Recent CMS heavy flavor and quarkonia measurements in HI collisions

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See Javier M. Blanco, Chad Flores and Ta-Wei Wang presentations at QM2017 for more details!

Why heavy flavour and quarkonia in HI?

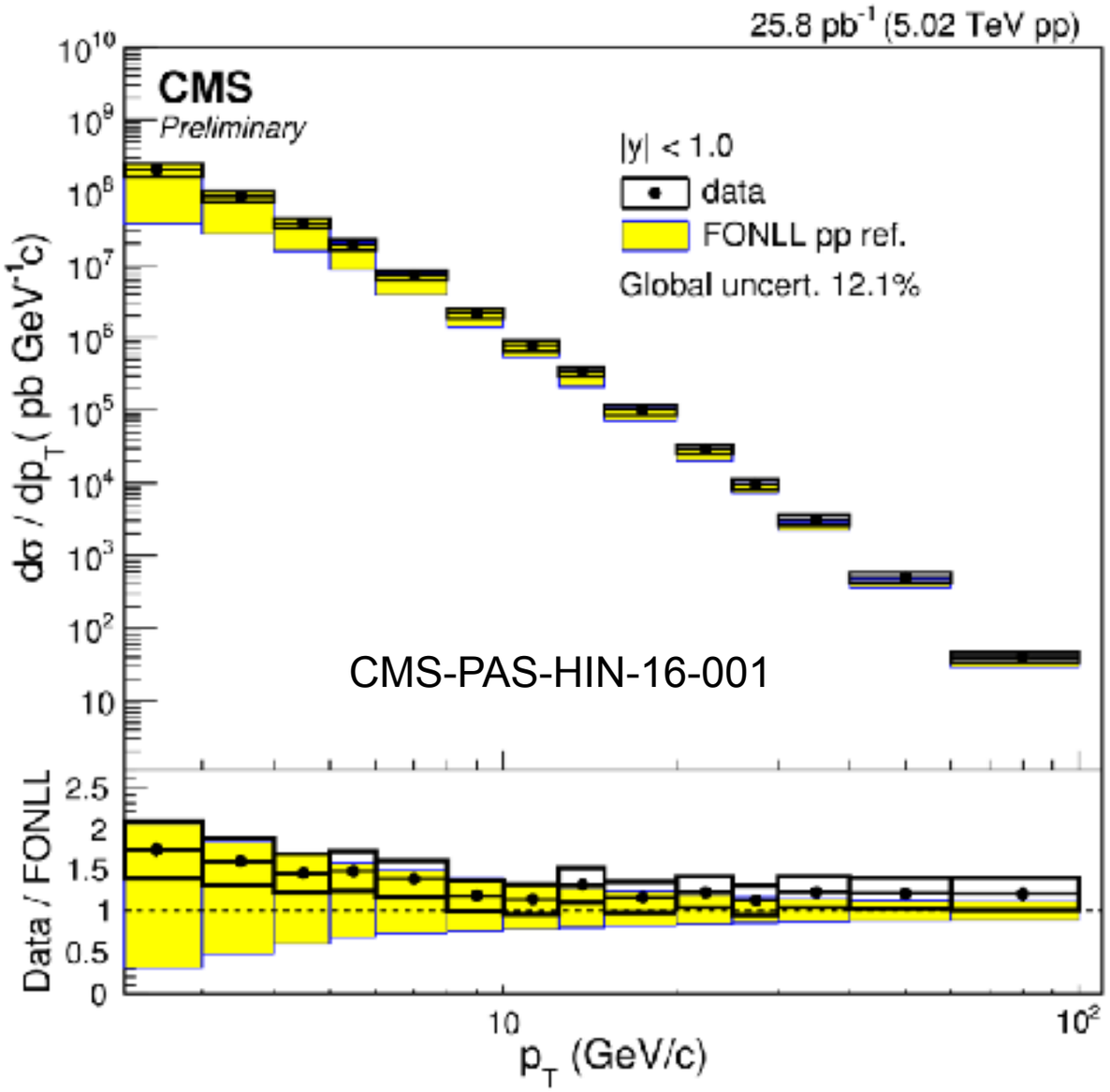
Why heavy flavour and quarkonia in HI?

… i guess you know it by now :)

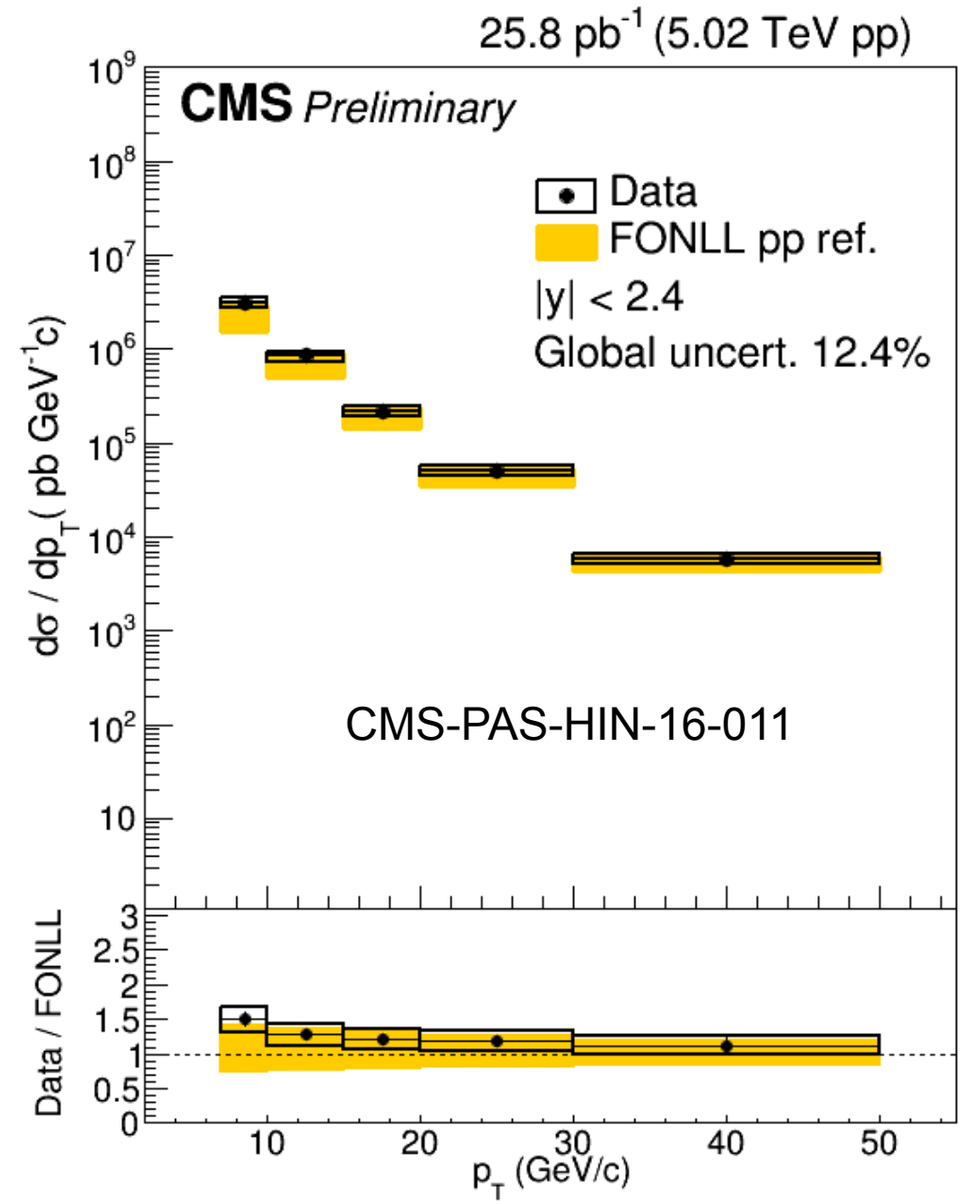
Open heavy flavours

D and B cross sections in pp collisions

D^0 at 5.02 TeV, |y|<1.0



B^+ measurement at 5.02 TeV, |y|<2.4

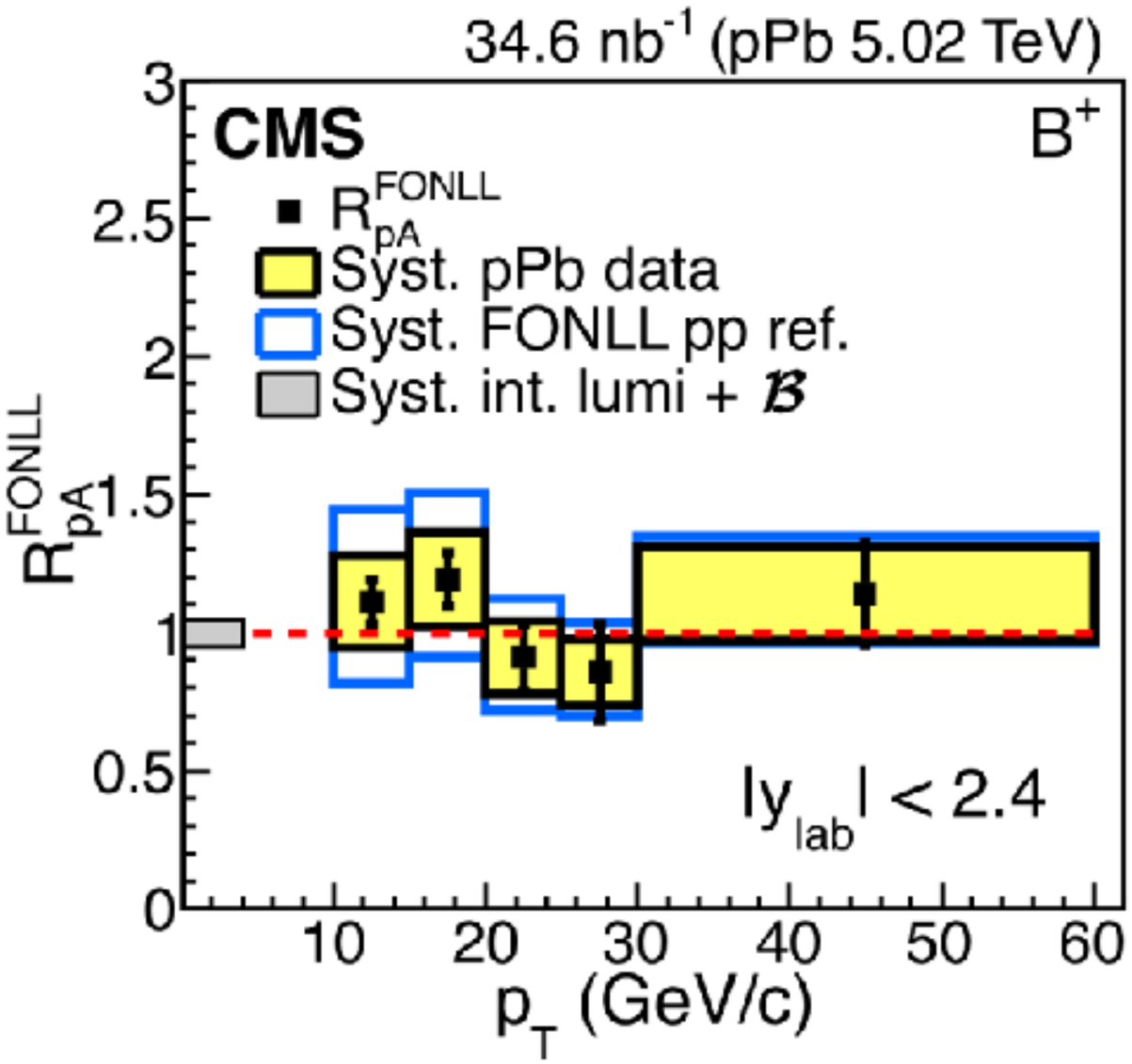


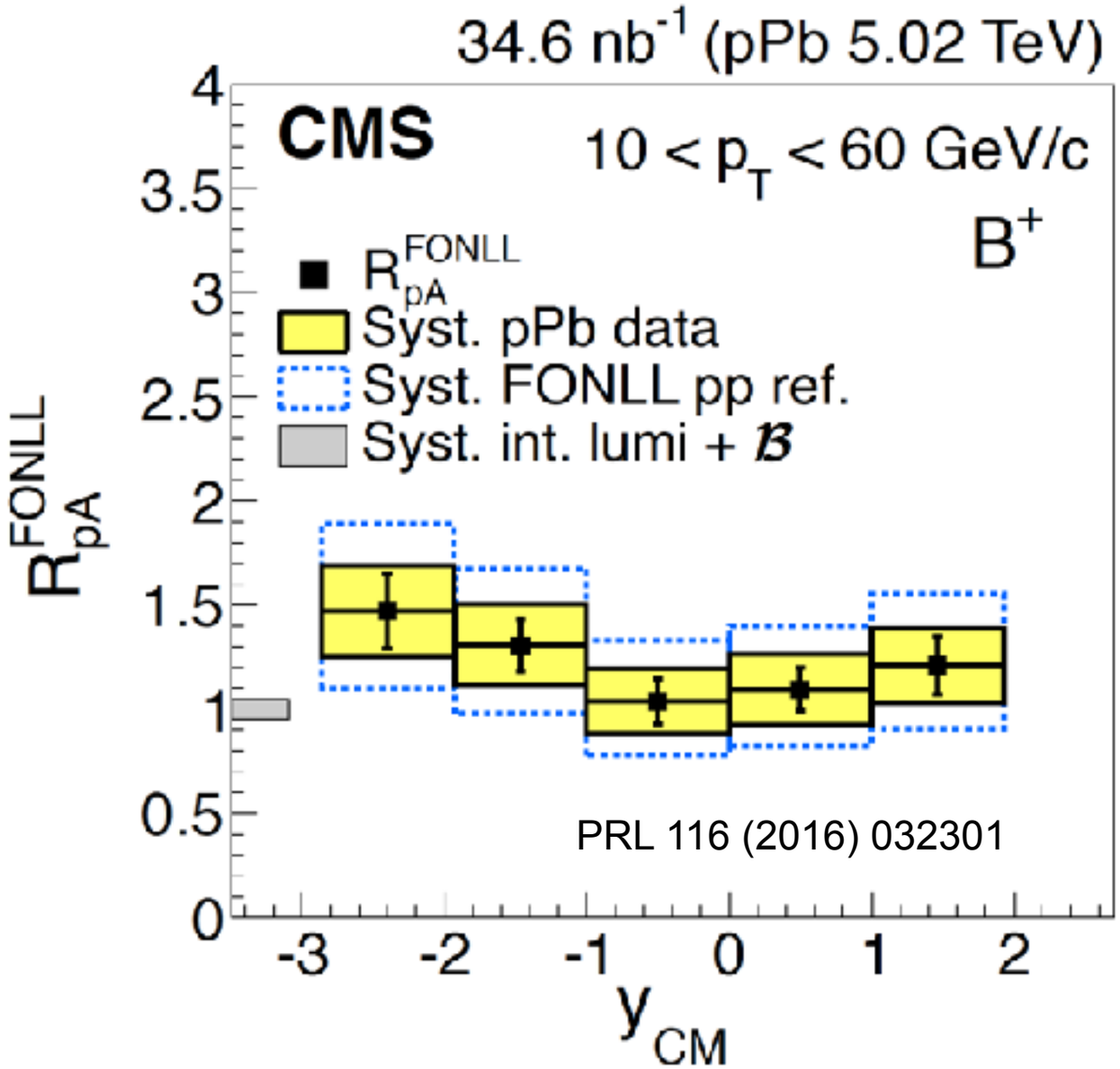
D and B meson production cross sections well described by NLO calculations:

→*D meson upper edge of FONLL calculations*

→*B meson consistent with central values of FONLL at higher p_T, slightly higher for p_T<15 GeV*

B meson production in pPb collisions



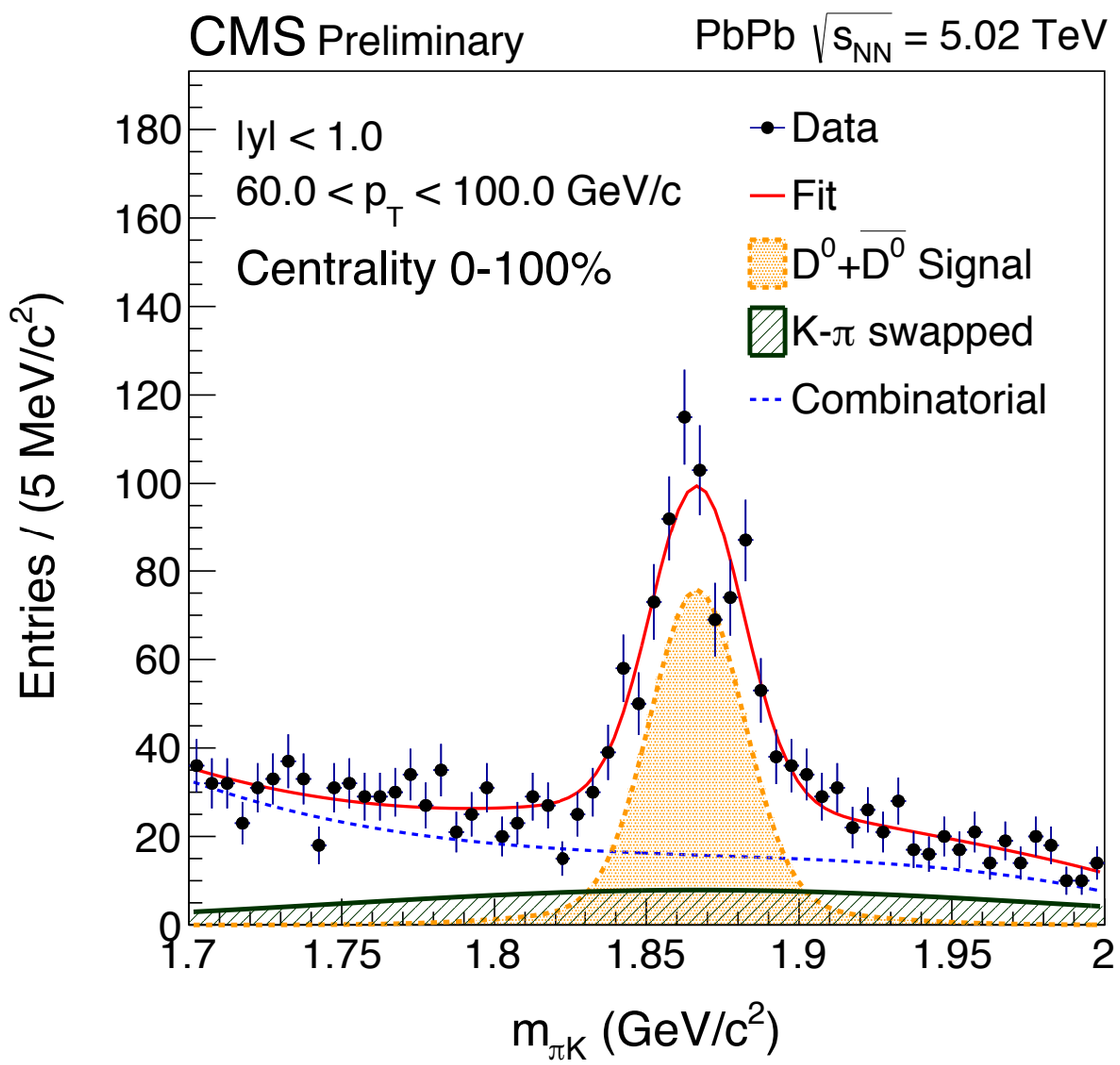


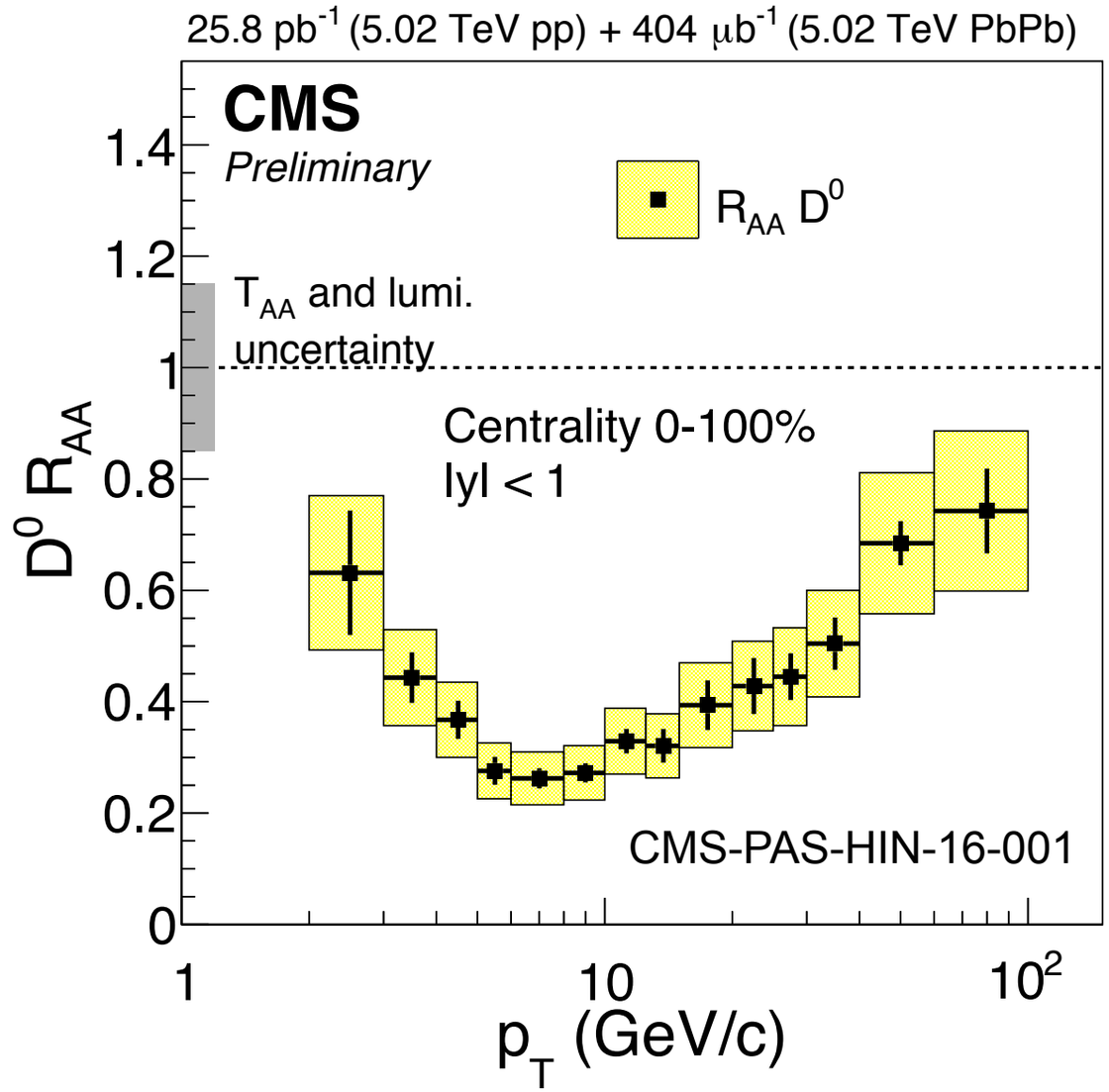
FONLL R_{pA} fully compatible with unity

No sizeable modification as a function of rapidity

D^0 meson R_{AA} at 5.02 TeV

D^0 R_{AA} measured from 2 to 100 GeV/c at central rapidity in 0-100%

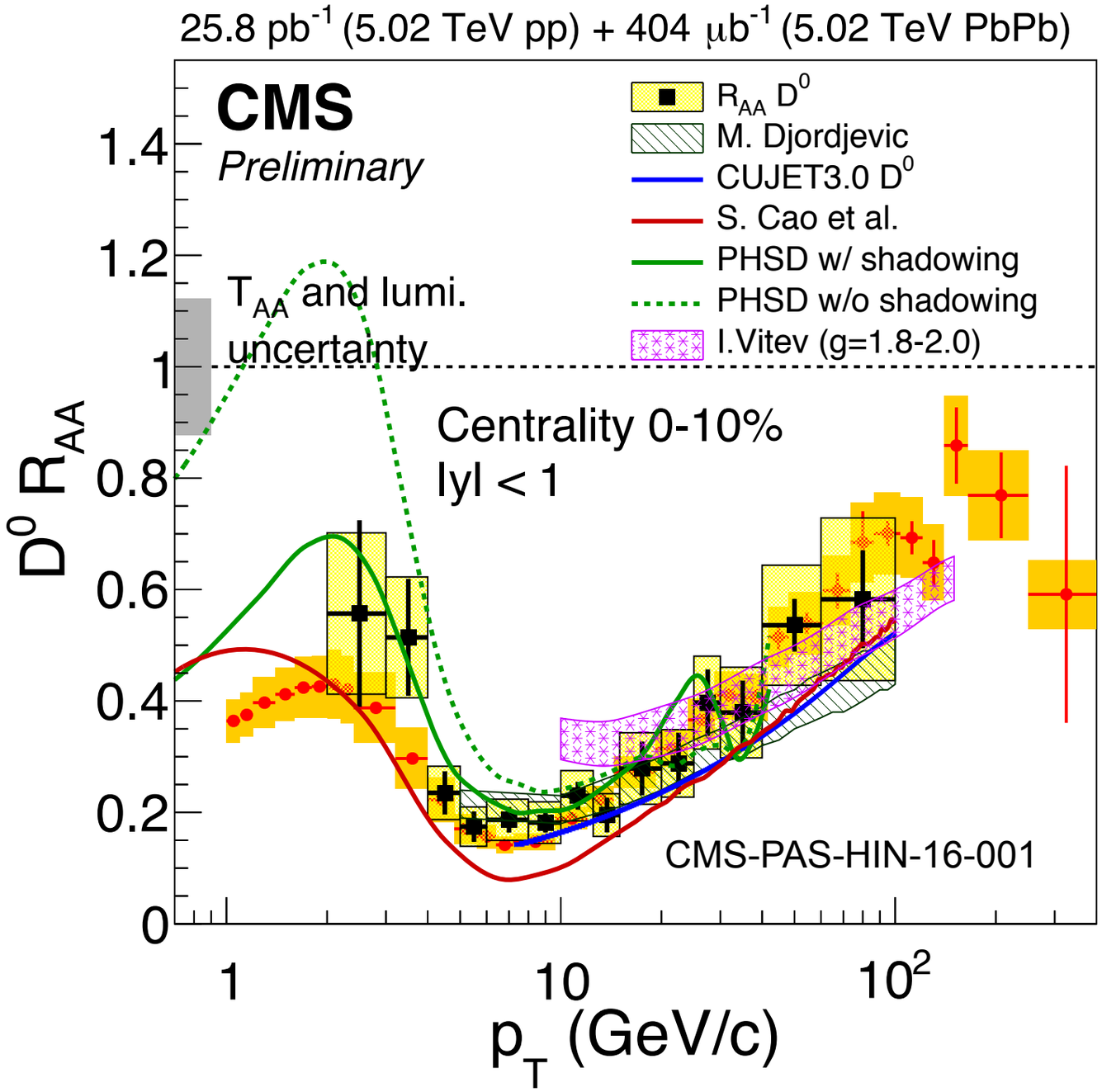




→ ~300 MB events recorded for low p_T analysis

→ Dedicated triggers designed to perform full track reconstruction at HLT and to reconstruct and identify D^0 meson events at HLT

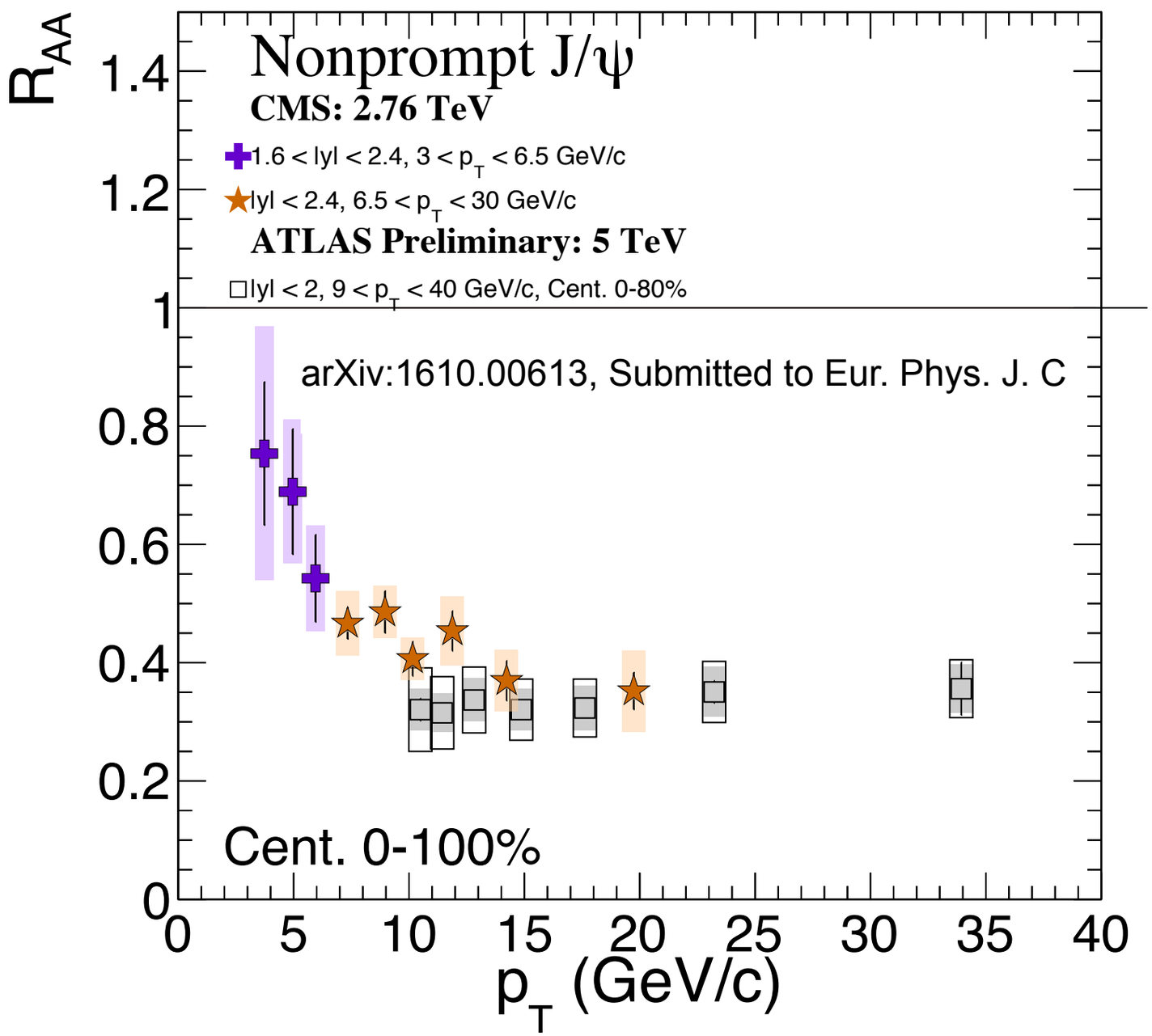
D^0 meson R_{AA} at 5.02 TeV



Several models describe the data within uncertainties:

- *hints at low p_T that collisional energy loss is non negligible*
- *pure collisional models can describe the R_{AA} up to high p_T (??)*
- *shadowing improve description of the data at low p_T*

R_{AA} of non prompt J/ψ at 2.76 TeV



CMS non prompt 1.6<|y|<2.4
CMS non prompt |y|<2.4
ATLAS non prompt |y|<2.9

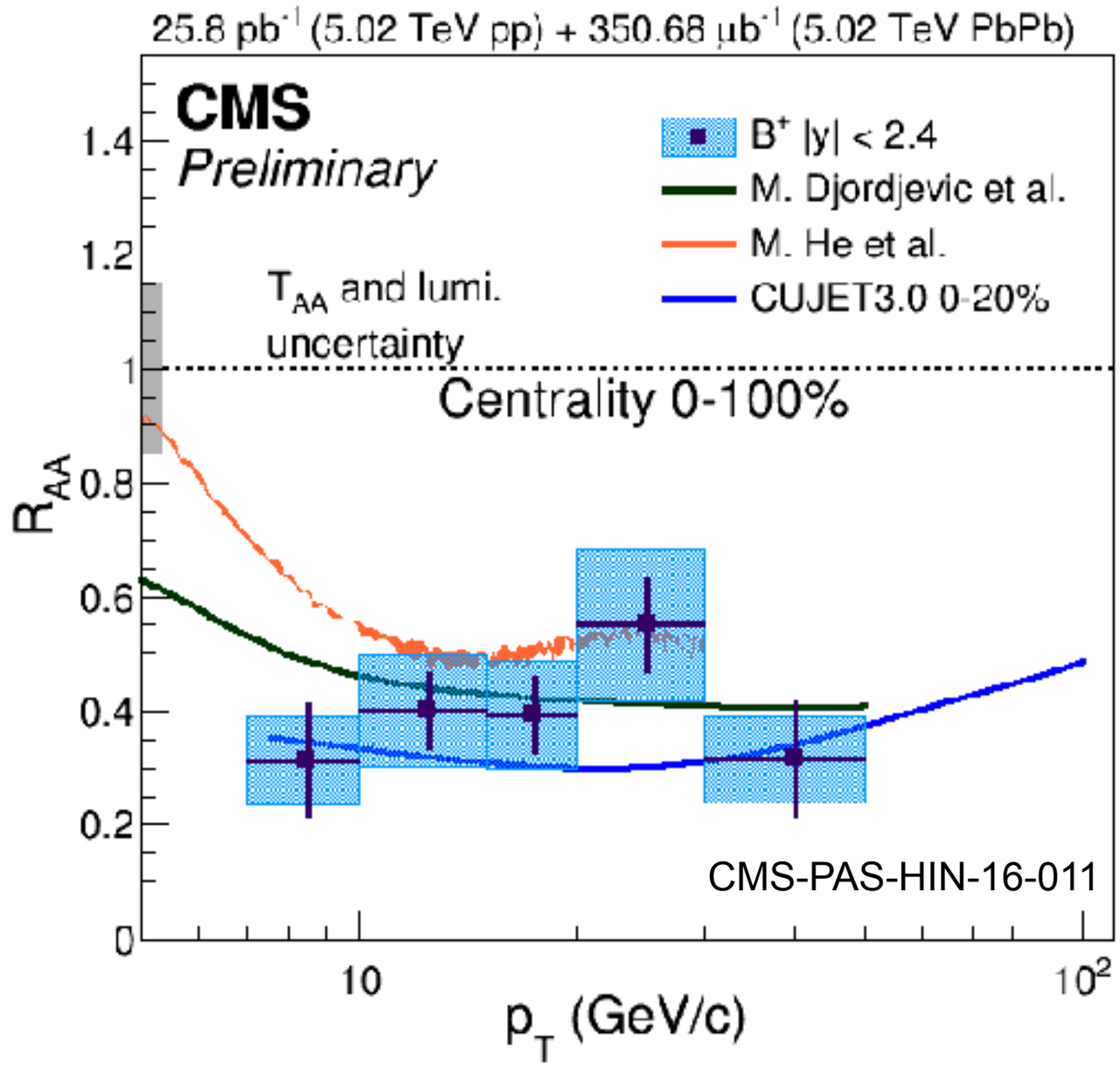
Strong suppression observed for non prompt J/ψ in PbPb collisions

Clear suppression as a function of p_T

2.76 TeV and 5.02 TeV results well consistent within uncertainties

Exclusive B^+ meson measurement in PbPb

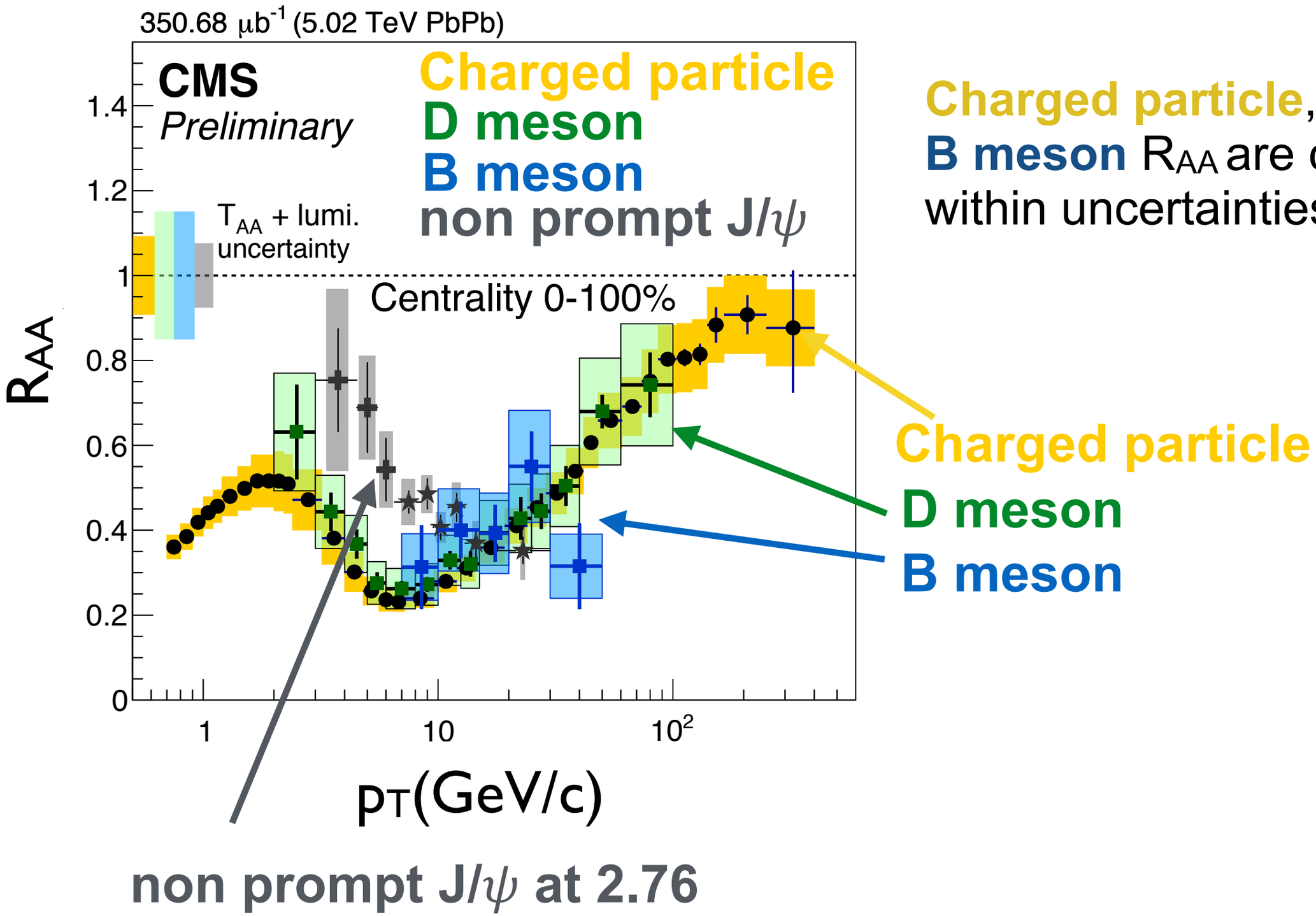
CMS B^+ production in PbPb at central rapidity |y|<2.4



Strong suppression (R_{AA}~0.4) observed in 0-100% PbPb collision for p_T>7 GeV/c

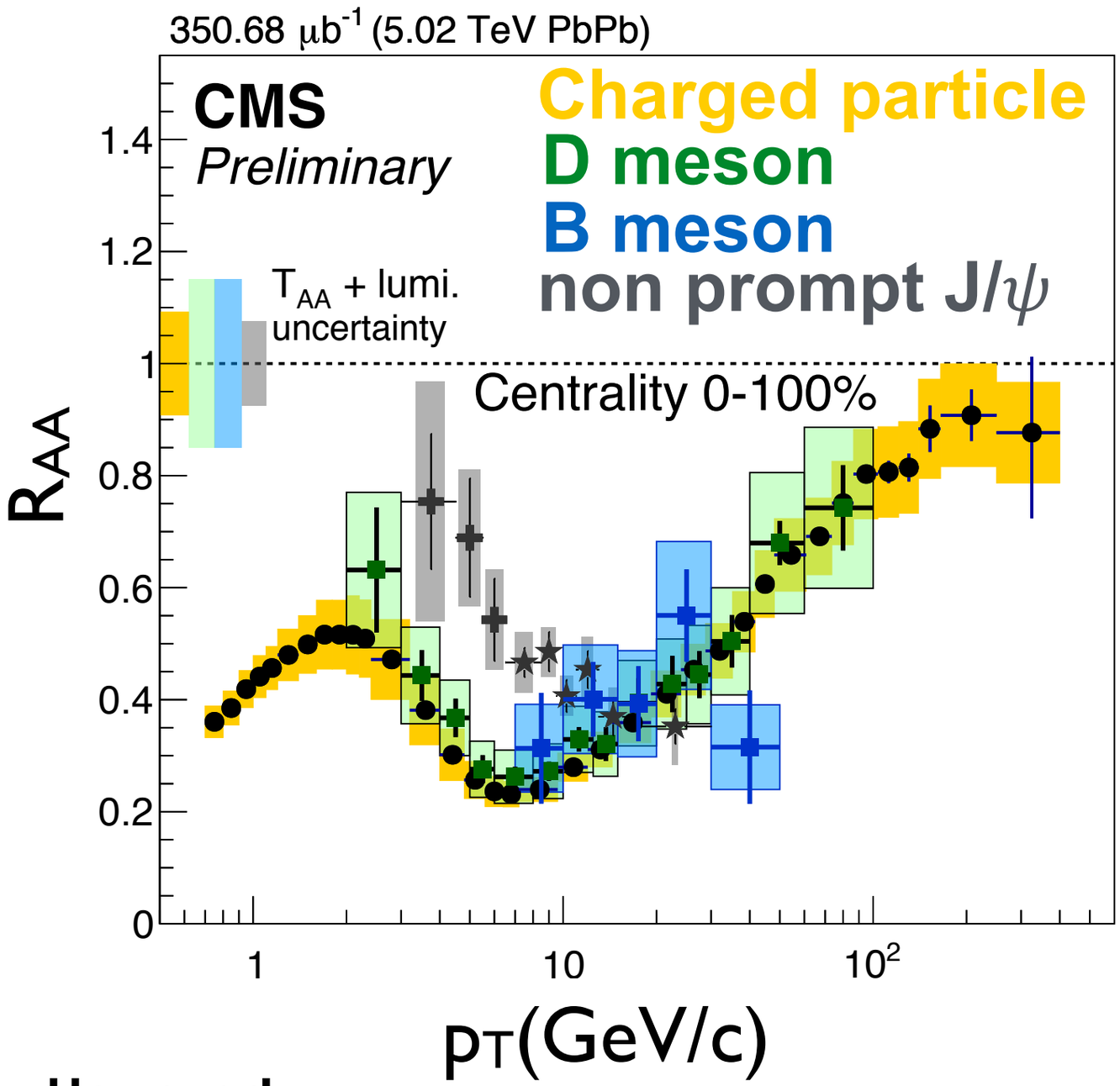
Well described by theoretical calculations that include radiative energy loss

Flavour dependence at 5.02 TeV

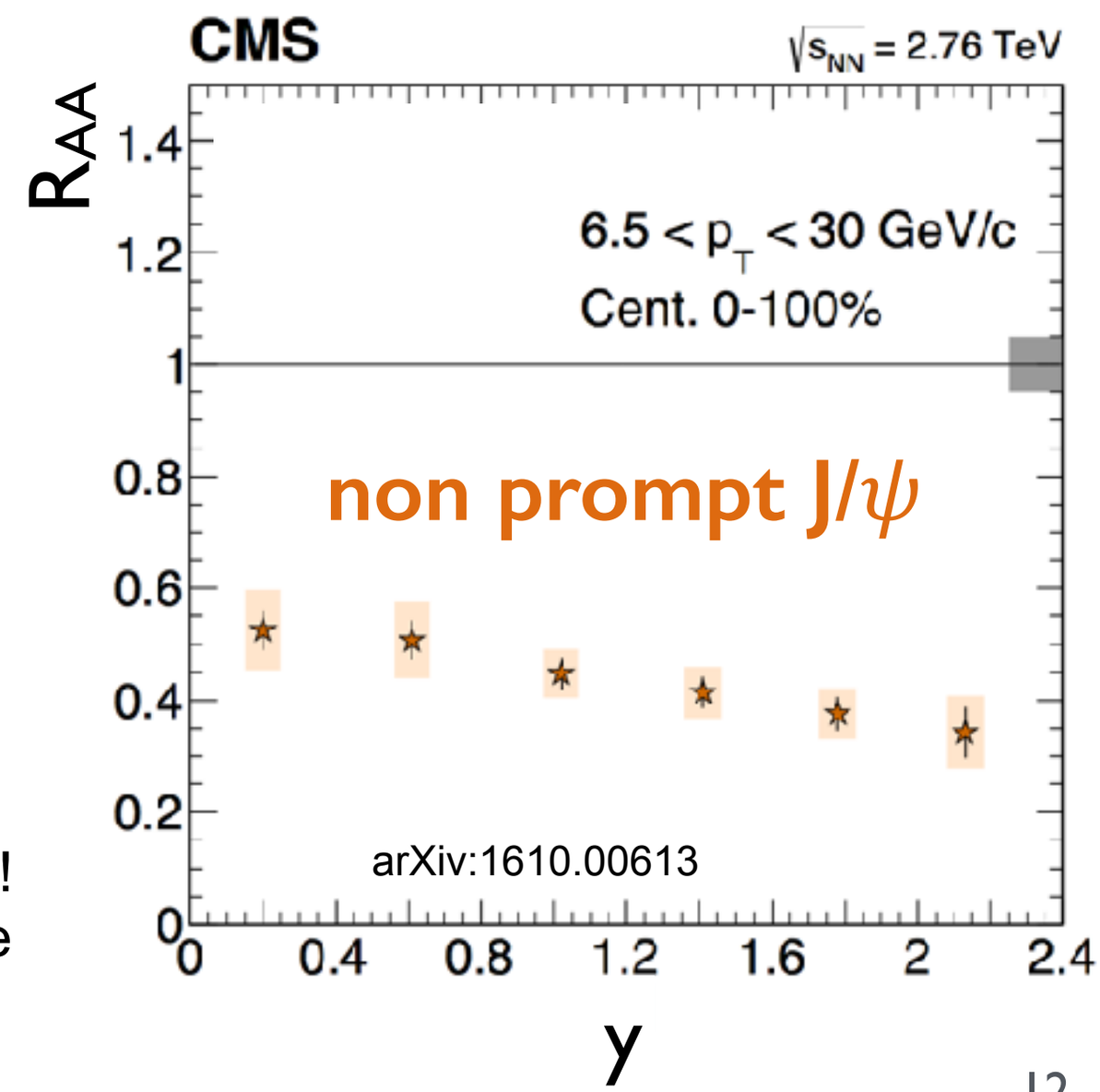


Charged particle, **D meson**, **B meson** R_{AA} are consistent within uncertainties!

