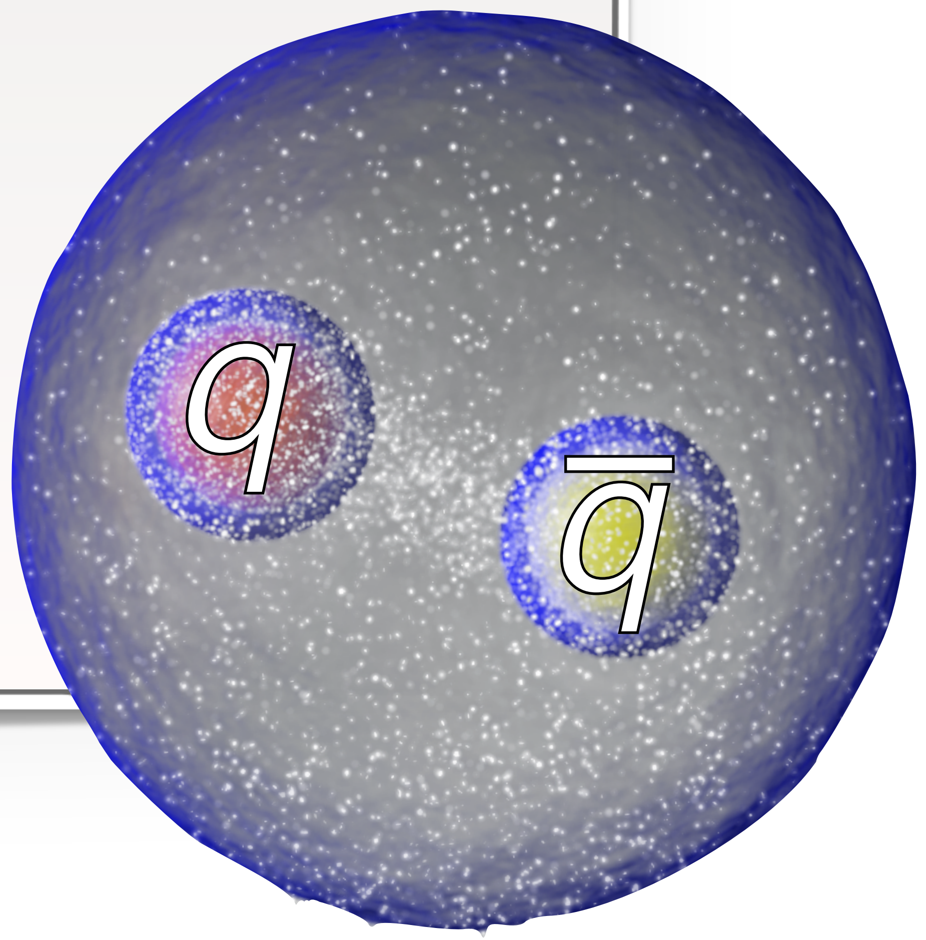
Quarkonia : Overview of LHC and prospectives towards RHIC



JaeBeom Park (CU Boulder)

- 2023 RHIC/AGS Annual Users's Meeting -

Boulder

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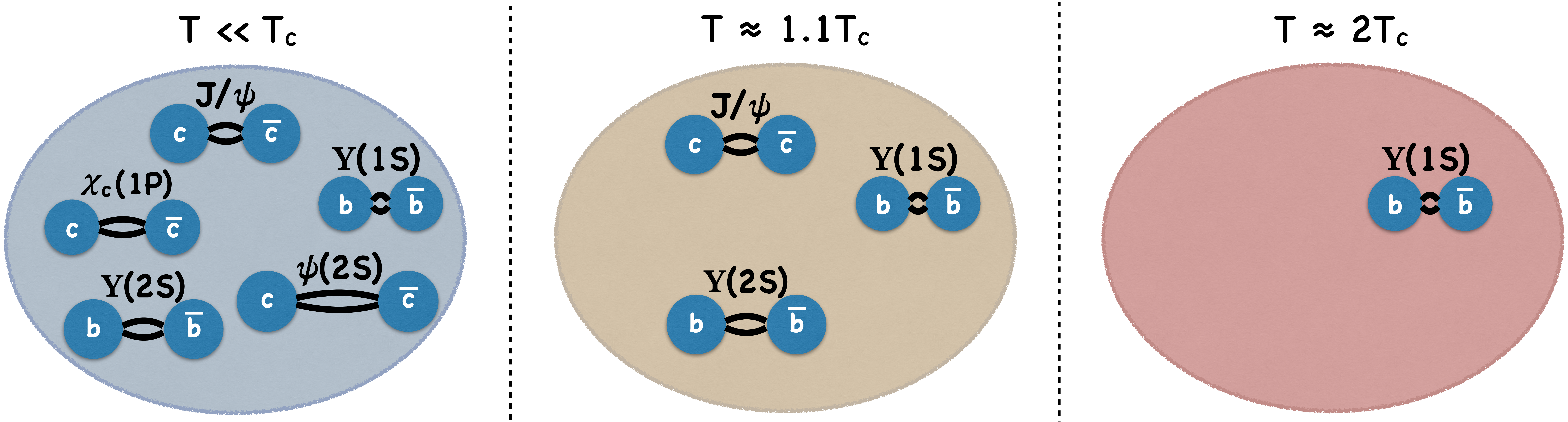
Quarkonia in heavy ion collisions

- What are the suppression/recombination mechanisms of quarkonia in QGP?
- What is the dominant process in the ‘measured’ quarkonium states?
- When are quarkonium states produced in the medium?
  - Are they created at early stages?
  - Bonus : is $q\bar{q}$ pair created early?
- Is the melting picture of Debye screening still valid?
- Does quarkonium production has connections to UE? (Even in pp?)

Motivation

Quarkonia : Bound states of quark and its anti-quark —> Powerful tool to study thermal properties of QGP

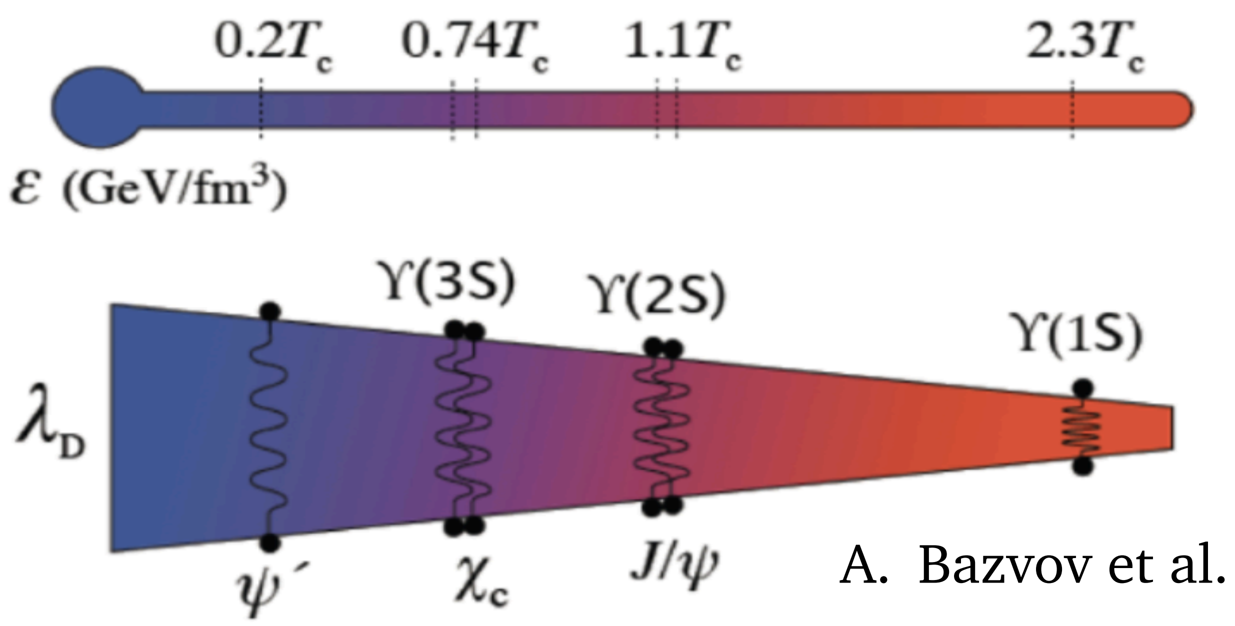


T. Matsui, H. Satz [PLB 178 (1986) 416]

S. Digal, P. Petreczky, H. Satz [PRD 64 (2001) 094015]

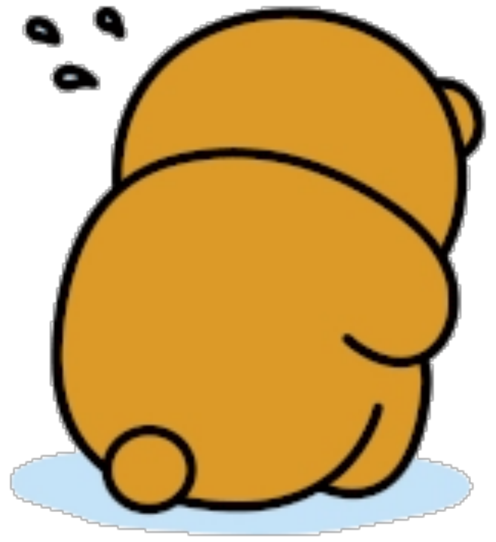
Sequential melting by Debye screening

→ Quarkonia as thermometer of the QGP



A. Bazvov et al. [arXiv:1904.09951]

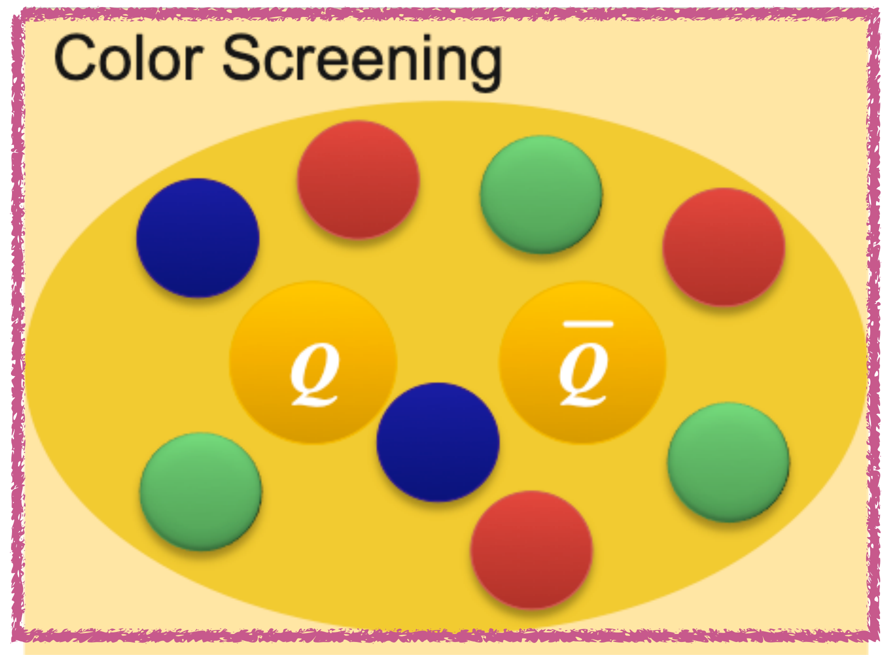
Not that simple anymore…

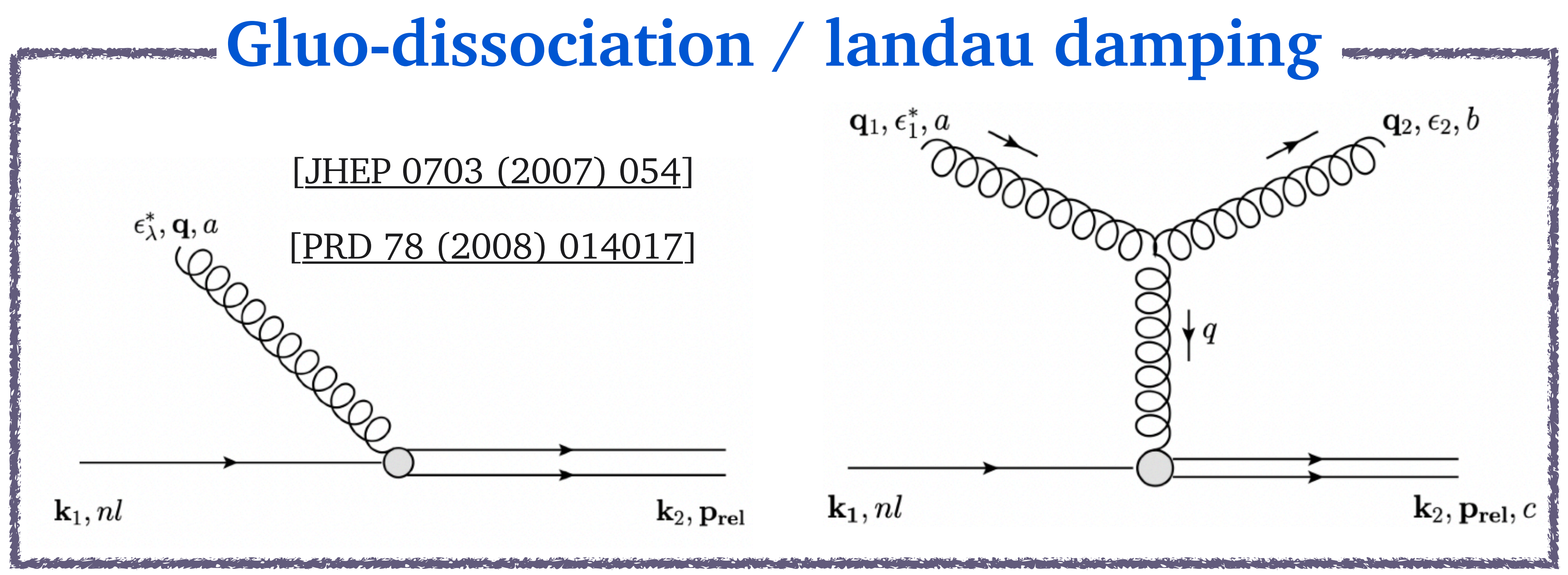


Motivation : in-medium effects

Suppression

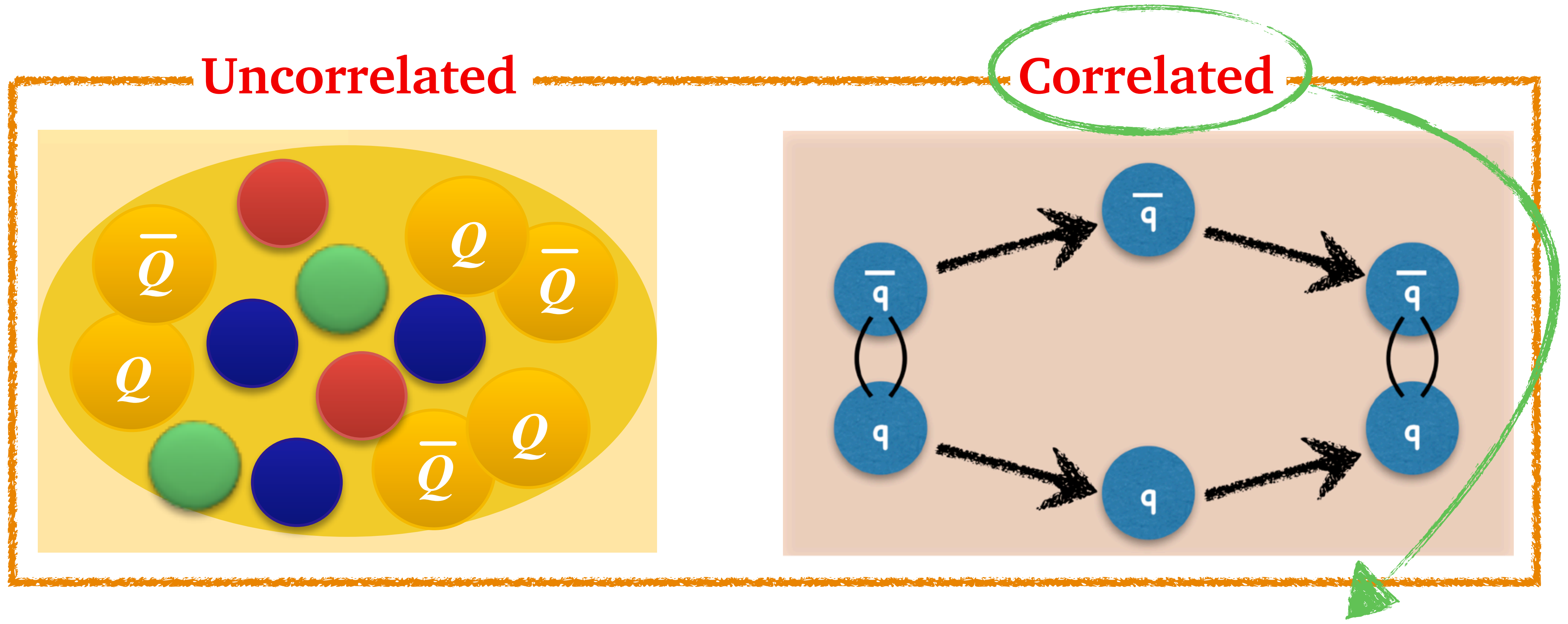
- Debye screening
  — static color screening : $\mathrm{ReV_s(r,T)}$
- Gluo-dissociation / Landau-damping
  — dynamical screening : $\mathrm{ImV_s(r,T)}$





Recombination (Regeneration)

- Uncorrelated recombination (off-diagonal)
- Correlated recombination (diagonal)



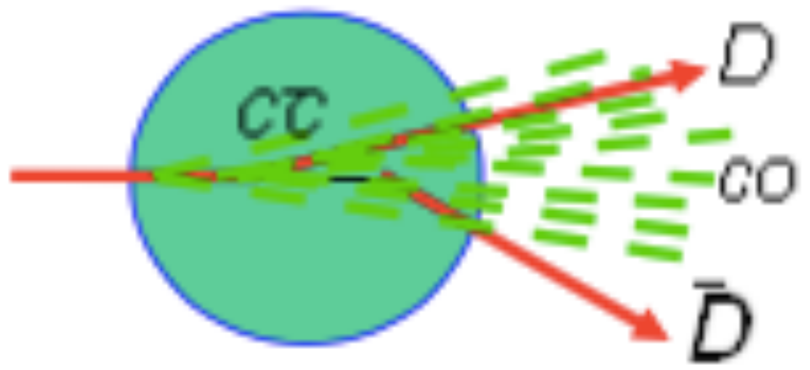
Recent theories :
Non-negligible even for Υ(1S)!

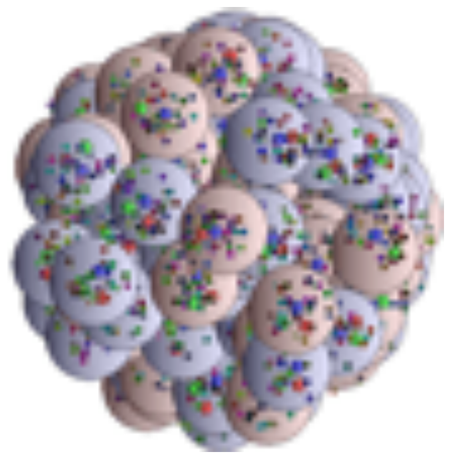
Motivation : CNM/initial state effects

[IJMP E 24 (2015) 1530008]

Initial/Final state effects of nucleus

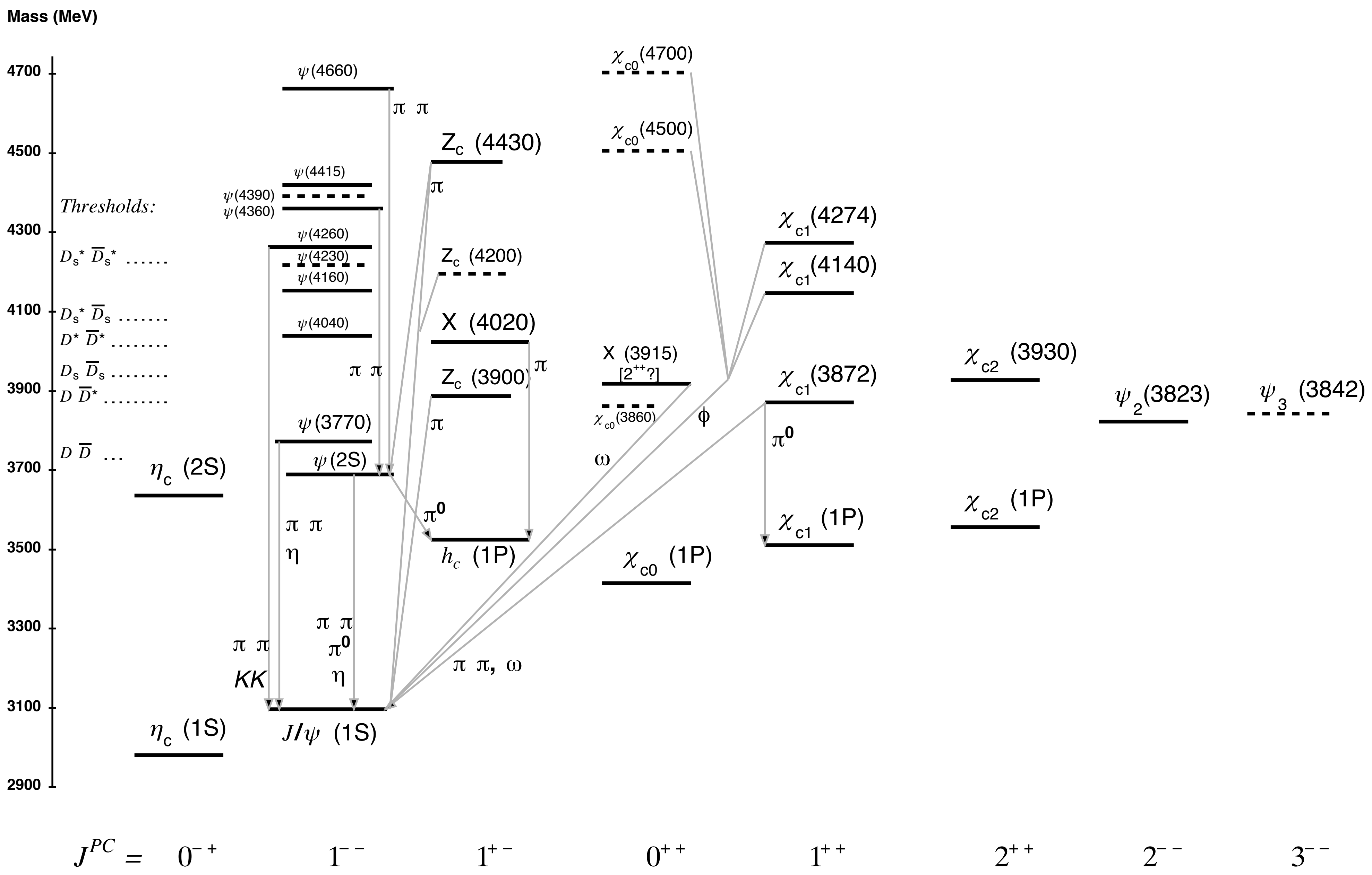
- nPDF, CGC, coherent energy loss (initial/final)
- co-mover, nuclear absorption, …





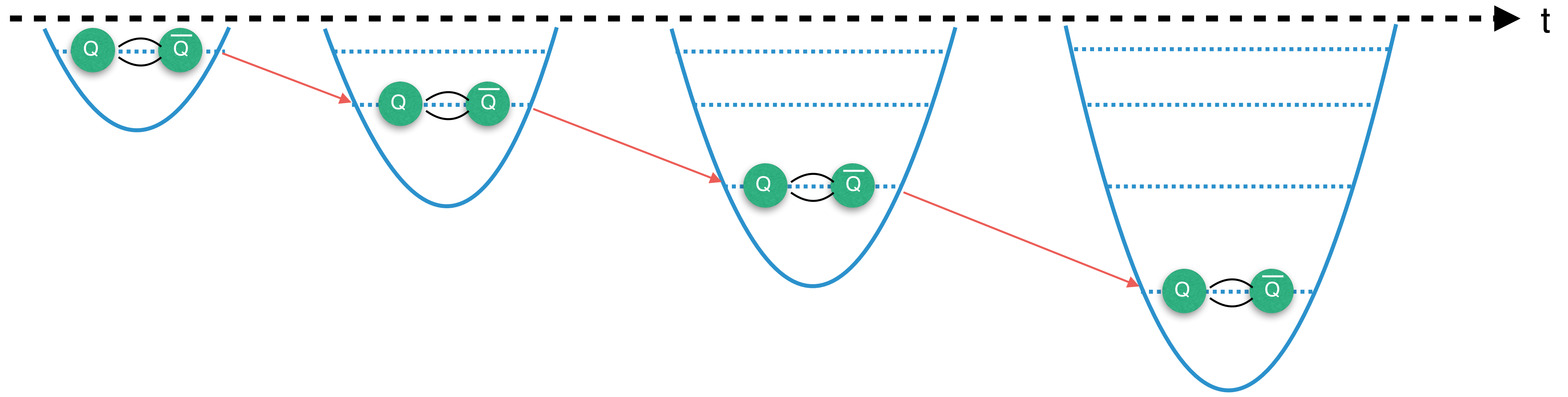
Feed-down contributions

- Various contributions from S- and P-wave states
- Strongly depends on p_T and changes versus centrality in heavy ion collisions

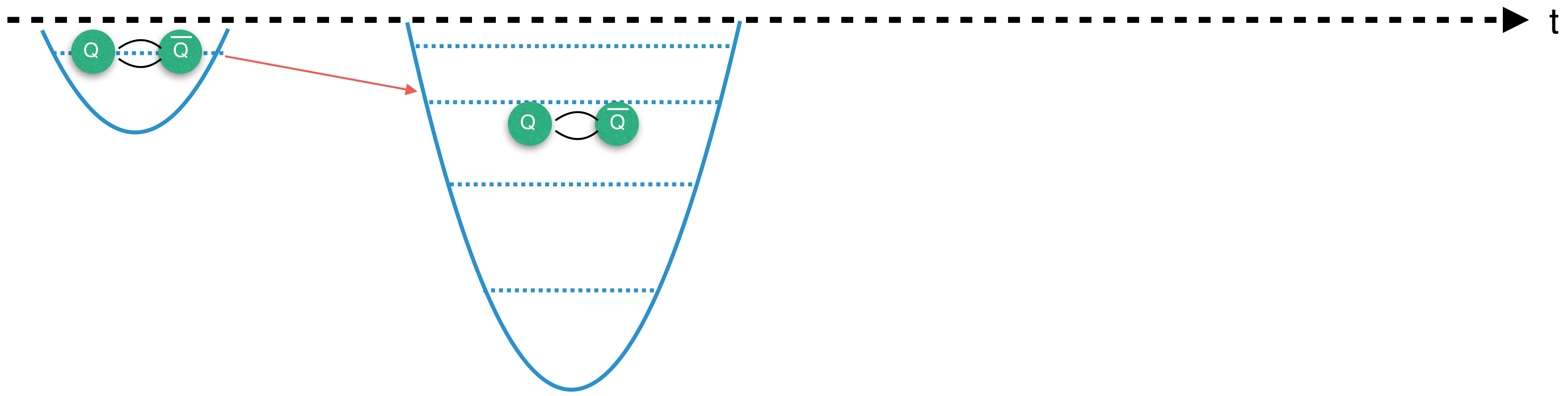


Motivation : Quarkonia in HIC

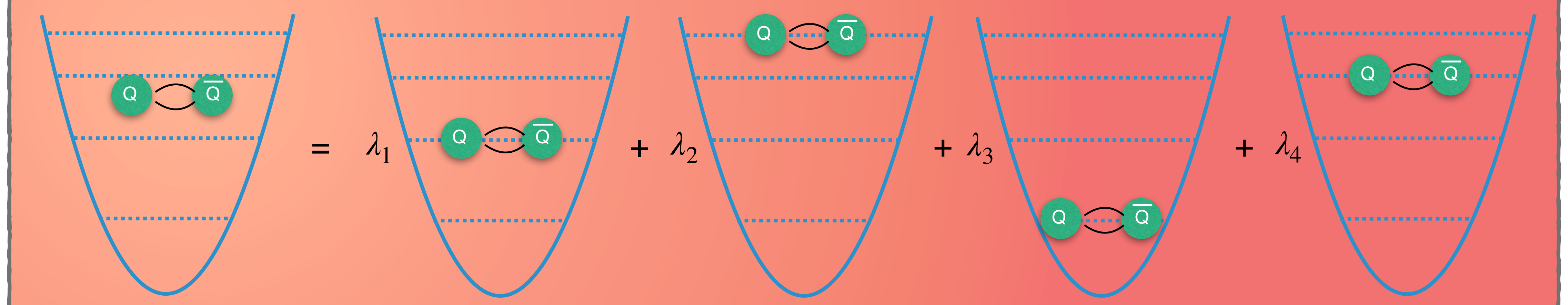
If the medium evolves slowly : state remains in a given eigenstate



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



Q-Qbar state = projection on various eigenstates

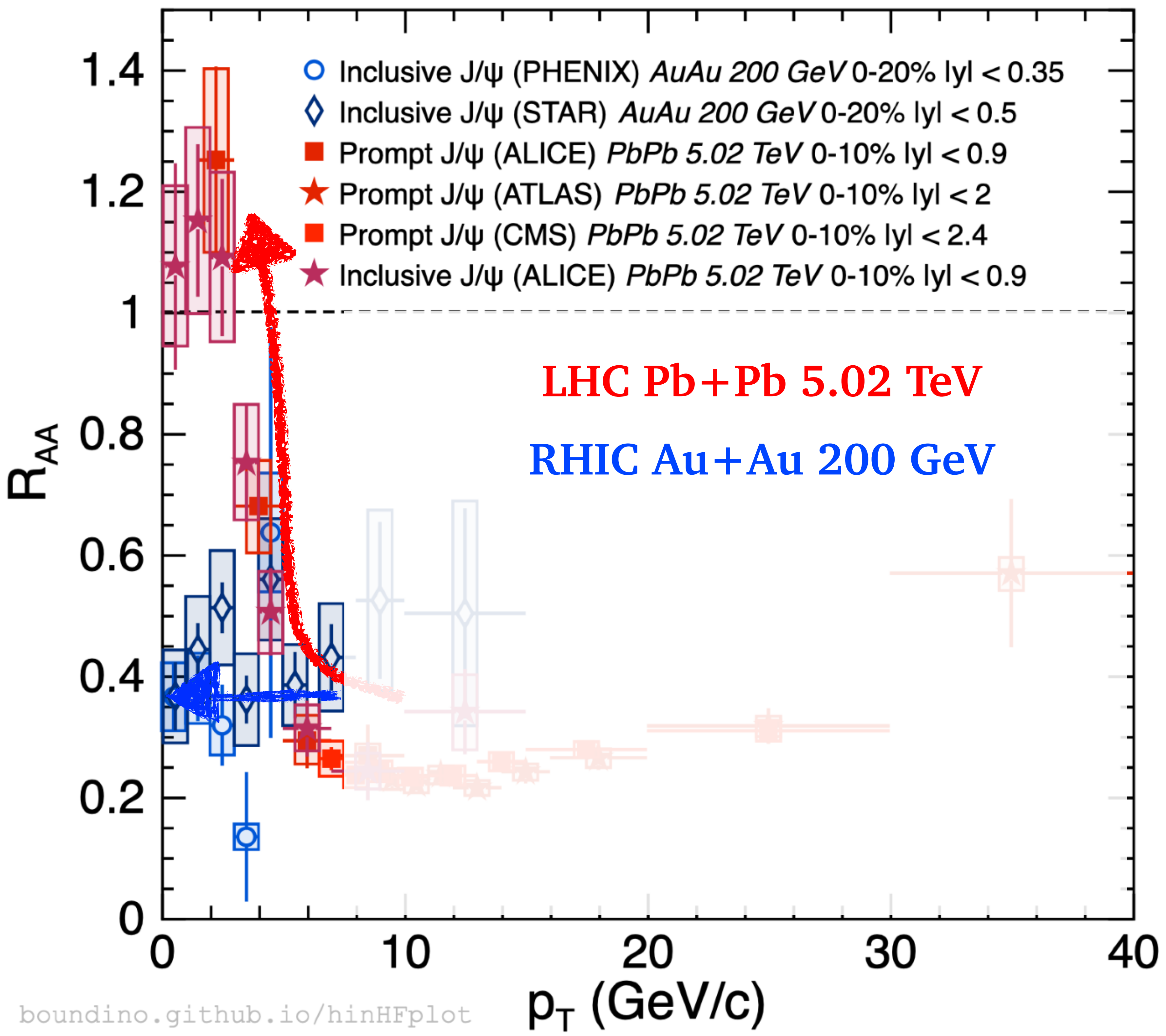


- Rapid expansion…
- Corona region..
- Formation time…
- …

Quarkonia in heavy ion : not a simple picture…

Overview of J/ψ in AA

→ PRL 98 (2007) 232301 → PLB 797 (2019) 134917
→ ALICE Preliminary → EPJC 78 (2018) 762
→ EPJC 78 (2018) 509 → arXiv:2303.13361



- Clear sign of **regeneration for J/ψ** at **low-p_T** in **LHC** energies (abundant charm cross section)

Overview of J/ψ in AA

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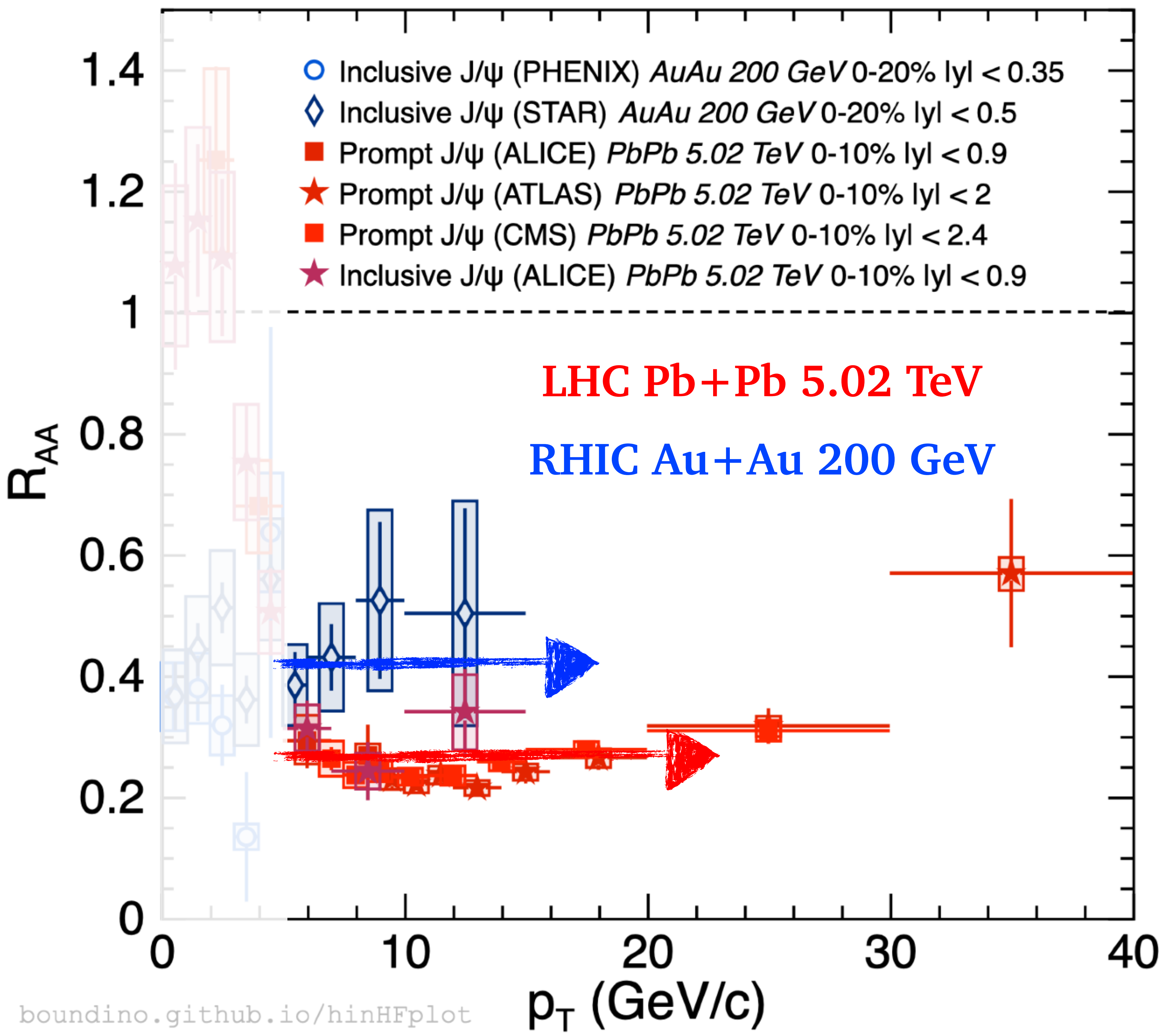

