New results on quarkonium at 5.02 TeV with CMS

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on behalf of the CMS Collaboration

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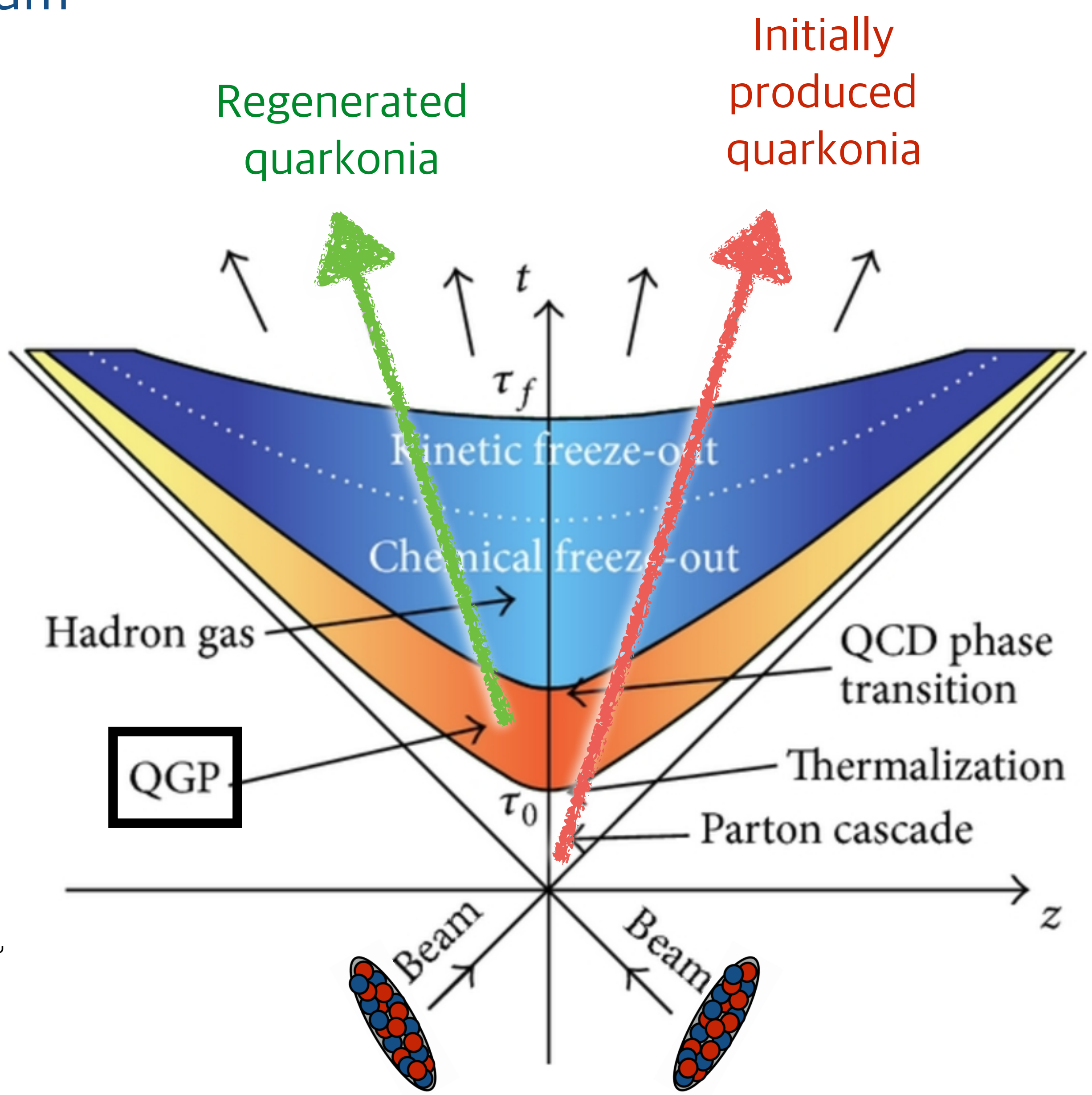
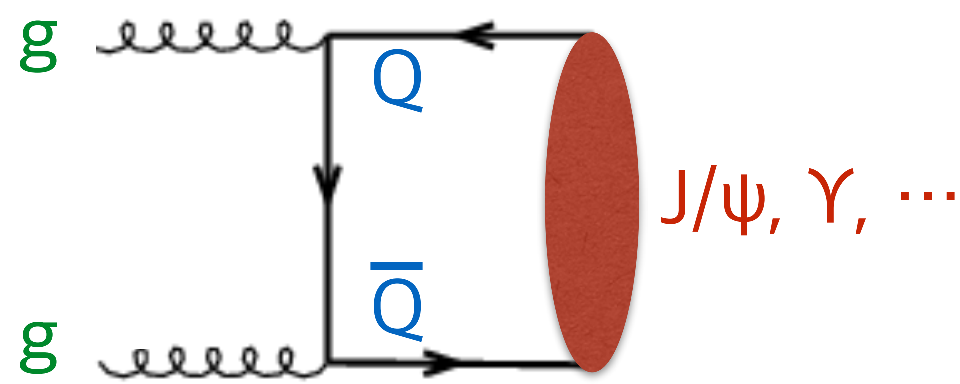
Why quarkonia?

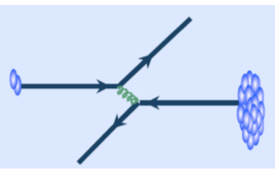
- Quarkonia: bound states of a heavy quark and its antiquark
- Important probes of initial and final state nuclear effects
  - Mainly produced at the early stage ($m_c >> \Lambda_{QCD}$),
    → experience the whole evolution of medium
  - by gluon-gluon hard scattering processes
    → sensitive to gluon PDFs

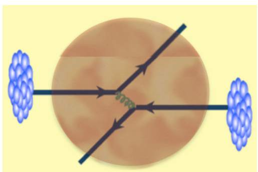


$$\tau^{Q\bar{Q}}_{\text{formation}} \lesssim \tau^{\text{QGP}}_{\text{formation}} < \tau^{\text{QGP}}_{\text{life}} < \tau^{\text{quarkonia}}_{\text{life}}$$

Nuclear effects on quarkonia



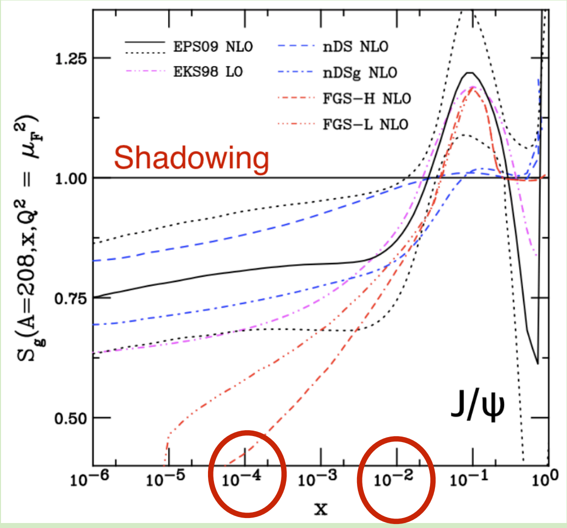




CNM effects in **pPb**

<Initial state>

- Nuclear PDFs
- Gluon saturation
- Parton E loss

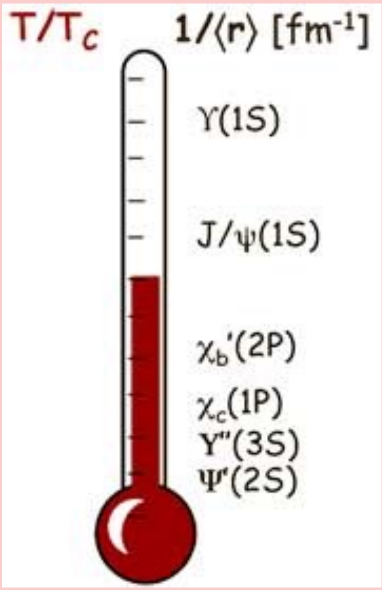


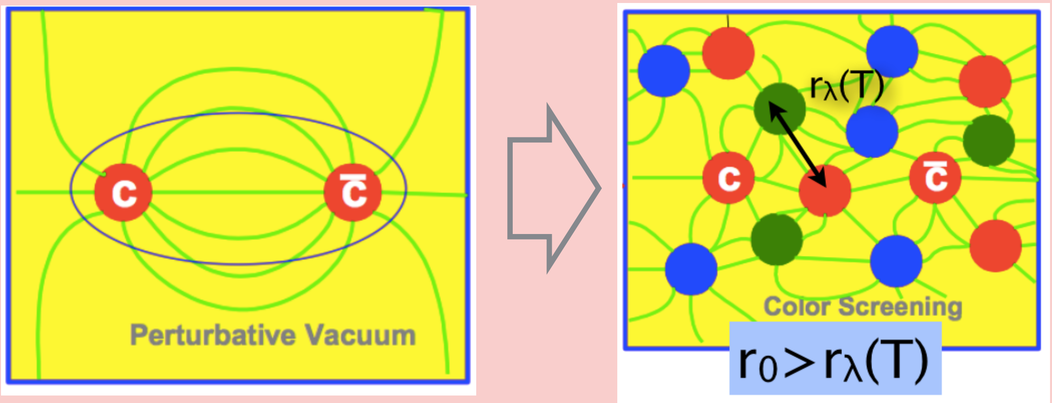
<Final state>

- Nuclear absorption
- Comover breakup
- Final state E loss

QGP effects in **PbPb**

- Debye screening
  → Sequential melting
- Regeneration





EPJC 61 (2009) 705

Quarkonia results at 5.02 TeV

	Charmonia	Bottomonia
pPb	J/ψ R_{pPb} **Today** EPJC 77 (2017) 269 Published last month! $\psi(2S)$ R_{pPb} **Today** CMS-PAS-HIN-16-015	$\Upsilon(nS)$ / $\Upsilon(1S)$ DR JHEP 04 (2014) 103
PbPb	$\psi(2S)$ / J/ψ DR **Today** PRL 118 (2017) 162301 Published last month!	$\Upsilon(nS)$ / $\Upsilon(1S)$ DR CMS-PAS-HIN-16-008 $\Upsilon(nS)$ R_{AA} **Today** CMS-PAS-HIN-16-023

- Nuclear modification factor

$$R_{heavy\text{-}ion} = \frac{\text{In heavy-ion}}{\text{In pp}}$$

- Double ratio

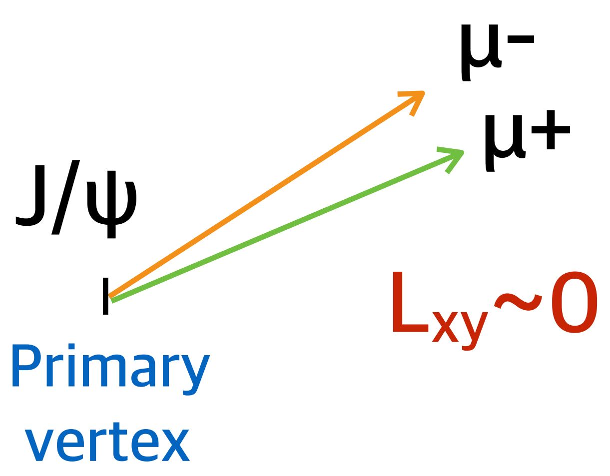
$$DR = \frac{\text{nS/1S in heavy-ion}}{\text{nS/1S in pp}}$$

Charmonia

Prompt vs. Nonprompt

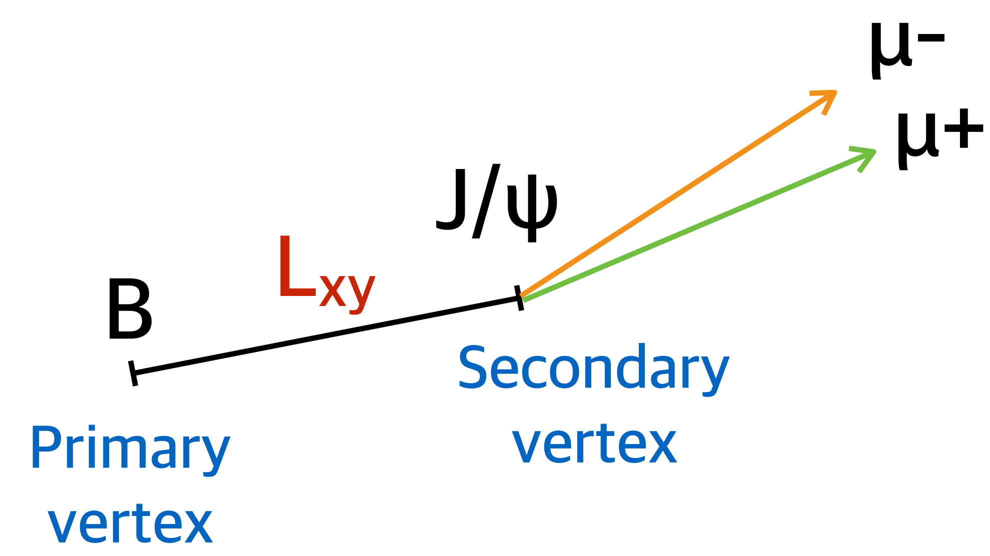
prompt J/ψ

- Directly produced J/ψ
- Feed down from ψ(2S) and X_c



nonprompt J/ψ

- From the decay of B hadrons
  (Lifetime of B ~ O(500) μm/c)



- Pseudo-proper decay length

$$l_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_{\mathrm{T}}(\mu^+\mu^-)}$$

PDG value

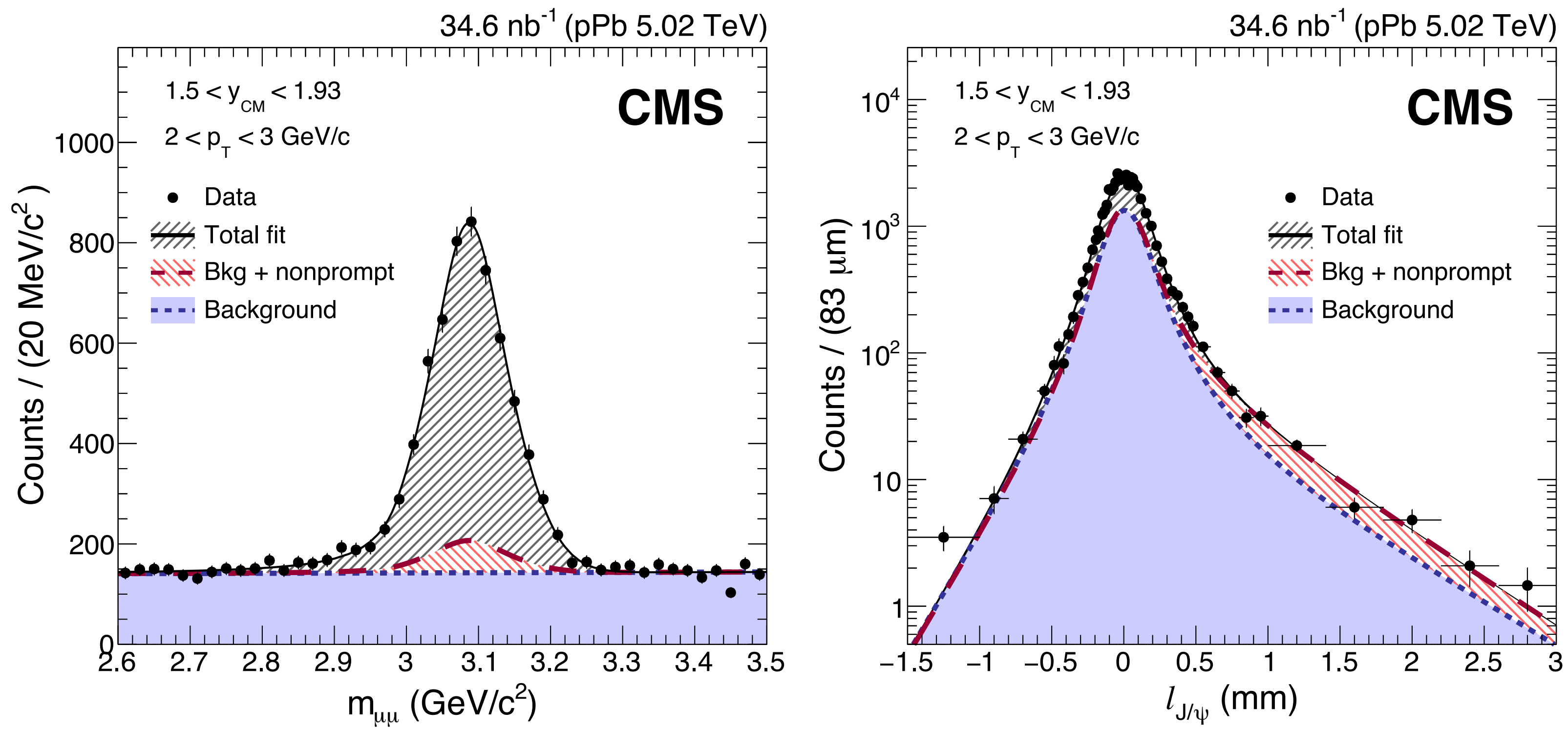
transverse distance between
PV and SV in laboratory frame

- IP resolution of CMS
  - transverse ~ 25-90 μm
  - longitudinal ~ 45-150 μm

Prompt charmonia selection

- J/ψ analysis: separation using 2D fits to $m_{\mu\mu}$ and $\ell_{J/\psi}$

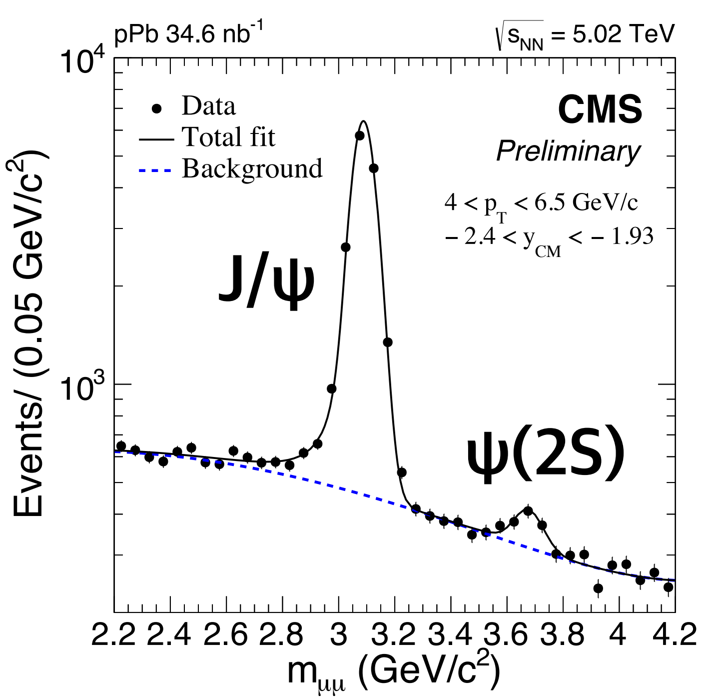
EPJC 77 (2017) 269

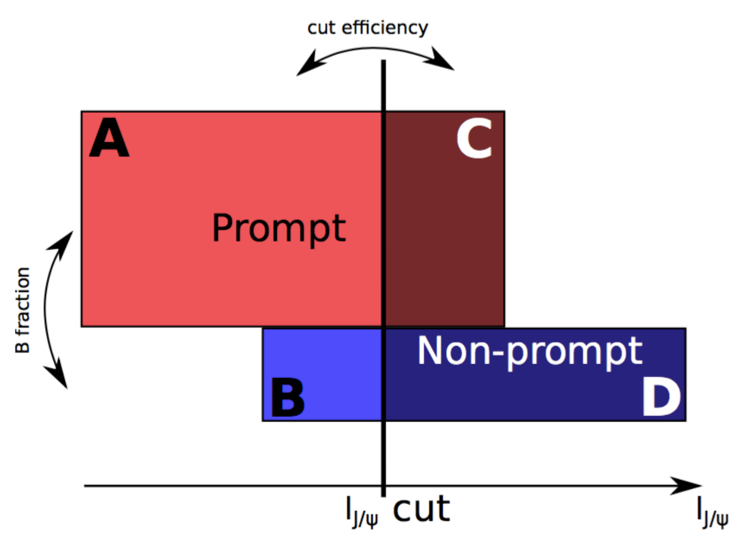


- ψ(2S) analysis: nonprompt rejection by a cut on $\ell_{J/\psi}$

CMS-PAS-HIN-16-015

PRL 118 (2017) 162301



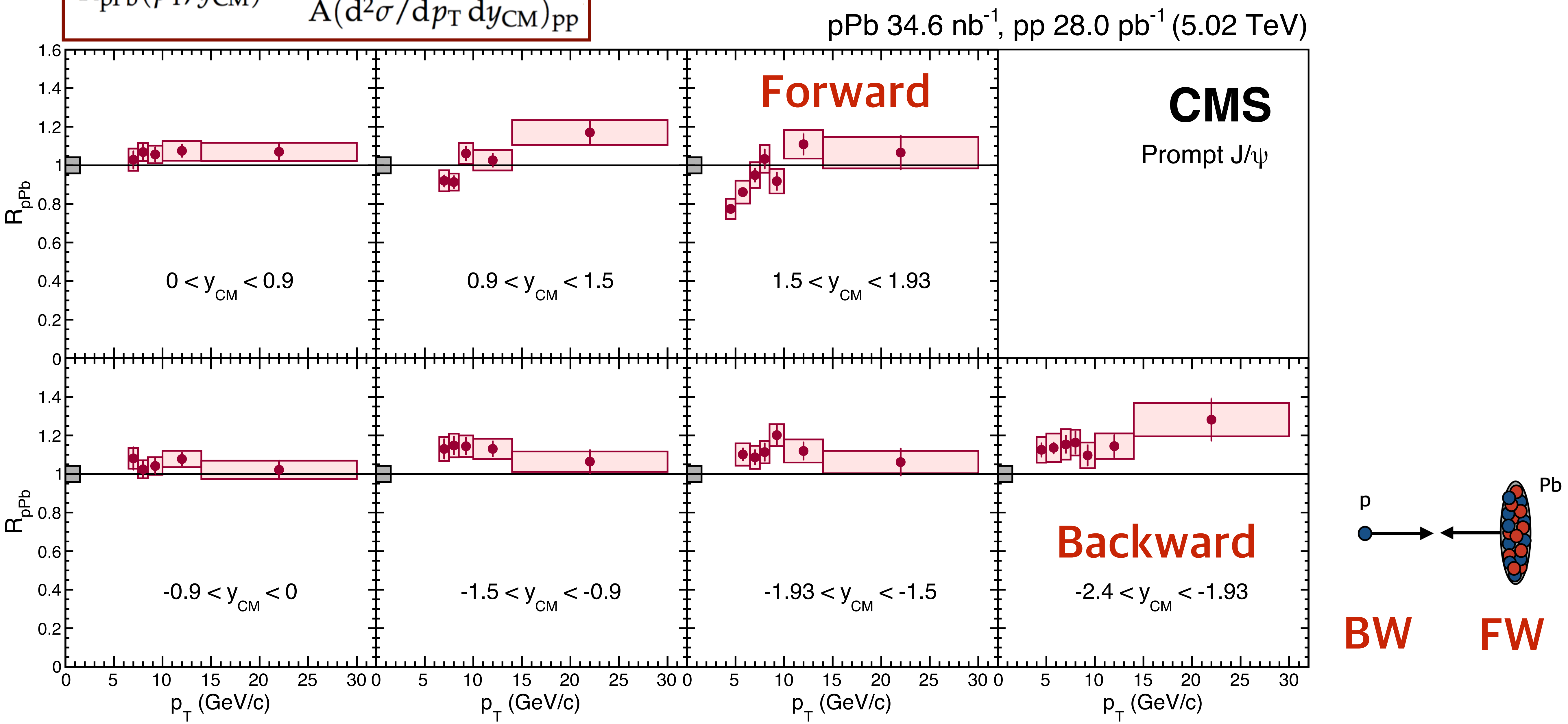


- 2D fit is not applicable due to the low statistics
- MC-based $\ell_{J/\psi}$ cut study
  - Keep ~90 % of prompt
  - Remove ~80 % of nonprompt

Prompt J/ψ R_{pPb} vs. p_T

$$R_{pPb}(p_T, y_{CM}) = \frac{(d^2\sigma/dp_T\,dy_{CM})_{pPb}}{A(d^2\sigma/dp_T\,dy_{CM})_{pp}}$$

EPJC 77 (2017) 269



- $R_{pPb} \gtrsim 1$ in mid- and backward y_{CM}
- Suppression at forward and low p_T is suggested → smaller x regions

Prompt J/ψ R_{pPb}: theory vs. experiement

$$R_{pPb}(p_T, y_{CM}) = \frac{(d^2\sigma/dp_T\,dy_{CM})_{pPb}}{A(d^2\sigma/dp_T\,dy_{CM})_{pp}}$$

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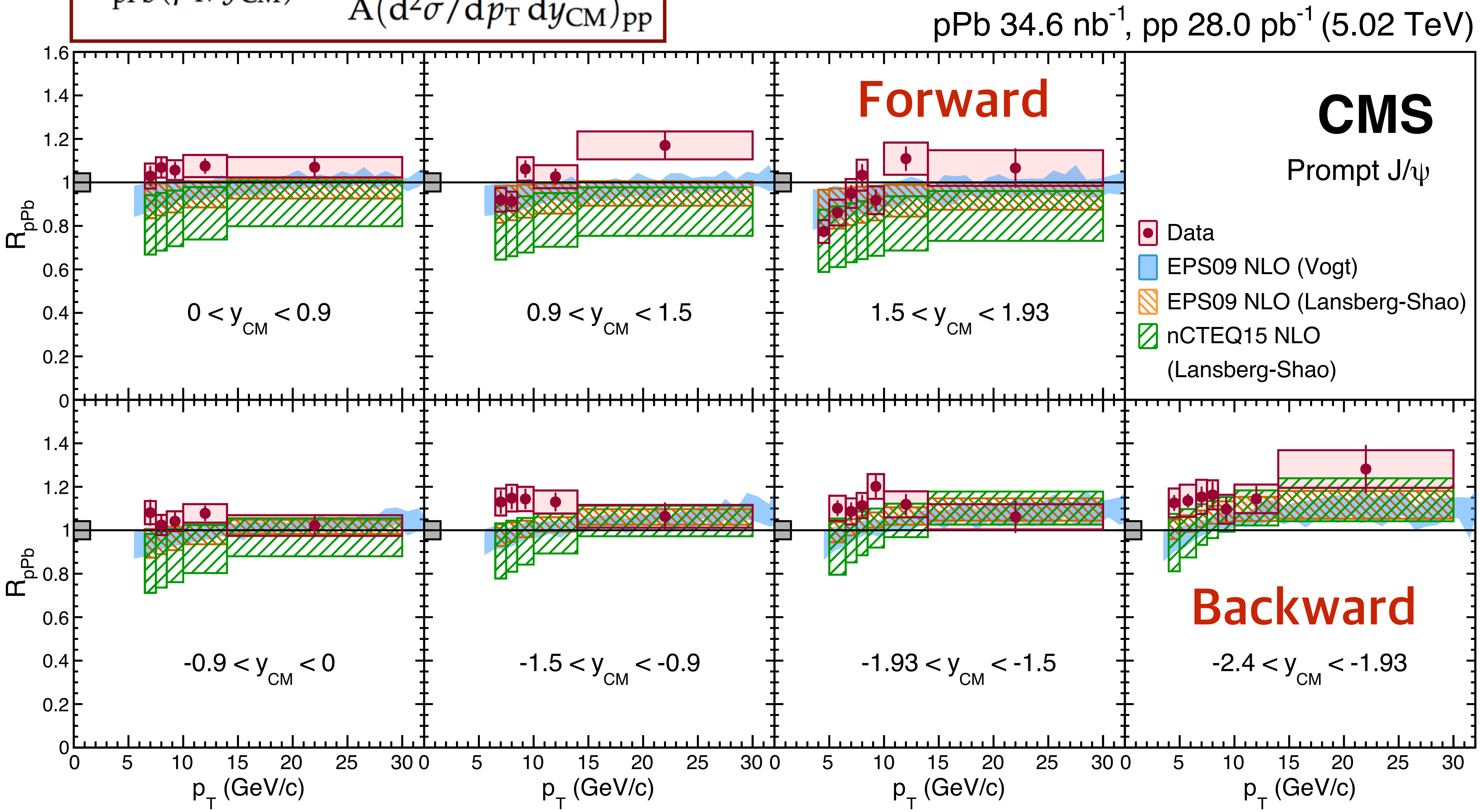
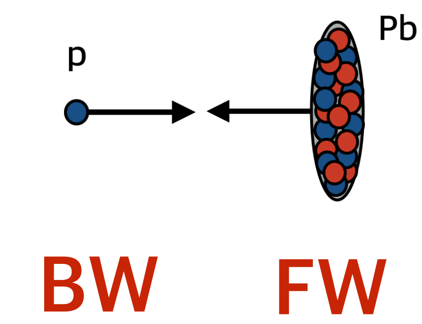
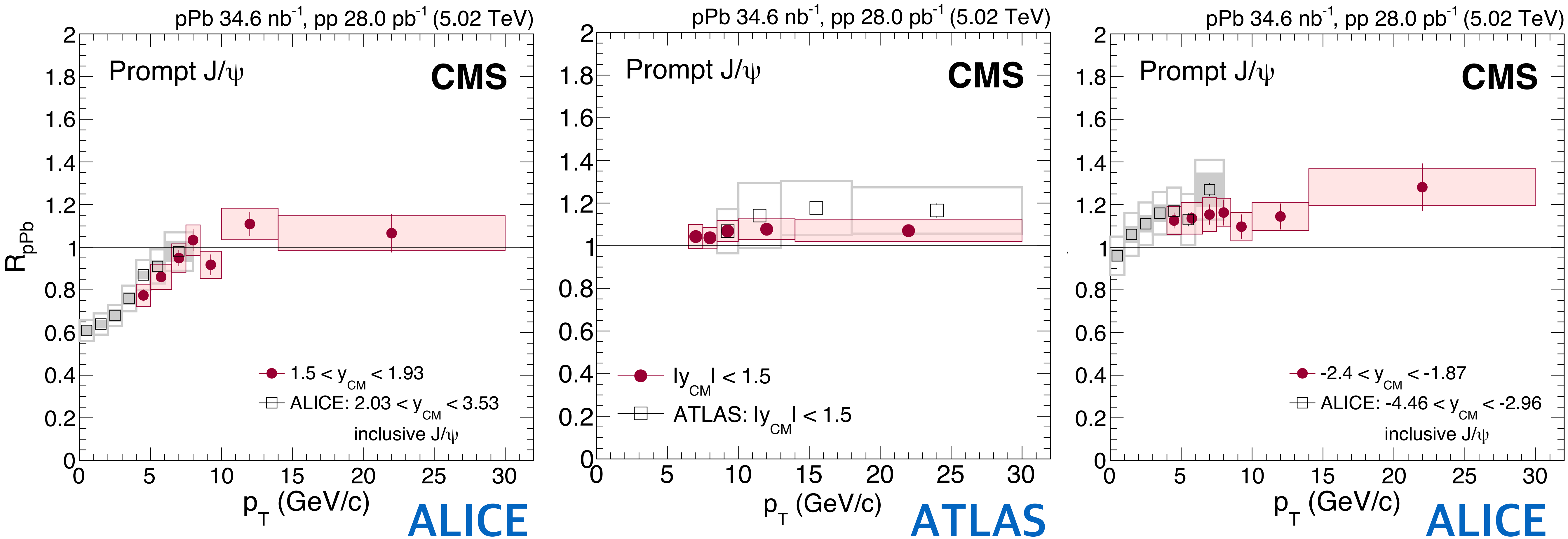




