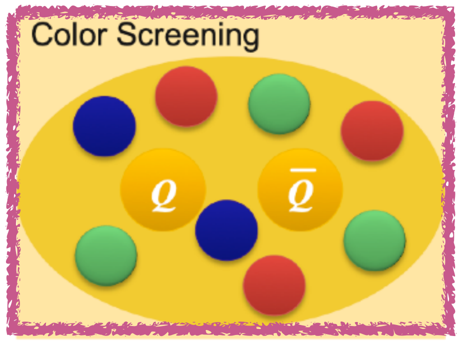
Recent results on Upsilon production in PbPb and pPb collisions by CMS

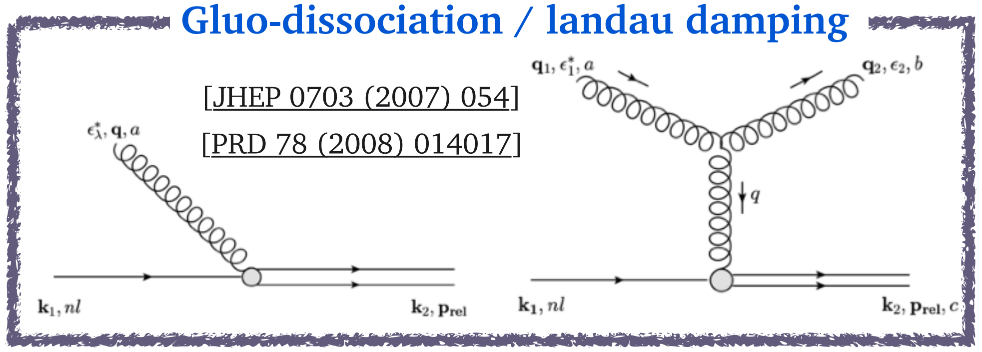
JaeBeom Park (Korea University)
on behalf of the CMS Collaboration

QWG 2022 : 15th International Workshop on Heavy Quarkonium
@ GSI Darmstadt (Germany)

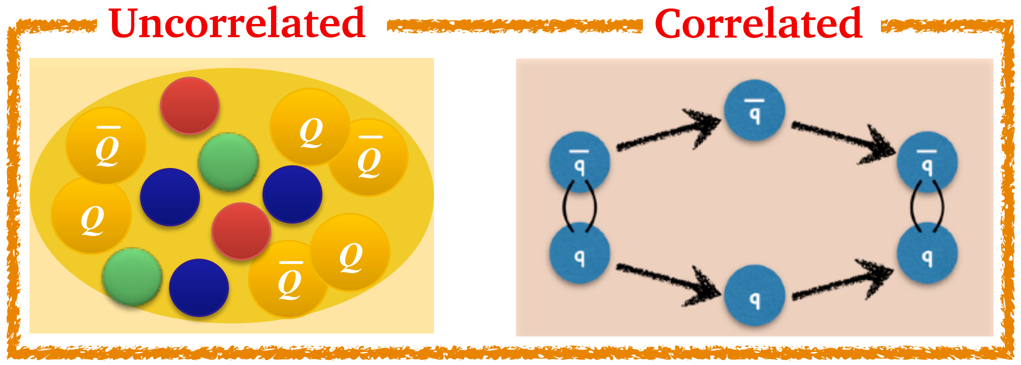
Quarkonium production in HIC

- **Suppression**
  - Debye screening
    -> static color screening - $ReV_s(r,T)$
  - Gluo-dissociation / Landau-damping
    -> dynamical screening - $ImV_s(r,T)$



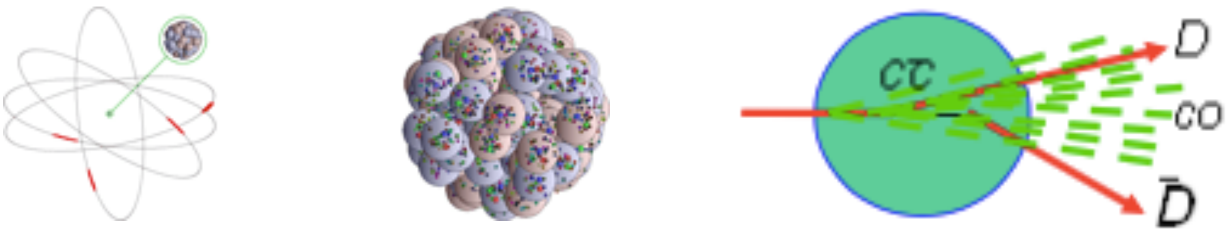


- **Recombination (Regeneration)**
  - Uncorrelated (off-diagonal) recombination
  - Correlated (diagonal) recombination

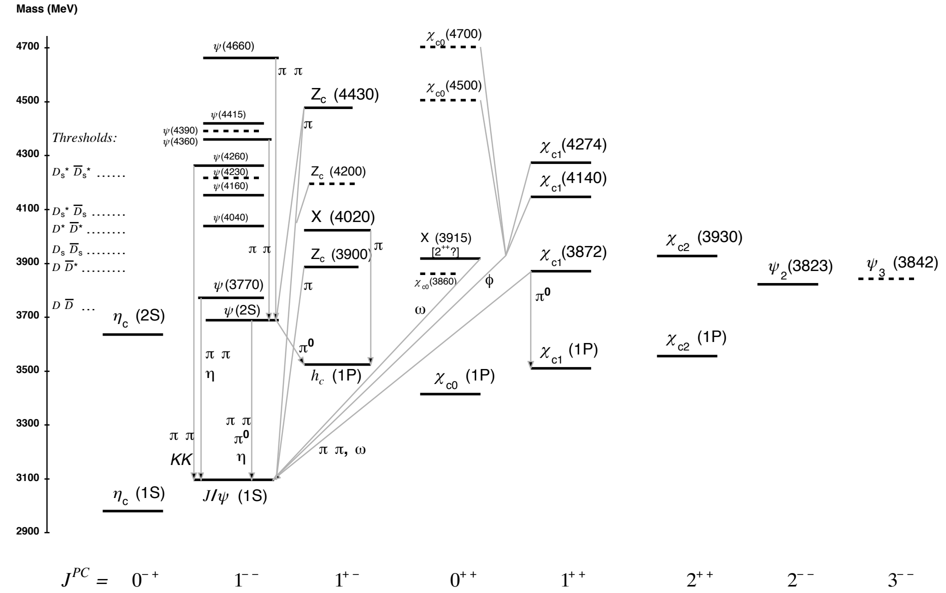


- **Initial/Final state effects of nucleus**
  - nPDF, CGC, coherent energy loss (initial/final)
  - co-mover breakup, nuclear absorption

[IJMP E 24 (2015) 1530008]



- **Feed-down contributions**



Inclusive Υ in HI with CMS

- Quarkonium production in PbPb collisions at 2.76 TeV *[JHEP 1205 (2012) 063]*
- Suppression of excited Υ(nS) in PbPb at 2.76 TeV *[PRL 107 (2011) 052302]*
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- Event activity of Υ(nS) in pPb at 5.02 TeV *[JHEP 04 (2014) 103]*
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- Suppression of Υ(nS) in PbPb at 5.02 TeV *[PRL 120 (2018) 142301]*
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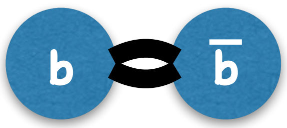
- Elliptic flow of Υ(1S) in pPb at 8.16 TeV *[CMS-PAS-HIN-21-001]*

Run1 : 2011-2013

PbPb : $\sqrt{s_{NN}}$ = 2.76 TeV, L = 166 μb^{-1}

pPb : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 34.6 nb^{-1}

pp : $\sqrt{s_{NN}}$ = 2.76 TeV, L = 5.4 pb^{-1}



Run2 : 2015-2018

PbPb : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 1.6+0.4 nb^{-1}

pPb : $\sqrt{s_{NN}}$ = 8.16 TeV, L = 186 nb^{-1}

pp : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 300+28 pb^{-1}

New Run2 results (April 2022)

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Run2 : 2015-2018

For Today

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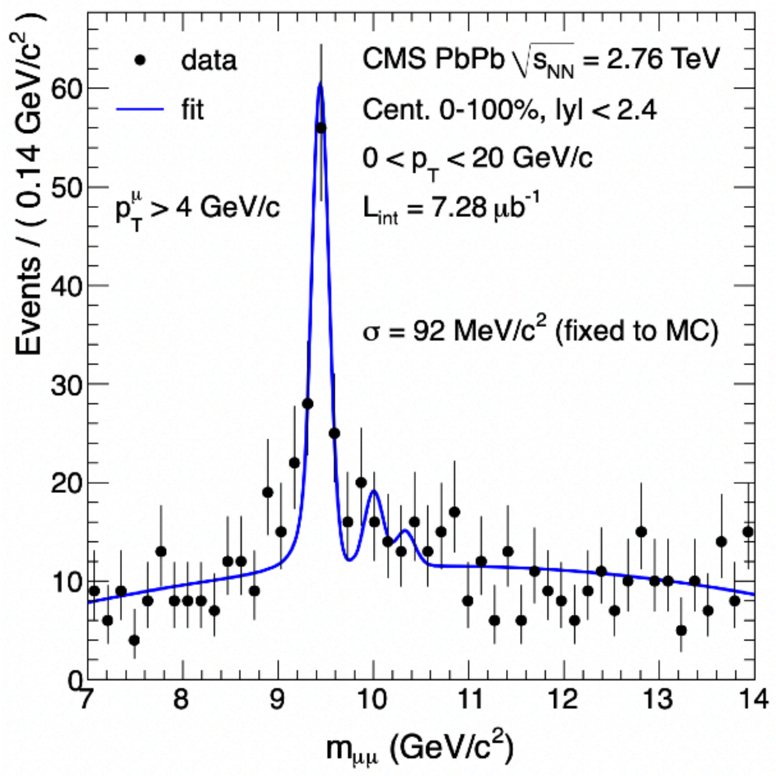

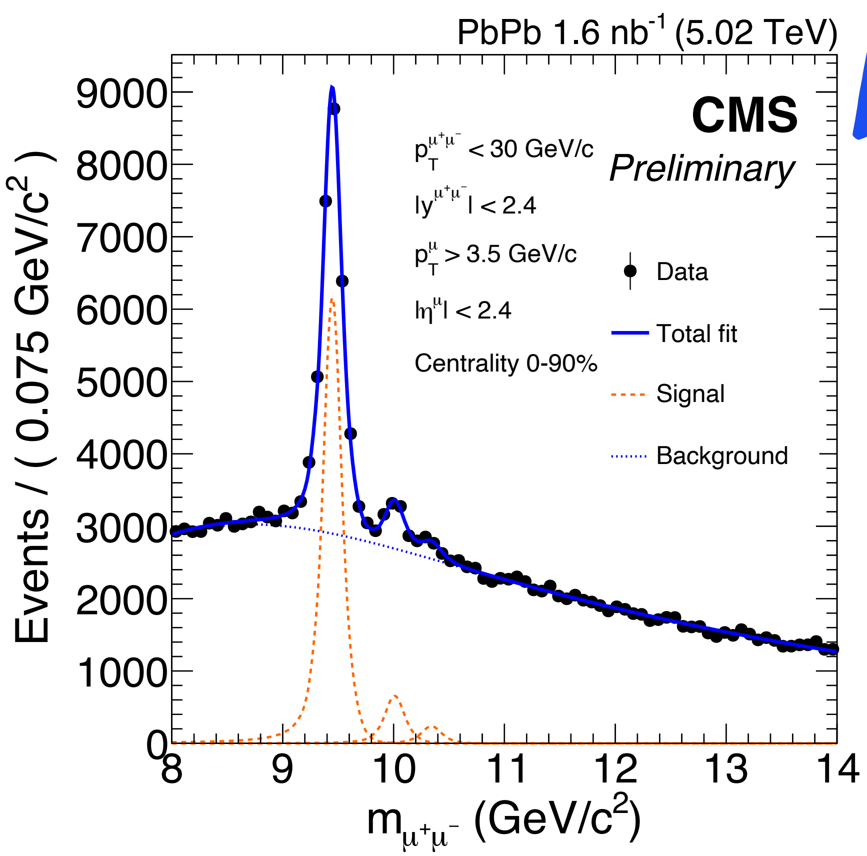

Run1 : 2011

PbPb : $\sqrt{s_{NN}}$ = 2.76 TeV, L = 7.28 μb^{-1}

- Quarkonium production in PbPb collisions at 2.76 TeV *[JHEP 1205 (2012) 063]*

- Enhanced statistics
- Improved analysis technique

Run2 : 2018

PbPb : $\sqrt{s_{NN}}$ = 5.02 TeV, L = 1.6nb^{-1}

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Inclusive Υ in HI with CMS

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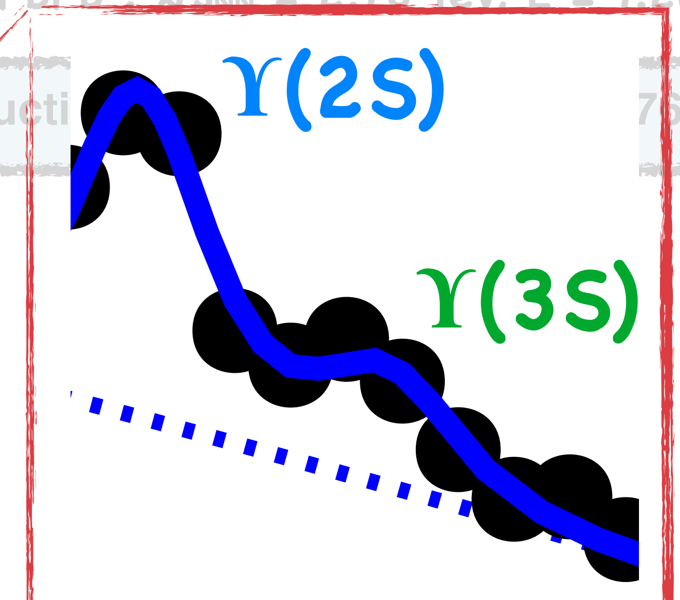
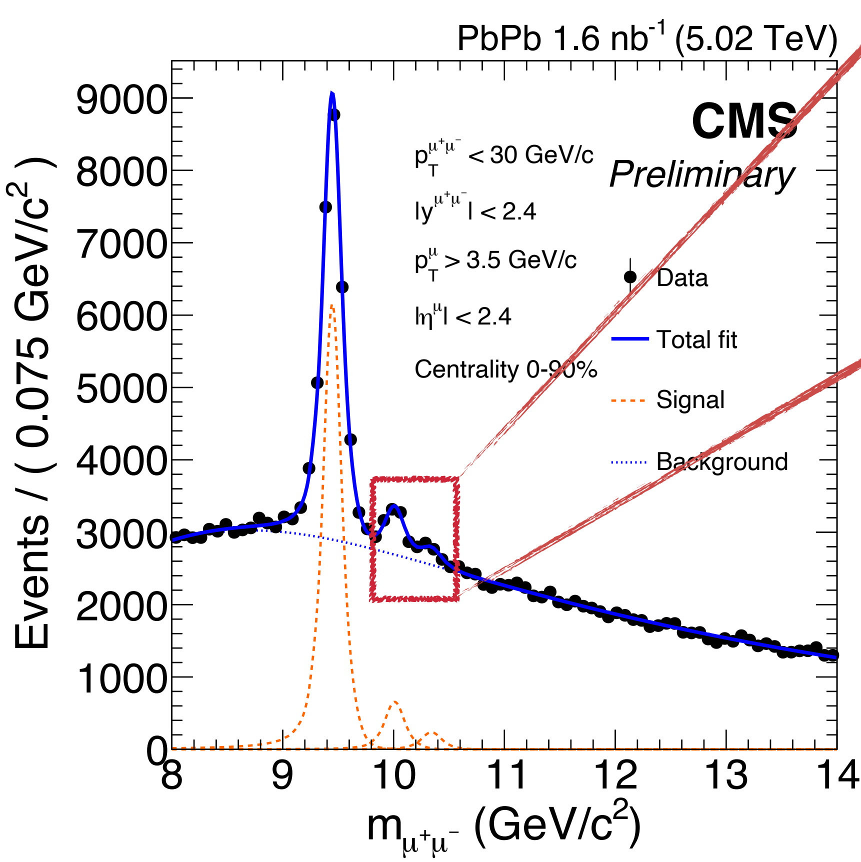
- Quarkonium producti... 76 TeV [JHEP 1205 (2012) 063]

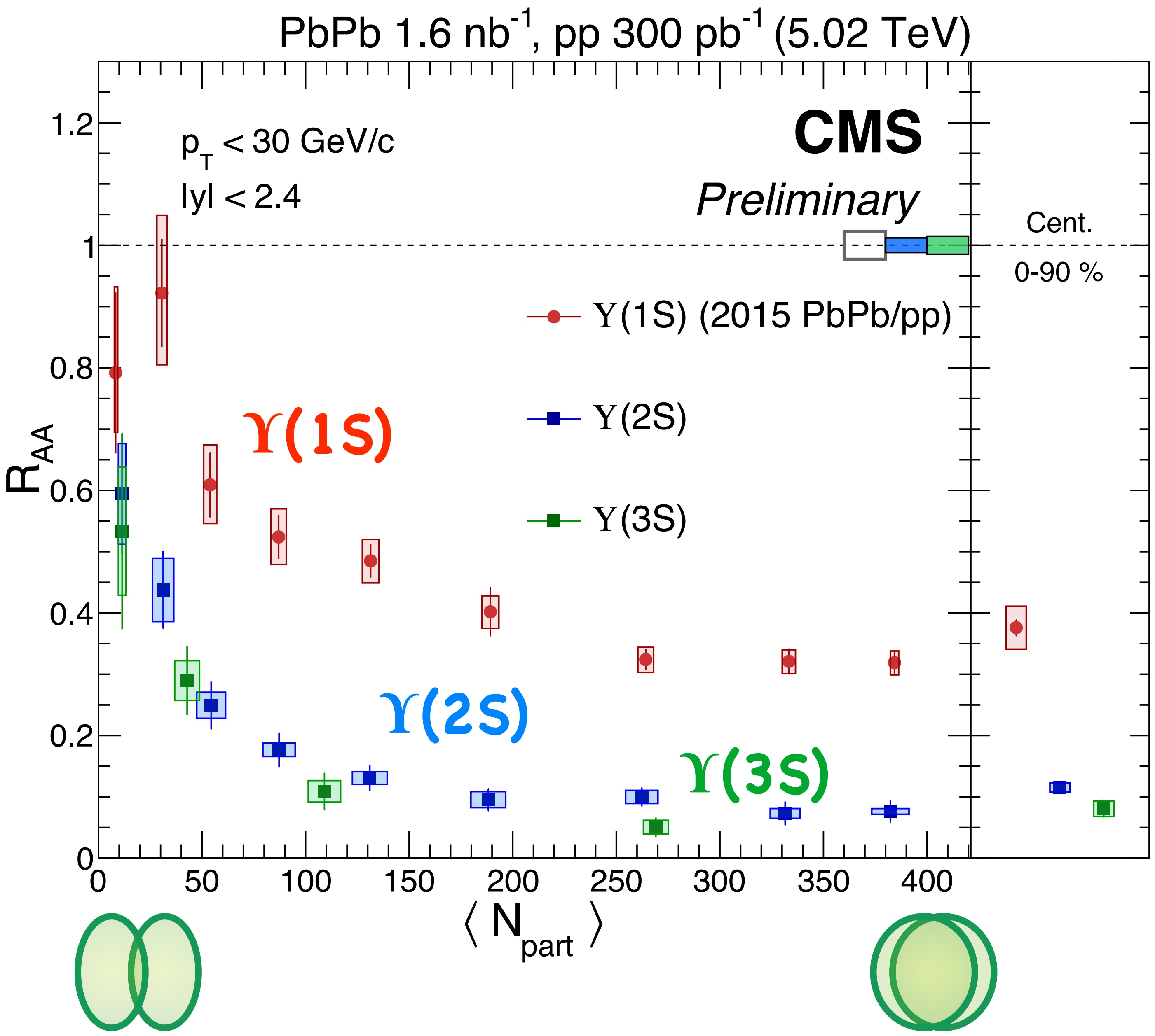




- **First observation of Υ(3S) in AA collision!**
- Boosted Decision Tree (BDT) method applied — Huge reduction of background level
- Significance > 5σ using discrete likelihood profiling

Sequential Υ suppression in PbPb

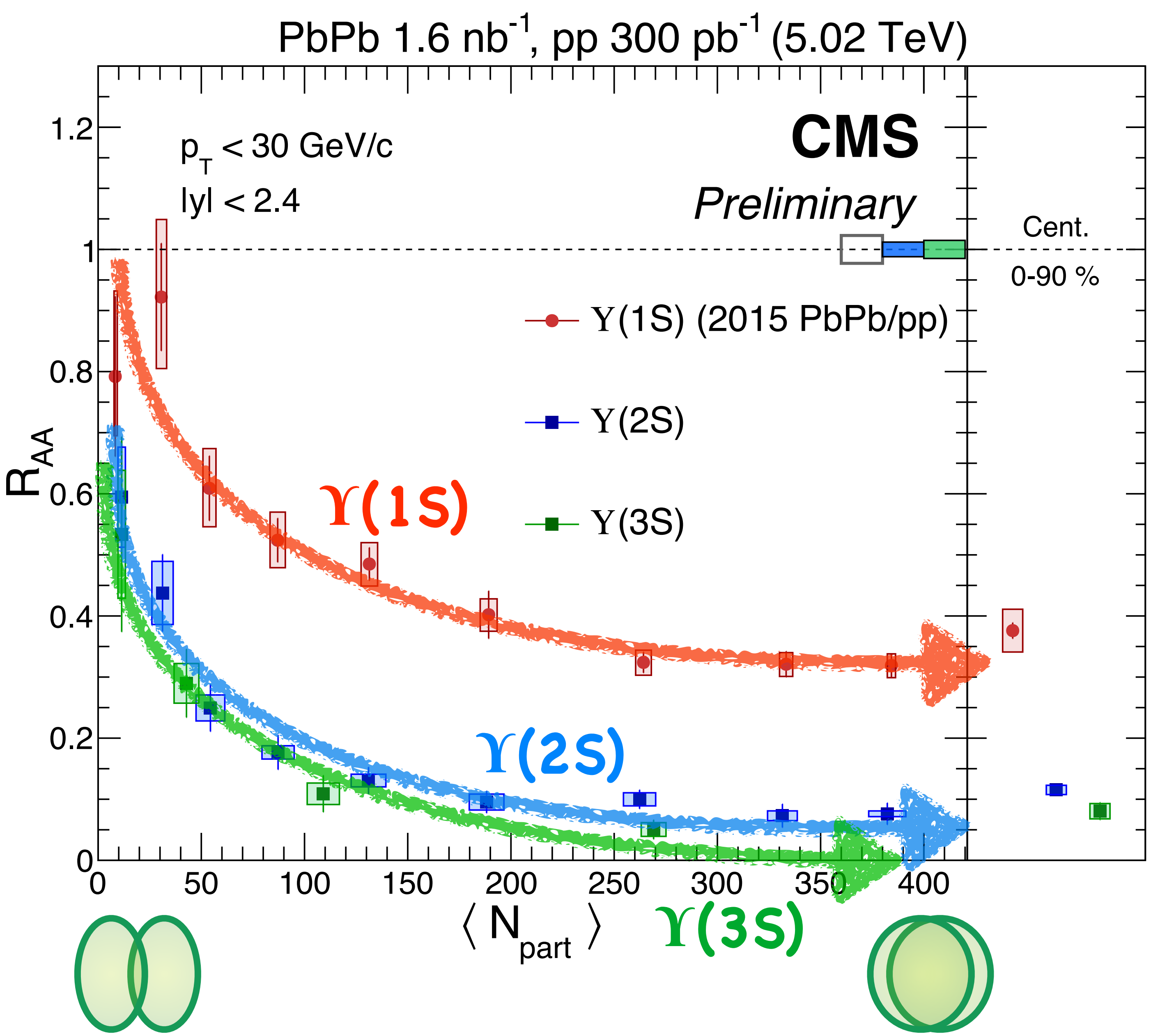
[CMS-PAS-HIN-21-007]



- Observation of Υ(3S) in PbPb!
  - Significance > 5σ
- Clear ordering of Υ suppression!
  $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$

Sequential Υ suppression in PbPb

[CMS-PAS-HIN-21-007]



