CENuM for the CMS heavy-ion program

— **JaeBeom Park** (Korea University) —

	Elliptic and triangular flow of charmonium states in heavy ion collisions *Inha University*	*Prof. Sungtae Cho* 09:30 - 09:55
10:00	**CENuM for the CMS heavy-ion program** *Inha University*	*재범 빅* 09:55 - 10:20
	Simulation for Heavy IoN Collision with Heavy-quark and ONia *Inha University*	*Jinjoo Seo* 10:20 - 10:45
11:00	**Remarks on the recent UPC and heavy quark results in CMS** *Inha University*	*Prof. 용선 김* 11:00 - 11:25
	Study of upsilon(1S) flow in pPb collision system with the CMS detector *Inha University*	*기수 이* 11:25 - 11:50
12:00	**Measurement of excited state Upsilons in PbPb collision with CMS** *Inha University*	*수환 이* 11:50 - 12:15

All results here!

CENuM in CMS

- **Korea University**
  - Team Leader : Byungsik Hong
  - Post-Doc : Seyoung Han, Jaebeom Park
  - PhD candidates : Kisoo Lee, Soohwan Lee, Junseok Lee (New)

- **Sejong University**
  - Team Leader : Yongsun Kim
  - PhD candidates : Yechan Cheon, Jeongho Kim (New)

Contribution in CMS

- **PAG/POG Leadership**
  - HIN PAG convener : Yongsun (2020. 09 - present)
  - Dilepton PinG leader : JaeBeom (2020. 09 - present)

    —> following new leader : Soohwan Lee (2years)
  - E/gamma miniPOG leader : Seyoung (2020. 11 - present)

- **Service work / run-preparation related tasks** (Soohwan, Kisoo, Junseok, …)
  - Muon T&P at low-p_T for 2018 PbPb
  - miniAOD 2018 PbPb : electrons, centrality calibrations/filters
  - Run3 MB trigger : ZDC online info, MC production & ZDC neutron number effect
  - Run3 ECAL : Threshold for ZS & SR for L1 trigger
  - 2018 PbPb photon identification using TMVA
  - HLT Run3 studies for muons & electrons & photons
  - Run3 dilepton trigger team

Recent results of CENuM CMS

- **Υ(1S) elliptic flow (v_2) in pPb 8.16 TeV**
  - First measurement in small systems!
  - Investigation of Υ(1S)-h correlation
  - Reported at Quark Matter 2022 (April)

- **J/ψ and ψ(2S) flow (v_2,v_3) in PbPb 5.02 TeV**
  - First measurement of ψ(2S) in PbPb!
  - Investigation of charmonium azimuthal correlation in QGP
  - Reported at Quark Matter 2022 (April)

- **Observation of Υ(3S) in PbPb 5.02 TeV**
  - Observation of Υ(3S) in PbPb!
  - Υ sequential suppression study
  - Reported at Quark Matter 2022 (April)

- **Υ(nS) modification factors in pPb 5.02 TeV**
  - All Υ(nS) states identified in pPb for the first time!
  - Υ sequential suppression study
  - Accepted in PLB

Screening : Beginning of the journey

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

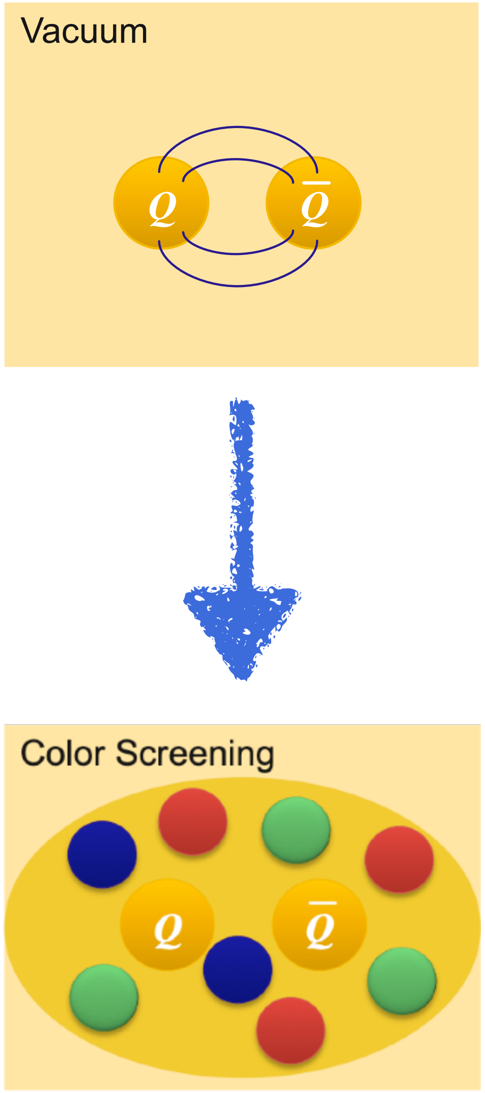
T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.



Quiz (2) : how many citations? ① 500-1000 ② 1000-2000 ③ 2000-3000 ④ 3000-4000

Screening : Beginning of the journey

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

Vacuum

J/ψ Suppression by Quark-Gluon Plasma Formation

T. Matsui (MIT, LNS), H. Satz (Bielefeld U. and Brookhaven)

Jun, 1986

7 pages

Published in: *Phys.Lett.B* 178 (1986) 416-422

Published: 1986

DOI: 10.1016/0370-2693(86)91404-8

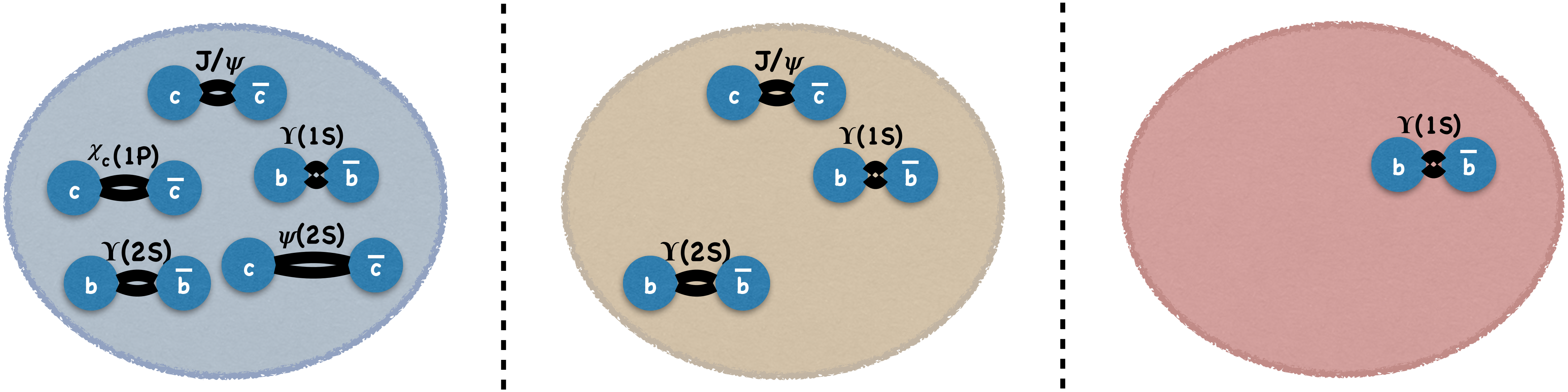
Report number: BNL-38344

View in: ADS Abstract Service

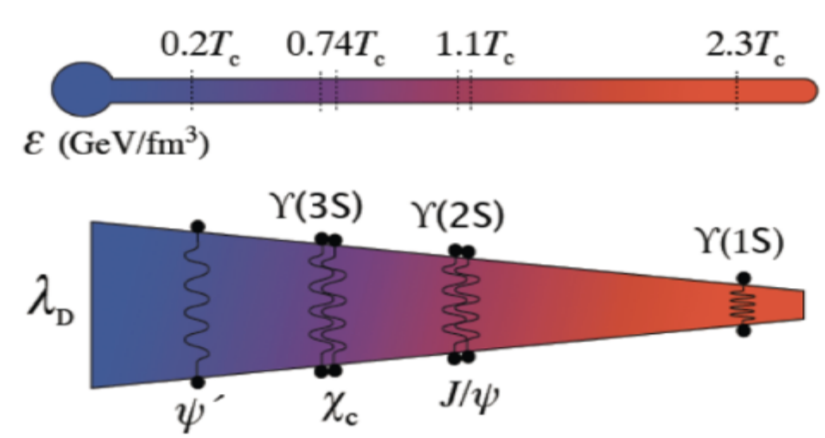
Quiz (2) : how many citations? ① 500-1000 ② 1000-2000 ③ 2000-3000 ✔ ④ 3000-4000

Quarkonia : QGP thermometer

$T \ll T_c$ | $T \approx 1.1T_c$ | $T \approx 2T_c$



T. Matsui, H. Satz [PLB 178 (1986) 416]   S. Digal, P. Petreczky, H. Satz [PRD 64 (2001) 094015]

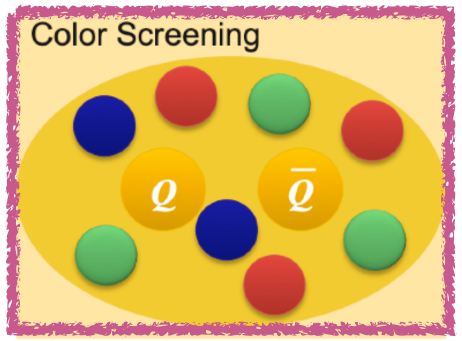


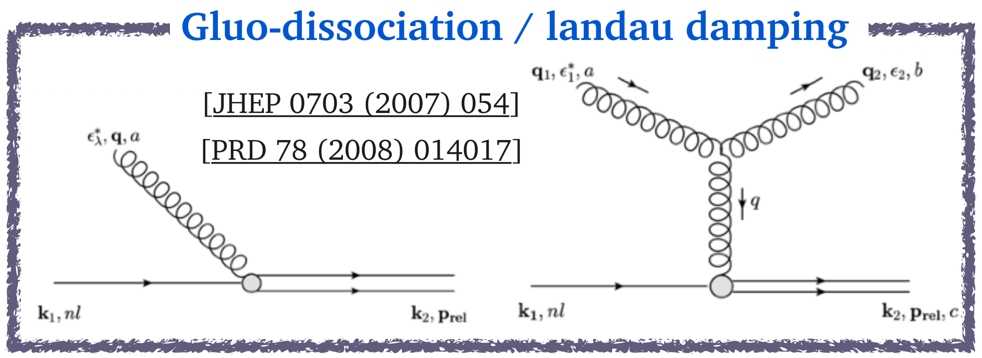
<u>Sequential melting by color screening</u>

→ Quarkonia as thermometer of QGP

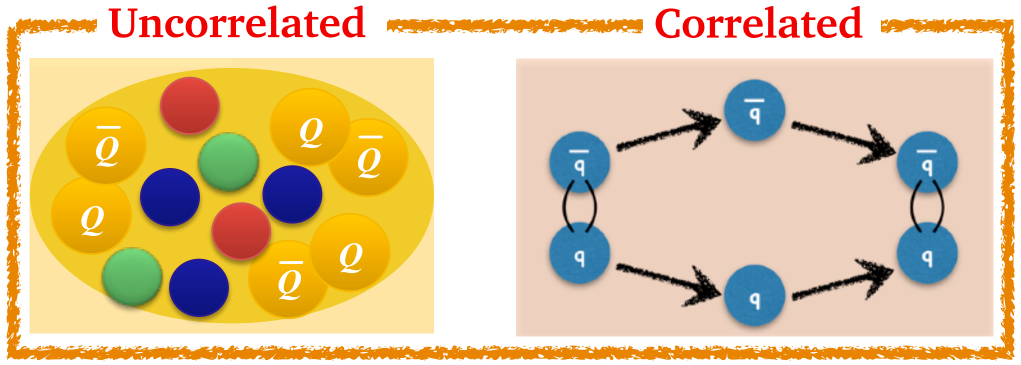
Various in-medium effects

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



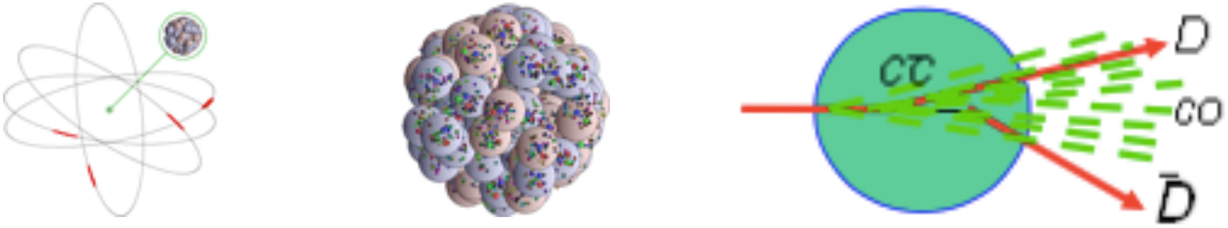


- **Recombination (Regeneration)**
  - Uncorrelated (off-diagonal) recombination
  - Correlated (diagonal) recombination

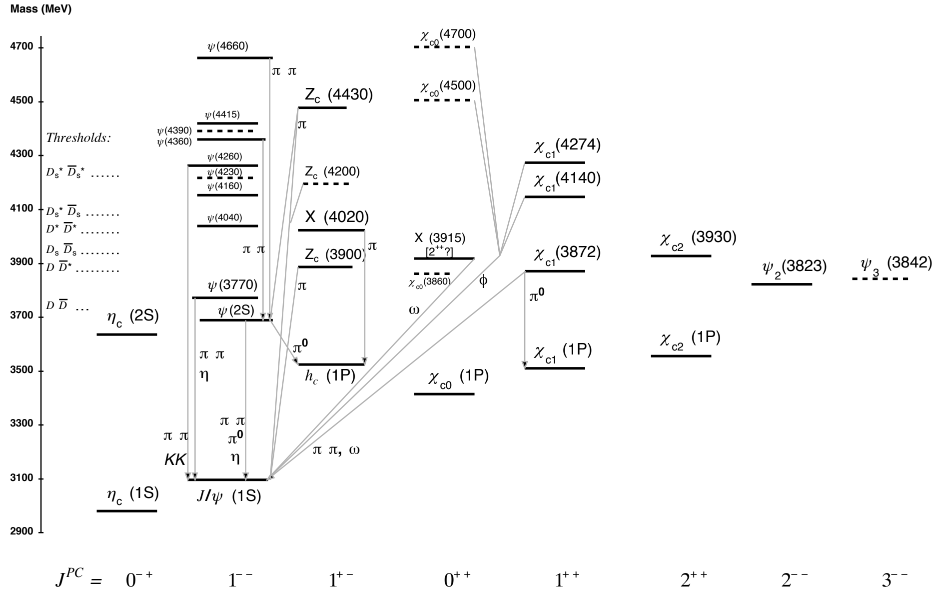


- **Initial/Final state effects of nucleus**
  - nPDF, CGC, coherent energy loss (initial/final)
  - co-mover breakup, nuclear absorption

[IJMP E 24 (2015) 1530008]



- **Feed-down contributions**



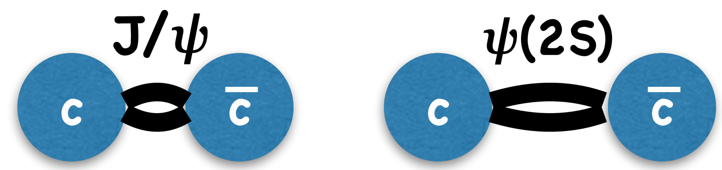
Some interesting remarks

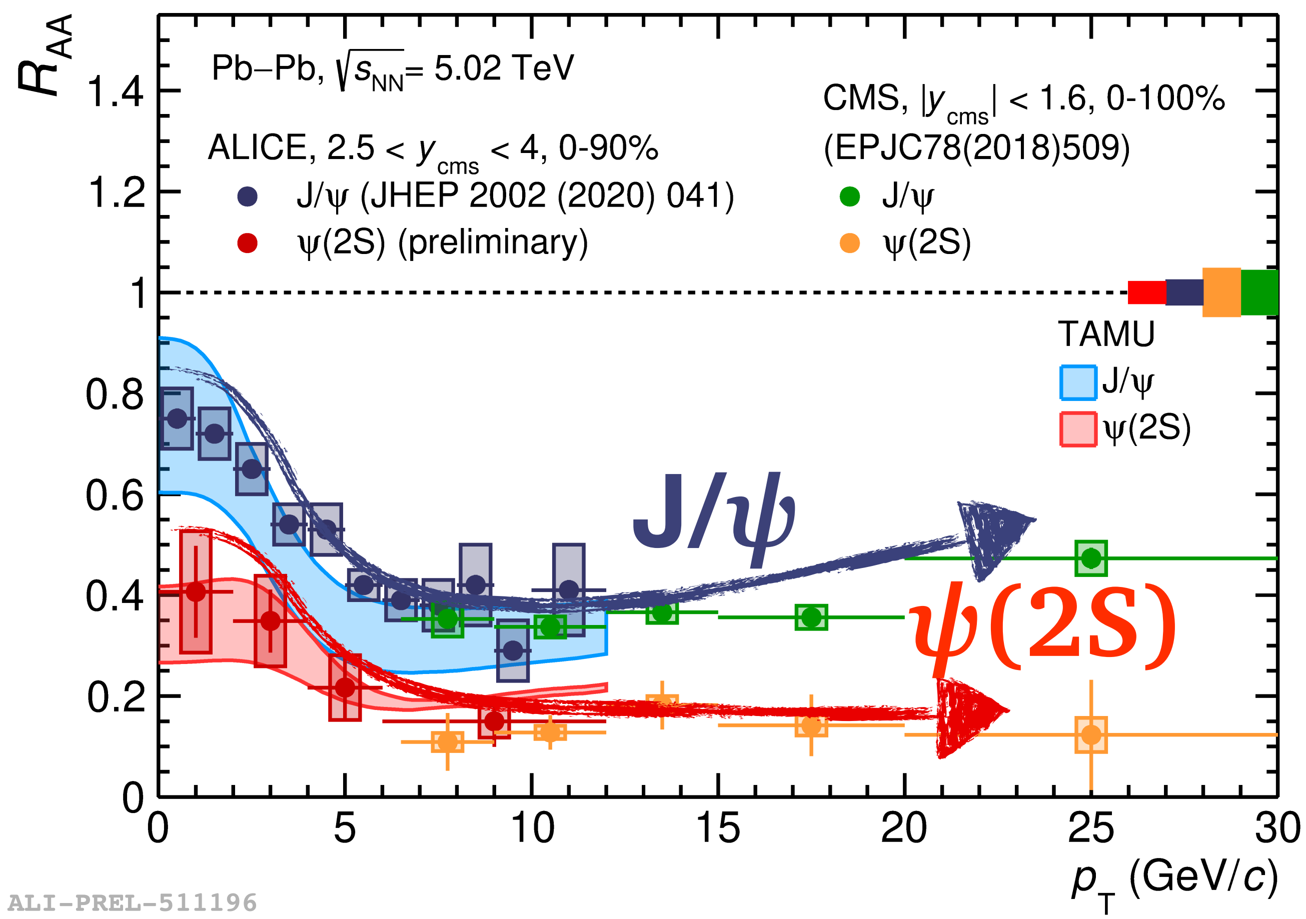
- Do quarkonia suffer only suppression and/or recombination at high-p_T?

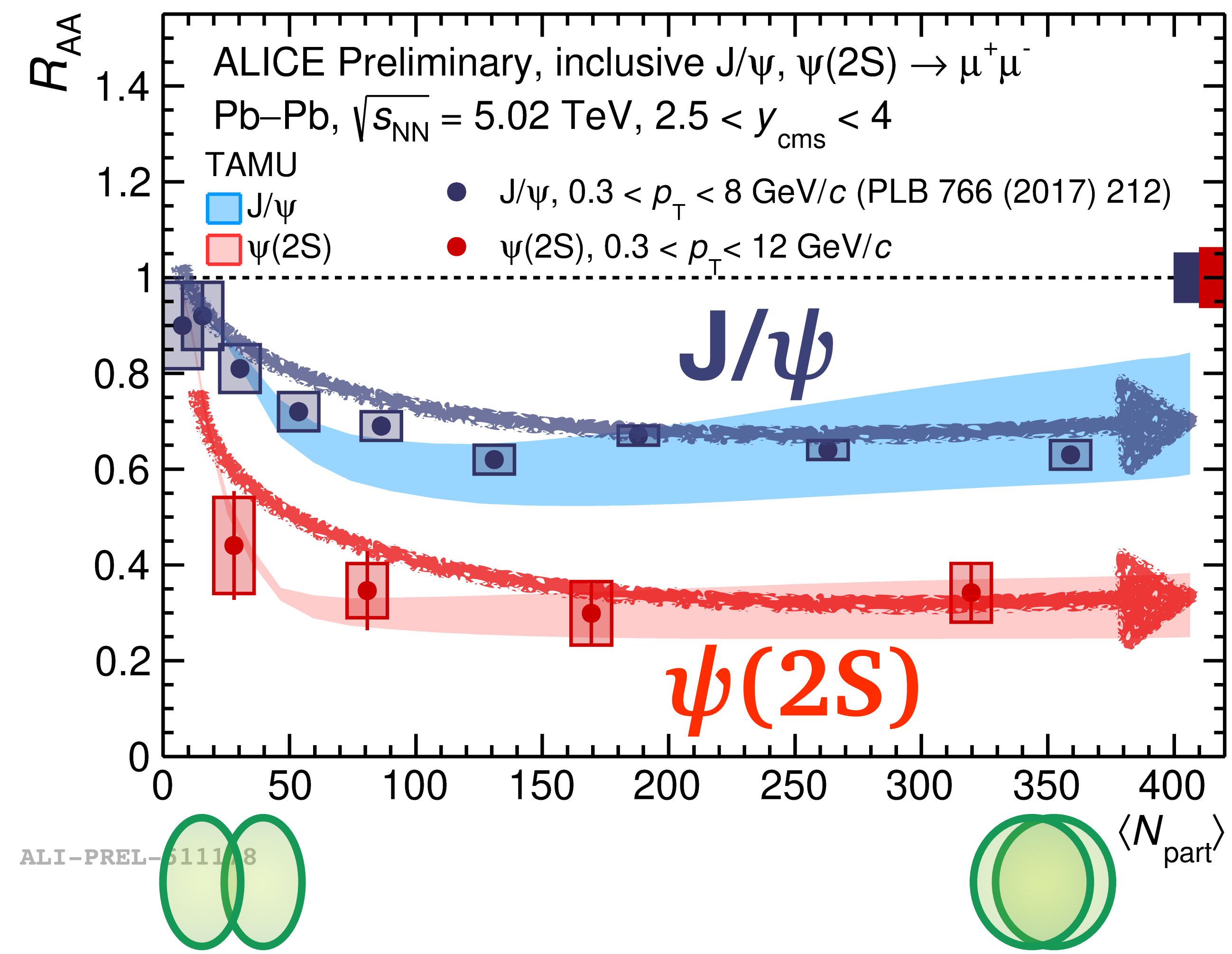
- Are the 'measured' quarkonium states coming from initial heavy quark pair?

- When are quarkonia formed inside medium?

Charmonia in AA



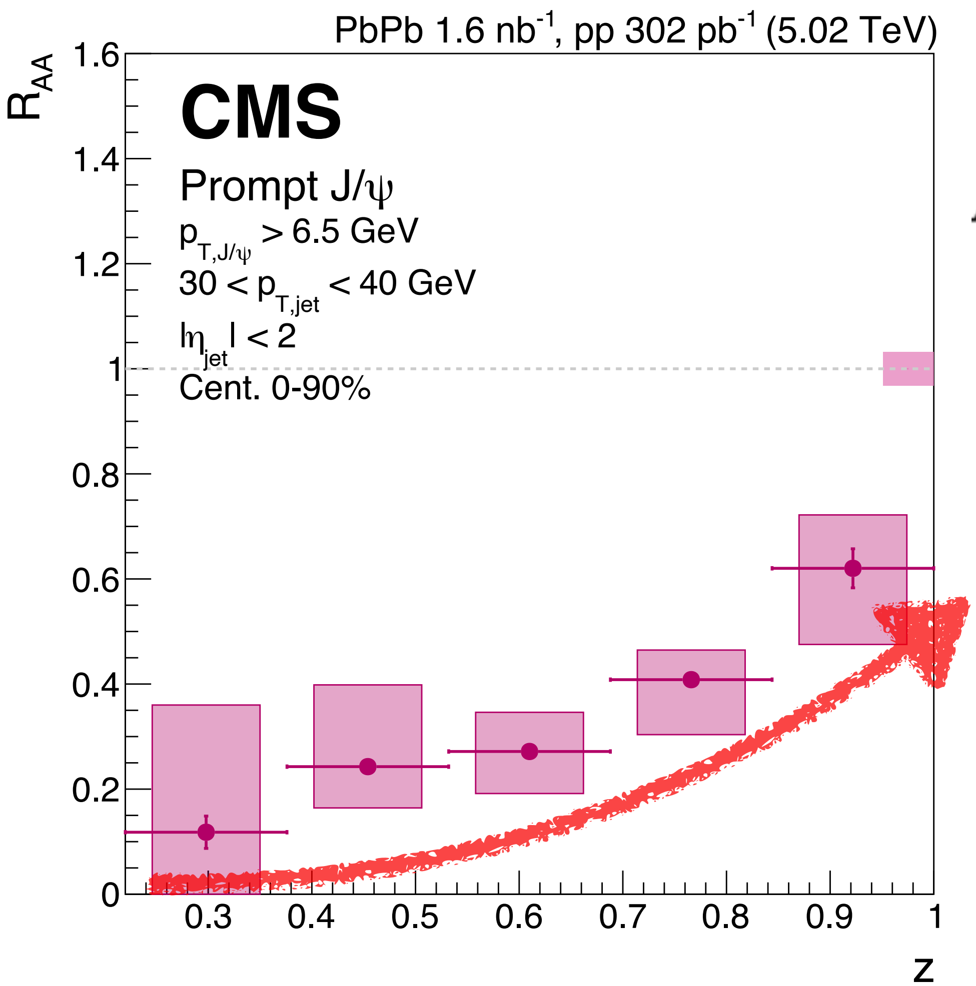


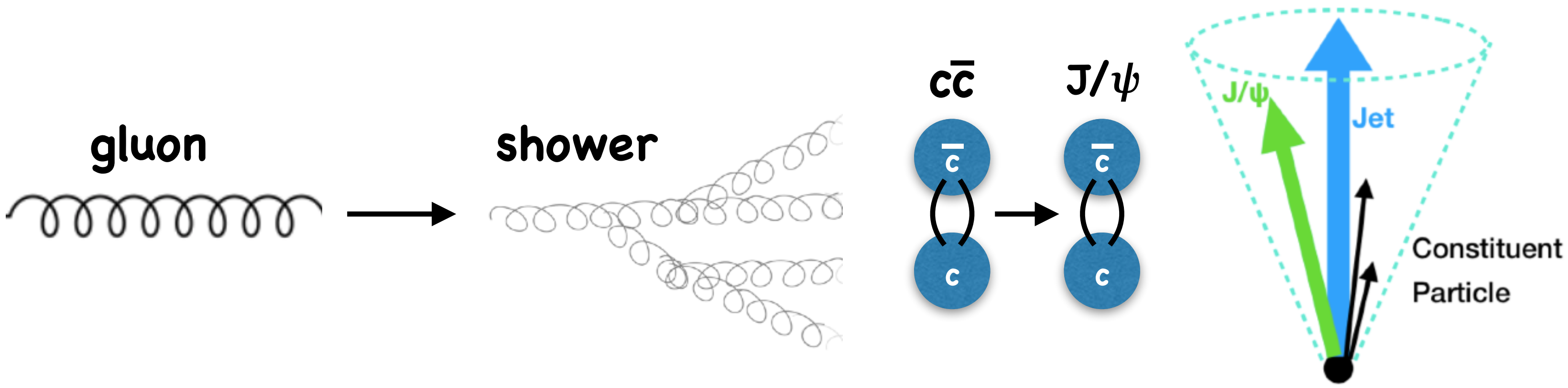


- Sequential suppression : ψ(2S) more suppressed than J/ψ
- Increasing trend at low-p_T : described by theory calculation including recombination

J/ψ in jets in PbPb

[PLB 805 (2020) 135434]

