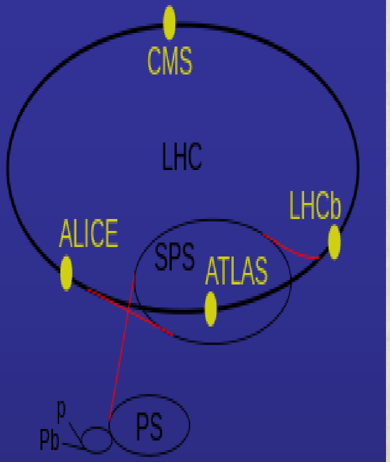
Quarkonium production at LHC: from pp to AA

E. Scomparin (INFN-Torino)



- ☐ A short introduction
  - → Building on the shoulders of giants
- ☐ LHC results
  - → New discoveries, better understanding
- ☐ Open points and prospects
  - → Future measurements at the LHC

GHP2017

7th Workshop of the APS Topical Group on Hadronic Physics

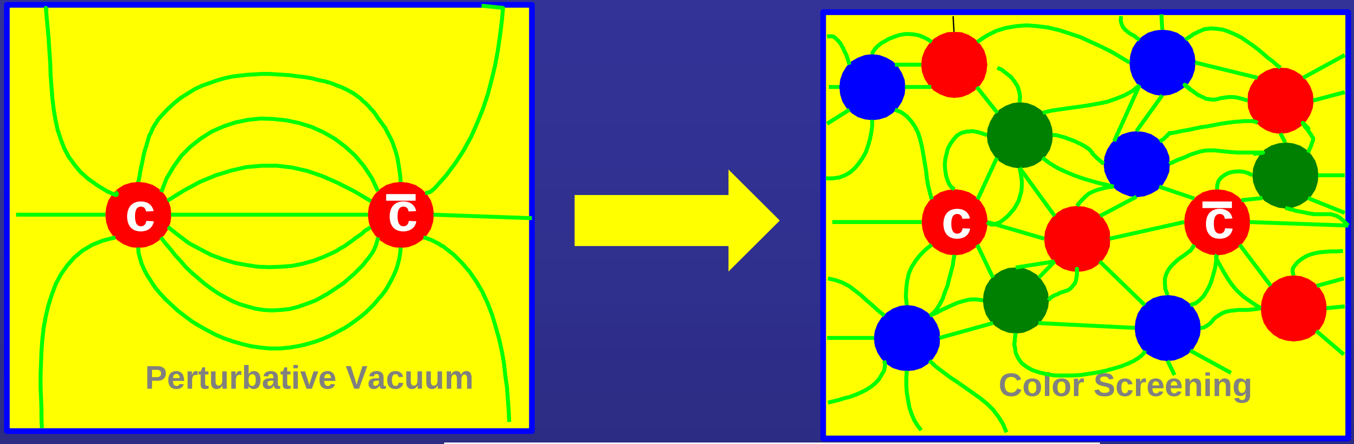
February 1-3, 2017
Washington, DC

Contact: ghpworkshops@gmail.com
https://www.aps.org/meetings/meeting.cfm?name=GHP17
Venue: Marriott Wardman Park, Washington, DC

Quarkonia in heavy-ions: color screening…

Screening of
strong interactions
in a QGP

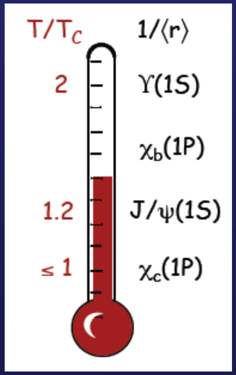
T. Matsui and H. Satz,
PLB178 (1986) 416

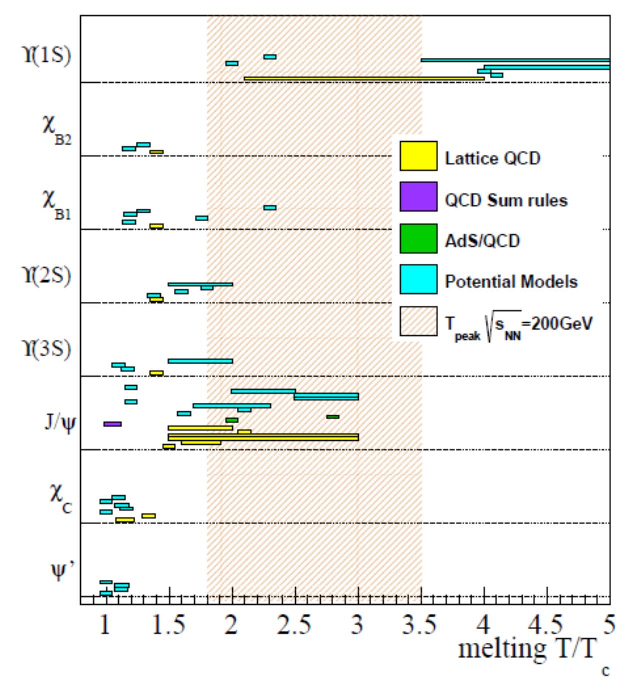


- Screening stronger at high T
- λ_D → maximum size of a bound state, decreases when T increases
- Different states, different sizes

Resonance melting

QGP
thermometer

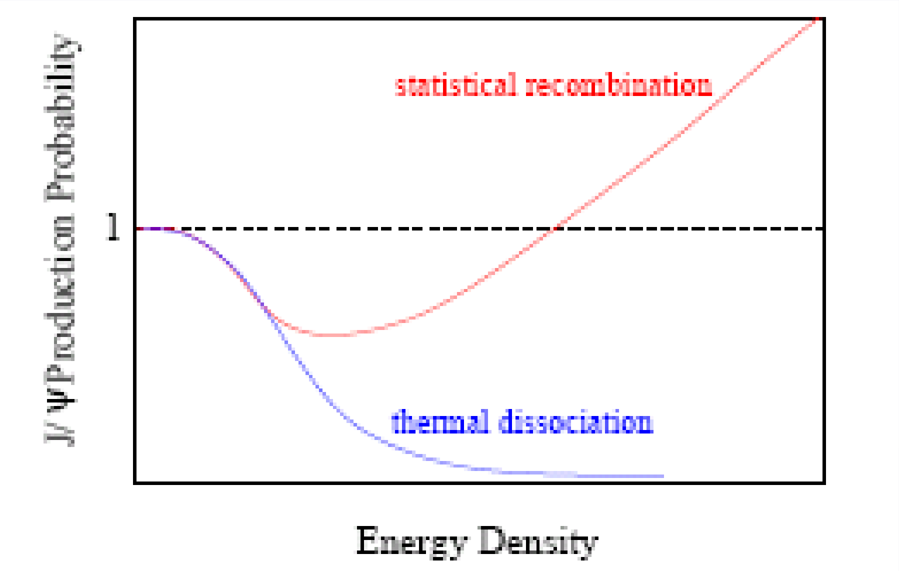




…and regeneration

At sufficiently high energy, the cc pair multiplicity becomes large

Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~85	~115



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

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

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

Disclaimer

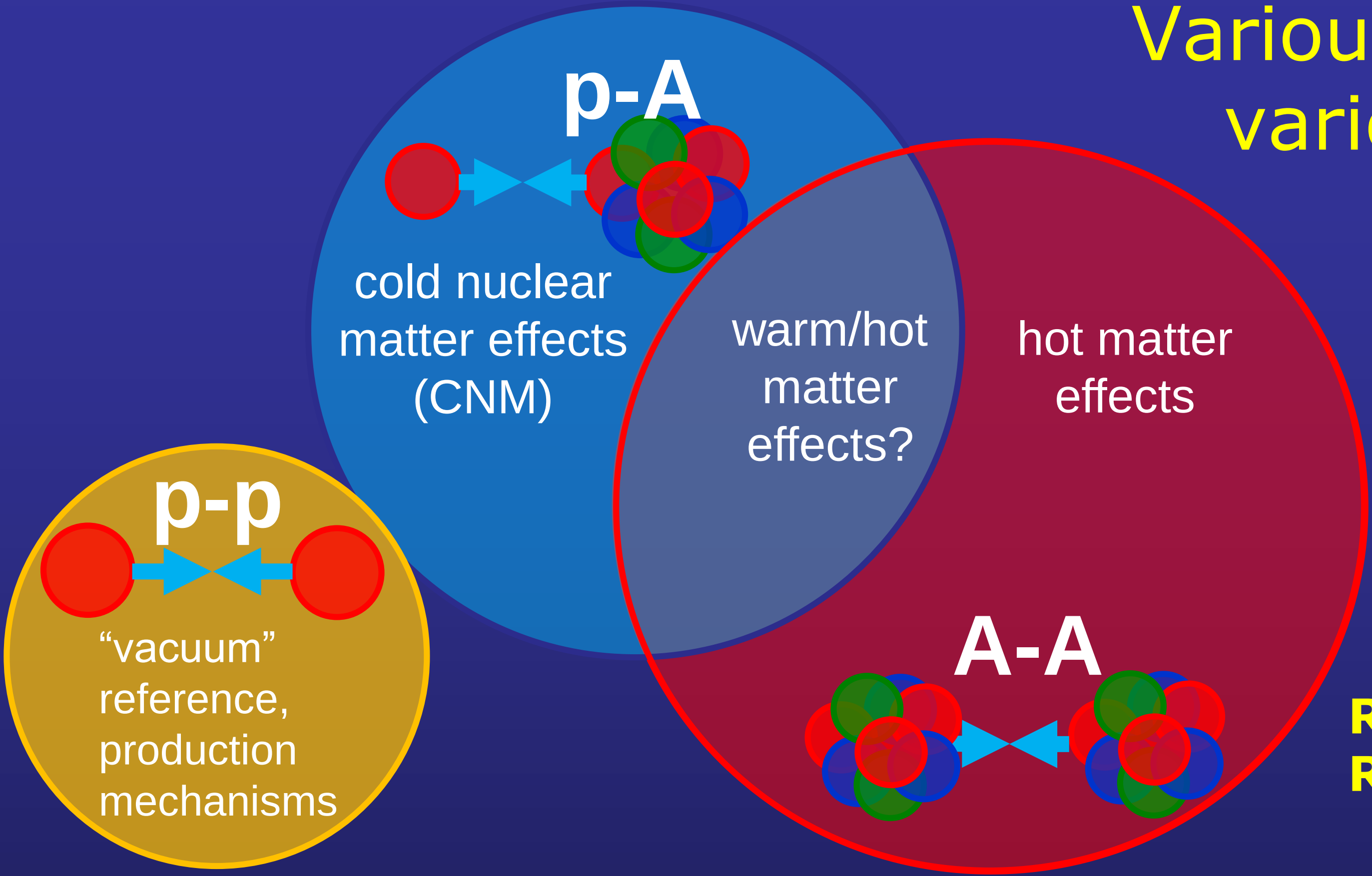
- ❑ Implementing a realistic quarkonium production in a realistic medium is a considerably difficult task

- ❑ Some open points
  - ❑ In high-energy heavy-ion collisions the QGP thermalization times are very short (~1 fm/c)
    → One should deal with in-medium formation of quarkonium rather than with suppression of already formed states
    → Heavy quark diffusion is relevant for quarkonium production

- ❑ Need to determine T_D , $M_\psi(T)$, $\Gamma_\psi(T)$ from QCD calculations (using spectral functions from EFT/LQCD)
- ❑ Need to know the fireball evolution from microscopic calculations
- ❑ A precise determination of the total open charm cross section is still lacking

Impressive advances on theory side but the availability of data for various colliding systems and energy remains a must!

Various systems, various effects



p-A

cold nuclear matter effects (CNM)

warm/hot matter effects?

hot matter effects

A-A

p-p

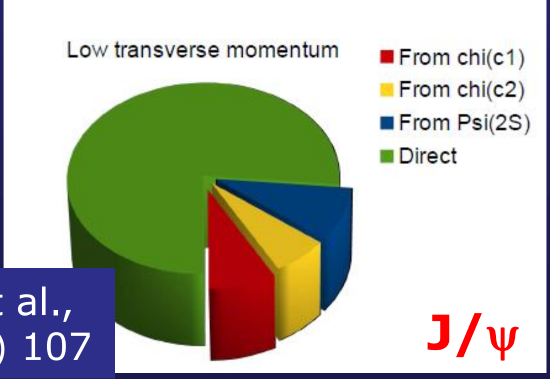
“vacuum” reference, production mechanisms

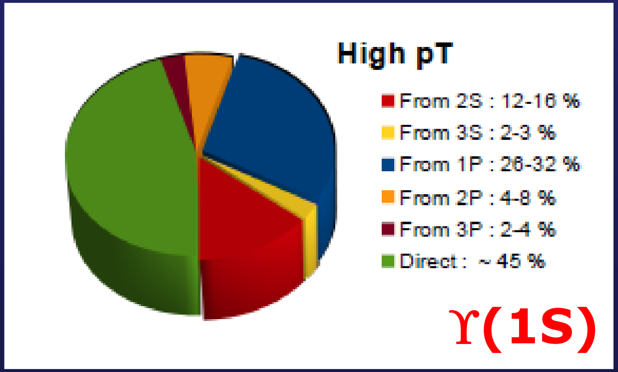
Quantify the yield modifications via the nuclear modification factor R_{AA}

$$R_{AA} = \frac{dN^{P}_{AA}}{\langle N_{Coll} \rangle \, dN^{P}_{pp}}$$

$R_{AA}<1$ suppression
$R_{AA}>1$ enhancement

Feed-down
(on prompt sources)
plays a
relevant role

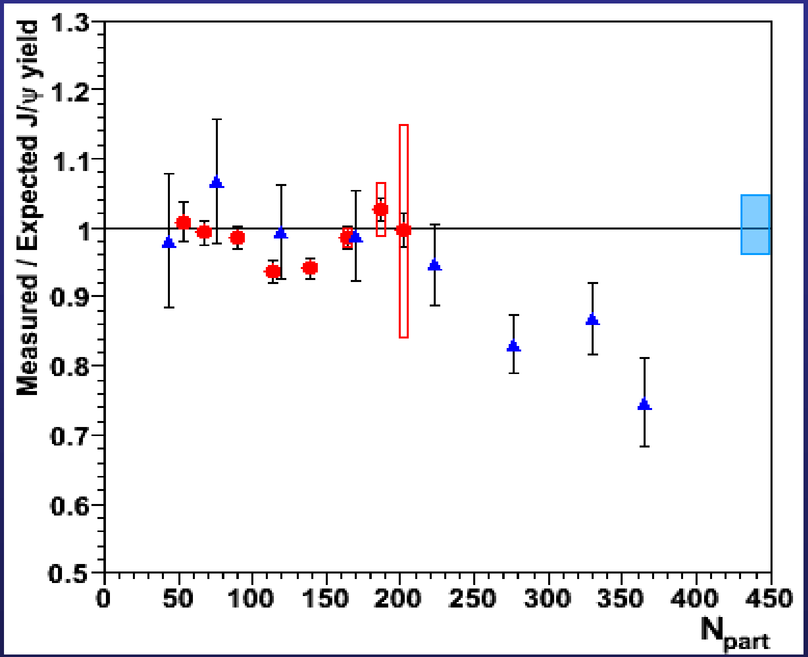




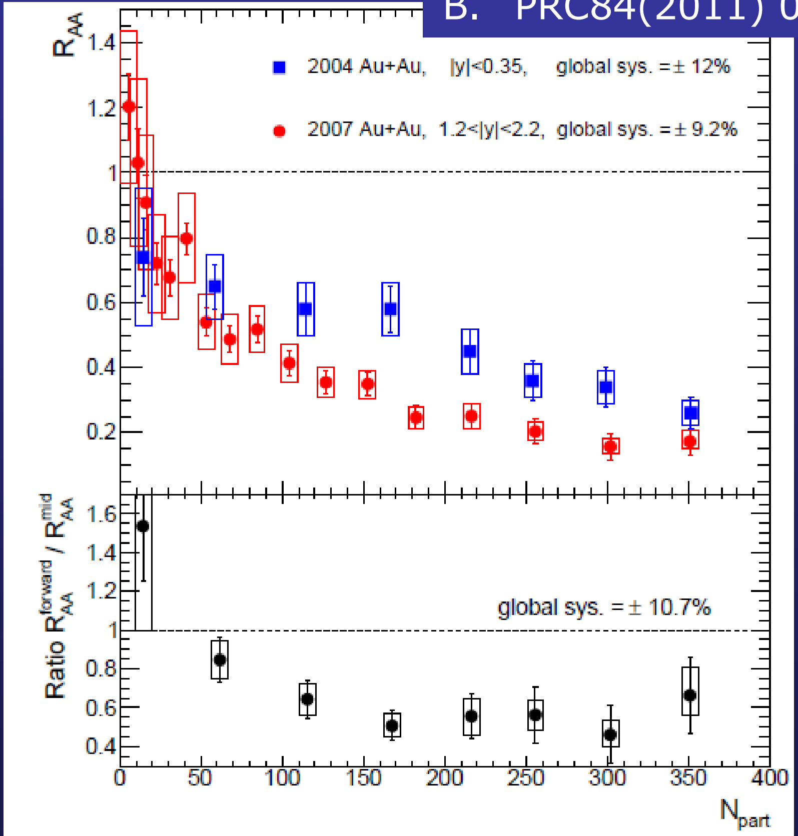
A. Andronic et al., EPJC 76 (2016) 107

The legacy of SPS/RHIC

- ☐ Several landmarks were established
  - ☐ J/ψ suppression beyond CNM effects at SPS (maximum suppression compatible with χ_c + ψ(2S) melting)
  - ☐ Much stronger ψ(2S) suppression relative to J/ψ at SPS
  - ☐ Strong y-dependence of J/ψ suppression at RHIC (possible indication of recombination)

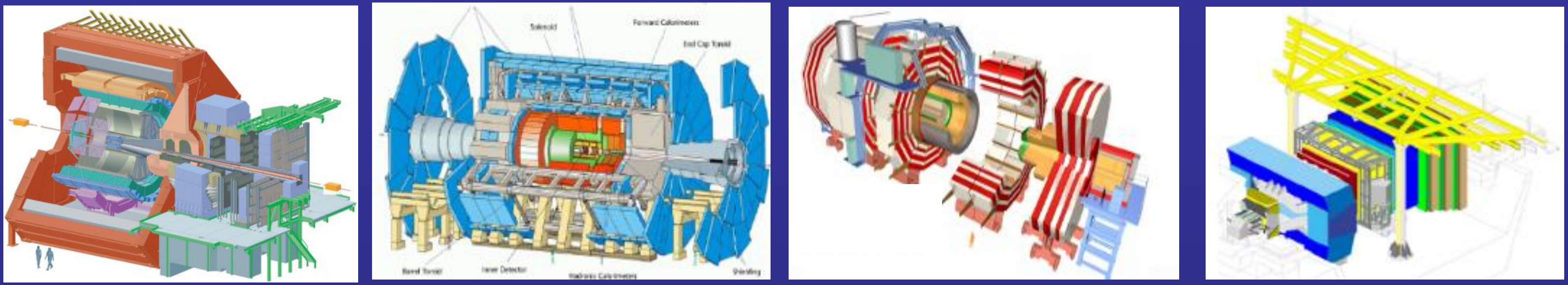


R.Arnaldi et al.(NA60)
NPA830 (2009) 345c



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

Quarkonium at LHC



- ❑ All the four experiments have investigated quarkonium production
  - ❑ Pb-Pb → mainly ALICE + CMS, p-Pb → 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!)

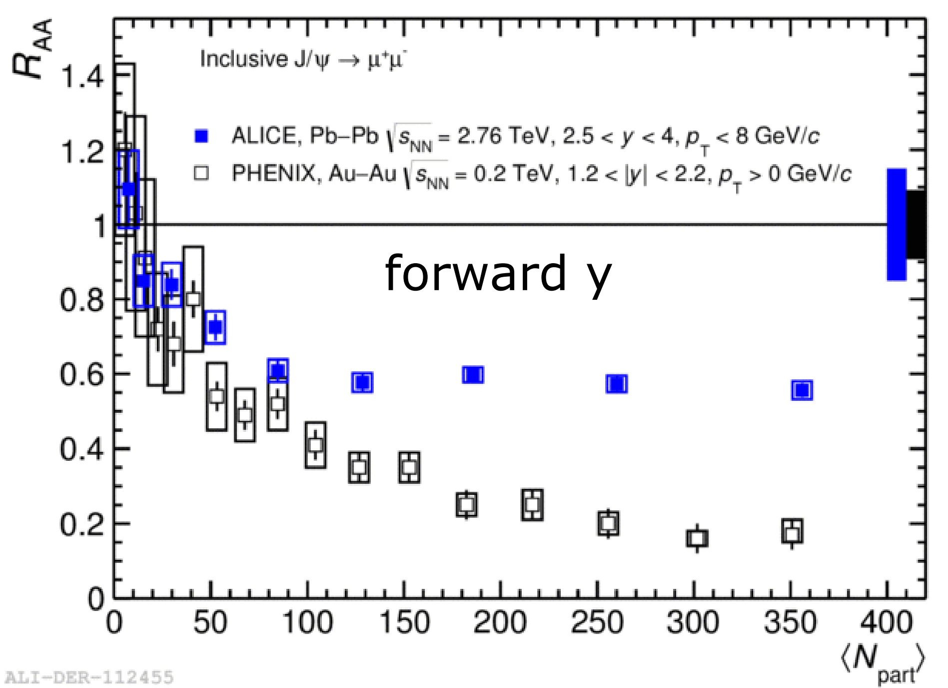
Data samples

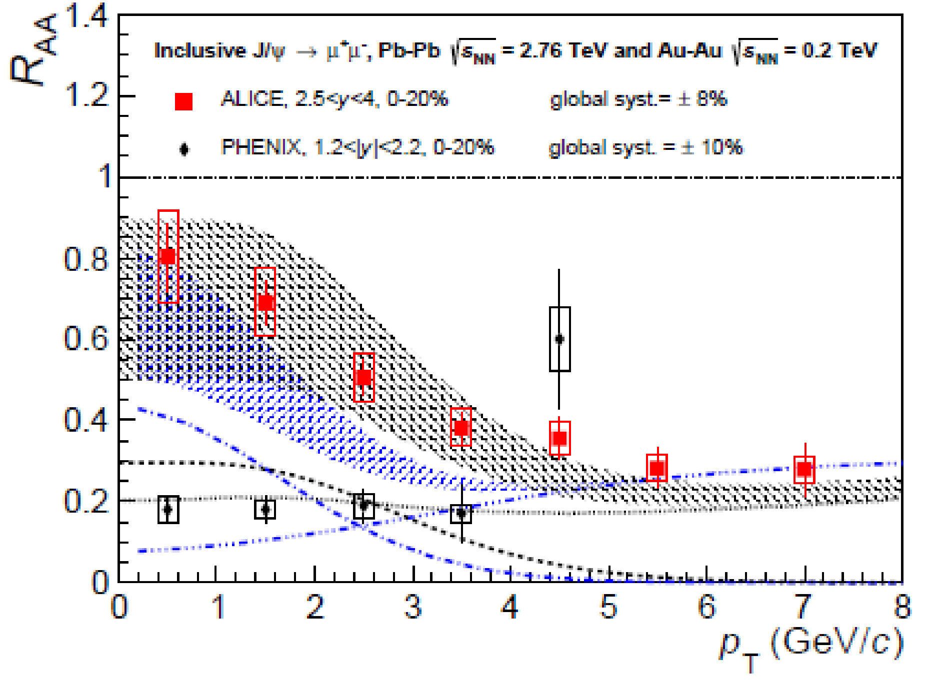
Run 1:
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, 2010 (9.7 μb^{-1}) + 2011 (184 μb^{-1})
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, 2013 (36 nb^{-1})
ref. p-p, $\sqrt{s}$ = 2.76 TeV, 2011 (250 nb^{-1}) + 2013 (5.6 pb^{-1})

Run 2:
Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, 2015 (600 μb^{-1})
p-Pb, $\sqrt{s_{NN}}$ = 8.16 TeV, 2016 (194 nb^{-1})
ref. p-p, $\sqrt{s}$ = 5.02 TeV, 2015 (30 pb^{-1})

Low-p_T J/ψ: ALICE (vs PHENIX)

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



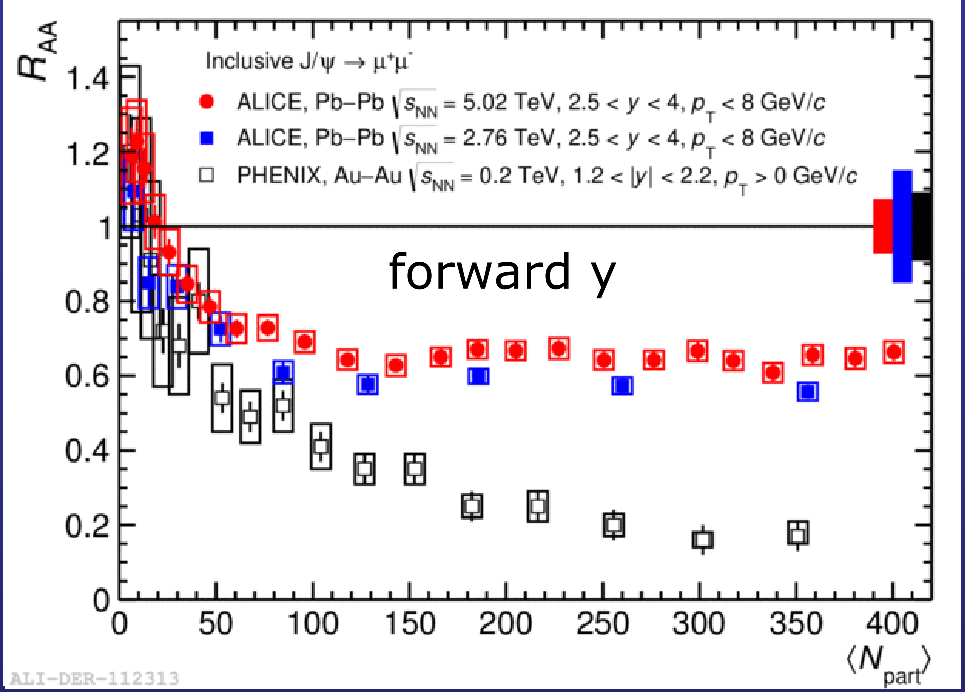


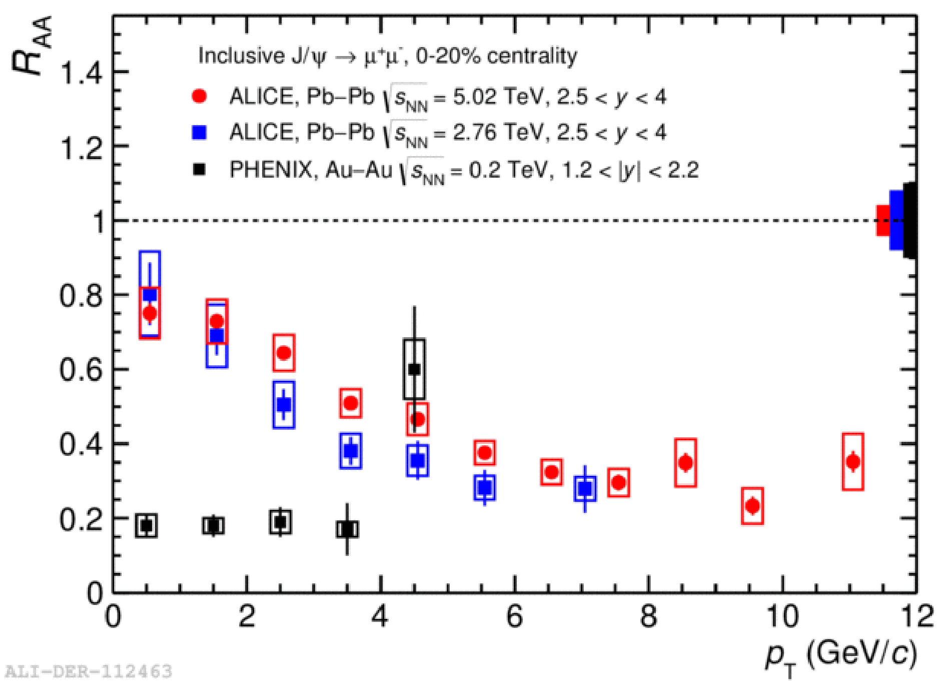
- J/ψ suppression, RHIC ($\sqrt{s_{NN}}$=0.2 TeV) vs LHC ($\sqrt{s_{NN}}$=2.76 TeV, 5.02 TeV)
- Results vs centrality dominated by low-p_T J/ψ
  - Systematically larger R_{AA} values for central events at LHC energy
  - R_{AA} increases at low p_T at LHC energy
  - More precise results at $\sqrt{s_{NN}}$=5.02 TeV, compatible with $\sqrt{s_{NN}}$=2.76 TeV

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

Low-p_T J/ψ: ALICE (vs PHENIX)

J.Adam et al, ALICE
PLB766(2017) 212





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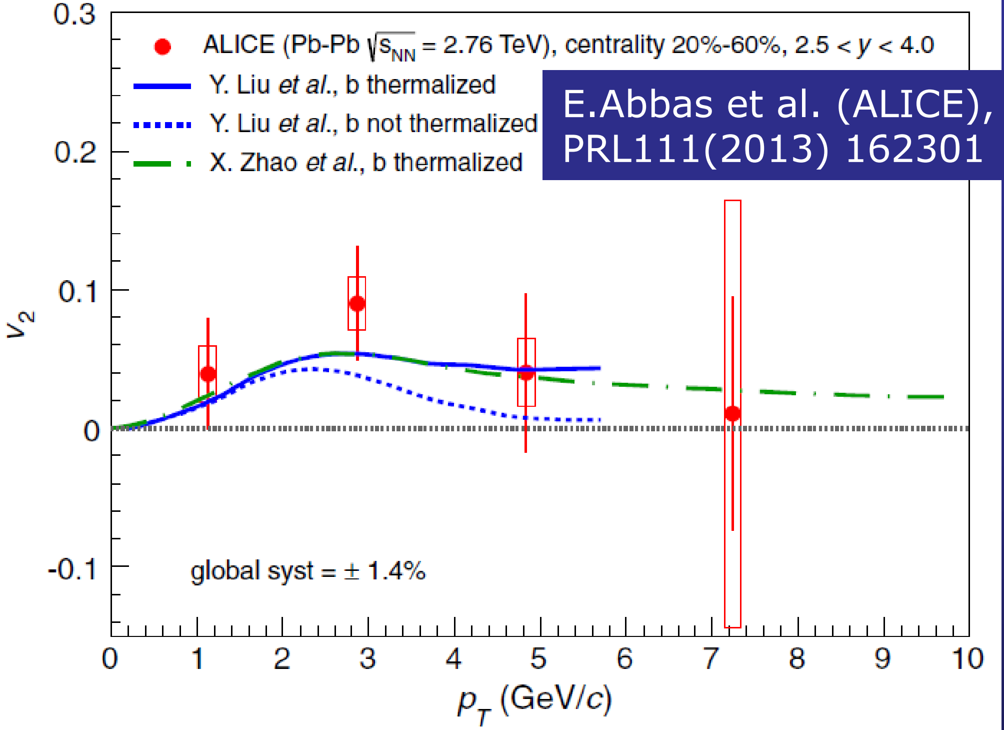
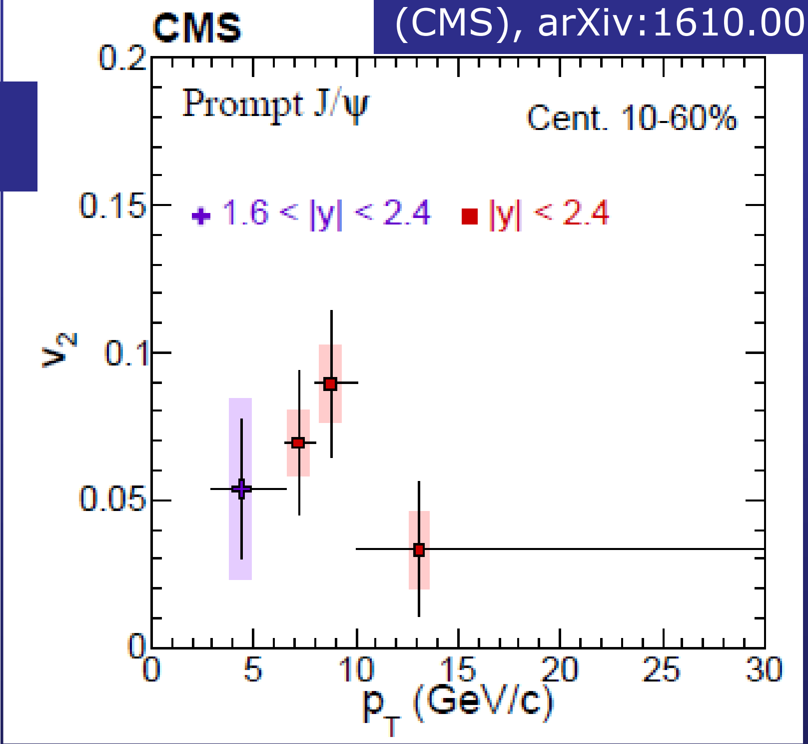
LHC energy → suppression + regeneration

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 → hints observed!



E.Abbas et al. (ALICE), PRL111(2013) 162301

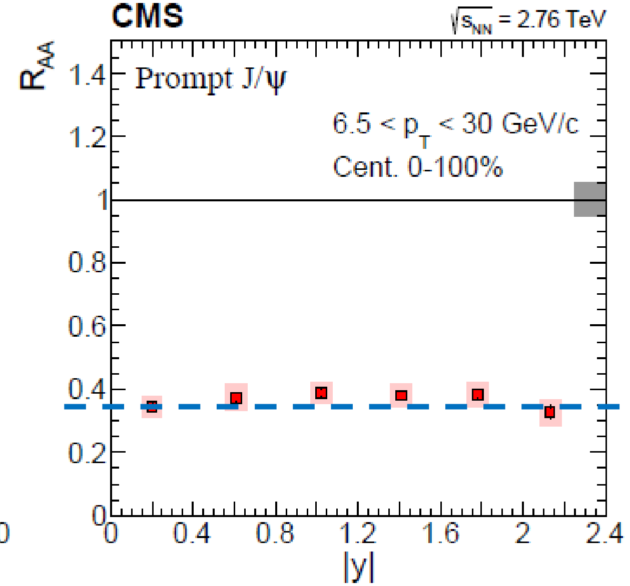


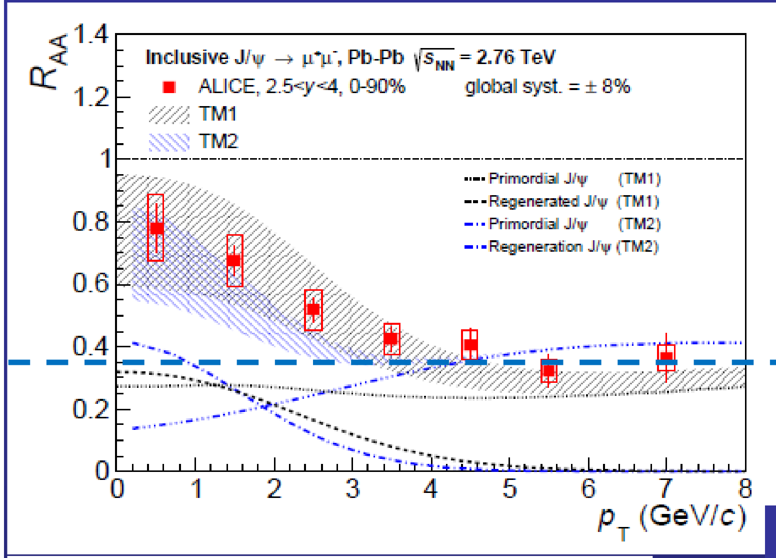
V. Khachatryan et al. (CMS), arXiv:1610.00613

- No signal of $v_2 \neq 0$ at RHIC energy
- v_2 remains significant even at large p_T, where the contribution of (re)generation should be negligible
  → Likely due to path length dependence of energy loss

V. Khachatryan et al. (CMS), arXiv:1610.00613

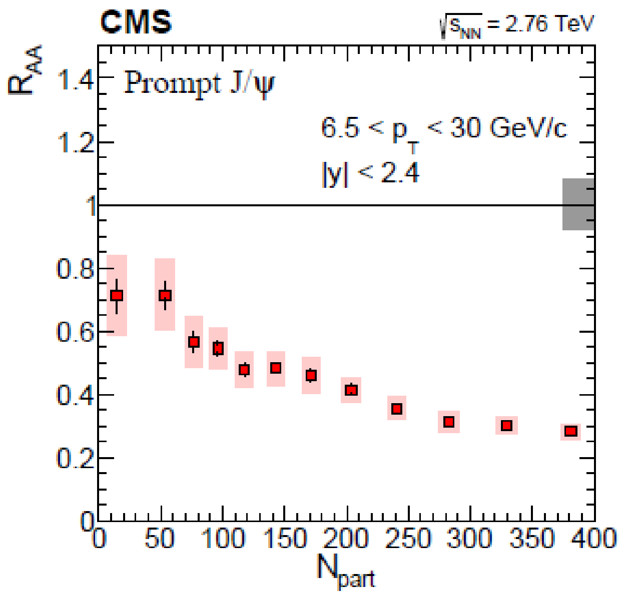
High-p_T J/ψ

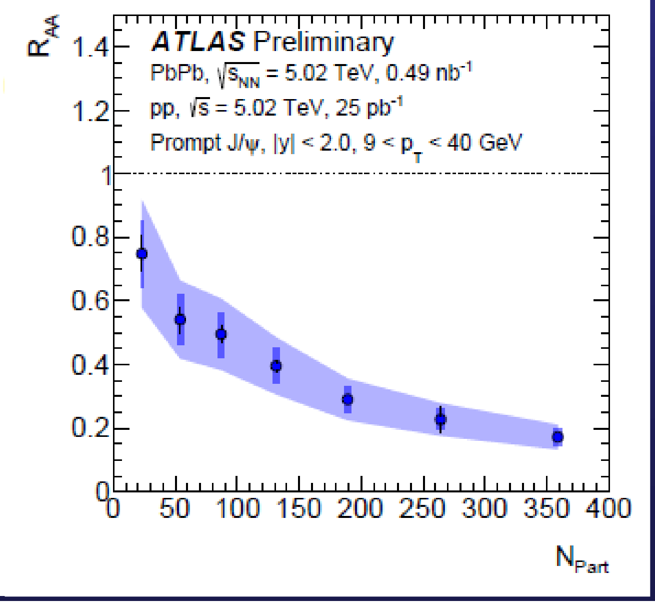




Strong high-p_T suppression: compatibility ALICE vs CMS OK (y-range contiguous)