Flavour dependence at 5.02 TeV



Charged particle, D meson, B meson R_{AA} are consistent within uncertainties!



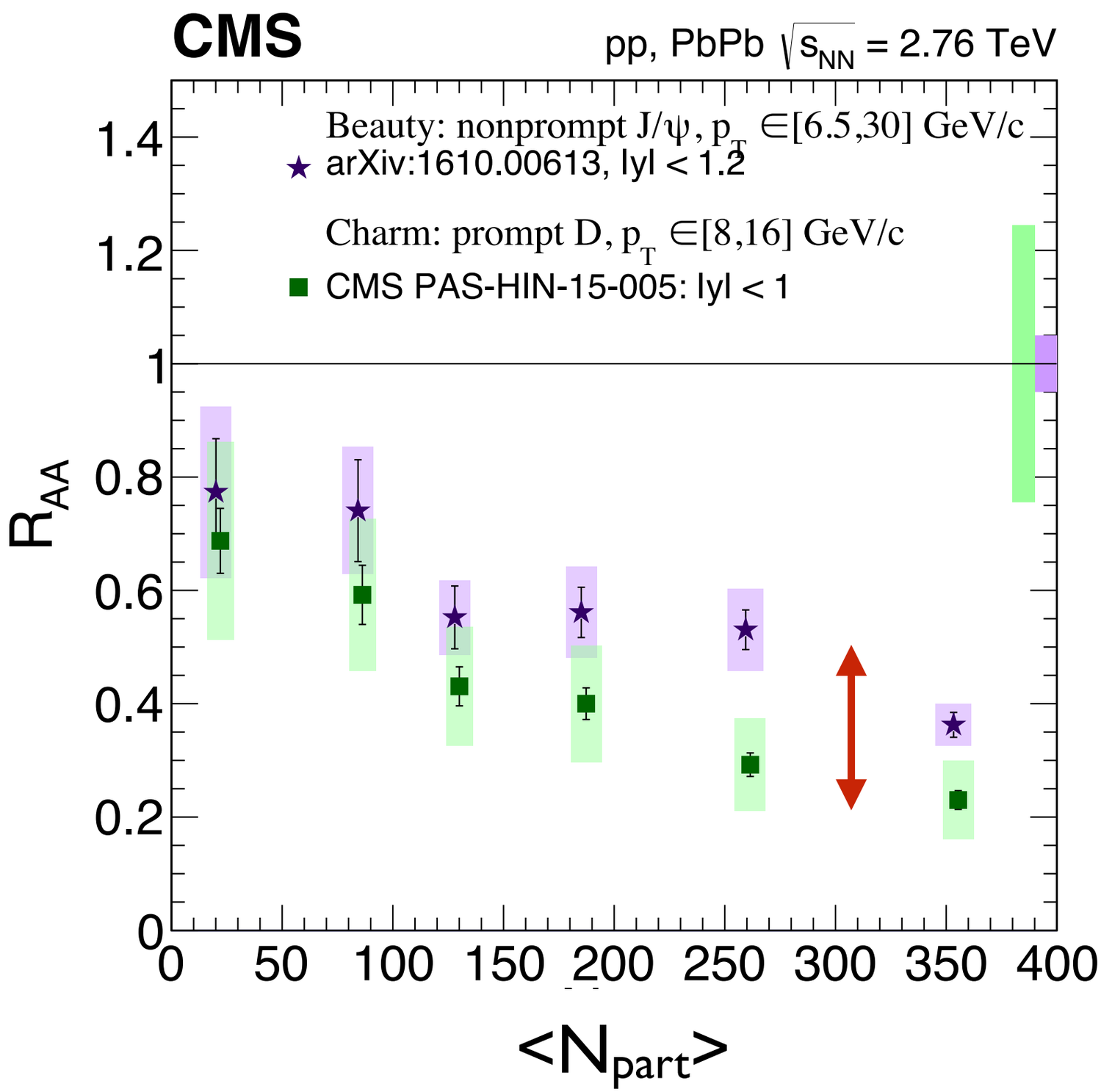
However!

B R_{AA} and D R_{AA} measured in different rapidities!

→ measurements in the same rapidity with more statistics needed to draw a firm conclusions

→ non prompt J/ψ to be measured at 5 TeV

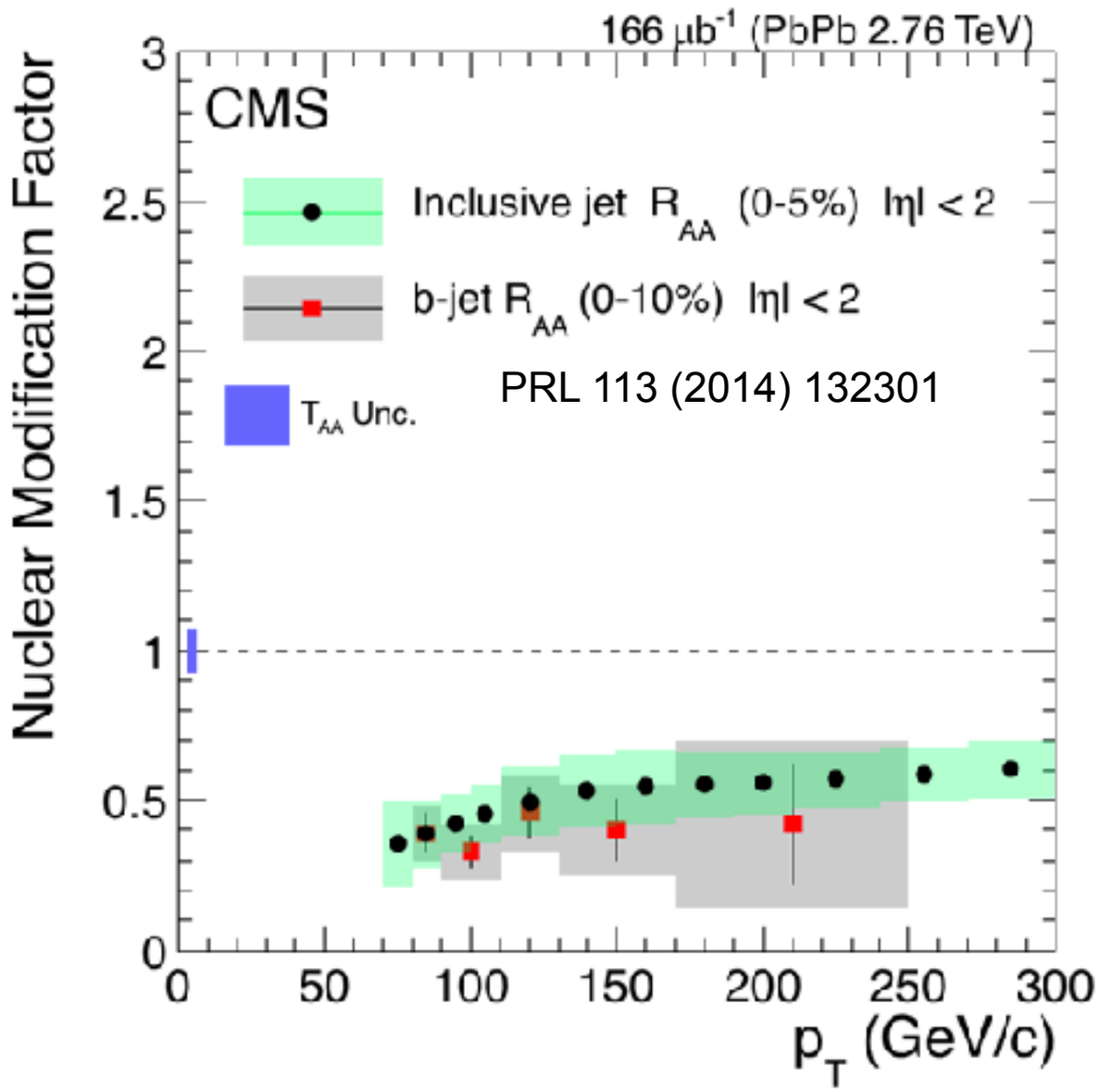
Flavour dependence at 5.02 TeV



Significant difference when we compared at low p_T in the same rapidity region **D meson** and **non prompt J/ψ**

→models explain the difference in the R_{AA} as due to a different E_{loss} for charm and beauty quarks

Flavour dependence at higher p_T



b-jet R_{AA}

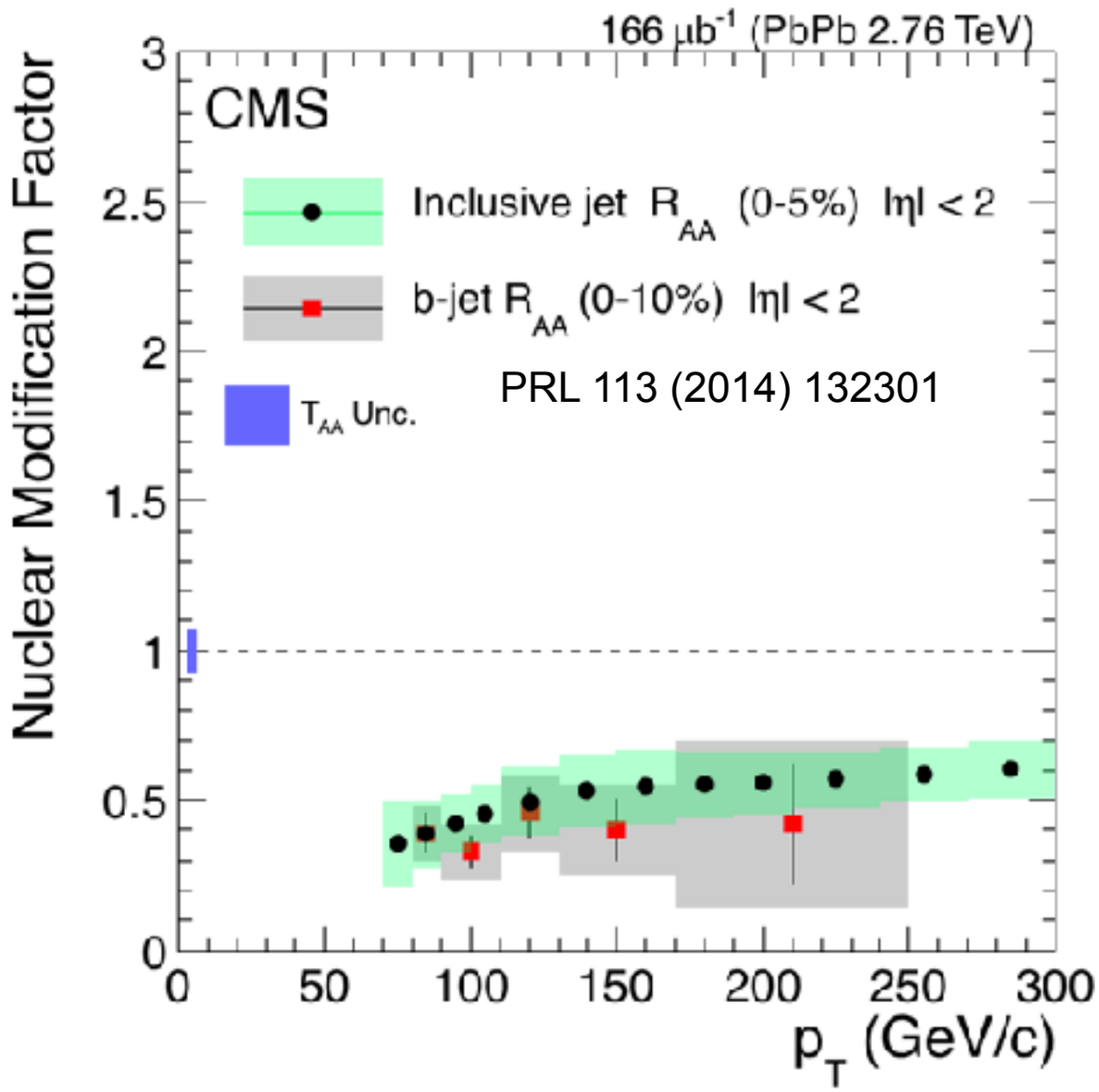
inclusive jet R_{AA}

Same suppression for b-jets and inclusive jets at high p_T

Mass difference negligible at high p_T

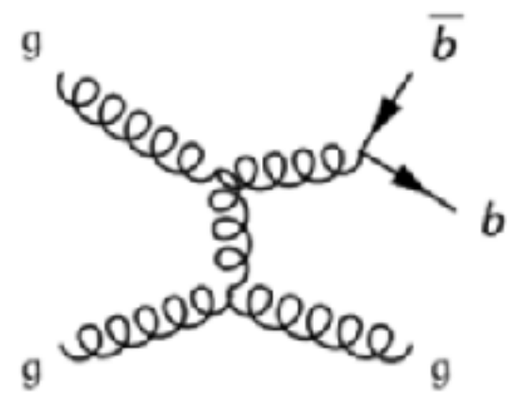
Large contribution of gluon splitting processes*? In GSP case, we are not measuring the b-quark E_{loss} but to some "fat" gluon E_{loss}*

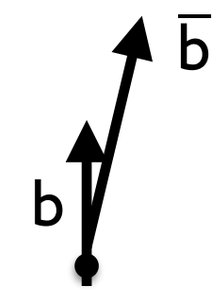
Flavour dependence at higher p_T



b-jet R_{AA}

inclusive jet R_{AA}





NLO process: Gluon splitting

→ dominant at low opening angles

Same suppression for b-jets and inclusive jets at high p_T

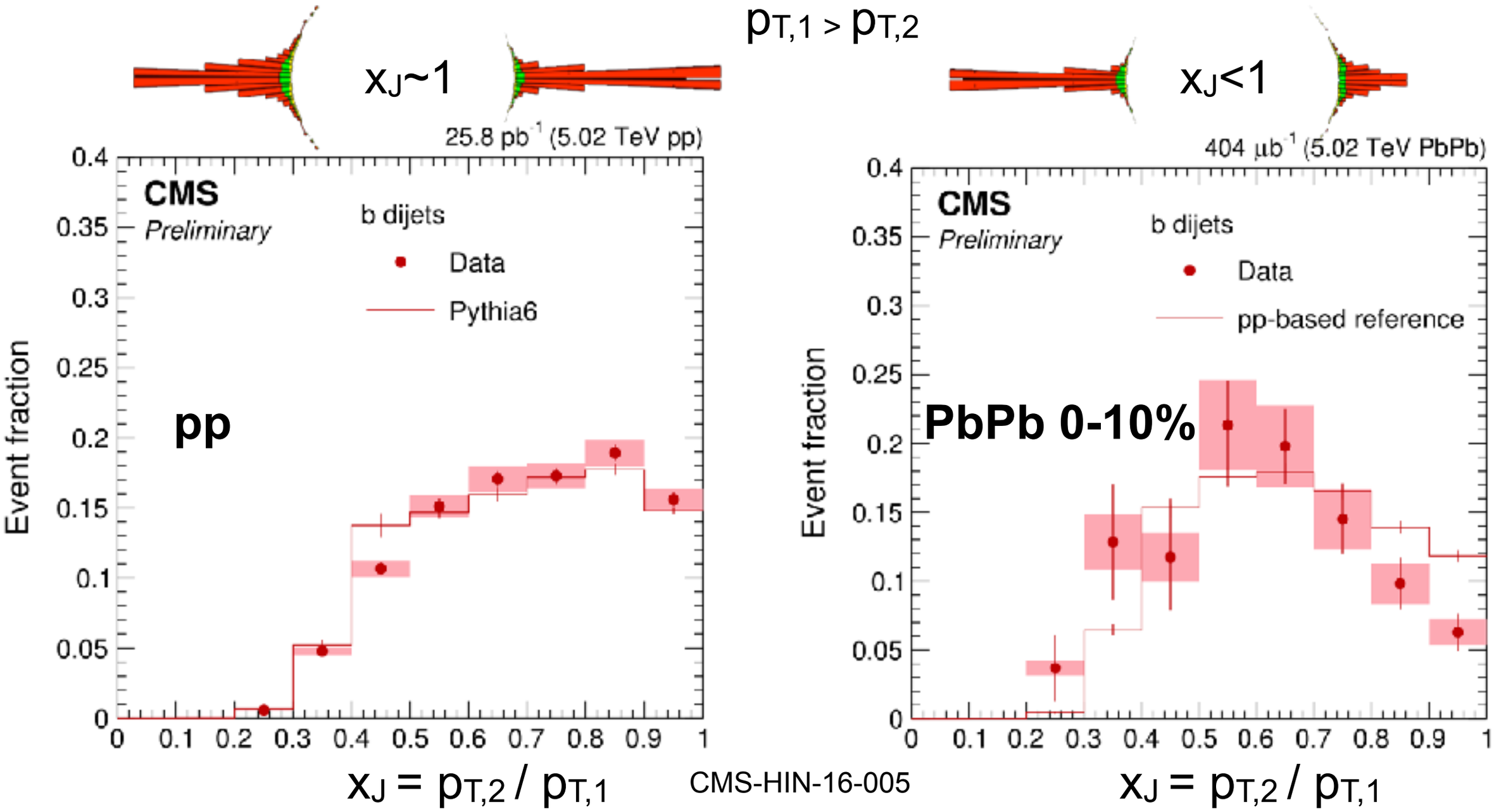
Mass difference negligible at high p_T

Large contribution of gluon splitting processes*? In GSP case, we are not measuring the b-quark E_{loss} but to some "fat" gluon E_{loss}*

Di-b-jet measurement in PbPb at 5.02 TeV

→ In back-to-back events $b\bar{b}$ production via gluon splitting processes is negligible

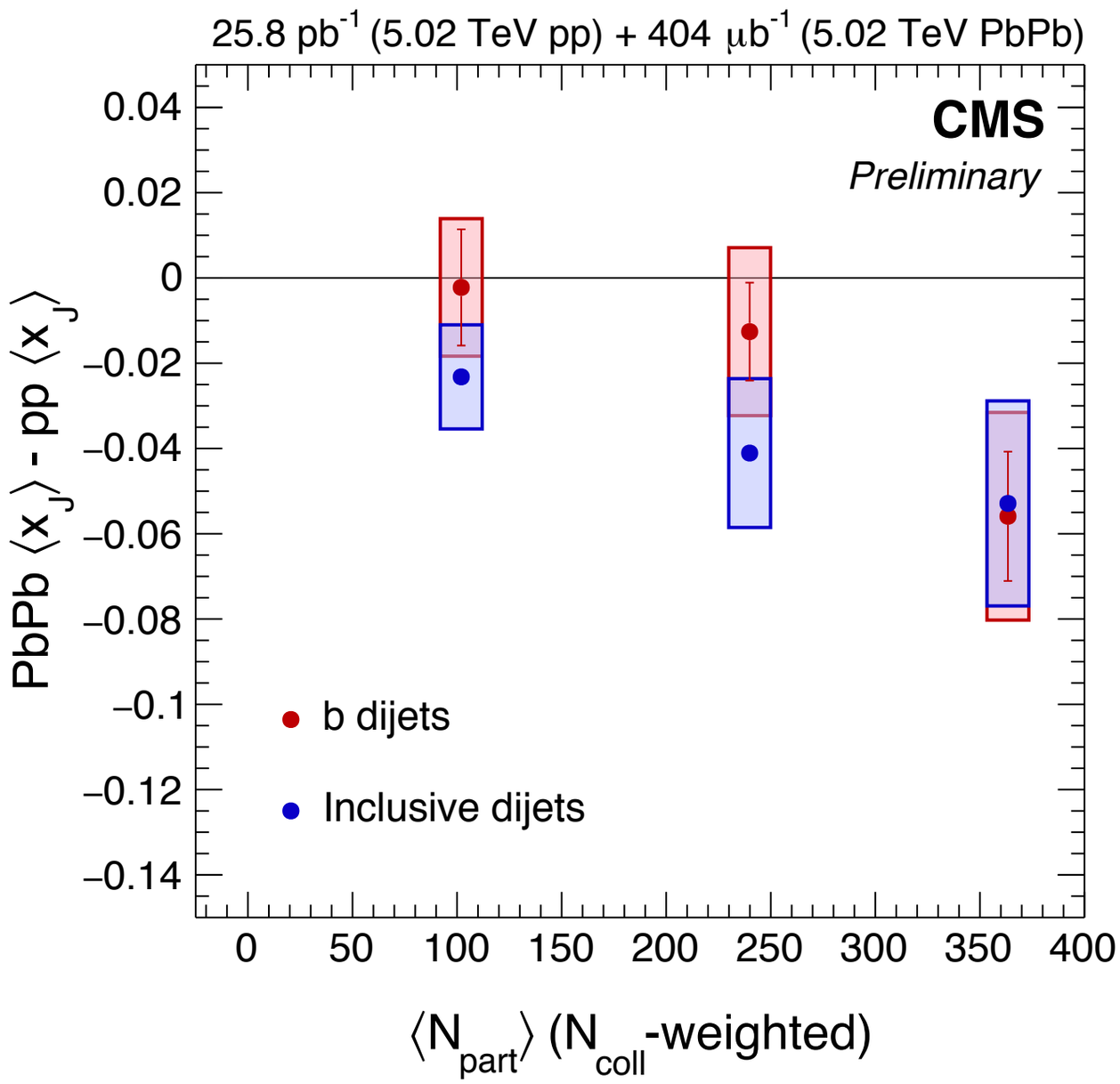
$p_{T,1} > p_{T,2}$



CMS-HIN-16-005

x_J distributions of di-b-jets significantly modified in central PbPb collisions!

Di-b-jet measurement in PbPb at 5.02 TeV



$$x_J = p_{T,2} / p_{T,1}$$

Same average asymmetry observed for inclusive jets!

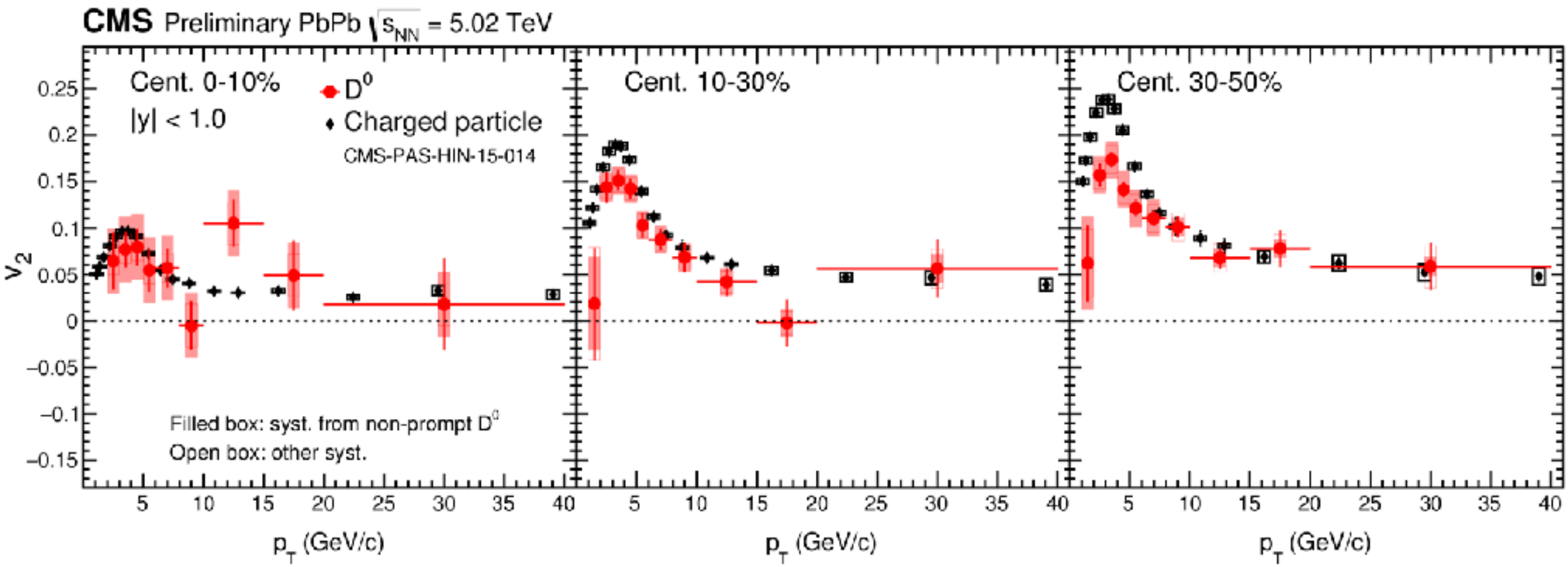
CMS-HIN-16-005

There is no significant difference in the suppression of inclusive and b-jets even after excluding the contribution of gluon splitting processes

D meson v_2 at 5.02 TeV in PbPb collisions

v_2 and v_3 in PbPb collisions at 5.02 TeV in different collision centralities

CMS-PAS-HIN-16-007

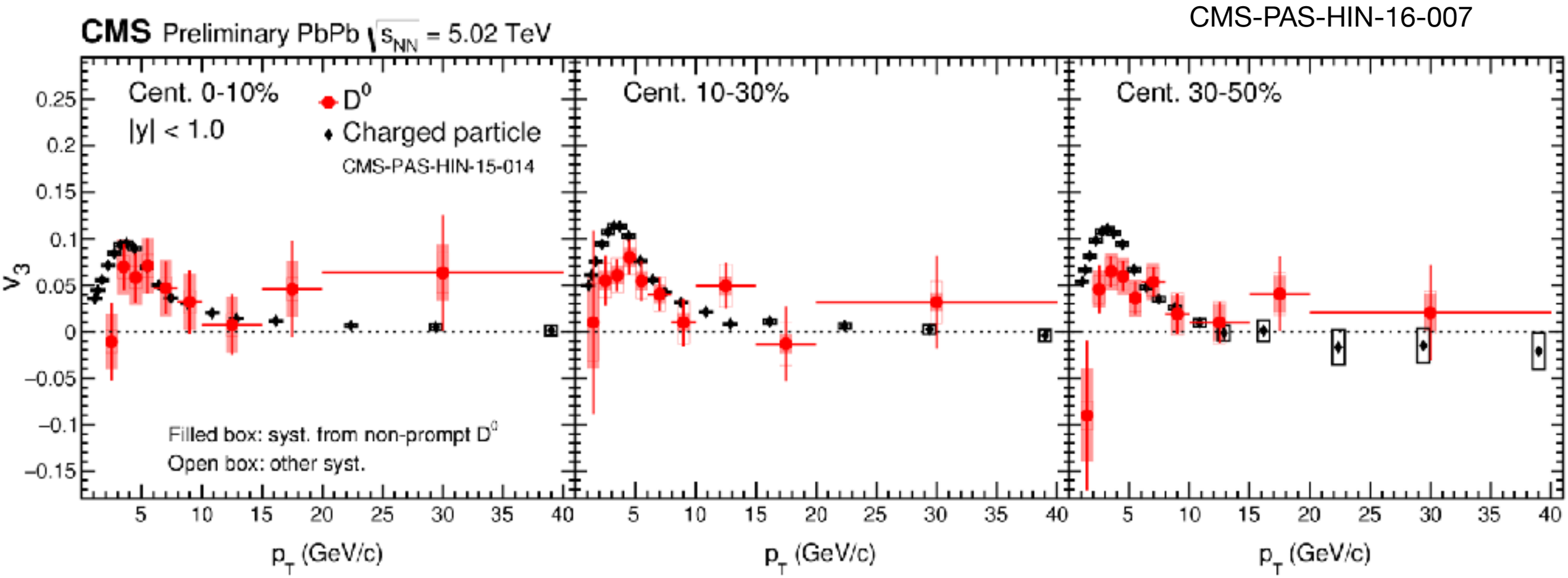


Significant confirmation of $v_2>0$ for D^0 at 5.02 TeV:

v_2 of D mesons larger than v_2 of charged particles

$v_2(0\text{-}10\%) < v_2(10\text{-}30\%) \sim v_2(30\text{-}50\%)$

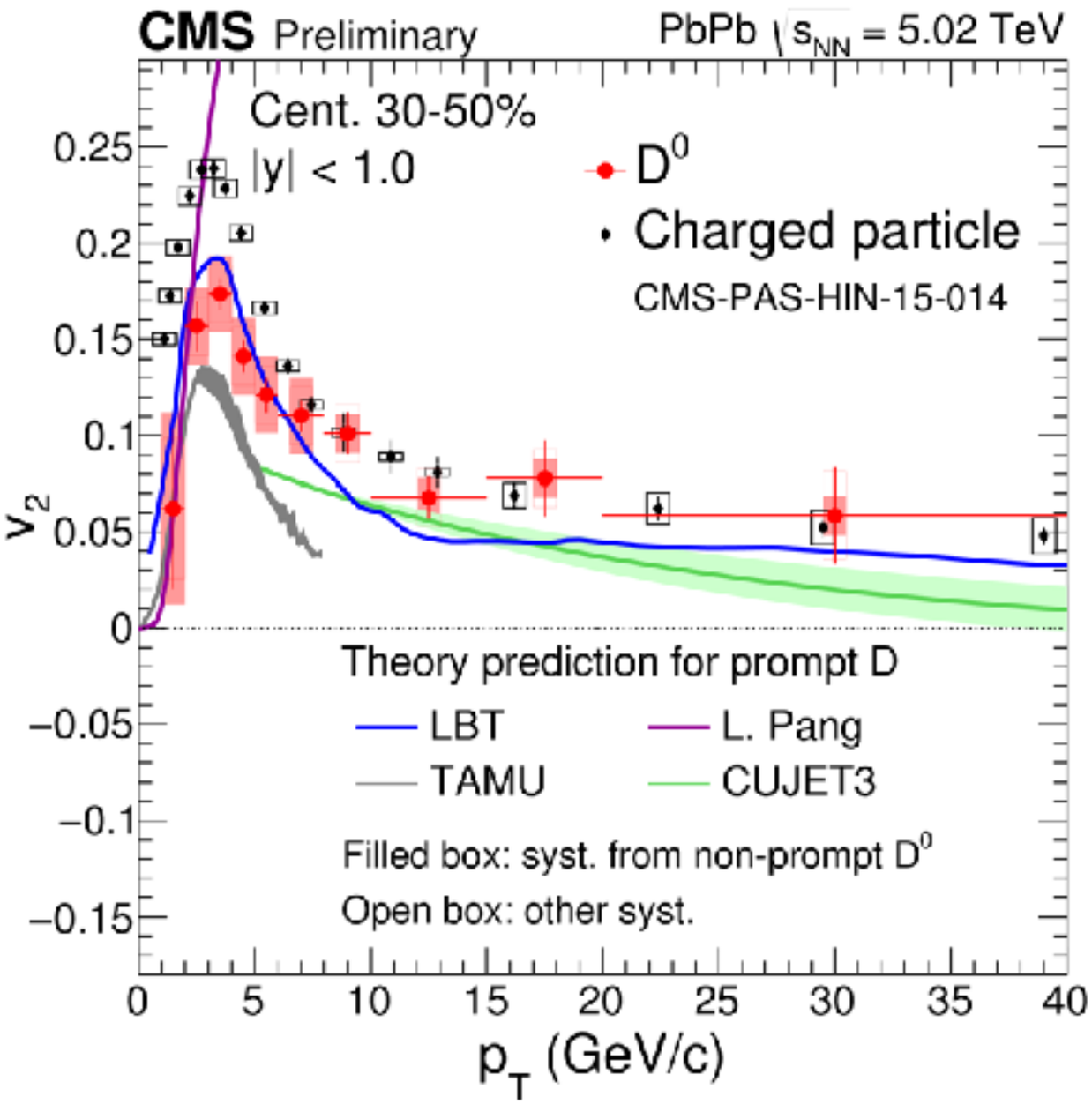
D meson v_3 at 5.02 TeV in PbPb collisions



First observation of v_3>0 for charm!

v_3 for charged particle larger than D^0 v_3 although not fully significative given current uncertainties

Comparison with models

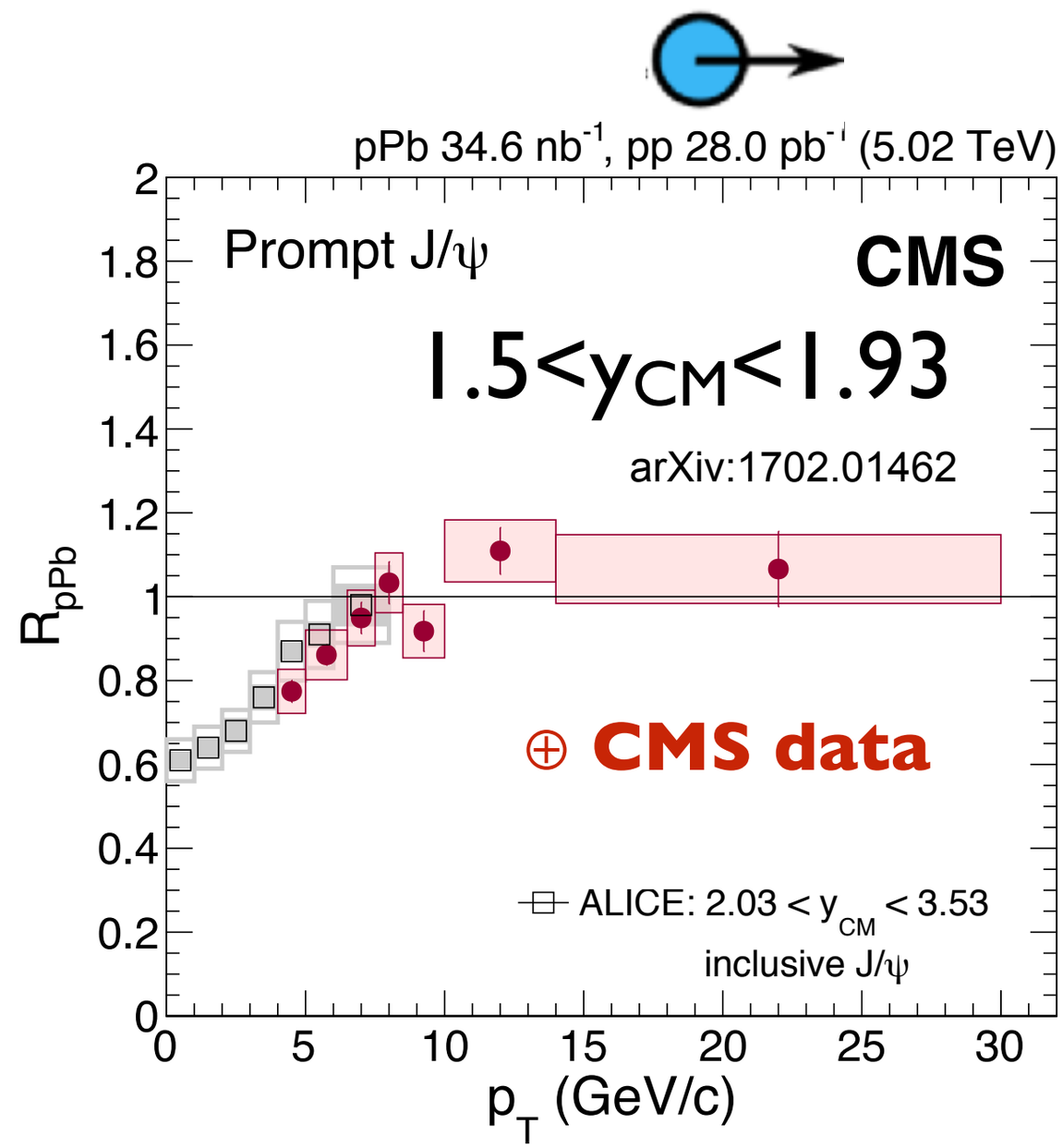


CMS-PAS-HIN-16-007

we need **charm quark diffusion** to describe the magnitude of the D meson v_2 (?)

