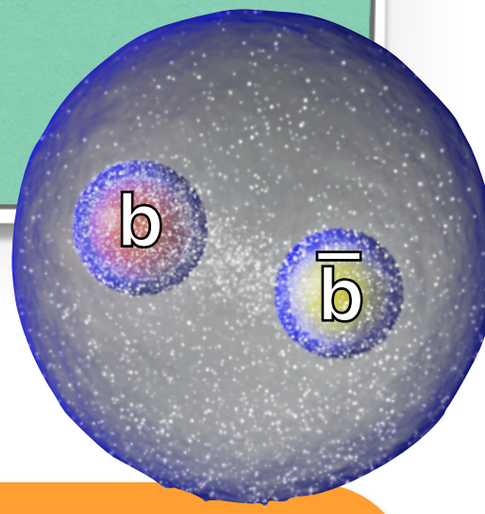
Bottomonia in heavy-ion collisions at LHC



JaeBeom Park (Korea University)

HF2022 : Heavy Flavours from small to large systems
@ Institute Pascal (France)

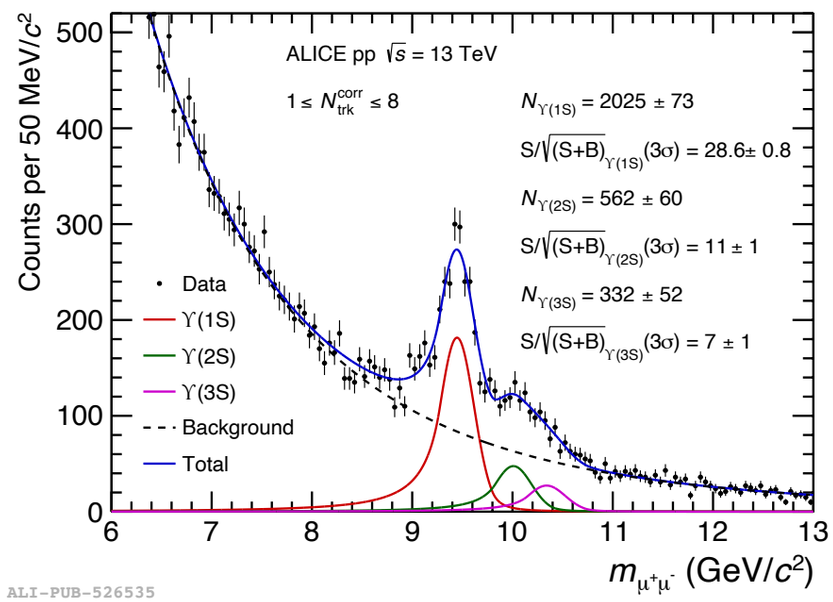
What have we learned so far for Upsilon modification in heavy-ion collisions?

What we learned from Upsilons in heavy ion collisions

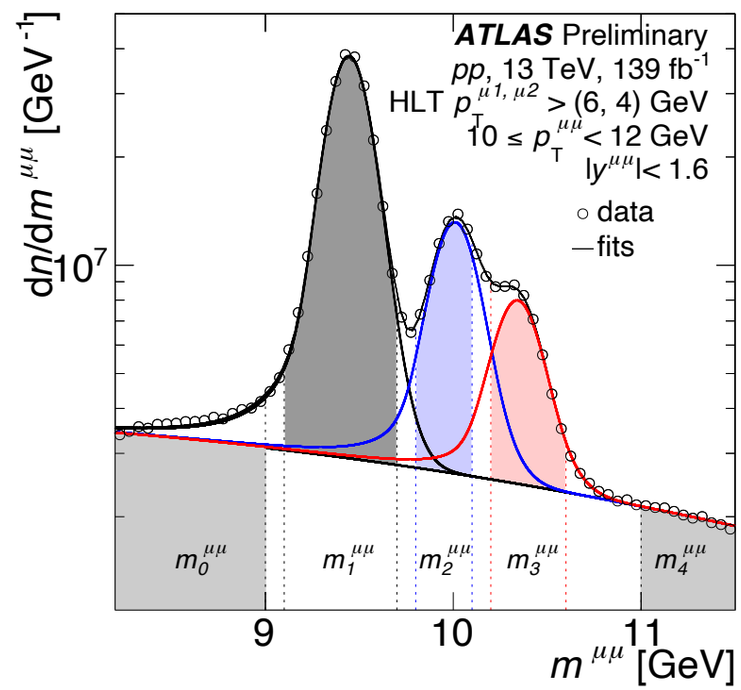
From data

☑ Excellent reconstruction in dimuon decay channel @ LHC!! (some difficulties exist in AA)

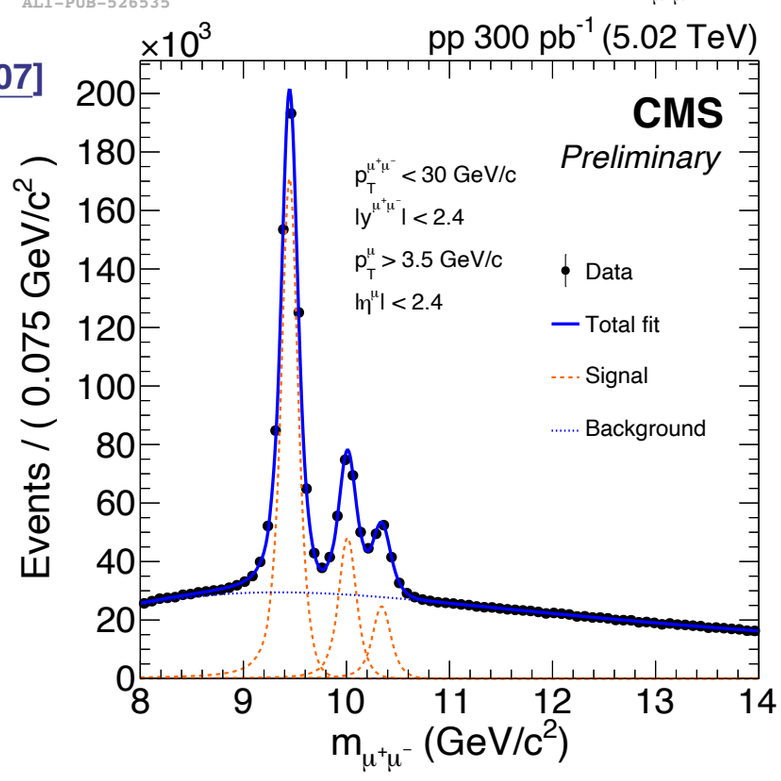
[arXiv:2209.04241]



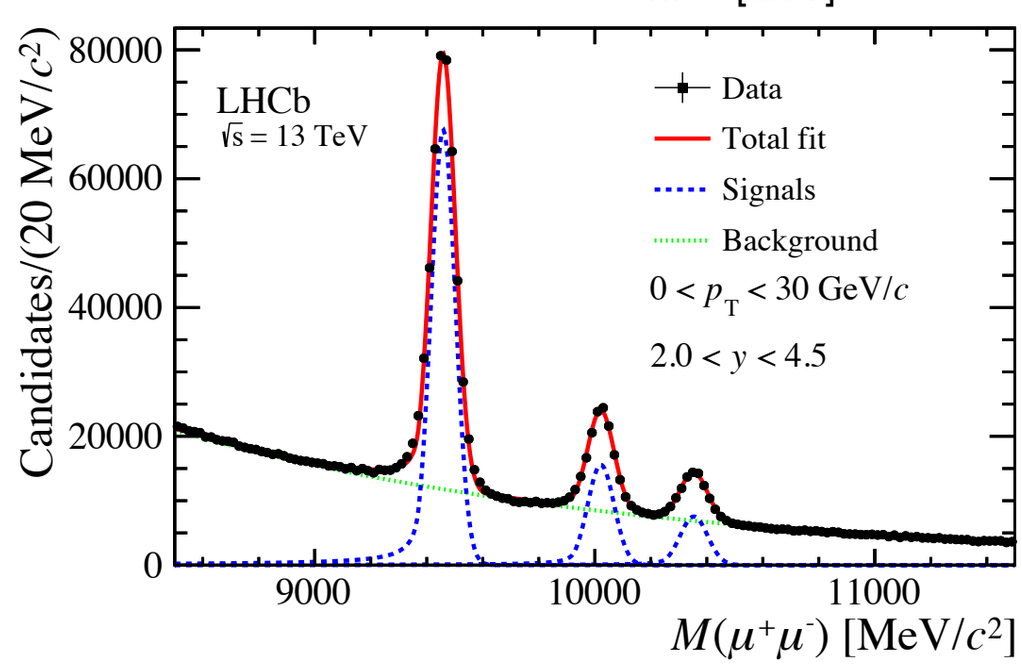
[ATLAS-CONF-2022-023]



[CMS-PAS-HIN-21-007]



[JHEP07(2018)134]



What we learned from Upsilons in heavy ion collisions

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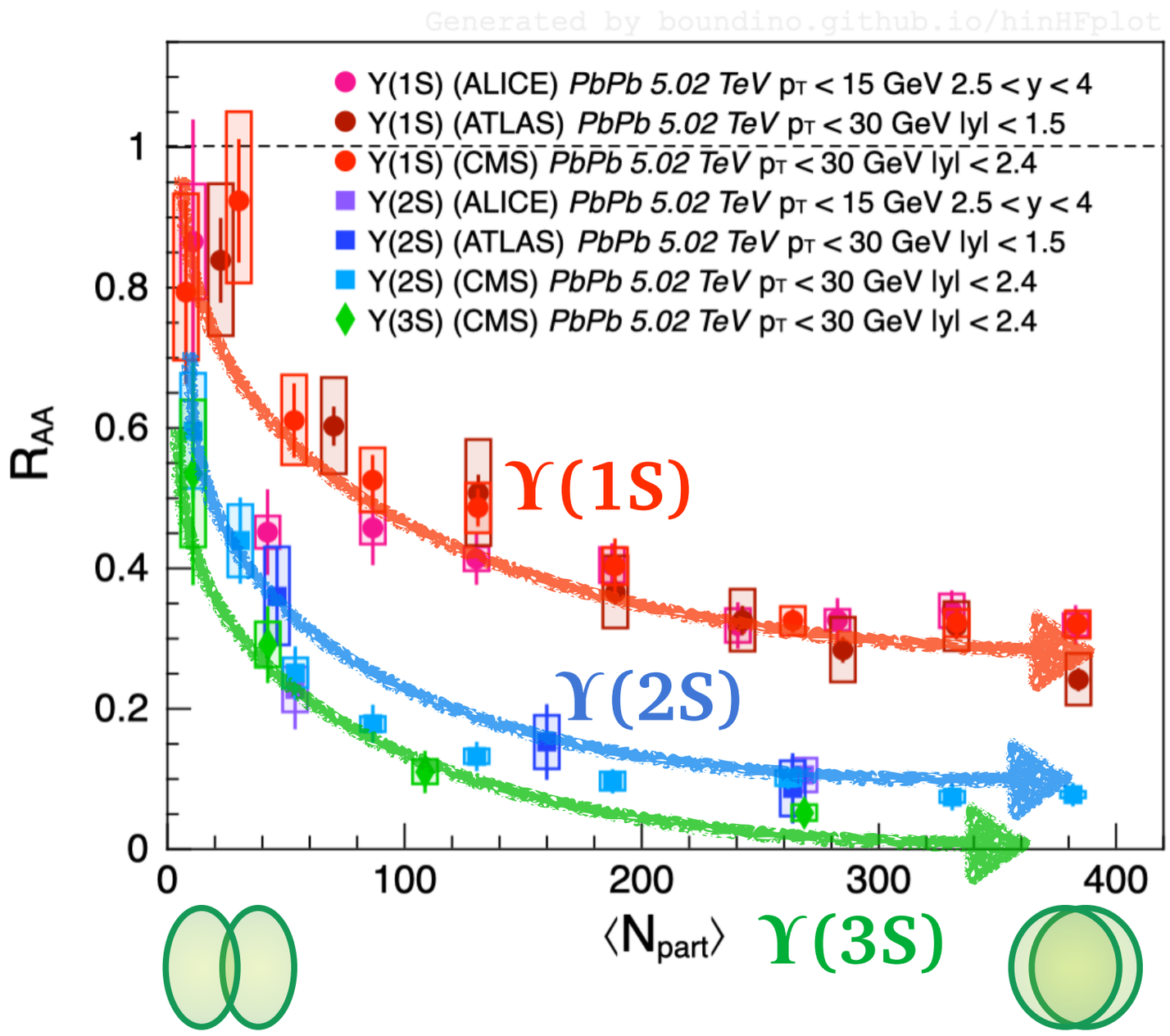
- ☑ Sequential suppression in AA @ LHC!!



[PLB 822 (2021) 136579] [CMS-PAS-HIN-21-007]
[PLB 790 (2019) 270] [arXiv:2205.03042]

- **Amount of suppression :**

  Υ(1S) < Υ(2S) < Υ(3S)

- **Binding energy :**

  Υ(1S) > Υ(2S) > Υ(3S)

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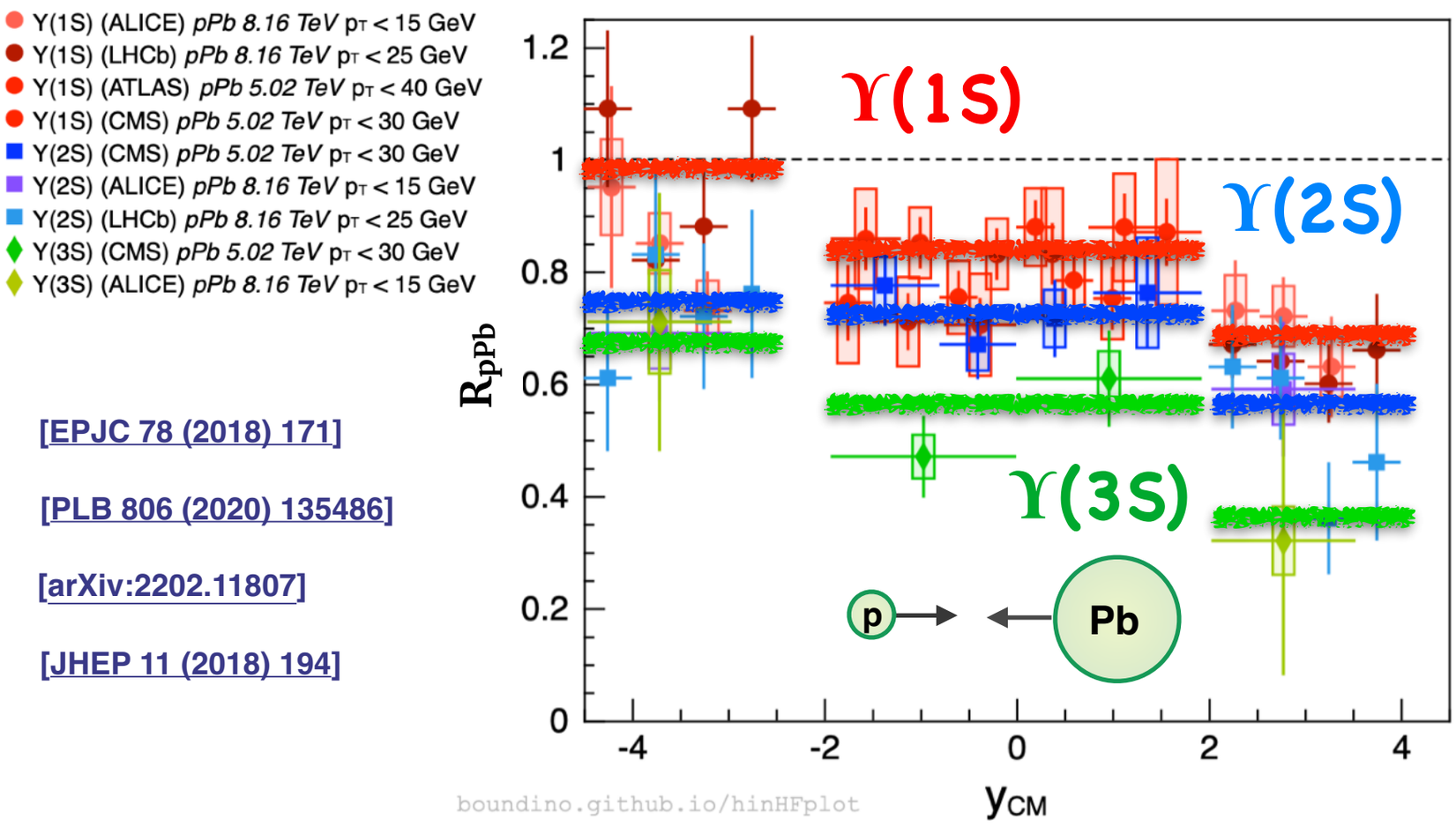

[EPJC 78 (2018) 171]

[PLB 806 (2020) 135486]

[arXiv:2202.11807]

[JHEP 11 (2018) 194]

- **Amount of suppression :**

  Υ(1S) < Υ(2S) < Υ(3S)

  absolute suppression smaller than PbPb

- **Binding energy :**

  Υ(1S) > Υ(2S) > Υ(3S)

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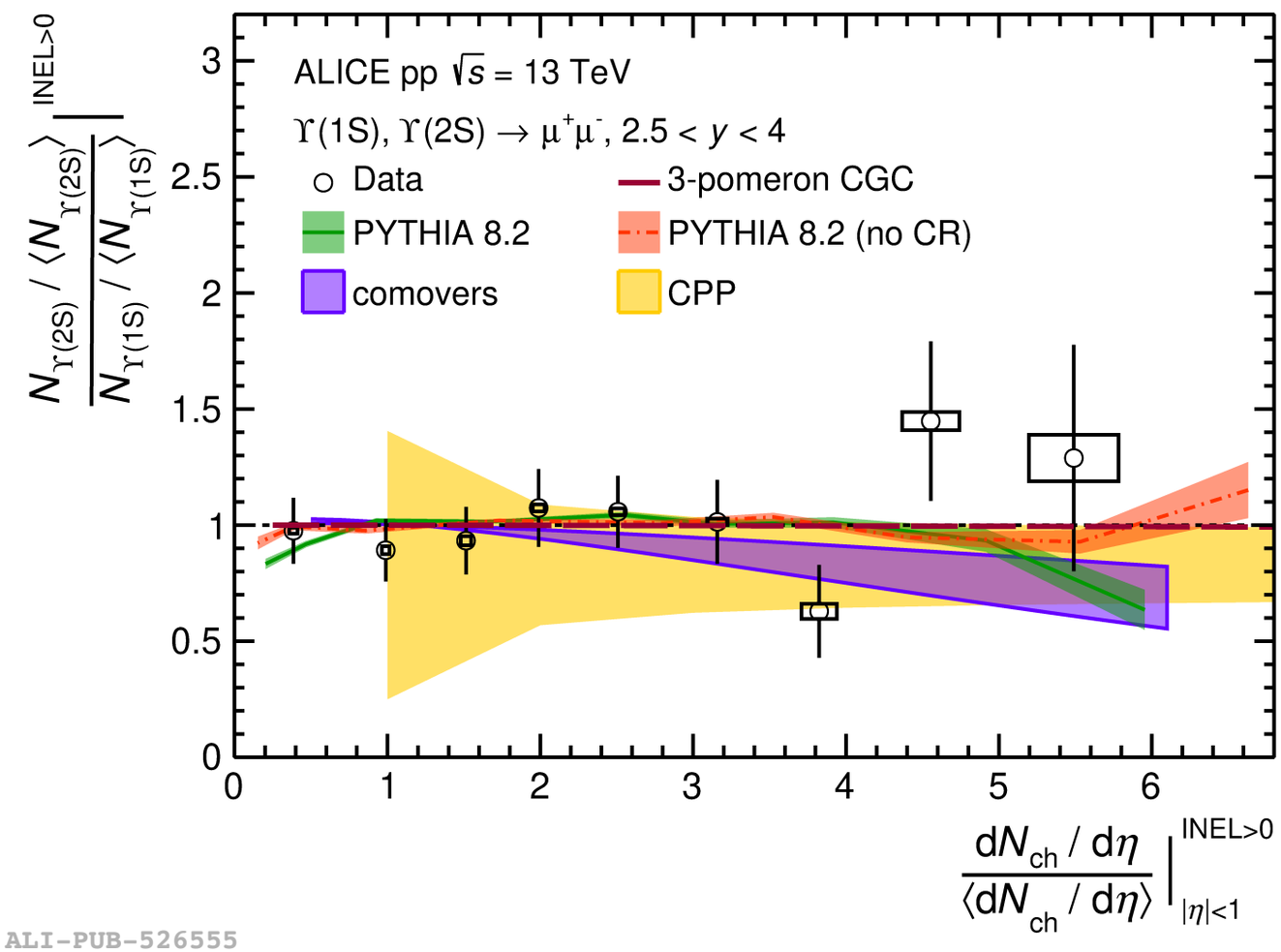

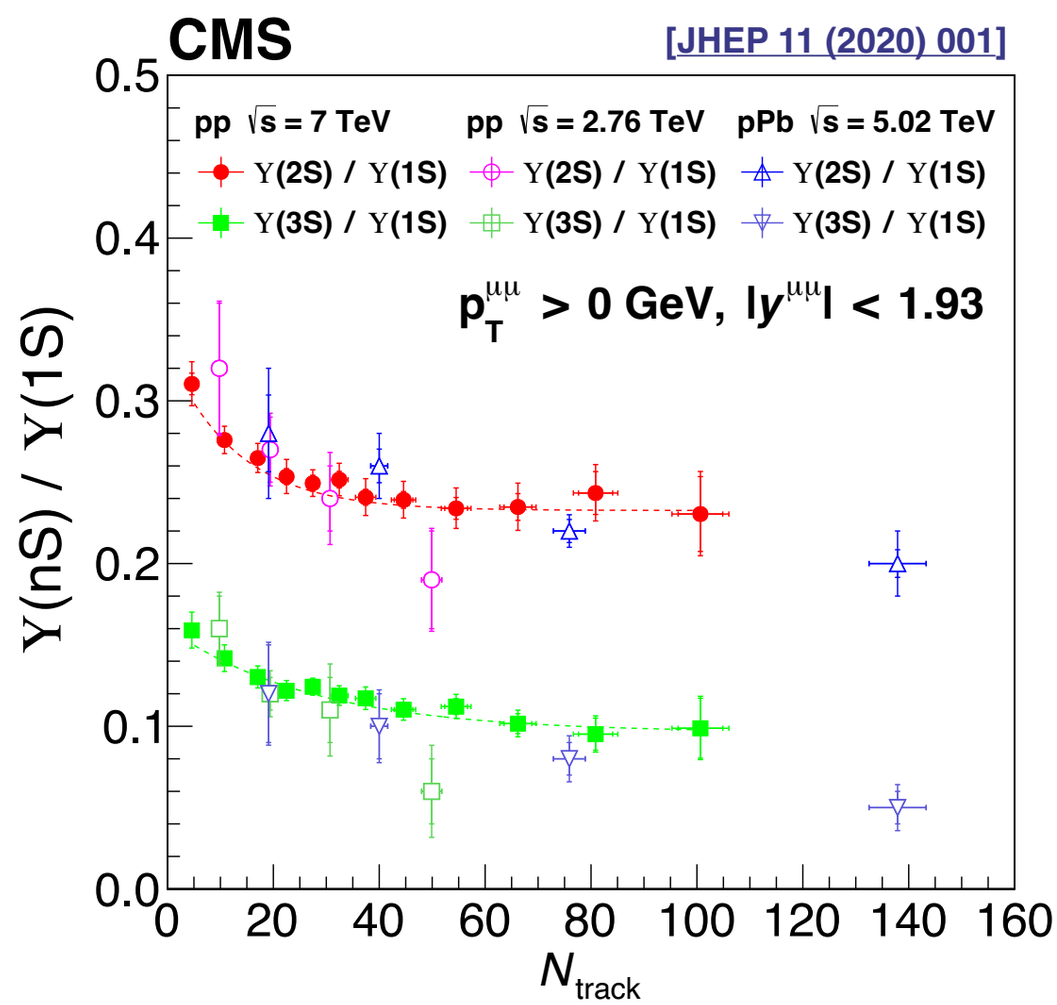

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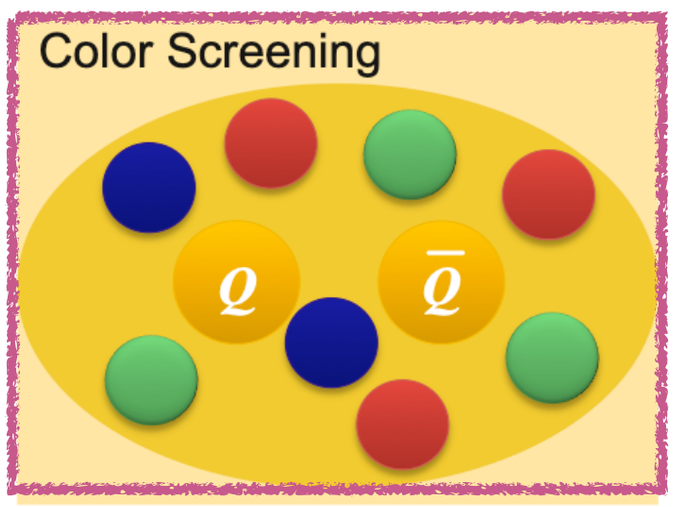
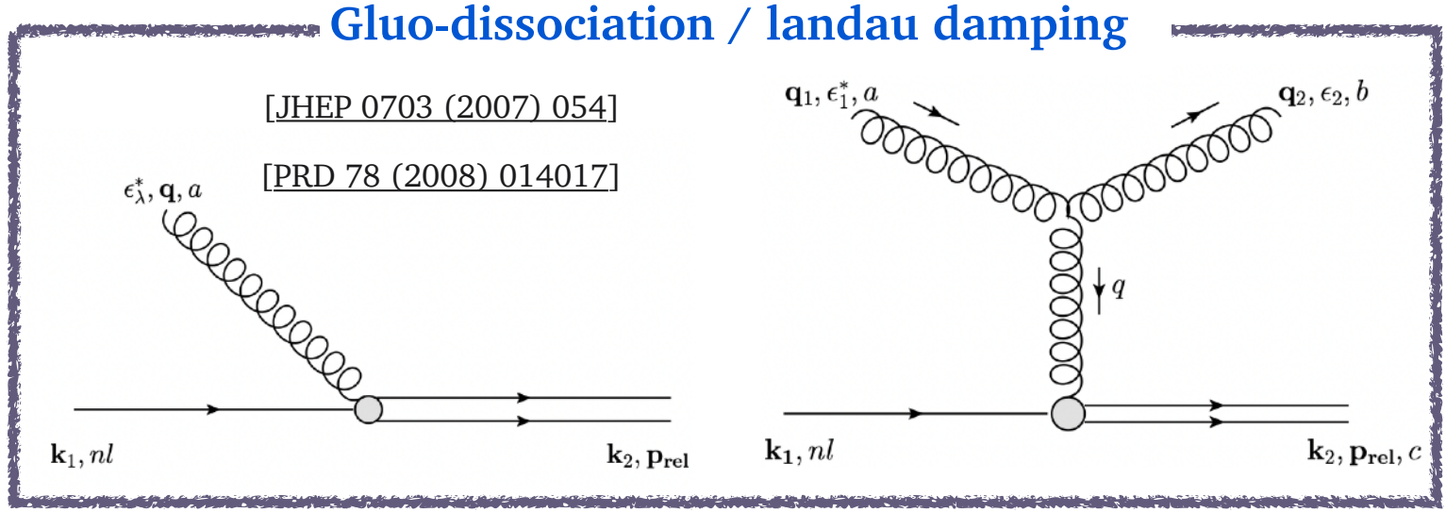
From theory

- ☑ Calculations for dissociation processes —> Suppression
  - — static/dynamical screening captured as real/imaginary part of the potential





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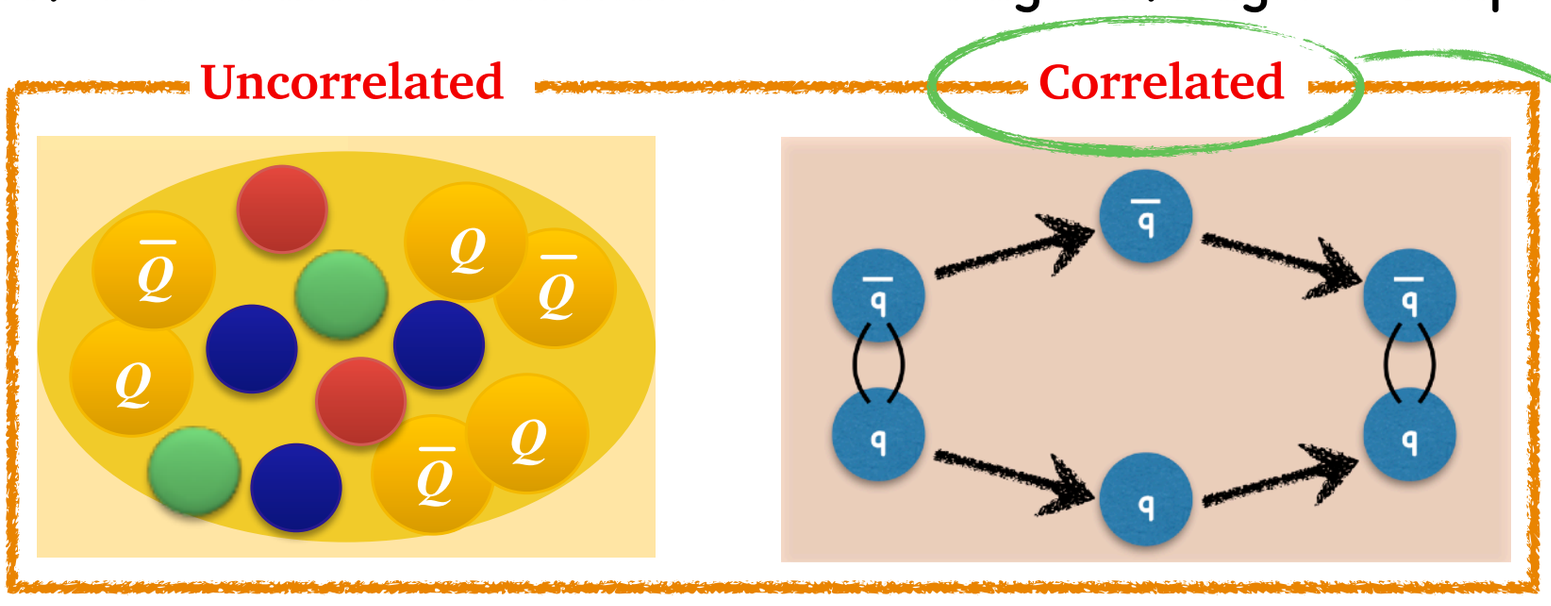

Recent theories :
Not so small anymore
even for Υ(1S)!

What we learned from Upsilons in heavy ion collisions

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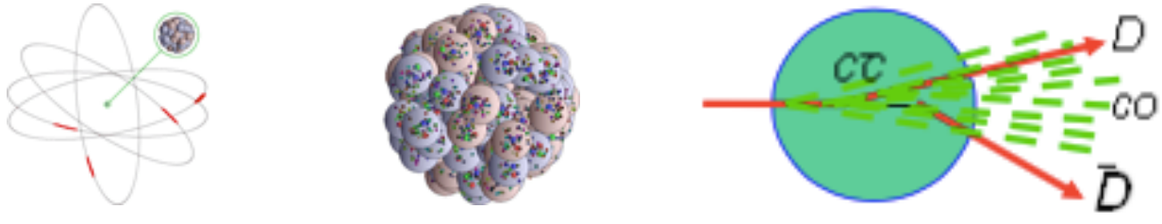
- ☑ Initial/Final state effect apart from hot-medium effects
  - — nPDF, CGC, coherent energy loss, comover breakup, etc.