- Clear sign of regeneration for J/ψ at low-p_T in LHC energies (abundant charm cross section)
- Stronger suppression at LHC than RHIC at high-p_T (higher medium energy density)

Overview of J/ψ in AA

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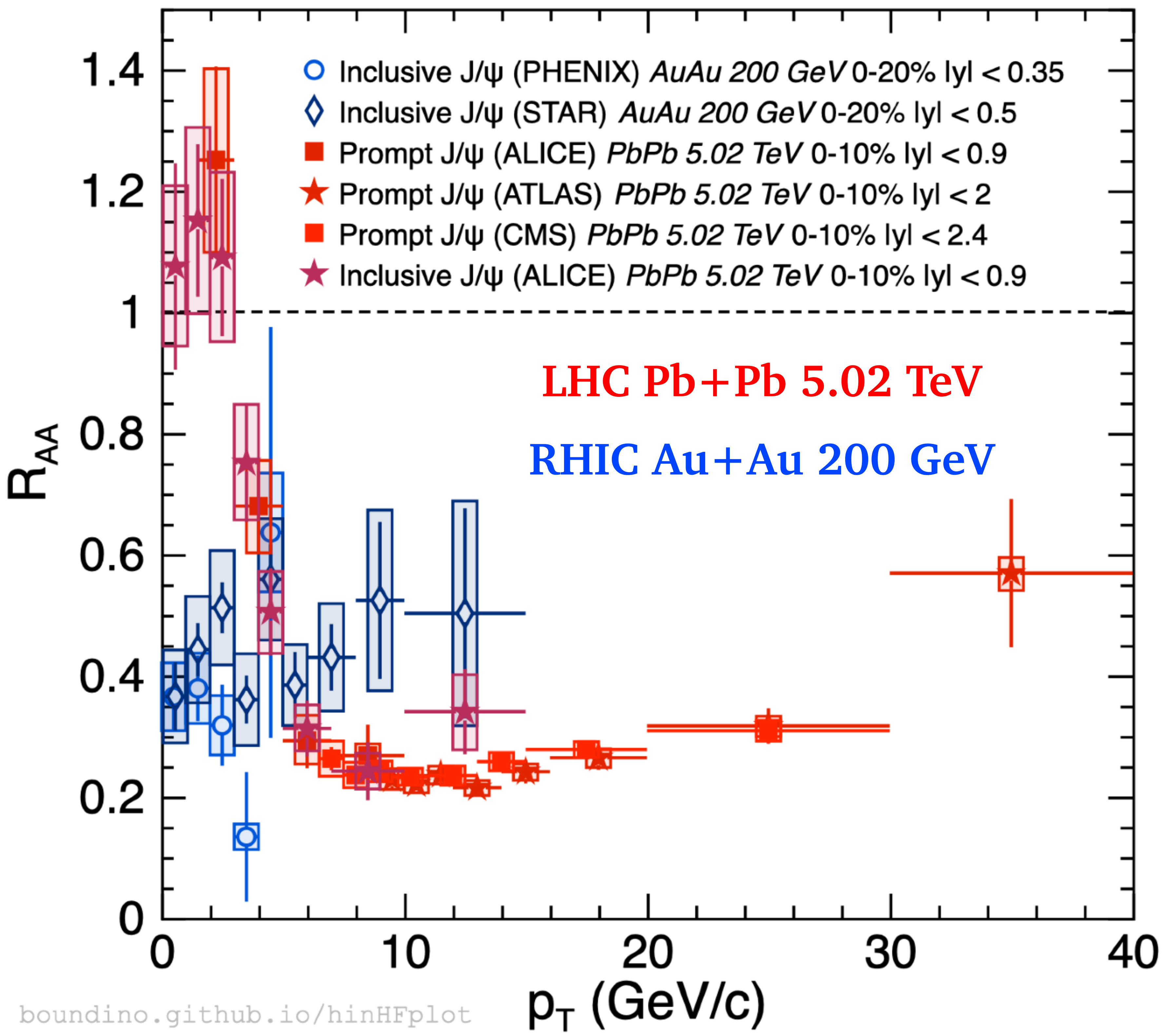
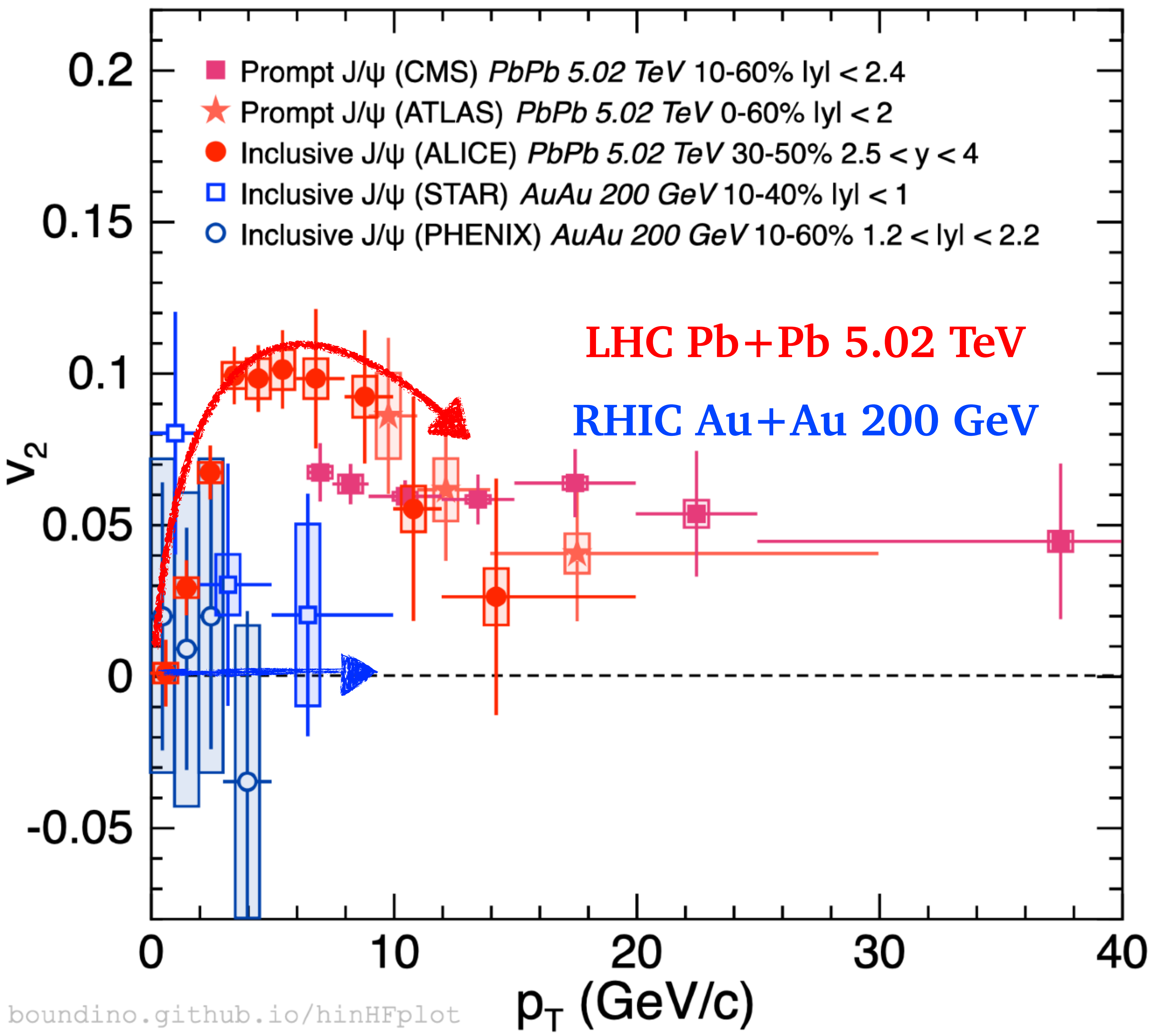
→ EPJC 78 (2018) 784 → CMS-PAS-HIN-21-008
→ PHENIX Preliminary → PRL 111 (2013) 052301
→ JHEP 10 (2020) 141

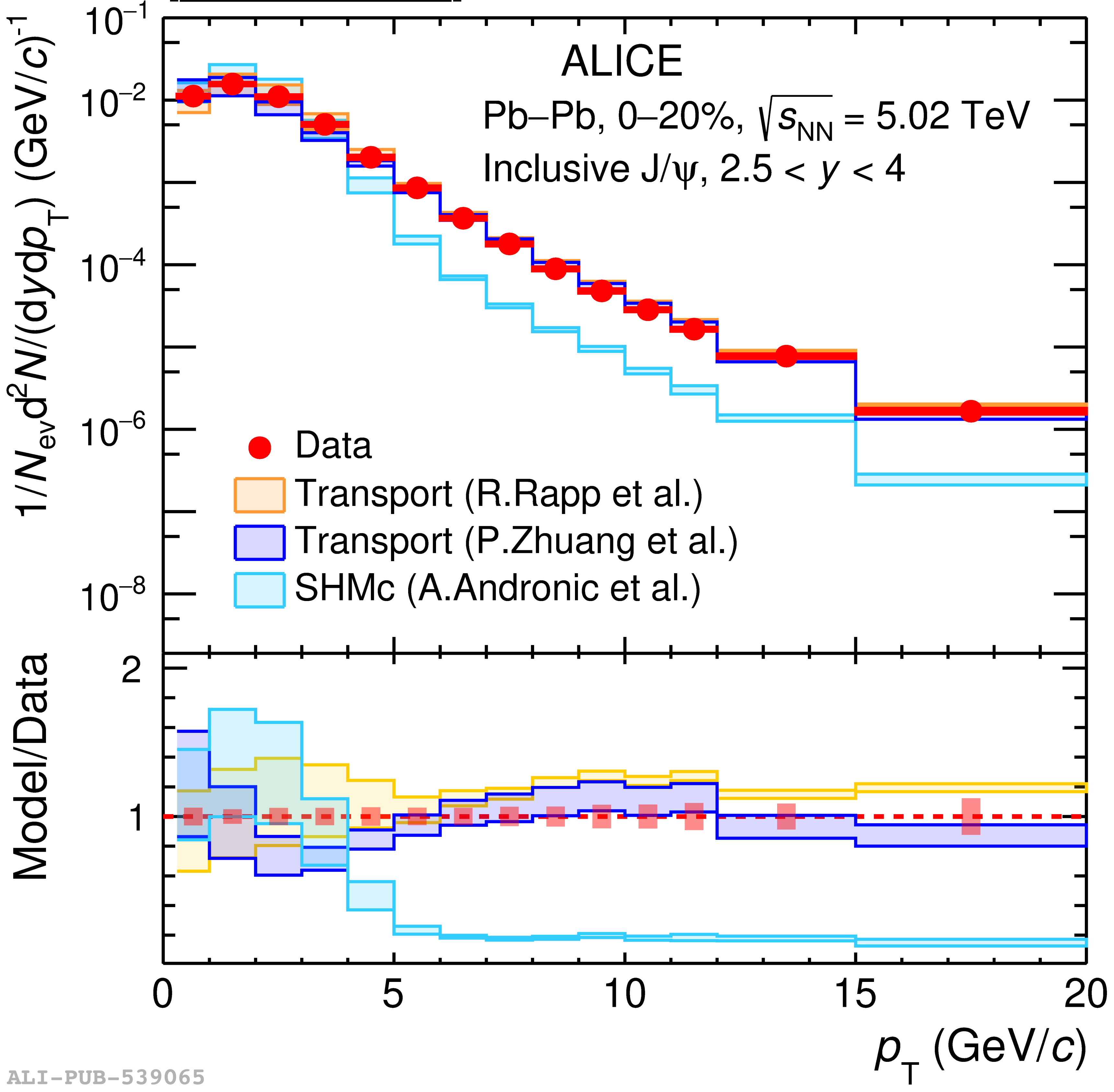




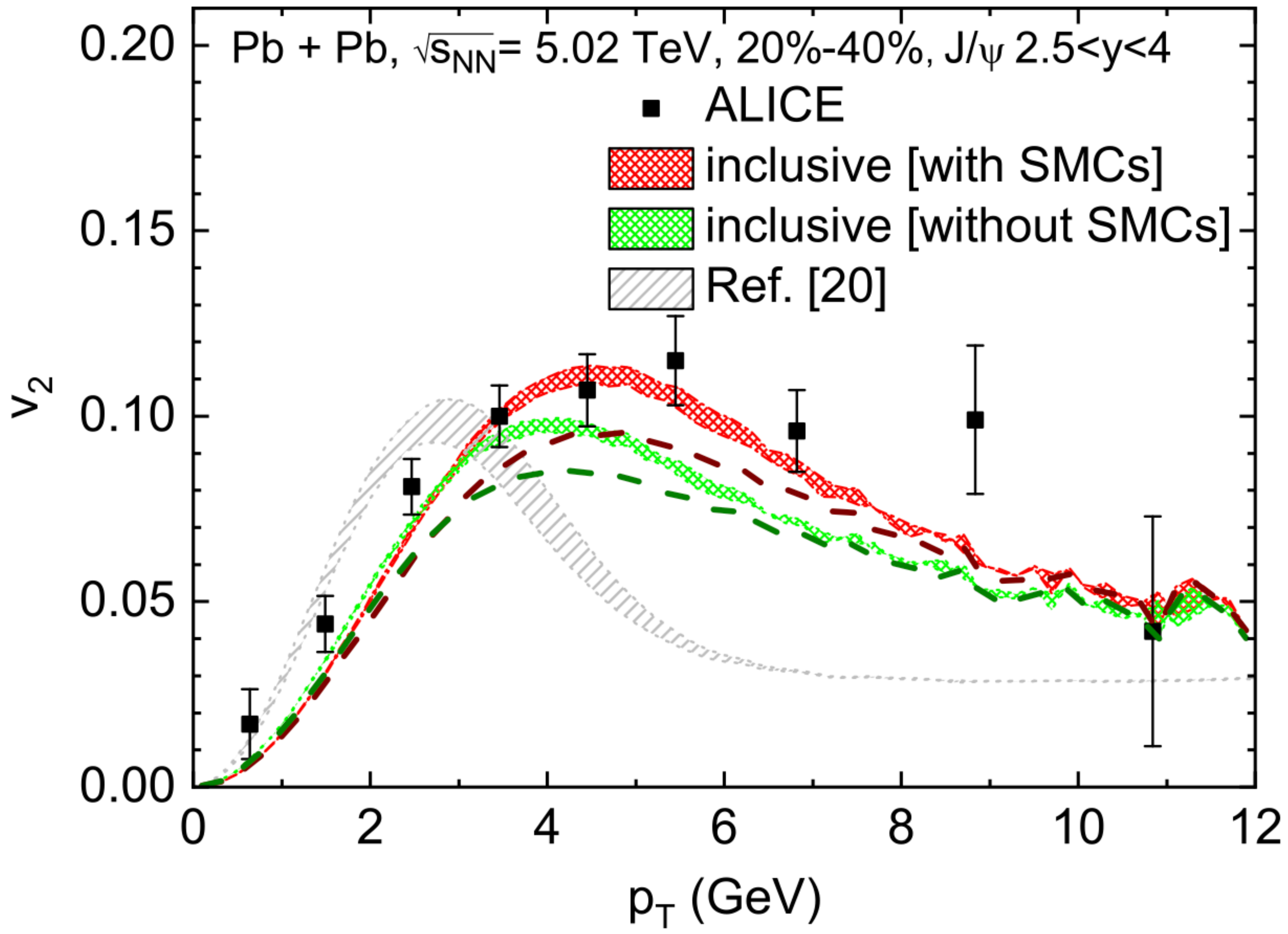
- Clear sign of regeneration for J/ψ at low-p_T in LHC energies (abundant charm cross section)
- Stronger suppression at LHC than RHIC at high-p_T (higher medium energy density)
- $v_2(J/\psi)$ LHC ≥ $v_2(J/\psi)$ RHIC at low-p_T : To be confirmed with more precision measurements

Overview of J/ψ in AA

[arXiv:2303.13361]



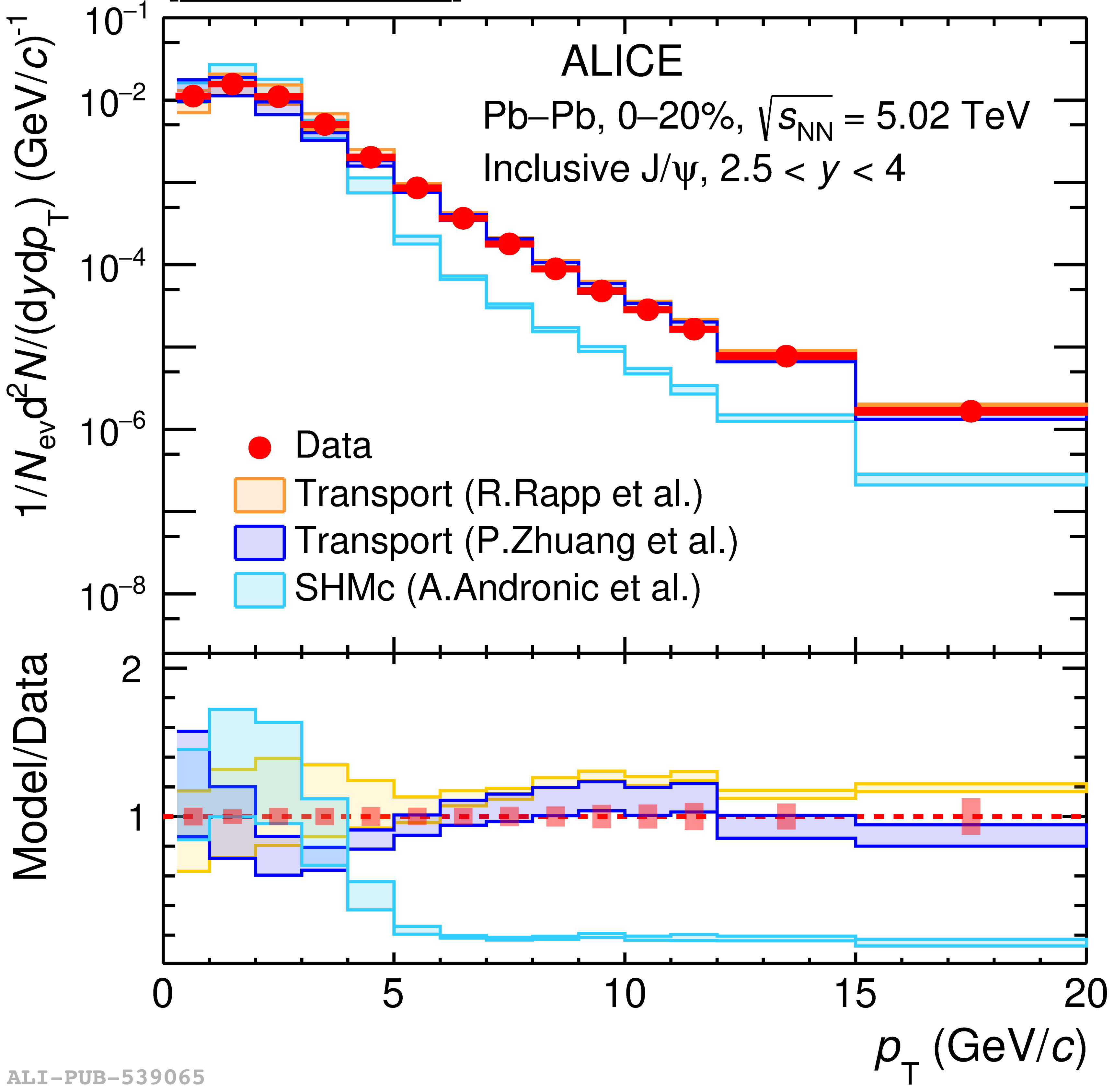
[PRL 128 (2022) 162301]



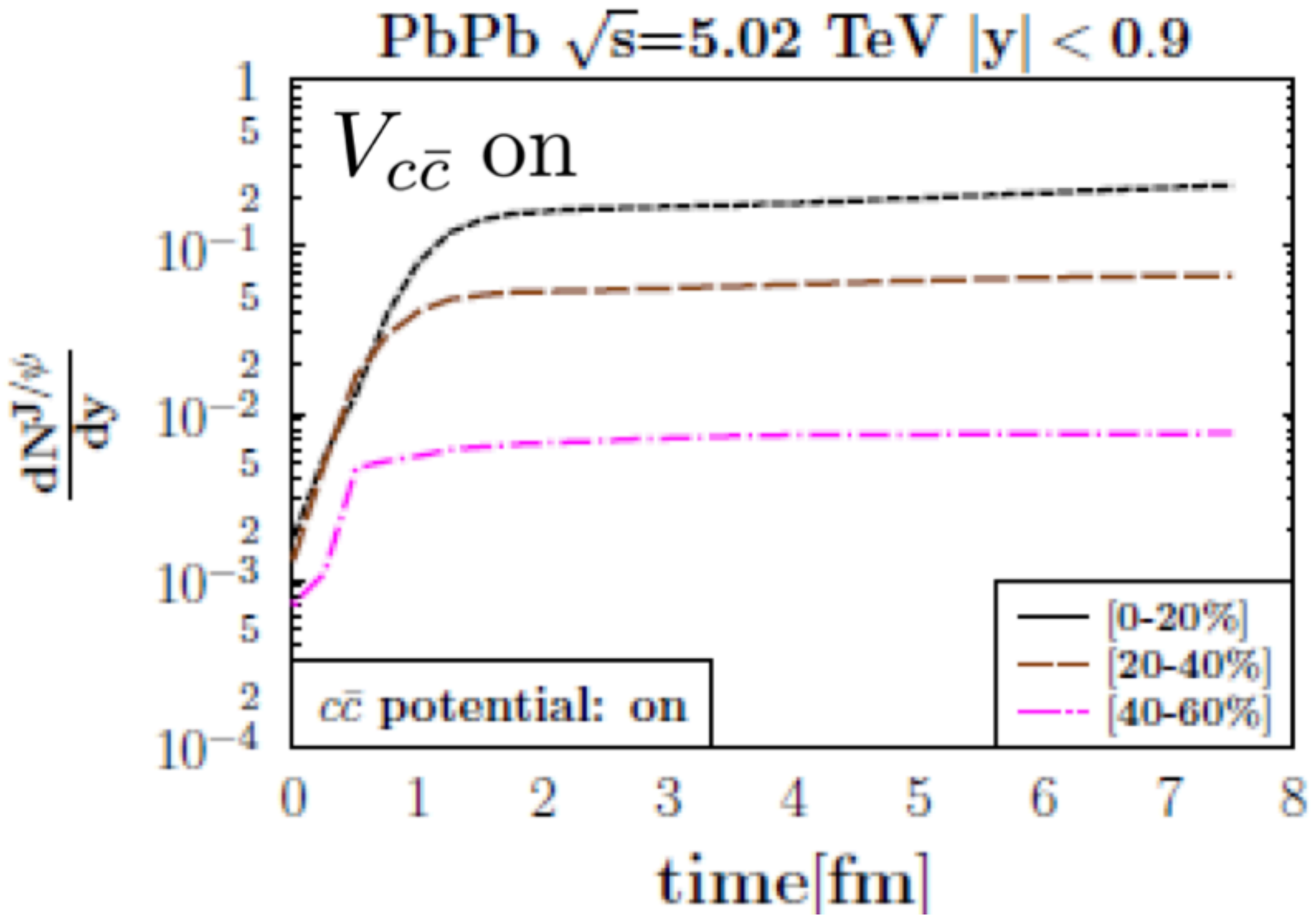
- Theoretical calculations doing qualitatively good jobs including recombination processes

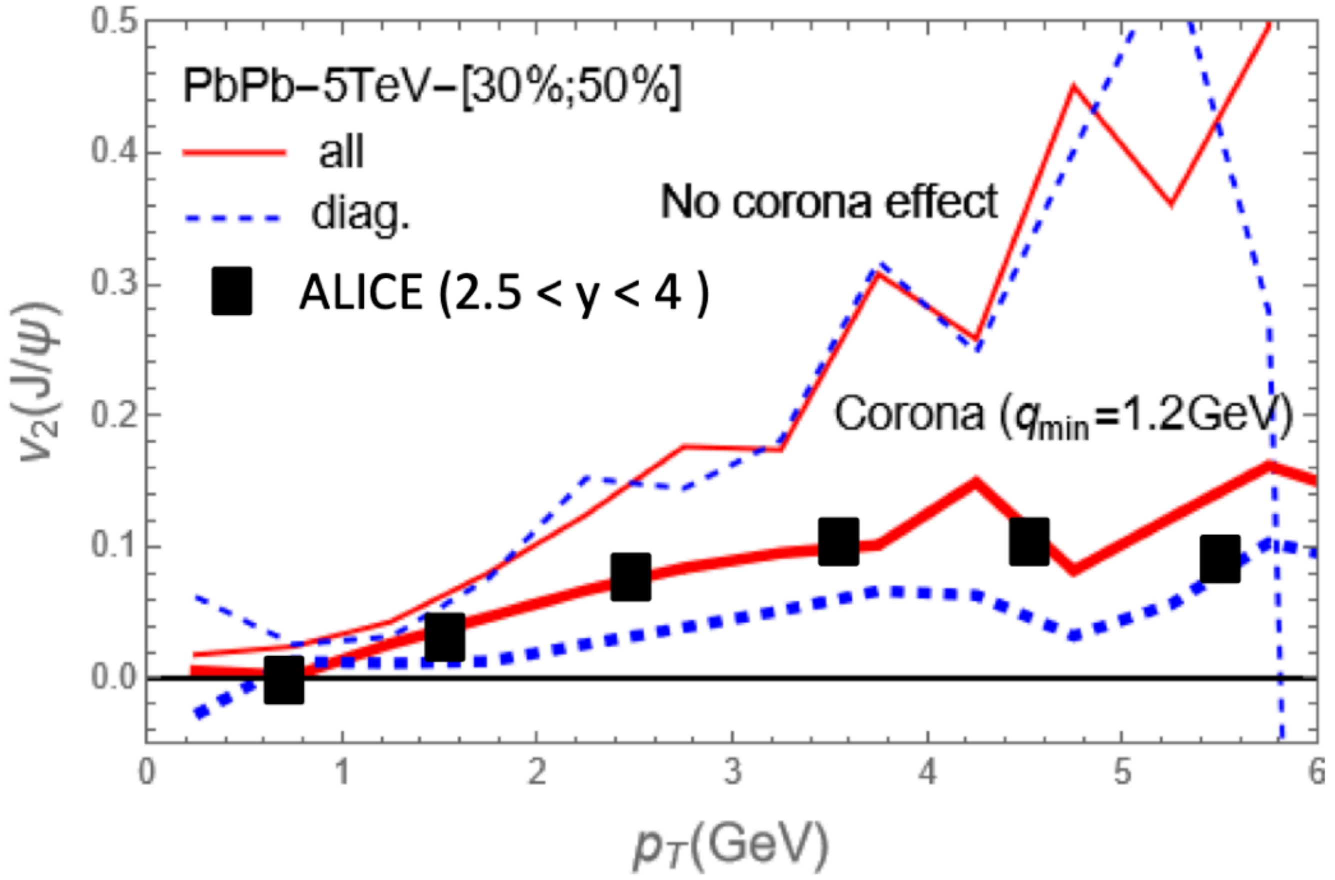
Overview of J/ψ in AA

[arXiv:2303.13361]



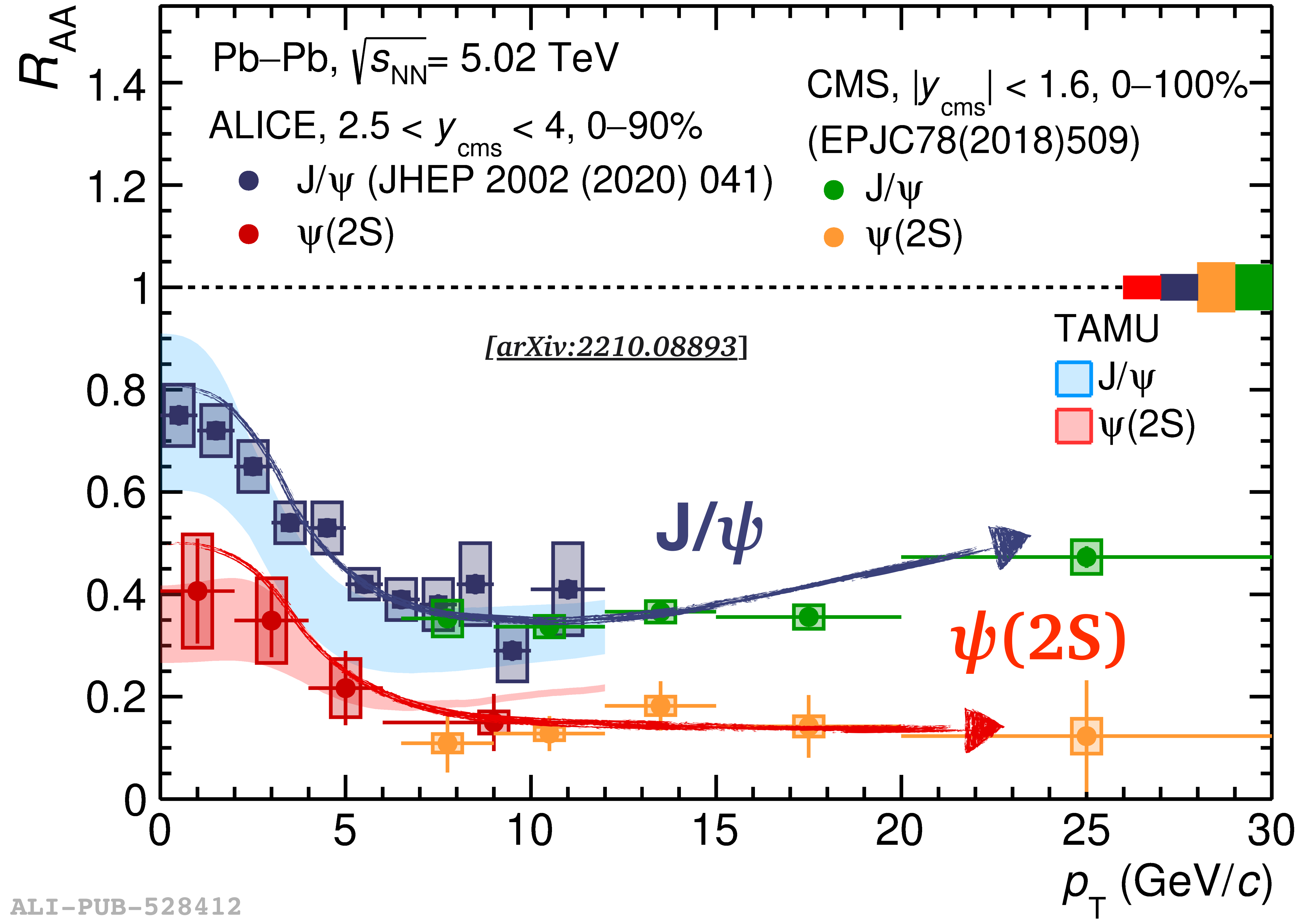
[HP23 P.B Gossiaux]

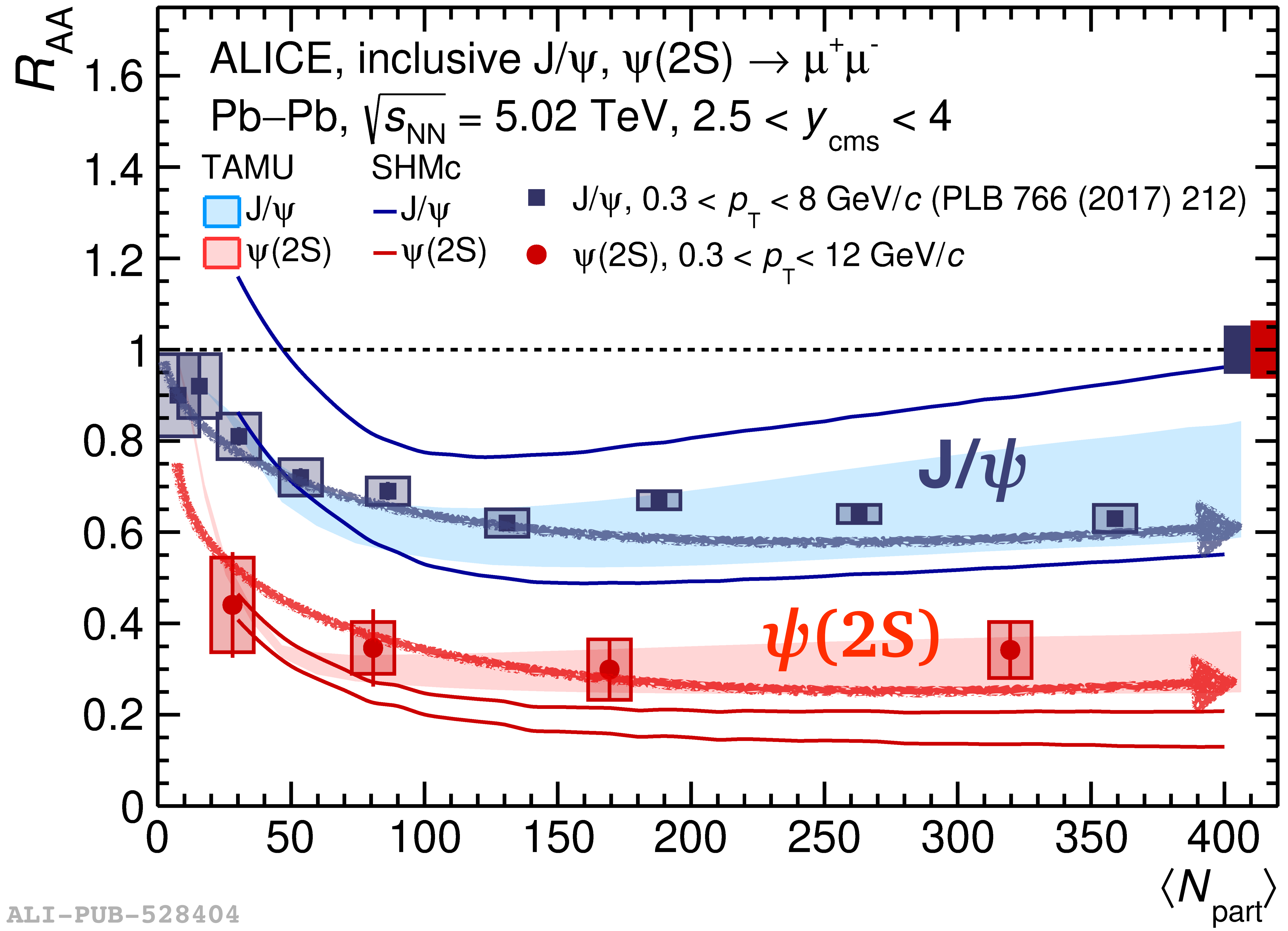




- Theoretical calculations doing qualitatively good jobs including recombination processes
- OQS inspired microscopic approaches suggesting dynamical recombination rather than instantaneous formation at the phase boundary

