

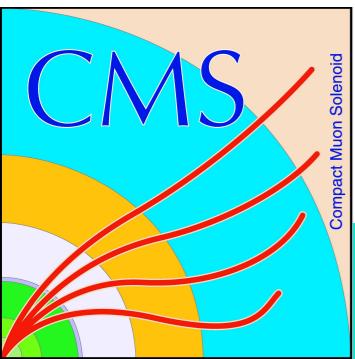
Probing QCD deconfinement with sequential quarkonium suppression of three $\Upsilon(nS)$ states with the CMS detector

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CMS Collaboration

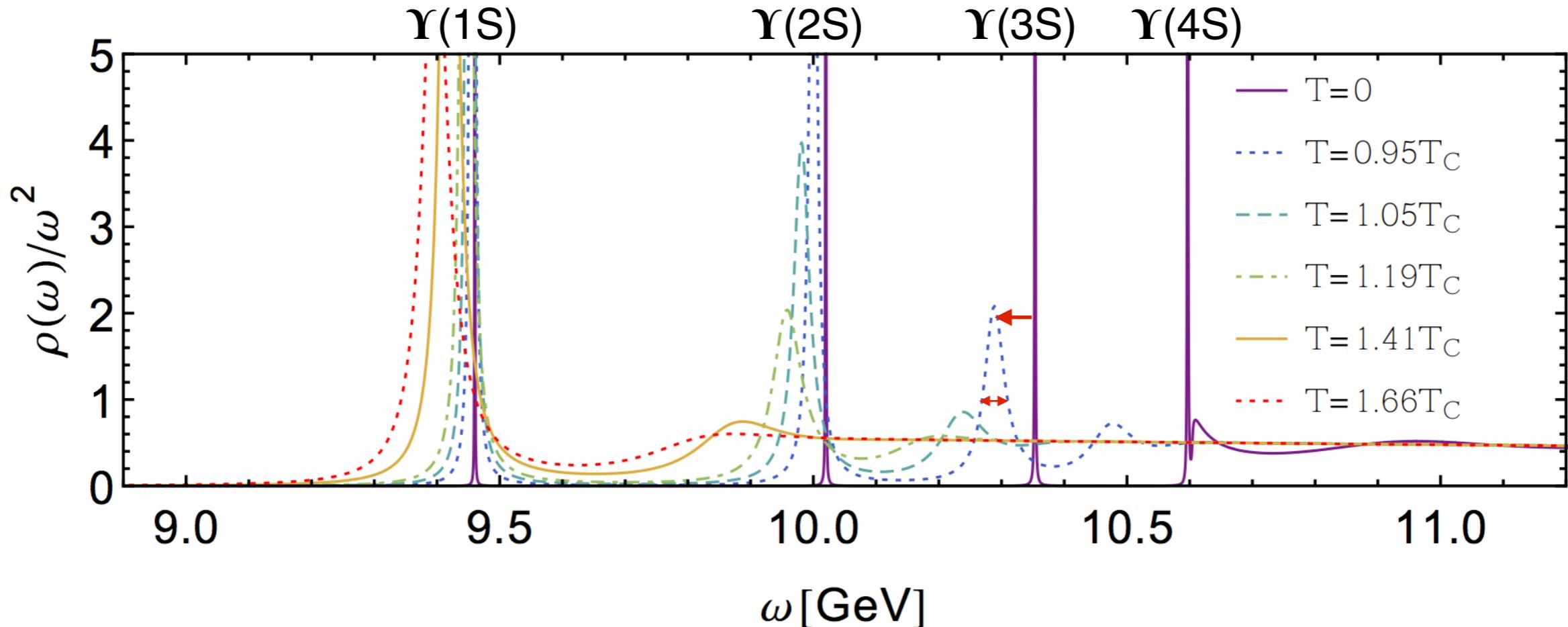
15th May, 2018

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Sequential melting of bottomonia

Spectral functions of bottomonium states in the QGP at various temperatures:



[Burnier, Y., Kaczmarek, O. & Rothkopf, A. J. High Energ. Phys. \(2015\) 2015: 1.](#)

- As temperature increases:
 - The **peaks broaden** and their **masses shift to lower values**.
 - Highest states broaden and shift first, followed **sequentially** by lower states.
 - Peaks eventually disappear completely —> States melt.
- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ melt at $2.66T_c$, $1.25T_c$ and $1.01T_c$.
- **Sequential melting of Υ states is sensitive to color deconfinement!**



Measuring Υ modification

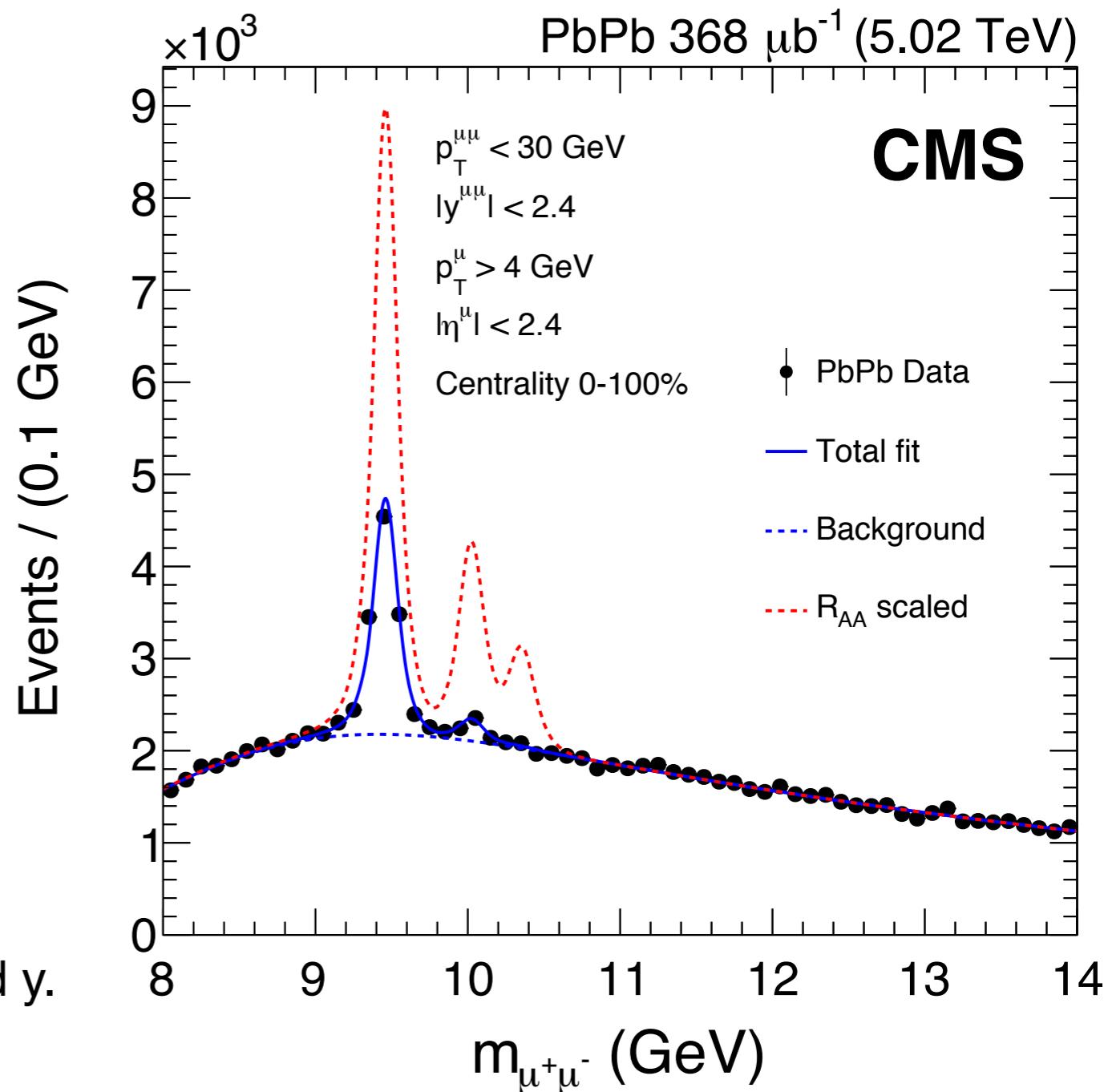
Study $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ modification in PbPb compared to pp at 5.02 TeV.

- Using dimuon decay channel.
- Suppression is quantified using:

$$R_{AA} = \frac{\left(\frac{\Upsilon(nS)}{N_{Events}^{MB}}\right)_{PbPb}}{\left(\frac{\Upsilon(nS)}{N_{Events}^{MB}}\right)_{pp}} \frac{1}{\langle N_{coll} \rangle}$$

Clear suppression of all three Υ states in PbPb!

- Explore R_{AA} as a function of centrality, p_T and y .
- Compare to theoretical models.
- Compare to 2.76 TeV data.



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RAA VS. collision centrality

Suppression of all three states across various levels of centrality.

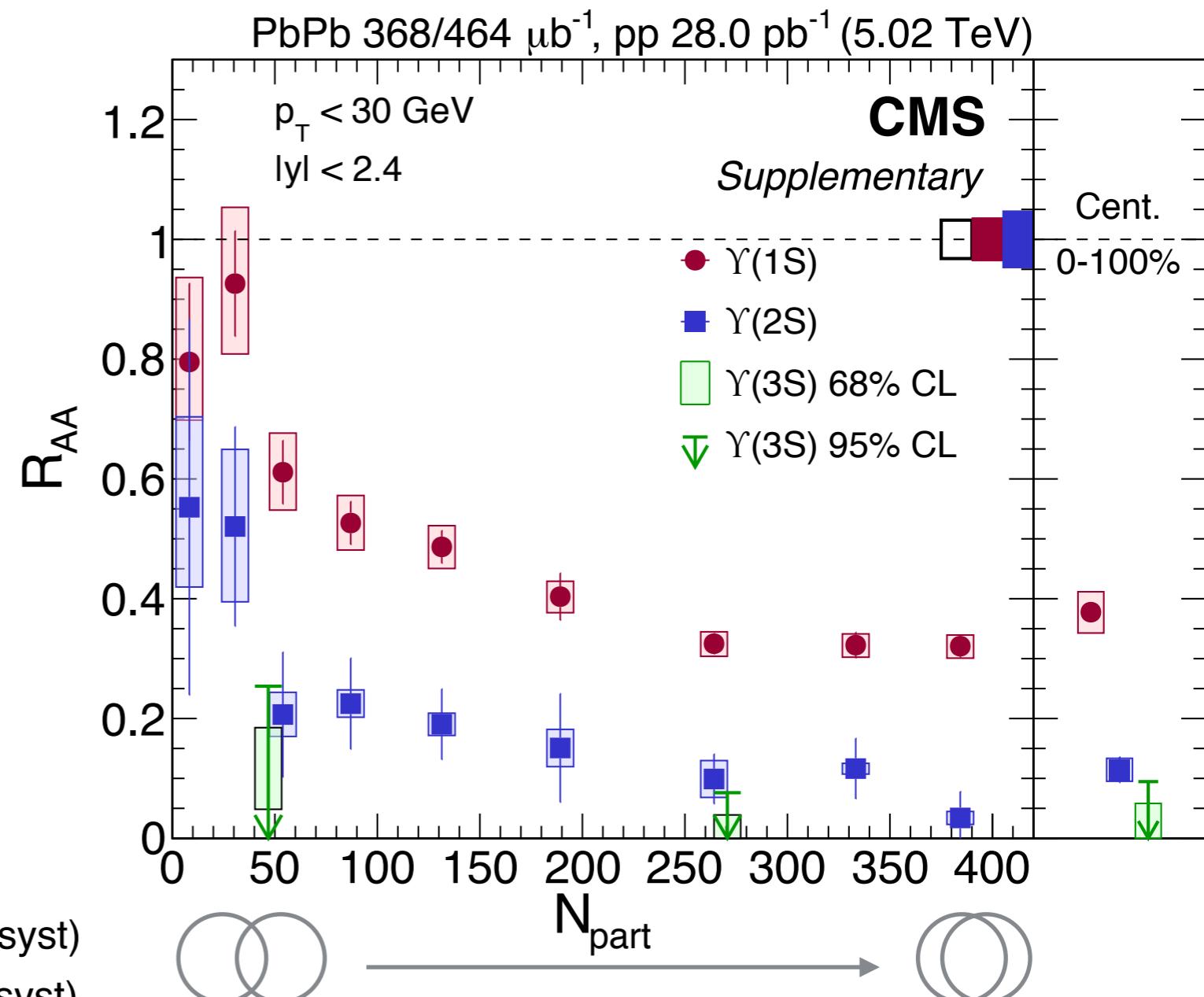
- More suppressed in central events.