[IJMP E 24 (2015) 1530008]



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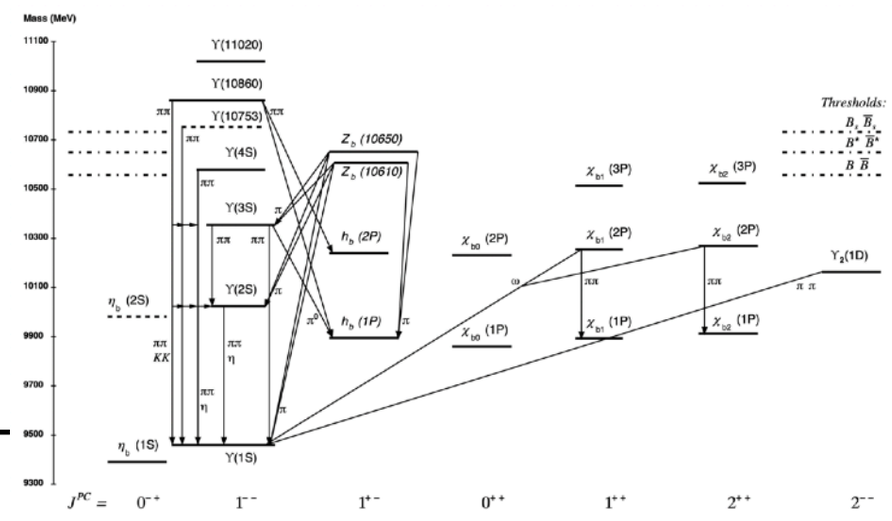
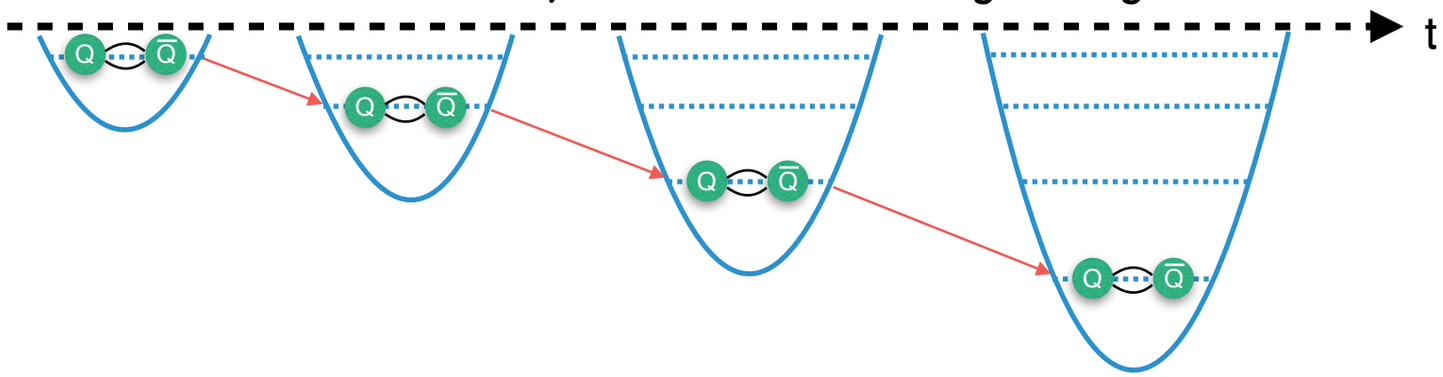
- ☑ Recombination process —> Enhancement
  - — correlated/uncorrelated recombination or off-diagonal/diagonal components
- ☑ Initial/Final state effect apart from hot-medium effects
  - — nPDF, CGC, coherent energy loss, comover breakup, etc.
- ☑ Huge contribution from feed-downs
  - — Υ(1,2,3S) all affected strongly depending on p_T

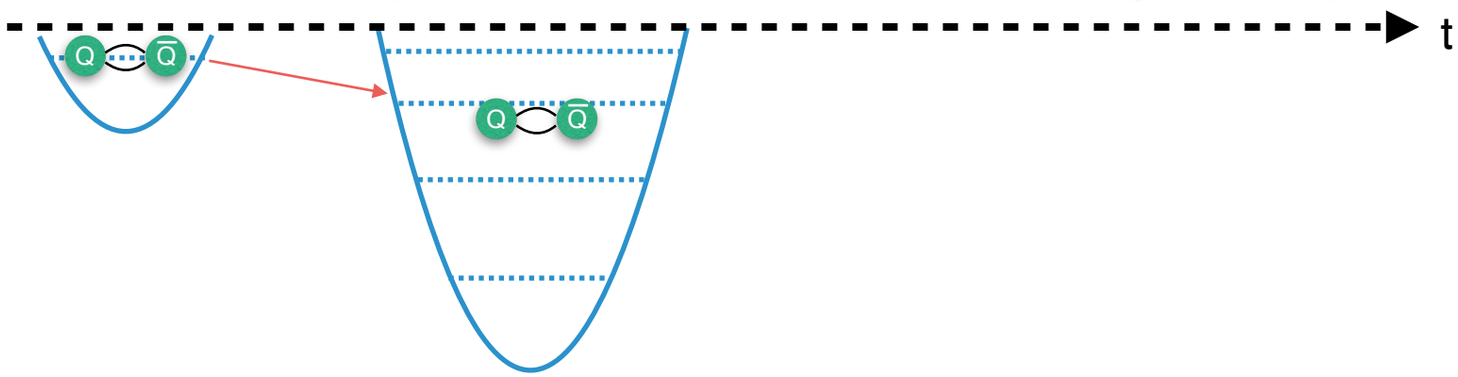


Quarkonia in media — not a simple picture…

If the medium evolves slowly : state remains in a given eigenstate

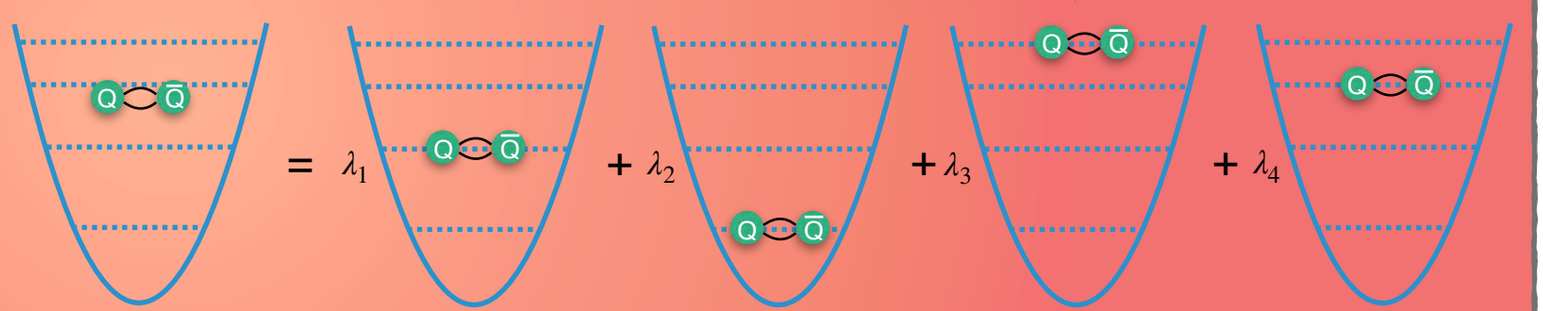


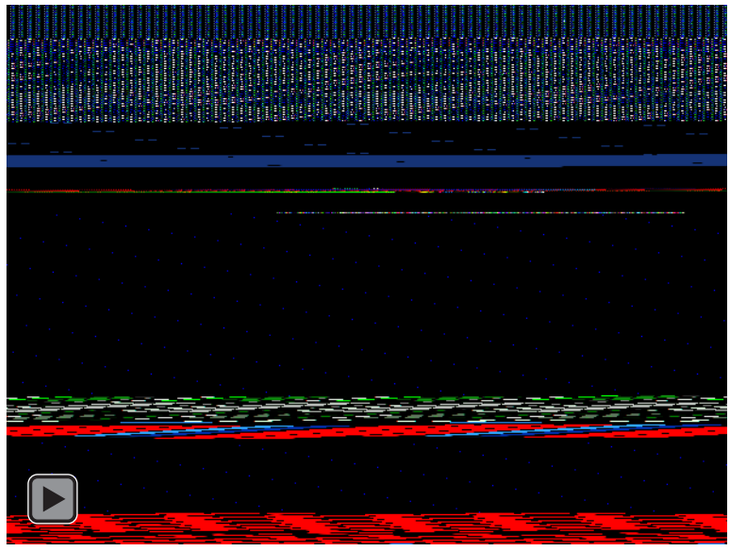
In reality : rapid expansion —> too fast to catch the change of the potential



- Rapid expansion…
- Corona region..
- Formation time…
- …

Q-Qbar state = projection on various eigenstates

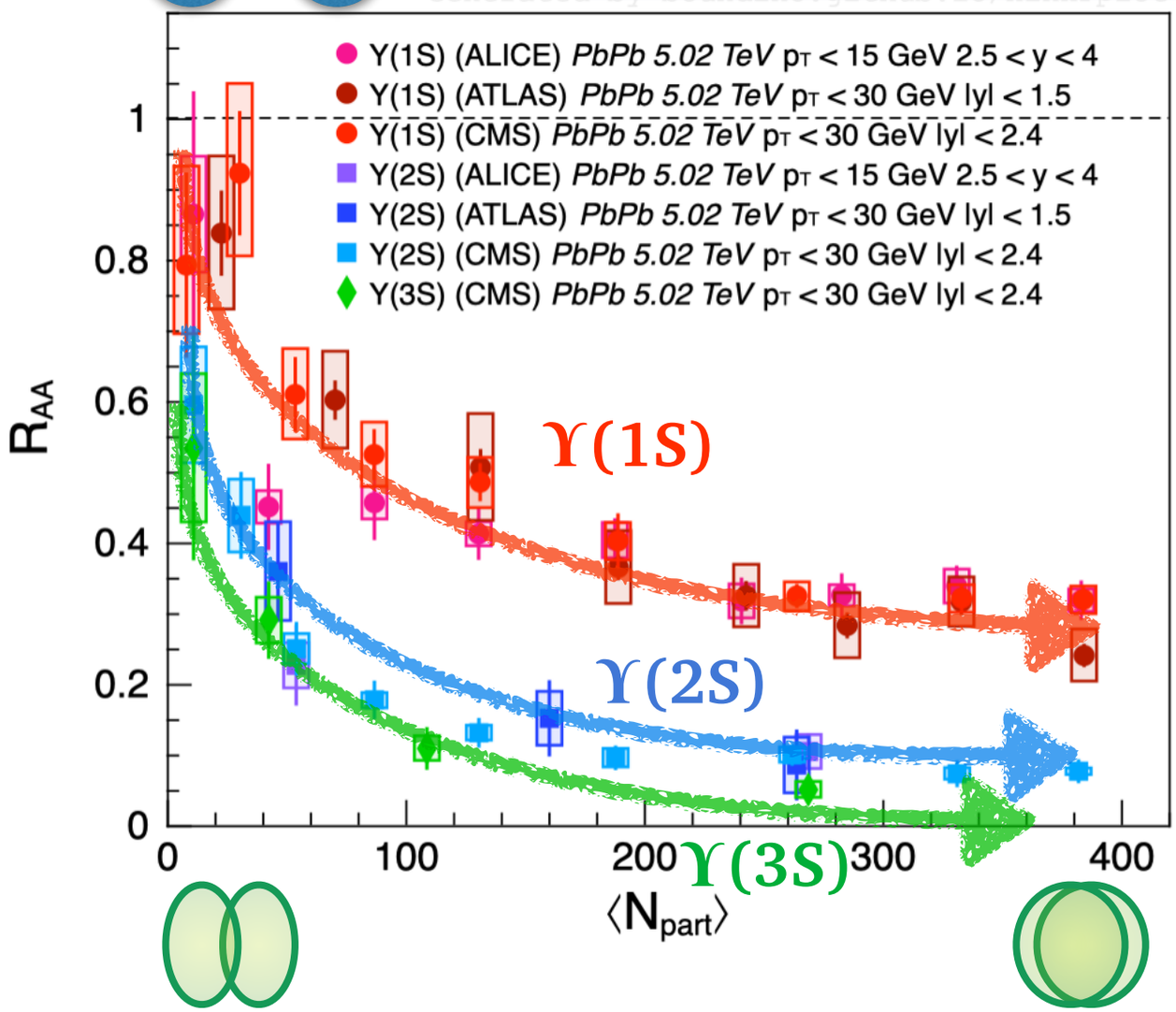


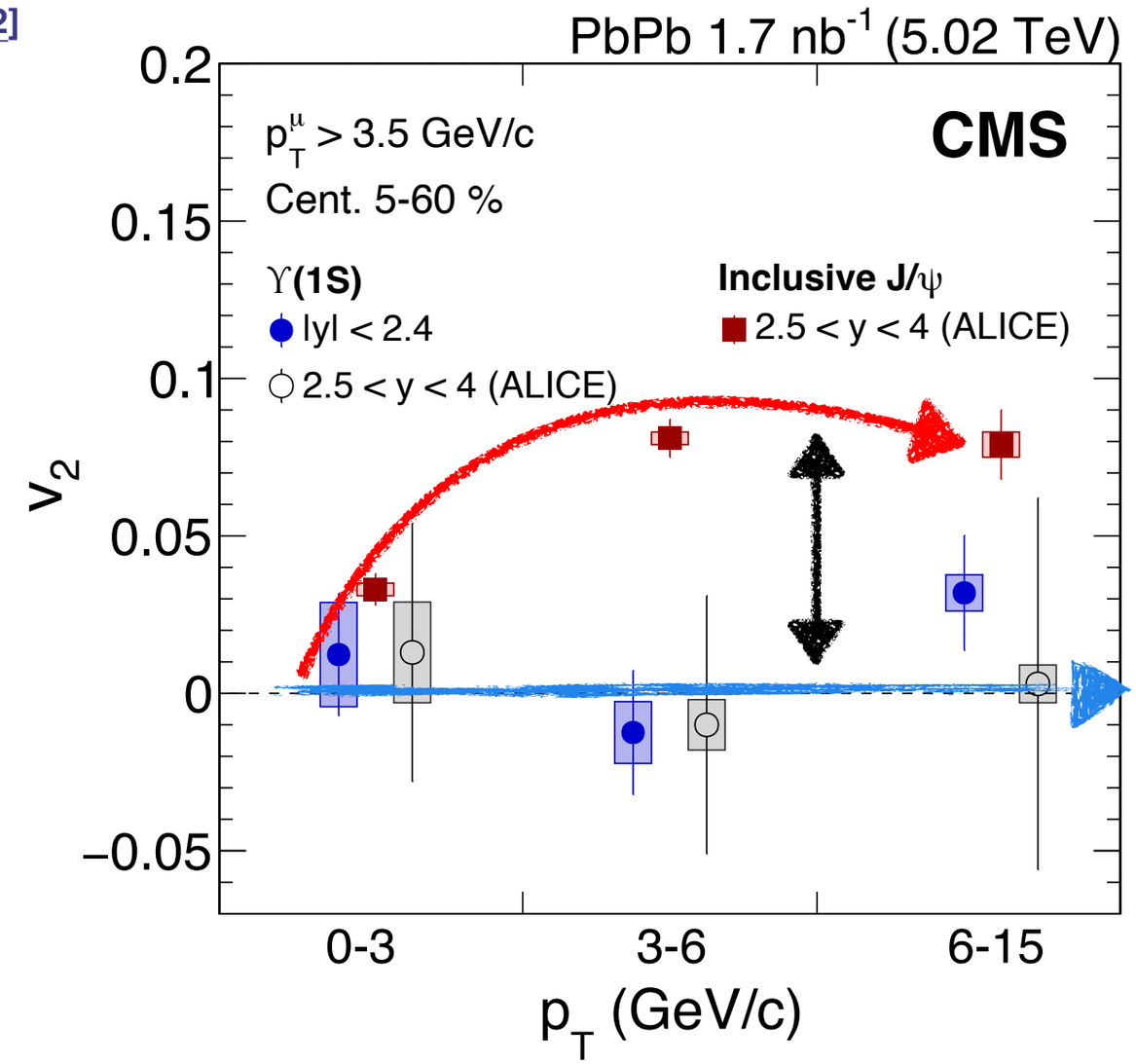


Start with familiar things..

Υ modification in AA

[PLB 822 (2021) 136579] [CMS-PAS-HIN-21-007] [PRL 123 (2019) 192301] [PLB 819 (2021) 136385]
[PLB 790 (2019) 270] [arXiv:2205.03042]

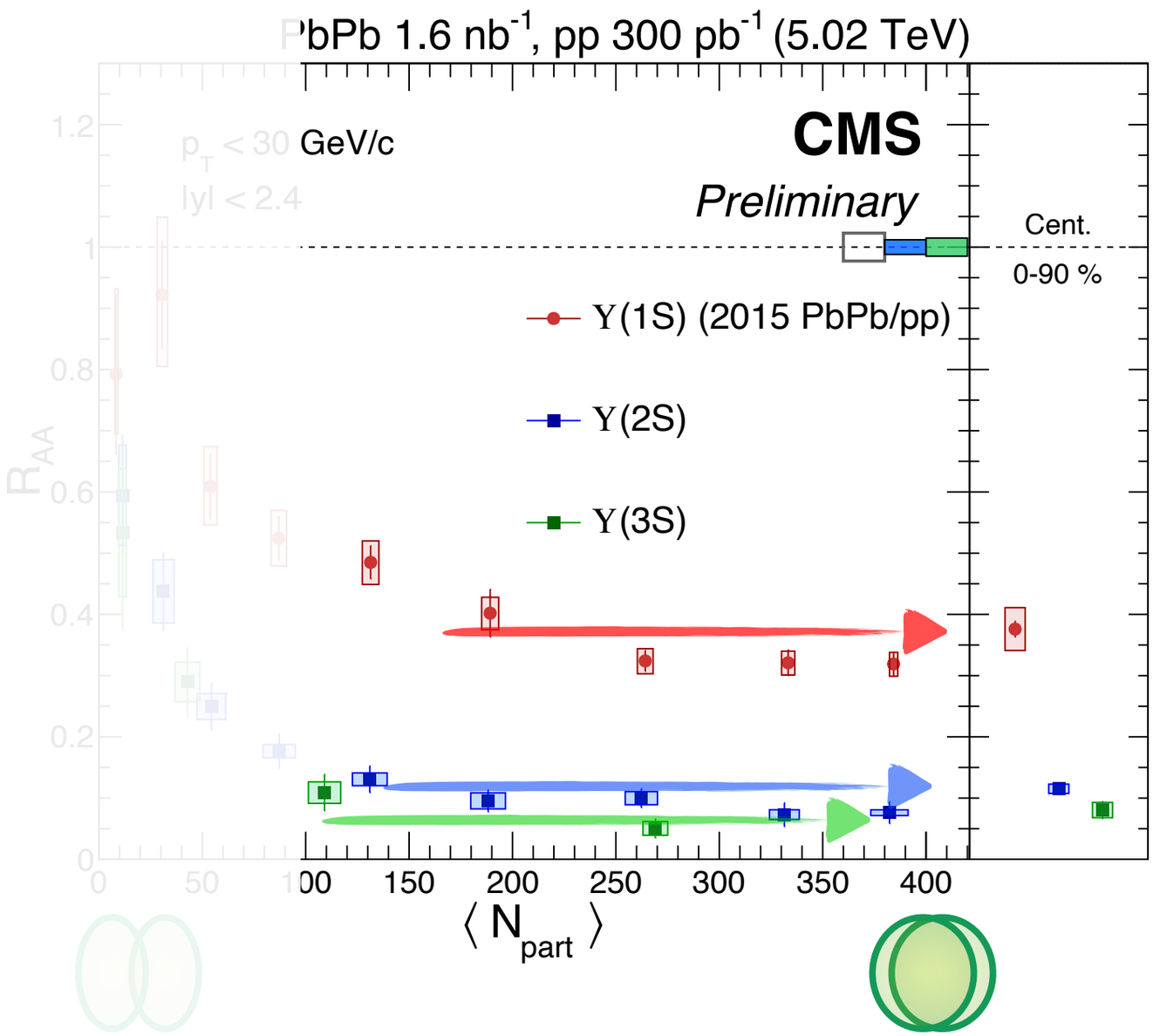




- Ordering of suppression : $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
- Υ(3S) observed in AA collisions
- $\Upsilon(1S)\ v_2 \approx 0 \longleftrightarrow J/\psi\ v_2 > 0$

Υ modification in AA

[CMS-PAS-HIN-21-007]

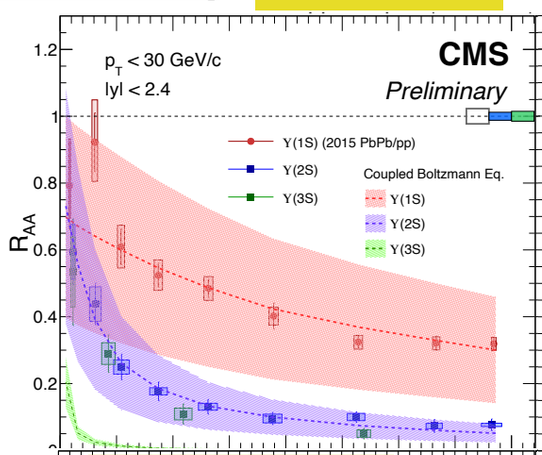


- Flattened in central collisions?
  - Dissociation ≈ Recombination?
  - Need more precision data

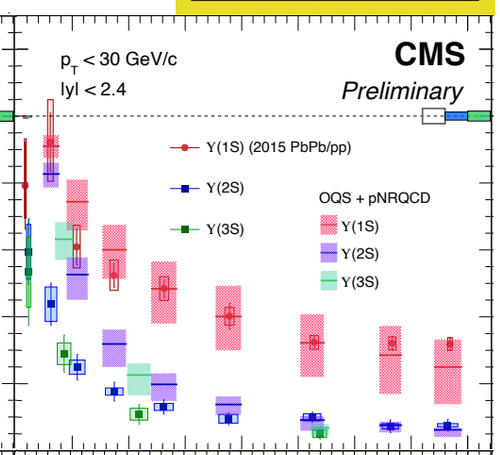
Theory comparison

[CMS-PAS-HIN-21-007]

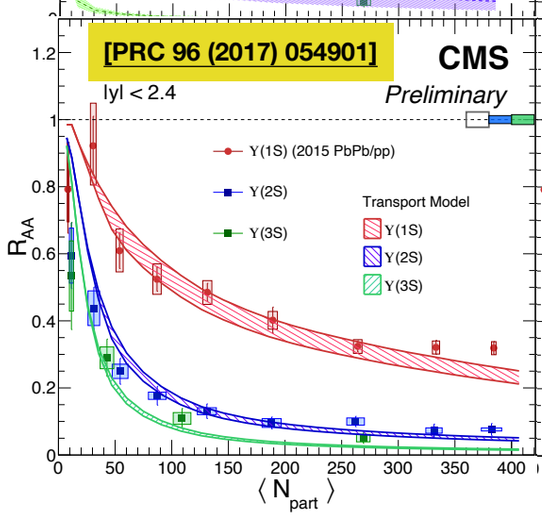
[arXiv:2009.05658]



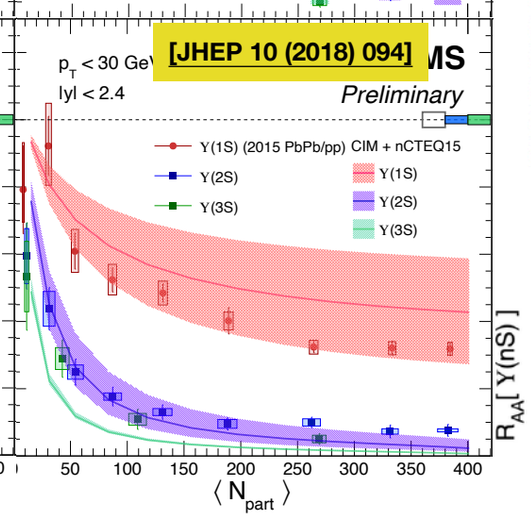
[PRD 104 (2021) 094049]



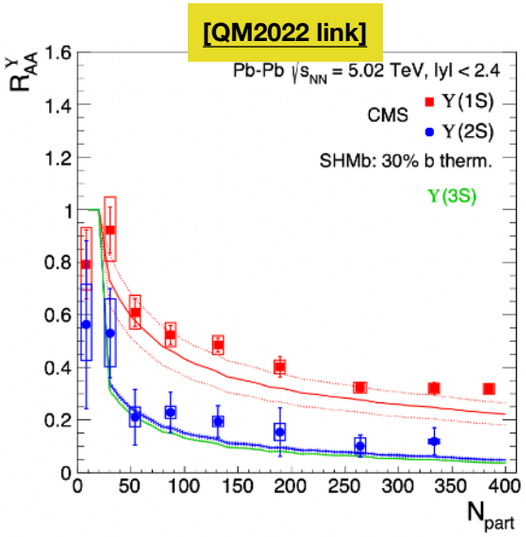
[PRC 96 (2017) 054901]



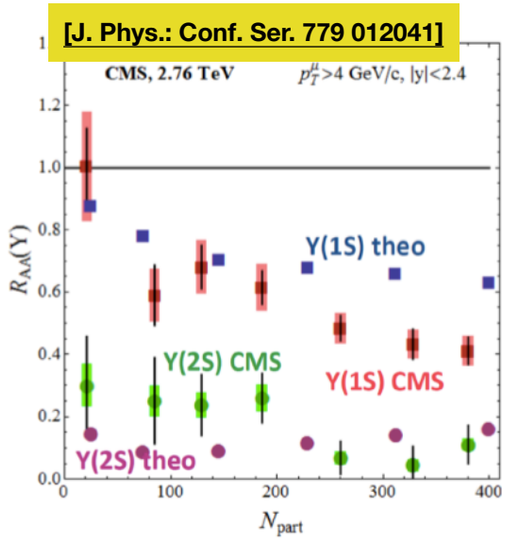
[JHEP 10 (2018) 094]



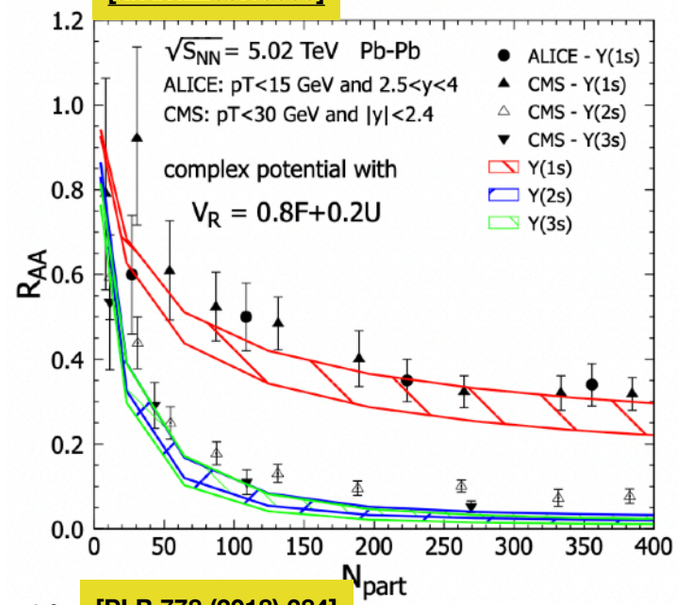
[QM2022 link]



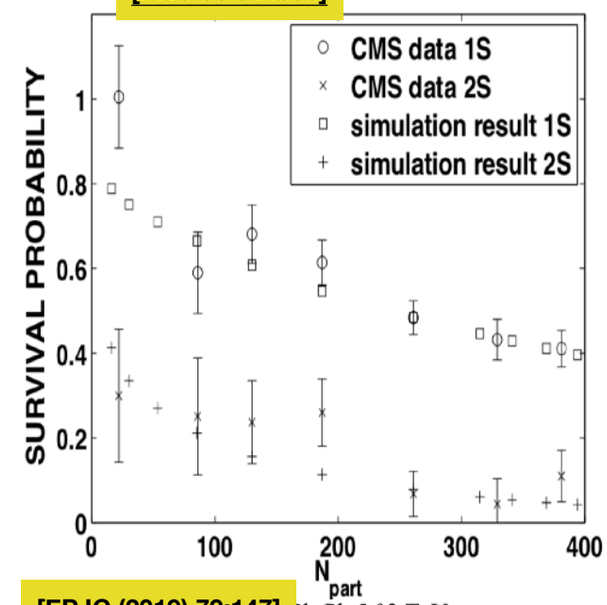
[J. Phys.: Conf. Ser. 779 012041]



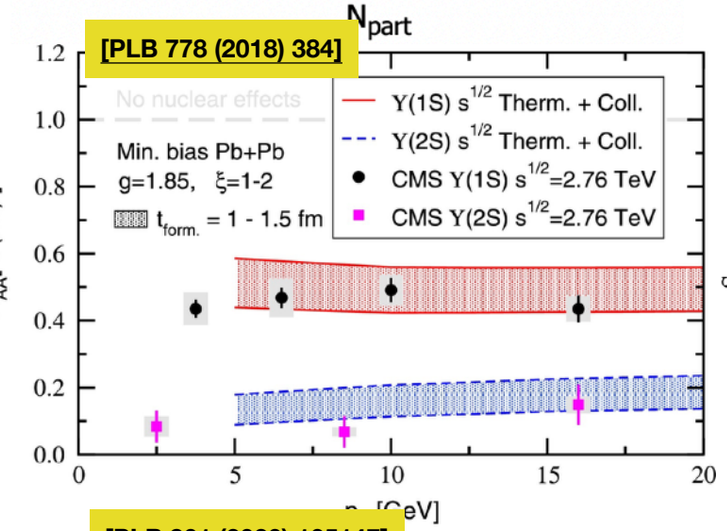
[arXiv:2208.10050]



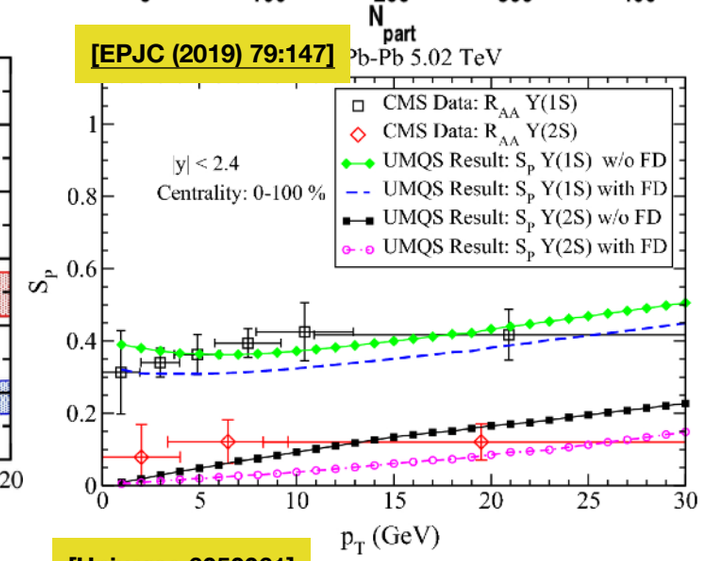
[PRC 88 044908]



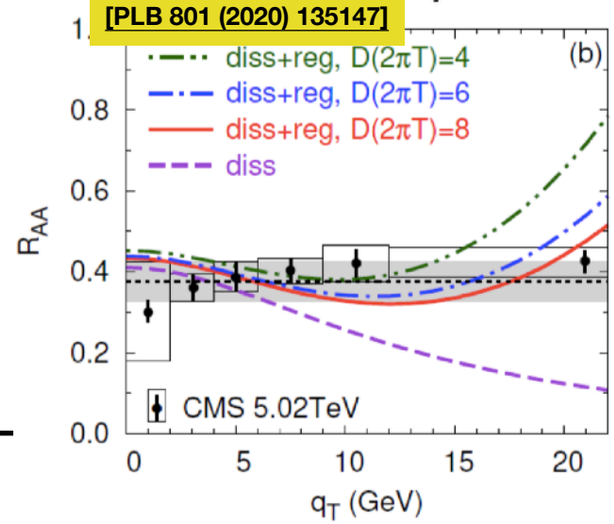
[PLB 778 (2018) 384]



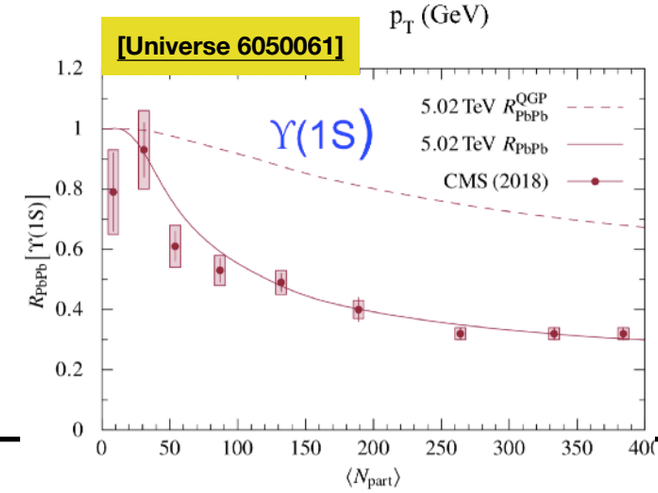
[EPJC (2019) 79:147]



[PLB 801 (2020) 135147]

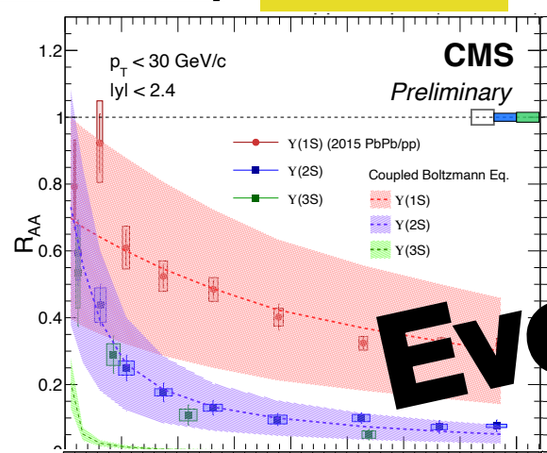


[Universe 6050061]



Theory comparison

[CMS-PAS-HIN-21-007]



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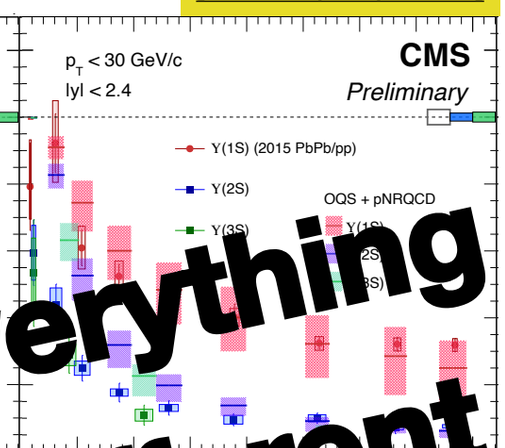
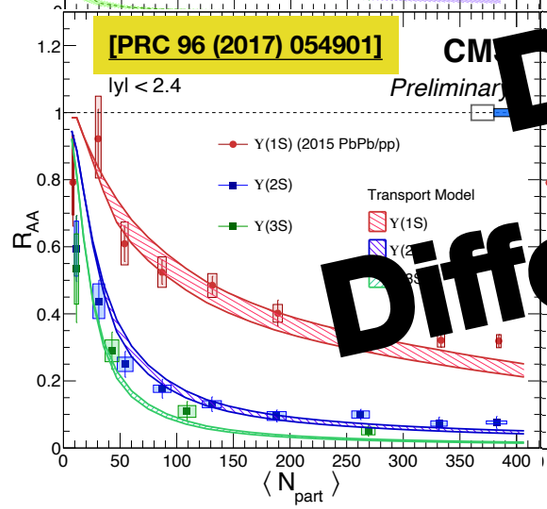
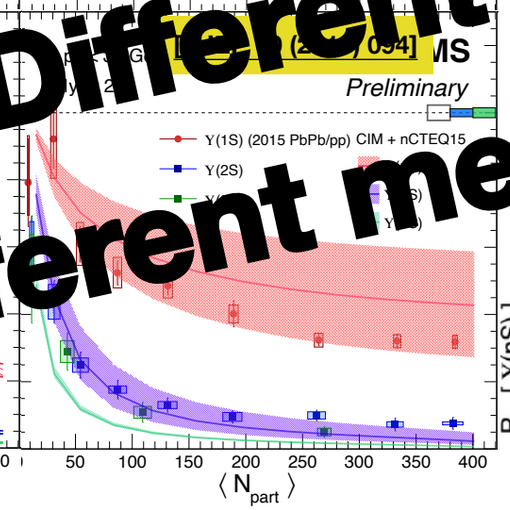


[PRD 104 (2021) 094049]

[PRC 96 (2017) 054901]





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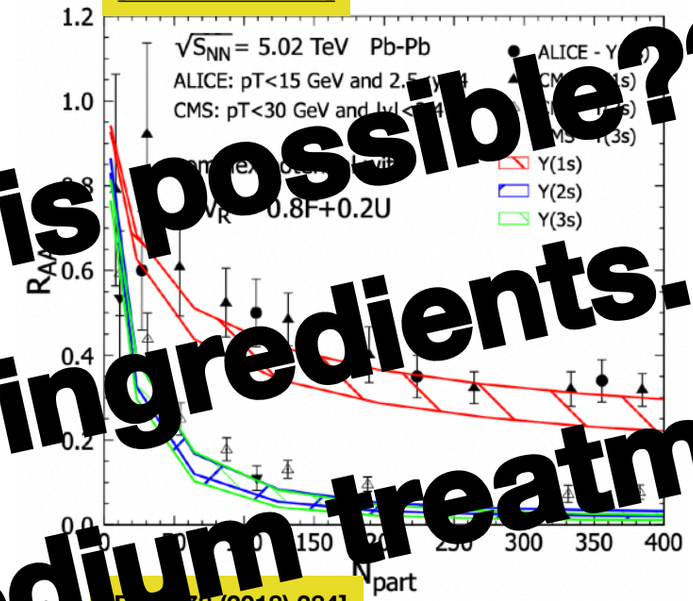
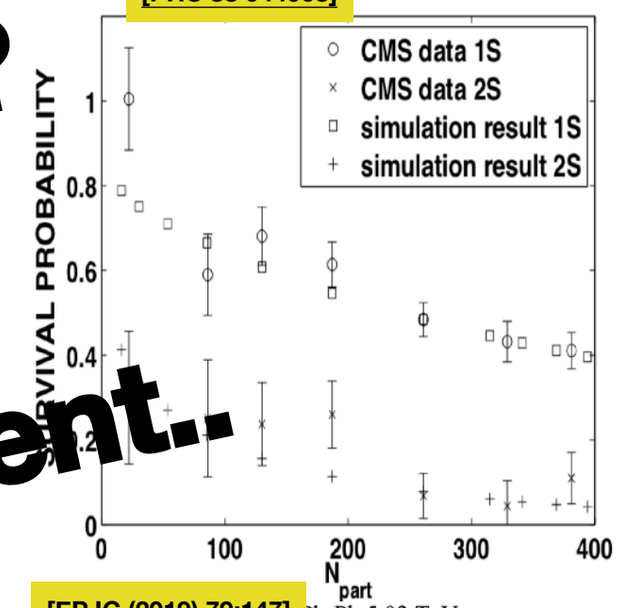
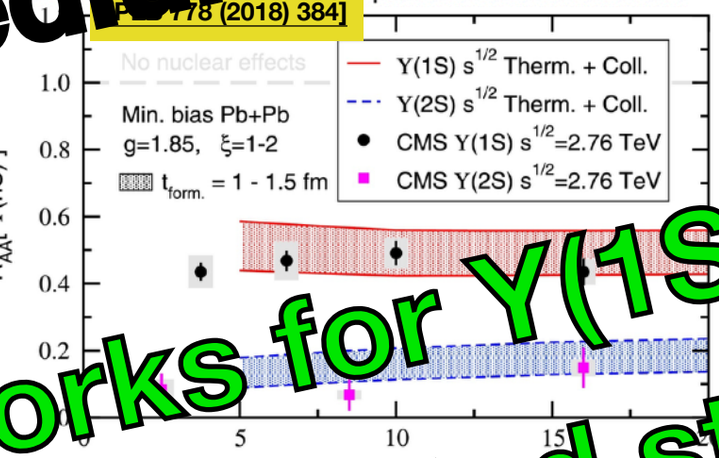


[PRC 88 044908]



[PLB 778 (2018) 384]



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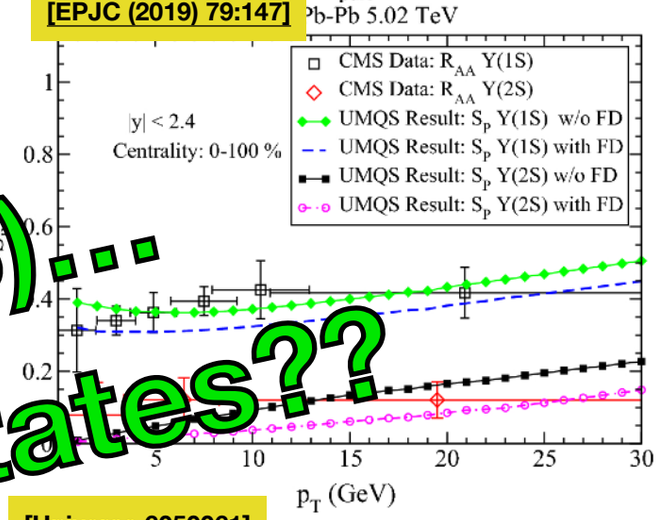
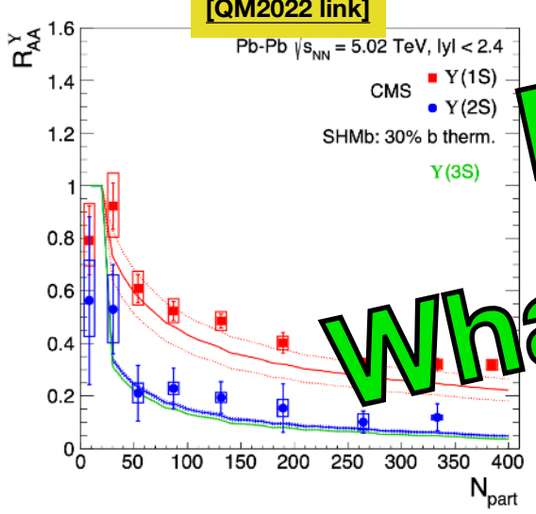
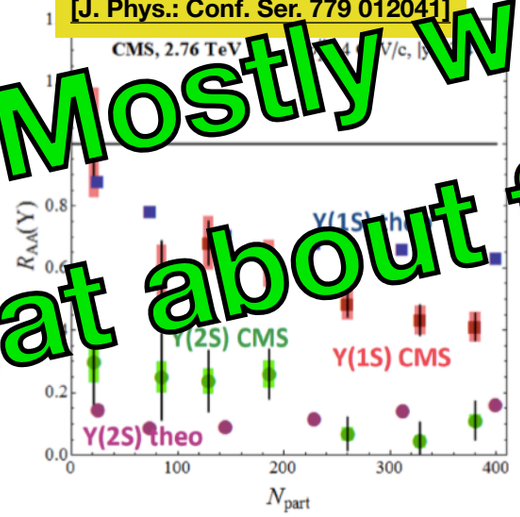


[QM2022 link]



[J. Phys.: Conf. Ser. 779 012041]



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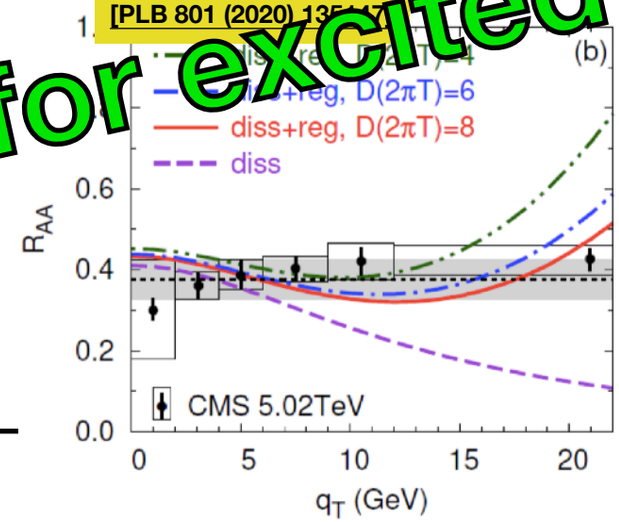

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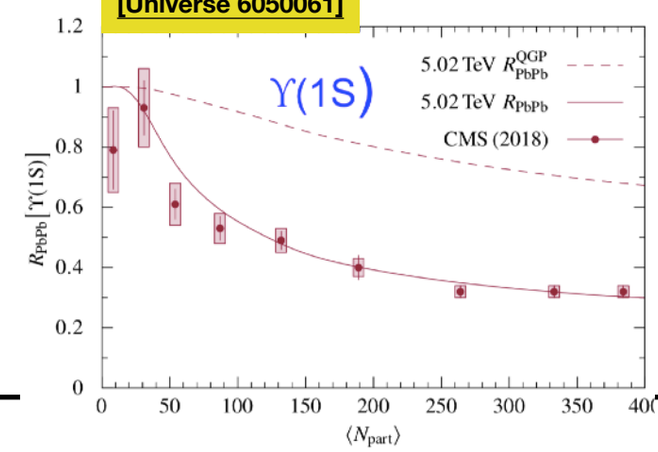


Everything is possible??

