



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science



# Quarkonium production in nuclear collisions

Rongrong Ma (BNL)



# *Why Quarkonium?*

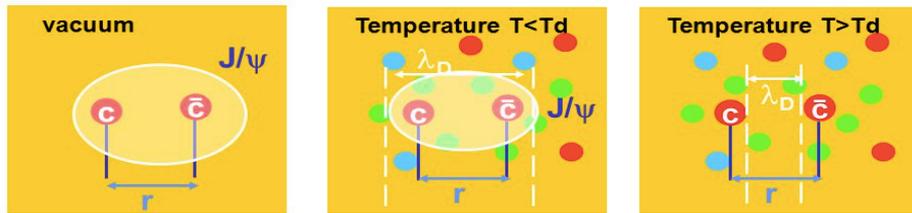
# *Why Quarkonium?*

- **Early creation:** experience entire evolution of quark-gluon plasma

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- **Proposed signature of deconfinement:** quark-antiquark potential 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*

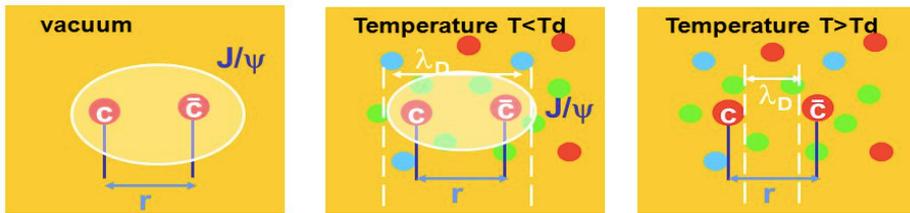


$$r_{q\bar{q}} \sim 1 / E_{binding} > r_D \sim 1 / T$$

# Why Quarkonium?

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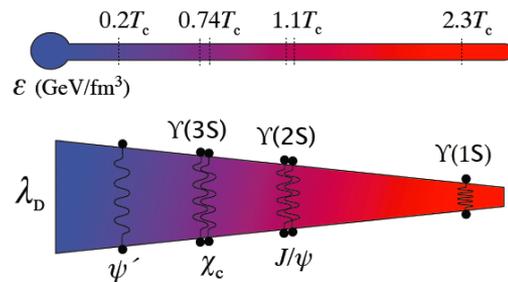
*T. Matsui and H. Satz  
PLB 178 (1986) 416*



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

- **“Thermometer”:** different states dissociate at different temperatures  $\rightarrow$  *sequential suppression*

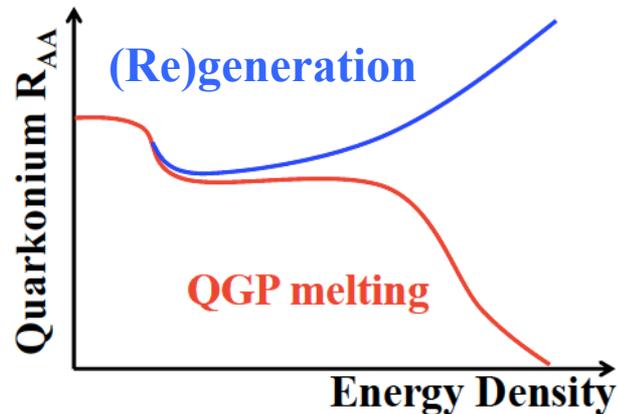
	J/ψ	ψ(2S)	Υ(1S)	Υ(2S)	Υ(3S)
E <sub>b</sub> (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200



# The Complications

## Other effects

- **(Re)generation**
  - *Deconfinement is a prerequisite*
  - Depend on species, energy,  $p_T$ , etc
- Medium-induced energy loss
  - Color-octet states; parton fragmentation
- Formation time
- **Feed-down contributions**



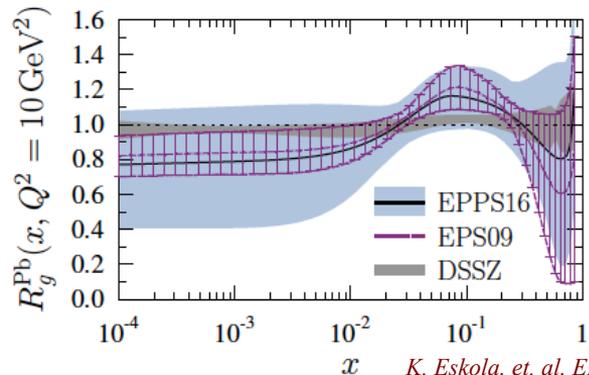
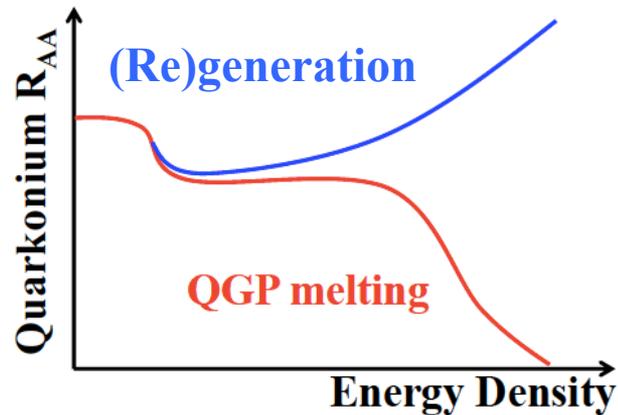
# The Complications

## Other effects

- **(Re)generation**
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  - Depend on species, energy,  $p_T$ , etc
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- Formation time
- **Feed-down contributions**

## Cold nuclear matter effects (CNM)

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



# *Experimental Quarkonium Talks at QM2018*

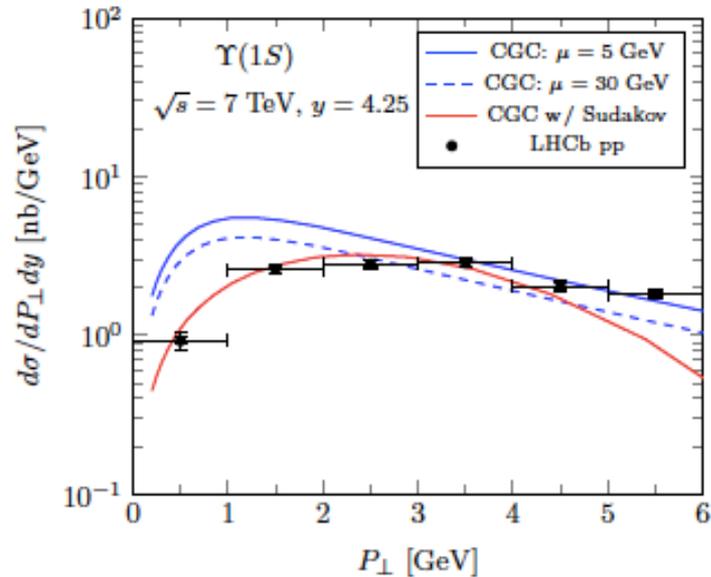
- Quarkonium measurements in nucleus-nucleus collisions with ALICE – [P. Dillenseger](#) (*Mon. 16:30*)
- Quarkonium production in p-A collisions with ALICE – [B. Paul](#) (*Wed. 16:50*)
- Probing QCD deconfinement with sequential quarkonium suppression of three  $\Upsilon(nS)$  states with the CMS detector – [S. Tuli](#) (*Tue. 11:30*)
- Beyond nPDF effects: prompt  $J/\psi$  and  $\psi(2S)$  production in pPb collisions with CMS – [G. Oh](#) (*Wed. 17:10*)
- Quarkonia production in large and small systems measured by ATLAS – [J. Lopez](#) (*Mon. 16:50*)
- Heavy Flavor production measurements in proton-lead and fixed target collisions at LHCb – [S. Chen](#) (*Tue. 12:50*)
- Upsilon Measurements in Au+Au Collisions at  $\sqrt{s_{NN}} = 200$  GeV with the STAR Experiment – [P. Wang](#) (*Tue. 11:10*)
- Recent Quarkonia Studies from the PHENIX Experiment – [J. Durham](#) (*Mon. 18:10*)

pp Collisions  
pA/dA Collisions  
AA Collisions

# Quarkonium Production in $pp$

Wed. 17:30  
K. Watanabe

## $\Upsilon(1S)$ in $p+p$ @ 7 TeV

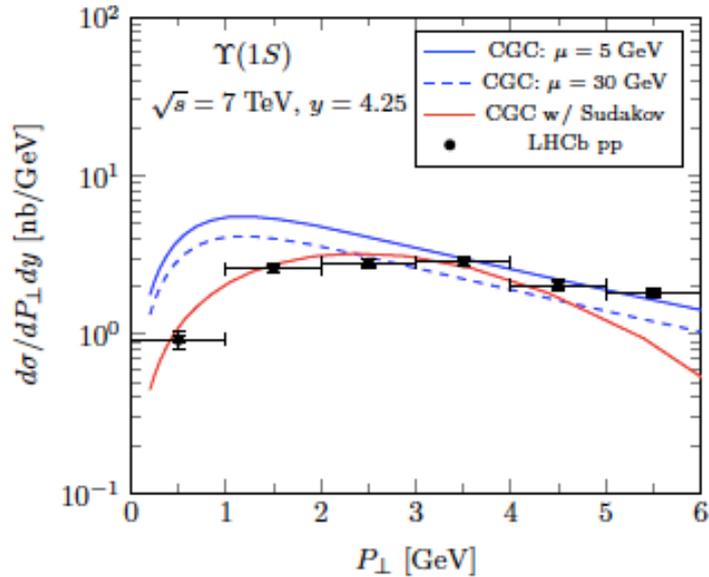


- CGC: addition of Sudakov summation can describe the  $\Upsilon(1S)$  production at low  $p_{\perp}$

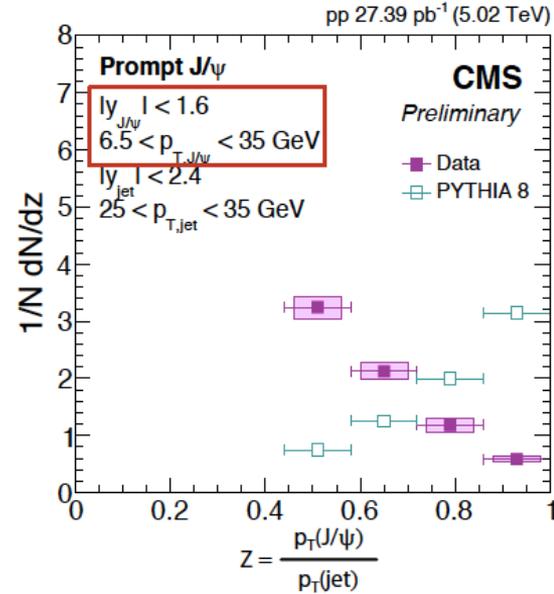
# Quarkonium Production in pp

Wed. 17:30  
K. Watanabe

## $\Upsilon(1S)$ in p+p @ 7 TeV



## $J/\psi$ FF in p+p @ 5.02 TeV



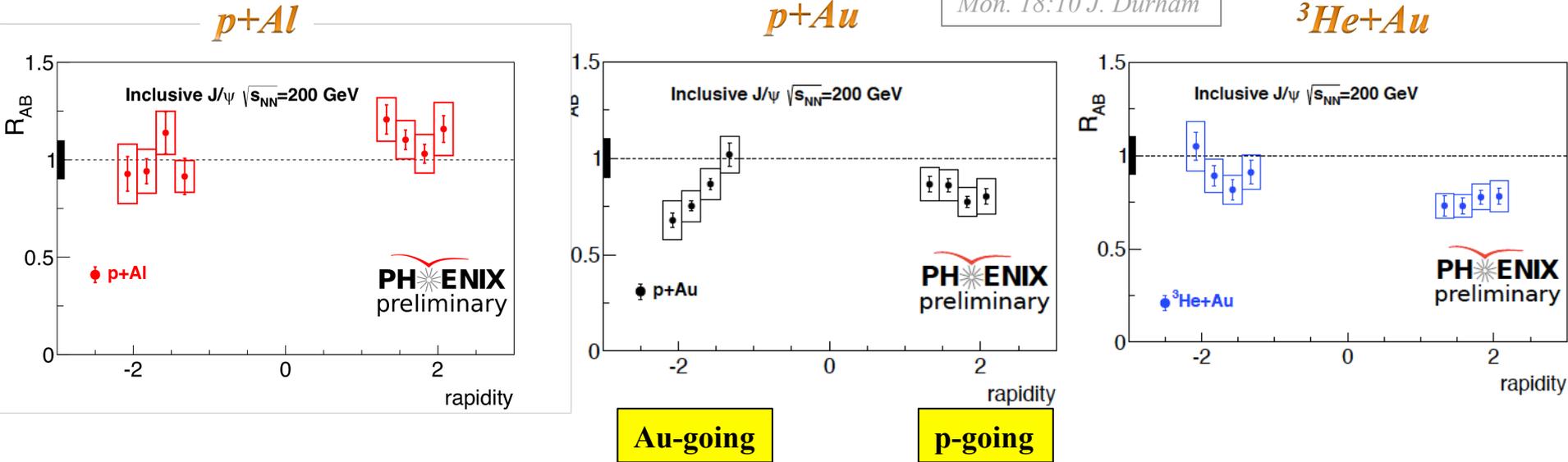
Wed. 17:10 G. Oh

- CGC: addition of Sudakov summation can describe the  $\Upsilon(1S)$  production at low  $p_T$
- $J/\psi$  production is accompanied by other hadrons
  - PYTHIA disagrees with data

