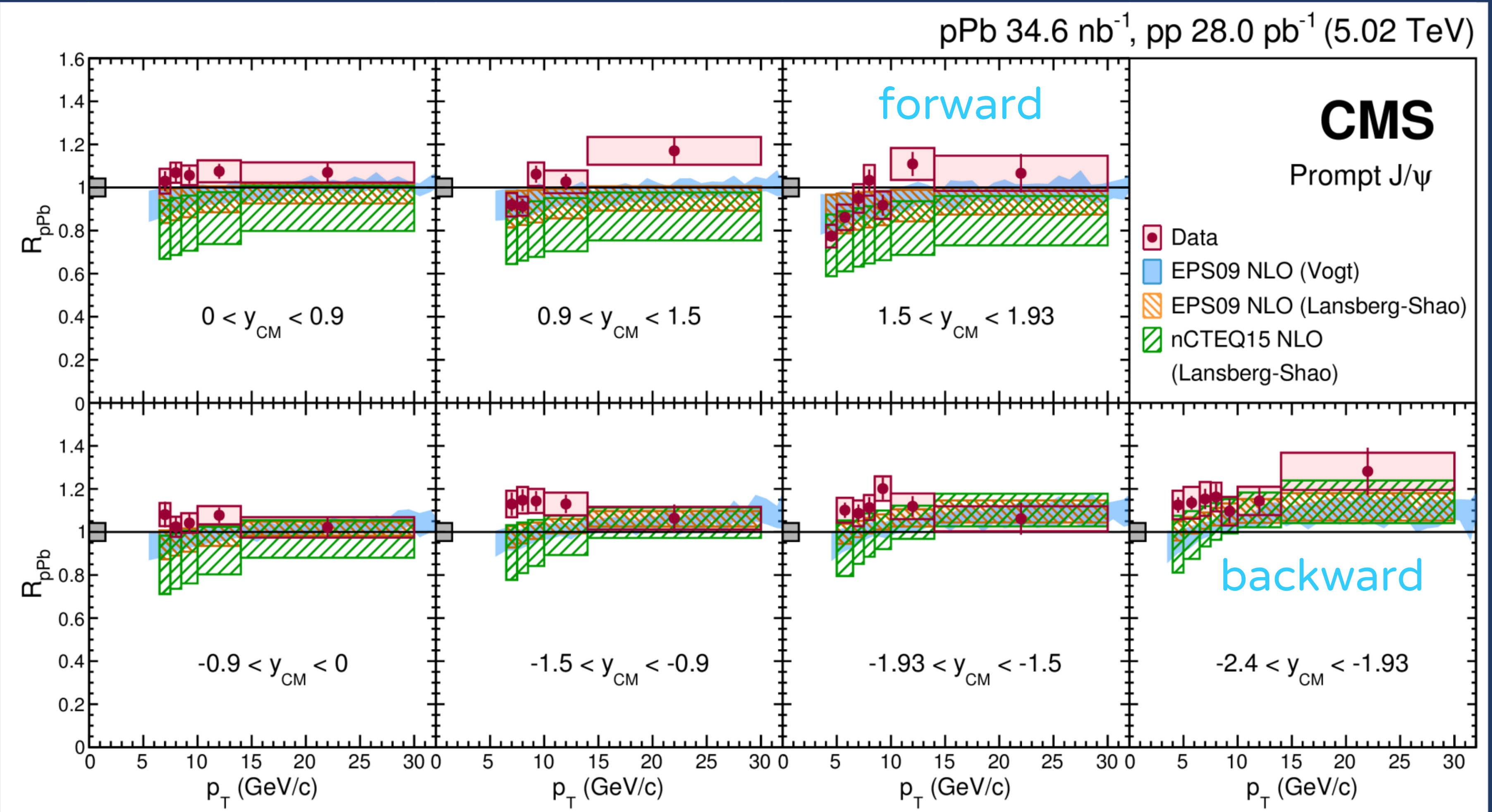


R_{pA} of high p_T prompt J/ψ shows

- values slightly higher than unity at mid and backward rapidity
- hint for stronger CNM effects at the edges of the y domain

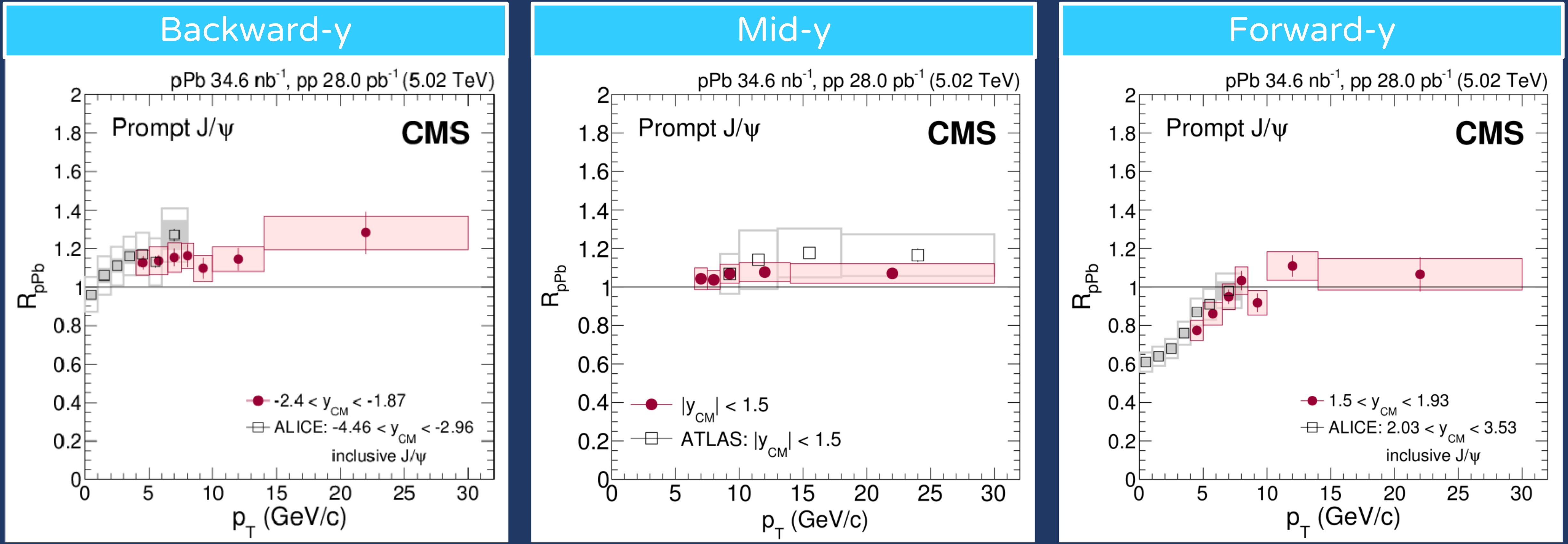


J/ψ R_{pA} at high p_T



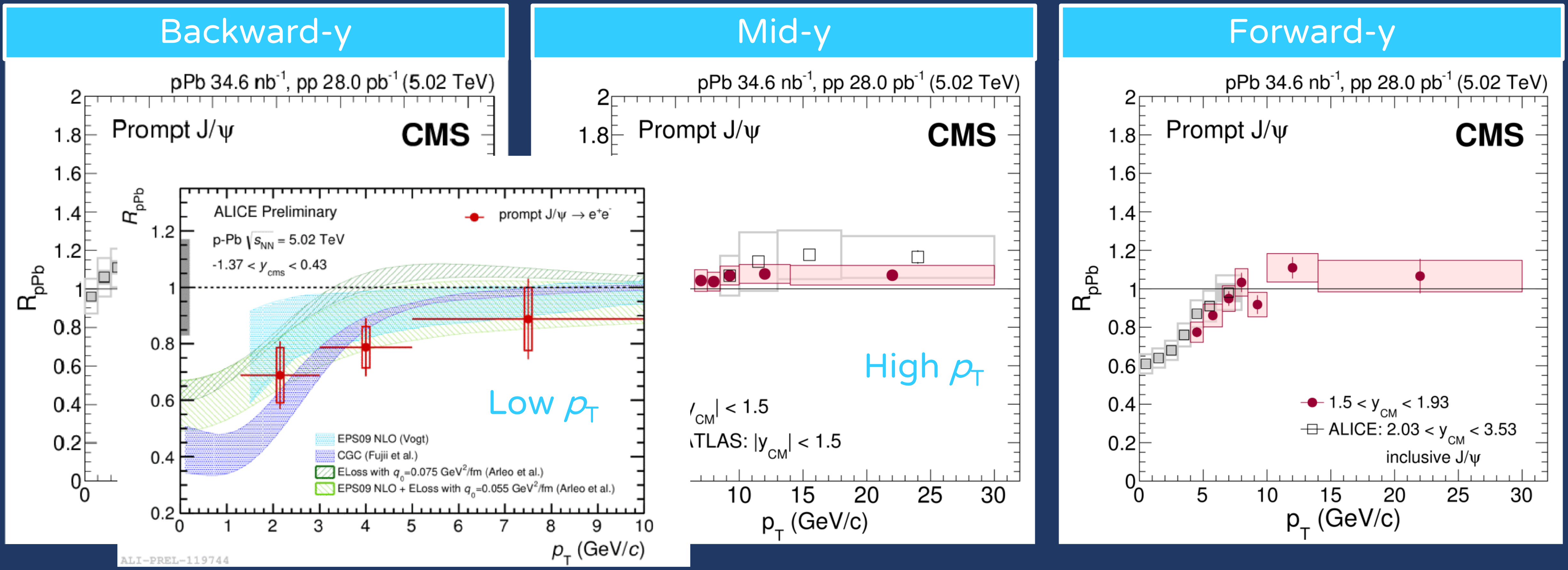
- Different shadowing implementations describe the data trend (even if slightly at the lower edge)