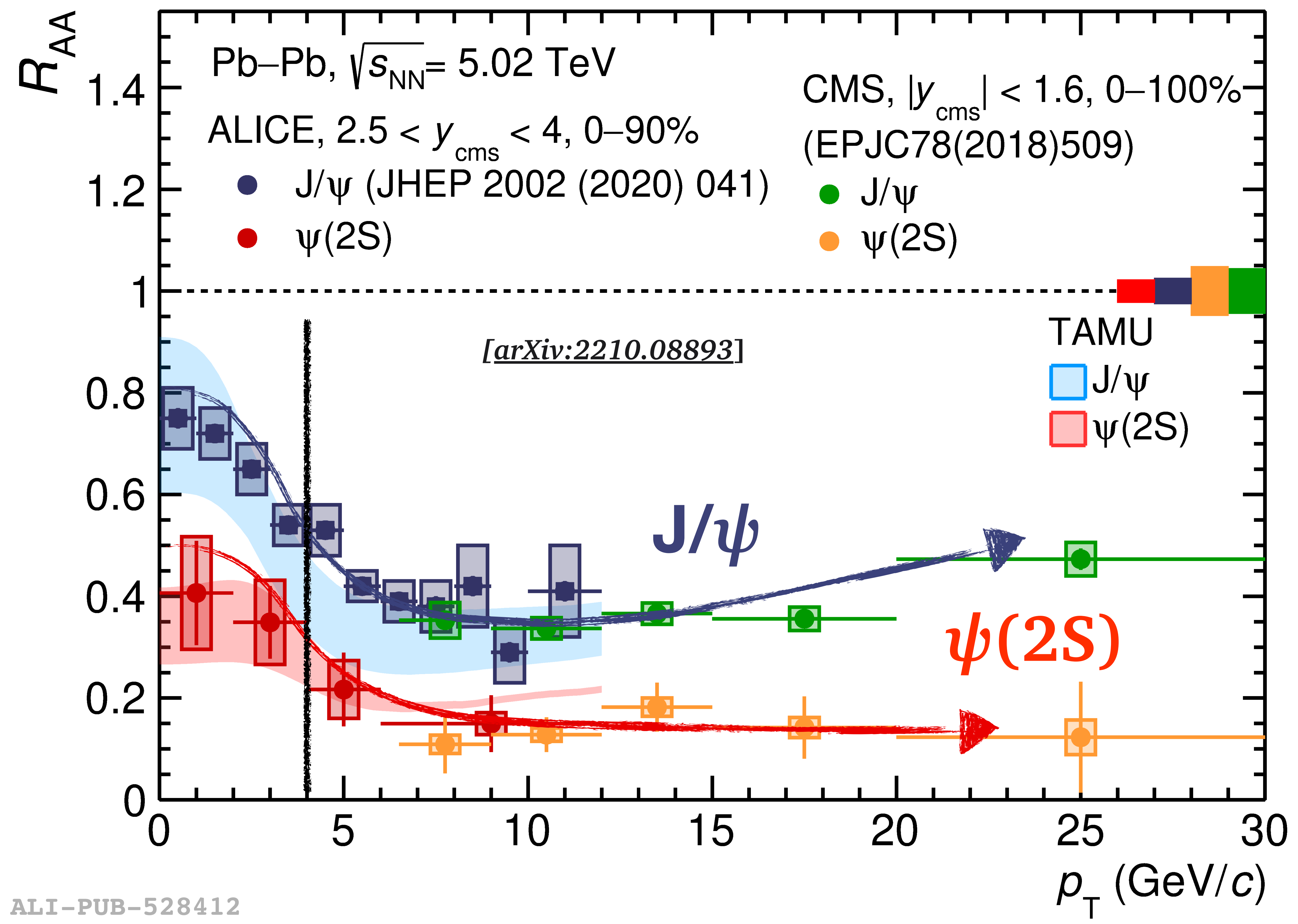
J/ψ & ψ(2S) in AA

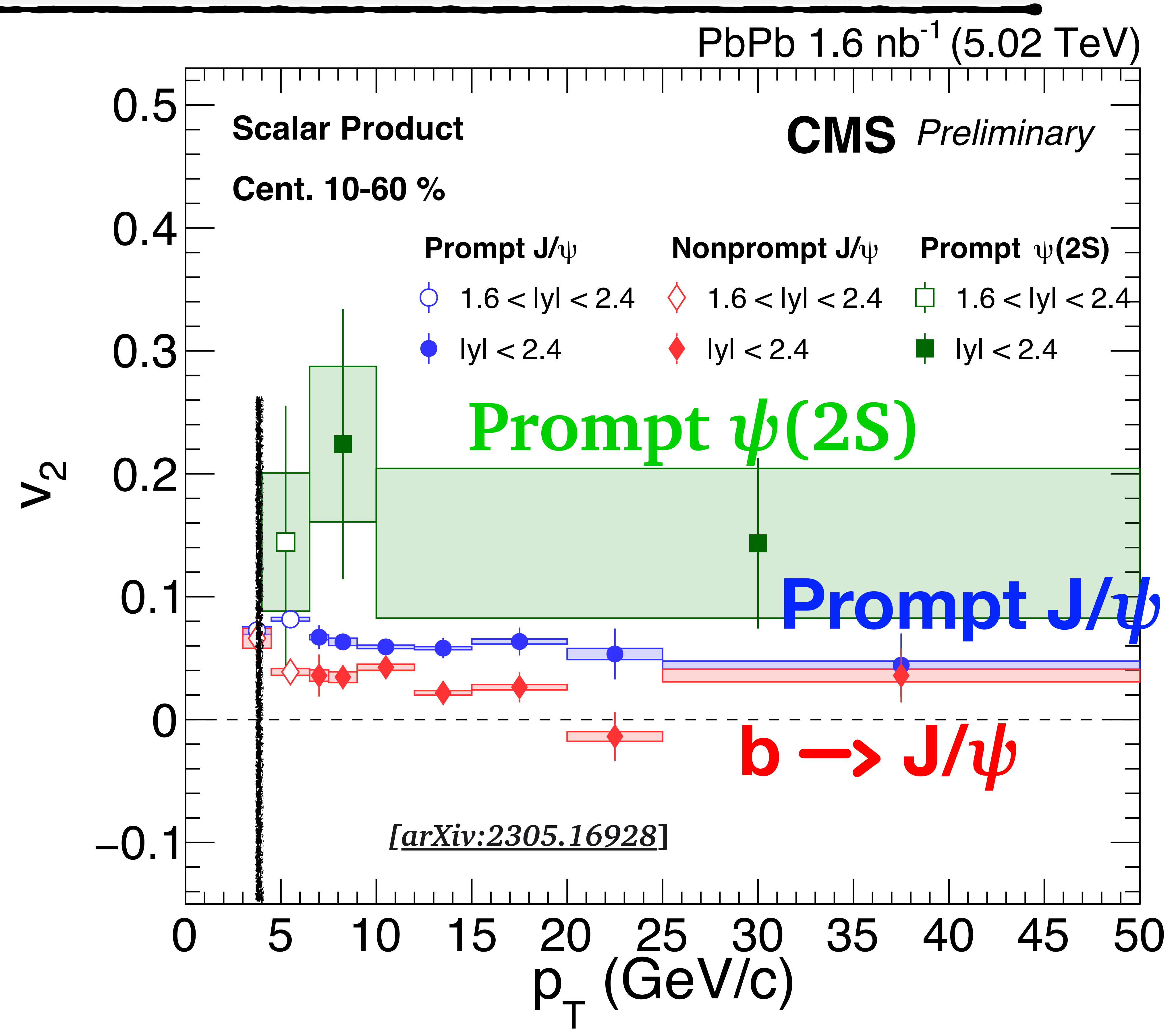




- Stronger suppression for ψ(2S) than J/ψ in all p_T & centrality region
- Similar trend of enhancement at low-p_T : qualitatively described by recombination effects

J/ψ & ψ(2S) in AA

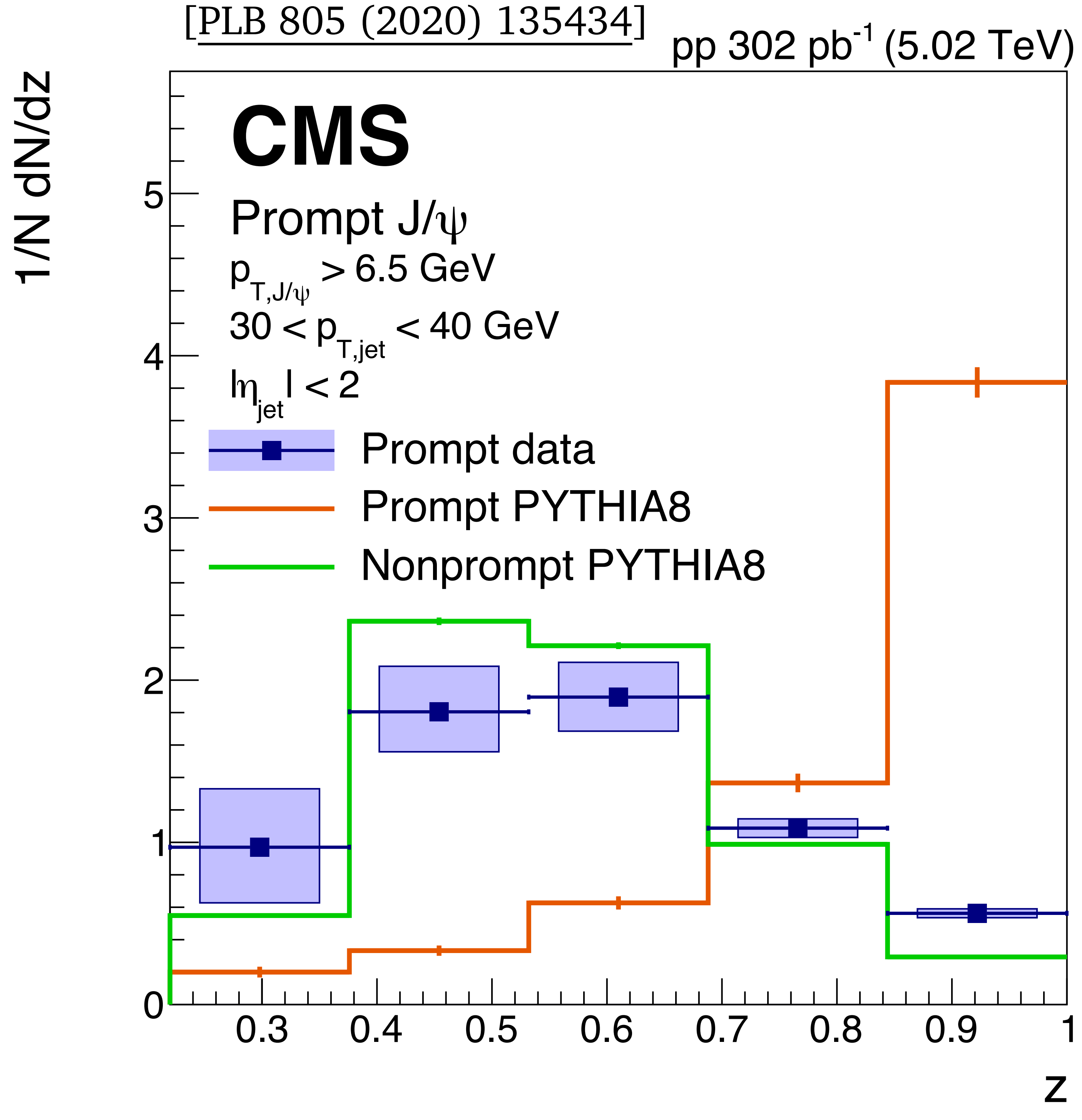




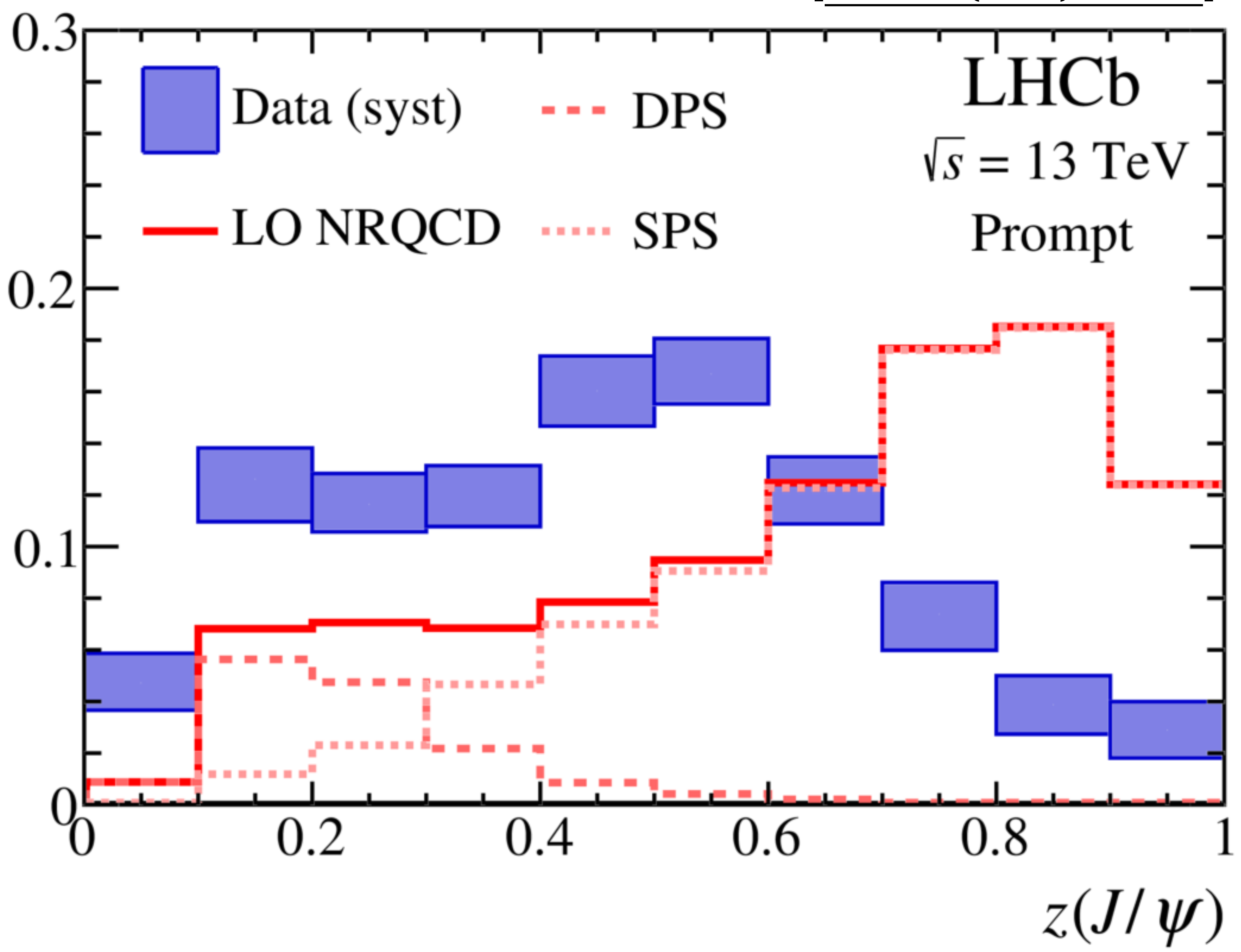
- Stronger suppression for ψ(2S) than J/ψ in all p_T & centrality region
- Similar trend of enhancement at low-p_T : qualitatively described by recombination effects
- prompt ψ(2S) v_2 ≥ prompt J/ψ v_2 : Dissociation propagated to v_2? Still huge unc.

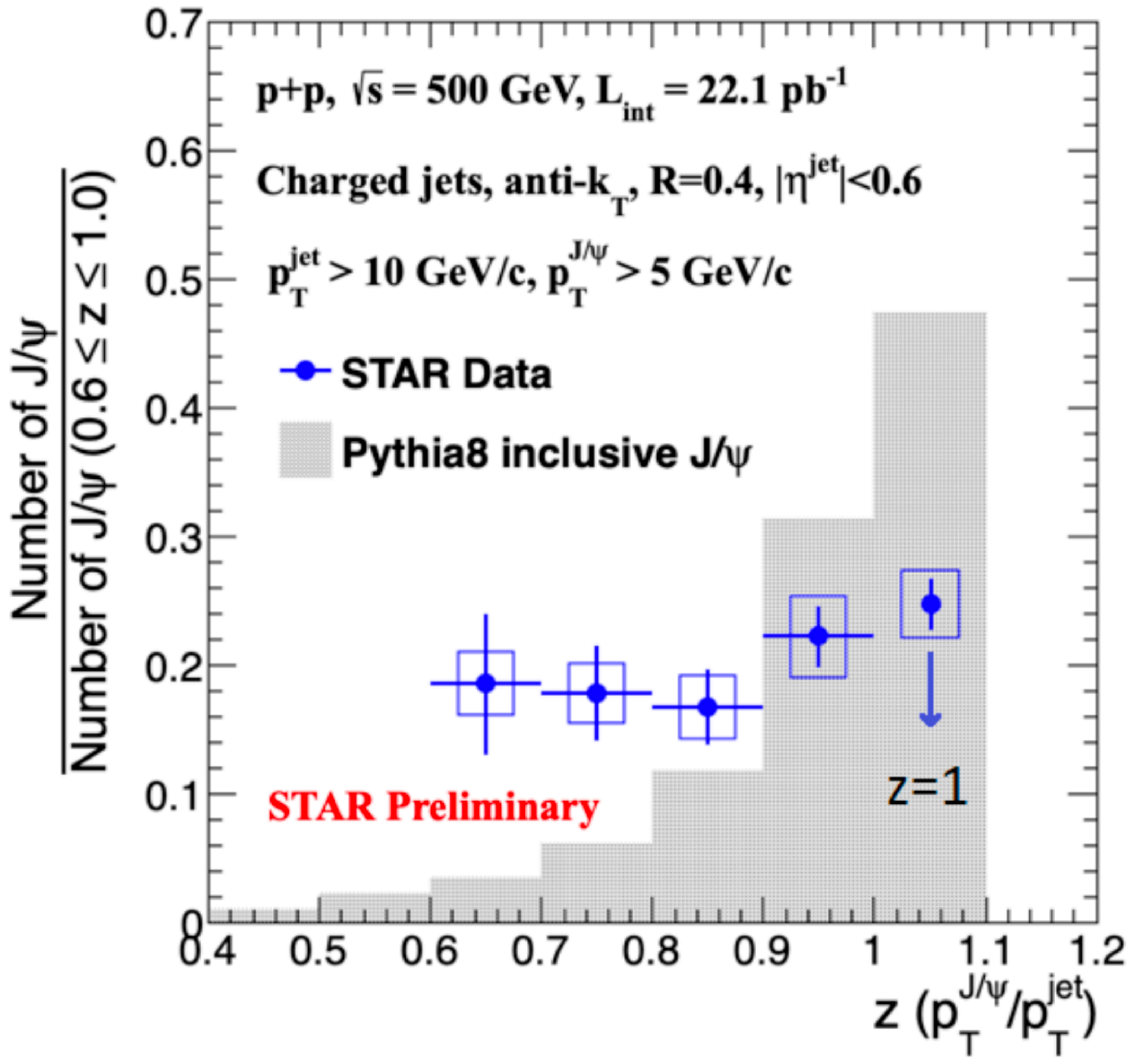
J/ψ in jets

[PLB 805 (2020) 135434]

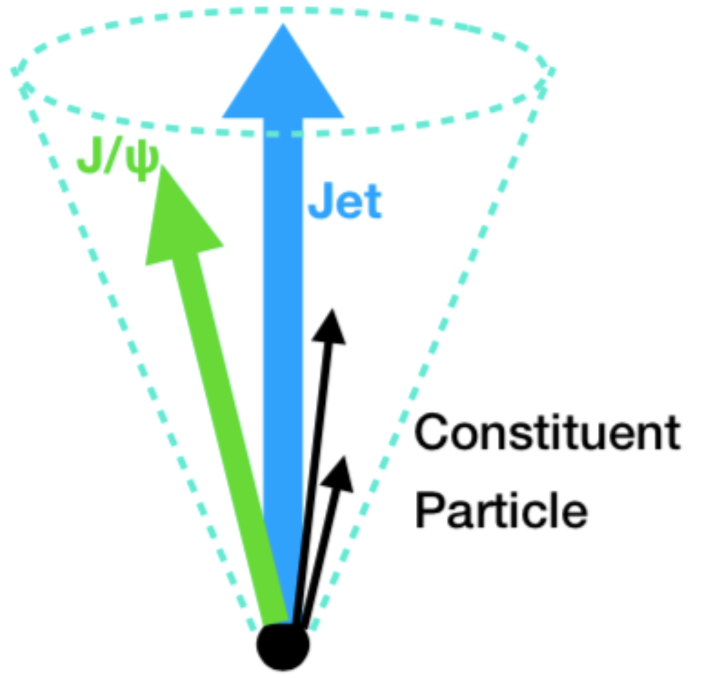


[PRL 118 (2017) 192001]



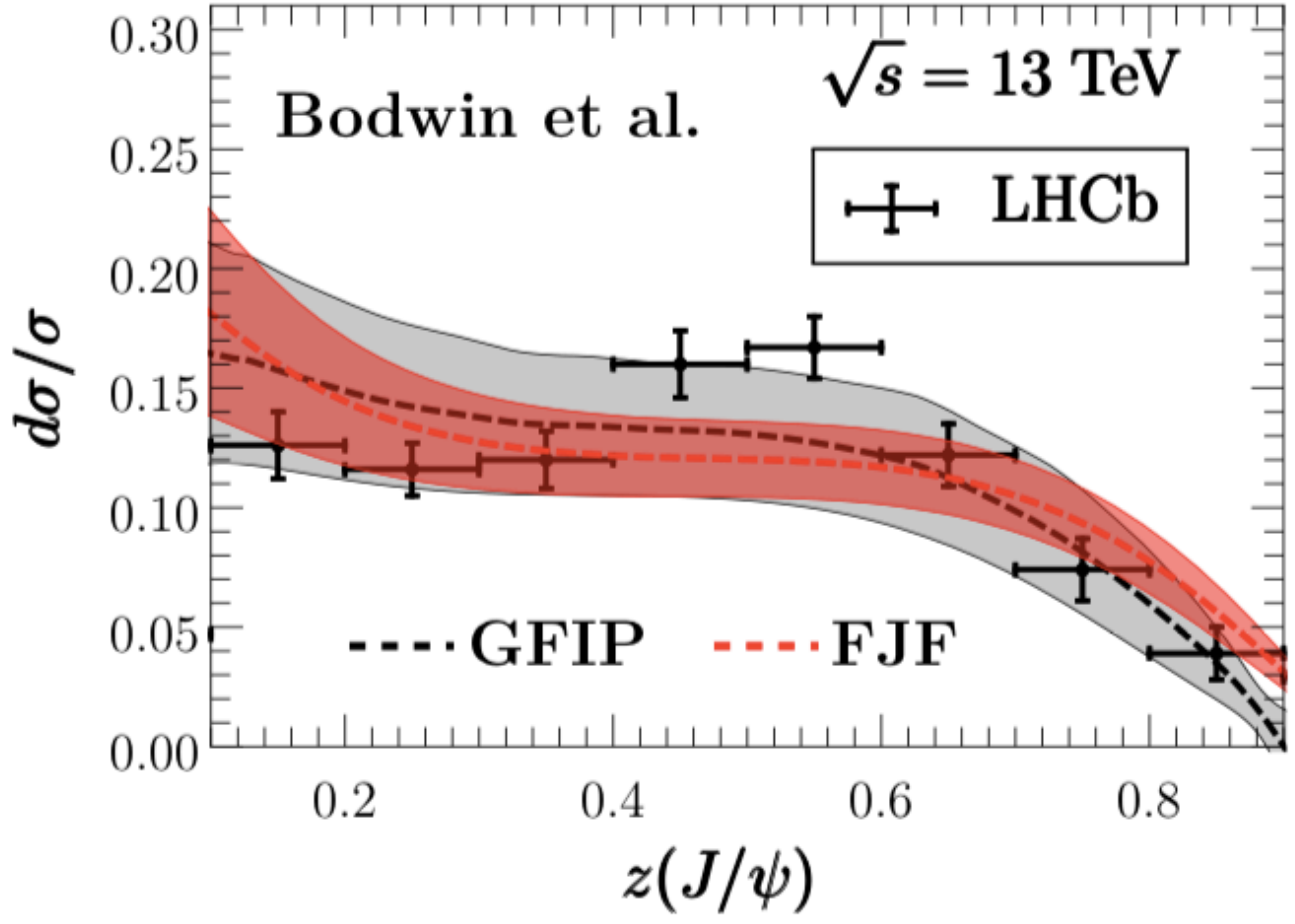


- Significant amount of J/ψ production in jets at high-p_T : Not supported by LO calculations
- Observed both at LHC and RHIC
- pp 8 TeV for $E_{J/\psi} > 15$ GeV : ~85% of J/ψ are produced within a jet [PLB 804 (2020) 135409]

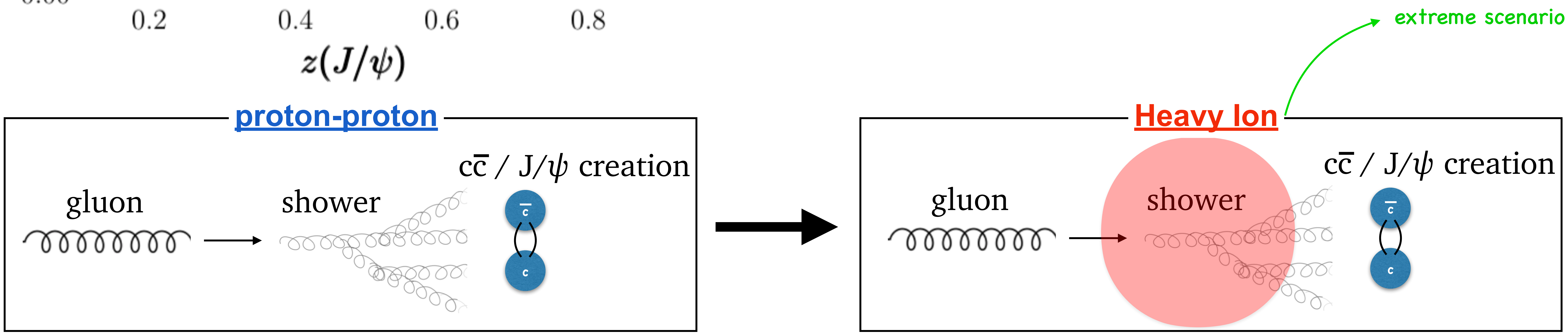


J/ψ in jets

[PRL 119 (2017) 032002]

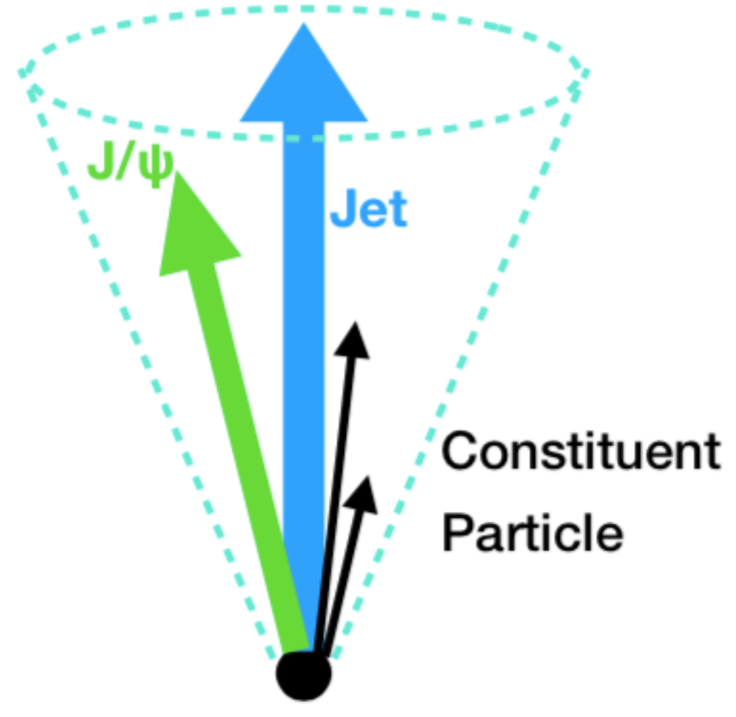


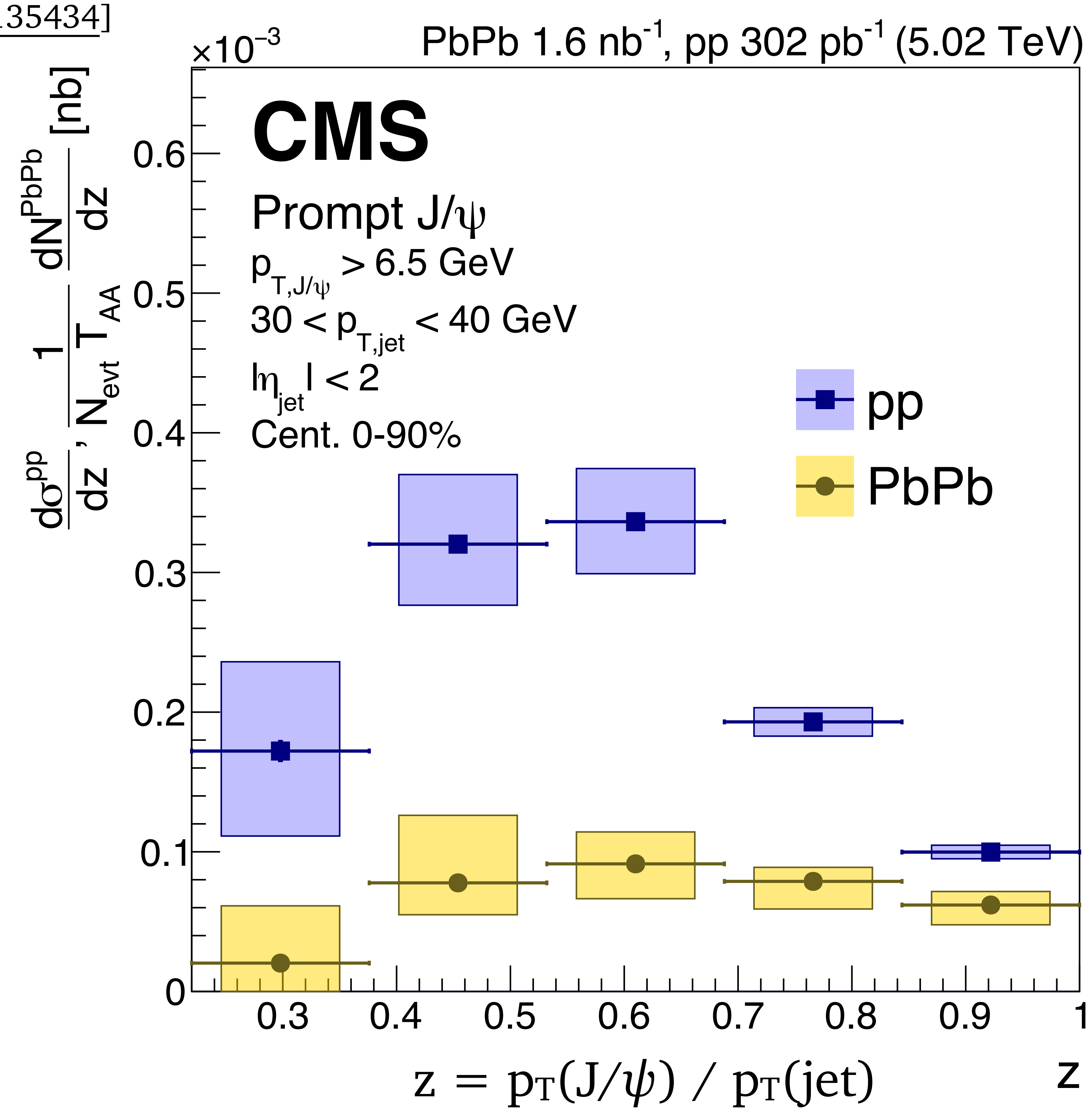
- GFIP and FJF improves describing the data — limitation of LO NRQCD in PYTHIA
- Suggests later J/ψ production from parton shower
- Towards heavy ion collisions : amount of suppression for high-p_T J/ψ lead by jet quenching?

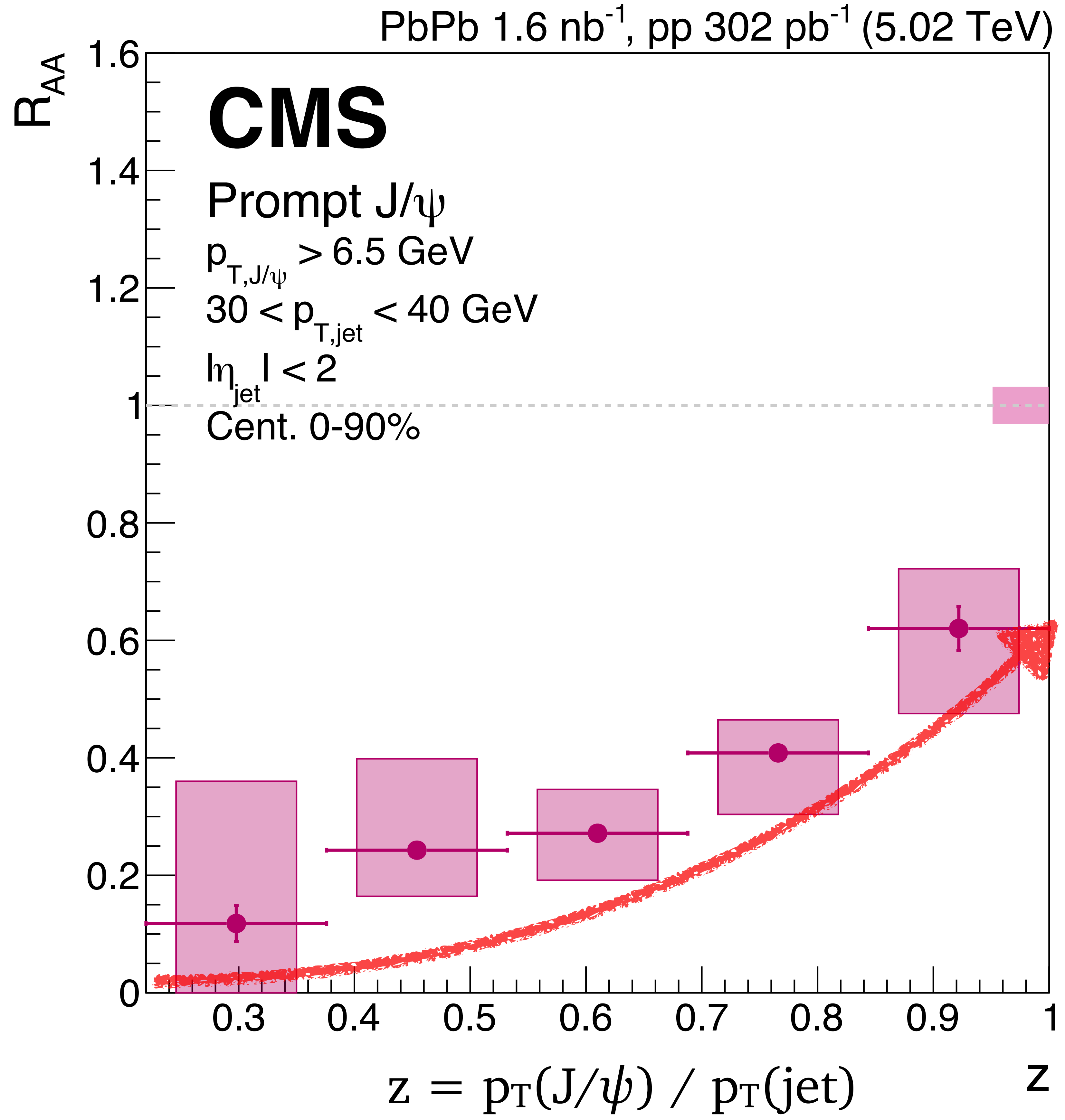


R_{AA} of J/ψ in jets

[PLB 805 (2020) 135434]



