Quarkonium Overview in A+A Collisions

Rongrong Ma (BNL)

INT Program INT-17-1b

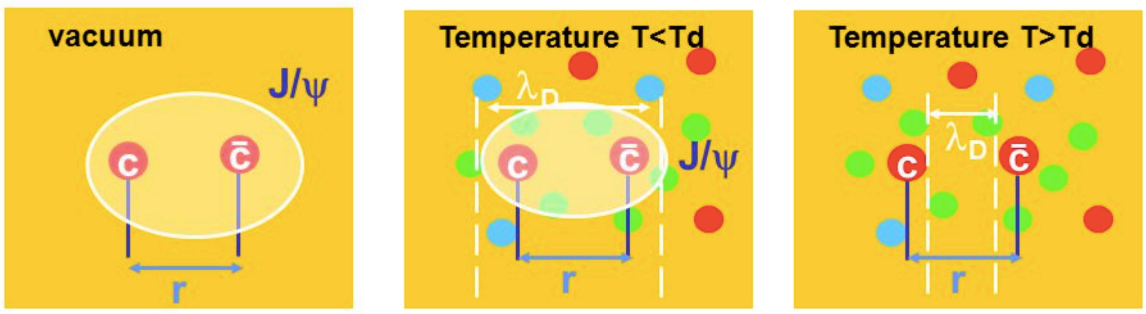
Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks

May 1 - June 8, 2017

The Promise

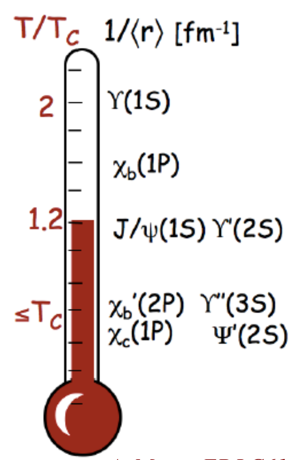
- **Evidence of deconfinement**: quark-antiquark potential is color-screened by surrounding partons → *dissociation*
  - **J/ψ suppression was proposed as a direct proof of QGP formation**

T. Matsui and H. Satz PLB 178 (1986) 416



$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

- **Thermometer**: different quarkonium states of different binding energies dissociate at different temperatures → *sequential melting*

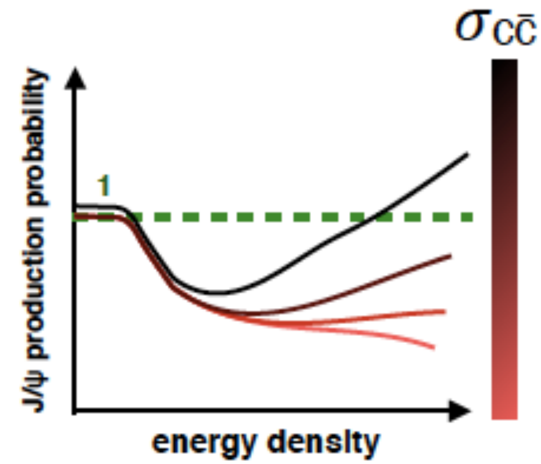


A. Mocsy EPJ C61 (2009) 705

Not So Fast

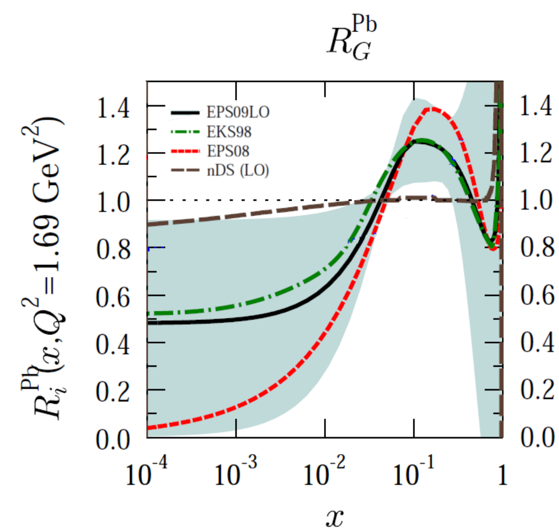
Hot medium effects

- **Regeneration**
  - ~115 cc pairs/central event at 5 TeV
  - Much smaller effect for bb
- Medium-induced energy loss
  - Color-octet states
- Formation time



Cold nuclear matter effects (CNM)

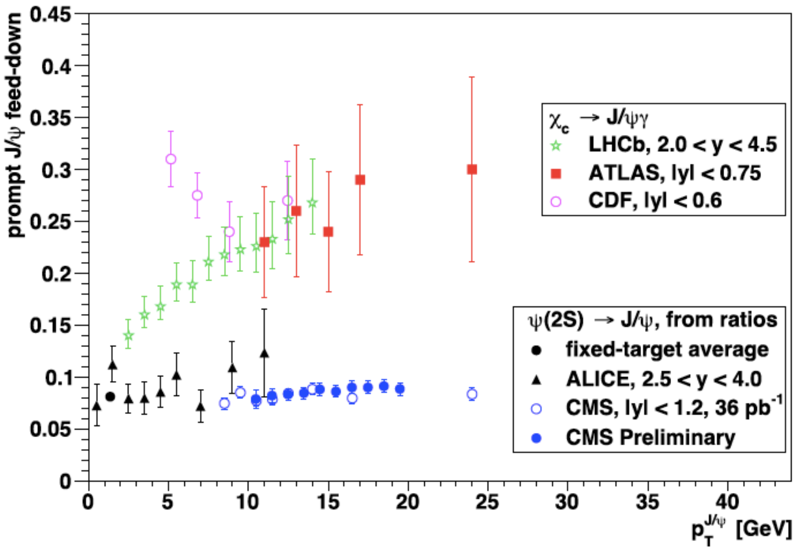
- Nuclear PDF: shadowing/anti-shadowing
- Coherent energy loss
- Nuclear absorption
- Interact with co-movers



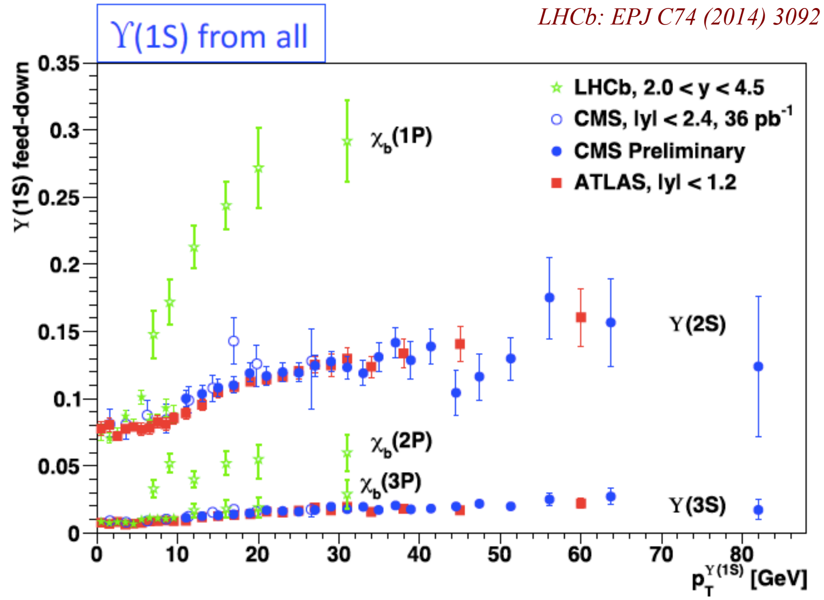
E.G. Ferreiro PRC 81 (2010) 064911

And the Feed-down Contribution

Woehri@Quarkonia'14



LHCb: EPJ C74 (2014) 3092



J/ψ feed-down	
χ_c	10-30% (vs. p_T)
ψ(2S)	~ 8%
B-hadron	0-50% (vs. p_T, $\sqrt{s}$)

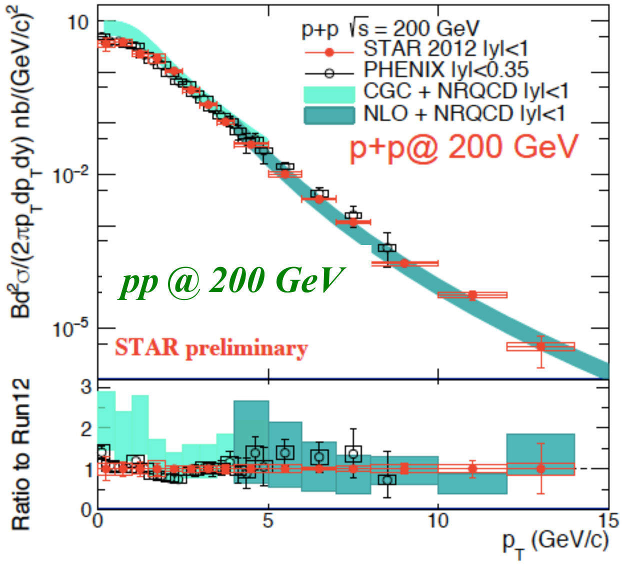
ϒ(1S) feed-down	
χ_b(1P)	10-30% (vs. p_T)
χ_b(2P+3P)	5%+1%
ϒ(2S+3S)	8-13%+1%

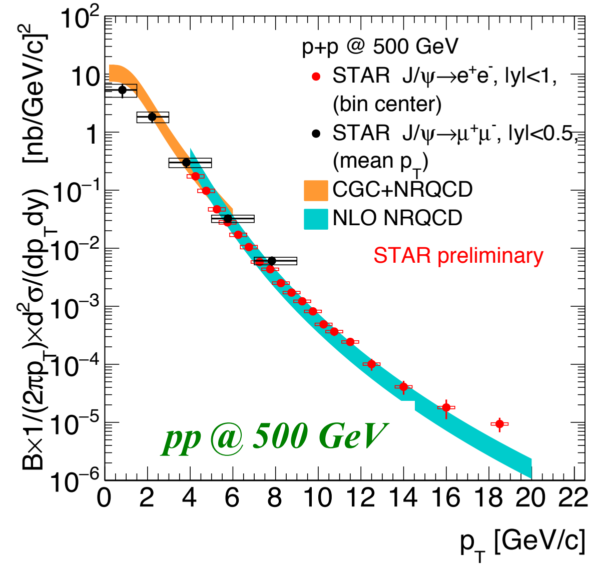
pp Collisions

pA/dA Collisions

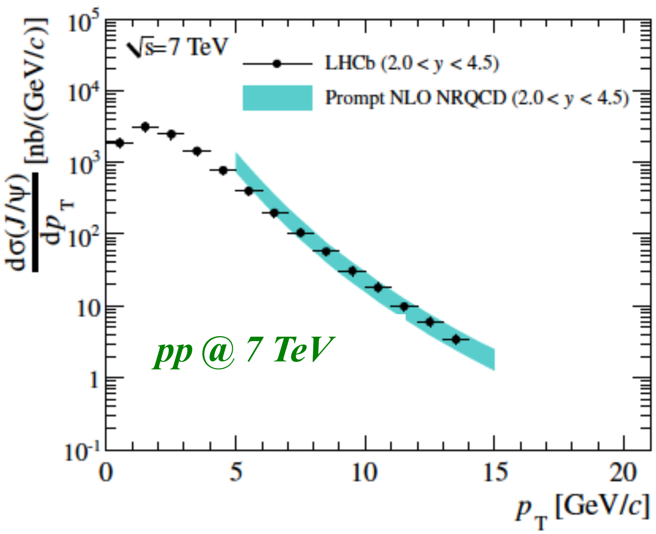
AA Collisions

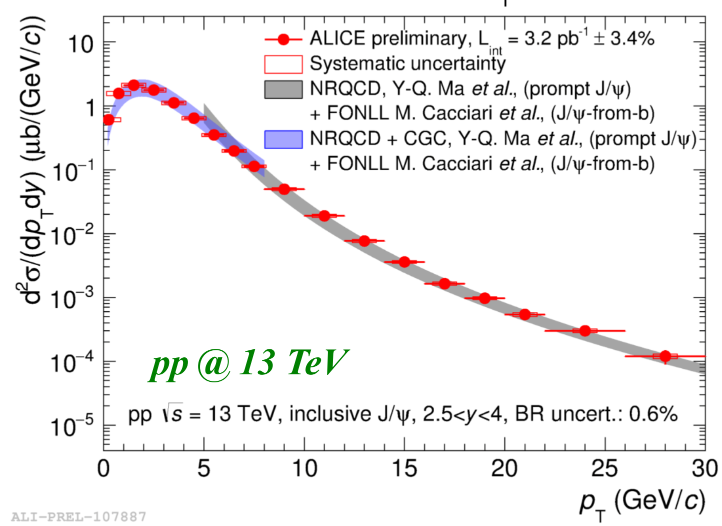
J/ψ Cross-section in pp Collisions





Y. Ma, et al, PRL 106 (2011) 042002
Y. Ma, R. Venugopalan, PRL 113 (2014) 192301
M. Cacciari, et al, JHEP 1210 (2012) 137
LHCb: EPJ C71 (2011) 1645



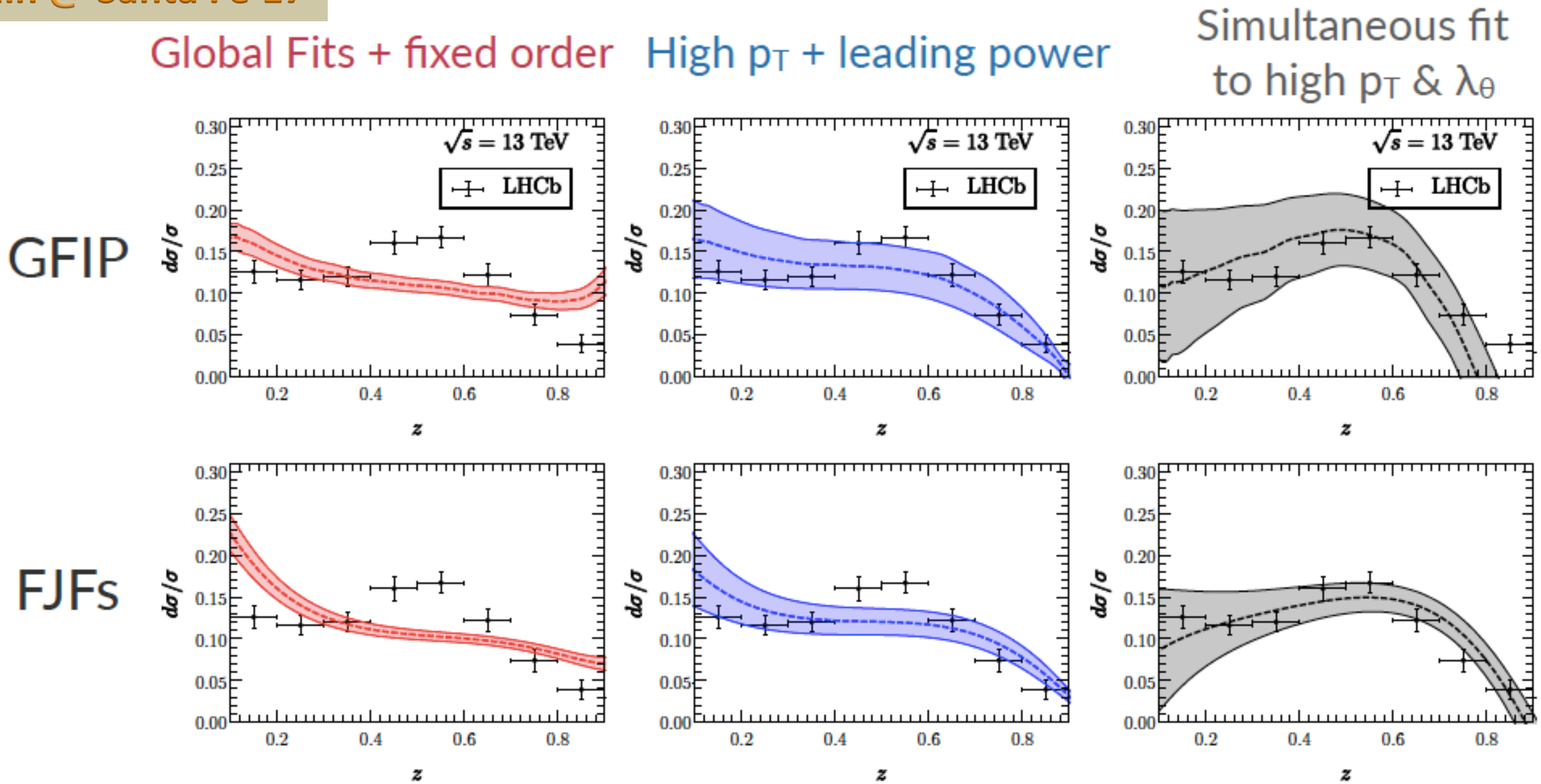


- Good description of *J/ψ* cross-section in pp collisions at $\sqrt{s} = 0.2 - 13$ TeV