pp Collisions  
**pA/dA Collisions**  
AA Collisions

# Large- $y$ $J/\psi$ in small system at RHIC

Mon. 18:10 J. Durham

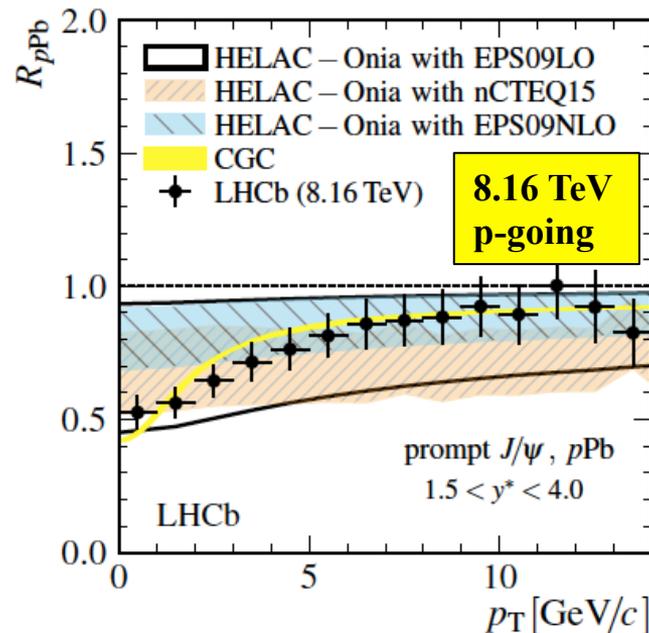
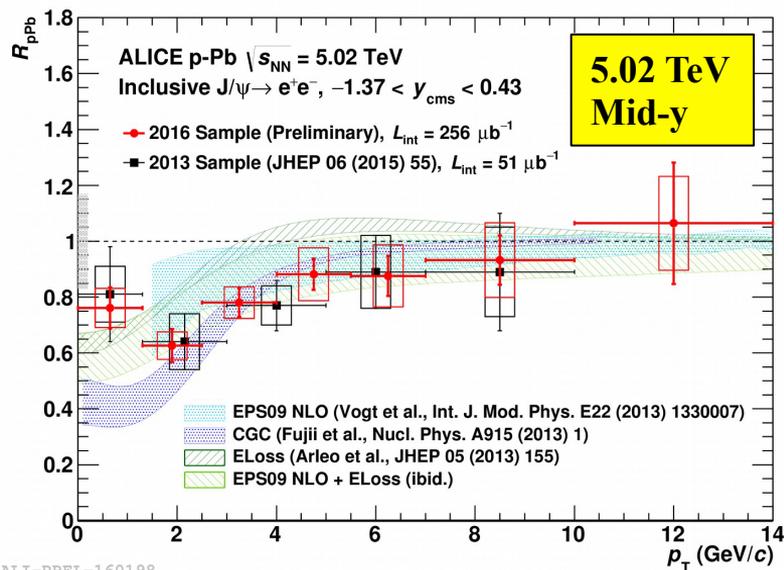


- **p/ $^3\text{He}$ -going:** about 10-20% suppression with Au nuclei. Consistent with shadowing expectation
- **Au/Al-going:** indication of suppression in p+Au collisions?

# $J/\psi$ Production in pPb

Wed. 16:50 B. Paul

Tue. 12:50 S. Chen



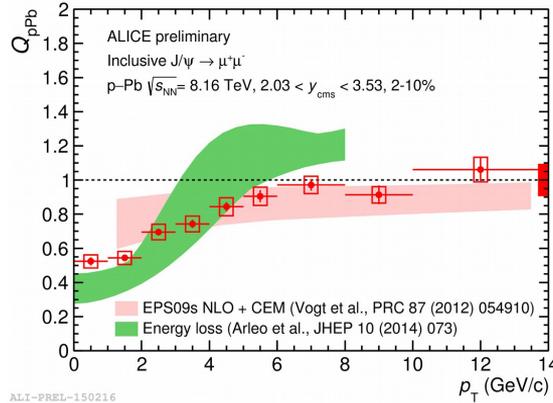
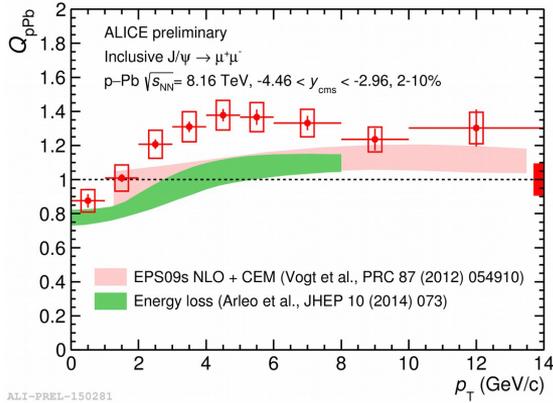
- Low  $p_T$ : significant suppression; High  $p_T$ : much smaller CNM effects
- While consistent with nPDF effects, data provide constraints on gluon distribution at low-x.

ALICE-PUBLIC-2018-007  
 LHCb: PLB 774 (2017) 159

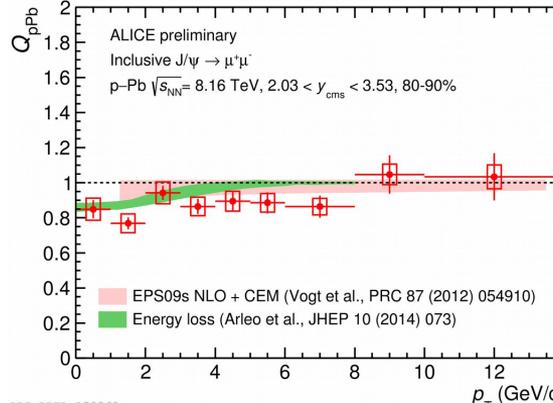
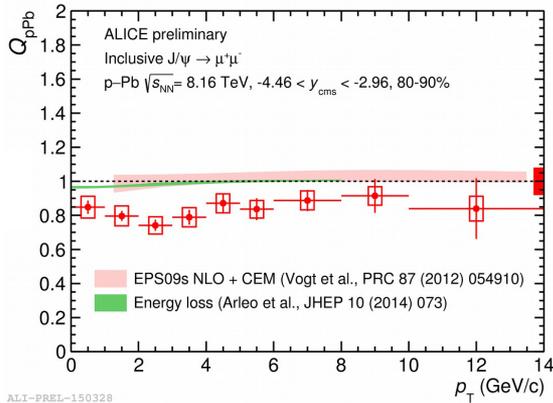
# $J/\psi$ $Q_{pPb}$ in Centrality Bins: data vs. model

Wed. 16:50 B. Paul

2-10%



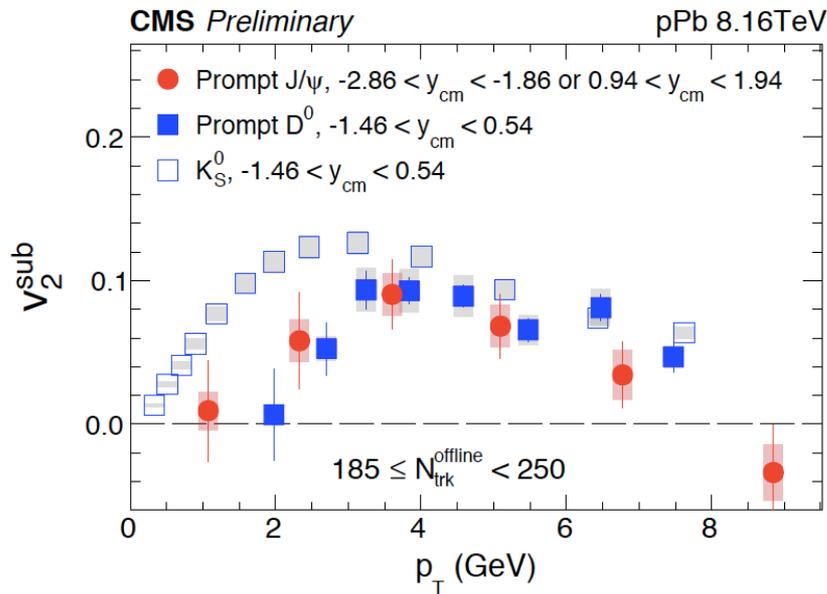
80-90%



- Models include nPDF or energy loss effects are not able to reproduce the  $J/\psi$  modification, especially for central pPb collisions.
- Need to go back to the drawing board

# $J/\psi$ Anisotropy in pPb

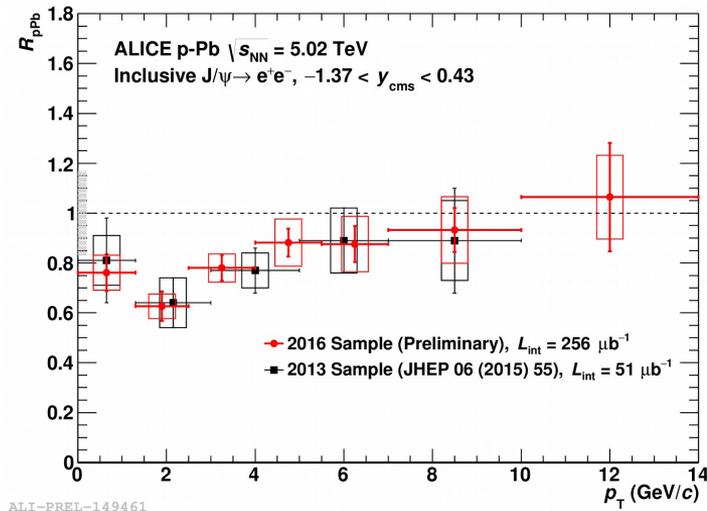
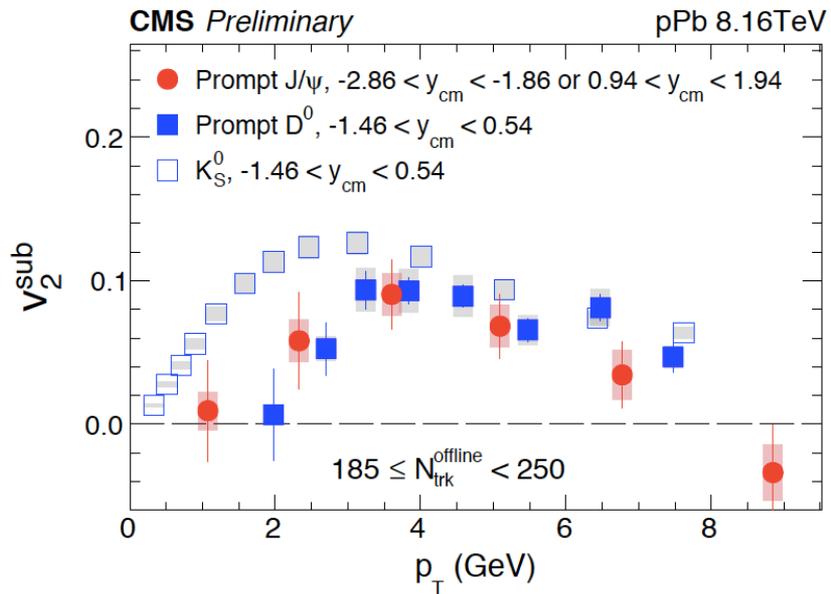
Wed. 17:10 G.Oh



- Significant  $J/\psi$   $v_2$  observed in  $2 < p_T < 7$  GeV/c in high-multiplicity pPb collisions

CMS: HIN-18-010  
ALICE: PLB 780 (2018) 7

# $J/\psi$ Anisotropy in pPb



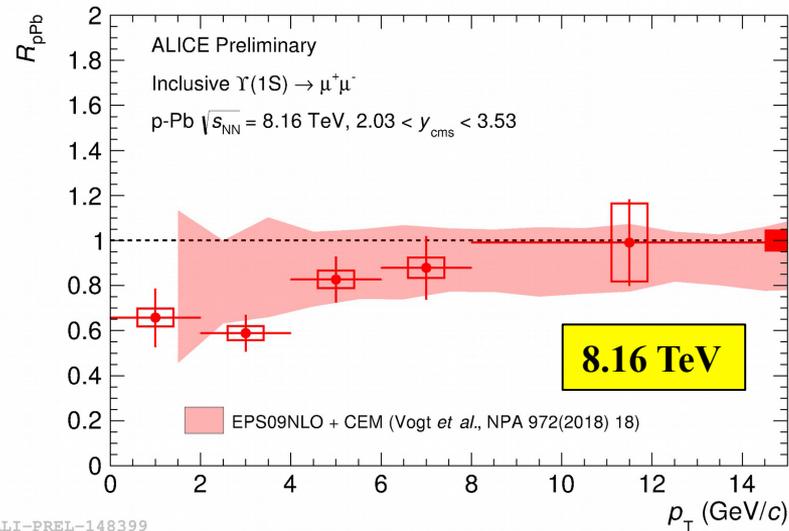
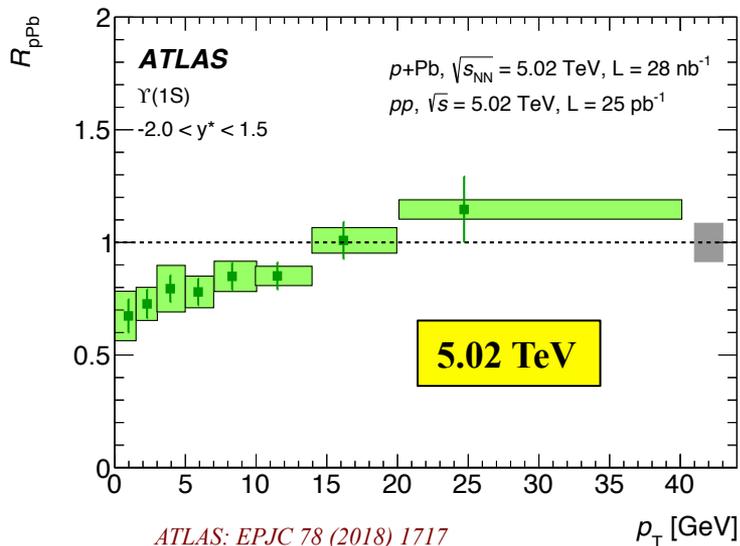
- Significant  $J/\psi$   $v_2$  observed in  $2 < p_T < 7$  GeV/c in high-multiplicity pPb collisions
- Same situation as other hard probes: large  $v_2$  but no significant suppression
  - *Is it flow or initial state effect or something else?*

