Inclusive quarkonium production in pp (and pPb) at the LHC

JaeBeom Park (Korea University)
- on behalf of ALICE/ATLAS/CMS/LHCb collaboration

QCD@LHC 2022 @ Saclay (France)

Associated production of J/psi plus W or Z at NLO and implications on NRQCD factorization
- Mathias Butenschoen link -

S-wave quarkonium production and polarization in potential NRQCD
- Xiangpeng Wang link -

Quarkonium in the QGP from unquenched lattice QCD
- Sajid Ali link -

Challenges in quarkonium and exotic-state production in small systems
- ELENA GONZALEZ FERREIRO link -

Exclusive J/psi photoproduction in nucleus-nucleus UPCs at the LHC in NLO QCD
- Vadim Guzey link -

A simple model to include initial-state and hot-medium effects in the computation of quarkonium nuclear modification factor
- MIGUEL ANGEL ESCOBEDO ESPINOSA link -

Heavy quarks and quarkonia in small systems
- Zaida Conesa Del Valle link -

Open heavy flavour/quarkonium associated production at the LHC
- Achim Geiser link -

Exclusive quarkonium production at the LHC
- Adam Matyja link -

Exotic Hadrons at LHC
- Mindaugas Sarpis link -

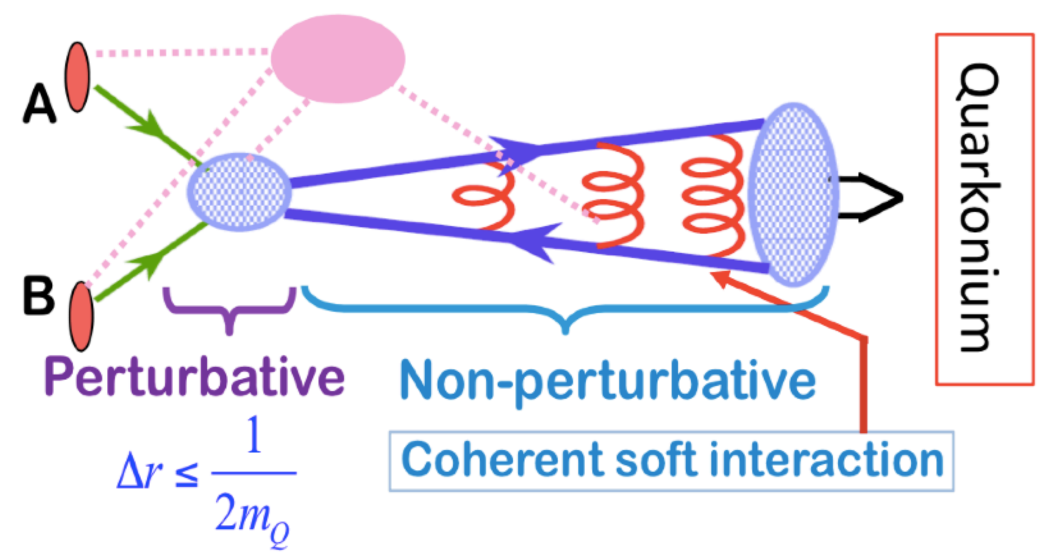
Joint TH EXP on quarkonia at the LHC
- Maxim Nefedov link -

Joint TH EXP on quarkonia at the LHC
- Valeriia Zhovkovska link -

- Valuable Theory, Experiment, and Plenary talks for quarkonia!
  - and enjoy excursion in Paris!

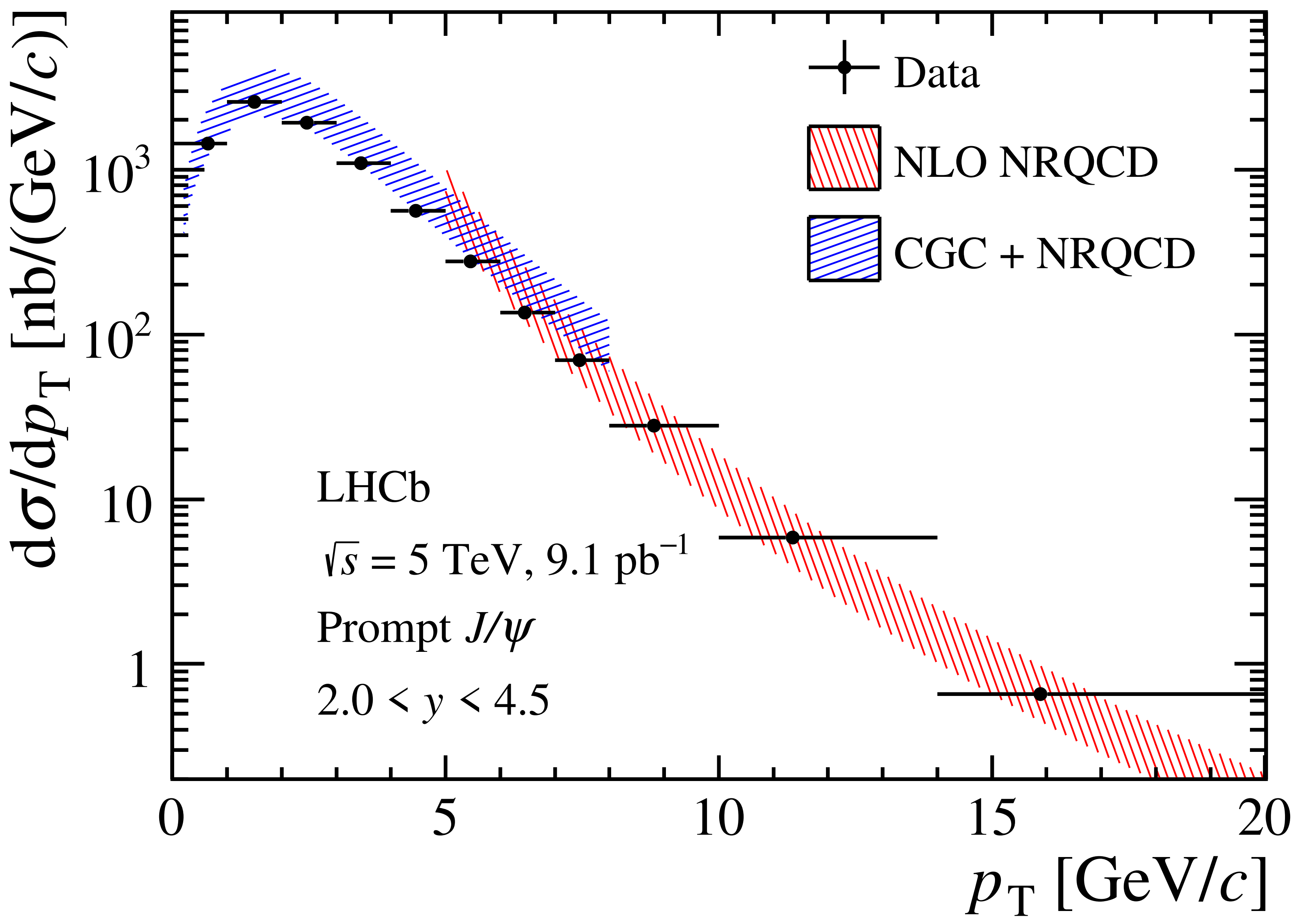
Motivation

- **Quarkonium production**
  - Perturbative in heavy quark pair
  - Non-perturbative in the evolution to bound state

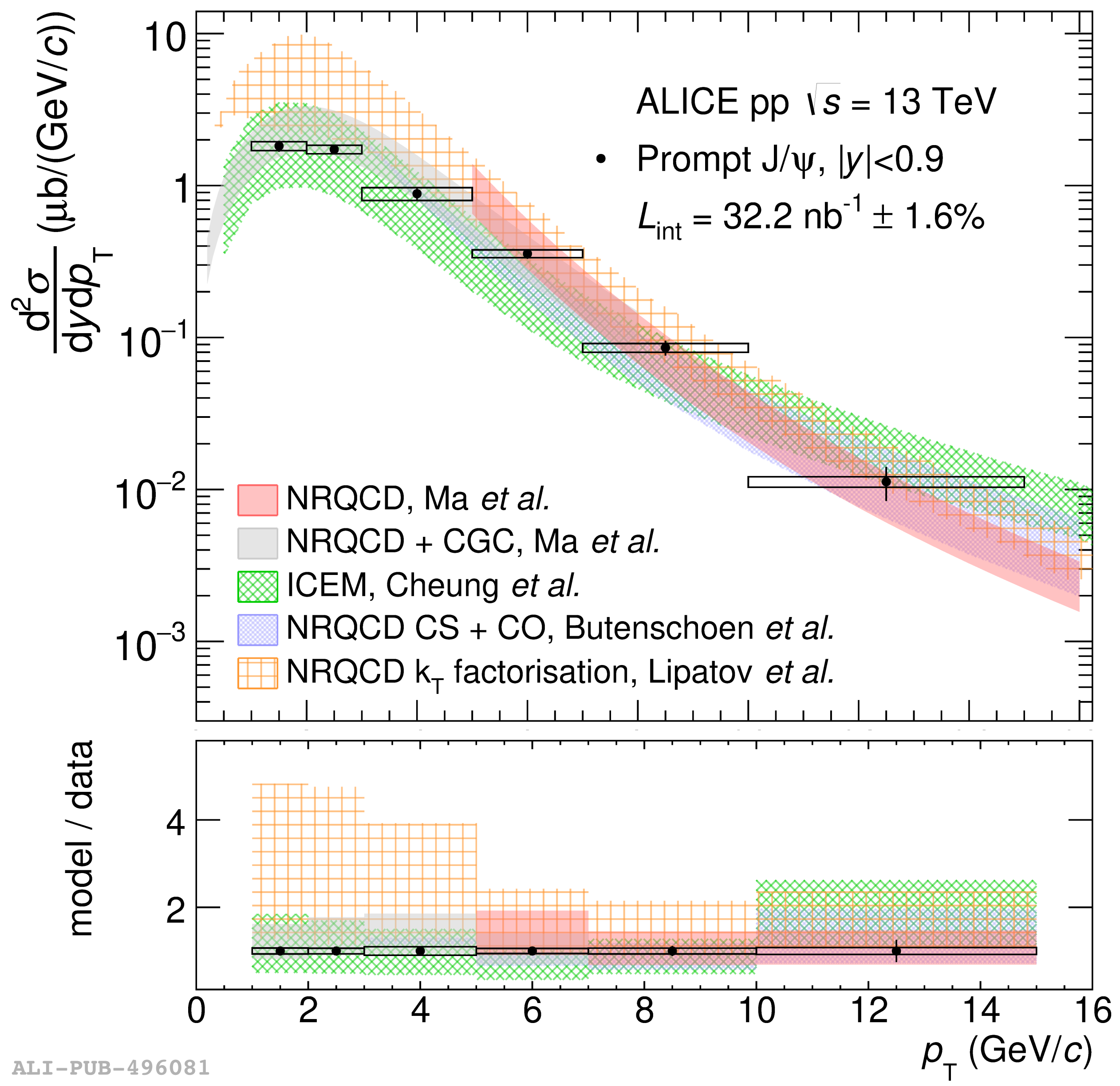


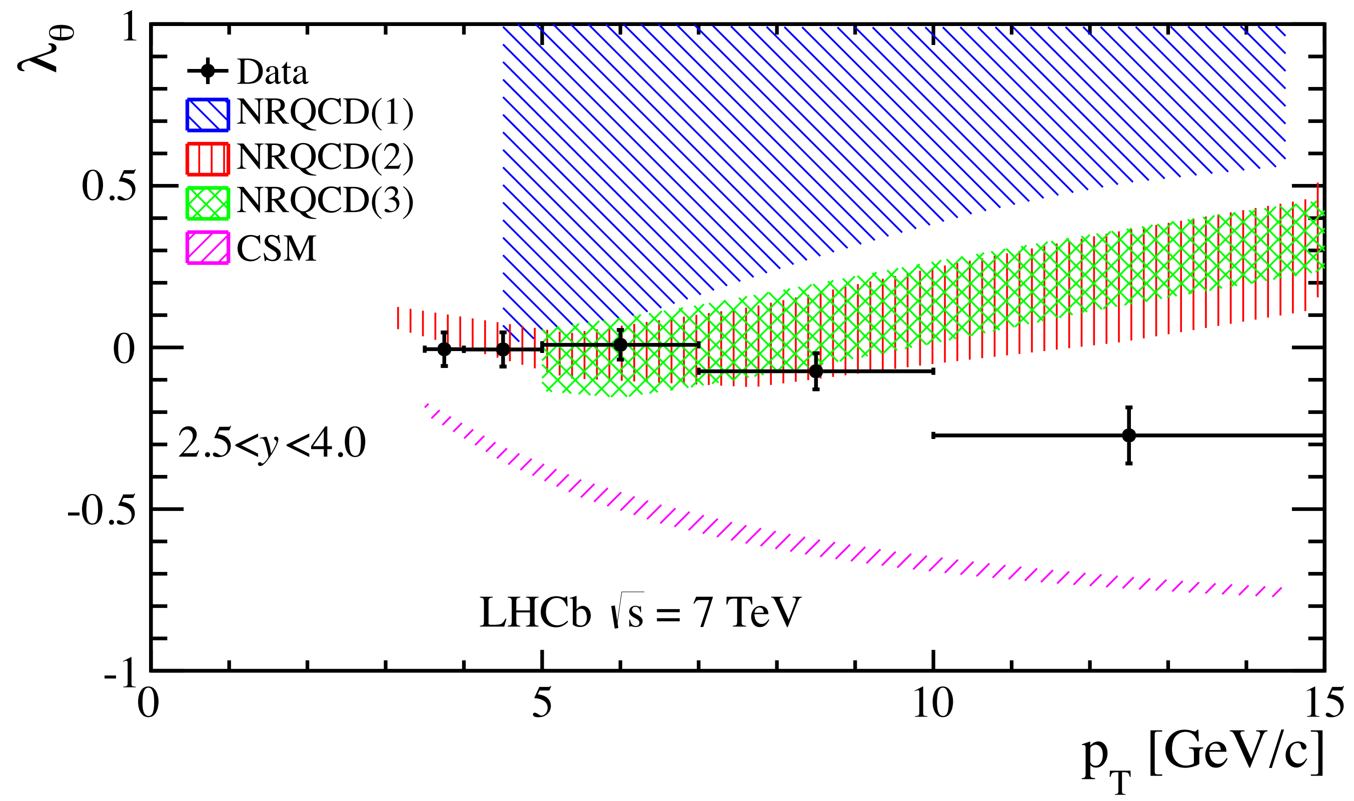
- **Various hadronization models : QSM, QEM, (p)NRQCD, …**
  - Tension b/w models and data in low/high p_T
  - No clear sign of polarization observed (up to 60 GeV/c for J/ψ)

[JHEP 11 (2021) 181]

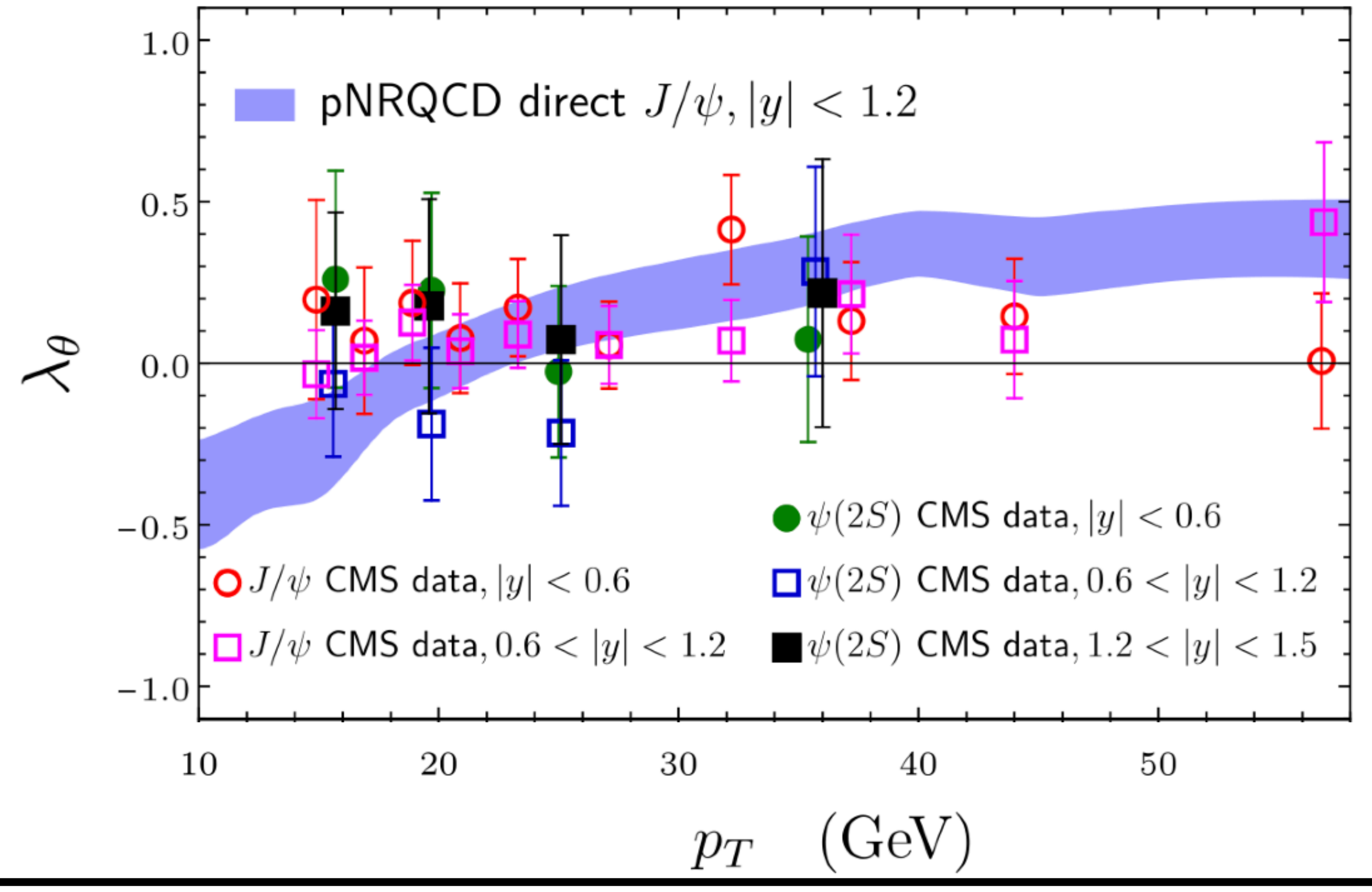


[JHEP 03 (2022) 190]





[EPJC 74 (2014) 2872]



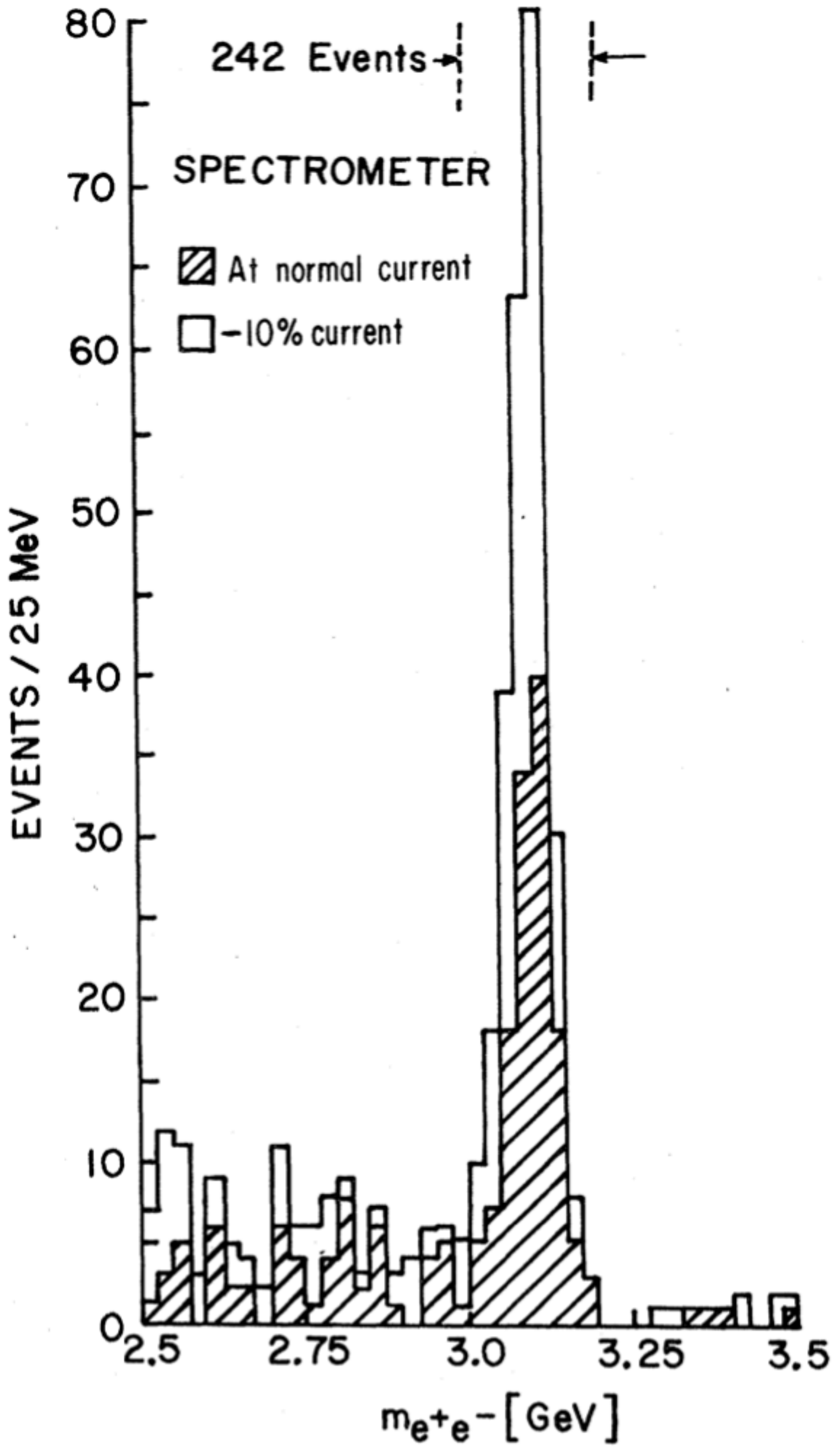
[PRD 105 (2022) L111503]

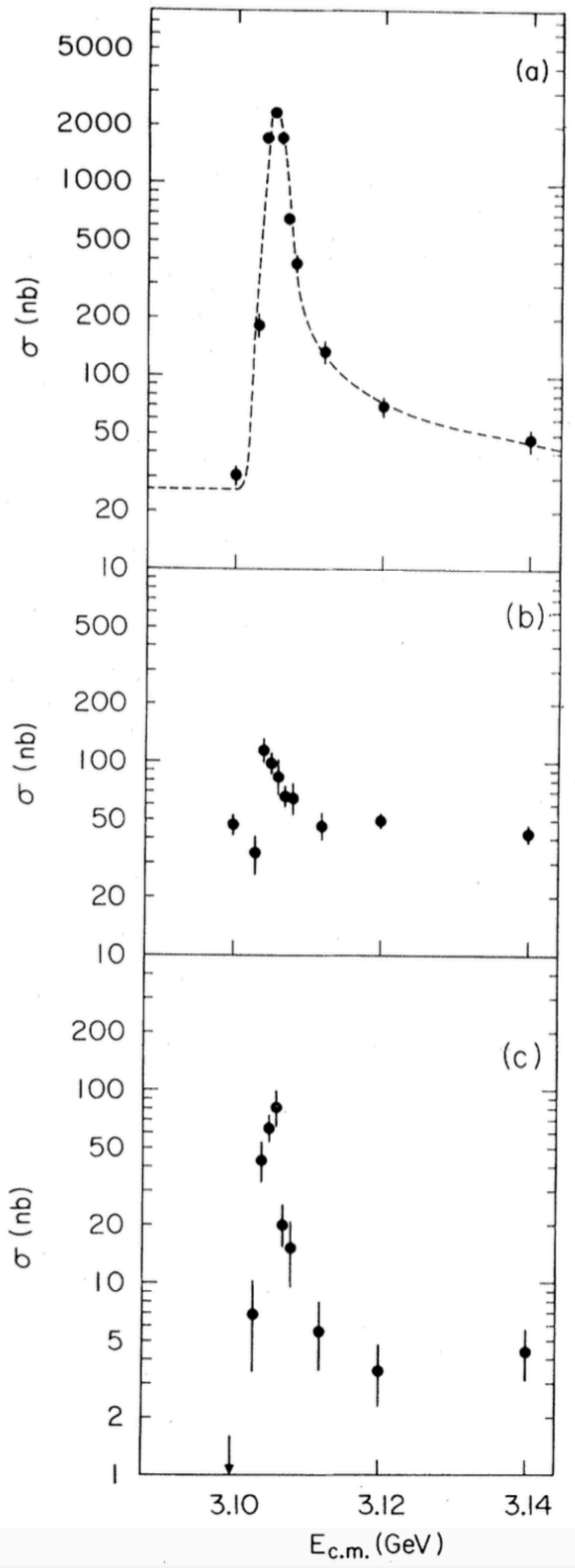
[PLB 727 (2013) 381]

Motivation

Production mechanism still under investigation since the "November Revolution" in 1974 (48 years)

[PRL 33 (1974) 1404]





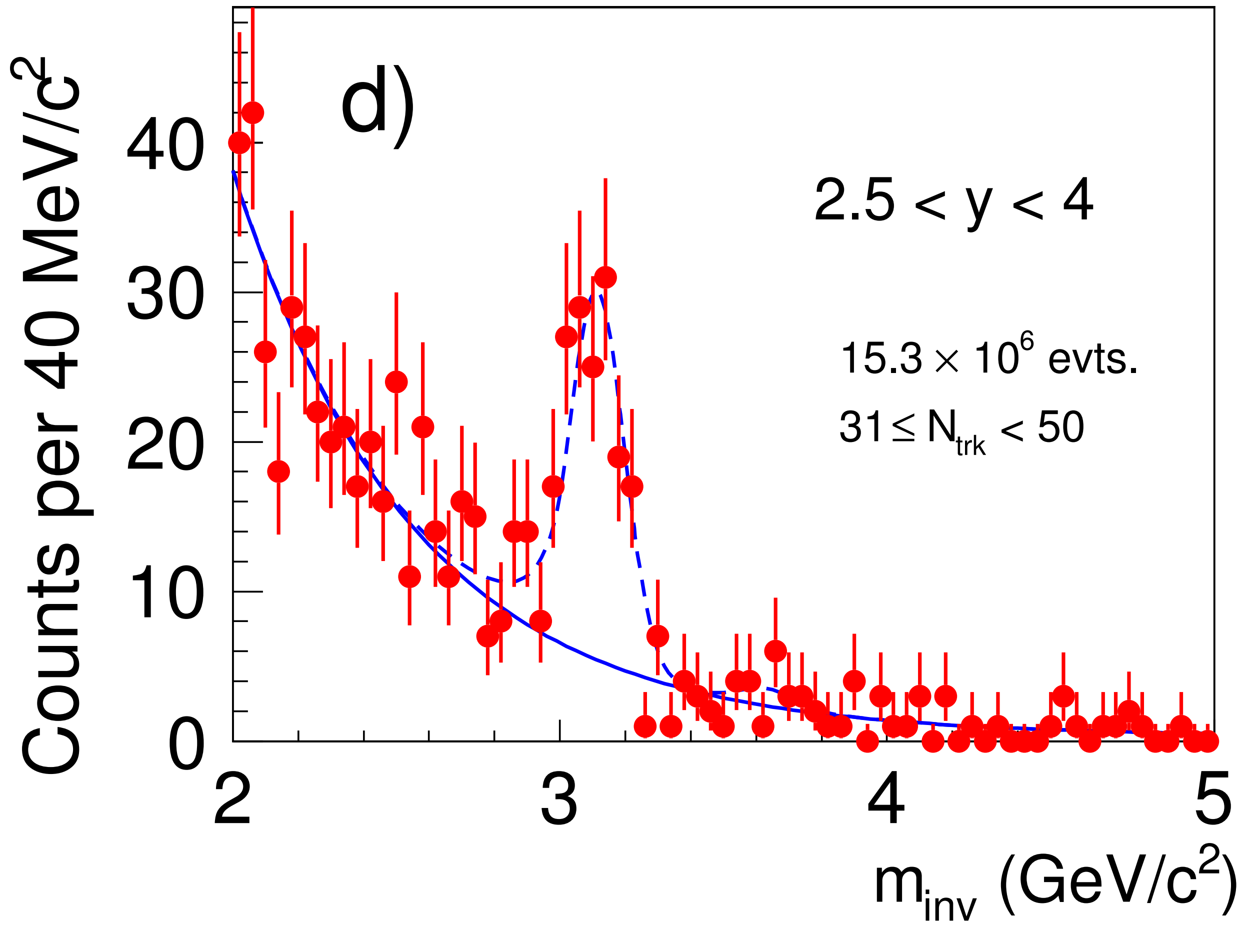
[PRL 33 (1974) 1406]

Quarkonia @ LHC : "Firsts" measurements

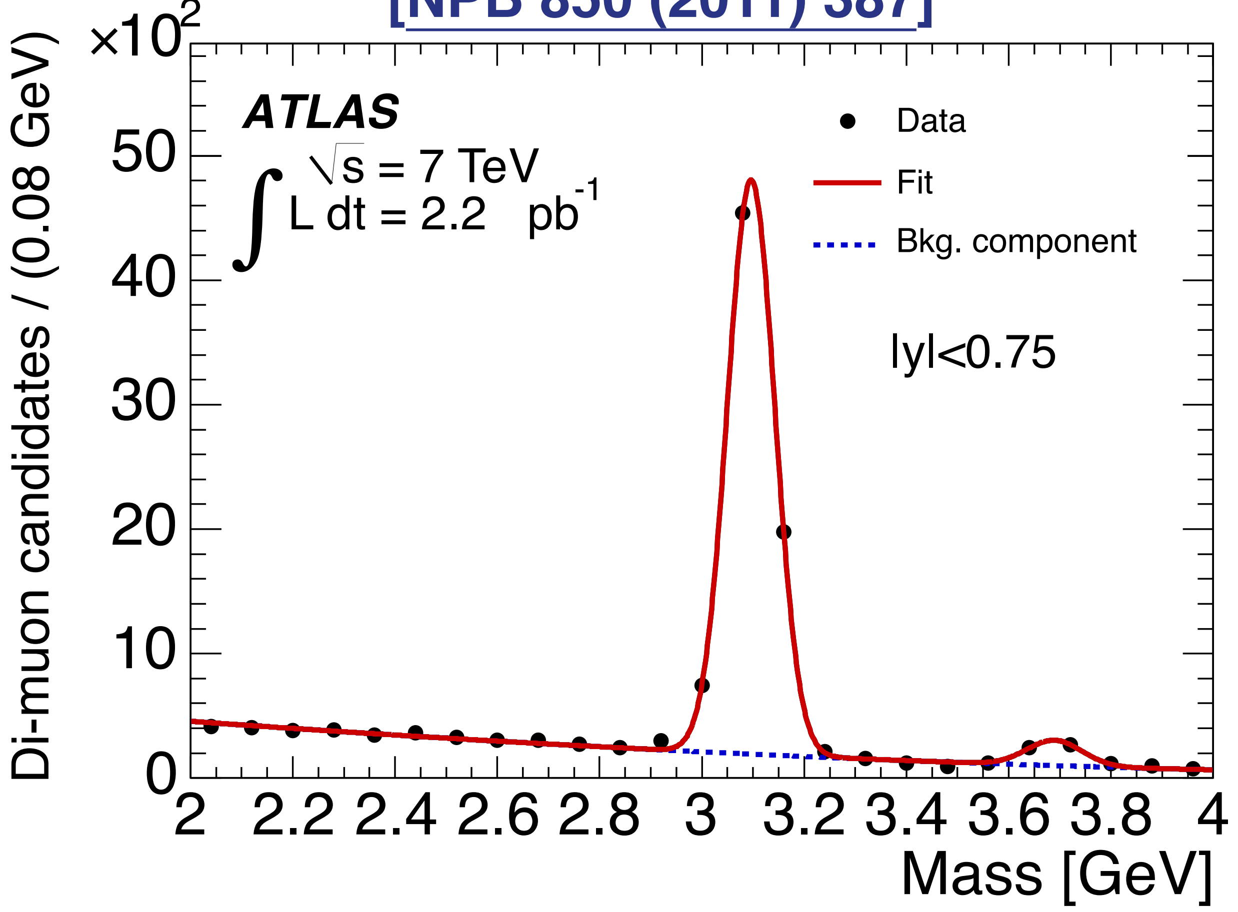
KOREA UNIVERSITY 1905

ALICE | ATLAS EXPERIMENT | CMS | LHCb

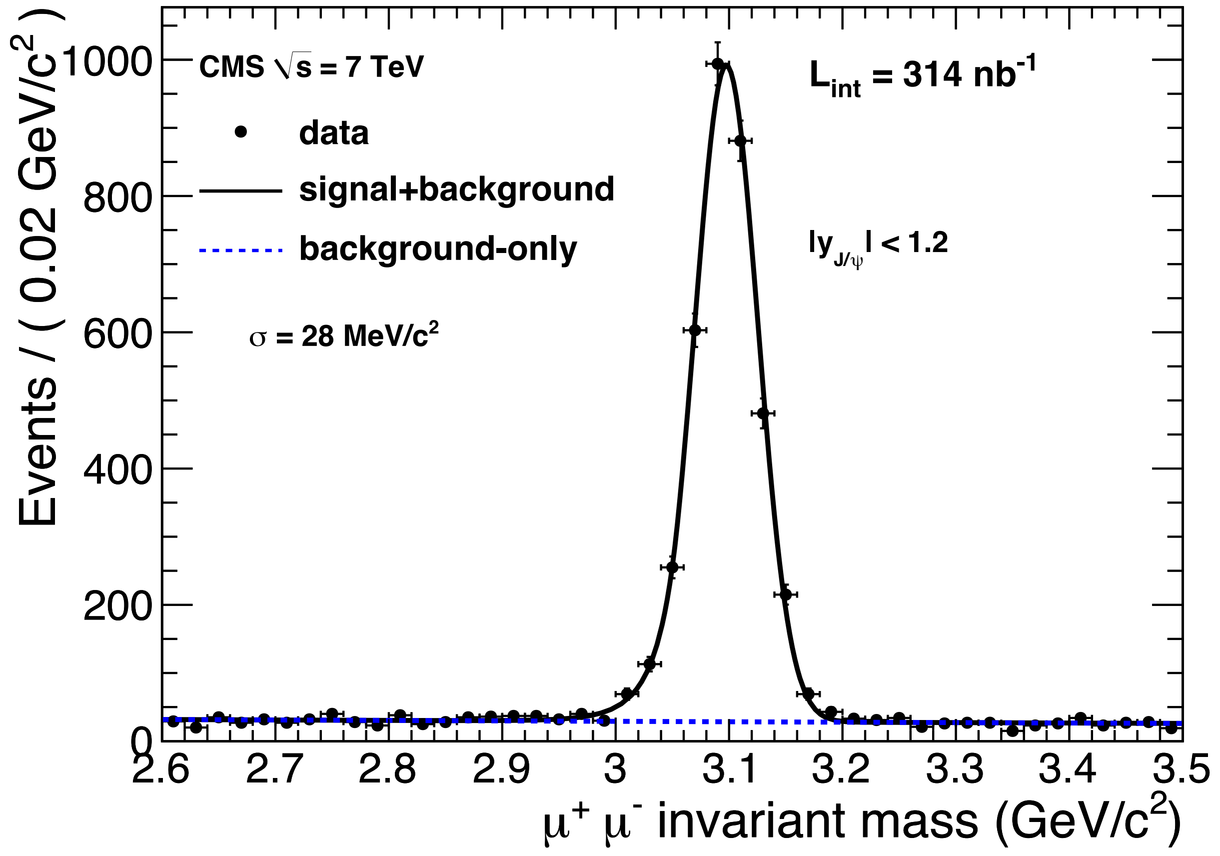
[PLB 712 (2012) 165]