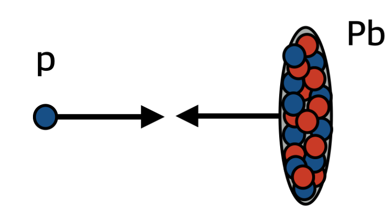
- $R_{pPb} \gtrsim 1$ in mid- and backward y_{CM}
- Suppression at forward and low p_T is suggested → smaller x regions
- nPDF models marginally lower but describes data

Prompt J/ψ R_{pPb}: exp vs. exp

Forward | **Mid-y_{CM}** | **Backward**



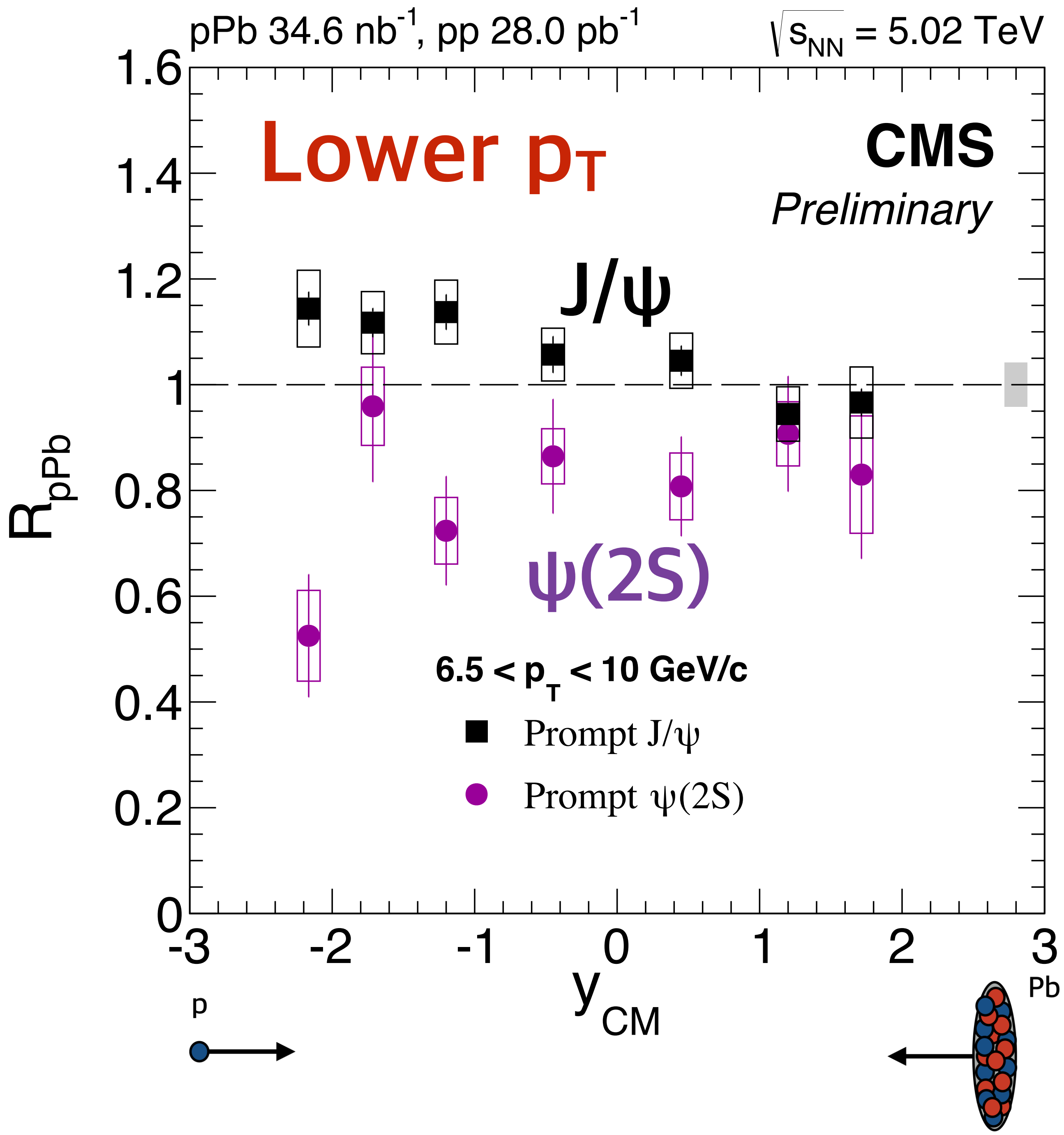
- CMS results extends previous LHC measurements
  - Forward y_{CM} and lower p_T: $R_{pPb} < 1$
  - Mid-y_{CM}: $R_{pPb} \sim 1$
  - Backward y_{CM} and higher p_T: $R_{pPb} > 1$

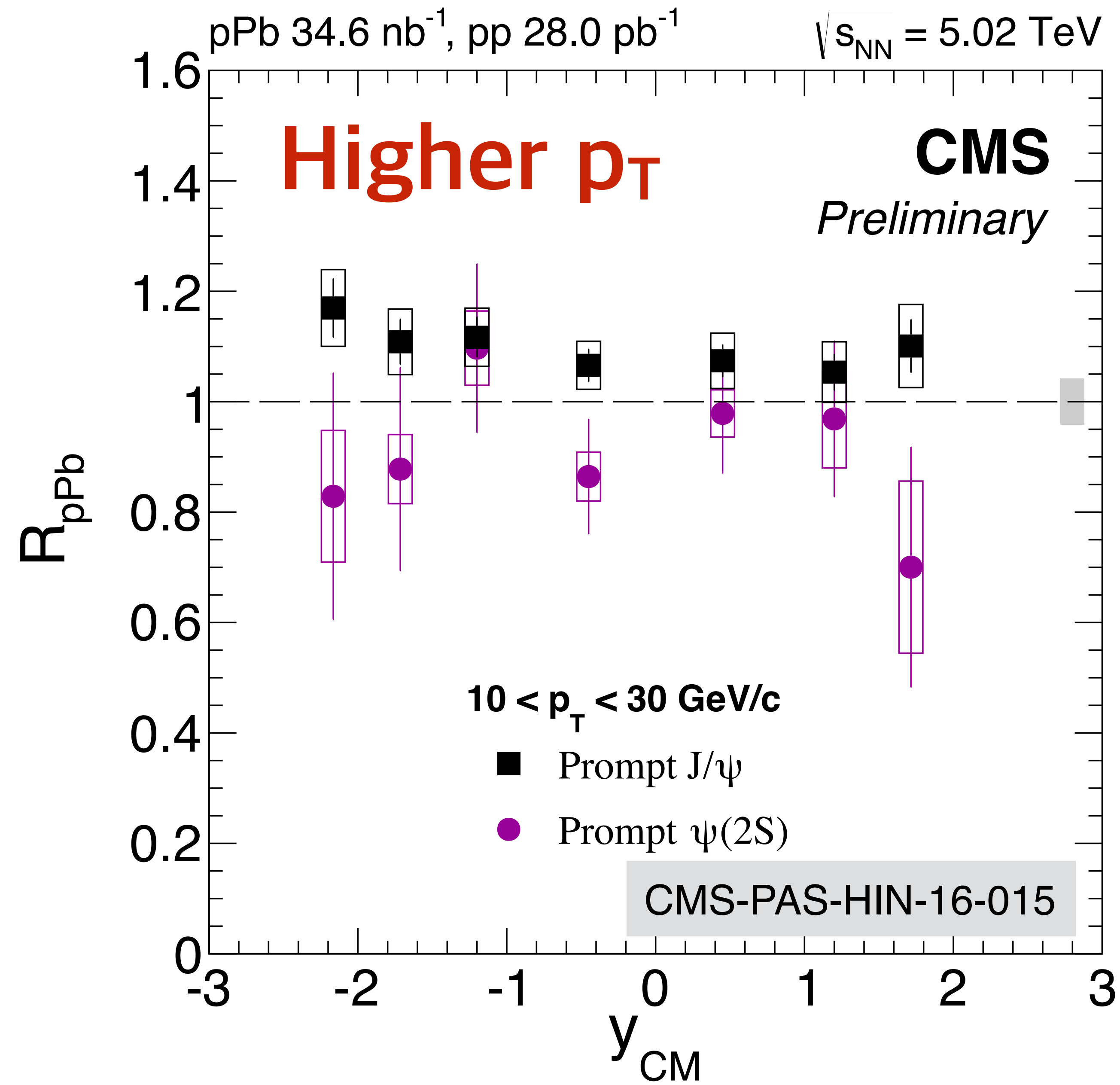


BW **FW**

EPJC 77 (2017) 269

Prompt ψ(2S) R_{pPb} vs. y_{CM}



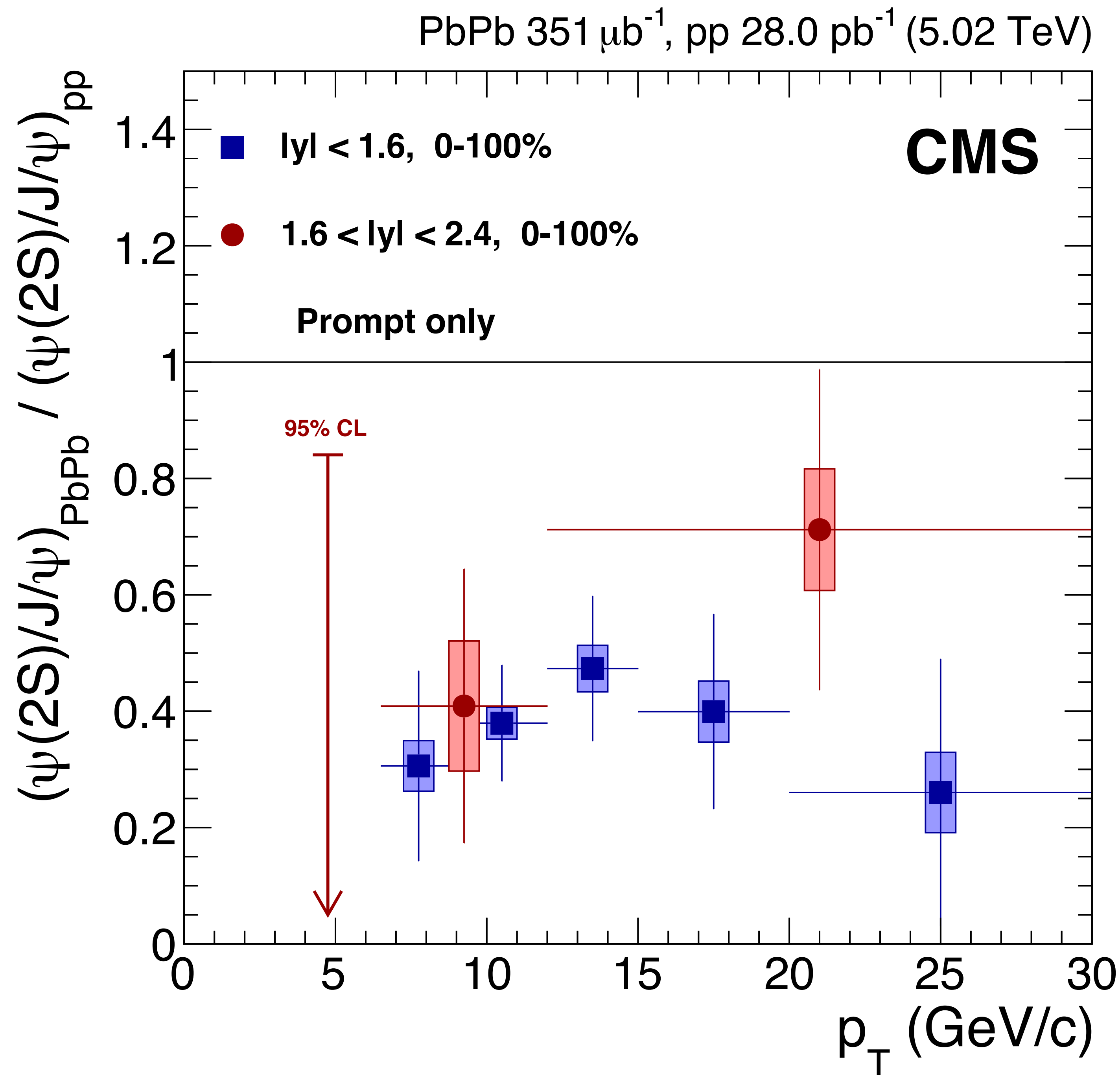


- ψ(2S) R_{pPb} < J/ψ R_{pPb} in all bins
- Final state effects on ψ(2S) at backward? (e.g., comover breakup)

ψ(2S) to J/ψ DR vs. p_T in PbPb

$$DR = \frac{\left[\frac{N(\psi(2S))}{N(J/\psi)}\right]_{\mathrm{PbPb}}}{\left[\frac{N(\psi(2S))}{N(J/\psi)}\right]_{\mathrm{pp}}} = \frac{R_{\mathrm{AA}}(\psi(2S))}{R_{\mathrm{AA}}(J/\psi)}$$

$$R_{\mathrm{AA}}(p_{\mathrm{T}}, y) = \frac{\mathrm{d}^2 N_{\Upsilon}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{< T_{\mathrm{AA}} > \mathrm{d}^2\sigma_{\Upsilon}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

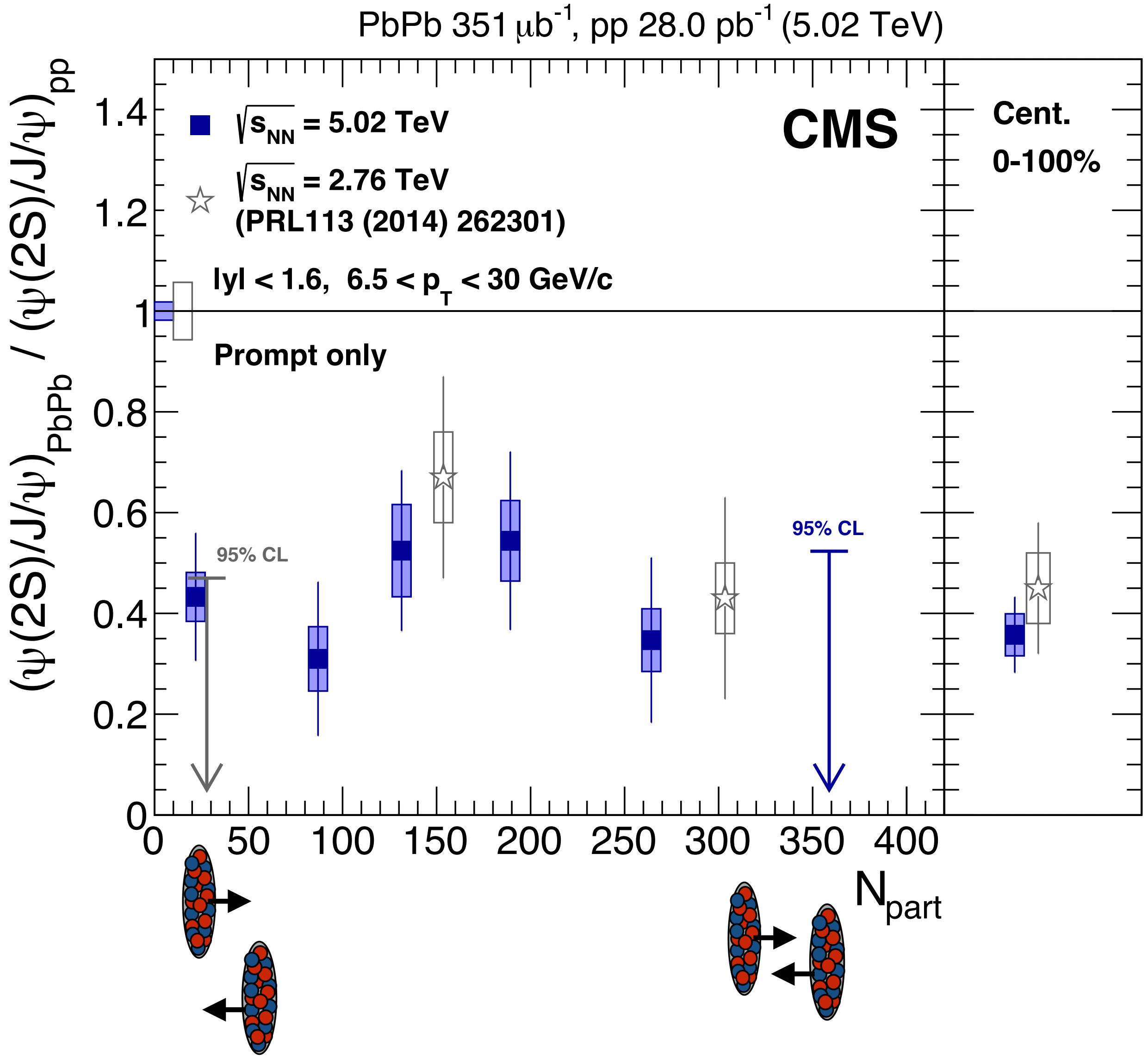


- ψ(2S) is suppressed with respect to J/ψ
- No significant p_T dependence

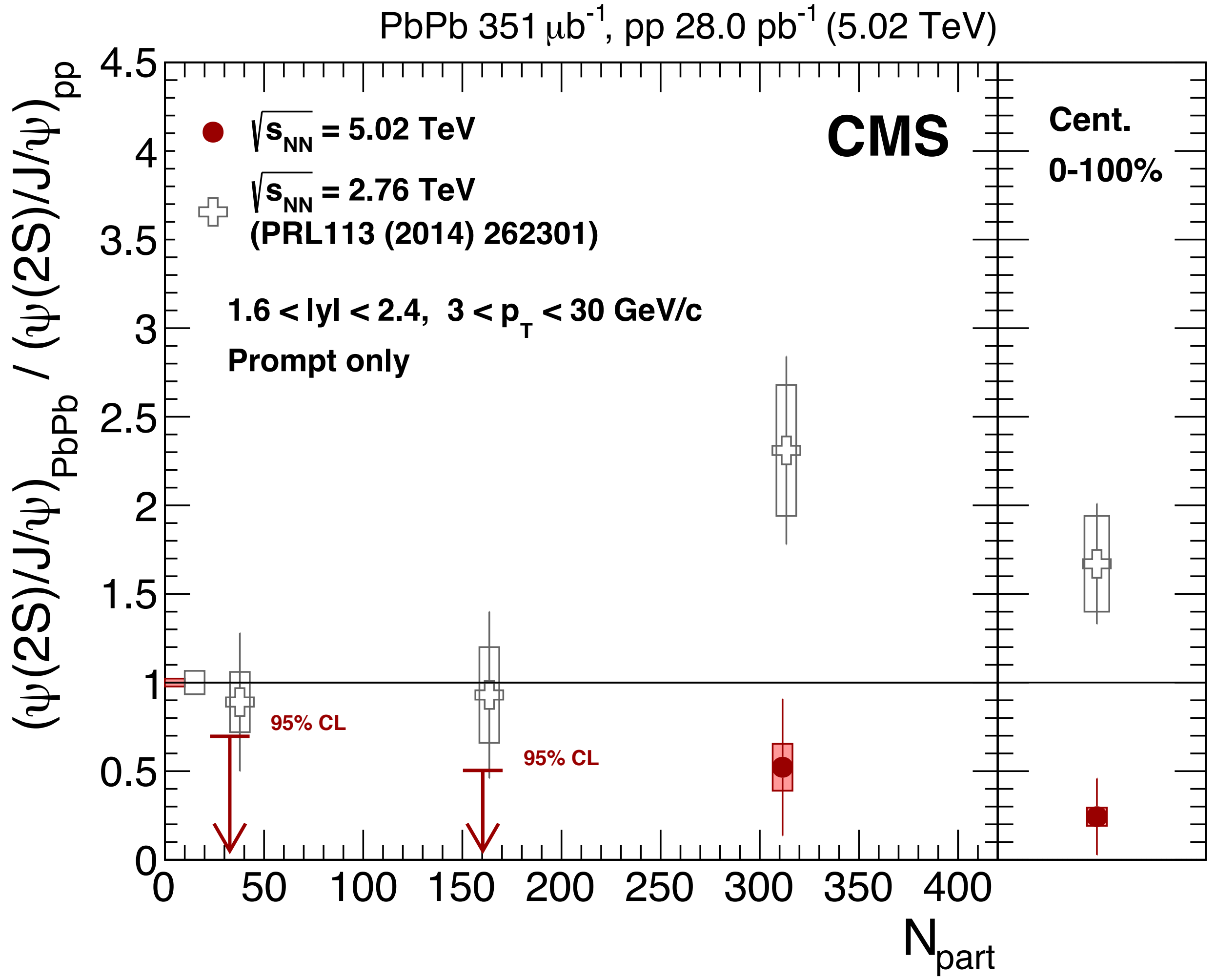
PRL 118 (2017) 162301

ψ(2S) to J/ψ DR vs. centrality in PbPb

|y| < 1.6
6.5 < p_T < 30 GeV/c



1.6 < |y| < 2.4
3 < p_T < 30 GeV/c



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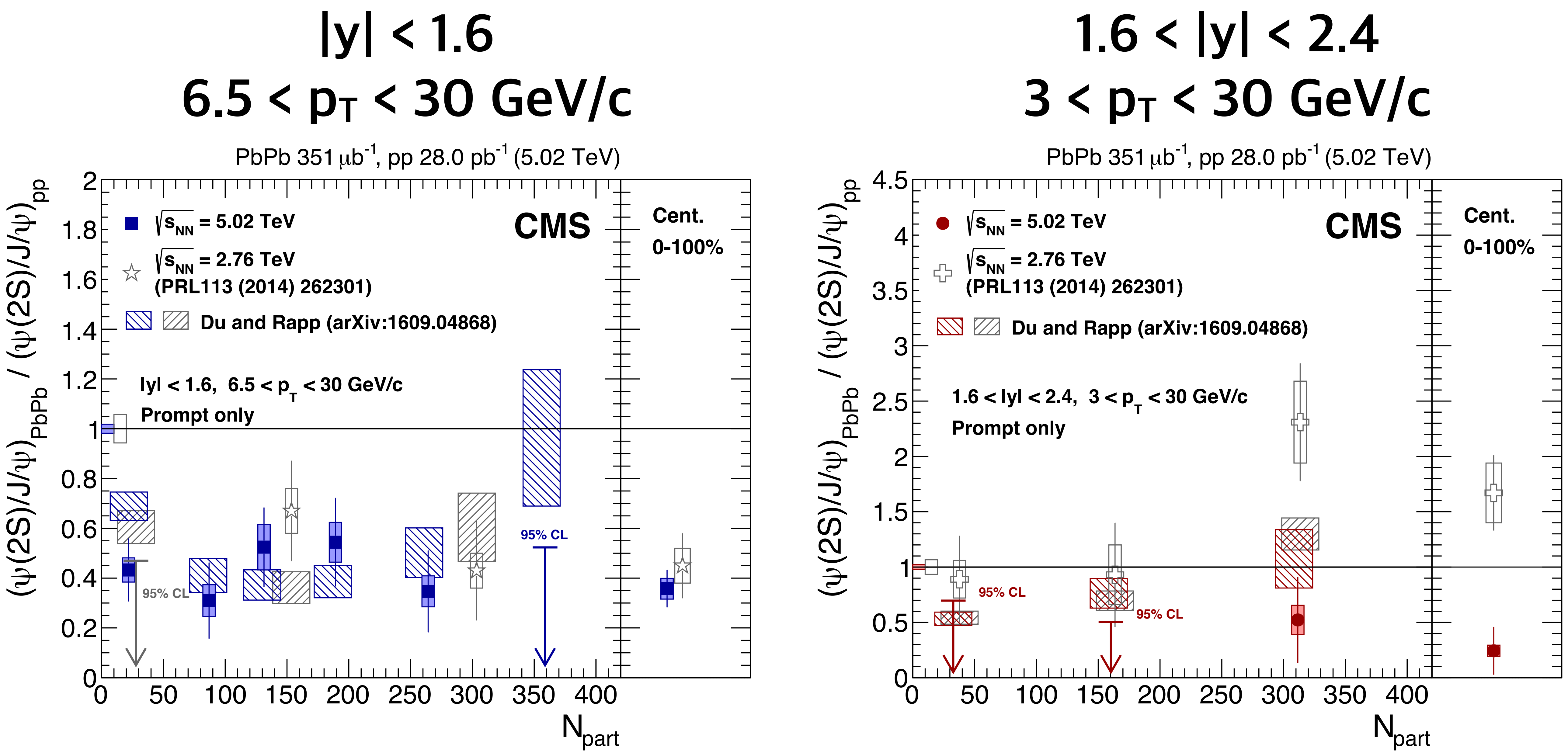
- No strong centrality dependence at 5.02 TeV
- Double ratios at 5.02 TeV are consistently lower than those at 2.76 TeV in 1.6 < |y| < 2.4 and 3< p_T < 30 GeV/c (right)

ψ(2S) to J/ψ DR: theory vs. experiments



PRL 118 (2017) 162301

- Transport Model
  - ψ(2S) regenerated later and more affected by flow than J/ψ
  - Larger transverse flow at 5.02 TeV than 2.76 TeV

Bottomonia

Bottomonia as golden probes

- Three ϒ states are characterized by similar kinematics but have different binding energies
- Negligible nonprompt fraction and less regeneration compared to charmonia

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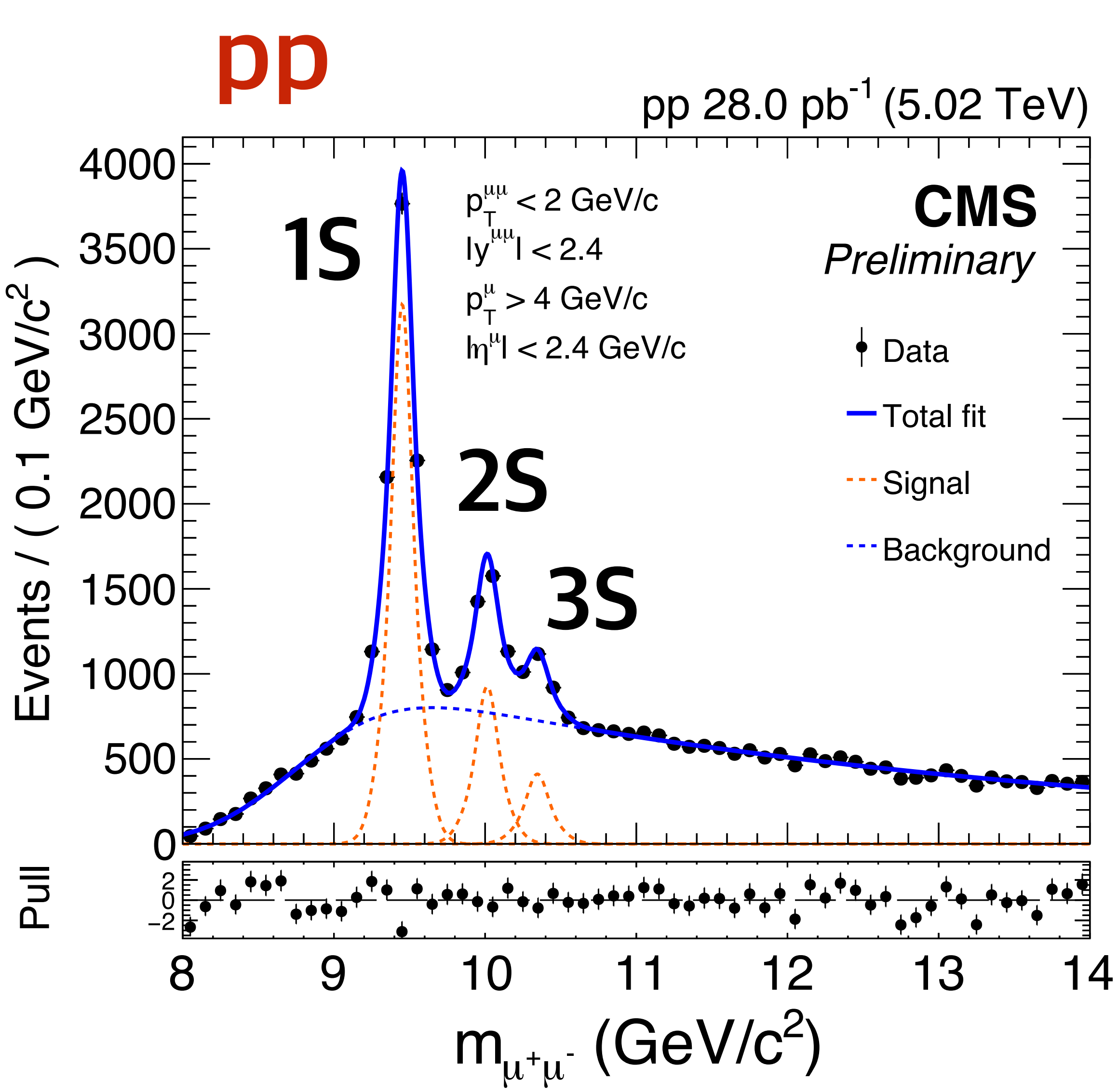

