Quarkonium production: results from LHC run-1

E. Scomparin (INFN-Torino)

Santa Fe

Jets and Heavy Flavor Workshop

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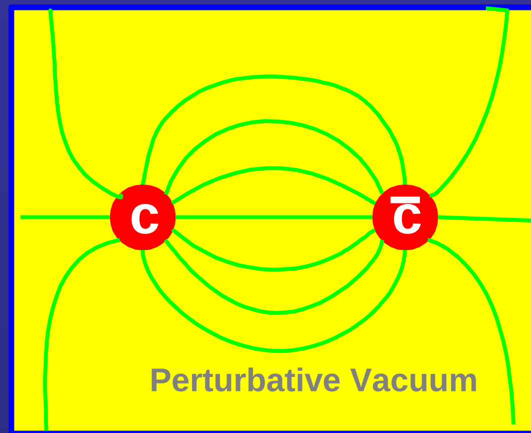
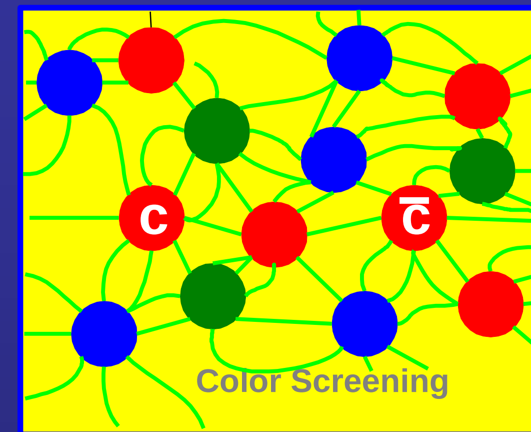
- Short introduction (color screening, regeneration…)
- Results from LHC run-1 (hot vs cold matter effects)
- Open points and prospects for run-2

Quarkonia: from color screening…

Screening of strong interactions in a QGP





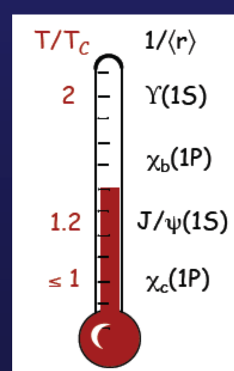
T. Matsui and H. Satz, PLB178 (1986) 416

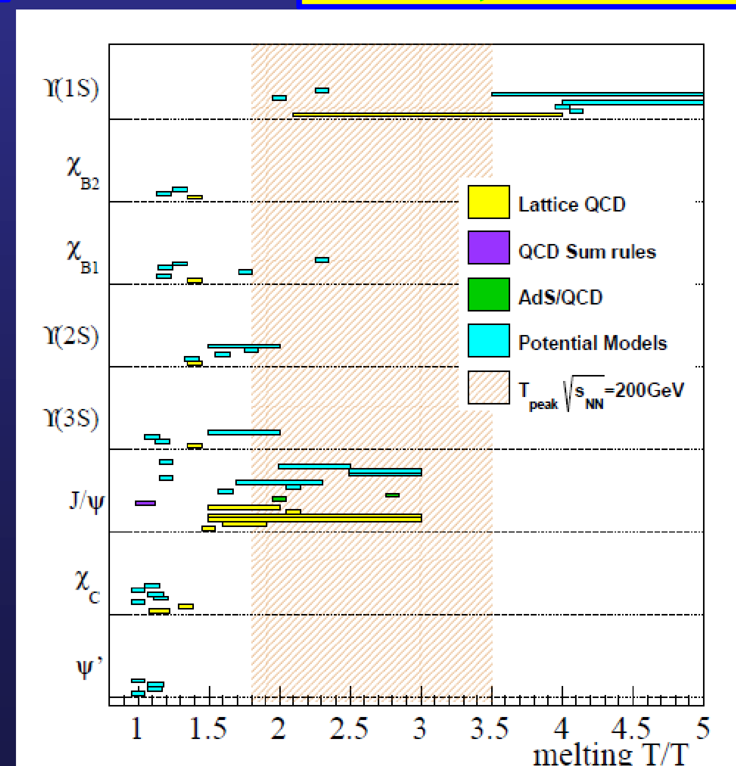
- Screening stronger at high T
- λ_D → maximum size of a bound state, decreases when T increases
- Different states, different sizes

Resonance melting

↓

QGP thermometer



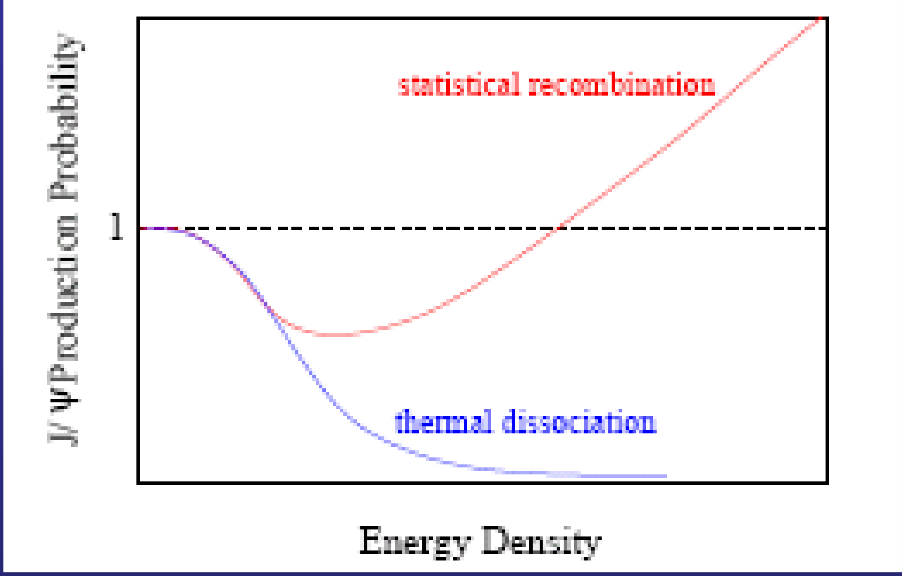


A. Adare et al. (PHENIX), arXiv:1404.2246

…to regeneration (charmonium!)

At sufficiently high energy, the cc pair multiplicity becomes large

Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76TeV
N_{ccbar}/event	~0.2	~10	~85



Statistical approach:

- ❑ Charmonium fully melted in QGP
- ❑ Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

Kinetic recombination:

- ❑ Continuous dissociation/regeneration over QGP lifetime

P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196
Thews, Schroedter and Rafelski, PRC63 054905 (2001)

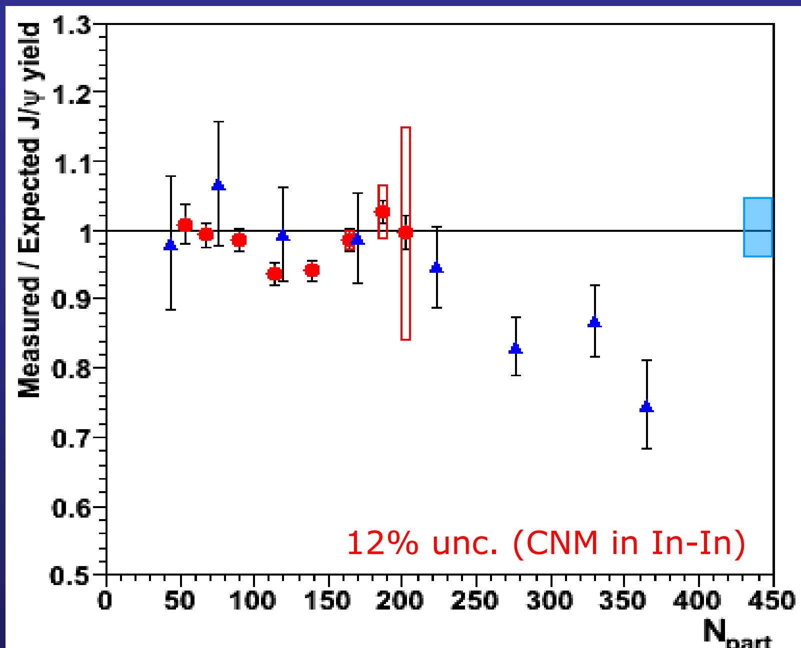
Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

if supported by data, charmonium looses status as "thermometer" of QGP
...and gains status as a powerful observable for the phase boundary

Low energy results: J/ψ from SPS & RHIC

SPS (NA38, NA50, NA60)
$\sqrt{s_{NN}}$ = 17 GeV

R.Arnaldi et al.(NA60) NPA830 (2009) 345c

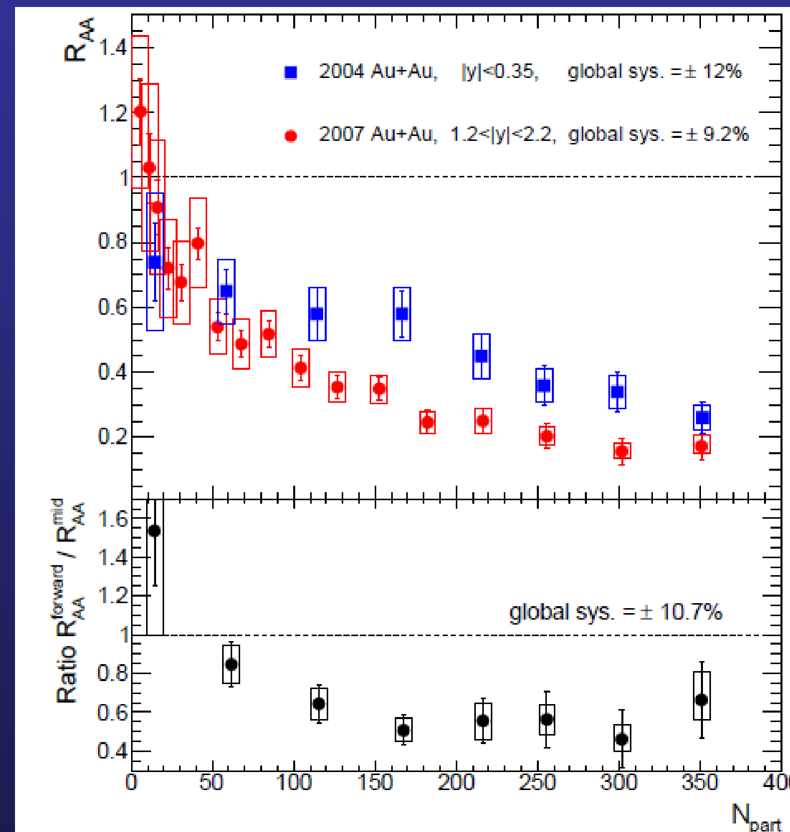


- First evidence of anomalous suppression (i.e. beyond CNM expectations) in Pb-Pb collisions

→ ~30% J/ψ suppression compatible with suppression of ψ(2S) and χ_c decays

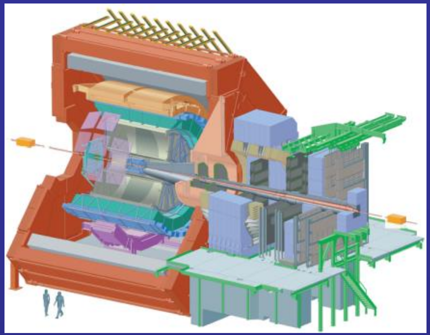
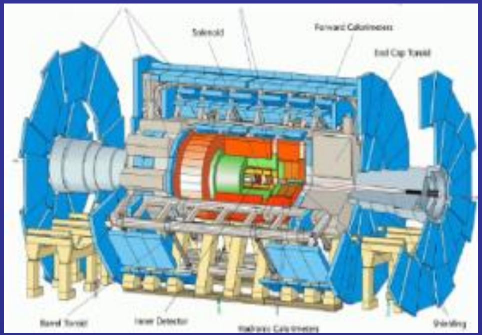
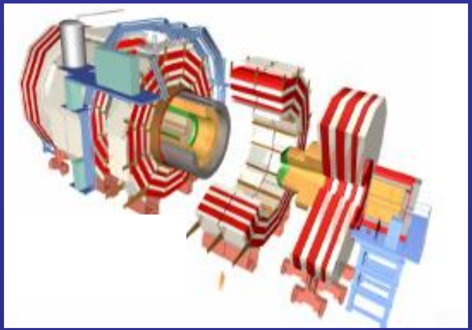
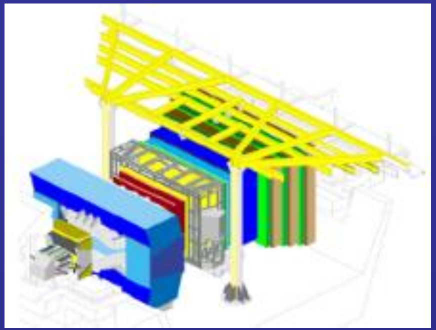
RHIC (PHENIX, STAR)
$\sqrt{s_{NN}}$ = 39, 62.4, 200 GeV

A. Adare et al. (PHENIX) PRC84(2011) 054912



- Suppression, with strong rapidity dependence, in Au-Au at $\sqrt{s}$= 200 GeV

Moving to LHC

- All the four experiments have investigated quarkonium production
  - Pb-Pb collisions → mainly ALICE + CMS
  - p-Pb collisions → all the 4 experiments

- Complementary kinematic ranges → excellent phase space coverage

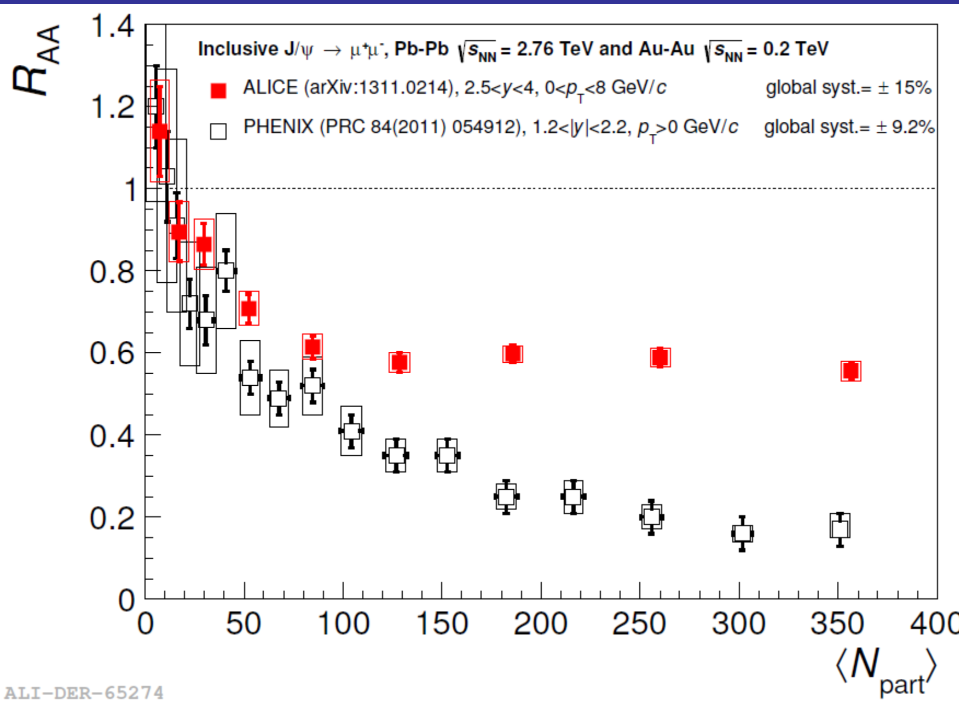
ALICE → forward-y ($2.5<y<4$, dimuons) and mid-y ($|y|<0.9$, electrons)
LHCb → forward-y ($2<y<4.5$, dimuons)
CMS → mid-y ($|y|<2.4$, dimuons)
ATLAS → mid-y ($|y|<2.25$, dimuons)
(N.B.: y-range refers to symmetric collisions →rapidity shift in p-Pb!)