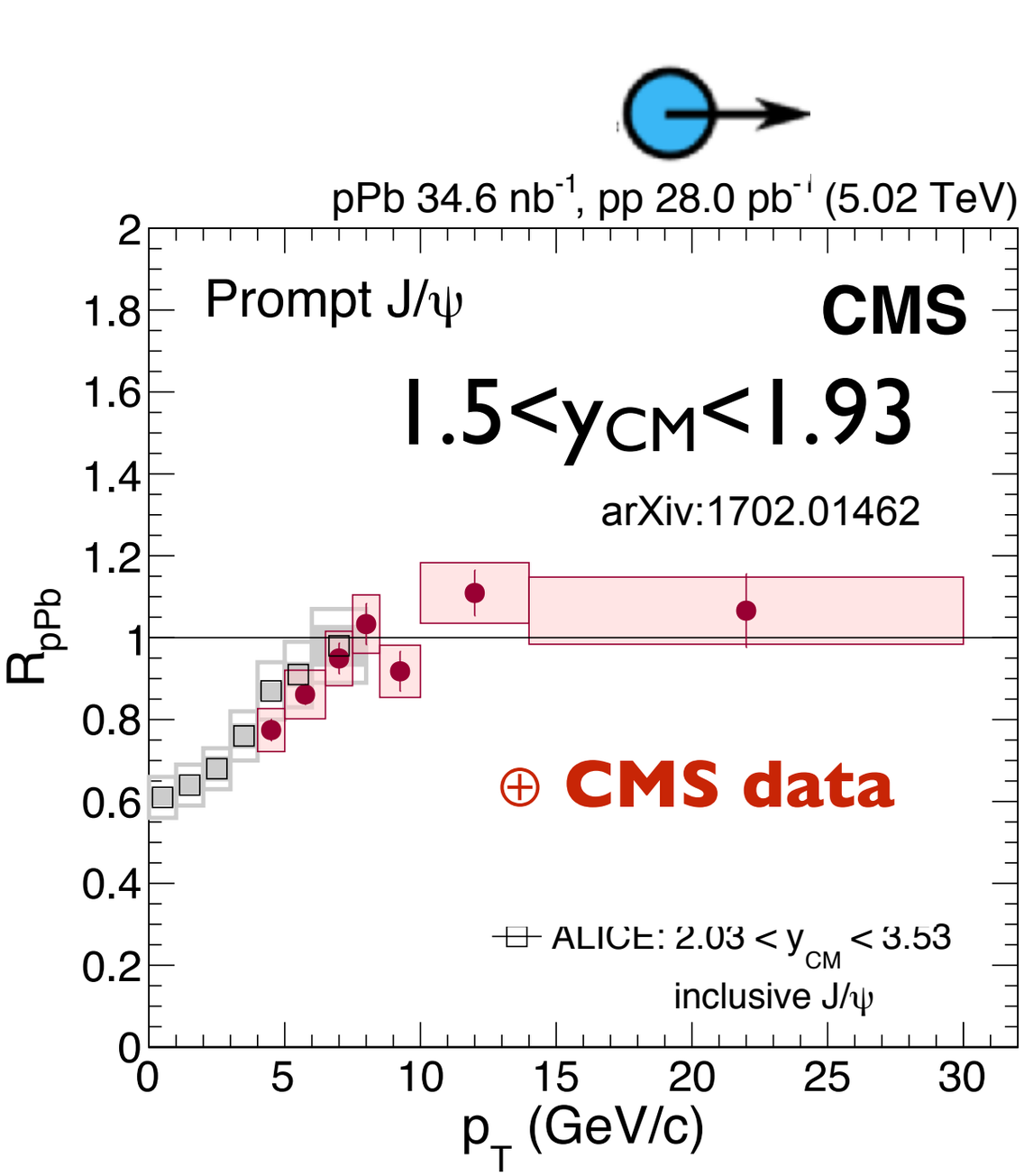
Charmonia and bottomonia

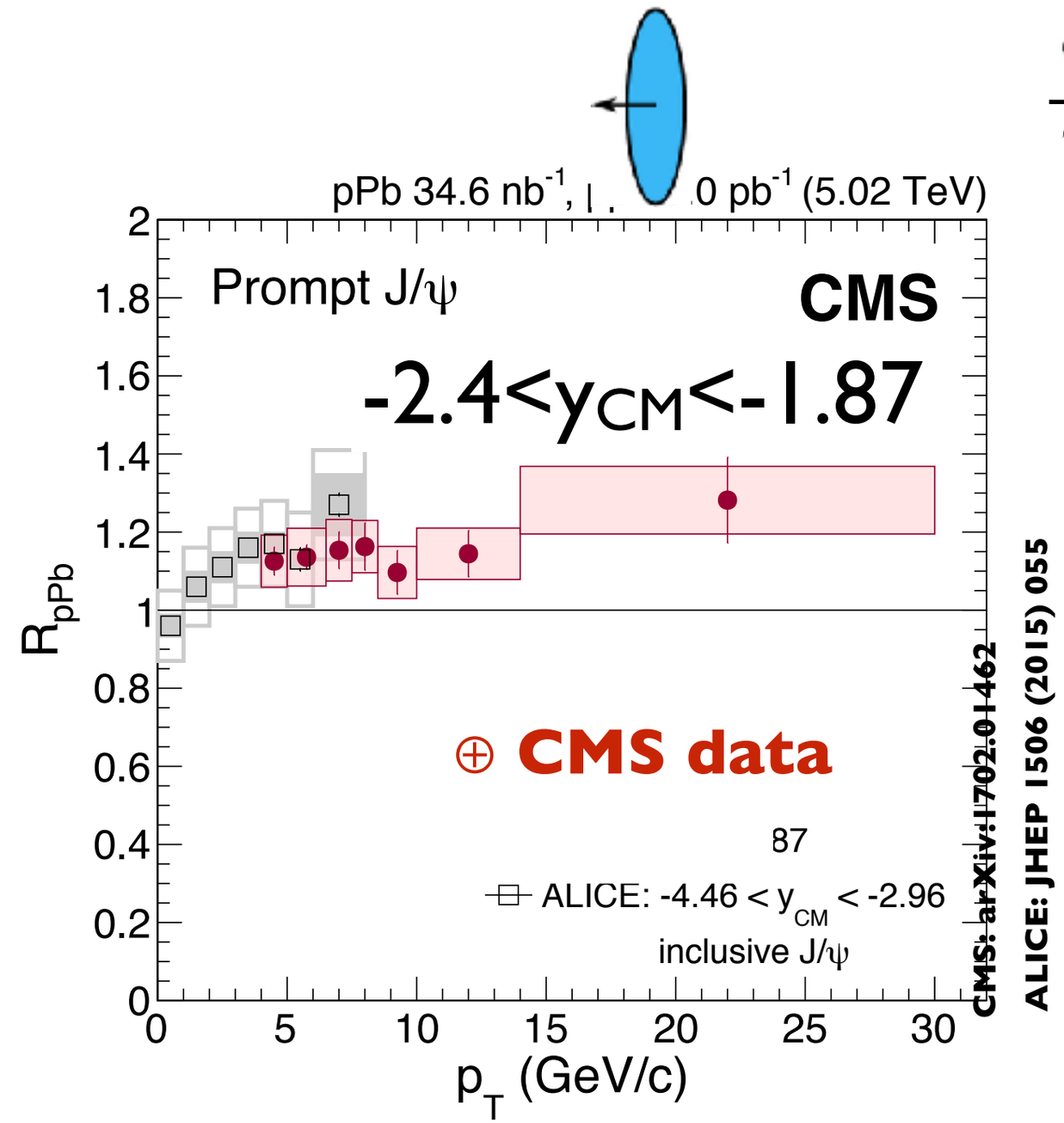
prompt J/ψ in pPb vs p_T at 5 TeV



→Significant decrease of R_{pA} at low p_T in the forward region as expected in presence of shadowing

prompt J/ψ in pPb vs p_T at 5 TeV

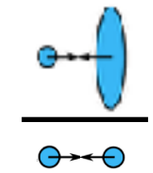


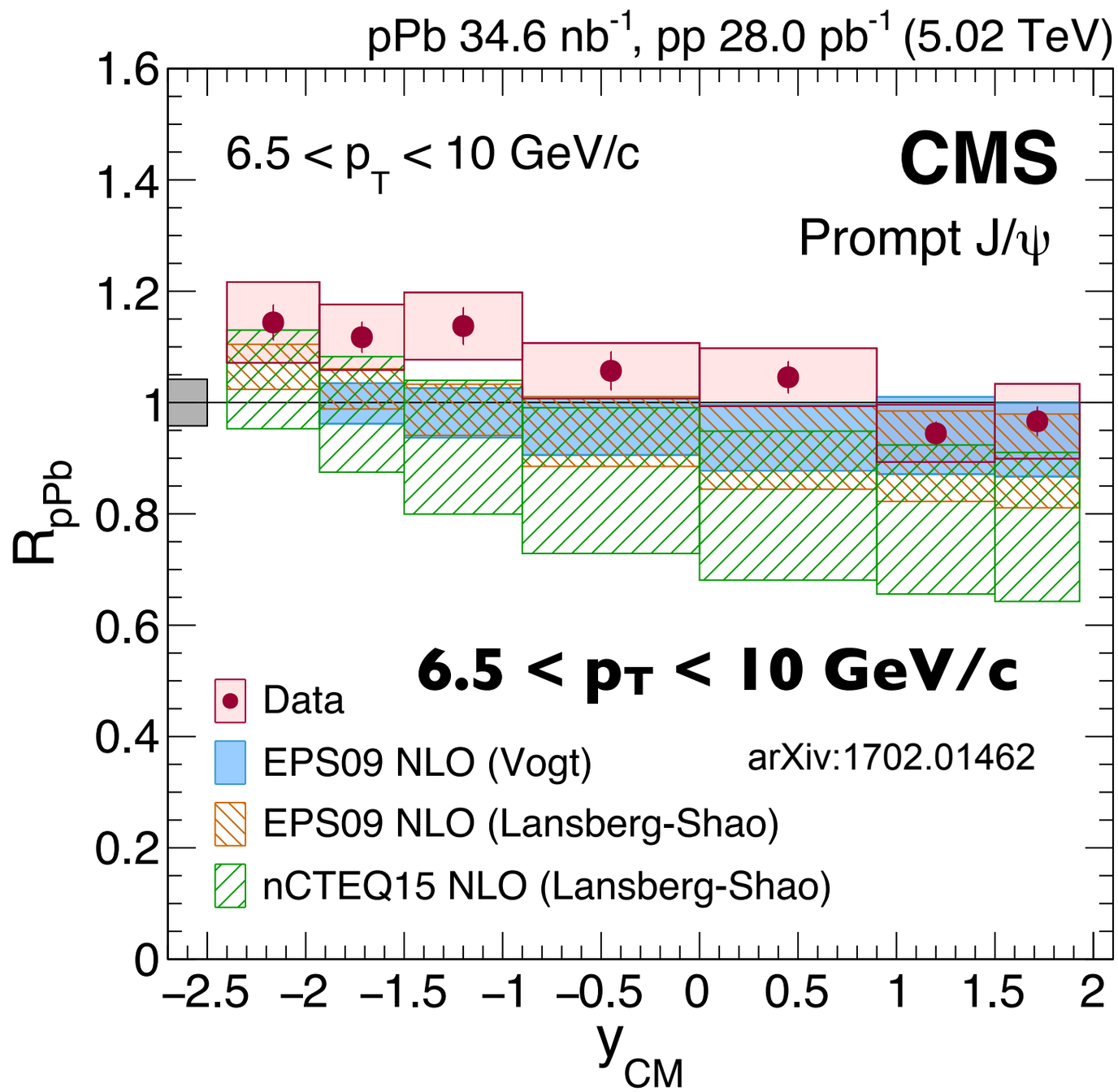


→Significant decrease of R_{pA} at low p_T in the forward region as expected in presence of shadowing

→R_{pA}>1 in the full p_T range

prompt J/ψ in pPb vs rapidity at 5 TeV

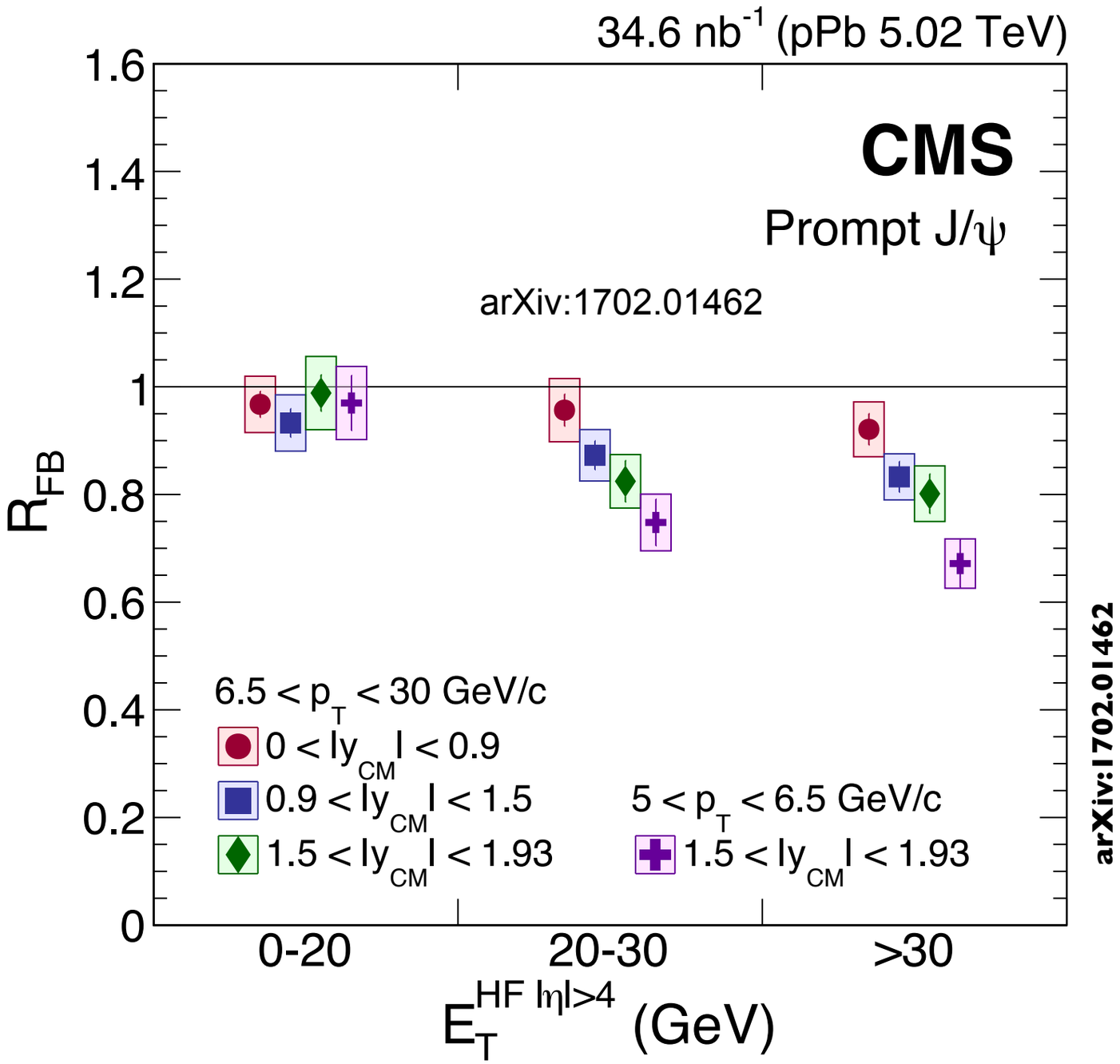


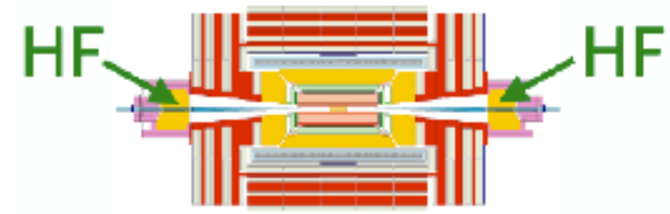


→R_{pA} decreases when going from backward to forward rapidities

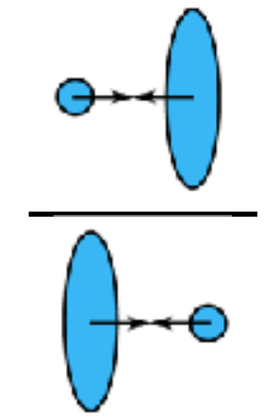
→Models that include shadowing slightly underestimated the R_{pA} but well reproduce the rapidity-trend

Forward/Backward J/ψ in pPb





muons measured in |η| < 2.4

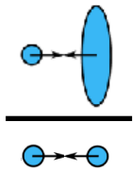


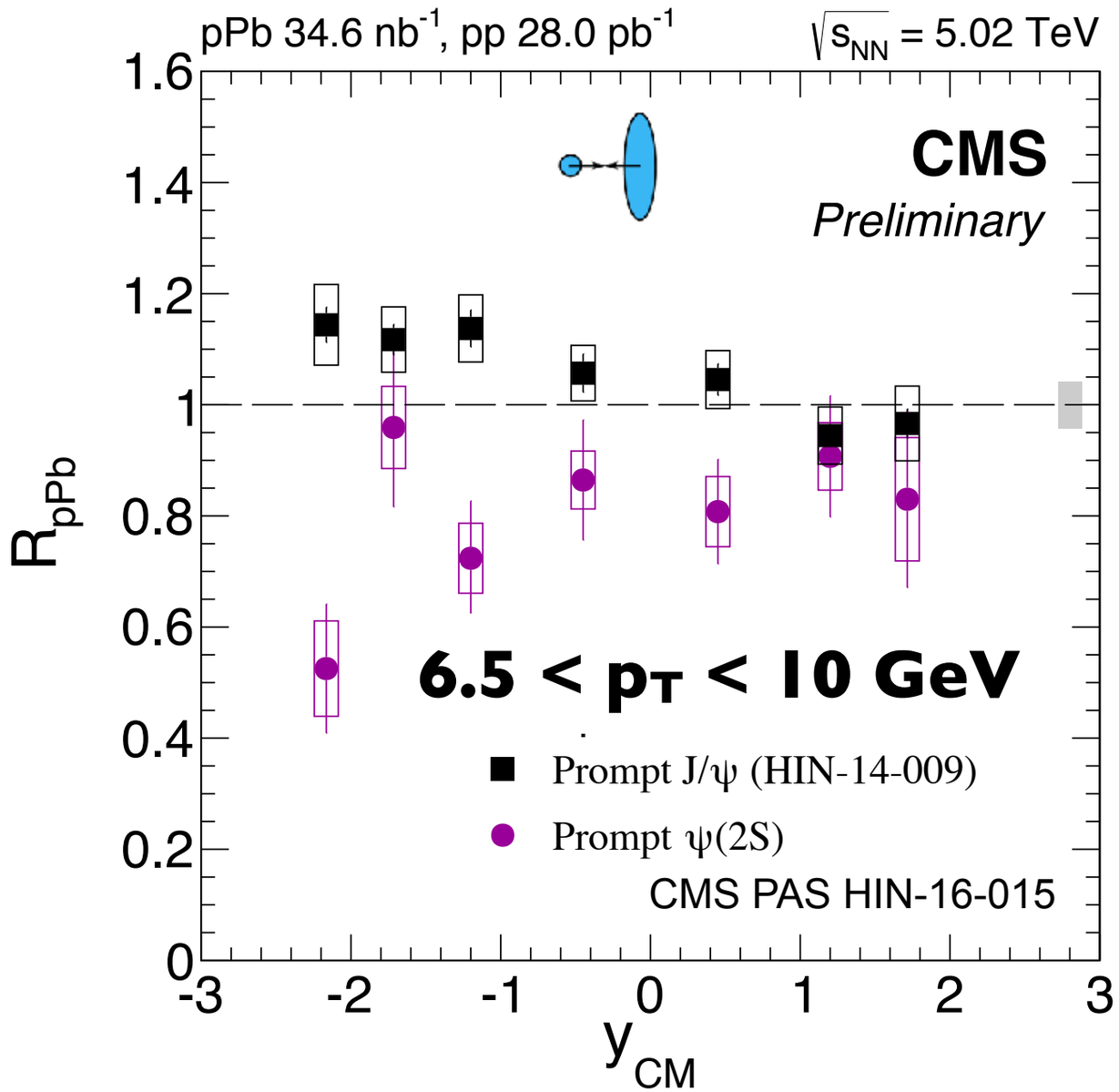
Event activity =
transverse energy deposited in the Hadron Forward calorimeters

larger event activity
~ more "central" pPb events

Forward/Backward asymmetry increases when going to "central" events

Prompt ψ(2S) in pPb



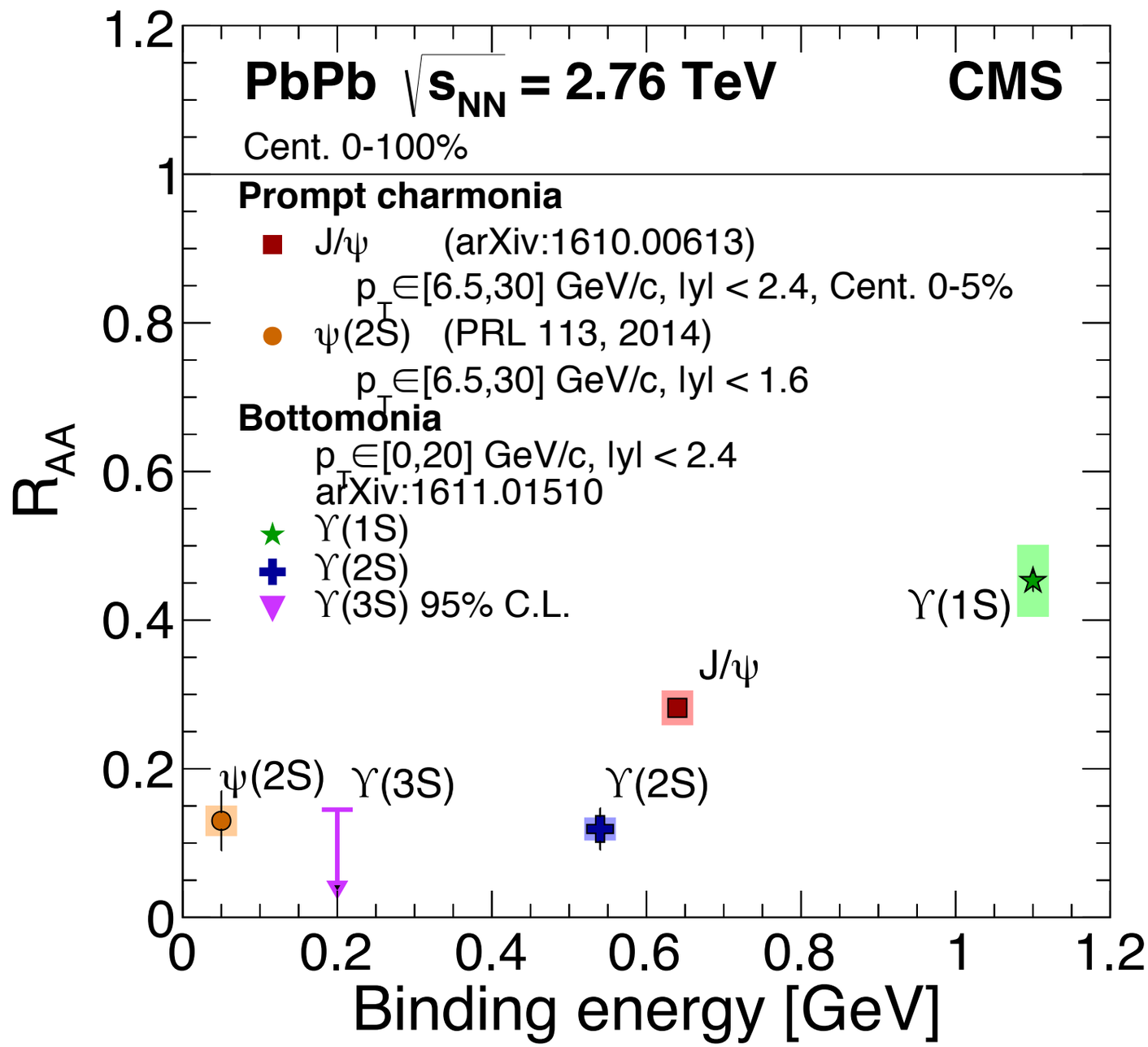


R_{pPb}(ψ(2S)) < R_{pPb}(J/ψ) at backward rapidity (Pb-going direction)

→ *initial state expected to be similar for 1s and 2s states*

→ *are we observing a different "final state" interaction for the two states?*

Quarkonia R_{AA} vs binding energy

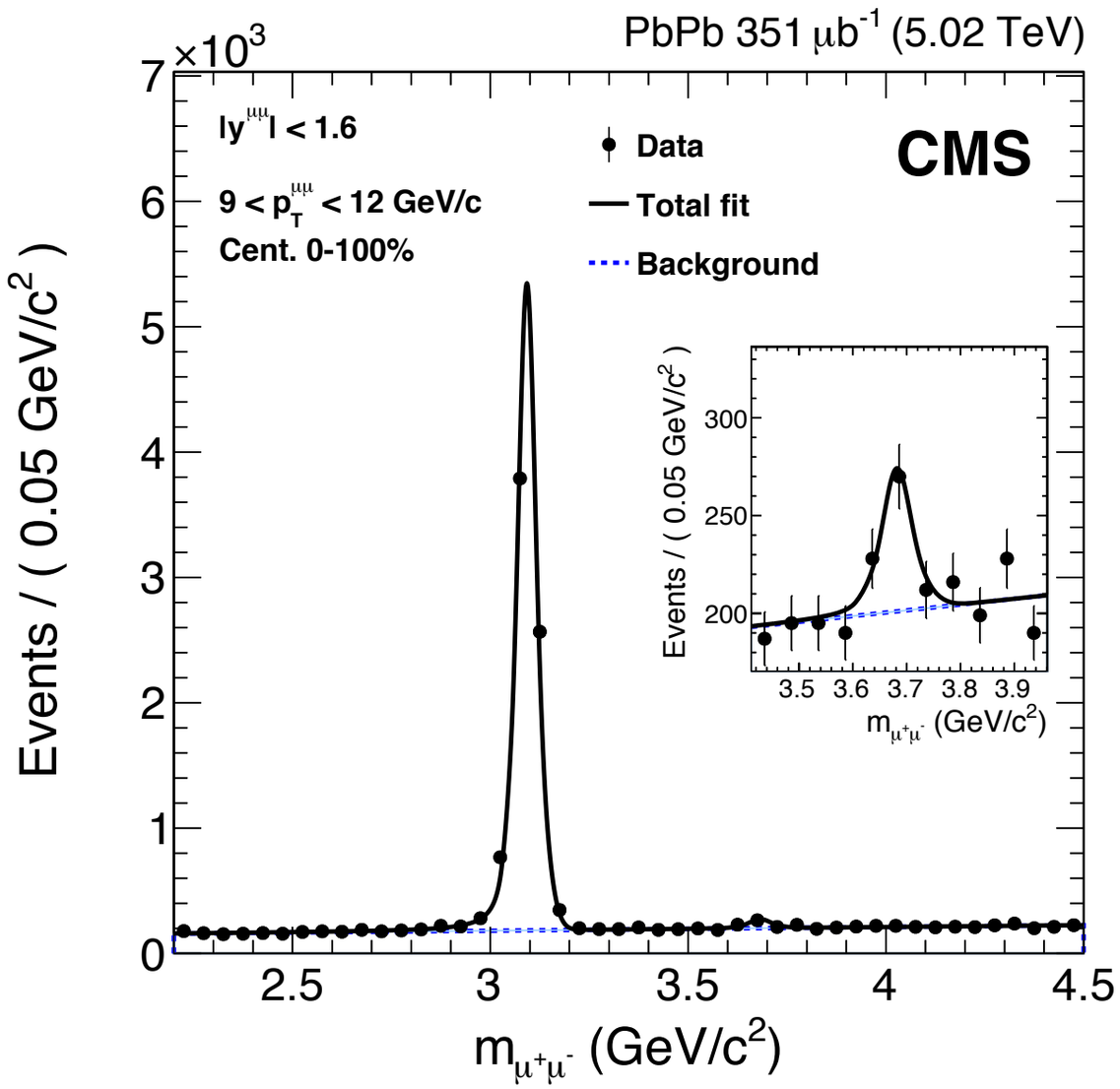


This was the state of the art at 2.76 TeV.

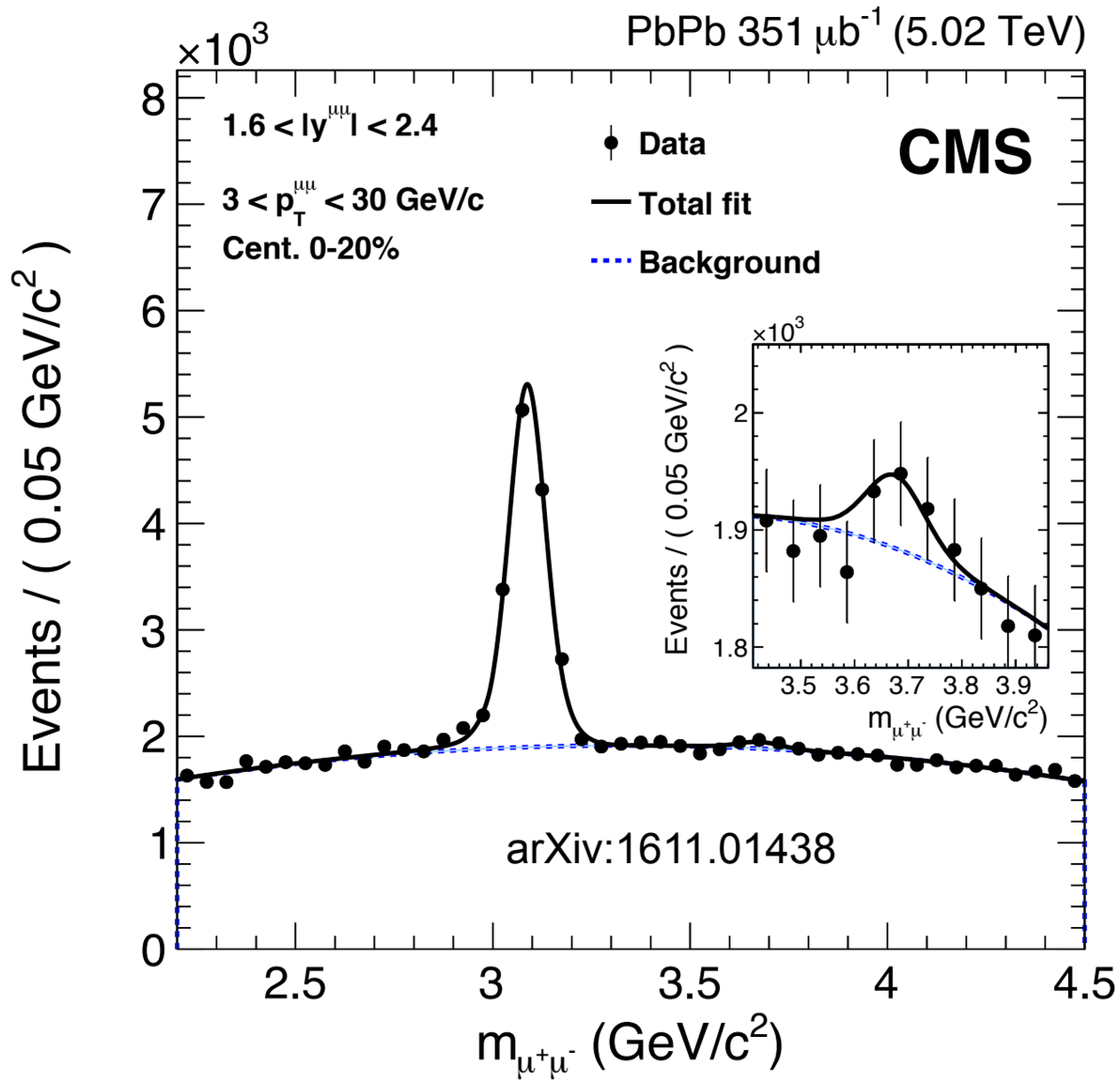
What happens when we move to 5.02 TeV and we increase the statistics?

J/ψ and ψ(2s) in PbPb collisions at 5 TeV

|y| < 0.9 ; 9 < p_T < 12 GeV/c
Cent: 0-100%



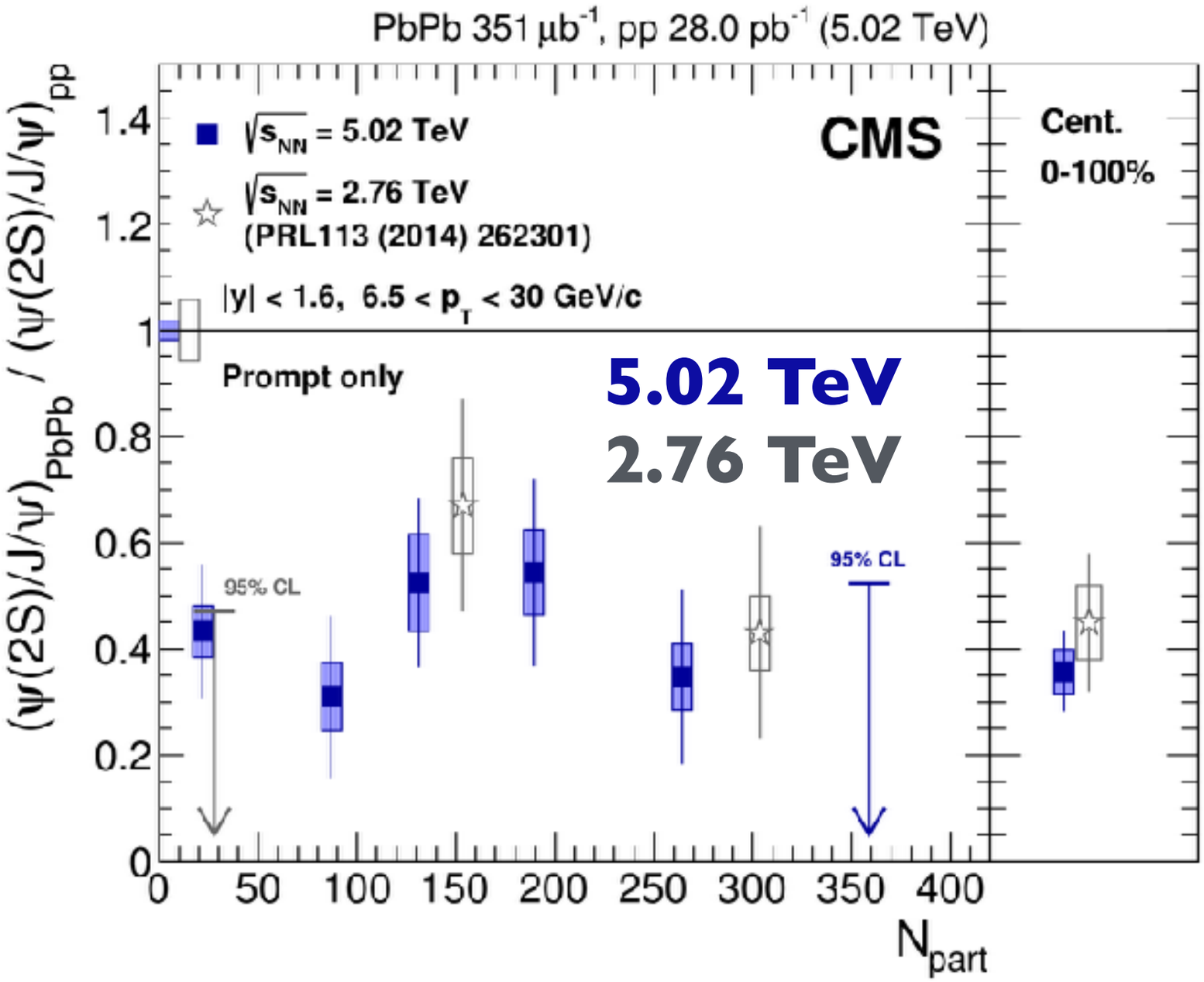
1.6 < |y| < 2.4 ; 3 < pT < 30 GeV/c
Cent: 0-20%



~350/μb collected during 2015 PbPb run!