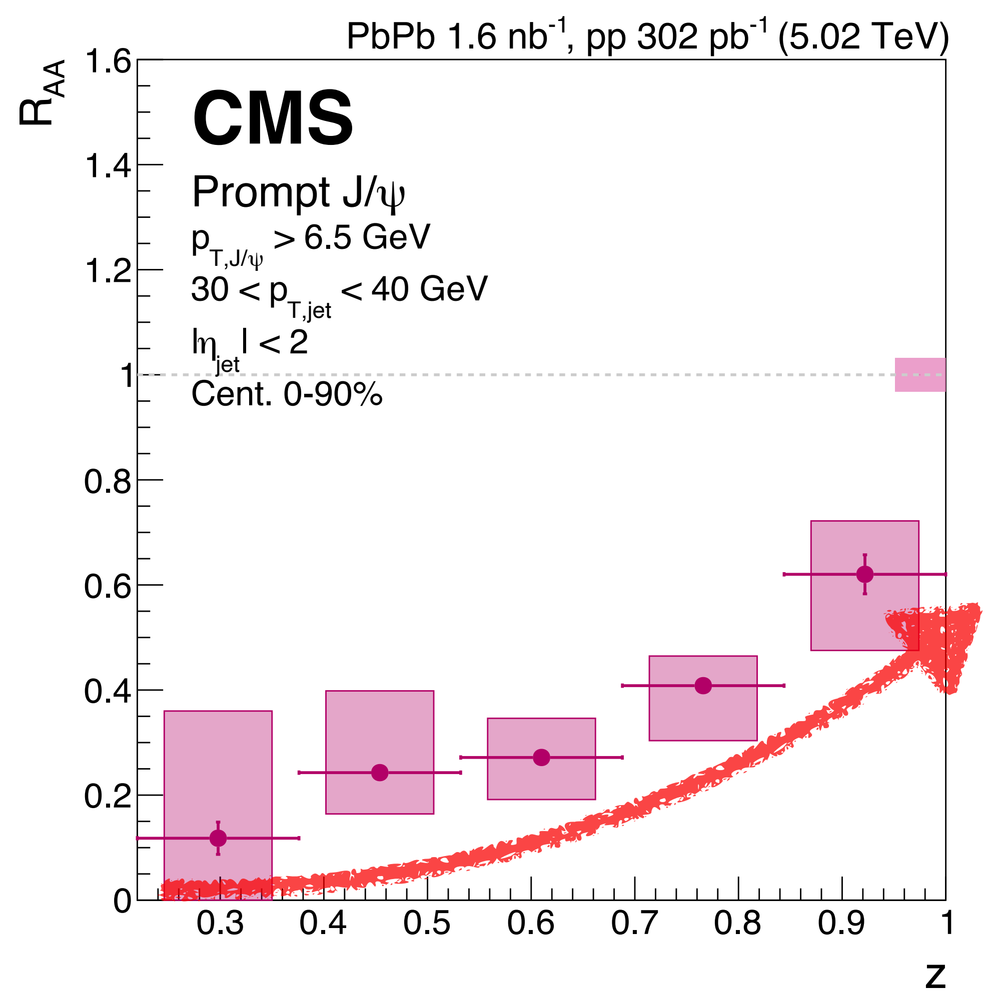


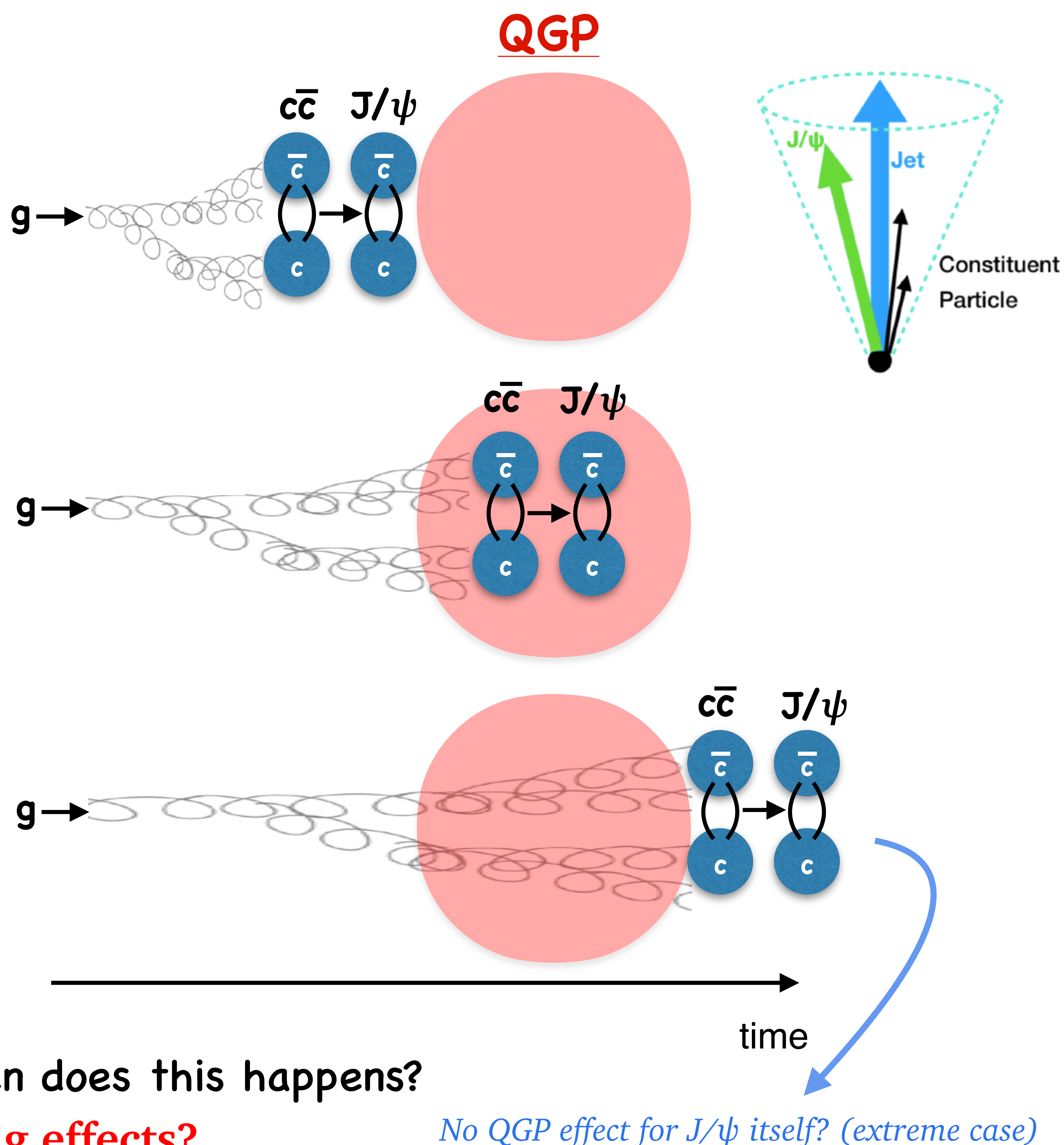


- Less suppression for isolated J/ψ
  : difference ~x5 (although large unc.)

J/ψ in jets in PbPb

[PLB 805 (2020) 135434]

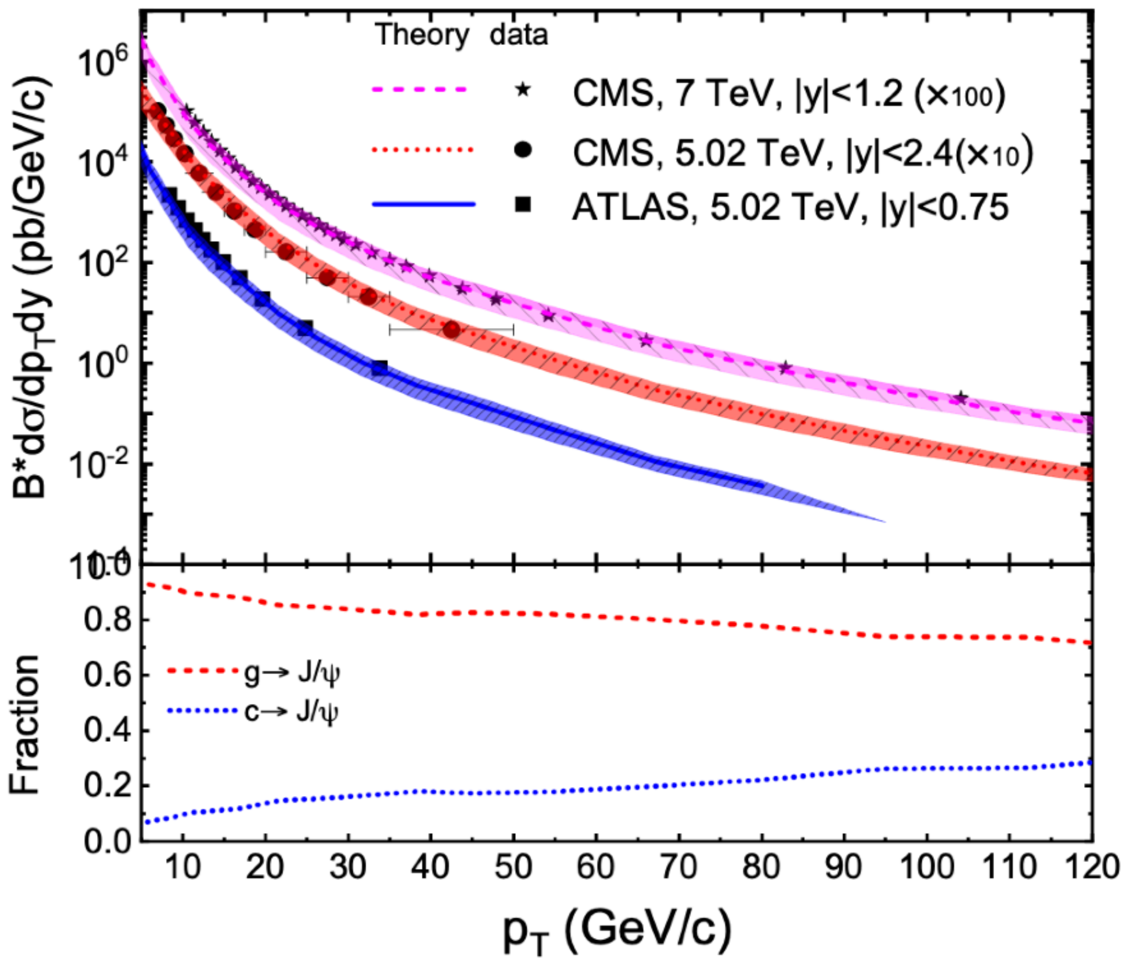


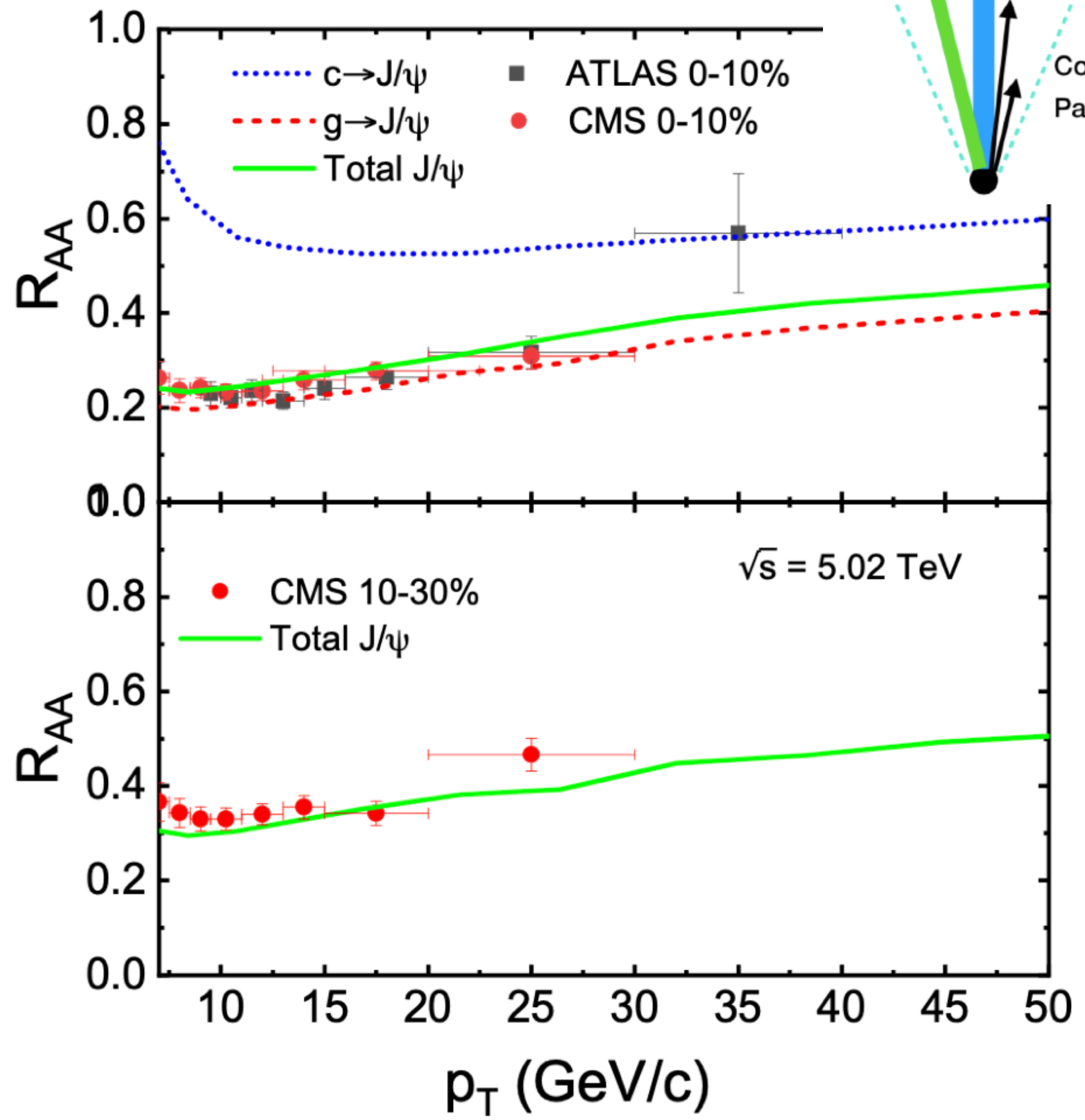


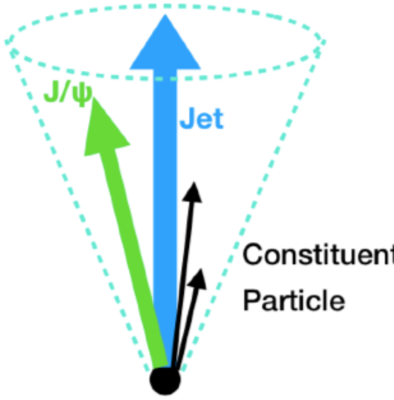
- Less suppression for isolated J/ψ
  : difference ~x5 (although large unc.)
- J/ψ production by parton shower : when does this happens?
  —> High-p_T J/ψ v_2 implies jet-quenching effects?

J/ψ in jets in PbPb

[arXiv:2208.08323]



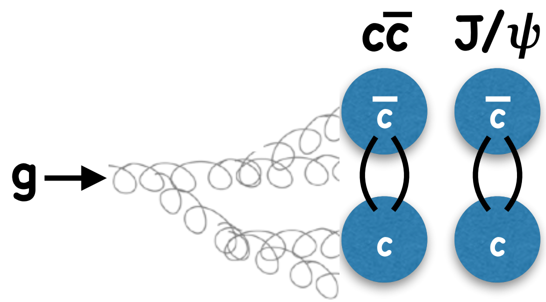


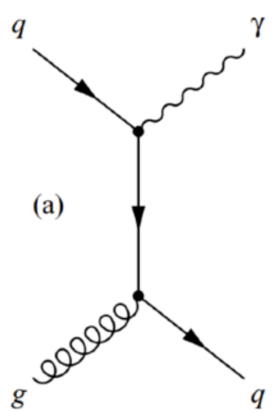


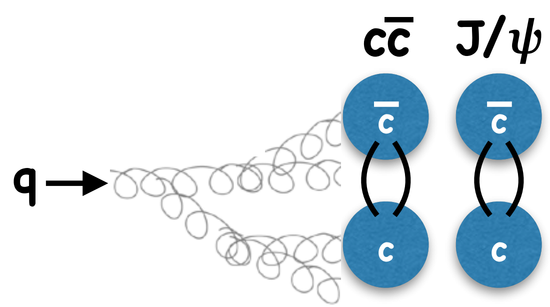
- Recent calculations from LBT group

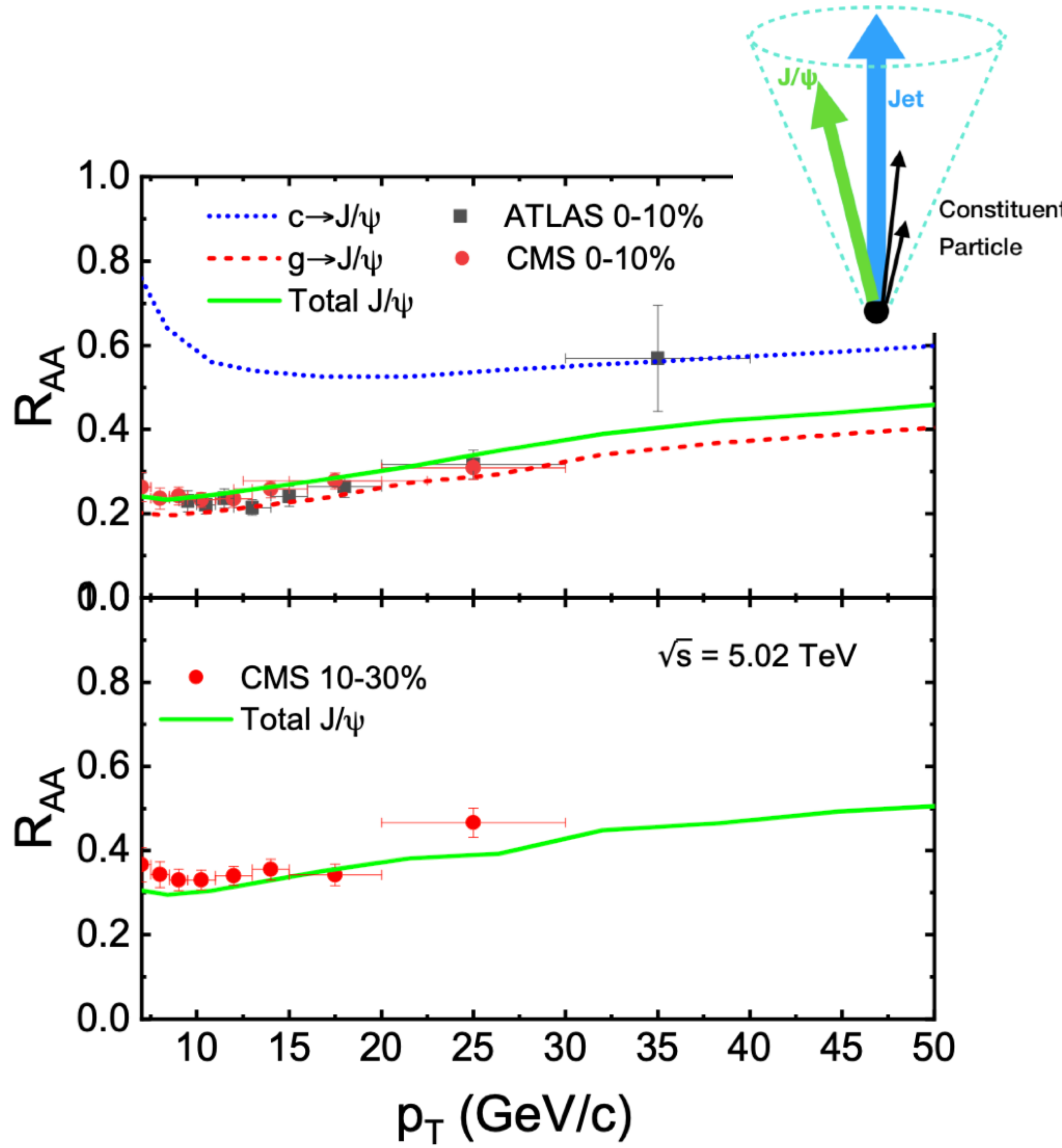
- NO J/ψ dissociation needed —> suppressed only by jet-quenching

J/ψ in jets in PbPb



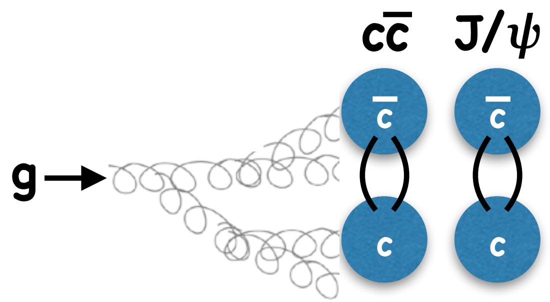


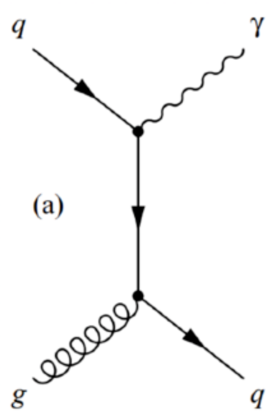


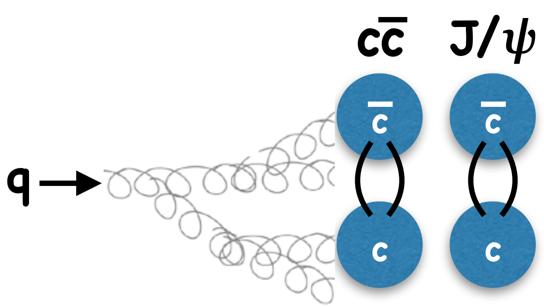


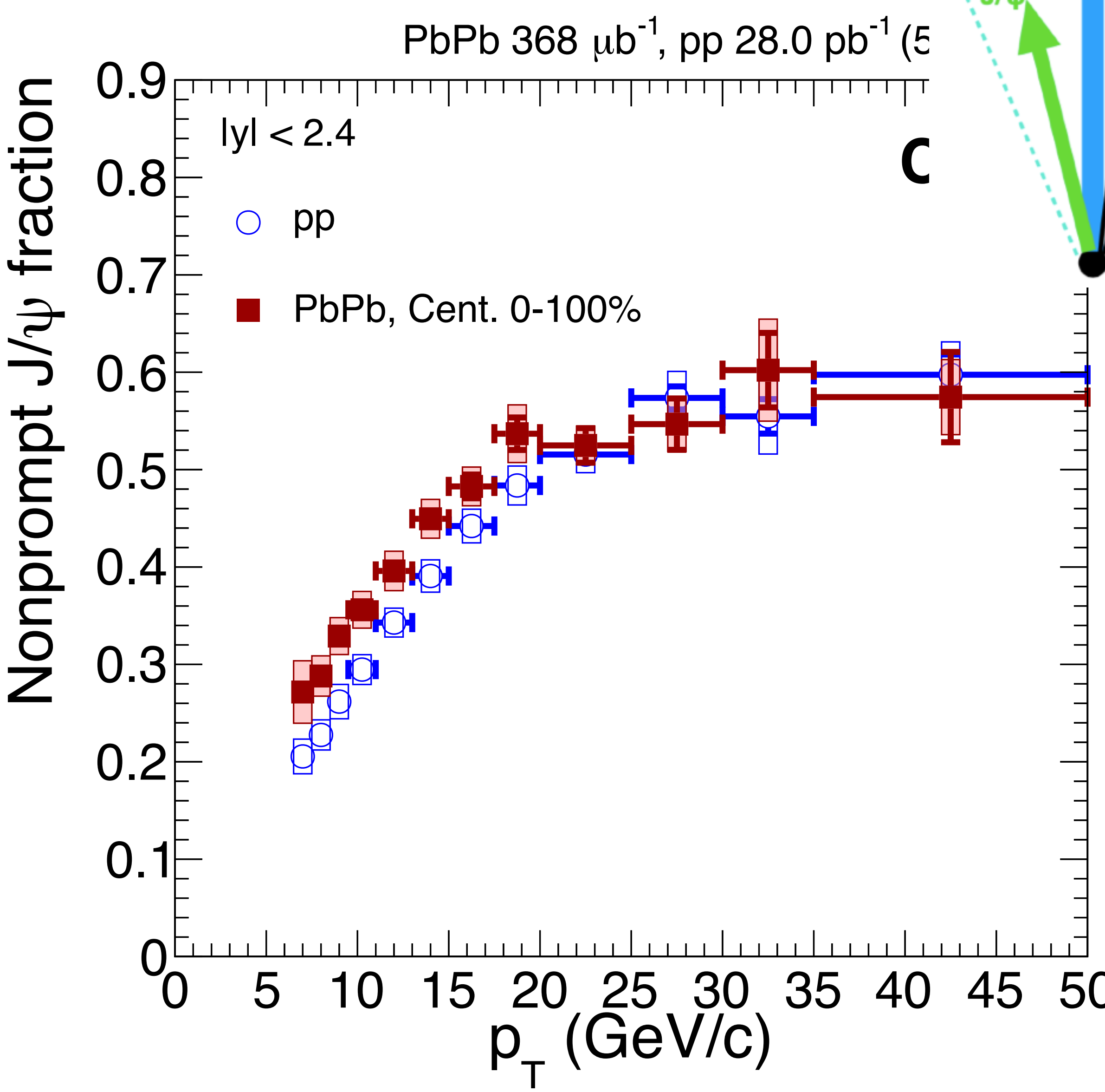
- Inclusive-jet vs gamma-jet sampling
  - –> Color charge dependence?
  - –> Quantifying jet-quenching contribution

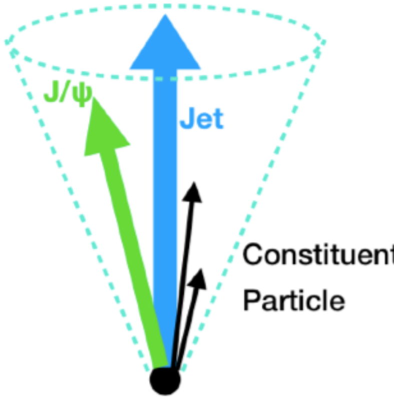
J/ψ in jets in PbPb











- Inclusive-jet vs gamma-jet sampling
  —> Color charge dependence?
  —> Quantifying jet-quenching contribution

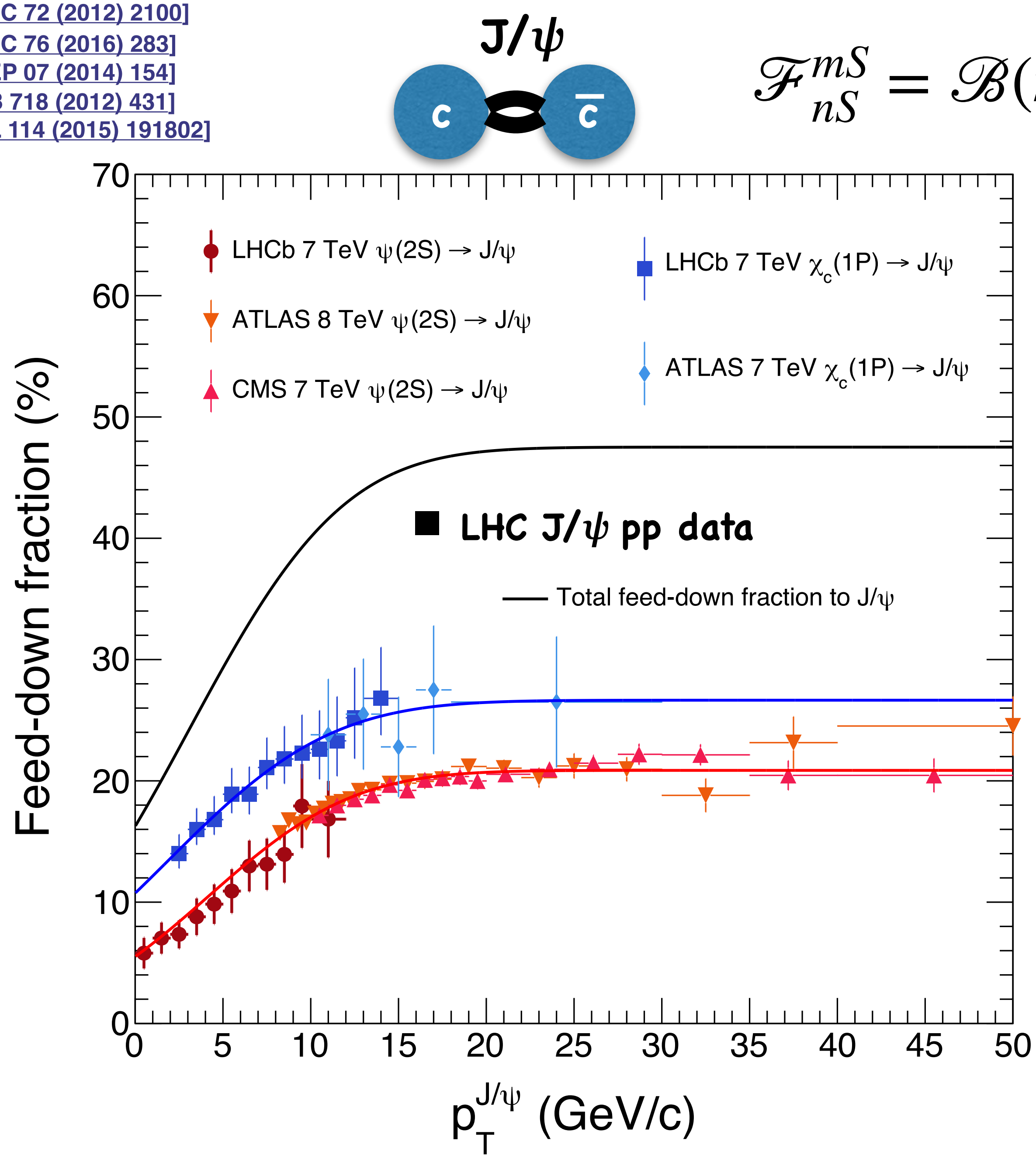
- Large b-fraction at high-p_T
  : Separation of prompt component
  —> flavor dependence comes for free