Different ingredients..

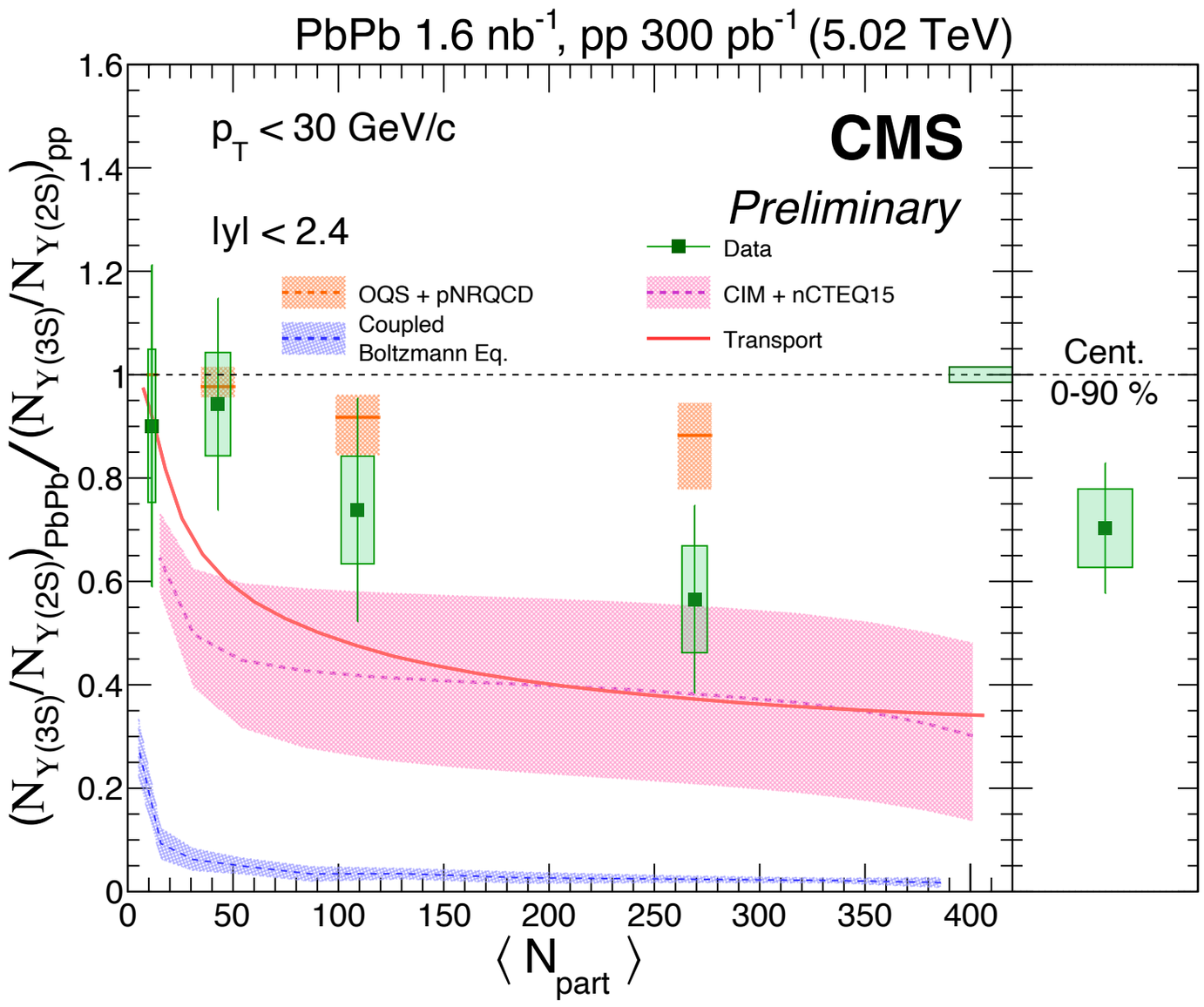
Different medium treatment..

Mostly works for Υ(1S)...

What about for excited states??

Excited states double ratio

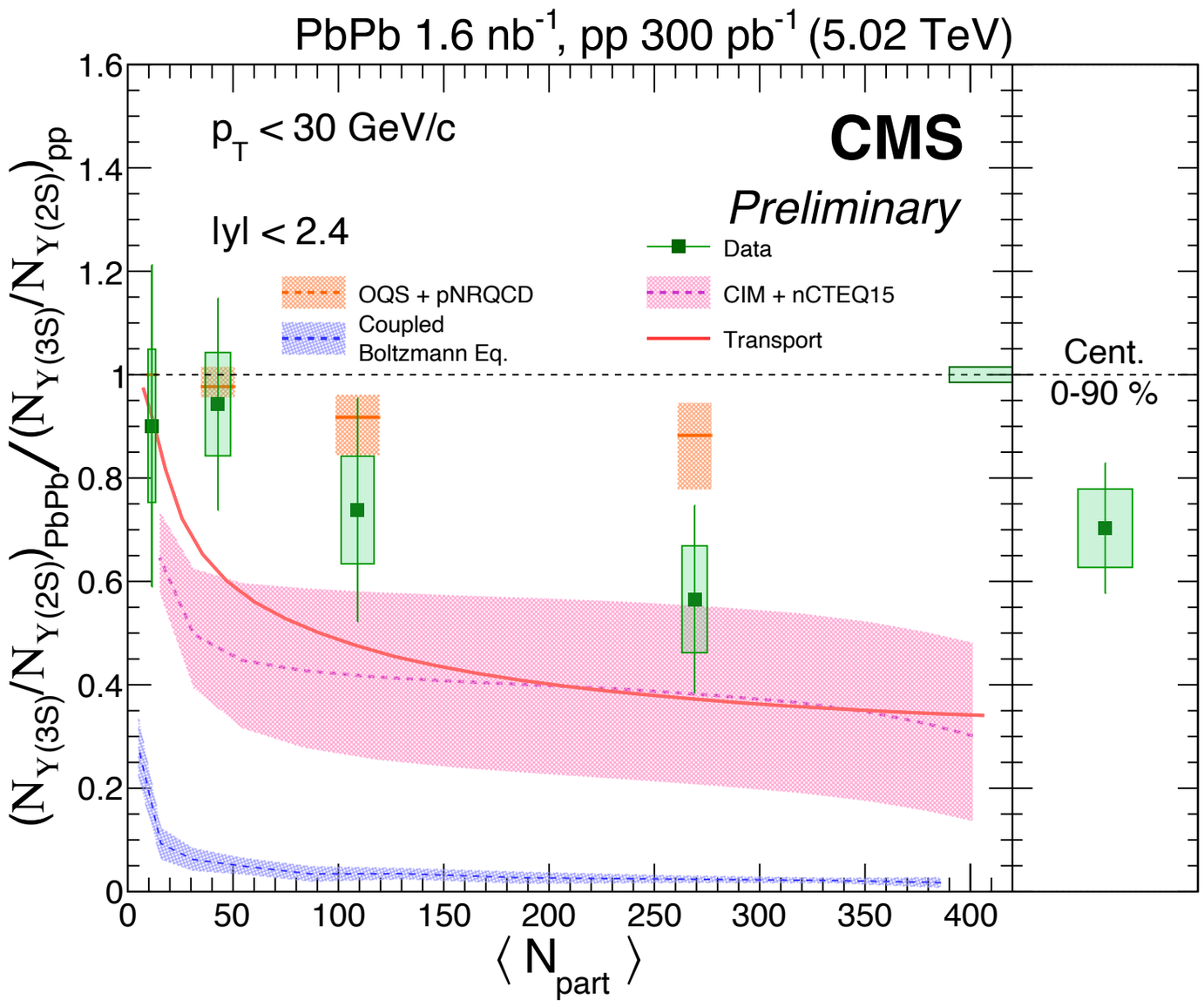
[CMS-PAS-HIN-21-007]

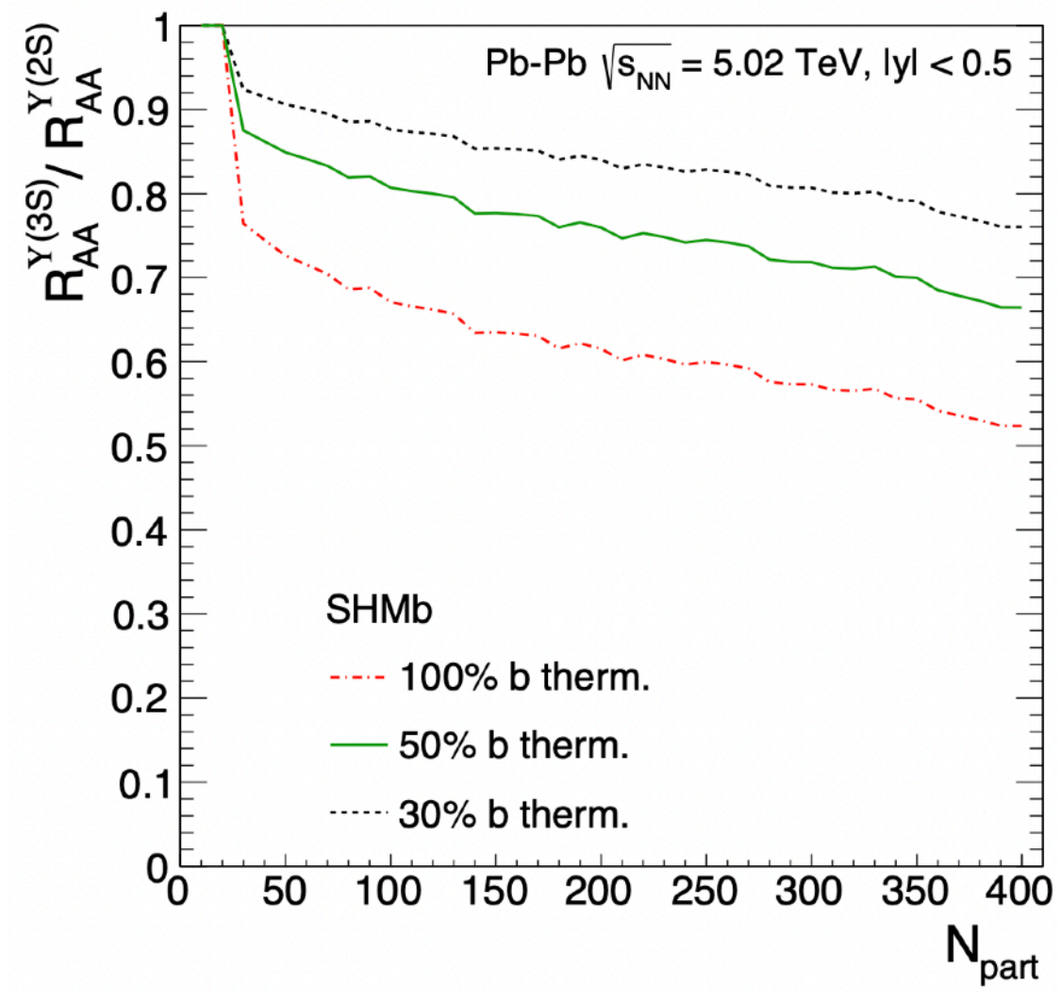


- CMS proposed Υ(3S)/Υ(2S) double ratio as a new observable to test theory models
- Sensitive to suppression & recombination due to the weaker binding energy than Υ(1S)
- Still statistical hungry measurement —> expect to be improved with Run3

Excited states double ratio

[CMS-PAS-HIN-21-007]

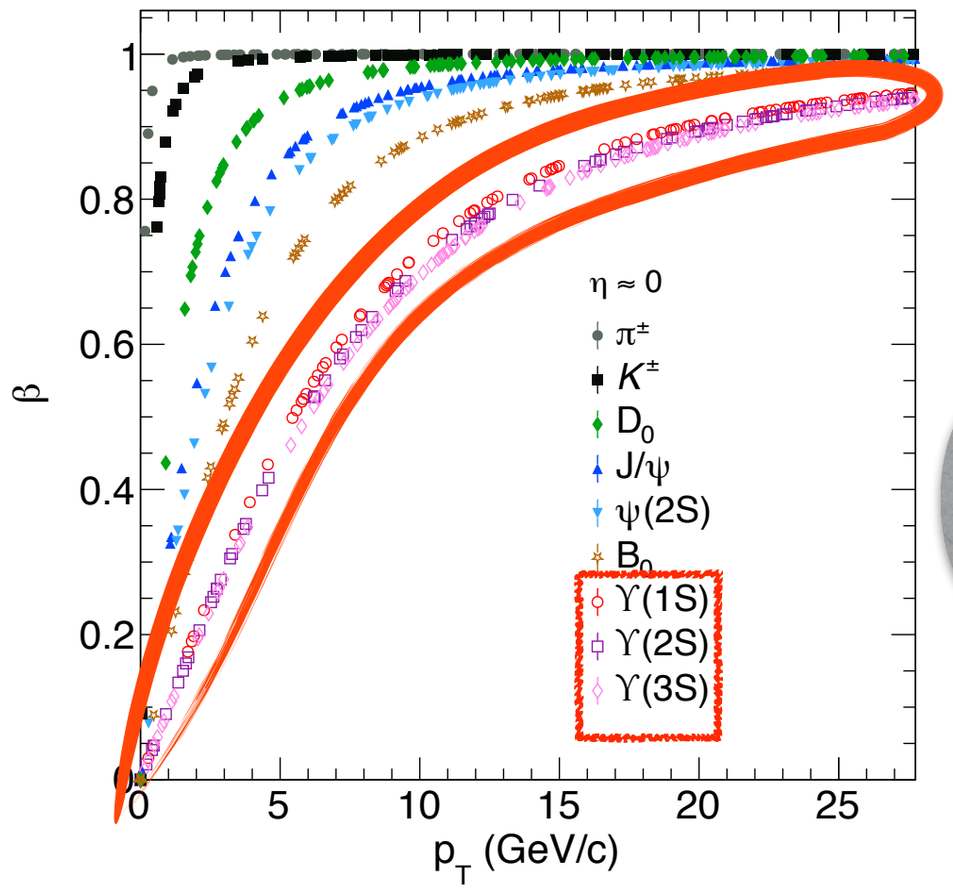


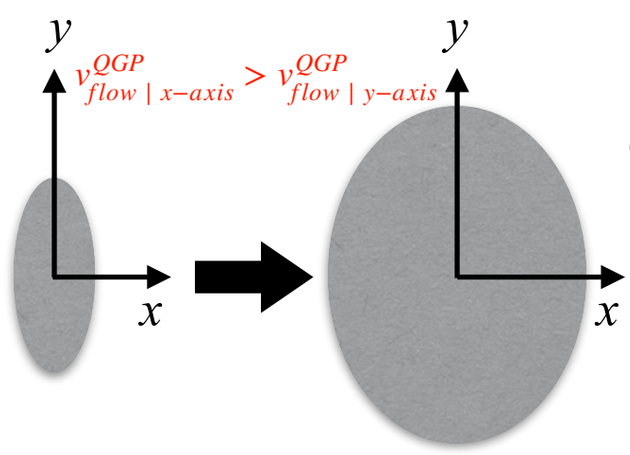


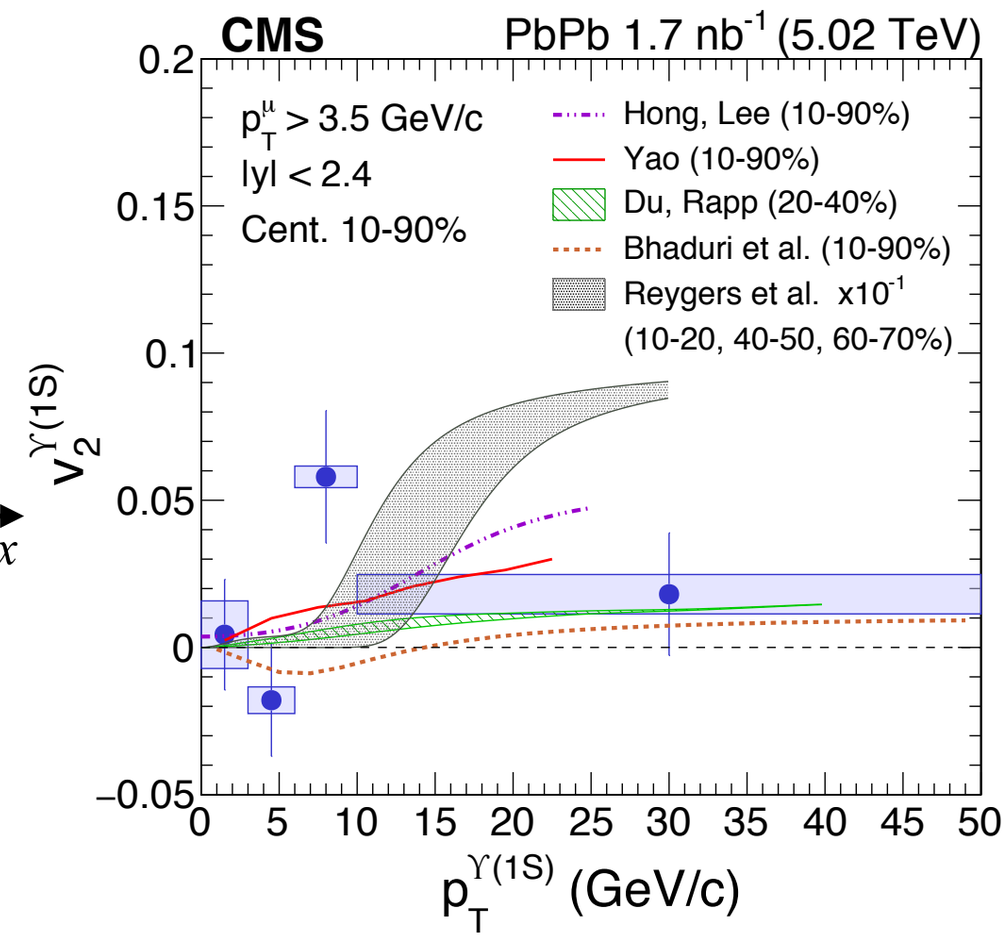
- Sensitive to degree of b thermalization?
  —> see also talk from Anton

Towards future prospects

- **Υ has much smaller velocity compared to other species**
  - Low-p_T : $v^{\Upsilon} < v^{QGP}_{flow}$ —> Cannot escape QGP
  - Intermediate p_T : $v^{\Upsilon} \simeq v^{QGP}_{flow}$ —> Effective travel distance longer for short-axis : v_2<0?
  - High-p_T : $v^{\Upsilon} > v^{QGP}_{flow}$ —> Experience initial geometry from fast QGP escape

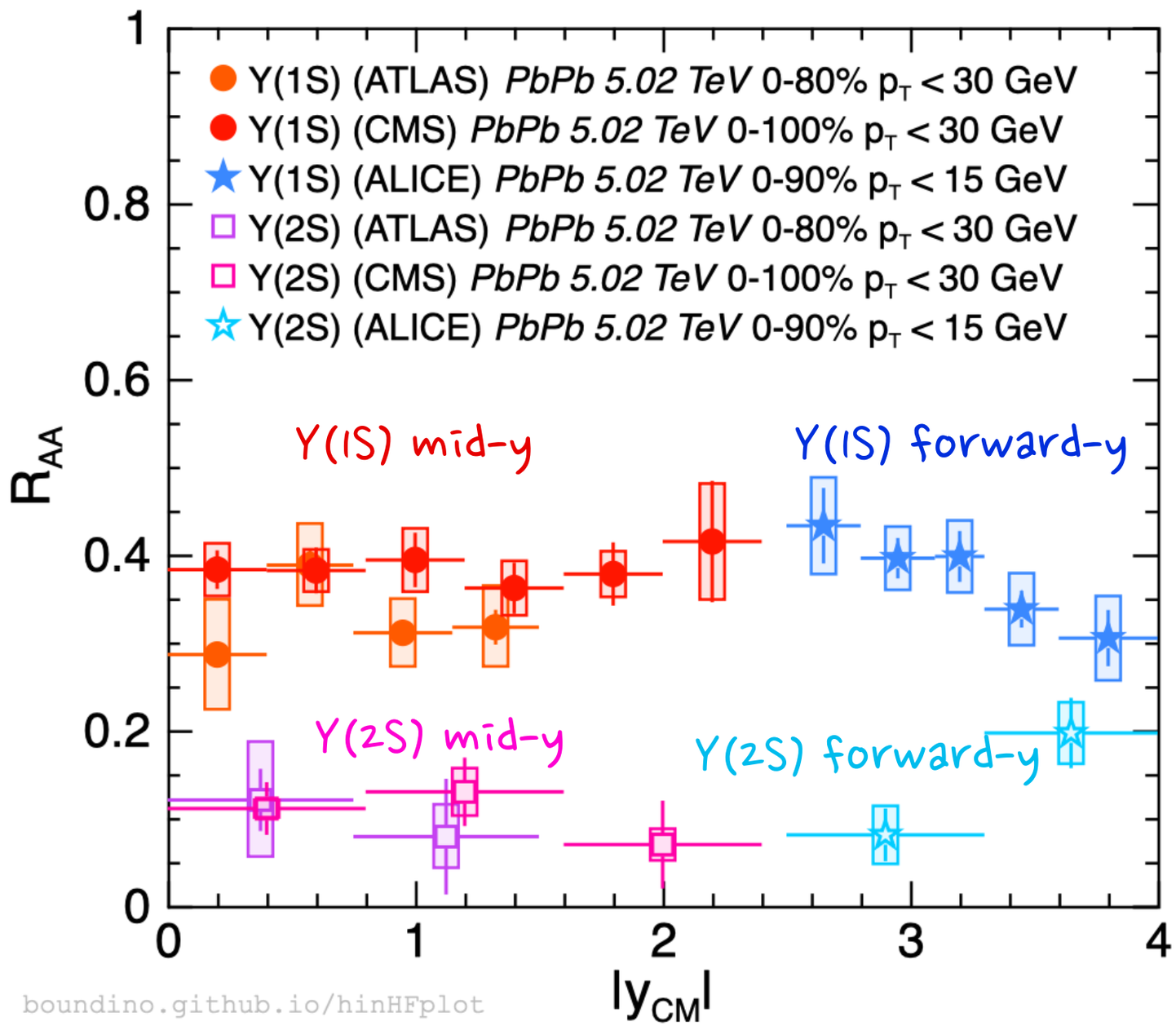






Towards future prospects

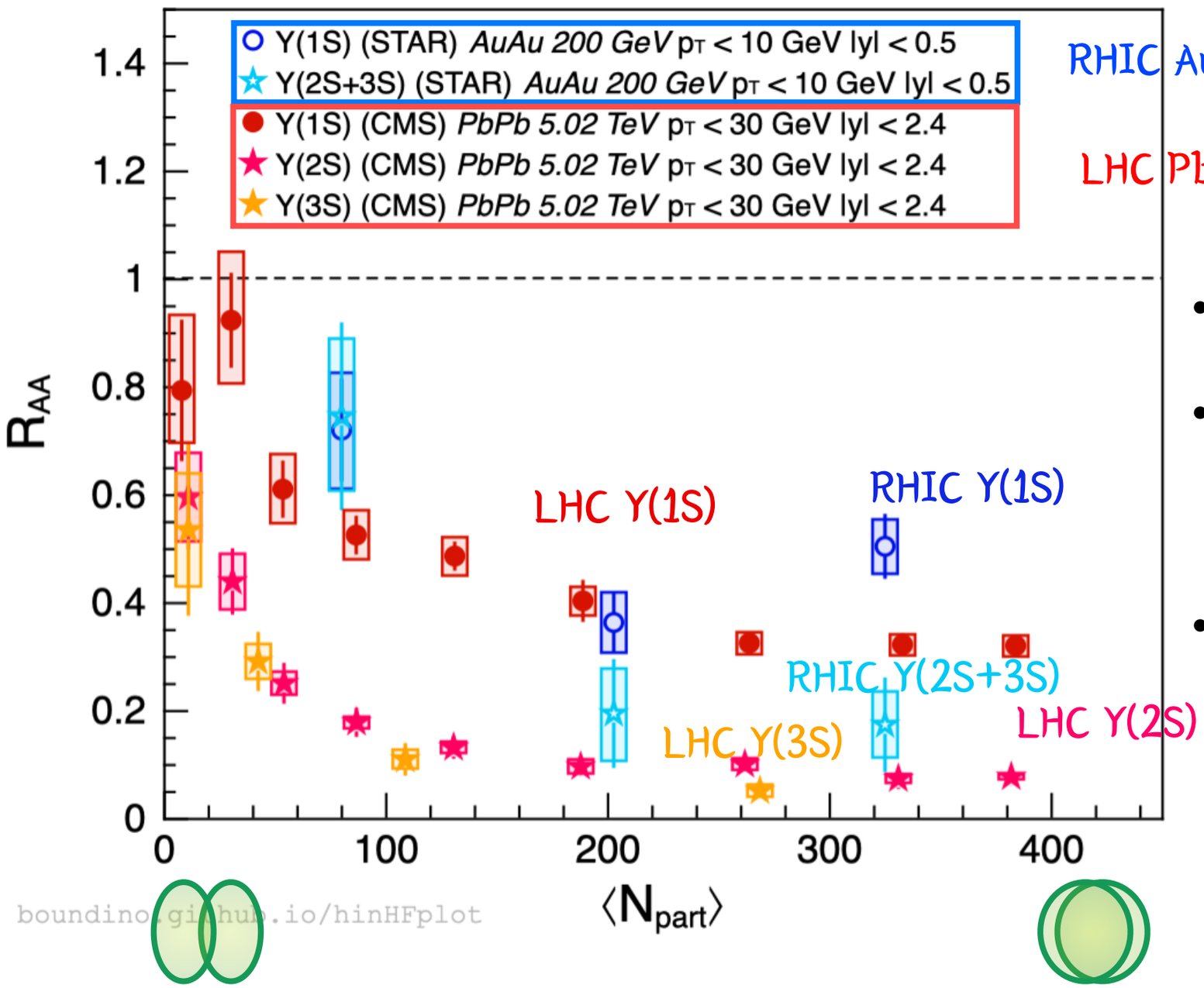
[arXiv:2205.03042] [PLB 822 (2021) 136579] [CMS-PAS-HIN-21-007]



- Rapidity dependent suppression?
- Different trend for Υ(1S) vs Υ(2S)?
- Caveat for interpolation pp results
  — Good to confirm with future LHCb

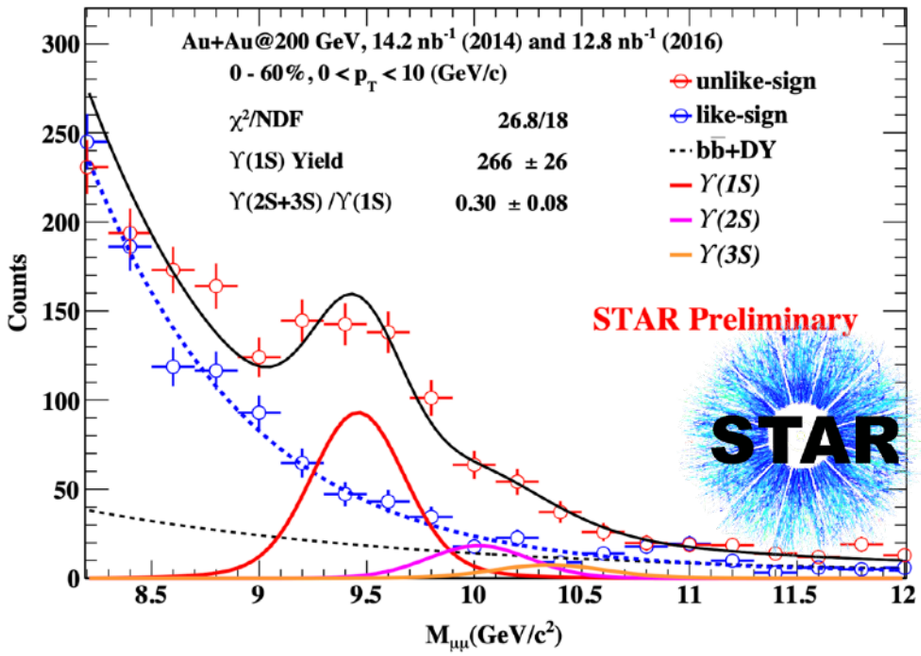
Υ R_{AA} RHIC vs LHC

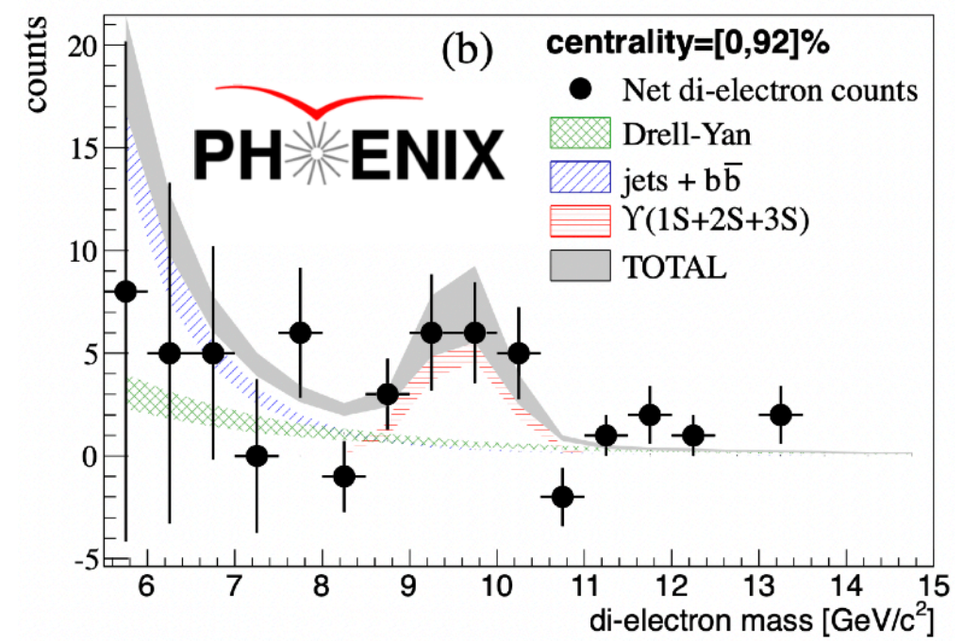
[CMS-PAS-HIN-21-007] [PLB 790 (2019) 270] [STAR Preliminary]



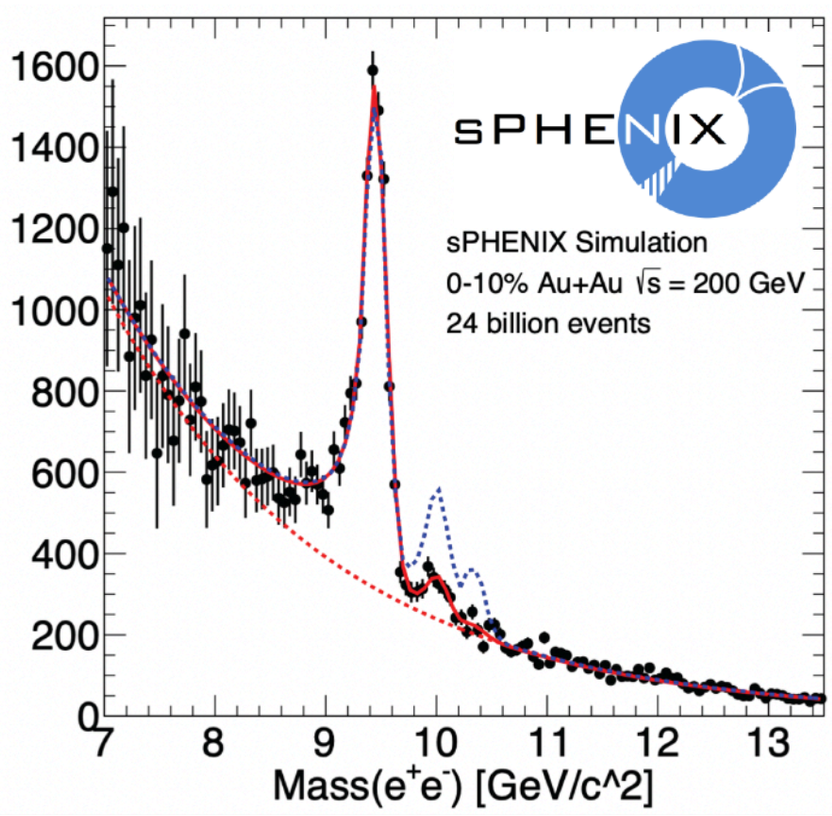
- Similar suppression in 0.2 vs 5.02 TeV?
- Different cold nuclear matter effects?
  - or not hot enough?
  - feed-down?
- Still large uncertainties…

