Experimental summary: heavy-flavour production at the LHC

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22-27 September 2016, Wuhan, China

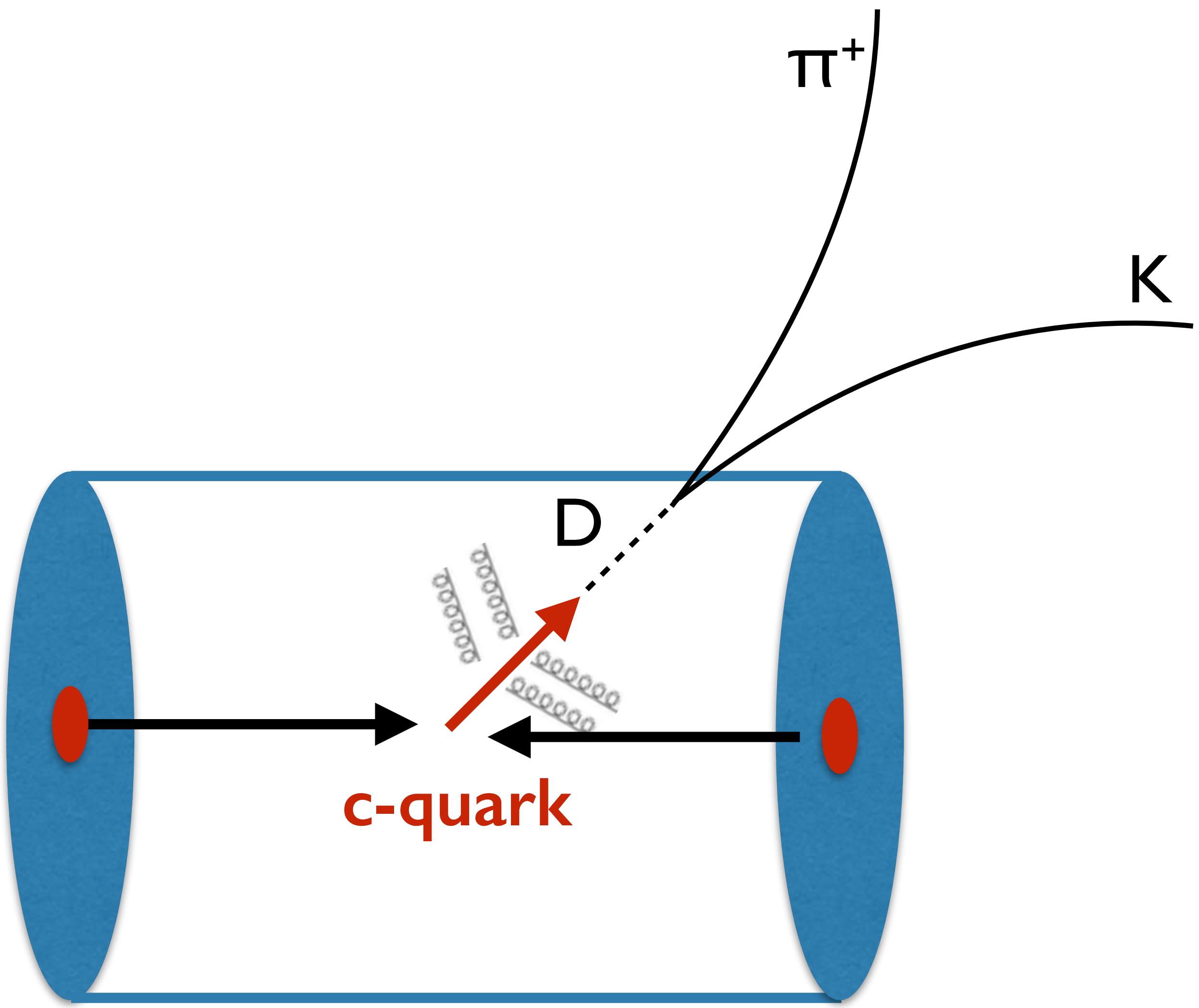
My list of questions

How do heavy-quarks lose energy ?

Does E_{loss} depends on the parton flavour?

Do we understand the HF production mechanism?

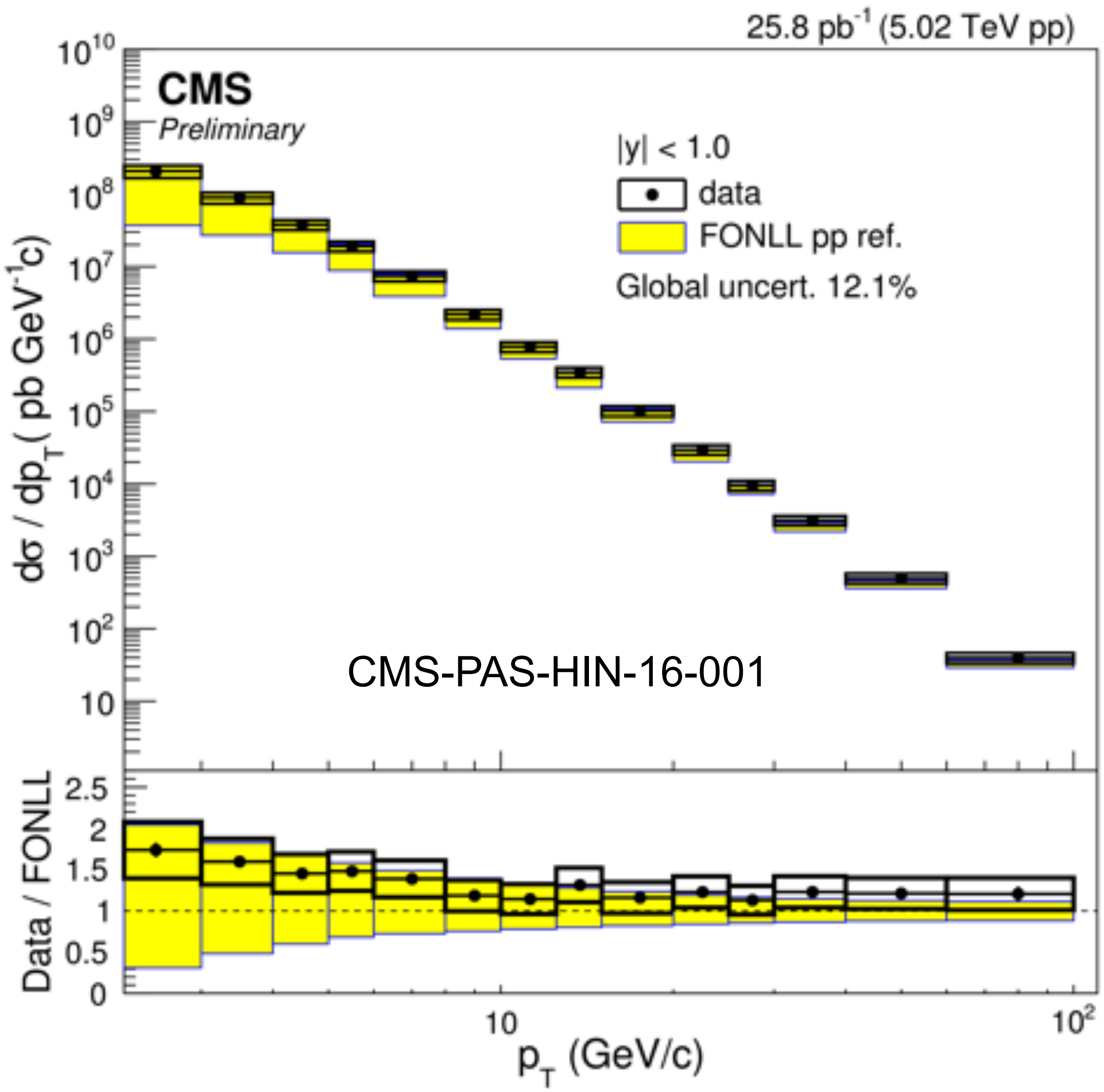
How initial state effects modifies it in HI?



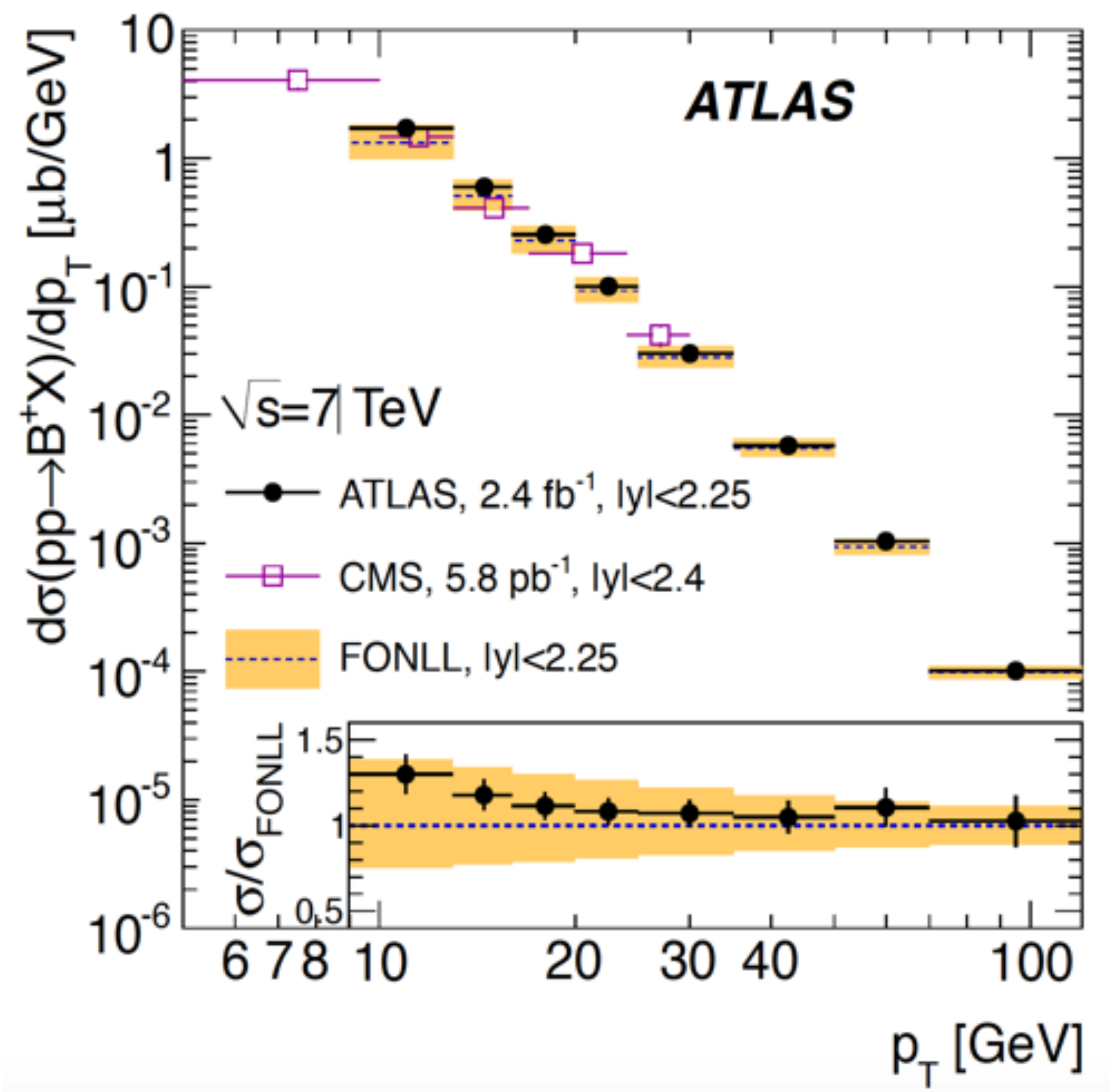
Do charm/beauty flow?

D and B cross sections at LHC in pp collisions

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



ATLAS B^+ measurement at 7 TeV, $|y|<2.25$



HF production cross sections well described by NLO calculations:

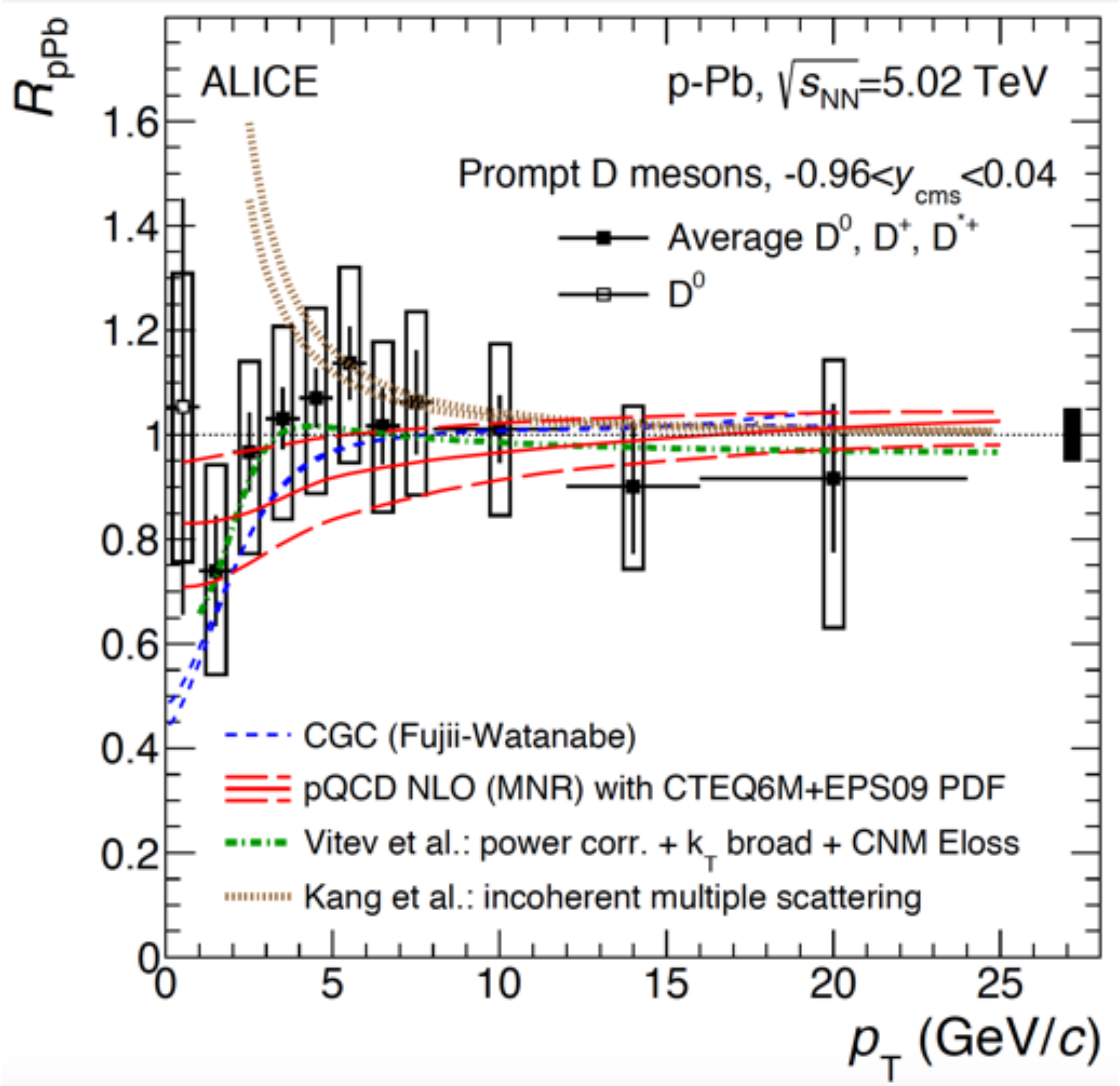
→*D meson upper edge of FONLL calculations*

→*B meson consistent with central values of FONLL*

J.Wang and T.W.Wang's talks, Saturday

D^0 production in pPb collisions

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



R_{pA}<1 at low p_T consistent with shadowing

R_{pA}~1 at high p_T

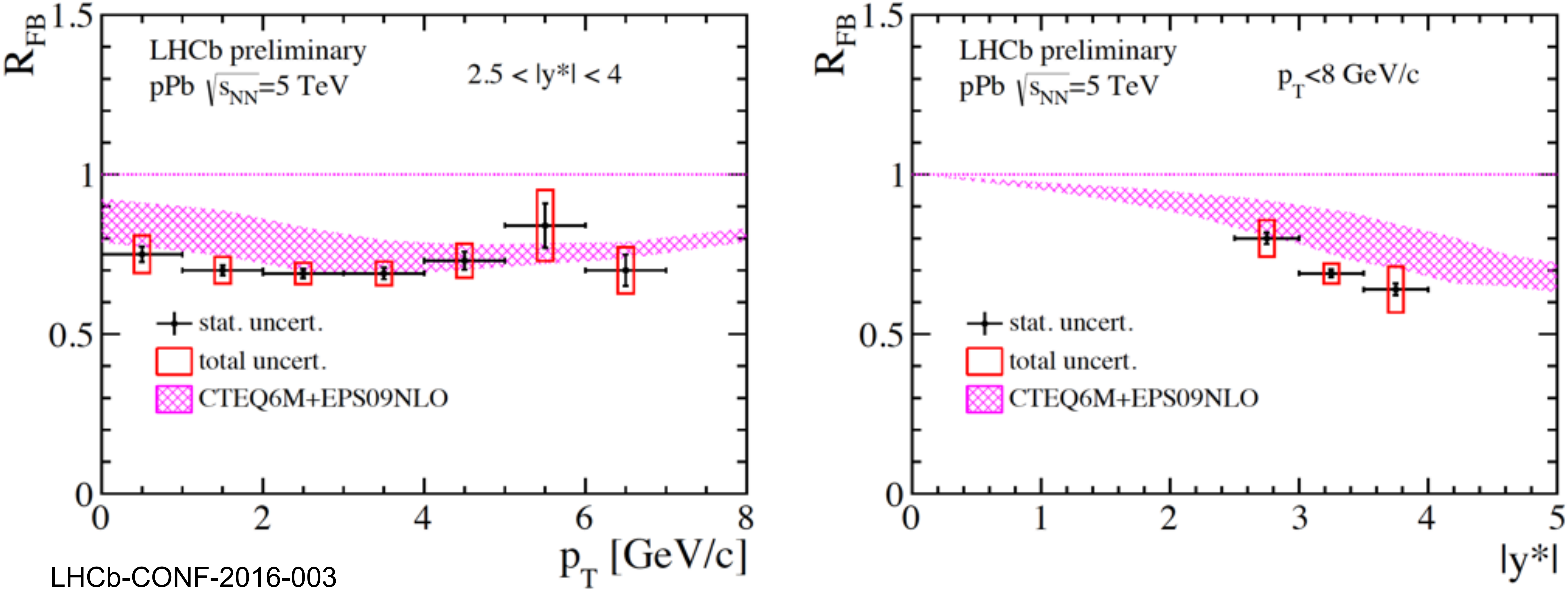
PRL 113 (2014) 232301

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

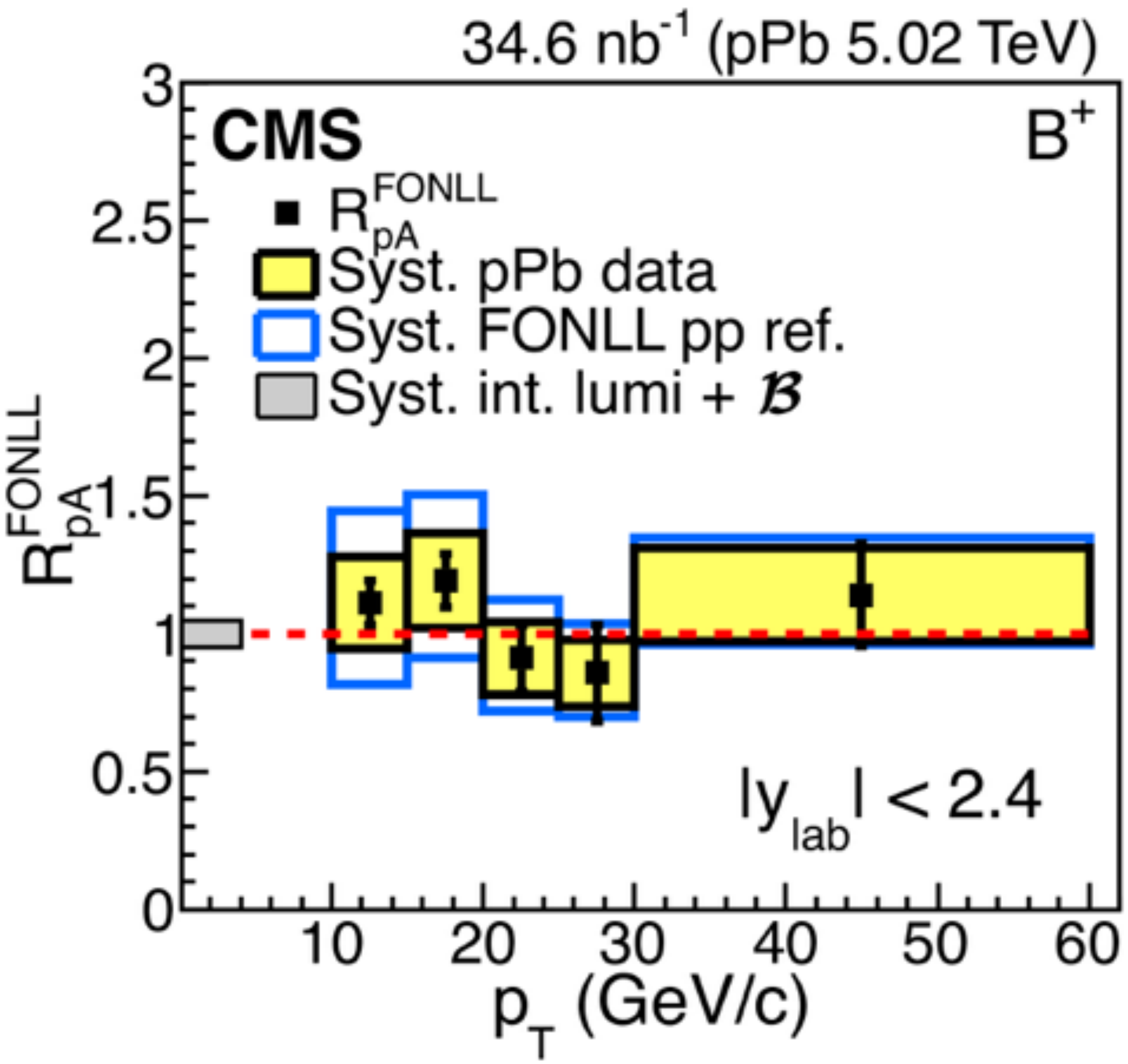


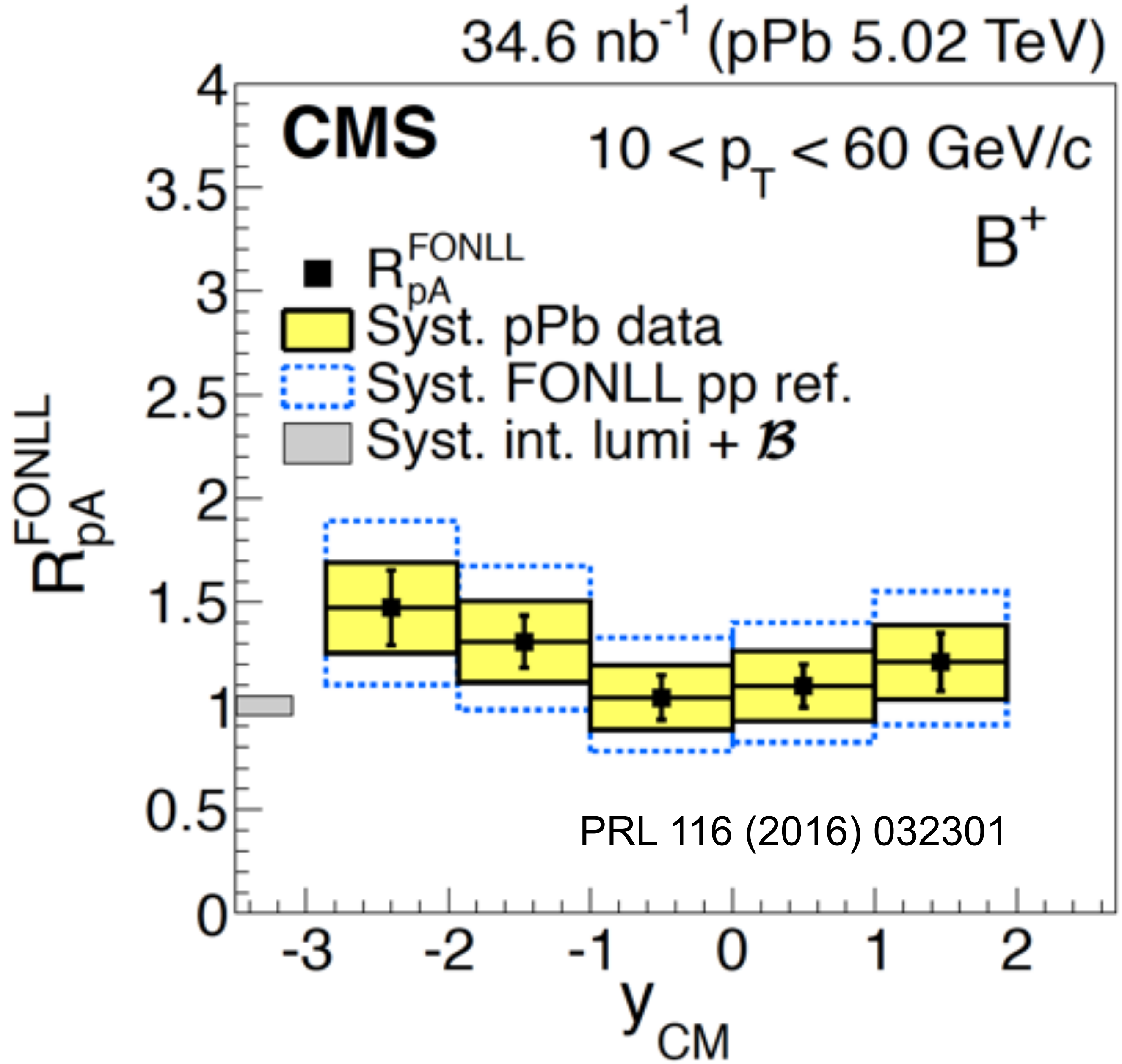
LHCb-CONF-2016-003

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

X. Zhu's talk, Saturday

B meson production in pPb collisions





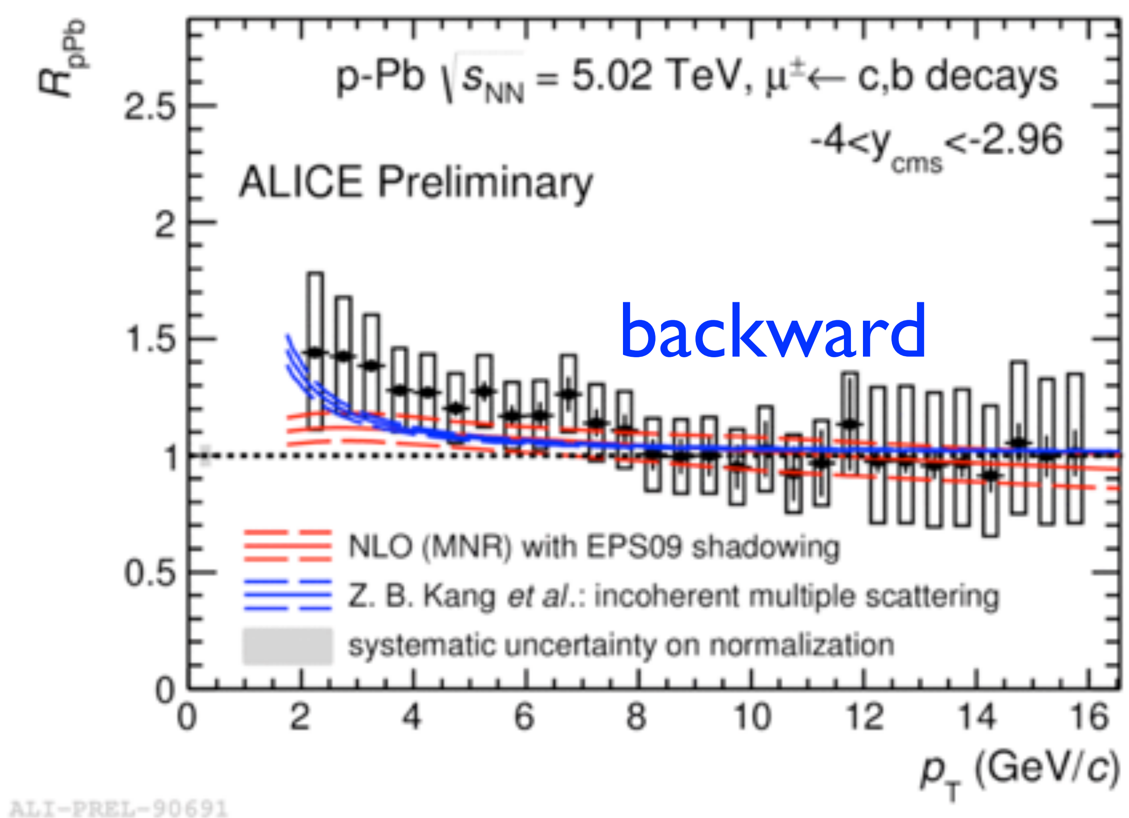
FONLL R_{pA} fully compatible with unity

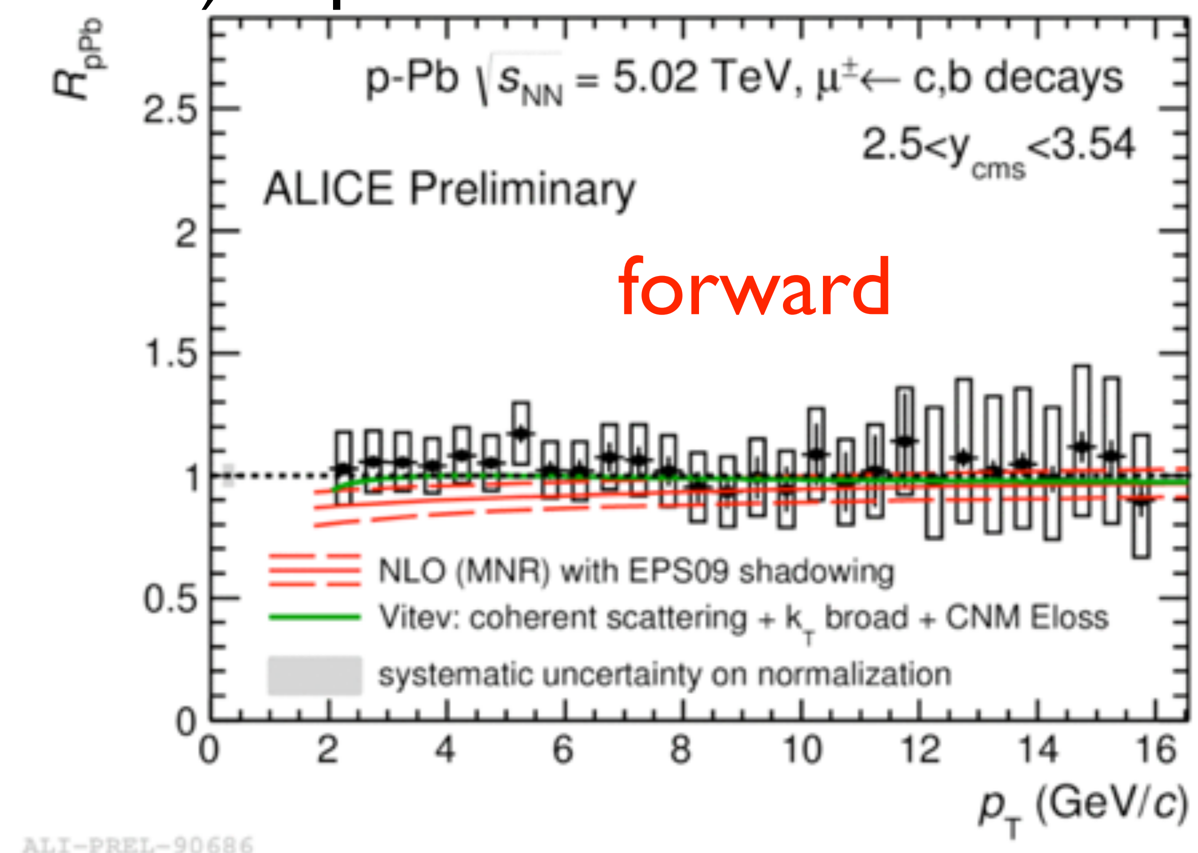
No sizeable modification as a function of rapidity