J/ψ in Jets

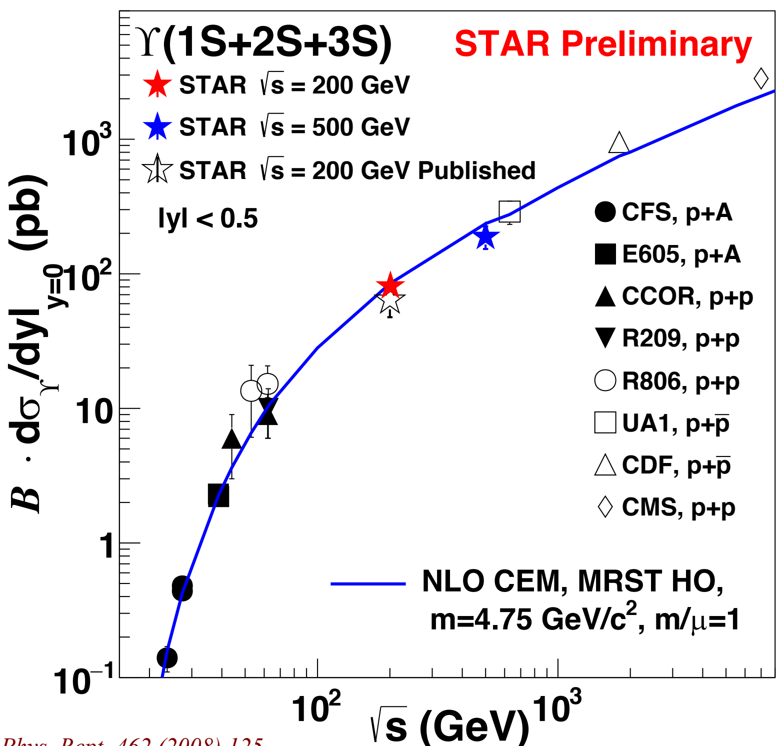
M. Butenschoen, B. Kniehl
PRD 84 (2011) 051501
G. Bodwin, et al, PRL 113 (2014) 022001
K. Chao, et al, PRL 108 (2012) 242004
LHCb: arXiv: 1701.05116

R. Bain @ Santa Fe'17

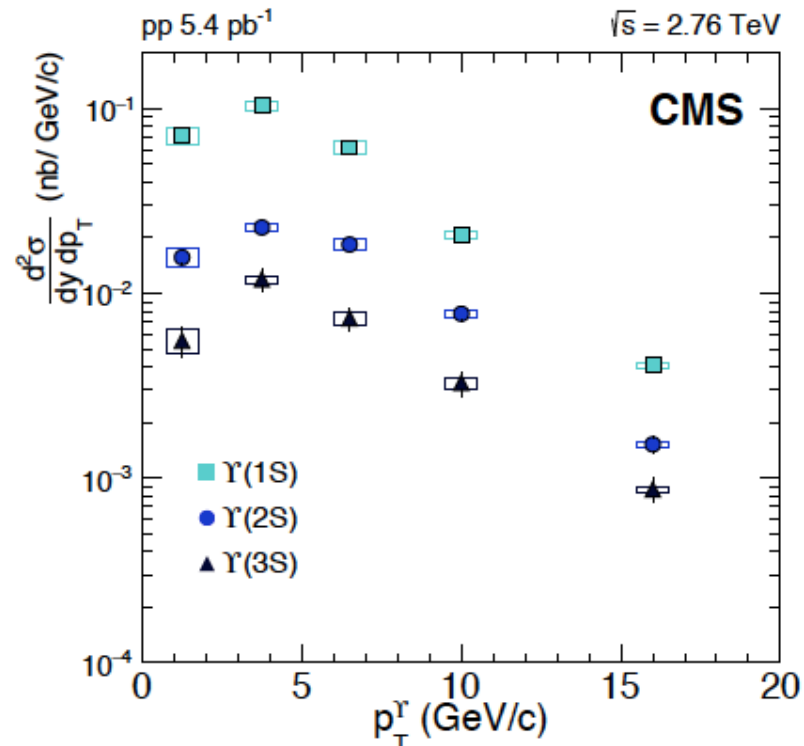


- Different LDME sets generate vastly different shapes.
- Looks like low p_T cross-section favor one set, while high p_T cross-section, polarization and jet fragmentation favor another. Hmmm ….

Υ Measurements in pp Collisions



R. Vogt, Phys. Rept. 462 (2008) 125



CMS: arXiv:1611.01510

- STAR: new cross-sections at 200 and 500 GeV → follow world-wide data trend predicted by CEM
- CMS: differential cross-section at 2.76 TeV for three states → precision measurements

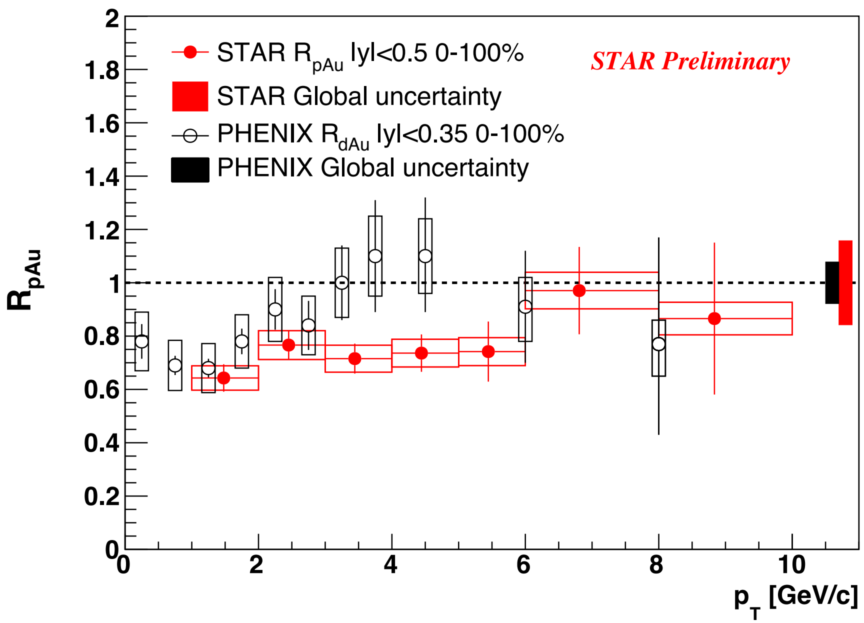
pp Collisions

pA/dA Collisions

AA Collisions

J/ψ Production in pA at 0.2 TeV

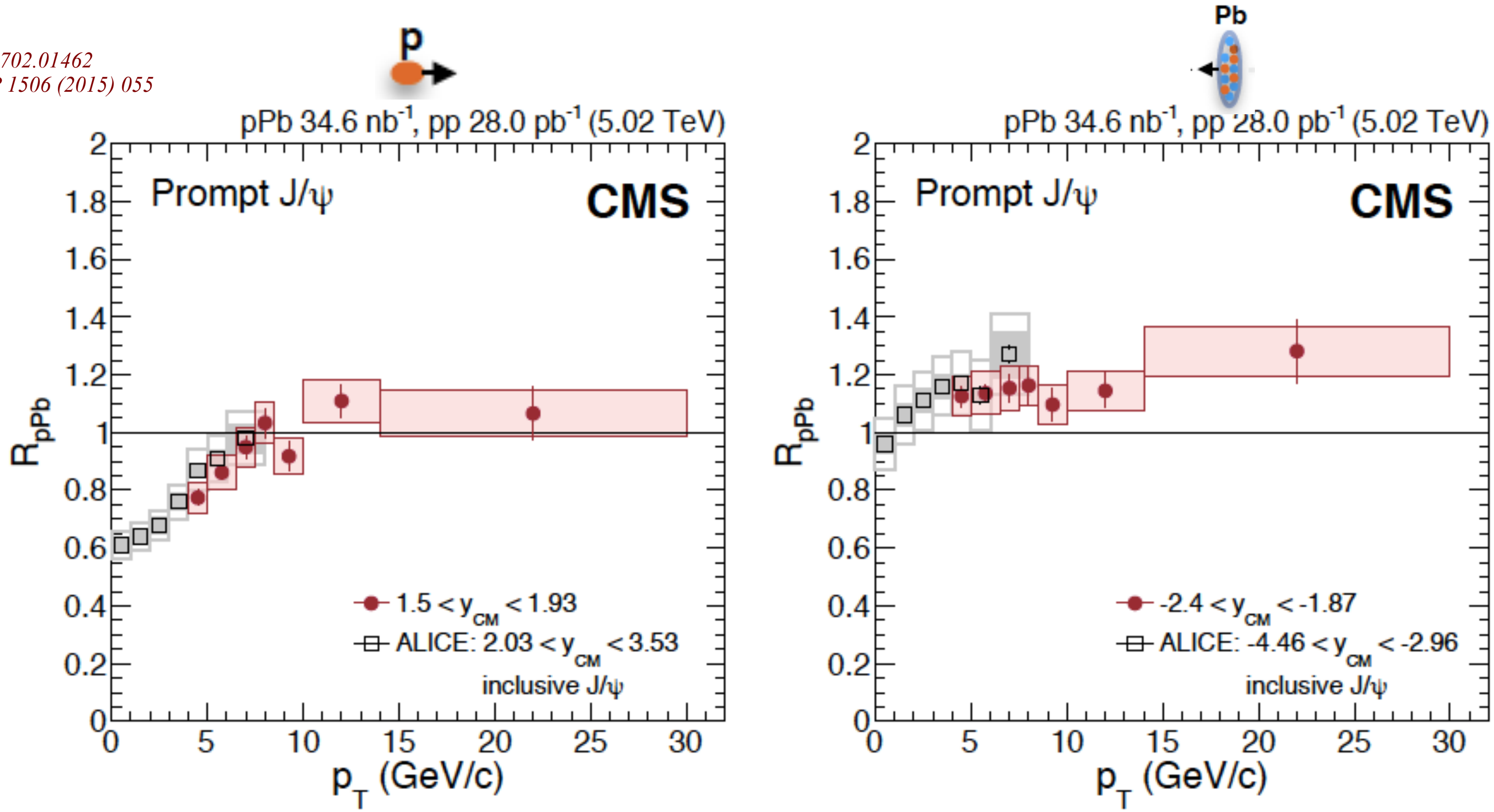
PHENIX, PRC 87 (2012) 034903



- R_{pAu} ~ 0.65 at 1 GeV/c and rises to 1 at high p_T
- R_{pAu} ~ R_{dAu} within uncertainties
  - There is tension at 3.5 – 5 GeV/c (1.4σ)

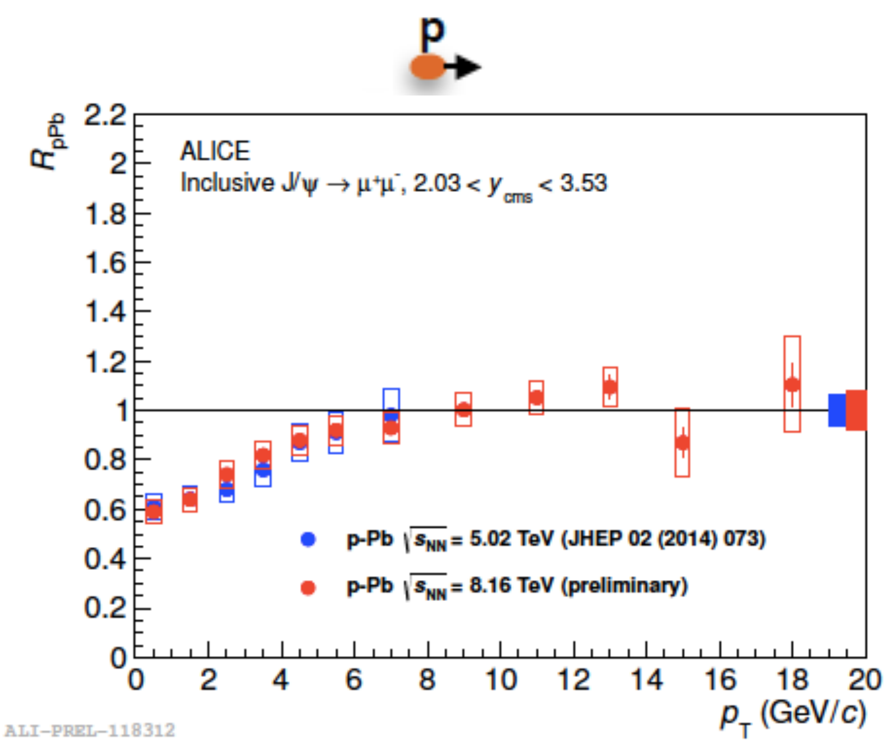
J/ψ Production in pA at 5.02 TeV

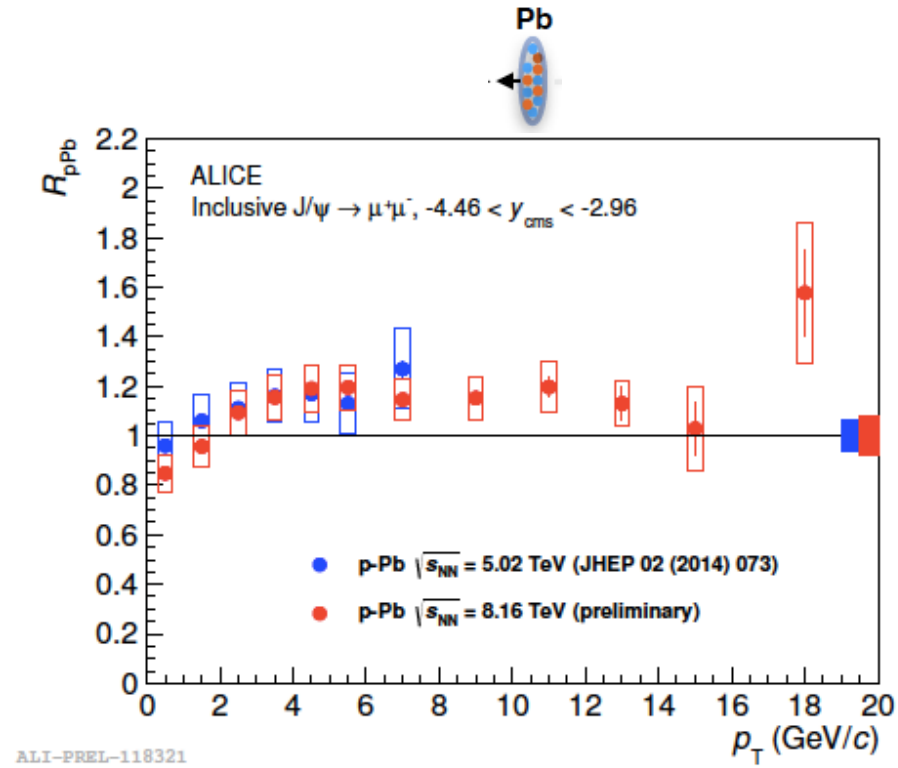
CMS: arXiv:1702.01462
ALICE: JHEP 1506 (2015) 055