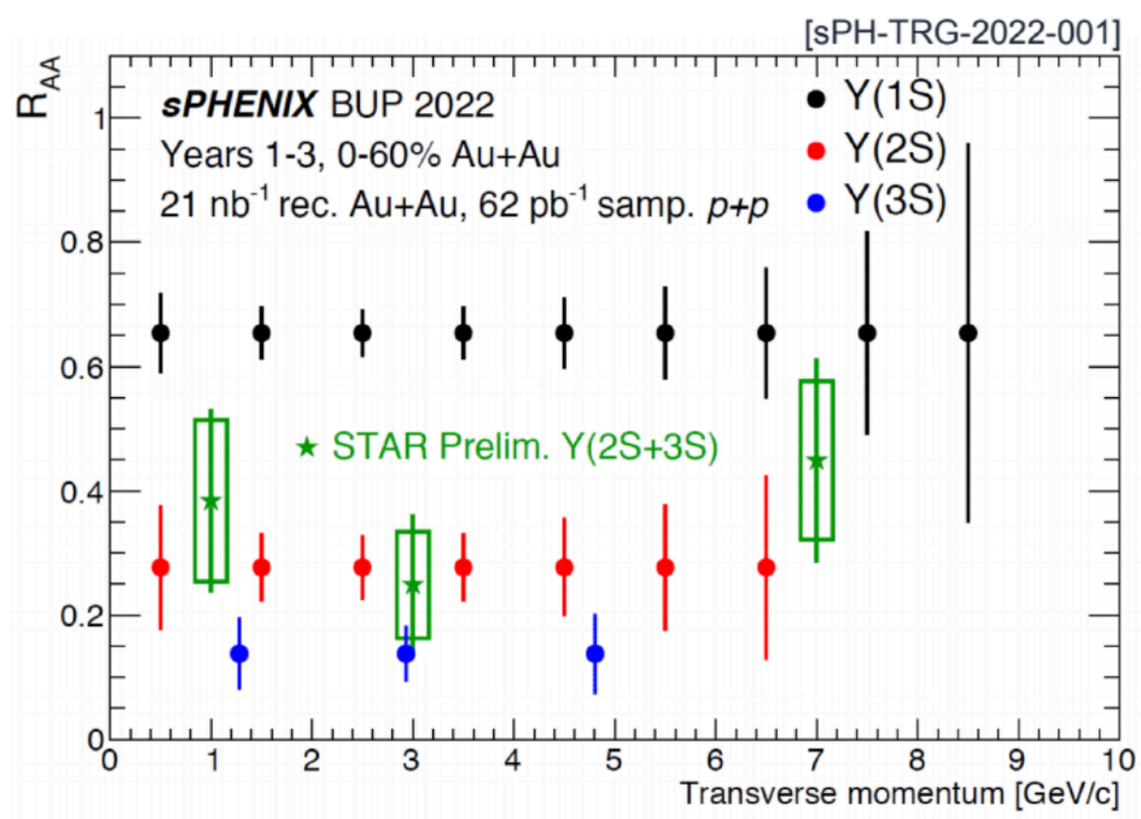
Future prospects @ RHIC





- Limitations in current RHIC measurements

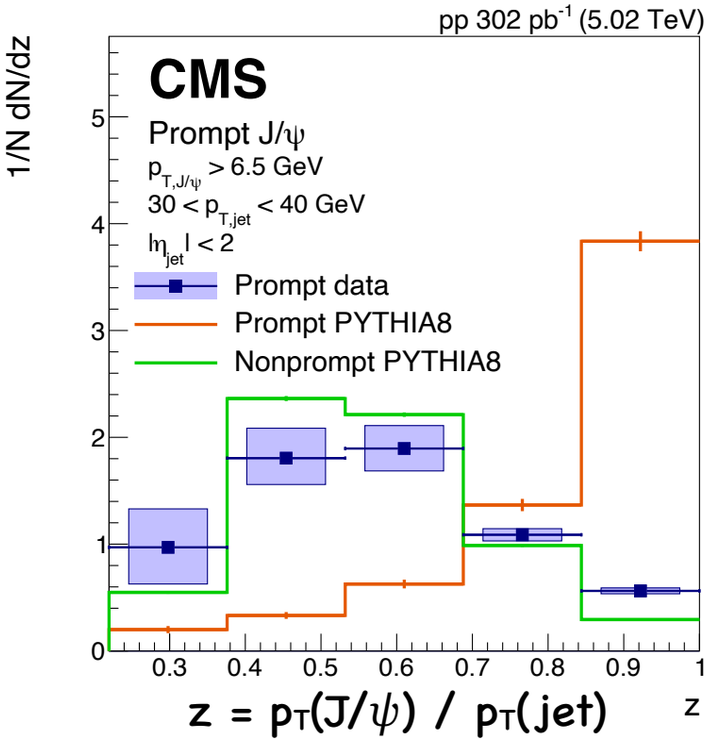




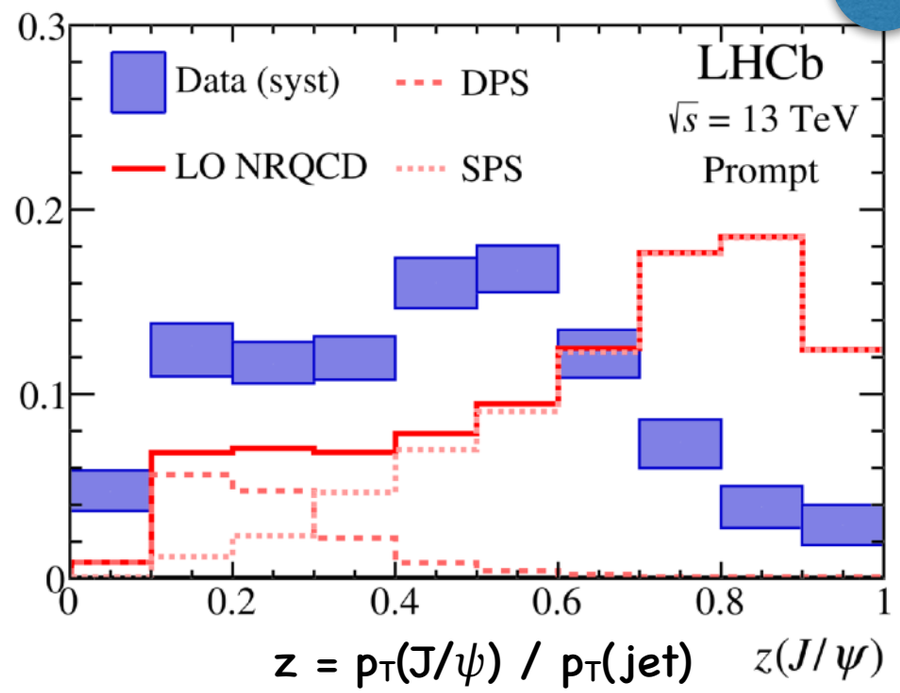
- To be confirmed with future experiments

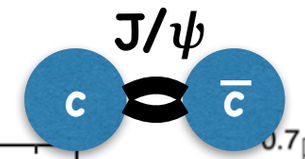
Towards future prospects

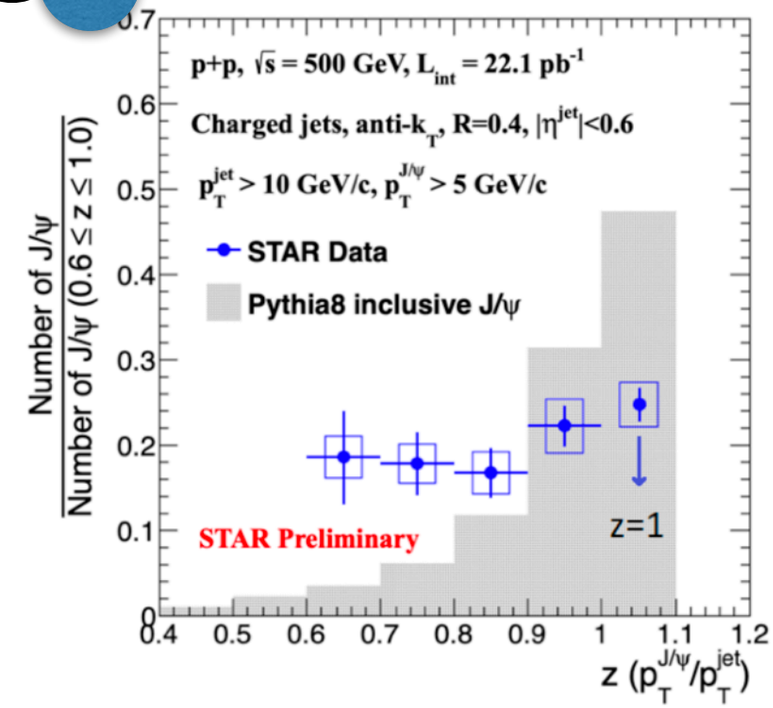
[PLB 805 (2020) 135434]

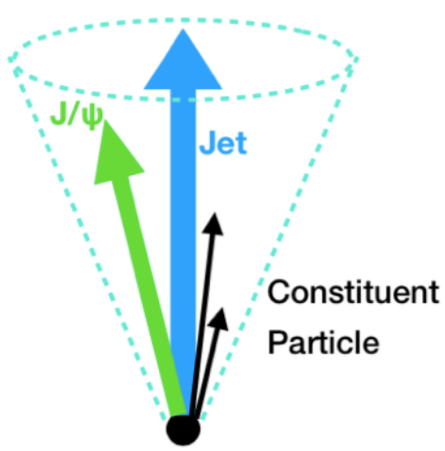


[PRL 118 (2017) 192001]









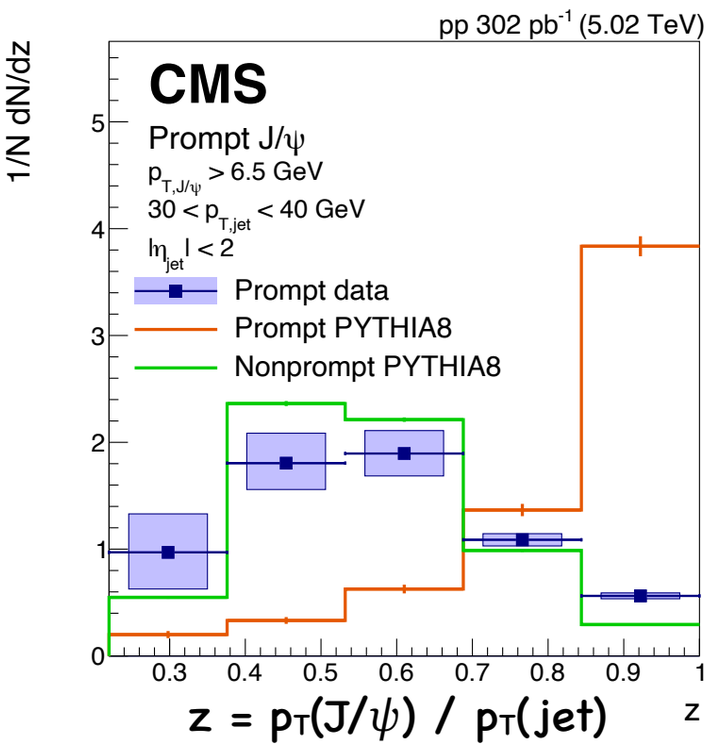
- Significant contribution from (inside) jets for J/ψ production!

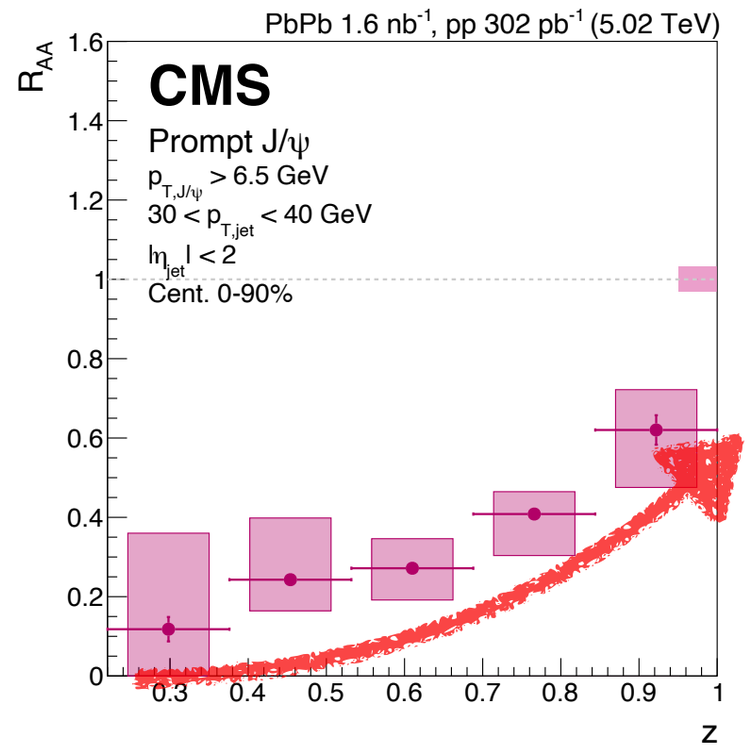
[CMS pp 8 TeV PLB 804 (2020) 135409]

~85% of J/ψ are produced within a jet
($E_{J/\psi}$ > 15 GeV, $|y_{J/\psi}|$ < 1, E_{jet} > 19 GeV, $|\eta_{jet}|$ < 1)

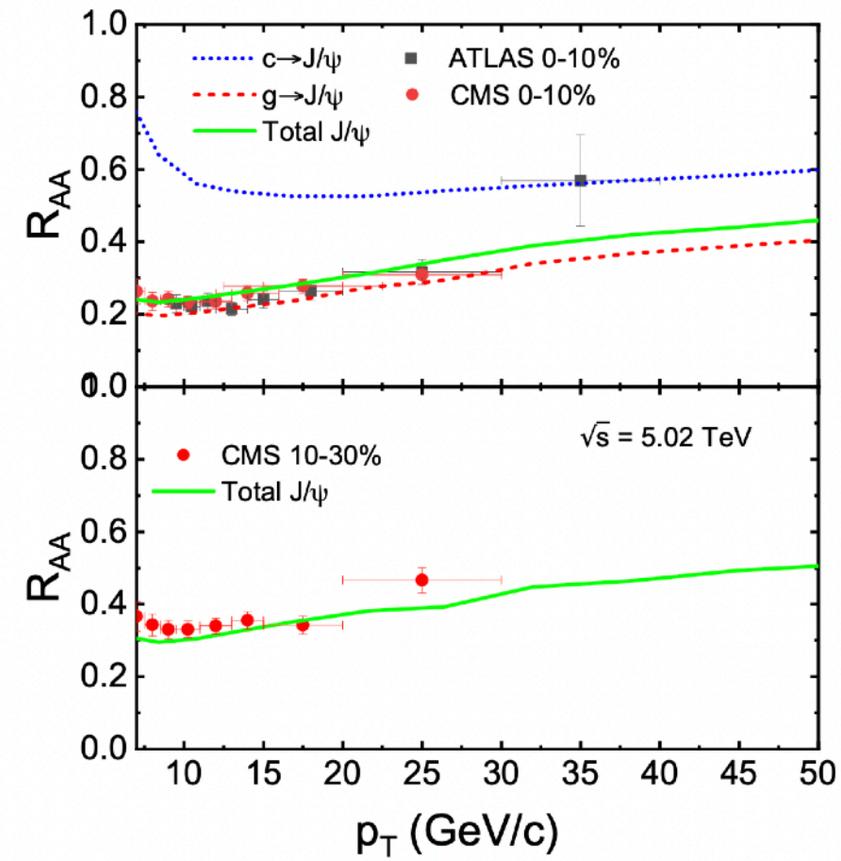
Towards future prospects

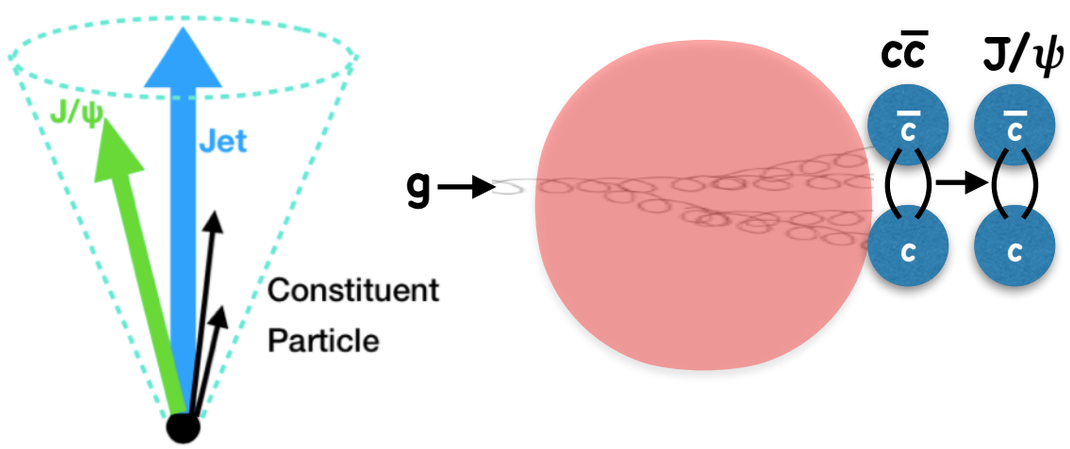
[PLB 805 (2020) 135434]





[arXiv:2208.08323]

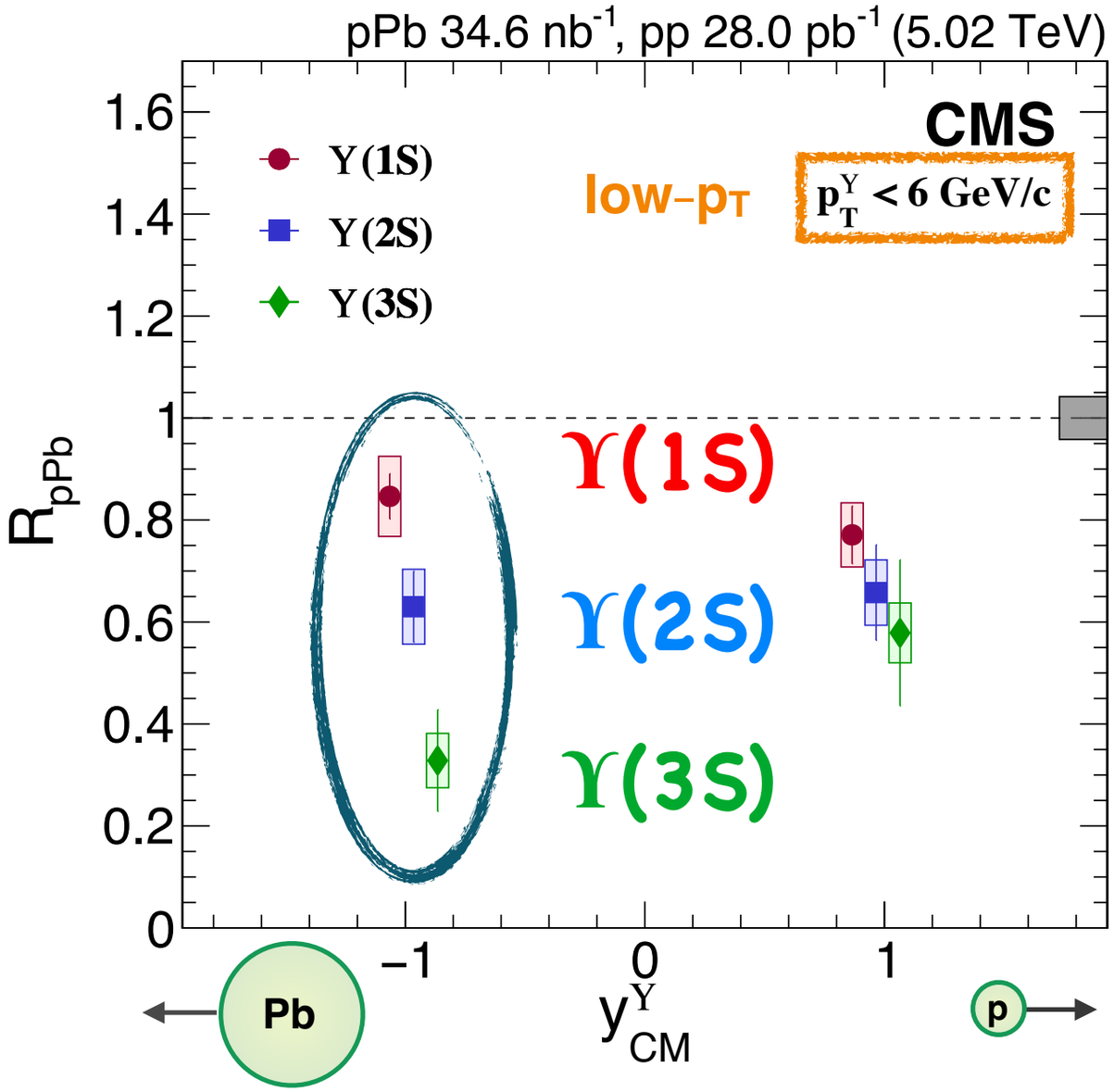


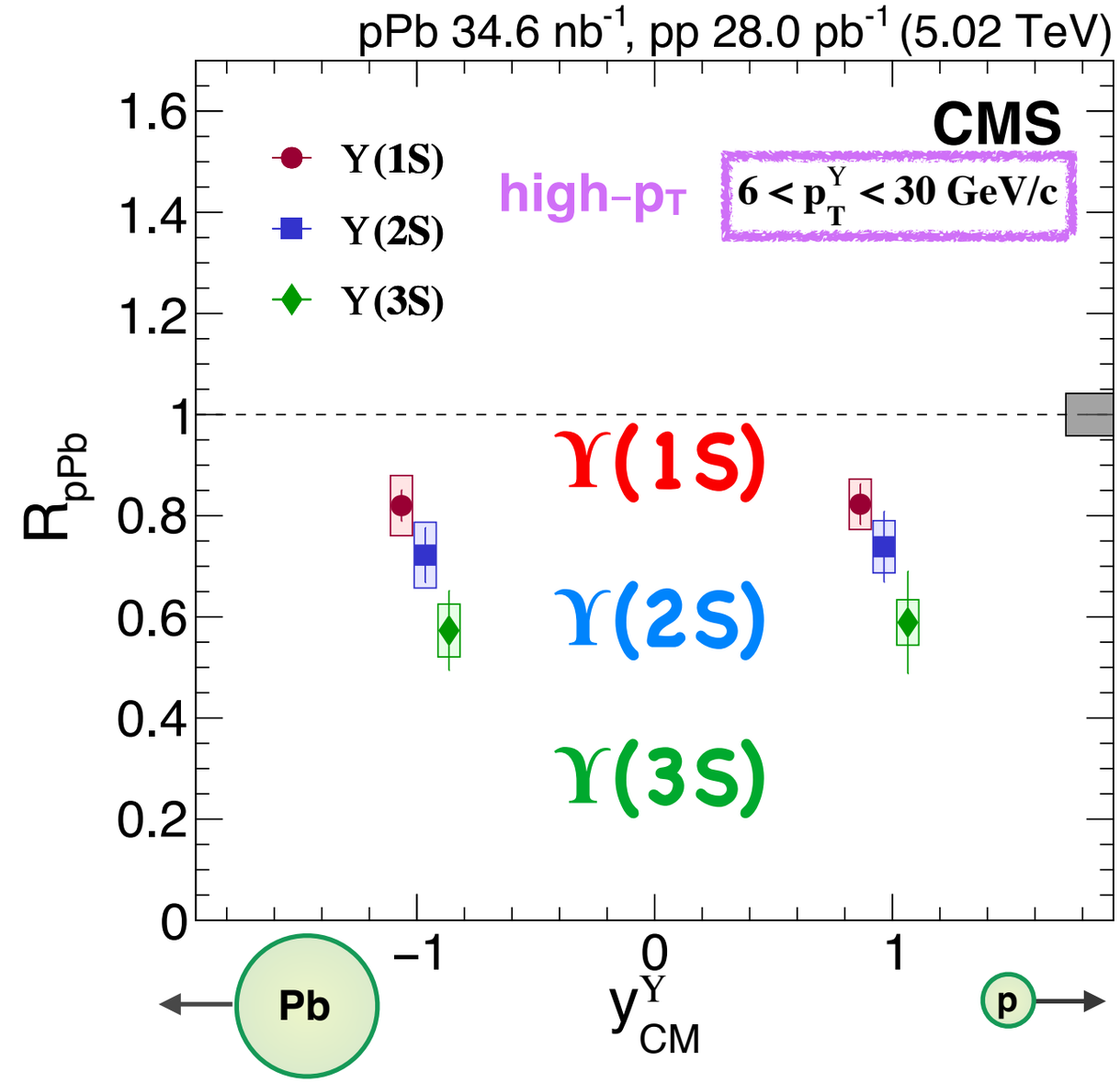


- Mandatory to include jet quenching for J/ψ suppression : Already ongoing studies e.g. LBT
- What about bottomonia?
  —> Measurement : Y in or associated with jets!

Sequential Υ suppression in pPb!

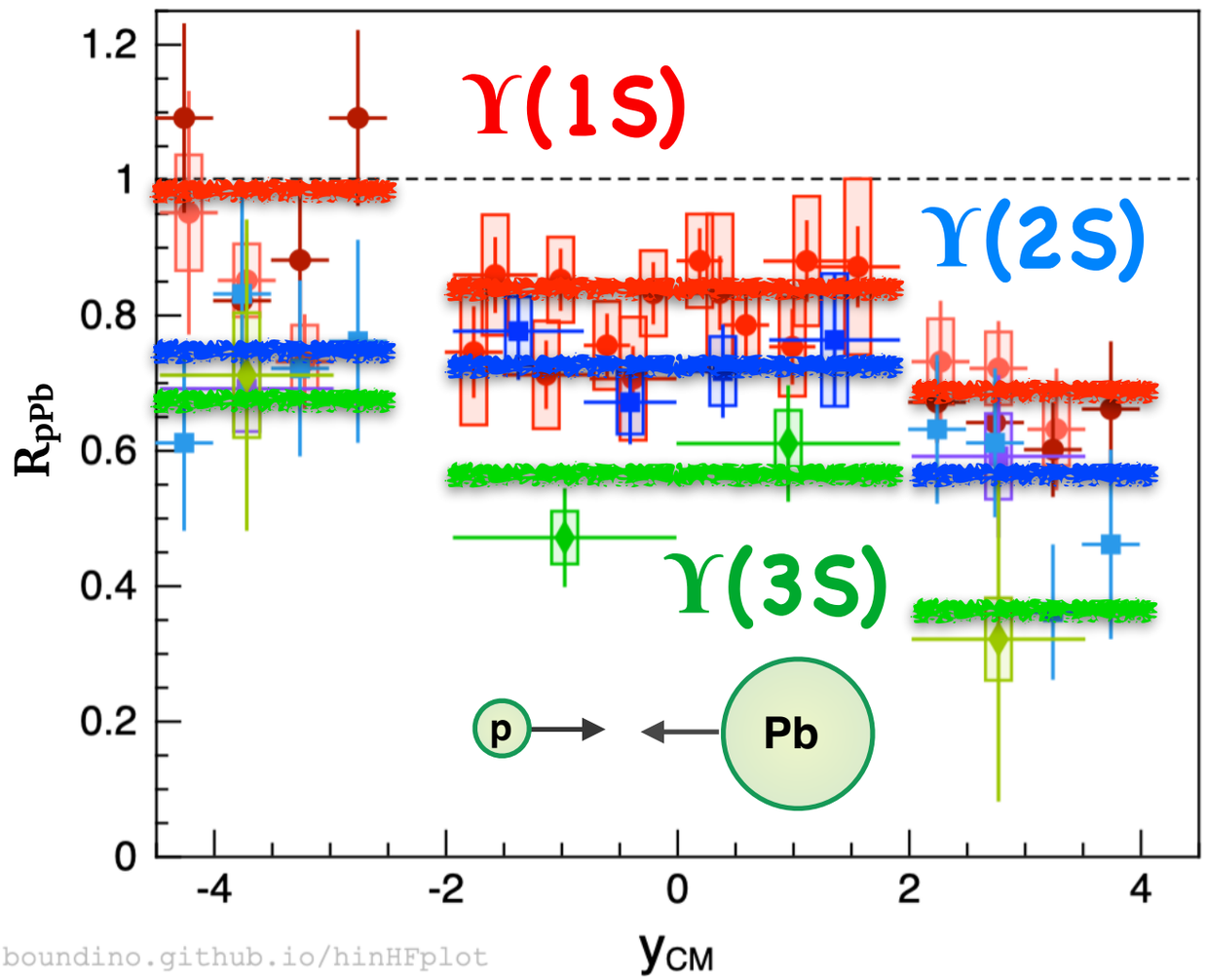
[arXiv:2202.11807]



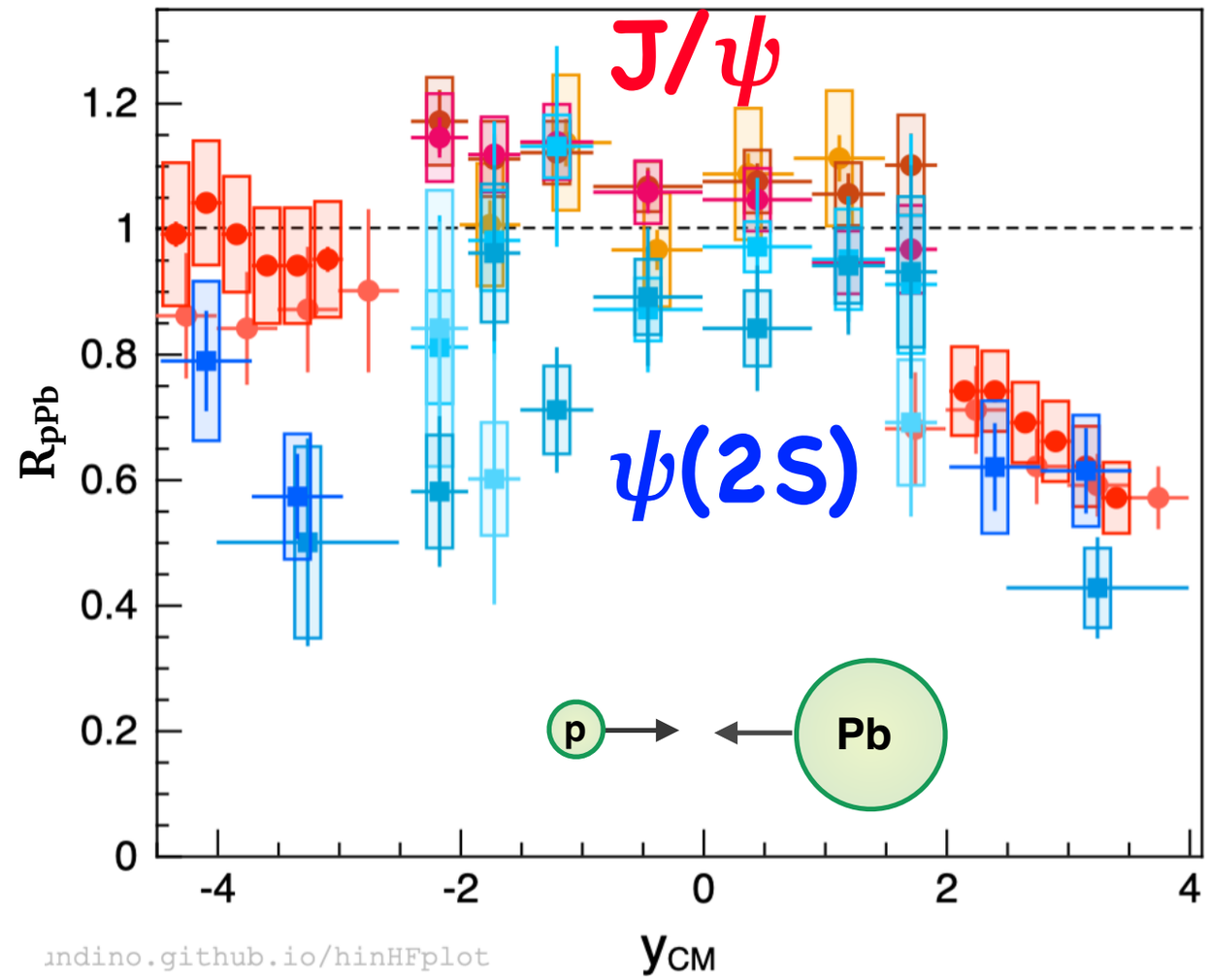


- Stronger suppression of excited states at *backward rapidity* & *low-p_T*

Quarkonium suppression @ LHC



[EPJC 78 (2018) 171] [arXiv:2202.11807] [JHEP 11 (2018) 194]
[PLB 806 (2020) 135486]

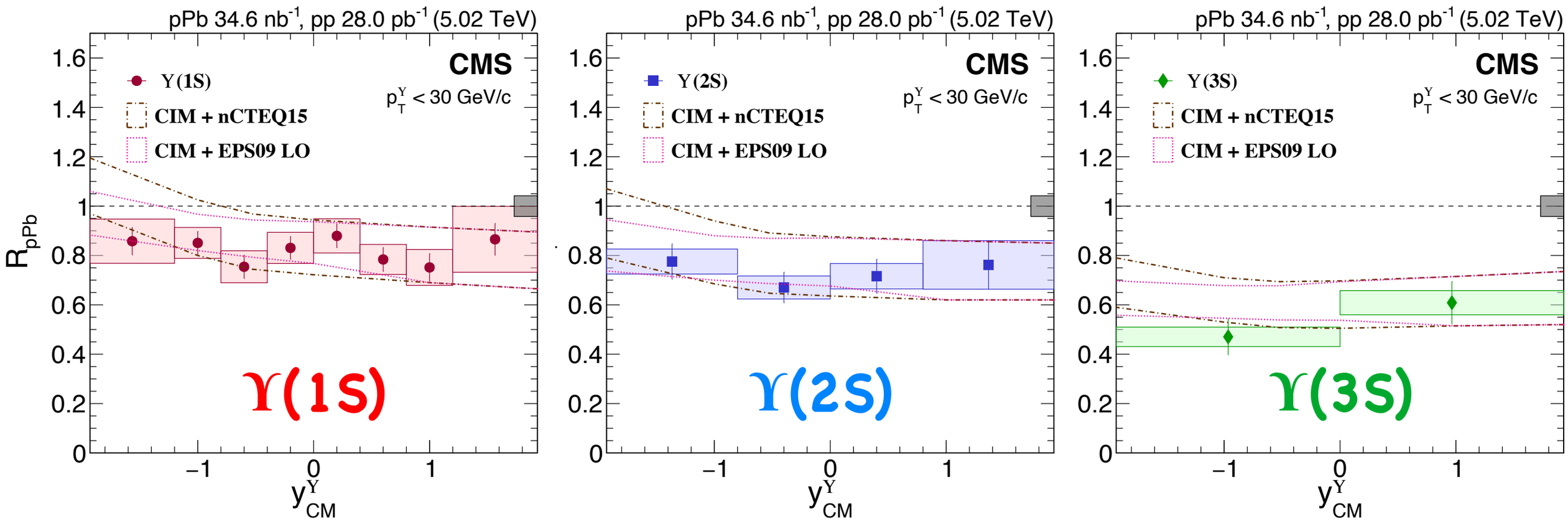


[EPJC 78 (2018) 171] [EPJC 77 (2017) 269] [PLB 774 (2017) 159]
[PLB 790 (2019) 509] [JHEP 03 (2016) 133] [JHEP 07 (2018) 160]
[JHEP 07 (2020) 237]

- Sequential suppression for both charmonia and bottomonia in pPb!
- Indication of additional final state effects for excited states

Bottomonia in pPb vs model

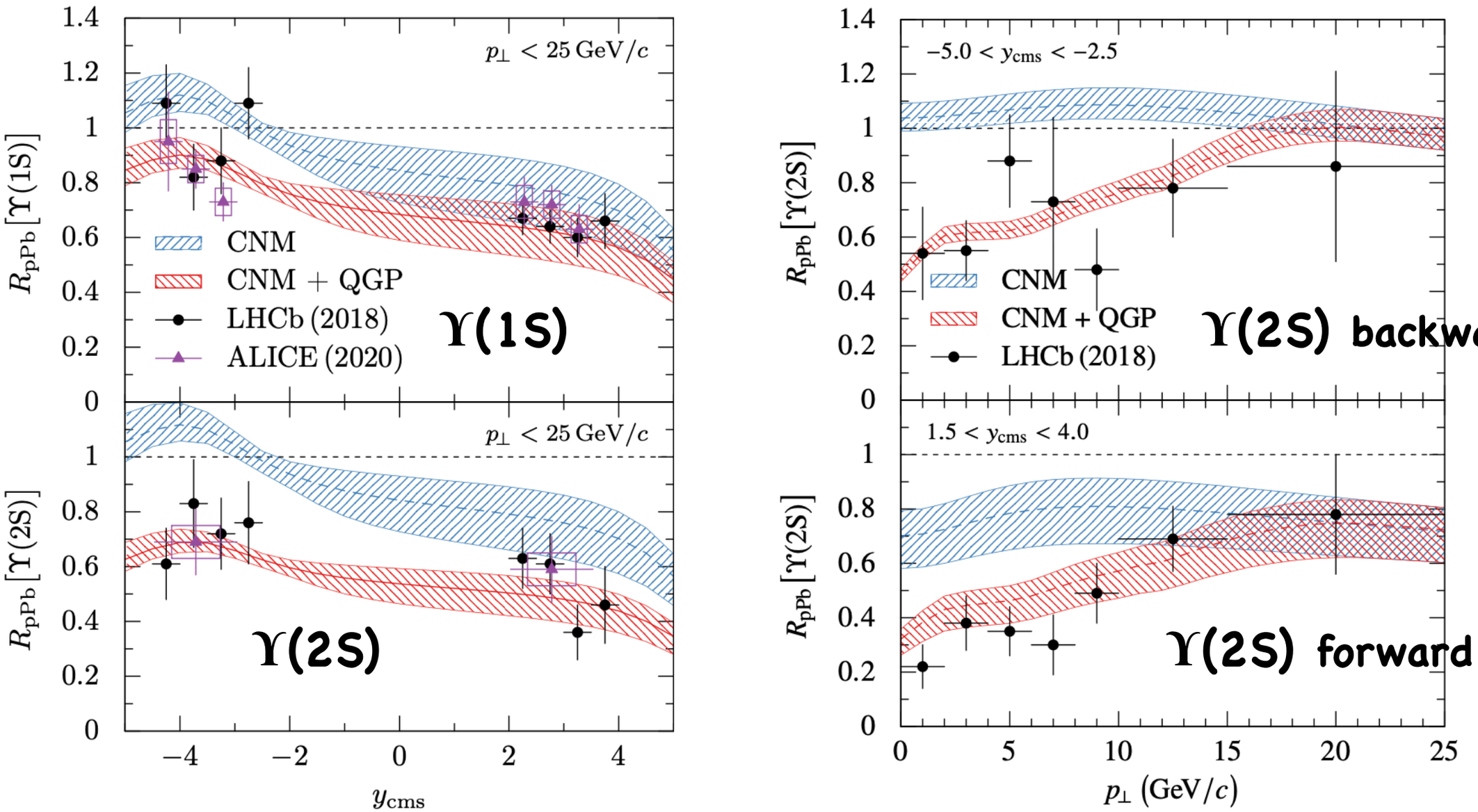
[arXiv:2202.11807]



- nPDF + comover breakup explains additional suppression of excited states?