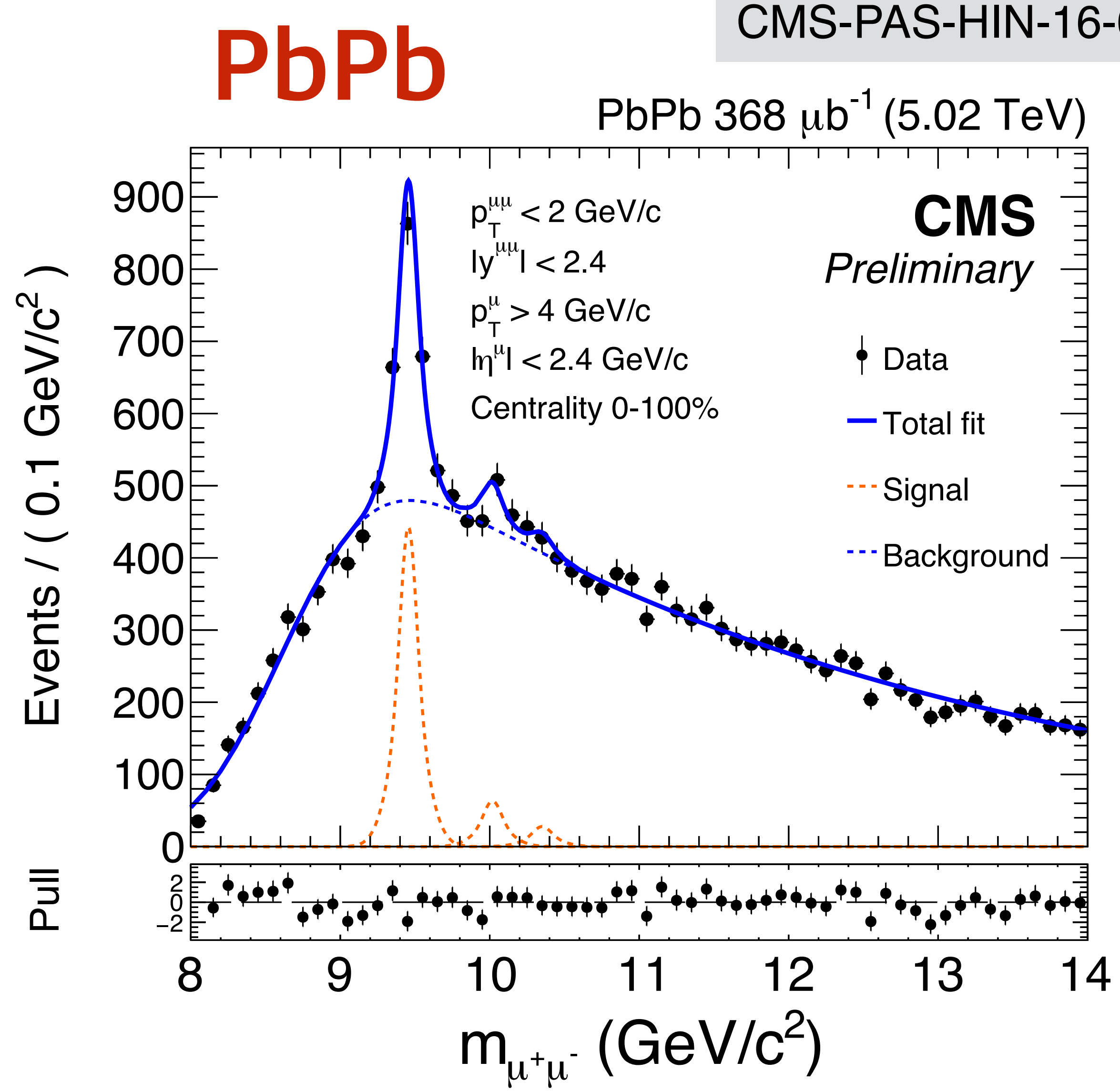

Υ(nS) R_{AA} vs. centrality

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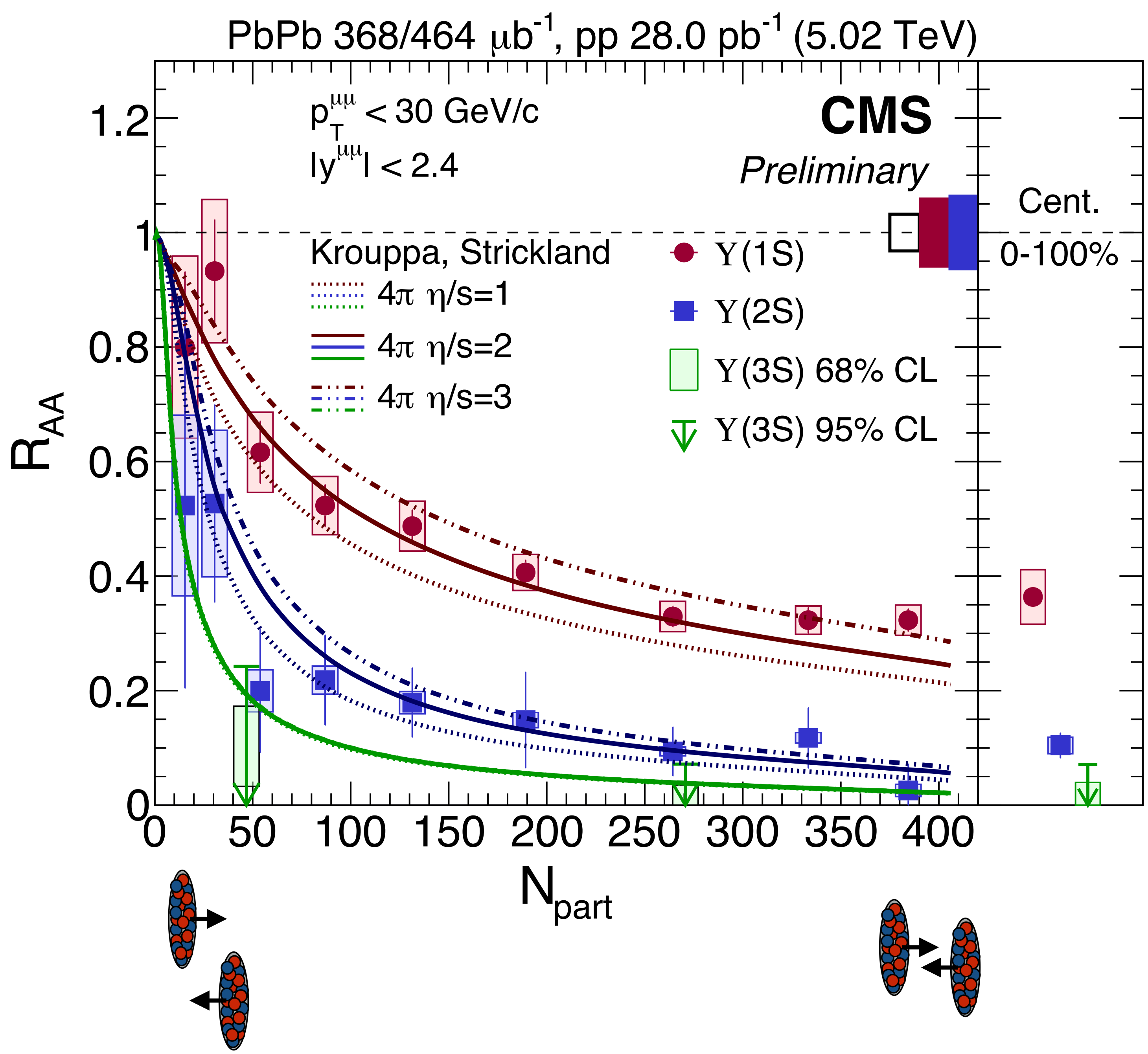
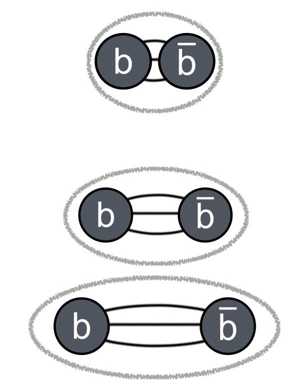


$$R_{\mathrm{AA}}(p_{\mathrm{T}},y) = \frac{\mathrm{d}^2 N_{\Upsilon}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}ay}{< T_{\mathrm{AA}} > \mathrm{d}^2\sigma_{\Upsilon}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

Υ(1S)

Υ(2S)

Υ(3S)



- All three states are suppressed with increasing centrality
- R_{AA}[Υ(1S)] > R_{AA}[Υ(2S)] > R_{AA}[Υ(3S)] → Sequential melting
- Hydrodynamic model overlaid

Υ(1S) R_{AA}: 2.76 vs. 5.02 TeV

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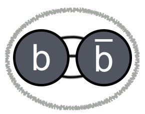
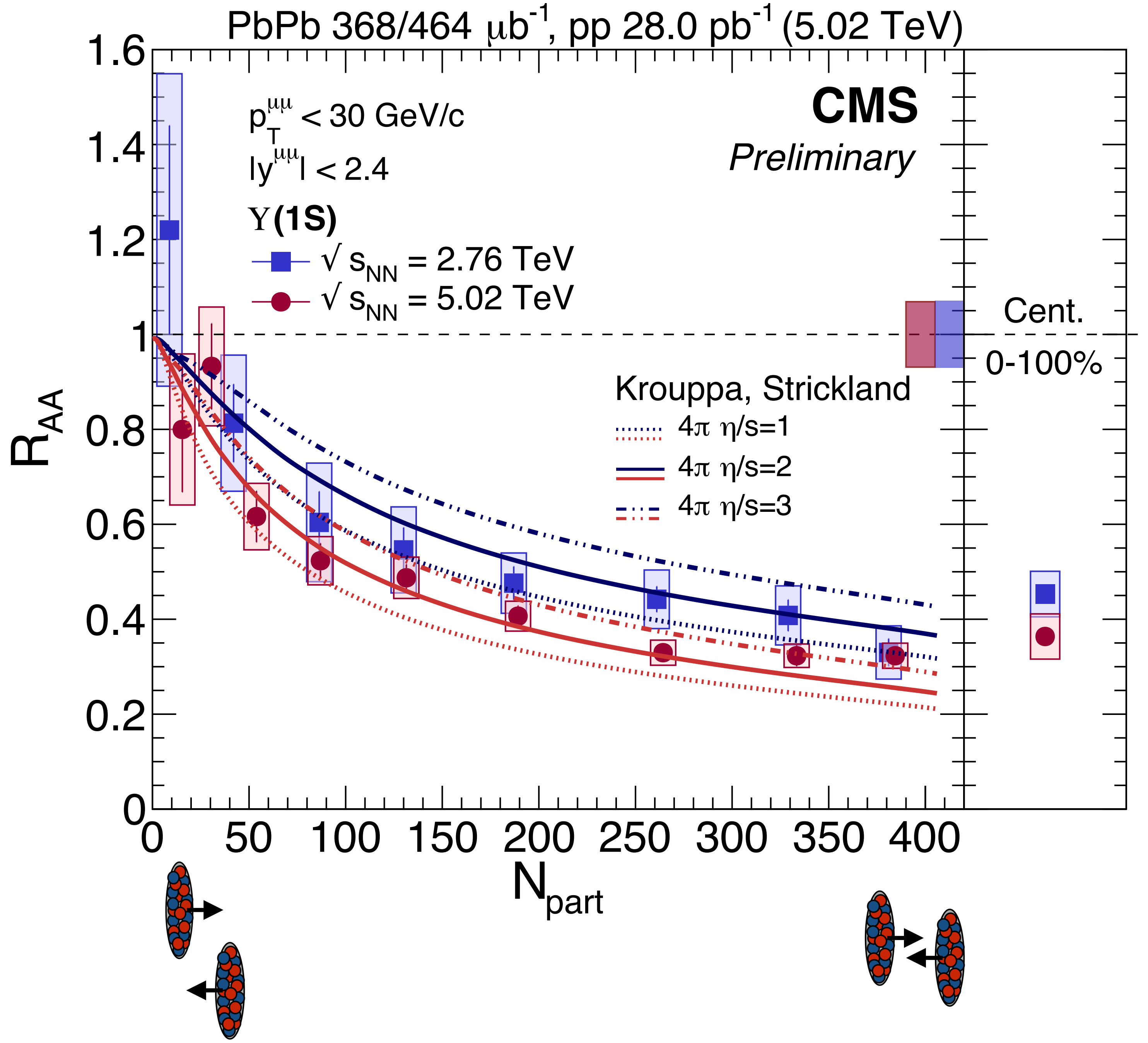
Υ(1S) 



$$R_{AA}(p_T, y) = \frac{d^2 N_{\Upsilon}^{AA}/dp_T a y}{< T_{AA} > d^2\sigma_{\Upsilon}^{pp}/dp_T dy}$$

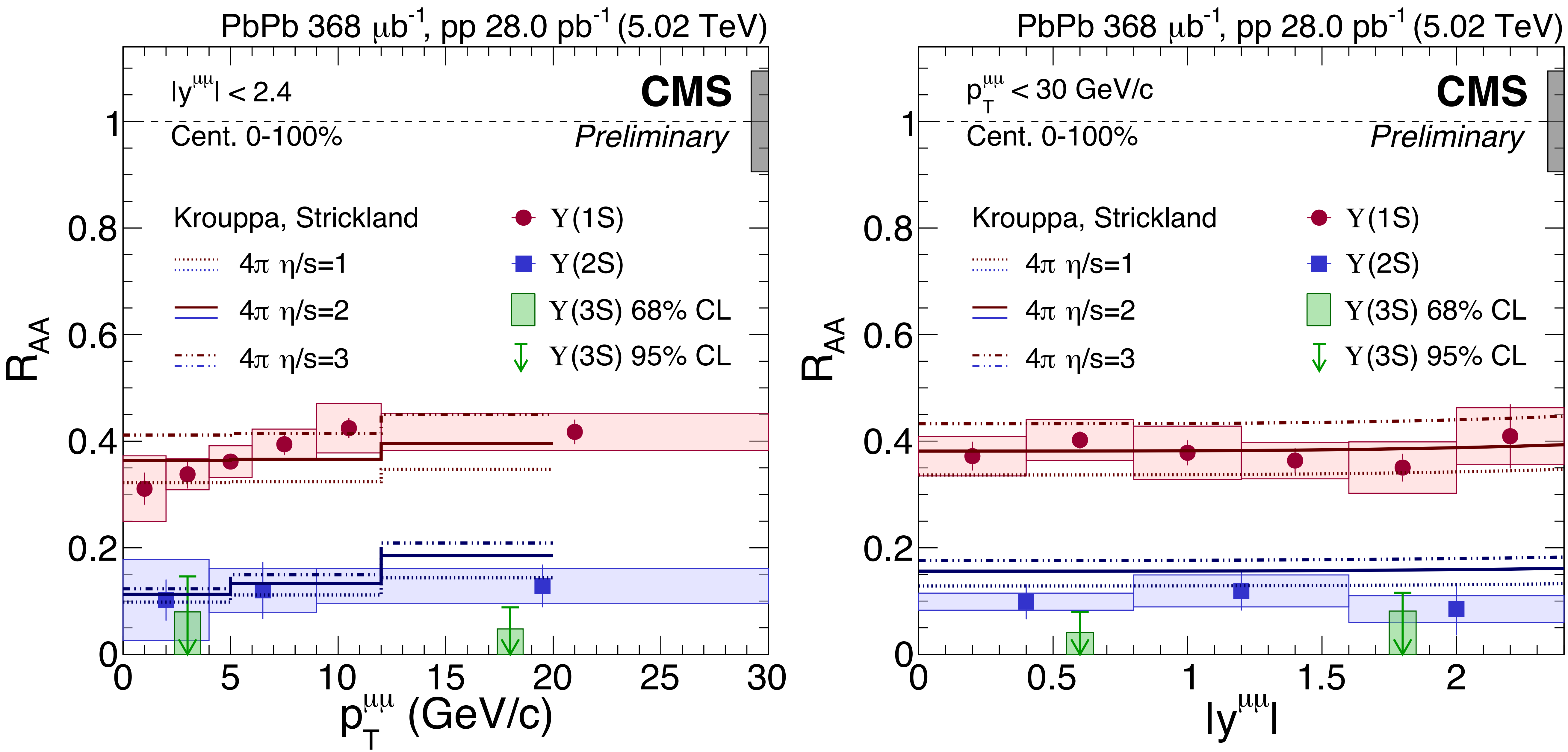
2.76 TeV

5.02 TeV

- Indication of larger suppression at higher energy
- Hydrodynamic model

→ initial medium T: ~550 MeV (2.76 TeV), ~630 MeV (5.02 TeV)

Υ(nS) R_{AA} vs. p_T and |y|



- No strong dependence on p_T and y
- The p_T dependent Υ(1S) R_{AA} shows a slight increase

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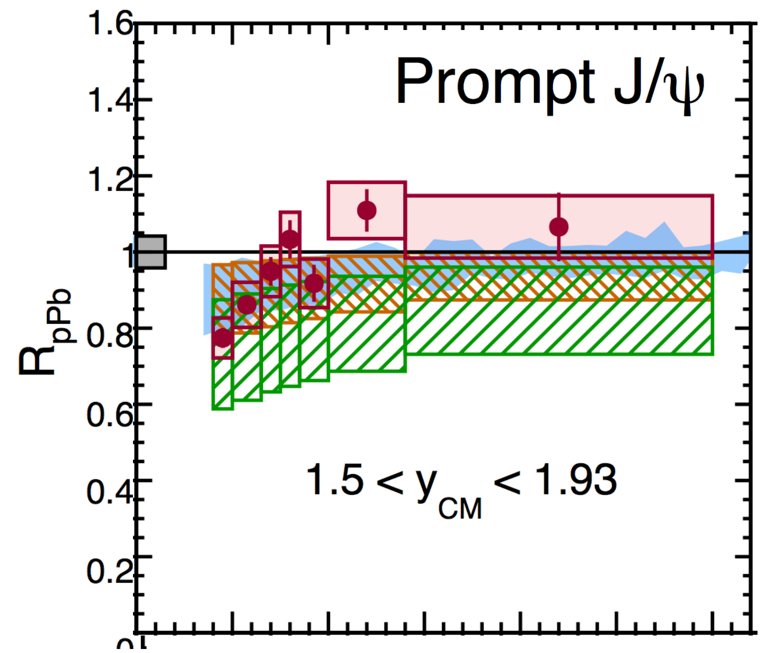
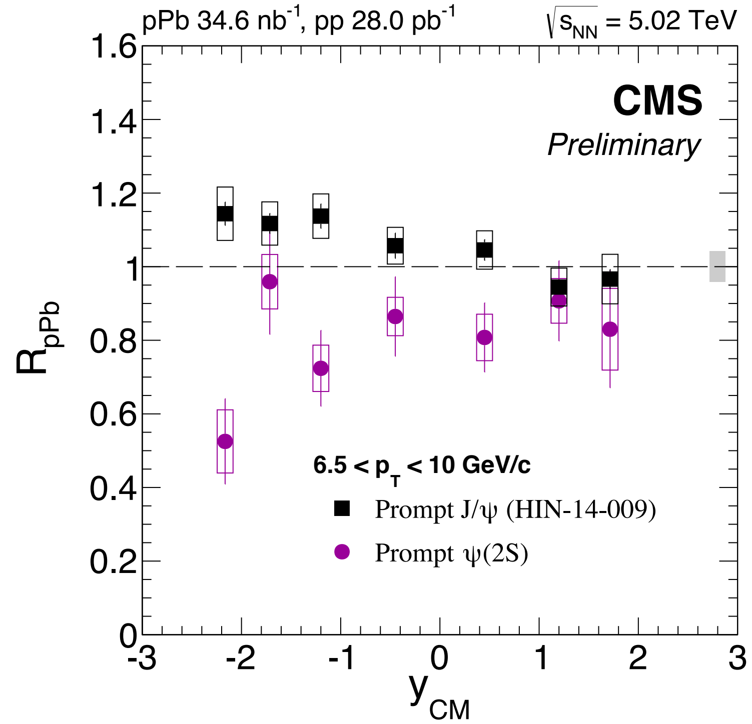
Summary

- **pPb collisions**
- J/ψ indicates shadowing at forward and low p_T
- Different nuclear effects on ψ(2S) from J/ψ

J/ψ

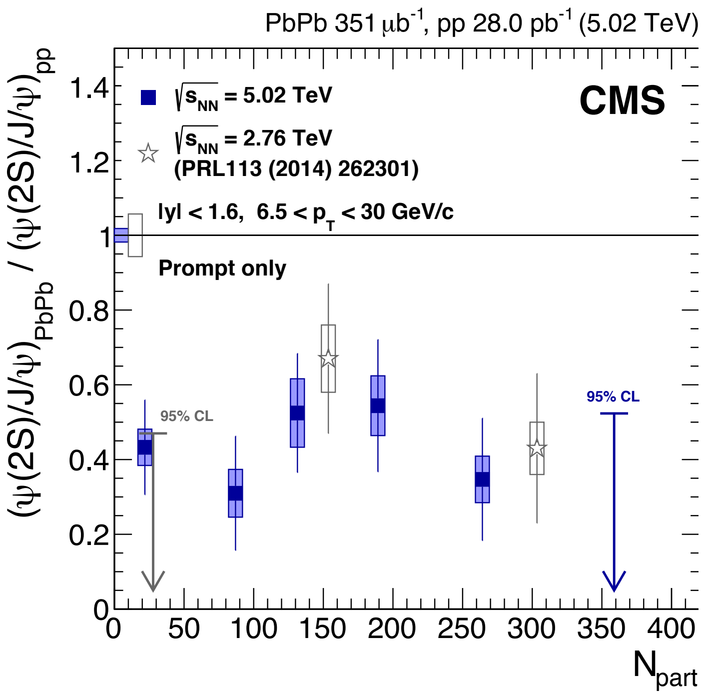


ψ(2S)

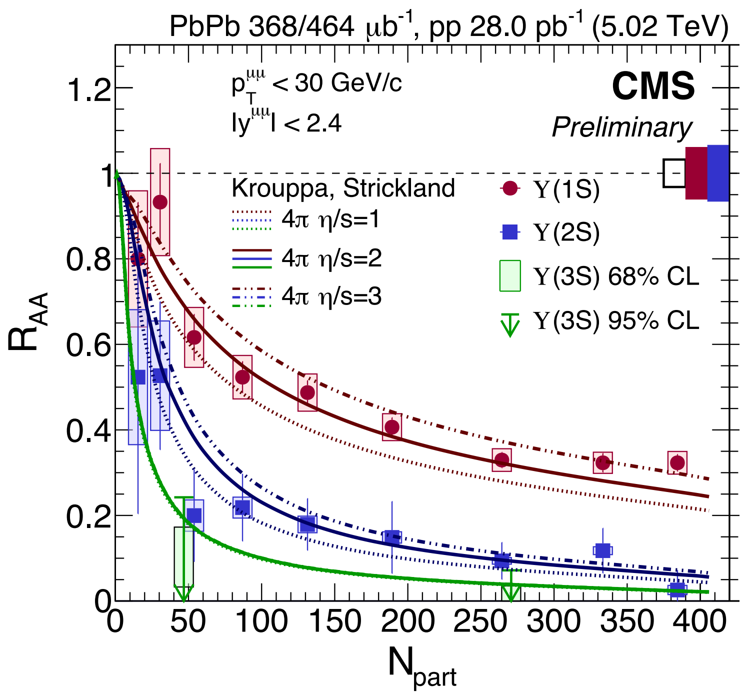


- **PbPb collisions**
- ψ(2S) suppressed w.r.t. J/ψ
→ Separate R_{AA} needed
- ϒ(nS) states agree with sequential melting scenario

ψ(nS)



ϒ(nS)

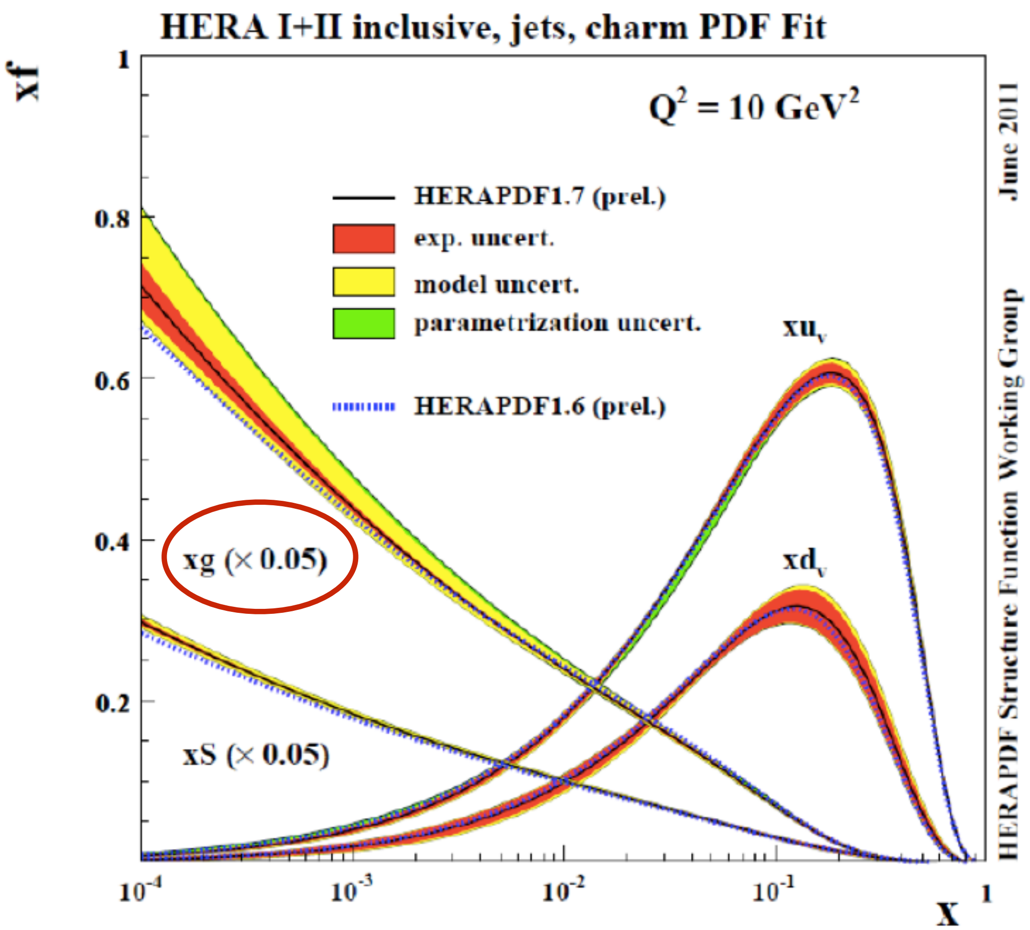


Backups

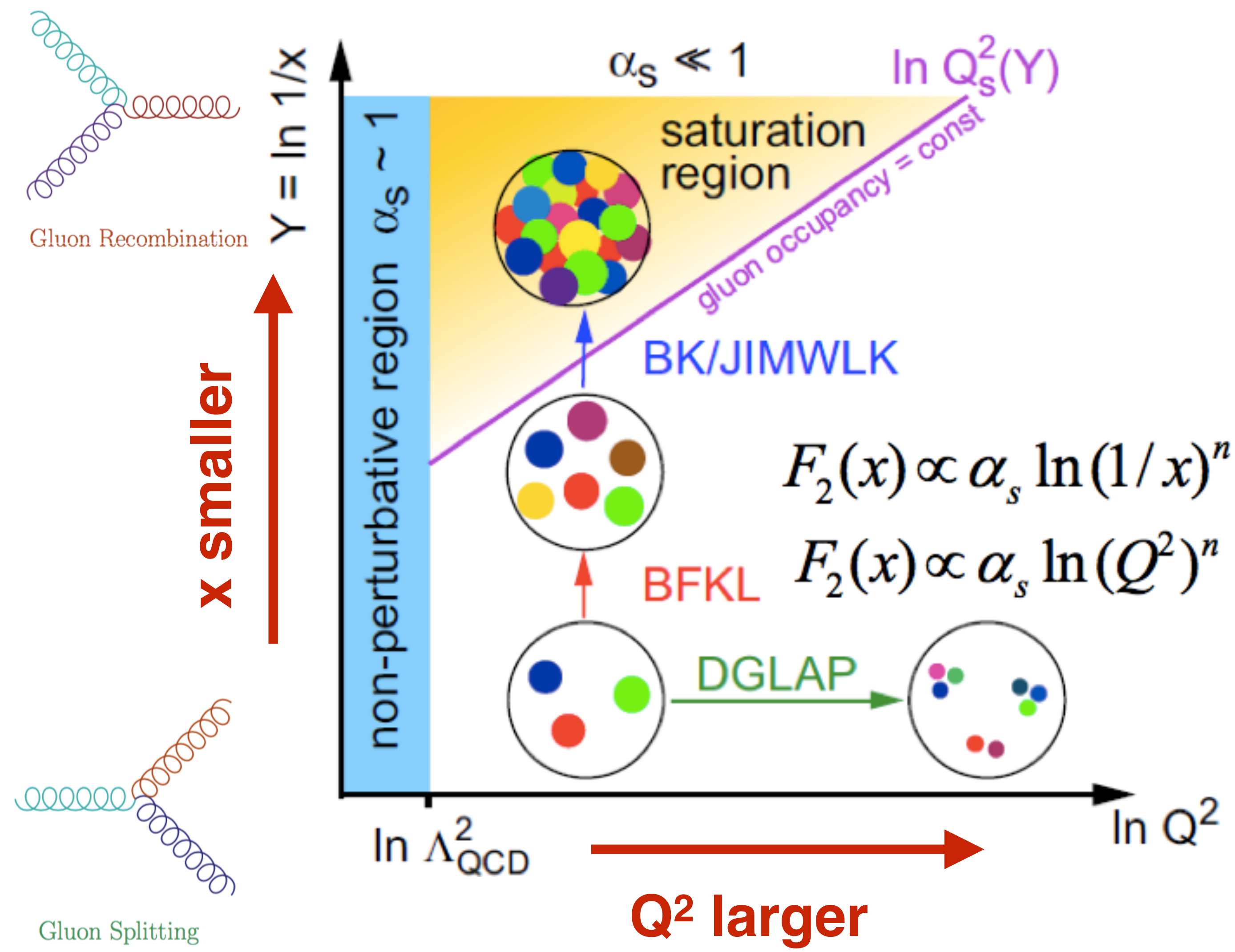
Parton Distribution Functions

arXiv.1111.5432v4

proton PDF



x: fraction of nucleon momentum carried by parton



- Gluon density significantly rises with decreasing x
- **When too many gluons** are squeezed in a confined hadron, gluons start to overlap and recombine → <u>saturation</u> in gluon distributions

Nuclear PDFs

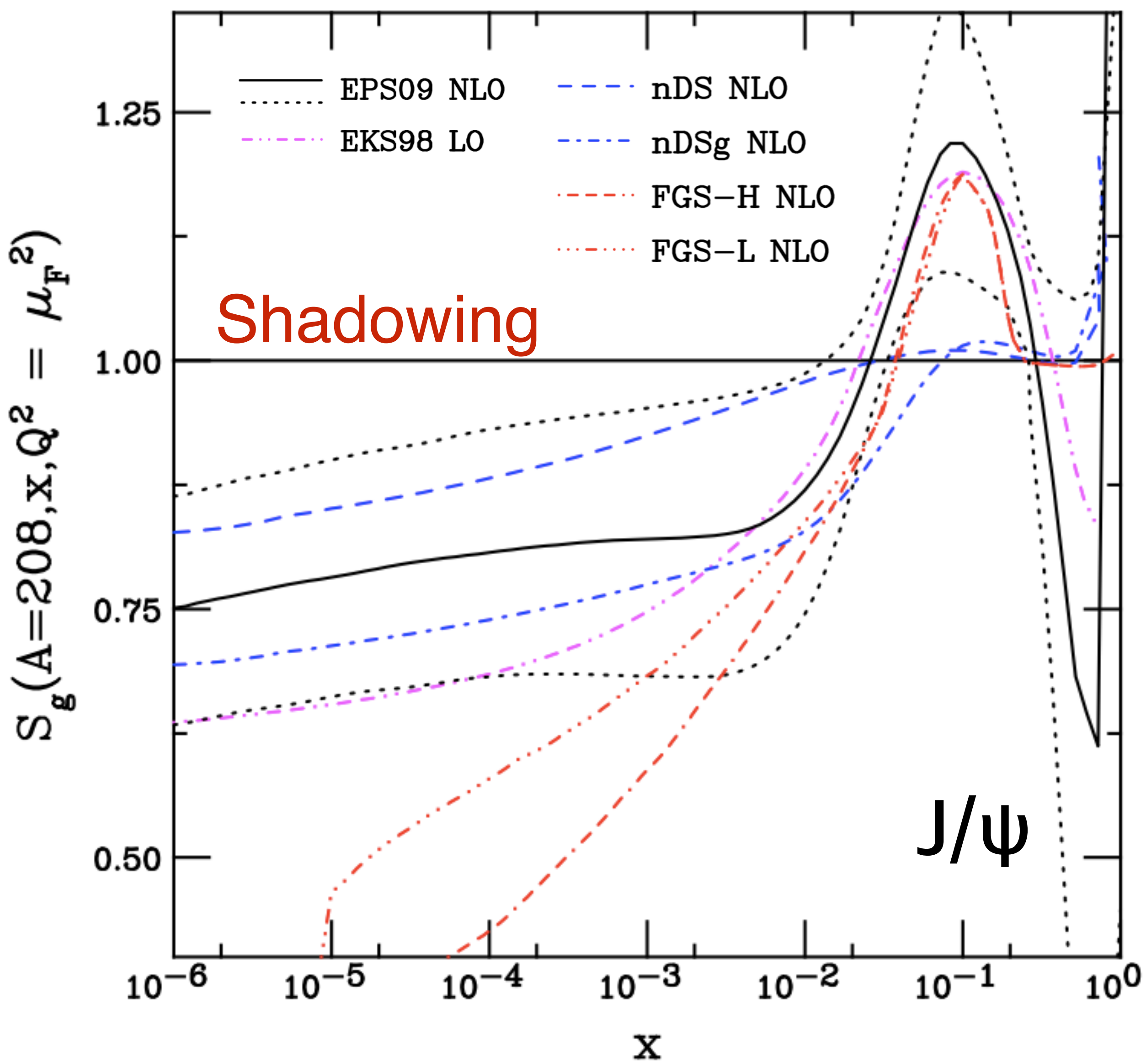
$$R_i^A(x,Q^2) = \frac{f_i^{p/A}(x,Q^2)}{f_i^p(x,Q^2)}$$

PDF in nuclei

u,d,s,g..