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

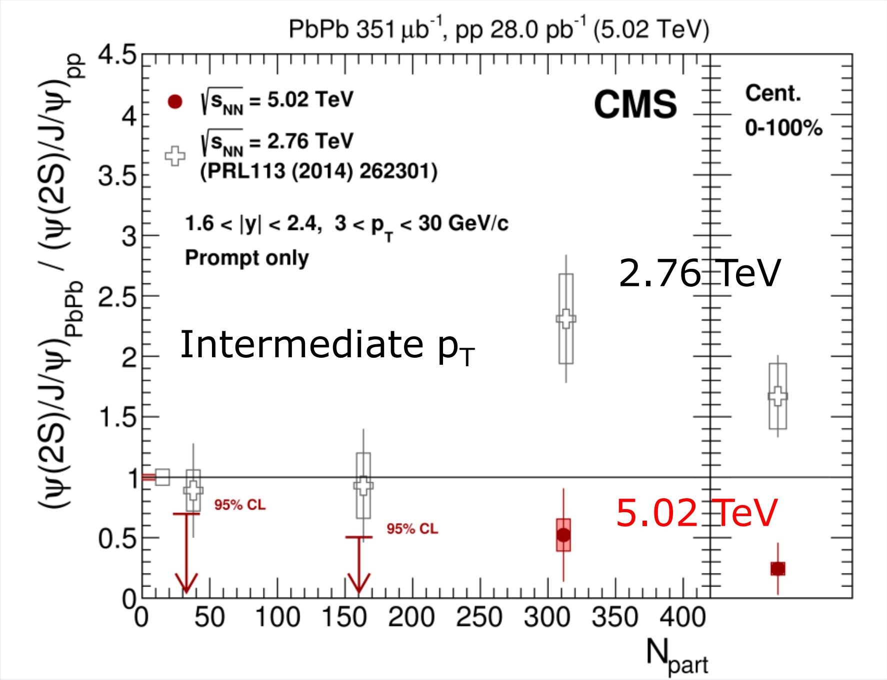


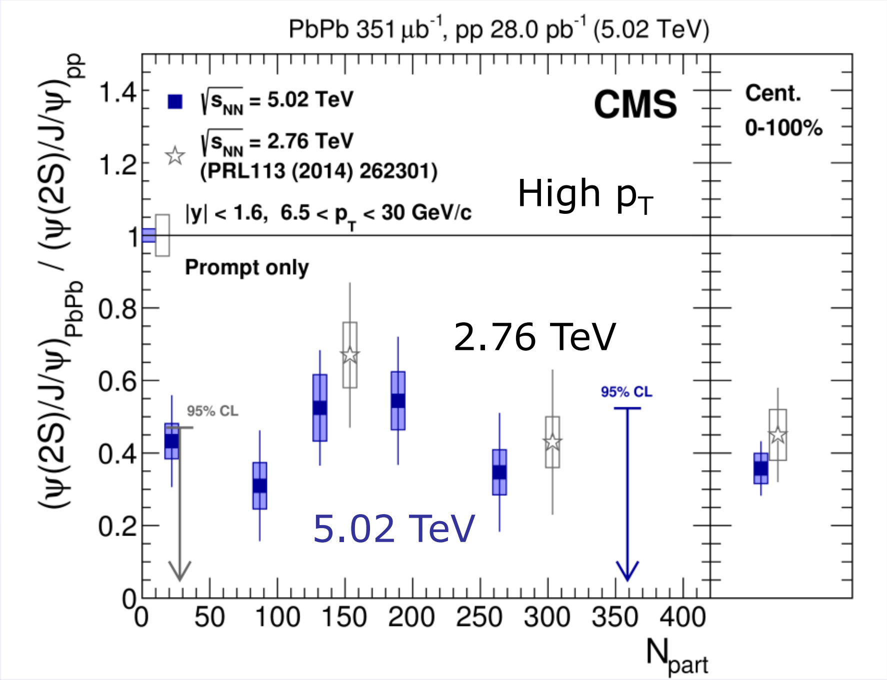


- ☐ Fine centrality binning
- ☐ Striking difference with respect to low-p_T J/ψ
- ☐ Increasing suppression with centrality at high p_T vs saturation at low p_T

ψ(2S) in Pb-Pb collisions

V. Khachatryan et al. (CMS), arXiv:1611.01438



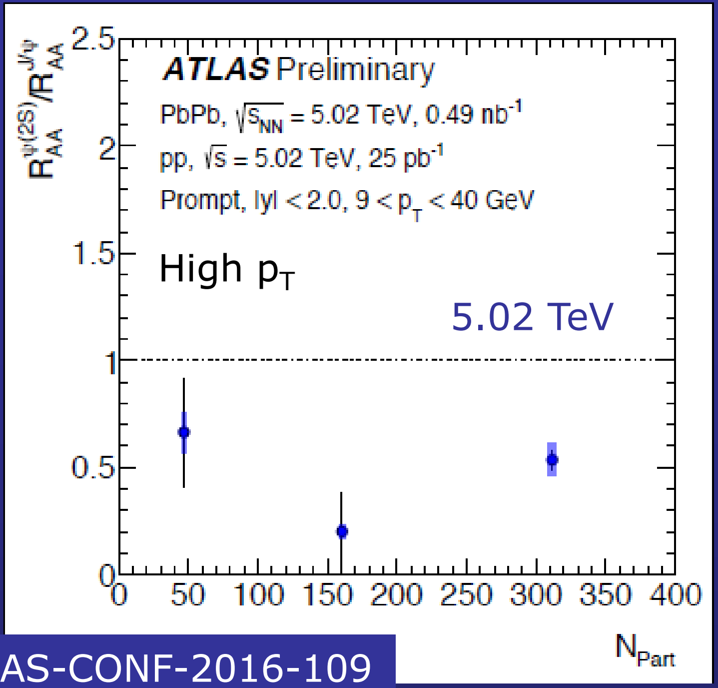


- Ratio $(\psi(2S)/J/\psi)_{PbPb}$/ $(\psi(2S)/J/\psi)_{pp}$ → naïve expectation <1
- Enhancement seen at 2.76 TeV, but not at 5.02 TeV
- ATLAS confirms suppression in the high-p_T region

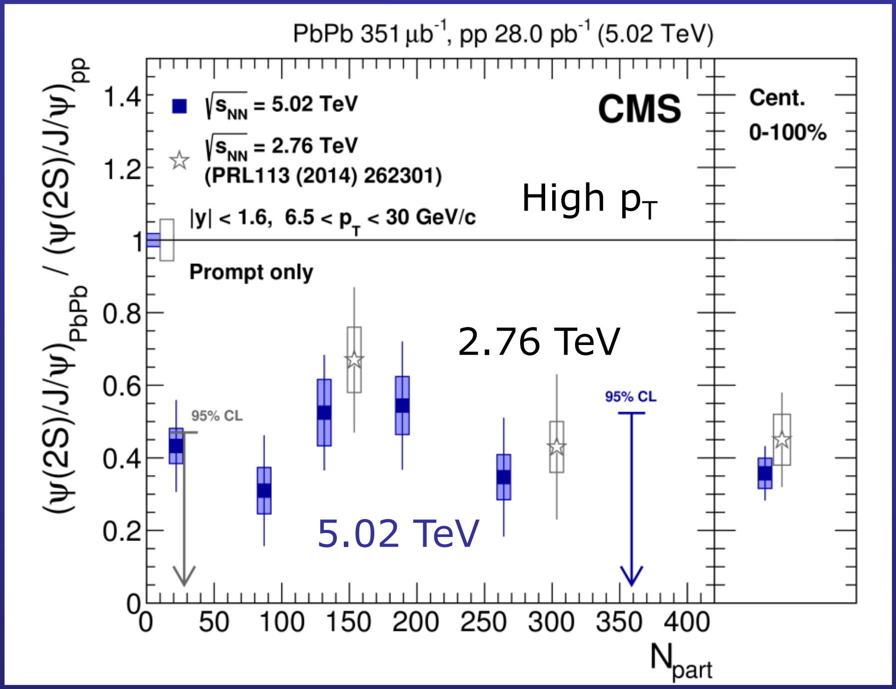
- Proposed mechanism (Rapp) for enhancement: ψ(2S) regeneration occurring later, when radial flow is already built-up. $\sqrt{s_{NN}}$ dependence of the effect not easy to explain

$\psi(2S)$ in Pb-Pb collisions

V. Khachatryan et al. (CMS), arXiv:1611.01438



ATLAS-CONF-2016-109



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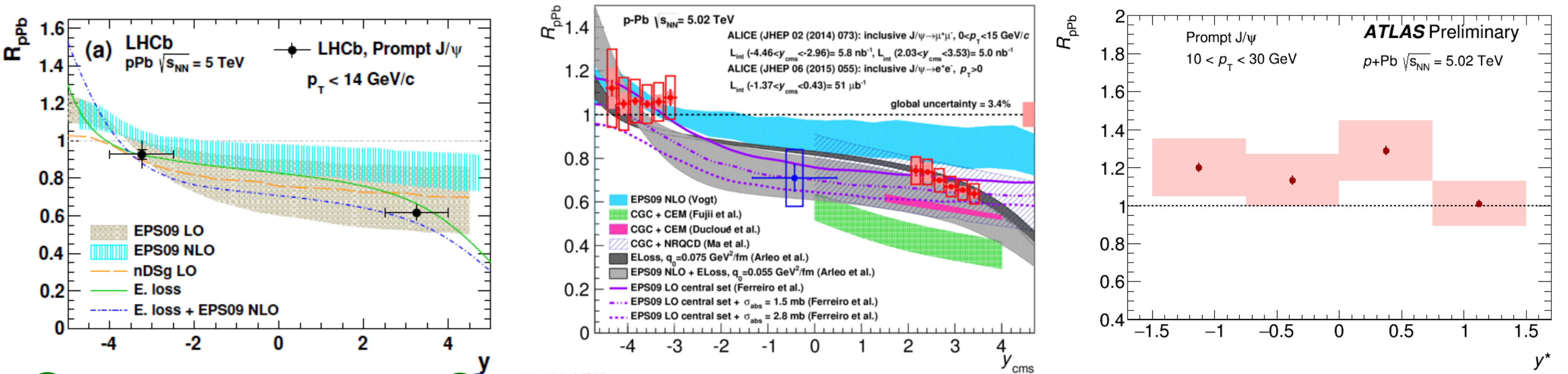
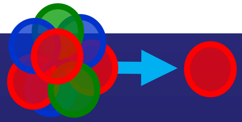
CNM effects: J/ψ in p-Pb collisions

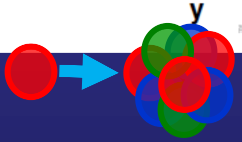
- ❑ R_{pPb} vs y → fair agreement ALICE vs LHCb, ATLAS refers to p_T>10 GeV/c



LHCB, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73, ATLAS-CONF-2015-023



Pb-p

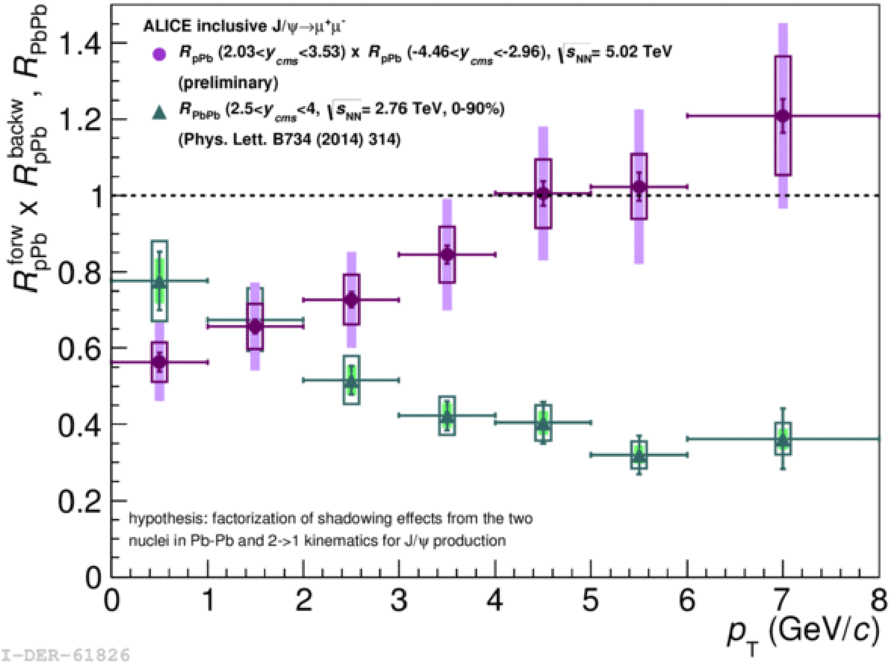


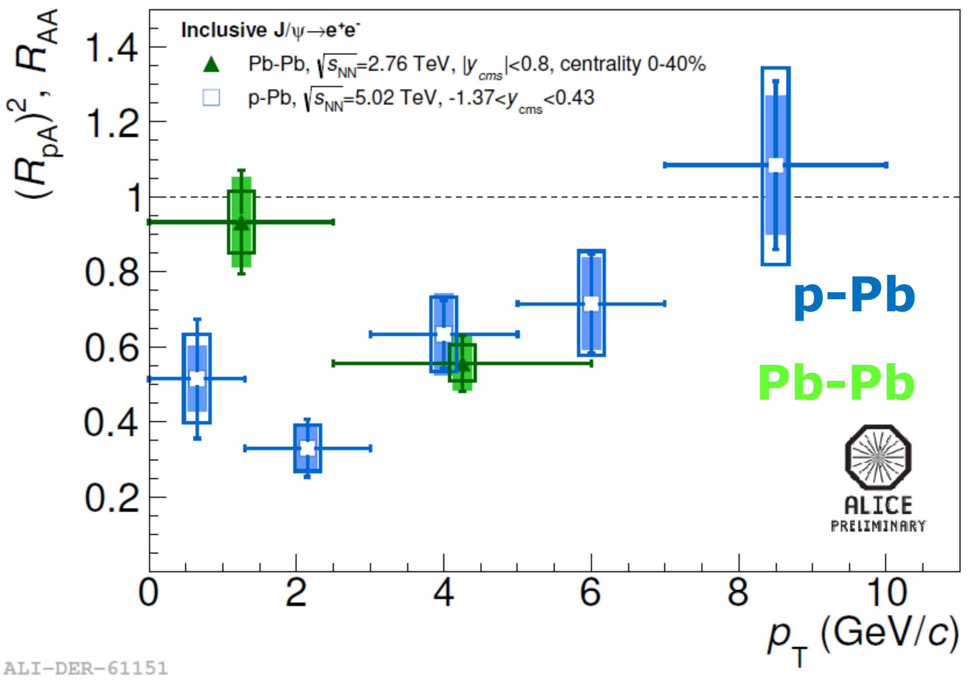
p-Pb

- ❑ LHC results can be described in terms of
  - shadowing
  - coherent energy loss
  - CGC approaches
- ❑ Suppression effects strong, in particular for y>0 and low p_T
- ❑ Investigation of CNM effects interesting
  - ❑ To learn about quarkonium behavior in cold matter
  - ❑ As a "background" for hot matter effects

CNM effects: from p-Pb to Pb-Pb

☐ If shadowing is the main CNM source → $R_{PbPb}^{CNM}=R_{pPb} \times R_{Pbp}$
(not quantitatively true for coherent energy loss, but $\sqrt{s_{NN}}$ dependence weak)

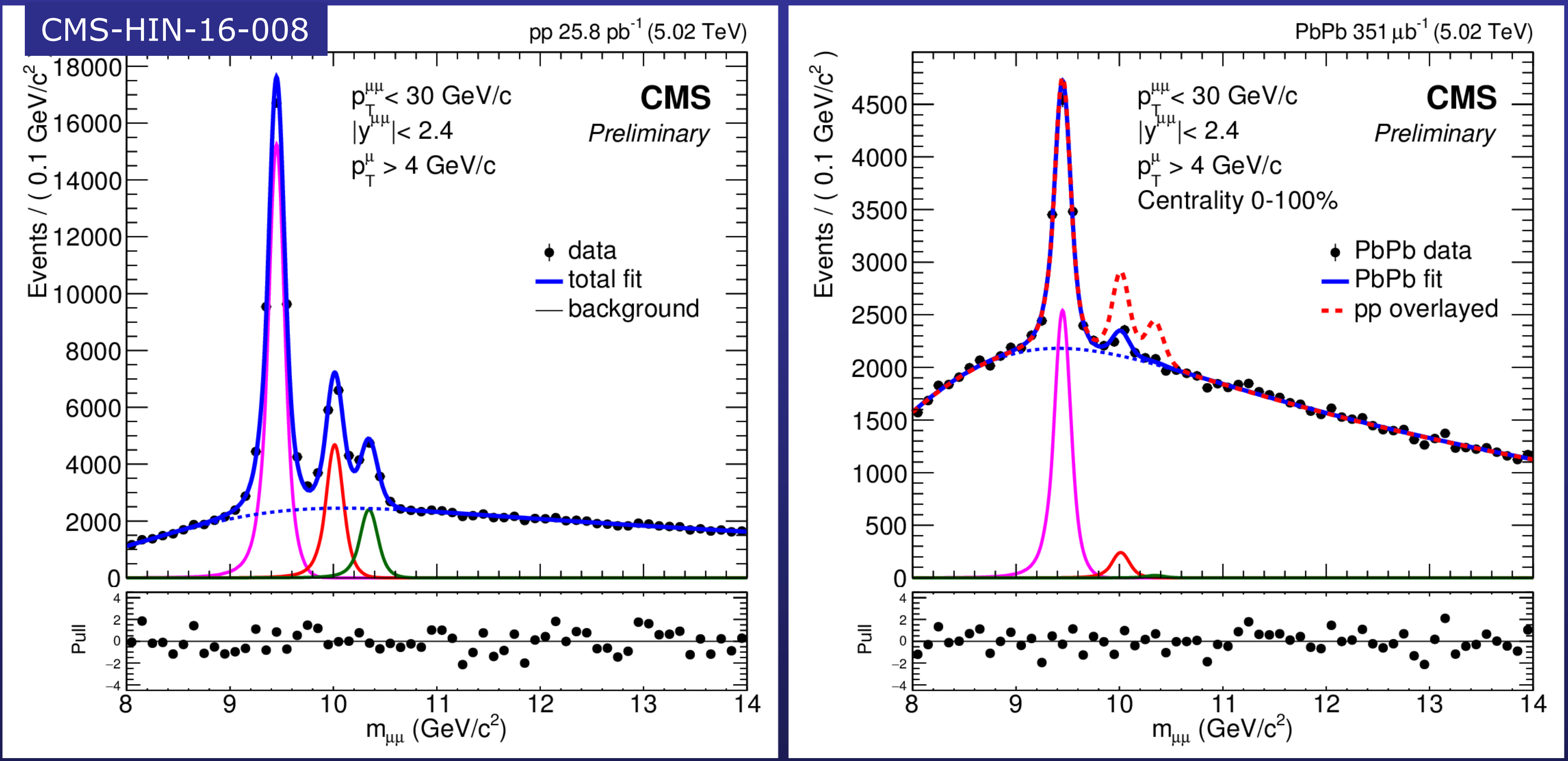




☐ This qualitative exercise confirms that
→ high p_T J/ψ suppression is not a CNM effect
→ at low p_T the observed suppression is consistent with CNM
(i.e. there is a balance of suppression+recombination in hot matter)

Bottomonium suppression

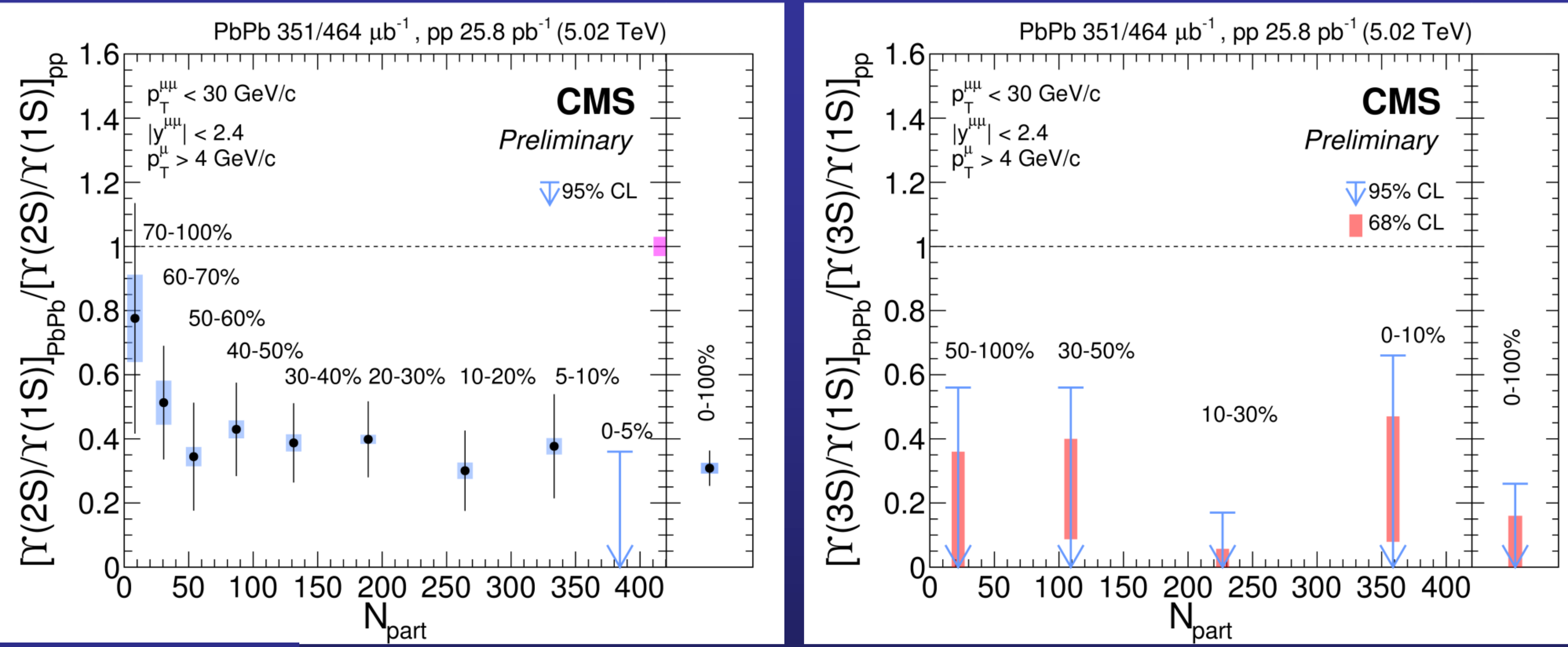
- ❑ Probably the most spectacular result from quarkonia at the LHC



CMS-HIN-16-008

- ❑ Recent CMS results at √s=5.02 TeV confirm the ϒ(2S,3S) suppression relative to the strongly bound ϒ(1S)!

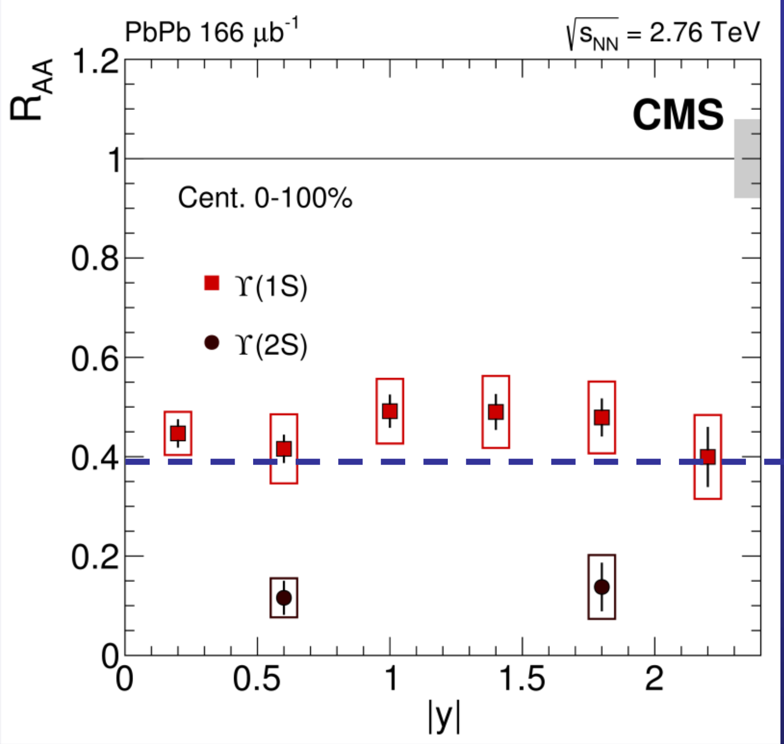
ϒ(2S) and ϒ(3S) suppression relative to ϒ(1S)



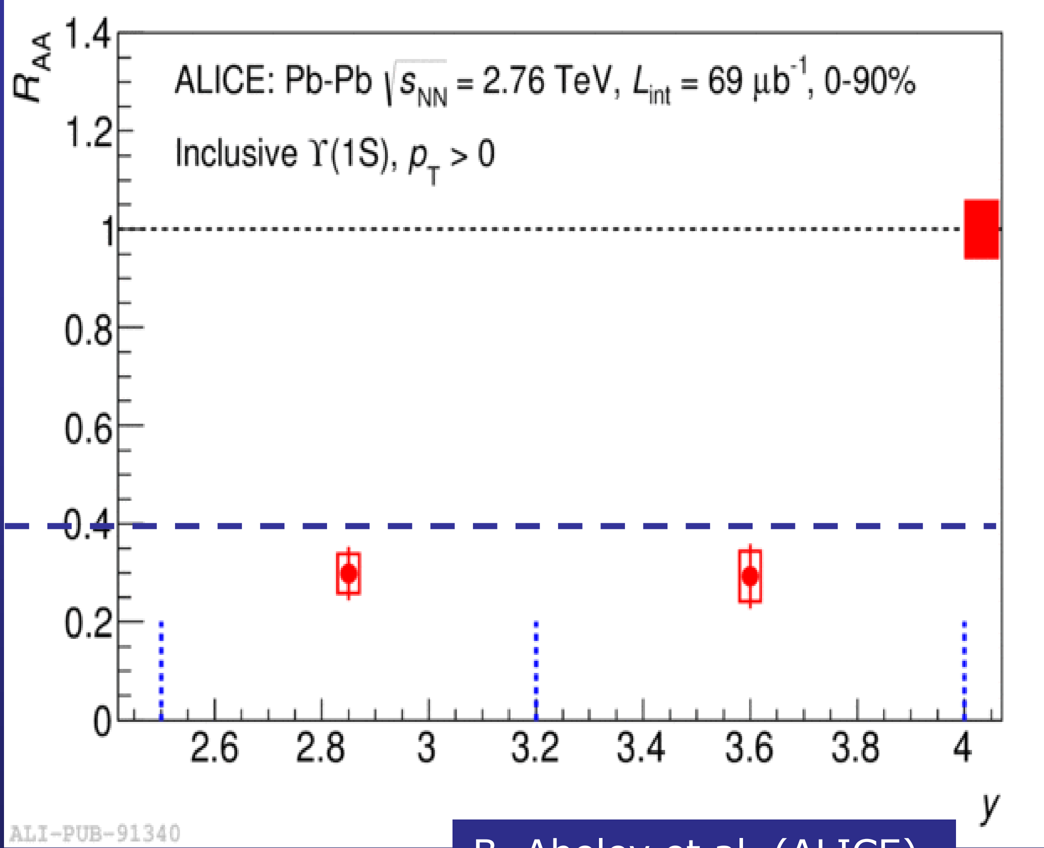
CMS-HIN-16-008

- ϒ(2S)/ ϒ(1S) integrated double ratios:
  $\sqrt{s_{NN}}$= 5 TeV → 0.31±0.06±0.02, $\sqrt{s_{NN}}$= 2.76 TeV → 0.21±0.07±0.02
- The suppression already saturates for semi-peripheral collisions
- Considered as an indication for sequential suppression

The ϒ(1S) nuclear modification factor



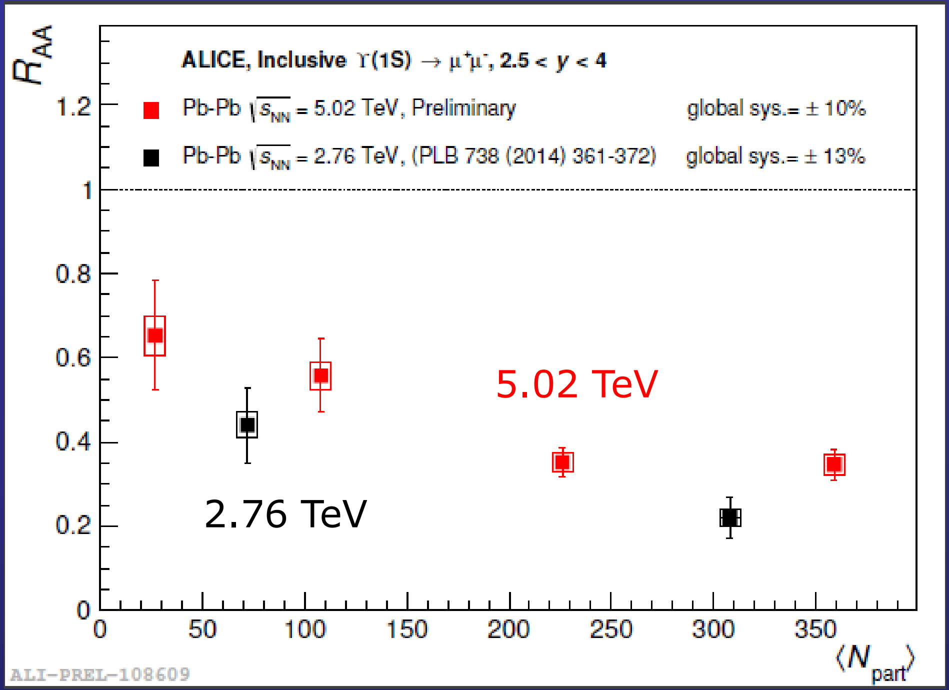
V.Khachatryan et al. (CMS), arXiv:1611.01510

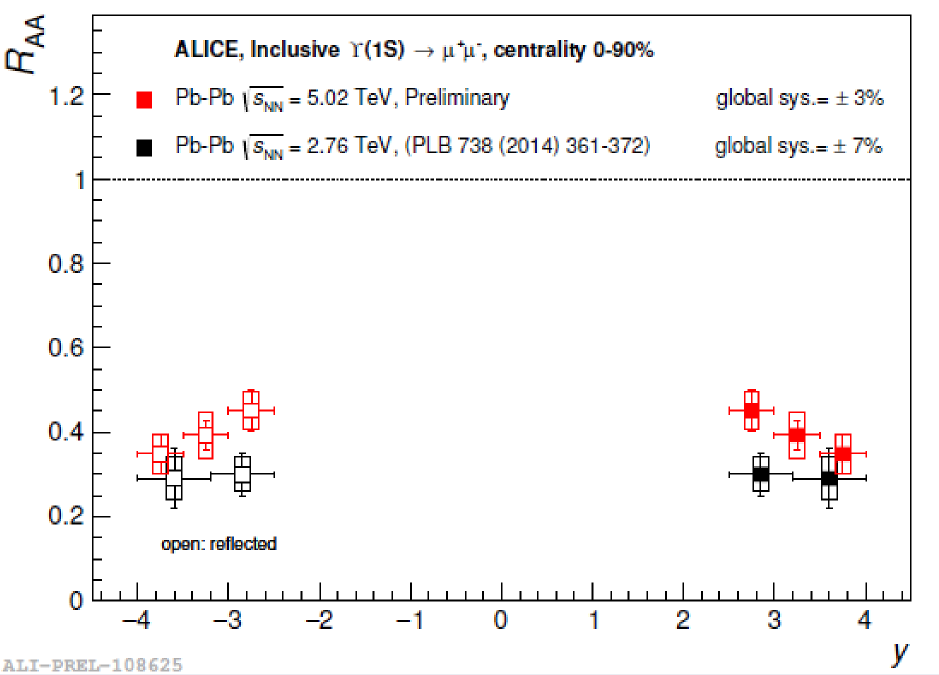


B. Abelev et al. (ALICE), PLB738 (2014) 361

- ❑ Two relevant features
  - ❑ Suppression of strongly bound (>1 GeV!) ϒ(1S): feed-down effect ?
  - ❑ Tendency for stronger suppression at forward-y: (re)combination-like ?

Forward Υ(1S): 2.76 vs 5.02 TeV

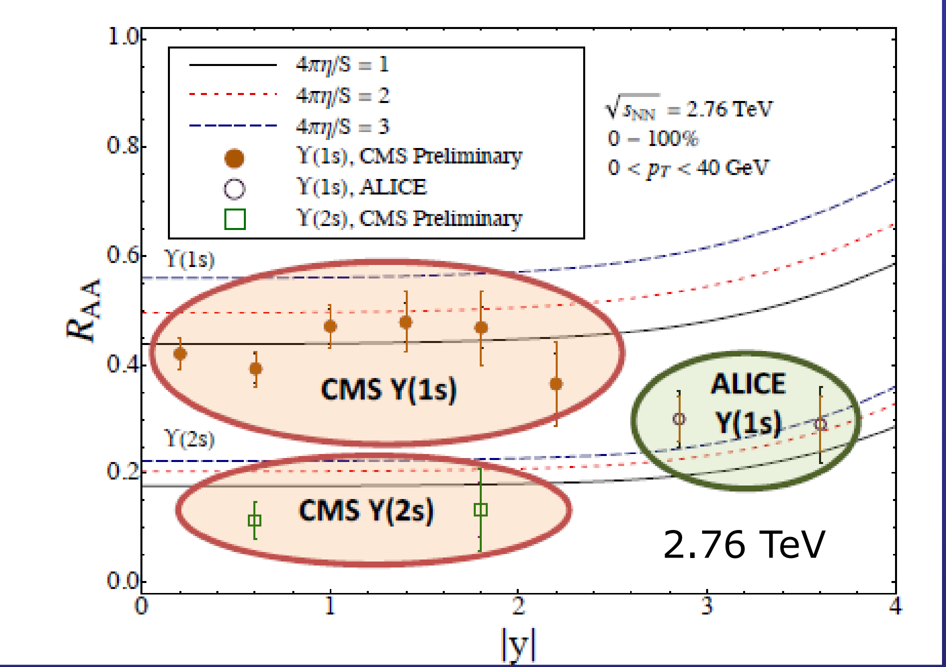


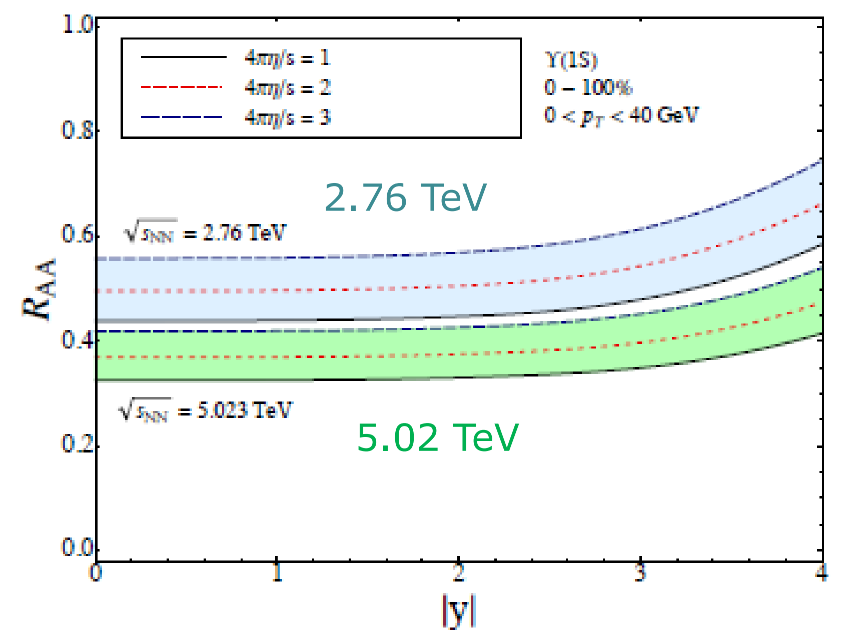


- Tendency to less suppression for the Υ(1S) when increasing collision energy

- R_{AA} (5.02 TeV, 0-90%)= 0.40 ± 0.03 (stat) ± 0.04 (syst)
  R_{AA} (2.76 TeV, 0-90%)= 0.30 ± 0.05 (stat) ± 0.04 (syst)
  → Integrated R_{AA} compatible at the two energies
  → Still, the y-dependence reminds recombination patterns

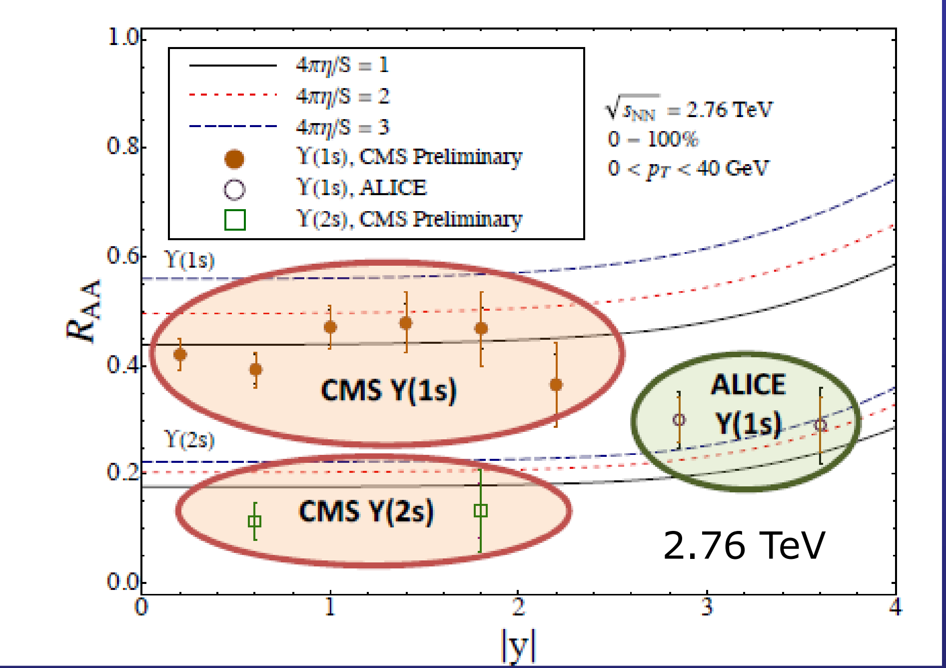
ϒ(1S) model comparison

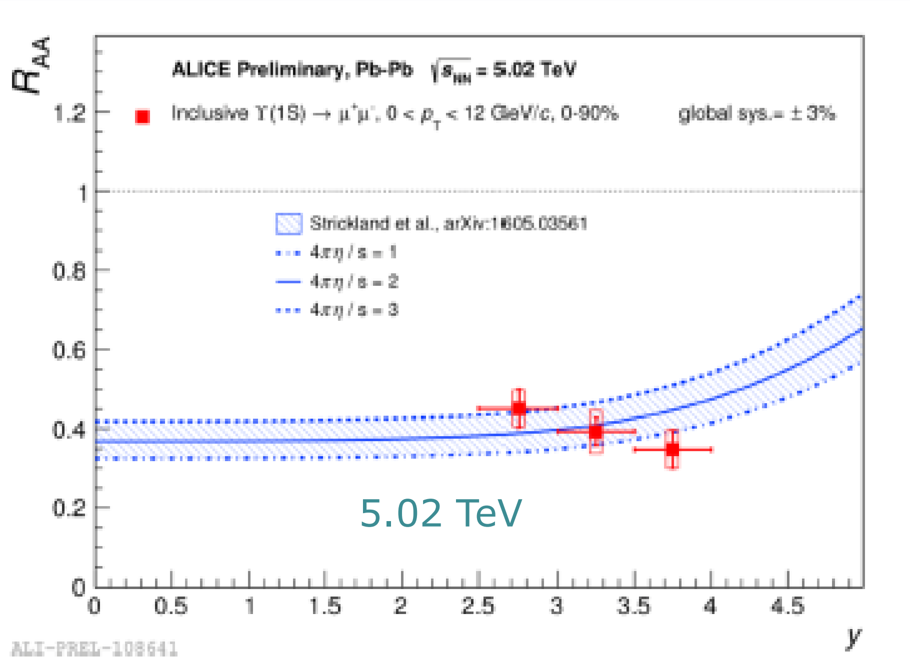




- Theory calculation (Strickland)
- $\sqrt{s_{NN}}$=2.76 TeV
  - → fair agreement with CMS result at central y
  - → tension with ALICE results at forward-y
- $\sqrt{s_{NN}}$=5.02 TeV
  - → stronger suppression is predicted
  - → Numerical agreement with ALICE, but opposite evolution between $\sqrt{s_{NN}}$=2.76 TeV and $\sqrt{s_{NN}}$=5.02 TeV