T.W. Wang's talk, Saturday

Heavy flavour leptons: LHC vs. RHIC

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





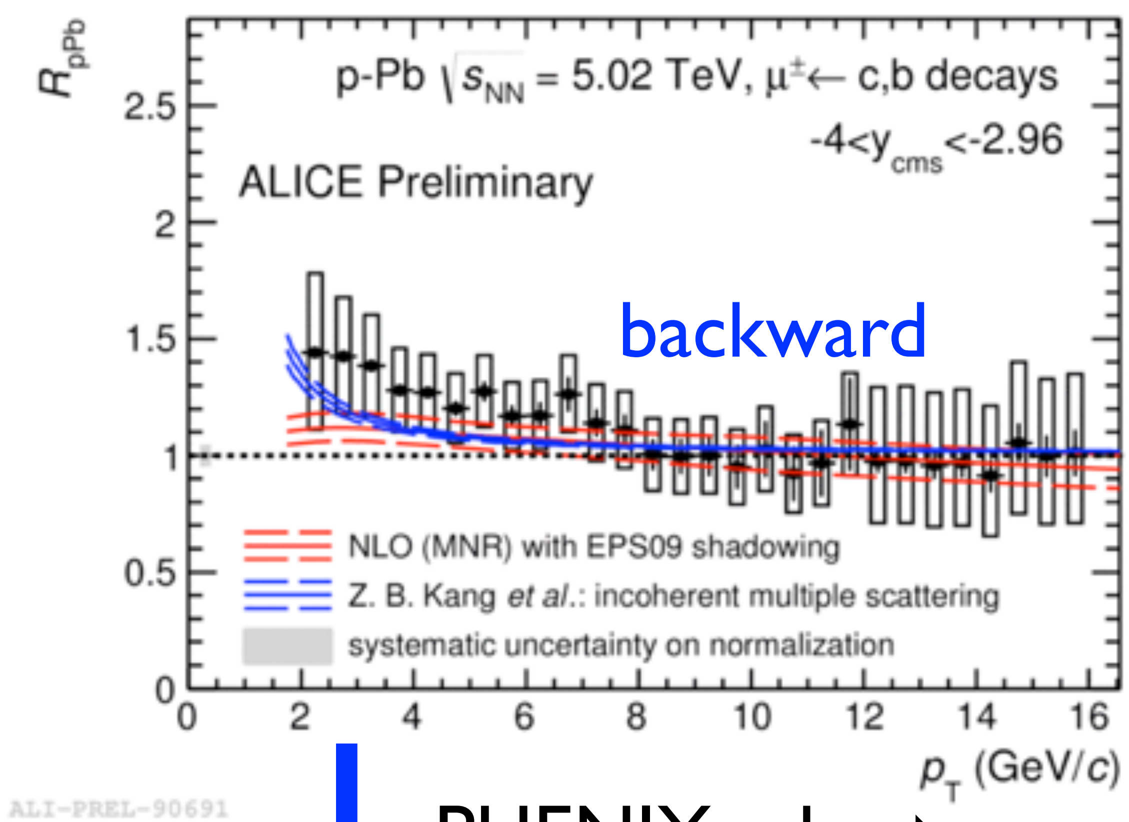
forward (shadowing)
backward (anti-shadowing)

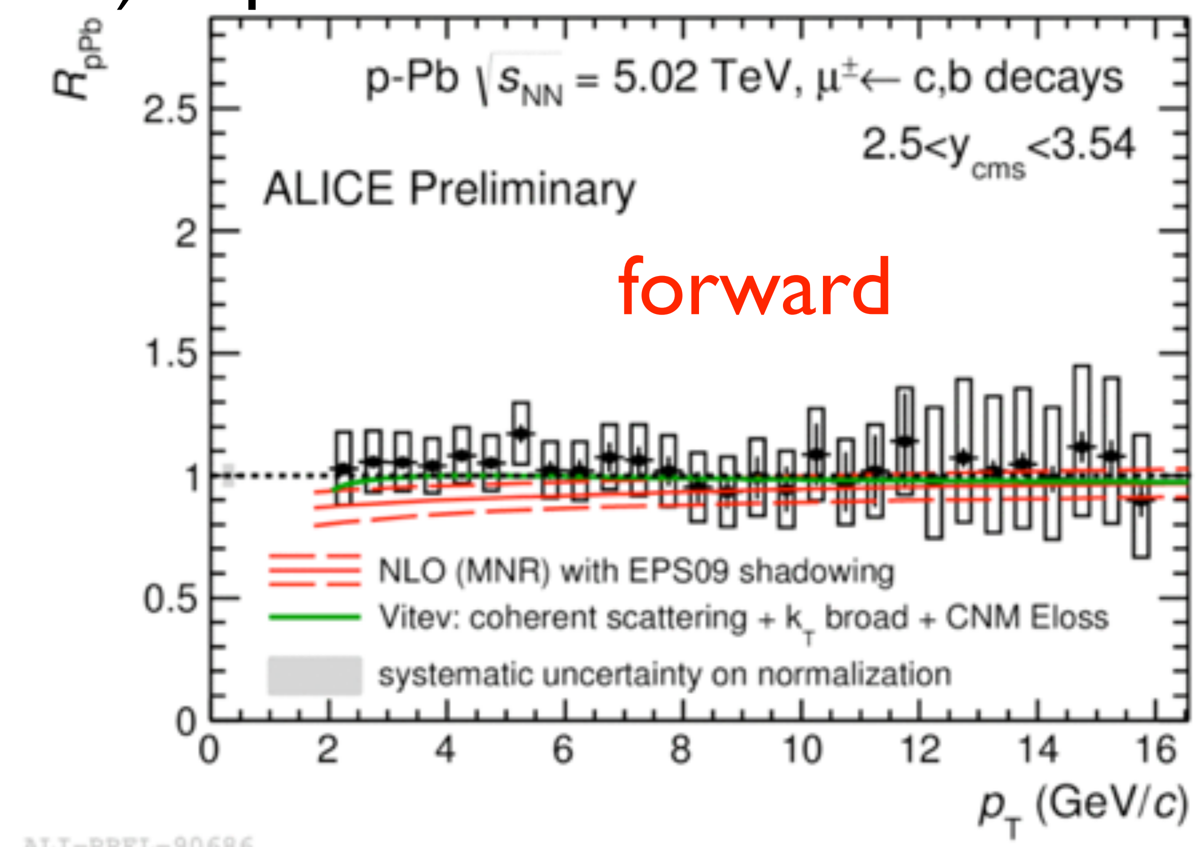
Models with CNM describe forward/backward rapidity at LHC

PRL112 (2014) 252301

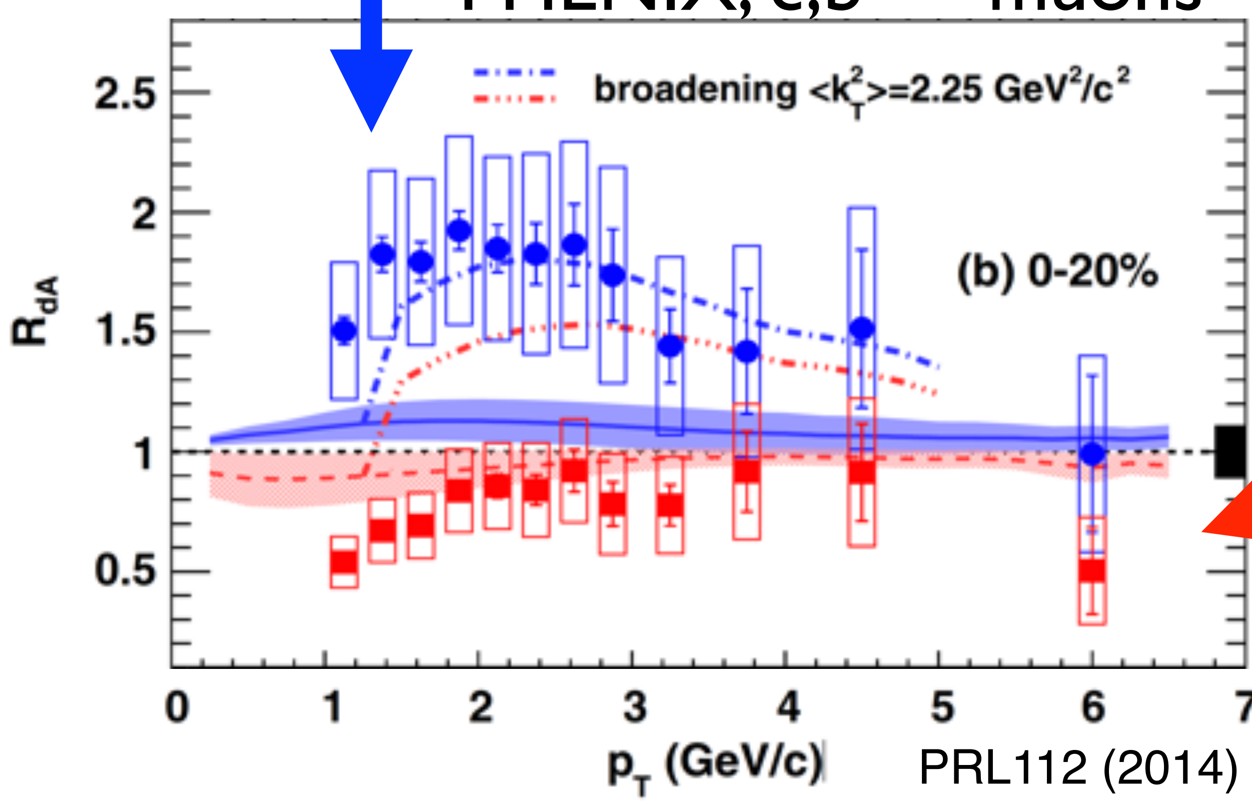
Heavy flavour leptons: LHC vs. RHIC

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!**

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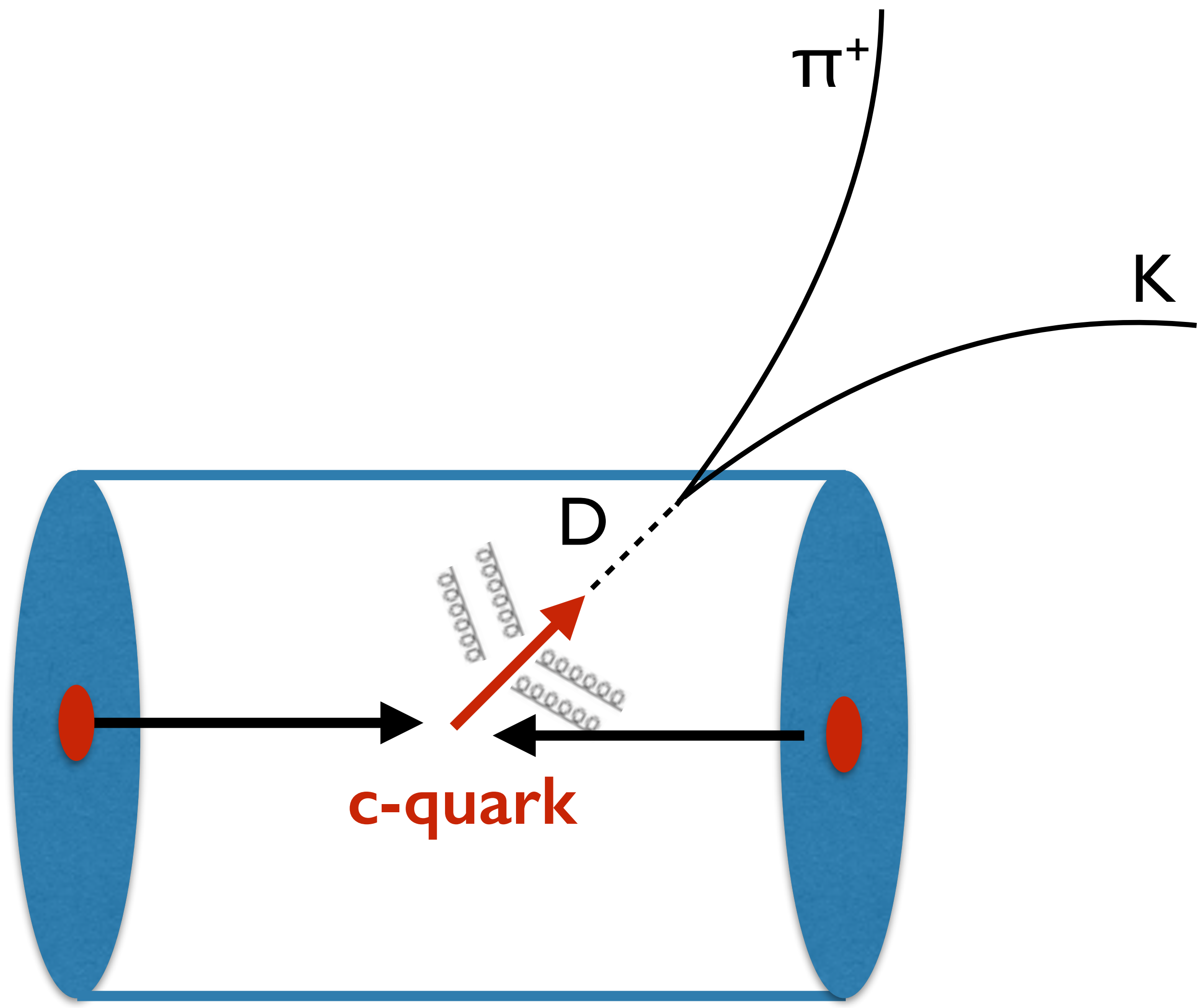
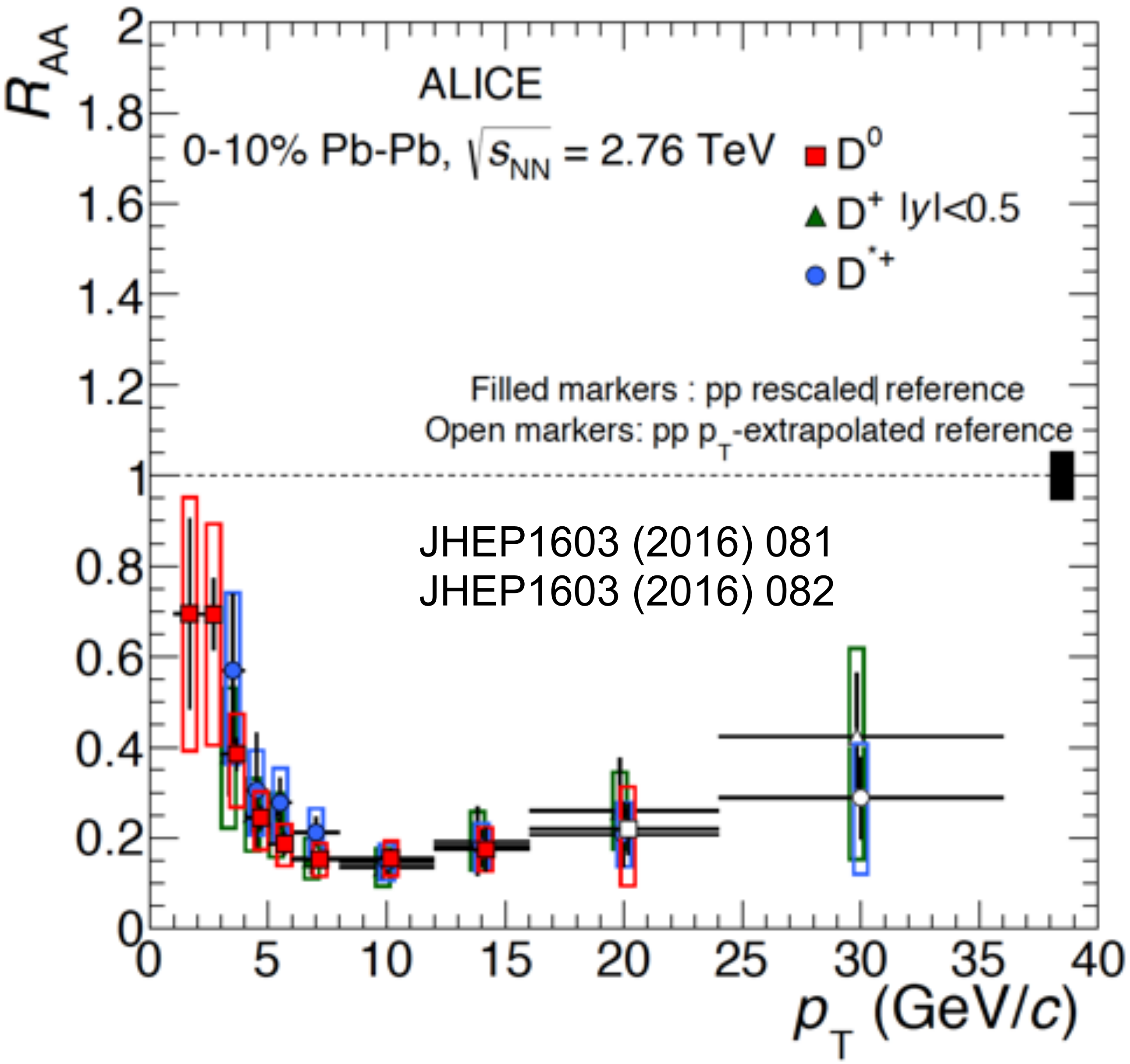
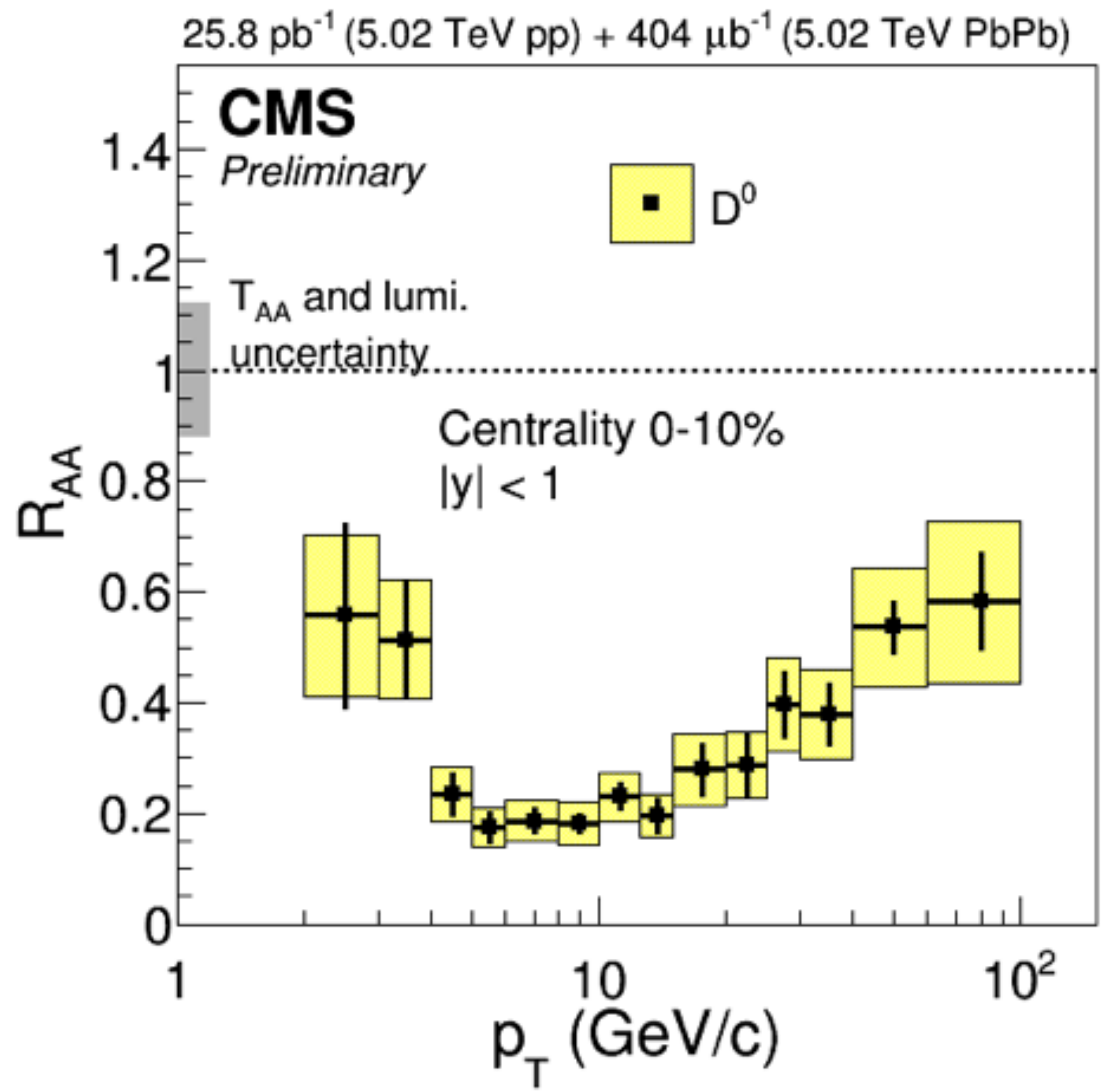


Do charm/beauty flow?

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:

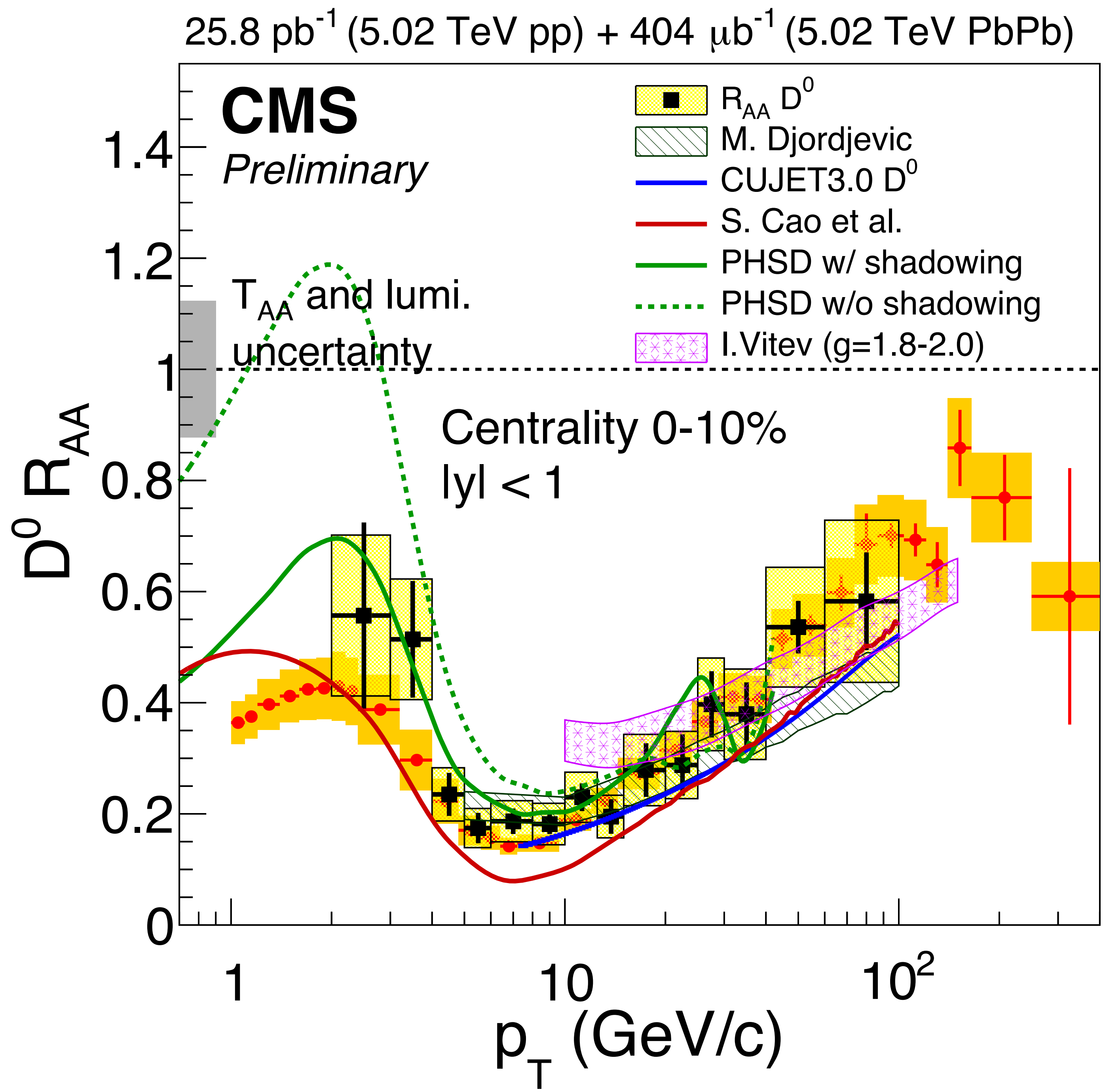
same suppression for D^0,D^+,D^{*+}

Similar suppression at 5.02 TeV:

Rising trend observed when going to high p_T

J.Wang's and A.Dubla's talks, Saturday

Comparison to theoretical calculations



CMS-PAS-HIN-16-001

D^0 R_{AA} measurement is well described by theoretical calculations!

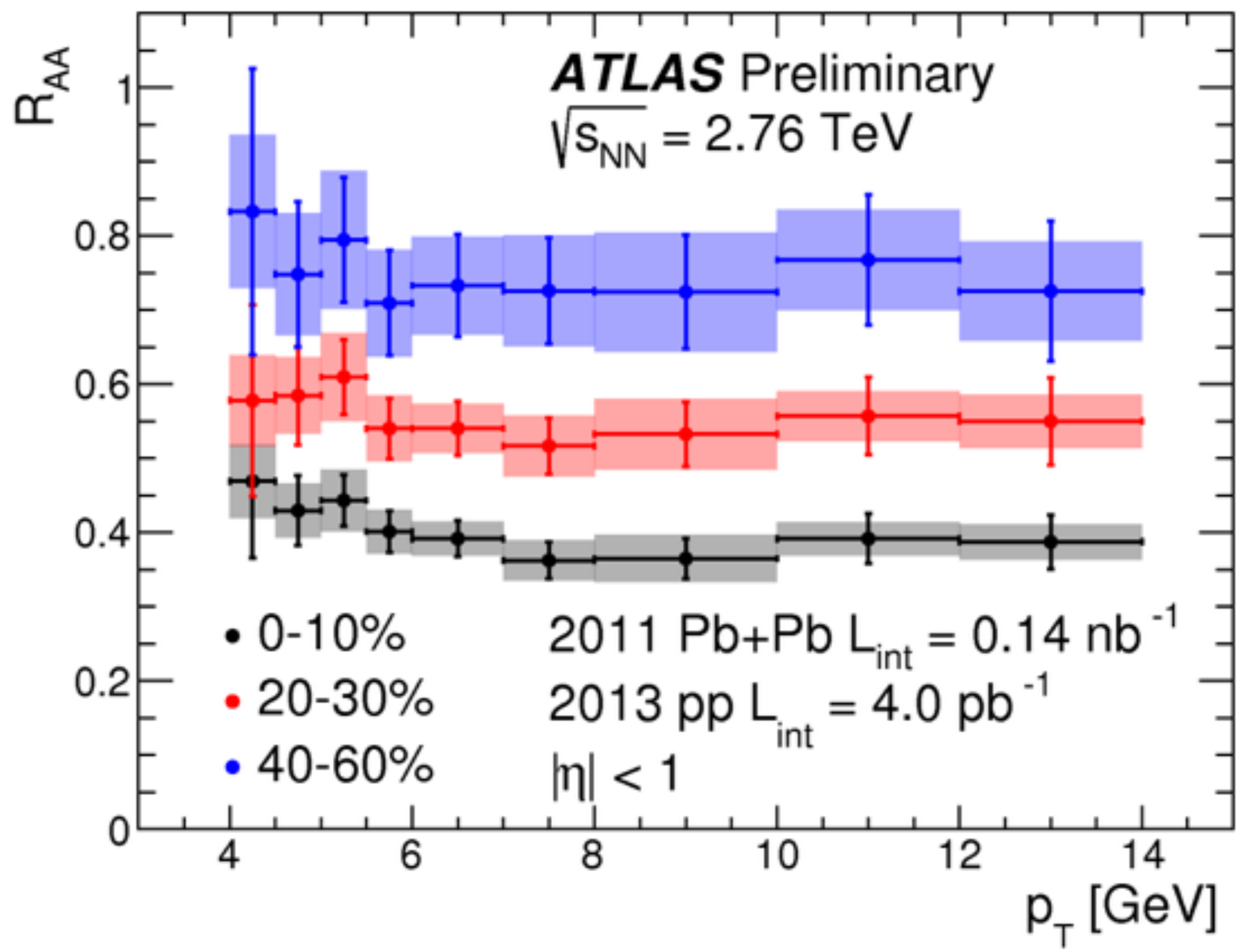
Seems to favour calculations that include:

- both collisional and radiative energy loss
- shadowing

J.Wang's talks, Saturday

R_{AA} of heavy flavour muons

R_{AA} of heavy-flavour muons at 2.76 TeV from ATLAS



ATLAS-CONF-2015-053

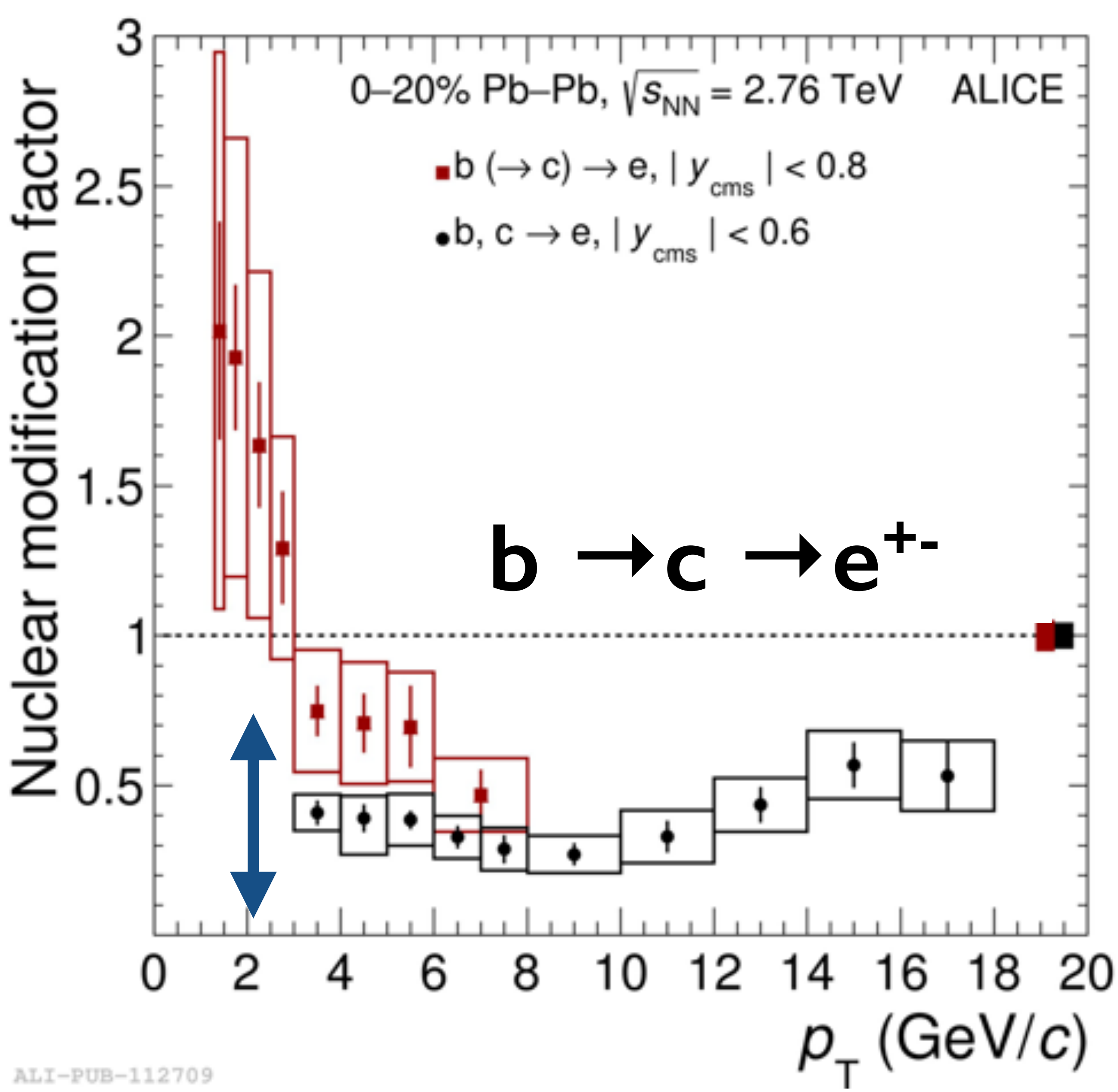
Strong suppression observed for for HF muons!