PDF in a free proton

R_{gluon}^{Pb}

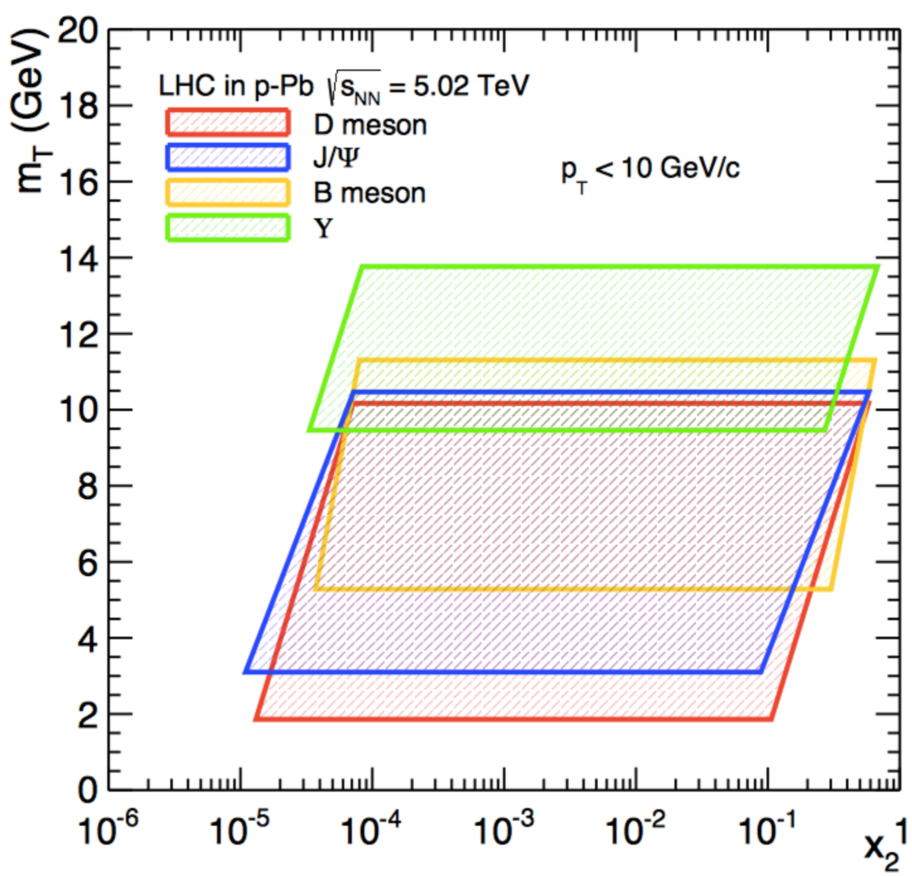


- nPDF modified compared to proton, especially at low x
- Measurements in low x is crucial to constrain nPDF models

arXiv:1507.04418

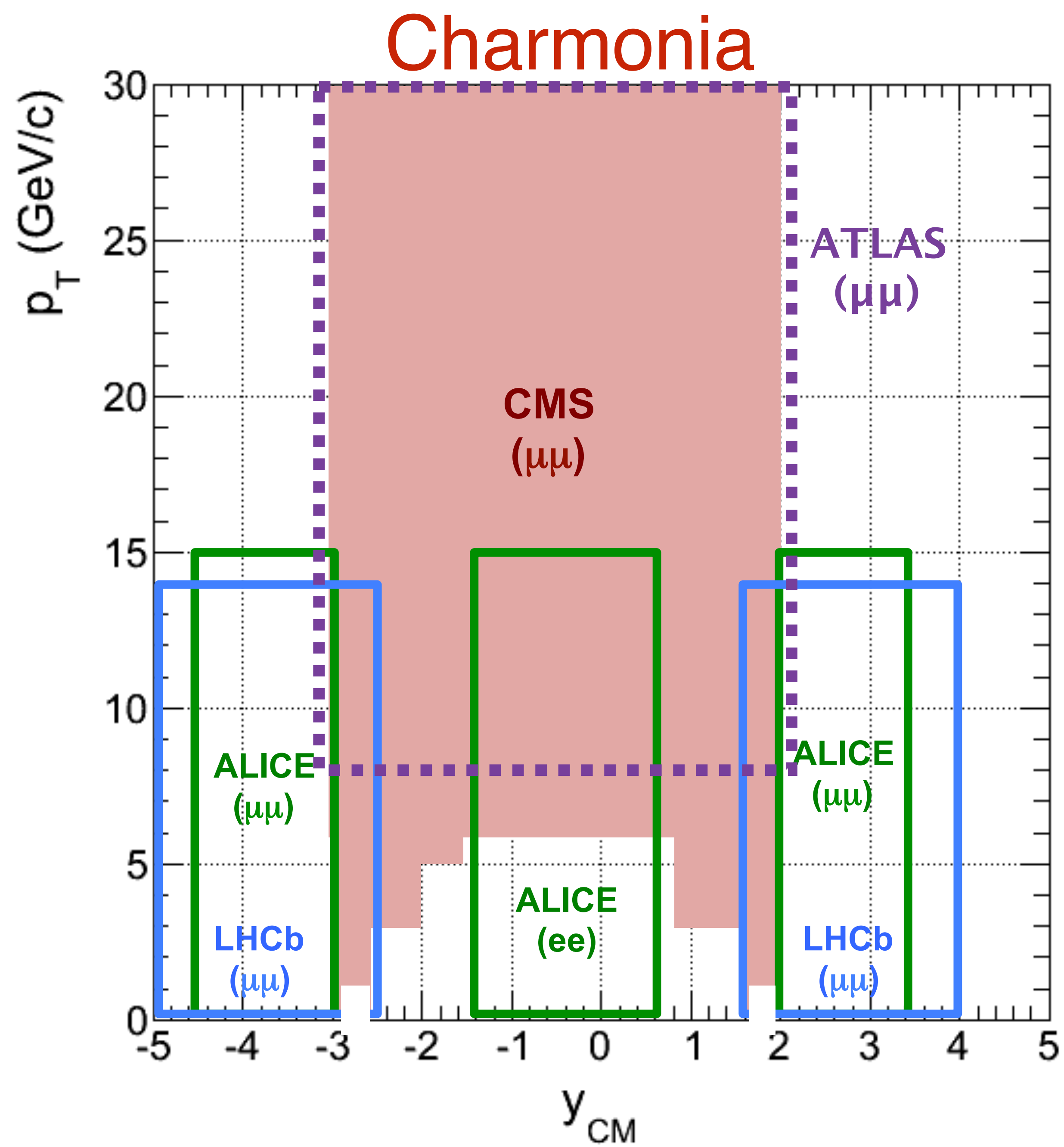
CMS coverage

- CMS at LHC allows the measurement of quarkonia with
  - Large production cross section
  - Wide coverage in x



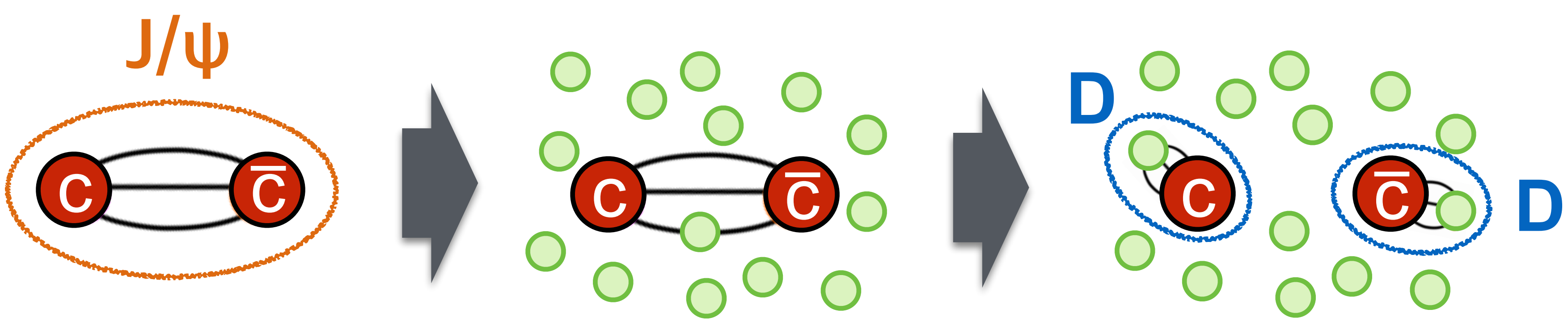
forward
y = +2.4

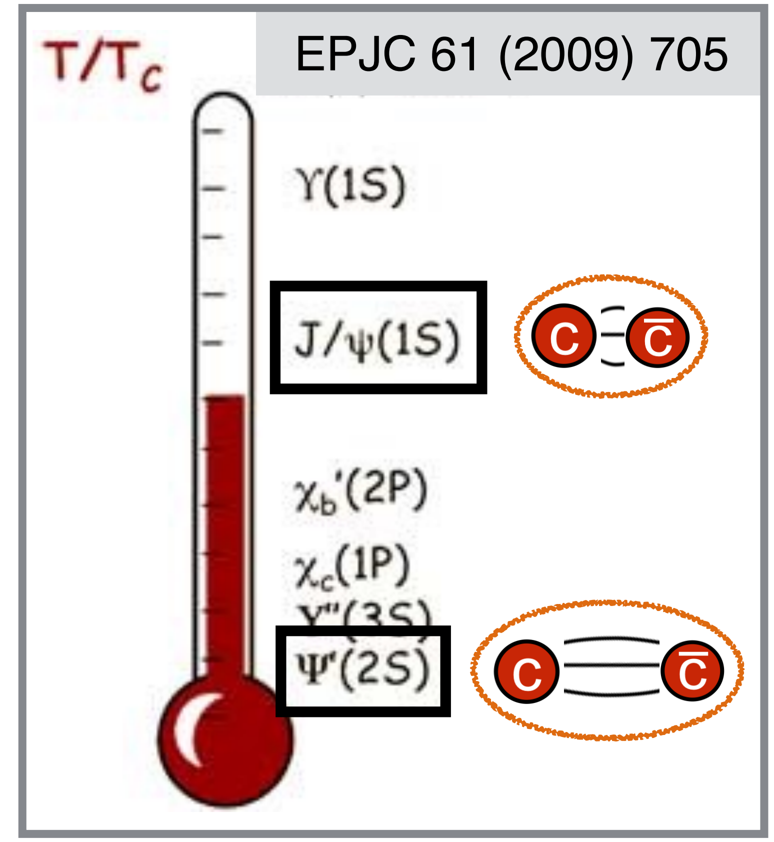
Backward
y= -2.4



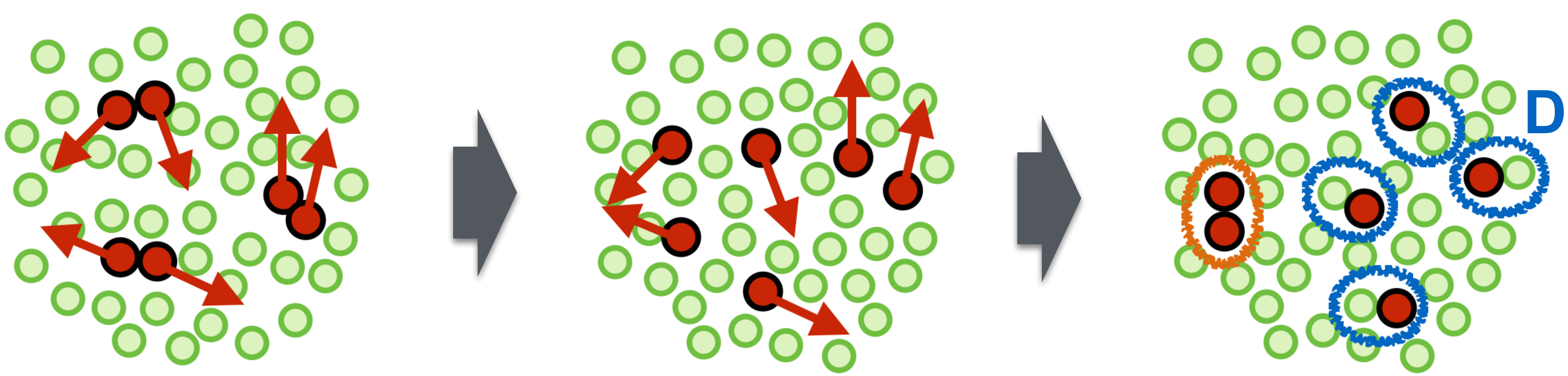
QGP effects

- Debye Screening
  - Sequential melting: thermometer for QGP
  - <u>Suppression</u> of charmonium yields compared to pp



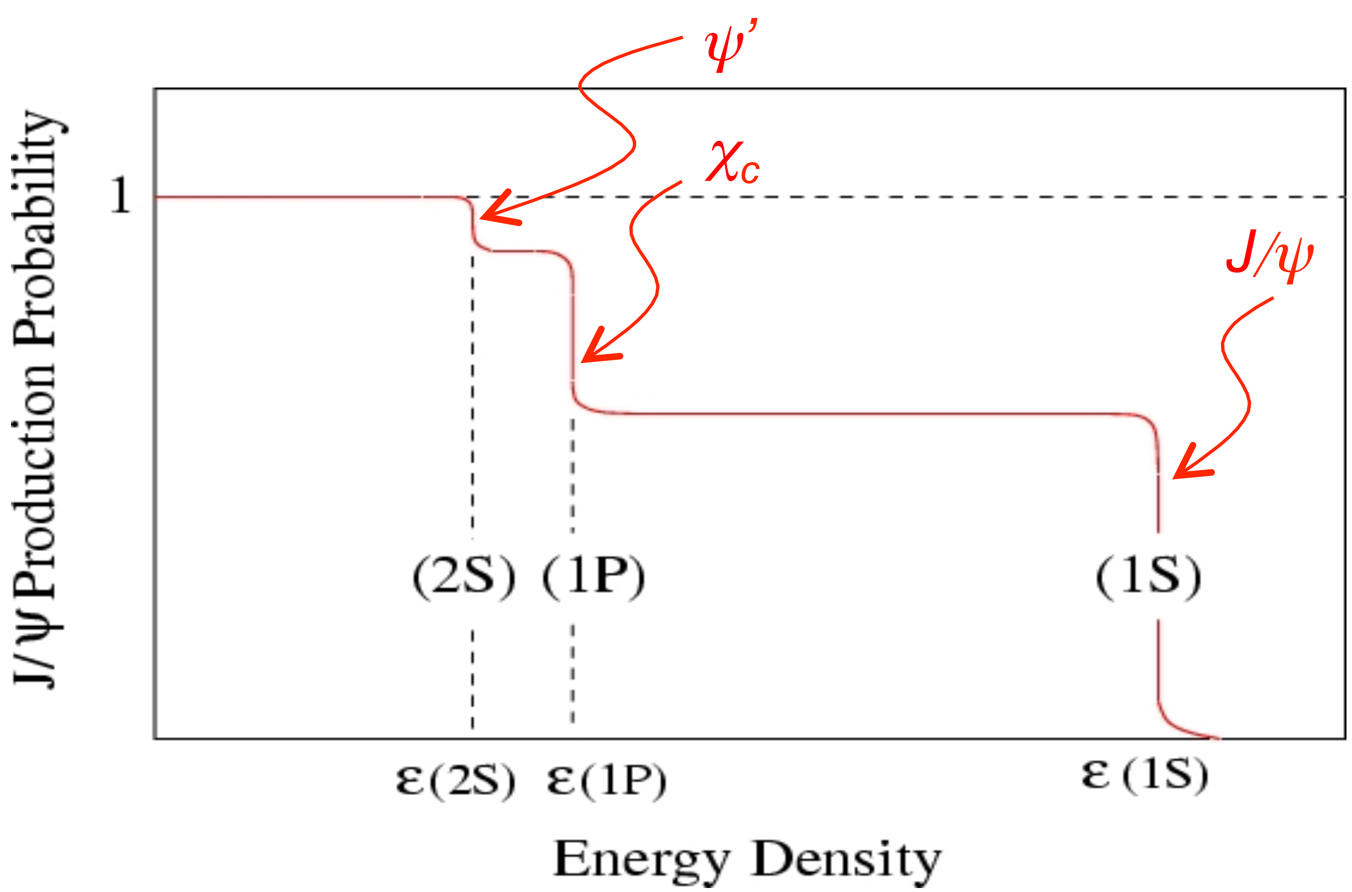


- Regeneration
  - Combination of initially uncorrelated charm and anticharm quarks
  - <u>Enhancement</u> of charmonium yields compared to pp



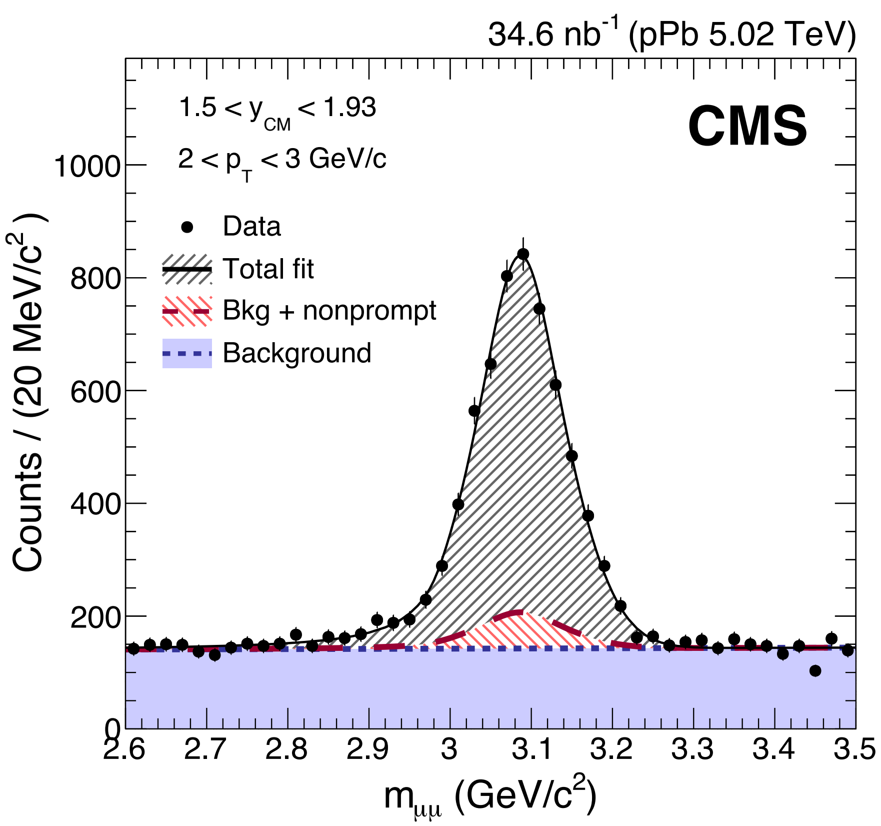
Sequential melting

Resonance	J/ψ	Ψ'	Υ(1S)	Υ(2S)	Υ(3S)
Mass [GeV]	3.10	3.68	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.54	0.20
Radius [fm]	0.25	0.45	0.14	0.28	0.39



Signal and background modeling

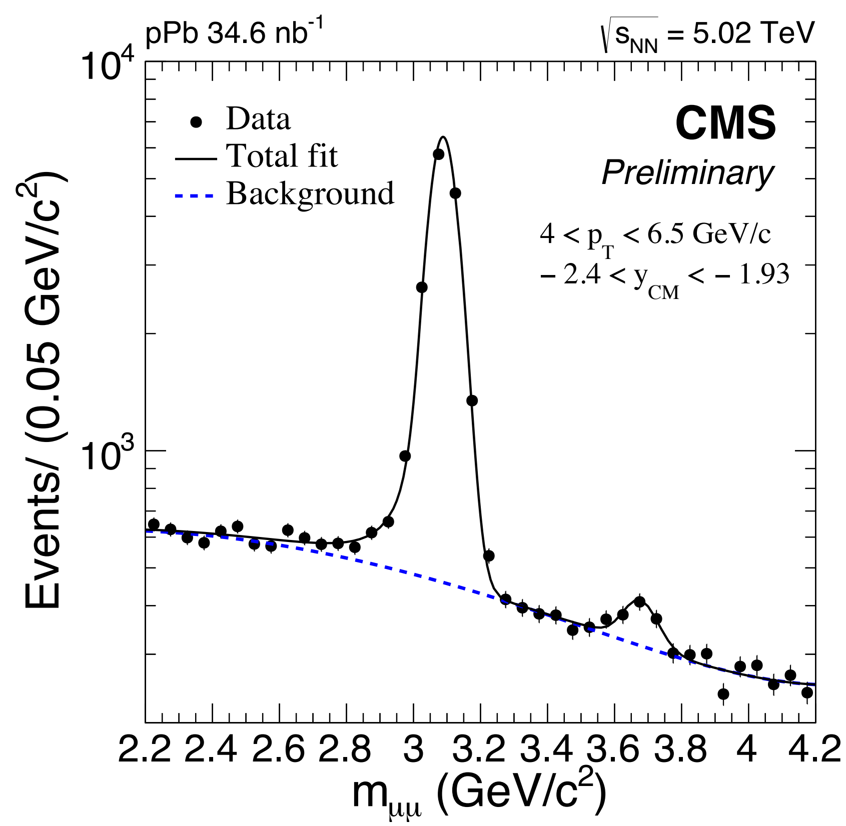
J/ψ



Sig: 1 G + 1 CB

Bkg: Exp

ψ(nS)

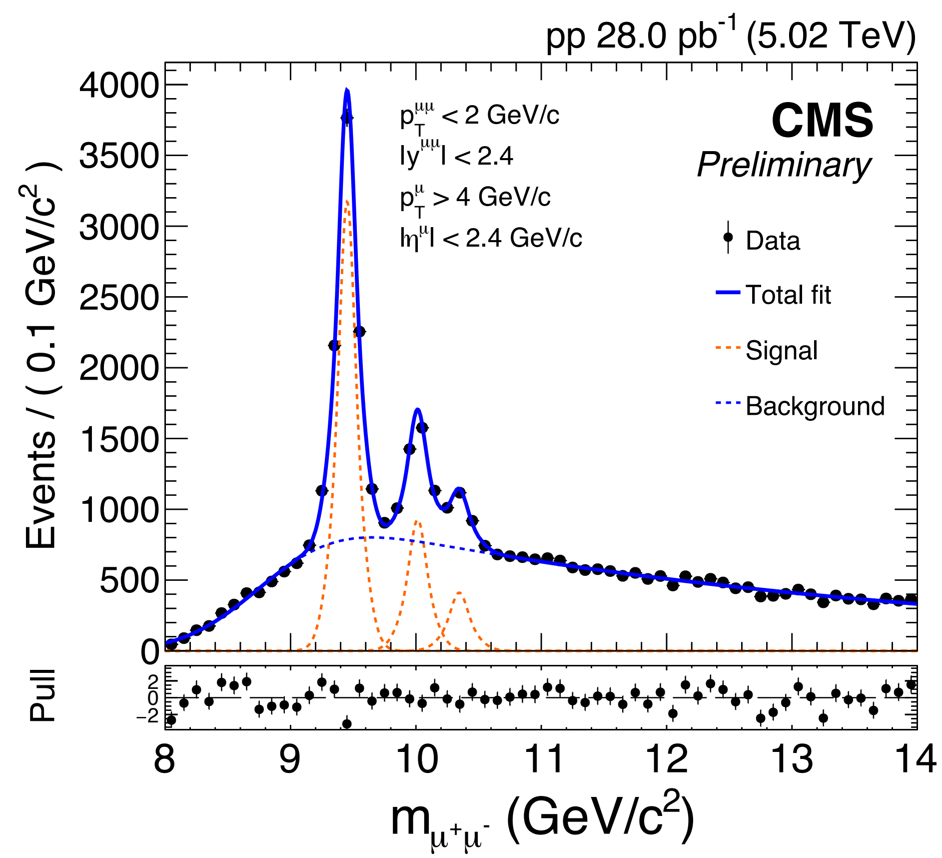


Sig: 1 G + 1 CB (pPb)

or 2 GB (PbPb)

Bkg: Chebychev poly

Υ(nS)



Sig: 2 CB

Bkg: Err x Exp

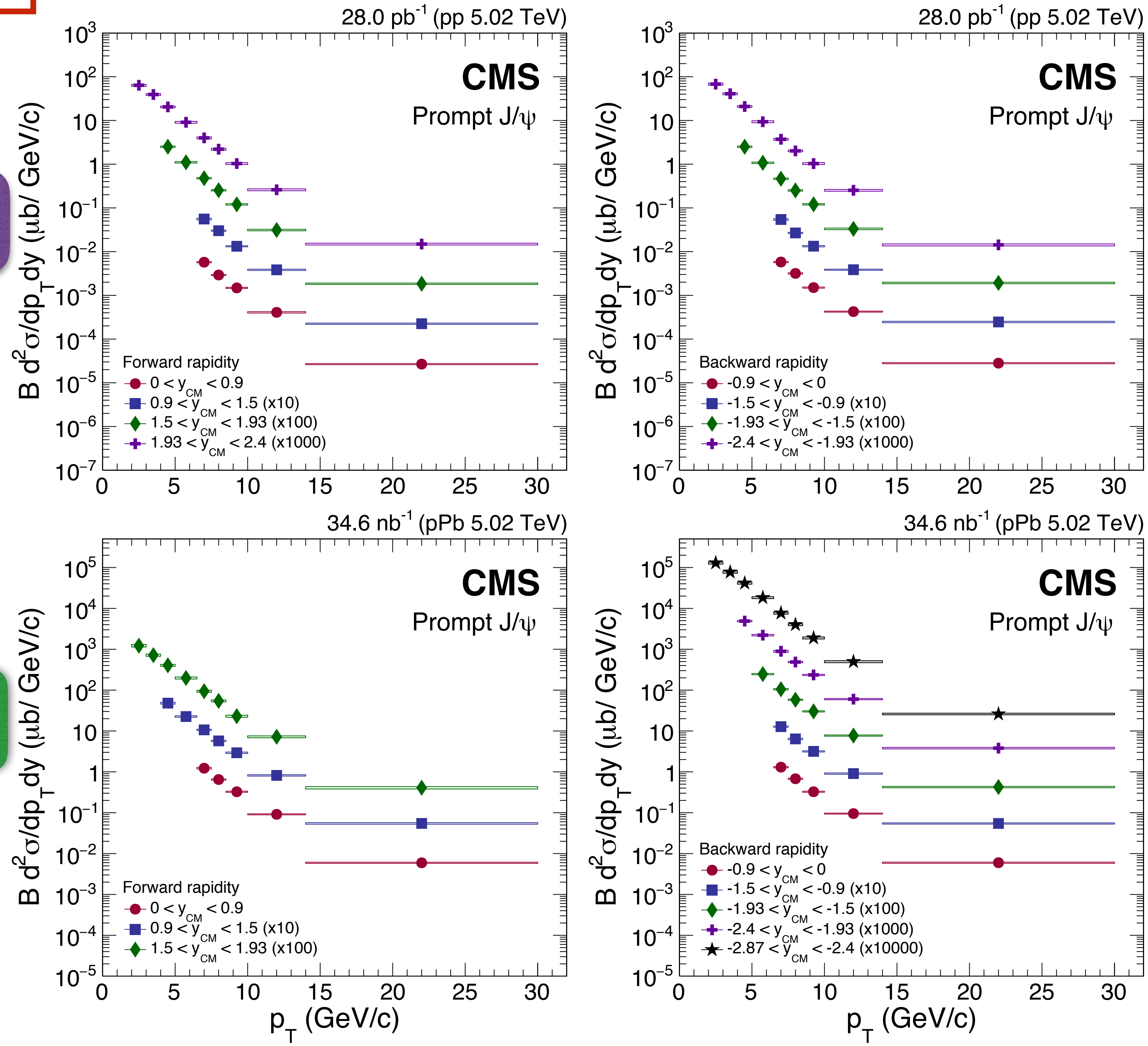
Prompt J/ψ cross sections

$$\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-)\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\,\mathrm{d}y_\mathrm{CM}} = \frac{N_\mathrm{Fit}^{\mathrm{J}/\psi}/(\mathrm{Acc}\,\varepsilon)}{\mathcal{L}_\mathrm{int}\,\Delta p_\mathrm{T}\,\Delta y_\mathrm{CM}}$$