Comparison among experiments



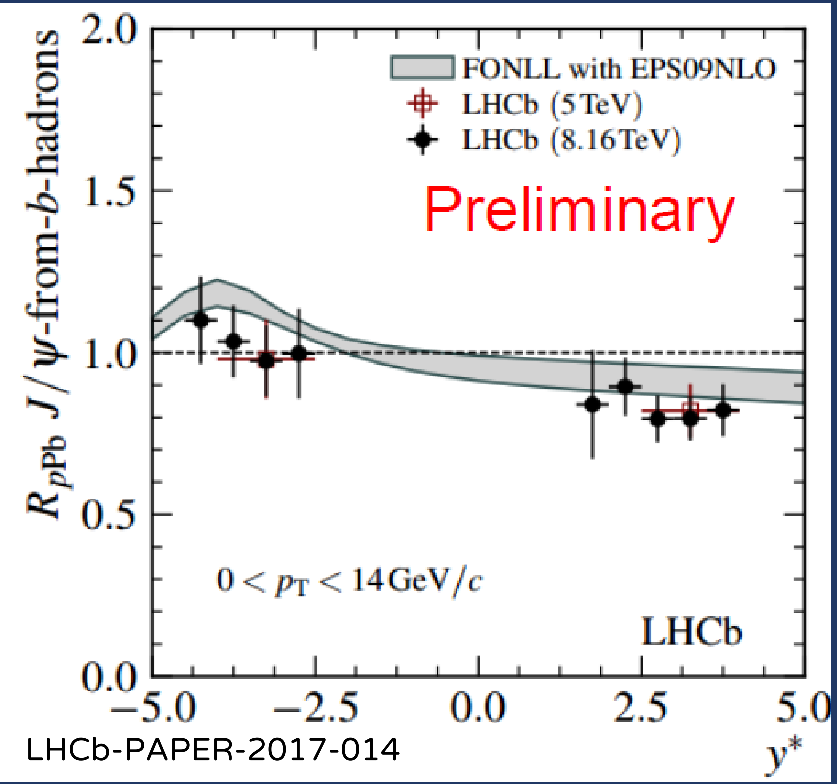
- Compilation of results from different experiments shows
  - Good compatibility in close rapidity ranges
  - Broad p_T coverage from 0 to 30 GeV/c
- Pattern confirms strongest CNM effects at low p_T and forward y

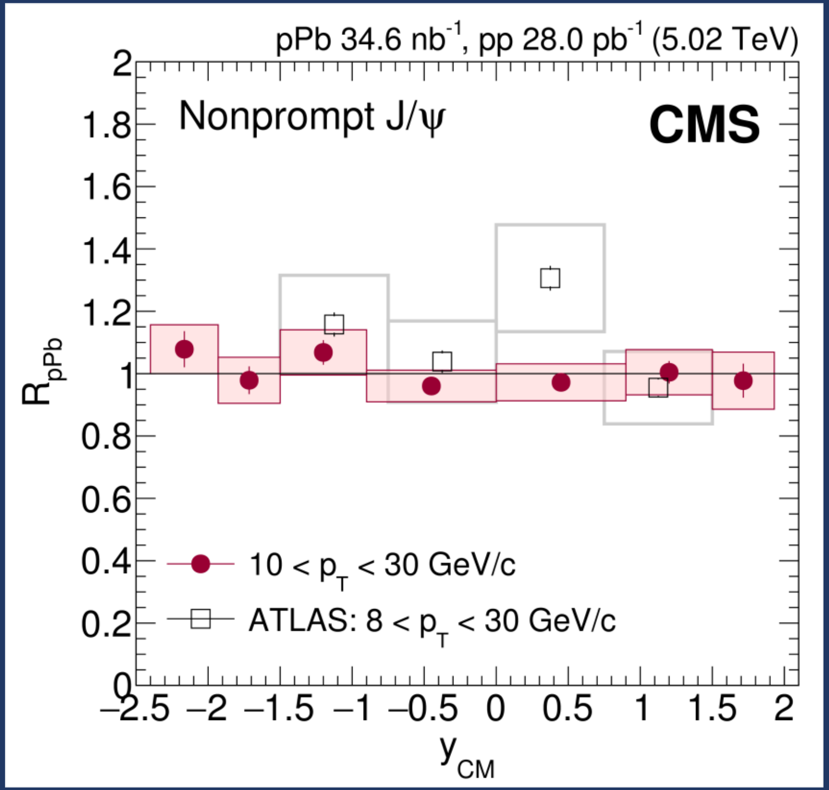
Comparison among experiments



➡ Same decreasing trend towards low pT observed also at mid-rapidity

R_{pA} of non-prompt J/ψ

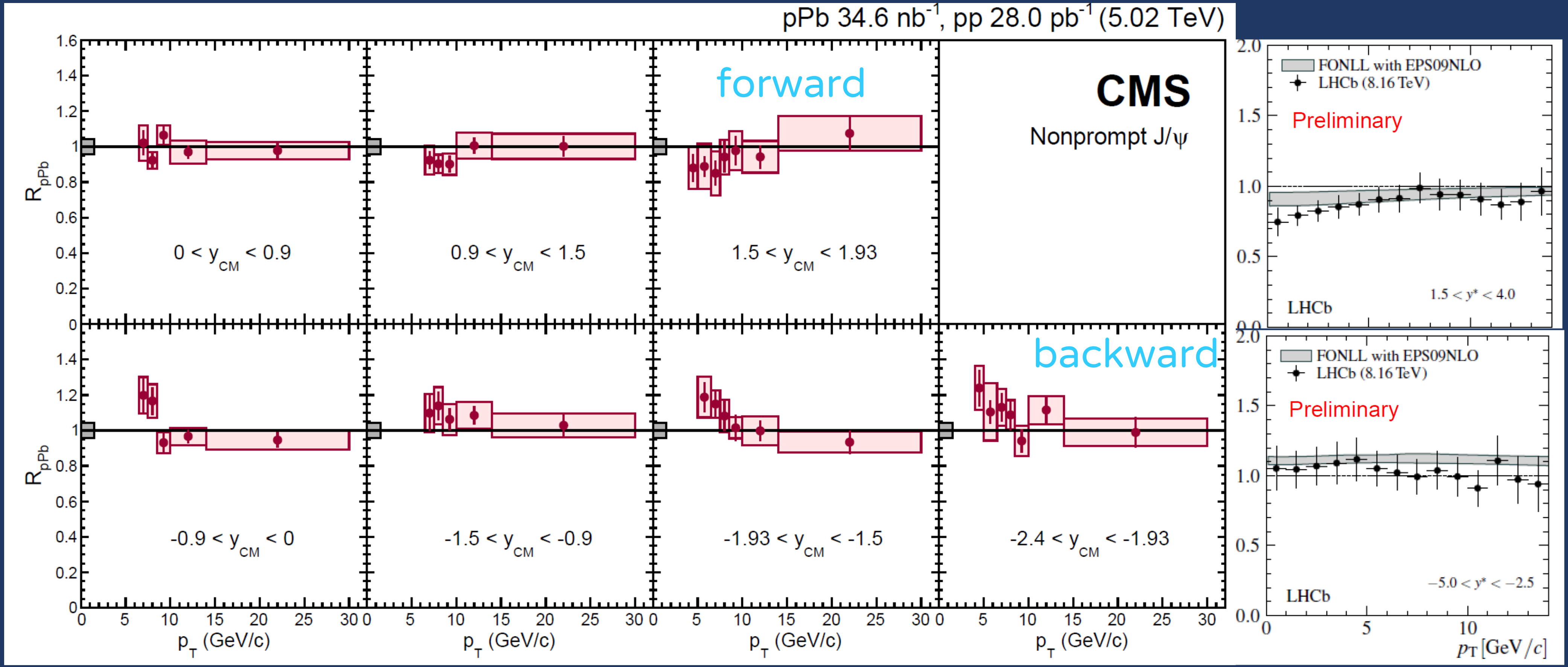




- Agreement between 5.02 and 8.16TeV results
- Small CNM effects on non-prompt J/ψ
- Overall agreement with FONLL+EPS09NLO

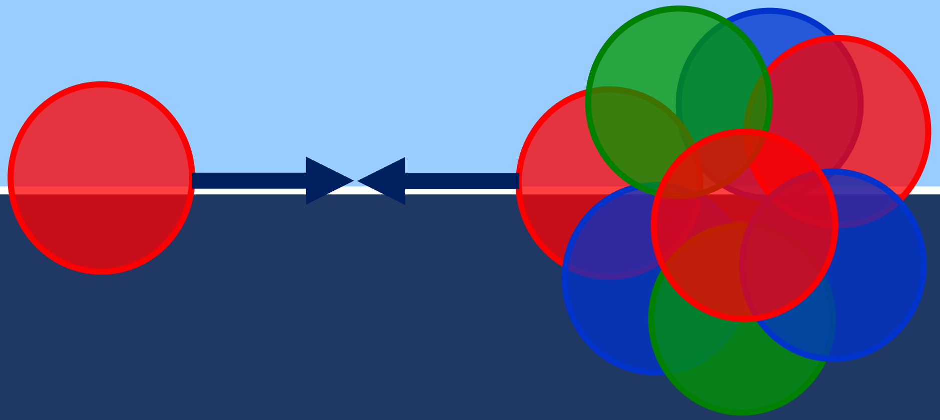
- Complementary y range covered by ATLAS, CMS and LHCb (but a different p_T range)
- Consistent ATLAS and CMS results
- no y dependence for high p_T non-prompt J/ψ

R_{pA} of non-prompt J/ψ



- complementary LHCb and CMS results
- high p_T non-prompt J/ψ show negligible CNM effects
- weak p_T dependence, significant only in the LHCb domain, where it reaches 30%