Clear suppression pattern observed as a function of centrality

Q. Hu's talk, Saturday

R_{AA} of beauty electrons

ALICE R_{AA} of beauty electrons (b → c → e^{+-}) at 2.76 TeV



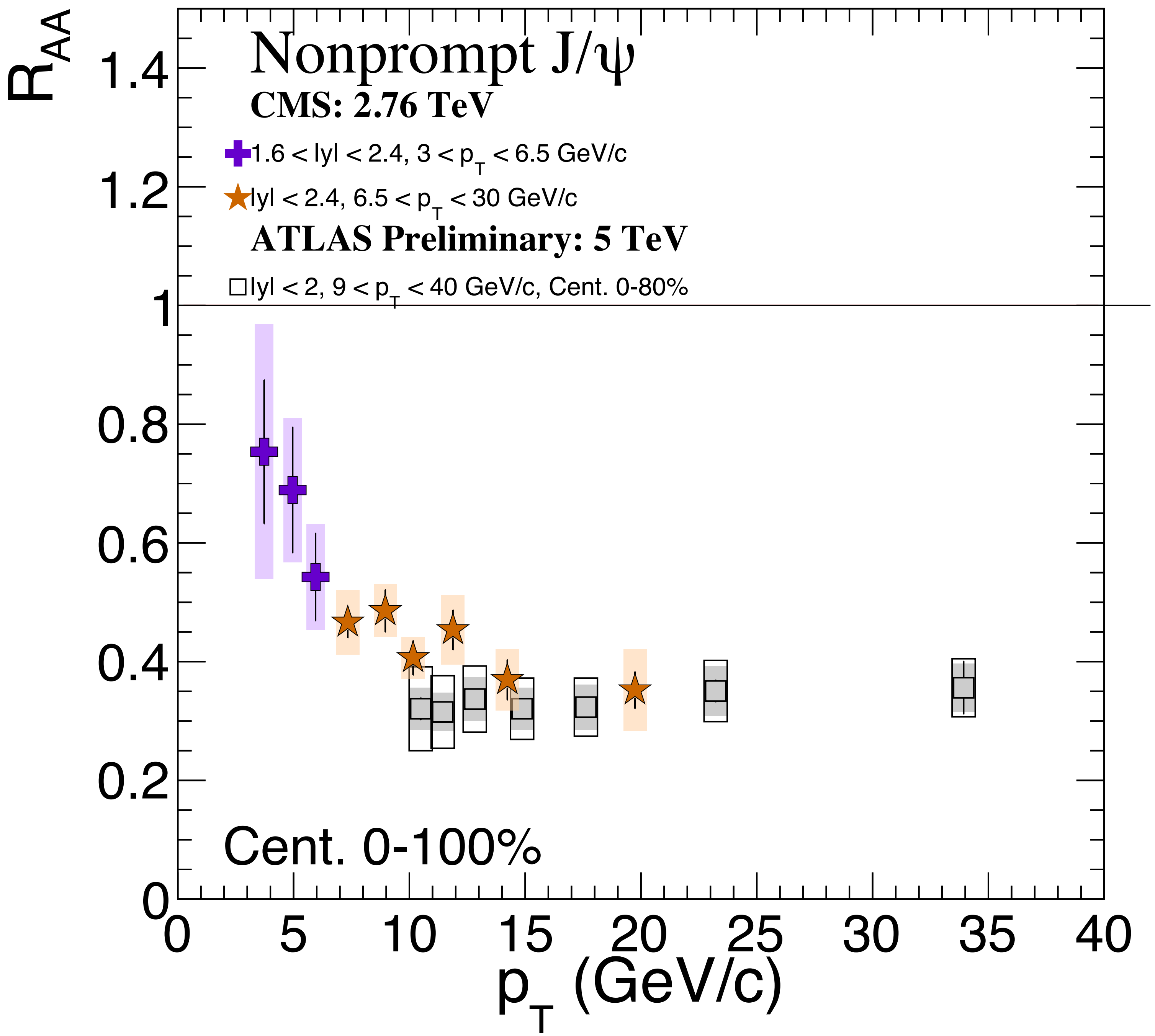
arXiv:1609.03898

Strong suppression observed for heavy-flavour (c,b) electrons and beauty electrons

Indication of difference suppression for charm and beauty electron vs. beauty electrons

A.Dubla's talks, Saturday

R_{AA} of non prompt J/φ at 2.76 TeV and 5 TeV



CMS non prompt 1.6<|y|<2.4

CMS non prompt |y|<2.4

ATLAS non prompt |y|<2.9

NEW RESULT

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

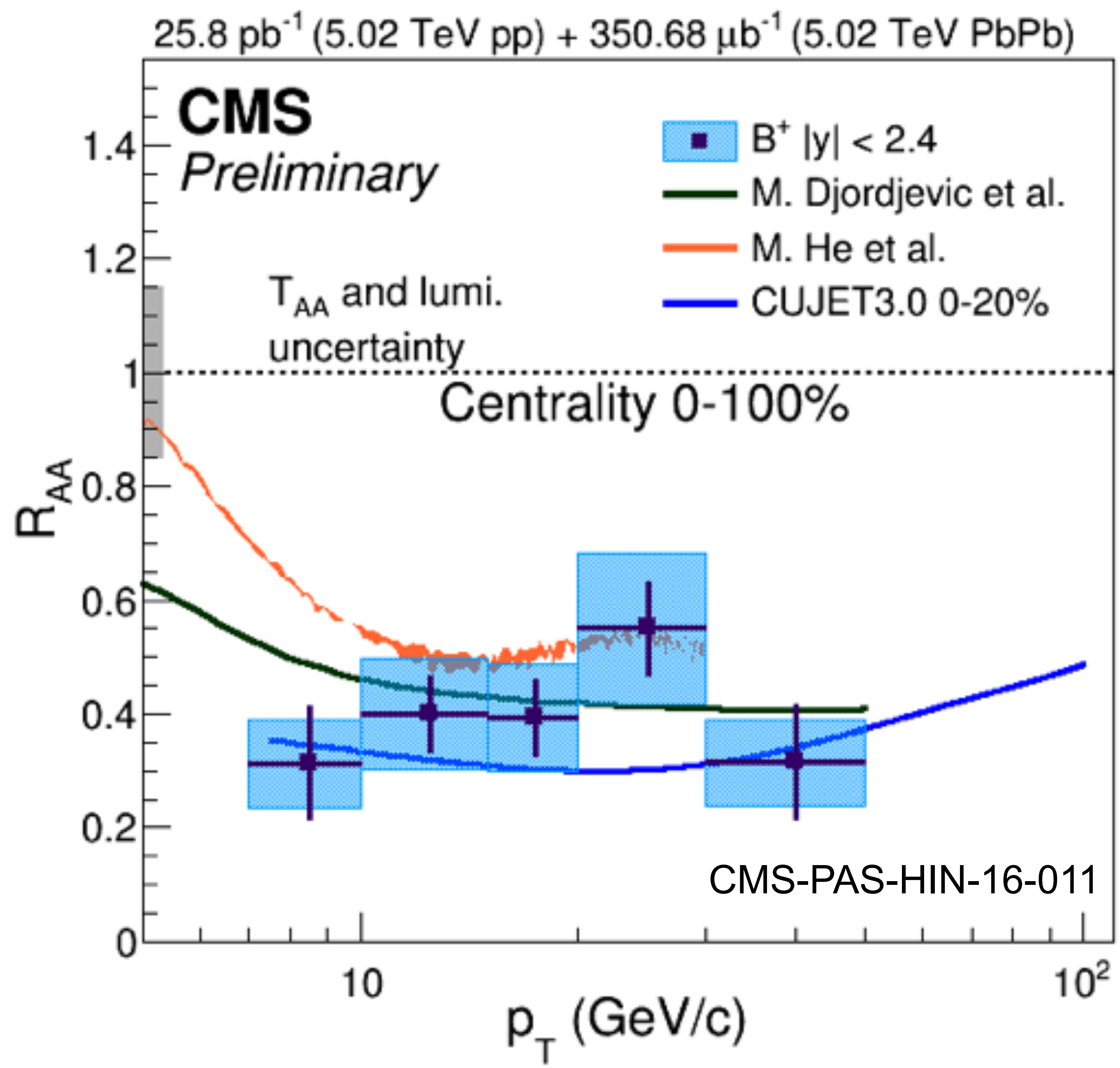
Clear suppression as a function of p_T

2.76 TeV and 5.02 TeV results well consistent within uncertaintiess

M. Jo's talk, Sunday

Exclusive B^+ meson measurement in PbPb

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



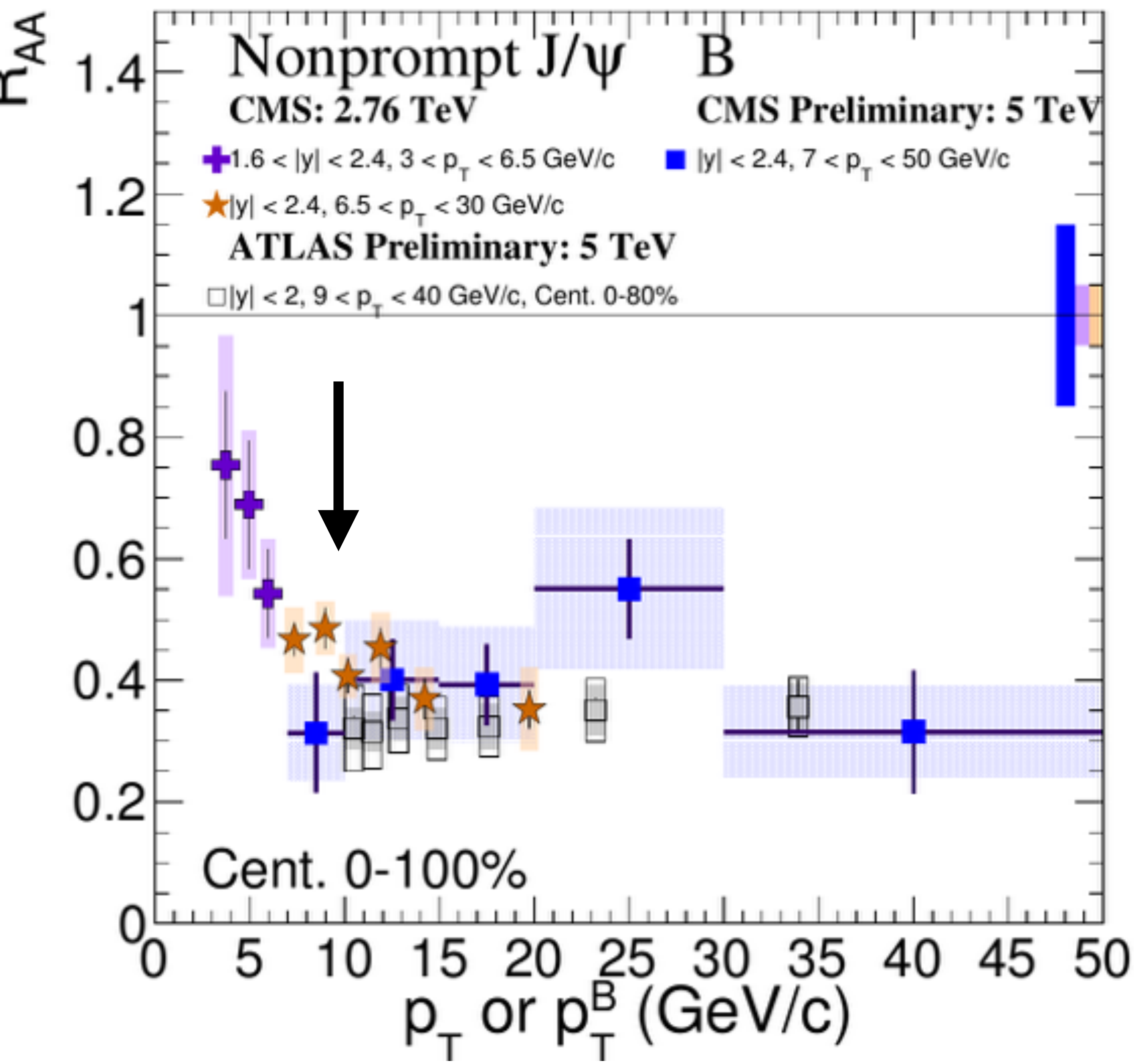
Strong suppression (R_{AA}~0.4) observed in 0-100% PbPb collision for p_T>7 GeV/c

Well described by theoretical calculations that include radiative energy loss

T.W. Wang's talk, Saturday

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

No tension between the two measurements!



To be handled with care!!

- *B meson p_T and non prompt J/φ are different! Need to correct for different kinematic*

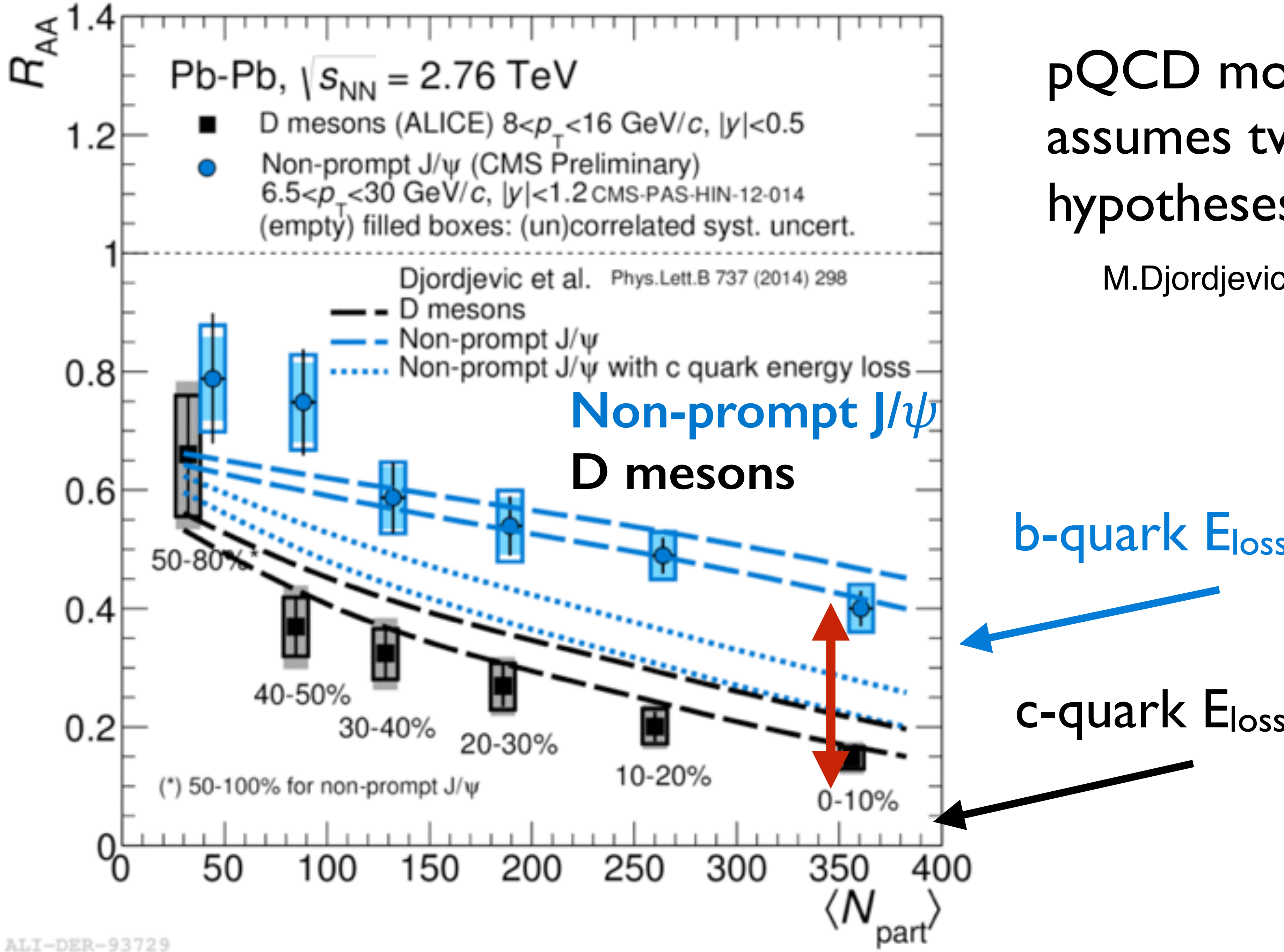
CMS non prompt 1.6<|y|<2.4
CMS non prompt |y|<2.4
ATLAS non prompt |y|<2.9
CMS B+ |y|<2.4

M. Ho's talk, Sunday

Flavour dependence of E_{loss} at 2.76 TeV

ALICE, JHEP 1511 (2015) 205

A. Dubla talk, Saturday



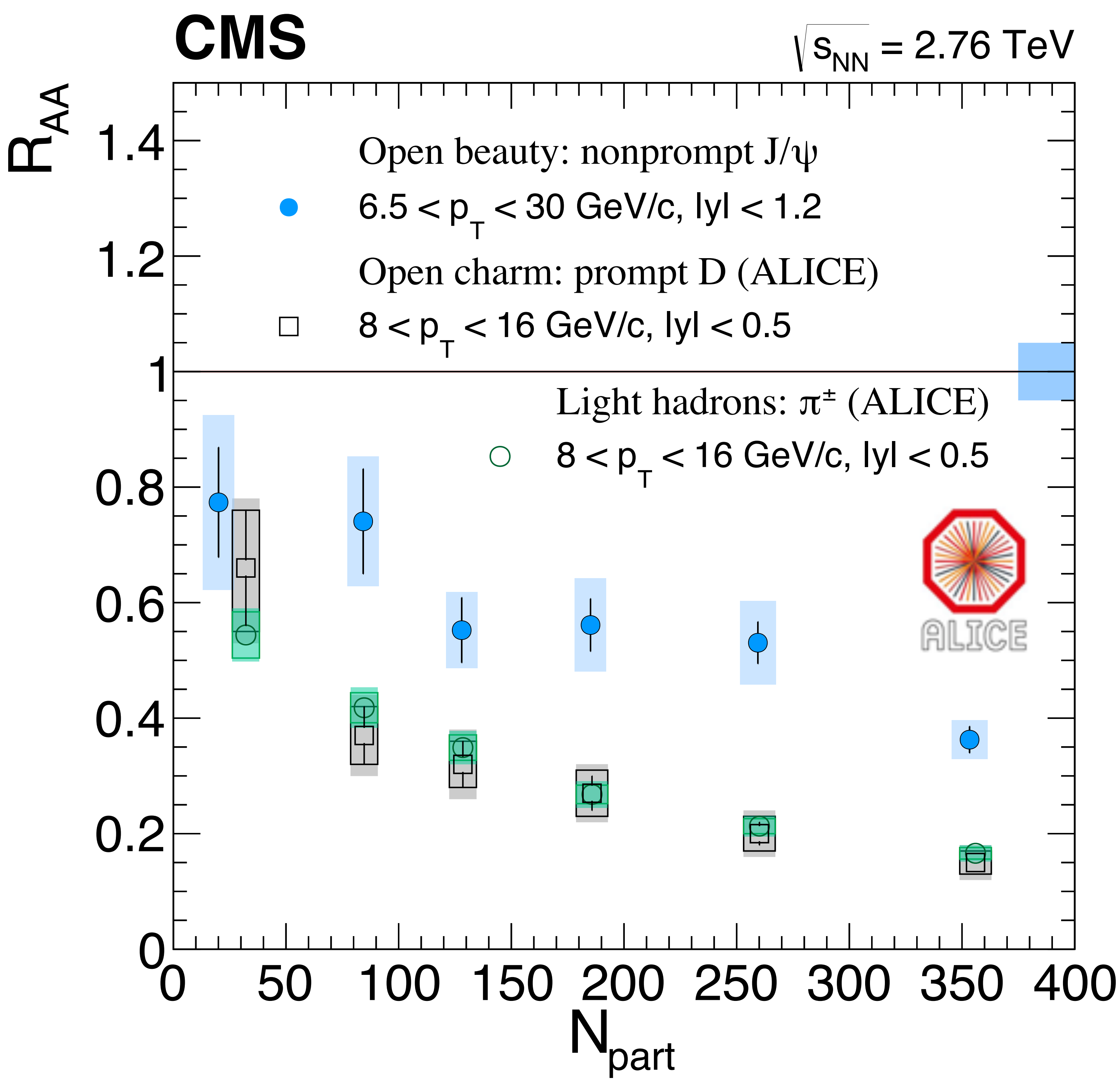
pQCD model (M.Djordjevic) that assumes two different mass hypotheses for non prompt J/ψ

M.Djordjevic, PRL 112, 042302 (2014)

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

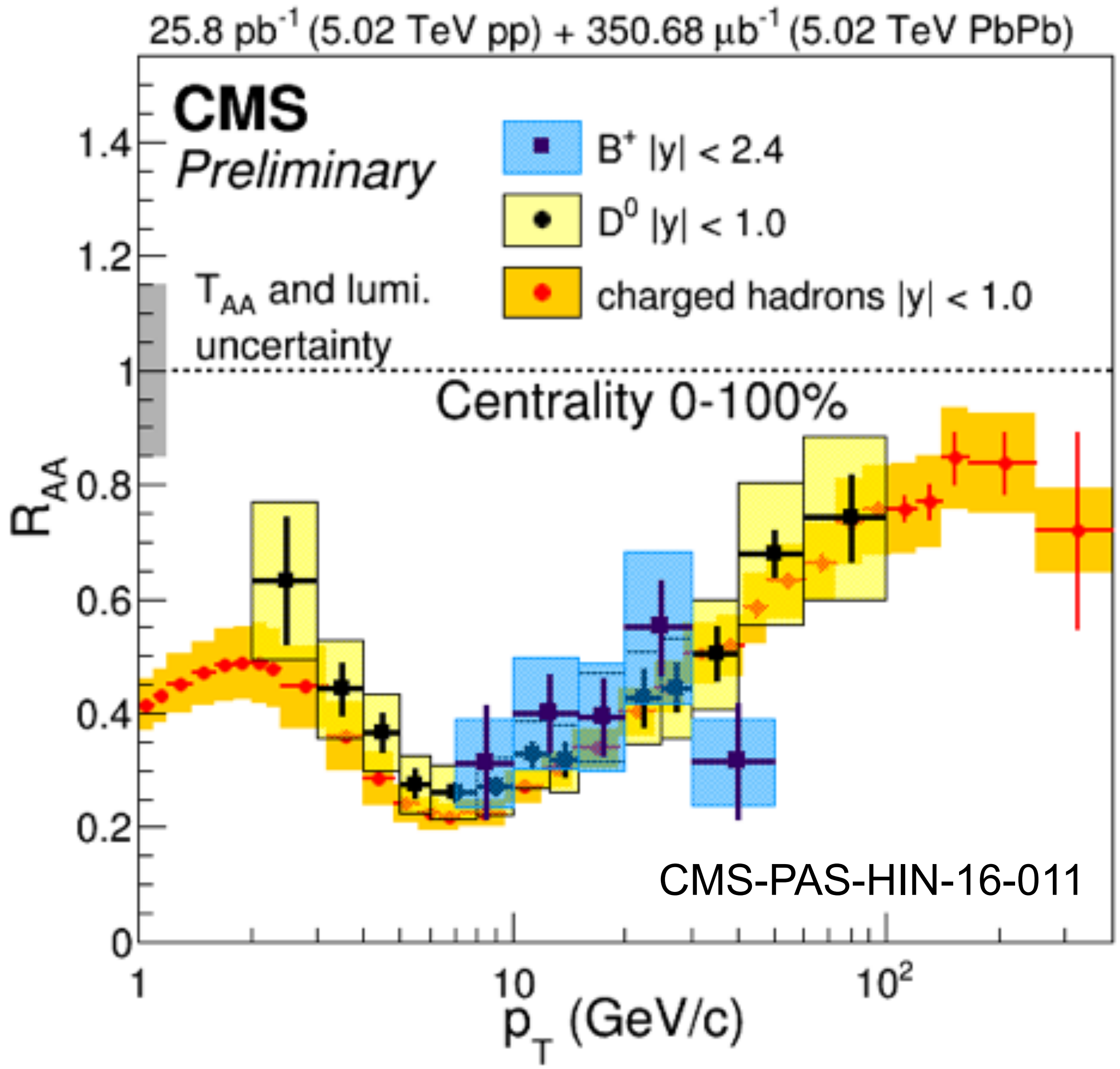
π^{+-}

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

M. Ho's talk, Sunday

Flavour dependence of E_{loss} at 5.02 TeV

R_{AA} of B, D and charged particle fully compatible within uncertainties in the available p_T range (**REMEMBER**: p_T^B >7 GeV/c)



B meson

D meson

charged particle

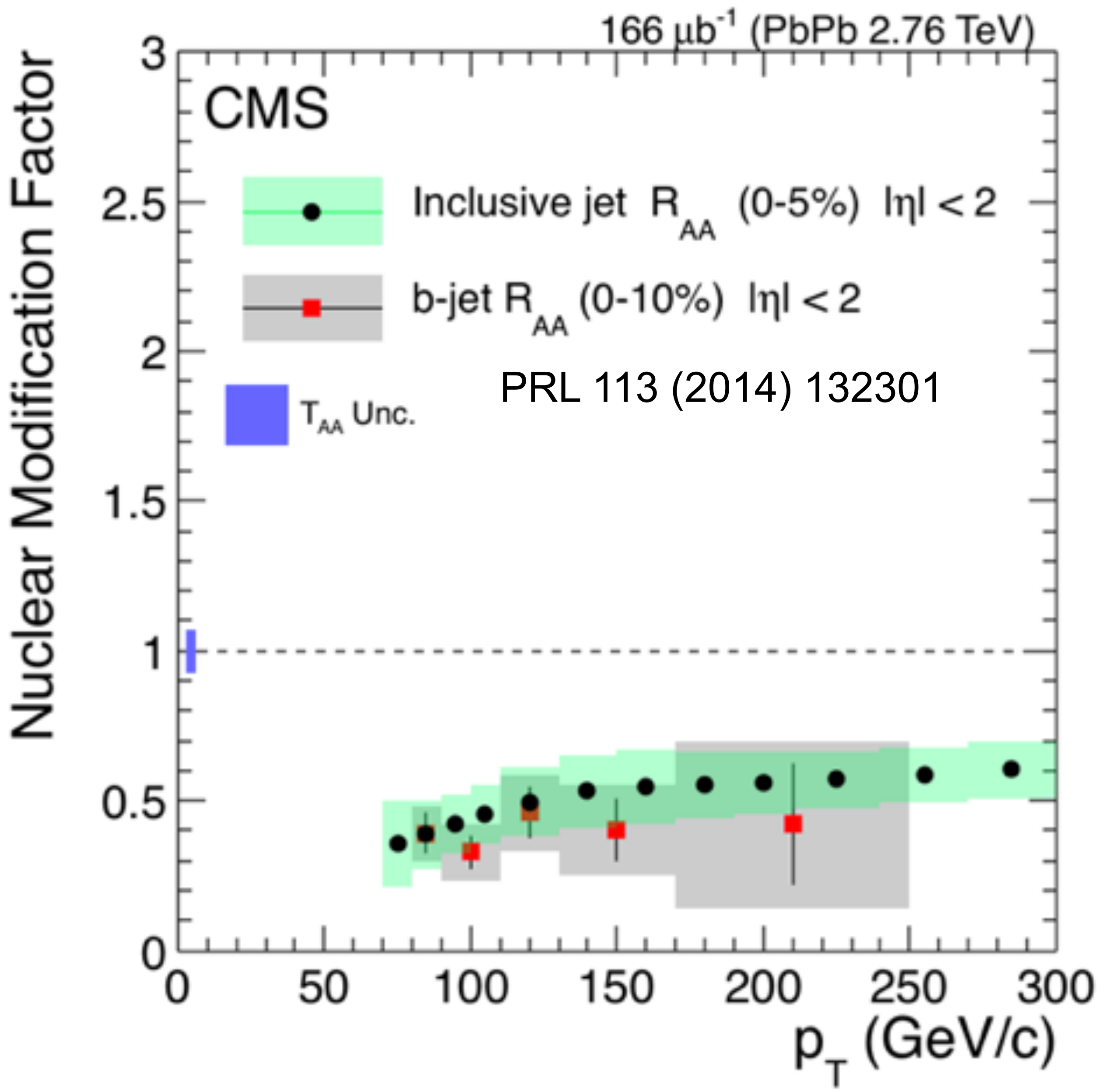
Does it mean that there is no flavour dependence?