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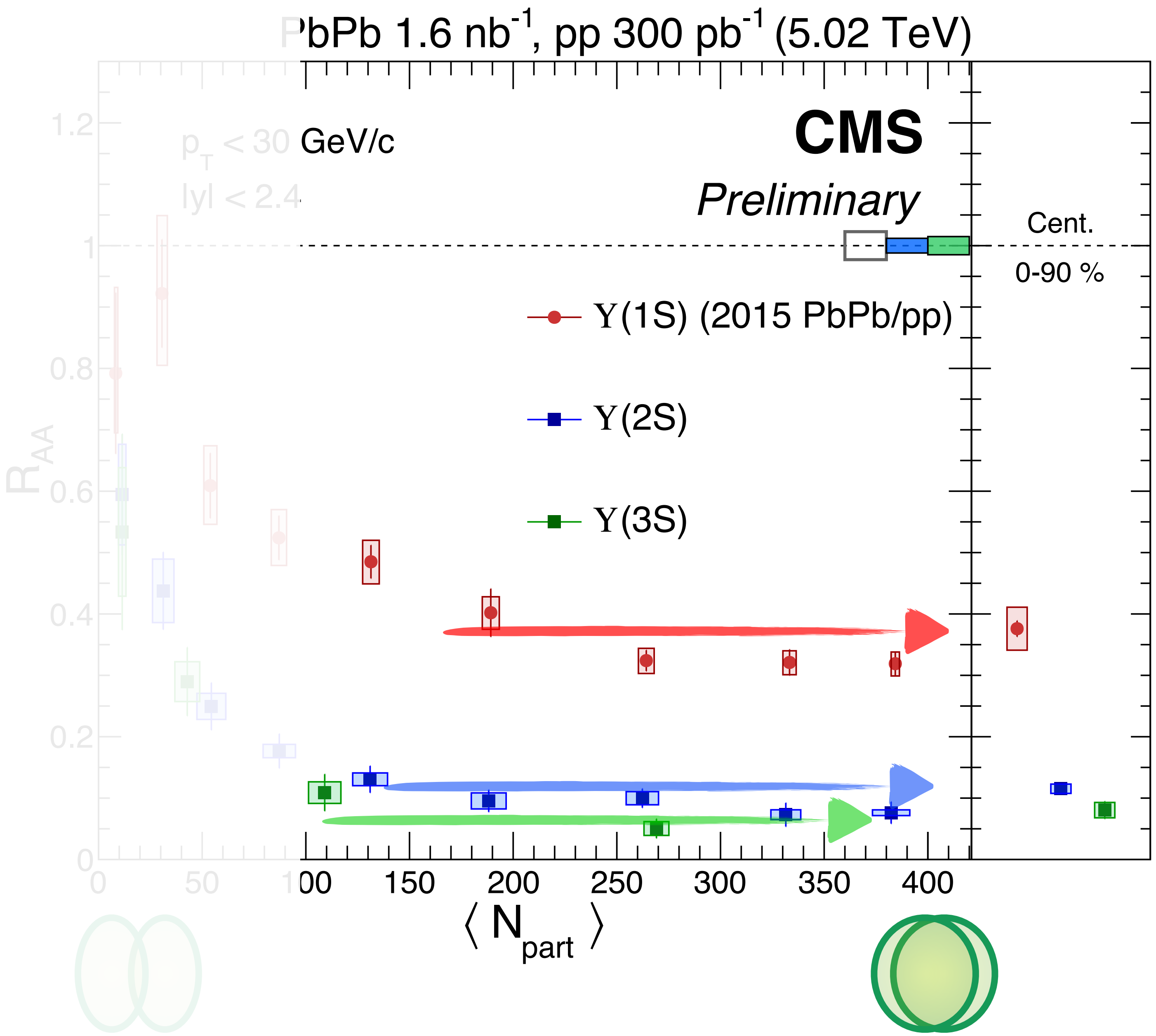
  $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
- Gradual decrease towards central collisions

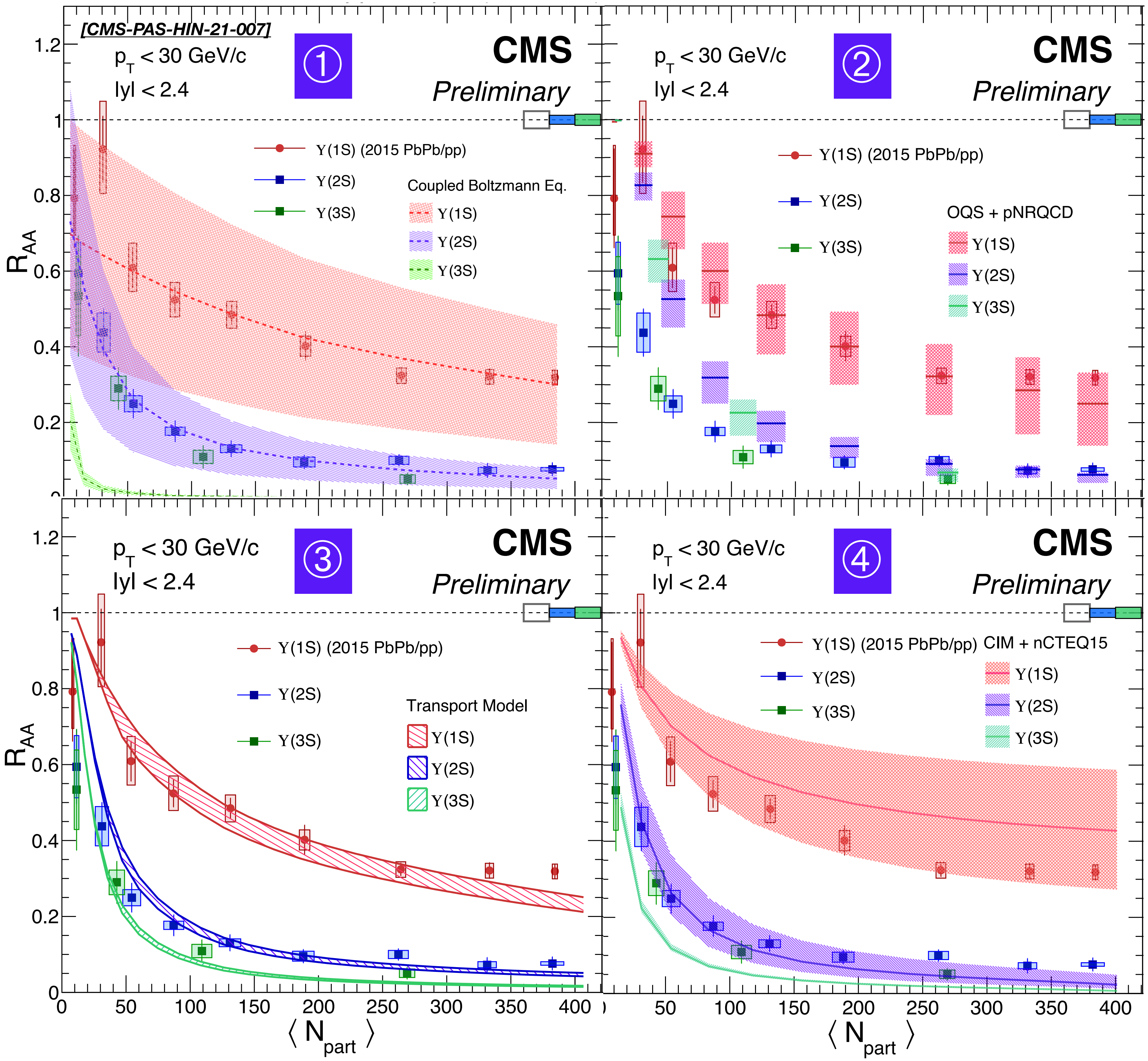
Sequential Υ suppression in PbPb

[CMS-PAS-HIN-21-007]



- Observation of Υ(3S) in PbPb!
  — Significance > 5σ
- Clear ordering of Υ suppression!
  R_{AA}(Υ(1S)) > R_{AA}(Υ(2S)) > R_{AA}(Υ(3S))
- Gradual decrease towards central collisions
- Flattened in central collisions?
  — Dissociation ≈ Recombination?
  — Need more precision data

Comparison with theory



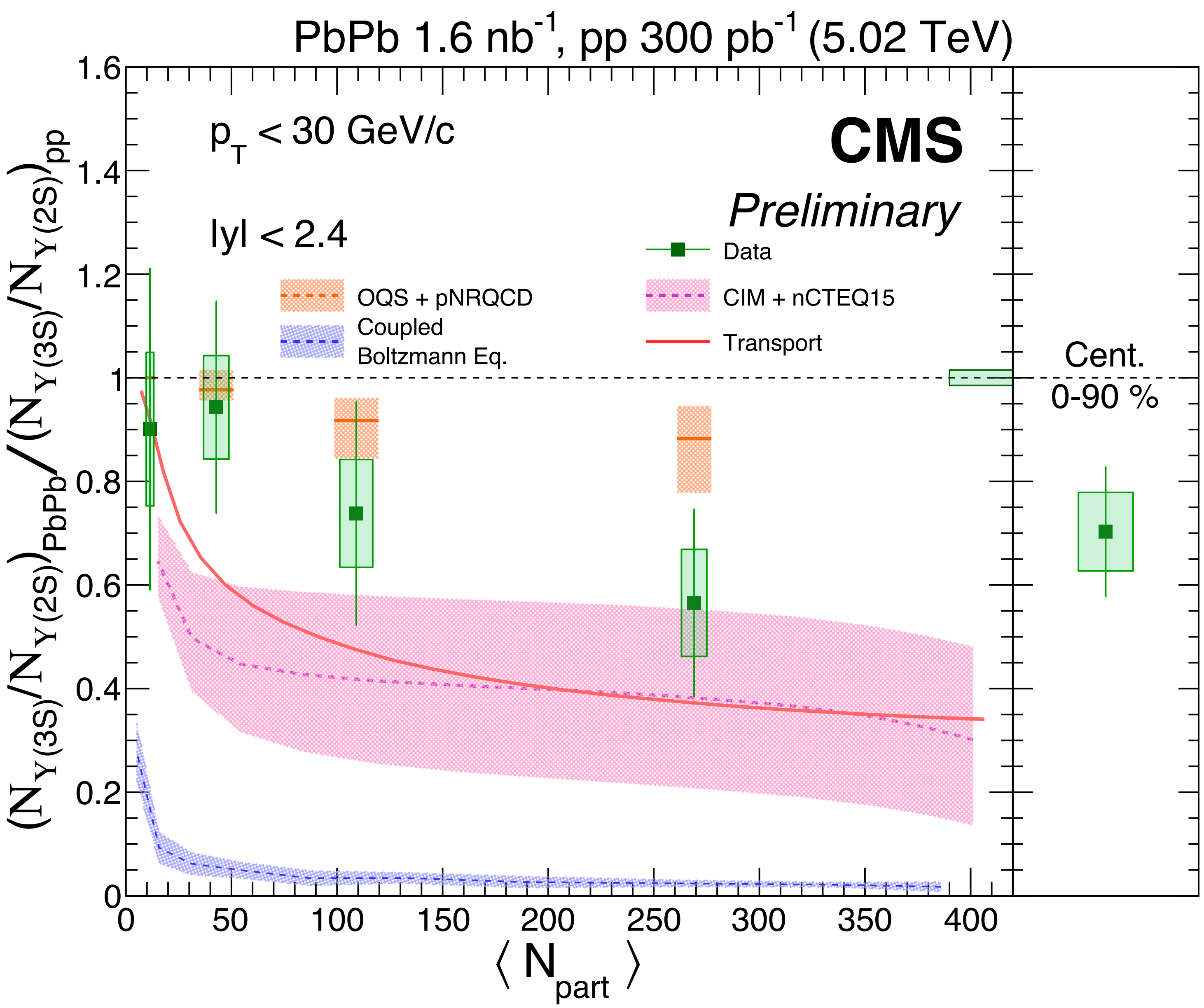
①	• Open Quantum system approach : Dissociation + Recombination • EPPS16 nPDF effect • no recombination for Υ(3S) • Feed-down included
②	• Open Quantum system : Dissociation + Recombination • no CNM effect • Feed-down included
③	• Transport model in kinetic rate equation : Dissociation + Recombination • EPS09 (NLO) nPDF effect • Feed-down included
④	• Comover as source of dissociation • nCTEQ15 nPDF effect • Feed-down included

- Agreement with Υ(1S) data despite some tensions at central collisions / high-p_T
- Very different predictions for excited states

—> Need constraints on excited states!

Excited states double ratio

[CMS-PAS-HIN-21-007]



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

Υ modification in pPb 5.02 TeV

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Run2 : 2015-2018

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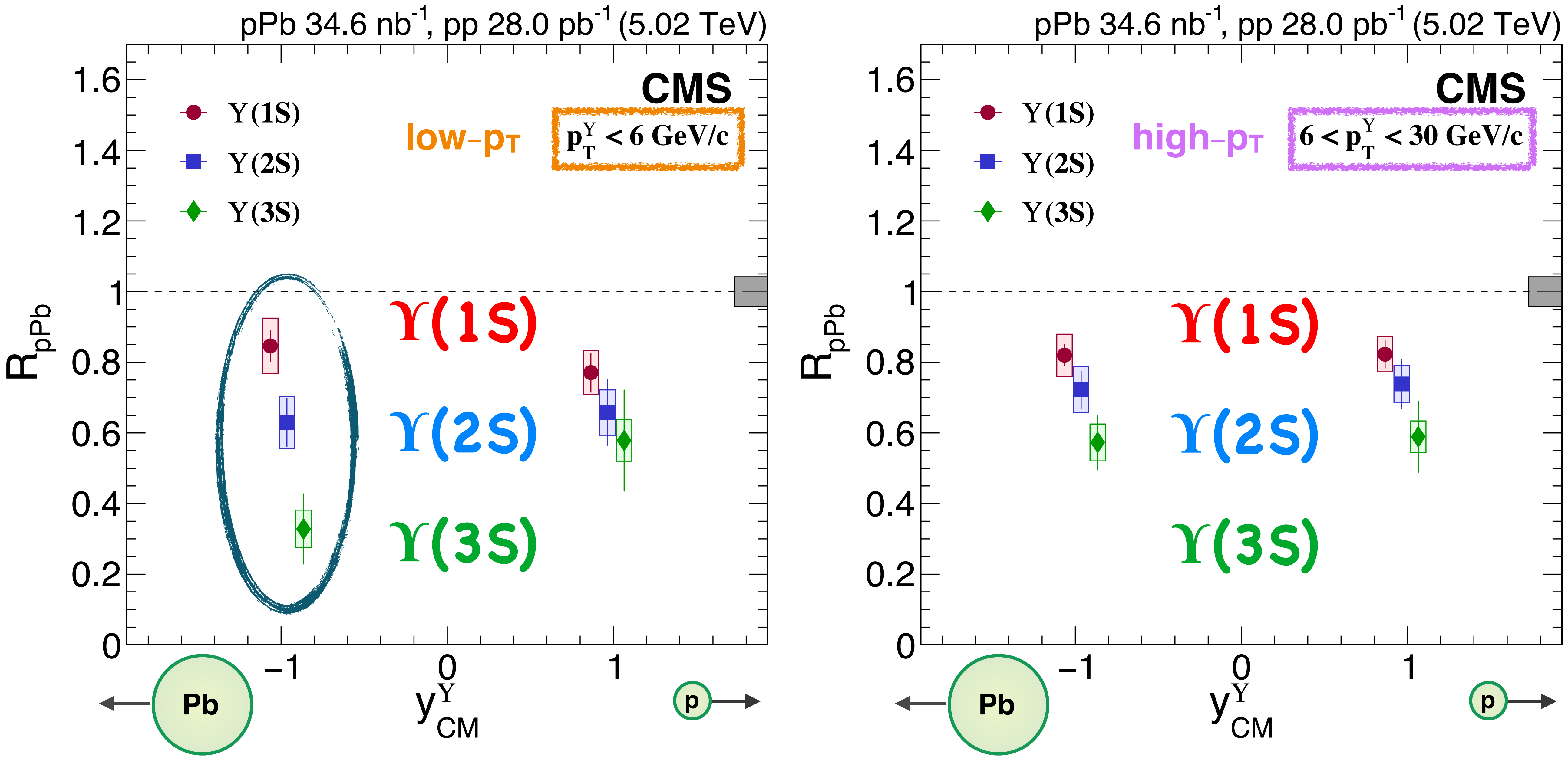
New Run2 results (April 2022)

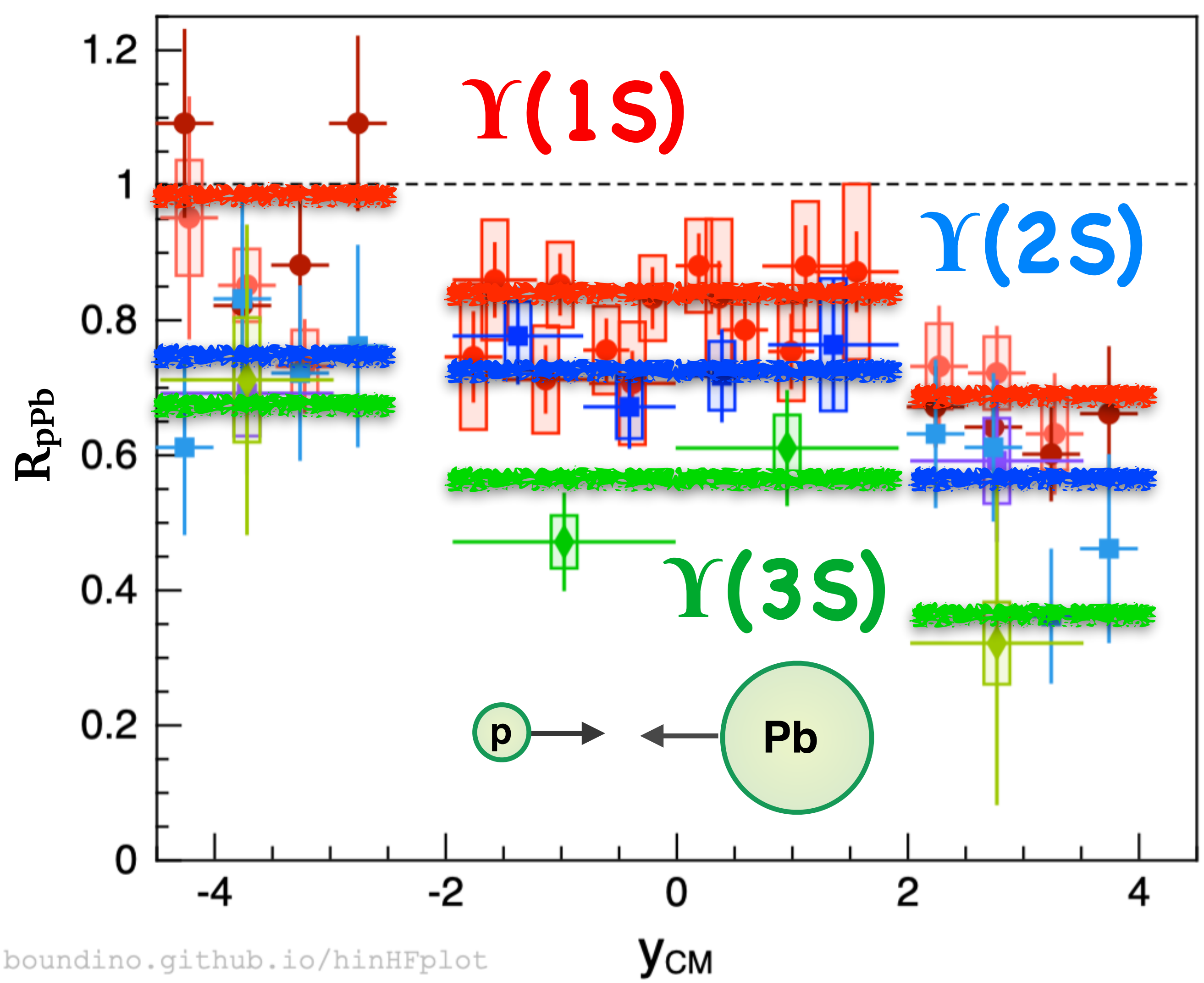
Sequential Υ suppression in pPb!

[arXiv:2202.11807]

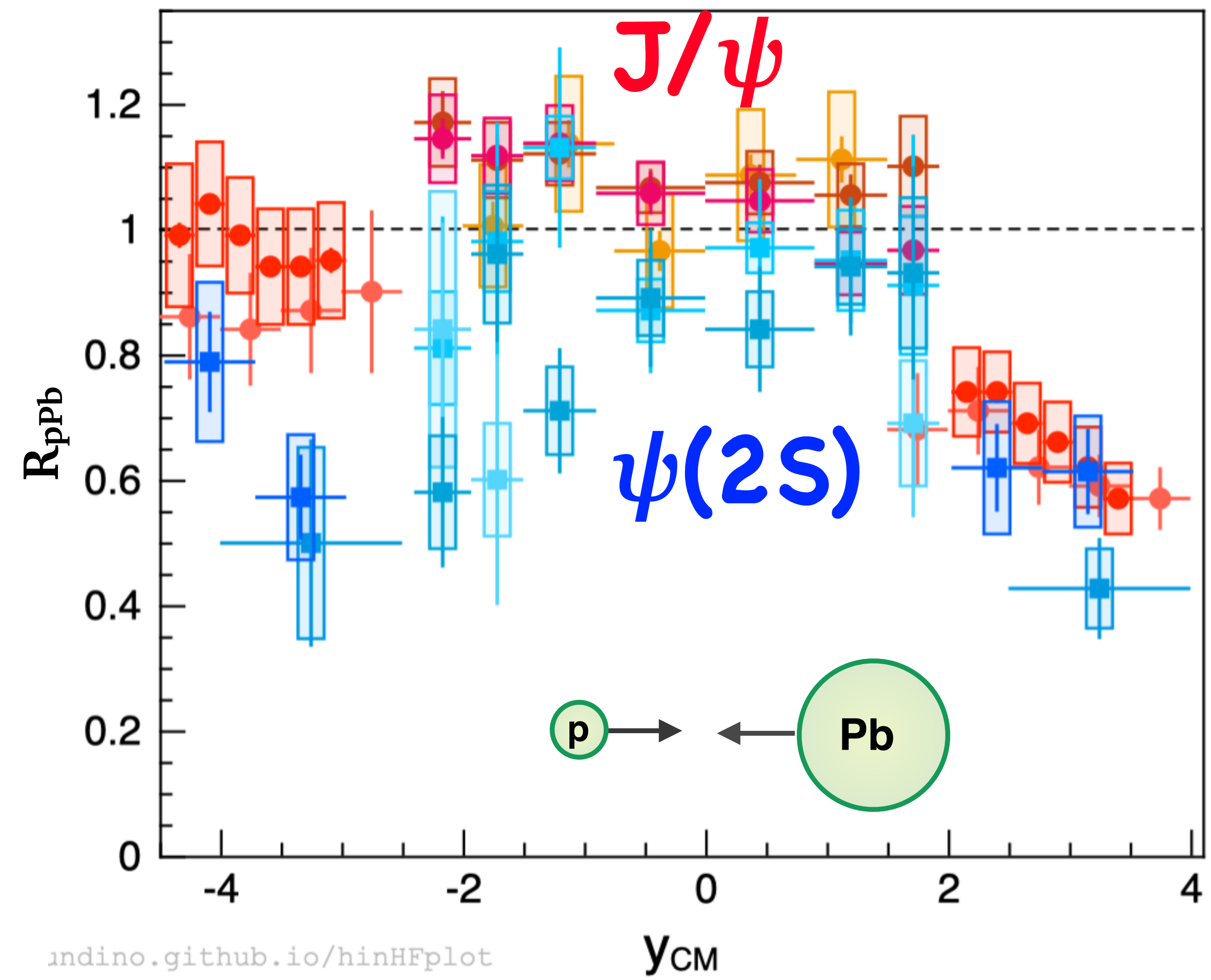


- Stronger suppression of excited states at *backward rapidity* & *low-p_T*

Quarkonium suppression @ LHC



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

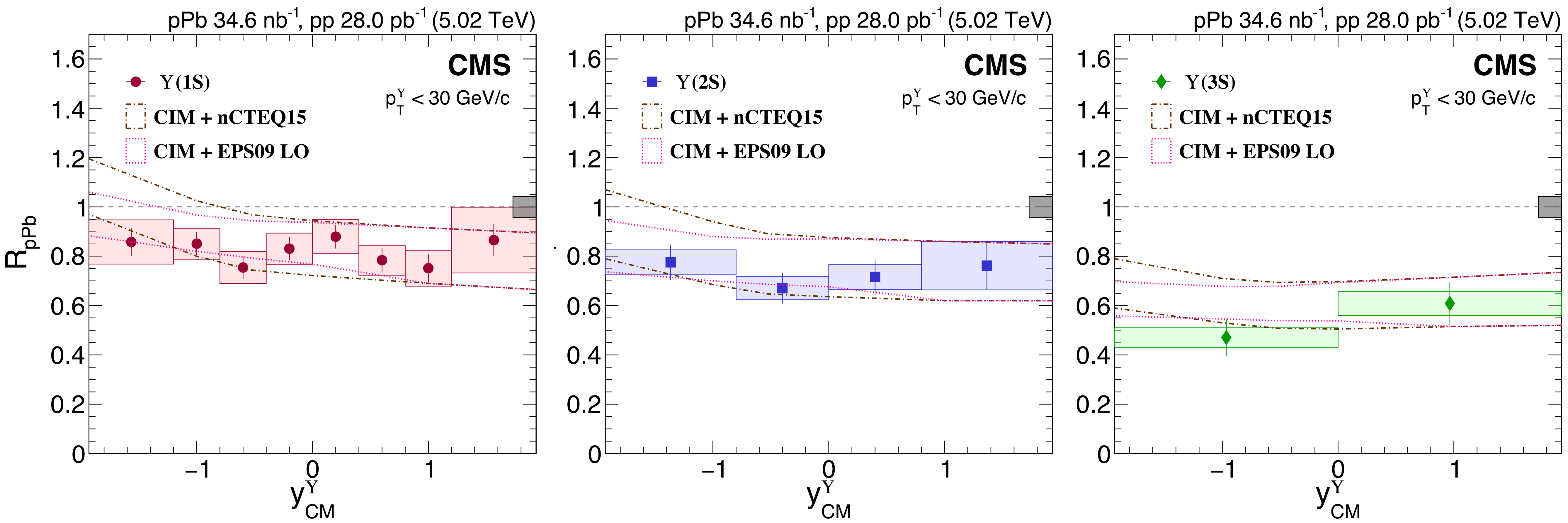


[EPJC 78 (2018) 171] [EPJC 77 (2017) 269] [PLB 774 (2017) 159]
[PLB 790 (2019) 509] [JHEP 03 (2016) 133] [JHEP 07 (2018) 160]
[JHEP 07 (2020) 237]