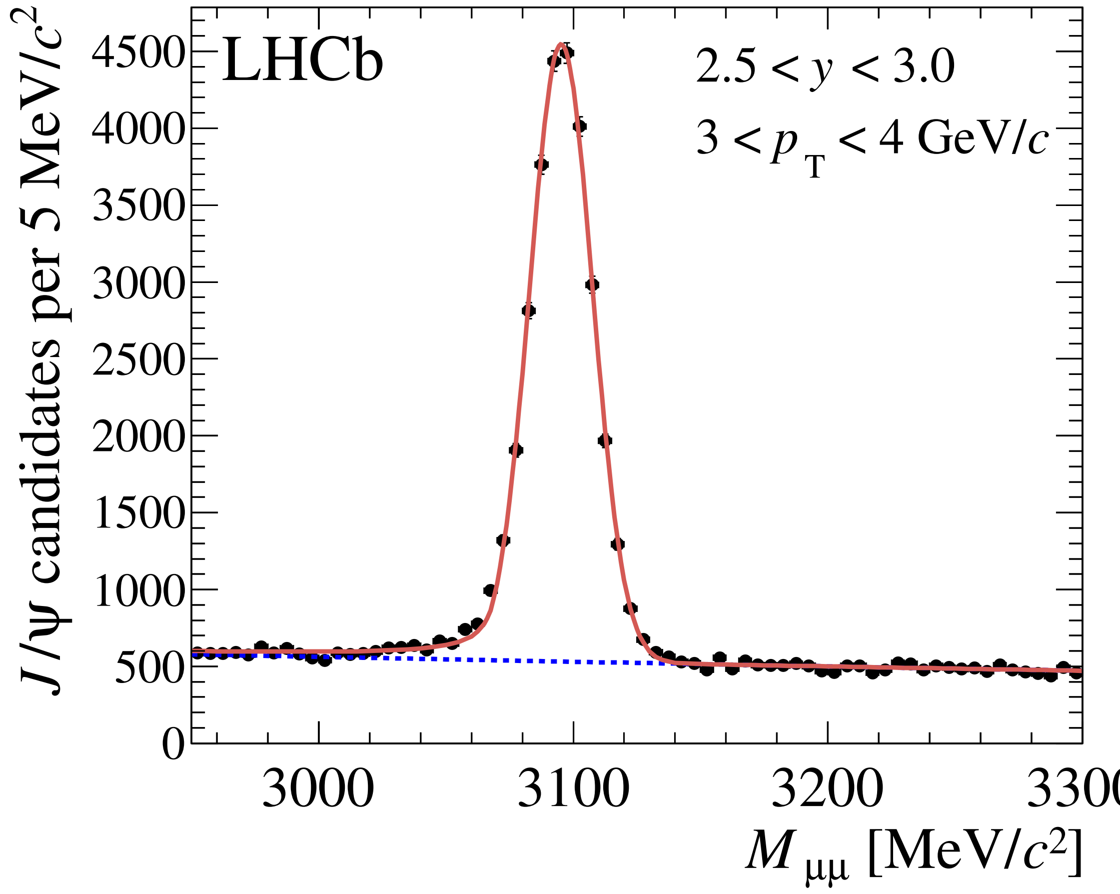
[NPB 850 (2011) 387]



[EPJC 71 (2011) 1575]



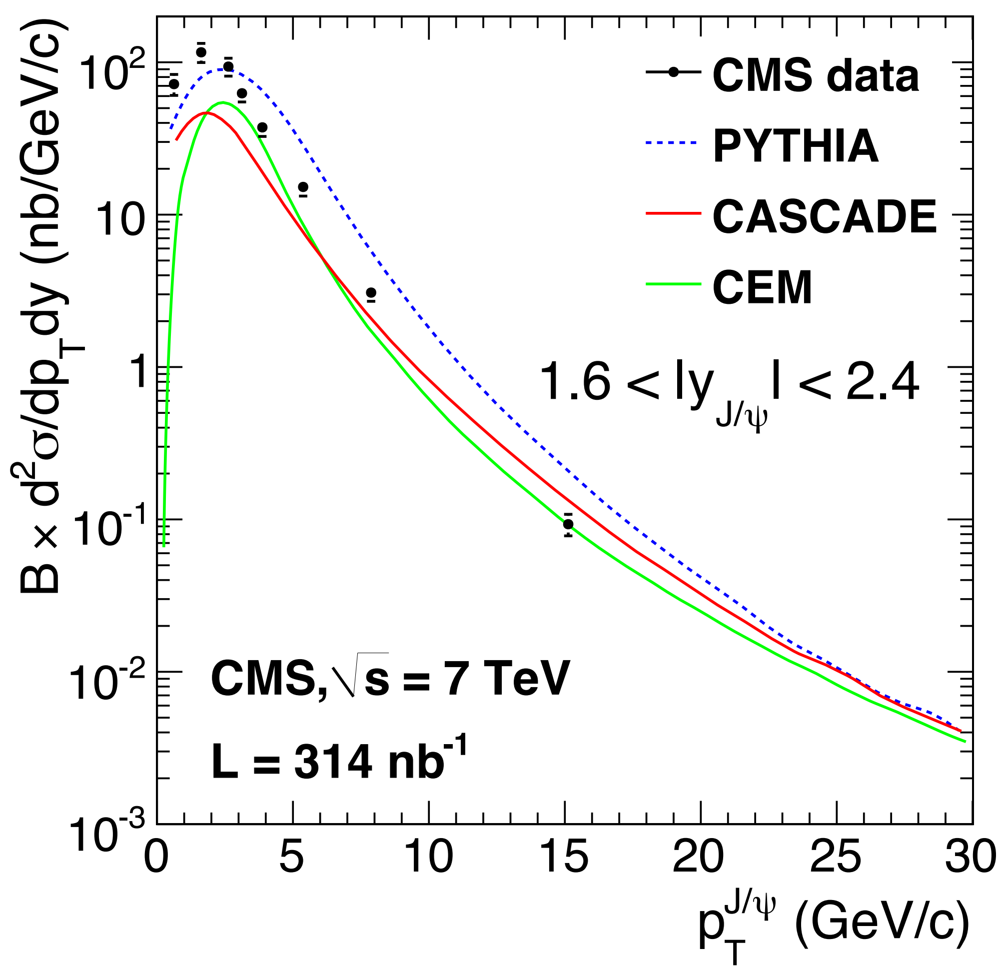
[EPJC 71 (2011) 1645]



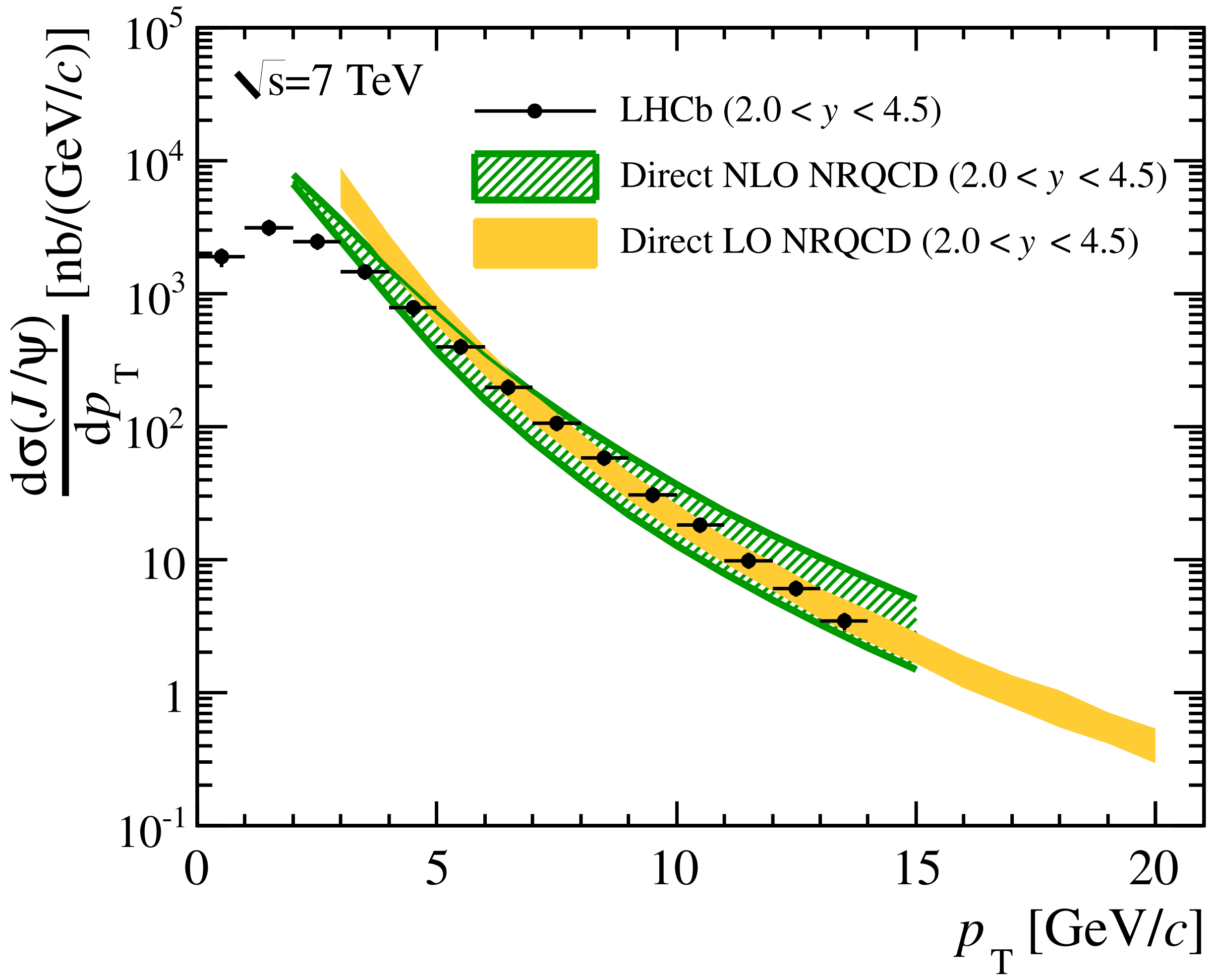
- First measurements of quarkonium production at the LHC!
- Clear J/ψ peak in dimuon mass spectra in all four experiments

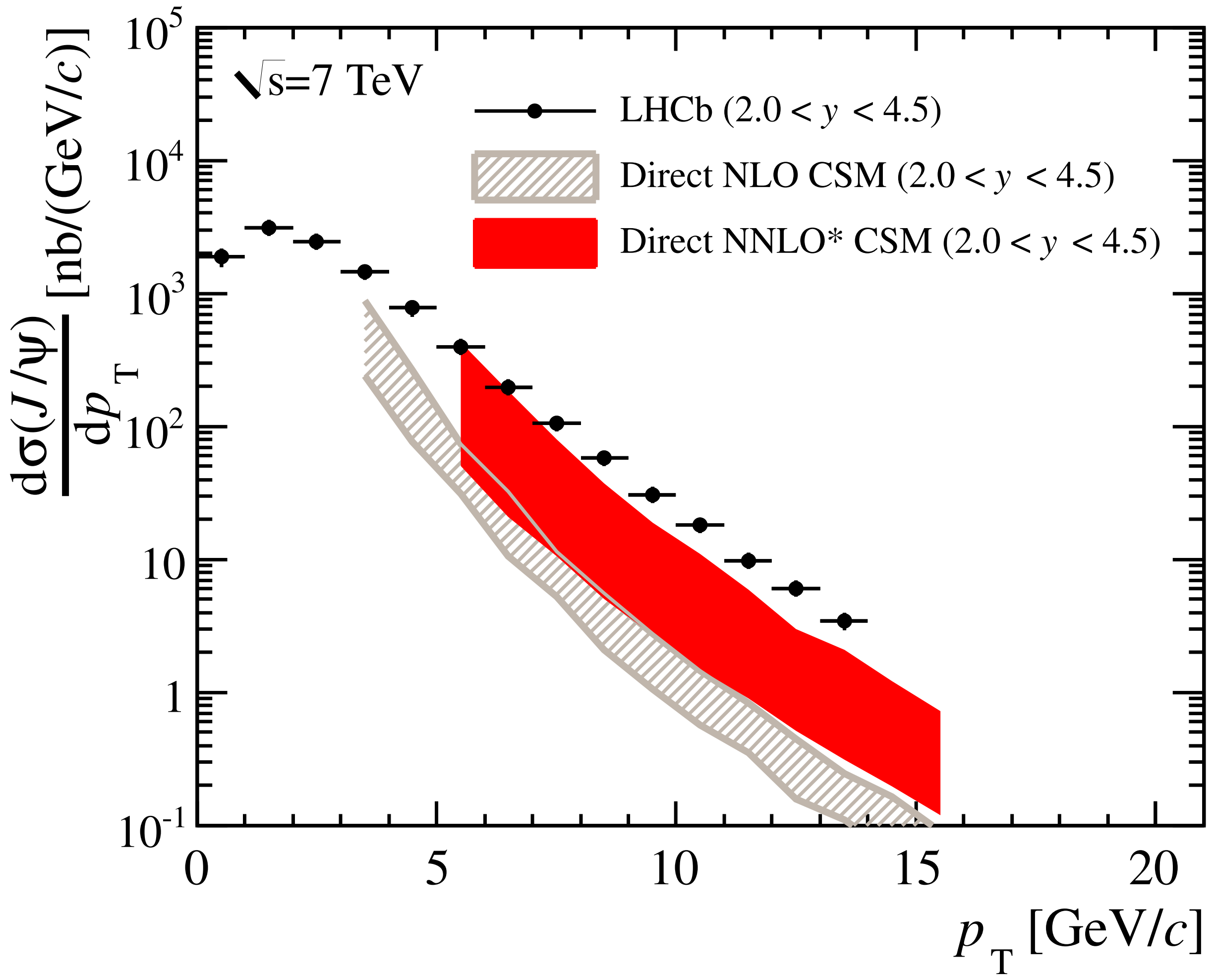
Quarkonia @ LHC : “Firsts” measurements

[EPJC 71 (2011) 1575]

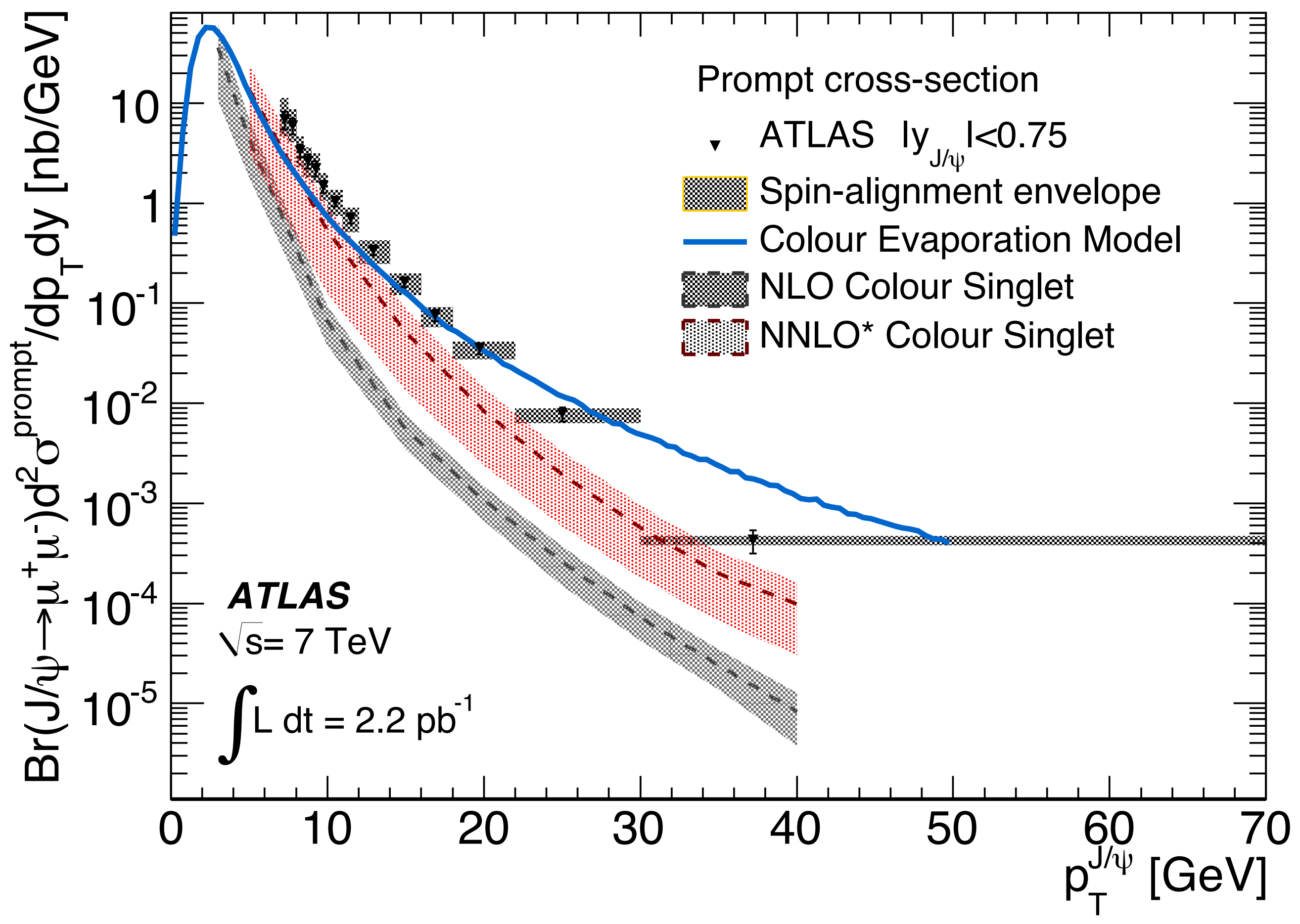


[EPJC 71 (2011) 1645]





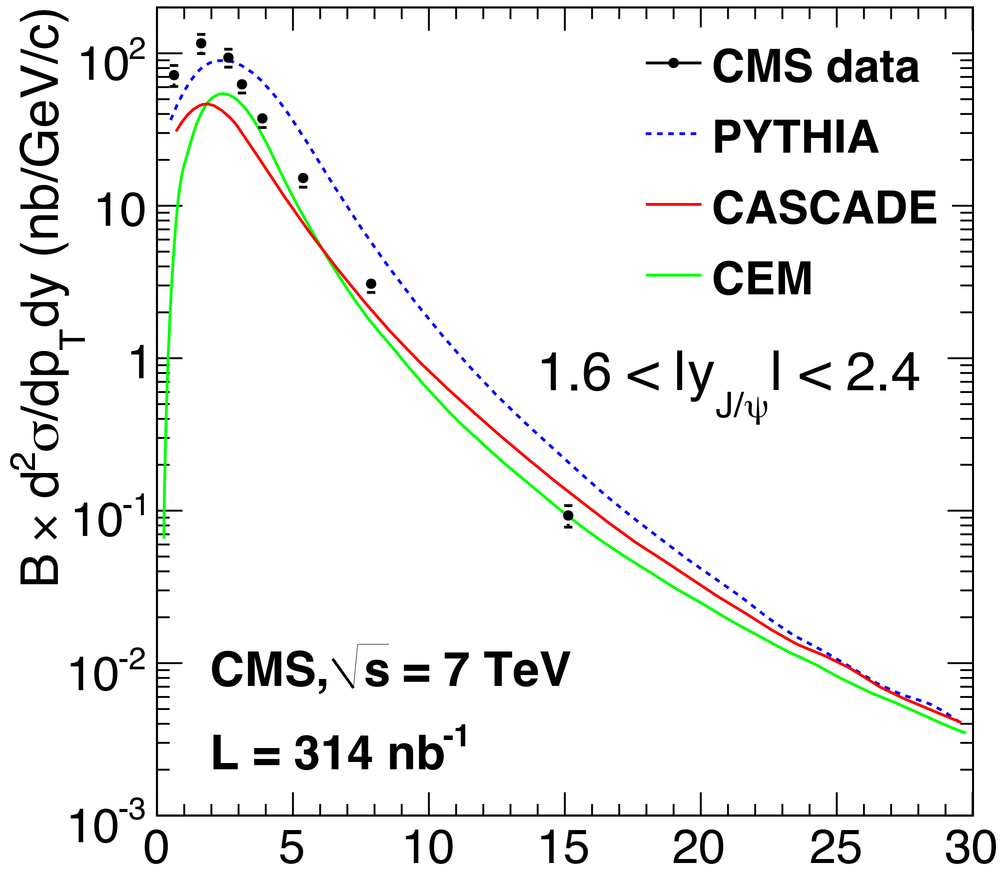
[NPB 850 (2011) 387]

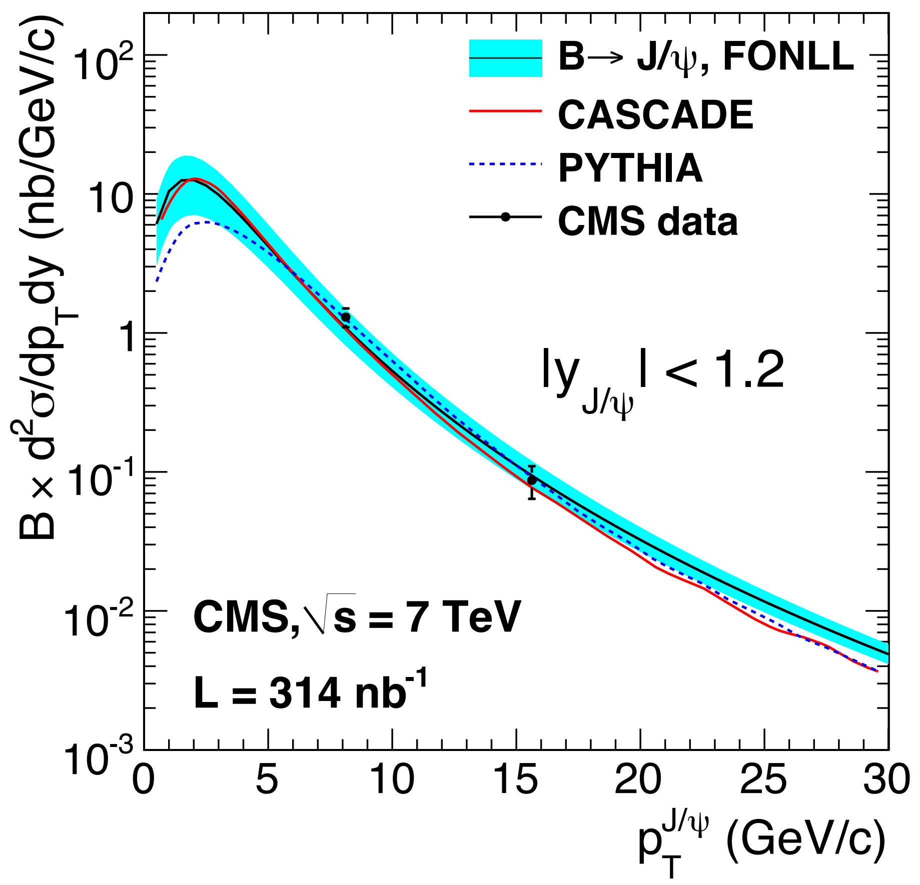


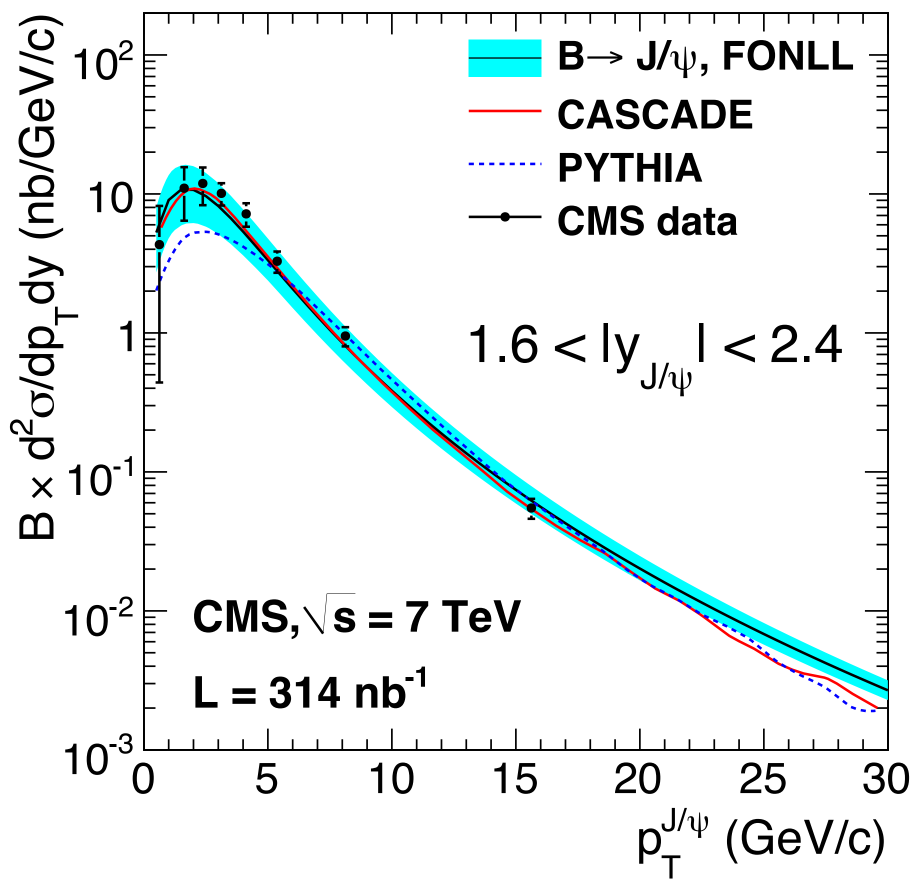
- Quite precision data already in Run1 with model comparisons (CS, CO, CE, NRQCD, …)

Quarkonia @ LHC : “Firsts” measurements

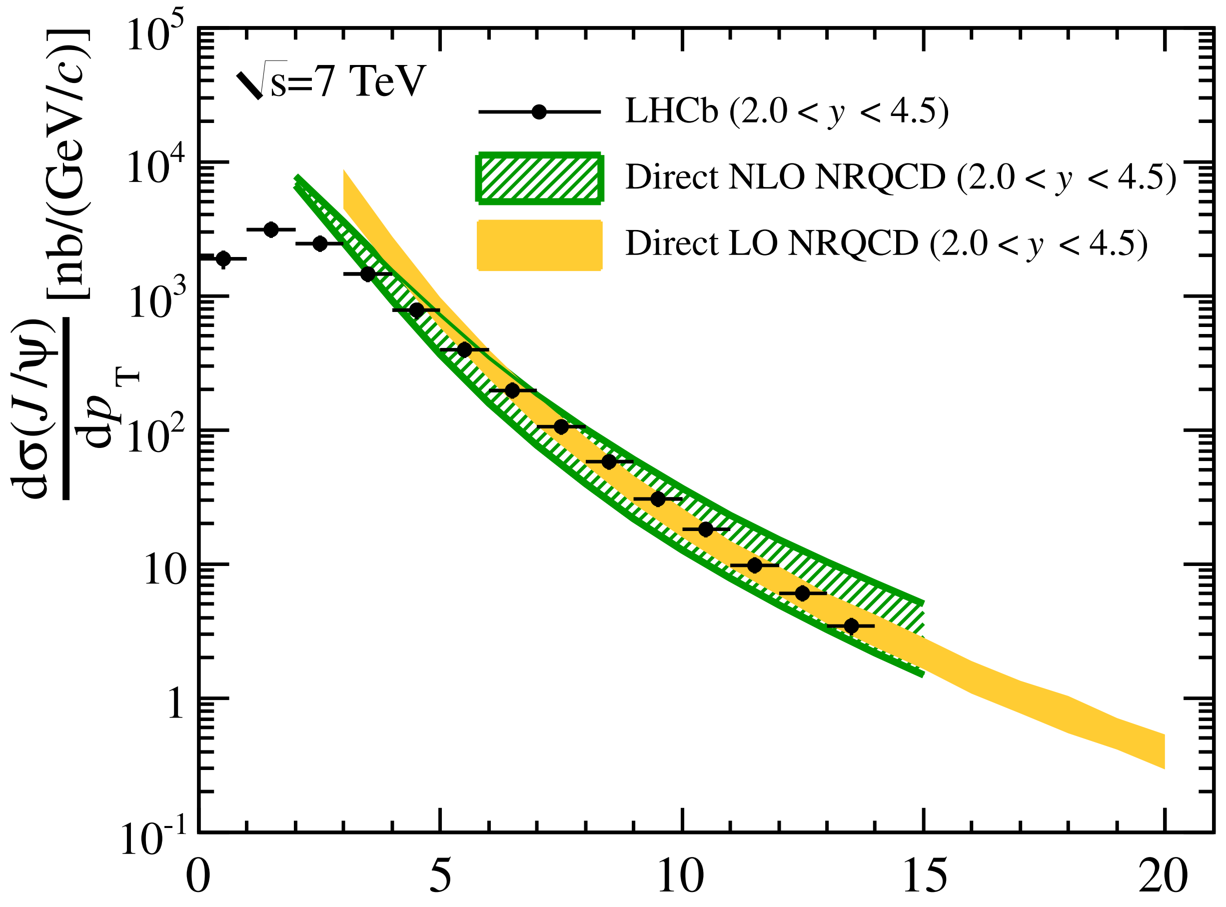
[EPJC 71 (2011) 1575]