- Forward rapidity: up to 40% suppression at low p_T
- Backward rapidity: about 10-20% enhancement

J/ψ Production in pA at 8.16 TeV

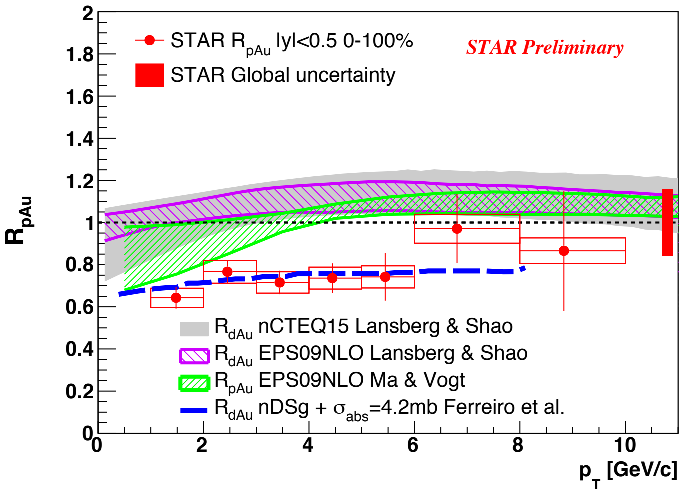




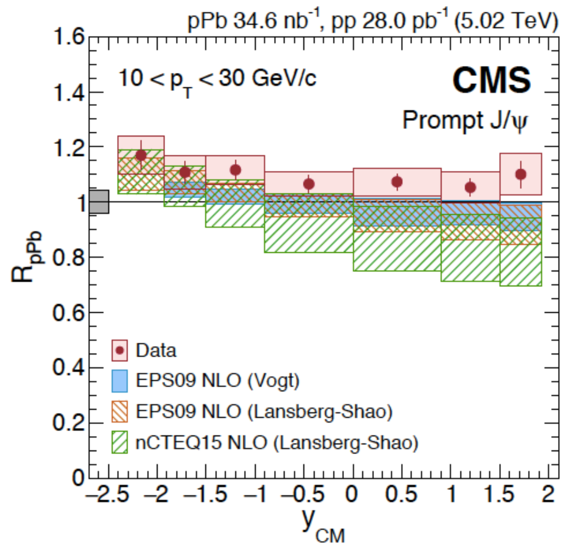
- Almost identical between 5.02 and 8.16 TeV.
- Saturation of CNM?

Model Prediction of J/ψ CNM

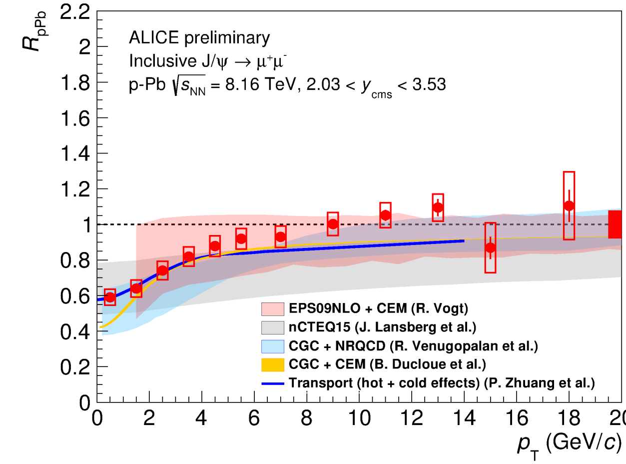
√s = 0.2 TeV



√s = 5.02 TeV



√s = 8.16 TeV



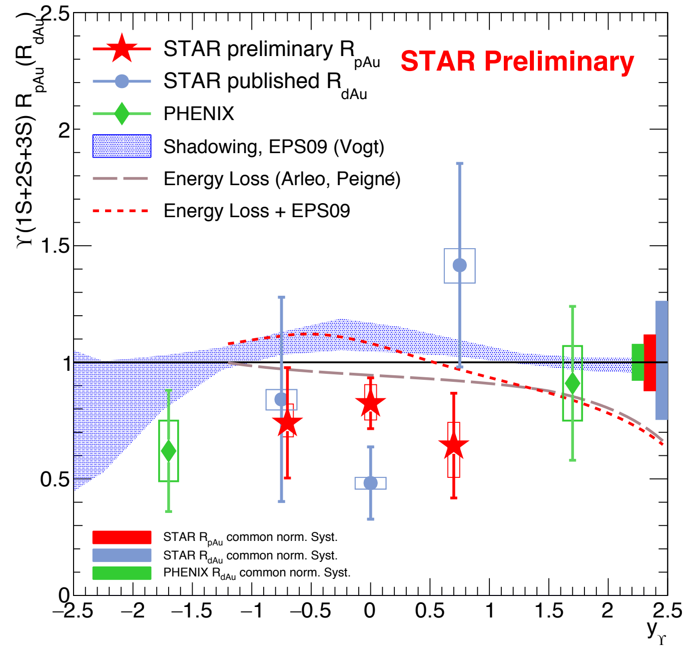
nCTEQ, EPS09+NLO: Lansberg Shao, Eur.Phys.J. C77 (2017) no.1, 1
Comp. Phys. Comm. 198 (2016) 238-259
Comp. Phys. Comm. 184 (2013) 2562-2570
CMS: arXiv:1702.01462

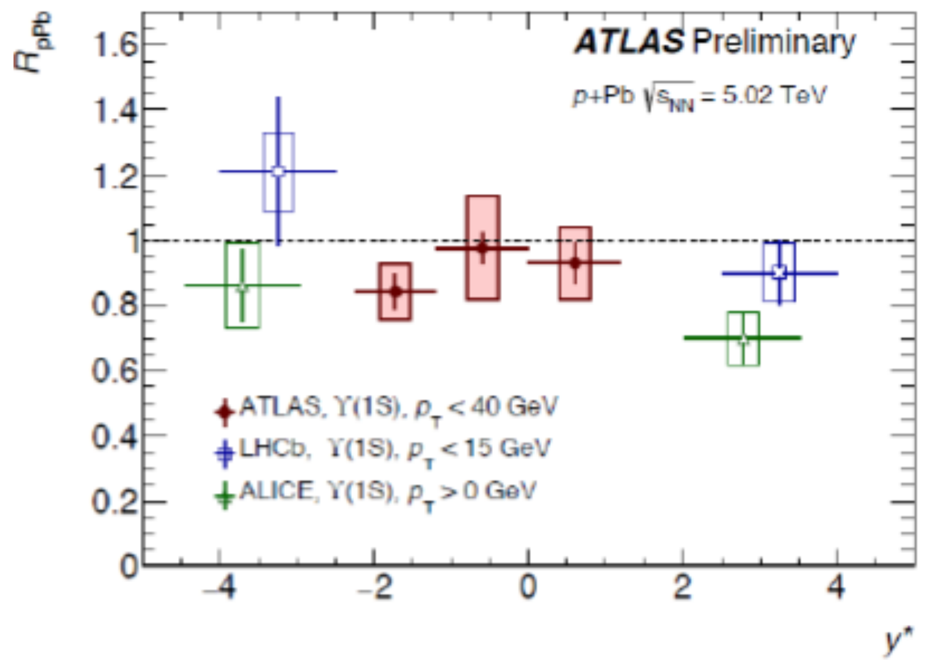
- nPDF effect along does a good job at LHC energies
  - At 5.02 TeV, data above model at high p_T and forward rapidity
  - At 0.2 TeV, additional suppression, such as nuclear absorption, is favored by data.
- At 8.16 TeV, other approaches (CGC, Transport model, etc) also agree well with data.

Υ R_{pA} vs. rapidity

R. Vogt, et. al, PoS ConfinementX 203 (2012)
F. Arleo, S. Peigne, JHEP 1303 (2013) 122
K. J. Eskola, et. al, JHEP 0904 (2009) 065
STAR: PLB 735 (2014) 127
PHENIX: PRC 87 (2013) 044909

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





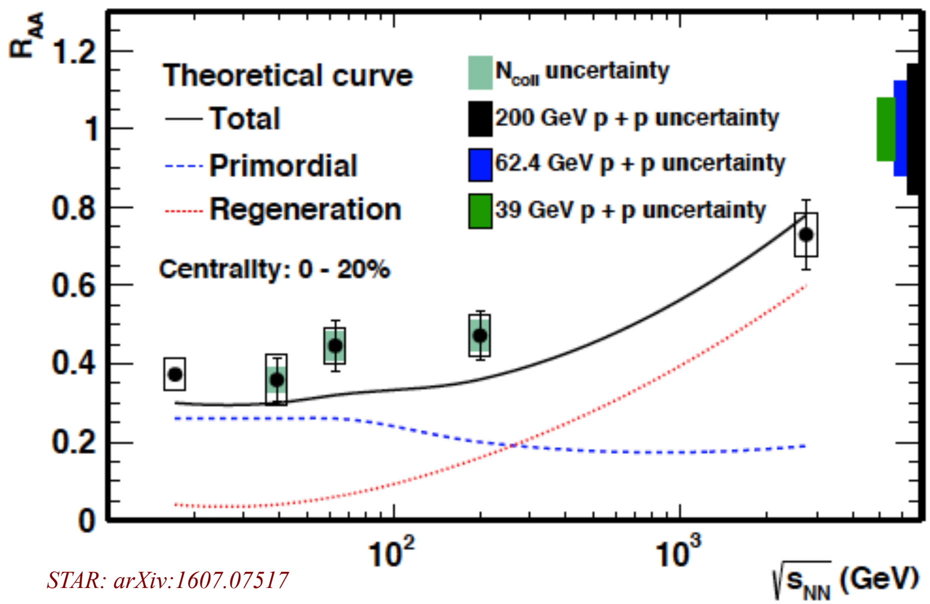
- RHIC: R_{pAu} = 0.82 ± 0.10(stat) ± 0.08(syst) ± 0.10(global)
  - Additional suppression mechanism seems needed beyond nPDF effects
- LHC: R_{pPb} ~ 1 with weak rapidity dependence → Need to improve precision

pp Collisions

pA/dA Collisions

AA Collisions

"Dissociation + Regeneration" Picture



STAR: arXiv:1607.07517

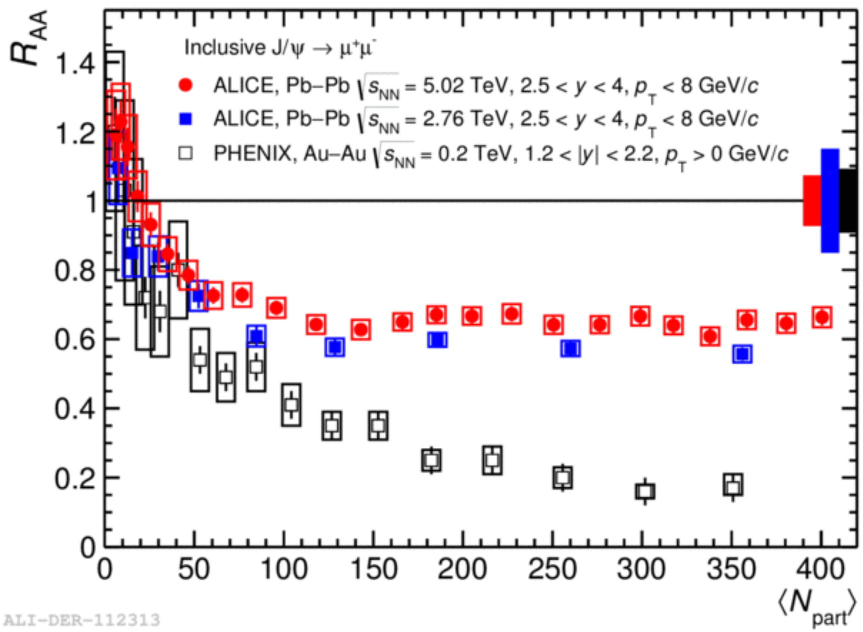
- Pretty successfully in describing the J/ψ production over a vast range of collision energy.

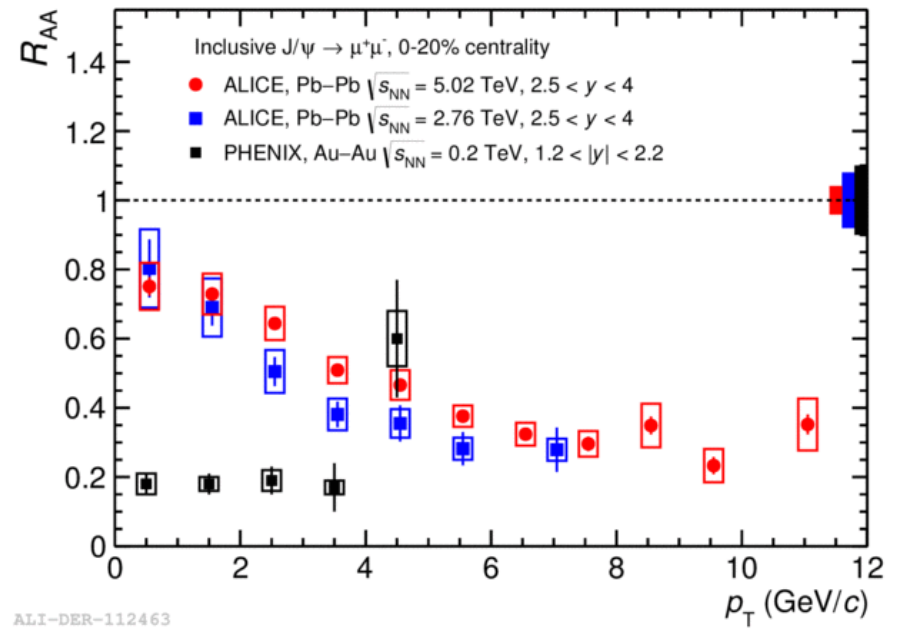
- More differential measurements to test the picture