J/ψ and ψ(2s) double ratio at 5.02 TeV

Central rapidity |y| < 1.6



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

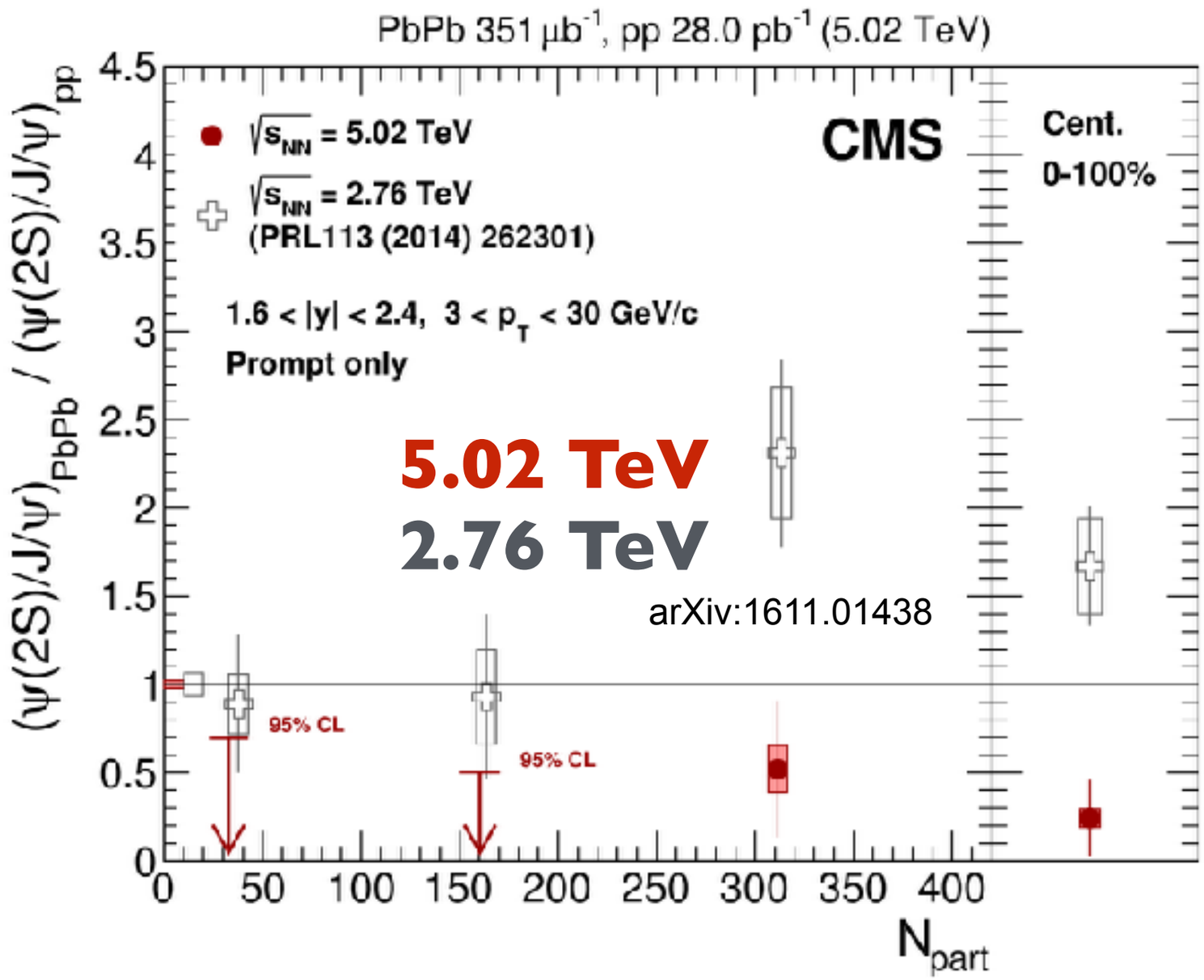
Larger relative suppression at 5.02 TeV w.r.t. to 2.76 TeV

→ *3σ effect in the centrality integrated sample*

arXiv:1611.01438

J/ψ and ψ(2s) double ratio at 5.02 TeV

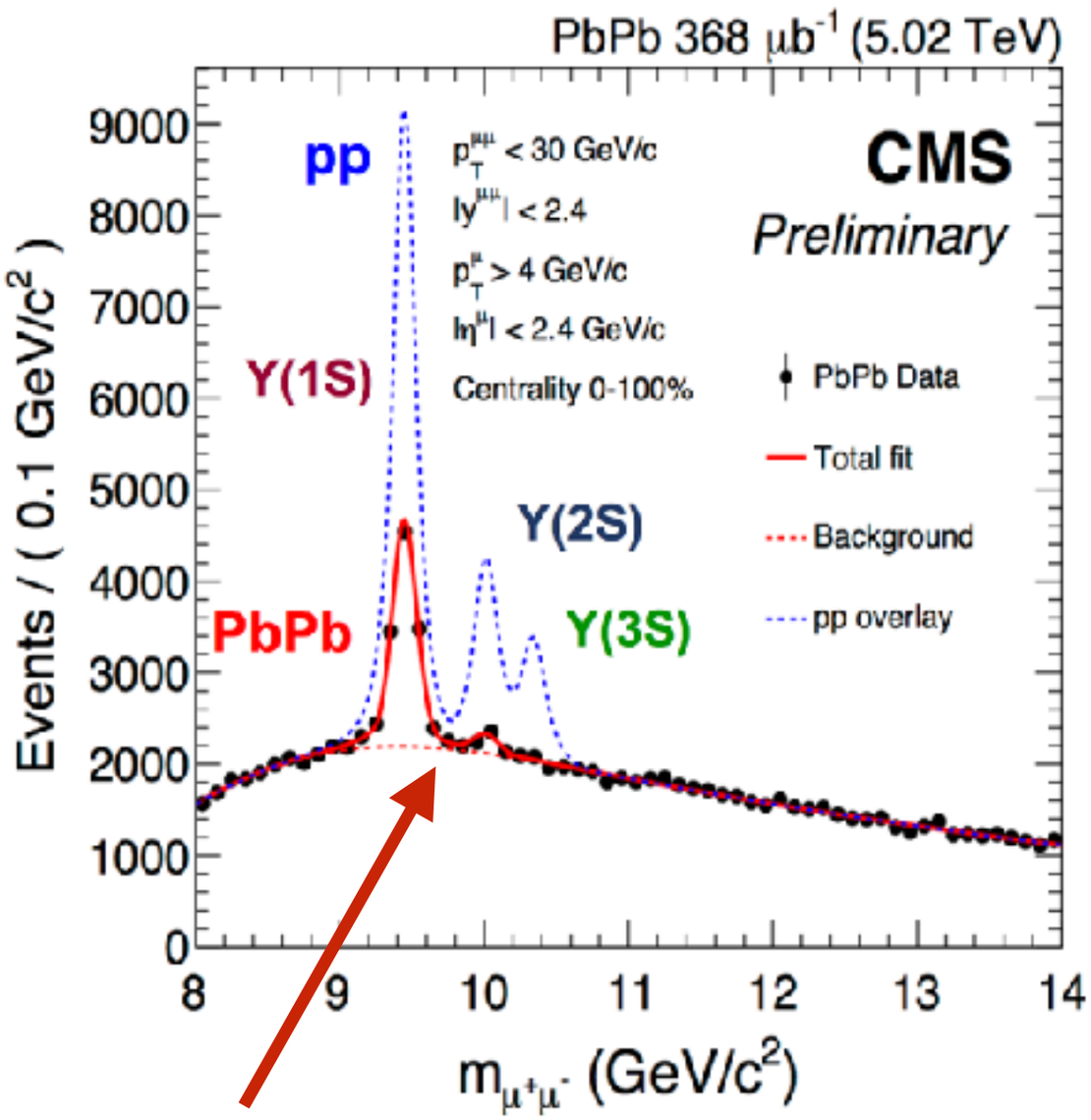
Forward rapidity 1.6<|y| <2.4



No indication of enhancement of the double ratio in central events at 5.02 TeV

→ *Still not understood! No evidence of bugs/problems in the 2.76 at the moment….*

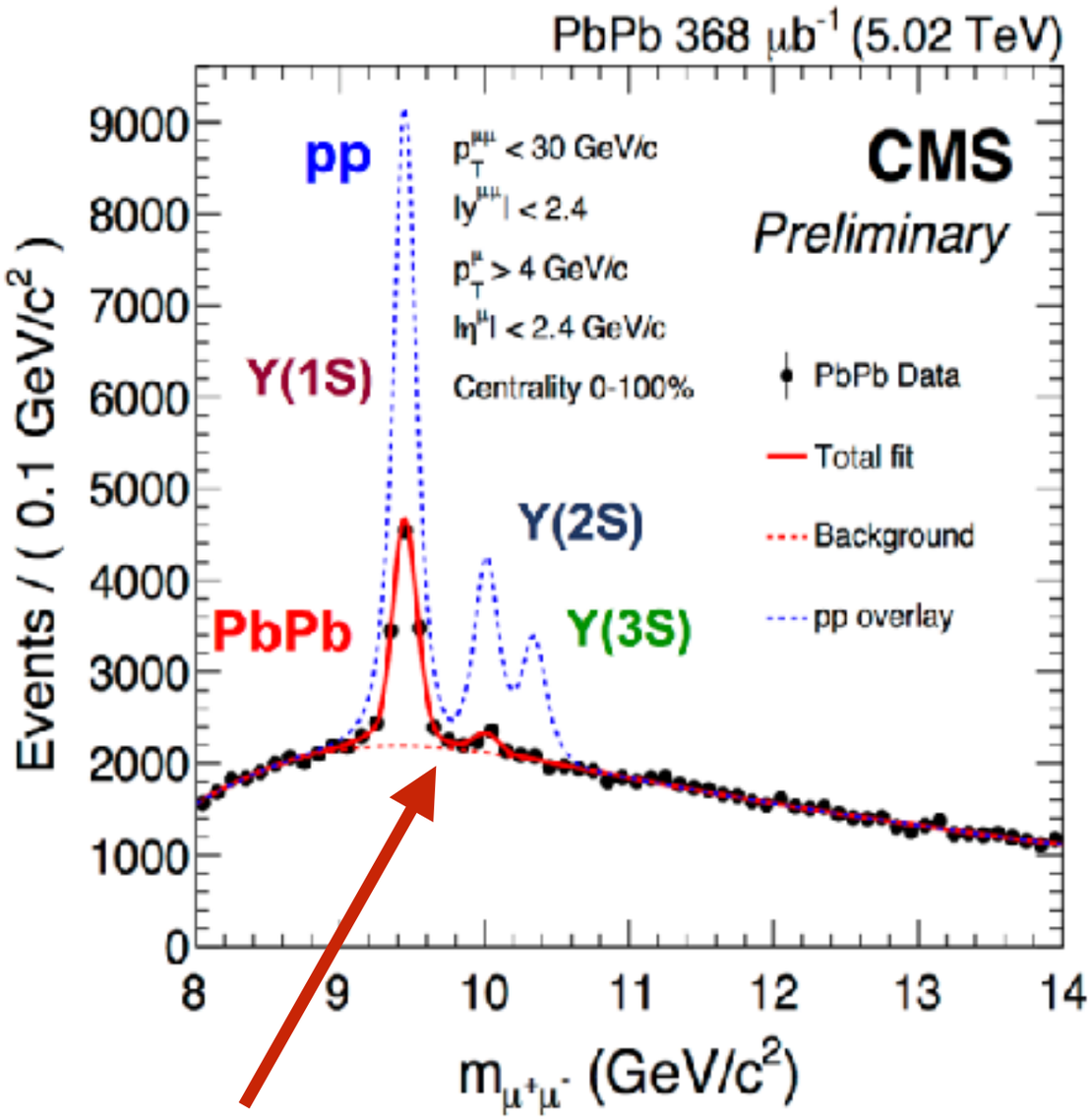
Upsilon suppression in PbPb at 5.02 TeV

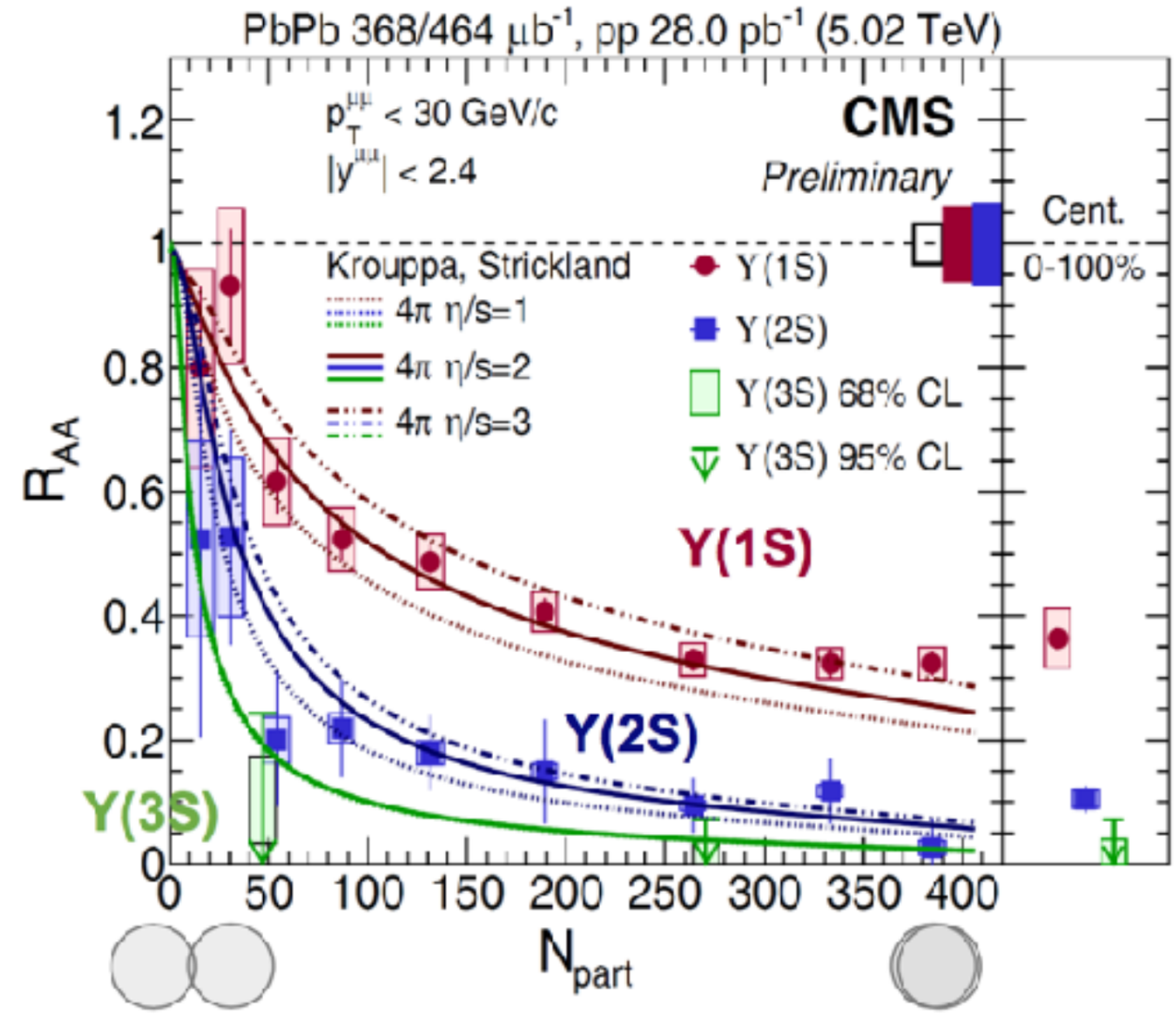


Still no sign of Υ(3s) even with large statistics sample

CMS PAS HIN-16-008

Upsilon suppression in PbPb at 5.02 TeV



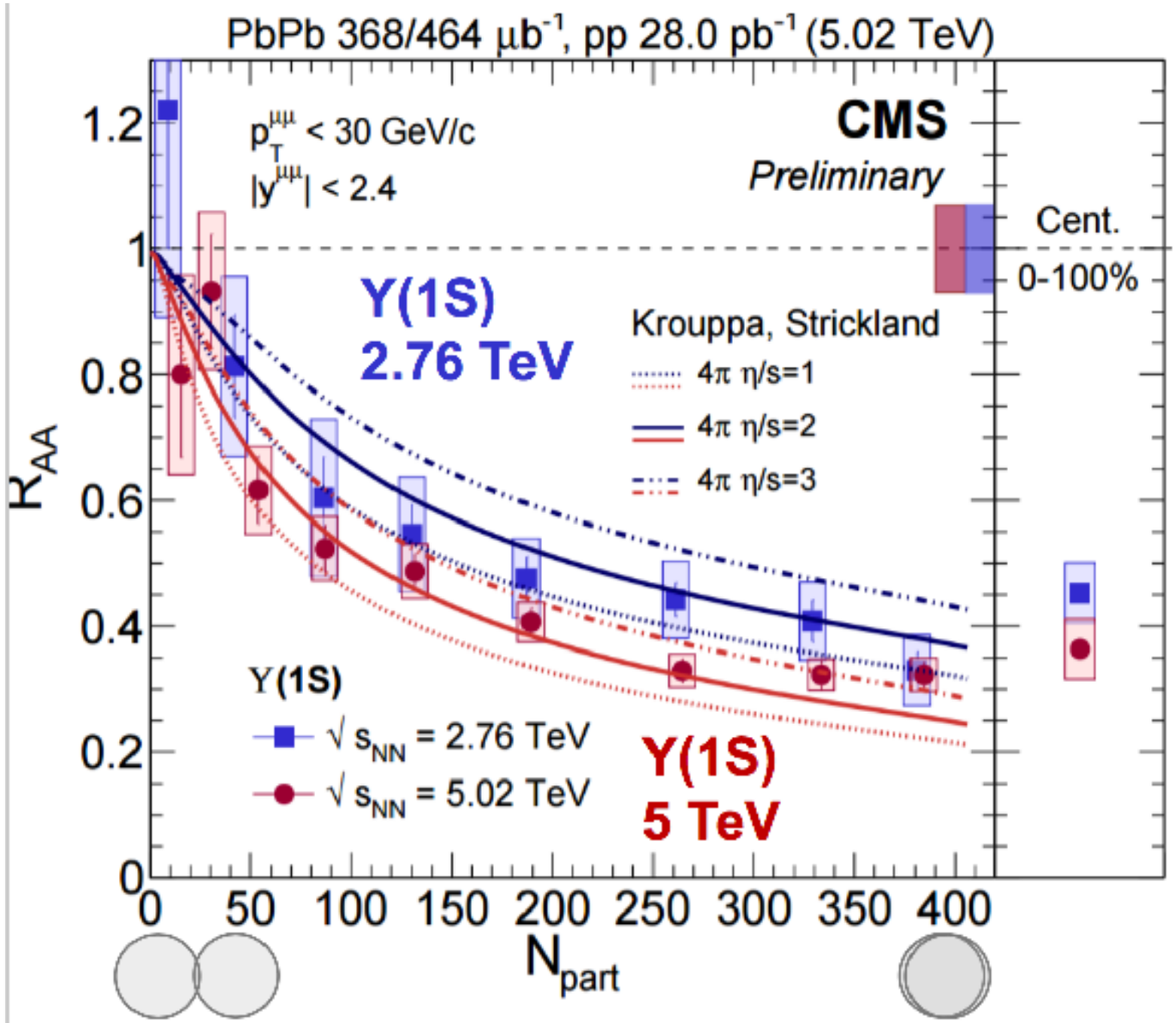


Still no sign of Y(3s) even with large statistics sample

Very high precision measurement of upsilon sequential suppression
→ *compatible with theoretical calculations*

CMS PAS HIN-16-008

Υ(1S) suppression: 5.02 vs 2.76 TeV

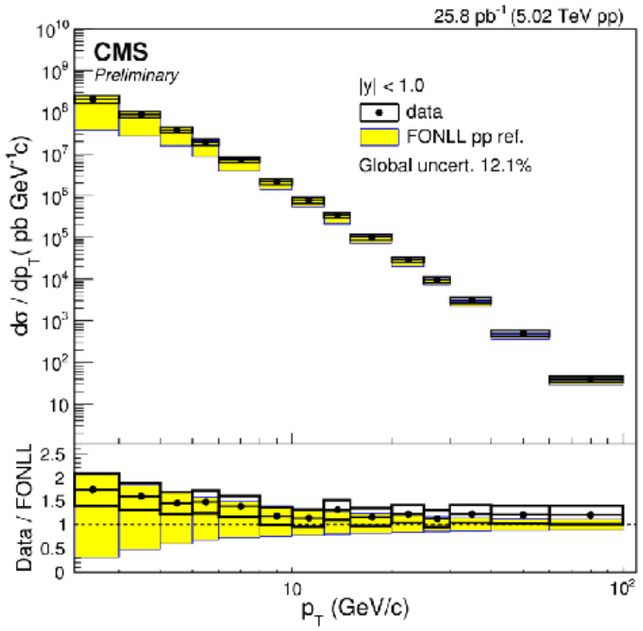


Evidence of stronger suppression of Υ(1S) at 5.02 TeV with respect to 2.76 as expected in case of a hotter and denser medium

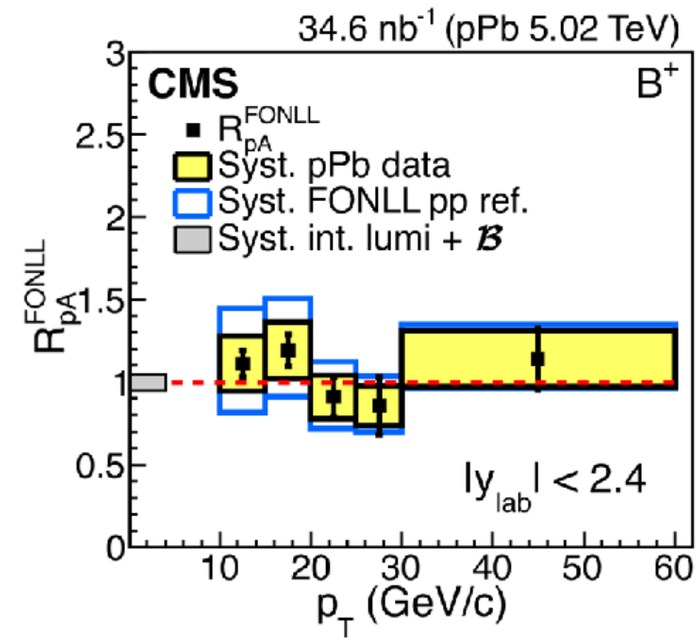
CMS PAS HIN-16-008

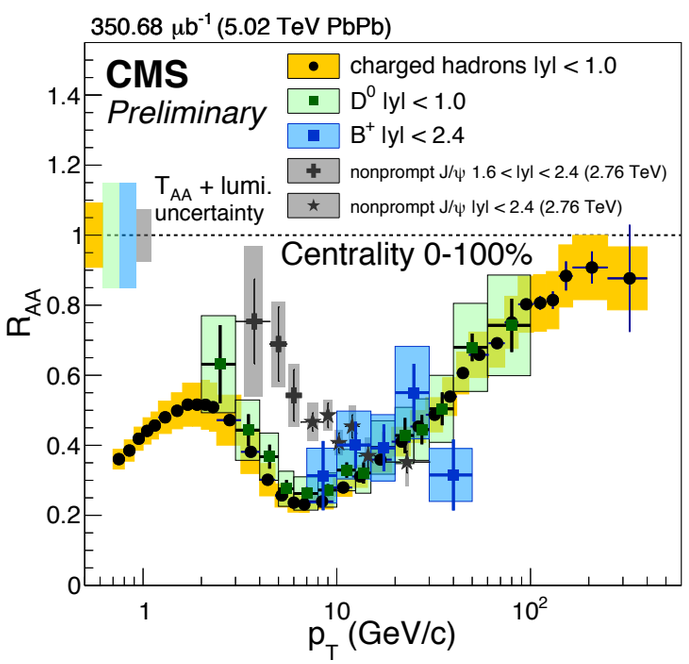
→ *difference due to energy very well described by models*

Summary (I)

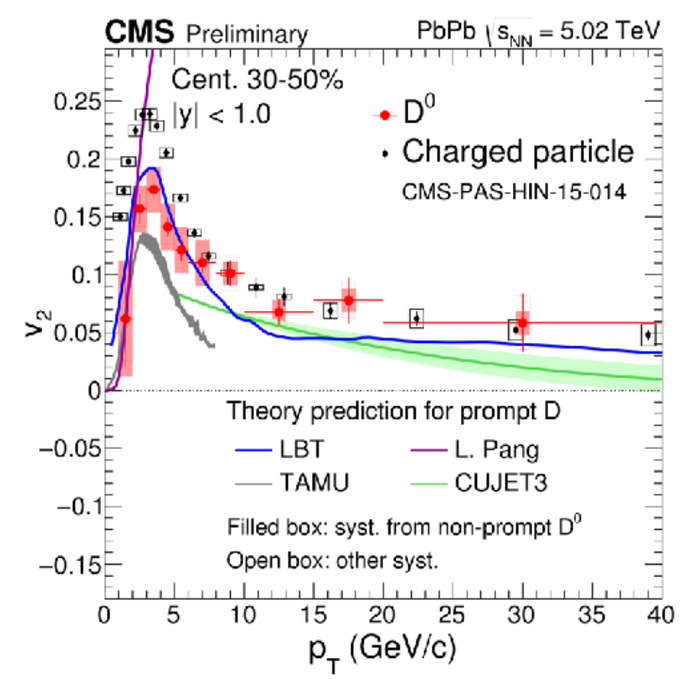


- Charm and beauty production well described by pQCD calculations
- pPb compatible with binary scaling
  →needs for more precise measurements

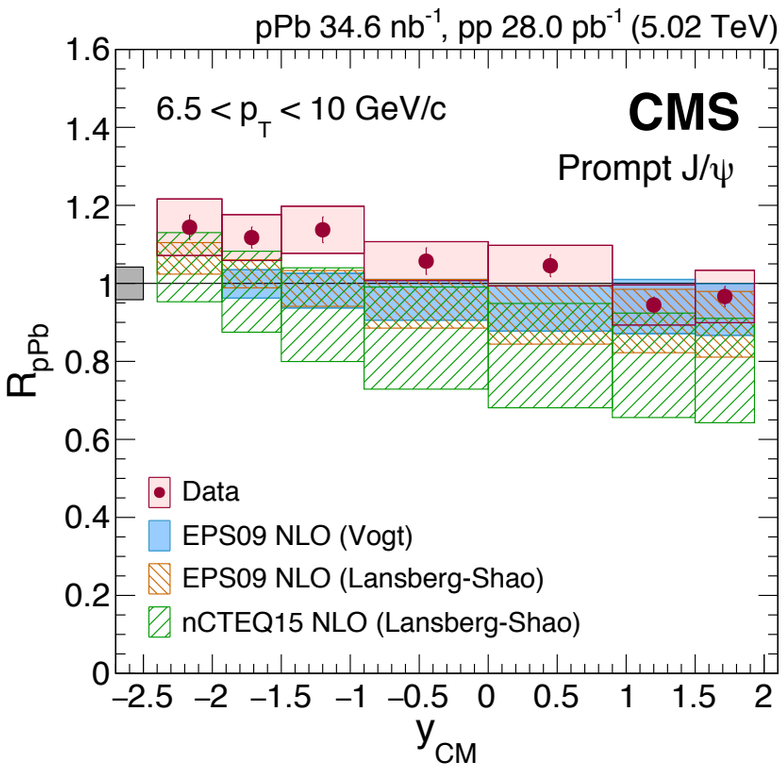




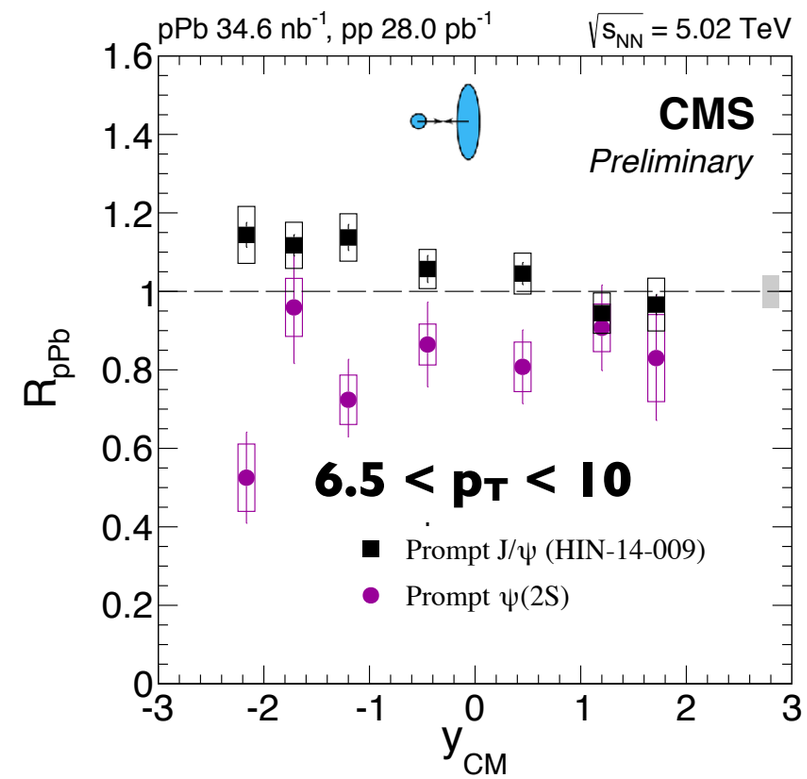
- Hints of flavour dependence at low p_T
- Flavour dependence seems to vanish at higher p_T
  →precise rapidity dependent measurement needed and higher statistics non prompt J/psi at 5 TeV
- Evidence of charm flow!

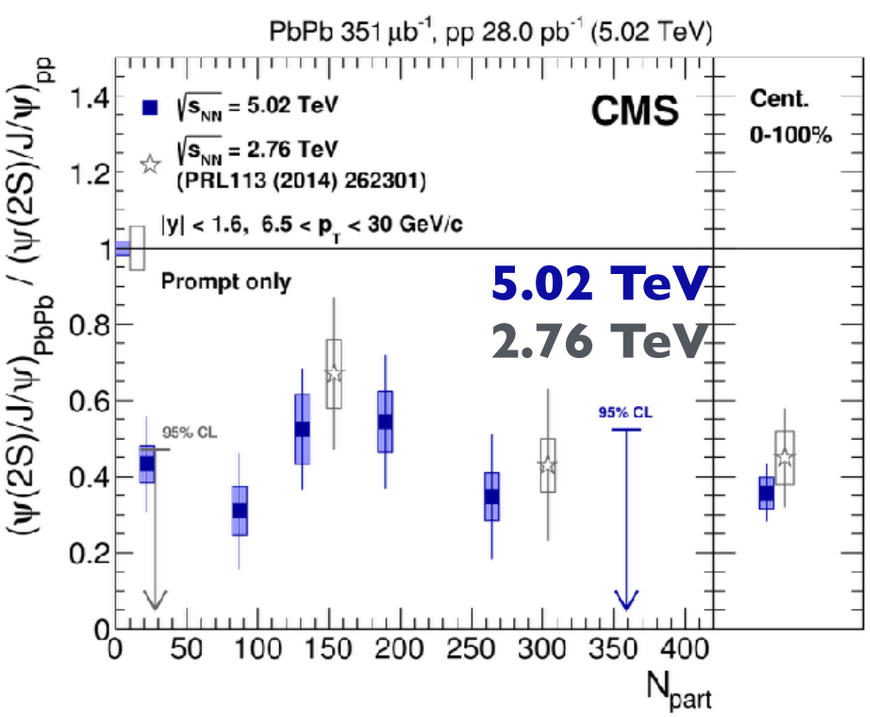


Summary (II)

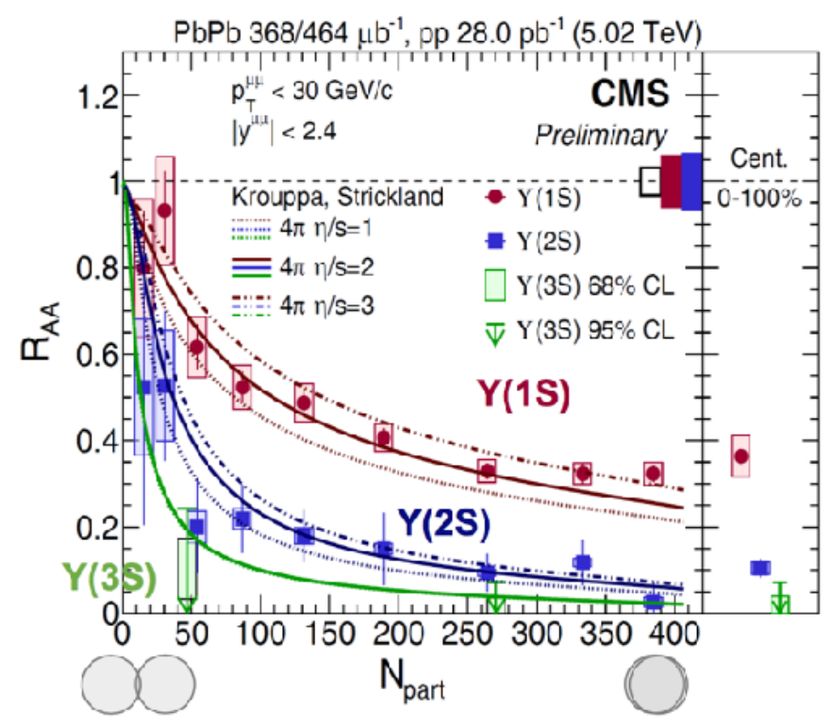


- Precise measurement of J/ψ in pPb vs rapidity
  →compatible with shadowing
- R_{pA} (J/ψ)< ψ(2s)
  →different final state effect?



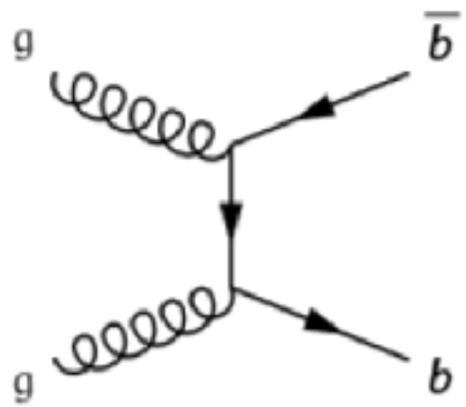


- Stronger suppression of ψ(2s) wrt J/ψ at 5.02 TeV!
- Precise measurement of sequential suppression at 5.02 TeV



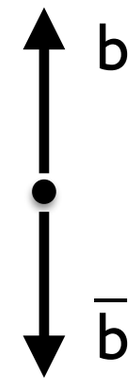
BACKUP

heavy quark production mechanism



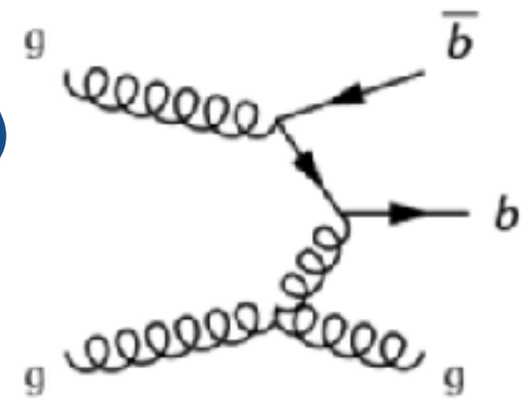
LO process: Flavour Creation (FCR)

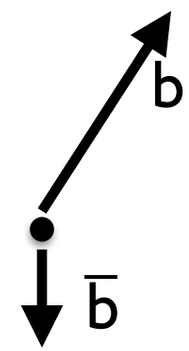
→ $b\bar{b}$ produced back-to-back in azimuthal plane and symmetric in p_T

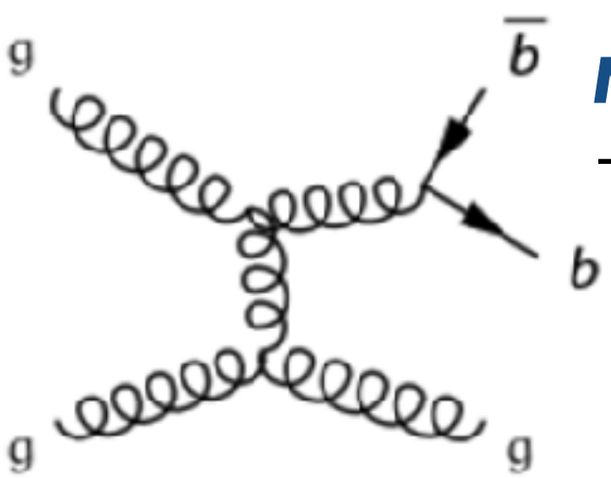


NLO process: Flavour Excitation (FEX)

→ $b\bar{b}$ pairs produced asymmetric in p_T and with a broad opening angle



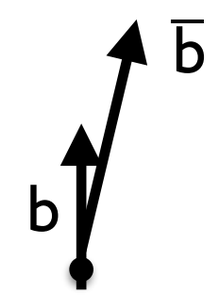




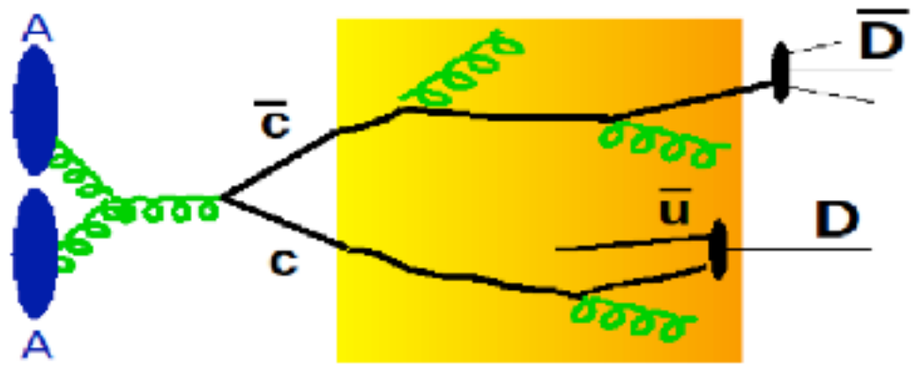
NLO process: Gluon splitting (GSP)

→ produced with small opening angles and asymmetric in p_T

→ $b\bar{b}$ are not involved in the hard scattering but produced later

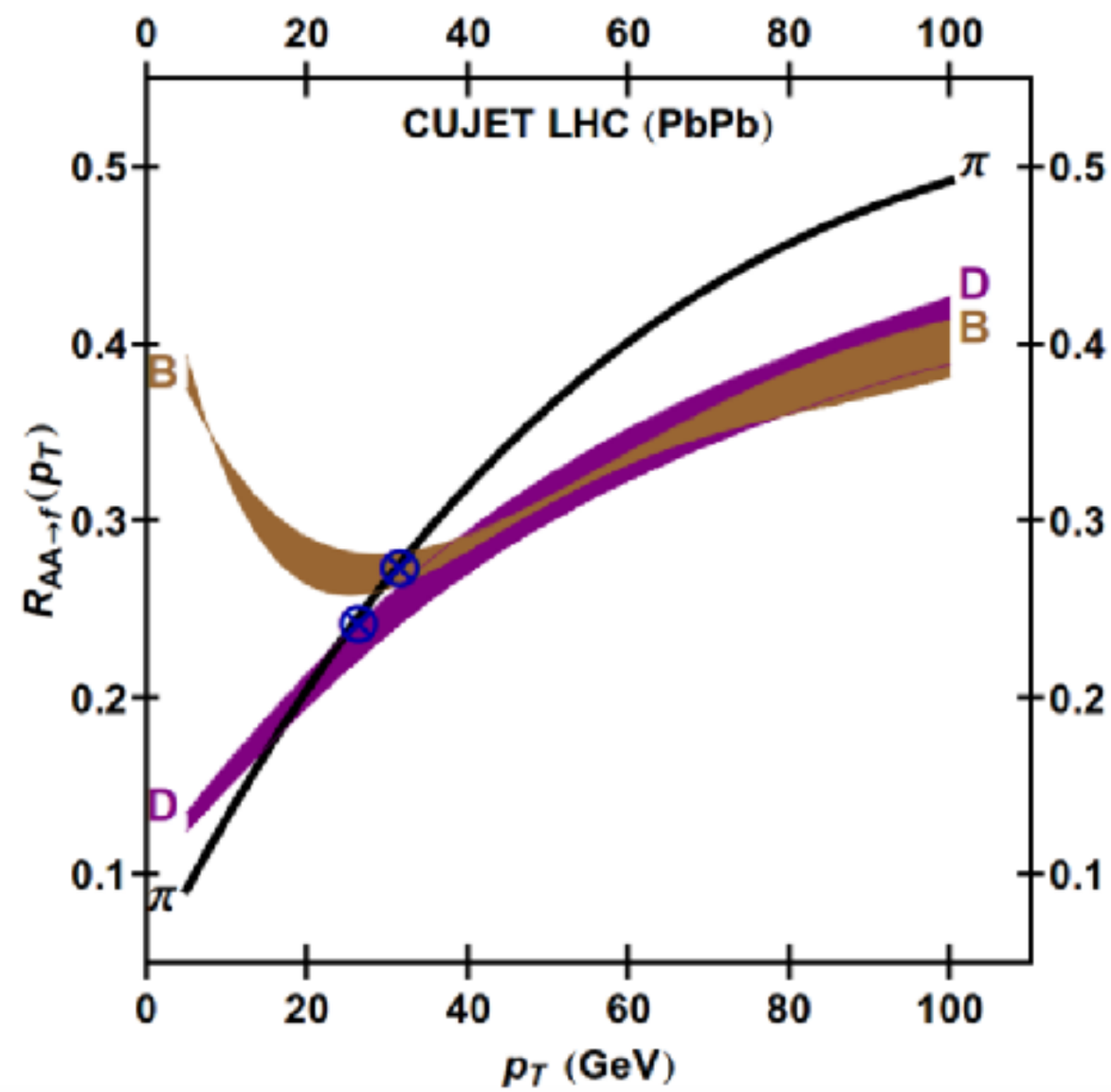


Reminder on HF energy loss



- produced early in the collision, they strongly interact with the deconfined medium

→ In-medium energy loss as a consequence of radiative and collisional processes.