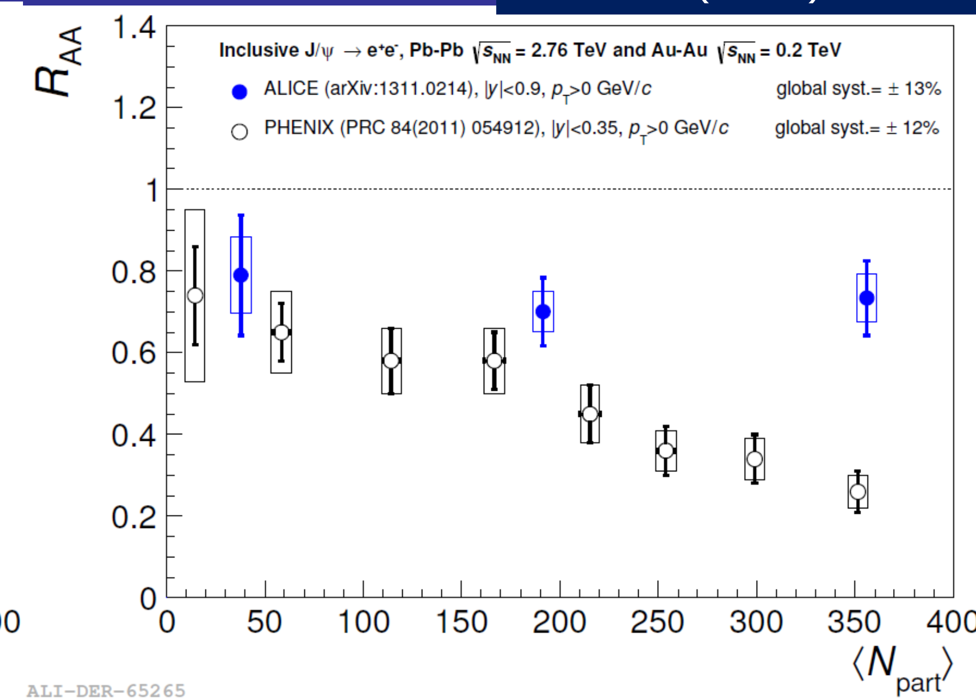
Data samples:
- Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, 2010 (9.7 μb^{-1}) + 2011 (184 μb^{-1})
- p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, 2013 (36 nb^{-1})
- ref. p-p, $\sqrt{s}$ = 2.76 TeV, 2011 (250 nb^{-1}) + 2013 (5.6 pb^{-1})

Charmonium (J/ψ, $\psi(2S)$)

Low p_T J/ψ: ALICE

B. Abelev et al., ALICE
PL B 734 (2014) 314





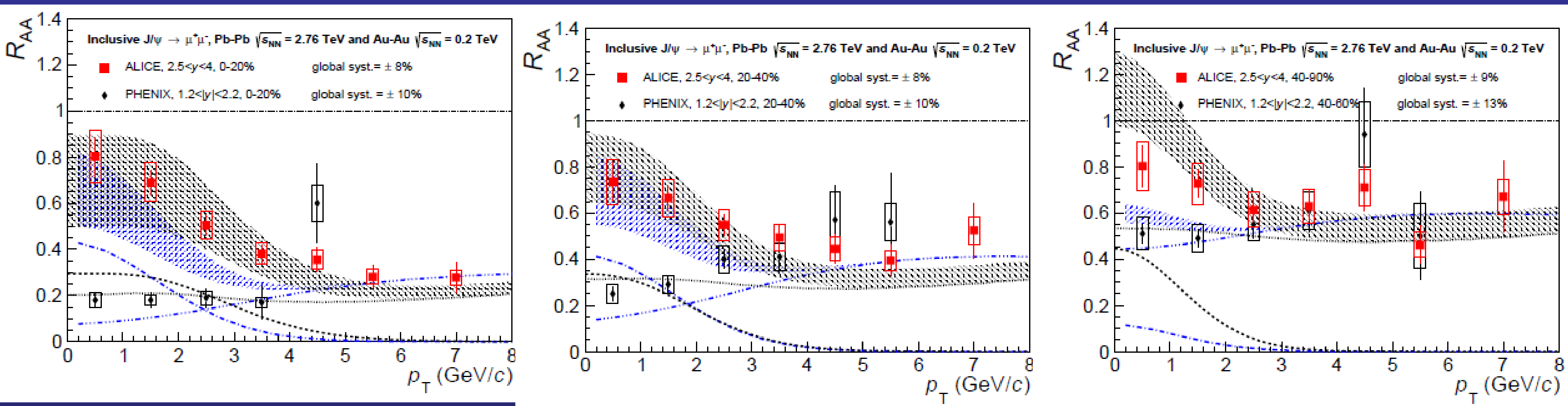
- Compare J/ψ suppression, RHIC ($\sqrt{s_{NN}}$=0.2 TeV) vs LHC ($\sqrt{s_{NN}}$=2.76 TeV)
- Results dominated by low-p_T J/ψ
  - Stronger centrality dependence at lower energy
  - Systematically larger R_{AA} values for central events in ALICE

Possible interpretation:
- RHIC energy → suppression effects dominate
- LHC energy → suppression + regeneration

How can this picture be validated?

R_{AA} vs p_T

- ❑ Charm-quark transverse momentum spectrum peaked at low-p_T
- ❑ Recombination processes expect to mainly enhance low-p_T J/ψ
  → Expect smaller suppression for low-p_T J/ψ → observed!



TM1 Zhao et al., Nucl.Phys.A859 (2011) 114

TM2 Zhou et al. Phys.Rev.C89 (2014)054911

ALICE, arXiv:1506.08804

- Primordial J/ψ (TM1)
- Regenerated J/ψ (TM1)
- Primordial J/ψ (TM2)
- Regeneration J/ψ (TM2)

- ❑ Models provide a fair description of the data, even if with different balance of primordial/regeneration components

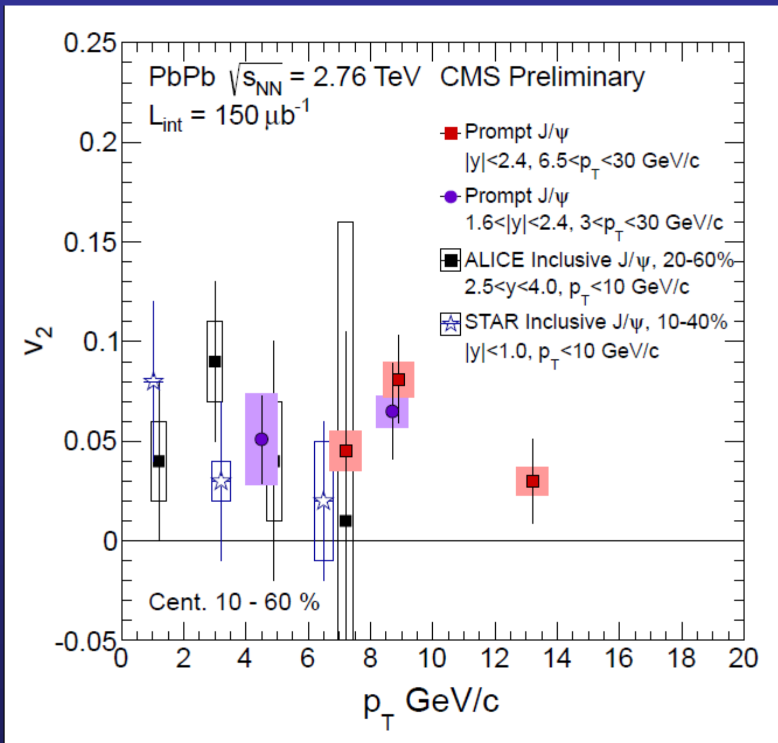
Still rather large theory uncertainties: models will benefit from precise measurement of σ_{cc} and CNM effects

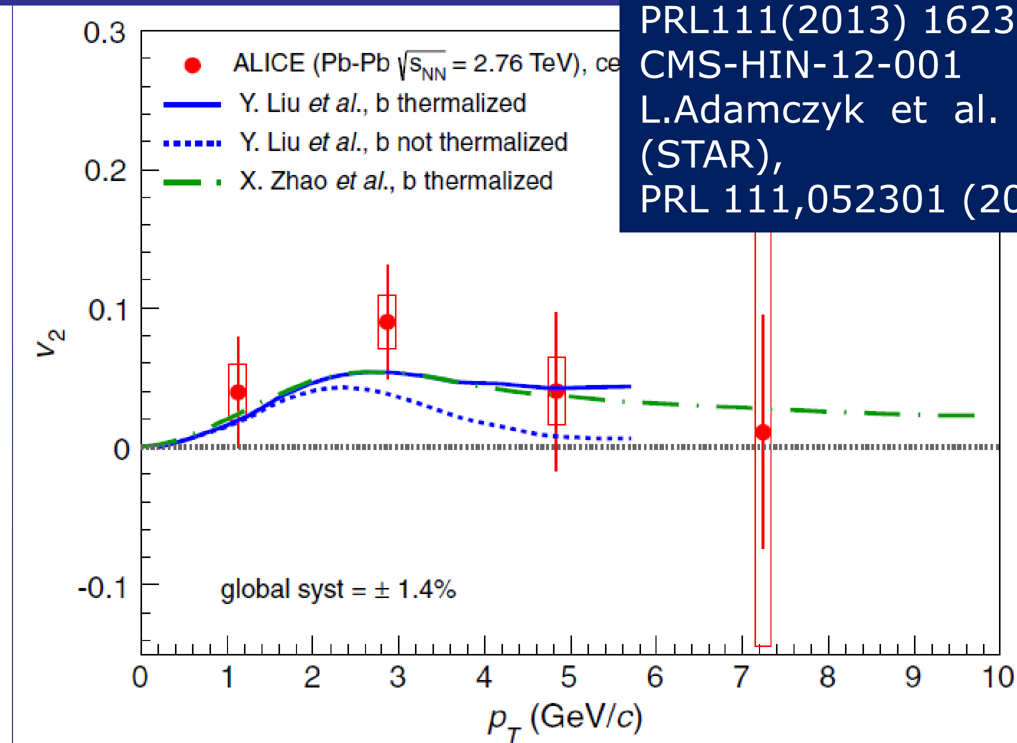
- ❑ Opposite trend with respect to lower energy experiments

Non-zero v_2 for J/ψ at the LHC

- The contribution of J/ψ from (re)combination could lead to a significant elliptic flow signal at LHC energy → observed!

E.Abbas et al. (ALICE), PRL111(2013) 162301,
CMS-HIN-12-001
L.Adamczyk et al. (STAR), PRL 111,052301 (2013)



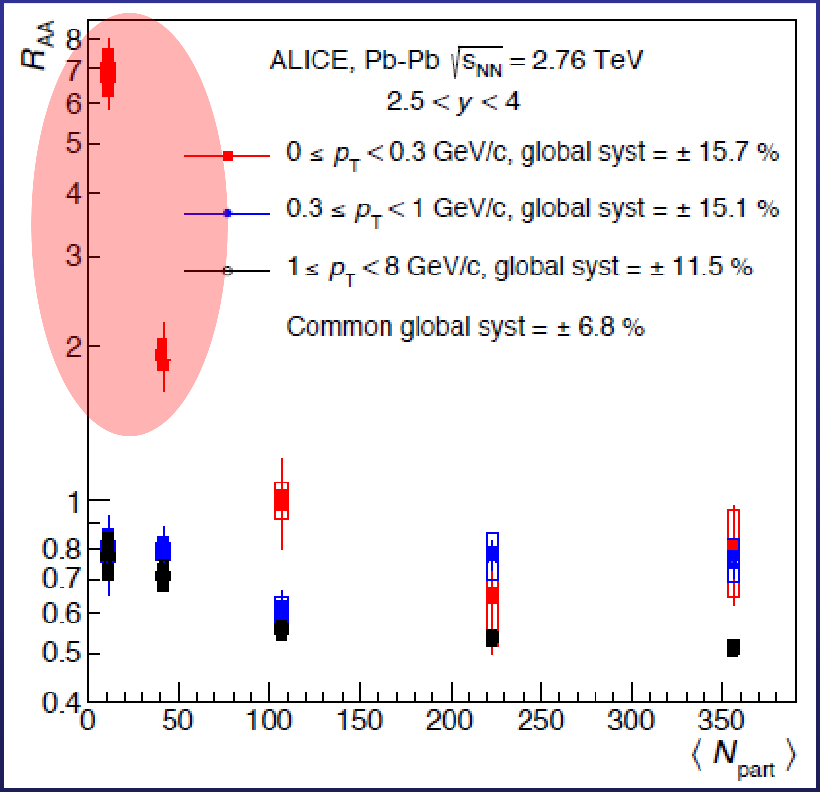


- A significant v_2 signal is observed by BOTH ALICE and CMS
- Fair agreement between ALICE data and transport models
- v_2 remains significant even in the region where the contribution of (re)generation should be negligible
  → Due to path length dependence of energy loss ?
- In contrast to these observations STAR measures v_2~0

J/ψ at very low p_T

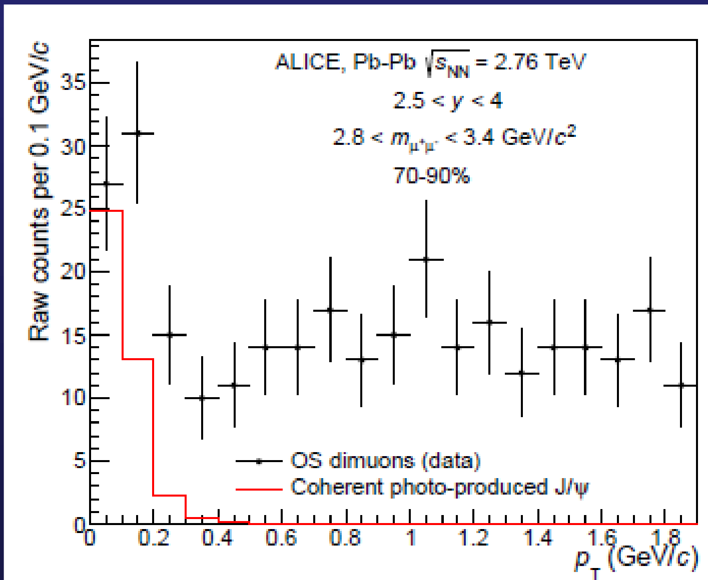
- Strong R_{AA} enhancement in peripheral collisions for $0<p_T<0.3$ GeV/c

ALICE, arXiv:1509.08802



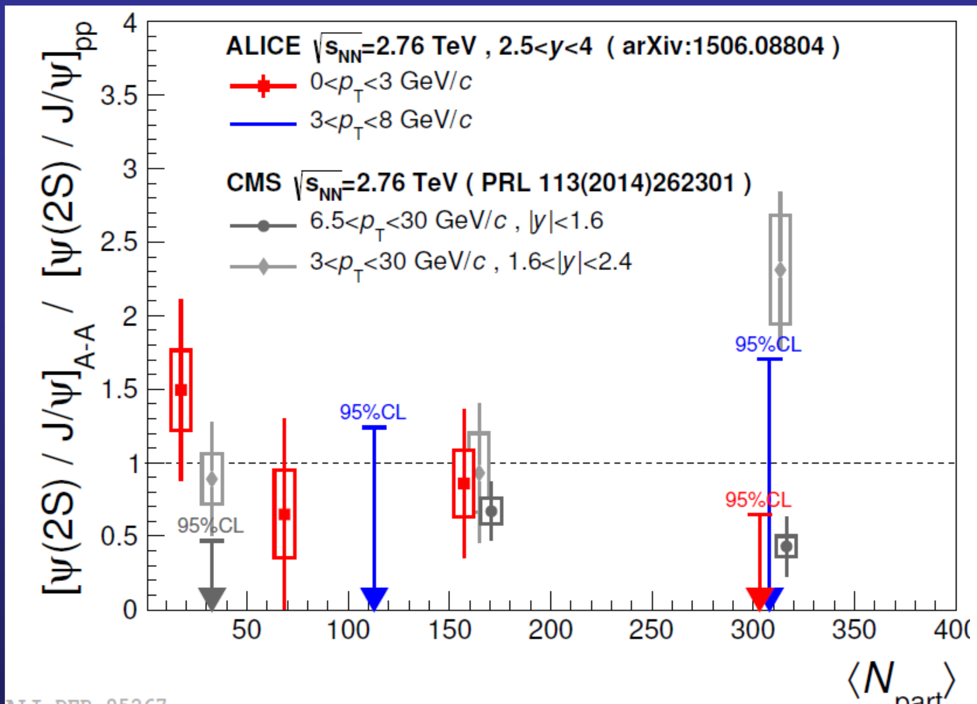
- Significance of the excess is 5.4 (3.4)σ in 70-90% (50-70%)
- Behaviour not predicted by transport models
- Excess might be due to coherent J/ψ photoproduction in PbPb (as measured also in UPC)

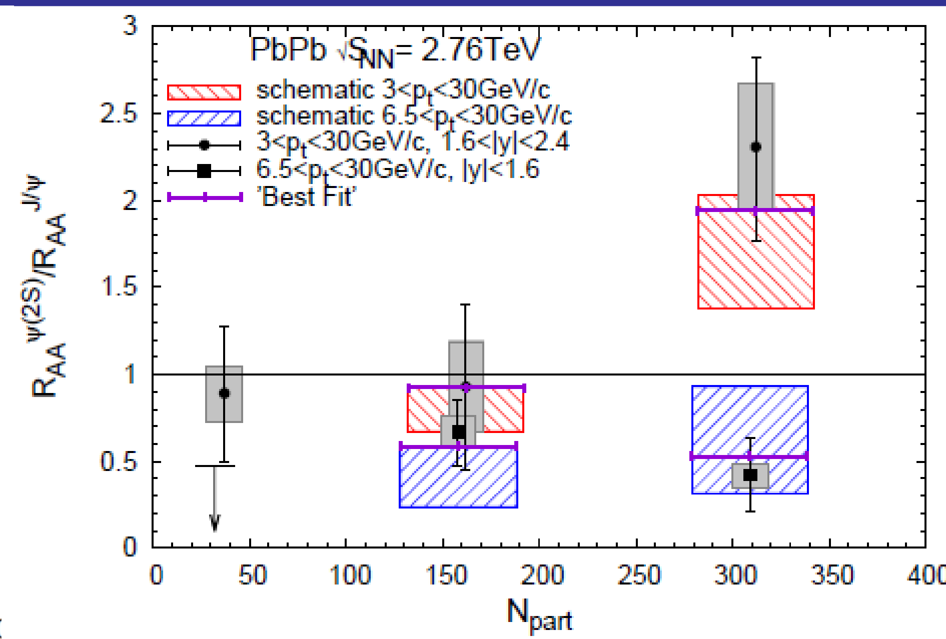
If excess is "removed" requiring $p_T^{J/\psi}$>0.3GeV/c
→ ALICE R_{AA} lowers by 20% at maximum (in the most peripheral bin)