Higher excited state RAA compatible with sequential suppression.

- $\Upsilon(3S)$ has smallest measured RAA of any hadron.

- Centrality integrated results:

- $\Upsilon(1S)$: $RAA = 0.378 \pm 0.013$ (stat) ± 0.035 (syst)
- $\Upsilon(2S)$: $RAA = 0.114 \pm 0.021$ (stat) ± 0.019 (syst)
- $\Upsilon(3S)$: $RAA < 0.094$ at 95% CL



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Two theoretical models for comparison

Krouppa and Strickland and Du, He and Rapp

Universe 2 (2016) 16

PRC 96 (2017) 054901

Both models incorporate:

- $\text{Re}[V]$ and $\text{Im}[V]$
- In-medium binding energies
- Internal energy potentials
- Feed down from excited states
- Directly produced $\Upsilon(1S)$ ~67%
- RAA below this value indicates melting of primordial $\Upsilon(1S)$

Krouppa and Strickland:

- Momentum-space anisotropy
- **No regeneration**
- Melting temperatures:
 $\Upsilon(1S, 2S, 3S)$: 600, 230, 170 MeV

- **Initial temperature:**
2.76 TeV: 544 - 552 MeV
- **5.02 TeV: 629 - 641 MeV (16% increase)**
- $\Upsilon(1S)$ RAA: ~25% decrease

Du, He and Rapp:

- Kinetic rate equation
- **Regeneration**
- Melting temperatures:
 $\Upsilon(1S, 2S, 3S)$: 500, 240, 190 MeV

- **Initial temperature:**
2.76 TeV: 520 - 750 MeV
- **5.02 TeV: 7% increase**
- $\Upsilon(1S)$ RAA: only slight decrease

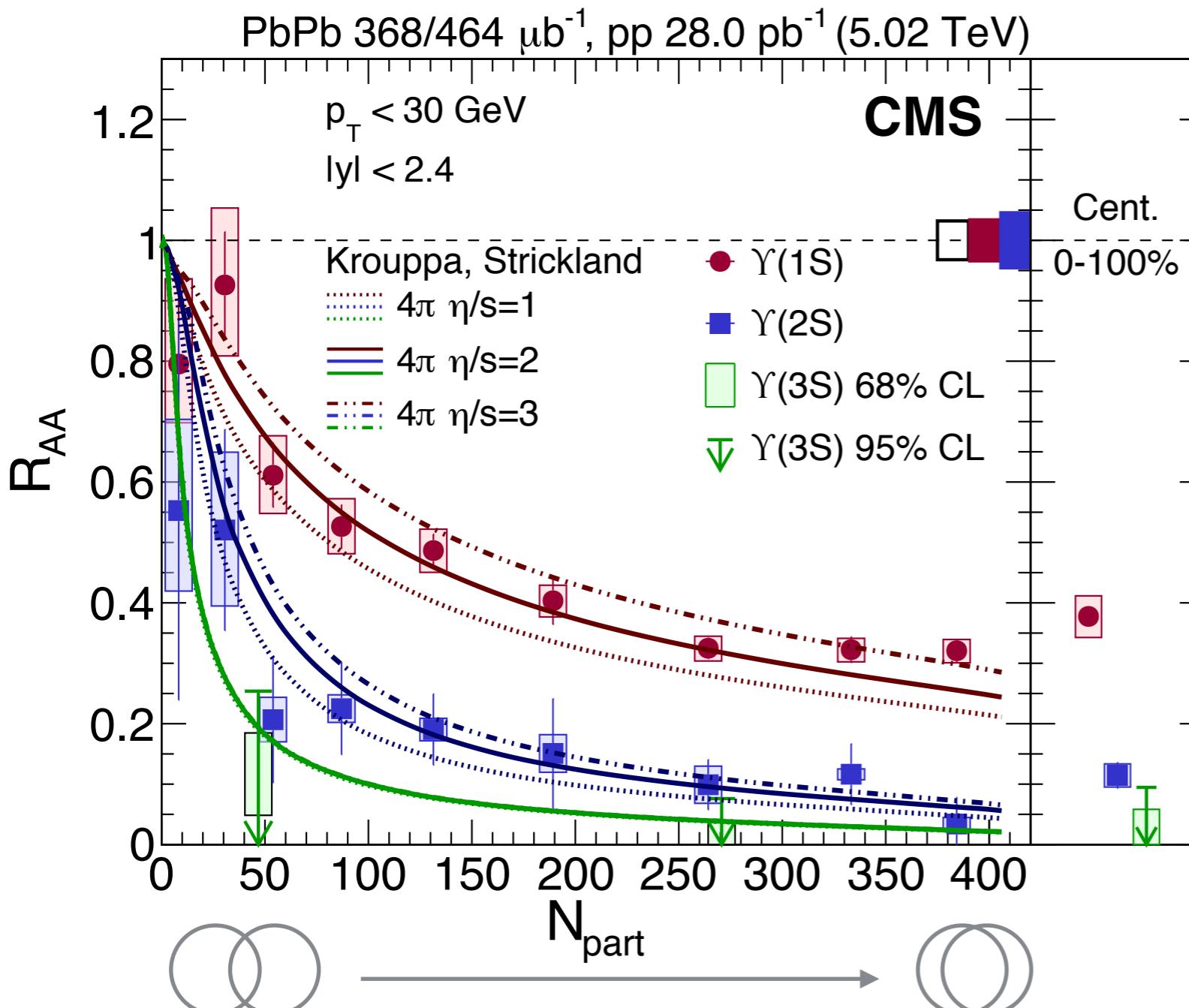
Other calculations include:

- K. Zhou, N. Xu and P. Zhuang, Nucl. Phys. A 931, 654 (2014)
- C. R. Singh, S. Ganesh, M. Mishra, G. Wolschin, arXiv:1802.09918





Comparison to Strickland et al.



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QGP hot enough to melt primordial
 $\Upsilon(1S)$!

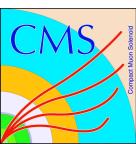
Initial QGP Temperature

4 π \cdot $\eta/s=1 \rightarrow 641 \text{ MeV}$

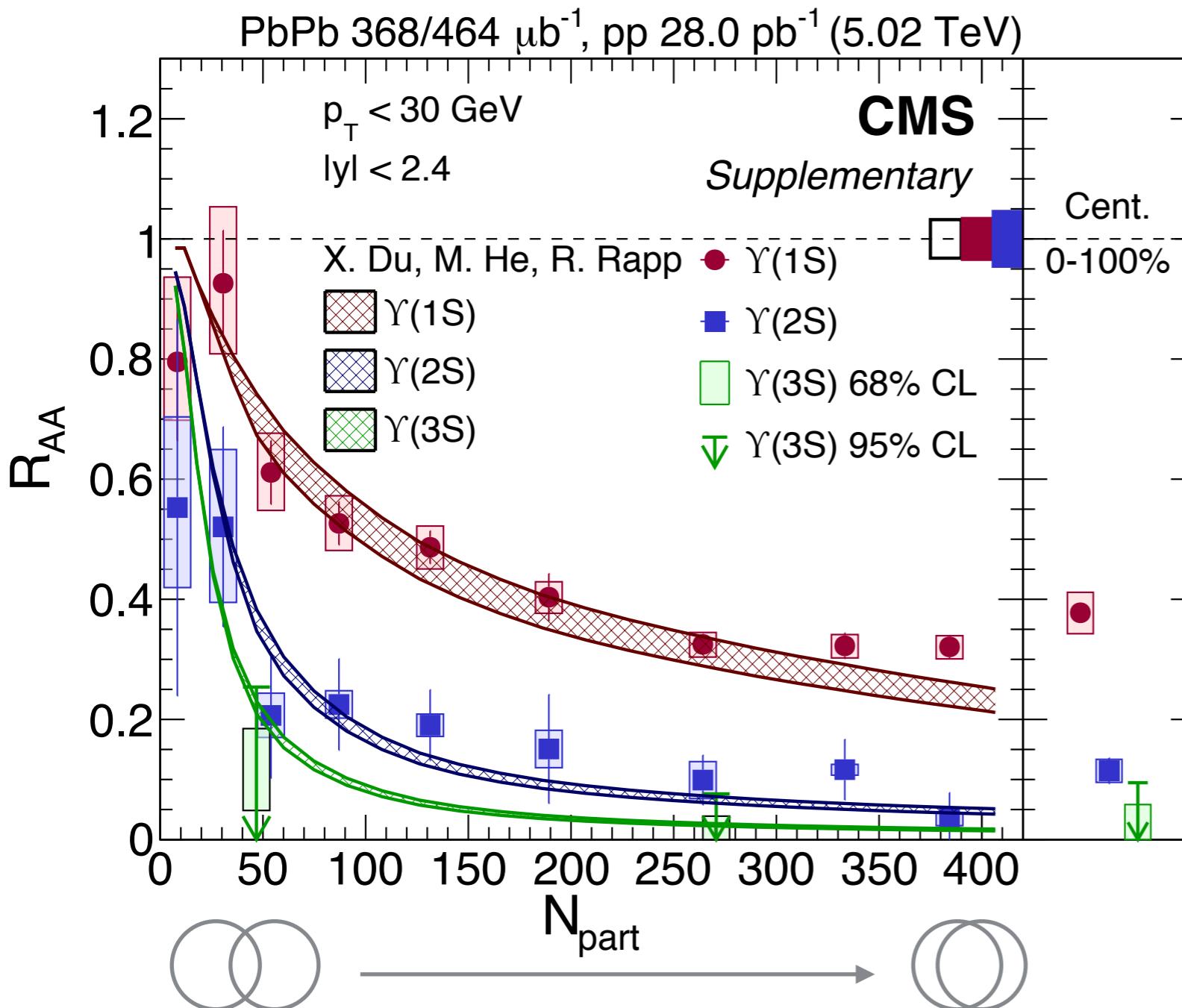
4 π \cdot $\eta/s=2 \rightarrow 632 \text{ MeV}$

4 π \cdot $\eta/s=3 \rightarrow 629 \text{ MeV}$

Initial QGP temperature 632 MeV



Comparison to Rapp et al.