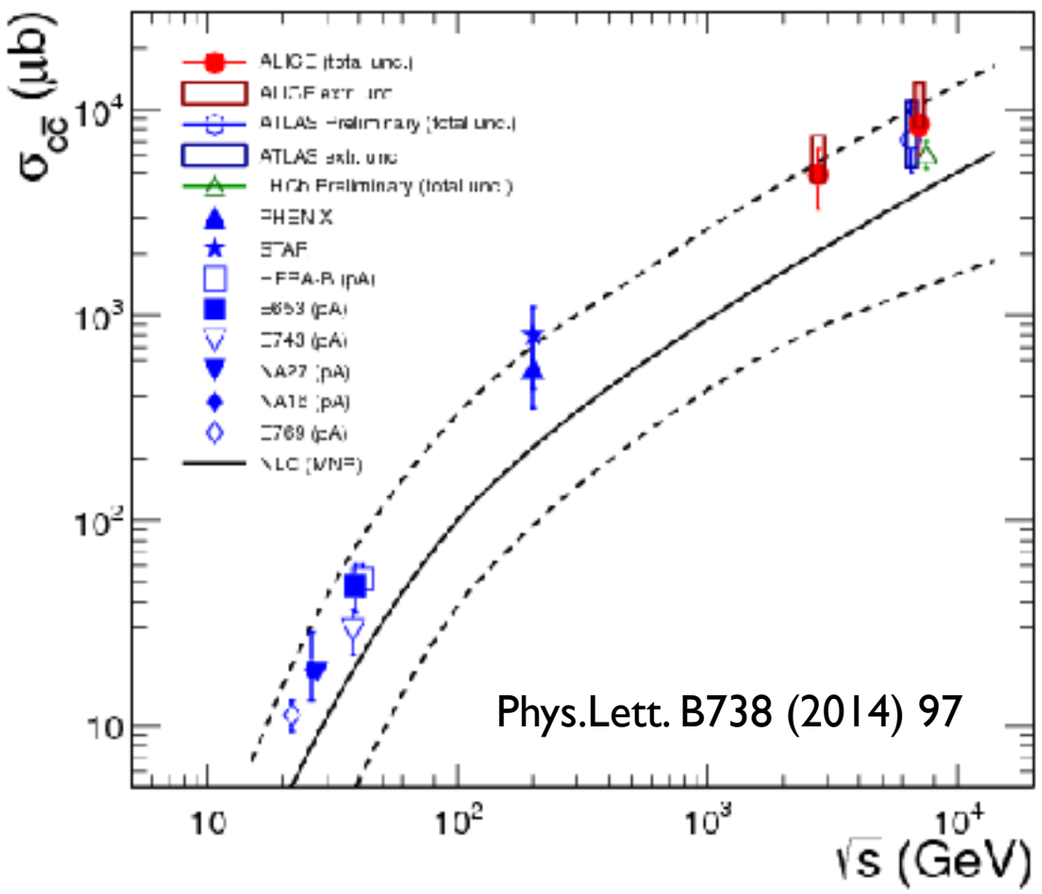
Flavour-dependence of radiative energy loss:

- Larger for gluons than for quarks
  E.g. in BDMPS model [1] $\langle\Delta E\rangle \propto \alpha_s C_R q L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \quad \rightarrow R_{AA}^{B} > R_{AA}^{D} > R_{AA}^{light} \text{ (??)}$$

Heavy-flavours in pp and pPb collisions

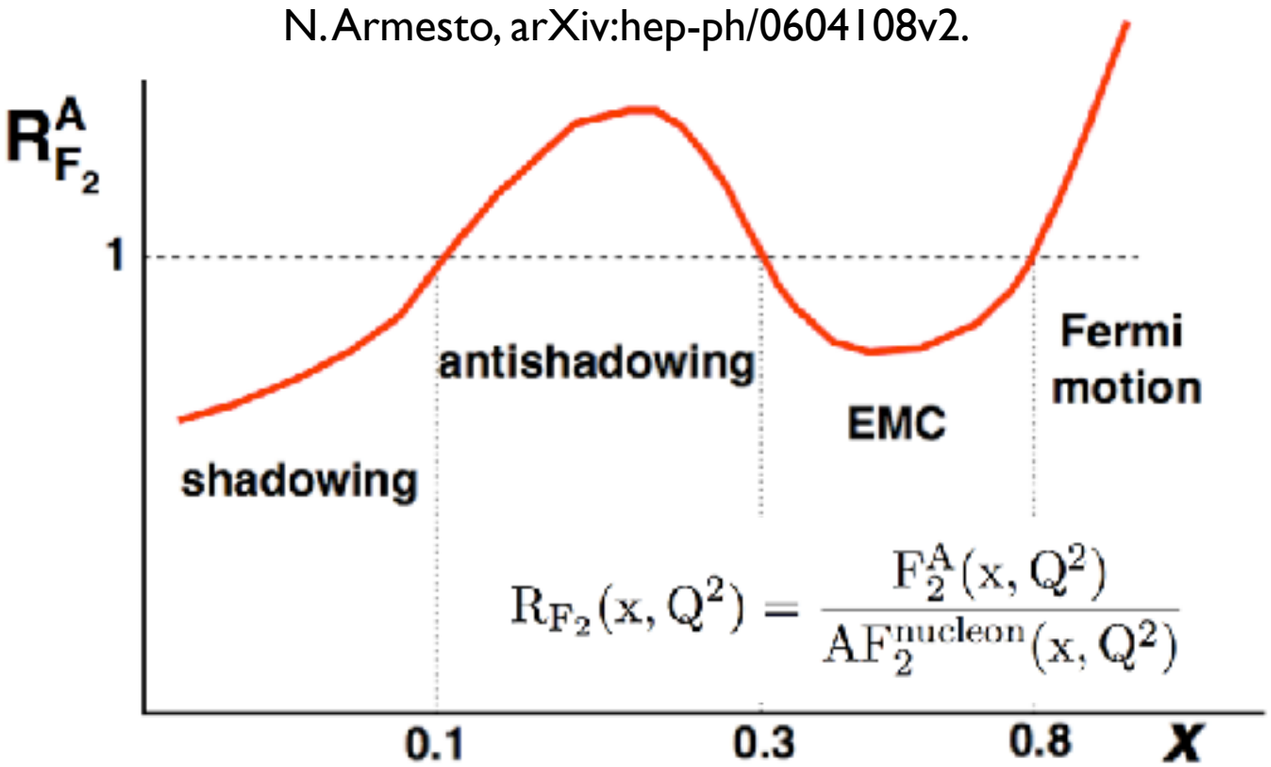
Heavy quarks produced in high Q^2 processes at early stages of the collisions



pp:

- test of pQCD calculations
- reference for pA and AA measurements

N. Armesto, arXiv:hep-ph/0604108v2.



pPb:

- test of cold nuclear matter effects
  - PDF modifications
  - saturation
  - final state effects
- collective evolution (hydro?)

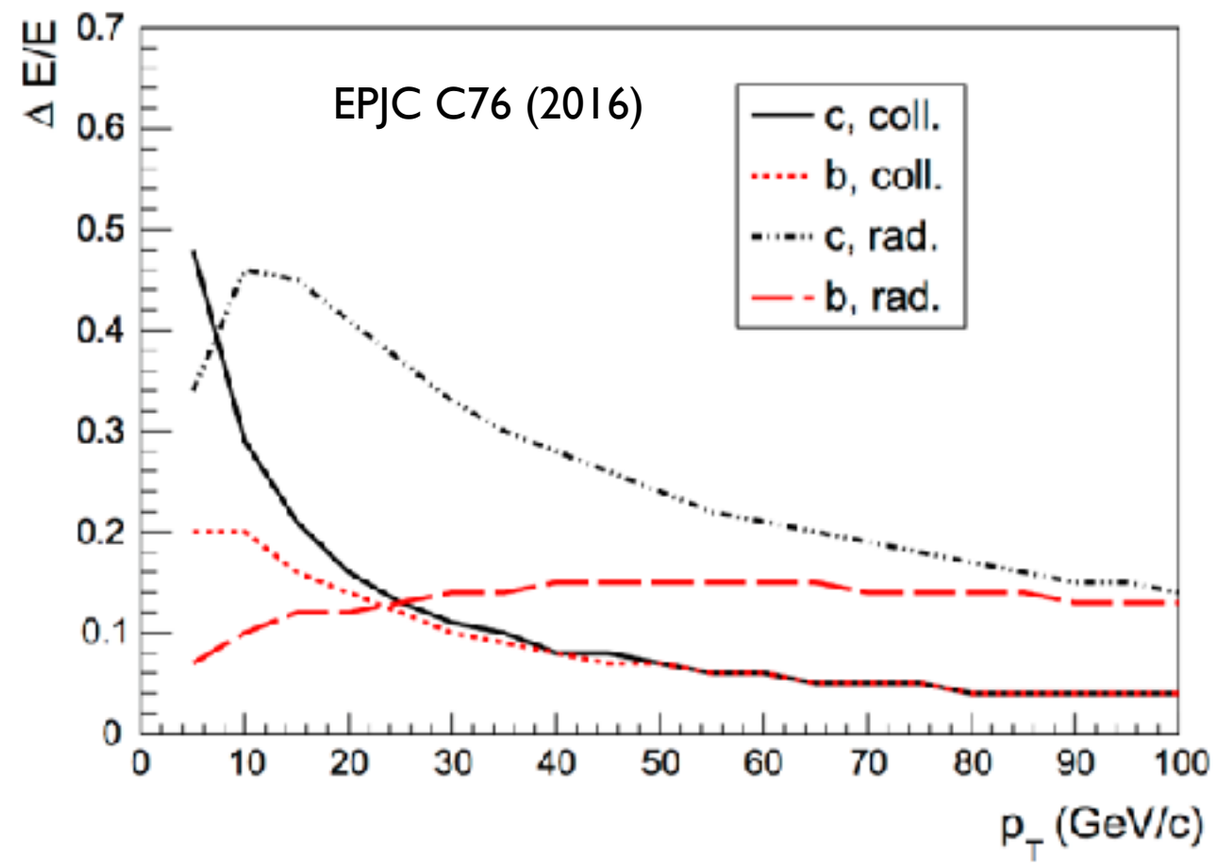
Heavy-flavours in PbPb collisions

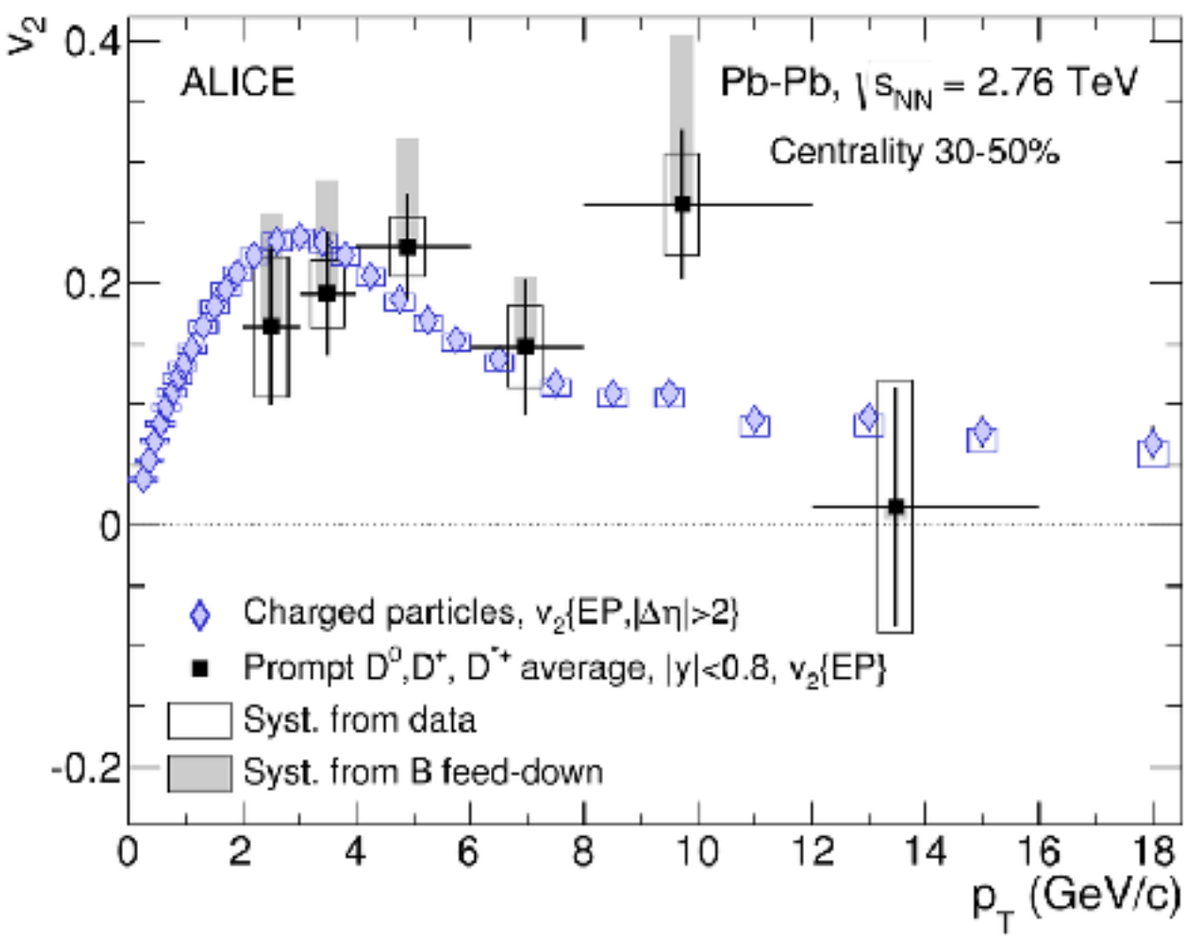
Heavy quark energy loss in PbPb:

- **collisional** vs **radiative** component

Flavour dependence energy loss:

- $\langle \Delta E \rangle \propto \alpha_s C_R q L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks





Collective behaviour:

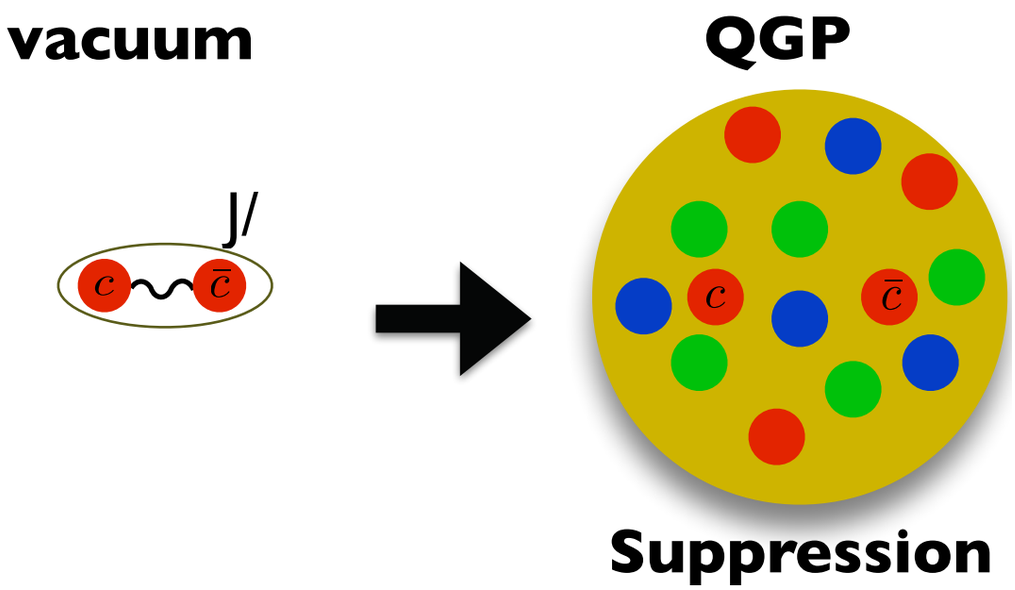
- v_n measurements to study collective behaviour of heavy quarks
- charm recombination in medium?

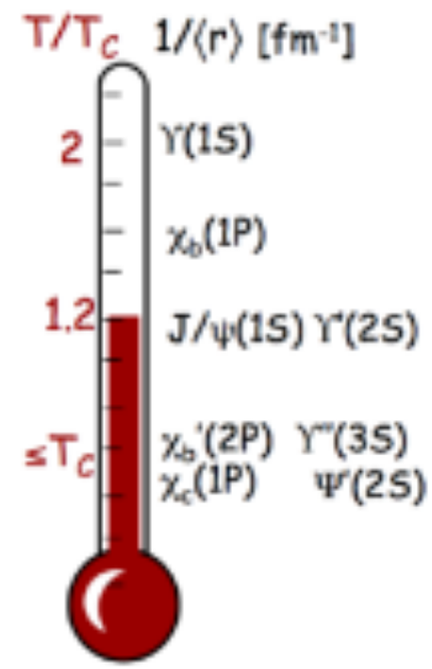
Charmonia in heavy-ion collisions

Charmonia are bound states of $c\bar{c}$

$$\tau^{c\bar{c}}_{\text{formation}} \lesssim \tau^{QGP}_{\text{formation}} < \tau^{QGP}_{\text{life}} < \tau^{\text{quarkonium}}_{\text{decay}}$$

The presence of QGP should affect charmonia production (yield and kinematics)





Less bounded states melts at lower temperature

T^{diss} (1S) > T^{diss} (2S) > …

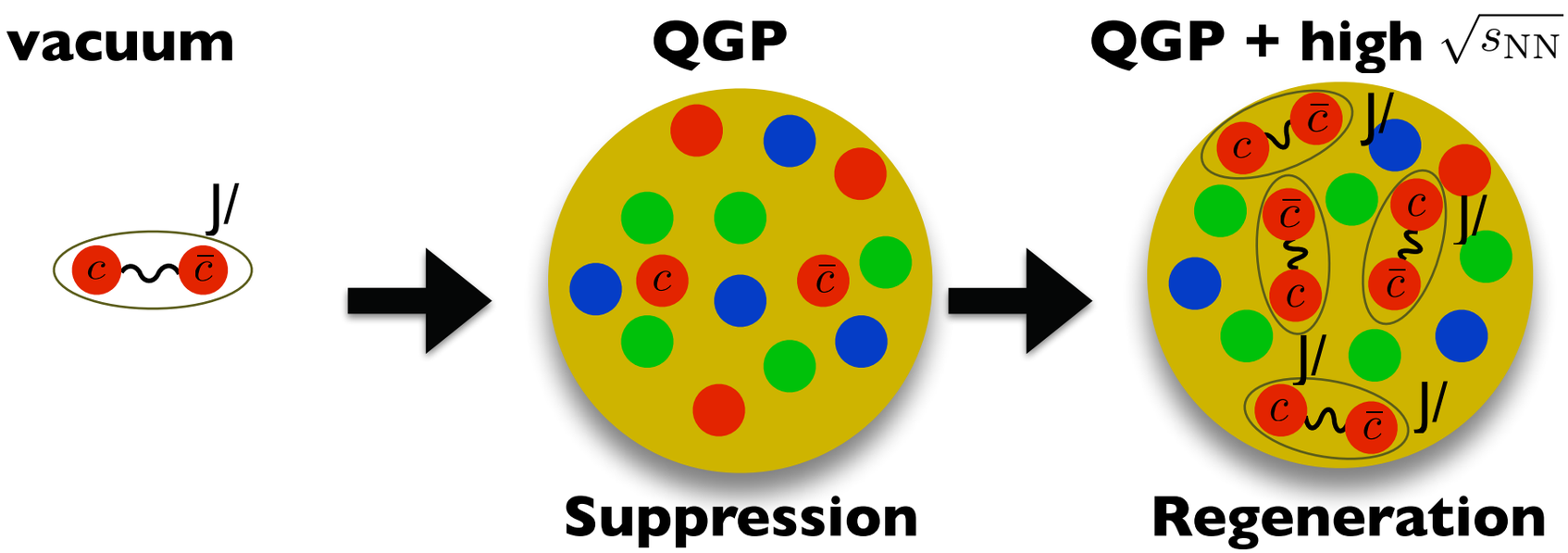
We should observe a hierarchy in the dissociation of different quarkonia states depending on their binding energies

Charmonia in heavy-ion collisions

Charmonia are bound states of $\bar{c}c$

$$\tau^{c\bar{c}}_{\text{formation}} \lesssim \tau^{QGP}_{\text{formation}} < \tau^{QGP}_{\text{life}} < \tau^{\text{quarkonium}}_{\text{decay}}$$

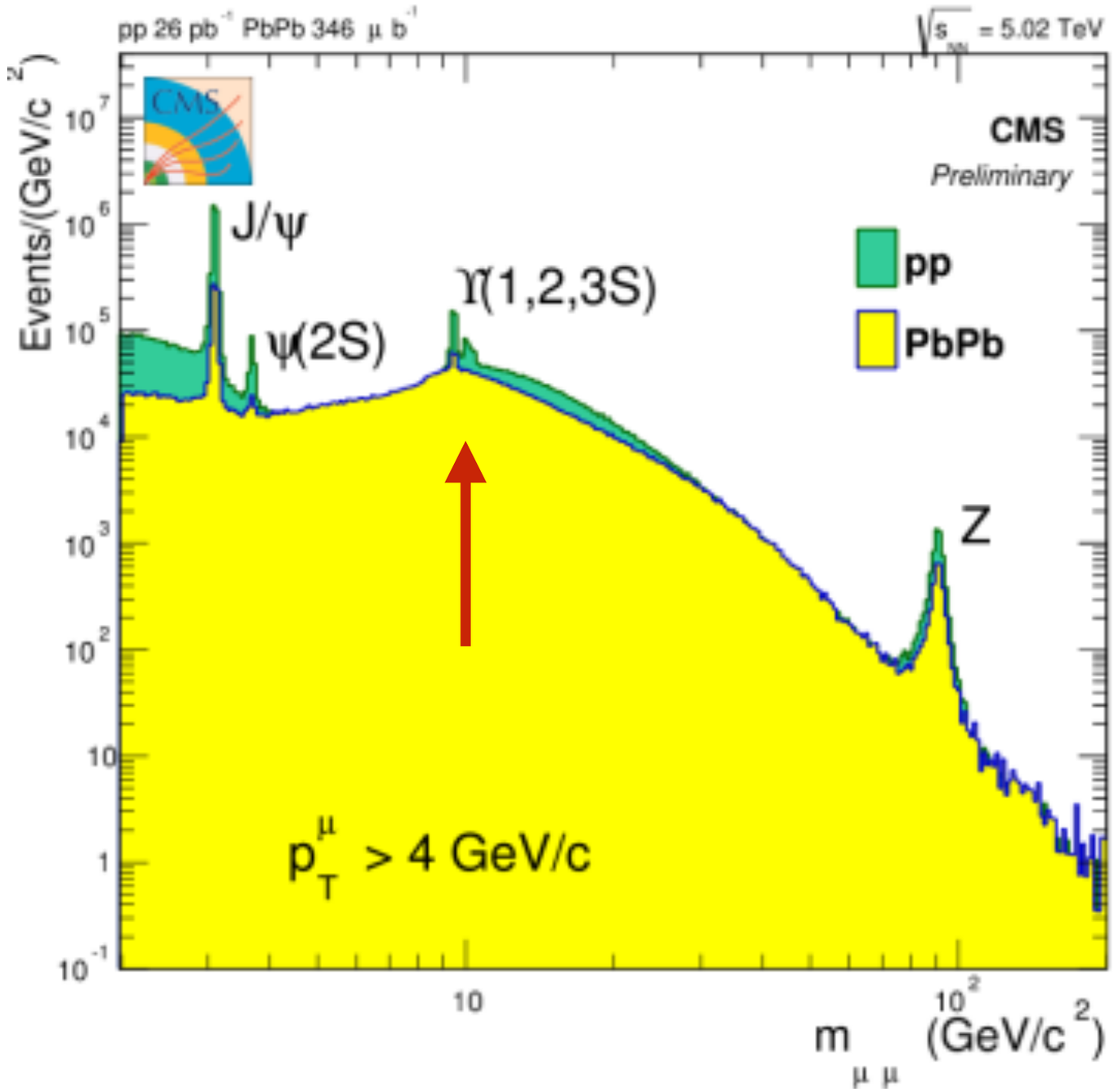
The presence of QGP should affect charmonia production (yield and kinematics)



Less bounded states melts at lower temperature
T^{diss} (1S) > T^{diss} (2S) > …

But life is not that easy, charm (re)combination in the medium is expected to play a significant role at LHC!

Bottomonia, a cleaner probe for the QGP



Y(nS) states are less likely to be created via recombination!

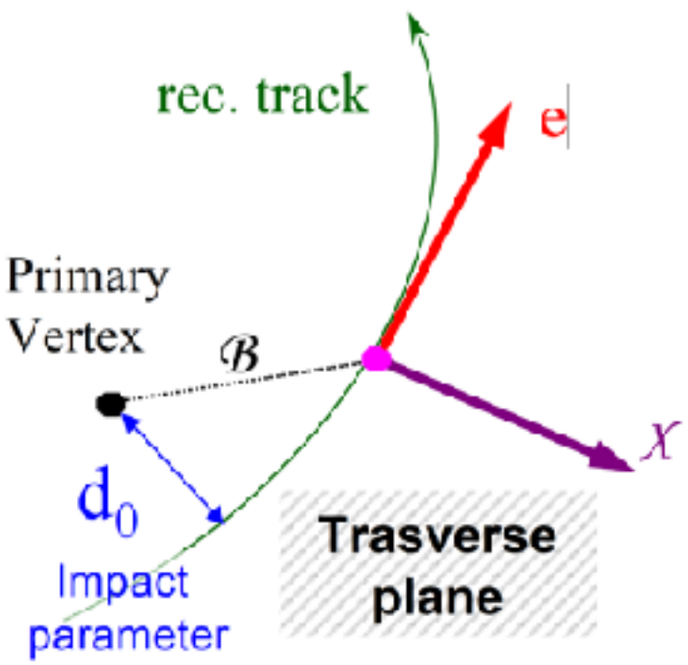
HF models overview

Table 11: Comparative overview of the models for heavy-quark energy loss or transport in the medium described in the previous sections.

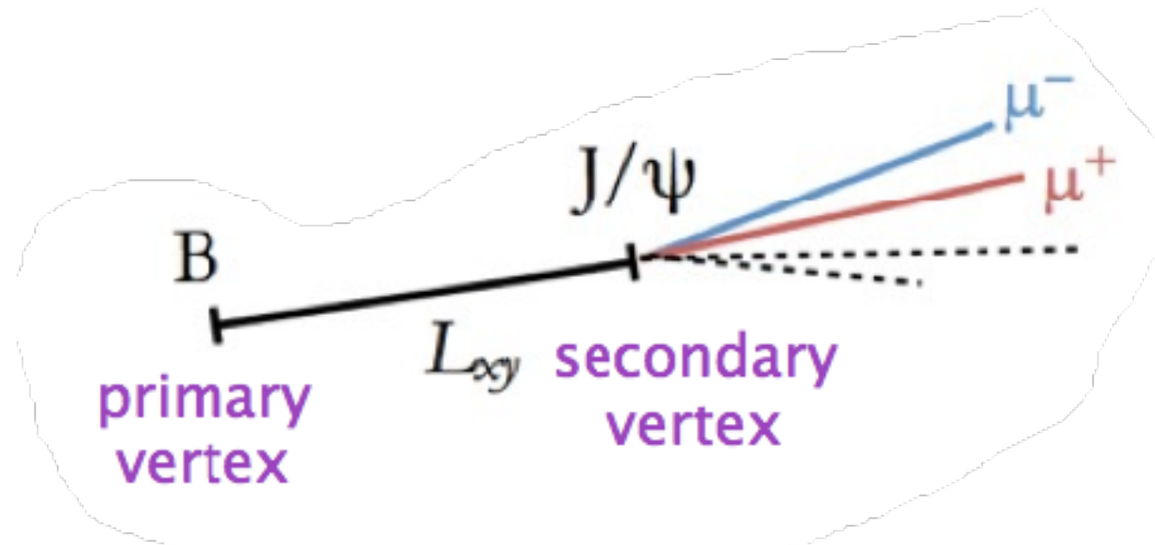
Model	*Heavy-quark production*	*Medium modelling*	*Quark–medium interactions*	*Heavy-quark hadronisation*	*Tuning of medium-coupling (or density) parameter(s)*
Djordjevic *et al.* [511–515]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss finite magnetic mass	fragmentation	Medium temperature fixed separately at RHIC and LHC
WHDG [459, 519]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
Vitev et al. [422, 460]	non-zero-mass VFNS no PDF shadowing	Glauber model nuclear overlap ideal fl. dyn. 1+1d Bjorken expansion	radiative energy loss in-medium meson dissociation	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
AdS/CFT (HG) [624, 625]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	AdS/CFT drag	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
POWLANG [507–509, 585, 586]	POWHEG (NLO) EPS09 (NLO) PDF shadowing	2+1d expansion with viscous fl. dyn. evolution	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume pQCD (or l-QCD U potential)
MC@$_s$HQ+EPOS2 [528–530]	FONLL EPS09 (LO) PDF shadowing	3+1d expansion (EPOS model)	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at LHC, slightly adapted for RHIC
BAMPS [537–540]	MC@NLO no PDF shadowing	3+1d expansion parton cascade	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
TAMU [491, 565, 606]	FONLL EPS09 (NLO) PDF shadowing	2+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss diffusion in hadronic phase	fragmentation recombination	assume l-QCD U potential
UrQMD [608–610]	PYTHIA no PDF shadowing	3+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume l-QCD U potential
Duke [587, 628]	PYTHIA EPS09 (LO) PDF shadowing	2+1d expansion viscous fl. dyn.	transport with Langevin eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at RHIC and LHC (same value)

[1506.03981]

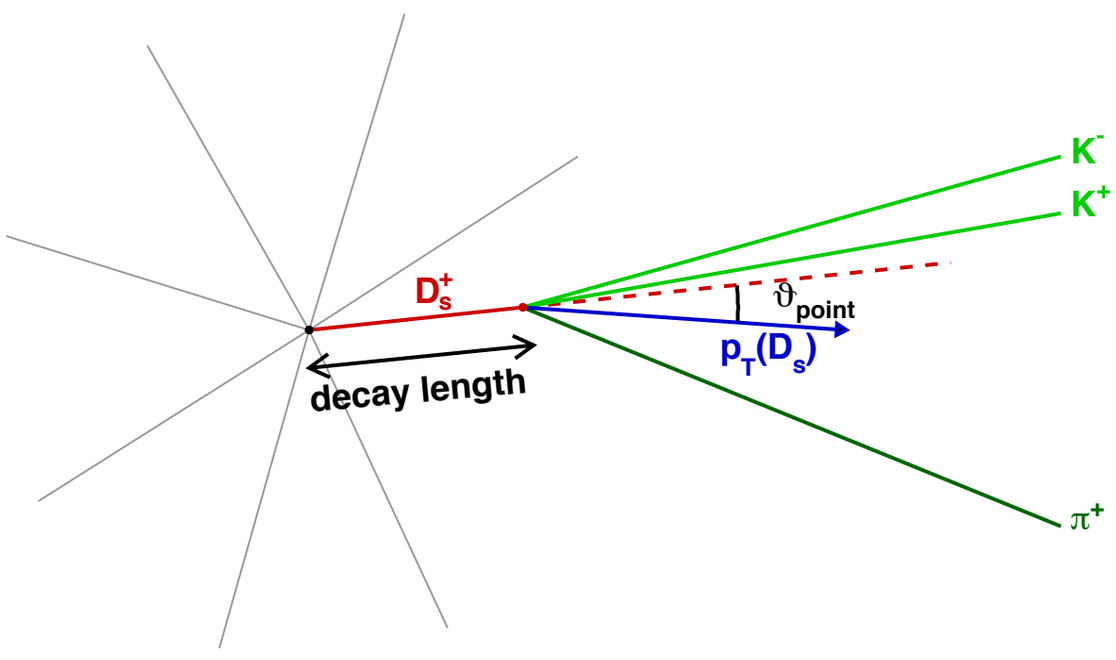
Our experimental tools



Semi-leptonic electrons and muons from c and b quarks



Displayed J/ψ from B decays



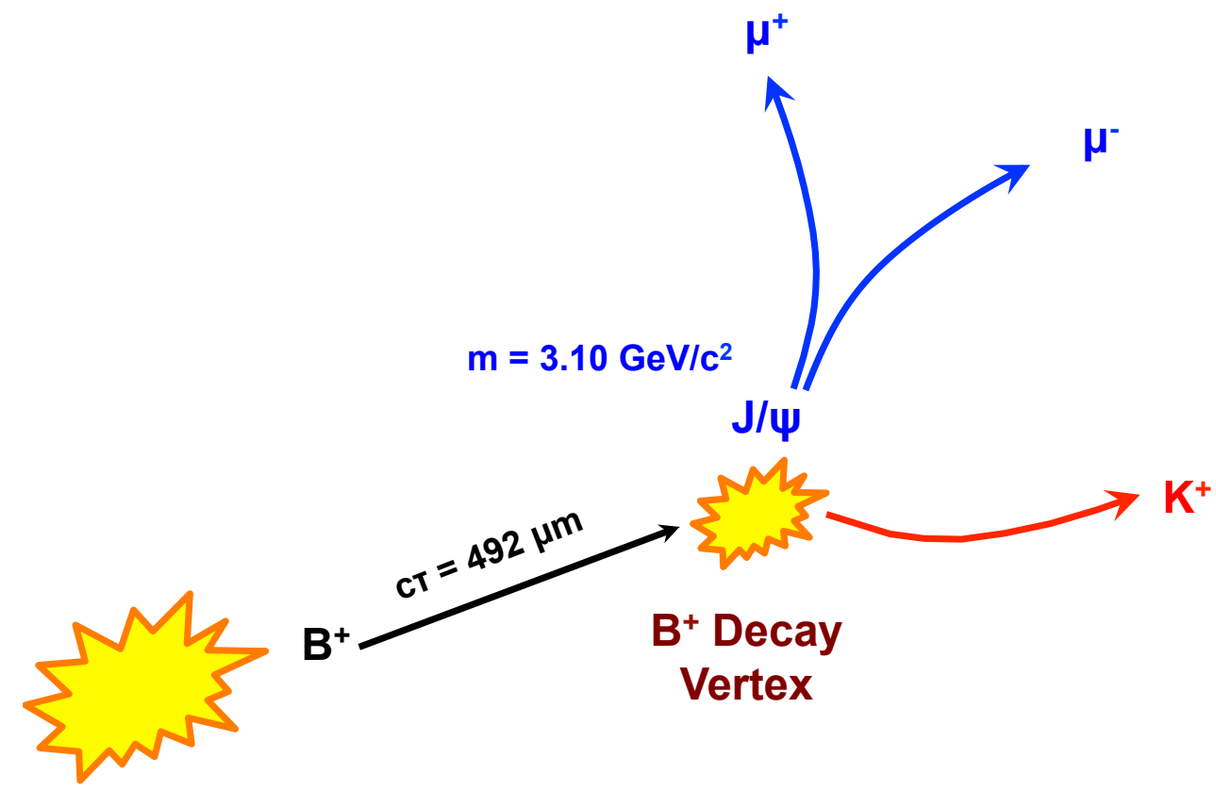
Fully reconstructed D meson decays:

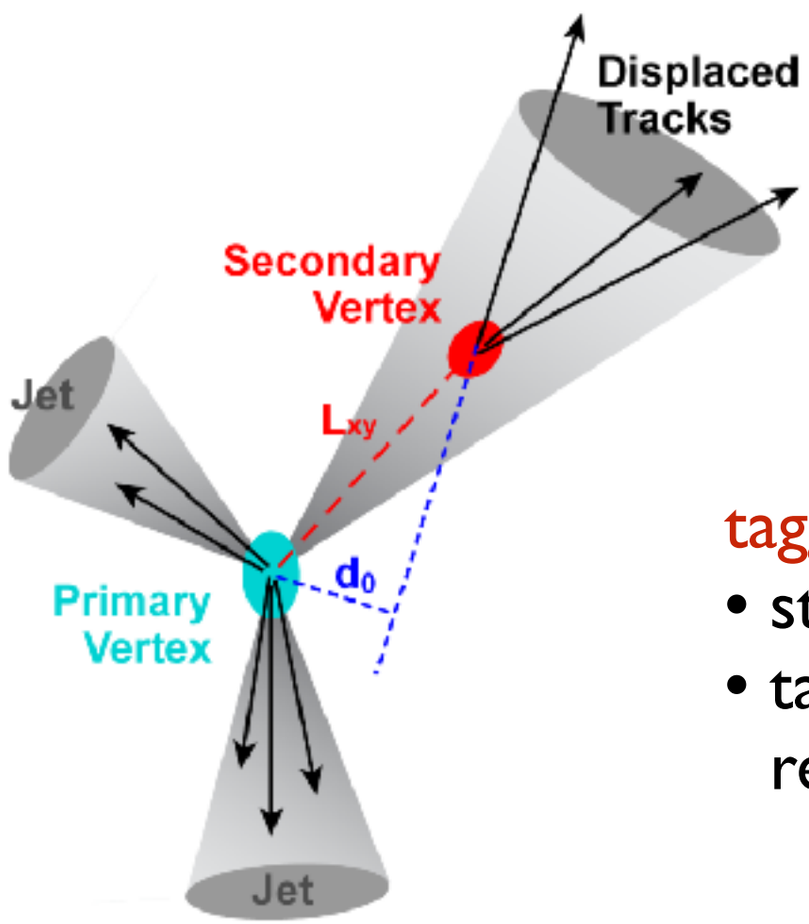
- $D^0 \rightarrow K^- + \pi^+$
- $D^+ \rightarrow K^- + \pi^+ + \pi^+$
- $D^{*+} \rightarrow D^0 + \pi^+$
- $D^+_s \rightarrow \phi + \pi^+$

Our experimental tools

Fully reconstructed B meson decays:

- $B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu^+\mu^-\ K^+$
- $B^0 \rightarrow J/\psi\ K^{0*} \rightarrow \mu^+\mu^-\ K^+\pi^-$
- $B_s \rightarrow J/\psi\ \phi \rightarrow \mu^+\mu^-\ K^+K^-$





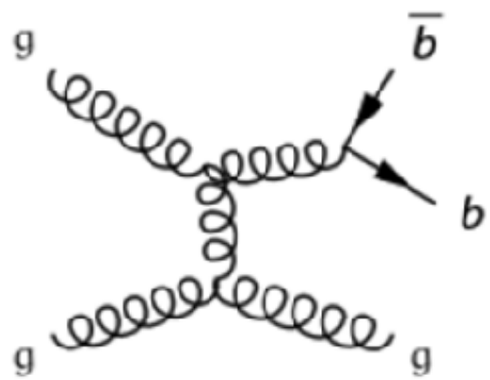
tagged c- and b-jets

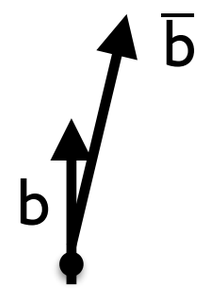
- standard jet reconstruction
- tagging based on the displacement with respect to the primary vertex

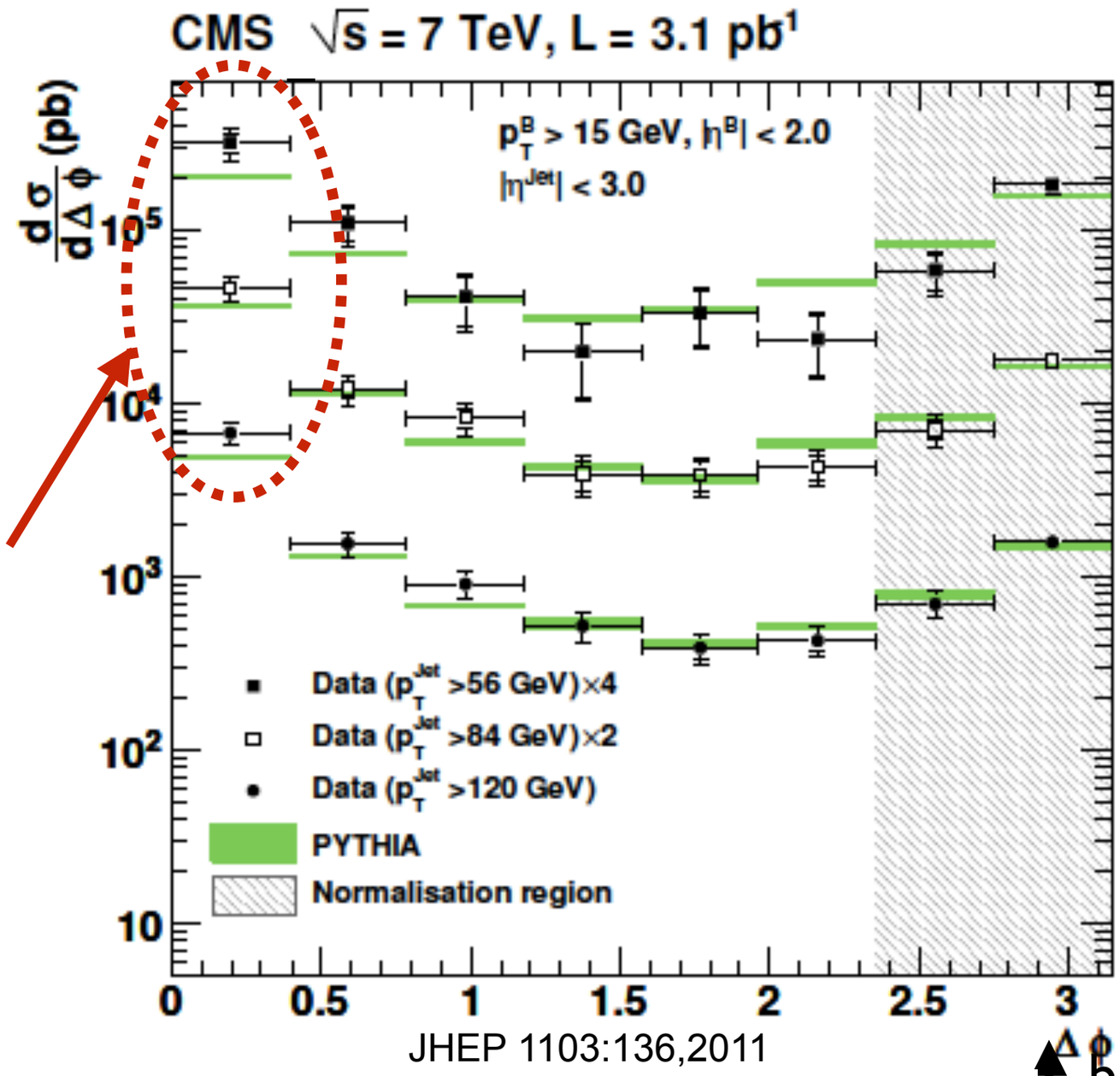
$B\bar{B}$ $\Delta\phi$ correlations

NLO process: Gluon splitting (GSP)

→ produced with small opening angles and asymmetric in p_T





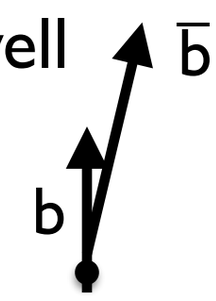


JHEP 1103:136,2011

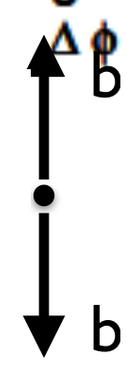
$B\bar{B}$ correlations strongly affected by gluon splitting processes at low $\Delta\phi$