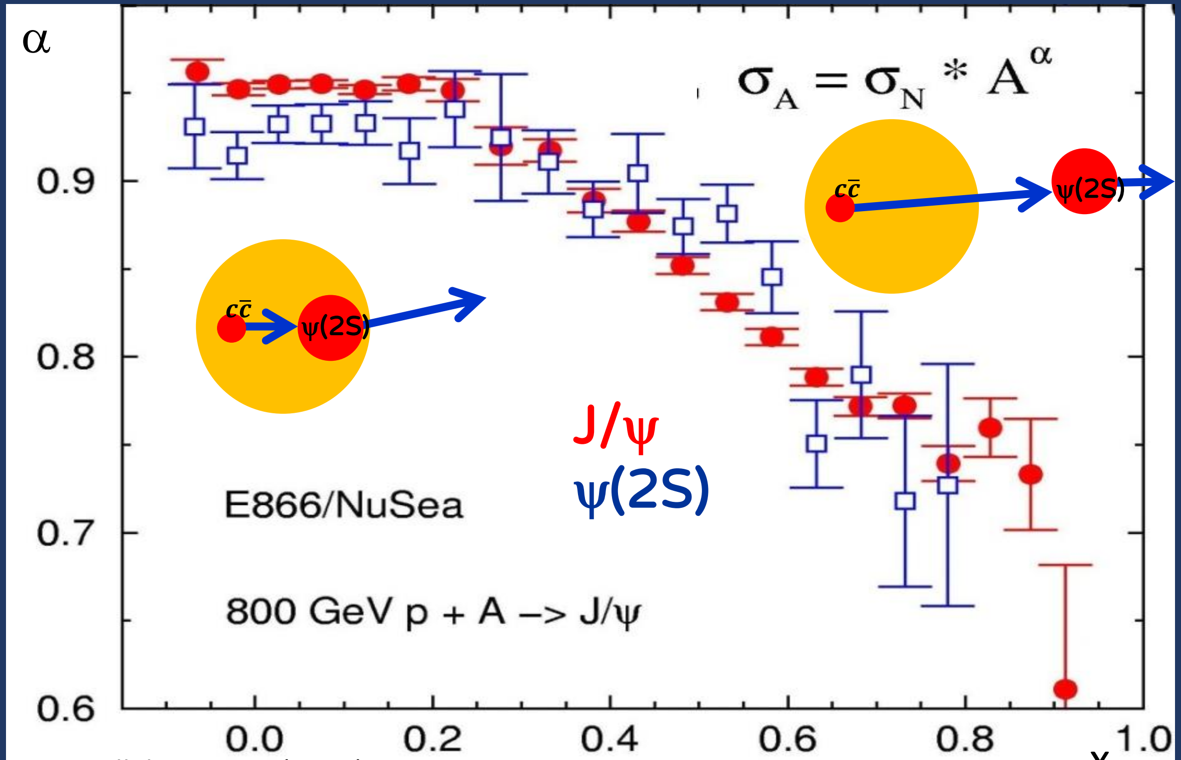
p-A collisions:
ψ(2S)



$\psi(2S)$ as a function of x_F

- Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA

- ψ(2S) production is modified by CNM effects depending on its kinematic



E866 Collab., PRL 84 (2000) 3256

mid-y (x_F~0): ψ(2S) suppression stronger than J/ψ one,
→ break-up of fully formed resonance traversing the nucleus

charmonium formation time < crossing time

fw-y (high x_F): suppression becomes roughly identical
→ dominated by energy loss

charmonium formation time>crossing time

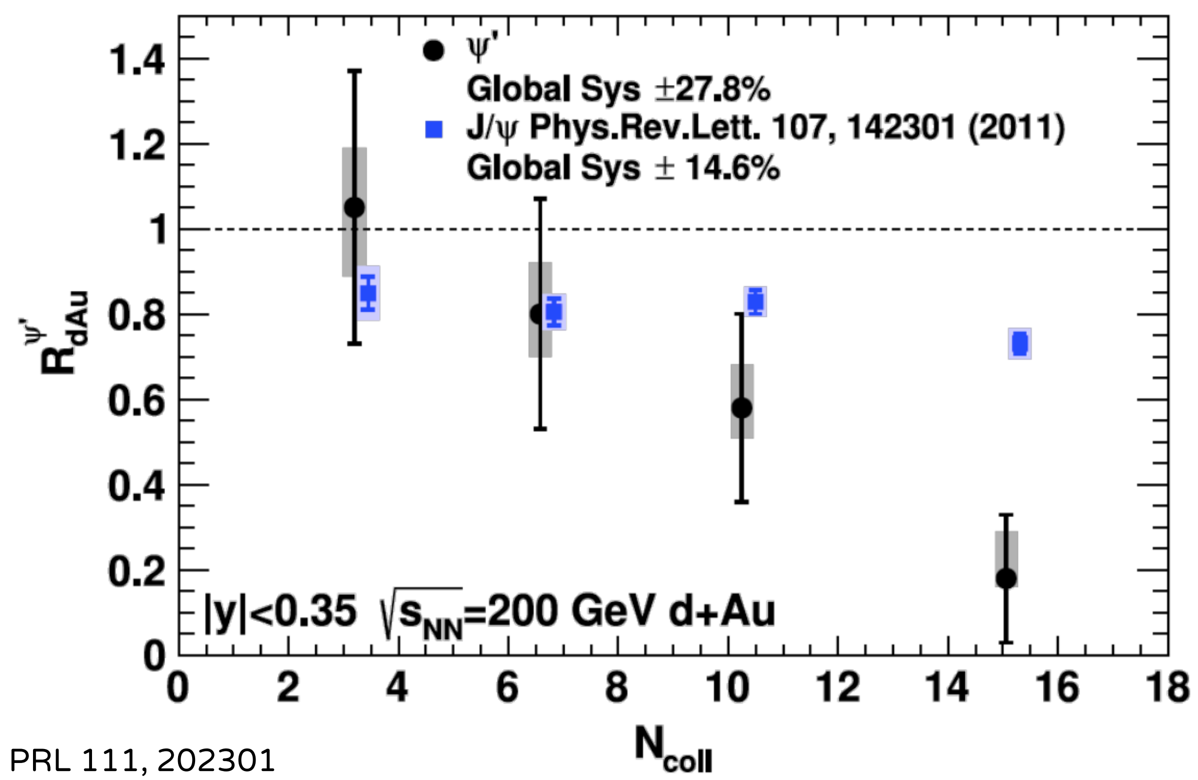
Experiment	√s (GeV)	τ (fm/c)
NA50/60	17-27	0.29-0.34
E866	38.8	0.28-0.02
HERA-B	41.6	0.28-0.003

$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

McGlinchey, Frawley,Vogt PRC 87 054910

ψ(2S) in pA collisions

➡ at RHIC and LHC energies, ψ(2S) suppression stronger than the J/ψ one



PRL 111, 202301

➡ unexpected because time spent by the cc pair in the nucleus (τ_c) is shorter than charmonium formation time (τ_f)

→ break up of the fully formed resonance in the nuclear medium should not play a role

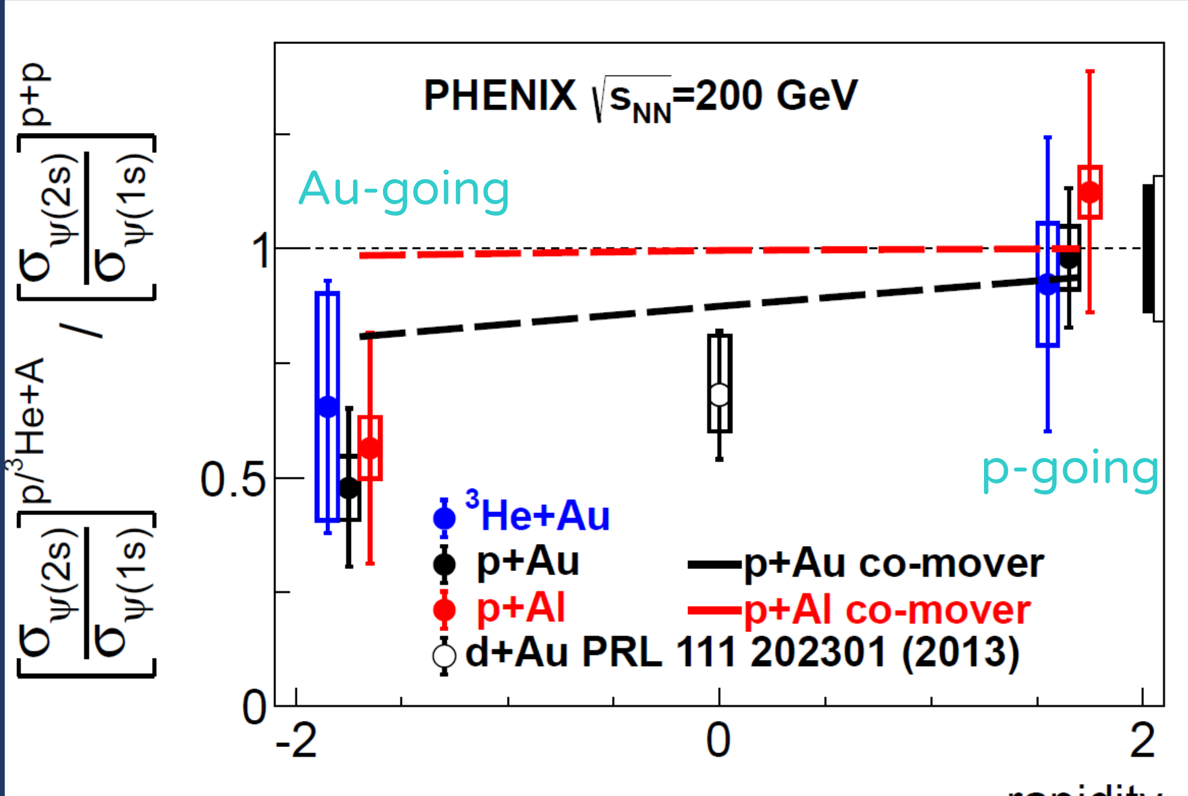
	√s (GeV)	τ (fm/c)
PHENIX	200	fw-y: 0.0035 bck-y: 0.28
ALICE	2760	fw-y: 10^{-4}-10^{-5} bck-y: 3-7 10^{-2}