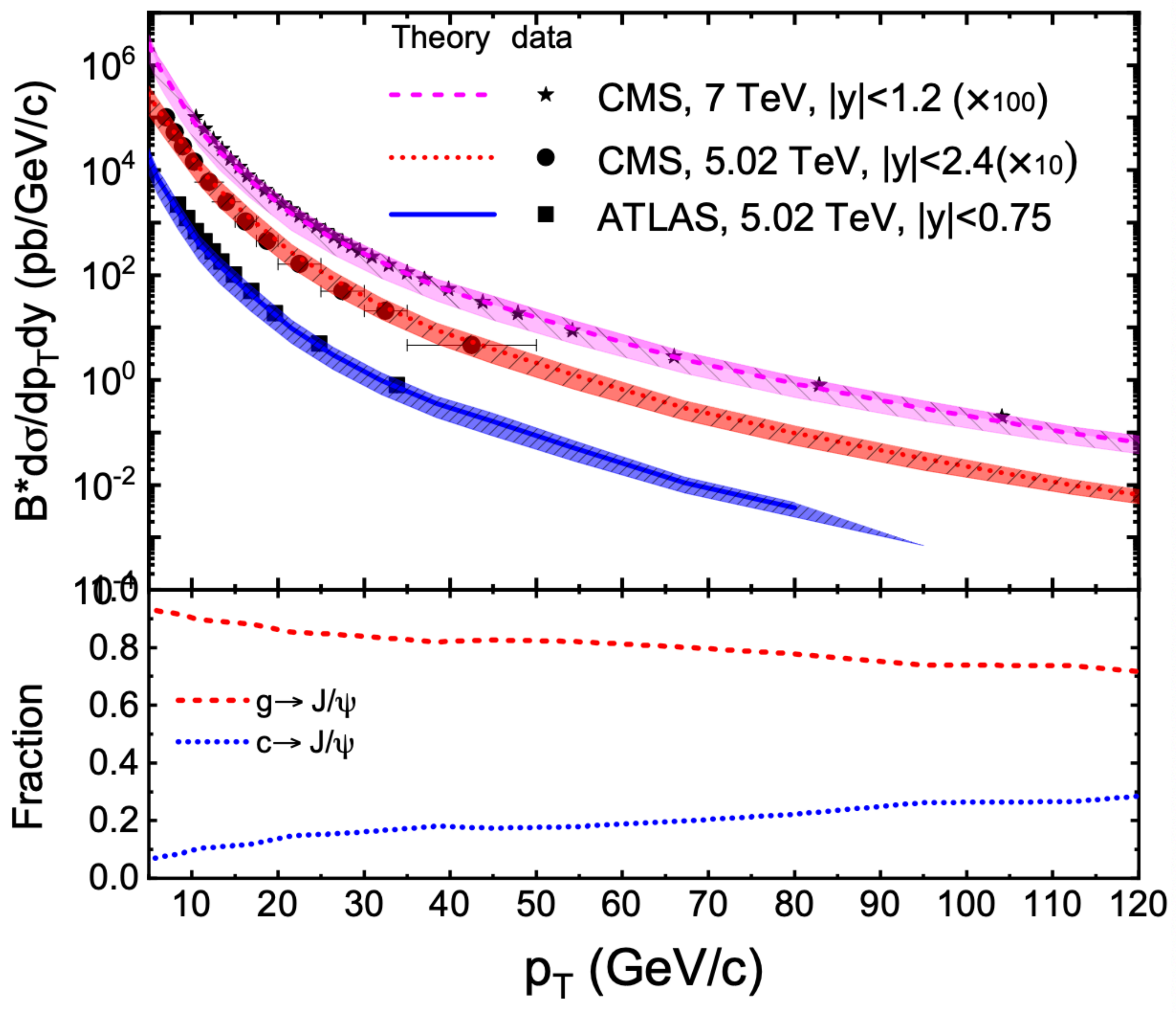


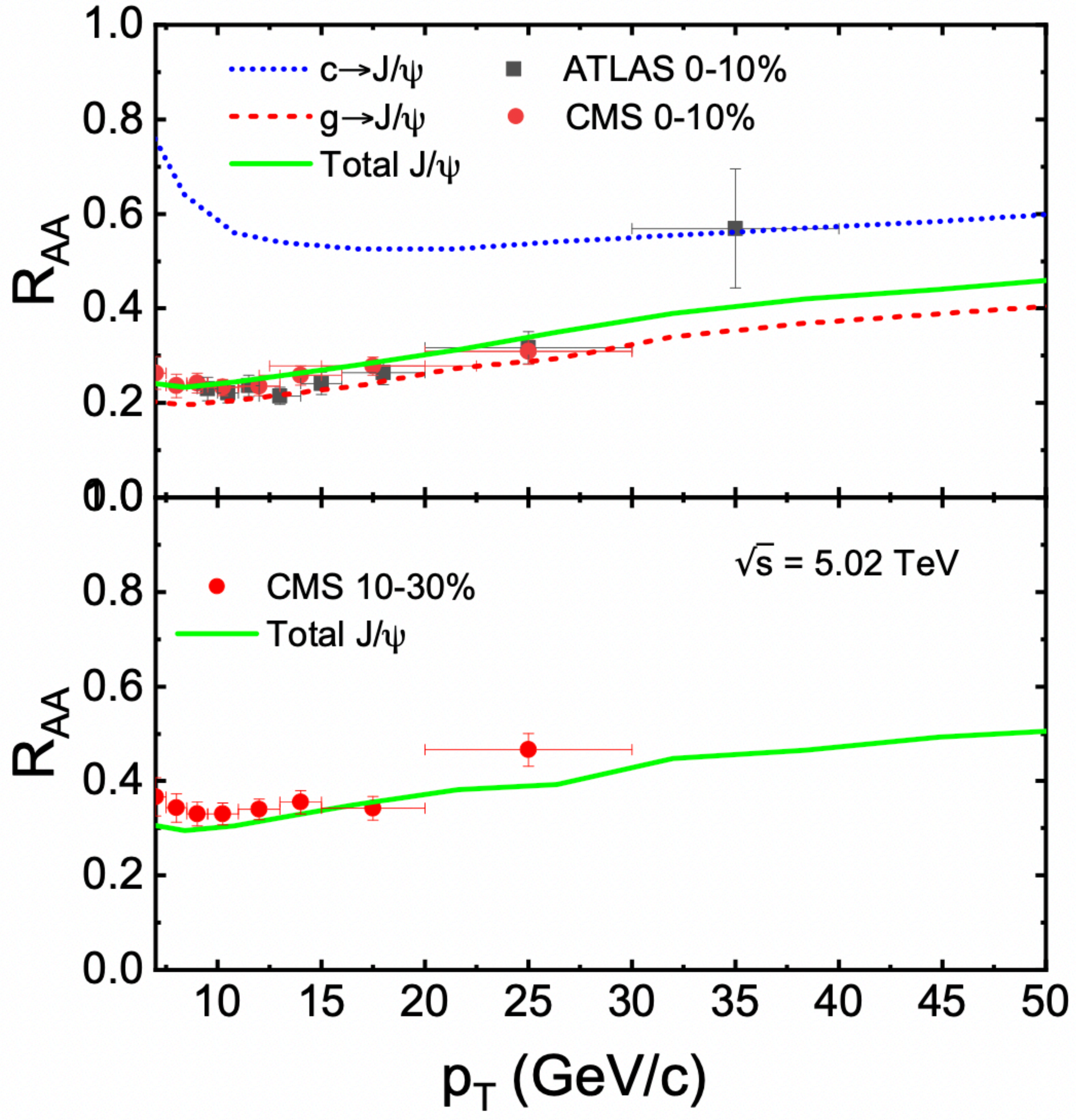


- Less suppression for isolated J/ψ : stronger suppression for more surrounding jet-activity
- Related to results of sizable v_2 at high-p_T? Increasing R_{AA} vs p_T for inclusive prompt J/ψ?

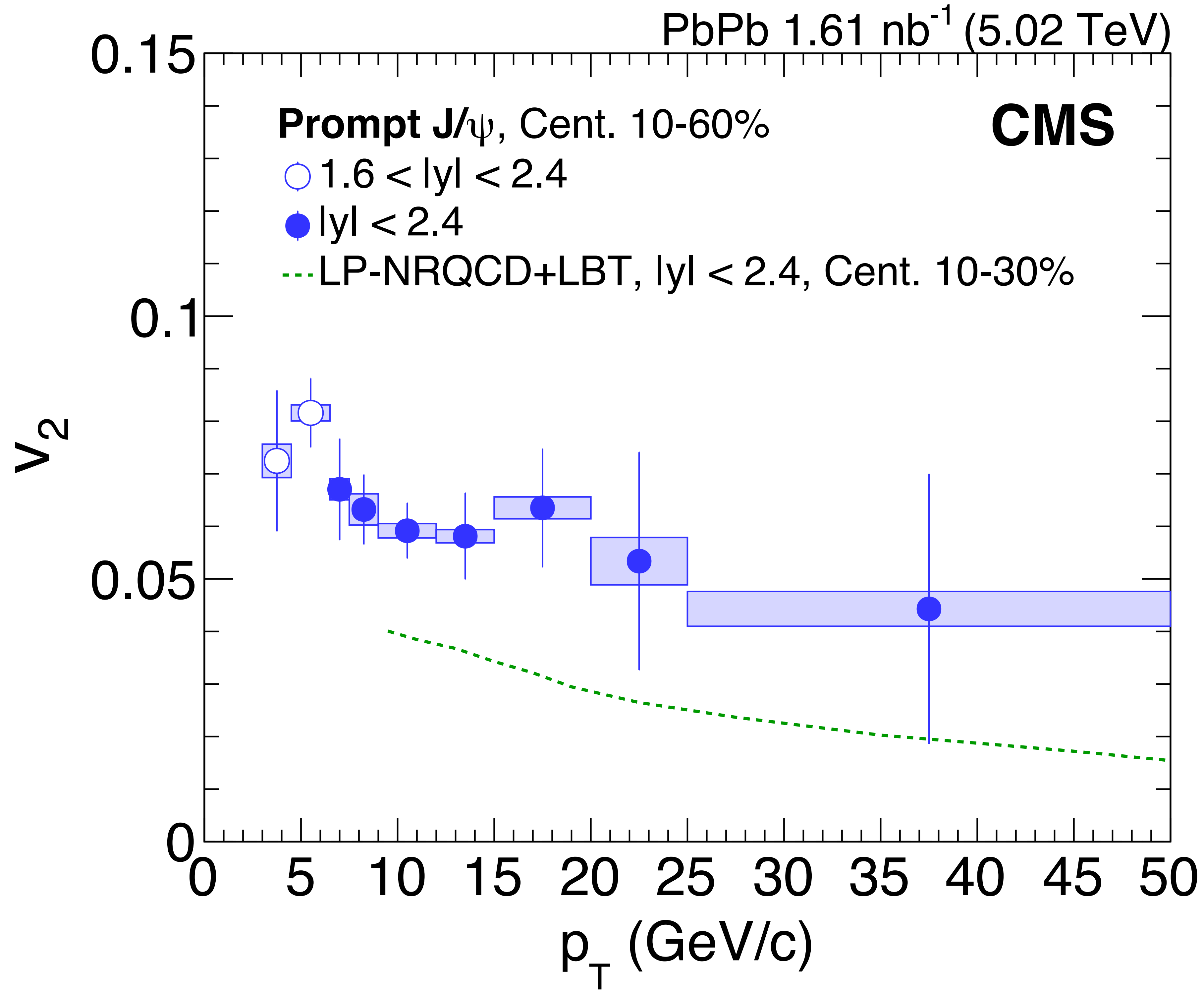
J/ψ in jets : Model comparison

[arXiv:2208.08323]





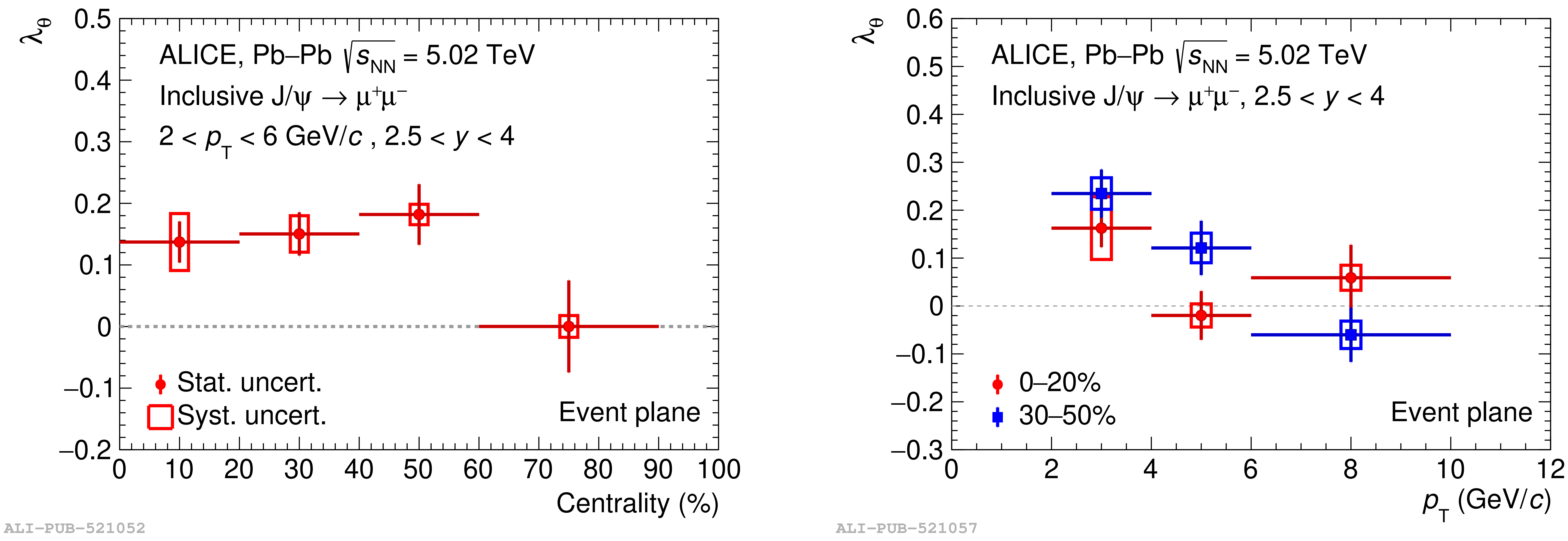
[arXiv:2305.16928]



- NRQCD + LBT based model — assume all high-p_T J/ψ coming from jet-fragmentation
- Good agreement in cross section and R_{AA} above 10 GeV/c
- Disagreement with latest v_2 measurements at high-p_T : still some parts missing…
- Future prospects w/ or w/o jets : γ-tagged D vs Inclusive D vs γ-tagged J/ψ vs Inclusive J/ψ

J/ψ polarization in AA

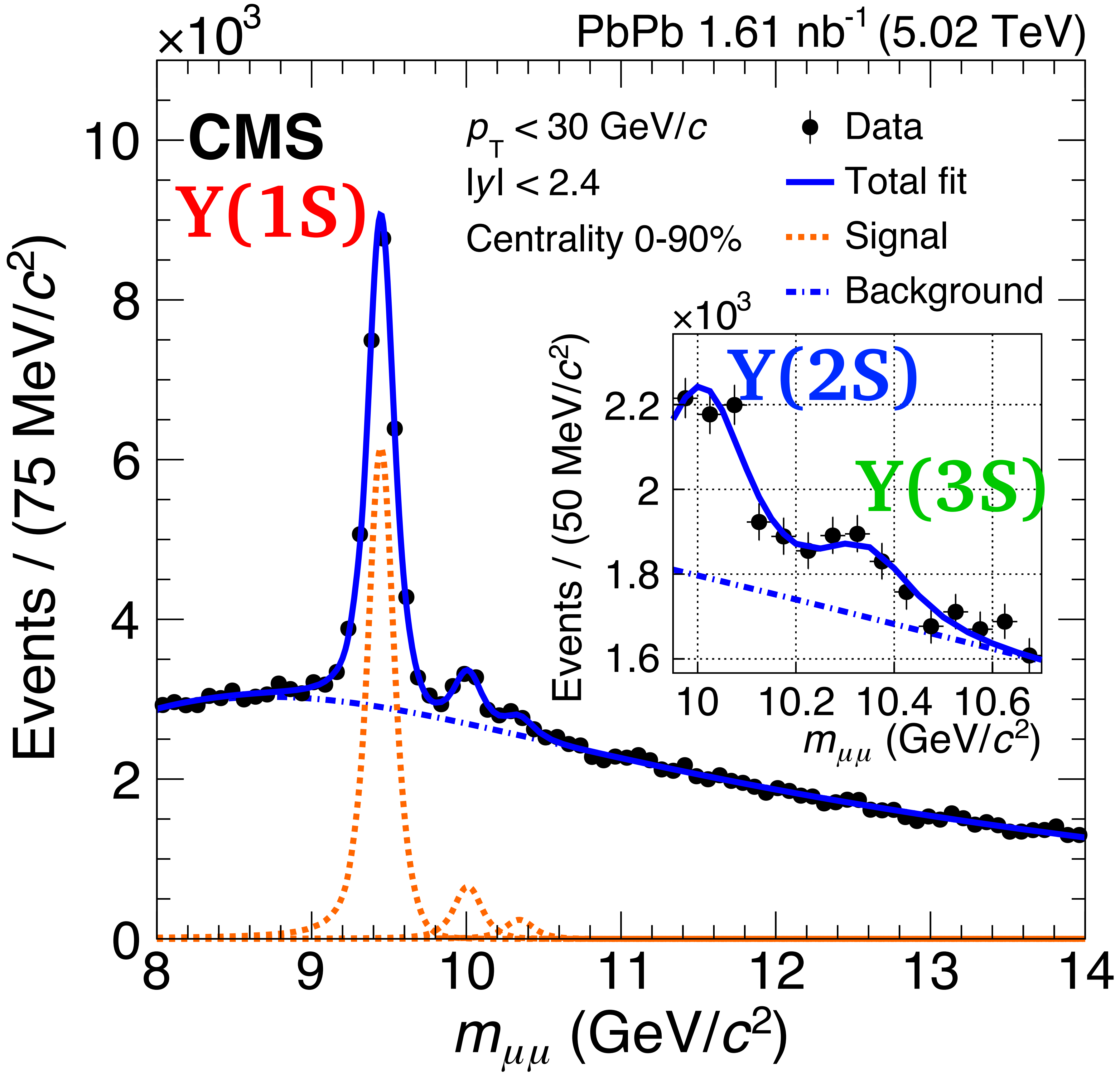
[PRL 131 (2023) 042303]



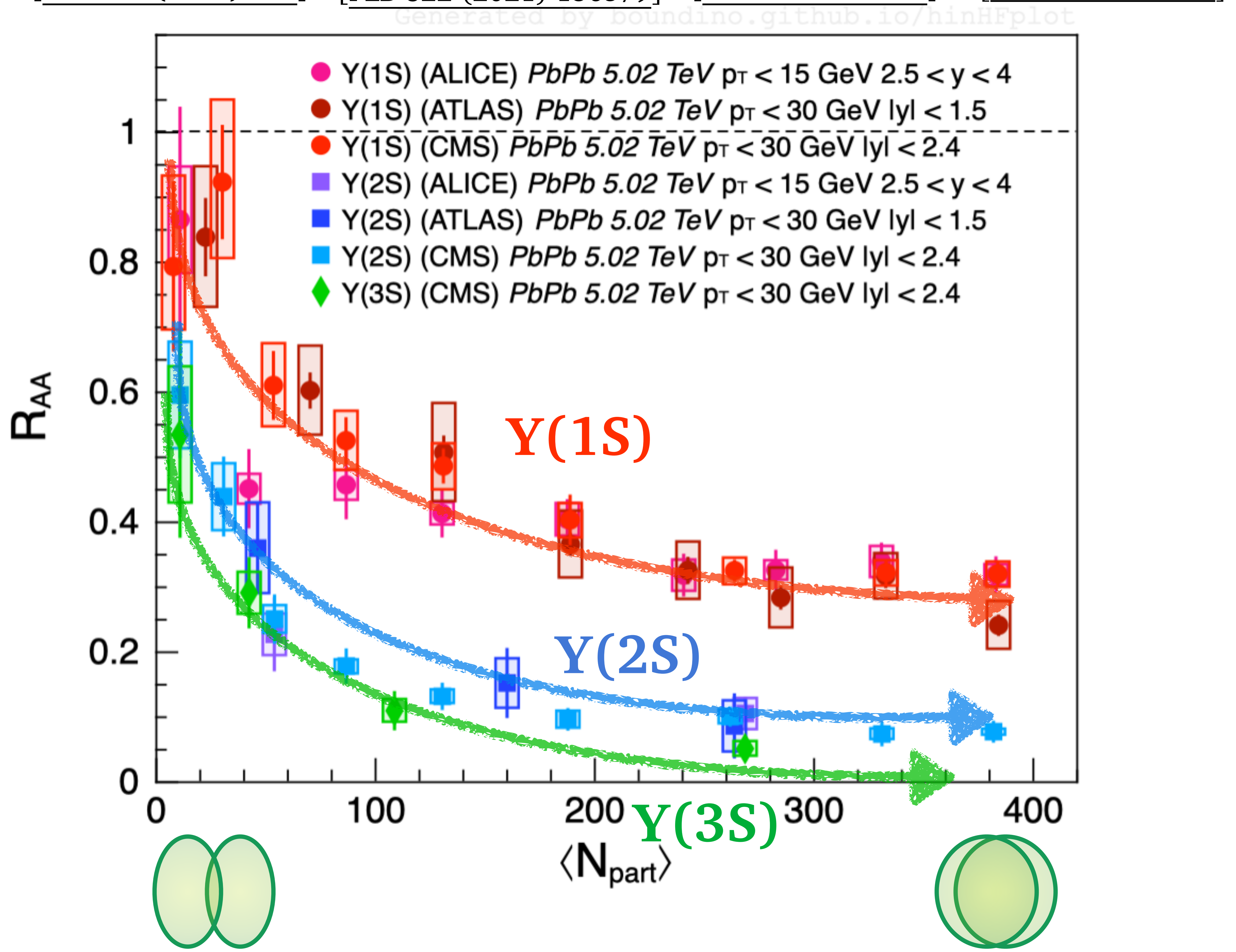
- Nonzero polarization w.r.t. the event plane in semi central collisions (~3.9 σ)
- No sign of polarization in pp collisions so far up to p_T = 60 GeV/c
- Electromagnetic field? Recombination? Spin alignment for vector meson?

Bottomonia in AA : LHC

[arXiv:2303.17026]



[PLB 790 (2019) 270] [PLB 822 (2021) 136579] [arXiv:2205.03042] [arXiv:2303.17026]



- Identification of all three Υ states at the LHC : Sequential suppression $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
- Gradual decrease versus centrality : implication of subdominant effect for static color screening

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Bottomonia in AA : Theory comparison

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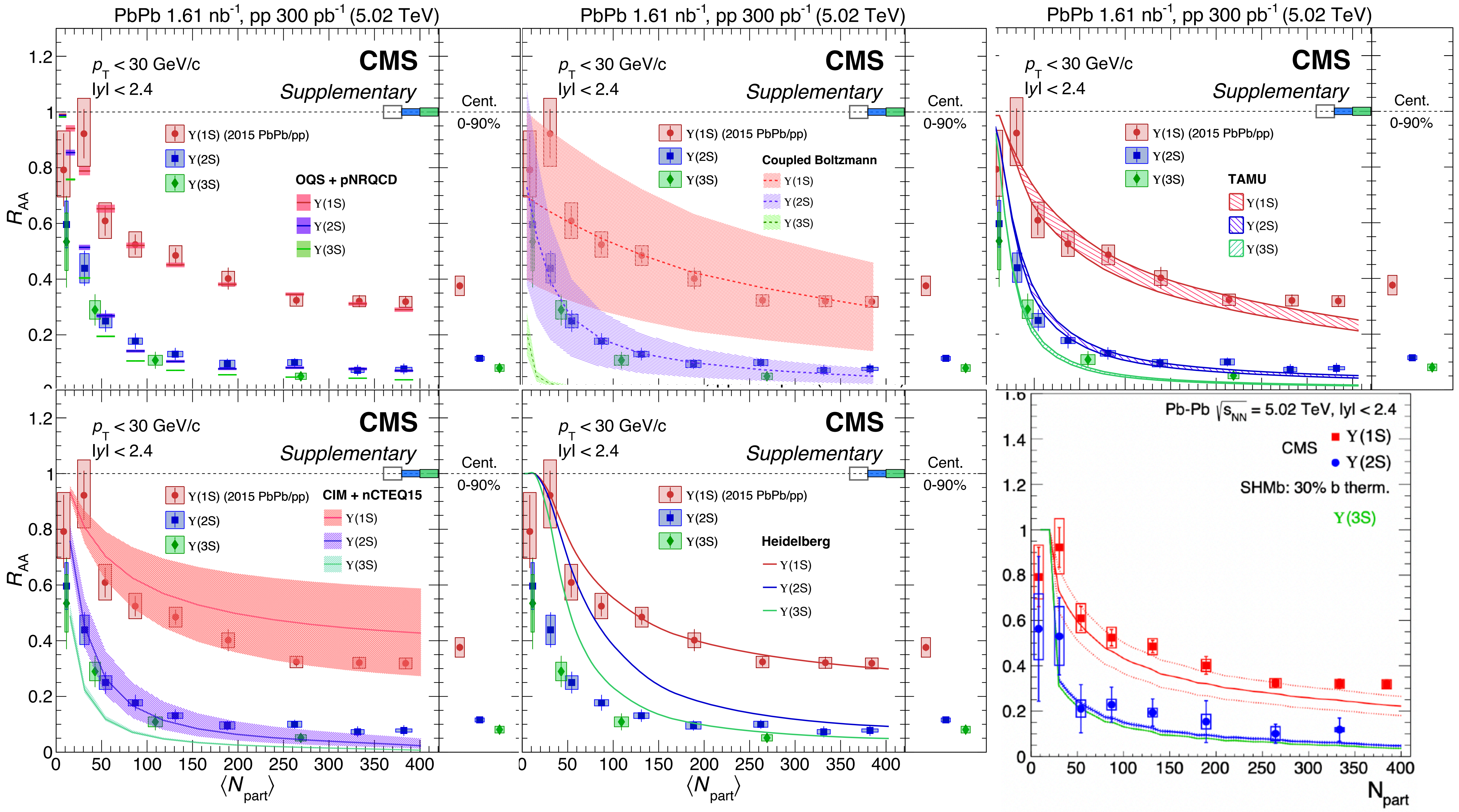
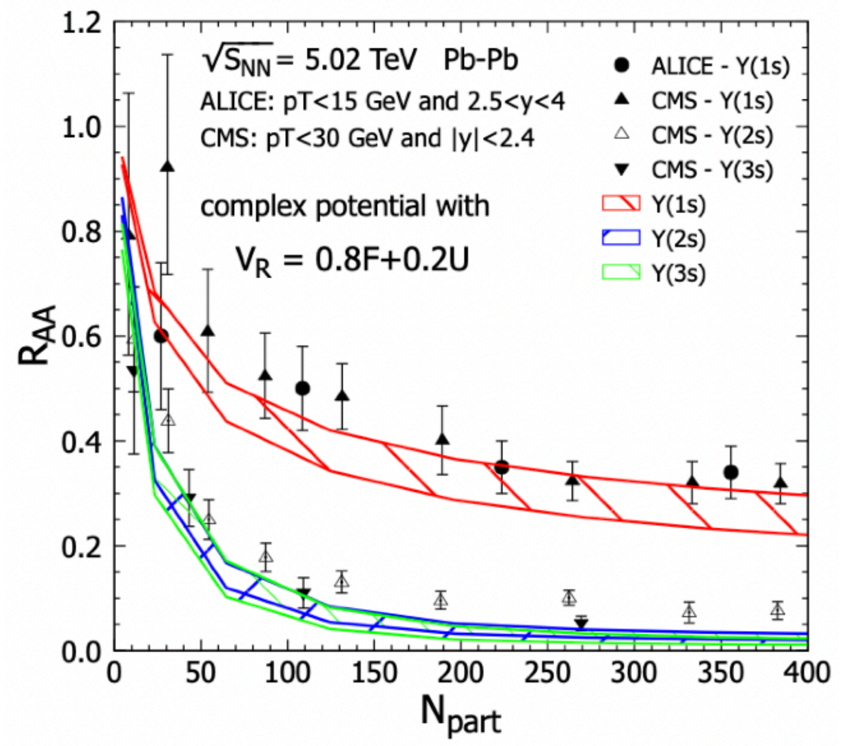
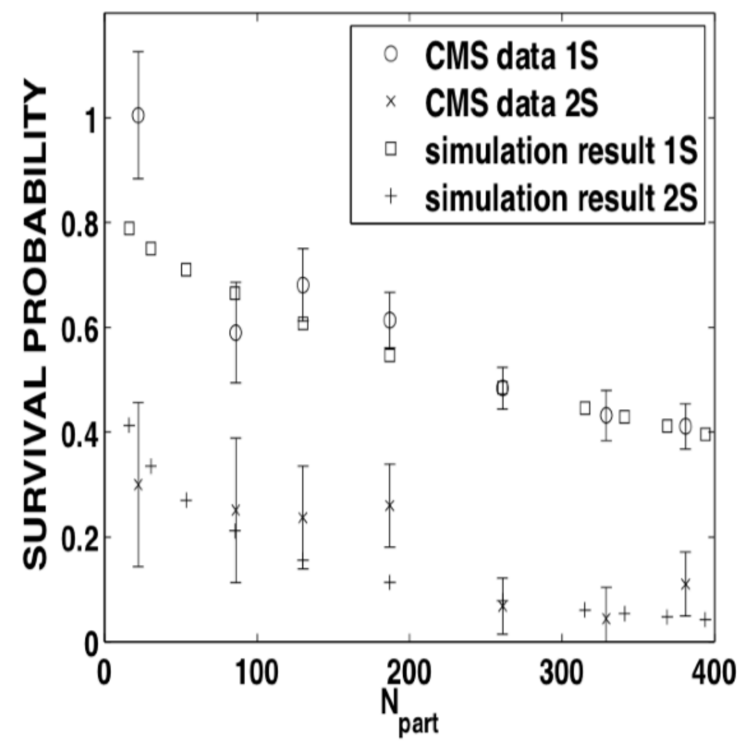
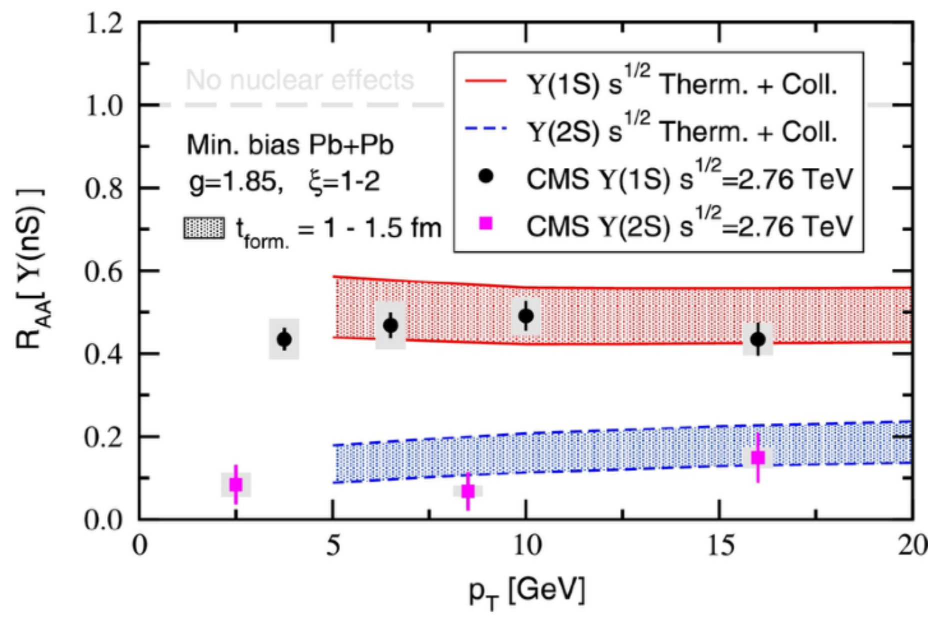
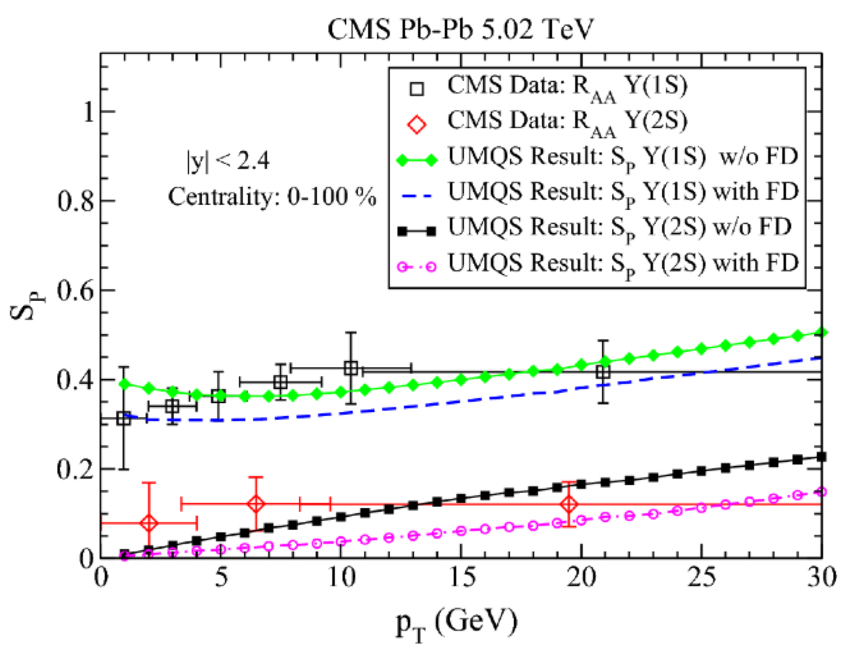
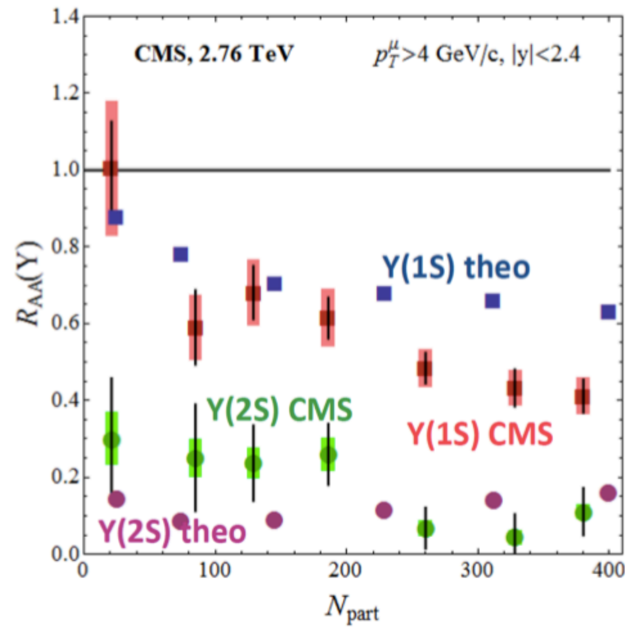


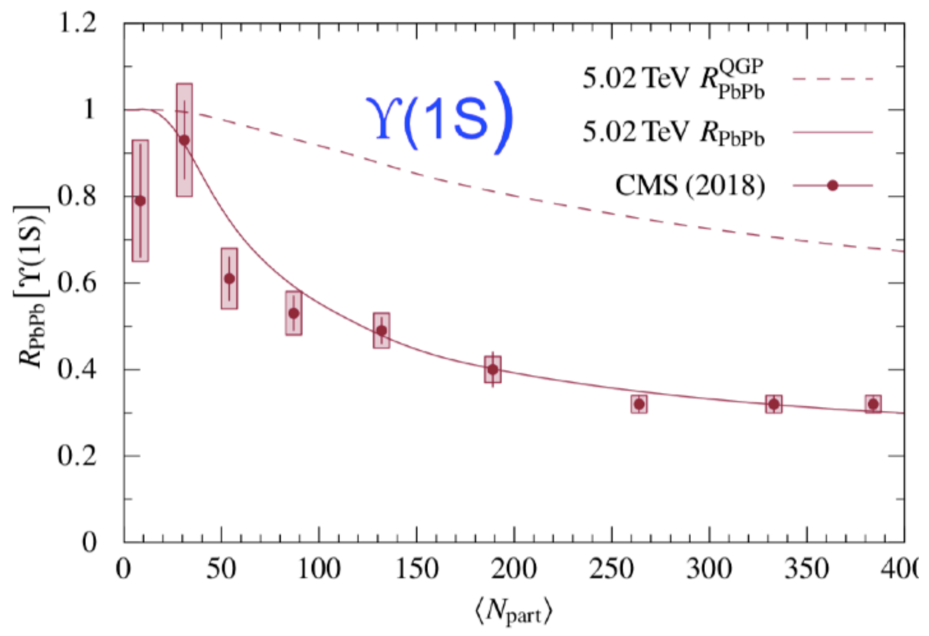


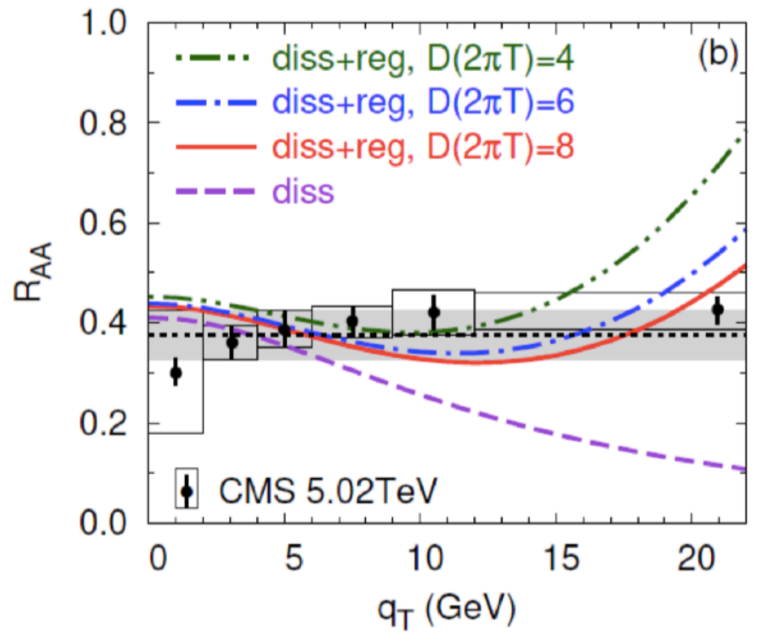












[arXiv:2303.17026] [EPJC (2019) 79:147] [J. Phys.: Conf. Ser. 779 012041]