QGP hot enough to melt primordial $\Upsilon(1S)$!

Temperature range $\sim 550 - 800 \text{ MeV}$

Initial temperature over large range produces similar $\Upsilon(1S)$ RAA

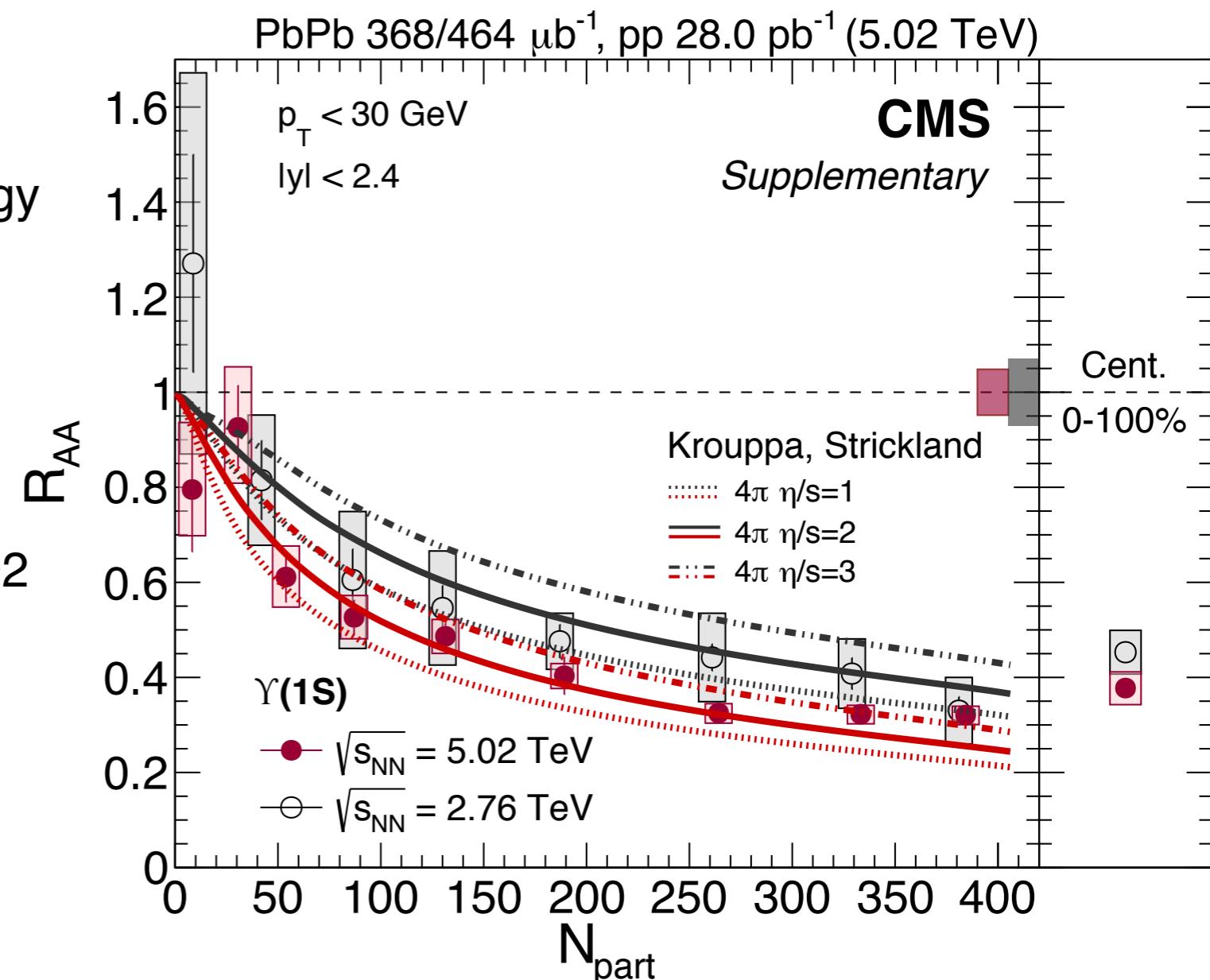
- Short formation time of $\Upsilon(1S)$
- Shields from the early phase of QGP where dissociation rates are high.

Model agrees with data.

Comparison to 2.76 TeV for $\Upsilon(1S)$

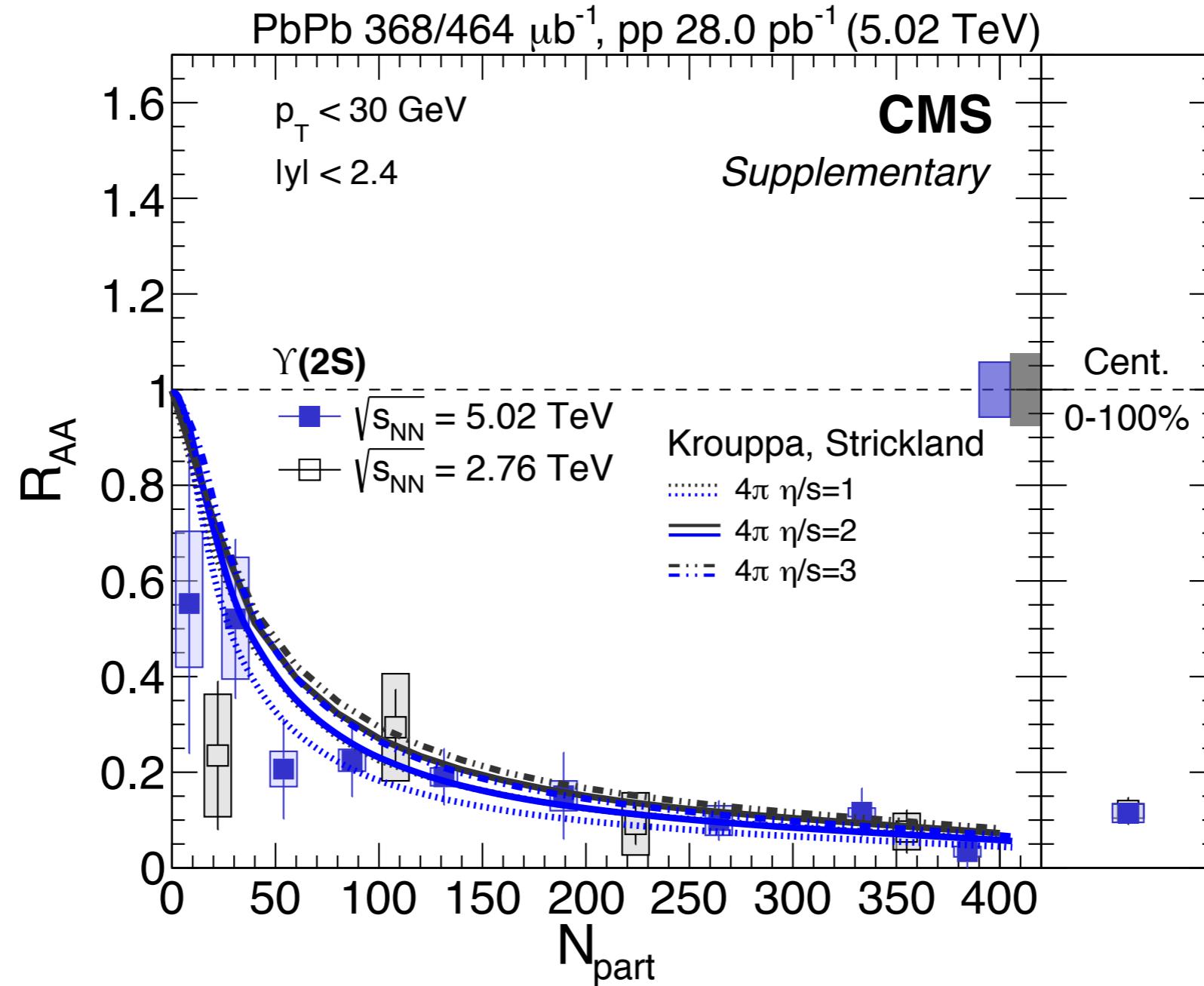
Larger suppression seen at higher energy
(compatible within uncertainties):
► Factor of 1.2 ± 0.15 (syst).

Strickland et al.:
► 16% **increase in temperature** at 5.02 TeV compared to 2.76 TeV
► ~25% decrease in $\Upsilon(1S)$ RAA
► At each energy, model agrees with corresponding data



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Comparison to 2.76 TeV for $\Upsilon(2S)$



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Suppression is consistent between two energies.
 Strickland et al. predict a small further suppression
 ➤ Compatible with our data.

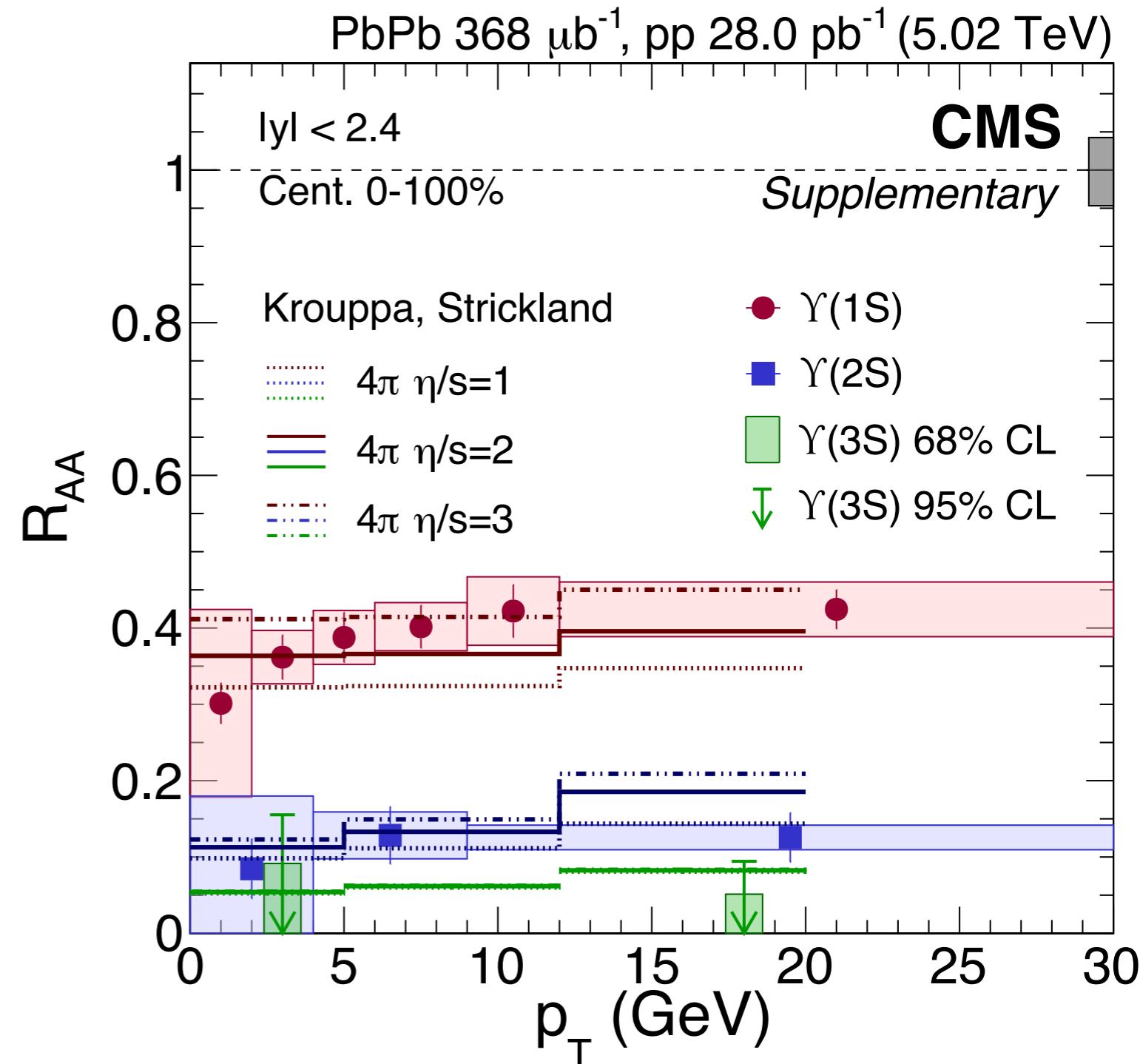
R_{AA} as a function of Υ p_T



$\Upsilon(nS)$: We observe no significant dependence of R_{AA} on p_T .