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

Bottomonia in pPb vs model

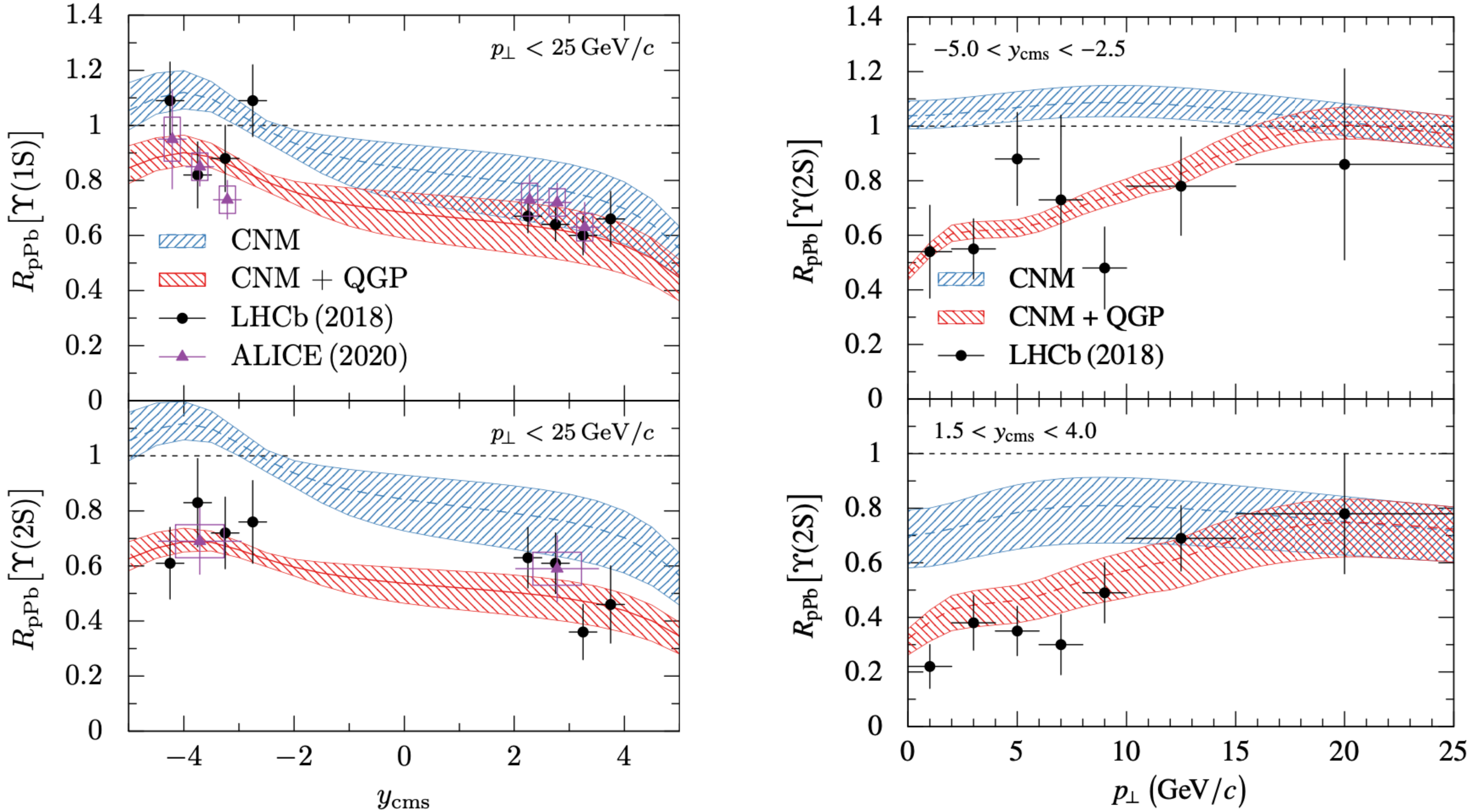
[arXiv:2202.11807]



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

Bottomonia in pPb vs model

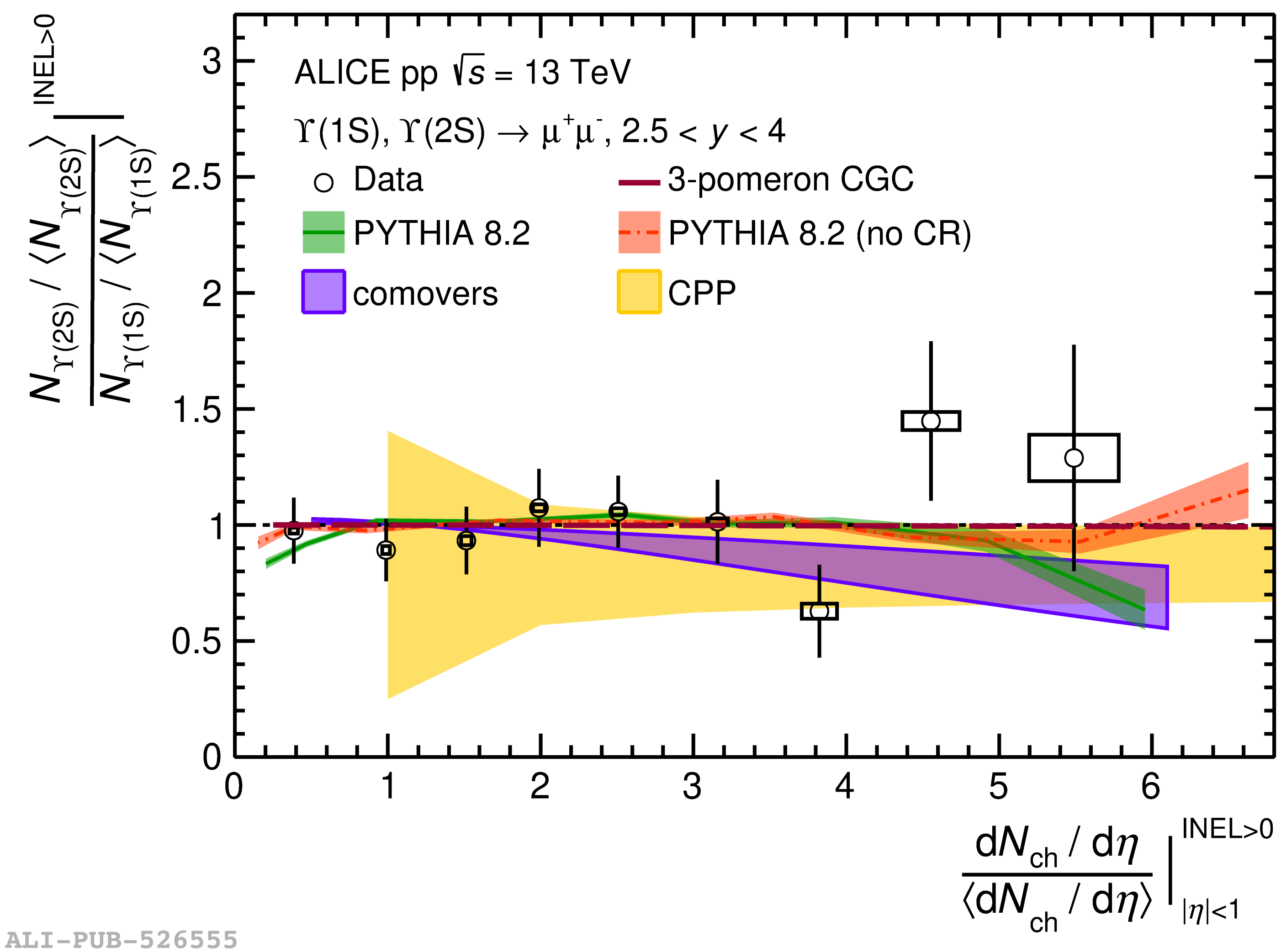
[JMPA 35 (2020) 2030016]



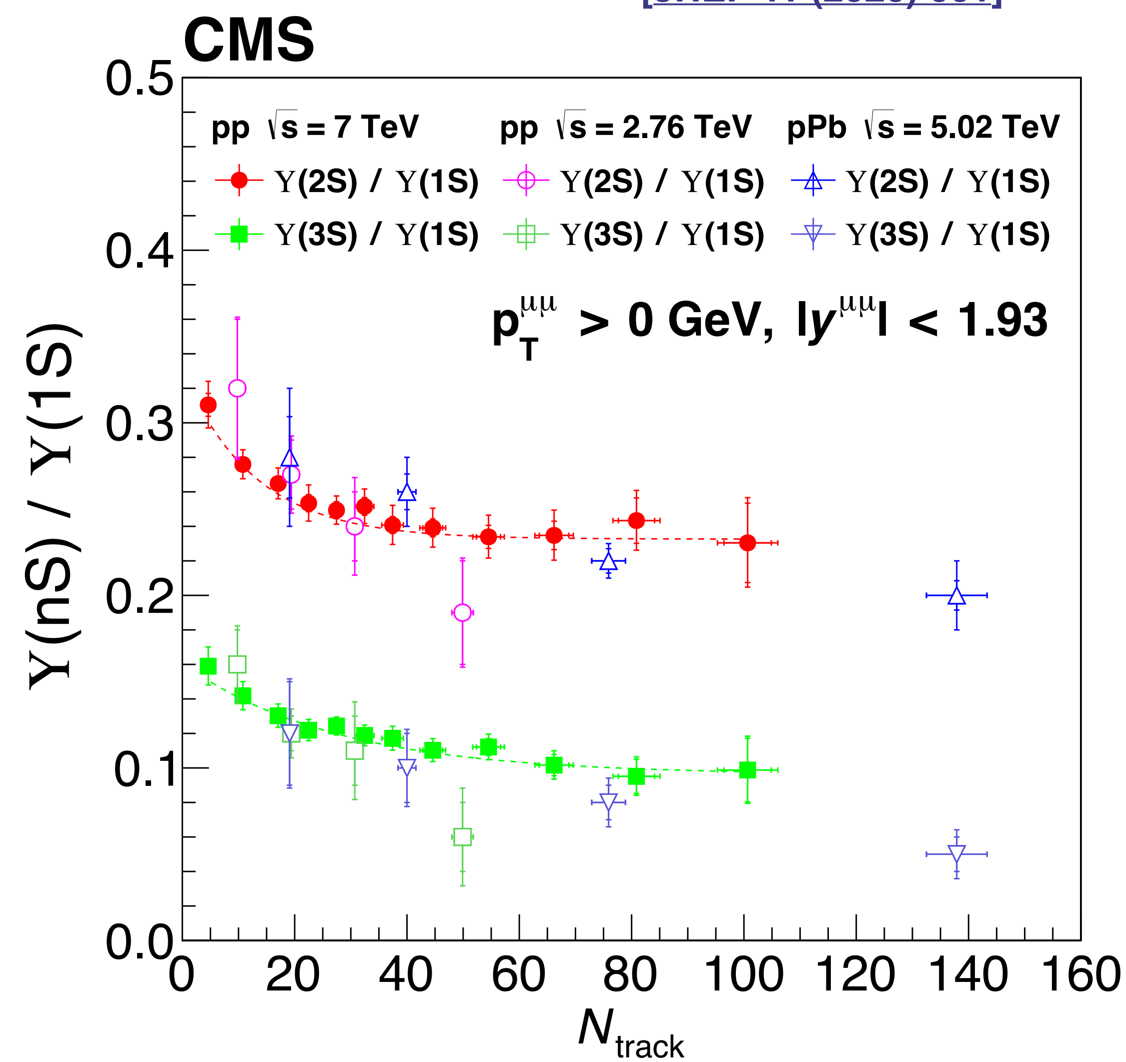
- nPDF + comover breakup explains additional suppression of excited states?
- Models with hot-medium effects describe Υ suppression in pPb collisions…

Multiplicity dependence?

[arXiv:2204.10253]



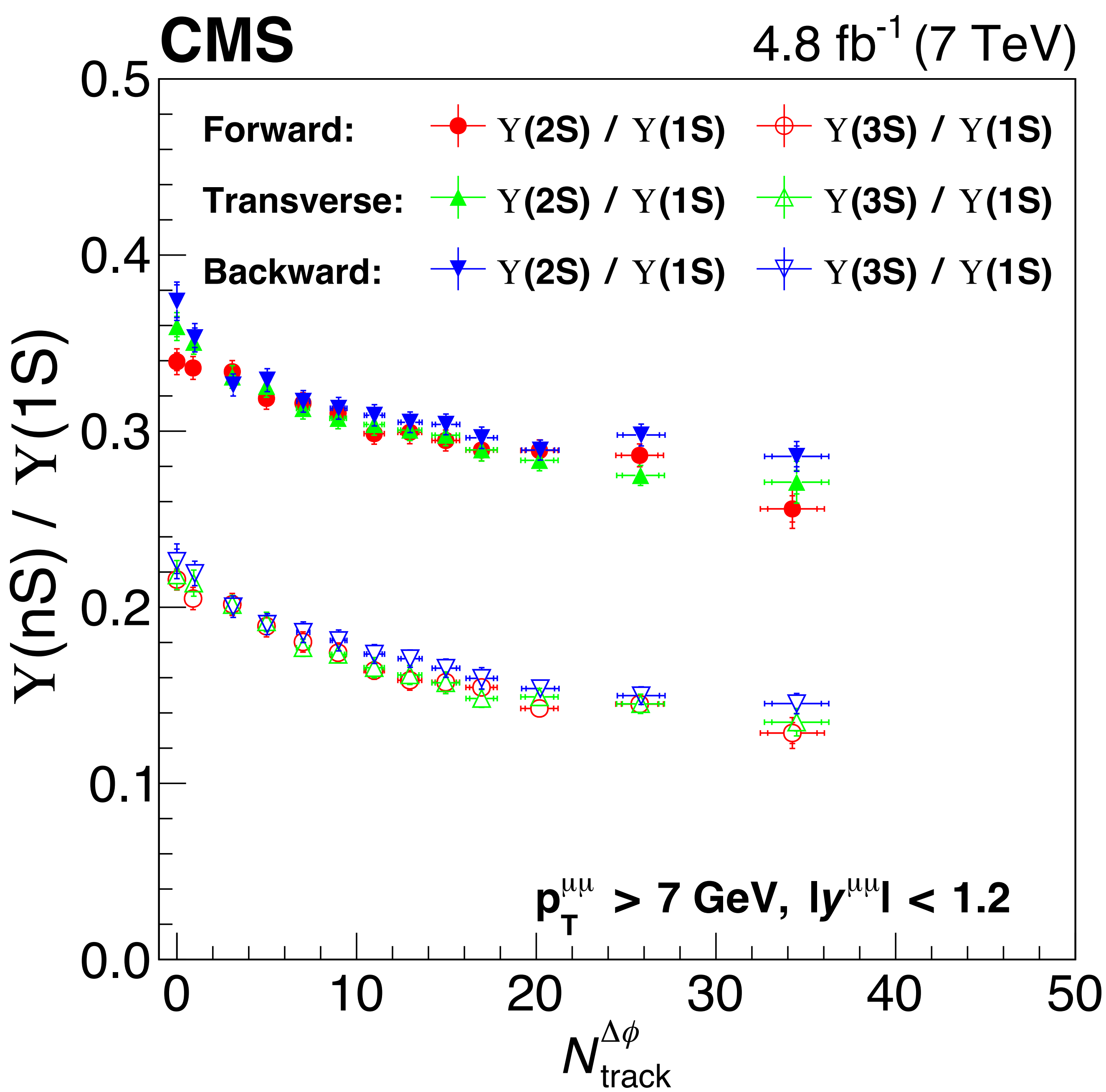
[JHEP 11 (2020) 001]

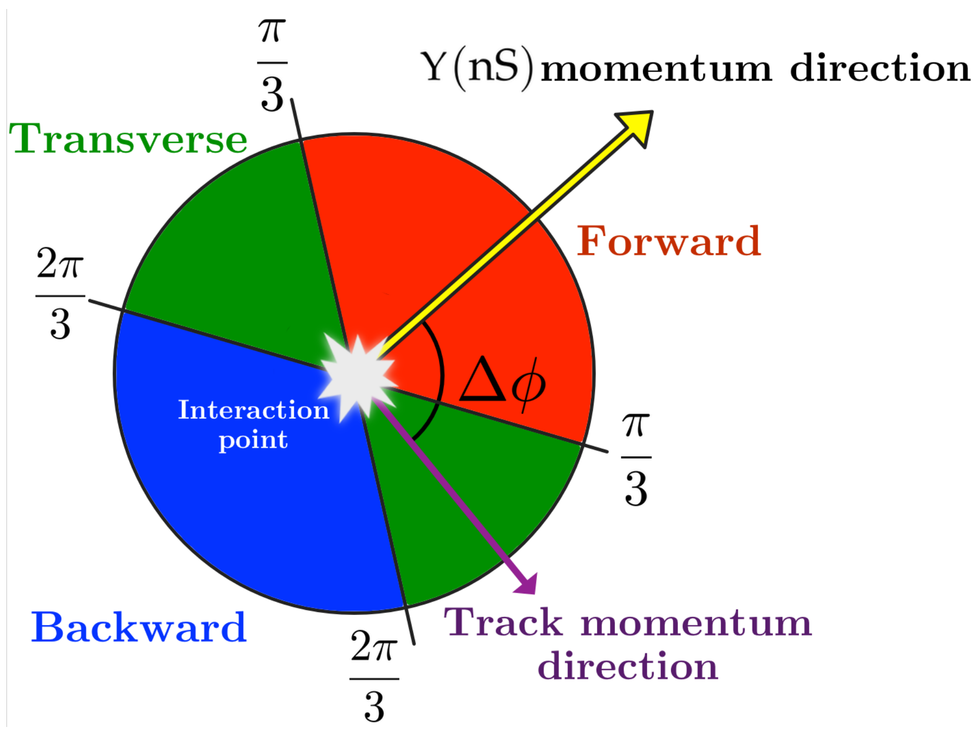


- Quarkonium production vs multiplicity sensitive to rapidity overlap region
- Suppression of excited-to-ground state ratio at higher multiplicity due to MPI / correlation / UE?

Azimuthal correlation

[JHEP 11 (2020) 001]

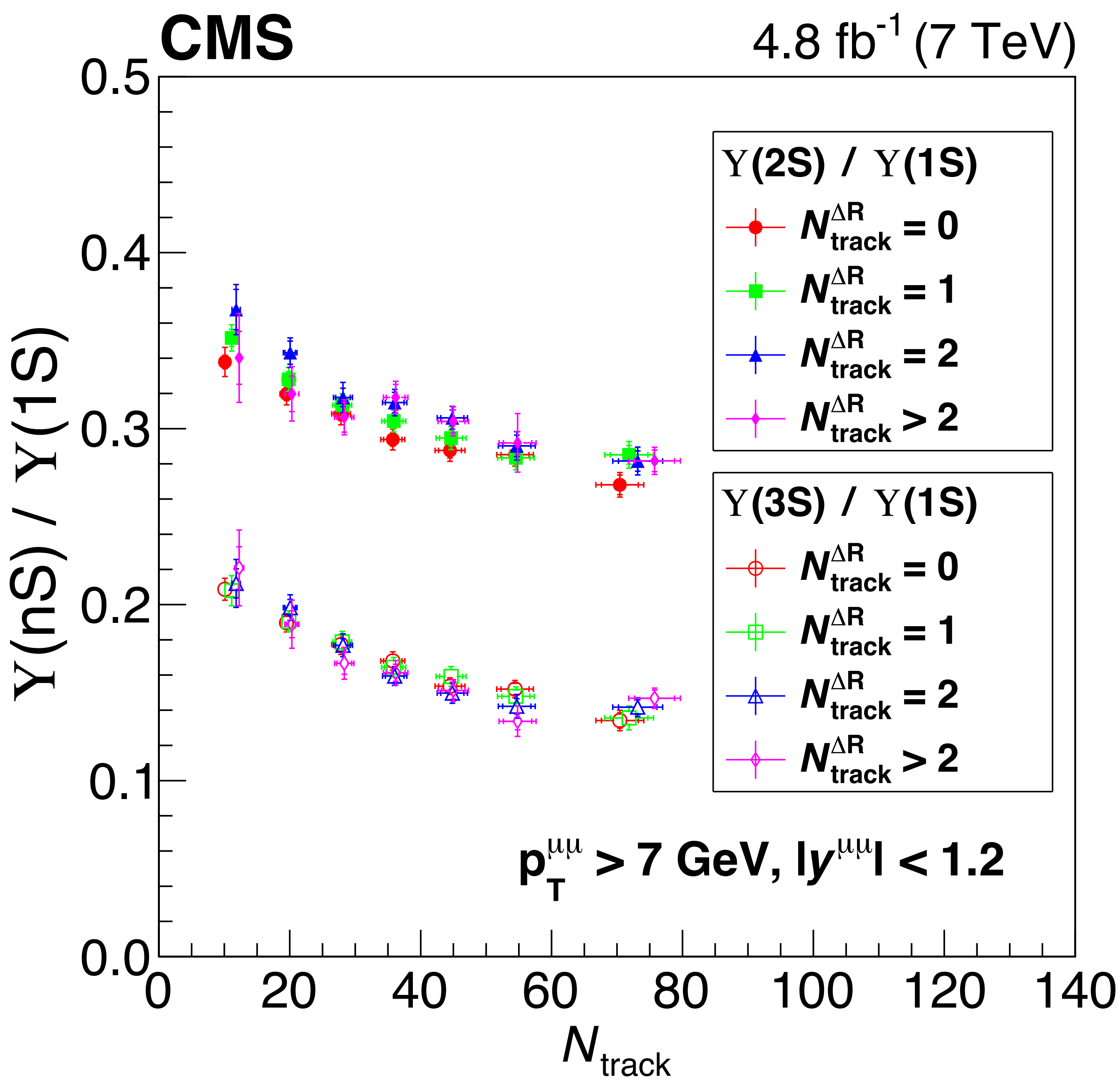


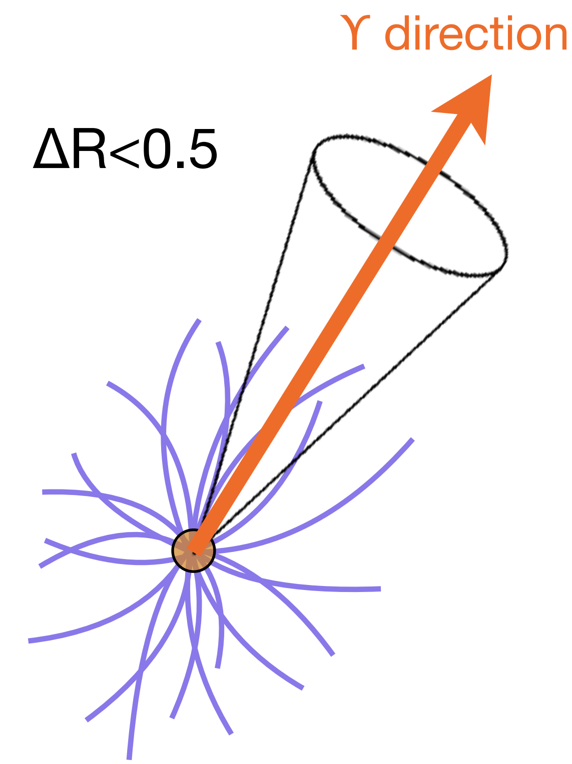


- ϒ(nS) / ϒ(1S) suppressed for all azimuthal region
- Similar suppression for all $N_{ch}^{\Delta\phi}$ itself implies connection to UE

Event-activity analysis

[JHEP 11 (2020) 001]

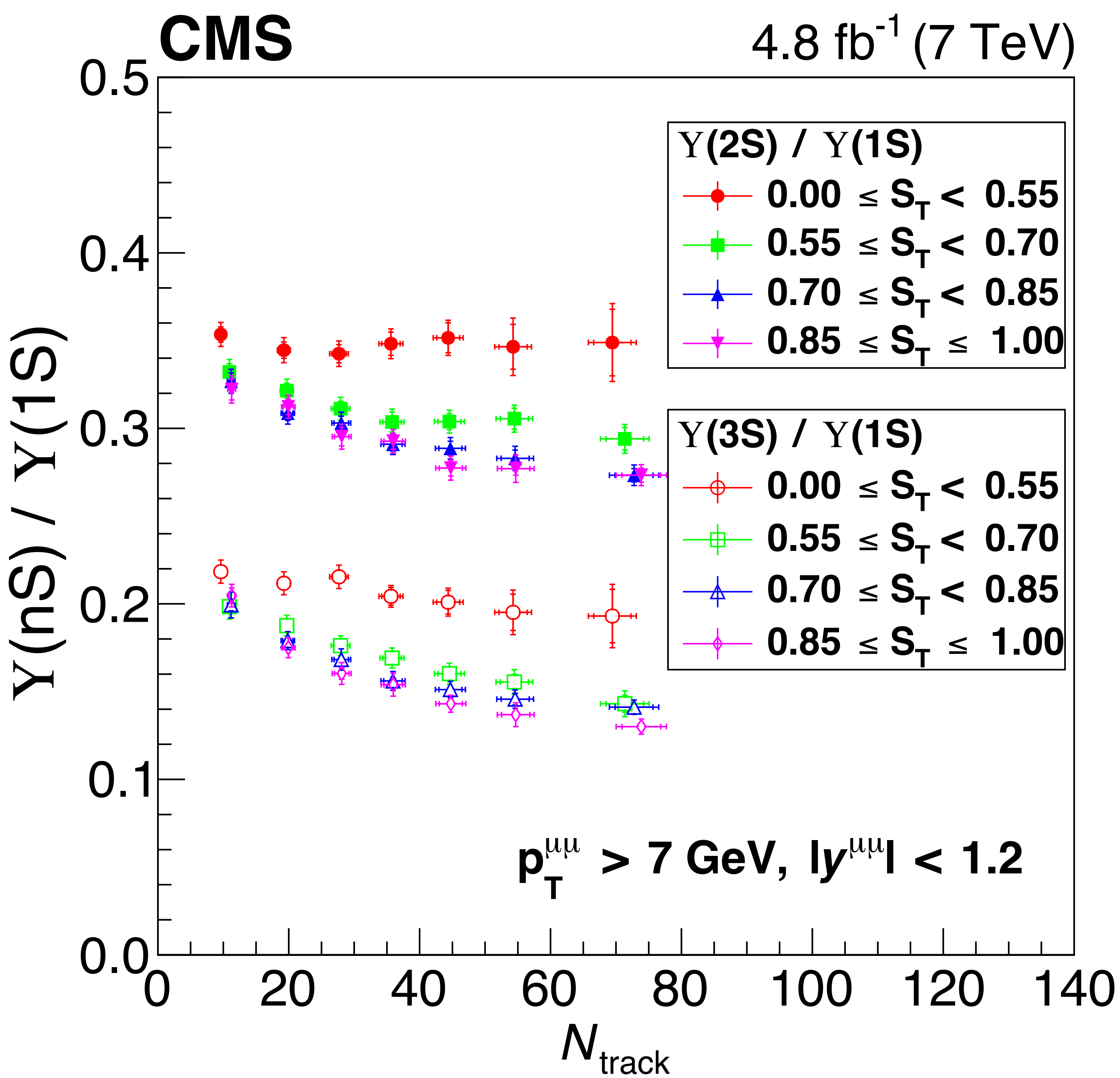


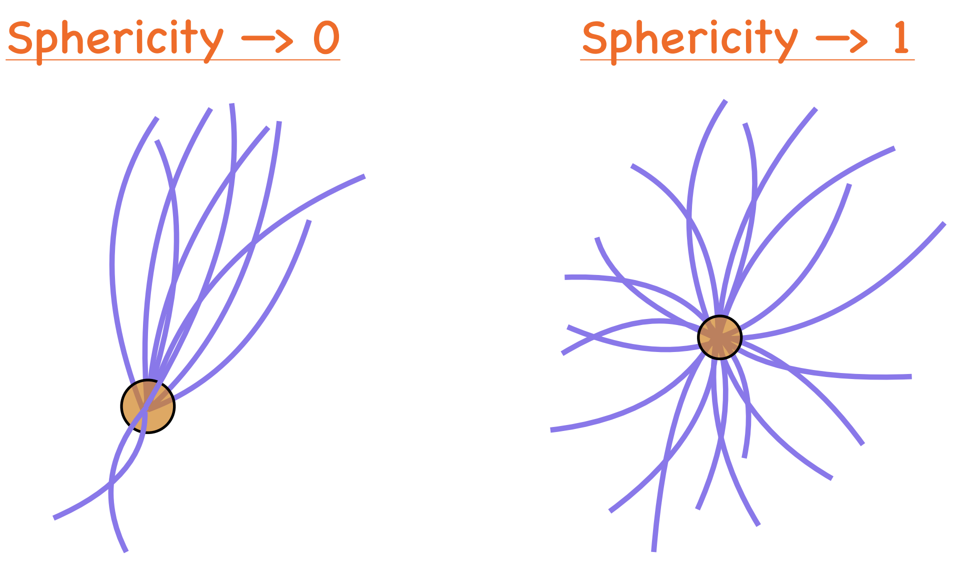


- $\Upsilon(nS)$ / $\Upsilon(1S)$ still suppressed for different N_{track} in a given cone size
- Different from comover breakup picture