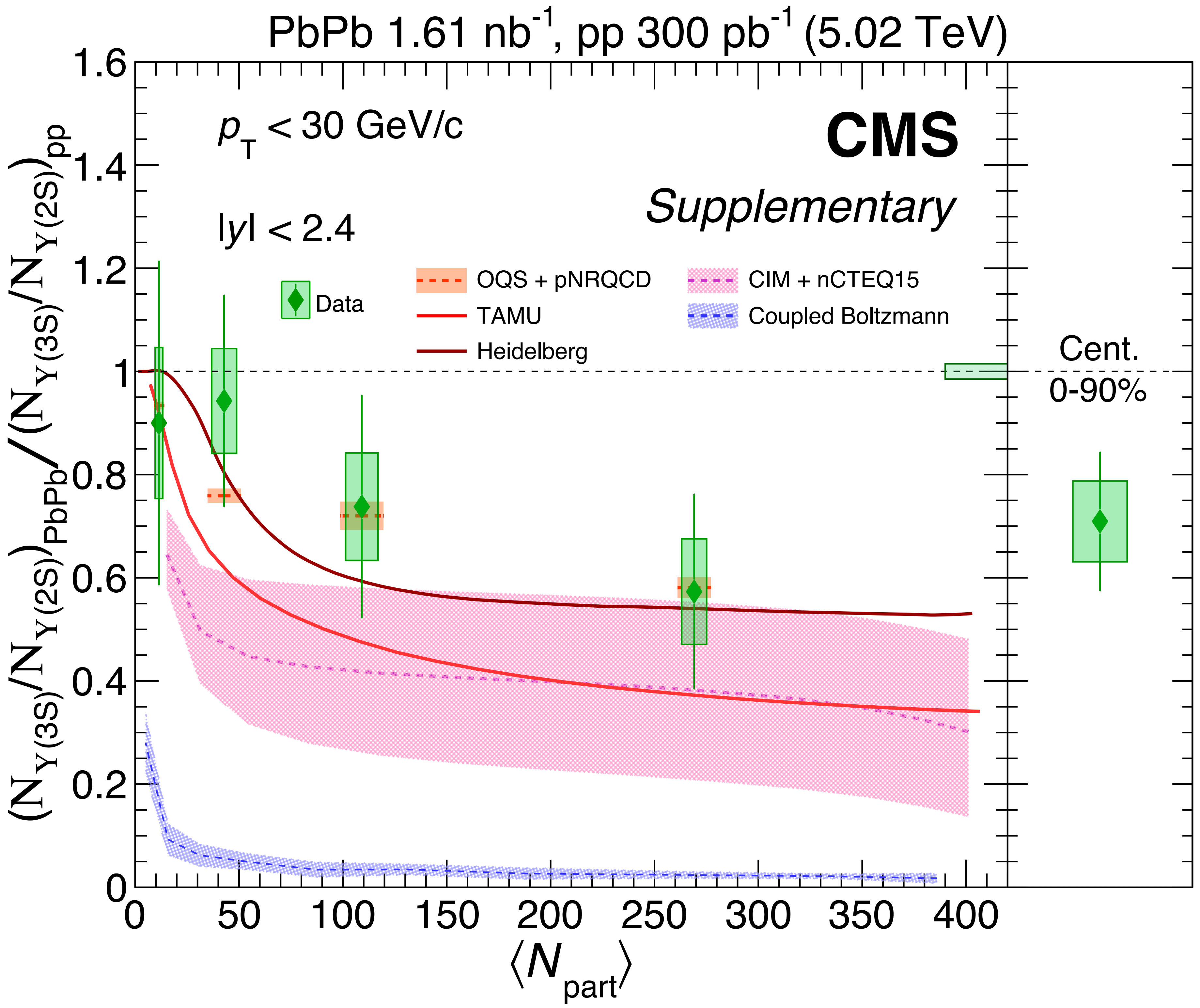
[Universe 6050061] [PLB 801 (2020) 135147] [PRC 88 044908]

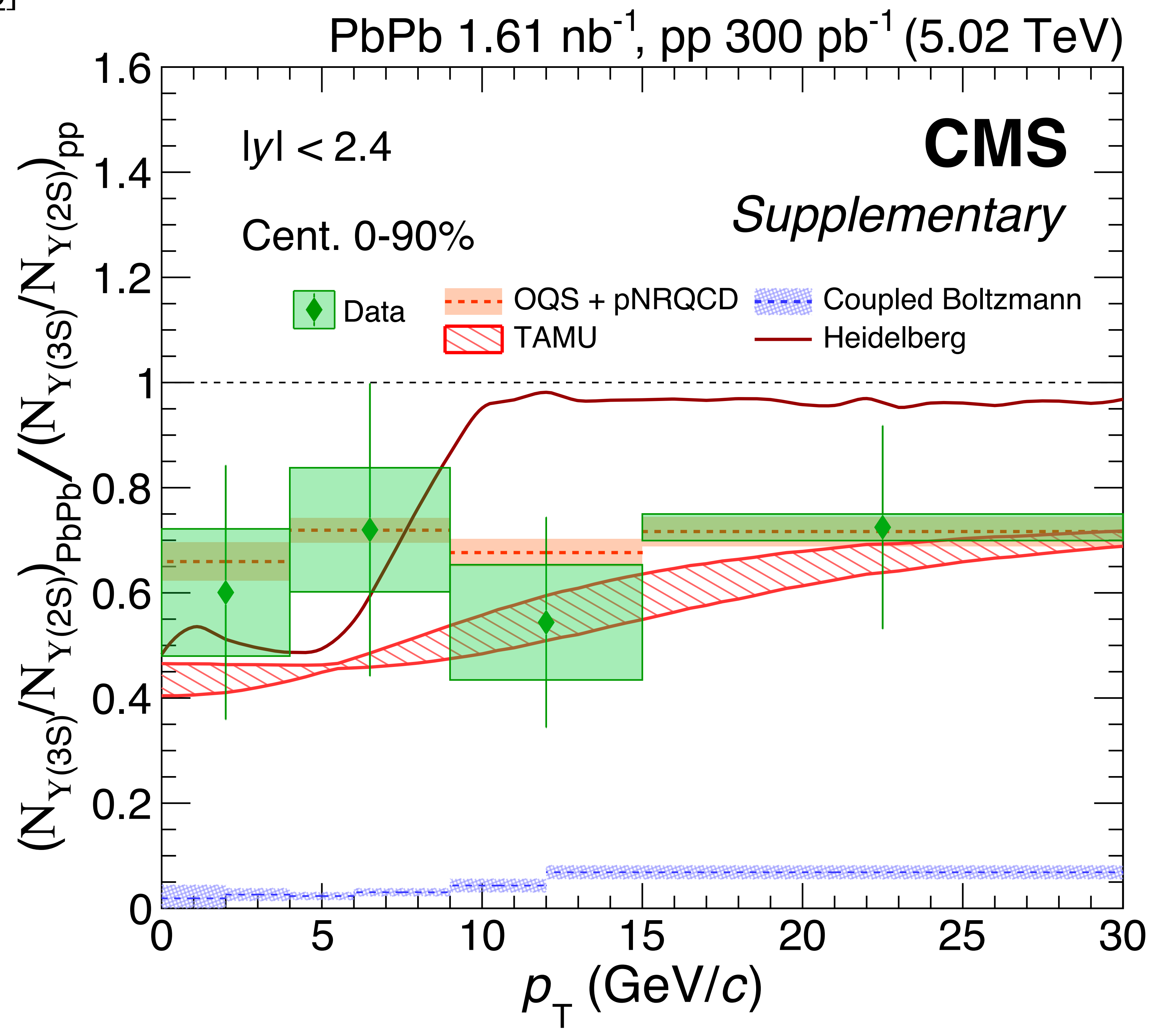
[arXiv:2208.10050] [PLB 778 (2018) 384] [QM2022 link]

Mostly works for Υ(1S)…

Bottomonia in AA : Theory comparison

[arXiv:2303.17026]





- Double ratio of Υ(2S)/Υ(3S) to probe the sensitivity of theory calculations
- Deviation among theory models start when looking at excited states

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Bottomonia in AA : Theory comparison

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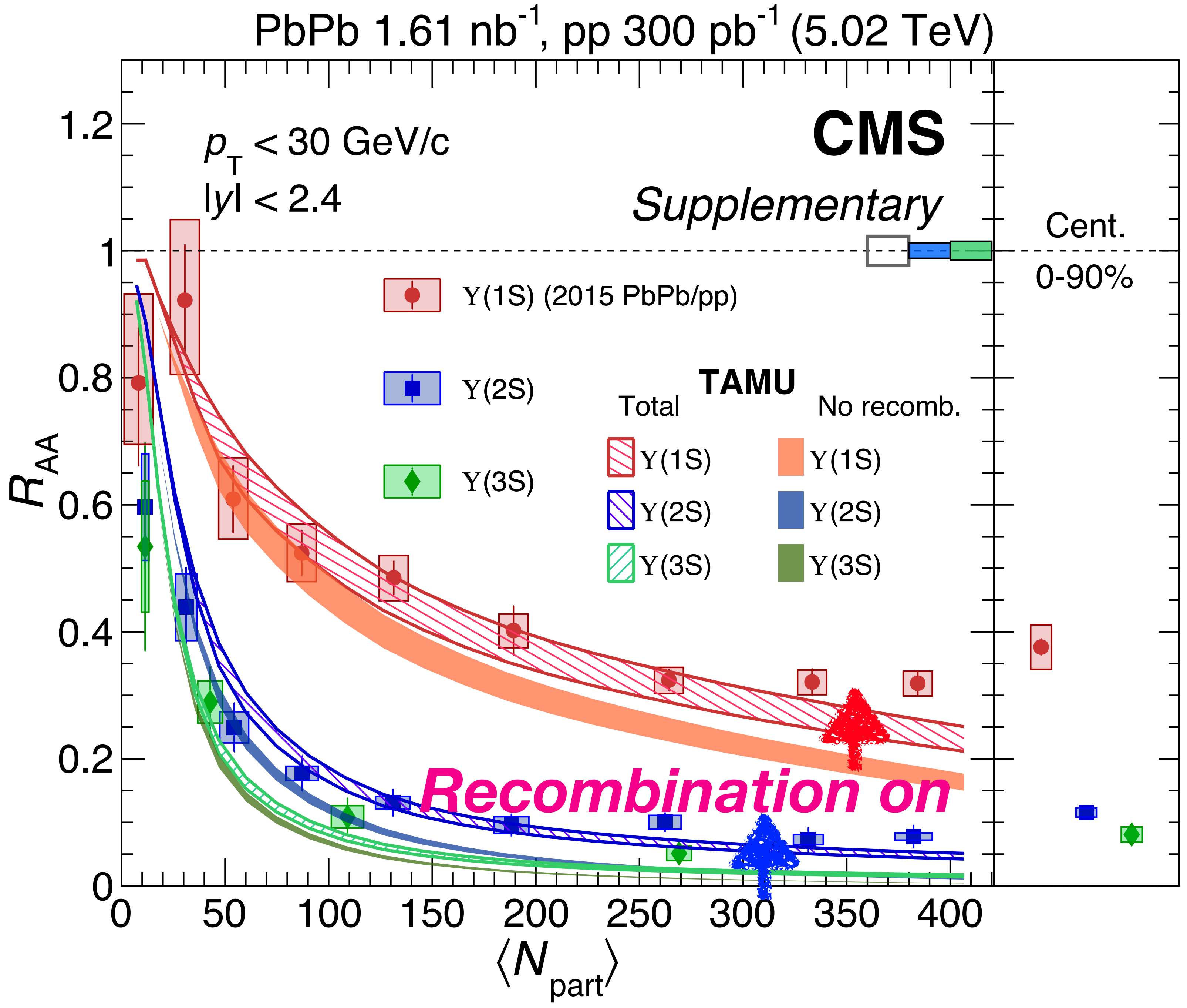
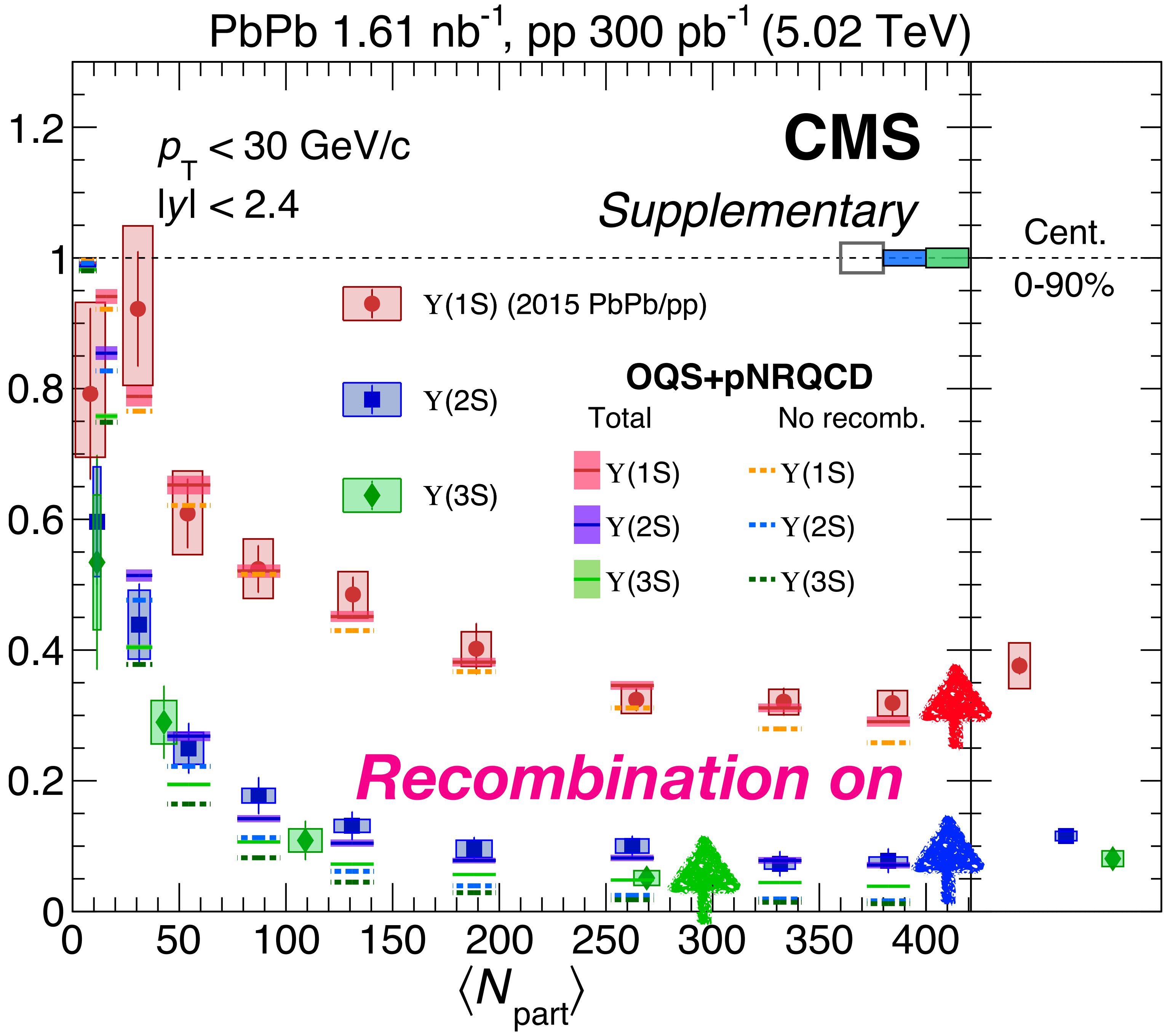
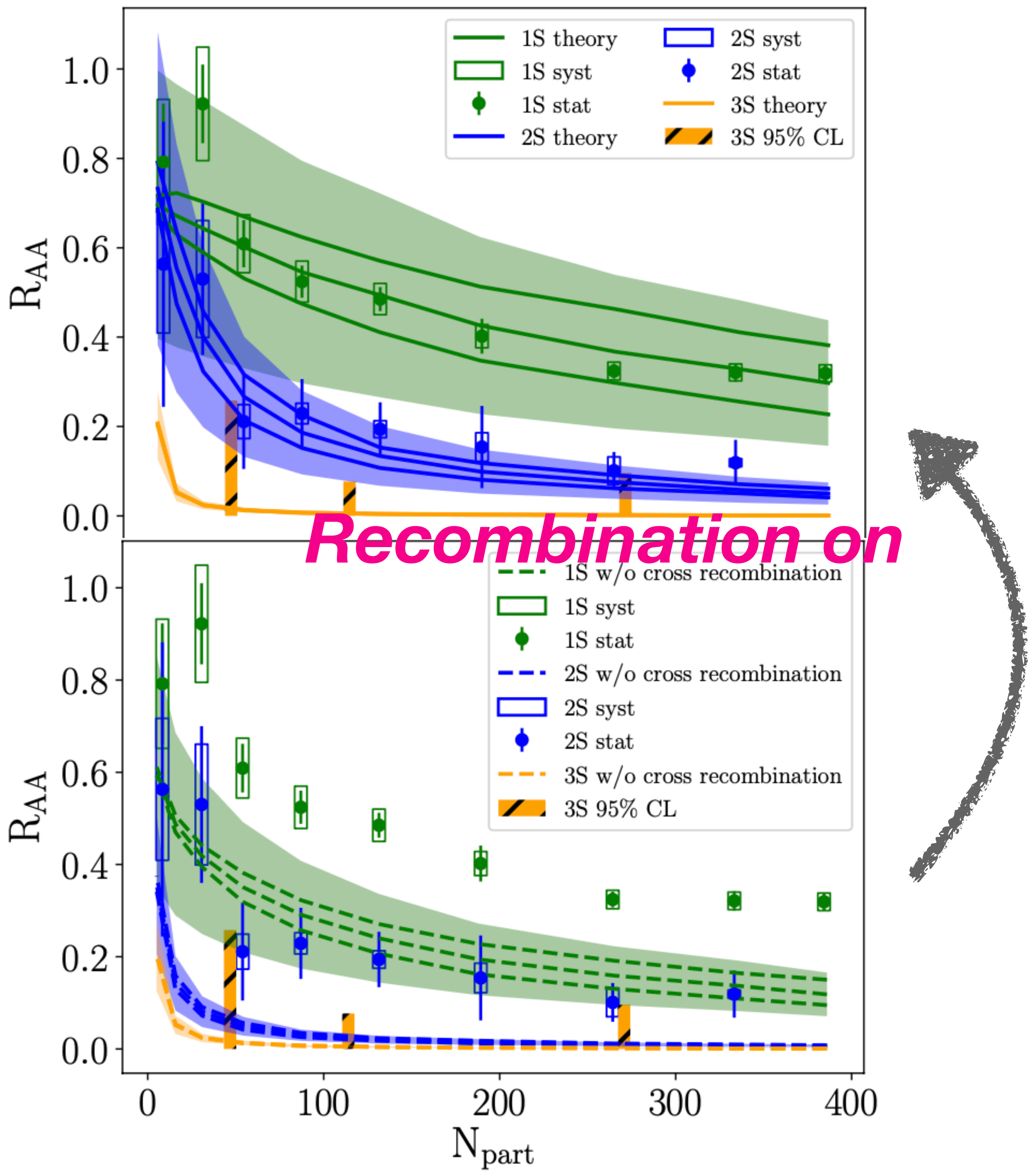
[PRC 96 (2017) 054901]



[arXiv:2302.11826]



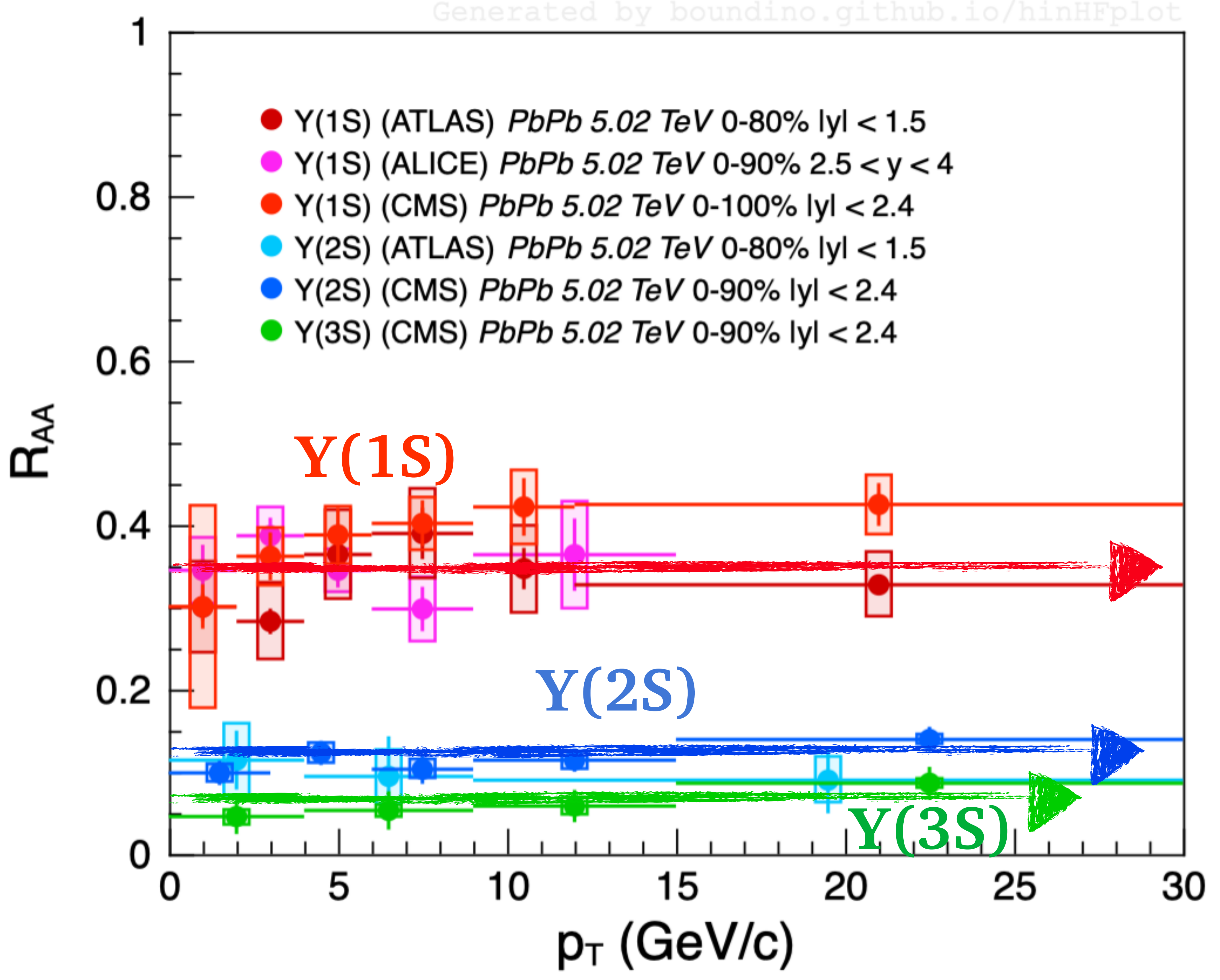
[JHEP 01 (2021) 046]

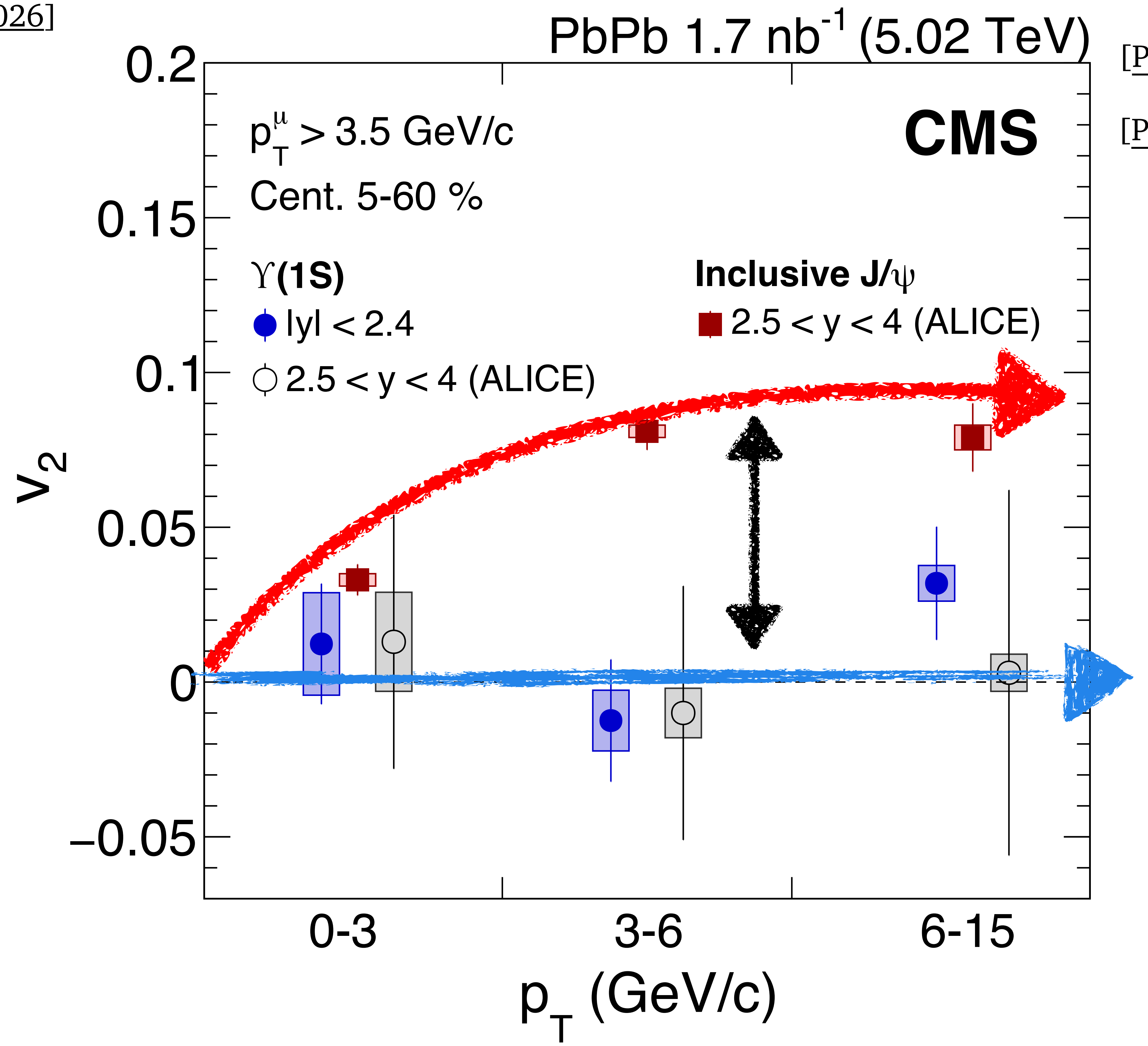


- Recent theory models suggest the importance of recombination for ϒ in heavy ion collisions : correlated recombination being the dominant source
- Larger effect for excited states — relative effect in some models not following the binding energy ordering e.g. recombination contribution in R_{AA} : ϒ(2S) > ϒ(3S) > ϒ(1S)

Bottomonia in AA : LHC

[PLB 790 (2019) 270] [PLB 822 (2021) 136579] [arXiv:2205.03042] [arXiv:2303.17026]





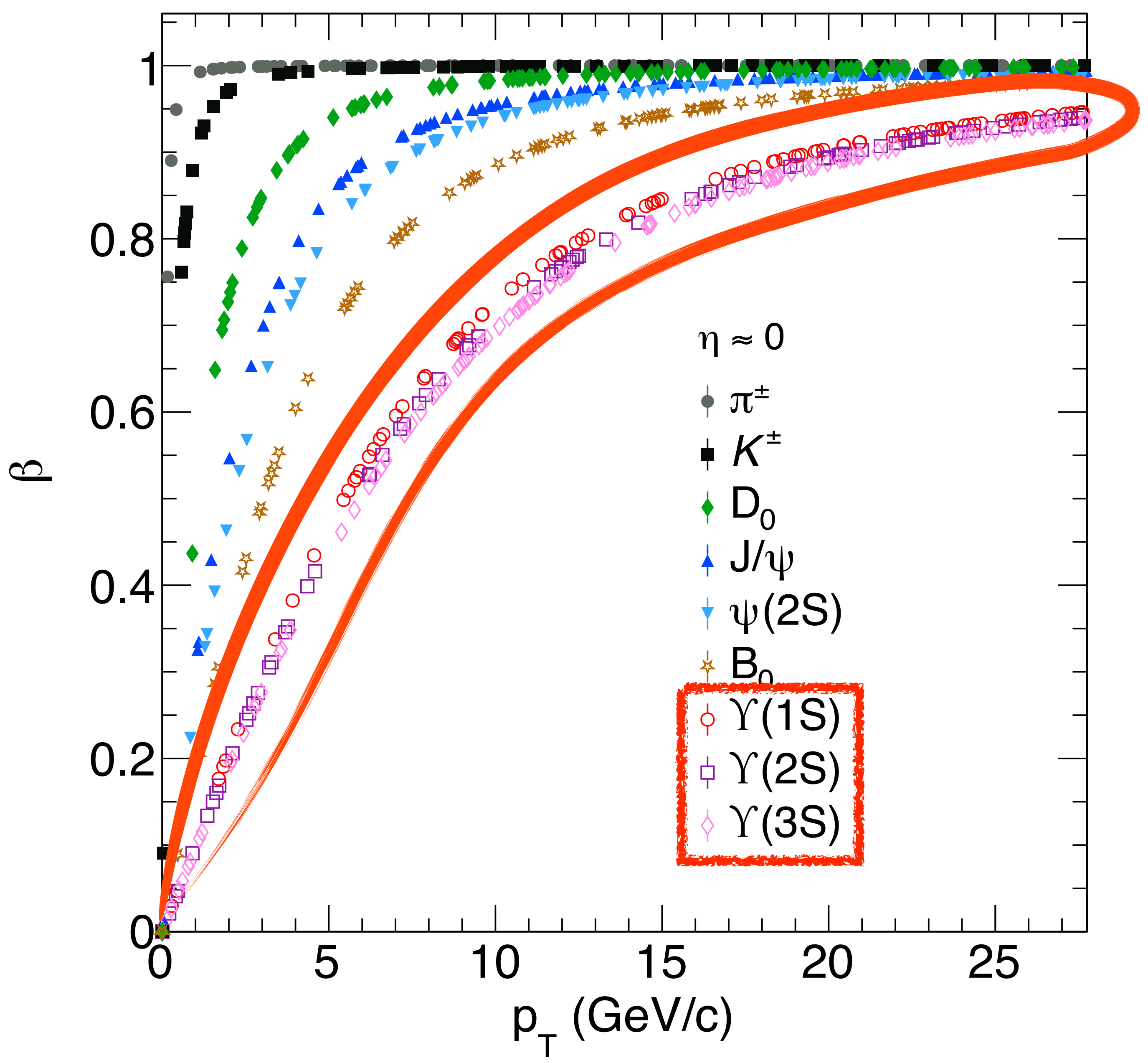
[PLB 819 (2021) 136385]

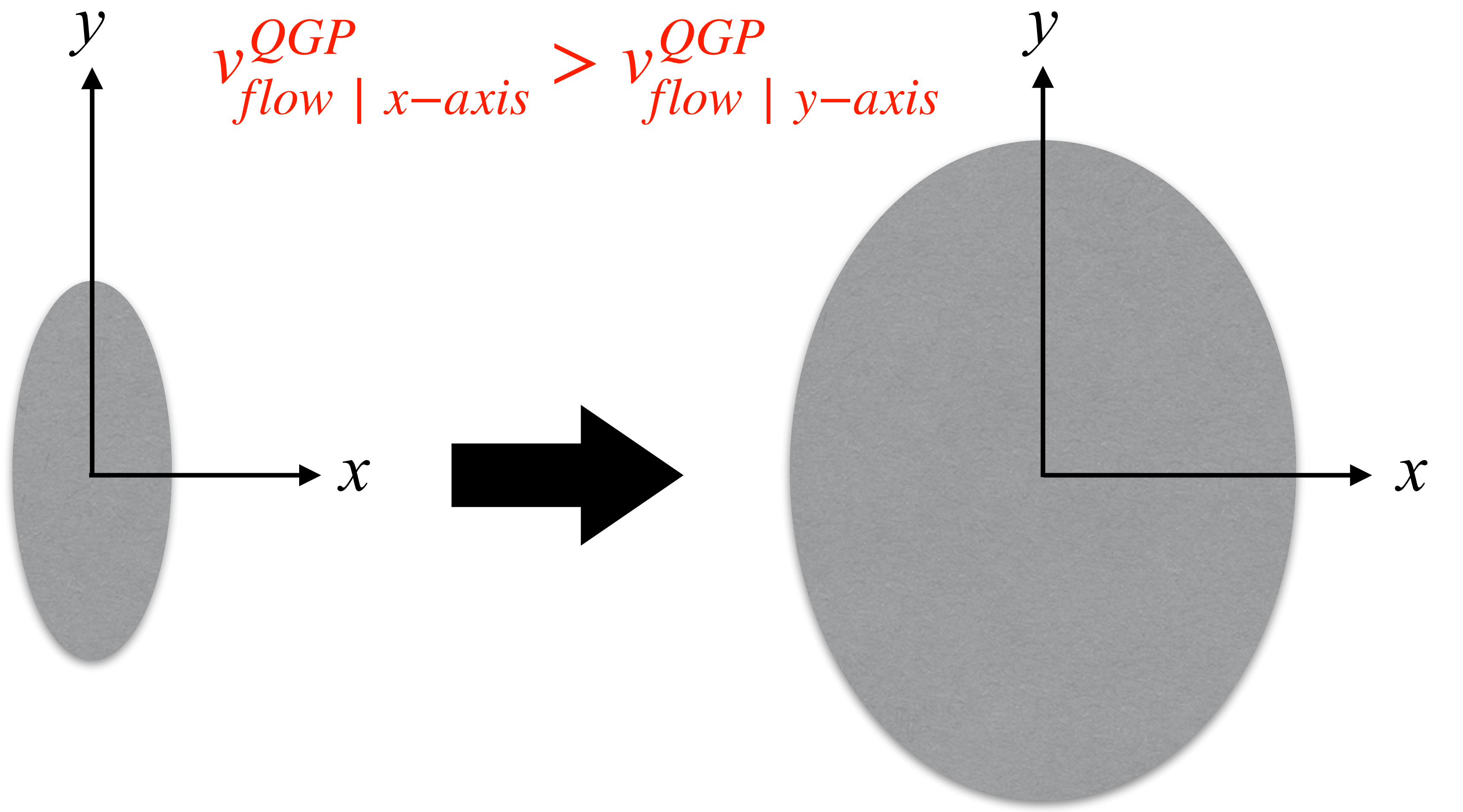
[PRL 123 (2019) 192301]

- Sequential suppression in all p_T region from 0 to 30 GeV/c
- **No v_2** observed in contrast to J/ψ : Different in-medium effects for charmonia and bottomonia