ψ(2S) in Pb-Pb: ALICE "vs" CMS

- ψ(2S) production modified in Pb-Pb with a strong kinematic dependence
- CMS → suppression at high p_T, enhancement at intermediate p_T





Du and Rapp arXiv:1504.00670

CMS, PRL113 (2014) 262301
ALICE, arXiv:1506.08804

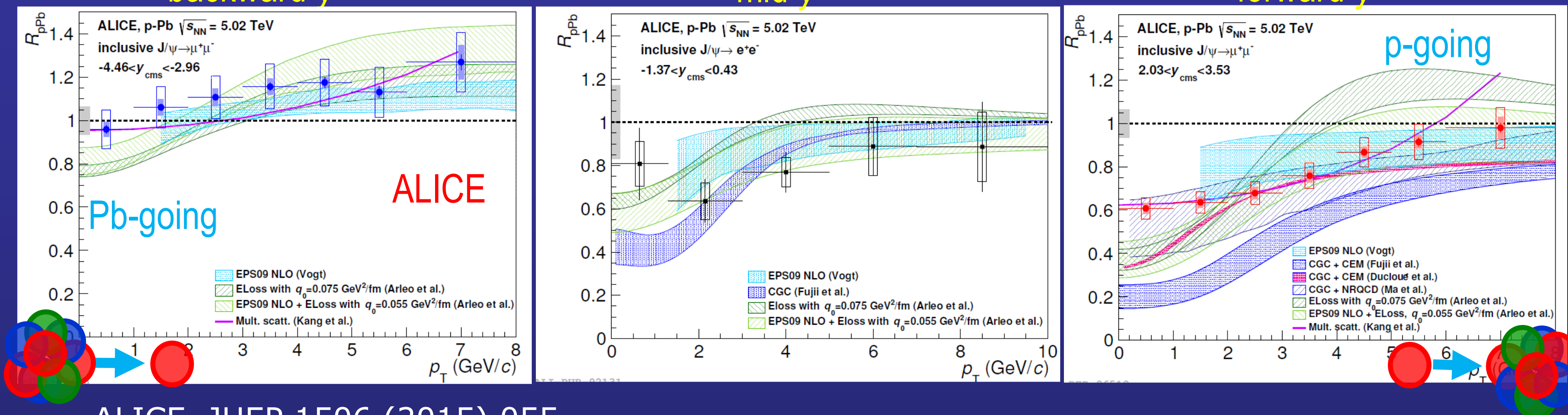
- Possible interpretation (Rapp et al.) → Re-generation for ψ(2S) occurs at later times wrt J/ψ, when a significant radial flow has built up, pushing the re-generated ψ(2S) at a relatively larger p_T

- Small tension, between ALICE and CMS, for central events?

CNM effects are not negligible!

- p-Pb collisions, $\sqrt{s_{NN}}$=5.02 TeV, R_{pPb} vs p_T

backward-y mid-y forward-y

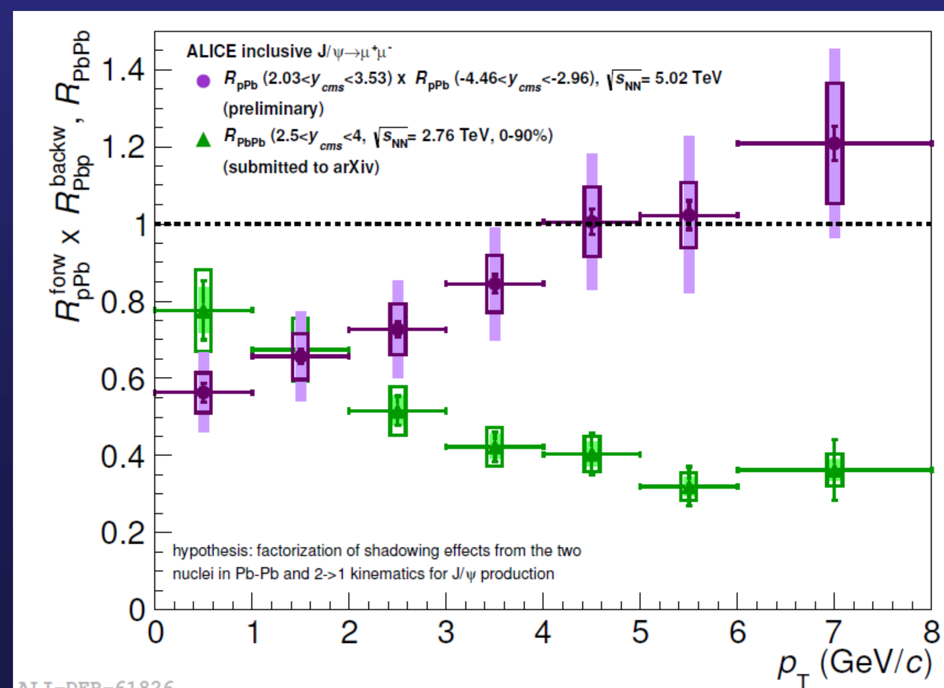


ALICE, JHEP 1506 (2015) 055

- Suppression at backward + central rapidity
- No suppression (enhancement?) at forward rapidity
- Fair agreement with models (shadowing + energy loss)

- (Rough) extrapolation of CNM effects to Pb-Pb $R_{PbPb}^{cold}=R_{pPb}\times R_{Pbp}$

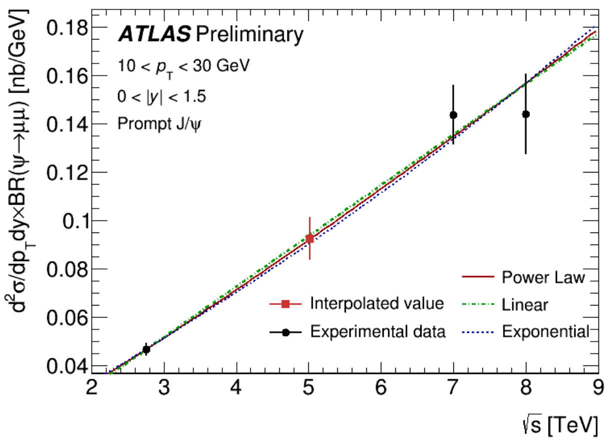
→ evidence for hot matter effects!

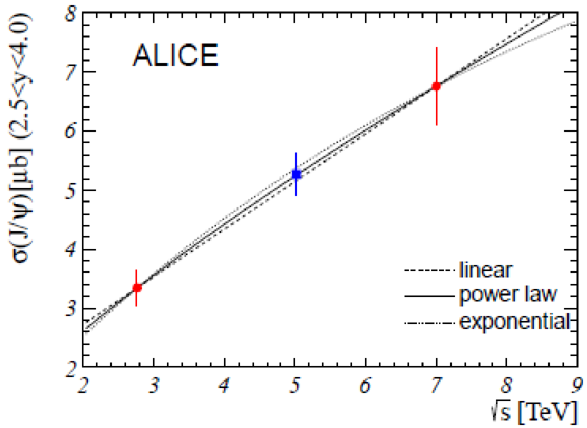


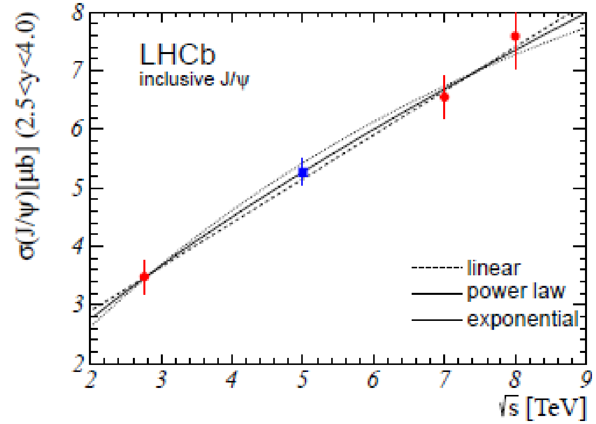
Building a reference σ_{pp} → interpolation

- Simple empirical approach adopted by ALICE, ATLAS and LHCb

CERN-LHCb-CONF-2013-013; ALICE-PUBLIC-2013-002.







Example: ALICE result

$$\sigma_{\rm incl} = 5.28 \pm 0.40_{\rm exp} \pm 0.10_{\rm inter} \pm 0.05_{\rm theo}\ \mu{\rm b} = 5.28 \pm 0.42\ \mu{\rm b}\ .$$

inter: spread of interp. with empirical functions
theo: spread of interp. with theory estimates

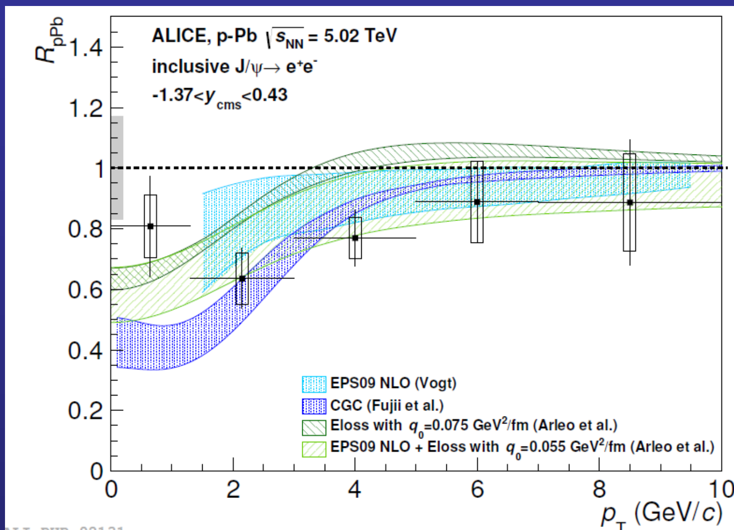
- $\psi(2S)$ → interpolation difficult, small statistics at $\sqrt{s}$=2.76 TeV
- Ratio $\psi(2S)$ / J/ψ → ALICE uses $\sqrt{s}$=7 TeV pp values (weak $\sqrt{s}$-dependence)

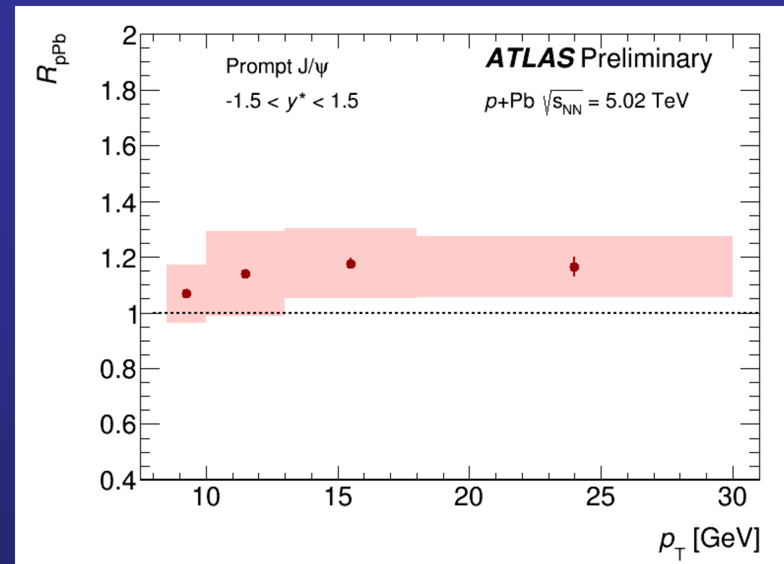
$$R_{pA}^{\psi(2S)} = R_{pA}^{J/\psi} \times \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pA}^{J/\psi}} \times \frac{\sigma_{pp}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}}$$

ALICE estimate (conservative)
→ 8% syst. unc. due to different $\sqrt{s}$
(using CDF/ALICE/LHCb results)

J/ψ R_{pPb}: ATLAS “vs” ALICE “vs” LHCb

- R_{pPb} vs p_T around midrapidity → fair agreement ATLAS vs ALICE





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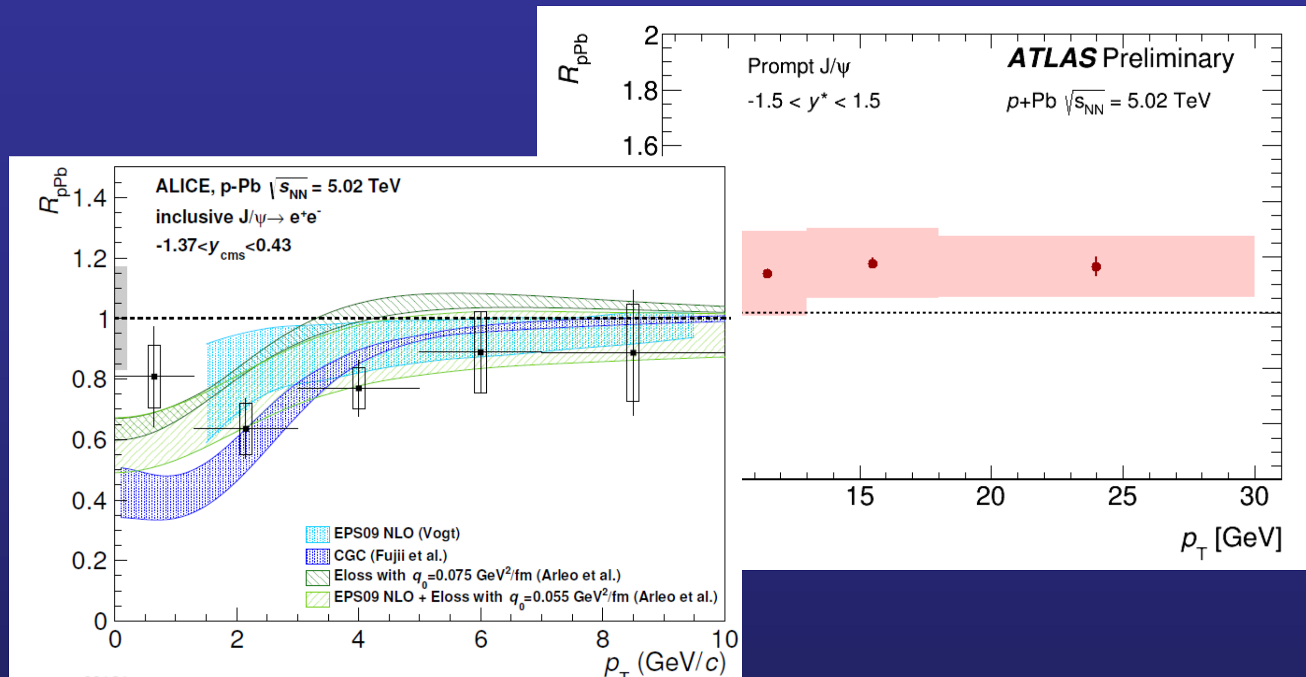

J/ψ R_{pPb}: ATLAS "vs" ALICE "vs" LHCb

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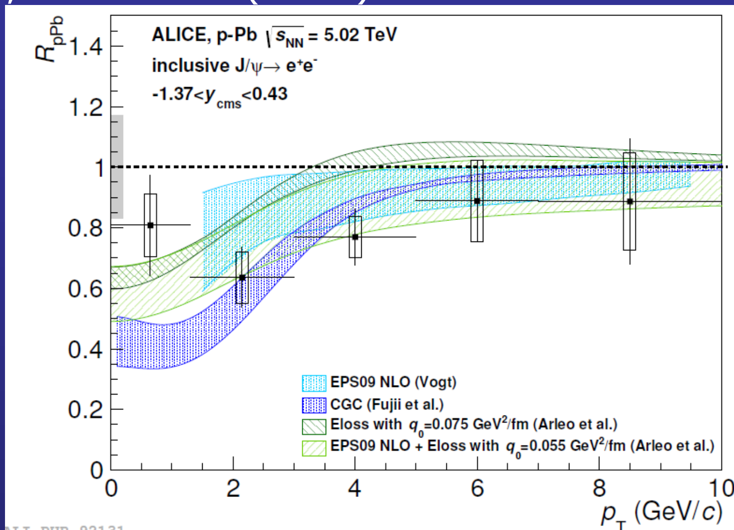
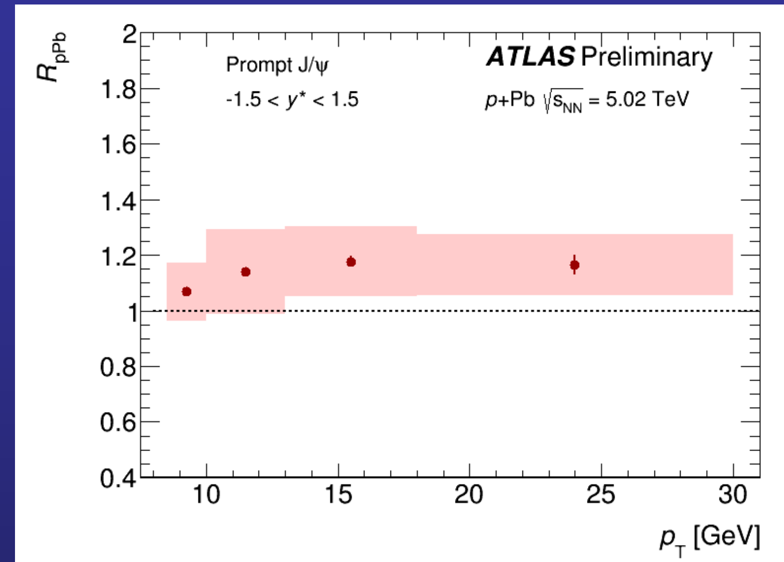
ALICE, JHEP 1506 (2015) 055