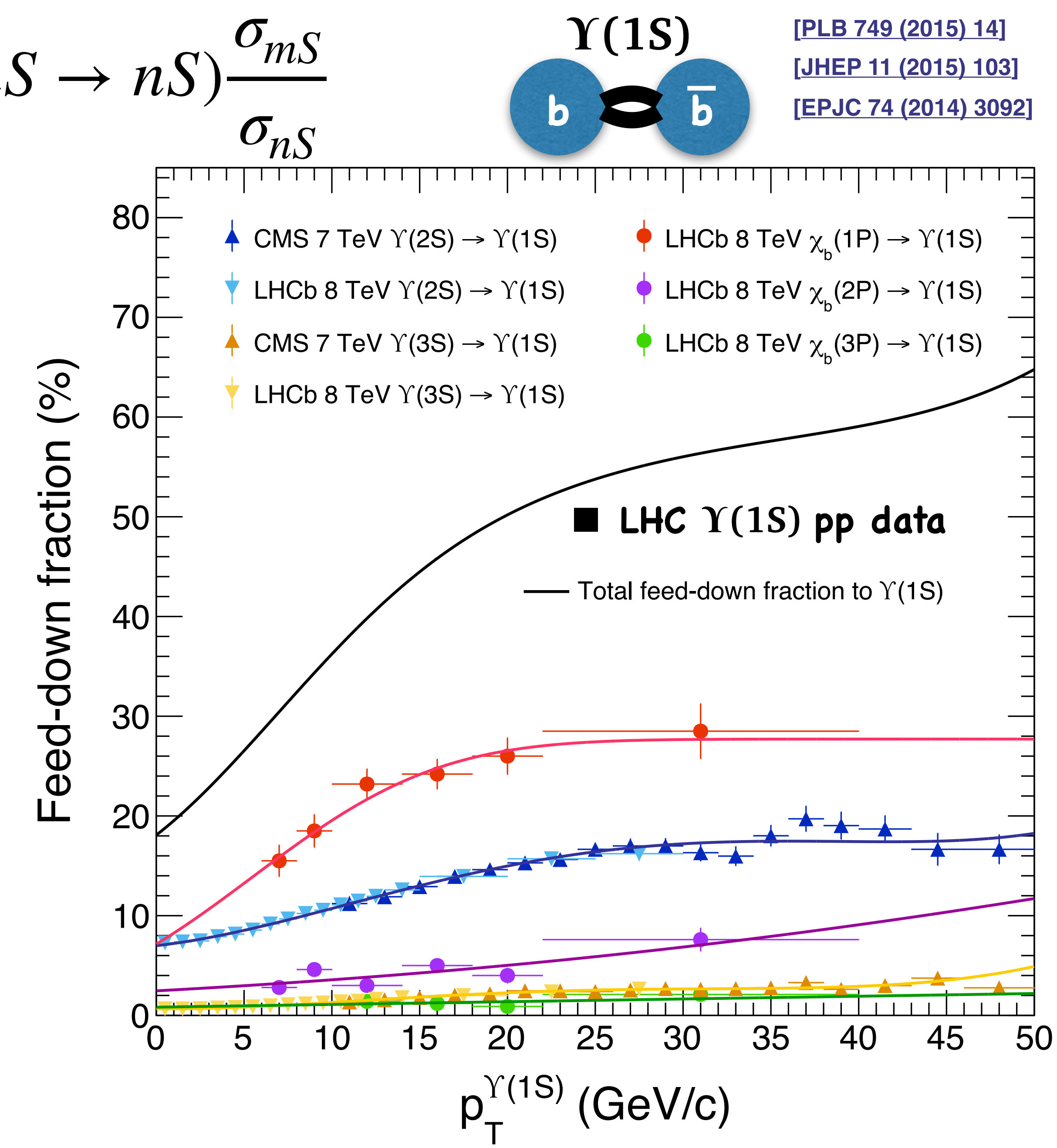
Quarkonium feed-down

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

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

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





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

Quarkonium feed-down

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

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

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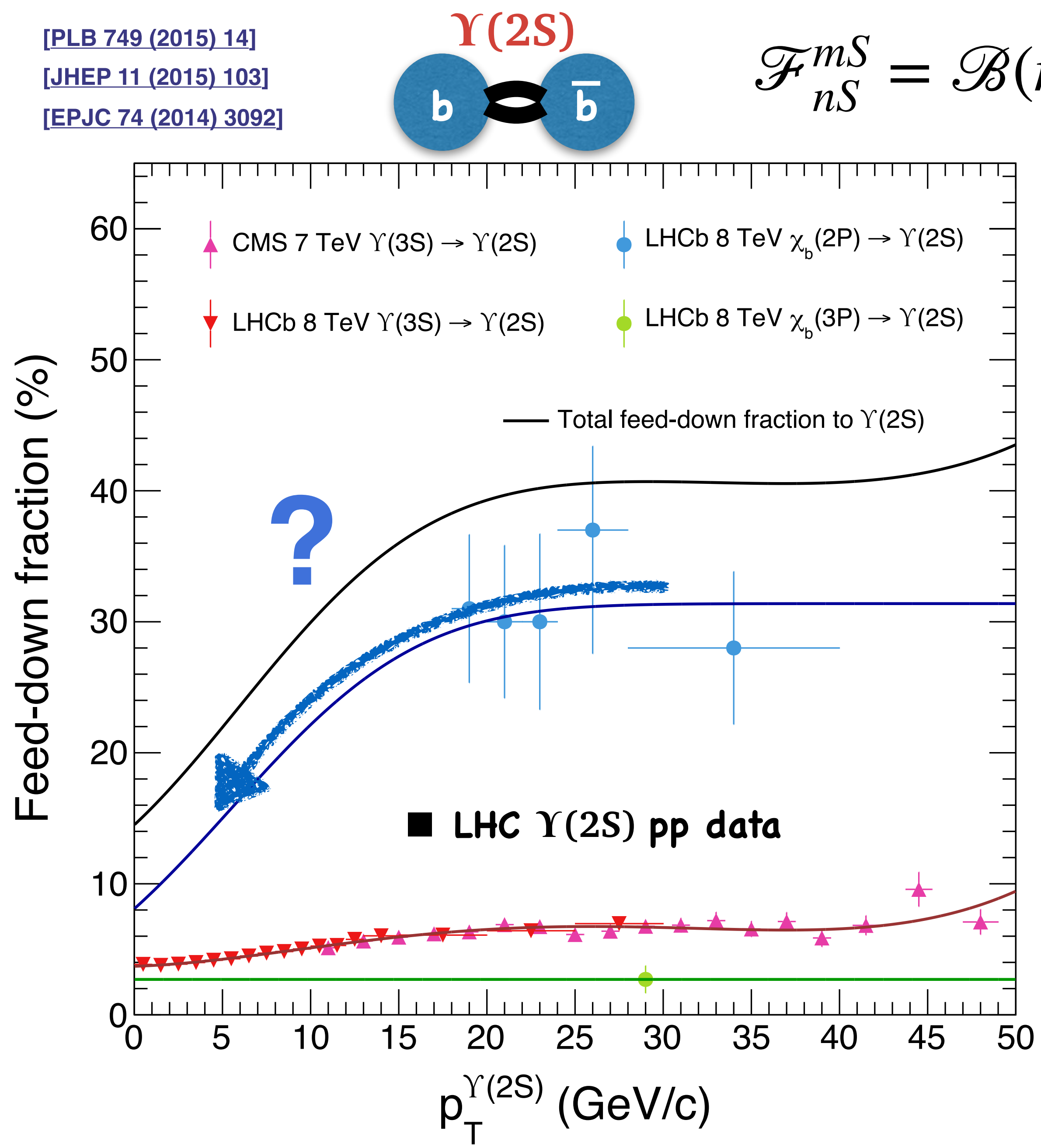
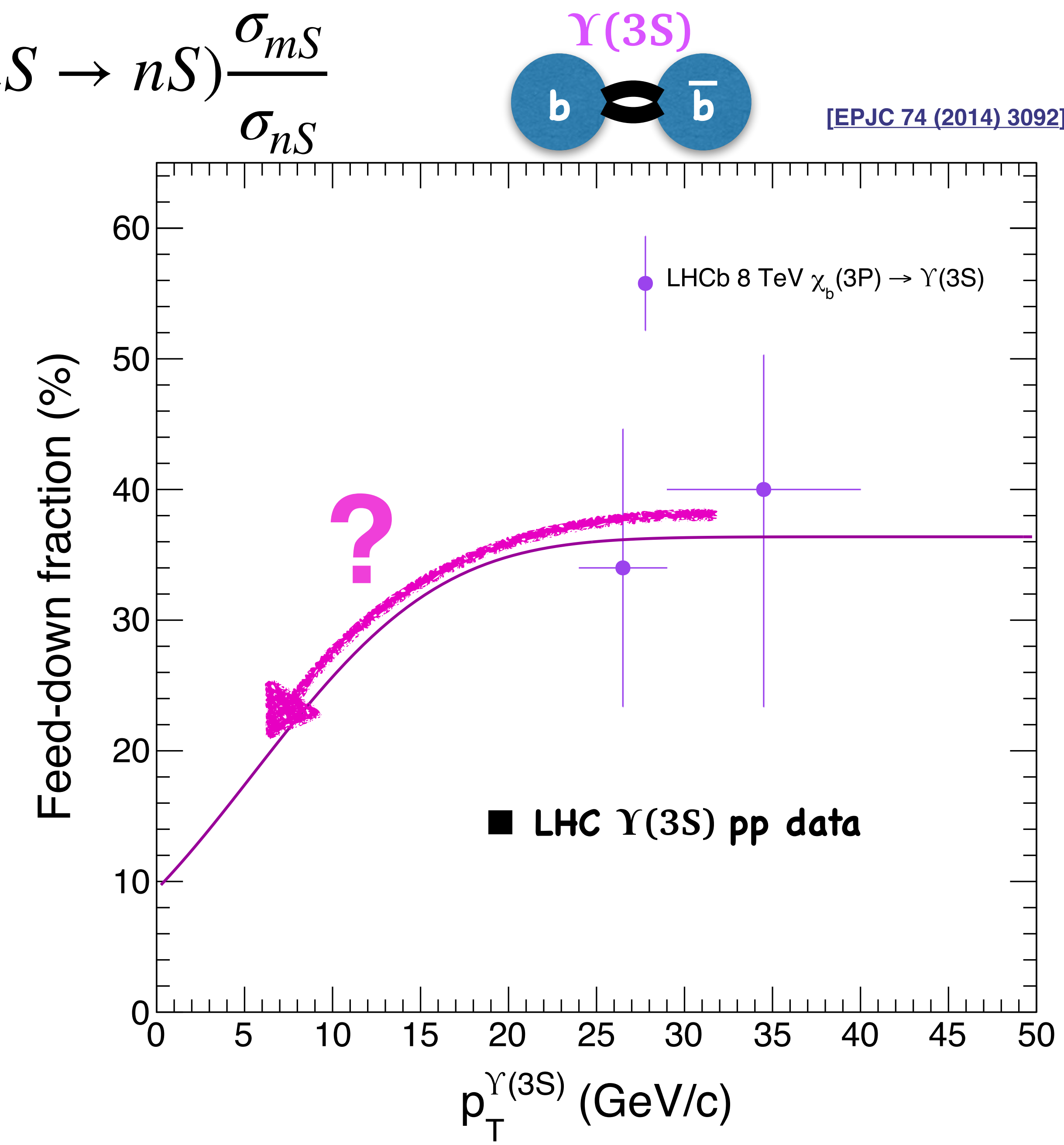
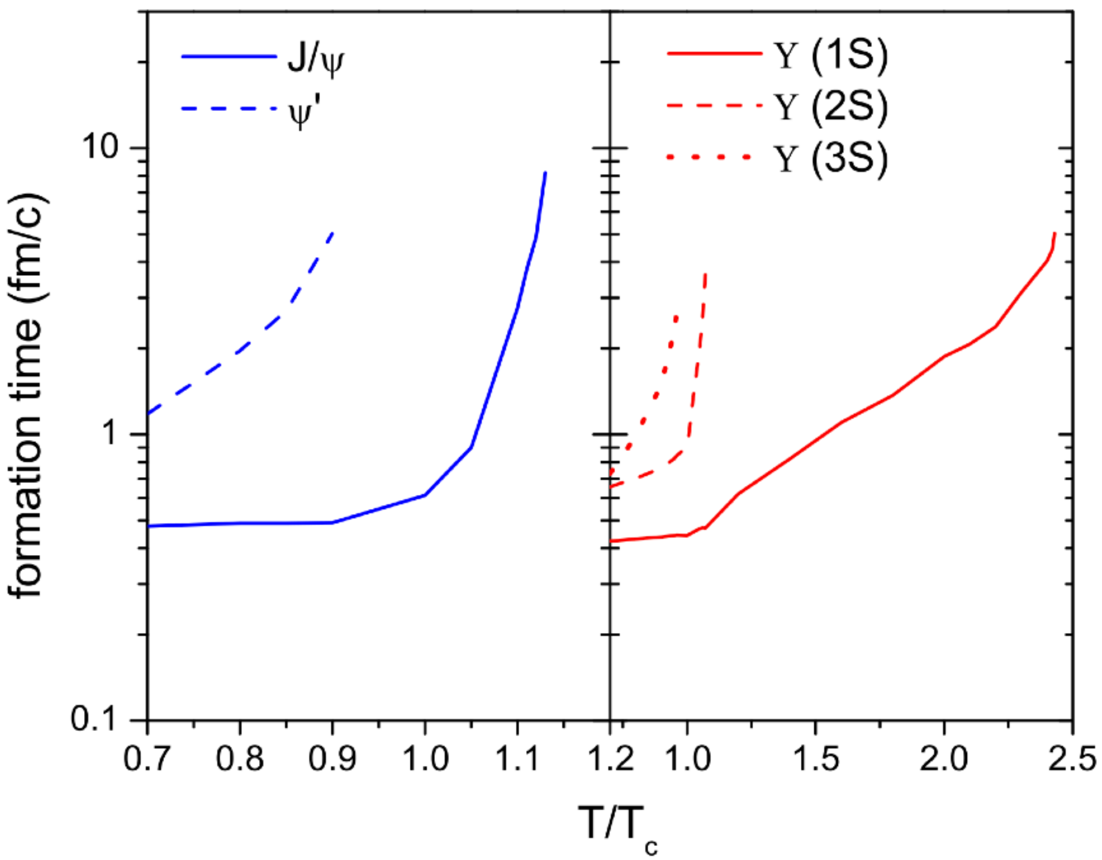




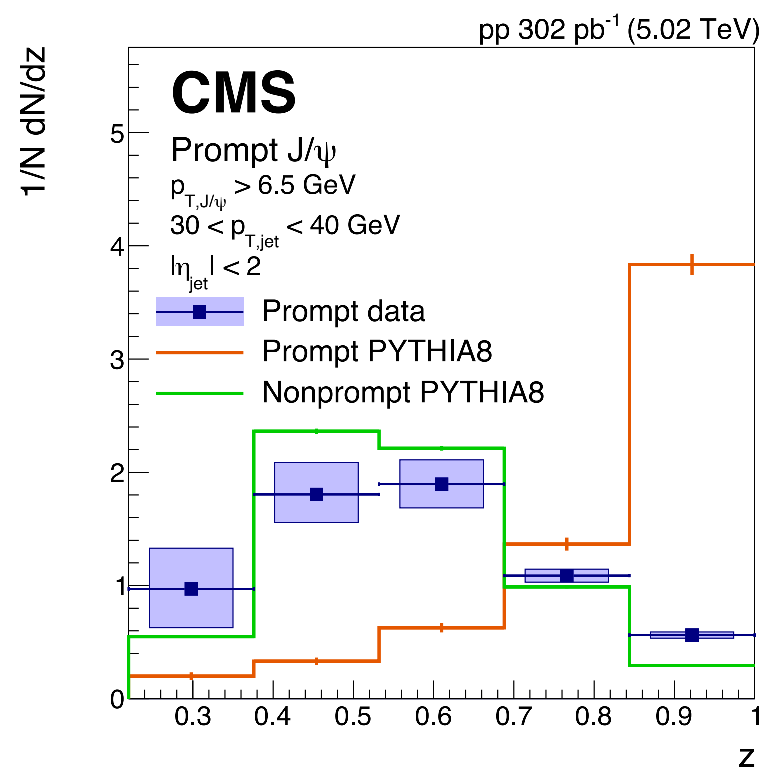
- Caveat for Y(2S) and Y(3S) : Still large! Decreasing towards low-p_T?

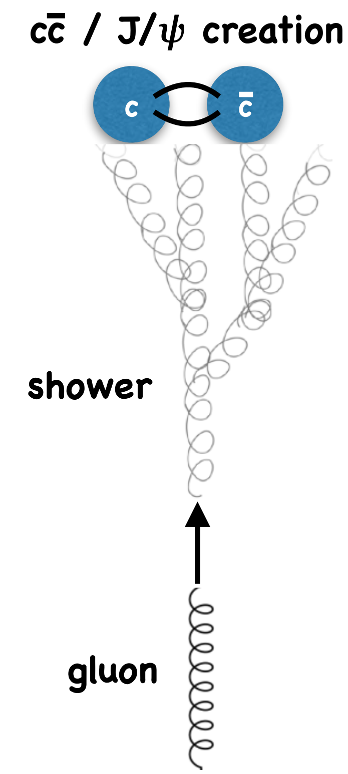
Quarkonium formation time

[NPPP 276 (2016) 137]

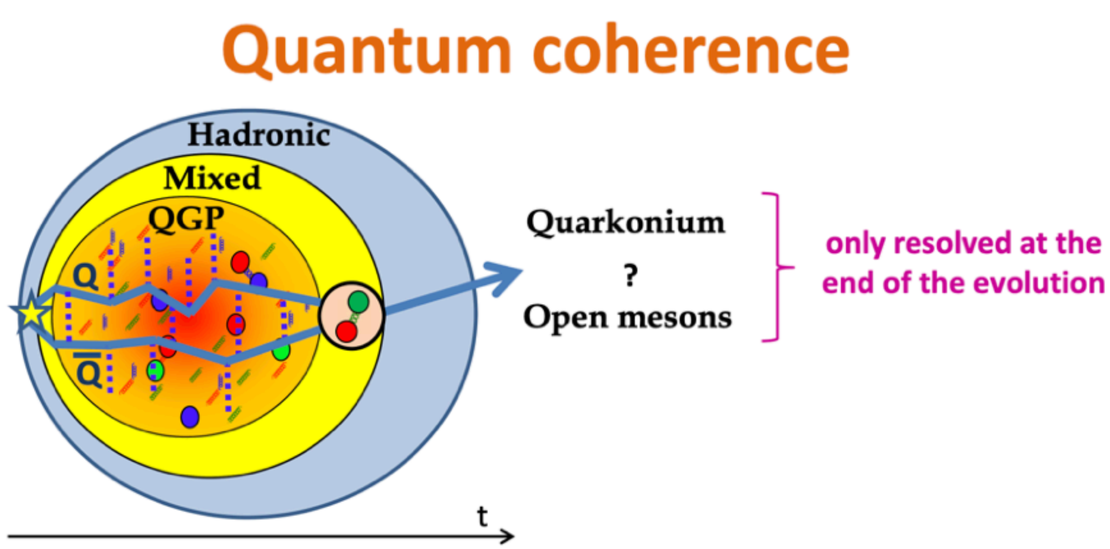


[PLB 805 (2020) 135434]
[PRL 118 (2017) 192001]





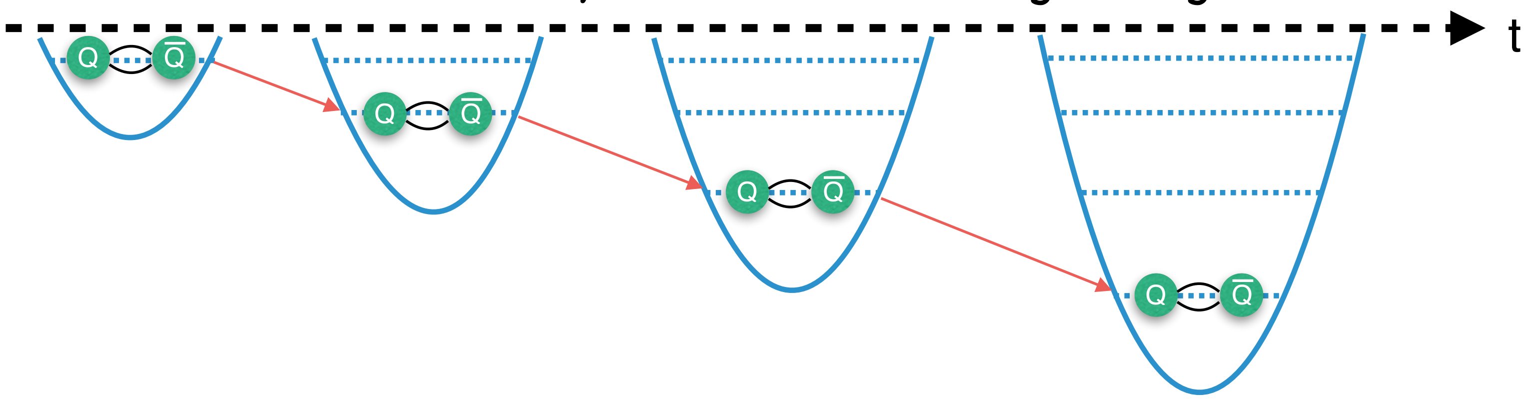
[P. Gossiaux SQM 2022]



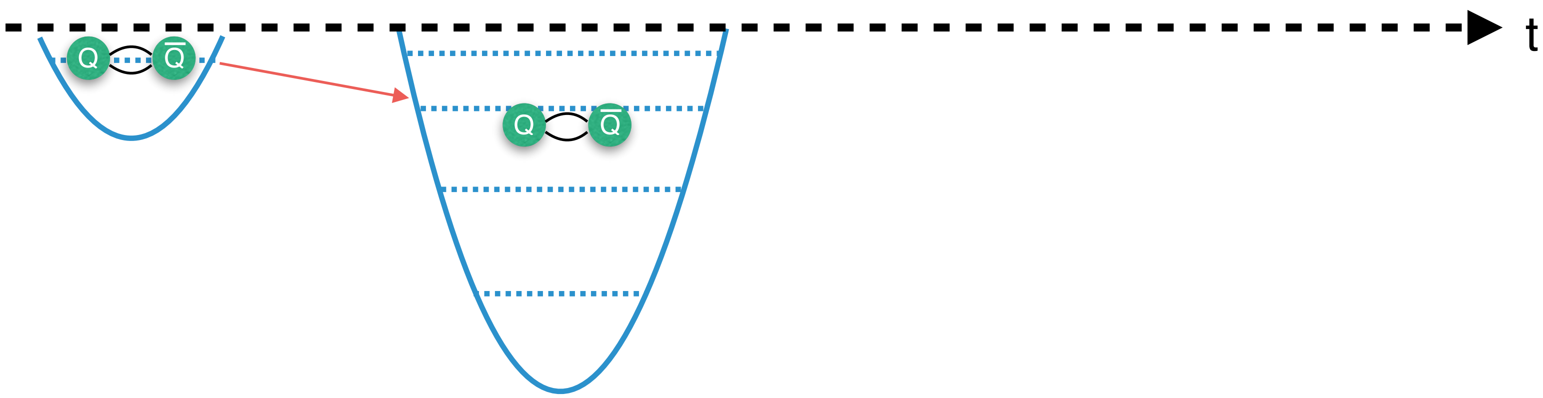
- Quarkonium formation time delayed above dissociation temperature?
- Temperature environment hot enough to modify quarkonium formation time scales?
- Even in pp : high-p_T J/ψ produced at later stages by parton shower

Quarkonium state in medium

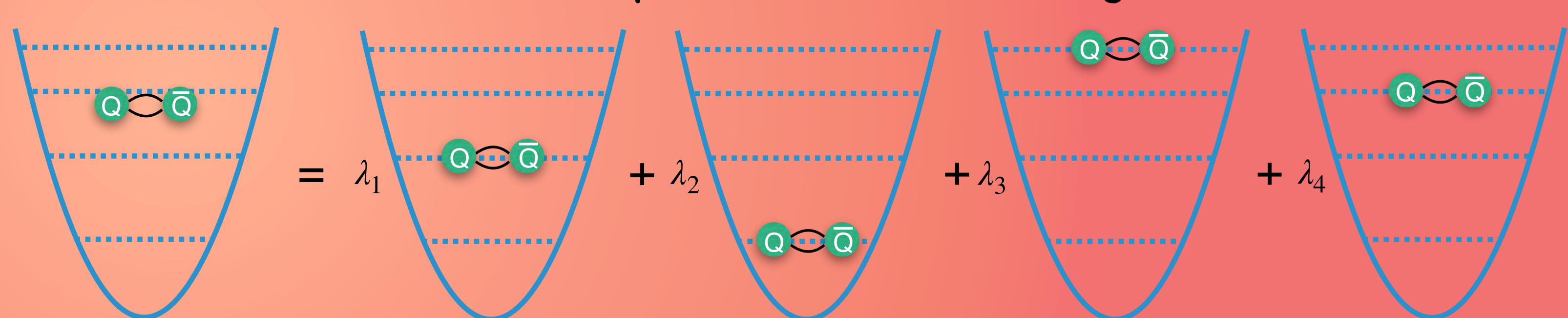
If the medium evolves slowly : state remains in a given eigenstate



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

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

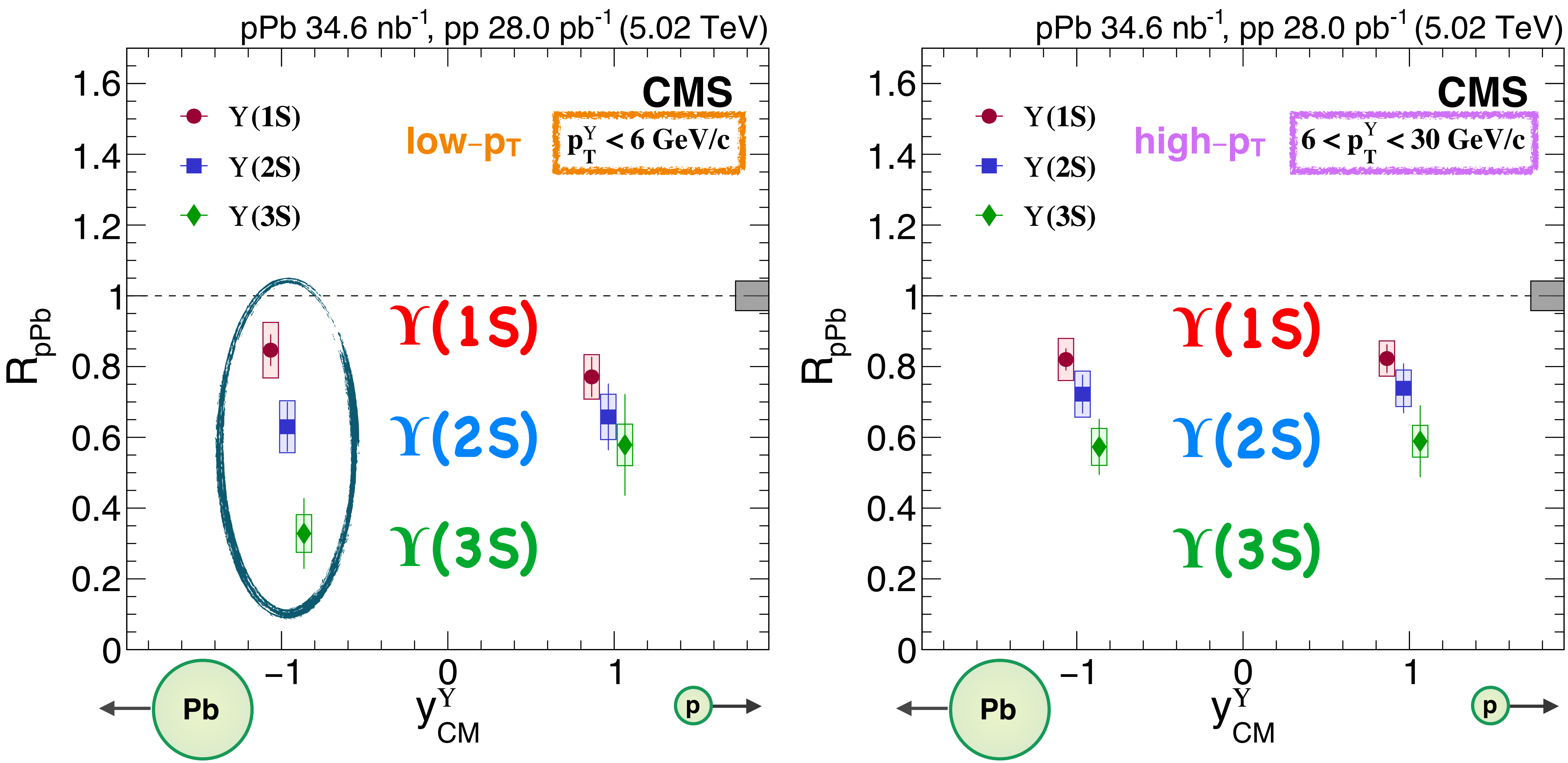
[P. Gossiaux SQM 2022]