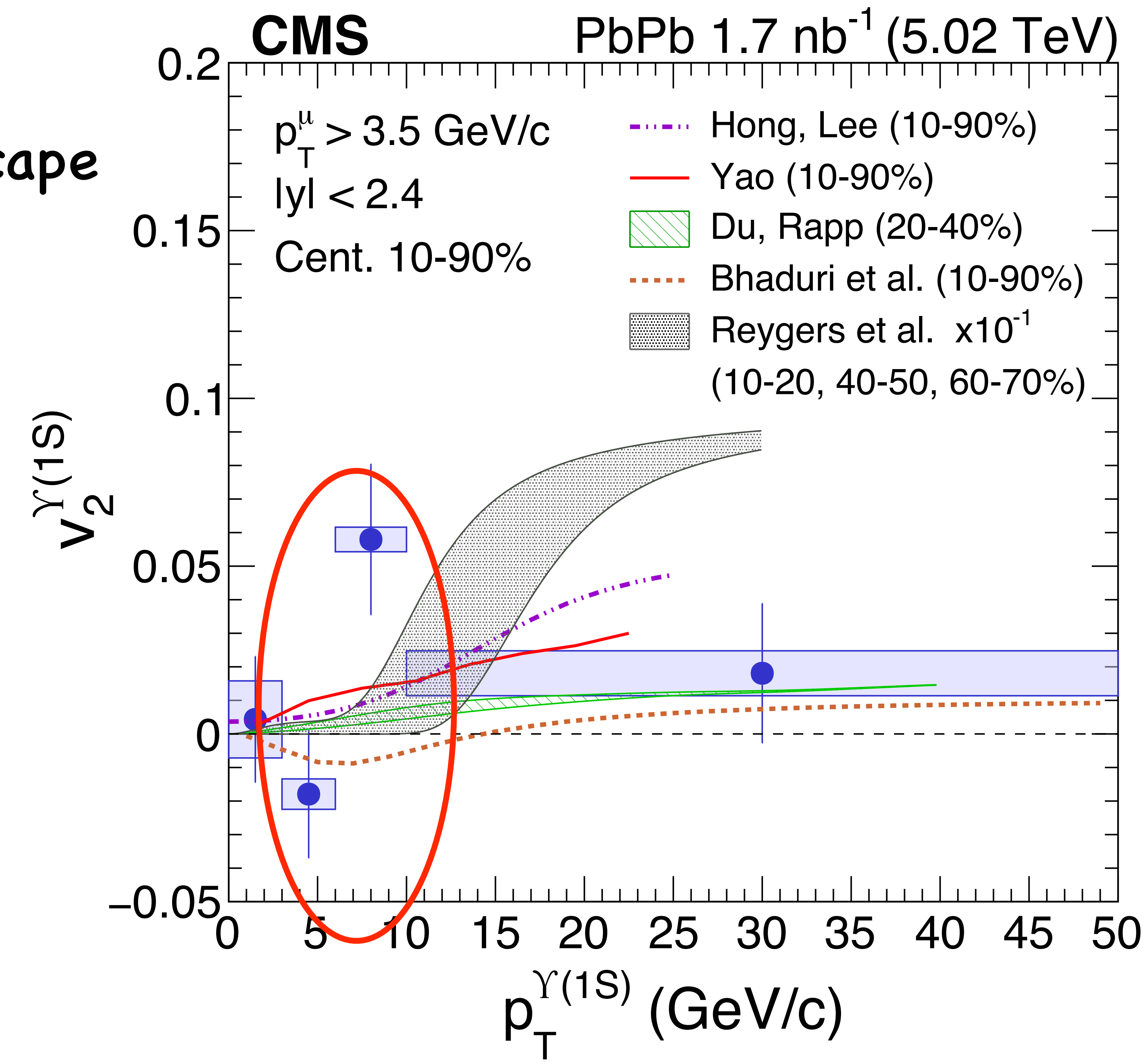
Bottomonia in AA : LHC

- Υ has much smaller velocity compared to other species
  - Low-p_T : $v^{\Upsilon} < v^{QGP}_{flow}$ $\longrightarrow$ Cannot escape QGP
  - Intermediate p_T : $v^{\Upsilon} \simeq v^{QGP}_{flow}$ $\longrightarrow$ Long effective travel distance (depending on axis direction)
    $\longrightarrow$ Even possible negative v_2
  - High-p_T : $v^{\Upsilon} > v^{QGP}_{flow}$ $\longrightarrow$ Experience initial geometry from fast QGP escape



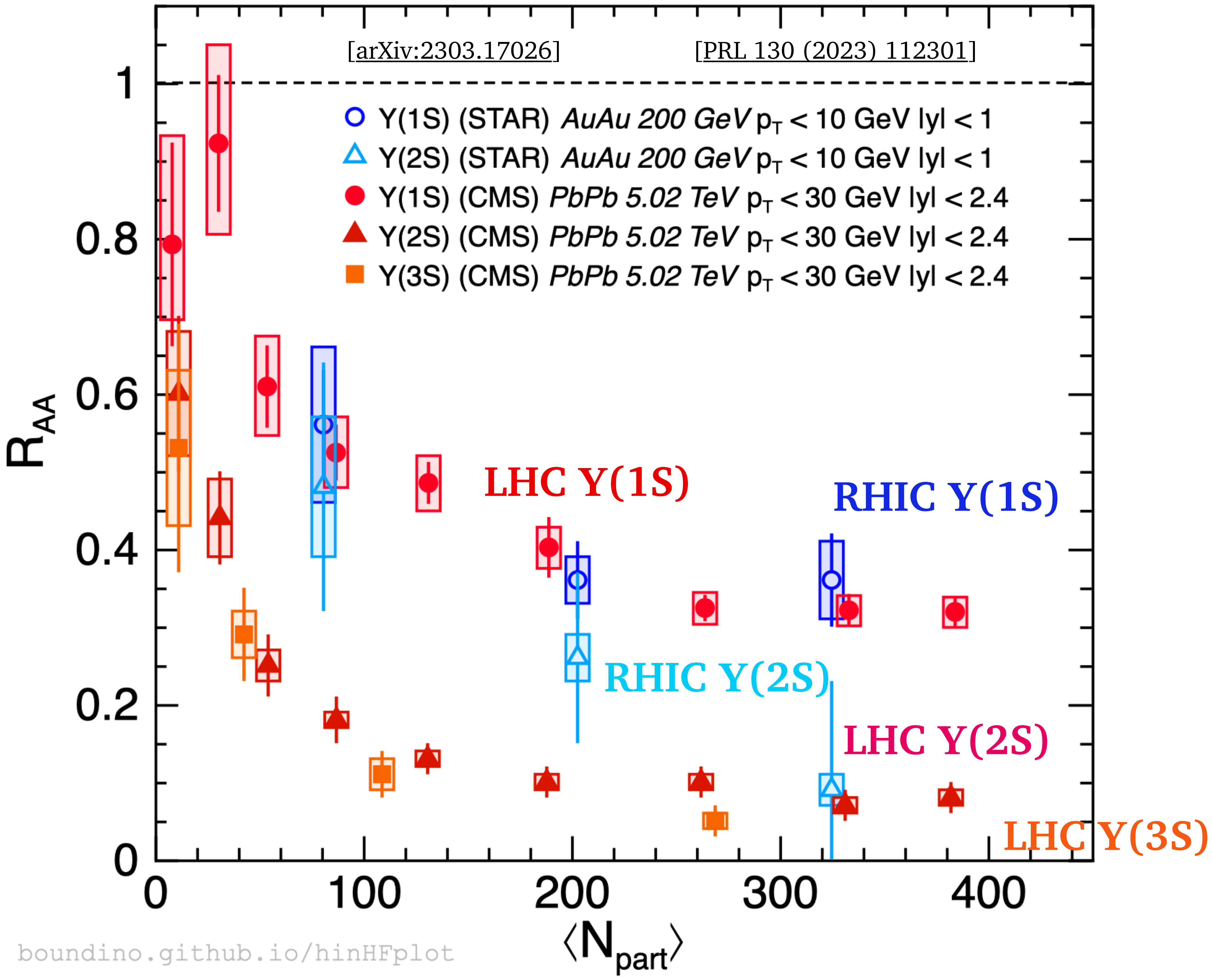


[PLB 819 (2021) 136385]



- Υ mesons are very slow!
  $\longrightarrow$ Even possible negative v_2? (Different effective path-length)

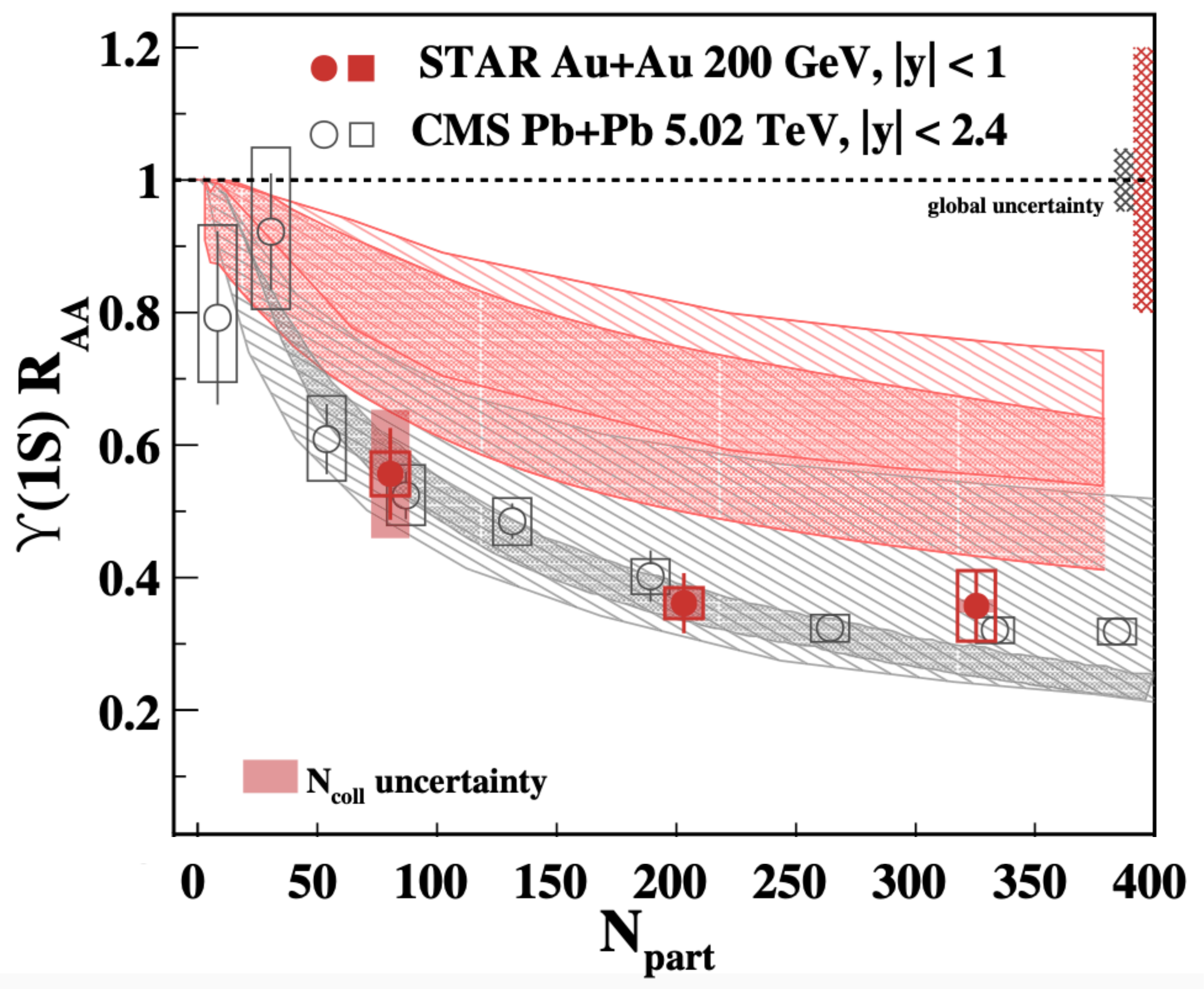
Bottomonia in AA : LHC vs RHIC



- Similar suppression for Y(1S) at 0.2 vs 5.02 TeV?
  - Different CNM effects?
  - Feed down
  - corona region
  - …

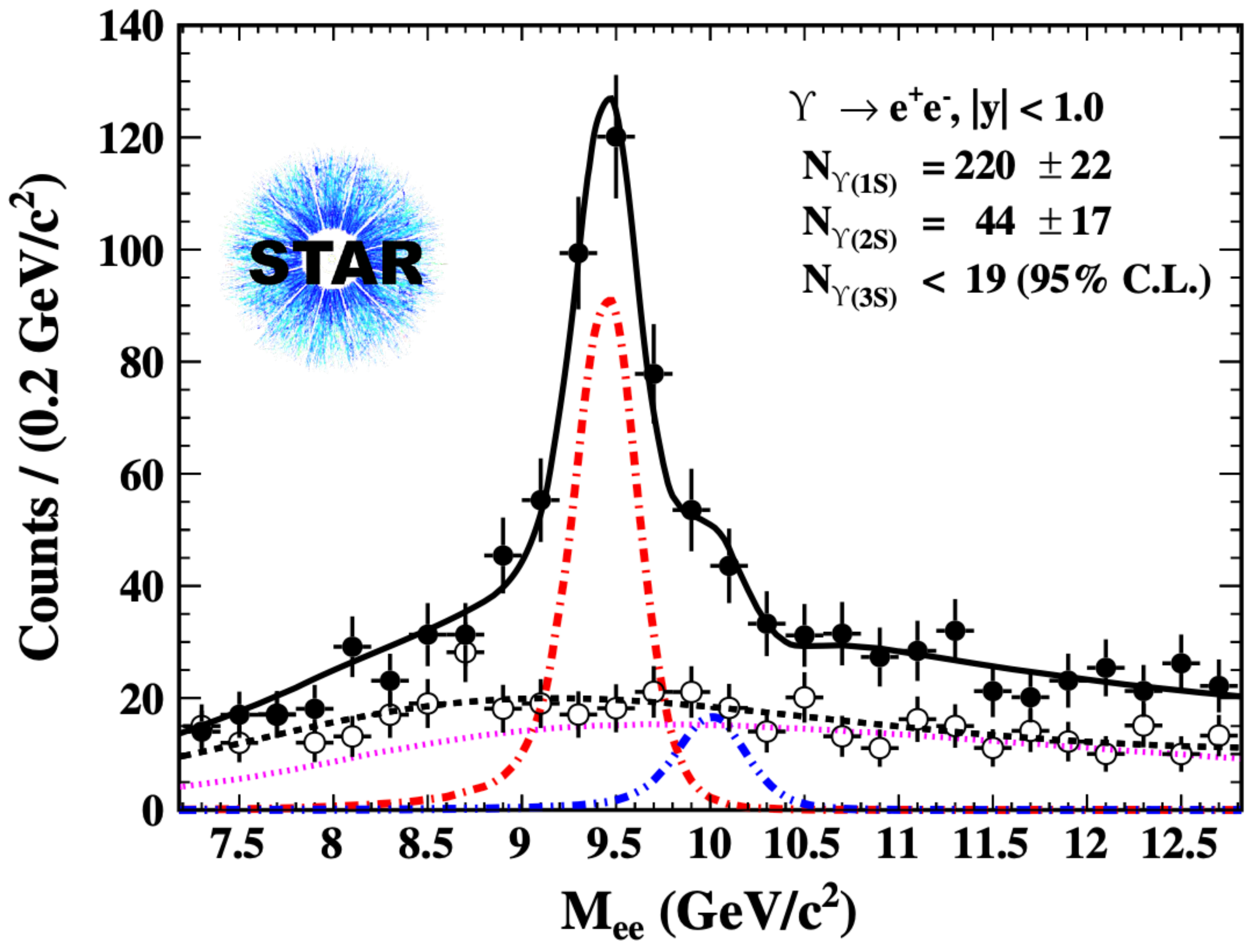
Bottomonia in AA : LHC vs RHIC

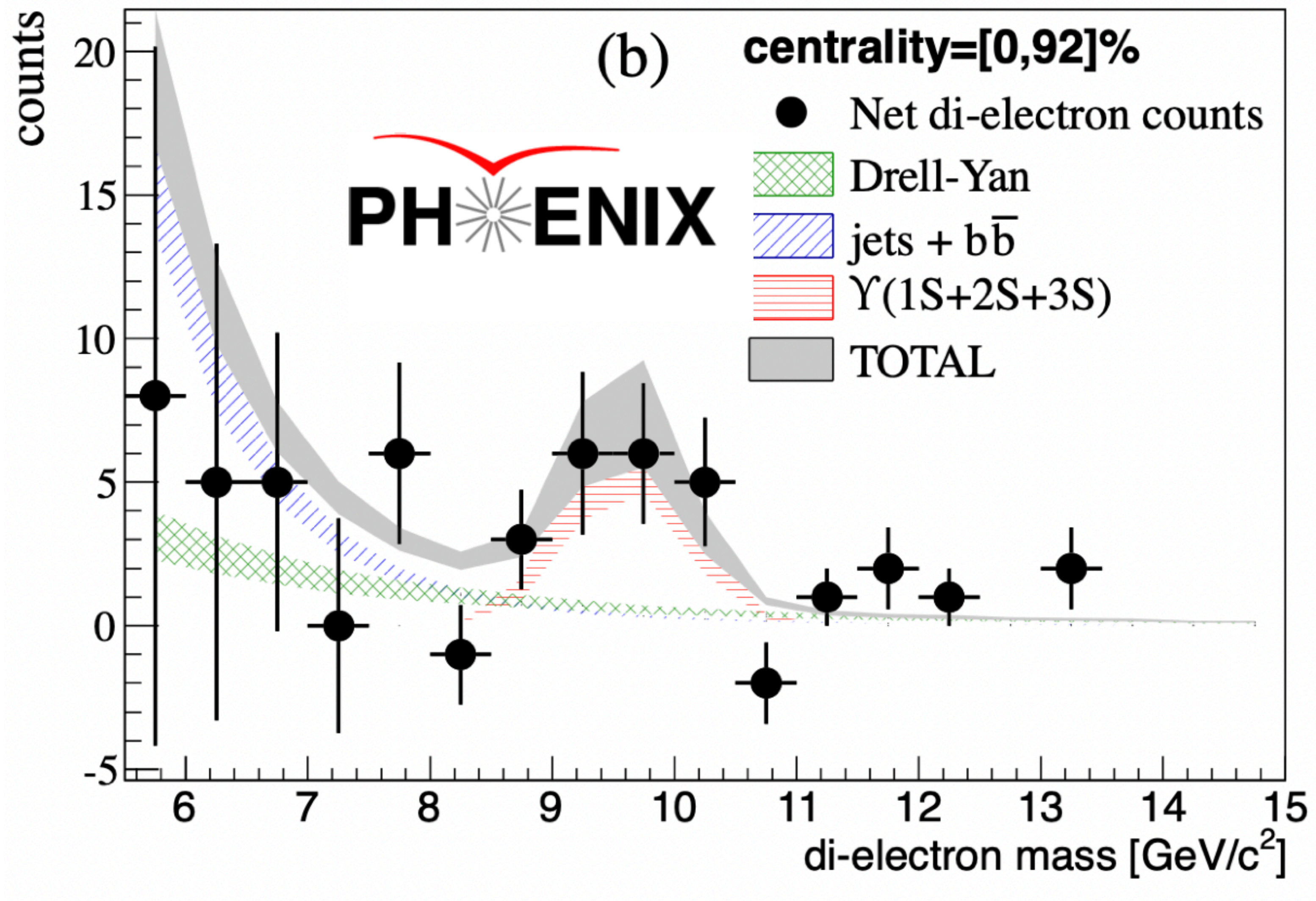
[PRL 130 (2023) 112301]

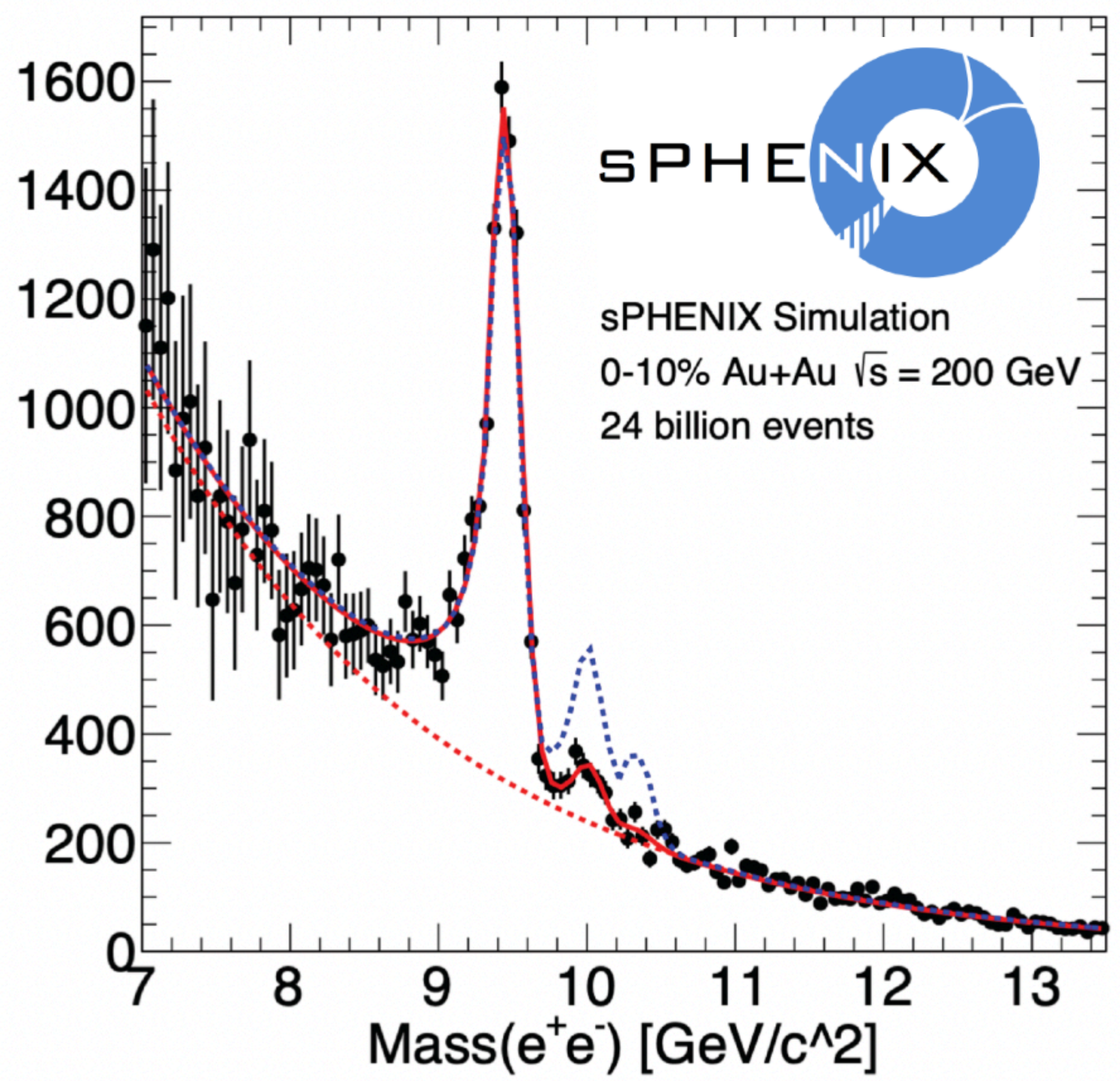


- Similar suppression for Υ(1S) at 0.2 vs 5.02 TeV?
  - Different CNM effects?
  - Feed down
  - corona region
  - …
- Theory calculations suggest stronger suppression at the LHC compared to RHIC
- Still large uncertainties for firm conclusions…

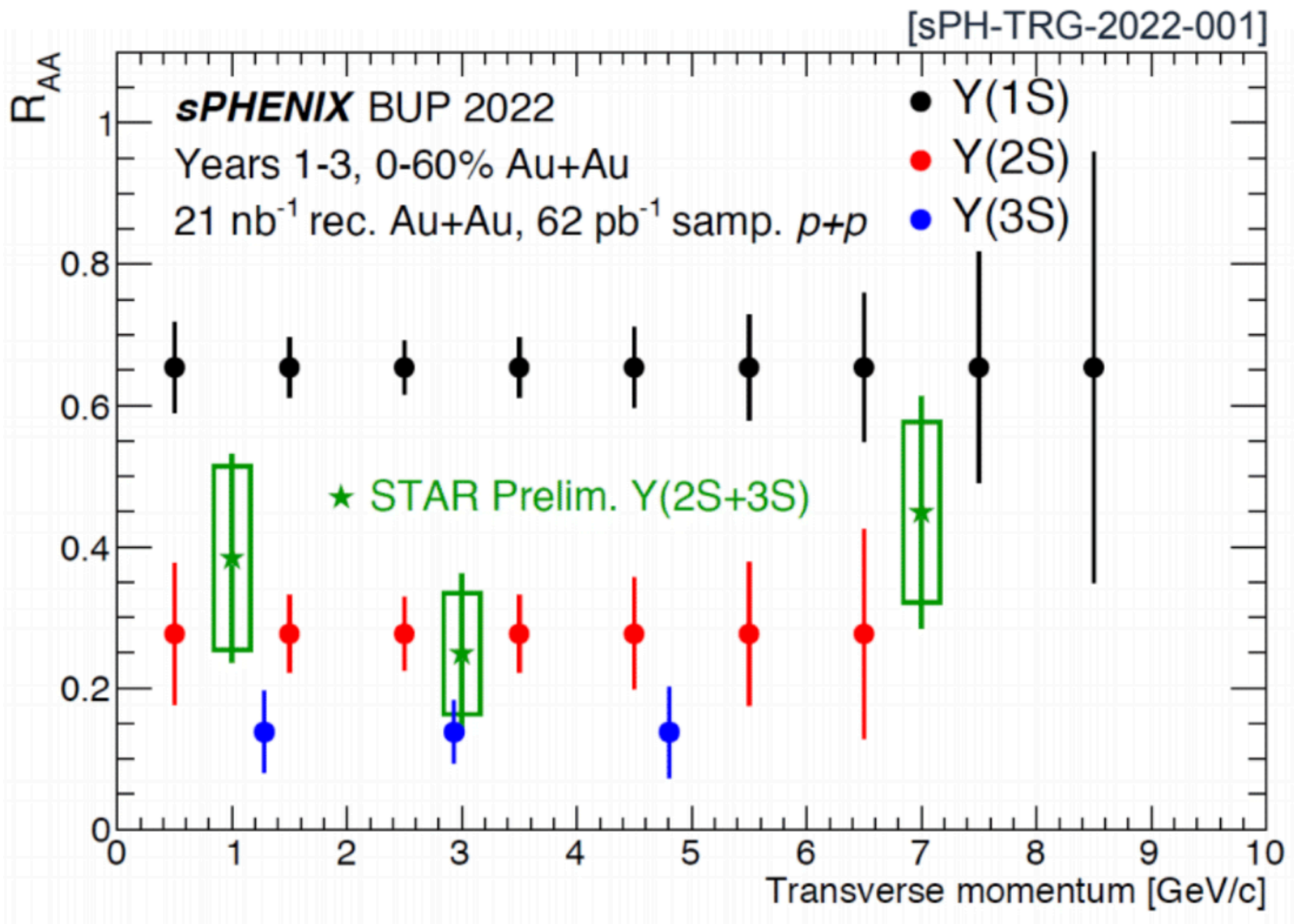
Future prospects at RHIC





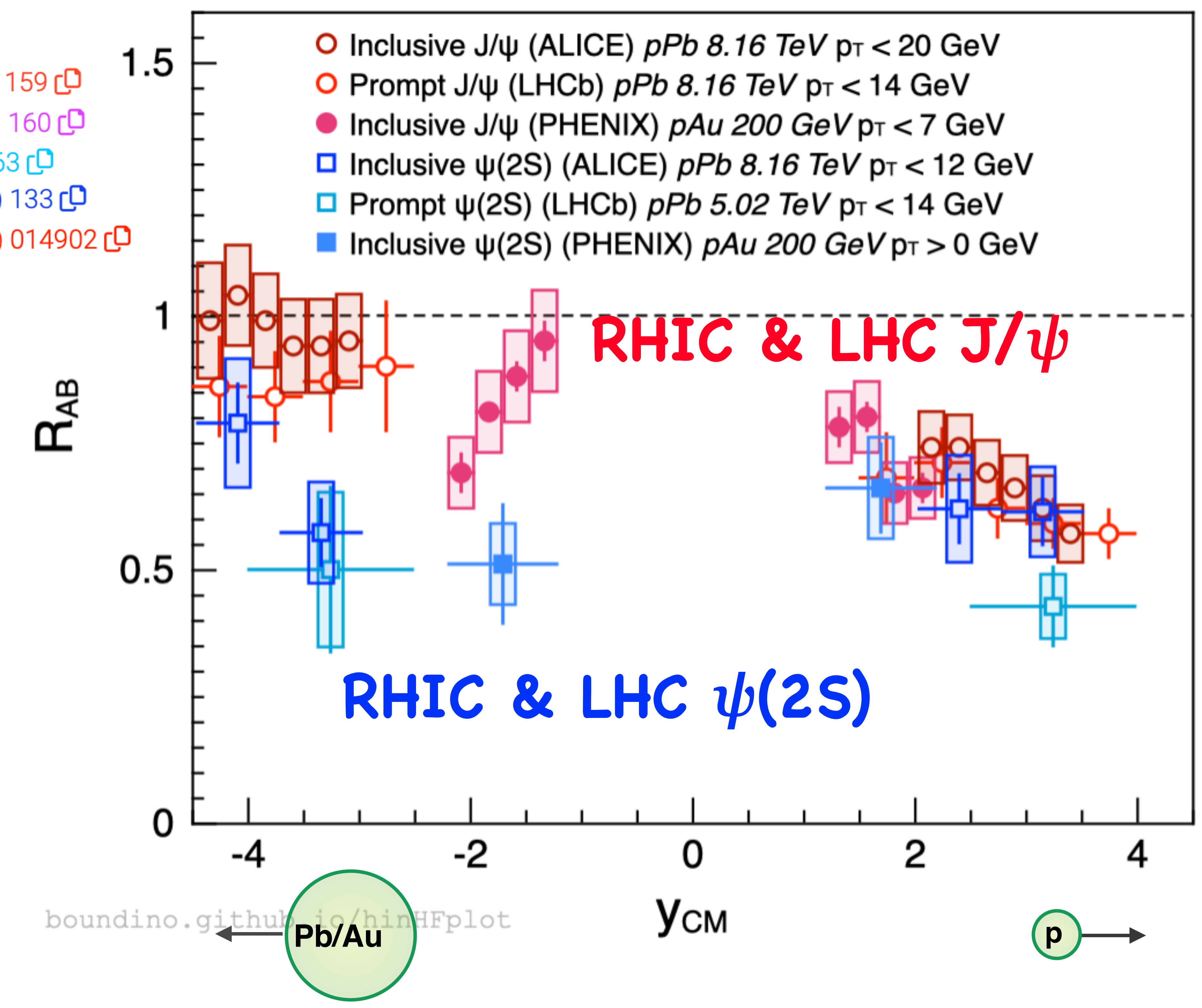


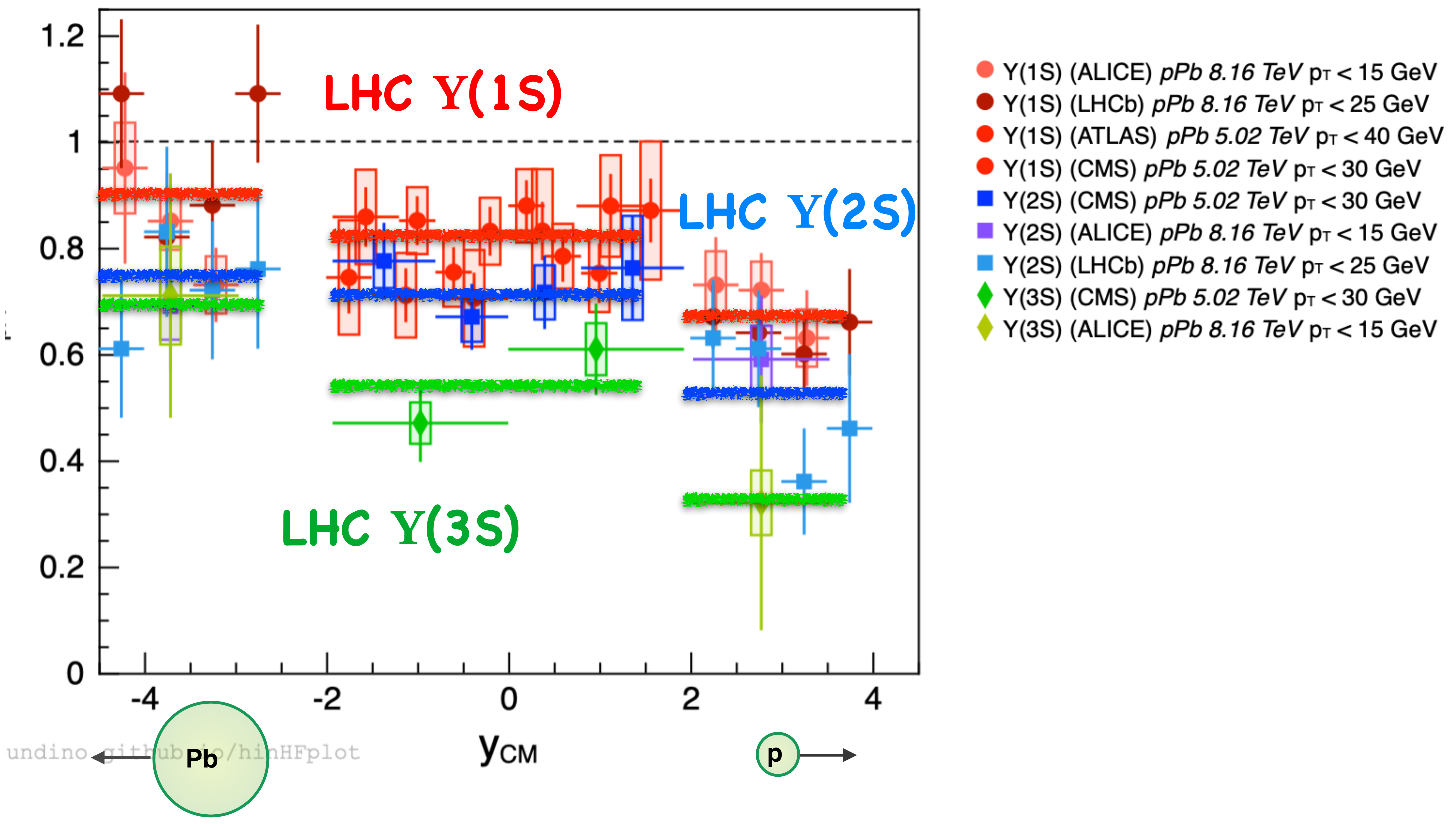
- Limitations on mass resolution in current RHIC measurements
- Capability of mass separation among Y states expected by sPHENIX
- Y medium response to be confirmed in the future



Small systems : R_{pA}

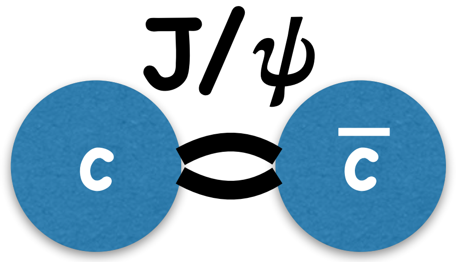
- PLB 774 (2017) 159
- JHEP 07 (2018) 160
- arXiv:2202.03863
- JHEP 03 (2016) 133
- PRC 102 (2020) 014902



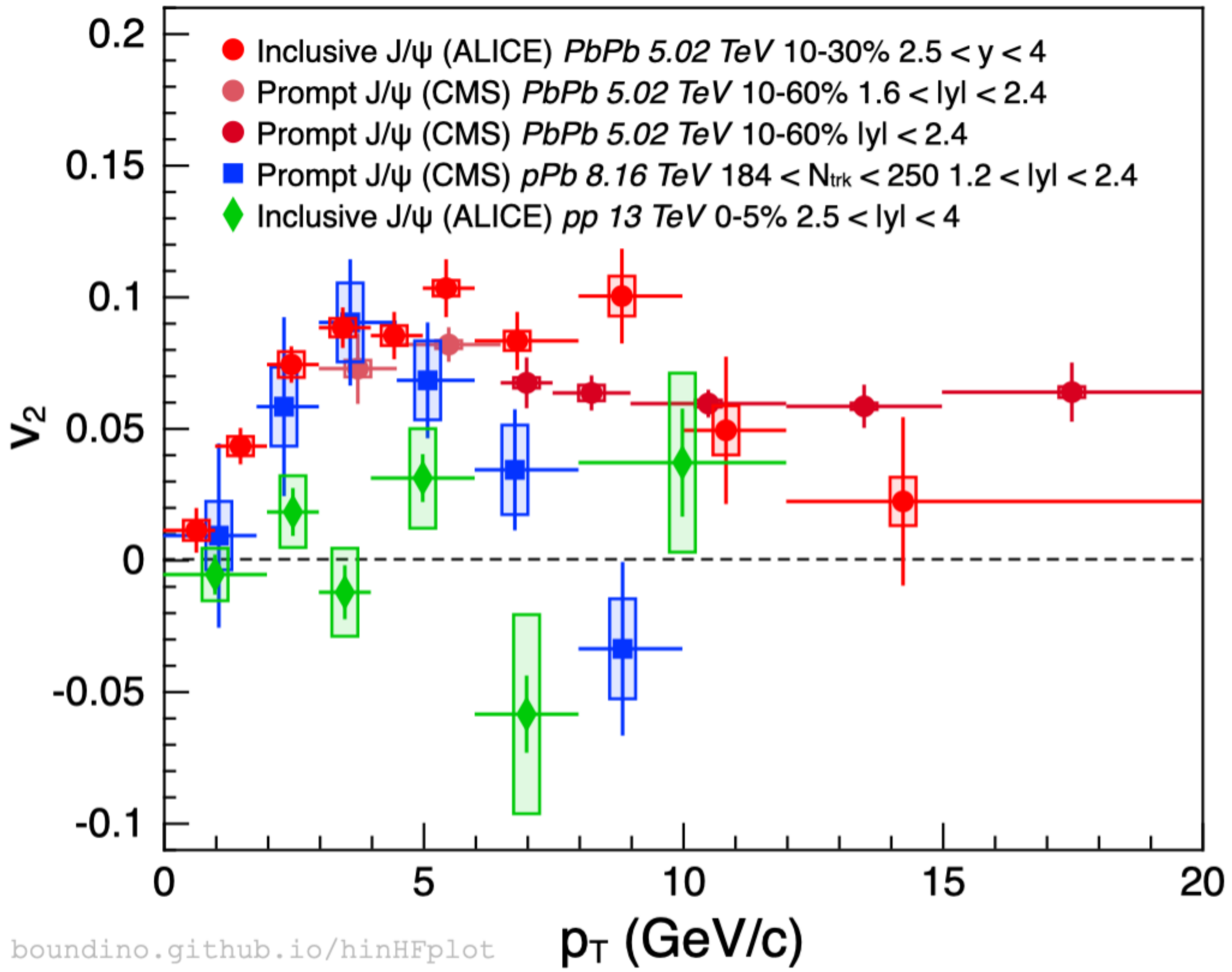


- Sequential modification for charmonia at both LHC & RHIC in pA collisions!
- Sequential modification for bottomonia at LHC in pPb collisions!