Not necessarily!

T.W. Wang's talk, Saturday

Flavour dependence at higher p_T

C.C. Peng's talk, Saturday



b-jet R_{AA}

inclusive jet R_{AA}

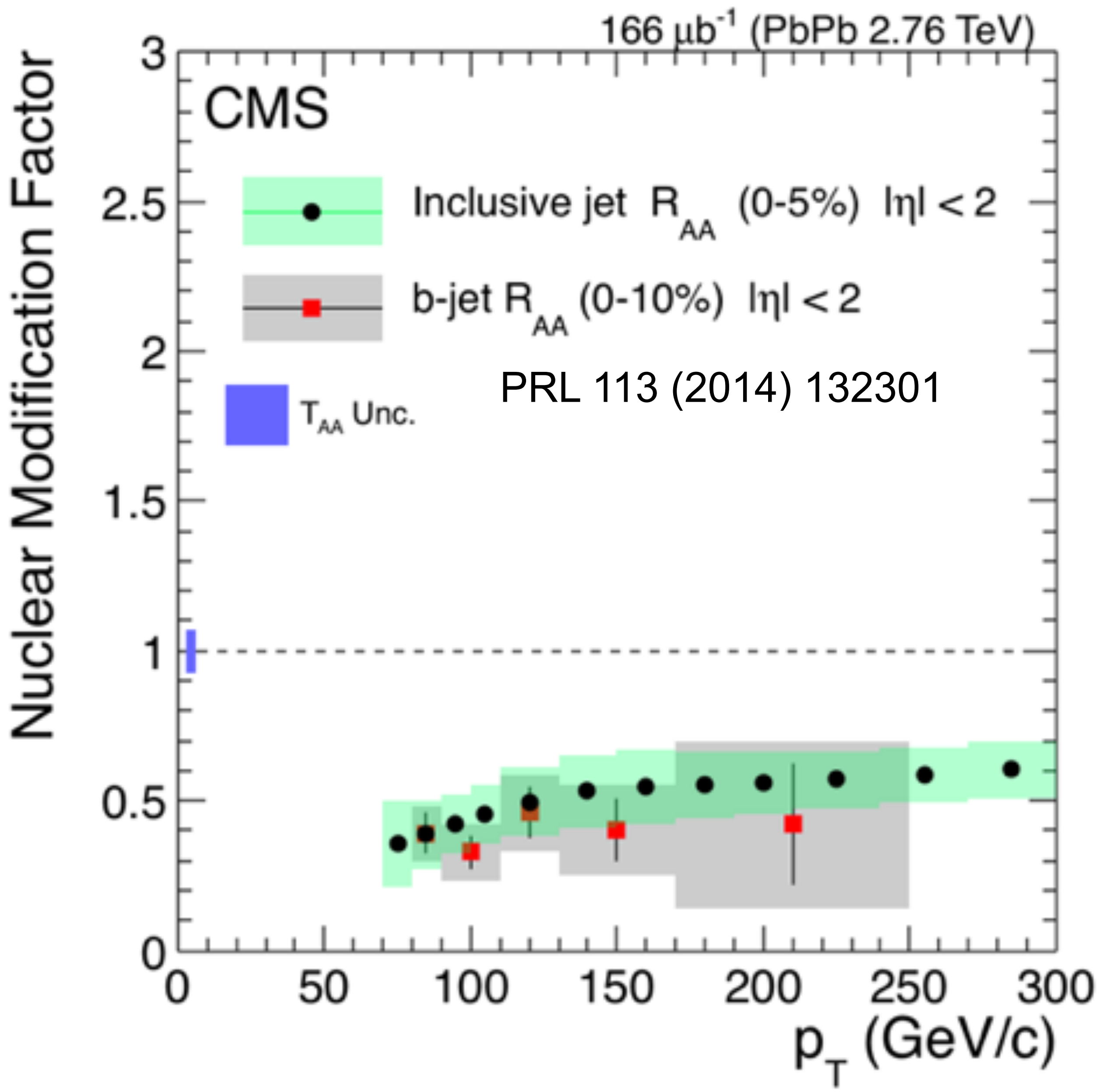
Same suppression for b-jets and inclusive jets at high p_T

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}*

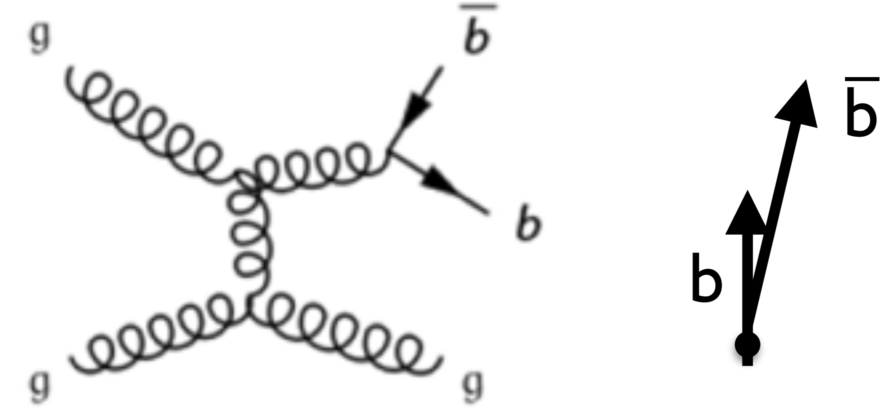
Flavour dependence at higher p_T

C.C. Peng's talk, Saturday



b-jet R_{AA}

inclusive jet R_{AA}



NLO process: Gluon splitting ~20%

→ dominant at low opening angles

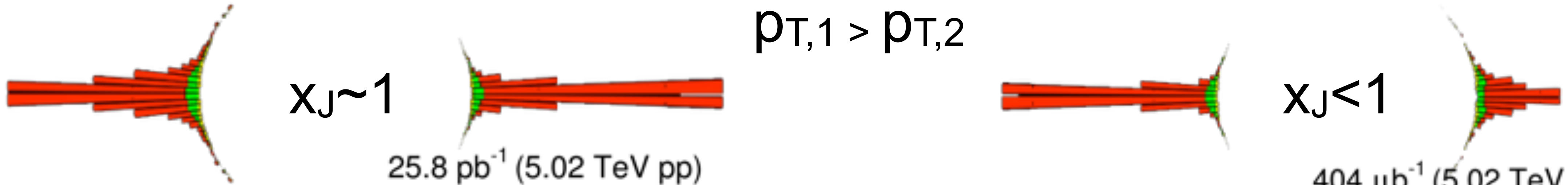
Same suppression for b-jets and inclusive jets at high p_T

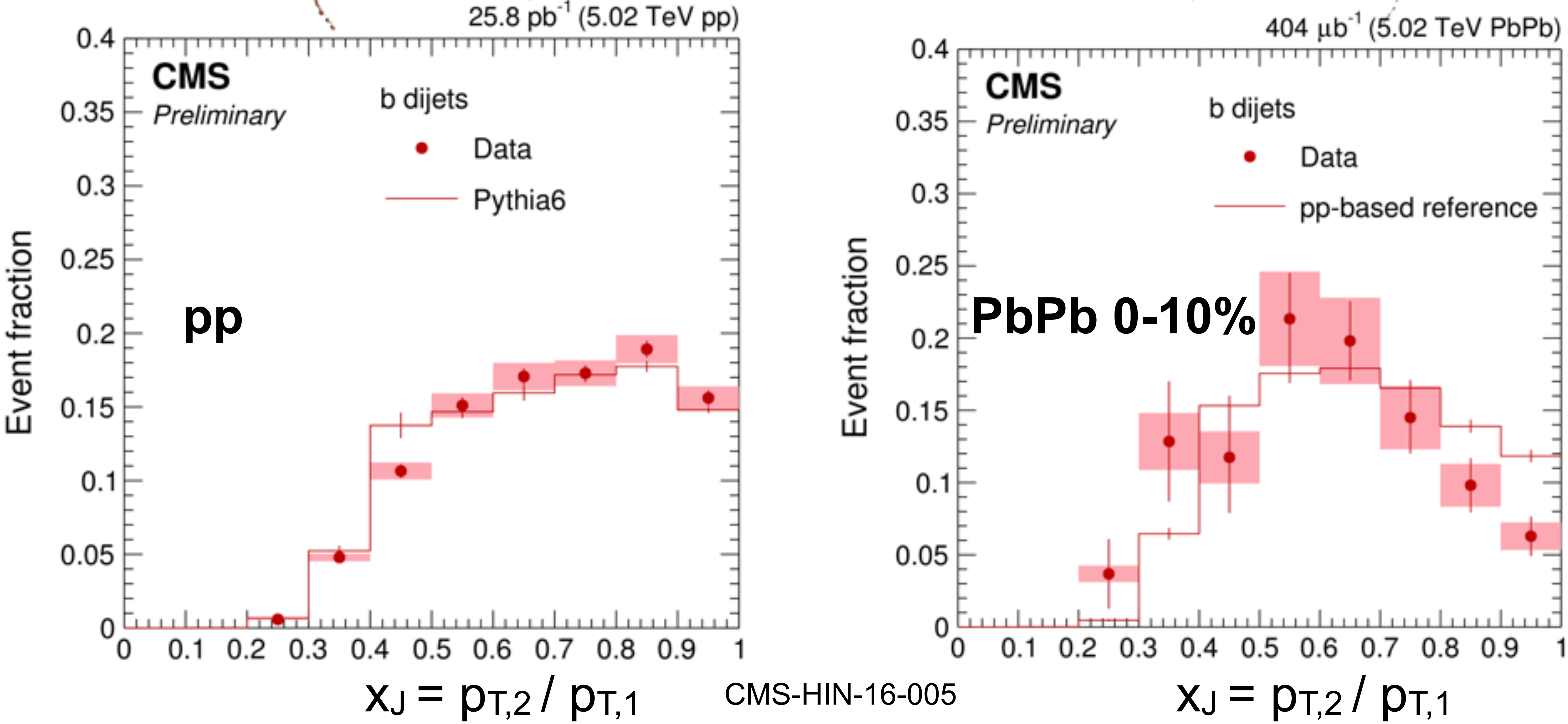
Mass difference negligible at high p_T

→***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

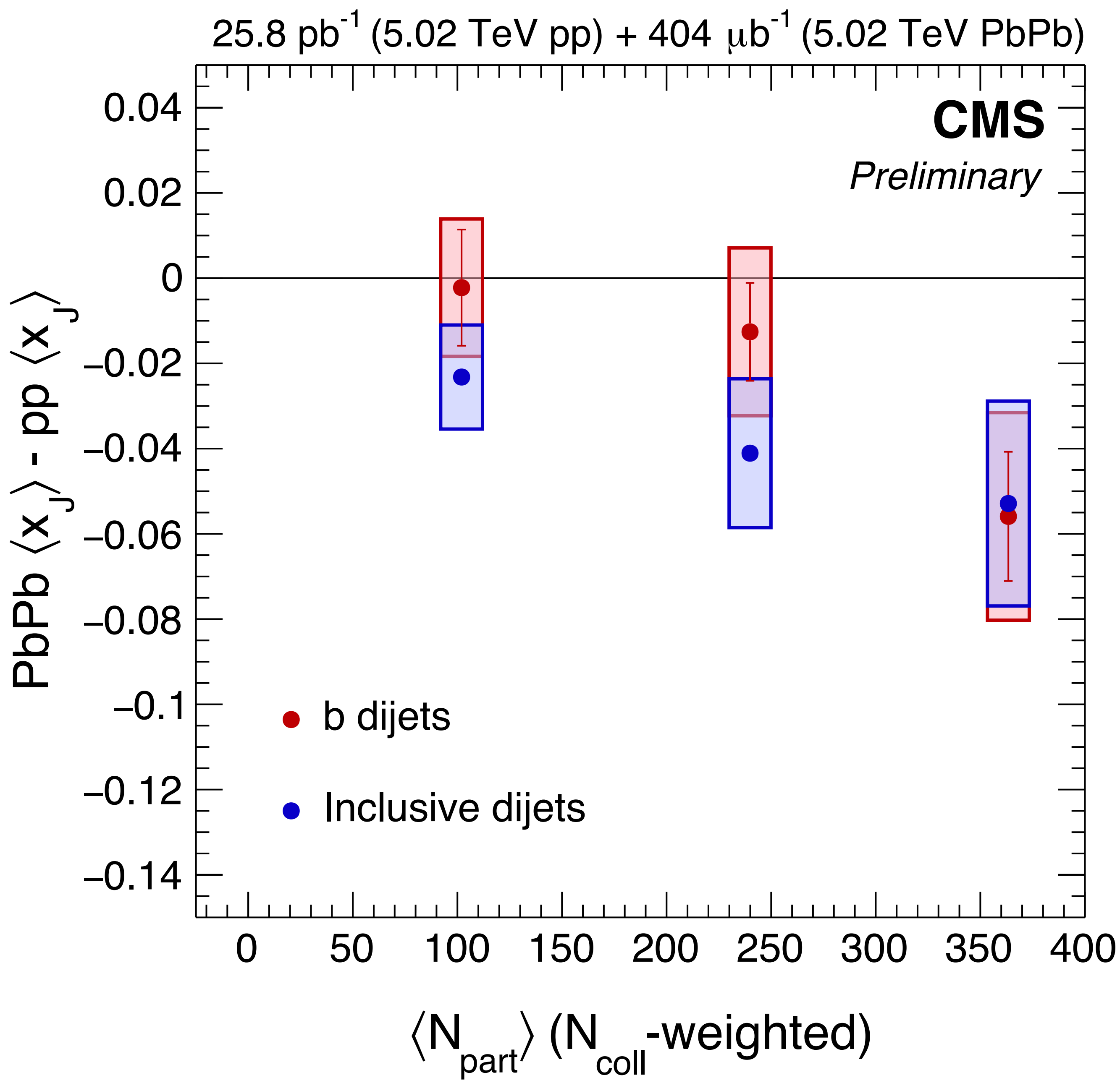




x_J distributions of di-b-jets significantly modified in central PbPb collisions!

C.C. Peng's talk, Saturday

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

C.C. Peng's talk, Saturday

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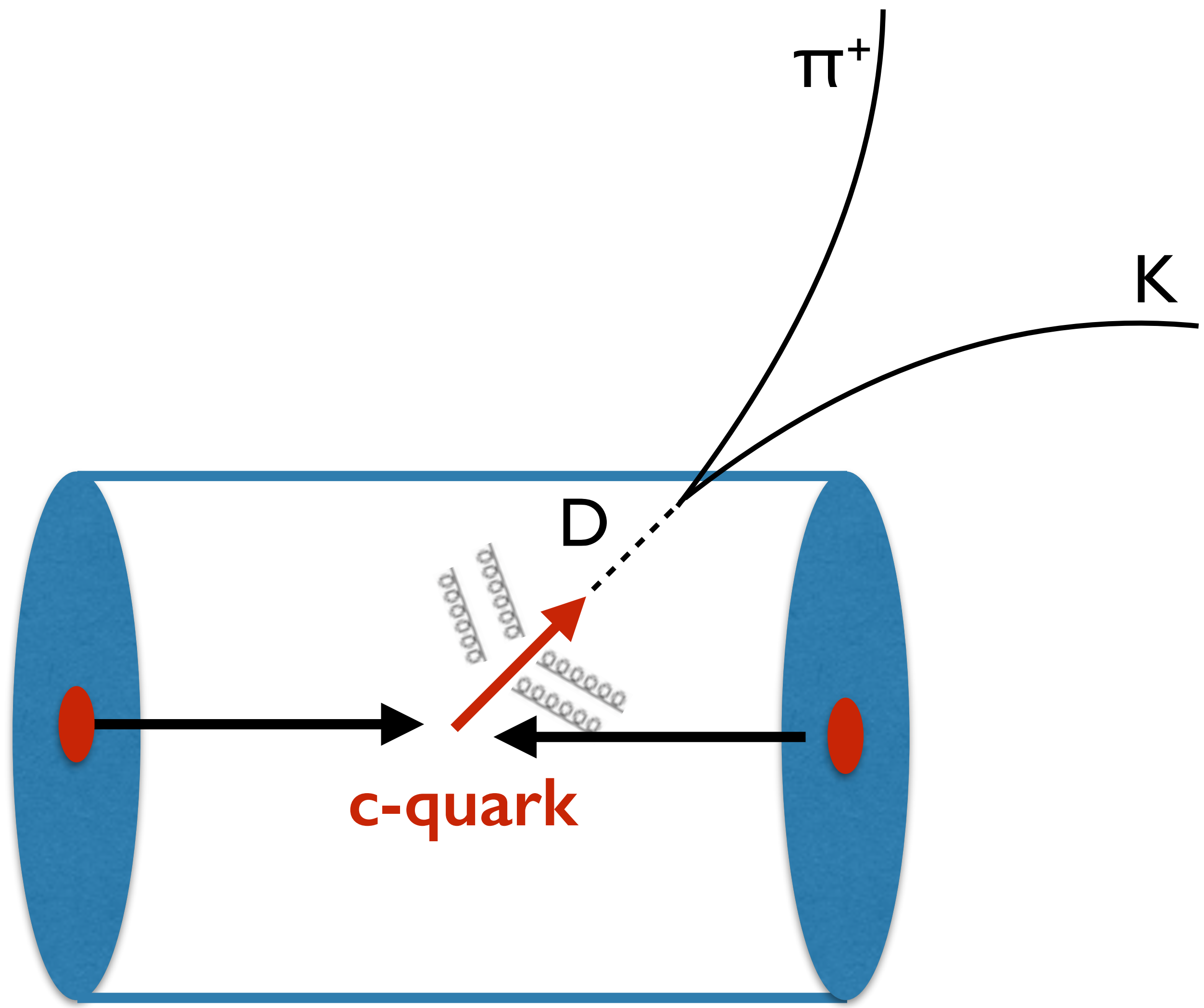
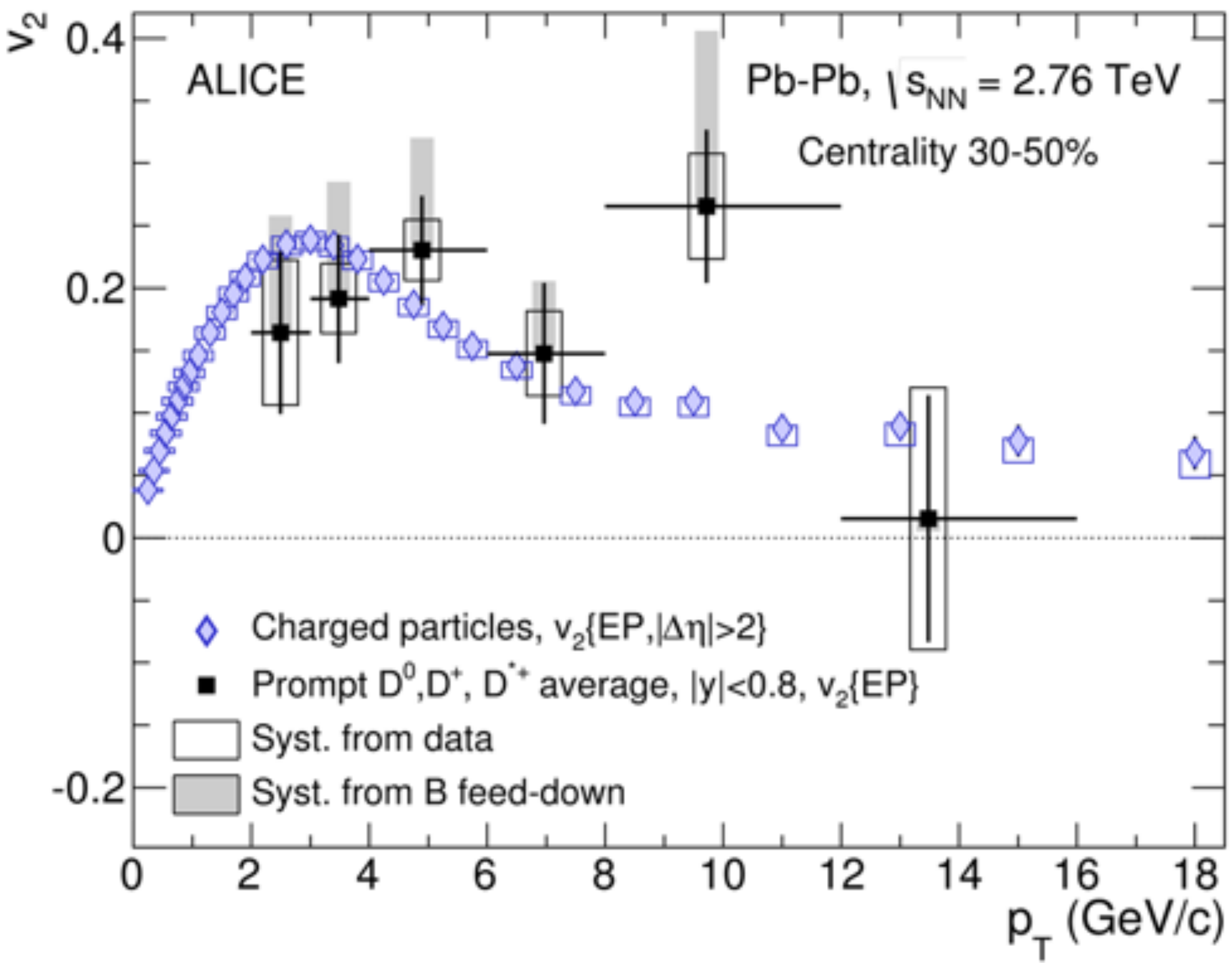


Do charm/beauty flow?

Does charm flow?

ALICE v_2 measurement in 30-50% at 2.76 TeV



PRL 111 (2013) 102301

→ D^0 meson $v_2>0$

→ compatible with v_2 of charged particles

BUT non zero v_2 doesn't necessarily imply that charm flows!

A ~small v_2 can be generated in the recombination of "static" charm with "flowing" light quarks!

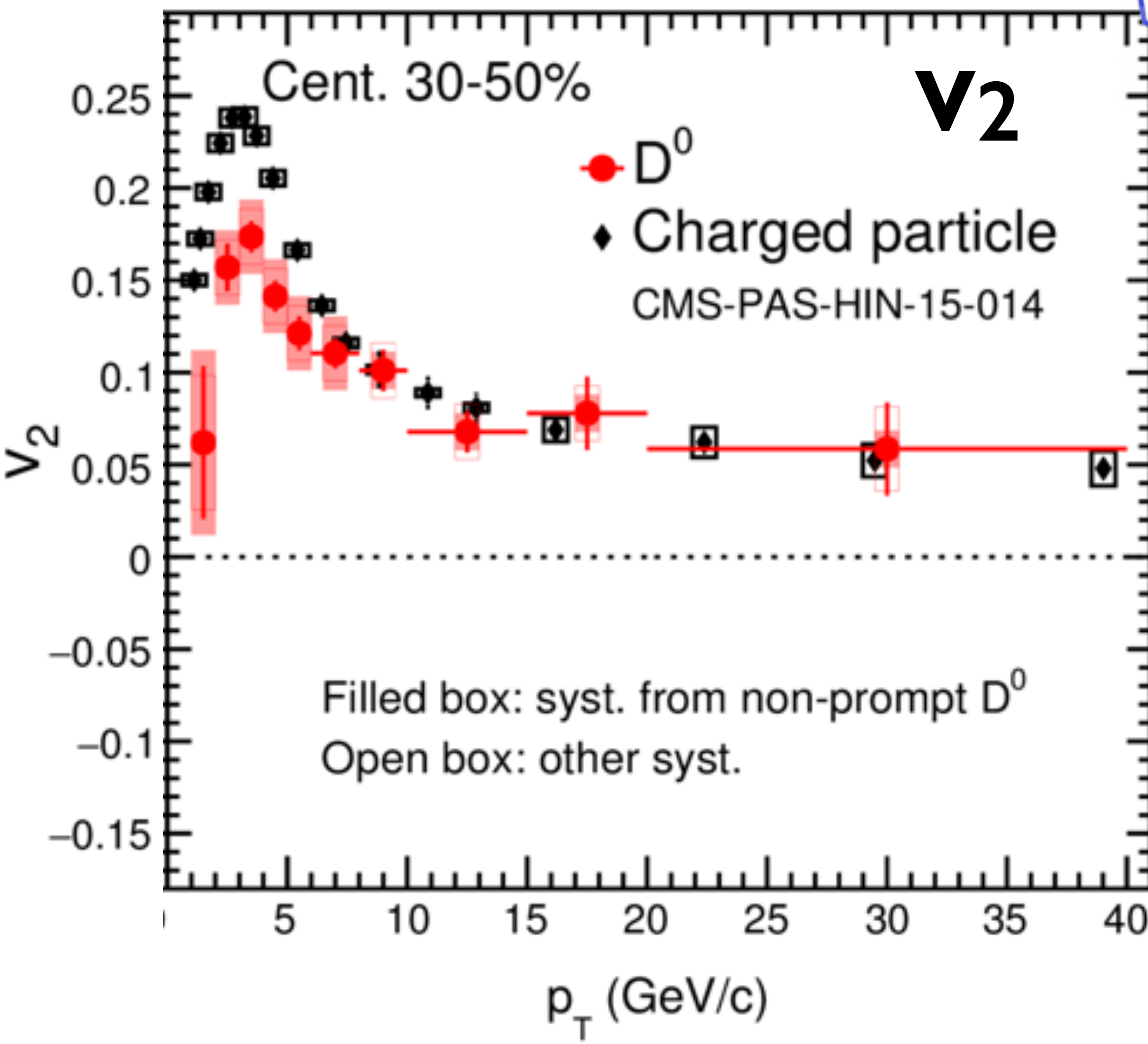
A.Dubla's talks, Saturday

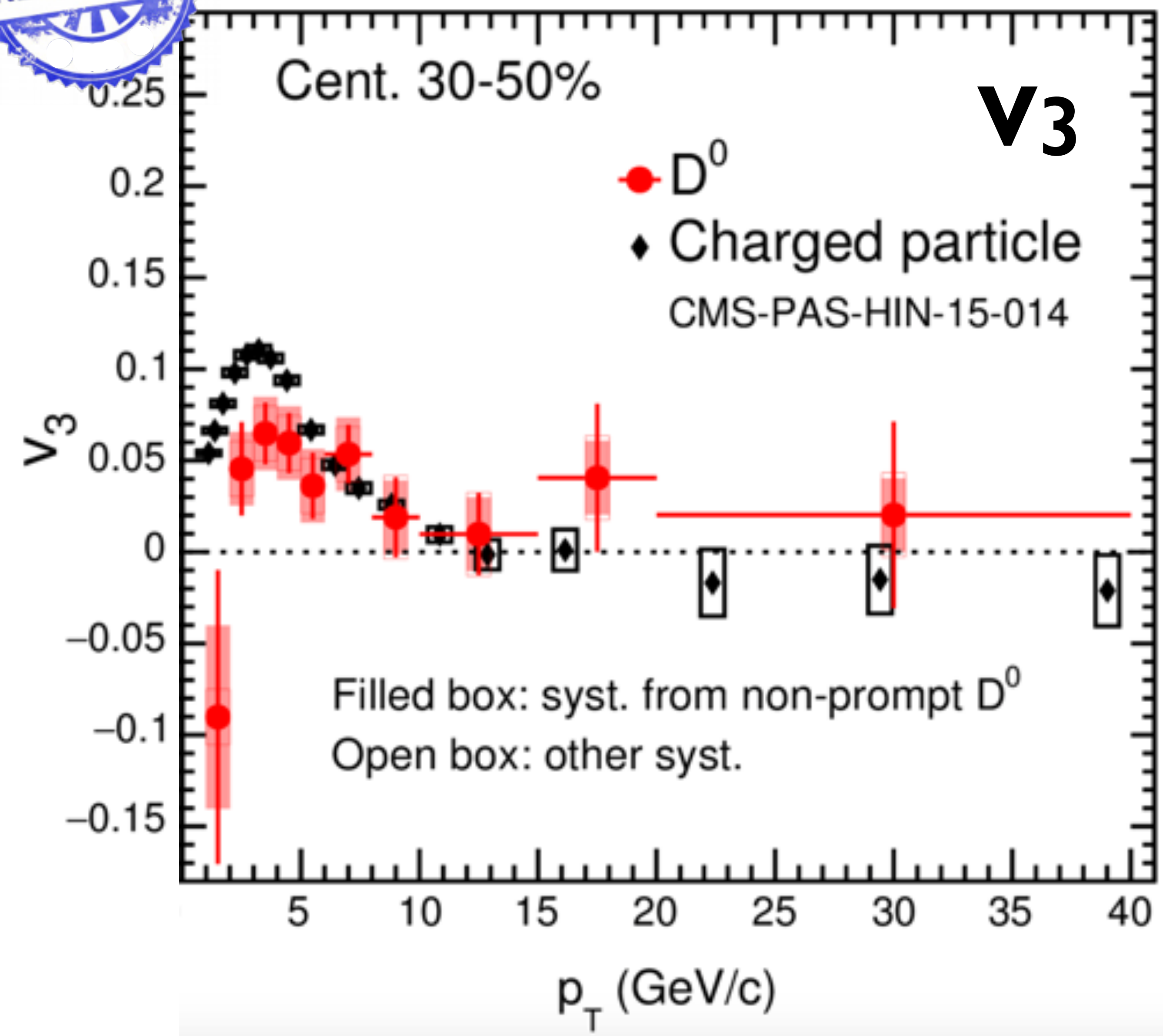
D meson v_n at 5.02 TeV in PbPb collisions

New CMS measurement of v_2 and v_3 in PbPb collisions at 5.02 TeV in different collision centralities

J.Sun's talks, Saturday

NEW RESULT





$v_2>0$ at high $p_T \rightarrow$ path length dependence!