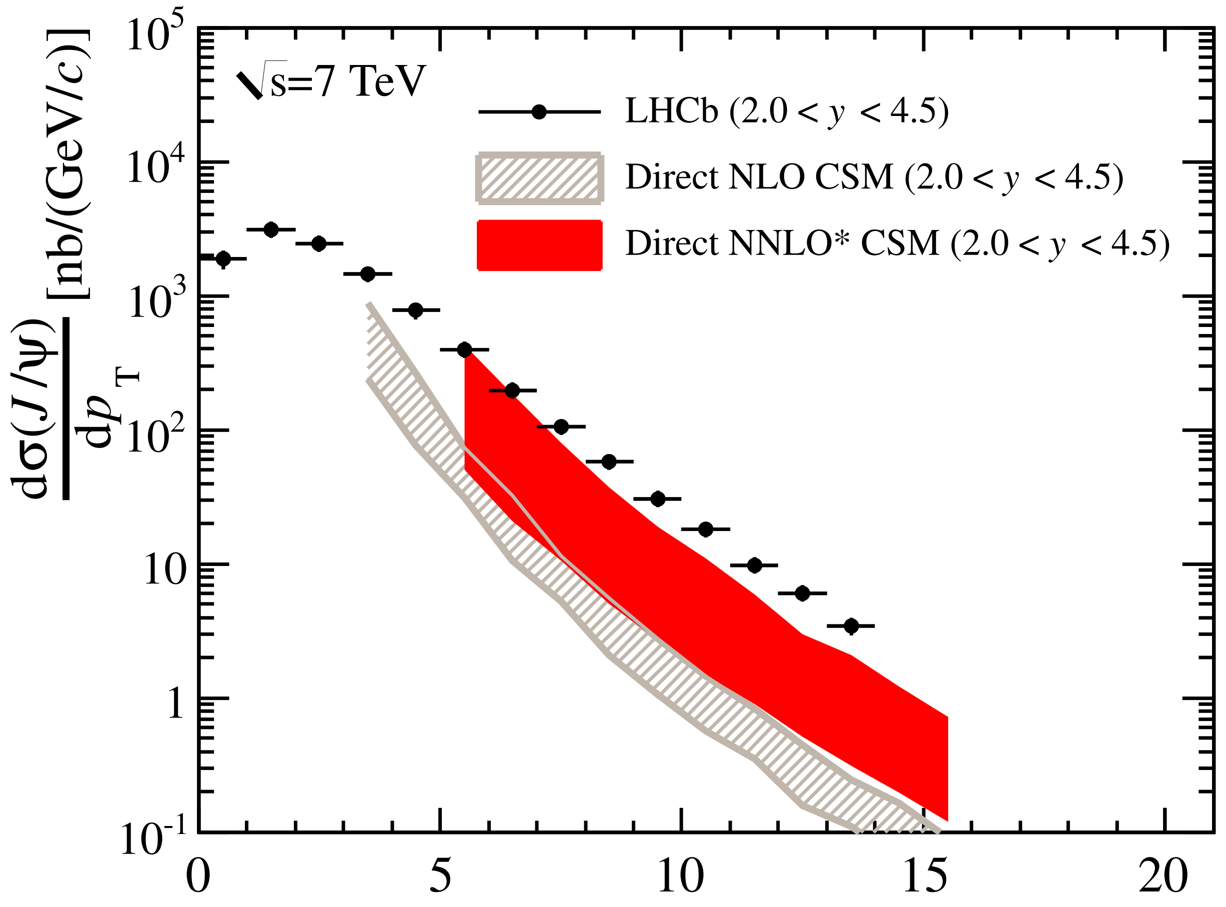


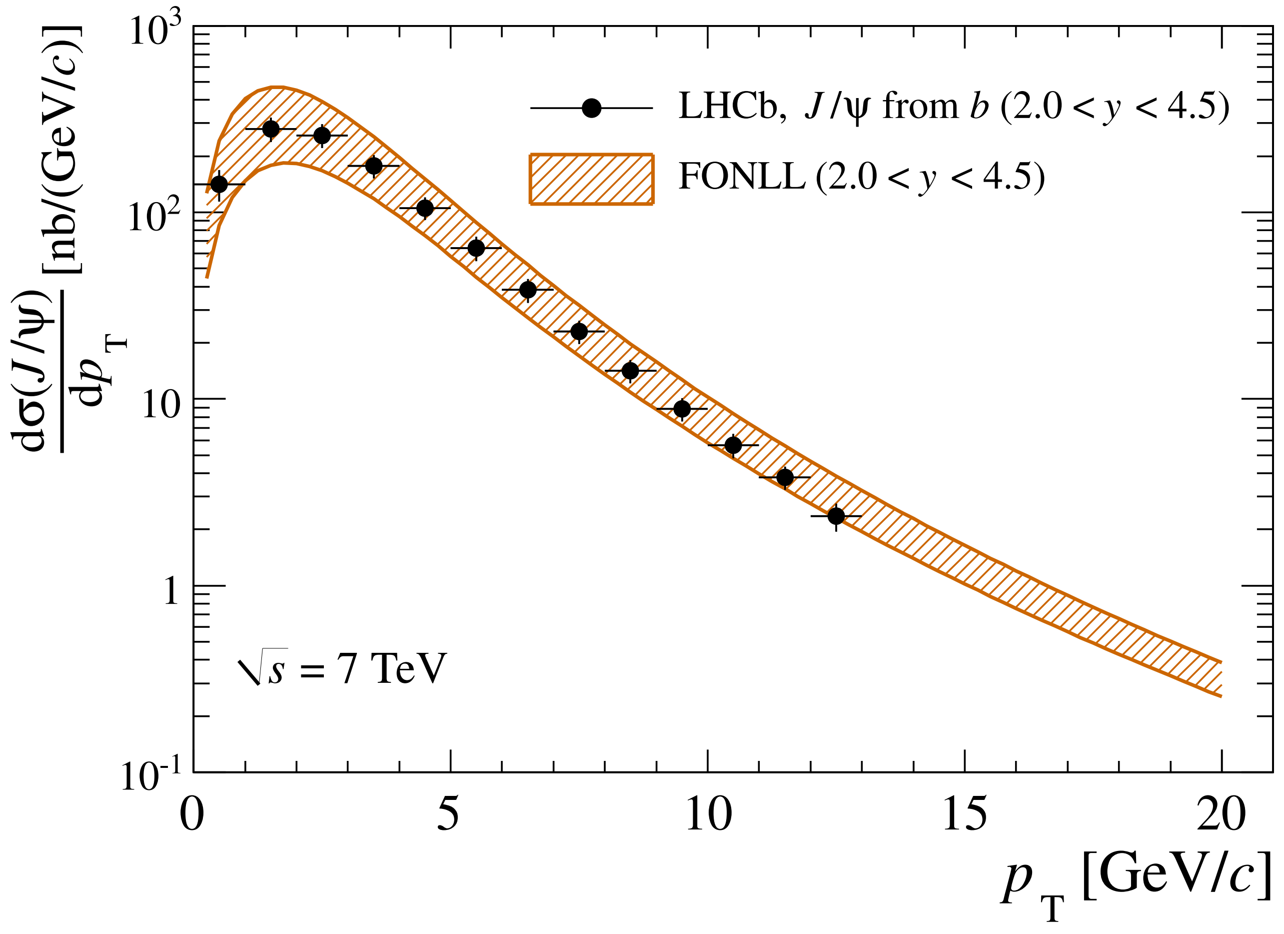




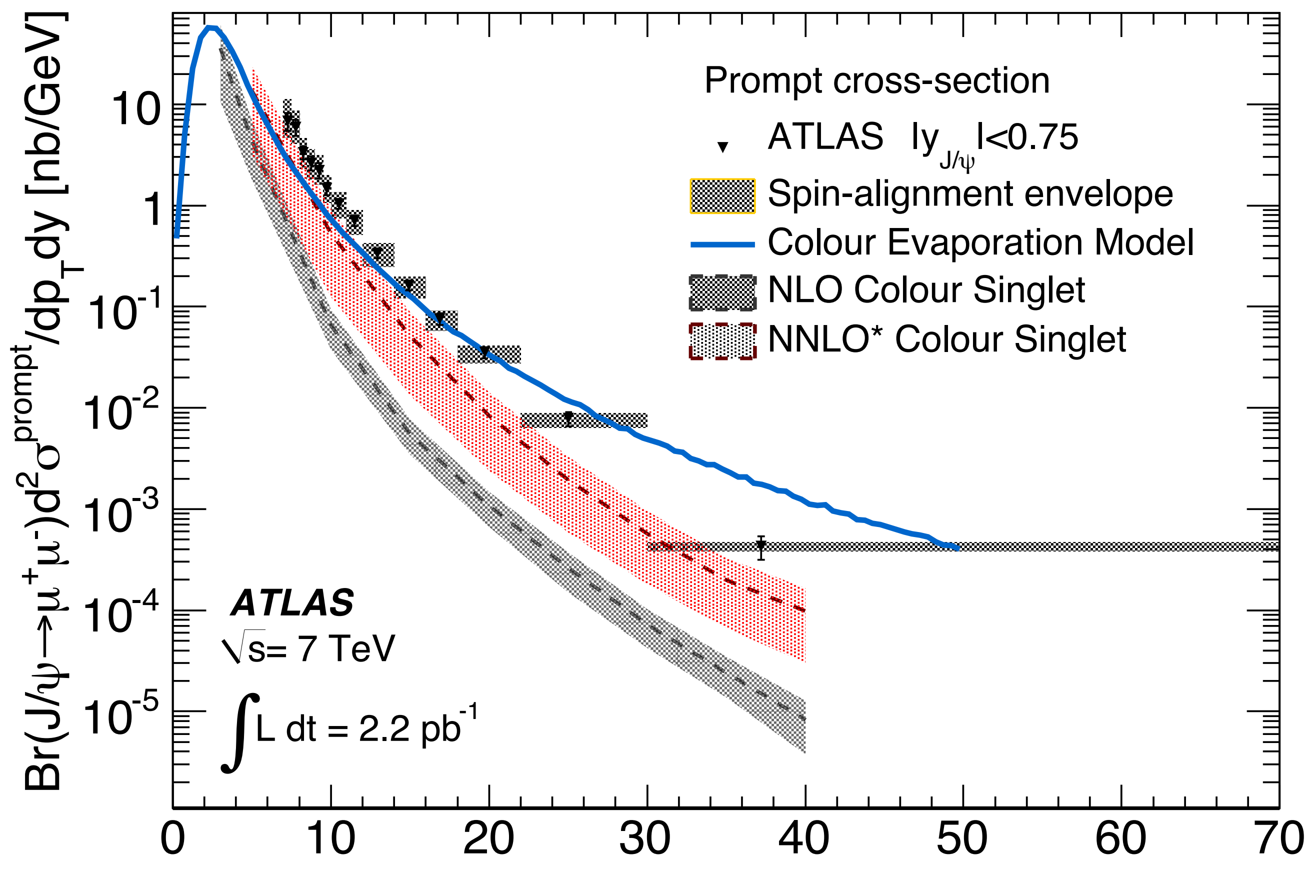
[EPJC 71 (2011) 1645]

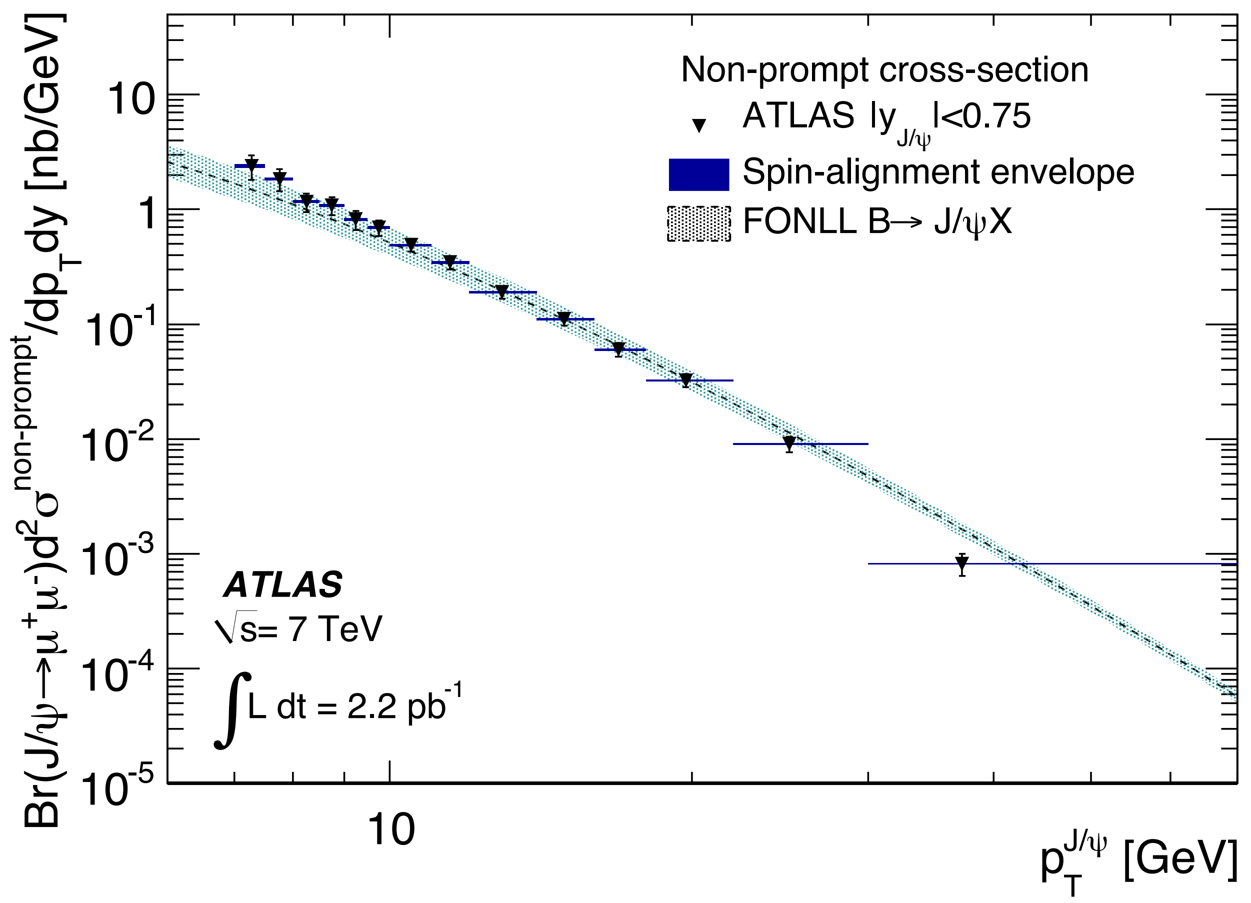






[NPB 850 (2011) 387]

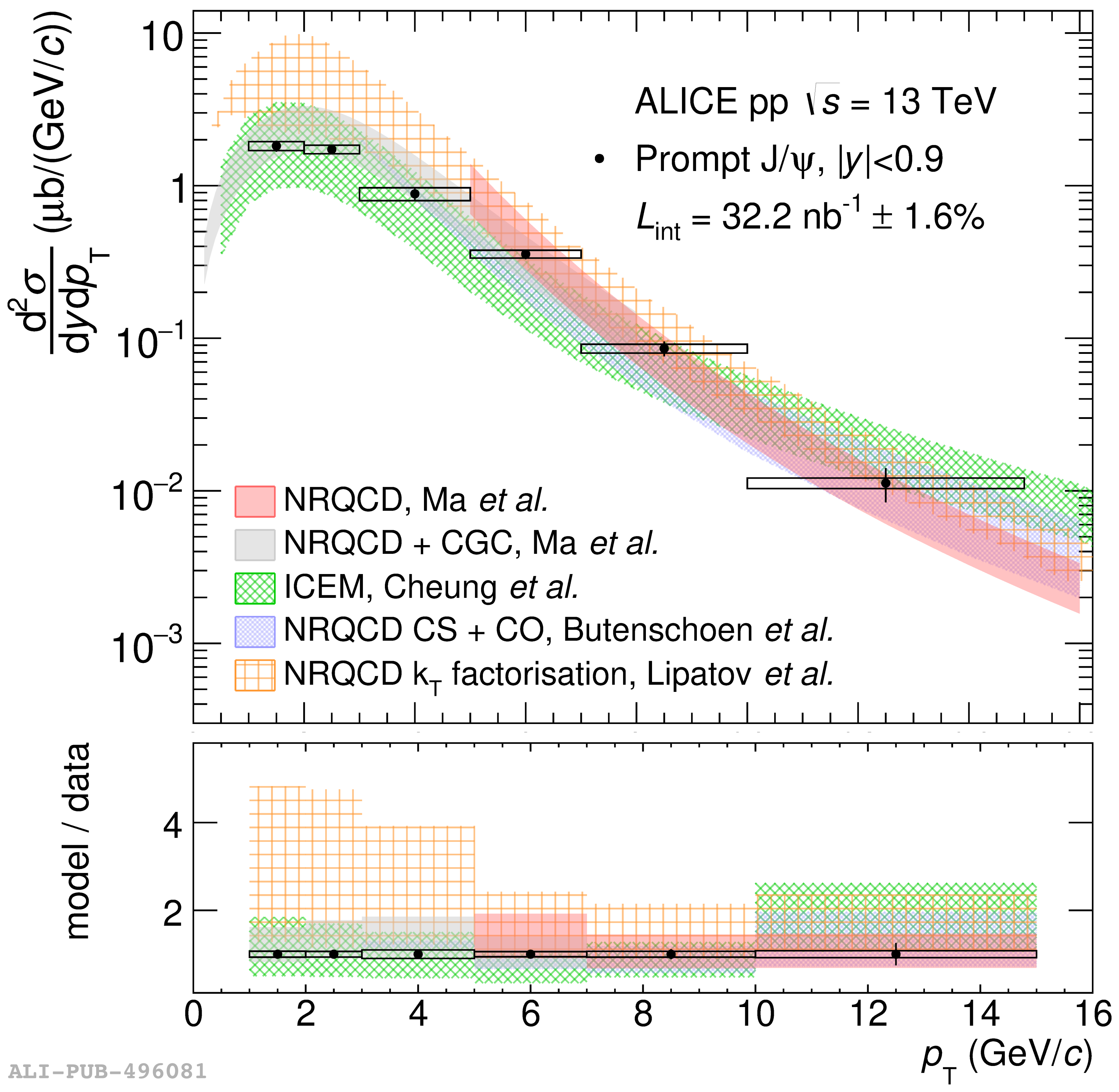




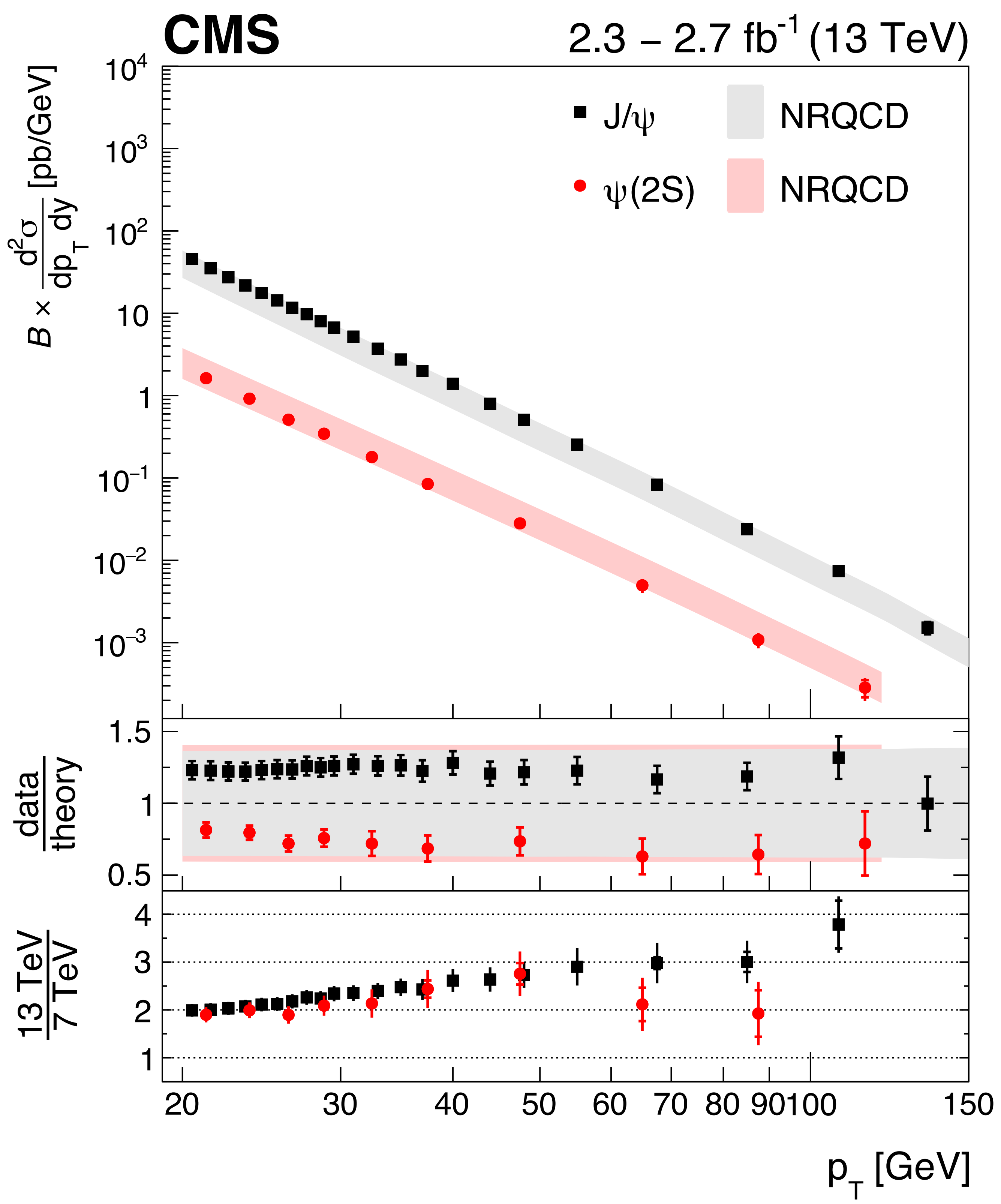
- Quite precision data already in Run1 with model comparisons (CS, CO, CE, NRQCD, …)
- Also constraints to FONLL with prompt and nonprompt separation

Cutting edge cross section

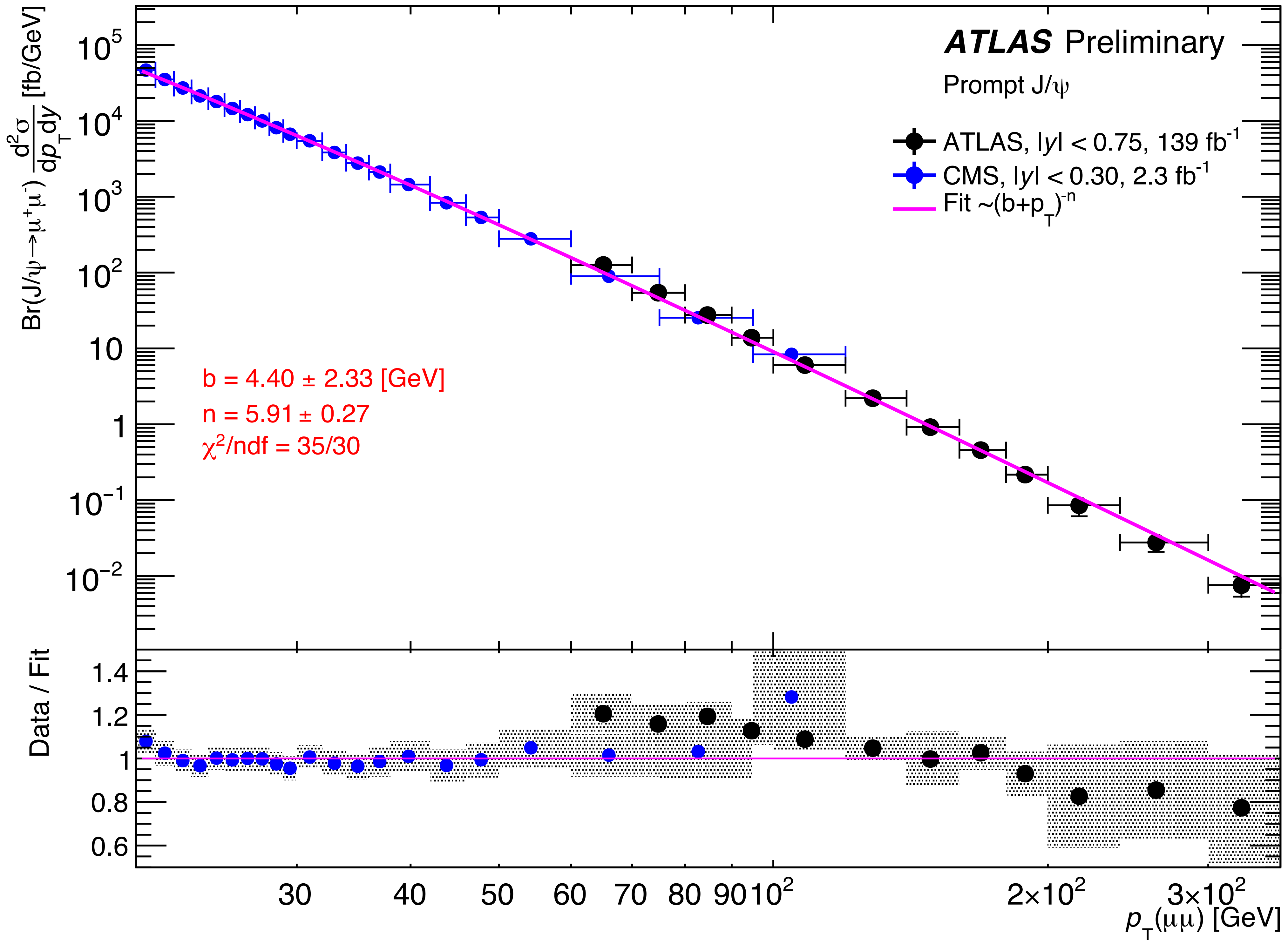
[JHEP 03 (2022) 190]



[PLB 780 (2018) 251]



[ATLAS-CONF-2019-047]

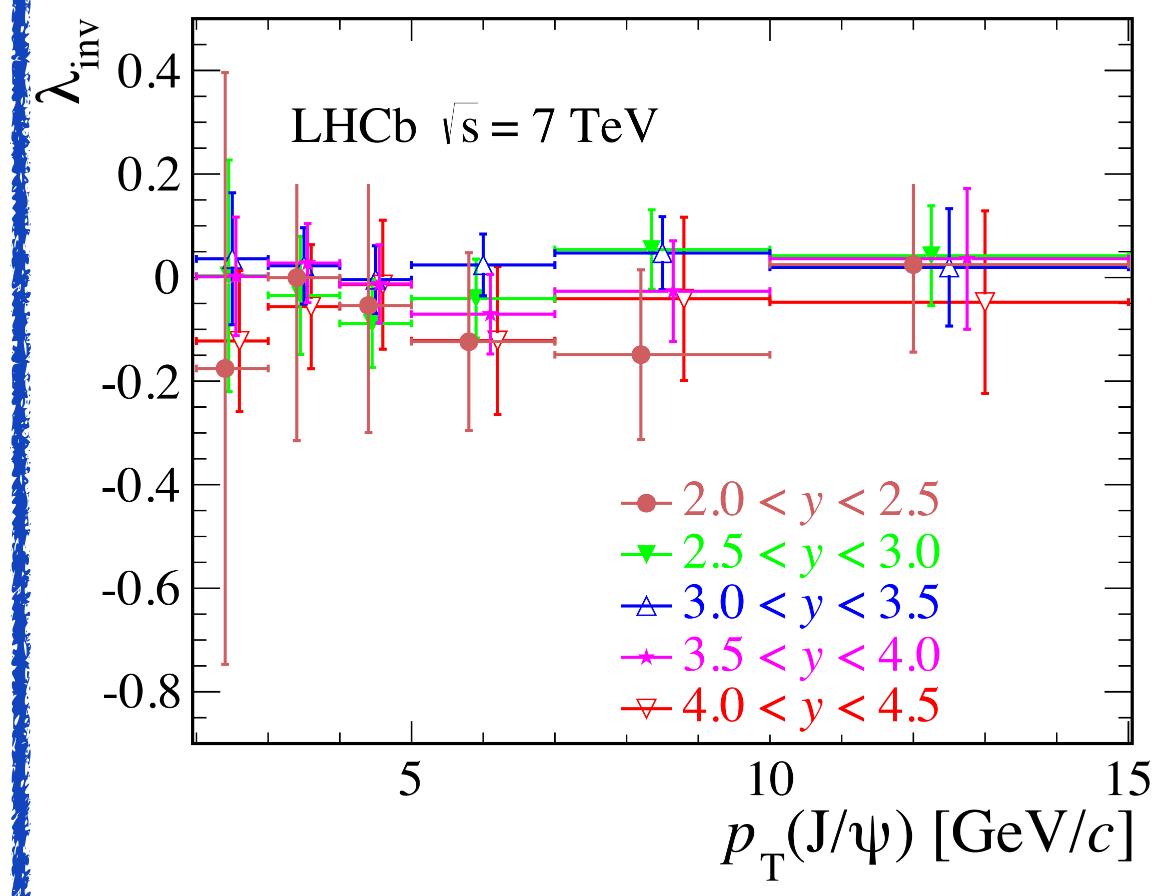


- Precision measurements for J/ψ mesons from low~high-p_T : 0~300 GeV/c
- Crucial constraints to theoretical developments (data uncertainty much smaller)

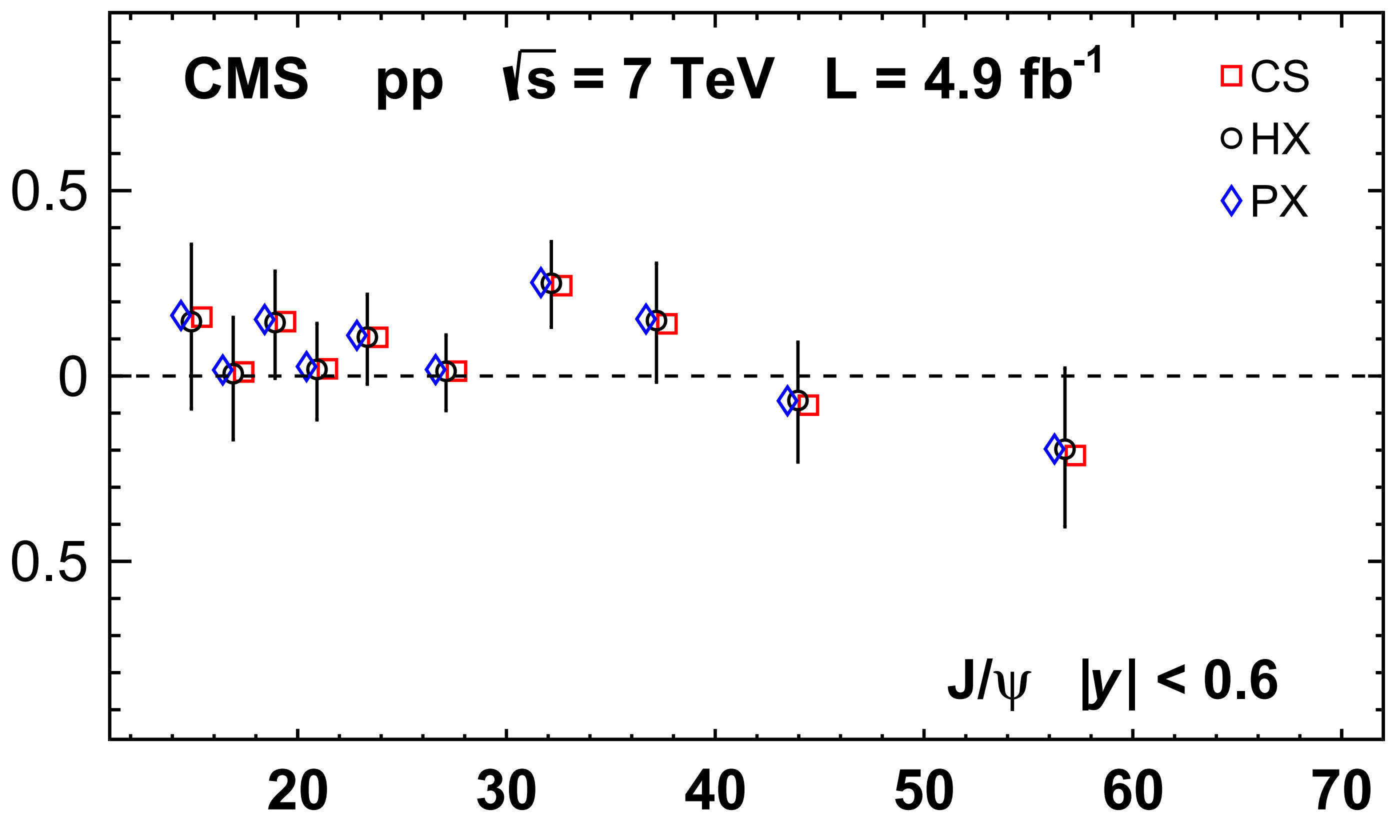
Polarization (1) : Charmonia

J/ψ

[EPJC 73 (2013) 2631]

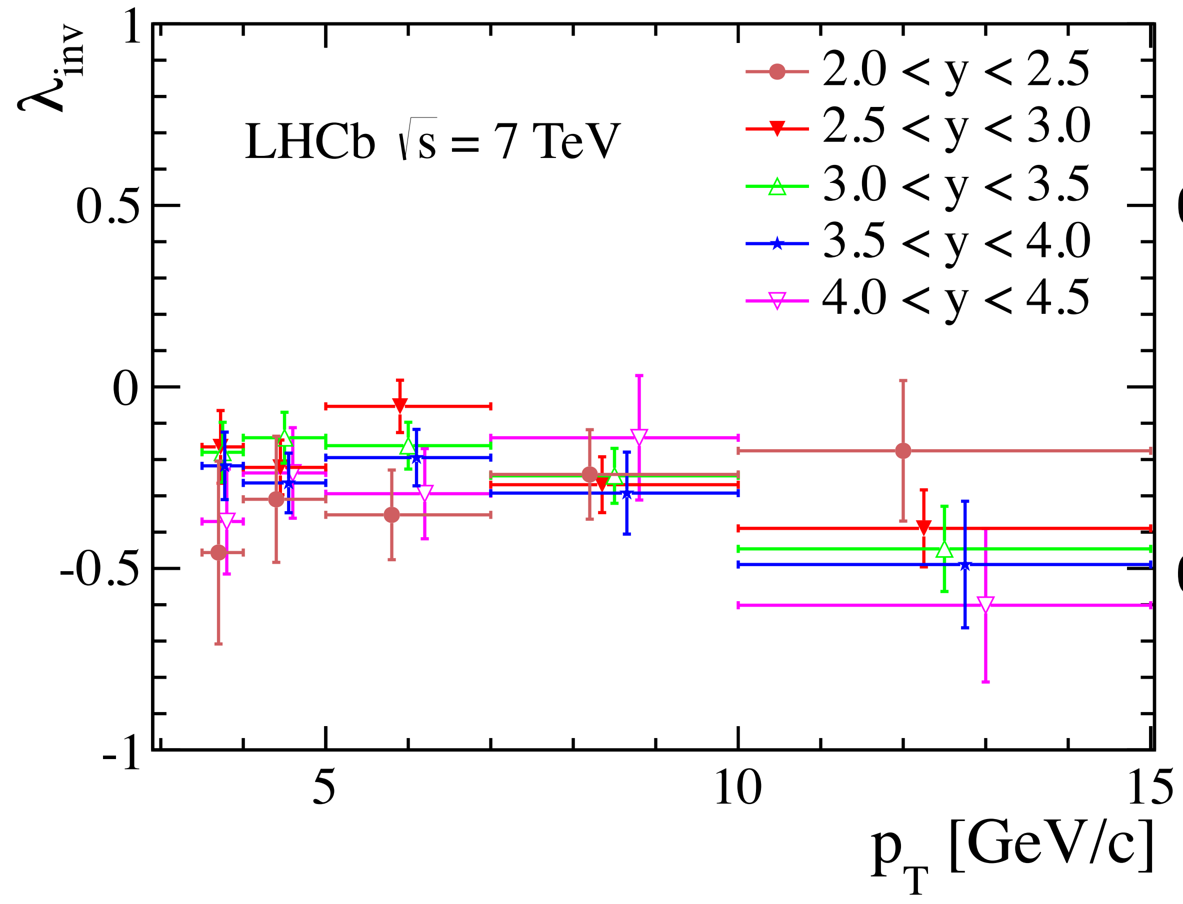


[PLB 727 (2013) 381]