Strickland et al. predict a modest increase in R_{AA} with p_T .

- High β Υ escape QGP before significant modification.
- However, even a 30 GeV/c Υ only has $\beta = 0.3$.
- Model is compatible with data.



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Comparison to Rapp et al. for $\Upsilon(1S)$ and $\Upsilon(2S)$



Model:

- Primordial and regeneration components have different p_T dependences.
- Total is the net effect.

$\Upsilon(1S)$ and $\Upsilon(2S)$:

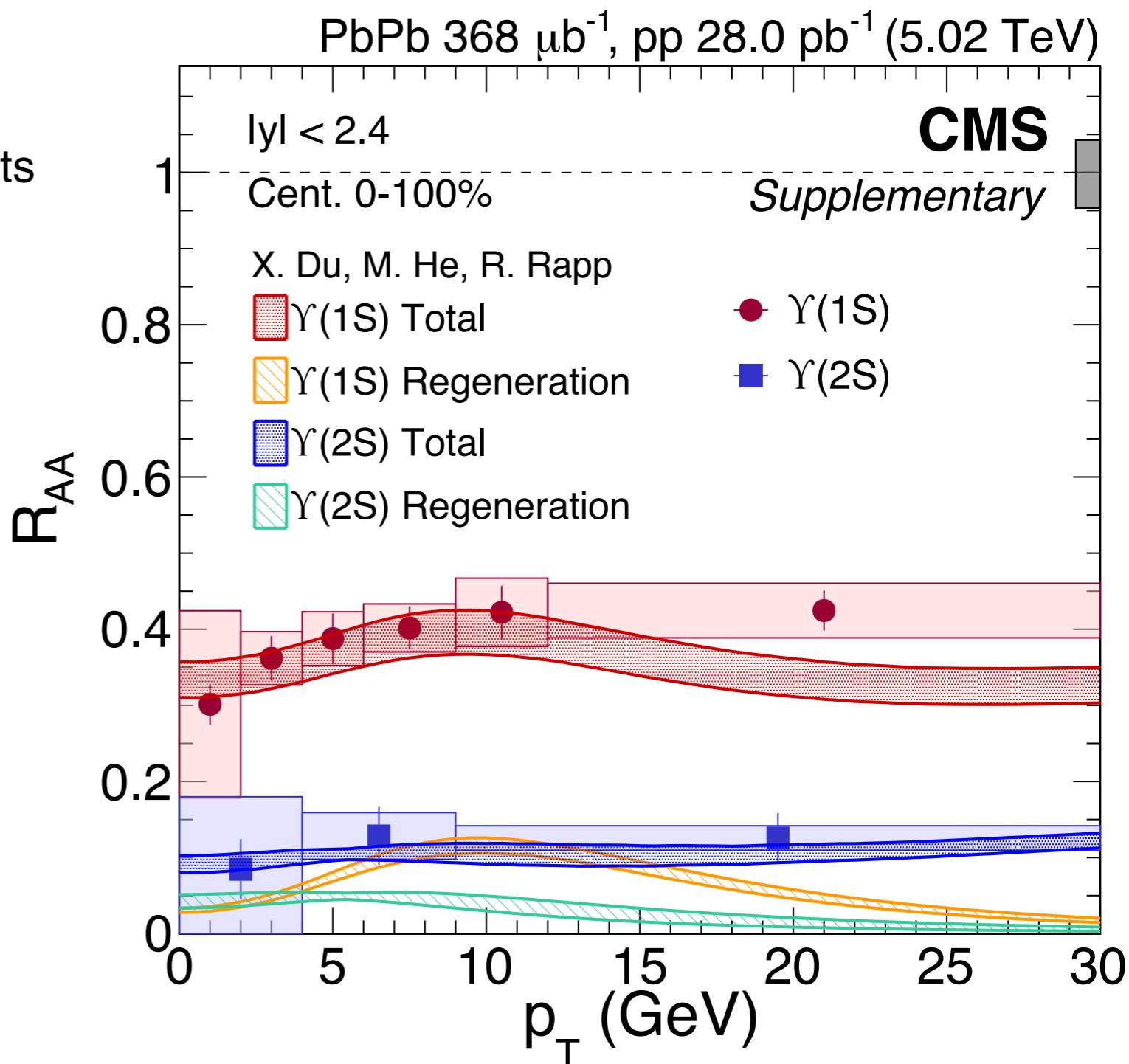
- Consistent with our data.
- Regeneration contribution to $R_{AA} \sim 0.1$

$\Upsilon(1S)$:

- Expects a regeneration bump $\sim 19\%$ between 0 and 9.5 GeV.
- Not visible within our uncertainties.

$\Upsilon(2S)$:

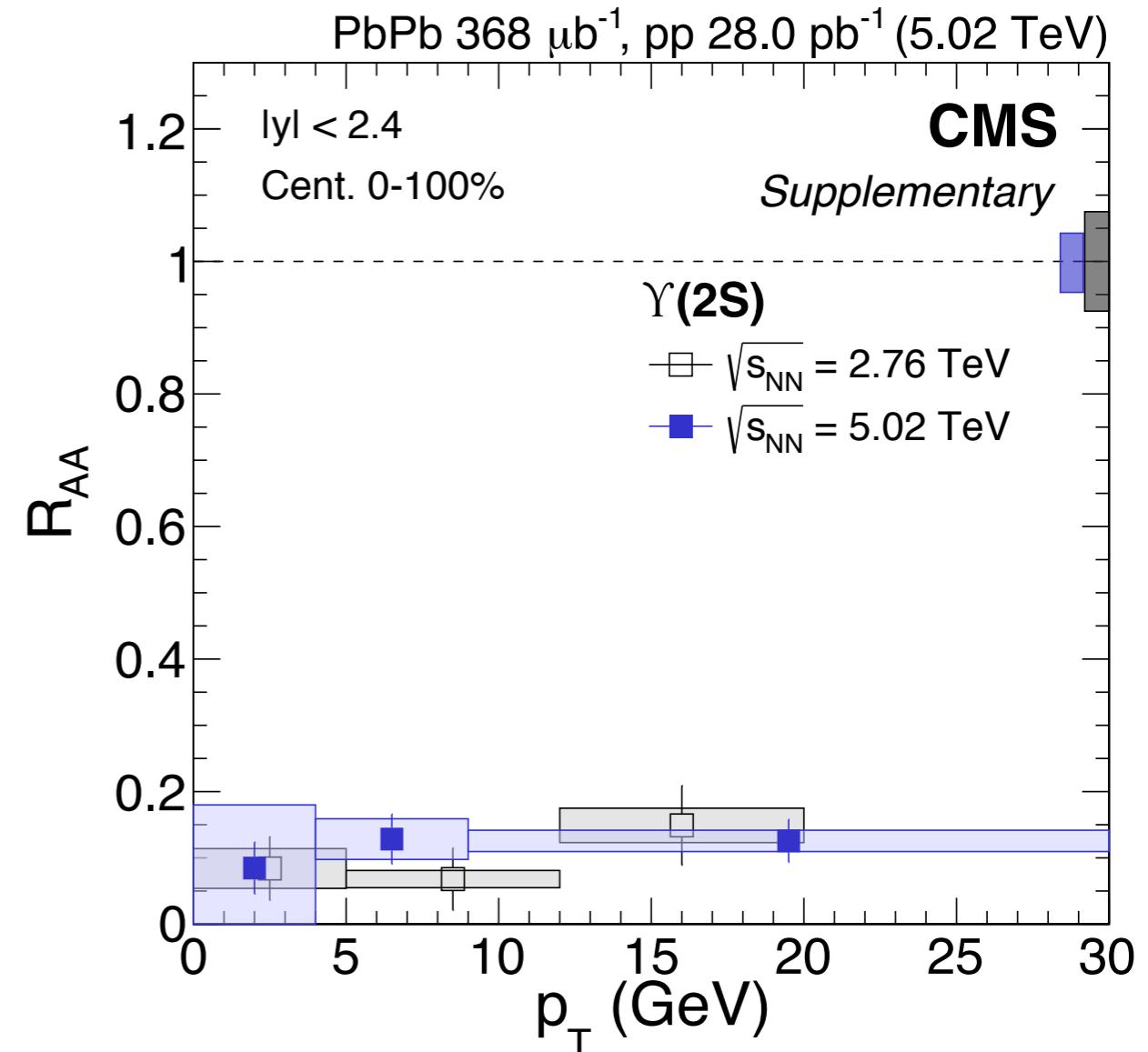
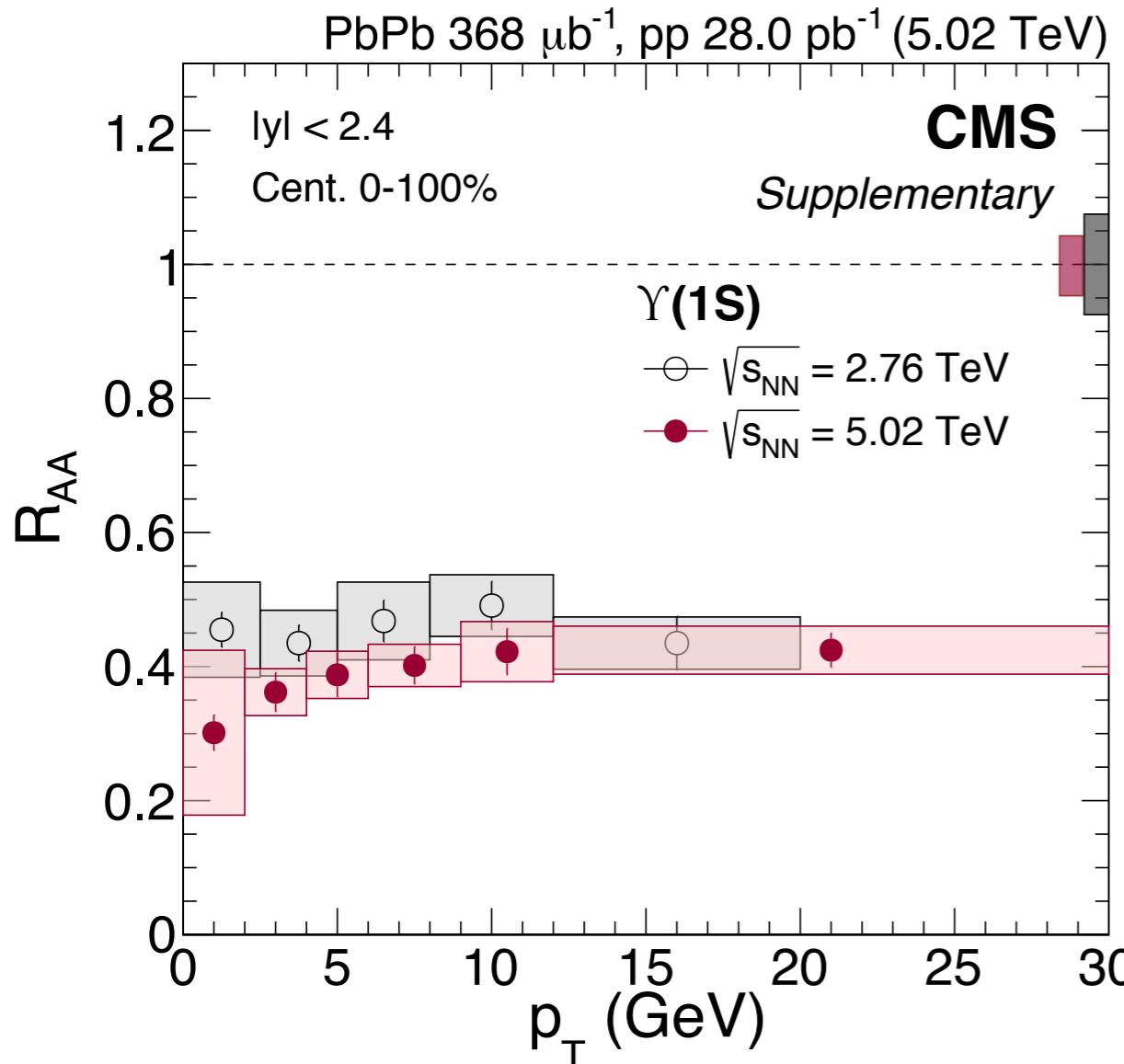
- Moderate monotonous rise p_T