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

- OQS to get rid of formation time?
  - However OQS deviates for Υ(3S) R_{AA} …

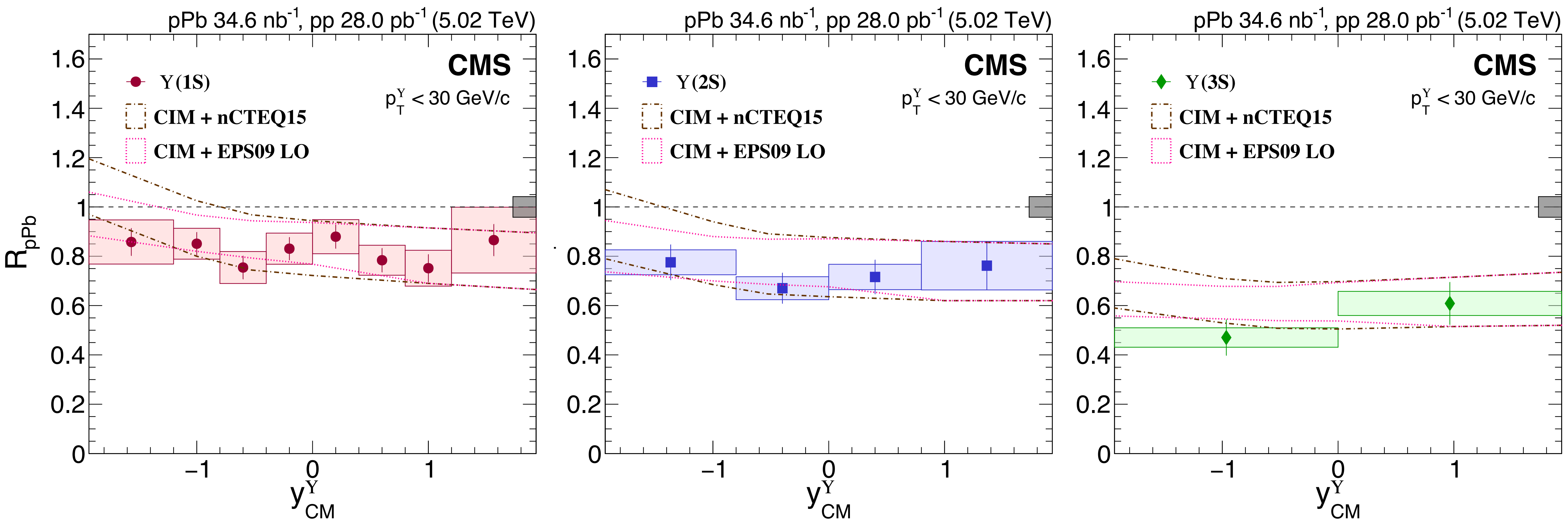
Sequential Υ suppression in pPb

[arXiv:2202.11807]



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

Bottomonia in pPb vs model



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

Comover vs transport in pA

Comover Interaction Model

- Survival probability of quarkonium interacting w comovers

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

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

- Depends on
  1) quarkonium dissociation rate —> matched to data
  2) comover density —> determined with N_{coll} & $dN_{ch}/d\eta$

Transport Model

- Thermal rate equation of quarkonium yields

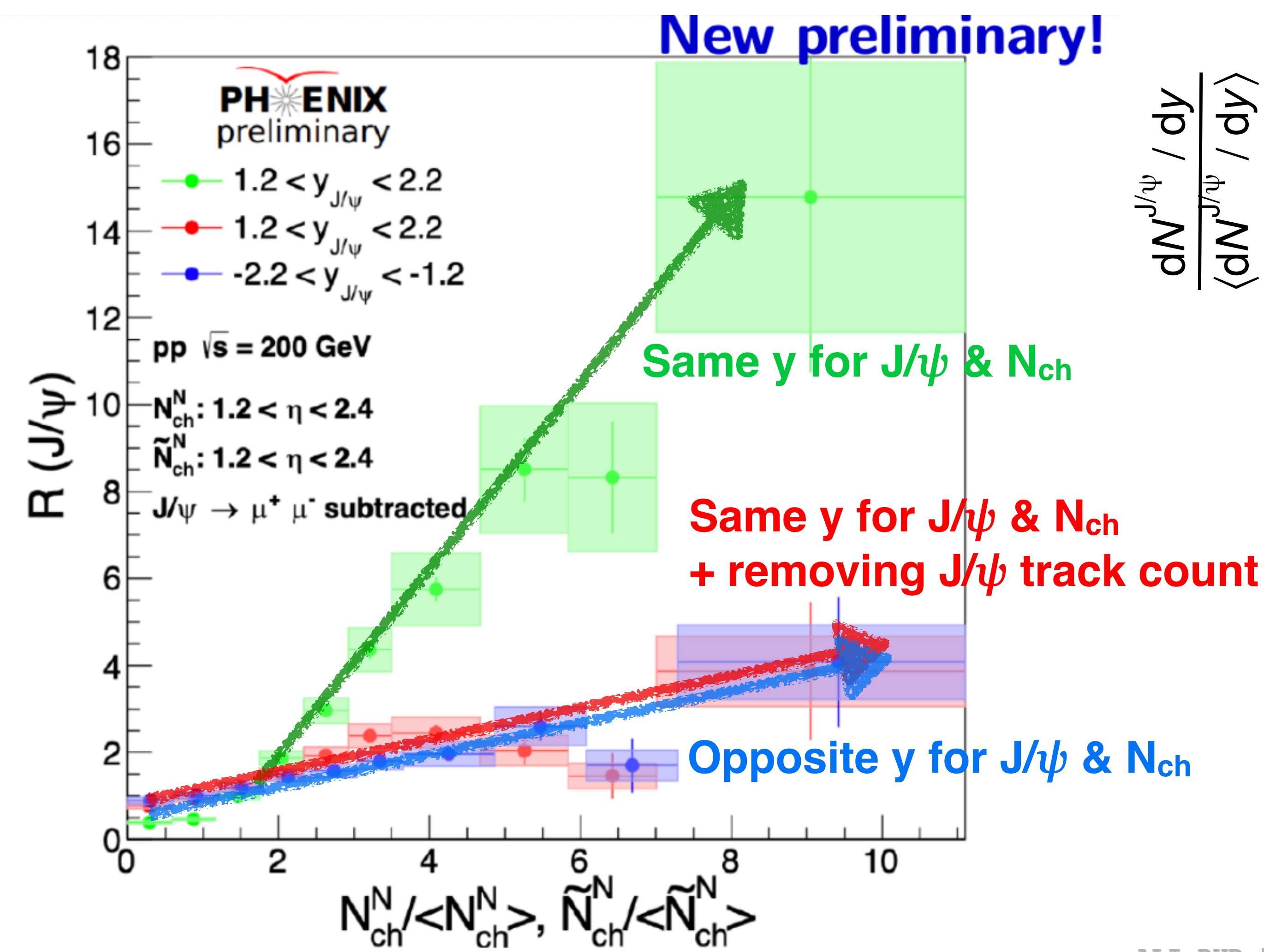
$$\frac{\mathrm{d}N_{\Psi}(\tau)}{\mathrm{d}\tau} = -\Gamma_{\Psi}(T(\tau))\left[N_{\Psi}(\tau) - N_{\Psi}^{\mathrm{eq}}(T(\tau))\right]$$

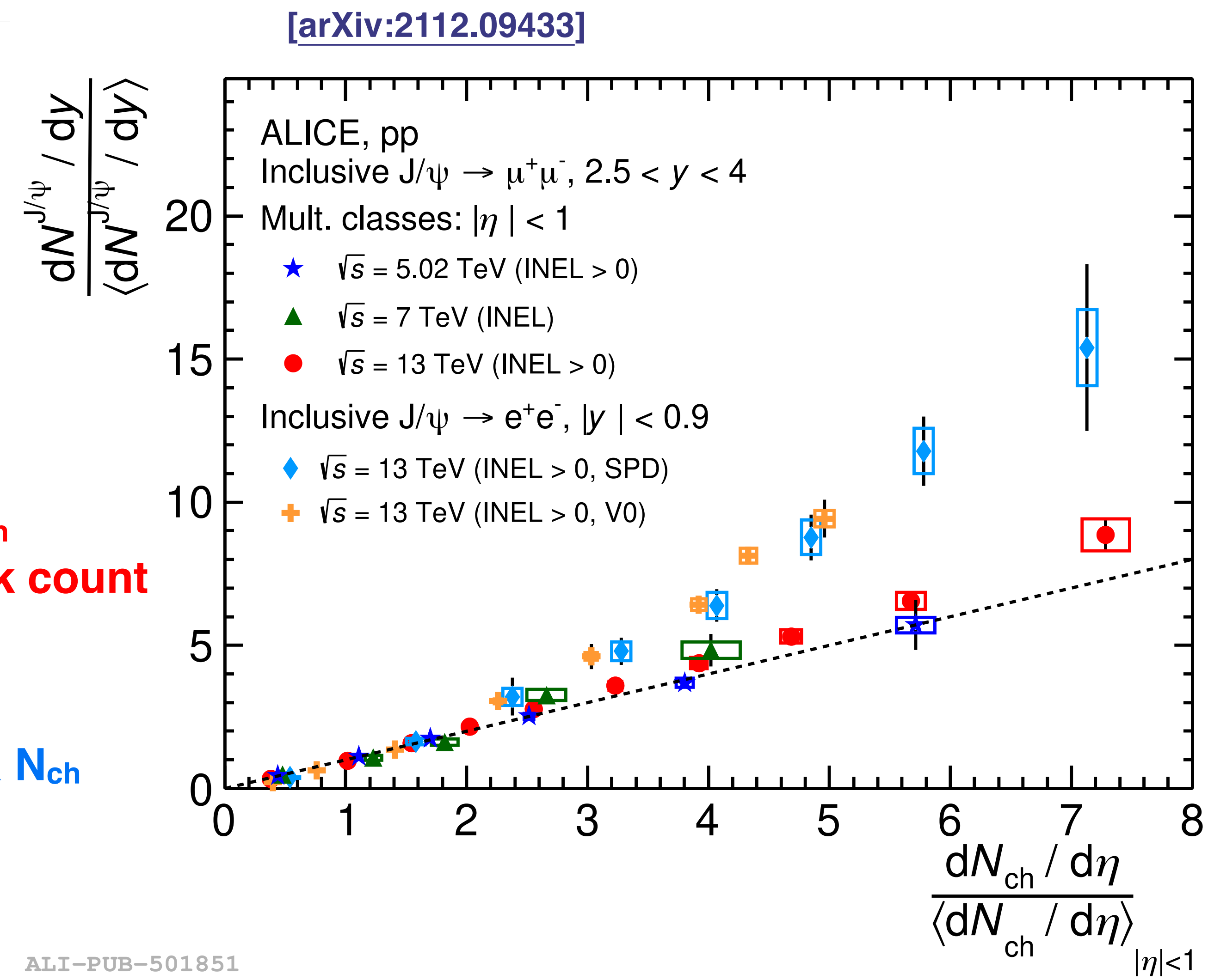
$$N_{\Psi}^{\mathrm{eq}}(T) = V_{\mathrm{FB}}\gamma_c^2 d_{\Psi}\int \frac{d^3p}{(2\pi)^3} f_{\Psi}^{\mathrm{eq}}(E_p;T)$$

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

- Comover breakup model 'actual' treatment similar to transport calculations?
- How much of modifications in pA to be considered in AA interpretation?

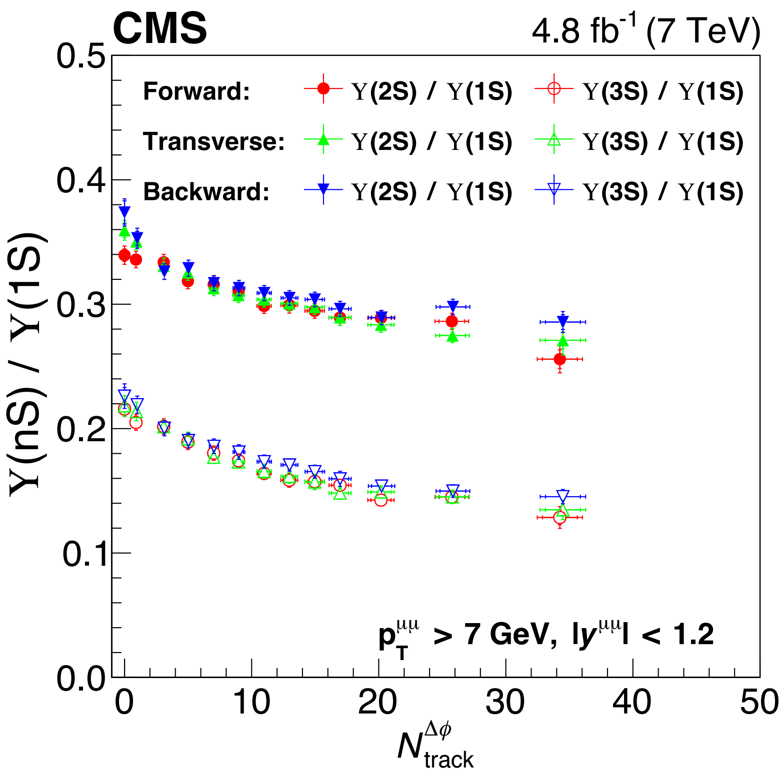
Multiplicity dependence

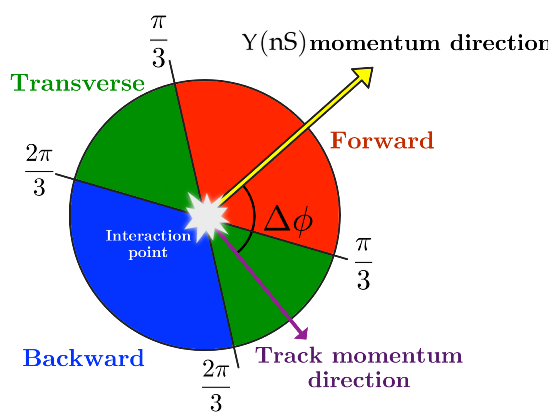




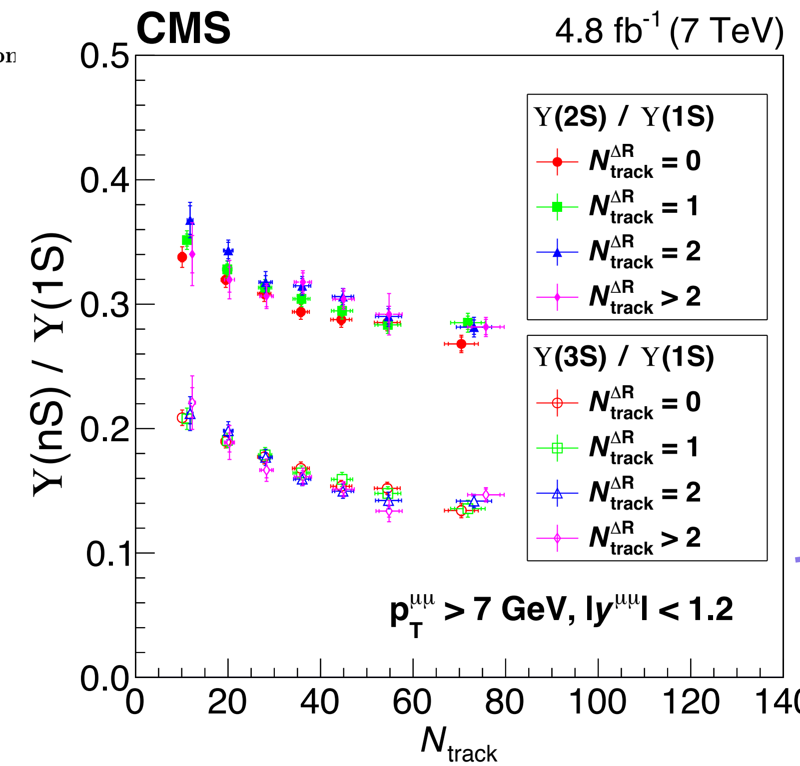
- Clear dependence on the choice of rapidity overlap b/w J/ψ & N_{ch}
- Discrepancy removed by excluding $J/\psi \rightarrow \mu^+\mu^-$ in track count
  - Indication of important role of MPI?

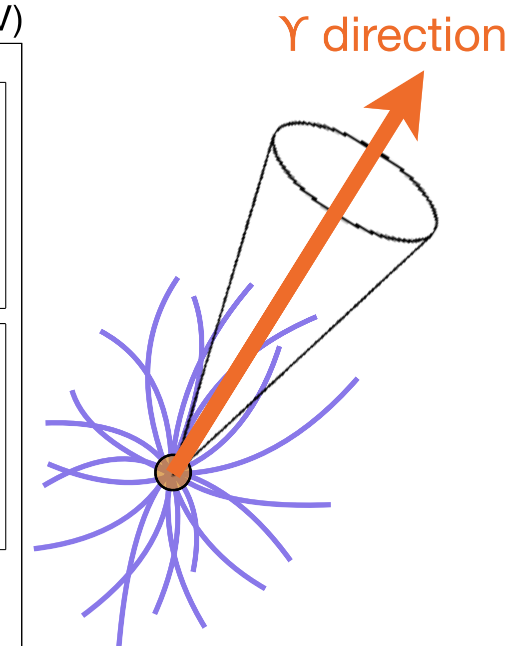
Υ vs multiplicity

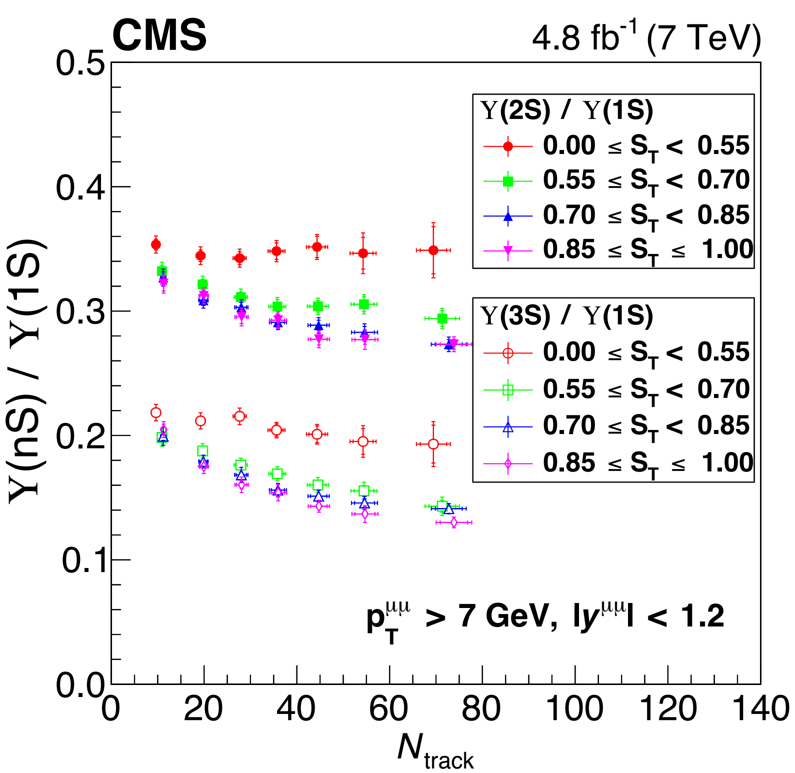




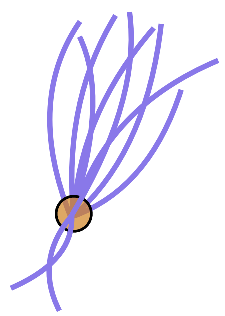
[JHEP 11 (2020) 001]



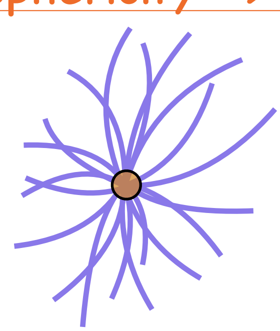




Sphericity —> 0



Sphericity —> 1



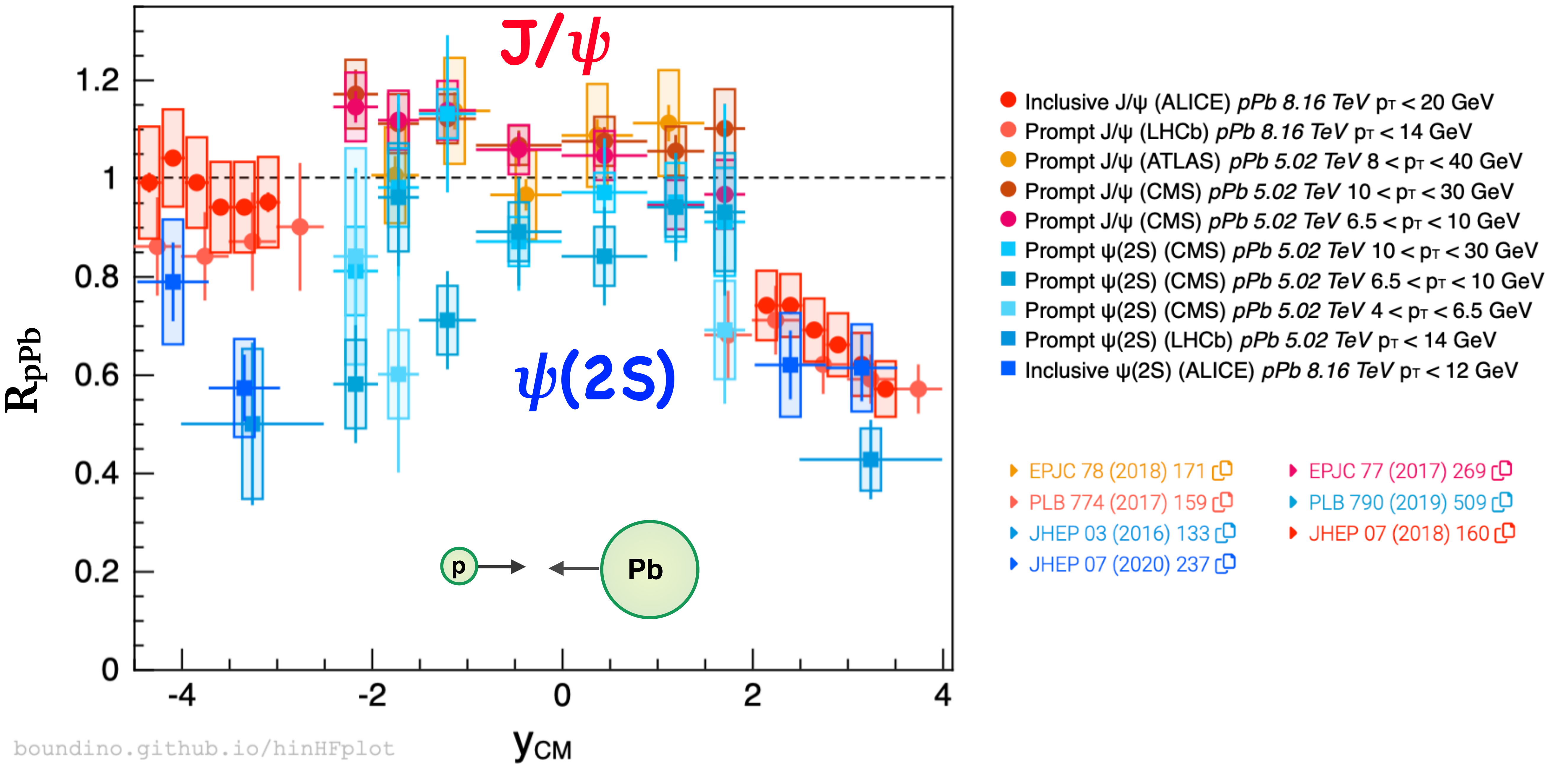
- Υ(nS) / Υ(1S) still suppressed for all azimuthal $N_{ch}^{\Delta\phi}$ & cone N_{ch}^{R}
  —> Different from comover picture
- Scaling with sphericity
  —> UE connection w jetty events?
- Need to be investigated with low-p_T Υ & J/ψ

Summary

- ☑ Great contribution of CENuM in HIN CMS
- ☑ Significant amount of analysis published
  + leading role in the CMS heavy ion the group
- ☑ Looking forward for Run3 data + unique measurements

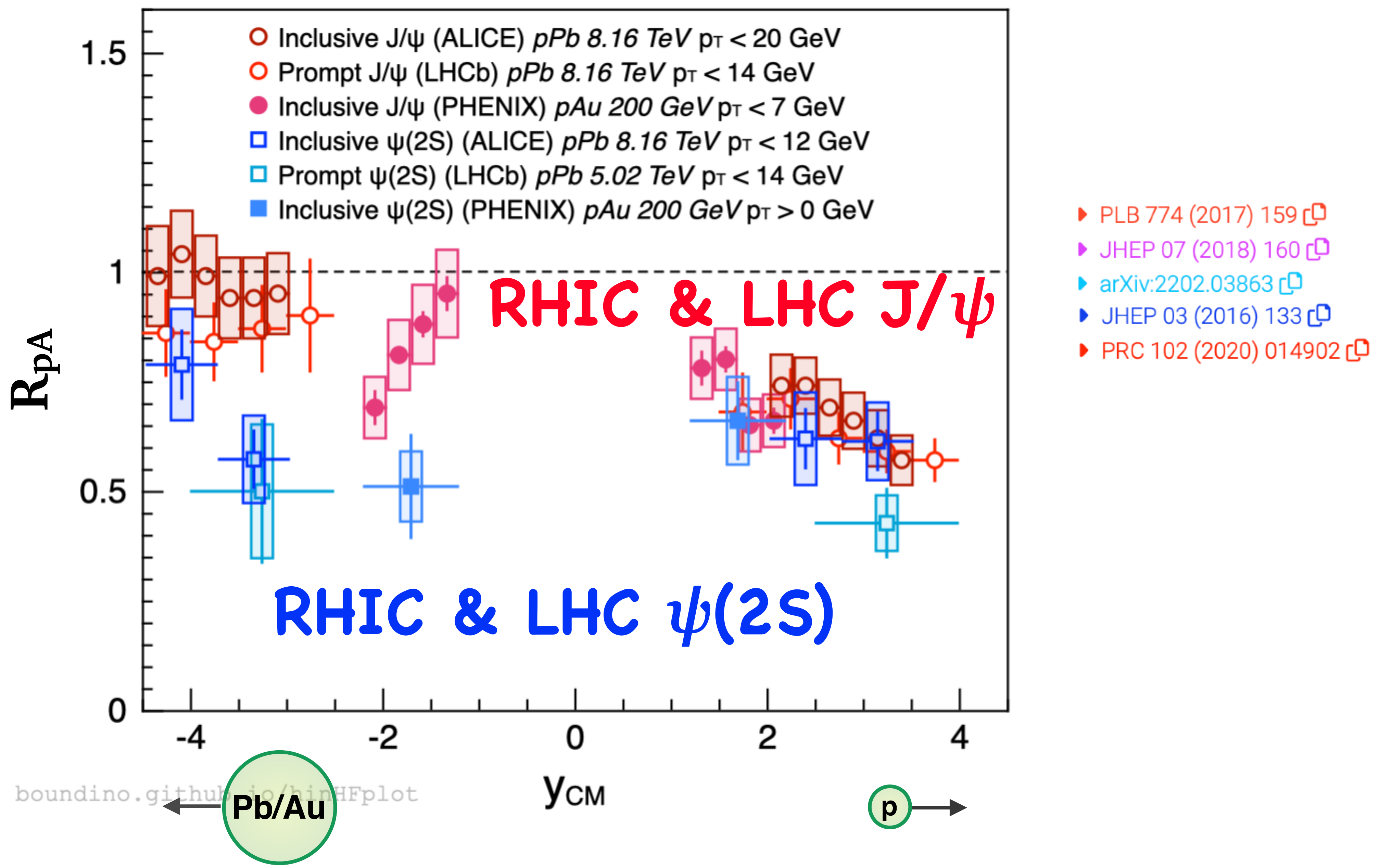
back-up

Charmonia in pPb @ LHC



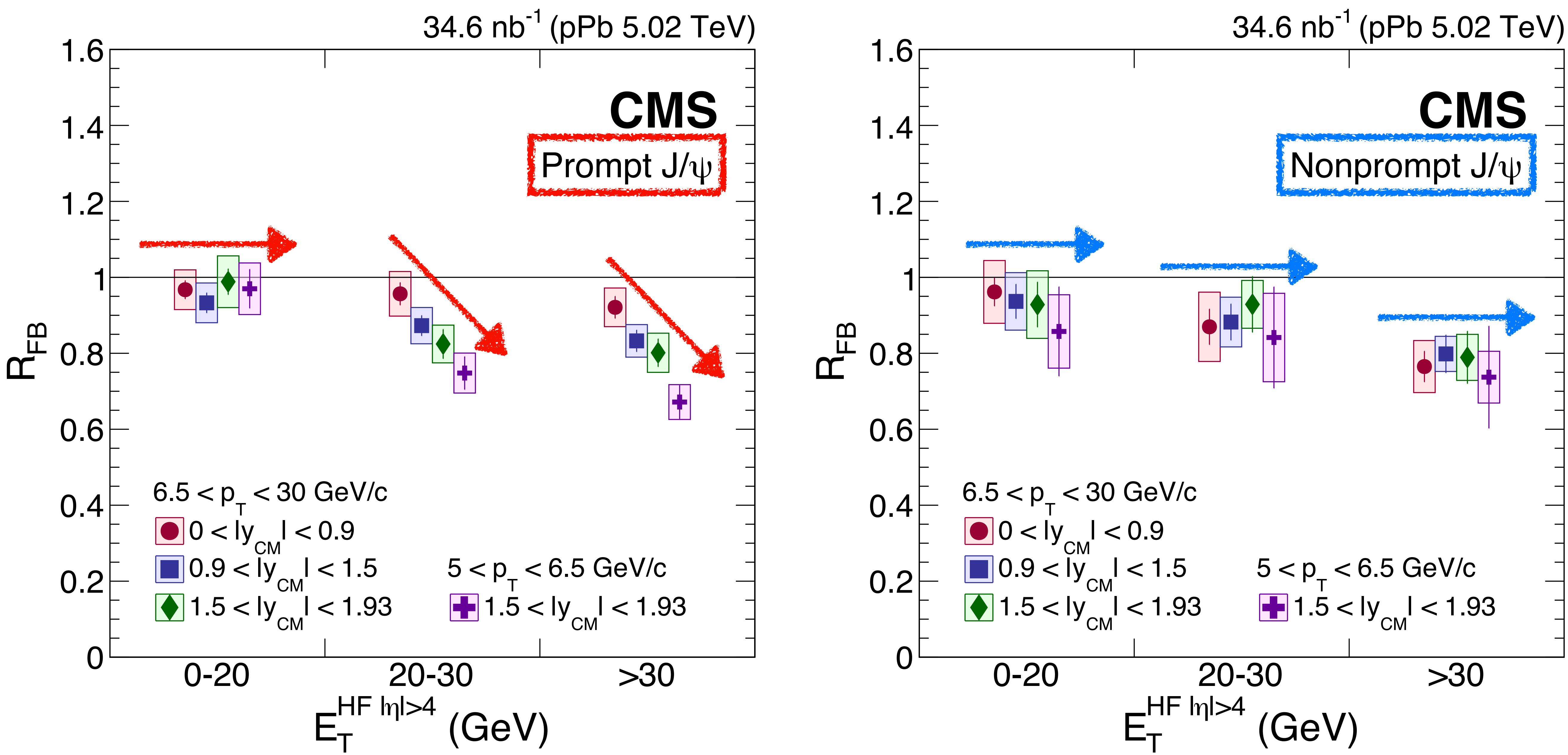
- Overall 'decreasing trend' towards forward rapidity —> nPDF based predictions
- Suppression for ψ(2S) : additional final state effects — comover breakup? dissociation?