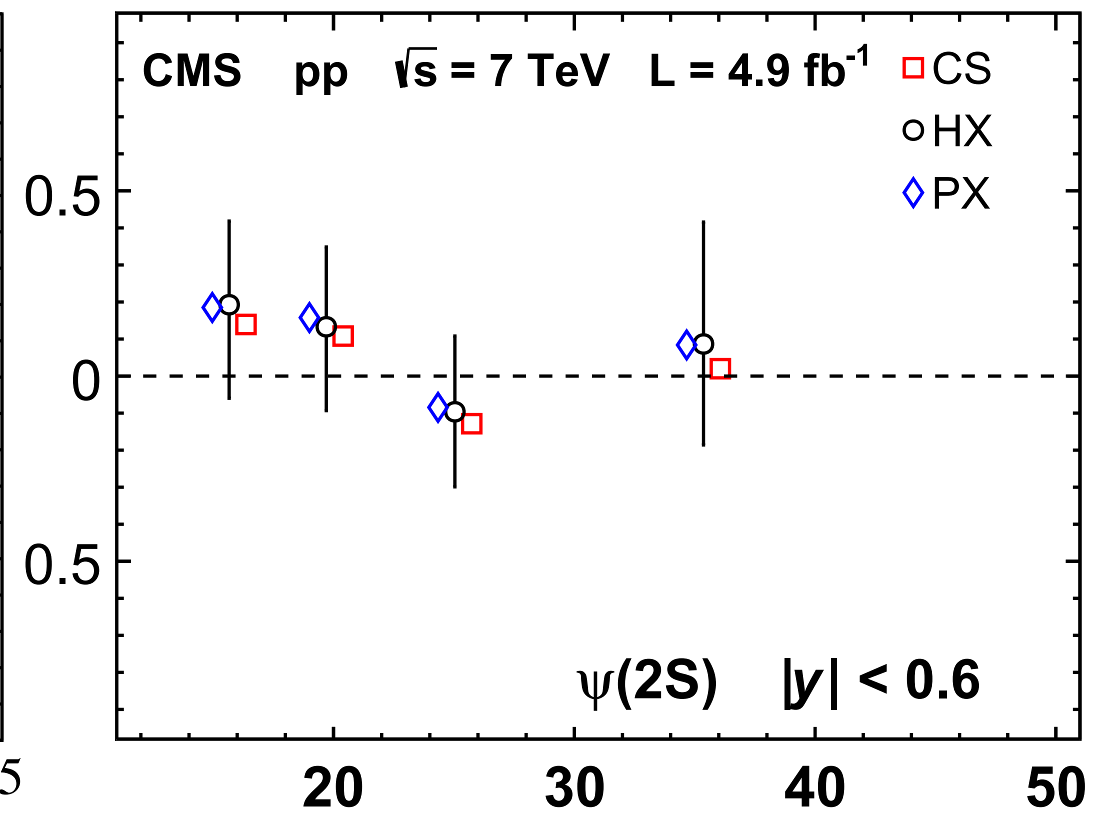


ψ(2S)

[EPJC 74 (2014) 2872]



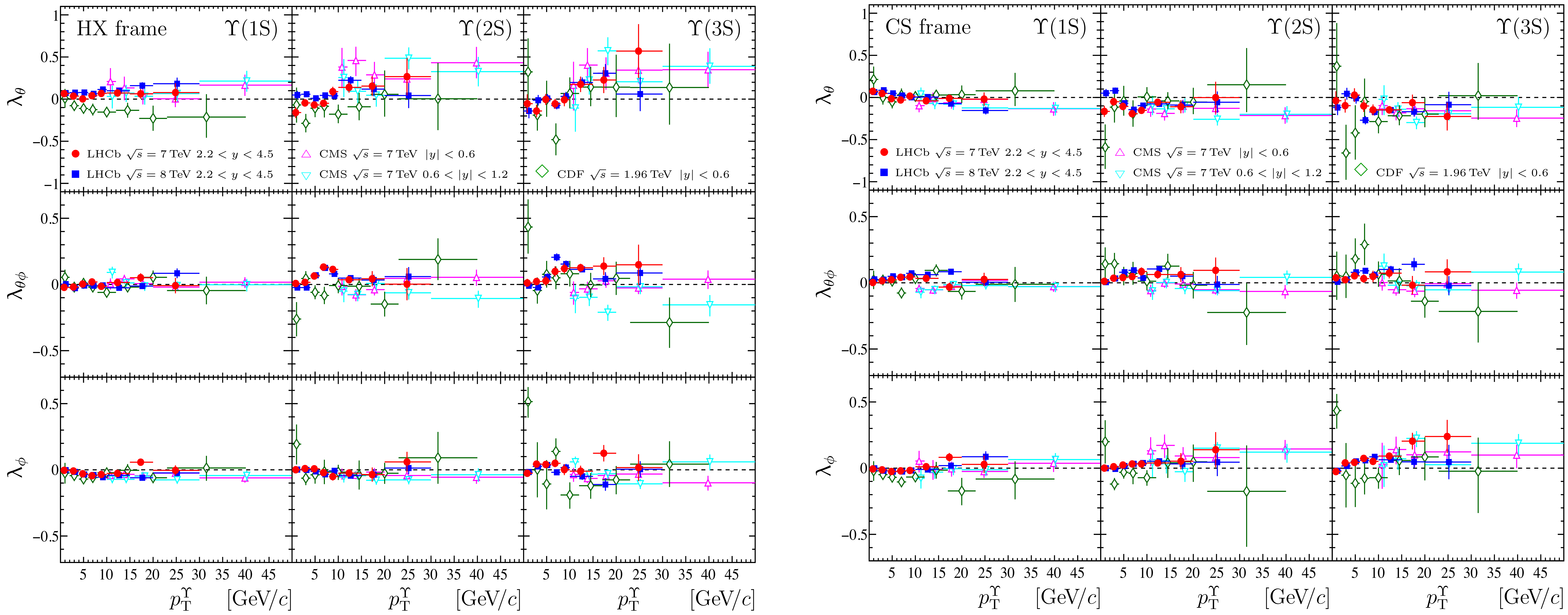
[PLB 727 (2013) 381]



- Measurements of S-wave charmonium states in various frames (CS, HX, …)
- No sign of nonzero polarization up to 60 (40) GeV/c for J/ψ and ψ(2S)

Polarization (2) : Bottomonia

[JHEP 12 (2017) 110]

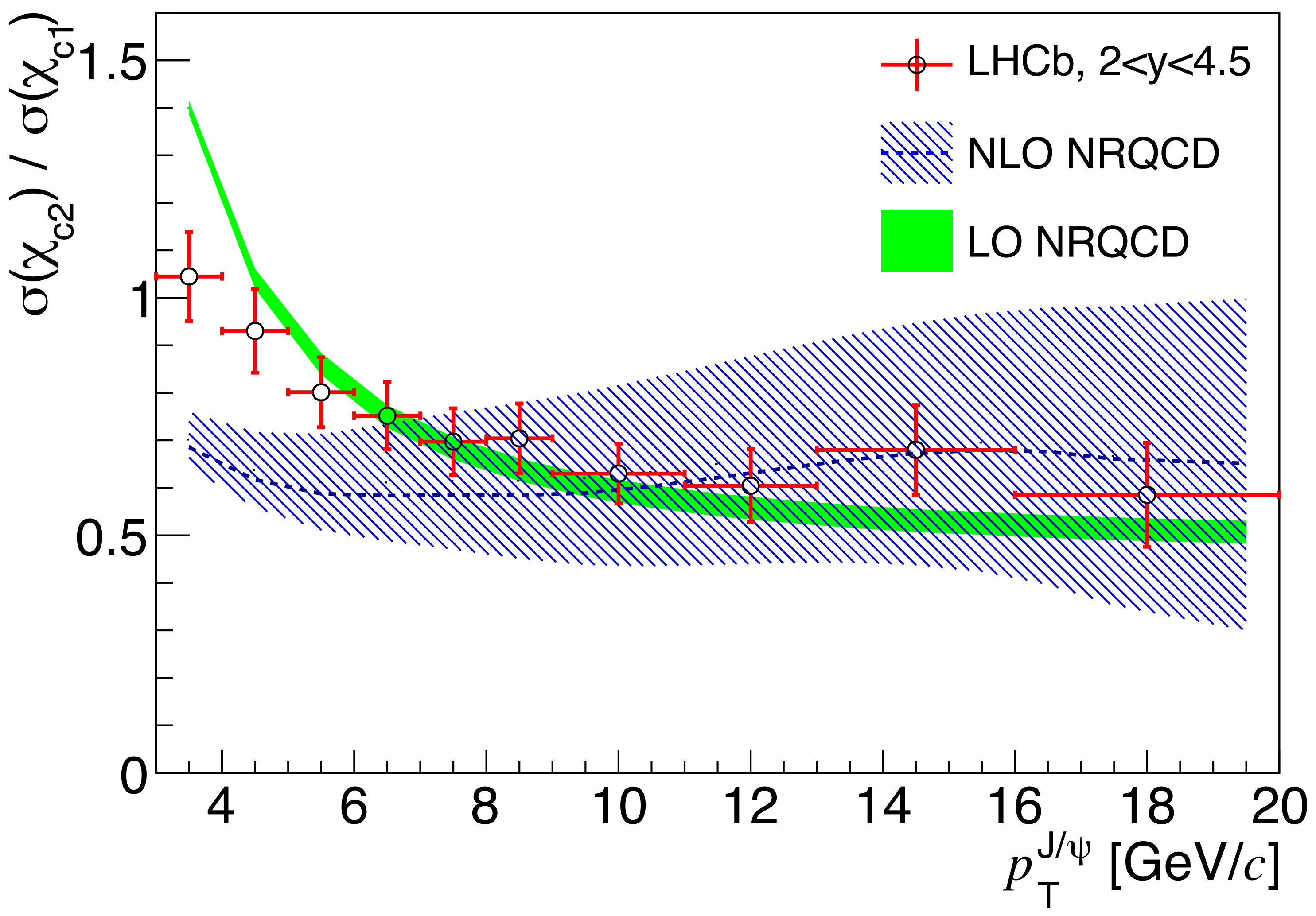


- Measurements of S-wave charmonium states in various frames (CS, HX, …)
- No sign of nonzero polarization up to 60 (40) GeV/c for J/ψ and ψ(2S)
- Similar results for Υ(1S), Υ(2S), Υ(3S) up to p_T = 50 GeV/c

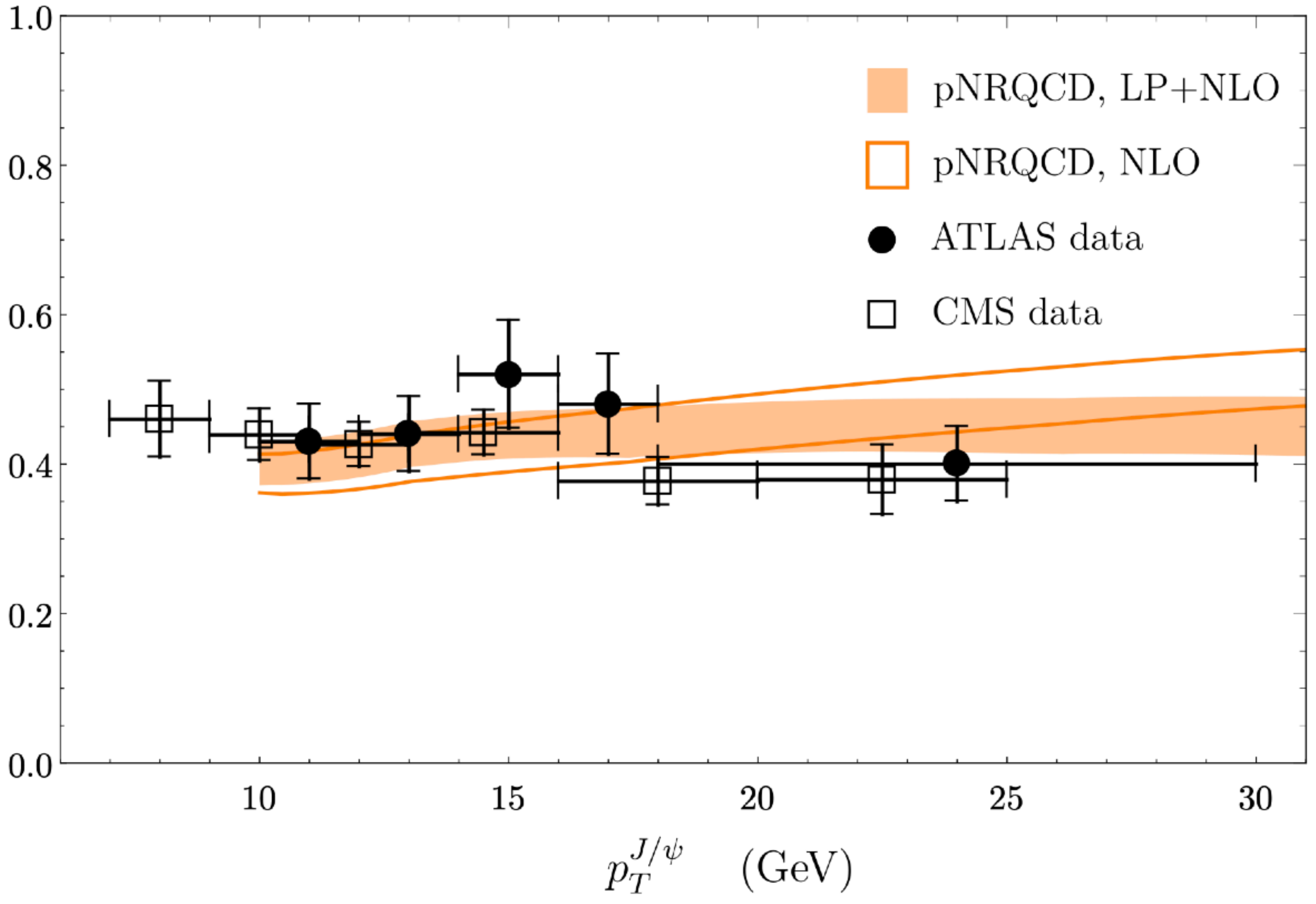
P-wave : Charmonia

$\chi_{c2}(1P)/\chi_{c1}(1P)$

[JHEP 10 (2013) 115]

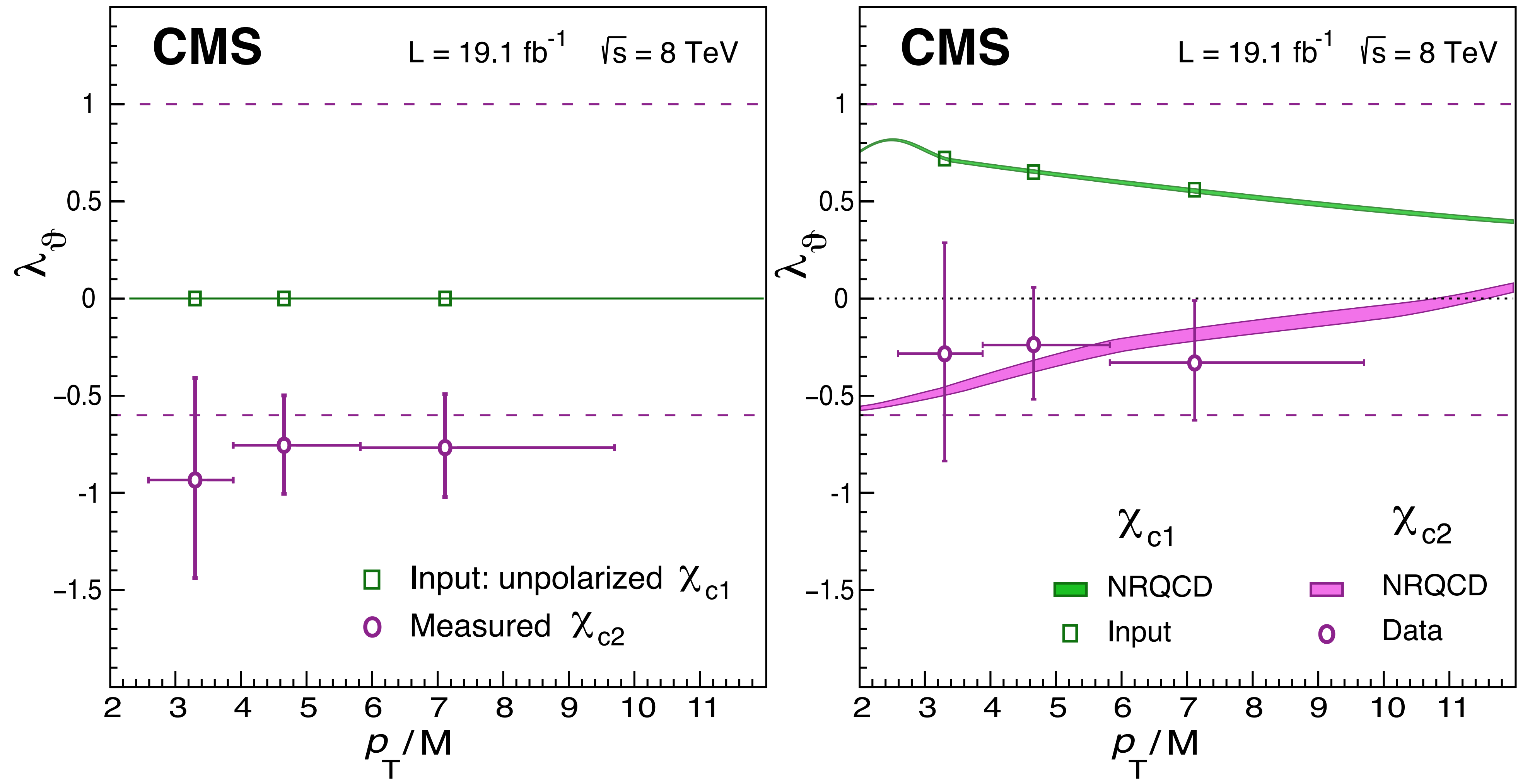


[JHEP 09 (2021) 032]



Polarization λ_θ

[PRL 124 (2020) 162002]



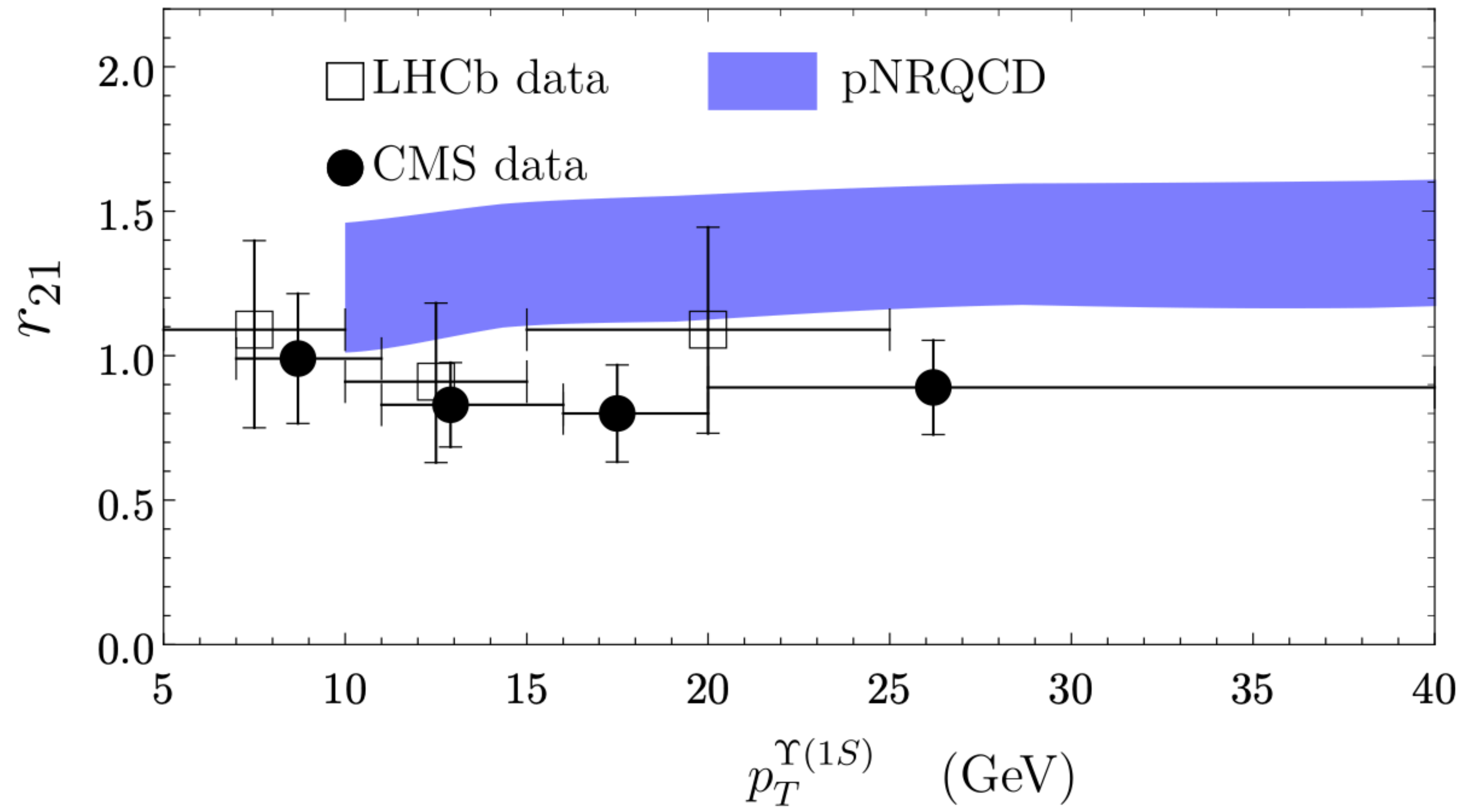
- NRQCD LDME test using $\chi_{c2}(1P)/\chi_{c1}(1P)$ ratio
- Recent studies based on pNRQCD at high-p_T region

- Interesting studies for 'relative' polarization of χ_{c1} vs χ_{c2}

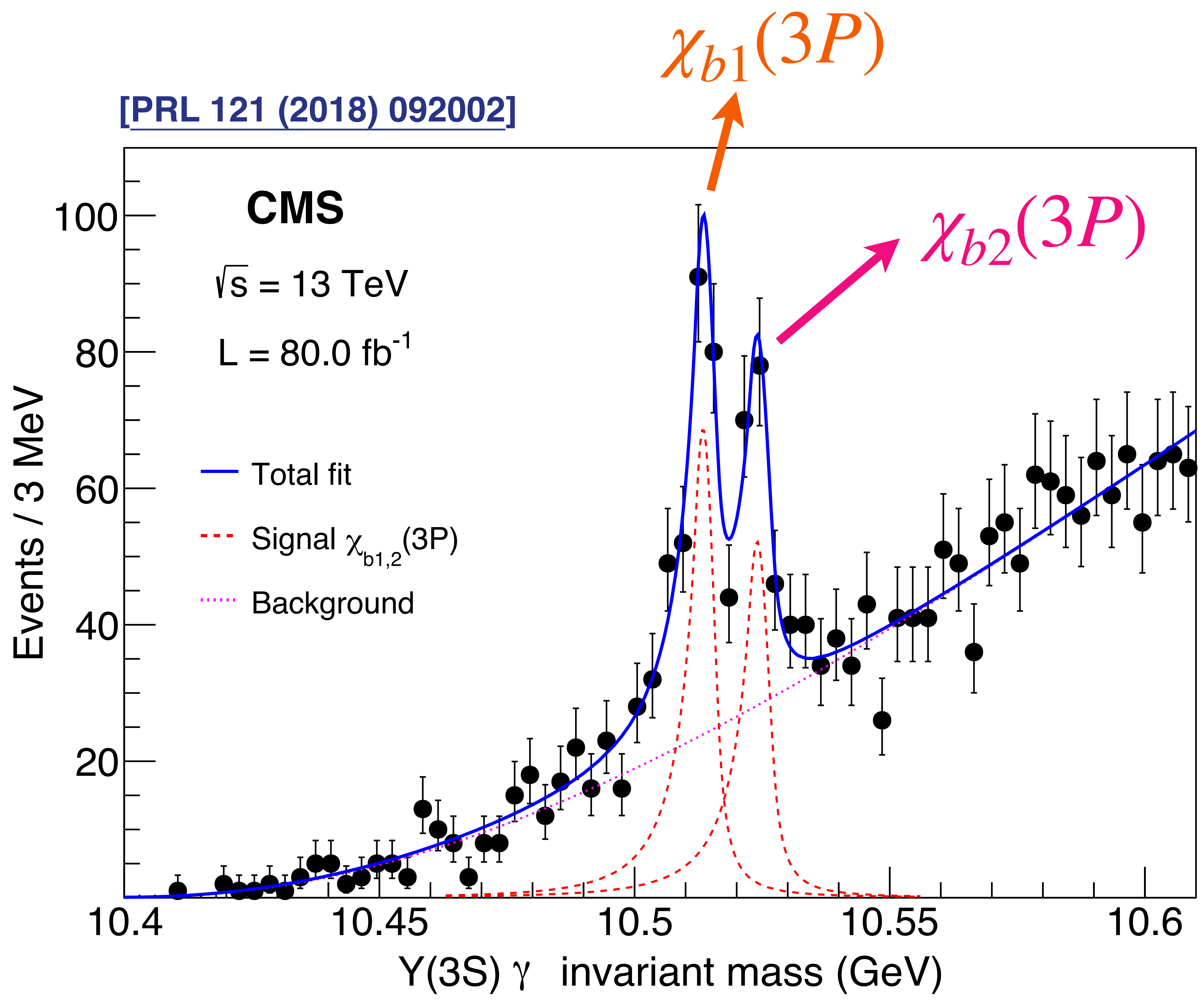
P-wave : Bottomonia

$\chi_{b2}(1P)/\chi_{b1}(1P)$

[JHEP 09 (2021) 032]



[PRL 121 (2018) 092002]



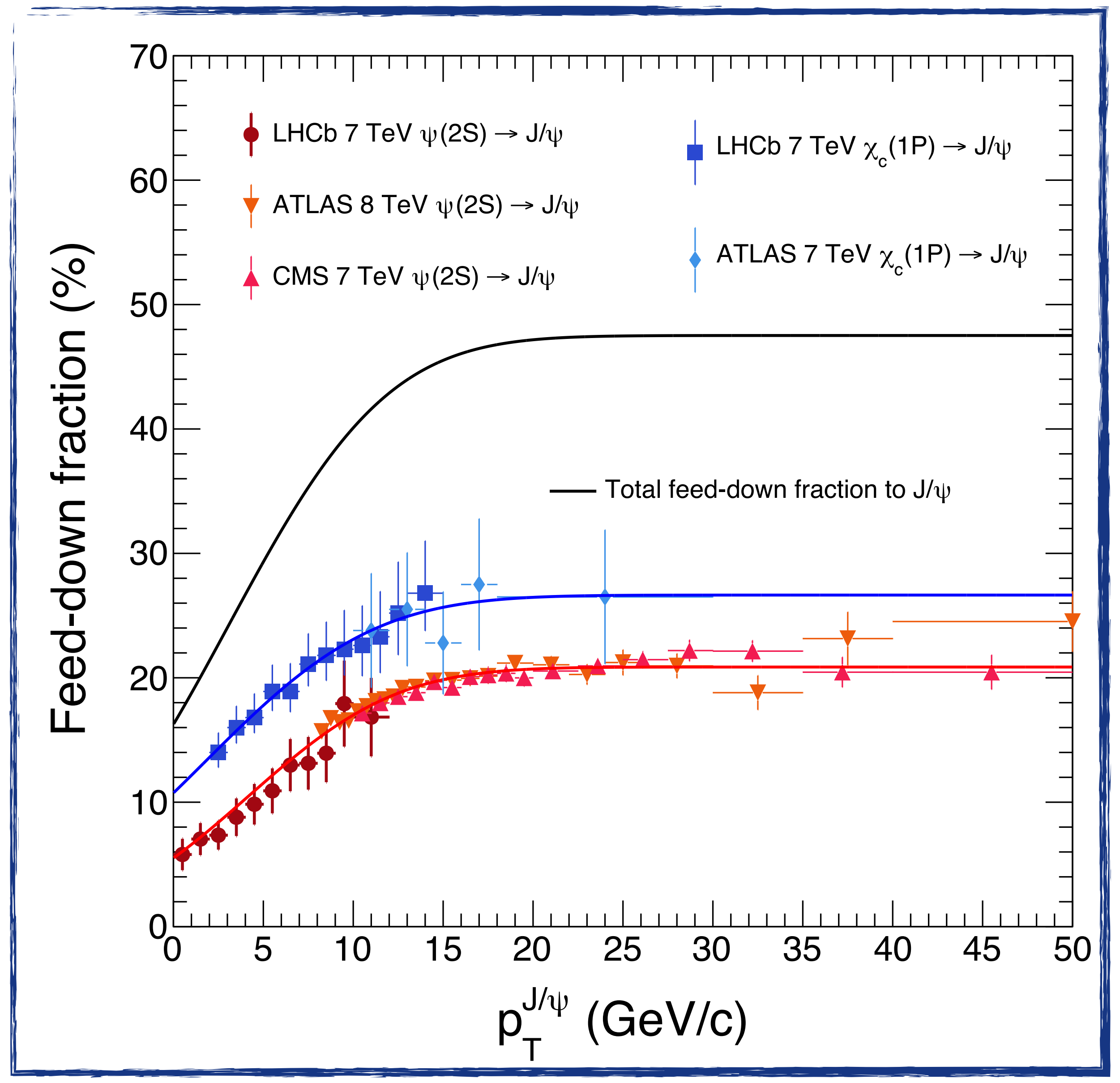
- NRQCD LDME test using $\chi_{b2}(1P)/\chi_{b1}(1P)$ ratio — small overestimations compared to data
- Observation of $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ with $\triangle M_{12} \approx 10$ MeV : Standard hierarchy of J=2 state heavier

Feed-down in pp @ LHC

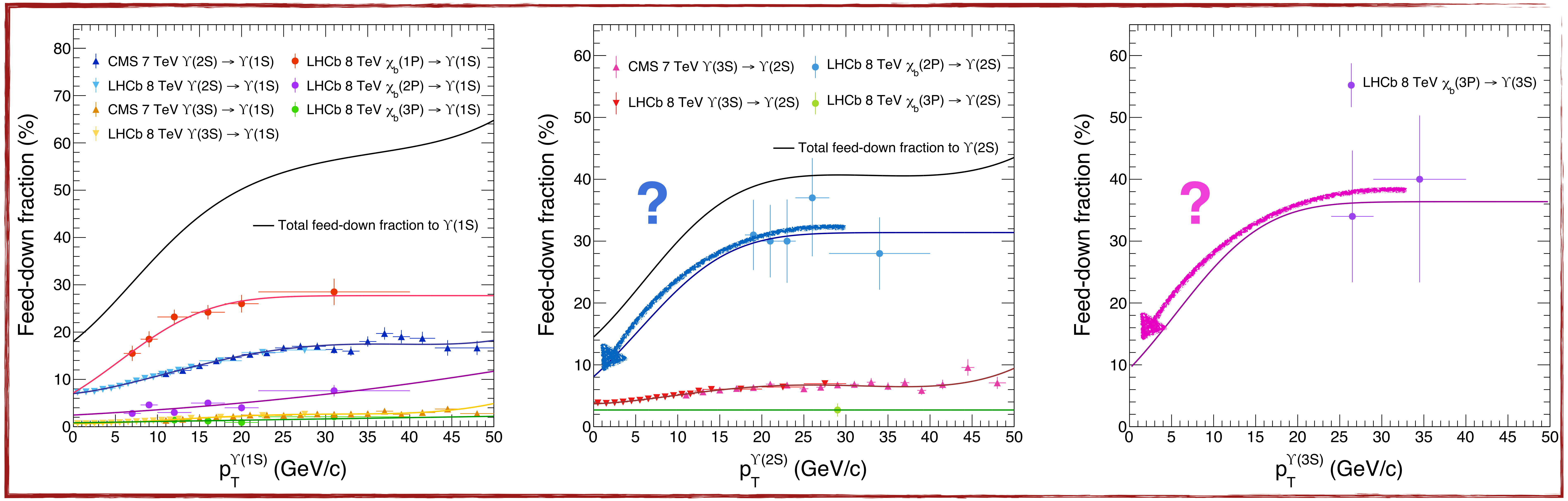
[EPJC 72 (2012) 2100] [JHEP 07 (2014) 154] [PLB 718 (2012) 431]
[EPJC 76 (2016) 283] [PRL 114 (2015) 191802]