CMS: HIN-18-010  
ALICE: PLB 780 (2018) 7

# $\Upsilon(1S)$ Suppressed in pPb

Mon. 16:50 J. Lopez

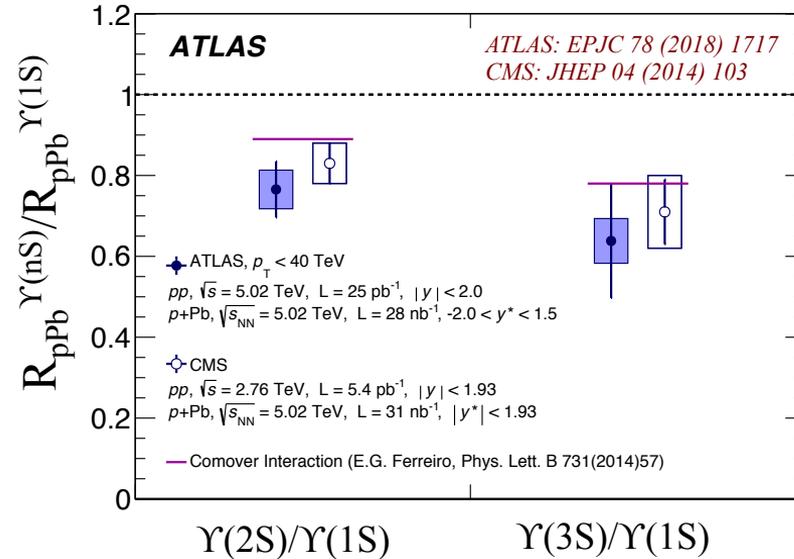
Wed. 16:50 B. Paul



- $\Upsilon(1S)$ : 30-40% suppression at low  $p_T$
- Need to be taken into account when interpreting results in PbPb collisions

# $\Upsilon(2S+3S)$ are More Suppressed

Mon. 16:50 J. Lopez



- Additional 25-35% suppression for excited states
- Final-state effects affect the ground and excited states differently

# $p+A$ Summary

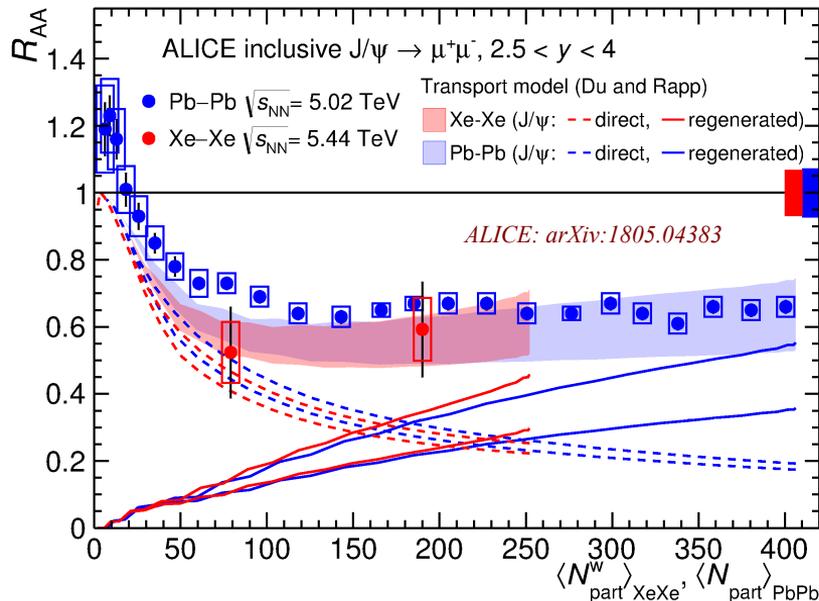
## pA collisions

- Significant suppression at low  $p_T$  for quarkonium
  - *Need to be taken into account when interpreting measurement in AA collisions*
  - Models (nPDF, energy loss) having difficulties to reproduce more differential measurements
- Excited quarkonium states more suppressed due probably to final-state effects
  - Needed for determine CNM effects for direct  $\Upsilon(1S)$
- Non-zero  $J/\psi$   $v_2$  observed in intermediate  $p_T$  region at the LHC energy
  - Collective motion for  $J/\psi$ . What is the origin?

pp Collisions  
pA/dA Collisions  
**AA Collisions**

# Low- $p_T$ $J/\psi$ in $Xe+Xe$

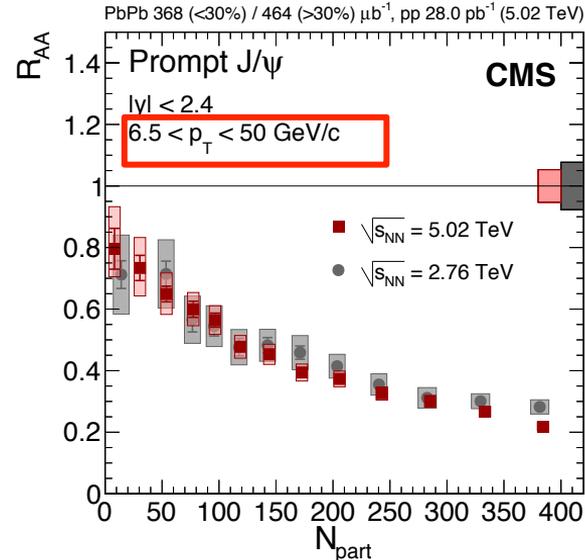
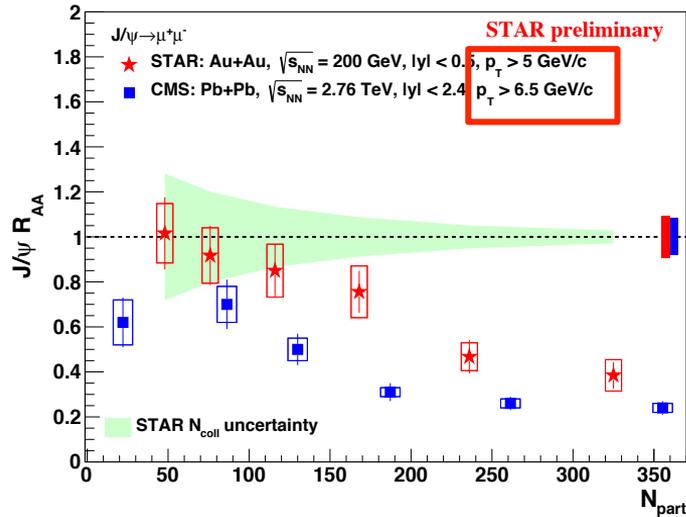
Mon. 16:30  
P. Dillenseger



- Similar level of suppression seen in  $Xe+Xe$  and  $Pb+Pb$
- Transport model consistent with data: interplay between dissociation and regeneration

# High- $p_T J/\psi$ : RHIC vs. LHC

CMS: JHEP 05 (2012) 063  
CMS: arXiv:1712.08959



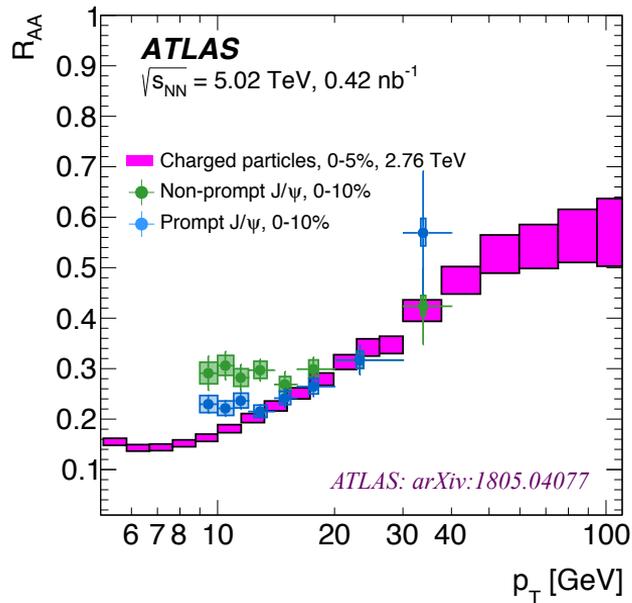
- Unlike low  $p_T$ ,  $R_{AA}$  decreases towards central collisions
  - CNM & regeneration effects small
- $R_{AA}^{RHIC} > \sim R_{AA}^{LHC/2.76TeV} > \sim R_{AA}^{LHC/5.02TeV}$



Dissociation  
In Effect

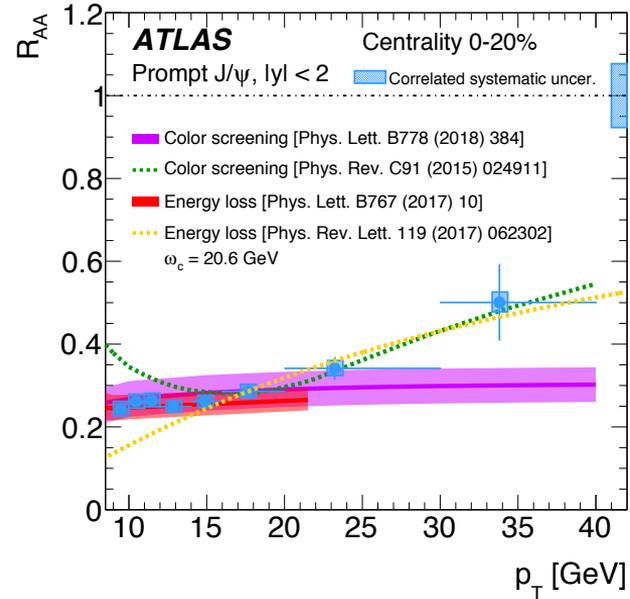
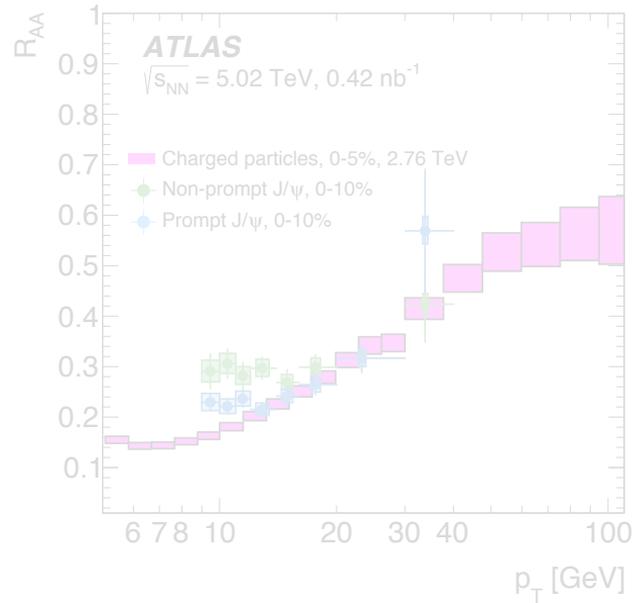
# High- $p_T$ $J/\psi$ : $R_{AA}$ vs. $p_T$

Mon. 16:50 J. Lopez



- An increasing trend is seen in  $J/\psi$   $R_{AA}$  vs.  $p_T$
- $J/\psi$   $R_{AA}$  follows charged-hadron  $R_{AA}$  above 12 GeV/c.