Charmonia in pA RHIC vs LHC



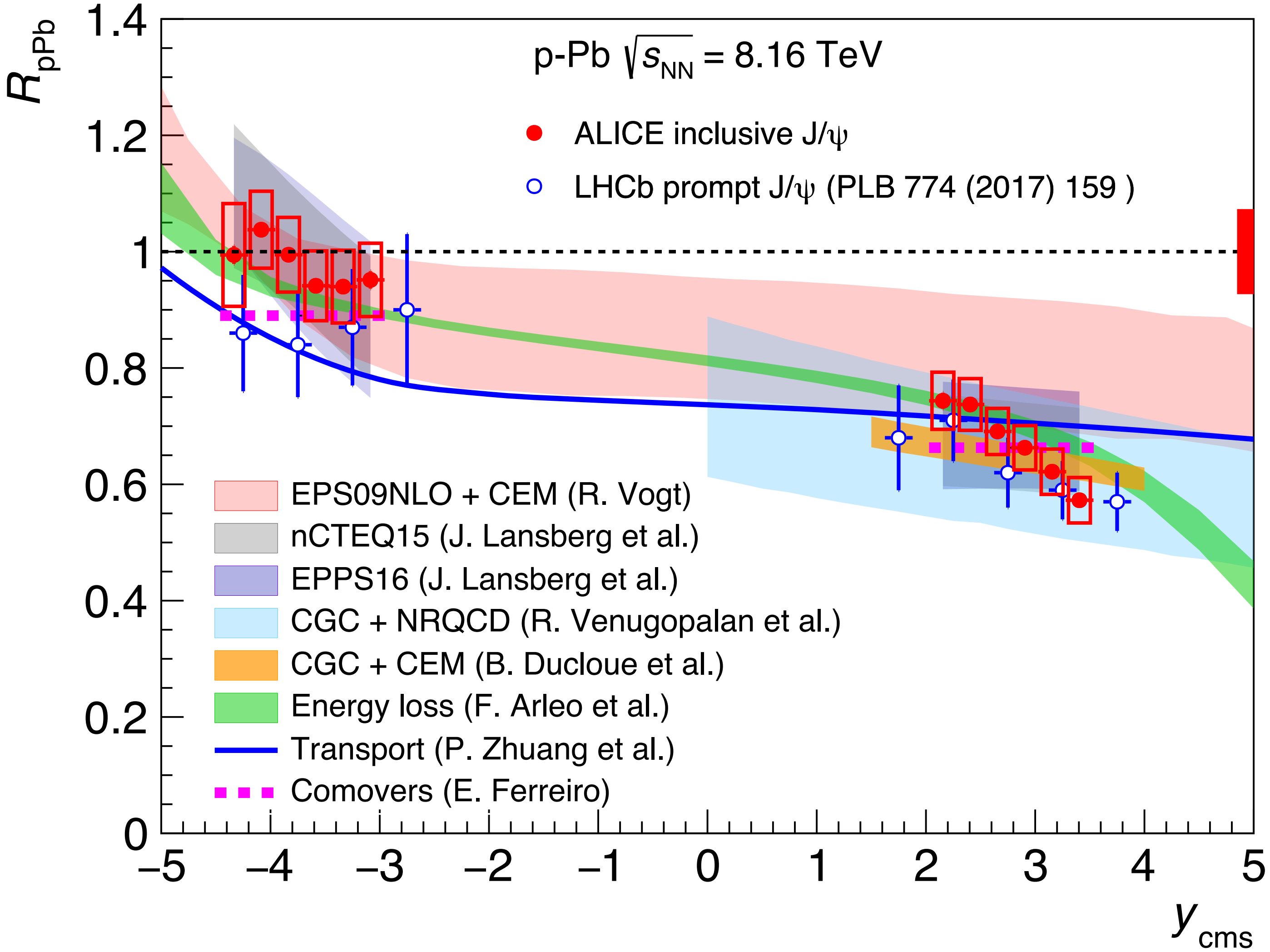
- Similar trend for both J/ψ & $\psi(2S)$ at RHIC and LHC
  - Similar 'amount' of initial/final effects?

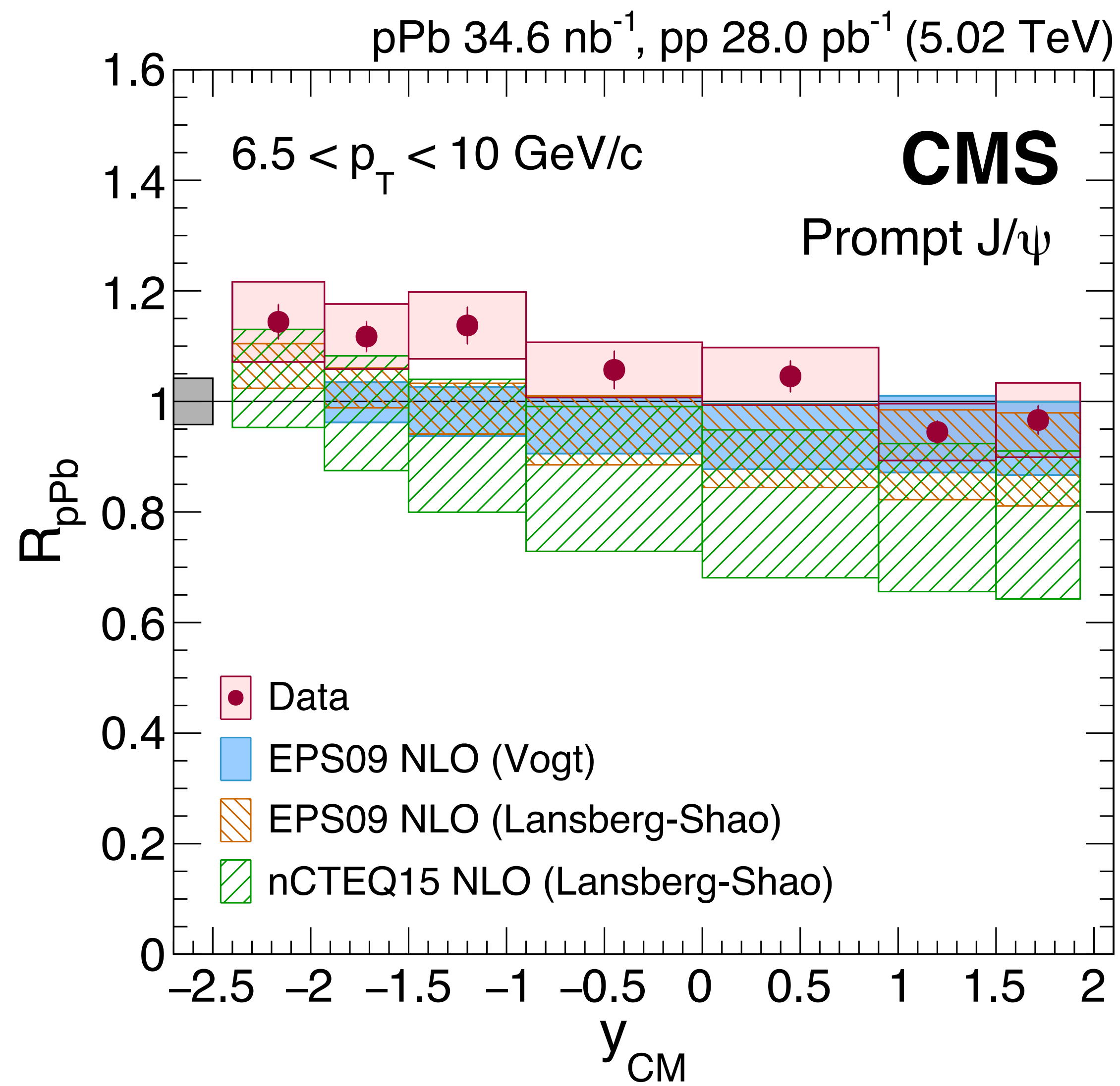
J/ψ in pA RHIC vs LHC



- Different event-activity dependence for charm & bottom

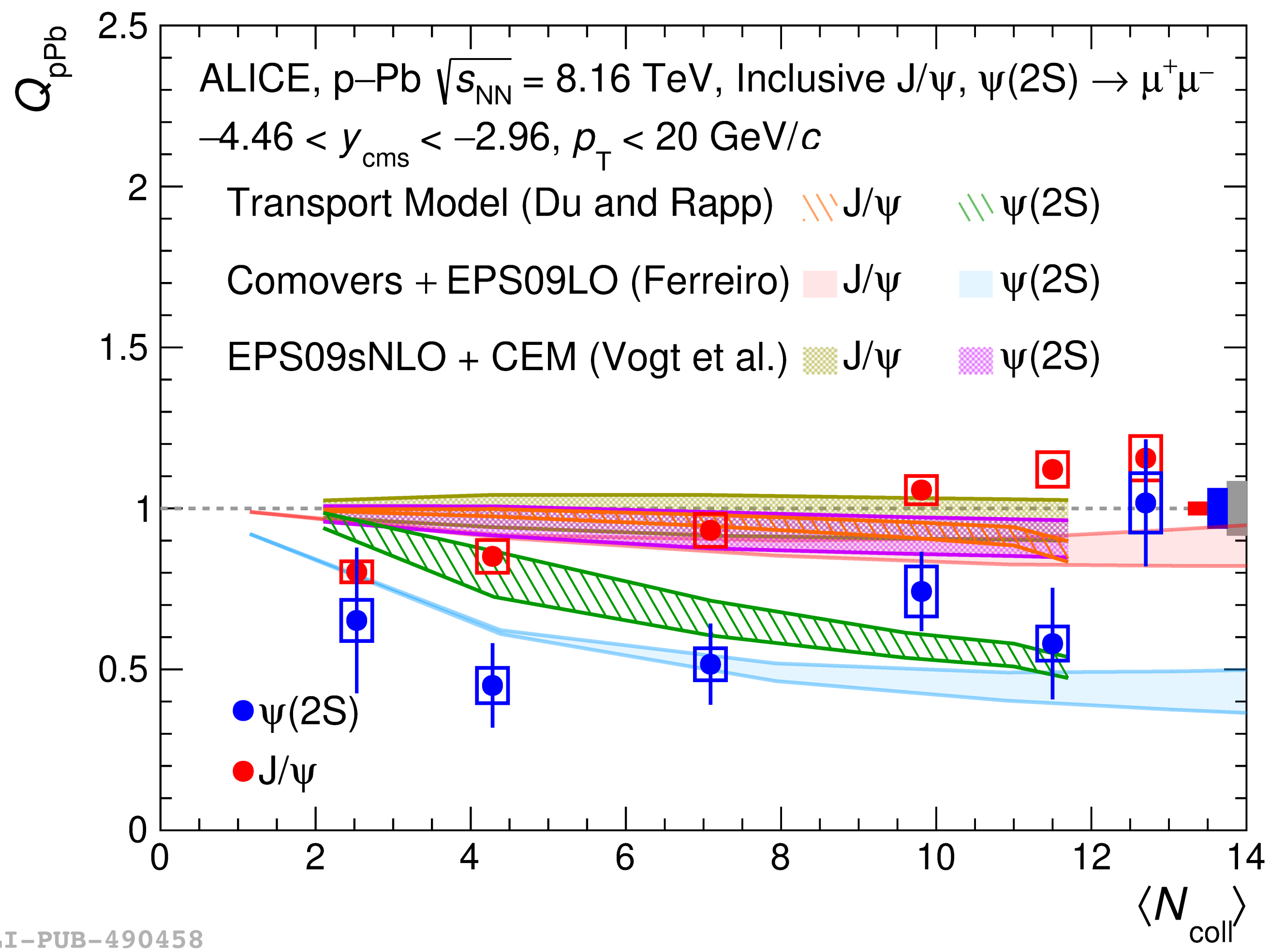
J/ψ in pPb vs model

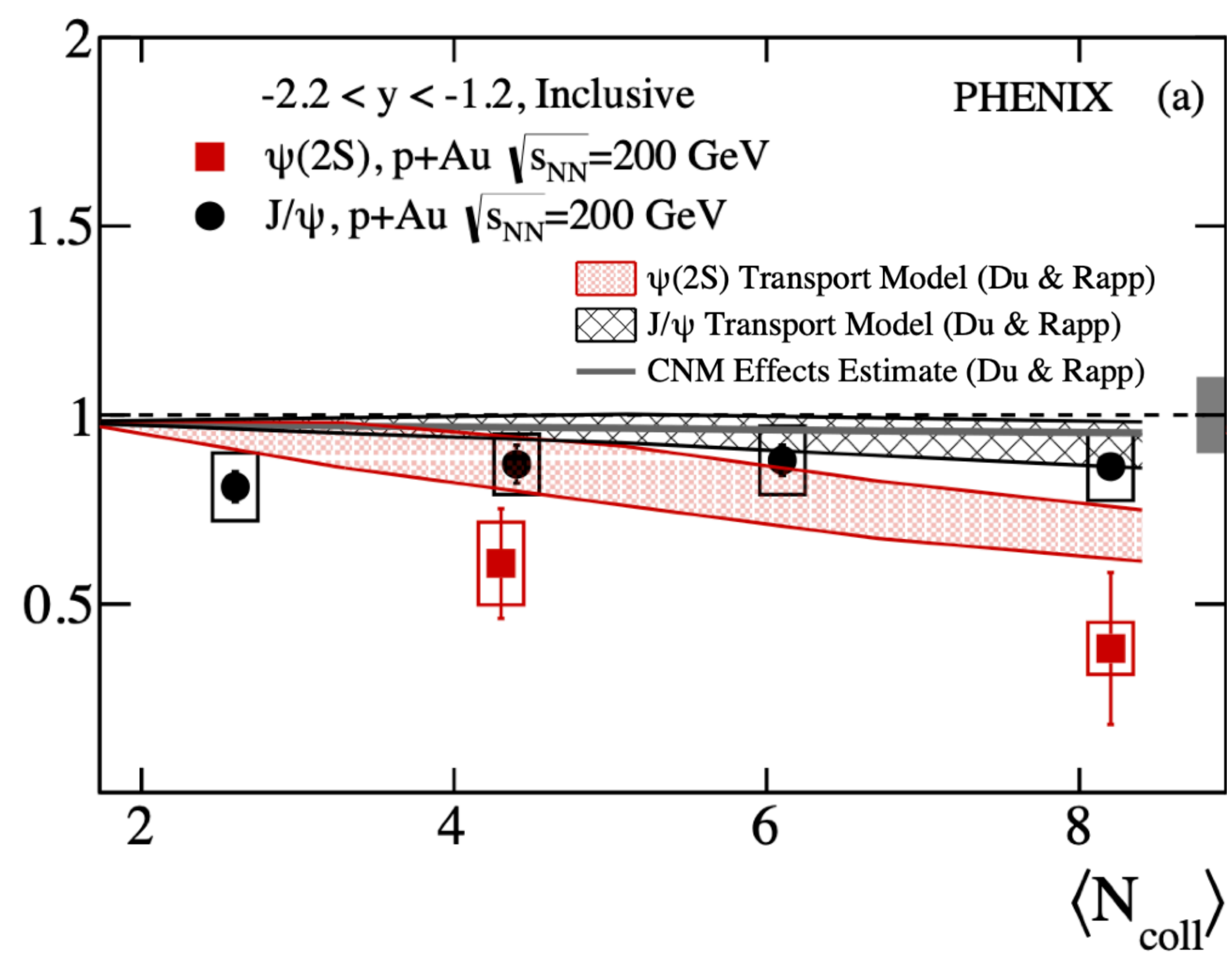




- J/ψ modification well explained by nPDF / CGC predictions
- Negligible contributions from final state effects (comover or hot nuclear matter)

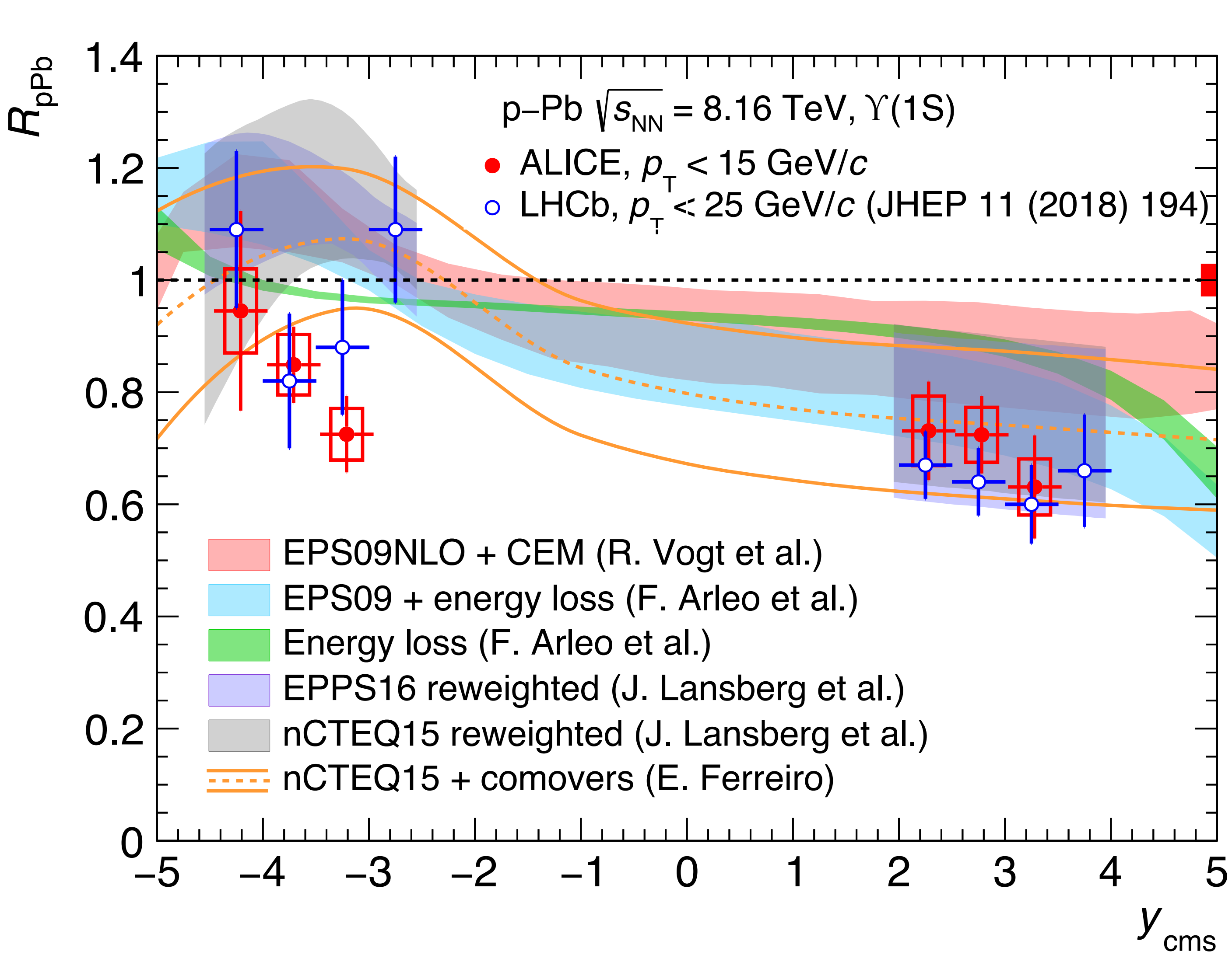
Charmonia in pA vs model

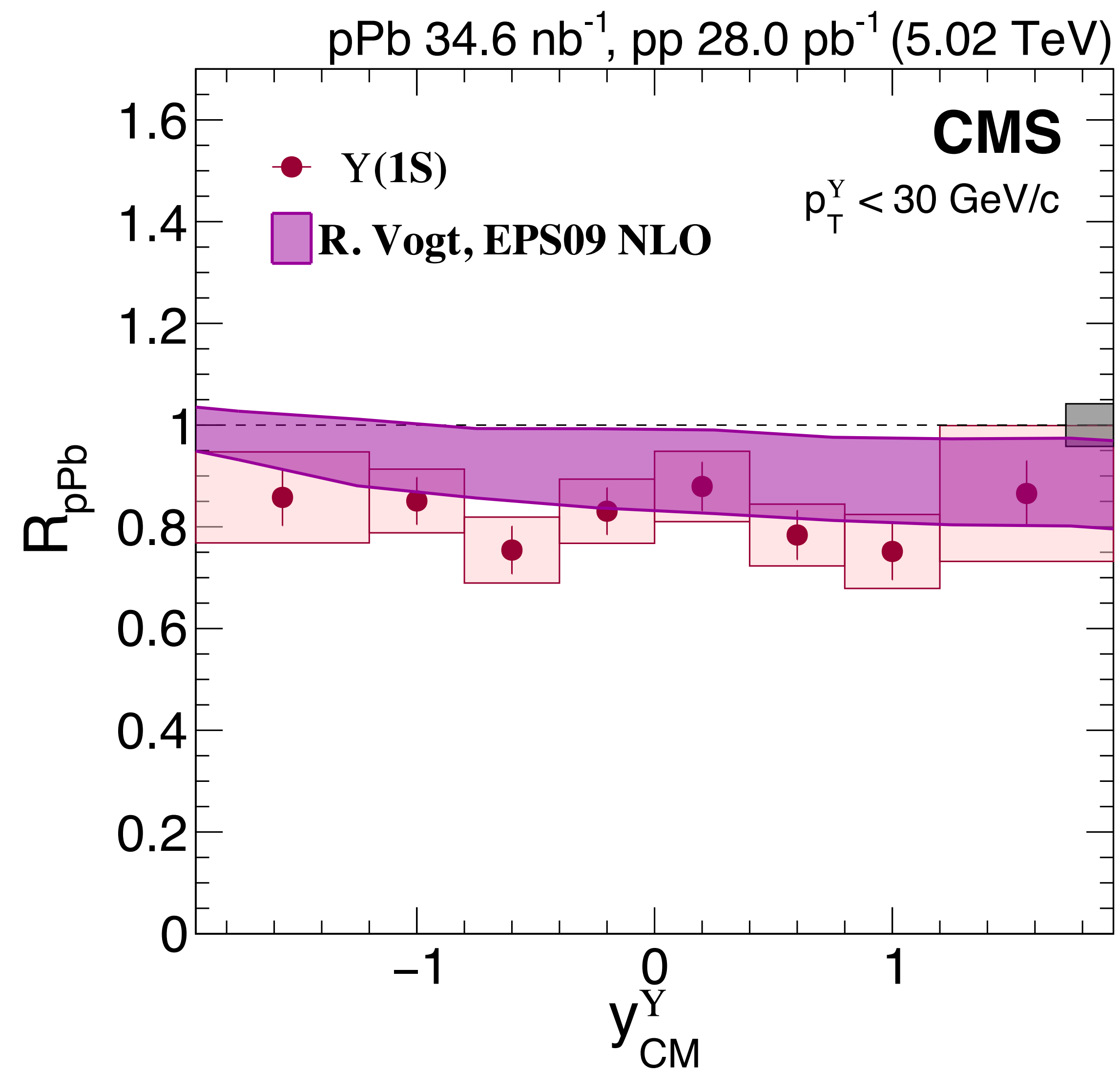




- Attempts to describe ψ(2S) suppression with comover breakup & QGP-like HNM effects
  - Tension b/w model & data in both RHIC and LHC
  - Similar nuclear absorption for J/ψ & ψ(2S) @ RHIC —> already hot in pAu 200 GeV?