Event-activity analysis

[JHEP 11 (2020) 001]





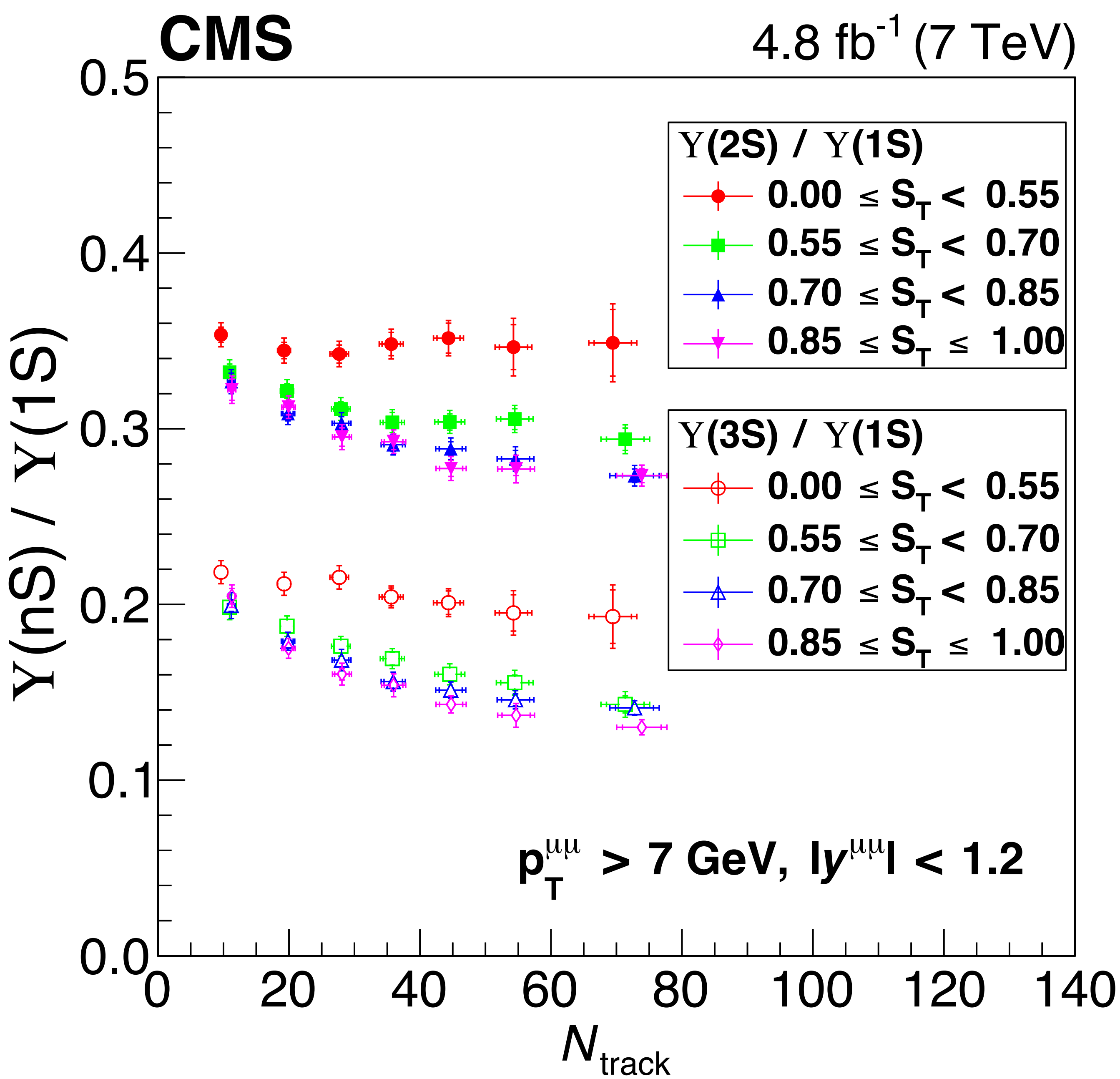
$$S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2} \qquad S^T_{xy} = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

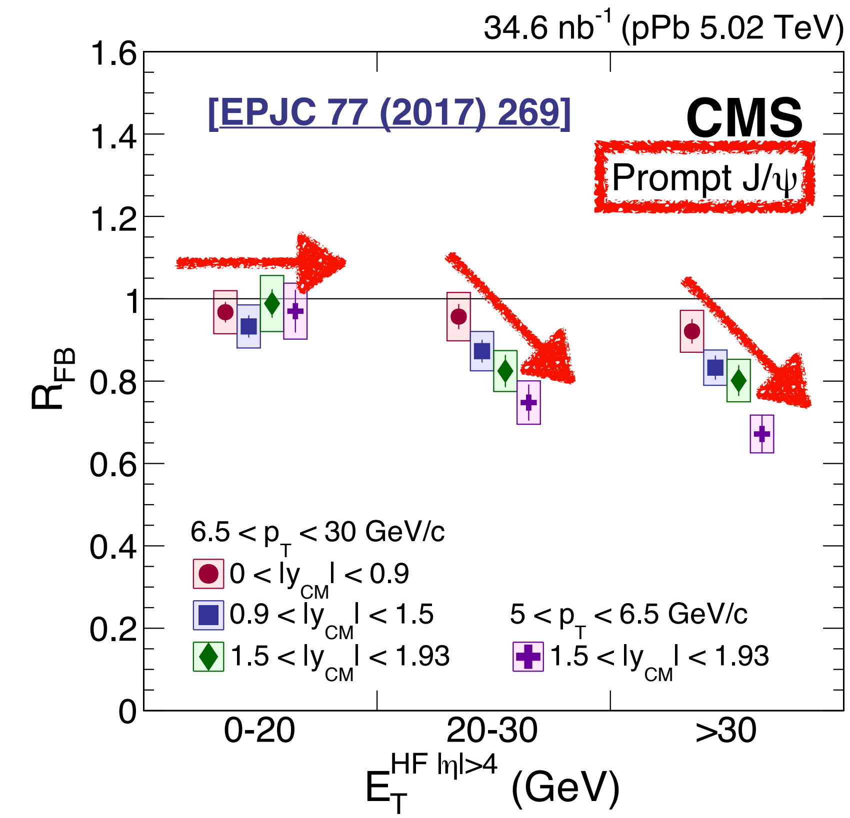
- Υ(nS) / Υ(1S) decreasing trend disappears for low-sphericity events
- Connection to UE jetty events?

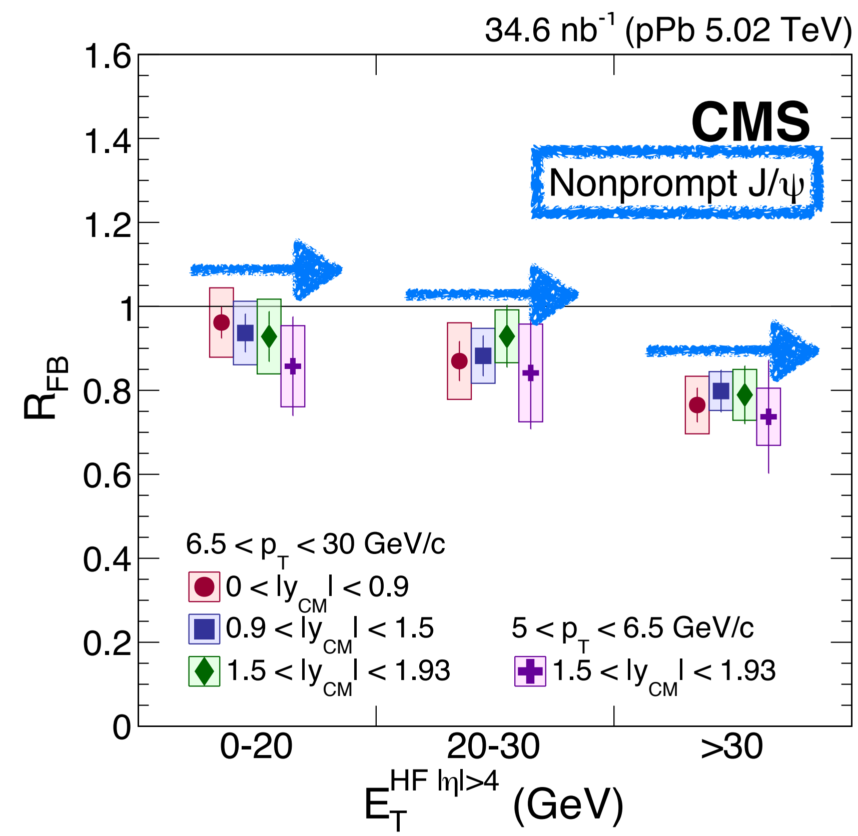
- **What about charmonia?**

Event-activity analysis

[JHEP 11 (2020) 001]







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

Elliptic flow of Υ(1S) in pPb

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- Nucle…

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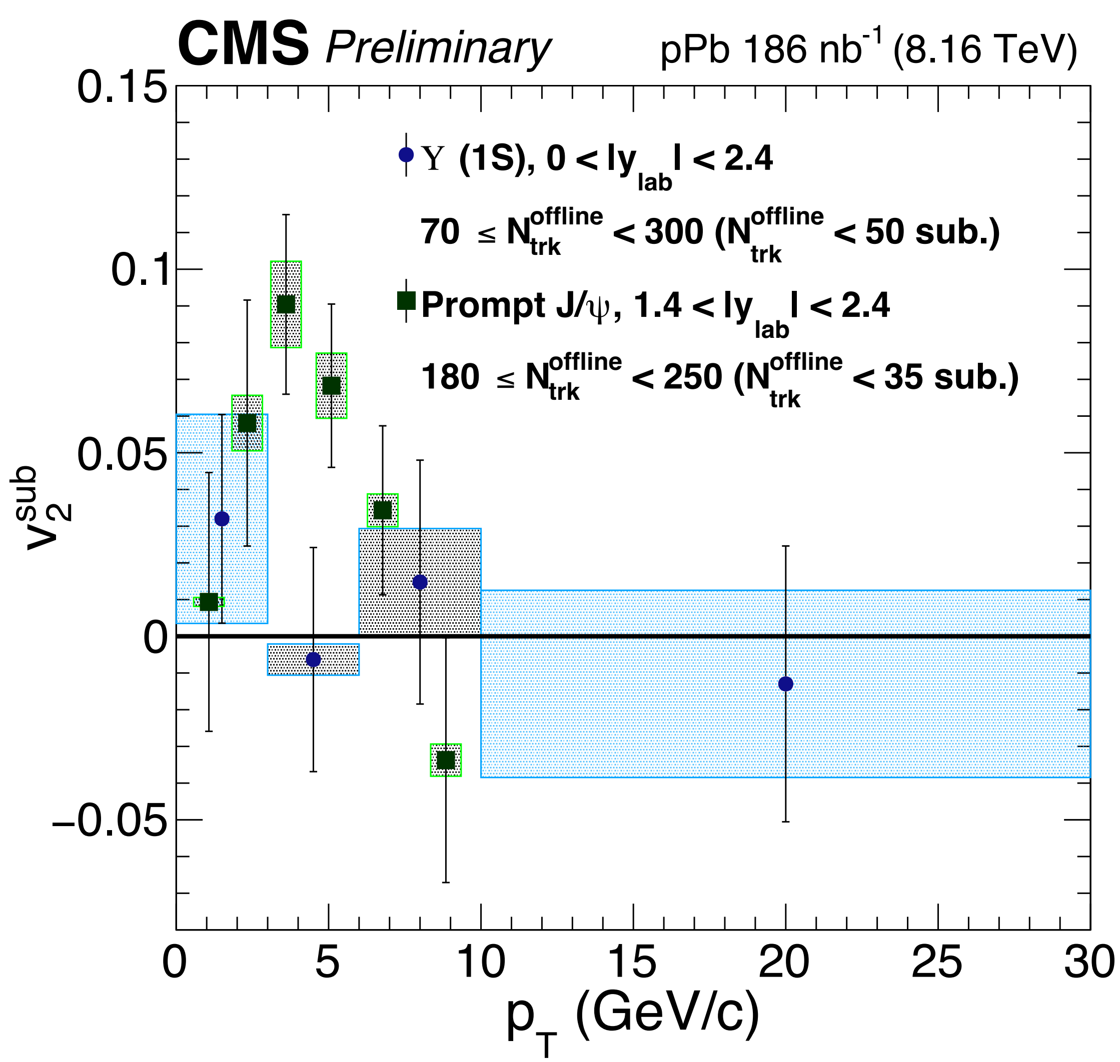
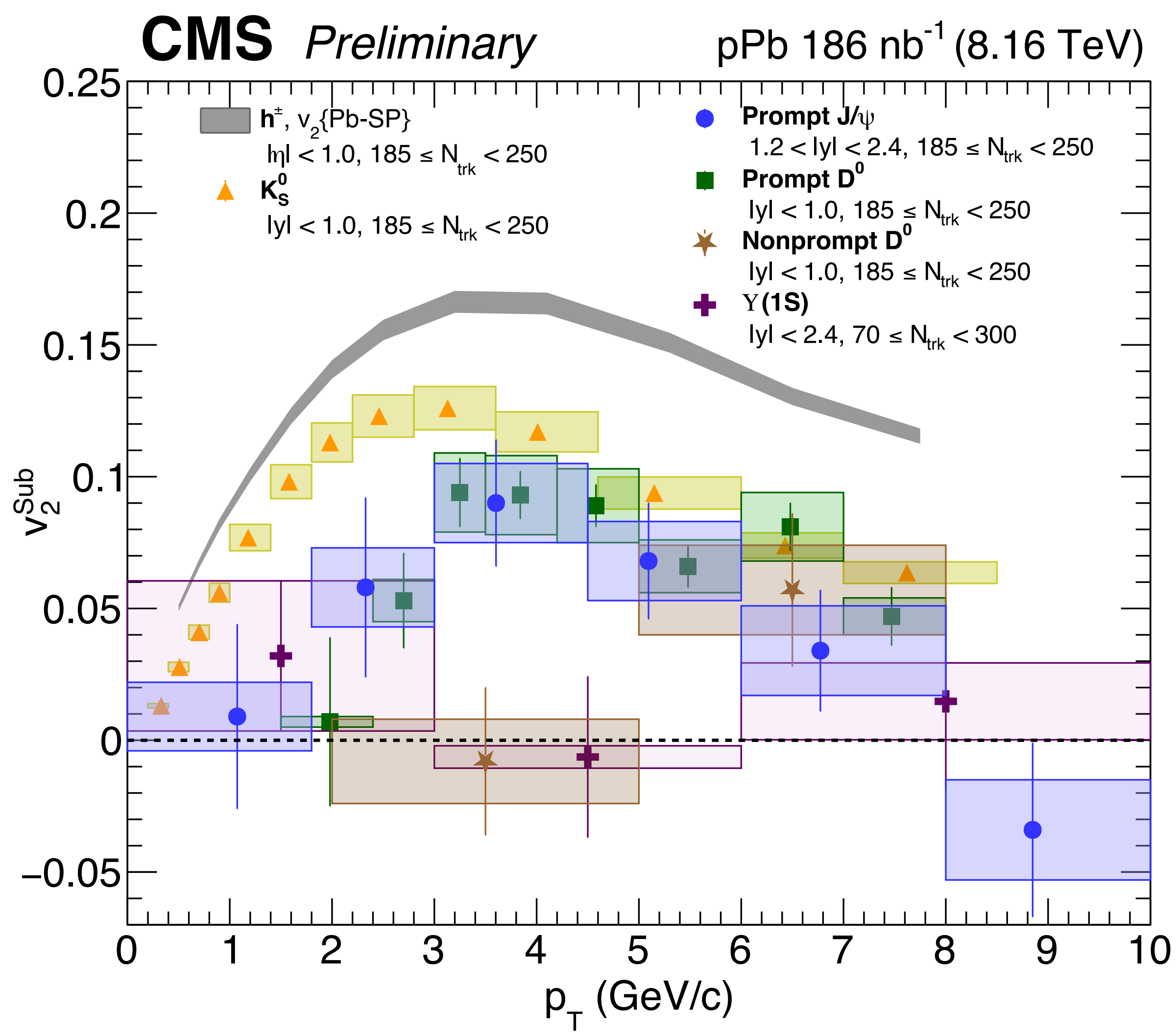
Elliptic flow (v_2) of Υ(1S) in pPb

[CMS-PAS-HIN-21-001]



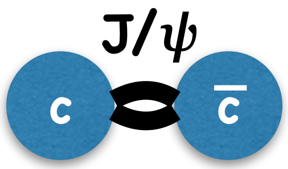


- First measurement of v_2 for Υ(1S) in small systems!
- No sizable v_2 observed in contrast to J/ψ

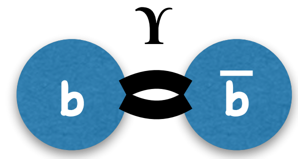
- Hierarchy of v_2 at low-p_T

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

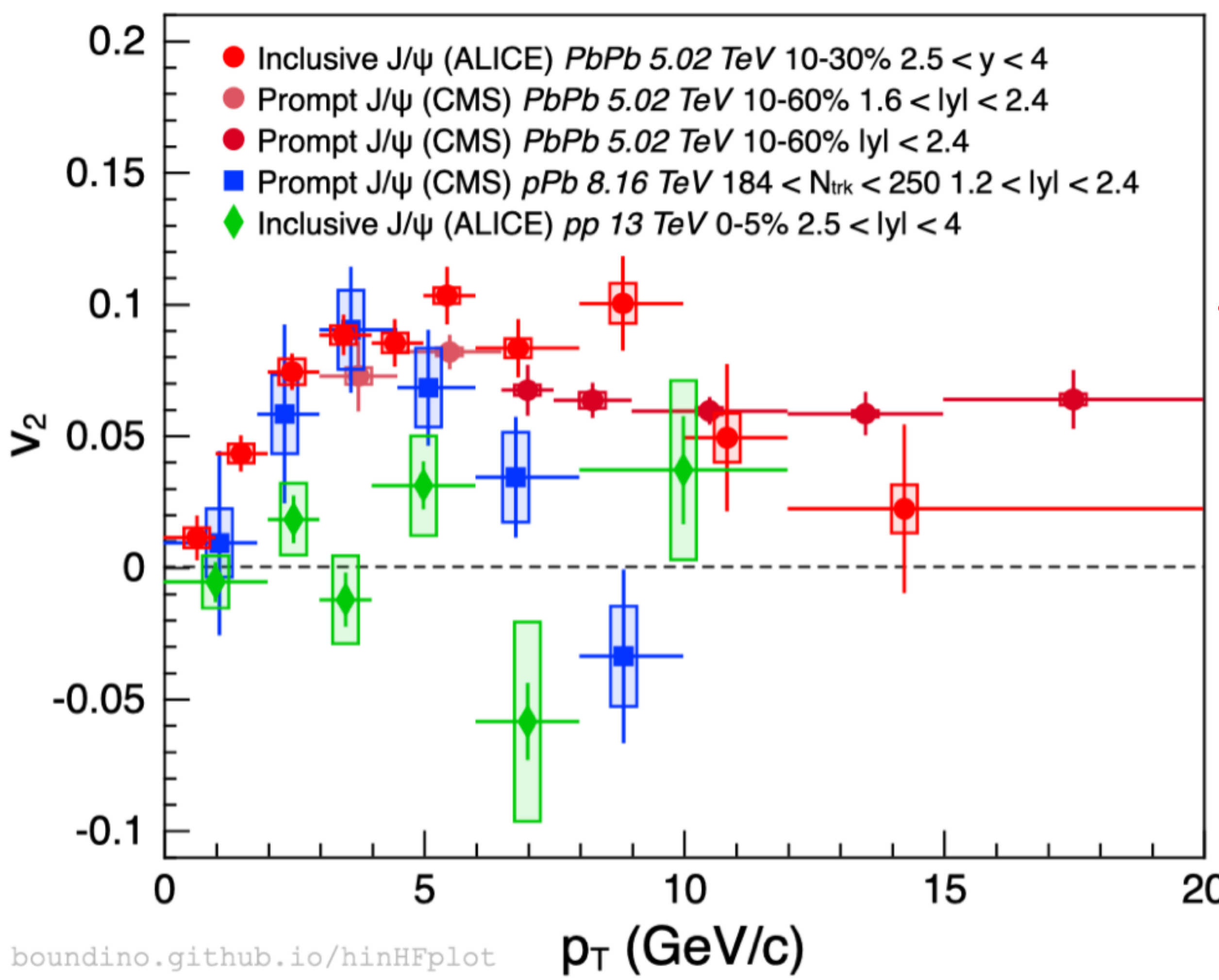
Quarkonium v_2 at LHC



- CMS-PAS-HIN-21-008
- JHEP 10 (2020) 141
- PLB 791 (2019) 172
- ALICE Preliminary



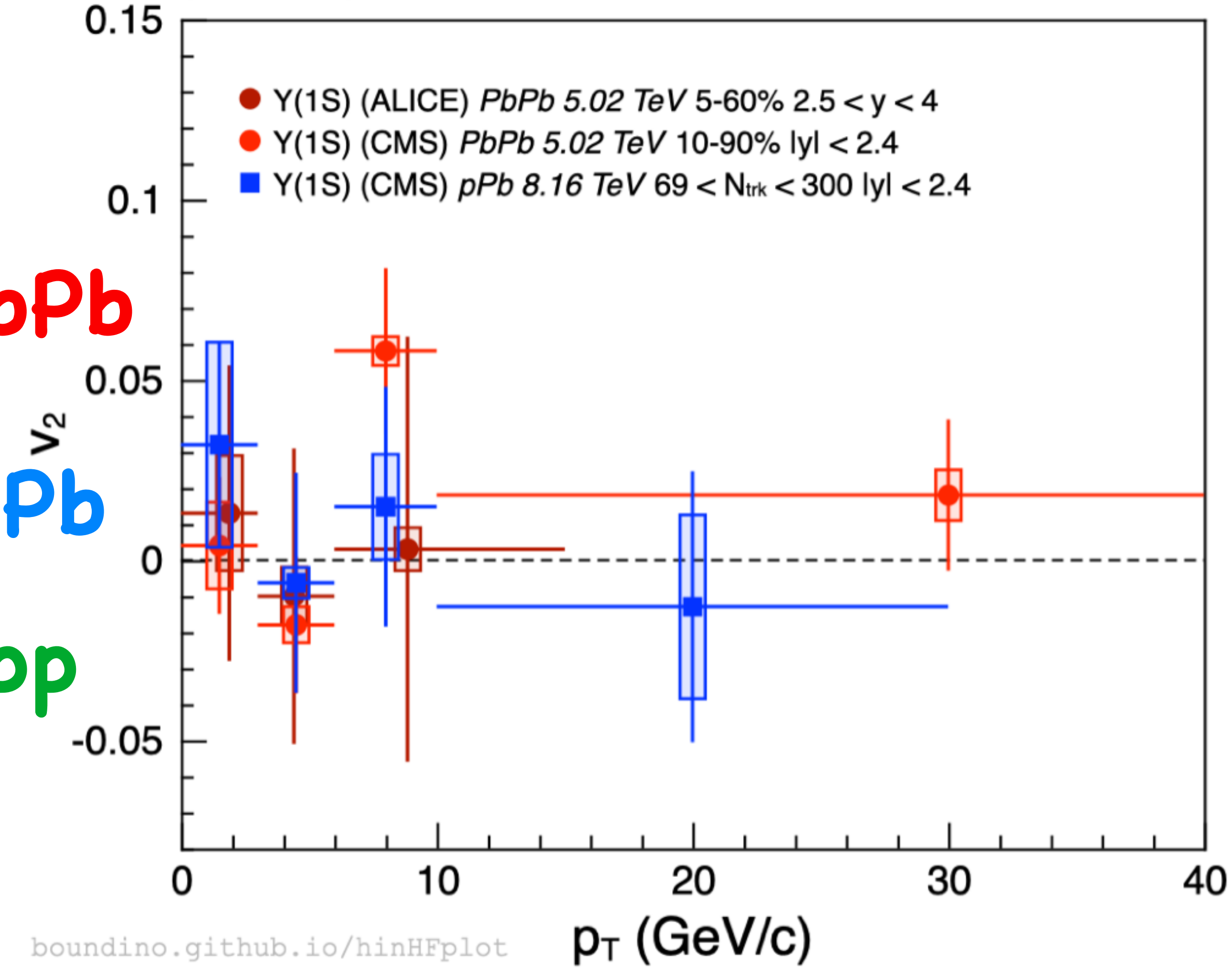
- PRL 123 (2019) 192301
- PLB 819 (2021) 136385
- CMS-PAS-HIN-21-001