	Dissociation	Regeneration	Shadowing
√s ↑	↑	↑	↑
p_T ↑	↓	↓	↓
y ↑	↓	↓	↑

J/ψ: Low p_T, Forward Rapidity

PHENIX: PRC 84 (2011) 054912
ALICE: PLB 734 (2014) 314
ALICE: PLB 766 (2017) 212

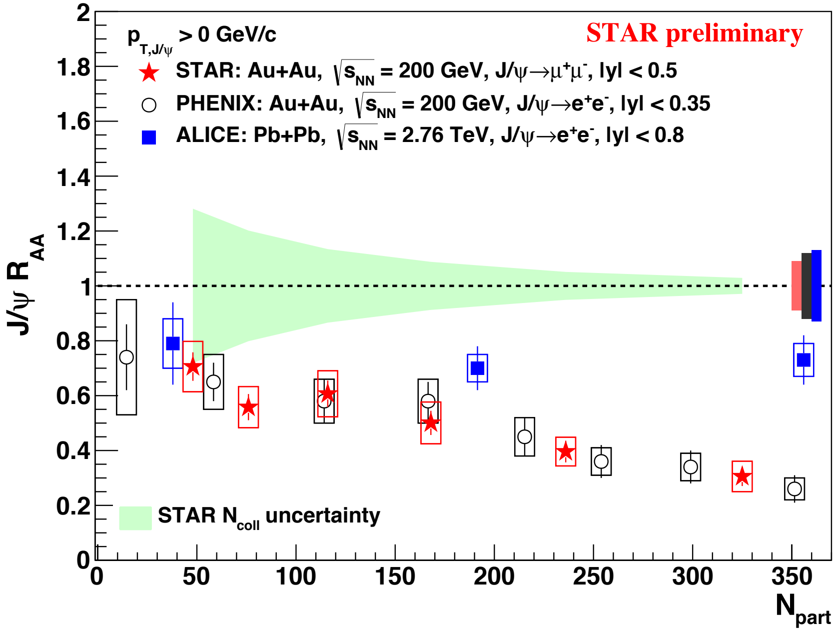


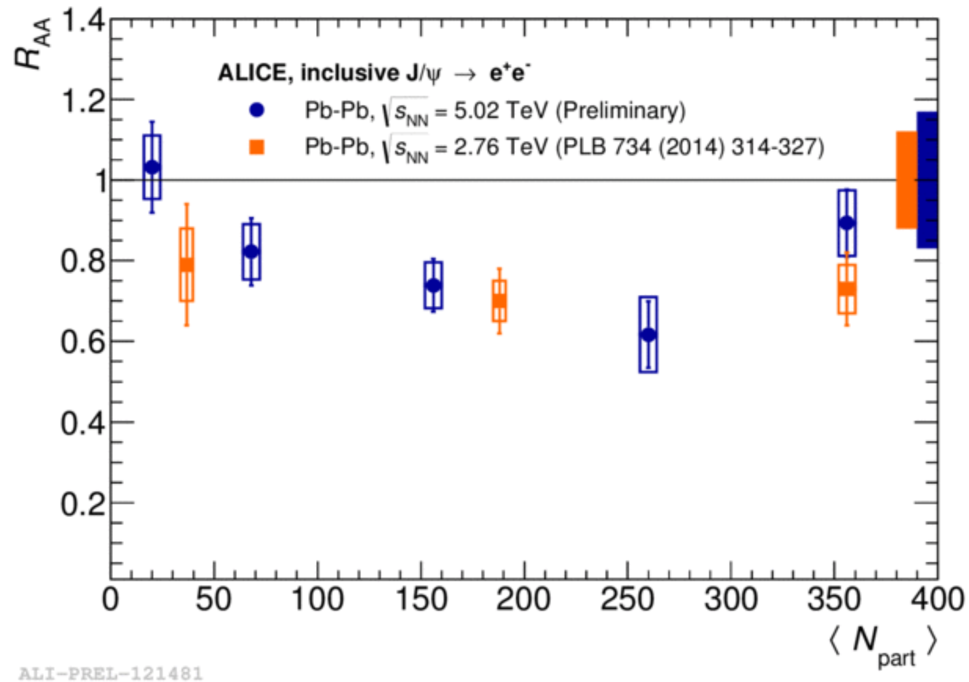


- At LHC, R_{AA} increases significantly as p_T deceases, but stays almost unchanged above $\langle N_{part} \rangle \sim 50$
- At RHIC, R_{AA} decreases considerably toward central collisions
- For central collisions, R_{AA}(5.02 TeV) >~ R_{AA}(2.76 TeV) >> R_{AA}(0.2 TeV)

J/ψ: Low p_T, Mid-Rapidity

ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301



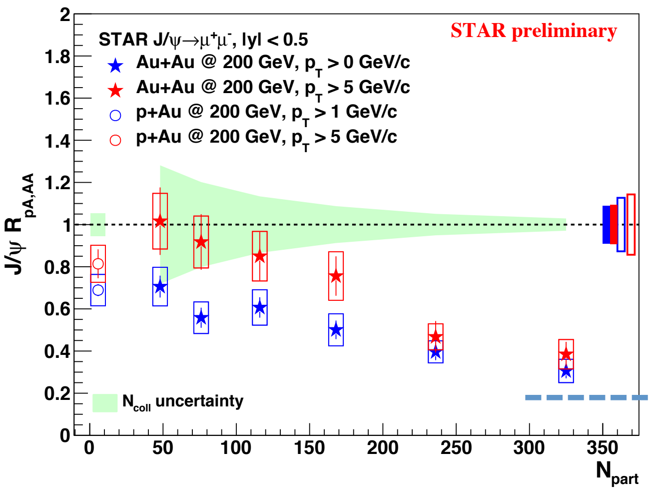


- ➢ Very similar picture as for forward rapidity

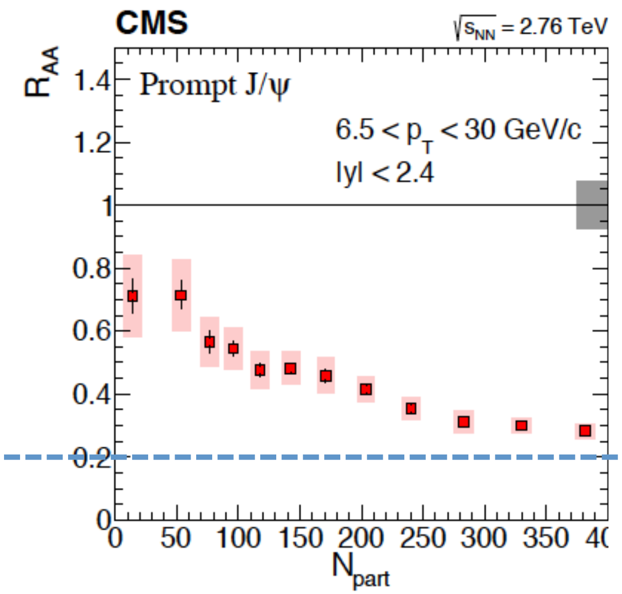
→ RHIC: dissociation outweighs regeneration
→ LHC: regeneration dominates at low p_T

J/ψ: High p_T, Mid-Rapidity

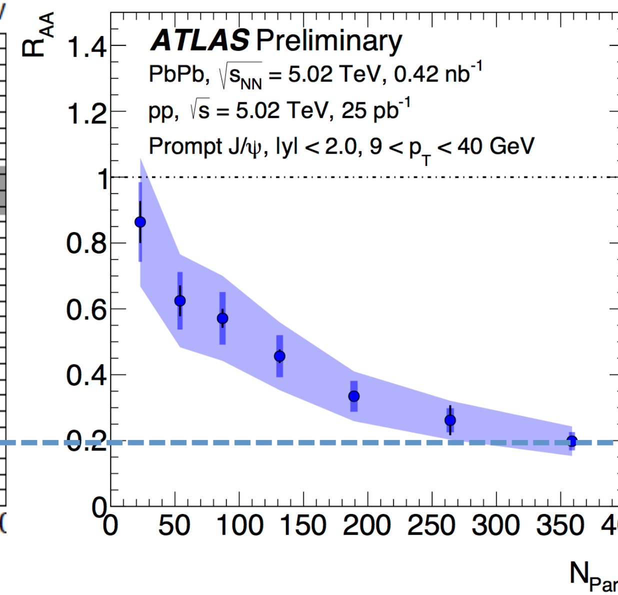
√s = 0.2 TeV



√s = 2.76 TeV



√s = 5.02 TeV



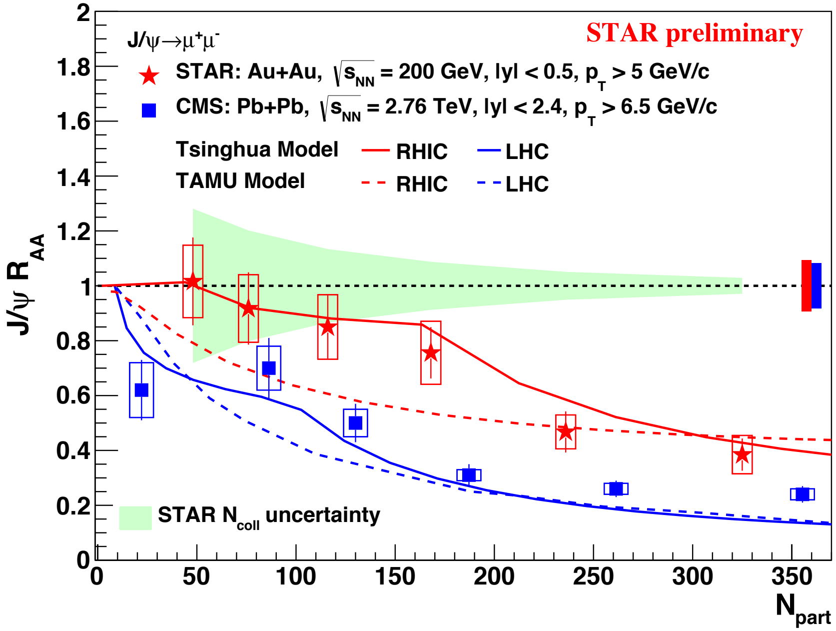
CMS: arXiv:1610.00613
ATLAS-CONF-2016-109

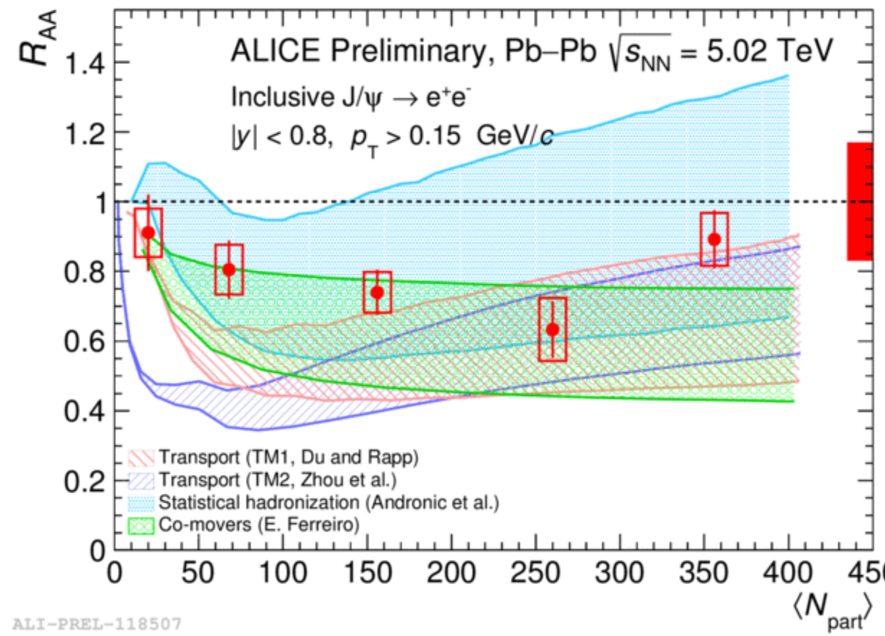
- Unlike low p_T
  - Decreasing R_{AA} towards central collisions in all collision energies
  - R_{AA}(5.02 TeV) <~ R_{AA}(2.76 TeV) <~ R_{AA}(0.2 TeV)

→ Dissociation in effect

Model Comparison

TAMU/Rapp: PRC 82 (2010) 064905, NPA 859 (2011) 114
Tsinghua/Zhou: PLB 678 (2009) 72, PRC 89 (2014) 05491
P. Braun-Munzinger, J. Stachel: PLB 490 (2000) 196, PLB 652 (2007) 659
E.G. Ferreiro, PLB 731 (2014) 57

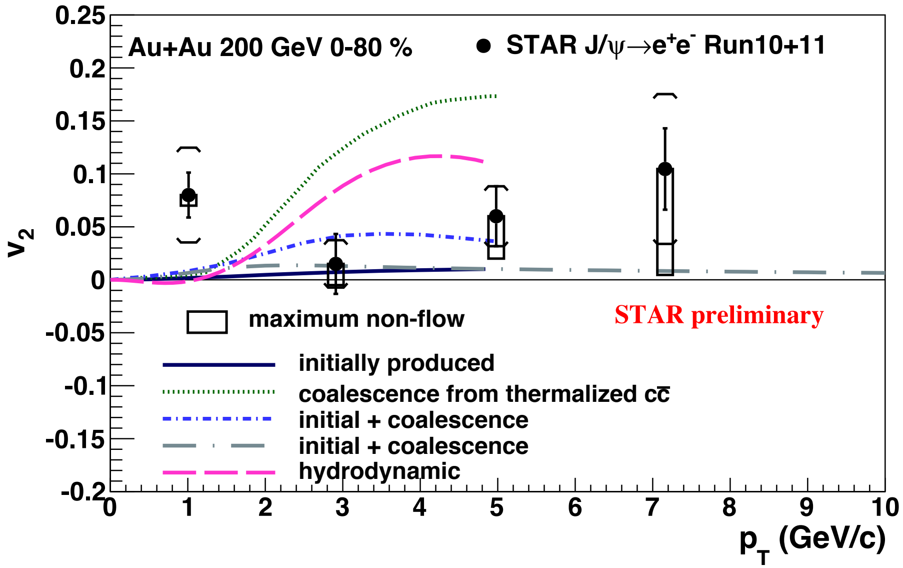


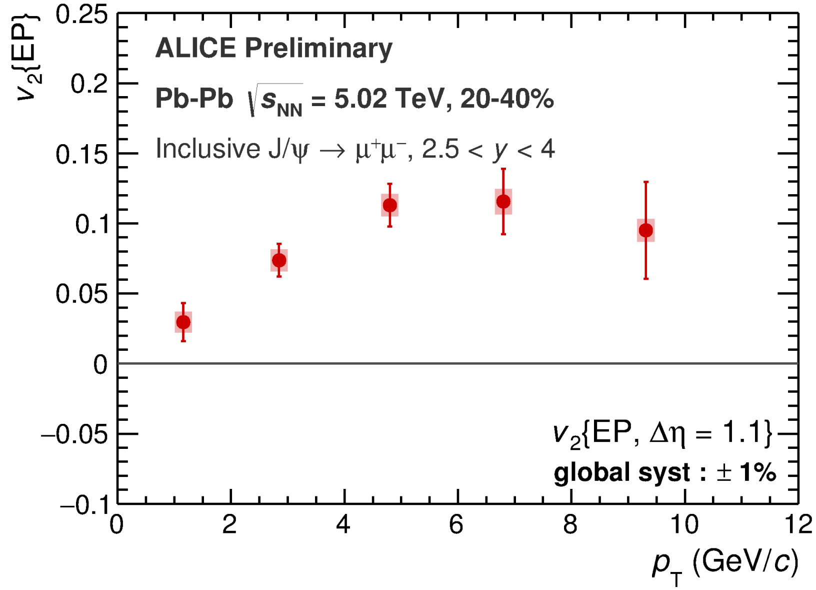


- Different models, e.g. transport models, Statistical Hadronization, Co-movers, implement suppression and recombination differently. Can qualitatively describe data.
- However, the used charm quark cross-section differ by almost a factor of 2 between different models → **need experimental commitment**

An Independent Handle: v_2

- Regenerated J/ψ should flow at both RHIC and LHC energies since charm quarks flow.