Forward (p-going) | **Backward (Pb-going)**

pp

pPb



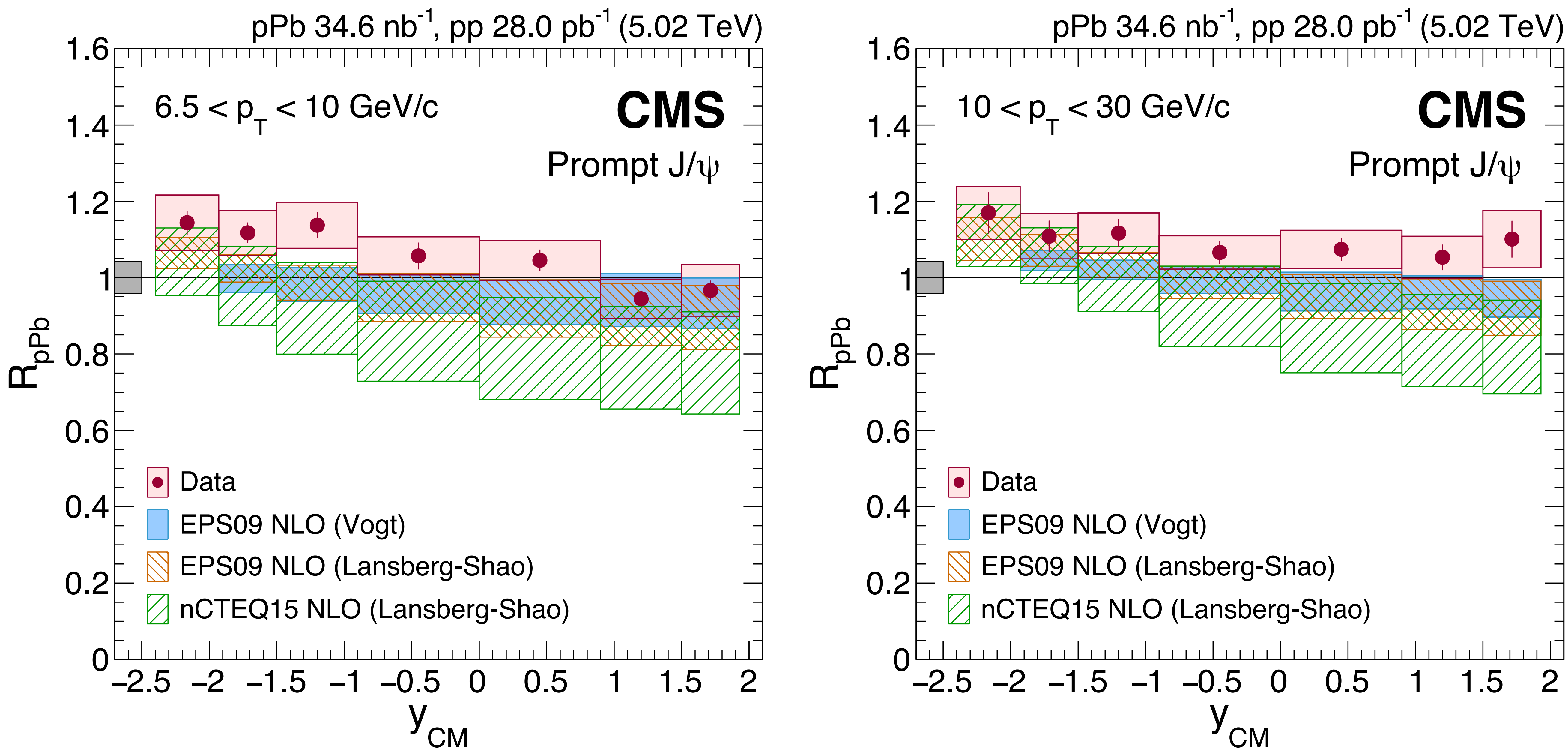
EPJC 77 (2017) 269

- pp: $-2.4 < y_{CM} < 2.4$
- pPb: $-2.87 < y_{CM} < 1.93$
- $2 < p_T < 30$ GeV/c

Prompt J/ψ R_{pPb} vs. y_{CM}

EPJC 77 (2017) 269

Lower p_T | **Higher p_T**

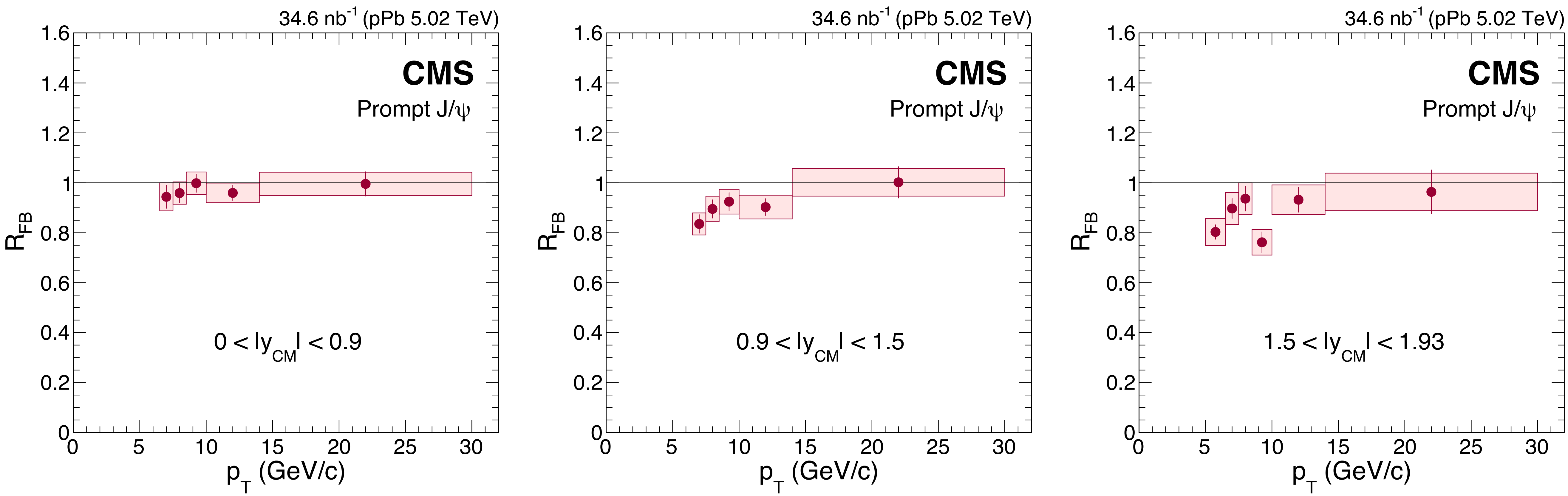


- Lower p_T: possible decrease of R_{pPb} for increasing y_{CM}
- Higher p_T: R_{pPb} is above unity for the whole y_{CM} range

Prompt J/ψ R_{FB} vs. p_T

EPJC 77 (2017) 269

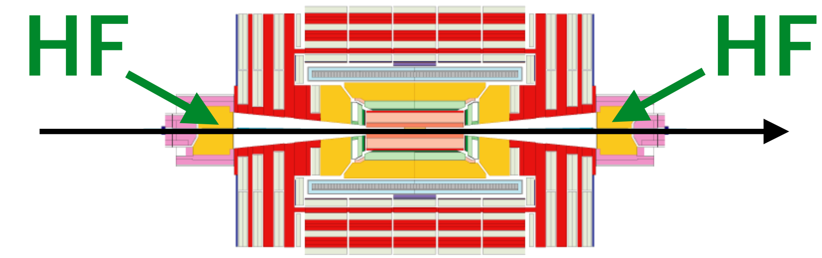
- An observable free from pp reference
- Luminosity uncertainty cancels
- Useful to study centrality dependence without N_{coll} information



- $R_{FB} < 1$ for $p_T \lesssim 7.5$ GeV/c and $|y_{CM}| > 0.9$
- Indication of a modest decrease with $|y_{CM}|$ in $6.5 < p_T < 10$ GeV

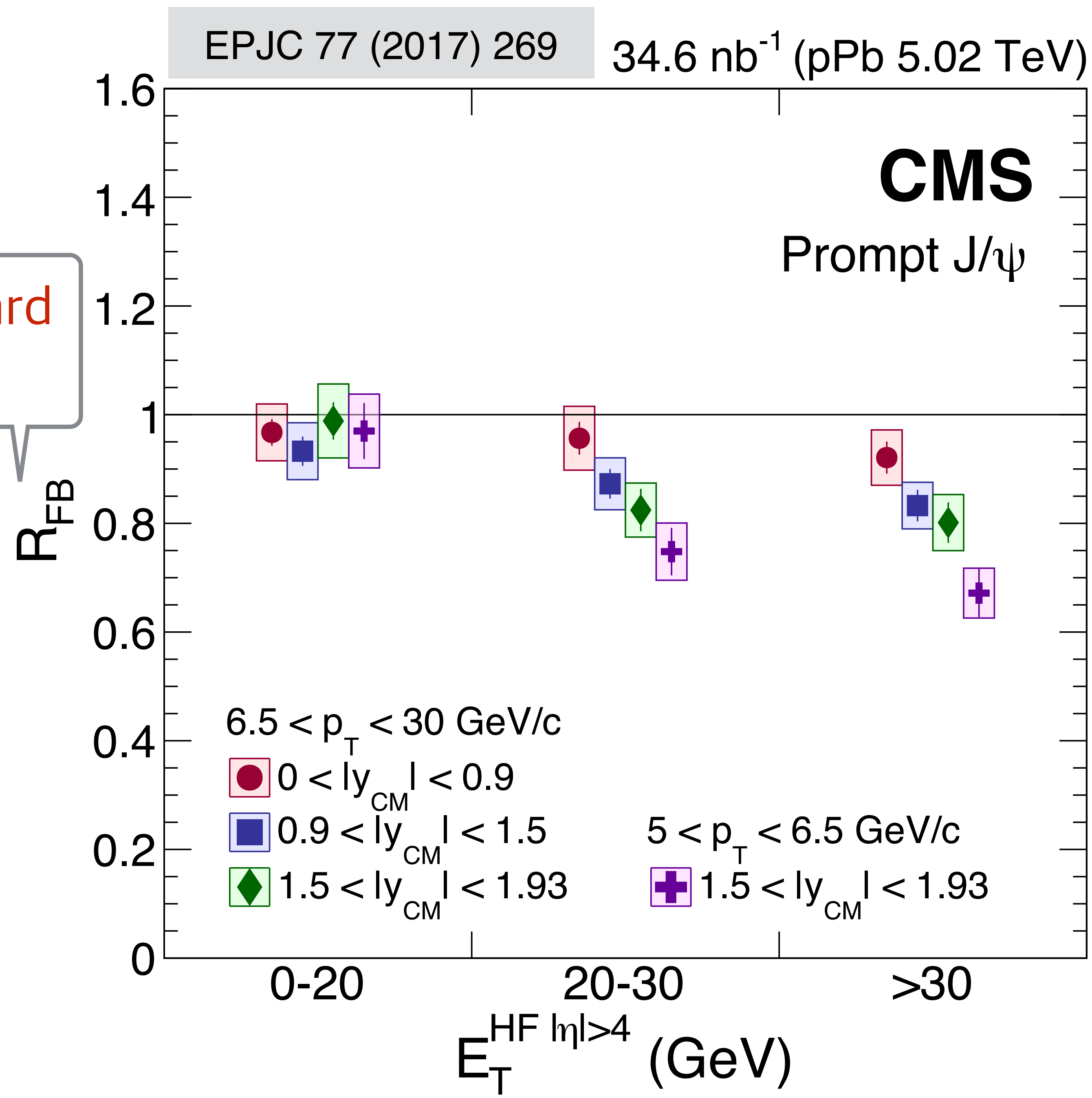
R_{FB} vs. event activity

- $E_T^{HF|\eta|>4}$: raw transverse energy deposited in Hadron Forward Calorimeter at $4 < |\eta| < 5.2$
- Centrality-like characterization in pPb



	$[E_T^{HF\|\eta\|>4}]$	$\langle E_T^{HF\|\eta\|>4}\rangle$	Frac
pPb	0–20	9.4	73%
min-	20–30	24.3	18%
bias	30–120	37.2	9%

Forward-to-backward production ratios

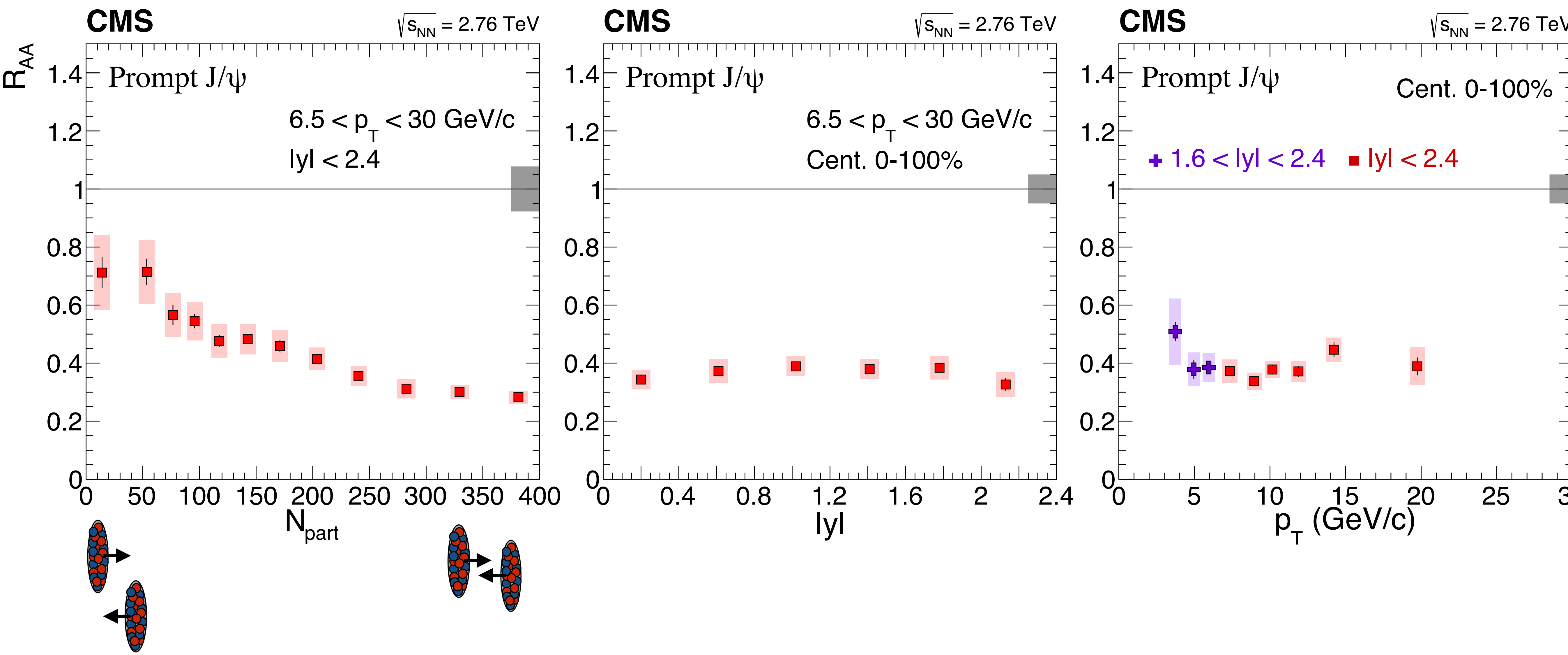


- R_{FB} decreases with $E_T^{HF|\eta|>4}$
- More significant for larger $|y_{CM}|$ and lower p_T
- Enhanced nuclear effects?

Prompt J/ψ R_{AA} vs. centrality, p_T, |y|

$$R_{AA} = \frac{N_{PbPb}}{T_{AA} \times \sigma_{pp}} = \frac{\text{QCD Medium}}{\text{QCD Vacuum}}$$

- R_{AA} < 1: suppression
- R_{AA} = 1: no medium effects
- R_{AA} > 1: enhancement

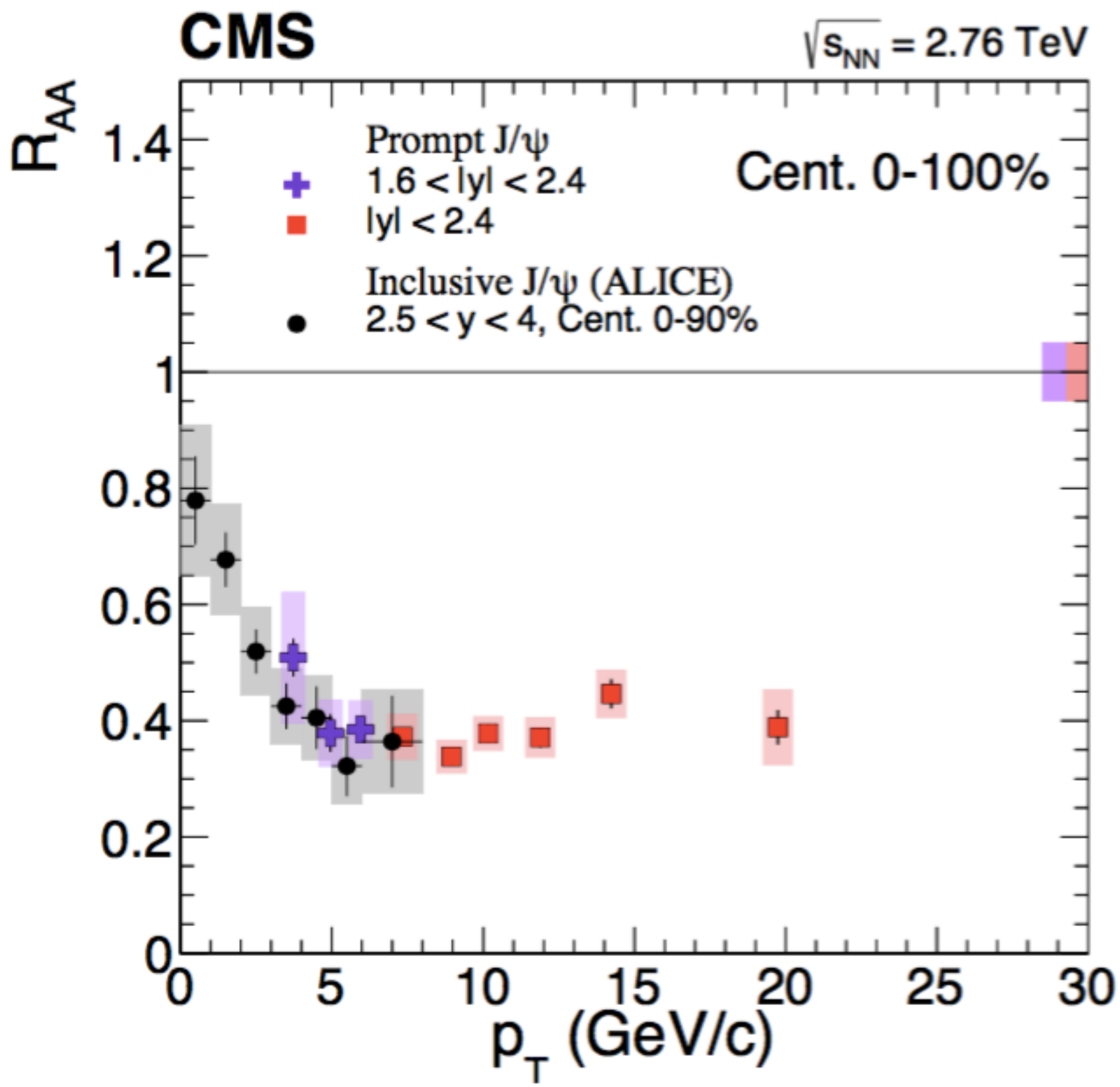


- Stronger suppression in more central collisions
- No significant rapidity or p_T dependence

EJPC 77 (2017) 252

Prompt J/ψ R_{AA}: CMS vs. ALICE

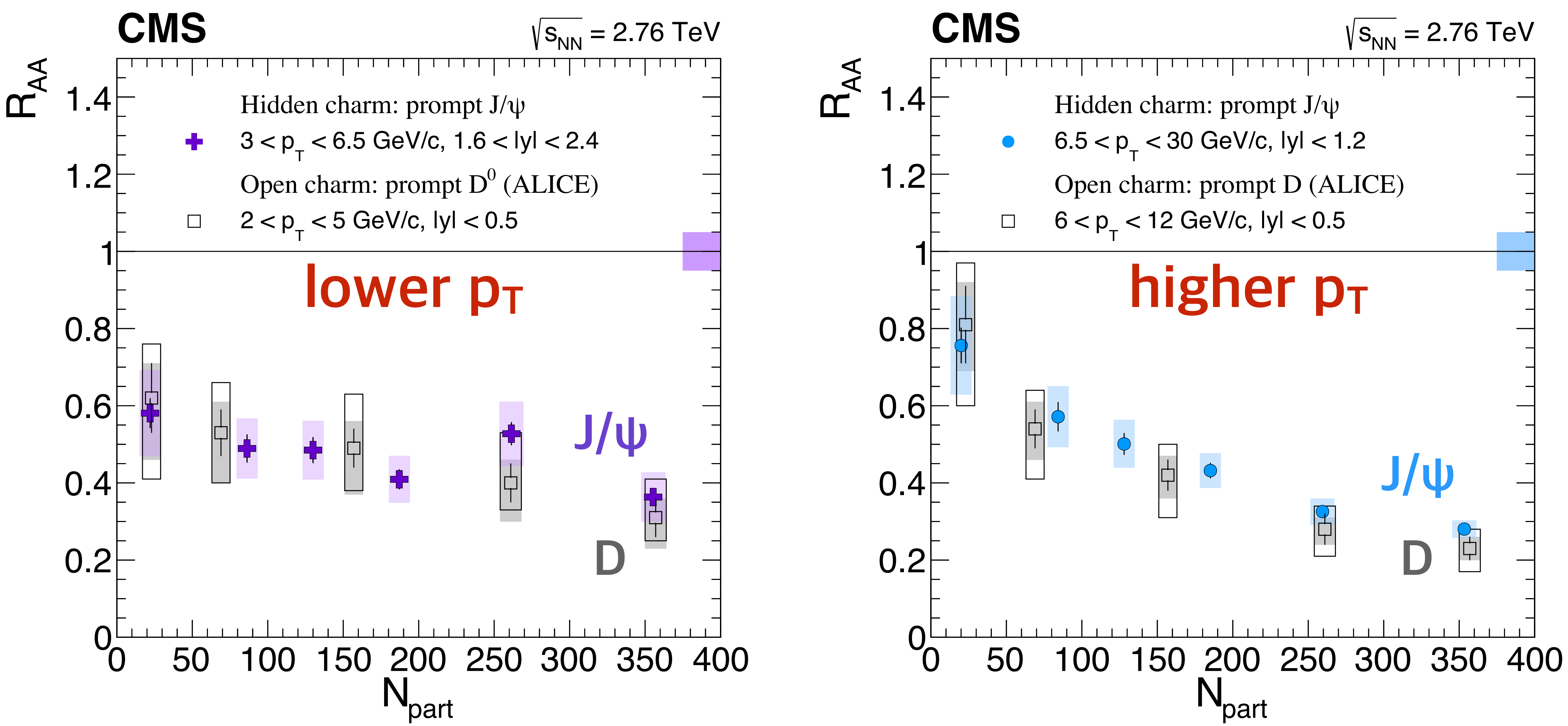
EJPC 77 (2017) 252



- Complements ALICE (starting from p_T = 0 GeV/c)

Open vs. Hidden charm

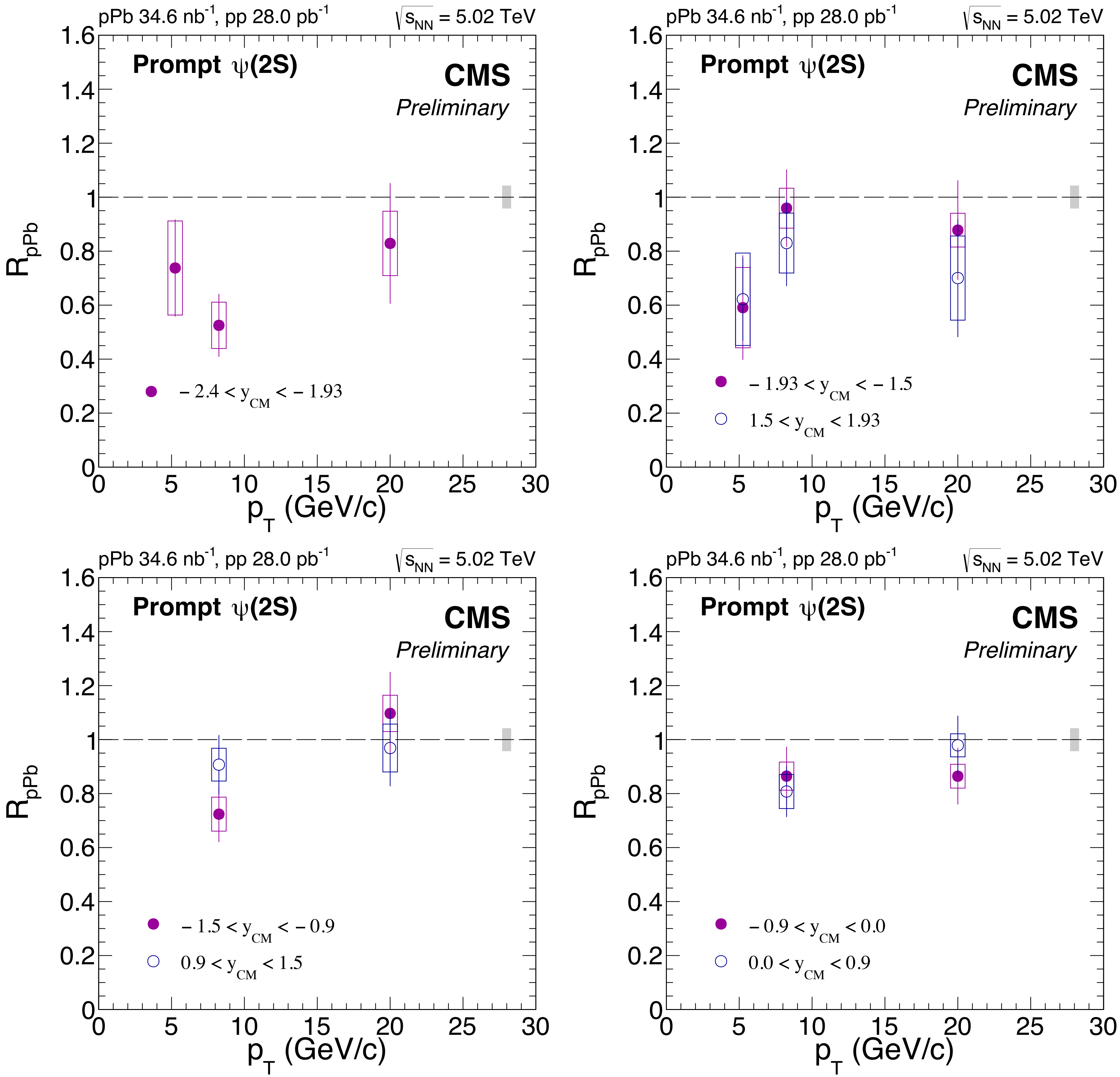
EJPC 77 (2017) 252



- J/ψ and D show a similar suppression
- Modification is an admixture of several mechanisms, and

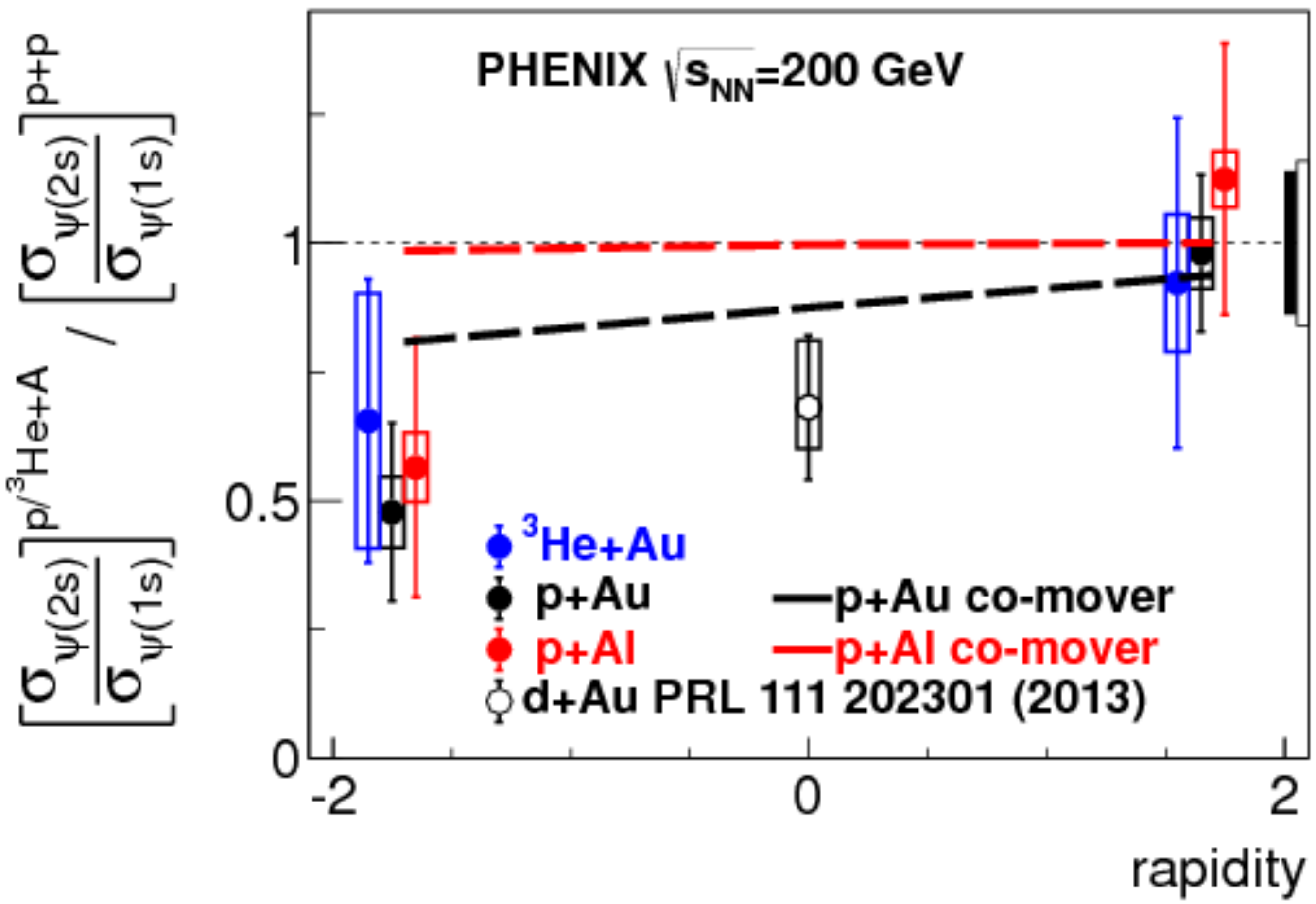
  Each processes would be different for open and hidden charm
  - e.g. Debye screening, regeneration, nuclear effects, feed-down, etc

