Quarkonium production in Pb-Pb collisions at the LHC

E. Scomparin (INFN-Torino)

INT Program INT-17-1b
Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks
May 1 - June 8, 2017

- LHC run 1 and (vs) run 2 → results, success and open problems

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A long journey, from SPS to LHC (via RHIC)

5.02

2.76

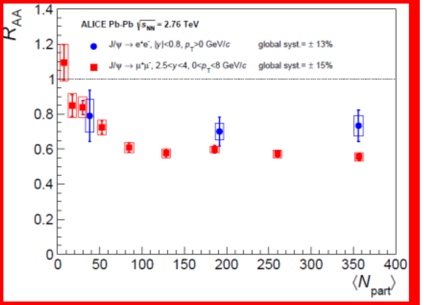
0.02

0.039

0.017

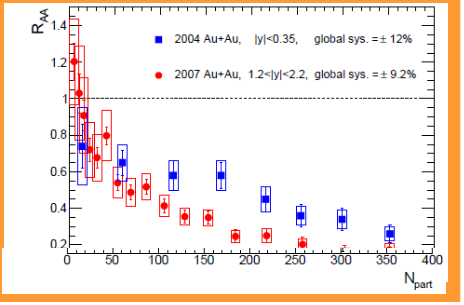
LHC

ALICE
ATLAS
CMS
LHCb



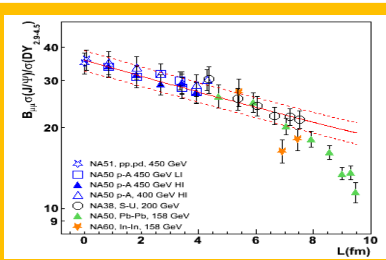
RHIC

PHENIX
STAR



SPS

NA38
NA50
NA60



1986 2000 2009 2017

A short historical timeline

- Lessons from the past
  - '80s: The original "promise" of quarkonium as a QGP signature
    → a simple and model-independent observable
  - '90s: high statistics data from the SPS, progress in phenomenology
    → the "QGP" vs "comovers" saga
  - '00s: Enter RHIC, the QGP does not melt the J/ψ → crisis
    → suppression vs recombination

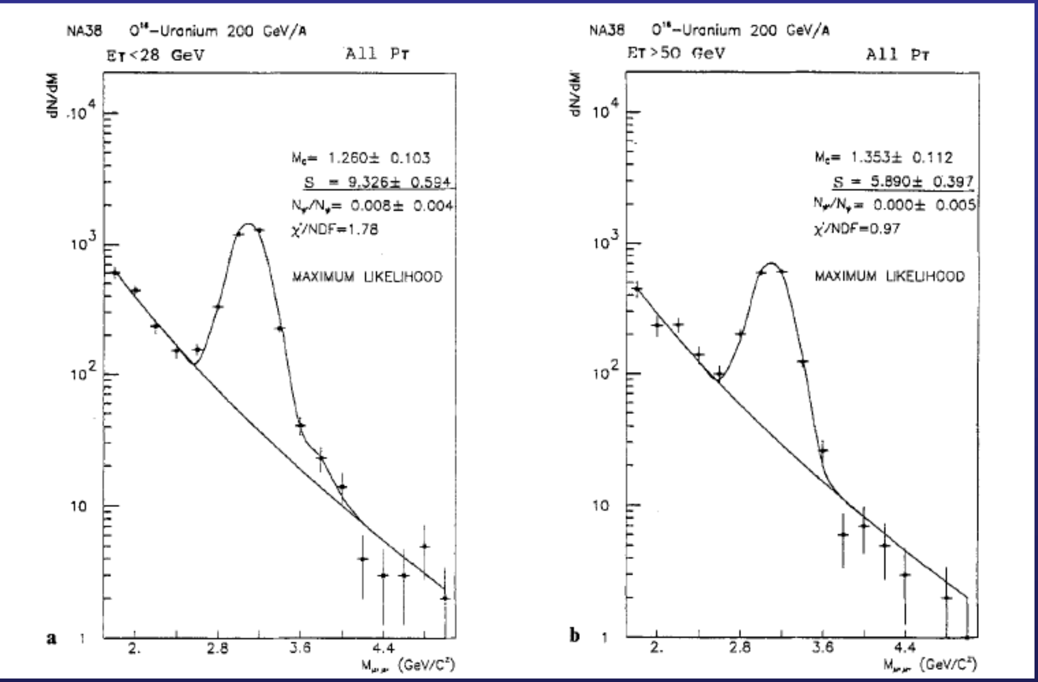
- Have LHC results improved our understanding of quarkonium vs QGP ?
  - '10s: "precision" data from the experiments
    → the bottomonium "revolution": back to the original vision ?
    → regeneration of charmonia: a new/different probe of QGP ?
  - '15s: LHC hits the top
    → more accurate data?
    → $\sqrt{s_{NN}}$ dependence?

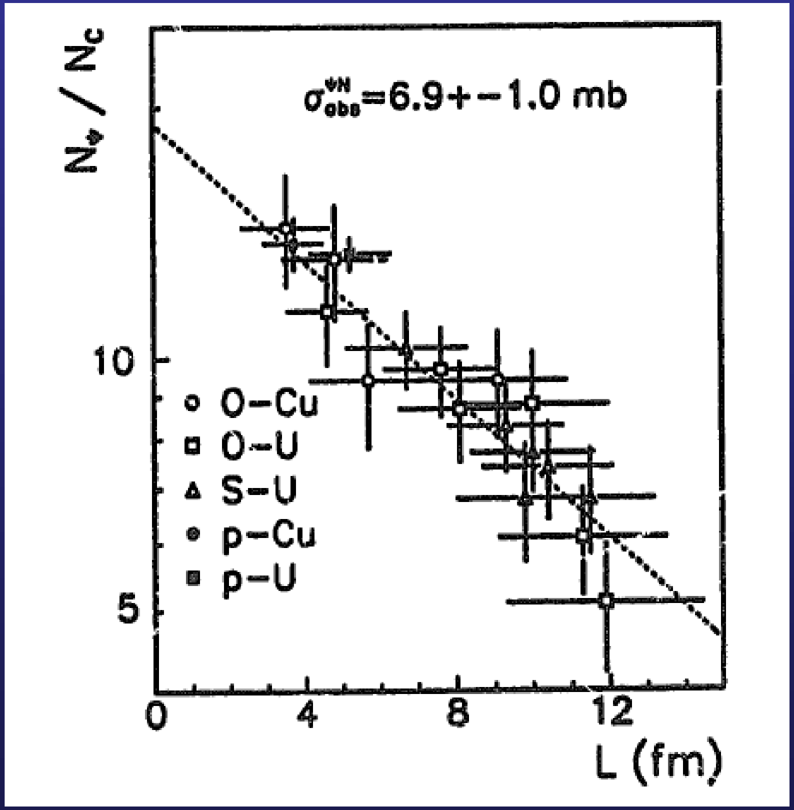
- Future measurements at the LHC
  - '20s: LHC run-3, run-4,…
    → can we access more rare probes ?

SPS, discovery of J/ψ suppression

"The history of quarkonia suppression as a "well calibrated smoking gun" for deconfinement can best be summarized as long and tortured…"
(J. Schukraft, QM2017)

1987: suppression seen in O-U (and then in S-U)

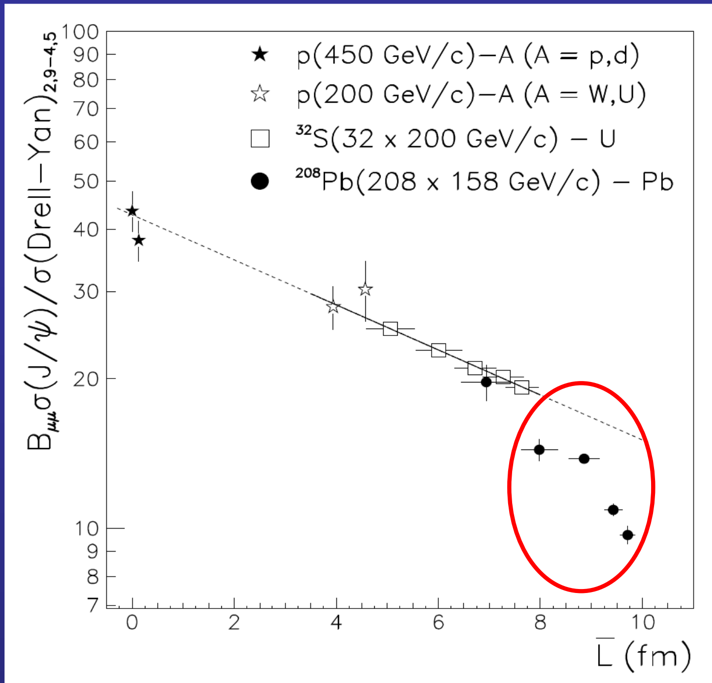




1992: suppression compatible with CNM

C. Gerschel and J. Huefner, Z. Phys. C 56 (1992) 71

Anomalous J/ψ suppression

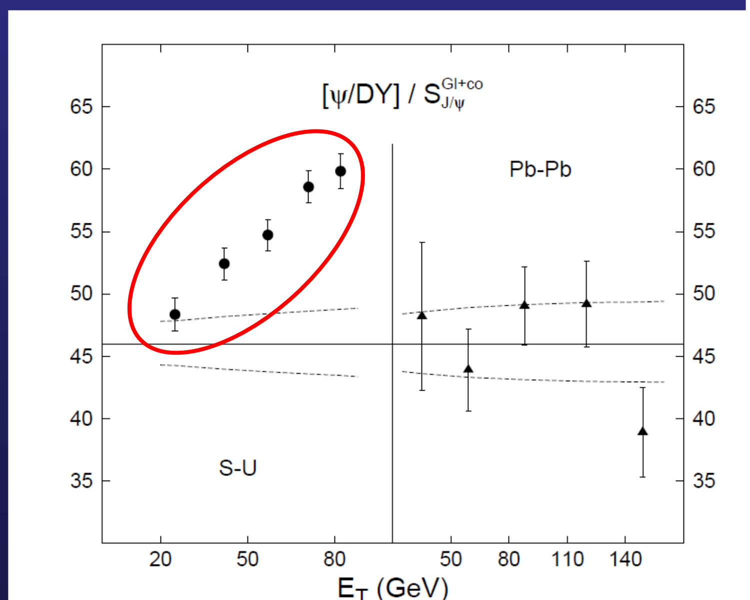


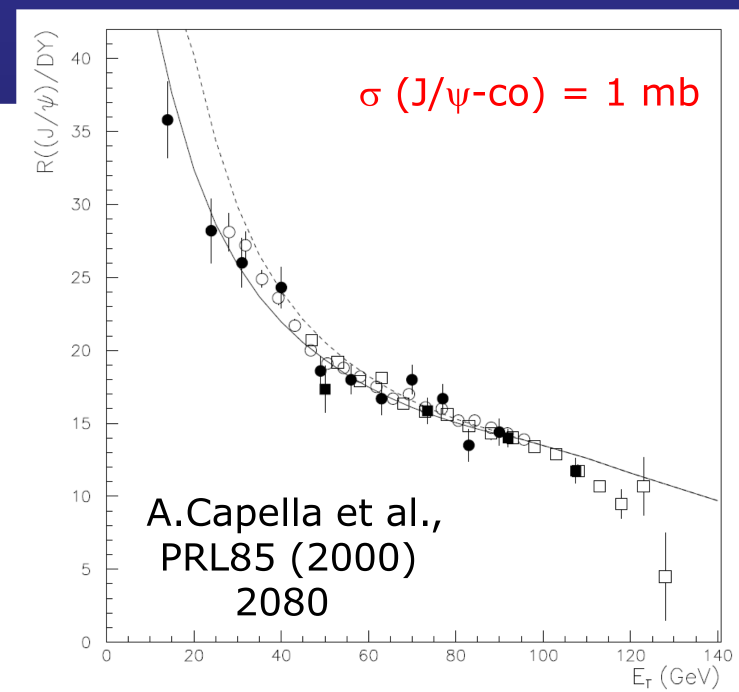
- **1996**:"anomalous" J/ψ suppression in Pb-Pb collisions (ψ/DY ratio)
- A signal of QGP or "simply" an effect of the (dense) hadronic phase?

The "comover" intepretation

The "QGP" interpretation

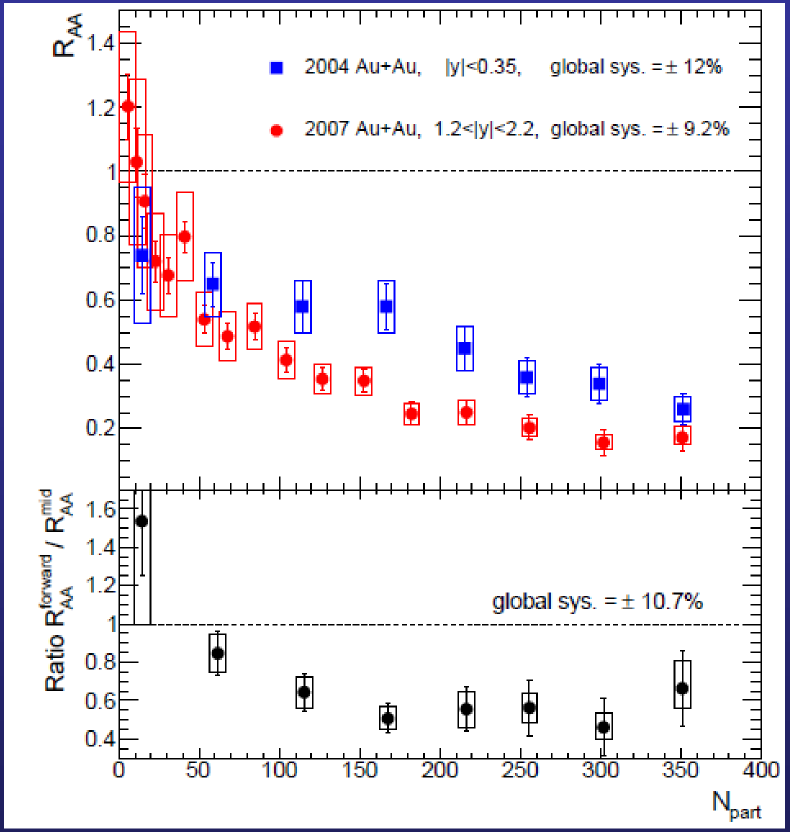
D.Kharzeev et al., Z. Phys.C74 (1997) 317

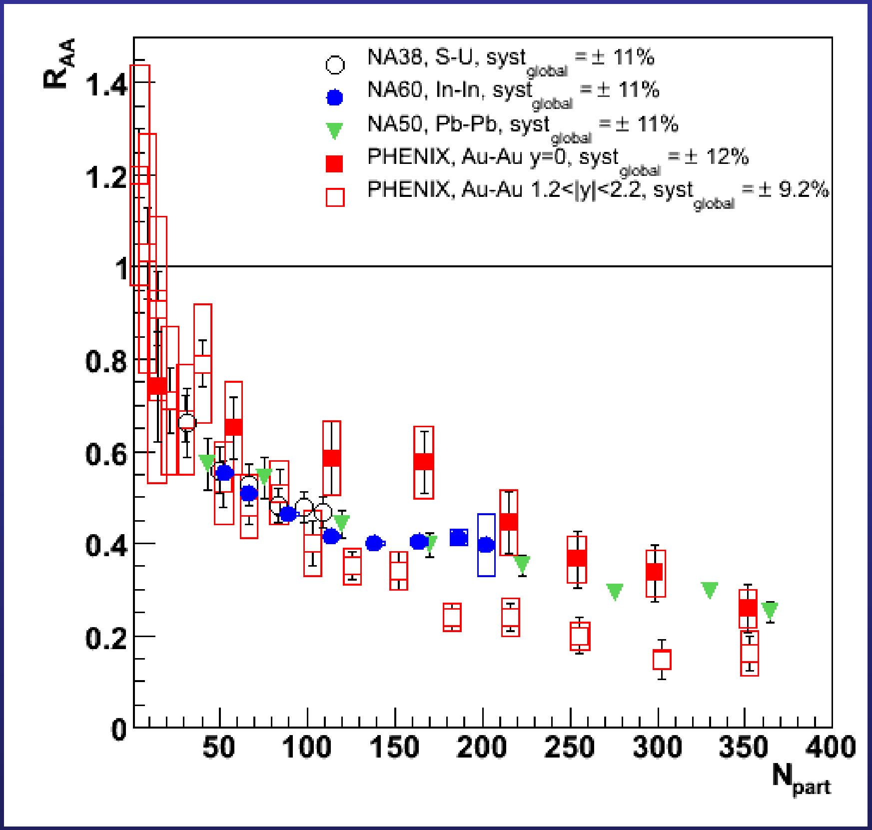




RHIC (vs SPS)

Here a quick look, to put LHC results into context → more in Zebo's seminar!





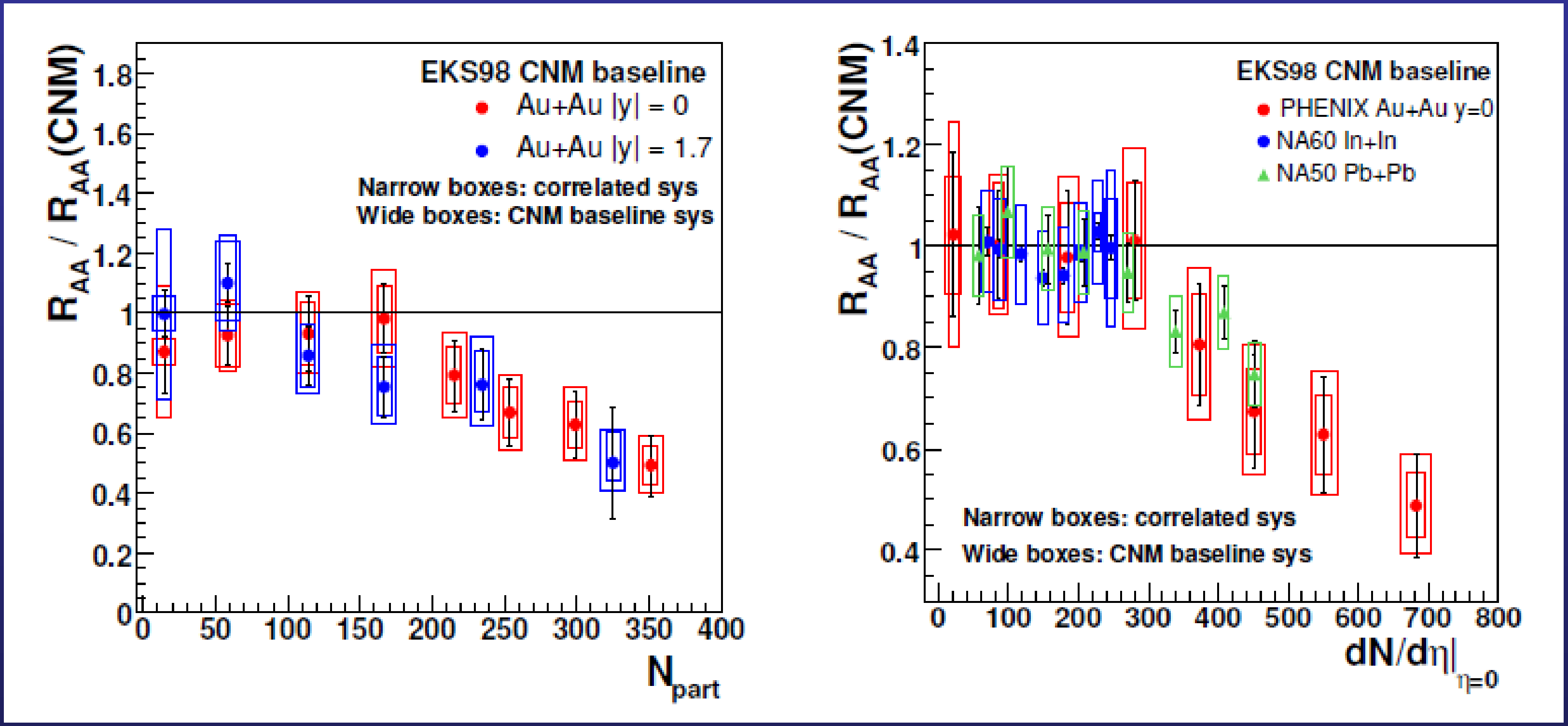
- ❑ **Suppression,** with strong **rapidity dependence**, in Au-Au at √s= 200 GeV
- ❑ Roughly **same suppression** at **SPS** and **RHIC** energy

Hints for **recombination** → evidence ?

Low energy results: J/ψ from SPS & RHIC

- Comparison of SPS and RHIC results

N.Brambilla et al. (QWG) EPJC71 (2011) 1534

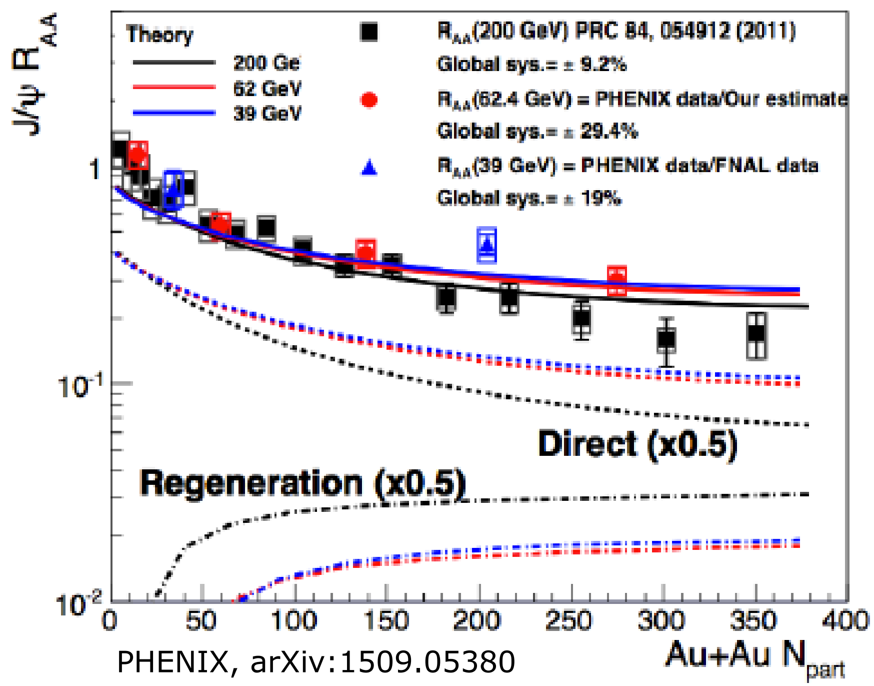


- Good agreement between SPS and RHIC patters if cold nuclear matter effects are taken into account

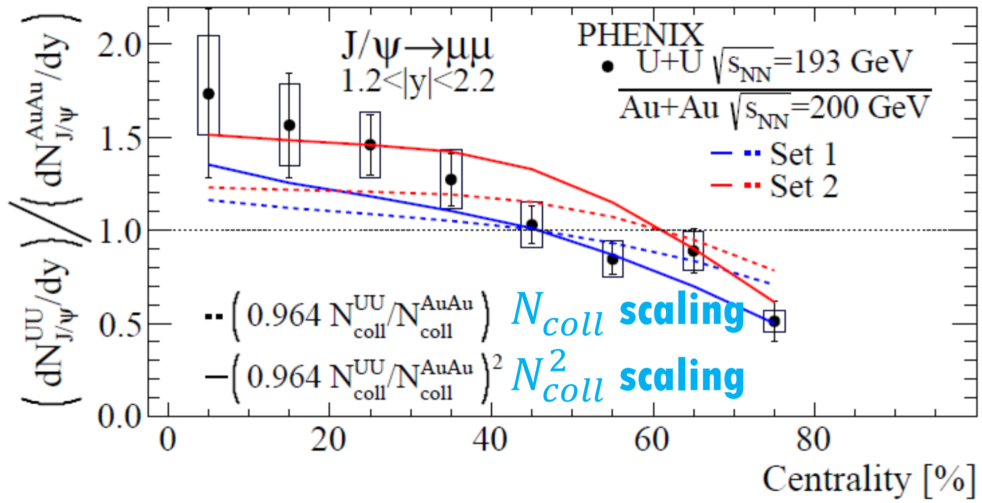
  → **Compensation of suppression/recombination effects?**

- Understanding cold nuclear matter effects and feed-down is essential for a quantitative assessment of charmonium physics

RHIC, more results



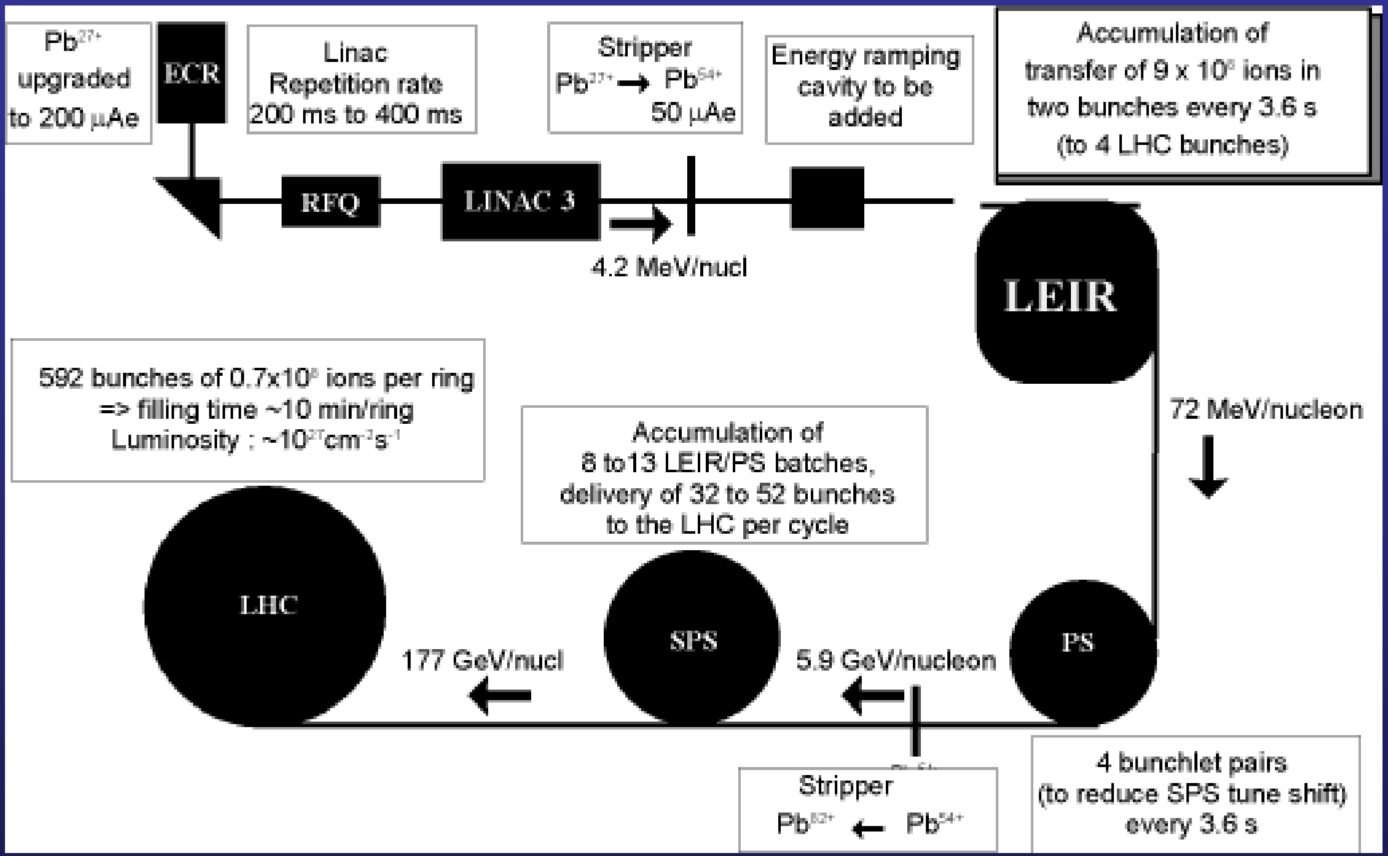
PHENIX, arXiv:1509.05380



- ❑ U-U collisions
- ❑ Results slightly favour N_{coll}^2 scaling → **(re)combination may win over suppression** when going from central Au-Au to U-U collisions
- ❑ Sharpening the understanding of J/ψ phenomenology → not straightforward

- ❑ “Beam energy scan”
- ❑ **Cancellation of suppression and recombination effects** over a factor 10 in $\sqrt{s_{NN}}$ (non negligible systematic uncertainties)

LHC, the ultimate facility for (quarkonium) studies in URHIC



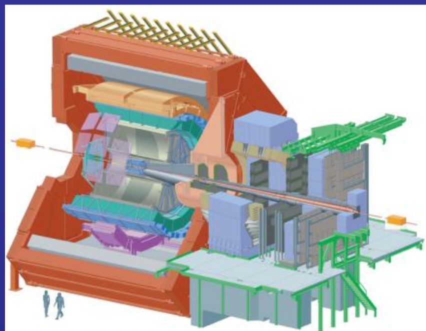
L_{peak} exceeds design

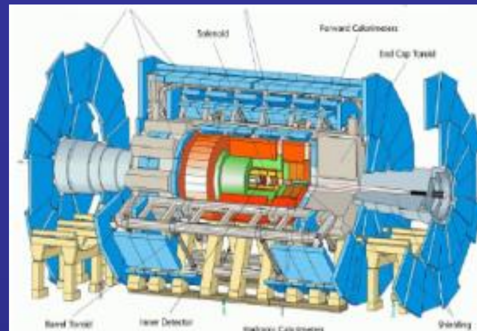
>10^{27} cm^{-2}s^{-1}

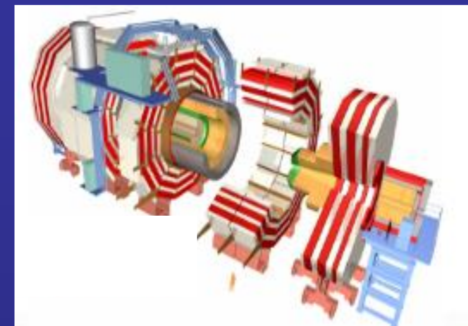
(but 7 orders of magnitude below pp)

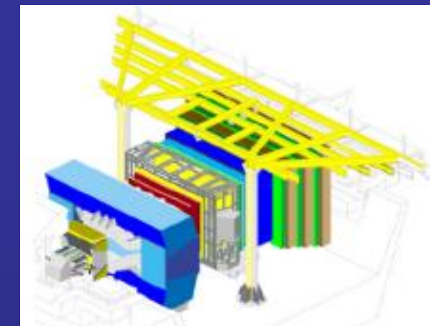
Run 1 → 2010-2013 : pp up to $\sqrt{s}$=8 TeV, Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
Run 2 → 2015-2018 : pp up to $\sqrt{s}$=13 TeV, Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV

4 experiments ...









- 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!)

…and several questions/missions

Mainly

- Solving the **"J/ψ puzzle"** (understand quantitatively suppression and re-combination)

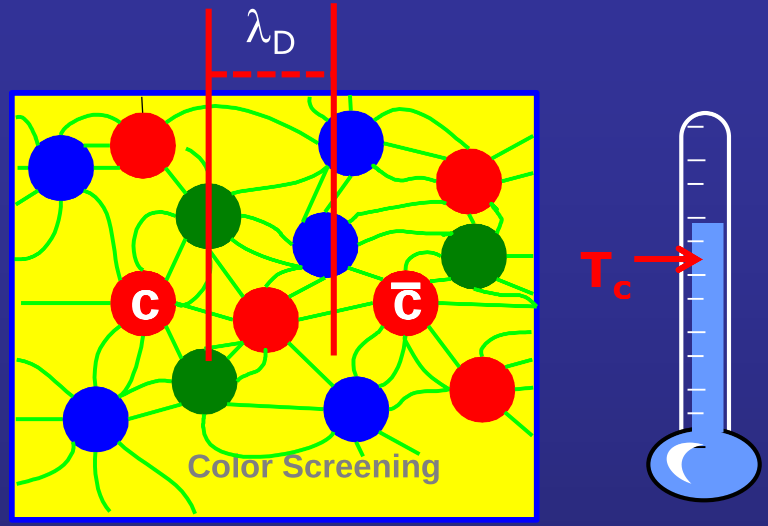
- Open the way to **bottomonium studies**

But also

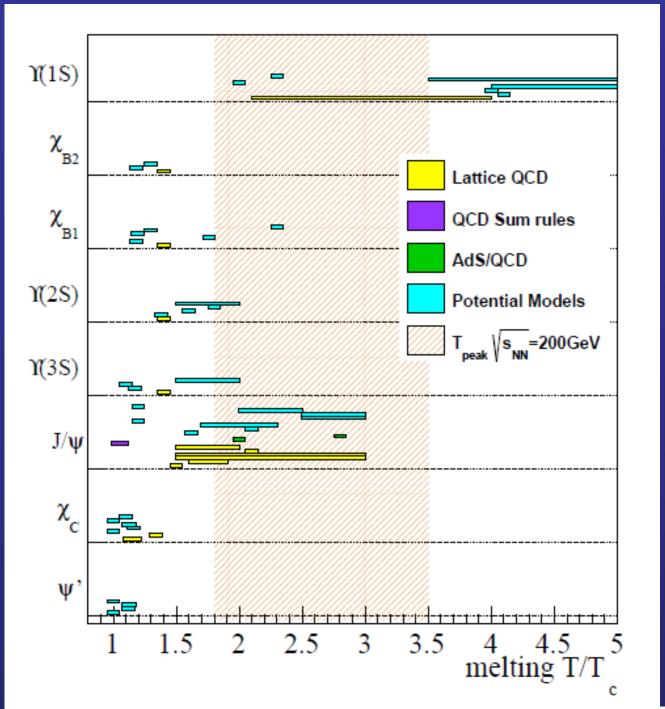
- Investigate the high-energy **√s-dependence** of suppression (and recombination) effects for charmonium and bottomonium

- Understand **feed-down** processes

J/ψ in AA collisions



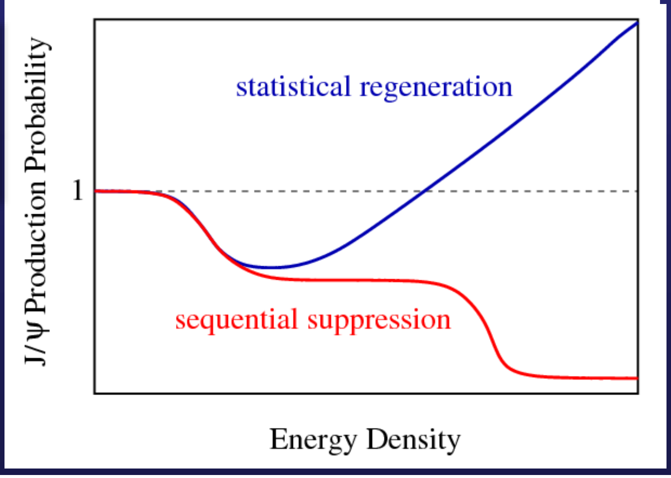
Quarkonium melting
→ QGP thermometer



From color screening

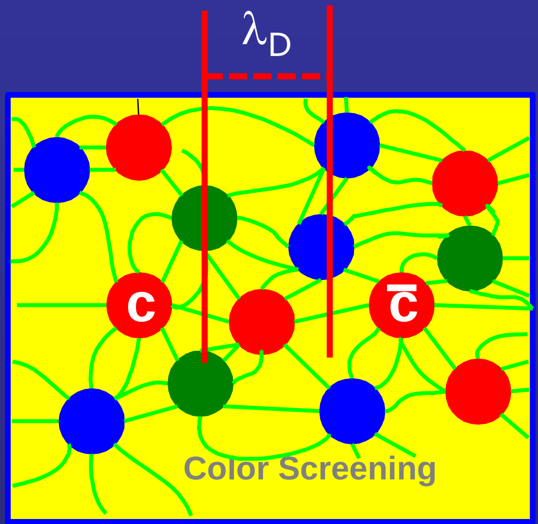
Central AA collisions	**SPS 20 GeV**	**RHIC 200 GeV**	**LHC 5 TeV**
N_{ccbar}/event	~0.2	~10	~115

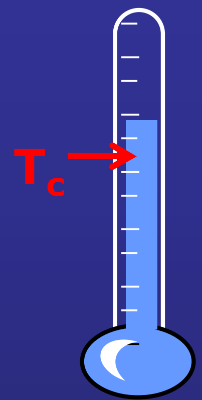
Quarkonium (re)generation
→ Heavy quark dynamics in QGP



to quark (re) combination

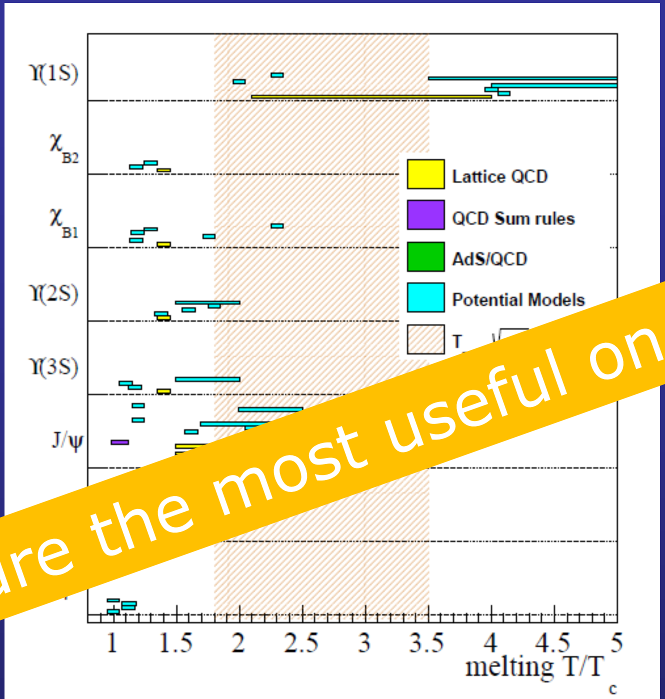
J/ψ in AA collisions





Quarkonium melting
→ QGP thermometer

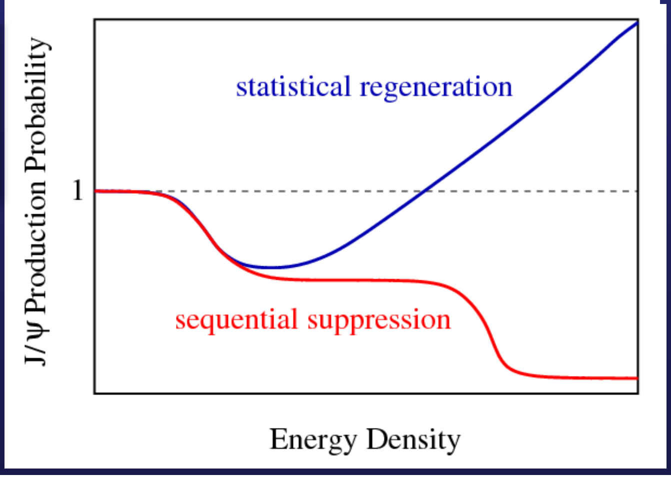
Is this traditional picture the most useful one ?



From color screening

Central A… collisi…	GeV	RHIC 200 GeV	LHC 5 TeV
N_{ccbar}/event	~0.2	~10	~115

Quarkonium (re)generation
→ Heavy quark dynamics in QGP



to quark (re) combination

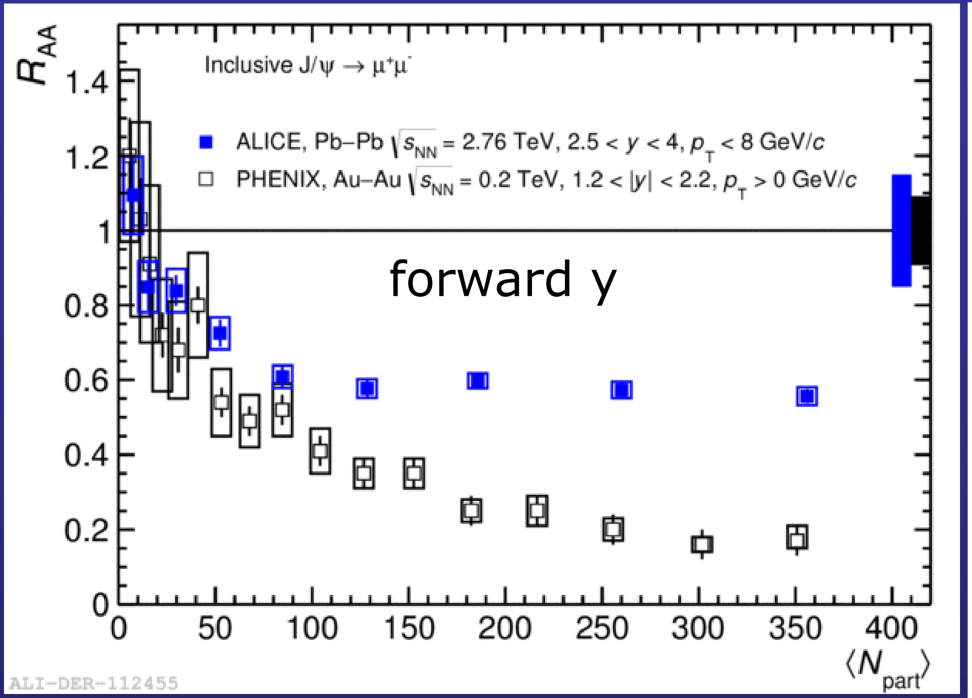
New trends ?

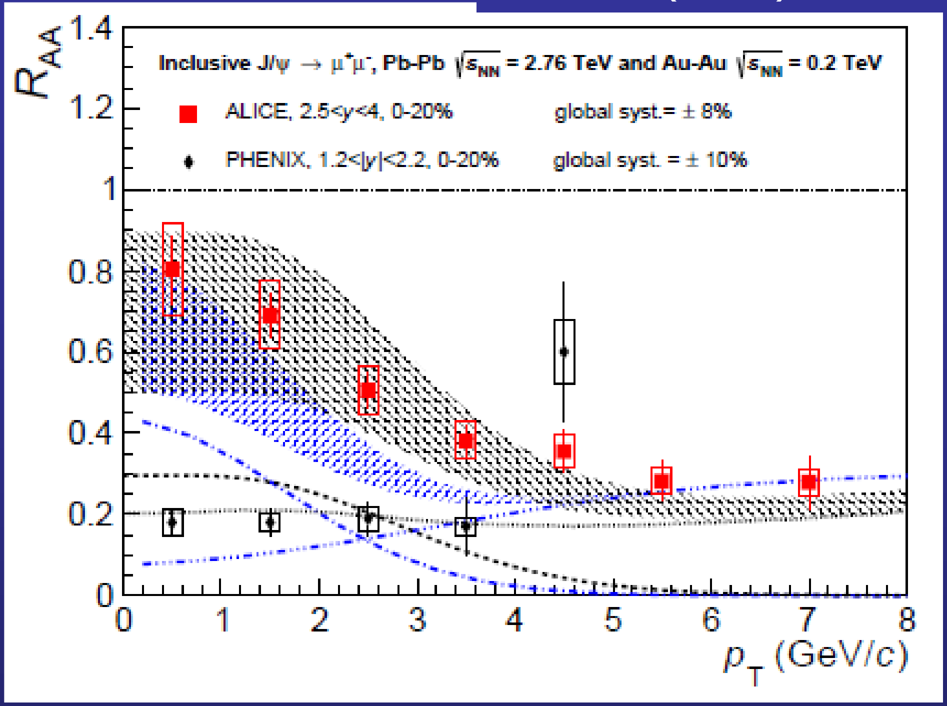
- Can **quarkonium dissociation** really be used as a **thermometer ?**
  - The search for threshold behavior(s) has proved to be difficult, continuous modifications of the spectral functions vs T
  - Try to get the temperature from elsewhere (photons? dileptons?) and learn about the modifications of QCD force in medium (Ralf)
    → in-medium binding energy and connection with potential
- Is **recombination** the really interesting observable at LHC?
  - Do observed levels of regeneration imply charm thermalization? Is charm equilibration time small with respect to QGP lifetime?
  - Can we get more smoking guns for regeneration ?
  - What do we still need to calibrate the regeneration component ?

With this perspective in mind, let’s look at the LHC results

Low-p_T J/ψ: run 1

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



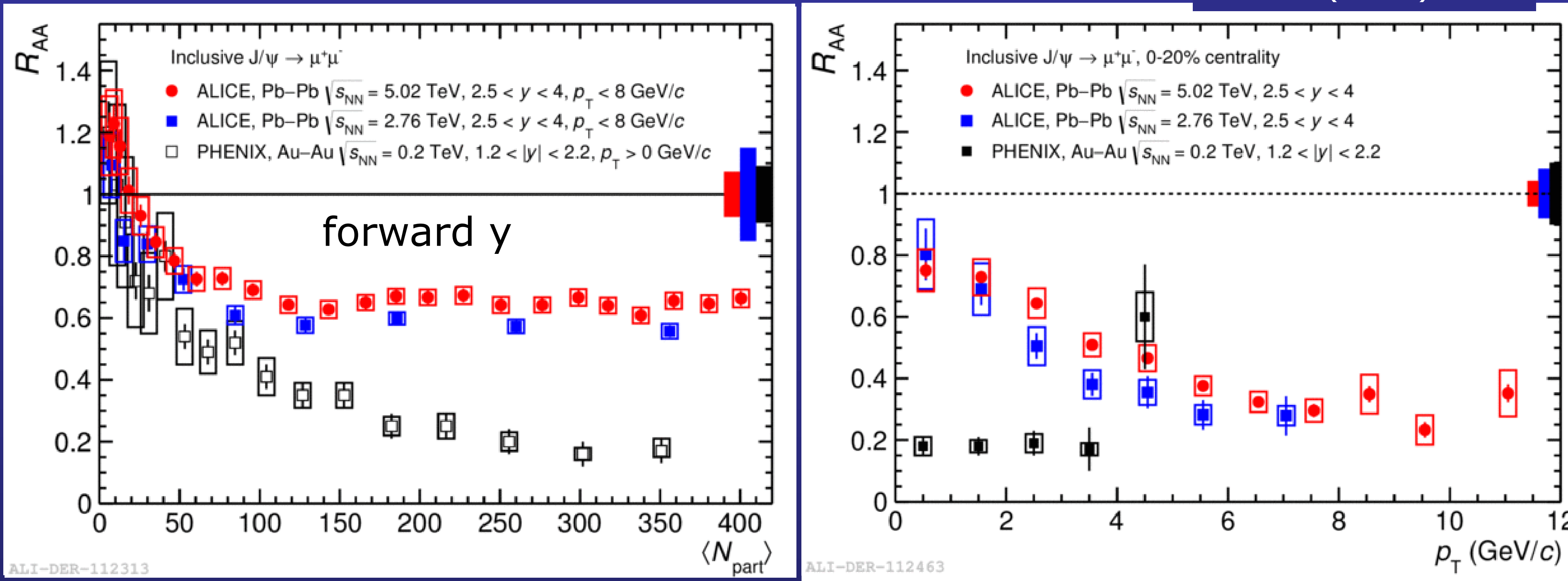


- Results vs centrality dominated by low-p_T J/ψ
  - Systematically **larger R_{AA} values** for **central** events at LHC
  - **R_{AA} increases at low p_T** at LHC

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

Low-p_T J/ψ: run 1

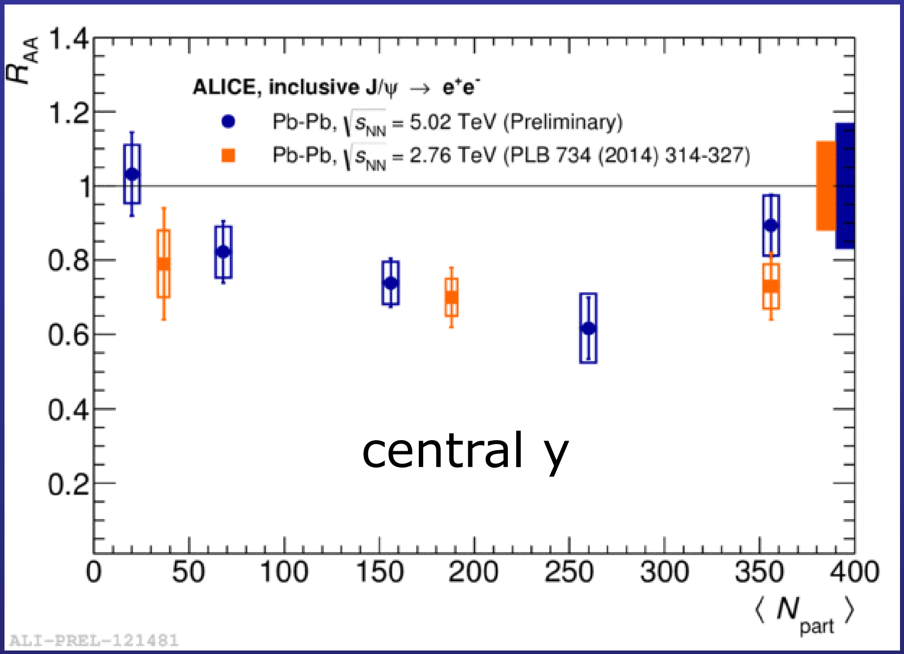
J.Adam et al, ALICE
PLB766(2017) 212

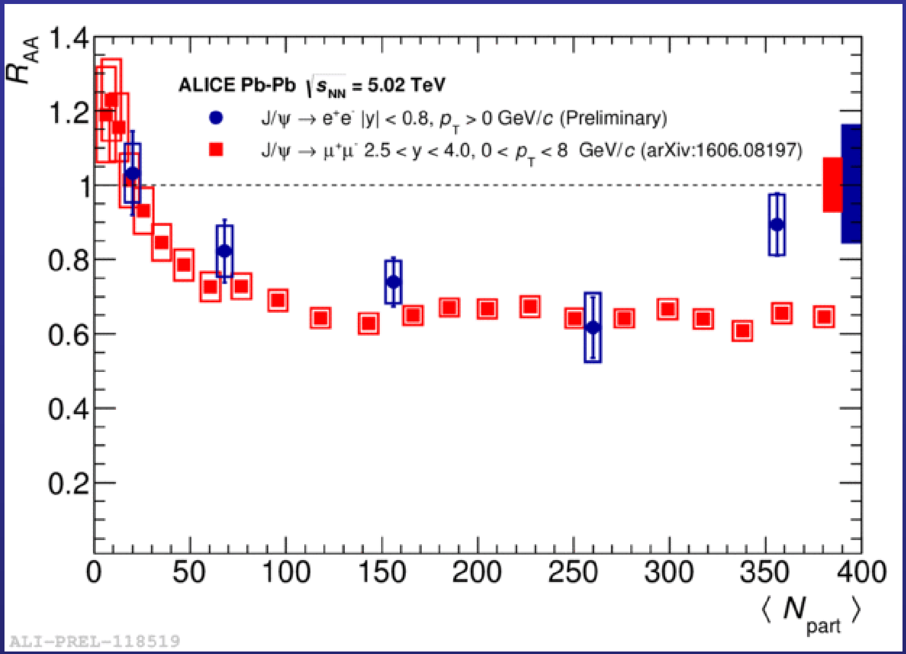


- Results vs centrality dominated by low-p_T J/ψ
  - Systematically **larger R_{AA} values** for **central** events at LHC
  - **R_{AA} increases at low p_T** at LHC
  - **Precise results at $\sqrt{s_{NN}}$=5.02 TeV**, compatible with $\sqrt{s_{NN}}$=2.76 TeV

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

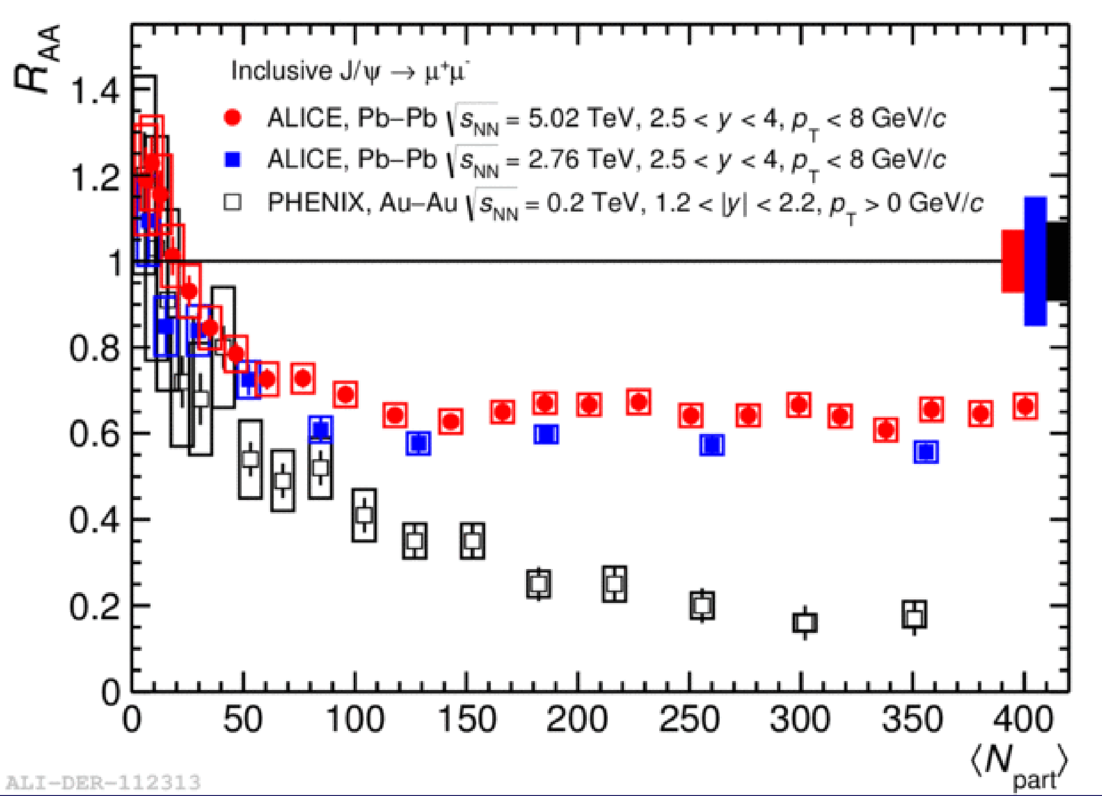
Low-p_T J/ψ: central vs forward-y





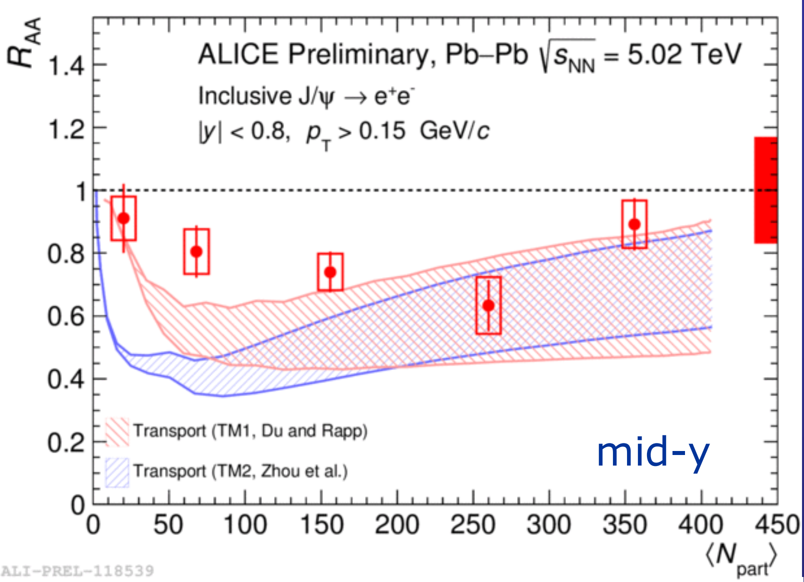
- Central Pb-Pb: **hints for a weaker suppression at y~0** with respect to forward-y results at $\sqrt{s_{NN}}$=5.02 TeV
  → expected in a (re)generation scenario (fluctuation cannot be excluded)
- **No significant $\sqrt{s_{NN}}$-dependence** of R_{AA} (5.02 vs 2.76 TeV), confirming forward-y observations

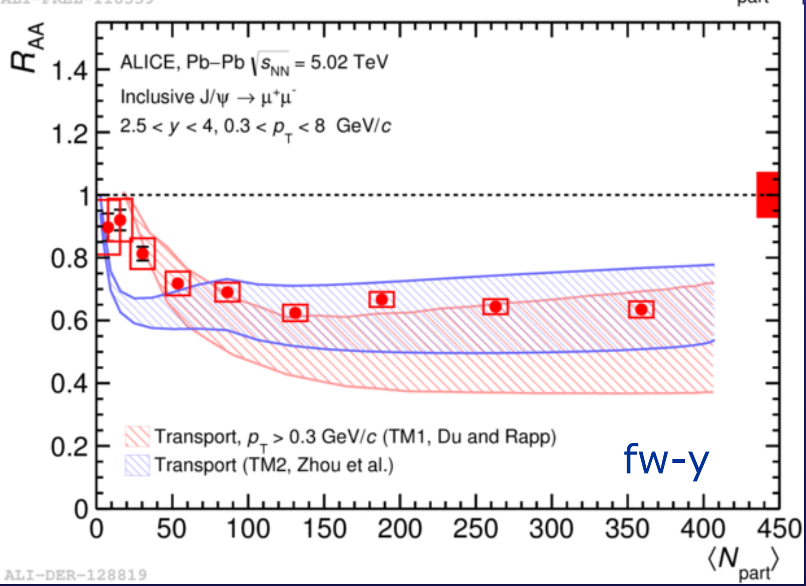
Comparing $\sqrt{s_{NN}}$=2.76 and 5.02 TeV



- Looks like the **"flattest" observable** in URHIC
  → No change between N_{part}=100 and N_{part}>400!
- **Accidental cancellation** of suppression and recombination ? (and same CNM effects)
- Does a trend exist, and a better accuracy is needed ?
- Or the observed scaling has a deeper meaning?