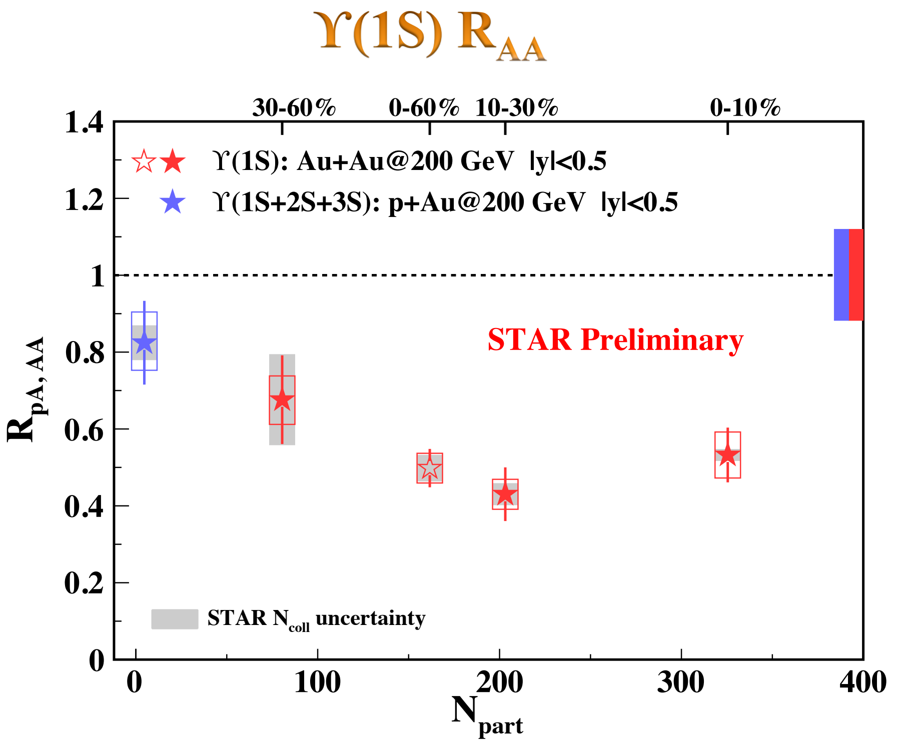


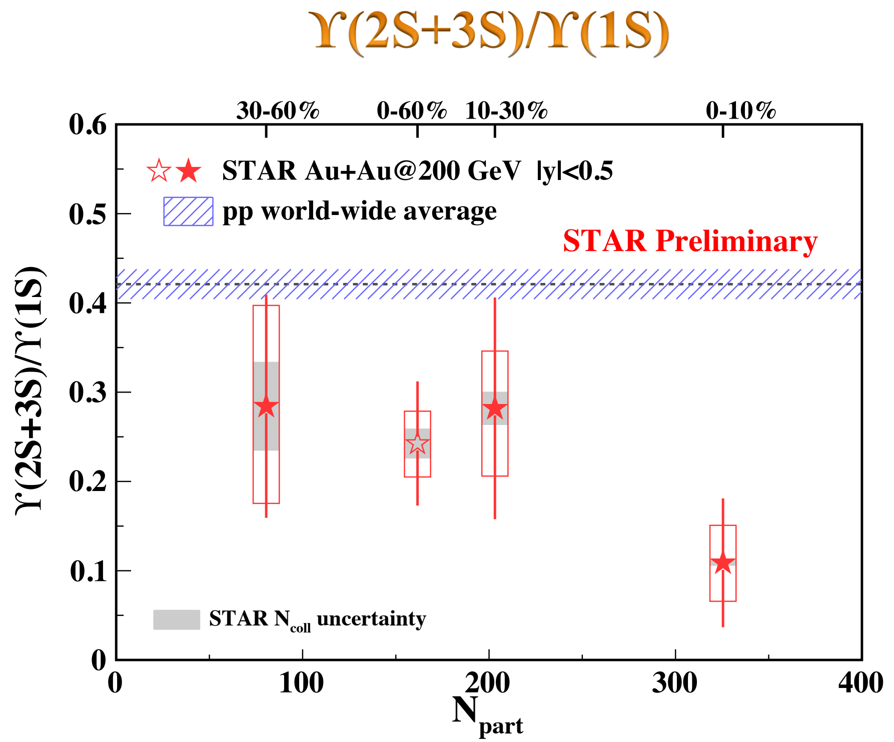


- RHIC: v_2 is consistent with 0 above 2 GeV/c → regeneration contribution is small
- LHC: v_2 is definitely above 0 → regeneration is important
  - **A sign of energy loss for high p_T?**

STAR, PRL 111 (2013) 052301; L. Yan, et al, PRL 97 (2006) 232301
V. Greco, et al, PLB 595 (2004) 202; X. Zha, et al, arXiv: 0806.1239
Y. Liu, et al,, NPA 834 (2010) 317
U.W. Heinz and C. Shen, (private communication)

Υ Suppression at RHIC





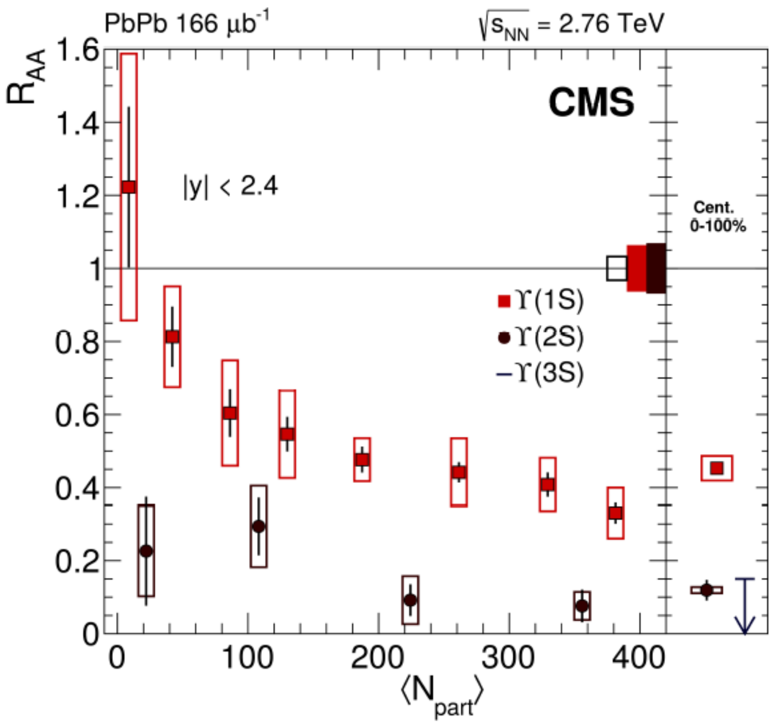
World-wide p+p: W. Zha, et. al, PRC 88 (2013) 067901

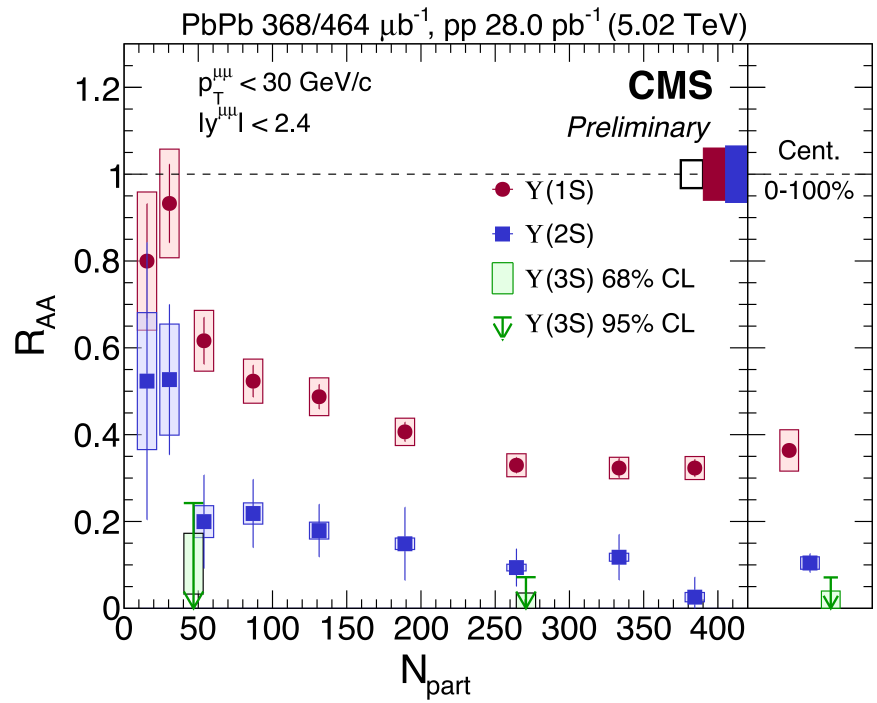
- Υ(1S) R_{AA} decreases towards more central collisions, and then levels up.
- Central: Υ(2S+3S) is more suppressed → sequential melting

Υ Suppression at LHC

CMS PAS HIN-16-023
CMS: arXiv:1611.01510

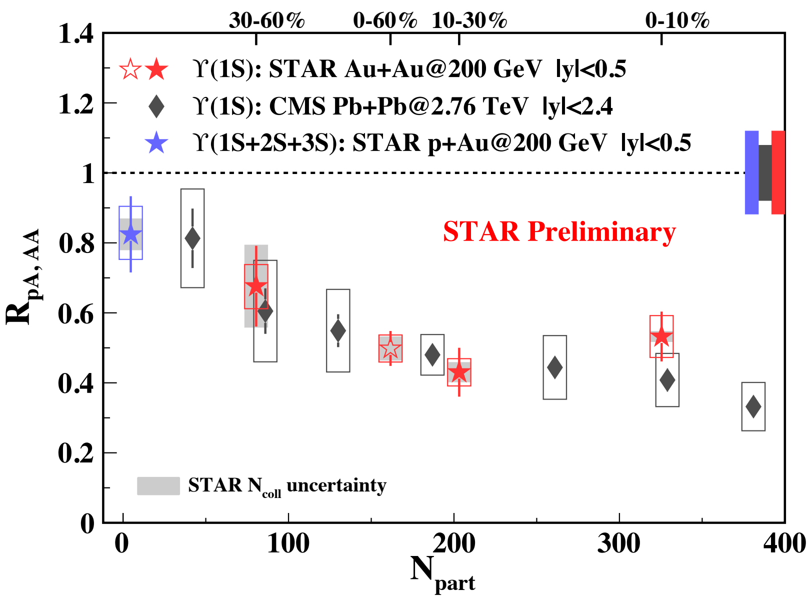
√s = 2.76 TeV **√s = 5.02 TeV**

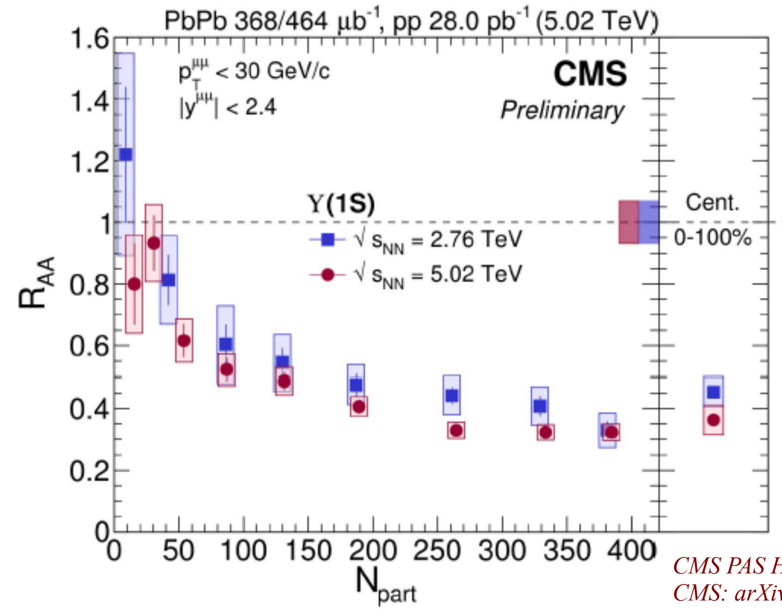




- Similar phenomena as seen at RHIC
- $\Upsilon(2S)$ and $\Upsilon(3S)$ are measured separately → sequential melting

$\Upsilon(1S)$ R_{AA} vs. Collision Energy





CMS PAS HIN-16-023
CMS: arXiv:1611.01510

- Very weak collision energy dependence. Could it be all due to the suppression of feed-down contributions? **May…be?**

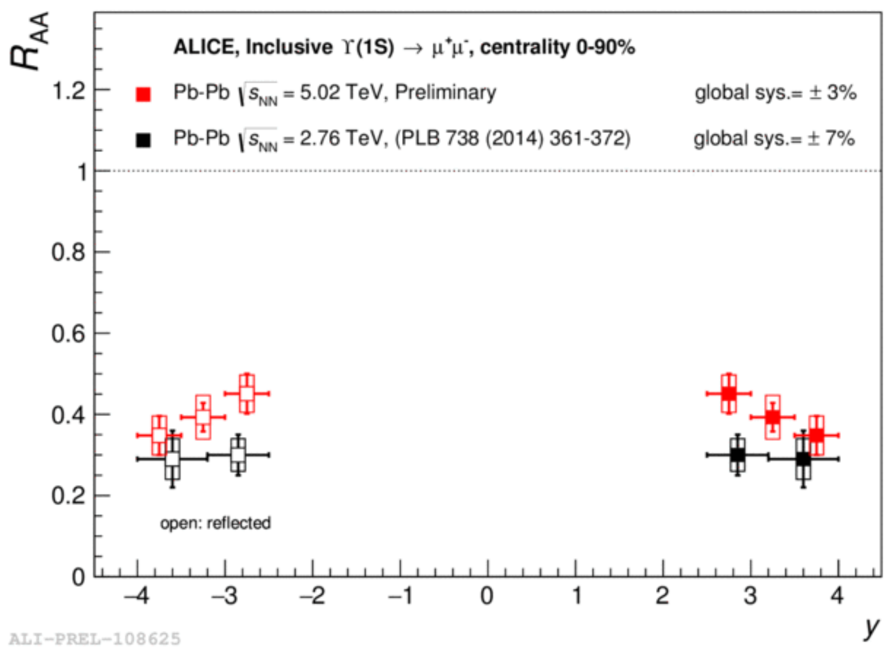
Rongrong's formula $R_{AA}^{direct} = R_{AA} / 0.7 / (R_{pA})^2$

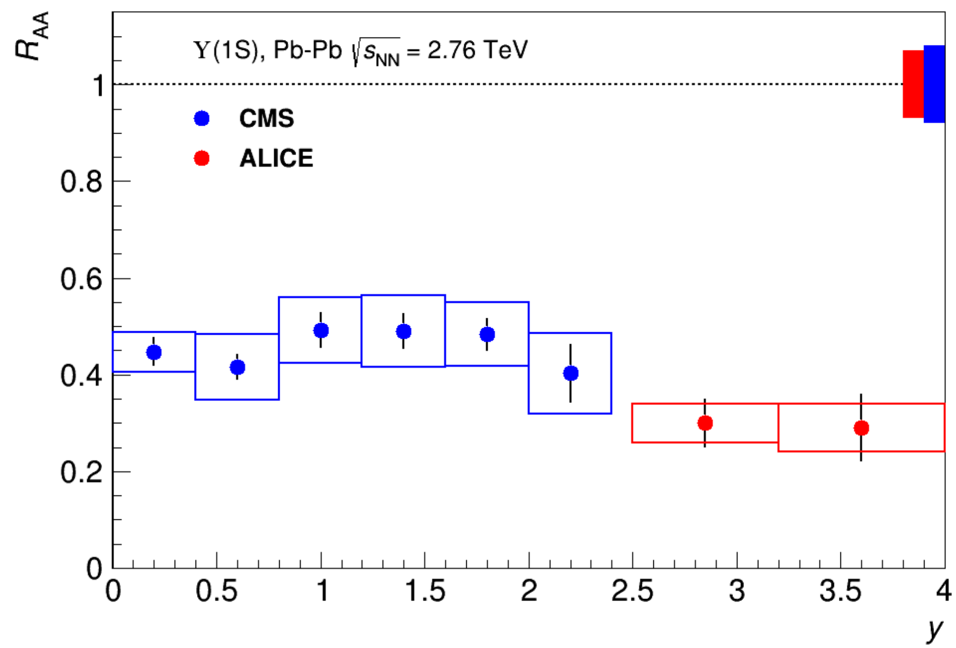
Υ(1S)	R_{pA}	R_{AA}	$R_{AA}^{direct**}$
√s = 0.2 TeV (0-10%)	0.82±0.16	0.53±0.11	1.13±0.39
√s = 2.76 TeV (5-10%)	0.9±0.1*	0.41±0.09	0.72±0.20

*R_{pPb} is eye-balled from 5.02 TeV measurements

Could it be Regeneration?