Prompt ψ(2S) R_{pPb} vs. p_T

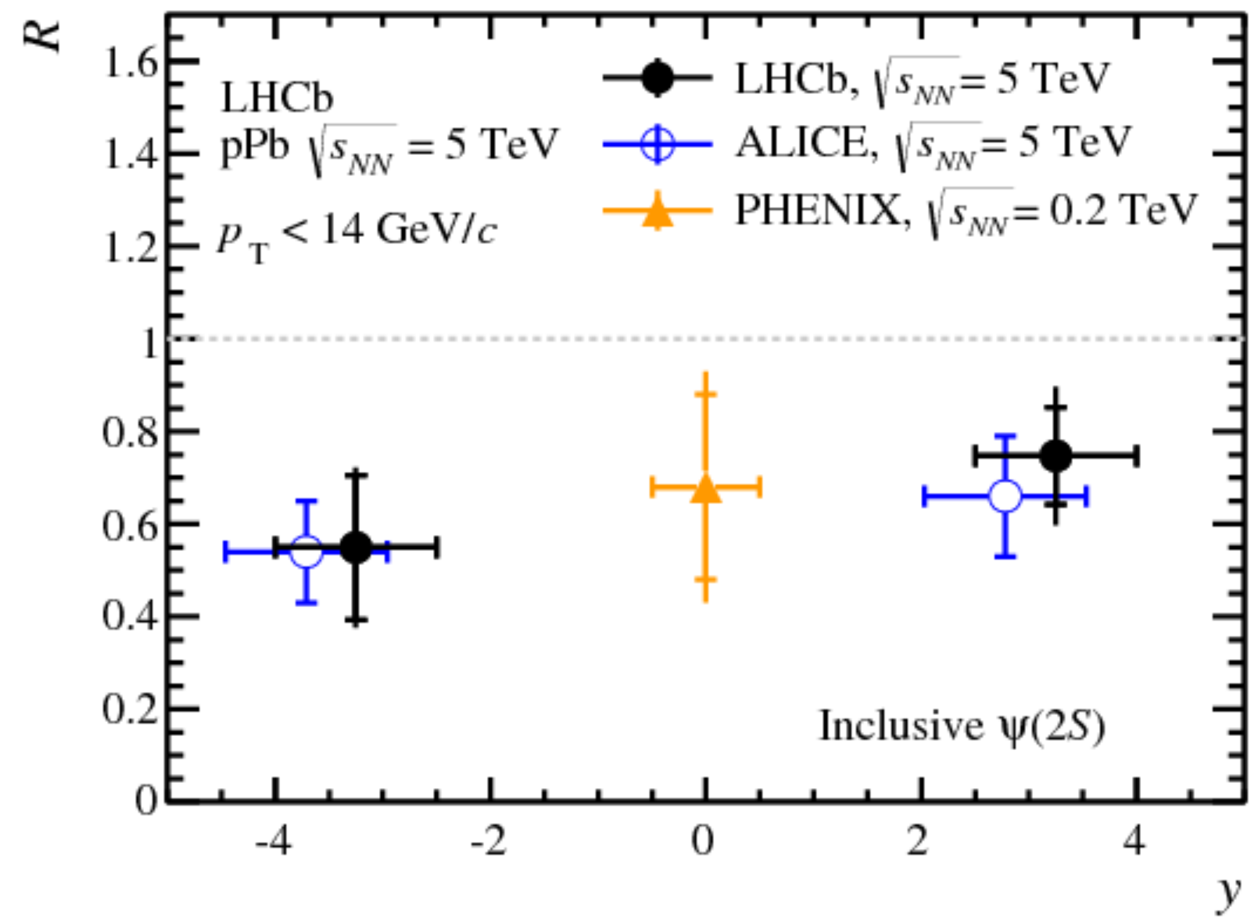


CMS-PAS-HIN-16-015

RHIC



LHC



BW

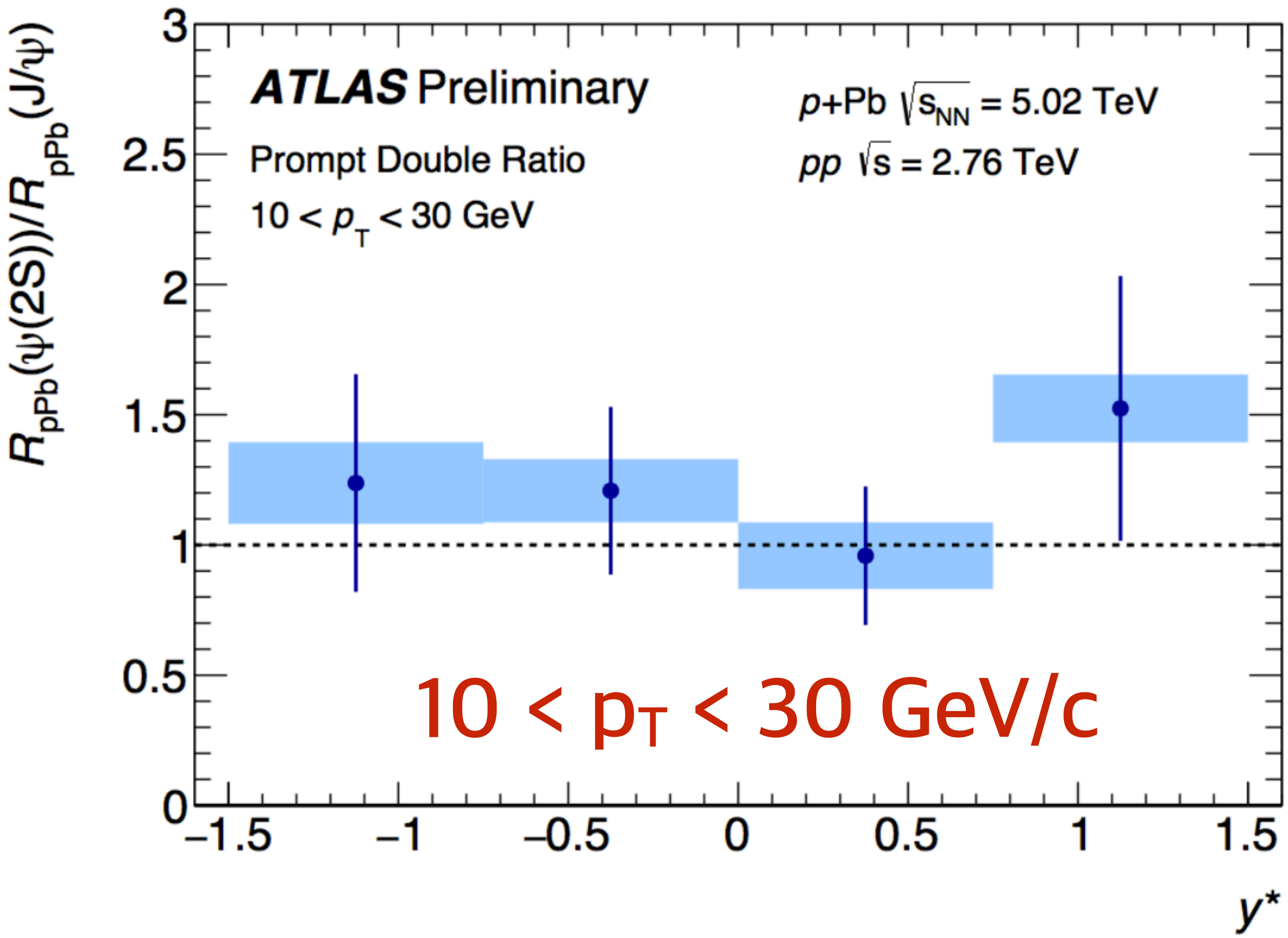
FW

PLC 95 (2017) 034904

JHEP 03 (2016) 133

- Hint for stronger suppression of ψ(2S) w.r.t. J/ψ at backward
- Co-mover model qualitatively agrees with data

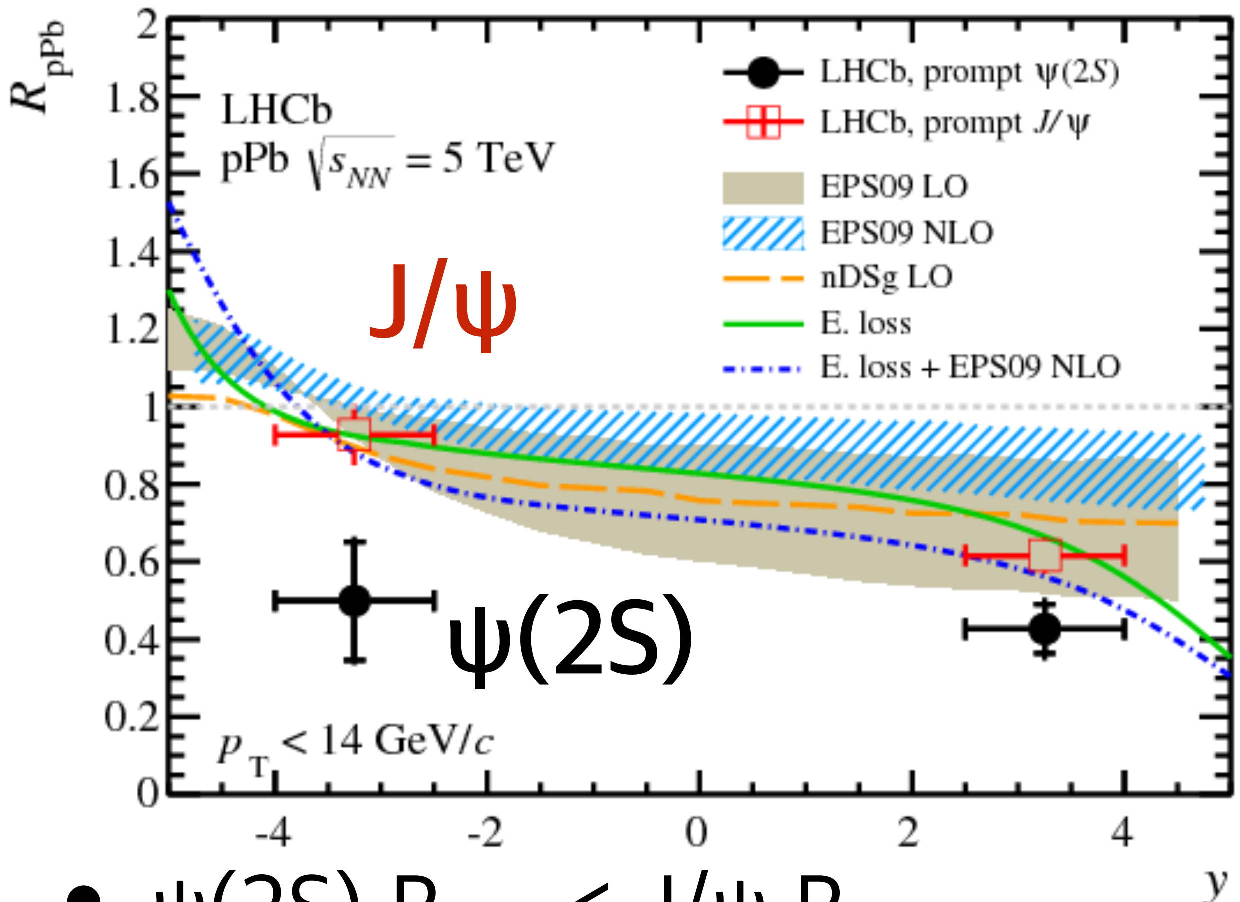
ψ(2S) to J/ψ DR vs. y: ATLAS



- Double Ratios consistent with unity
- Higher p_T and mid-y compared to ALICE and LHCb

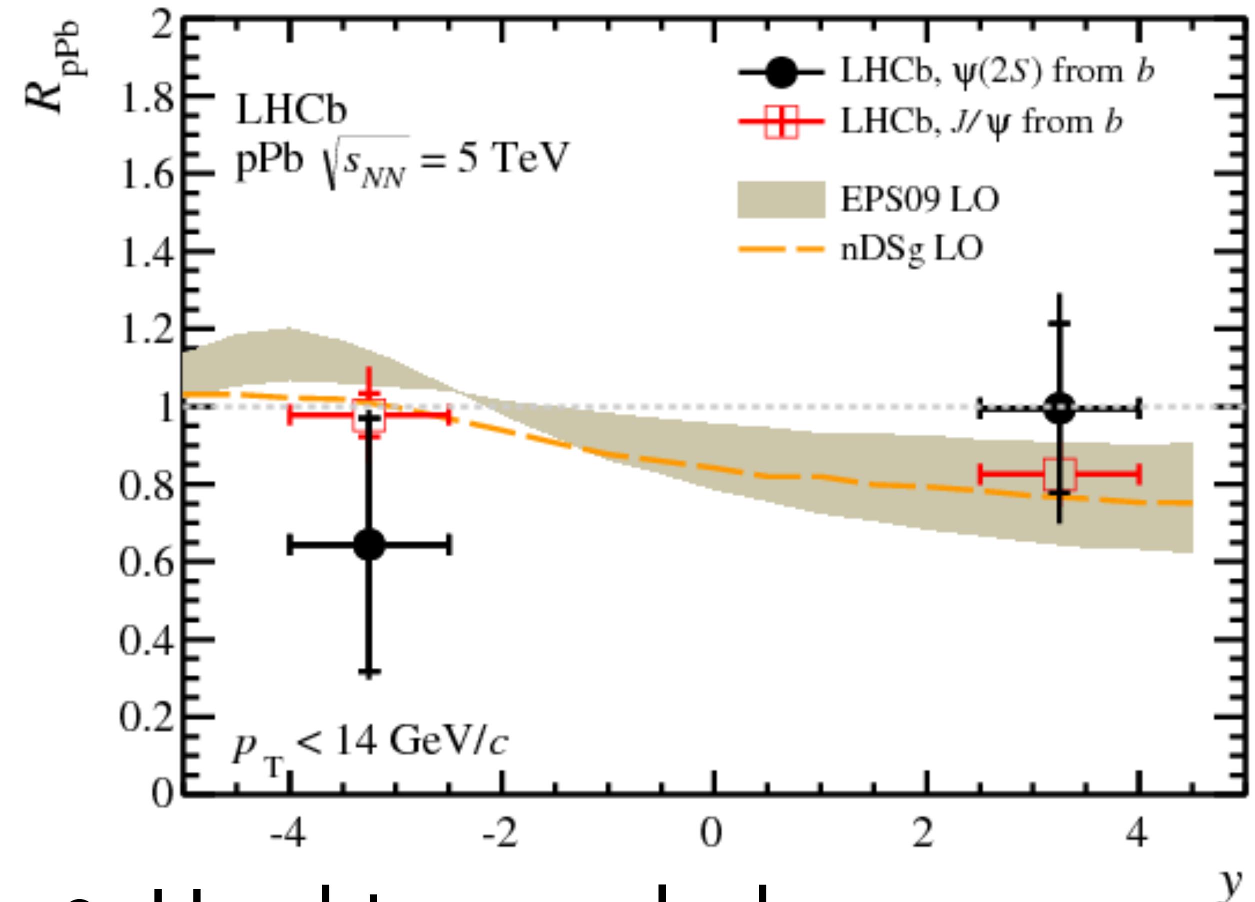
J/ψ and ψ(2S) R_{pPb} vs. y: LHCb

Prompt



- ψ(2S) R_{pPb} < J/ψ R_{pPb}
- Results are not well described by shadowing and E loss
- Final state effects suggested (interaction of cc_bar pair with the dense medium created)

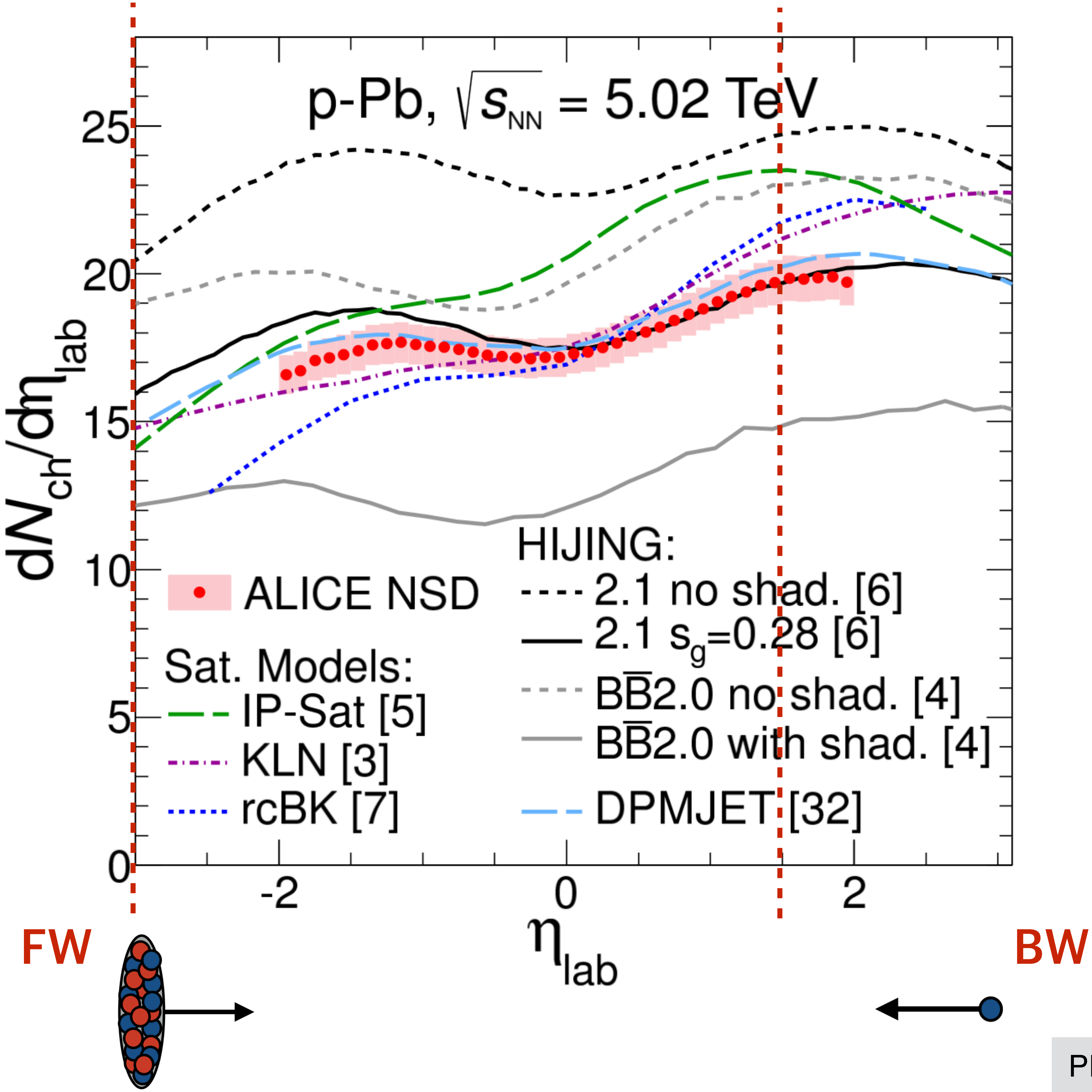
Nonprompt



- Hard to conclude (arge statistical uncertainties)

JHEP 03 (2016) 133

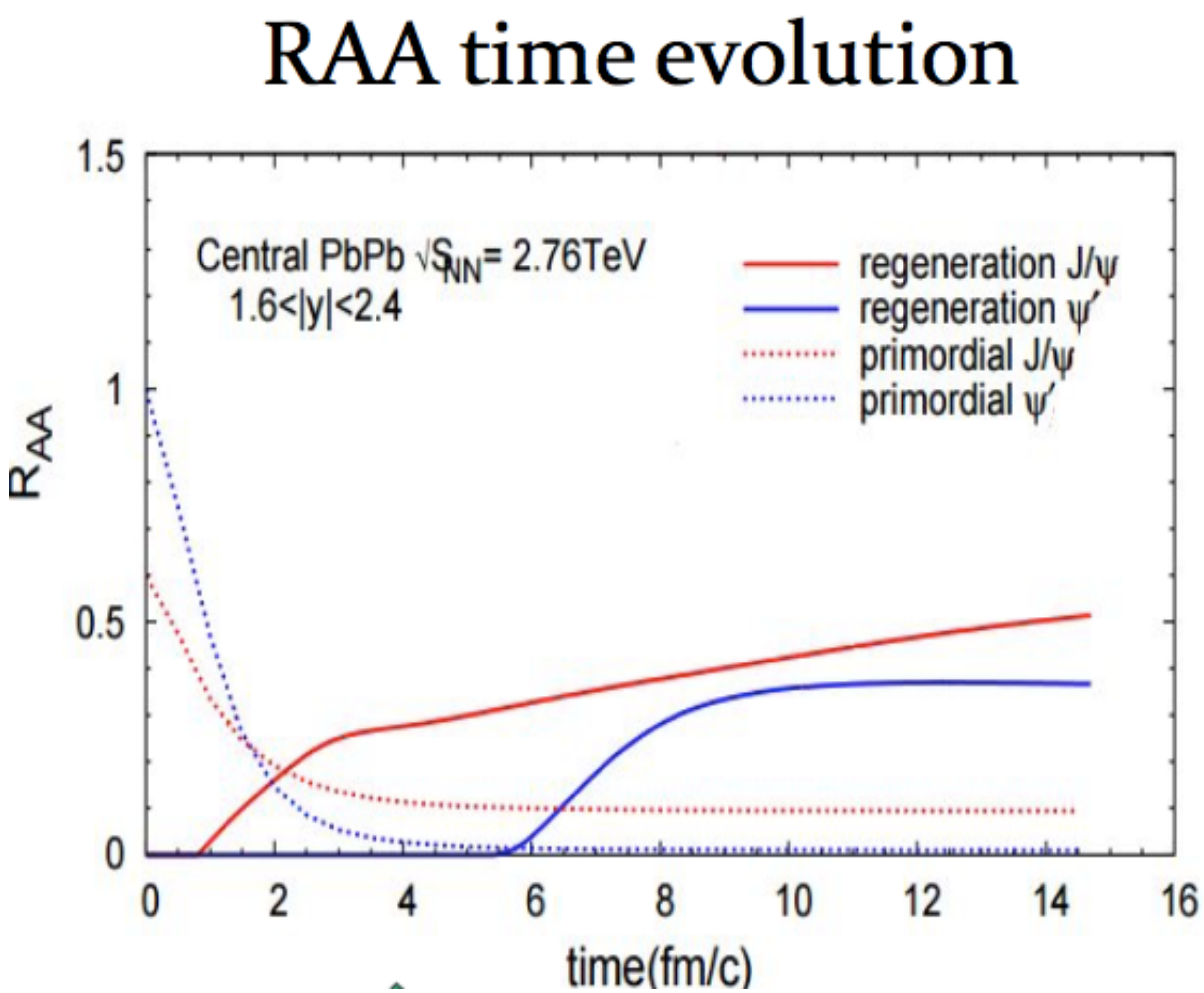
η density of charged particles in pPb

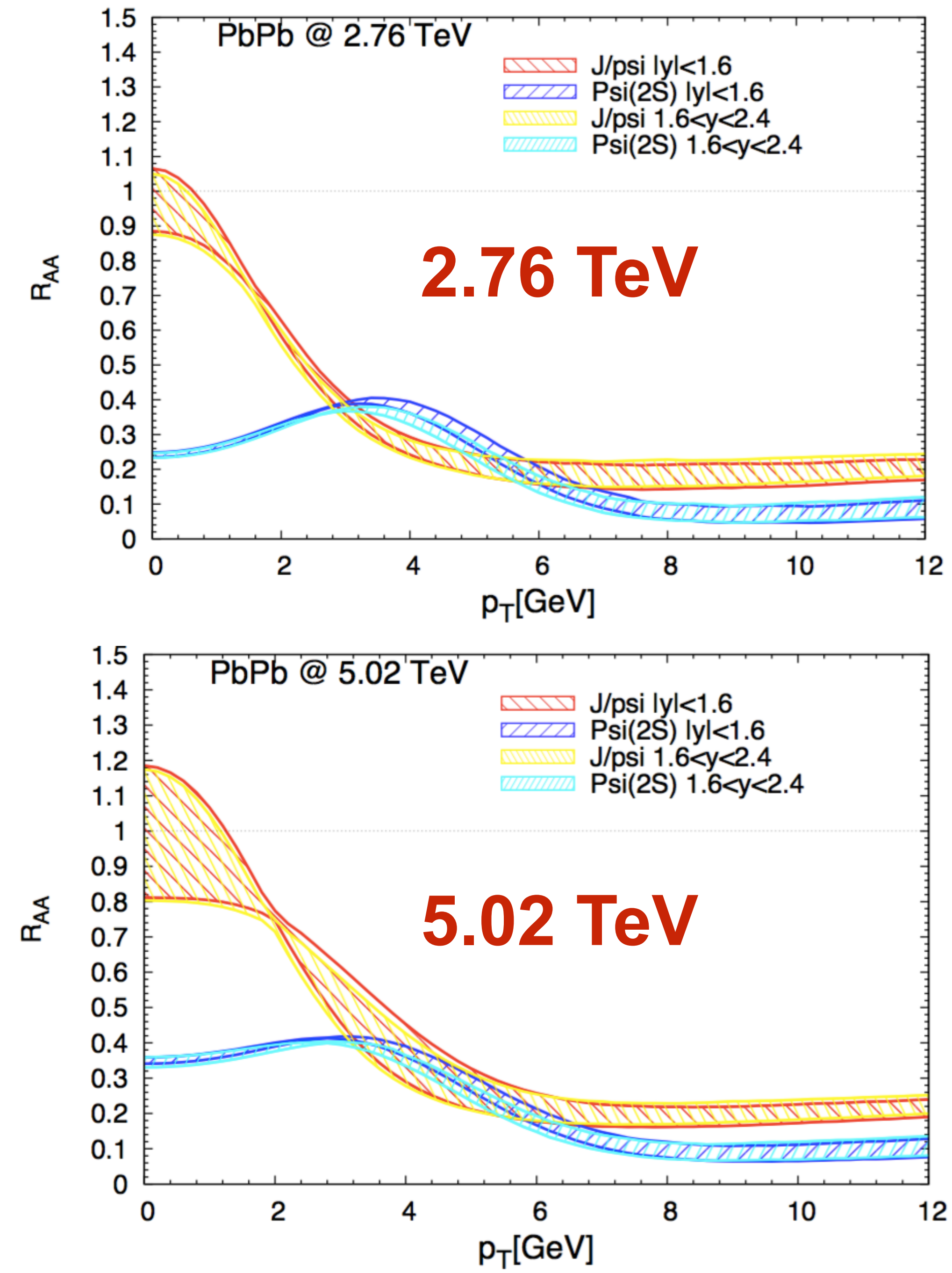


PRL 110 (2013) 032301

Transport model for ψ(2S) to J/ψ DR

arXiv.1609.04848



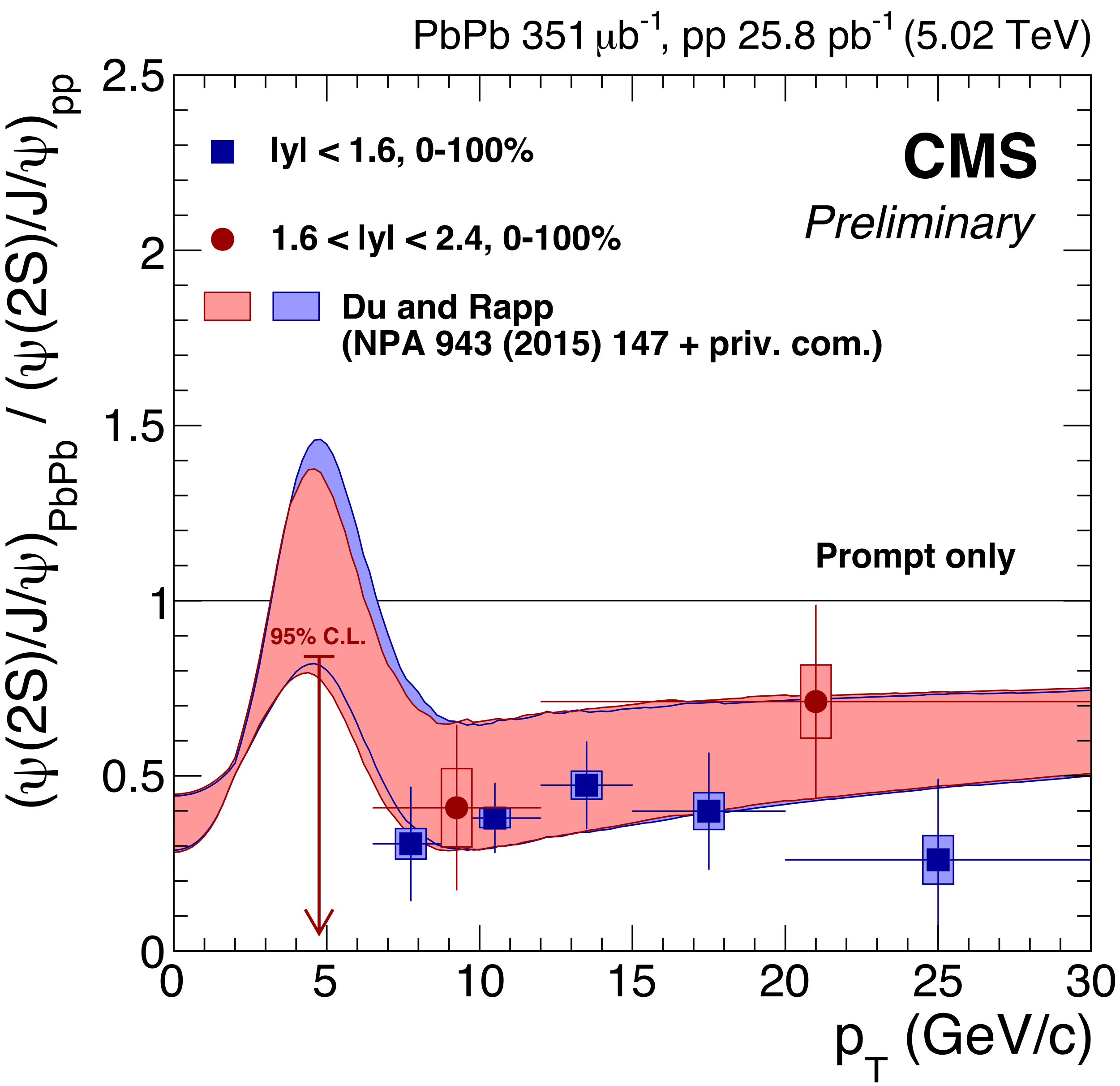


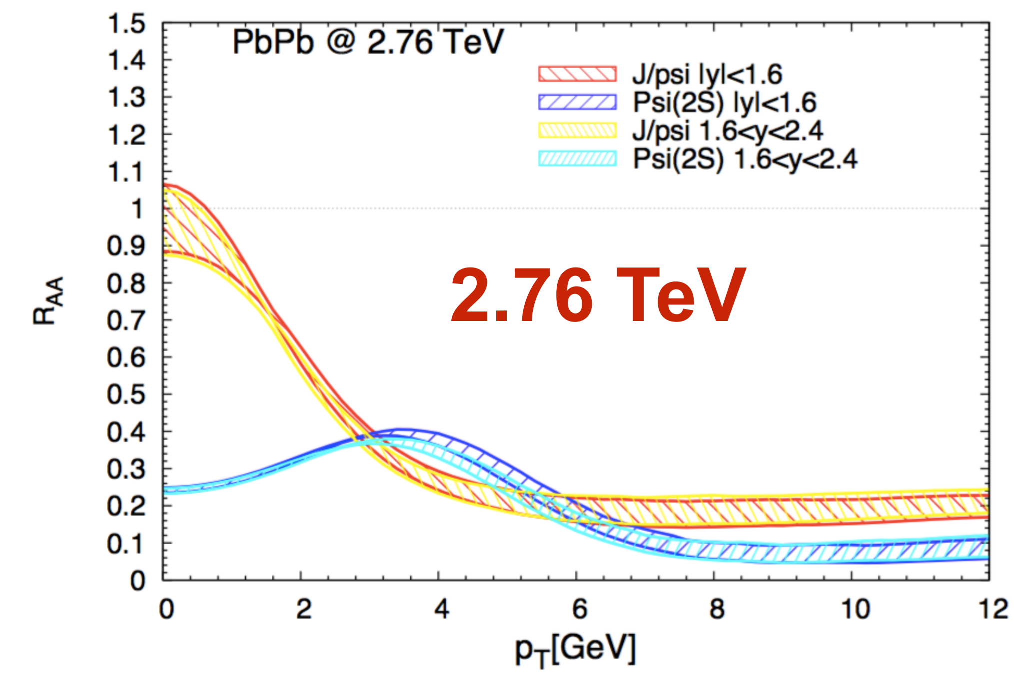
- Most ψ(2S) regenerated later than J/ψ
- transverse-flow pushes ψ(2S) to higher p_T
- DR >1 possible while to total yield ψ(2S) remains smaller than that of J/ψ