Bottomonia in pPb vs model

[JMPA 35 (2020) 2030016]



- nPDF + comover breakup explains additional suppression of excited states?
- Models with hot-medium effects describe Y suppression in pPb collisions…

Comover vs transport models

Comover Interaction Model

- Survival probability of quarkonium interacting w comovers

$$\tau \frac{d\rho^{\psi}}{d\tau}(b,s,y) = -\sigma^{co-\psi}\rho^{co}(b,s,y)\rho^{\psi}(b,s,y)$$

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

- Depends on
  1) quarkonium dissociation rate
  2) comover density

Transport Model

- Thermal rate equation of quarkonium yields

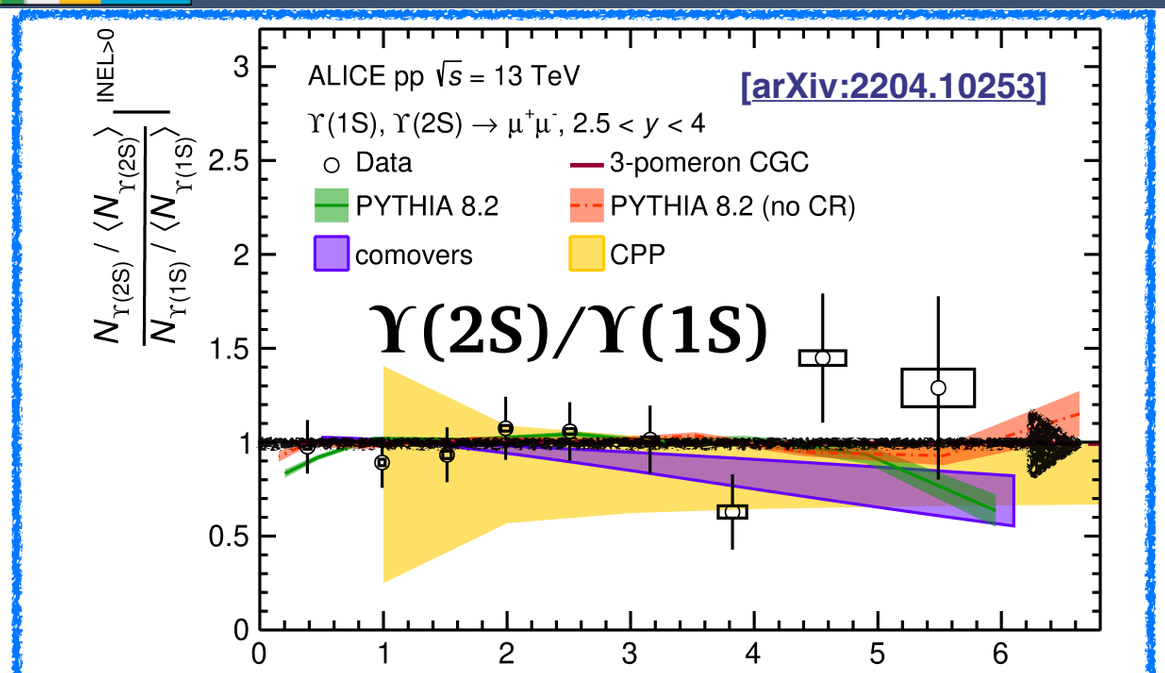
$$\frac{dN_{\Psi}(\tau)}{d\tau} = -\Gamma_{\Psi}(T(\tau))\left[N_{\Psi}(\tau) - N^{eq}_{\Psi}(T(\tau))\right]$$

$$N^{eq}_{\Psi}(T) = V_{FB}\gamma_c^2 d_{\Psi}\int\frac{d^3p}{(2\pi)^3}f^{eq}_{\Psi}(E_p;T)$$

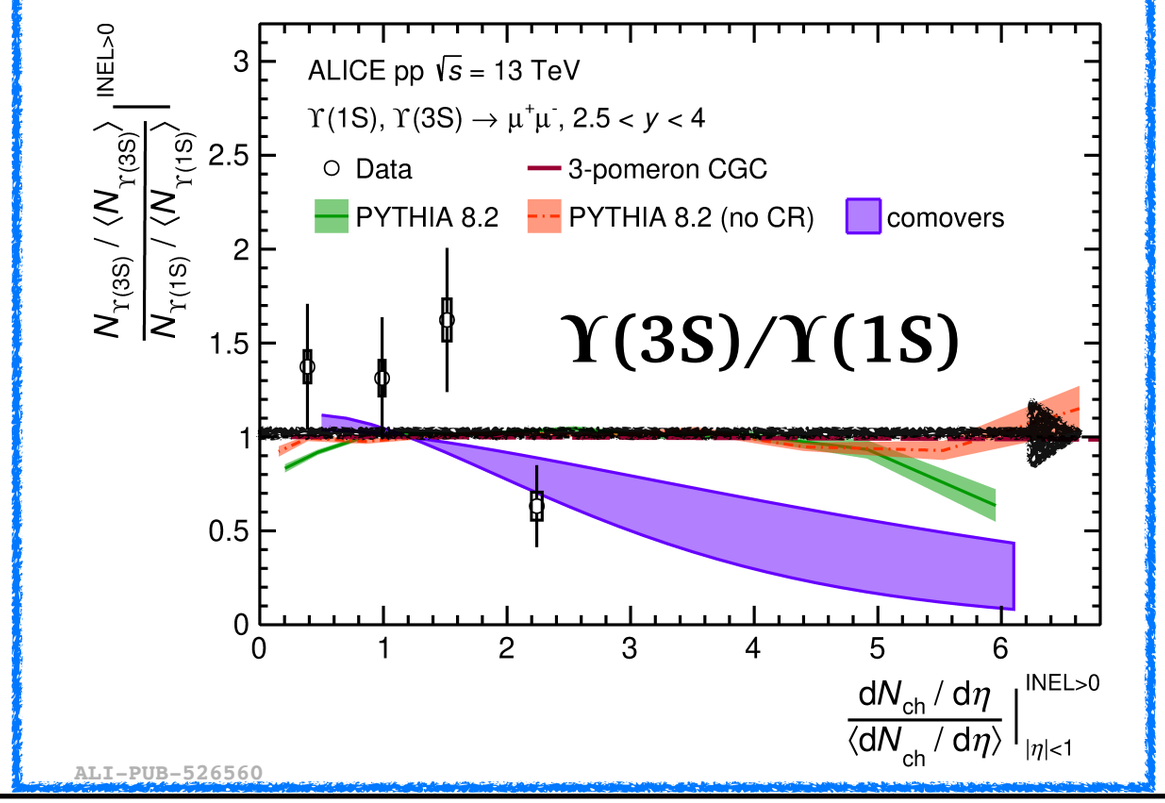
- Dissociation rate depending on T (E. density)
- Medium evolution matched to $dN_{ch}/d\eta$

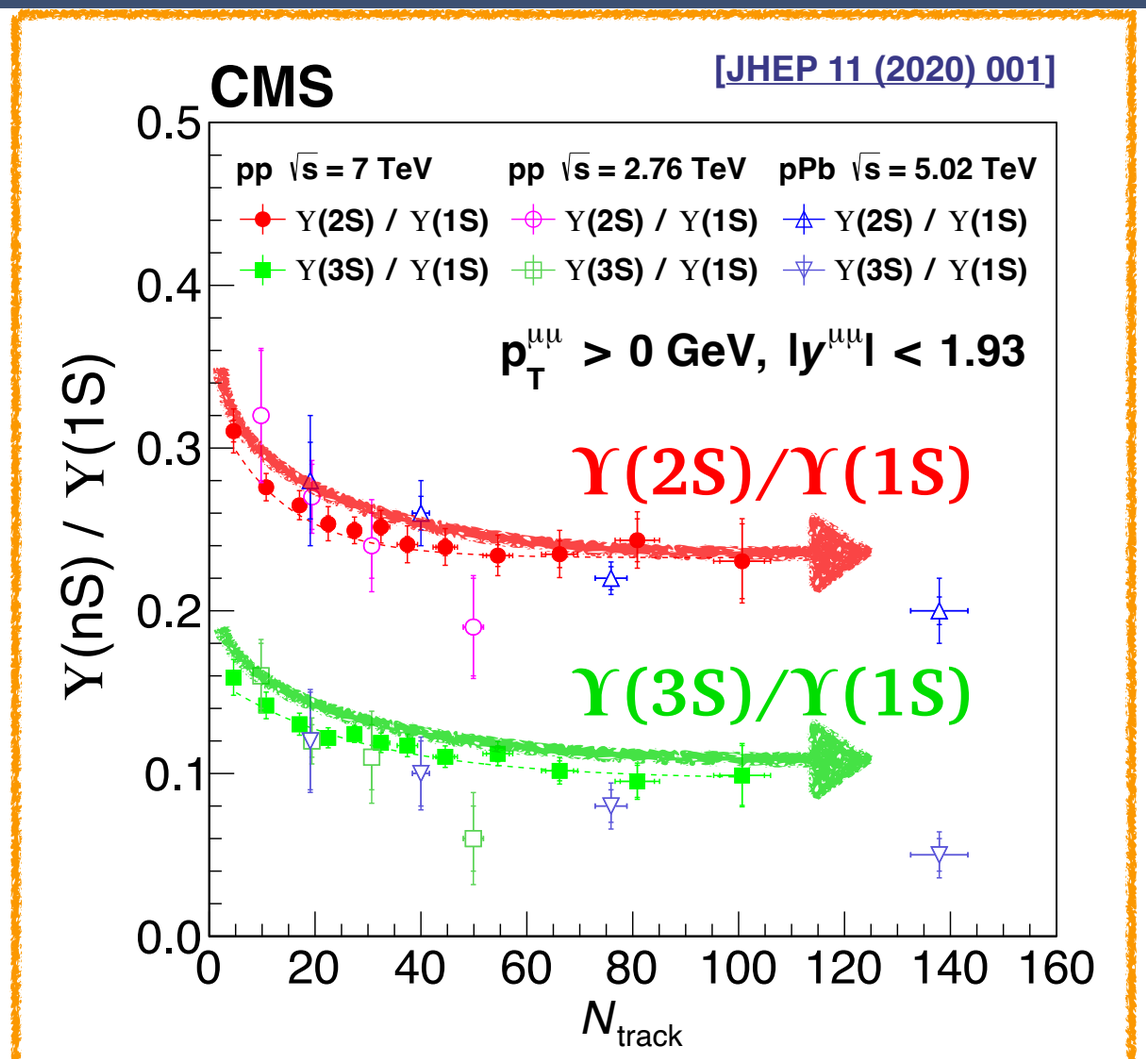
- CIM vs Transport calculation 'actual' treatment similar?
- How much of modifications in pA to be considered in AA interpretation?

Multiplicity dependence?



Y, N_{ch} same rapidity region (SRR)



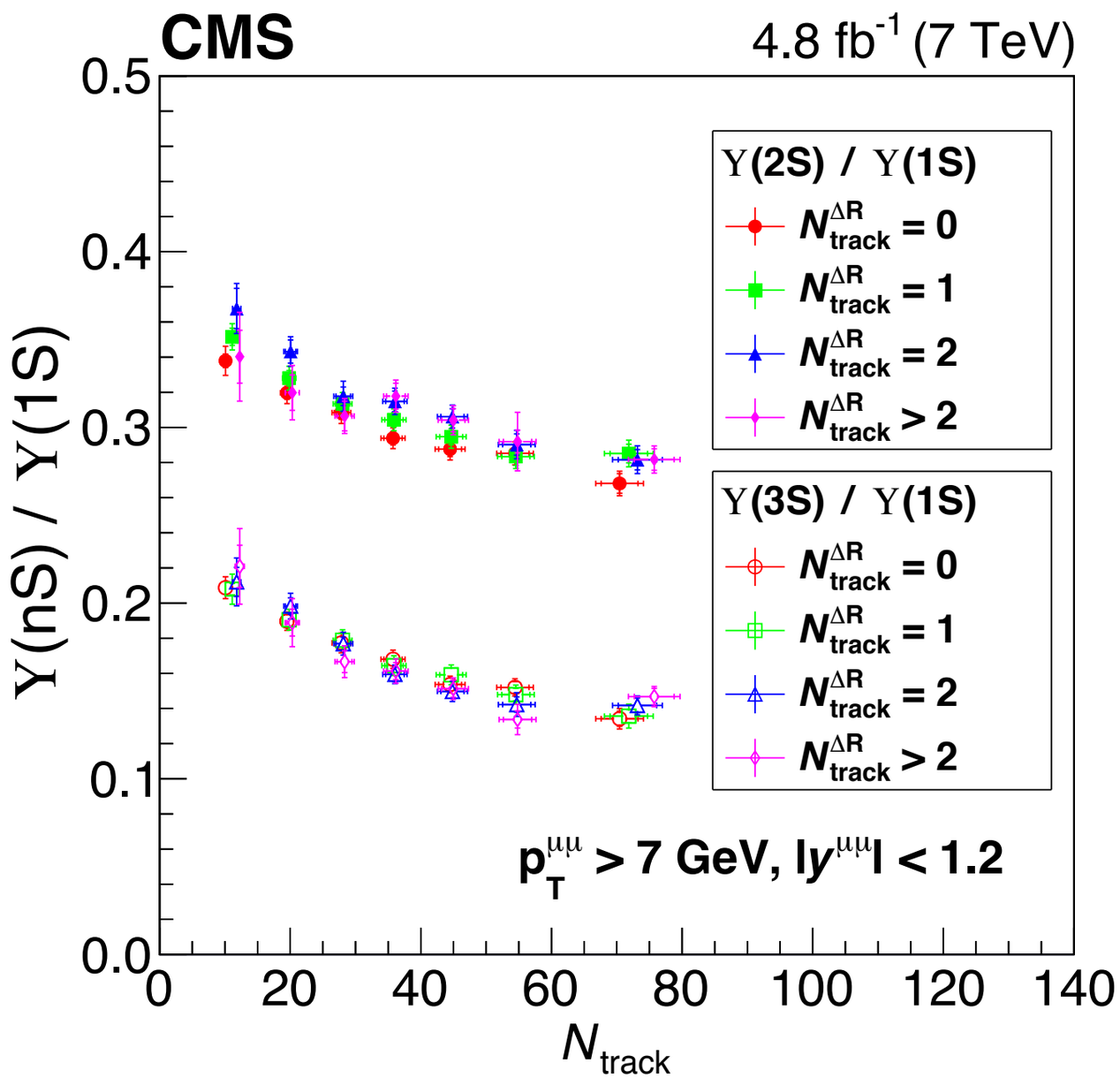


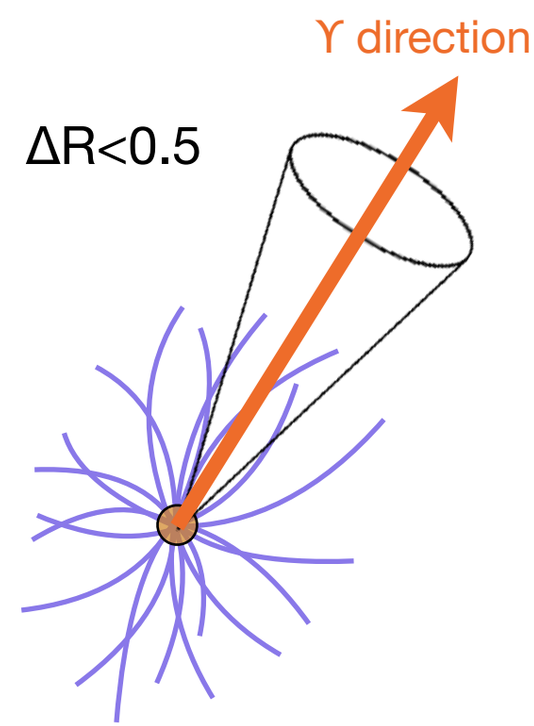
Y, N_{ch} different rapidity region (DRR)

- Quarkonium production sensitive to SRR/DRR
- Excited-to-ground state suppression in SRR due to MPI/UE/correlation?

Event-activity analysis

[JHEP 11 (2020) 001]

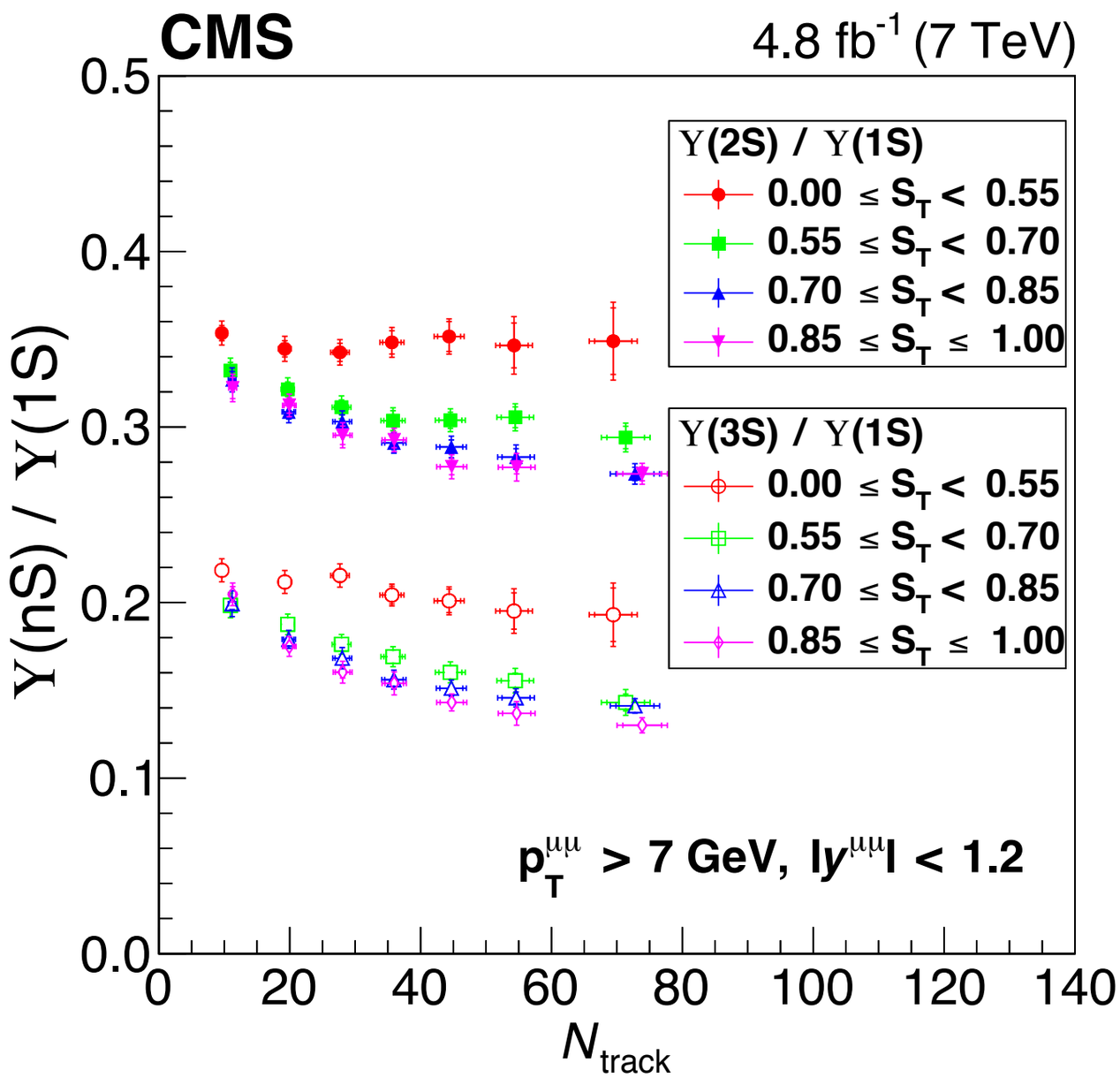




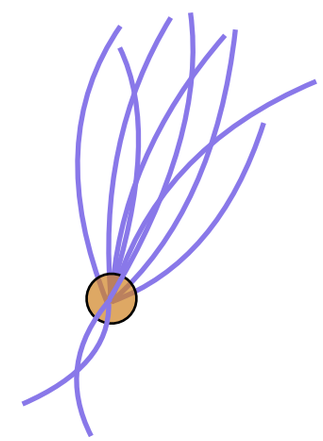
- Υ(nS) / Υ(1S) still suppressed for different N_{track} in a given cone size
- Different from comover breakup picture?
  - Thresholds might be better? ($N_{trk}^{\Delta R} > 0, 3, 5 \ldots$)
- Caveat for p_T region!

Event-activity analysis

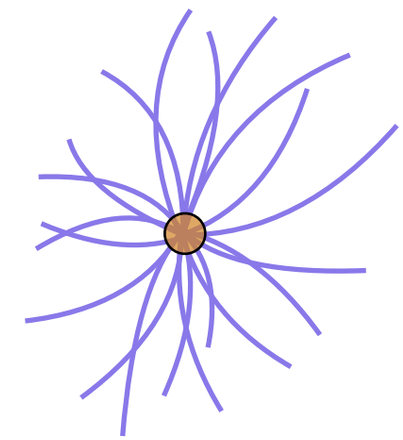
[JHEP 11 (2020) 001]



Sphericity —> 0



Sphericity —> 1



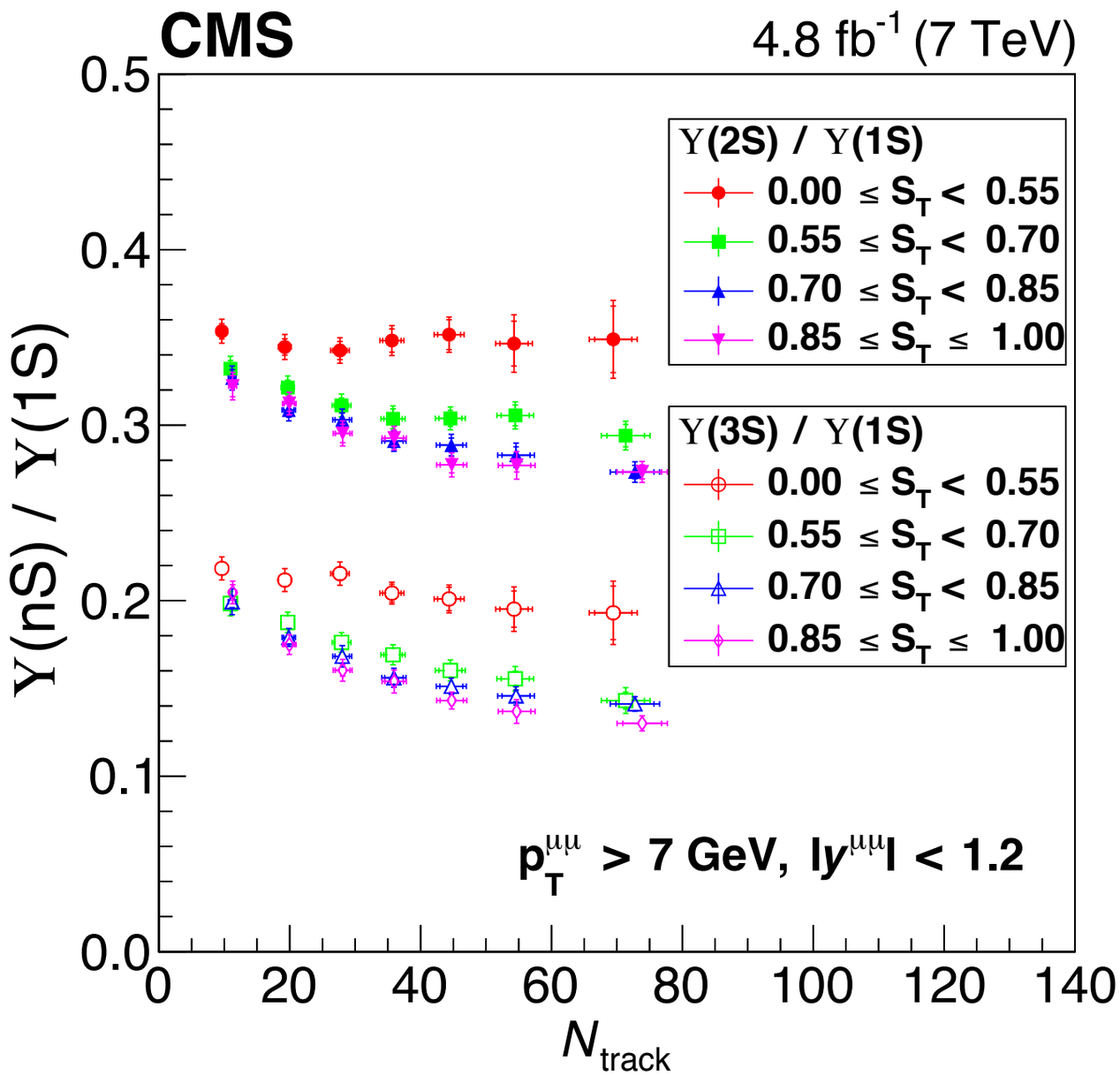
$$S_T \equiv \frac{2\lambda_2}{\lambda_1+\lambda_2} \qquad S_{xy}^T = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

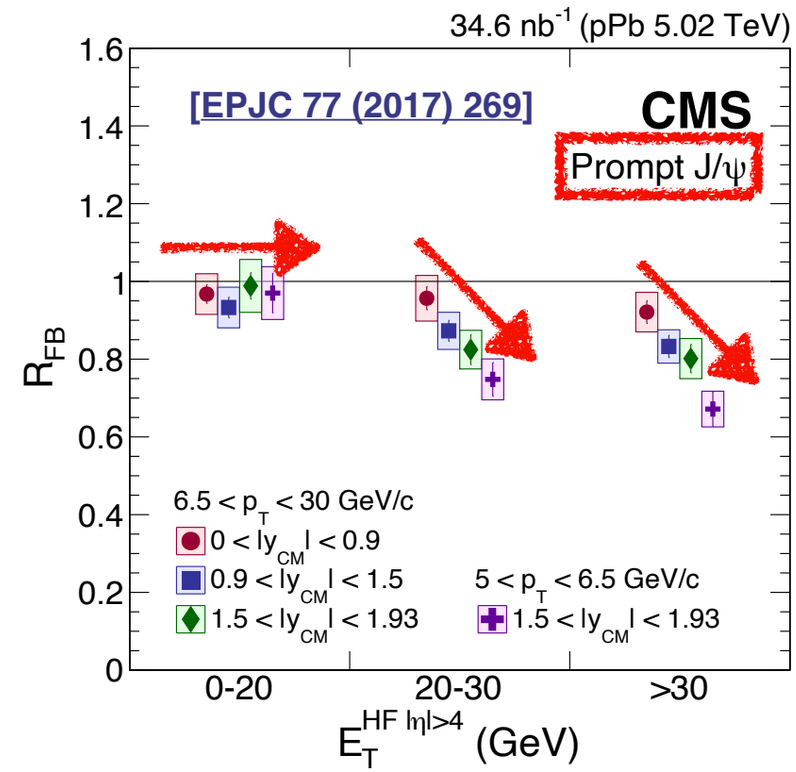
- Υ(nS) / Υ(1S) decreasing trend disappears for low-sphericity events
- Connection to UE jetty events?
  - Caveat for p_T region!

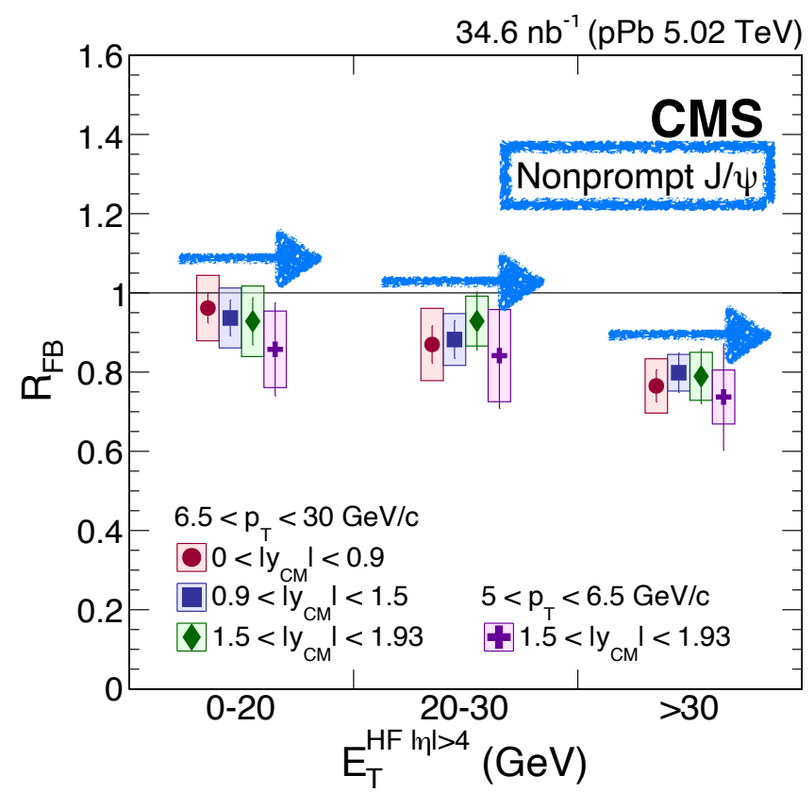
- What about charmonia?

Event-activity analysis

[JHEP 11 (2020) 001]

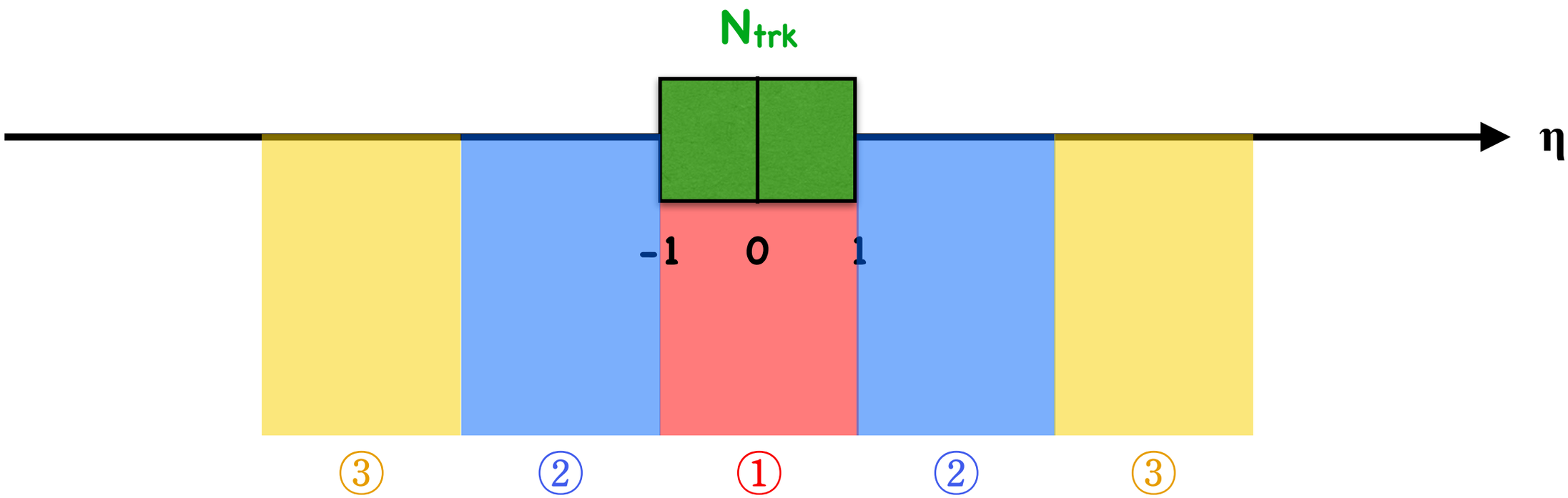






- What about charmonia? We already know the different event-activity dependence for charm vs beauty

Towards future prospect

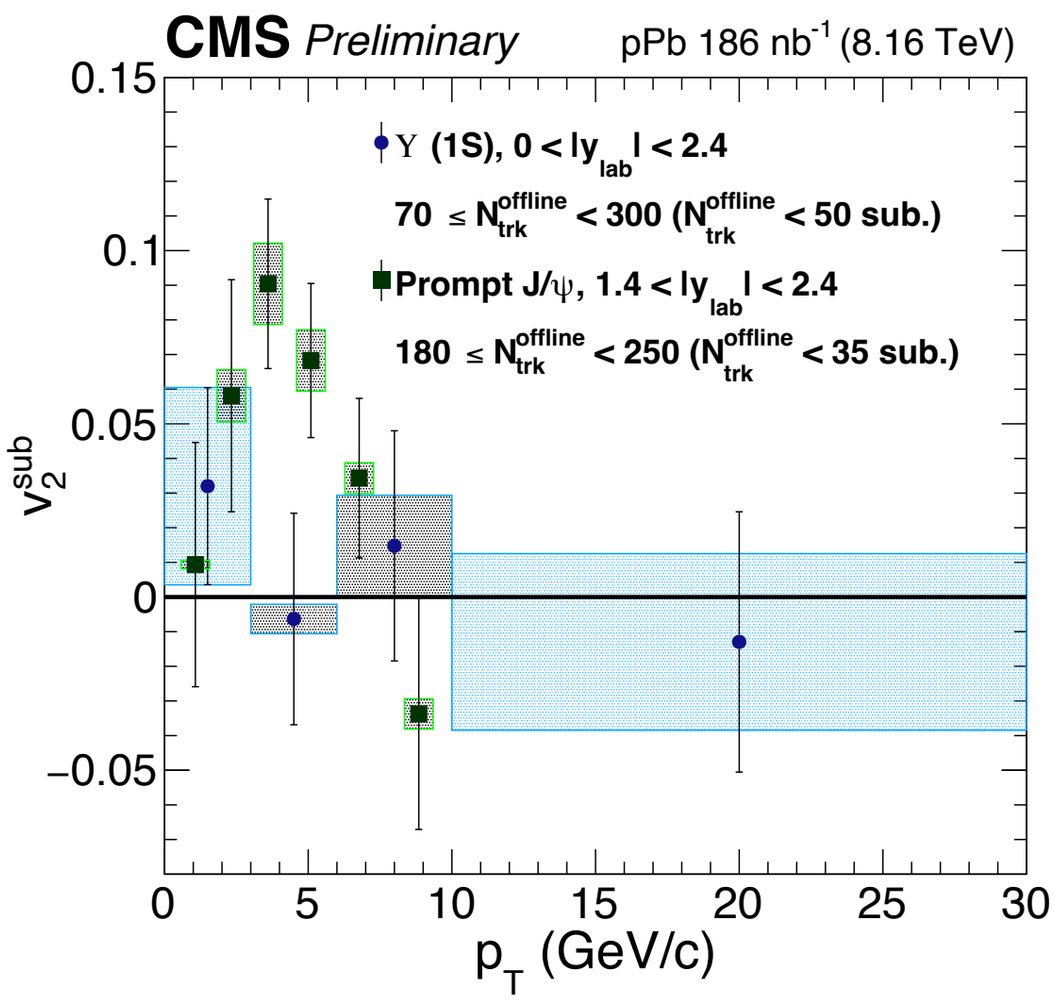


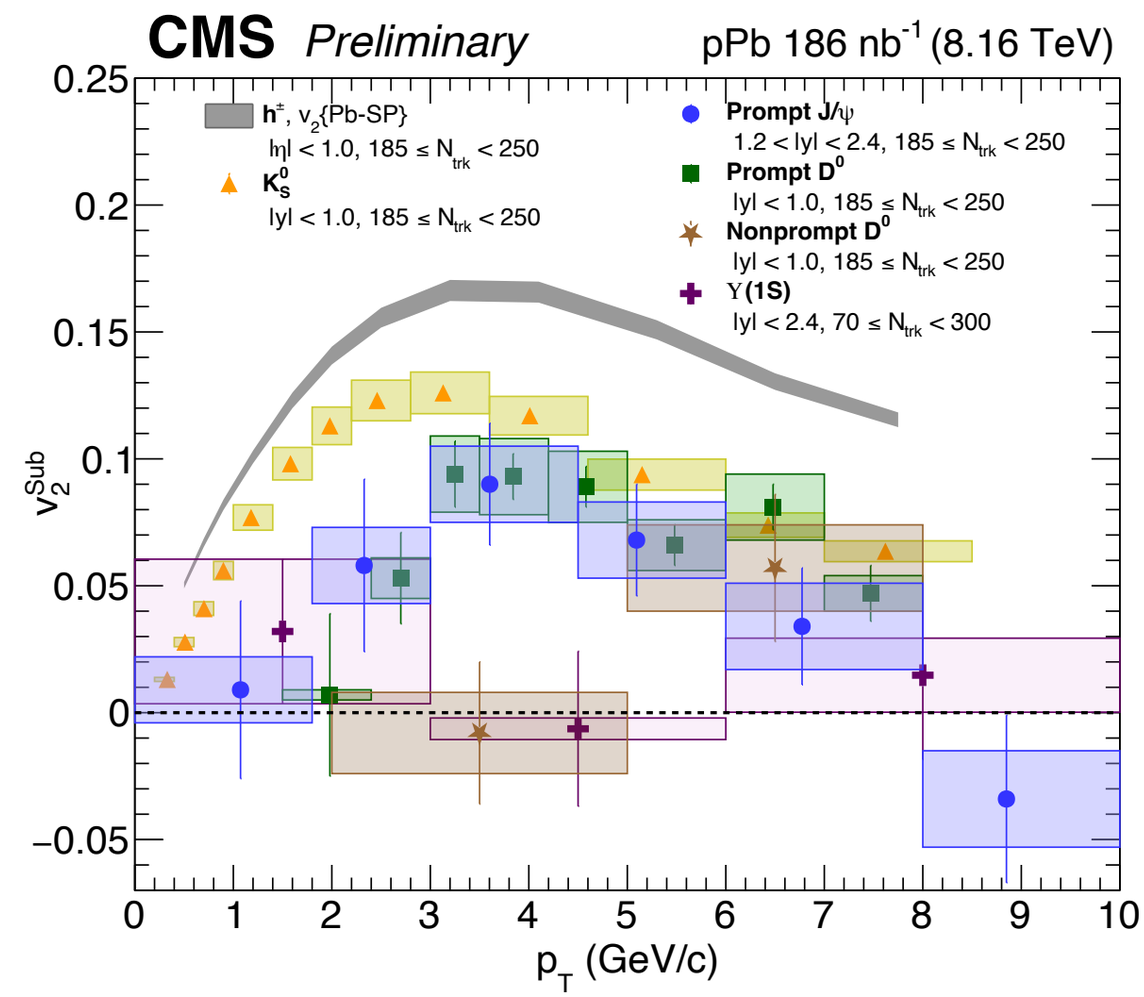
ATLAS : |y| < 1.6-2.0
CMS : |y| < 2.4
ALICE : 2.5 < y < 4.0
LHCb : 2.0 < y < 4.5