ALICE: PLB 738 (2014) 361
CMS: arXiv:1611.01510

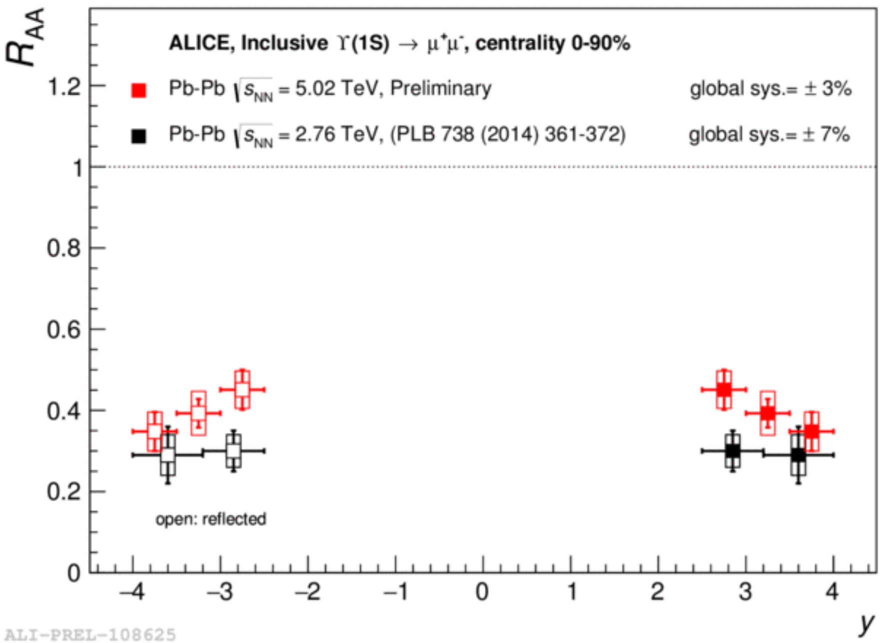


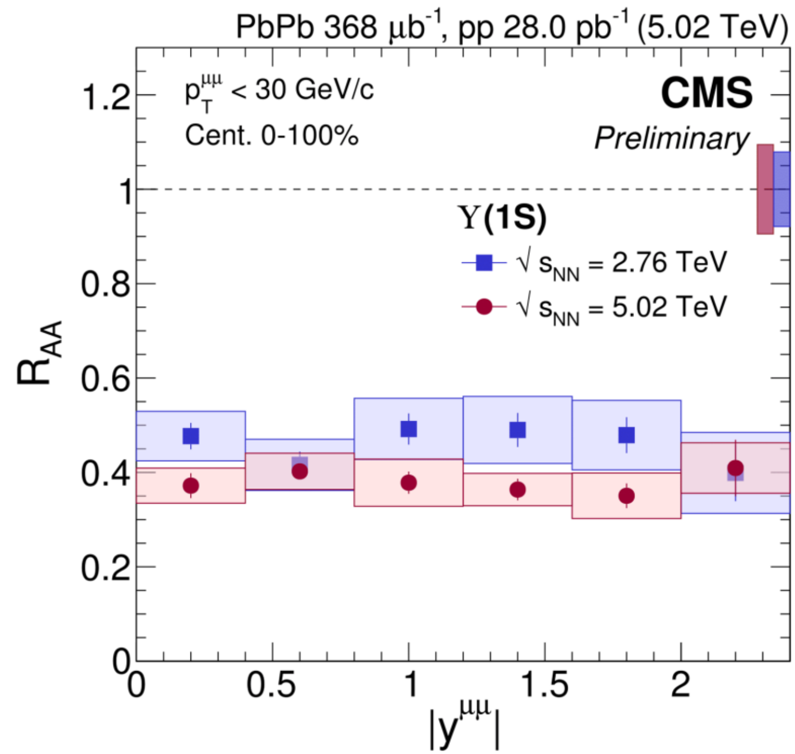


- Υ(1S) looks almost like the new "J/ψ": larger suppression at lower collision energy and forward rapidity.
- Need to quantify the role of CNM

However …

ALICE: PLB 738 (2014) 361
CMS: arXiv:1611.01510
CMS-PAS-HIN16-023

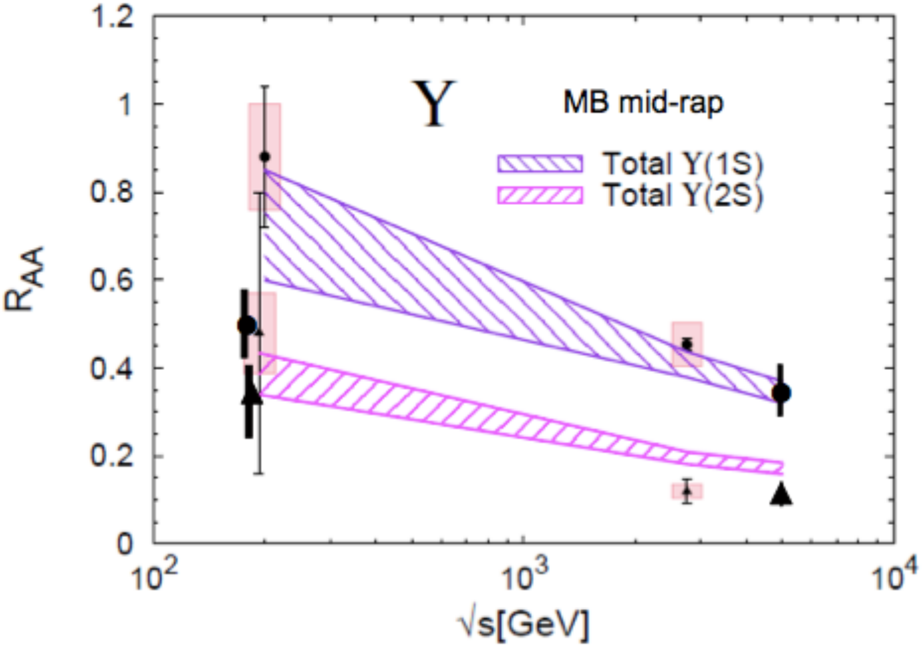


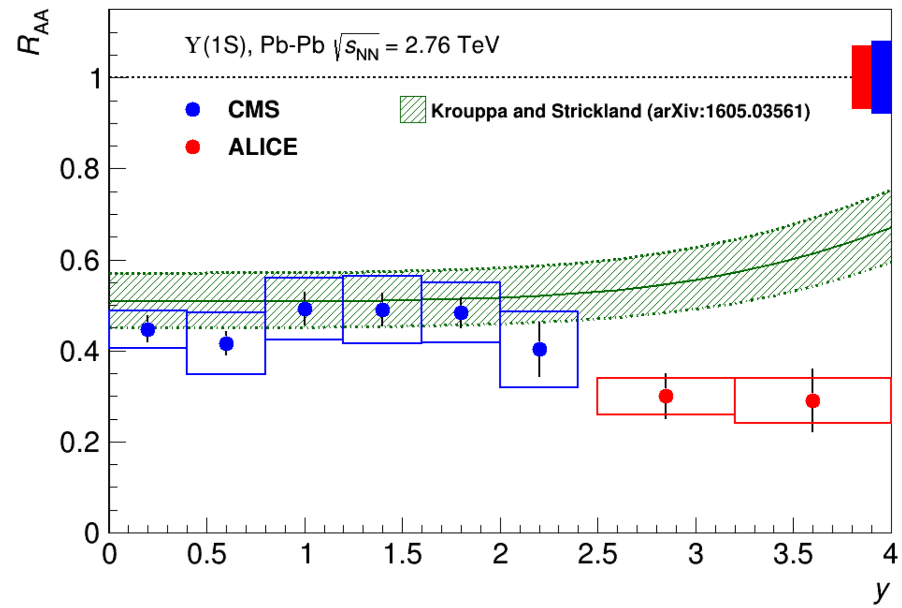


- ALICE: less suppression at 5.02 TeV at forward-y
- CMS: more suppression at 5.02 TeV at mid-y
- Tension? Intriguing physics? Uncertainties? Other effects?

What Do Models Say?

R. Rapp @ QM'17

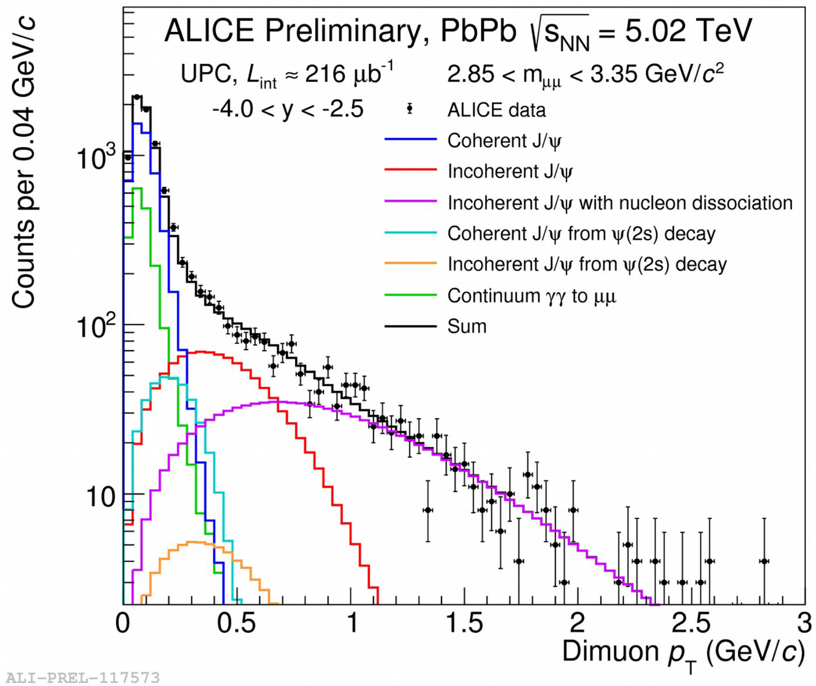


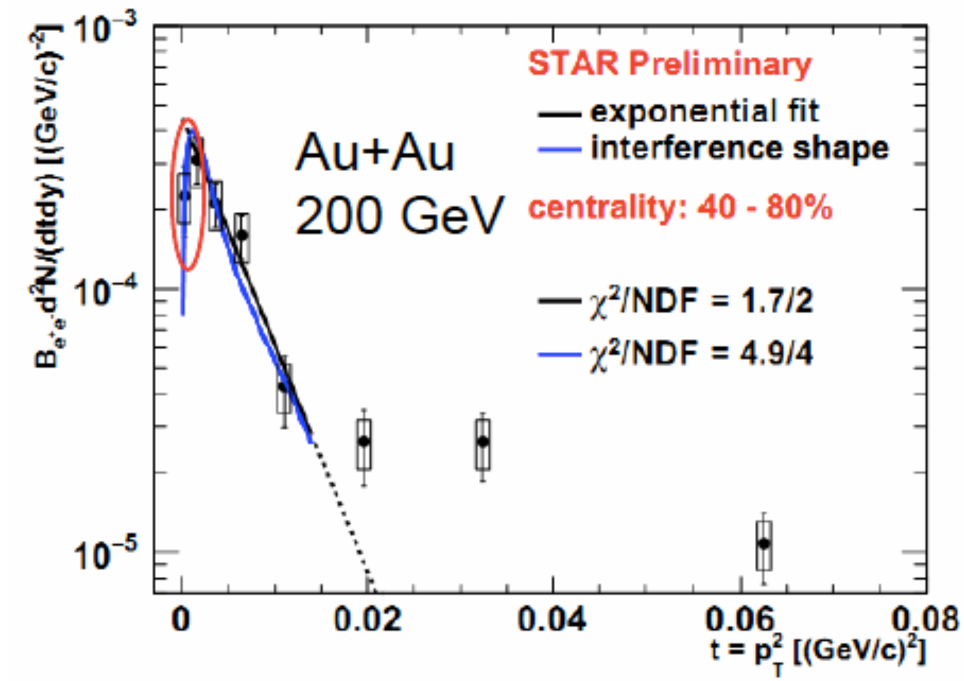


- Rapp model includes CNM and regeneration: describes Υ(1S) R_{AA} at RHIC and LHC fairly well, but under-estimates Υ(2S) suppression
- Strickland model does not include CNM or regeneration: very successful in describing 5.02 TeV measurements, but disagrees with RHIC data and ALICE 2.76 TeV data at forward rapidity.

→ Need further theoretical development

A Welcome Surprise: Excess of Low-p_T J/ψ





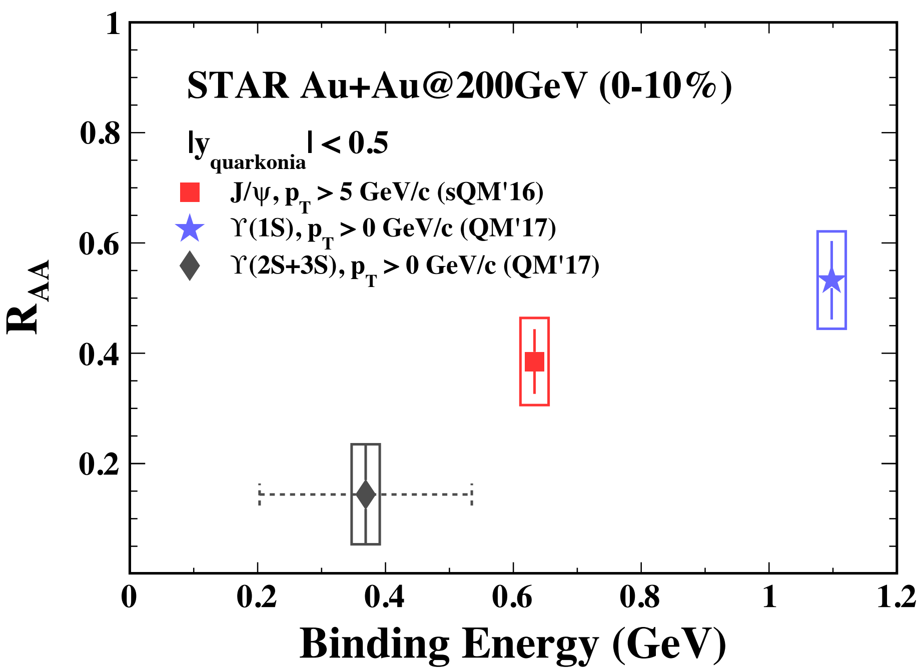
- Huge excess of J/ψ yield at low p_T in peripheral AA collisions. Exhibit characteristics of coherent photon-nuclear production.
- If under theoretical control, can be used to probe hot medium.
  - Great theoretical challenge, e.g. how the violent hadronic interaction affect the coherent process.