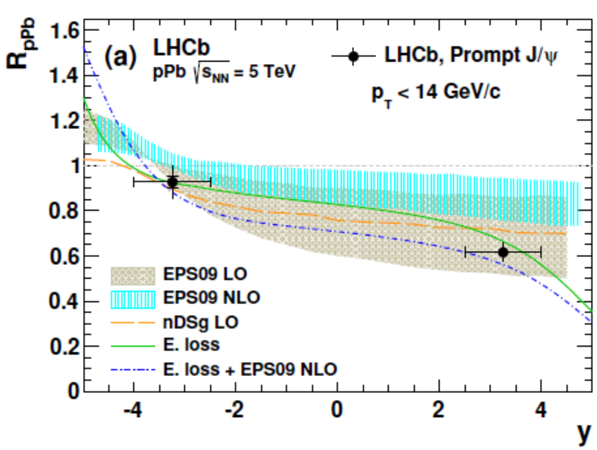
ATLAS-CONF-2015-023

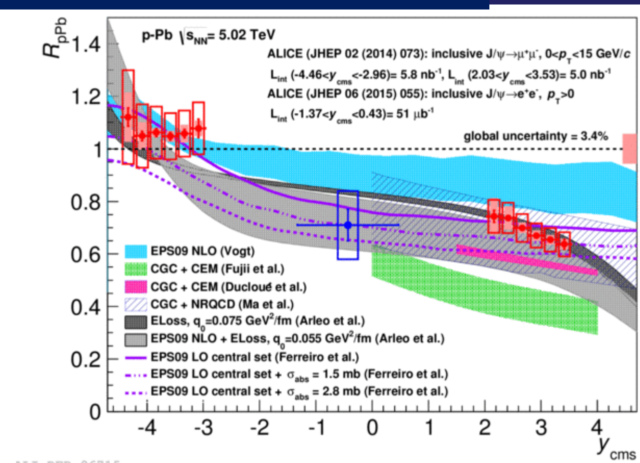


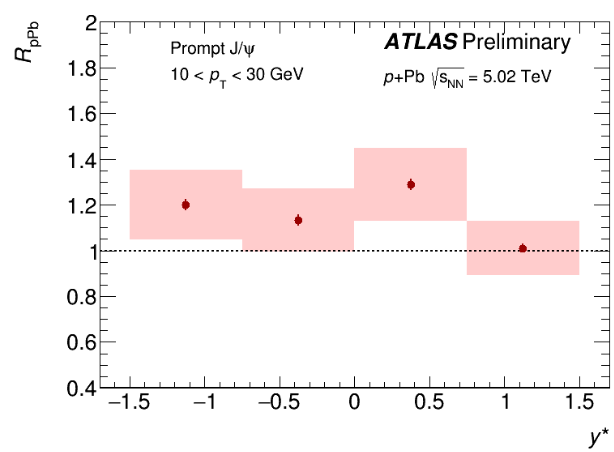


- ❑ R_{pPb} vs y → fair agreement ALICE vs LHCb, ATLAS refers to p_T>10 GeV/c

LHCB, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73







ψ(2S) in p-Pb collisions

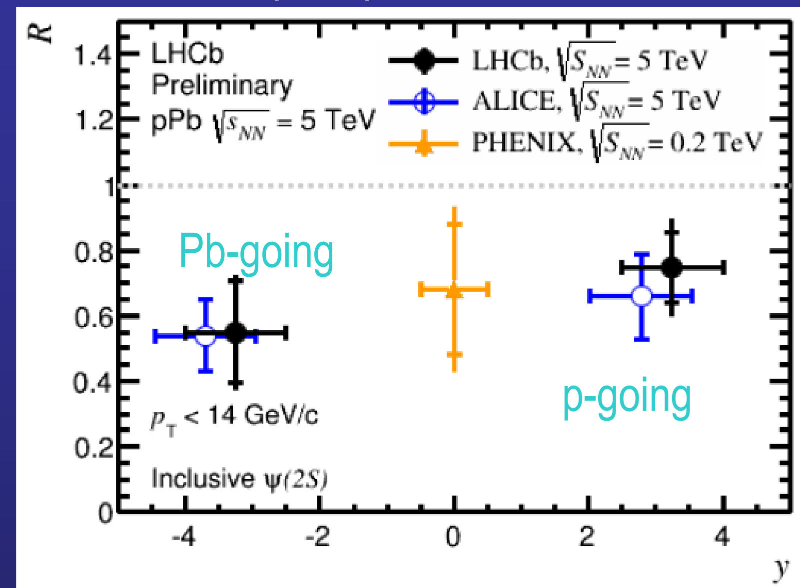
ALICE, JHEP 1412(2014)073, LHCb-CONF-2015-005
PHENIX, PRL 111 (2013) 202301

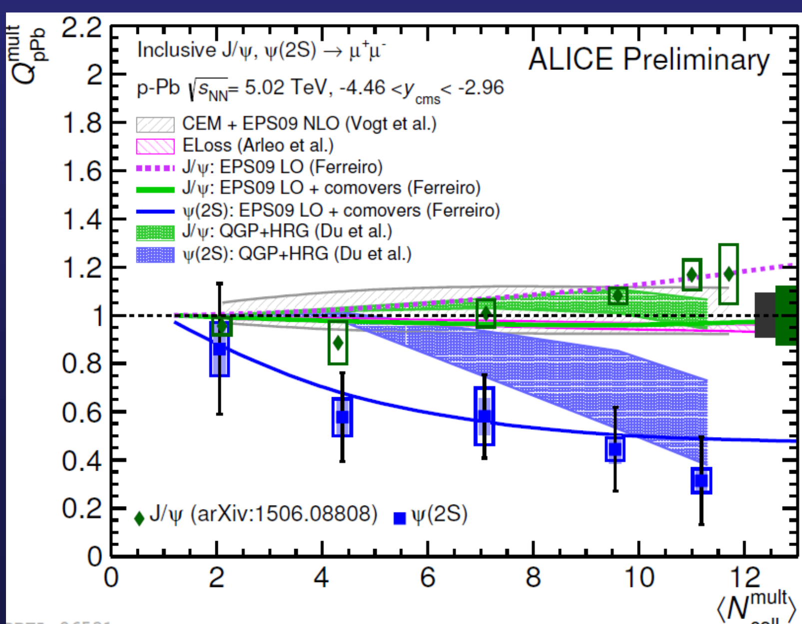
- ψ(2S) suppression is stronger than the J/ψ one at RHIC and LHC

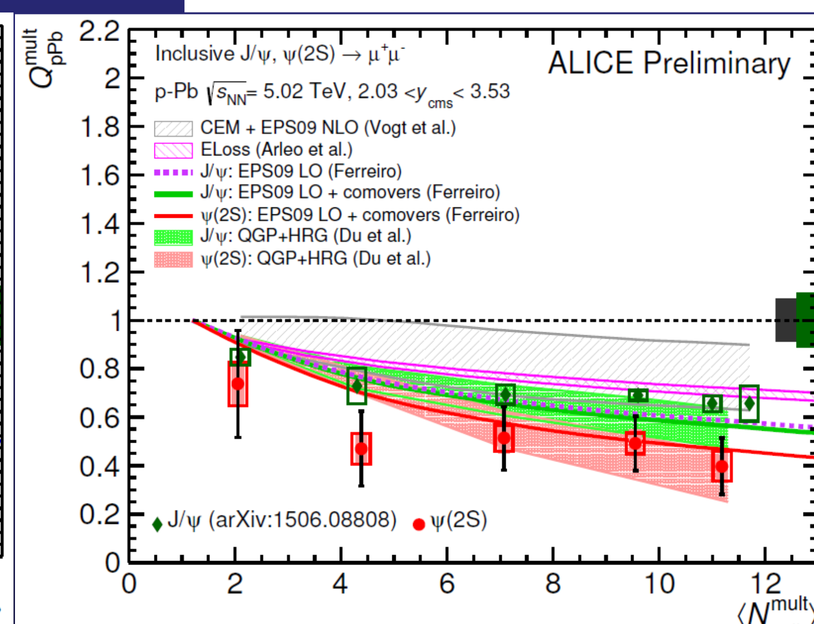
→ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

→ time spent by the cc pair in the nucleus (τ_c) is smaller than charmonium formation time (τ_f) implies identical final state nuclear effects

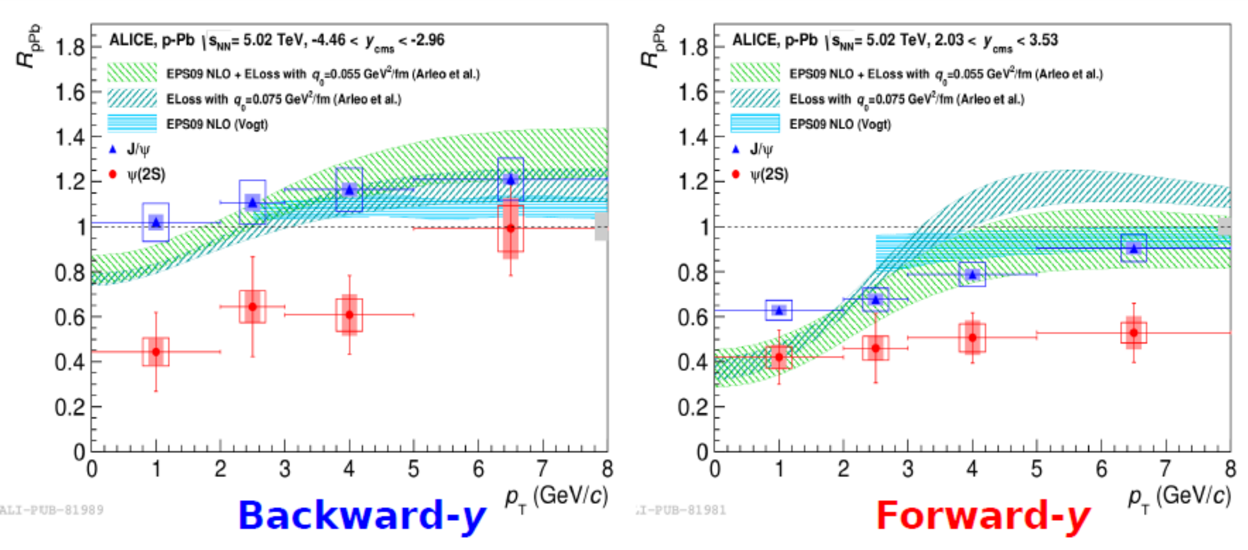
→ Only QGP+hadron resonance gas (Rapp) or comovers (Ferreiro) models describe the stronger ψ(2S) suppression





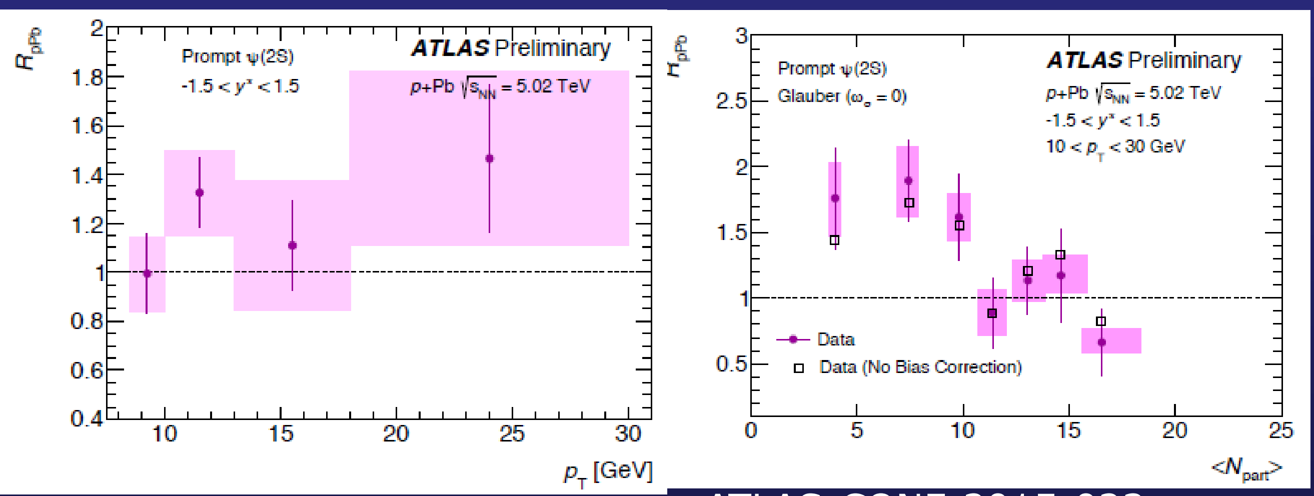


ψ(2S) in p-Pb: p_T dependence



ALICE, JHEP 12 (2014) 073

- ALICE (low p_T) : rather strong suppression, possibly vanishing at backward y and p_T> 5 GeV/c



ATLAS-CONF-2015-023

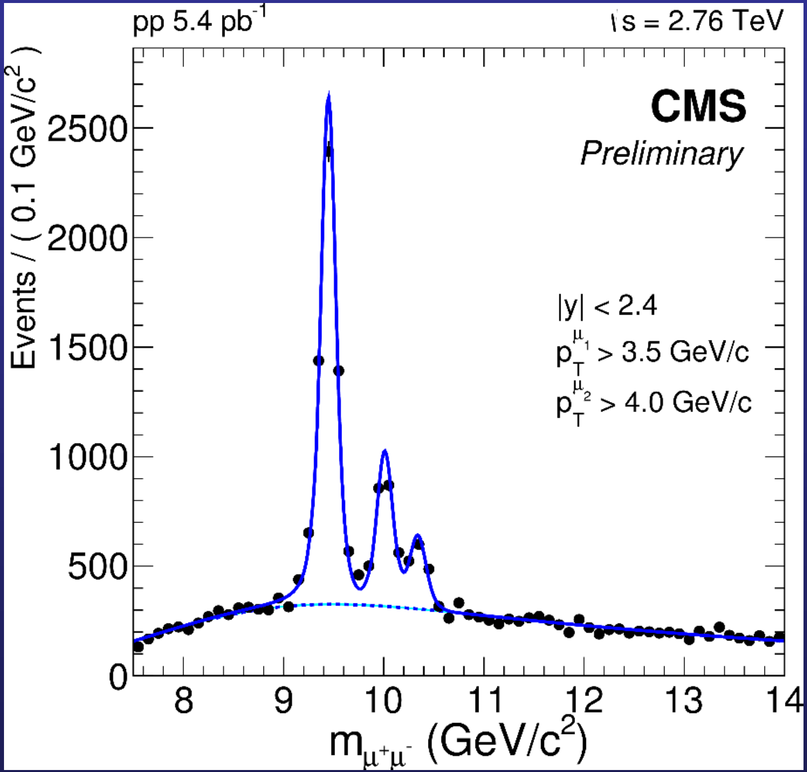
- ATLAS (high p_T) : larger uncertainties, hints for strong enhancement, concentrated in peripheral events

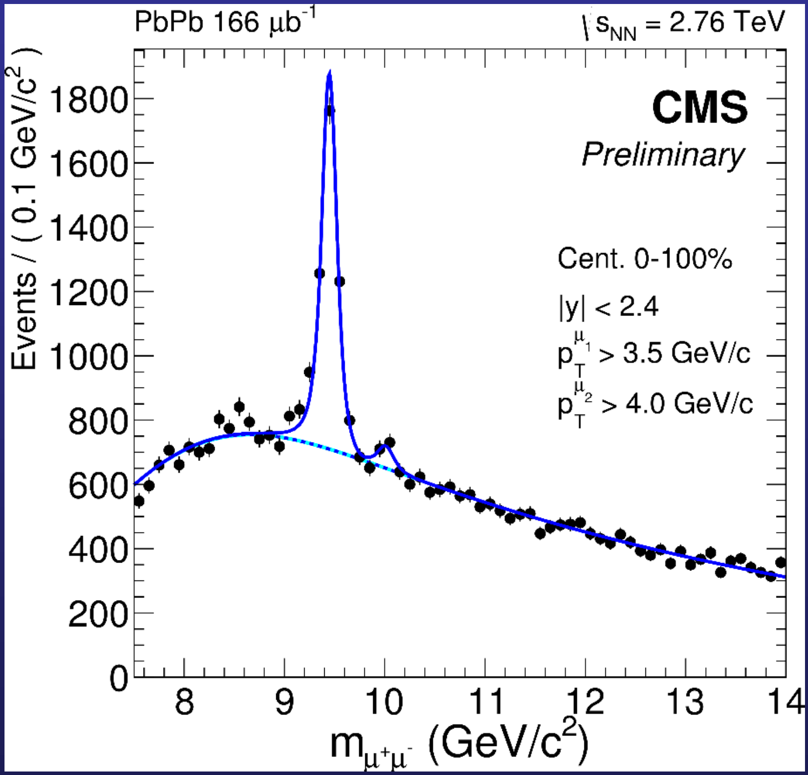
- Possible tension between ALICE and ATLAS results ?
- Wait for final results from ATLAS