Comparison with theory models





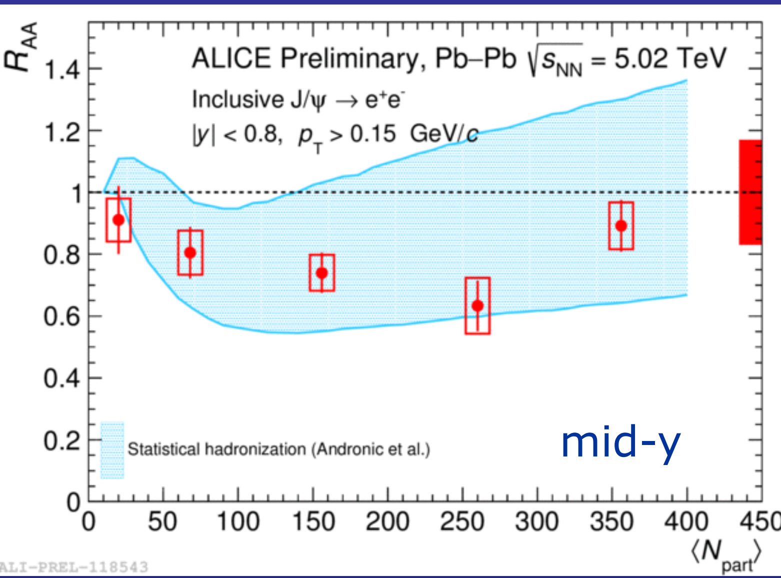
Transport models

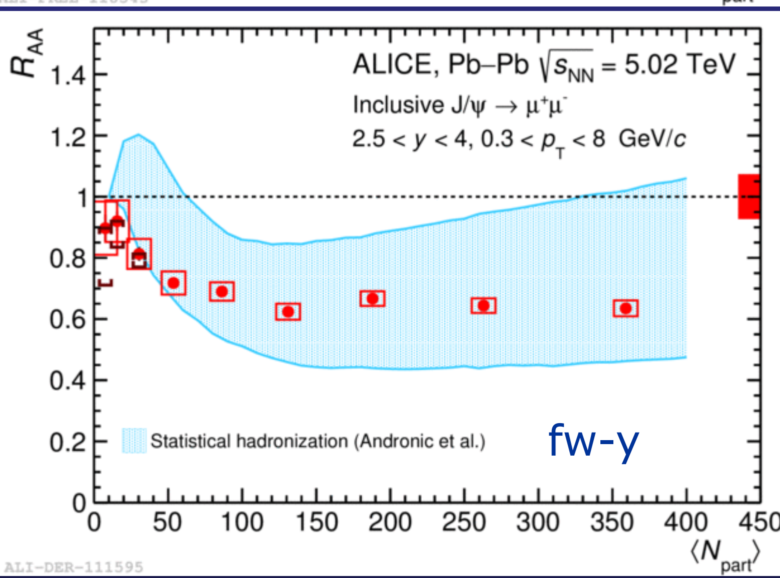
- Based on thermal rate equations including continuous dissociation and regeneration of the J/ψ in QGP and hadronic phase
- σ_{cc} consistent witn FONLL

X. Zhao, R. Rapp NPA 859 (2011) 114
K. Zhou et al, PRC 89 (2011) 05491

Model	$d\sigma_{cc}/dy$[mb] mid-y	$d\sigma_{cc}/dy$[mb] fw-y	nPDF
Transport, TM1	0.72	0.57	EPS09
Transport, TM2	0.86	0.82	EPS09

Comparison with theory models





Statistical hadronization

- J/ψ produced at chemical freeze-out according to their statistical weights
- σ_{cc} from LHCb pp measurement at $\sqrt{s}$ = 7 TeV + FONLL

A. Andronic et al., NPA 904-905 (2013) 535

Model	$d\sigma_{cc}/dy$ [μb] mid-y	$d\sigma_{cc}/dy$ [mb] fw-y	nPDF
Transport, TM1	0.72	0.57	EPS09
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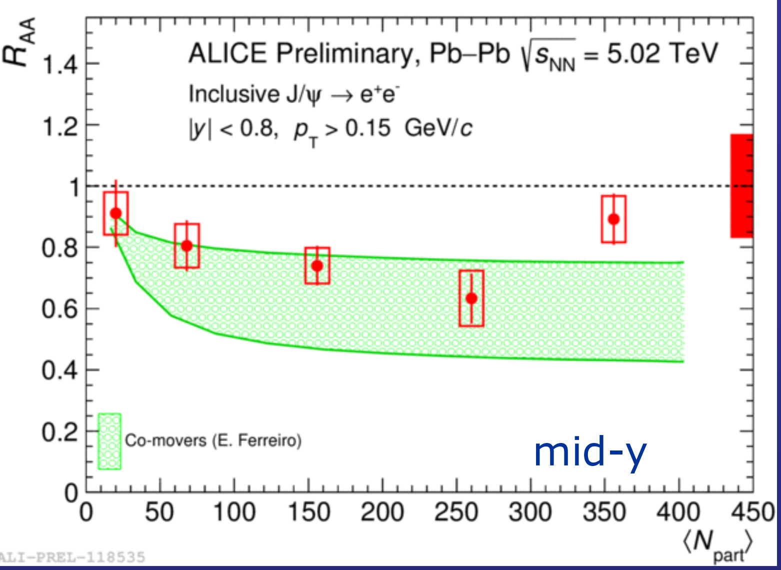

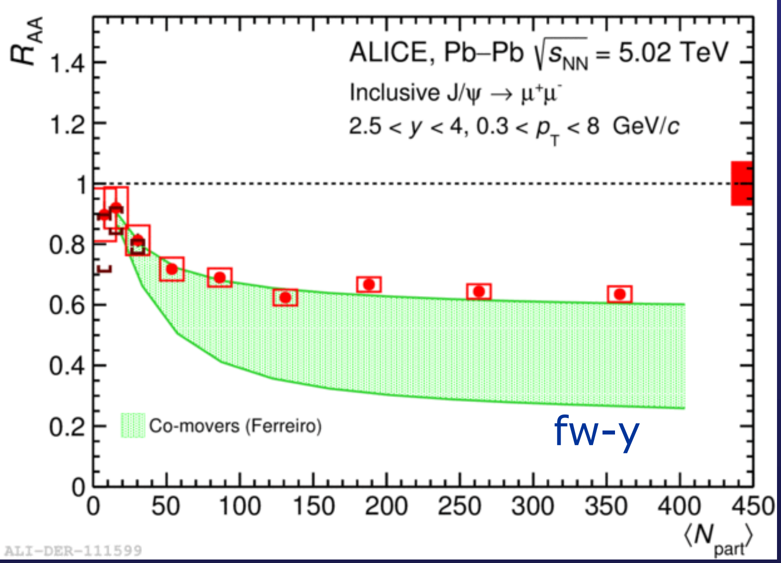

Comover model

- J/ψ are dissociated via interactions with partons/hadrons in the same *y*-range + regeneration contribution
- $\sigma_{J/\psi\text{-comovers}}$ = 0.65 mb (from lower energy results)

E. Ferreiro, PLB749 (2015) 98, PLB731 (2014) 57

Model	$d\sigma_{cc}/dy$ [μb] mid-y	$d\sigma_{cc}/dy$ [mb] fw-y	nPDF
Transport, TM1	0.72	0.57	EPS09
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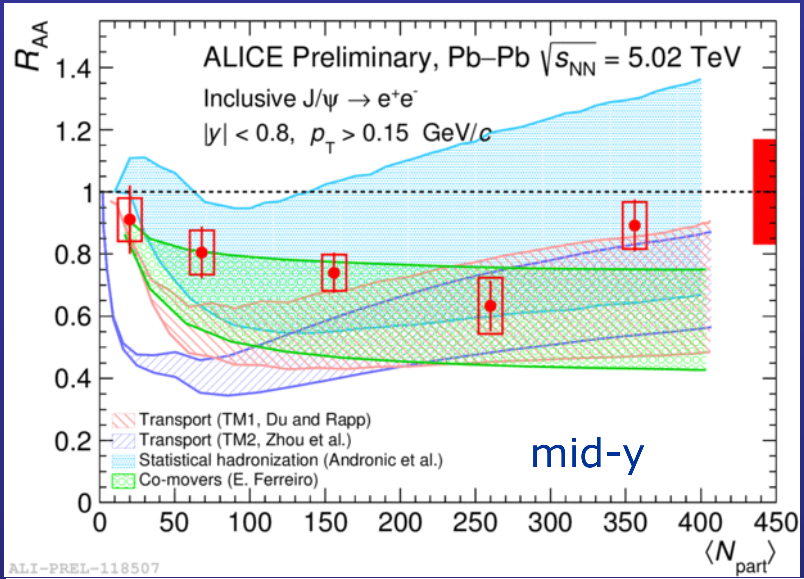
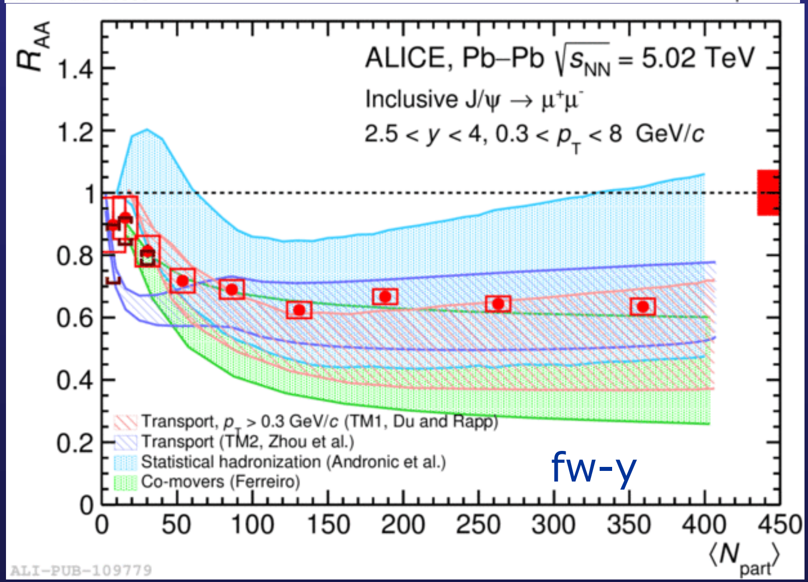
Stat. Hadroniz.	0.79	0.45	EPS09
Comovers	0.55	0.45-0.7	Glauber Gribov

Comparison with theory models





- All theory models fairly describe the data, as already the case at $\sqrt{s_{NN}}$ = 2.76 TeV
- but still large uncertainties associated to charm cross section and shadowing

Model	$d\sigma_{c\bar{c}}/dy$ [μb] mid-y	$d\sigma_{c\bar{c}}/dy$ [mb] fw-y	nPDF
Transport, TM1	0.72	0.57	EPS09
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Stat. Hadroniz.	0.79	0.45	EPS09
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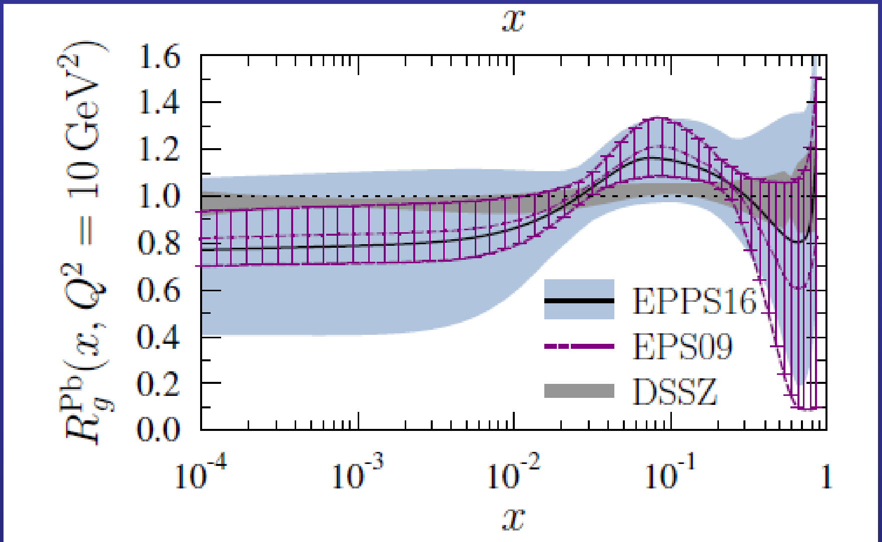
Shadowing uncertainties

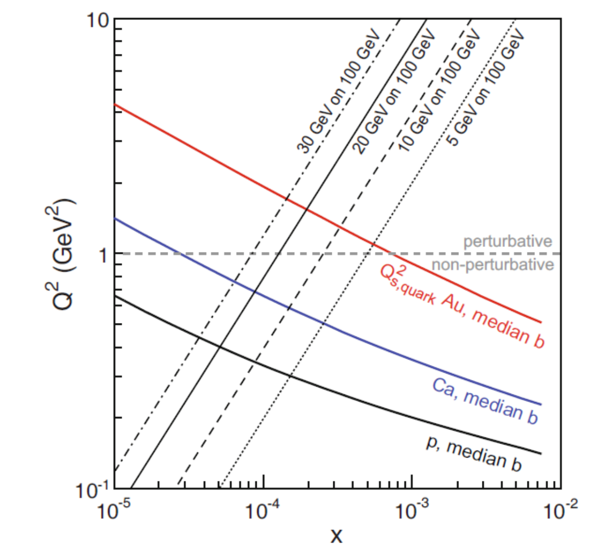


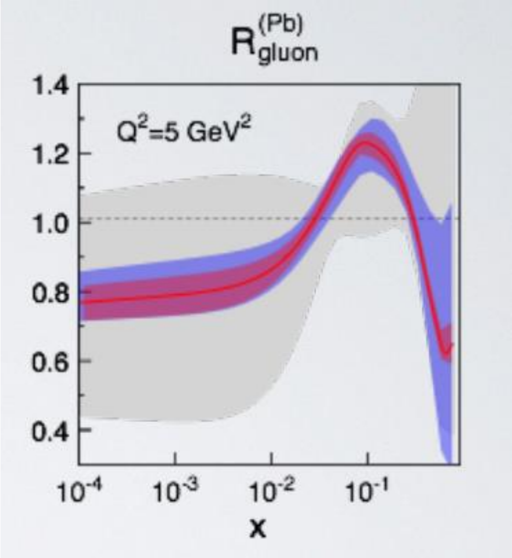
- Recent EPPS16 fits confirm **substantial uncertainties on gluon nPDF** → application to J/ψ production models would increase current (already large) uncertainties

- Use directly J/ψ data in p-Pb to constrain the nPDFs ? (JPL)

- **EIC** → prospects for substantial improvements (on a longer timescale)

- Is kinematic reach good enough at least for charmonia?

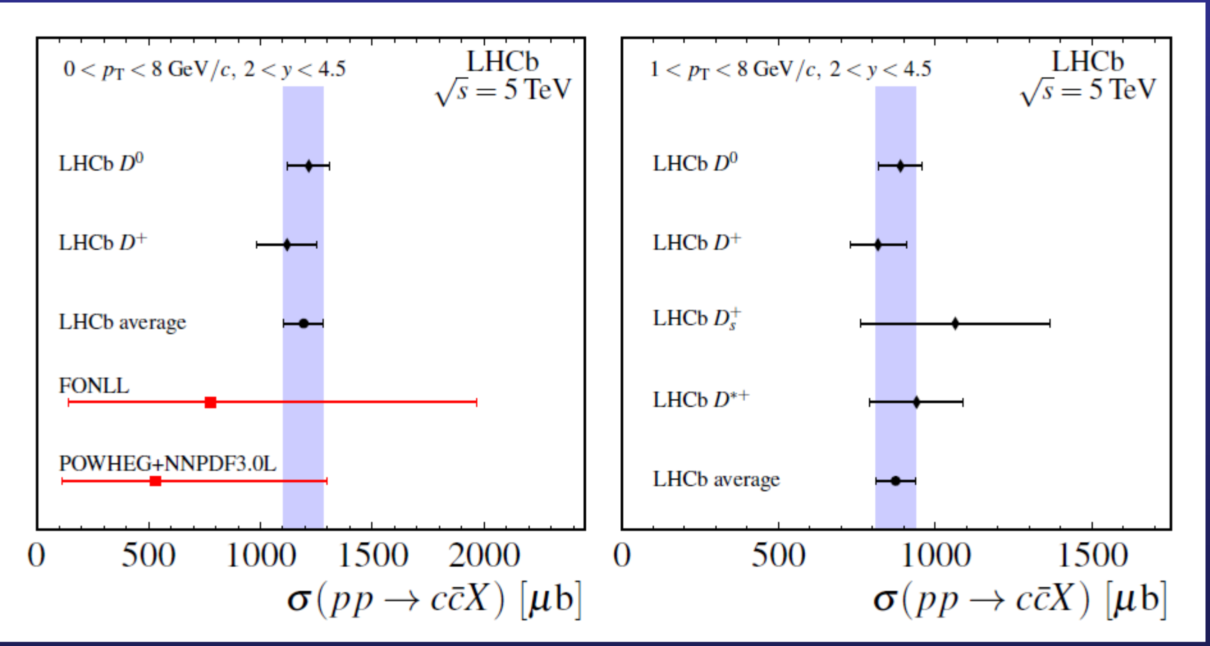




Open charm cross section in pp

- **Crucial ingredient** to any calculation at LHC energy
- Input values definitely too sparse among various theory groups

- LHCb results are the most promising way forward
  → Estimate of p_T-integrated charm cross section (2<y<4.5)



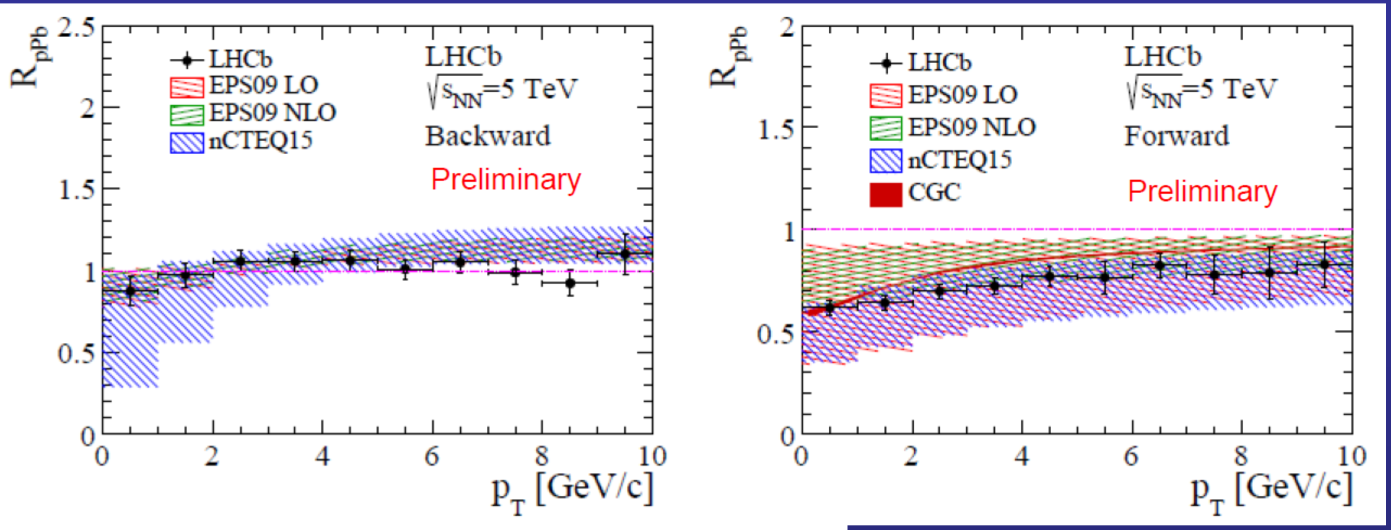
$$\sigma(pp \to c\bar{c}X)_{p_T < 8\,\mathrm{GeV}/c,\, 2.0 < y < 4.5} = 1193 \pm 3 \pm 67 \pm 58\,\mu\mathrm{b},$$

(warning: was 1395 μb in v1)

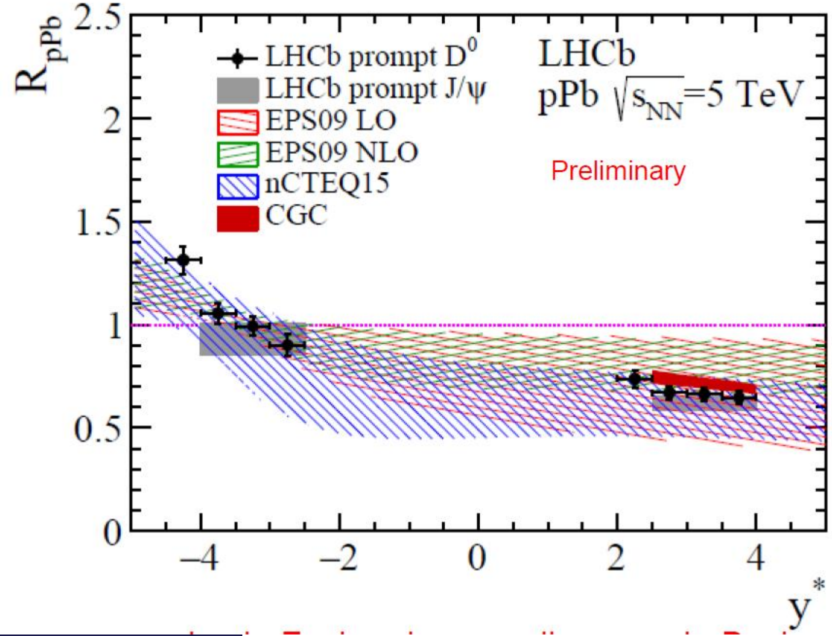
gives
$d\sigma/dy$=0.477±0.036 mb

Good constraint!

Open charm and CNM effects



- **Size of CNM effects** also crucial for open charm cross section that enters Pb-Pb calculations



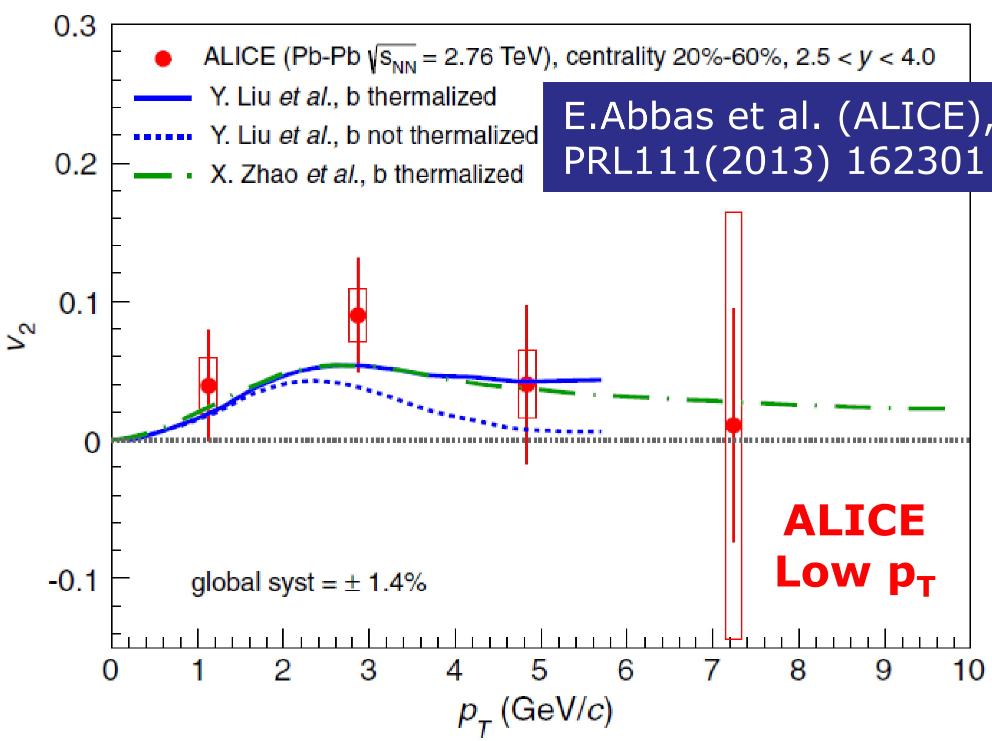
- New **LHCb** results (LHCP2017)

→ 30% suppression at forward-y
→ From no suppression to enhancement at backward-y

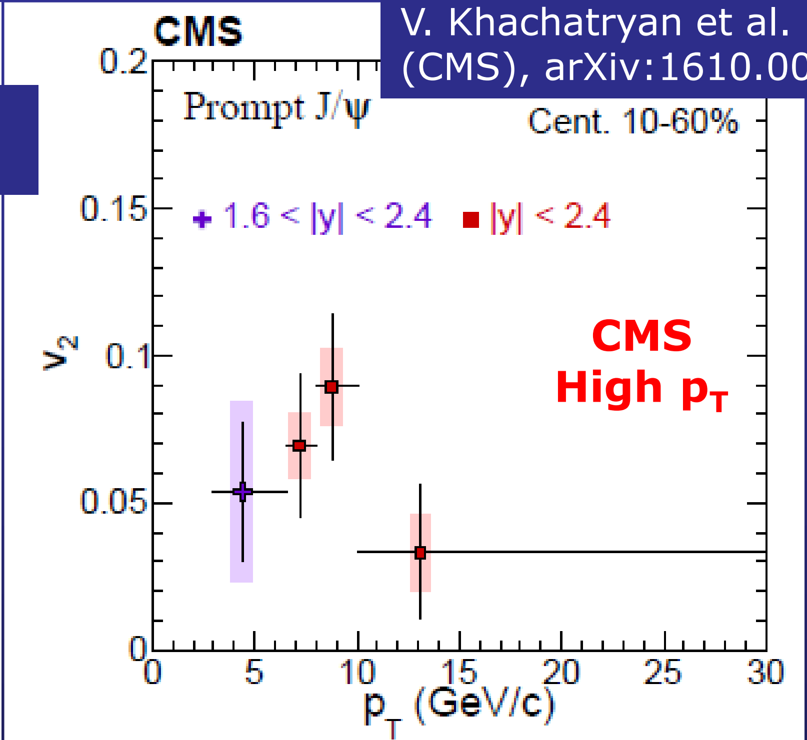
- Good constraints on CNM effects on open charm
- **R_{pPb} (D) ~ R_{pPb} (J/ψ) !**

J/ψ v_2

- The contribution of J/ψ from (re)combination could lead to an **elliptic flow** signal at LHC energy → hints observed in run-1 results



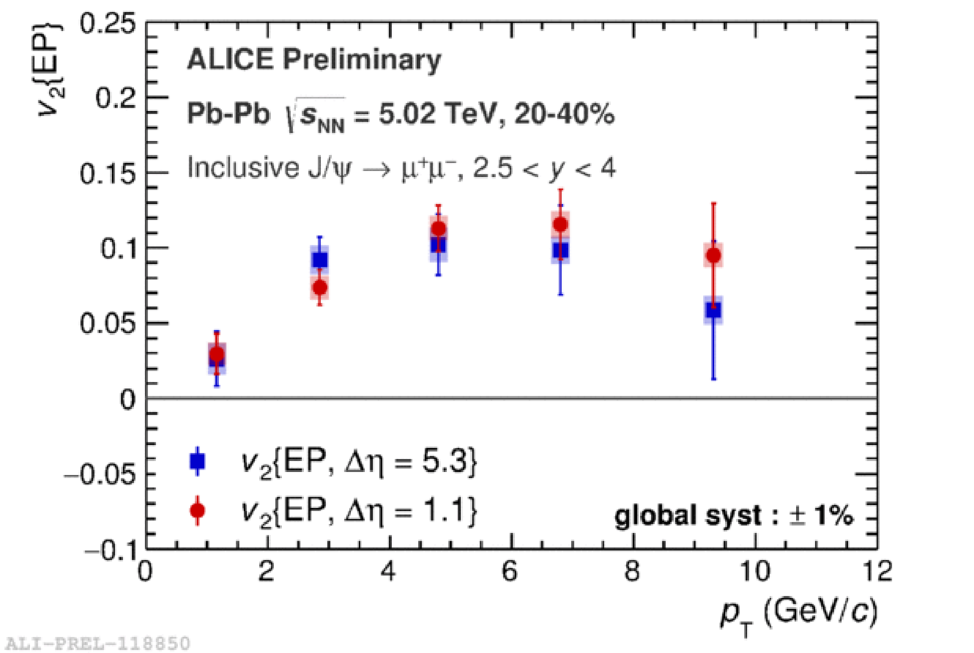
E.Abbas et al. (ALICE), PRL111(2013) 162301



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

- v_2 remains significant **at large p_T (~10 GeV/c)** where the contribution of (re)generation should be negligible
  → Likely due to **path length dependence of energy loss**

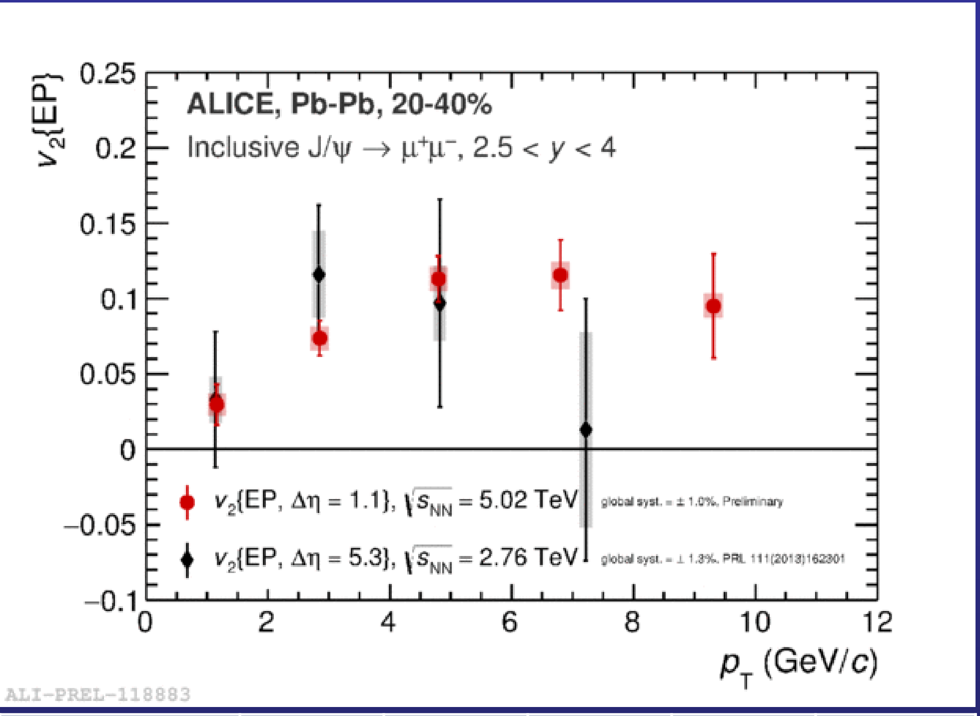
New J/ψ v_2 results



p_T (GeV/c)	0-2	2-4	4-6	6-8	8-12
Δη=1.1	2.2σ	6.3σ	7.4σ	5.0σ	2.8σ
Δη=5.3	1.4σ	6.2σ	5.0σ	3.3σ	1.3σ

- J/ψ v_2 studied in run 2, two independent determinations of the event plane
- **From hint to evidence for a non-zero v_2 signal**, maximum for $4<p_T<6$ GeV/c, 20-40% centrality
- A significant fraction of observed J/ψ comes from charm quarks which thermalized in the QGP

New J/ψ v_2 results



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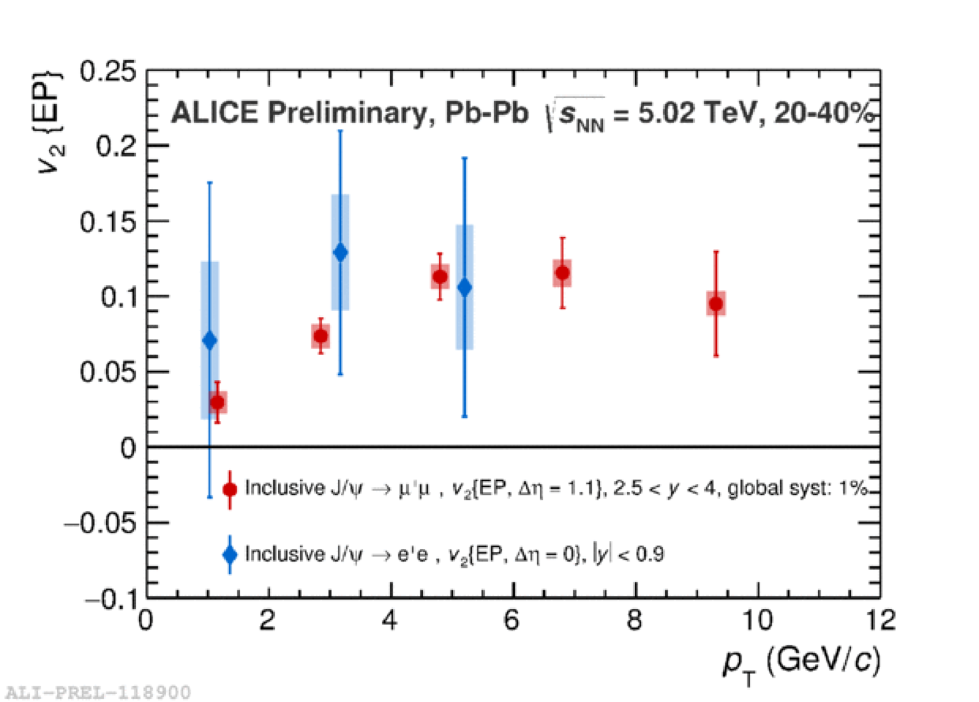

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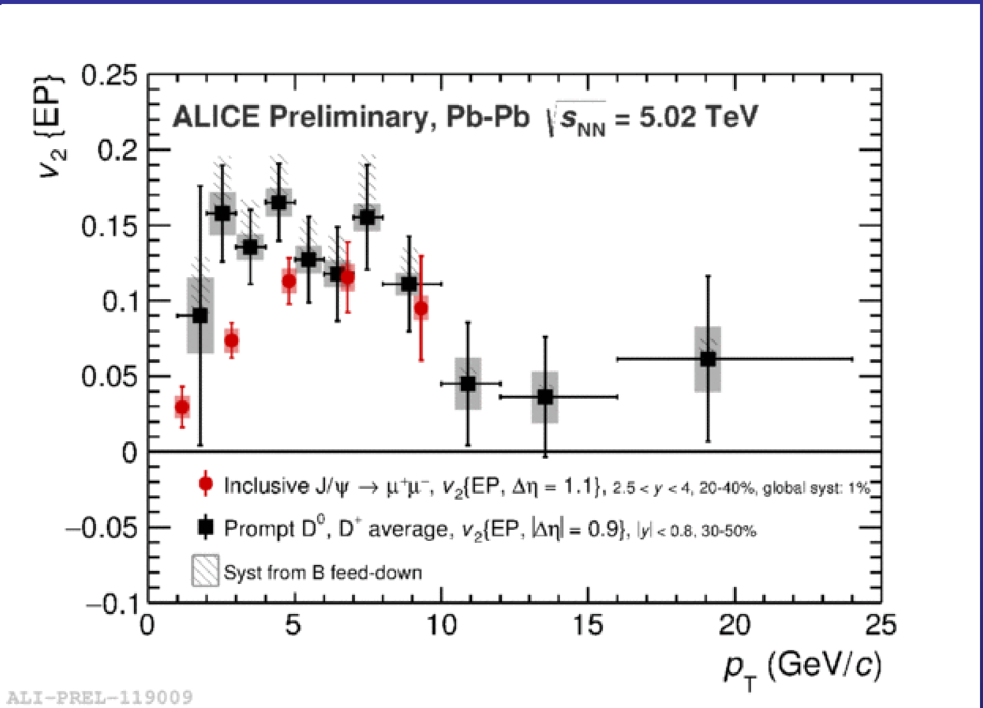

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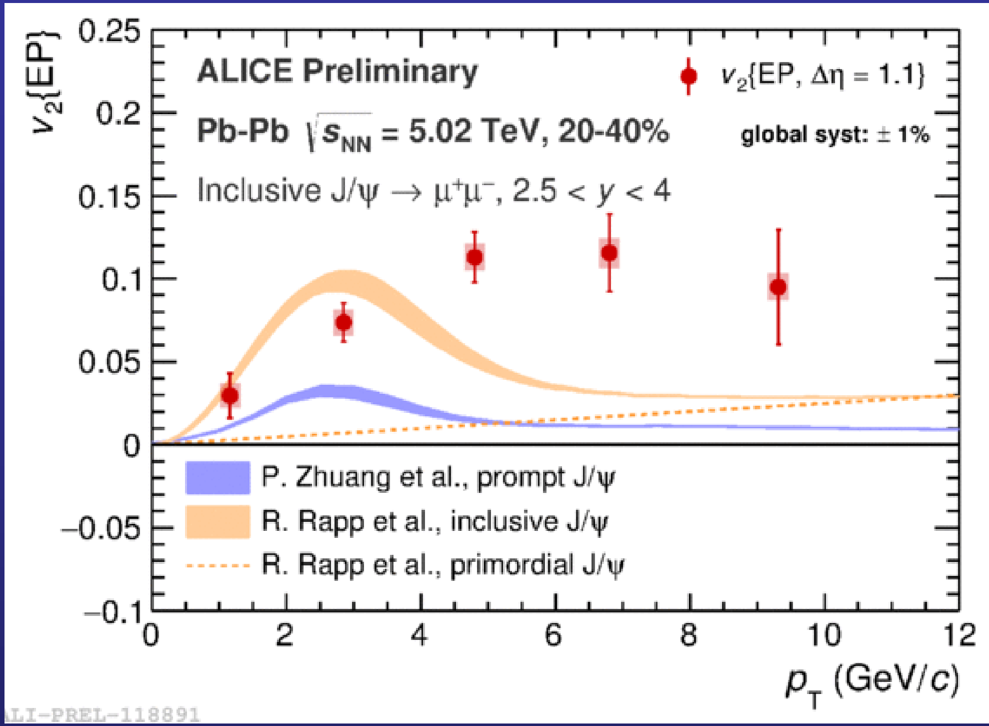
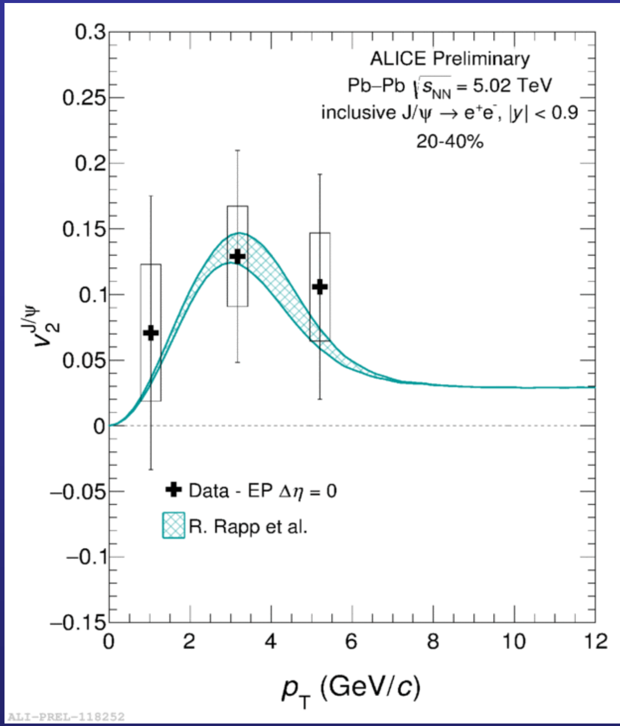
- J/ψ v_2 studied in run 2, two independent determinations of the event plane
- **From hint to evidence for a non-zero v_2 signal**, maximum for 4<p_T<6 GeV/c, 20-40% centrality
- Agreement, within uncertainties, with run-1 results
- Agreement, within uncertainties, between forward and central y
- Comparison closed vs open charm → Learn about **light vs heavy quark flow**
- A significant fraction of observed J/ψ comes from charm quarks which thermalized in the QGP

J/ψ elliptic flow: theory comparison

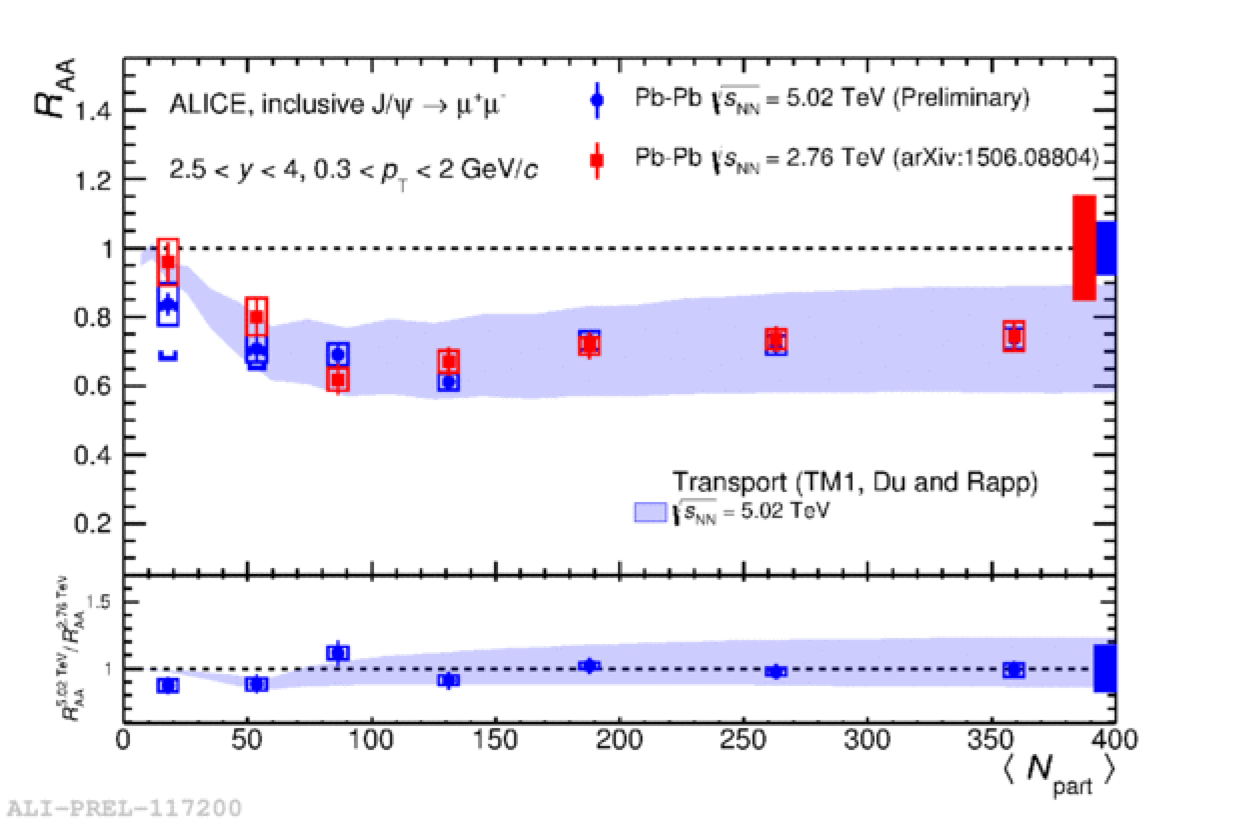




- ❑ J/ψ v_2 is compared to transport model calculations
- ❑ **Maximum v_2 at p_T ~ 3.0 GeV/c** results from an interplay between the regeneration component, dominant at lower p_T, and the primordial plus non-prompt J/ψ components which take over at higher p_T
- ❑ Difficulties in reproducing the pattern up to high p_T

Still on R_{AA} – more differential

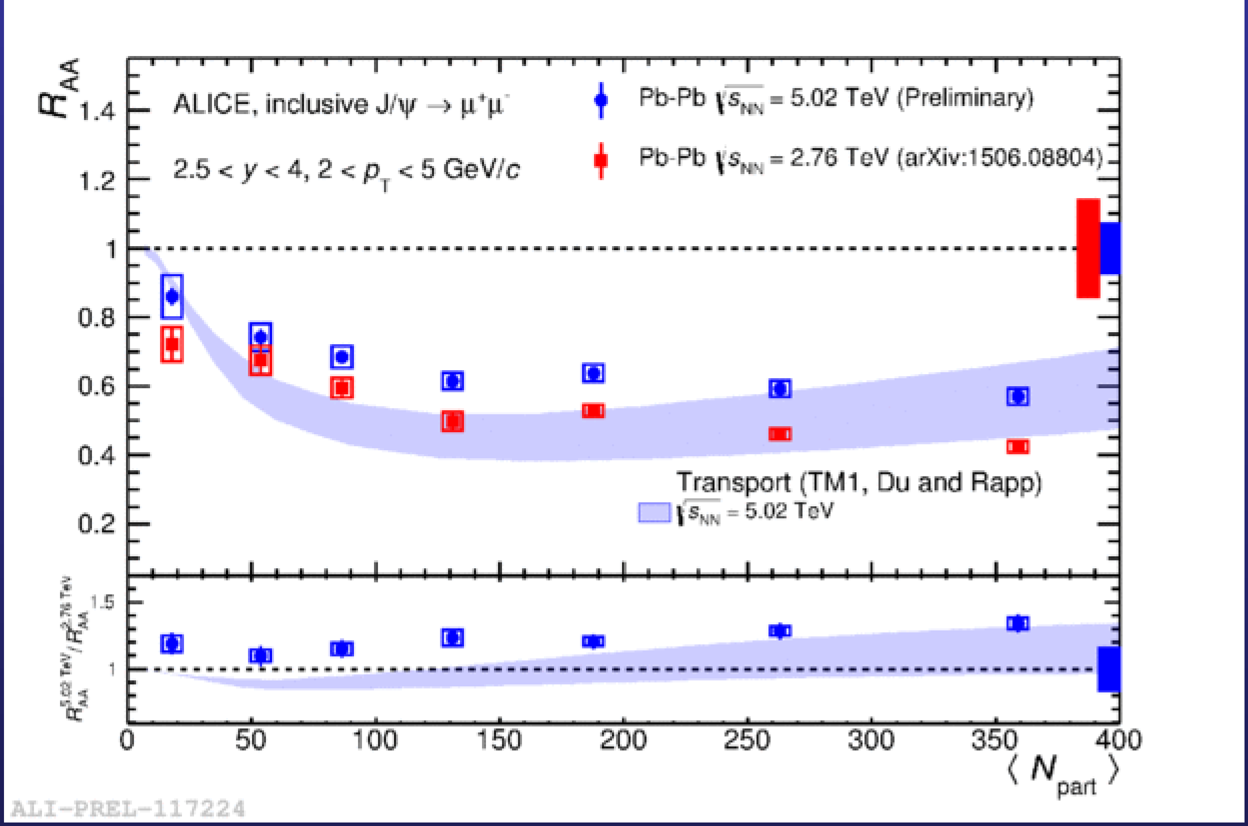
- Explore the **centrality dependence of R_{AA} for various p_T intervals**, and compare run 2 results to theory models and to run 1



0.3<p_T<2 GeV/c

Still on R_{AA} – more differential

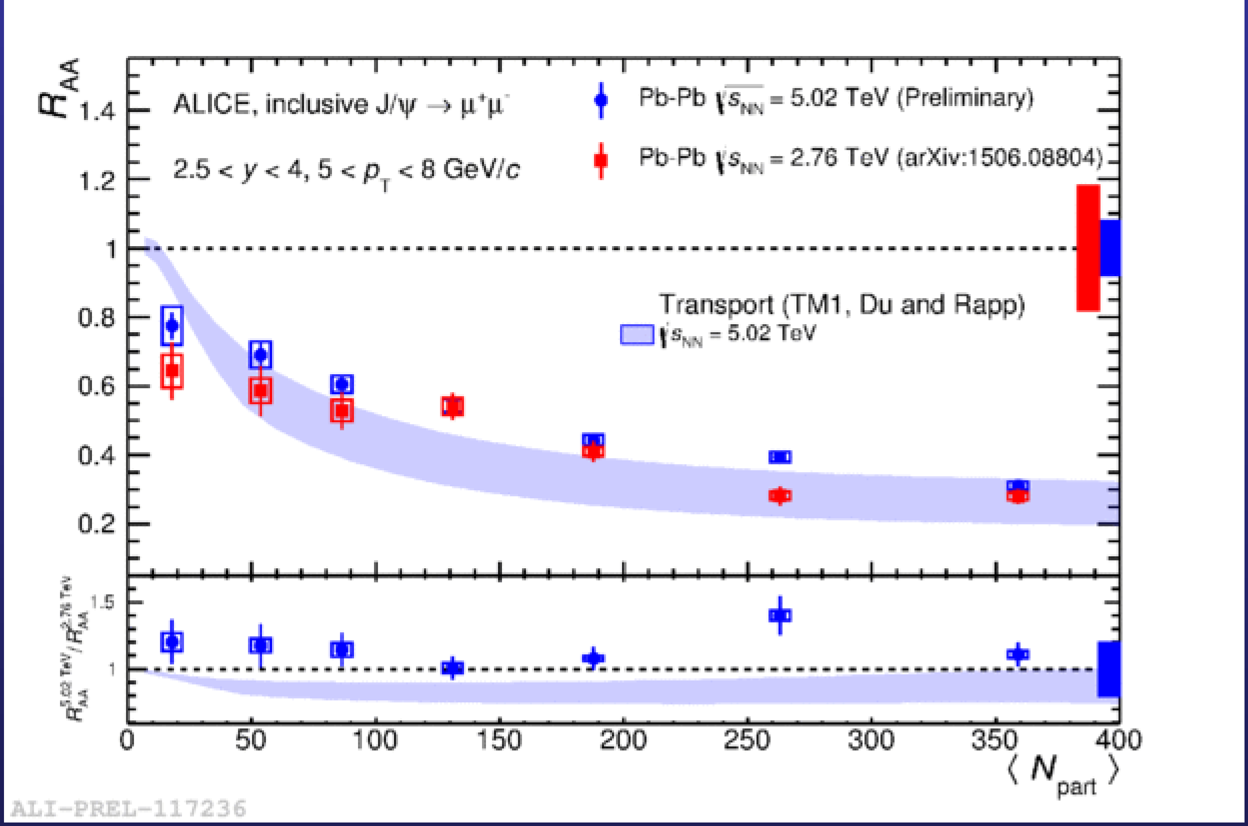
- Explore the **centrality dependence of R_{AA} for various p_T intervals**, and compare run 2 results to theory models and to run 1



2<p_T<5 GeV/c

Still on R_{AA} – more differential

❑ Explore the **centrality dependence of R_{AA} for various p_T intervals**, and compare run 2 results to theory models and to run 1



5<p_T<8 GeV/c

Still on R_{AA} – more differential

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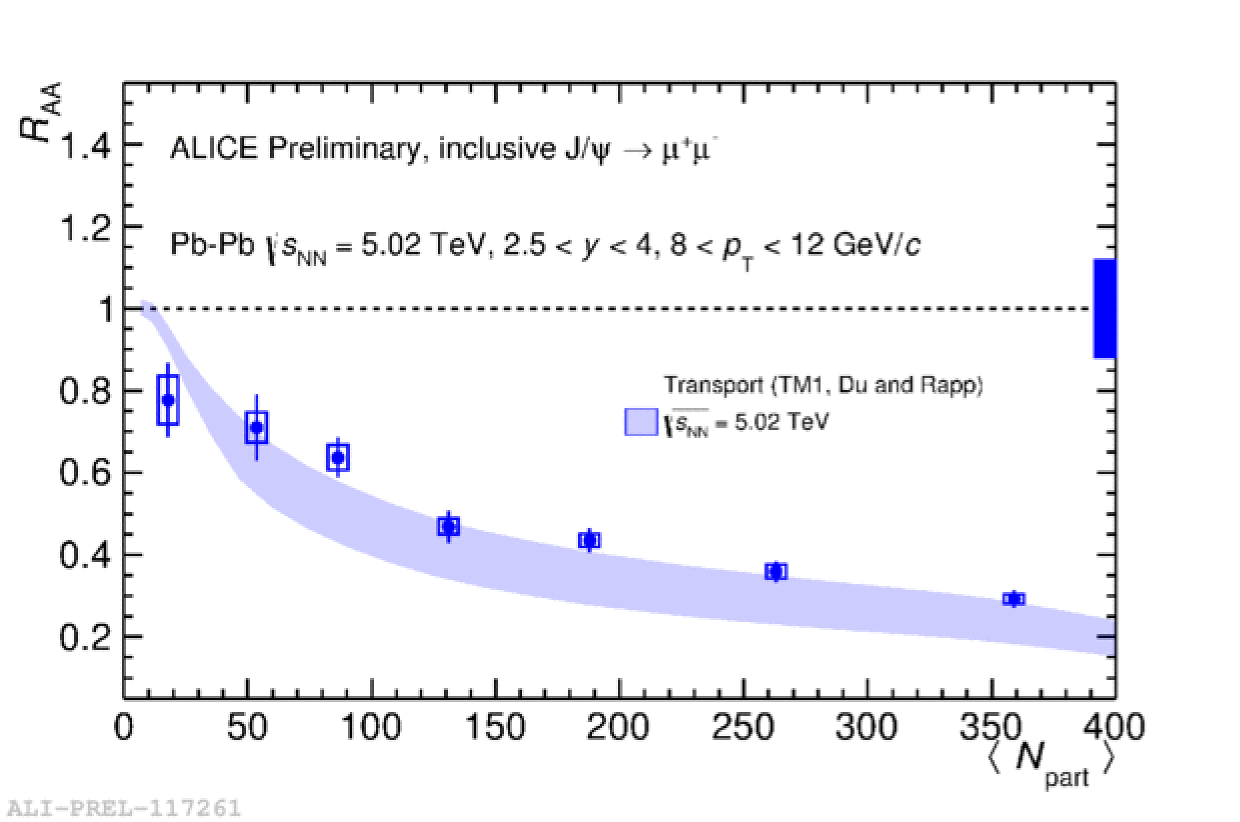
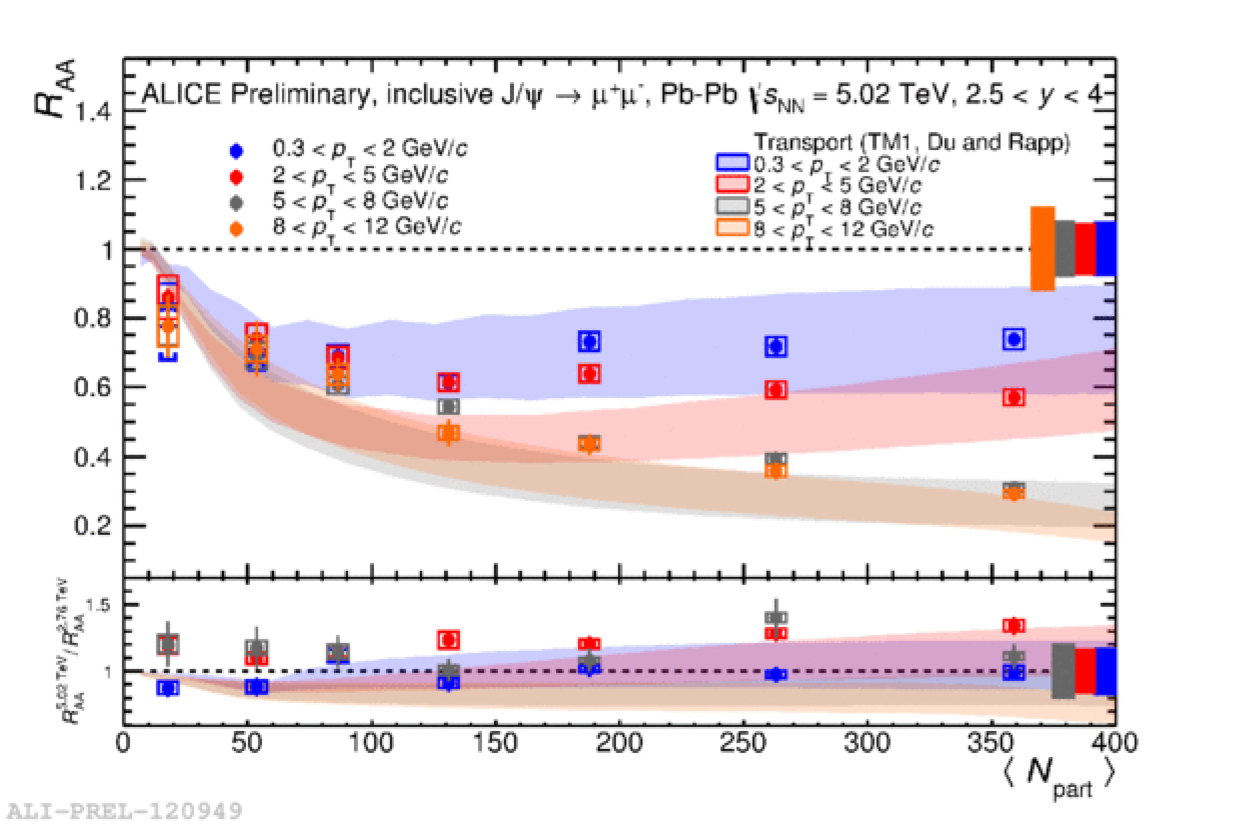


8<p_T<12 GeV/c

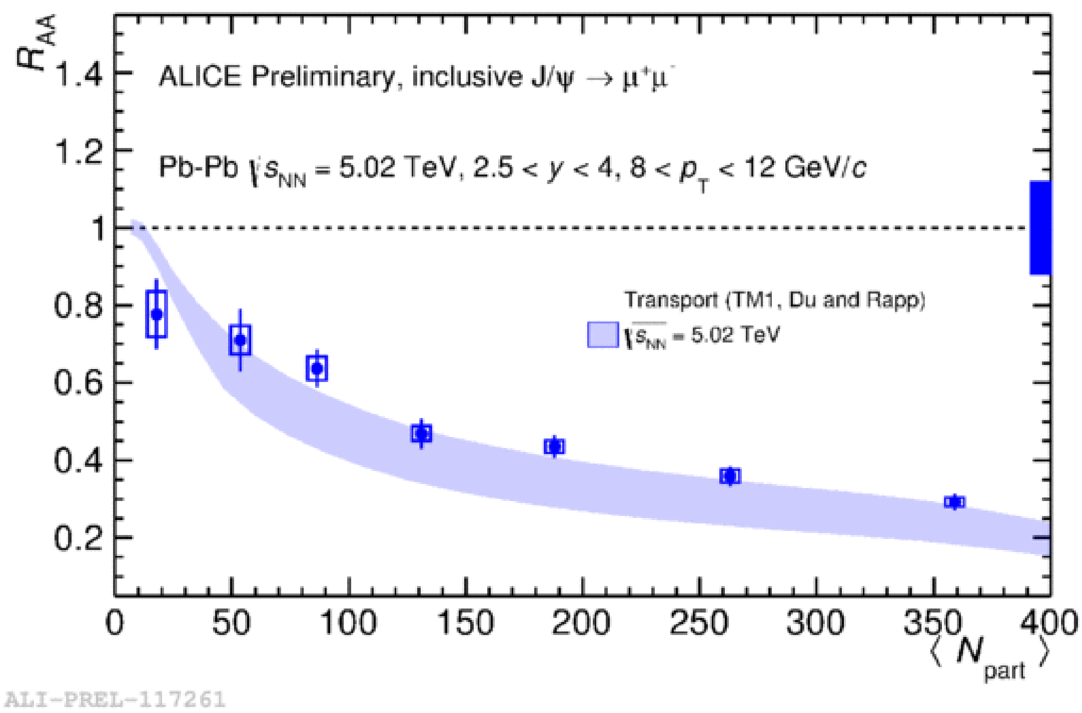
Still on R_{AA} – more differential

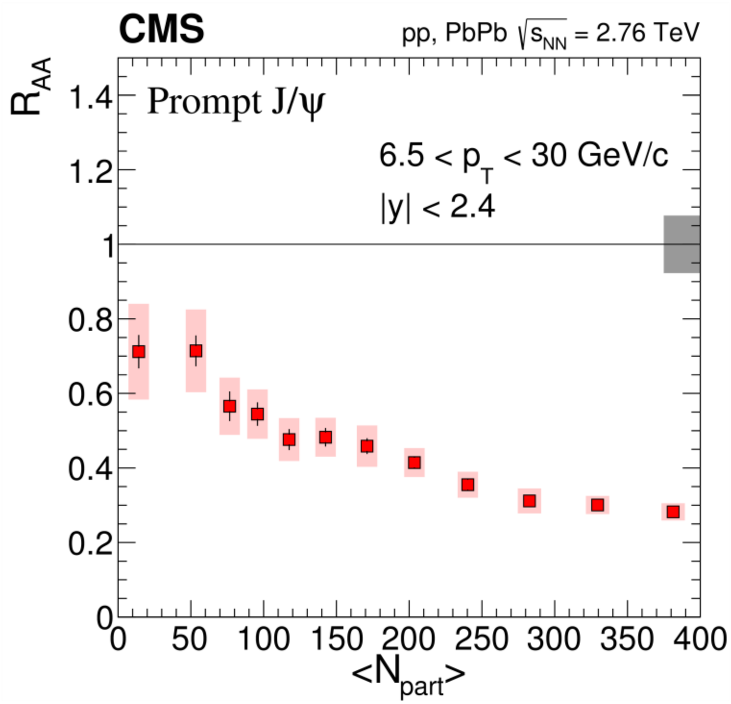
- ❑ Explore the **centrality dependence of R_{AA} for various p_T intervals**, and compare run 2 results to theory models and to run 1



- ❑ "Flatness" of R_{AA} vs N_{part} disappears when plotted in p_T bins
- ❑ Theory comparison → some tension for semi-peripheral events

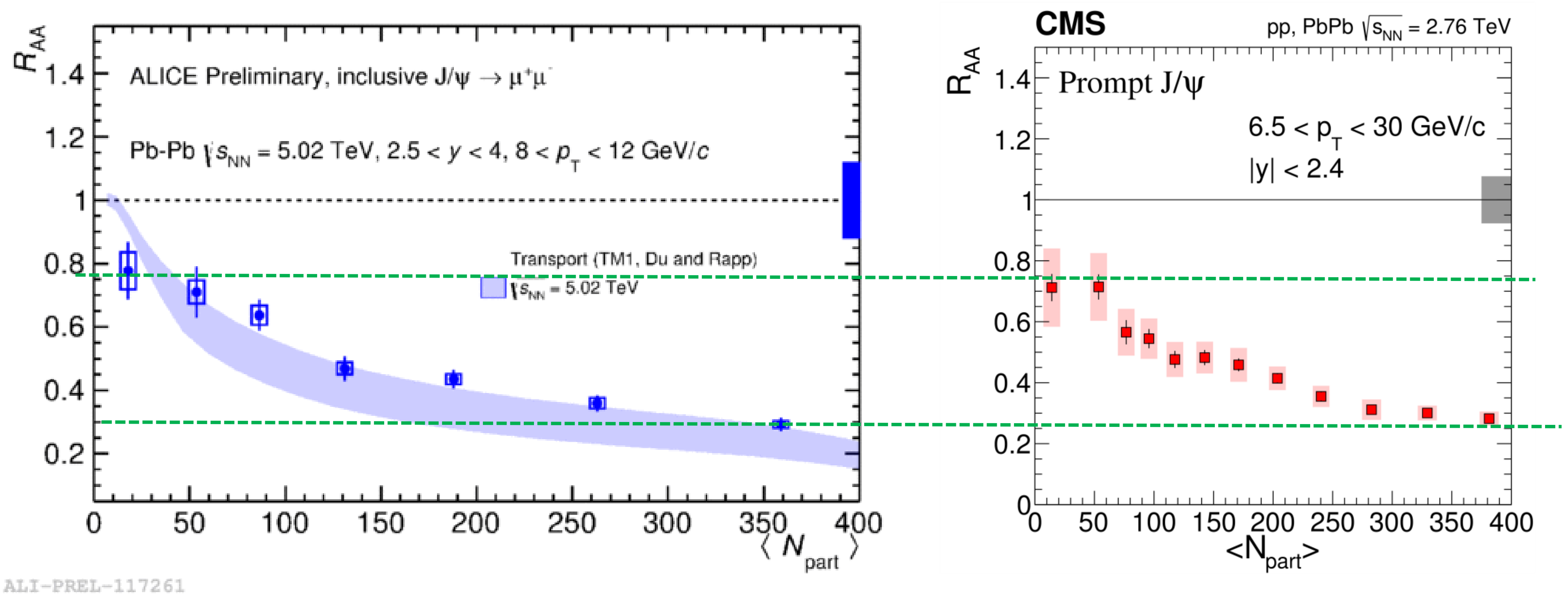
High-p_T J/ψ - ALICE vs CMS





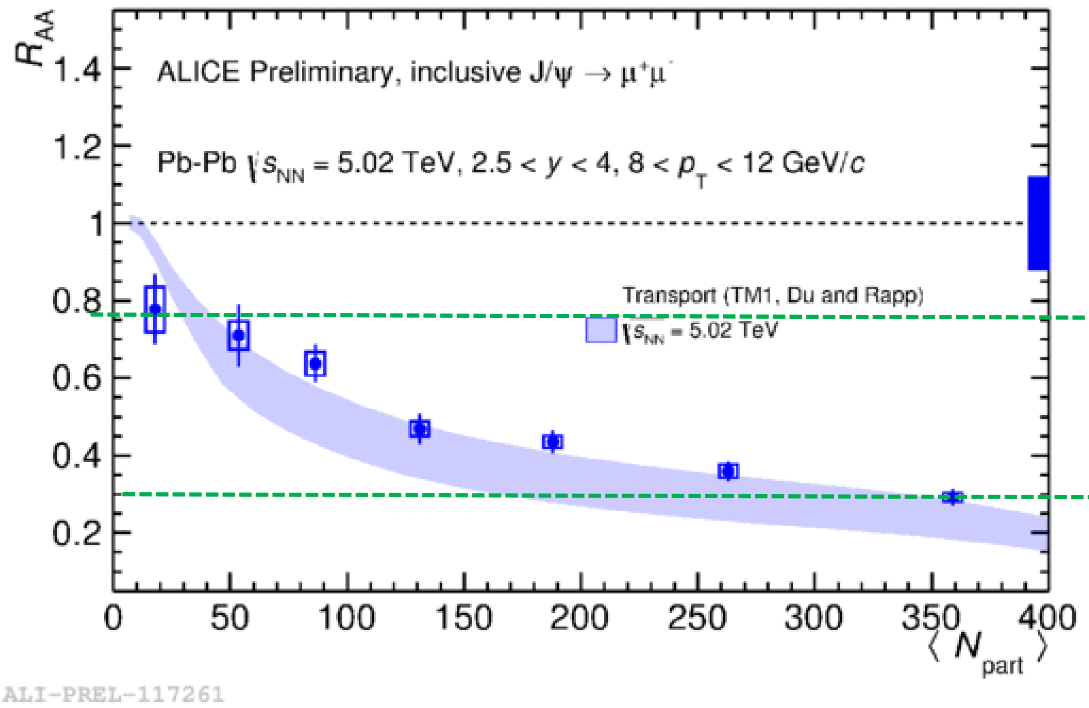
- **Consistent results on high p_T J/ψ** between ALICE and CMS (in spite of different energy AND rapidity domain (forward vs central y))

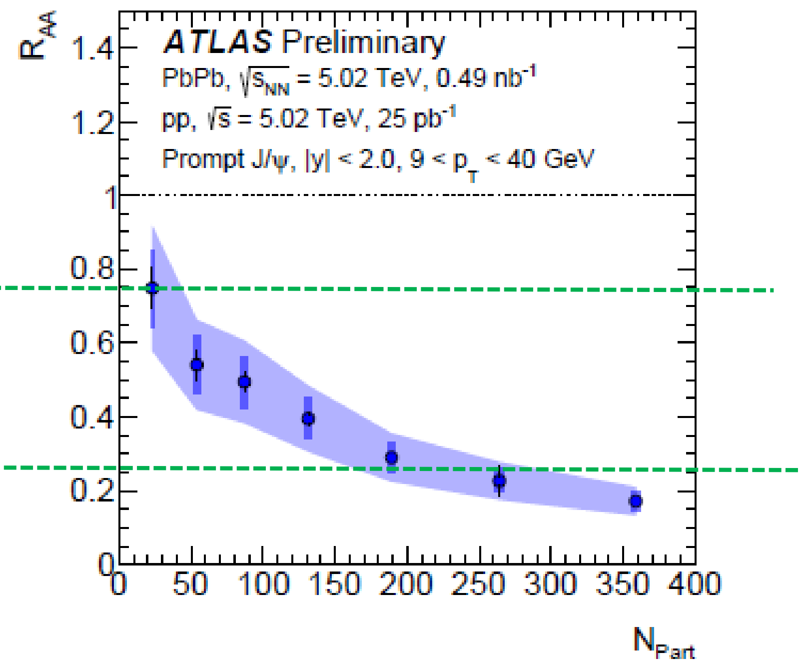
High-p_T J/ψ - ALICE vs CMS



- **Consistent results on high p_T J/ψ** between ALICE and CMS (in spite of different energy AND rapidity domain (forward vs central y))

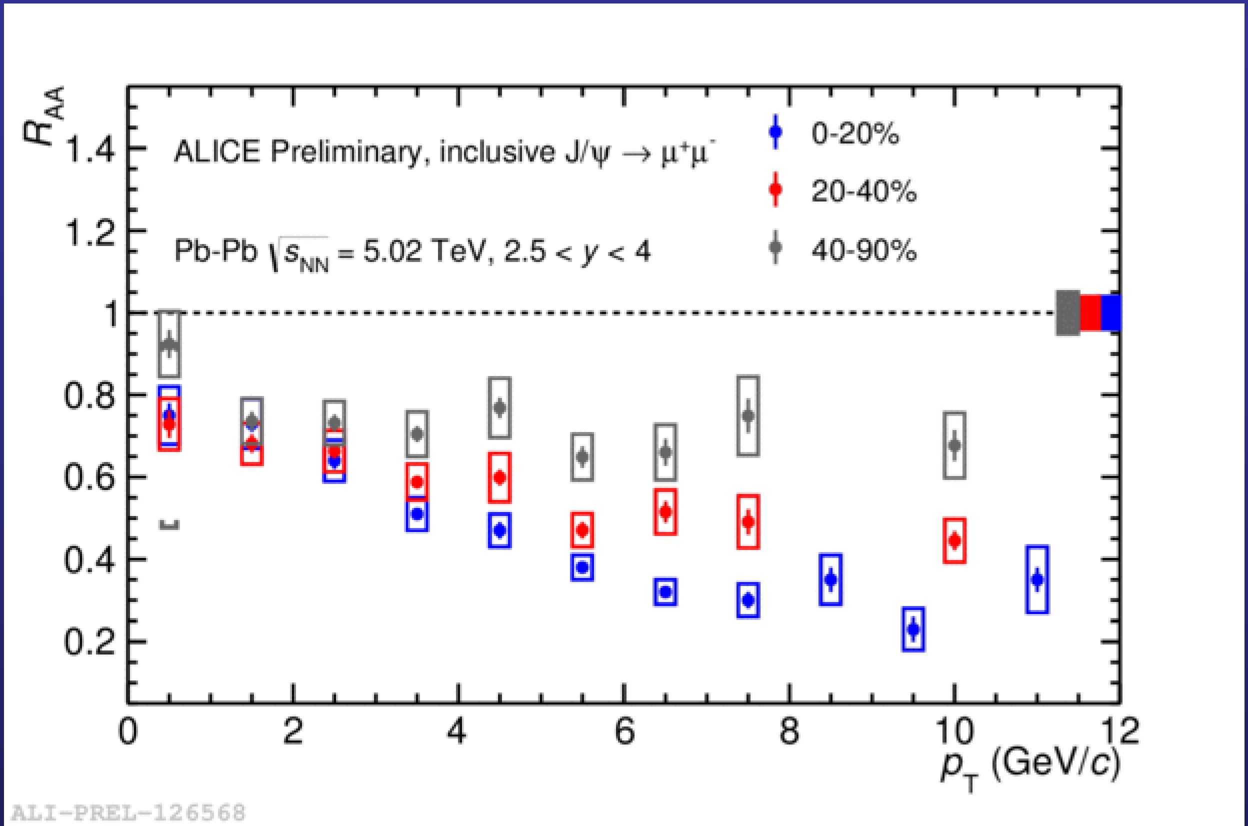
High-p_T J/ψ - ALICE vs ATLAS





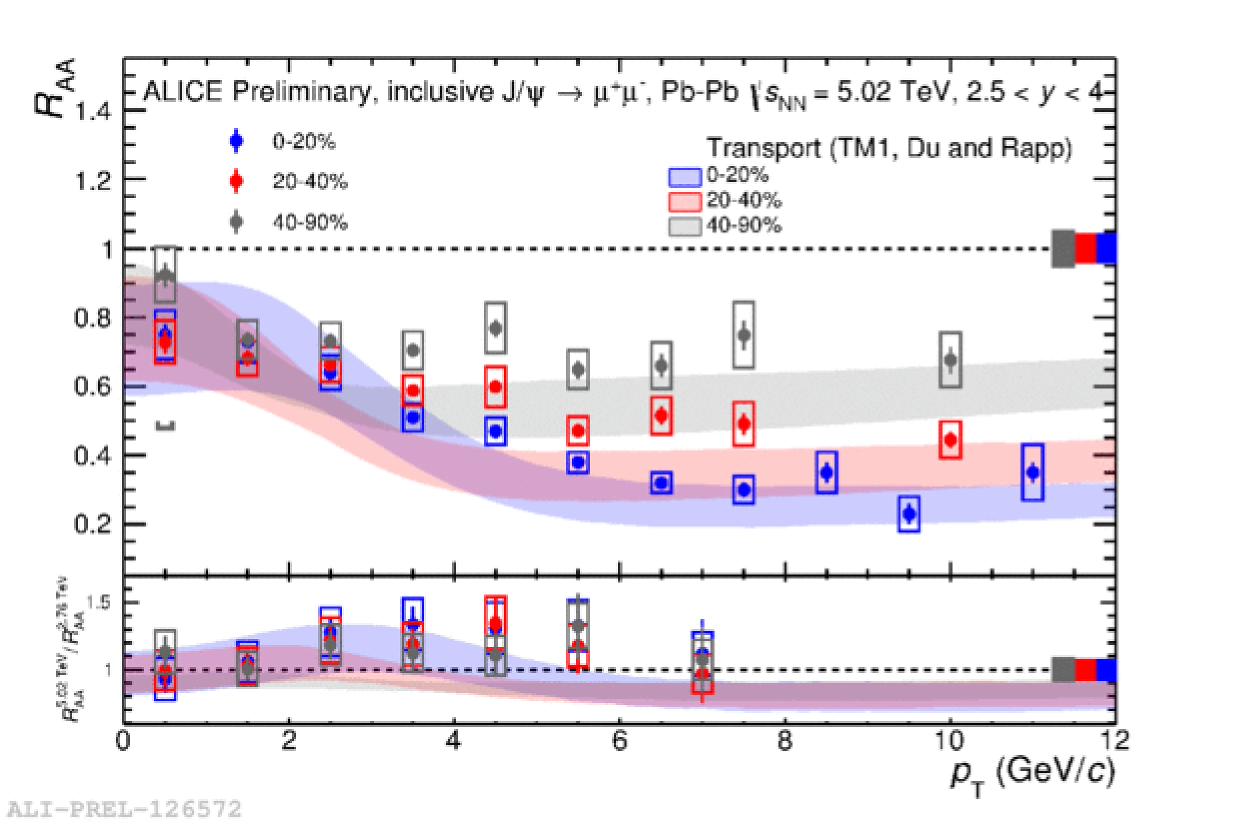
- **Consistent results on high p_T J/ψ** between ALICE and ATLAS (here same energy and different rapidity range)
- Hint for stronger suppression at mid-rapidity for central events (R_{AA}~ 0.2 vs 0.3) ?
- Warning: inclusive vs prompt!