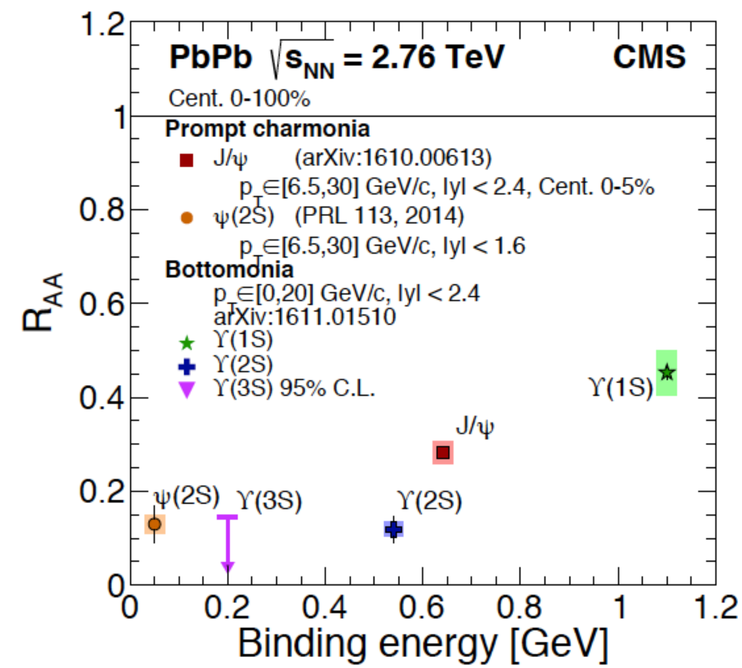
W. Zha, arXiv:1705.01460

Summary

- Have we fulfilled the initial promise?

(Cautiously optimistic) YES



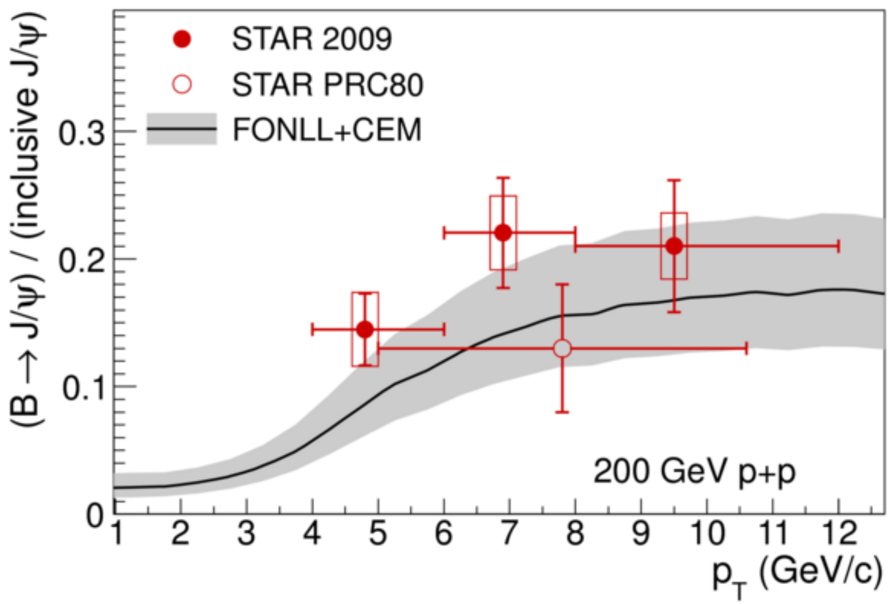


- Other effects (CNM, regeneration, etc) also play important roles.
- The "cloud": do we understand quarkonium production in pp?

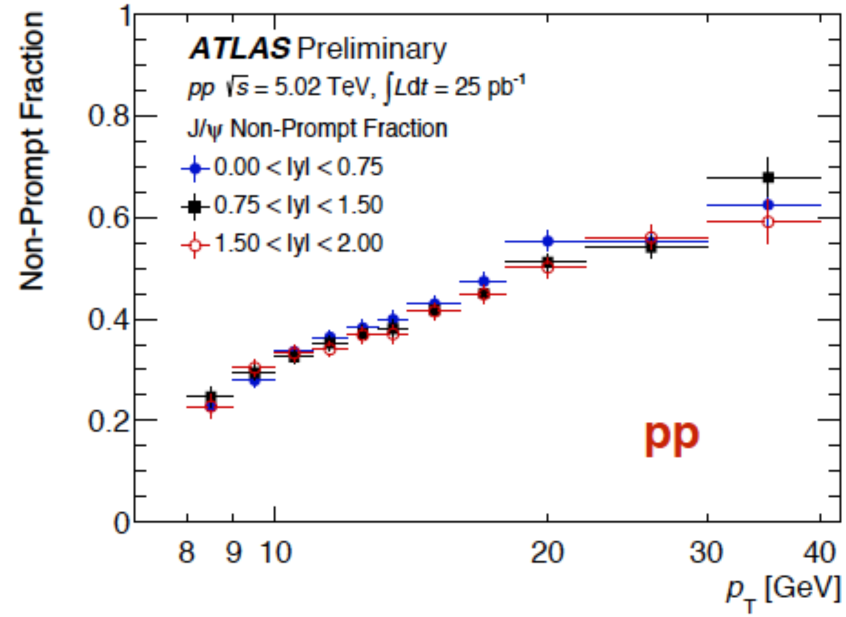
Backup

Non-prompt J/ψ fraction

√s = 0.2 TeV



√s = 5.02 TeV

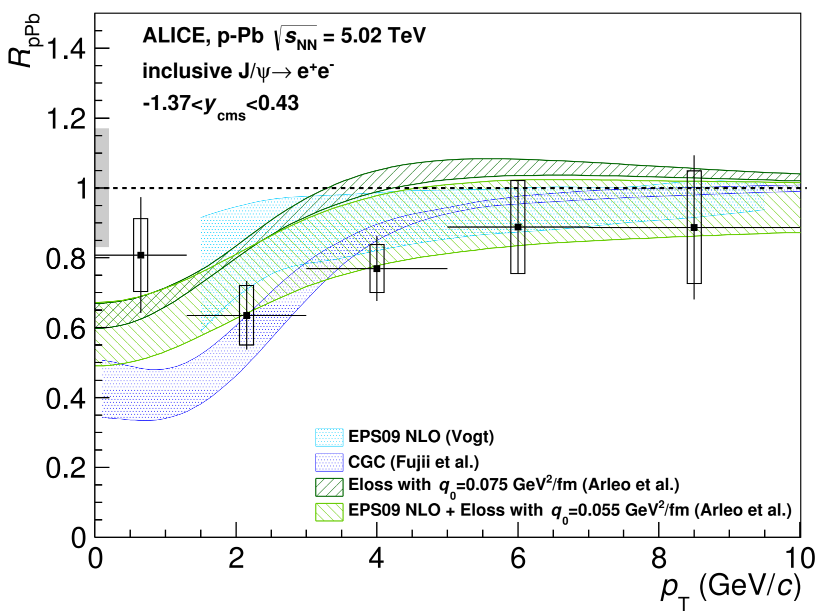


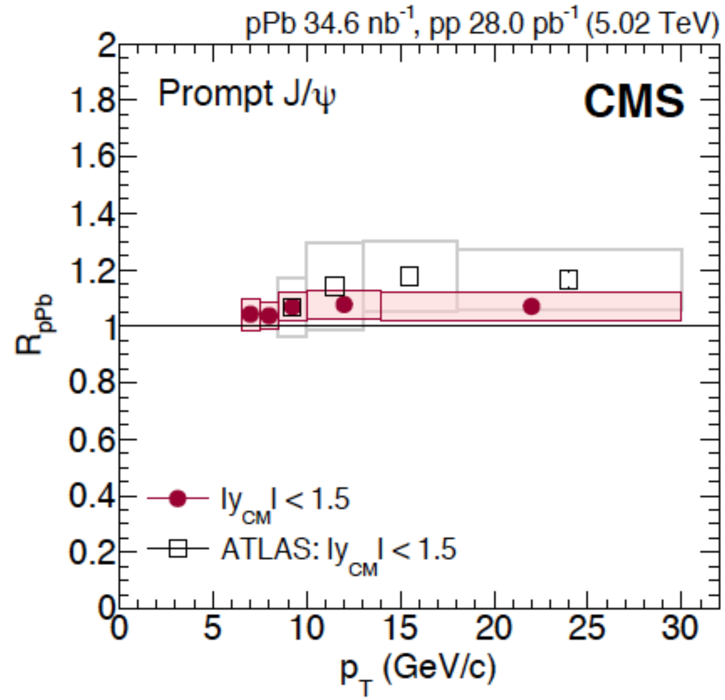
- Strong dependence on p_T and √s

J/ψ Production in pA at 5.02 TeV

CMS: arXiv:1702.01462
ALICE: JHEP 1506 (2015) 055

Mid-rapidity

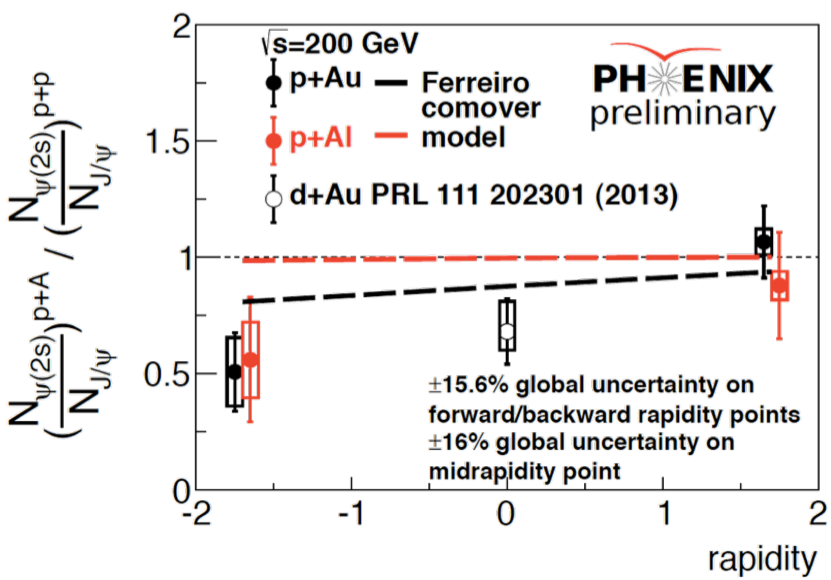




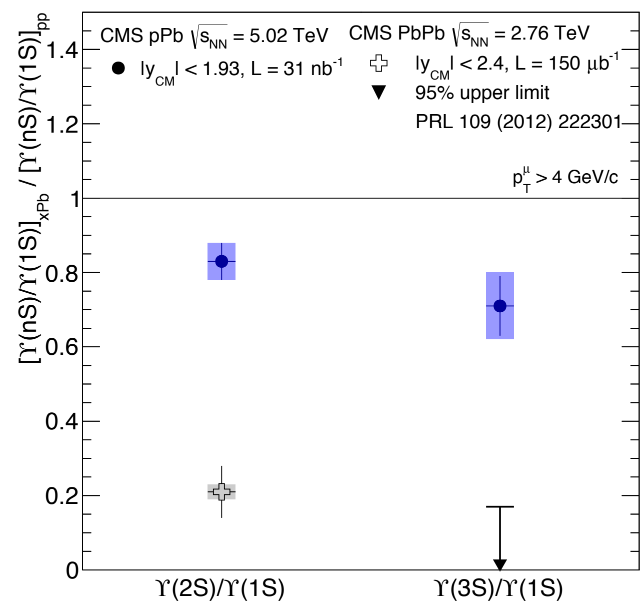
- At mid-rapidity, about 20% suppression below 5 GeV/c and consistent with 1 at high p_T

Excited States More Suppressed

ψ' @ √s = 0.2 TeV



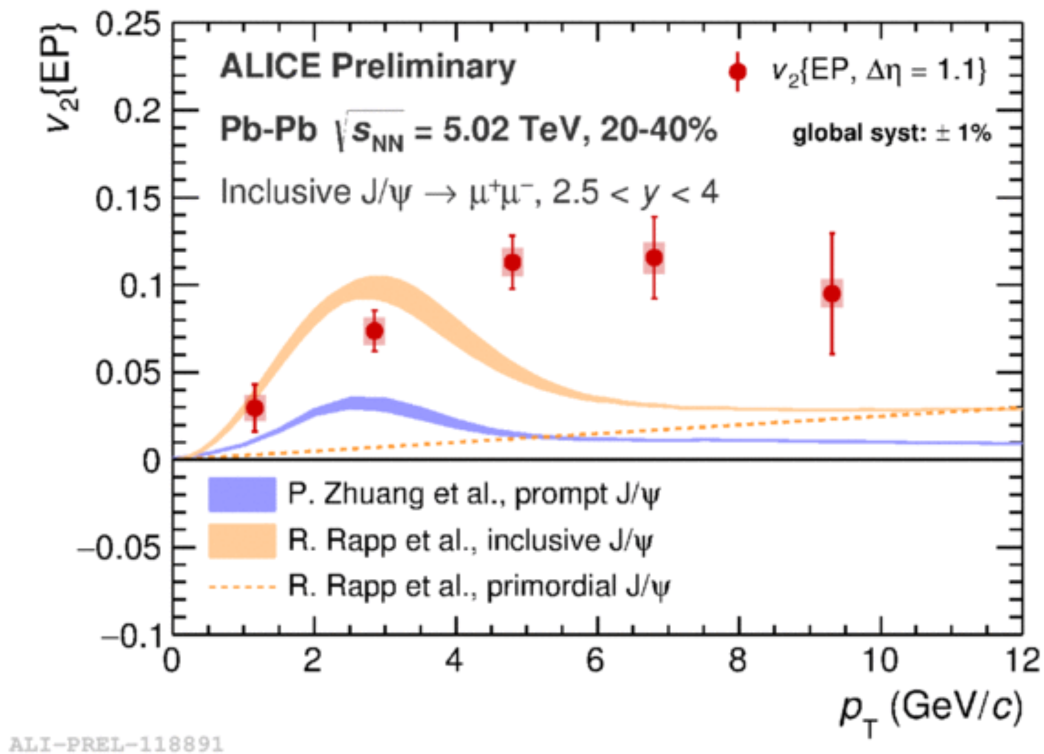
ϒ @ √s = 0.2 TeV



CMS: JHEP 04 (2014) 103

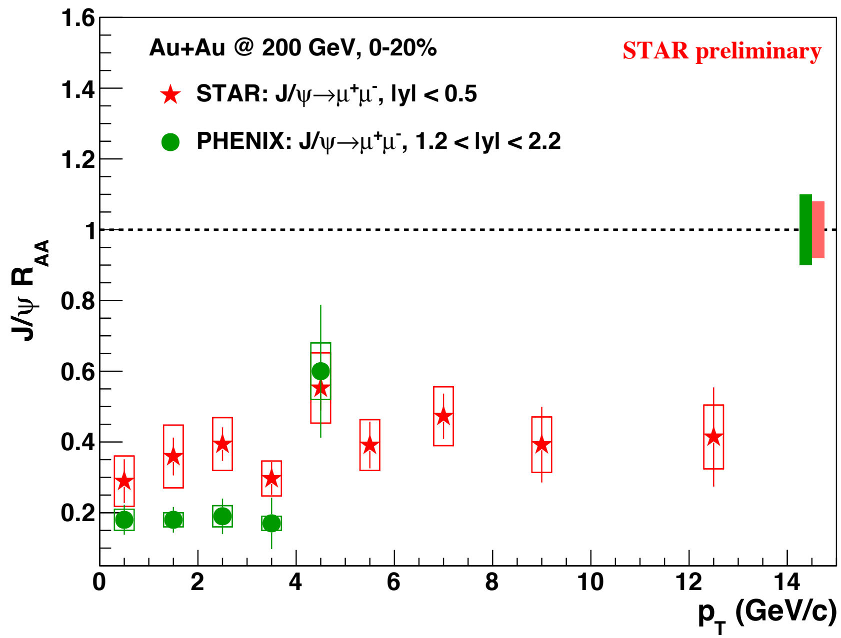
- Additional suppression of excited states compared to the ground state; likely caused by final-state effects, such as co-mover interactions.
- Important for taking out feed-down contribution in AA collisions.