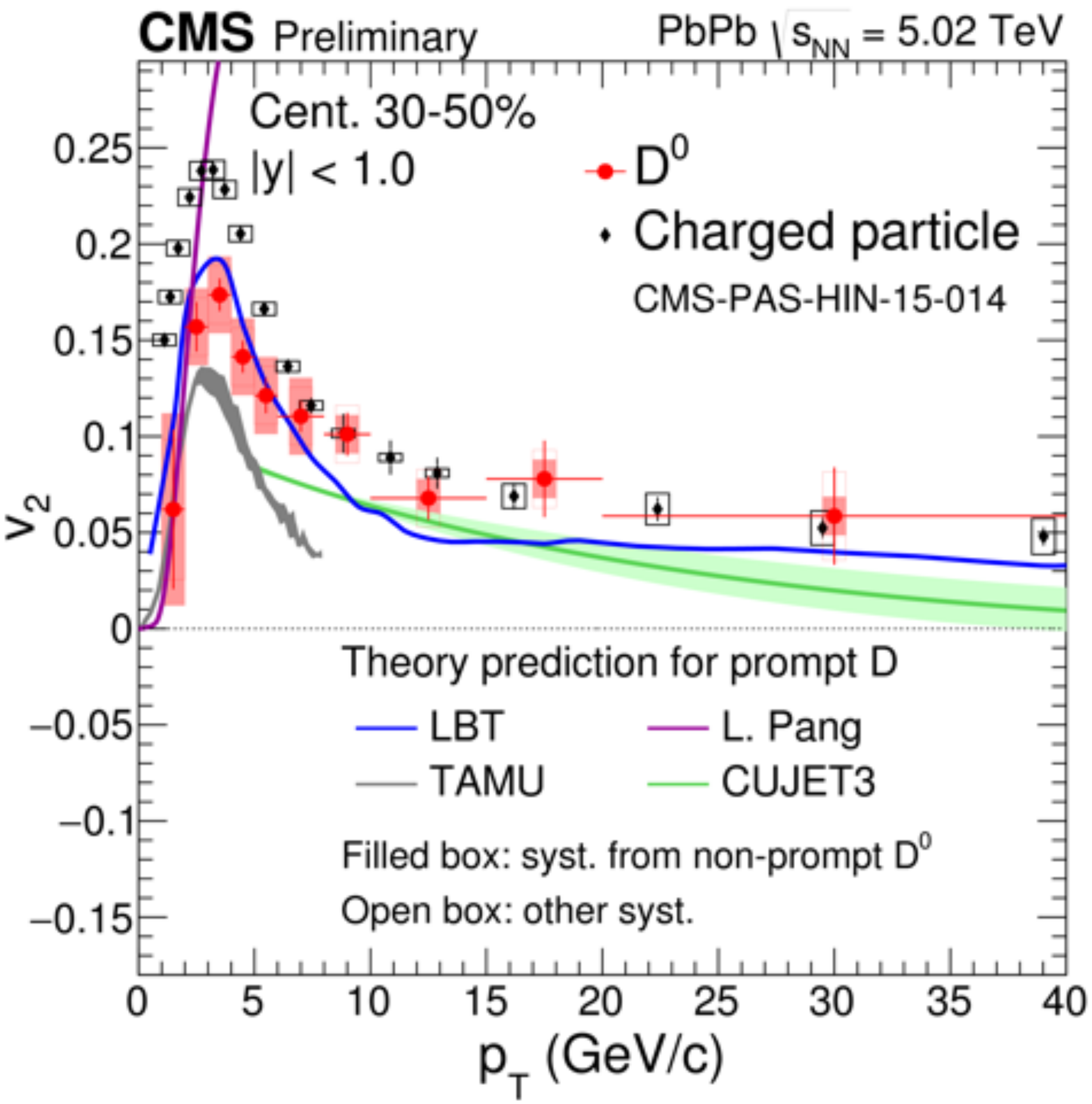
$v_2>0$ for D^0 at low p_T

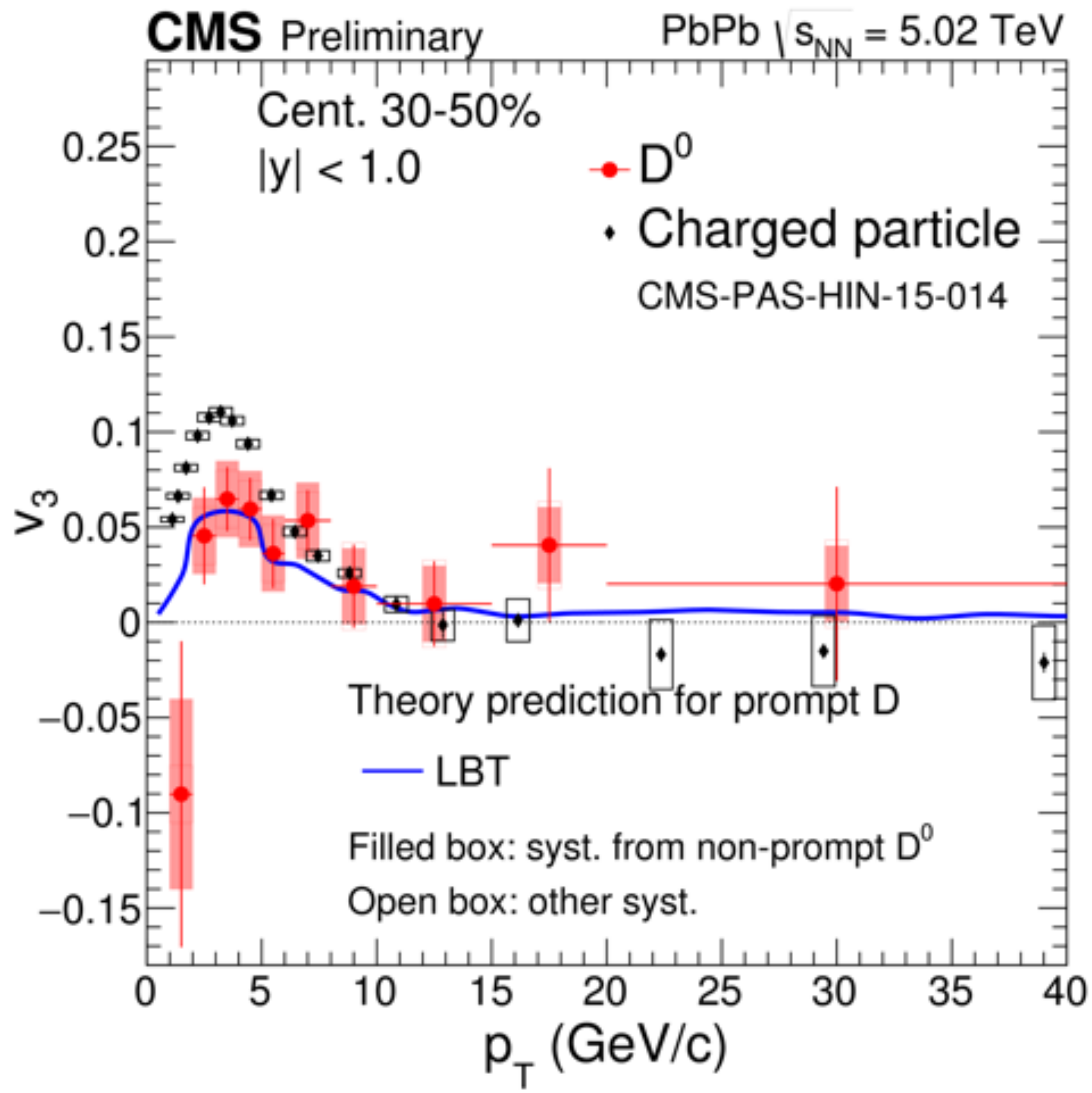
v_2 (D) > v_2 (charged particles)

First observation of $v_3>0$ for charm!

v_3 (D) > v_3 (charged particles) although with large uncertainties

Comparison with models



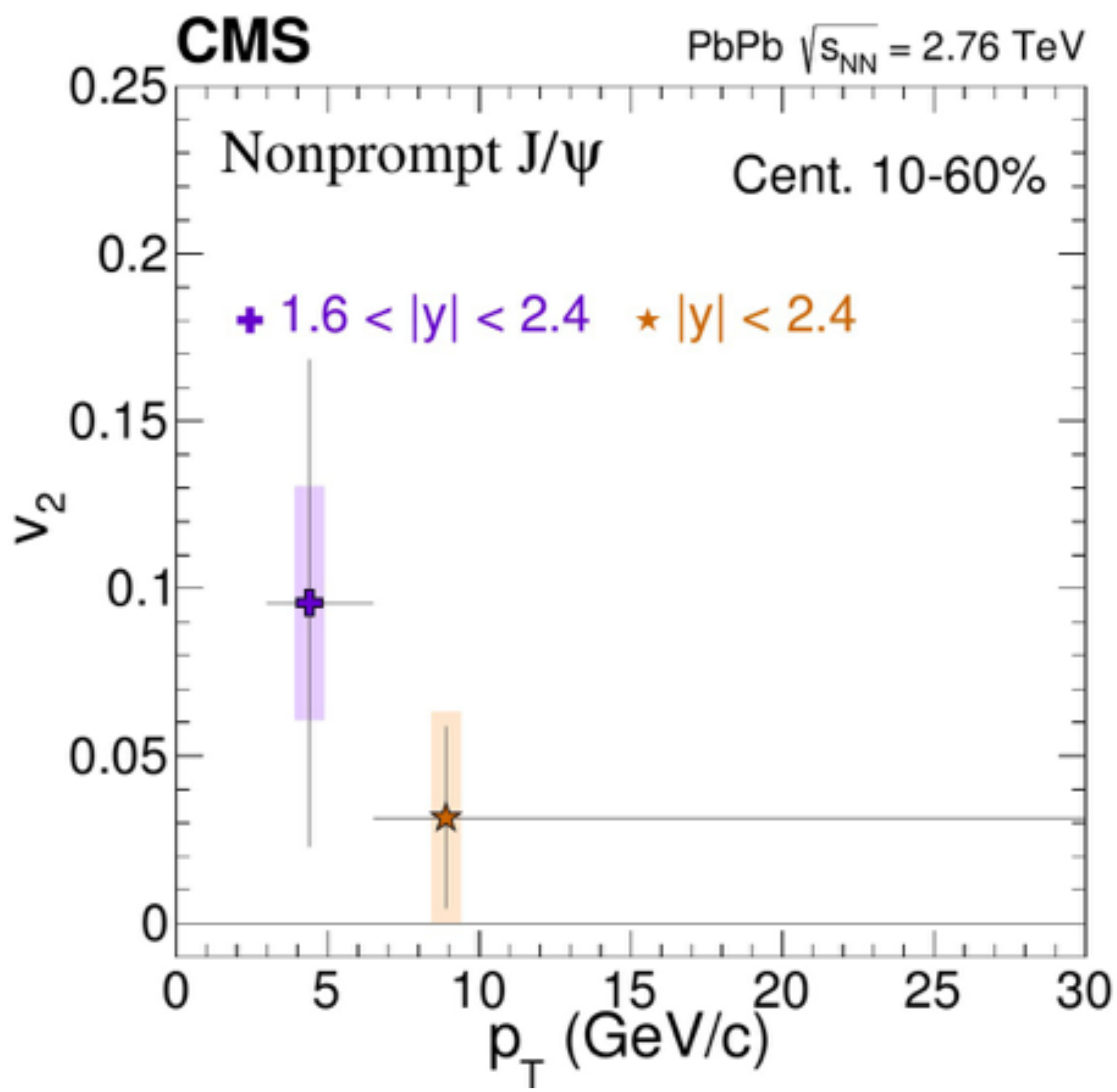


v_2 and v_3 are well described by models that include **charm quark diffusion** AND **charm recombination** in the medium.

J.Sun's talks, Saturday

v_2 of non prompt J/φ

New measurement of v_2 of non prompt J/φ in PbPb collisions at 2.76 TeV

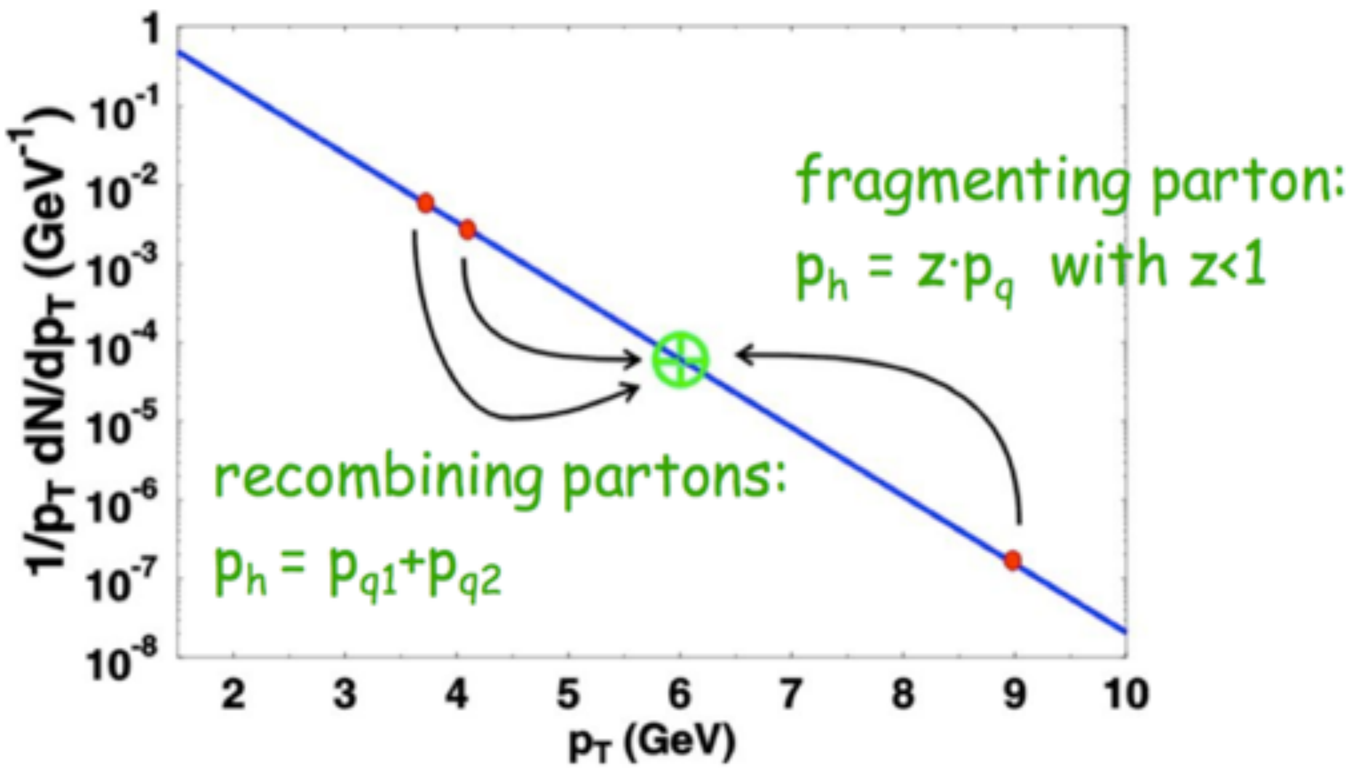


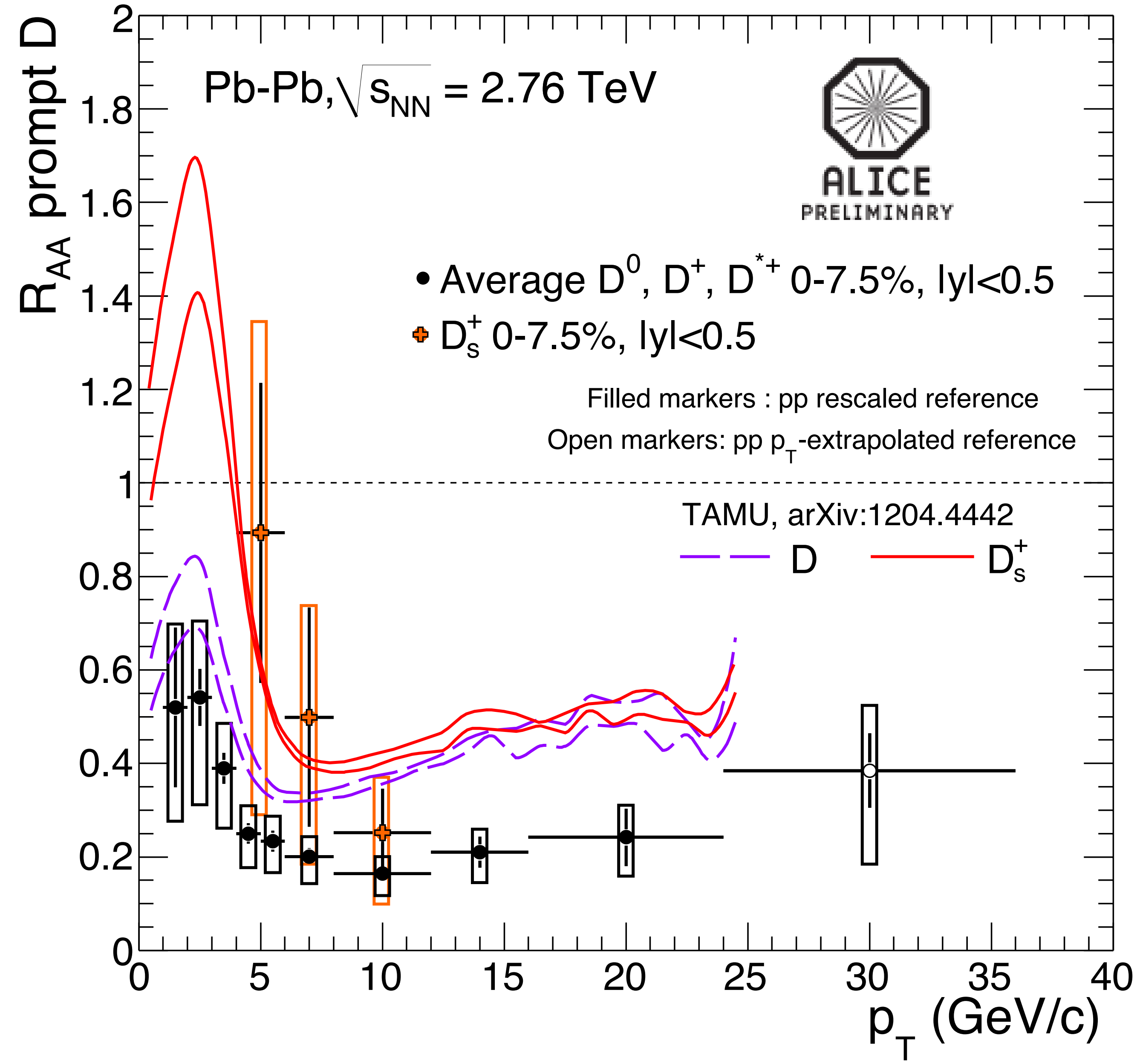
→Central value of v_2 of non prompt J/φ but still compatible in 2σ with 0
Looking to see the new measurement with Run2 data with higher statistics!

J.Sun's talks, Saturday

D_s as a probe for charm recombination

R_{AA} of D_s > R_{AA} D^0 if coalescence is a relevant production mechanisms for charm as a consequence of the strangeness enhancement in PbPb collisions





Central values of D_s R_{AA}> D^0 R_{AA}

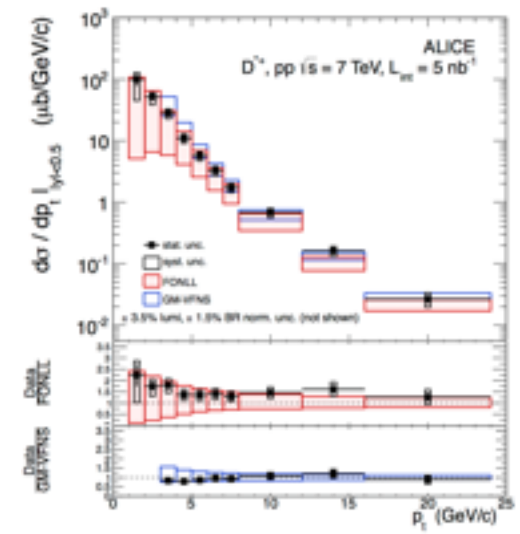
not yet significant given current uncertainties

→ ***Waiting to see new D_s results with higher statistics from Run2 data!***

Conclusions (I)

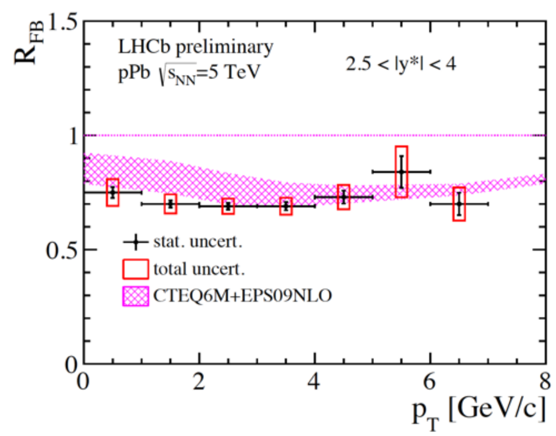
Do we understand the production mechanism?

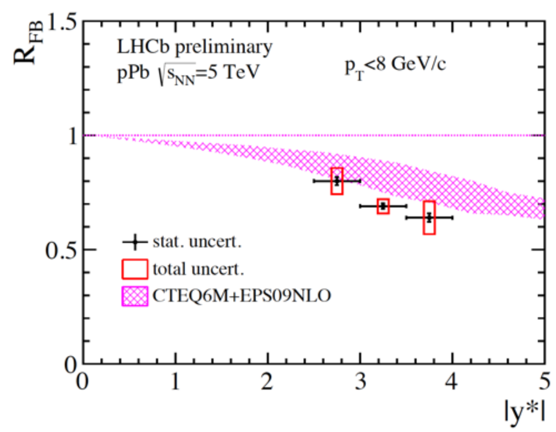
- charm and beauty production are well described by pQCD calculations at both energies 2.76 and 5.02 TeV



Is the initial state modified?

- the HF production cross sections are consistent with the prediction of CNM models at LHC energies.
- measurements still not precise enough to discriminate the various CNM results (very promising results from LHCb thus..)
- Still in apparent contraction with RHIC results in which CNM based models do not describe forward/backward results (????)





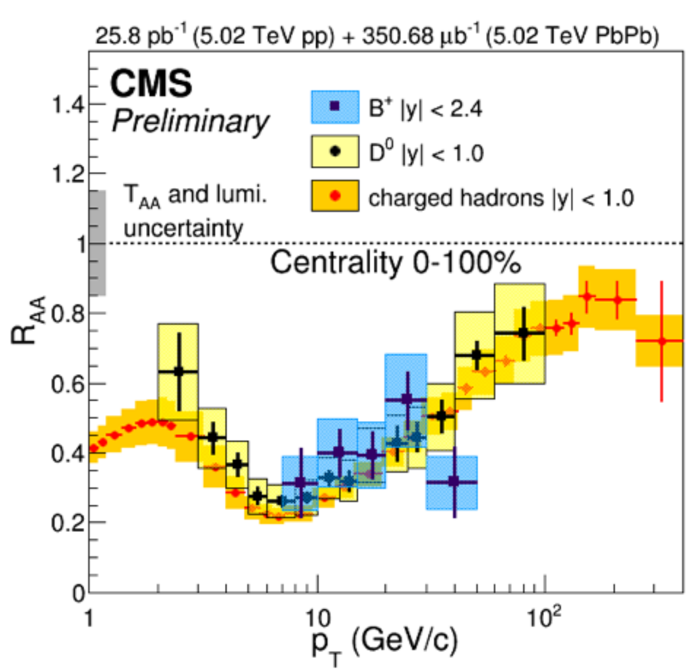
Conclusions (II)

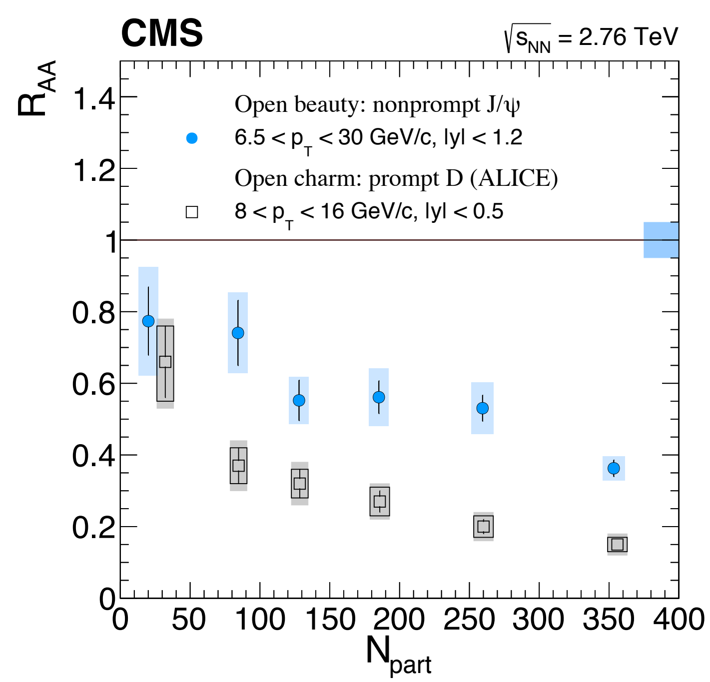
<u>How do HF lose energies?</u>

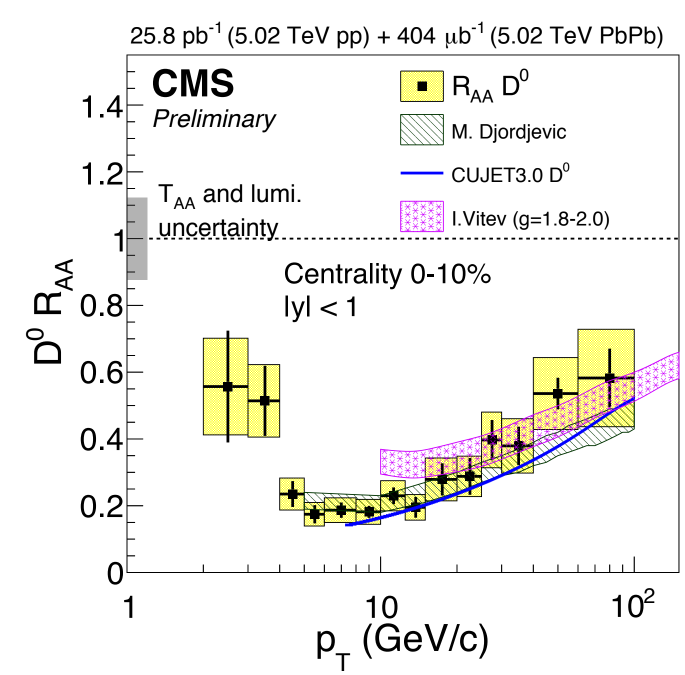
- charm and beauty strongly interact with the medium and lose energy
- At low p_T indications of R_{AA} (B)>R_{AA} (D)
- At high p_T (>7-10 GeV) R_{AA} (light)~R_{AA} (D)~R_{AA} (B)

→ A conclusive statement is not not possible but:

- sizeable radiative energy loss for charm and beauty
- non negligible contribution of collisional processes at low p_T
- hints of flavour dependence at low p_T (caveats as usual…)
- indications of mild/no flavour dependence at higher p_T







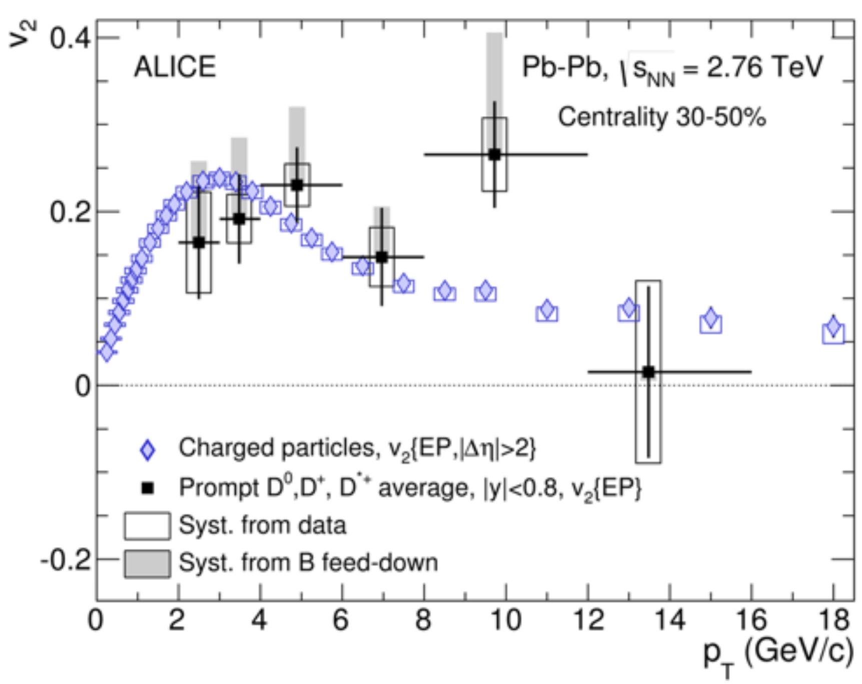
Conclusions (III)

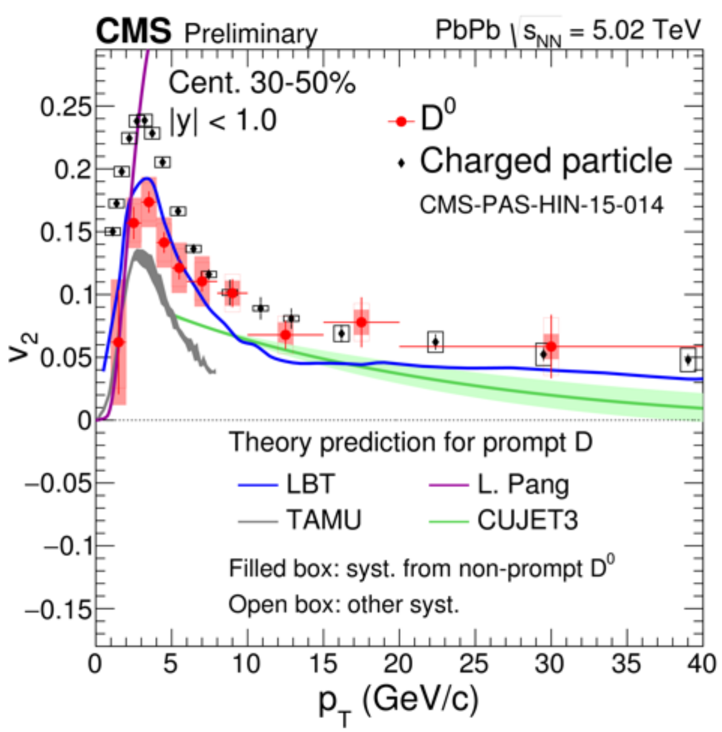
Do heavy quarks participate in the collective expansion of the medium?