R_{AA} vs p_T – for various centralities



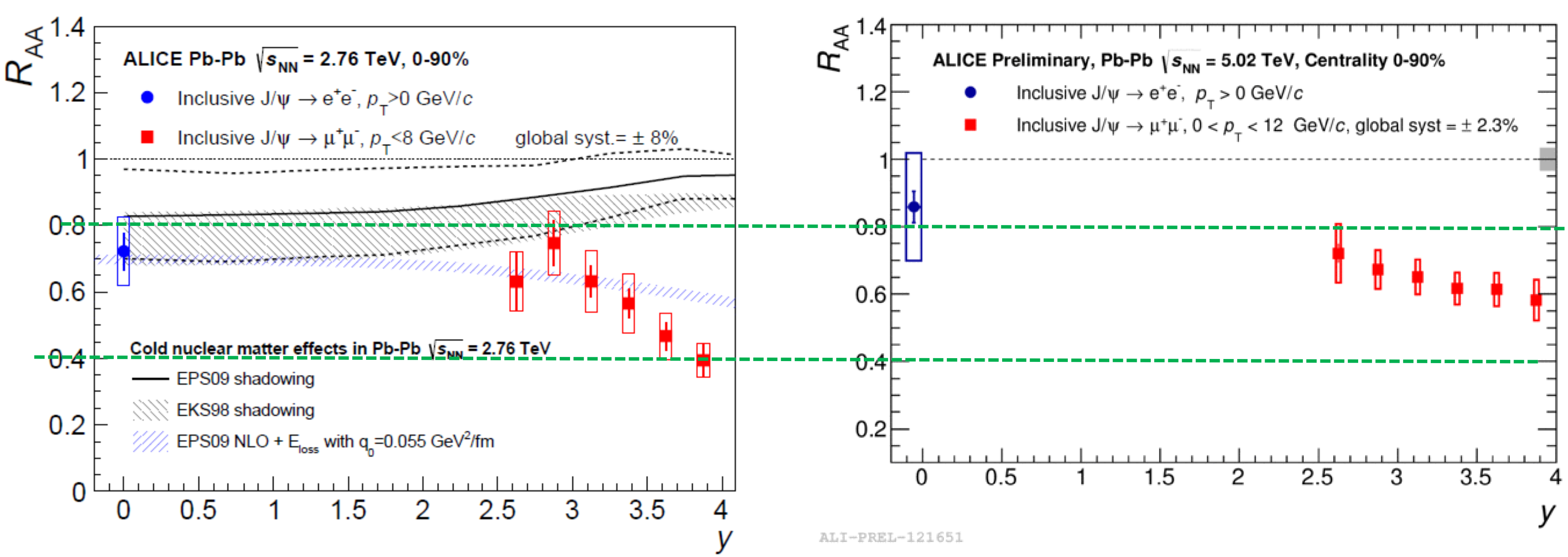
- ❑ Complementary information to R_{AA} vs centrality in p_T bins
- ❑ **From no to strong increase of R_{AA}** at low p_T going to central events

R_{AA} vs p_T – for various centralities



- Complementary information to R_{AA} vs centrality in p_T bins
- **From no to strong increase of R_{AA}** at low p_T going to central events
- Theory comparison → some tension for semi-peripheral events

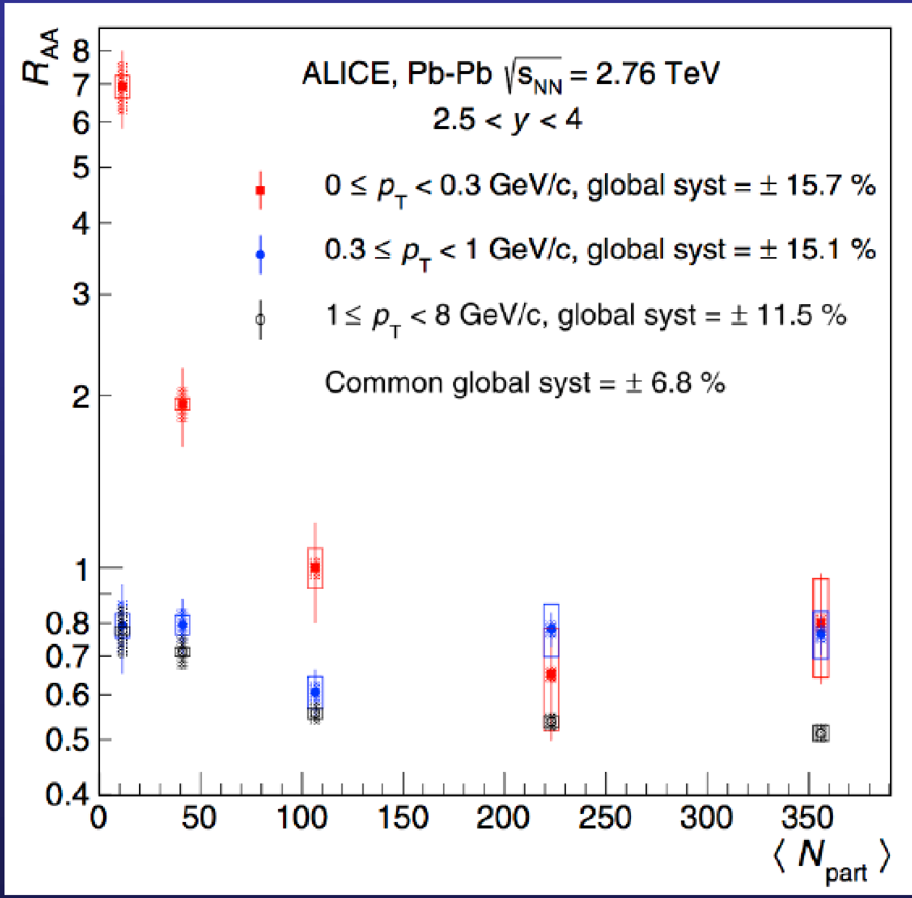
R_{AA} vs y



- Suppression agrees with foreseen shadowing effects at not too large y (balance of suppression and regeneration effects?)
- **Steeper rapidity dependence seems present at $\sqrt{s_{NN}}$=2.76 TeV**
- Hardly related to the slightly different p_T coverage

(Very) low-p_T J/ψ

- 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)



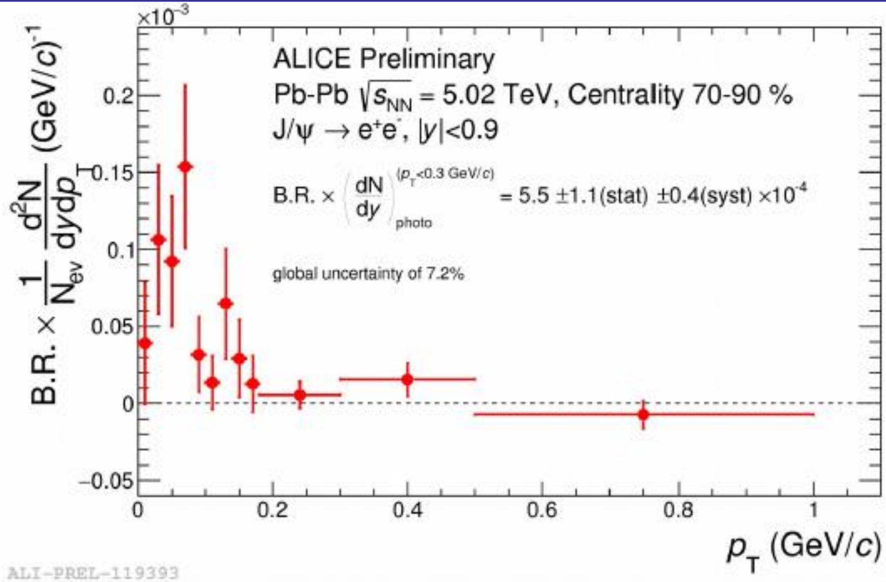
- Likely due to **photoproduction** in events with b<2R (recently observed at RHIC too!)

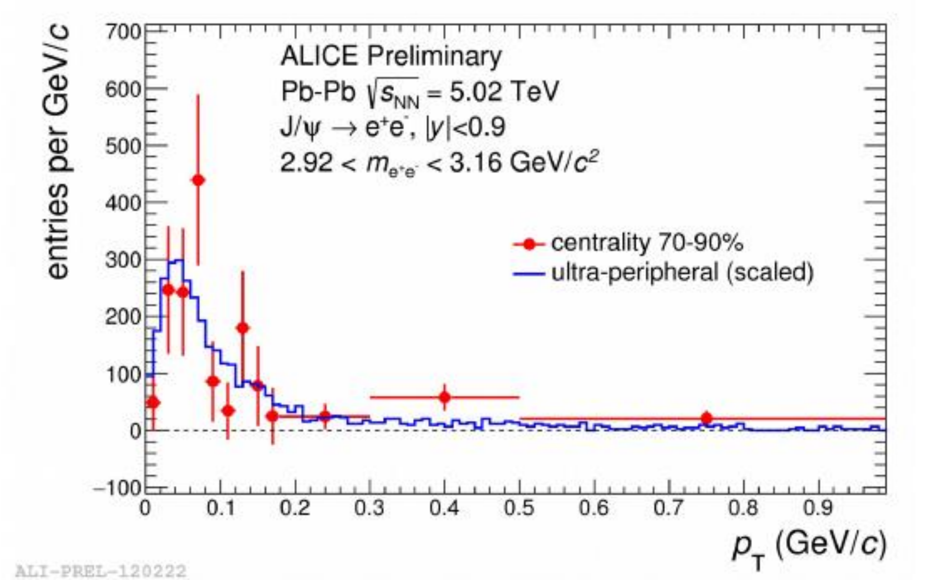
- ~75% of the signal expected for p_T<0.3 GeV/c
- ALICE **peripheral R_{AA} lowers by max 20%** when photoproduction removed

- 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

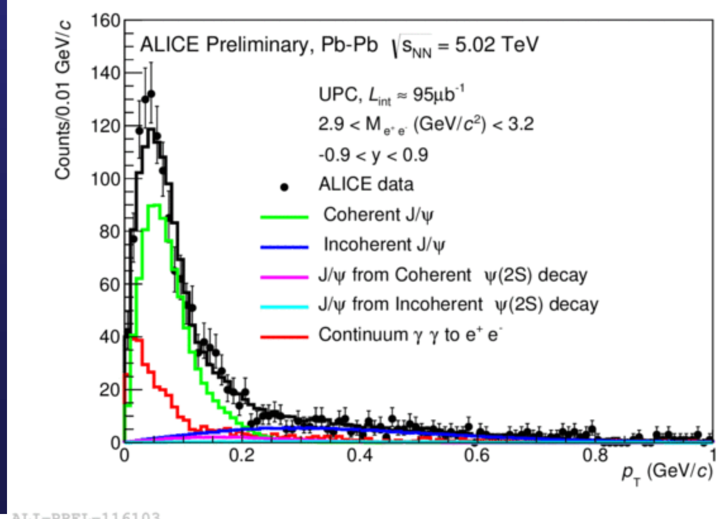
If under theory control, could it be used as a probe of hot matter ?

(Very) low p_T J/ψ

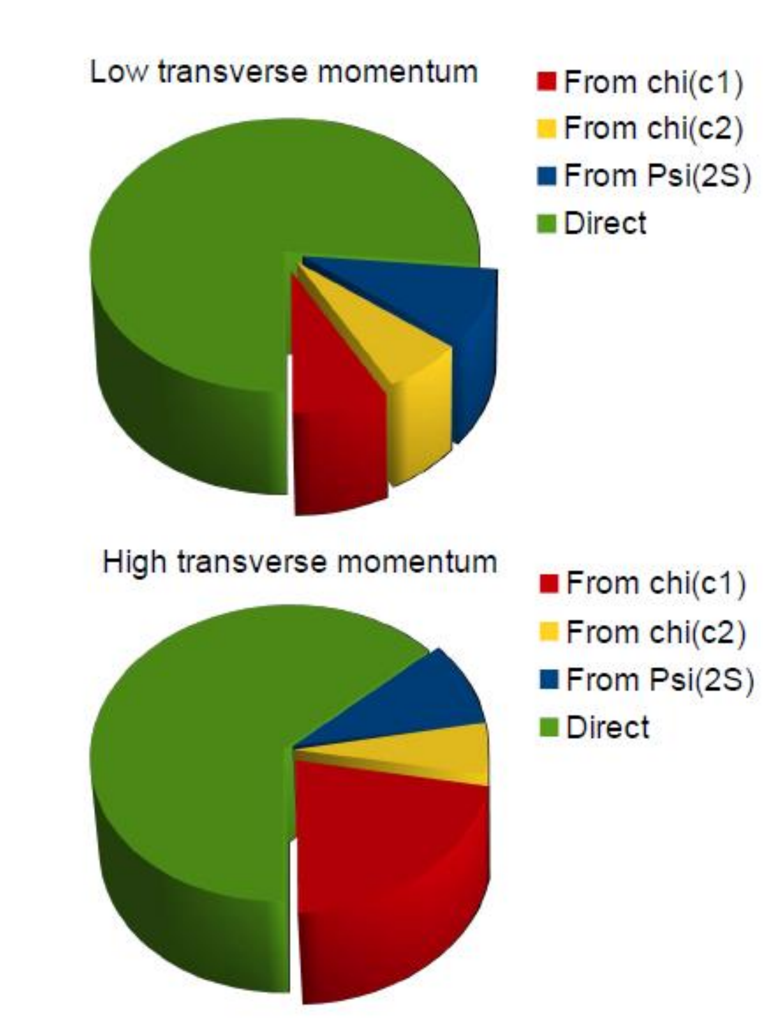




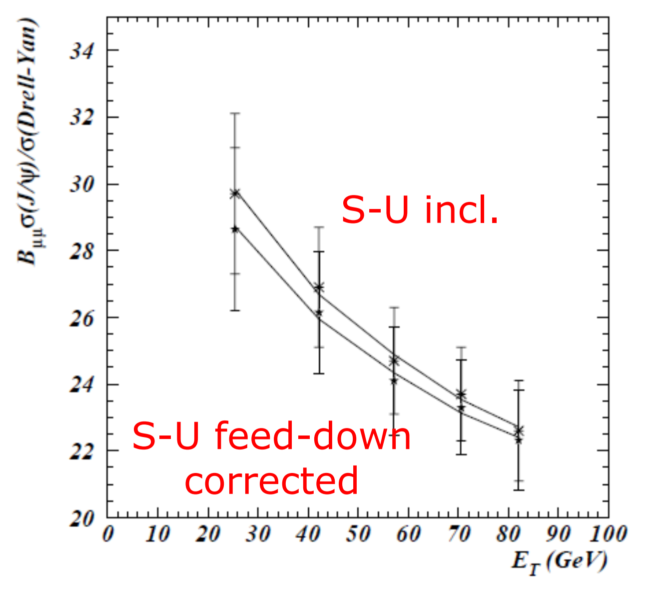
- Low-p_T J/ψ excess recently seen **also at central rapidity**
- Signal is compatible with the one observed in ultra-peripheral collisions (no hadronic activity)
- (Weaker) signal also observed for 50-70% centrality



Feed-down



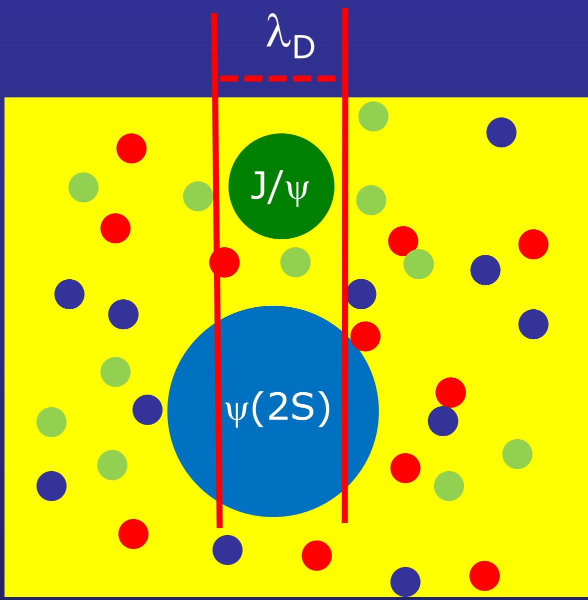
- ❑ Cannot be addressed precisely until today!
- ❑ If **ψ(2S) and χ_c** were precisely measured in Pb-Pb their contribution could be subtracted out and obtain **direct J/ψ**
- ❑ Explicitly done (only ?) by NA50, for ψ(2S) when comparing p-A and S-U data



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

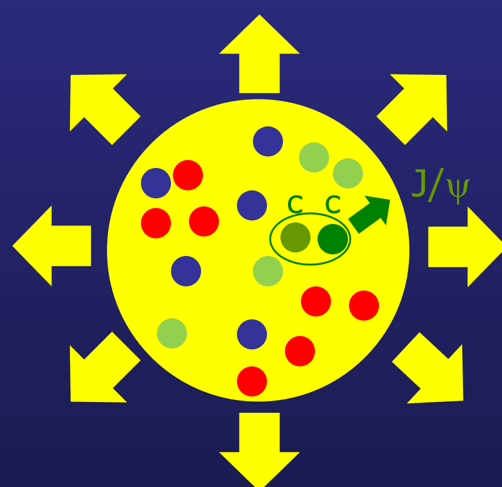
ψ(2S) in Pb-Pb

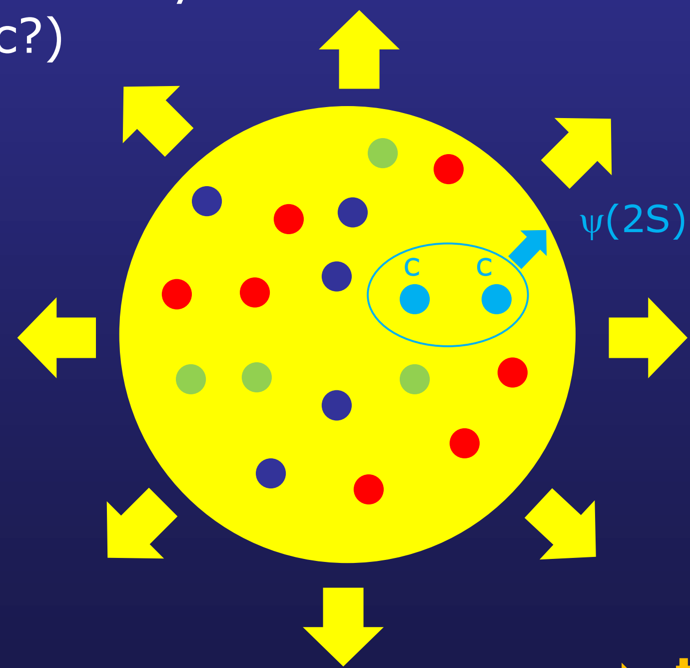
- Binding energy ~$(2m_D - m_\psi)$ → **ψ(2S) ~ 60 MeV, J/ψ ~ 640 MeV**



- Expect **much stronger dissociation effects** for the weakly bound ψ(2S) state

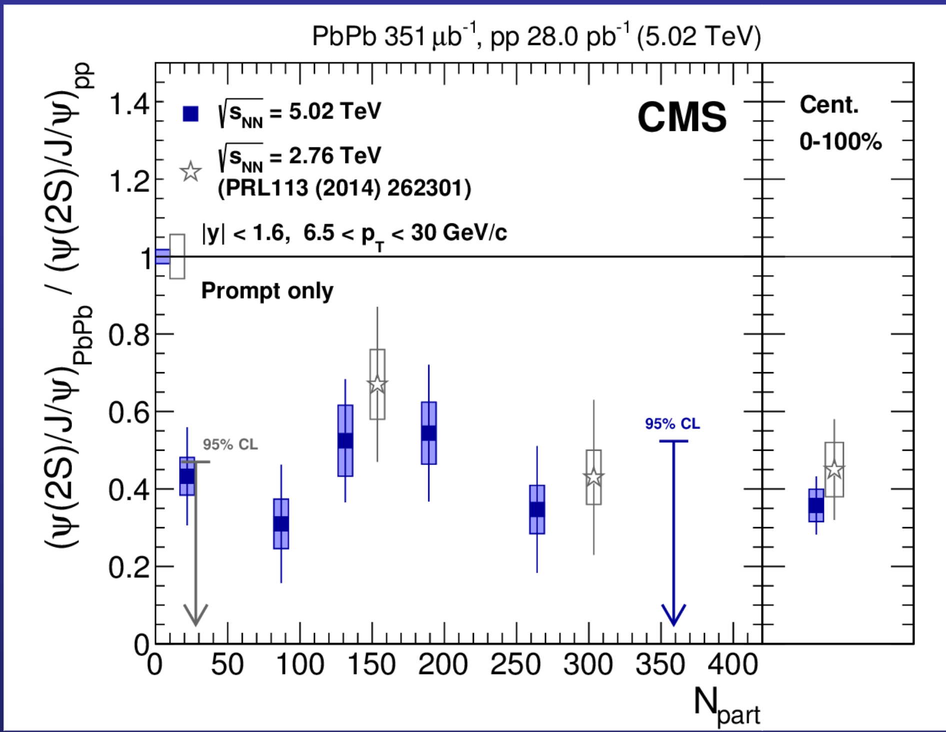
- Effect of re-combination on ψ(2S) more subtle
  → important when the system is **more diluted** (even hadronic?)

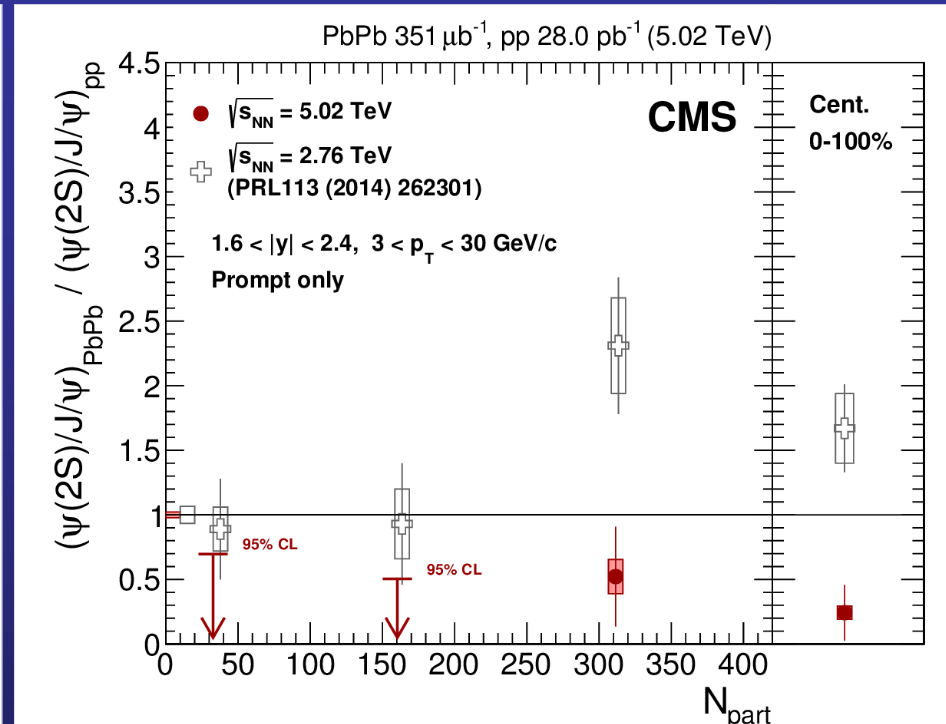




Important test for models!

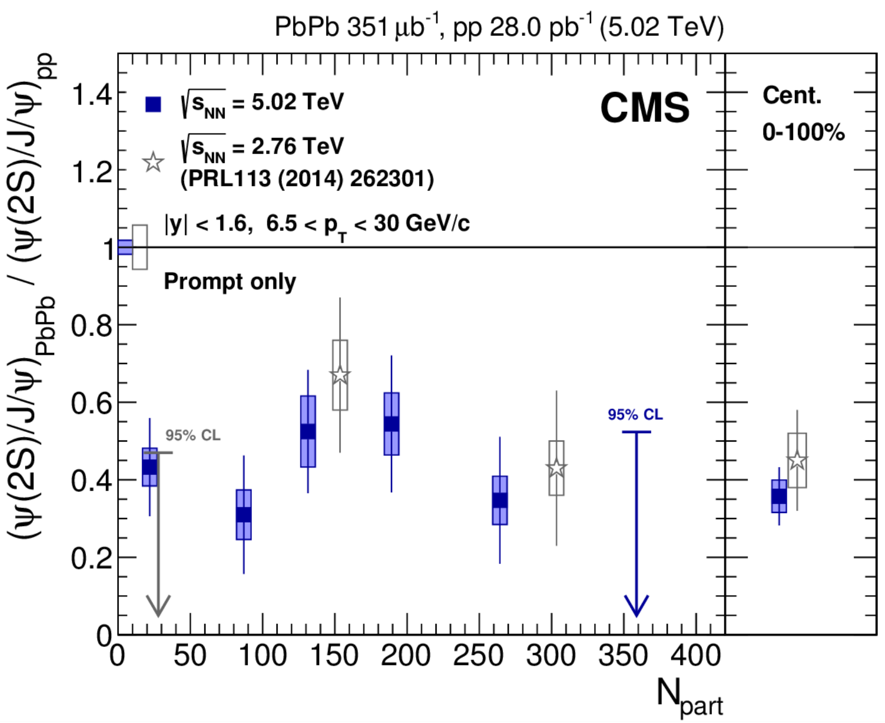
ψ(2S): 5.02 vs 2.76 TeV

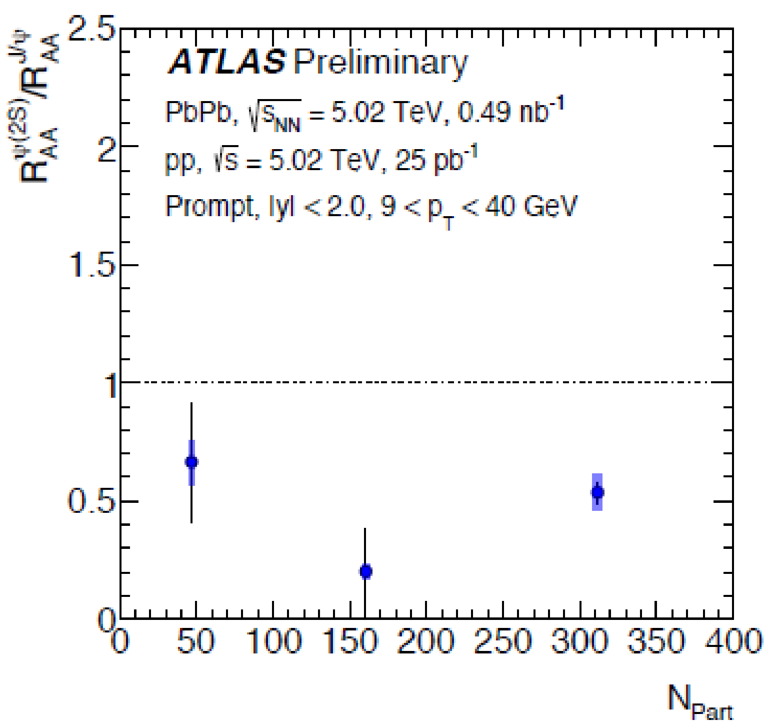




- CMS studies two p_T ranges: high (6.5-30 GeV/c) and low (3-30 GeV/c) p_T
- **High p_T**
  → strong suppression wrt J/ψ at both $\sqrt{s_{NN}}$=2.76 and 5.02 TeV
- **Intermediate p_T**
  →from enhancement at $\sqrt{s_{NN}}$=2.76 TeV to suppression at 5.02 TeV

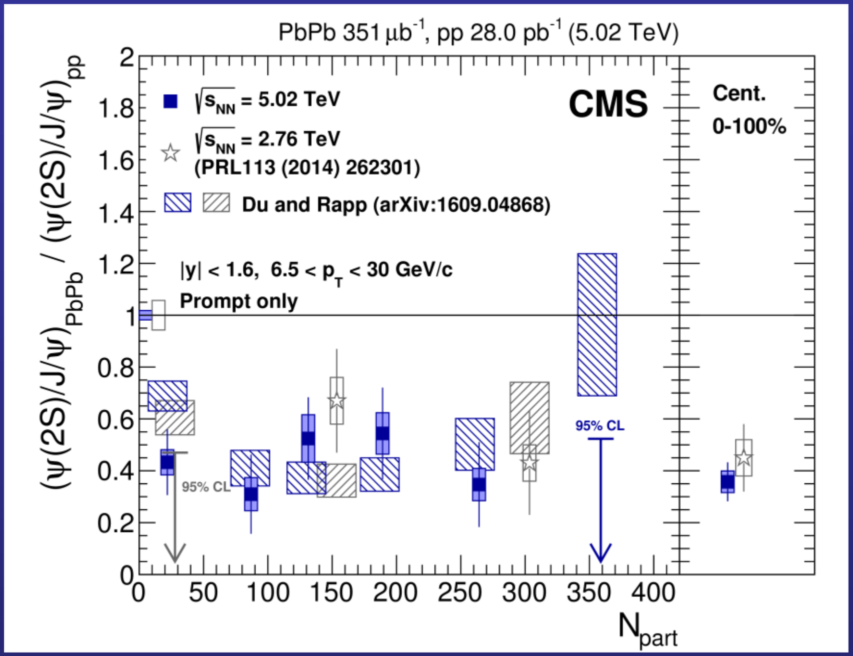
ψ(2S): 5.02 vs 2.76 TeV

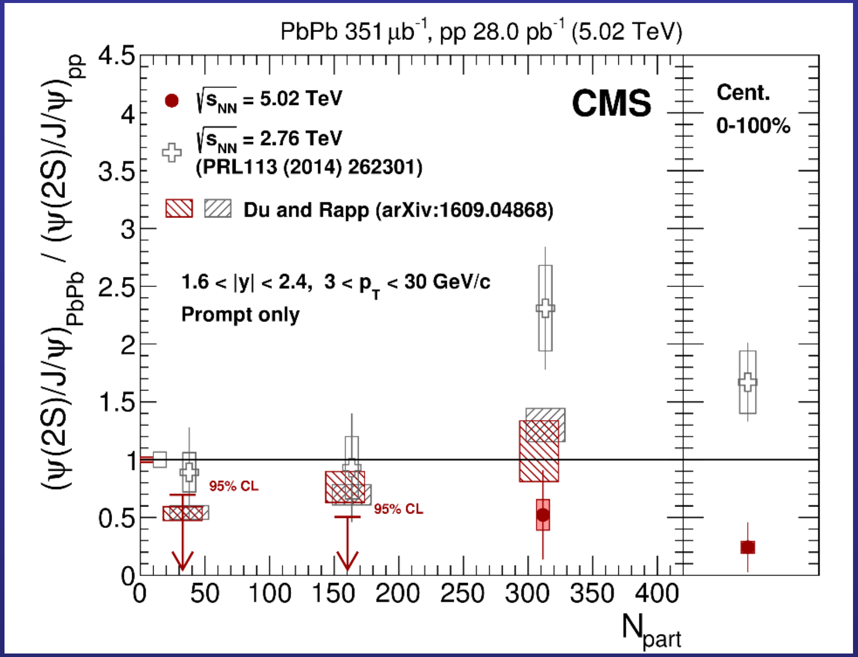


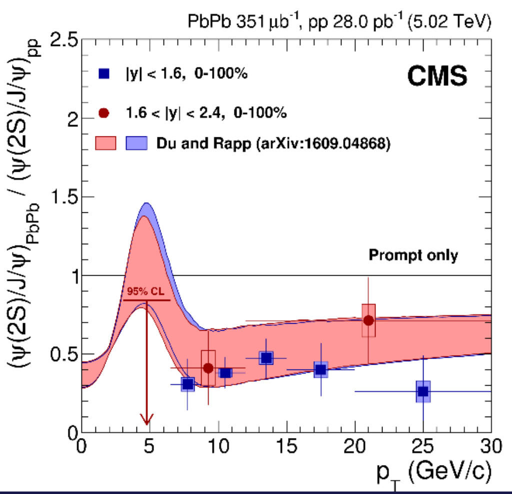


- ❑ CMS studies two p_T ranges: high (6.5-30 GeV/c) and low (3-30 GeV/c) p_T
- ❑ **High p_T**
  → strong suppression wrt J/ψ at both $\sqrt{s_{NN}}$=2.76 and 5.02 TeV
- ❑ **Intermediate p_T**
  →from enhancement at $\sqrt{s_{NN}}$=2.76 TeV to suppression at 5.02 TeV
- ❑ **ATLAS confirms** suppression in the high-p_T region (9-40 GeV/c)

ψ(2S): 5.02 vs 2.76 TeV

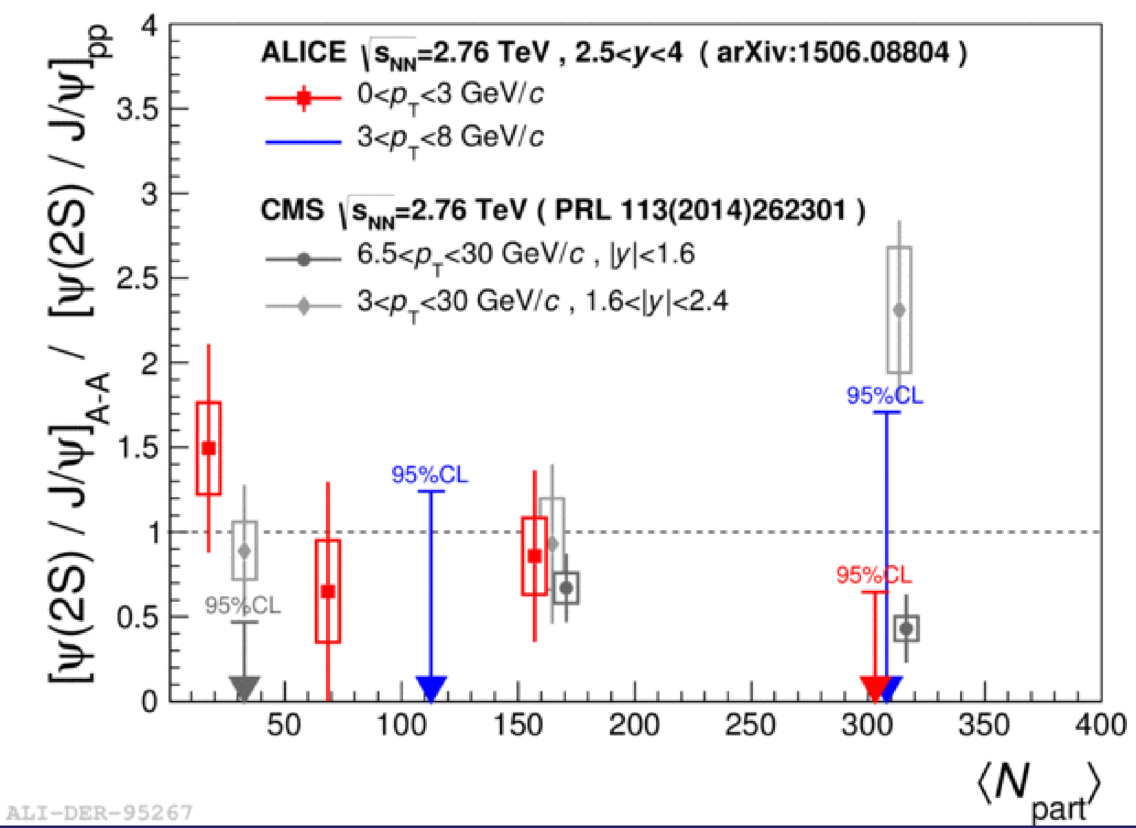






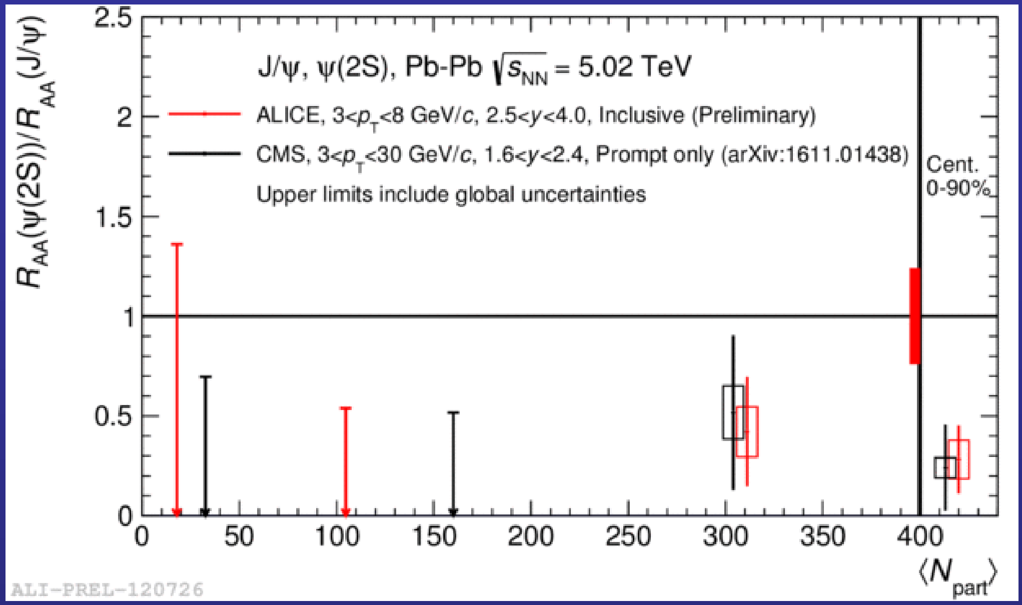
- **Hypothesis: ψ(2S) regeneration** occurring at higher p_T due to larger flow push
- Even in this way the $\sqrt{s_{NN}}$ results are not quantitatively reproduced
- Issue of ψ(2S) regeneration **still open!**

ALICE results

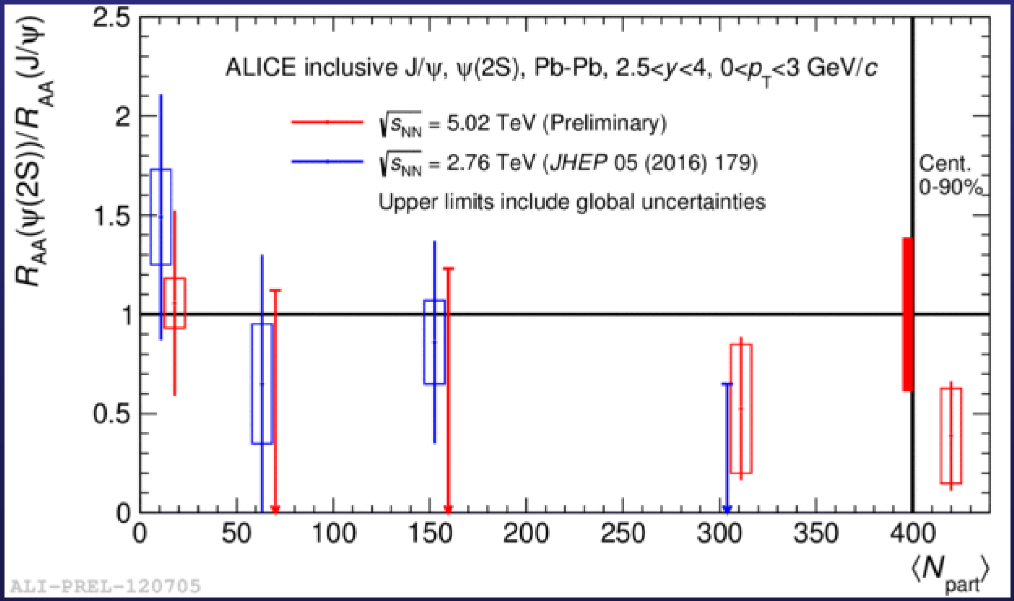


- Run 1
- Different y-range
- **Suppression at low p_T**
- **Results are not conclusive in $3<p_T<8$ GeV/c**, where CMS sees ψ(2S) enhancement, some tension may be present

ALICE results



- Run 2 results
- **Good agreement with CMS in the common p_T range**
- Agreement between $\sqrt{s_{NN}}$=2.76 and 5.02 TeV results in the low-p_T bin

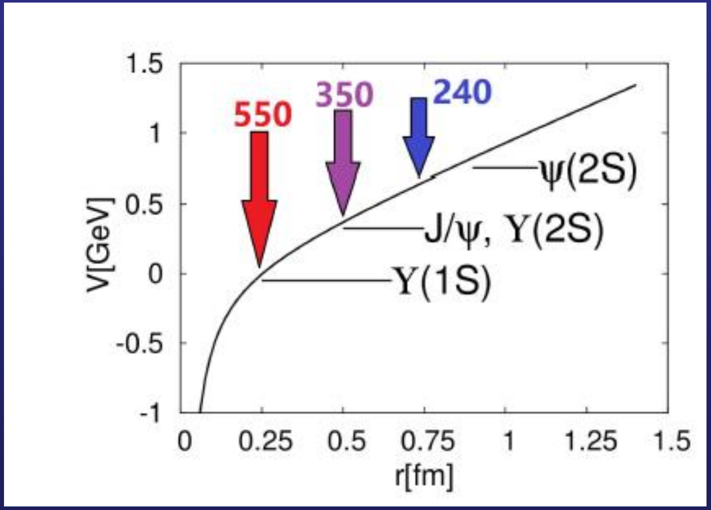


- Overall quality of the ψ(2S) results still needs improvement
- Accurate results in different kinematic ranges could constrain the fraction of primordial and regenerated charmonia, and be sensitive to different medium temperature and flow…

Bottomonium in A-A

- For high-energy collisions, several appealing features
- **Re-combination effects not strong** → simpler interpretation?
- **Υ(1S) very strongly bound**, $E_b=(2m_B-m_{\Upsilon(1S)}) \sim 1100$ MeV
  → probe of hot QGP
- Together with Υ(2S) (E_b~500 MeV) and Υ(3S) (E_b~200 MeV)
  → provide (very) different sensitivity to the medium

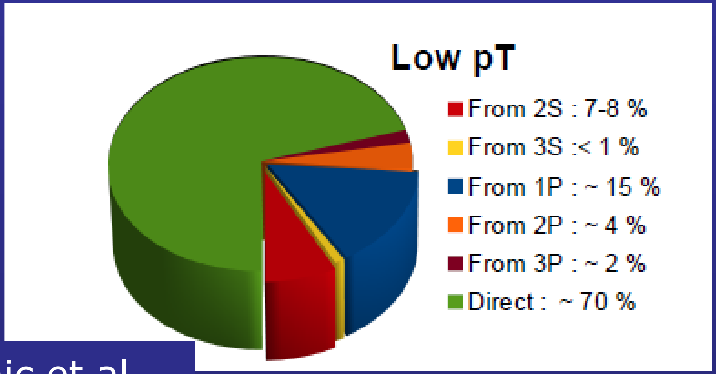
Can we finally rely T with quarkonium (dis)appearance ?

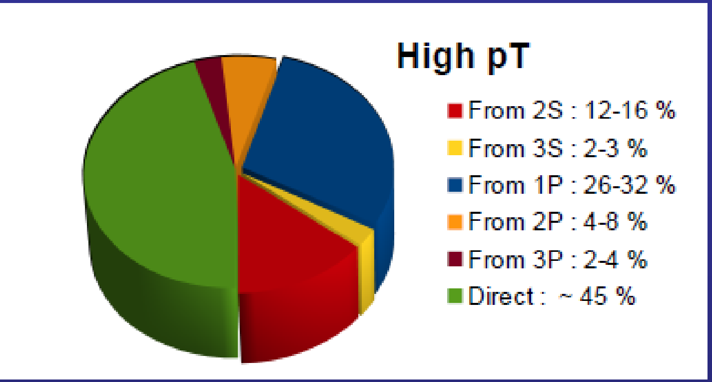


- Some interesting features of bottomonium
  - **Binding energy of Υ(2S) and J/ψ are very similar** → Role of regeneration for J/ψ should become evident, presence of regeneration for Υ more delicate to assess
  - Observation of **direct Υ(1S) suppression** would imply screening of the Coulomb part of the potential (Rapp)
    → can we reach experimental evidence for direct 1S suppression? Need control over feed-down and CNM effects

Feed-down

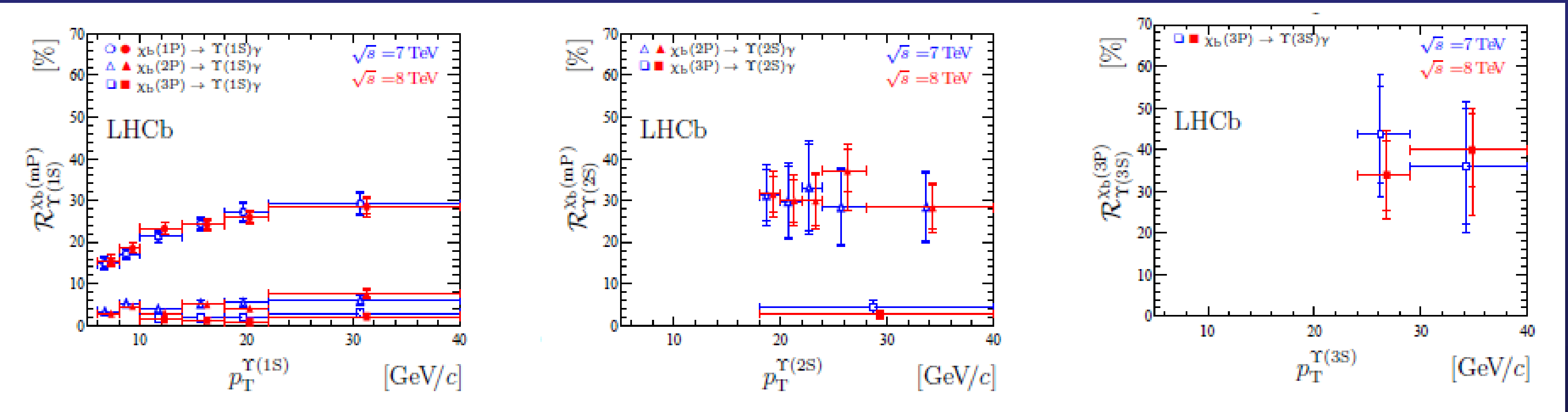
- The **feed-down** structure of the bottomonium sector is **not trivial**
  → has an impact on the interpretation of the results





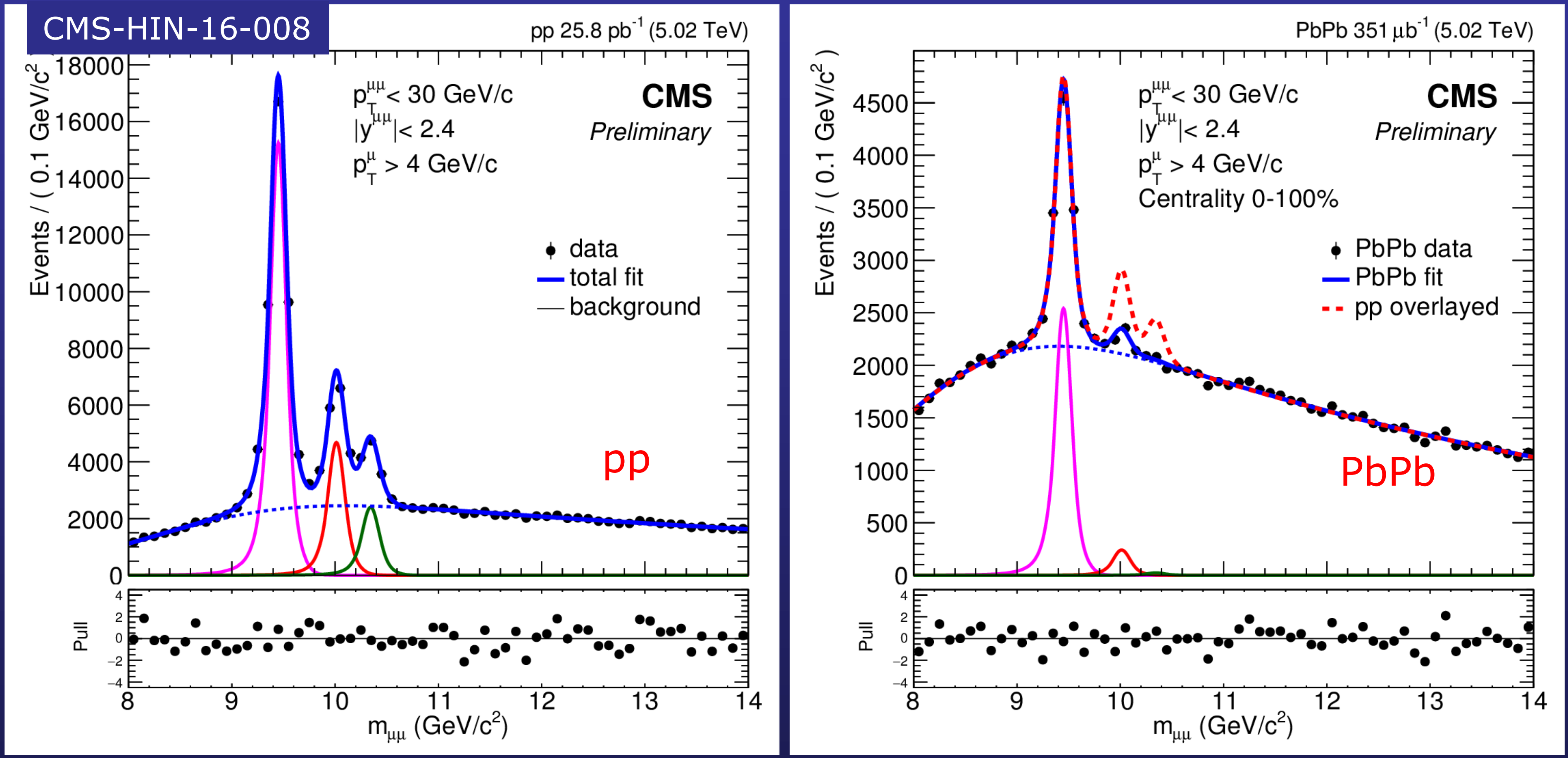
A. Andronic et al., EPJC 76 (2016) 107

Recent improvements thanks in particular to LHCb data!



Bottomonium (sequential) suppression ?