Bottomonium (Υ(1S), Υ(2S), Υ(3S))

ϒ suppression in Pb-Pb collisions

- Relatively low beauty cross section → weak regeneration effects
- Kinematic coverage down to $p_T=0$ for all experiments





CMS-HIN-15-001

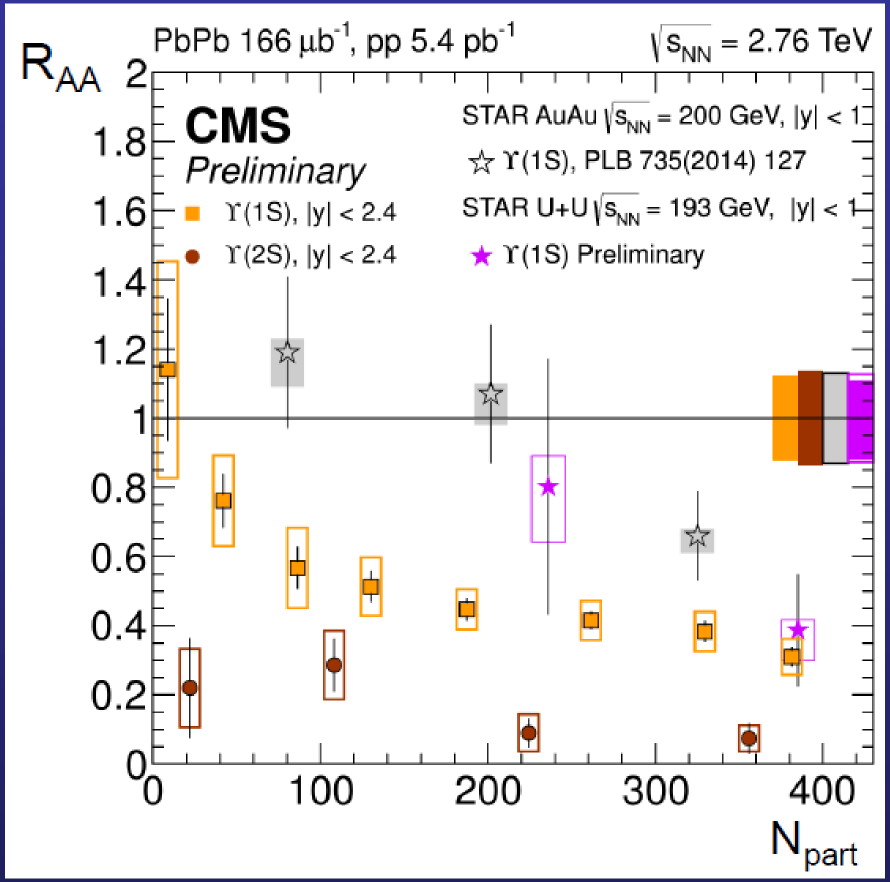
Strong relative suppression of more loosely bound states

$R_{AA}(\Upsilon(1S))= 0.43\pm0.03\pm0.07$
$R_{AA}(\Upsilon(2S))= 0.13\pm0.03\pm0.02$
$R_{AA}(\Upsilon(3S))< 0.14$ at 95% CL

Υ suppression in Pb-Pb collisions

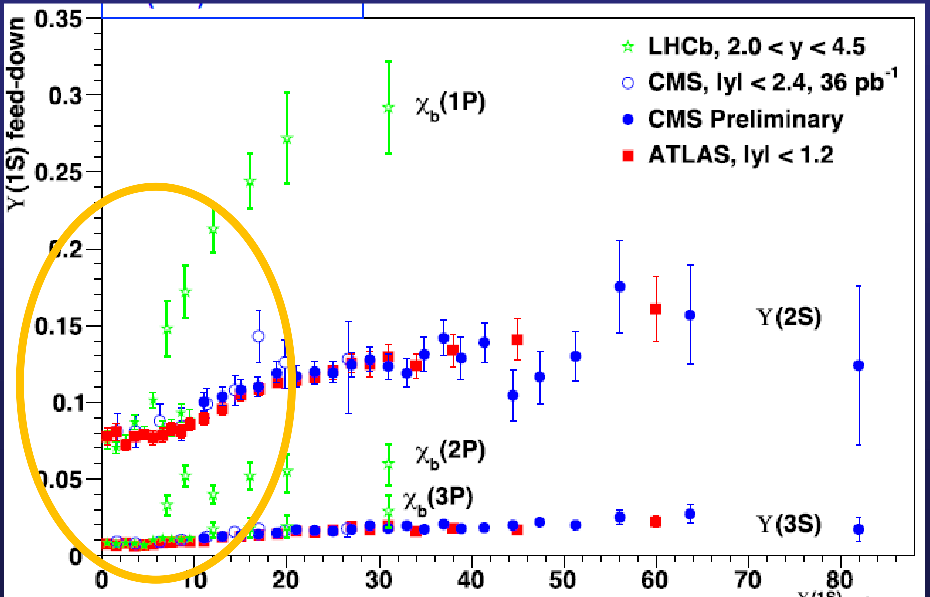
- Reanalysis of 2011 CMS data:
  - Improved reconstruction
  - High statistics pp reference (x20)

CMS, PRL109 (2012) 222301 and HIN-15-001
STAR, PLB735 (2014) 127 and preliminary U+U



CMS-HIN-15-001

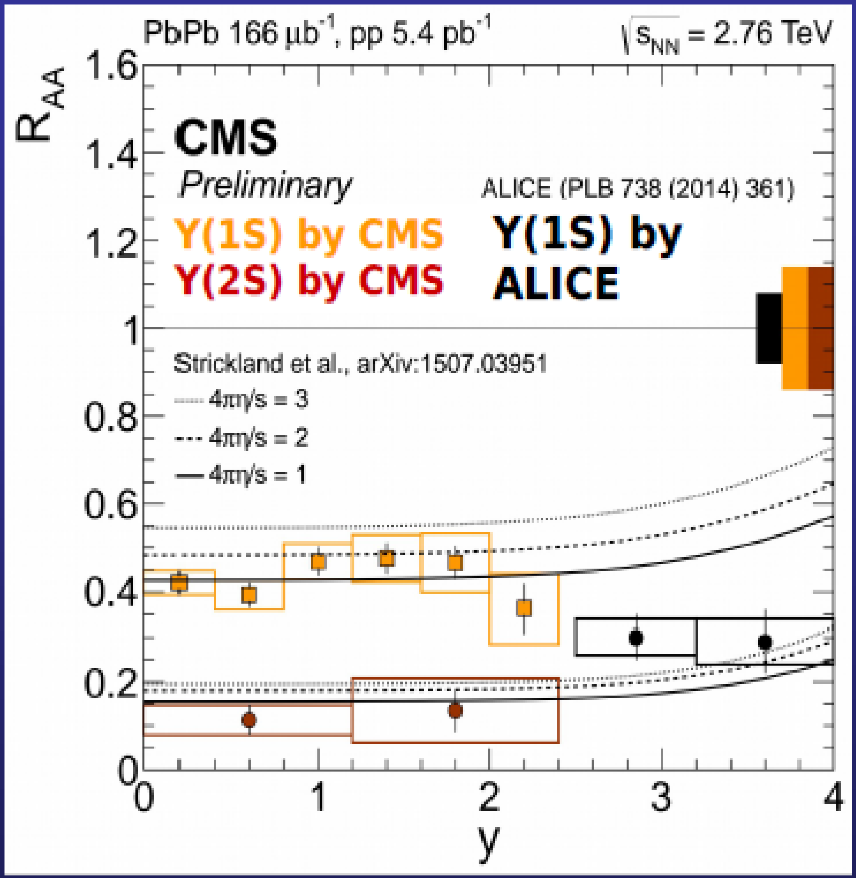
- Feed-down from excited states seems not enough to explain the observed Υ(1S) suppression

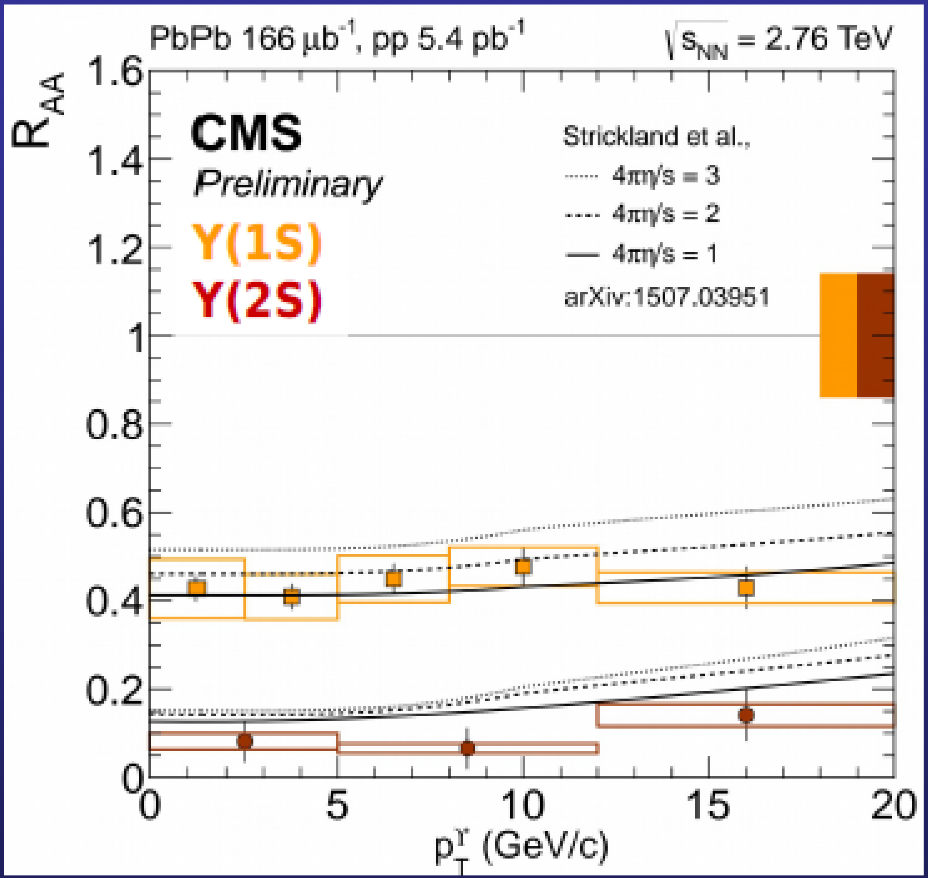


H. Wöhri, QWG2014

- Υ(2S) binding energy similar to that of the J/ψ, but bottomonium suppression much larger
  → recombination effects negligible

R_{AA} vs p_T and y, comparison with models

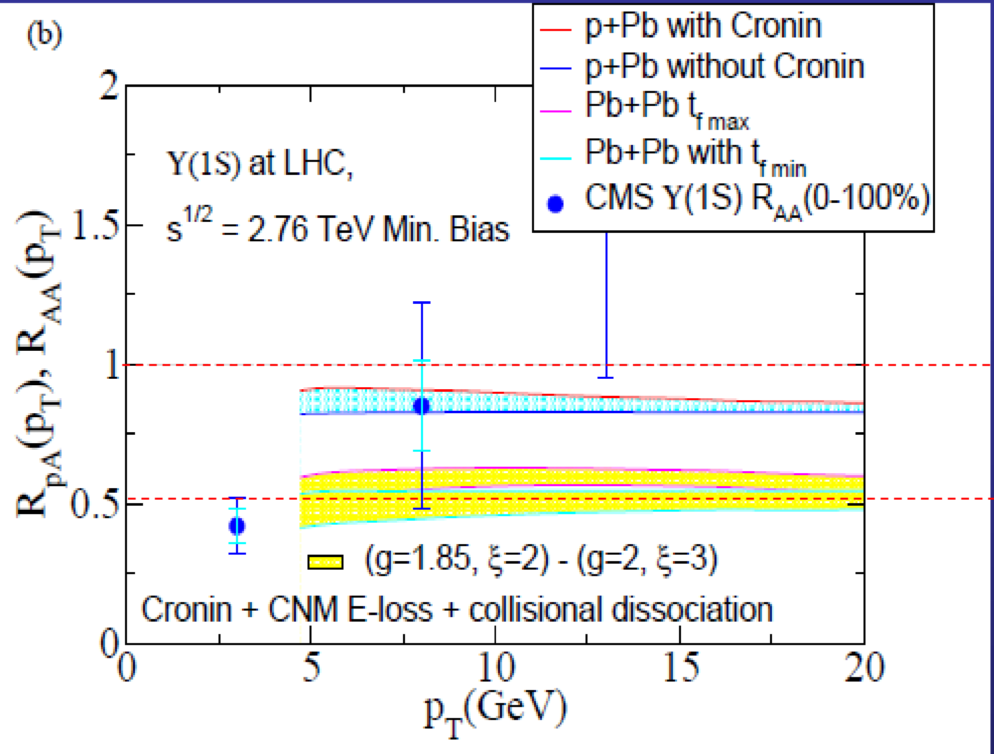




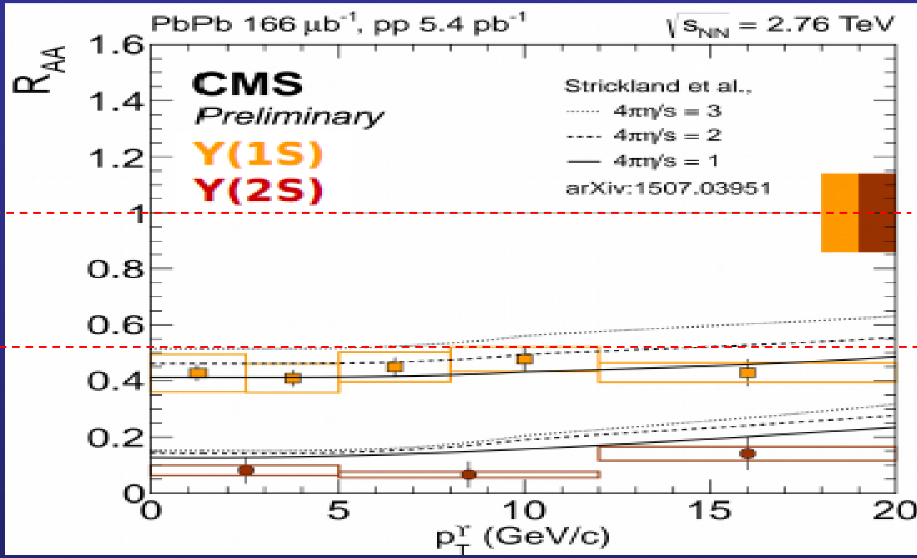
CMS-HIN-15-001

- No significant p_T dependence of R_{AA}
- Hints for a decrease of R_{AA} at large y (comparison ALICE – CMS)
- Could suggest the presence of sizeable recombination effects at mid-rapidity (?)