Υ(1S) model comparison





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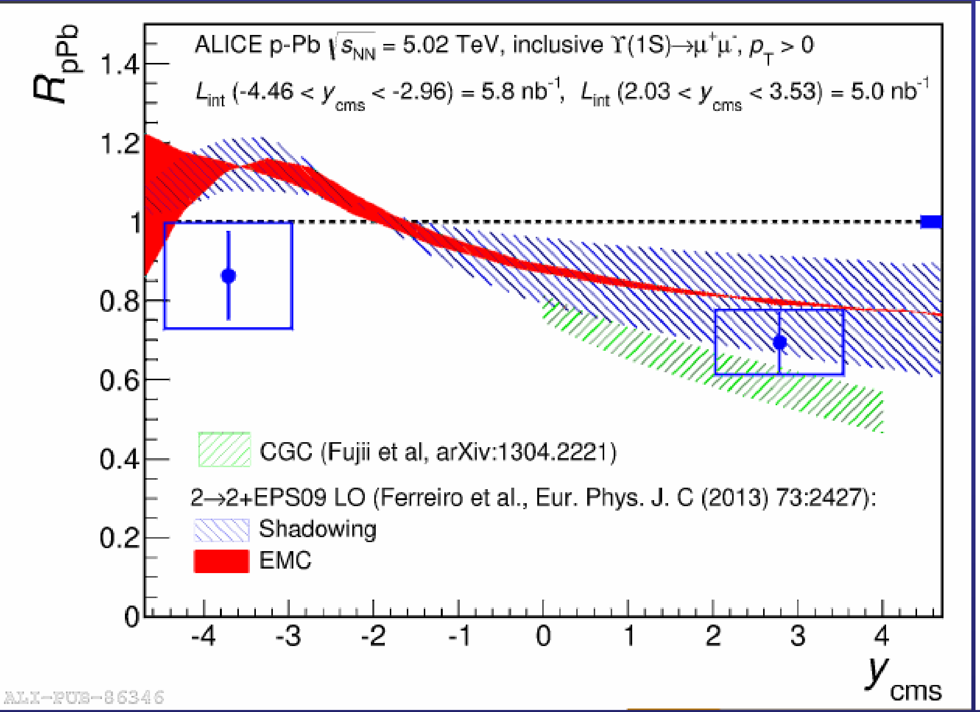
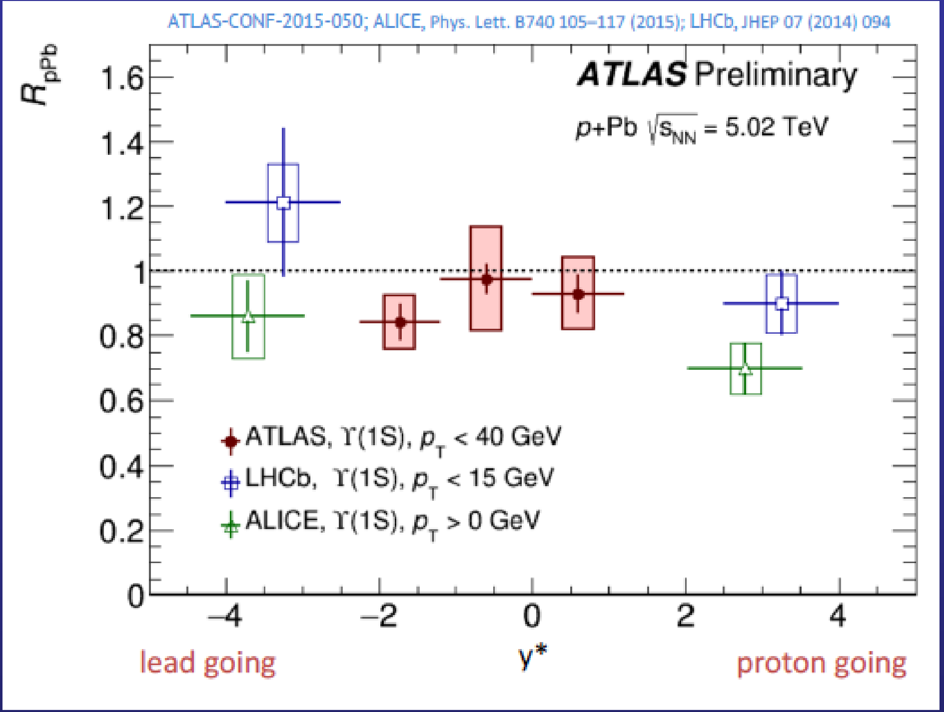
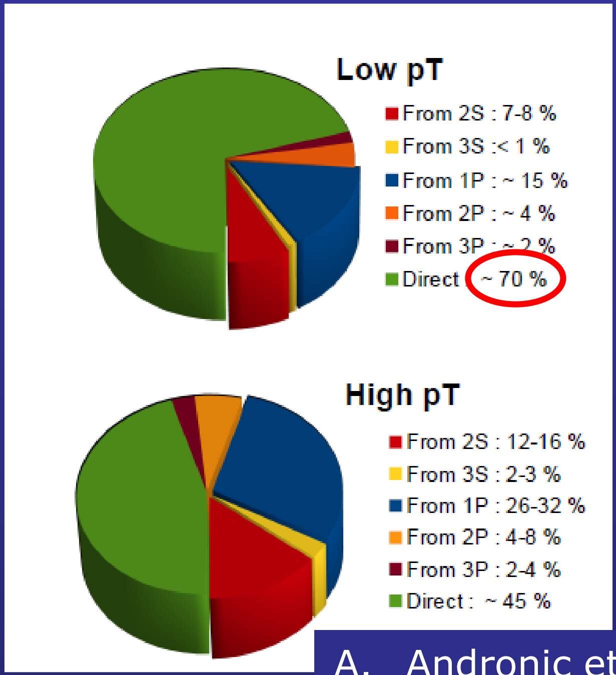
ϒ(1S) suppression in p-Pb



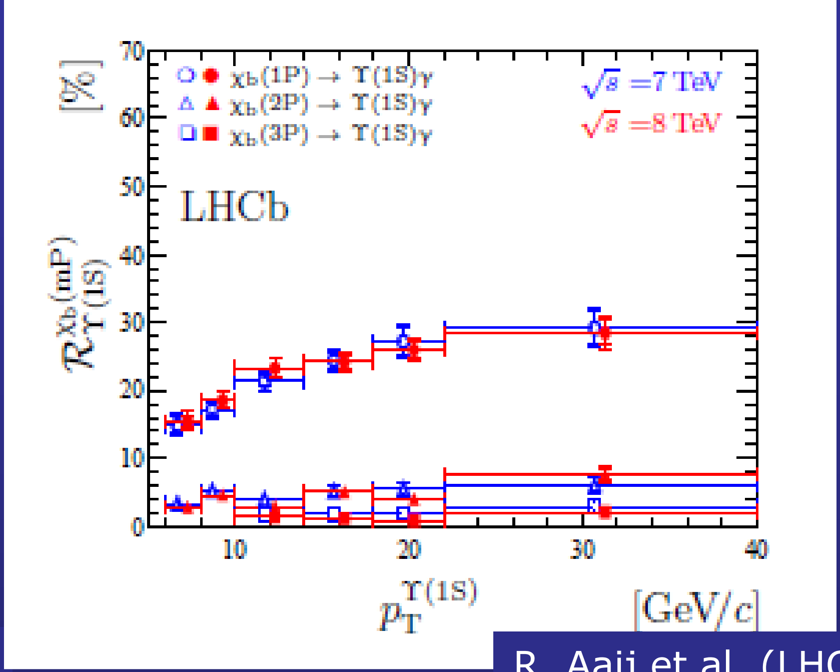


- Uncertainties are still large
- No real tension between ALICE and LHCb but the range of "allowed" values is clearly rather large
- CNM effect generally smaller than for charmonia, but not negligible
  - → applying the $R_{PbPb}^{CNM}=R_{pPb} \times R_{Pbp}$ prescription on central ALICE results may give a sizeable effect ($0.70 \times 0.86 \sim 0.60$!)
  - → More precise data needed! → LHC run-2

Feed-down effects on $\Upsilon(1S)$



A. Andronic et al.,
EPJC 76 (2016) 107

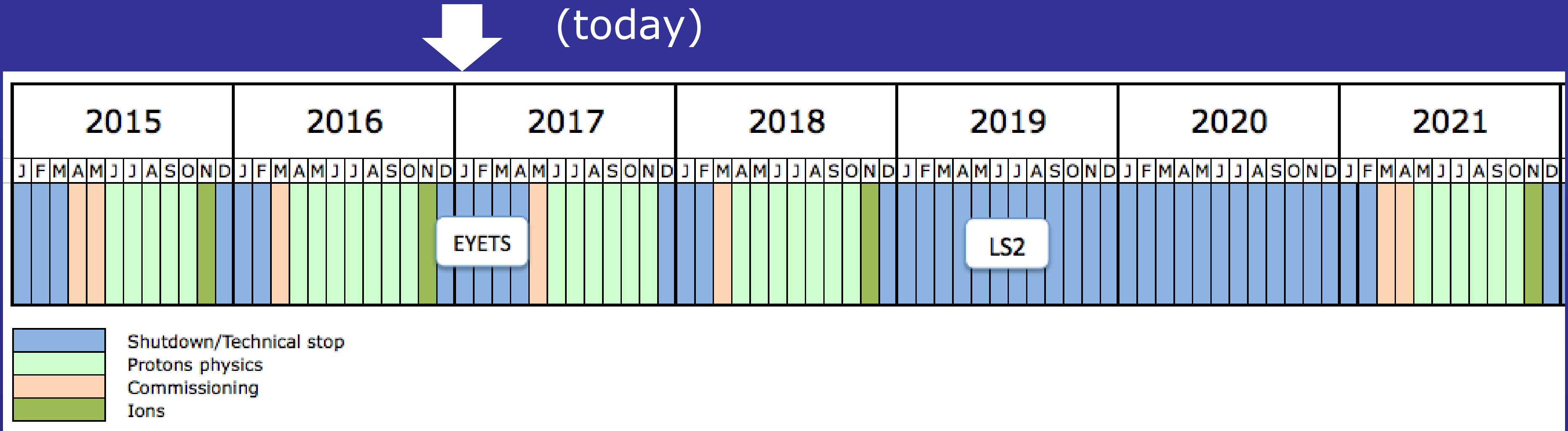


R. Aaij et al. (LHCb),
Eur.Phys.J. C74 (2014) 3092

- Recent improvement in feed-down studies at the LHC
- Feed-down on $\Upsilon(1S)$ at low p_T, where HI data are available, is ~30%
- ALICE R_{AA}^{incl} ($\Upsilon(1S)$) =0.30 and assuming full suppression of excited states R_{AA}^{dir} ($\Upsilon(1S)$) ~0.3/0.7~0.4, lower than CNM-induced effects (R_{AA}^{CNM}~0.6)

- But seen the present level of uncertainties, still no final experimental evidence for direct $\Upsilon(1S)$ suppression can be established

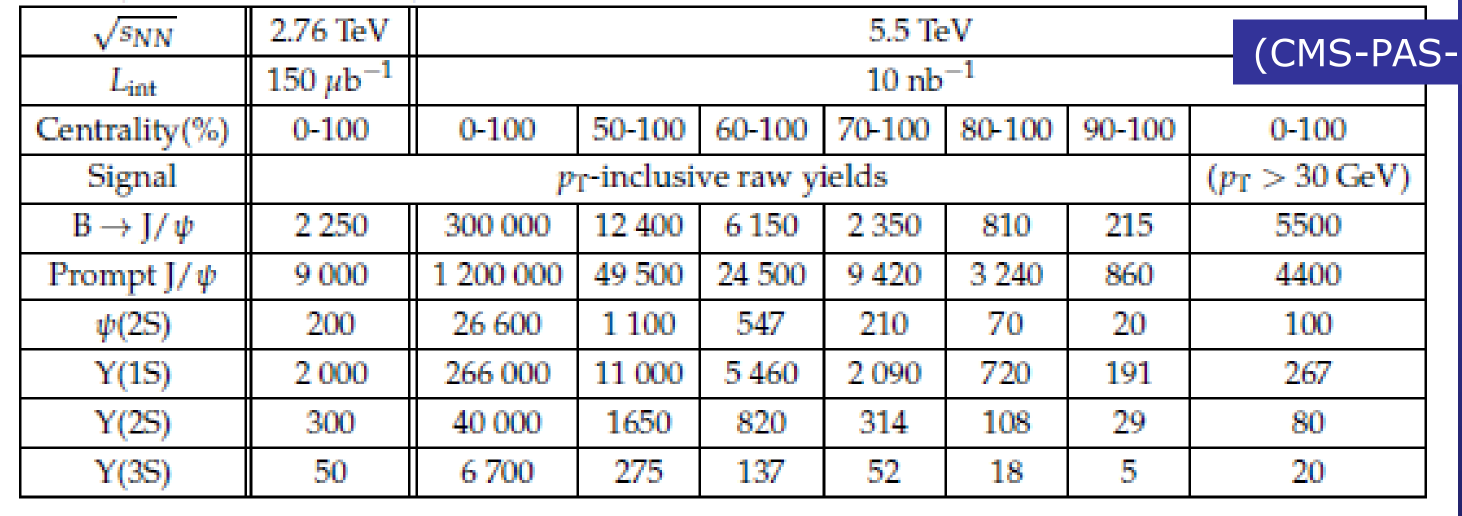
Future of LHC heavy-ion program



- EYETS: CMS pixel upgrade (for pp luminosity)
- 2018: Pb-Pb run, maximum available energy, L= 10^{27} cm^{-2} s^{-1}
- LS2: ALICE upgrades apparatus (TPC, ITS, MFT) → stand 50 kHz event rate expected for run-3 and improve tracking
  LHCb upgrades tracker → higher granularity, push towards central collisions
  ATLAS new muon small wheel → reduce fake trigger
  CMS muon upgrade → add GEM for p_T resolution, RPC for reducing background (better time resolution), extend coverage to $\eta>2.4$
- 2021-2023: LHC run-3, experiments require $L_{int}>10$ nb^{-1} for Pb-Pb (compared to $L_{int}\sim 1$ nb^{-1} for run-2)
  Possibility of accelerating lighter ions under discussion
- 2026-2029: LHC run-4

Prospects for quarkonium studies

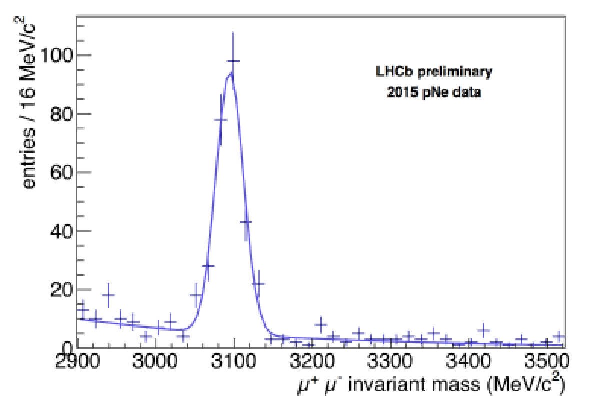
- ❑ Factor ~10 gain in run-3 beneficial for ψ(2S), ϒ(2S), ϒ(3S) studies and for all non-R_{AA} analyses (example: flow)
  → Possibility of investigating (very) peripheral collisions



(CMS-PAS-FTR-13-025)

$\sqrt{s_{NN}}$	2.76 TeV	5.5 TeV						
L_{int}	150 μb^{-1}	10 nb^{-1}						
Centrality(%)	0-100	0-100	50-100	60-100	70-100	80-100	90-100	0-100
Signal	p_T-inclusive raw yields							($p_T > 30$ GeV)
$B \rightarrow J/\psi$	2 250	300 000	12 400	6 150	2 350	810	215	5500
Prompt J/ψ	9 000	1 200 000	49 500	24 500	9 420	3 240	860	4400
ψ(2S)	200	26 600	1 100	547	210	70	20	100
ϒ(1S)	2 000	266 000	11 000	5 460	2 090	720	191	267
ϒ(2S)	300	40 000	1650	820	314	108	29	80
ϒ(3S)	50	6 700	275	137	52	18	5	20

- ❑ LHCb → SMOG system
- ❑ Fixed-target physics at the LHC!
  → p-A collisions $\sqrt{s_{NN}}$~100 GeV
  → Pb-A collisions, $\sqrt{s_{NN}}$~60 GeV
- ❑ Cover a region between SPS and RHIC!



Conclusions

- LHC run-1 very successful in terms of quality of quarkonium results
- Evidence likely established for
  - → J/ψ re-generation
  - → Υ “sequential” suppression
- Hints for
  - → J/ψ elliptic flow
  - → Strong ψ(2S) suppression (enhancement at intermediate p_T?)
- CNM studies via p-Pb
  - → J/ψ compatible with shad/CGC/energy loss (qualitative)
  - → Υ studies still need more integrated luminosity

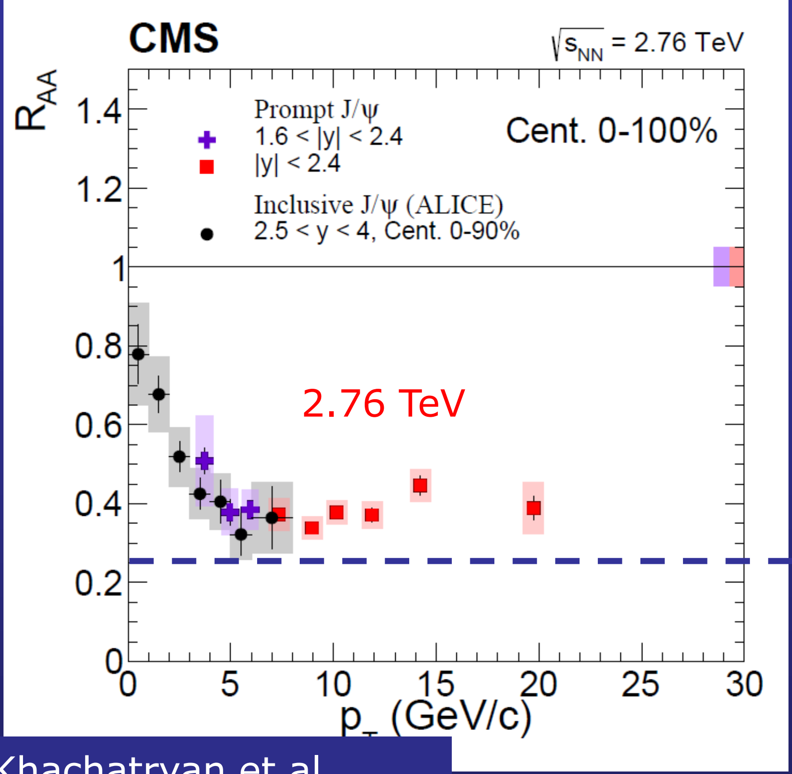
- LHC run-2 very promising, more in terms of quality of data than for seeing different behaviors wrt run-1
  - → J/ψ R_{AA} and Υ(2S)/Υ(1S) double ratio consistent between 2.76 and 5 TeV

- LHC run-3, factor 10 gain in integrated luminosity, precision physics

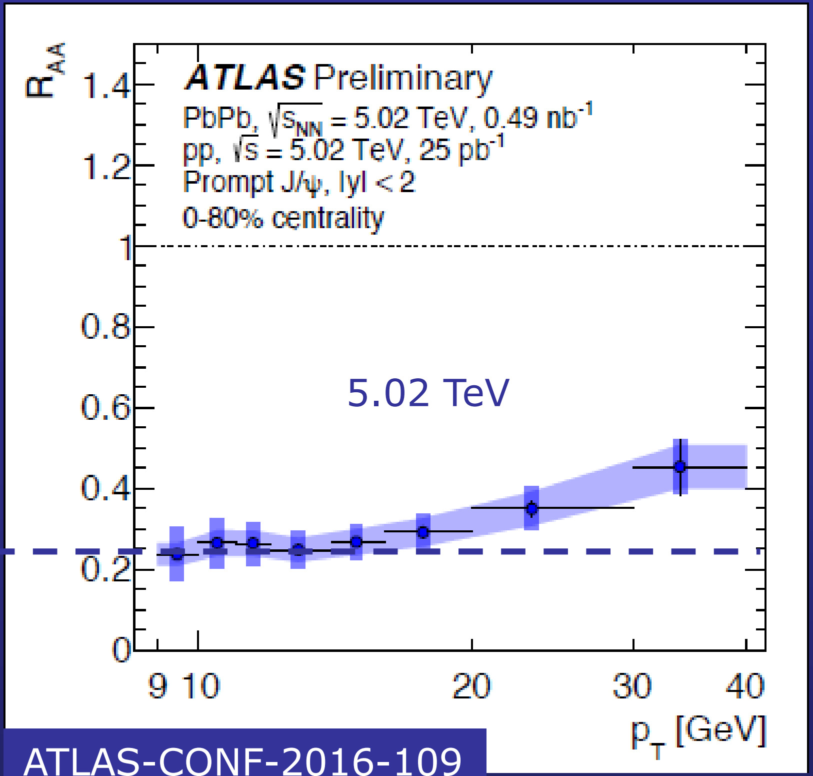
Next week in Chicago → Quark Matter 2017
Expect plenty of new data!!!

Other stuff

High-p_T J/ψ: CMS (+ATLAS)



V. Khachatryan et al. (CMS), arXiv:1610.00613



ATLAS-CONF-2016-109

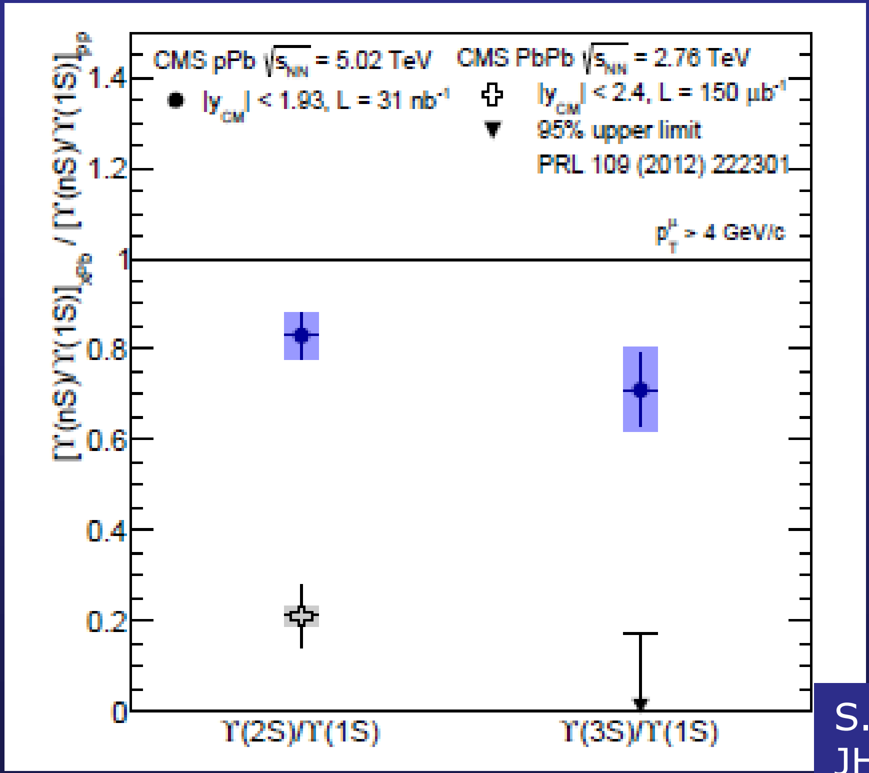
- Maximum J/ψ suppression at p_T~10 GeV/c, then increase beyond p_T=20 GeV/c, as seen for inclusive hadron production
- Is a model description in terms of energy loss needed?
- Compatibility ATLAS (5.02 TeV) vs CMS (2.76 TeV): within uncertainties
- Effect of the different $\sqrt{s}$ likely small, if any

CNM effects: the Υ family

- ALICE has, for p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV

$$\Upsilon(2S)/\Upsilon(1S)=0.27 \pm 0.08 \pm 0.04 \ (2.03<y<3.53)$$
$$\Upsilon(2S)/\Upsilon(1S)=0.26 \pm 0.09 \pm 0.04 \ (-4.46<y-2.96)$$

to be compared with $\Upsilon(2S)/\Upsilon(1S)=0.26 \pm 0.08$ in pp at $\sqrt{s}=7$ TeV ($2.5<y<4$)
→ No indication for different effects on $\Upsilon(2S)$ and $\Upsilon(1S)$



- CMS results have smaller uncertainties and show a stronger CNM effect on $\Upsilon(2S)$ with respect to $\Upsilon(1S)$

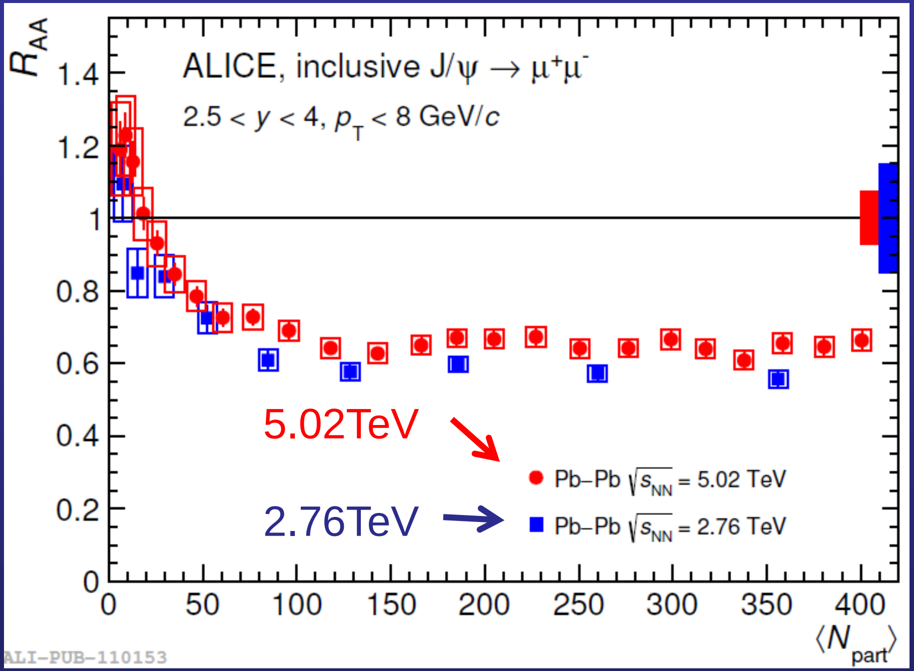
- Still, the result shows that only a (small) fraction of the suppression observed in Pb-Pb for $\Upsilon(2S)$ with respect to $\Upsilon(1S)$ can be ascribed to CNM

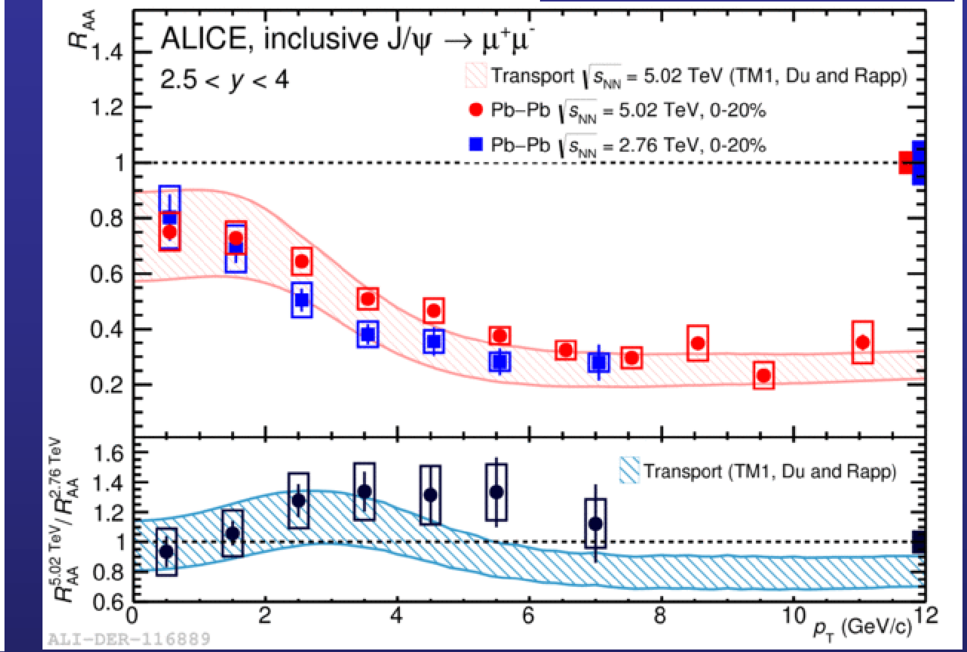
S. Chatrchyan et al. (CMS), JHEP04(2014) 103

ALICE, J/ψ run-2 results

- Pb-Pb collisions @ $\sqrt{s_{NN}}$=5.02 TeV

J.Adam et al, ALICE
PLB766(2017) 212





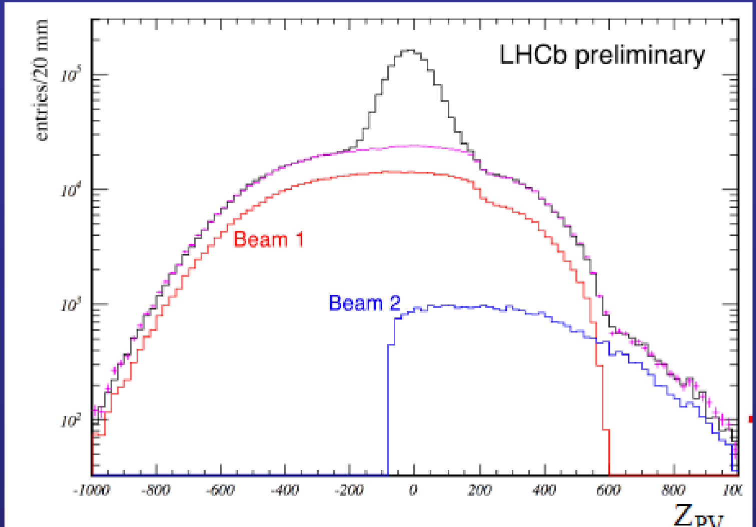
- Similar centrality dependence at the two energies
- R_{AA} @ 5.02TeV ~15% higher than at 2.76TeV, even if within uncertainties

- R_{AA} increases at low p_T, at both energies, as expected in a regeneration scenario
- Hint for an increase of R_{AA}, at 5.02TeV, in $2<p_T<6$ GeV/c

All results support a suppression + (re)combination in the QGP

LHCb enters the Pb-Pb game

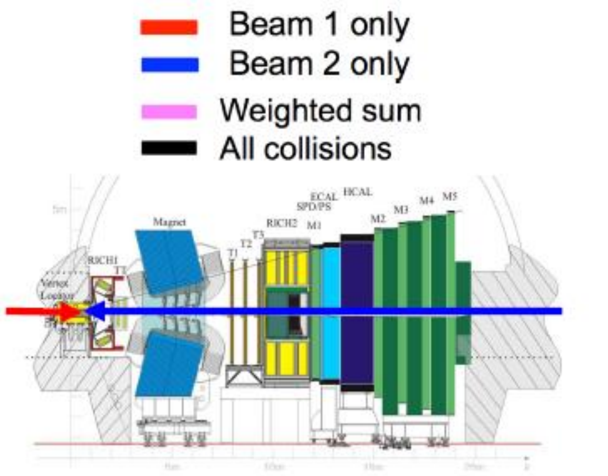
- ☐ Data taken in 2015: Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV (now being analysed)
- ☐ New promising development: fixed target at the LHC

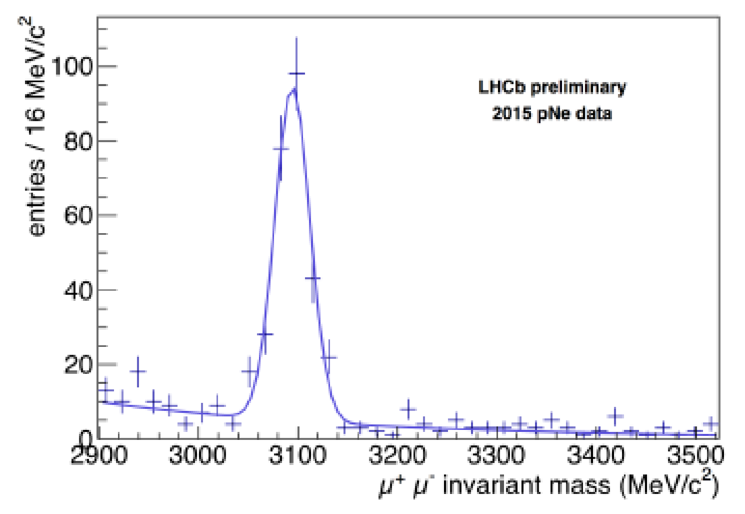


Distribution of primary vertex positon

- ➢ pHe at $\sqrt{s_{NN}} = 110$ GeV
- ➢ pNe at $\sqrt{s_{NN}} = 87$ GeV, 110GeV
- ➢ pAr at $\sqrt{s_{NN}} = 69$ GeV, 110 GeV
- ➢ PbNe at $\sqrt{s_{NN}} = 54$ GeV
- ➢ PbAr at $\sqrt{s_{NN}} = 69$ GeV

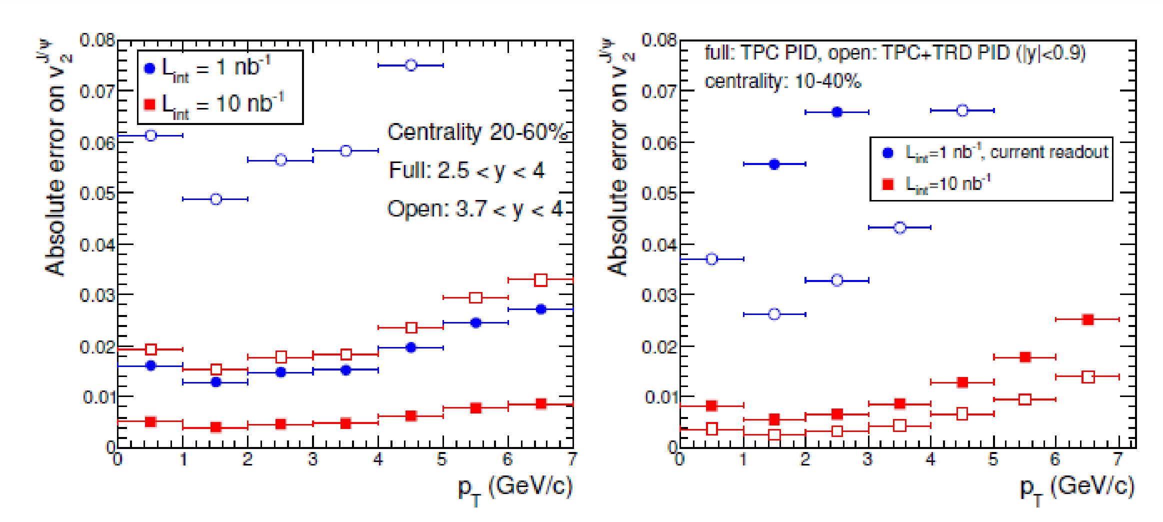
SMOG
System for
Measuring the
Overlap with Gas





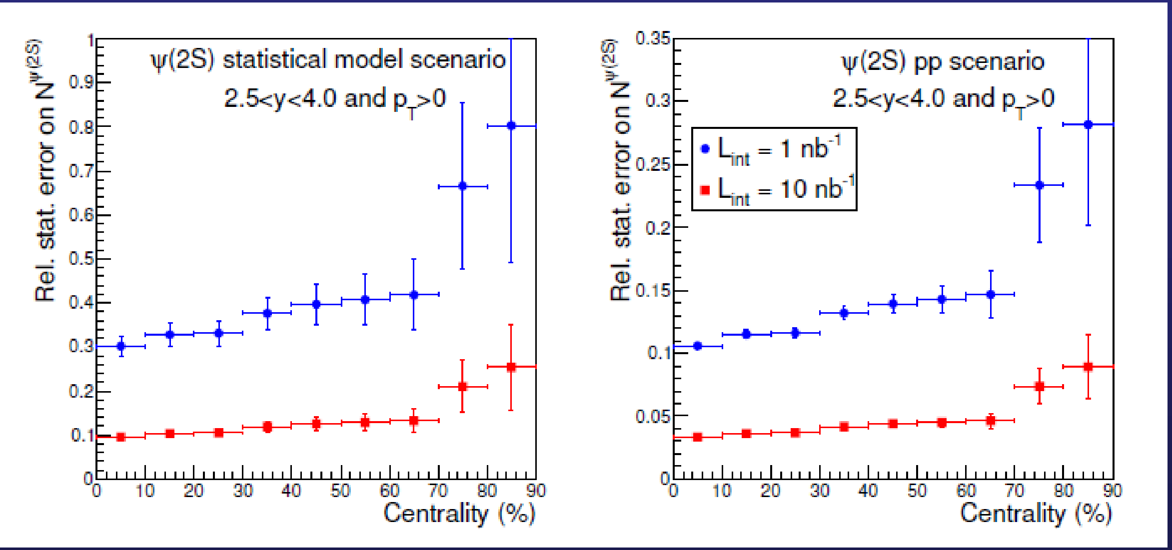
- ☐ Further measurements just took place, during the 2016 p-Pb data taking

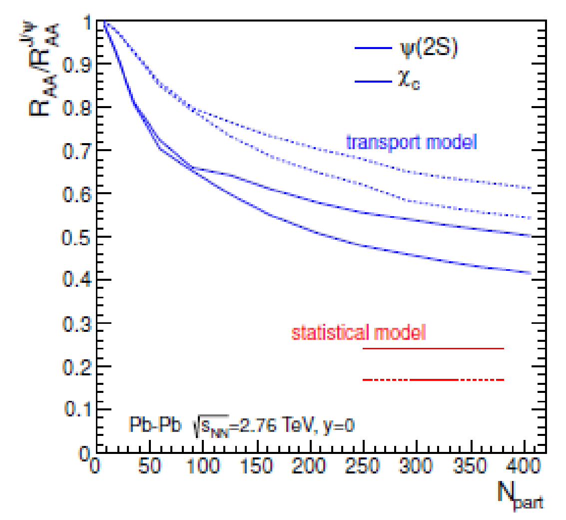
ALICE projected highlights



v_2 measurement for J/ψ at mid- and forward-y

ψ(2S) precision measurement only in run-3





LHCb highlights

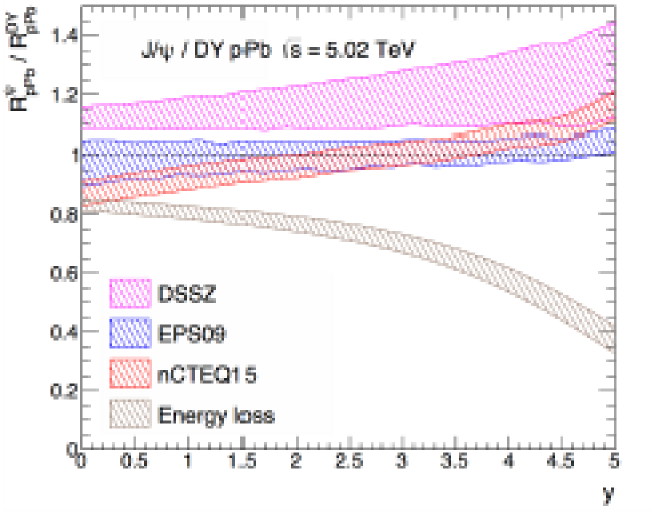


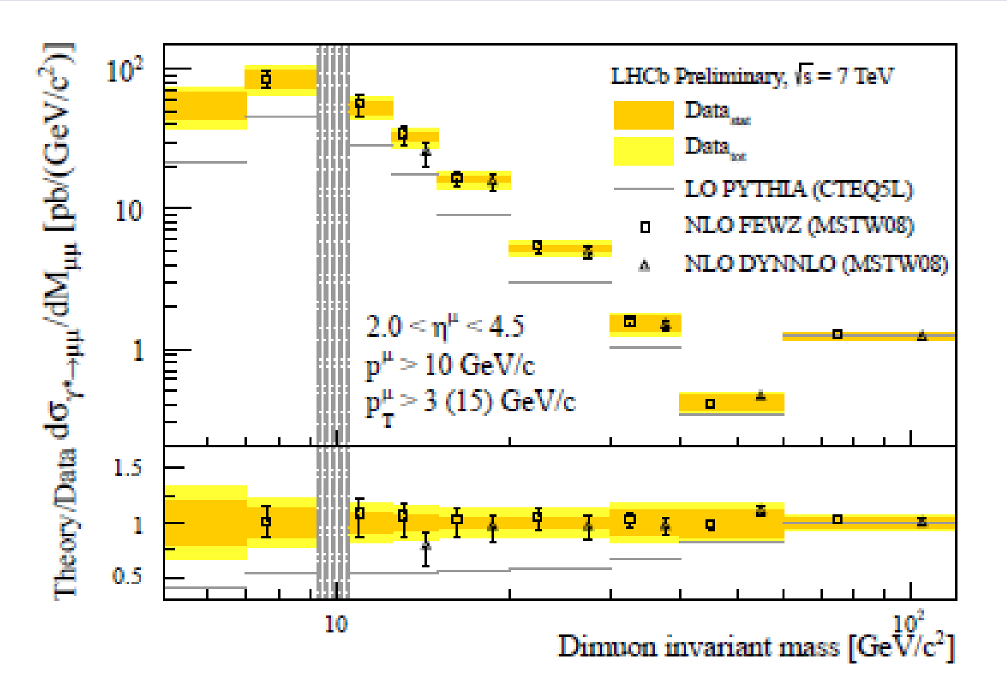
Figure 3: Double ratio $\mathcal{R}^{\psi/\mathrm{DY}}_{\mathrm{pPb}}$ in p–Pb collisions at $\sqrt{s}$ = 5.02 TeV for the various nPDF sets and in the coherent energy loss model.