- **Rapidity gap study for excited-to-ground state ratio vs event multiplicity**
- **$\psi(2S)/J/\psi$ or $\Upsilon(nS)/\Upsilon(1S)$ vs N_{trk} for ①, ②, ③ in fixed N_{trk} region**
- **Take advantage of wide rapidity range from all LHC experiments : possible for both pp and pPb**

Elliptic flow (v_2) of Υ(1S) in pPb

[CMS-PAS-HIN-21-001]



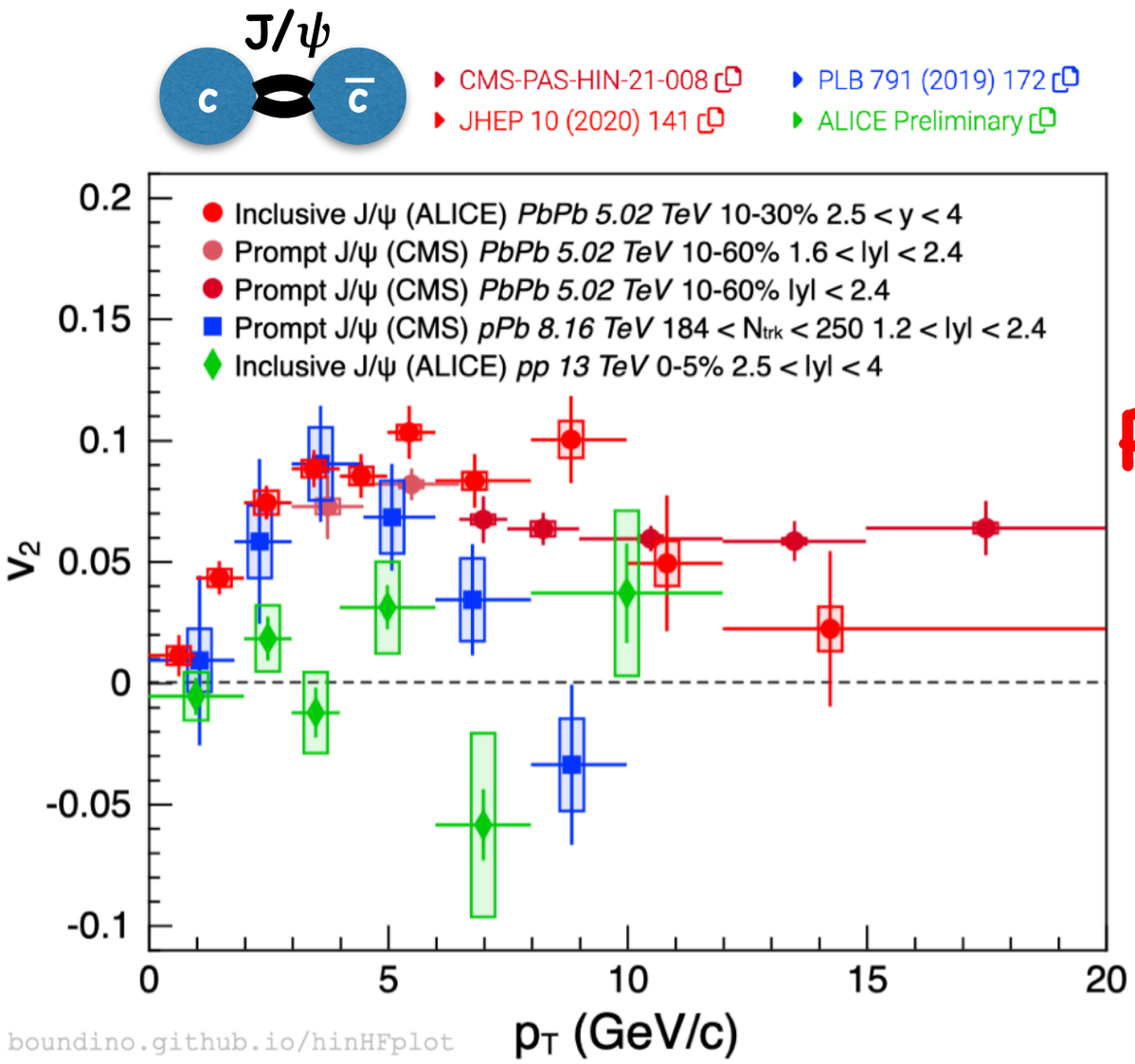


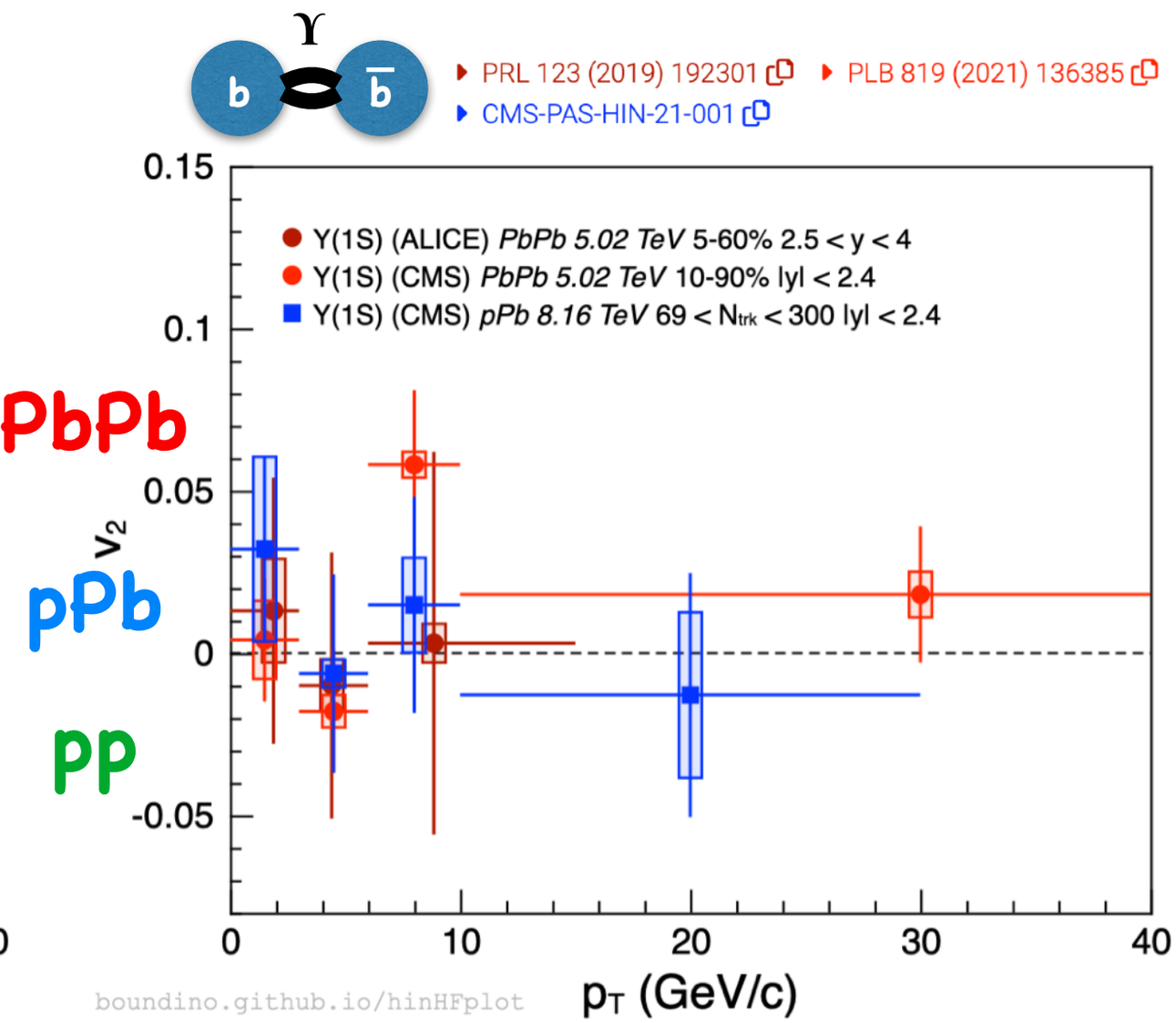
- First measurement of v_2 for Υ(1S) in small systems!
- No sizable v_2 observed in contrast to J/ψ

- Hierarchy of v_2 at low-p_T

charged hadrons > K^0_S > Prompt D^0 ≈ Prompt J/ψ > Nonprompt D^0 ≈ Υ(1S) ≈ 0

Quarkonium v_2 at LHC





J/ψ : PbPb $v_2 \geq$ pPb $v_2 >$ pp $v_2 \approx 0$

Υ(1S) : PbPb $v_2 \approx$ pPb $v_2 \approx 0$

- J/ψ PbPb v_2 at low-p_T because of recombination —> then what about pPb?
- Upsilons : No v_2 but sequential suppression in both pPb & PbPb

Quarkonium feed-down

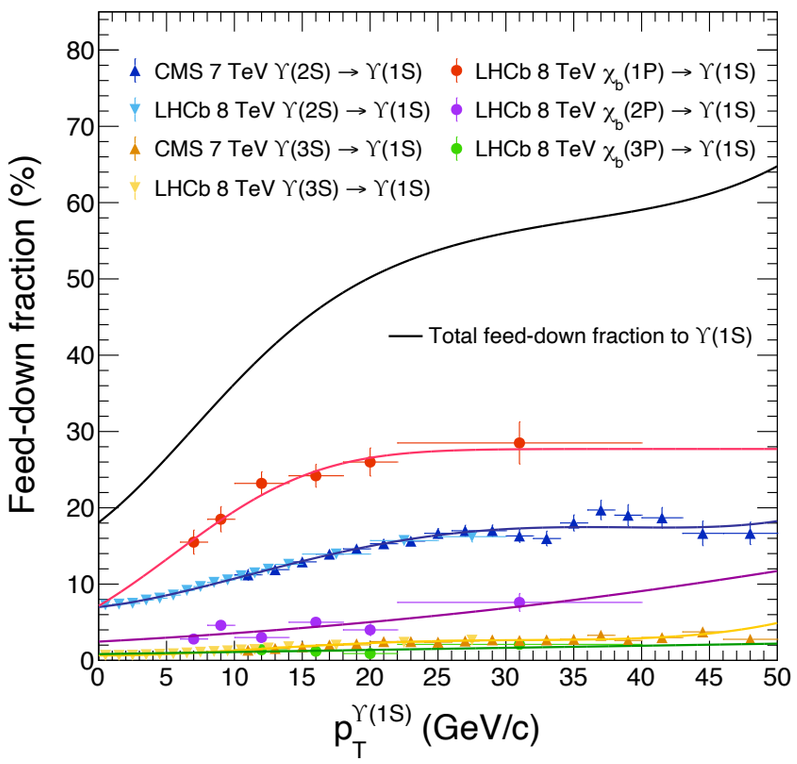
[PLB 749 (2015) 14] [JHEP 11 (2015) 103] [EPJC 74 (2014) 3092]

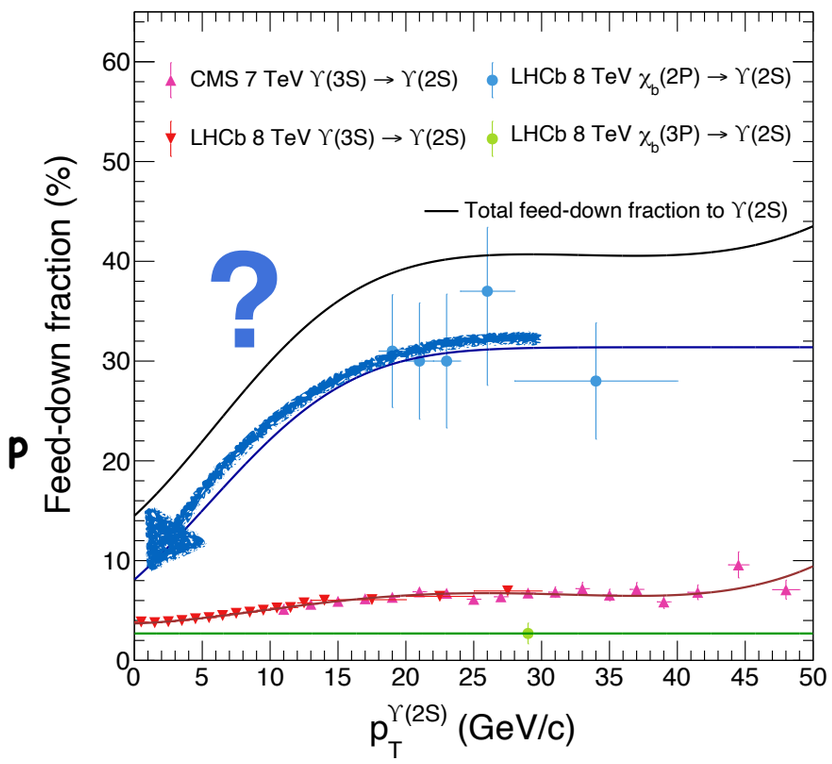
$$\mathcal{F}_{nS}^{mS} = \mathcal{B}(mS \to nS)\frac{\sigma_{mS}}{\sigma_{nS}}$$

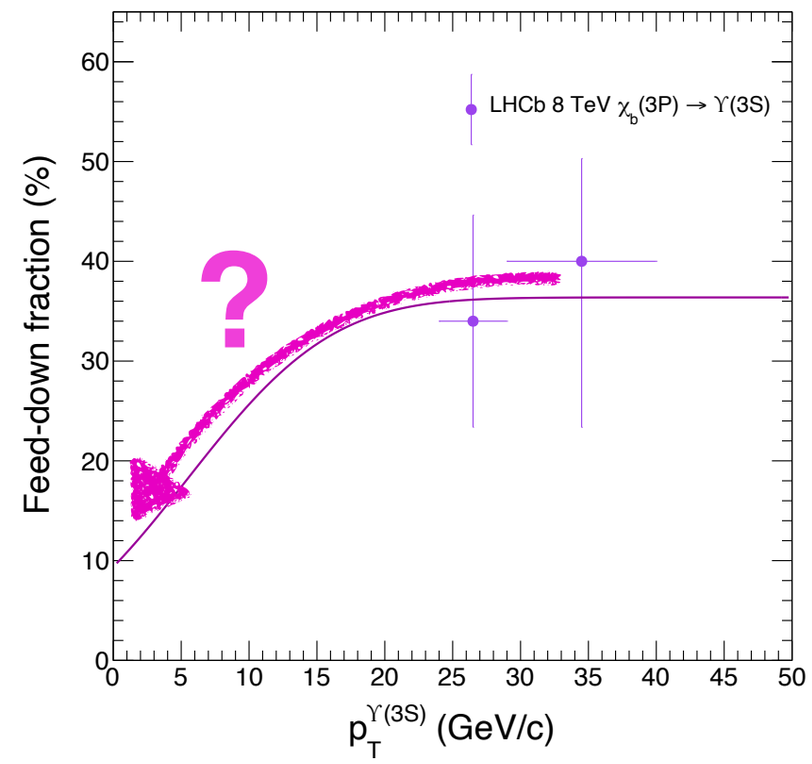
$\Upsilon(1S)$

$\Upsilon(2S)$

$\Upsilon(3S)$







- Significant contributions from feed-down! —> Crucial on data interpretation
- Caveat for Y(2S) and Y(3S) : Still large! Decreasing towards low-p_T?

Questions / Discussion

☑ **What can we learn from bottomonium production in heavy ion collisions?**

➡ Binding energy dependent suppression & medium temperature profiling still valid?

☑ **When are Υ(nS) states formed in AA collisions?**

➡ QGP too hot at the beginning? Production time delayed towards late stages?

➡ Does this even matter?

☑ **What is the mechanism of recombination for quarkonia in QGP?**

➡ Uncorrelated recombination purely statistical?

➡ Correlated (diagonal) recombination happening until chemical freeze out?

☑ **How should we interpret quarkonium measurements in pA?**

➡ Sequential suppression for both charmonia & bottomonia!
— How can we distinguish final state CNM vs HNM effects?

➡ No collective behavior for Υ(1S) in contrast to J/ψ
— why J/ψ v_2 similar for pPb & PbPb? and also why comparable with D^0 v_2 in pPb?

☑ **How can we disentangle feed-down contributions?**

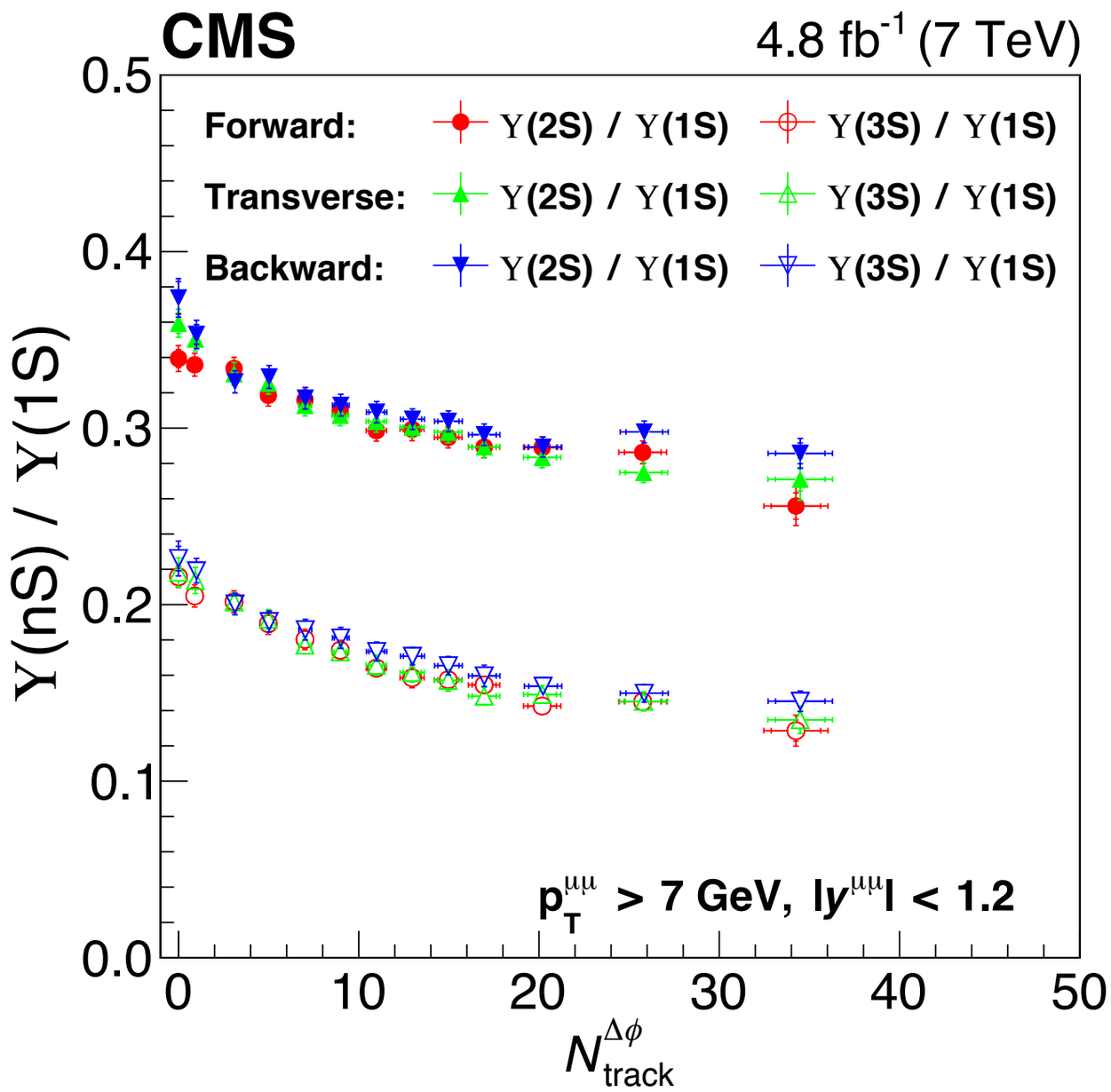
➡ Very strong dependence on p_T…

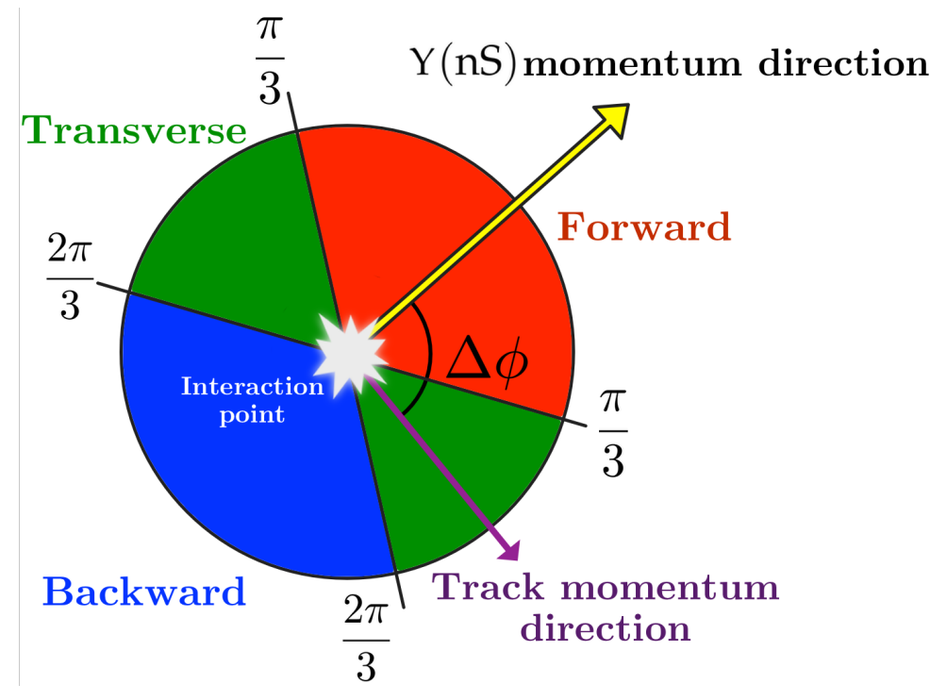
➡ Challenge for (higher) P-states measurements towards lower p_T region

back-up

Azimuthal correlation

[JHEP 11 (2020) 001]

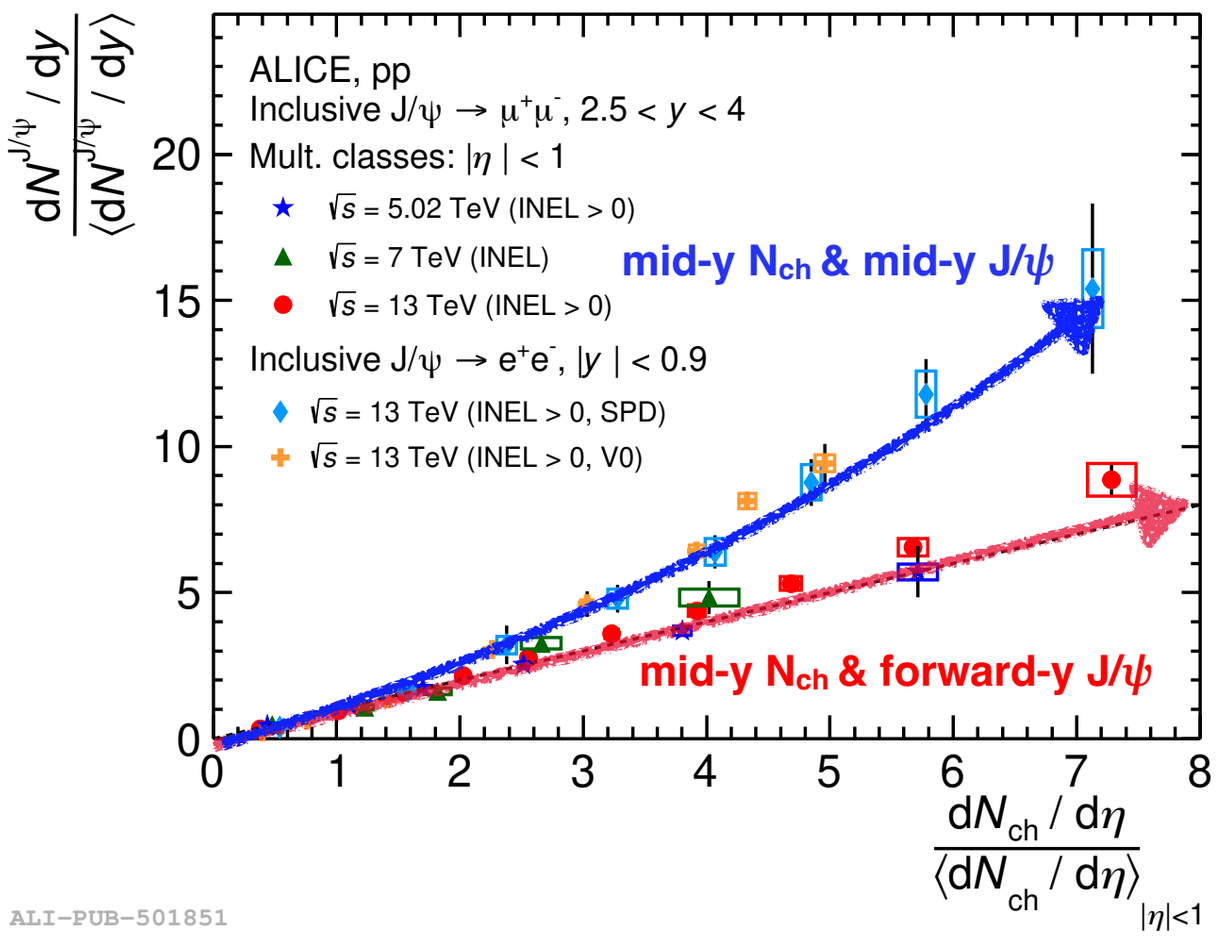




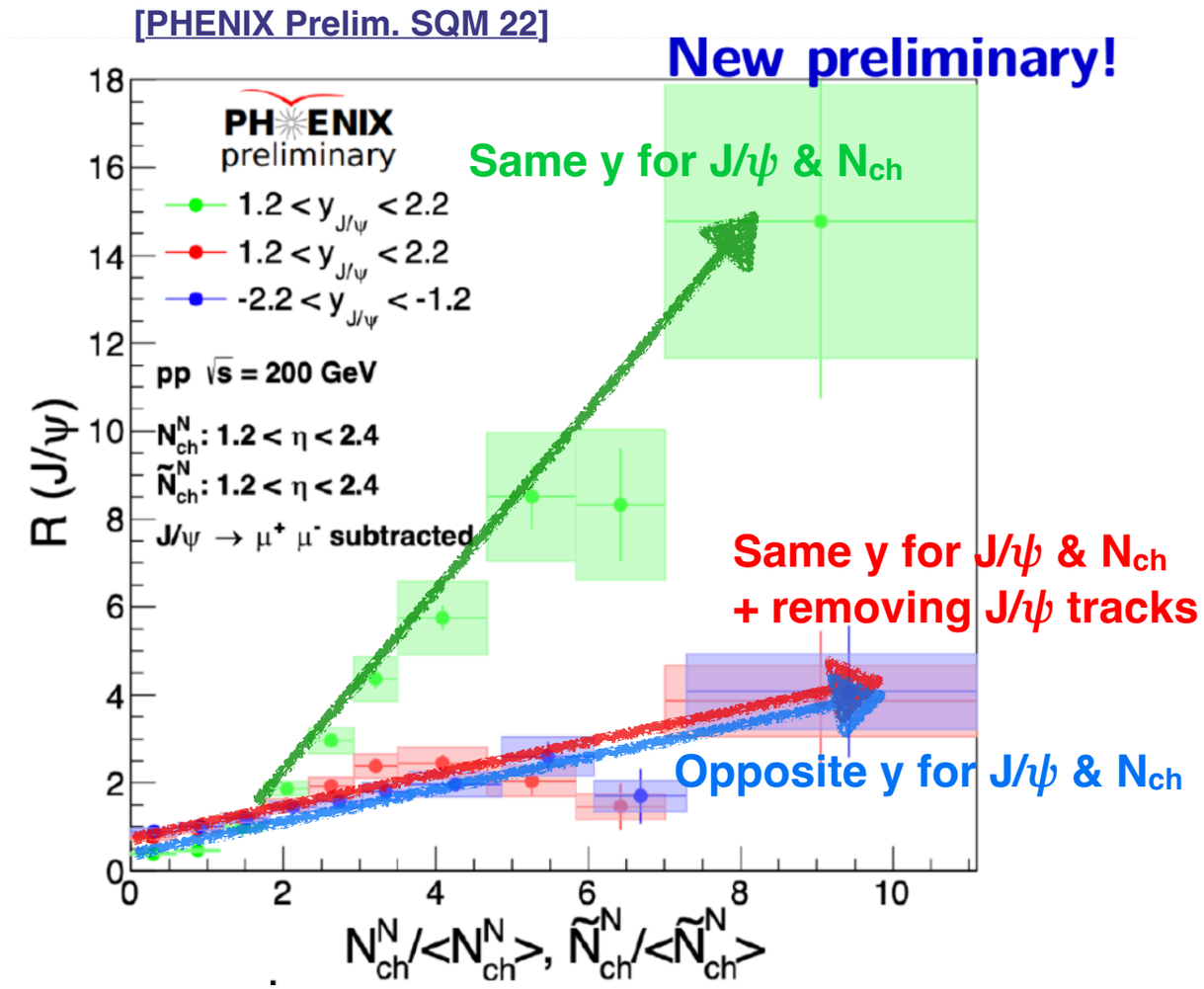
- Υ(nS) / Υ(1S) suppressed for all azimuthal region
- Similar suppression for all $N_{ch}^{\Delta\phi}$ itself implies connection to UE

Multiplicity dependence?

[JHEP 06 (2022) 015]



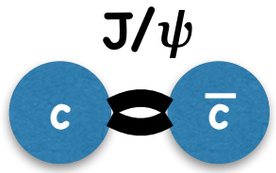
[PHENIX Prelim. SQM 22]



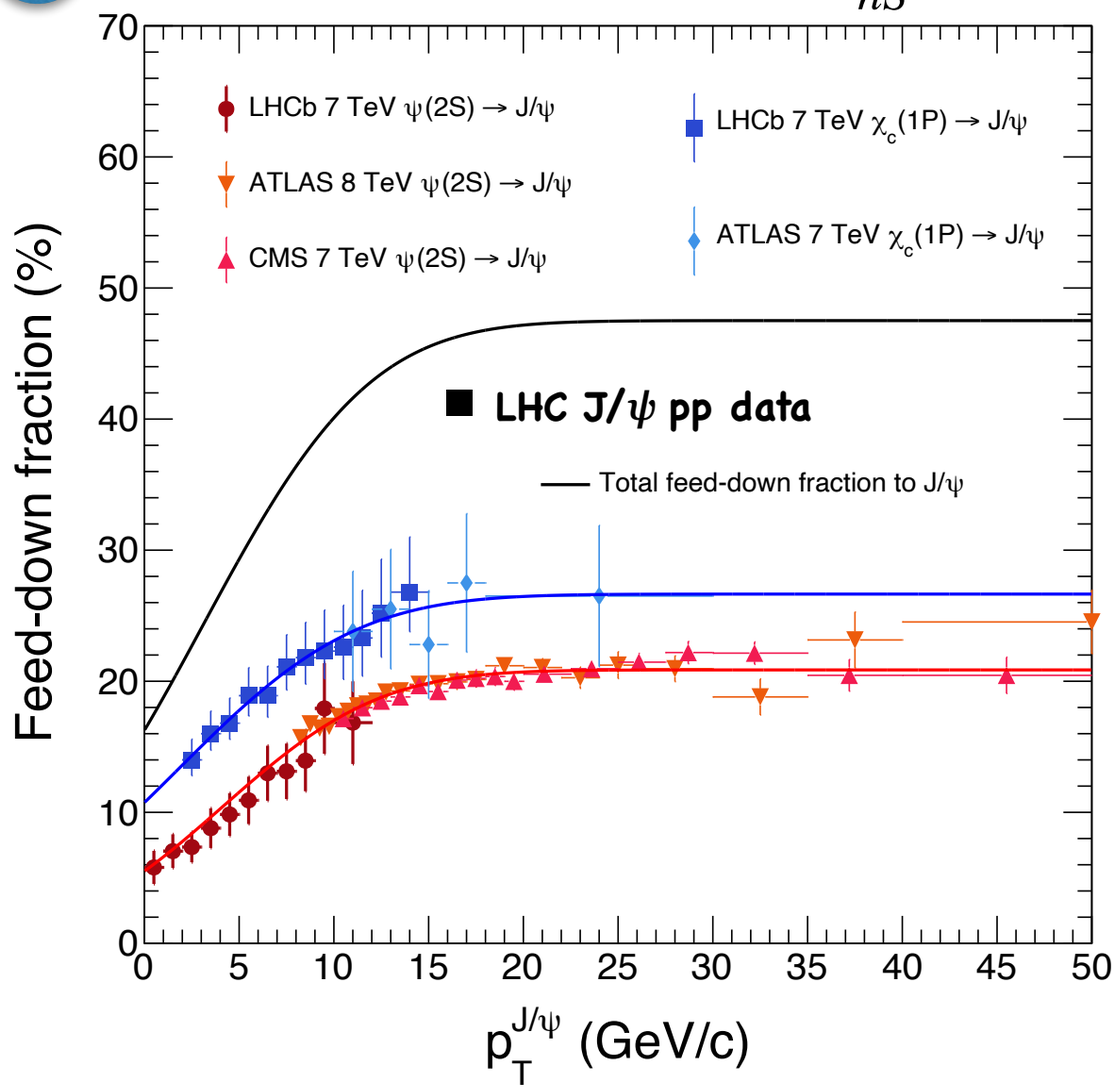
- Quarkonium production increases in case of POI & N_{ch} at the same y
- Production behavior becomes similar after removing tracks from POI?
  - hint of MPI or correlation?