# High- $p_T$ $J/\psi$ : $R_{AA}$ vs. $p_T$

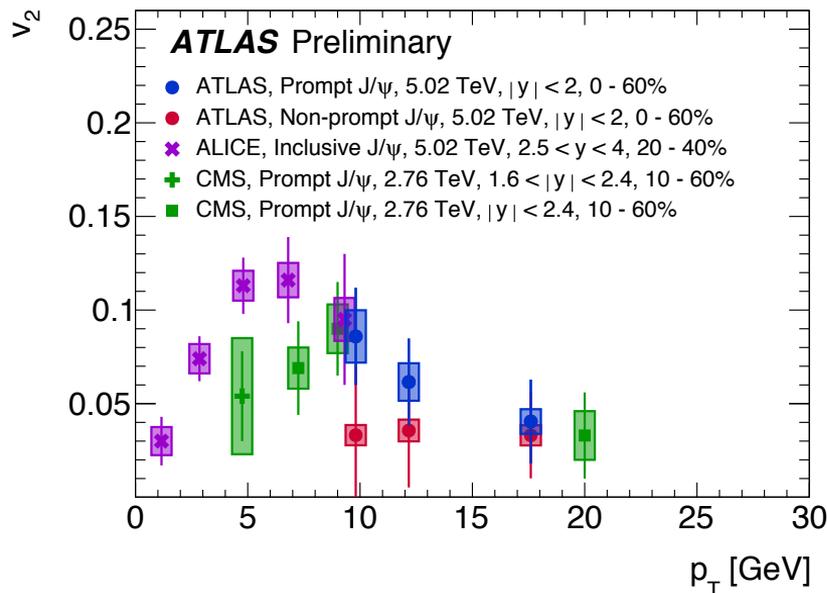


- Data are consistent with both color-screening and energy loss scenarios
- Data at higher  $p_T$  with better precision are crucial to distinguish between models

# LHC: $J/\psi$ $v_2$ vs. $p_T$

Mon. 16:30 P. Dillenseger

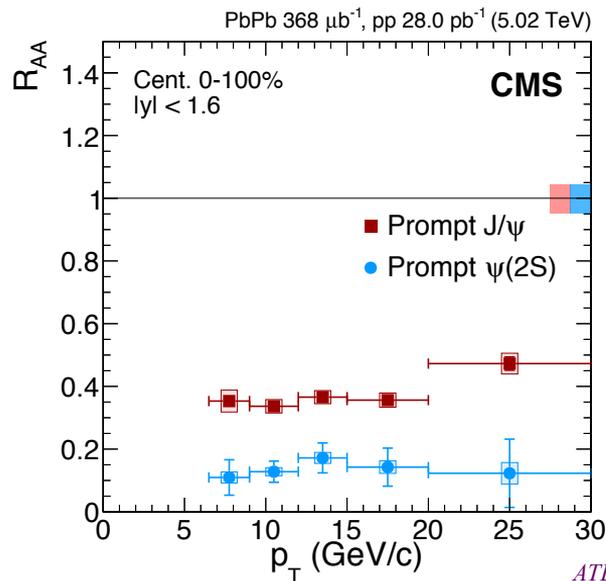
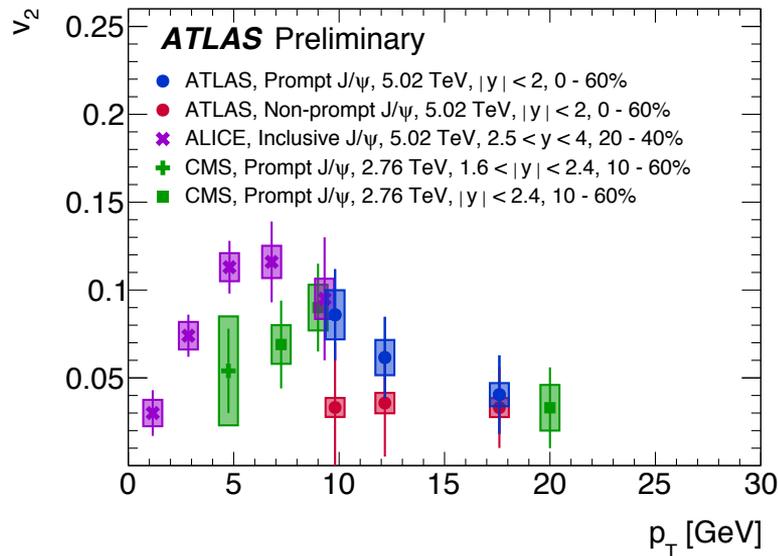
Mon. 16:50 J. Lopez



ATLAS-CONF-2018-013  
ALICE: PRL 119 (2017) 242301

- $J/\psi$   $v_2$  persists up to 20 GeV/c; not described by transport models
- Due to path-length dependence of parton energy loss?

# LHC: $J/\psi$ $v_2$ vs. $p_T$



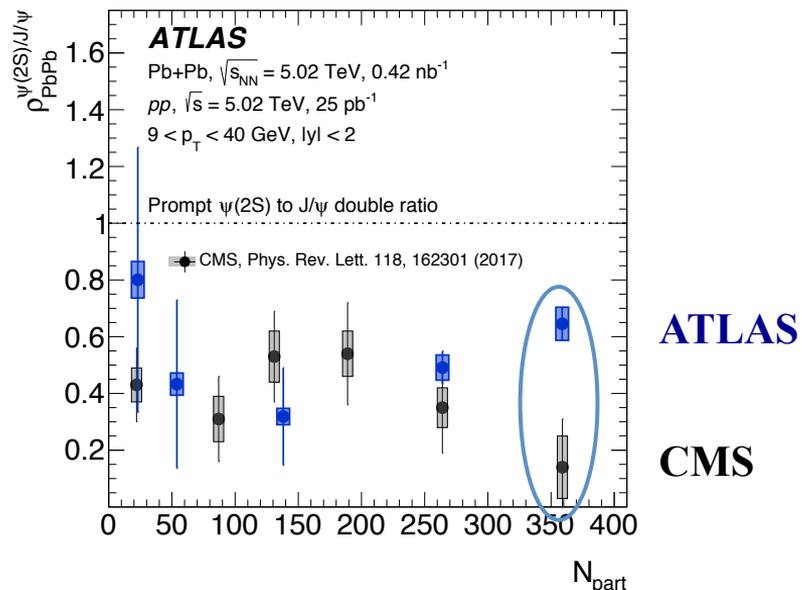
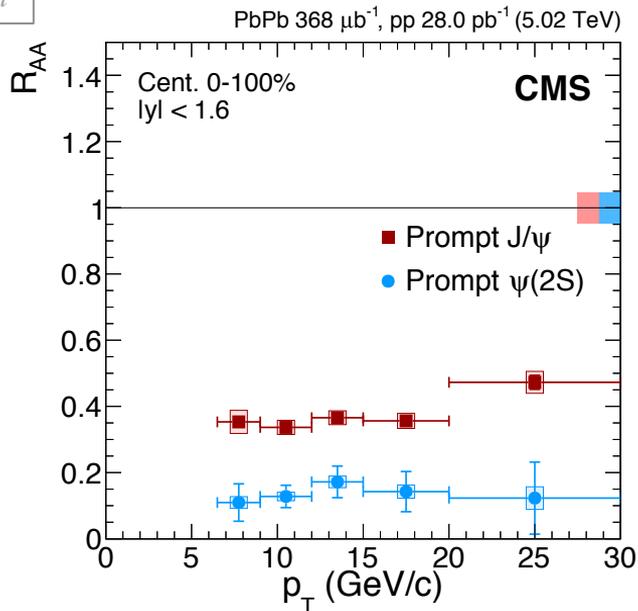
ATLAS-CONF-2018-013  
ALICE: PRL 119 (2017) 242301  
CMS: arXiv:1712.08959

- $J/\psi$   $v_2$  persists up to 20 GeV/c; not described by transport models
- Due to path-length dependence of parton energy loss?
- However, different suppression for  $\psi(2S)$  and  $J/\psi$  at high  $p_T$ . Hmmm ...

# Sequential Suppression for Charmonium

Wed. 17:10 G.Oh

Mon. 16:50 J. Lopez



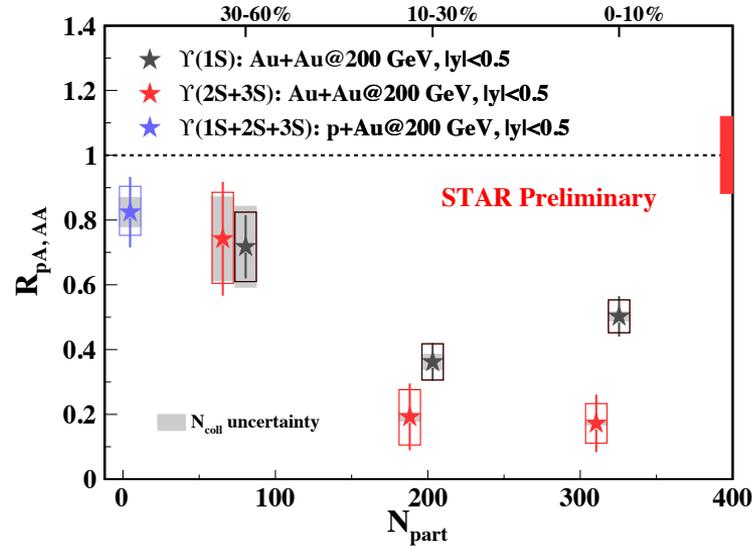
- $R_{AA}^{\psi(2\text{S})} < R_{AA}^{J/\psi}$  across  $p_T$  and cent. bins  $\rightarrow$  sequential suppression
- Tension in central collisions?

CMS: arXiv:1712.08959  
ATLAS: arXiv:1805.04077

# Sequential Suppression for Bottomonium

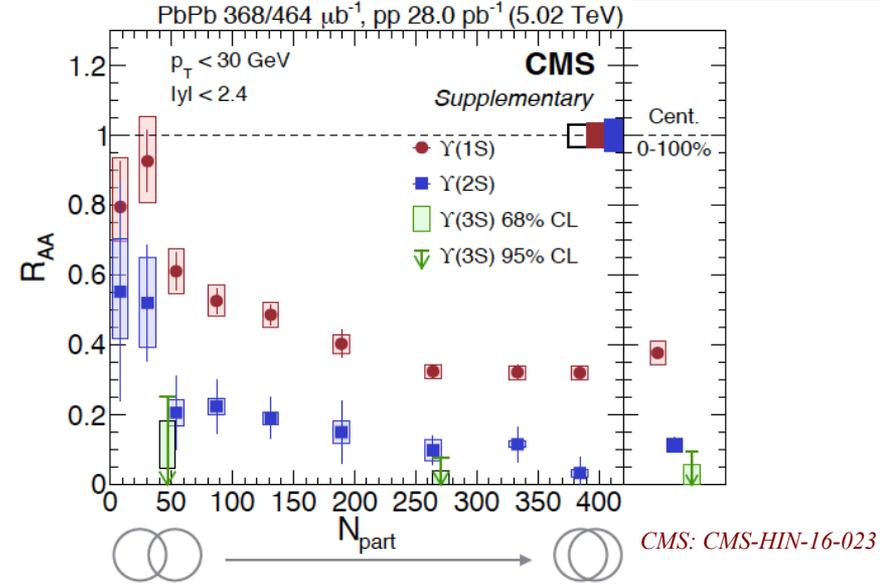
Tue. 11:10 P. Wang

**Au+Au @ 200 GeV**



Tue. 11:30 S. Tuli

**Pb+Pb @ 5.02 TeV**



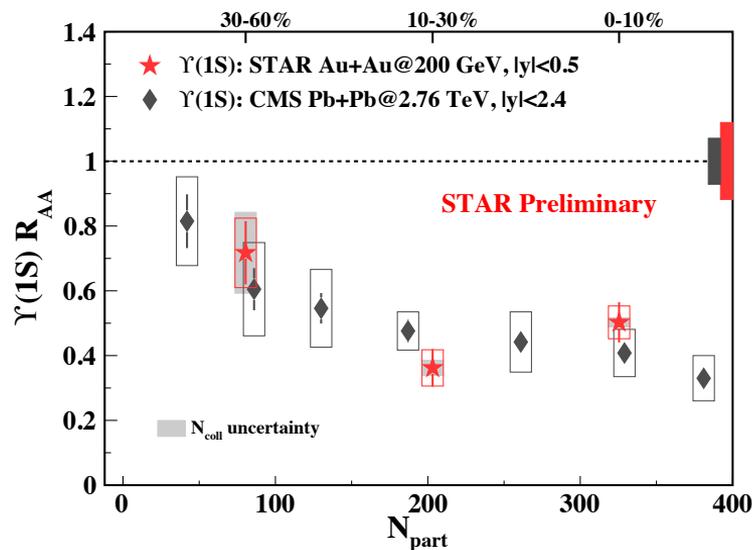
- $R_{AA}^{\text{peri}} > R_{AA}^{\text{cent}}$ : increasing hot medium effects
- RHIC:  $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)}$  in 0-10% central
- LHC:  $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$  in all centrality



**sequential  
suppression**

# Inclusive $\Upsilon(1S) R_{AA}$ : RHIC vs. LHC

0.2 TeV vs. 2.76 TeV

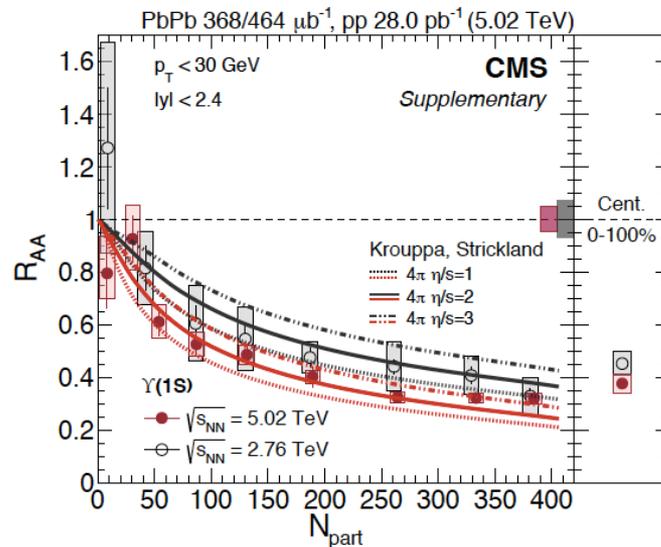
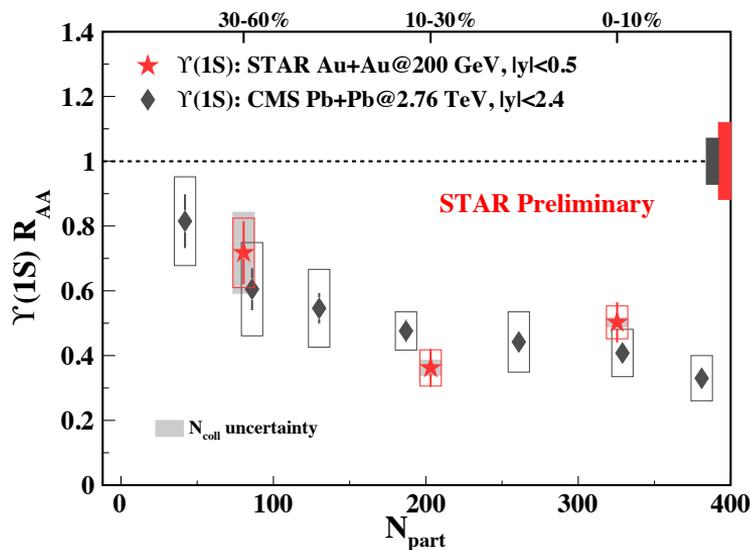