- v_2 and v_3 significantly > 0 for D^0
- v_2 and v_3 of D^0 are slightly smaller than the values for the inclusive particles

→ Comparison with theoretical calculations:

- favour models that include both charm **diffusion** and charm **recombination** in the medium
- suggests that **charm participates in the collective motion of the fireball**





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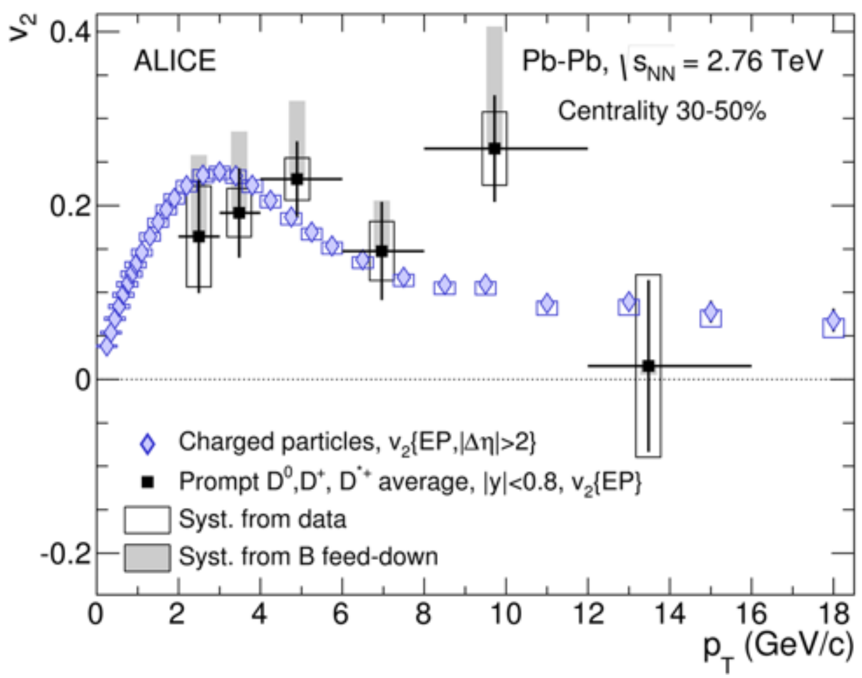
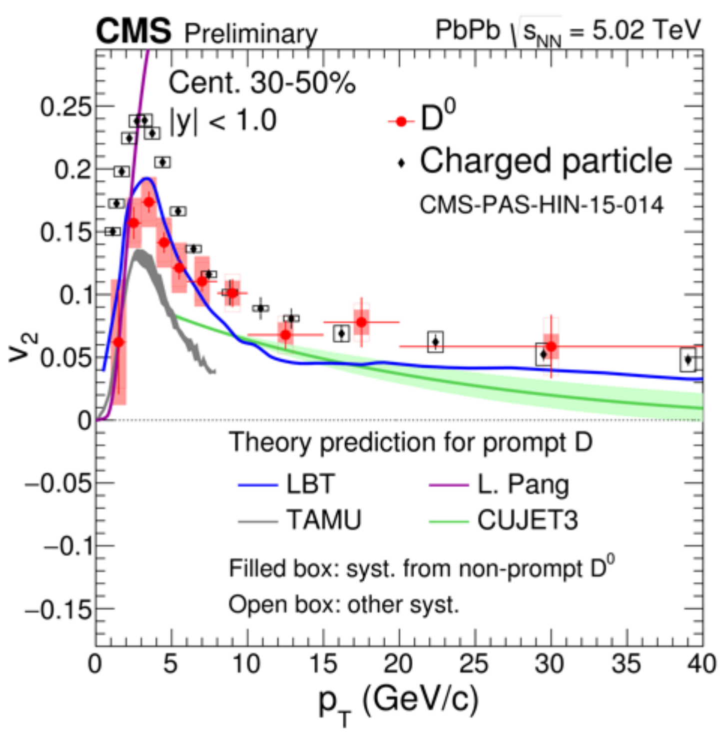
- suggests that **charm participates in the collective motion of the fireball**

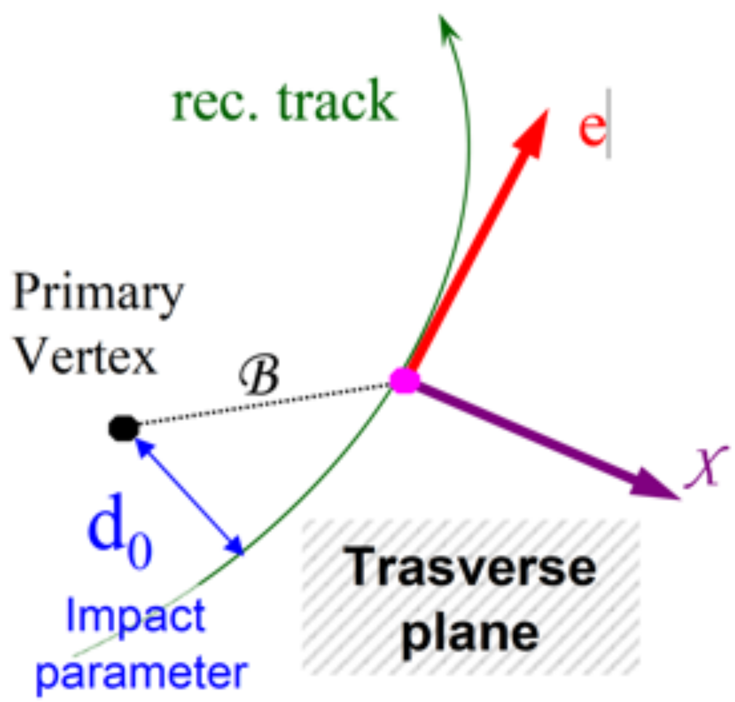


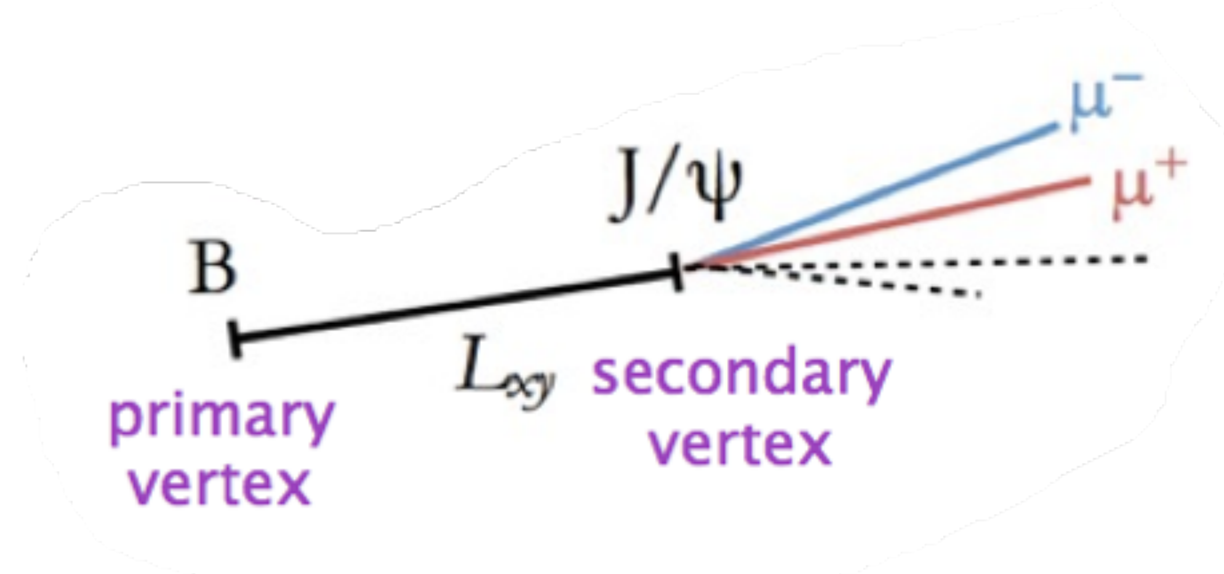


Thank you for your attention!

BACKUP

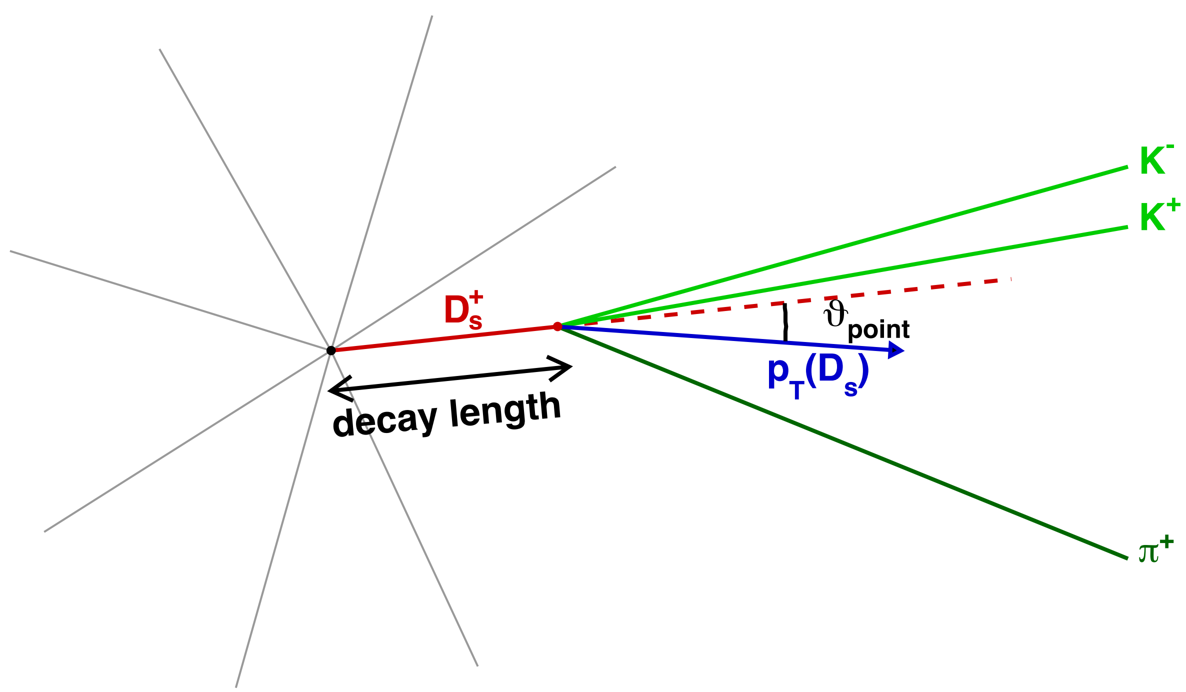
Our experimental tools





Displayed J/ψ from B decays

Semi-leptonic electrons and muons from c and b quarks



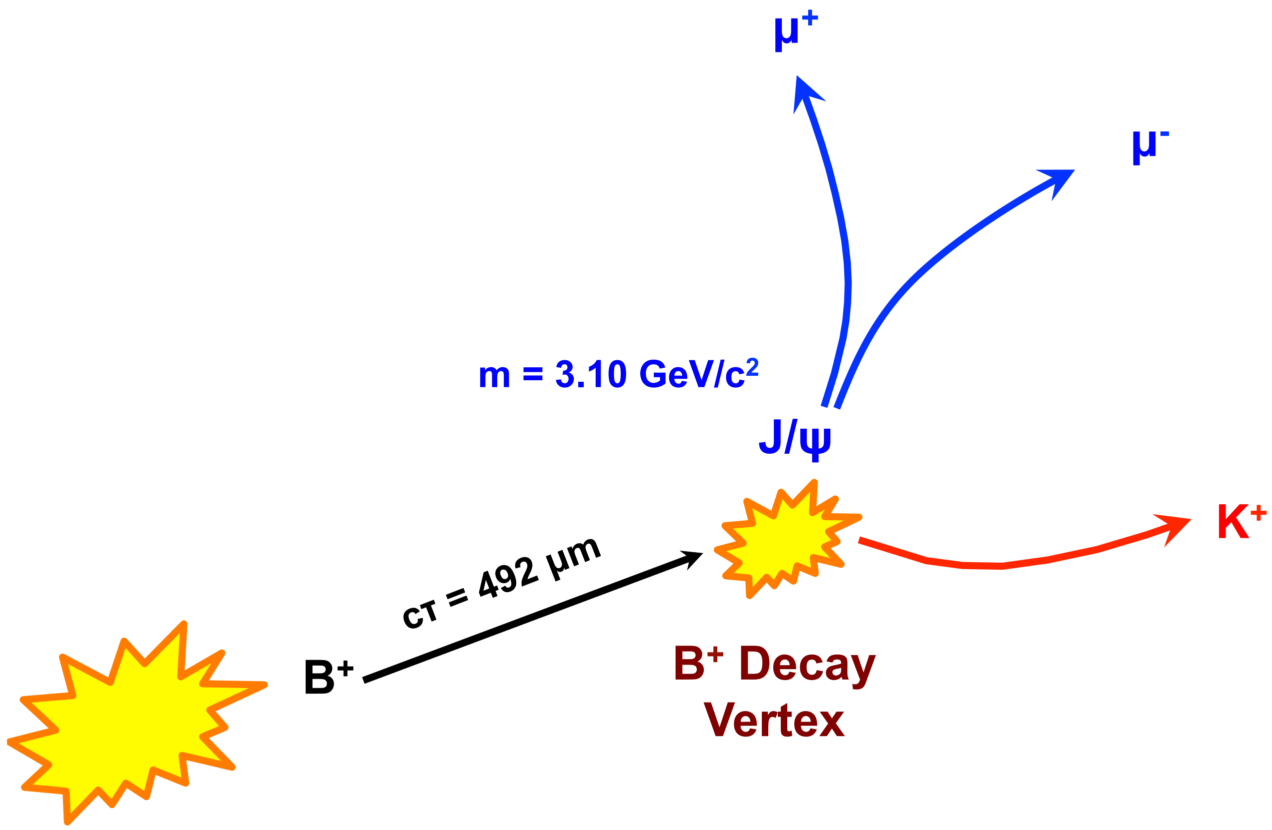
Fully reconstructed D meson decays:

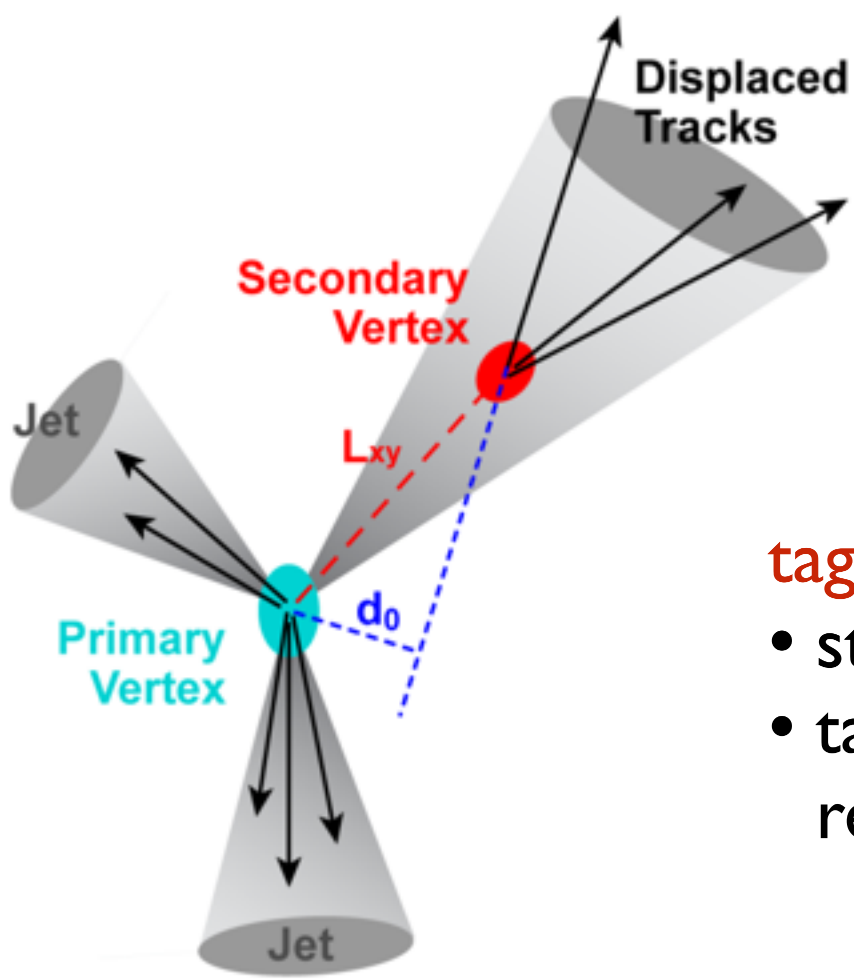
- $D^0 \rightarrow K^- + \pi^+$
- $D^+ \rightarrow K^- + \pi^+ + \pi^+$
- $D^{*+} \rightarrow D^0 + \pi^+$
- $D^+_s \rightarrow \phi + \pi^+$

Our experimental tools

Fully reconstructed B meson decays:

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

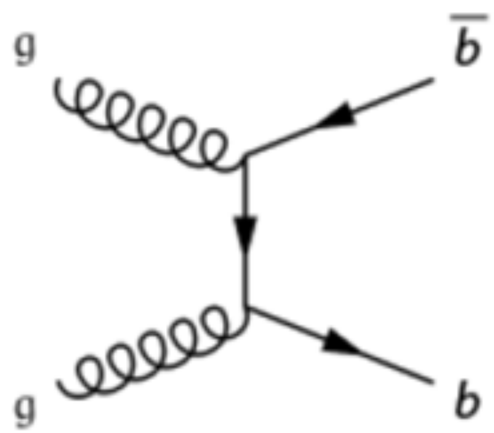




tagged c- and b-jets

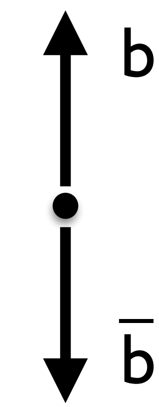
- standard jet reconstruction
- tagging based on the displacement with respect to the primary vertex

heavy quark production mechanism



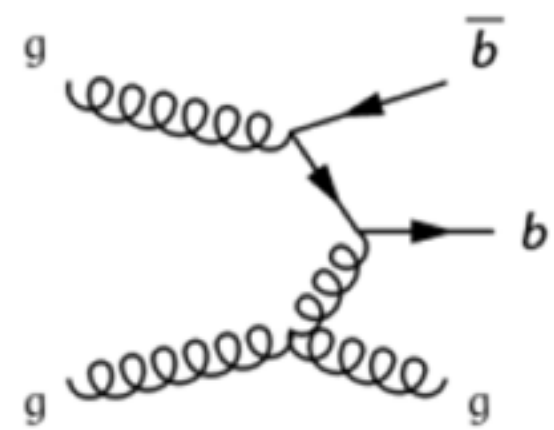
LO process: Flavour Creation (FCR)

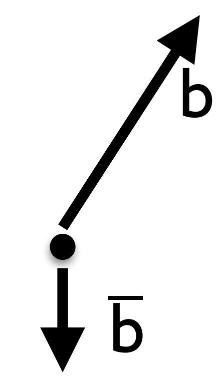
→ $b\bar{b}$ produced back-to-back in azimuthal plane and symmetric in p_T

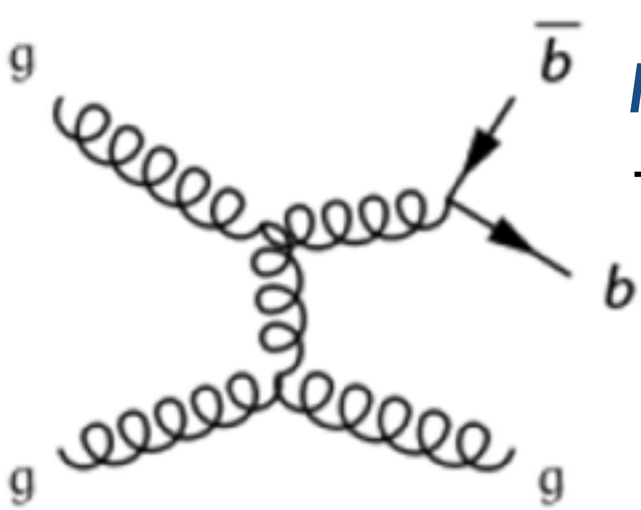


NLO process: Flavour Excitation (FEX)

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



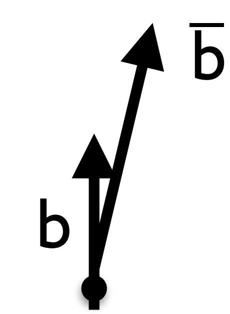




NLO process: Gluon splitting (GSP)

→ produced with small opening angles and asymmetric in p_T

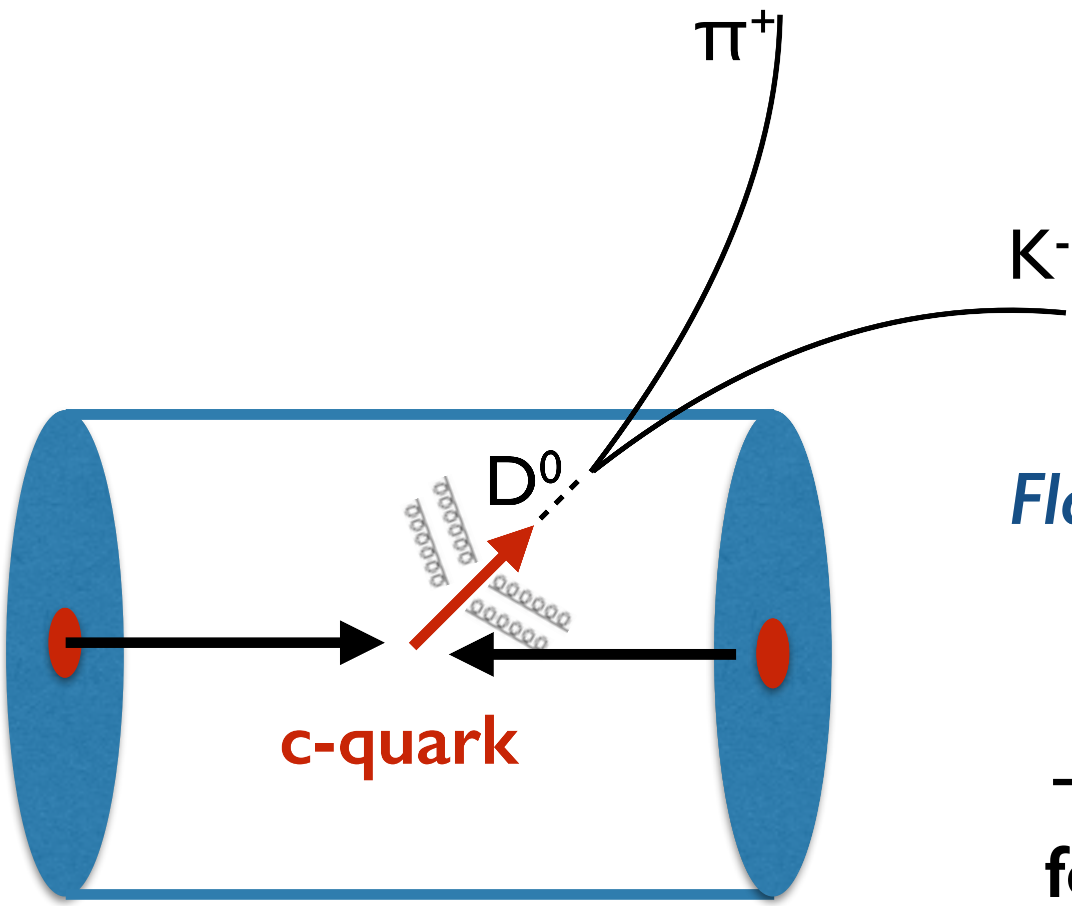
→ $b\bar{b}$ are not involved in the hard scattering but produced later

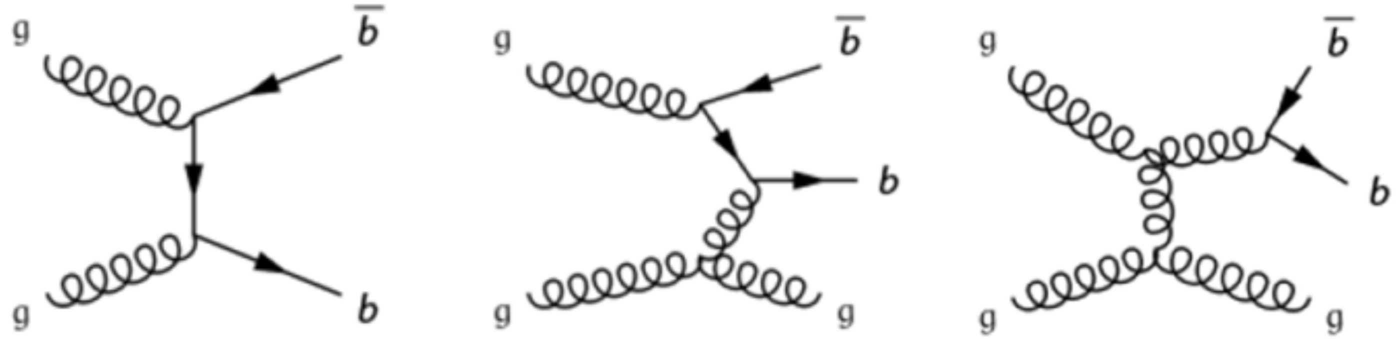


HQ production mechanisms

Do we understand the production mechanism?

- high Q^2 processes + large mass:
  → calculated in pQCD down to low p_T
- Very short formation time ~0.1 fm/c
  → much smaller than QGP formation time
  → production is not affected by the medium



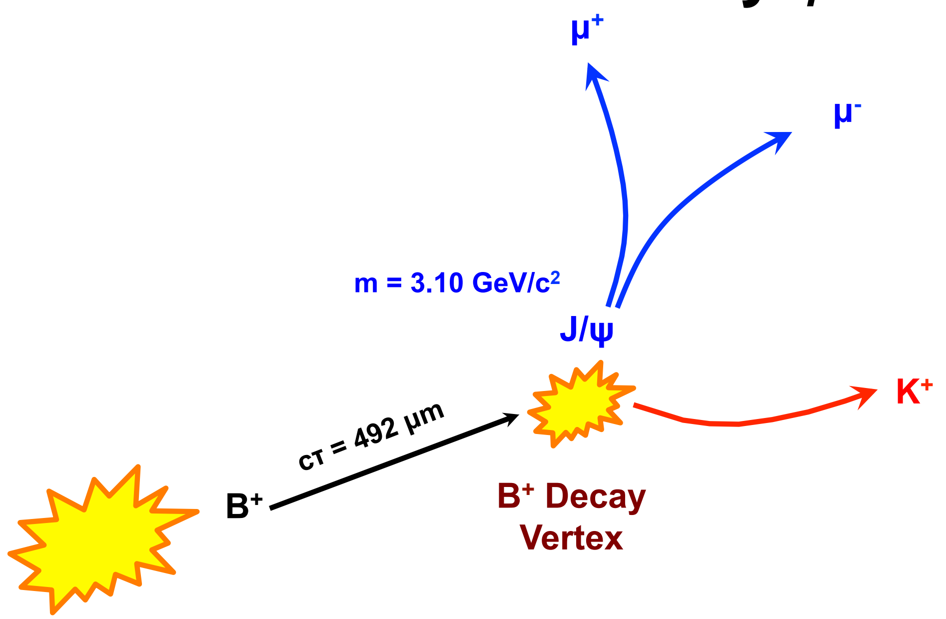


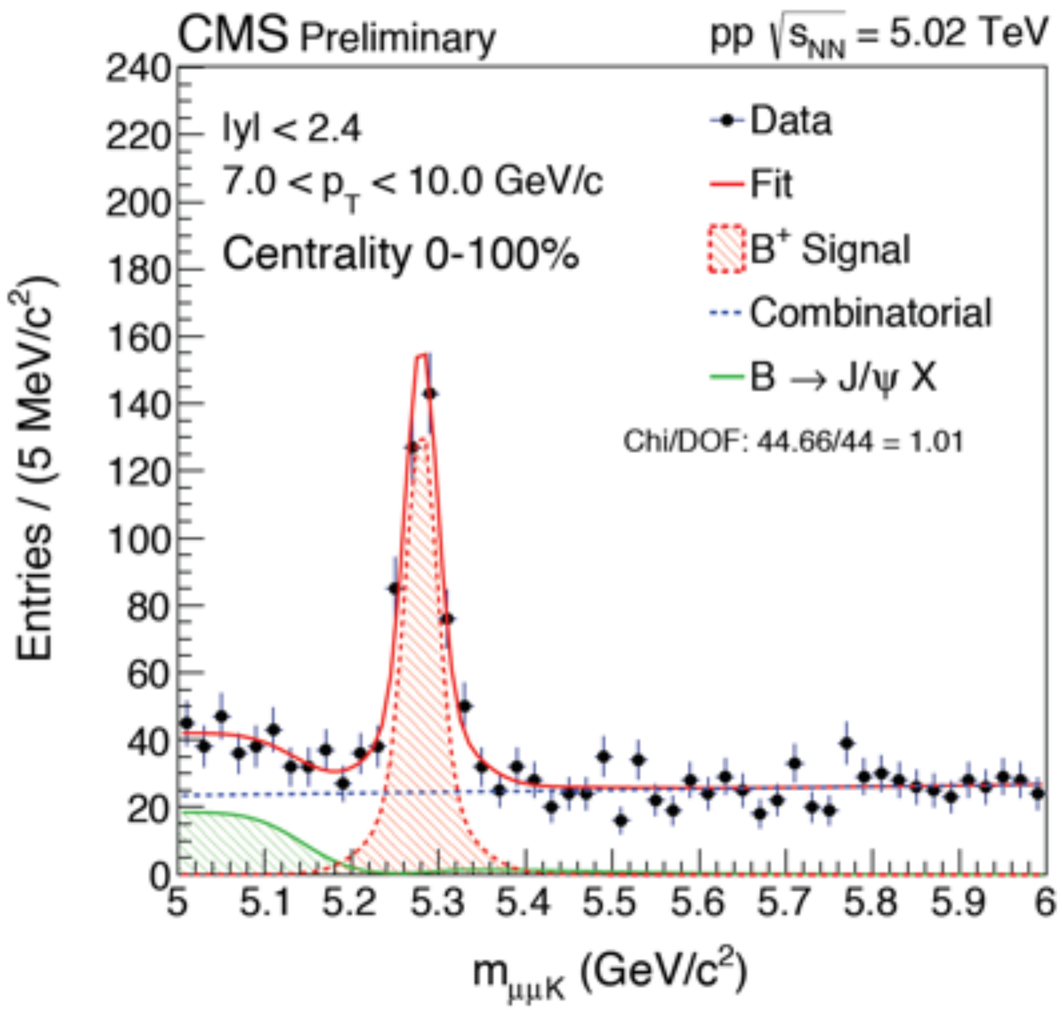
Flavour Creation *Flavour Excitation* *Gluon splitting*

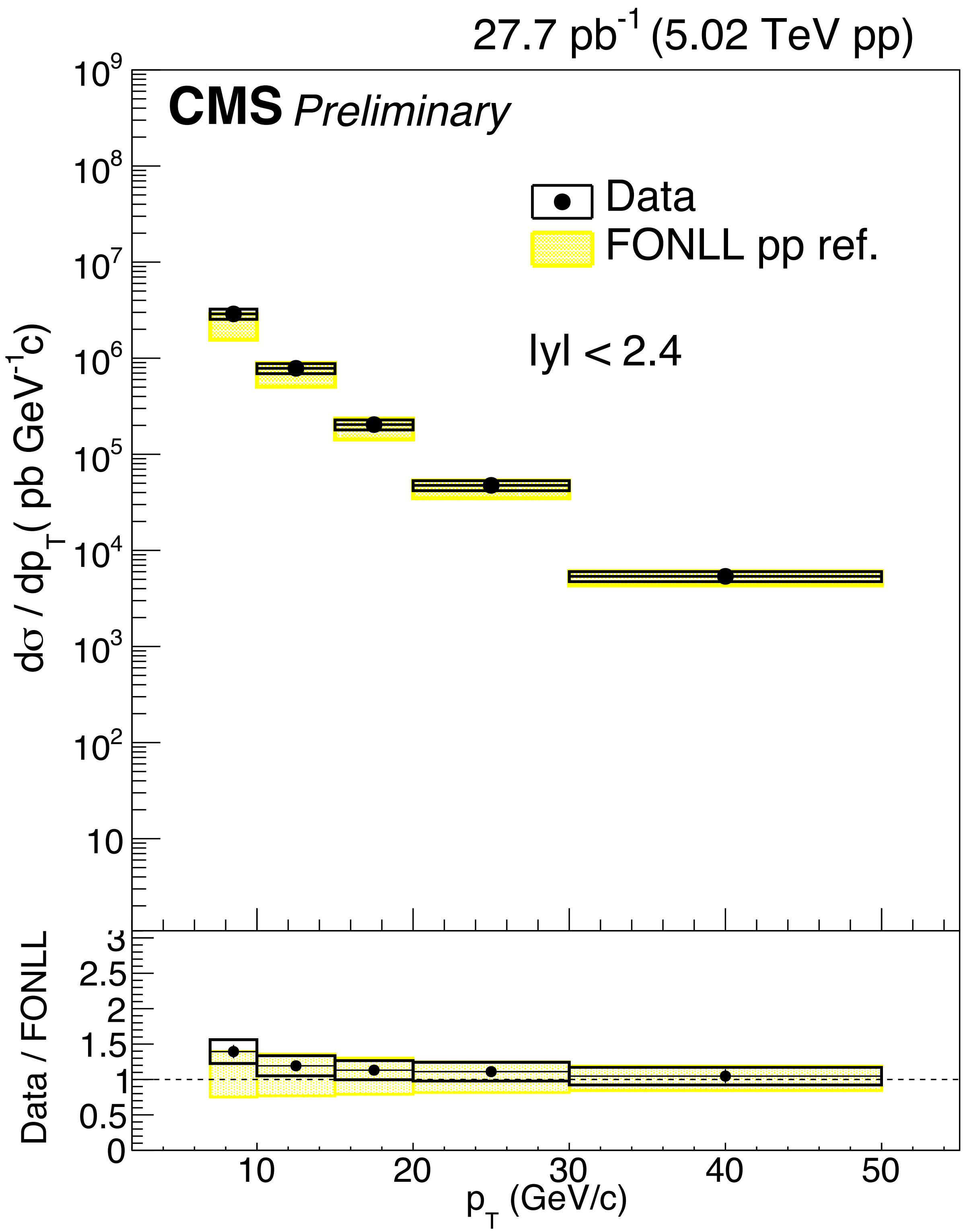
→ **main difficult on theory side is to account for the logarithmic divergent terms that arise from gluon splitting processes**