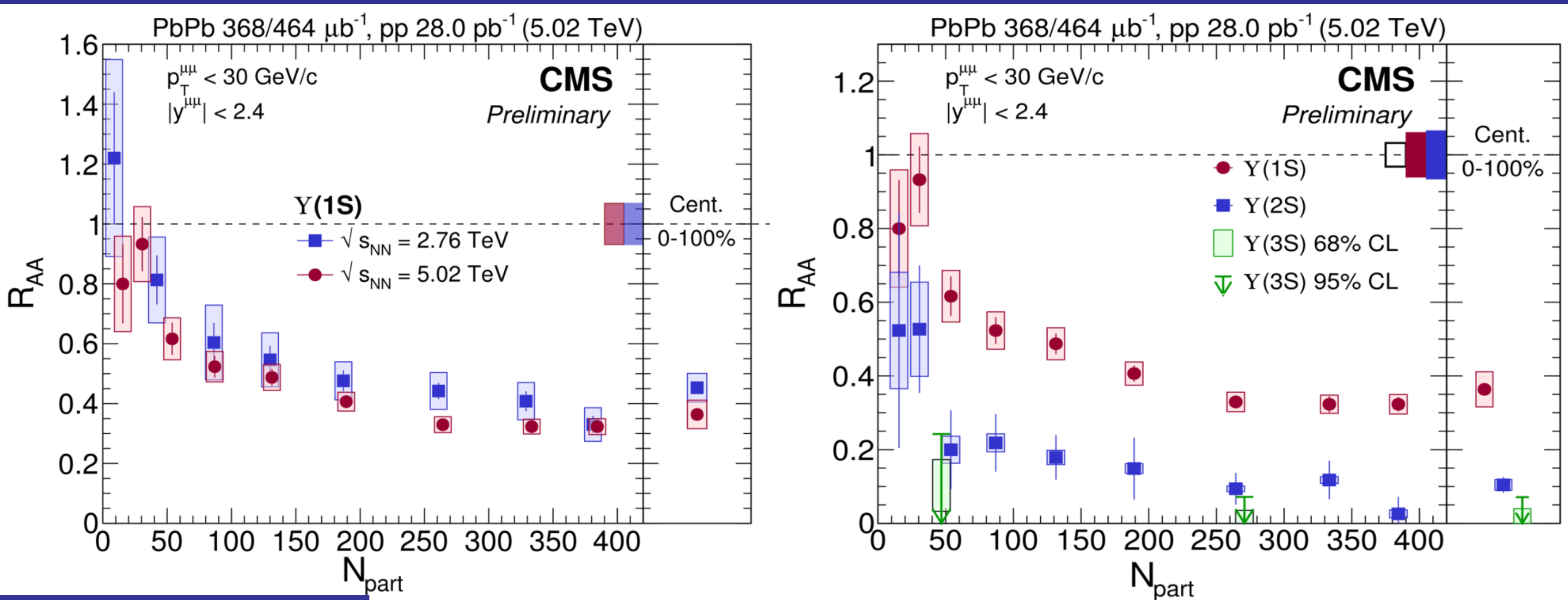
- Probably the **most spectacular result** from quarkonia in HI at the LHC



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

Recent R_{AA} results

- $\sqrt{s_{NN}}$=2.76 TeV, strong centrality dependence, **up to factor ~2 and ~8 suppression for ϒ(1S) and ϒ(2S), respectively**

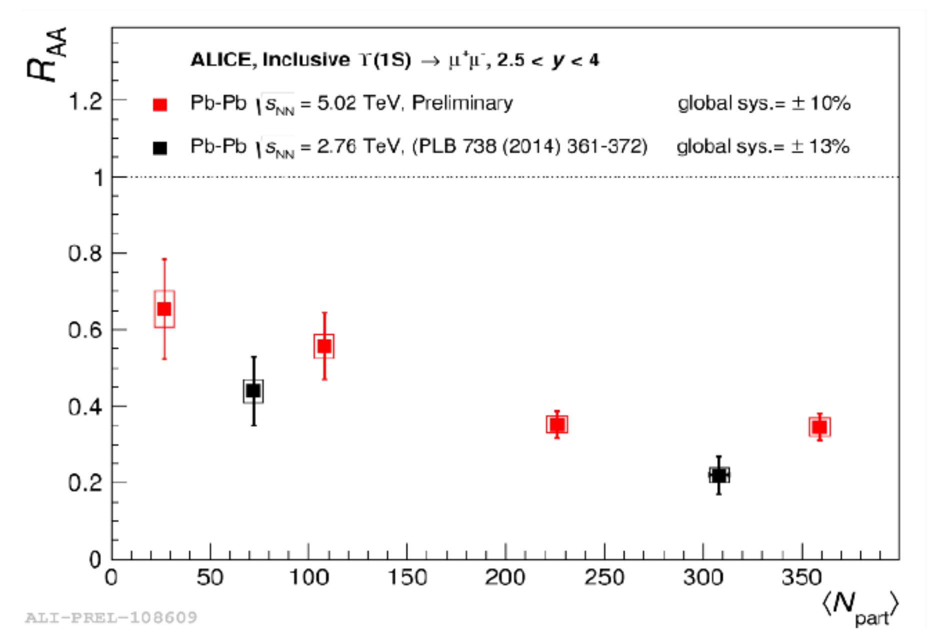


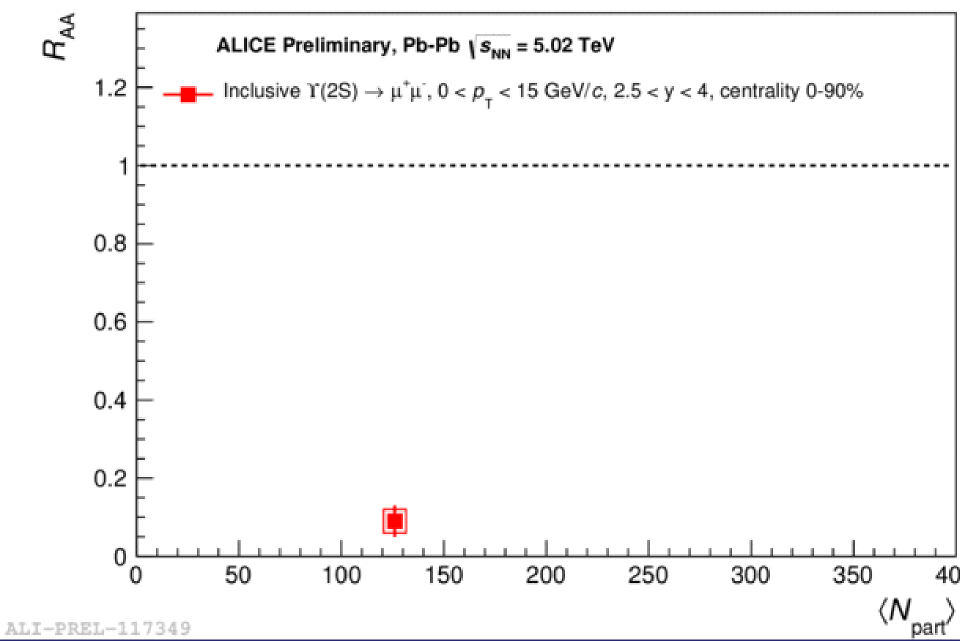
CMS-PAS-HIN16-023

V. Khachatryan et al.,CMS arXiv:1611.01510

- **New CMS results at $\sqrt{s_{NN}}$=5.02 TeV**
  - → Indications for slightly stronger suppression
  - → No ϒ(3S) left !

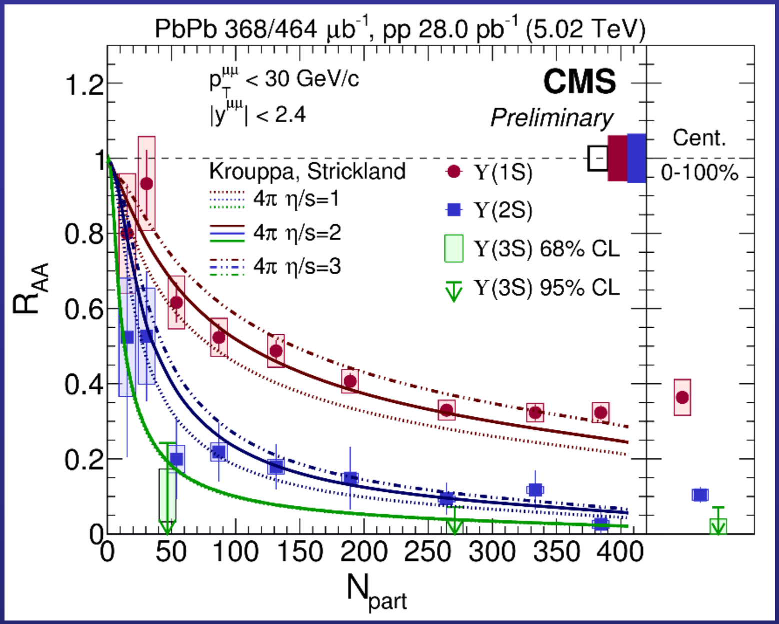
R_{AA} vs N_{part} – ALICE results

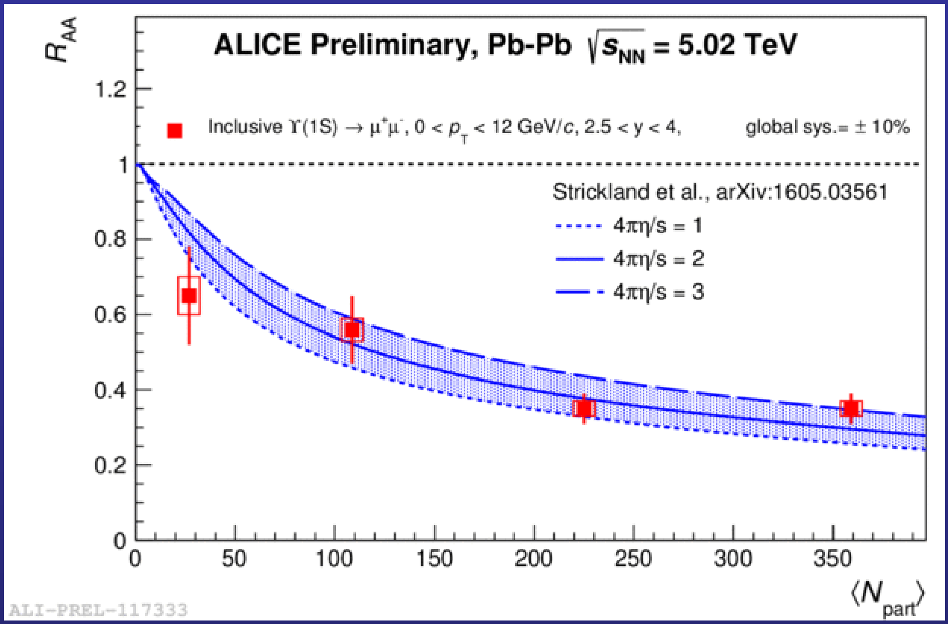


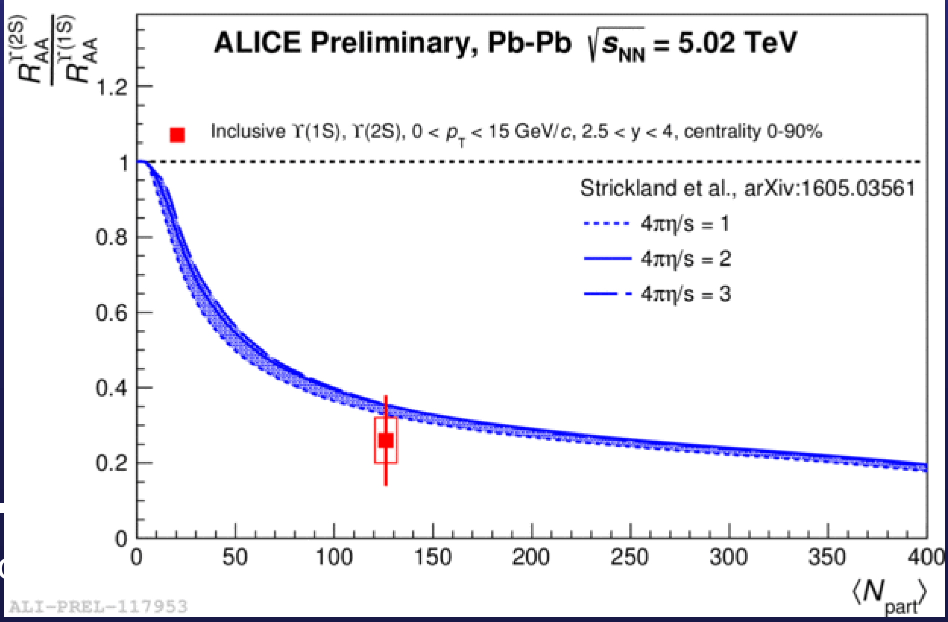


- **Complementary observations** in the range **2.5<y<4**
- Qualitatively similar behavior at central (CMS) and forward (ALICE) y
  - ϒ(1S) suppression similar at the two energies
  - Stronger suppression for ϒ(2S) wrt ϒ(1S) at 5.02 TeV

Theory calculations

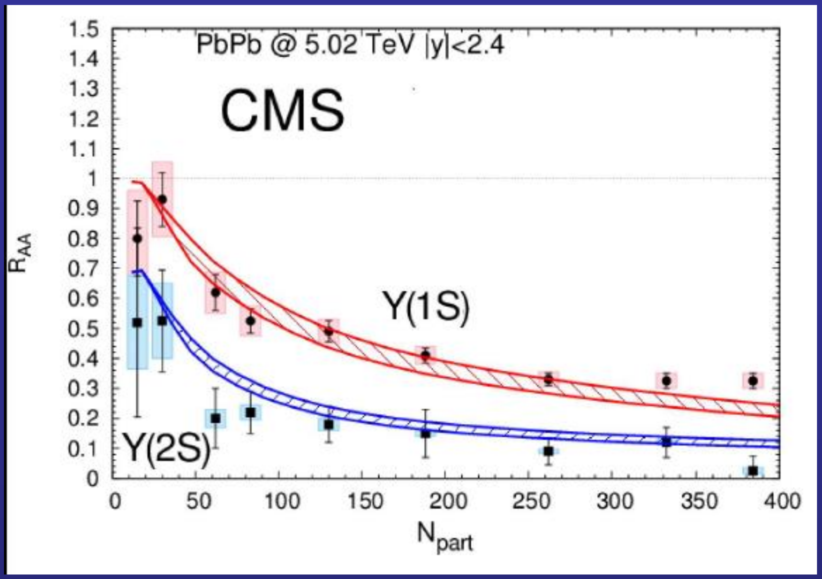


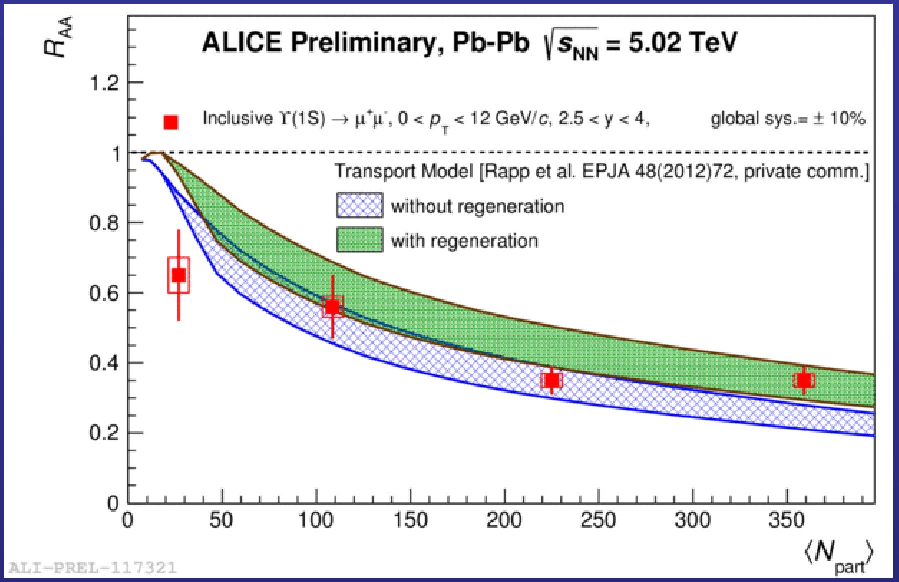


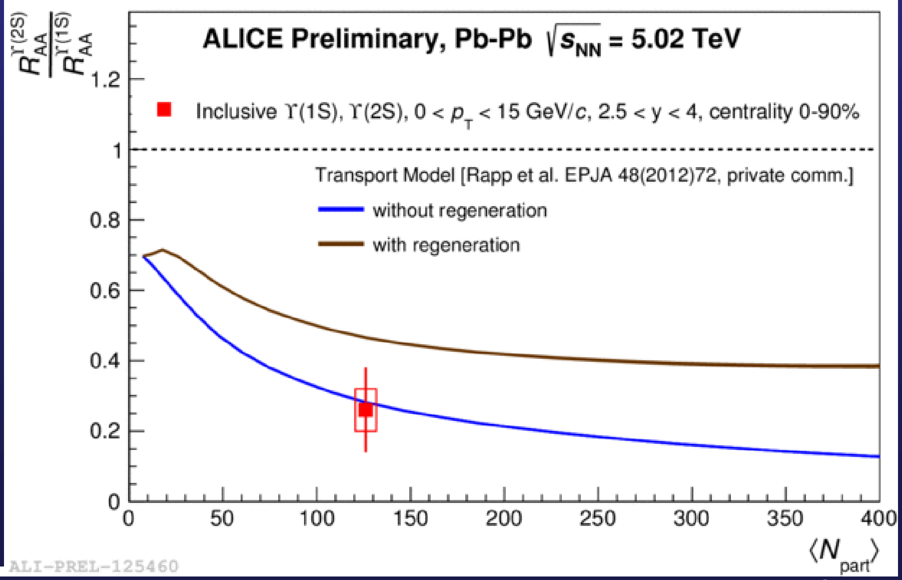


- **Anisotropic hydrodynamical model** (Strickland)
- Good description of the $\sqrt{s_{NN}}$=5.02 TeV data for both 1S and 2S states
  - No regeneration component
  - No CNM effects

Theory calculations







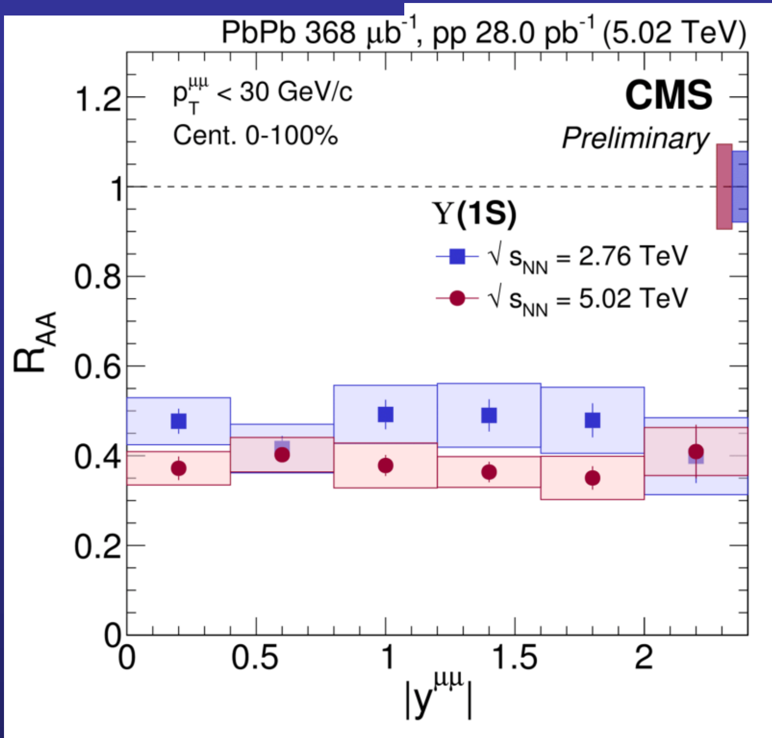
- **Transport model (Rapp)**
- Good description of the $\sqrt{s_{NN}}$=5.02 TeV data for 1S
  - Regeneration component small for Υ(1S) → not clearly needed
  - Includes CNM effects
- For Υ(2S) at forward-y, regeneration effects look overestimated

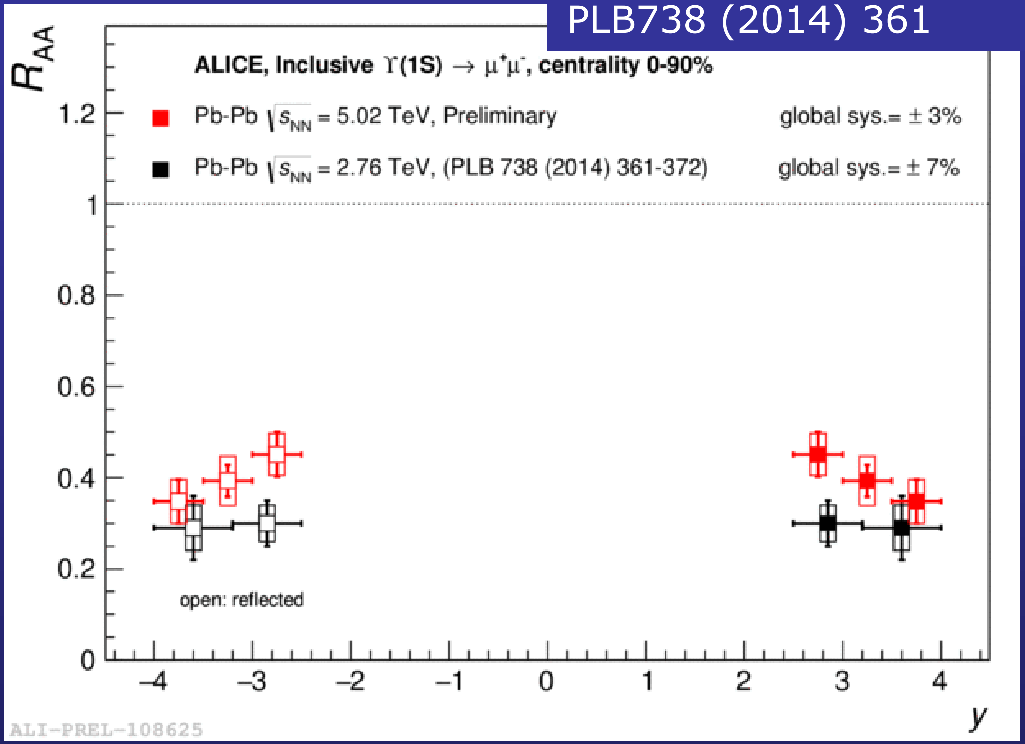
V. Khachatryan et al., CMS arXiv:1611.01510

CMS-PAS-HIN16-023

R_{AA} vs y: ALICE and CMS Υ(1S)

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

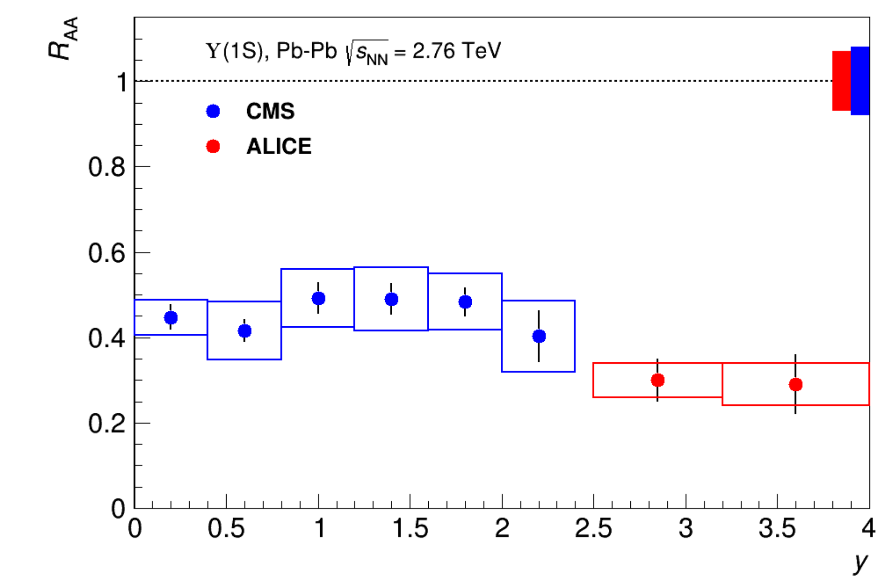


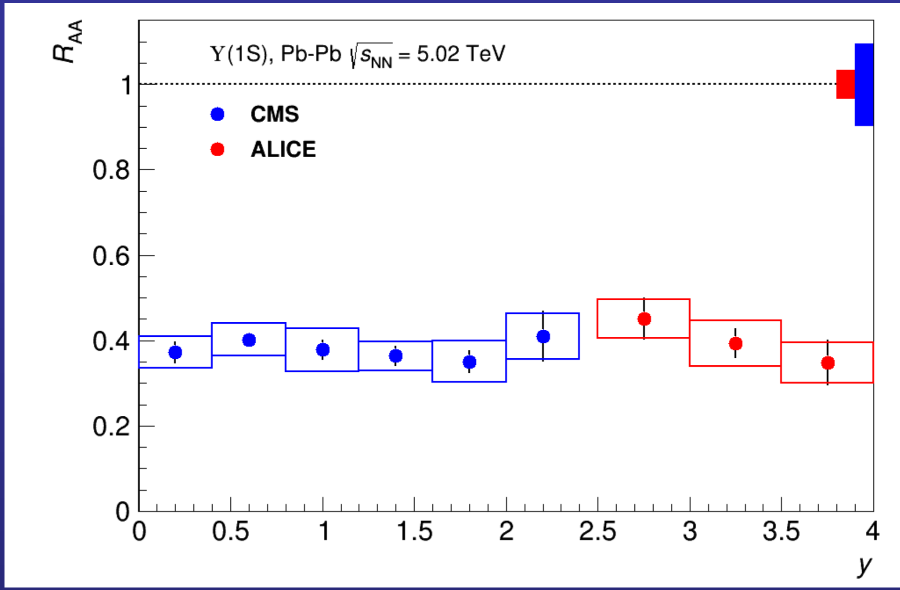


- Second look at ALICE vs CMS results
- ALICE → hints for **less suppression** at $\sqrt{s_{NN}}$= 5.02 TeV
- CMS → hints for **more suppression** at $\sqrt{s_{NN}}$= 5.02 TeV

- Compare R_{AA} vs y for the two experiments in a single plot

R_{AA} vs y: ALICE and CMS ϒ(1S)



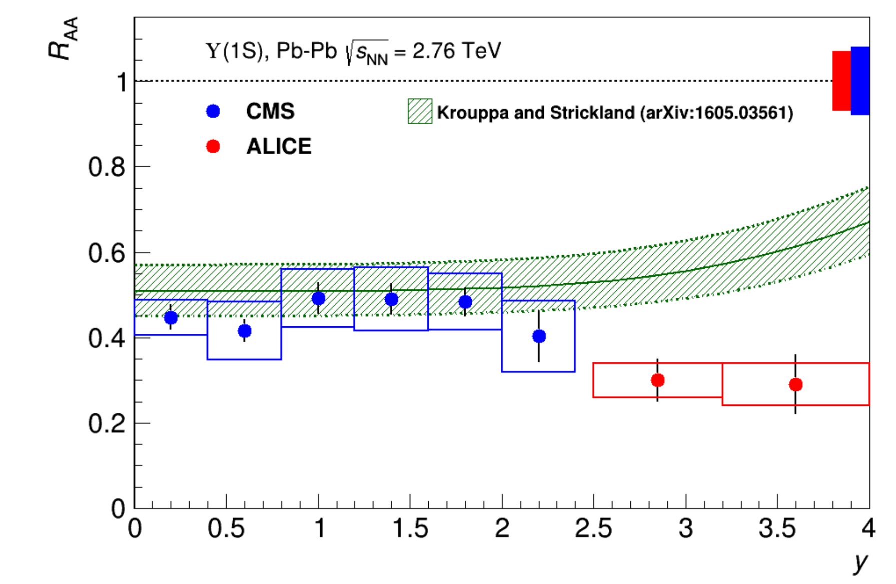


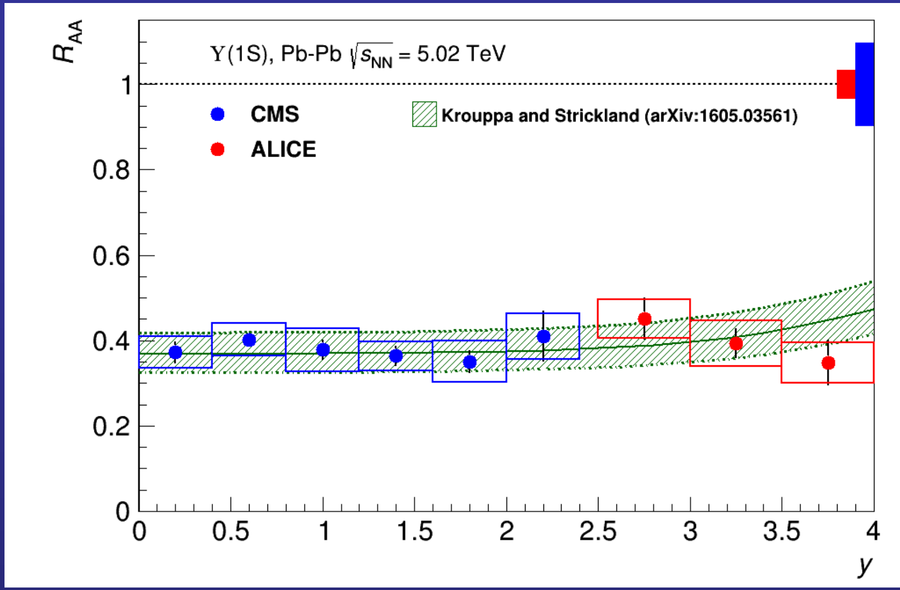
- Suppression **increases** with y at **$\sqrt{s_{NN}}$=2.76 TeV**
- Suppression **constant** vs y at **$\sqrt{s_{NN}}$=5.02 TeV**

- $\sqrt{s_{NN}}$=2.76 TeV: typical features of a **(re)generation pattern,** which seems to vanish at $\sqrt{s_{NN}}$=5.02 TeV

- Systematic uncertainties not negligible
- Can the y-dependence of CNM effects play a role? Not likely

R_{AA} vs y: ALICE and CMS Υ(1S)



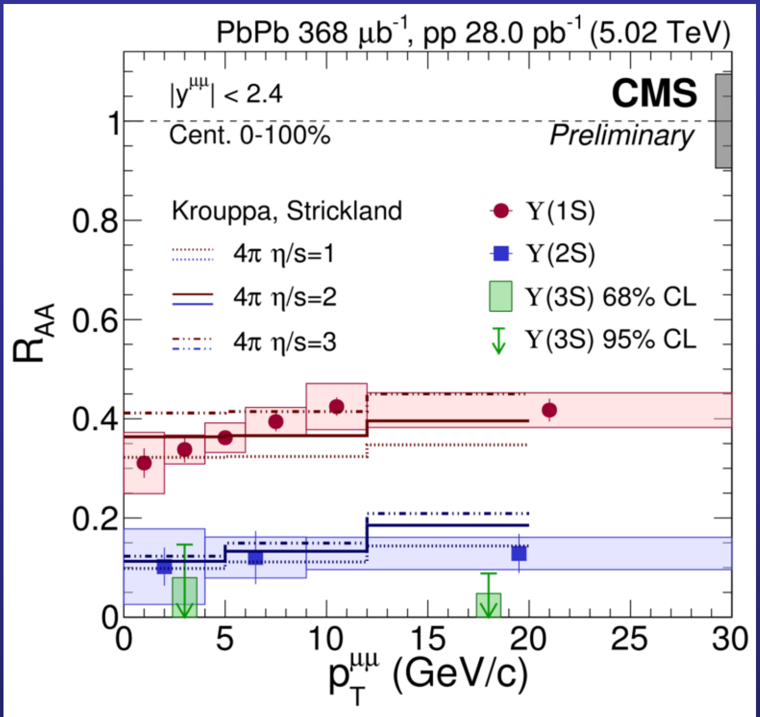


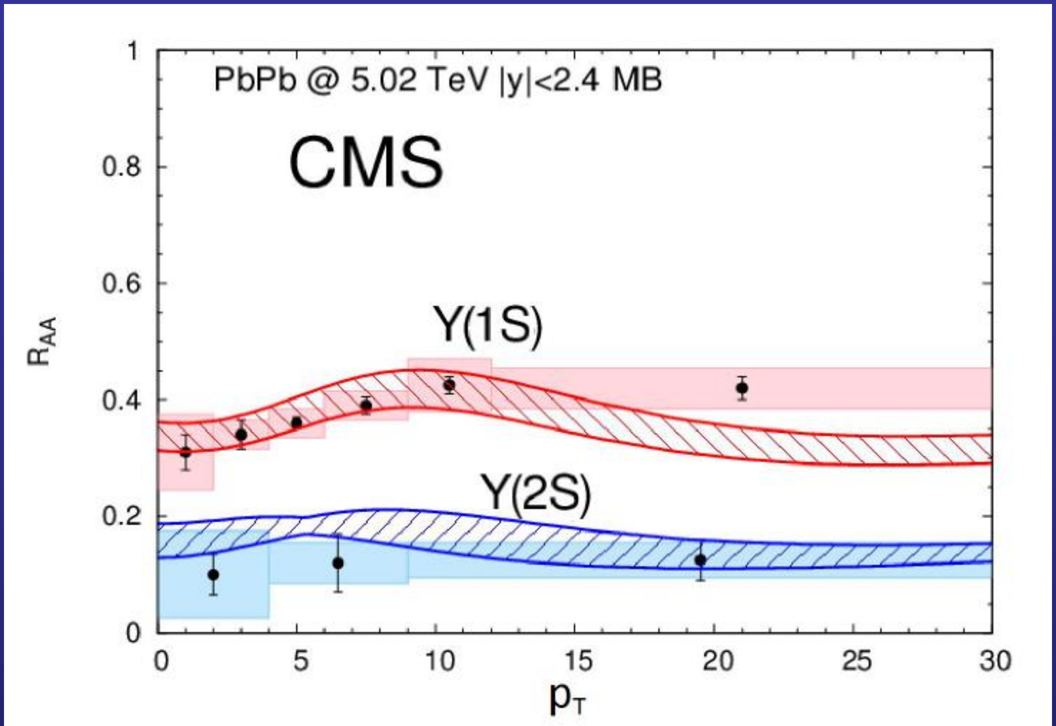
- Suppression **increases** with y at **$\sqrt{s_{NN}}$=2.76 TeV**
- Suppression **constant** vs y at **$\sqrt{s_{NN}}$=5.02 TeV**

- $\sqrt{s_{NN}}$=2.76 TeV: typical features of a **(re)generation pattern,** which seems to vanish at $\sqrt{s_{NN}}$=5.02 TeV

- Systematic uncertainties not negligible
- Can the y-dependence of CNM effects play a role? Not likely

R_{AA} vs p_T: CMS ϒ(1S) and ϒ(2S)



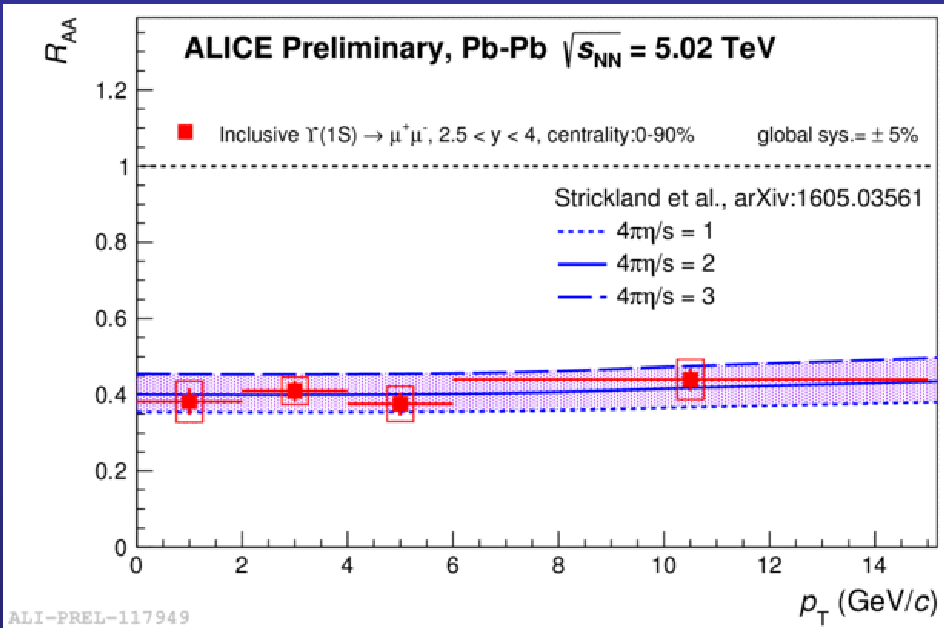


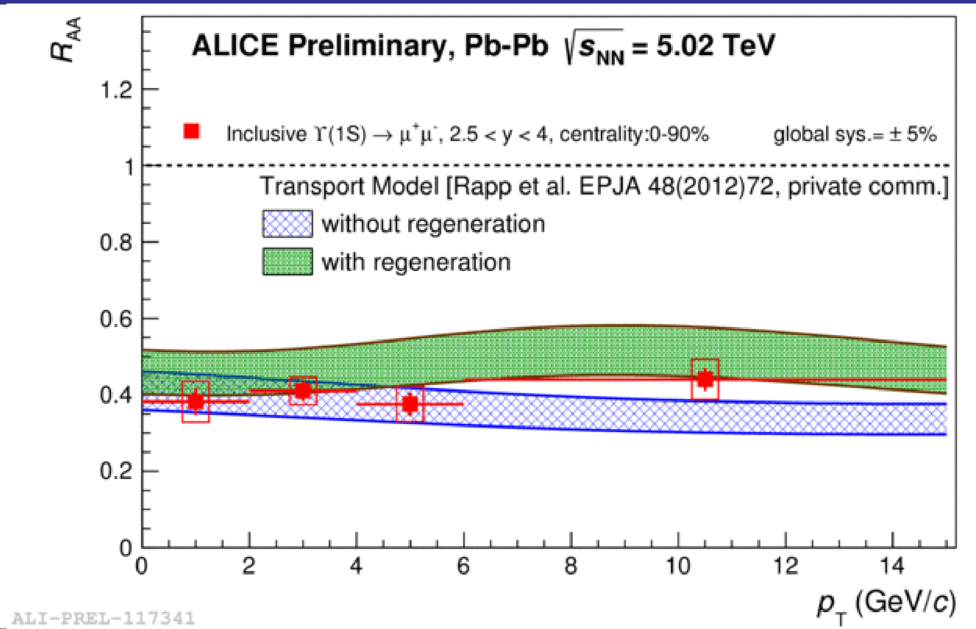
V. Khachatryan et al., CMS arXiv:1611.01510

CMS-PAS-HIN16-023

- **Weak or no dependence of R_{AA} vs p_T**
- Fair agreement with theoretical models (Strickland, Rapp)
- Slight rise at p_T~10 GeV/c in transport model
  → radial flow of coalescing b-quarks (not thermalized!)

R_{AA} vs p_T: ALICE $\Upsilon(1S)$

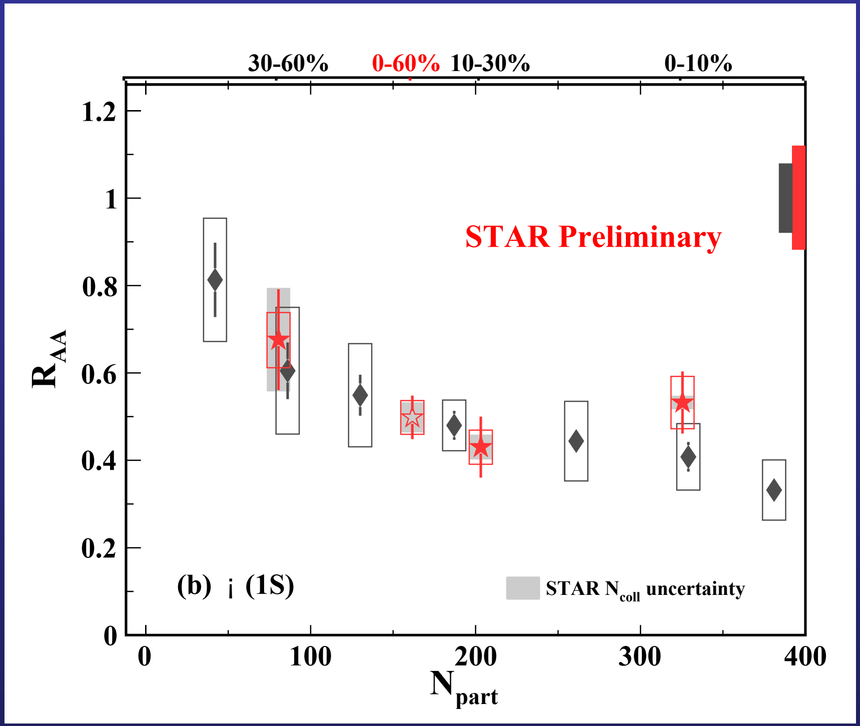


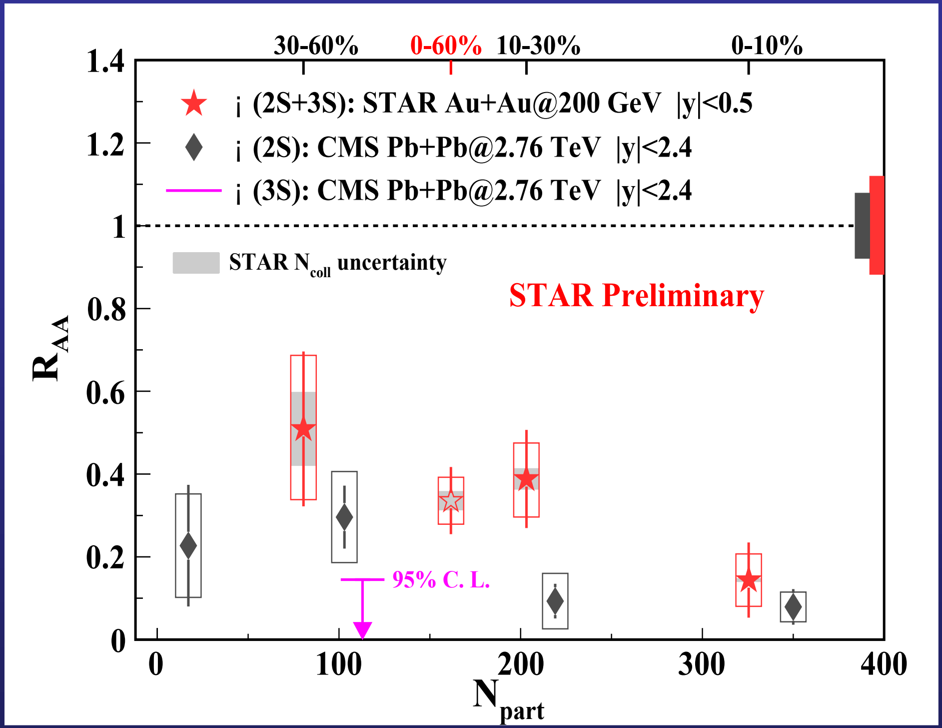


- ❑ Possibly flatter p_T dependence than in mid-y CMS result
- ❑ Regeneration component leads to slightly overestimating the result (it was the case also for the $\Upsilon(2S)$)

First precision results from STAR

- ❑ New pp reference (run-15) AND combination of $\mu^+\mu^-$ (run 14) and e^+e^- (run 11) Au-Au data samples





- ❑ **Evidence for suppression of the 3 ϒ states** ALSO at RHIC energy

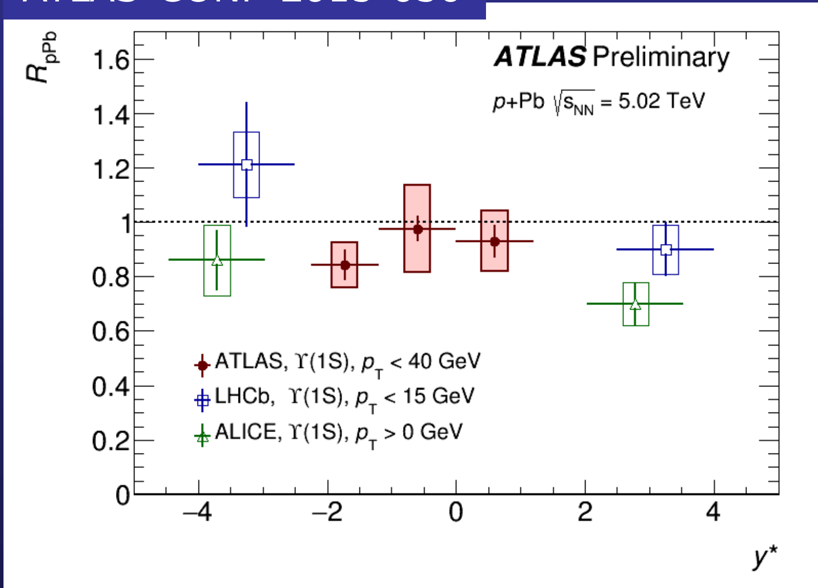
- ❑ Hints for ϒ(2S)+ϒ(3S) less suppressed up to semi-central events and then compatible with CMS for central → effect related to energy density ?
- ❑ ϒ(1S) identical at RHIC and LHC → dominated by feed-down ?

Experimental evidence for direct ϒ(1S) suppression ?

- ❑ Direct ϒ(1S) suppression implies **QGP temperatures at least ~2 T_c,**

- ❑ **Experimental** evidence for direct ϒ(1S) suppression needs control over
  - ❑ **Feed-down** from S and P bottomonium states
    Recent LHCb results imply a ~ **30% effect at (fairly) low p_T in pp**
  - ❑ Size of **CNM effects → weak but not precisely known**

ATLAS-CONF-2015-050



- ❑ Starting from CMS results and assuming all the remaining Pb-Pb ϒ(1S) are direct

R_{AA}^{incl} ϒ(1S) ~ 0.36

R_{AA}^{direct} ϒ(1S) ~ 0.36/0.7 = 0.51

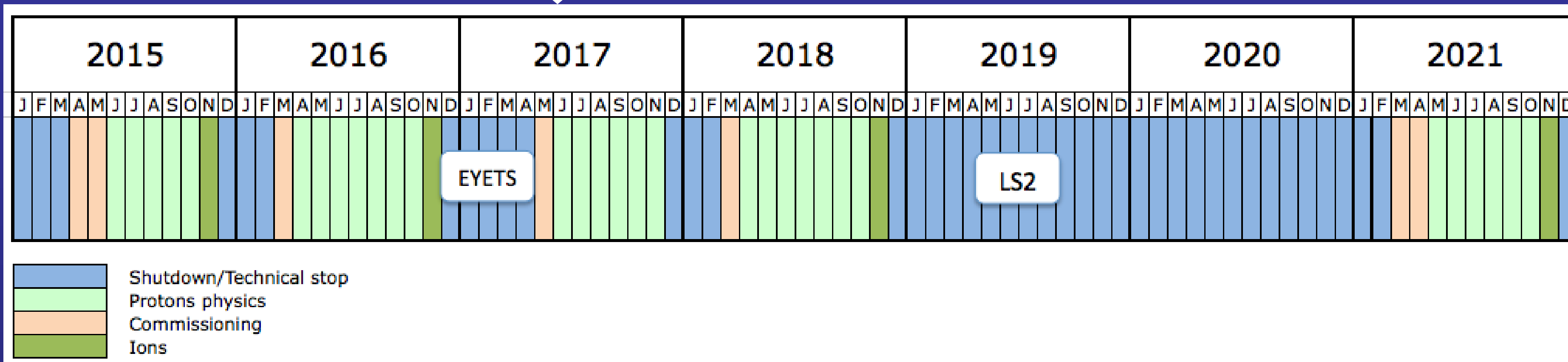
CNM effects (-1σ level)

→ $(R_{pA}$ -1σ$)^2$ ~ 0.8^2=0.64

- ❑ **Experimental indication for direct ϒ(1S) suppression!**

Future of LHC heavy-ion program

(today)



- **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 η>2.4
- **2021-2023:** LHC run-3, experiments require L_{int}>10 nb^{-1} for Pb-Pb (compared to L_{int} ~ 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** surely beneficial for $\psi(2S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ studies and for all non-R_{AA} analyses (see next slide)
  → Possibility of investigating (very) **peripheral collisions**

- Possibility of accelerating **lighter ions**
  - Once considered very useful in the frame of detecting **"threshold" effects and/or scaling behaviors** for various observables
  - …but we have now extensively seen that threshold effects are not really detectable
  - **Asymmetric collisions** (see Cu+Au @RHIC) are in principle interesting but admittedly it is not easy to extract physics out of it

Prospects for quarkonia studies

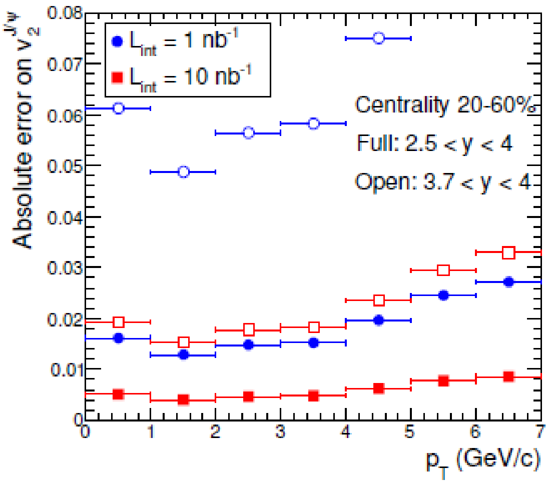
- **CMS prospects** for run-3 (CMS-PAS-FTR-13-025)

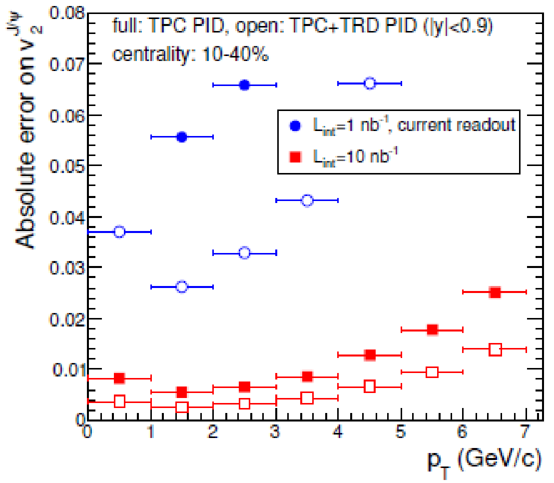
$\sqrt{s_{NN}}$	2.76 TeV	5.5 TeV						
L_{int}	150 μb^{-1}	10 nb^{-1}						
Centrality(%)	0-100	0-100	50-100	60-100	70-100	80-100	90-100	0-100
Signal	p_T-inclusive raw yields							($p_T > 30$ GeV)
$B \to J/\psi$	2 250	300 000	12 400	6 150	2 350	810	215	5500
Prompt J/ψ	9 000	1 200 000	49 500	24 500	9 420	3 240	860	4400
$\psi(2S)$	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

- **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 %

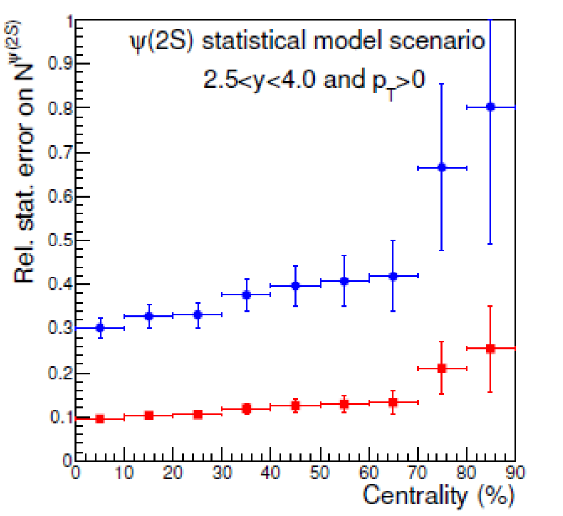
ALICE projected highlights

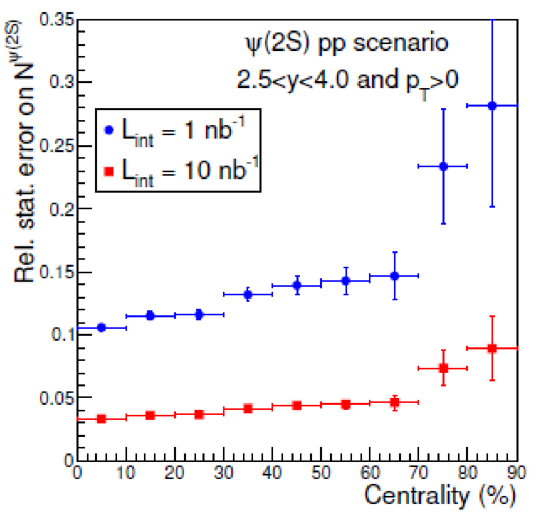


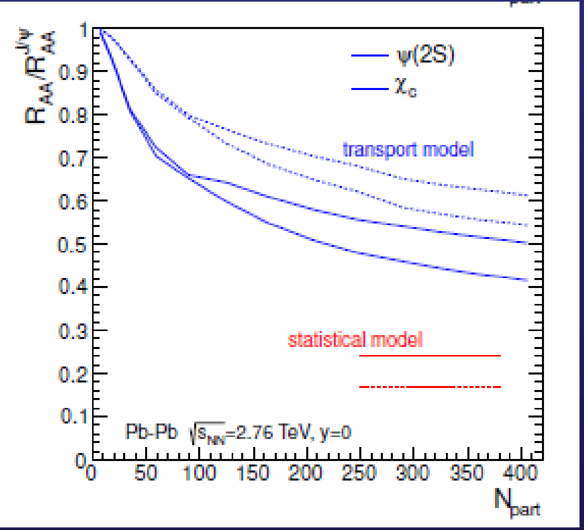


v_2 measurement for J/ψ at mid- and forward-y

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







LHCb highlights

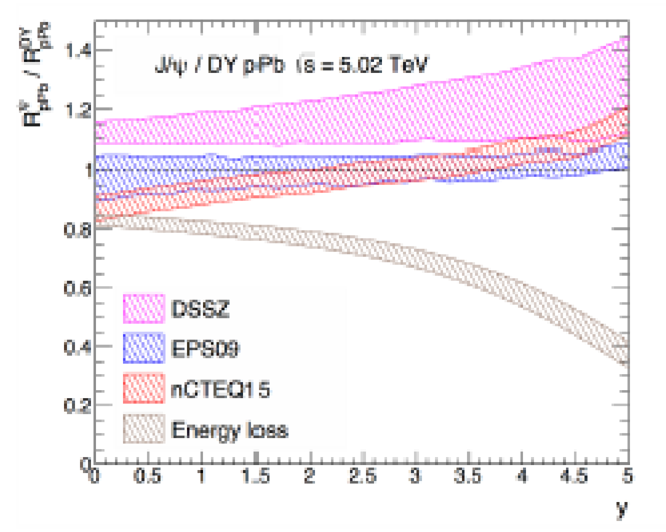
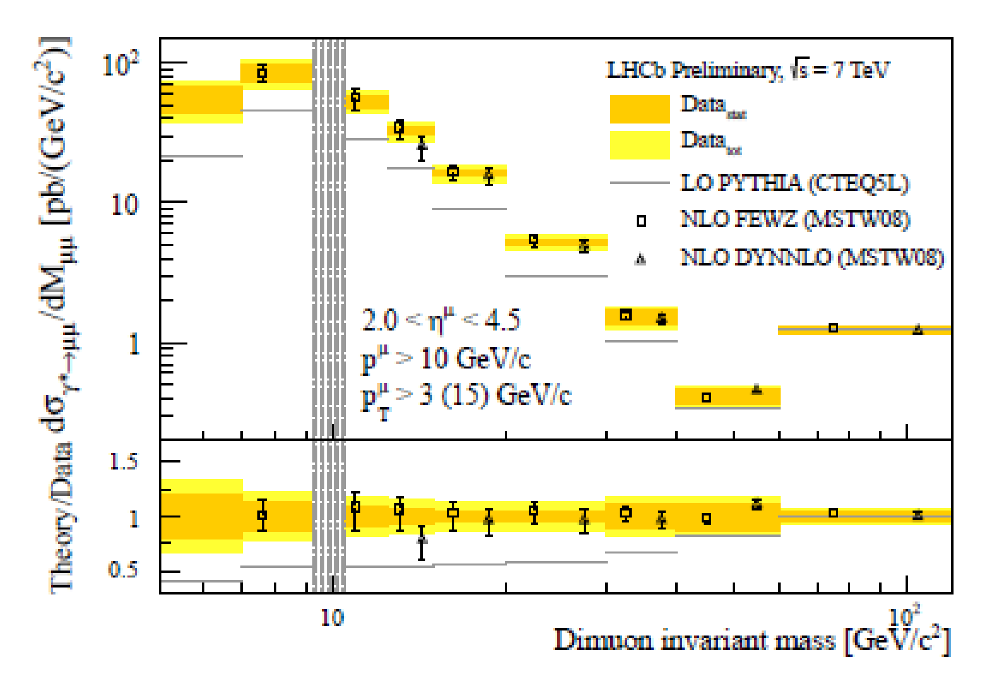


Figure 3: Double ratio $\mathcal{R}^{\psi/DY}_{pPb}$ in p-Pb collisions at $\sqrt{s}$ = 5.02 TeV for the various nPDF sets and in the coherent energy loss model.

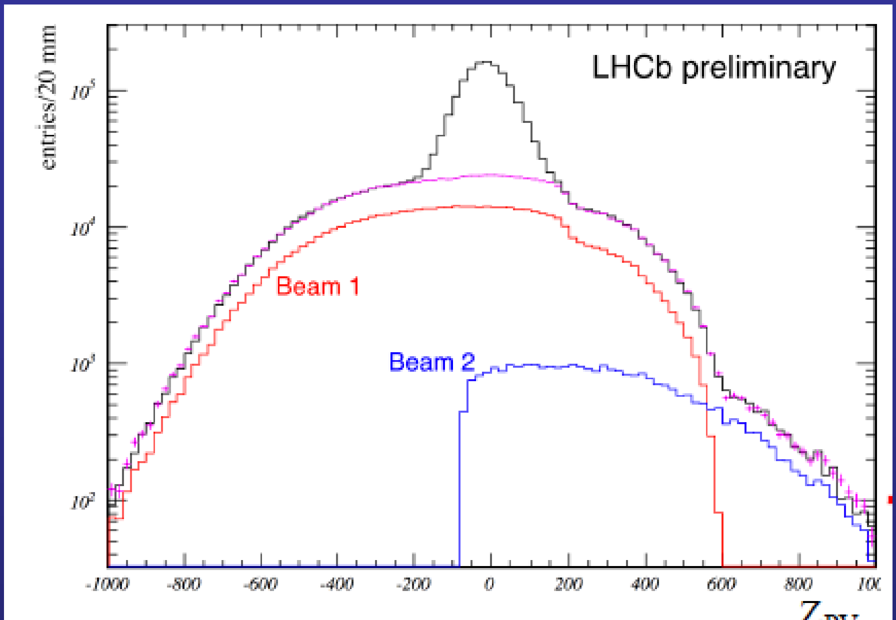
- Possibility of measuring **Drell-Yan production** in p-Pb collisions
  → (decisive) test of the **energy loss picture**
  → Good handle on **nPDF**

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

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

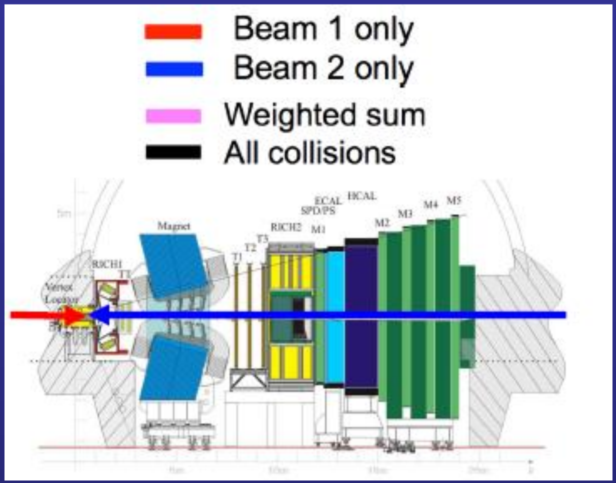


LHCb fixed target

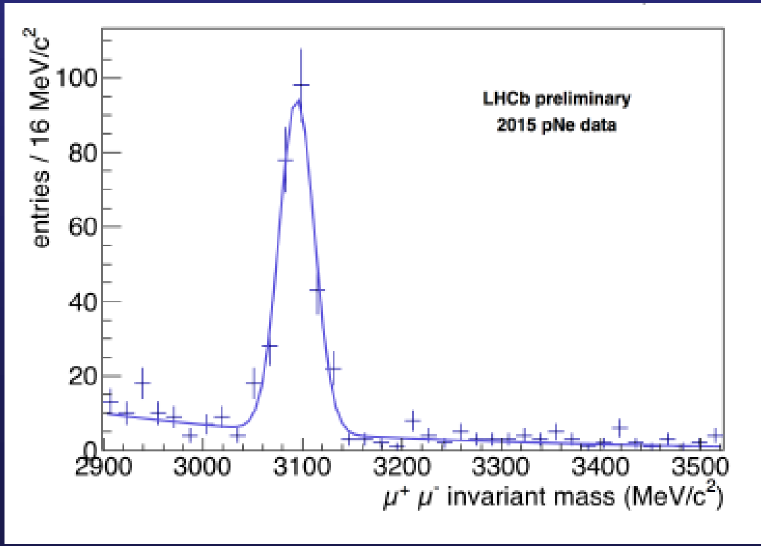


Distribution of primary vertex positon

SMOG (System for Measuring the Overlap with Gas)

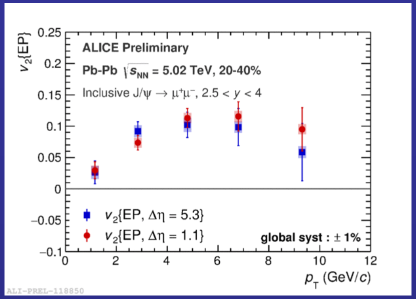


- pHe at $\sqrt{s_{NN}} = 110$ GeV
- pNe at $\sqrt{s_{NN}} = 87$ GeV, 110GeV
- pAr at $\sqrt{s_{NN}} = 69$ GeV, 110 GeV
- PbNe at $\sqrt{s_{NN}} = 54$ GeV
- PbAr at $\sqrt{s_{NN}} = 69$ GeV

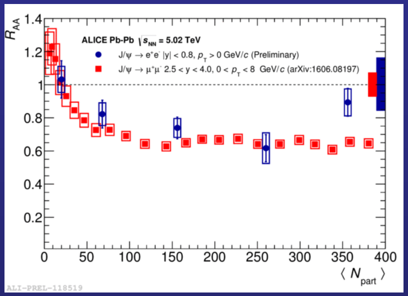


- **Further measurements took place** in 2016 (p-Pb @ $\sqrt{s_{NN}}$=5 TeV)

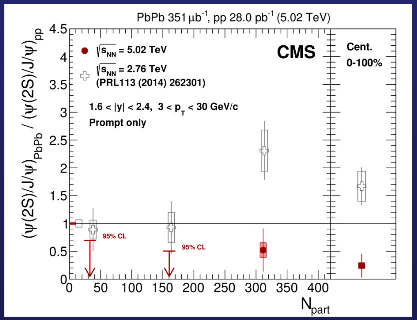
Charmonia – Highlights!



The J/ψ flows! → Heavy quarks thermalize in the QGP and can (re)create charmonia (ALICE)

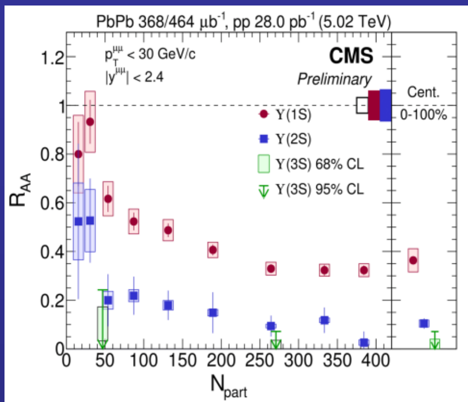


Precise new data on **J/ψ suppression and regeneration!** → R_{AA} at $\sqrt{s_{NN}}$=5.02 TeV (ALICE)

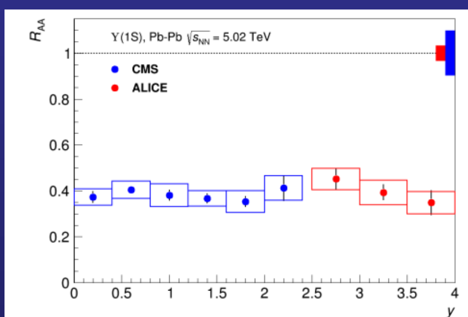


Complete set of **ψ(2S) results** (complex $\sqrt{s_{NN}}$-dependence)
Deeper insight on charmonia in medium (CMS+ALICE)

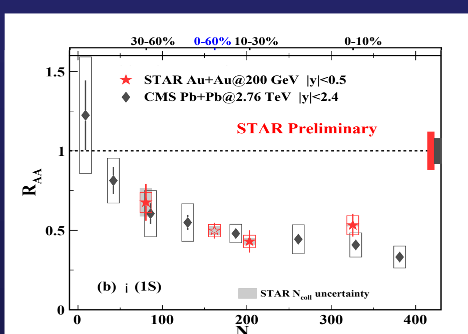
Bottomonia – Highlights!