Bottomonia in pPb vs model



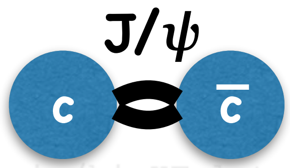


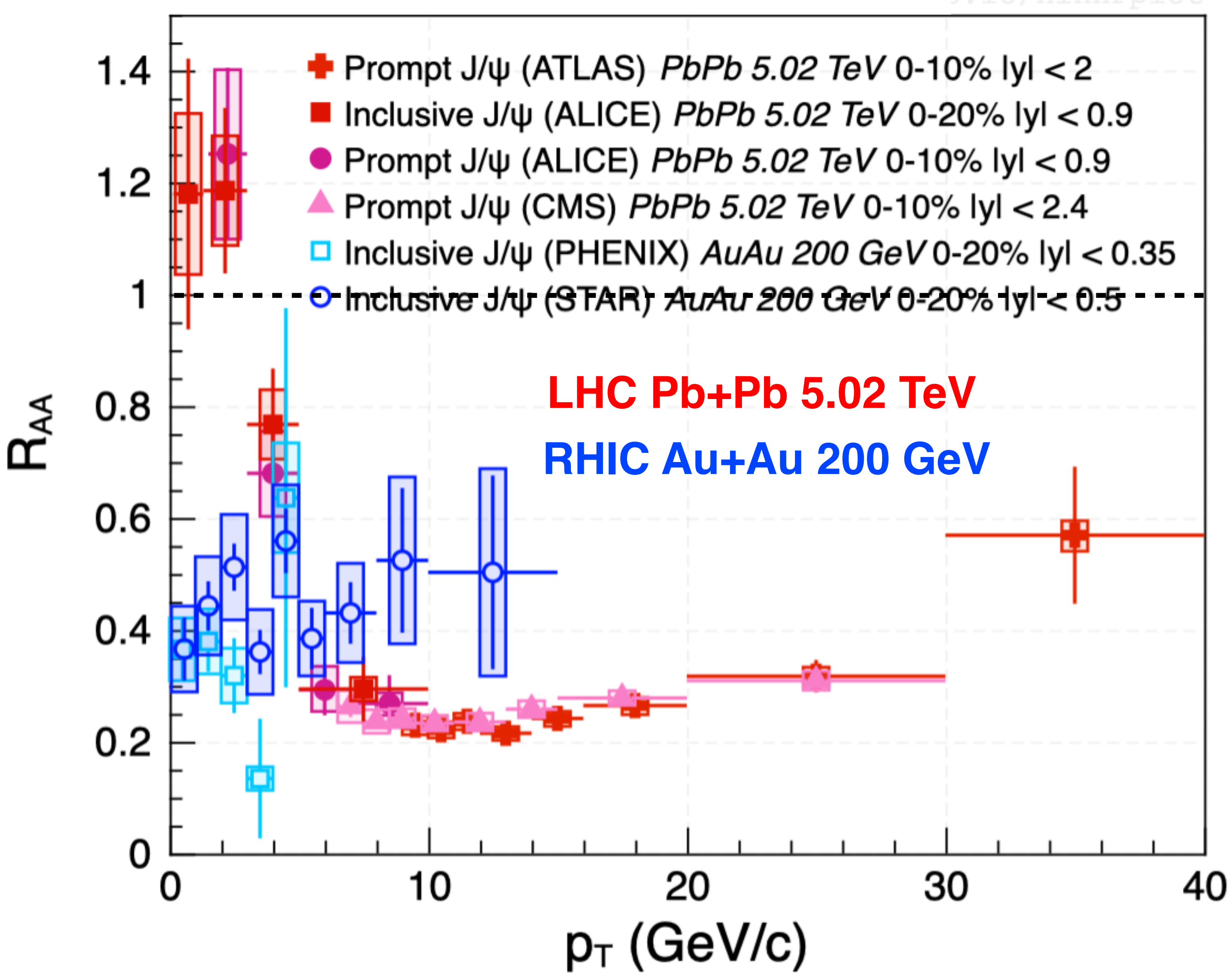
- Υ(1S) R_{pPb} data in agreement with nPDF calculations

J/ψ modification in AA

X. Bai, Tue 09:00

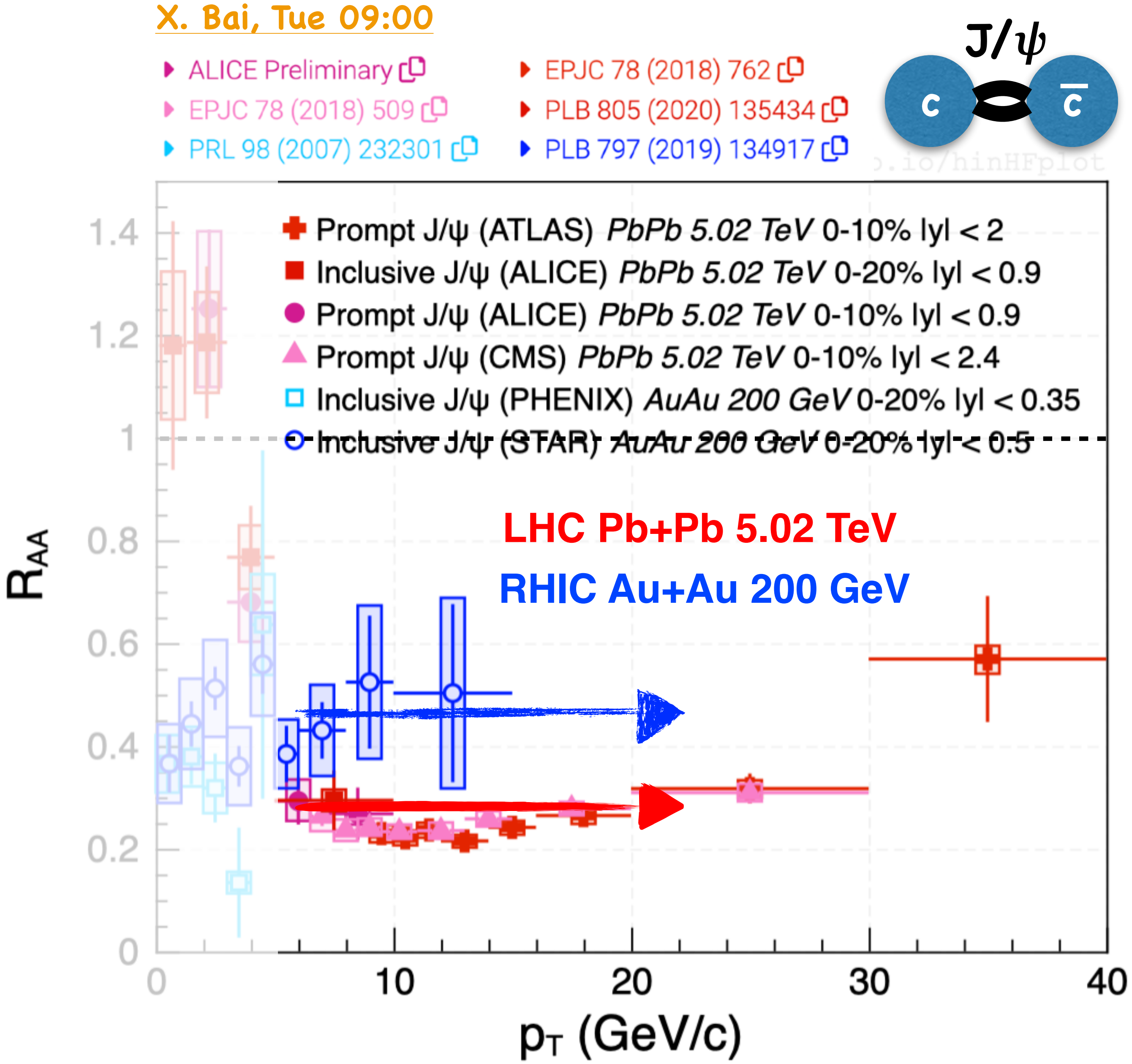
- ALICE Preliminary
- EPJC 78 (2018) 509
- PRL 98 (2007) 232301
- EPJC 78 (2018) 762
- PLB 805 (2020) 135434
- PLB 797 (2019) 134917





J/ψ modification in AA

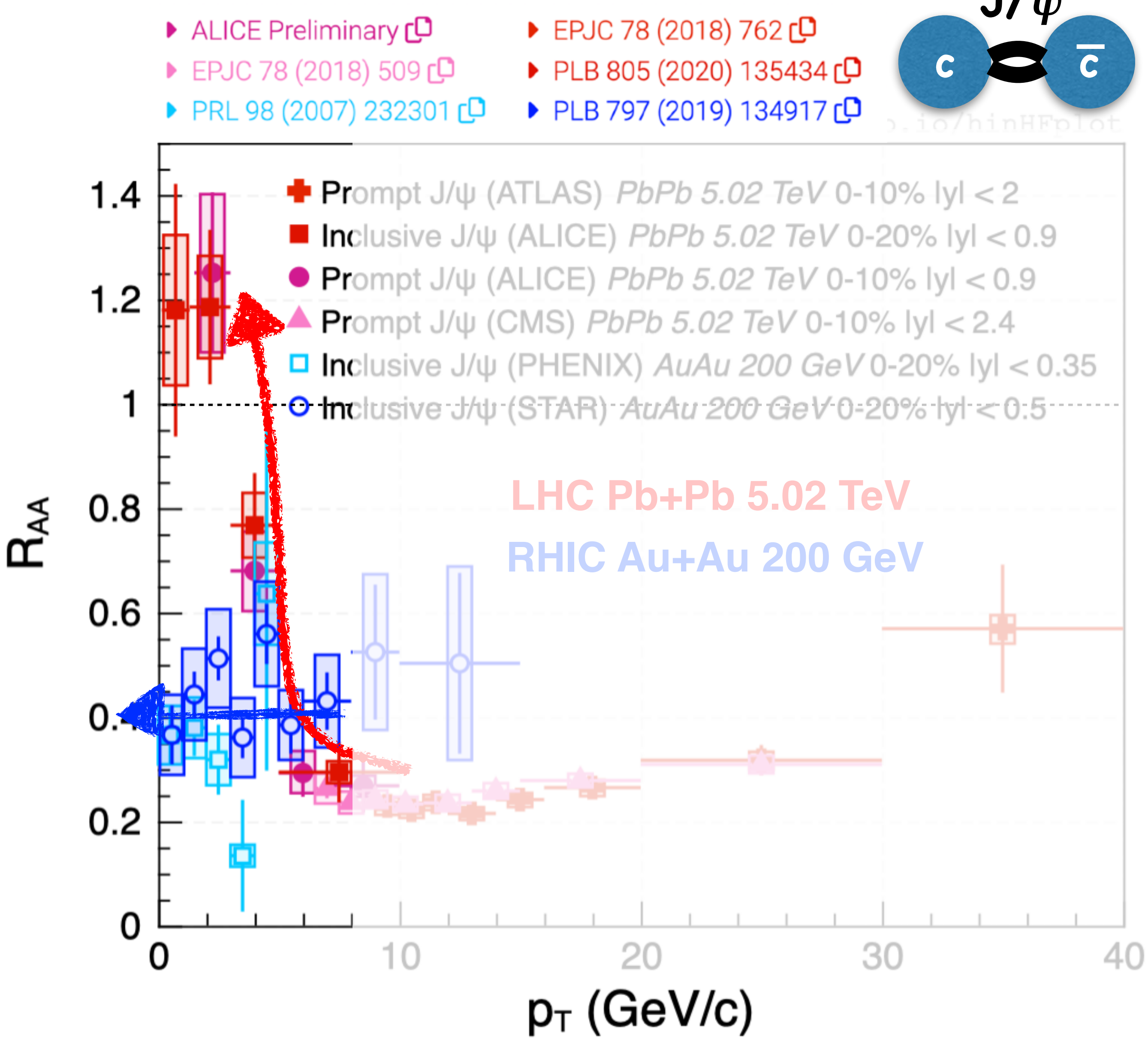
X. Bai, Tue 09:00



- R_{AA}(J/ψ) RHIC > R_{AA}(J/ψ) LHC at high-p_T : Stronger suppression at LHC (higher temperature)

J/ψ modification in AA

X. Bai, Tue 09:00



- R_{AA}(J/ψ) RHIC > R_{AA}(J/ψ) LHC at high-p_T : Stronger suppression at LHC (higher temperature)
- Enhancement at low-p_T in LHC energies : Sign of recombination (abundant charm cross section)

J/ψ modification in AA

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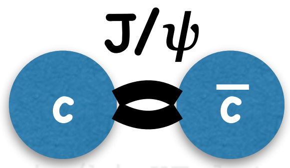
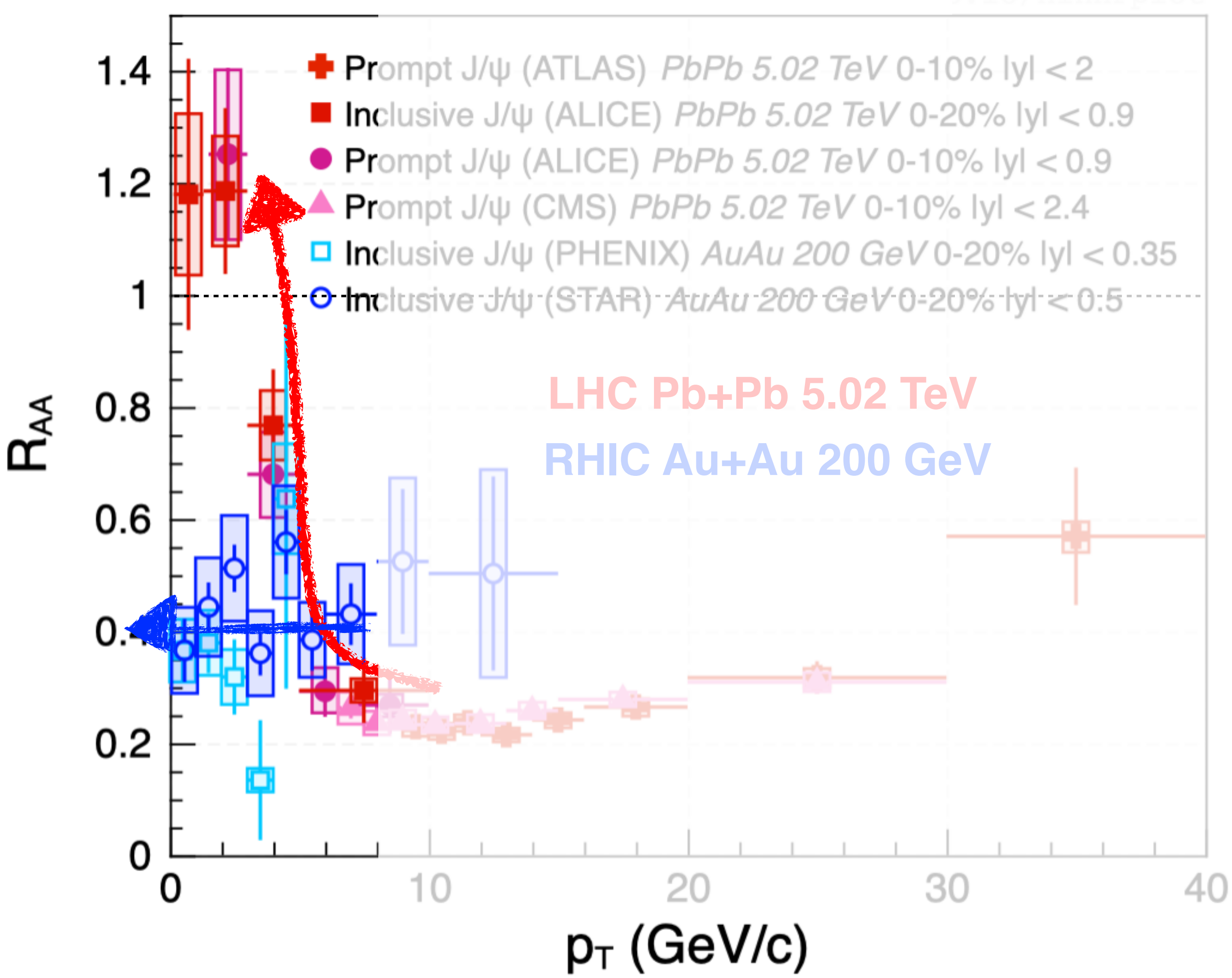
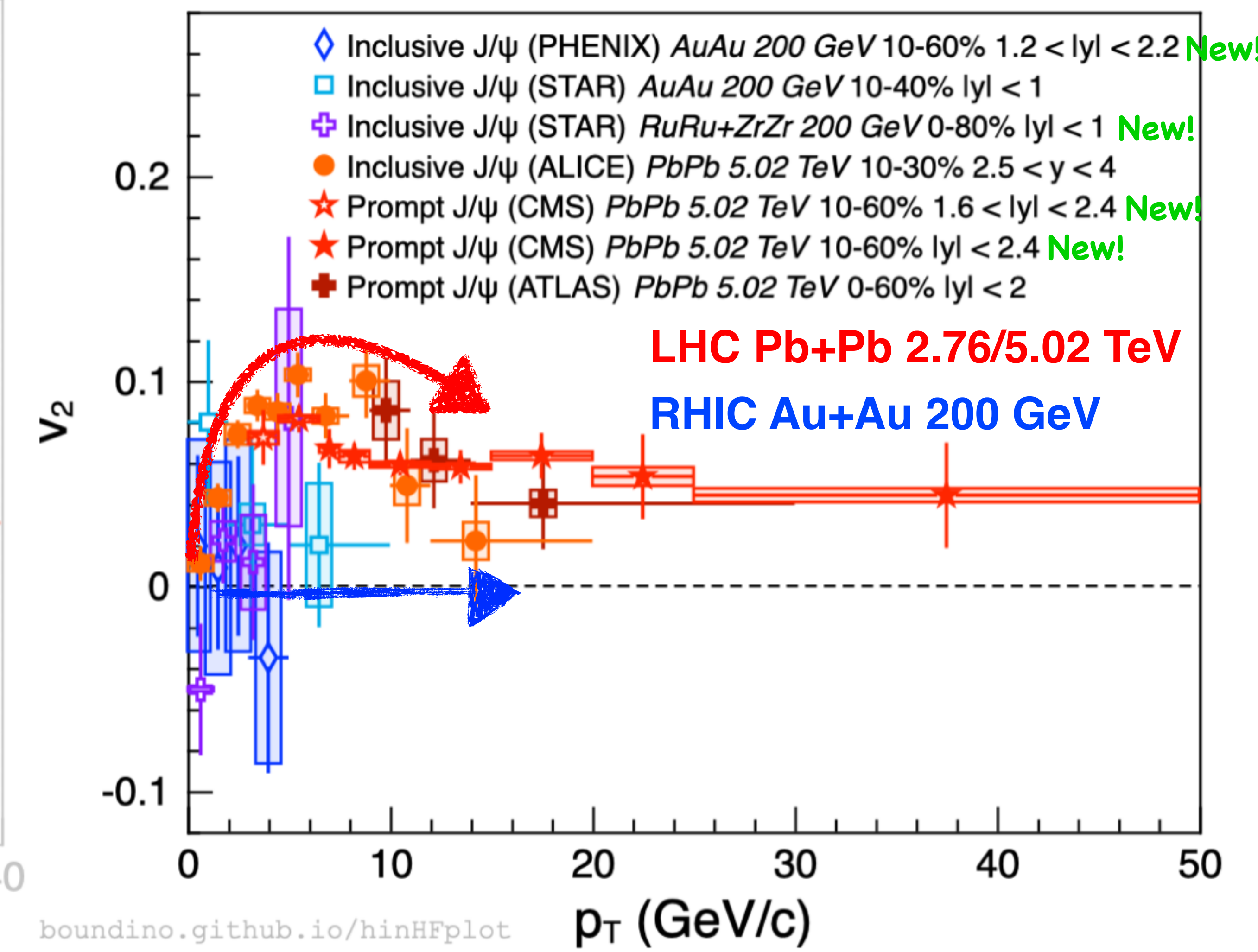


G. Bak, Tue 09:40

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

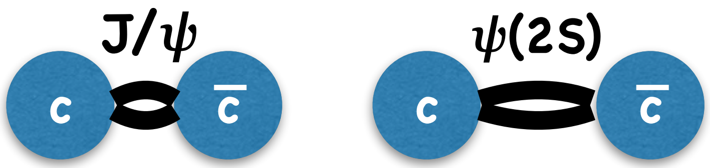




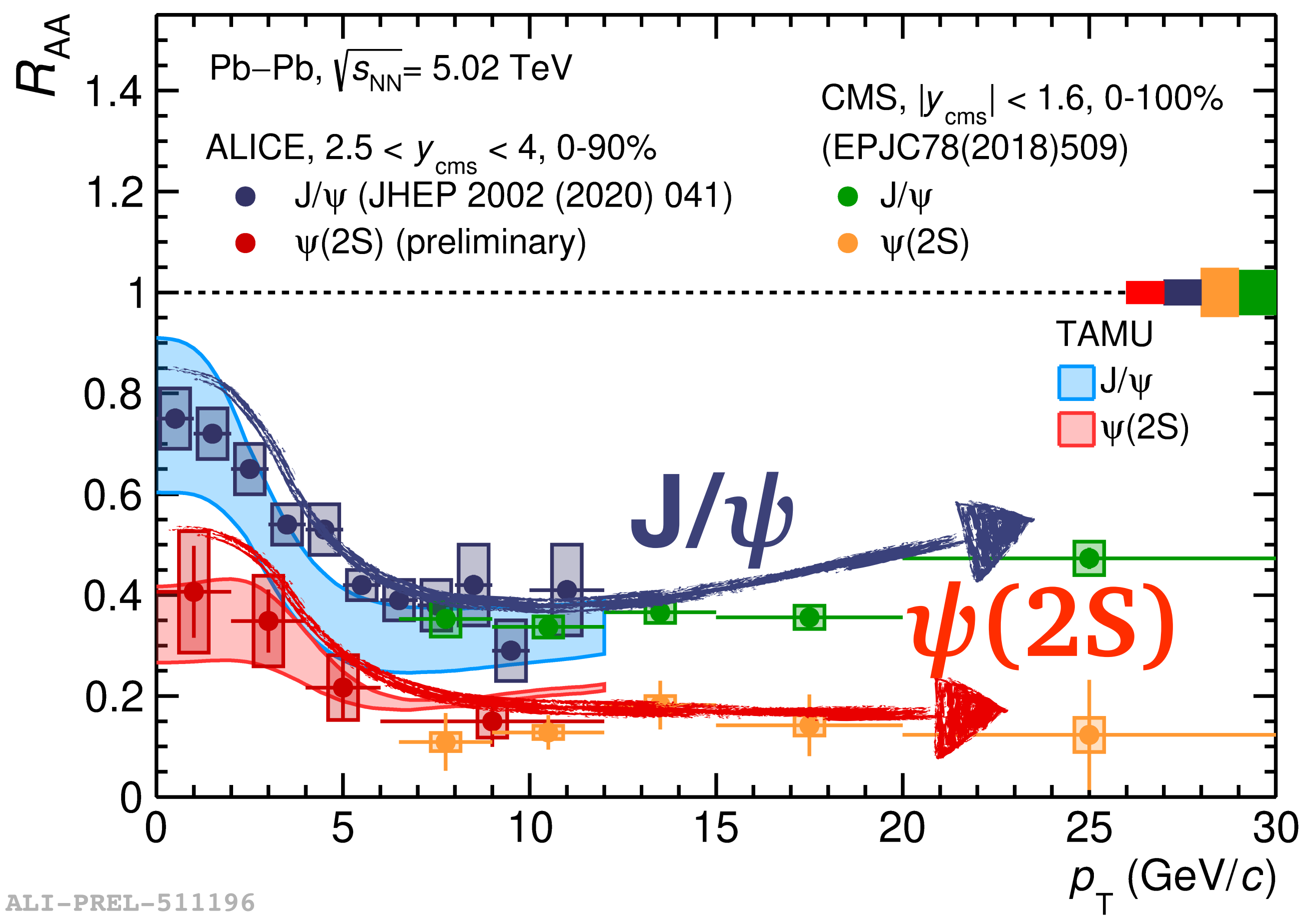
- $R_{AA}(J/\psi)$ **RHIC** > $R_{AA}(J/\psi)$ **LHC** at high-p_T : Stronger suppression at LHC (higher temperature)
- Enhancement at low-p_T in LHC energies : Sign of recombination (abundant charm cross section)
- $v_2(J/\psi)$ **LHC** ≥ $v_2(J/\psi)$ **RHIC** at low-p_T —> Precision need to be improved

J/ψ modification in AA

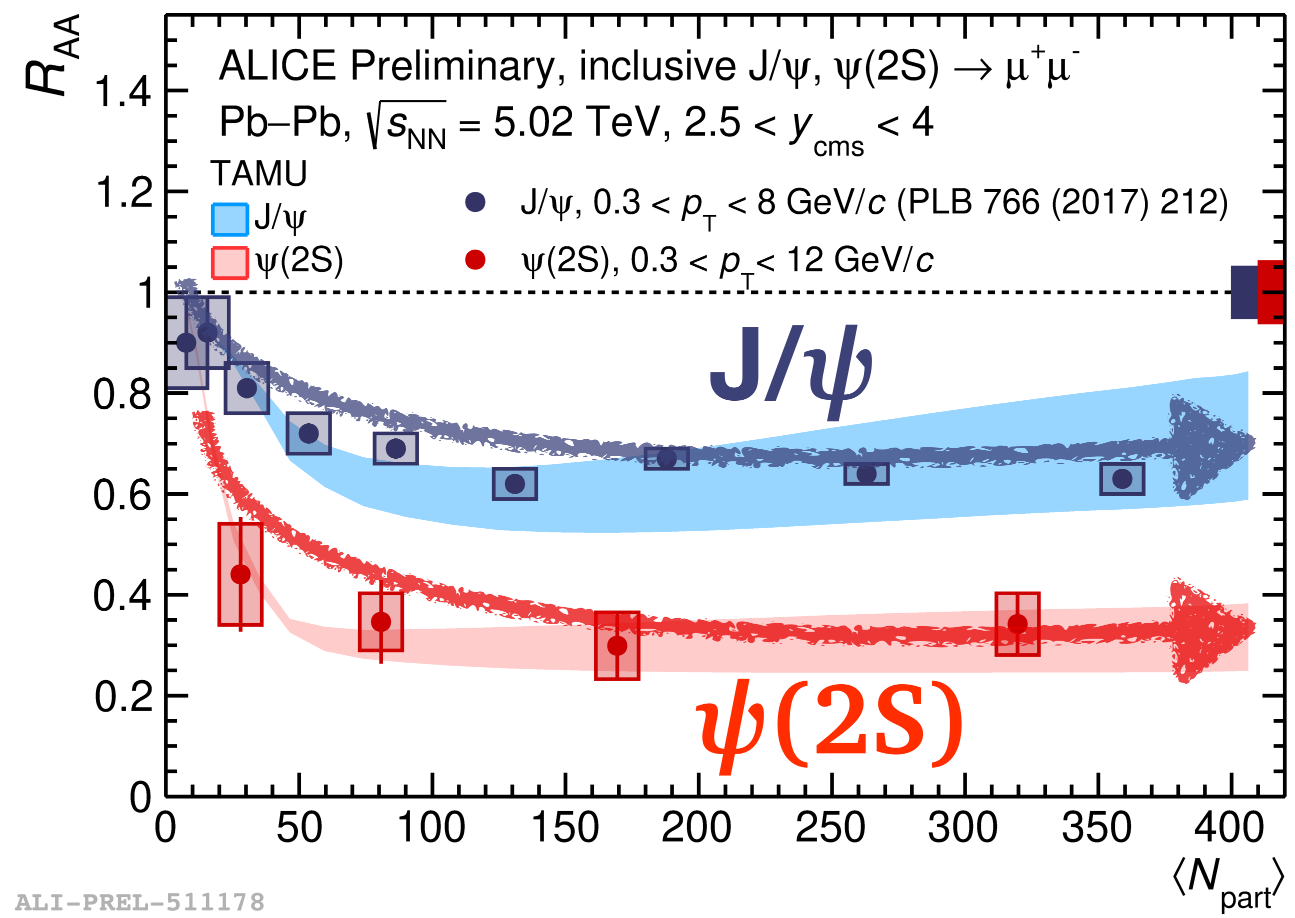
H. Hushnud, Tue 10:00



New!



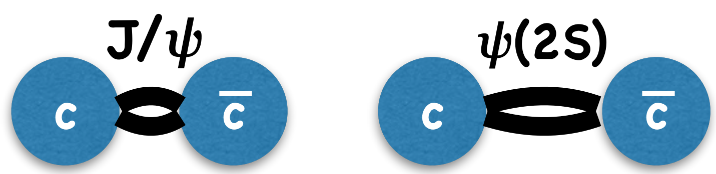
New!