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

● LHC J/ψ pp data



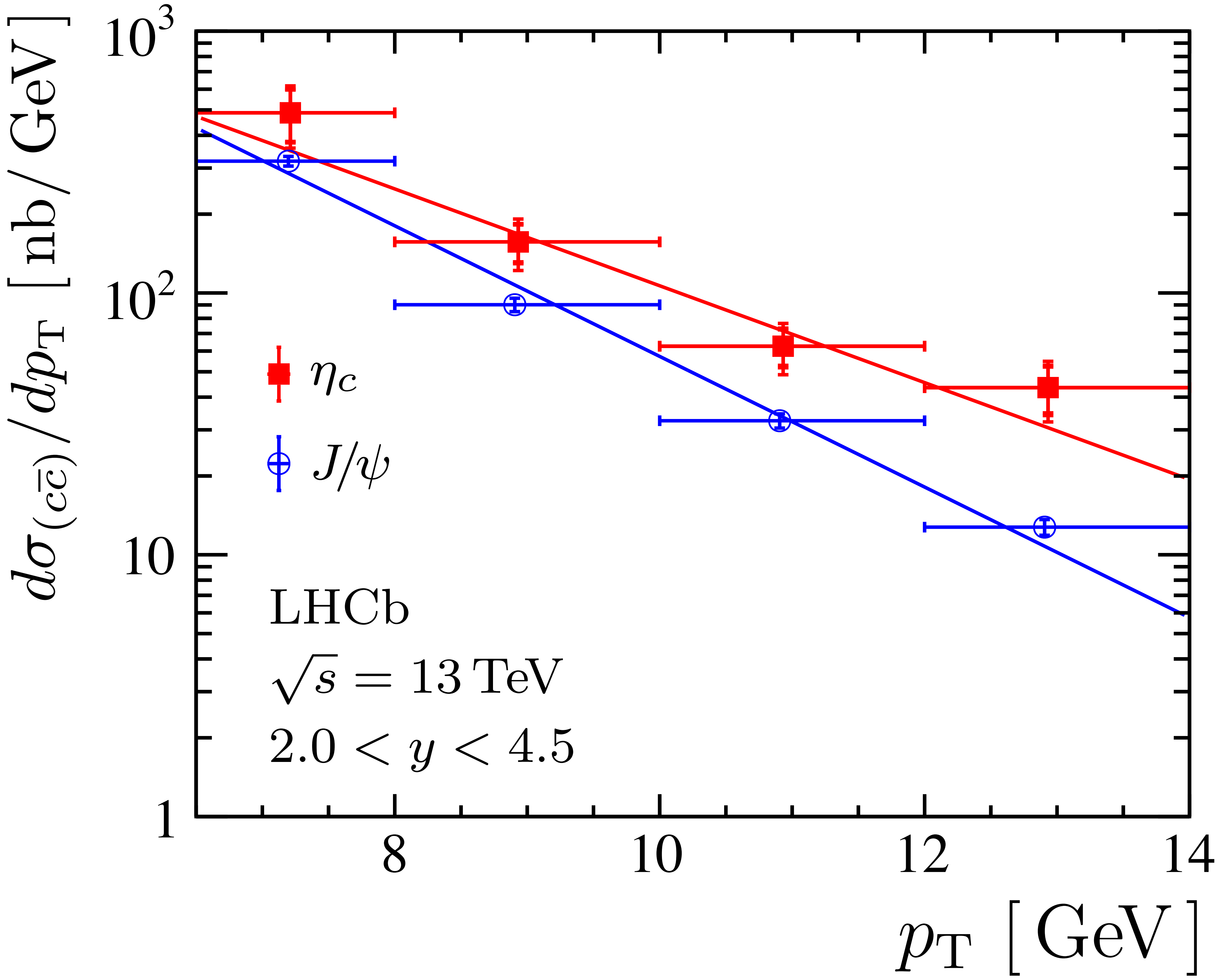
● LHC Υ(nS) pp data



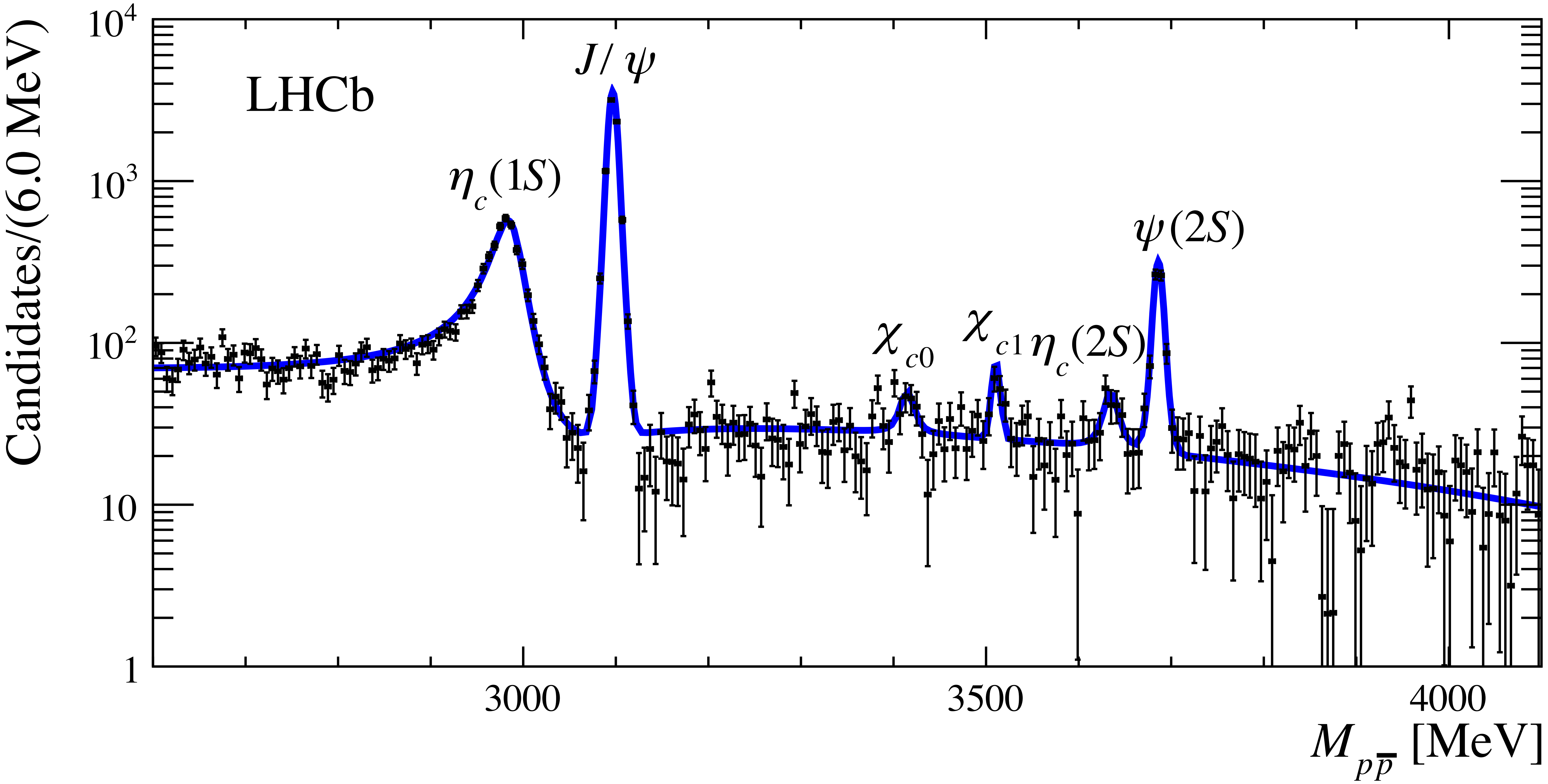
- Significant amount of feed-down contribution observed in both charmonia and bottomonia
- Lack of information for χ_b(mP) –> Υ(nS) : limited on both data and theory

η_c meson @ LHC

[EPJC 80 (2020) 191]

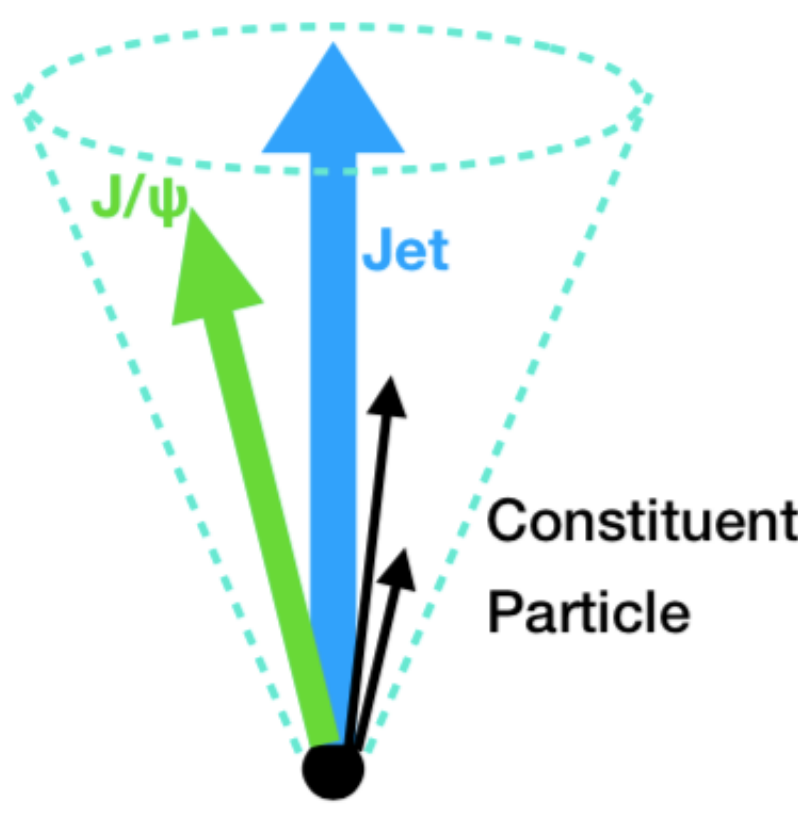


[PLB 769 (2017) 305]



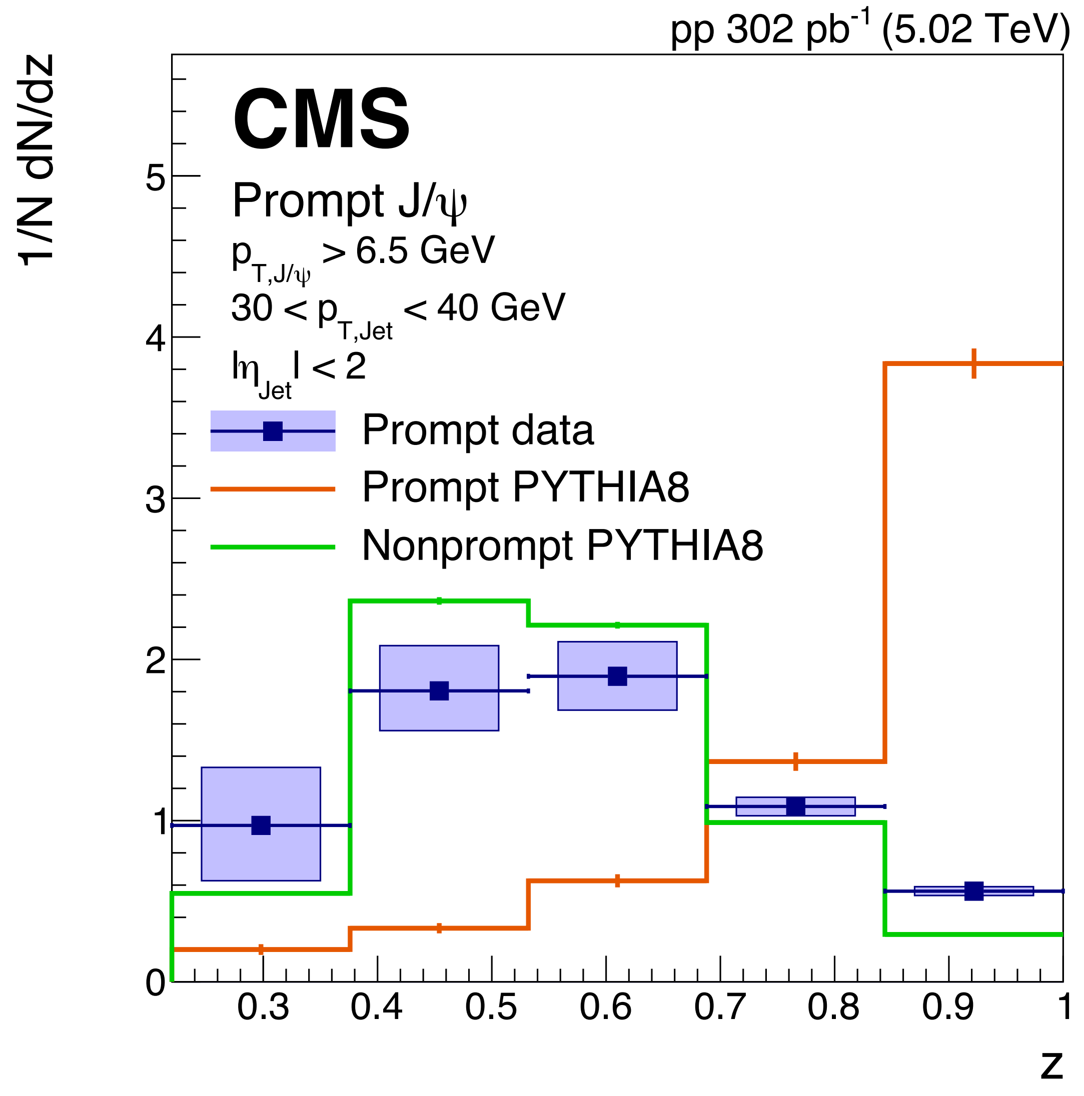
- Only CS for $\eta_c(1S)$ production? p_T shape could be sensitive to possible CO contribution…
- Ratio of $\eta_c(2S)/\psi(2S)$ suggested to be a cleaner probe : free from feed-down corrections

J/ψ in jets

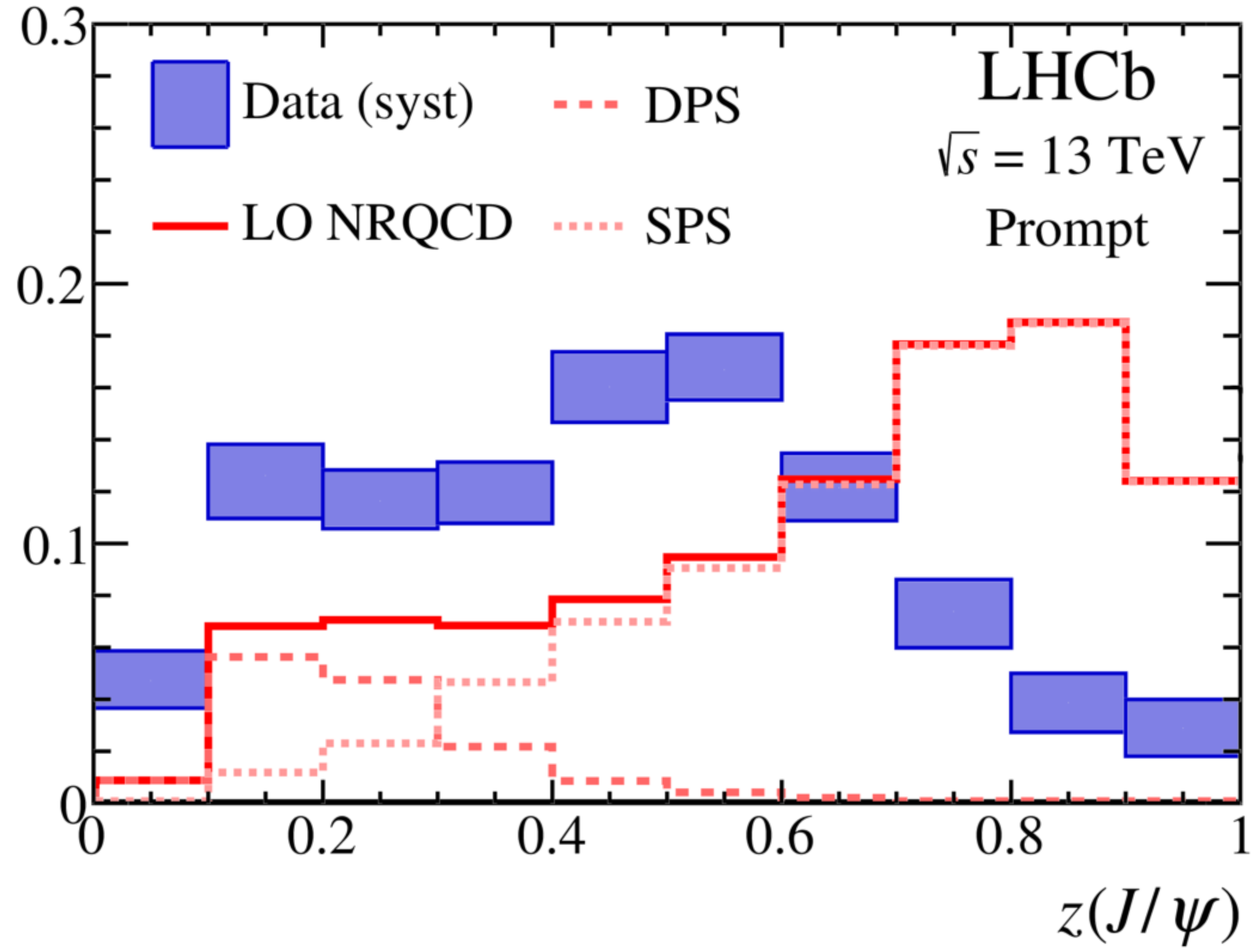


$z = p_{T,\,J/\psi} \,/\, p_{T,\,jet}$

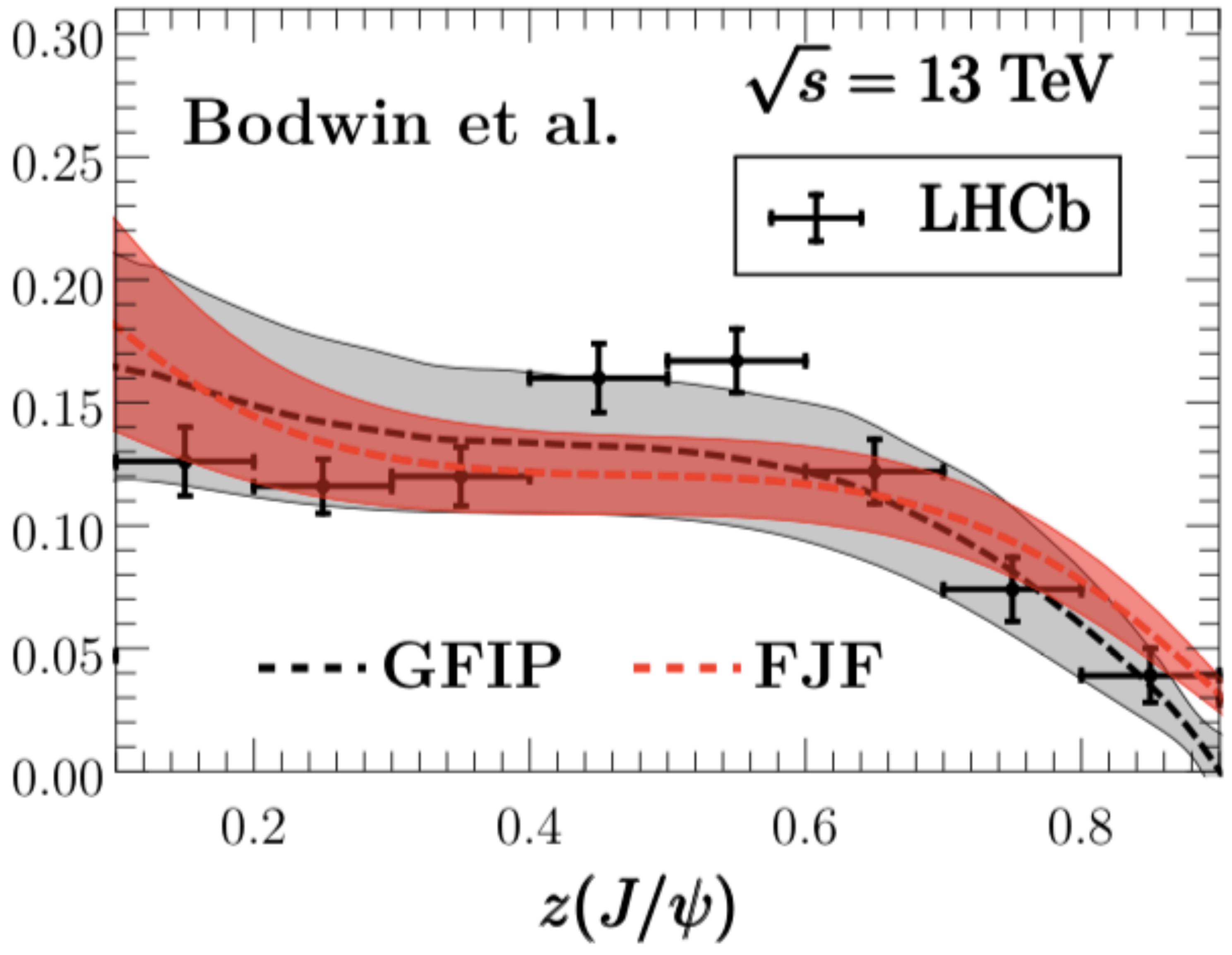
[PLB 825 (2021) 136842]



[JHEP 11 (2021) 181]



[PRL 119 (2017) 032002]



- PYTHIA show discrepancy for the amount of jet-fragmentation of J/ψ production
- Improvement possible with inclusion of improved of jet & gluon fragmentation functions

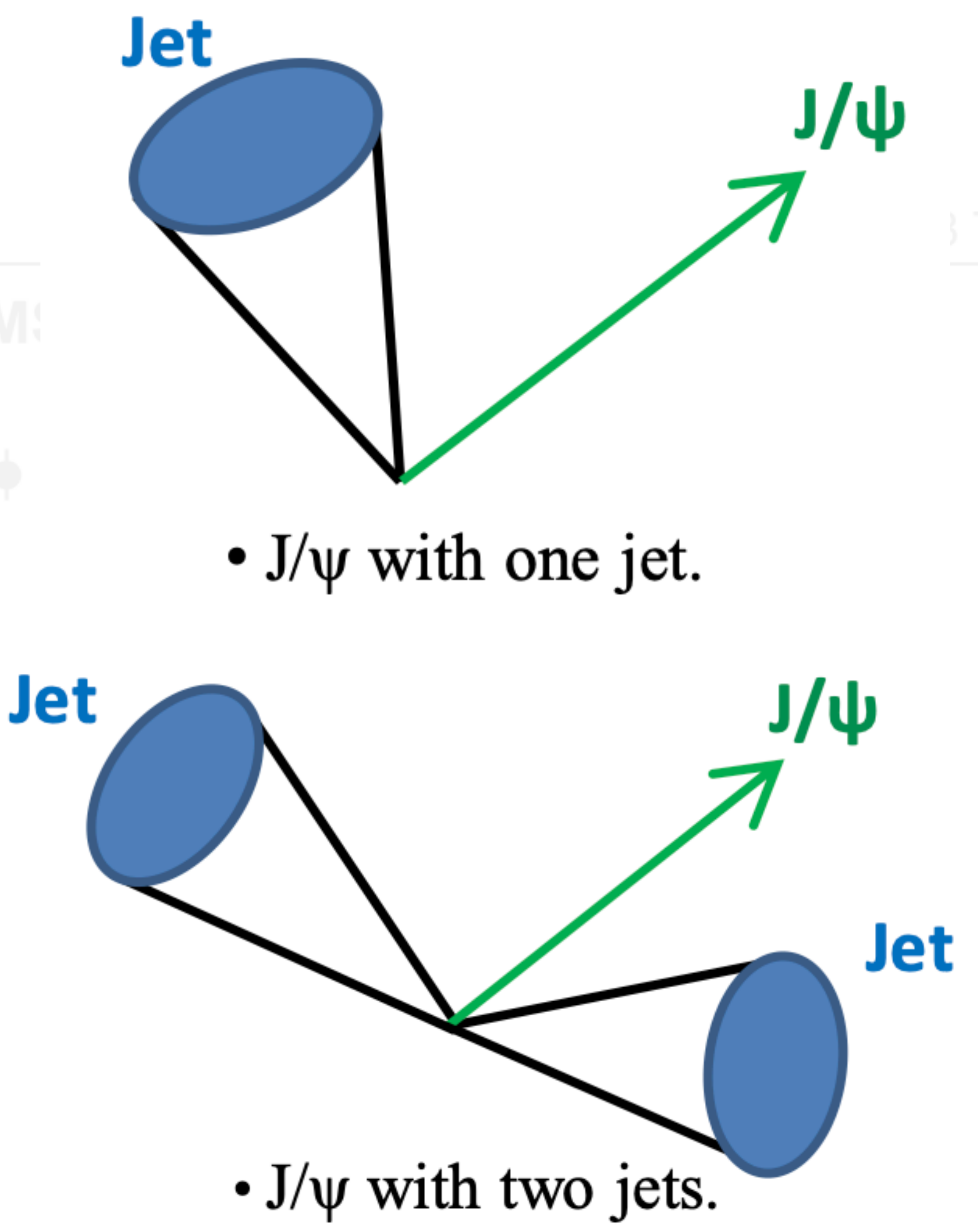
J/ψ in *jets*

[PLB 804 (2020) 135409]

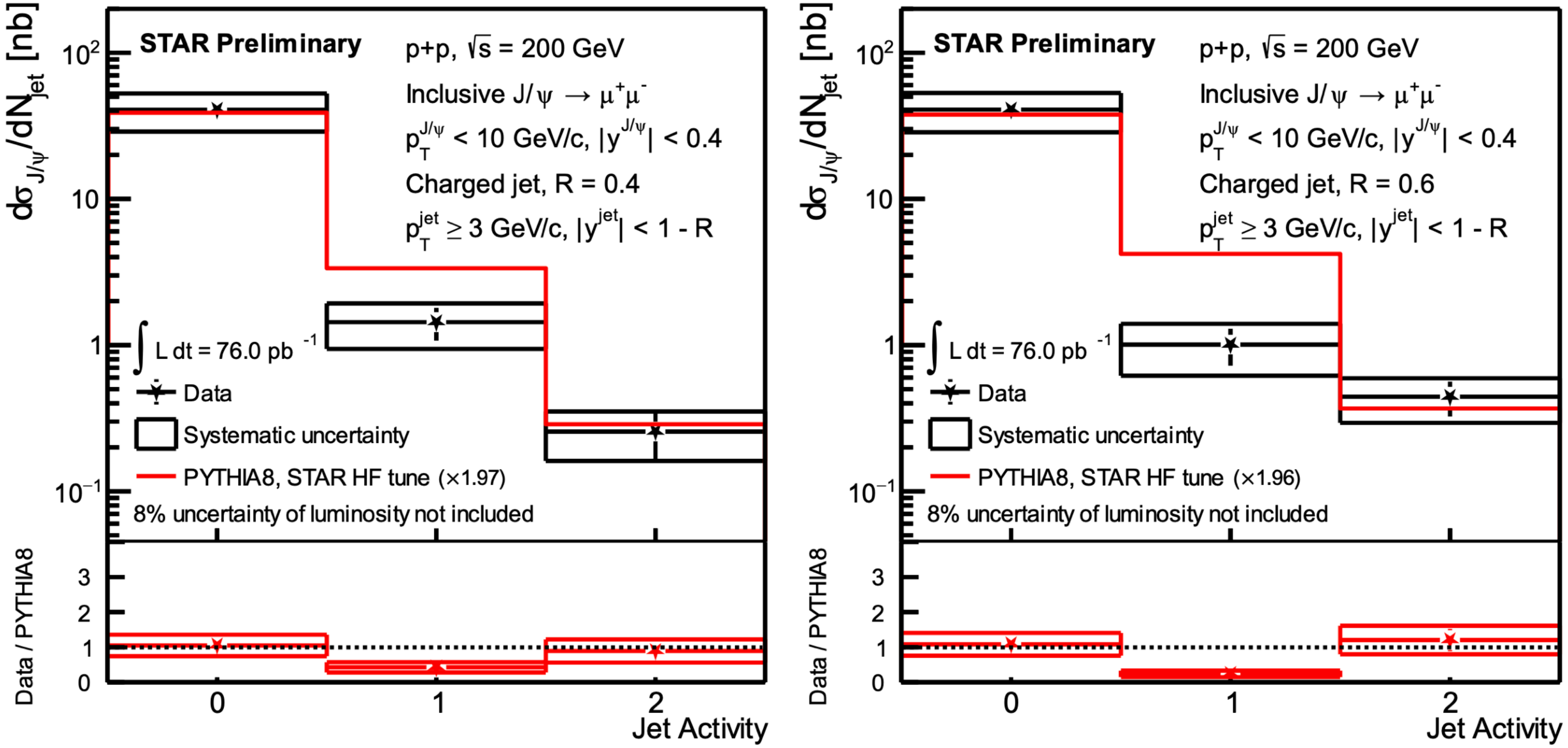
- Production of J/ψ in jets compared with NRQCD LDME parameter sets based on FJF
- BCKL set in agreement in all three z ranges —> predicts also small polarization at high-p_T

  : Caveat of deviation with other results (η_c, measurements in B factories, …)

J/ψ in jets



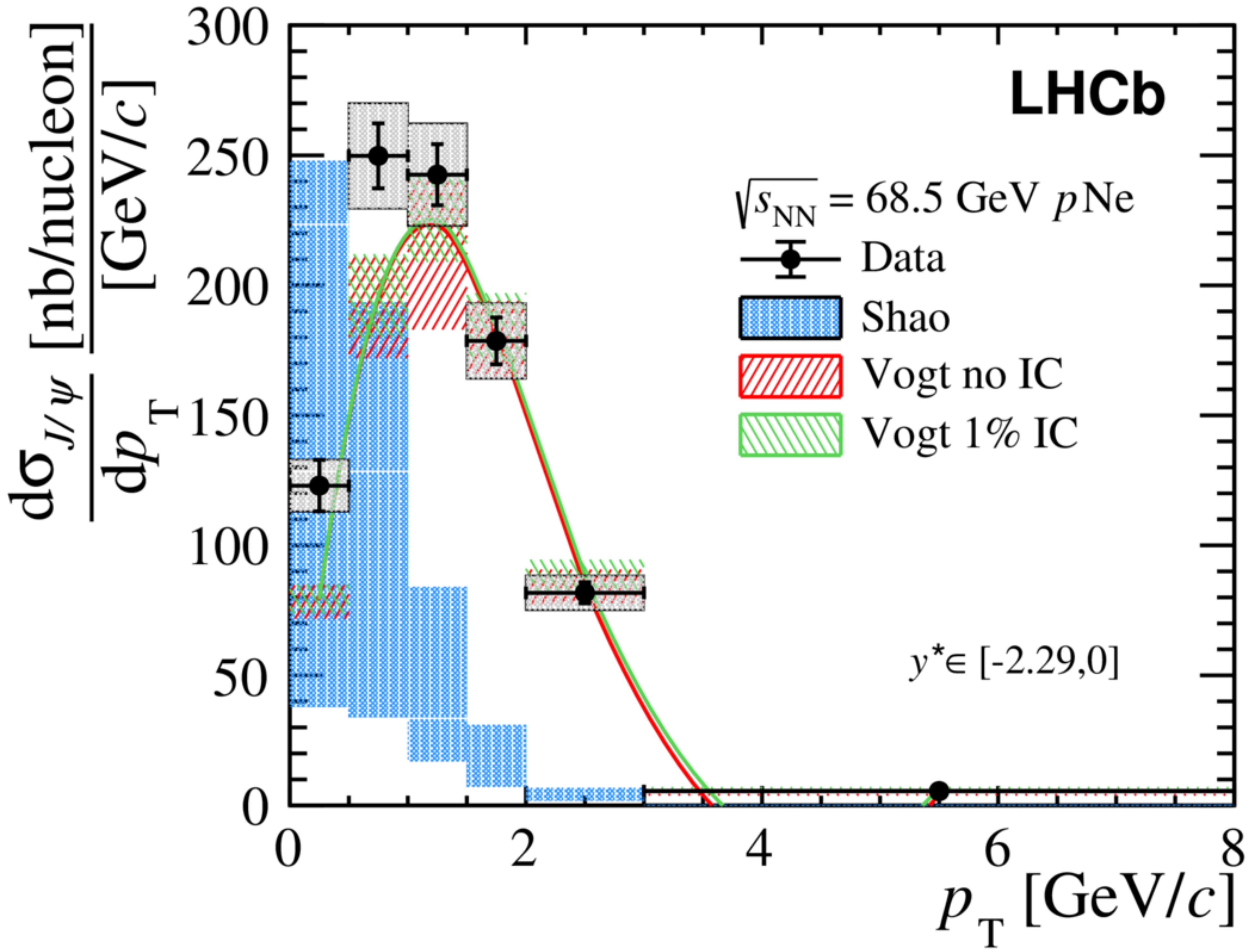
[STAR:QM_Poster]



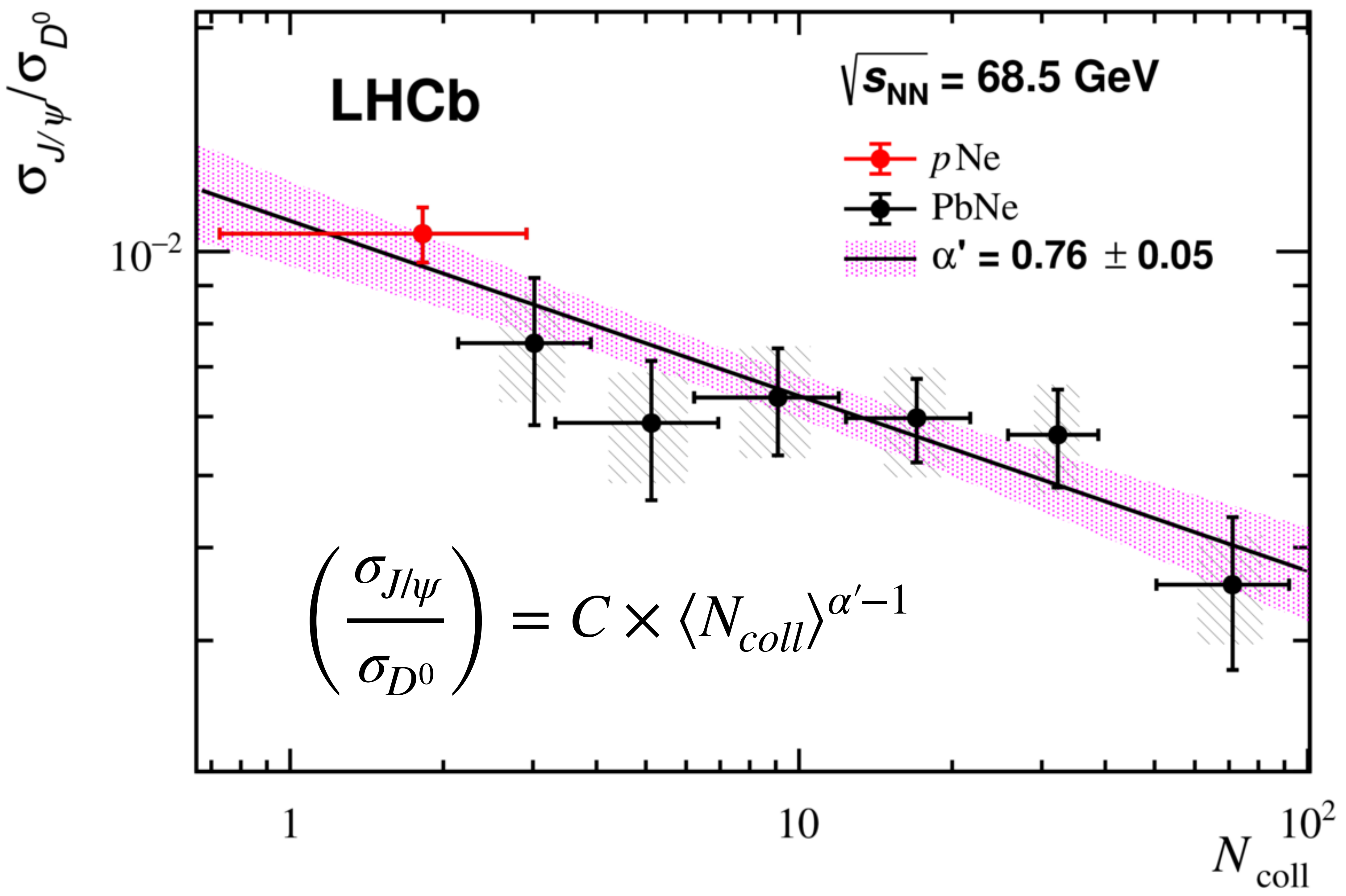
- Worth looking at jet multiplicity and the relative angle?
  – Already ongoing attempts in pp 200 GeV