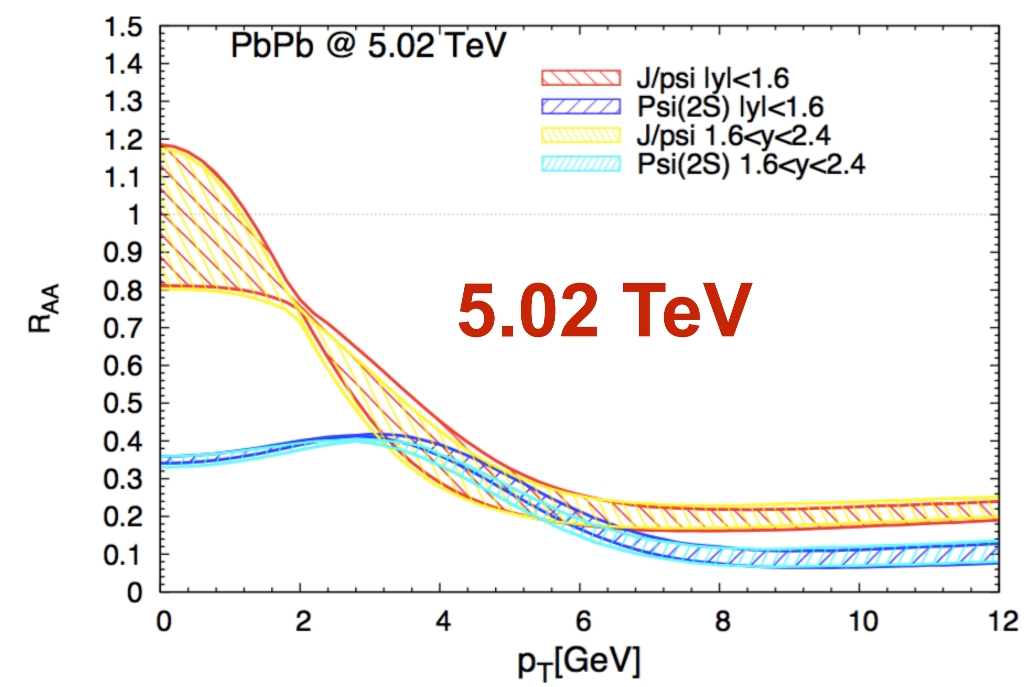
- Due to the larger flow at 5.02 TeV, more regenerated J/ψ are pushed to higher p_T

Transport model for ψ(2S) to J/ψ DR

arXiv.1609.04848



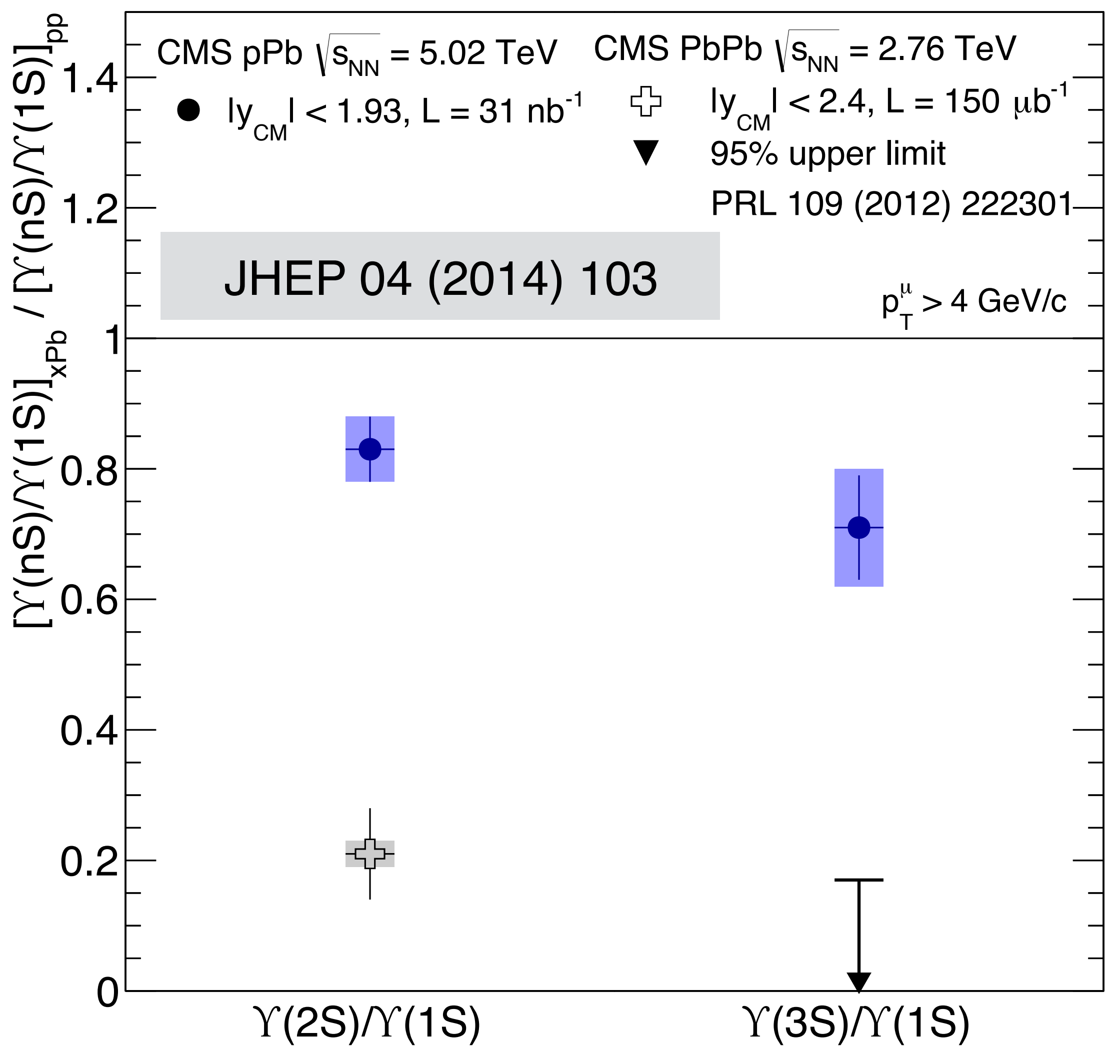




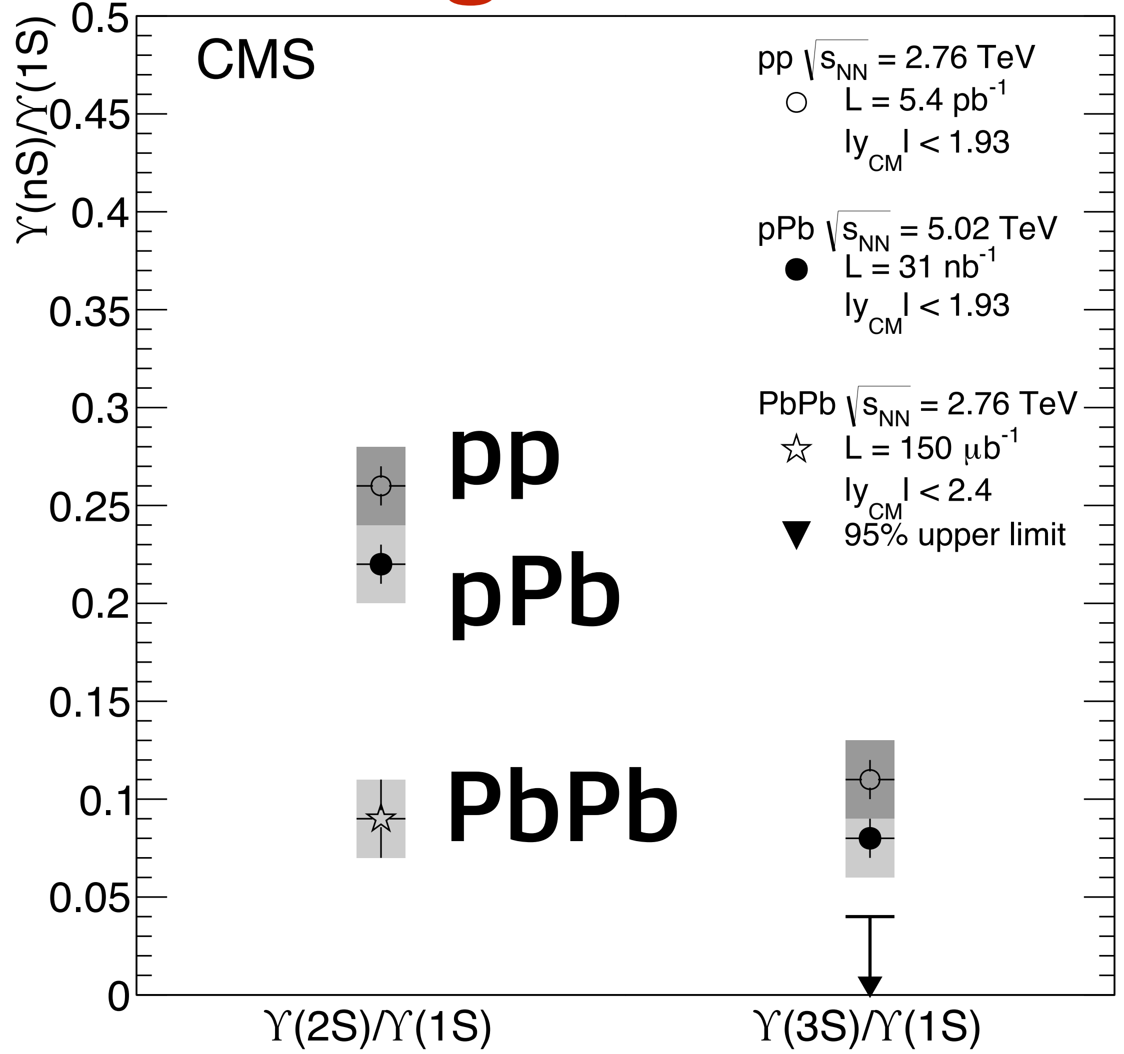
- Due to the larger flow at 5.02 TeV, more regenerated J/ψ are pushed to higher p_T

Υ(nS) cross sections

Double Ratios



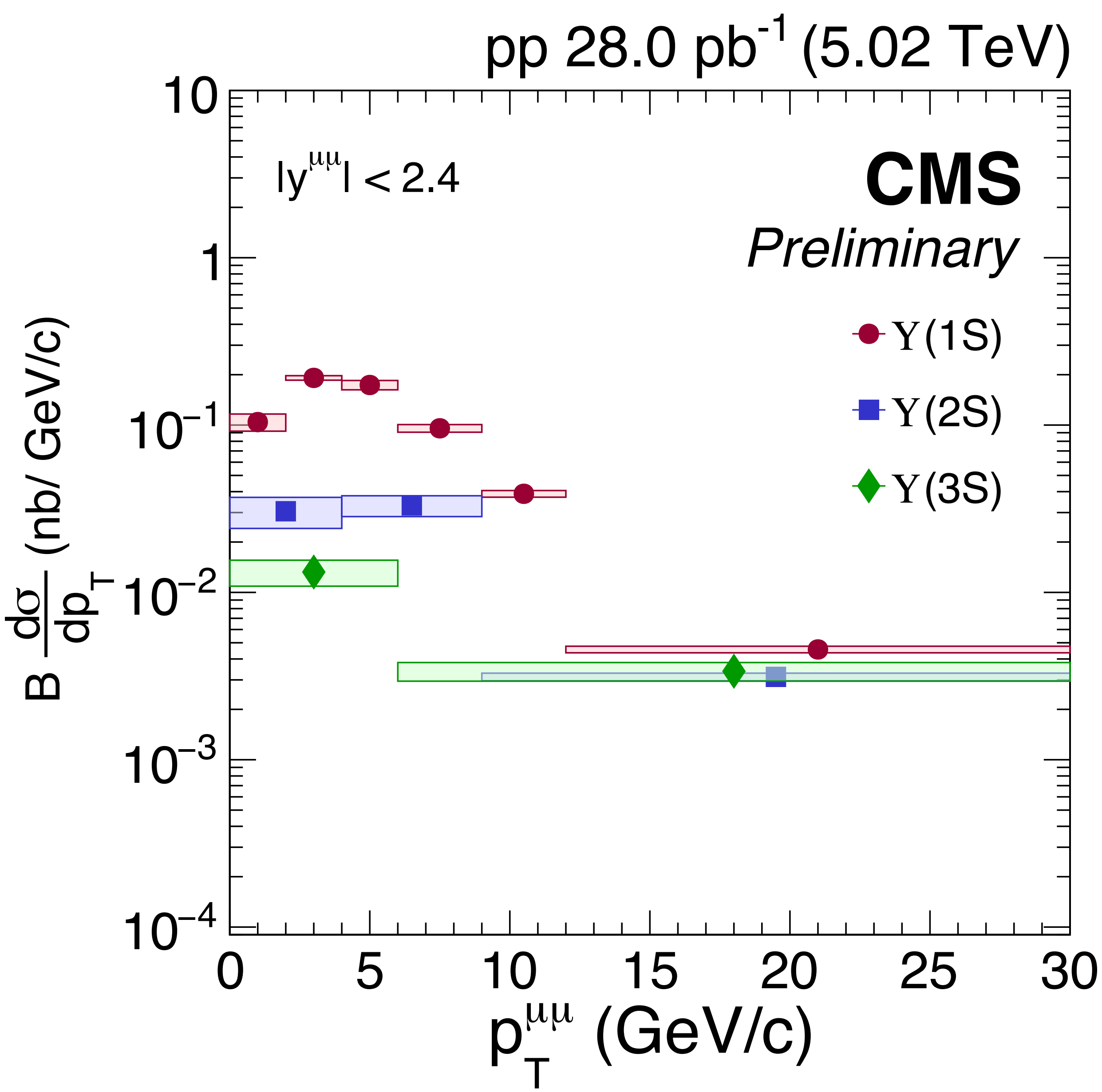
Single Ratios



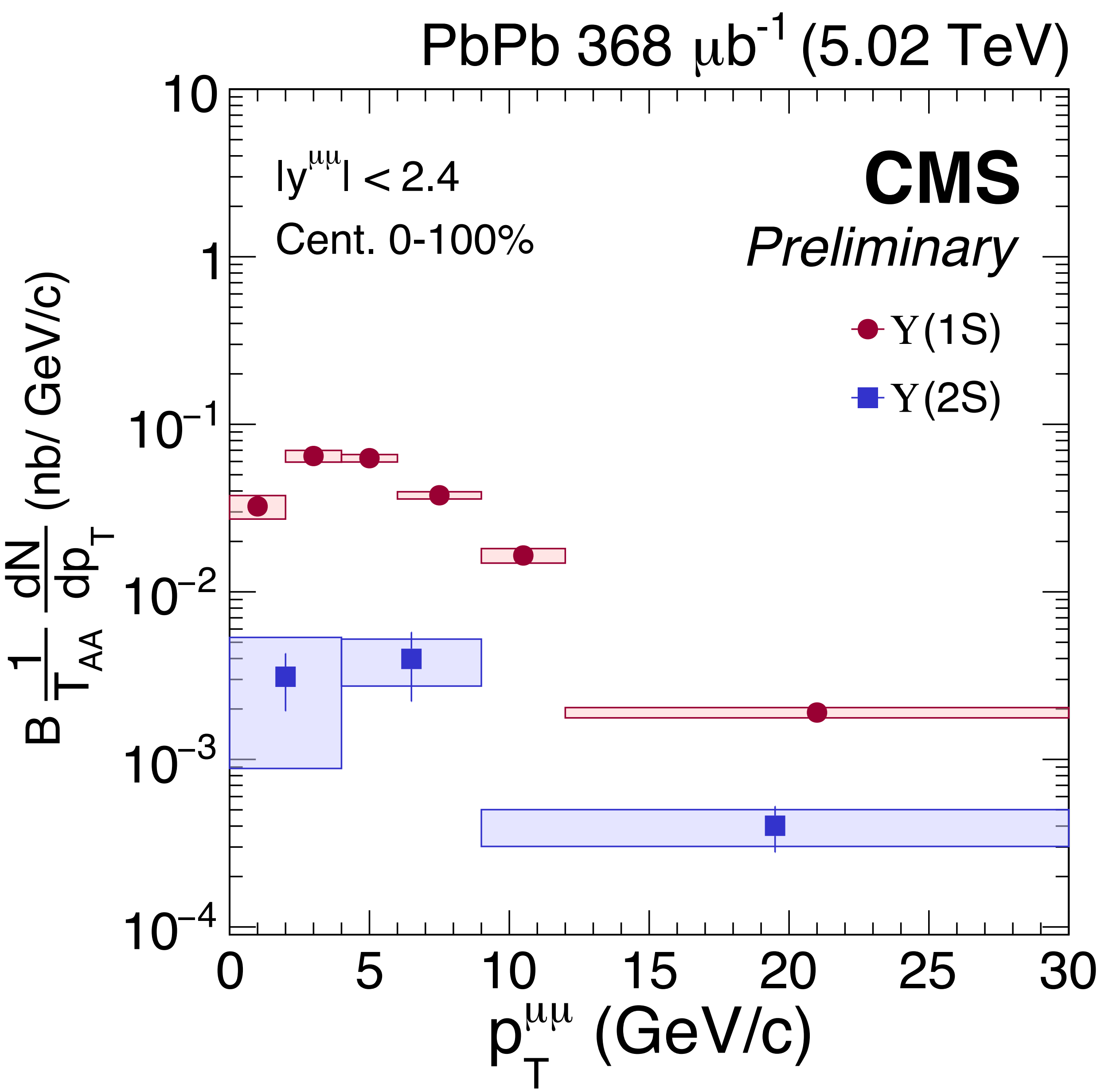
- **pPb vs pp** : Excited states are suppressed more than Υ(1S) in pPb compared to pp
- **PbPb vs pPb** : Additional final state effects in PbPb that affect the excited states more than Υ(1S)

Υ(nS) cross sections

pp

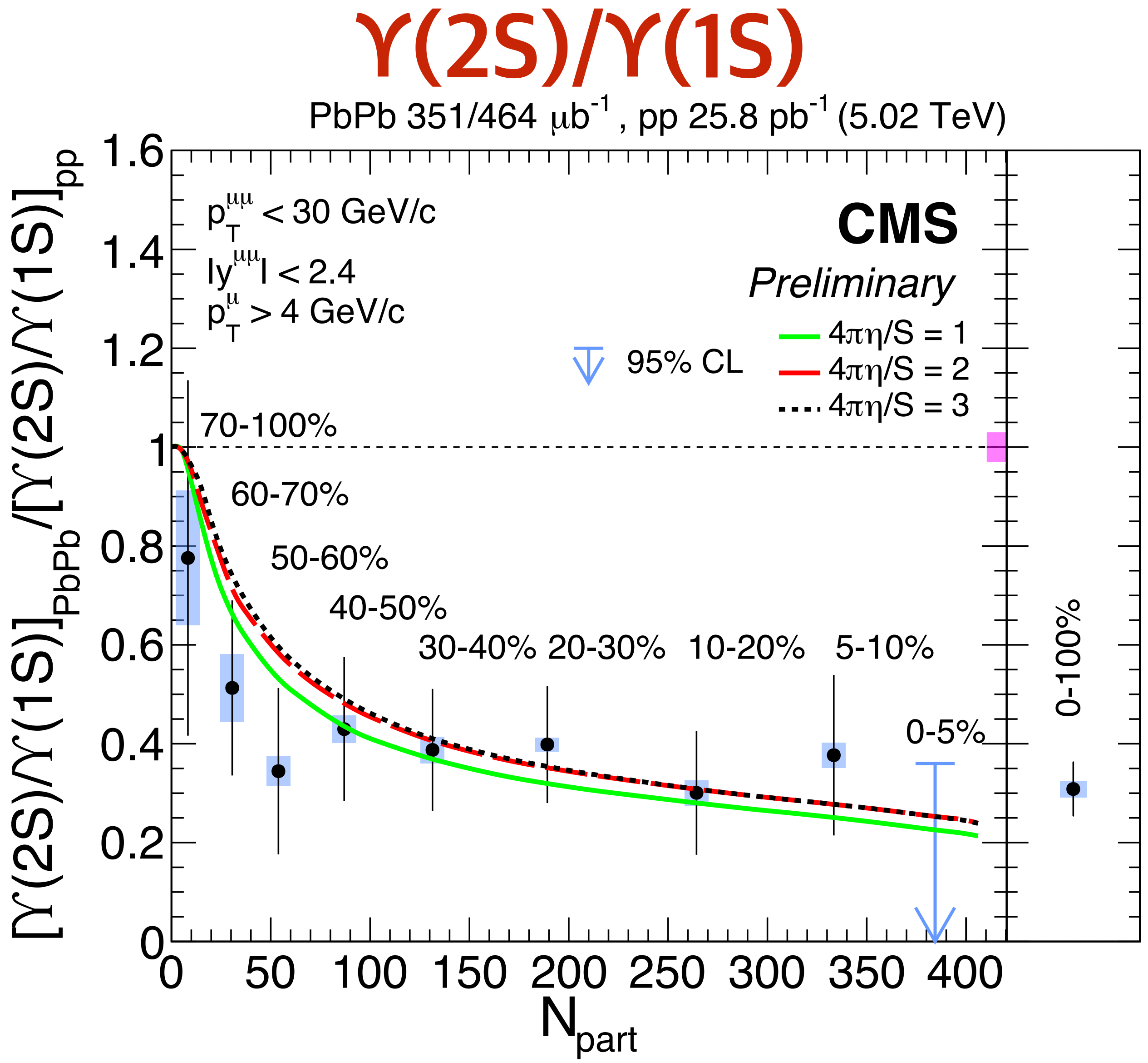


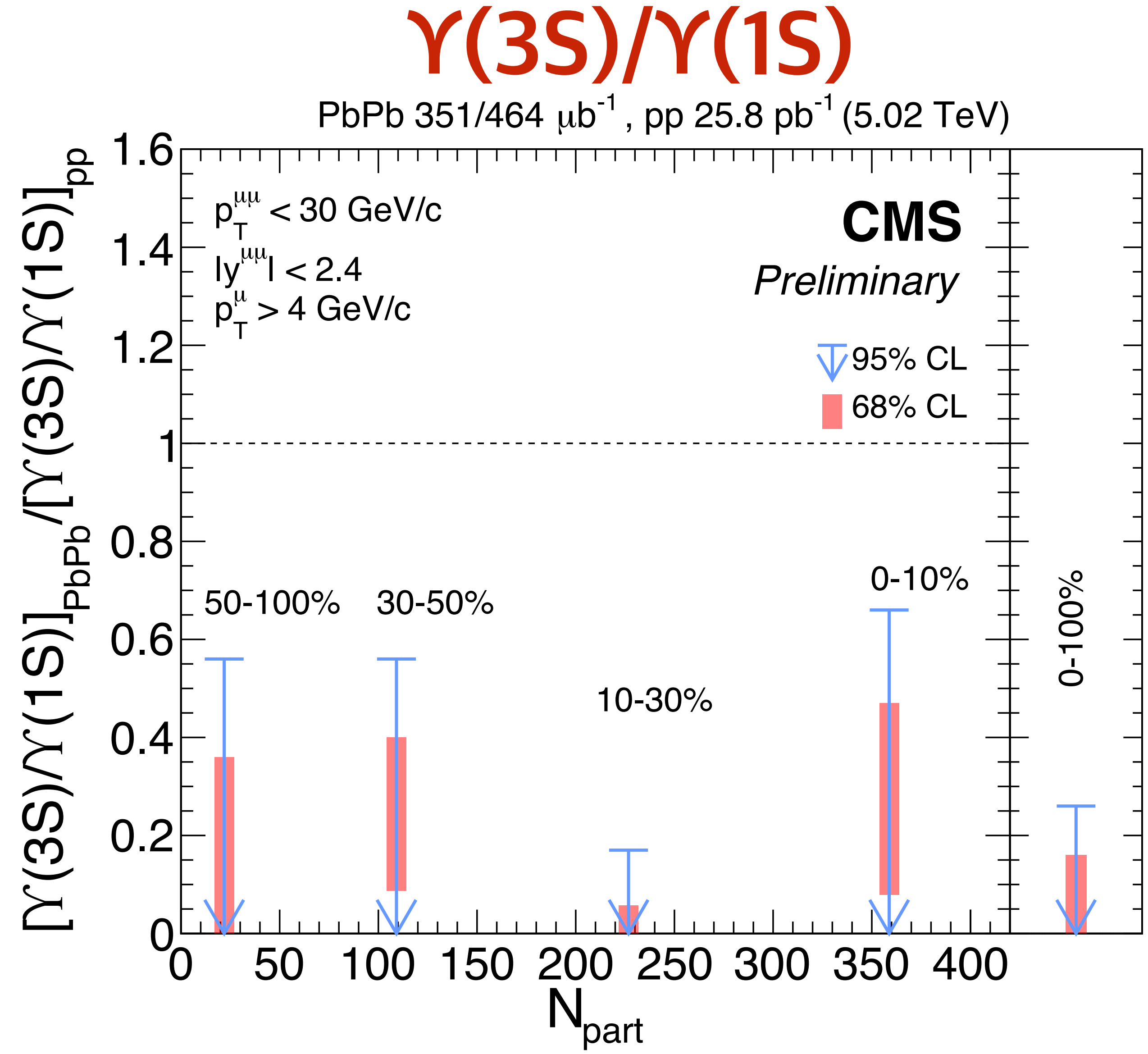
PbPb



CMS-PAS-HIN-16-023

Υ(nS) to Υ(1S) DR in PbPb



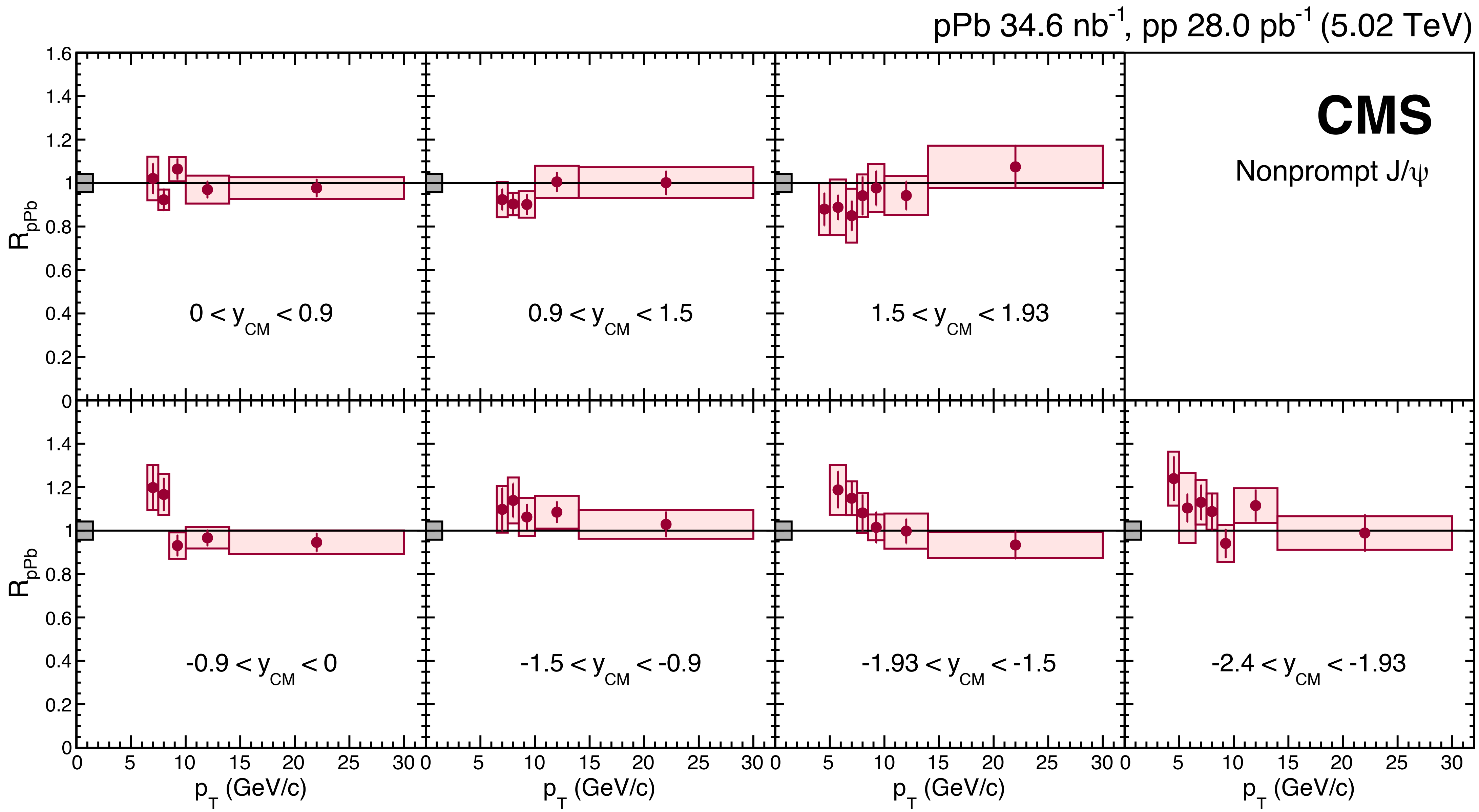


- Υ(2S) is more suppressed than Υ(1S)
  - Stronger suppression in more central collisions
  - Consistent with unity at peripheral 70-100 %
  - Hydrodynamic model (Krouppa, Strickland) describes data
- Υ(3S) is strongly suppressed in all centralities