High p_T ϒ: model comparison

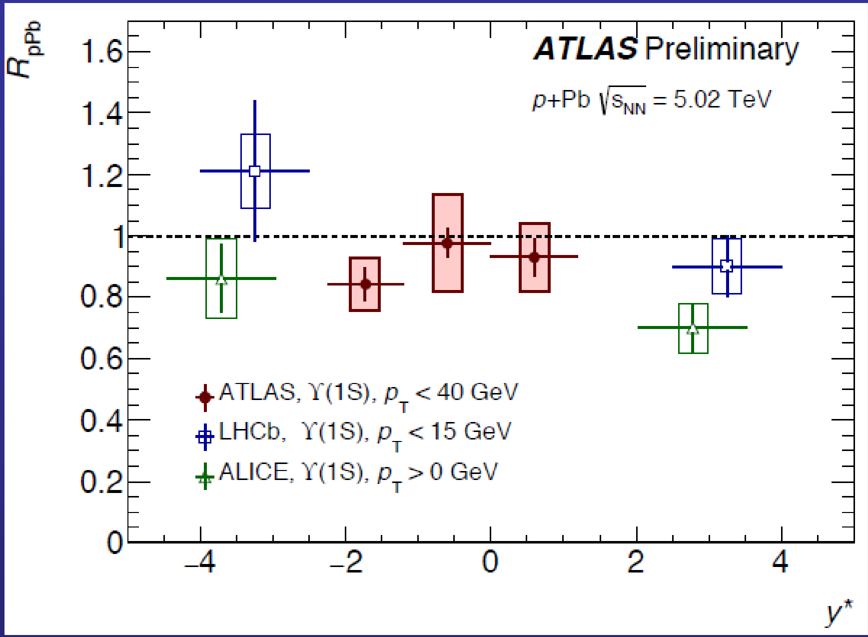


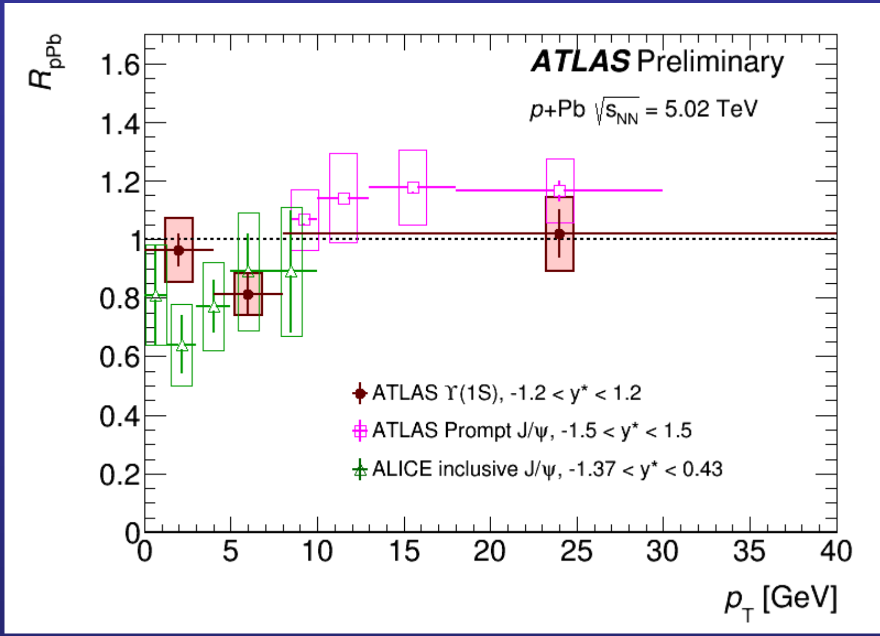
Sharma and Vitev,
Phys. Rev. C 87, 044905 (2013)



- ❑ High p_T ϒ suppression
- ❑ Propagation effects through QGP
  - ❑ Quenching of the color octet component
  - ❑ Collisional dissociation model
- ❑ Approximation: initial wave function of the quarkonia well approximated by vacuum wavefunctions in the short period before dissociation
- ❑ CNM effects accounted for (shadowing + Cronin)

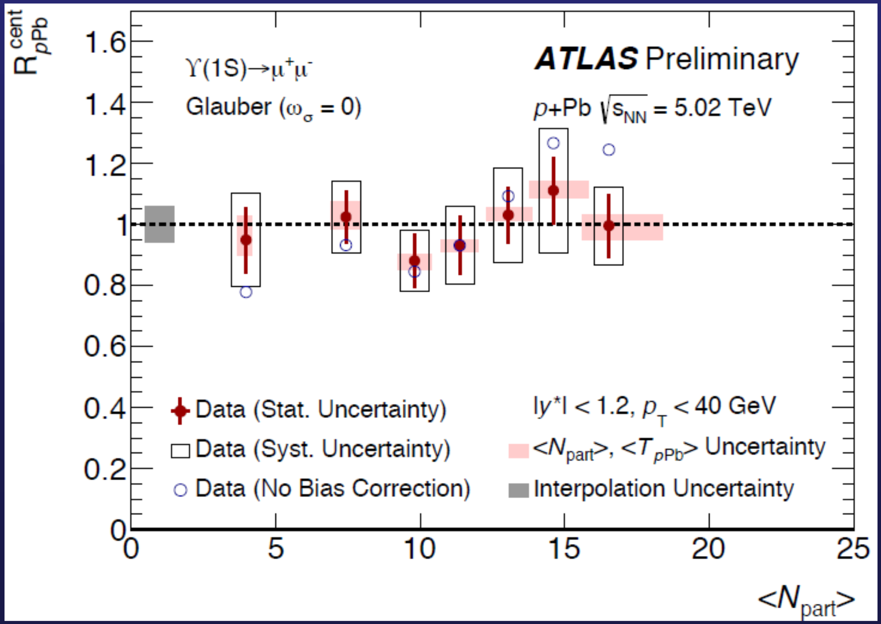
Weak CNM effects for bottomonium





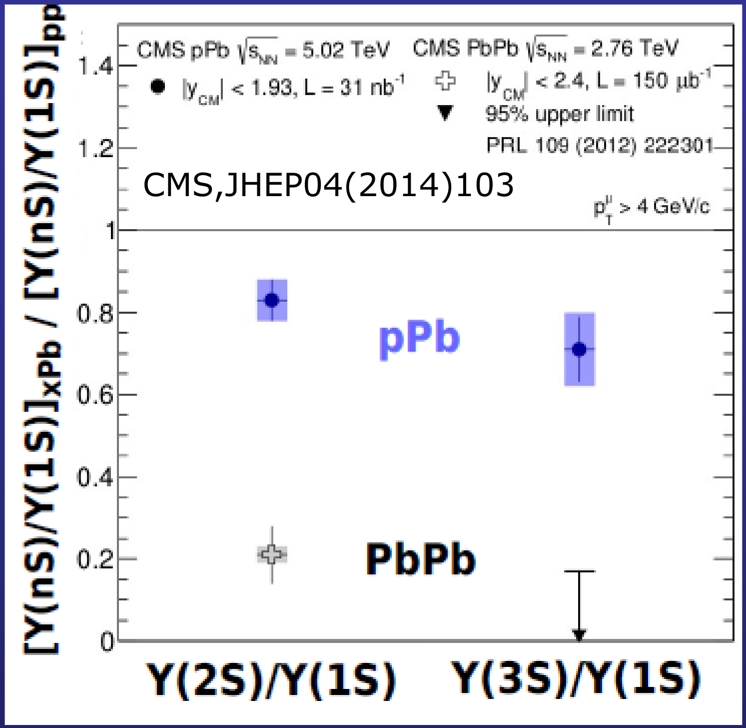
- R_{pPb} close to 1 and with no significant dependence on y, p_T and centrality

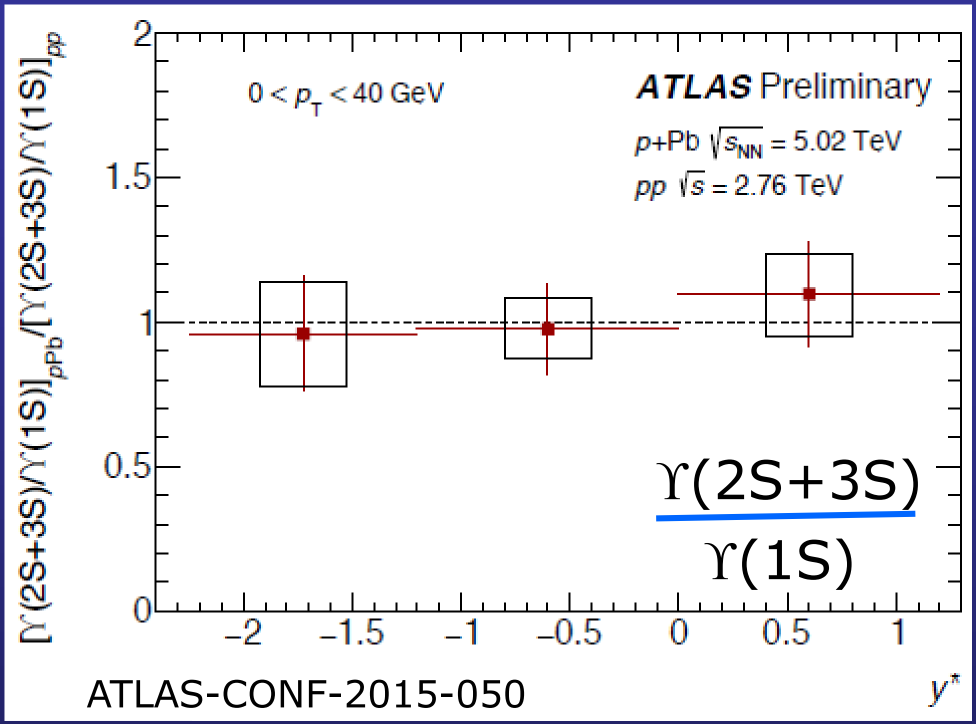
- Fair agreement ALICE vs LHCb (within large uncertainties)



ALICE, Phys. Lett. B 740 (2015) 105
ATLAS-CONF-2015-050
LHCb, JHEP 07(2014)094

Yield ratios for bottomonium in p-Pb





CMS

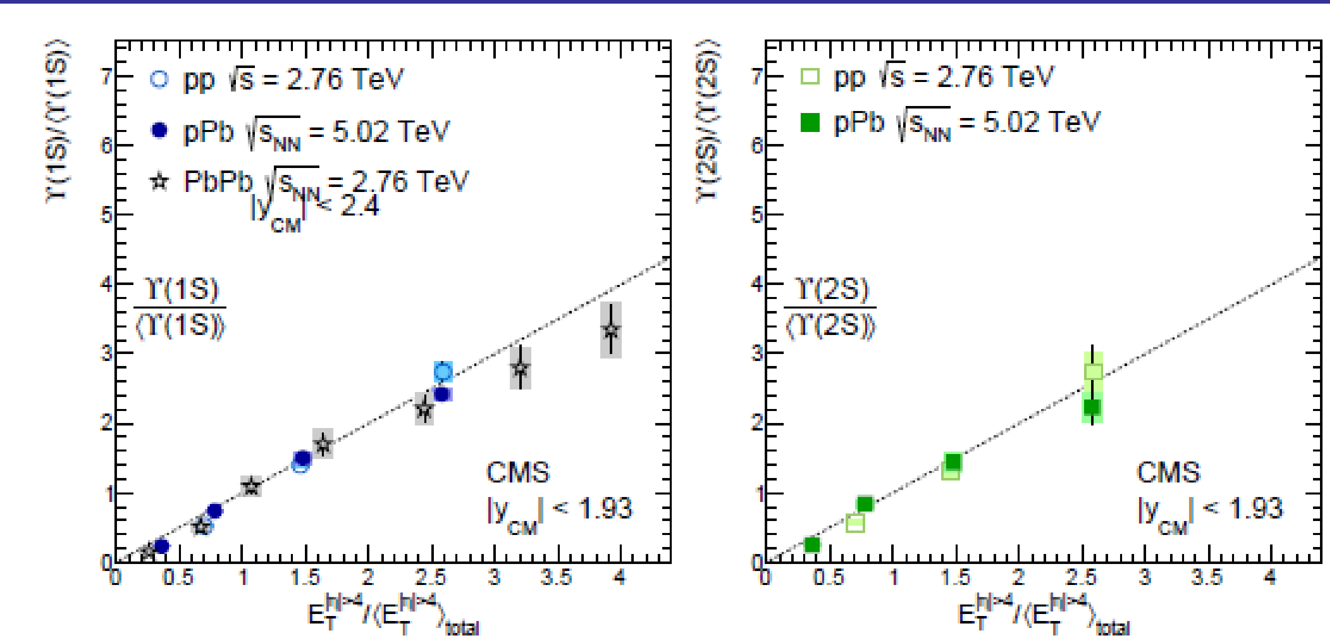
- **Excited states suppressed** with respect to $\Upsilon(1S)$
- Initial state effects similar for the various $\Upsilon(ns)$ states

→ **Final states effects** at play?

ATLAS

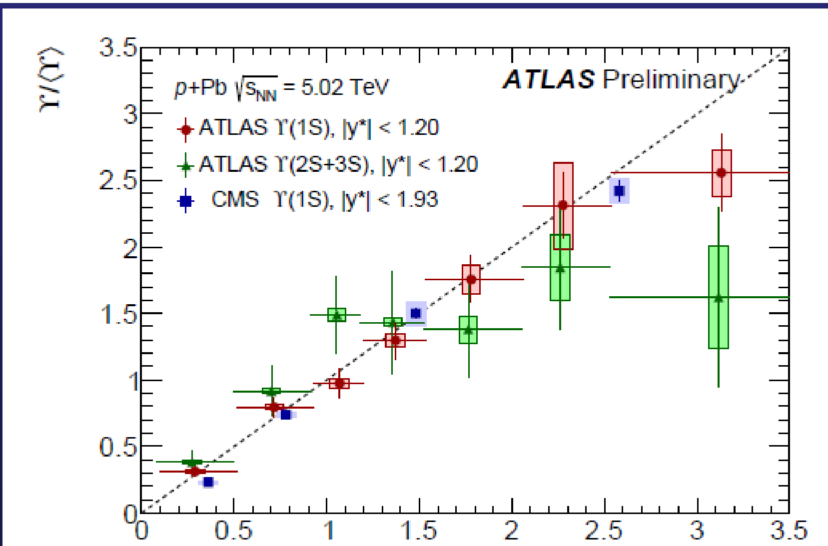
- no strong y (and p_T) dependence
- **agreement with CMS** within uncertainties

Self-normalized ϒ cross sections



Similar behaviour observed for J/ψ (ALICE)
(PLB712 (2012) 165-175)

CMS, JHEP 04 (2014) 103



ATLAS-CONF-2015-050

- All the ratios increase with increasing forward transverse energy
- When Pb nuclei are involved
  → Increase partly due to larger number of N-N collisions
- Increase observed also in pp collisions
  → multiple partonic interactions ?

From run-1 ro run-2

- Charmonium highlight → evidence for a new mechanism which enhances the J/ψ yield, in particular at low p_T, with respect to low-energy experiments

- In addition
  - Indications for J/ψ azimuthal anisotropy (non-zero v_2)
  - Significant final state effects on ψ(2S) in p-Pb, likely related to the (hadronic) medium created in the collision

- Bottomonium highlight → evidence for a stronger suppression of 2S and 3S states compared to 1S. Effect not related to CNM and compatible with sequential suppression of "bottomonium" states

- In addition
  - 1S is also suppressed (~50-60%). Feed-down effect only?
  - y-dependence of 1S suppression to be understood

From run-1 to run-2

- ❑ Prospects for run-2
  → Collect a ~1 order of magnitude larger integrated luminosity

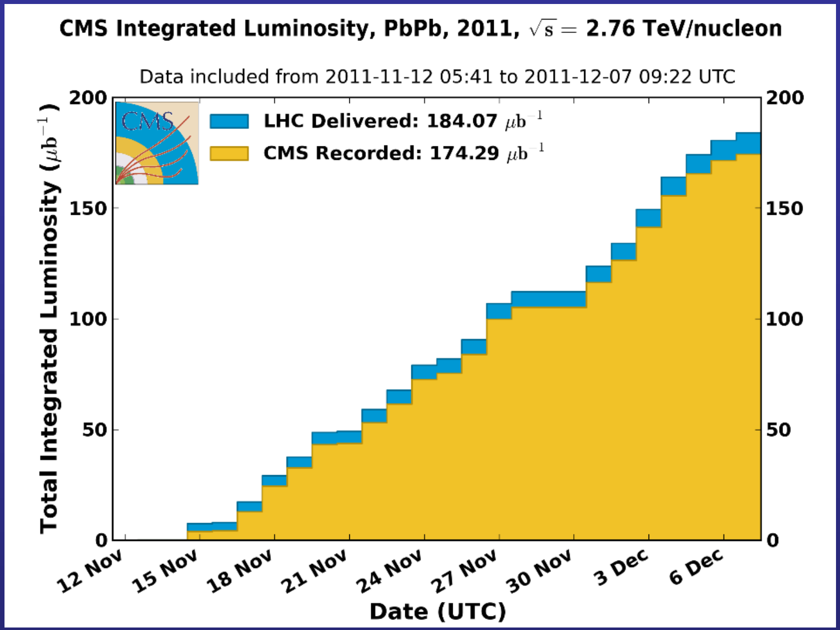
- ❑ High-statistics J/ψ sample
  → Comparison with run-1 AND with theoretical predictions crucial to confirm/quantify our understanding in terms of regeneration
  → more precise v_2 results also needed

- ❑ Significant ψ(2S) sample
  → Crucial: run-1 results "exploratory" (and interpretation not clear)

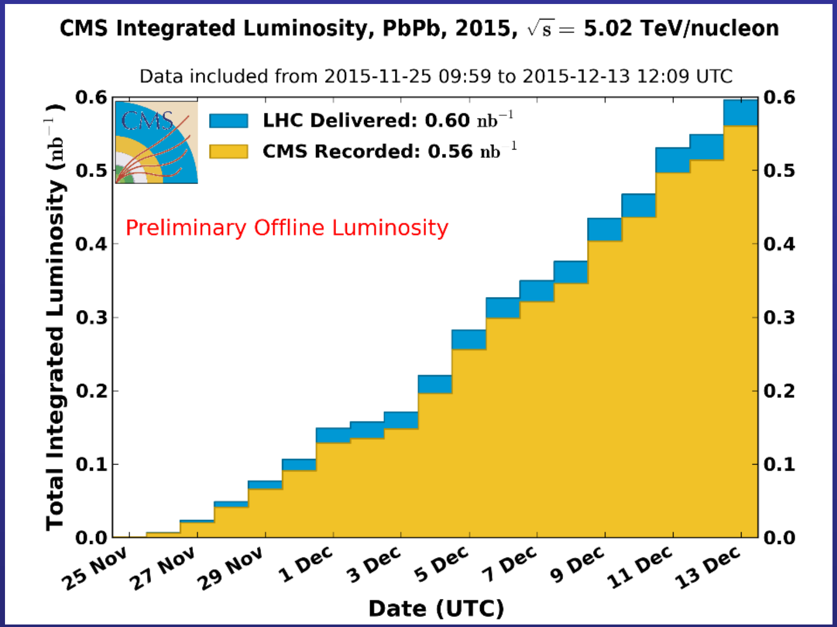
- ❑ High-statistics ϒ(1S) sample
  → A significant increase in 1S suppression with respect to run-1 might imply that a high-T QGP is formed ("threshold" scenario)