Gluon splitting (GS) contribution not well modelled by most of the calculations

→*GS contribution underestimated by models*



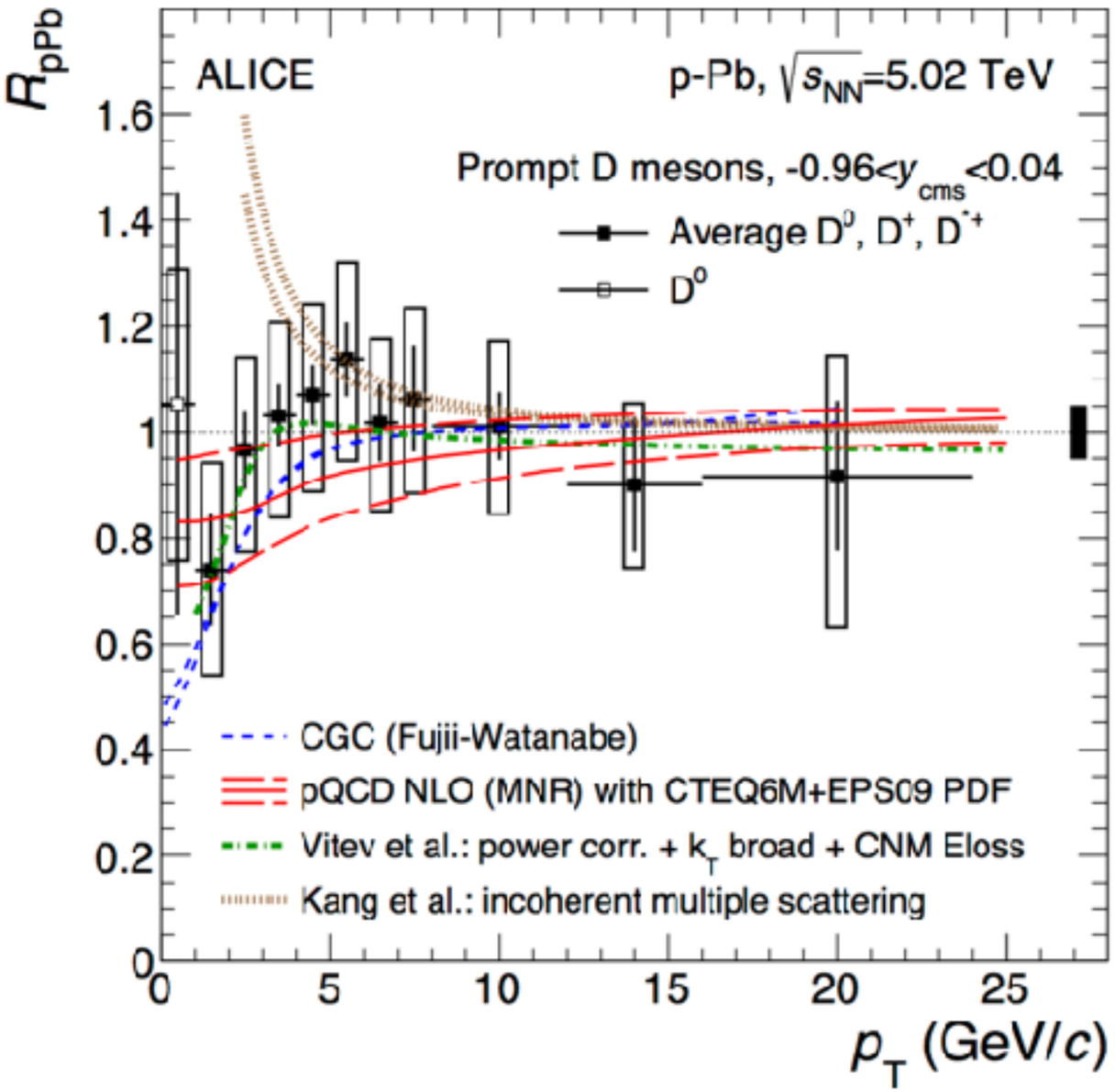
$\Delta\phi(B\text{-}\bar{B})$

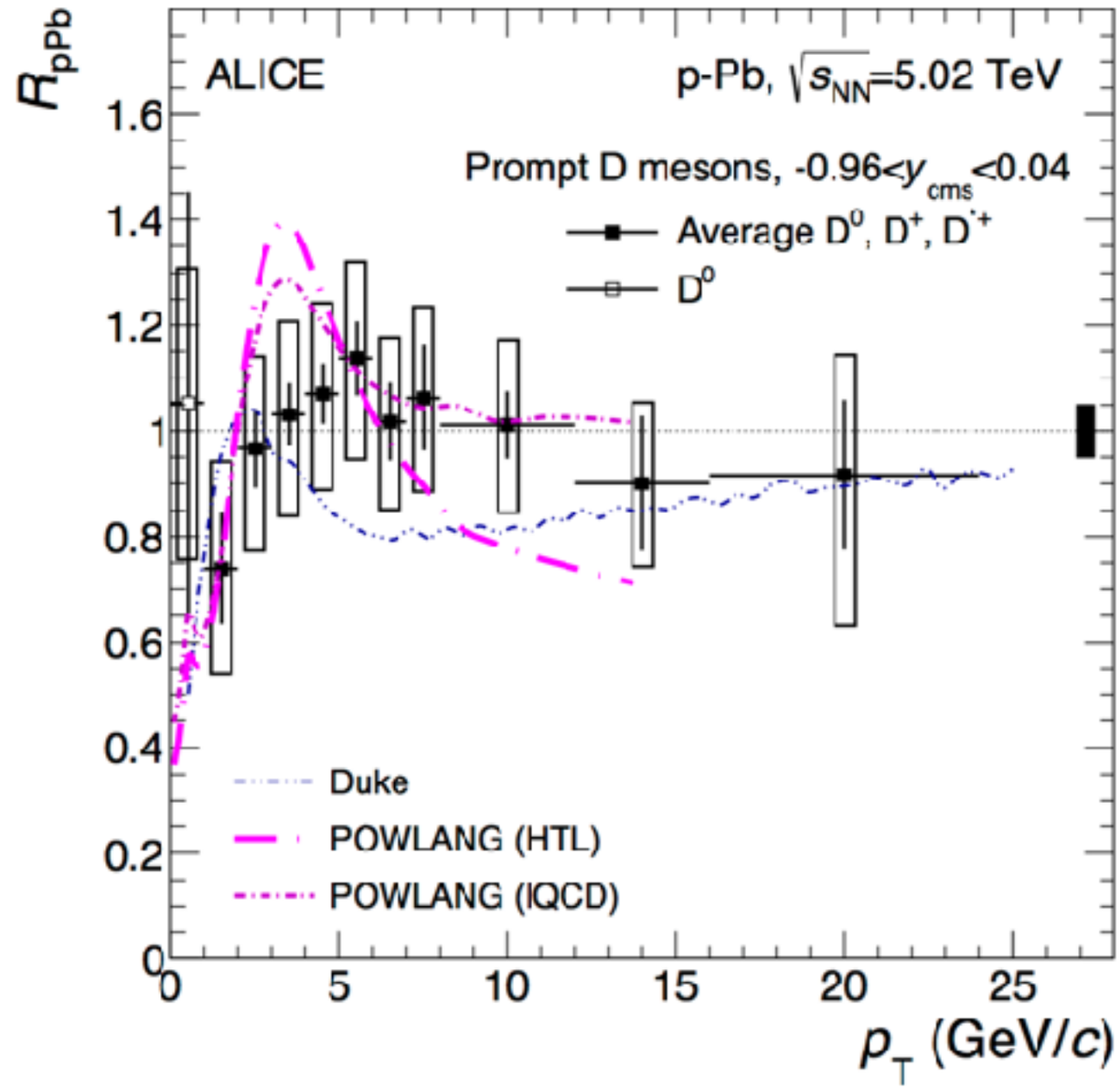


D^0 production in pPb collisions

ALICE D measurements at 5.02 TeV, |y|<0.5

ALICE, arXiv:1605.07569



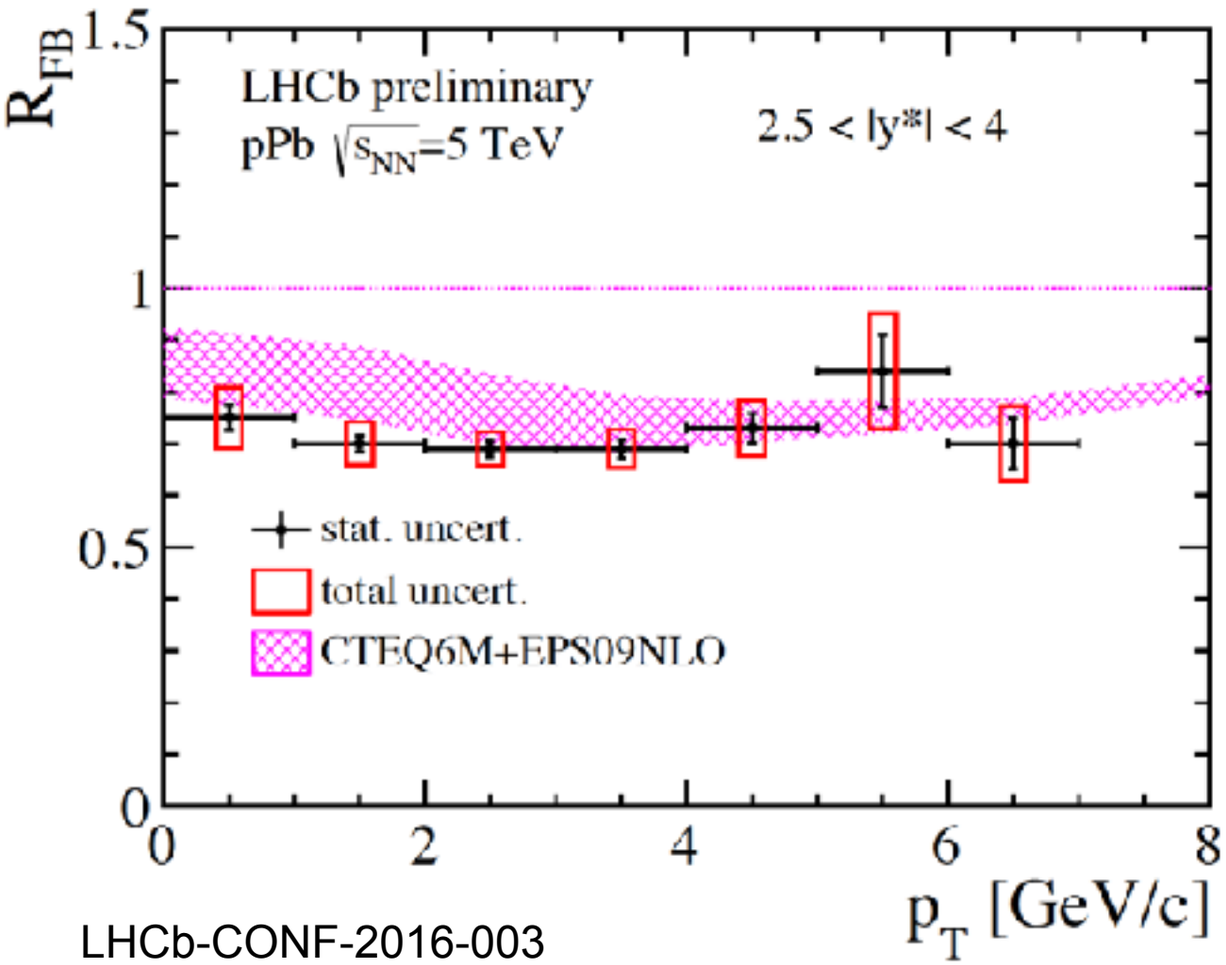


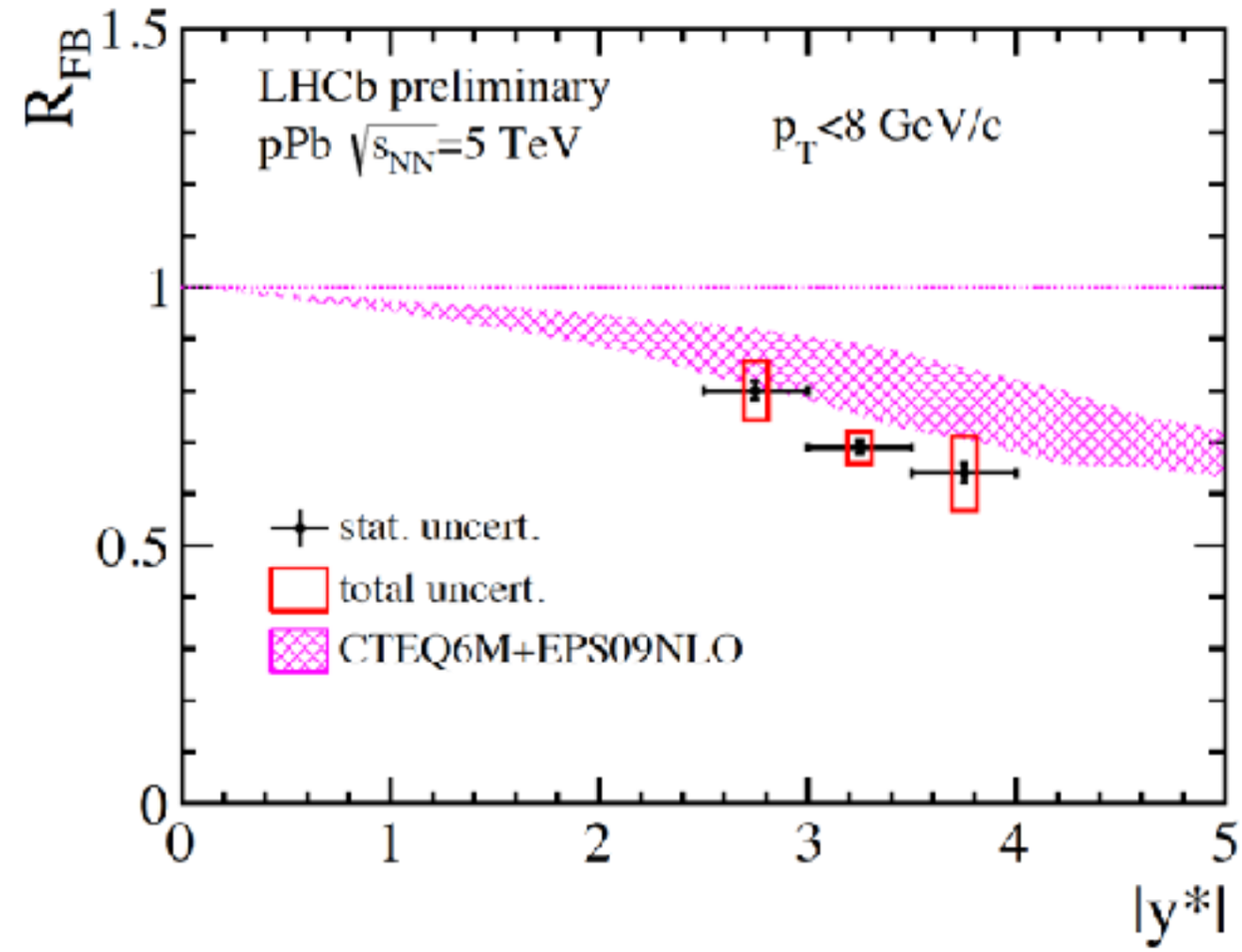
R_{pA} well described by Cold Nuclear Matter (CNR) models and consistent with unity at high p_T!

Not possible to discriminate between various models with current uncertainties

D^0 meson R_{pA} at 5.02 TeV

LHCb D^0 measurement at 5.02 TeV in forward(F) and backward (B) region as a function of transverse momentum and rapidity

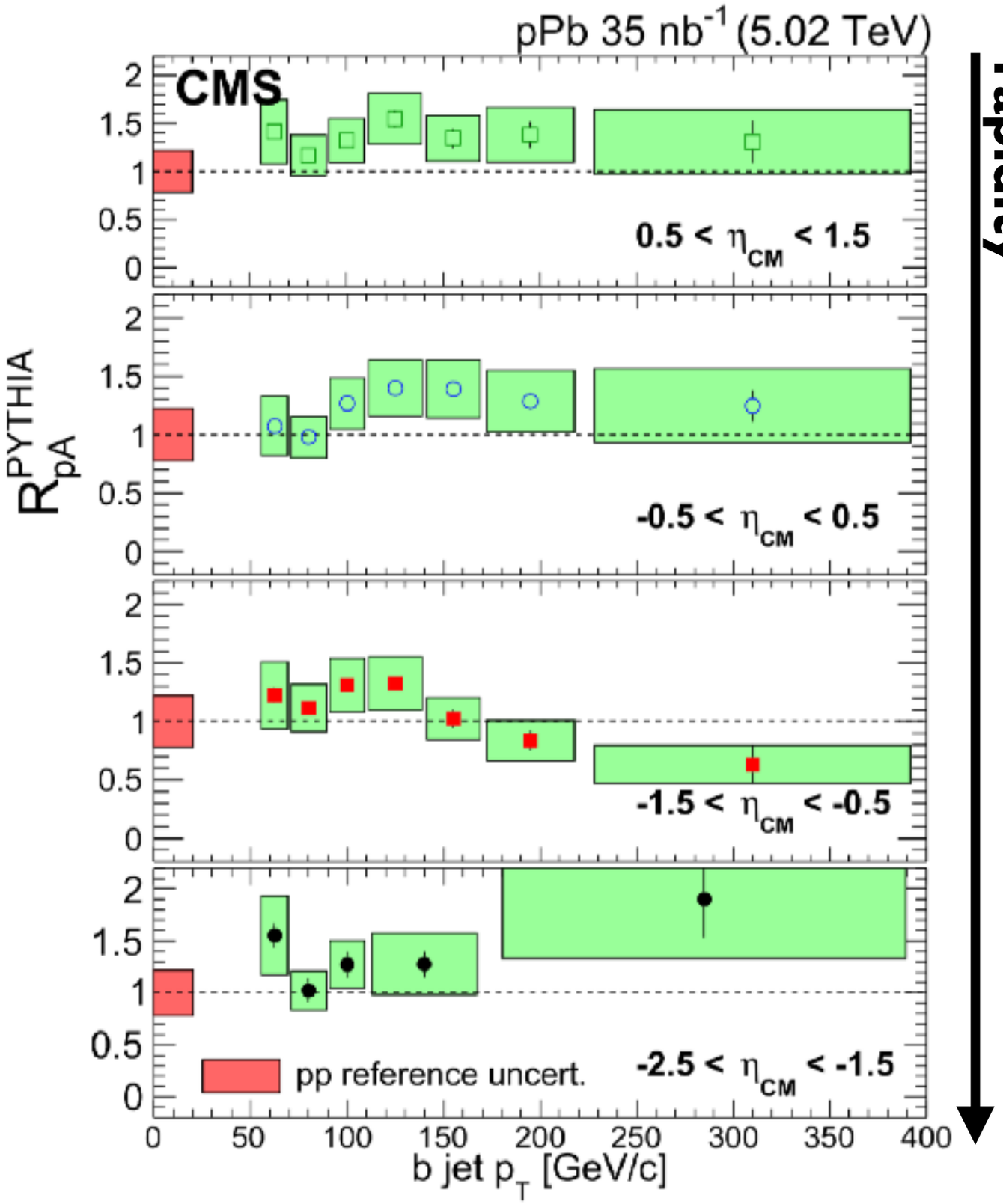




LHCb-CONF-2016-003

R_{pA} and R_{FB} described by to NLO prediction that include EPS09 parametrisation of the nuclear PDFs

b-jet nuclear modification factor in pPb



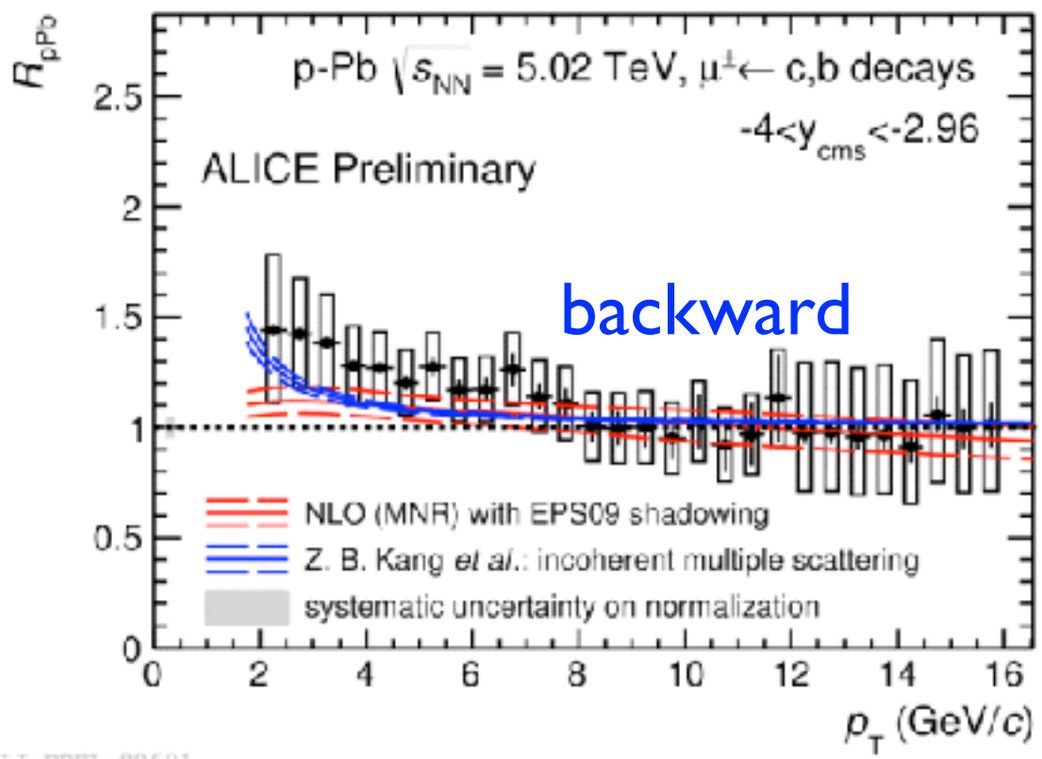
CMS b-jet R_{pA} in bins of transverse momentum and pseudo-rapidity

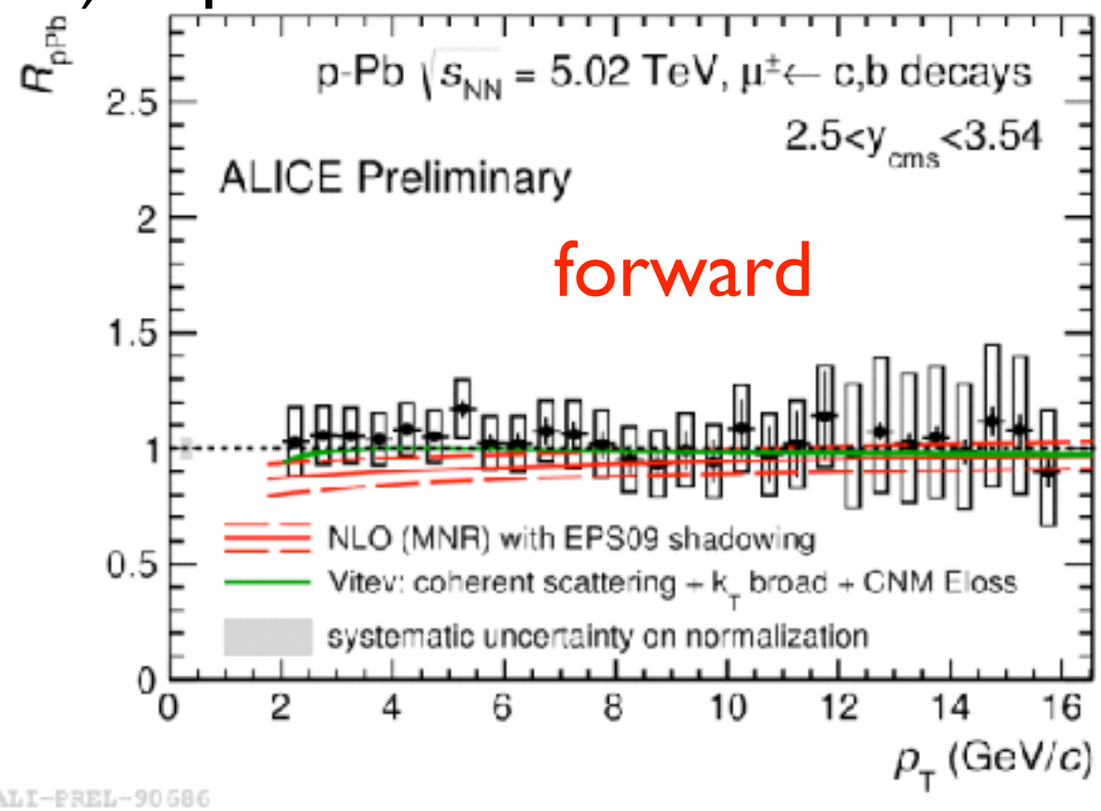
PYTHIA R_{pA} consistent with unity as a function of p_T and pseudo-rapidity

CMS, PLB 754 (2016) 59

Heavy flavour leptons: LHC vs. RHIC

ALICE heavy flavour muons (c,b→muons) in pPb collisions at 5.02 TeV





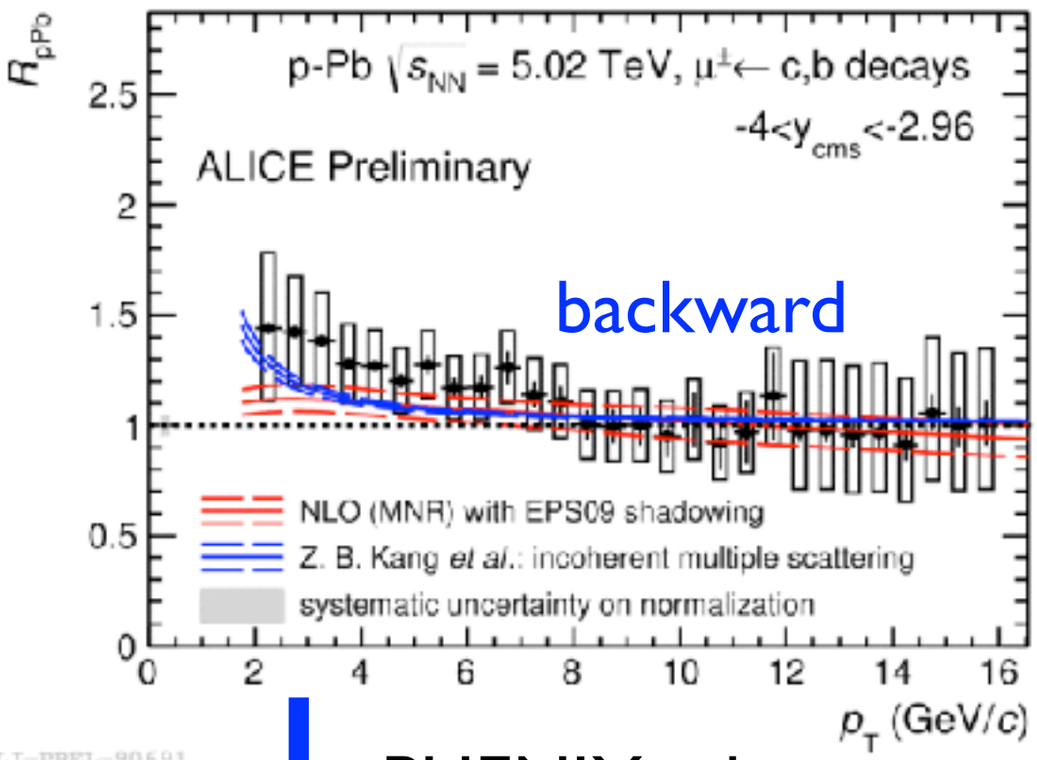
forward (shadowing)
backward (anti-shadowing)

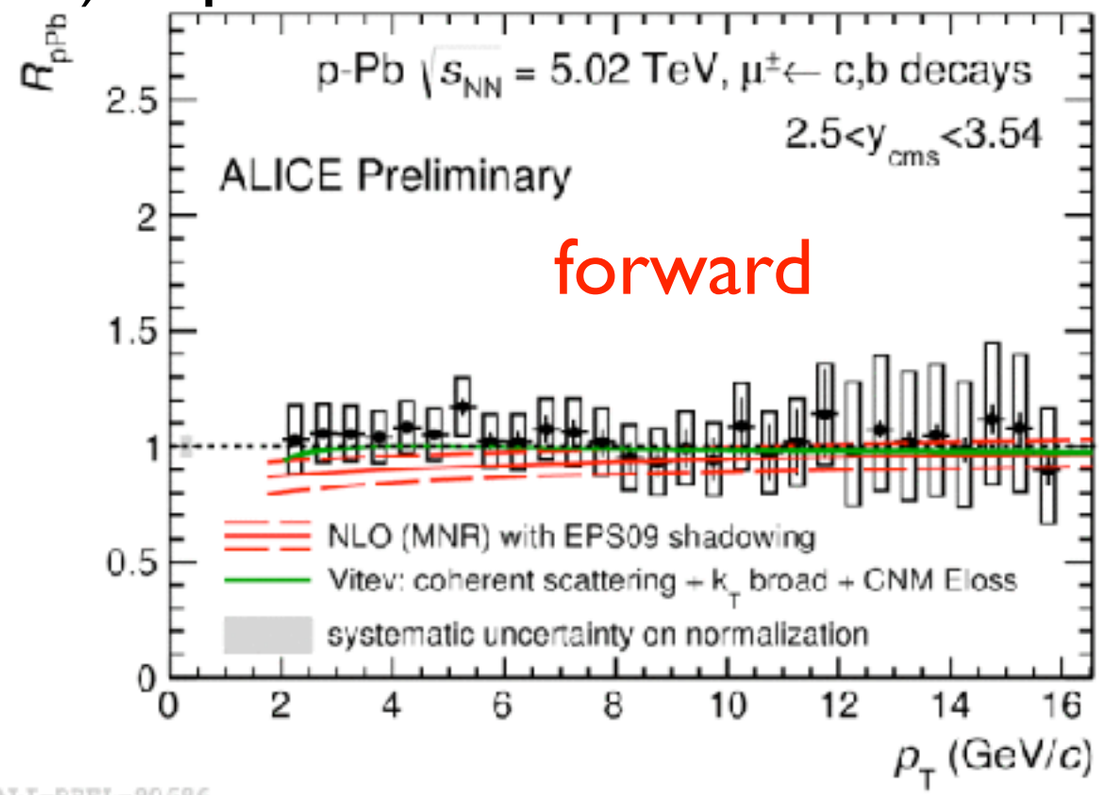
Models with CNM describe forward/backward rapidity at LHC

PRL112 (2014) 252301

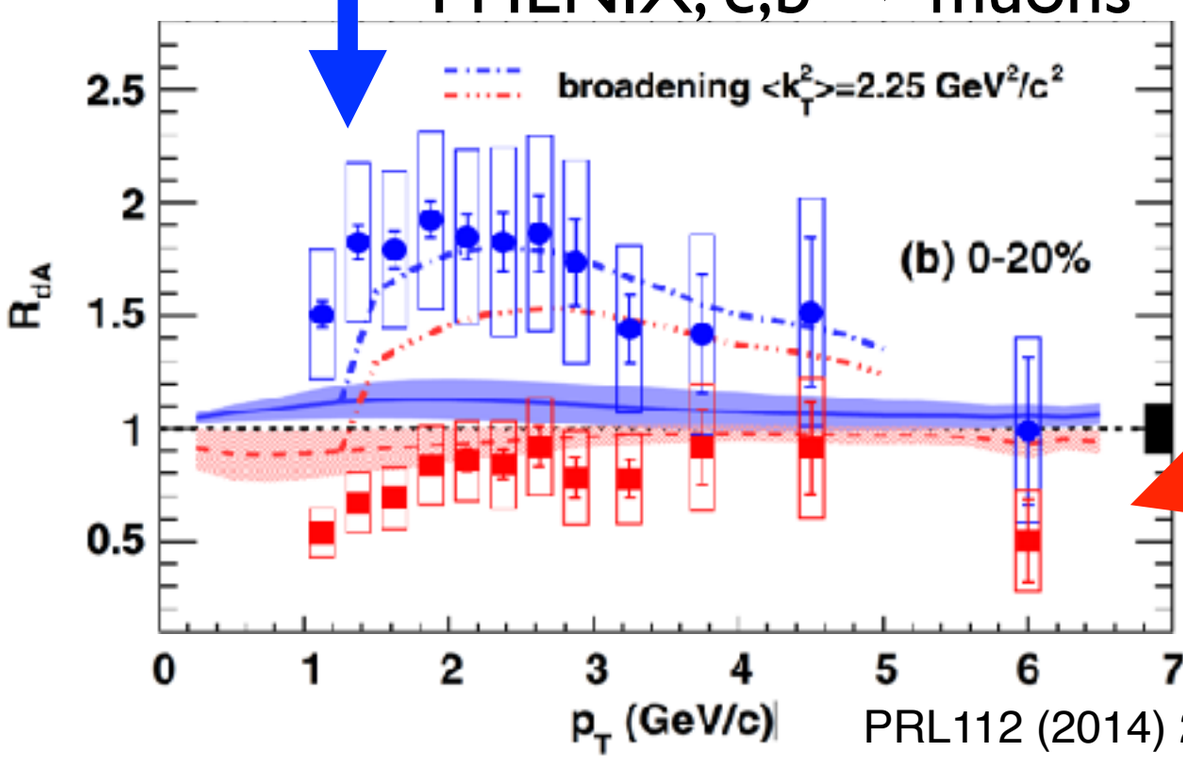
Heavy flavour leptons: LHC vs. RHIC

ALICE heavy flavour muons (c,b→muons) in pPb collisions at 5.02 TeV





PHENIX, c,b → muons



PRL112 (2014) 252301

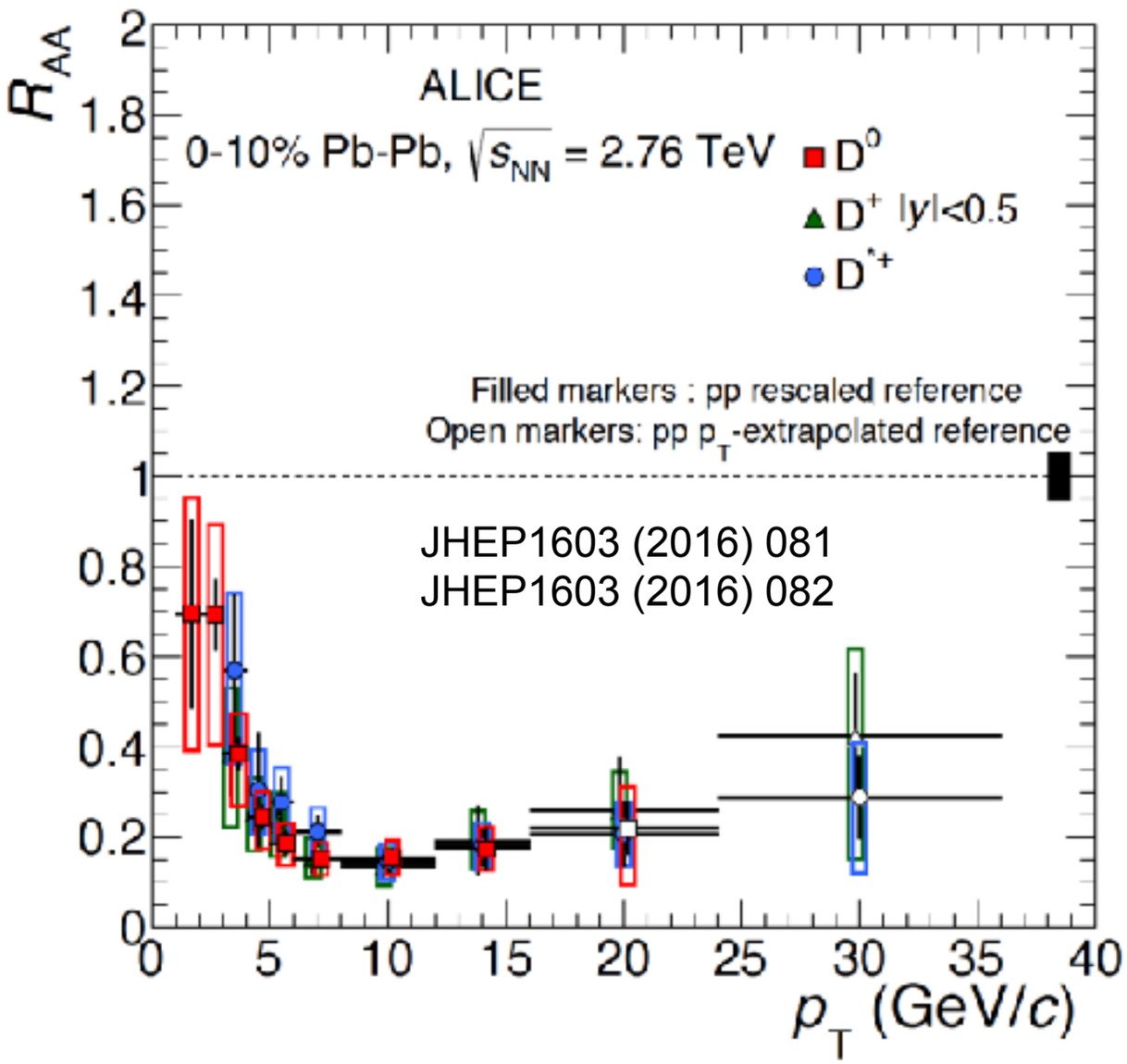
forward (shadowing)
backward (anti-shadowing)