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Comparison to 2.76 TeV for $\Upsilon(1S)$ and $\Upsilon(2S)$

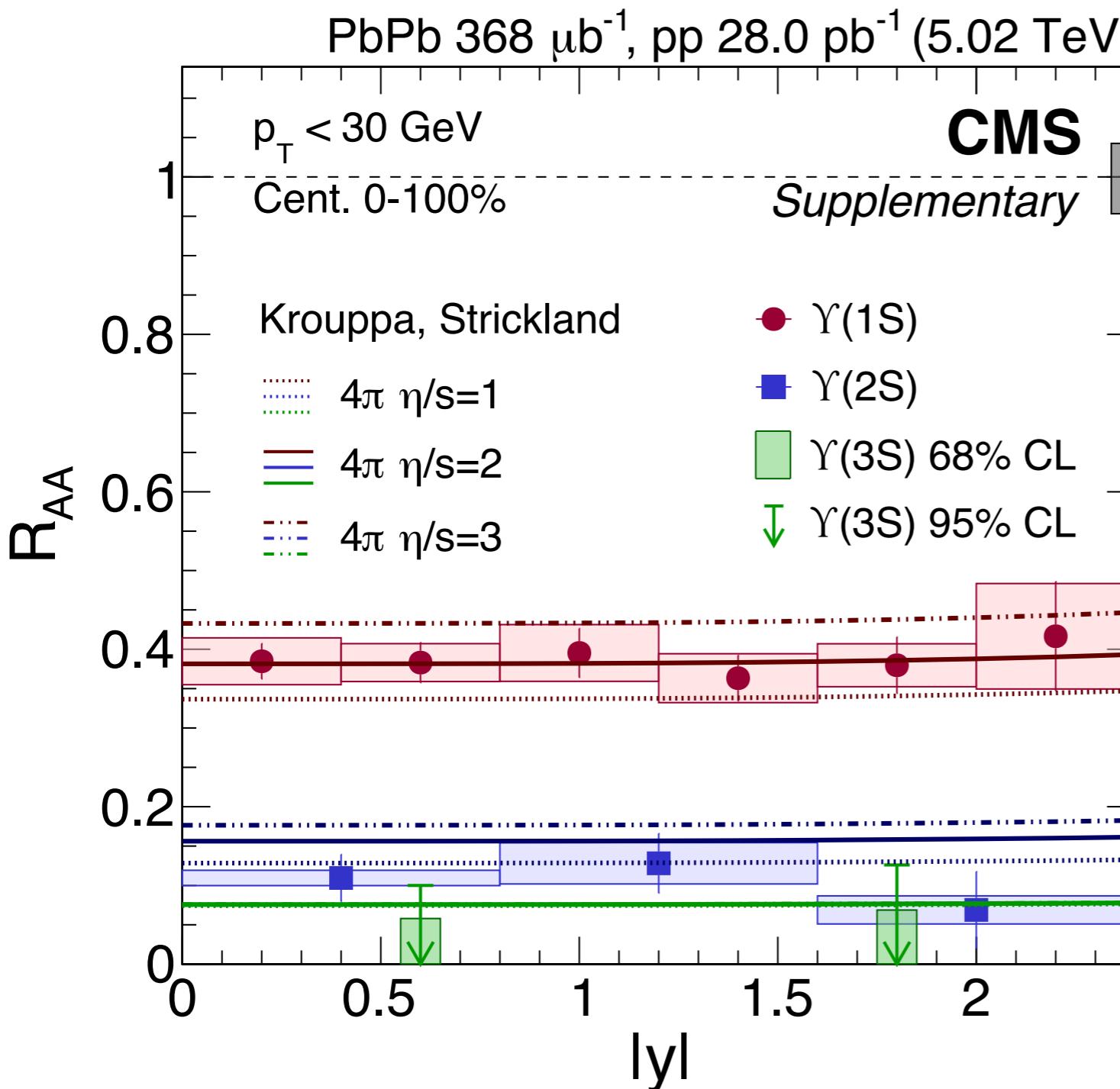


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$\Upsilon(1S)$ and $\Upsilon(2S)$:

- ▶ Suppression is consistent between two energies.
- ▶ At both energies, we observe no significant dependence of R_{AA} on p_T .

R_{AA} as a function of Υ rapidity



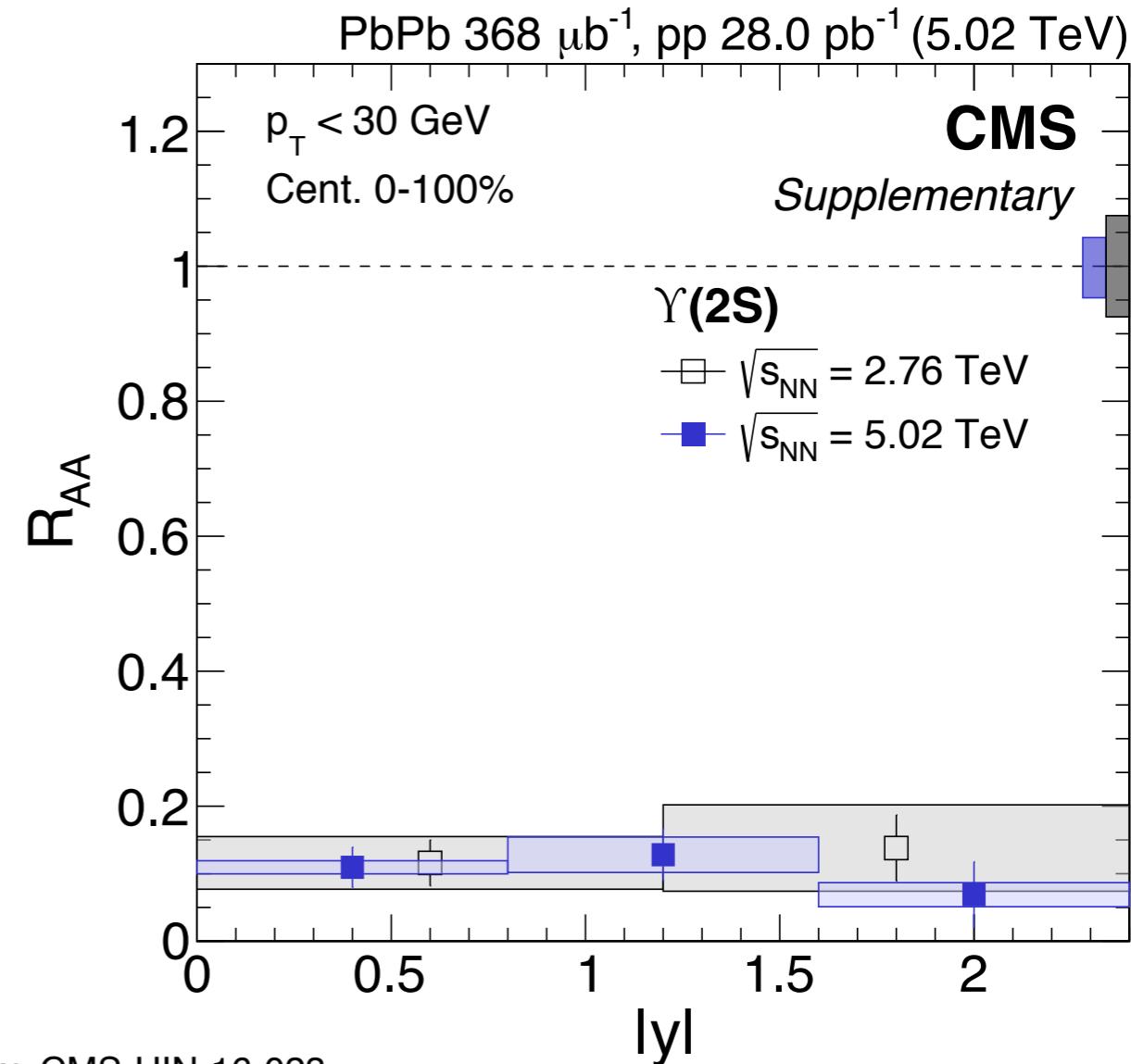
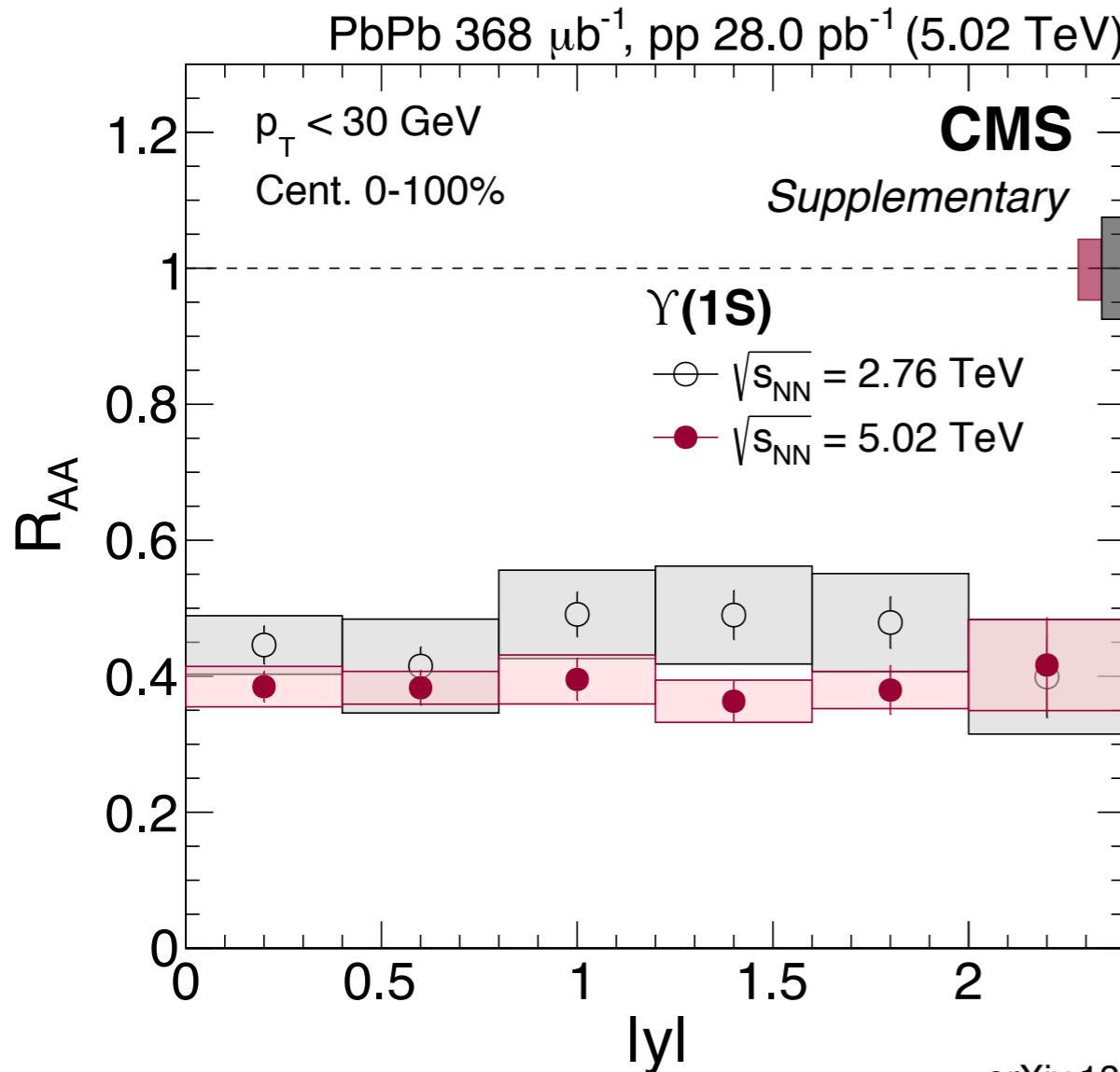
$\Upsilon(nS)$: We observe no significant dependence of R_{AA} on y .
 Strickland et al. predict slight increase in R_{AA} with y .