Fixed target J/ψ results

[arXiv:2211.1164]



[arXiv:2211.11652]



- Results compared to HELAC-Onia (+CT14NLO & nCTEQ15 PDF) and ICEM model
  —> caveat of HELAC-Onia computation ingredients?
- J/ψ-to-D^0 ratio : α' compatible with expectations from atomic mass number scaling
  —> no evidence of QGP-like effect in PbNe @ 68.5 GeV

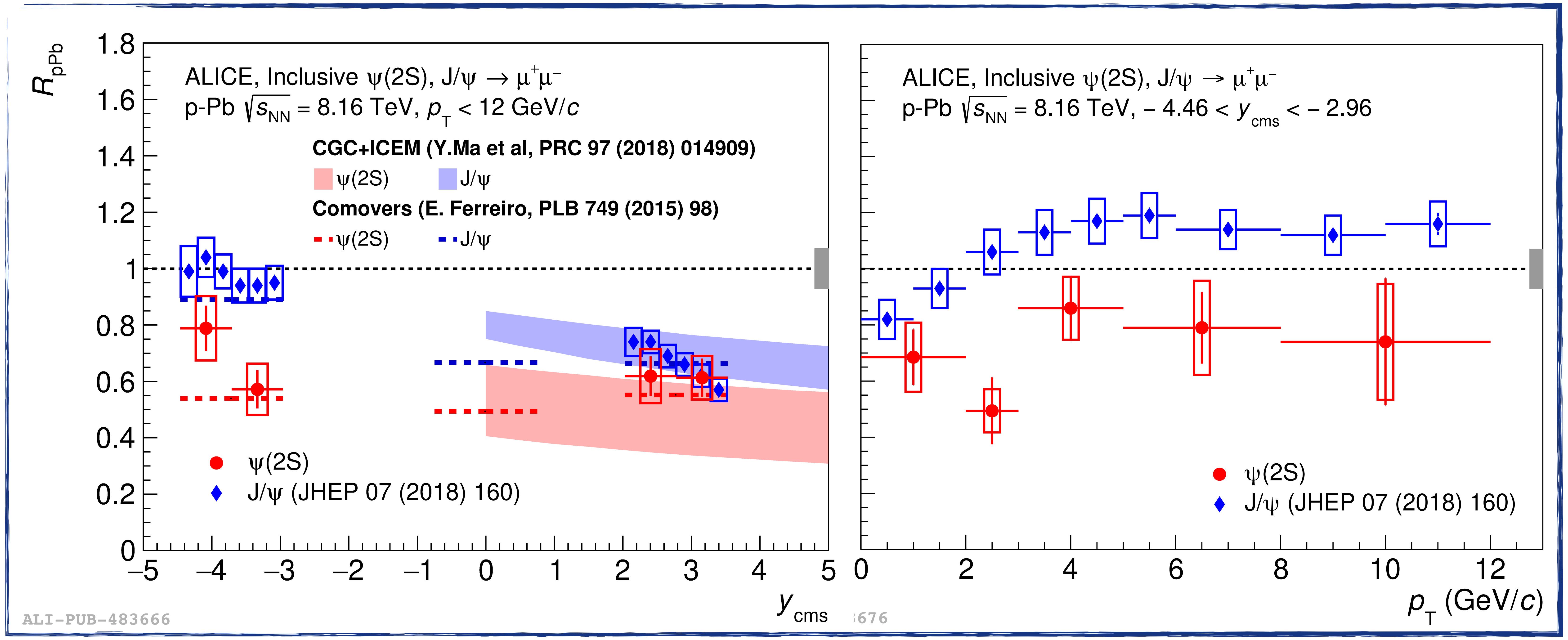
Quarkonia in pA

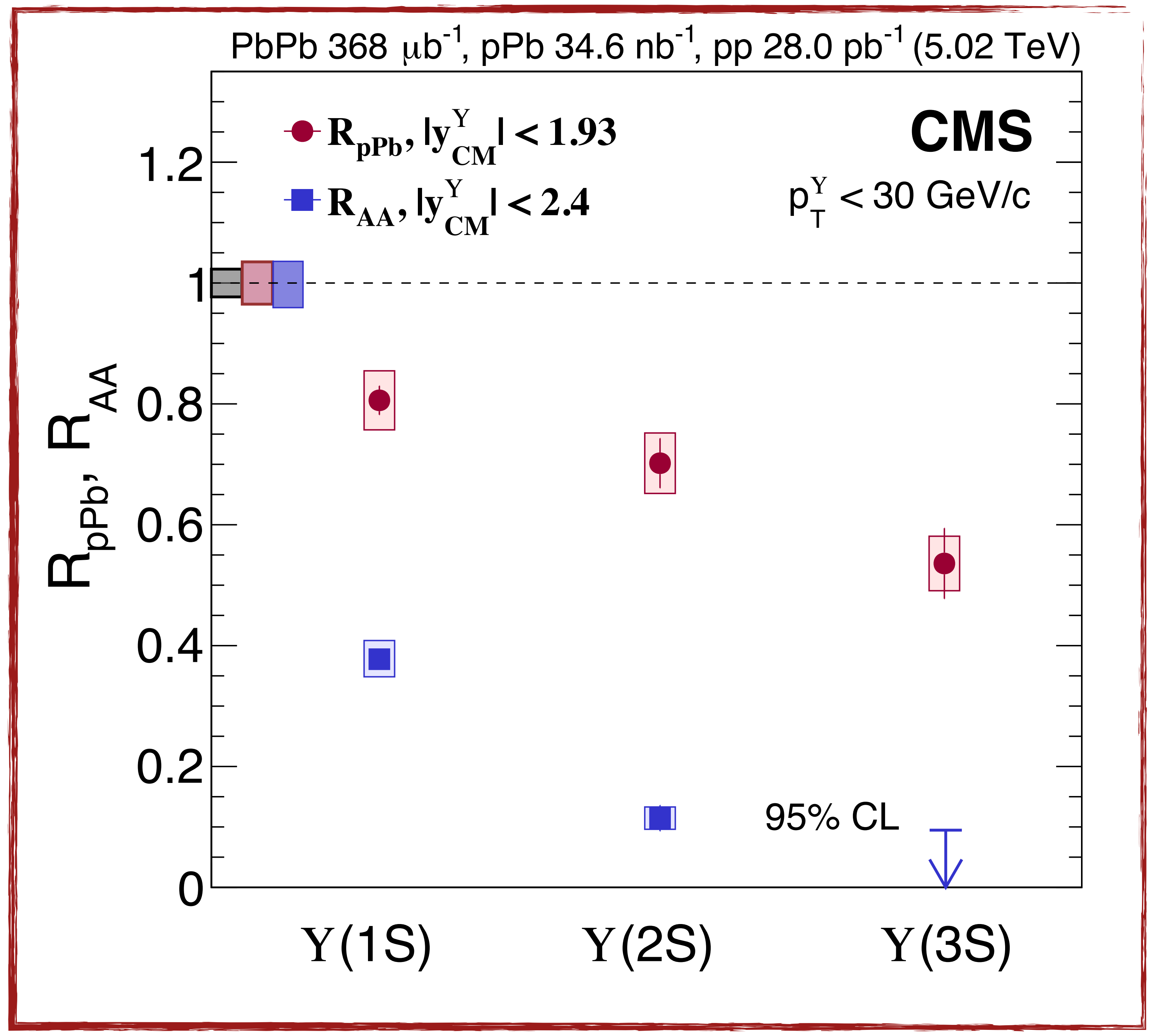
[JHEP 07 (2020) 237]

J/ψ & ψ(2S)

ϒ(nS)

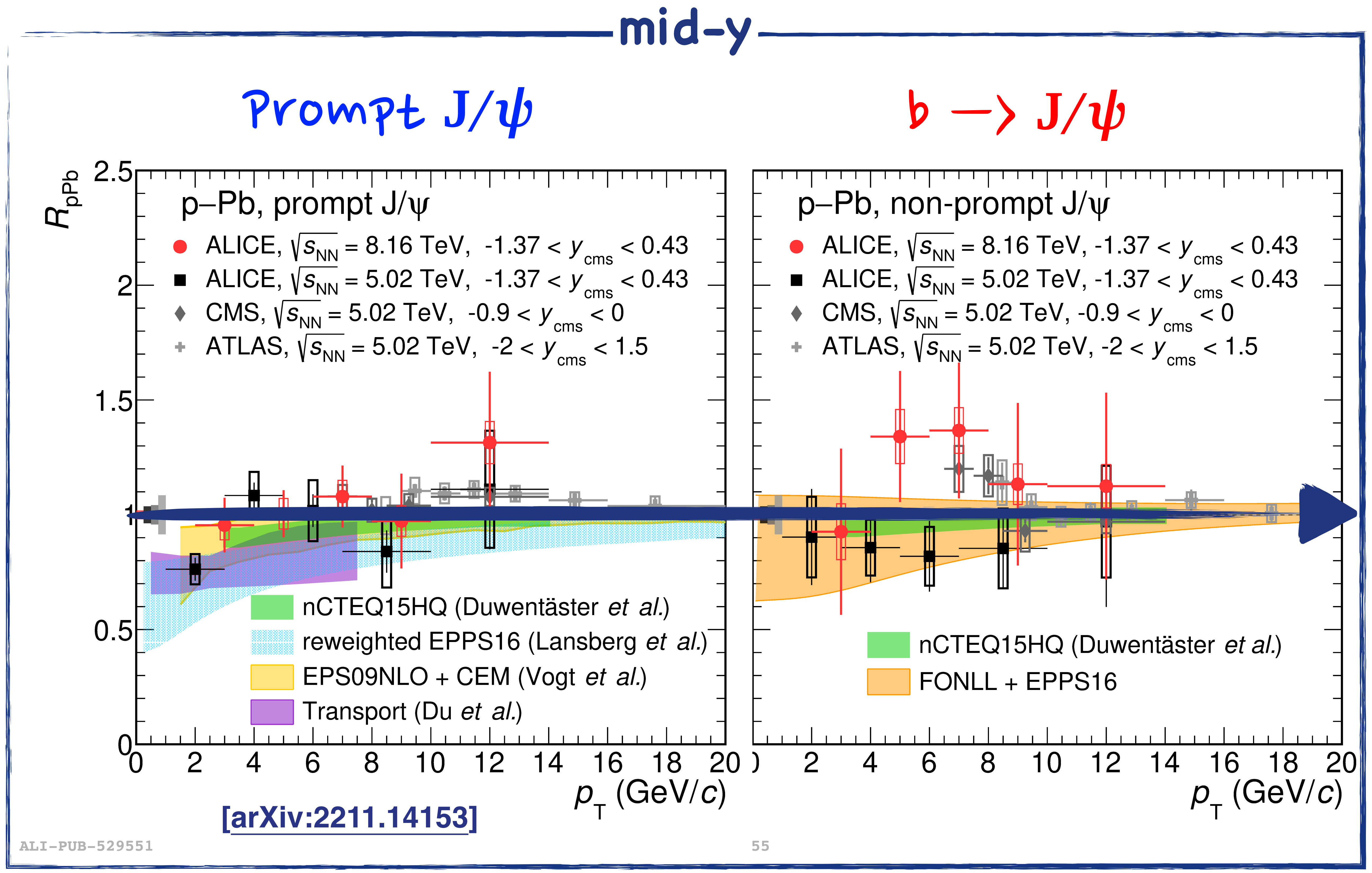
[PLB 835 (2022) 137397]

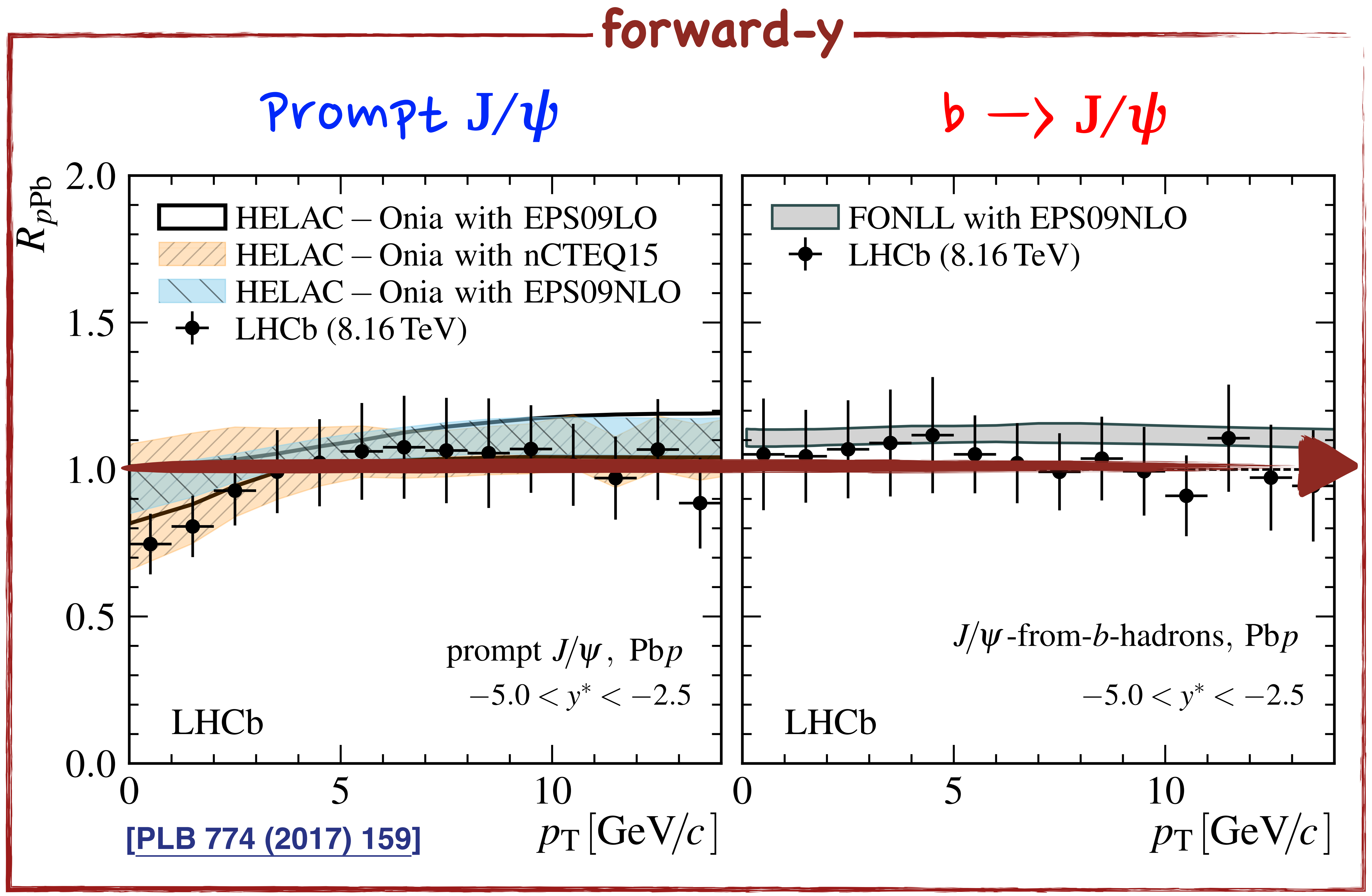




- Stronger suppression for ψ(2S) than J/ψ — also for ϒ(1S), ϒ(2S), ϒ(3S)
- Origin of additional suppression for excited quarkonium states still under investigation
  - comover breakup? possible CGC? hot nuclear matter effect?

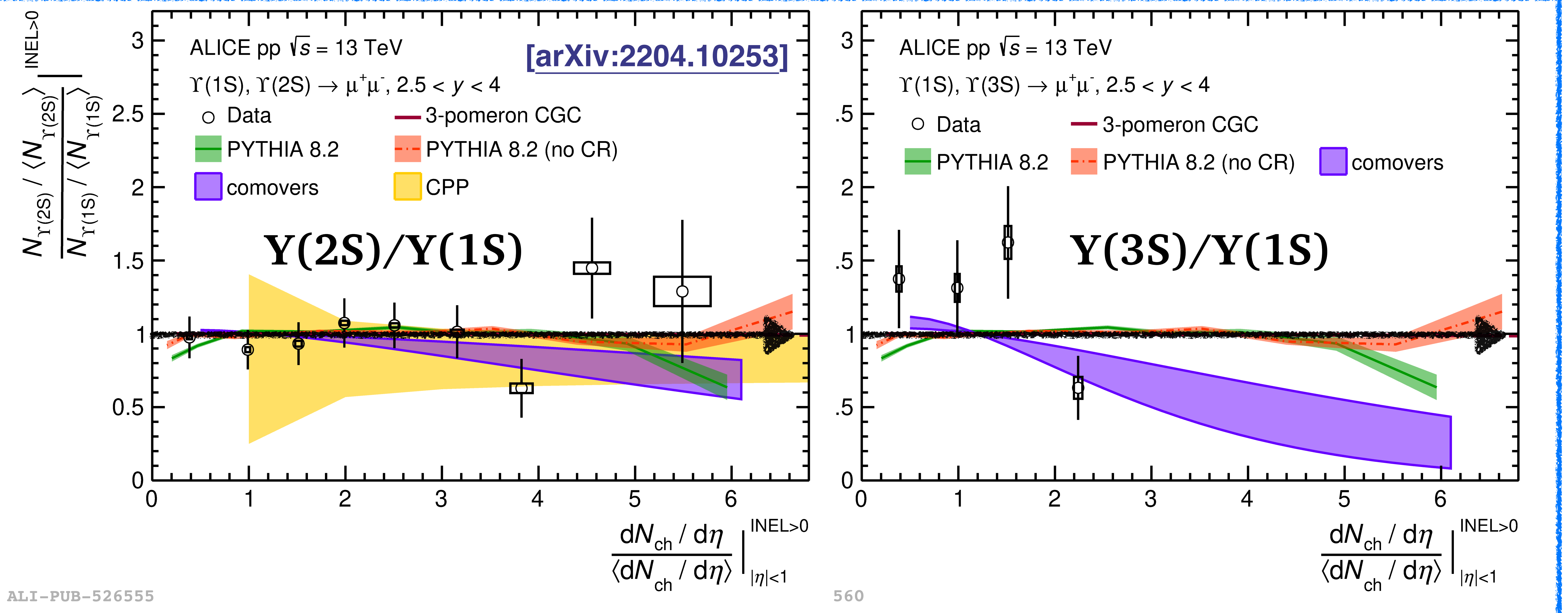
Prompt J/ψ vs b —> J/ψ in pA



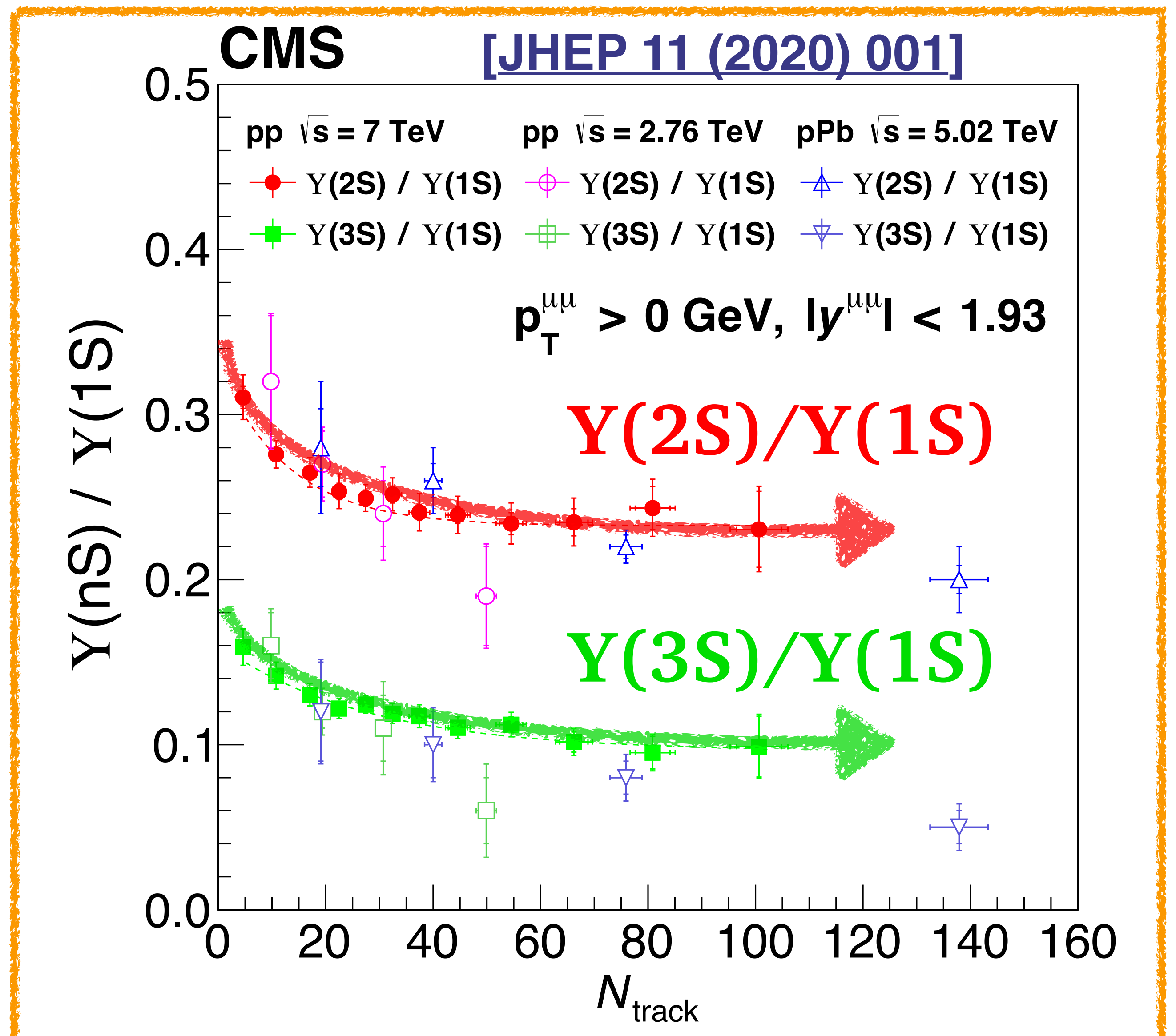


- Indication of different in-medium effects for charm vs bottom at forward-y
- Not seen at mid-y? —> Need better precision to resolve flavour dependent nuclear effects

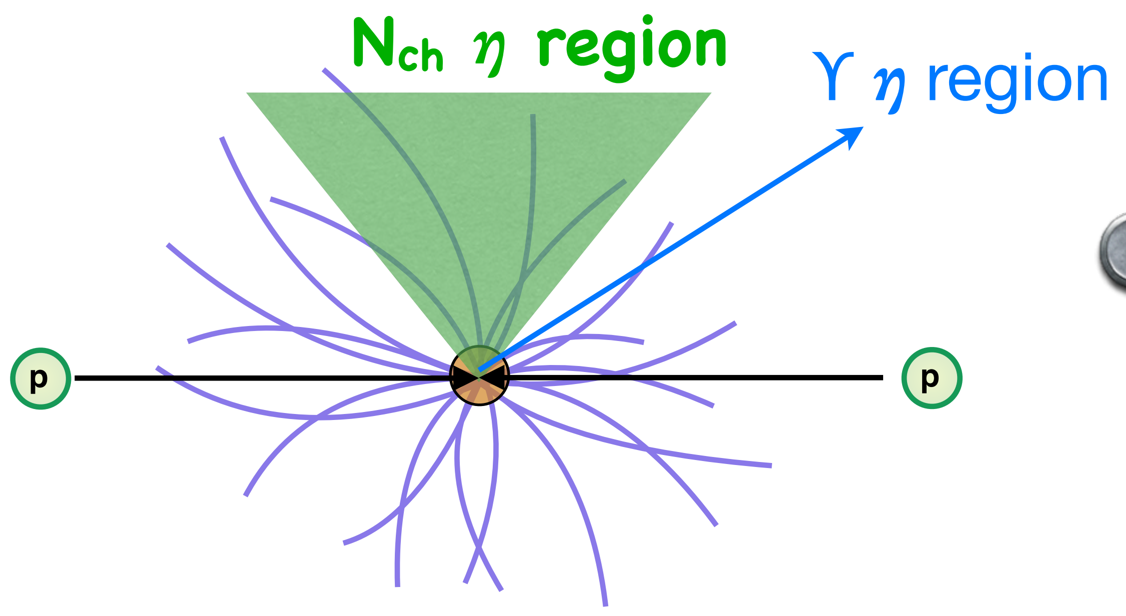
ϒ in pp w UE study



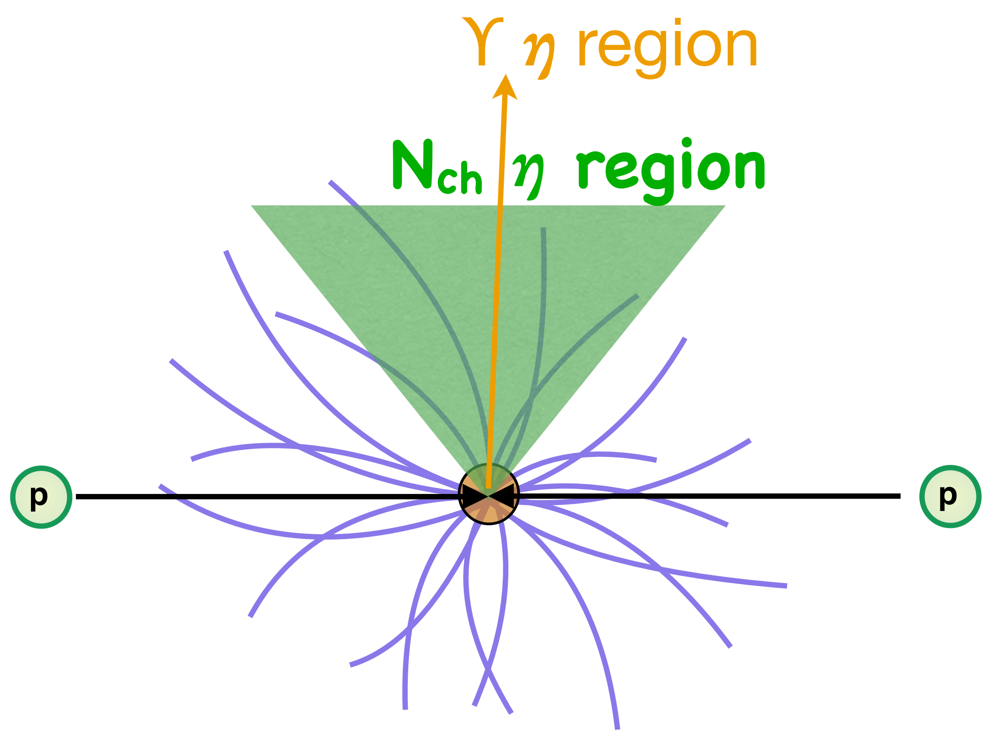
ϒ, N_{ch} different rapidity region (DRR)



ϒ, N_{ch} same rapidity region (SRR)



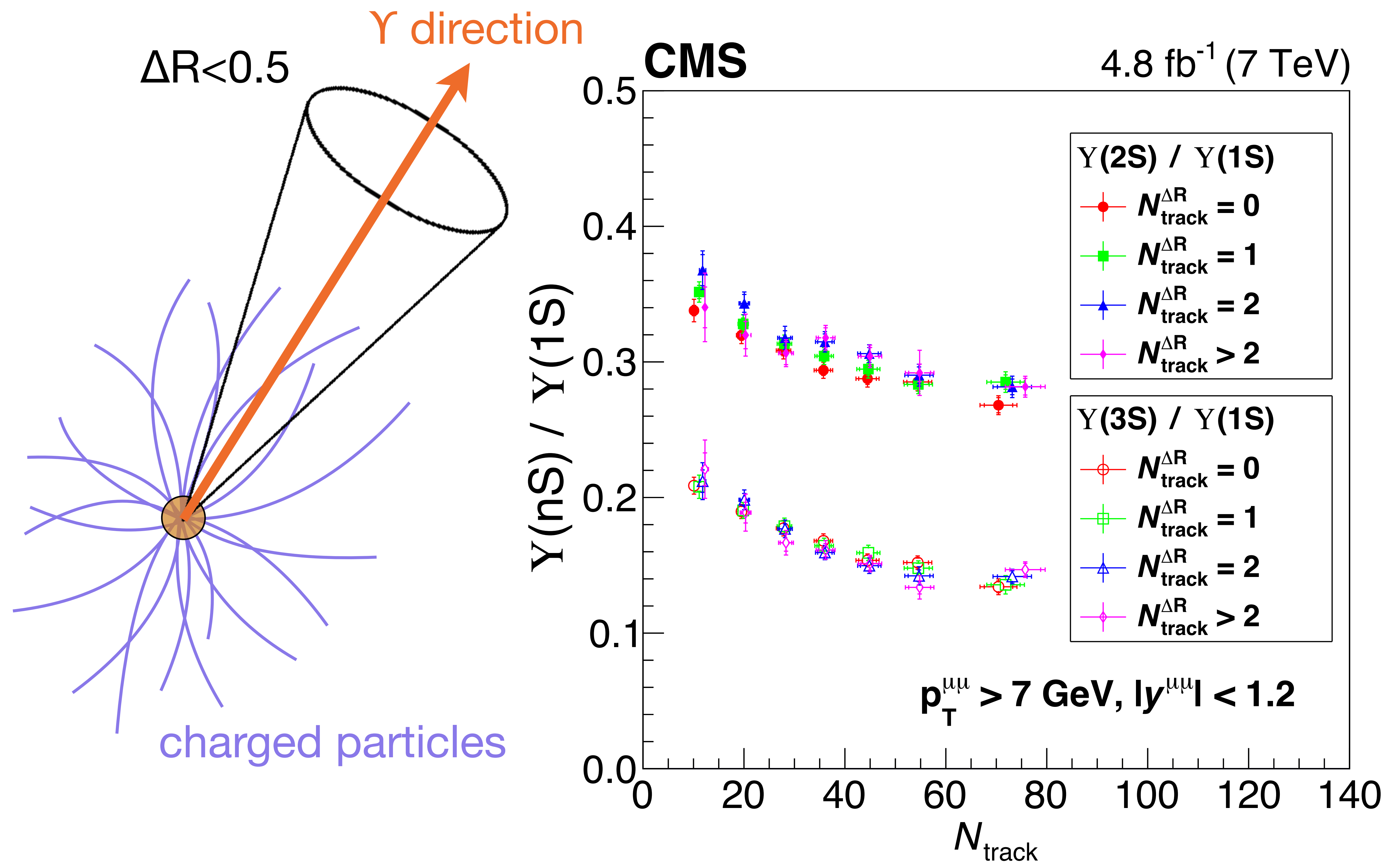
- Different excited-to-ground state ratio for DRR vs SRR?
  - Need improved precision + exact multiplicity & p_T matching
  - Related to MPI/UE/correlation/...?

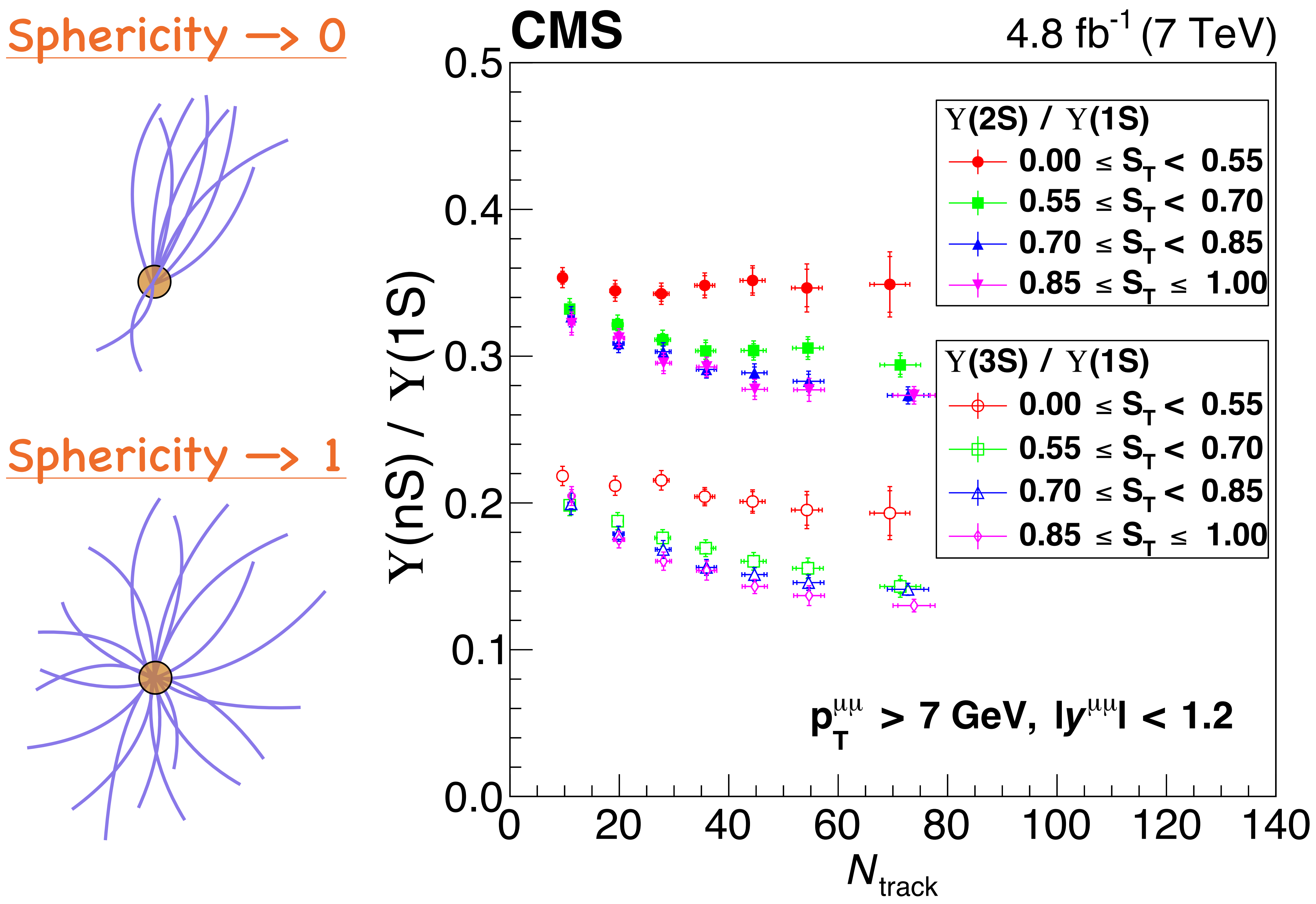


Υ in pp w UE study

[JHEP 11 (2020) 001]

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





- No dependence of N_{track} within cone ΔR<0.5
  - Different from comover model expectation (n.b. p_T>7 GeV/c / N_{track} cutoff values)
- Decrease disappears in low-sphericity
  - Connection with UE for jetty events?