PbPb

pPb

pp



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

$\Upsilon(1S)$: 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

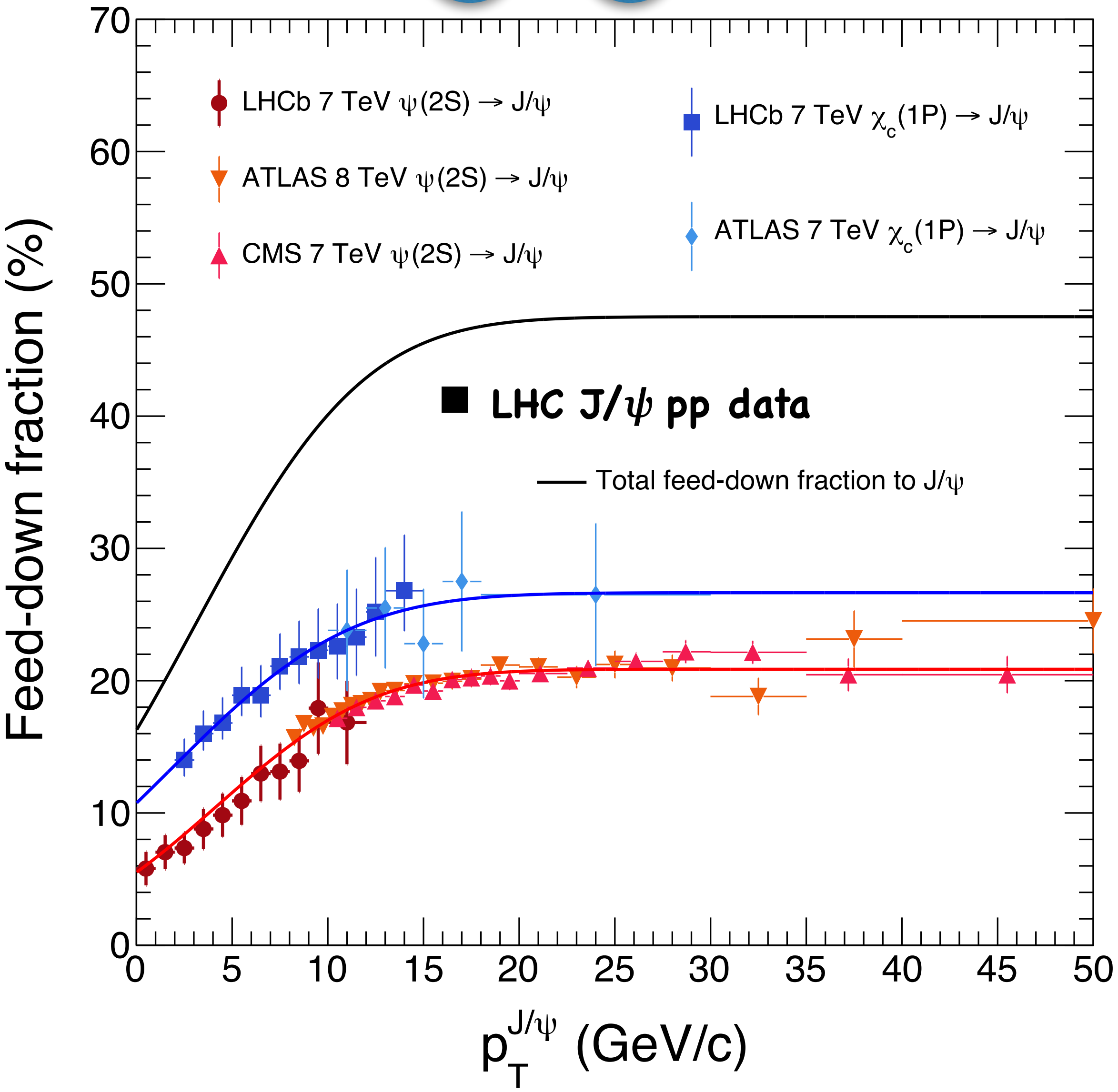
[EPJC 72 (2012) 2100]
[EPJC 76 (2016) 283]
[JHEP 07 (2014) 154]
[PLB 718 (2012) 431]
[PRL 114 (2015) 191802]

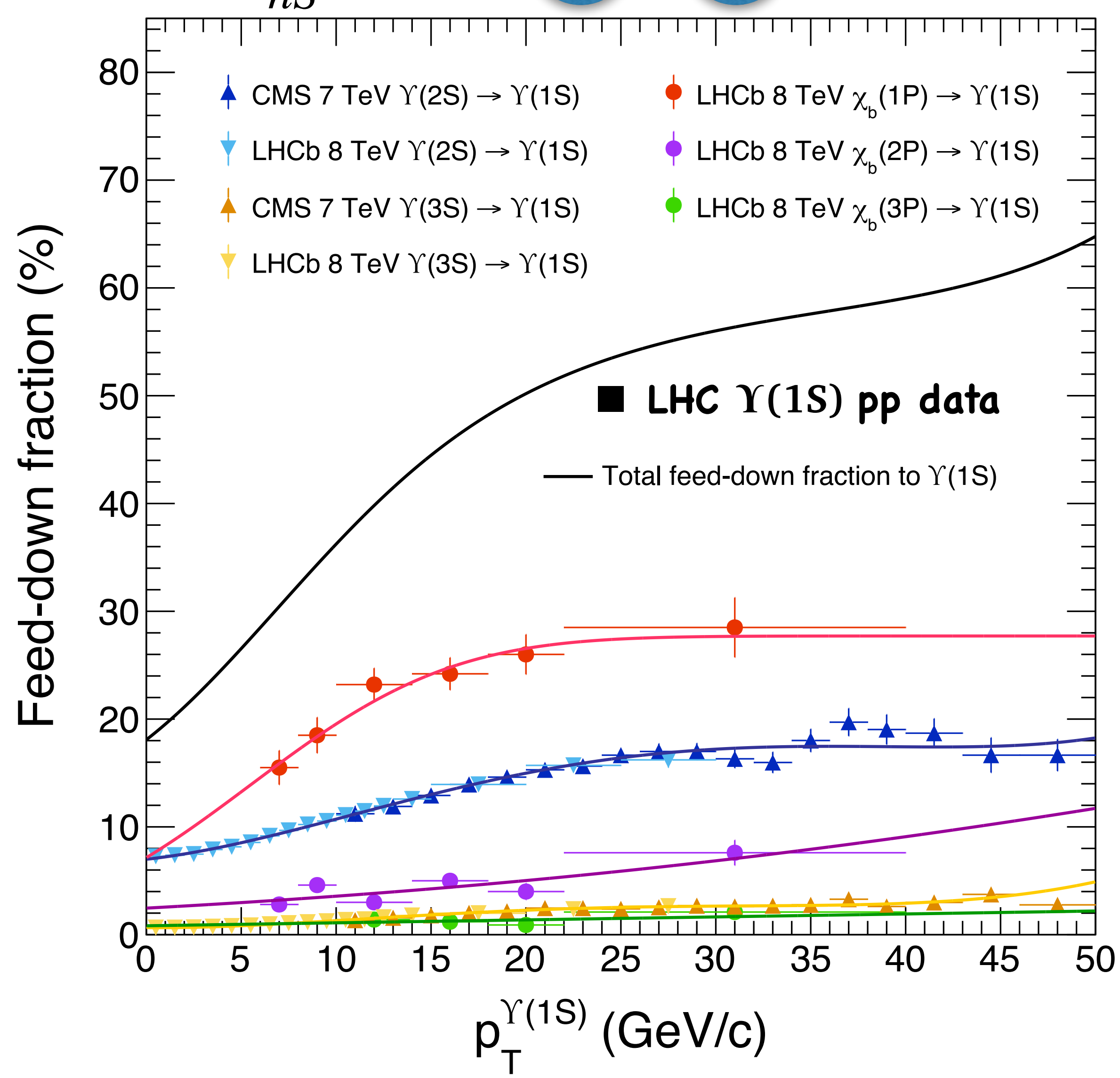
J/ψ

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

ϒ(1S)

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

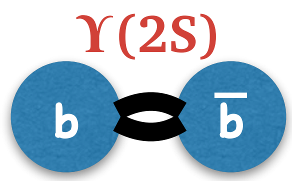




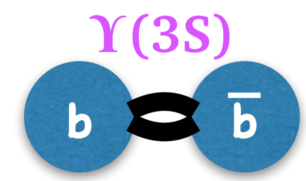
- Significant contributions from feed-down! —> Crucial on data interpretation
- Advantage of ψ(2S) : almost free from feed-down effects!

Quarkonium feed-down

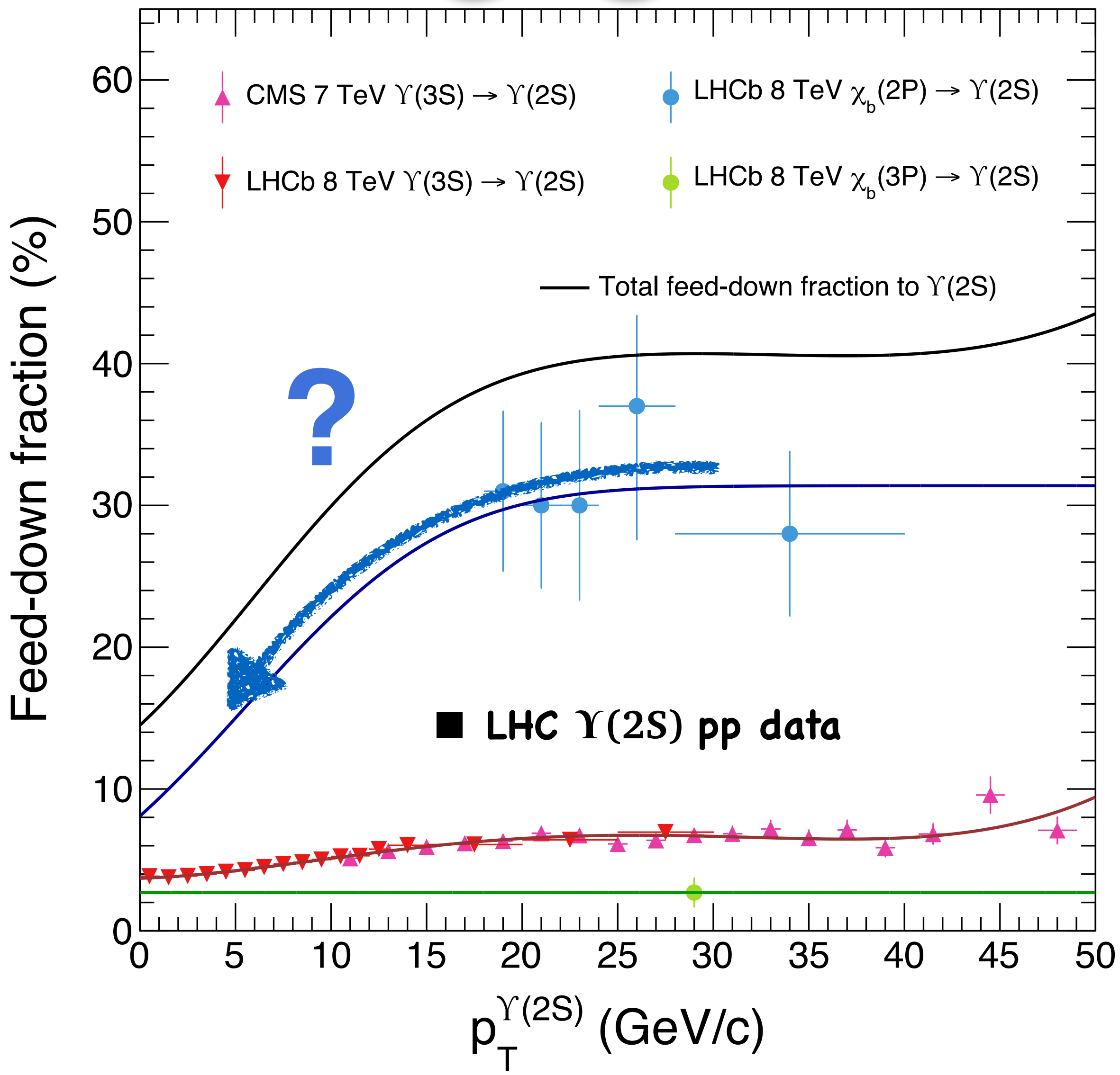
[PLB 749 (2015) 14]
[JHEP 11 (2015) 103]
[EPJC 74 (2014) 3092]

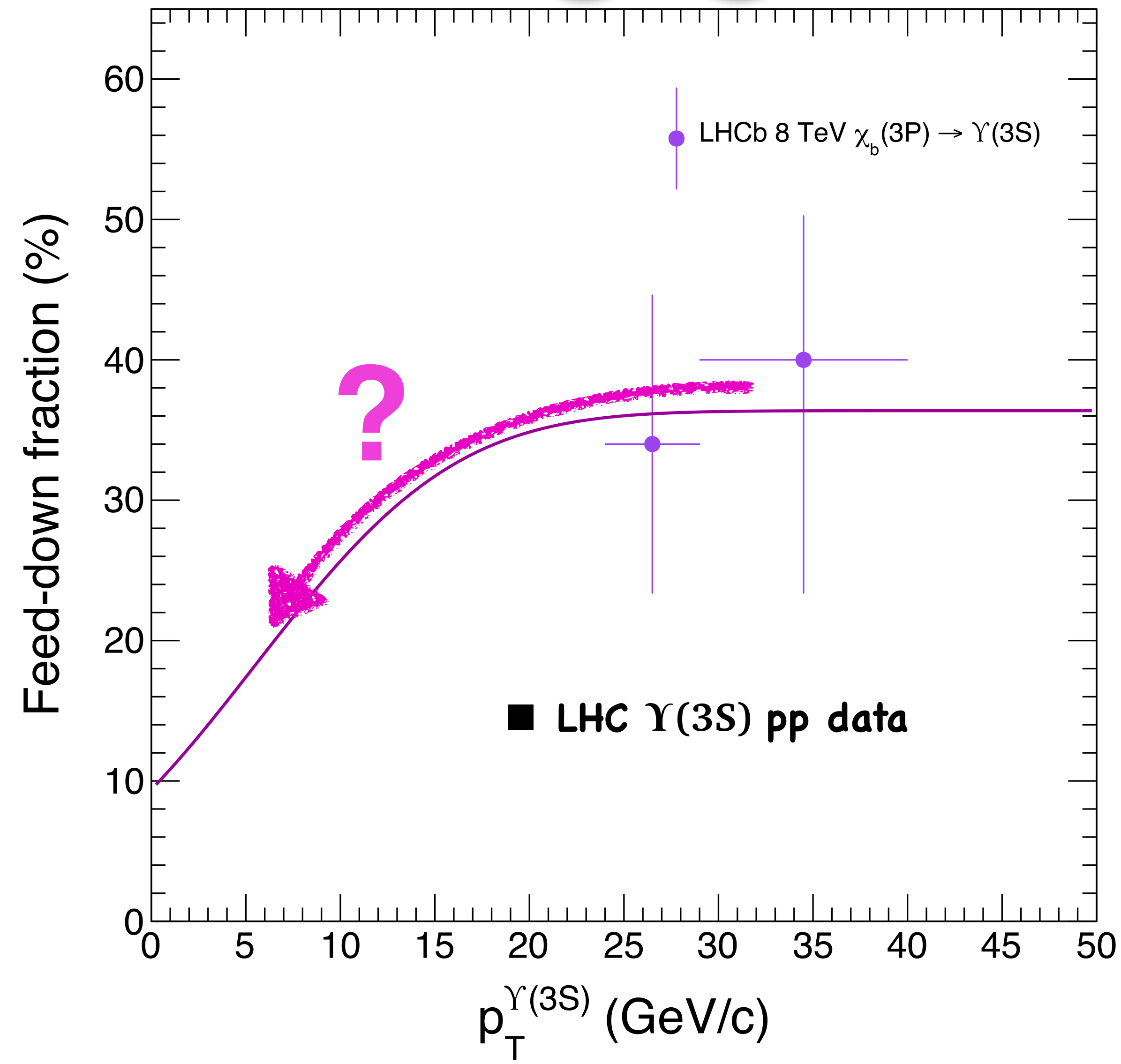


$$\mathscr{F}^{mS}_{nS} = \mathscr{B}(mS \rightarrow nS)\frac{\sigma_{mS}}{\sigma_{nS}}$$



[EPJC 74 (2014) 3092]





- Caveat for Y(2S) and Y(3S) : Still large! Decreasing towards low-p_T?

Summary

☑ **Important achievements from CMS to 'bottomonia in media'**

➡ 11 public results with many of them "firsts"

☑ **Reveal of sequential Υ suppression in AA**

➡ Observed Υ(3S) in PbPb collisions

➡ 3S/2S double ratio expected to be a model discriminator

☑ **Sequential suppression of Υ(nS) in pPb**

➡ Need sophisticated studies to understand the nature of the suppression in small systems

☑ **Elliptic flow (v_2) of Υ(1S) in pPb**

➡ No collective behavior in contrast to J/ψ

: what is the origin of flow for charmonia and bottomonia?

☑ **Large amount of feed-down contribution and very p_T-dependent**

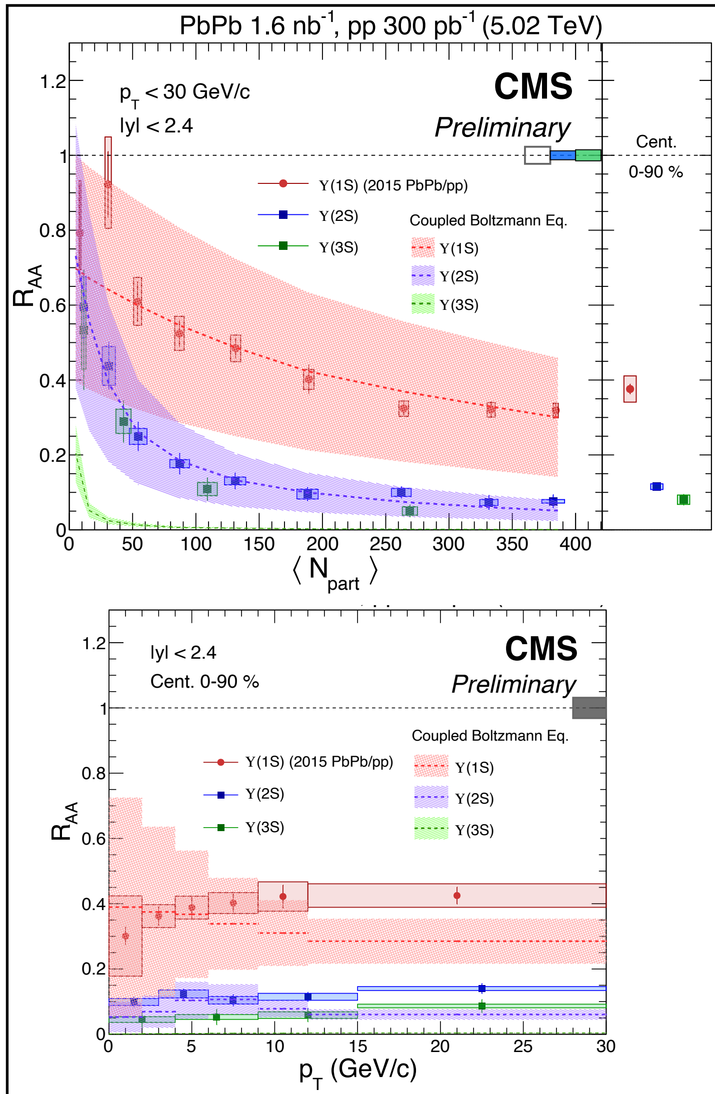
➡ Crucial for physics interpretation — Need to consider their different binding energies

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

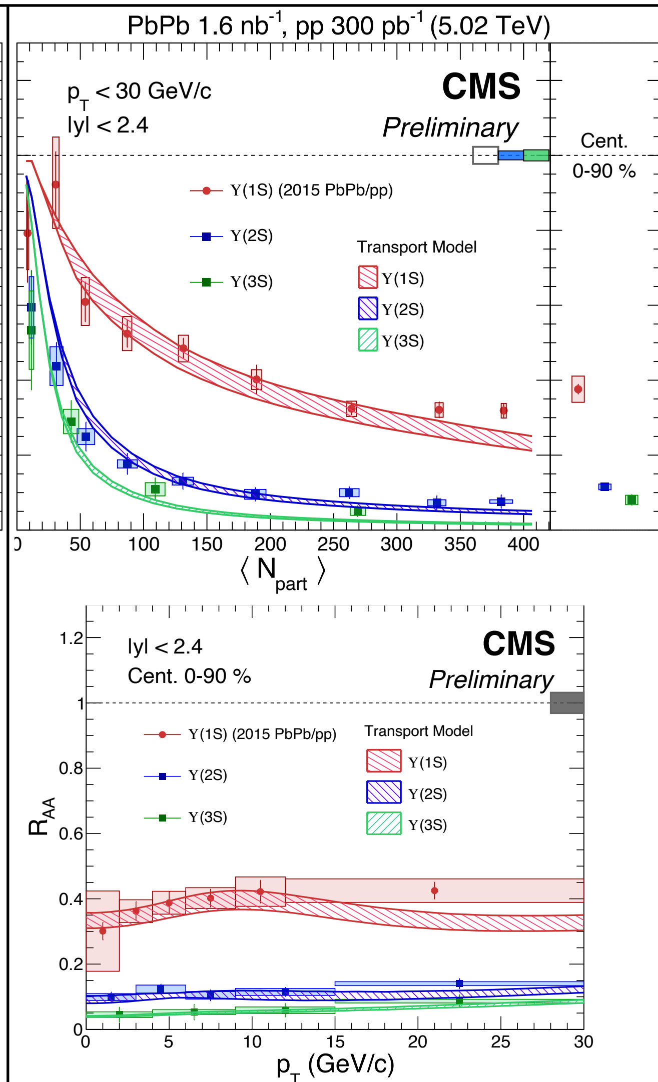
back-up

Comparison with theory

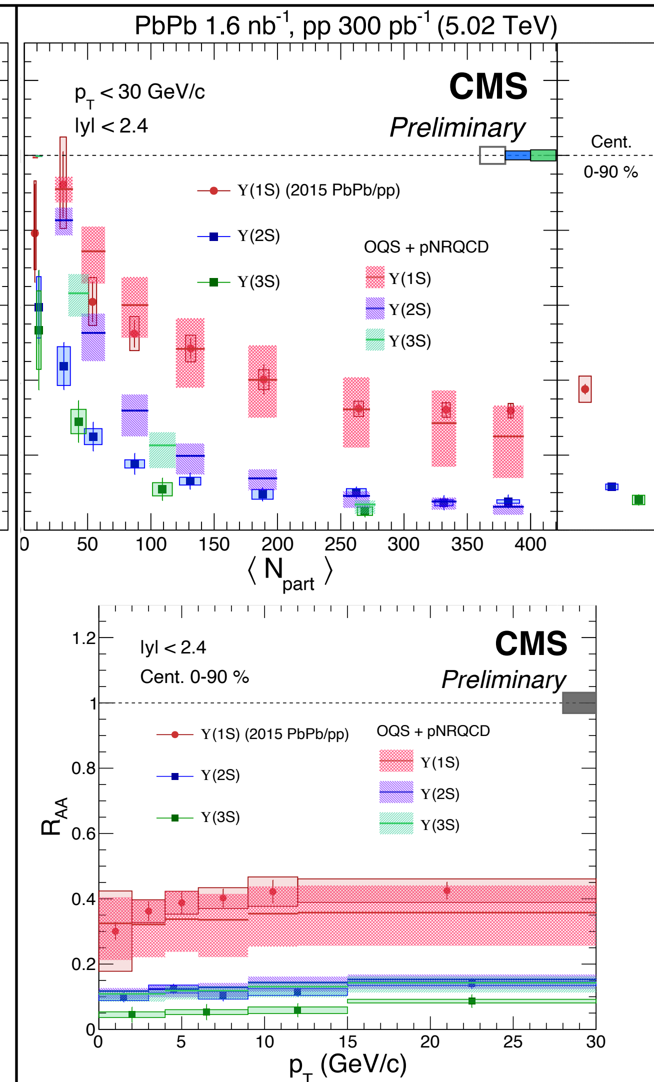
[CMS-PAS-HIN-21-007]



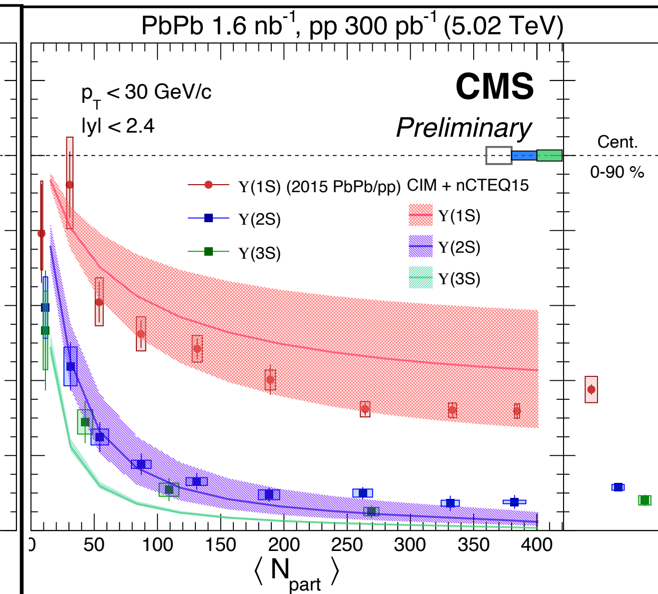
- Open Quantum system approach
  : Dissociation + Recombination
- EPPS16 nPDF effect
- no recombination for ϒ(3S)
- Feed-down included