B production at LHC in pp collisions

New measurement of $B^+ \rightarrow J/\psi\ K^+$ production by CMS at 5.02 TeV:

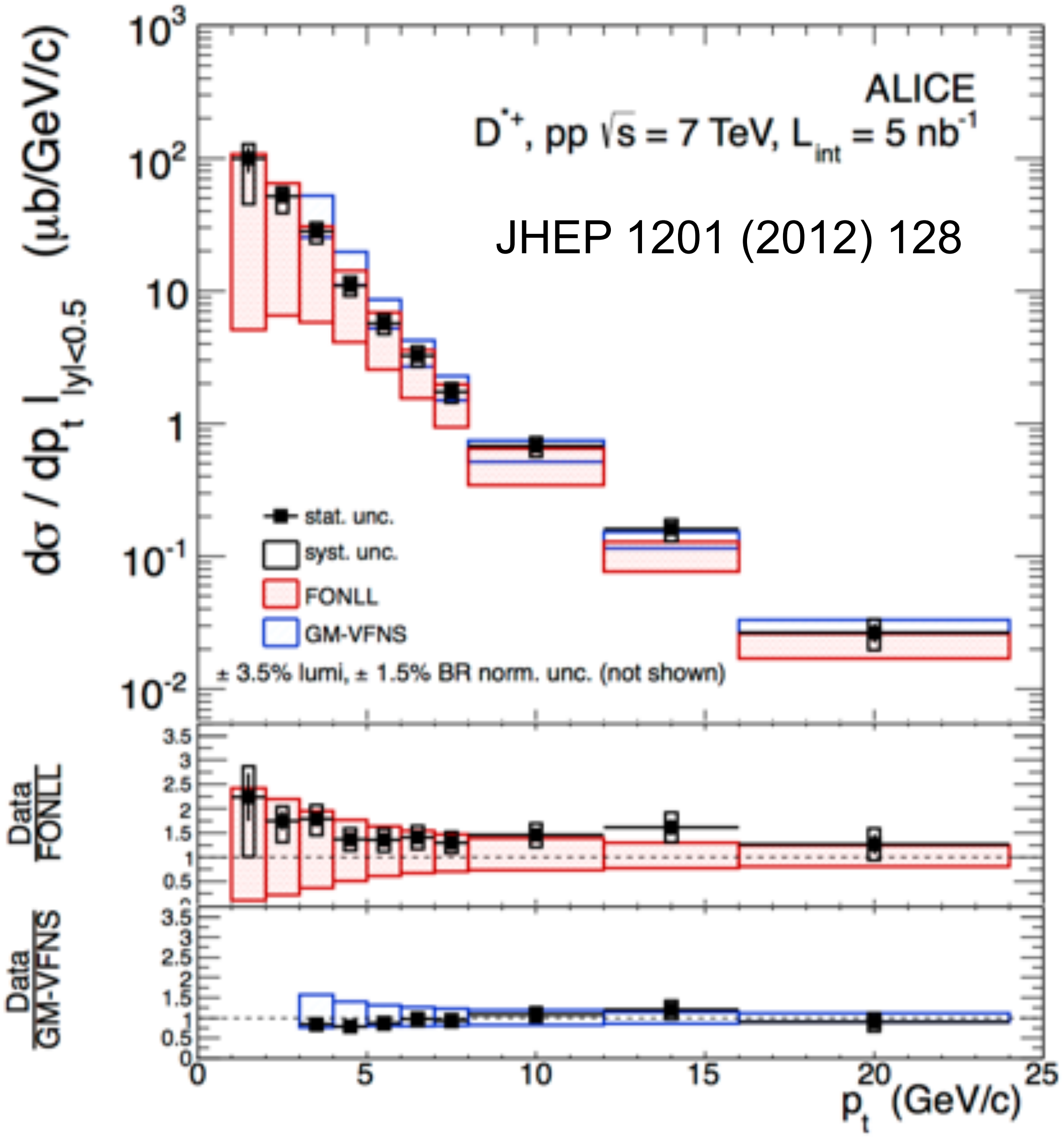




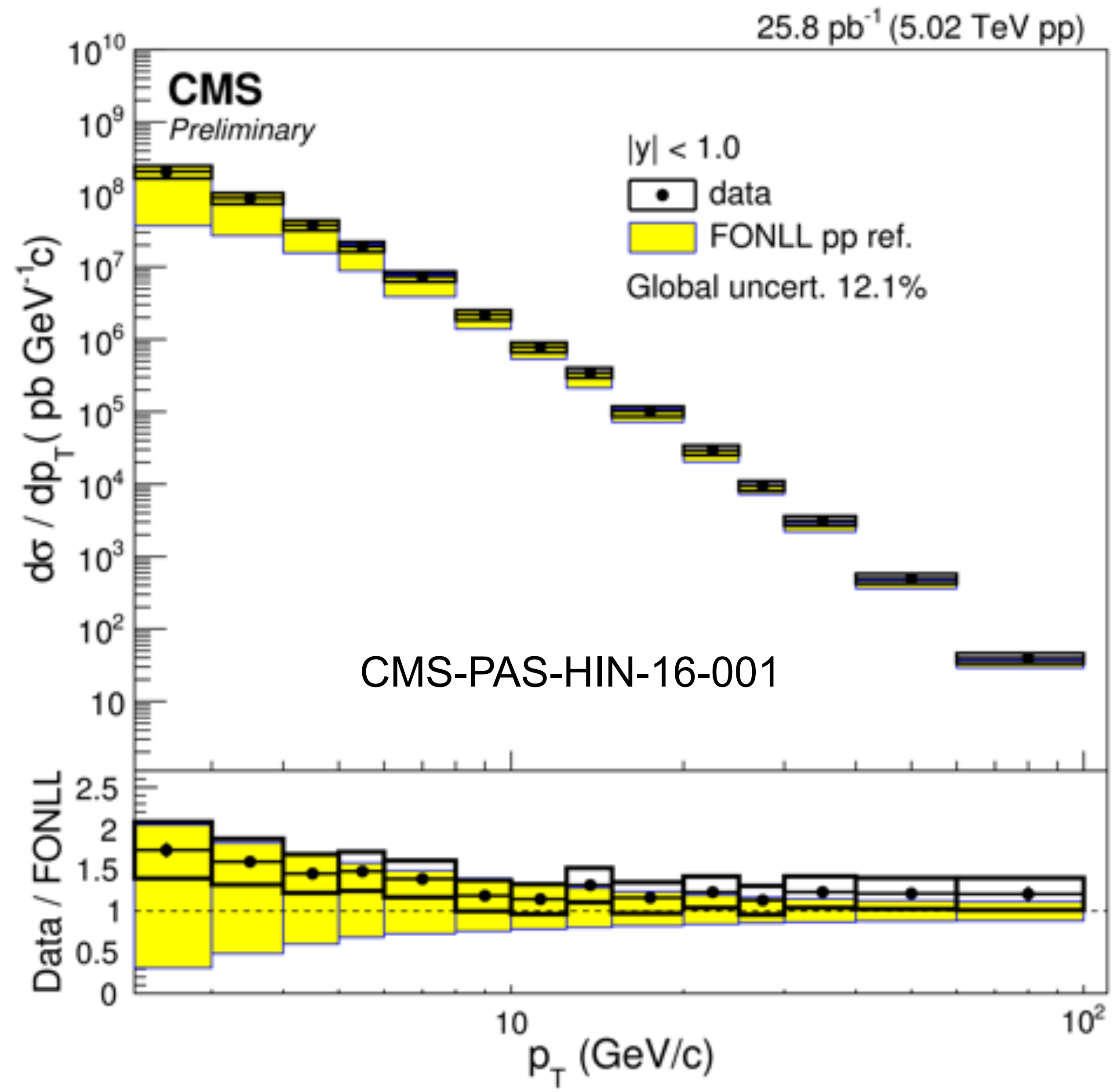


D production at LHC in pp collisions

ALICE D^{*+} at 7 TeV, |y|<0.5



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



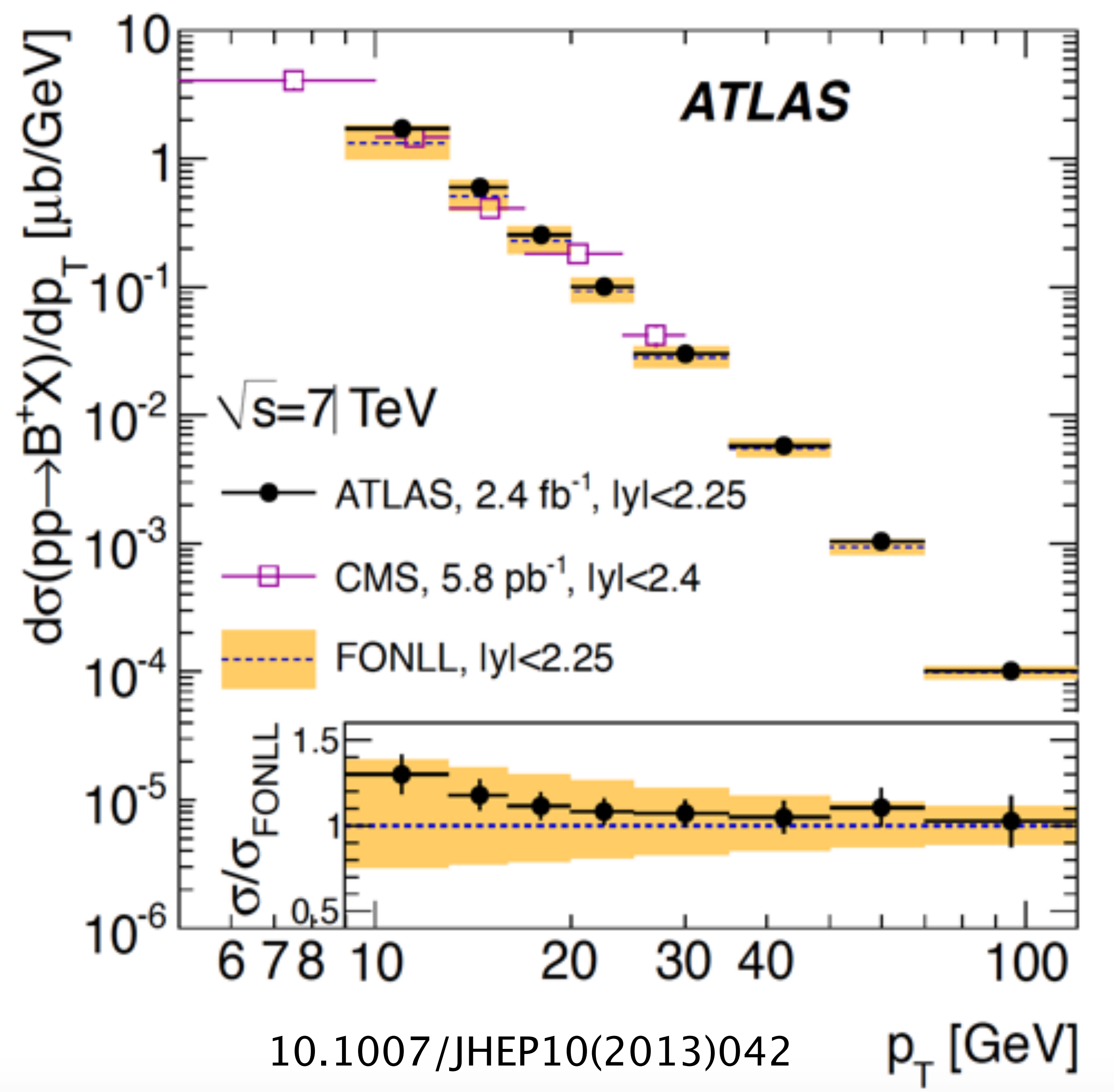
D meson production cross sections well described by NLO calculations:

→*upper edge of FONLL calculations*

→*consistent with central values of GM-VFNS*

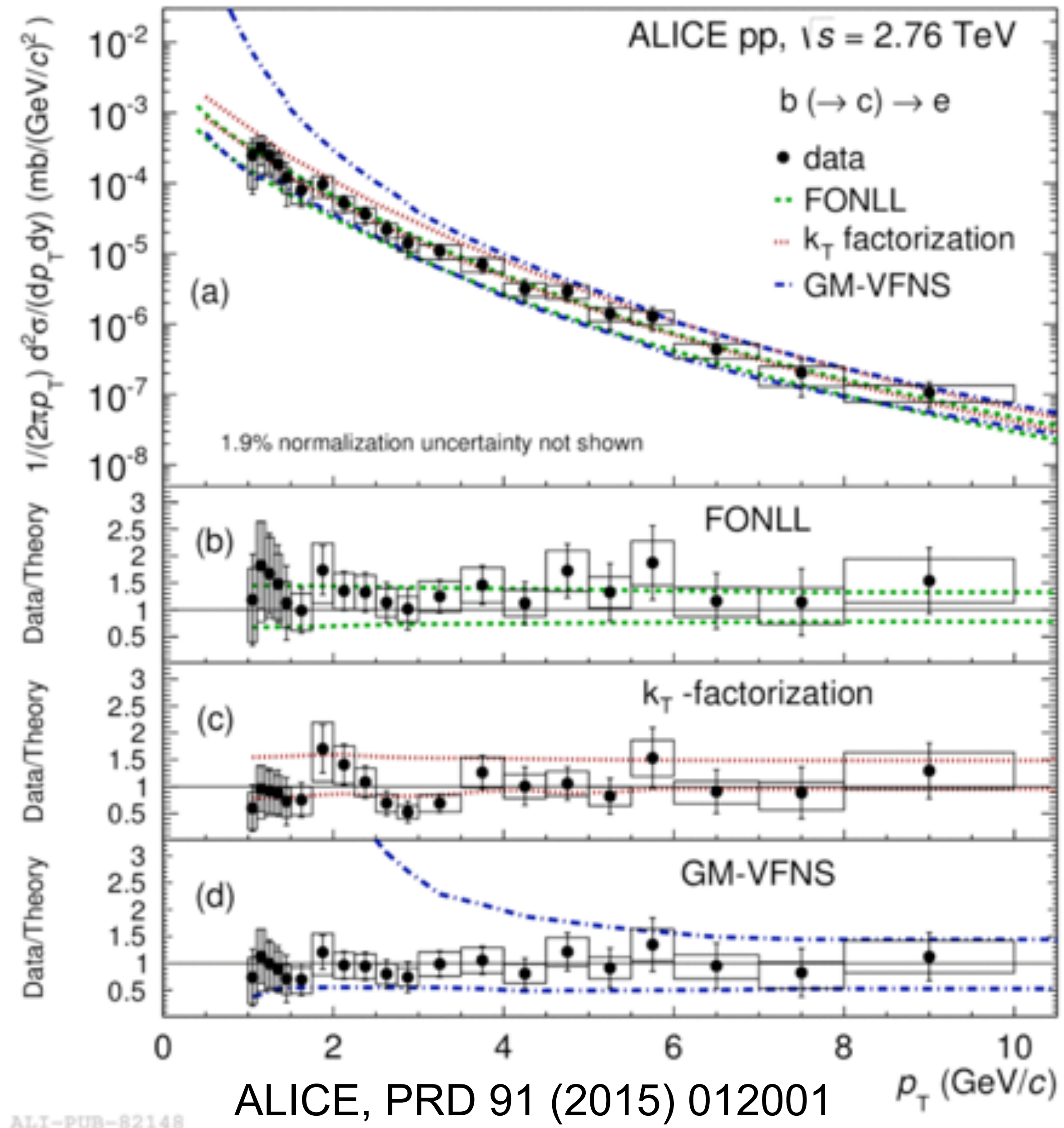
B production at LHC in pp collisions

ATLAS B^+ measurement at 7 TeV, $|y|<2.25$



10.1007/JHEP10(2013)042

ALICE b->e^{+-}, $|y|<0.8$



ALICE, PRD 91 (2015) 012001

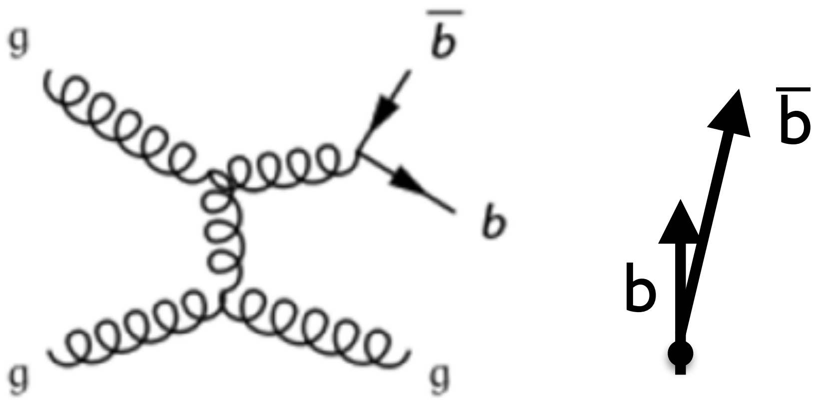
B meson production cross sections well described by NLO calculations:

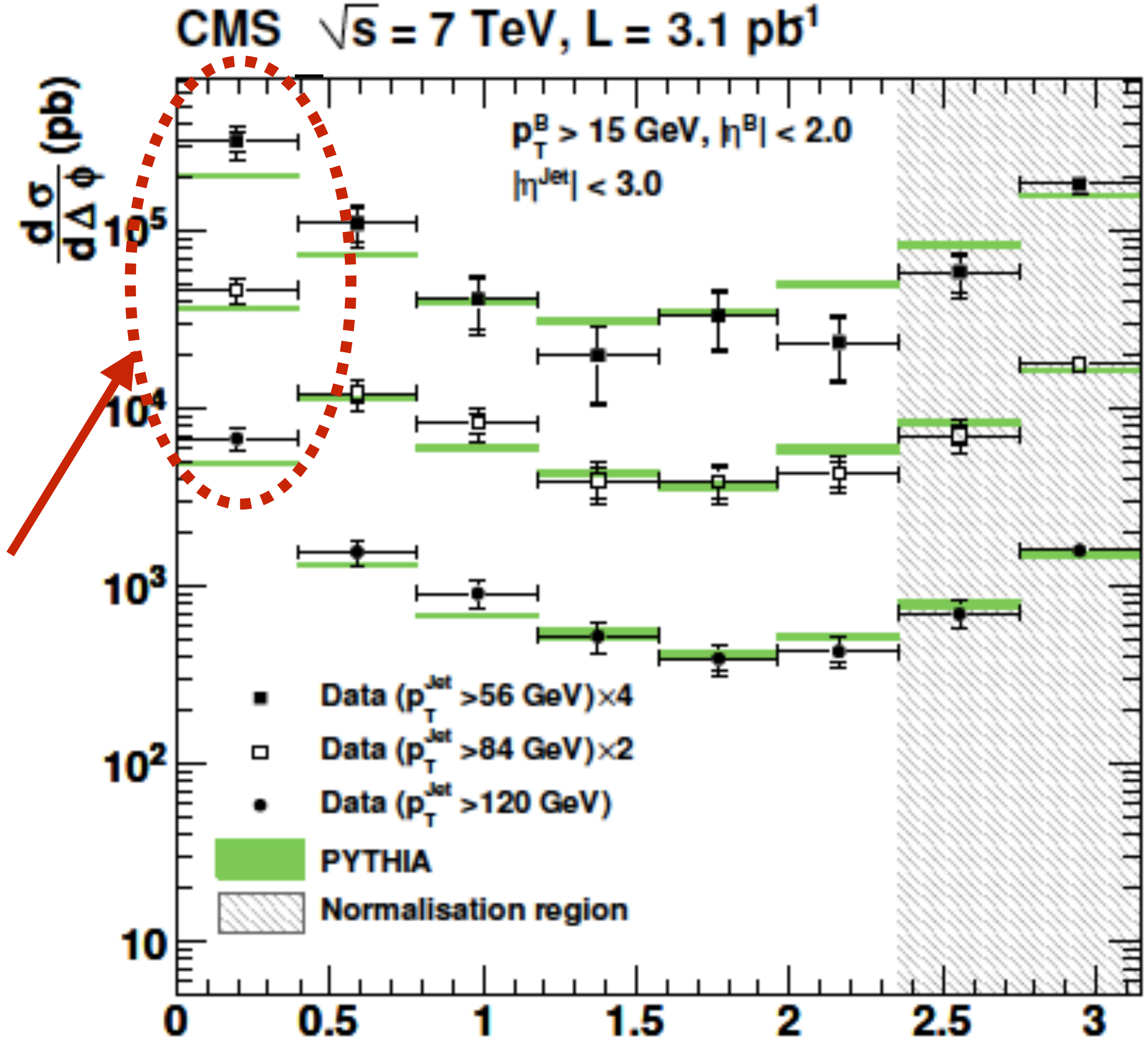
→*compatible with central values of FONLL, GM-VFNS and k_T-factorisation*

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

NLO process: Gluon splitting (GSP)

→ produced with small opening angles and asymmetric in p_T



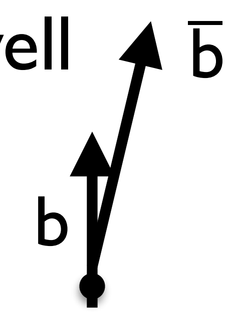


JHEP 1103:136,2011

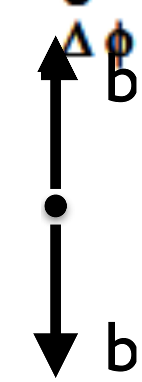
$B\bar{B}$ correlations strongly affected by gluon splitting processes at low $\Delta\phi$

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

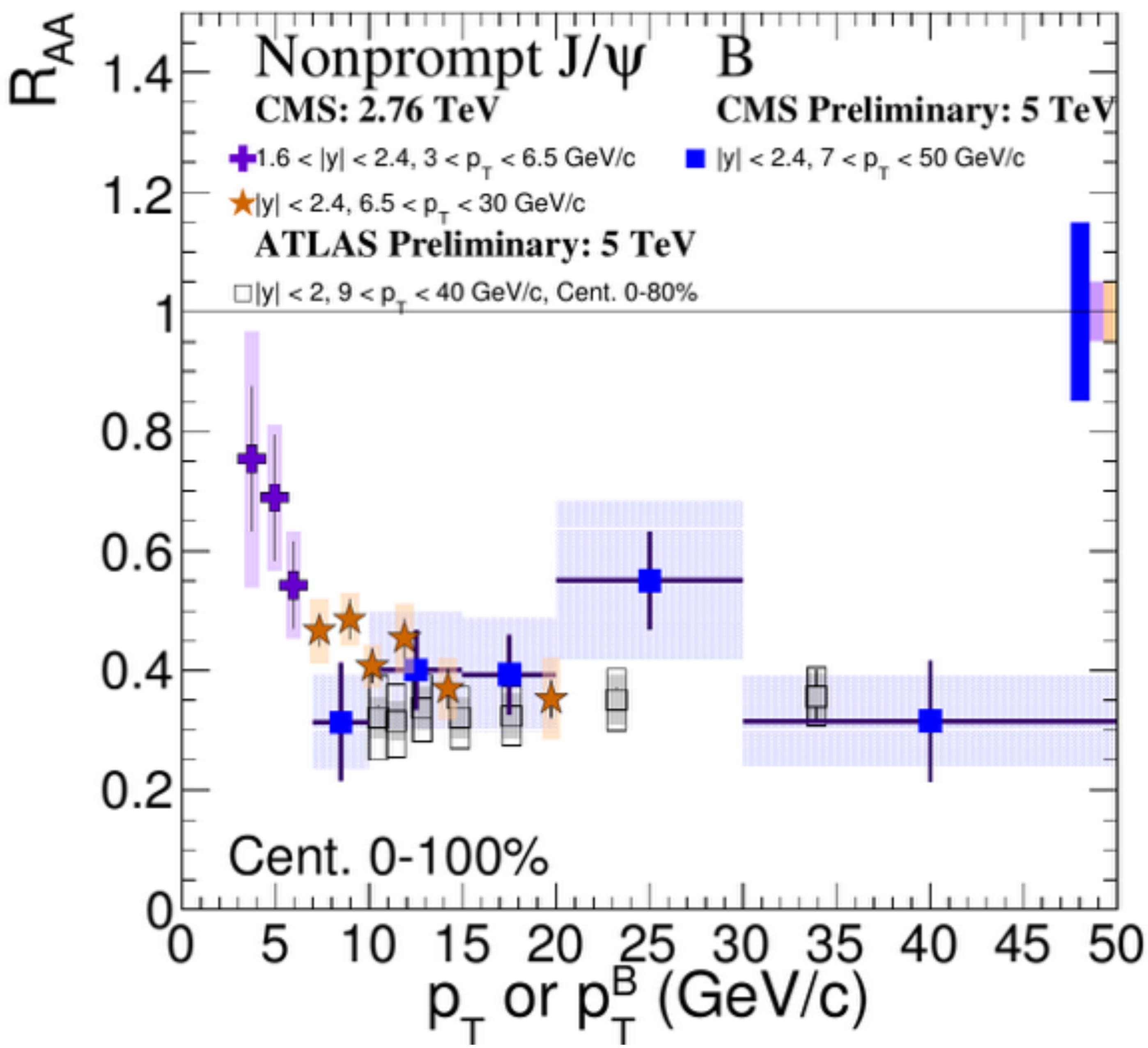
→GS contribution underestimated by PYTHIA



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



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

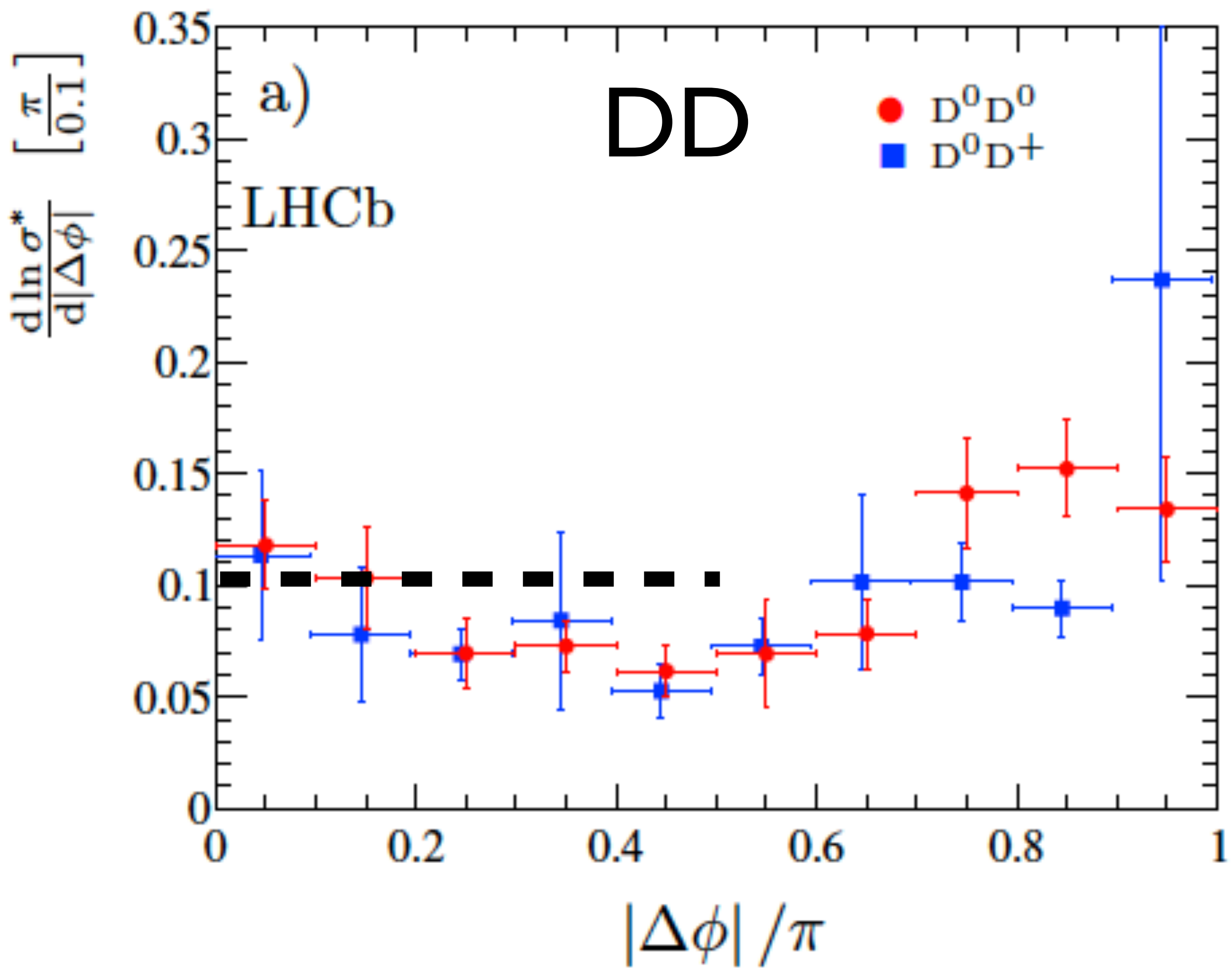


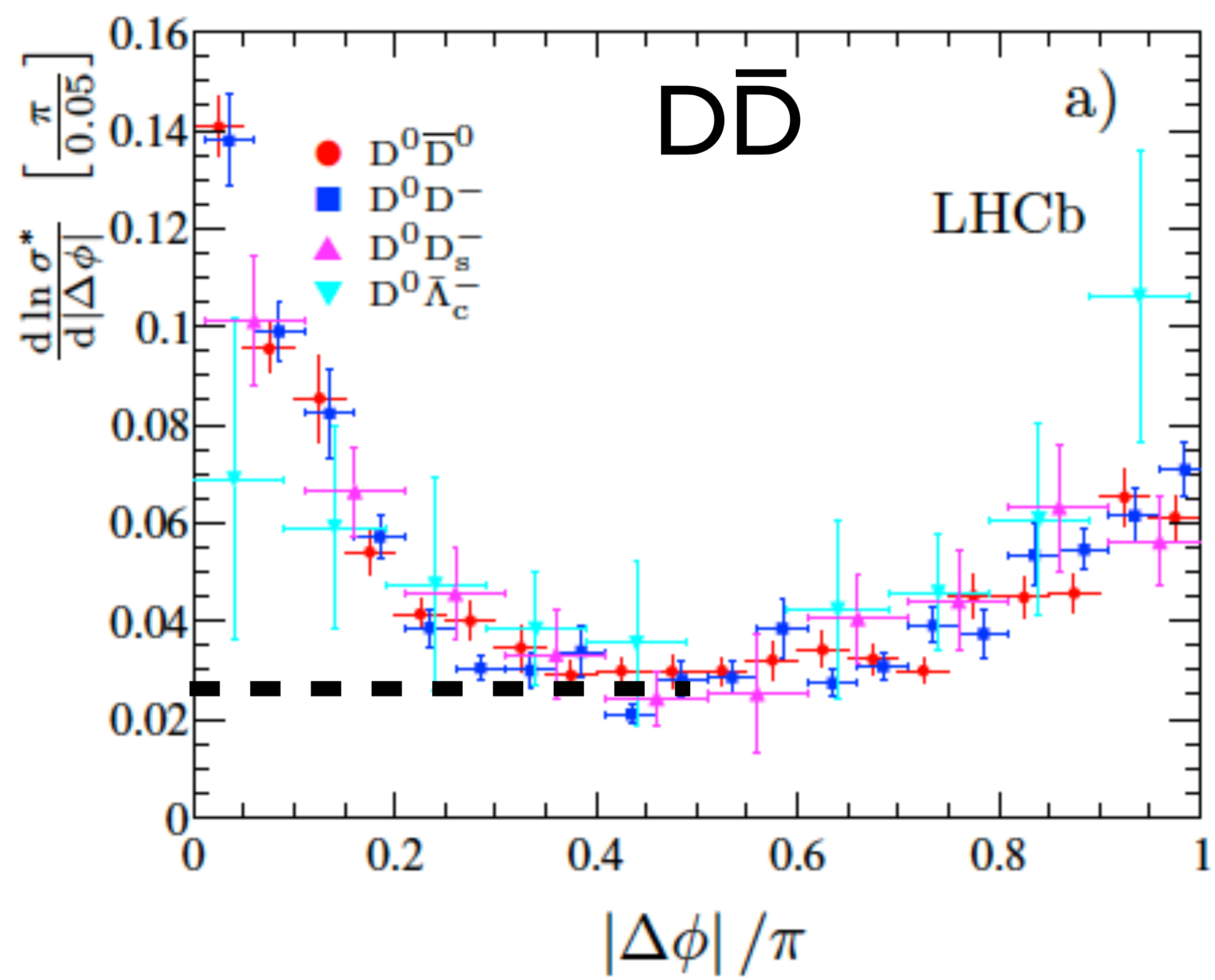
The B$^+$ R_{AA} at 5.02 TeV and non-prompt J/φ at 2.76 fully compatible within uncertainties!