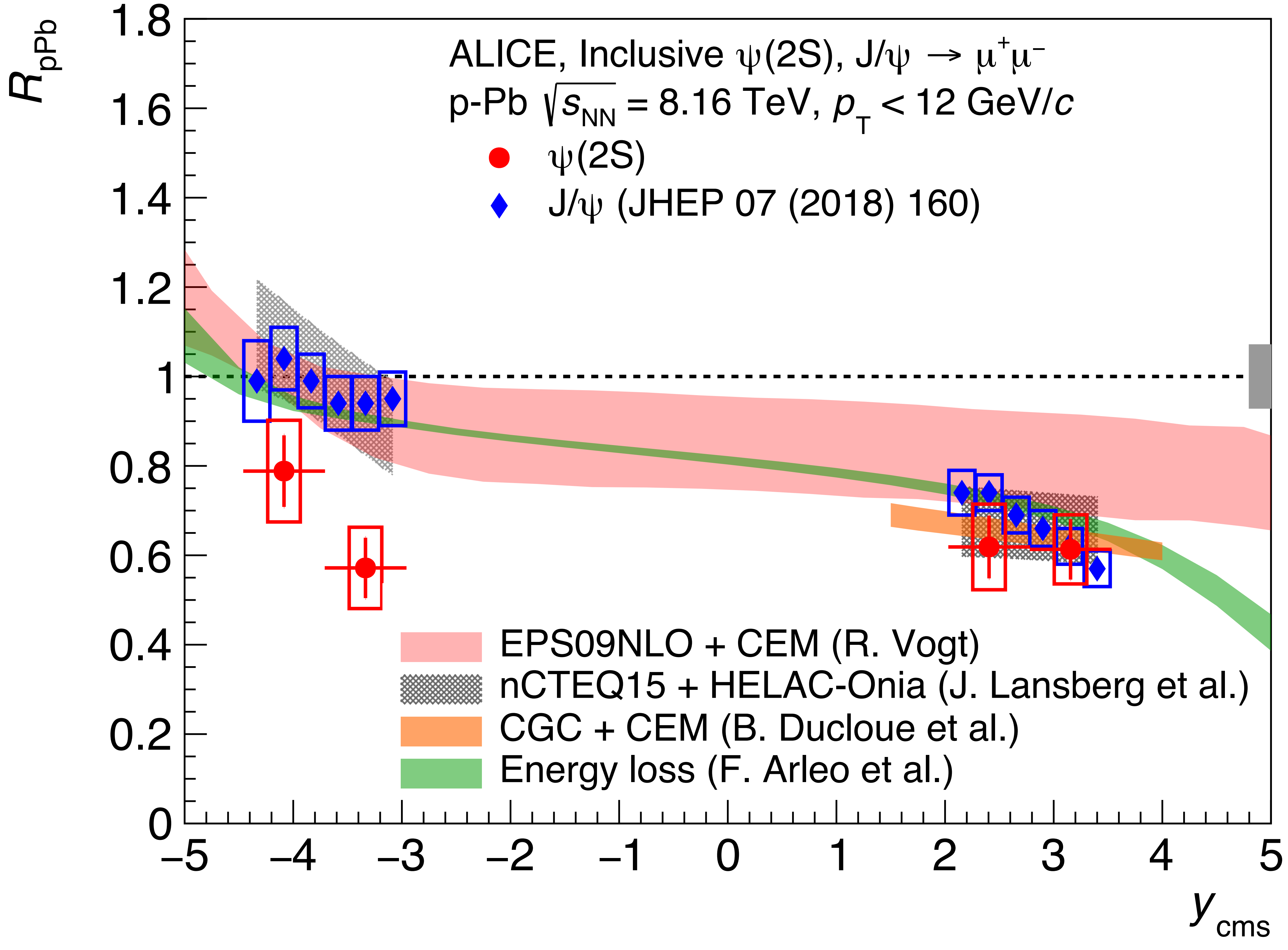
Summary

- Successful achievement of quarkonium measurements in the past $\sim$10 years @ LHC
- Precision cross section results in inclusive quarkonium production for S-wave quarkonium
  : uncertainty smaller than theory calculations
- No significant polarization observed for S-wave quarkonium states from low- to high-p_T
- J/ψ in jets or associated with jet(s) as new probes to understand quarkonium production
- Puzzle of quarkonium modification in pA collisions still not resolved
- Mystery of yield ratios w.r.t UE in pp collisions
  — rapidity gap study to be done sophisticatedly

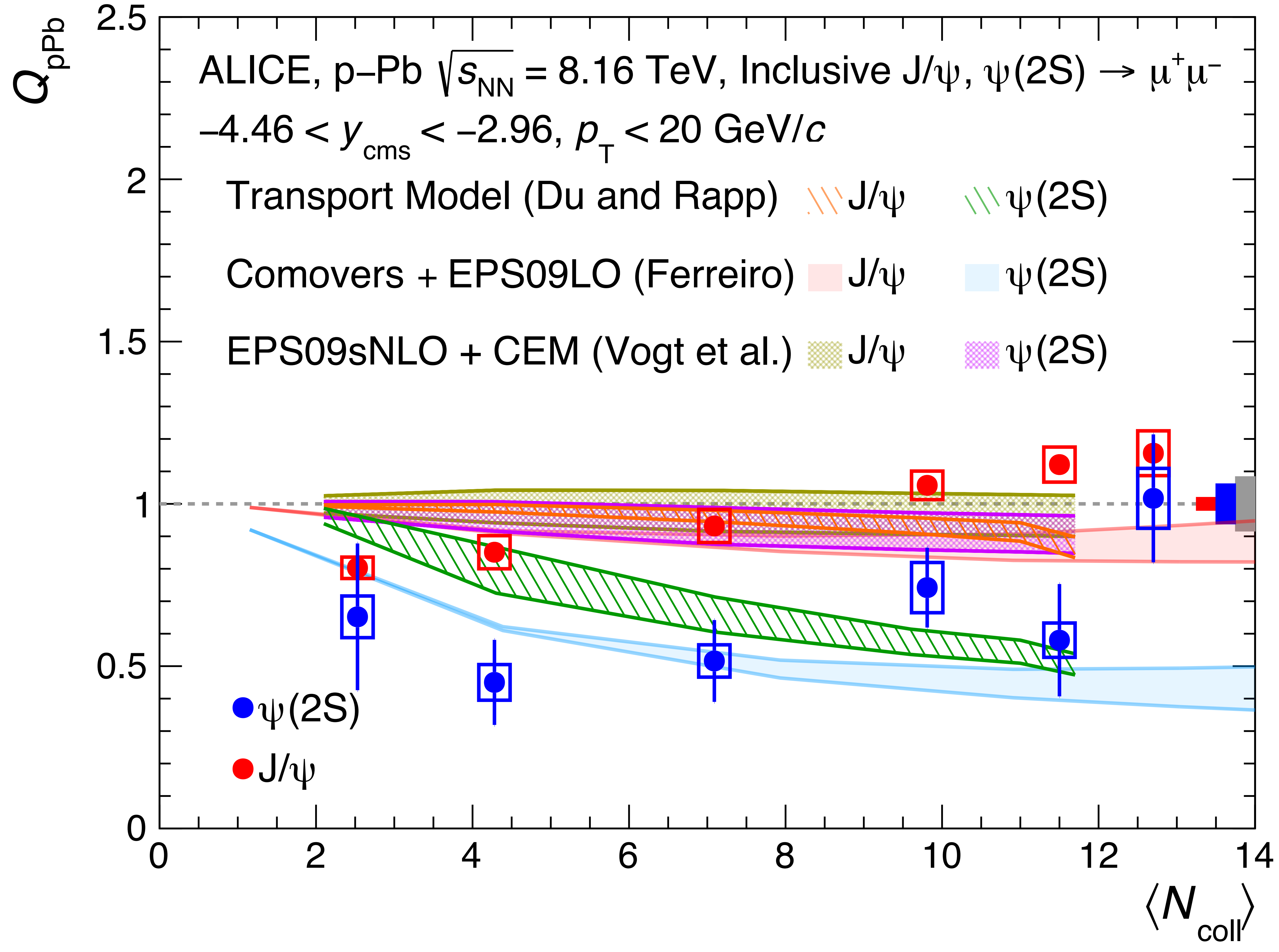
Back-up

Charmonia in pPb

[JHEP 07 (2020) 237]



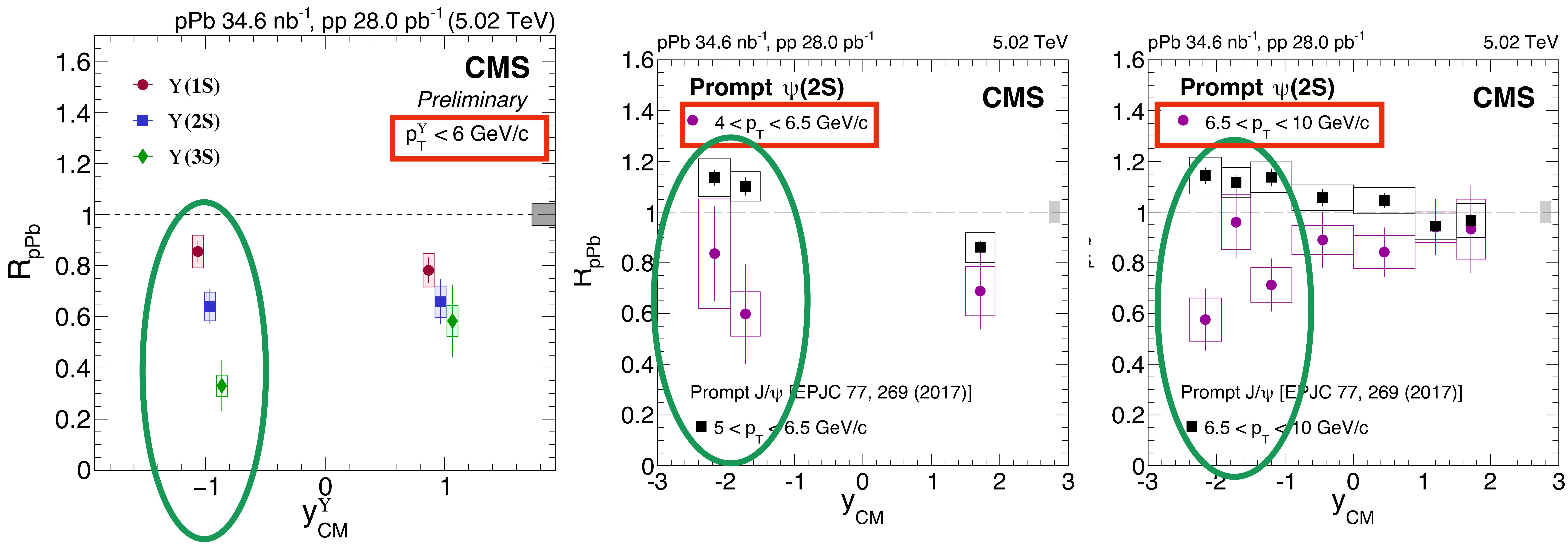
[JHEP 02 (2021)002]



- Agreement with nPDF modification for J/ψ
- Additional suppression for $\psi(2S)$: hint for comover breakup

Quarkonium production in pPb

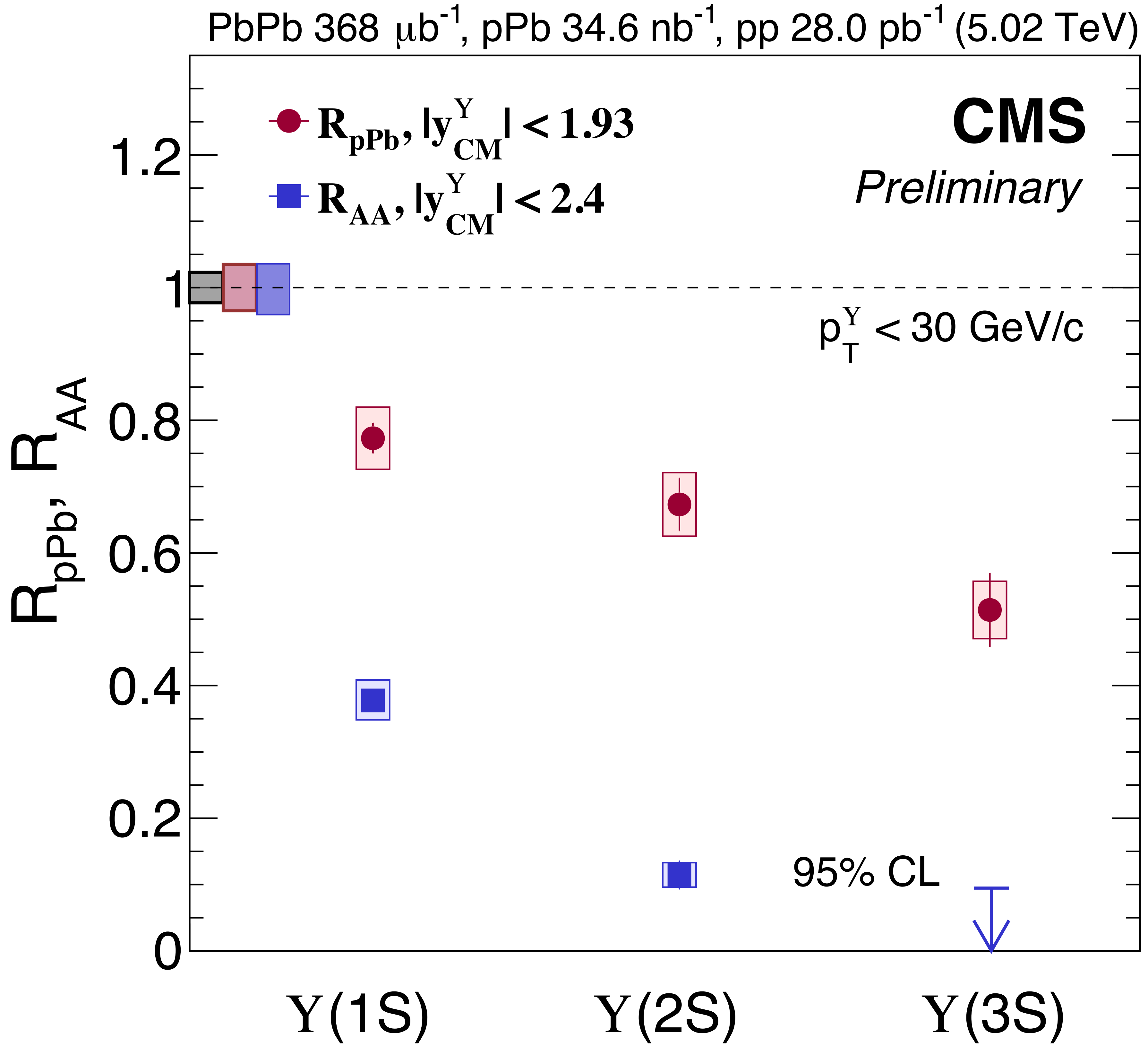
[PLB 835 (2022) 137397]
[PLB 790 (2019) 509]



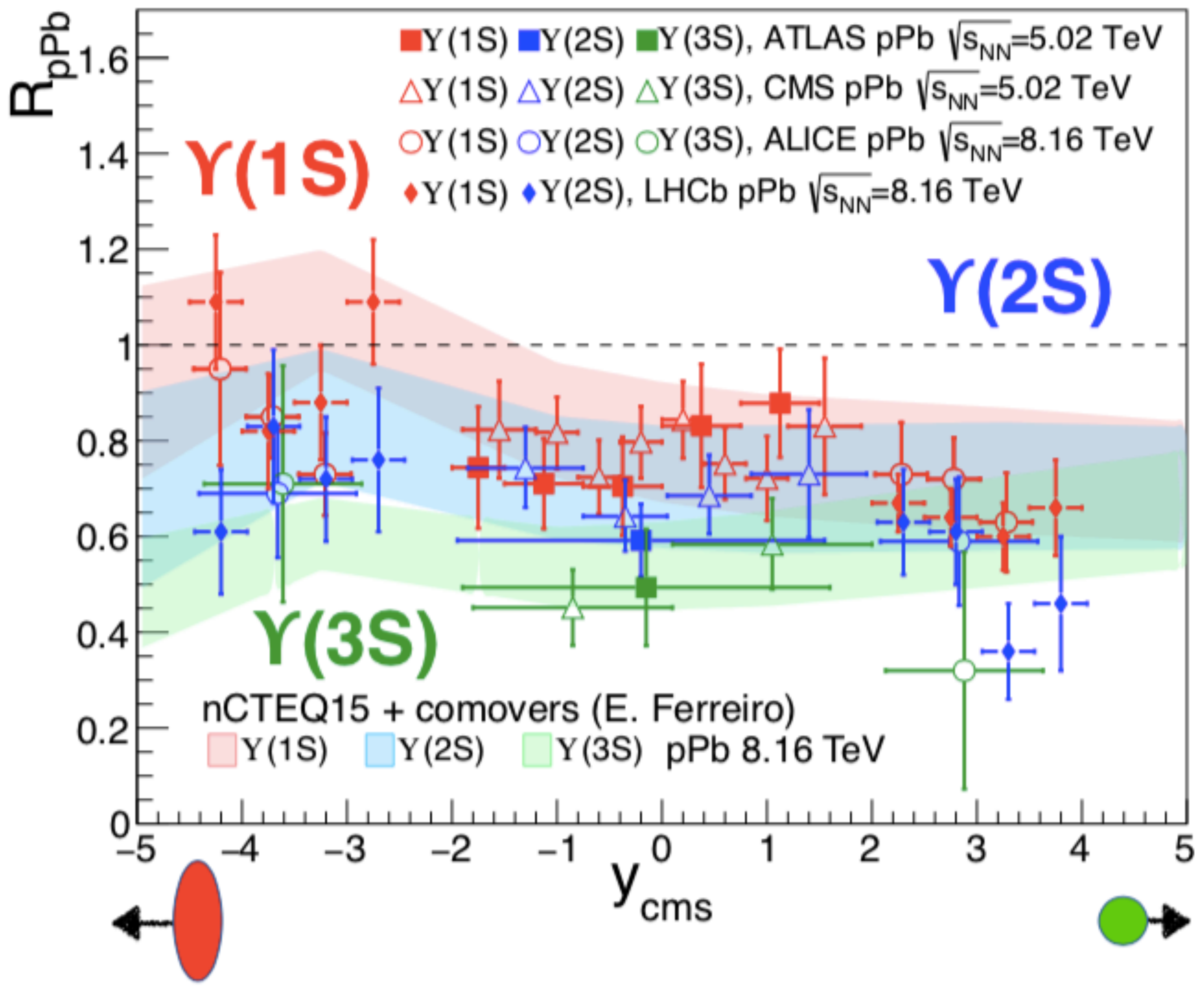
Similar trend observed for bottomonia and charmonia

Υ pPb at LHC

[PLB 835 (2022) 137397]



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

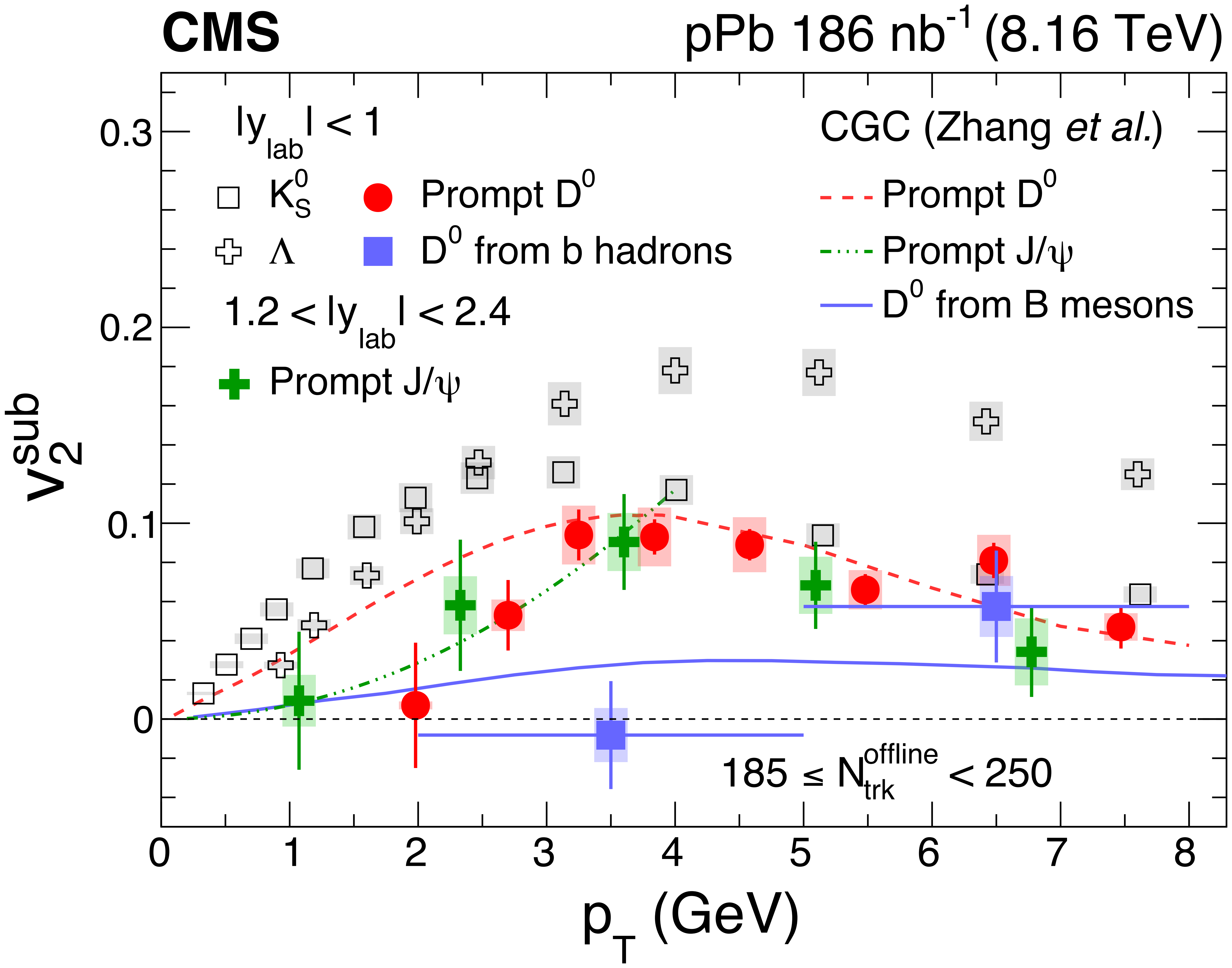


1. Sequential suppression : R_{pPb}(Υ(1S)) > R_{pPb}(Υ(2S)) > R_{pPb}(Υ(3S))

2. Possible description with comover interaction model

Flow in pPb

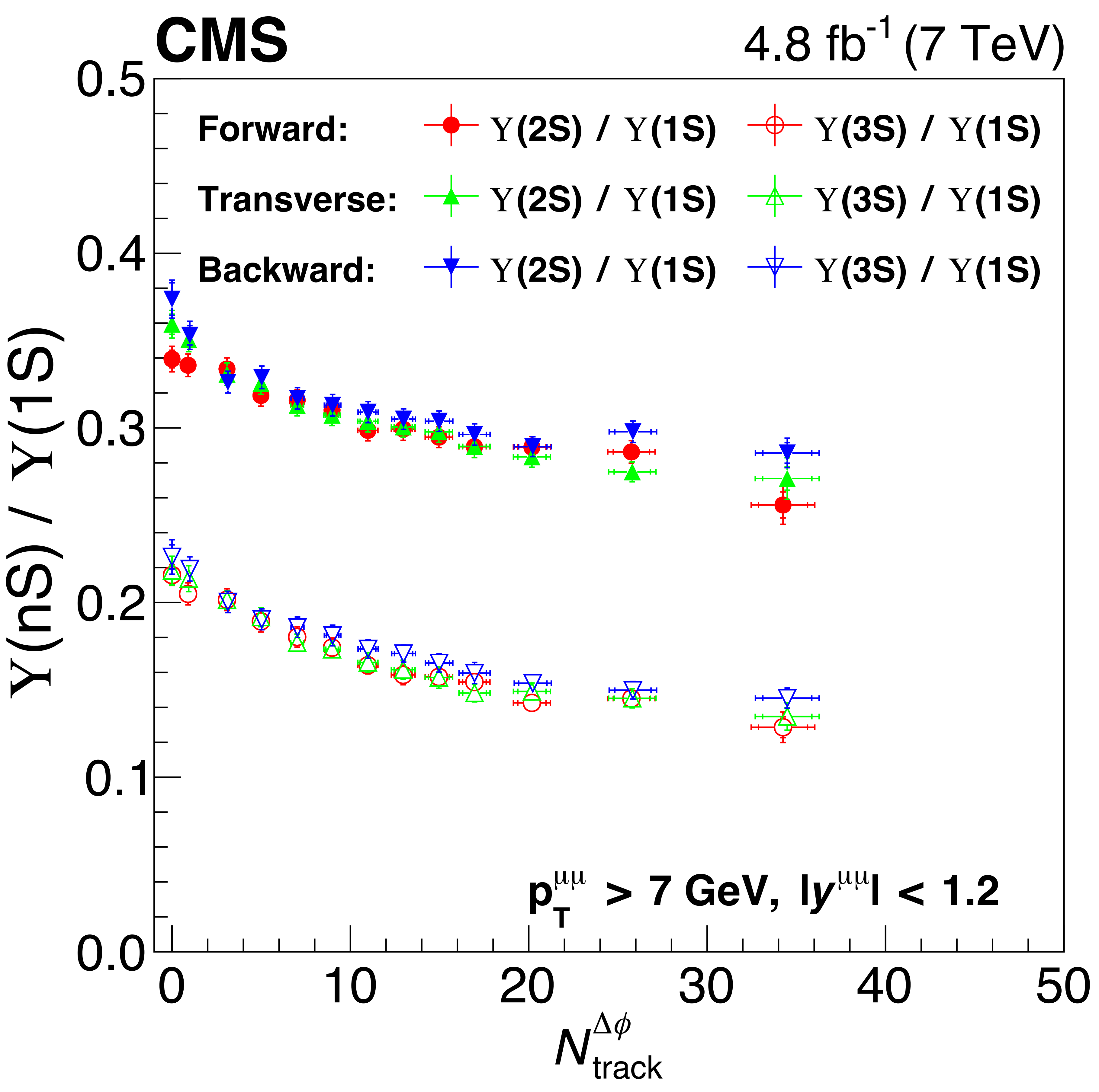
[PLB 813 (2020) 136036]

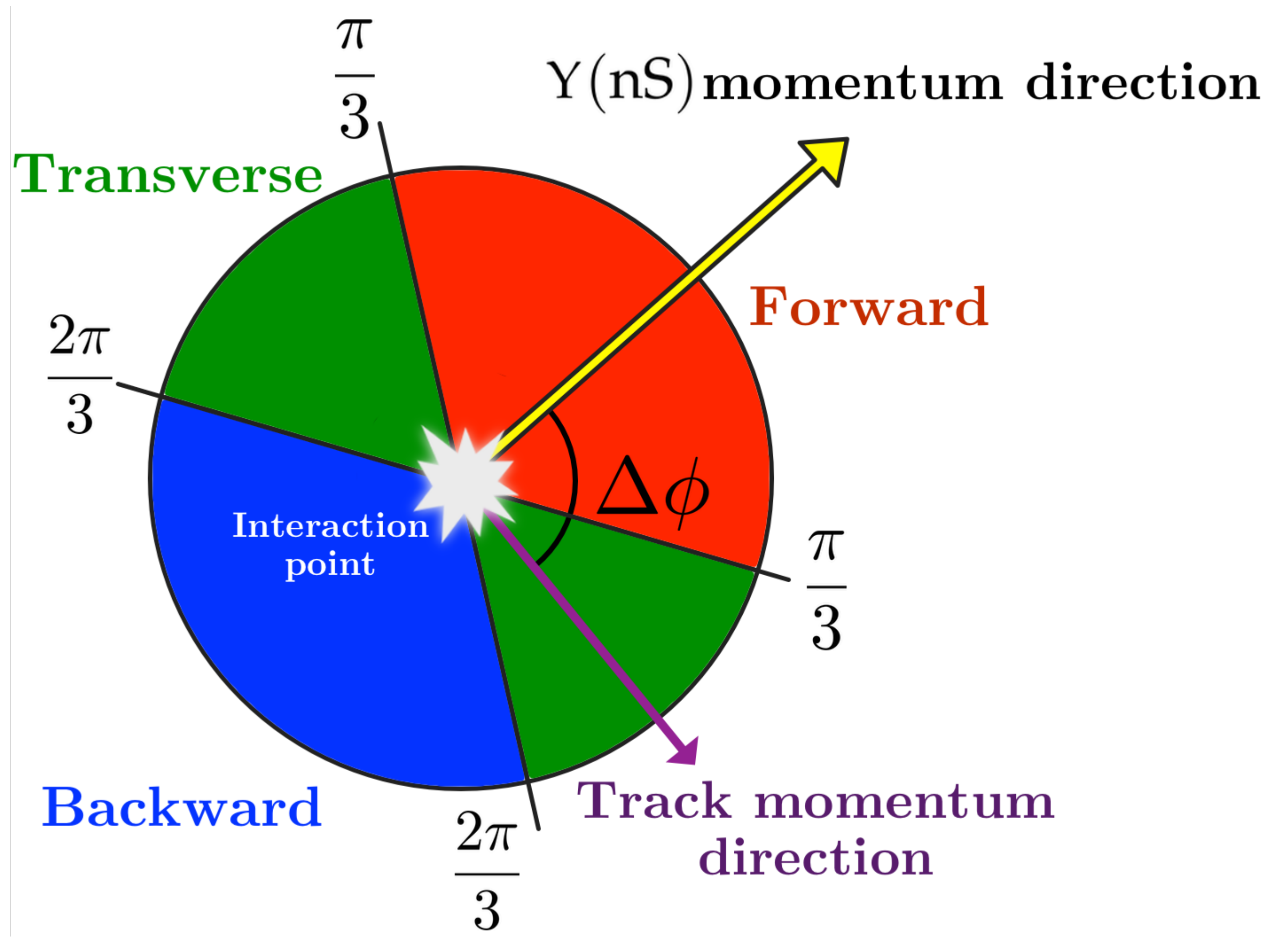


- Still not clear the feature of finite J/ψ v_2
- Compatible with prompt D^0

Υ in pp w UE study

[JHEP 11 (2020) 001]