- $R_{AA}^{RHIC} \sim R_{AA}^{LHC/2.76\text{TeV}}$ : likely due to CNM + suppression of excited states

# Inclusive $\Upsilon(1S) R_{AA}$ : RHIC vs. LHC

0.2 TeV vs. 2.76 TeV vs. 5.02 TeV

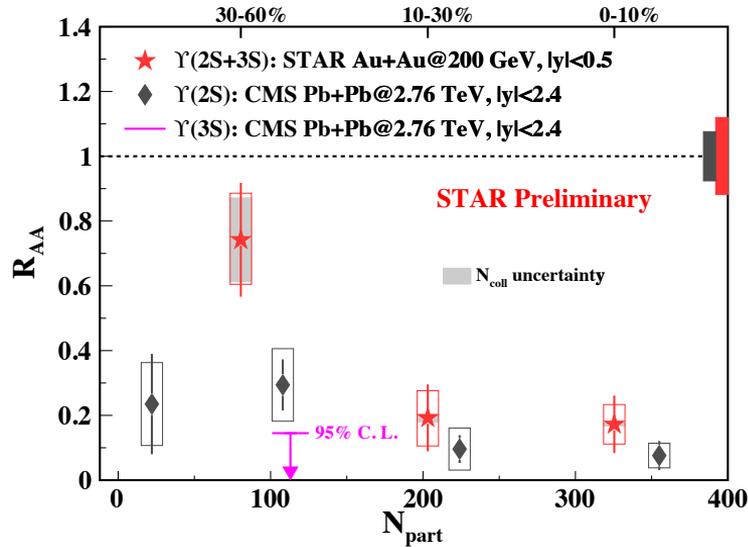
CMS: CMS-HIN-16-023  
CMS: PLB 770 (2017) 357



- $R_{AA}^{\text{RHIC}} \sim R_{AA}^{\text{LHC}/2.76\text{TeV}}$ : likely due to CNM + suppression of excited states
- $R_{AA}^{\text{LHC}/2.76\text{TeV}} > \sim R_{AA}^{\text{LHC}/5.02\text{TeV}}$ : onset of direct  $\Upsilon(1S)$  suppression?

# Excited $\Upsilon R_{AA}$ : RHIC vs. LHC

0.2 TeV vs. 2.76 TeV

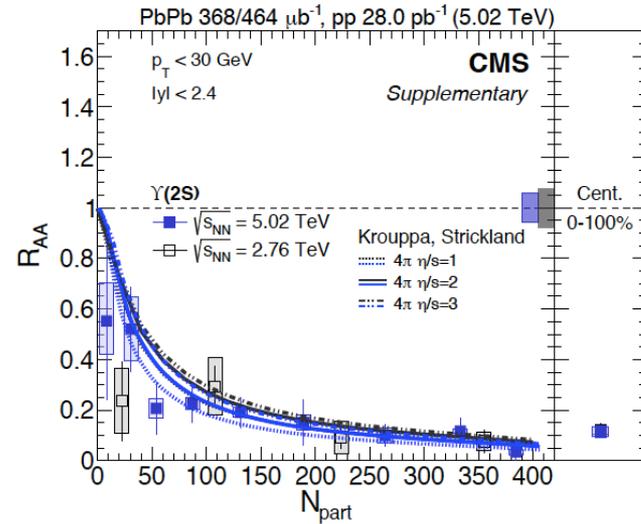
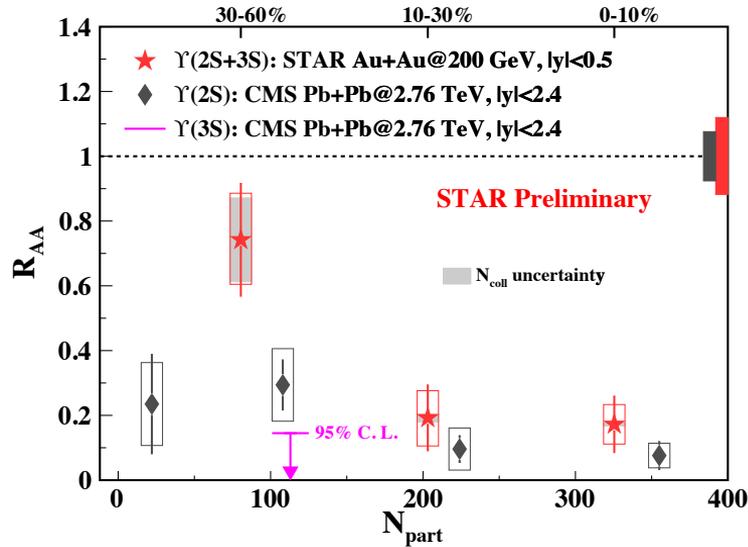


- $R_{AA}^{\text{RHIC}} > \sim R_{AA}^{\text{LHC}/2.76\text{TeV}}$ : indication of less melting at RHIC peripheral?

# Excited $\Upsilon R_{AA}$ : RHIC vs. LHC

0.2 TeV vs. 2.76 TeV vs. 5.02 TeV

CMS: CMS-HIN-16-023  
CMS: PLB 770 (2017) 357



- $R_{AA}^{\text{RHIC}} > \sim R_{AA}^{\text{LHC}/2.76\text{TeV}}$ : indication of less melting at RHIC peripheral?
- $R_{AA}^{\text{LHC}/2.76\text{TeV}} \sim R_{AA}^{\text{LHC}/5.02\text{TeV}}$ : complete dissociation in the medium

# *$\Upsilon$ Suppression: Data vs. TAMU model*

*X. Du, M. He, R. Rapp PRC 96 (2017) 054901*

- T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

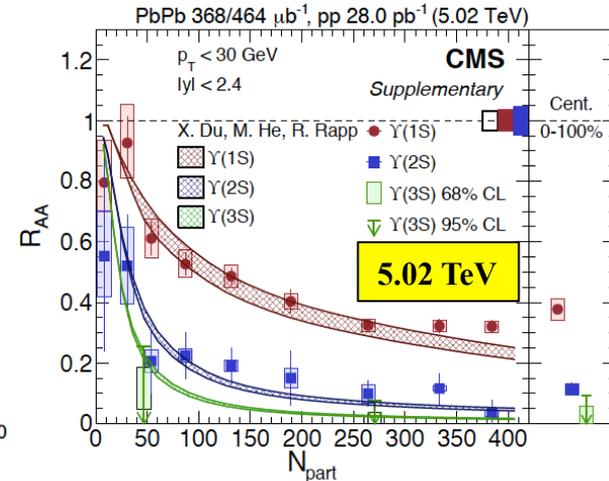
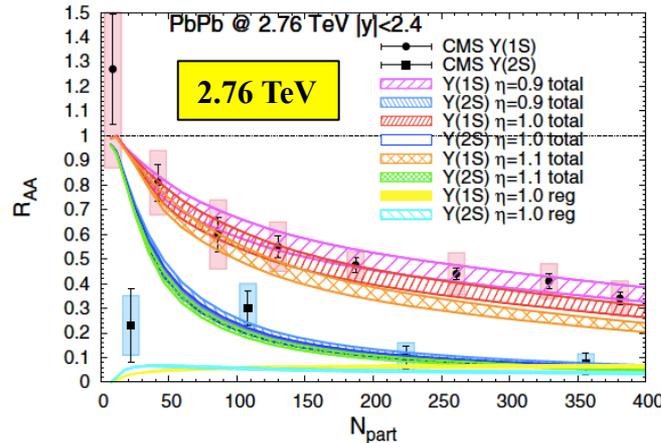
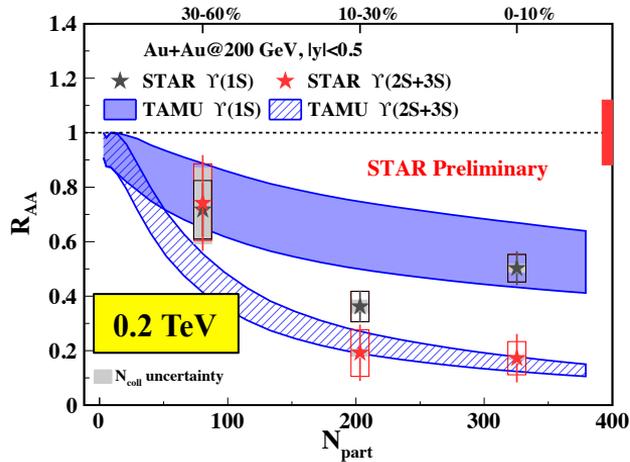
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sqrt{s}$ (TeV)	<b>0.2</b>	<b>2.76</b>	<b>5.02</b>
$T_{\text{disso}}$ (MeV)	500	240	190	$T_0^{\text{QGP}}$ (MeV)	310	555	594

# $\Upsilon$ Suppression: Data vs. TAMU model

X. Du, M. He, R. Rapp PRC 96 (2017) 054901

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	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sqrt{s}$ (TeV)	0.2	2.76	5.02
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- Good description of  $\Upsilon$  suppression from RHIC to LHC energies.

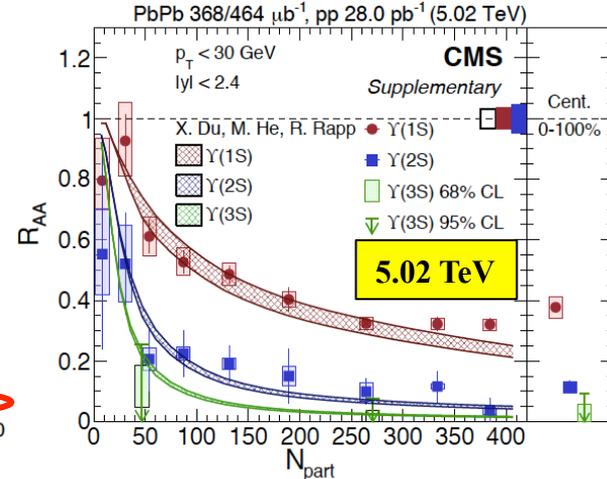
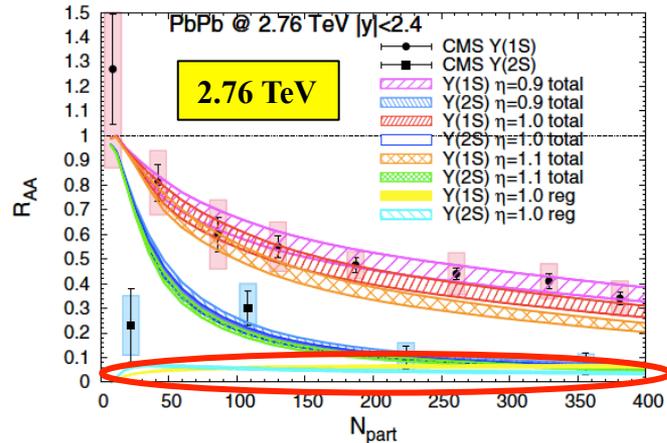
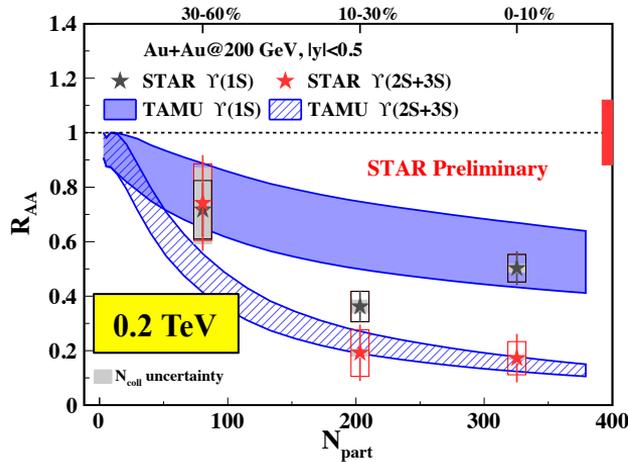
CMS: CMS-HIN-16-023  
CMS: PLB 770 (2017) 357

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X. Du, M. He, R. Rapp PRC 96 (2017) 054901

- T-dependent binding energy; Kinetic rate equation; Include CNM and regeneration

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sqrt{s}$ (TeV)	0.2	2.76	5.02
$T_{\text{disso}}$ (MeV)	500	240	190	$T_0^{\text{QGP}}$ (MeV)	310	555	594



- Good description of  $\Upsilon$  suppression from RHIC to LHC energies.
- Non-negligible regeneration, especially for  $\Upsilon(2S)$

CMS: CMS-HIN-16-023  
CMS: PLB 770 (2017) 357

# *$\Upsilon$ Suppression: Data vs. lattice-potential model*

*B. Krouppa, A. Rothkopf, M. Strickland  
PRD 97 (2018) 016017*

- Complex potential (lQCD); aHydro medium; No regeneration or CNM

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
$T_{\text{disso}}(\text{MeV})$	600	230	170