McGlinchey, Frawley,Vogt PRC 87 054910

➡ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

ψ(2S) in pA collisions at RHIC

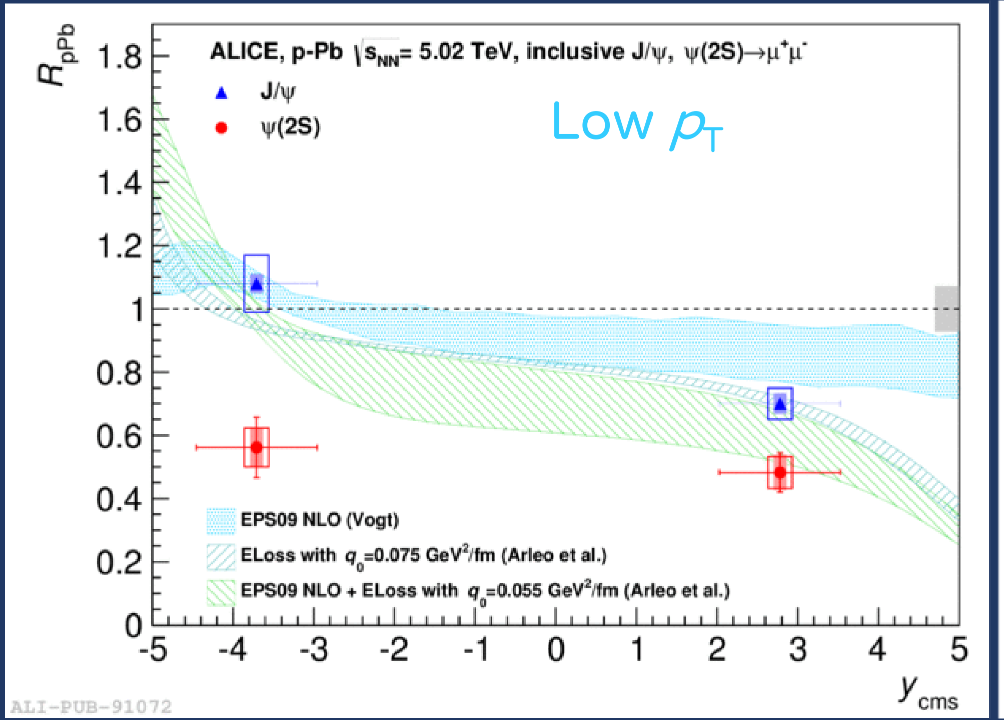
➡ at RHIC and LHC energies, ψ(2S) suppression stronger than the J/ψ one

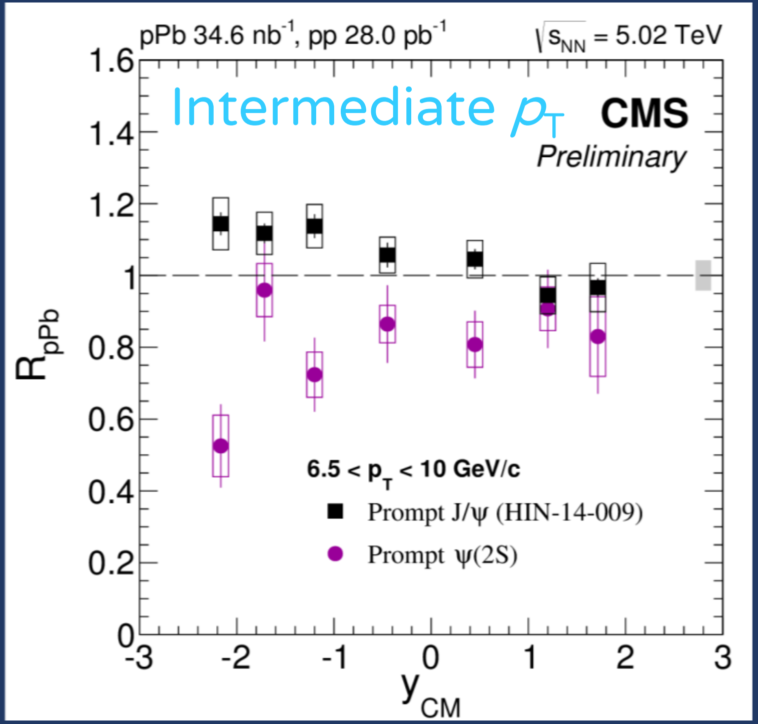


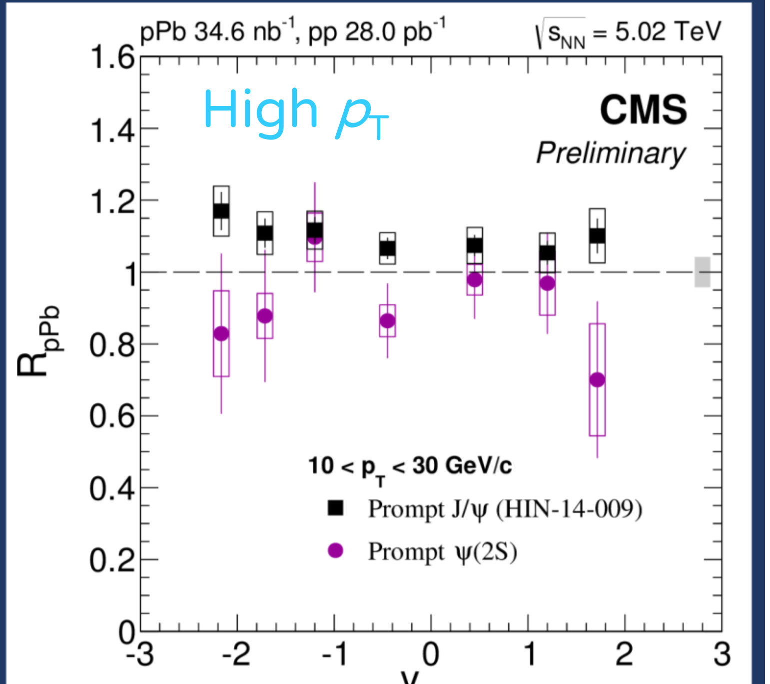
PHENIX: 1609.06550

- Suppression is more important at backward-y
- Final state effects needed to explain the behaviour

ψ(2S) RpA at LHC







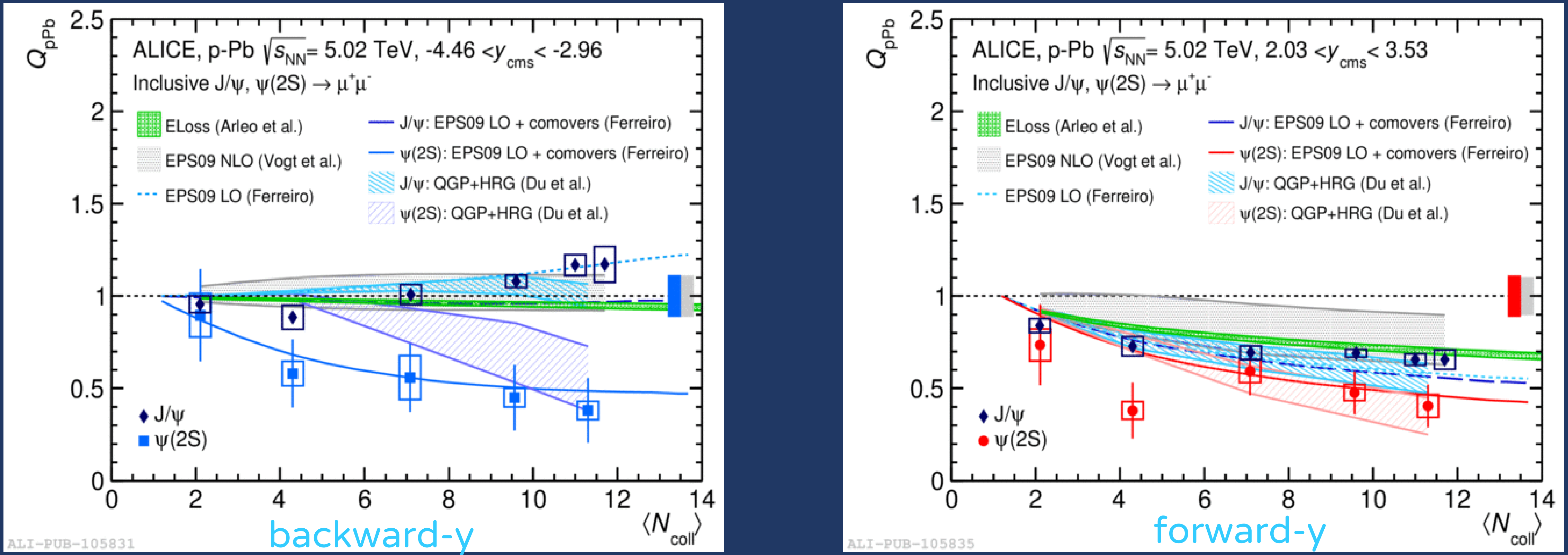
CMS-PAS-HIN-16-015

- Stronger ψ(2S) suppression with respect to the J/ψ one, mainly:
  - at backward rapidity
  - at the low(est) p_T

- Backward-y: size of ψ(2S) suppression rather similar between ALICE and CMS
- Forward-y: suppression is more important in the ALICE p_T range
- Comparison with models in the high p_T range would be interesting!