Full information on ϒ(1S) and ϒ(2S) R_{AA} available at BOTH $\sqrt{s_{NN}}$=2.76 and 5.02 TeV (CMS)
→ **Evidence for hierarchy of suppression!**



Understand the **y-dependence of ϒ(1S) suppression**
→ Intriguing effect or trivially within uncertainty ?



First set of **precise results from RHIC** now available!
→ Look for a unified description from low to high energy

Backup

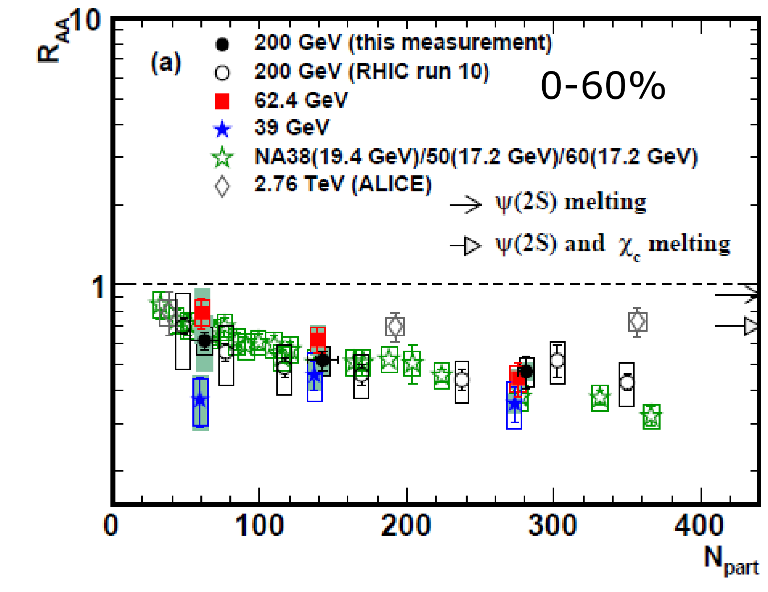
J/ψ - RHIC energy

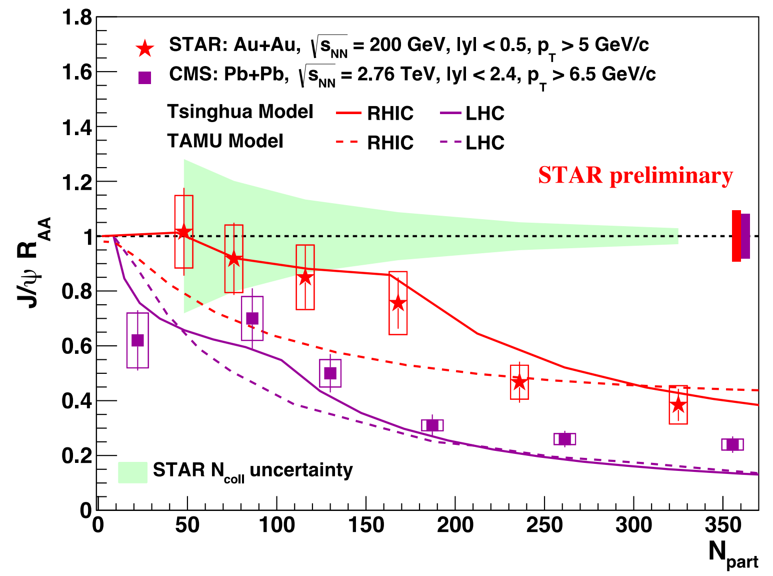
- Recent highlights by STAR
- Systematic exploration of **J/ψ suppression at lower energies**
- **High p_T J/ψ suppression**

L. Adamczyk et al. (STAR), arXiv:1607.07517

Reference cross section at low RHIC energy

Interpolation of SPS/FNAL **results**



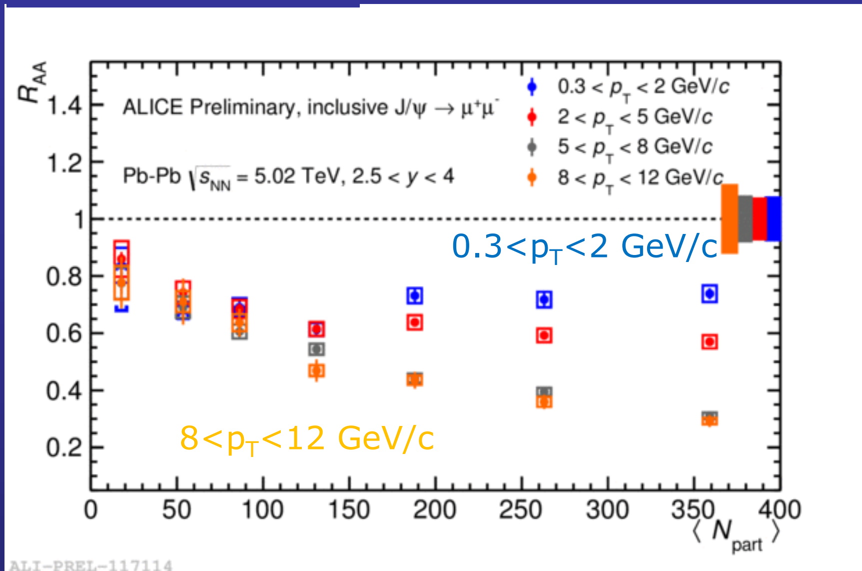


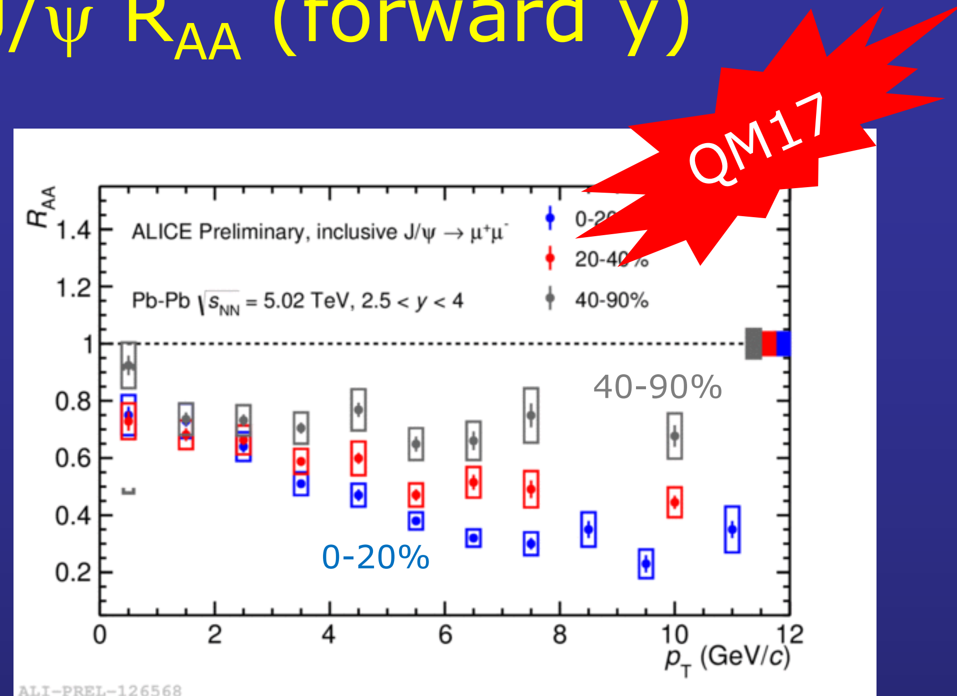
- **No significant energy dependence of R_{AA} up to $\sqrt{s_{NN}}$=200 GeV**
  → (Almost) exact compensation of suppression and (re)combination

- **High p_T J/ψ, R_{AA}^{LHC}<R_{AA}^{RHIC}** (opposite behavior at low p_T)

Multi-differential J/ψ R_{AA} (forward y)

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

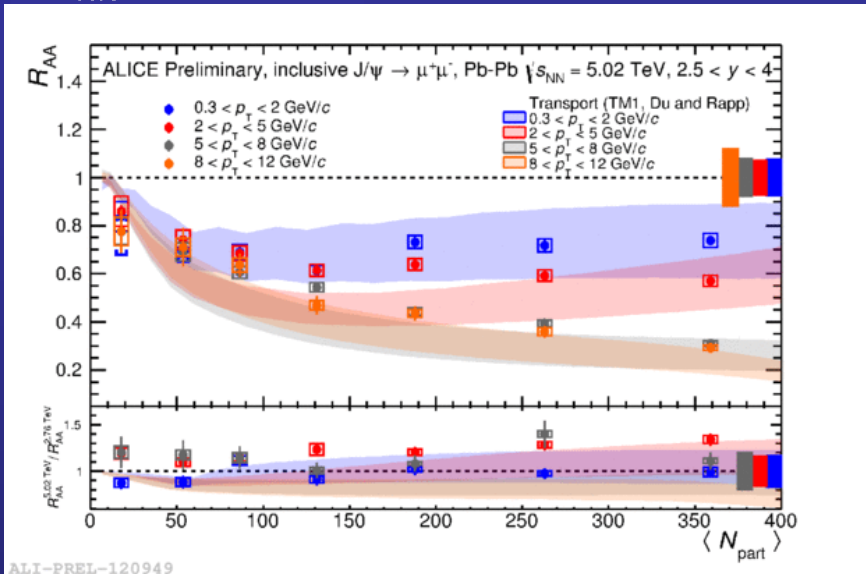


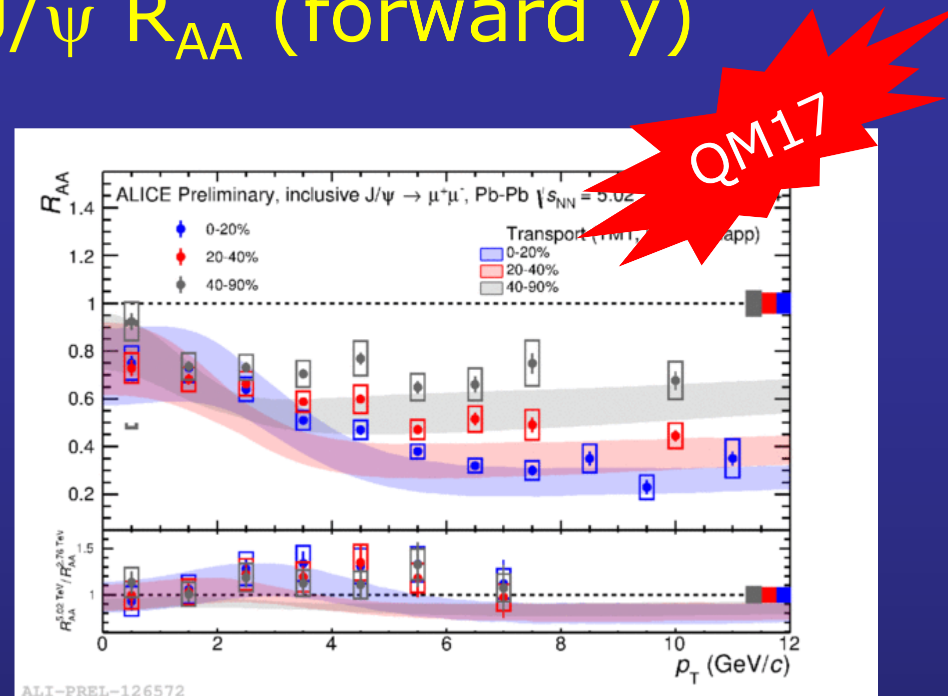


- ❑ R_{AA} vs p_T for different centrality bins (and viceversa) at $\sqrt{s_{NN}}$=5.02 TeV
- ❑ Features seen in LHC run-1 results are confirmed
- ❑ New results include
  - → Smaller statistical AND systematical uncertainties
  - → Increase of the p_T reach up to 12 GeV/c
- ❑ **Striking features observed**
  - → **R_{AA} vs centrality (almost) flat in 0<p_T<2 GeV/c**
  - → **~80% suppression for central events at p_T~10 GeV/c**
- ❑ Precise results open up the way to discriminating comparisons with models

Multi-differential J/ψ R_{AA} (forward y)

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



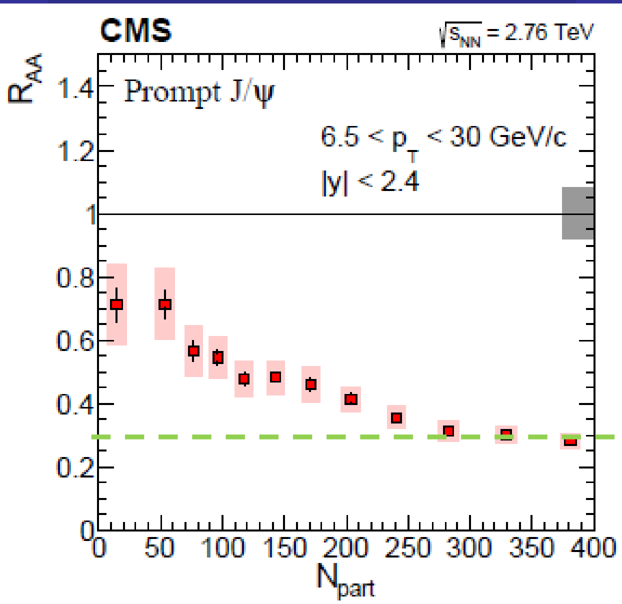


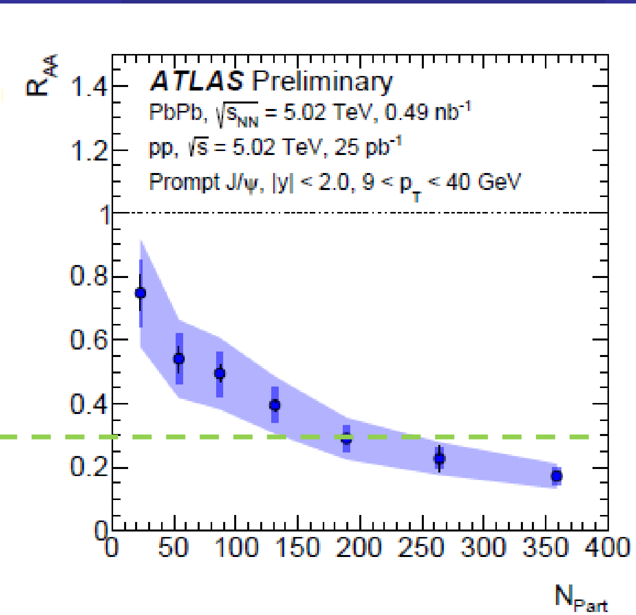
- ❑ R_{AA} vs p_T for different centrality bins (and viceversa) at $\sqrt{s_{NN}}$=5.02 TeV
- ❑ Features seen in LHC run-1 results are confirmed
- ❑ New results include
  - → Smaller statistical AND systematical uncertainties
  - → Increase of the p_T reach up to 12 GeV/c
- ❑ **Striking features observed**
  - → **R_{AA} vs centrality (almost) flat in $0<p_T<2$ GeV/c**
  - → **~80% suppression for central events at p_T~10 GeV/c**
- ❑ Precise results open up the way to discriminating comparisons with models

High-p_T J/ψ

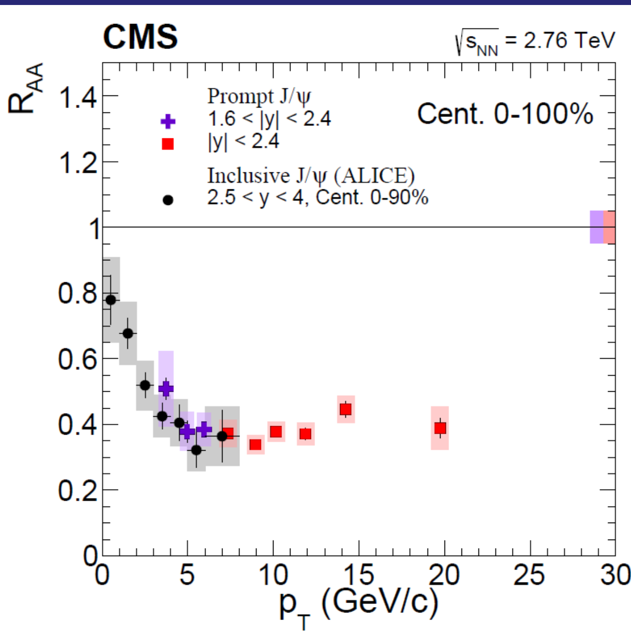
V. Khachatryan et al. (CMS), arXiv:1610.00613

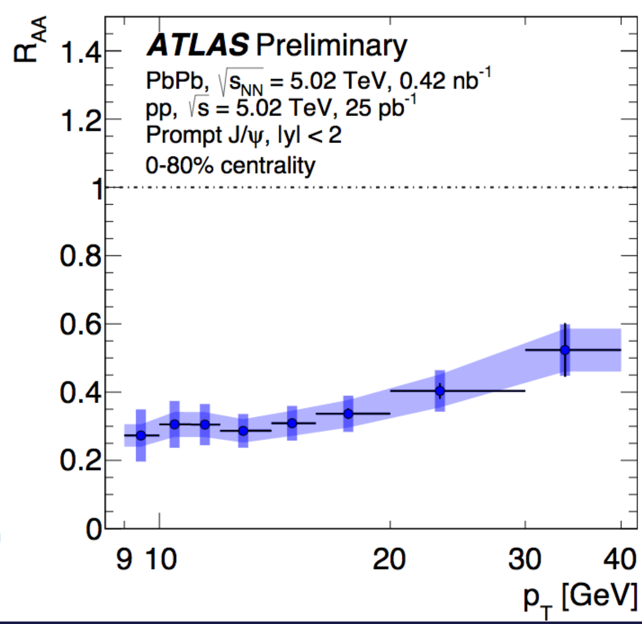
ATLAS-CONF-2016-109





- Fine centrality binning
- Striking difference with respect to low-p_T J/ψ
- **Suppression increases with centrality** at high p_T , **down to R_{AA}~0.2**
- **$\sqrt{s_{NN}}$-dependent effects are weak**

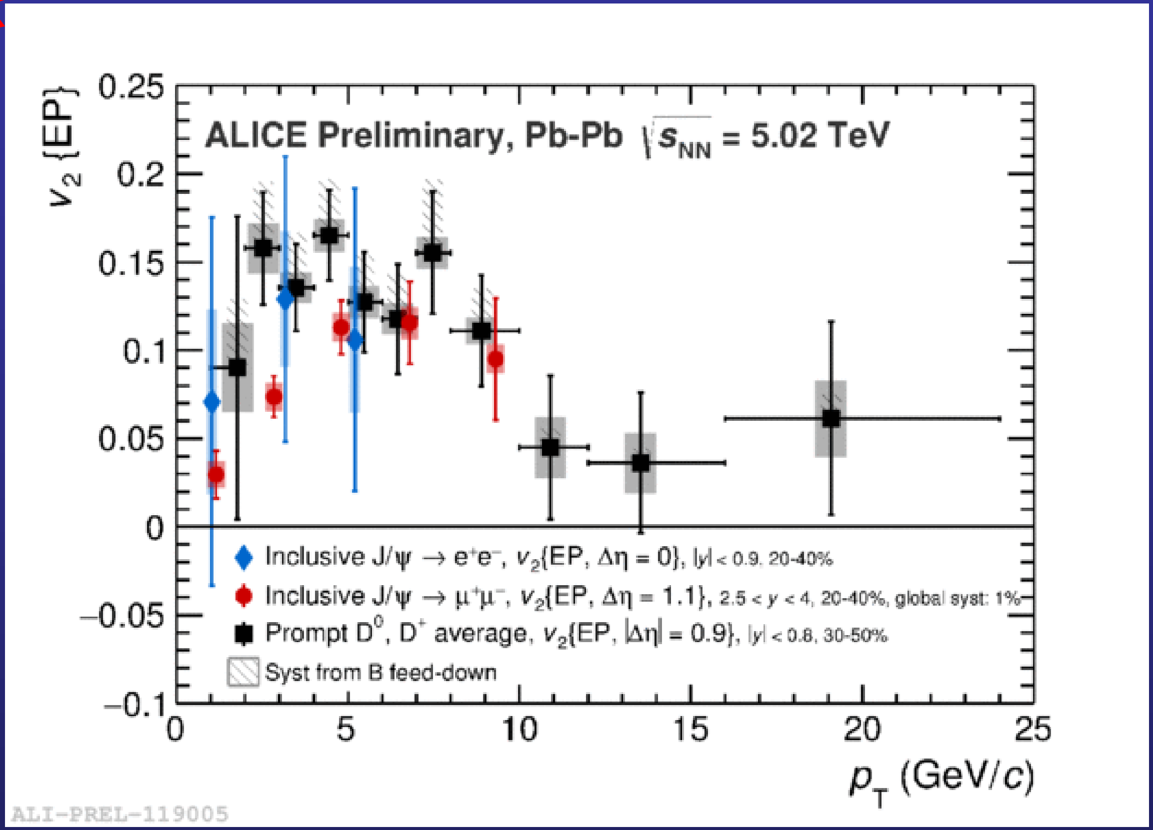




- **R_{AA} increases for p_T > 20 GeV/c**
- Related to energy loss effects, rather than dissociation ?

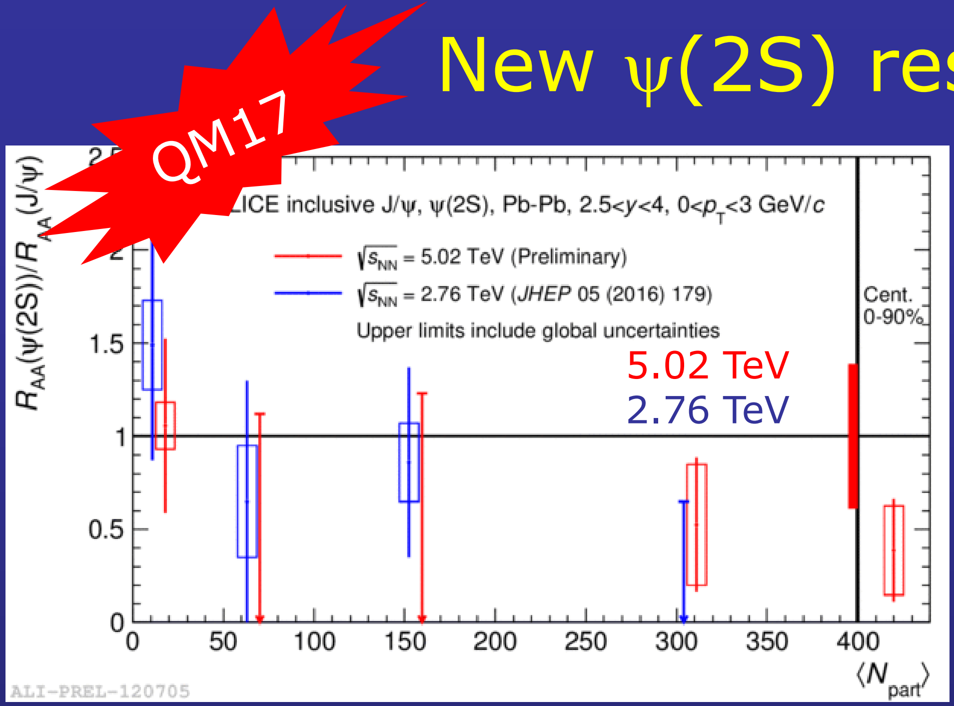
Elliptic flow- closed vs open charm

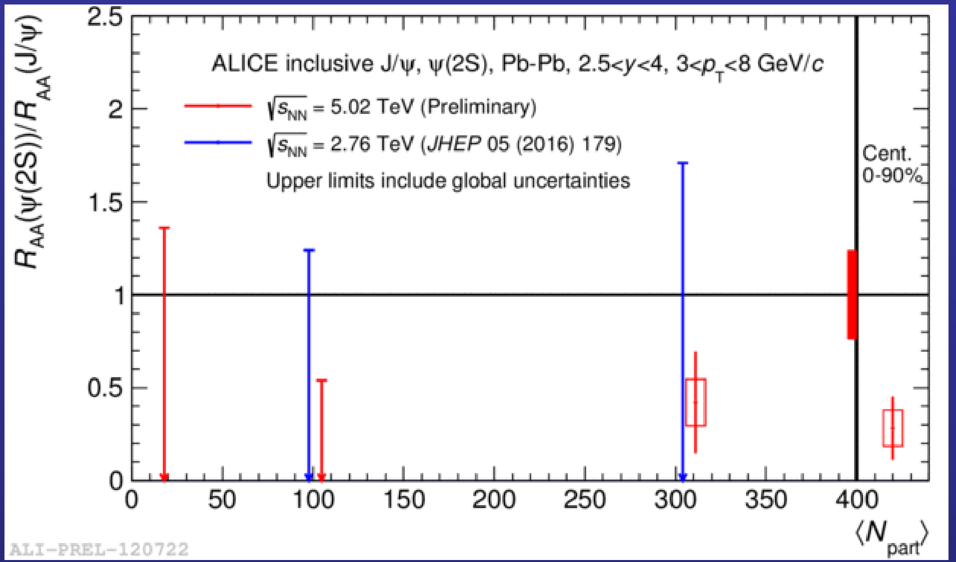
QM17



- At p_T~5 GeV/c, **$v_2^{J/\psi}$ and v_2^D are compatible**
- Note different y-region (2.5<y<4 for J/ψ, |y|<0.8 for D^0) and slightly different centrality selection (20-40% vs 30-50%)
- ALICE results at midrapidity confirm the observed signal
- Charm quarks strongly interact with the medium

New ψ(2S) results from ALICE



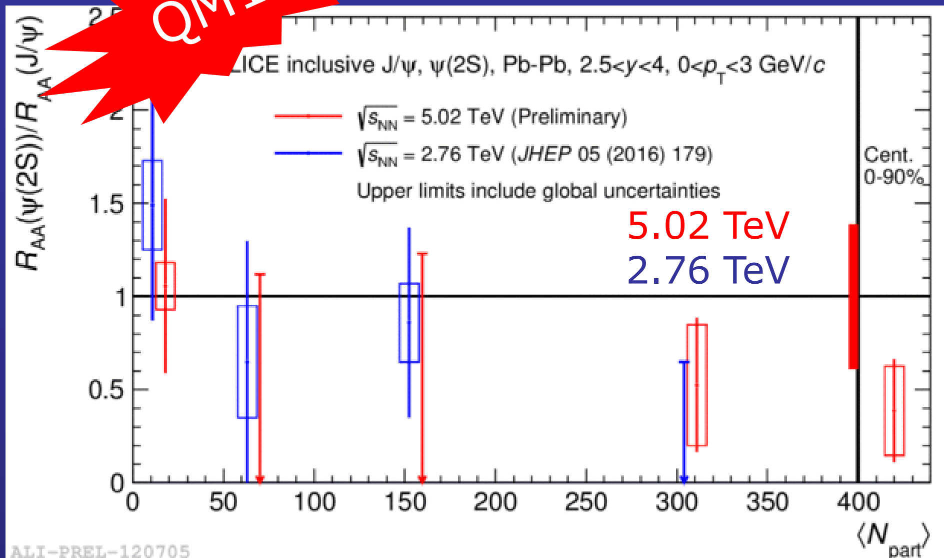


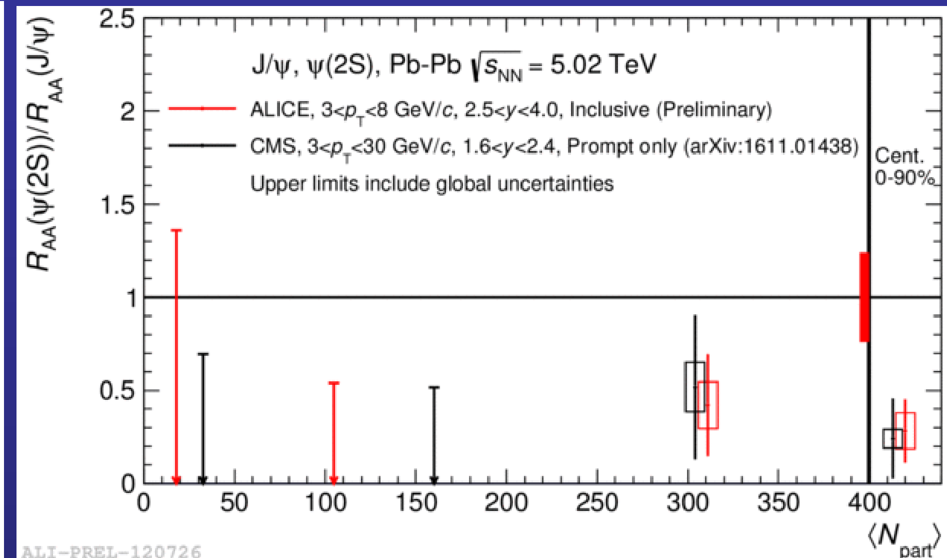
- ALICE accesses forward y and extends coverage **down to $p_T = 0$**
- Uncertainties are generally rather large (S/B sub-optimal)
- $\sqrt{s_{NN}}$=2.76 and 5.02 TeV result are compatible
- Indications for **suppression at low AND intermediate p_T**
- Enhancement seen by CMS at $\sqrt{s_{NN}}$=2.76 TeV remains somewhat "isolated"

- General comment: ψ(2S) can be **heavily affected by the hadronic medium,** do we have a quantitative understanding of processes occurring at (very) late stages?
- Should ψ(2S) be treated together with (light) hadronic resonances ?

QM17

New ψ(2S) results from ALICE





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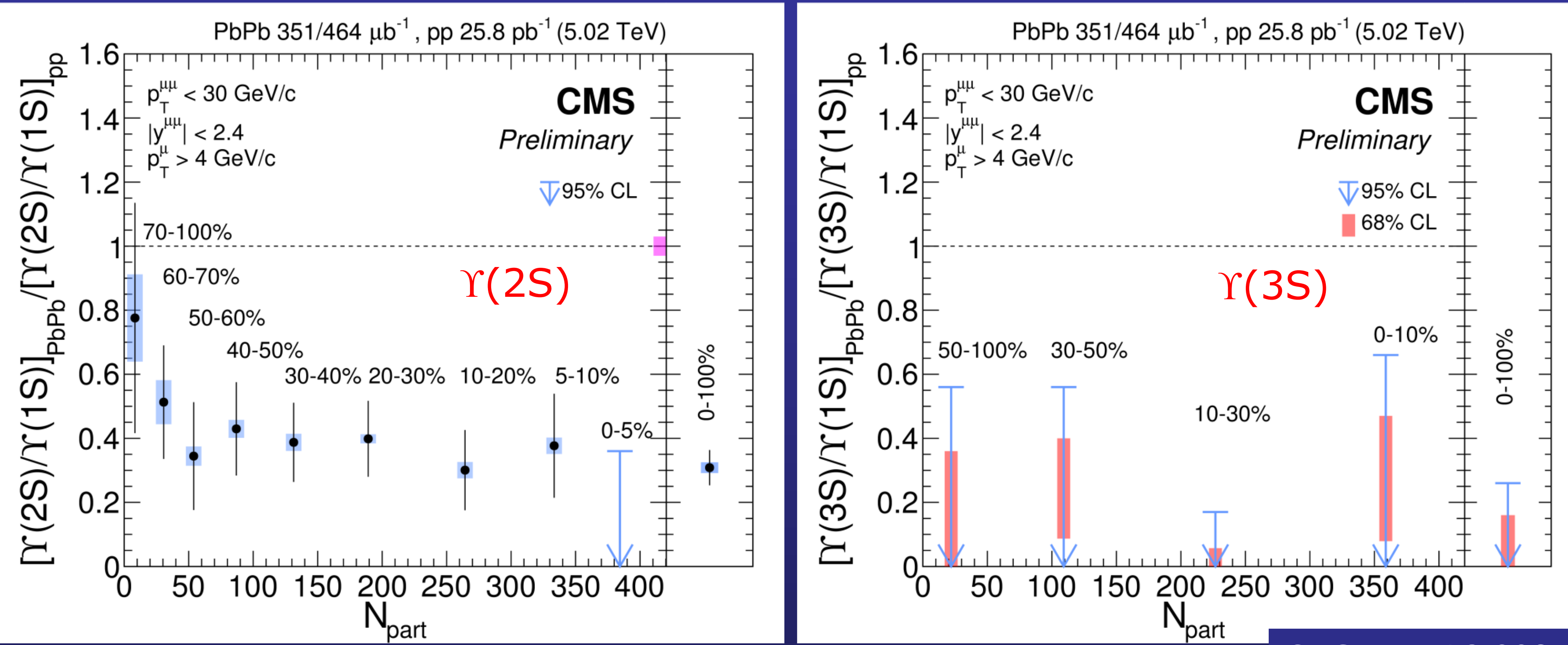
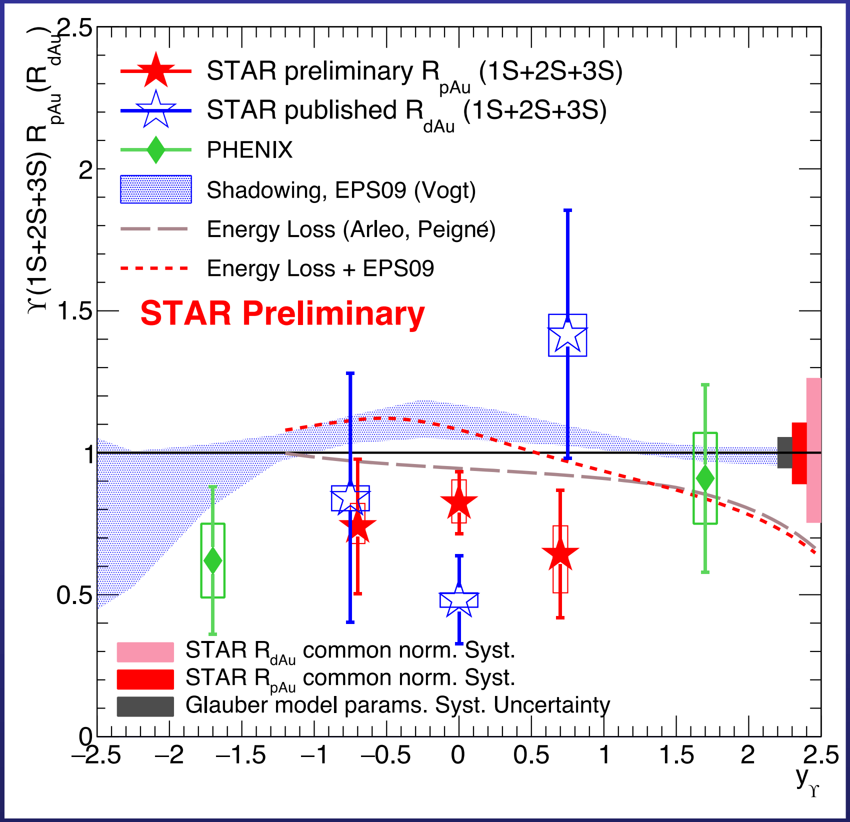
ϒ(2S) and ϒ(3S) suppression relative to ϒ(1S)



CMS-HIN-16-008

- ϒ(2S)/ ϒ(1S) integrated double ratios: $\sqrt{s_{NN}}$= 5 TeV → 0.308±0.055±0.017, $\sqrt{s_{NN}}$= 2.76 TeV → 0.21±0.07±0.02
- The ϒ(2S) relative suppression already **saturates for semi-peripheral collisions**

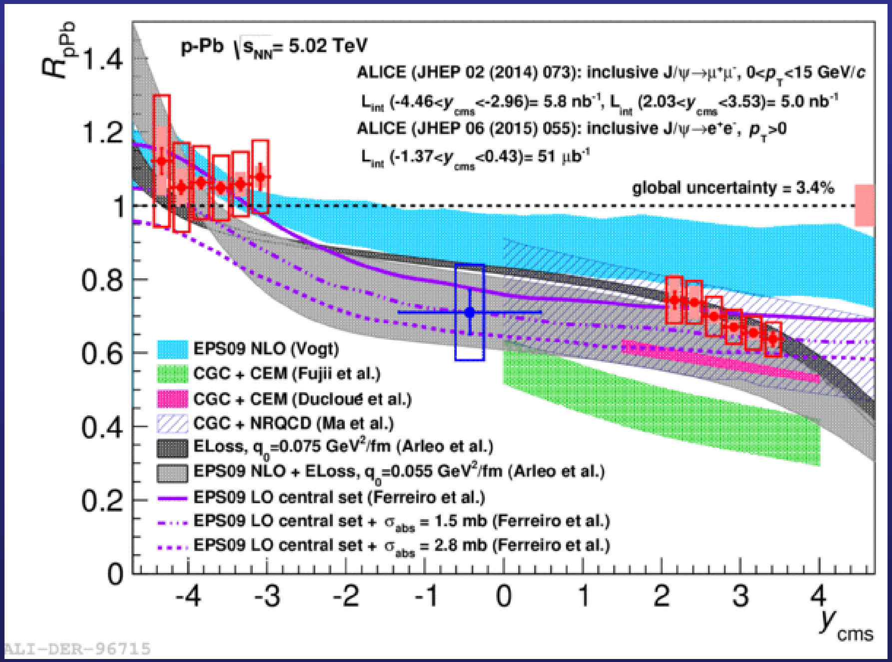
R_{pAu} at RHIC, new STAR result

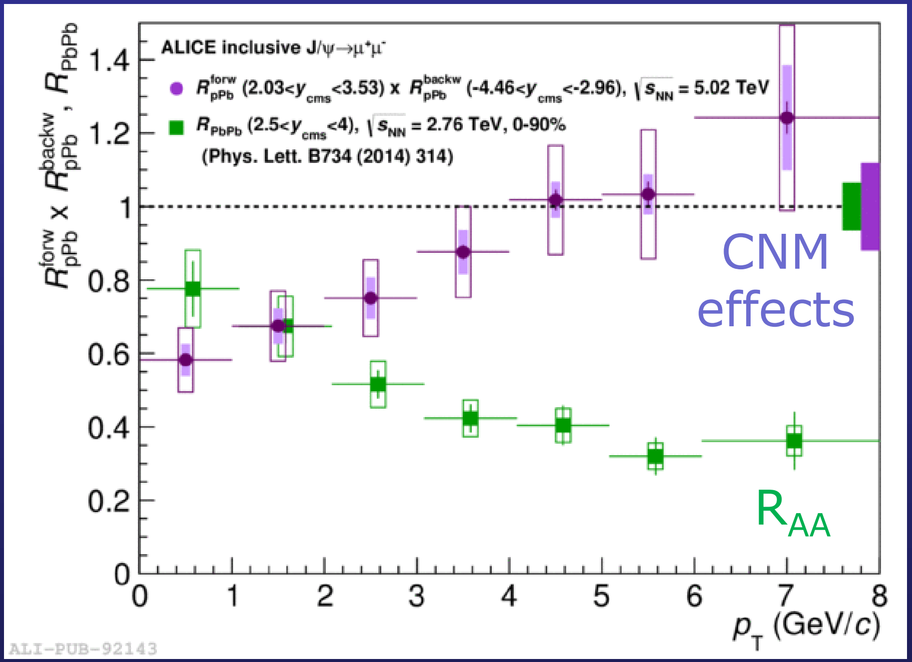


- Strong improvement with respect to previous d-Au results
- Hint of Υ(1S+2S+3S) suppression in p+Au collisions:
  → **R_{pA} (|y|<0.5): 0.82 $\pm$ 0.10 $^{+0.08}_{-0.07}$**
- Shadowing calculations give R_{pAu}>1 at midrapidity

CNM effects - charmonia

- LHC energy → **Strong CNM effects** observed at **forward-y and low p_T**
- Can be described via **shadowing + coherent energy loss** and also via a **ColorGlassCondensate** approach



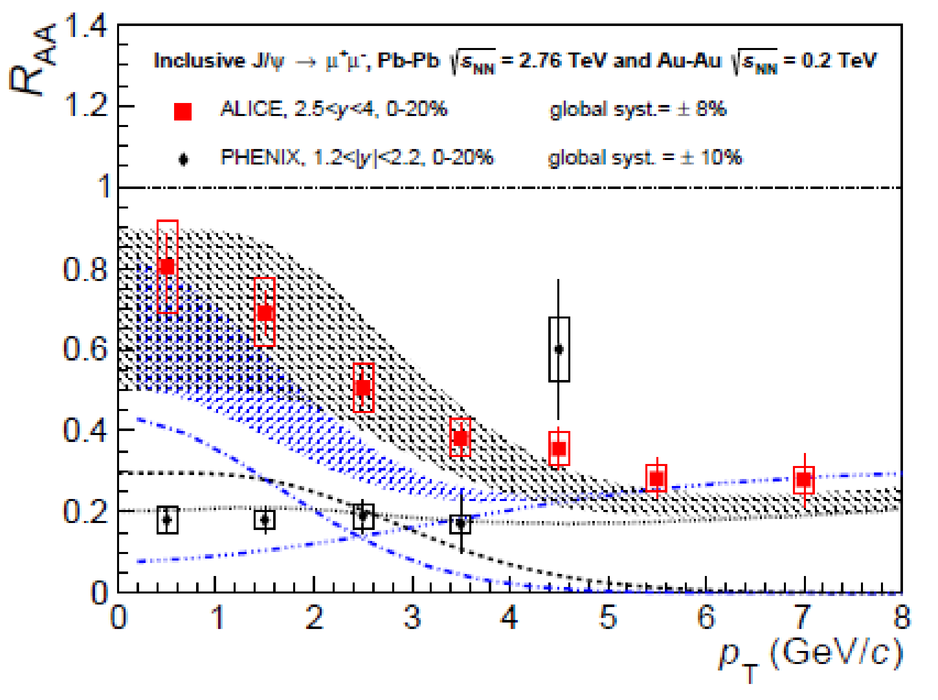


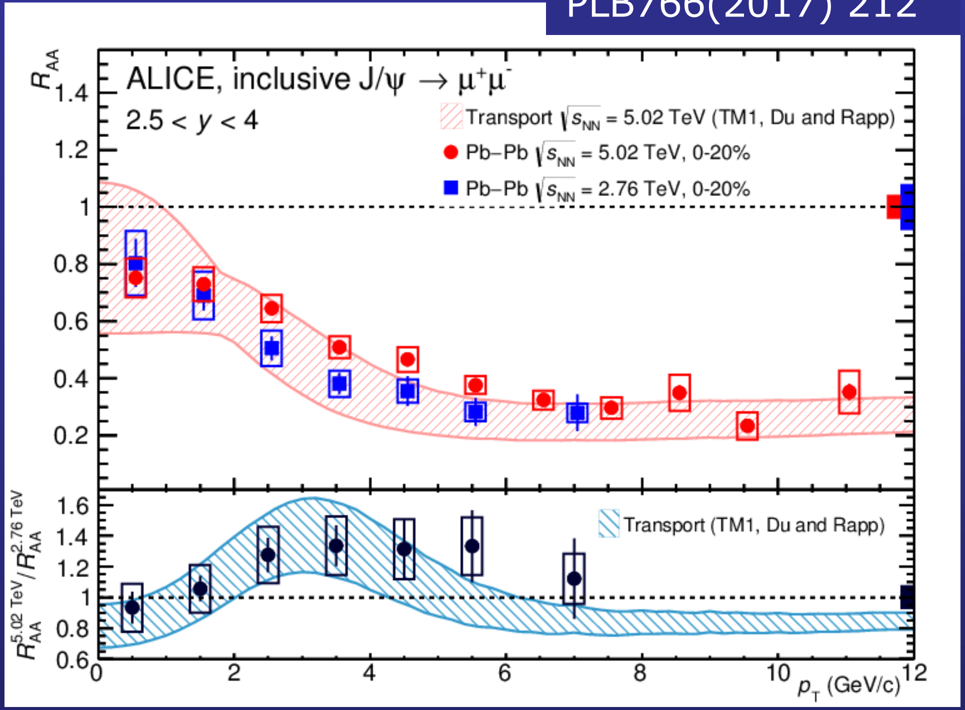
- Qualitative extrapolations of CNM effects to Pb-Pb imply **strong high p_T suppression** and hints for **J/ψ enhancement at low p_T**

J/ψ R_{AA} vs p_T (at low p_T)

J.Adam et al, ALICE
JHEP 05(2016) 179

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



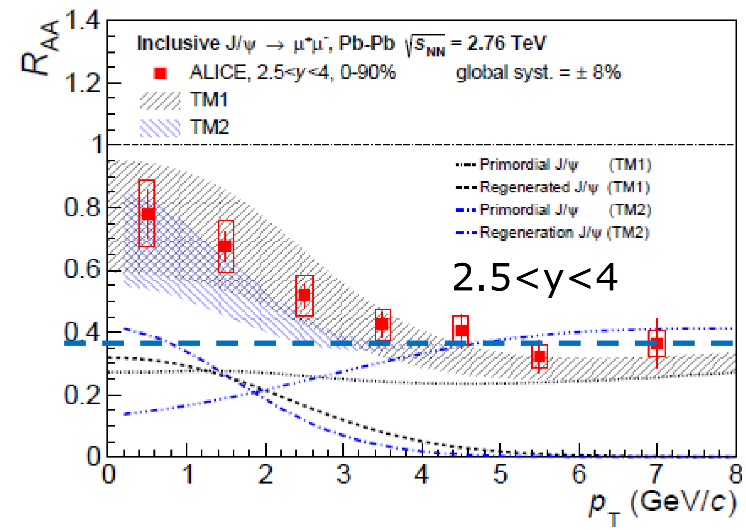


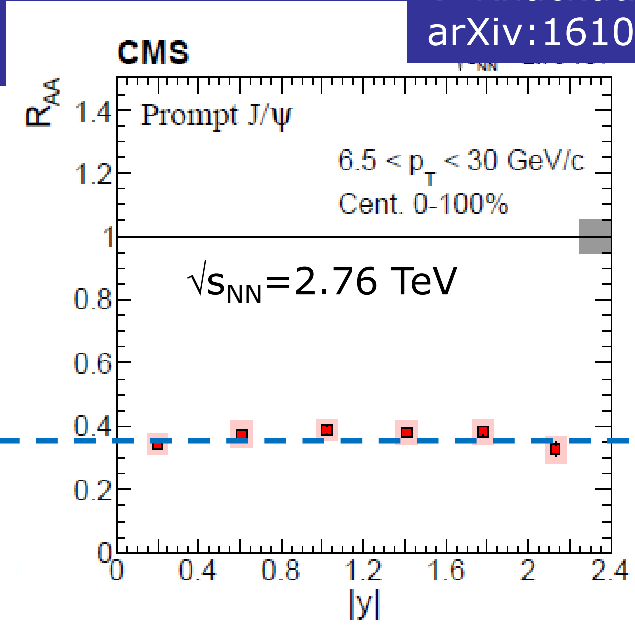
- ❑ Typical feature at both $\sqrt{s_{NN}}$=2.76 and 5.02 TeV → **reduced suppression at low p_T** (where the bulk of charm quarks is produced)
- ❑ Effect not visible at RHIC

- ❑ Fair agreement with theory calculations including (re)generation
- ❑ Comparison still suffers from **non-negligible uncertainties in the model inputs** → role of cold nuclear matter, open charm cross section

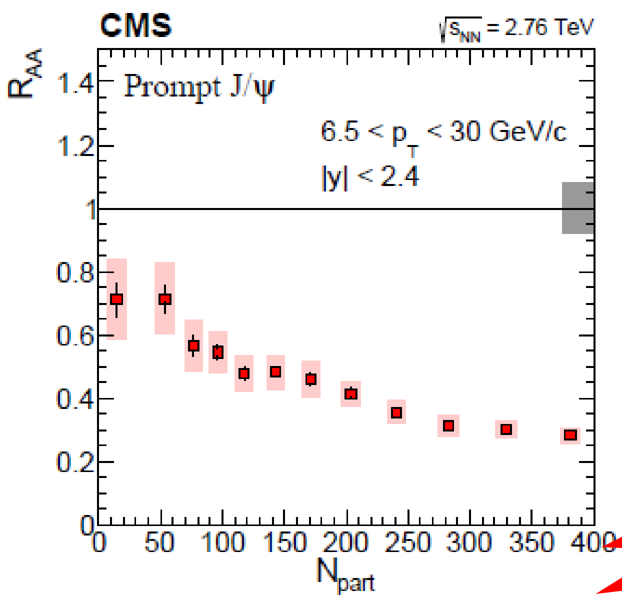
High-p_T J/ψ at LHC

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





- **J/ψ suppression stronger at high-p_T,** with no significant y dependence (ALICE vs CMS)



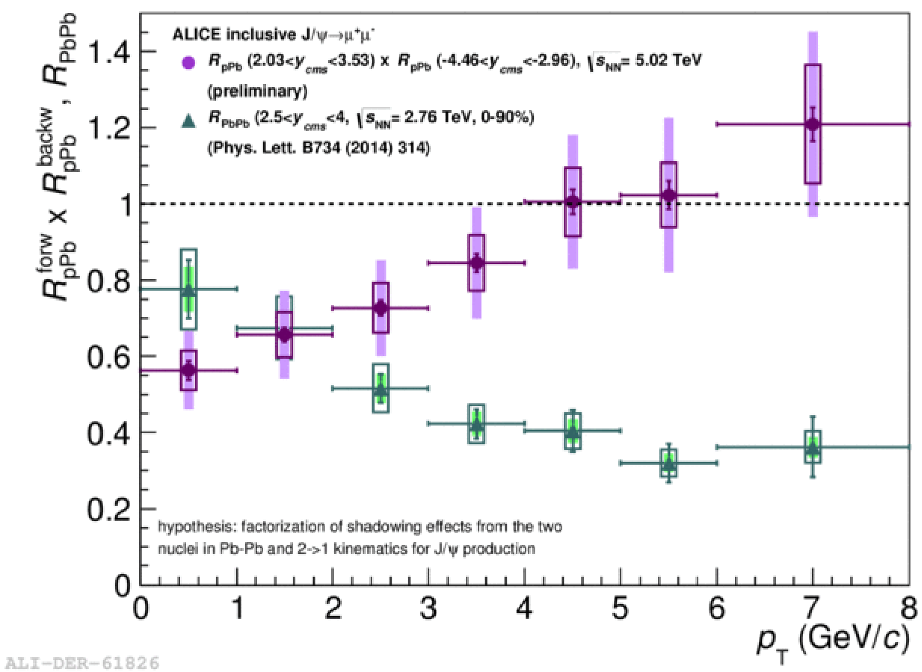
- New high statistics result from CMS from round-2 → R_{AA} in fine centrality bins
- Striking difference with respect to low-p_T J/ψ results → **Continuously increasing suppression (high p_T) vs saturation (low p_T)**

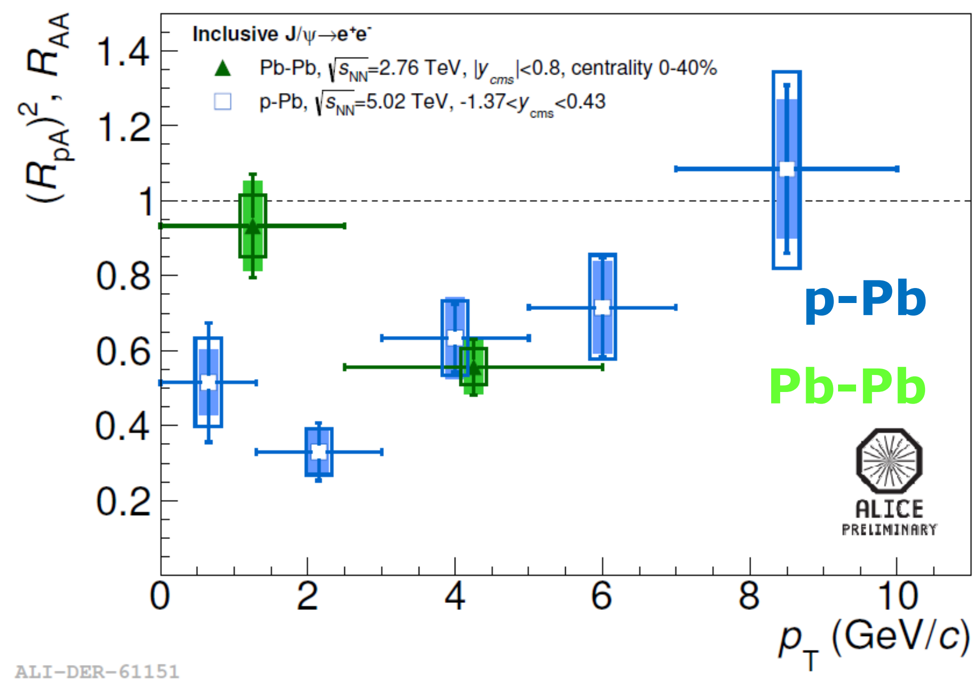
QM17

Up to a factor ~5 for central events

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)





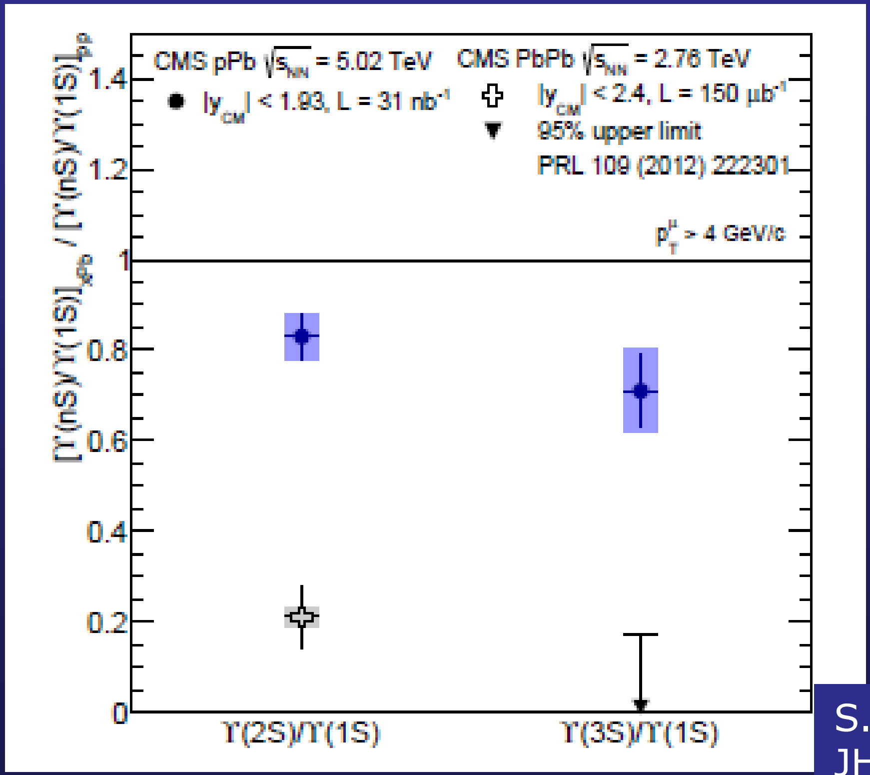
- This (cautious) exercise confirms that
  → high p_T J/ψ suppression is not a CNM effect
  → at low p_T the observed suppression is consistent with CNM
  (i.e. there is a balance of suppression+recombination in hot matter)

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 Υ(2S) and Υ(1S)

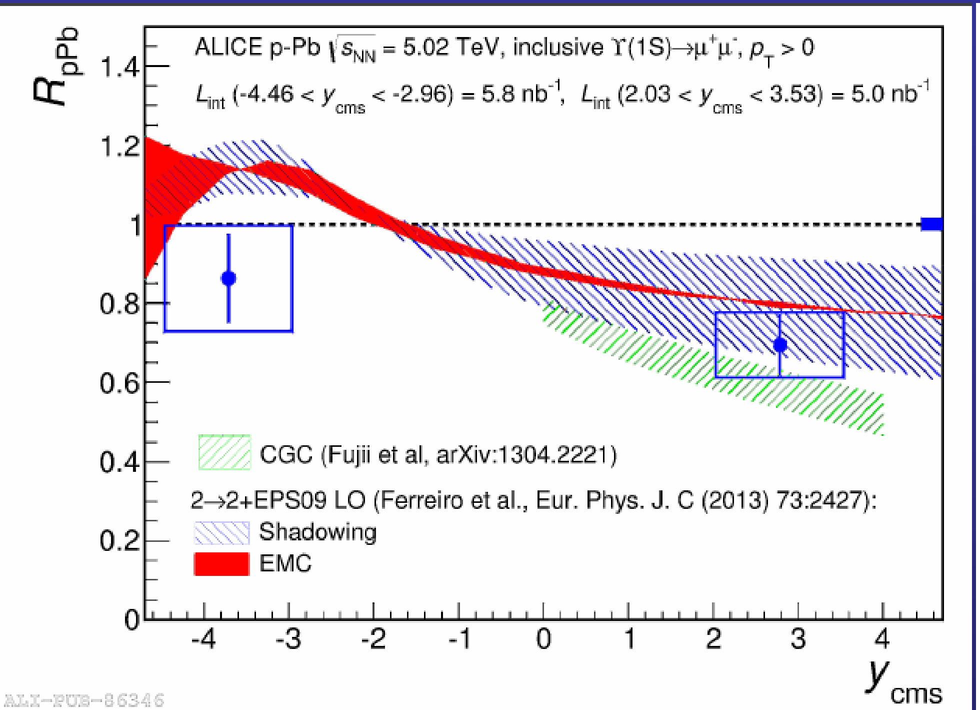


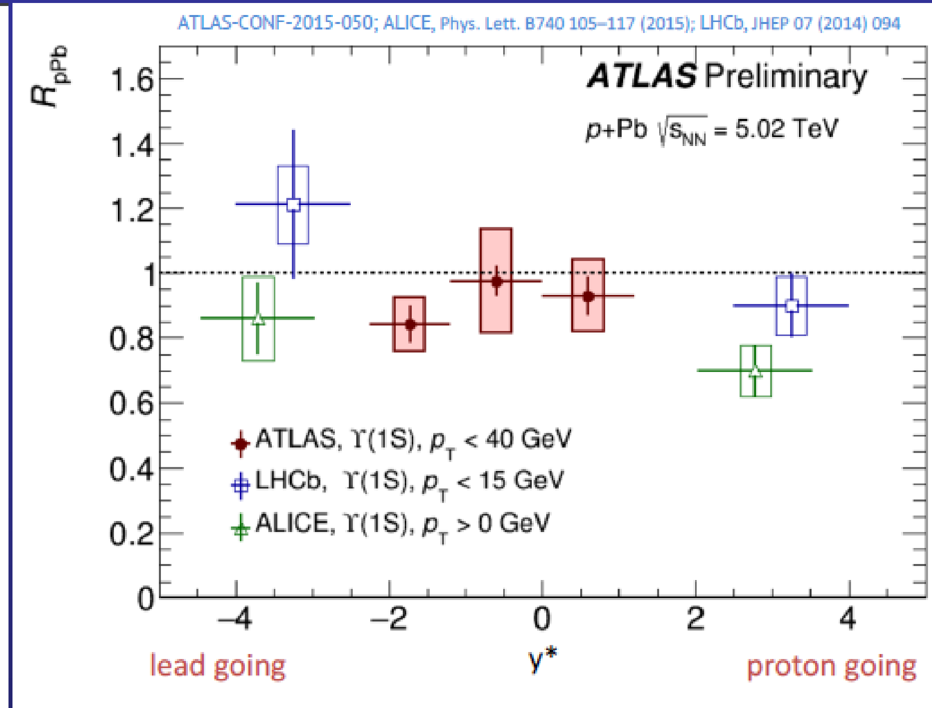
- CMS results have smaller uncertainties and show a stronger CNM effects on Υ(2S) with respect to Υ(1S)

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

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

Υ(1S) suppression in p-Pb

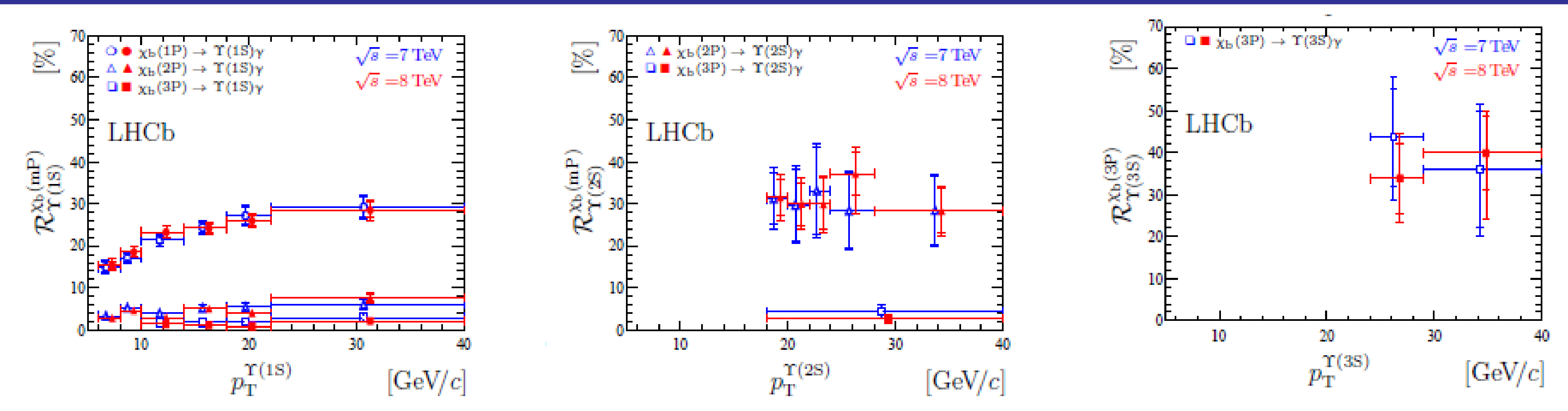




- Uncertainties are still not negligible → LHC run-2
- No real tension between ALICE and LHCb but the range of “allowed” values is clearly rather large
- CNM effect generally smaller than for charmonia, but not negligible → applying the $R_{PbPb}^{CNM}=R_{pPb} \times R_{Pbp}$ prescription on ALICE results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