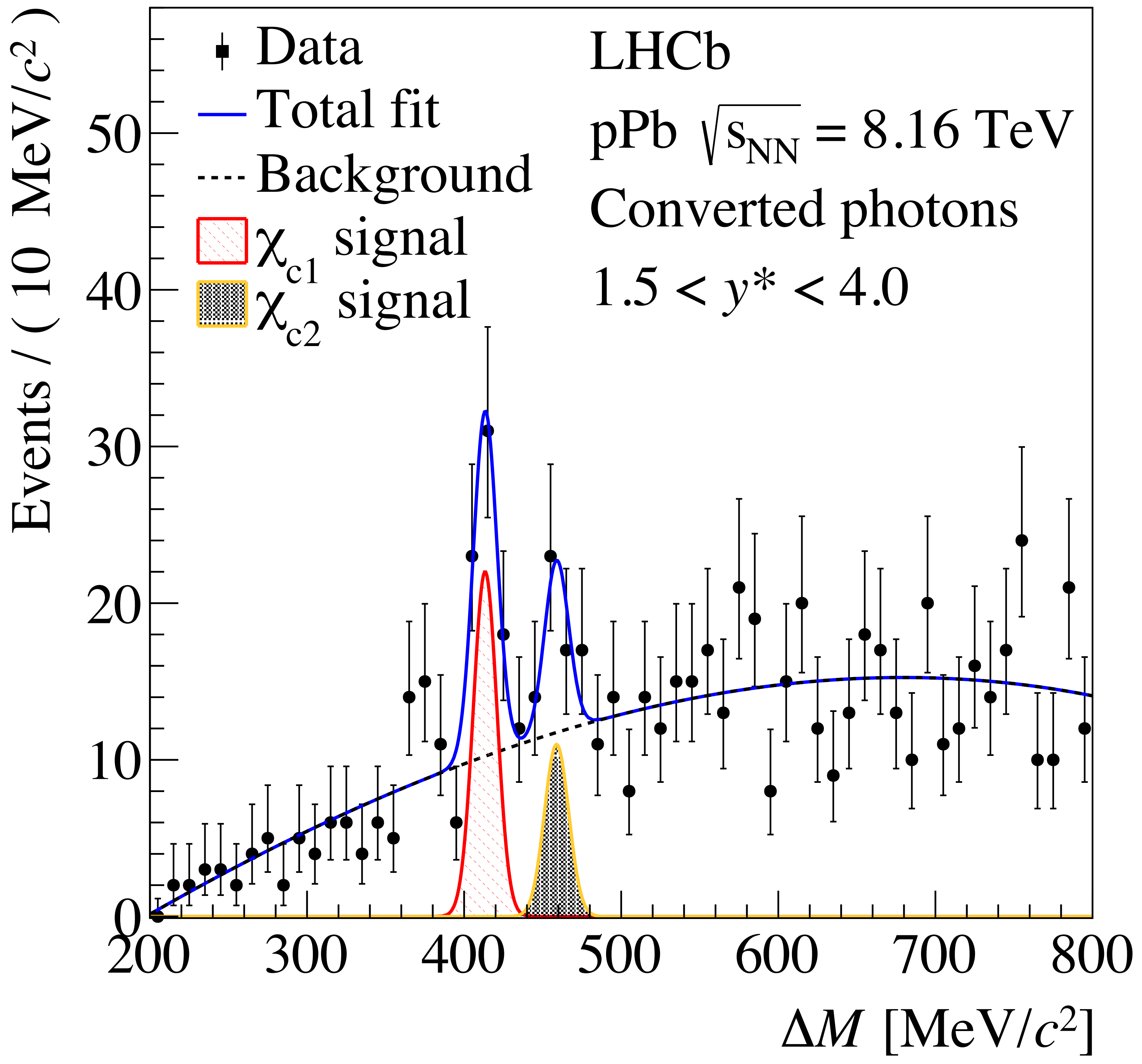


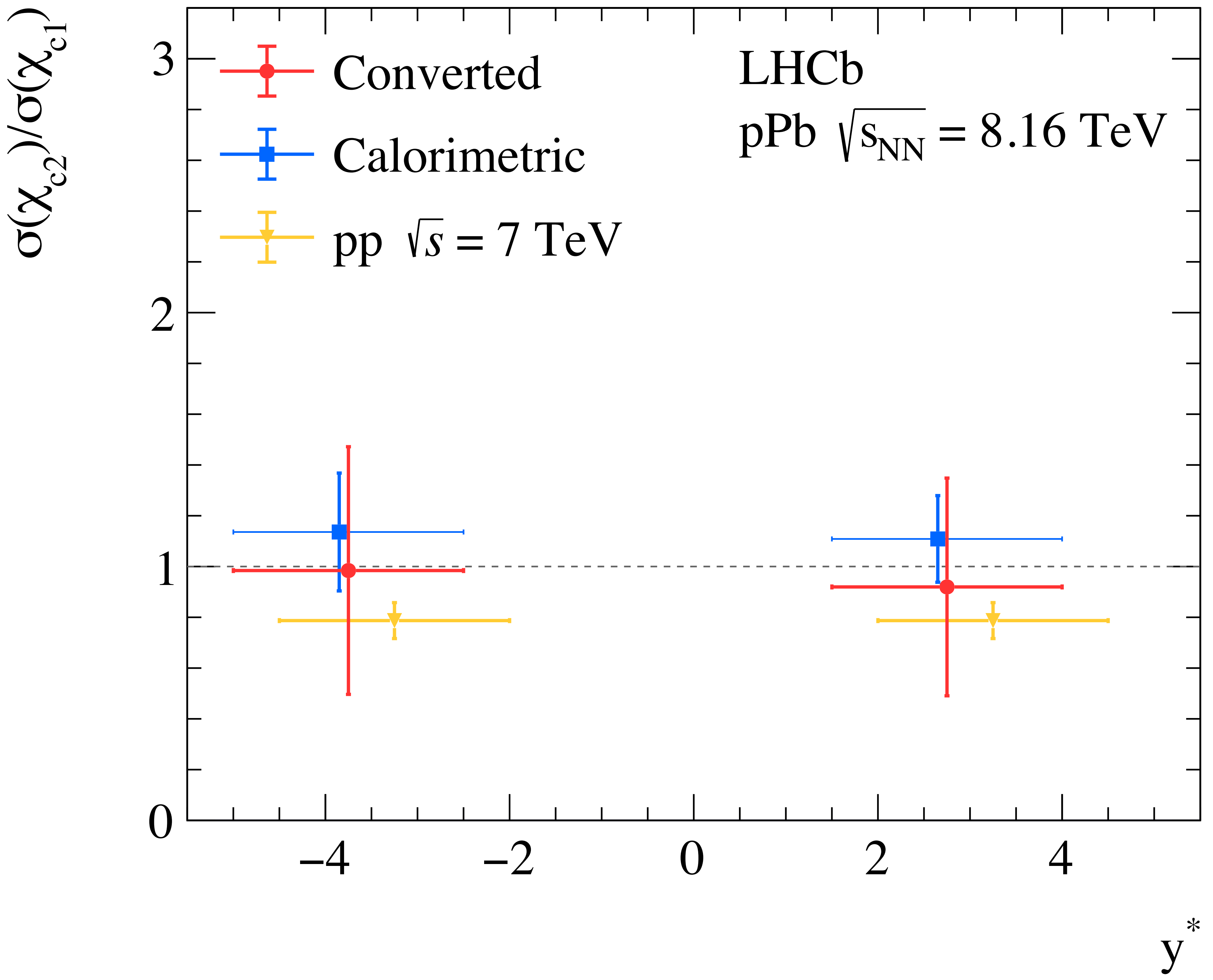


- If Υ-particle correlation only
  - —> Only affect forward region
- Decreasing trend for all regions : Linked with UE!
  - No clear ordering
  - Note : Υ p_T > 7 GeV/c)

P-wave state in pPb

[PRC 103 (2021) 064905]

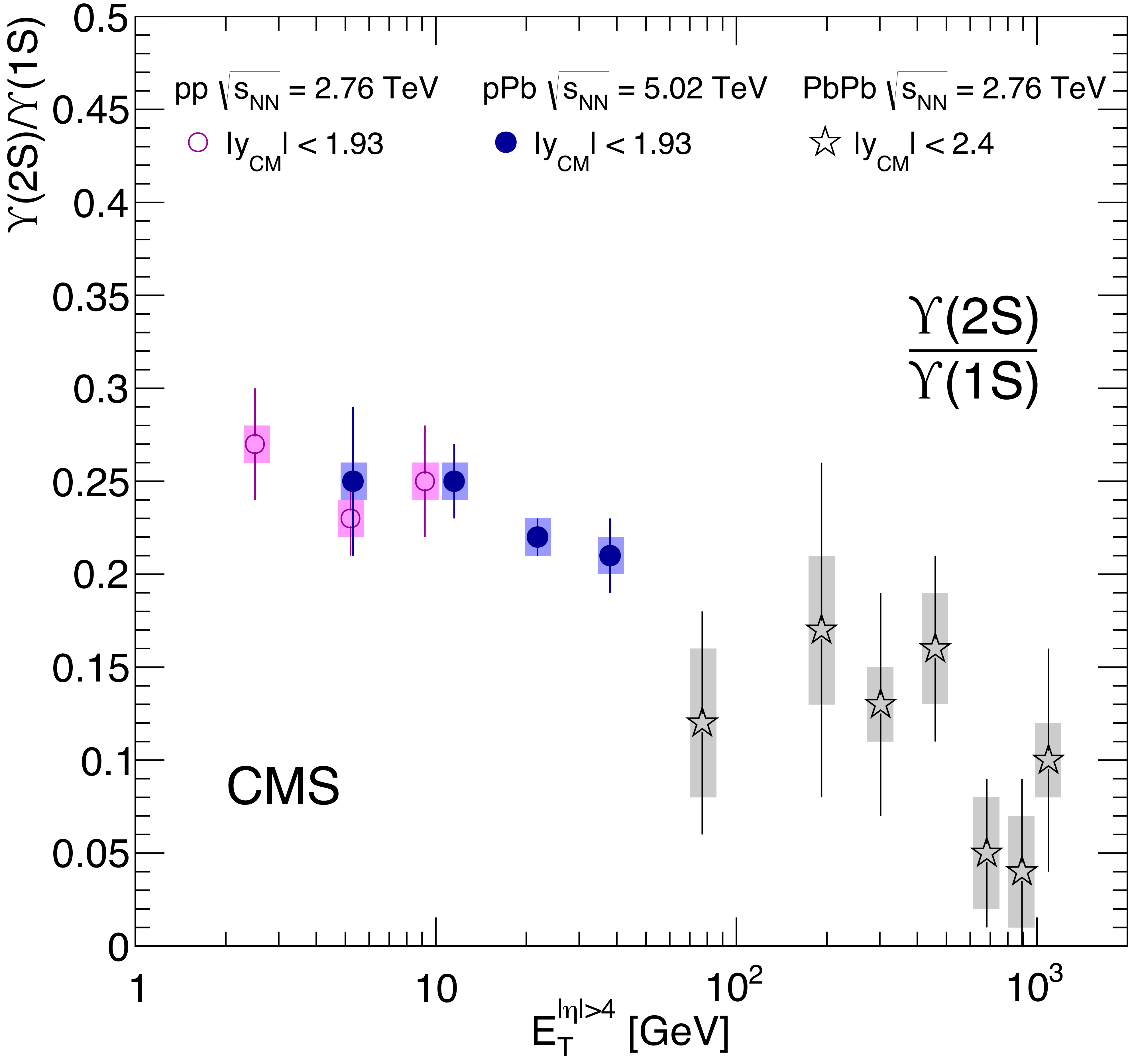


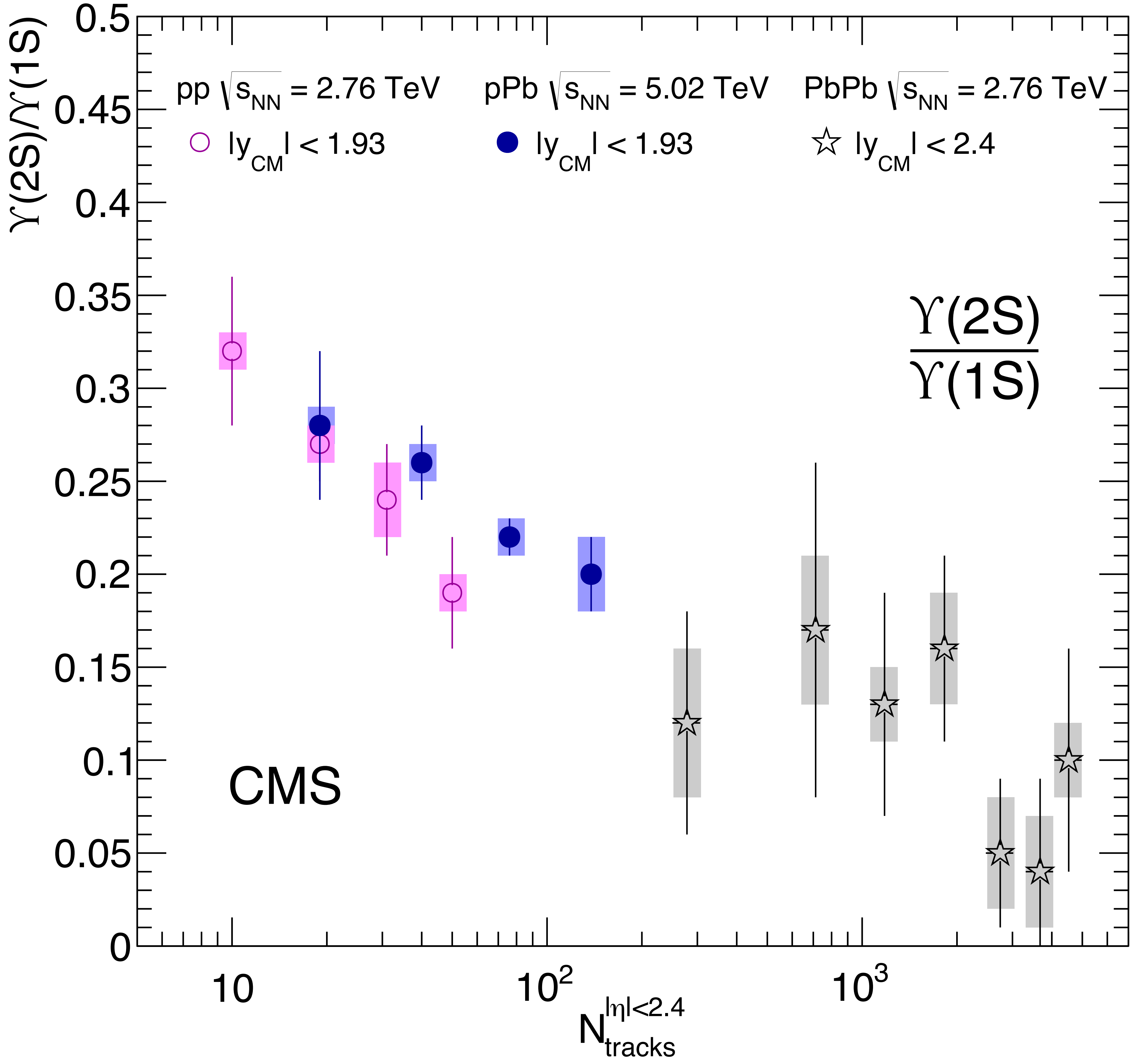


- First measurement of χ_c states in pPb
- Agreement with pp measurements

Υ(nS)/Υ(1S) vs E_T & N_{trk}

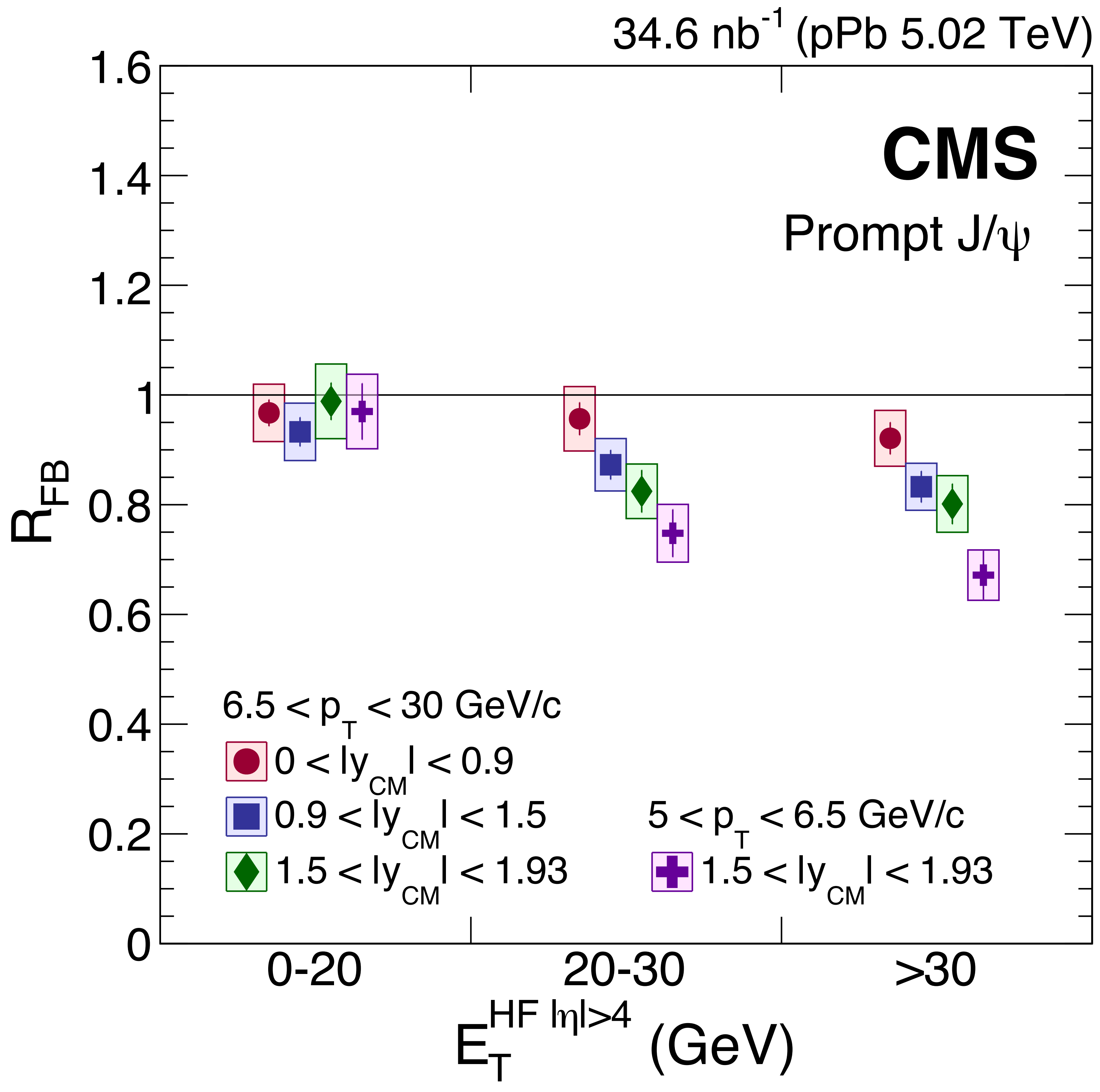
[JHEP 04 (2014) 103]

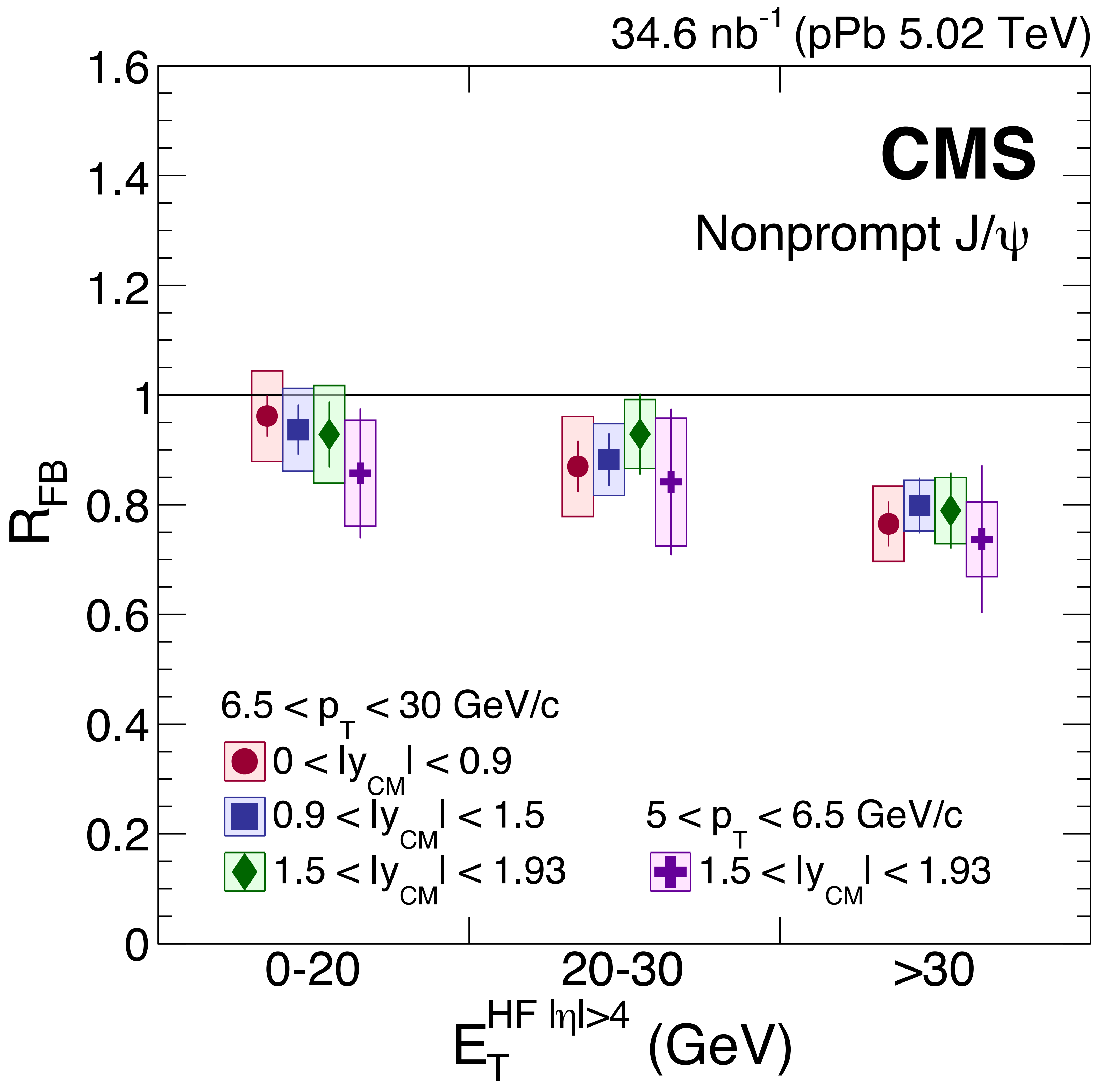




Prompt vs nonprompt J/ψ in pA

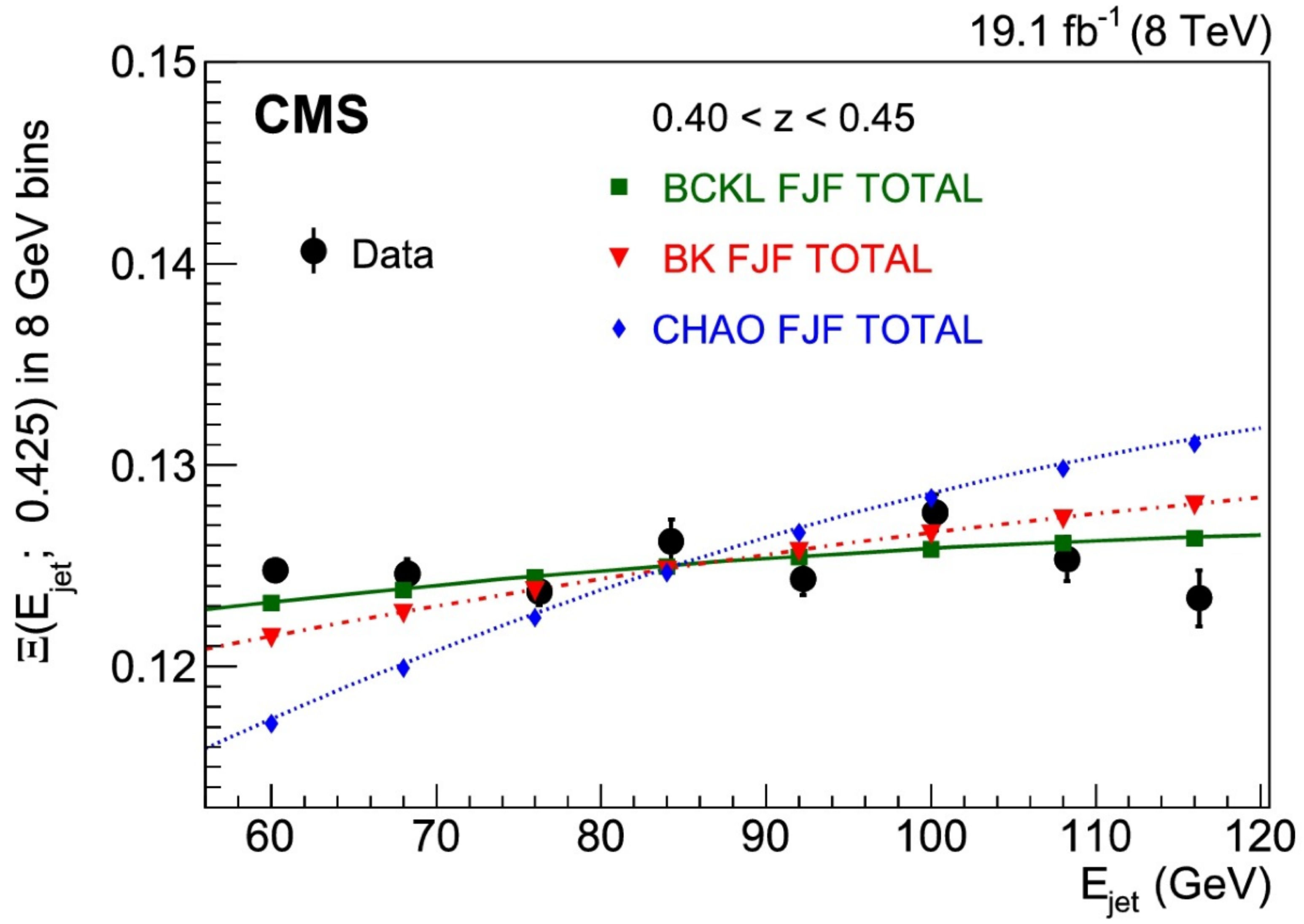
[EPJC 77 (2017) 269]

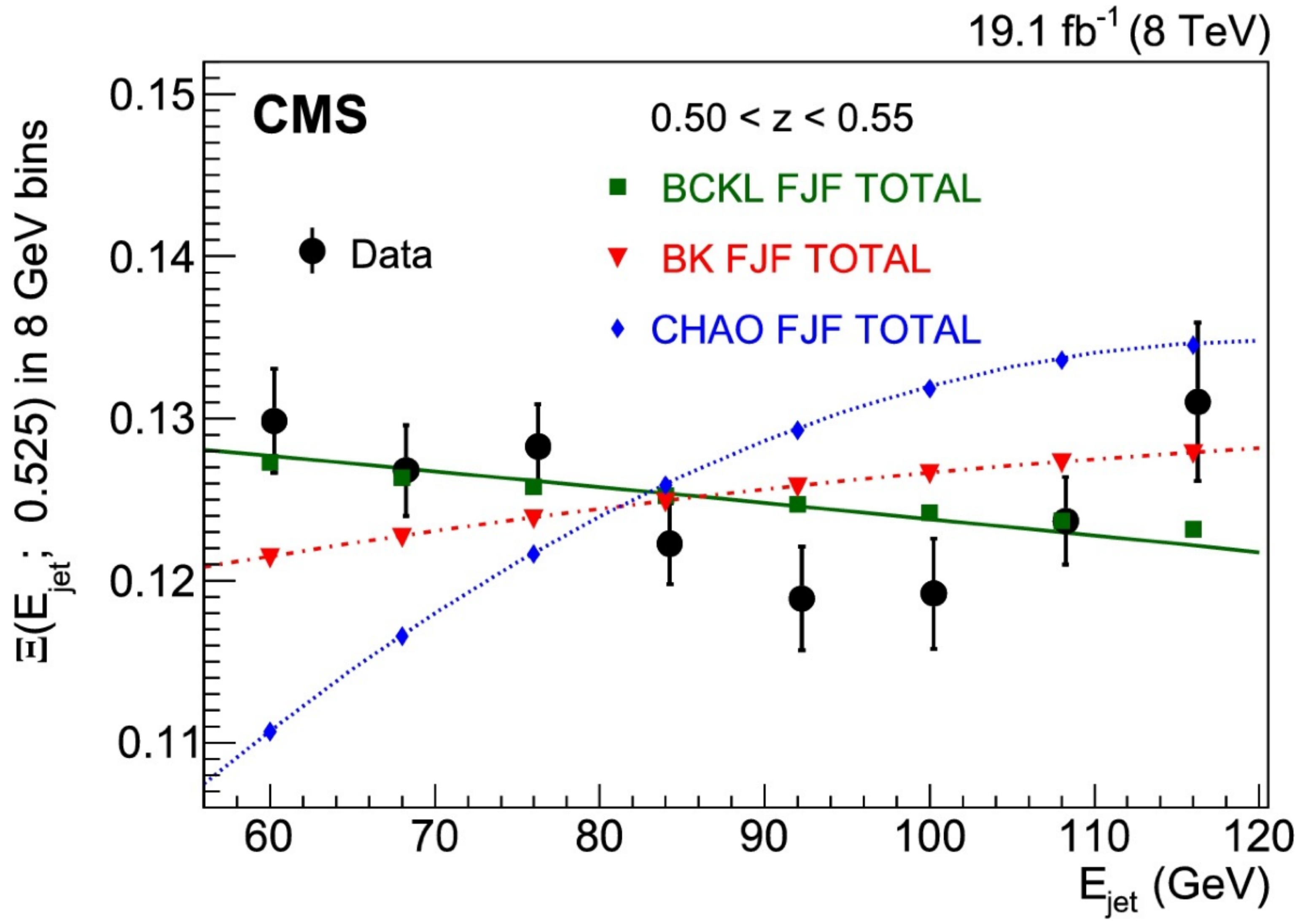




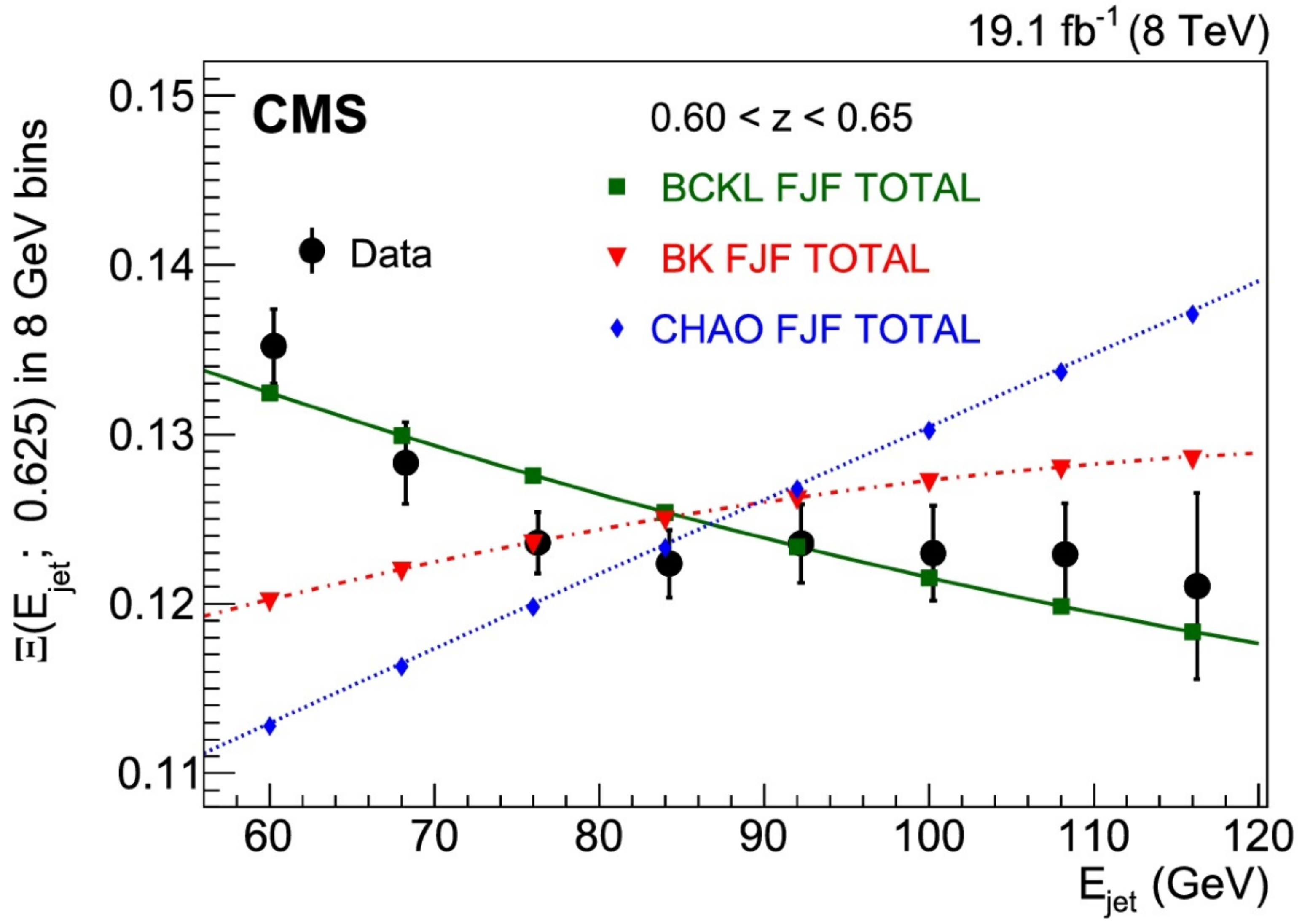
J/ψ in jets FJF LDME set test

[PLB 804 (2020) 135409]



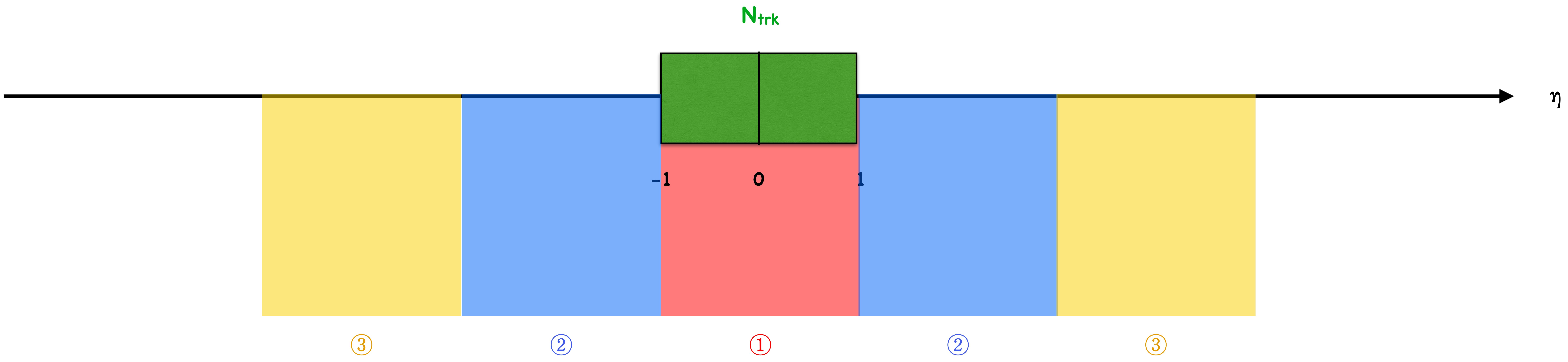


$$\Xi(E_c; z_1) \equiv \frac{N(E_c; z_1)}{\int_{0.3}^{0.8} N(E_c; z)\, dz}$$



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

Rapidity gap measurement



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

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