- Away from mid rapidity, QGP is cooler.
- In CMS y range, decrease in temperature is small.
- Model is consistent with our data.

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Comparison to 2.76 TeV for $\Upsilon(1S)$ and $\Upsilon(2S)$



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$\Upsilon(1S)$ and $\Upsilon(2S)$:

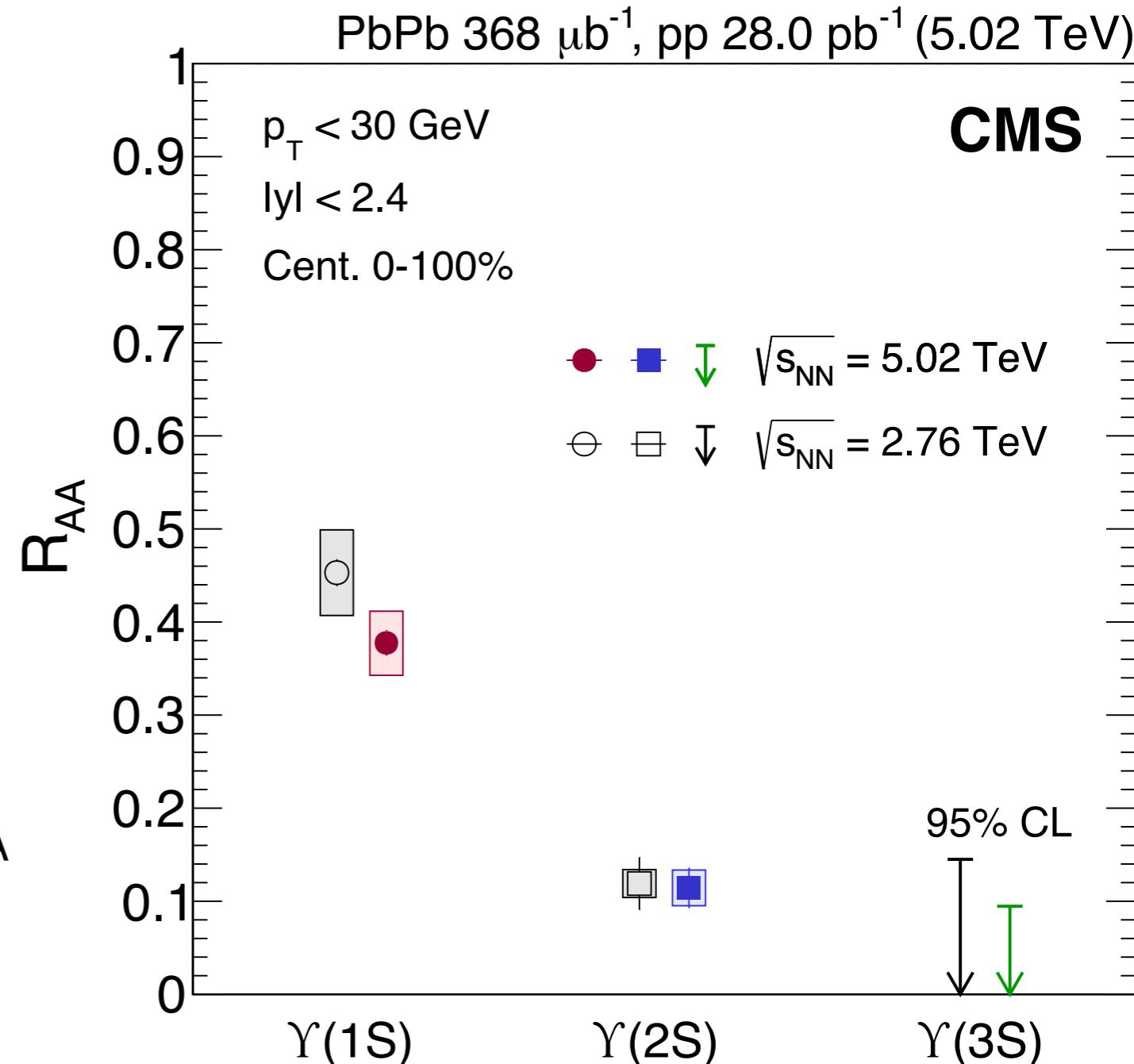
- ▶ Suppression is consistent between two energies.
- ▶ At both energies, we observe no significant dependence of R_{AA} on y .

Summary: $\Upsilon(nS)$ comparison to 2.76 TeV



Sequential melting at both energies!

- $\Upsilon(1S)$: R_{AA} is lower at higher energy
 - Compatible within uncertainties.
 - Factor of 1.2 ± 0.15 (syst).
- $\Upsilon(2S)$: R_{AA} is similar at both energies:
 - Models predict very small additional suppression at higher energy.
 - Rapp et al.:
 - predict ~ 0.01 (abs) decrease in R_{AA}
 - Indication of regeneration.

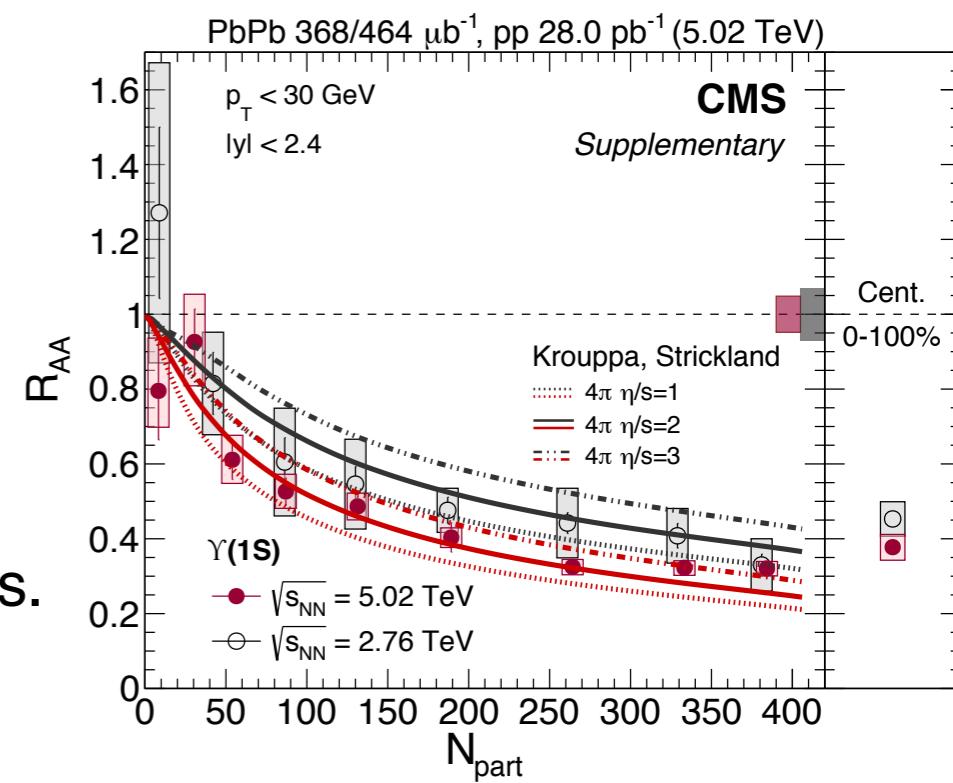
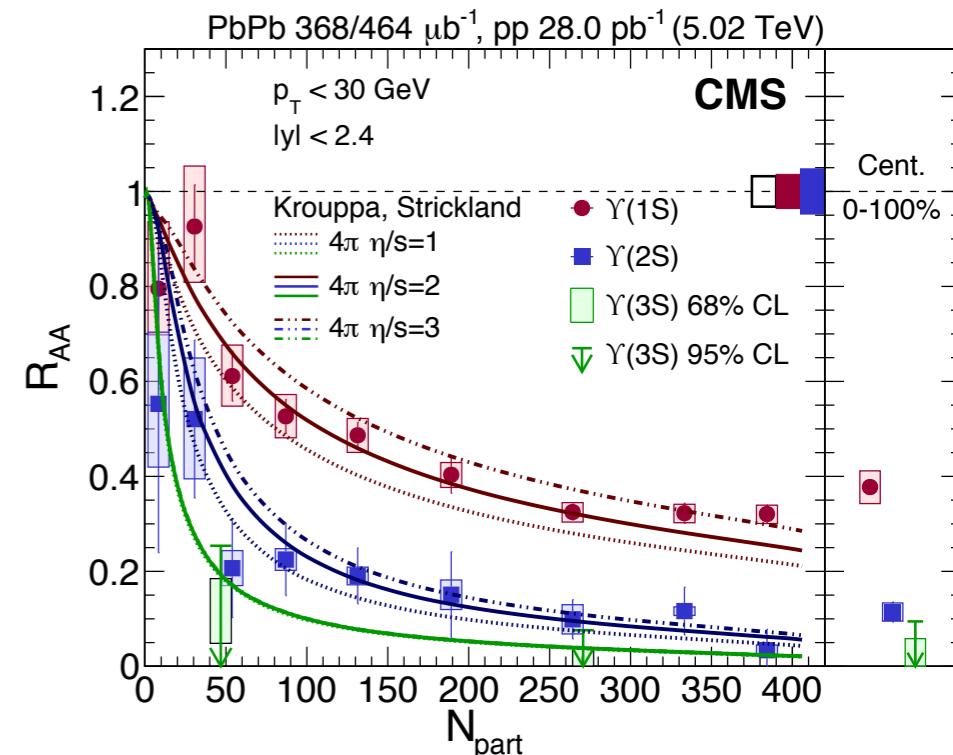