- 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



- Comover as source of dissociation
- nCTEQ15 nPDF 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

Comparison with theory

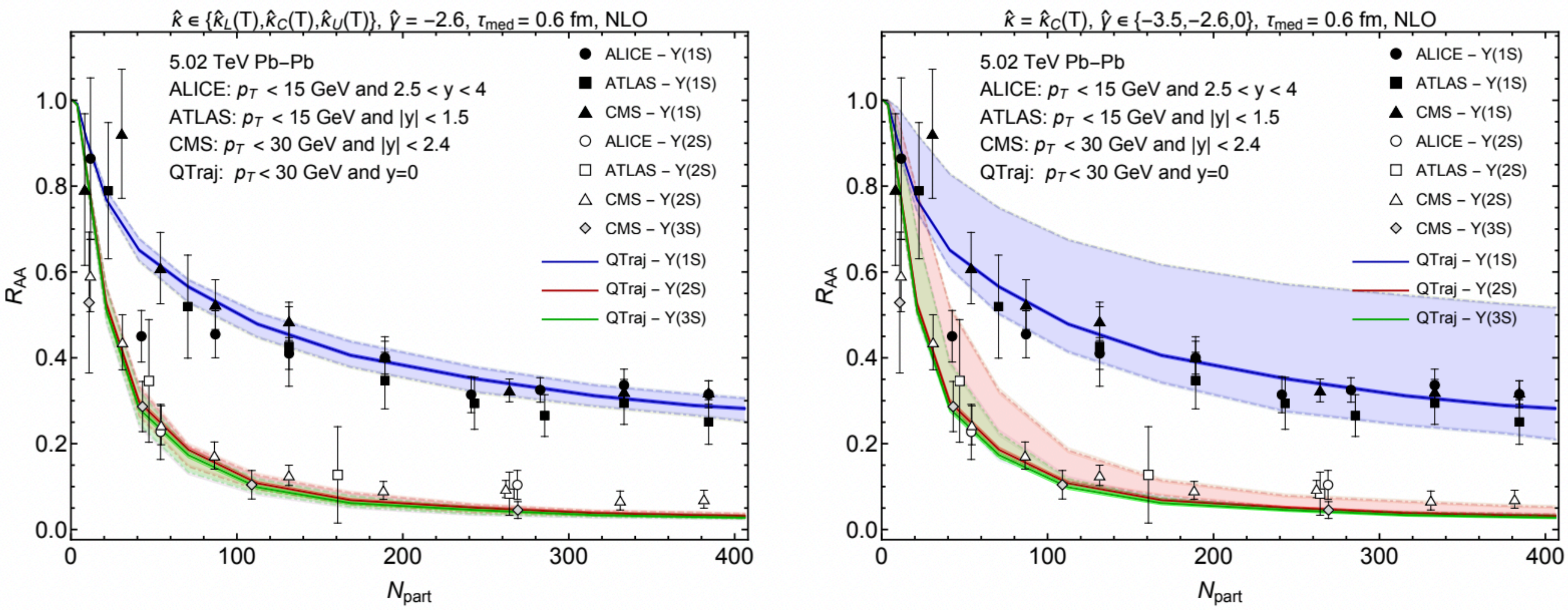
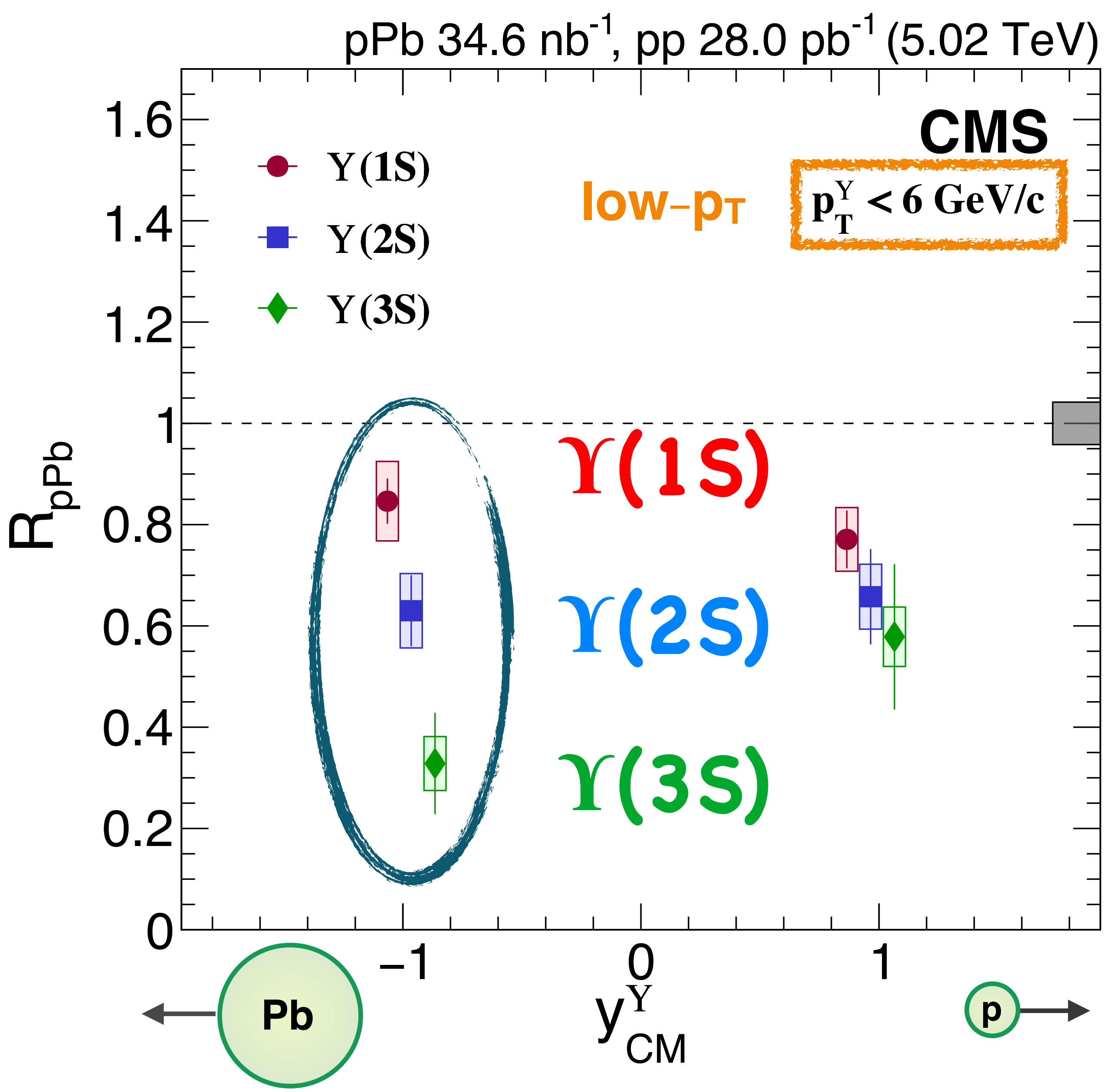


Figure 4. R_{AA} for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ as a function of N_{part}. The left panel shows variation of $\hat{\kappa} \in \{\kappa_L(T), \kappa_C(T), \kappa_U(T)\}$ and the right panel shows variation of $\hat{\gamma}$ in the range $-3.5 \leq \hat{\gamma} \leq 0$. In 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.

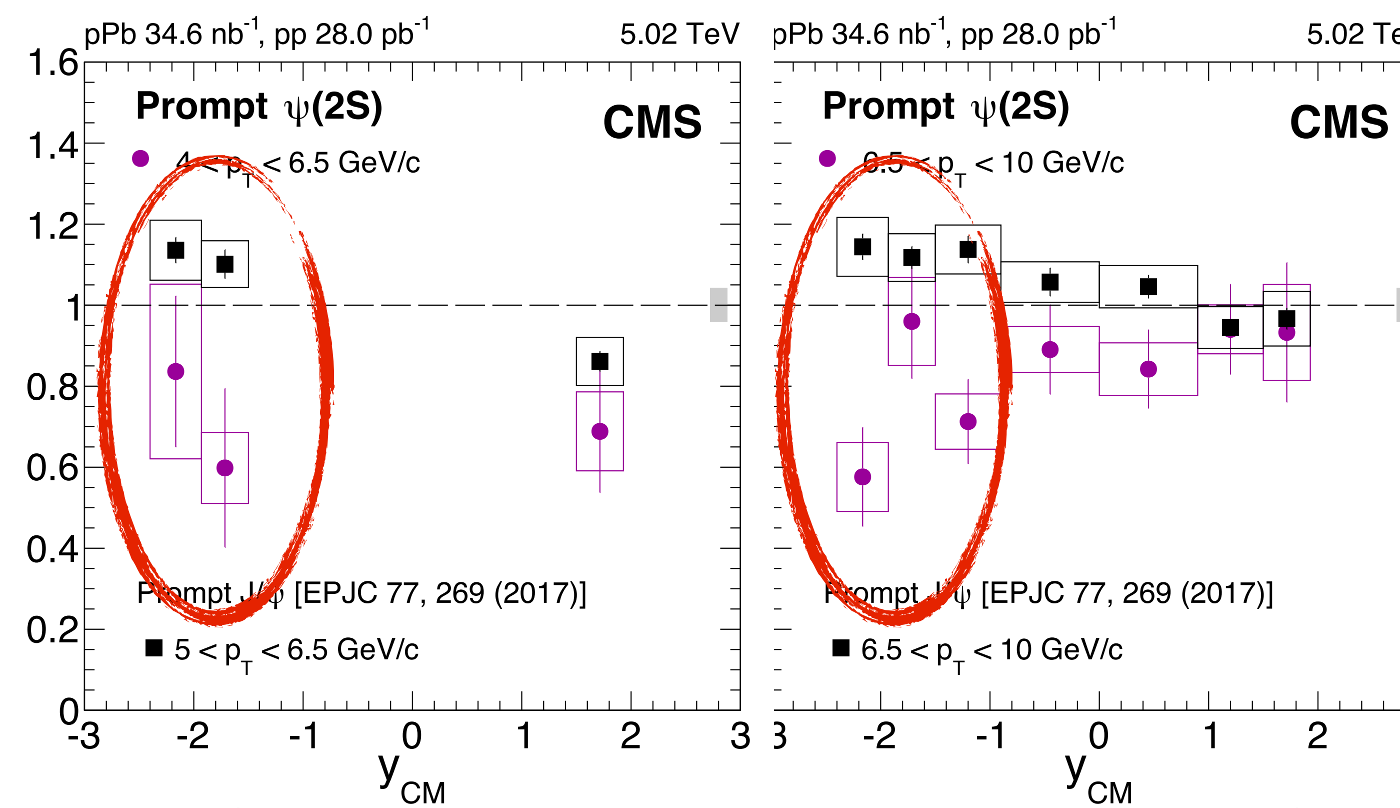
- New updated results at NLO binding energy over temperature
  : still some tension because of the similar R_{AA} of Υ(2S) & Υ(3S)

Sequential Υ suppression in pPb!

[arXiv:2202.11807]

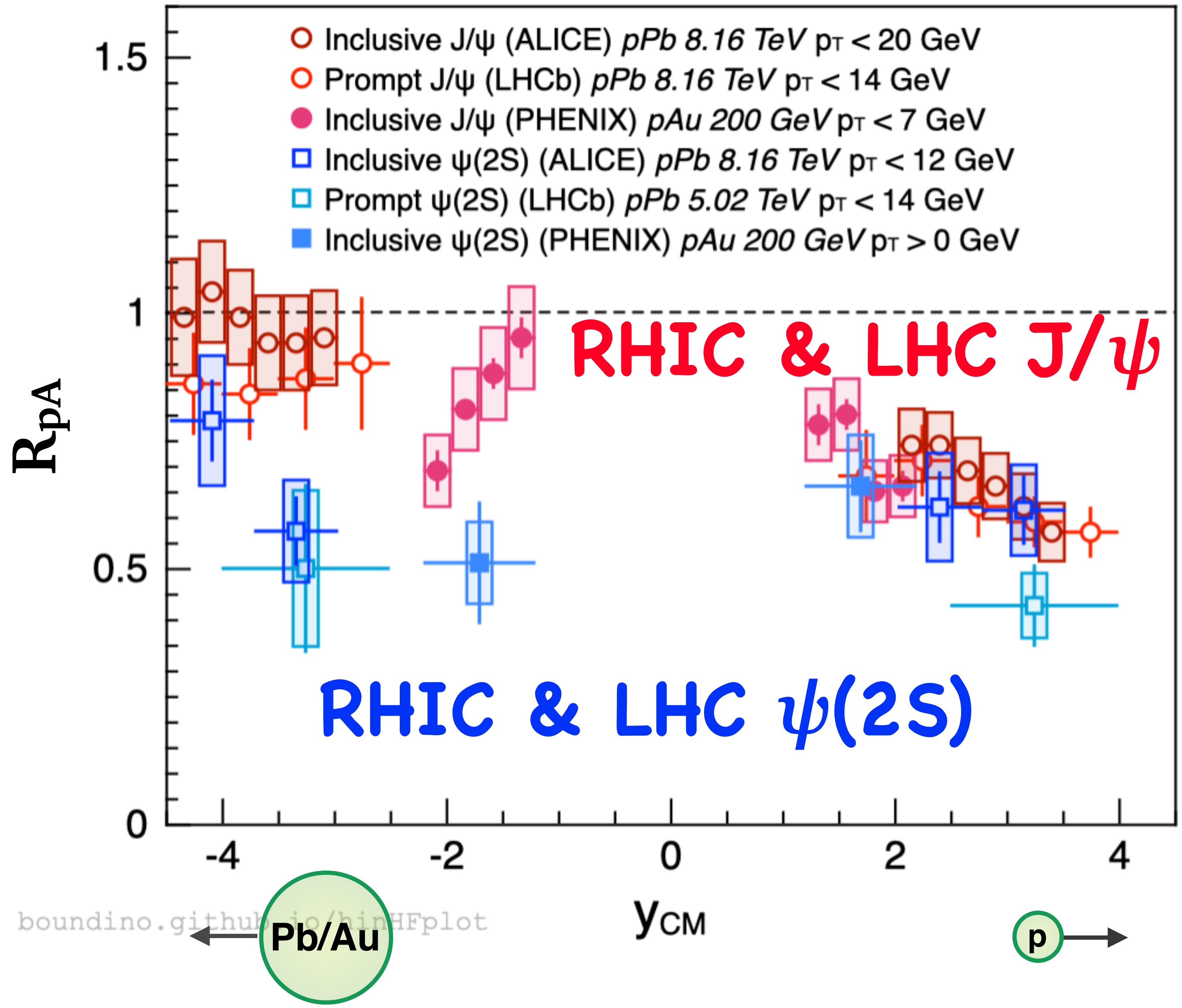


[PLB 790 (2019) 509]



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

Charmonia in pA RHIC vs LHC

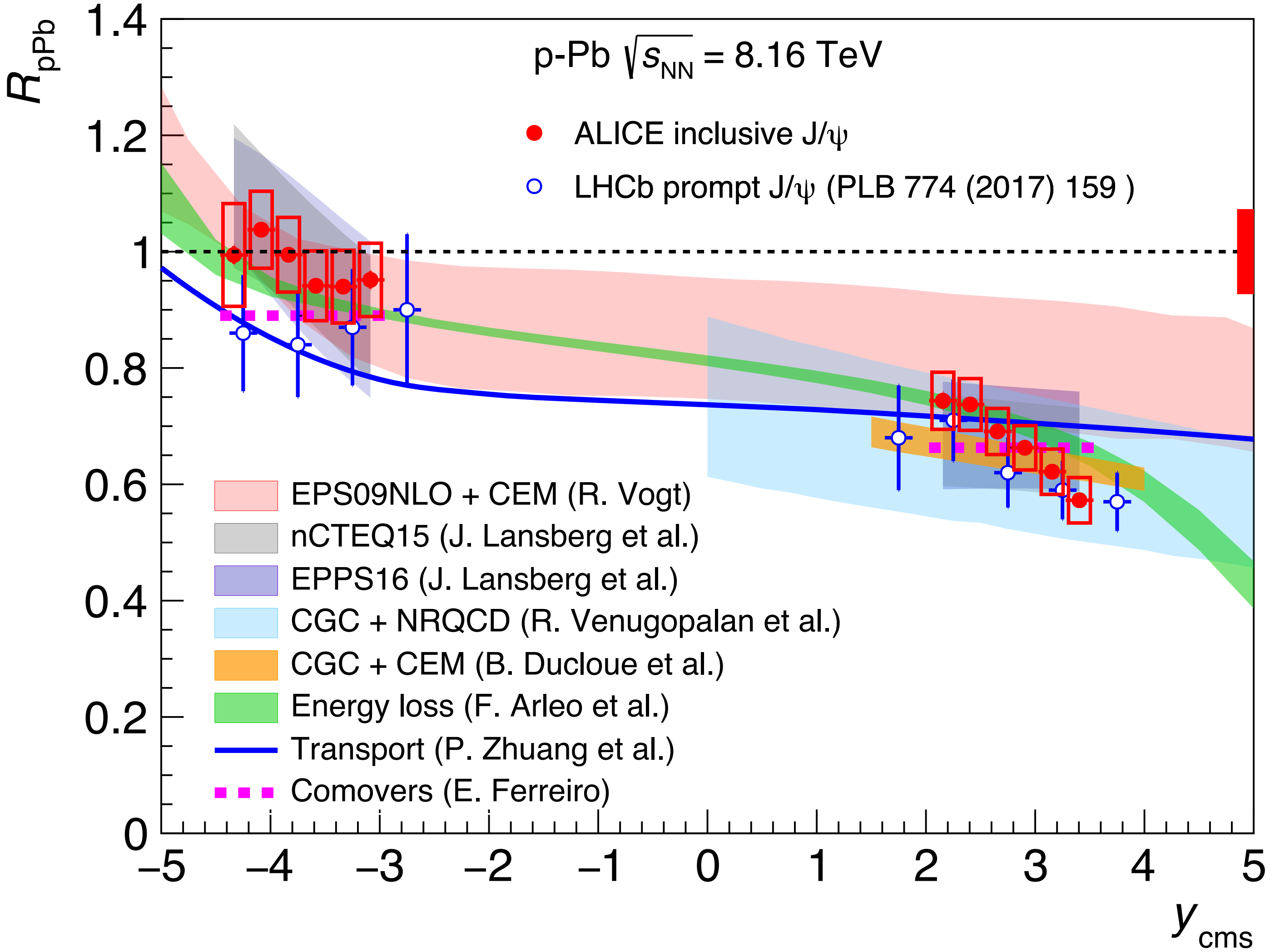


- PLB 774 (2017) 159
- JHEP 07 (2018) 160
- arXiv:2202.03863
- JHEP 03 (2016) 133
- PRC 102 (2020) 014902

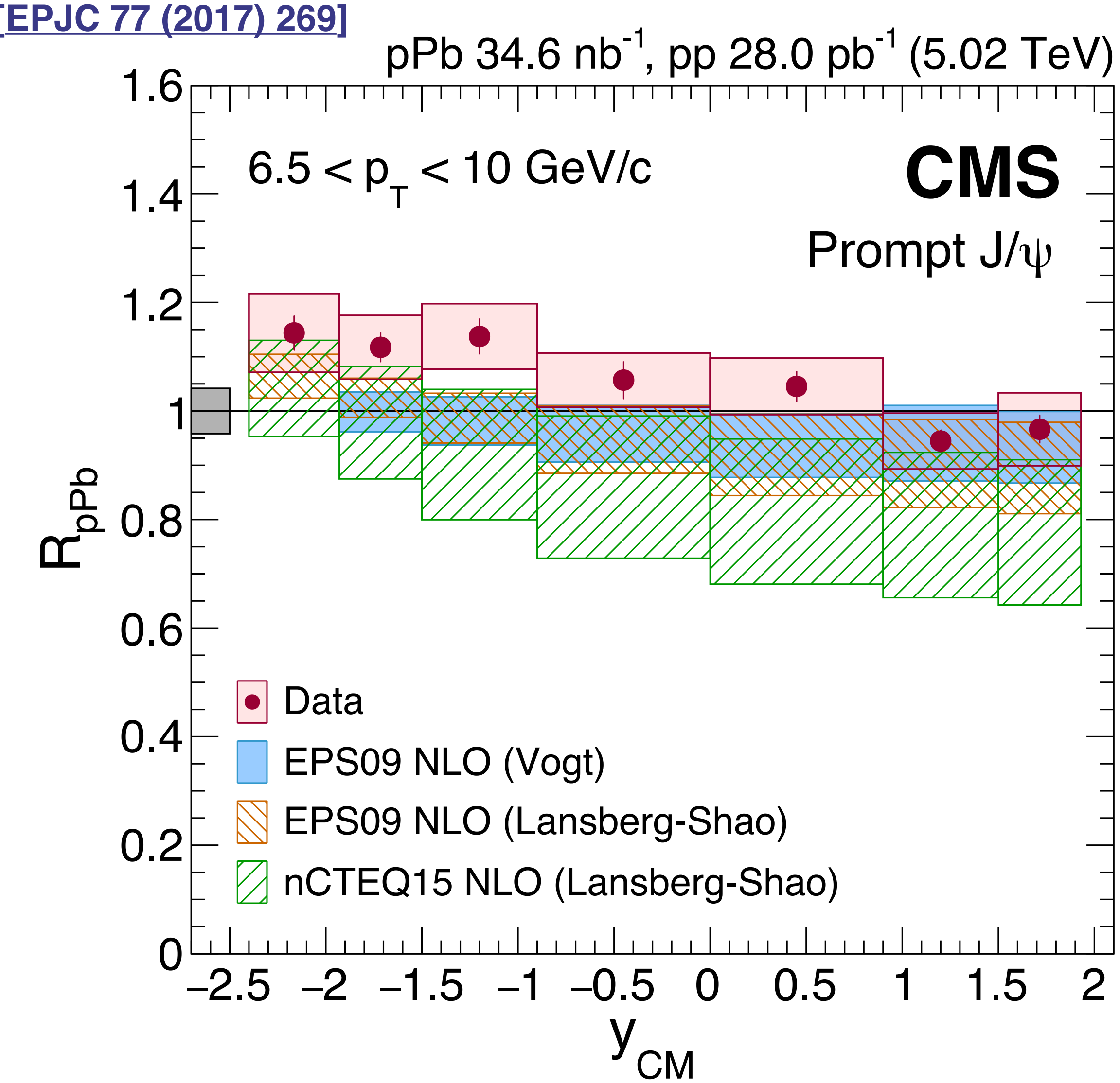
- Similar trend for both J/ψ & ψ(2S) at RHIC and LHC
  - Similar 'amount' of initial/final effects?