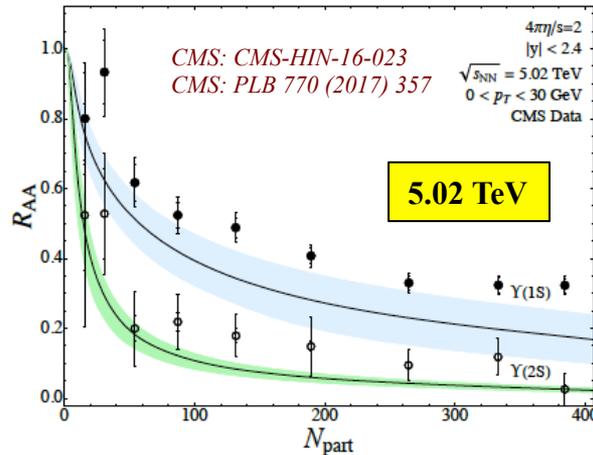
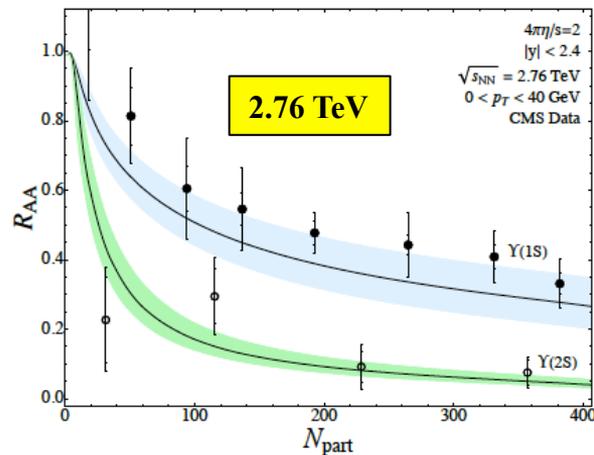
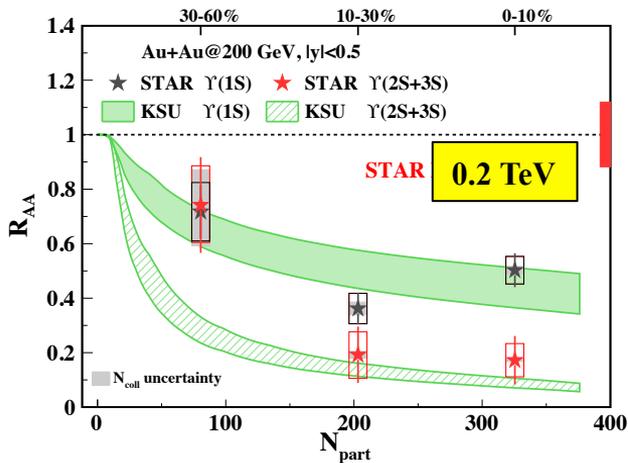
$\sqrt{s}$ (TeV)	<b>0.2</b>	<b>2.76</b>	<b>5.02</b>
$T_0^{\text{QGP}}(\text{MeV})$	440	545	632

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- Describe RHIC data reasonably well
- Lies consistently below the experimental data at LHC. Regeneration to rescue?

# AA Summary

## AA collisions

- Low  $p_T$ : new  $J/\psi$  data in Xe+Xe compatible with Pb+Pb  $\rightarrow$  **regeneration**
- High  $p_T$ : increasing suppression towards central collisions  $\rightarrow$  **dissociation**
- Even higher  $p_T$ : increasing  $R_{AA}$  and non-zero  $v_2$   $\rightarrow$  **similar to charged hadrons**
- **Multi-dimensional measurements of  $\Upsilon$  suppression from RHIC and LHC with improved precision  $\rightarrow$  sequential suppression**
  - Powerful tests to model calculations
- Hint of direct  $\Upsilon(1S)$  suppression at 5.02 TeV?

# *Discussion*

- **p+p: production mechanism still not fully understood**
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  - Need to think hard about the sizable  $J/\psi$   $v_2$

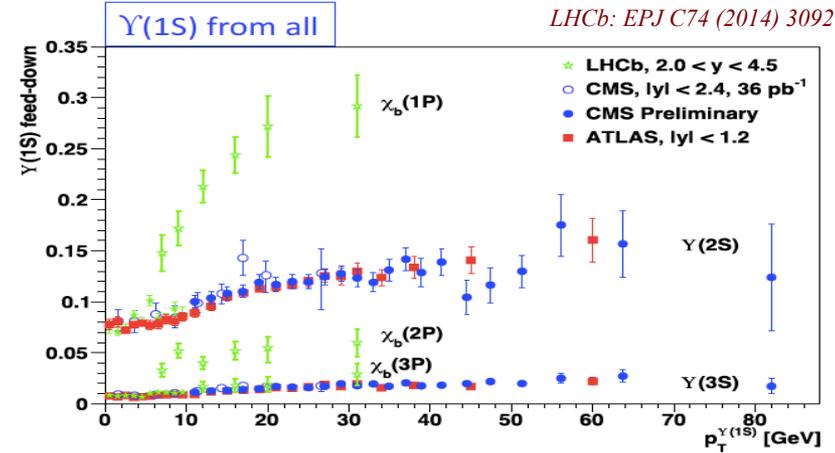
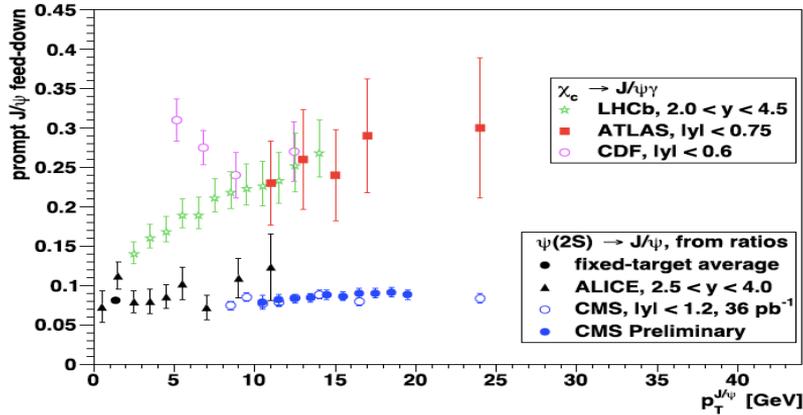
# Discussion

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- **p+A: CNM effects on quarkonium fairly well understood**
  - Need to think hard about the sizable  $J/\psi$   $v_2$
- **A+A: are we in a position to extract medium temperature?**
  - Better control of feed-down contribution & further reduce uncertainties on heavy quark cross section
  - New observables, e.g.  $J/\psi$  polarization,  $\Upsilon$   $v_2$ , etc may shed more lights
  - Precision measurements of individual  $\Upsilon$  states at both RHIC and LHC are in the planning.

# Backup

# And the Feed-down Contribution

Woehri@Quarkonia'14

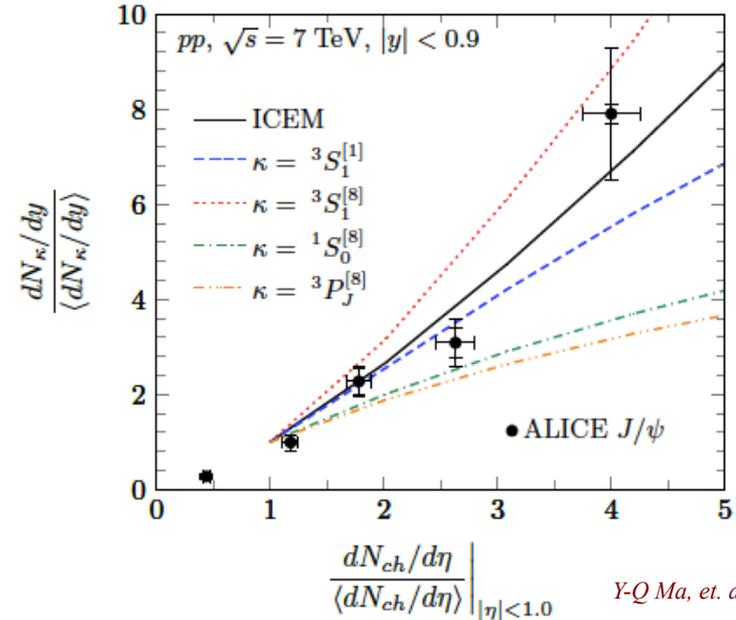
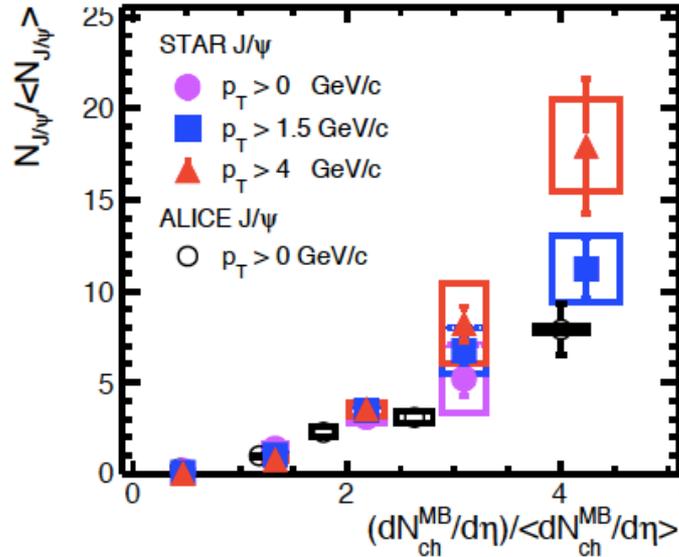


LHCb: EPJ C74 (2014) 3092

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

Y(1S) feed-down	
$\chi_b(1P)$	10-30% (vs. $p_T$ )
$\chi_b(2P+3P)$	~5%+1-2%
$Y(2S+3S)$	8-13%+1-2%

# *J/ψ Production vs. Event Activity*



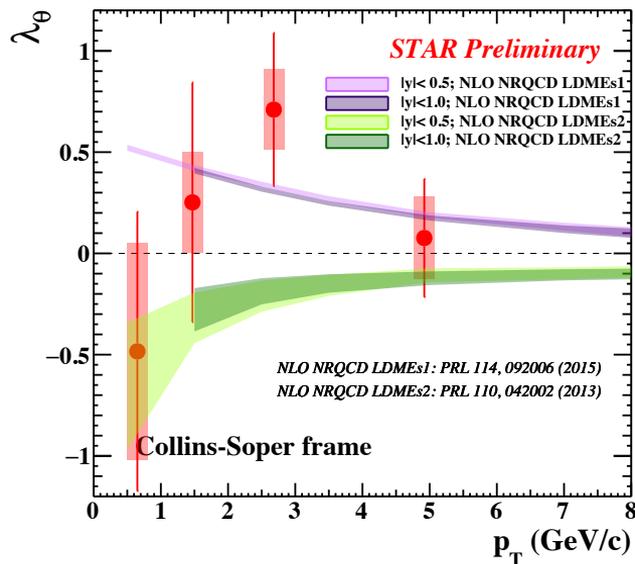
STAR: arXiv:1805.03745

Y-Q Ma, et. al, 1803.11093

- Strong increase of J/ψ production vs. event activity with weak  $\sqrt{s}$  dependence
- CGC+ICEM model can reproduce the trend → different intermediate states have different trends

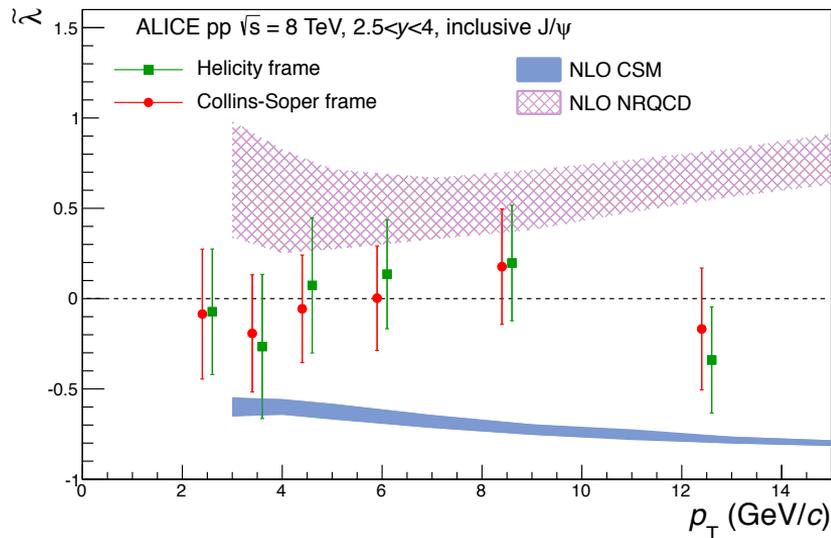
# $J/\psi$ Polarization

$p+p @ 200 \text{ GeV}$



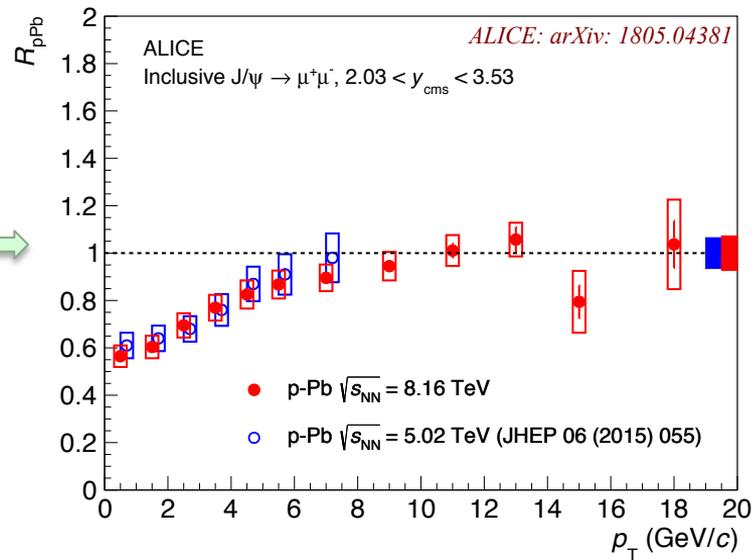
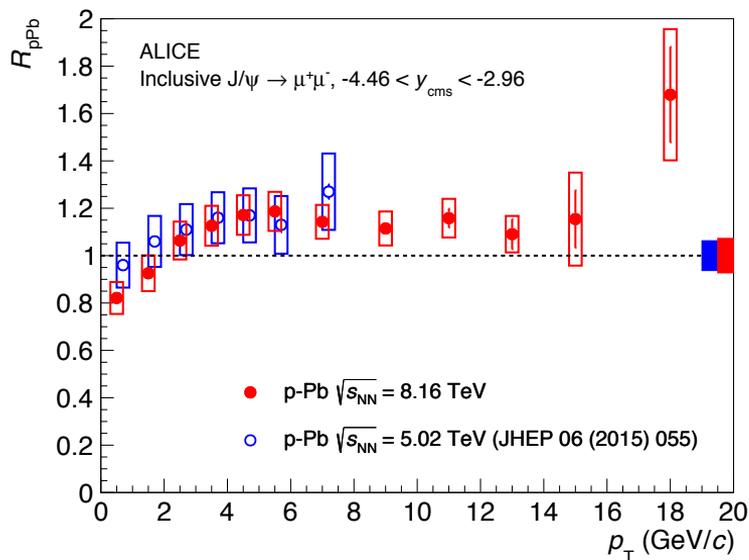
$p+p @ 8 \text{ TeV}$