- J/ψ & ψ(2S) measurements in a wide p_T range at LHC
- Larger suppression for ψ(2S) than J/ψ
- Increasing trend at low-p_T : described by theory calculation including recombination

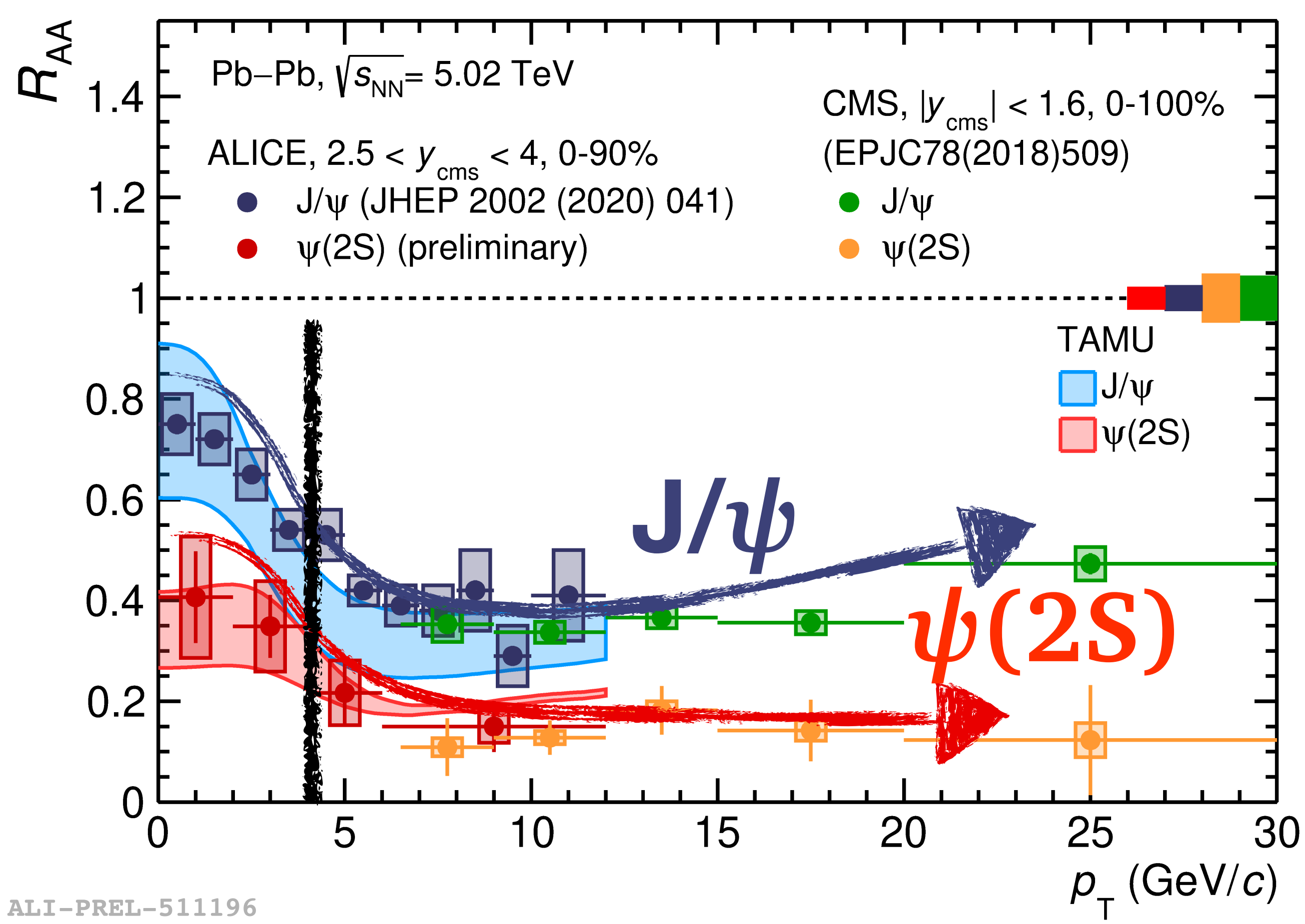
J/ψ modification in AA

H. Hushnud, Tue 10:00

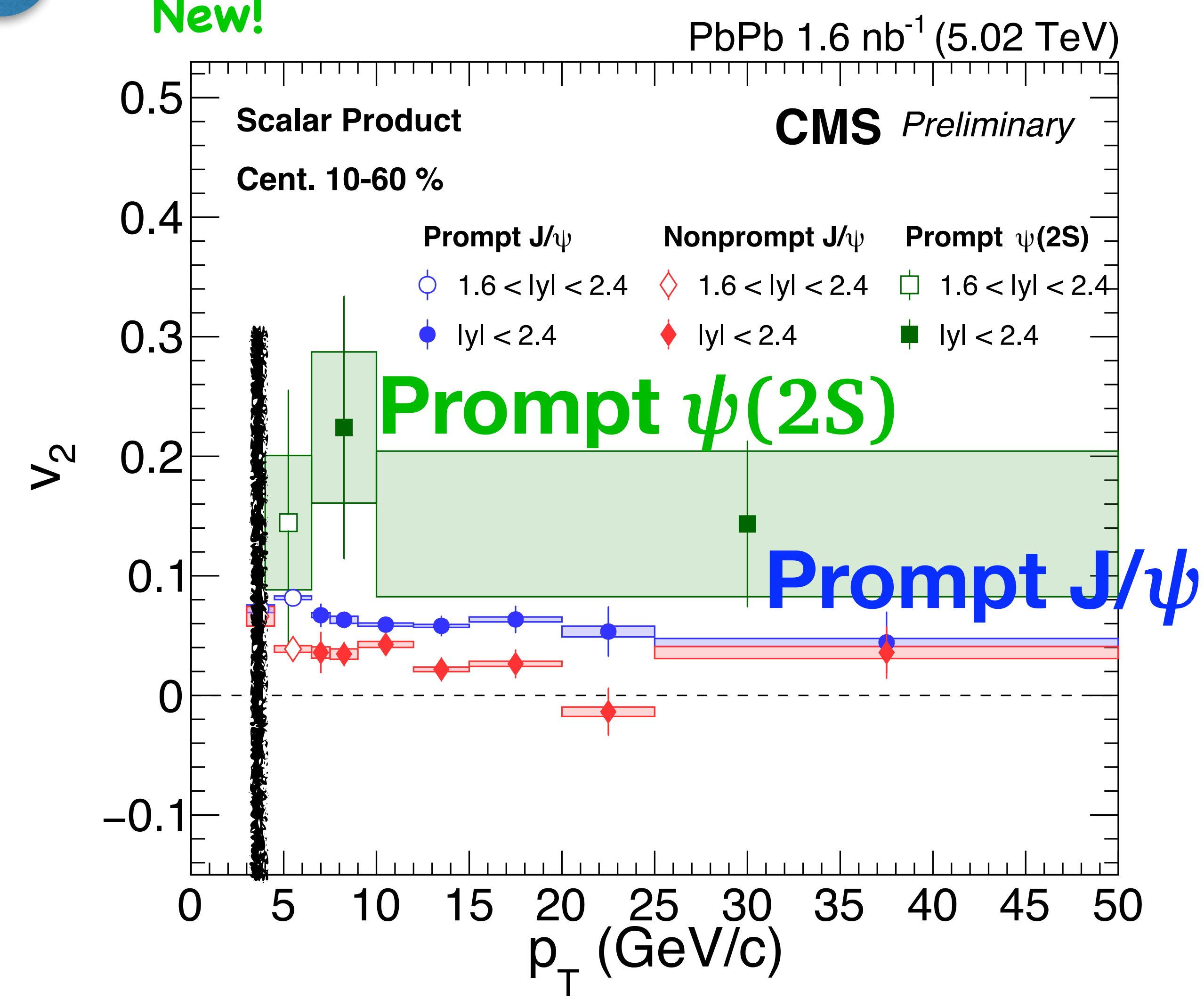


G. Bak, Tue 09:40

New!



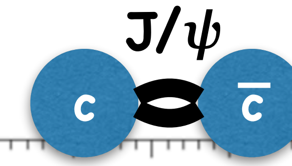
New!

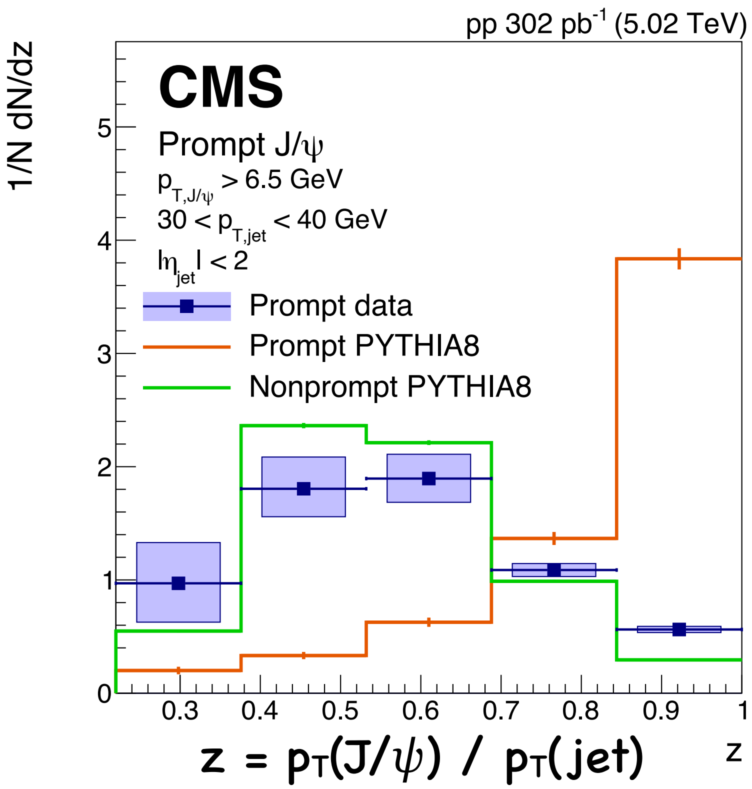


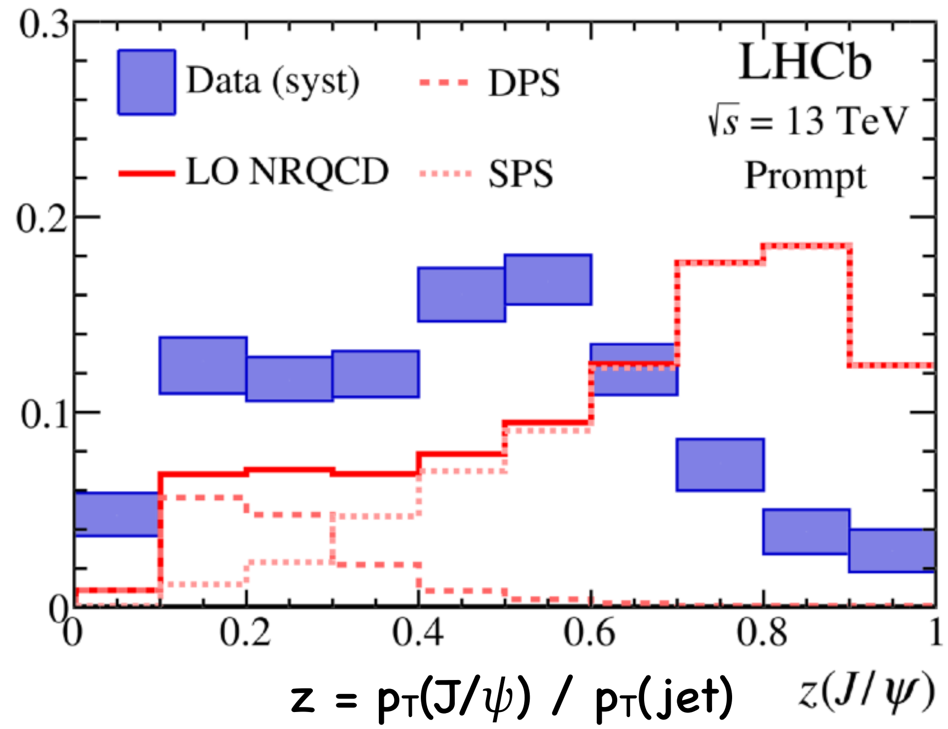
- J/ψ & ψ(2S) measurements in a wide p_T range at LHC
- Larger suppression for ψ(2S) than J/ψ
- prompt ψ(2S) v_2 ≥ prompt J/ψ v_2
  - Different amount of recombination? Path-length dependent dissociation? etc…

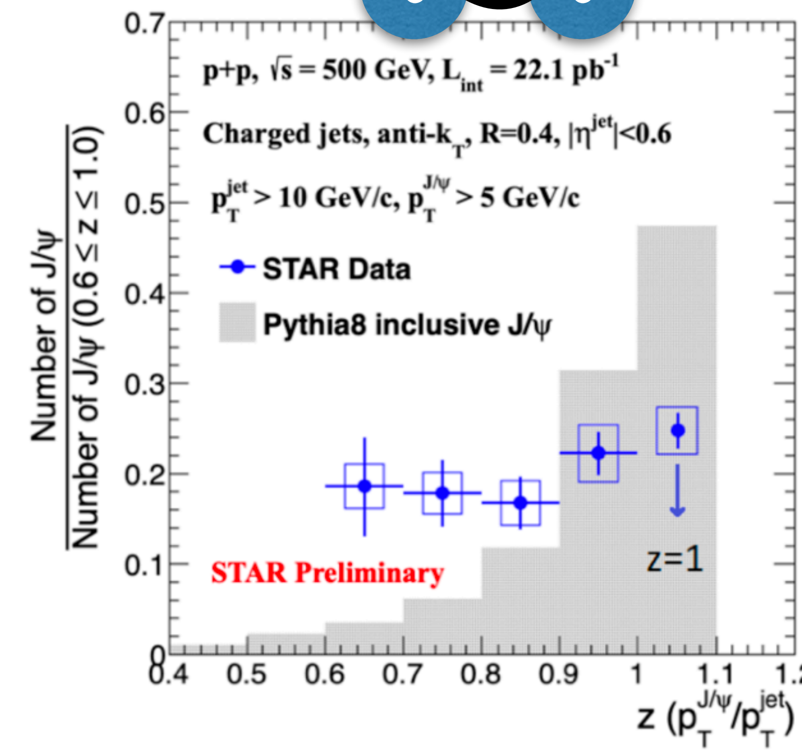
Charmonia in jets

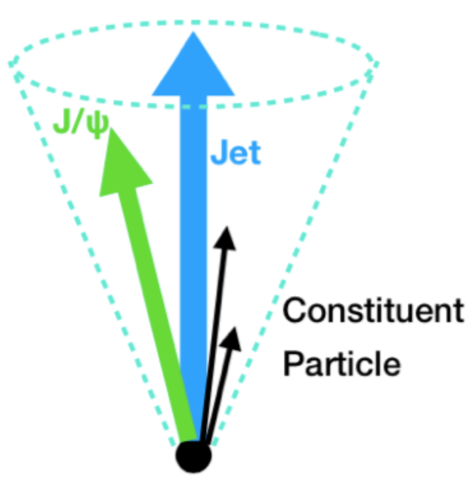
G. Bak, Tue 09:40 [PLB 805 (2020) 135434] N. Cooke, Tue POS-HF-02 [PRL 118 (2017) 192001]











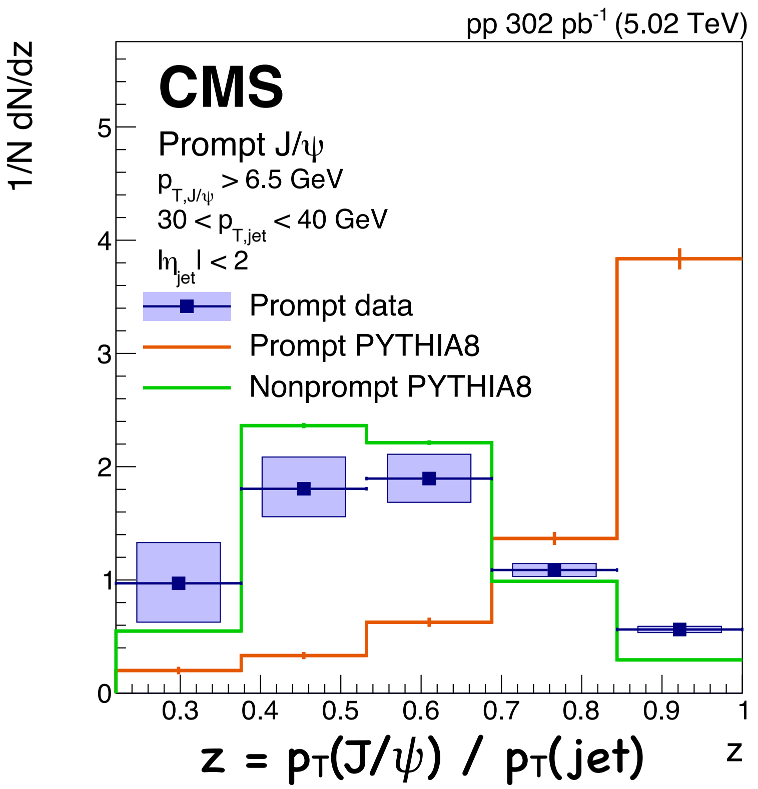
- Significant contribution from (inside) jets for J/ψ production!

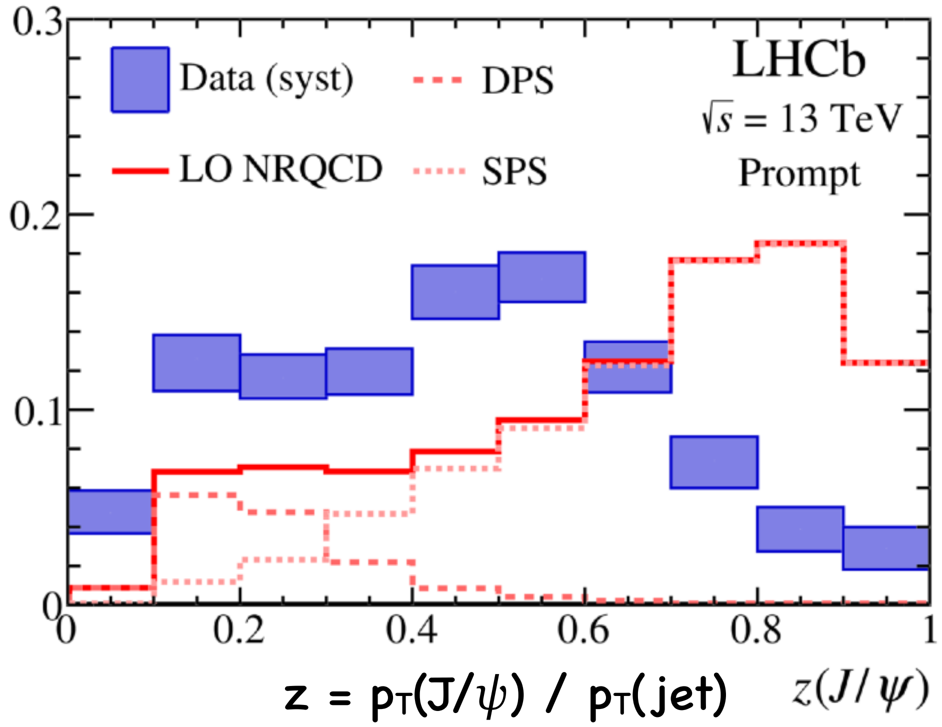
[CMS pp 8 TeV PLB 804 (2020) 135409]

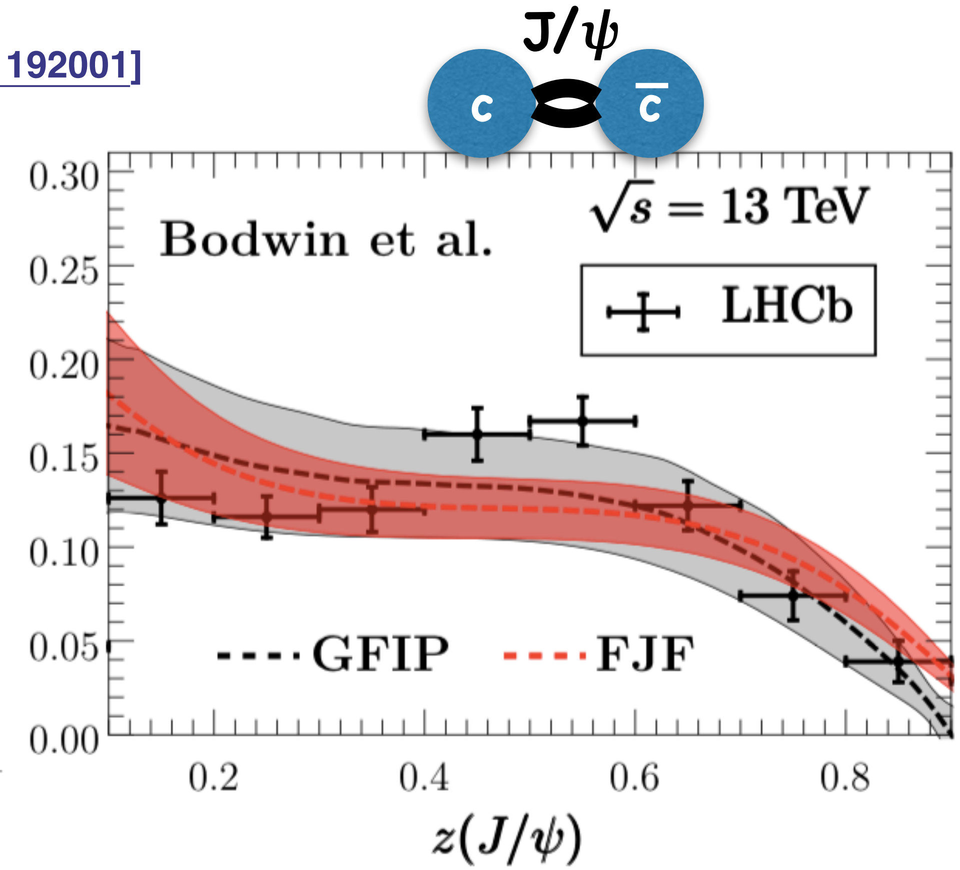
~85% of J/ψ are produced within a jet
($E_{J/\psi}$ > 15 GeV, $|y_{J/\psi}|$ < 1, E_{jet} > 19 GeV, $|\eta_{jet}|$ < 1)

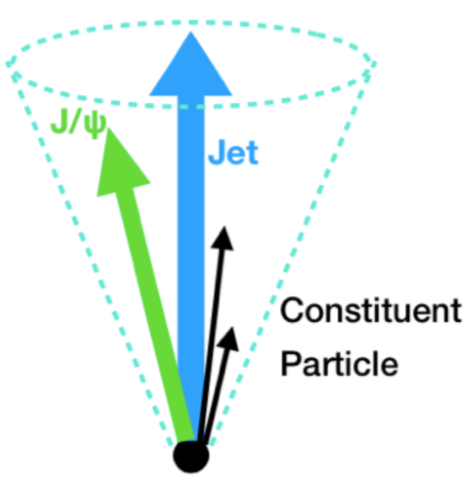
Charmonia in jets

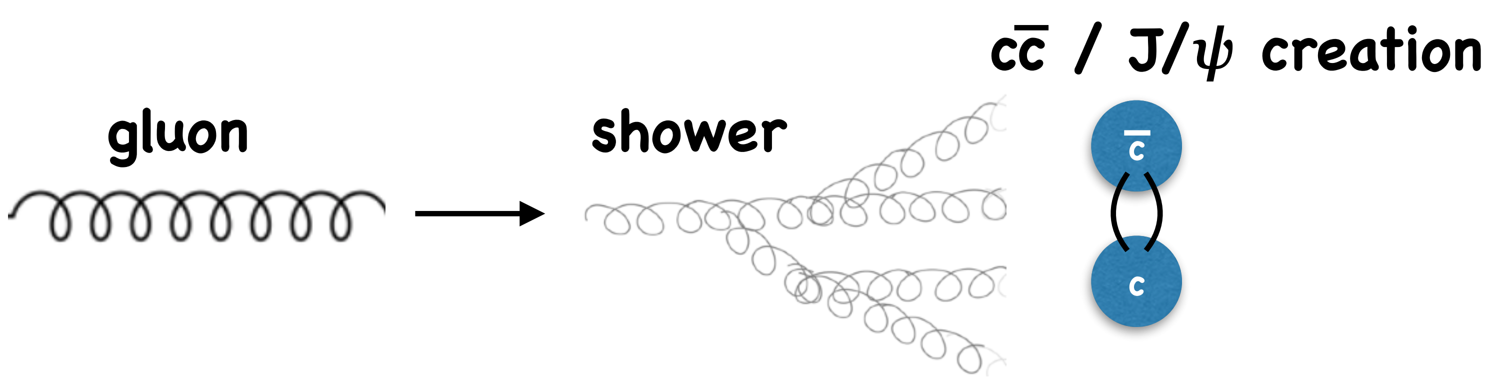
G. Bak, Tue 09:40 [PLB 805 (2020) 135434] N. Cooke, Tue POS-HF-02 [PRL 118 (2017) 192001]





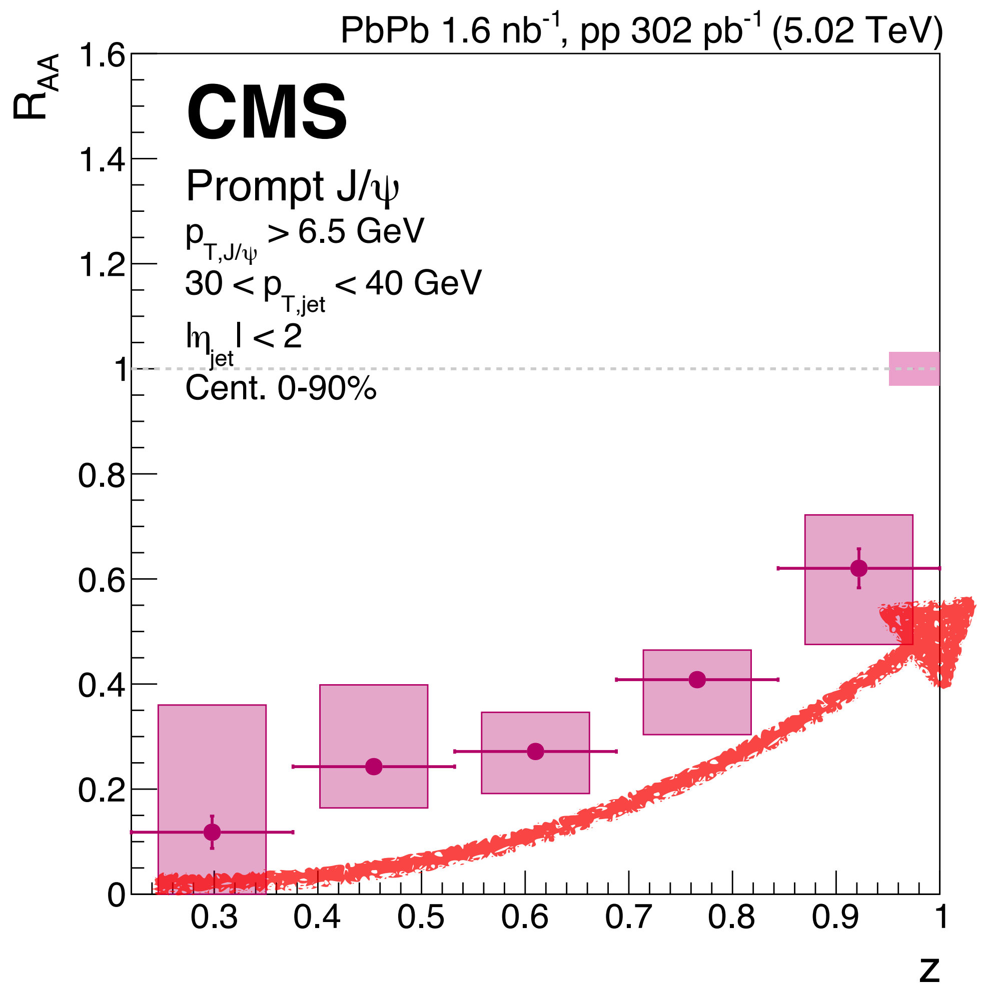


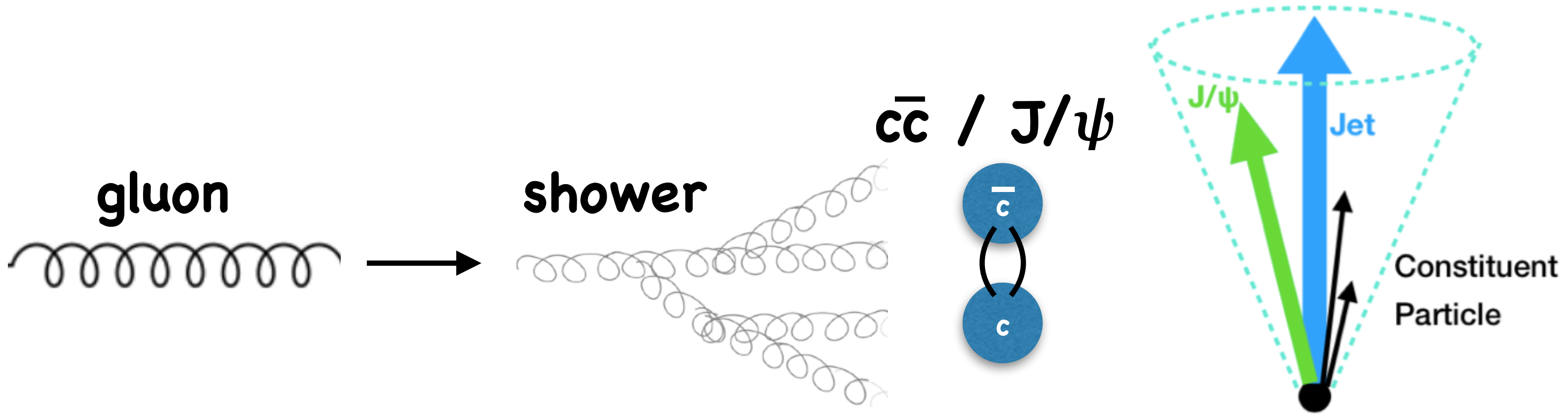




- Later production by parton shower

[PLB 805 (2020) 135434] G. Bak, Tue 09:40



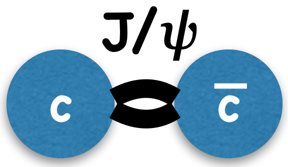


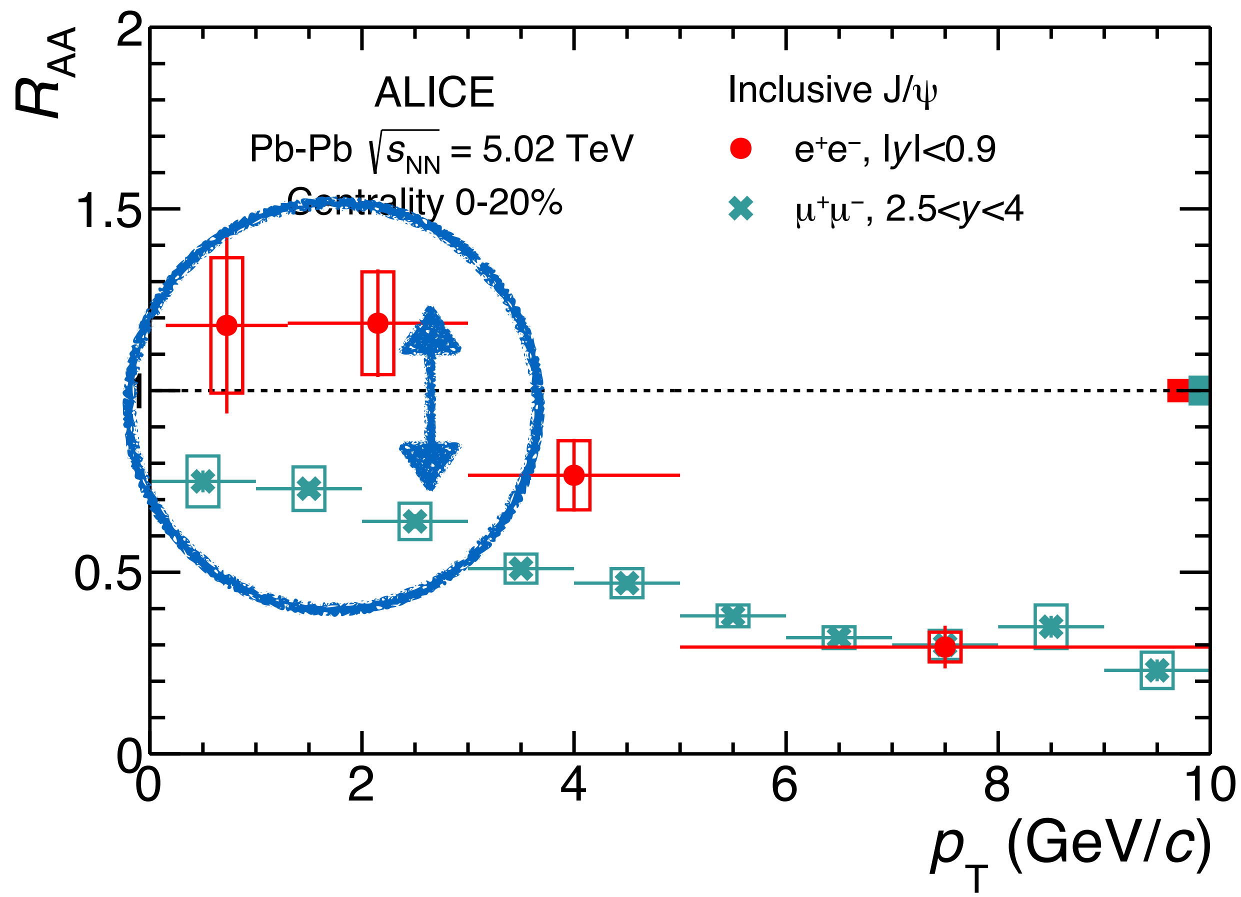
- Less suppression for isolated J/ψ
  : difference ~x5 (although large unc.)