Feed-down

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

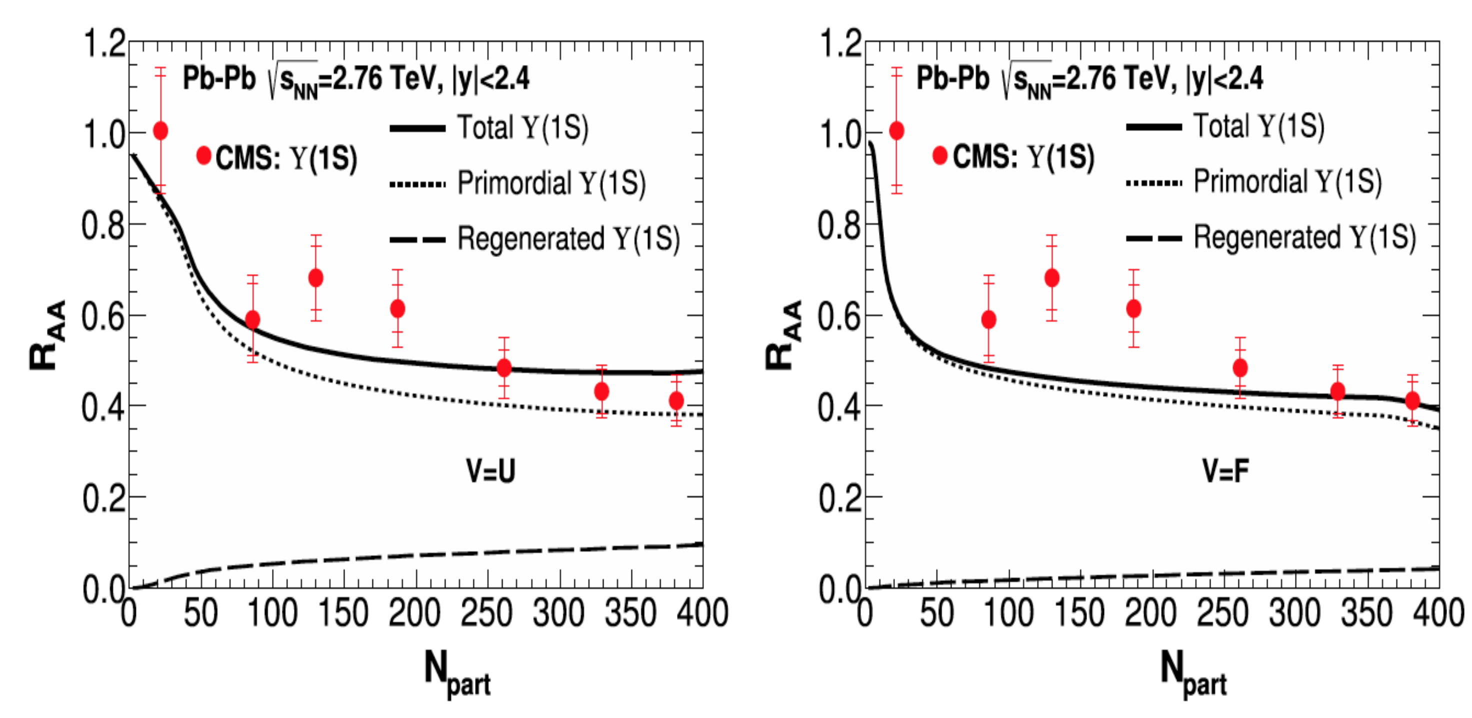


- ❑ Recent news
  - ❑ Feed-down to Υ(1S) is smaller than believed (~50% → ~30%)
  - ❑ Feed-down to Υ(3S) (unseen in PbPb!) is very strong (~40%)

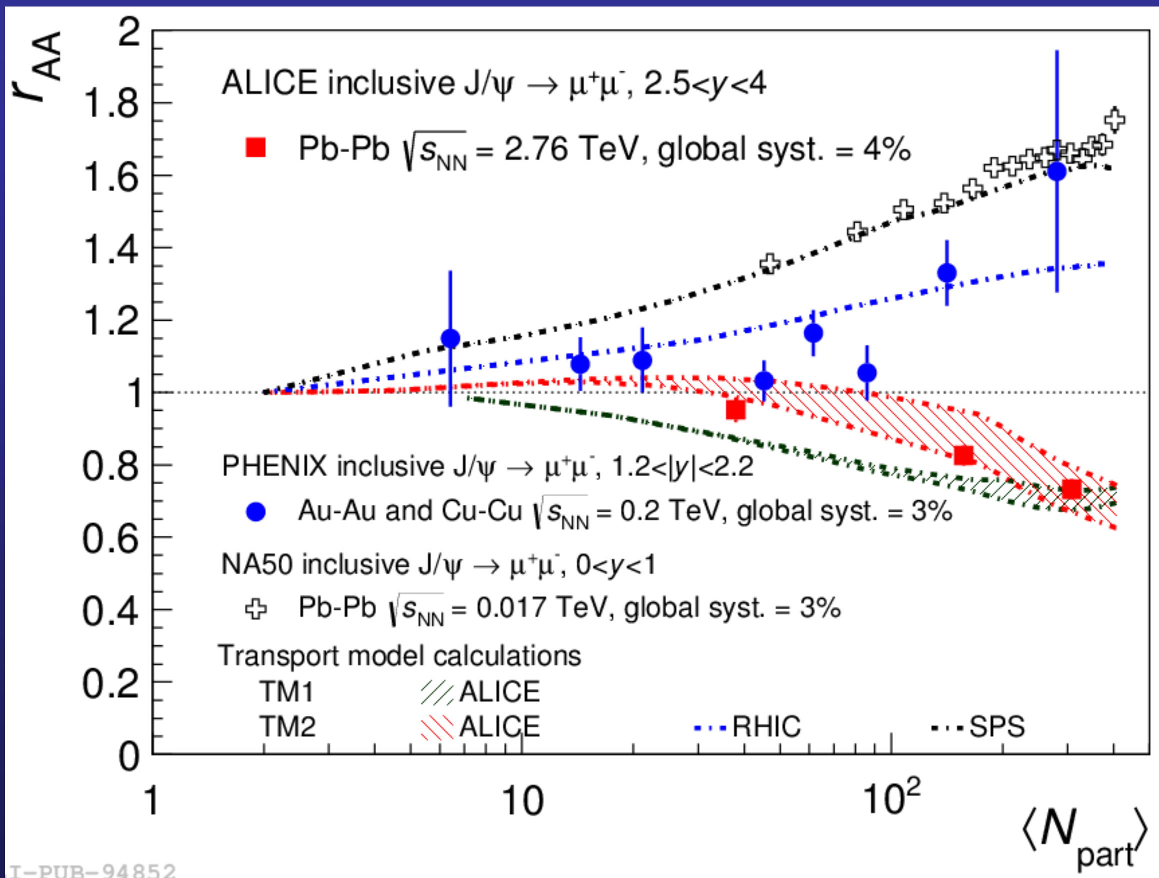
low P_T	direct	from χ_b	from Υ'	from χ_b'	from Υ''	from χ_b''
Υ	~ 70%	~ 15%	≃ 8%	~ 5%	≃ 1%	~ 1%
Υ'	~ 63%	–	–	~ 30%	≃ 4%	~ 3%
Υ''	~ 60%	–	–	–	–	~ 40%

(HP2016, Lansberg)

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


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}

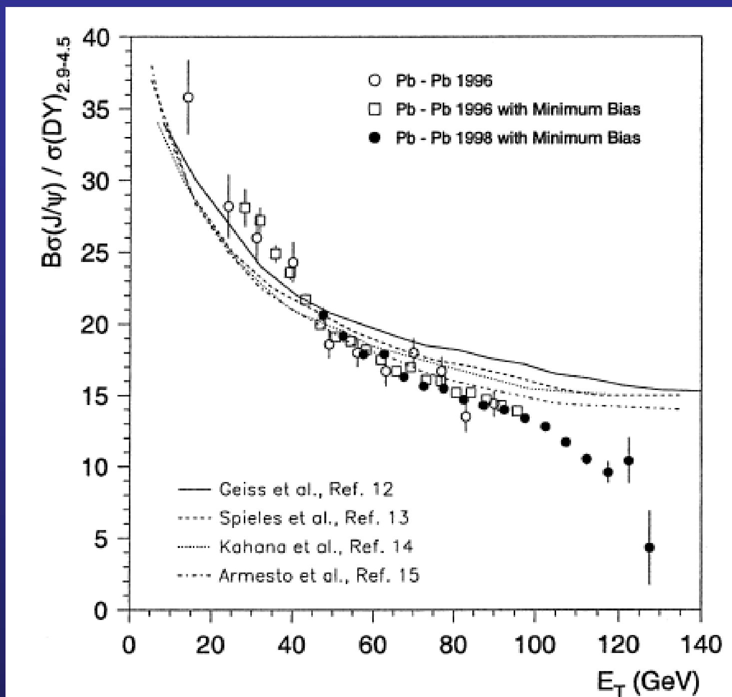
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$



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

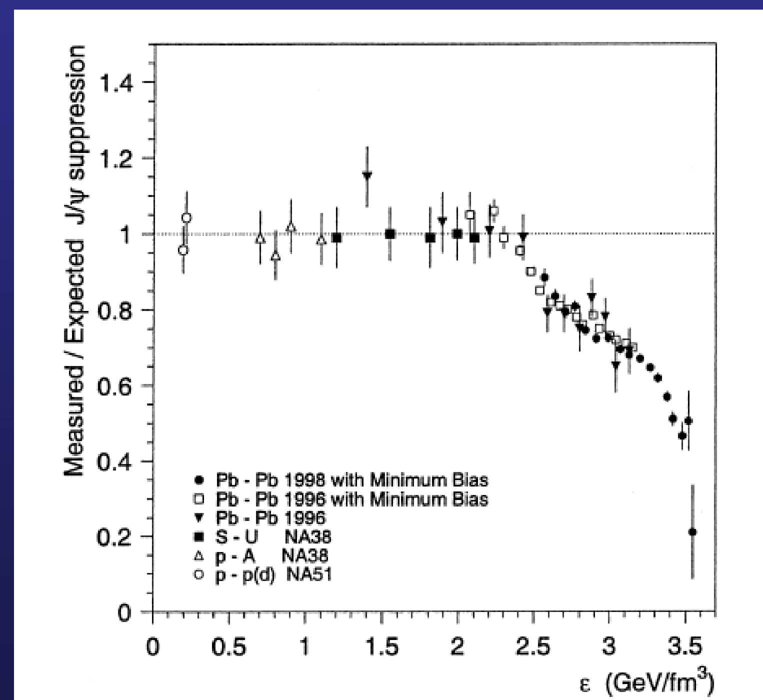
More accurate data allowed more stringent conclusions…

1994-2000: really "heavy" ions in the SPS (Pb-Pb collisions)
February 2000 → "New state of matter created at CERN" press release



Evidence for deconfinement of quarks and gluons
from the J/ψ suppression pattern
measured in Pb-Pb collisions at the CERN-SPS

NA50 Collaboration



- ❑ Clear suppression beyond CNM effects measured by NA50

1) Sharp onset of suppression
2) "Conventional" models found to disagree with data

…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....

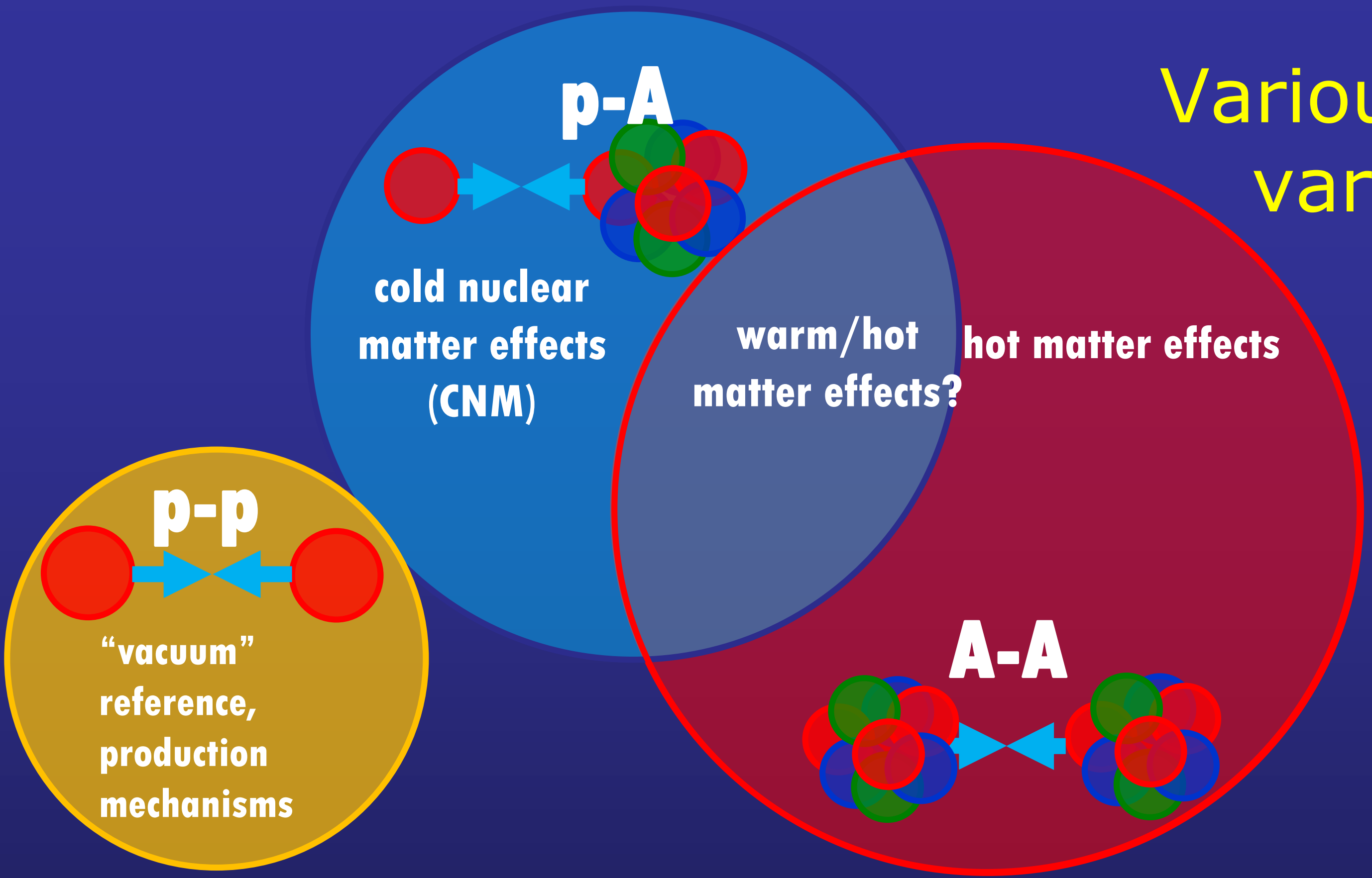
- The possibility of an enhancement of charmonium production in nuclear collisions was considered from the very beginning!

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.

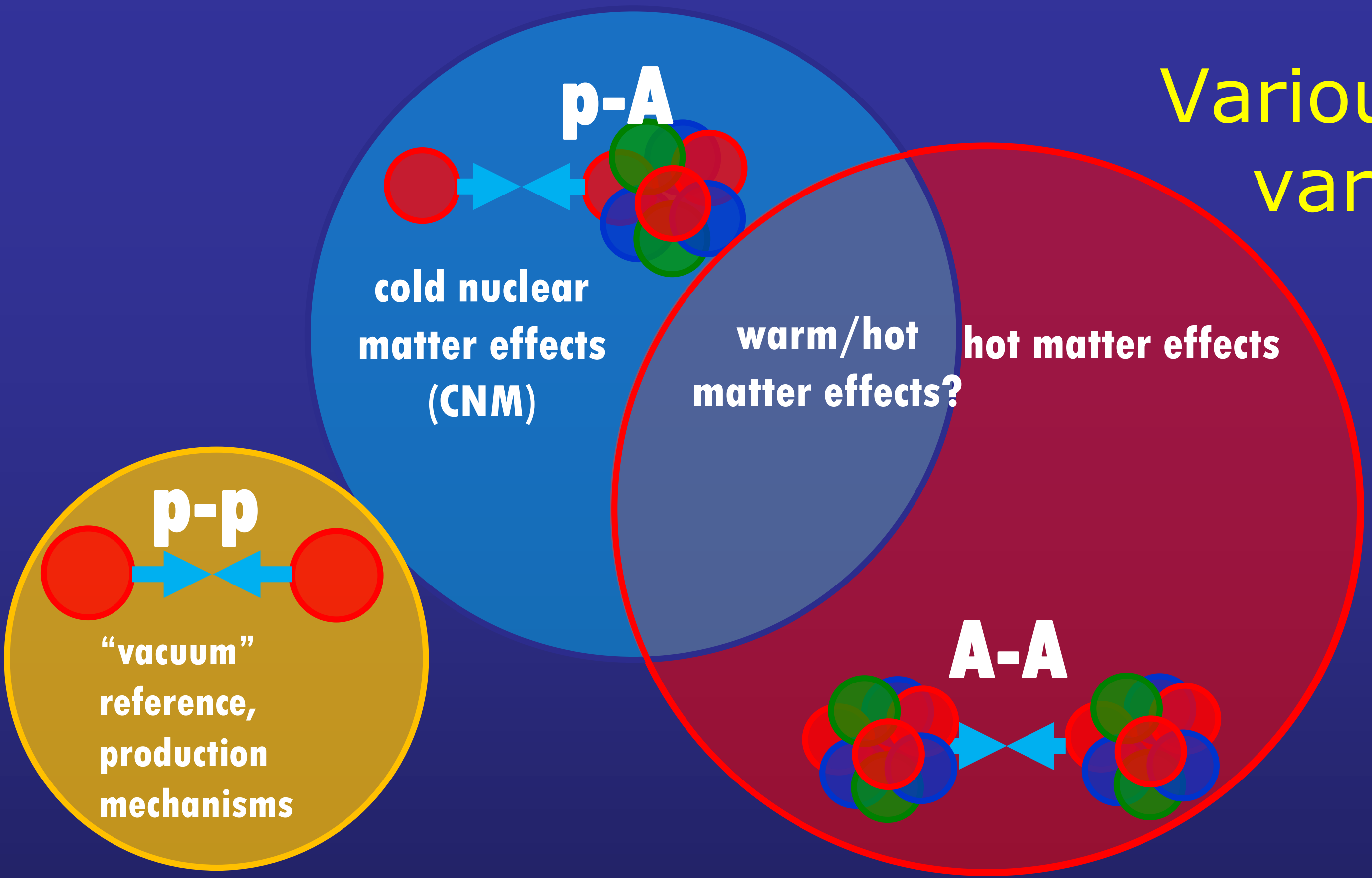
(even if, at that time, correctly discarded because of the small open charm cross section at the energies then available)

Various systems, various effects



- CNM: nuclear shadowing, color glass condensate, parton energy loss, resonance break-up (RHIC energy)
- Hot matter effects: suppression vs re-generation
- "Warm" matter effects: hadronic resonance gas

Various systems, various effects



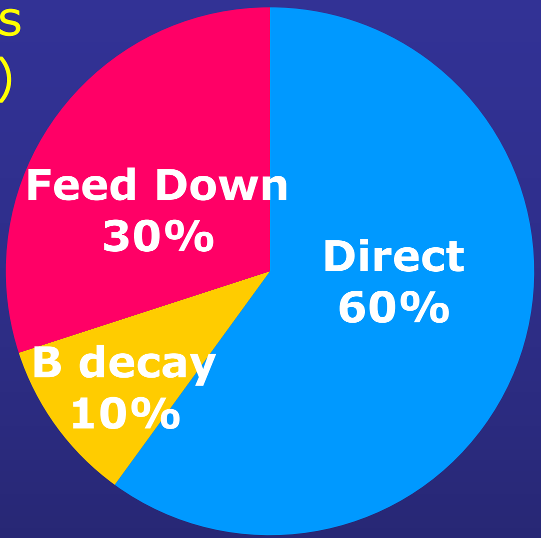
Quantify the yield modifications via the nuclear modification factor R_{AA}

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

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

Sources of heavy quarkonia

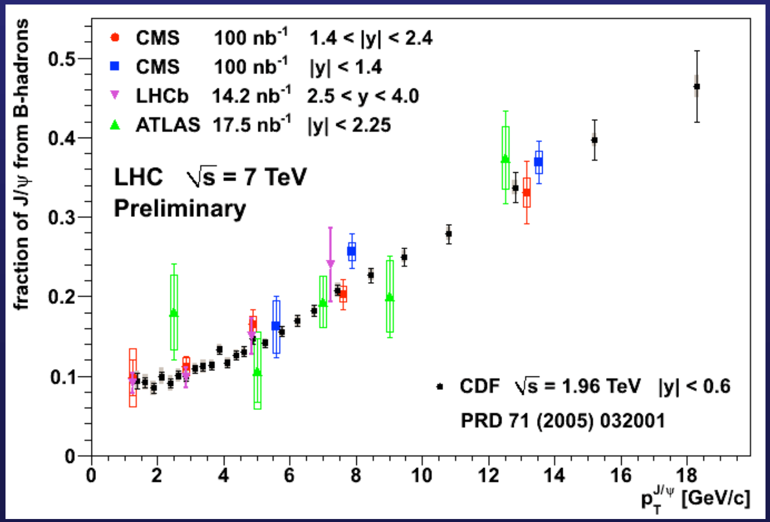
- Quarkonium production can proceed:
  - directly in the interaction of the initial partons
  - via the decay of heavier hadrons (feed-down)



- For J/ψ (at CDF/LHC energies) the contributing mechanisms are:

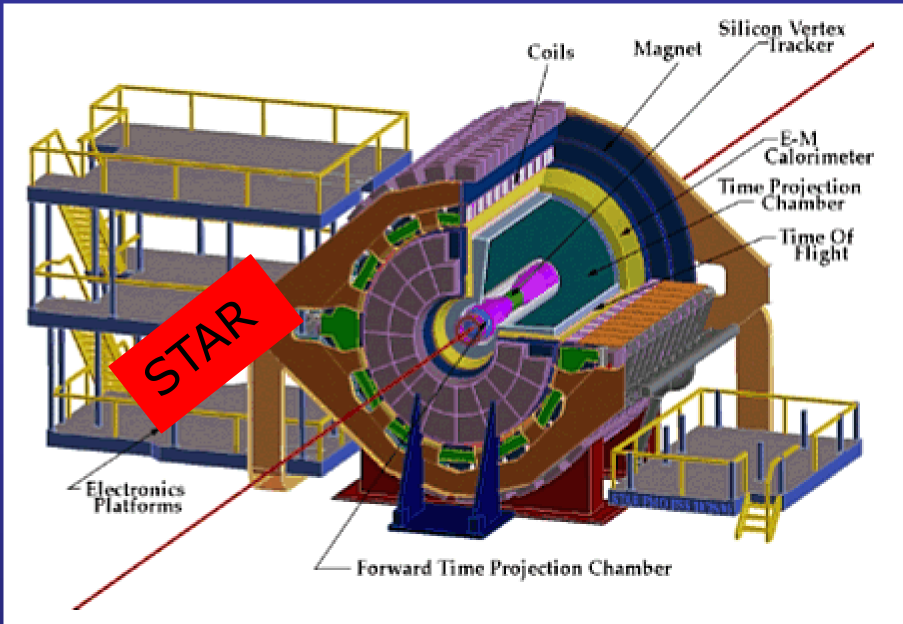
Prompt
- Direct production
- Feed-down from higher charmonium states:
  ~ 8% from ψ(2S), ~25% from χ_c

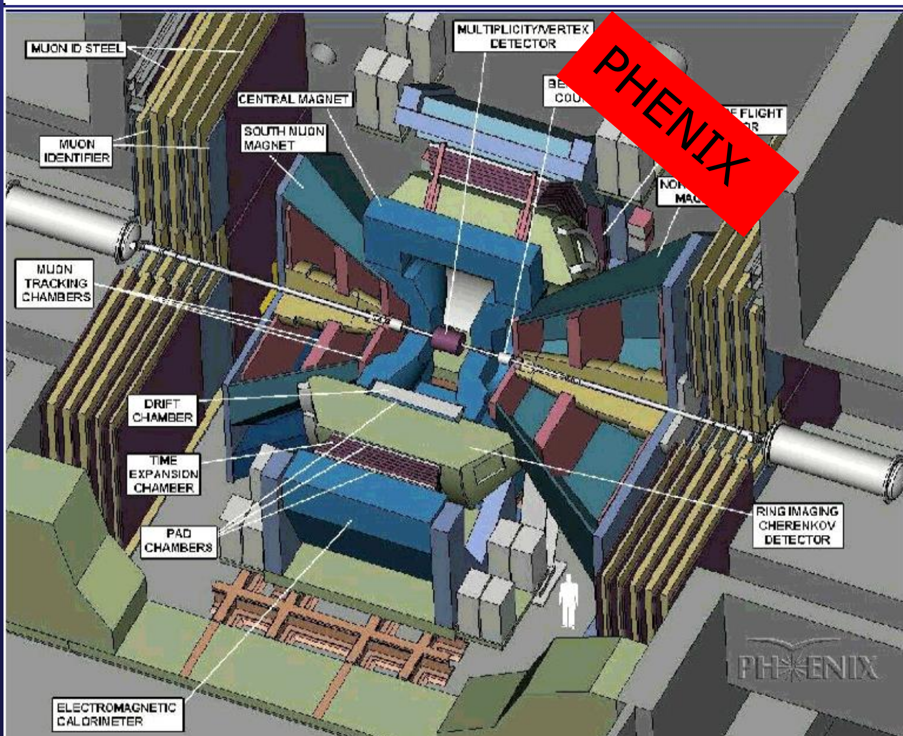
Non-prompt
- B decay
  contribution is p_T dependent
  ~10% at p_T~1.5GeV/c



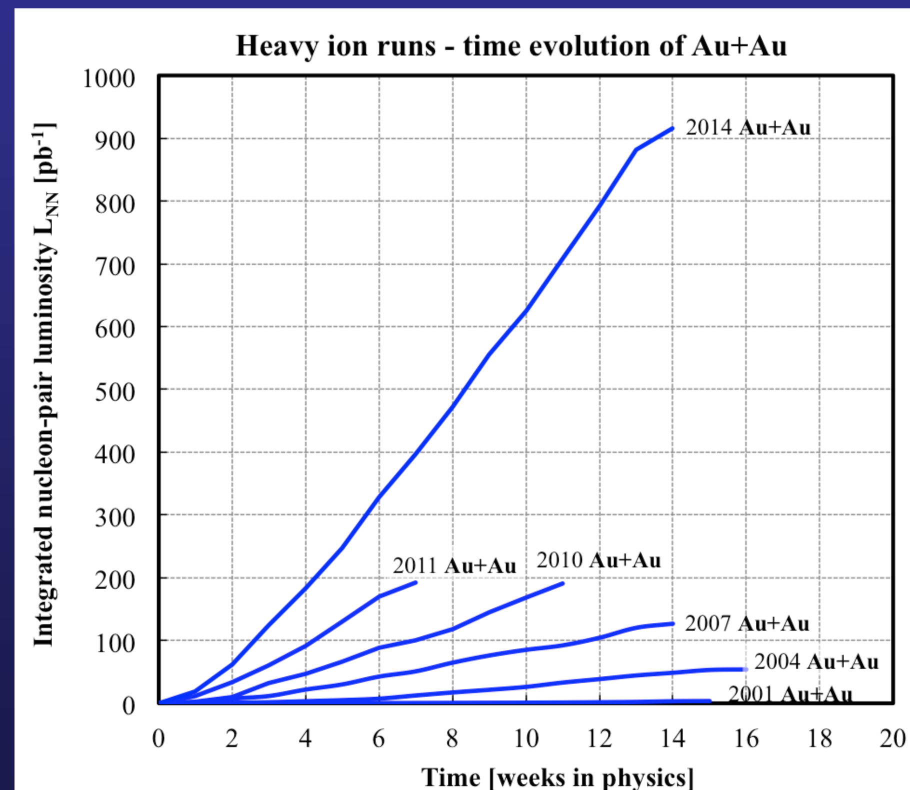
- B-decay component "easier" to separate →displaced production

Quarkonium at RHIC





- Kinematic coverage
  - PHENIX $1.2<|y|<2.2$ ($\mu^+\mu^-$), $|y|<0.35$ (e^+e^-)
  - STAR $|y|<1$ (e^+e^-) (recently $|y|<0.5$ $\mu^+\mu^-$)



$$L = L_{NN} / (197)^2$$

Quarkonium at RHIC

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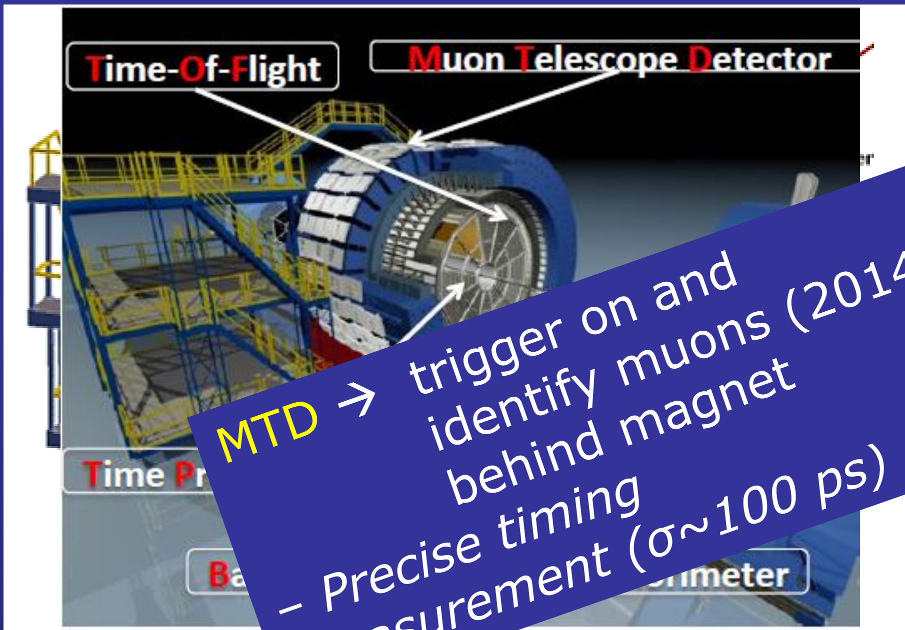
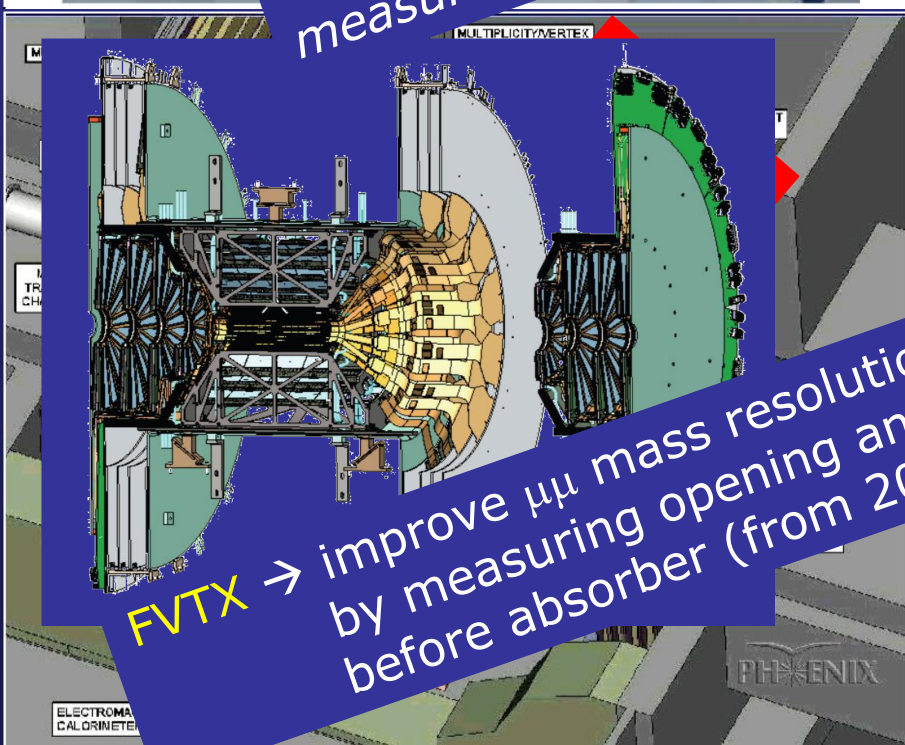
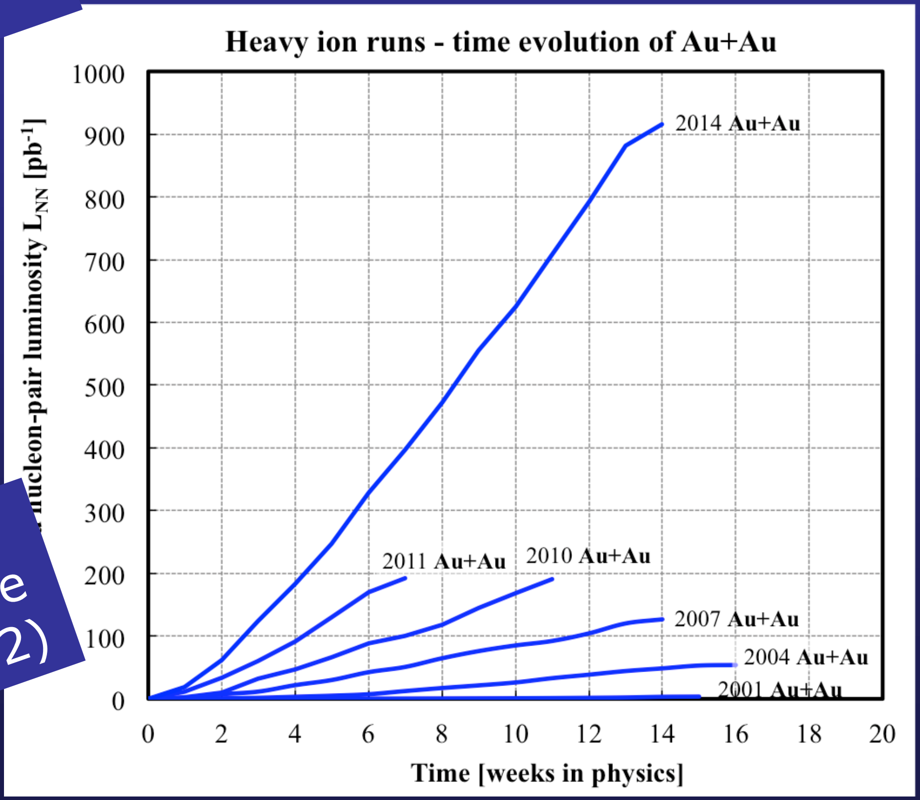


MTD → trigger on and identify muons (2014) behind magnet – Precise timing measurement (σ~100 ps)



FVTX → improve $\mu\mu$ mass resolution by measuring opening angle before absorber (from 2012)



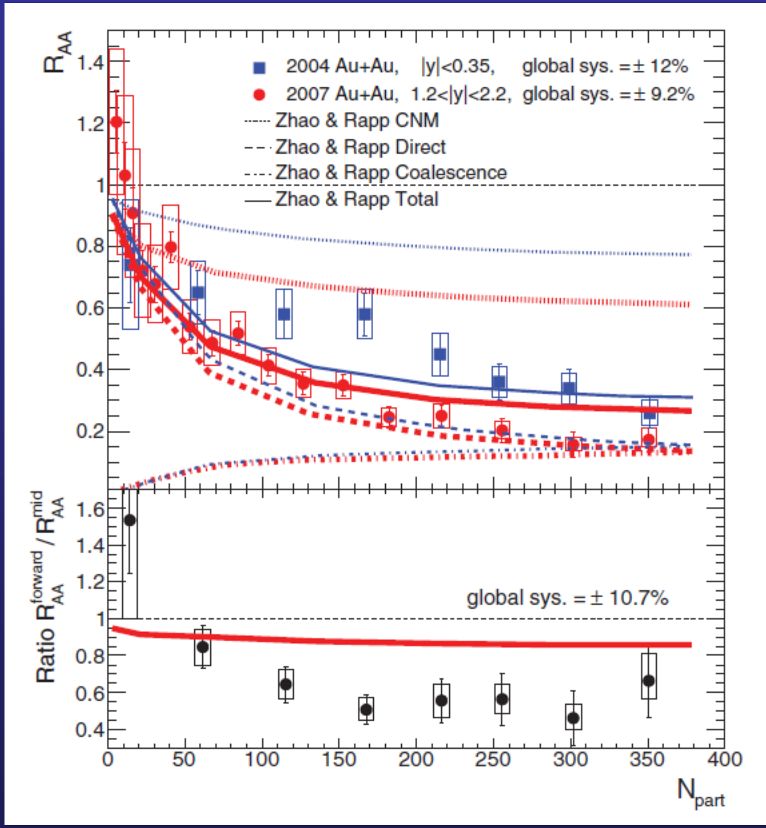
$$L = L_{NN} / (197)^2$$

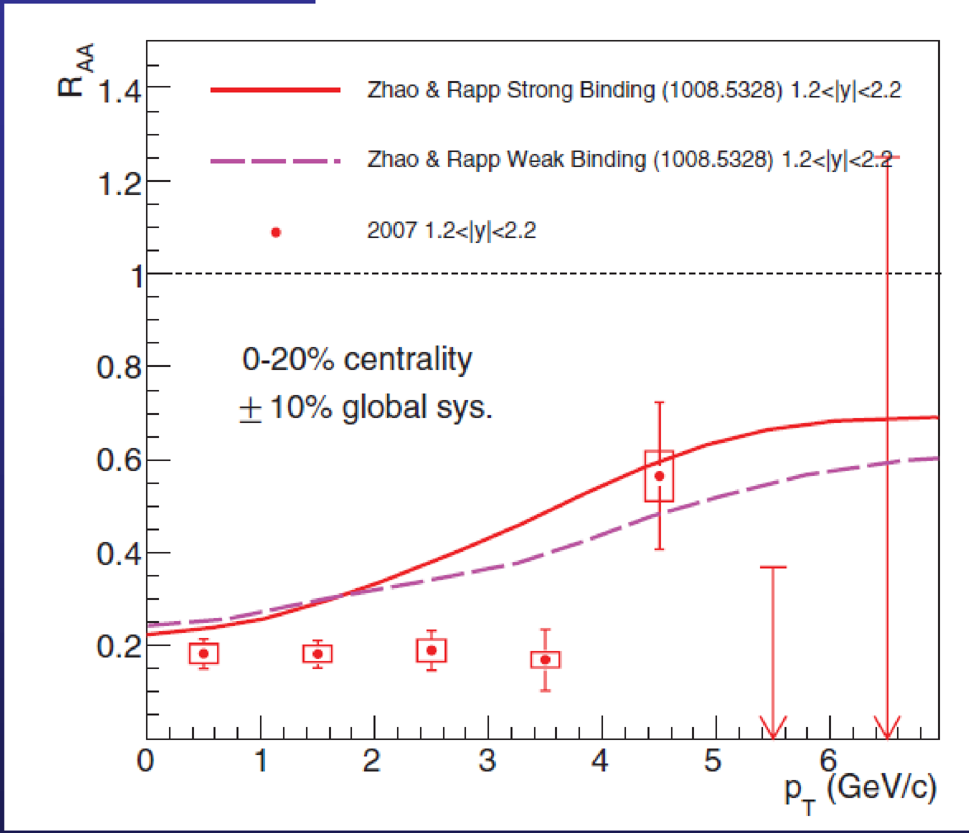
Selected RHIC results

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

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

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



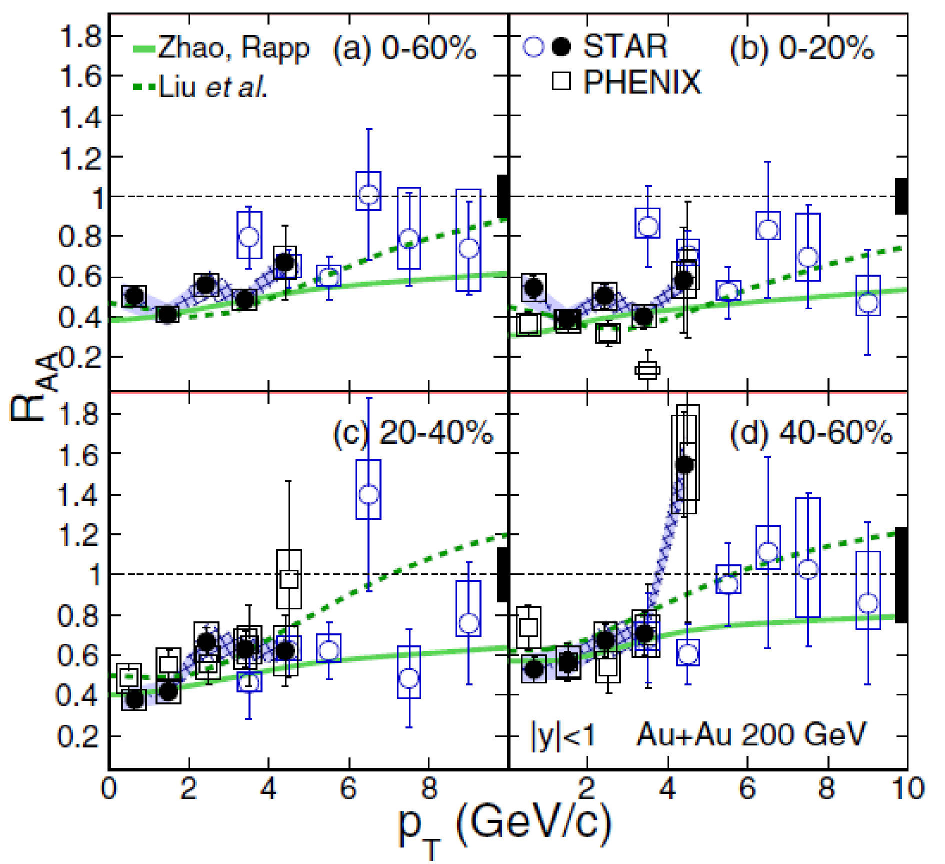


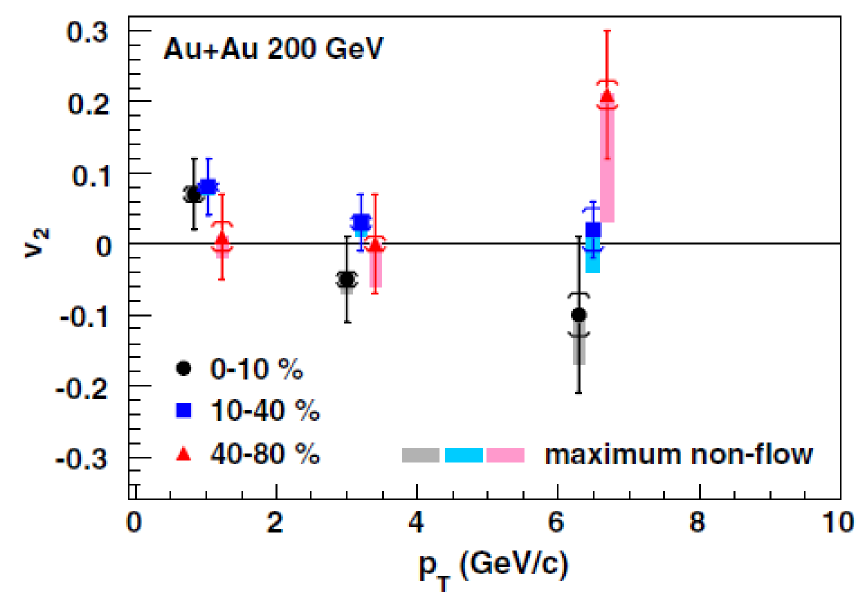
- **Suppression**, with strong **rapidity dependence**, in Au-Au at $\sqrt{s}$= 200 GeV
- Qualitatively, but not quantitatively in agreement with models

Selected RHIC results

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

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

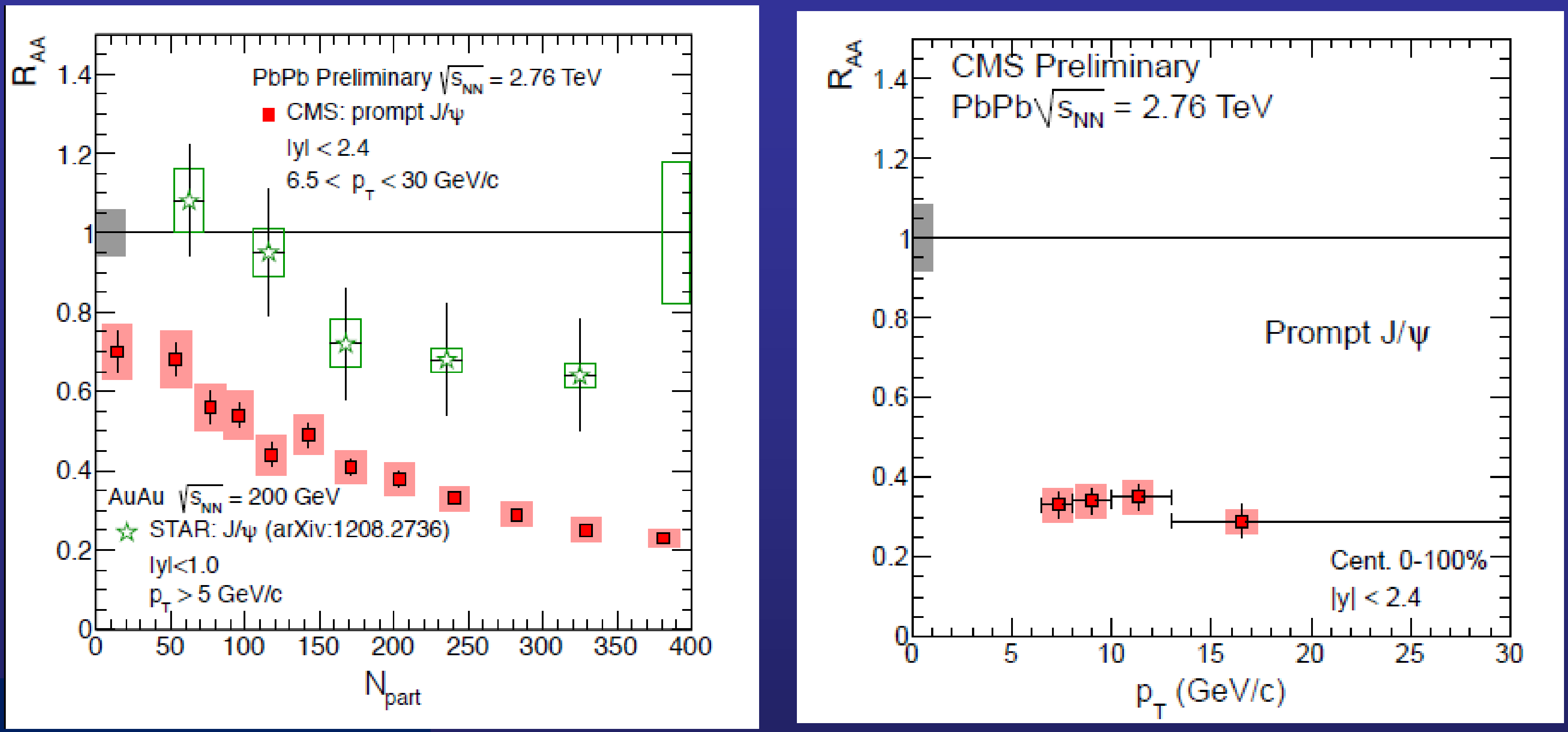




- ❑ Good coverage from low to high p_T
- ❑ R_{AA} increases with p_T
- ❑ No significant J/ψ elliptic flow

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



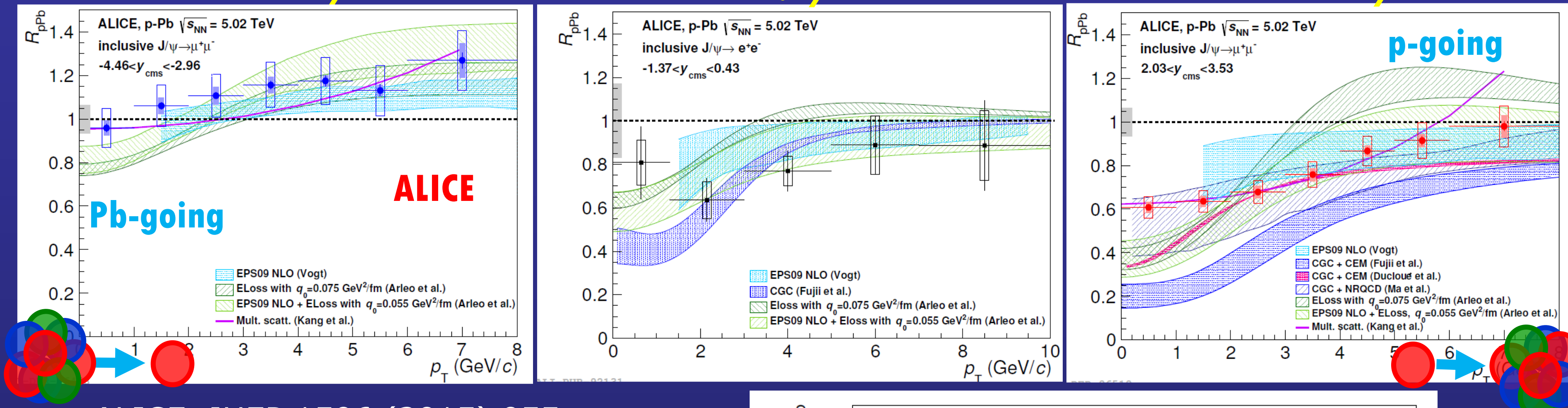
CMS-PAS HIN-12-2014

- 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 effects are not negligible!

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

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

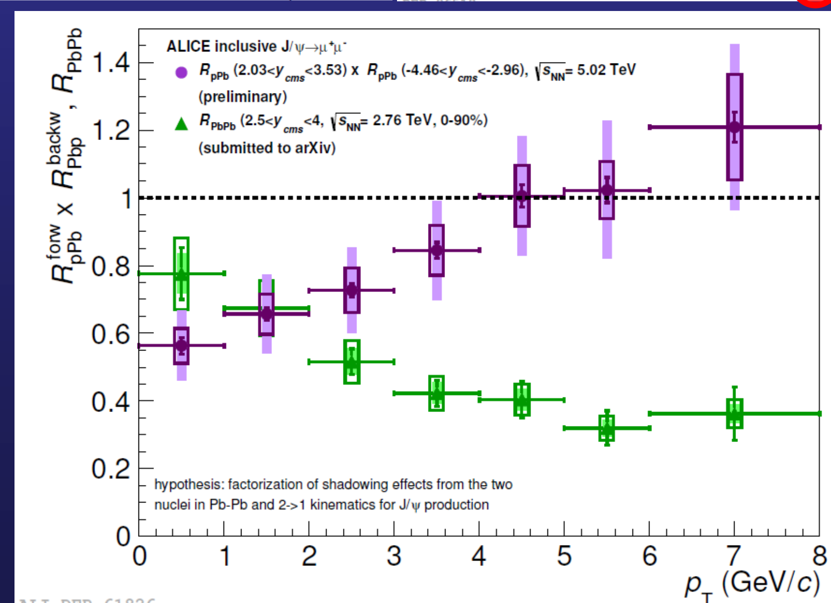


ALICE, JHEP 1506 (2015) 055

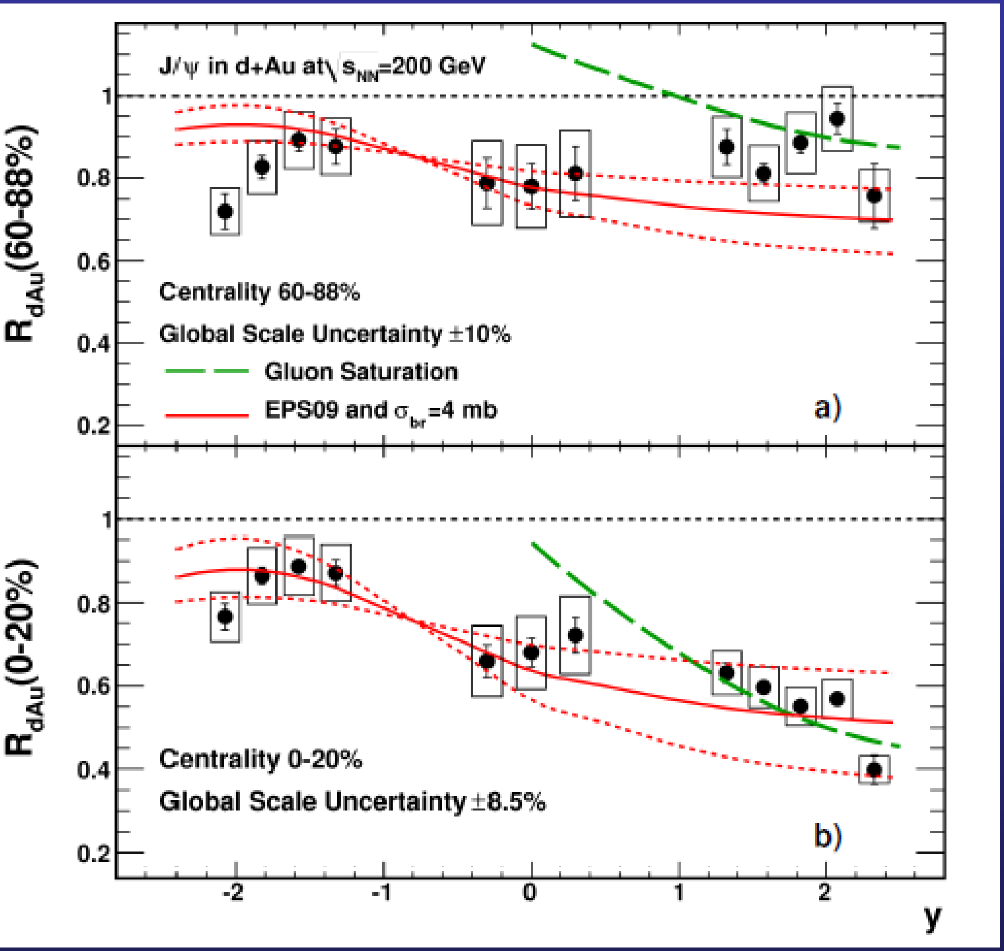
- Fair agreement with models (shadowing/CGC + energy loss)

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

→ Evidence for hot matter effects!



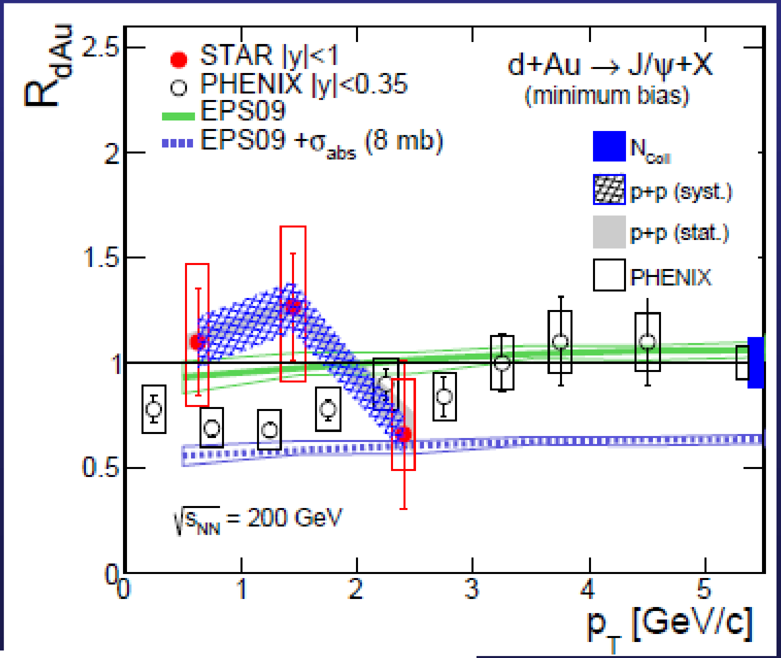
CNM at RHIC energy



PHENIX, PRL107 (2011) 142301

- 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 ($\sigma_{J/\psi-N}$ ~ 4 mb)

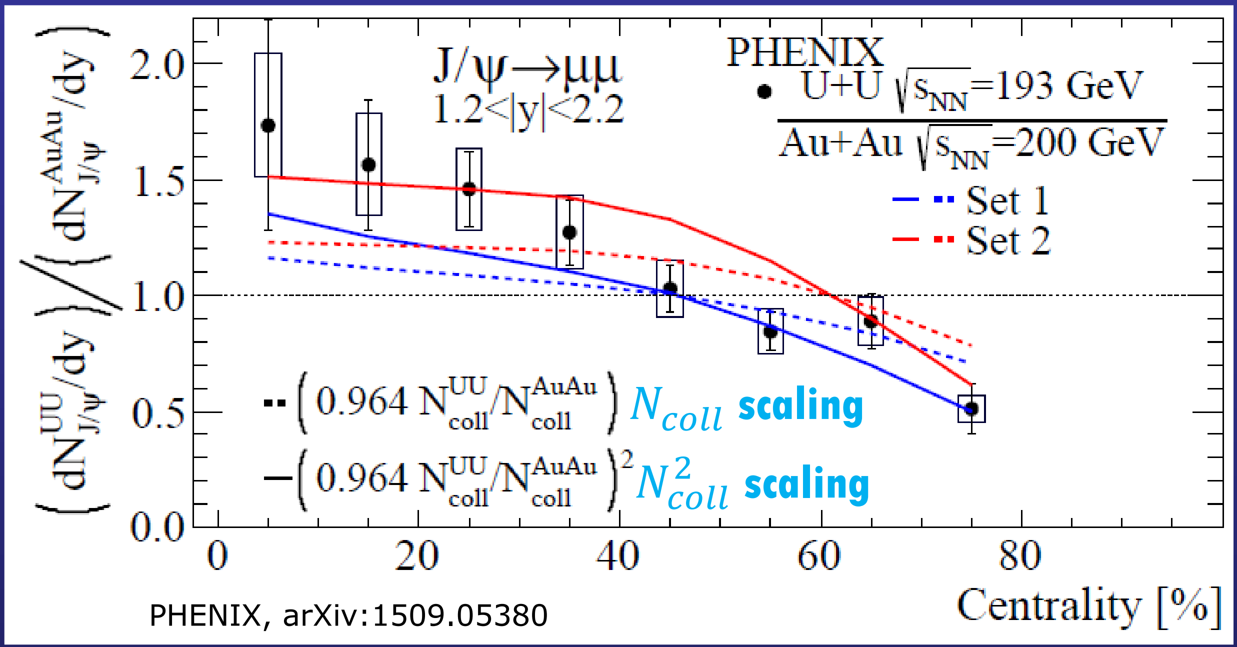
STAR, arXiv:1602.02212



- Transverse momentum dependence more difficult to reproduce

Recent RHIC results: U-U!