Small systems : flow



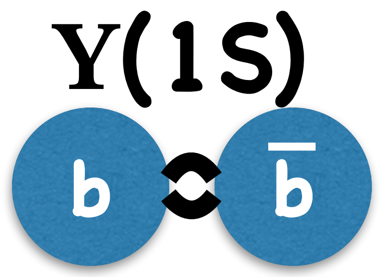
- CMS-PAS-HIN-21-008
- JHEP 10 (2020) 141
- PLB 791 (2019) 172
- ALICE Preliminary



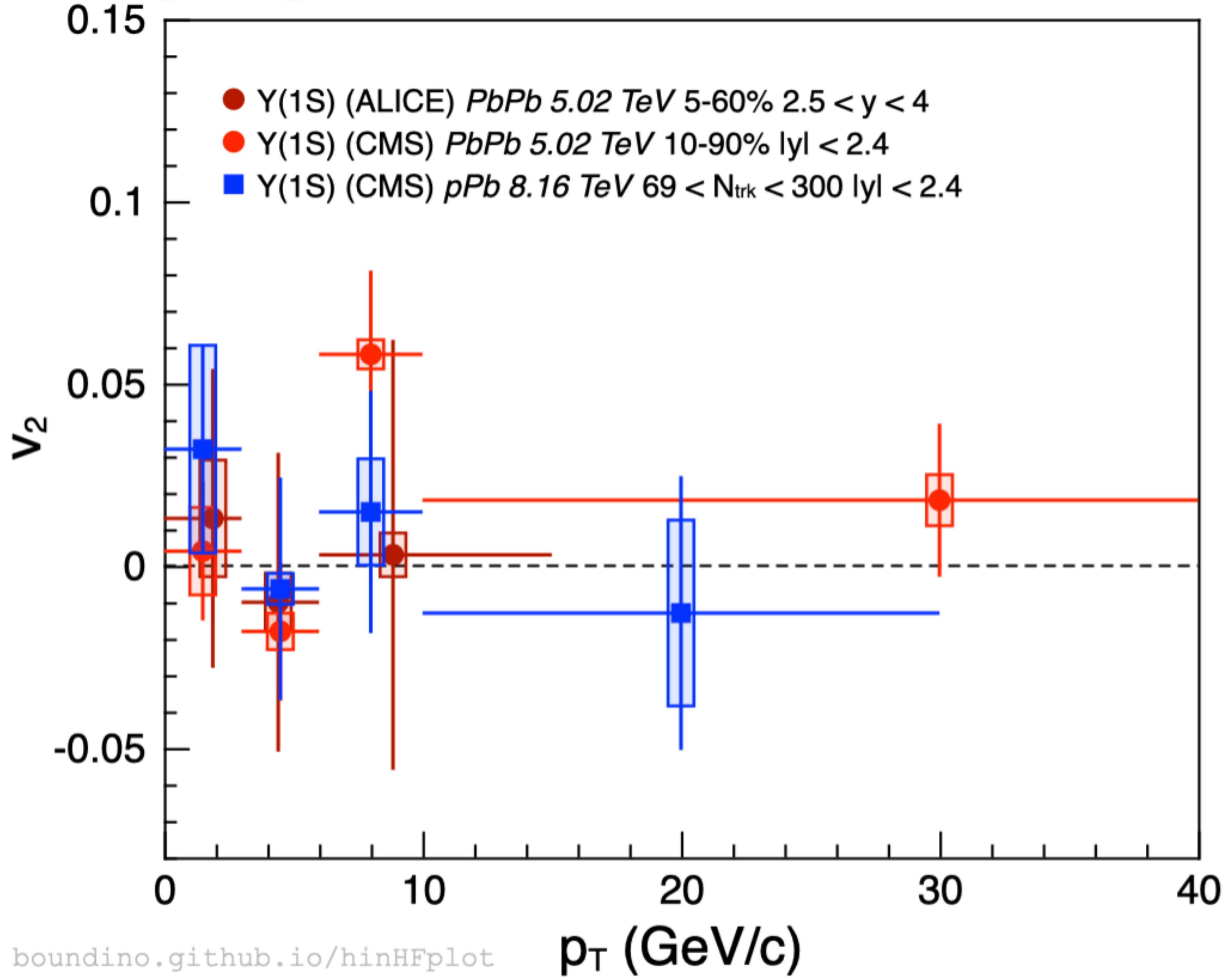
PbPb

pPb

pp



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



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

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

Summary

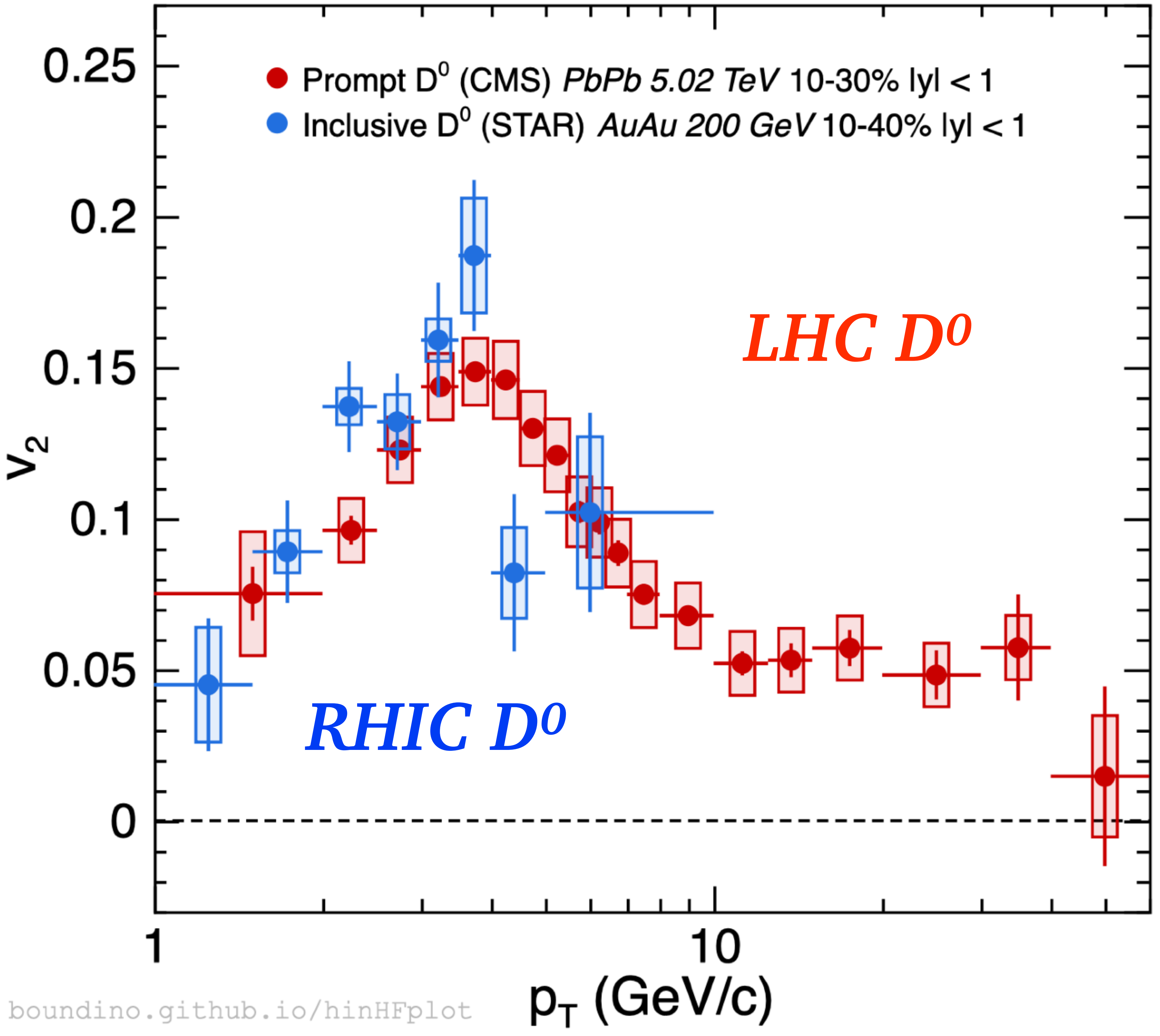
- Enormous studies done in quarkonium production and medium response in both theory and experiment
- Clear signature of recombination effects for charmonia at low-p_T in LHC energies compared to RHIC
- Sequential suppression observed for Υ(1S), Υ(2S), and Υ(3S) in PbPb collisions
- Production inside jets to be studied in more detail both in theory and experiment
- Sophisticated studies needed of dynamical recombination effects for bottomonia in AA collisions
- Still unclear of the feature in small systems
- Many new useful measurements expected at RHIC to further study / confirm the understanding of the dynamics of quarkonia in heavy ion collisions

Back-up

Open vs Hidden charm in AA

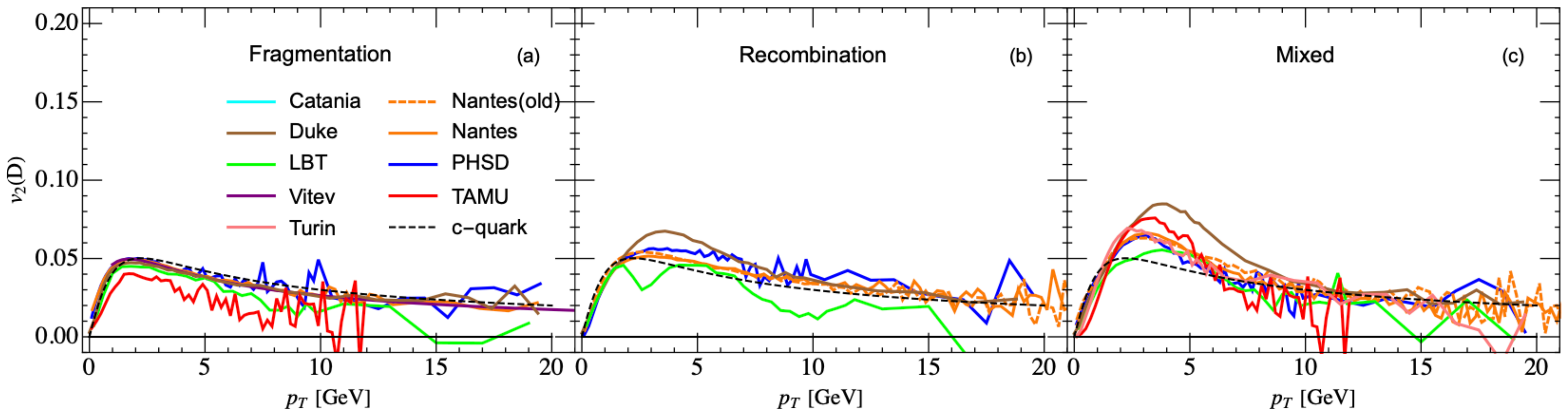
[HP23 Jiaxing Zhao]

→ PLB 816 (2021) 136253 → PRL 118 (2017) 212301



	Frag.	Recom.	Recom. Form	Charmed hadrons involved
Catania	Peterson	Phase space Wigner function	$W(x,p)=\prod_{i=1}^{N_q-1} A_W \exp\left(-\frac{x_i^2}{\sigma_{ri}^2}-p_i^2\sigma_{ri}^2\right)$	S-wave, D0,Ds, D*+,D*0,D*s,several excited states of \Lambda_c,\Sigma_c
Duke	Pythia 6.4/ Peterson	Momentum space Wigner function	$W(p)=g_h\frac{(2\sqrt{\pi}\sigma)^3}{V}e^{-\sigma^2p^2},$	S-wave,D,D*
LBT	Pythia 6.4/ Peterson	Momentum space Wigner function	$W_s(p) = g_h\frac{(2\sqrt{\pi}\sigma)^3}{V}e^{-\sigma^2p^2},$ $W_p(p) = g_h\frac{(2\sqrt{\pi}\sigma)^3}{V}\frac{2}{3}\sigma^2p^2e^{-\sigma^2p^2}.$	S-wave,P-wave,D,Ds,D*, \Lambda_c,\Sigma_c,\Xi_c. \Omega_c
Nantes	HQET	Phase space Wigner function	$W(x_Q,x_q,p_Q,p_q)=\exp\left(\frac{(x_q-x_Q)^2-[(x_q-x_Q)\cdot u_Q]^2}{2R_c^2}-\alpha_d^2(u_Q\cdot u_q-1)\right)$	S-wave, D0
PHSD	Peterson	Phase space Wigner function	$W_s(r,p) = \frac{8(2S+1)}{36}e^{-\frac{r^2}{\sigma^2}-\sigma^2p^2},$ $W_p(r,p) = \frac{2S+1}{36}\left(\frac{16}{3}\frac{r^2}{\sigma^2}+\frac{16}{3}\sigma^2p^2-8\right)e^{-\frac{r^2}{\sigma^2}-\sigma^2p^2},$	S-wave, P-wave D+,D0,Ds, D*+,D*0,D*s
TAMU	thermal density correlated HQET	Resonance amplitude	$\frac{\gamma_M}{\Gamma}v_{rel}g_\sigma\frac{4\pi}{k^2}\frac{(\Gamma m)^2}{(s-m^2)^2+(\Gamma m)^2}$	D+,D0,Ds and few excited states. Charm baryons+missing baryons
Turin	Pythia 6.4/ String fragmentation	Invariant mass criterion	$M_D < M_{Cluster} < M_{max.}$	(prompt) D+,D0,Ds,\Lambda_c, \Xi_c,\Omega_c
Los Alamos	HQET	–	–	S-wave, D+,D0,Ds, charm-baryons

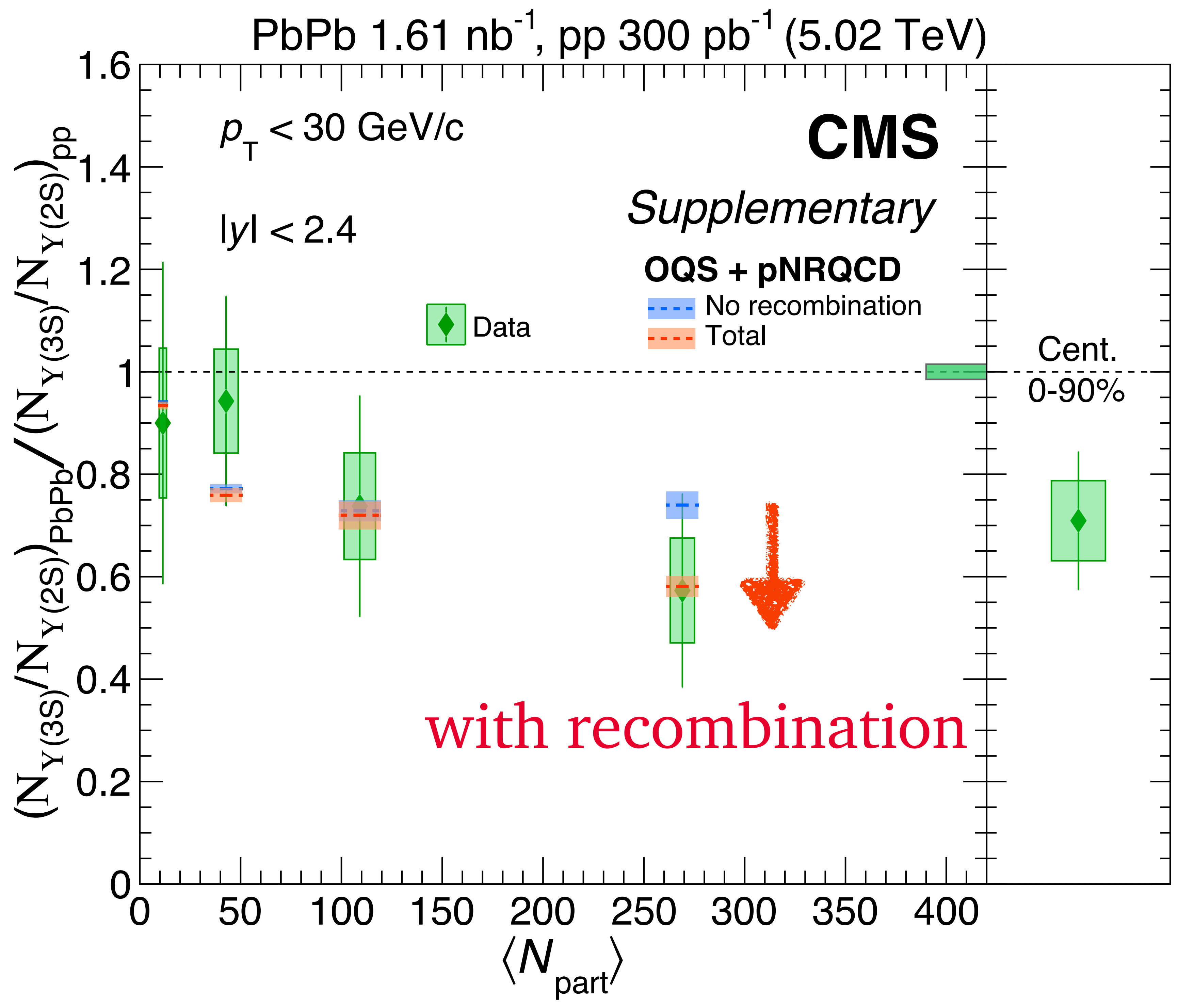
D



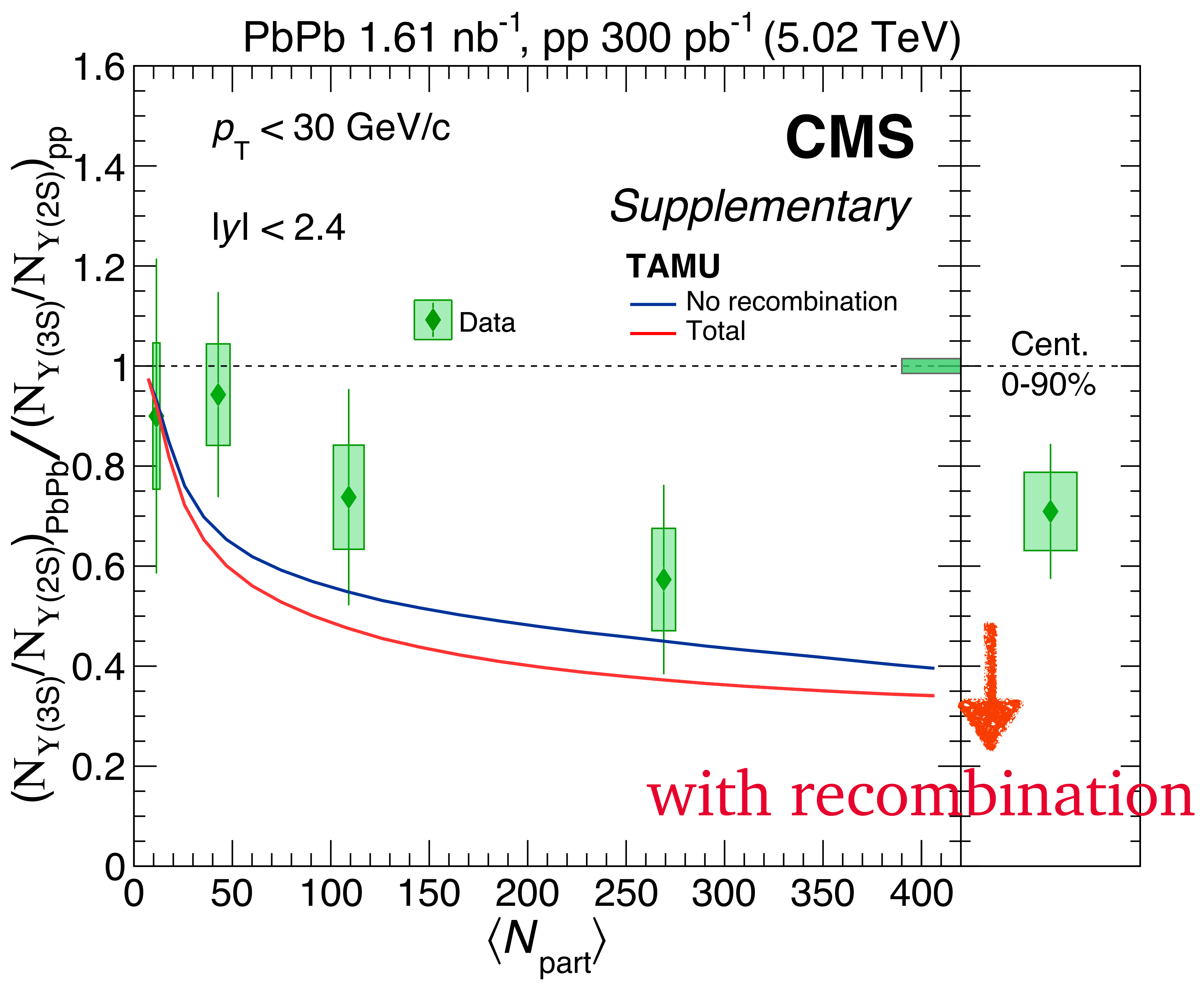
- Similar v_2 for STAR & CMS : expected?
  : need more precision data from RHIC
- Similar results although of the very different medium response mechanisms
  : Efforts to disentangle ingredients both on theory & experiment

Recombination effect

OQS + pNRQCD

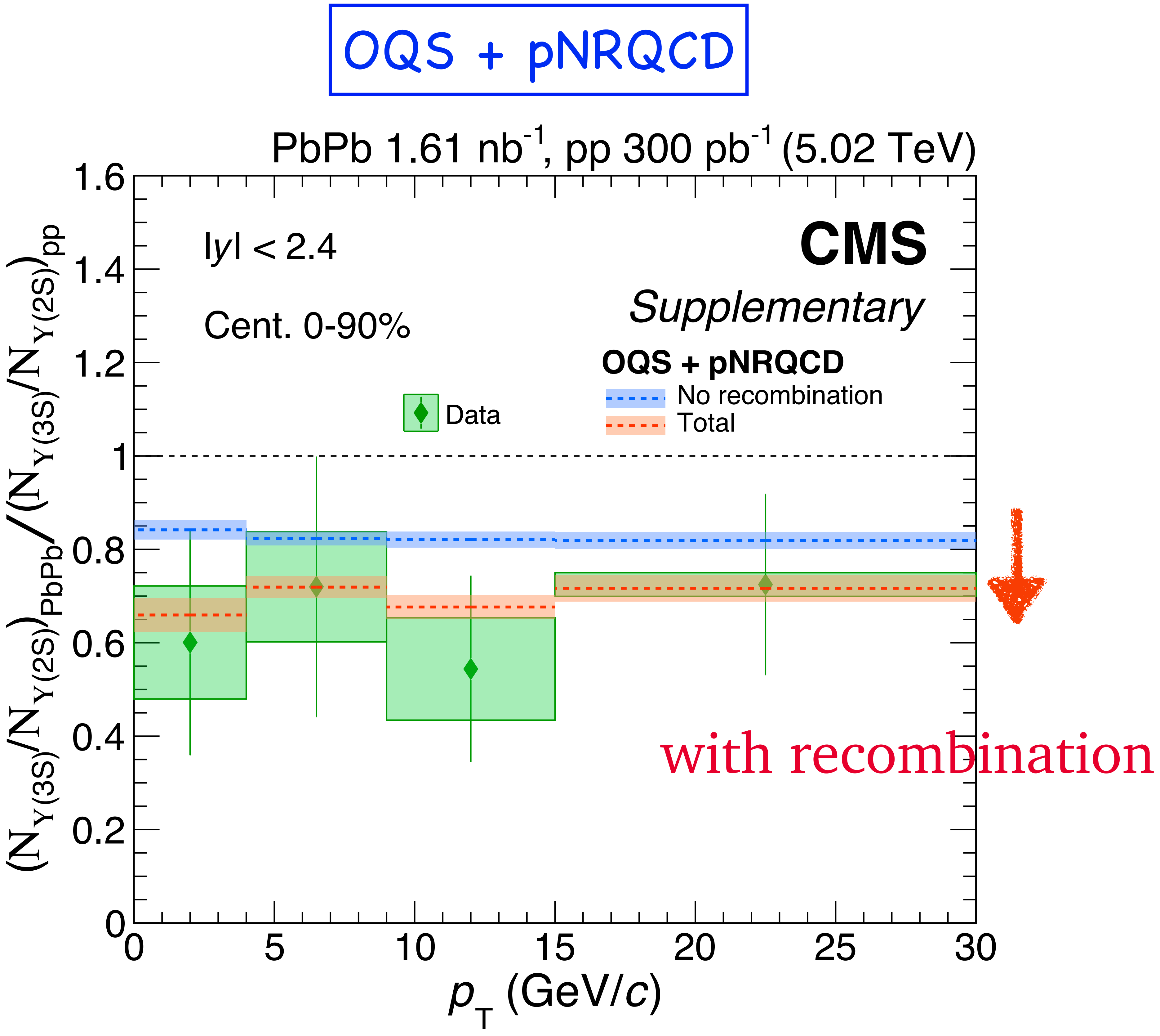


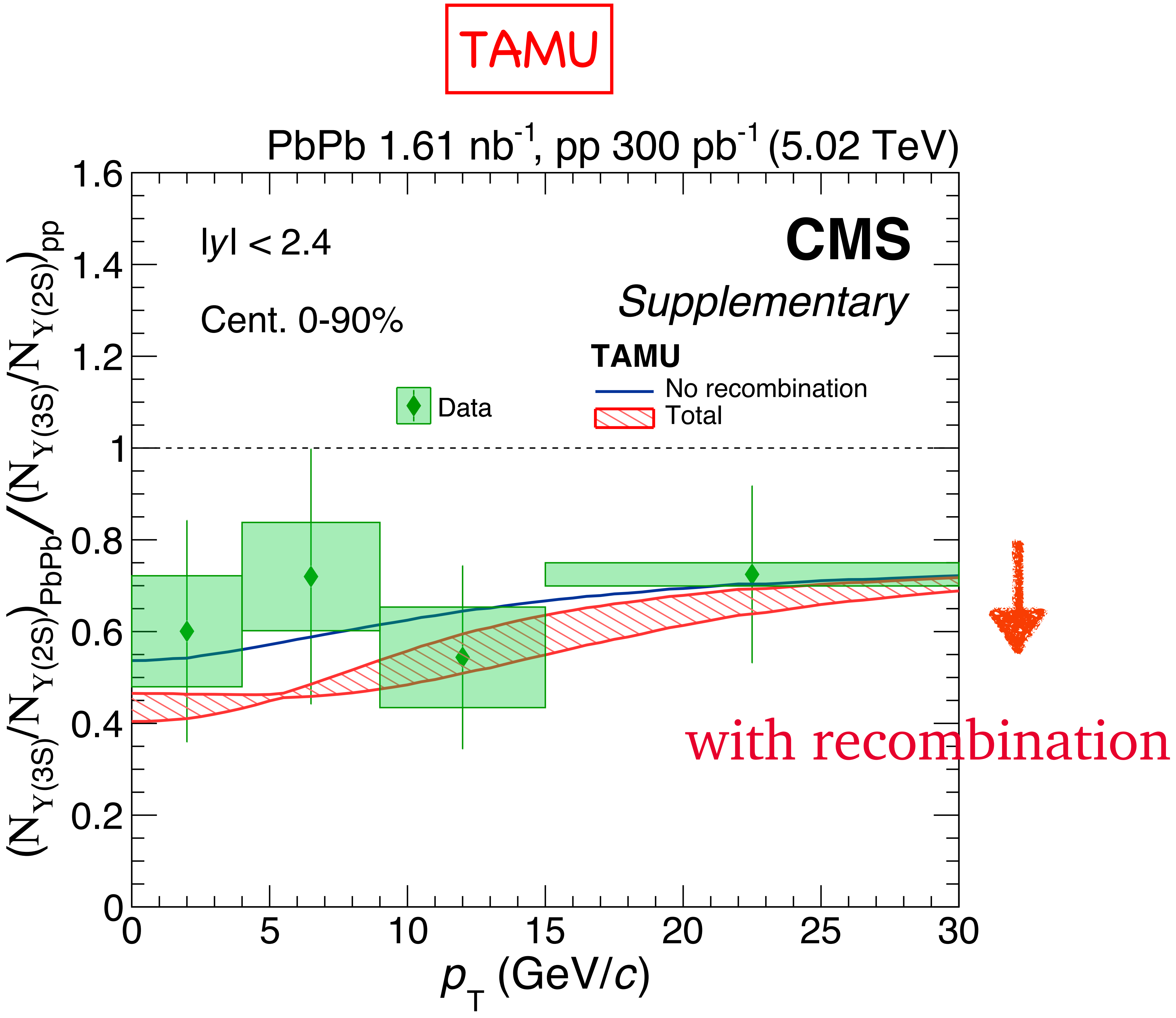
TAMU



- Decrease of Y(3S)/Y(2S) double ratio w/ recomb. —> more recomb. for Y(2S)!
- Suppression : Y(3S) > Y(2S) > Y(1S) <—> Recombination : Y(2S) > Y(3S) > Y(1S)

Recombination effect





- Similar finding seen vs p_T : Larger recombination for Y(2S) than Y(3S)
- Important for sophisticated treatment of recombination for excited states

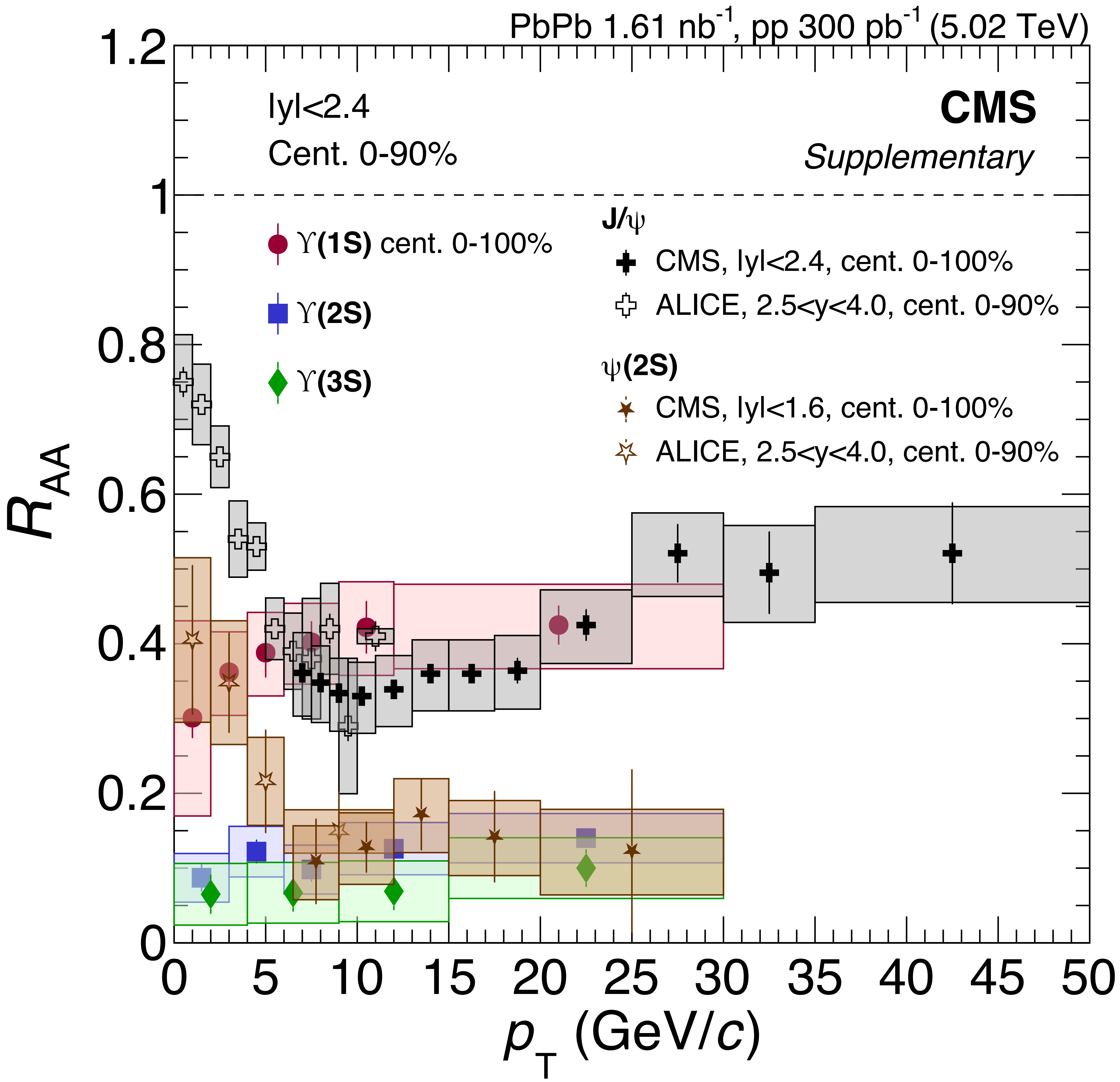
Quarkonia R_{AA}

[PLB 790 (2019) 270]

[EPJC 78 (2018) 509]

[JHEP 02 (2020) 041]

[arXiv:2210.08893]



- R_{AA} of five S-wave quarkonium states vs p_T
- Enhancement of R_{AA} for charmonia at low-p_T
  - Abundant charm production
- Towards high-p_T
  - When (if any) start to see increase vs p_T?
  - Interesting to see how much coming from jet-fragmentation

Feed down correction

[PRC 107 (2023) 054905]

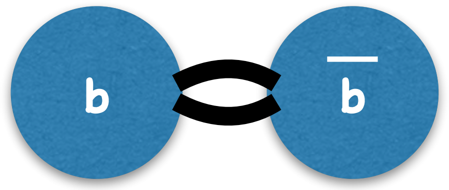
[JHEP 11 (2015) 103]

[PLB 749 (2015) 14]

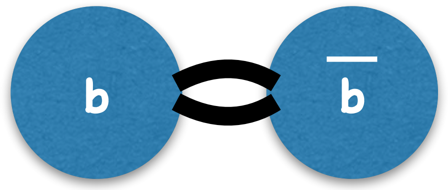
[EPJC 74 (2014) 3092]

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

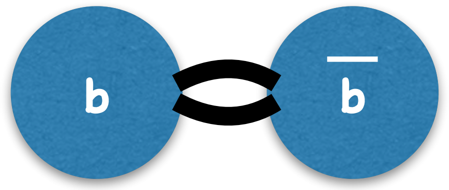
Υ(1S)