- ☐ Possibility of measuring Drell-Yan production in p-Pb collisions

→ (decisive) test of the energy loss picture

→ Good handle on nPDF

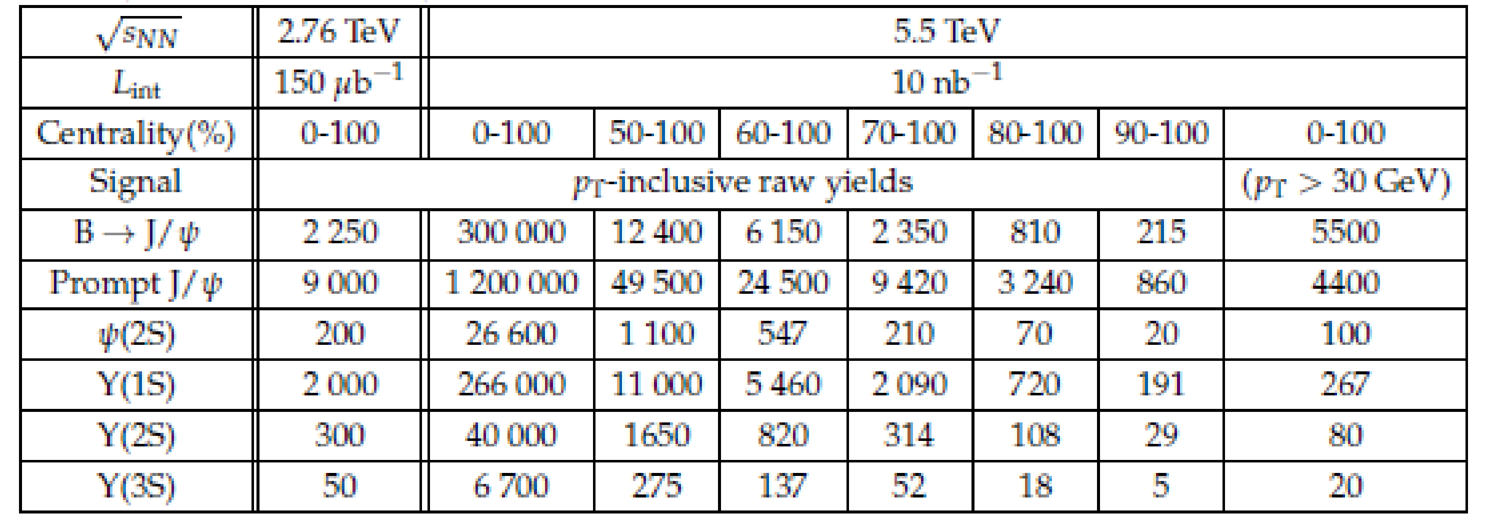
- ☐ Reference for quarkonium production in Pb-Pb collisions, as in very old times ?



- ☐ Measured in pp collisions, via fits to the muon isolation distributions

Prospects for quarkonia studies

- **CMS prospects** for run-3 (CMS-PAS-FTR-13-025)



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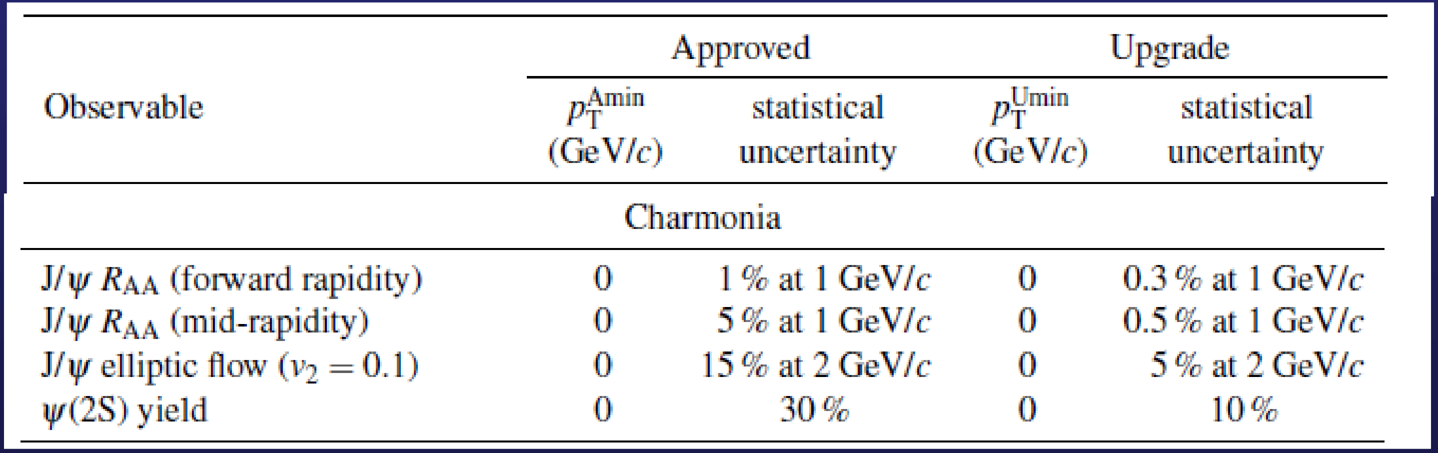
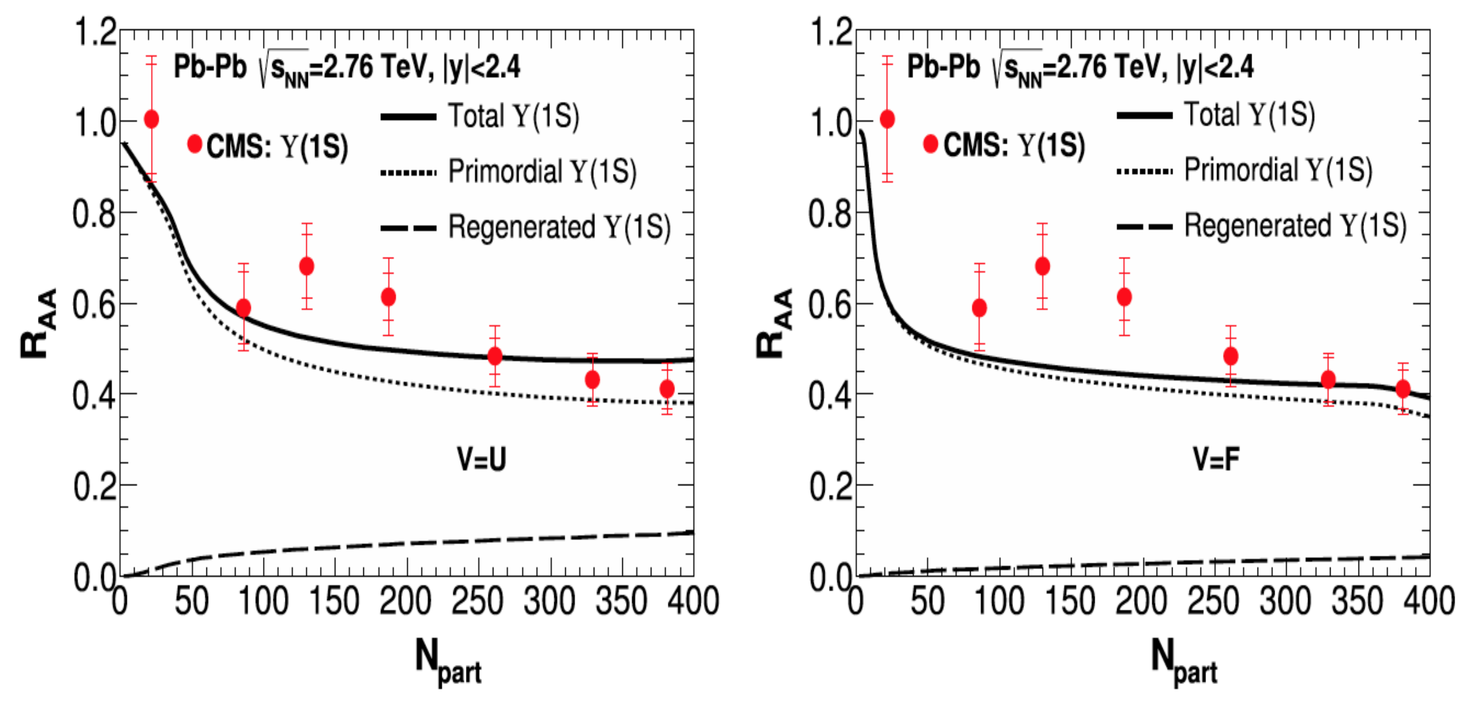
$\Upsilon(2S)$	300	40 000	1650	820	314	108	29	80
$\Upsilon(3S)$	50	6 700	275	137	52	18	5	20

- **ALICE prospects** for run-3 (Upgrade Letter of Intent)



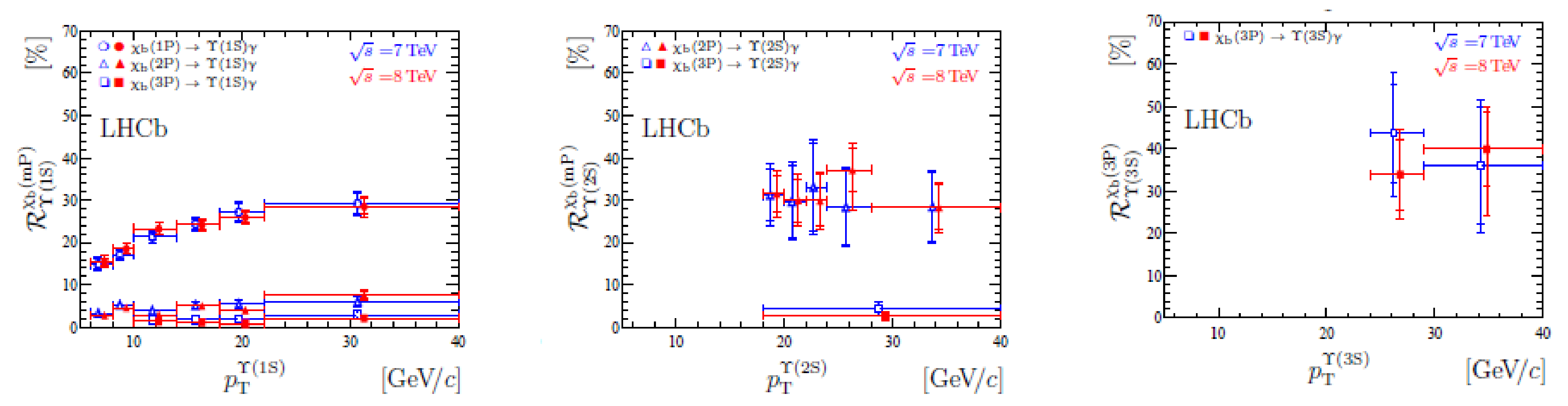
Observable	Approved		Upgrade	
	p_T^{Amin} (GeV/c)	statistical uncertainty	p_T^{Umin} (GeV/c)	statistical uncertainty
Charmonia				
J/ψ R_{AA} (forward rapidity)	0	1 % at 1 GeV/c	0	0.3 % at 1 GeV/c
J/ψ R_{AA} (mid-rapidity)	0	5 % at 1 GeV/c	0	0.5 % at 1 GeV/c
J/ψ elliptic flow ($v_2 = 0.1$)	0	15 % at 2 GeV/c	0	5 % at 2 GeV/c
$\psi(2S)$ yield	0	30 %	0	10 %



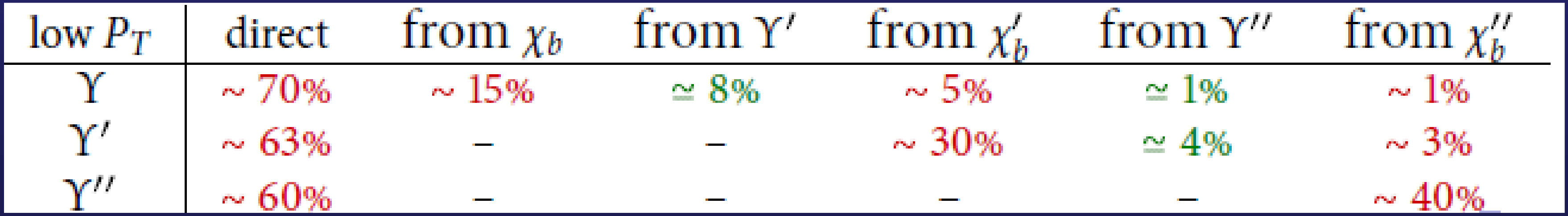
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV, |y|<2.4
CMS: Υ(1S)
Total Υ(1S)
Primordial Υ(1S)
Regenerated Υ(1S)
V=U
V=F
R_{AA}
N_{part}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
50
100
150
200
250
300
350
400

Feed-down

- ❑ Systematic measurements by LHC pp experiments have enormously improved the situation



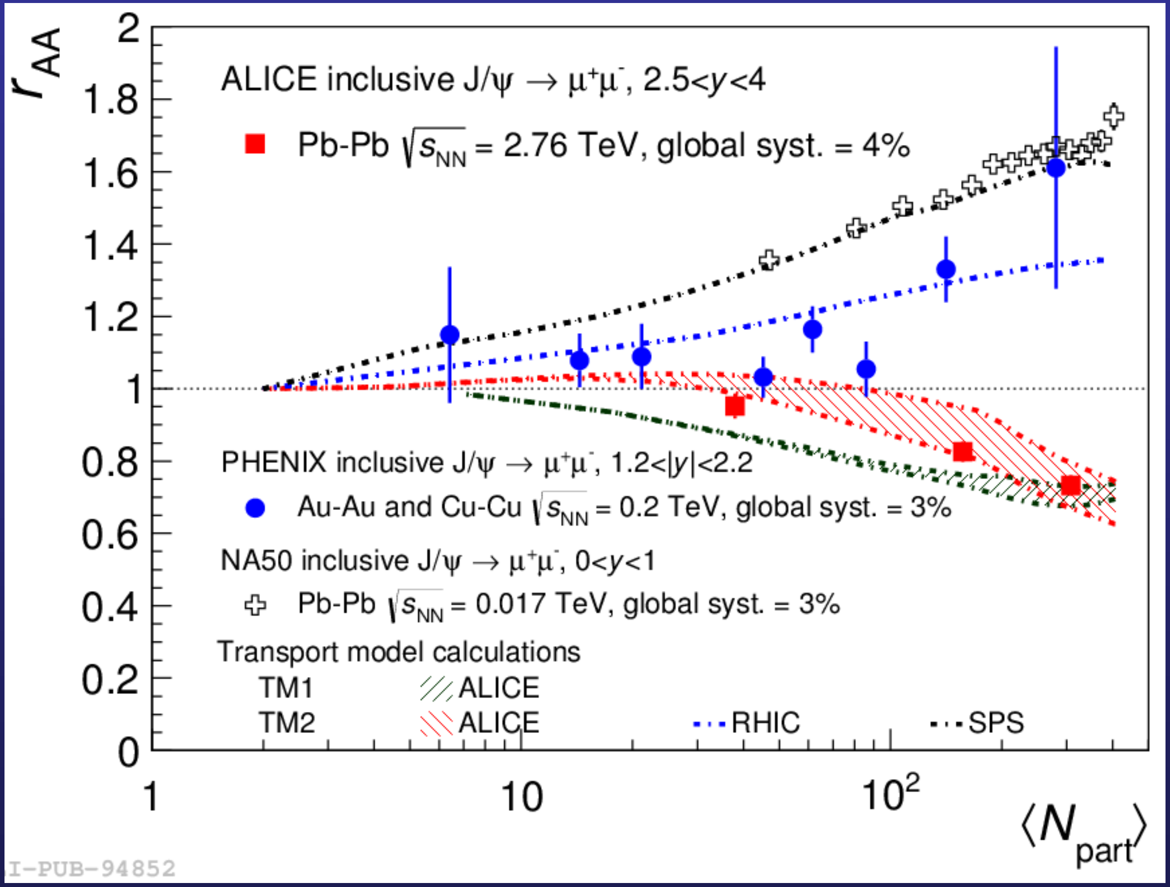
- ❑ Recent news
  - ❑ Feed-down to ϒ(1S) is smaller than believed (~50% → ~30%)
  - ❑ Feed-down to ϒ(3S) (unseen in PbPb!) is very strong (~40%)



low P_T	direct	from χ_b	from Υ'	from χ_b'	from Υ''	from χ_b''
Υ	$\sim 70\%$	$\sim 15\%$	$\simeq 8\%$	$\sim 5\%$	$\simeq 1\%$	$\sim 1\%$
Υ'	$\sim 63\%$	–	–	$\sim 30\%$	$\simeq 4\%$	$\sim 3\%$
Υ''	$\sim 60\%$	–	–	–	–	$\sim 40\%$

(HP2016, Lansberg)

- ❑ Can CMS "correct" their ϒ(1S) R_{AA} for ϒ(2S) feed-down ?



$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

- r_{AA} centrality evolution strongly depends on √s
- decreasing r_{AA} trend, observed at LHC
  → due to (re)combination, which dominates J/ψ production at low p_T
- transport models, already describing J/ψ R_{AA}, also reproduce the r_{AA} evolution

…leaving a well-traced path for the following collider studies..

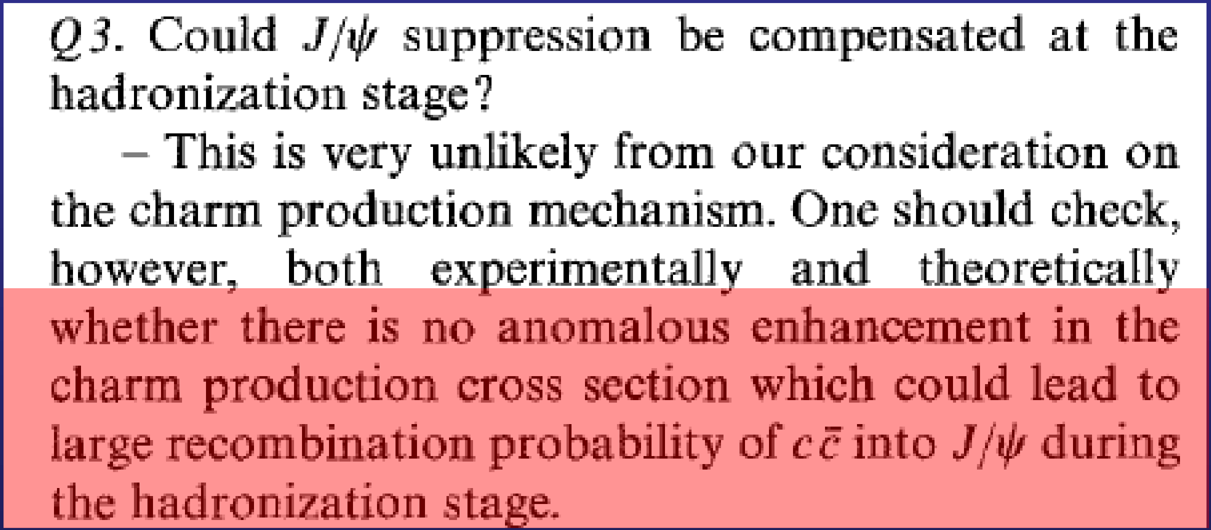
Collider	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
RHIC	PHENIX STAR	Au-Au, Cu-Cu, Cu-Au, U-U	200, 193, 62, 39	2000-2015
		p-A, d-Au	200	
		pp	200-500	
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760 5020	2010/2011 2015
		p-Pb	5020	2013
		pp	2760, 7000, 8000, 13000	2010-2015

…that continue up to now

Still a bit of history….

- The possibility of an enhancement of charmonium production in nuclear collisions was considered from the very beginning!

From T.Matsui QM87 proceedings



$Q3$. Could J/ψ suppression be compensated at the hadronization stage?

– This is very unlikely from our consideration on the charm production mechanism. One should check, however, both experimentally and theoretically whether there is no anomalous enhancement in the charm production cross section which could lead to large recombination probability of $c\bar{c}$ into J/ψ during the hadronization stage.

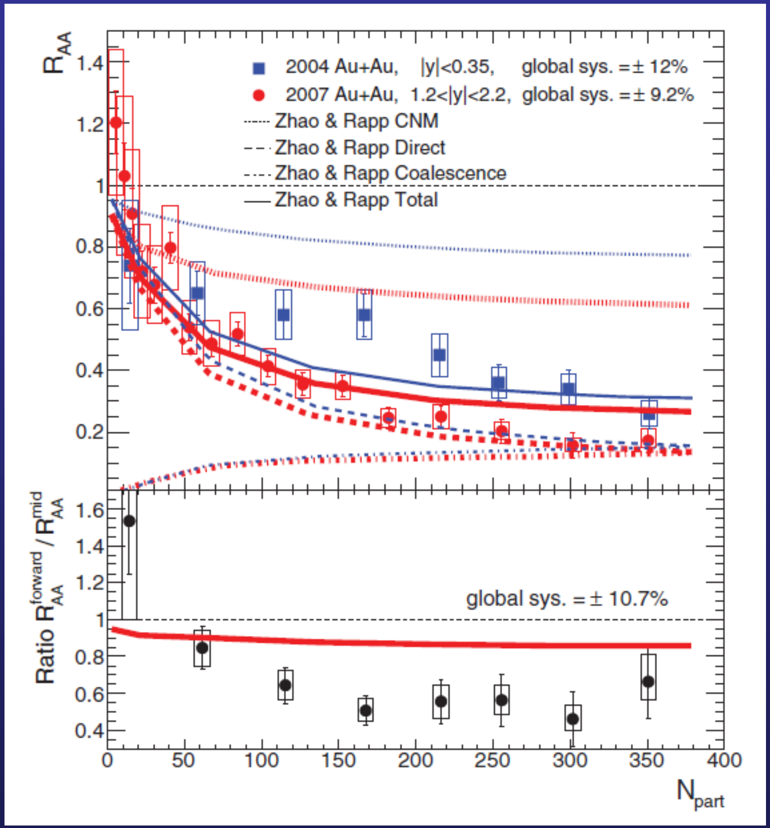
(even if, at that time, correctly discarded because of the small open charm cross section at the energies then available)

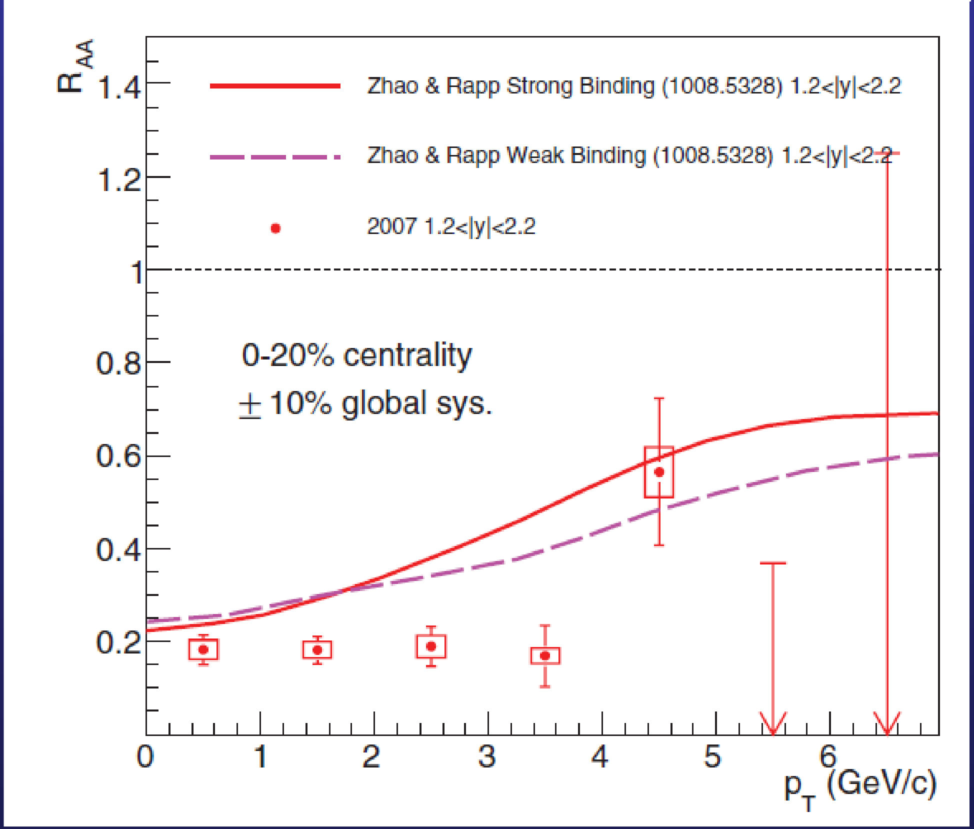
Selected RHIC results

PHENIX, $\sqrt{s_{NN}}$ =200 GeV

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

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



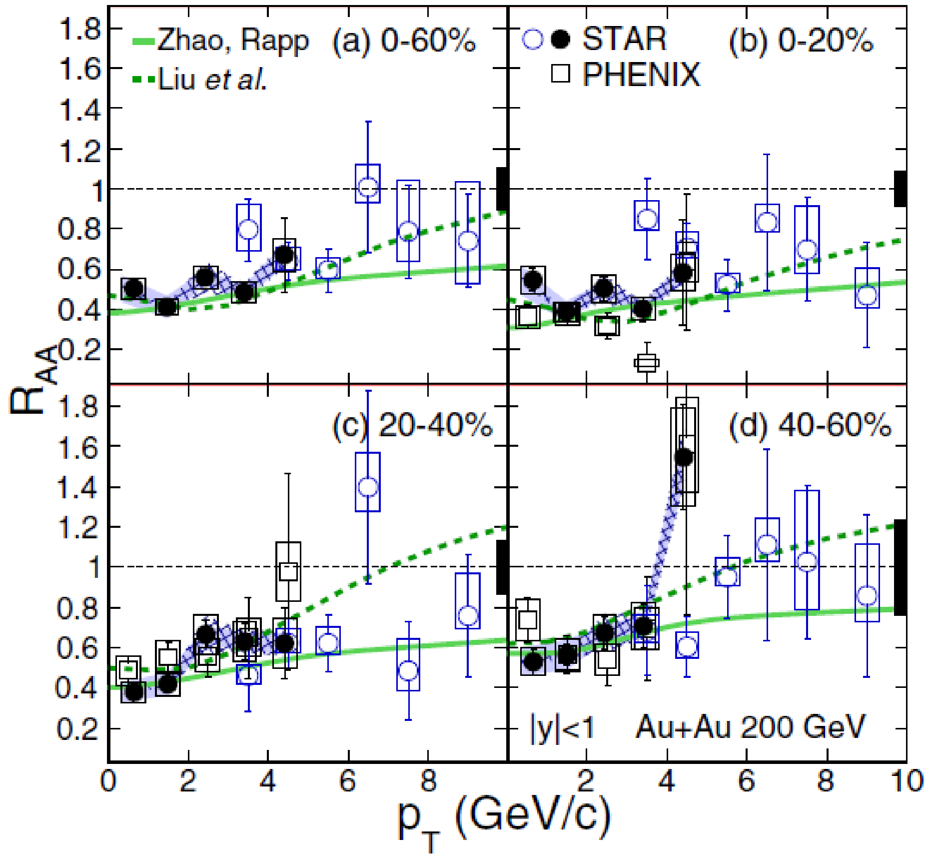


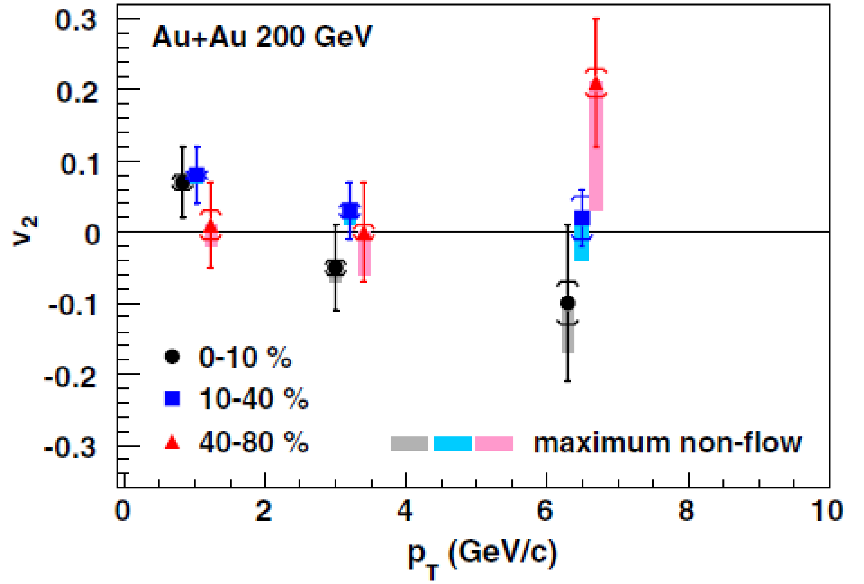
- ❑ Suppression, with strong rapidity dependence, in Au-Au at √s= 200 GeV
- ❑ Qualitatively, but not quantitatively in agreement with models

Selected RHIC results

STAR, $\sqrt{s_{NN}}$ =200 GeV

Adamczyk et al. (STAR), PRC90 (2014) 024906
Adamczyk et al. (STAR), PRL111 (2013) 052301



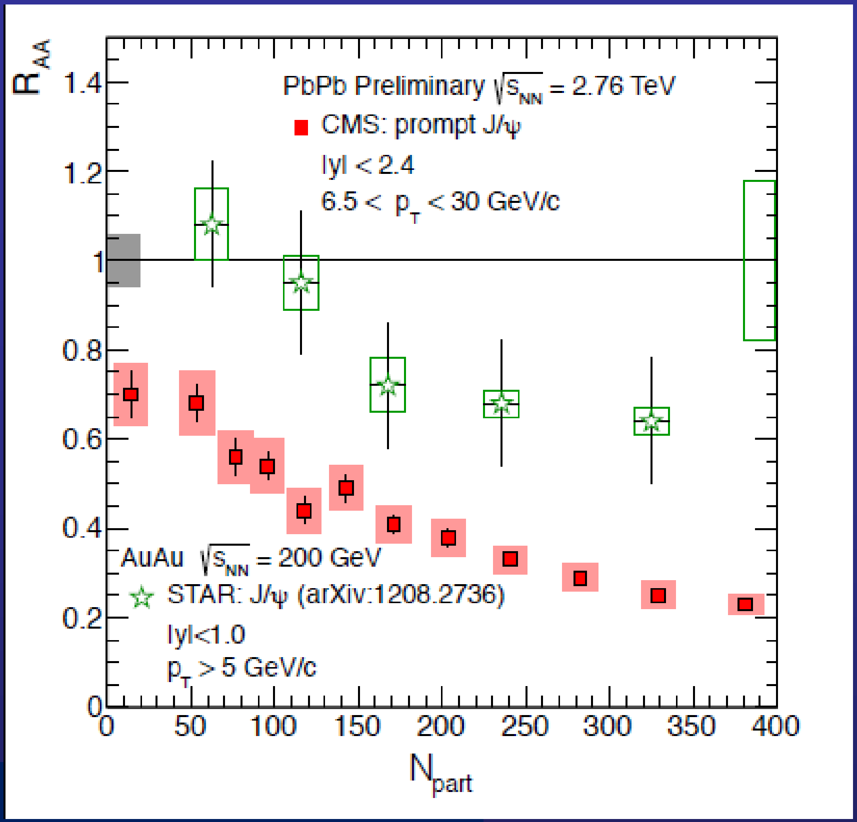


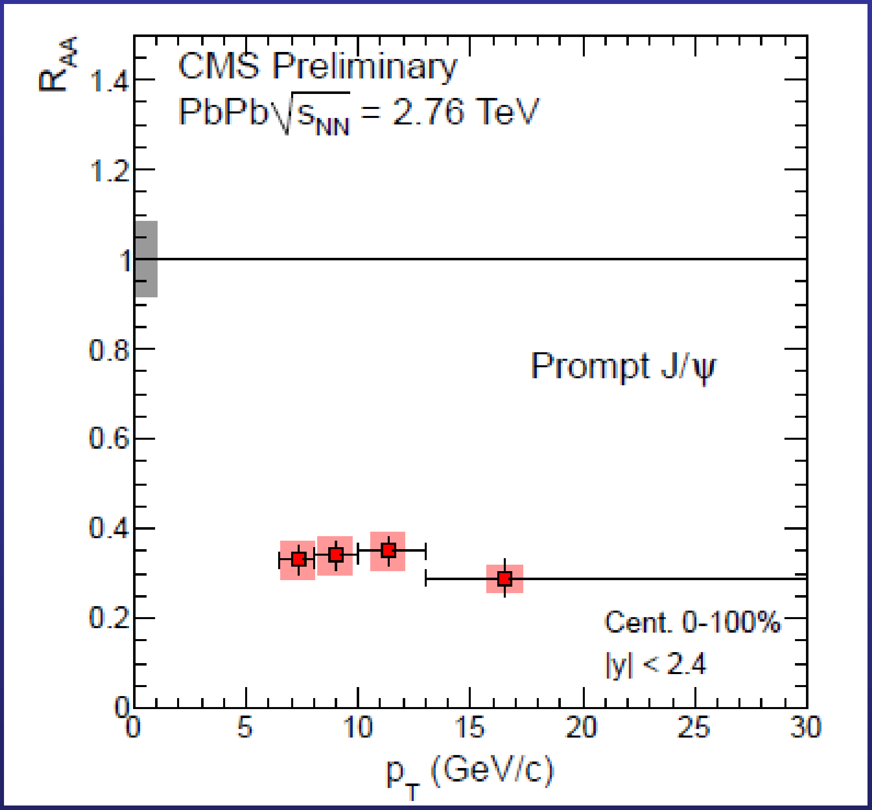
- Good coverage from low to high p_T
- R_{AA} increases with p_T
- No significant J/ψ elliptic flow

Re-generation expected to enhance low-p_T production
Re-generated J/ψ should inherit charm quark flow