ψ(2S) in pA collisions at LHC

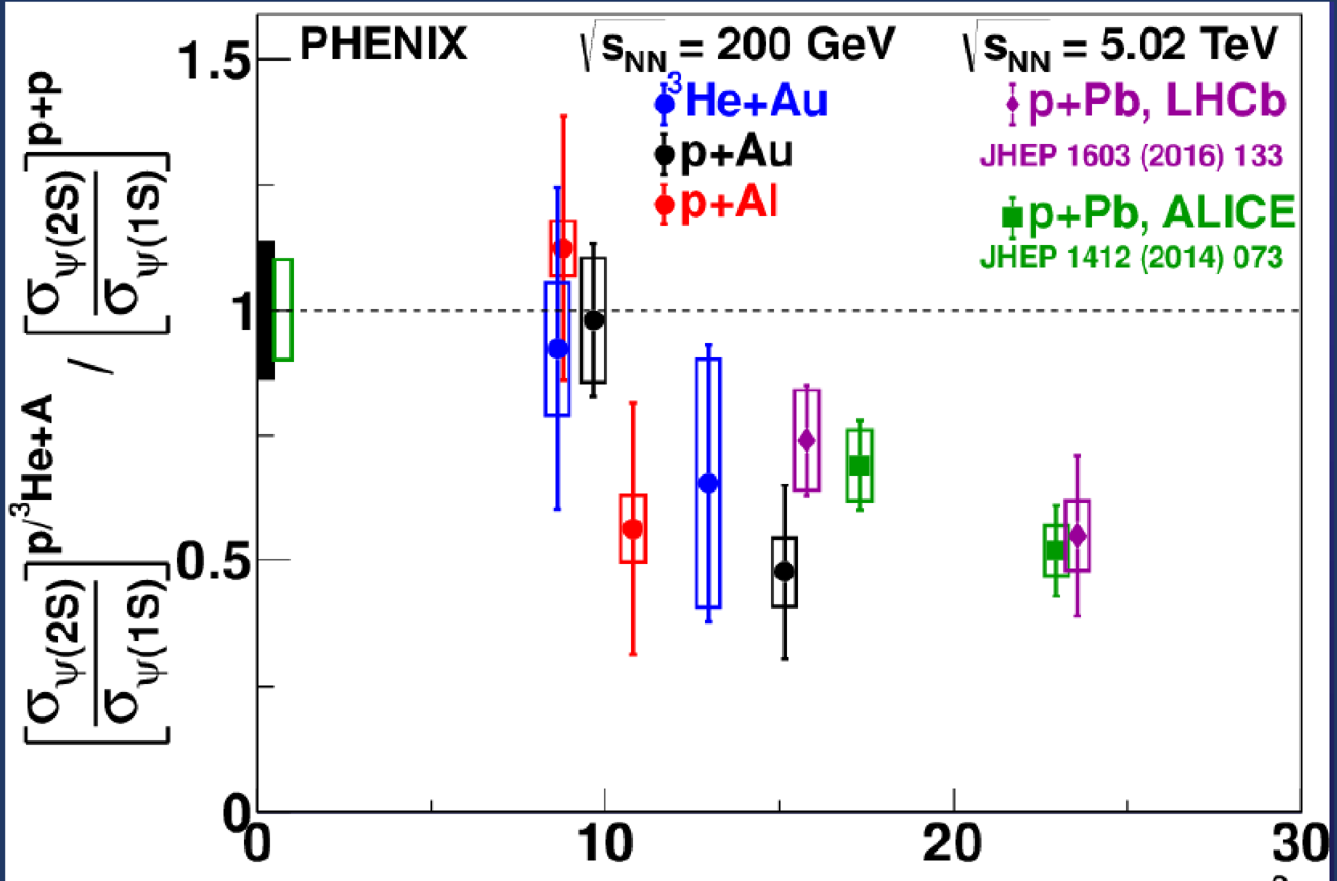
- Suppression is stronger in central collisions



- Clear evidence for a stronger ψ(2S) suppression, wrt J/ψ, at backward rapidity
- QGP+hadron resonance gas (Rapp) or comover (Ferreiro) models describe the stronger ψ(2S) suppression

ψ(2S) in pA at RHIC and LHC

Under the assumption that the ψ(2S) is suppressed by final state effects, RHIC and LHC results can be compared in terms of comoving particle densities

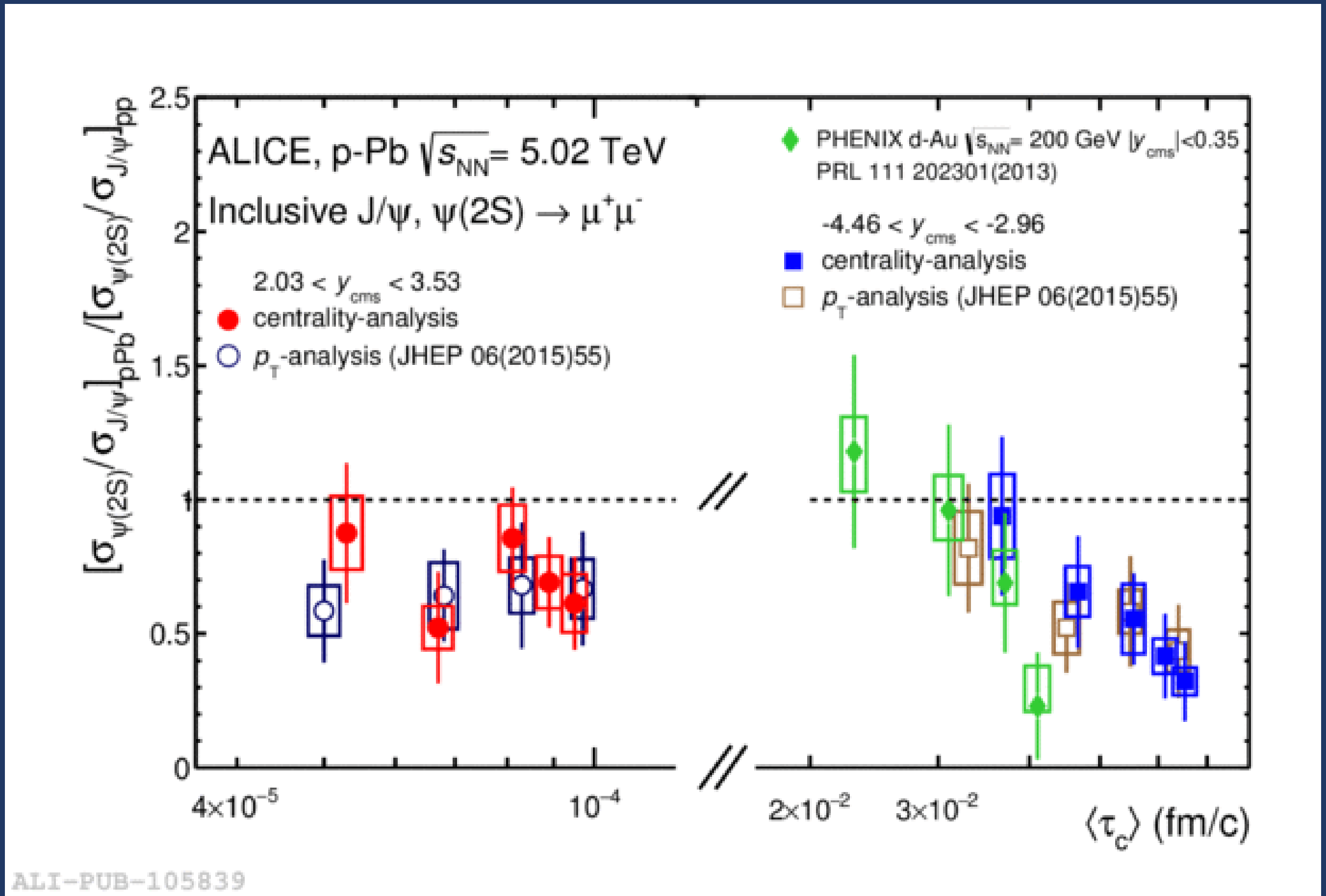


Comoving particle density → $(dN/d\eta)_{AMPT}$ / ($\langle S_T \rangle$) (fm^{-2})

- Largest comoving particle density reached at LHC, at backward-y
- Backward-y RHIC data reach a similar comoving particle density as forward LHC
- Double ratio decreases, increasing the comoving particle density
  → Consistent with the ψ(2S) break-up in final state interactions

ψ(2S) in pA at RHIC and LHC

Relative J/ψ and ψ(2S) suppression is studied as a function of the crossing times

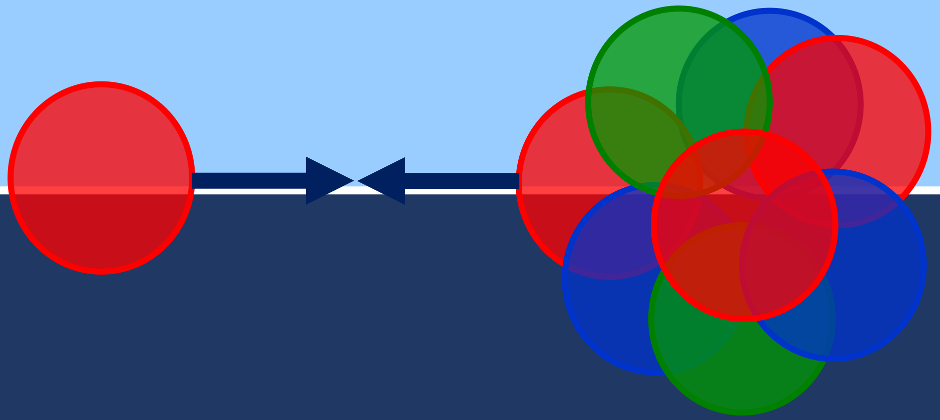


- Within uncertainties a scaling between RHIC and LHC is observed
- At backward-y, where the largest τ_c are reached, a decreasing trend is observed

  → Even if the quarkonium formation time is larger than τ_c, is a fraction of the cc pairs hadronizing inside the nucleus?

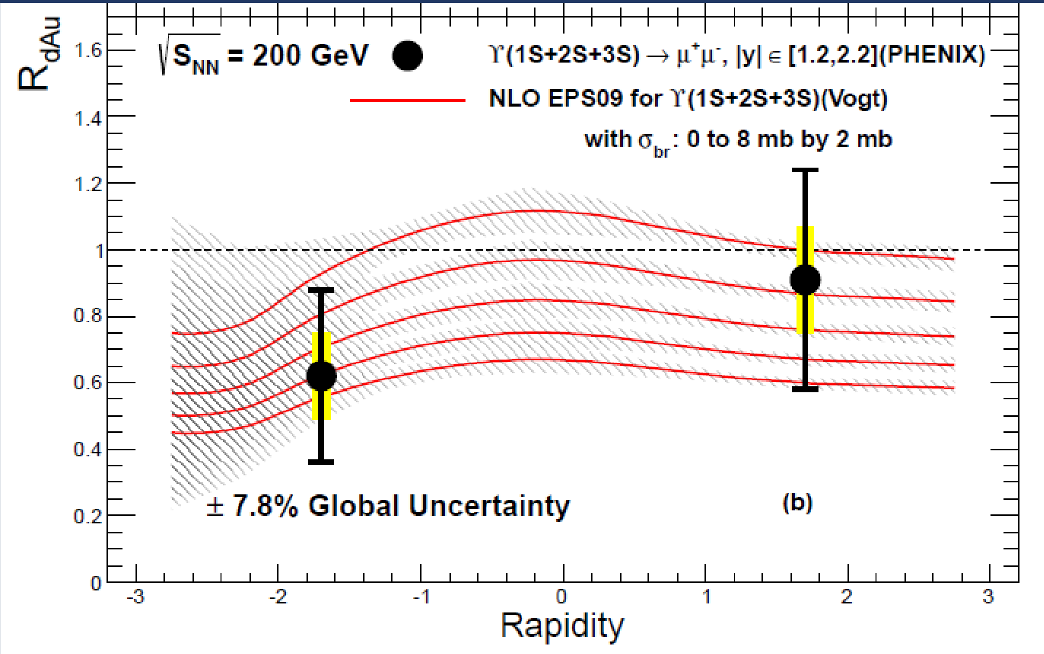
- At forward-y, τ_c<<τ_f by 2-3 order of magnitude.
  → In principle no final state effects related to cold nuclear matter can play a role, only comover interaction