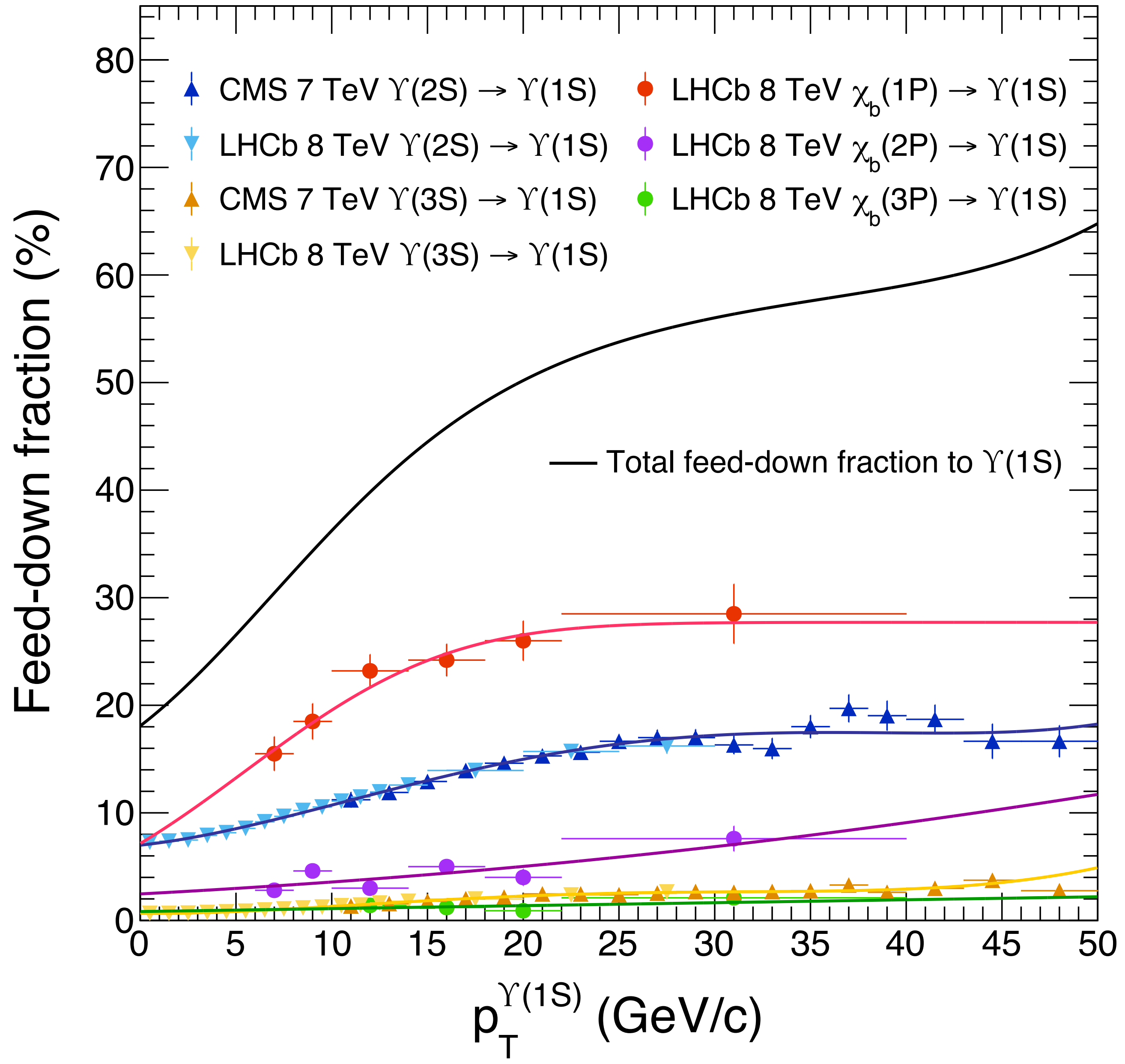


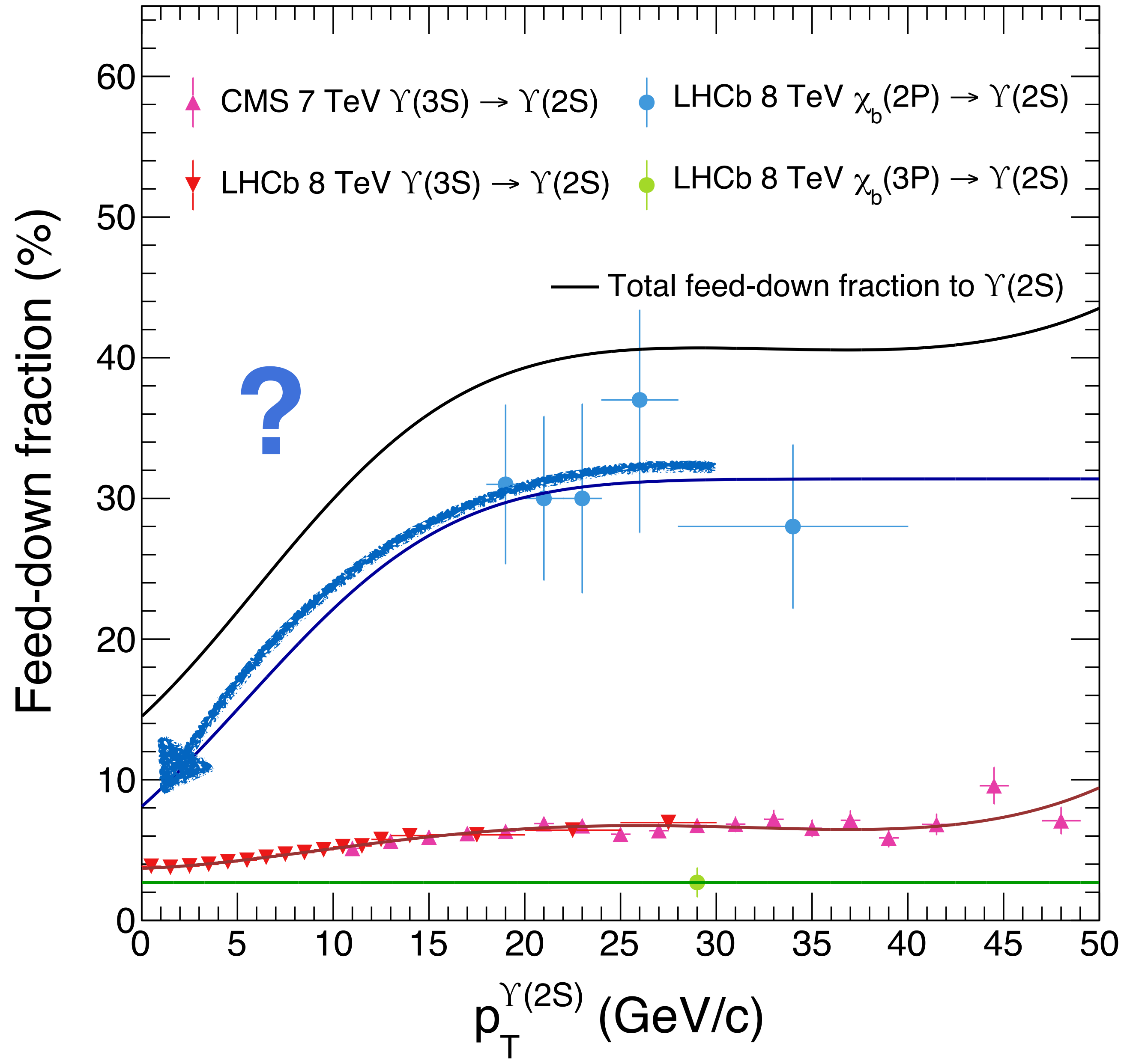
Υ(2S)

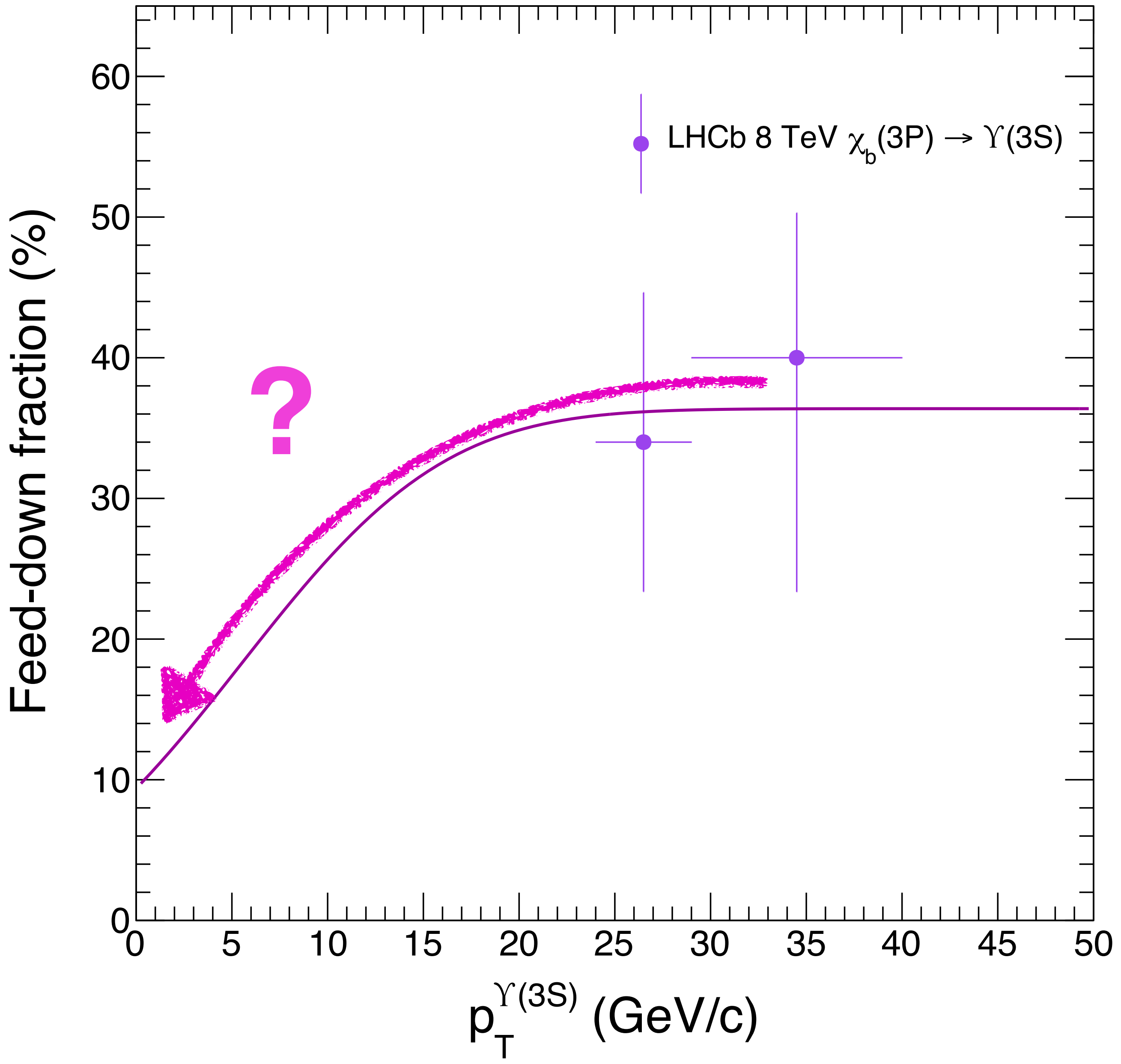


Υ(3S)









Comover vs Transport

Comover Interaction Model

- Survival probability of quarkonium interacting w comovers

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

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

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

Transport Model

- Thermal rate equation of quarkonium yields

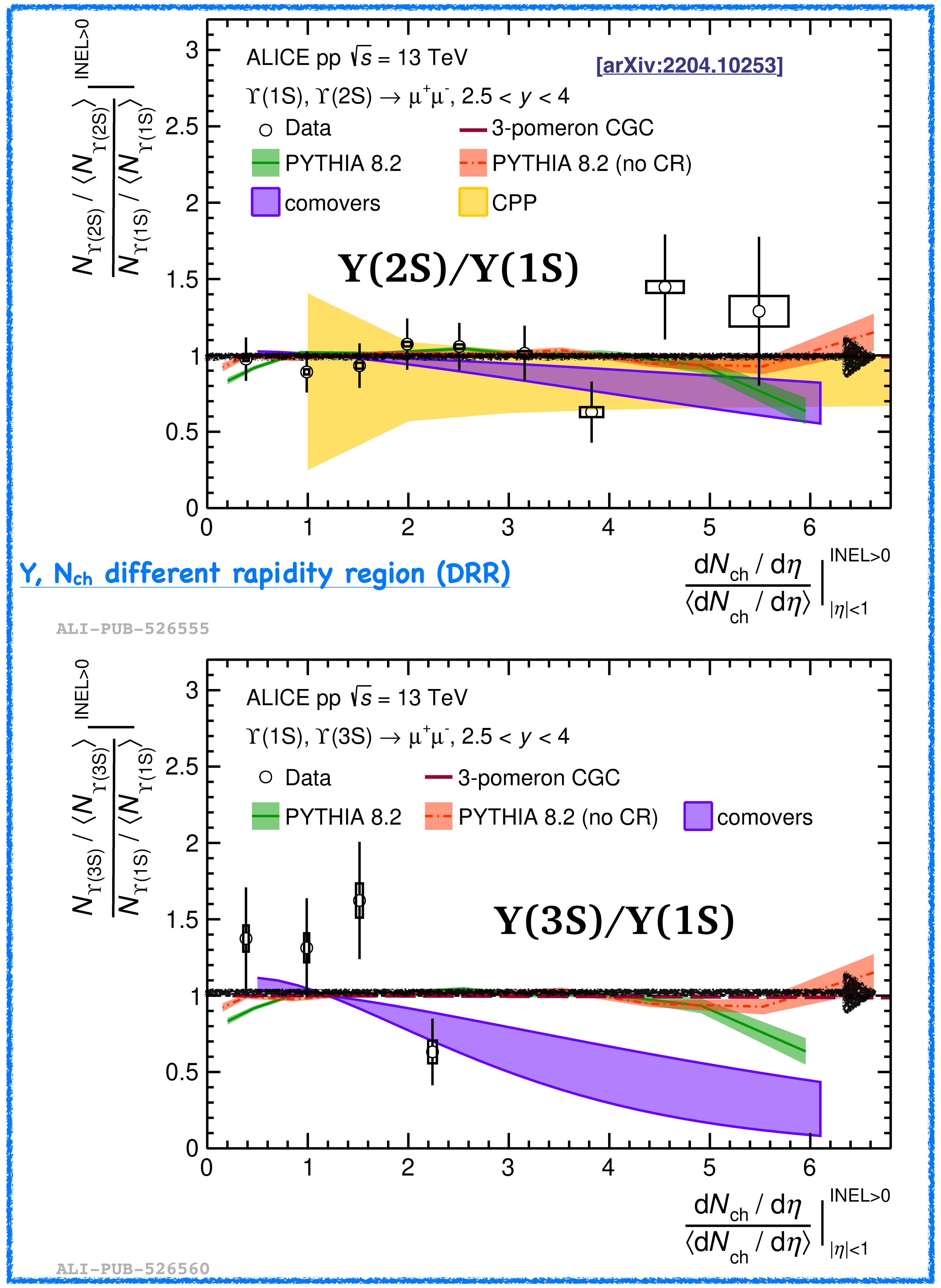
$$\frac{dN_{\Psi}(\tau)}{d\tau} = -\Gamma_{\Psi}(T(\tau))\left[N_{\Psi}(\tau) - N_{\Psi}^{eq}(T(\tau))\right]$$

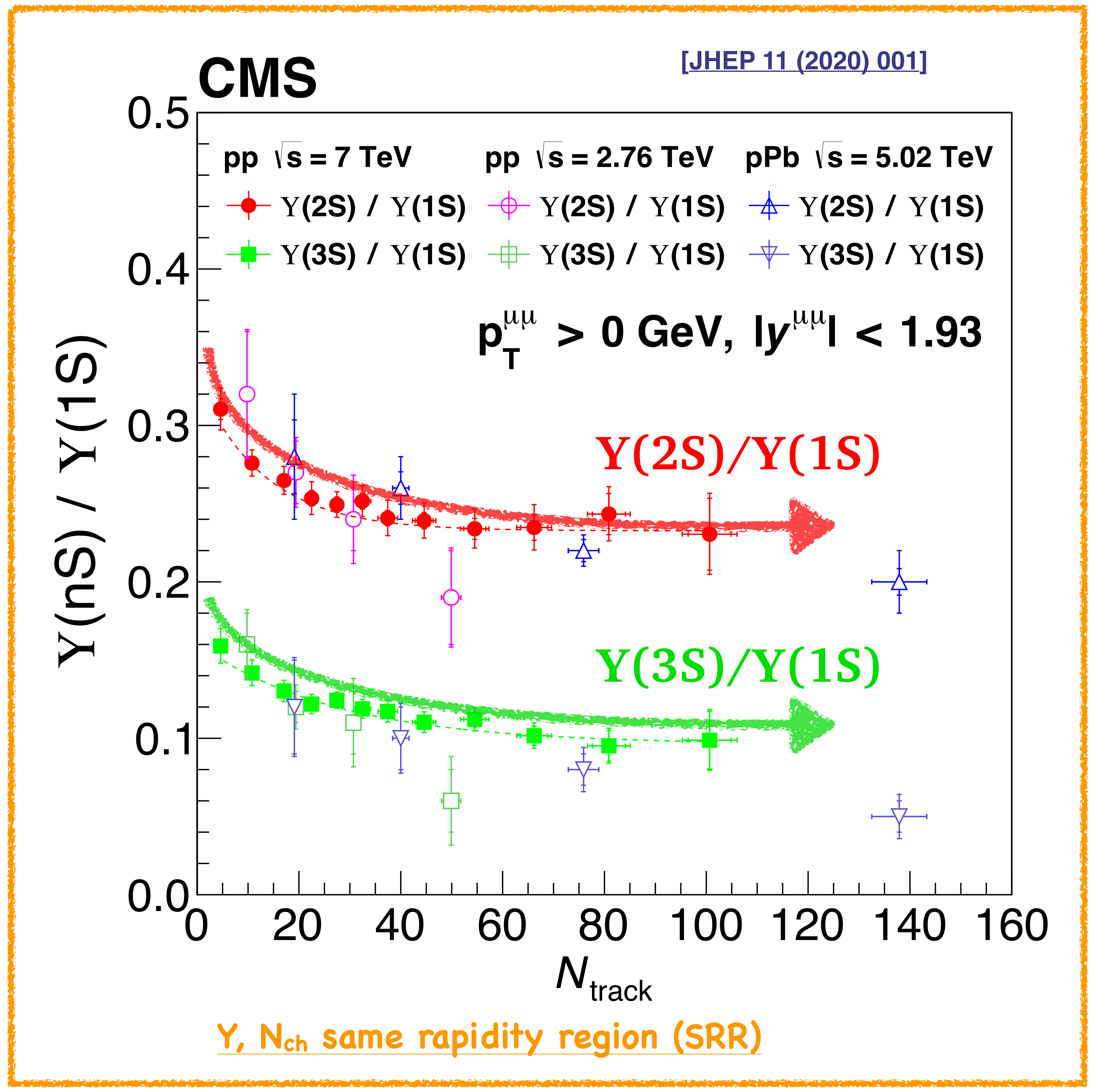
$$N_{\Psi}^{eq}(T) = V_{FB}\gamma_c^2 d_{\Psi}\int \frac{d^3p}{(2\pi)^3} f_{\Psi}^{eq}(E_p;T)$$

- 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?

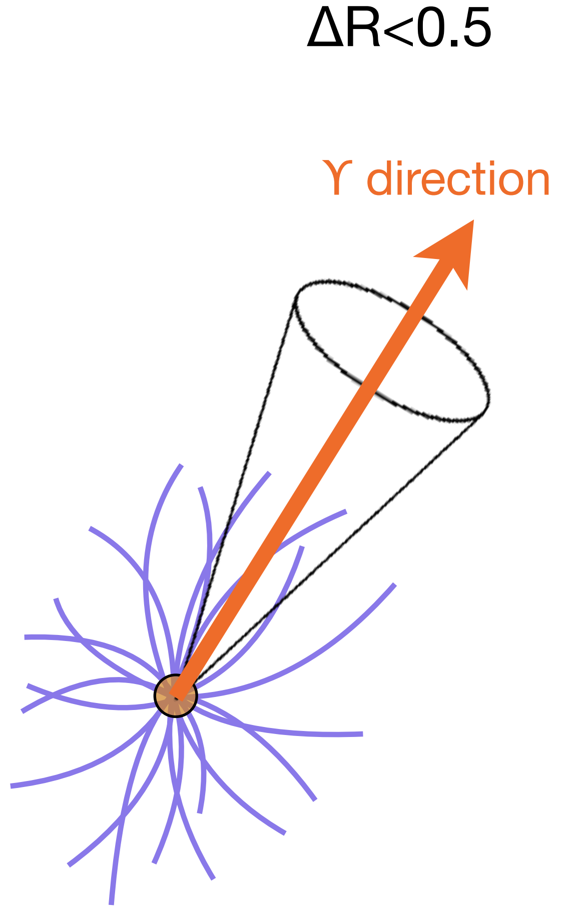
Multiplicity dependence

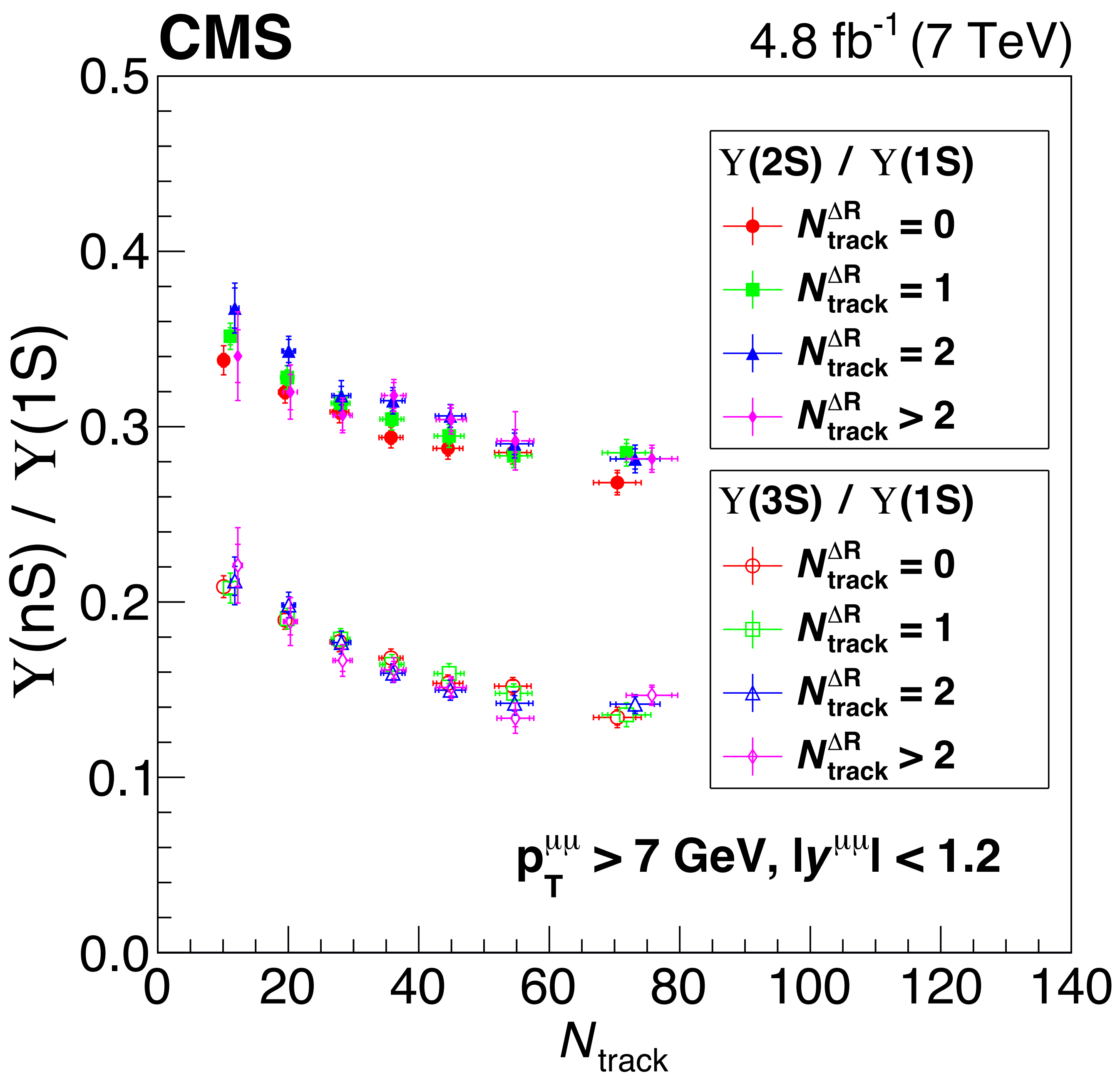


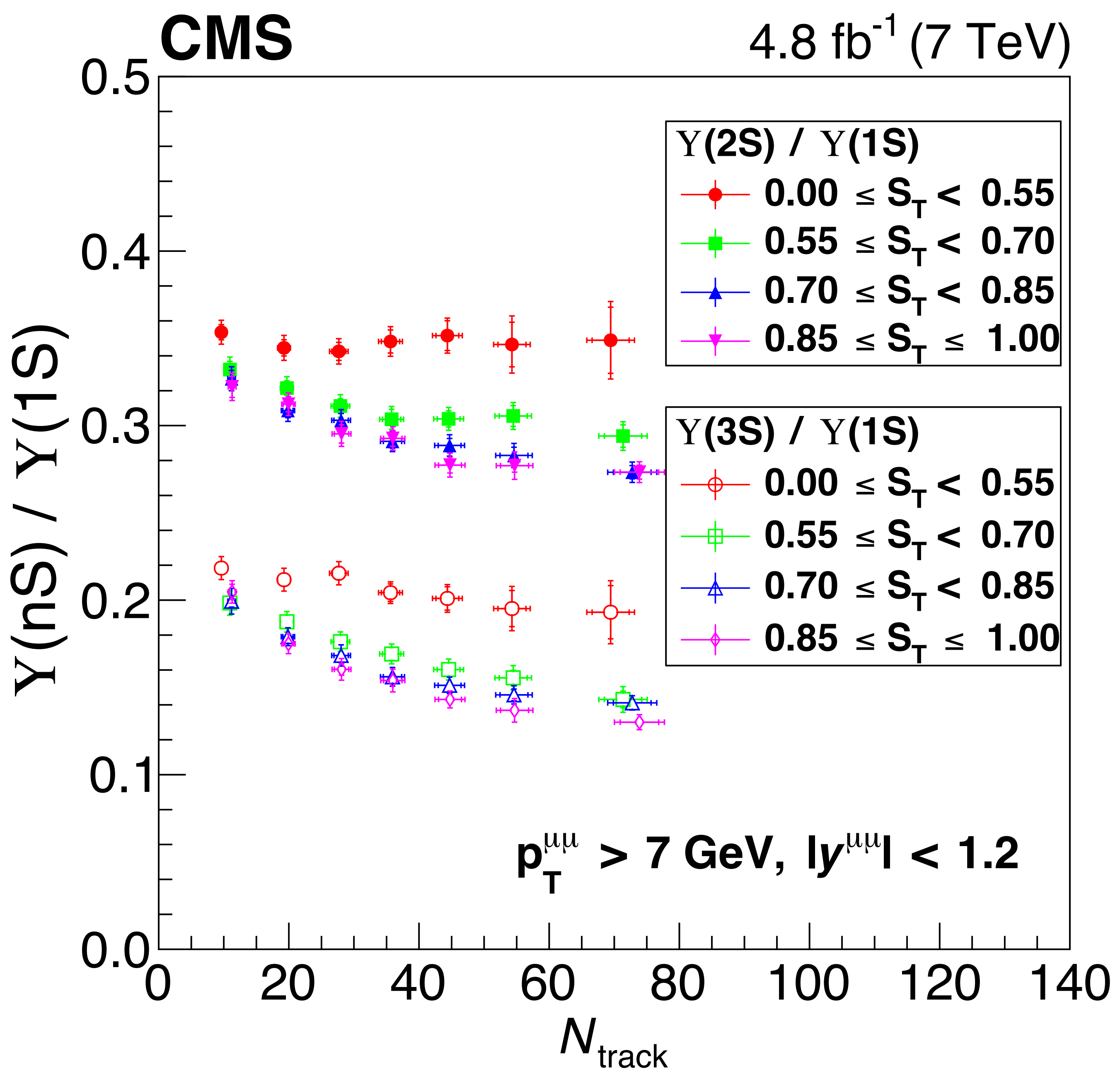


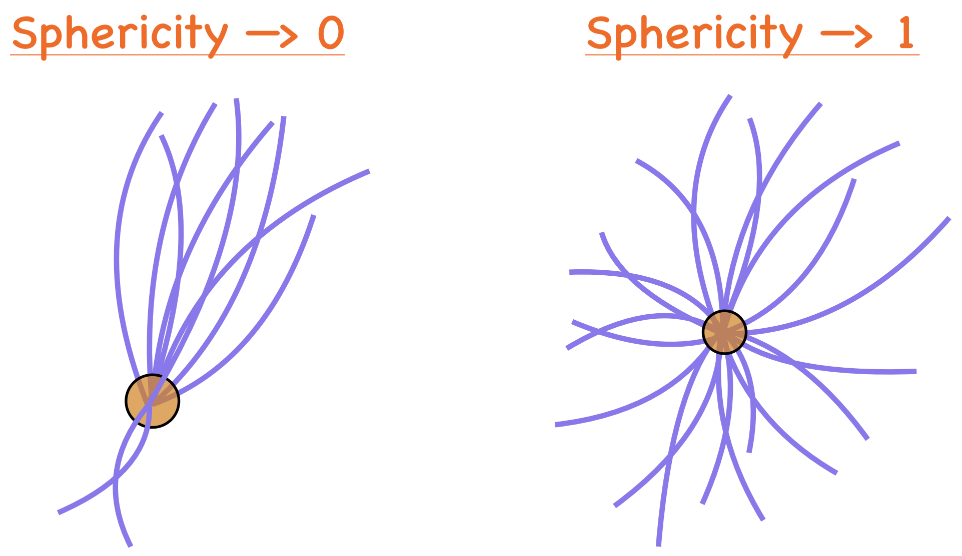
- Quarkonium production sensitive to DRR/SRR
- Excited-to-ground state suppression in DRR due to MPI/UE/correlation?

Multiplicity dependence





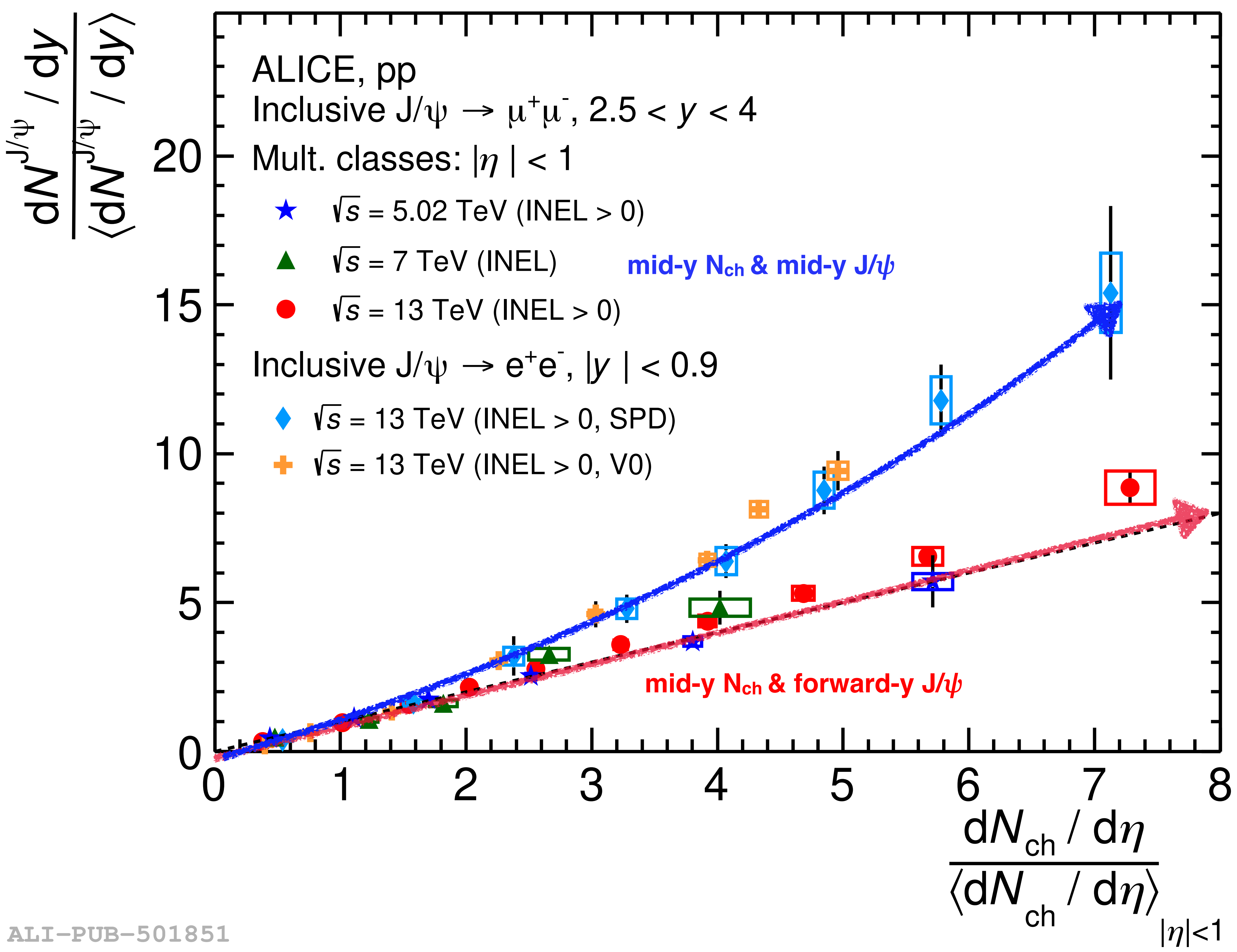




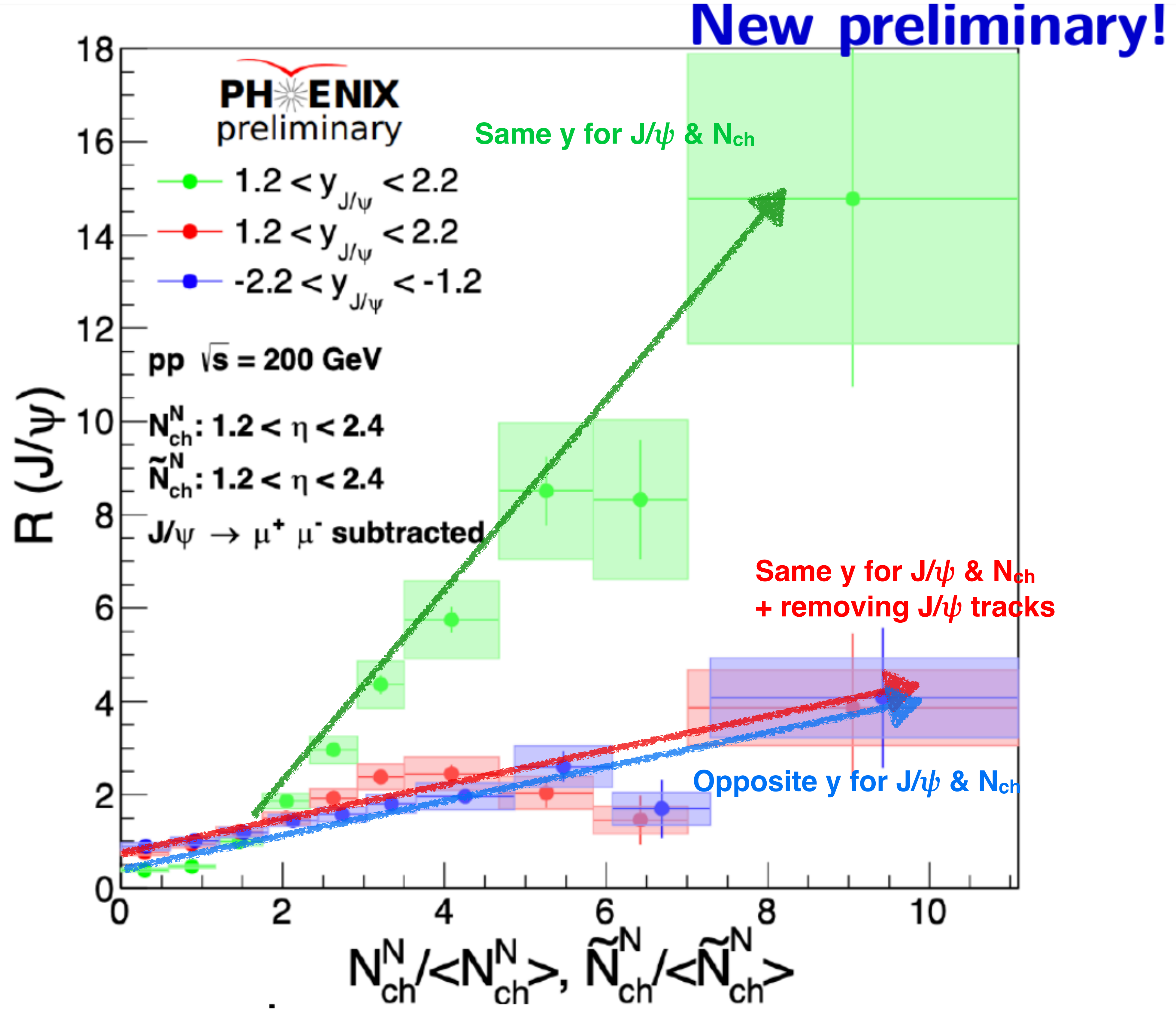
$$S_T \equiv \frac{2\lambda_2}{\lambda_1 + \lambda_2} \qquad S_{xy}^T = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix}$$

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?