Quarkonium feed-down

[EPJC 72 (2012) 2100]
[EPJC 76 (2016) 283]
[JHEP 07 (2014) 154]
[PLB 718 (2012) 431]
[PRL 114 (2015) 191802]



$$\mathcal{F}_{nS}^{mS} = \mathcal{B}(mS \to nS)\frac{\sigma_{mS}}{\sigma_{nS}}$$



- Significant contributions from feed-down! —> Crucial on data interpretation
- Advantage of ψ(2S) : almost free from feed-down effects!

Comparison with theory

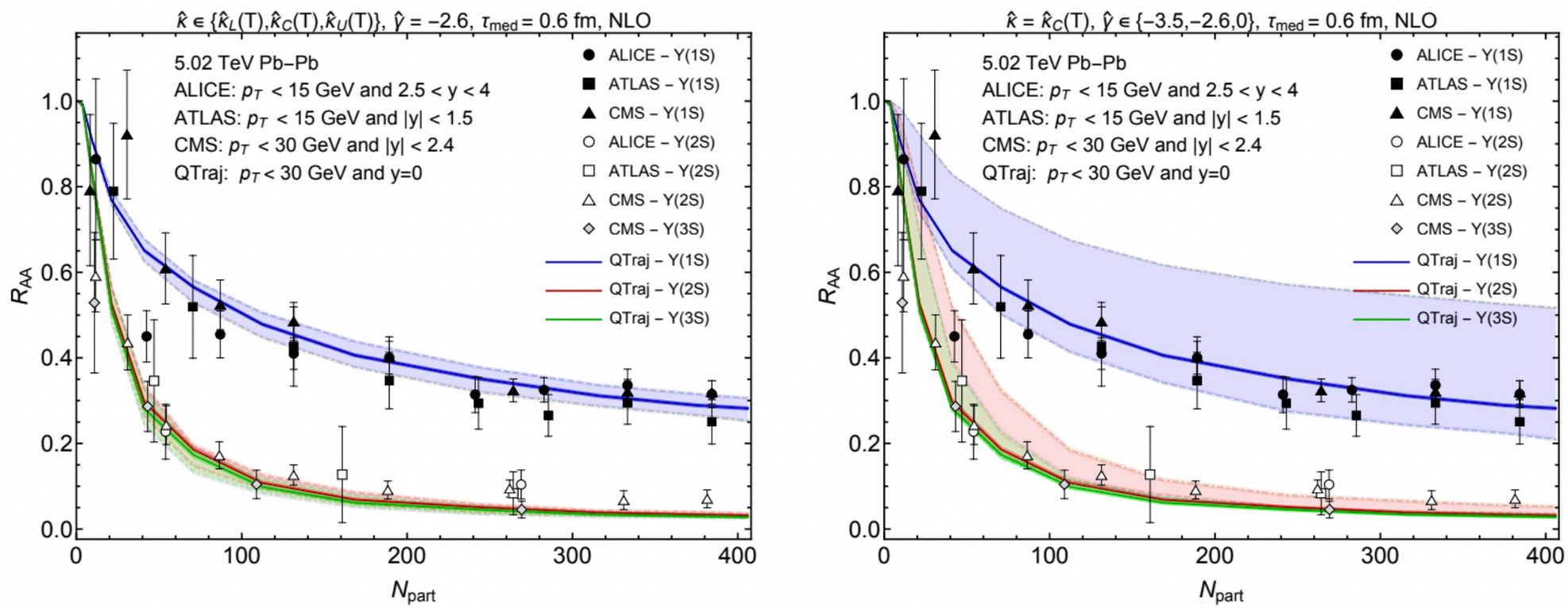
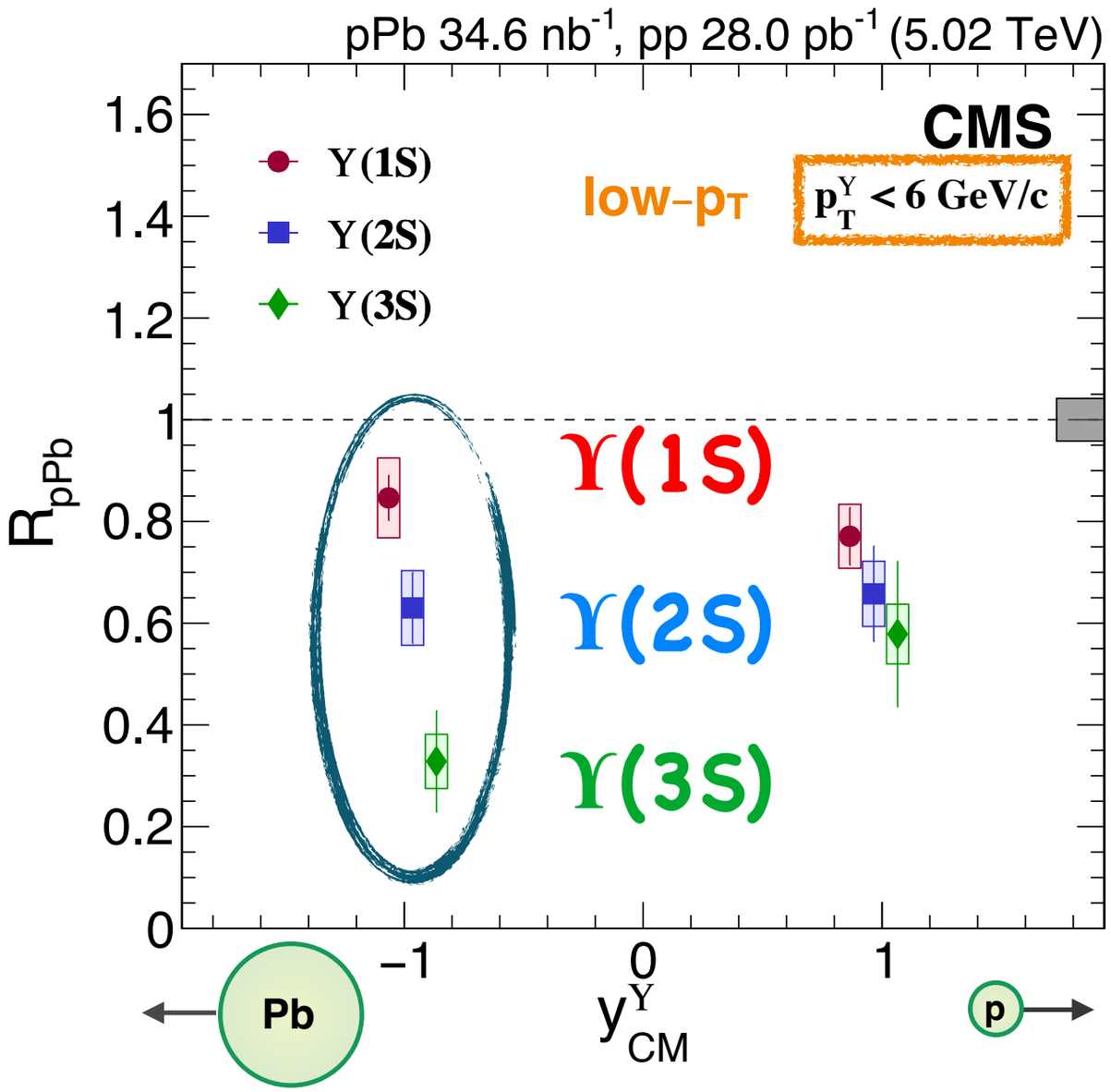


Figure 4. R_{AA} for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ as a function of $N_{\rm part}$. The left panel shows variation of $\hat{\kappa} \in \{\kappa_L(T), \kappa_C(T), \kappa_U(T)\}$ and the right panel shows variation of $\hat{\gamma}$ in the range $-3.5 \leq \hat{\gamma} \leq 0$. In both panels, the solid line corresponds to $\hat{\kappa} = \hat{\kappa}_C(T)$ and the best fit value of $\hat{\gamma} = -2.6$. The experimental measurements shown are from the ALICE [2], ATLAS [3], and CMS [4, 11] collaborations.

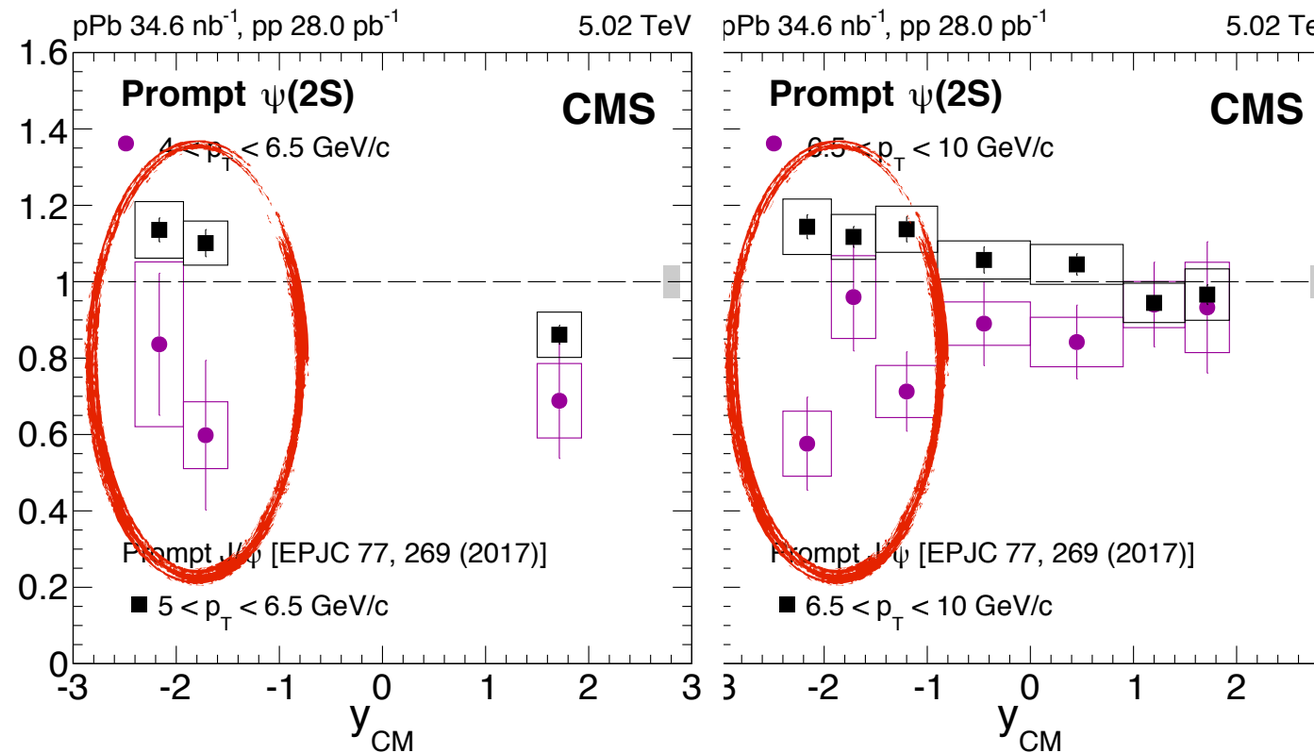
- New updated results at NLO binding energy over temperature
  : still some tension because of the similar R_{AA} of Υ(2S) & Υ(3S)

Sequential Υ suppression in pPb!

[arXiv:2202.11807]

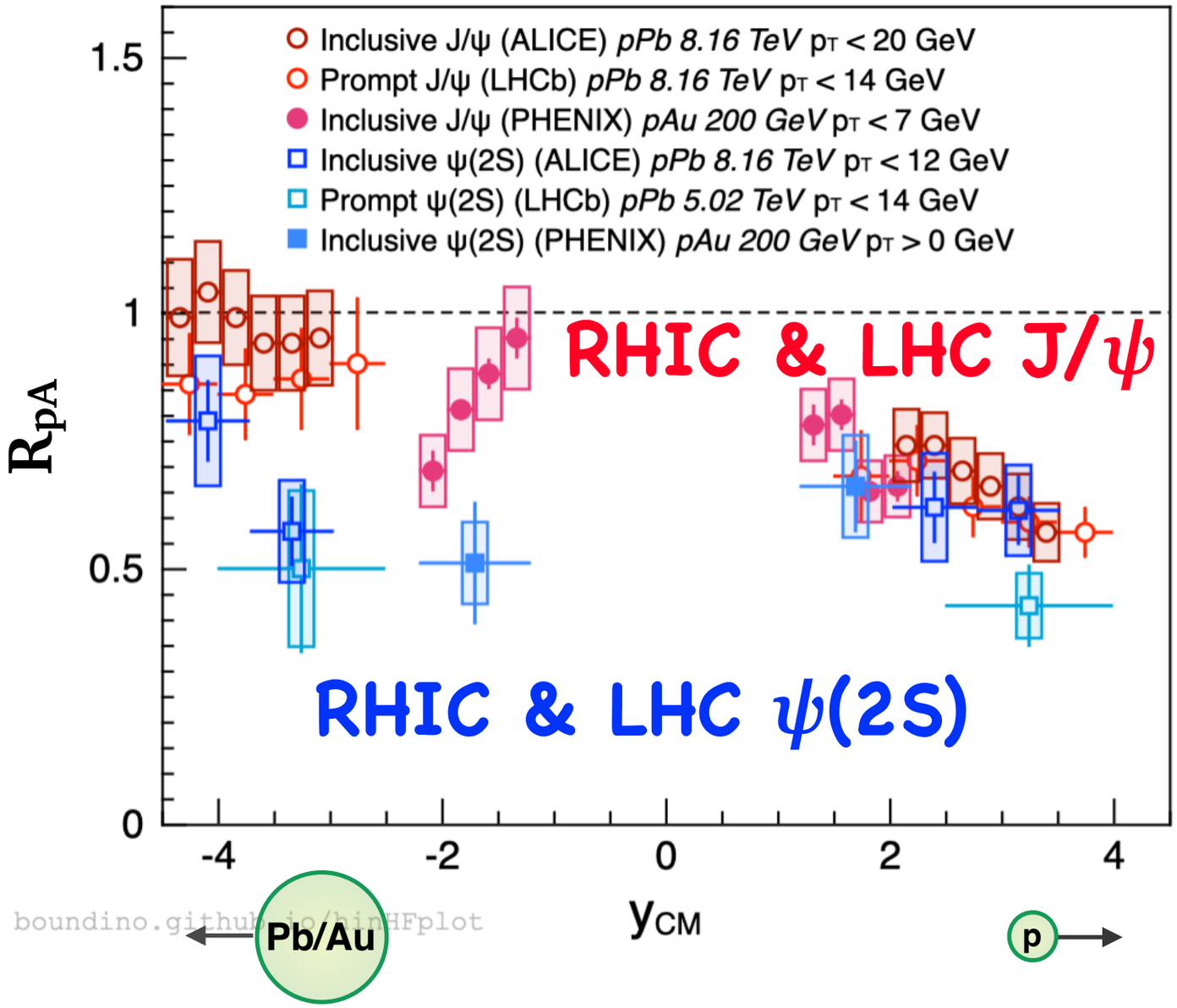


[PLB 790 (2019) 509]



- Stronger suppression of excited states at *backward rapidity* & *low-p_T*
- Similarity between charmonia and bottomonia?

Charmonia in pA RHIC vs LHC

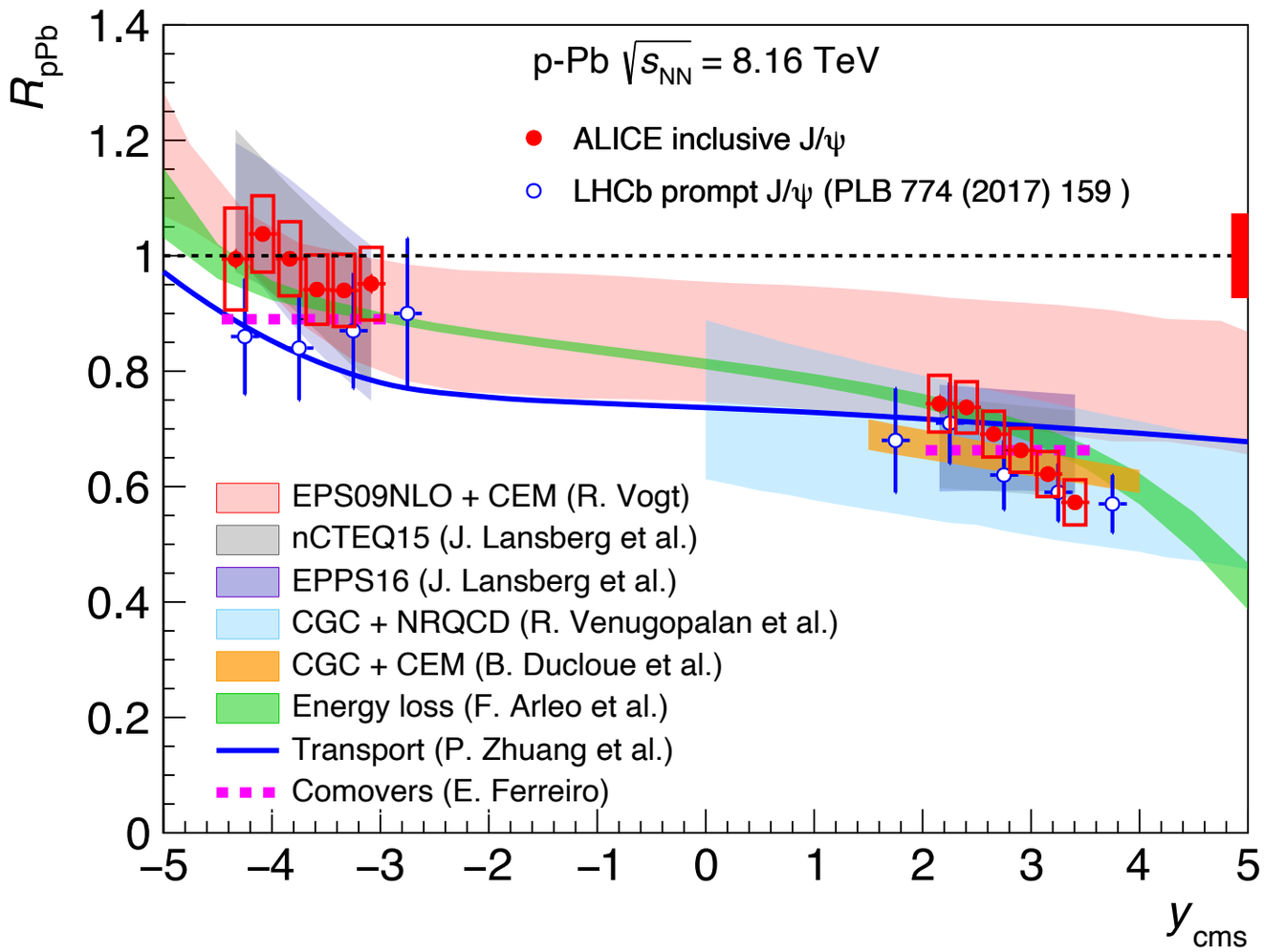


- PLB 774 (2017) 159
- JHEP 07 (2018) 160
- arXiv:2202.03863
- JHEP 03 (2016) 133
- PRC 102 (2020) 014902

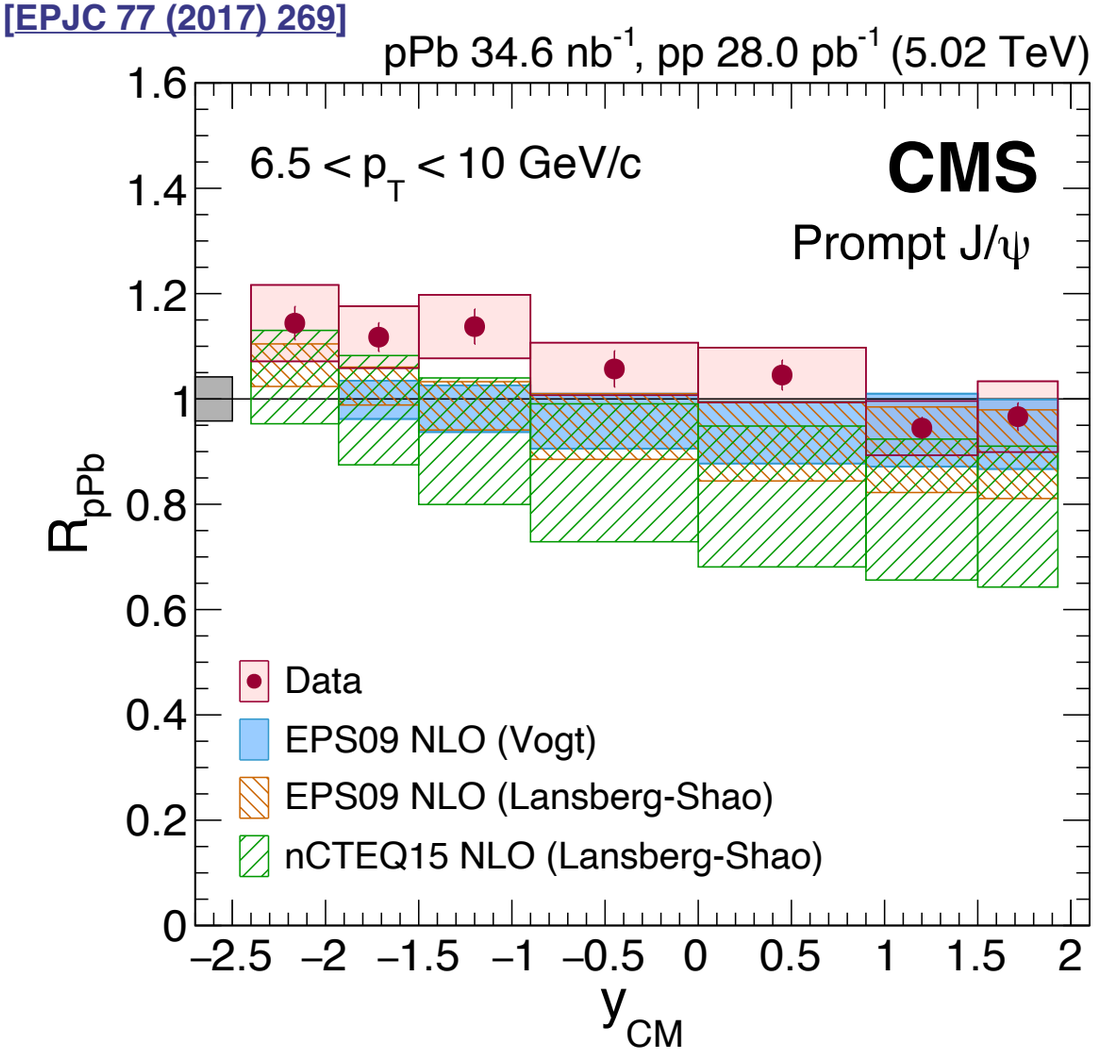
- Similar trend for both J/ψ & ψ(2S) at RHIC and LHC
  - Similar 'amount' of initial/final effects?

J/ψ in pPb vs model

[JHEP 07 (2018) 160]



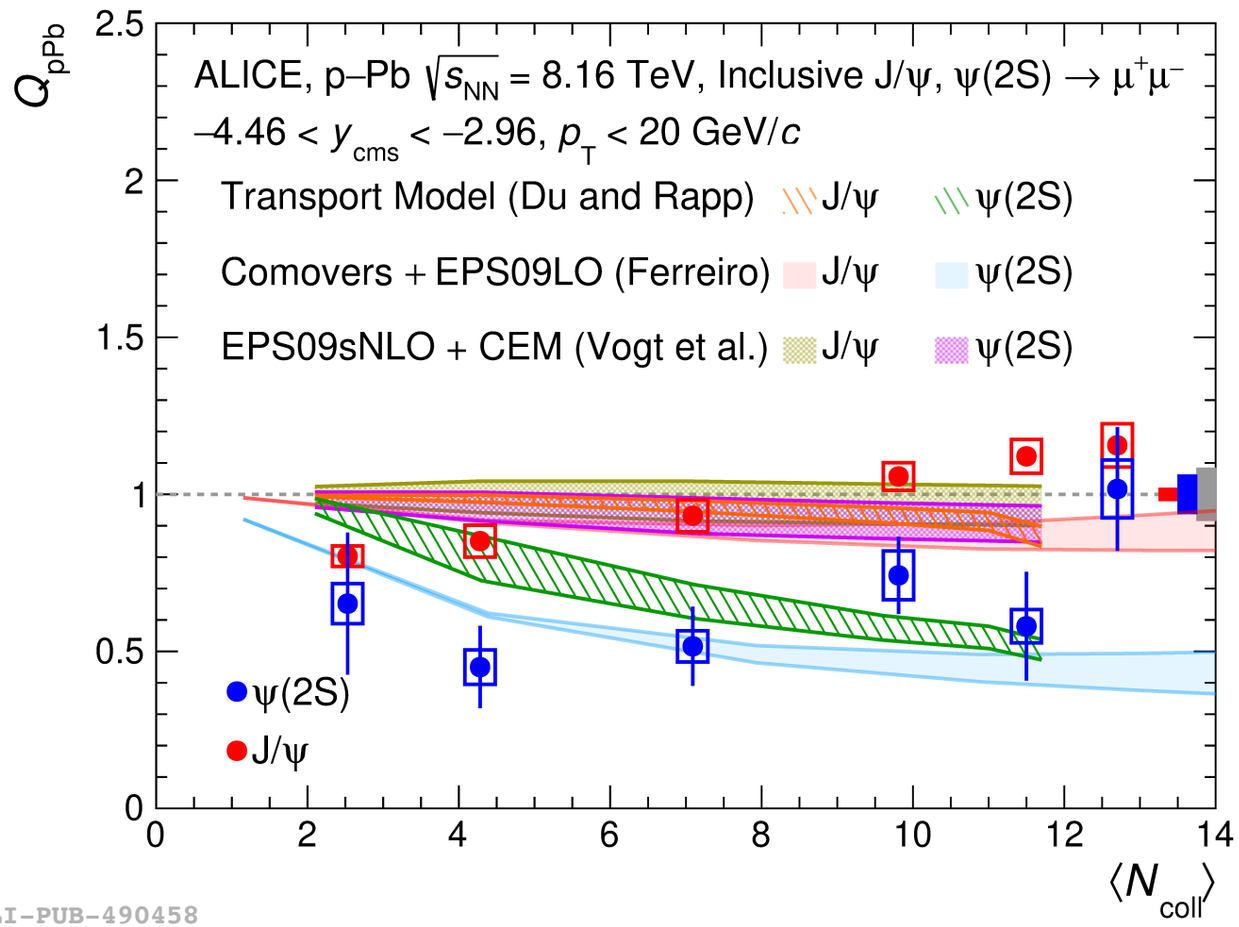
[EPJC 77 (2017) 269]



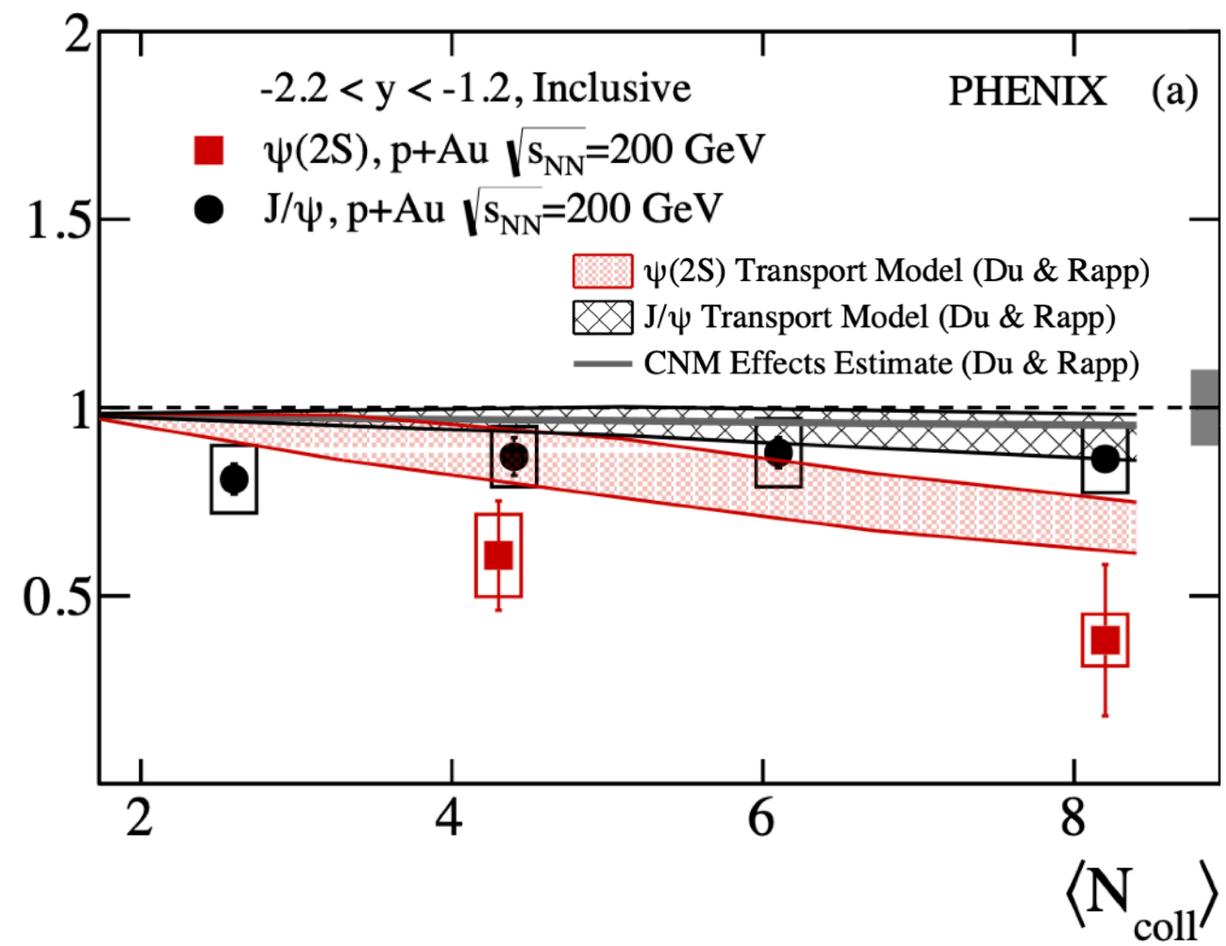
- J/ψ modification well explained by nPDF / CGC predictions
- Negligible contributions from final state effects (comover or hot nuclear matter)

Charmonia in pA vs model

[JHEP 02 (2021) 002]



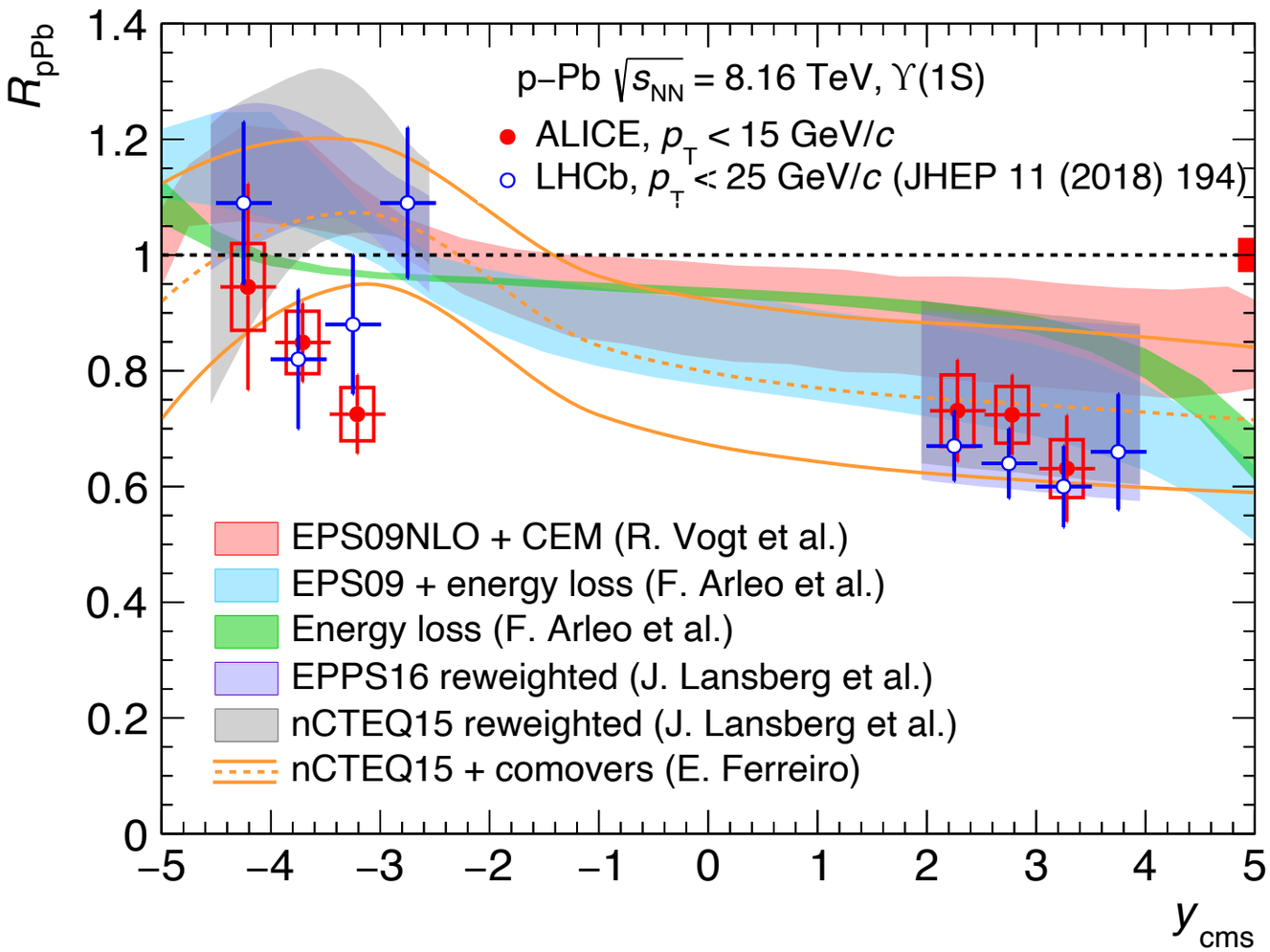
[PRC 105 (2022) 064912]



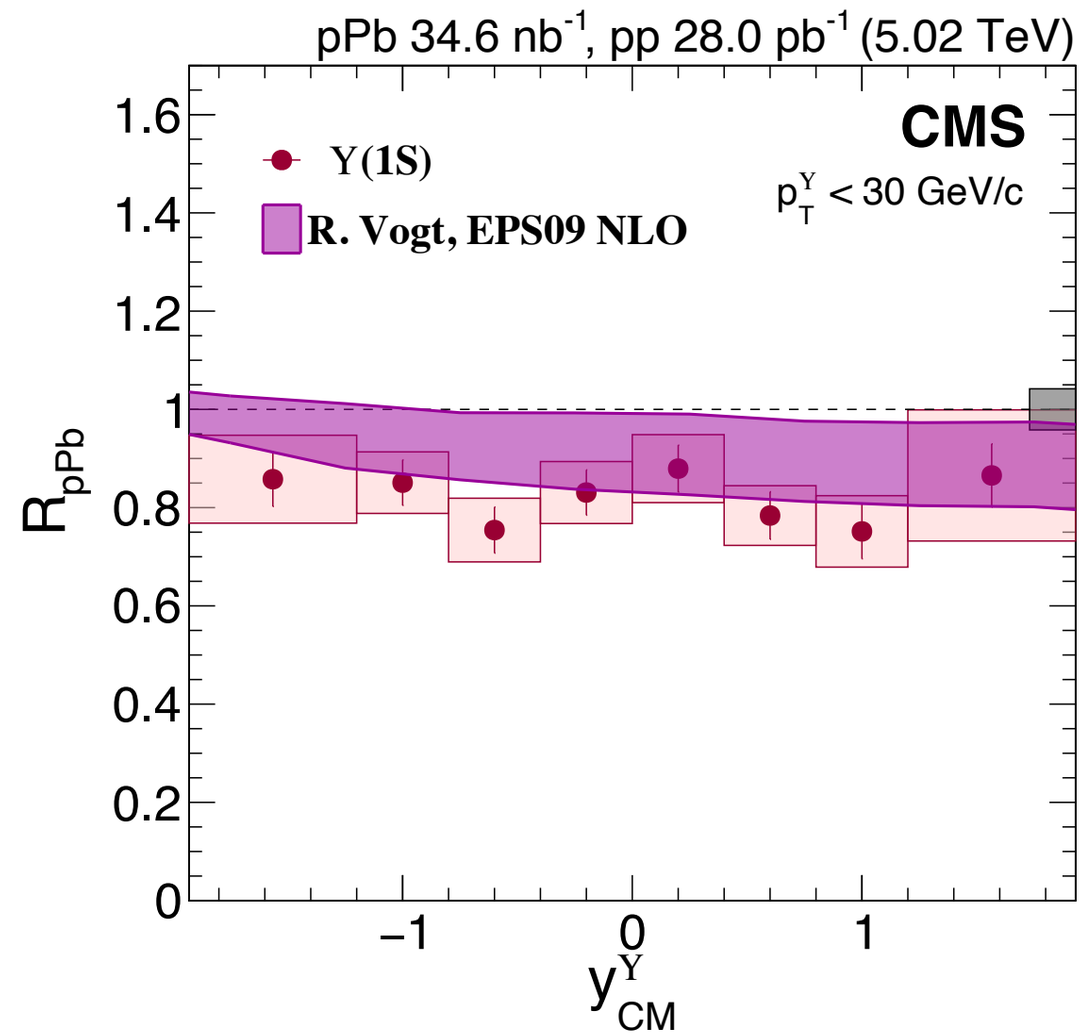
- Attempts to describe ψ(2S) suppression with comover breakup & QGP-like HNM effects
  - Tension b/w model & data in both RHIC and LHC
  - Similar nuclear absorption for J/ψ & ψ(2S) @ RHIC —> already hot in pAu 200 GeV?