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



in central U-U wrt Pb-Pb

1) stronger suppression due to color screening
ε_{AuAu} ~ 80-85% ε_{UU}

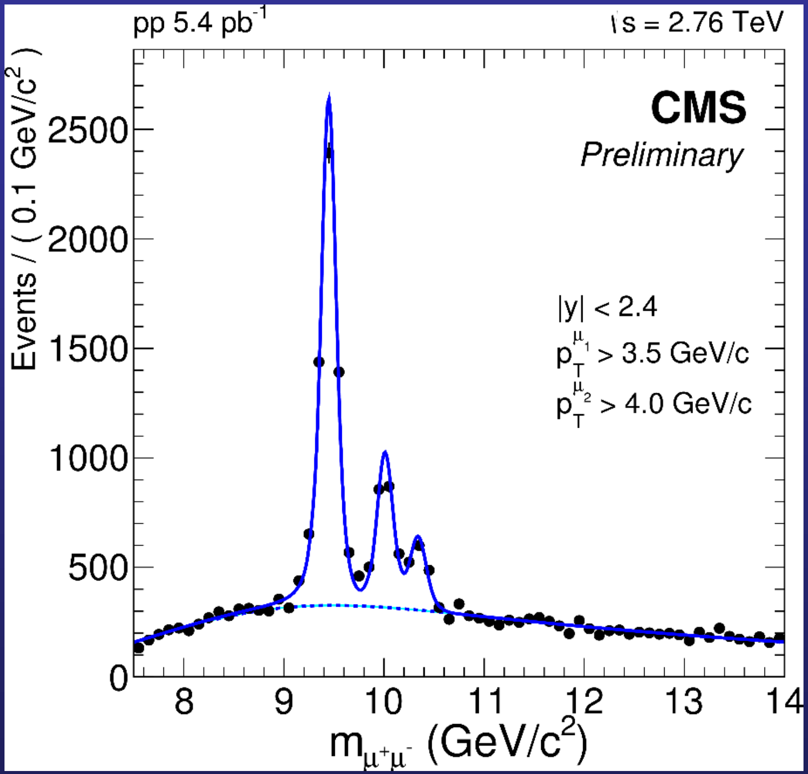
2) J/ψ recombination favoured by 25% larger N_{coll} in UU
$N_{J/\psi}^{stat} \sim N_c^2 \sim N_{coll}^2$

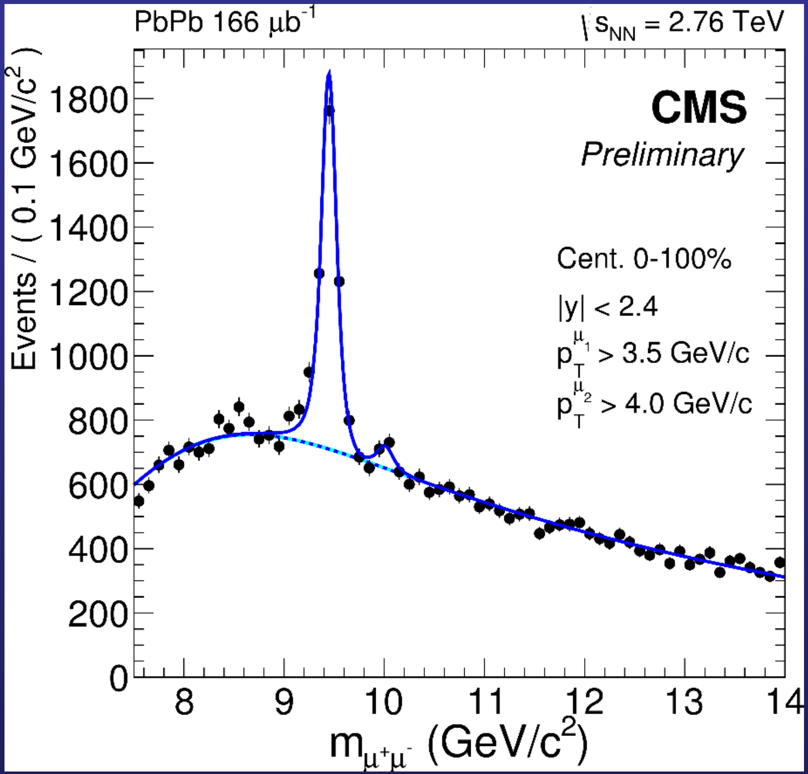
- results slightly favour N_{coll}^2 scaling → (re)combination wins over suppression when going from central U-U to Au-Au collisions

- quantitative comparison depends on the choice of the uranium Woods-Saxon parametrizations

Υ suppression in Pb-Pb collisions

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





CMS-HIN-15-001

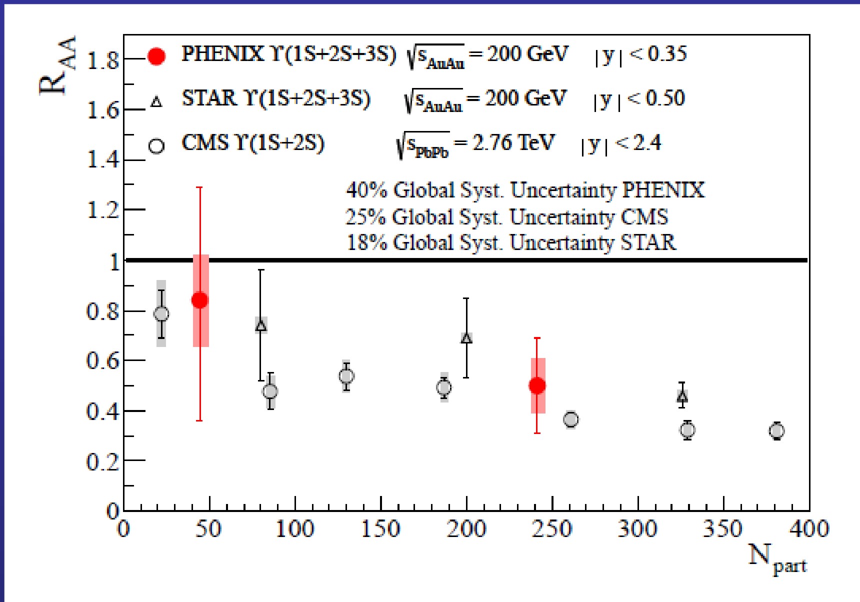
Strong relative suppression of more loosely bound states

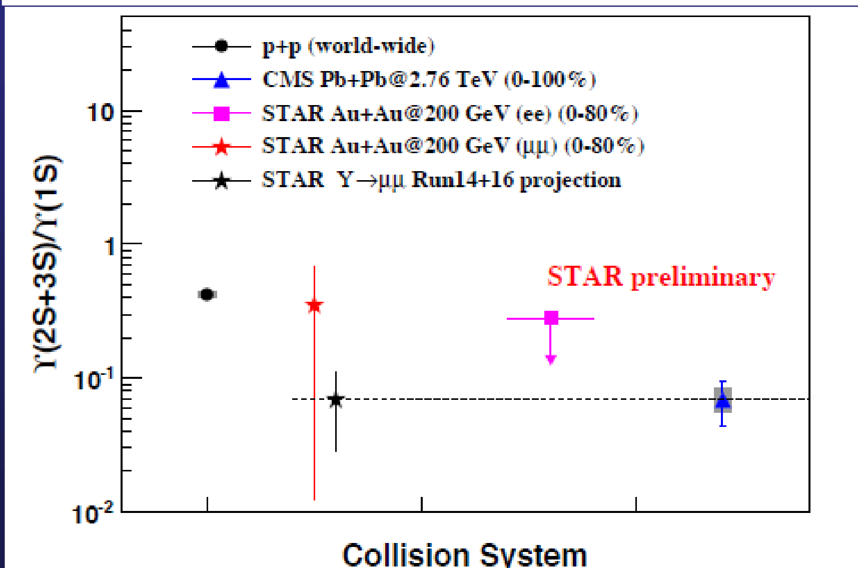
$R_{AA}(\Upsilon(1S)) = 0.43 \pm 0.03 \pm 0.07$

$R_{AA}(\Upsilon(2S)) = 0.13 \pm 0.03 \pm 0.02$

$R_{AA}(\Upsilon(3S)) < 0.14$ at 95% CL

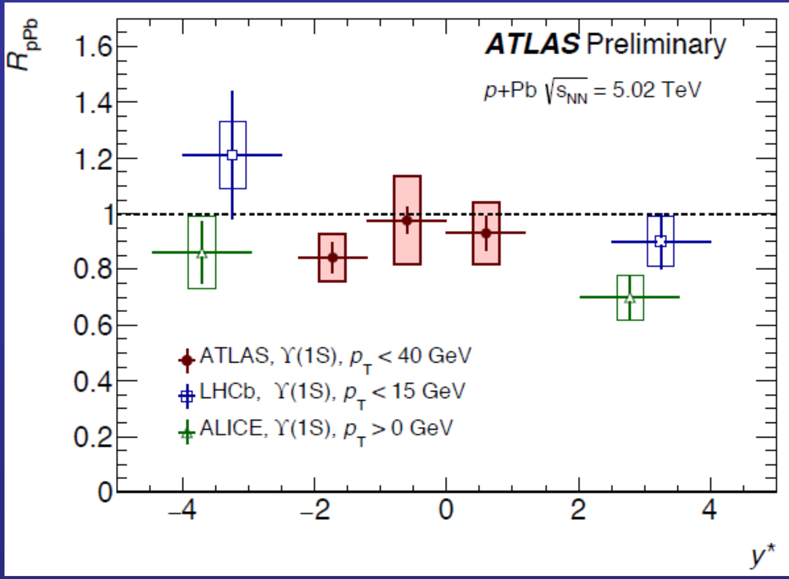
Bottomonium results at RHIC

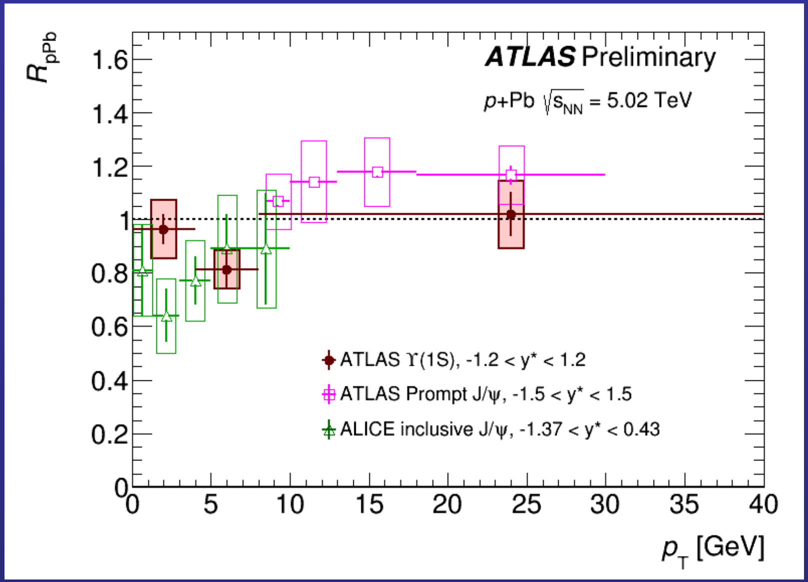


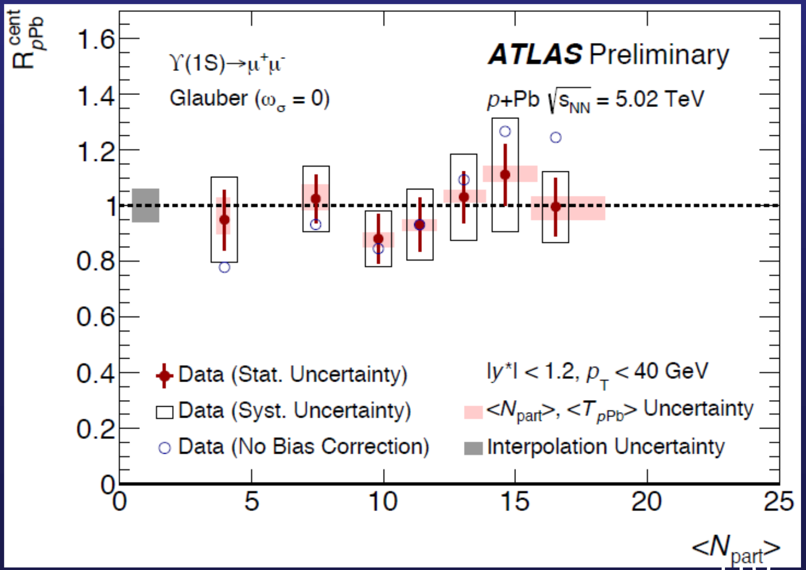


- ❑ Both PHENIX/STAR have published results on Υ
- ❑ Mutual agreement between experiments but still large stat+syst uncertainties
- → Need upgraded detectors and higher luminosity
- ❑ Recent results with the STAR MTD on the ratio excited/ground state
- ❑ Consistent with dielectron measurement within large uncertainties
- ❑ Factor 7 more statistics on this measurement with full Run14+ Run16 data

Weak CNM effects for bottomonium



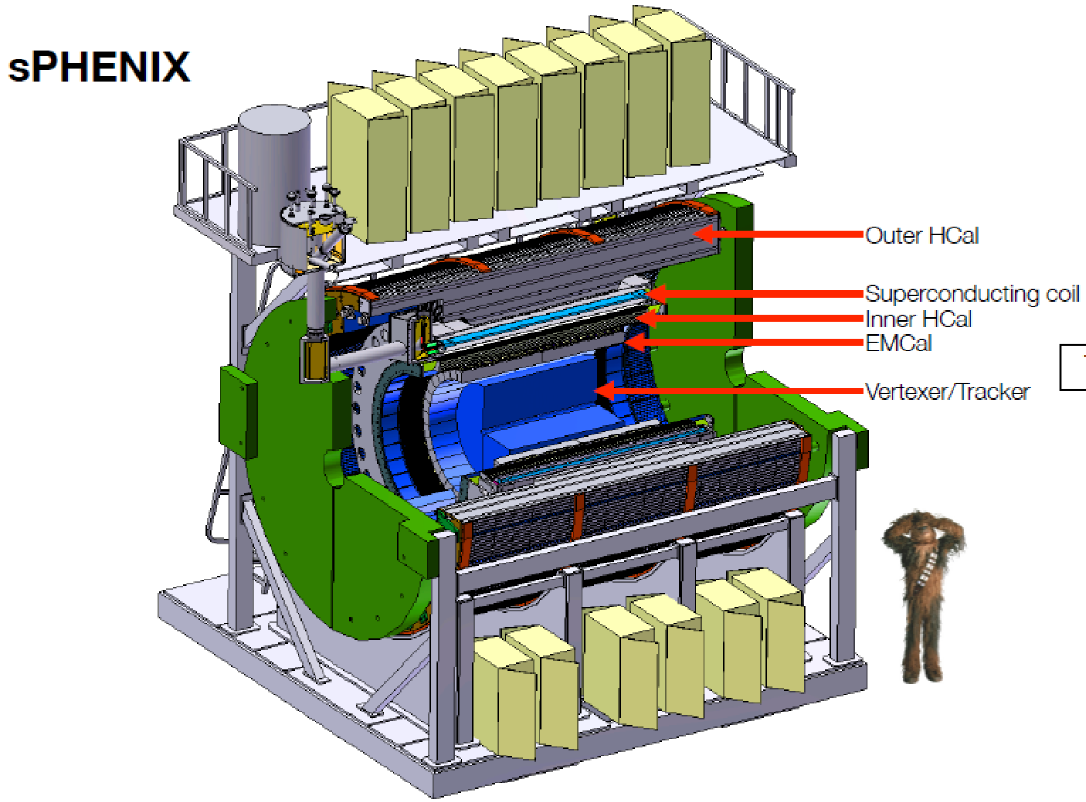




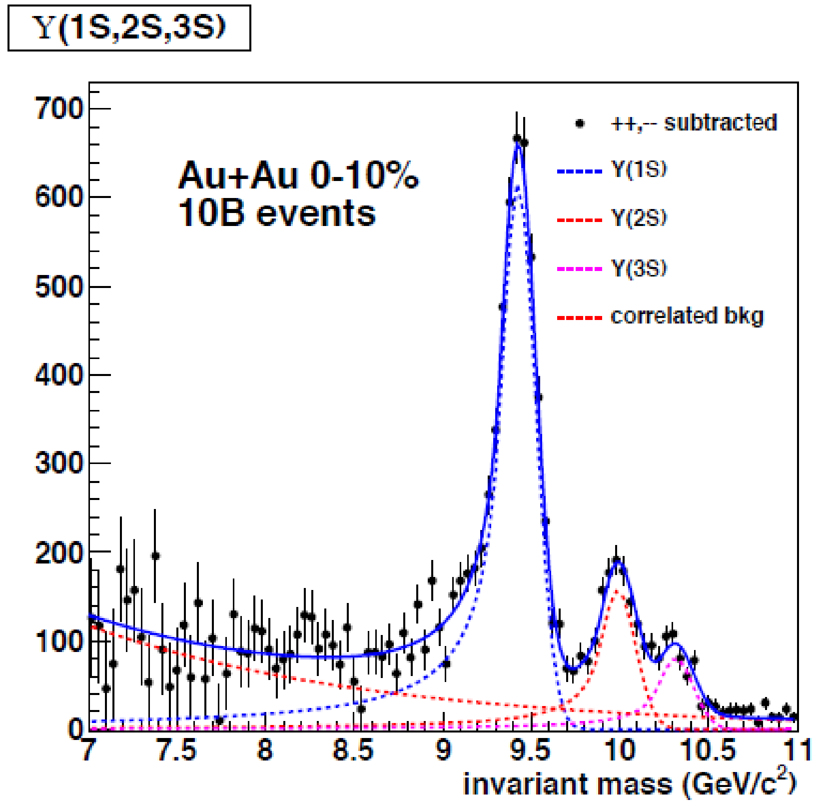
- R_{pPb} close to 1 and with no significant dependence on y, p_T and centrality
- Fair agreement ALICE vs LHCb (within large uncertainties)

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

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)

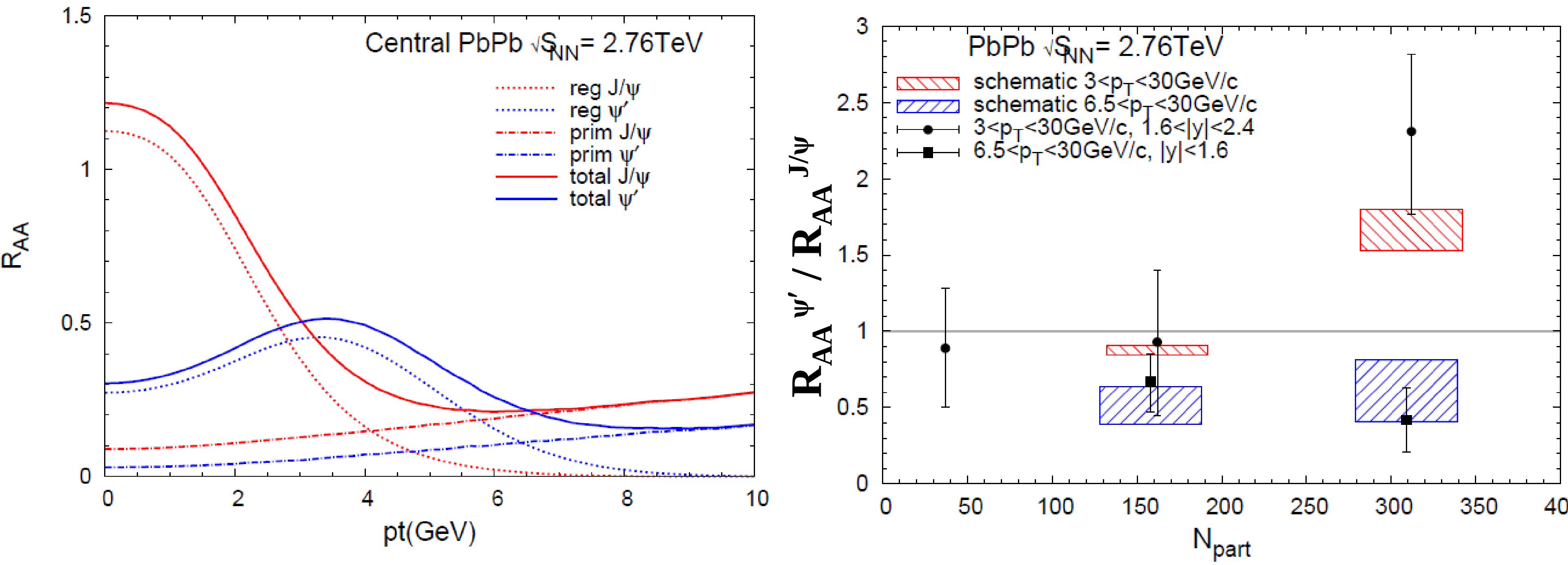
	p_T^{Υ} (GeV/c)	$\mathcal{R}^{\chi_b(1P)}_{\Upsilon(nS)}$	$\mathcal{R}^{\chi_b(2P)}_{\Upsilon(nS)}$
Υ(1S)	6–8	$14.8 \pm 1.2 \pm 1.3$	$3.3 \pm 0.6 \pm 0.2$
	8–10	$17.2 \pm 1.0 \pm 1.4$	$5.2 \pm 0.6 \pm 0.3$
	10–14	$21.3 \pm 0.8 \pm 1.4$	$4.0 \pm 0.5 \pm 0.3$
	14–18	$24.4 \pm 1.3 \pm 1.2$	$5.2 \pm 0.8 \pm 0.4$
	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

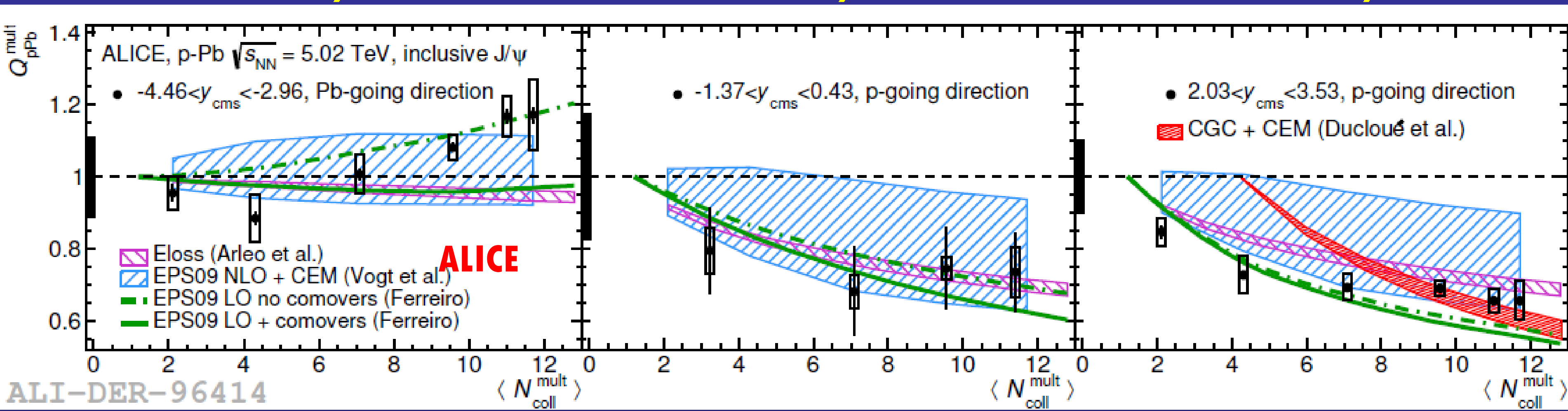
Charmonium: the ψ(2S) puzzle



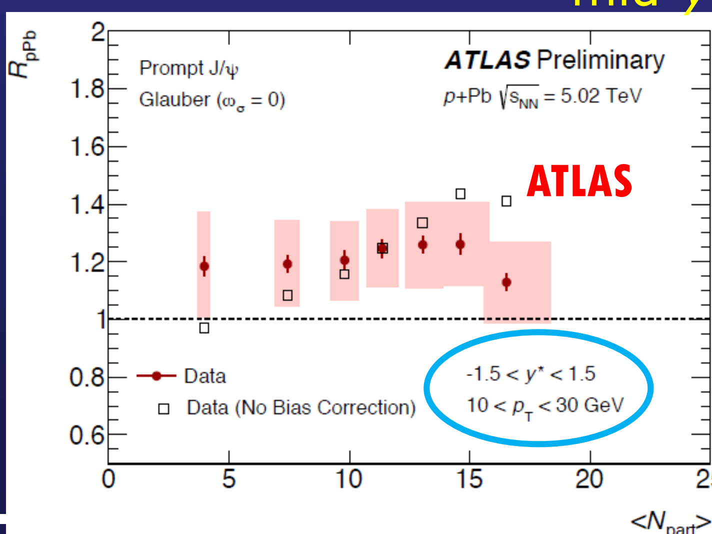
- ❑ The regeneration of ψ′ mesons occurs significantly later than for J/ψ's
- ❑ Despite a smaller total number of regenerated ψ′, the stronger radial flow at their time of production induces a marked enhancement of their R_{AA} relative to J/ψ's in a momentum range pt ≃ 3-6 GeV/c.

J/ψ R_{pPb}: centrality dependence

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



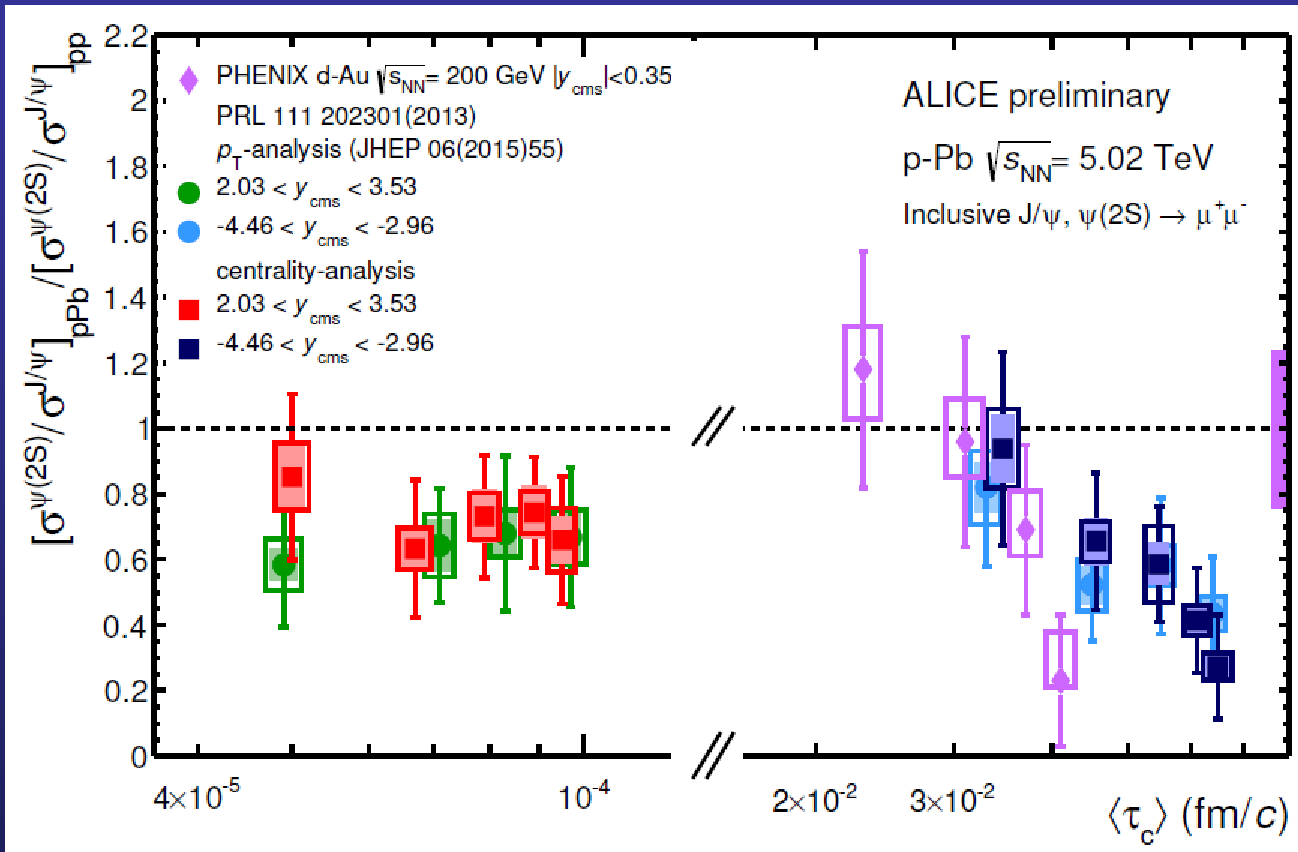
mid-*y*



- 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

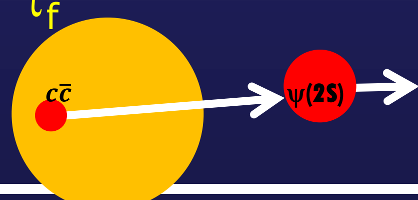
Dependence of suppression on τ_c



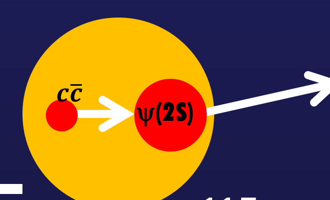
$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

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

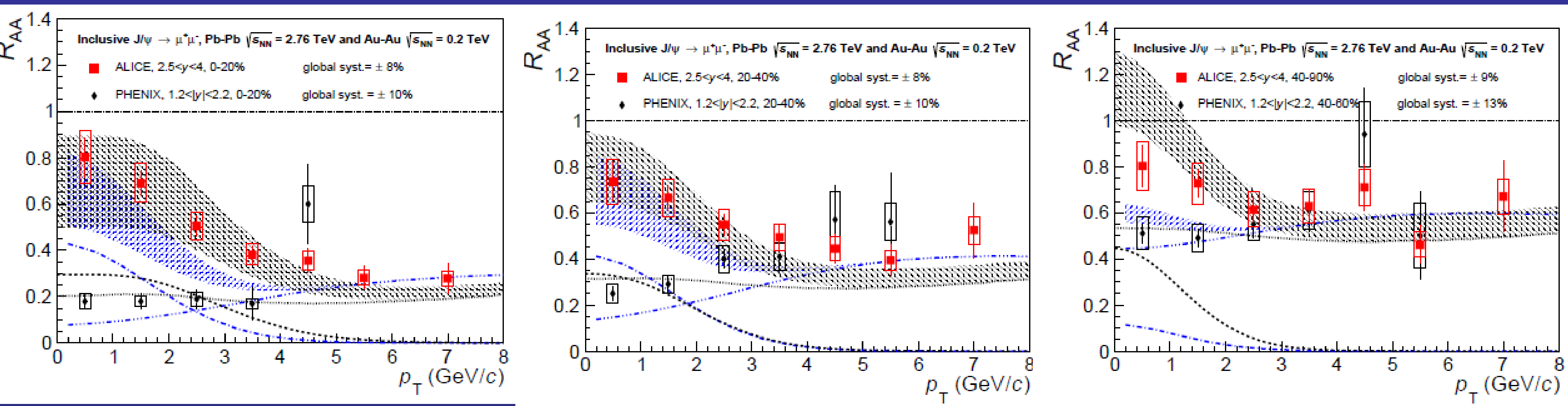
Forward-y: $\tau_c << \tau_f$
interaction with nuclear matter cannot play a role



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



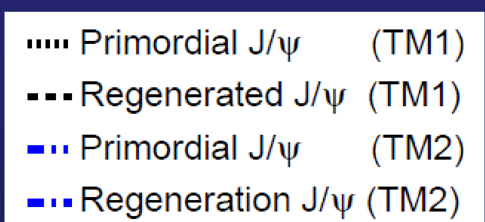
R_{AA} vs p_T



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

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

ALICE, arXiv:1506.08804



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

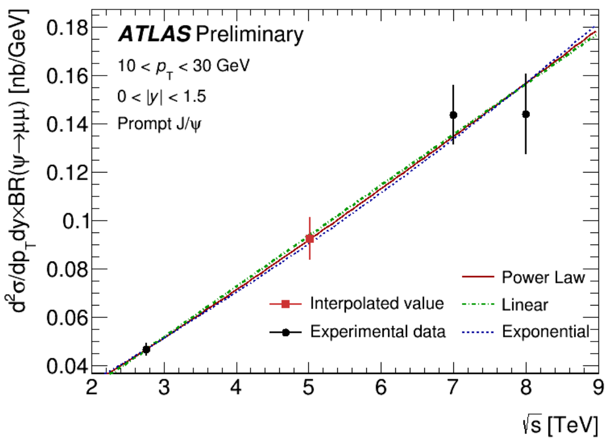
Still rather large theory uncertainties: models will benefit from precise measurement of σ_{cc} and CNM effects

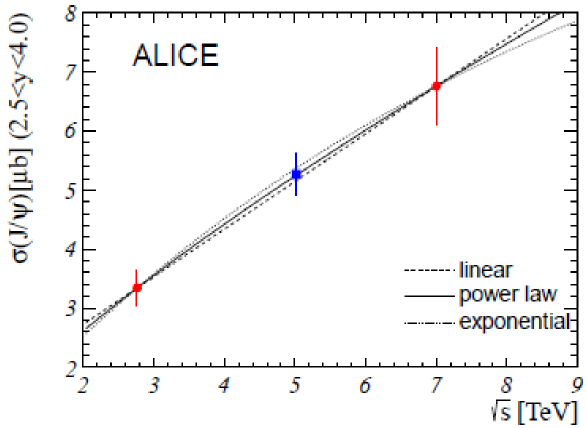
- ❑ Opposite trend with respect to lower energy experiments

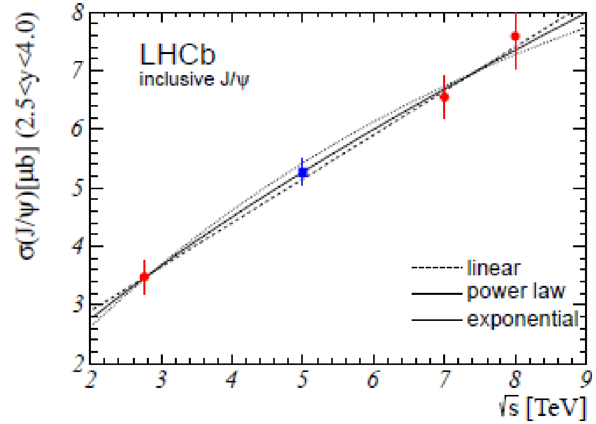
Building a reference σ_{pp} → interpolation

- Simple empirical approach adopted by ALICE, ATLAS and LHCb

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







Example: ALICE result

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

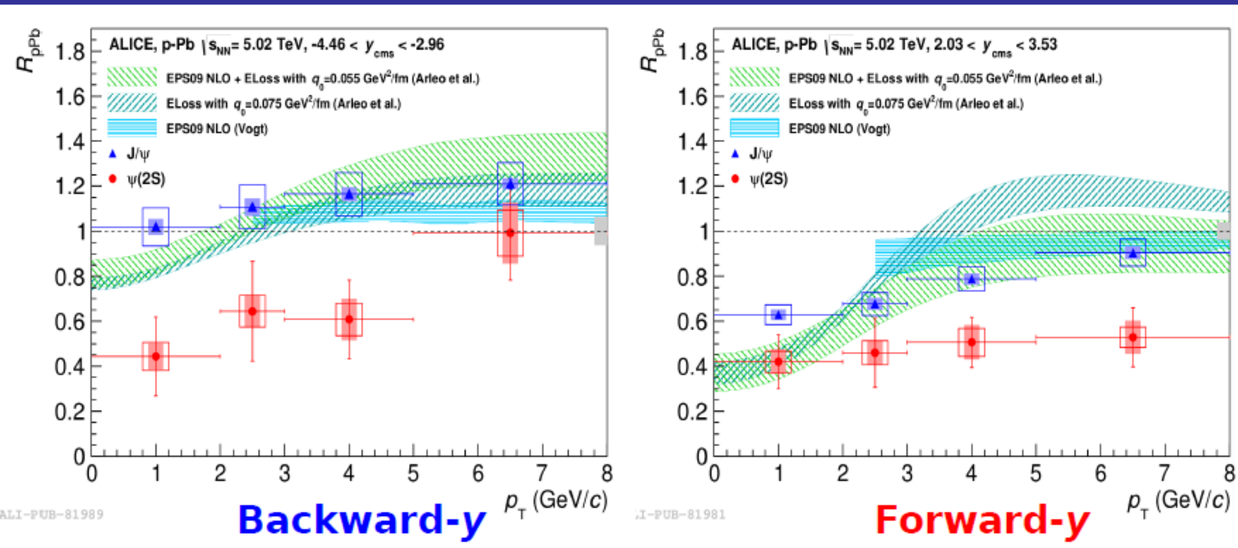
inter: spread of interp. with empirical functions
theo: spread of interp. with theory estimates

- 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)

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

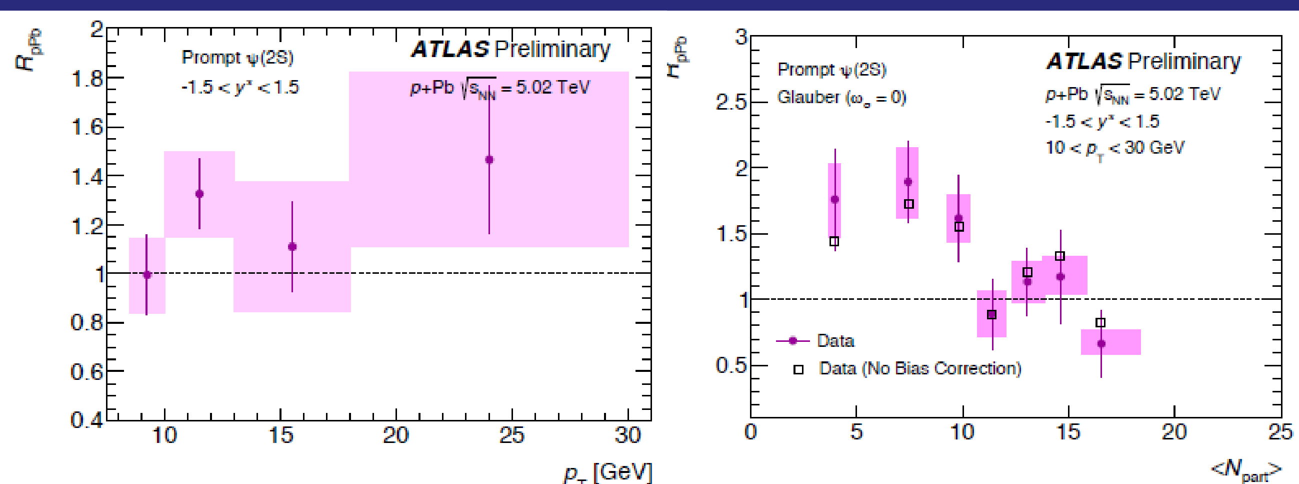
ALICE estimate (conservative)
→ 8% syst. unc. due to different √s
(using CDF/ALICE/LHCb results)

ψ(2S) in 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

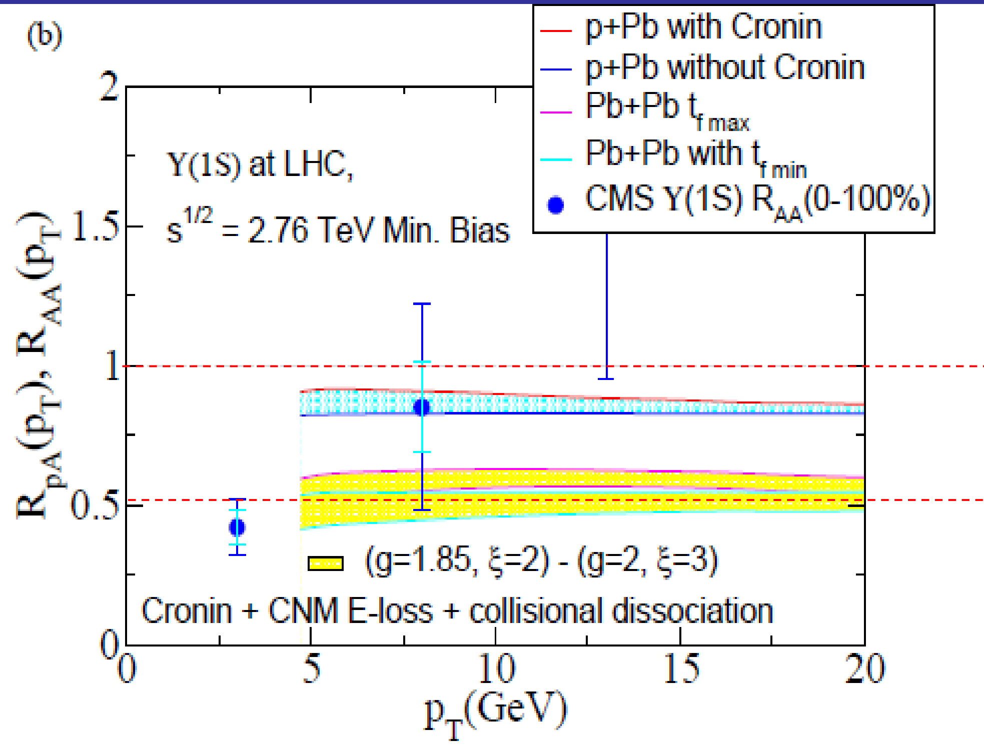


- ATLAS (high p_T) : larger uncertainties, hints for strong enhancement, concentrated in peripheral events

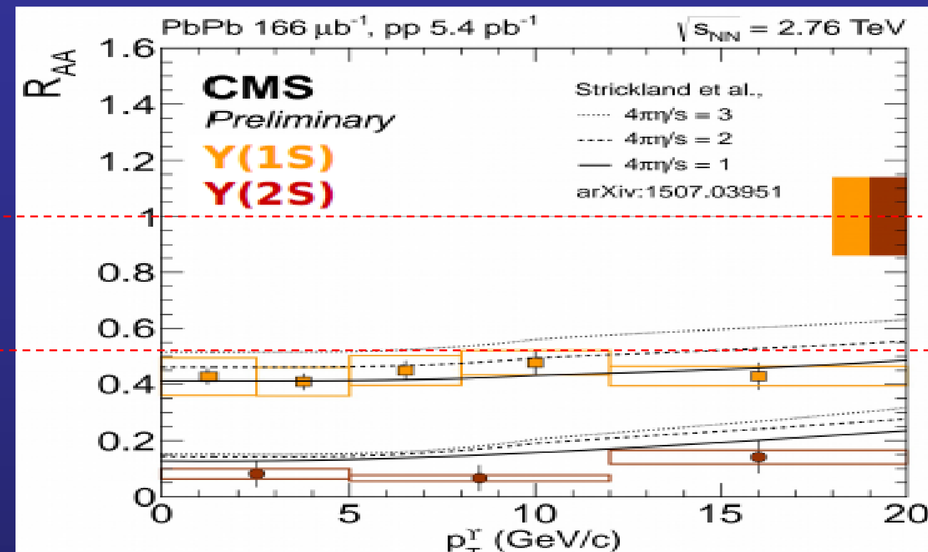
ATLAS-CONF-2015-023

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

High p_T Υ: model comparison

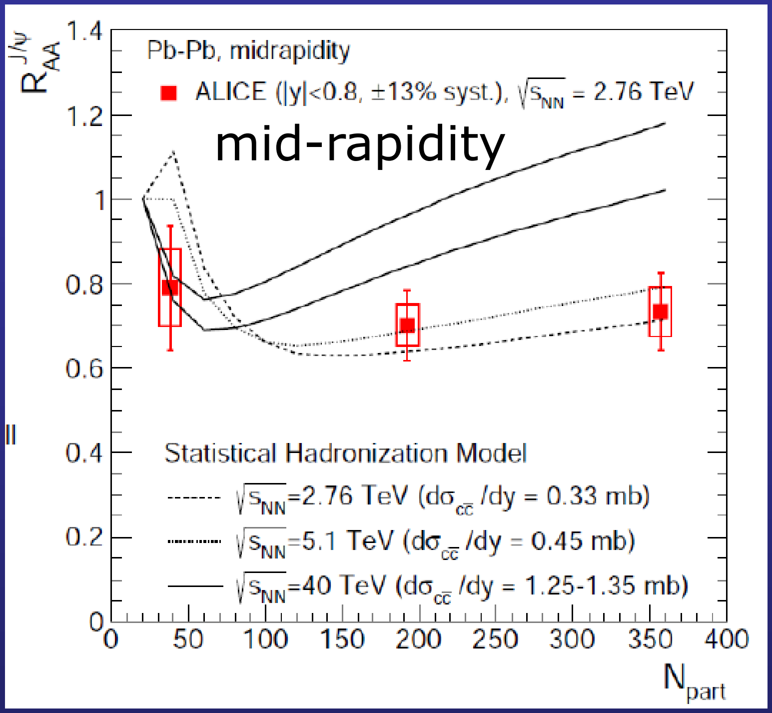


Sharma and Vitev,
Phys. Rev. C 87, 044905 (2013)

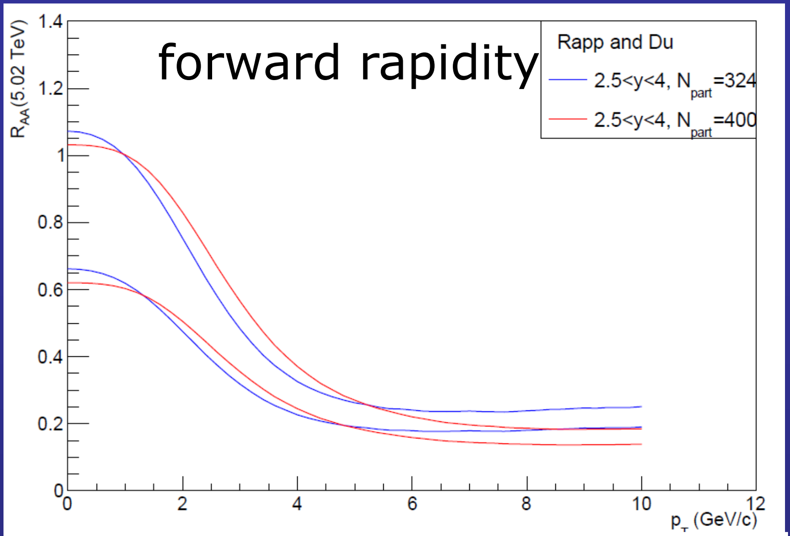


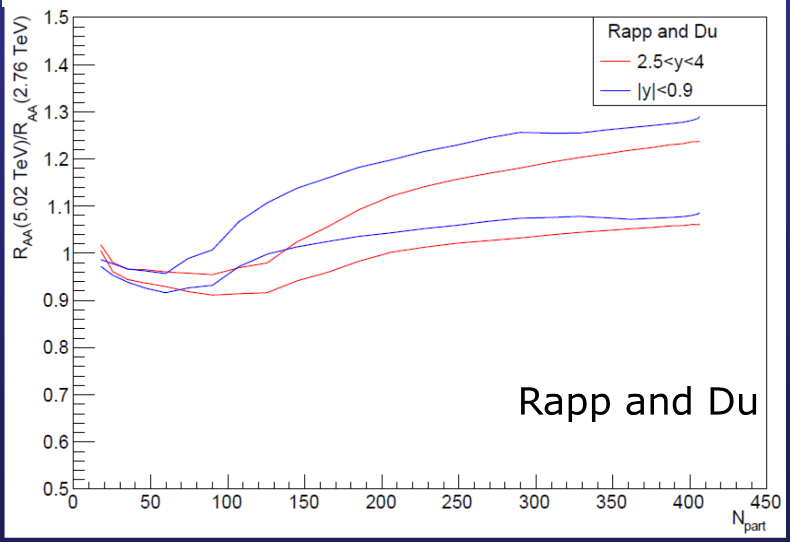
- High p_T Υ suppression
- Propagation effects through QGP
  - Quenching of the color octet component
  - Collisional dissociation model
- Approximation: initial wave function of the quarkonia well approximated by vacuum wavefunctions in the short period before dissociation
- CNM effects accounted for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

Some J/ψ predictions for run-2



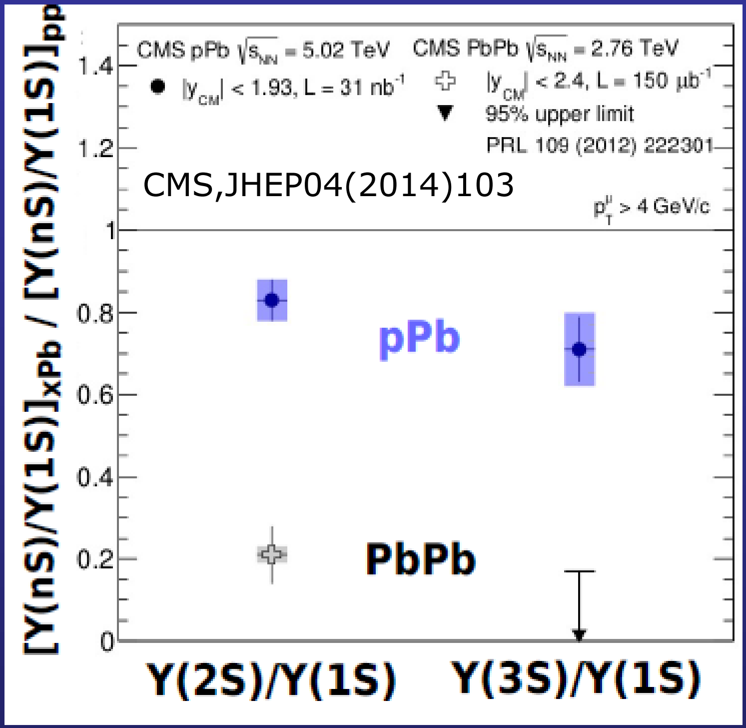
PBM, Andronic, Redlich and Stachel

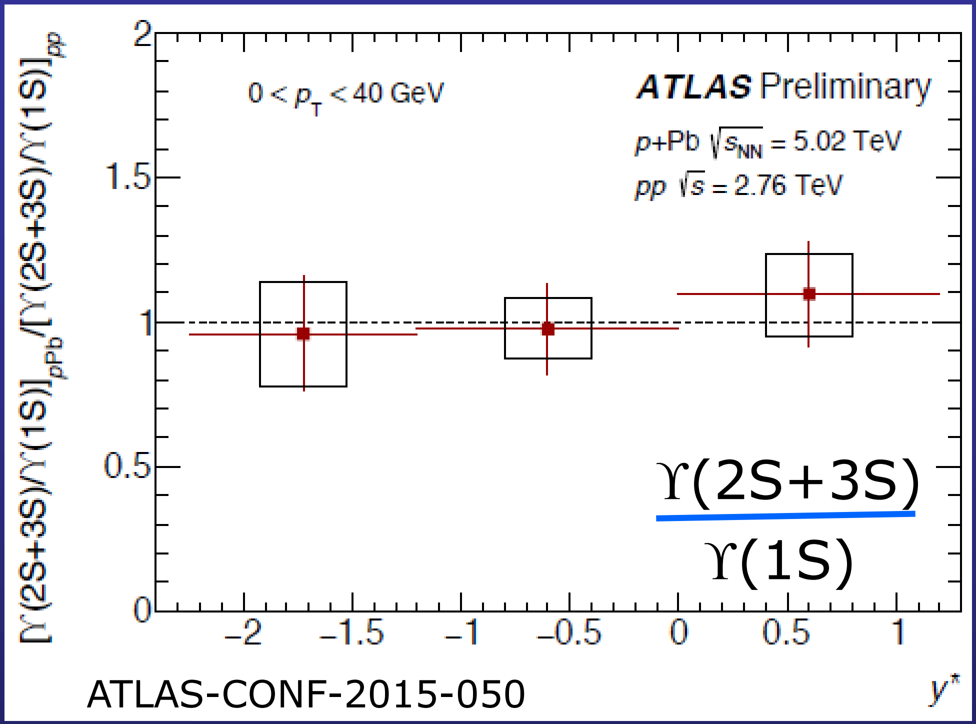




- First predictions for (both statistical and transport models) indicate a moderate increase in R_{AA}, when comparing $\sqrt{s_{NN}}$=5.02 and 2.76 TeV
- Theoretical uncertainties are larger than the predicted increase
  → Provide quantities where at least partial cancellation of uncertainties takes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

Yield ratios for bottomonium in p-Pb





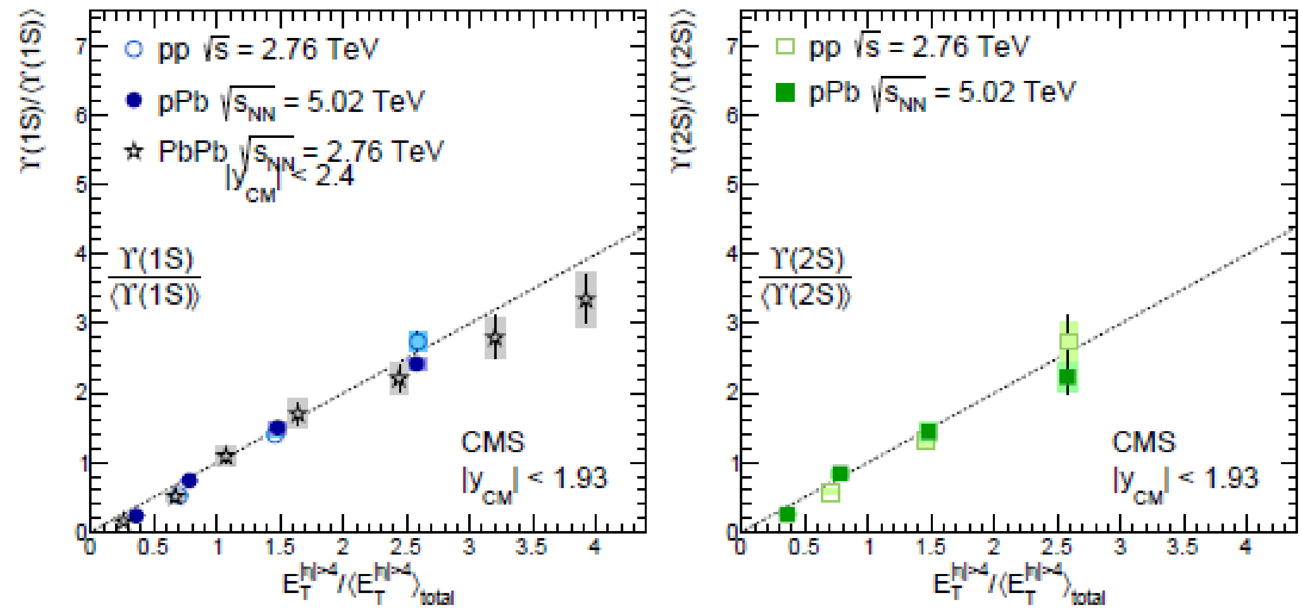
CMS

- Excited states suppressed with respect to $\Upsilon(1S)$
- Initial state effects similar for the various $\Upsilon(ns)$ states
  → Final states effects at play?

ATLAS

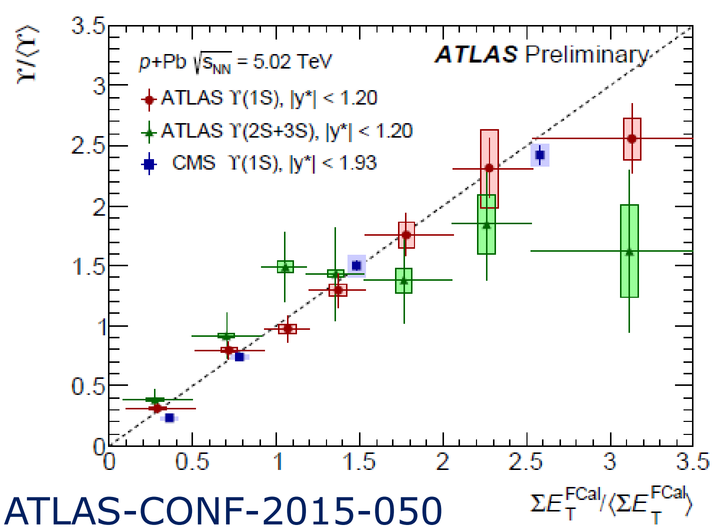
- no strong y (and p_T) dependence
- agreement with CMS within uncertainties

Self-normalized ϒ cross sections



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

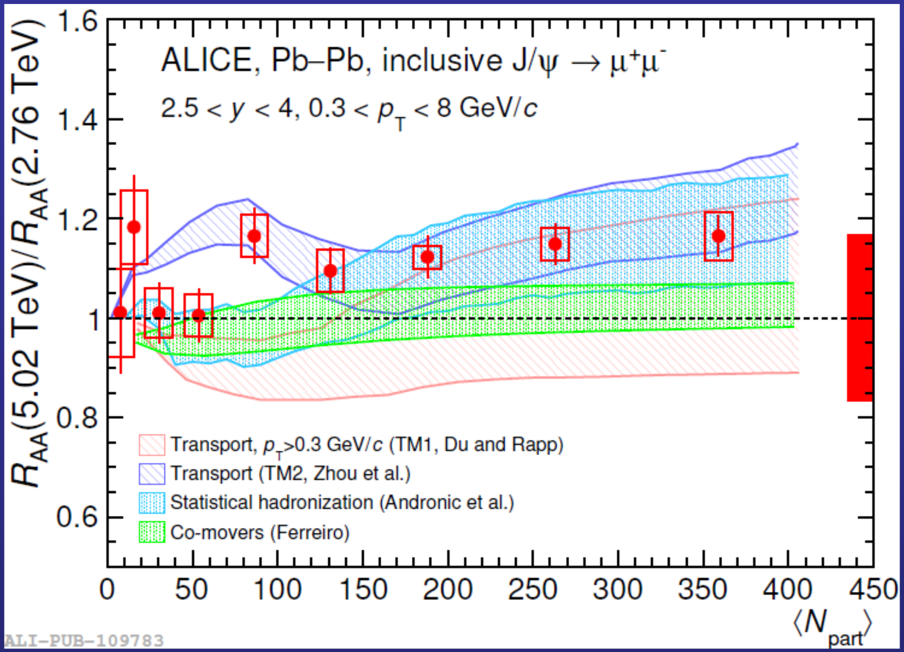
CMS, JHEP 04 (2014) 103

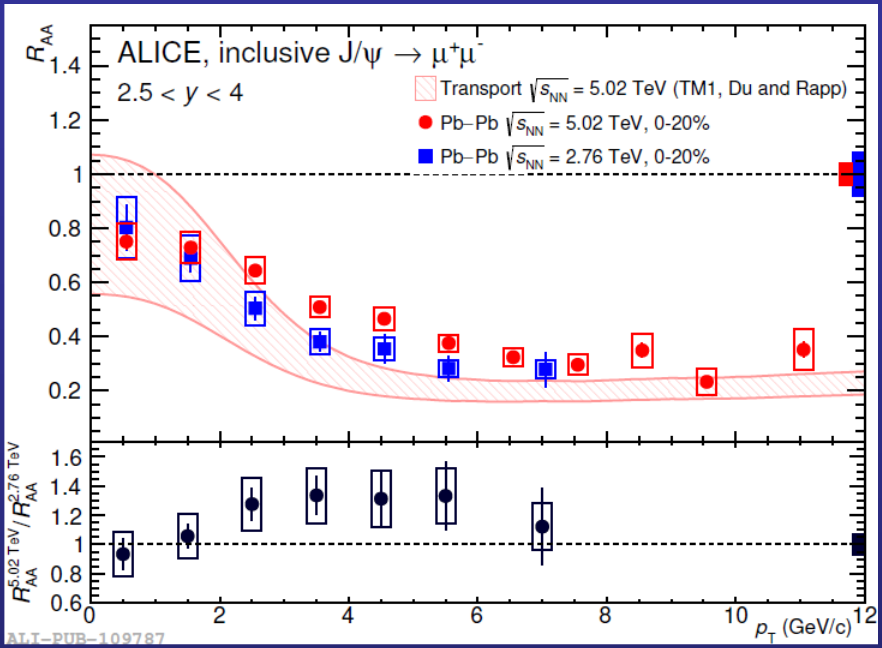


ATLAS-CONF-2015-050

- 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 ?