Models with CNM describe forward/backward rapidity at LHC

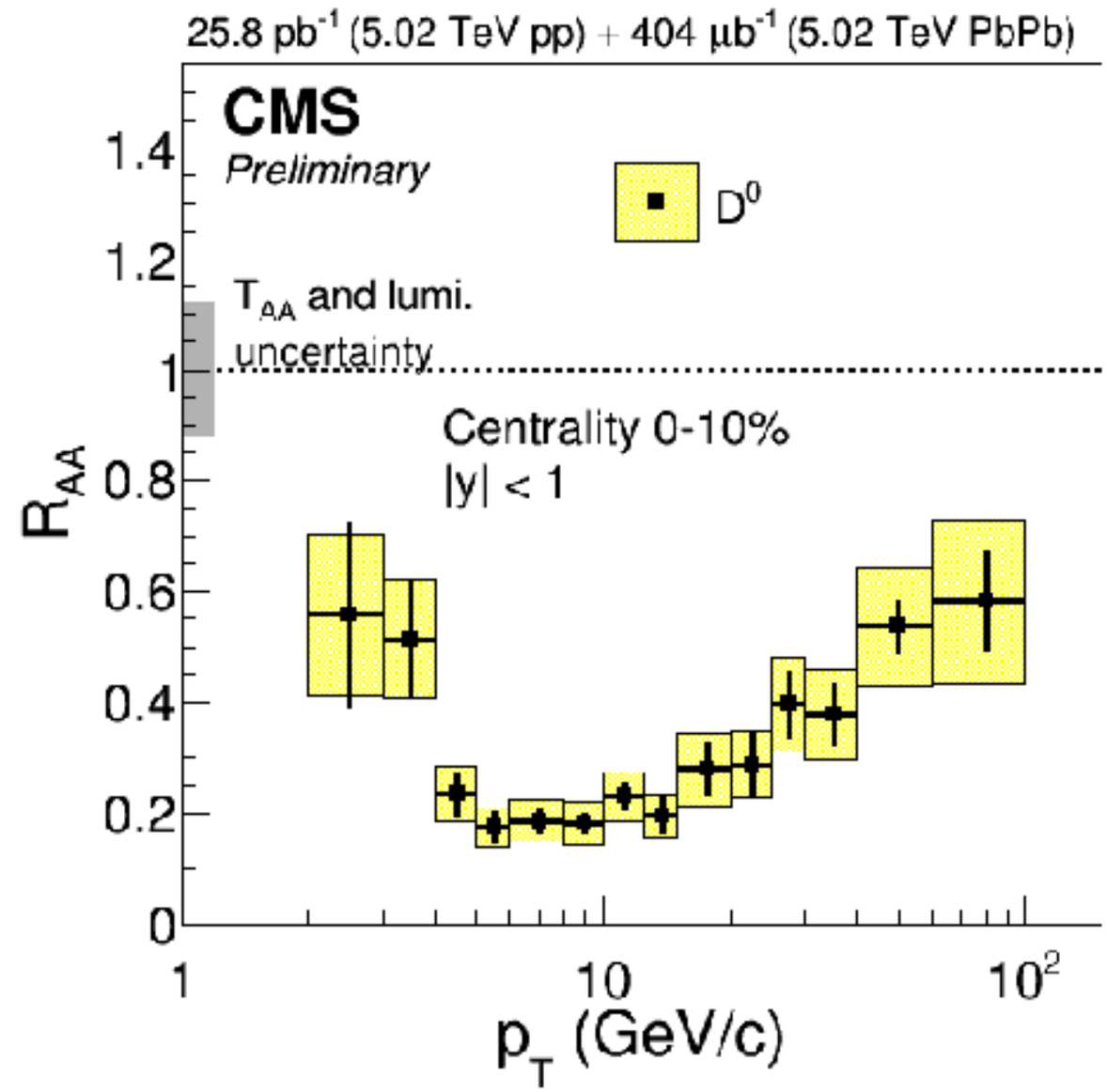
→ **Not possible at RHIC**

D meson R_{AA} in 0-10%

ALICE D^0 R_{AA} **|y|<0.5** at **2.76 TeV**



CMS D^0 R_{AA} **|y|<1.0** at **5.02** TeV



CMS-PAS-HIN-16-001

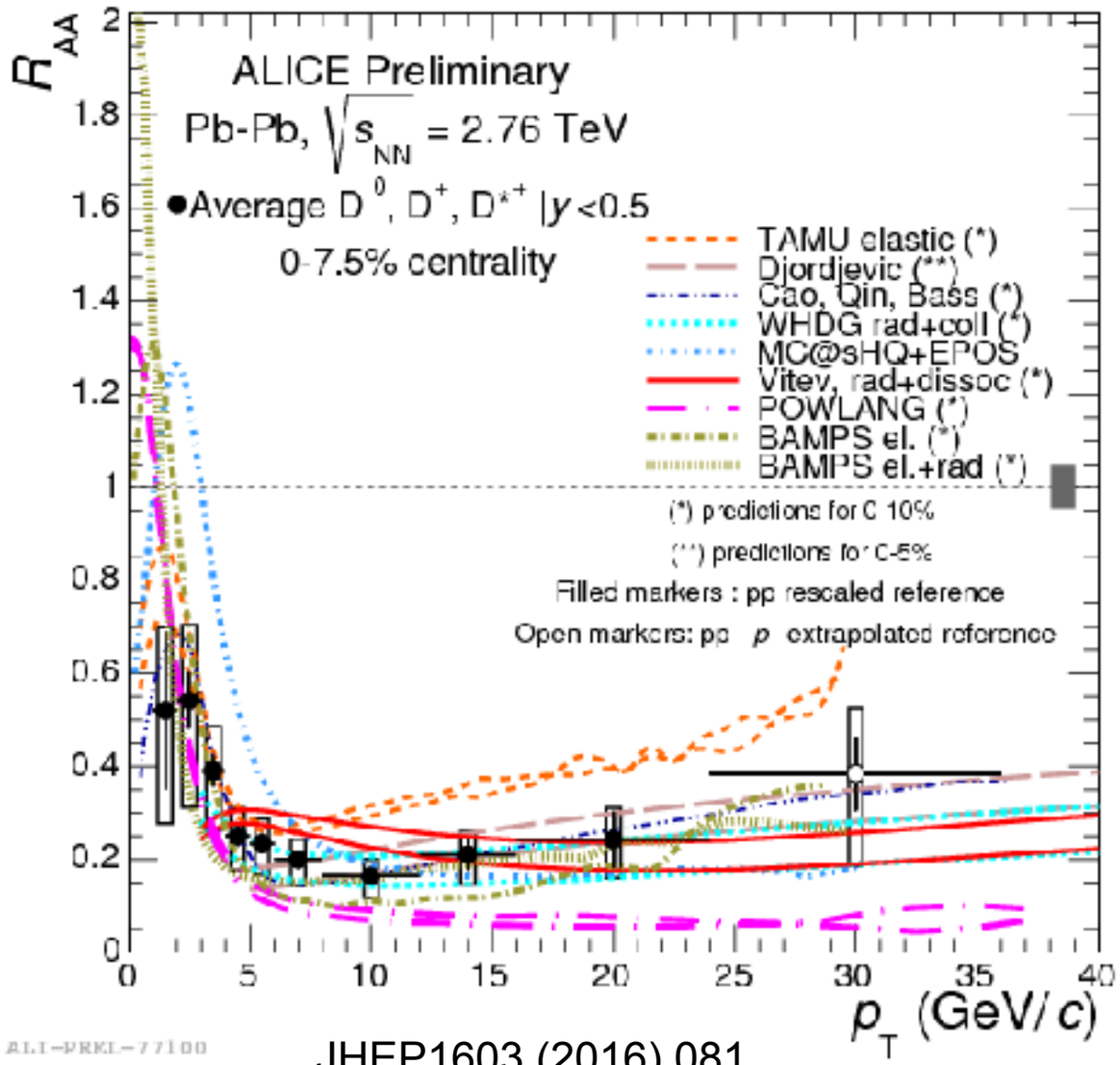
Strong suppression at 2.76 TeV:

same suppression for D^0,D^+,D^{*+}

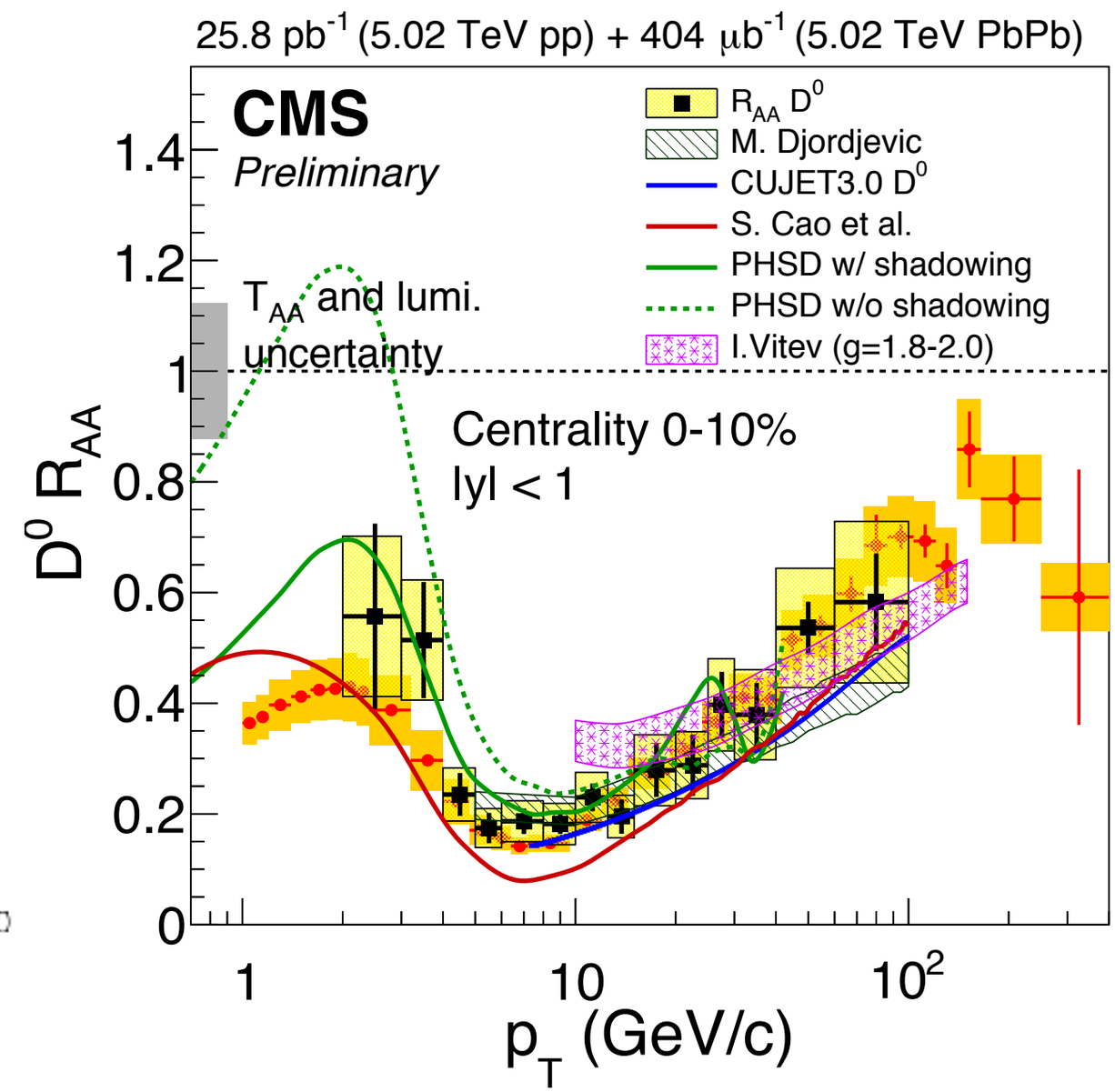
Similar suppression at 5.02 TeV:

Rising trend observed when going to high p_T

Comparison to theoretical calculations



JHEP1603 (2016) 081
JHEP1603 (2016) 082

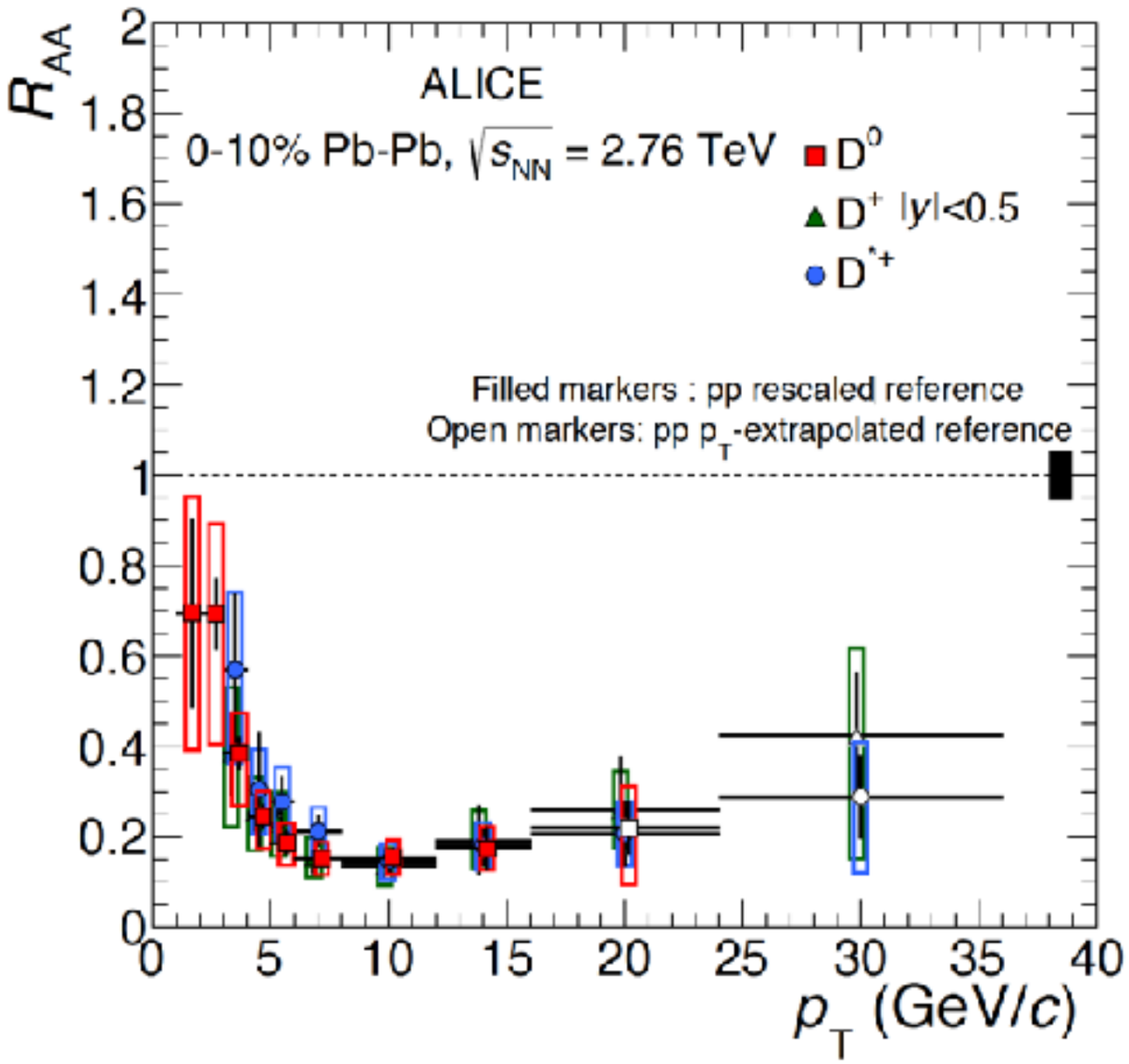


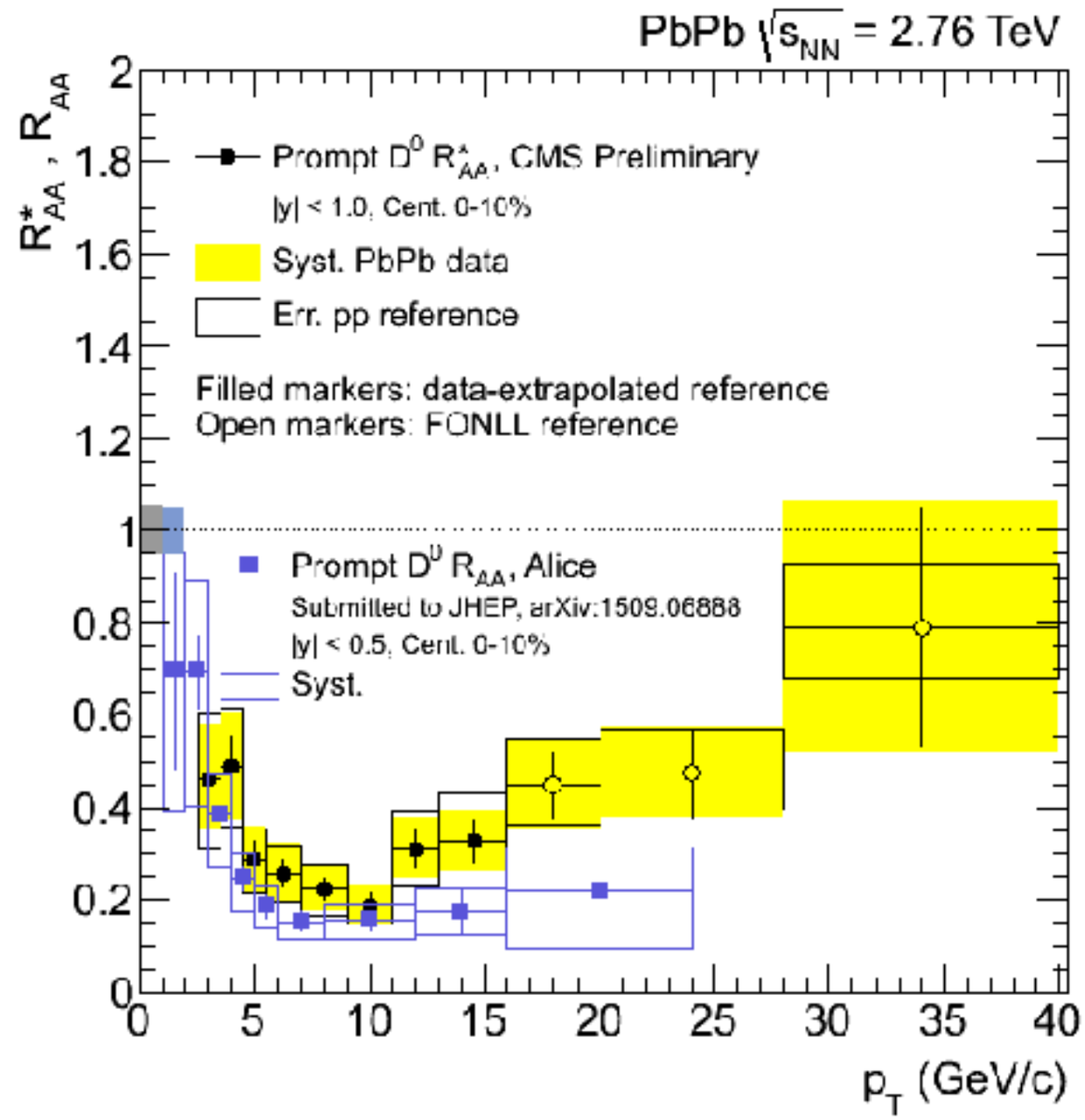
CMS-PAS-HIN-16-001

Several models describe the data within uncertainties:

- *hints at low p_T that collisional energy loss is non negligible*
- *pure collisional models can describe the R_{AA} up to high p_T (??)*
- *shadowing improve description of the data at low p_T*

D meson R_{AA} at 2.76 TeV





Strong suppression in central PbPb events:

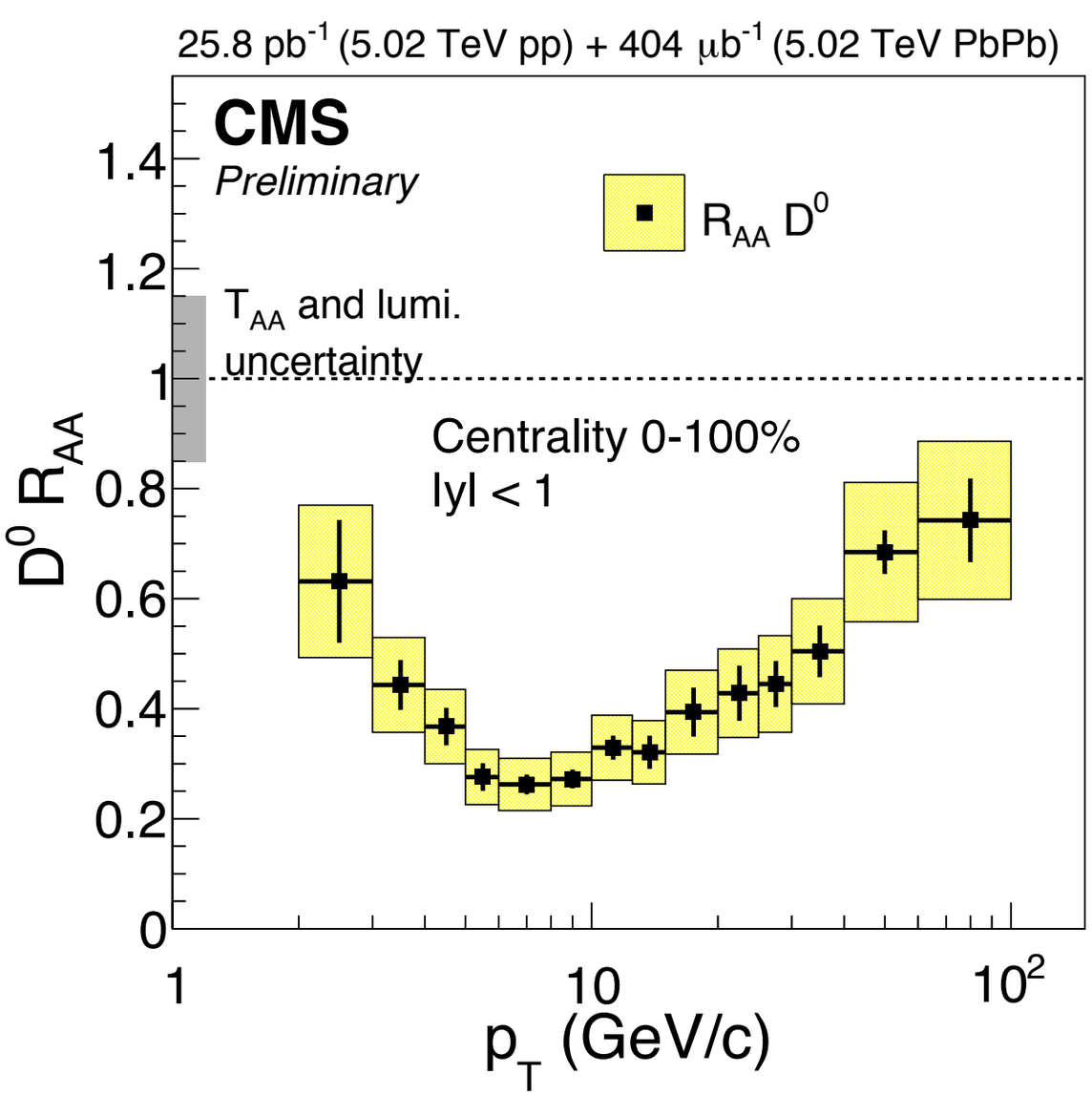
same suppression for D^0,D^+,D^{*+} indicate independence from fragmentation

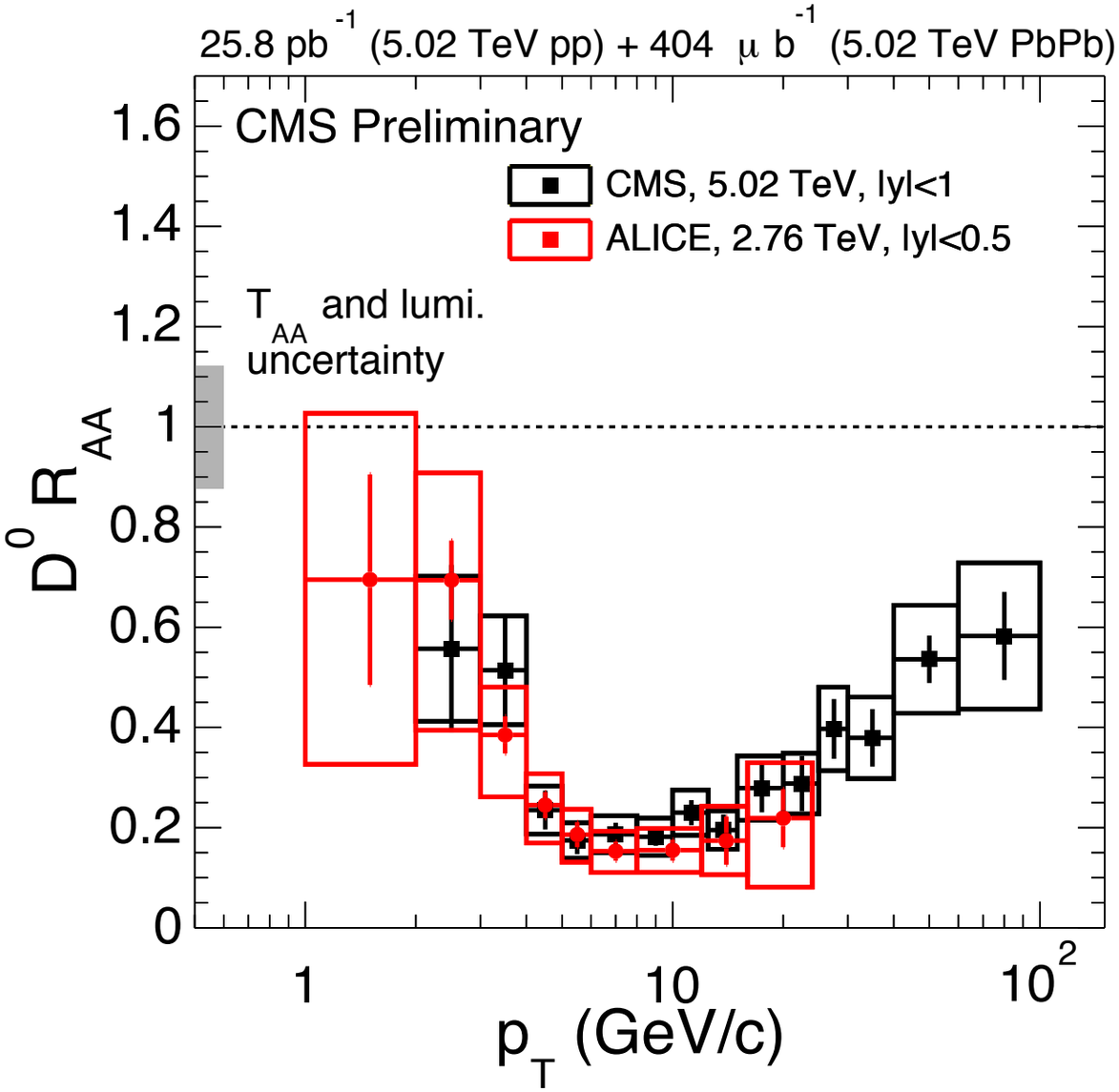
ALICE and **CMS** in good agreement

Differences at higher p_T due to different pp references

D^0 meson R_{AA} at 5.02 TeV

CMS D^0 R_{AA} $|y|<1.0$ at 5.02 TeV





Strong suppression observed at 5.02 TeV

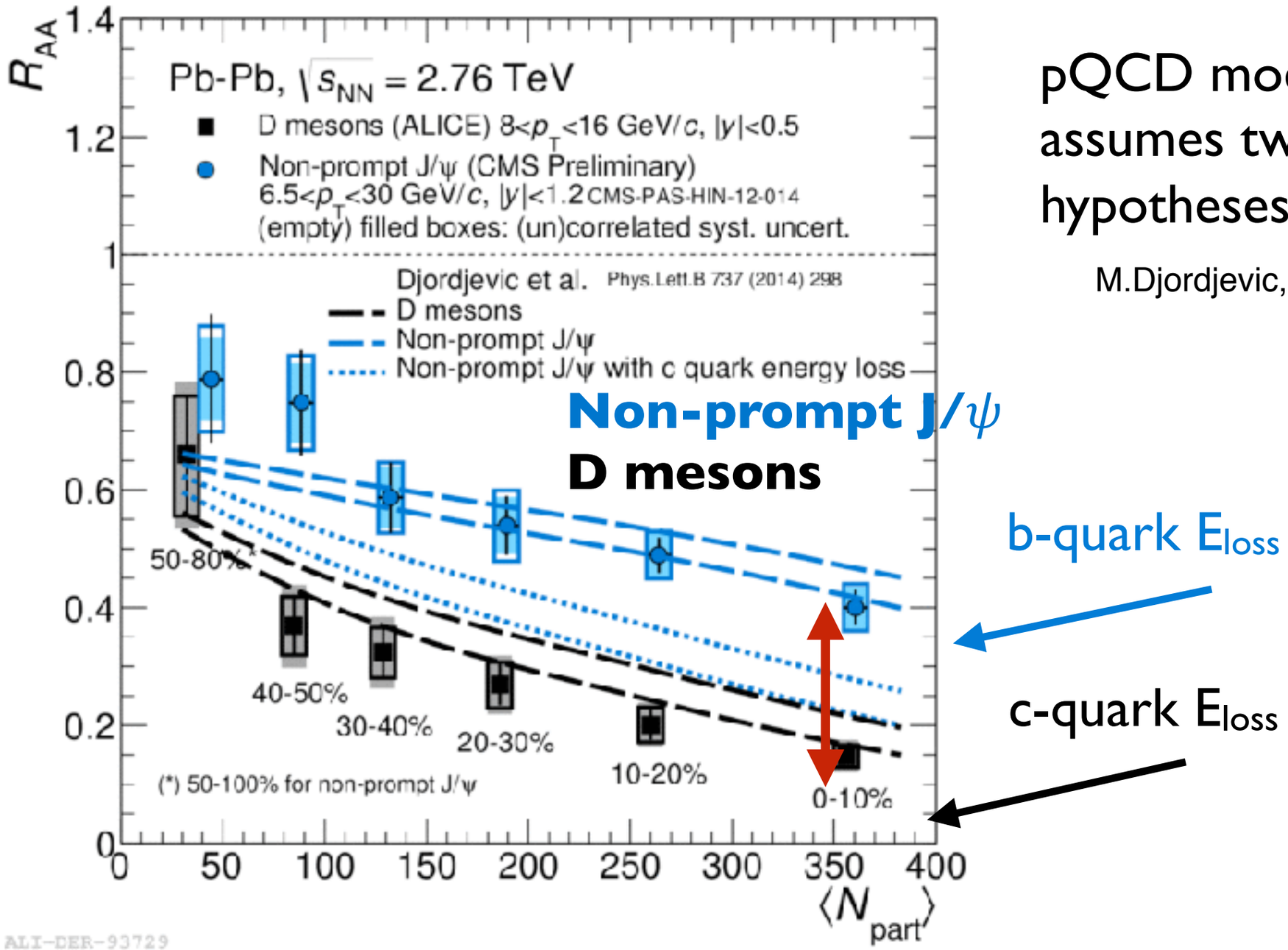
Rising trend observed when going to high p_T

Similar suppression observed at 2.76 and 5.02 TeV by CMS and ALICE

Caveat: different rapidities

Flavour dependence of E_{loss} at 2.76 TeV

ALICE, JHEP 1511 (2015) 205



pQCD model (M.Djordjevic) that assumes two different mass hypotheses for non prompt J/ψ

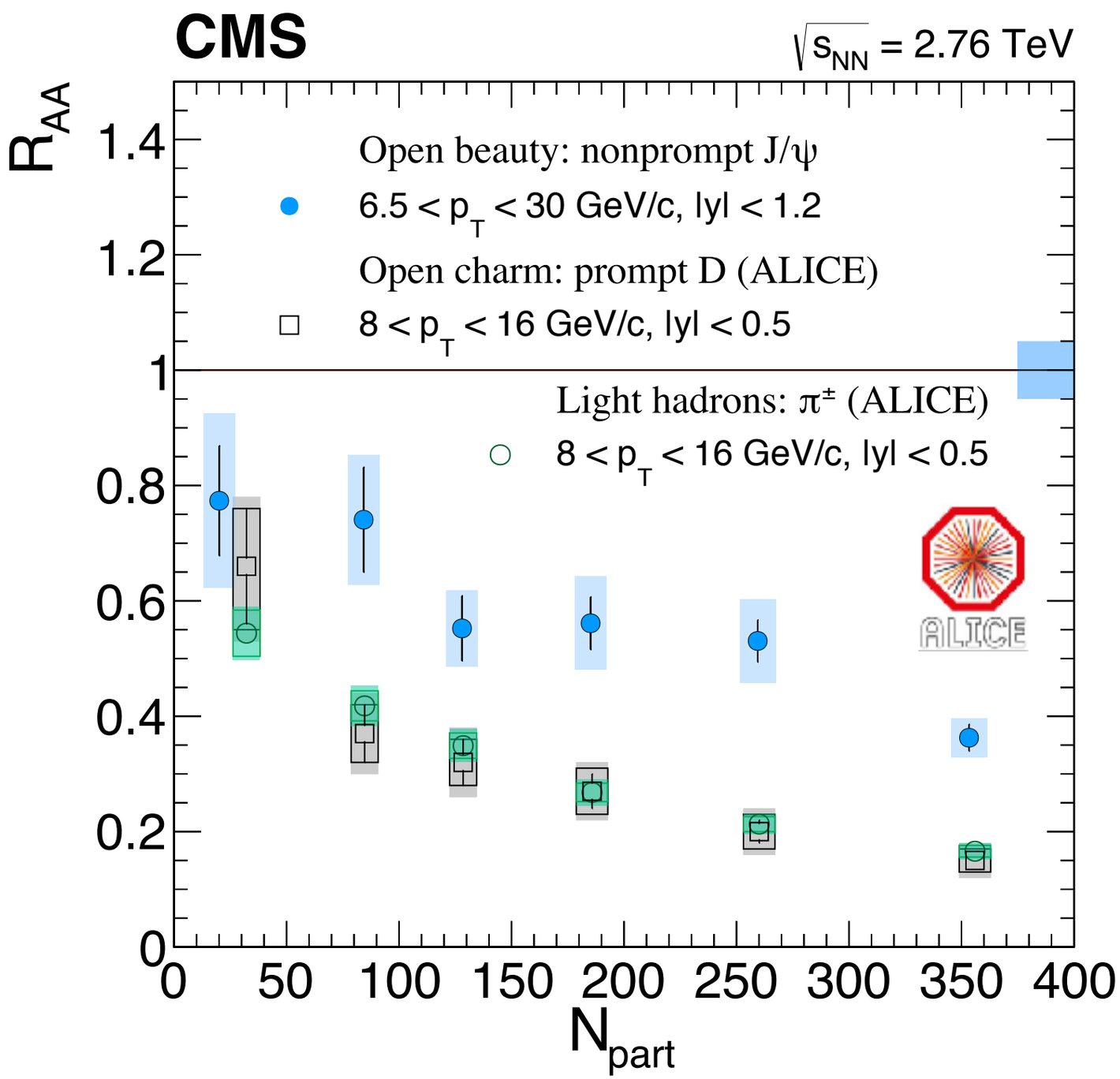
M.Djordjevic, PRL 112, 042302 (2014)

b-quark E_{loss}

c-quark E_{loss}

***According to this model**, the difference R_{AA} for non prompt J/ψ and B can be attributed to a difference in the E_{loss} of charm and beauty quarks*

Flavour dependence of E_{loss} at 2.76 TeV



CMS-PAS-HIN-15-005

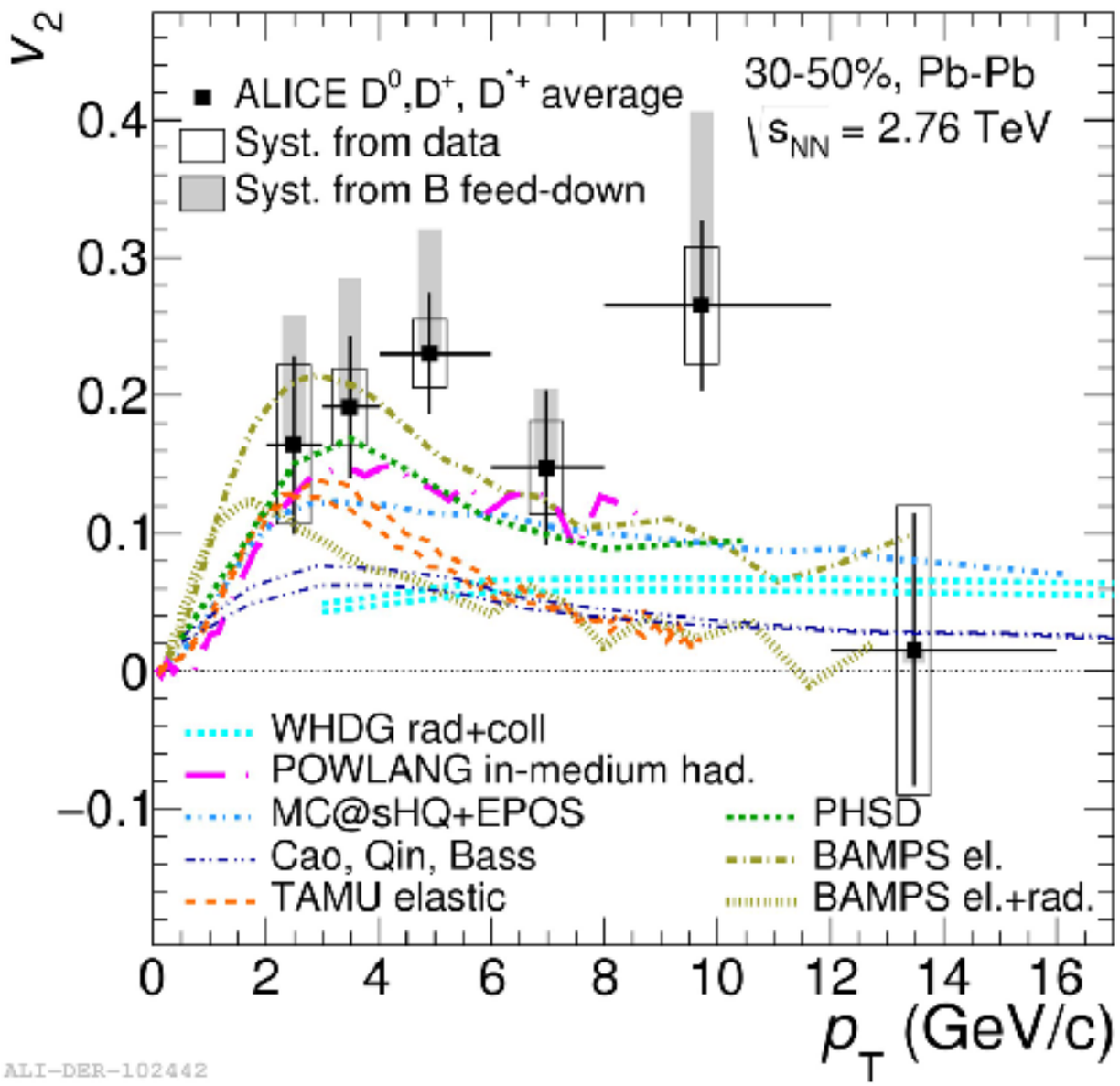
Non-prompt J/ψ

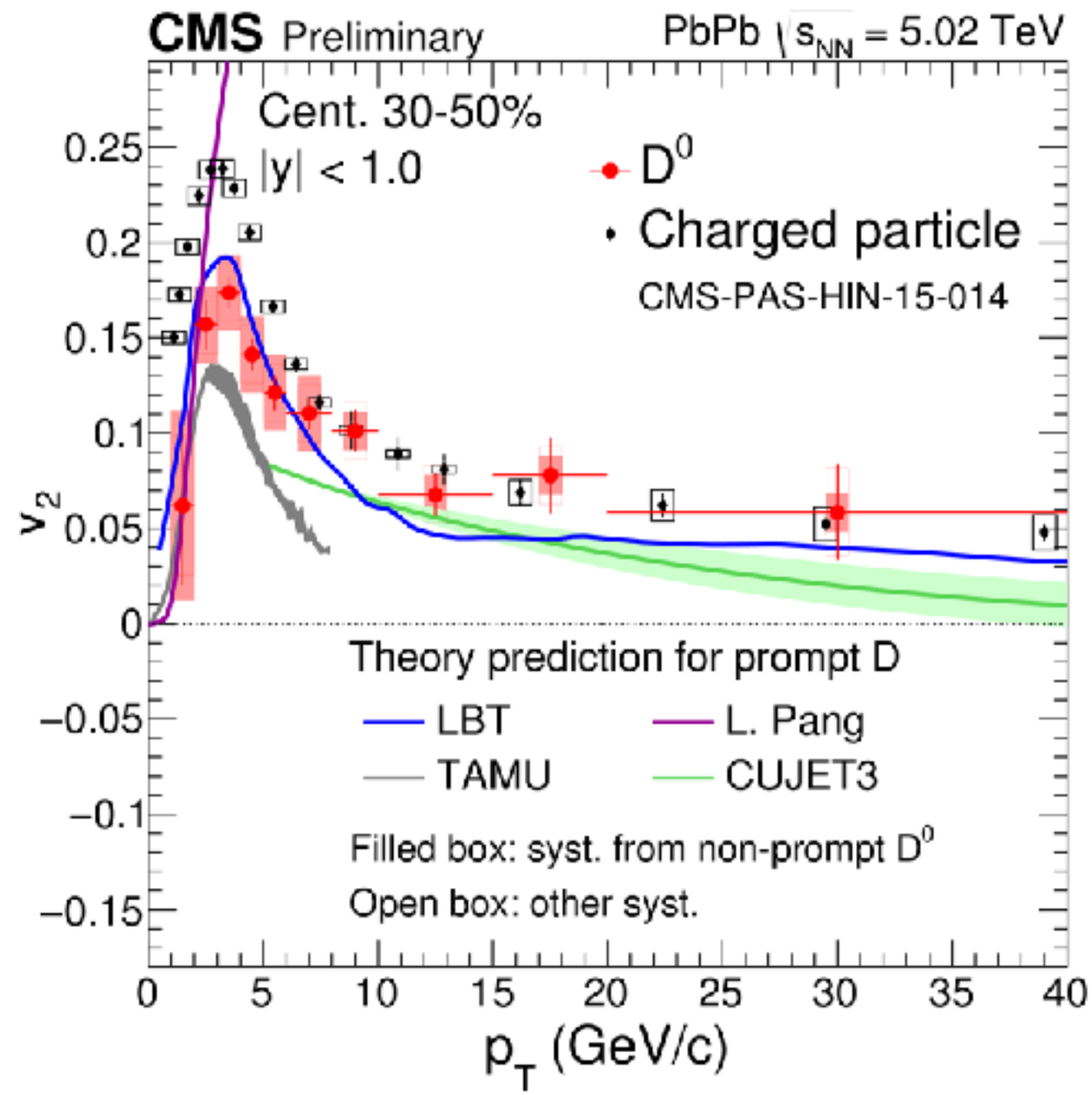
D mesons

π^{+-}

No change in the physics message when comparing to the final result of non prompt J/ψ R_{AA} from CMS

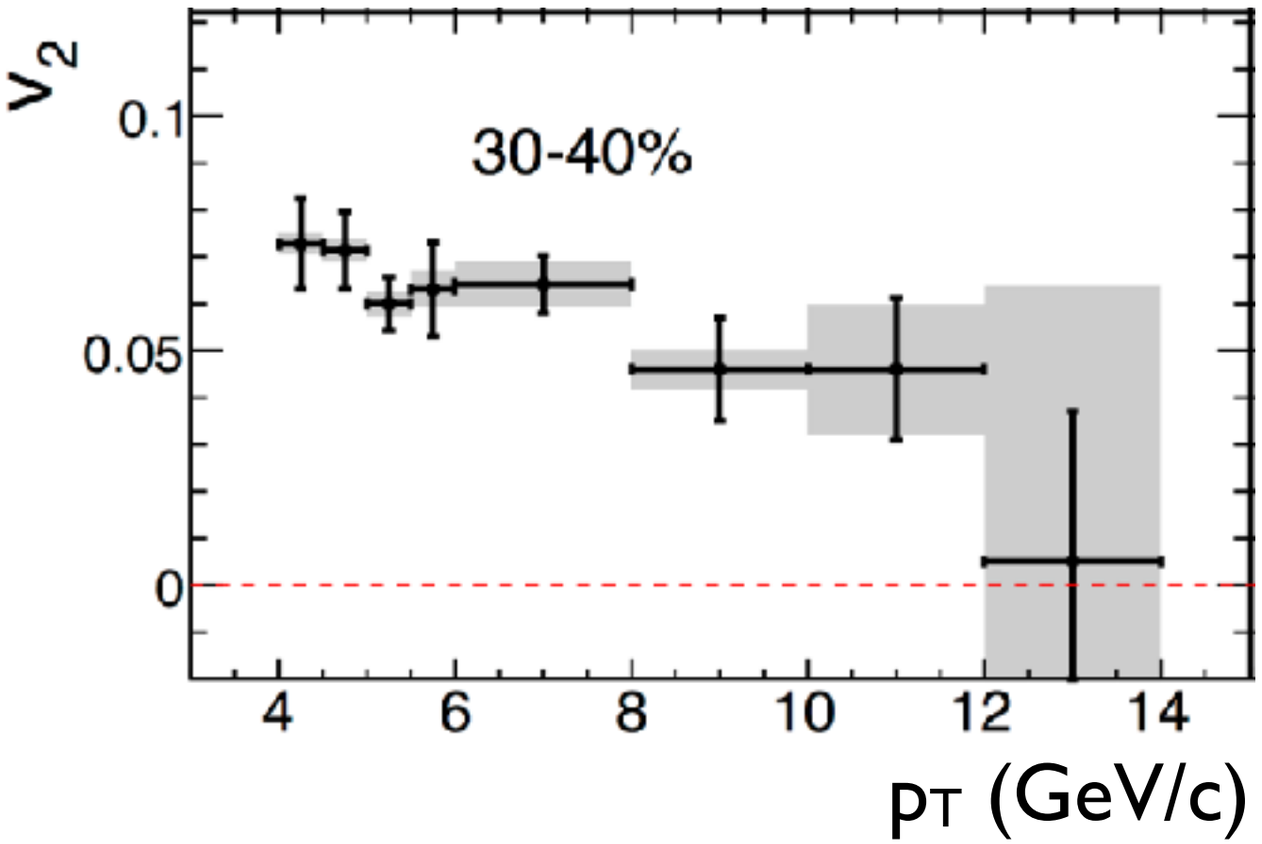
Comparison with models

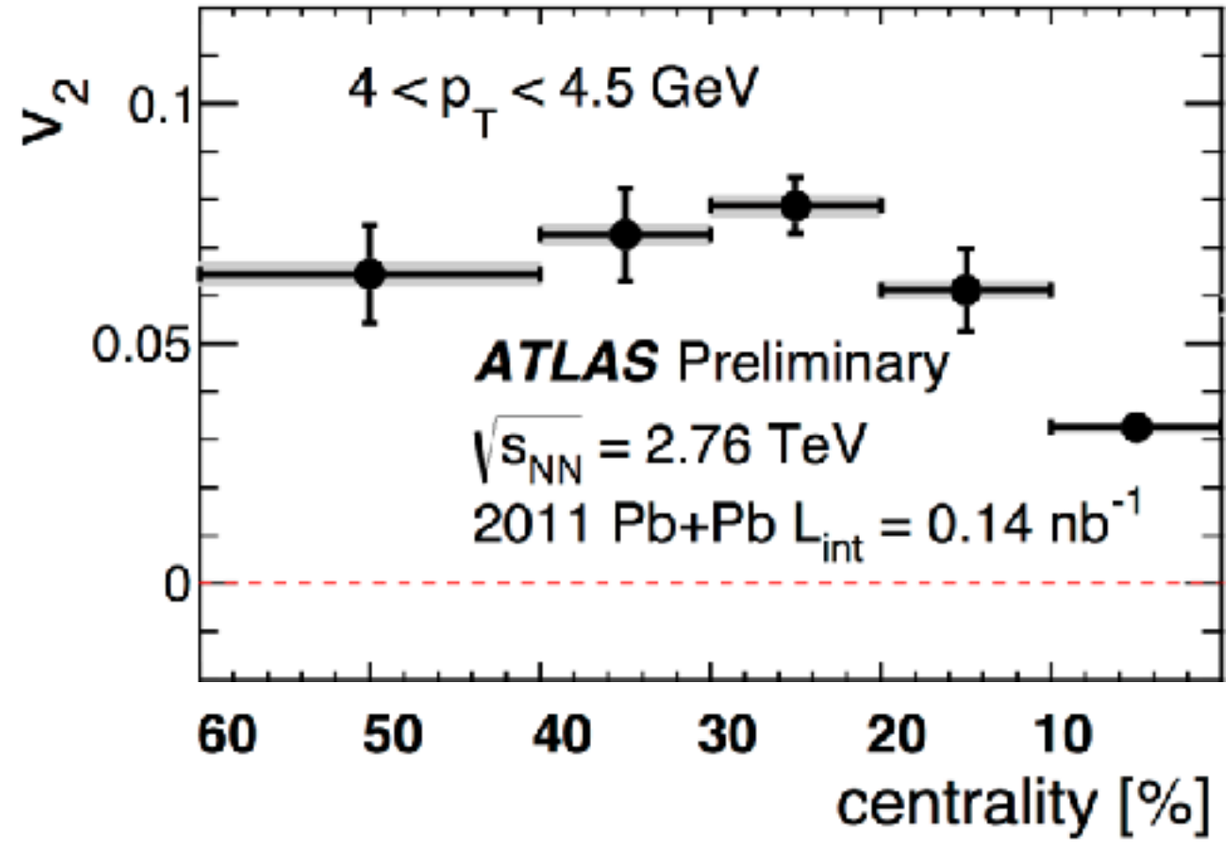




we need **charm quark diffusion** to describe the magnitude of the D meson v_2!