} not seen

CMS results: prompt J/ψ at high p_T



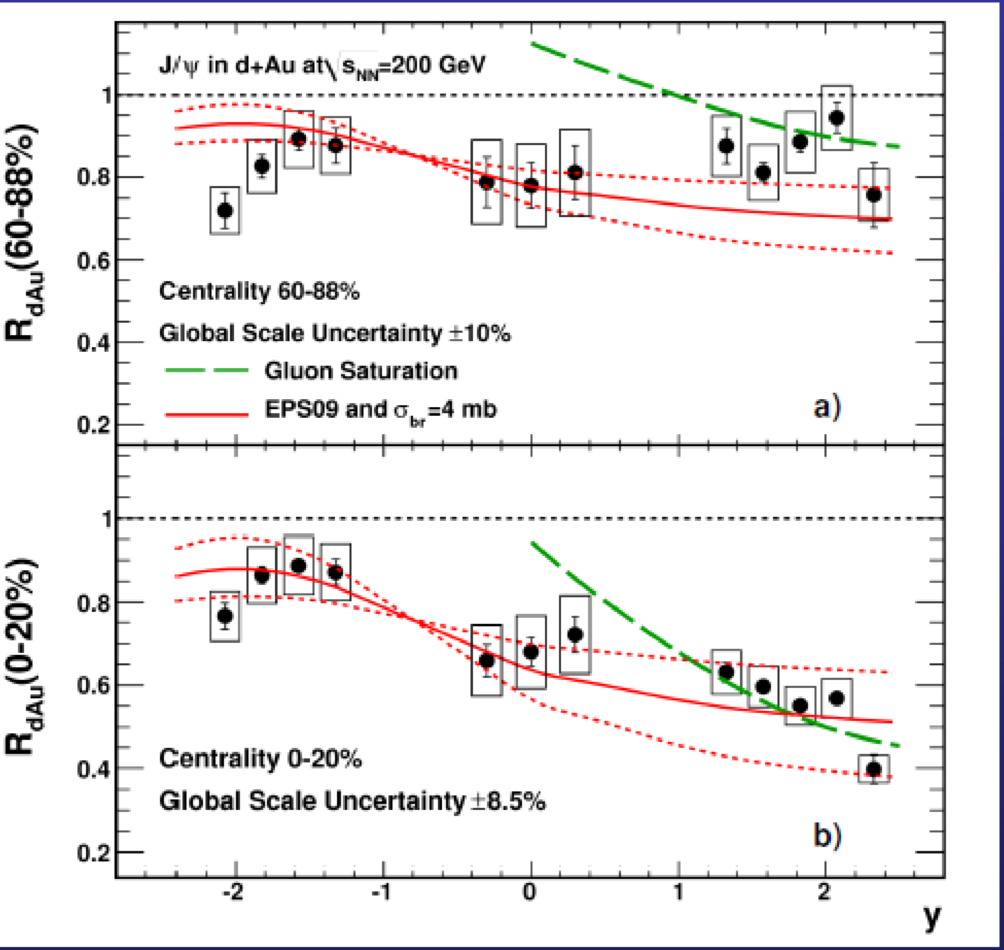


CMS-PAS HIN-12-2014

- ❑ Striking difference with respect to “ALICE vs PHENIX”
  - ❑ No saturation of the suppression vs centrality
  - ❑ High-p_T RHIC results show weaker suppression
- ❑ No significant p_T dependence from 6.5 GeV/c onwards
- ❑ (Re)generation processes expected to be negligible

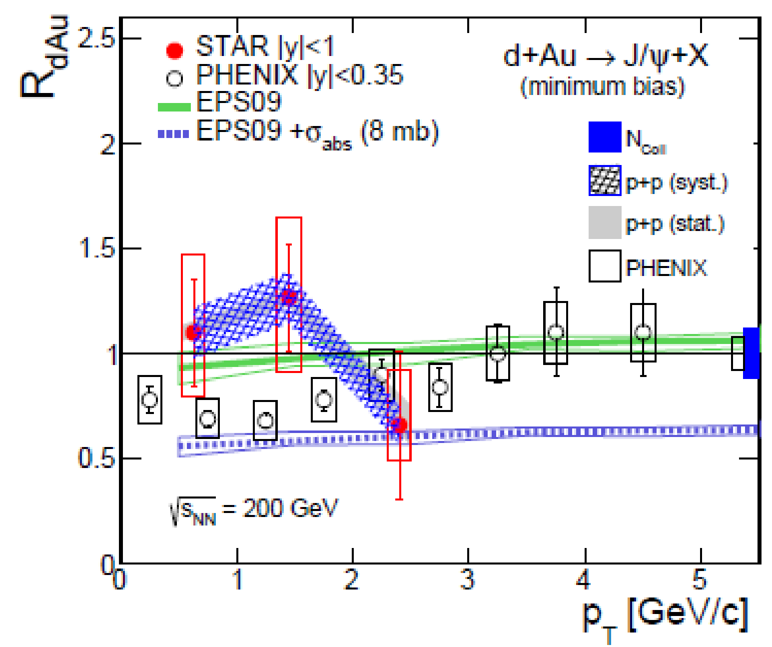
CNM at RHIC energy

- Significant CNM effects also at RHIC energy
- Contrary to LHC results, J/ψ data allow (need) a contribution from J/ψ breakup in nuclear matter ($\sigma_{J/\psi\text{-}N}$ ~ 4 mb)



PHENIX, PRL107 (2011) 142301

STAR, arXiv:1602.02212



- Transverse momentum dependence more difficult to reproduce

$\psi(2S)$ in p-Pb collisions

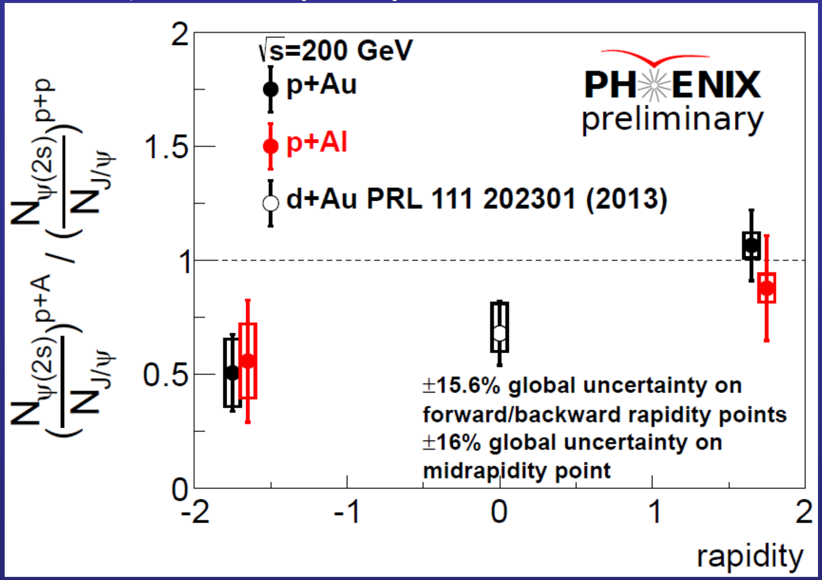
❑ $\psi(2S)$ suppression is stronger than the J/ψ one at RHIC and LHC

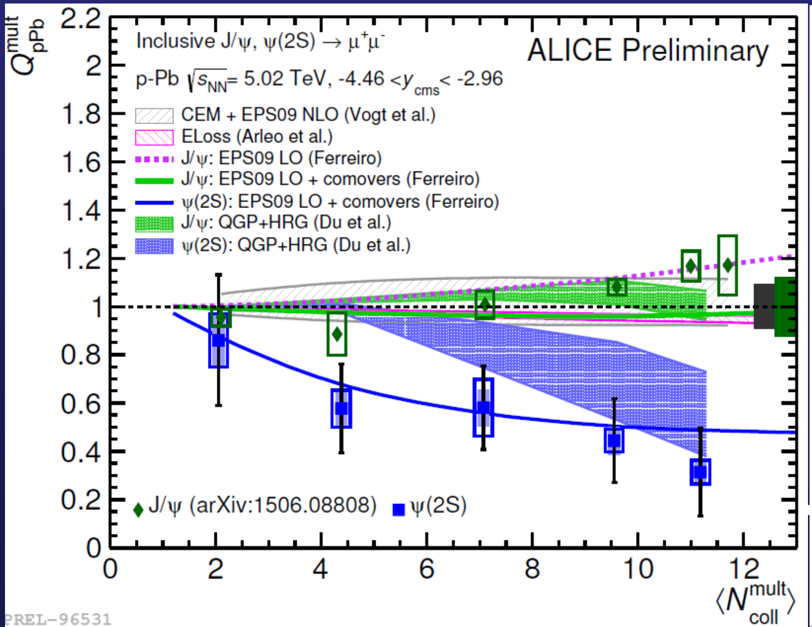
→ shadowing and energy loss, almost identical for J/ψ and $\psi(2S)$, do not account for the different suppression

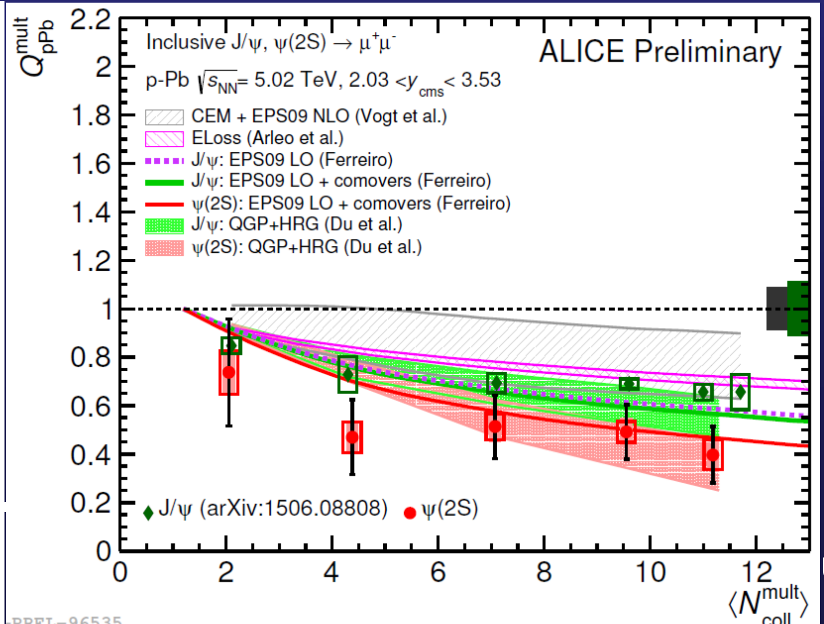
→ Only QGP+hadron resonance gas (Rapp) or comovers (Ferreiro) models describe the strong $\psi(2S)$ suppression at LHC

❑ Accurate Pb-Pb results still missing!

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

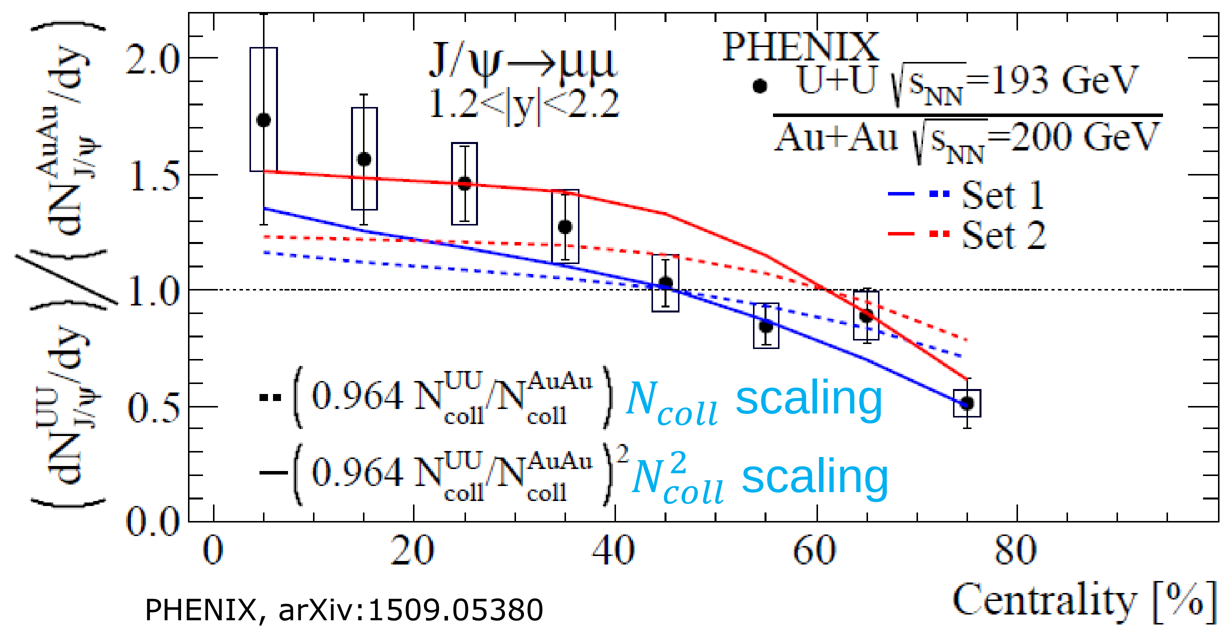






Recent RHIC results: U-U!

(re)combination/suppression role investigated comparing U-U and AuAu



PHENIX, arXiv:1509.05380

in central U-U wrt Pb-Pb

1) stronger suppression due to color screening
$\varepsilon_{AuAu} \sim$ 80-85% ε_{UU}

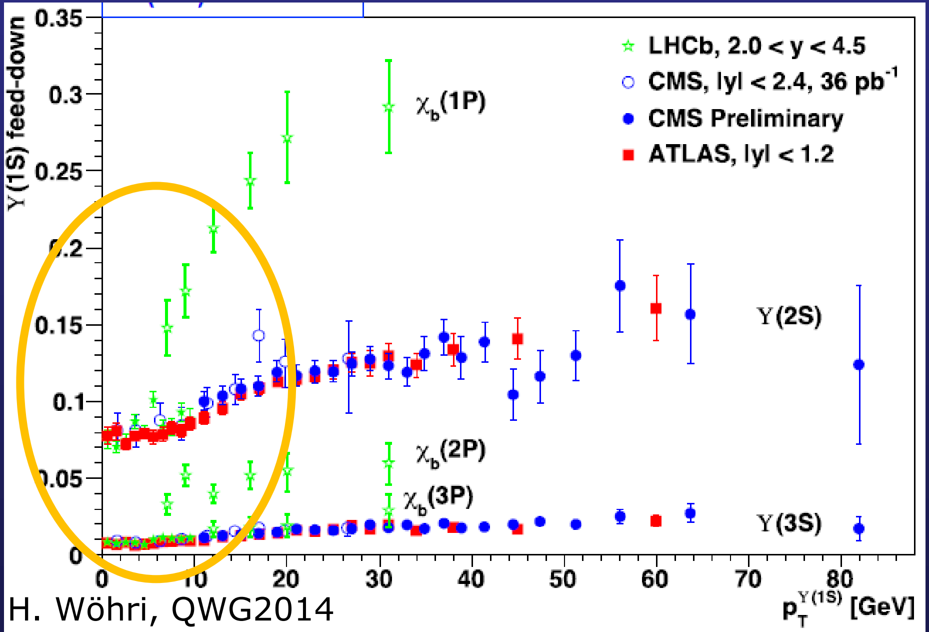
2) J/ψ recombination favoured by 25% larger N_{coll} in UU
$N^{stat}_{J/\psi} \sim N_c^2 \sim N_{coll}^2$

- results slightly favour N^2_{coll} scaling → (re)combination wins over suppression when going from central U-U to Au-Au collisions
- quantitative comparison depends on the choice of the uranium Woods-Saxon parametrizations

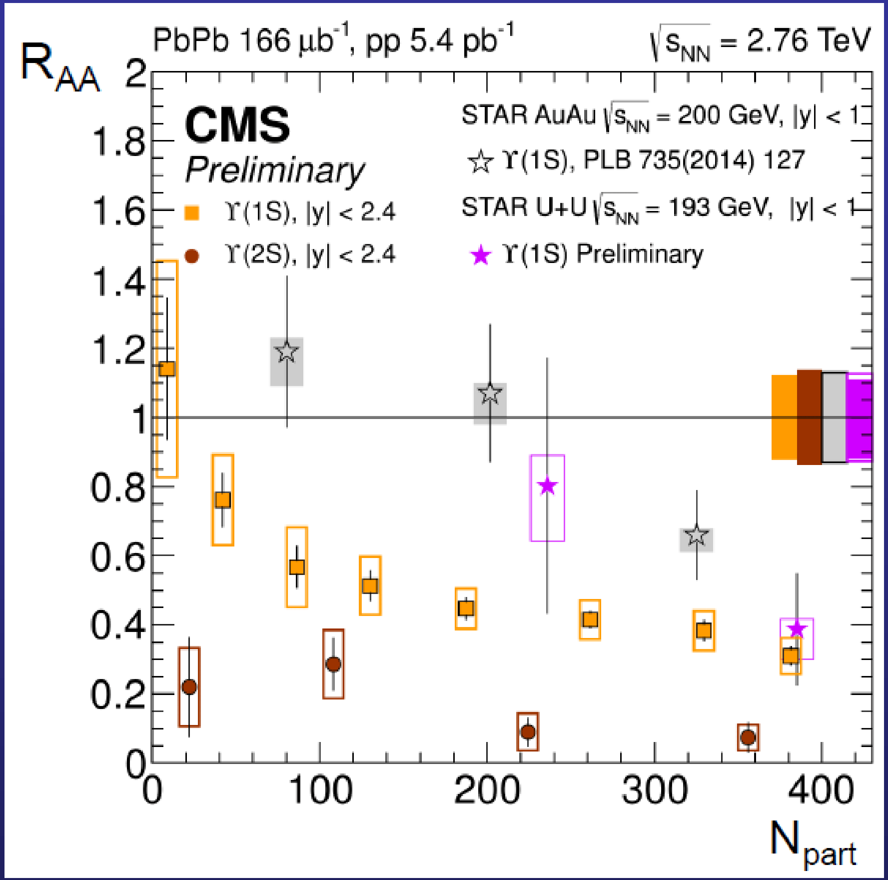
Υ suppression in Pb-Pb: RHIC and LHC

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

- Strong Υ(1S) suppression
- Feed-down from excited states seems not enough to explain it!
- Similar suppression at RHIC and LHC energy, a priori unexpected



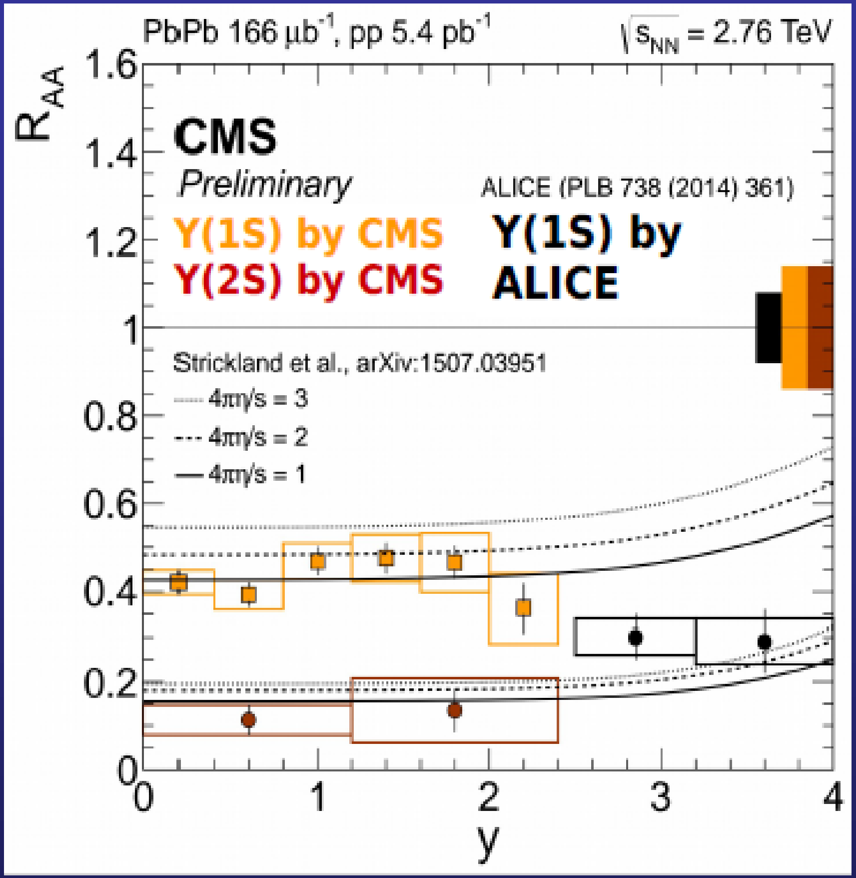
H. Wöhri, QWG2014

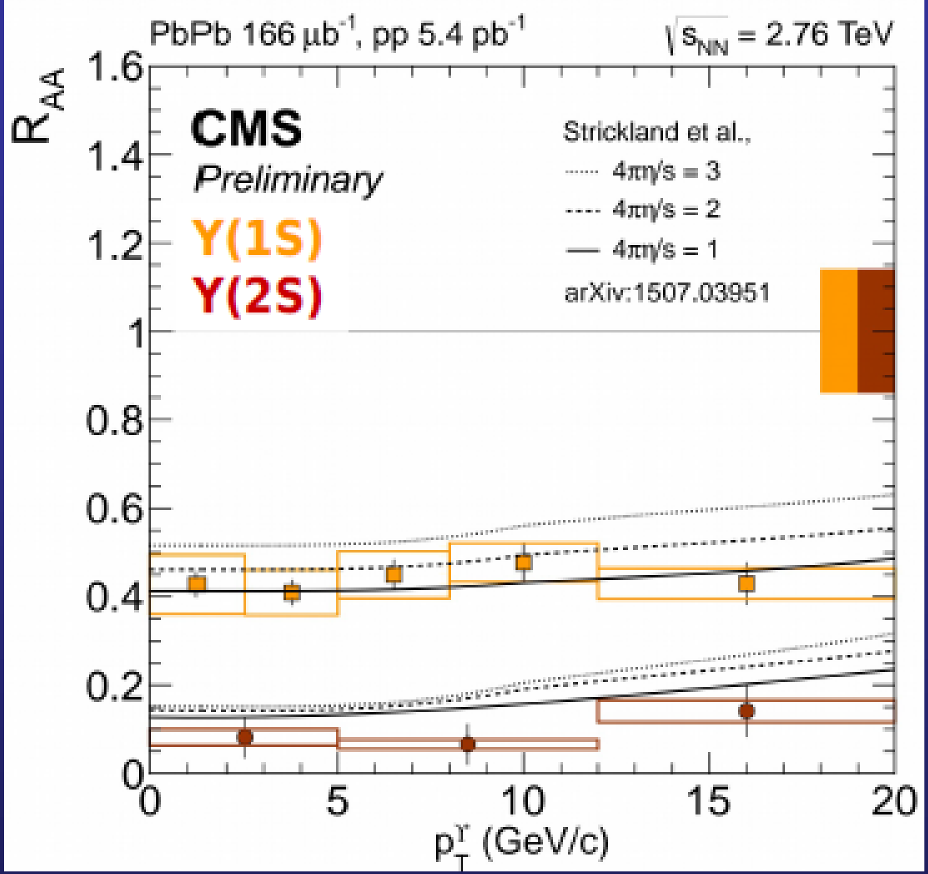


CMS-HIN-15-001

- 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

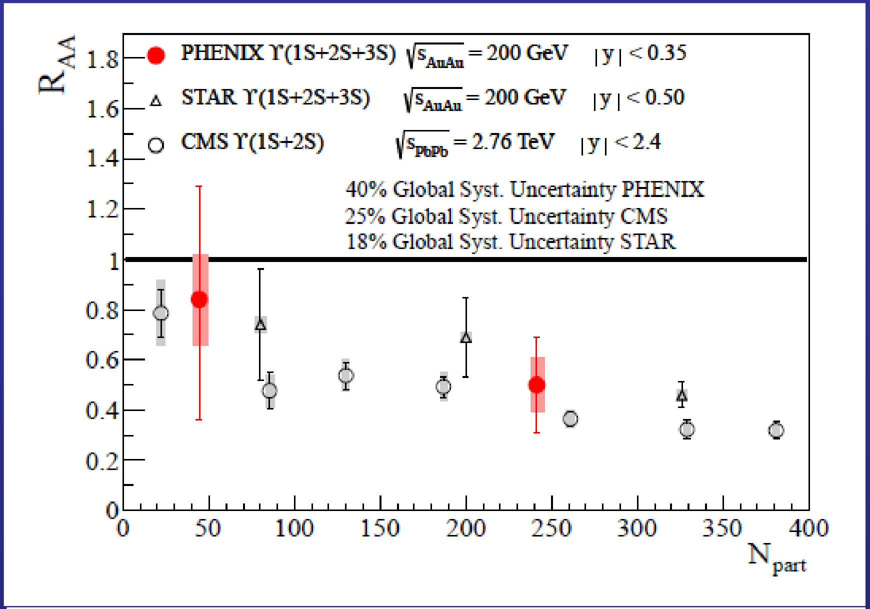


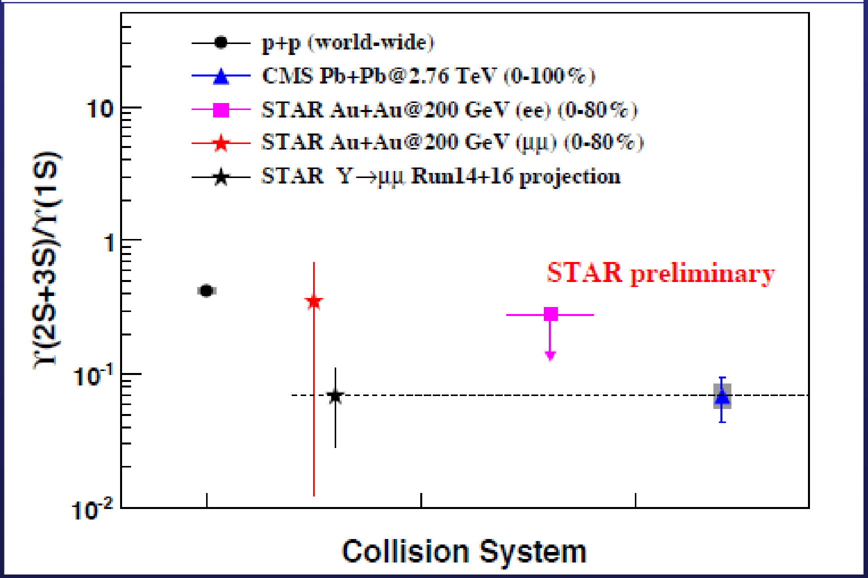


CMS-HIN-15-001

- 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 (?)

Bottomonium results at RHIC





❑ Both PHENIX/STAR have published results on Υ

❑ Mutual agreement between experiments but still large stat+syst uncertainties

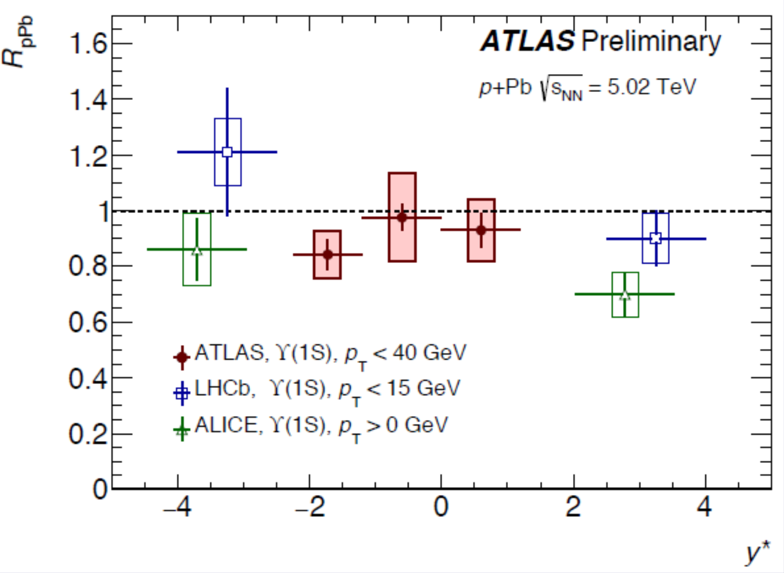
→ Need upgraded detectors and higher luminosity

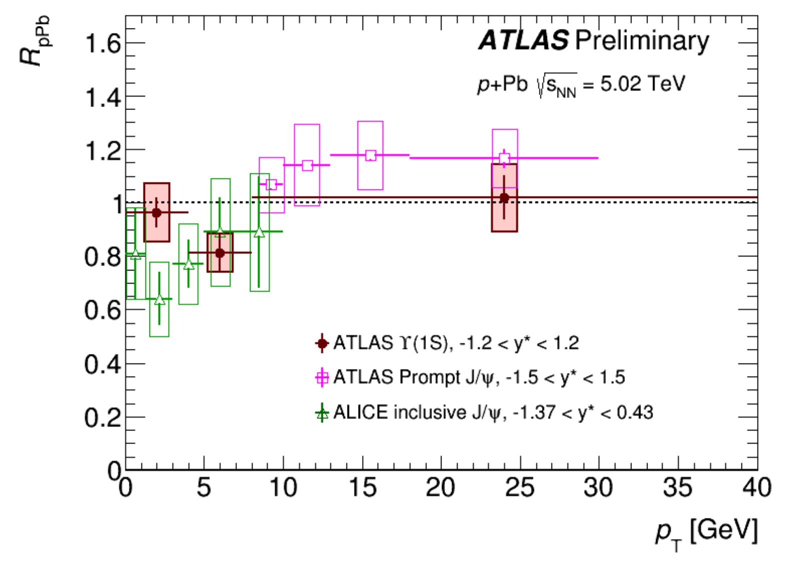
❑ Recent results with the STAR MTD on the ratio excited/ground state

❑ Consistent with dielectron measurement within large uncertainties

❑ Factor 7 more statistics on this measurement with full Run14+ Run16 data

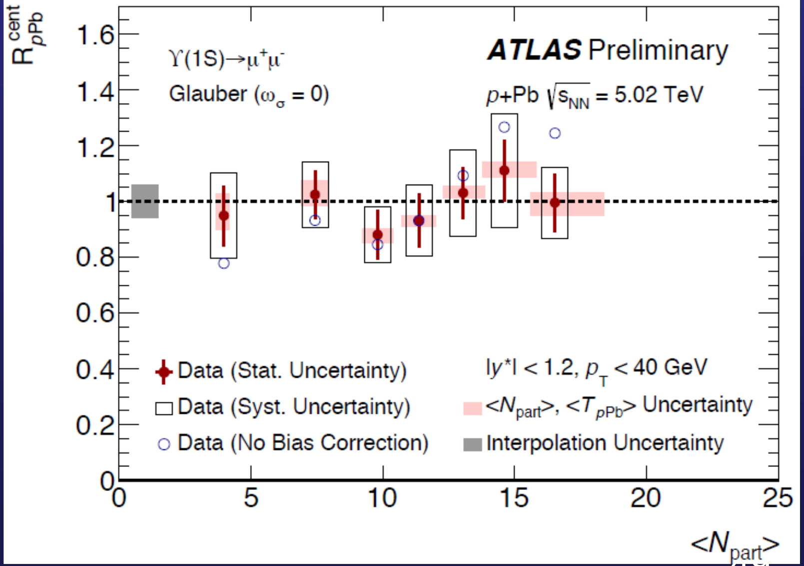
Weak CNM effects for bottomonium





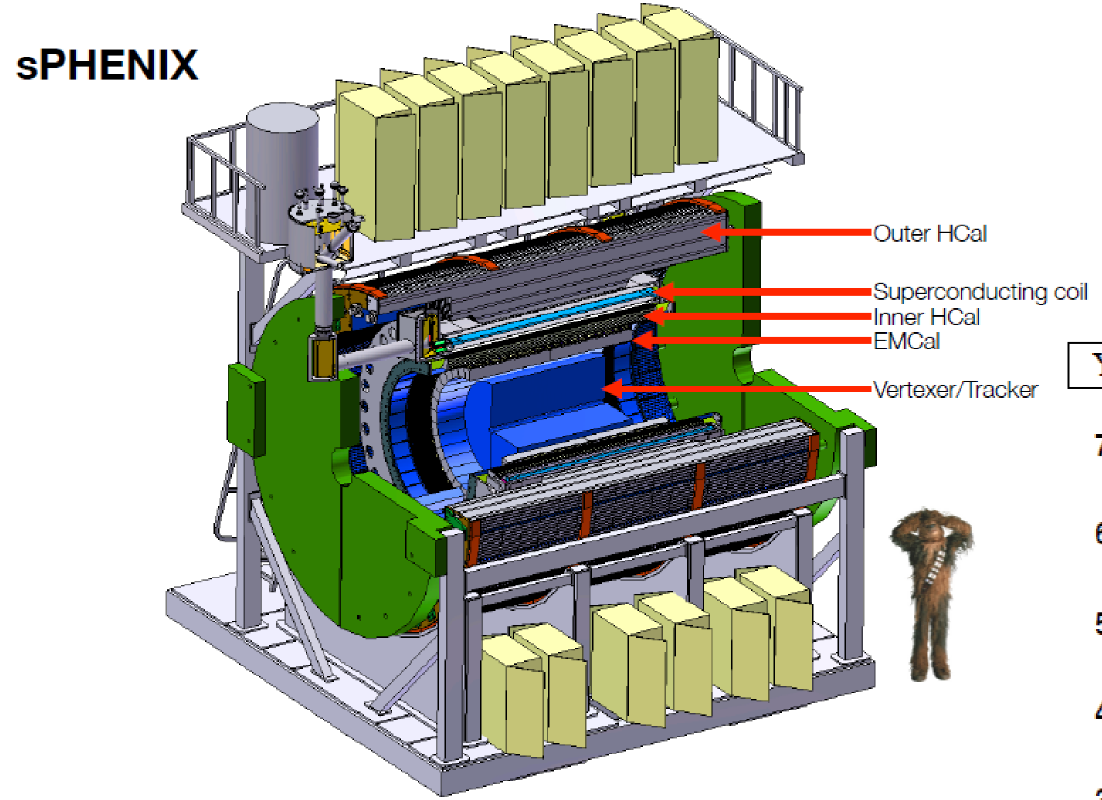
- R_{pPb} close to 1 and with no significant dependence on y, p_T and centrality

- Fair agreement ALICE vs LHCb (within large uncertainties)

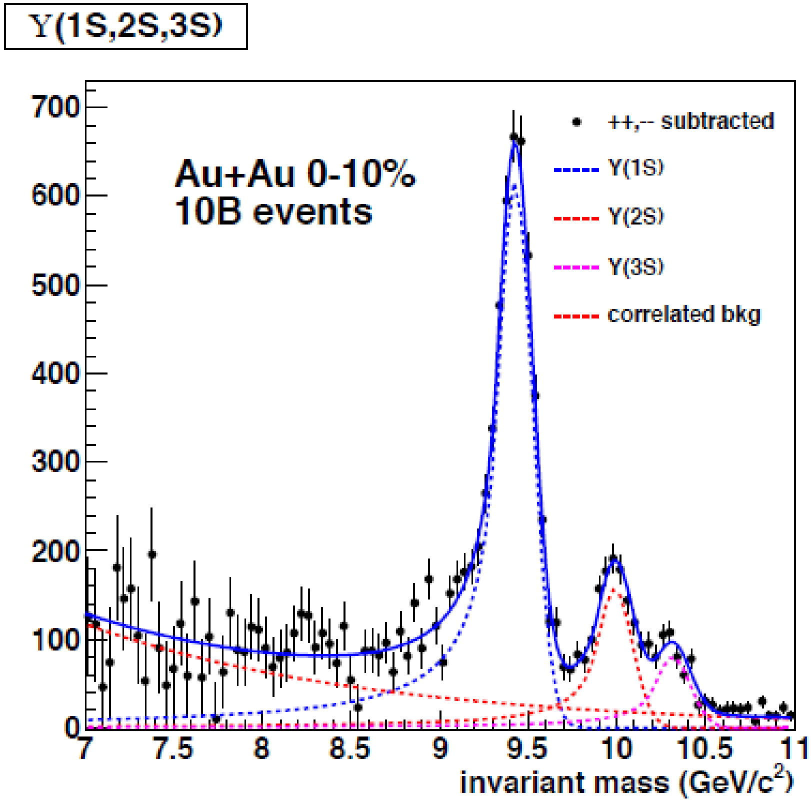


ALICE, PLB 740 (2015) 105
ATLAS-CONF-2015-050
LHCb, JHEP 07(2014)094

The future of RHIC - sPHENIX



- ☐ BaBar 1.5 T superconducting solenoid
- ☐ Full em/hadronic calorimetry
- ☐ Precision tracking/vertexing

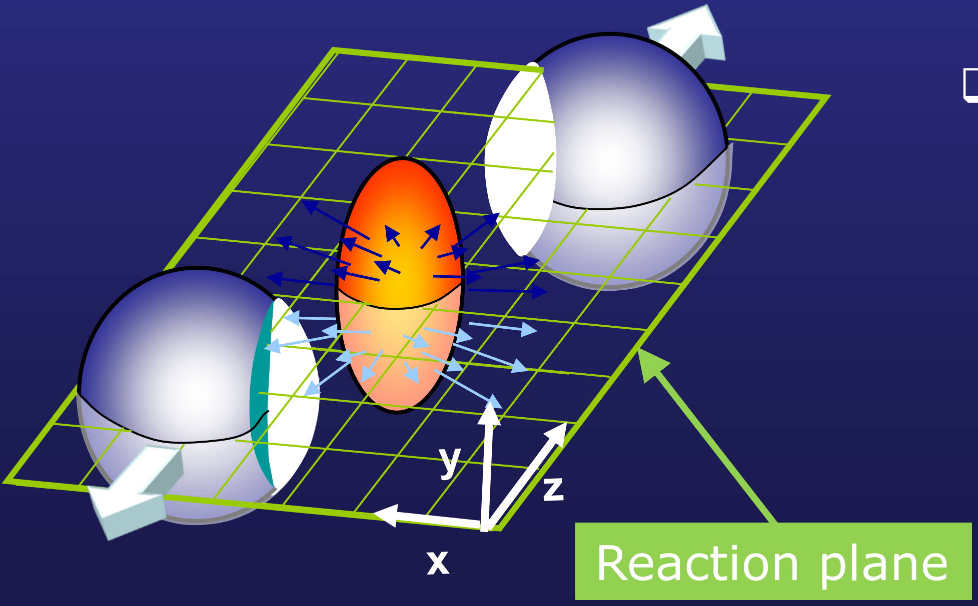


- ☐ Physics program
  - → Light and HF jets, photons, upsilons and their correlations

Anisotropic transverse flow

- ❑ In collisions with b ≠ 0 (non central) the fireball has a geometric anisotropy, with the overlap region being an ellipsoid

- ❑ Macroscopically (hydrodynamic description)
  - ❑ The pressure gradients, i.e. the forces "pushing" the particles are anisotropic (φ-dependent), and larger in the x-z plane
  - ❑ φ-dependent velocity → anisotropic azimuthal distribution of particles



- ❑ Microscopically
  - ❑ Interactions between produced particles (if strong enough!) can convert the initial geometric anisotropy in an anisotropy in the momentum distributions of particles, which can be measured

Anisotropic transverse flow

- ❑ Starting from the azimuthal distributions of the produced particles with respect to the reaction plane Ψ_{RP}, one can use a Fourier decomposition and write