CMS-PAS-HIN-16-008

Nonprompt J/ψ R_{pPb} vs. p_T

EPJC 77 (2017) 269

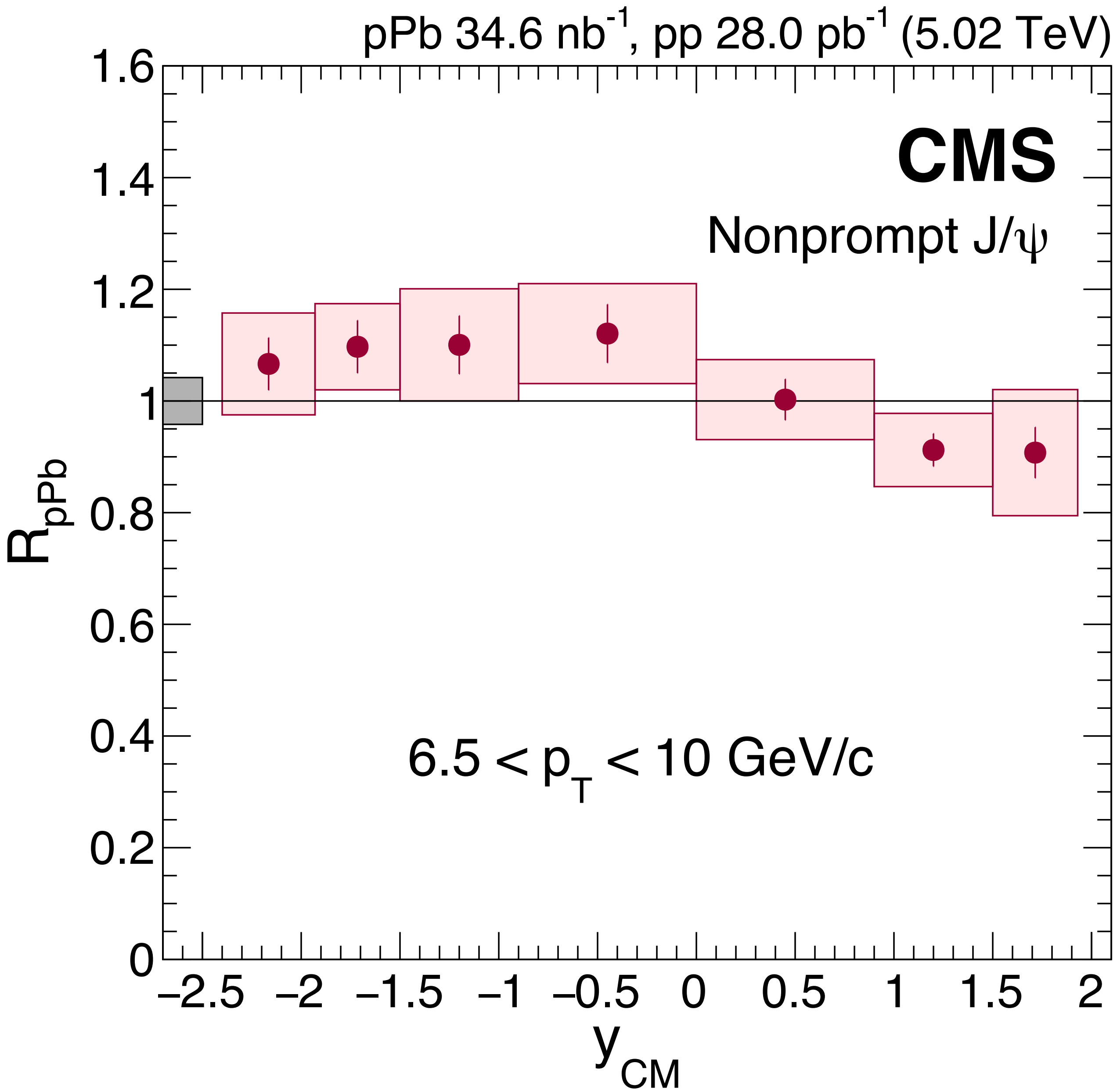


- RpPb ~ 1 in all y_{CM} bins analyzed
- Possible enhancement at backward and low p_T (≲ 7.5 GeV/c)

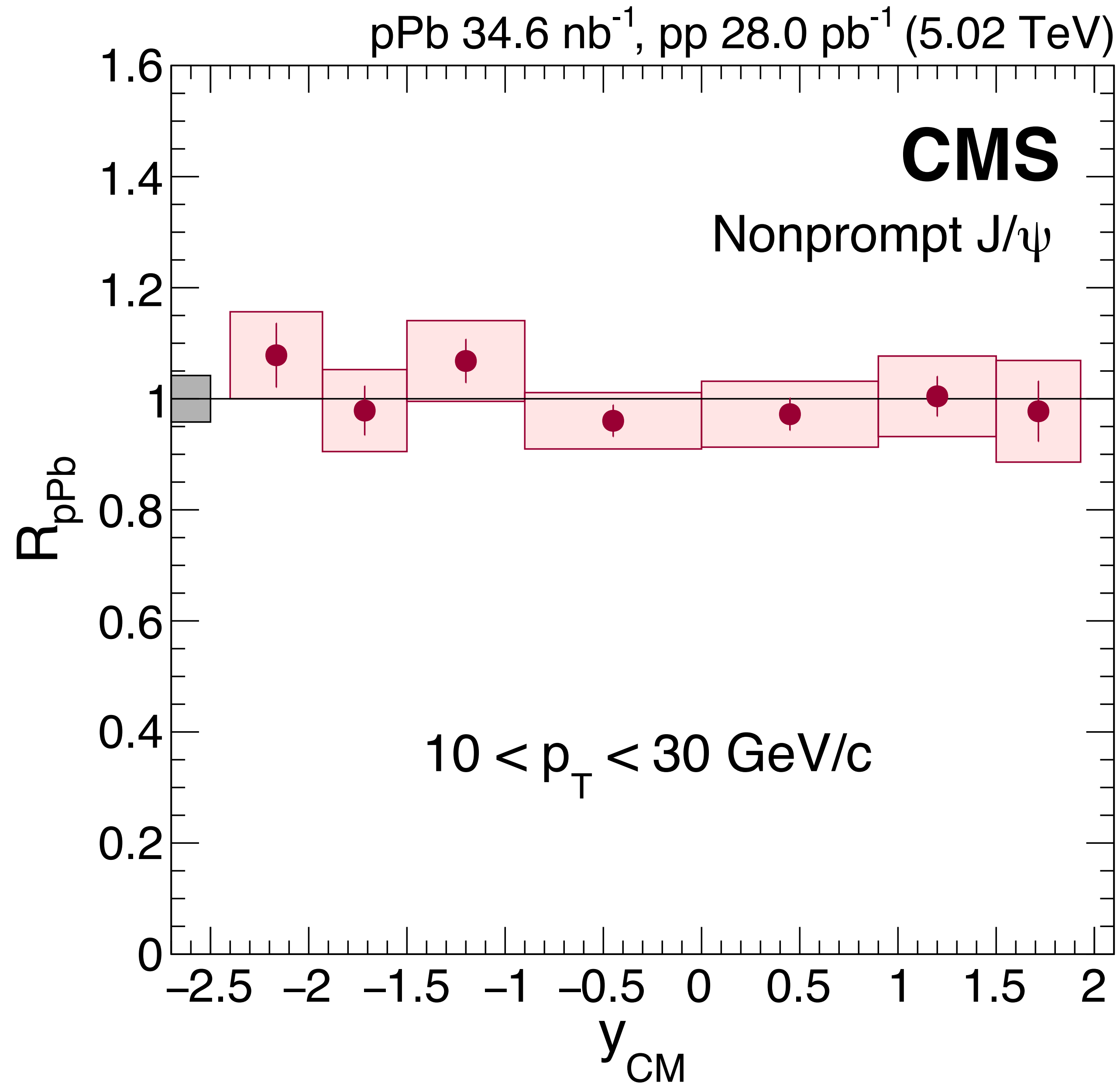
Nonprompt J/ψ R_{pPb} vs. p_T

EPJC 77 (2017) 269

Lower p_T



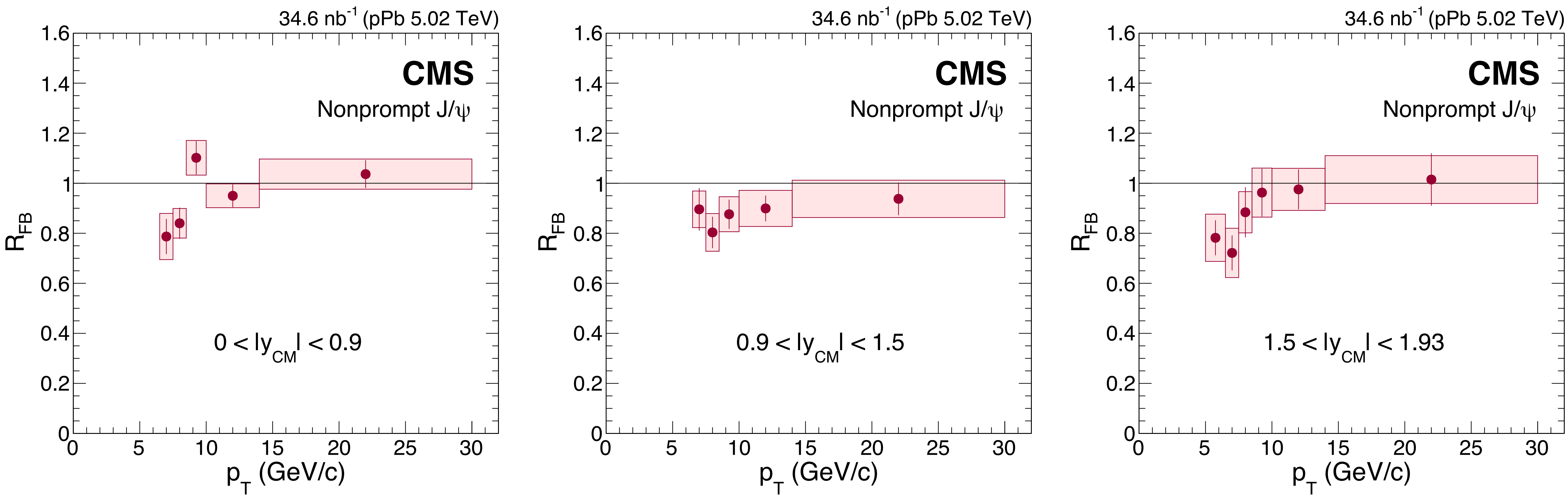
Higher p_T



- Lower p_T: possible decrease of R_{pPb} at forward
- Higher p_T: R_{pPb} is consistent with unity

Nonprompt J/ψ R_{pPb} vs. p_T

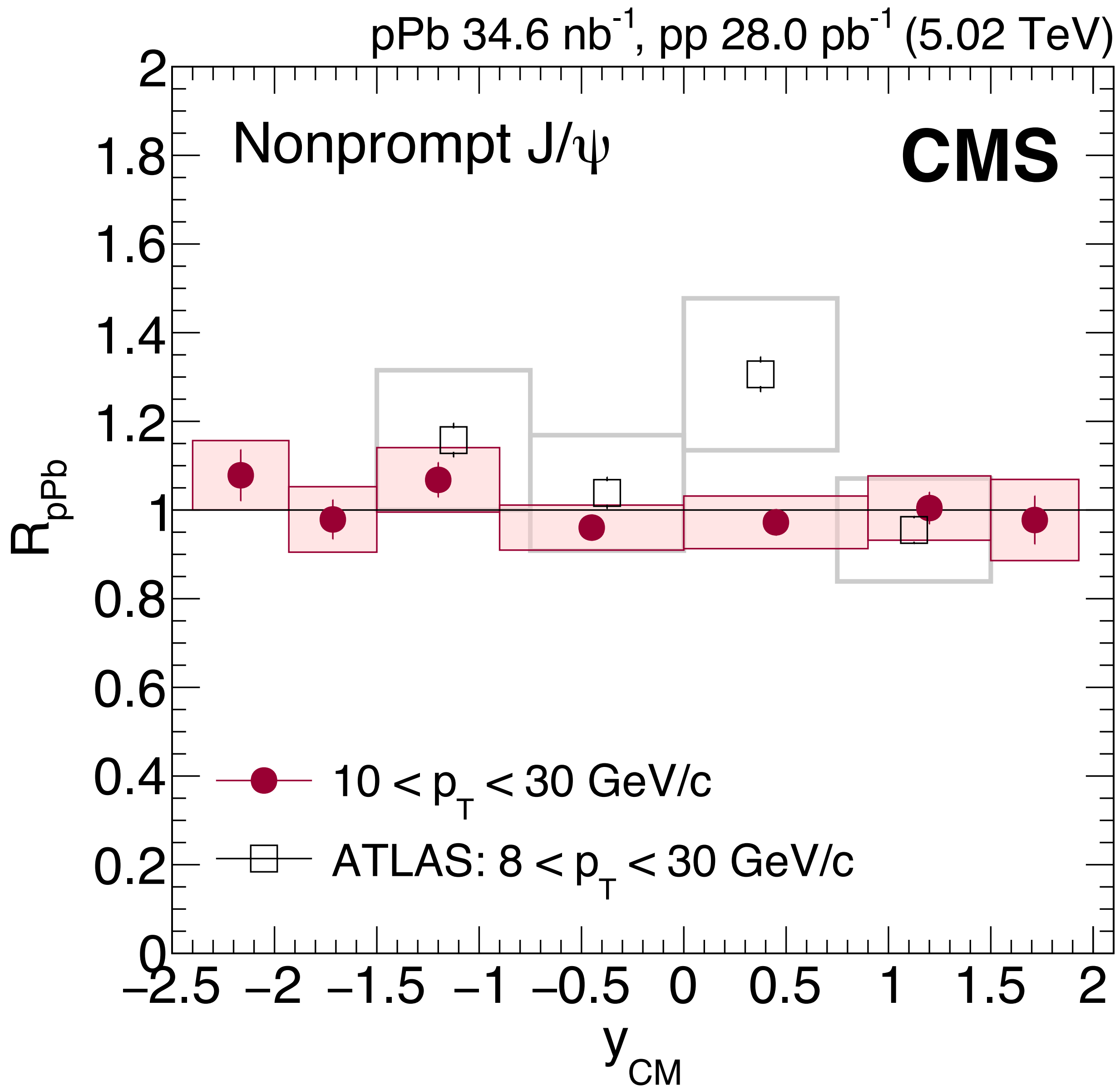
EPJC 77 (2017) 269

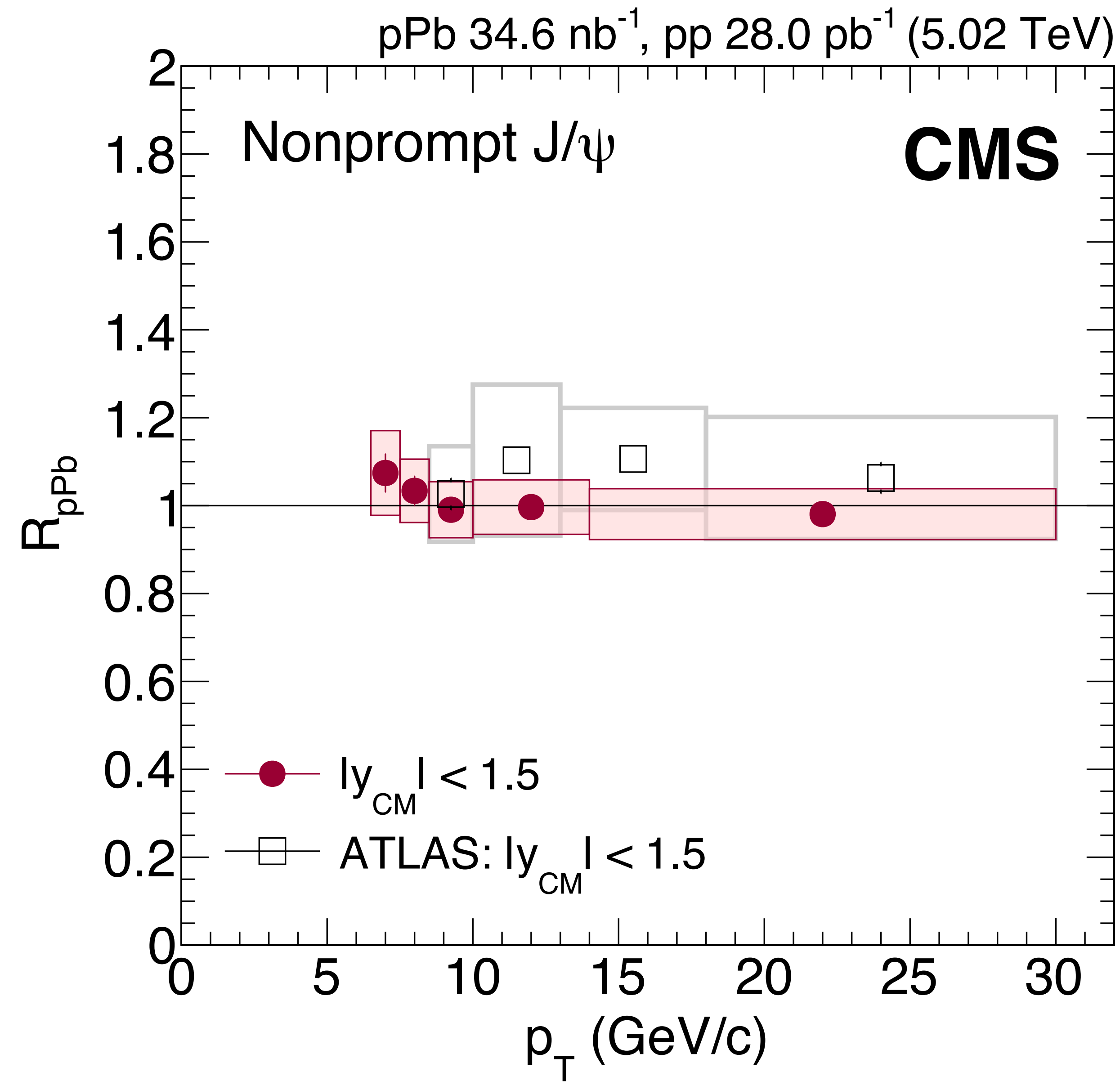


- R_{FB} seems to increase slightly with p_T in all y_{CM} bins

Nonprompt J/ψ R_{pPb}: CMS vs. ATLAS

EPJC 77 (2017) 269

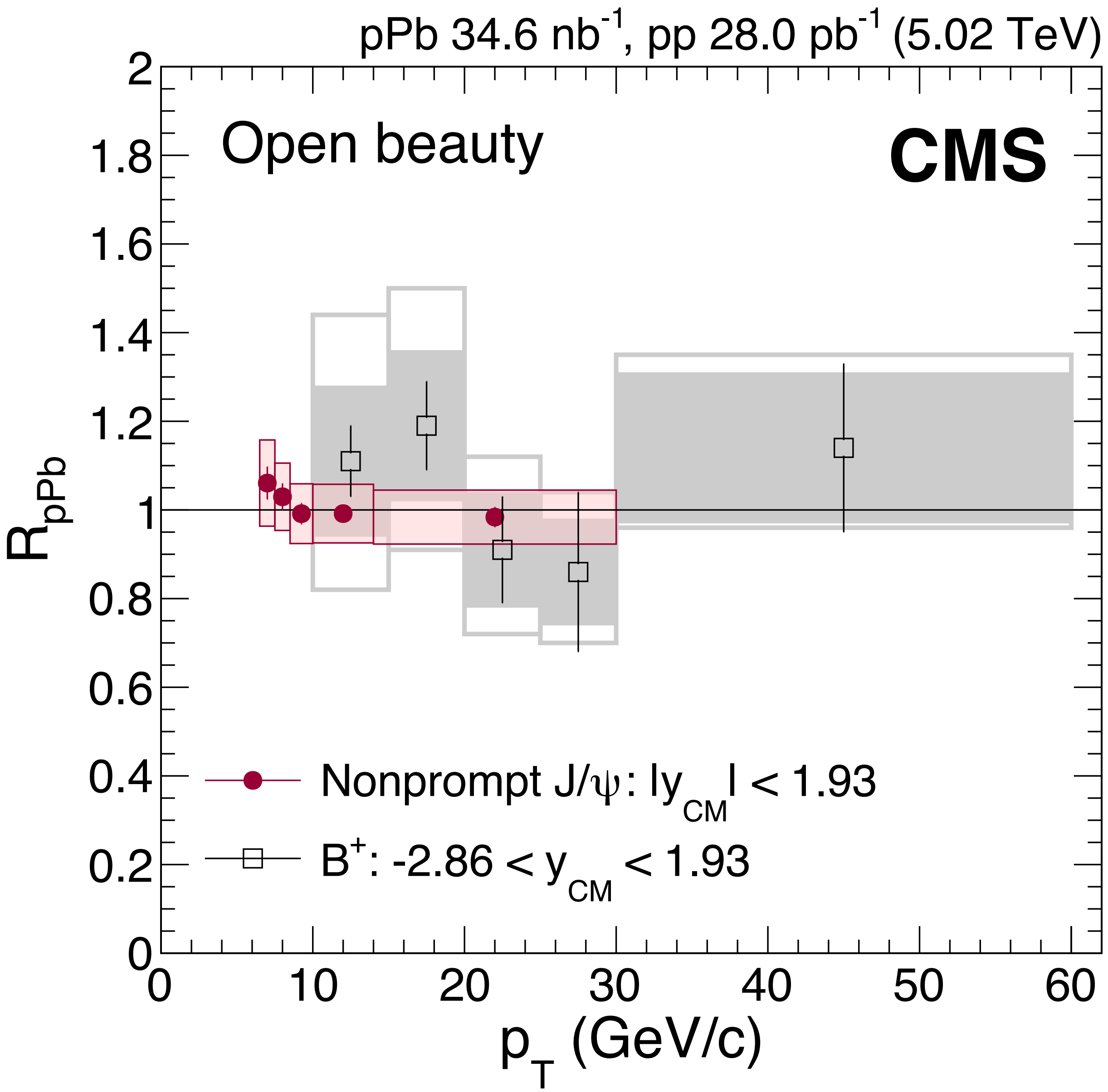


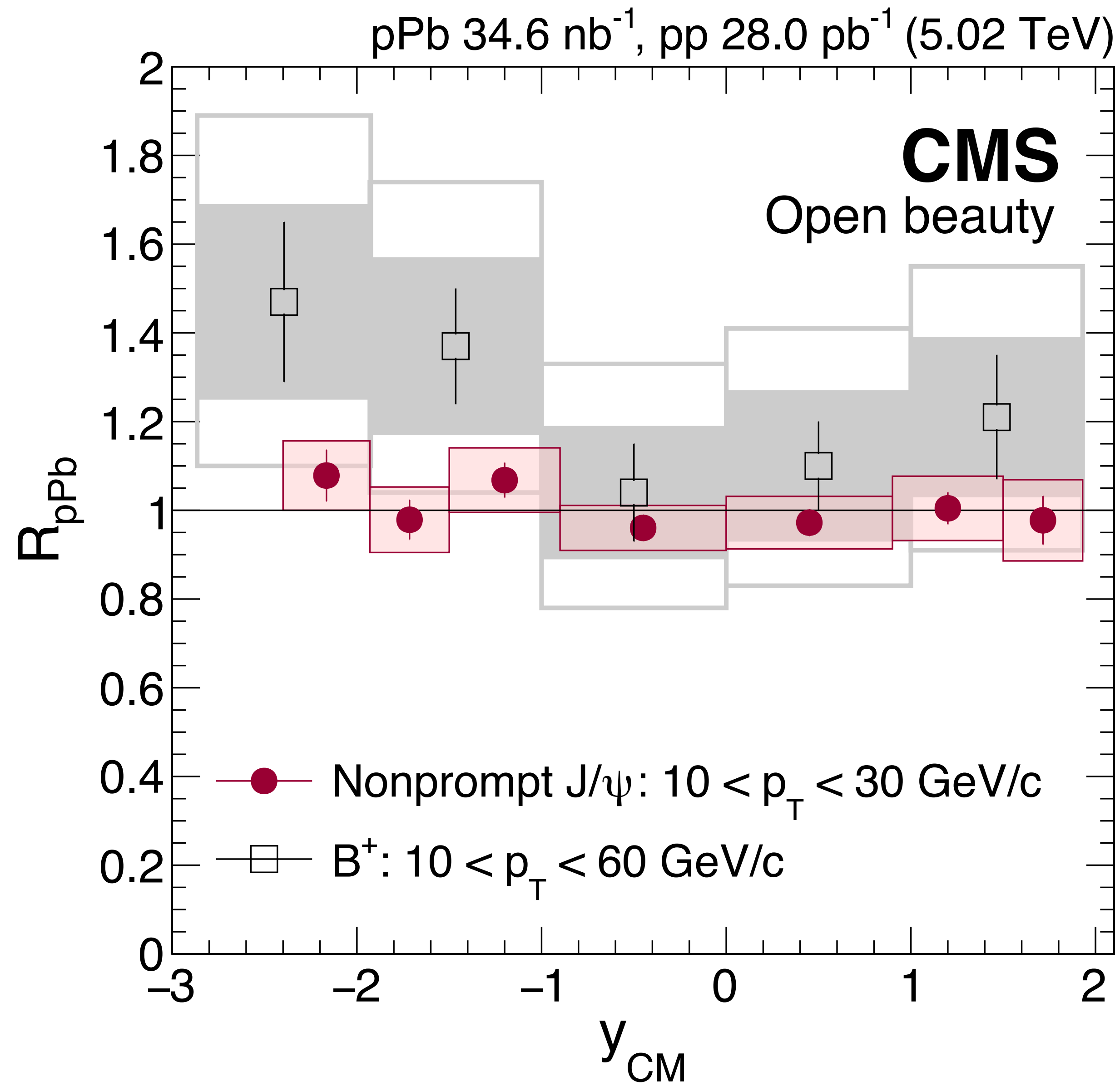


- CMS results are integrated over $|y_{CM}| < 1.5$
- ATLAS using interpolated pp reference
- Two results are in agreement

Nonprompt J/ψ vs. B mesons

EPJC 77 (2017) 269

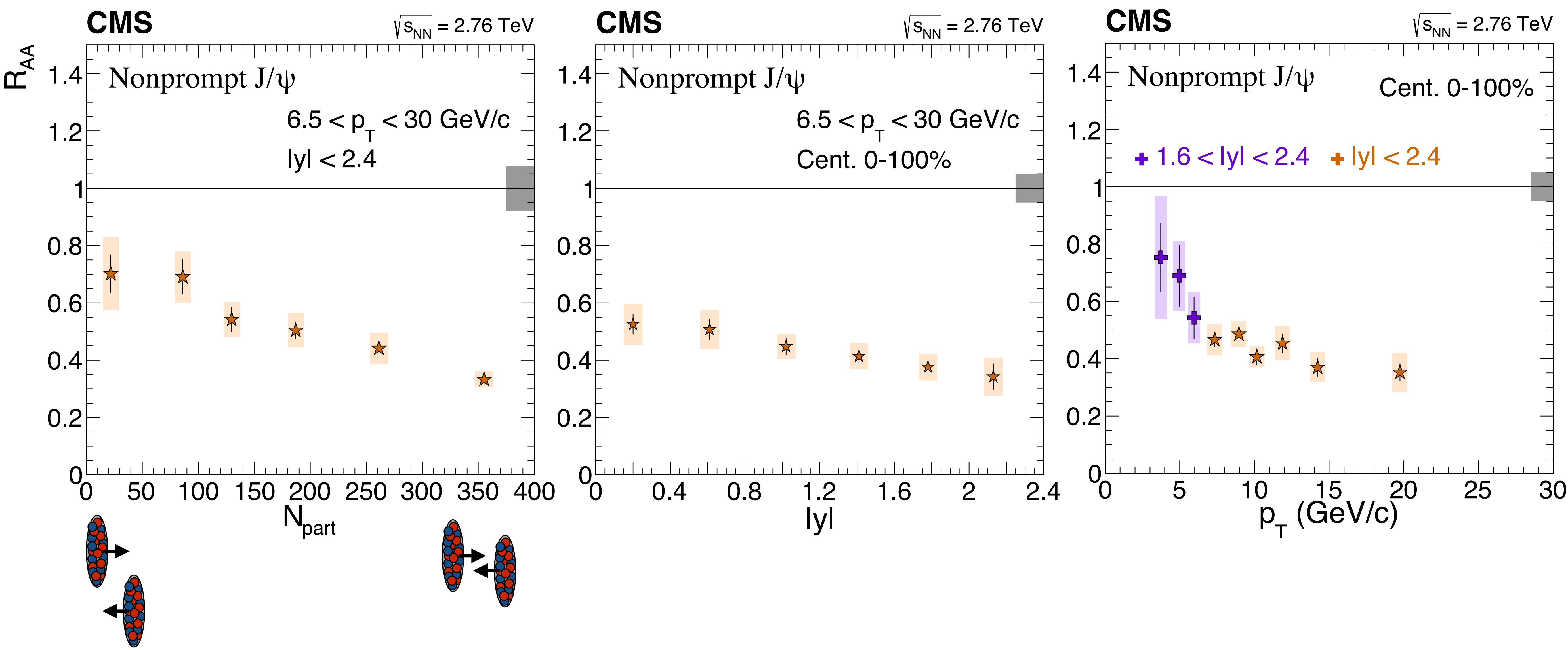




- Nonprompt J/ψ results are integrated over $|y_{CM}| < 1.93$
- B meson using FONLL calculation as a reference
- Two results are in agreement

Nonprompt J/ψ R_{AA} vs. centrality, p_T, |y|

EJPC 77 (2017) 252



- Stronger suppression in more central collisions
- No significant rapidity or p_T dependence