Heavy-flavour muons at 2.76 TeV



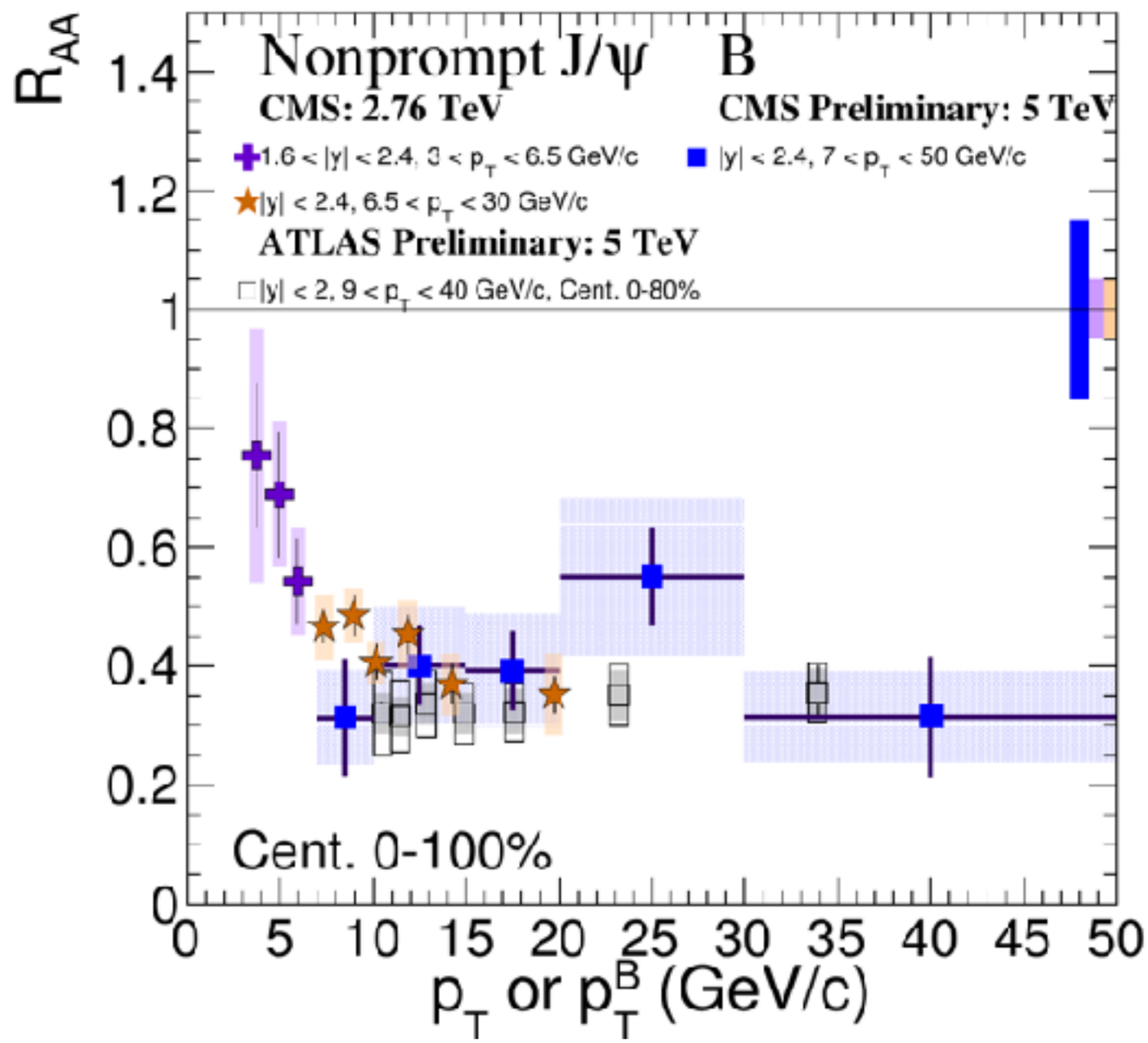


ATLAS-CONF-2015-053

Positive v_2 for muons from heavy-flavour decays (b+c) at LHC:

- include the contributions of beauty to v_2 that is currently unknown
- **v_2 of heavy flavour muons < v_2 (D^0) from ALICE**

Non-prompt J/φ at 2.76 TeV vs B^+ at 5.02 TeV



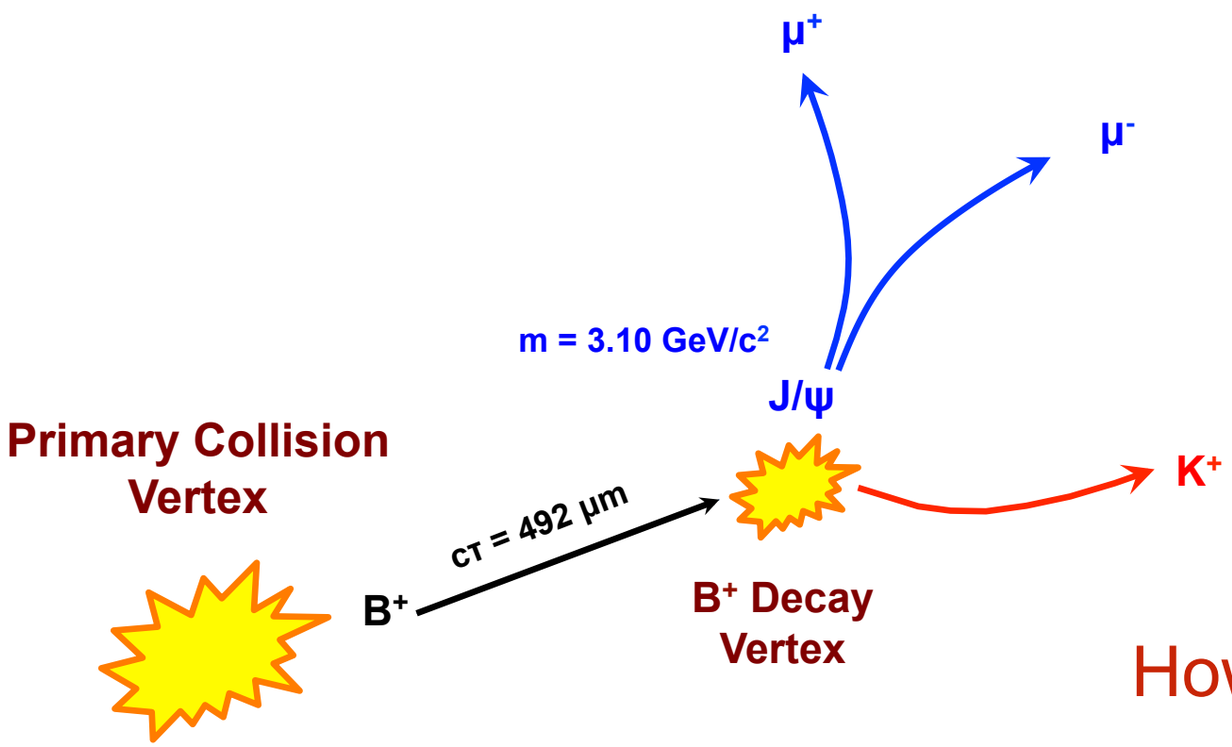
The B^+ R_{AA} at 5.02 TeV and non-prompt J/φ at 2.76 fully compatible within uncertainties!

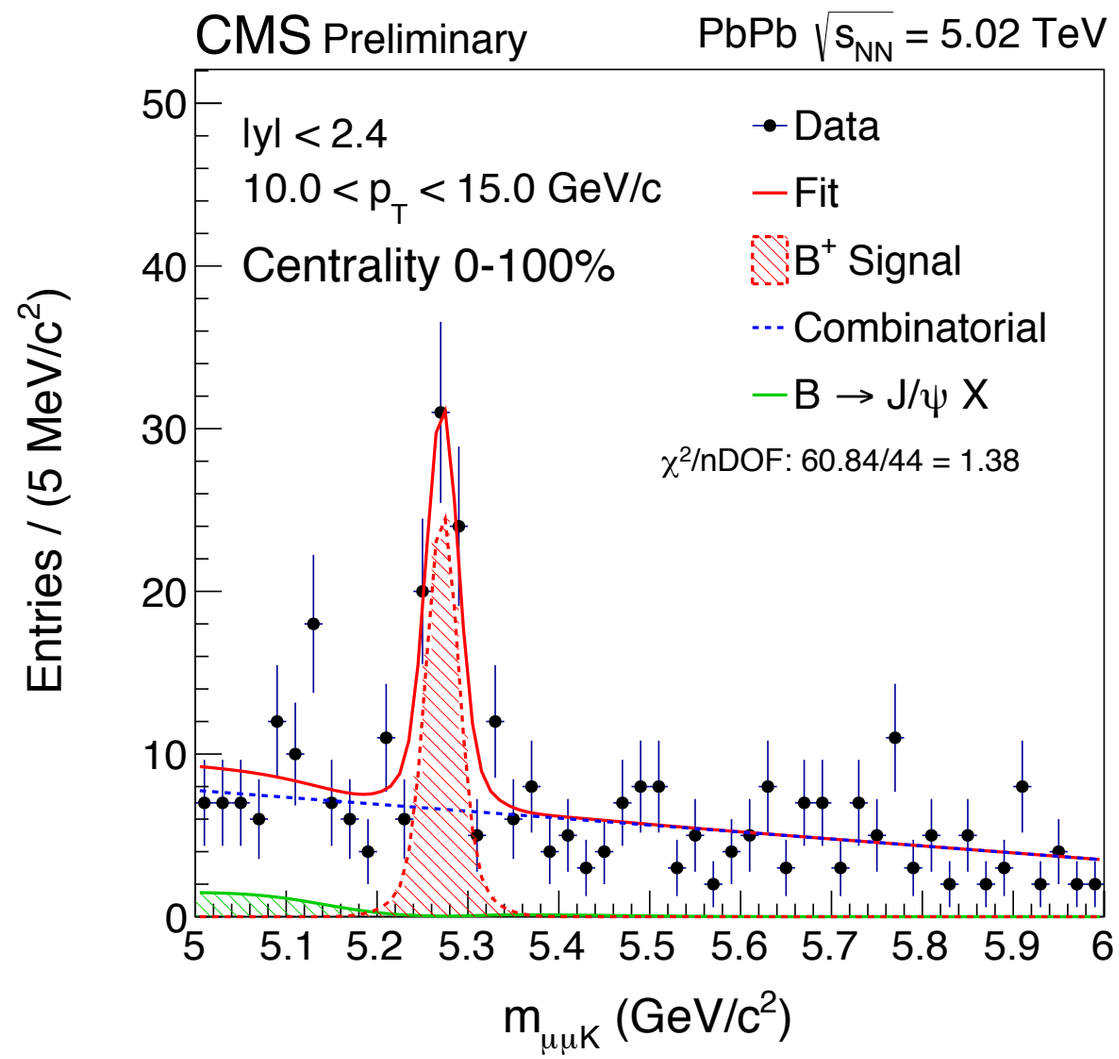
BIG CAVEAT: different energies!

Exclusive B-meson measurements

Exclusive B mesons can span the full range and get closer to the parton kinematic!

$$B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu^+\mu^-\ K^+$$



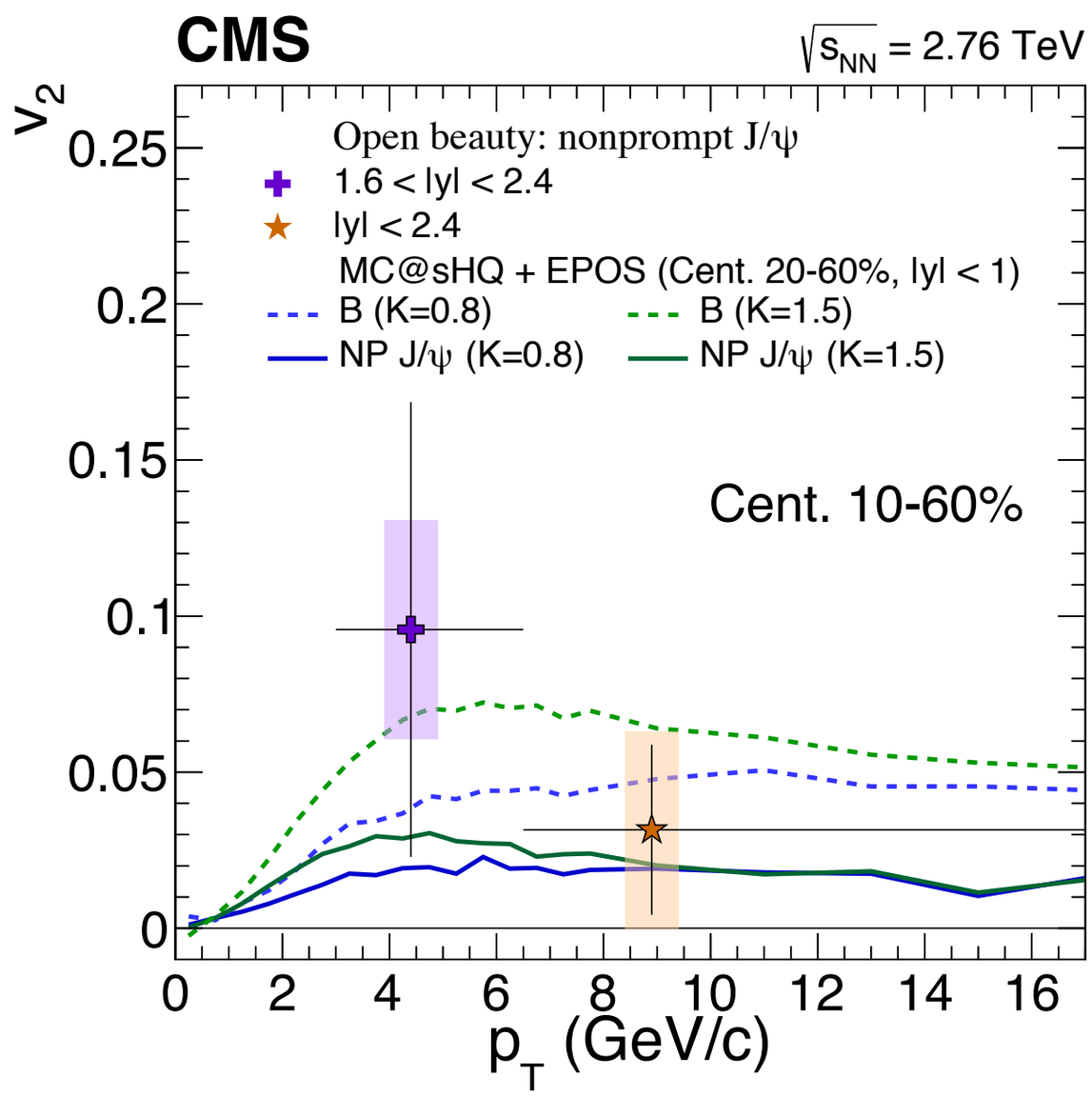


How do we reconstruct B mesons in CMS?

→ Clean and high statistics sample collected by triggering on muons!

v_2 of non prompt J/ψ

v_2 of non prompt J/ψ in PbPb collisions at 2.76 TeV

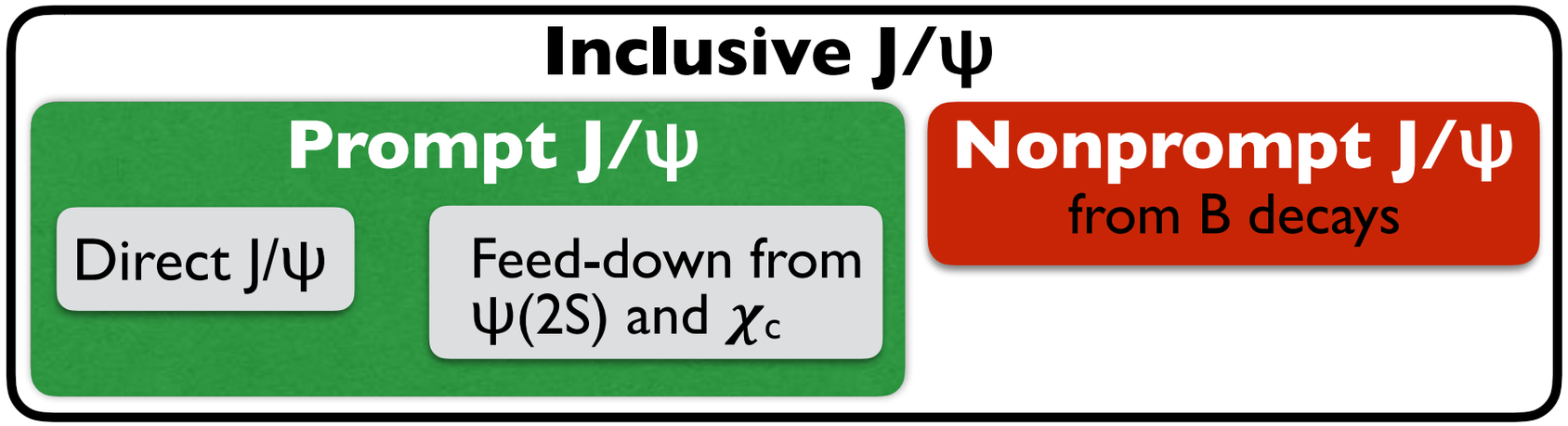


→Compatible within uncertainties with theoretical calculations

Looking to see the new measurement with Run2 data with higher statistics!

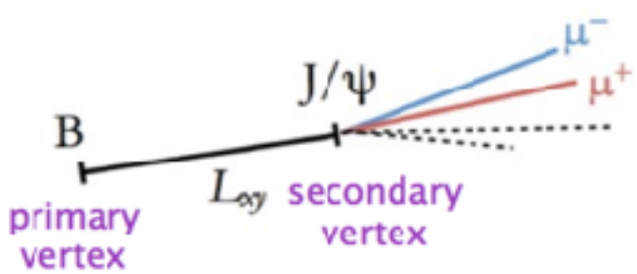
arXiv:1610.00613, Submitted to Eur. Phys. J. C

prompt and non prompt charmonia



- **Prompt component:**
  affected by color screening and regeneration in the QGP
- **Nonprompt component:**
  reflects E_{loss} of b quarks in the medium

Separation of components based on **pseudo-proper decay length** ($\ell_{J/\psi}$):



$$\ell^{3D}_{J/\psi} = L_{xyz} \cdot \frac{m_{J/\psi}}{p_{\mu\mu}}$$

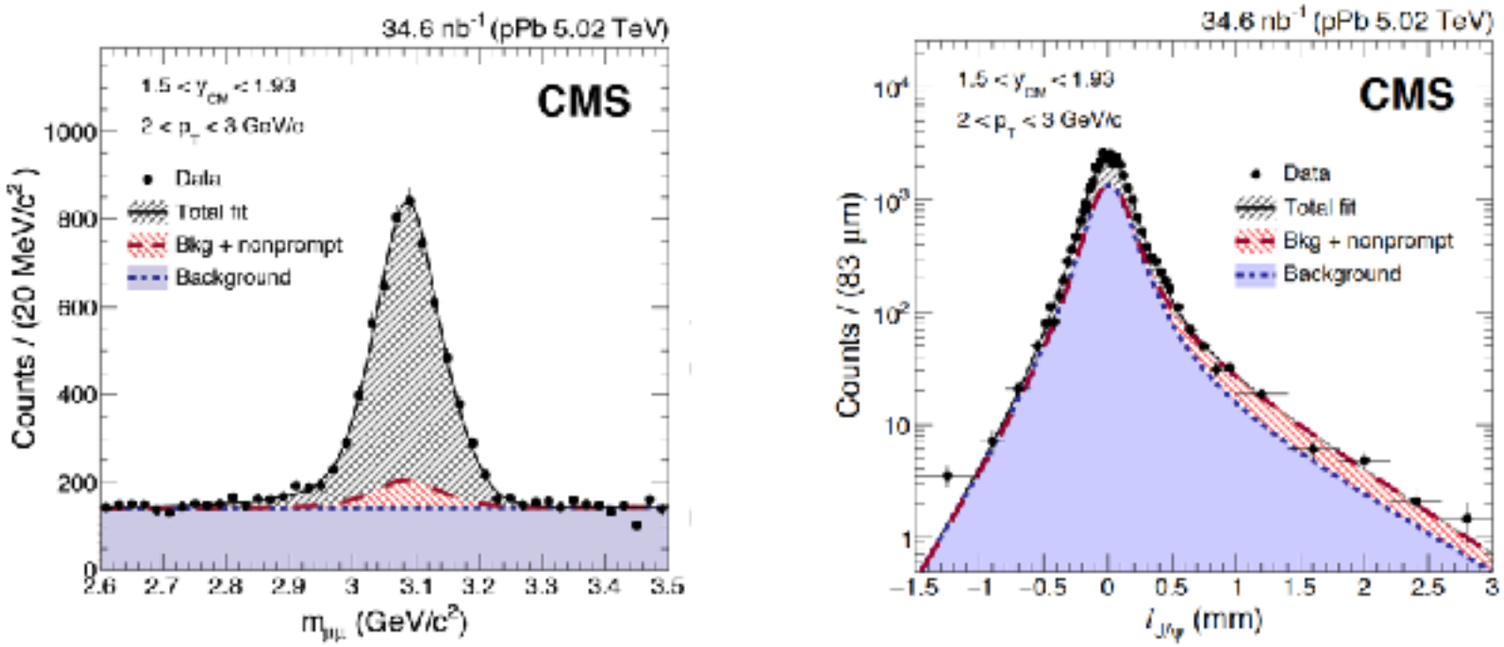
This talk:
prompt charmonia

Ta-Wei Wang's talk (8th):
nonprompt charmonia
& full B reconstruction

prompt and non prompt charmonia

Two techniques to separate components:

1. **2D fits of dimuon mass and pseudo-proper decay length**

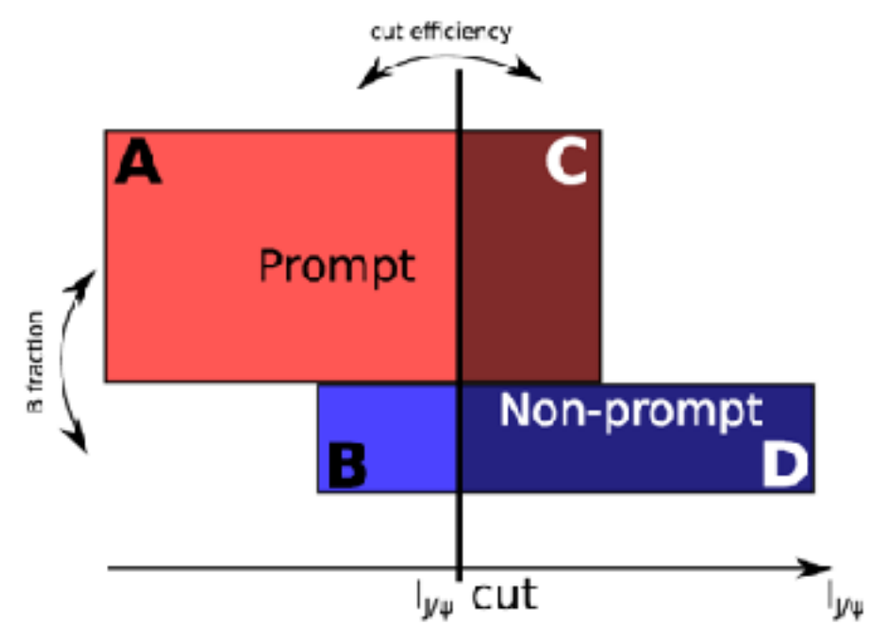


arXiv:1702.01462

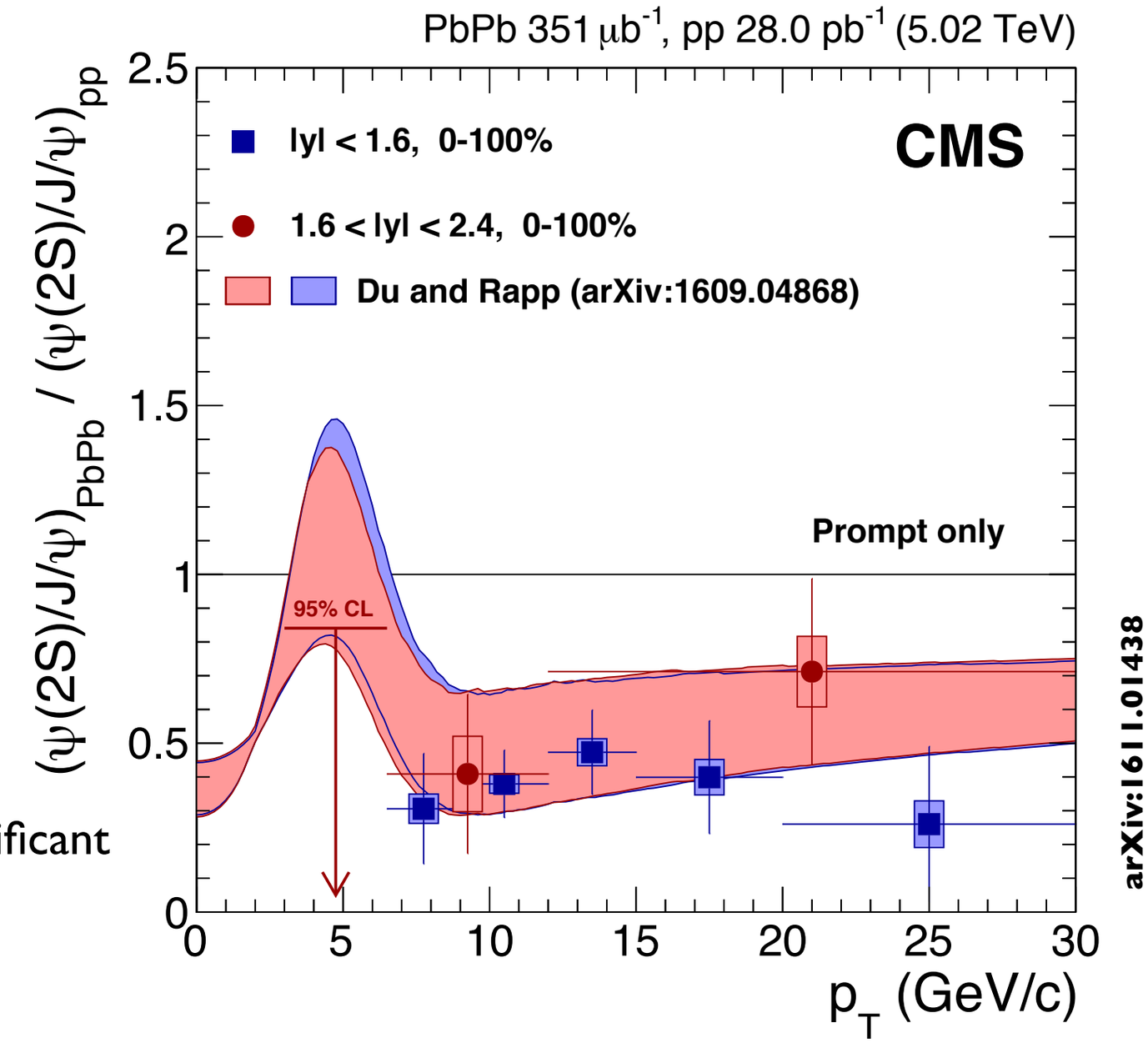
2. **Rejecting nonprompt using a cut on $\ell_{J/\psi}$**
   (can be used with low stats: ψ(2S) analyses)

Correction (from data) to account for remaining nonprompt contamination:

- Using reverted $\ell_{J/\psi}$ cut
- MC efficiency of $\ell_{J/\psi}$ cut



ψ(2S) /J/ψ vs p_T

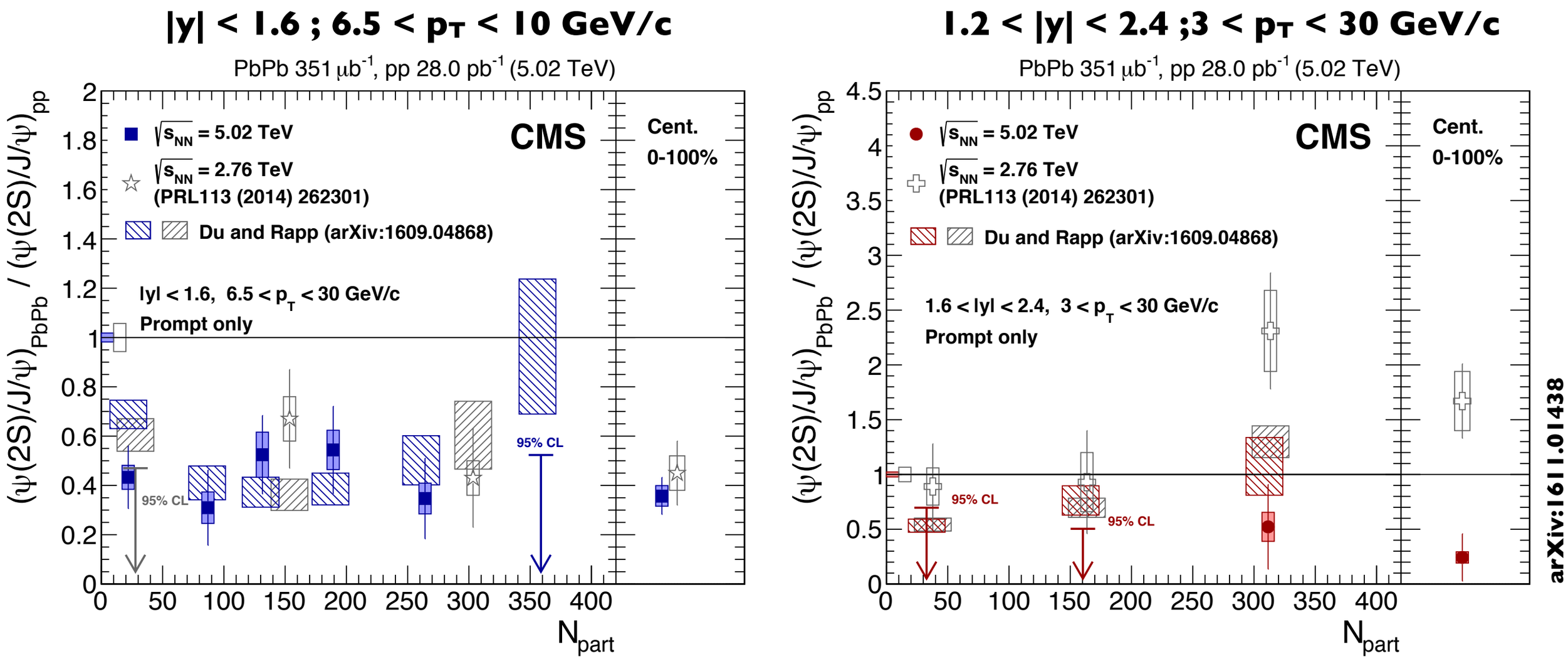


95% CL where no significant ψ(2S) signal in PbPb

- $R_{AA}(\psi(2S))/R_{AA}(J/\psi) < 1$ in all bins → **ψ(2S) is more suppressed than J/ψ**
- No p_T dependence within uncertainties
- X. Du and R. Rapp: transport model with temperature dependent reaction rates
  → ψ(2S) regenerated later than J/ψ in the fireball evolution?

ψ(2S) /J/ψ vs centrality

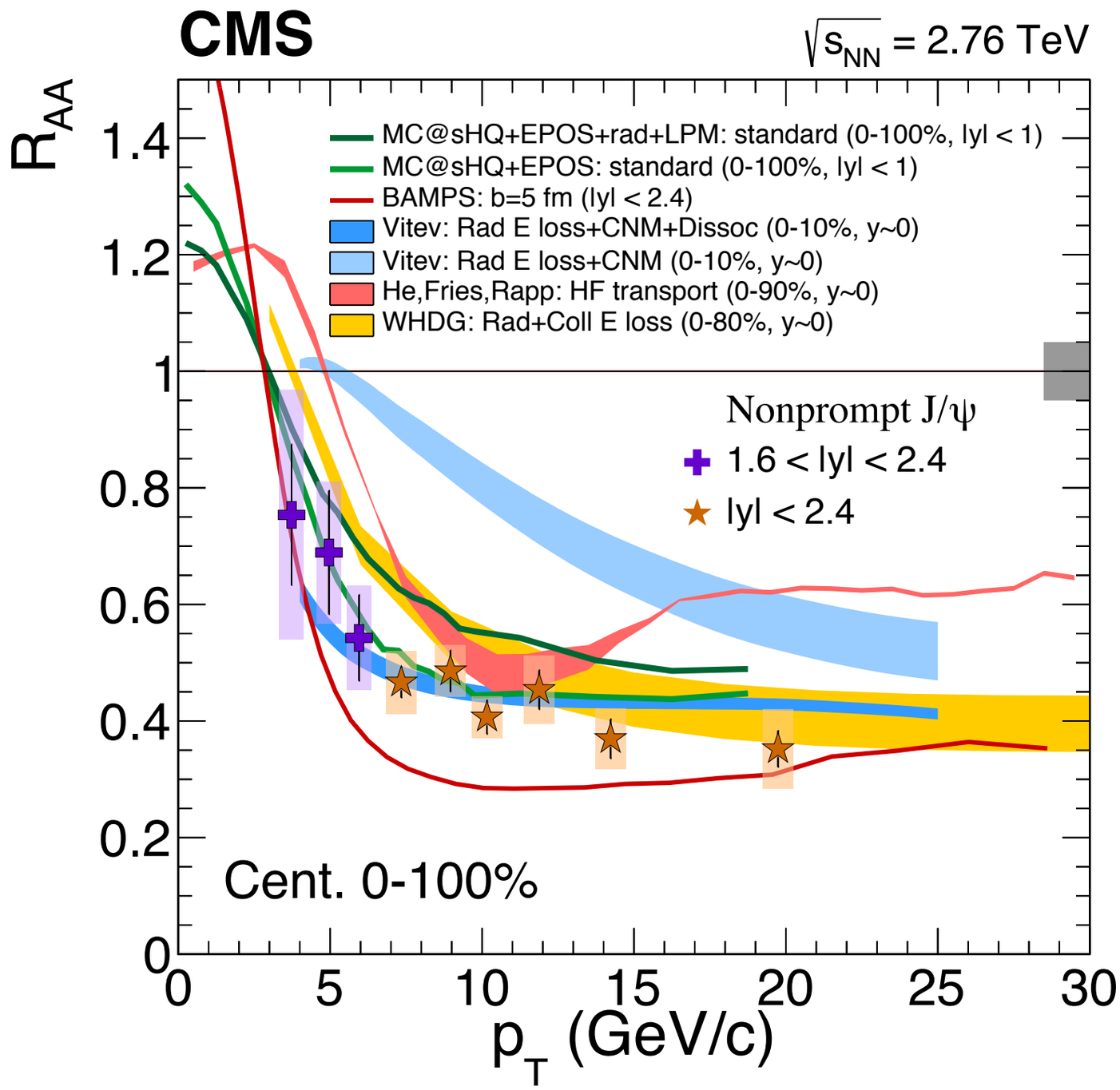
2.76 vs. 5.02 TeV



CMS results vs centrality, p_T and rapidity can help to constrain the model:

- Relative contribution of primordial and regenerated charmonia
- Dissociation and regeneration rates
- Temperatures at which J/ψ and ψ(2S) regenerate
- …

Comparison to theoretical calculations



CMS non prompt 1.6<|y|<2.4
CMS non prompt |y|<2.4

arXiv:1610.00613, Submitted to Eur. Phys. J. C

Strong suppression observed for non prompt J/φ in PbPb collisions

Clear suppression as a function of p_T