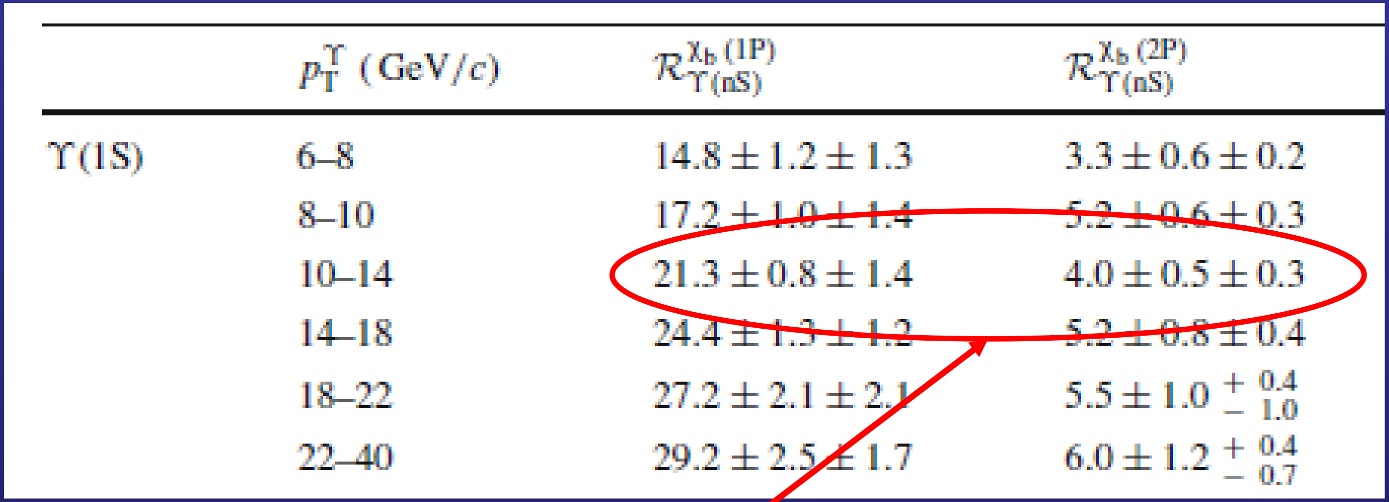
$$\frac{dN}{d(\varphi-\Psi_{RP})}=\frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos\left(2\left(\varphi-\Psi_{RP}\right)\right)+....\right)$$

- ❑ The terms in $\sin(\varphi-\Psi_{RP})$ are not present since the particle distributions need to be symmetric with respect to Ψ_{RP}
- ❑ The coefficients of the various harmonics describe the deviations with respect to an isotropic distribution
- ❑ From the properties of Fourier's series one has

$$v_n=\left\langle\cos\left[n\left(\varphi-\Psi_{RP}\right)\right]\right\rangle$$

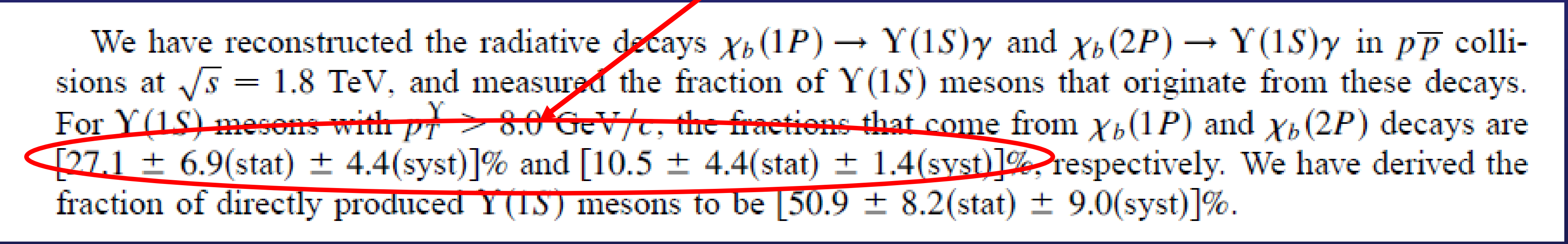
On feed-down fractions

- 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

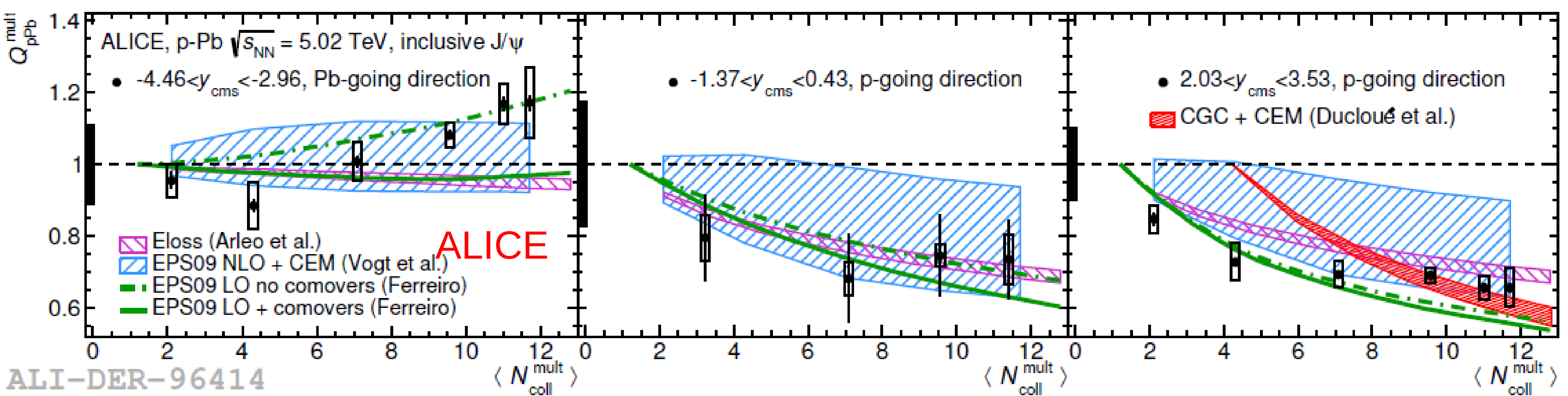


We have reconstructed the radiative decays $\chi_b(1P) \to \Upsilon(1S)\gamma$ and $\chi_b(2P) \to \Upsilon(1S)\gamma$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, and measured the fraction of $\Upsilon(1S)$ mesons that originate from these decays. For $\Upsilon(1S)$ mesons with $p_T^{\Upsilon} > 8.0$ 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)]%.

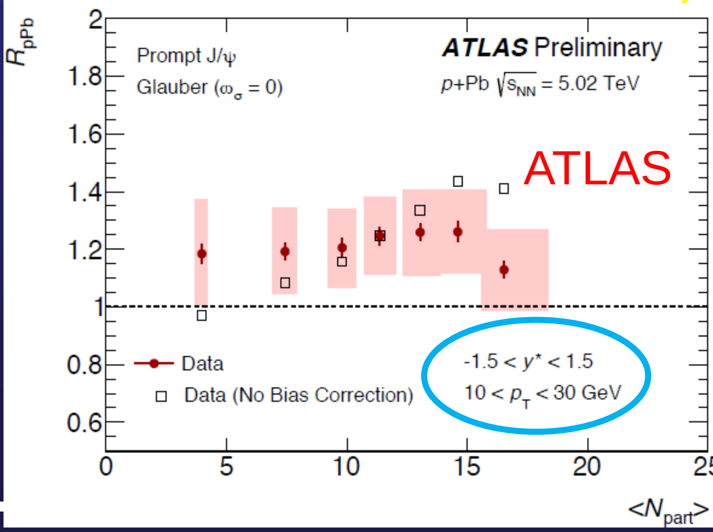
- At the limit of uncertainties or do we have a problem here ?
- Difficult to reach 50% including 2S and 3S

J/ψ R_{pPb}: centrality dependence

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



mid-*y*

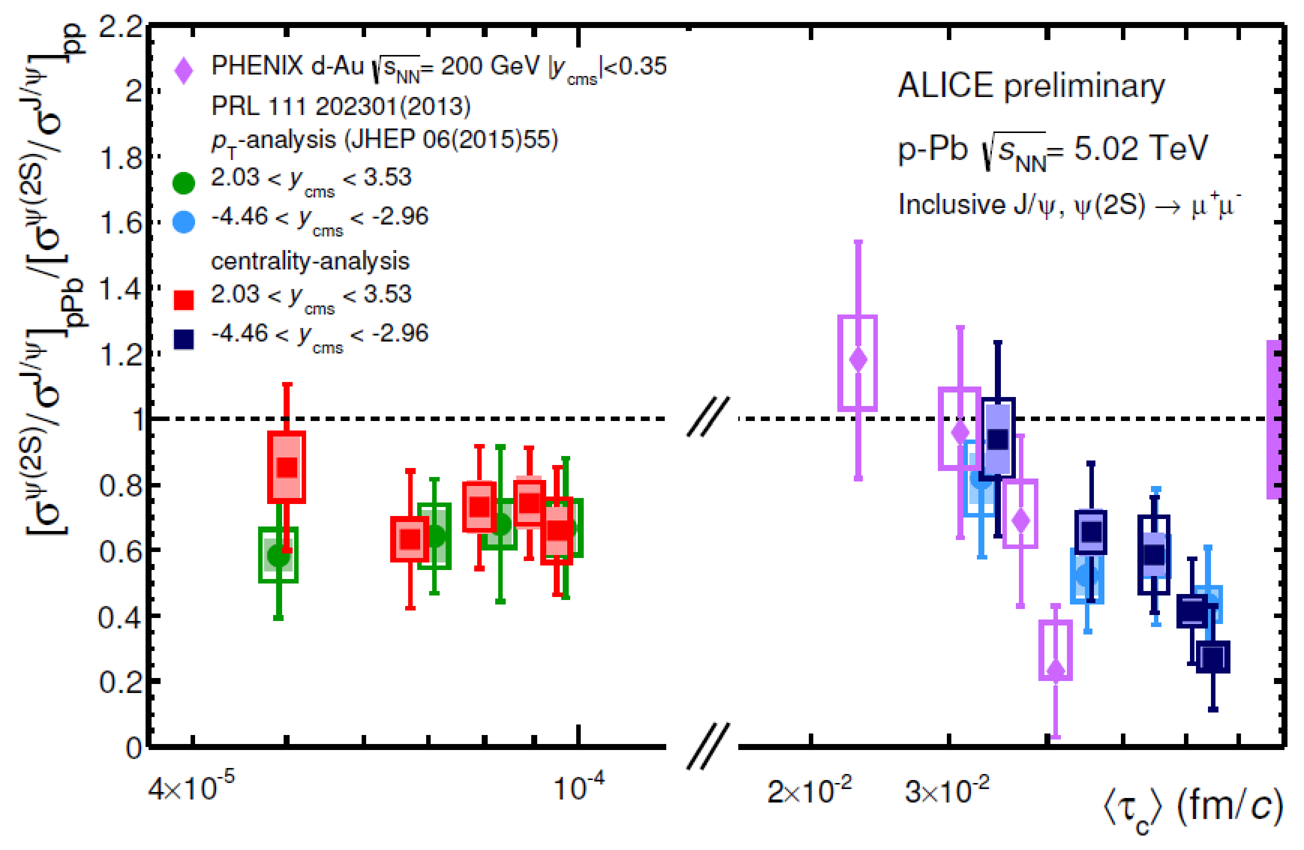


- ALICE:
- mid and fw-y: suppression increases with centrality
- backward-y: hint for increasing Q_{pA} with centrality

- 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

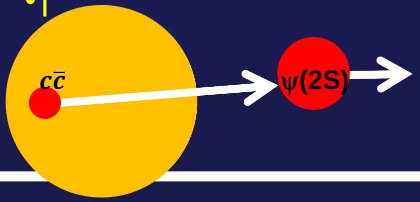


$$\tau_c = \frac{\langle L \rangle}{\langle \beta_z \gamma \rangle}$$

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

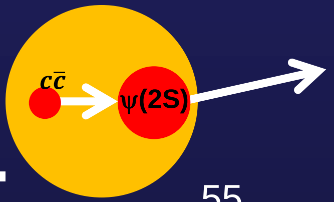
Forward-y: $\tau_c << \tau_f$

interaction with nuclear matter cannot play a role

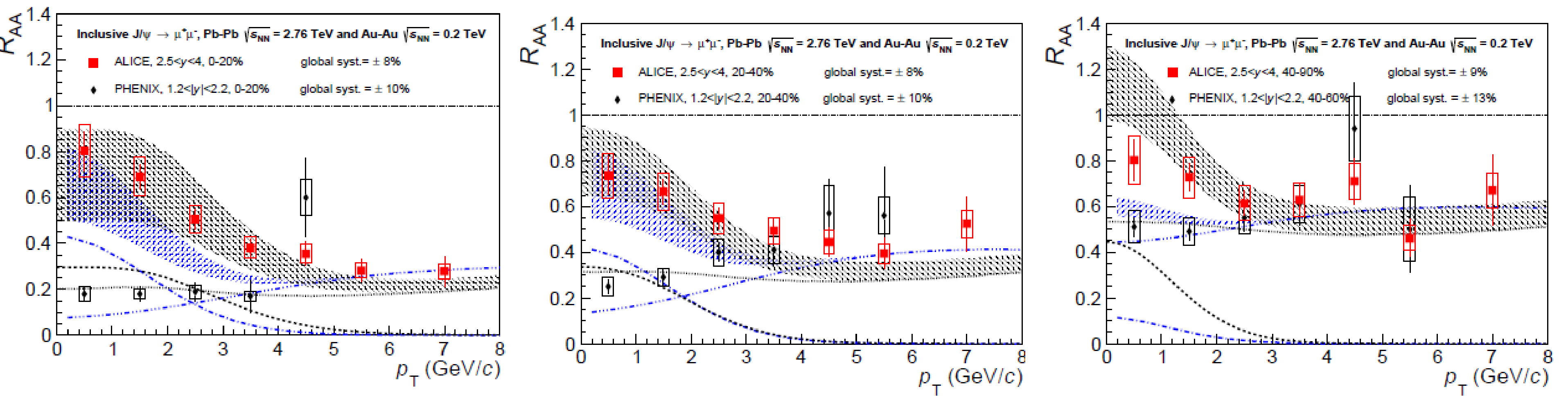


Backward-y: $\tau_c \lesssim \tau_f$

indication of effects related to break-up in the nucleus?



R_{AA} vs p_T



▧ 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

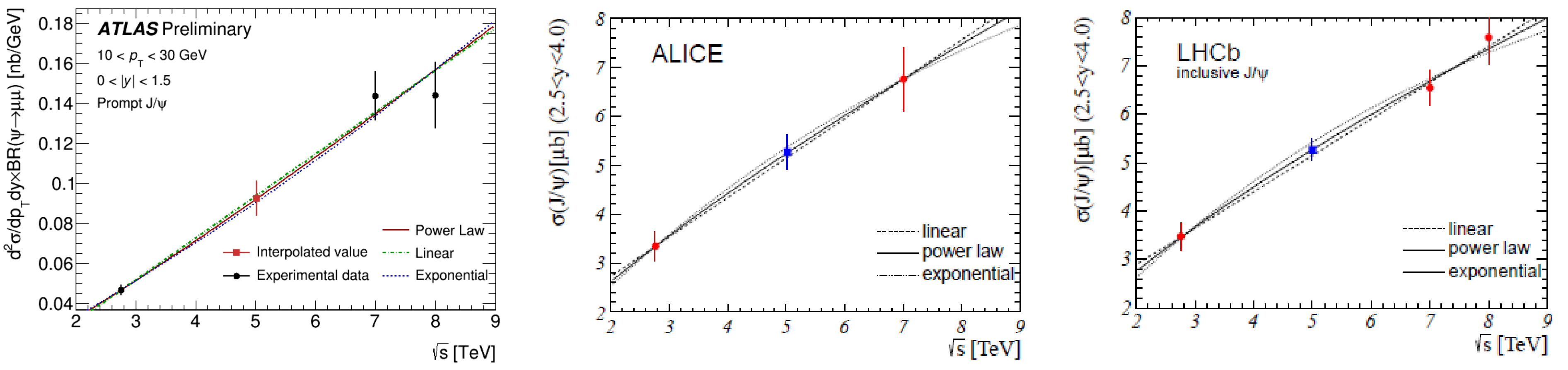
Still rather large theory uncertainties: models will benefit from precise measurement of σ_{cc} and CNM effects

- ☐ Opposite trend with respect to lower energy experiments

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

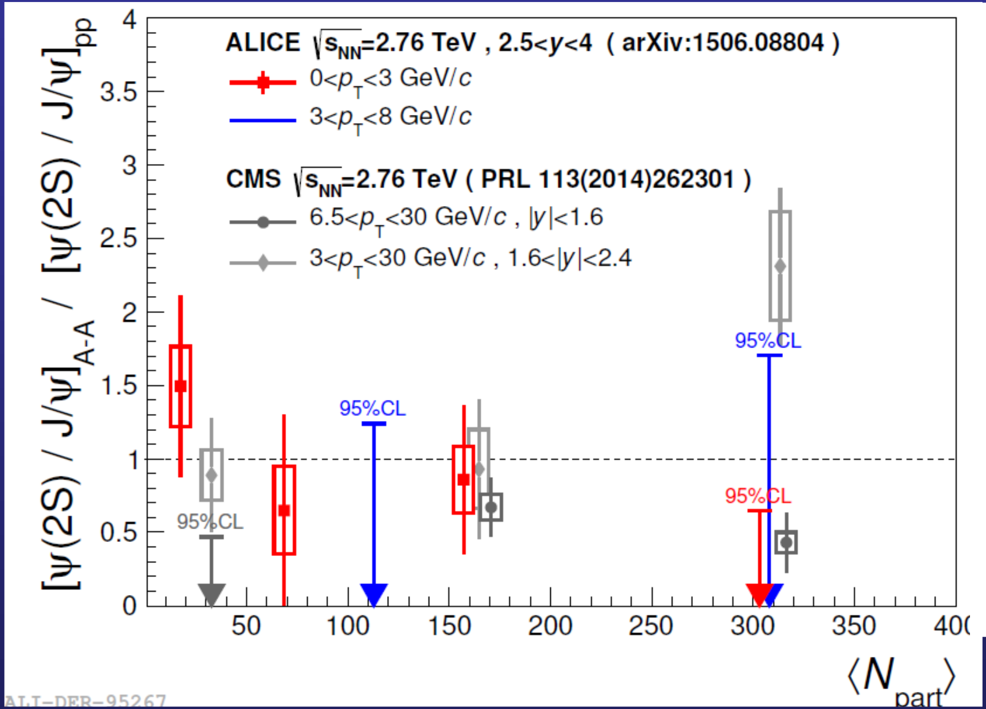
- ❑ ψ(2S) → interpolation difficult, small statistics at √s=2.76 TeV
- ❑ Ratio ψ(2S) / J/ψ → ALICE uses √s=7 TeV pp values (weak √s-dependence)

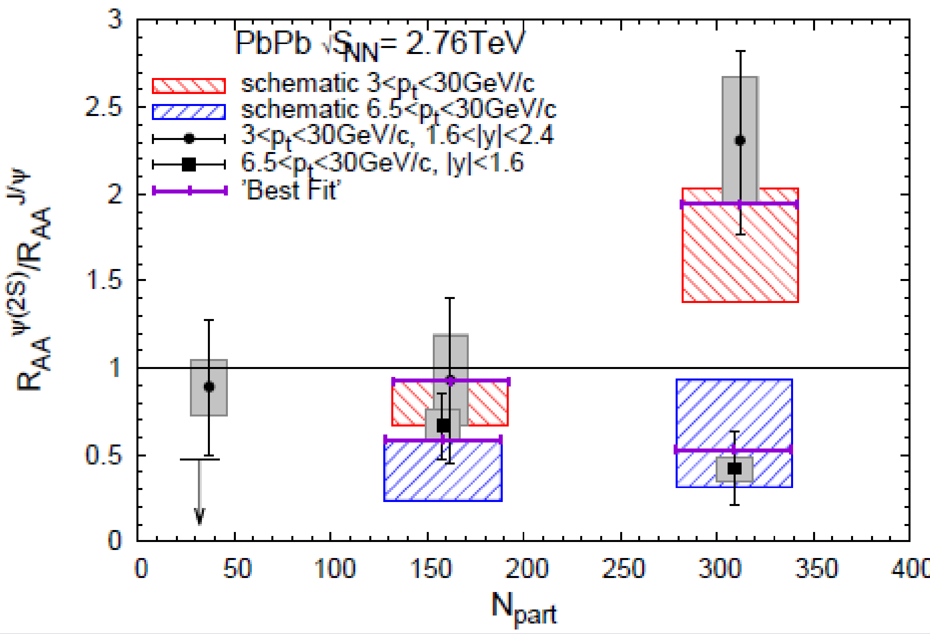
$$R_{pA}^{\psi(2S)} = R_{pA}^{J/\psi} \times \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pA}^{J/\psi}} \times \frac{\sigma_{pp}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}}$$

ALICE estimate (conservative)
→ 8% syst. unc. due to different √s
(using CDF/ALICE/LHCb results)

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



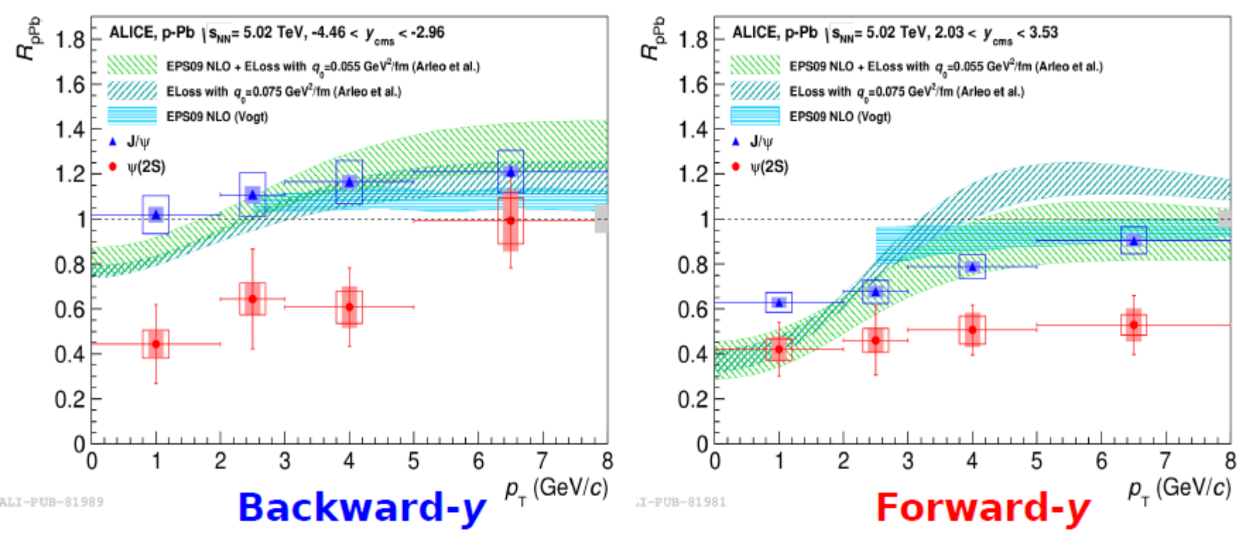


Du and Rapp arXiv:1504.00670

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

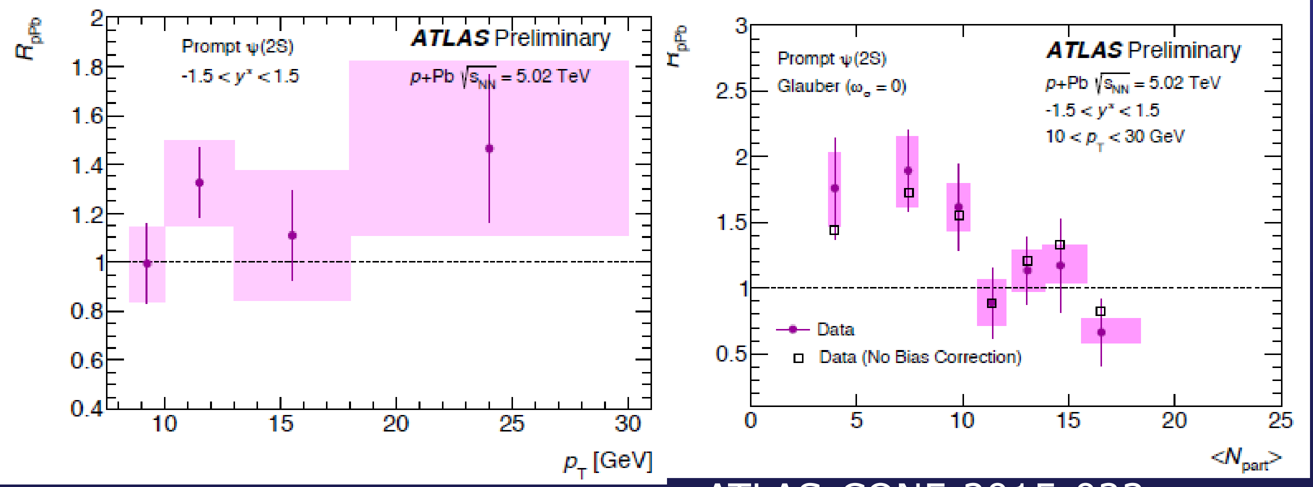
- ☐ Possible interpretation (Rapp et al.) → Re-generation for ψ(2S) occurs at later times wrt J/ψ, when a significant radial flow has built up, pushing the re-generated ψ(2S) at a relatively larger p_T
- ☐ Small tension, between ALICE and CMS, for central events?

$\psi(2S)$ 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

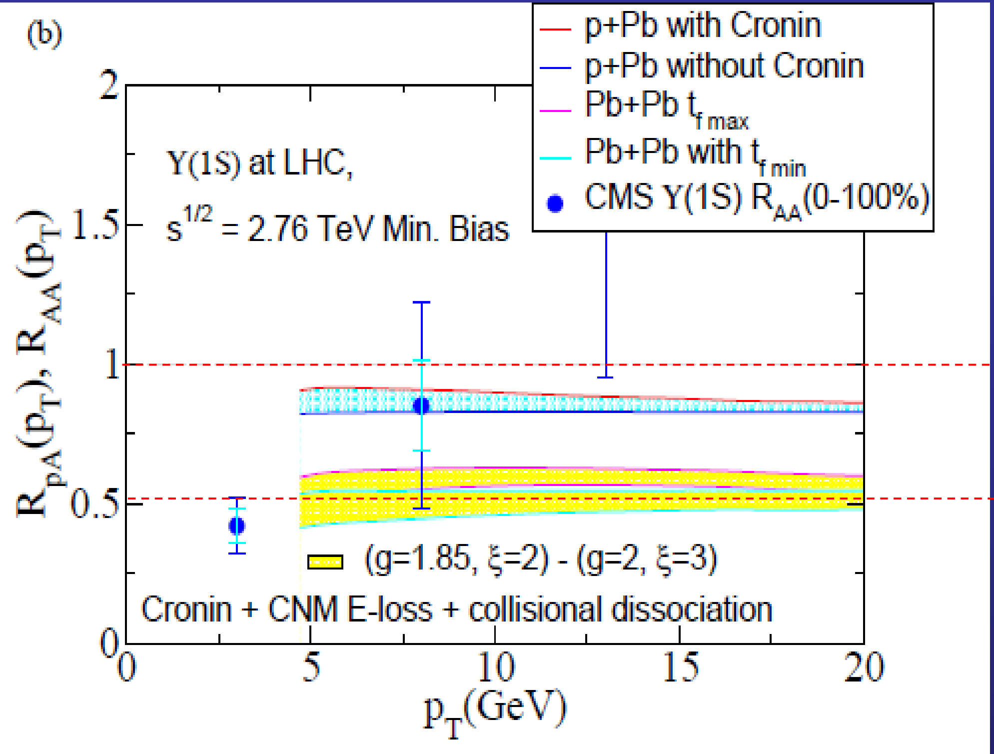


ATLAS-CONF-2015-023

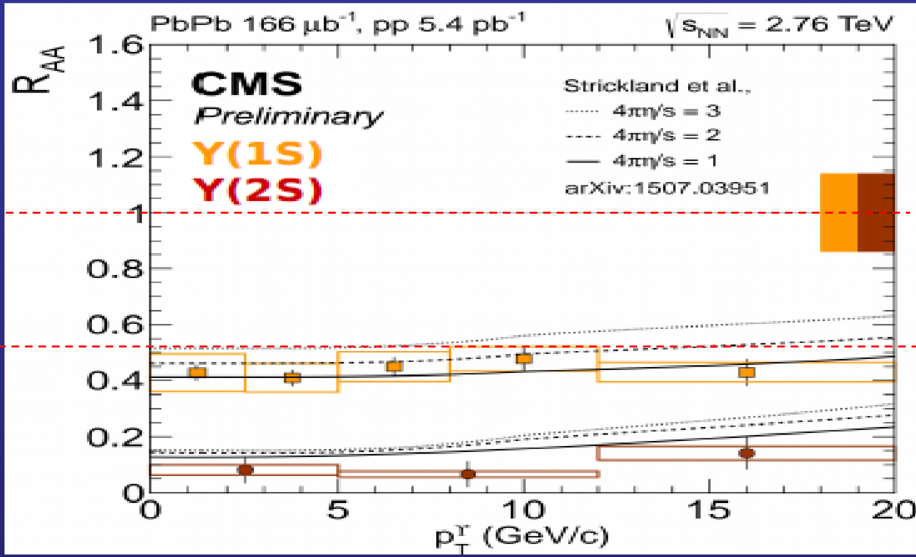
- ATLAS (high p_T) : larger uncertainties, hints for strong enhancement, concentrated in peripheral events

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

High p_T Υ: model comparison



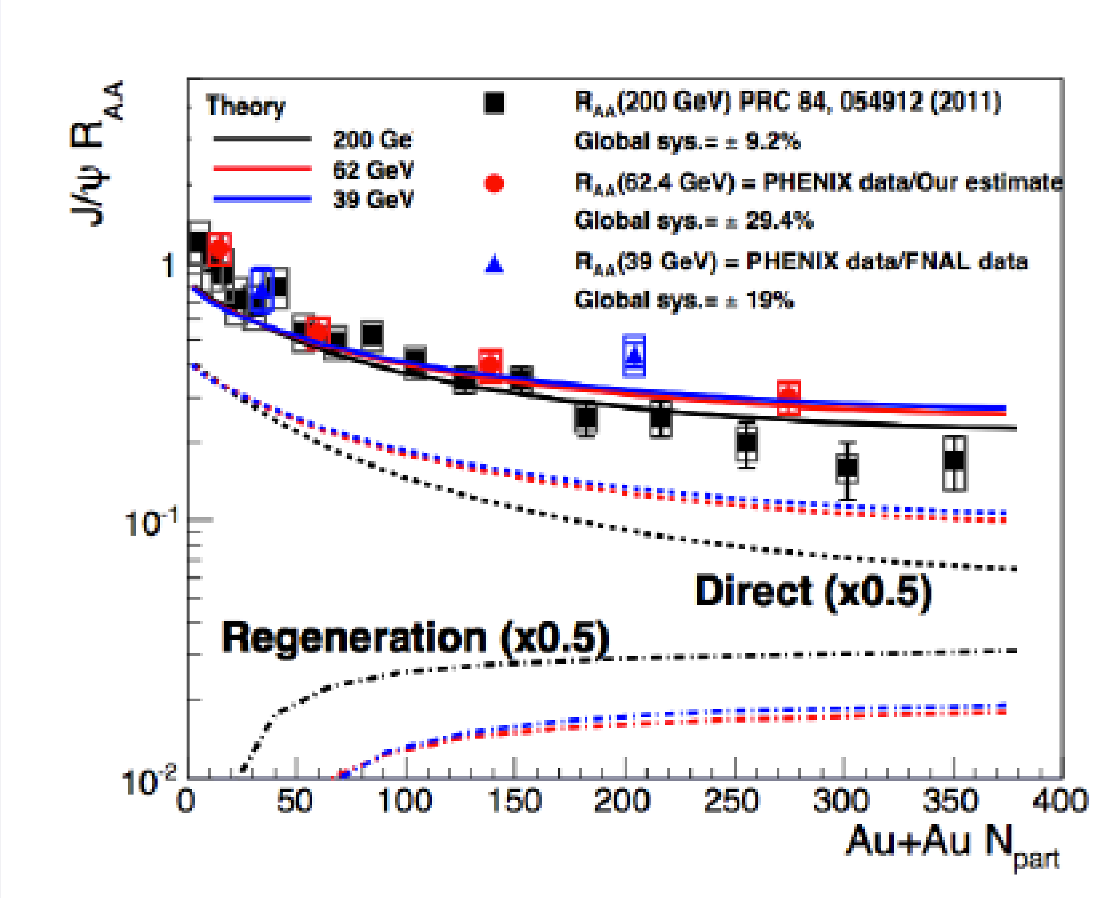
Sharma and Vitev,
Phys. Rev. C 87, 044905 (2013)



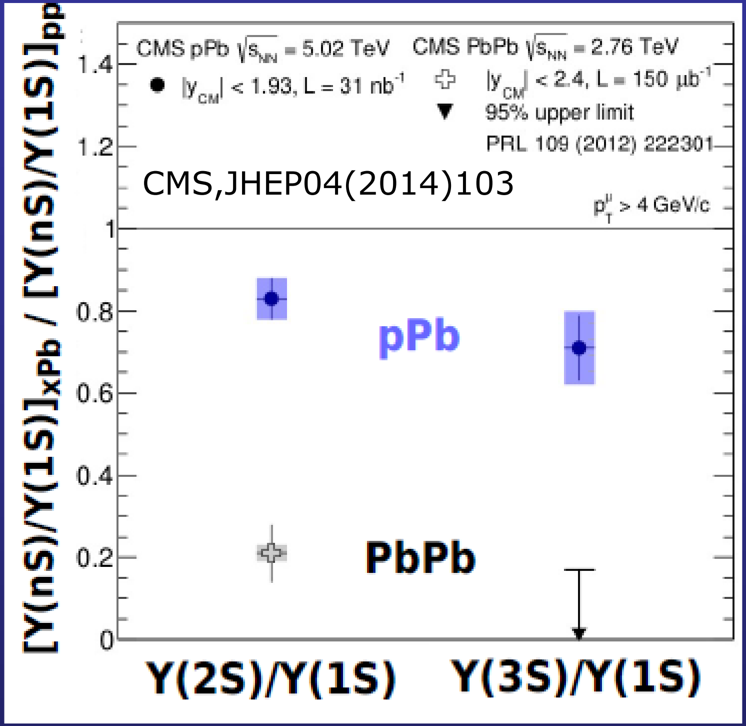
- High p_T Υ suppression
- Propagation effects through QGP
  - Quenching of the color octet component
  - Collisional dissociation model
- Approximation: initial wave function of the quarkonia well approximated by vacuum wavefunctions in the short period before dissociation
- CNM effects accounted for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

Suppression vs $\sqrt{s_{NN}}$ (RHIC)

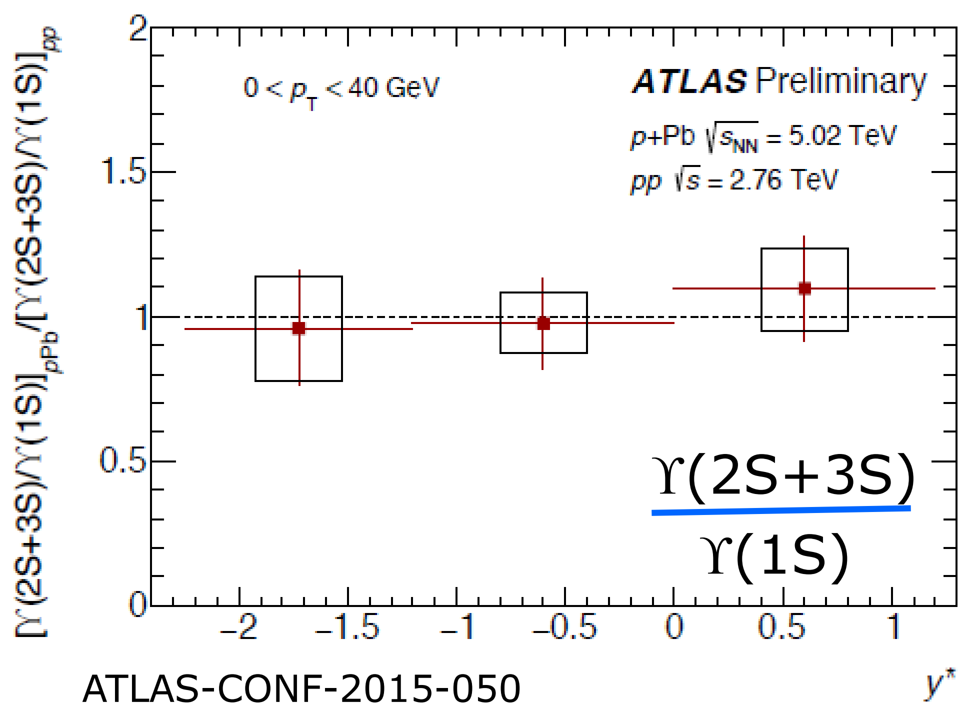
- At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression



Yield ratios for bottomonium in p-Pb



CMS,JHEP04(2014)103



ATLAS-CONF-2015-050

CMS

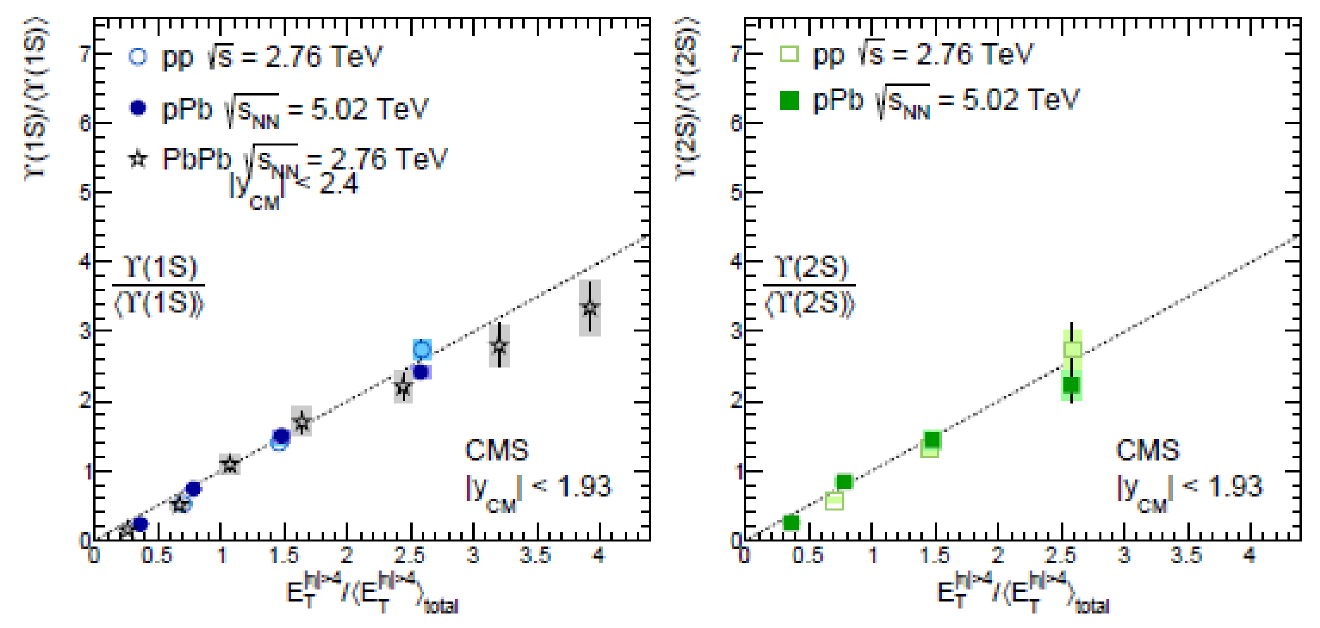
- ❑ Excited states suppressed with respect to Υ(1S)
- ❑ Initial state effects similar for the various Υ(ns) states

→ Final states effects at play?