- ❑ Differential ϒ(2S) and ϒ(3S) results from run-1 are limited by statistics
  → Centrality and p_T-dependent studies important to assess details of sequential suppression

LHC performance run-2



Run 1



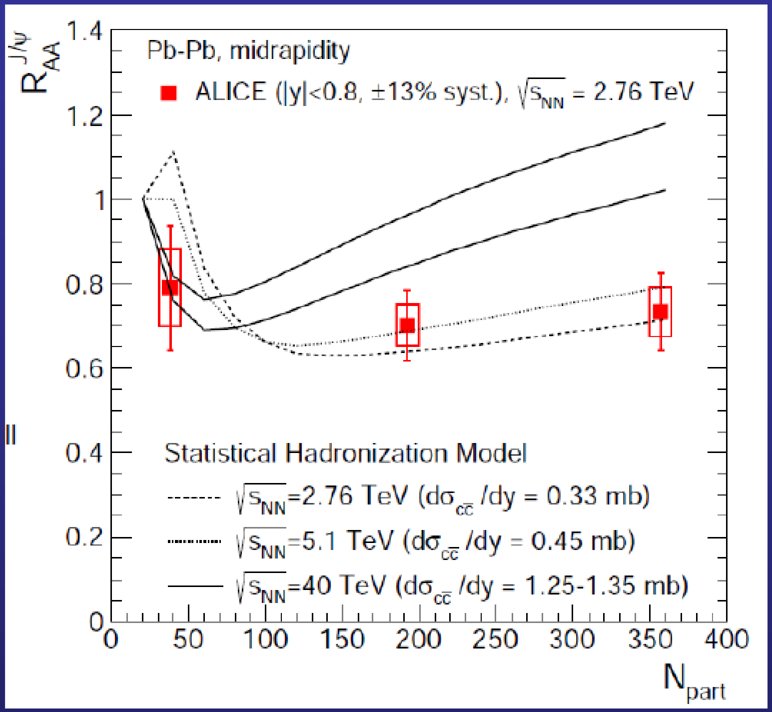
Run 2

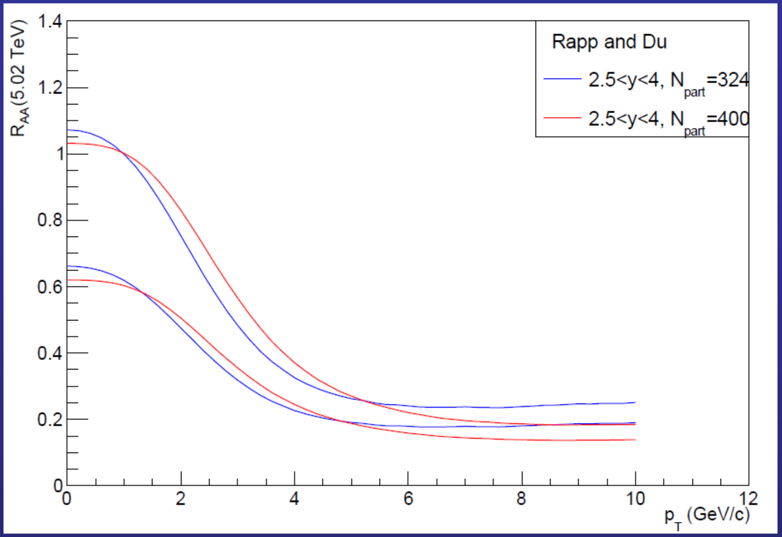
- ❑ Integrated luminosity → more than a factor 3 delivered by the LHC with respect to run 1 (2011 Pb-Pb)
- ❑ Short pp run at $\sqrt{s}$ = 5.02 TeV at the beginning of the HI period → L_{int} = 30 pb^{-1} , good reference for BOTH Pb-Pb and p-Pb results
- ❑ Data analysis quickly progressing

Some J/ψ predictions for run-2

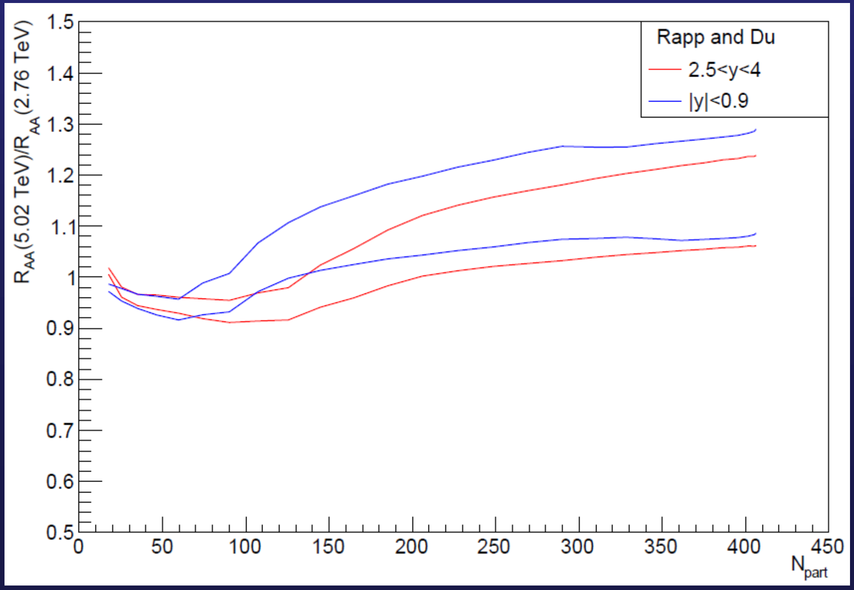
mid-rapidity

forward rapidity





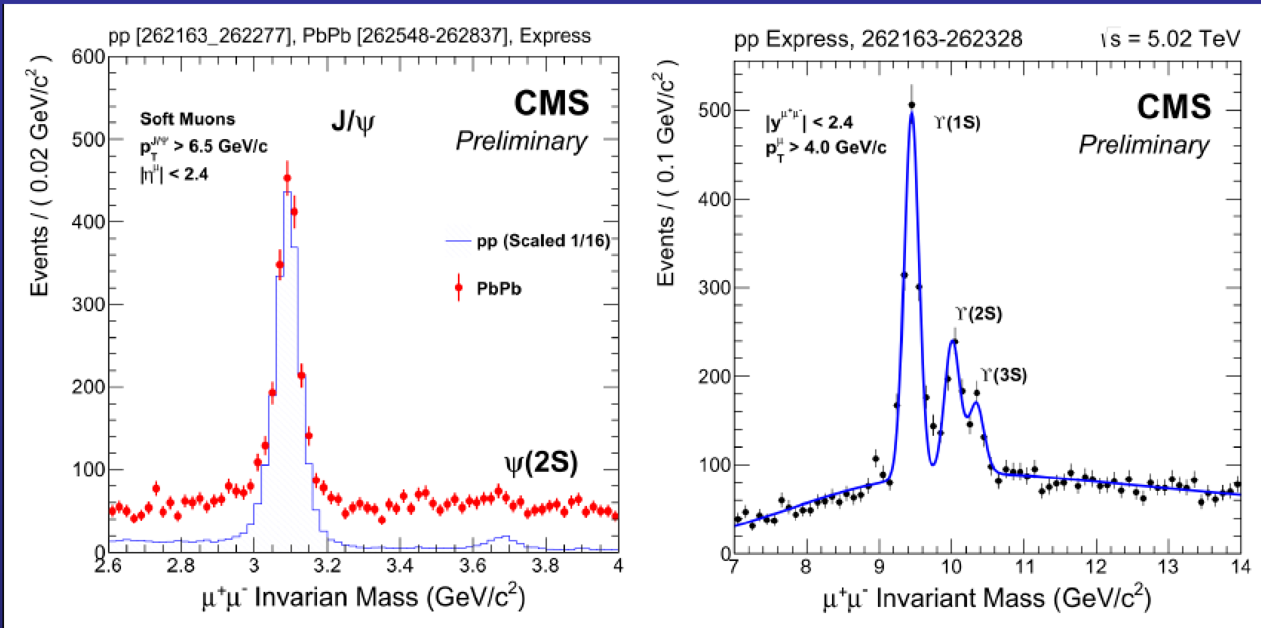
Rapp and Du



PBM, Andronic, Redlich and Stachel

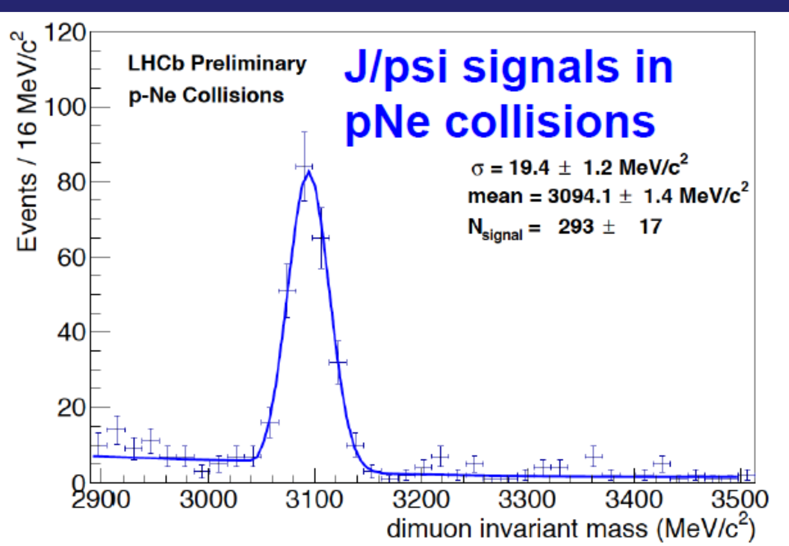
- First predictions for (both statistical and transport models) indicate a moderate increase in R_{AA}, when comparing $\sqrt{s_{NN}}$=5.02 and 2.76 TeV
- Theoretical uncertainties are larger than the predicted increase
  - → Provide quantities where at least a partial cancellation of uncertainties takes place (double ratios of R_{AA})

Some performance plots from run-2

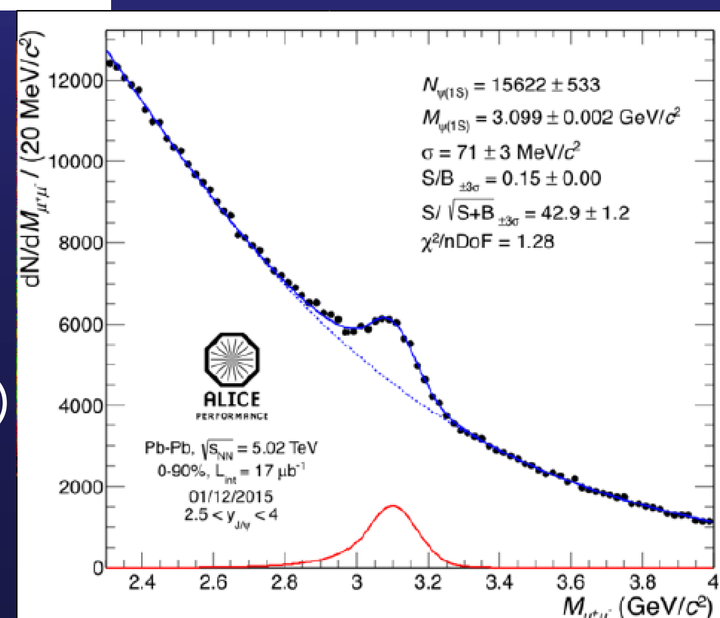


Charmonia/bottomonia signals well visible!

Expect first results very soon!

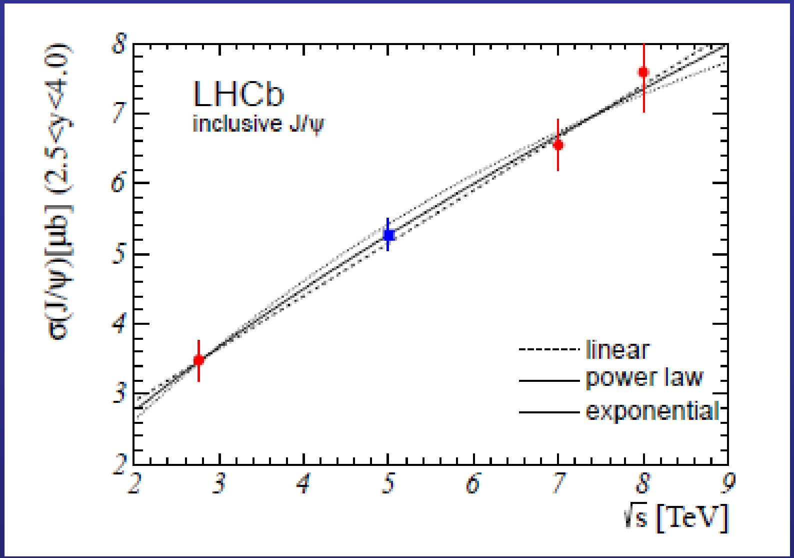


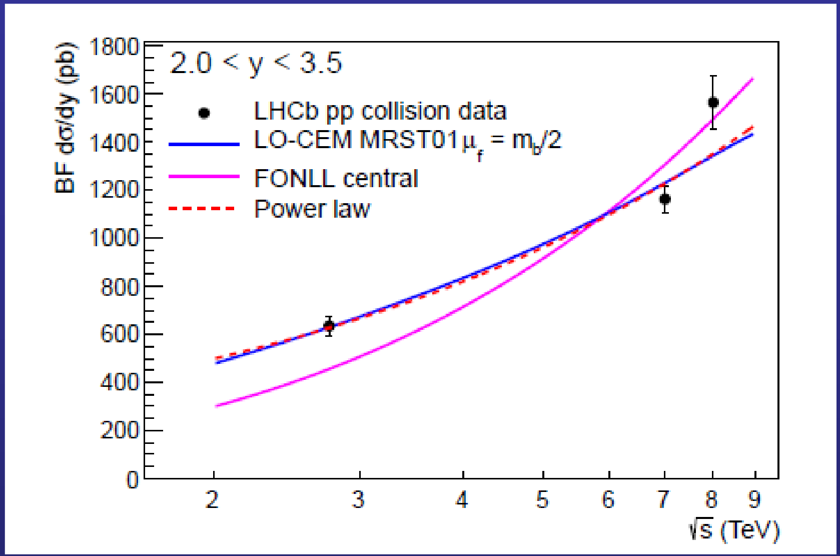
LHCb: first Pb-Pb run and p-A beam-gas collisions ($\sqrt{s_{NN}}$=110 GeV)



More info

Other ingredients/caveats to the "puzzle"





- ❑ Caveat: ALICE takes reference data from LHCb measurements
  Contrary to J/ψ, these exhibit a √s-dependence which disagrees with FONLL expectations, and even with (usual) empirical shapes

On feed-down fractions

- Usually they are not supposed to vary strongly with √s (or y)
- New LHCb pp results could alter the picture inherited by CDF (relative to p_Υ>8 GeV/c)

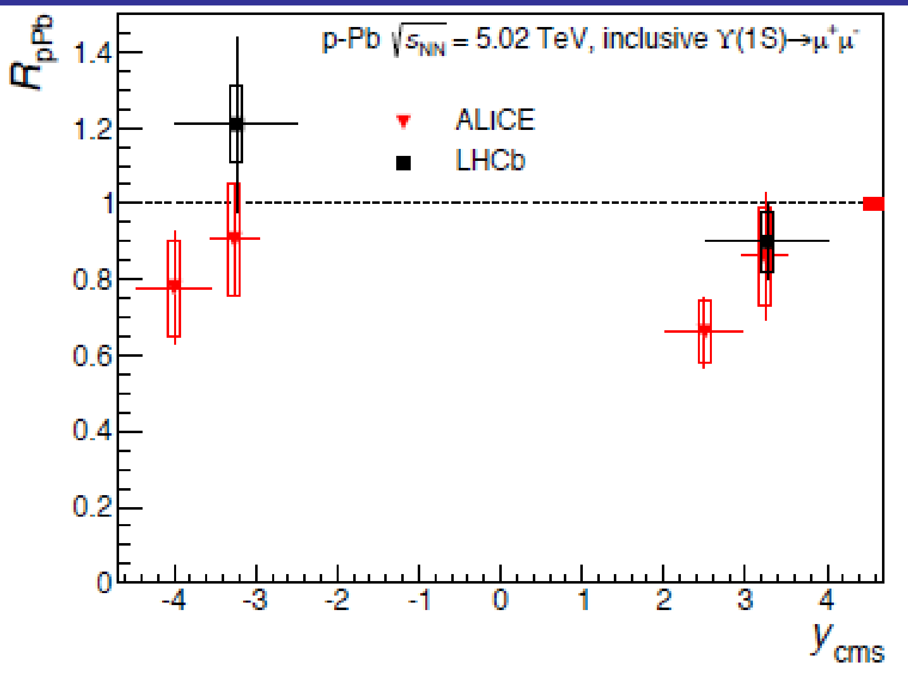
	p_T^Υ (GeV/c)	$\mathcal{R}^{\chi_b(1P)}_{\Upsilon(nS)}$	$\mathcal{R}^{\chi_b(2P)}_{\Upsilon(nS)}$
$\Upsilon(1S)$	6–8	$14.8 \pm 1.2 \pm 1.3$	$3.3 \pm 0.6 \pm 0.2$
	8–10	$17.2 \pm 1.0 \pm 1.4$	$5.2 \pm 0.6 \pm 0.3$
	10–14	$21.3 \pm 0.8 \pm 1.4$	$4.0 \pm 0.5 \pm 0.3$
	14–18	$24.4 \pm 1.3 \pm 1.2$	$5.2 \pm 0.8 \pm 0.4$
	18–22	$27.2 \pm 2.1 \pm 2.1$	$5.5 \pm 1.0 ^{+0.4}_{-1.0}$
	22–40	$29.2 \pm 2.5 \pm 1.7$	$6.0 \pm 1.2 ^{+0.4}_{-0.7}$