J/ψ in pPb vs model

[JHEP 07 (2018) 160]



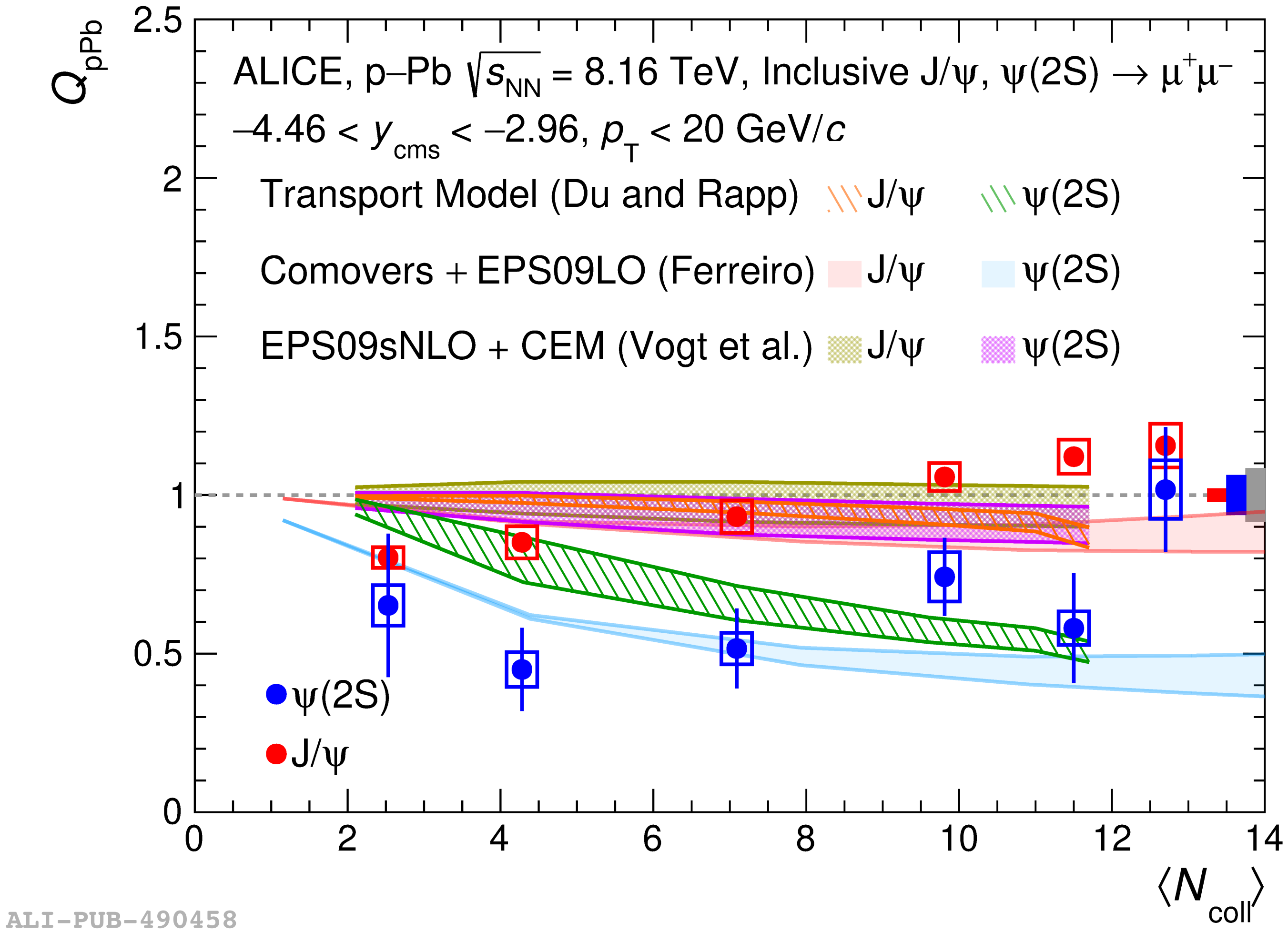
[EPJC 77 (2017) 269]



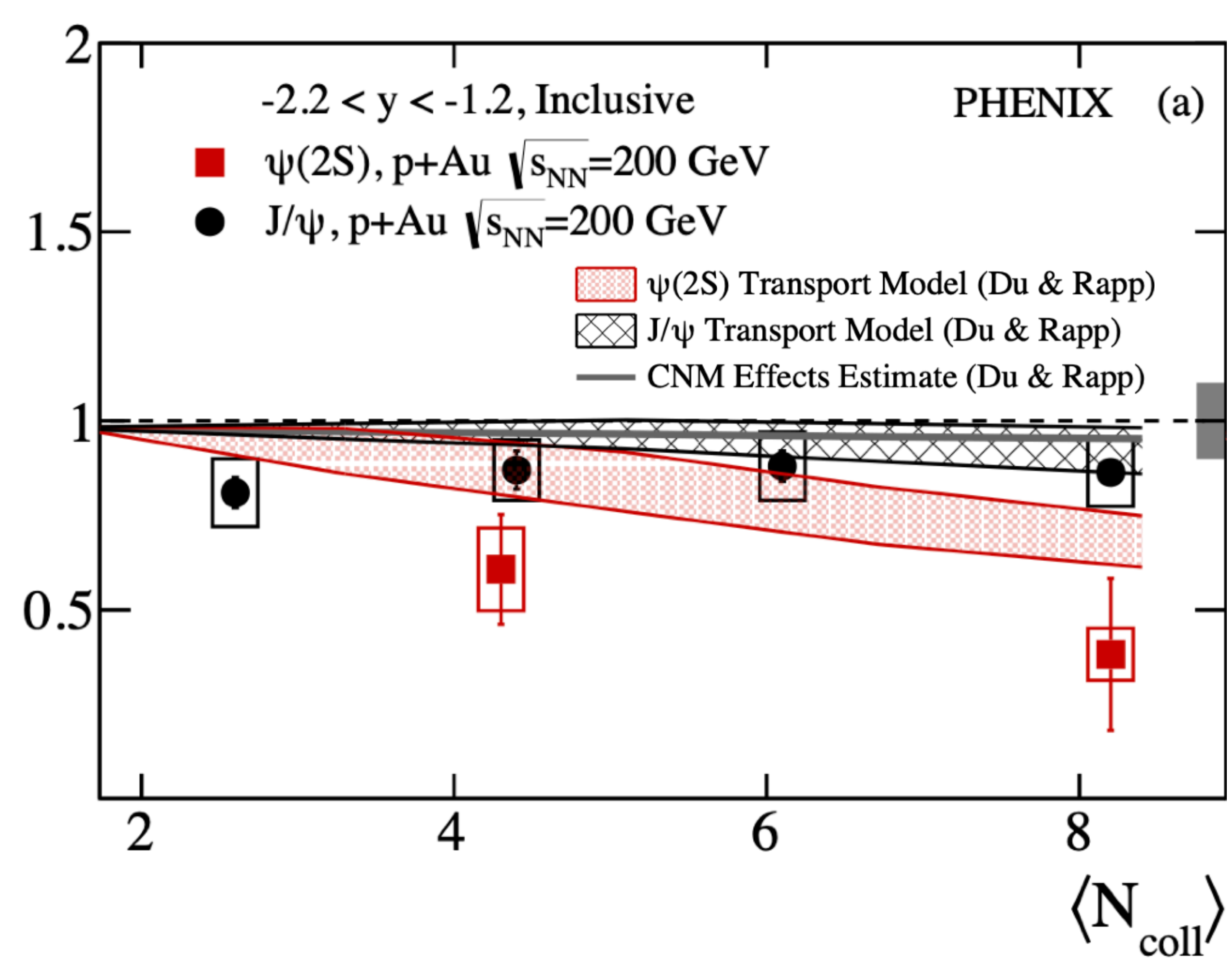
- J/ψ modification well explained by nPDF / CGC predictions
- Negligible contributions from final state effects (comover or hot nuclear matter)

Charmonia in pA vs model

[JHEP 02 (2021) 002]



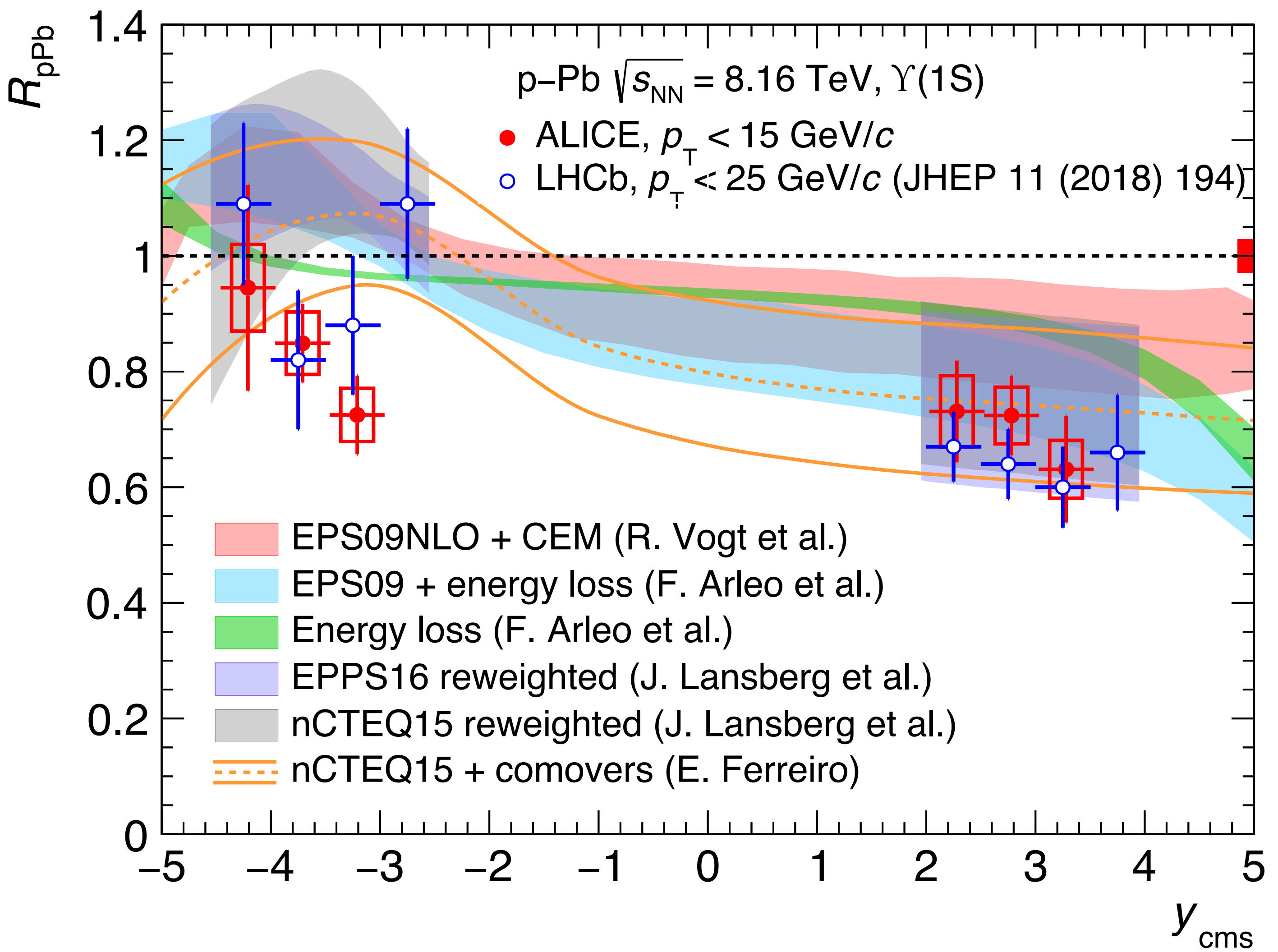
[PRC 105 (2022) 064912]



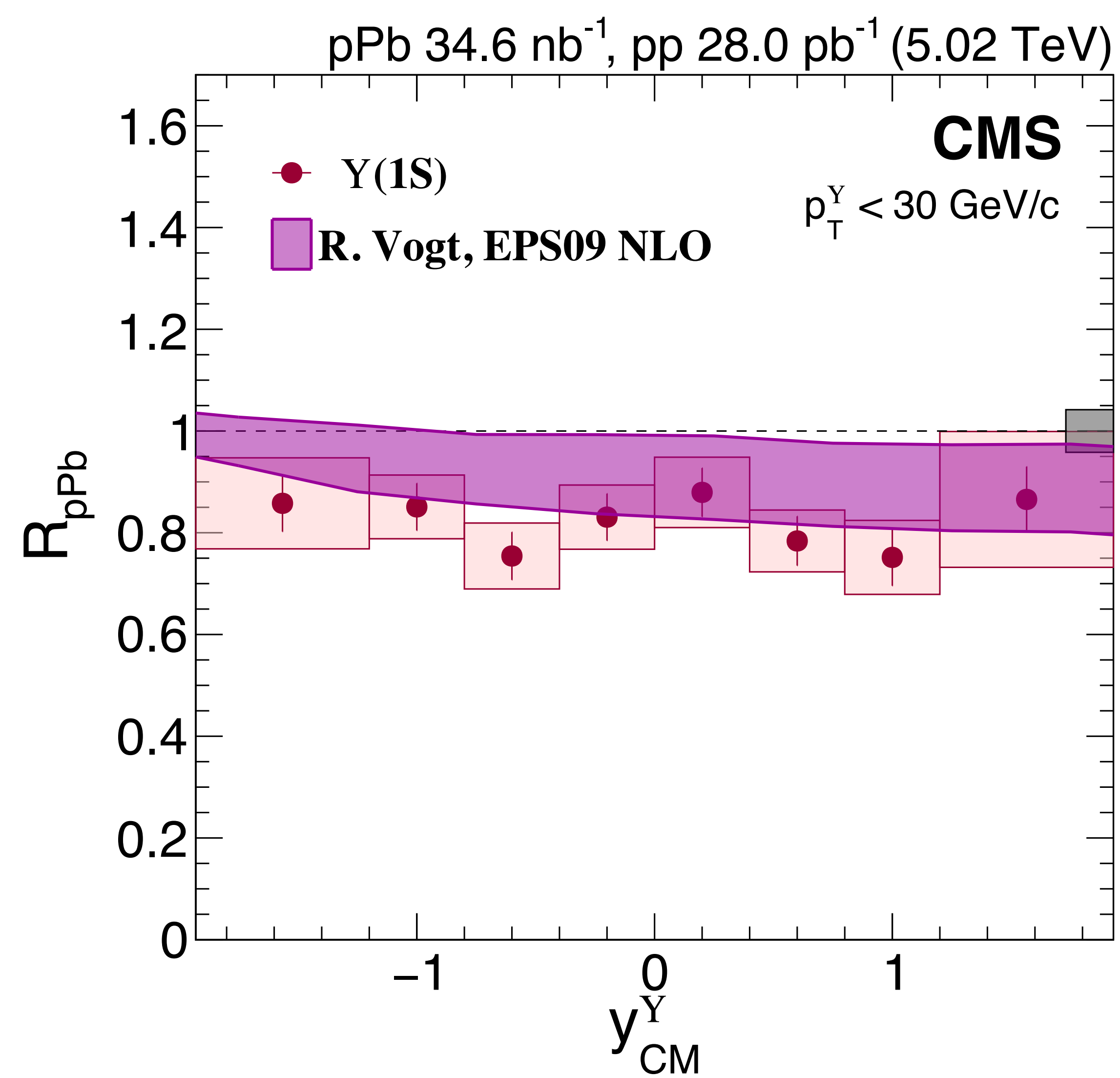
- Attempts to describe ψ(2S) suppression with comover breakup & QGP-like HNM effects
  - Tension b/w model & data in both RHIC and LHC
  - Similar nuclear absorption for J/ψ & ψ(2S) @ RHIC —> already hot in pAu 200 GeV?

Bottomonia in pPb vs model

[PLB 806 (2020) 135486]



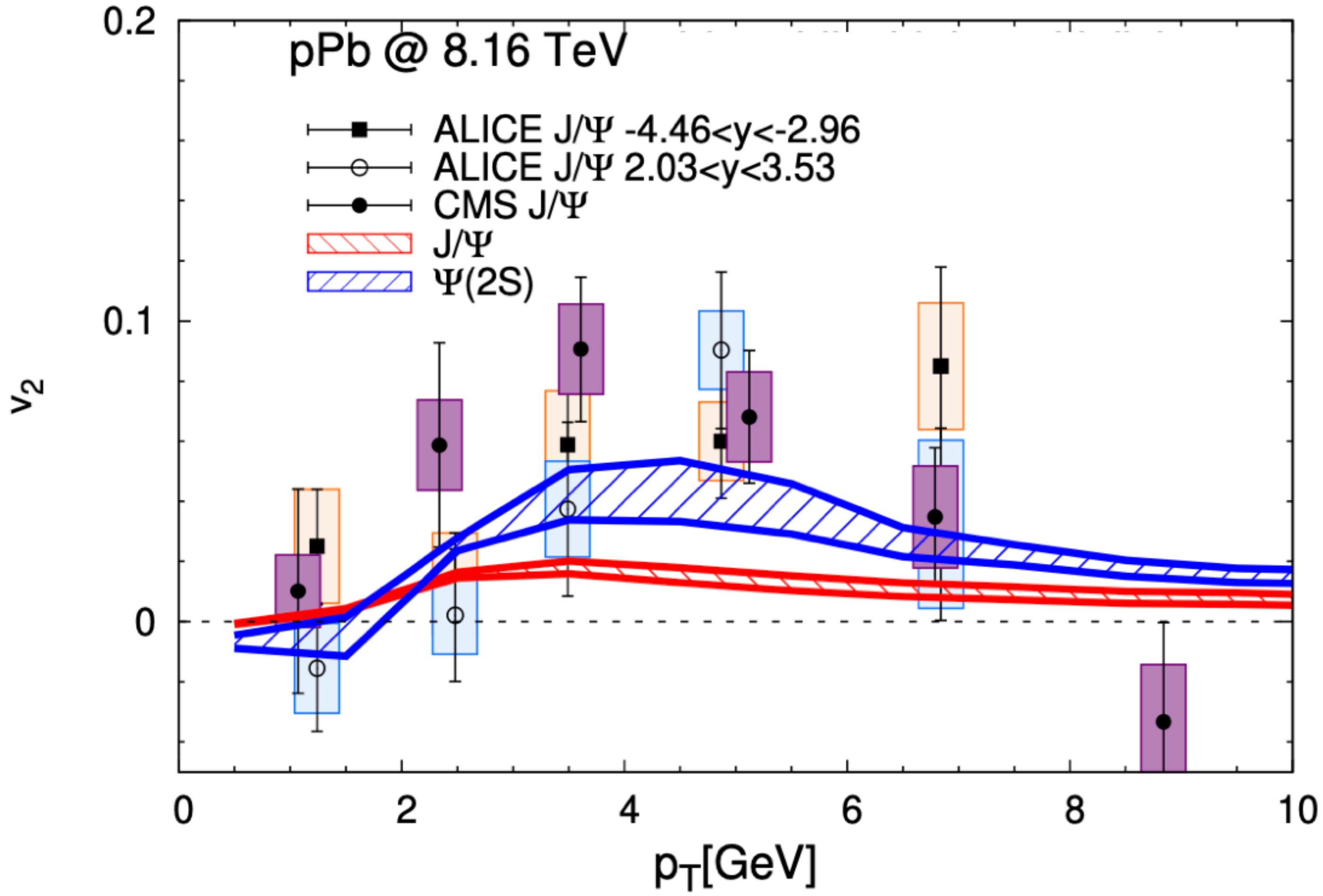
[arXiv:2202.11807]



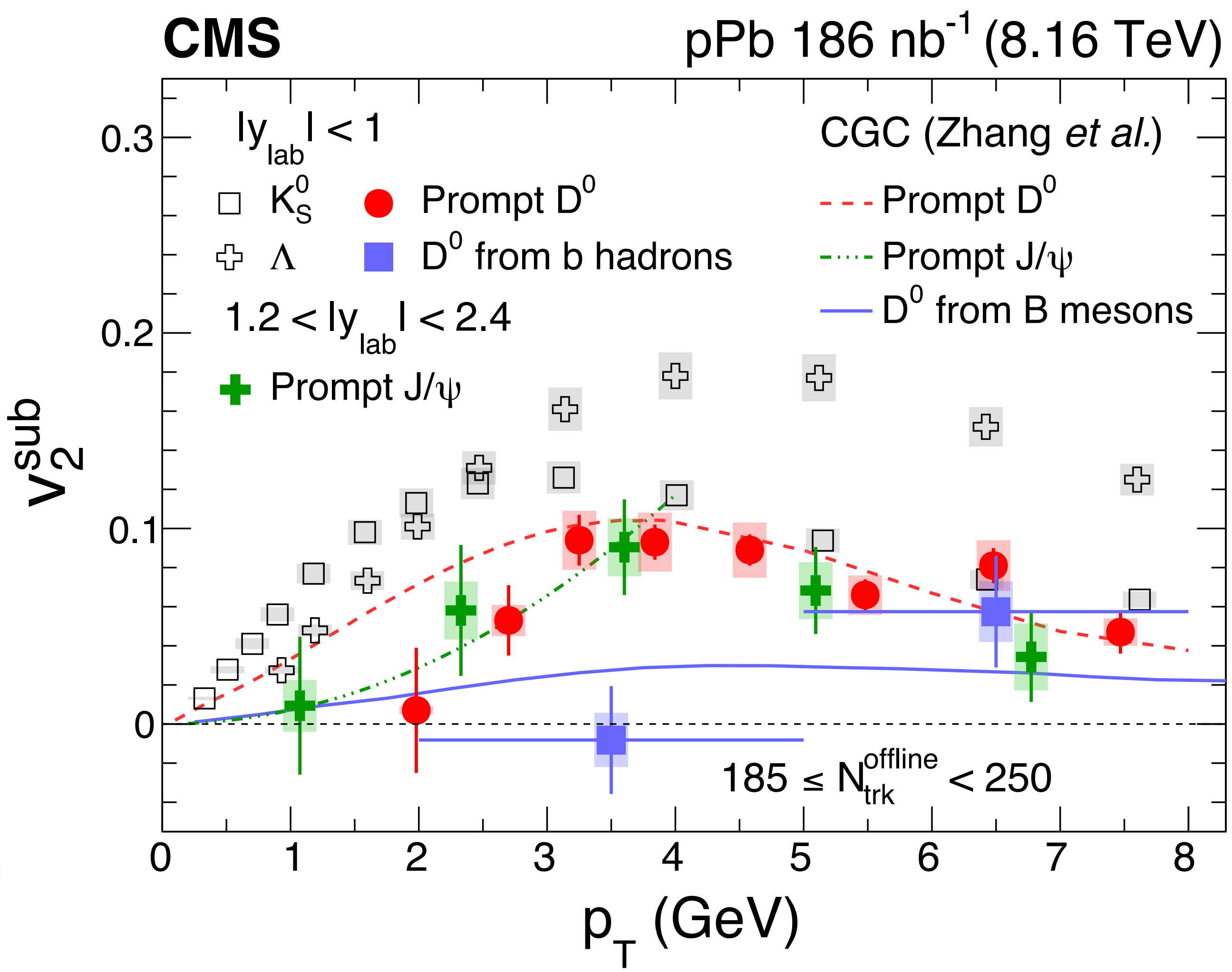
- ϒ(1S) R_{pPb} data in agreement with nPDF calculations

J/ψ flow in pPb vs model

[JHEP 03 (2019) 015]



[PLB 813 (2021) 136036]

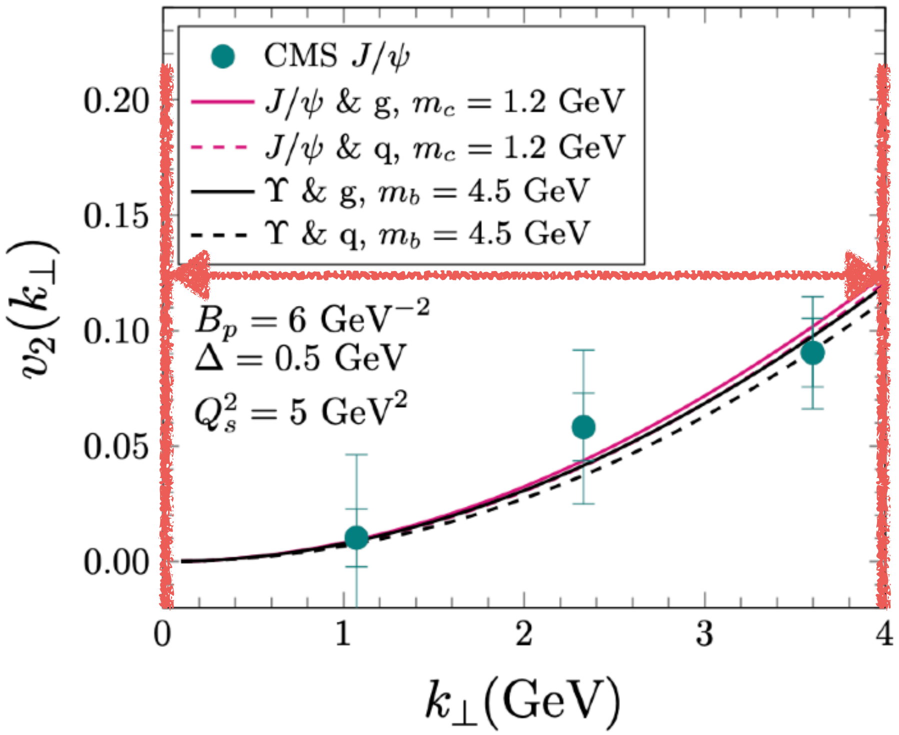


- Transport model underestimate J/ψ v_2
  - predicts larger v_2 for ψ(2S)

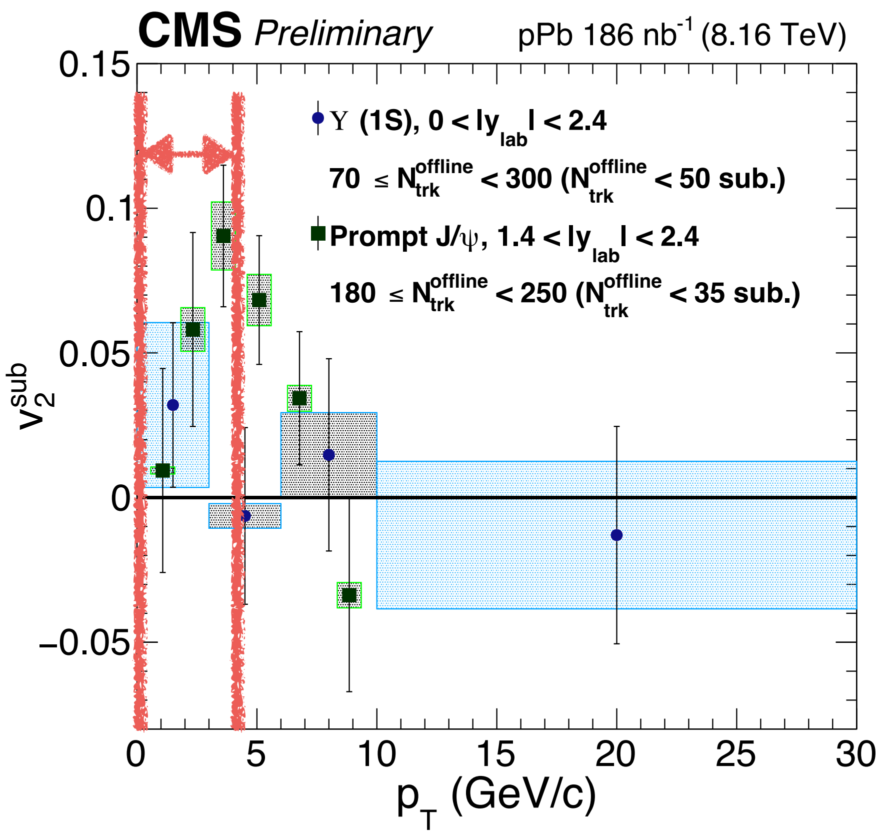
- Qualitatively in agreement with CGC?
  N.B. J/ψ v_2 keeps increasing vs p_T
  : discrepancy for p_T>4 GeV/c