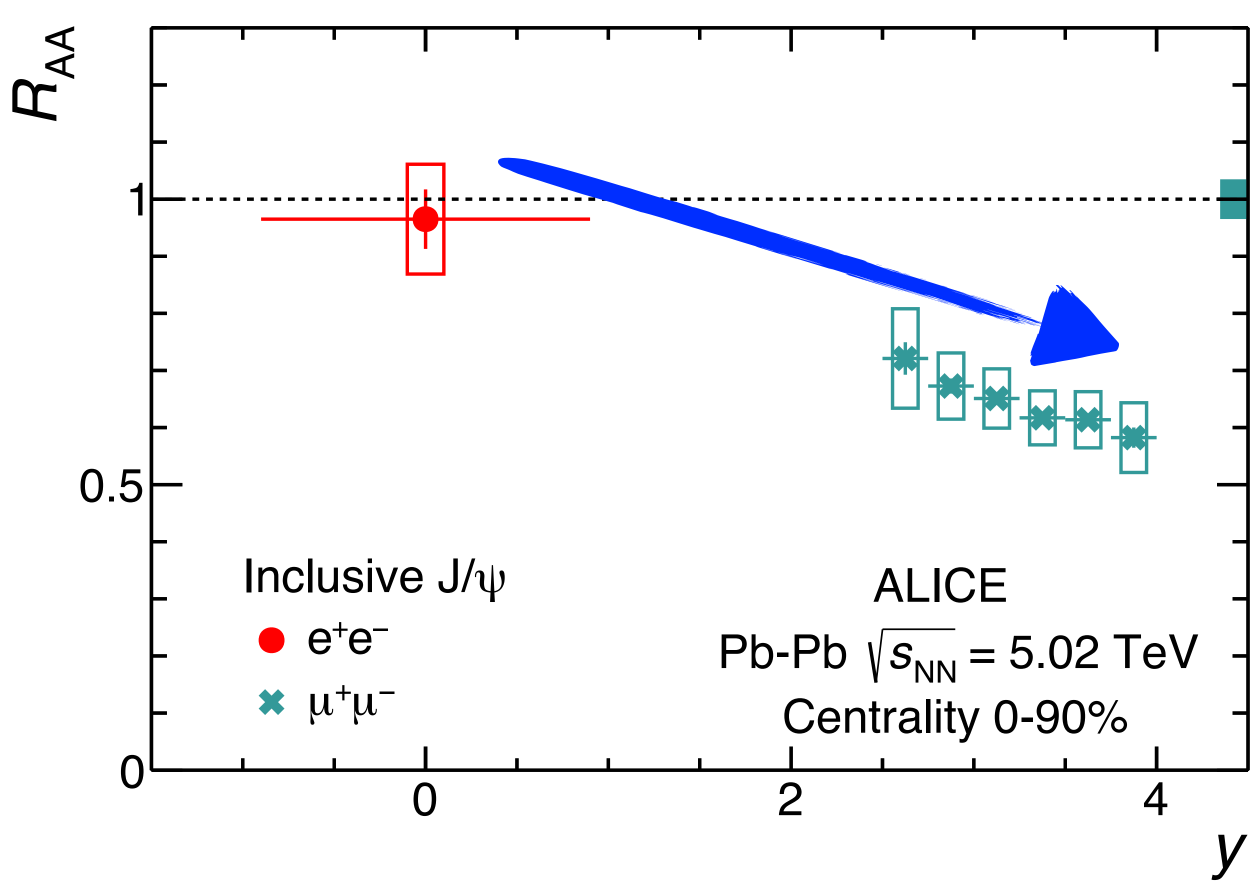
J/ψ modification in AA

PLB 805 (2020) 135434

JHEP 02 (2020) 041

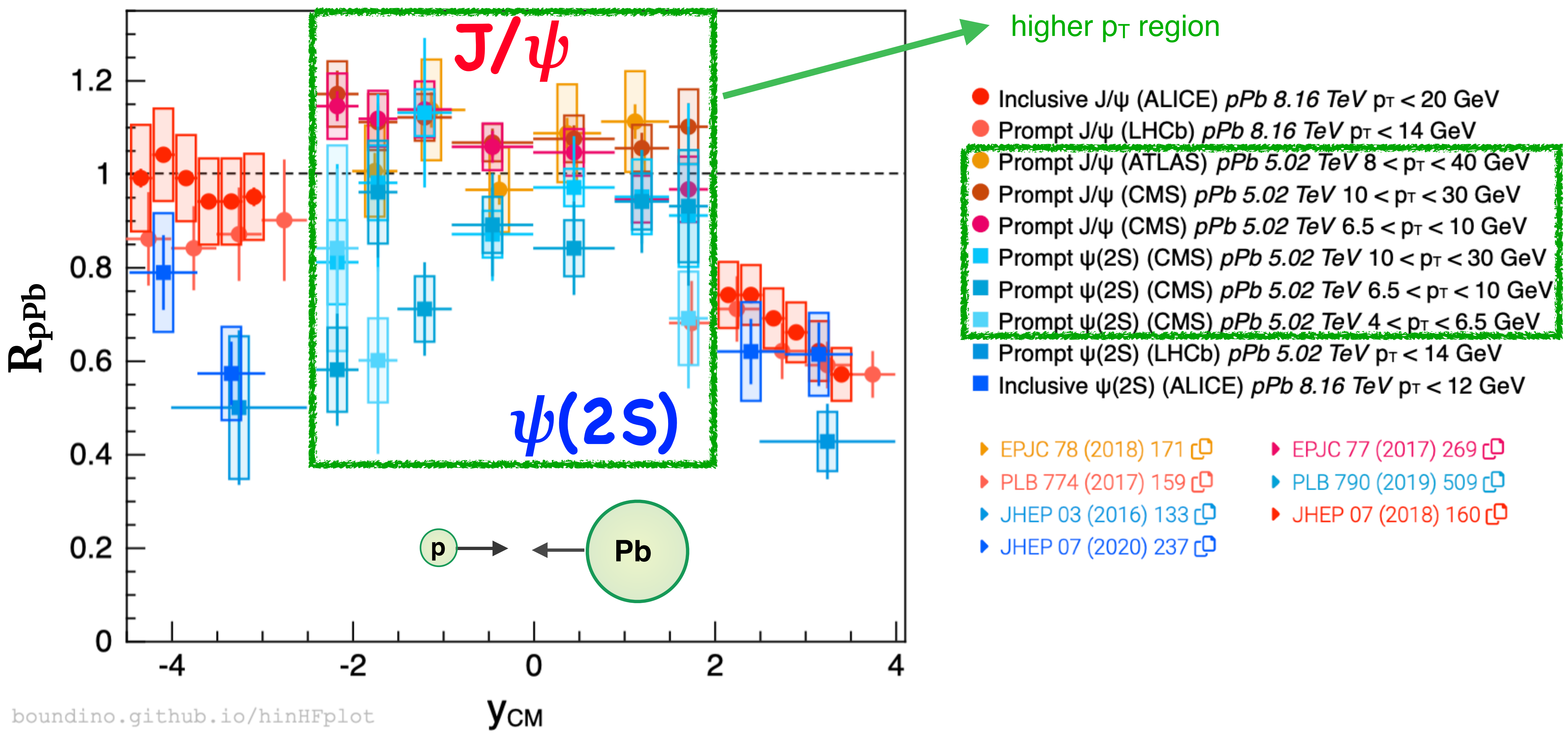






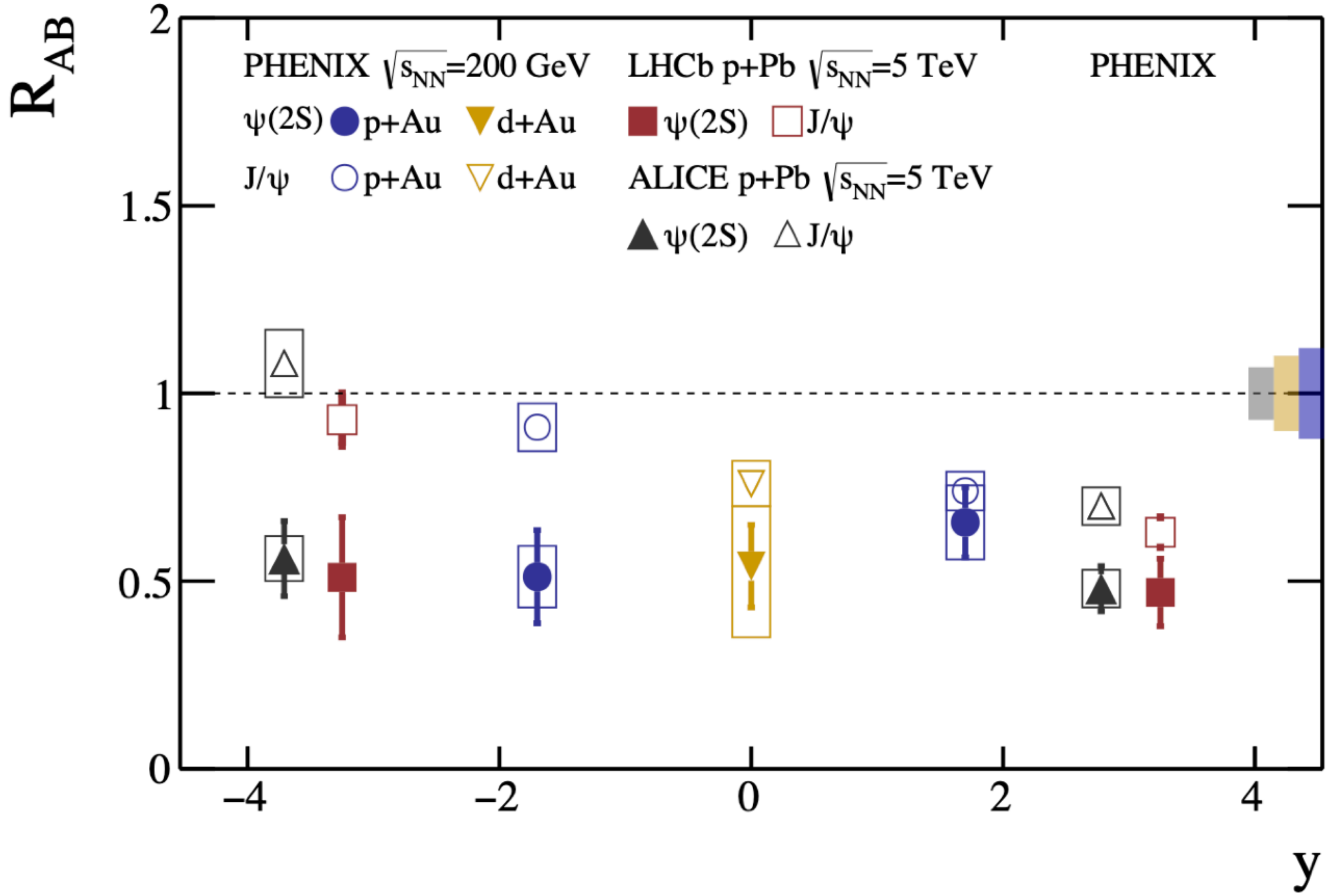
- Less enhancement (or larger suppression) of J/ψ towards forward rapidity

Charmonia in pPb

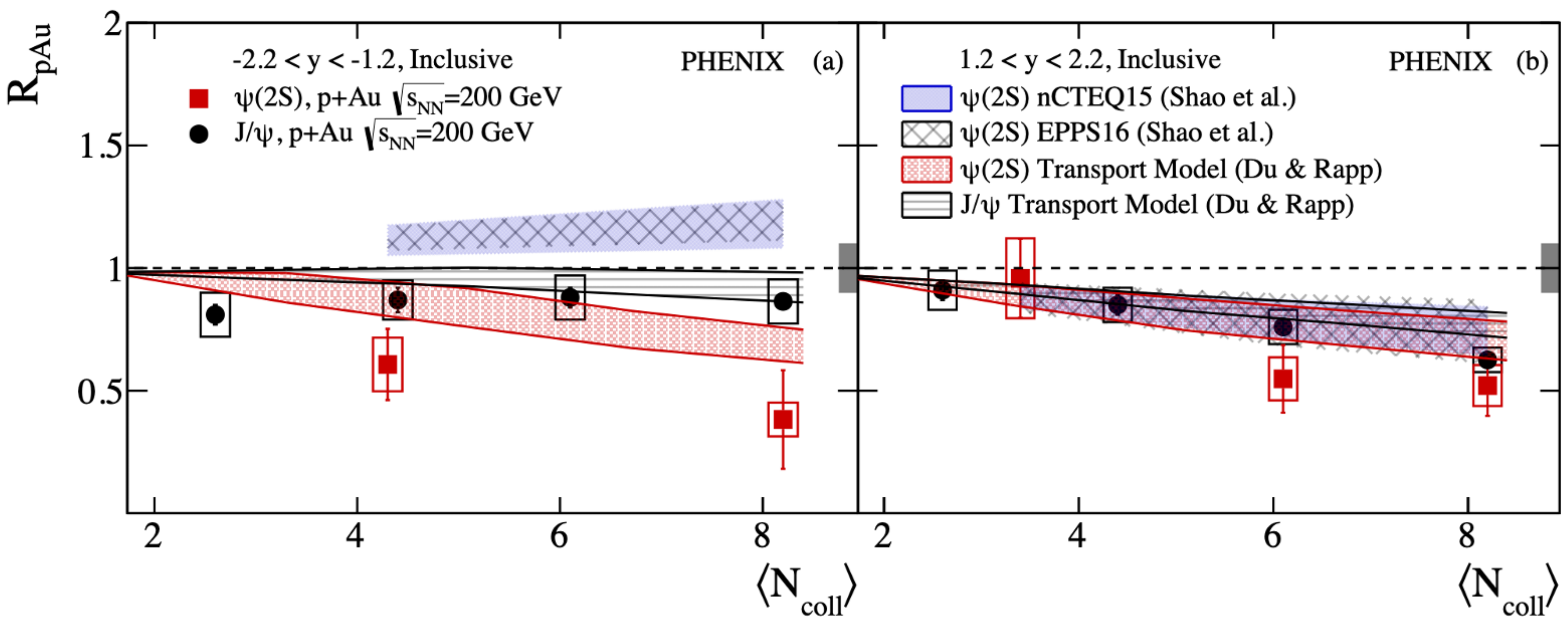


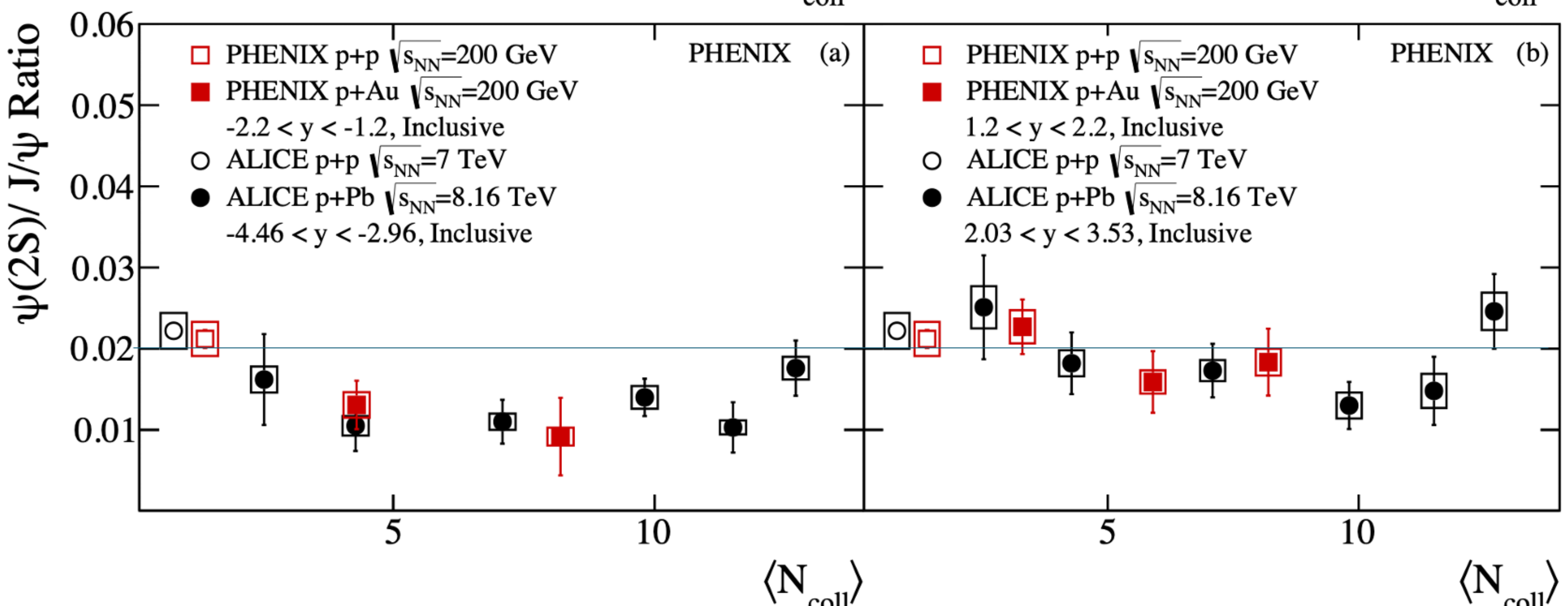
- Overall 'decreasing trend' towards forward rapidity
  —> Consistent with nPDF based predictions
- Suppression for $\psi(2S)$: final state effects from comover-breakup?

Charmonia in p(d)A



Charmonia in p(d)A

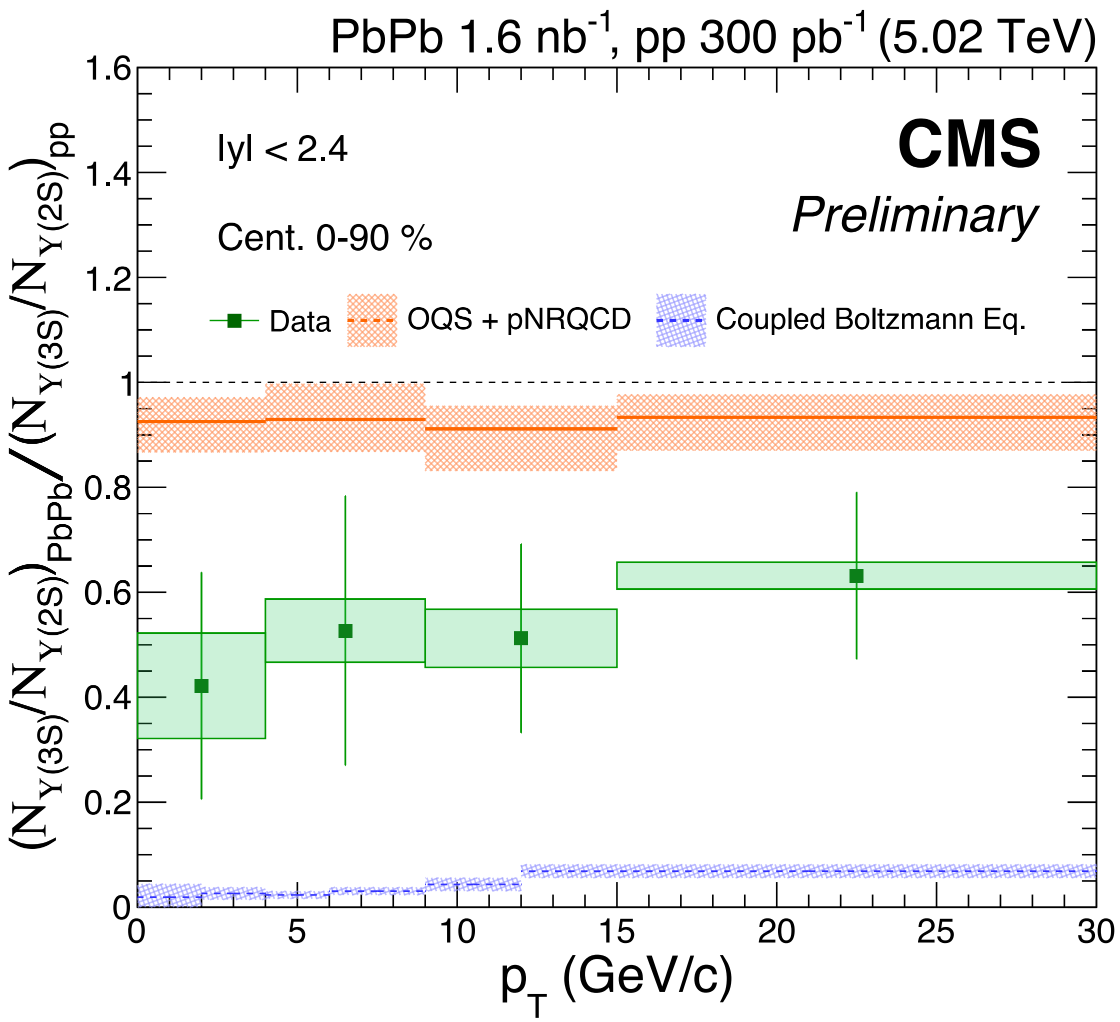




PRC 102 (2022) 014902

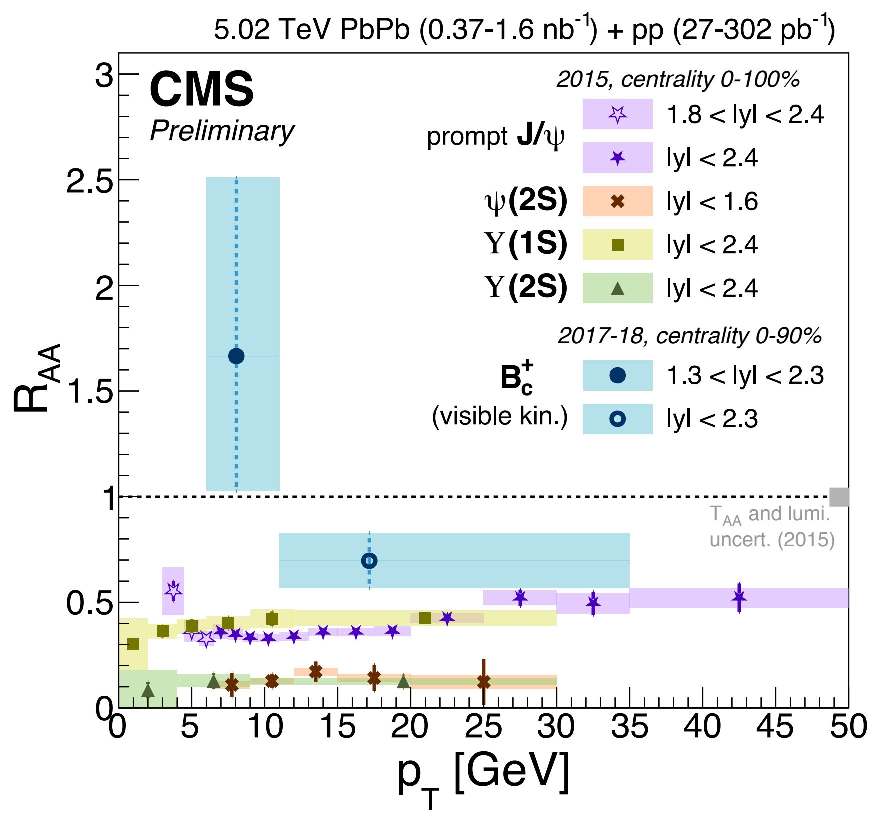
Υ(3S)/Υ(2S) double ratio & Υ recombination

[CMS-PAS-HIN-21-007]

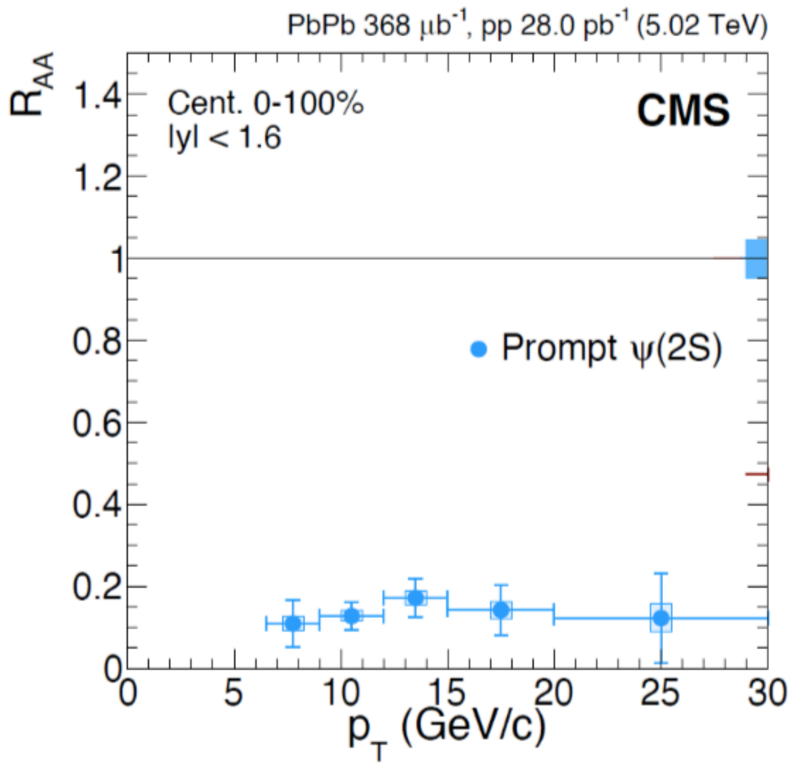


- Double ratio of Υ(3S) / Υ(2S) as a discriminator for Upsilon in-medium effects?
- Significant contribution from recombination processes? Quite model-dependent…

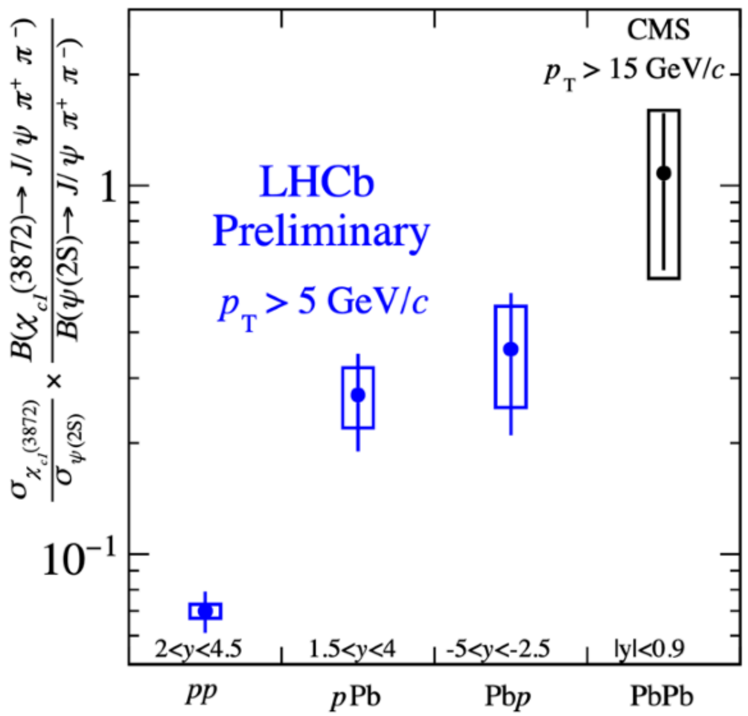
Bc / X(3872)



5.02 TeV PbPb (0.37-1.6 nb^{-1}) + pp (27-302 pb^{-1})
CMS
Preliminary
2015, centrality 0-100%
prompt J/ψ
1.8 < |y| < 2.4
|y| < 2.4
ψ(2S) |y| < 1.6
Υ(1S) |y| < 2.4
Υ(2S) |y| < 2.4
2017-18, centrality 0-90%
B_c^+
(visible kin.)
1.3 < |y| < 2.3
|y| < 2.3
T_{AA} and lumi. uncert. (2015)
R_{AA}
p_T [GeV]



PbPb 368 μb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)
Cent. 0-100%
|y| < 1.6
CMS
Prompt ψ(2S)
R_{AA}
p_T (GeV/c)



CMS
p_T > 15 GeV/c
LHCb
Preliminary
p_T > 5 GeV/c
2<y<4.5
1.5<y<4
-5<y<-2.5
|y|<0.9
pp
pPb
Pbp
PbPb