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Conclusions

Recap for Υ in 5.02 TeV data

- Help determine **temperature of early stage QGP** in PbPb.
 - Temperature high enough to melt $\Upsilon(1S)$
 - Strickland et al.: 632 MeV
 - Rapp et al.: ~550 - 800 MeV
- Comparisons to 2.76 TeV:
 - Strickland et al. agree with corresponding data
 - Higher temperature (16%)
 - Greater suppression of $\Upsilon(1S)$ (~25%)



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Back Up

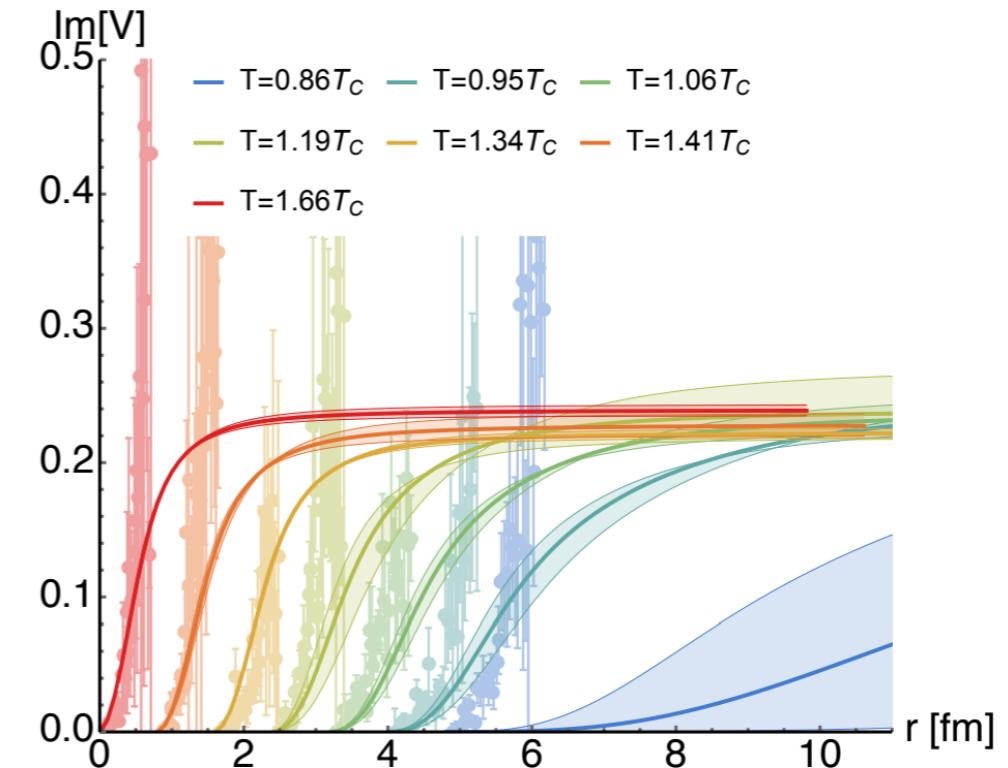
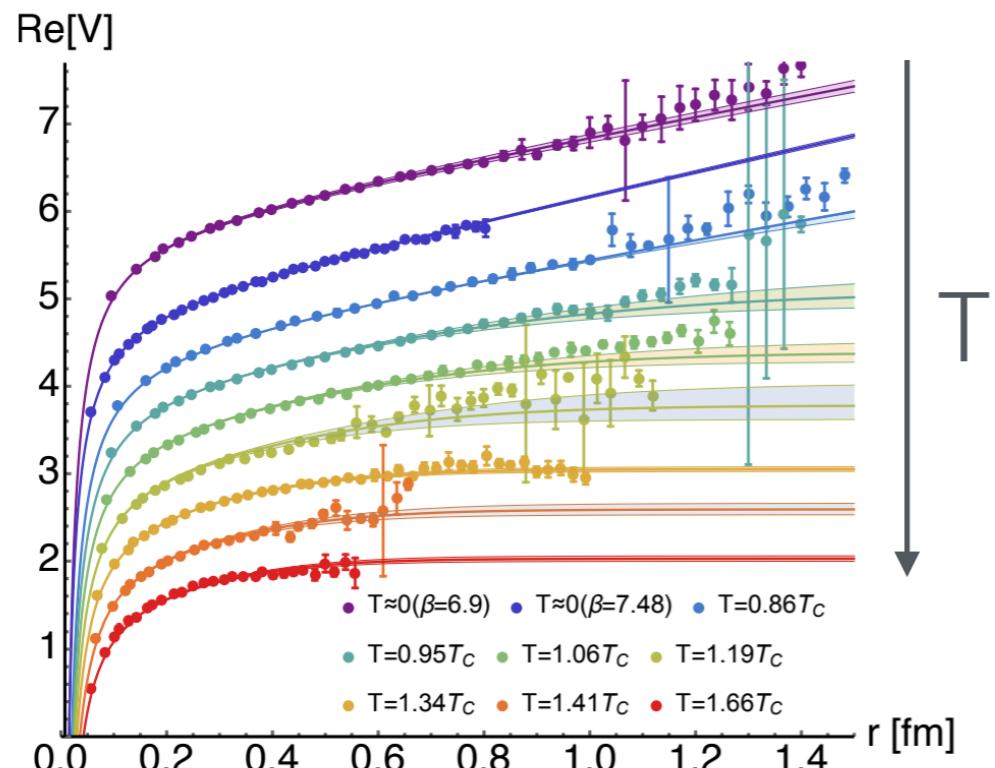
The in-medium heavy-quark potential

In 1986, Matsui and Satz proposed suppression of J/ ψ in Quark Gluon Plasma produced in heavy ion collisions.

In 2007, Laine, Philipsen, Romatschke and Tassler

- Formalized the static in-medium heavy-quark potential, $V(r, T)$
- Showed that it has real and imaginary parts.

Figures from 2015 paper by Burnier, Kaczmarek and Rothkopf showing $\text{Re}[V]$ and $\text{Im}[V]$:



Burnier, Y., Kaczmarek, O. & Rothkopf, A. J. High Energ. Phys. (2015) 2015: 1.

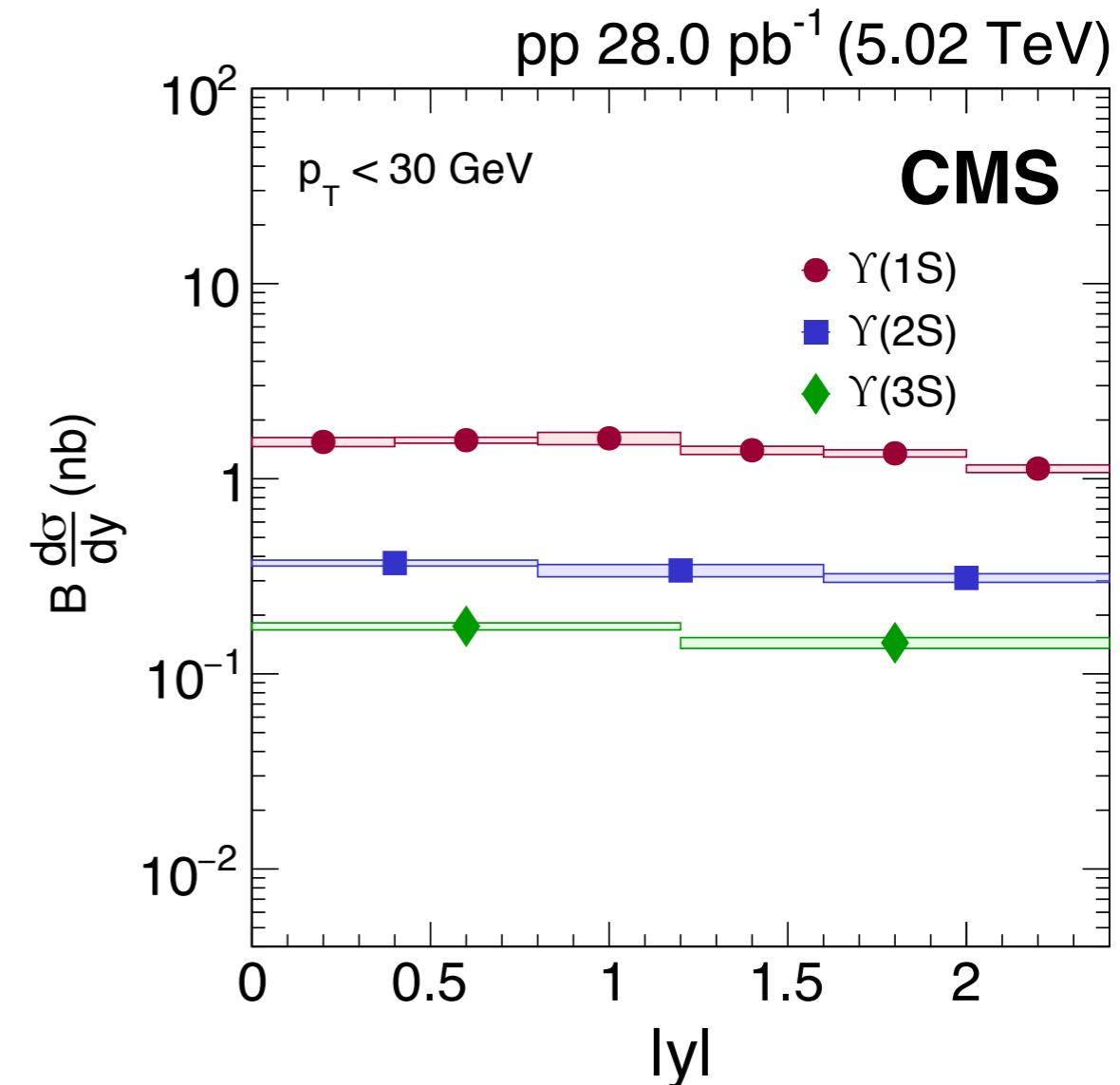
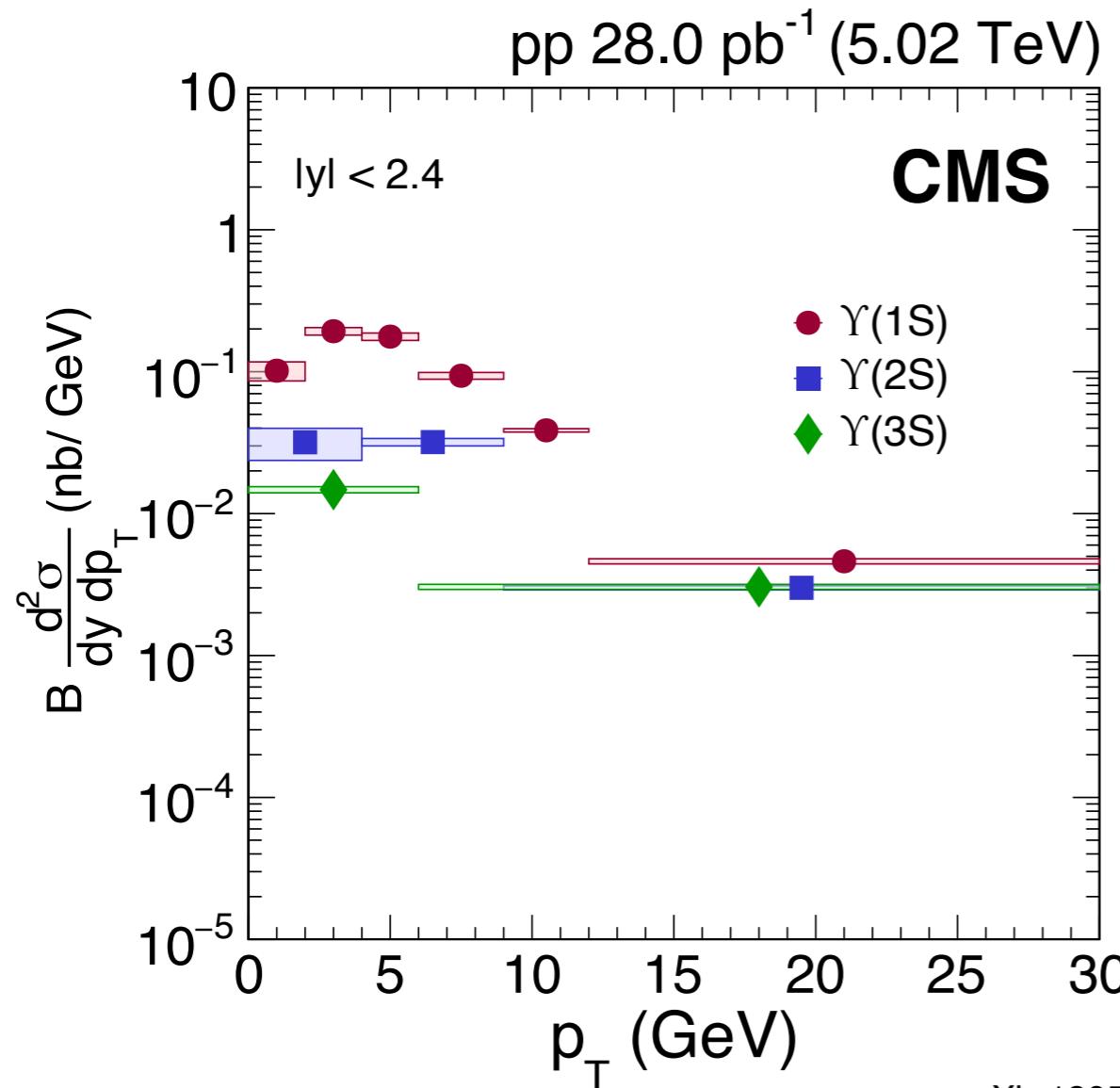
$\text{Re}[V]$: time-dependent Debye **screening** potential.