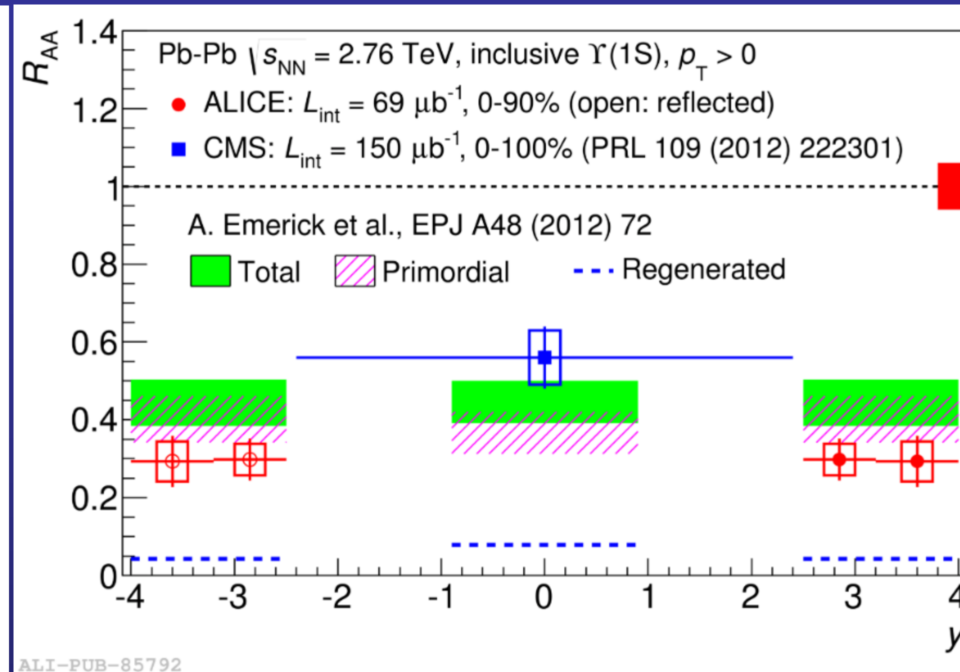
LHCb

We have reconstructed the radiative decays $\chi_b(1P) \to \Upsilon(1S)\gamma$ and $\chi_b(2P) \to \Upsilon(1S)\gamma$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, and measured the fraction of $\Upsilon(1S)$ mesons that originate from these decays. For $\Upsilon(1S)$ mesons with $p_T^\Upsilon > 8.0$ GeV/c, the fractions that come from $\chi_b(1P)$ and $\chi_b(2P)$ decays are [27.1 ± 6.9(stat) ± 4.4(syst)]% and [10.5 ± 4.4(stat) ± 1.4(syst)]%, respectively. We have derived the fraction of directly produced $\Upsilon(1S)$ mesons to be [50.9 ± 8.2(stat) ± 9.0(syst)]%.

- At the limit of uncertainties or do we have a problem here ?
- Difficult to reach 50% including 2S and 3S

Can we take CNM into account ?





- ❑ Apply the simple $R_{pPb} \times R_{Pbp}$ recipe on ALICE pPb
- ❑ Would give 0.78×0.86 = 0.67 for 3.25<y<4
  0.91×0.66 = 0.60 for 2.5<y<3.25
  (but see also LHCb result)

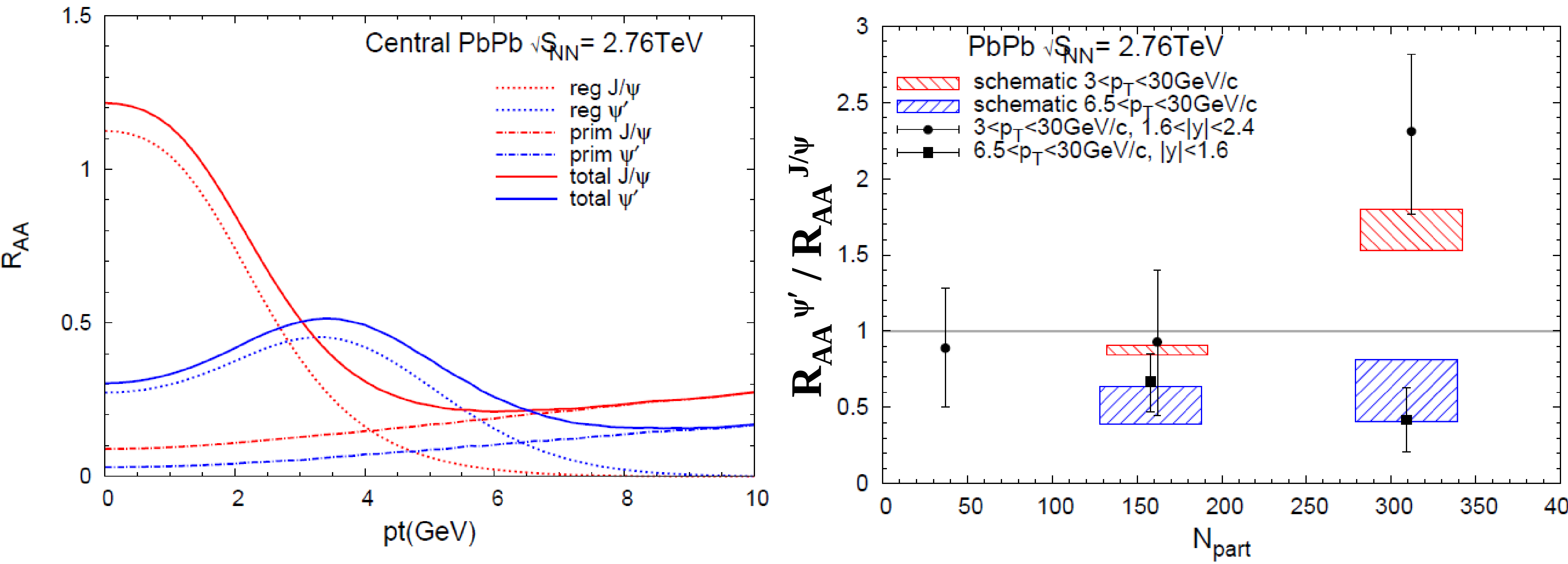
→ ~0.5 "anomalous" suppression at forward-y

- ❑ No results from CMS (for the moment ?)
- ❑ Assuming a "smooth" y-interpolation of CNM

→ ~0.8-0.9 "anomalous" suppression at central-y

→ Need new/better pPb data ?

Charmonium: the ψ(2S) puzzle



- The regeneration of ψ′ mesons occurs significantly later than for J/ψ's
- Despite a smaller total number of regenerated ψ′, the stronger radial flow at their time of production induces a marked enhancement of their R_{AA} relative to J/ψ's in a momentum range pt ≃ 3-6 GeV/c.

J/ψ in Pb-Pb: from run-1 to run-2

- Evidence for smaller suppression compared to RHIC
  → Occurrence of recombination is at present the only explanation
- p_T-dependence of R_{PbPb} also compatible with recombination

- Although qualitative interpretation looks unambiguous, the quantitative assessment of the effects at play needs refinement
- Values for $d\sigma_{cc}/dy$ evolved. At present, in the forw.-y ALICE domain:
  - SHM → 0.15 – 0.25 mb (y=4 and y=2.5) – no shadowing
  - Zhao and Rapp → 0.5 mb – "empirical" shad. vs no shad.
  - Zhuang et al. → 0.4 – 0.5 mb – EKS98 shadowing
  - Ferreiro et al. → 0.4 – 0.6 mb + Glauber-Gribov shad. ~ nDSG(min.) > EKS98

- LHC run-2 → (almost) a factor 2 gain in $\sqrt{s}$
  → would it be possible to extract $d\sigma_{cc}/dy$ which gives the best fit to run-1 results, extrapolate to run-2 energy (FONLL?) and give predictions ?

- Suppression persists up to the largest investigated p_T
  - Higher p_T reach in run-2 → increase of R_{PbPb} ? Predictions ?

- Interesting indication for azimuthal anisotropies. Run-2 needs
  - Experiment → (much) larger statistics
  - Theory → solid predictions

J/ψ in p-Pb: run-1 summary

- p-Pb data: characterization of CNM effects in terms of shadowing plus coherent energy loss (no break-up) looks satisfactory

- Uncertainties on shadowing calculations are large, could one use the LHC data to better constrain shadowing ?

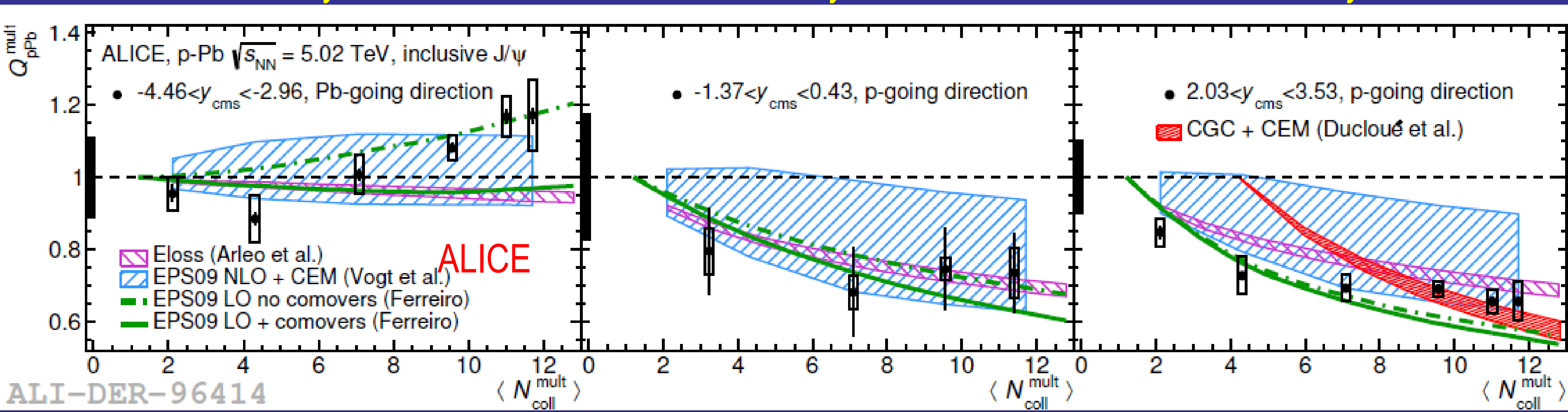
- Effects are strong, R_{pPb}~ 0.6 at low p_T and central to forward rapidity
  → Strong influence of CNM effects in Pb-Pb in the corresponding kinematic region

- The simple estimate $R_{PbPb}^{CNM}=R_{pPb}\times R_{Pbp}$ (inspired to a shadowing scenario) leads, once this effect is factorized out, to an even steeper p_T-dependence of R_{PbPb}

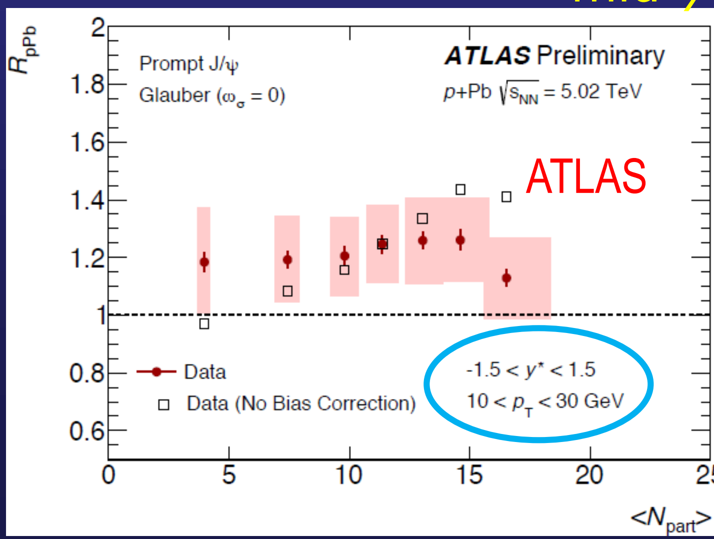
- Also for p-Pb, run-2 energy predictions (√s~8 TeV), with parameters TUNED on run-1 results, would allow a crucial test of our understanding of the involved mechanisms

J/ψ R_{pPb}: centrality dependence

backward-*y* mid-*y* forward-*y*



mid-*y*

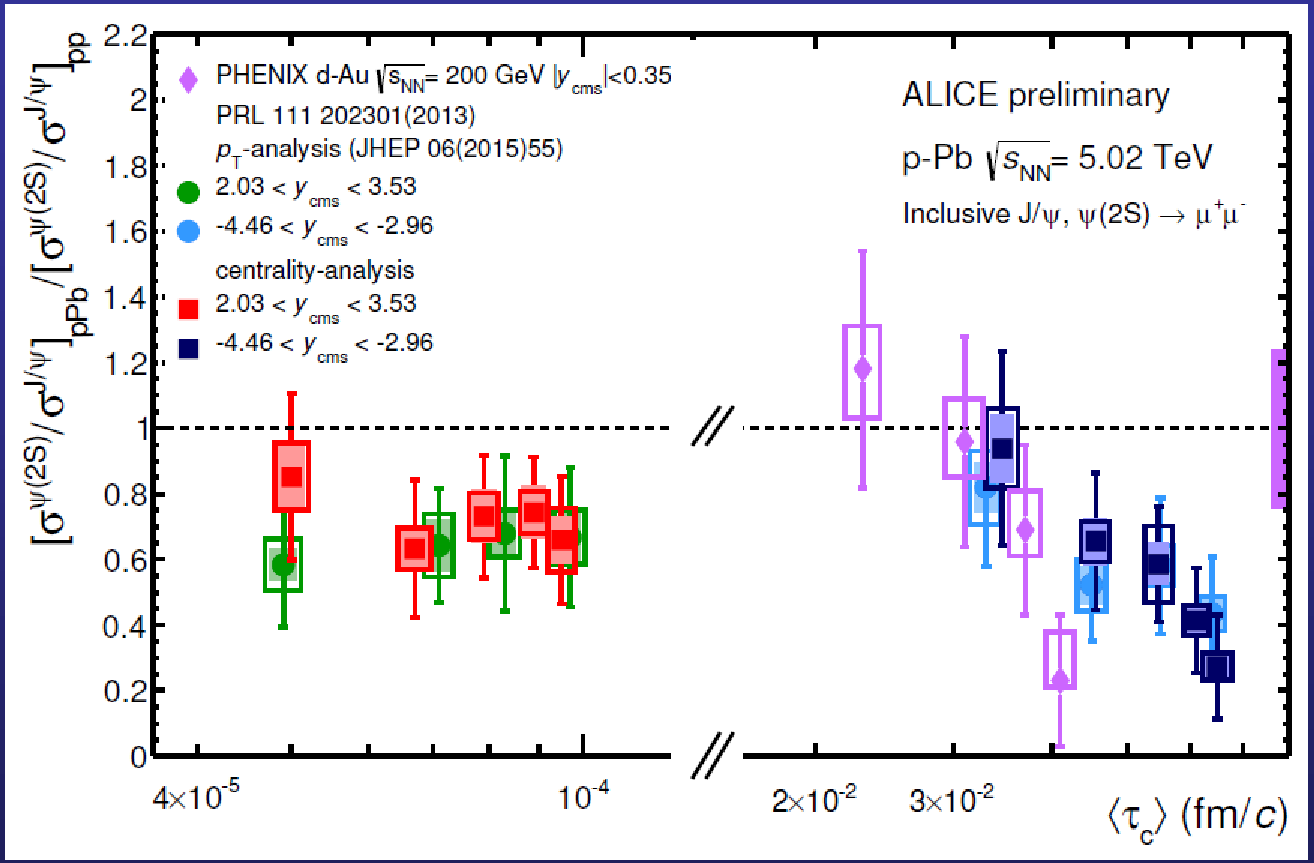


- ALICE:
- mid and fw-y: suppression increases with centrality
- backward-y: hint for increasing Q_{pA} with centrality

- Shadowing and coherent energy loss models in fair agreement with data

- ATLAS
- Flat centrality dependence in the high p_T range

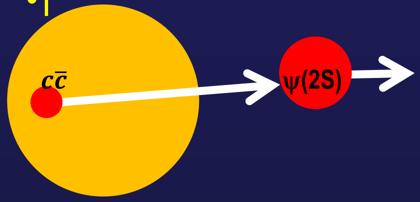
Dependence of suppression on τ_c



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

D. McGlinchey, A. Frawley and R.Vogt, PRC 87,054910 (2013)

Forward-y: $\tau_c << \tau_f$
interaction with nuclear matter cannot play a role



Backward-y: $\tau_c \lesssim \tau_f$
indication of effects related to break-up in the nucleus?