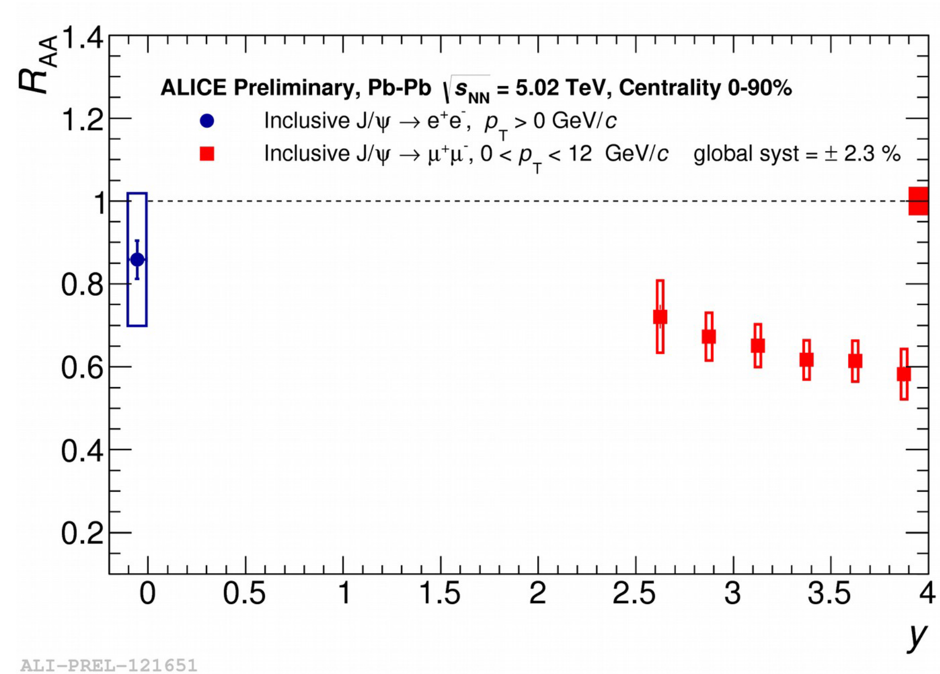
J/ψ v_2 Compared with Models



J/ψ: Low p_T, Mid vs. Forward

PHENIX: PRC 84 (2011) 054912

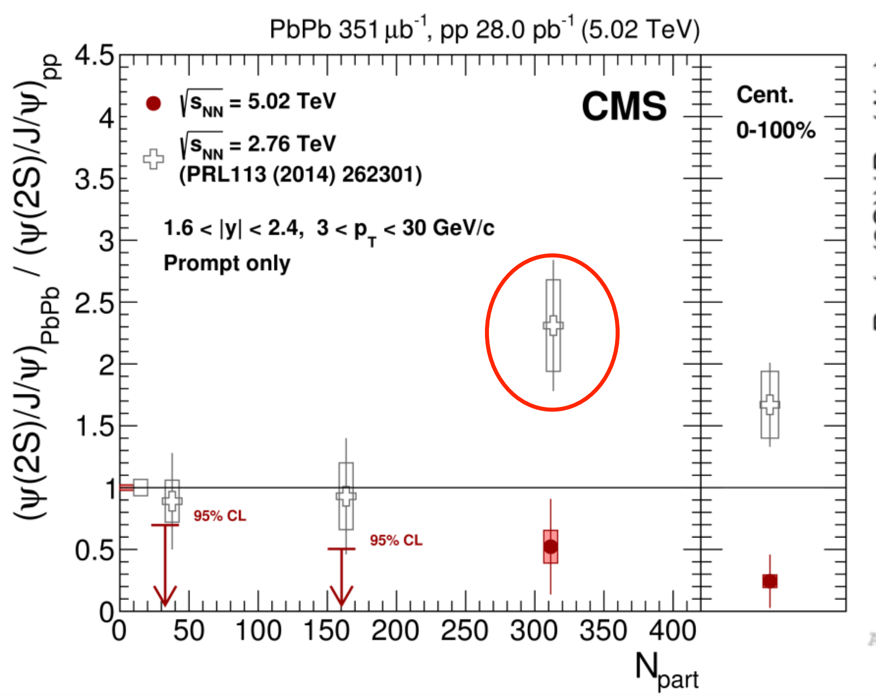


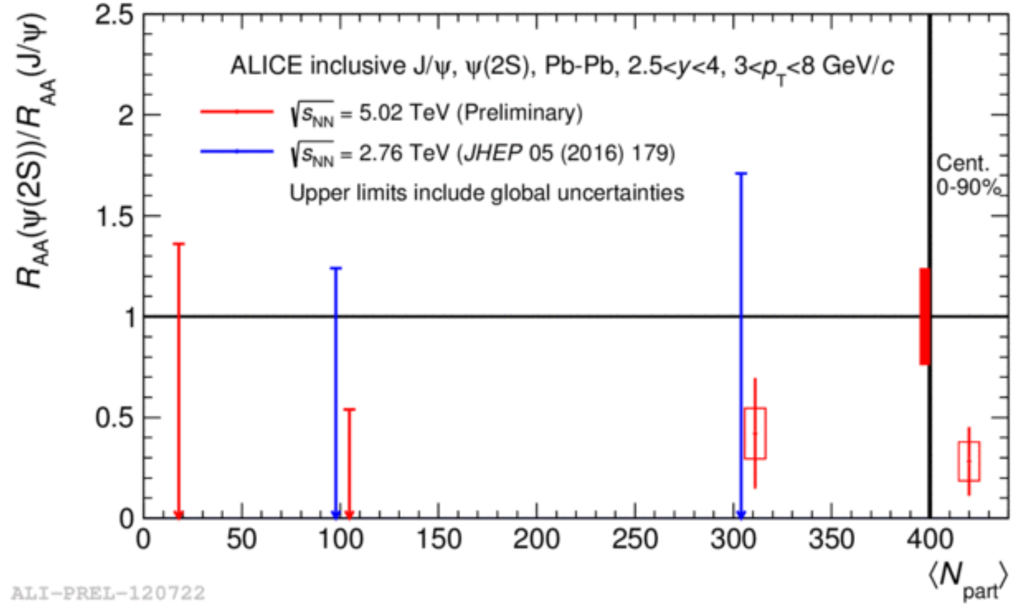


- At both RHIC and LHC, indication of enhanced production at mid-rapidity compared to forward rapidity. Could be less CNM and/or more regeneration.

The ψ' Puzzle

CMS: arXiv: 1611.01438

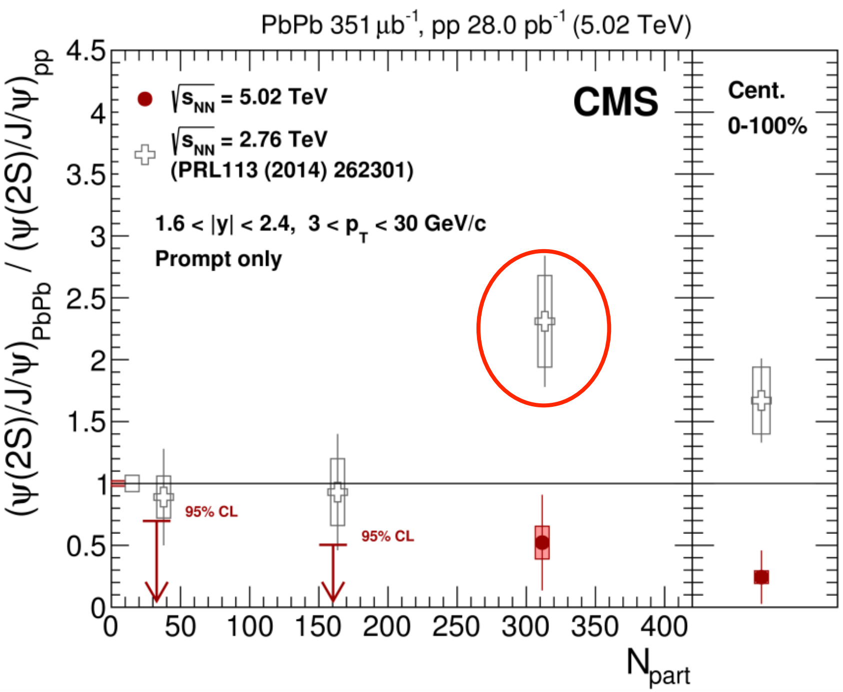




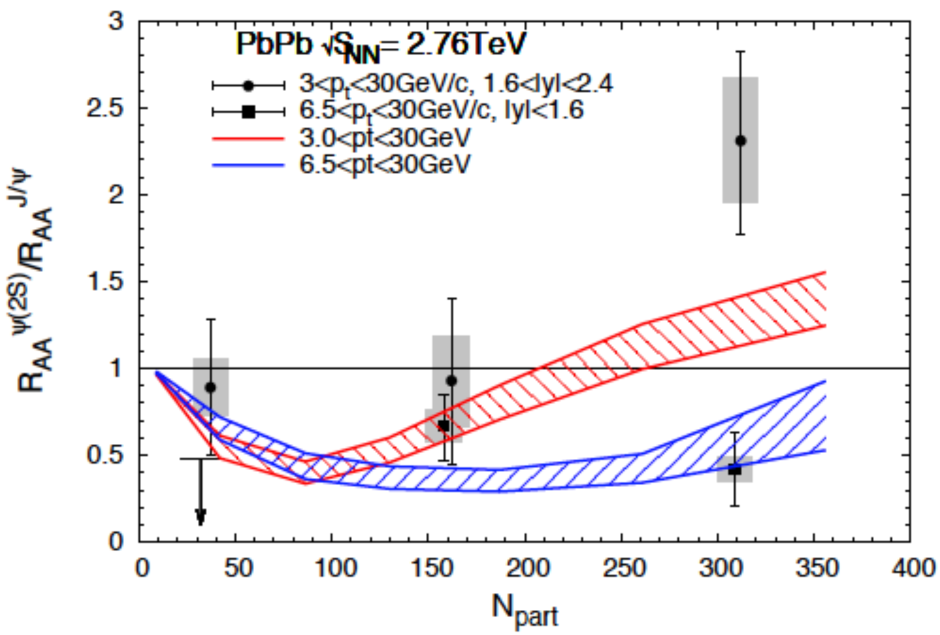
- The measurements are consistent with a dissociation picture, i.e. $R_{AA}(\psi') \ll R_{AA}(J/\psi)$, except for ($\sqrt{s}$ = 2.76 TeV, $1.6 < |y| < 2.4$, $p_T > 3$ GeV/c).
- The CMS point is above 95% CL of ALICE measurement at a slightly different rapidity window.

The ψ' Puzzle

CMS: arXiv: 1611.01438



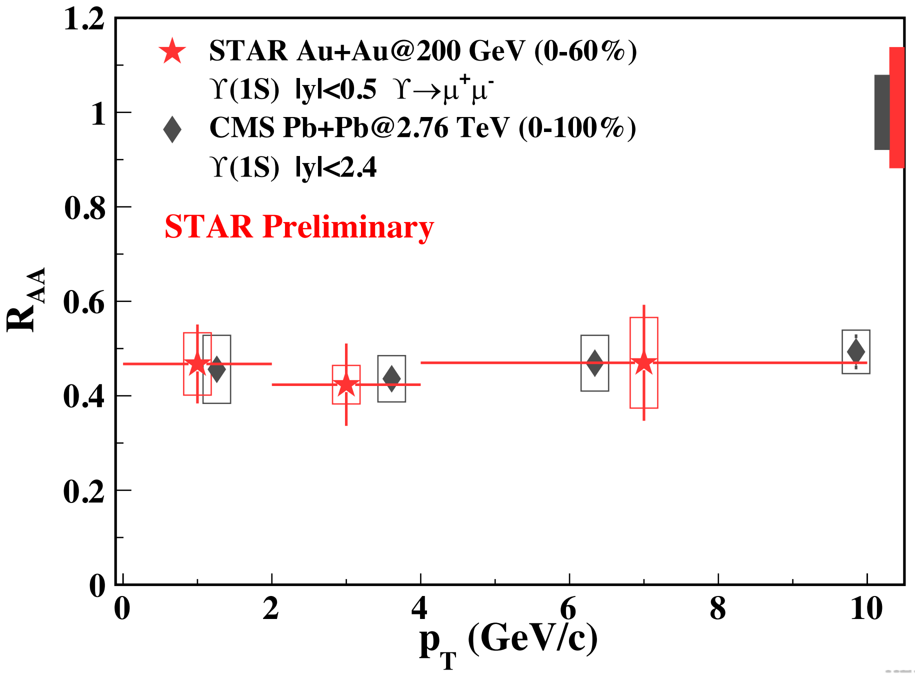
X. Du and R. Rapp: arXiv: 1609.04868

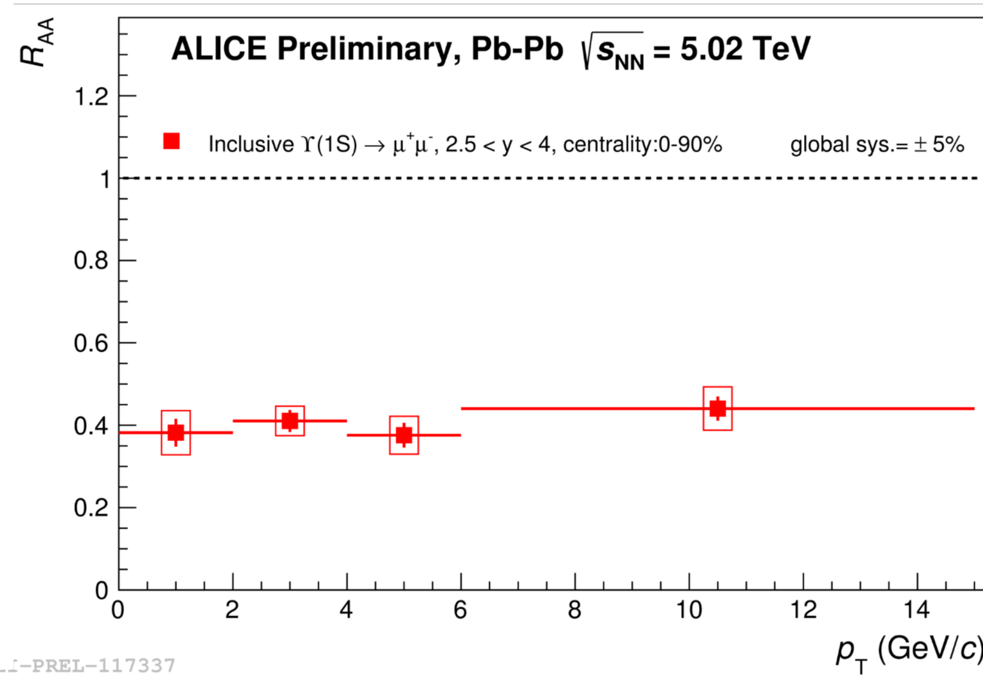


- The measurements are consistent with a dissociation picture, i.e. $R_{AA}(\psi')$ << $R_{AA}(J/\psi)$, except for ($\sqrt{s}$ = 2.76 TeV, 1.6 < |y| < 2.4, p_T > 3 GeV/c).
- The CMS point is above 95% CL of ALICE measurement at a slightly different rapidity window.
- The latest calculation (TAMU) assuming ψ' regenerated as a later stage when radial flow is built up under-shoots the enhancement.

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

CMS: arXiv:1611.01510





- $\Upsilon(1S)$ R_{AA} is flat as a function of p_T from 0.2 to 5.02 TeV
- Additional constraints to model calculations