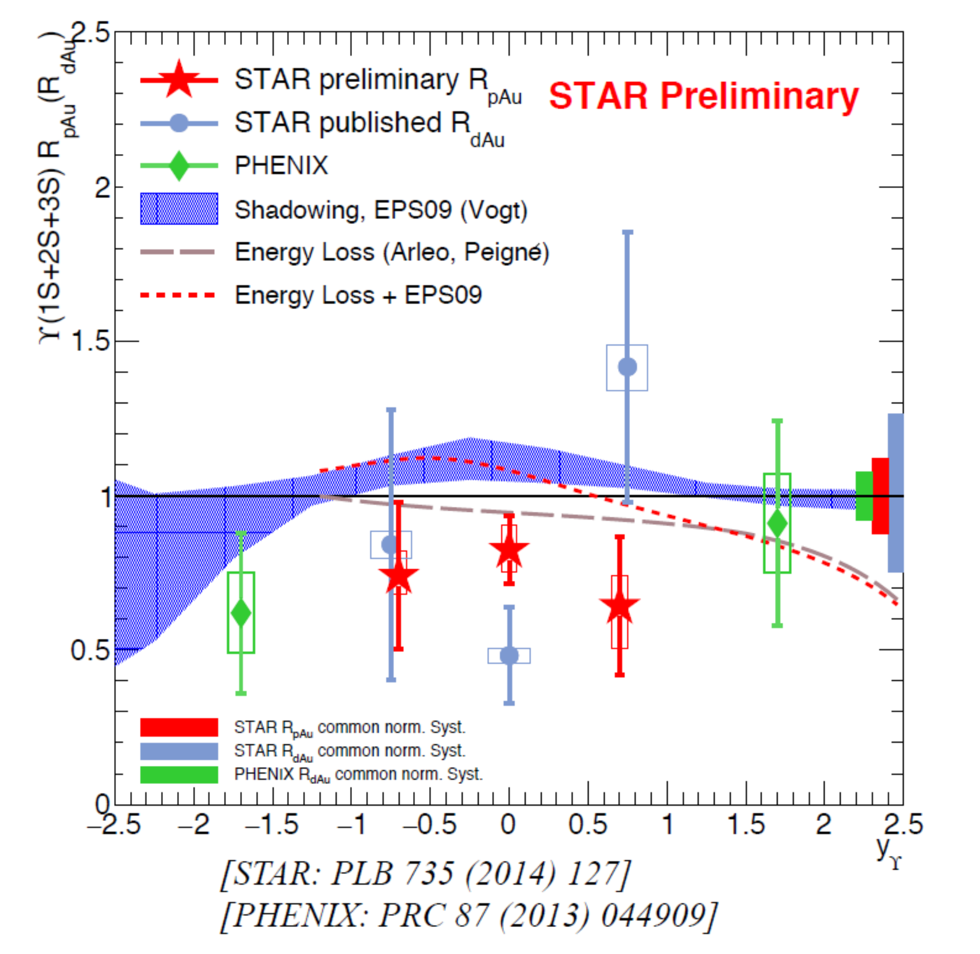
p-A collisions:
Υ



ϒ in pA and dA at RHIC

- ϒ(1S+2S+3S) measured in both pA and dA
  - Large uncertainties for R_{dAu} prevent a clear understanding of the ϒ y-evolution
  - Need for bb break-up in nucler matter not obvious

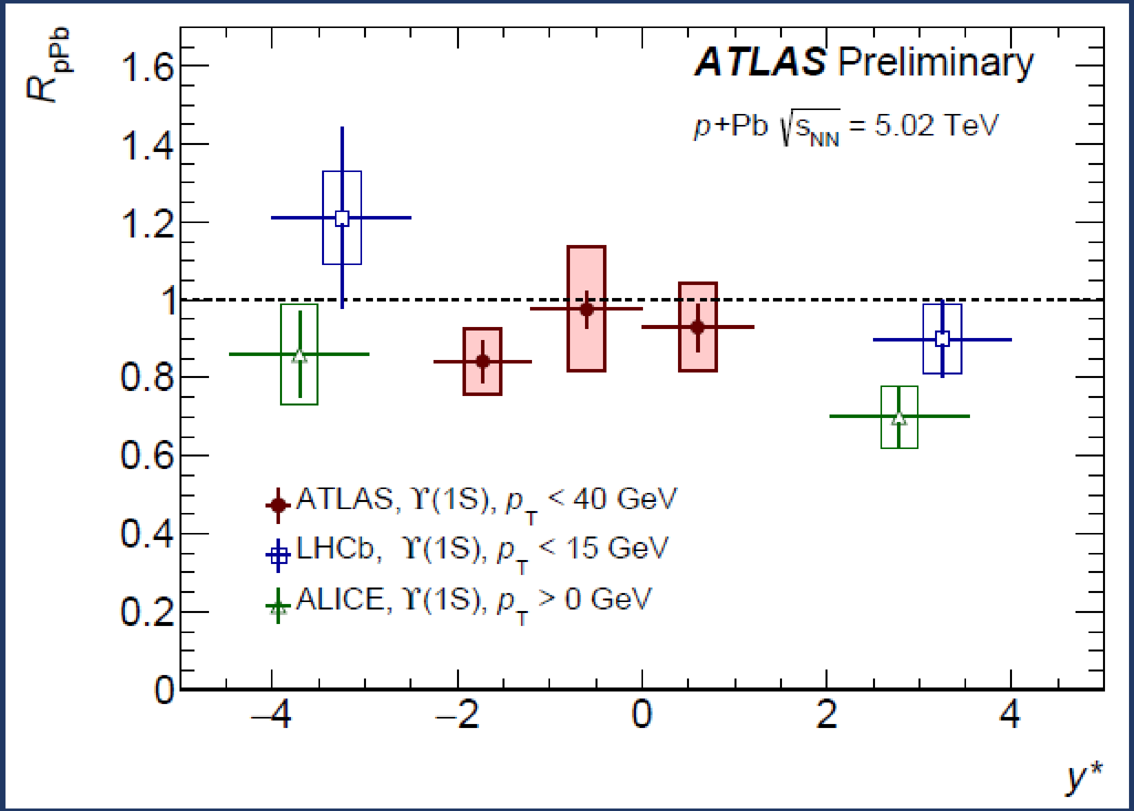




- New STAR R_{pA} (~0.8), with improved precision wrt R_{dAu}, suggest cold nuclear matter effects on ϒ(1S+2S+3S) at mid-y

RpA ϒ(1S) at LHC

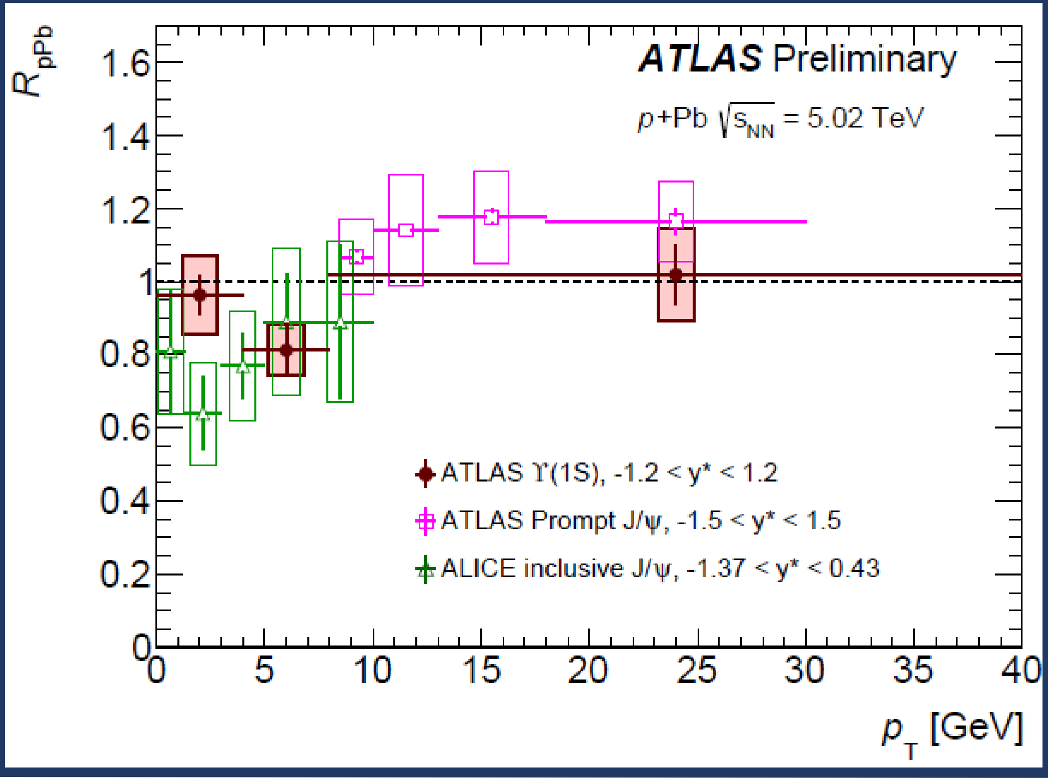
- Wide y coverage explored by ALICE, ATLAS and CMS