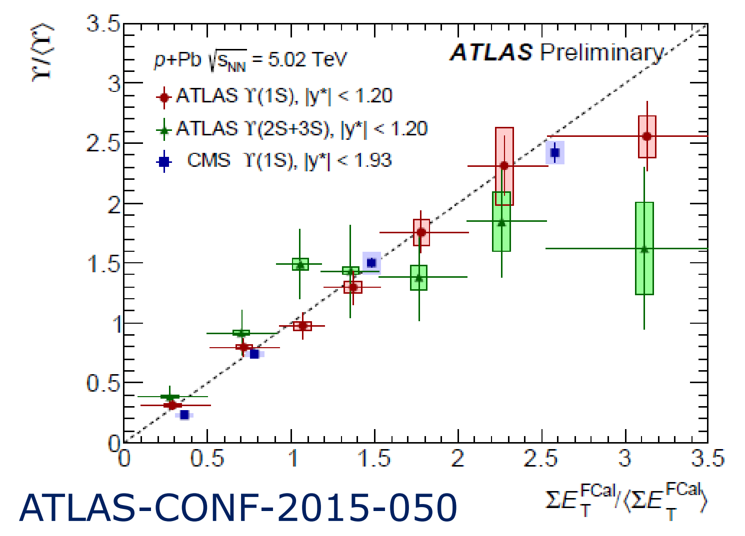
ATLAS

- ❑ 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)

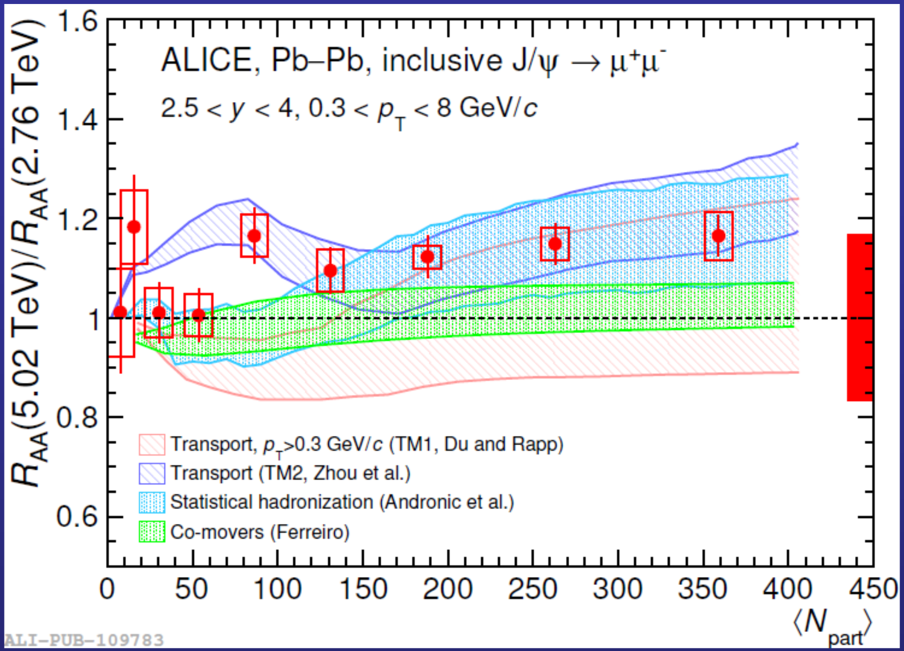


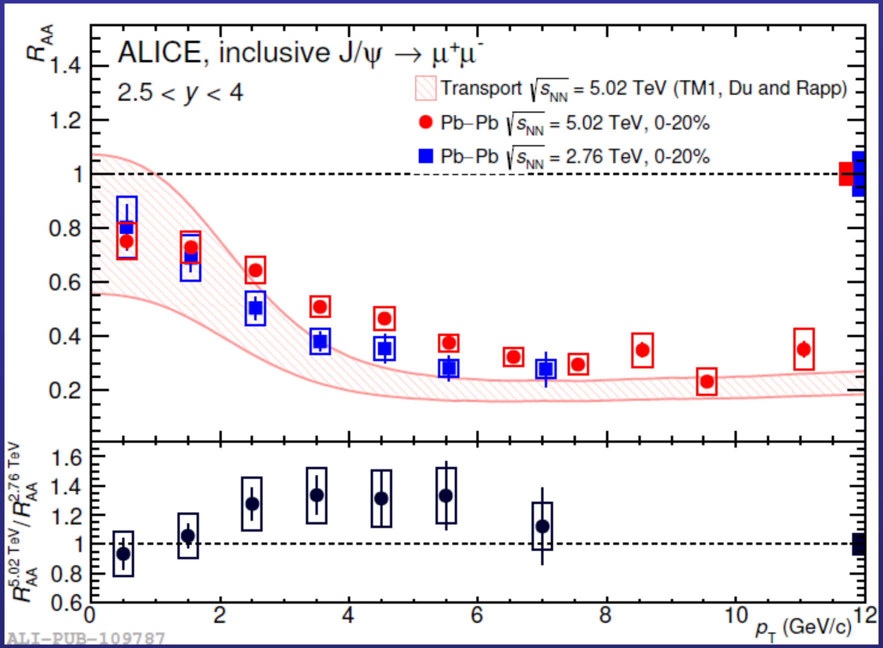
ATLAS-CONF-2015-050

CMS, JHEP 04 (2014) 103

- ☐ 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 ?

Comparison with models



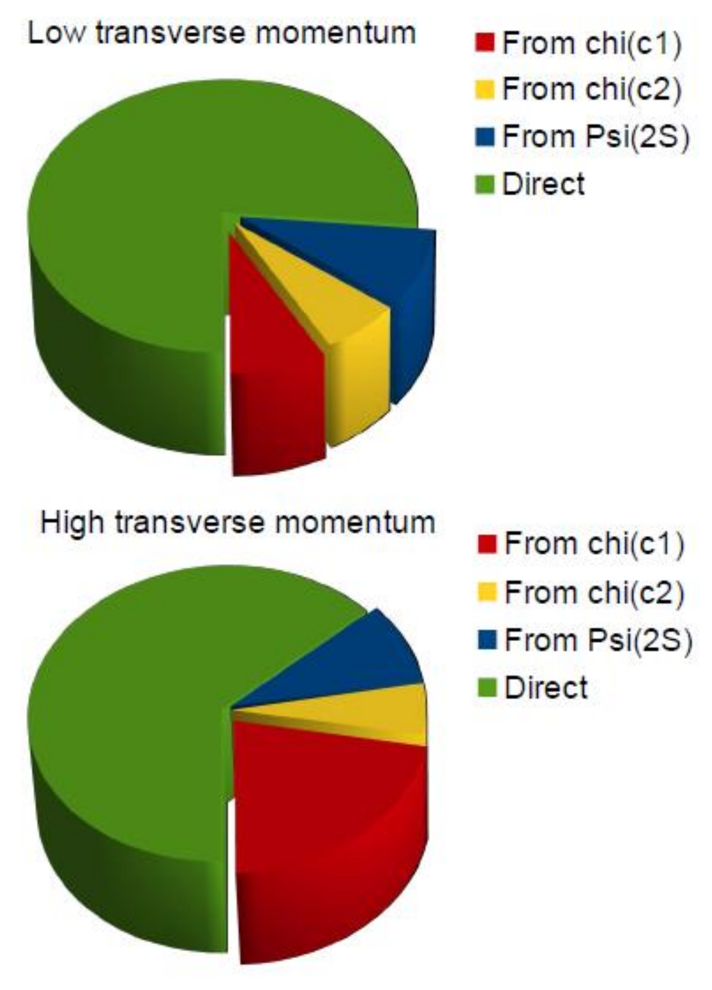


- Theoretical and experimental uncertainties reduced in the R_{AA} double ratio
- Centrality dependence of the R_{AA} ratio is rather flat

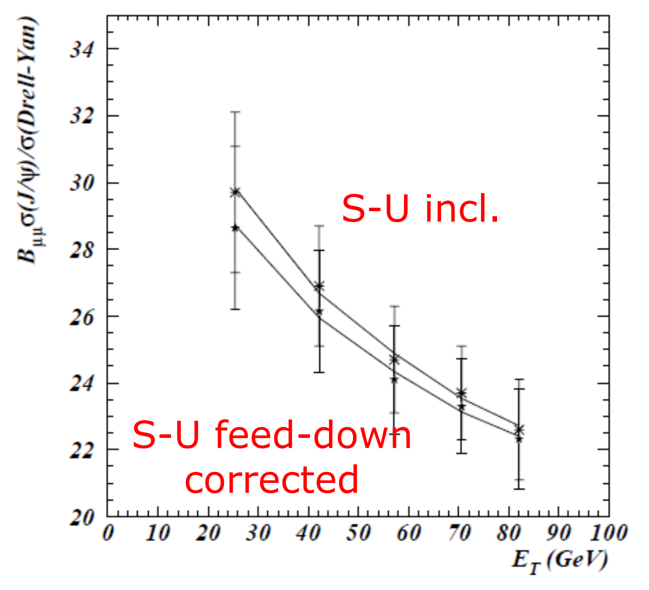
- R_{AA} increases at low p_T, at both energies, as expected in a regeneration scenario
- Hint for an increase of R_{AA}, at 5.02TeV, in 2<p_T<6 GeV/c

→ Also $\sqrt{s_{NN}}$=5.02TeV results support a picture where a combination of J/ψ suppression and (re)combination occurs in the QGP

Feed-down



- Cannot be addressed precisely until today!
- If $\psi(2S)$ and χ_C were precisely measured in Pb-Pb their contribution could be subtracted out and obtain direct J/ψ
- Explicitly done (only ?) by NA50, for $\psi(2S)$ when comparing p-A and S-U data

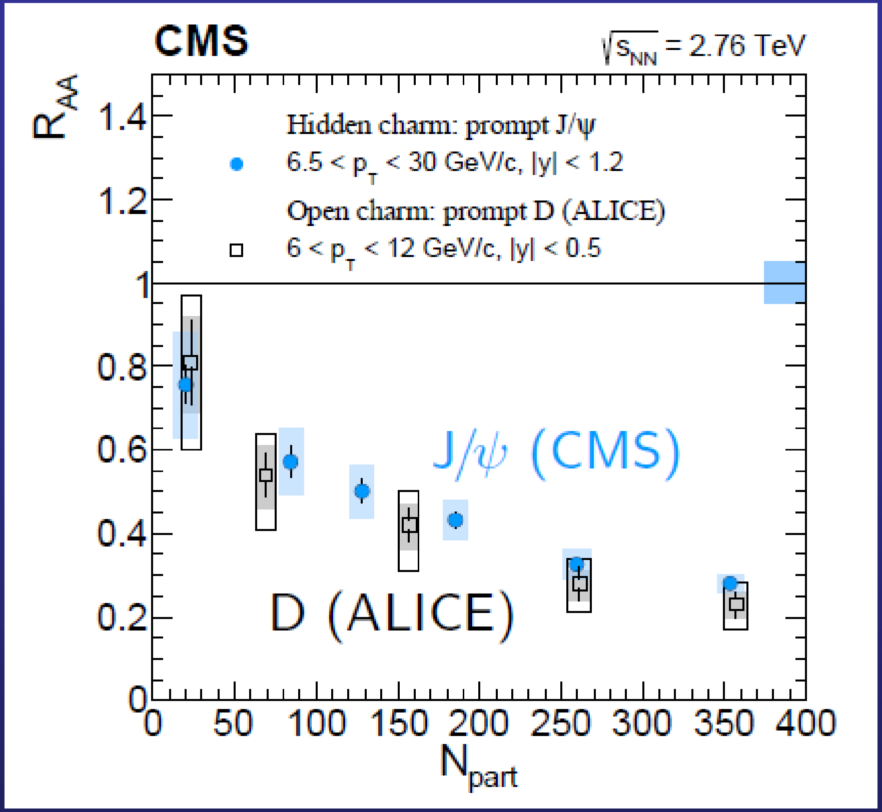


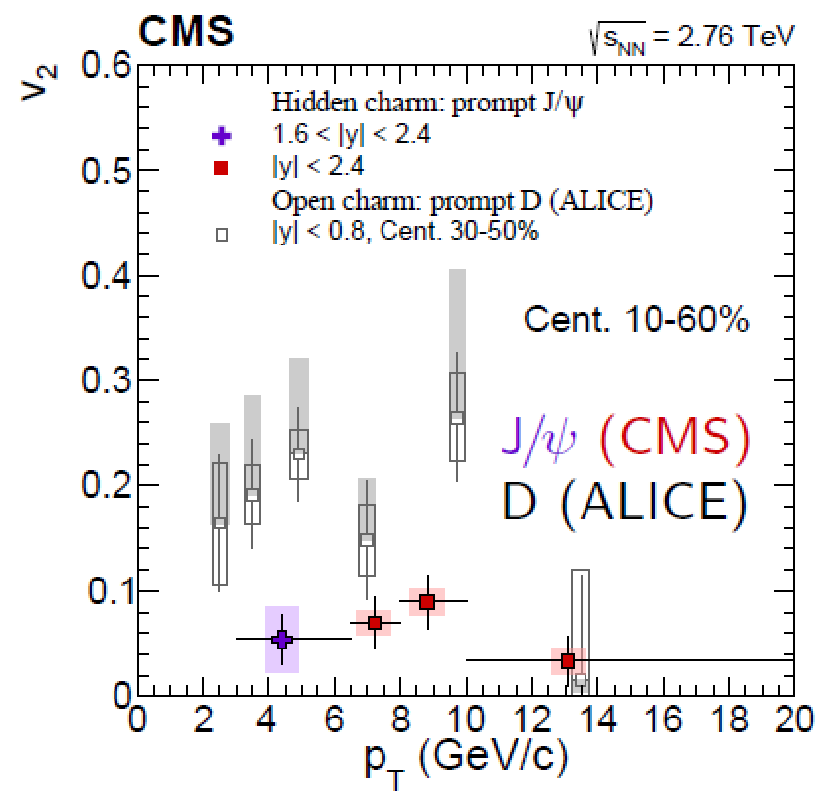
S-U incl.

S-U feed-down corrected

- We are still very far at the LHC! Needed for a quantitative understanding

Comparing R_{AA} and v_2 for closed/open charm





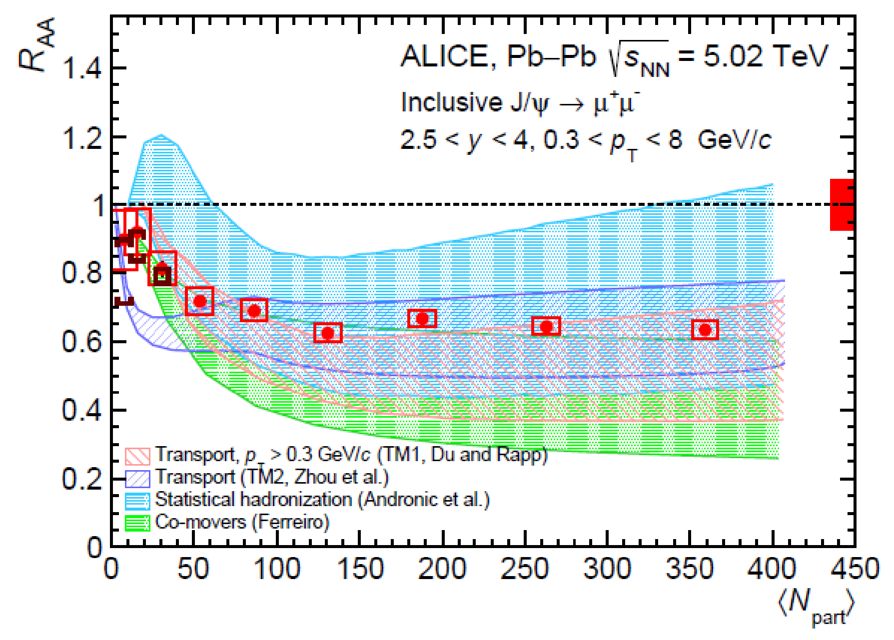
- ❑ CMS final results from HP2016
- ❑ Striking similarity for R_{AA}, v_2 systematically lower for J/ψ
- ❑ Interesting but not trivial comparison (same-p_T comparison can probe different HQ kinematics, …)
- ❑ Need a solid theory support

Low-p_T J/ψ: open questions

- Reasonably good set of data → fundamental to investigate re-combination issues

- Quantitative interpretation made difficult by the significant spread in crucial quantities of the models, such as (√s=5 TeV)

$$(d\sigma/dy)_{cc}\begin{cases}\text{0.42 mb (Statistical, Andronic)}\\ \text{0.57 mb (Transport, Du/Rapp)}\\ \text{0.82 mb (Transport, Zhou et al.)}\\ \text{0.45-0.70 mb (Comover, Ferreiro)}\end{cases}$$



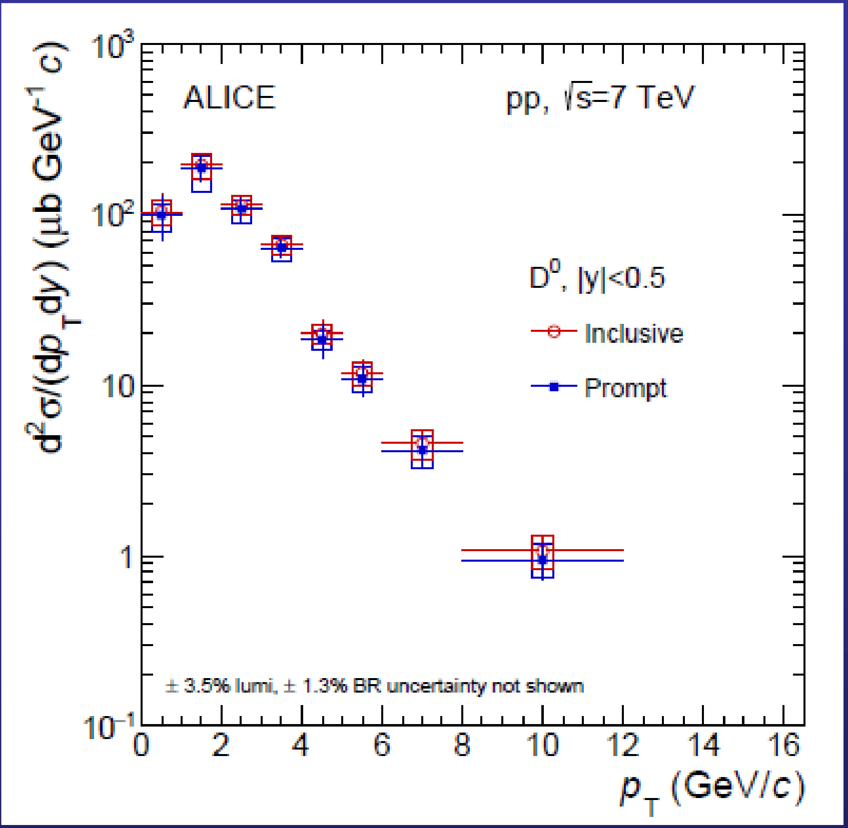
- Recent LHCb estimates (LHCB-CONF-2016-003) suggest values on the low-side of this range (caveat, extrapolation, to be updated with their √s=5 TeV data
- Starting from their

$$\sigma_{D0}(p_T<8\ \text{GeV}/c, 2.5<y<4) = 713 \pm 95(\text{LHCb}) \pm 47(\text{interp.})\ \mu\text{b}$$

one gets

$$(d\sigma/dy)_{cc}=0.44 \pm 0.06(\text{LHCb}) \pm 0.03(\text{interp.}) \pm 0.02(\text{FF})\ \text{mb} = 0.44\pm0.07\ \text{mb}$$

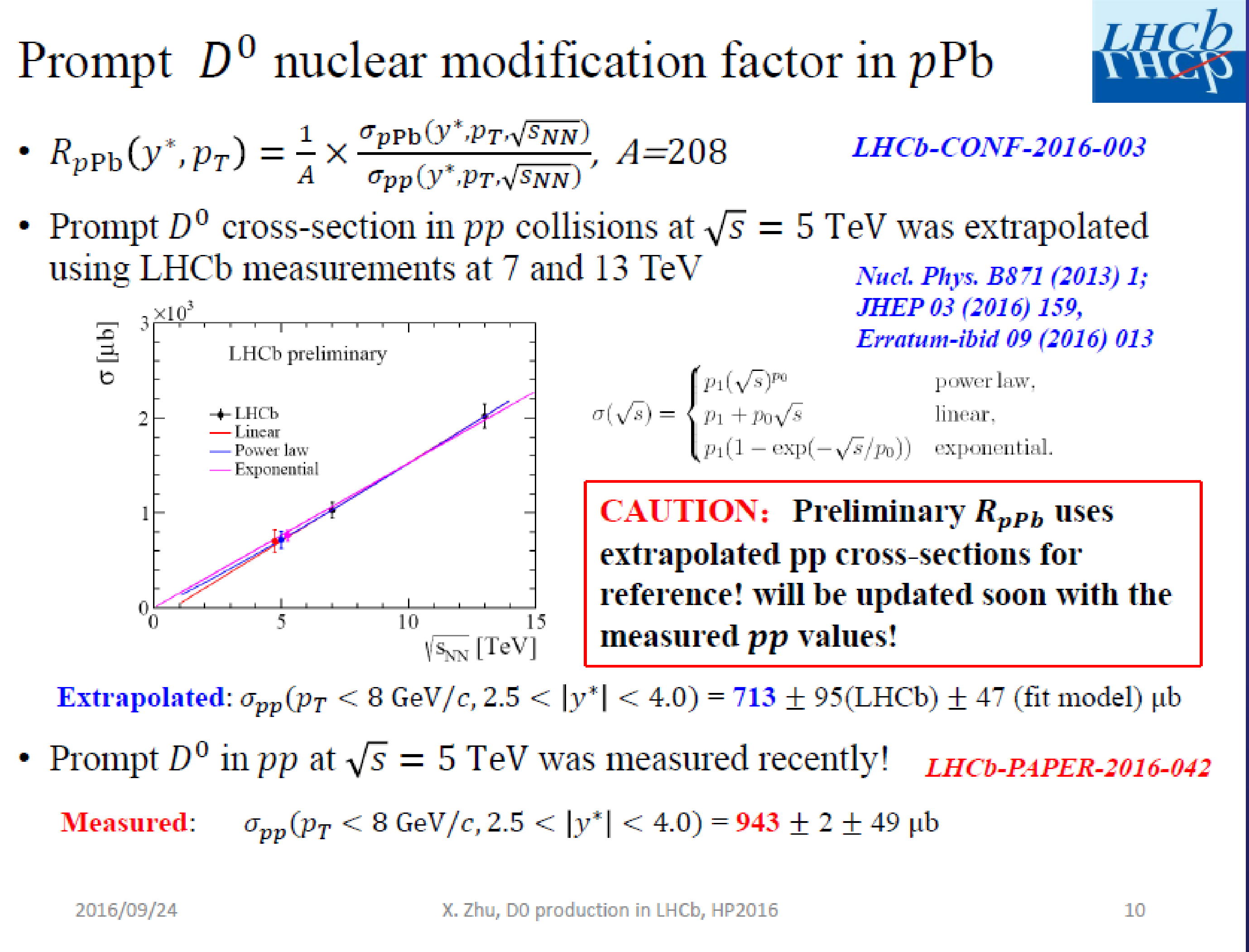
Low-p_T J/ψ: open questions



- Precise measurements of open charm cross section are mandatory
- Best results available today (ALICE, LHCb) have uncertainties of about 20%
- If there is no space for a significant improvement, model uncertainties are not getting smaller
- Theorists, please, agree on using the same input values !

$$d\sigma^{c\bar{c}}_{\mathrm{pp,\,7\,TeV}}/dy = 988 \pm 81\,(\mathrm{stat.})^{+108}_{-195}\,(\mathrm{syst.}) \pm 35\,(\mathrm{lumi.}) \pm 44\,(\mathrm{FF}) \pm 33\,(\mathrm{rap.\,shape})\ \mu\mathrm{b}.$$

- CNM (shadowing) is the other main source of uncertainty (see later)



Prompt D^0 nuclear modification factor in pPb

- $R_{p\mathrm{Pb}}(y^*, p_T) = \frac{1}{A} \times \frac{\sigma_{p\mathrm{Pb}}(y^*, p_T, \sqrt{s_{NN}})}{\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})}$, A=208

LHCb-CONF-2016-003

- Prompt D^0 cross-section in pp collisions at $\sqrt{s} = 5$ TeV was extrapolated using LHCb measurements at 7 and 13 TeV

Nucl. Phys. B871 (2013) 1;
JHEP 03 (2016) 159,
Erratum-ibid 09 (2016) 013

$$\sigma(\sqrt{s}) = \begin{cases} p_1(\sqrt{s})^{p_0} & \text{power law,} \\ p_1 + p_0\sqrt{s} & \text{linear,} \\ p_1(1-\exp(-\sqrt{s}/p_0)) & \text{exponential.} \end{cases}$$

CAUTION: Preliminary R_{pPb} uses extrapolated pp cross-sections for reference! will be updated soon with the measured *pp* values!

Extrapolated: $\sigma_{pp}(p_T < 8\ \mathrm{GeV}/c, 2.5 < |y^*| < 4.0) = 713 \pm 95(\mathrm{LHCb}) \pm 47\ (\text{fit model})\ \mu\mathrm{b}$

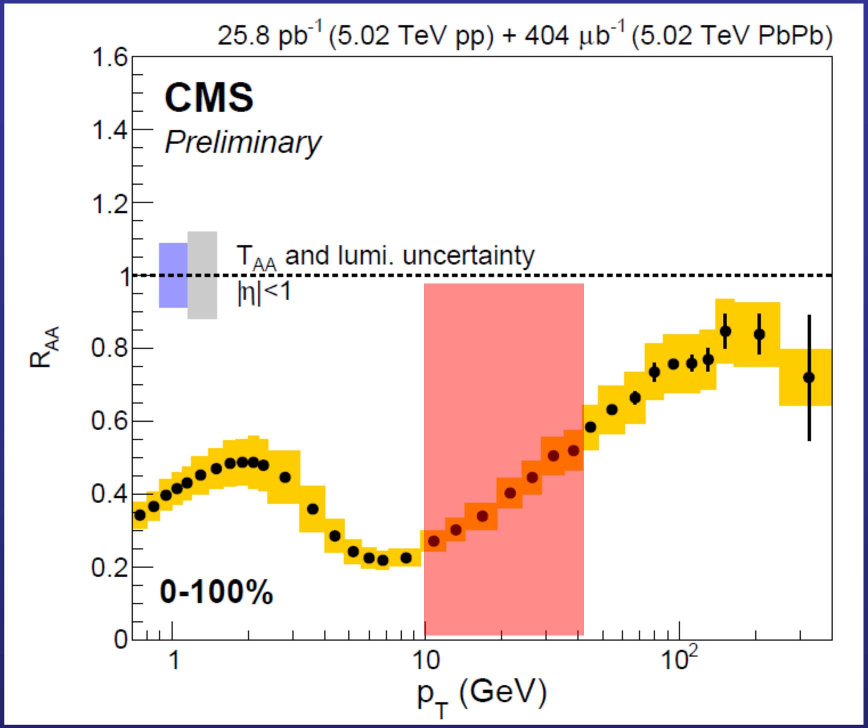
- Prompt D^0 in pp at $\sqrt{s} = 5$ TeV was measured recently! *LHCb-PAPER-2016-042*

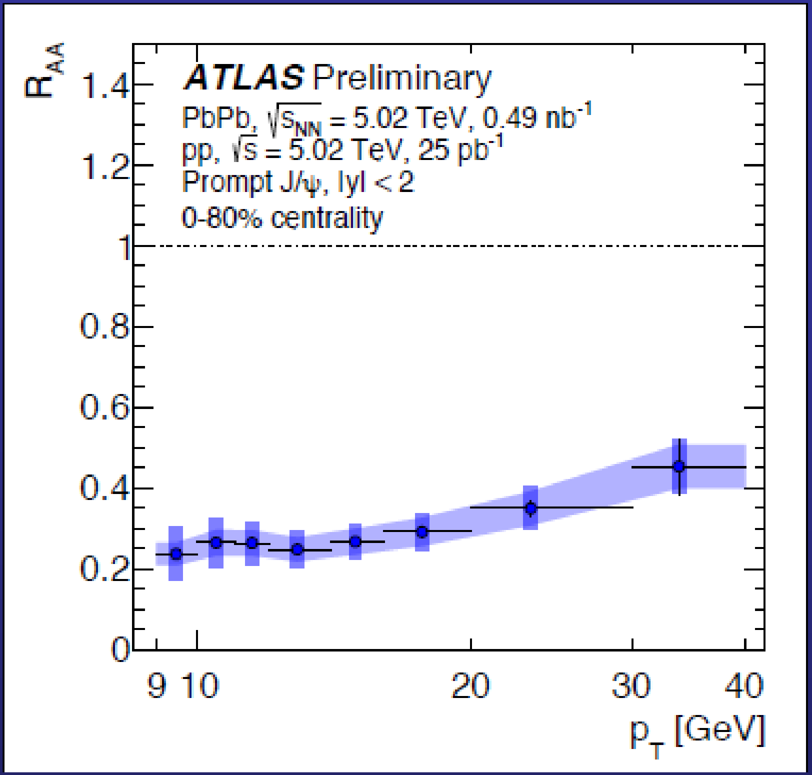
Measured: $\sigma_{pp}(p_T < 8\ \mathrm{GeV}/c, 2.5 < |y^*| < 4.0) = 943 \pm 2 \pm 49\ \mu\mathrm{b}$

2016/09/24 X. Zhu, D0 production in LHCb, HP2016 10

Fresh news → LHCb cross section updated
Brings to $(d\sigma/dy)_{cc}$=0.58 mb, with rather small uncertainties!

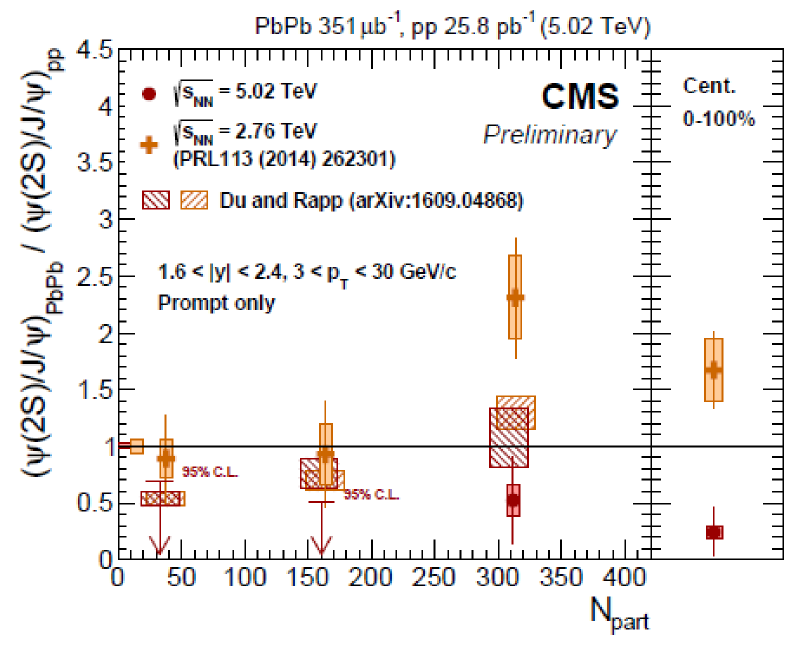
High-p_T J/ψ: CMS (+ATLAS)

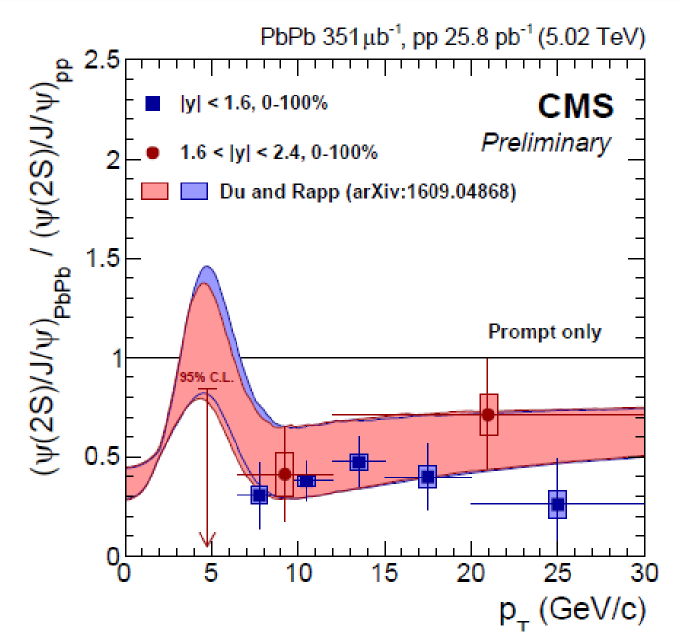


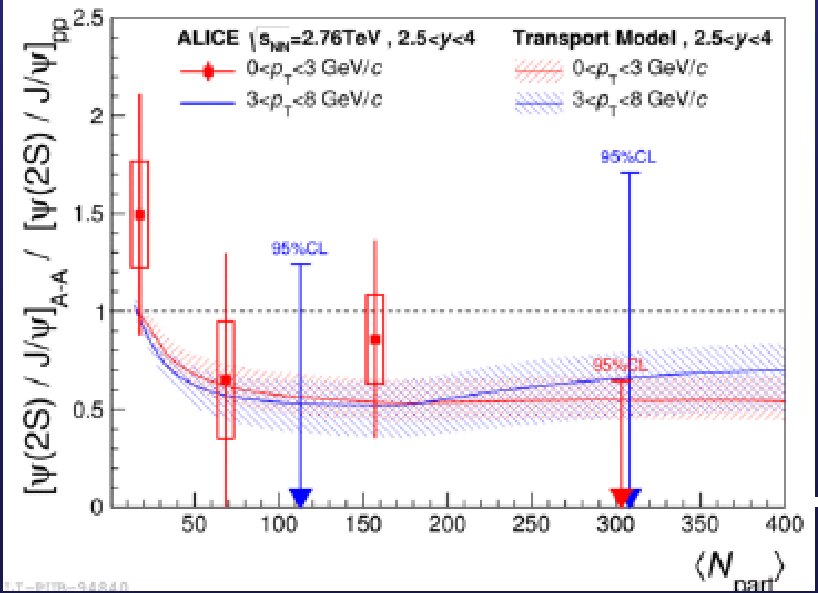


- ❑ Maximum J/ψ suppression, then increase beyond p_T=20 GeV/c
- ❑ Similar behavior as for hadrons ?
- ❑ Is a model description in terms of energy loss needed?
- ❑ Compatibility ATLAS vs CMS: factor~2 more suppression for ATLAS
- ❑ Could it be an effect of the different √s ? Wait for CMS run-2 results

ψ(2S): 5.02 vs 2.76 TeV





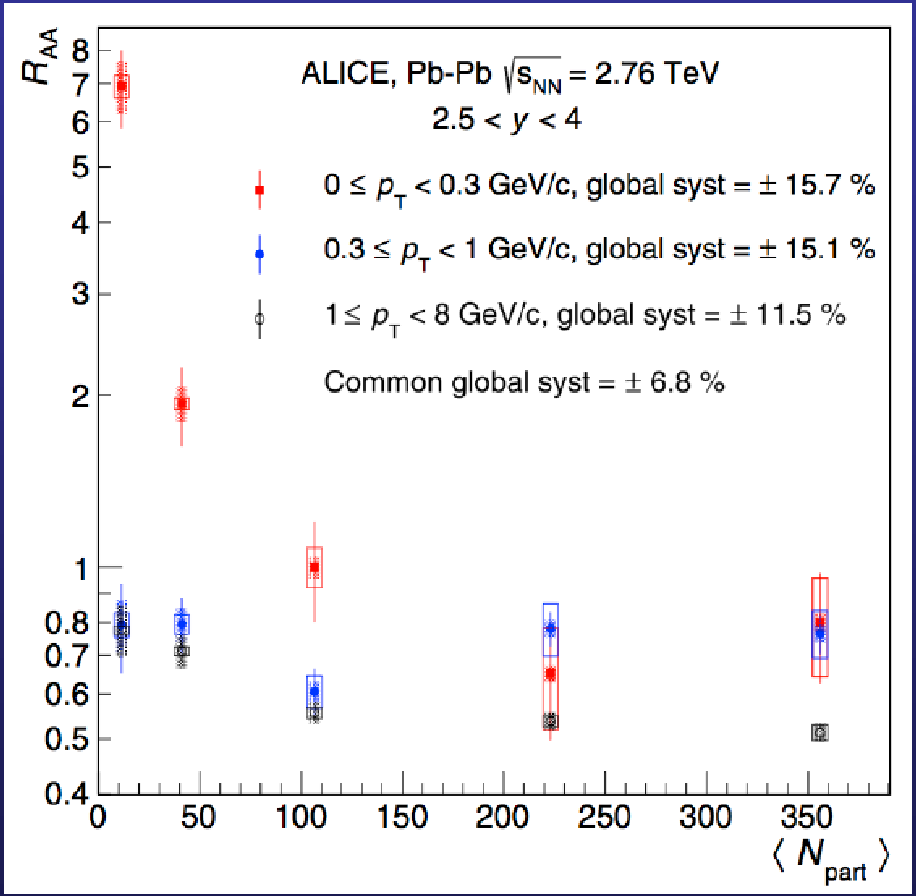


- ❑ ψ(2S) regeneration occurring at higher p_T due to larger flow push
- ❑ Smart ad-hoc explanation for the enhancement at 2.76 TeV, still needed? Debate still open!
- ❑ Quality of ALICE results should improve in run-2 in order to give valuable input

Photonuclear production: LHC

- ❑ A new source of J/ψ in hadronic Pb-Pb collision

→ Low p_T "excess" (huge R_{PbPb} values for p_T<0.3 GeV/c)



- ❑ Likely due to photoproduction in events with b>2R (recently observed at RHIC too!)

- ❑ ~75% of the signal expected for p_T<0.3 GeV/c
- ❑ ALICE peripheral R_{AA} lowers by max 20% when photoproduction removed

- ❑ At the same time
  - → A "background" for hadronic R_{PbPb} studies (anyway concentrated in peripheral events, where theory calculations are less reliable)
  - → A "signal" of a known process in a "non-standard" environment

If under theory control, could it be used as a probe of hot matter ?

Cold nuclear matter: the J/ψ

- ❑ Originally studied (pA collisions) as a mean to calibrate cold nuclear matter effects for hot matter studies (in particular for quarkonia!)