- Significant screening of the linear rise of $\text{Re}[V]$ for large r .

$\text{Im}[V]$: **Scattering** and absorption of gluons from the medium with the heavy quark system.



Cross section of $\Upsilon(nS)$ in pp

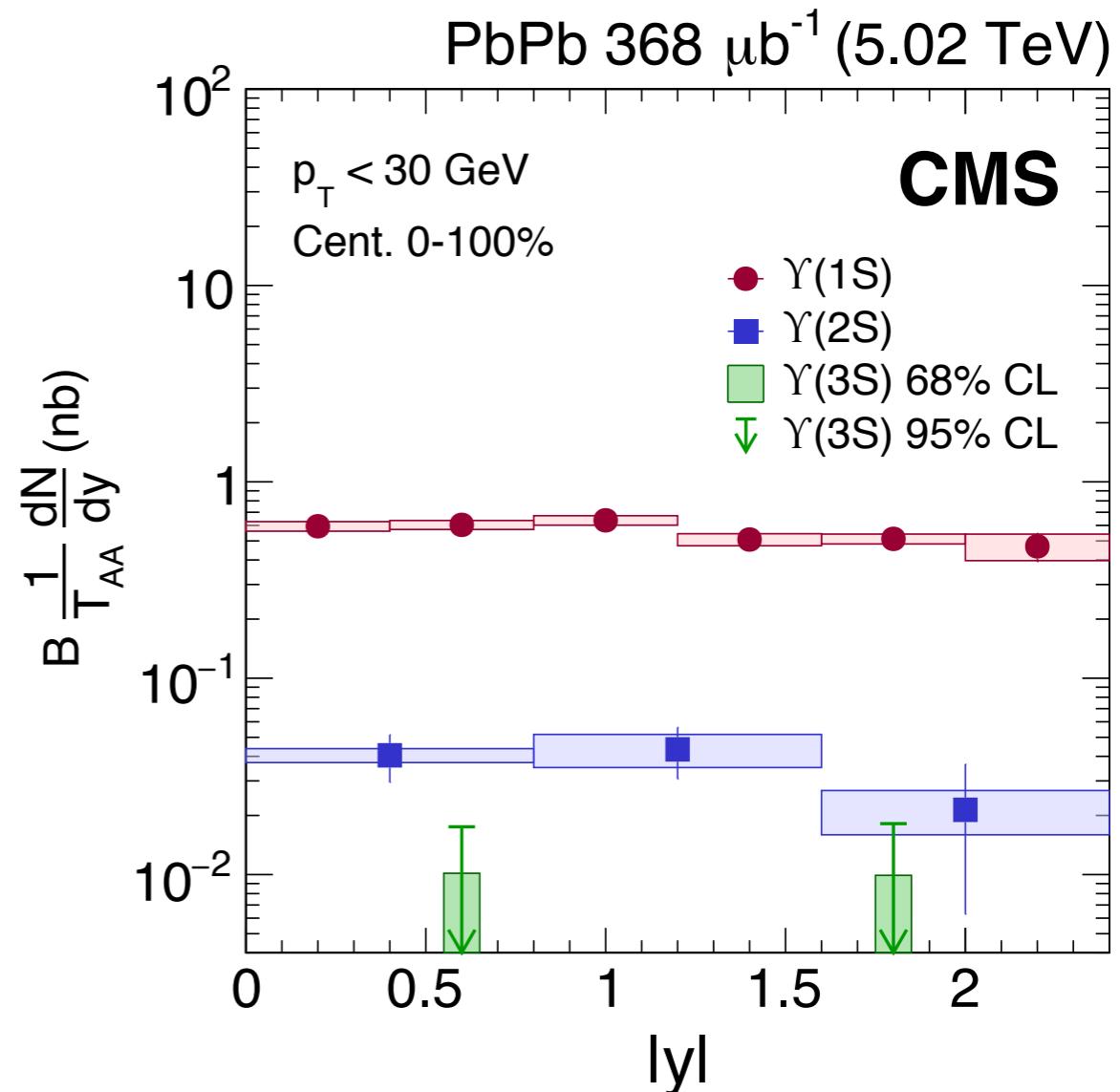
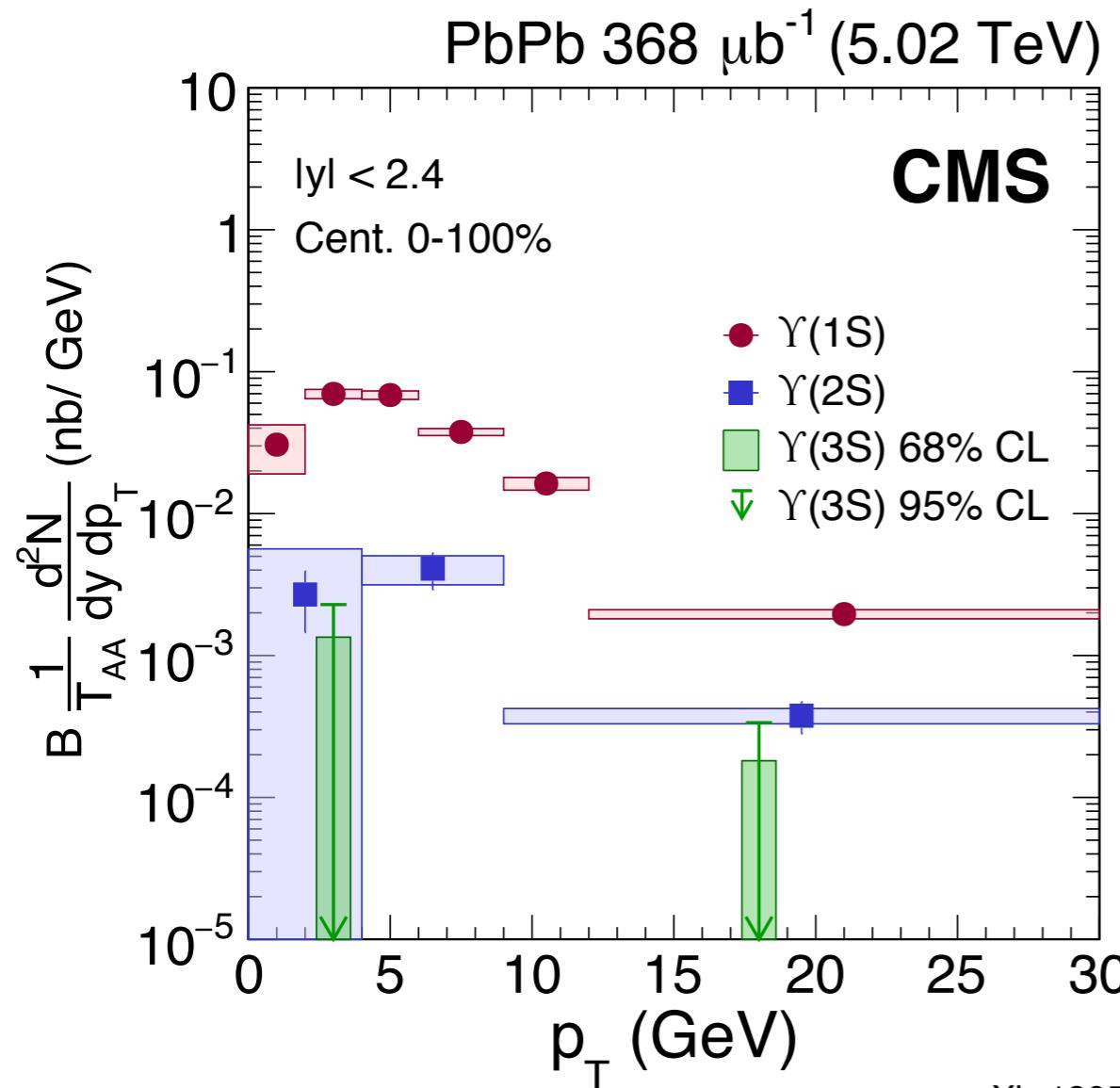


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- Cross section of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ in pp collisions at 5.02 TeV as functions of the kinematic variables p_T and y .
- These can be used as the pp reference for any heavy ion collisions system at this energy. (On going work to determine R_{pA} .)



Cross section of $\Upsilon(nS)$ in PbPb



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- The cross section of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ in PbPb collisions at 5.02 TeV as functions of the kinematic variables p_T and y .
- Dividing the PbPb cross section by the pp cross section and correcting gives us the nuclear modification factor.