Bottomonia in pPb vs model

[PLB 806 (2020) 135486]



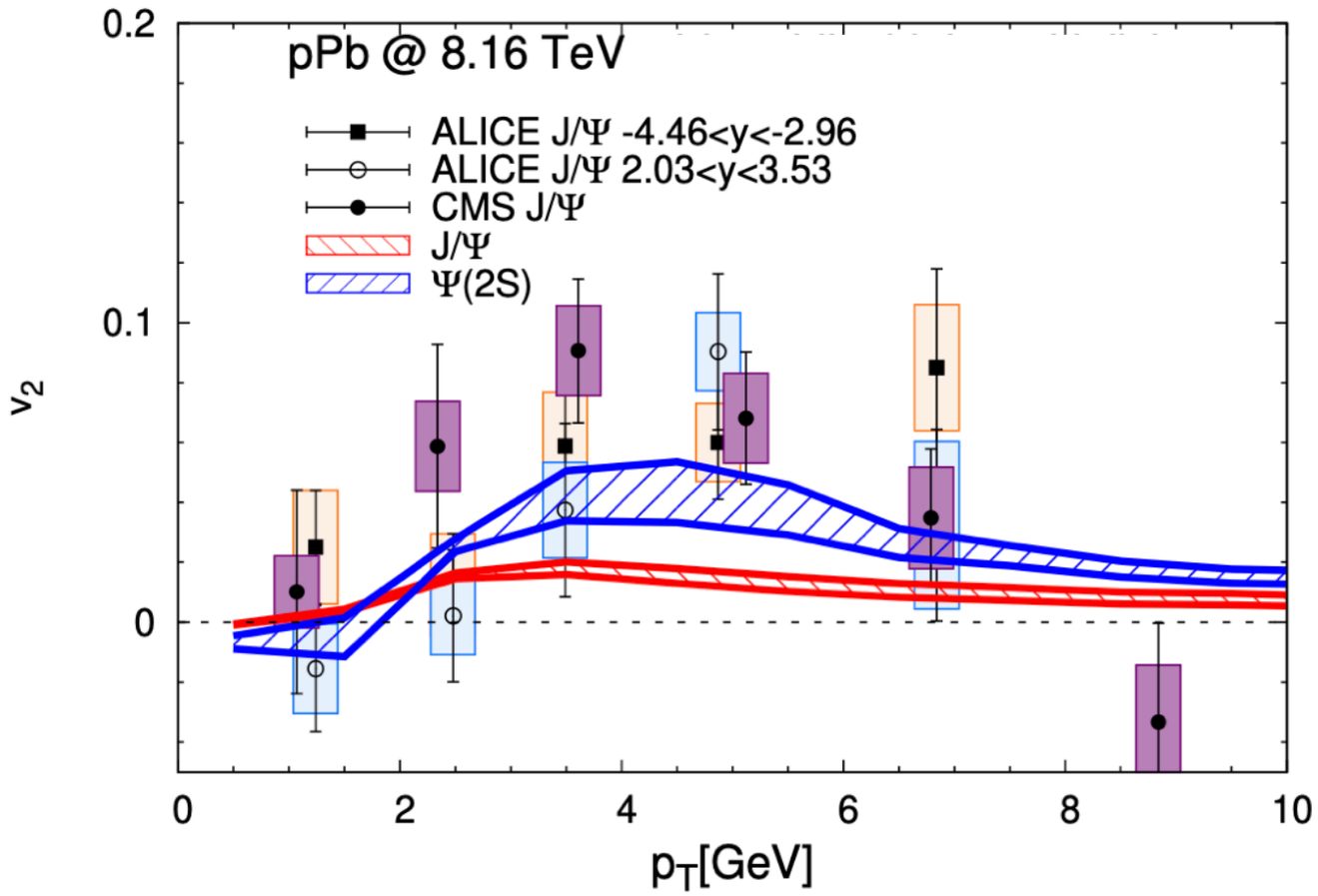
[arXiv:2202.11807]



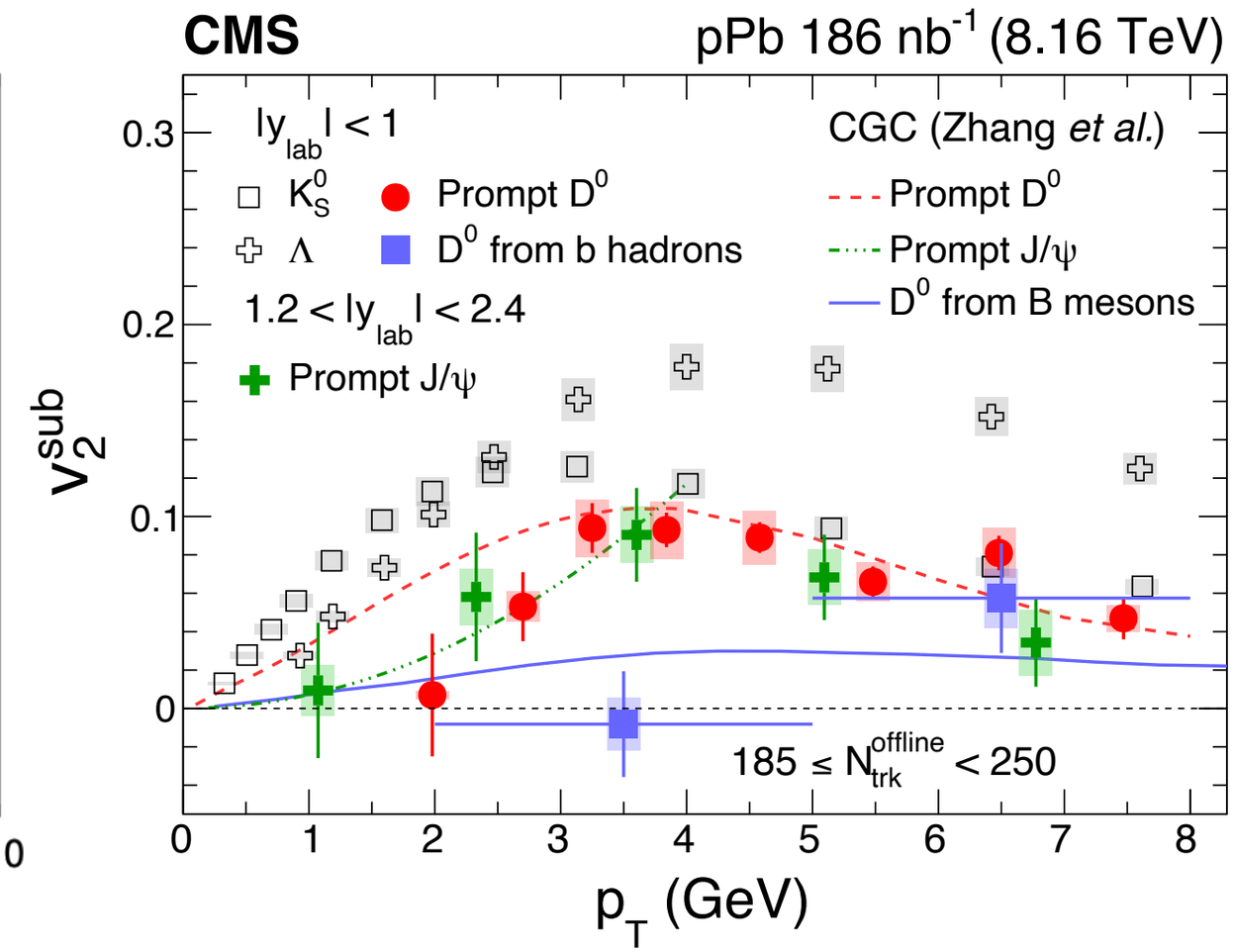
- Y(1S) R_{pPb} data in agreement with nPDF calculations

J/ψ flow in pPb vs model

[JHEP 03 (2019) 015]



[PLB 813 (2021) 136036]

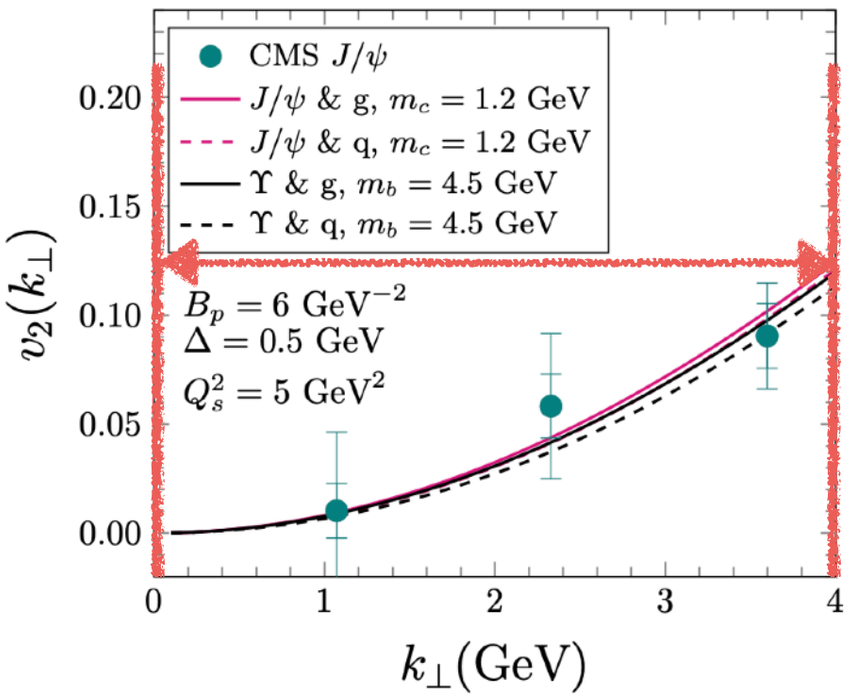


- Transport model underestimate J/ψ v_2
  - predicts larger v_2 for ψ(2S)

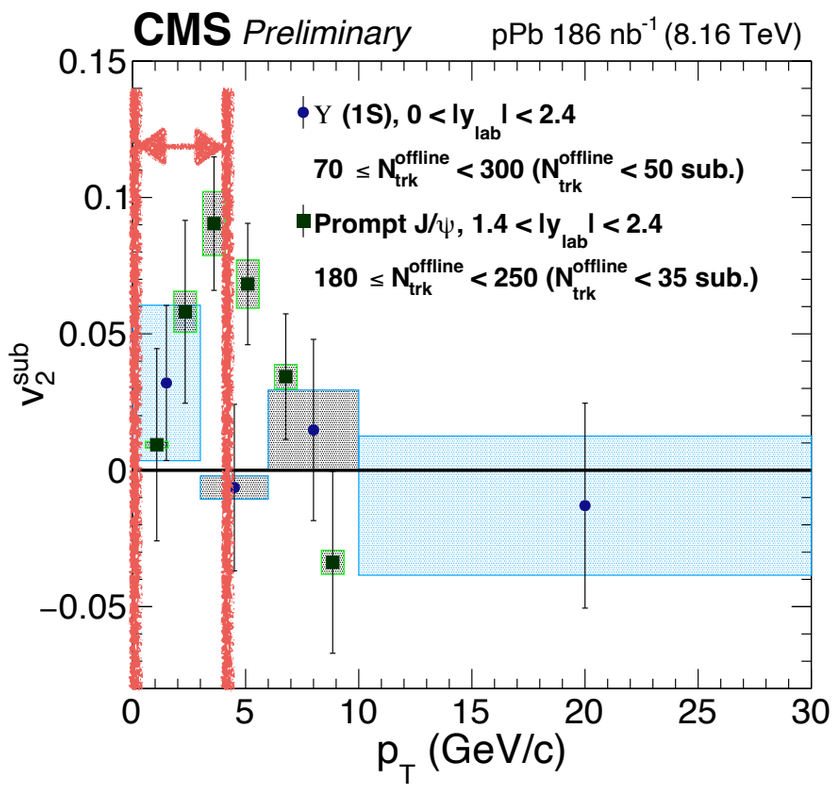
- Qualitatively in agreement with CGC?
  N.B. J/ψ v_2 keeps increasing vs p_T
  : discrepancy for p_T>4 GeV/c (LO only)

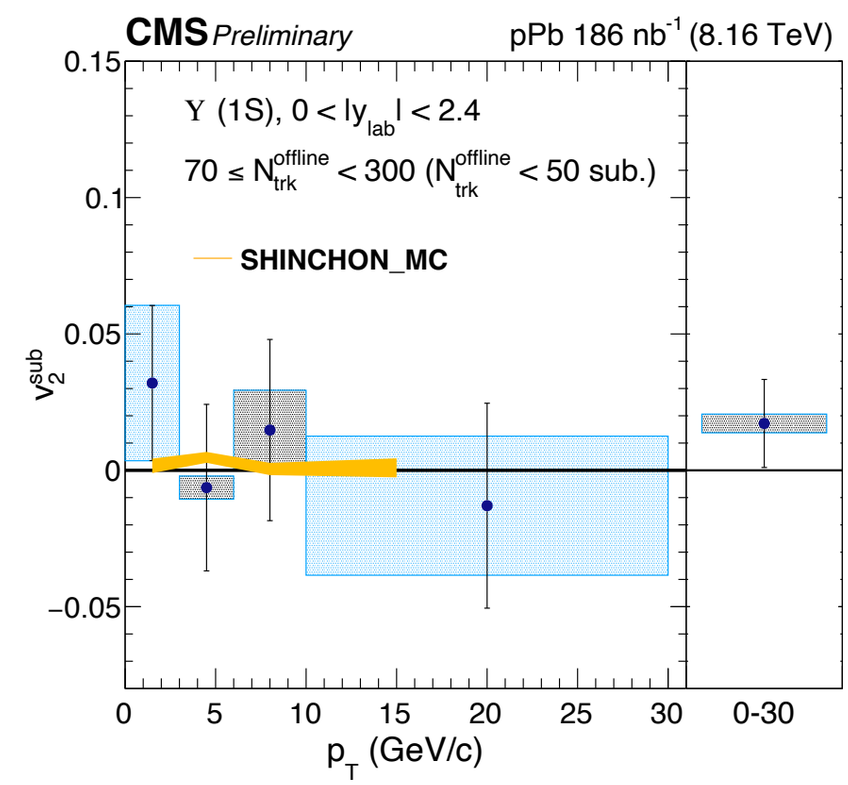
Υ(1S) flow in pPb vs model

[PRD 102 (2020) 034010]



[CMS-PAS-HIN-21-001]

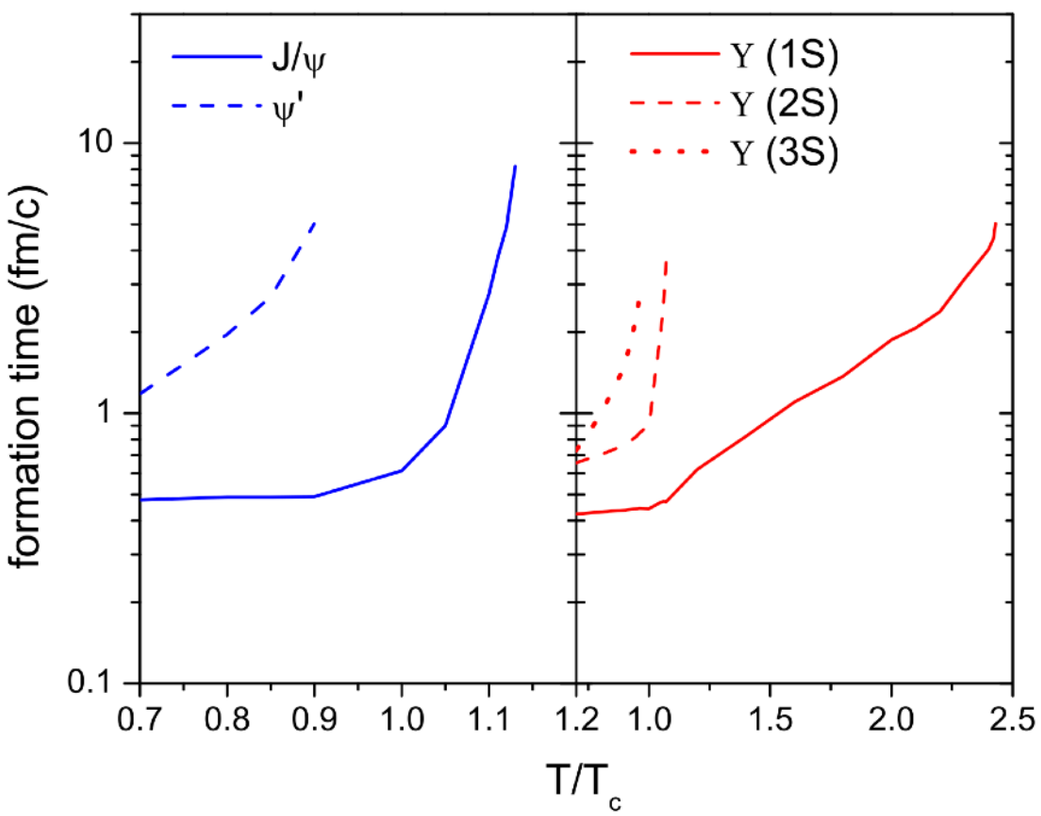




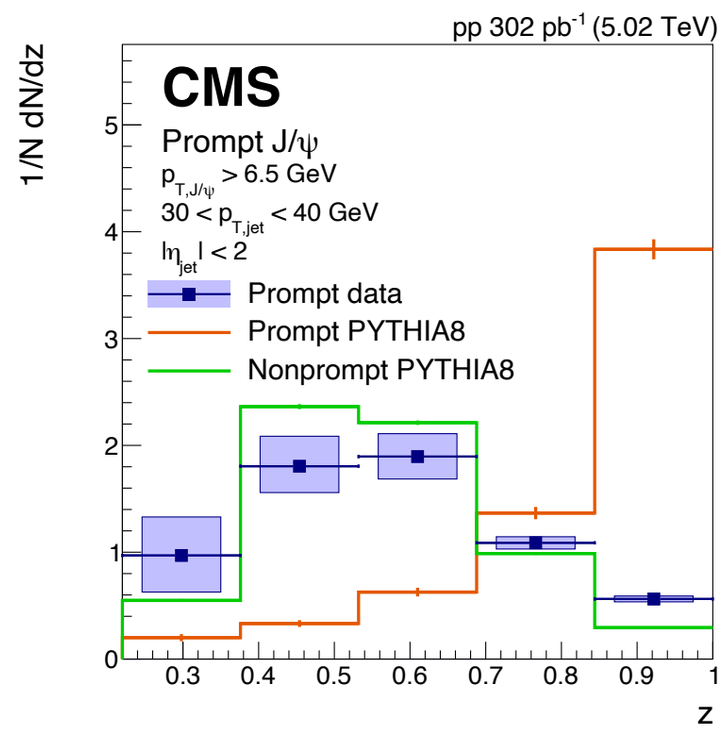
- Similar v_2 predicted by CGC for J/ψ and Υ(1S) - CMS Υ(1S) v_2 consistent with zero — N.B. limitations for higher-order QCD calculations (works only $p_T \leq 5$ GeV/c)
- Very small v_2 predicted considering only QGP-like dissociation

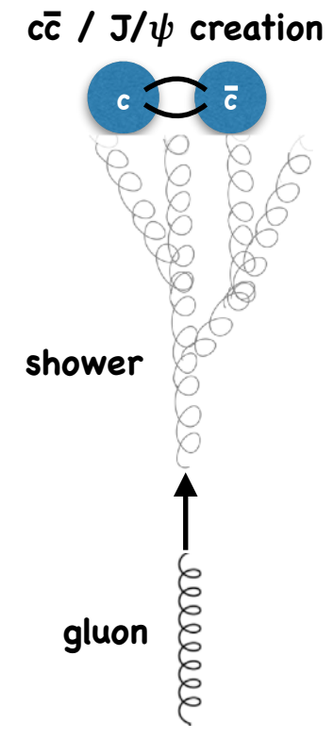
Quarkonium formation time

[NPPP 276 (2016) 137]

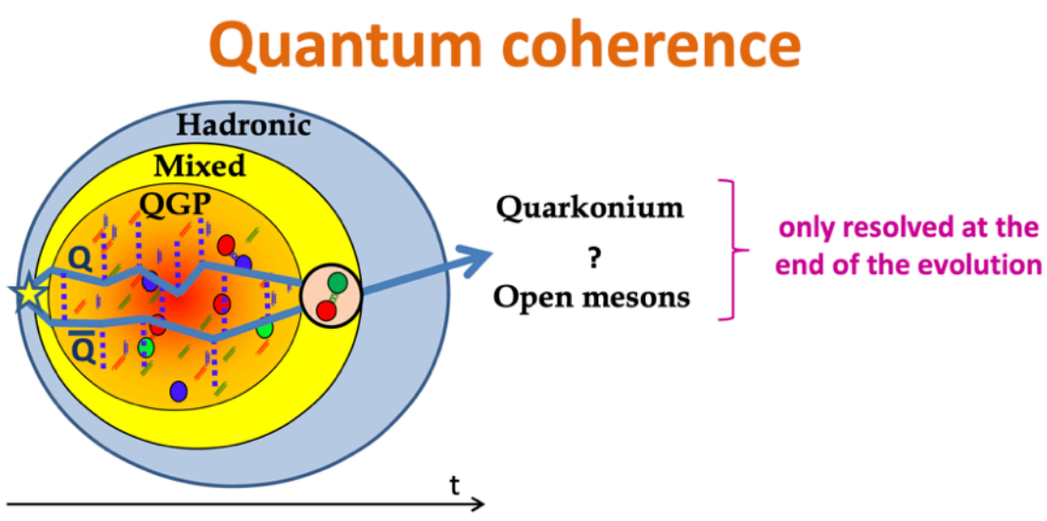


[PLB 805 (2020) 135434]
[PRL 118 (2017) 192001]





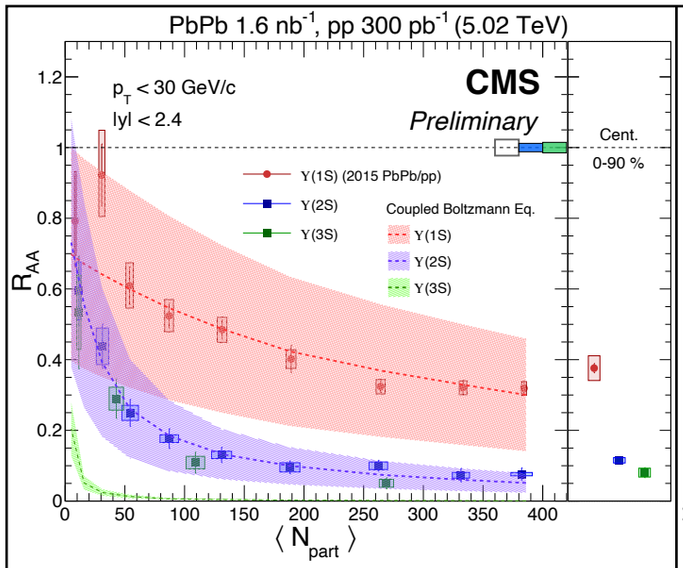
[P. Gossiaux SQM 2022]

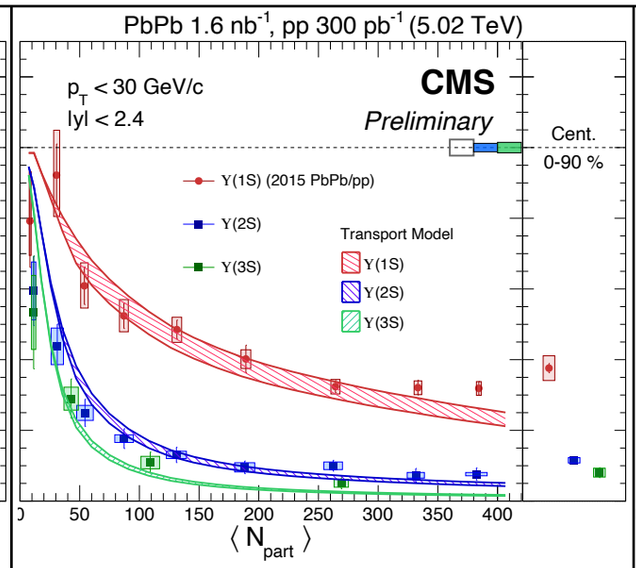


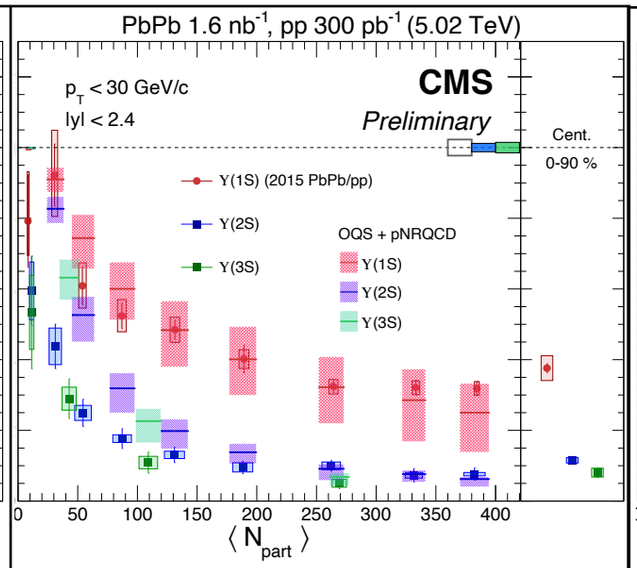
- Quarkonium formation time delayed above dissociation temperature?
- Temperature environment hot enough to modify quarkonium formation time scales?
- Even in pp : high-p_T J/ψ produced at later stages by parton shower

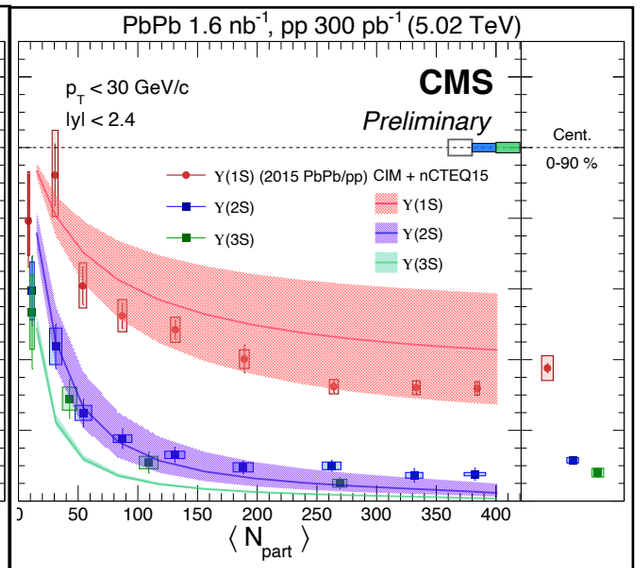
Comparison with theory

[CMS-PAS-HIN-21-007]

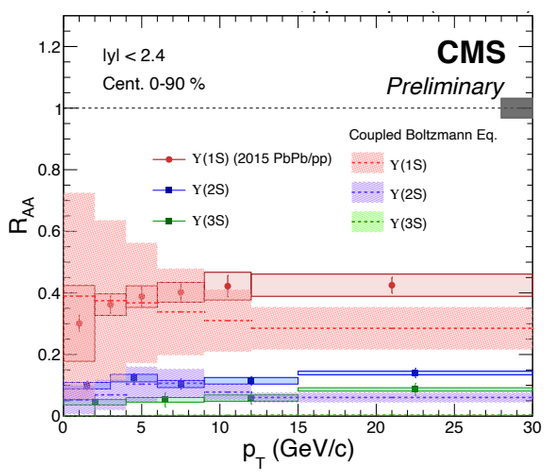




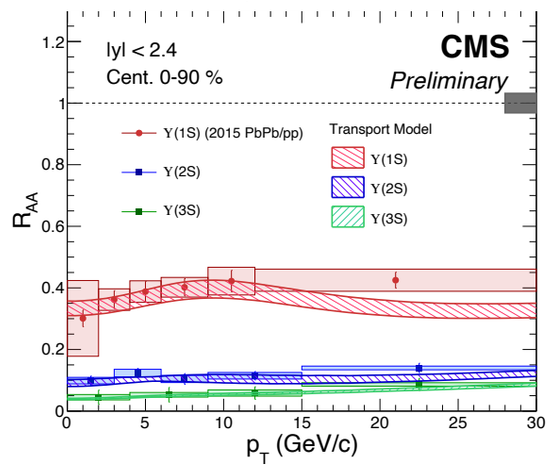




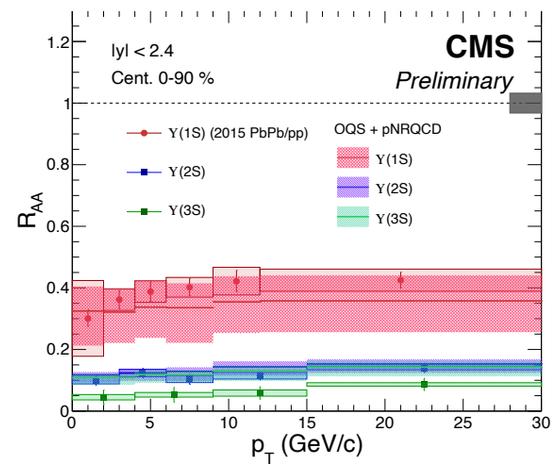
- Comover as source of dissociation
- nCTEQ15 nPDF effect
- Feed-down included



- Open Quantum system approach
  : Dissociation + Recombination
- EPPS16 nPDF effect
- no recombination for Υ(3S)
- Feed-down included



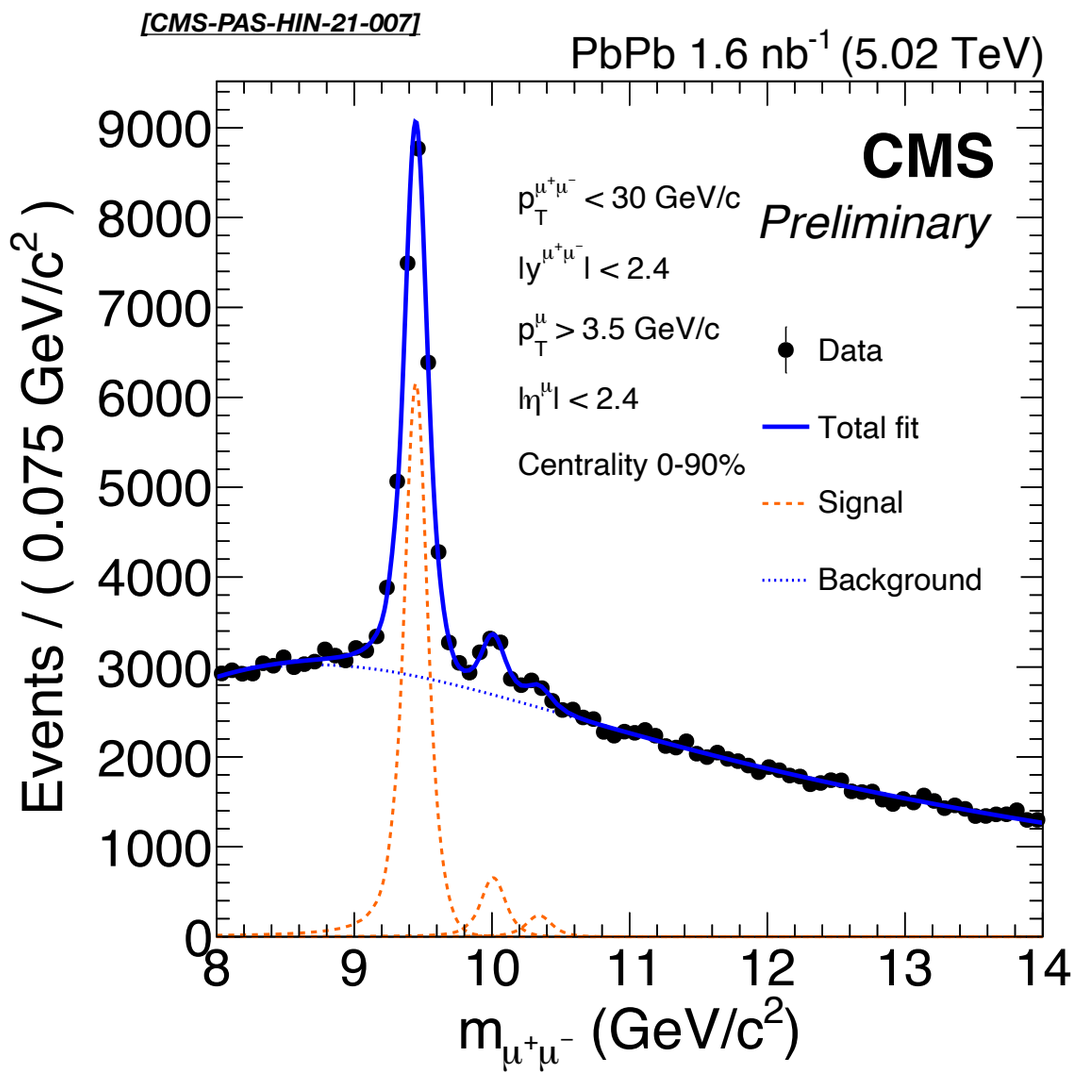
- Transport model in kinetic rate equation
  : Dissociation + Recombination
- EPS09 (NLO) nPDF effect
- Feed-down included



- Open Quantum system
  : Dissociation + Recombination
- no CNM effect
- Feed-down included

- **Models qualitatively describe R_{AA} for Υ(1S) (tension in some cases at central collisions / high-p_T)**
- **Despite similar R_{AA} of Υ(1S), very different calculations for excited states**

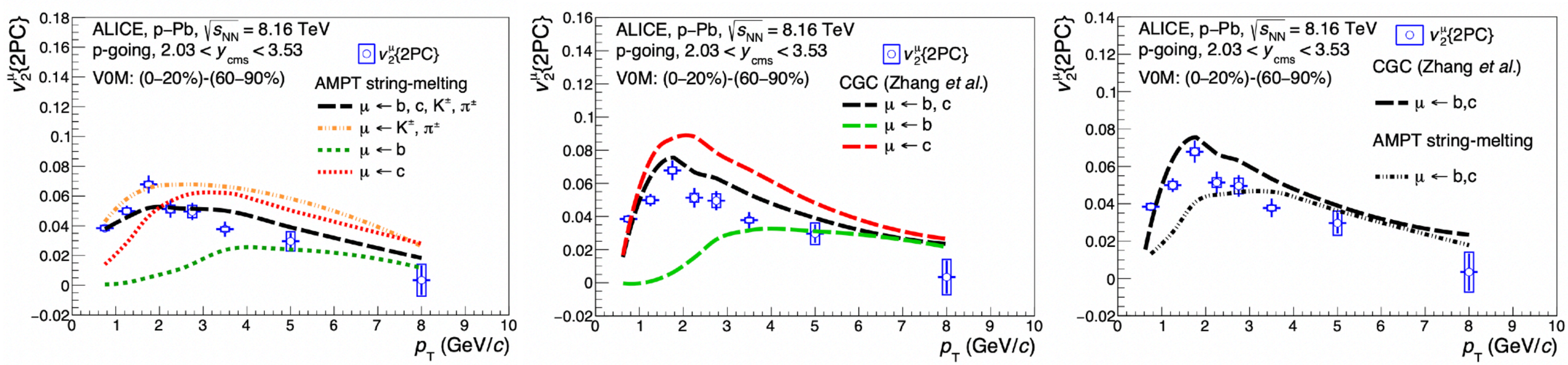
Υ(3S) in PbPb



- Υ(3S) observed with discrete likelihood profile > 5 sigma in PbPb collisions
- MVA BDT technique applied to reduce the background level in PbPb

Muon v_2 in pPb

[arXiv:2210.08980]



- AMPT qualitatively in agreement with data including light & heavy quark v_2
- CGC agreement with data using contributions from charm & beauty quark
  : do not include light quarks —> overestimation at low-p_T
- Comparable results at high-p_T for AMPT & CGC & data