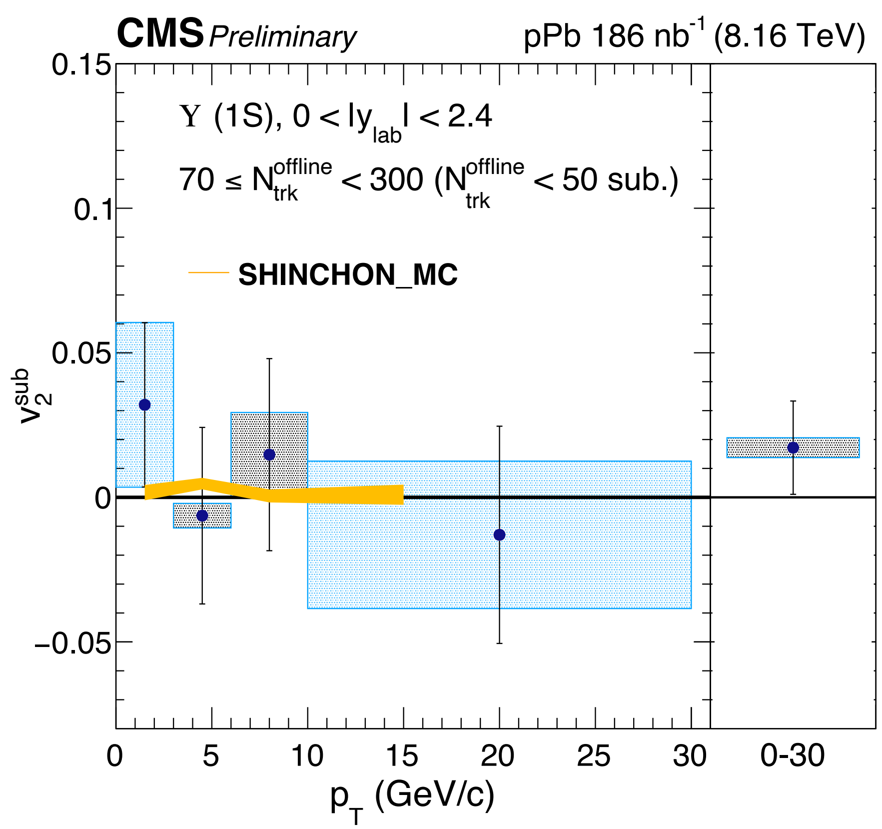
Υ(1S) flow in pPb vs model

[PRD 102 (2020) 034010]



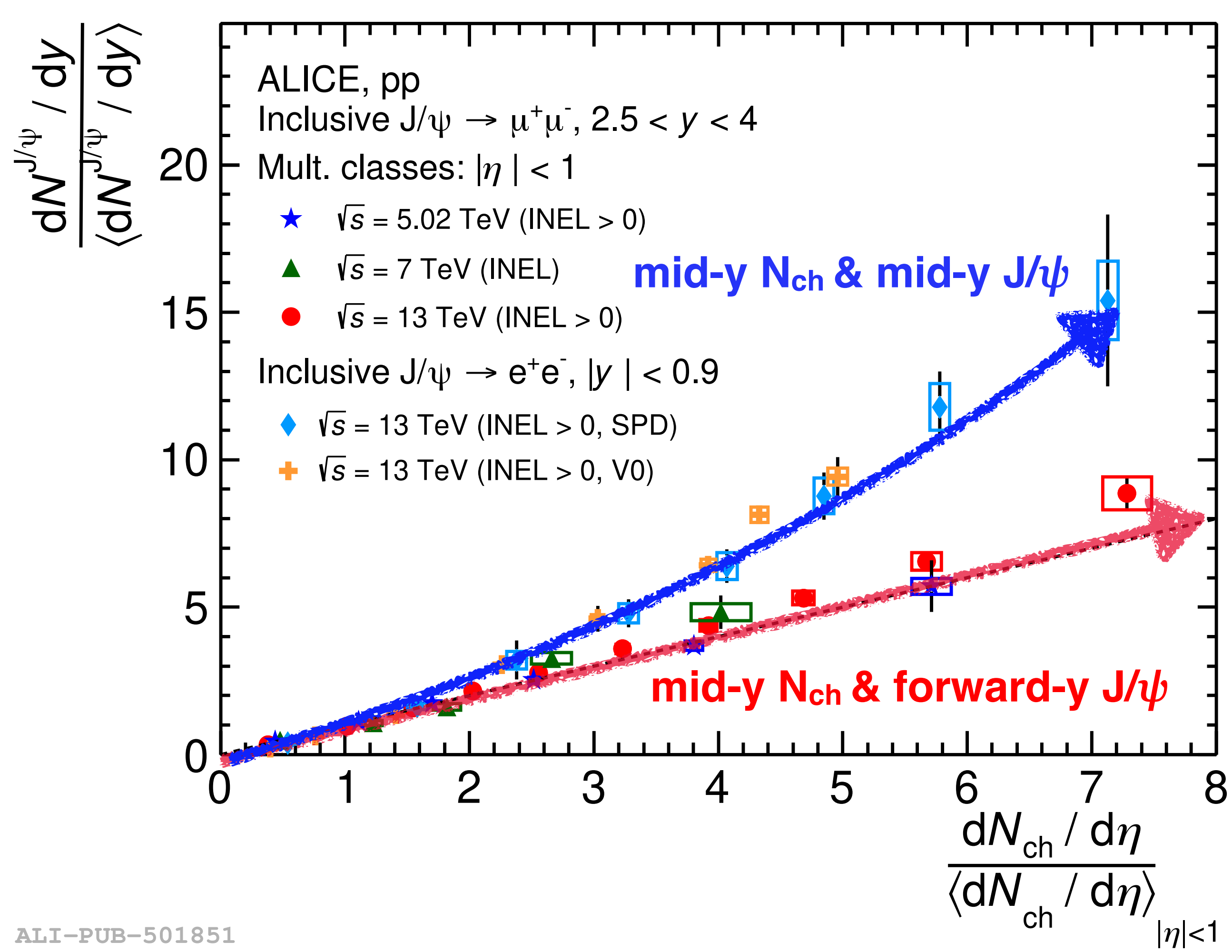
[CMS-PAS-HIN-21-001]

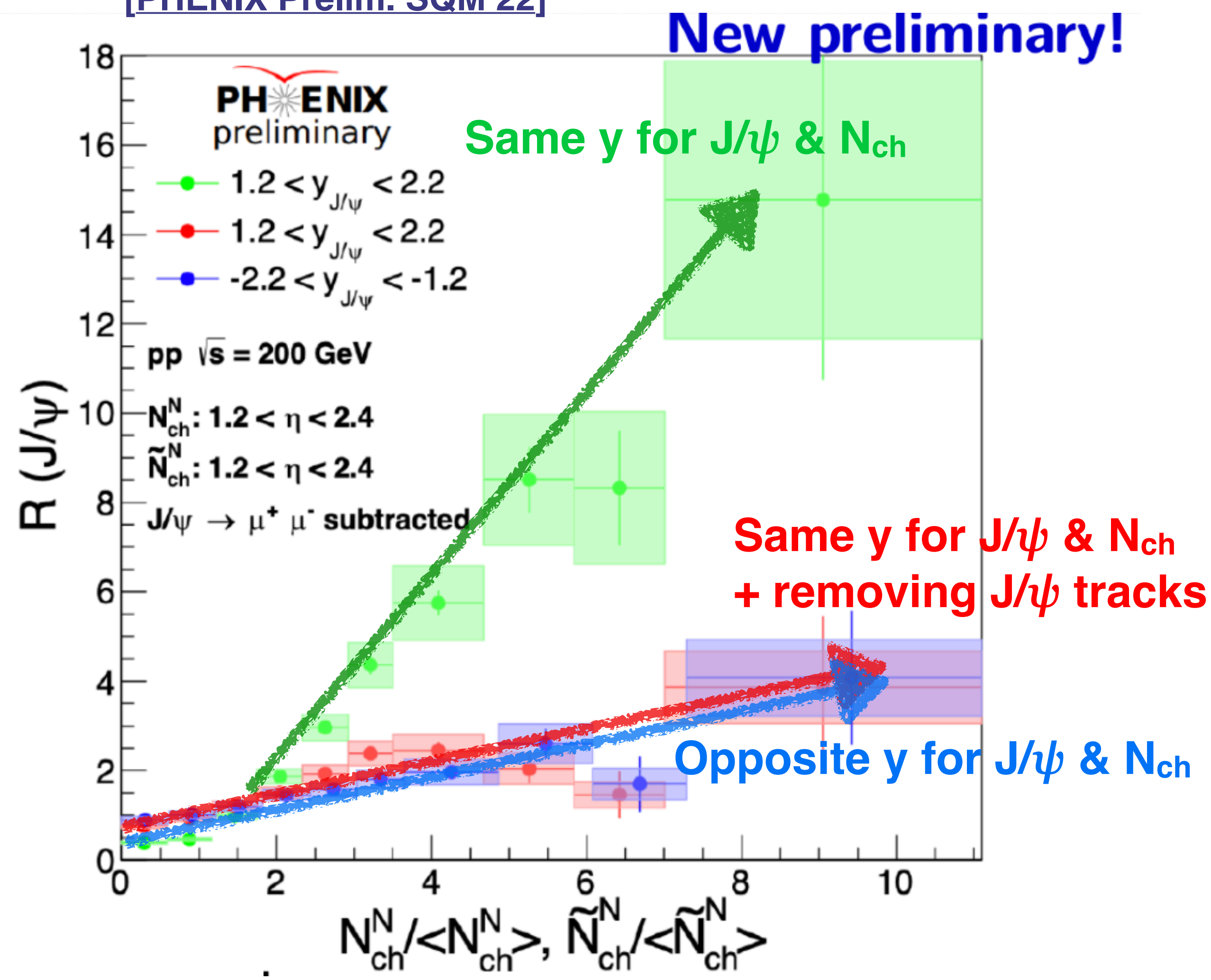




- Similar v_2 predicted by CGC for J/ψ and Υ(1S) - CMS Υ(1S) v_2 consistent with zero
  - N.B. limitations for higher-order QCD calculations (works only $p_T \leq 5$ GeV/c)
- Very small v_2 predicted considering only QGP-like dissociation

Multiplicity dependence?

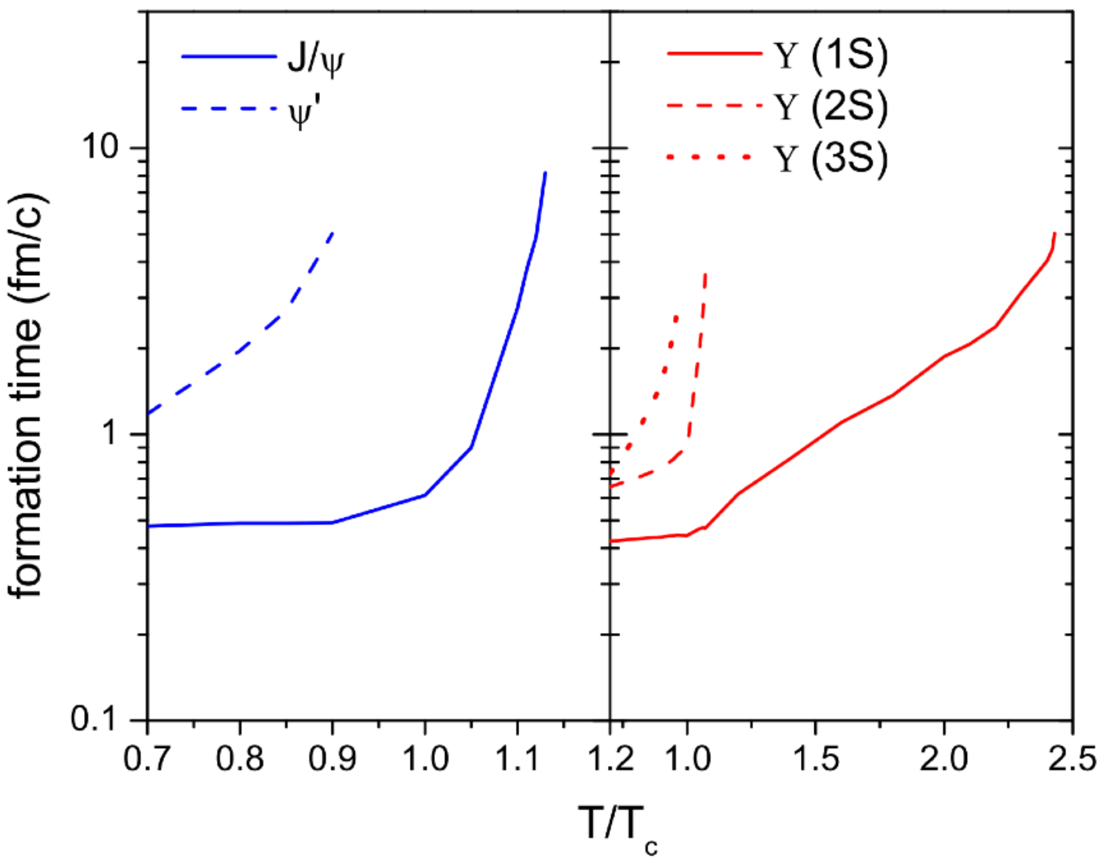




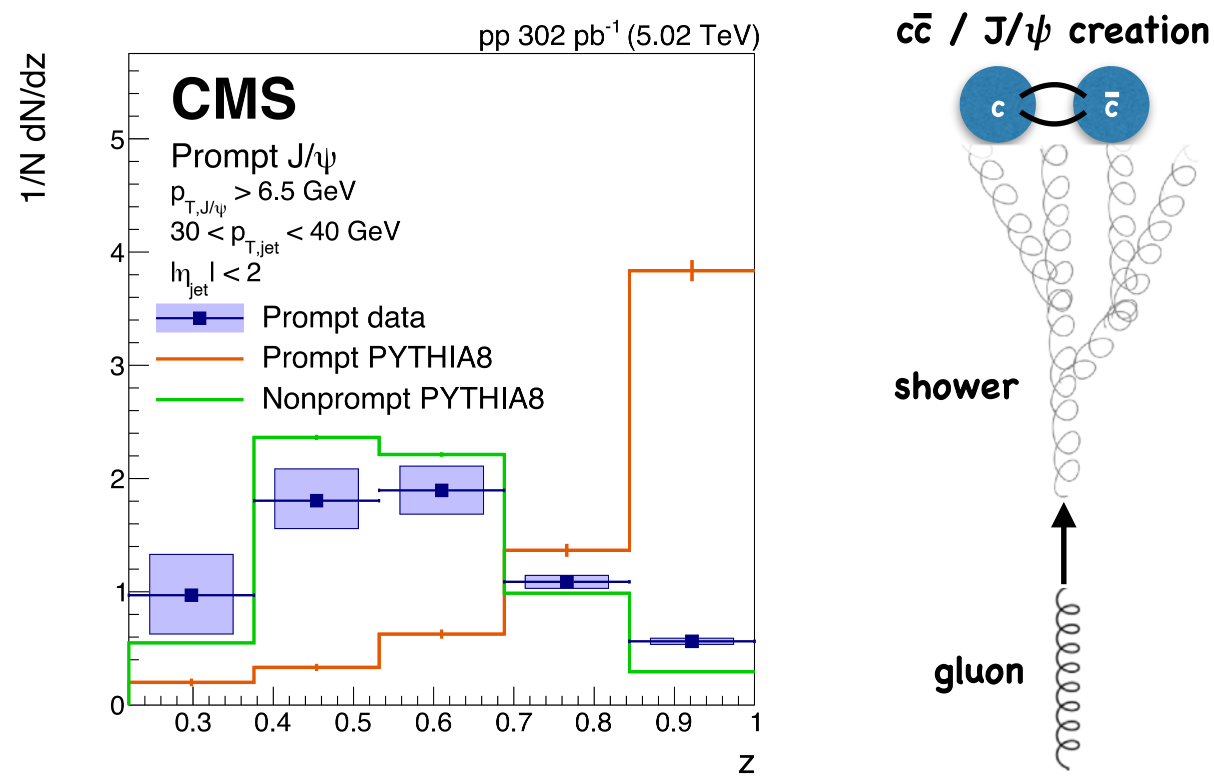
- Quarkonium production increases in case of POI & N_{ch} at the same y
- Production behavior becomes similar after removing tracks from POI?
  - hint of MPI or correlation?

Quarkonium formation time

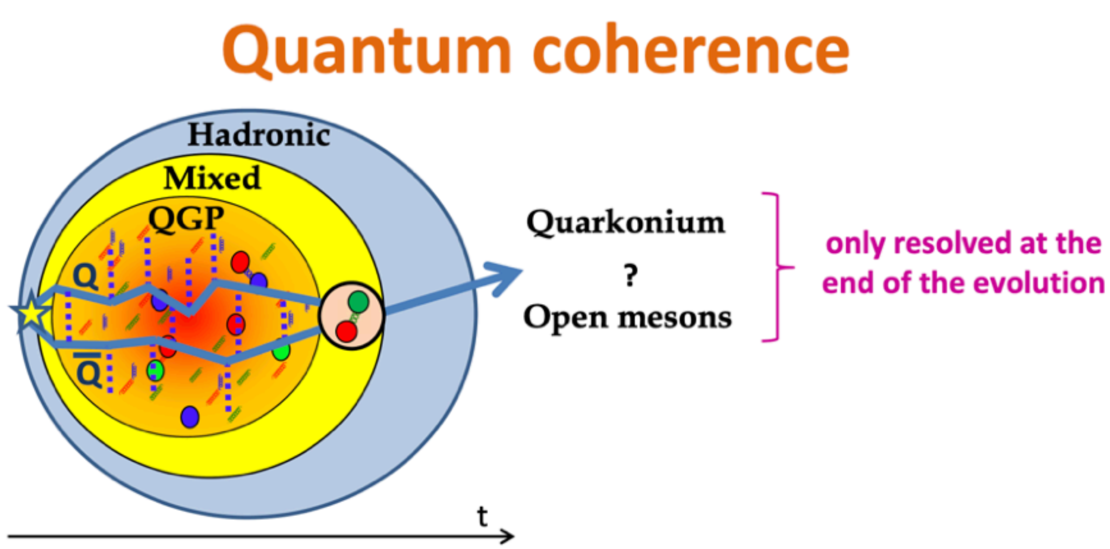
[NPPP 276 (2016) 137]



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



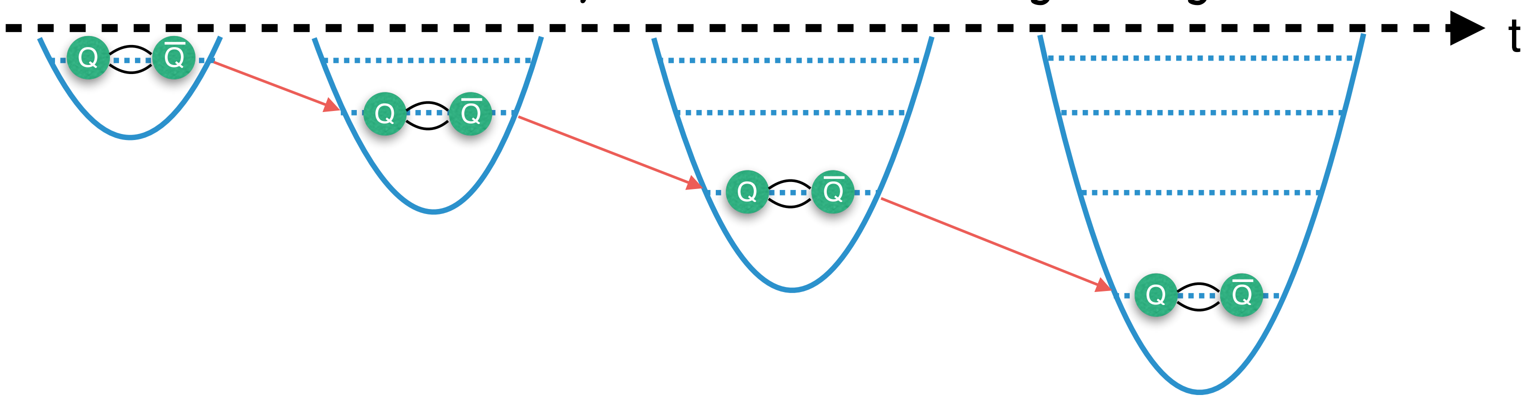
[P. Gossiaux SQM 2022]



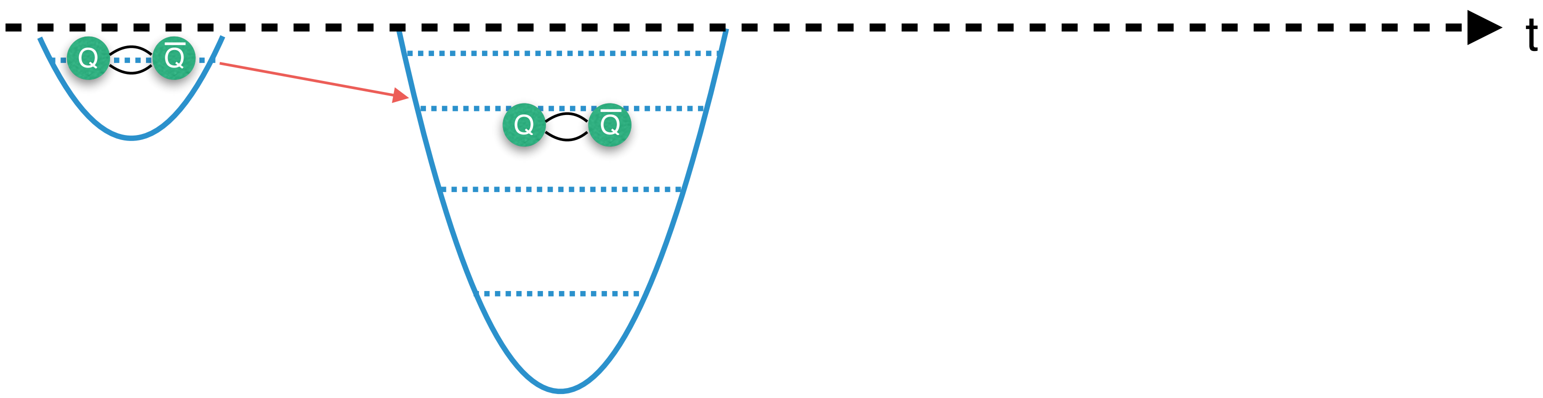
- Quarkonium formation time delayed above dissociation temperature?
- Temperature environment hot enough to modify quarkonium formation time scales?
- Even in pp : high-p_T J/ψ produced at later stages by parton shower

Quarkonium state in medium

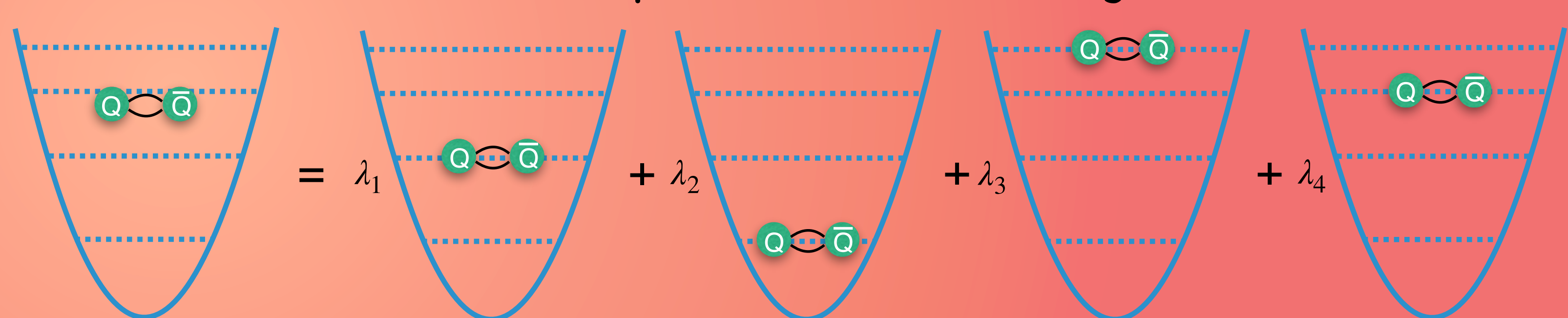
If the medium evolves slowly : state remains in a given eigenstate



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



Q-Qbar state = projection on various eigenstates



[M. Strickland SQM 2021]

Open quantum system (OQS) approach

Probe = heavy-quarkonium state

Medium = light quarks and gluons that comprise the QGP

- Can treat heavy quarkonium states propagating through QGP using an open quantum system approach

$$H_{\rm tot} = H_{\rm probe} \otimes I_{\rm medium} + I_{\rm probe} \otimes H_{\rm medium} + H_{\rm int}$$

[P. Gossiaux SQM 2022]

regime	SU3 ?	Dissipation ?	3D / 1D	Num method	year	remark	ref
NRQCD ⇔ QBM	No	No	1D	Stoch potential	2018		Kajimotoet al. , Phys. Rev. D 97, 014003 (2018), 1705.03365
	Yes	No	3D	Stoch potential	2020	Small dipole	R. Sharma et al Phys. Rev. D 101, 074004 (2020), 1912.07036
	Yes	No	3D	Stoch potential	2021		Y. Akamatsu, M. Asakawa, S. Kajimoto (2021), 2108.06921
	No	Yes	1D	Quantum state diffusion	2020		T. Miura, Y. Akamatsu et al, Phys. Rev. D 101, 034011 (2020), 1908.06293
	Yes ✓	Yes ✓	1D	Quantum state diffusion	**2021**		Akamatsu & Miura, EPJ Web Conf. 258 (2022) 01006, 2111.15402
	No	Yes	1D	Direct resolution	**2021**		O. Ålund, Y. Akamatsu et al, Comput. Phys. 425, 109917 (2021), 2004.04406
	Yes ✓	Yes ✓	1D	Direct resolution	**2022**		S Delorme et al, https://inspirehep.net /literature/ 2026925
pNRQCD (i)	Yes	No	1D+	Direct resolution	2017	S and P waves	N. Brambilla et al, Phys. Rev. D96, 034021 (2017), 1612.07248
(i) Et (ii)	Yes	No	1D+	Direct resolution	2017	S and P waves	N. Brambilla et al, Phys. Rev. D 97, 074009 (2018), 1711.04515
(i)	Yes	No	Yes	Quantum jump	**2021**	See SQM 2021	N. Brambilla et al. , JHEP 05, 136 (2021), 2012.01240 & *Phys.Rev.D* 104 (2021) 9, 094049, 2107.06222
(i)	Yes ✓	Yes ✓	Yes ✓	Quantum jump	**2022**		N. Brambilla et al. 2205.10289
(iii)	Yes ✓	Yes ✓	Yes ✓	Boltzmann (?)	2019		Yao & Mehen, Phys.Rev.D 99 (2019) 9, 096028, 1811.07027
NRQCD & « pNRQCD »	Yes	Yes	1D	Quantum state diffusion	**2022**		Miura et al. http://arxiv.org/abs/2205.15551v1
Other	No	Yes	1D	Stochastic Langevin Eq.	2016	Quadratic W	Katz and Gossiaux