ALICE: arXiv:1805.04374



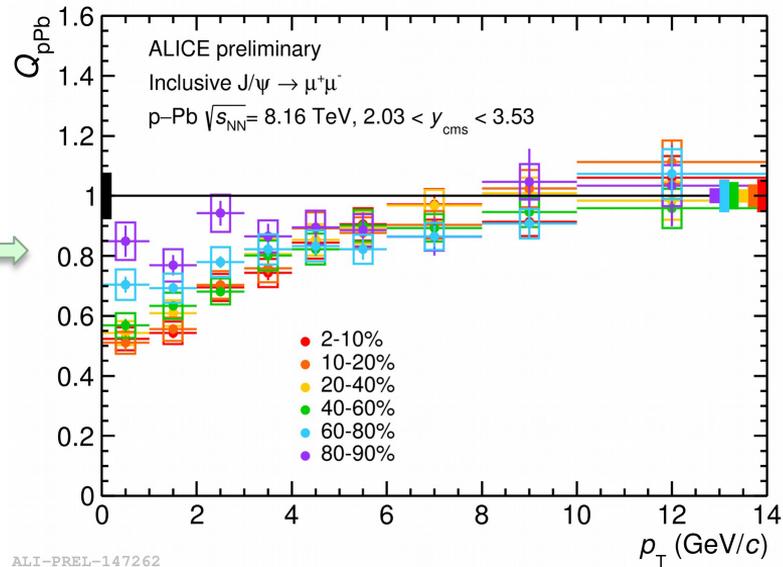
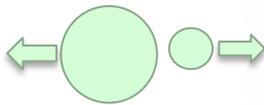
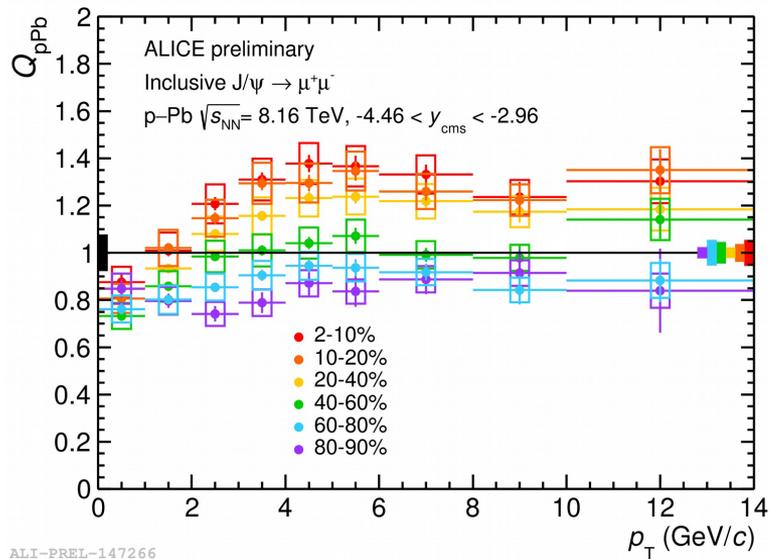
- Very different polarization predictions for different models
- Measurements of better precision are essential

# $J/\psi$ Production in pPb at LHC



- A slightly enhancement shows up at backward-y above 3 GeV/c while strong suppression at forward-y below 6 GeV/c
- No visible energy dependence. Saturation of CNM?

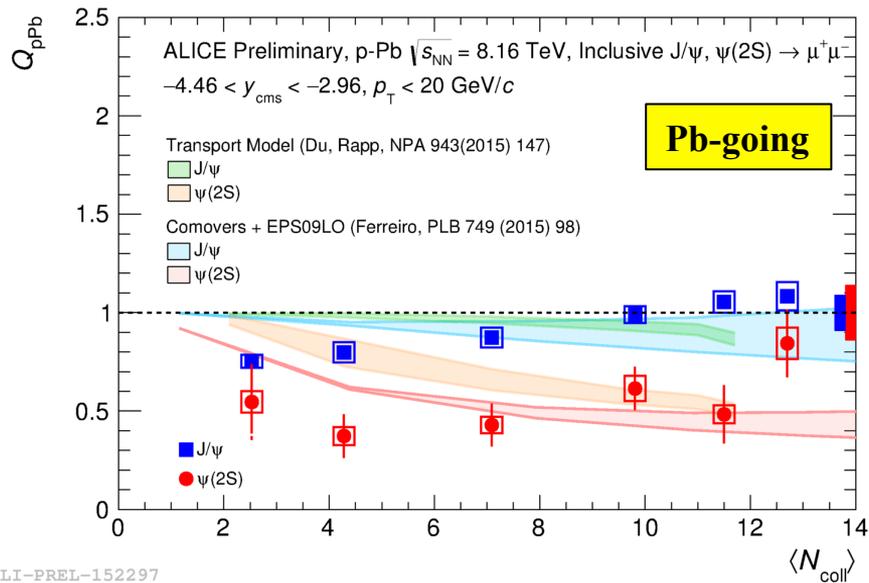
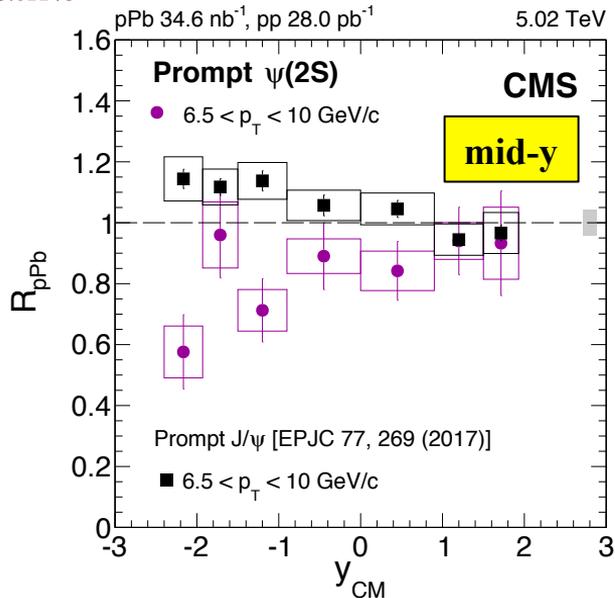
# $J/\psi$ $Q_{pPb}$ vs. $p_T$ in Centrality Bins



- Clear trend in different centrality bins
  - Backward-y: suppression to enhancement from peripheral to central collisions
  - Forward-y: stronger suppression at low  $p_T$  in central collisions, while  $Q_{pPb} \sim 1$  for high  $p_T$  in all centrality bins.

# $\psi(2S)$ Suppression in 5.02 TeV pPb

CMS: arXiv:1805.02248

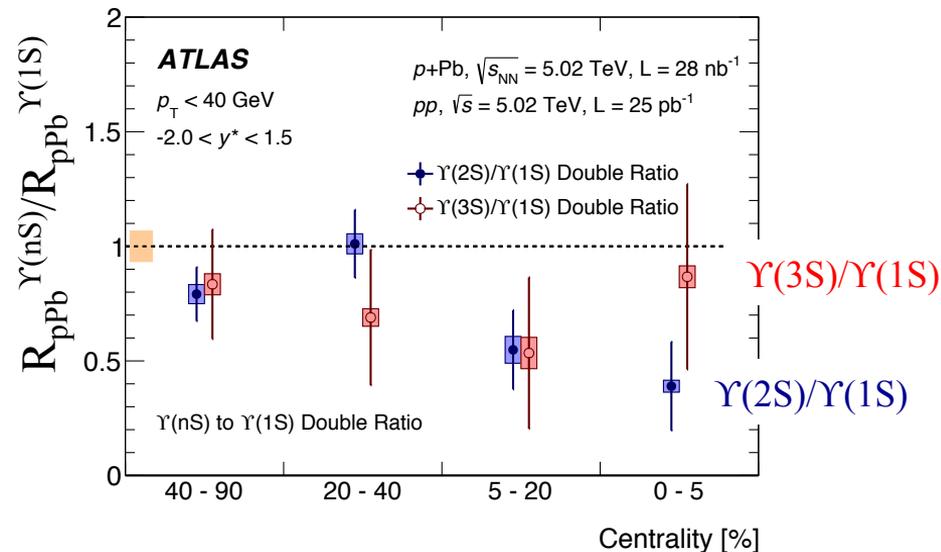
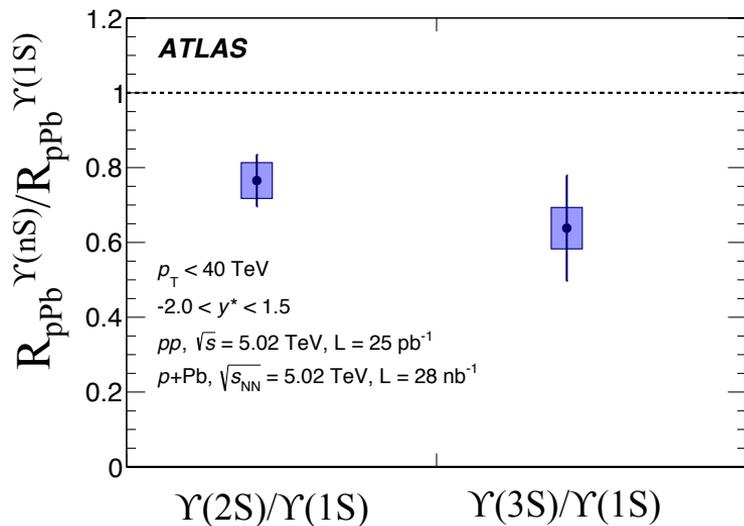


- $R_{pPb}^{\psi(2S)} < R_{pPb}^{J/\psi}$  at high-multiplicity regions (central-y, Pb-going)
- Final-state effects needed to account for the additional suppression
- Co-mover and transport models describe data qualitatively, but not quantitatively

# $\Upsilon(2S+3S)$ are More Suppressed

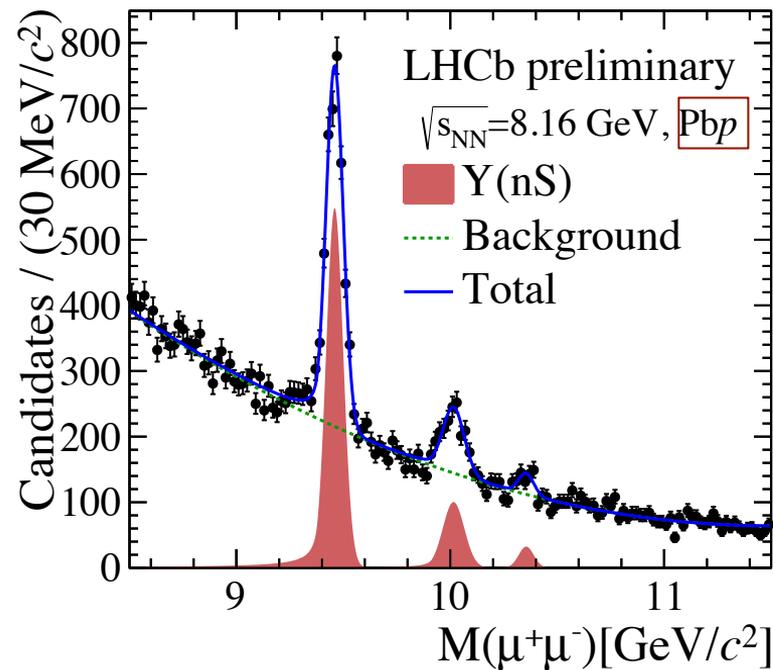
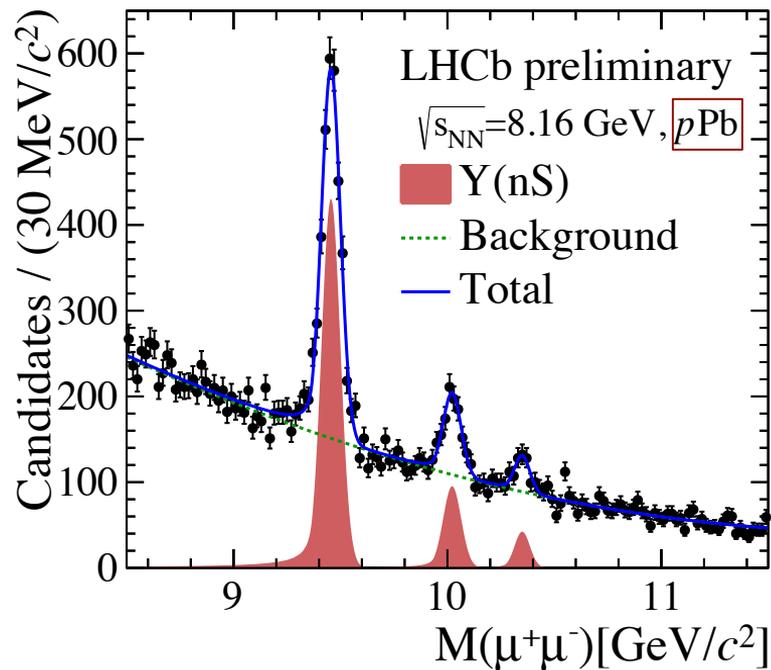
Mon. 16:50 J. Lopez