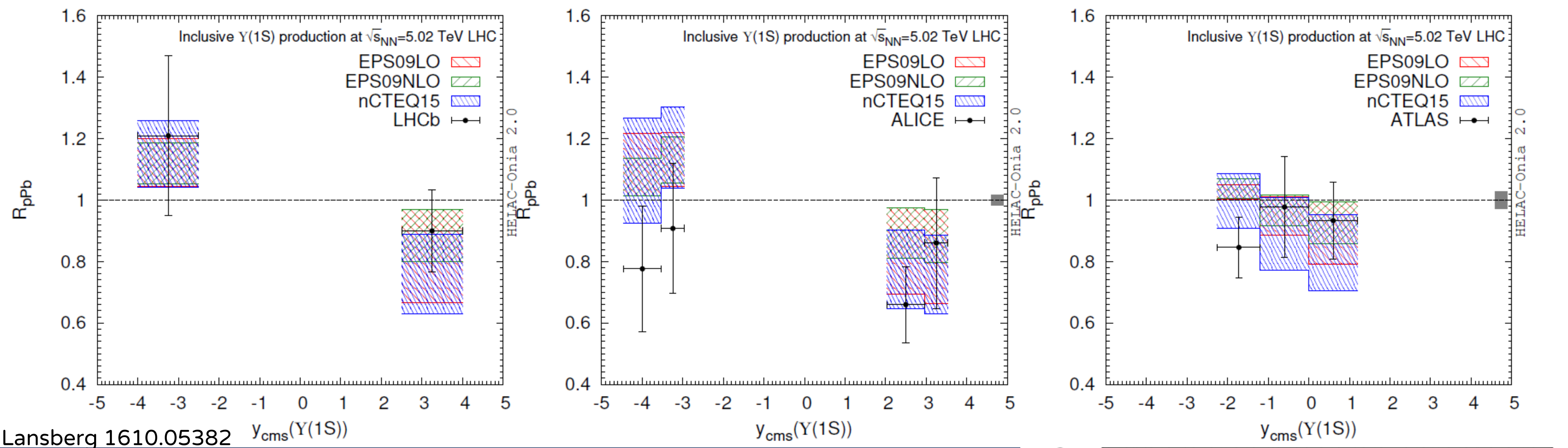
- p_T dependence not conclusive so far

- ALICE and LHCb compatible within uncertainties, but LHCb values systematically larger

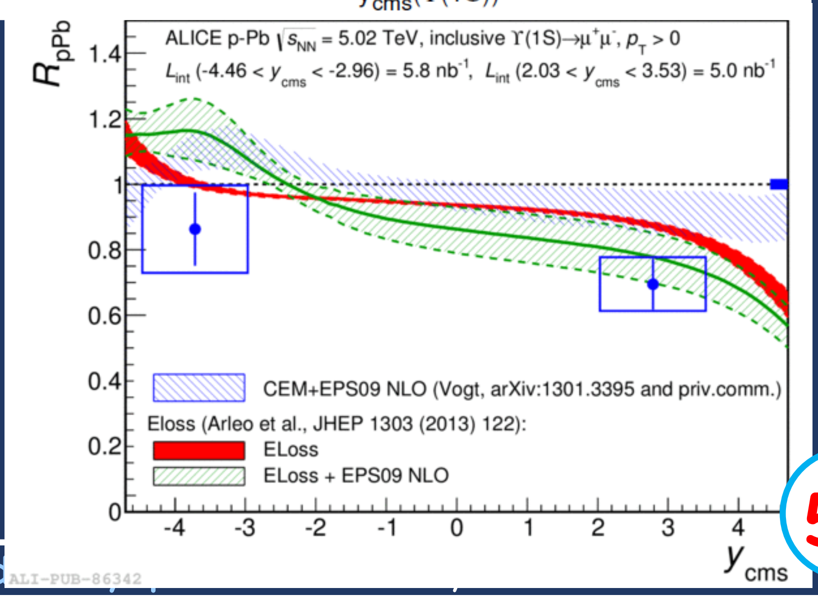
- Hint for a stronger ϒ(1S) suppression at forward-y in ALICE data, while mid- and backward-y is compatible with no modification



R_{pA} $\Upsilon(1S)$ at LHC

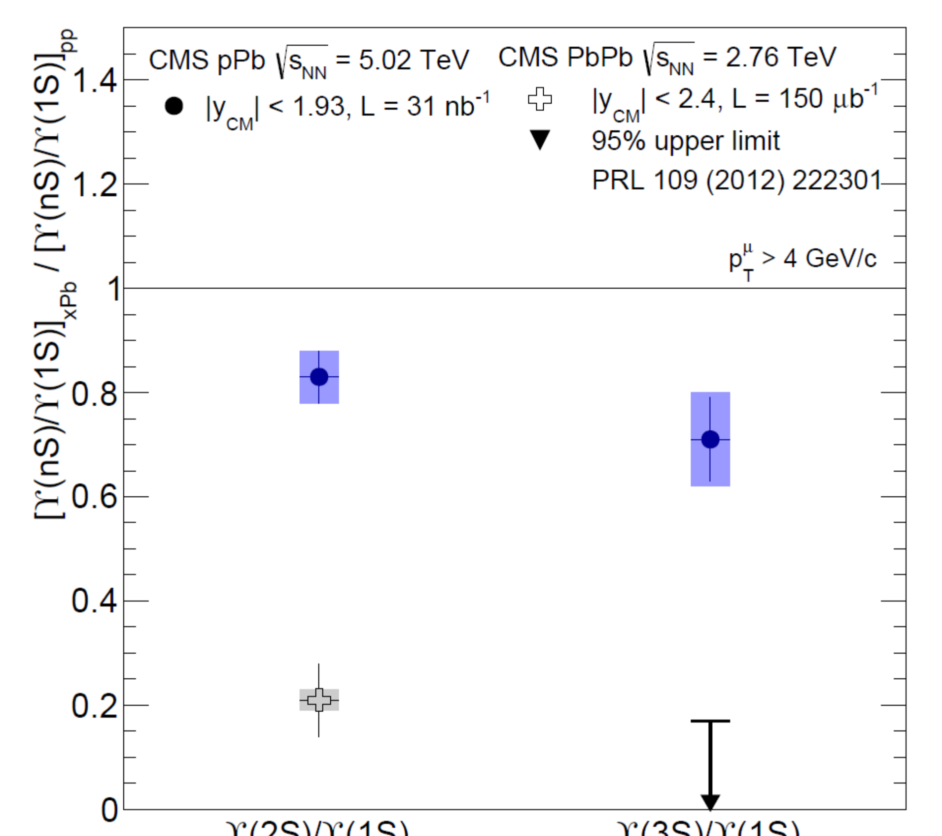


Lansberg 1610.05382



- R_{pA} compatible, within uncertainties, with modifications due to shadowing and/or energy loss
- At backward-y, models tend to be closer to LHCb measurement, while they overestimate the ALICE R_{pA}

Excited Υ states



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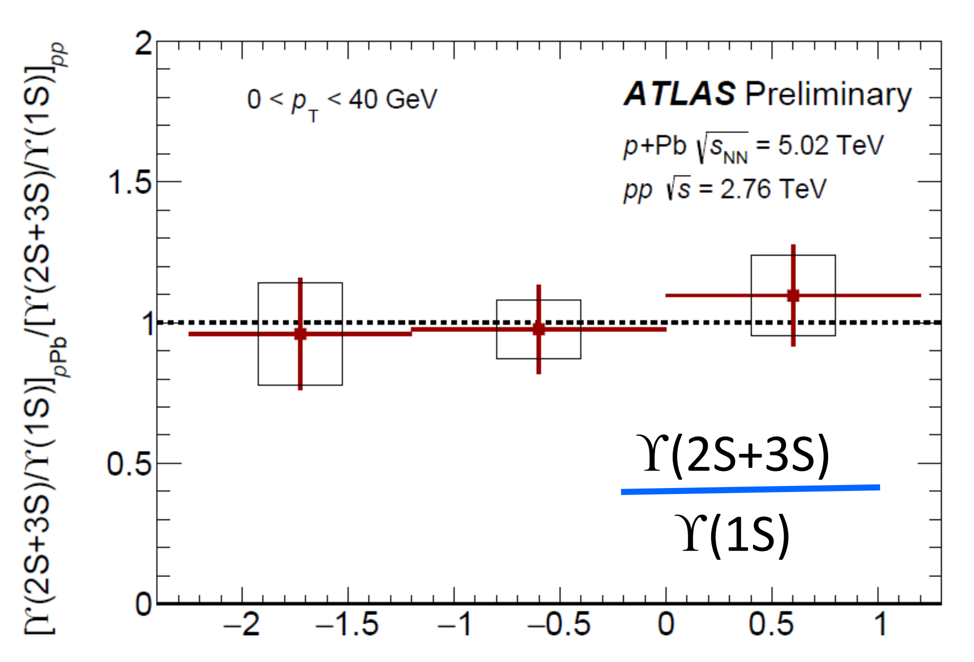
➡ Excited bottomonium states are more suppressed than the ground state already in pA collisions

→ Similar initial state effects for all the Υ states
→ Suggestive of final state effects at play on 2S and 3S states?