Comparison with models



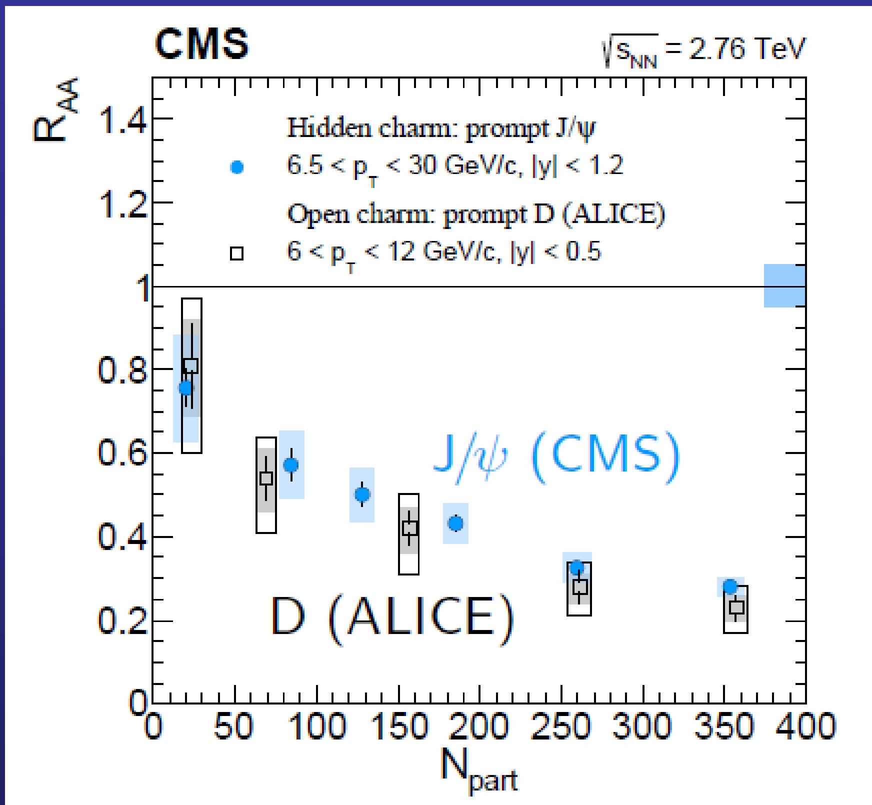


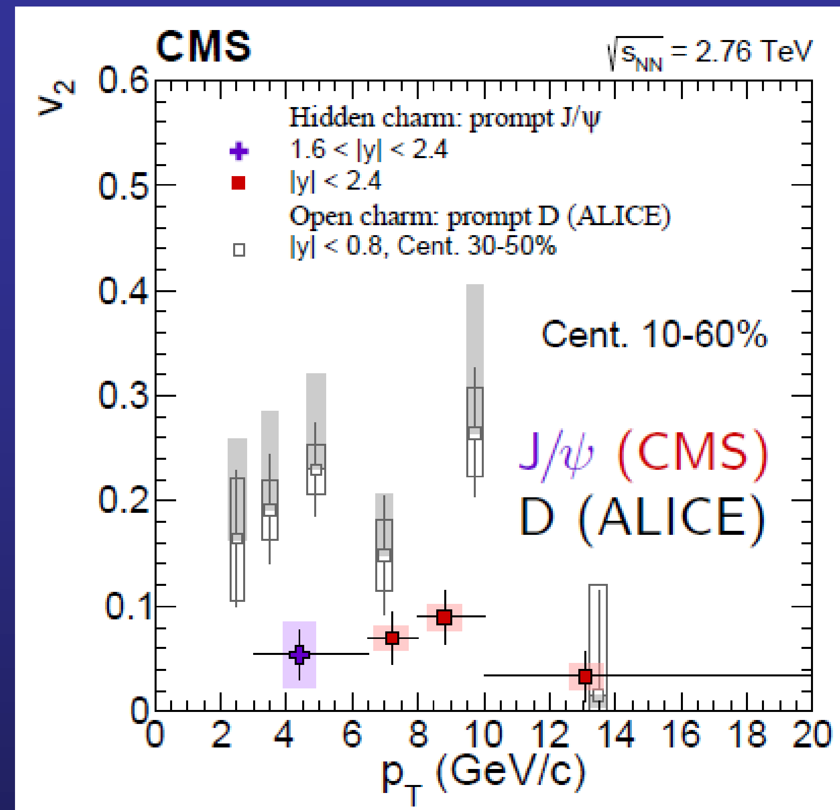
- Theoretical and experimental uncertainties reduced in the R_{AA} double ratio
- Centrality dependence of the R_{AA} ratio is rather flat

- 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

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



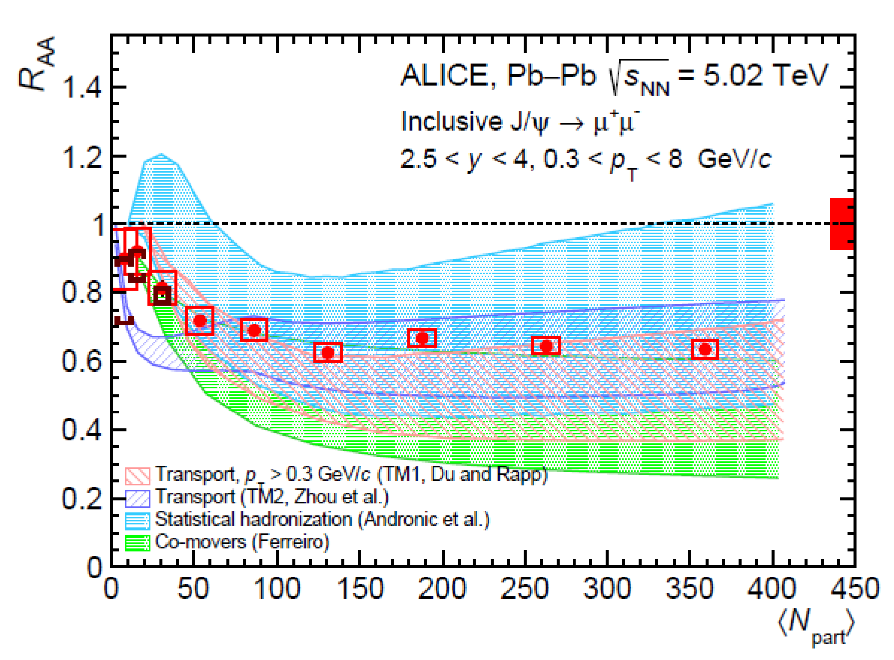


- CMS final results from HP2016
- Striking similarity for R_{AA}, v_2 systematically lower for J/ψ
- Interesting but not trivial comparison (same-p_T comparison can probe different HQ kinematics, …)
- Need a solid theory support

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 ($\sqrt{s}$=5 TeV)

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



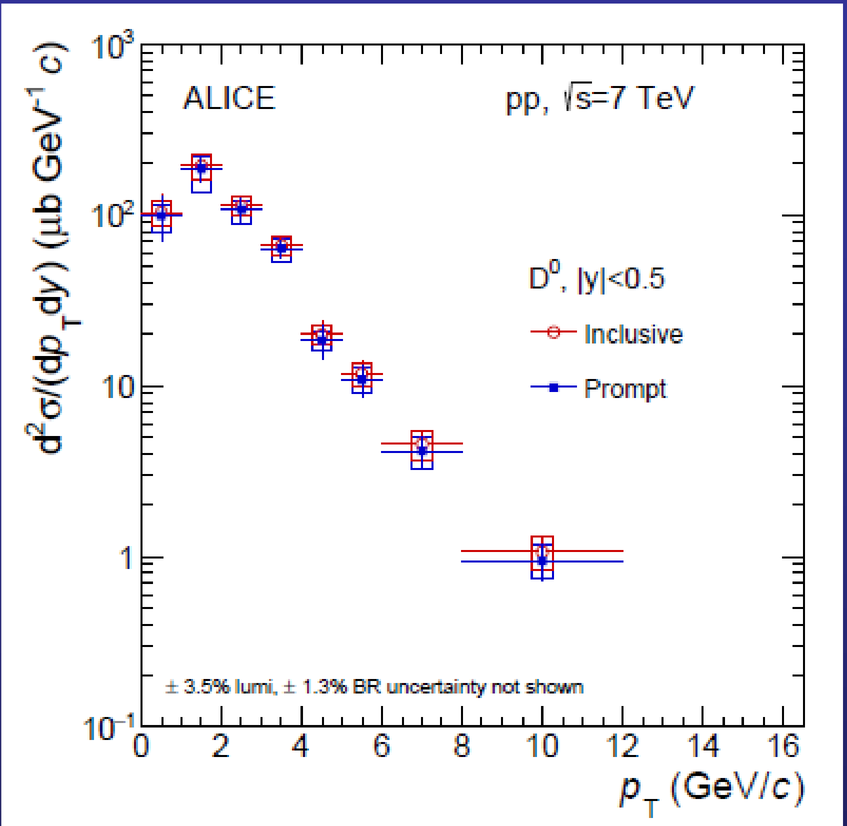
- Recent LHCb estimates (LHCB-CONF-2016-003) suggest values on the low-side of this range (caveat, extrapolation, to be updated with their $\sqrt{s}$=5 TeV data
- Starting from their

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

one gets

$$(d\sigma/dy)_{cc} = 0.44 \pm 0.06(\mathrm{LHCb}) \pm 0.03(\mathrm{interp.}) \pm 0.02(\mathrm{FF})\ \mathrm{mb} = 0.44 \pm 0.07\ \mathrm{mb}$$

Low-p_T J/ψ: open questions

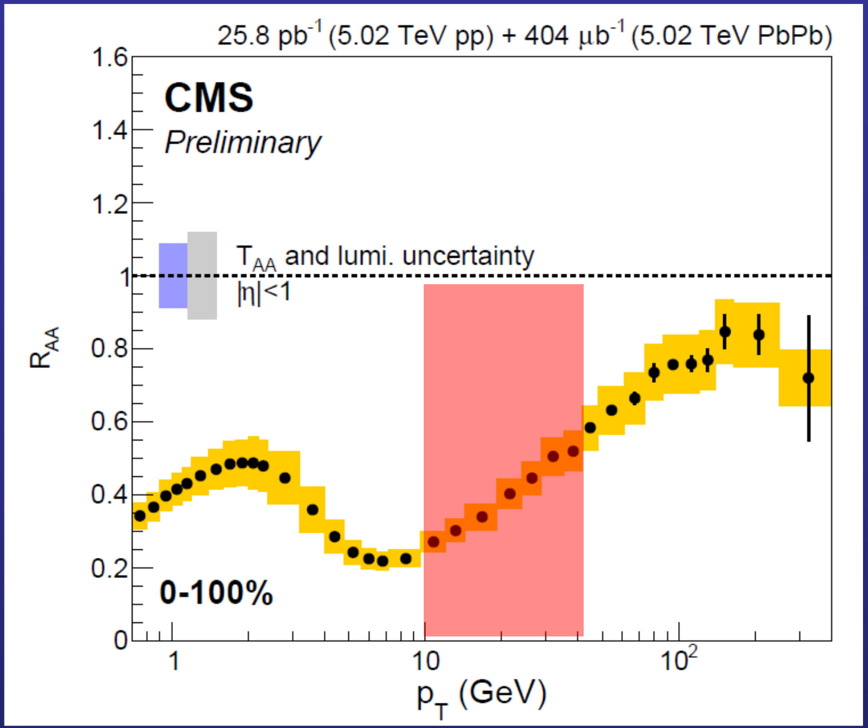


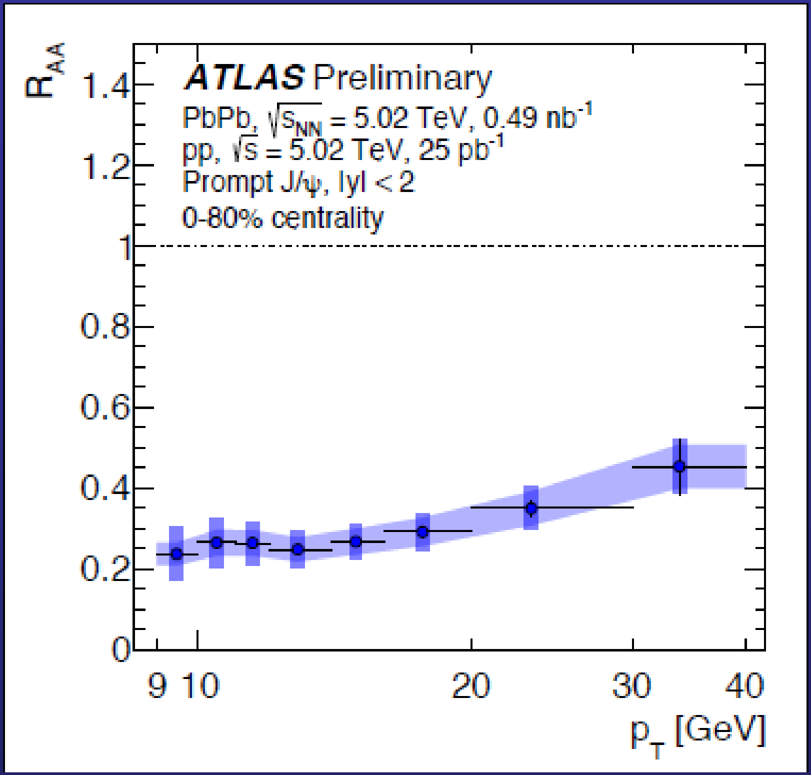
- Precise measurements of open charm cross section are mandatory
- Best results available today (ALICE, LHCb) have uncertainties of about 20%
- If there is no space for a significant improvement, model uncertainties are not getting smaller
- Theorists, please, agree on using the same input values !

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

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

High-p_T J/ψ: CMS (+ATLAS)



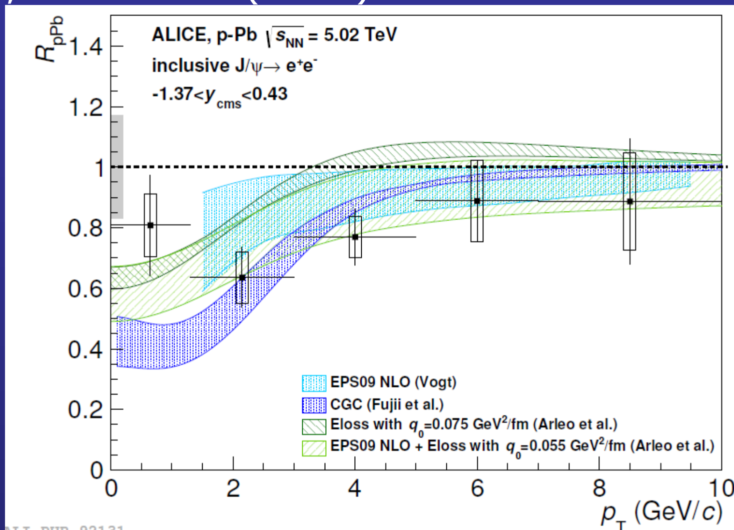


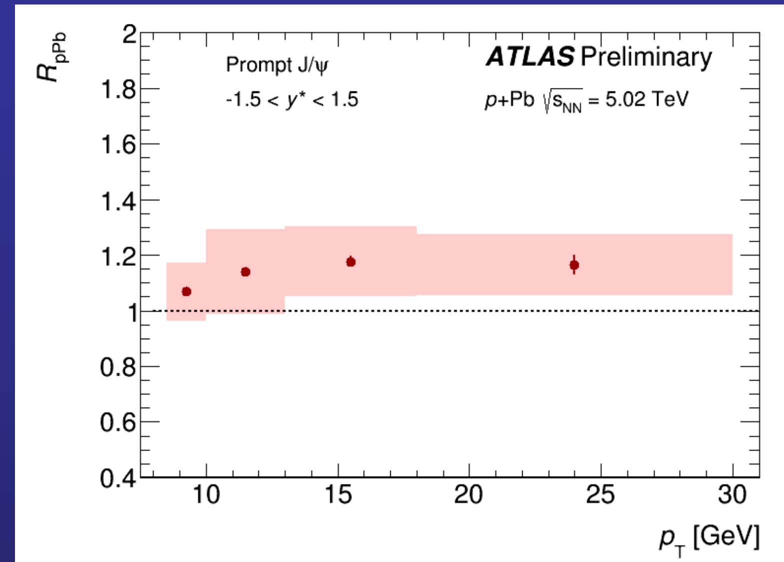
- Maximum J/ψ suppression, then increase beyond p_T=20 GeV/c
- Similar behavior as for hadrons ?
- Is a model description in terms of energy loss needed?
- Compatibility ATLAS vs CMS: factor~2 more suppression for ATLAS
- Could it be an effect of the different √s ? Wait for CMS run-2 results

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)

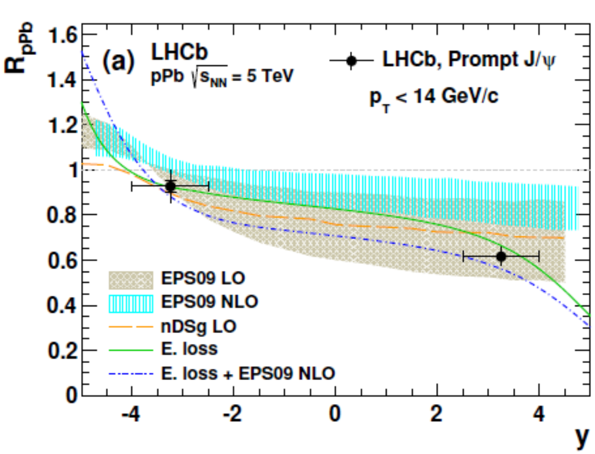
ALICE, JHEP 1506 (2015) 055 | ATLAS-CONF-2015-023

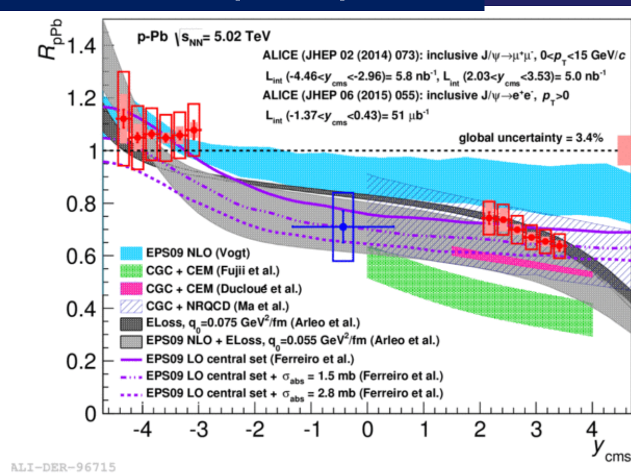


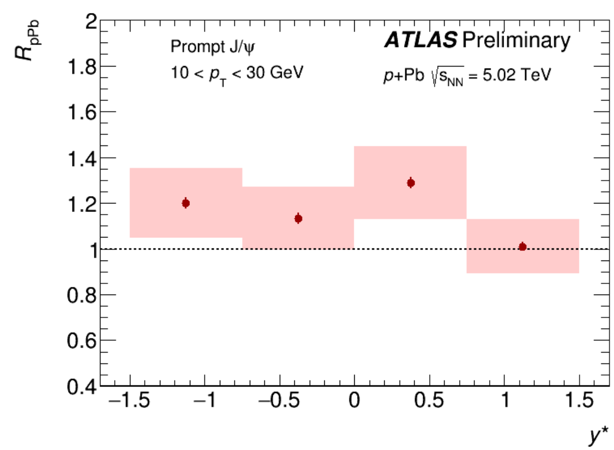


- ❑ R_{pPb} vs y → fair agreement ALICE vs LHCb, ATLAS refers to p_T>10 GeV/c

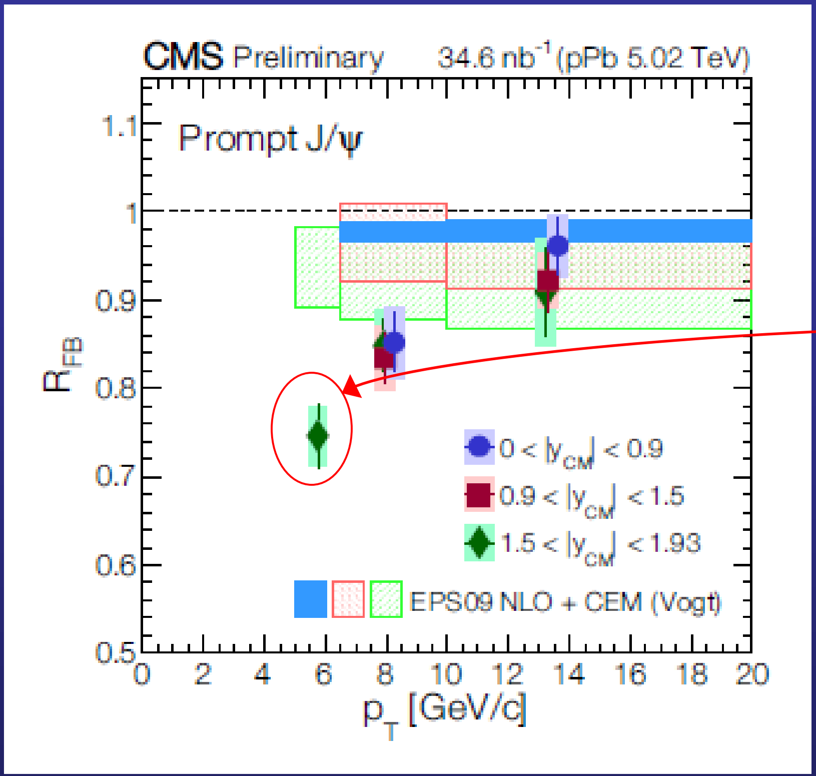
LHCB, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73

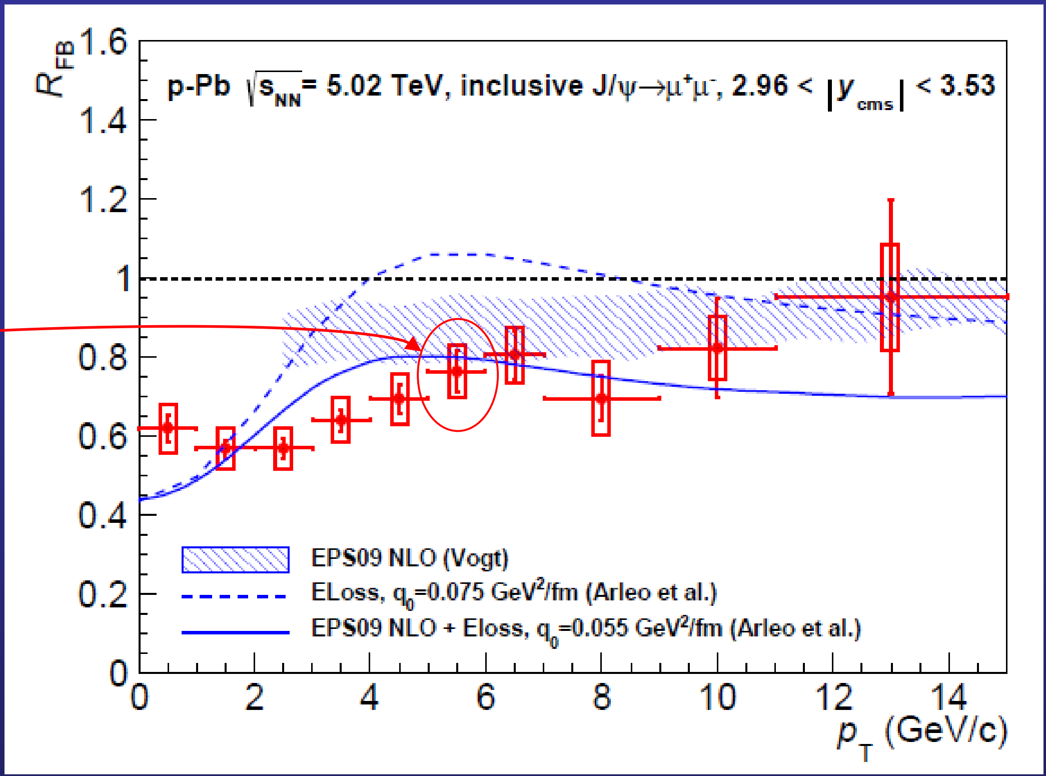






R_{FB} from CMS





- 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 { $2\cdot10^{-5} < x < 9\cdot10^{-5}$; $1\cdot10^{-2} < x < 6\cdot10^{-2}$

- 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 → $1\cdot10^{-2} < x < 5\cdot10^{-2}$

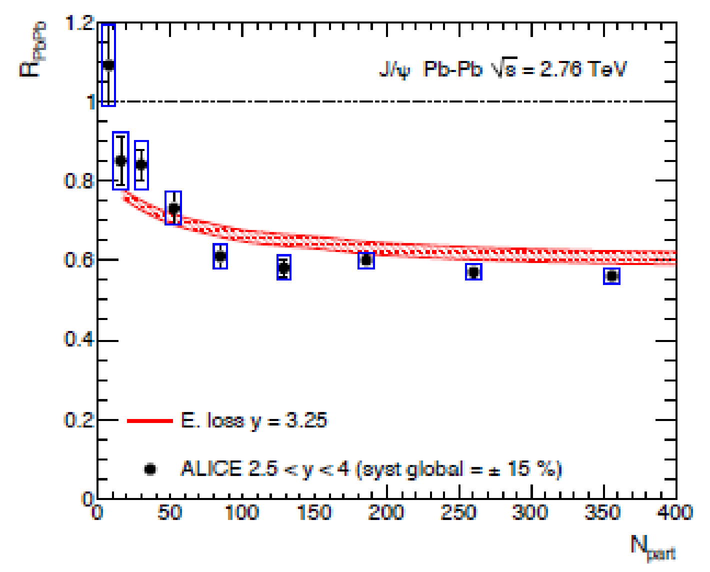
→ Partial compensation between $\sqrt{s_{NN}}$ shift and y-shift

- 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)

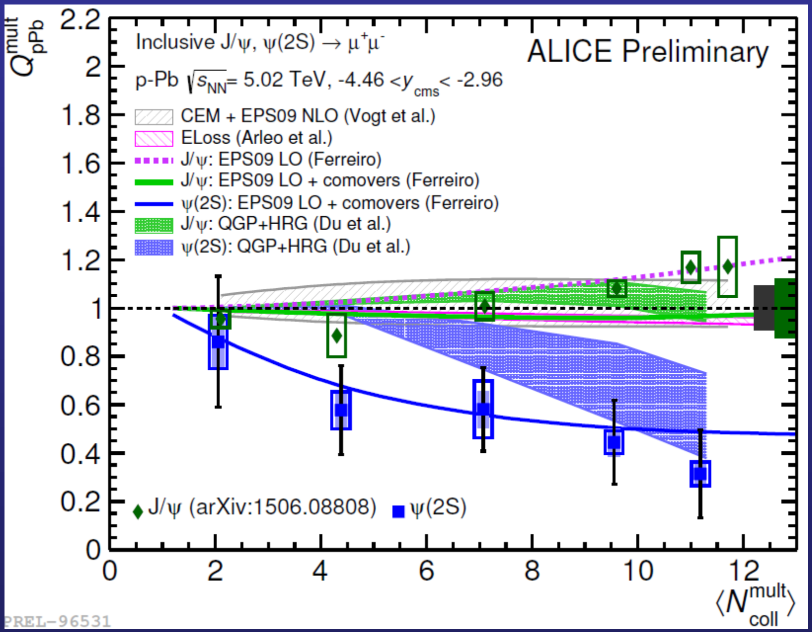
  …which does not exclude hot matter effects which partly compensate each other

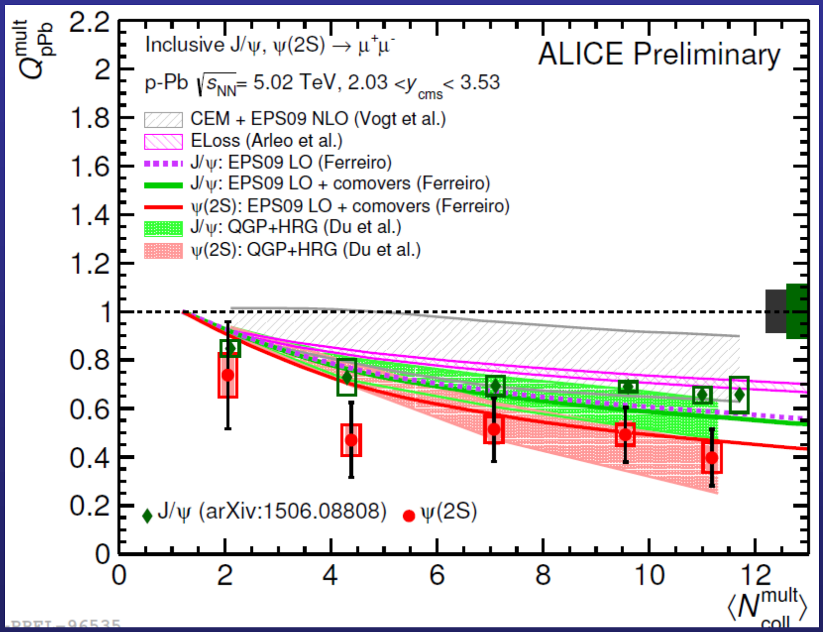


F. Arleo and S. Peigne, arXiv:1407.5054

Cold nuclear matter: the 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





- Results show a (much) stronger ψ(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)

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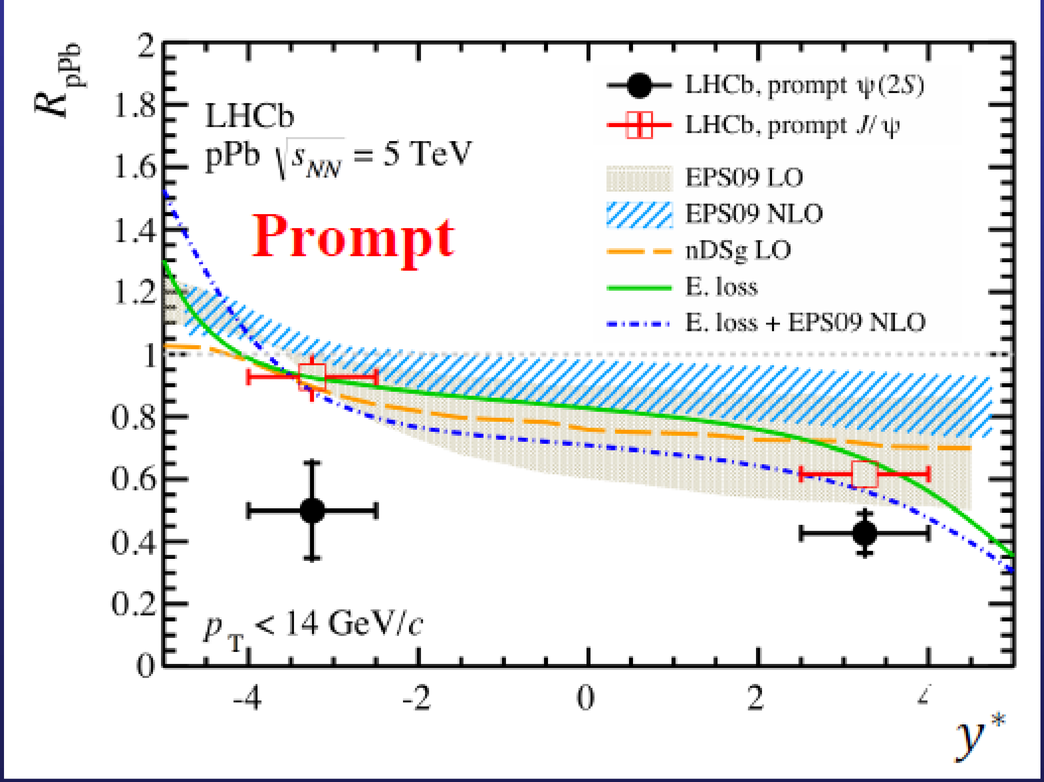
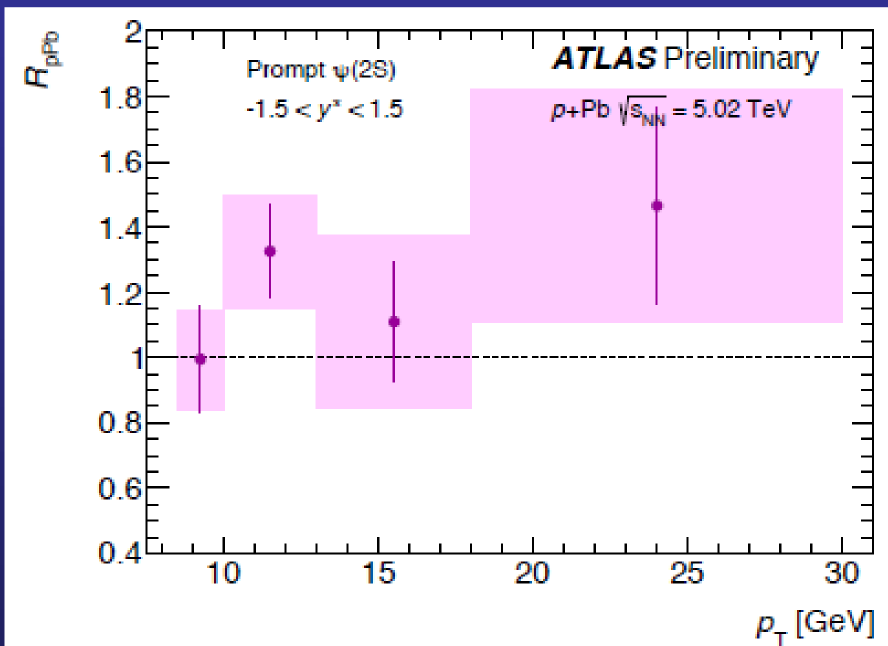
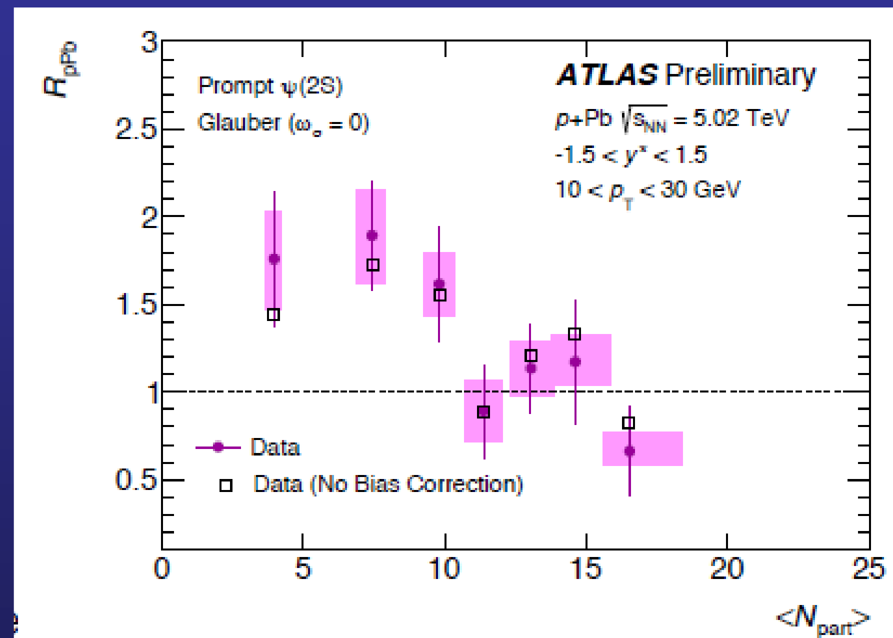


Nicely confirmed by LHCb!

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 ?

The comovers are back again

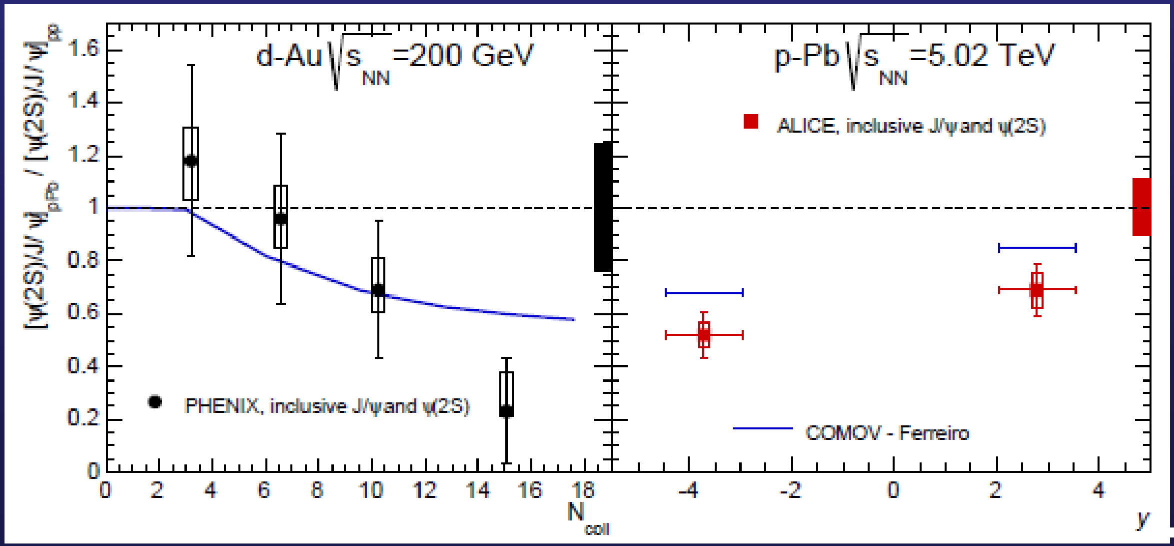
- A subject of "epic" battles in the '90s (comovers vs QGP!)
- Entered a "dormant" state in RHIC years, now re-proposed for the Υ

- 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 (?!)

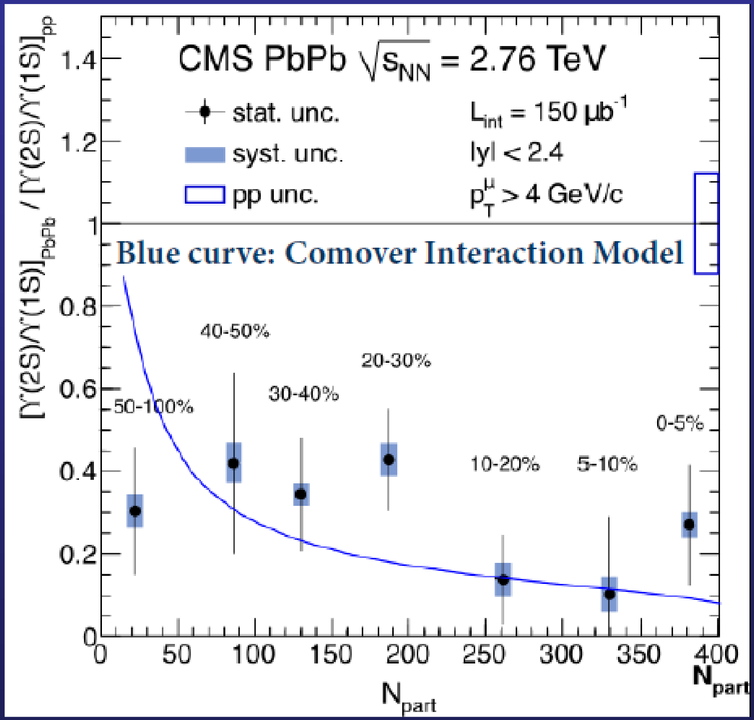


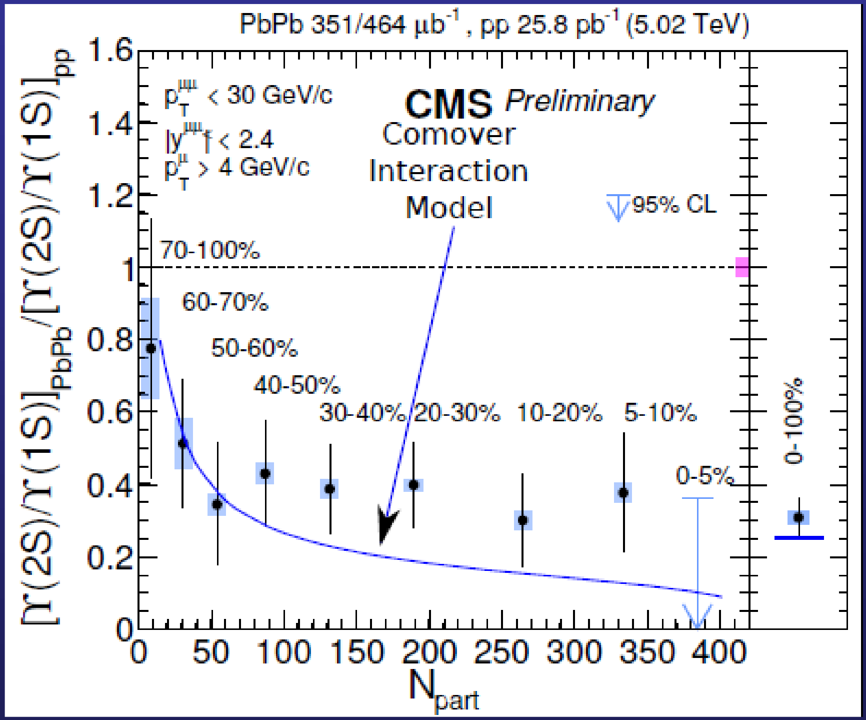
p-Pb only!

The comovers are back again

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

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

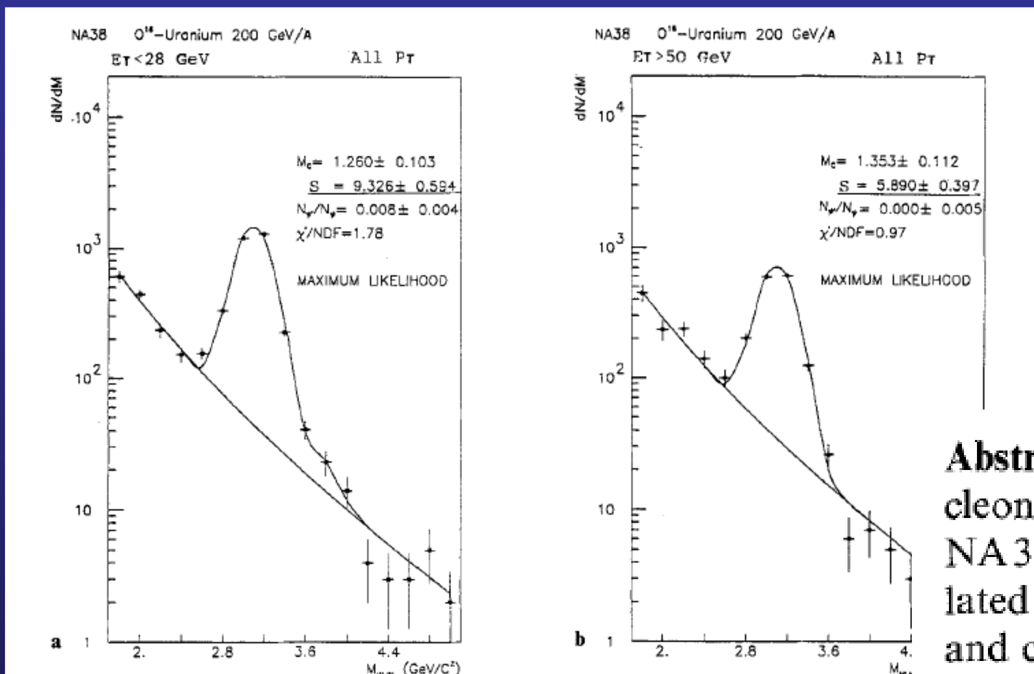




- (Surprisingly), a qualitative agreement is found
- Is the physics of bottomonia simply "driven" by $dN_{ch}/d\eta$??

The beginning…

- "If high-energy heavy ion collisions lead to the formation of a quark-gluon plasma, then **color screening prevents cc binding** in the deconfined interior of the interaction region" (Matsui, Satz, 1986)



- NA38, O-U collisions at the **CERN SPS**
- 200 GeV/nucleon (lab system! $\sqrt{s_{NN}}$=19.4 GeV)

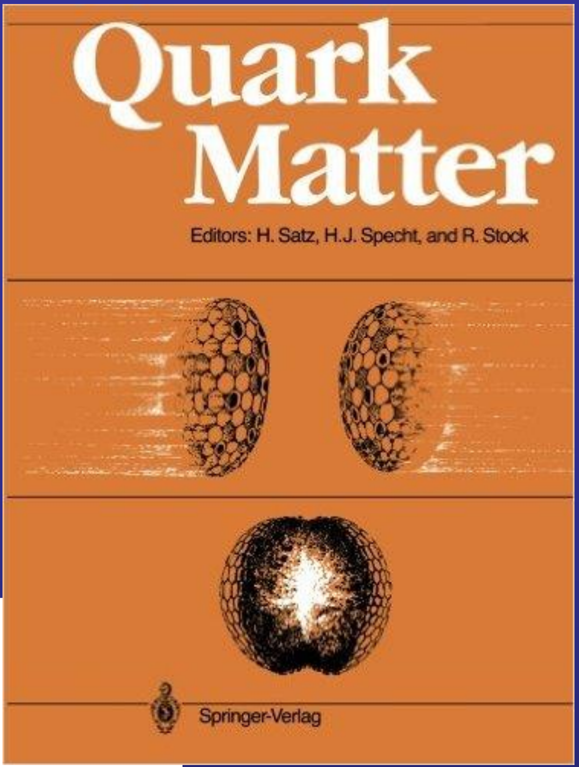
Quark Matter 87

First evidence for J/ψ suppression in nuclear collisions!

Abstract. The dimuon production in 200 GeV/nucleon oxygen-uranium interactions is studied by the NA38 Collaboration. The production of J/Ψ, correlated with the transverse energy ET, is investigated and compared to the continuum, as a function of the dimuon mass M and transverse momentum PT. A value of 0.64 ± 0.06 is found for the ratio (Ψ/Continuum at high ET)/(Ψ/Continuum at low ET), from which the J/Ψ relative suppression can be extracted. This suppression is enhanced at low PT.

…and the feedback of the audience….

From the QM87 summary talk



The most provocative observation, reported by NA 38 [13], was that J/ψ production seems to be suppressed by $\sim 30\%$ in high E_T events. The second provocative

3 Puzzles

3.1 J/Psi suppression

$$N_\psi / N_c = \begin{cases} 9.3 \pm 0.6 & \text{for } E_T < 28 \text{ GeV} \\ 5.9 \pm 0.4 & \text{for } E_T > 50 \text{ GeV.} \end{cases}$$

This 30% reduction of ψ production caused the most controversy at Quark Matter '87.

There are naturally several caveats that need further consideration. First, there is the problem of prov-

- Competing sources of J/ψ dissociation involving hadronic interactions (with cold nuclear matter and/or hadronic medium) can reproduce the observations if σ_{diss}~1-2 mb

A **signature of deconfinement**,
or just a **generic signature** for dense matter formation?

Where do we stand, after 30 years ?

- A wealth of high-quality data have been accumulated, at various facilities (SPS, RHIC, LHC) for various collision systems

- Do experimental results allow us to
  1) Understand the phenomenology of quarkonium in HI ?
  2) Extract quantitative/detailed information on the QGP features ?

- In this talk
→ **The "push" from experiments is very strong**
Let's discuss lots of high quality new data

- As for all observables in HI, interaction with theory is mandatory → see next talk

However, given the charming history, some extra care and
additional checks may be in order before declaring victory: to be quantitative, regeneration calculations
need as input the total charm cross section (missing so far); a second unambiguous example for heavy quark
recombination would be very helpful (eg B_c); the spectre of final state recombination at the hadron (D +
D → J/ψ + X) rather than parton level has to be very convincingly excluded (no easy feat given the many
uncertainties in general associated with rate calculations in hadronic afterburners).

the transition from primordial production with Cronin effect to regeneration
from a near-thermal source, respectively. These observations not only prove the presence of regeneration
processes, but imply vigorous reinteractions of charm and charmonia in the QGP, with large interaction rates
and p_T spectra approaching thermalization, necessitating a strong coupling to the bulk medium

The primordially produced
charm- and bottom-quark p_T-spectra from binary NN collisions are significantly harder than thermal spectra
and thus provide unfavorable phase-space overlap for the formation of quarkonium bound states

Disclaimer

- Although the **“screening+recombination”** picture is conceptually simple and attractive, a realistic description implies a sophisticate treatment

- Some examples
  - At high-energy the QGP thermalization times can be very short
    → **In-medium formation of quarkonium** rather than suppression of already formed states
    → **Heavy quark diffusion** is relevant for quarkonium production

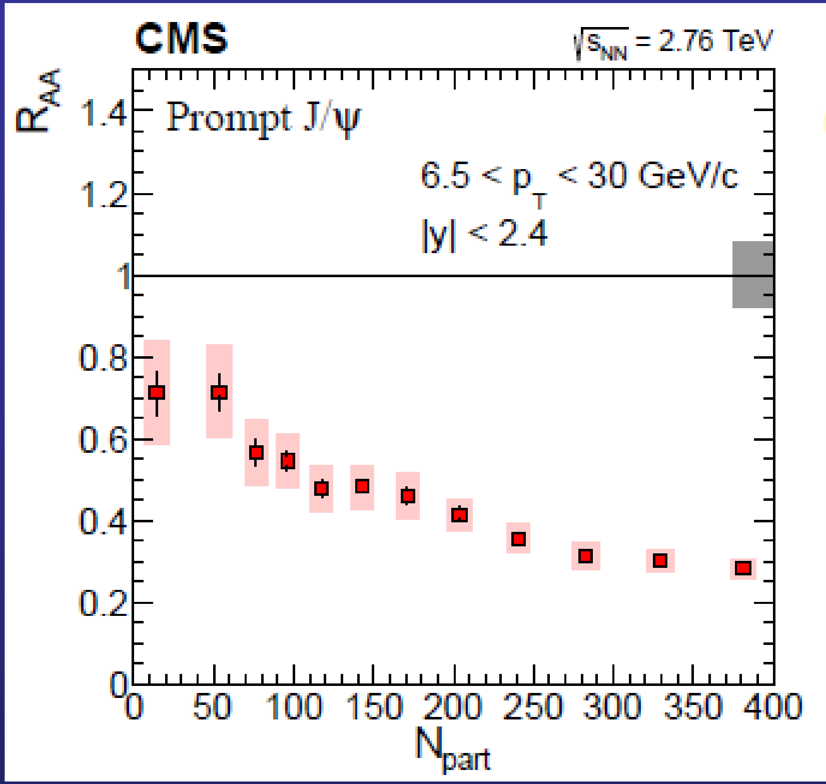
- Need
  - T_D, $M_\psi(T)$, $\Gamma_\psi(T)$ from QCD calculations (using spectral functions from **EFT/LQCD**)
  - **Fireball evolution** from microscopic calculations
  - Precise determination of the **total open charm cross section**

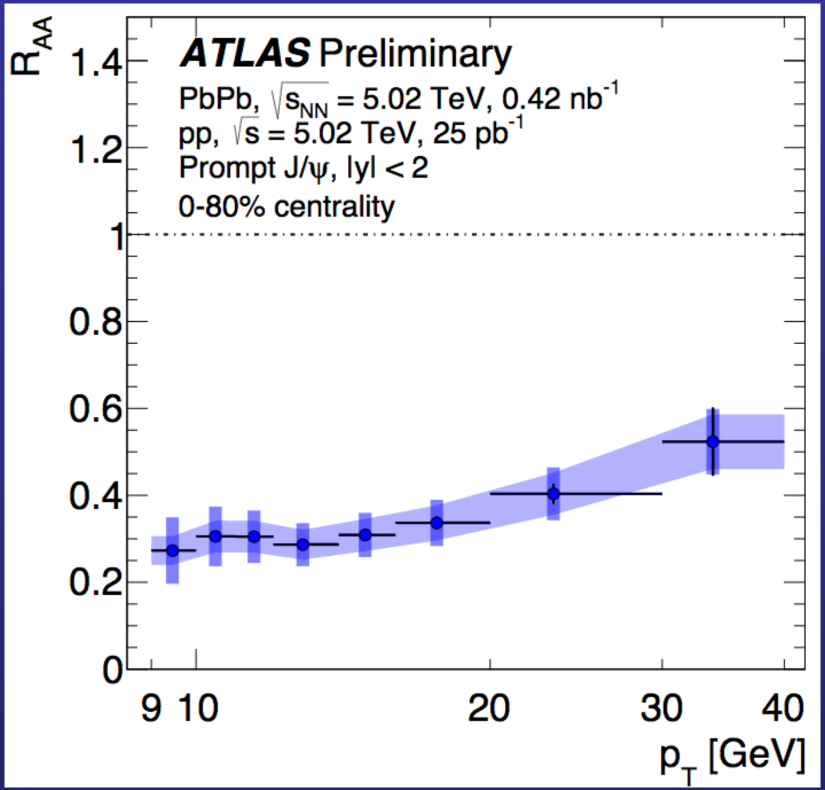
Impressive advances on theory side but the availability of data for various colliding systems and energy remains a must!

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

High-p_T J/ψ

ATLAS-CONF-2016-109



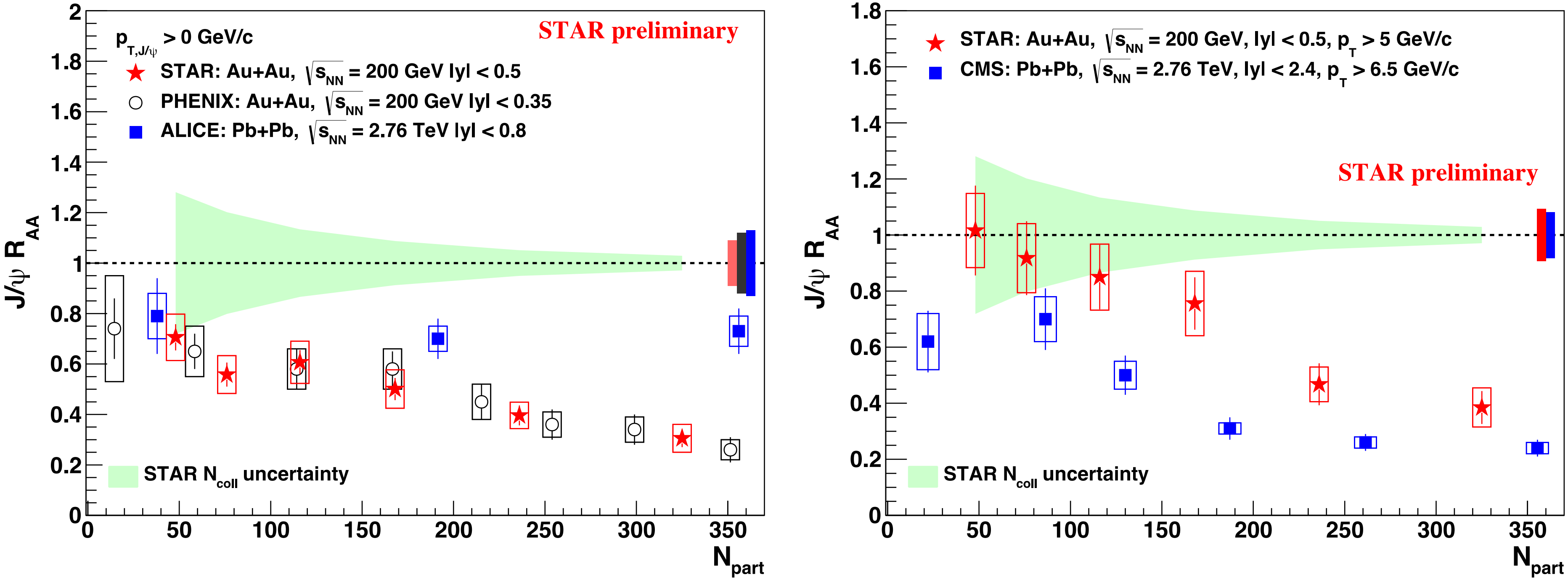


- ❑ Striking difference with respect to low-p_T J/ψ
- ❑ **Suppression increases with centrality** at high p_T , **down to R_{AA}~0.3**

- ❑ **R_{AA} increases for p_T > 20 GeV/c**
- ❑ Related to energy loss effects, rather than dissociation ?

J/ψ - RHIC energy

- ❑ Recent highlights by STAR
- ❑ **Low vs high p_T J/ψ suppression**

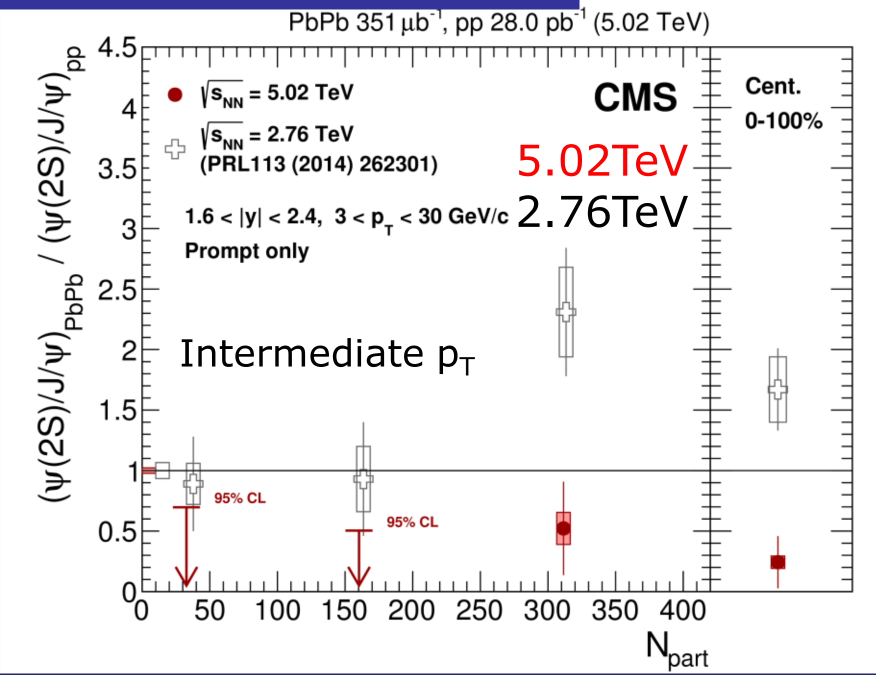


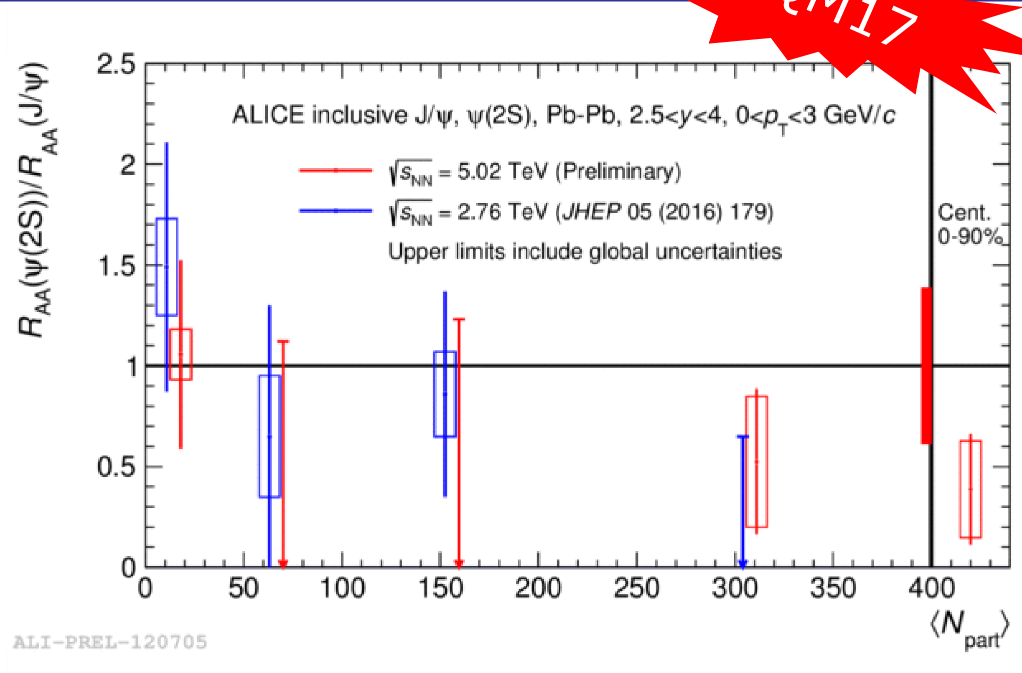
- ❑ **Low p_T J/ψ, $R_{AA}^{LHC} > R_{AA}^{RHIC}$** ← strong regeneration
- ❑ **High p_T J/ψ, $R_{AA}^{LHC} < R_{AA}^{RHIC}$** ← weak (or no) regeneration

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

Double ratios ψ(2S)/J/ψ

QM17





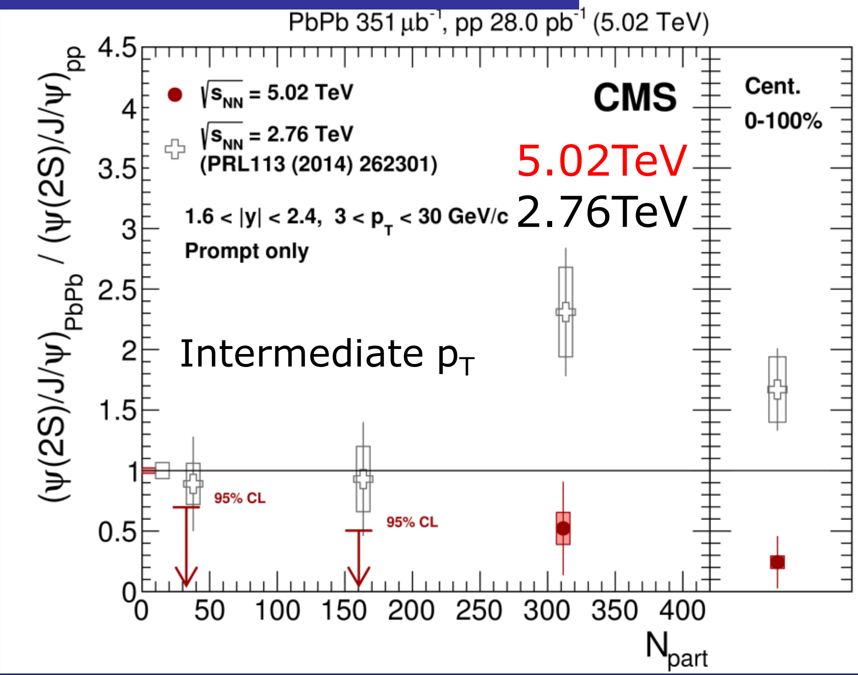
- $(\psi(2S)/J/\psi)_{PbPb}/ (\psi(2S)/J/\psi)_{pp}$ → << 1 in a dissociation scenario
- CMS (intermediate p_T), **enhancement** to **suppression** for increasing $\sqrt{s_{NN}}$
- ALICE extends down to p_T=0, suppression is seen

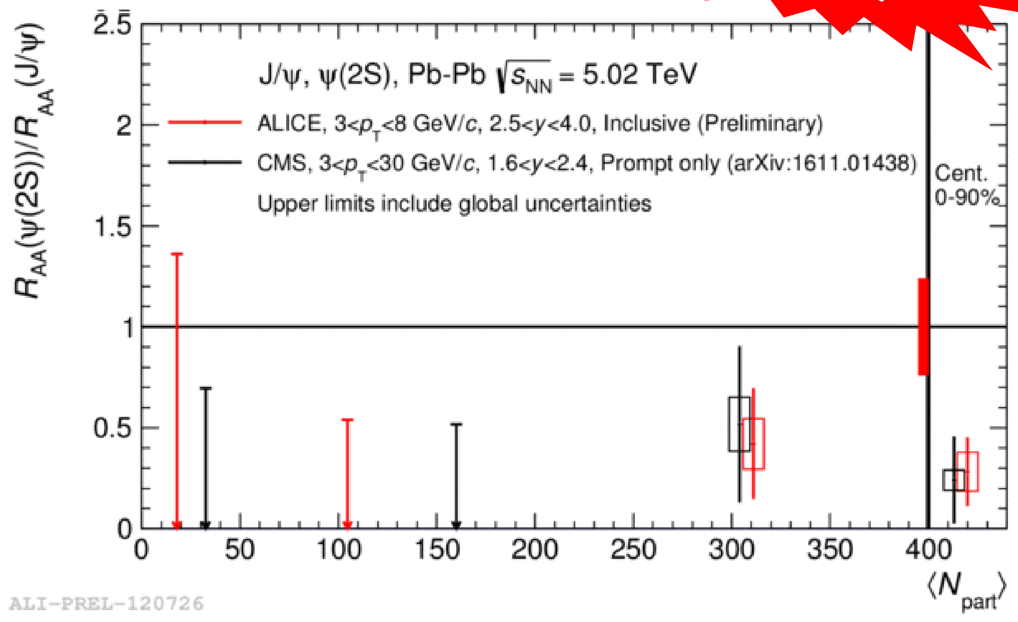
- Proposed mechanism (Rapp) for enhancement: **ψ(2S) regeneration mainly occurring later**, when radial flow is already built-up

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

Double ratios ψ(2S)/J/ψ

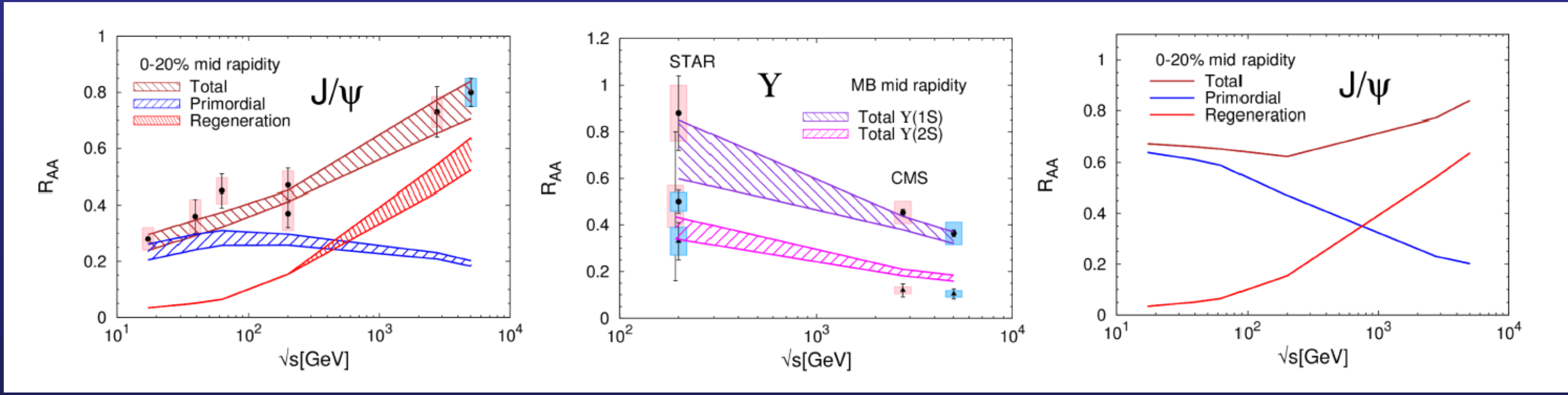
QM17





- $(\psi(2S)/J/\psi)_{PbPb} / (\psi(2S)/J/\psi)_{pp}$ → << 1 in a dissociation scenario
- CMS (intermediate p_T), **enhancement** to **suppression** for increasing $\sqrt{s_{NN}}$
- ALICE extends down to p_T=0, suppression is seen
- Good compatibility at $\sqrt{s_{NN}}$=5.02 TeV in the common p_T range

- Proposed mechanism (Rapp) for enhancement: **ψ(2S) regeneration mainly occurring later**, when radial flow is already built-up



0-20% mid rapidity
Total
Primordial
Regeneration
J/ψ
R_AA
√s[GeV]
STAR
Υ
MB mid rapidity
Total Υ(1S)
Total Υ(2S)
CMS
R_AA
√s[GeV]
0-20% mid rapidity
Total
Primordial
Regeneration
J/ψ
R_AA
√s[GeV]

Conclusions

- Lots of high-quality new results have become available at QM2017

- **Charmonia (J/ψ, ψ(2S))**
  Firm evidence for J/ψ elliptic flow and strong re-generation effects
  → Charm quarks thermalize in the deconfined medium

- **Bottomonia (Υ(1S), Υ(2S), Υ(3S))**
  Suppression effects strongly correlated with binding energy
  → Evidence for resonance melting in a hot QGP