ATLAS: EPJC 78 (2018) 1717



- **Additional 25-35% suppression for excited states**; larger suppression in central collisions
- Final-state effects affect the ground and excited states differently

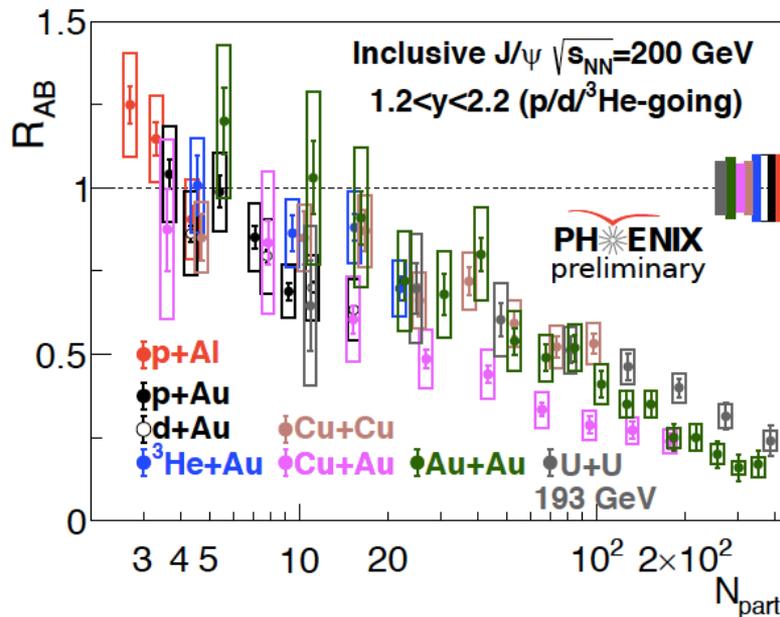
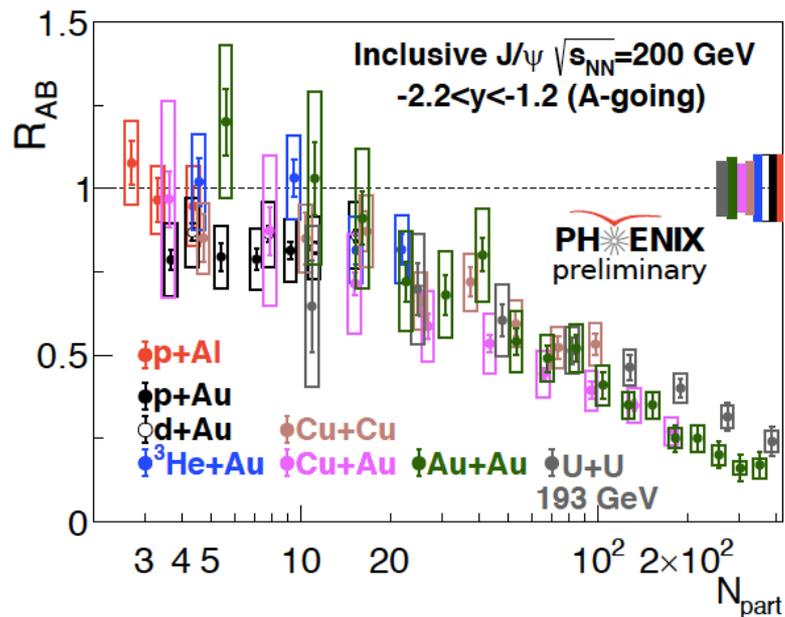
# *LHCb will Contribute*



- Clean separation of three  $\Upsilon$  states in pPb and Pbp collisions
- Looking forward to precise measurement of CNM effects at large rapidity

# $J/\psi R_{AA}$ vs. $N_{part}$ at RHIC

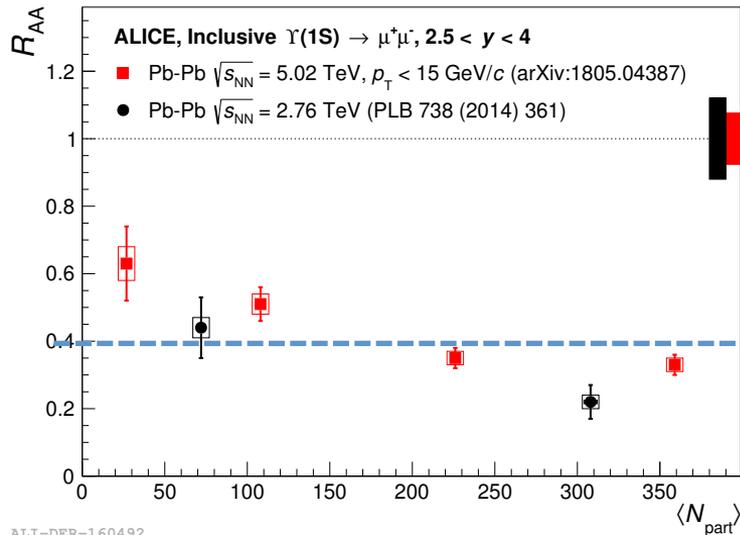
Mon. 18:10 J. Durham



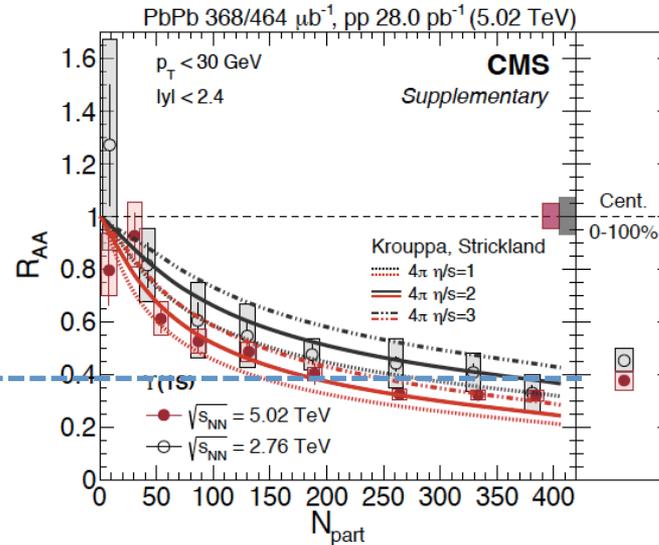
- A scaling of  $J/\psi R_{AA}$  vs.  $N_{part}$  is seen at both forward and backward rapidities

# Inclusive $\Upsilon(1S)$ $R_{AA}$ : Forward vs. Mid

*forward-y*



*Mid-y*

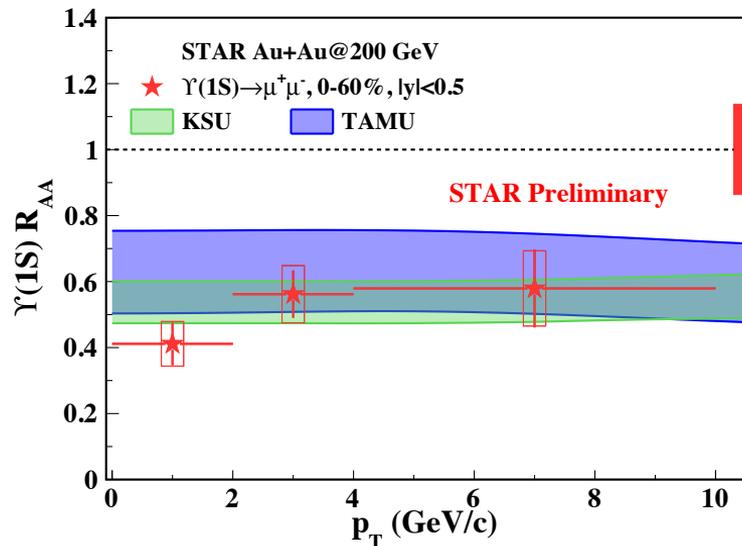


CMS: CMS-HIN-16-023  
CMS: PLB 770 (2017) 357

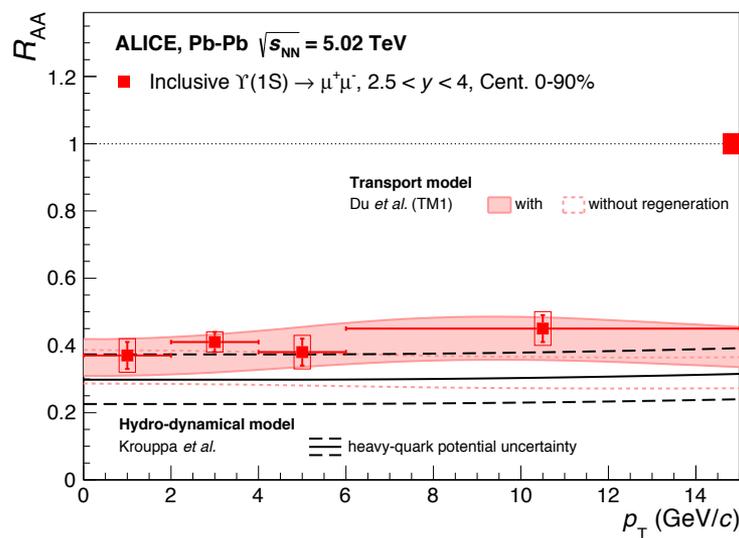
- Seems different energy dependence at forward rapidity
- But the uncertainties are relatively large

# $\Upsilon(1S) R_{AA}$ vs. $p_T$ : Data vs. Model

0.2 TeV



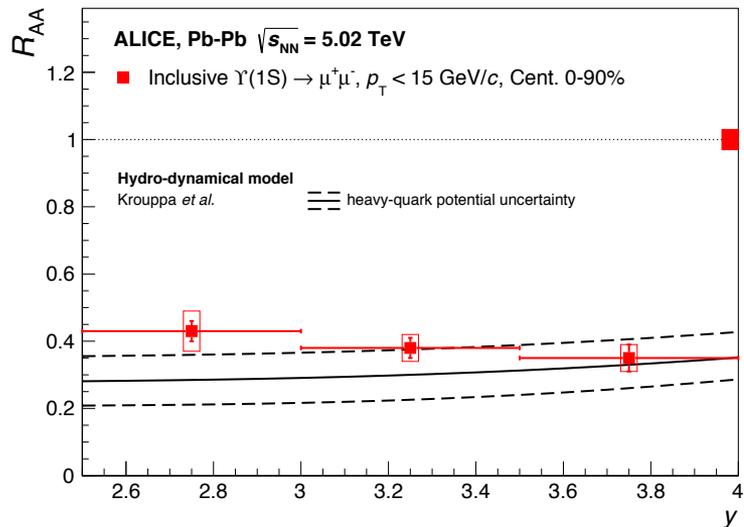
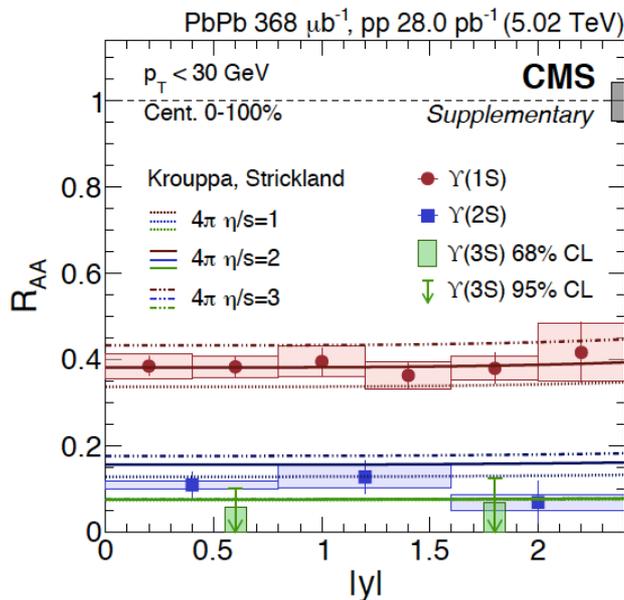
5.02 TeV



- No strong  $p_T$  dependence at both RHIC and LHC
- Models can well reproduce the shape

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X. Du, M. He, R. Rapp PRC 96 (2017)  
054901  
ALICE: arXiv:1805.04387*

# $\Upsilon(1S) R_{AA}$ vs. Rapidity at 5.02 TeV



- Interplay between dissociation and regeneration changes vs.  $y$
- No strong rapidity dependence at 5.02 TeV PbPb collisions