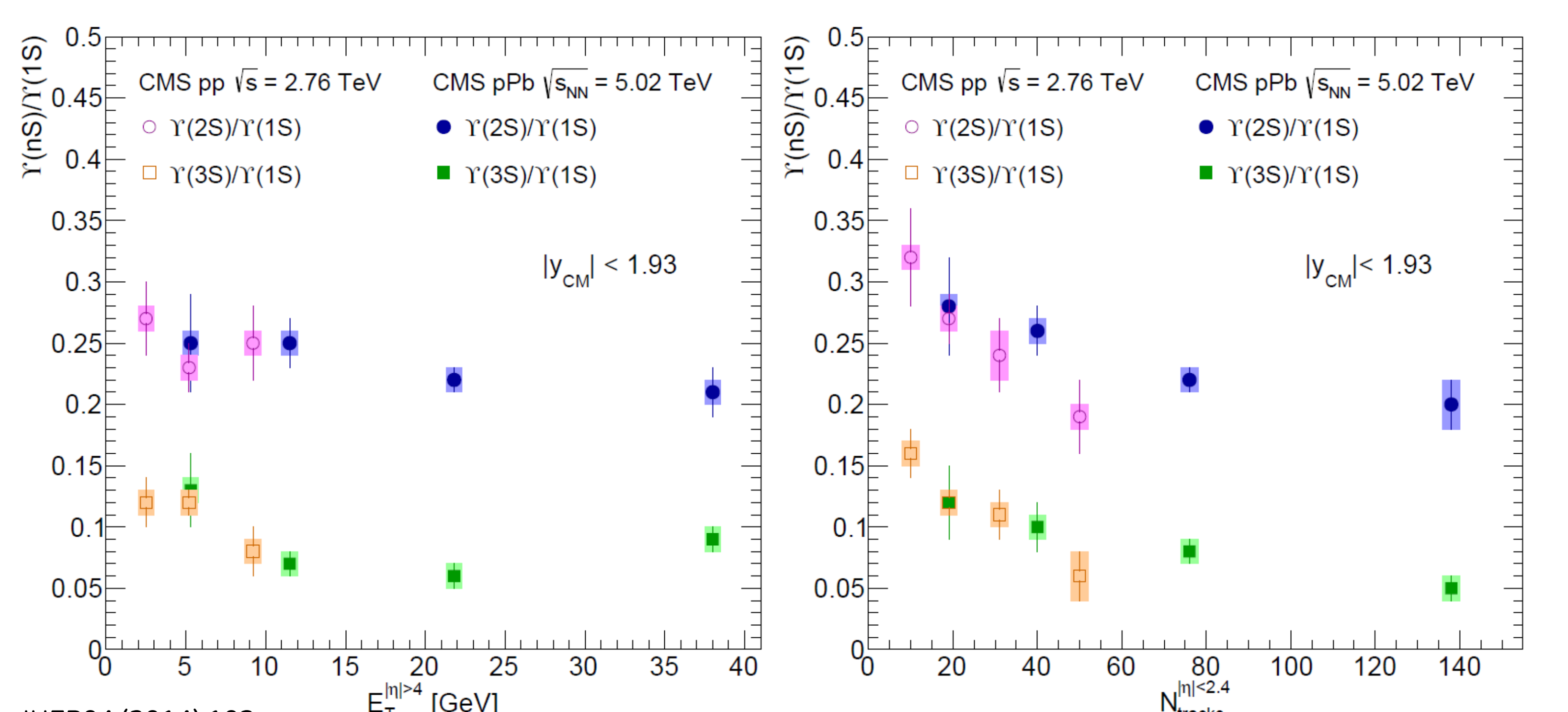


ATLAS-CONF-2015-50

➡ ATLAS suggests no difference between excited and ground states, even is still compatible with CMS within uncertainties

Excited Υ states

➡ Suppression increases with event multiplicity, but with a different trend depending on the adopted estimator

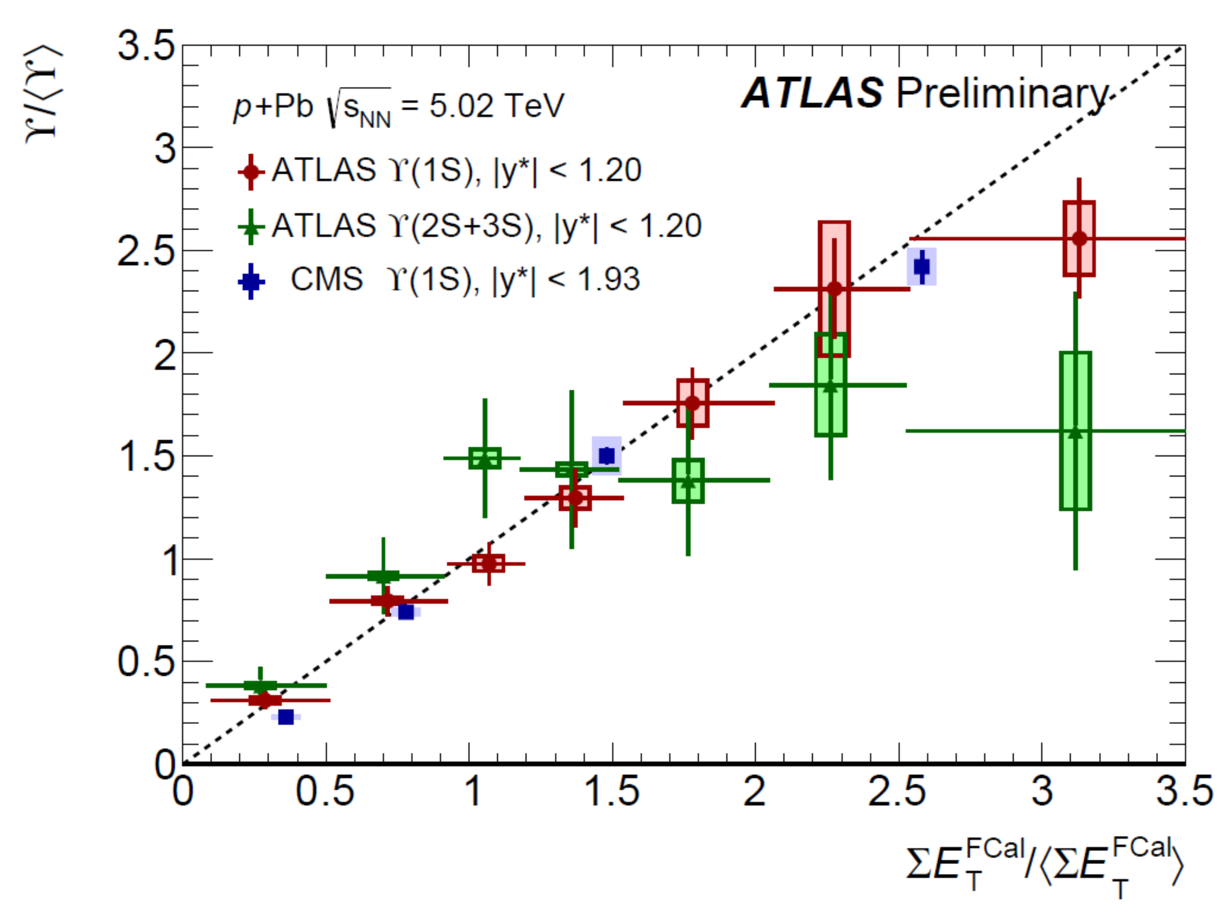


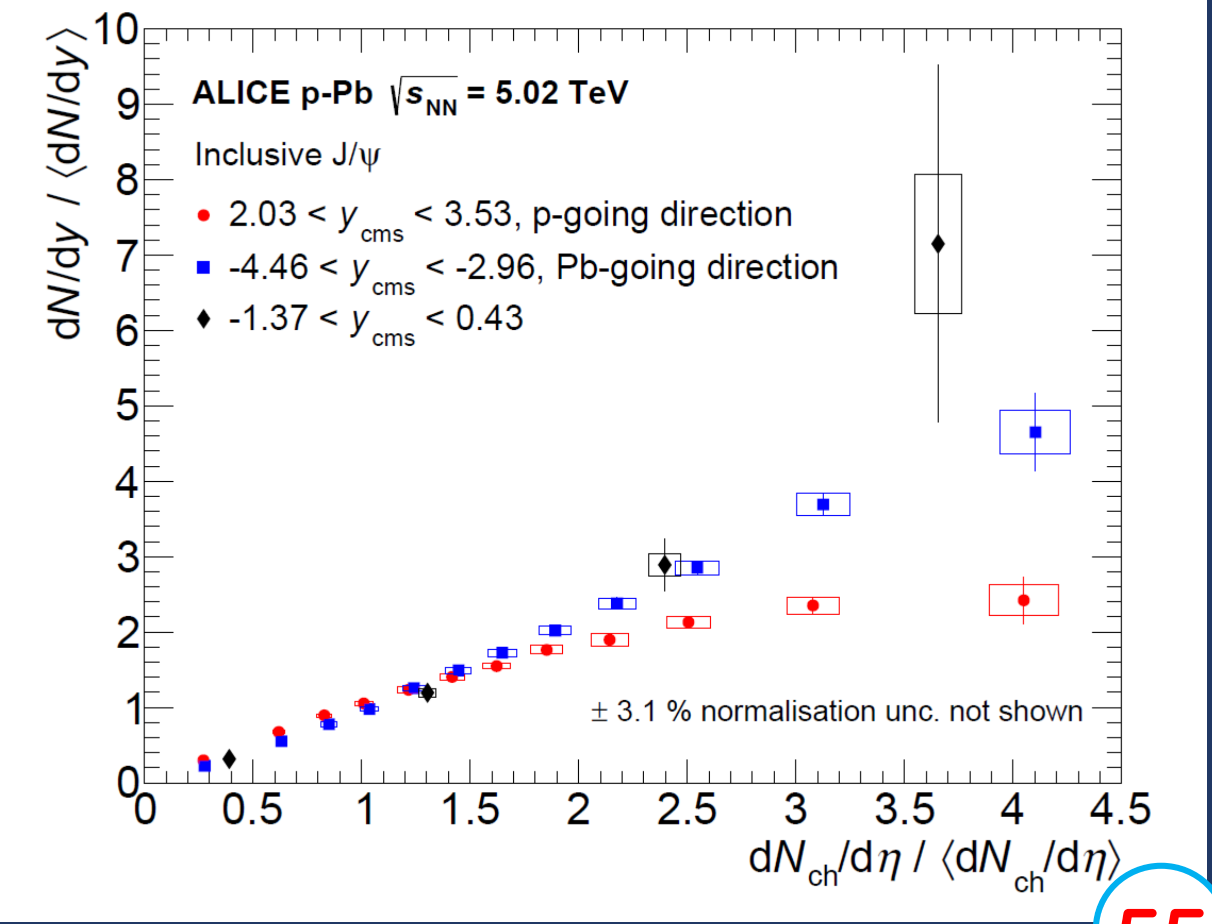
JHEP04 (2014) 103

Larger number of particles produced with ground state or suppression of excited states?

Self normalized ratios vs event activity

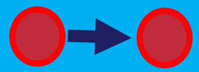
- Increase of the self-normalized yields vs event activity
- Compatible trends observed by ATLAS and CMS



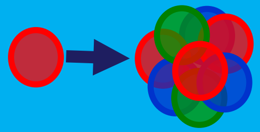


Conclusions

Several quarkonium states now accessible with high precision in p-A and d-A

pp 

Cross-sections, double ratio and non-prompt contributions precisely measured over a broad kinematic range

pA 

Interplay of shadowing and energy loss describes J/ψ and Υ production in p-Pb

Stronger suppression observed on ψ(2S) due to QGP-like effects in pA

Many new results still to come….

Thanks!