- ❑ Gradually emerged as a field of its own

- ❑ Older descriptions in terms of nuclear matter absorption, parametrized through a single effective parameter $\sigma_{\psi N}$, refined adding more and more effects

- ❑ SPS energy → nuclear absorption (effective)
- ❑ RHIC energy → nuclear absorption + shadowing
- ❑ LHC energy → ~~nuclear absorption~~ + shadowing/CGC + energy loss + comovers + ….

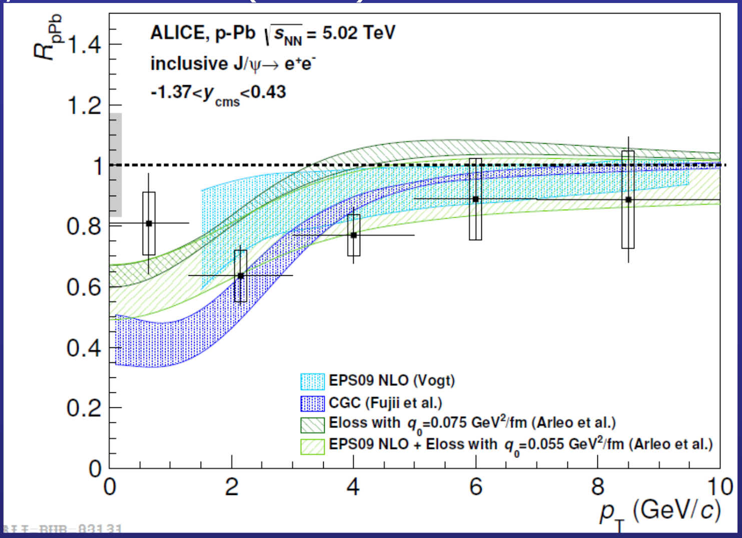
Resonable set of results available (more to come soon)
→ Enough to go beyond the qualitative comparison data/models ?

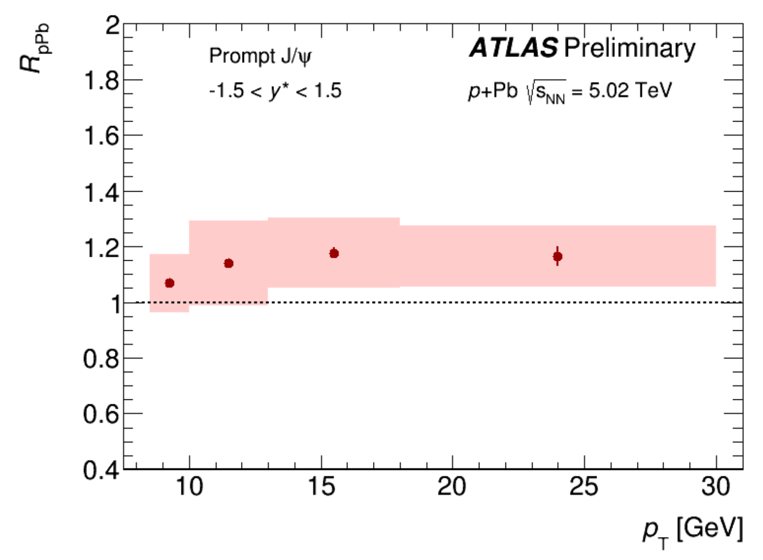
J/ψ R_{pPb}: ATLAS “vs” ALICE “vs” LHCb

- ❑ R_{pPb} vs p_T at y~0 → fair agreement ALICE vs ATLAS (extends to high p_T)

ALICE, JHEP 1506 (2015) 055

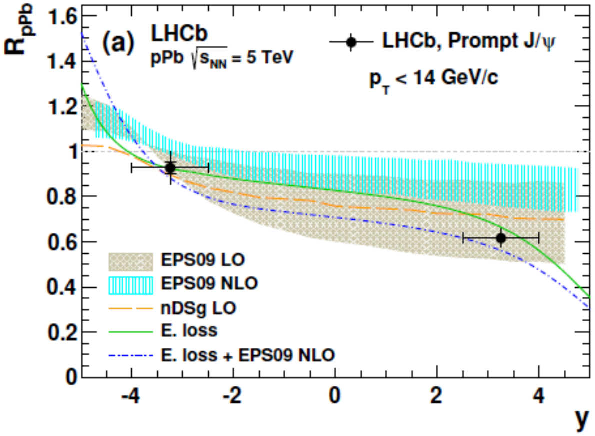
ATLAS-CONF-2015-023

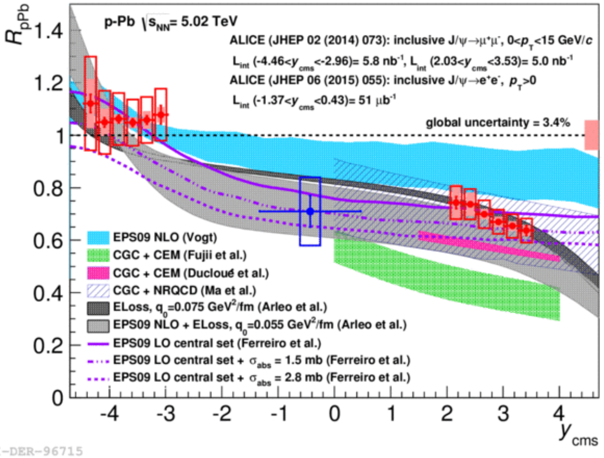


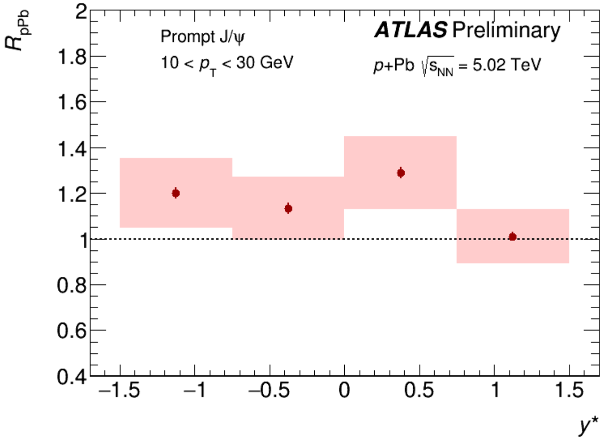


- ❑ R_{pPb} vs y → fair agreement ALICE vs LHCb, ATLAS refers to p_T>10 GeV/c

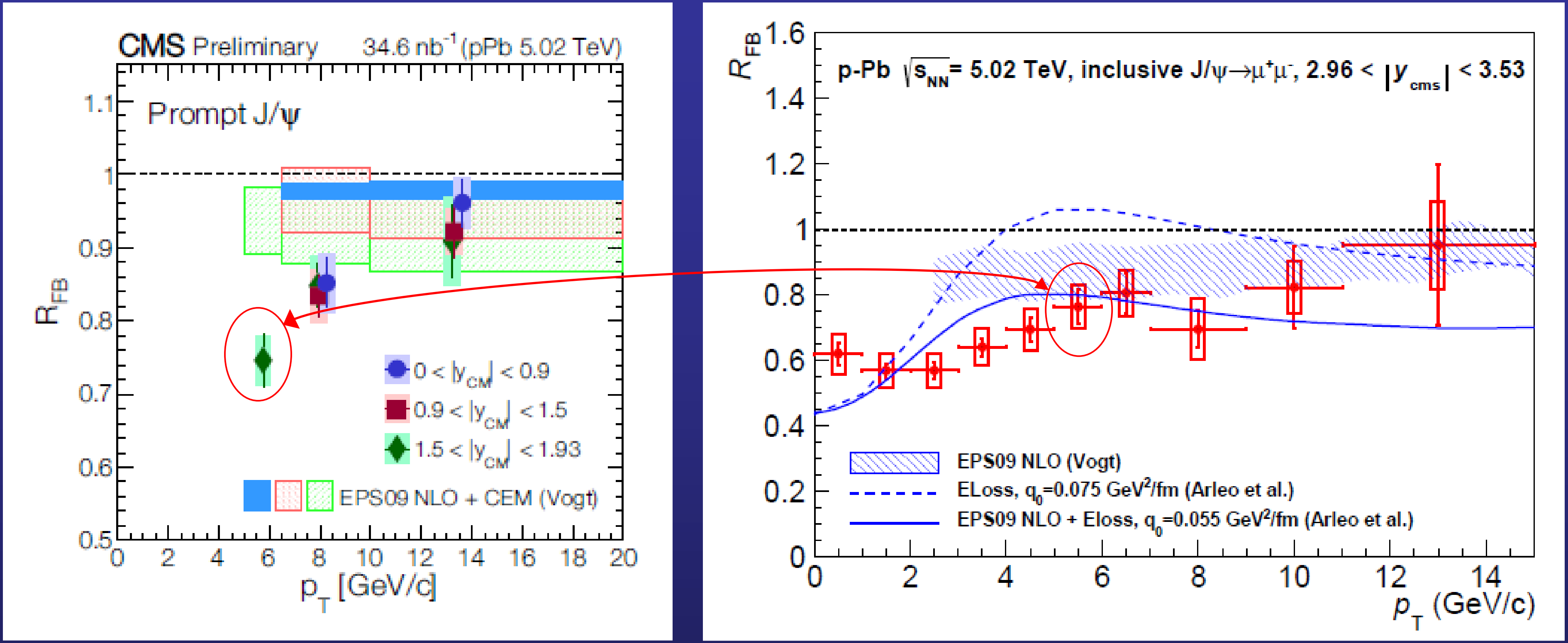
LHCB, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73







R_{FB} from CMS



- ❑ Comparing R_{FB} from ALICE and CMS
- ❑ Good compatibility at forward y (slightly more forward for ALICE)
- ❑ Check shadowing (y-effect or different calculation?)
- ❑ R_{FB} pros/cons: reduced uncertainties vs less sensitivity to models

CNM effects: from p-Pb to Pb-Pb

- x-values in Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $2.5<y_{cms}<4$ $\left\{ \begin{array}{l} 2\cdot10^{-5} < x < 9\cdot10^{-5} \\ 1\cdot10^{-2} < x < 6\cdot10^{-2} \end{array} \right.$

- x-values in p-Pb $\sqrt{s_{NN}}=5.02$ TeV, $2.03 < y_{cms} < 3.53$ → $2\cdot10^{-5} < x < 8\cdot10^{-5}$
- x-values in p-Pb $\sqrt{s_{NN}}=5.02$ TeV, $-4.46 < y_{cms} < -2.96$ → $1\cdot10^{-2} < x < 5\cdot10^{-2}$

→ Partial compensation between $\sqrt{s_{NN}}$ shift and y-shift

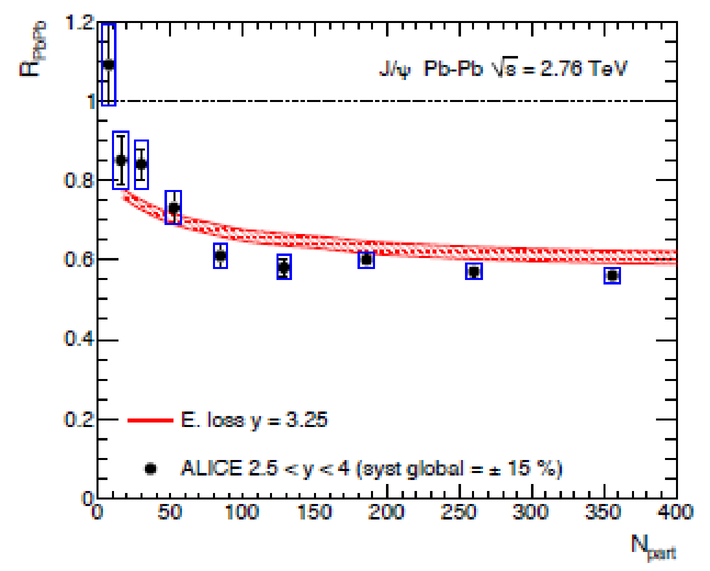
- If CNM effects are dominated by shadowing
  - $R_{PbPb}^{CNM} = R_{pPb} \times R_{Pbp} = 0.75 \pm 0.10 \pm 0.12$
  - $R_{PbPb}^{meas} = 0.57 \pm 0.01 \pm 0.09$

} "compatible" within 1-σ

- Same kind of "agreement" in the energy loss approach (Arleo)

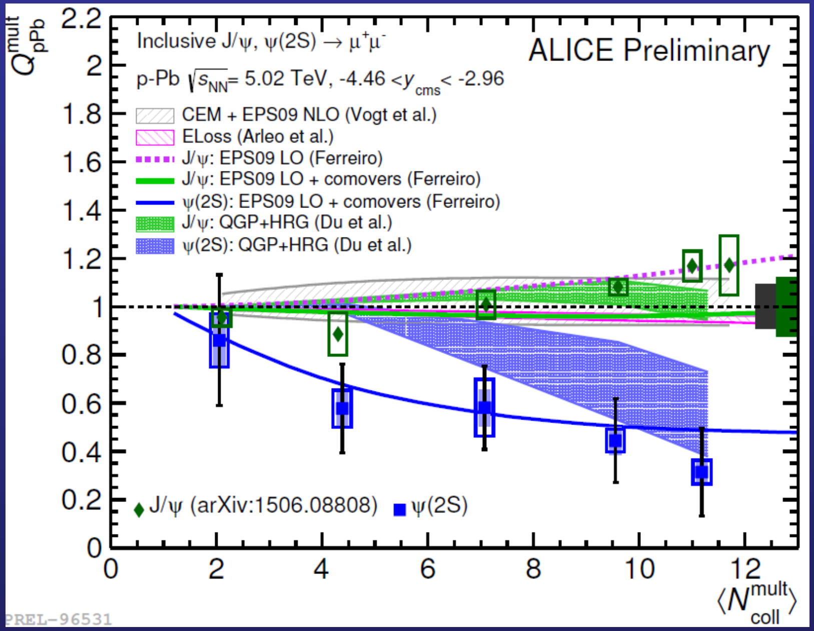
  …which does not exclude hot matter effects which partly compensate each other

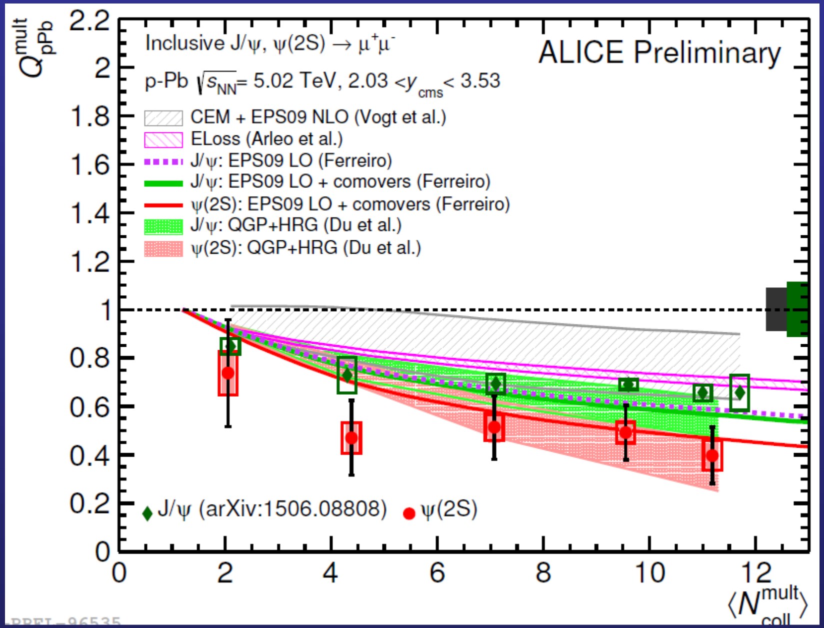
F. Arleo and S. Peigne, arXiv:1407.5054



Cold nuclear matter: the $\psi(2S)$

- In principle should be affected by CNM in the same way as the J/ψ
- Formation times should prevent any "nuclear absorption"
- Shadowing/energy loss cancel, at least at first order

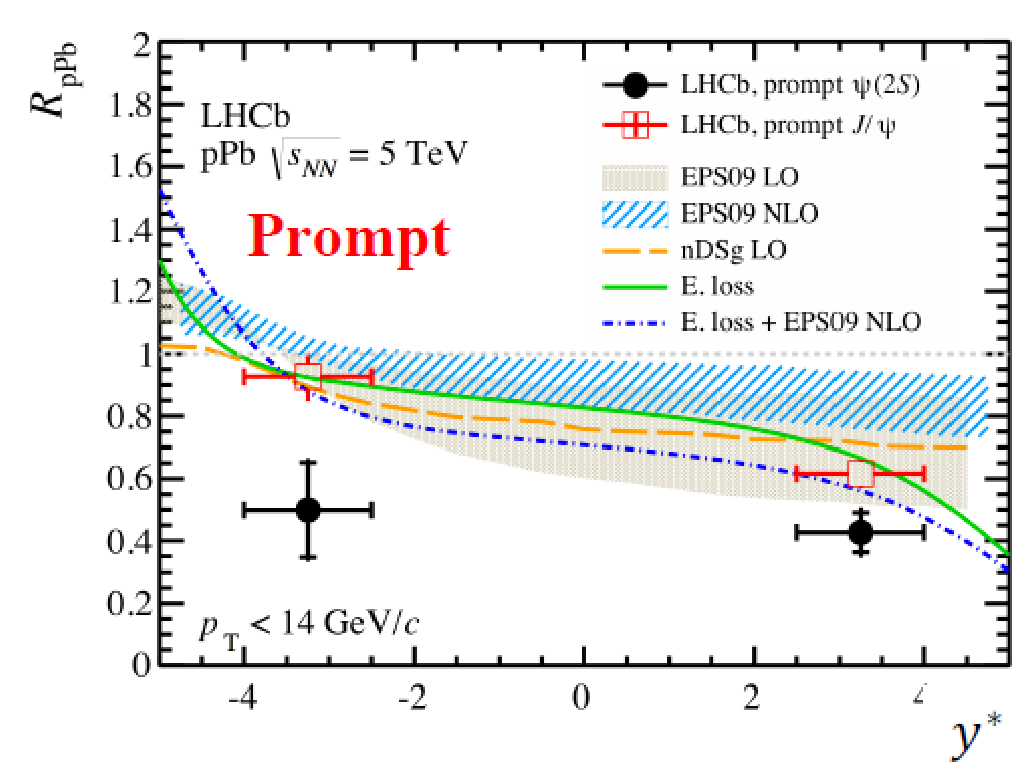




- Results show a (much) stronger $\psi(2S)$ suppression
- Not a "real" surprise, already seen by PHENIX even if with large uncertainties
- Very strong rapidity dependence, compatible with an effect related with the hadronic activity (not so strange, seen the weak binding)

Cold nuclear matter: the ψ(2S)

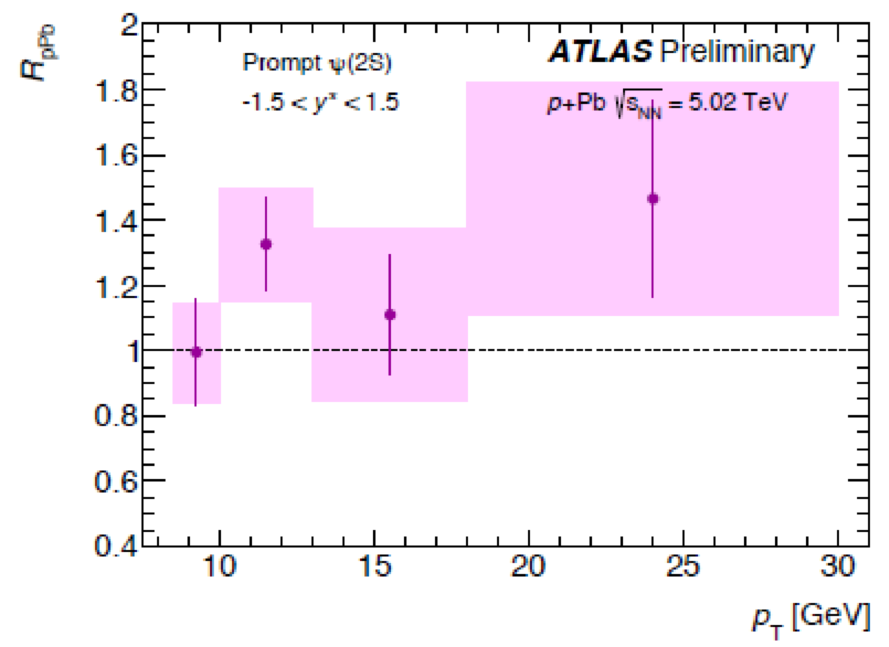
- ❑ In principle should be affected by CNM in the same way as the J/ψ
- ❑ Formation times should prevent any "nuclear absorption"
- ❑ Shadowing/energy loss cancel, at least at first order

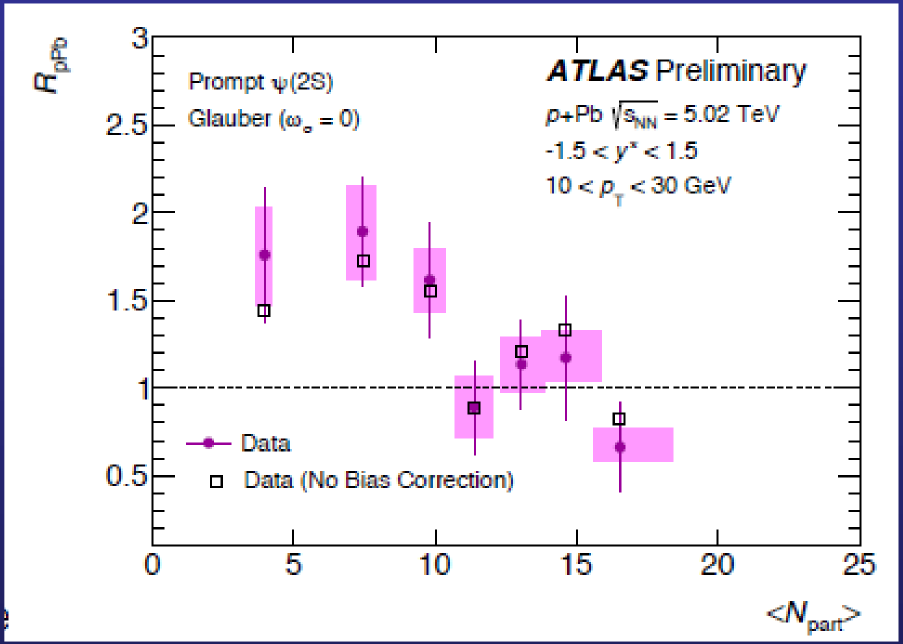


Nicely confirmed by LHCb!

ATLAS on ψ(2S) in p-Pb

- ☐ High p_T, rather large uncertainties
- ☐ Hints for strong enhancement, concentrated in peripheral events

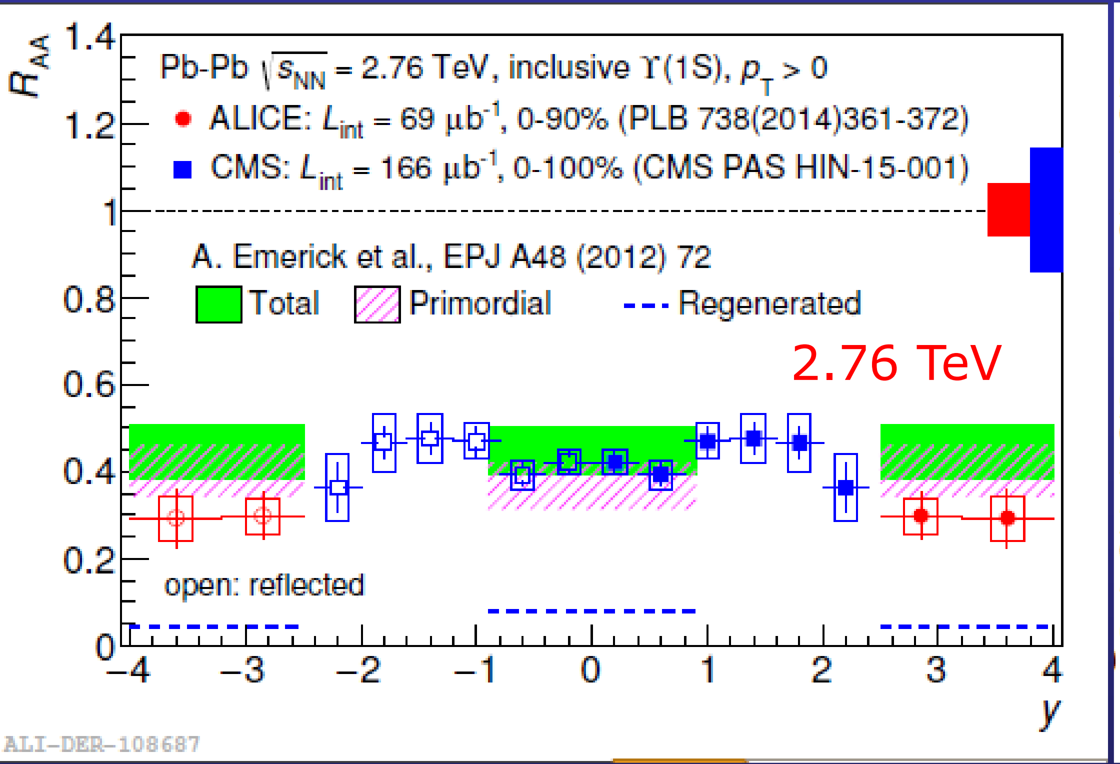


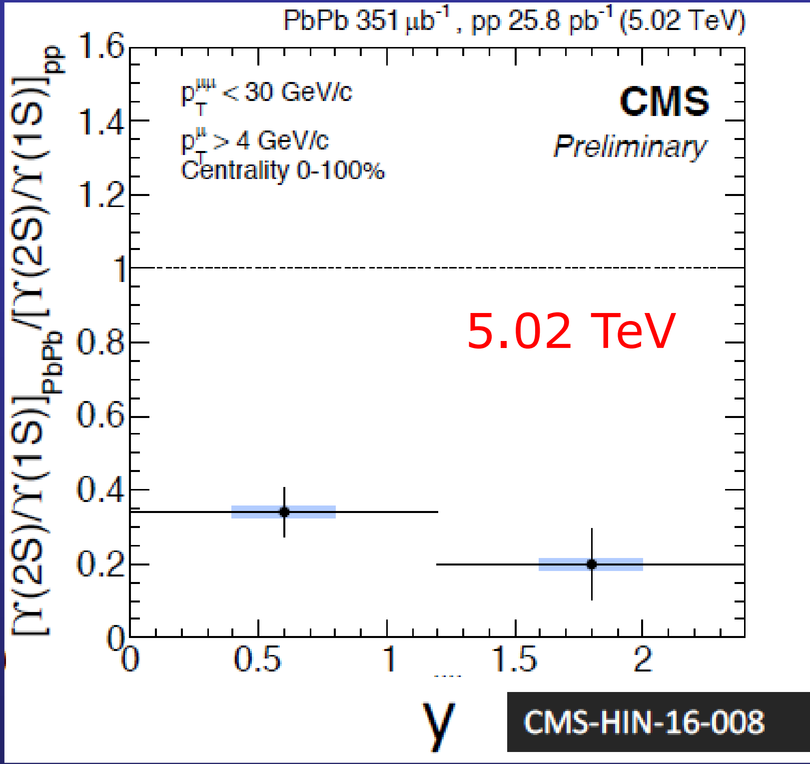


ATLAS-CONF-2015-023

- ☐ Possible tension with ALICE results (sees $R_{pPb} < 1$ at forward-y up to p_T= 8 GeV/c), even if it is difficult to conclude
- ☐ Issues with the centrality assignment ?

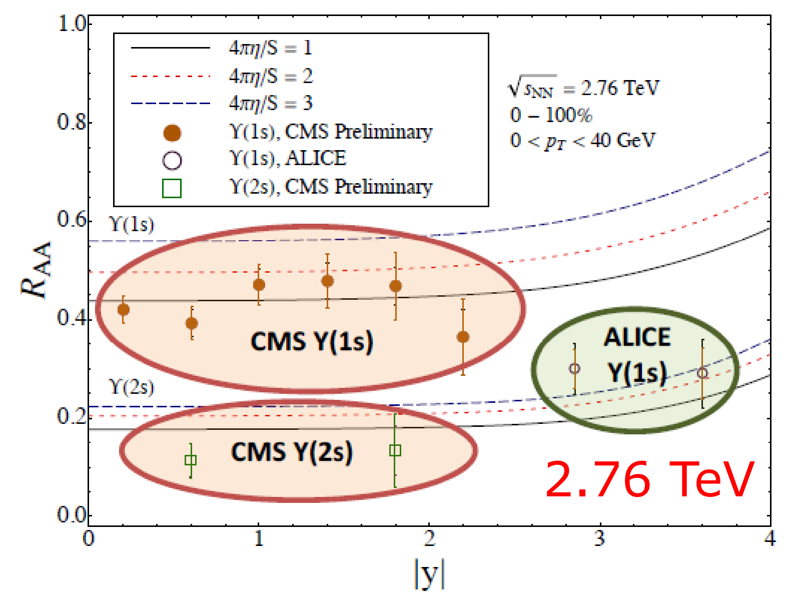
R_{AA} vs y

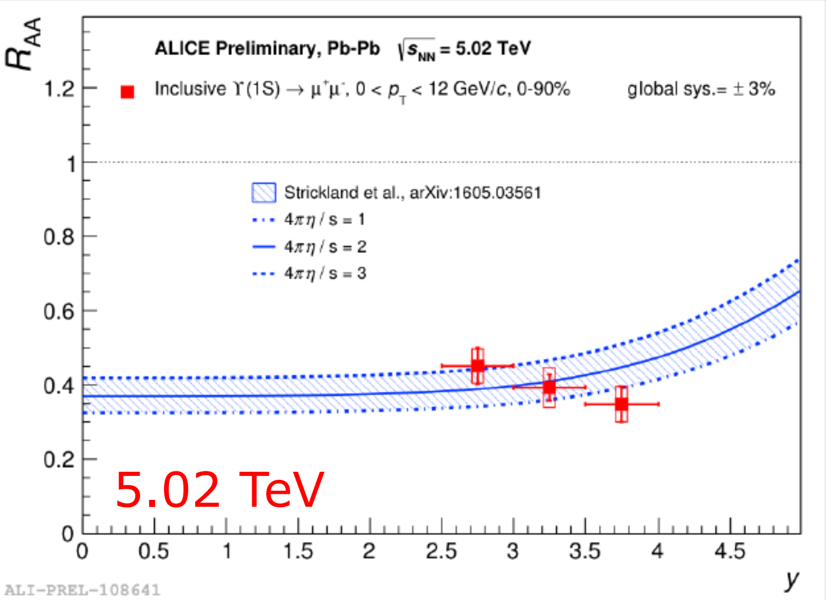


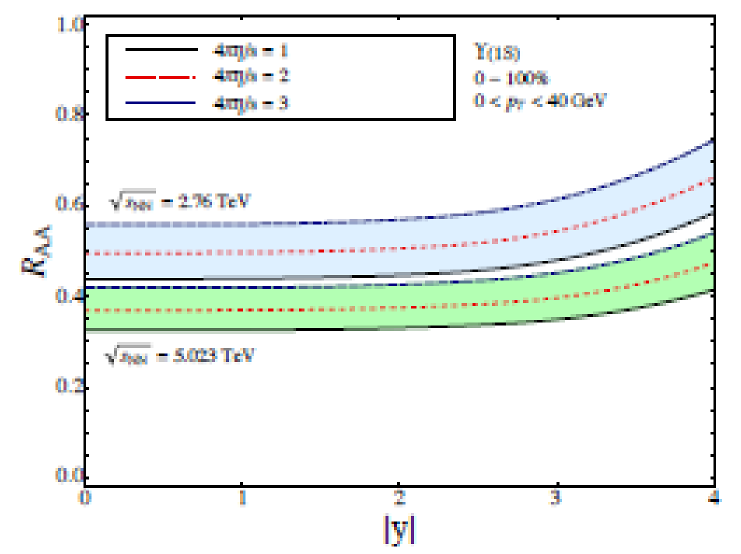


- ❑ Both the y-dependence of ϒ(1S) at 2.76 TeV and ϒ(2S) at 5 TeV "seriously" remind a recombination pattern. Transport models hardly catch the y-dependence
- ❑ N.B., also here we are still at the level of consistency within uncertainties

R_{AA} vs y







- Strickland's approach: model early time dynamics, complex potential,..
- Catches the main features of the results but
  - → misses y-dependence
  - → predicts smaller R_{AA} at 5 TeV wrt 2.76 TeV
  - → reproduces 5 TeV data but with a different tendency

The comovers are back again

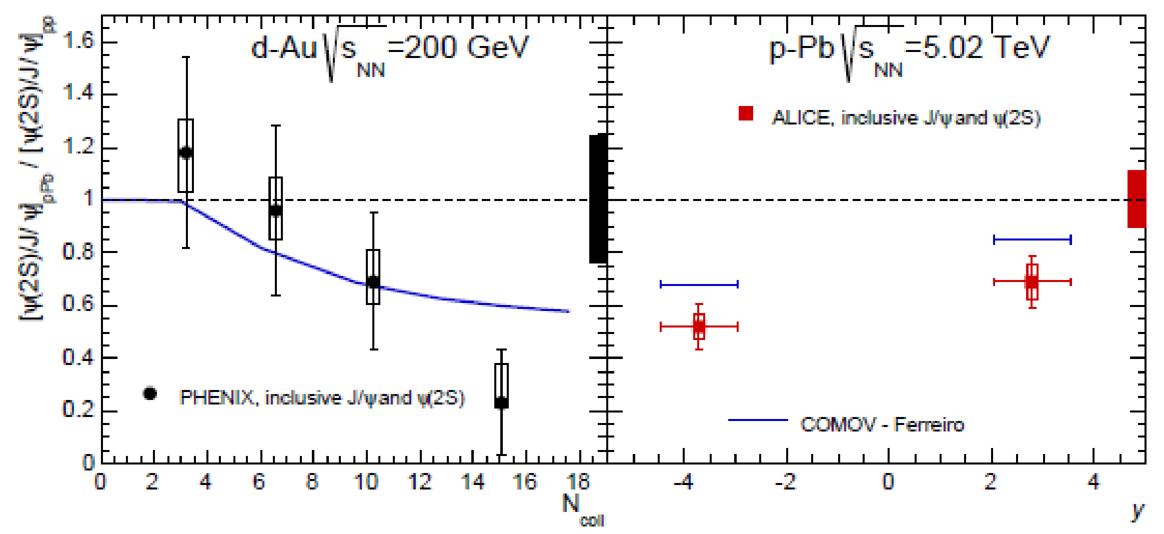
☐ A subject of "epic" battles in the '90s (comovers vs QGP!)
☐ Entered a "dormant" state in RHIC years, now re-proposed for the Υ

☐ Old survival probability formula

$$S_Q^{co}(b,s,y) = \exp\left\{-\sigma^{co-Q}\,\rho^{co}(b,s,y)\,\ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

which gave fair results at SPS with $\sigma^{co\text{-}J/\psi}$=0.65 mb and $\sigma^{co\text{-}\psi(2S)}$=6 mb

☐ Also does well at RHIC and LHC (2S/1S ratio), same parameters (?!)

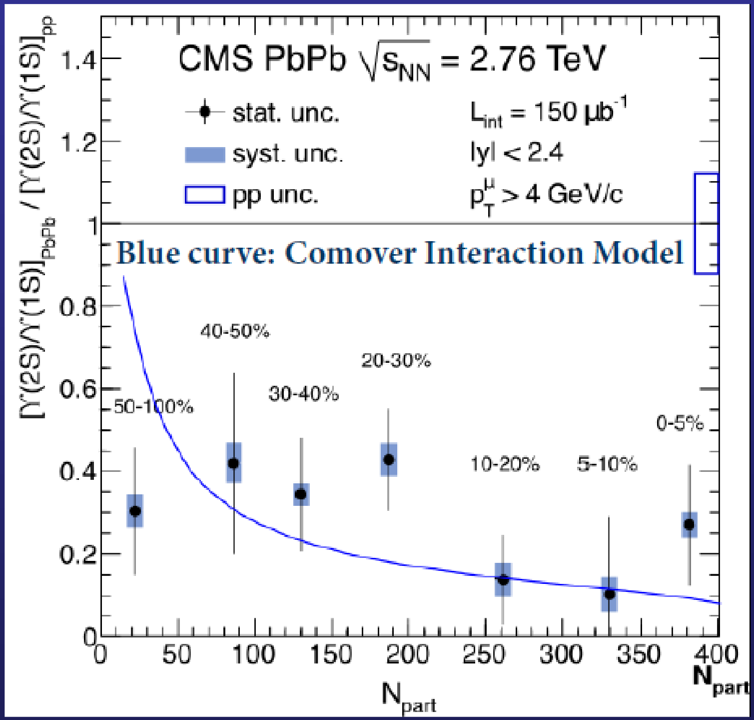


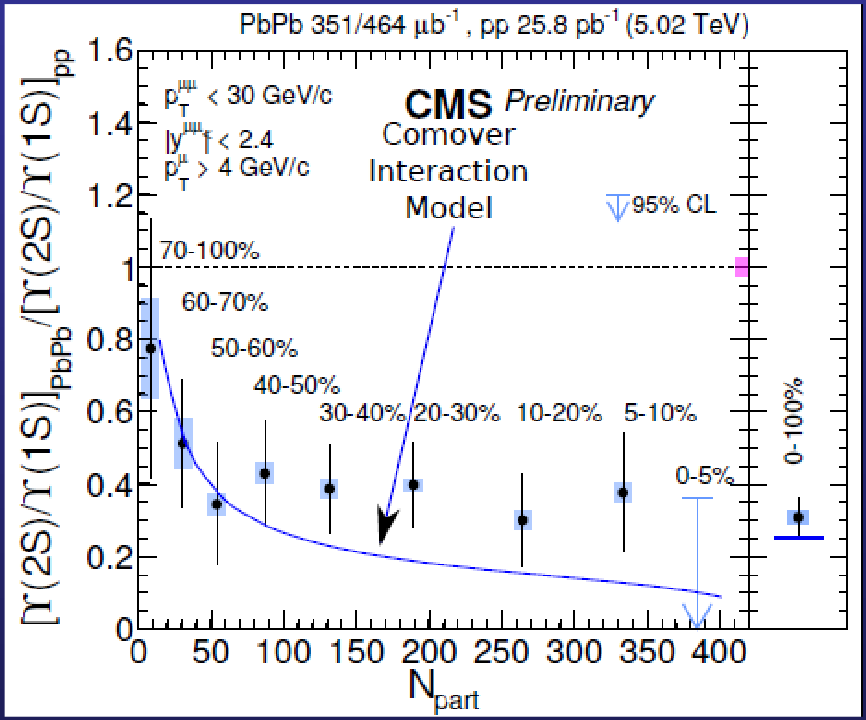
p-Pb only!

The comovers are back again

- ☐ Refining the comover cross section (and fixing parameters on CMS double ratios for pPb)

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





- ☐ (Surprisingly), a qualitative agreement is found
- ☐ Is the physics of bottomonia simply “driven” by $dN_{ch}/d\eta$??