BIG CAVEAT: different energies!

DD and D$\bar{\text{D}}$ correlations

DD and D$\bar{\text{D}}$ correlations measured by LHCb at 5.02 TeV

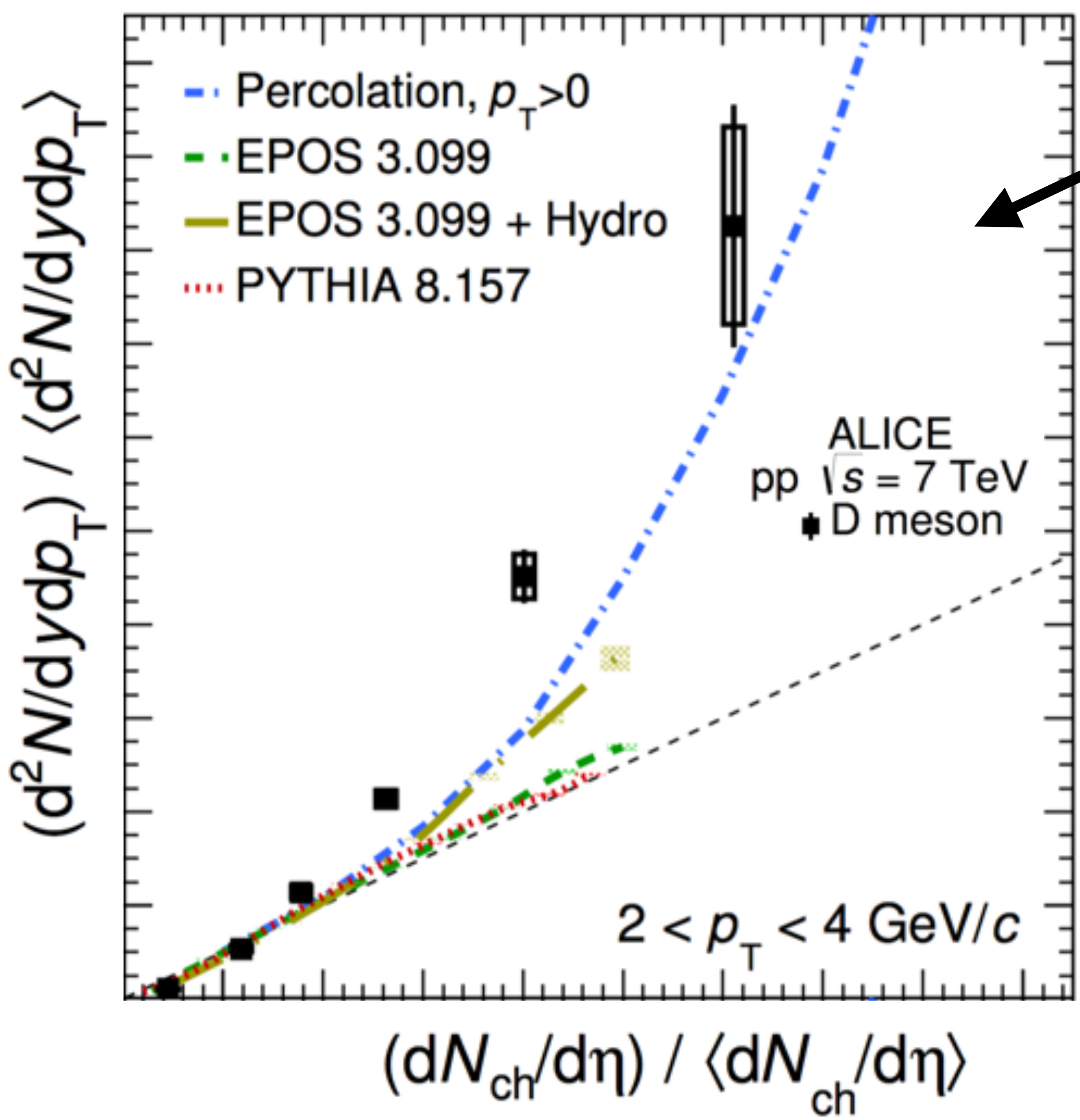




D$\bar{\text{D}}$ correlation show an enhancement with respect to DD correlation at low $\Delta\phi$ consistent with consistent contribution from gluon splitting

$c\bar{c}$ pairs produce by gluon splitting processes

HQ production as a function of multiplicity

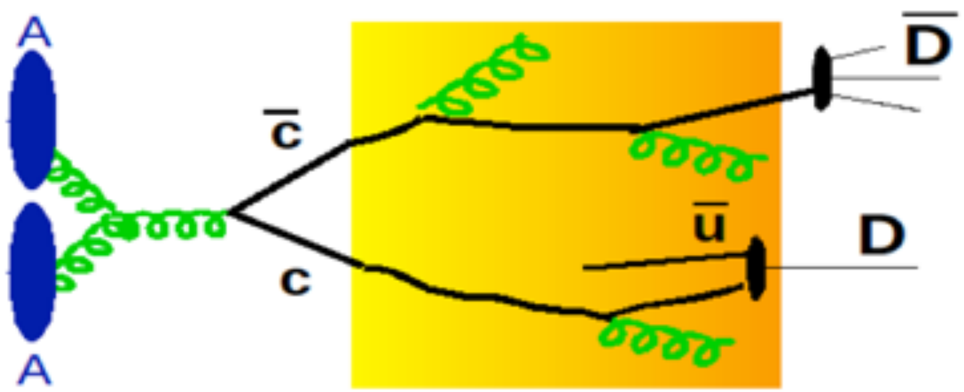


Strong dependence of D meson yield vs multiplicity

Need to include Multi-Particle-Interaction (MPI) to describe experimental data

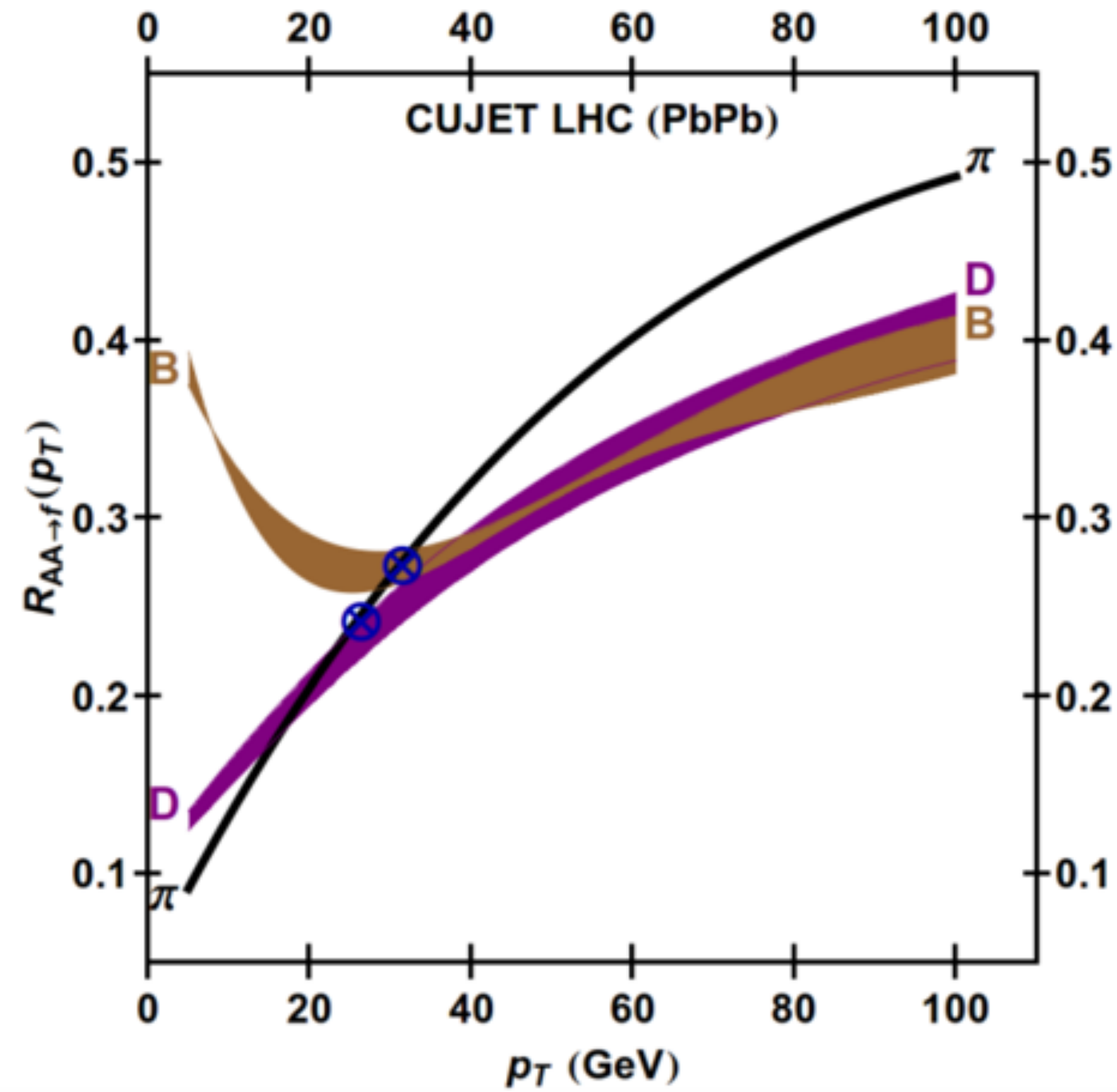
ALICE data favours MPI models that includes a non linear dependence vs multiplicity (hydro?)

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.

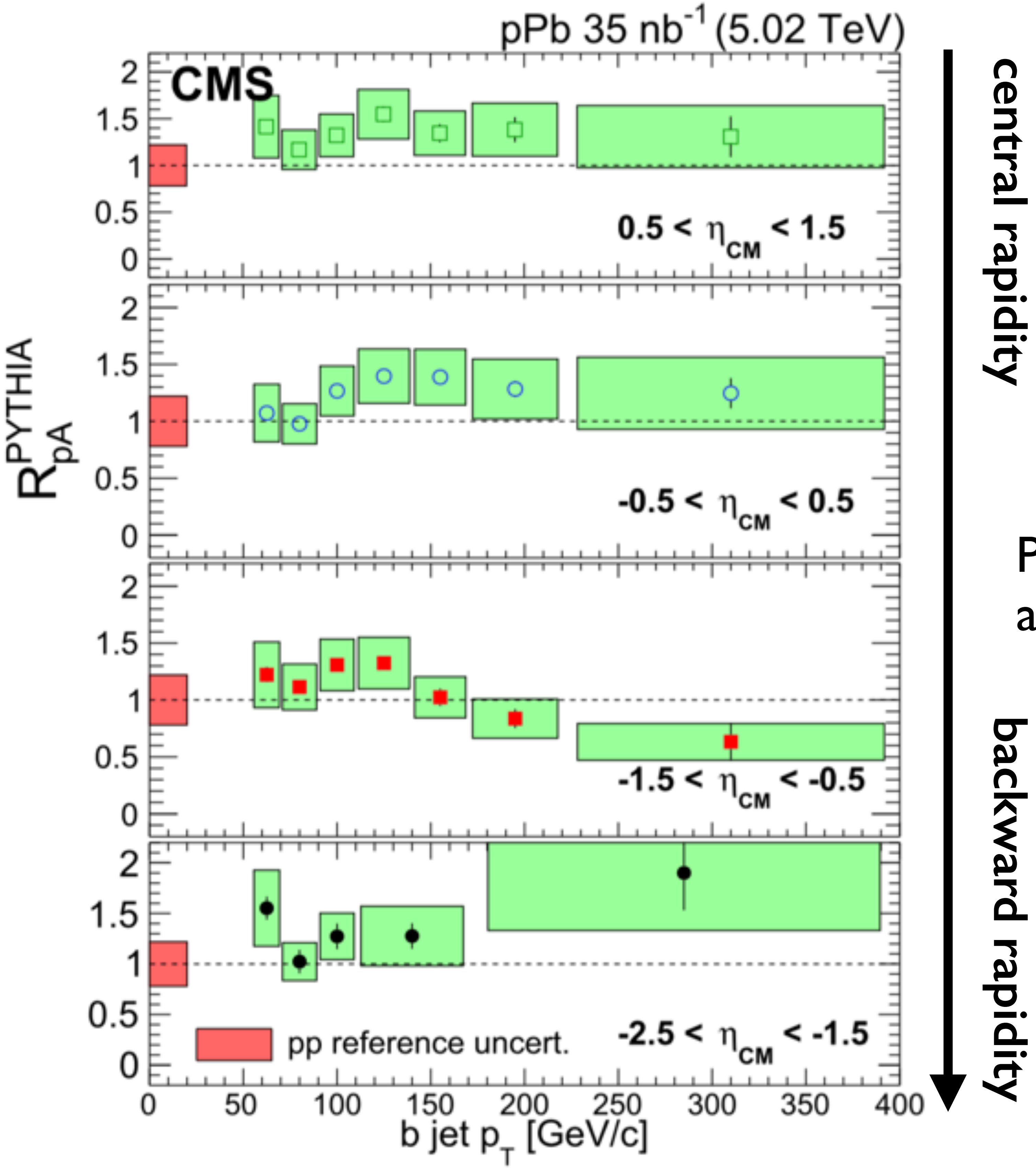


Flavour-dependence of radiative energy loss:

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

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

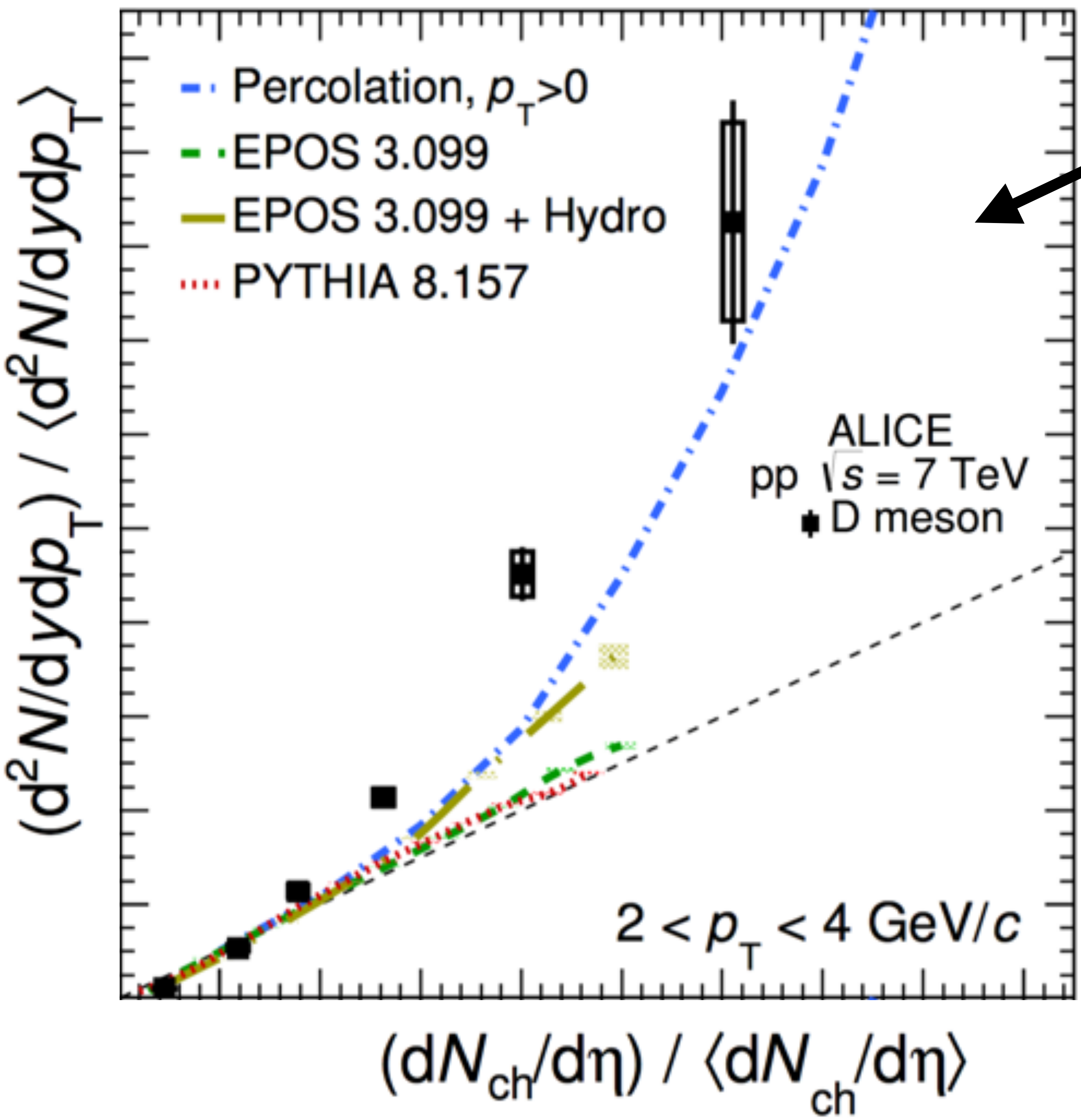
b-jet nuclear modification factor in pPb



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

HQ production as a function of multiplicity

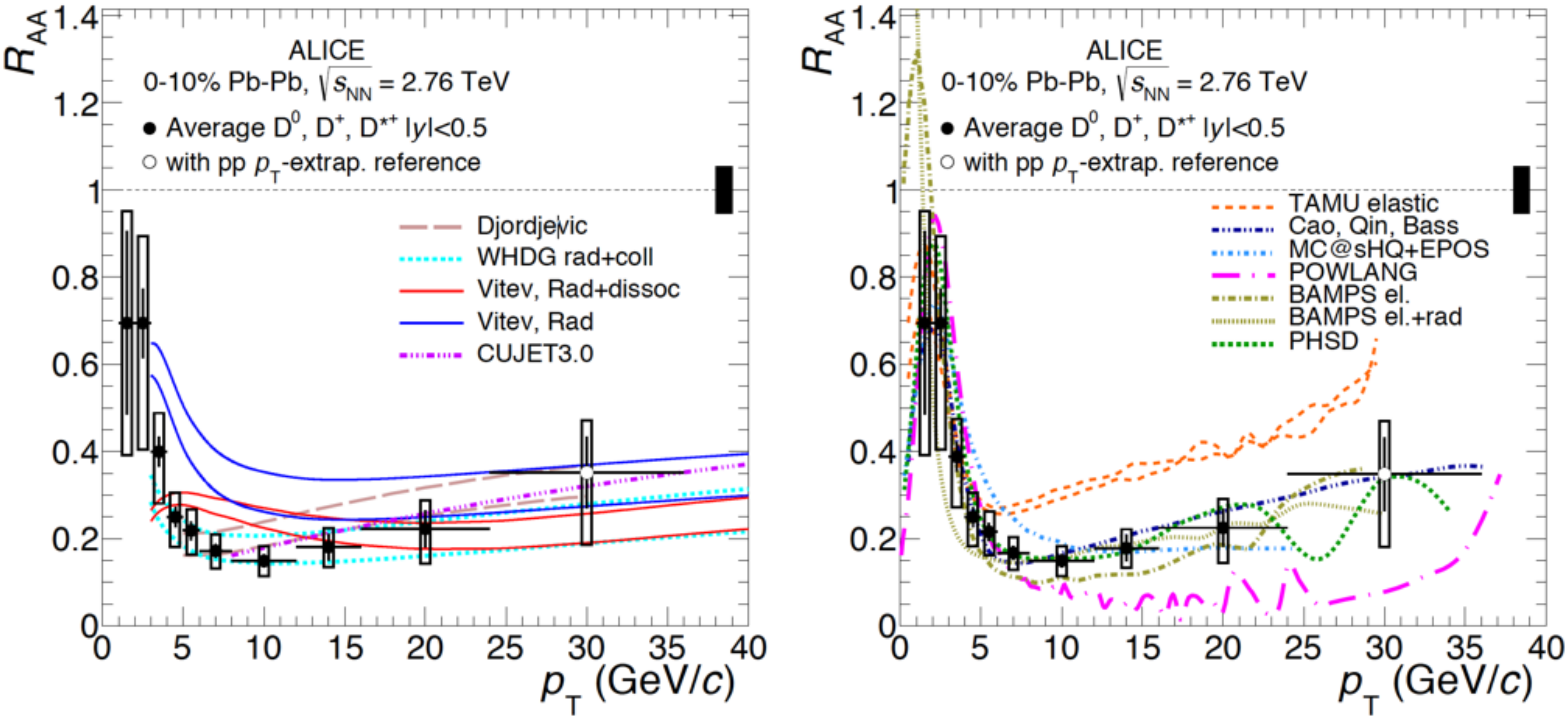


Strong dependence of D meson yield vs multiplicity

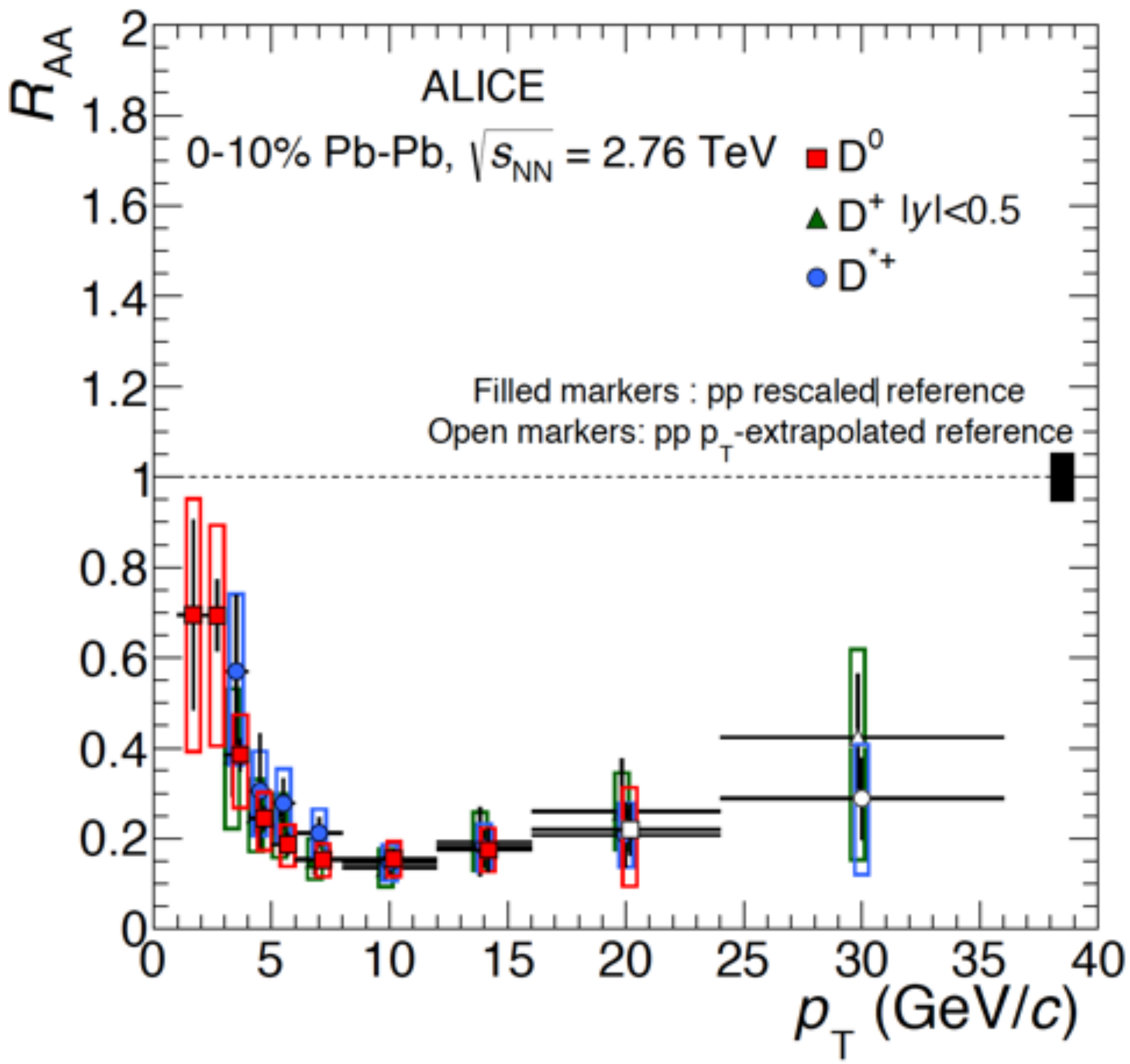
Need to include Multi-Particle-Interaction (MPI) to describe experimental data

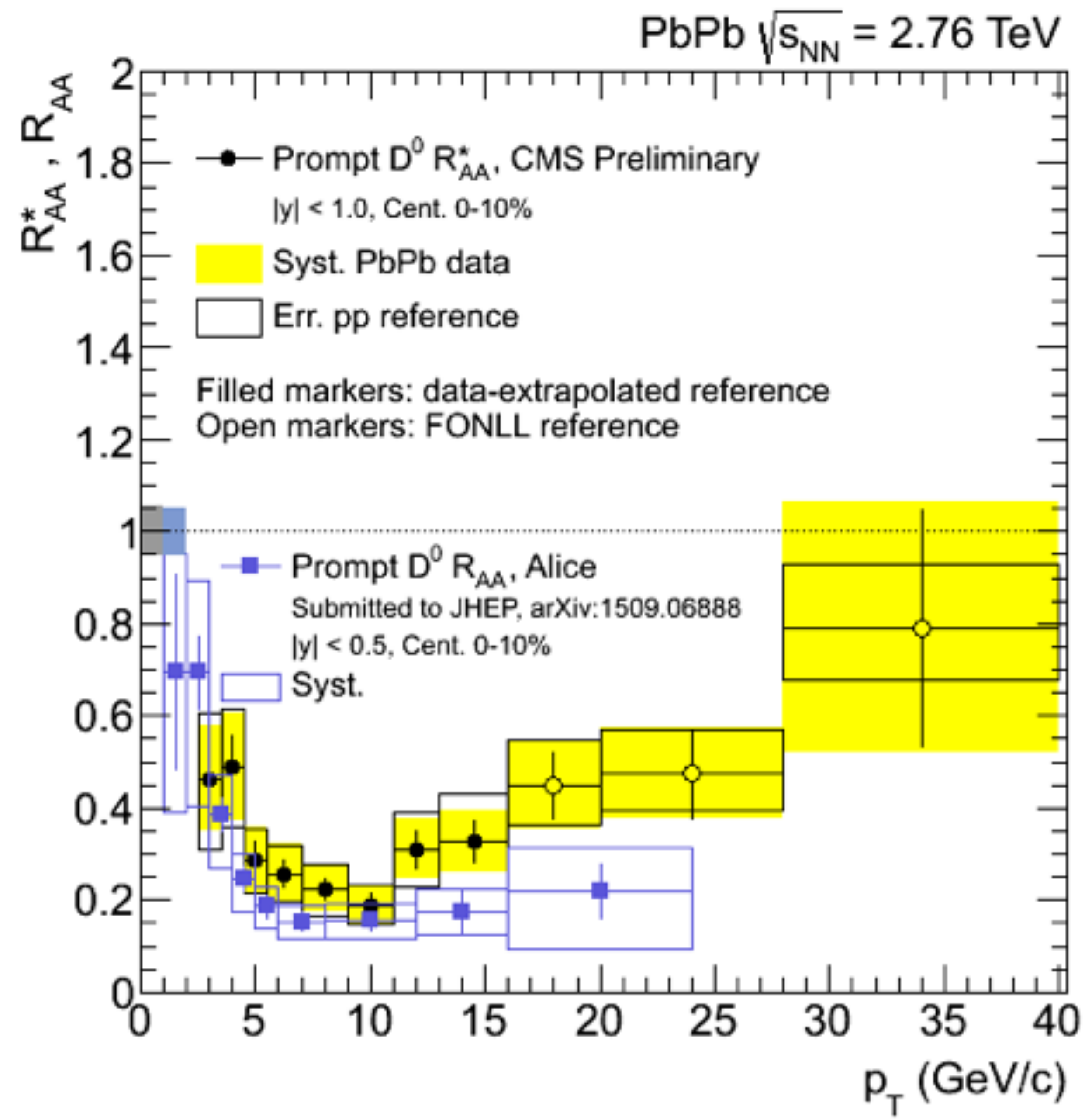
ALICE data favours MPI models that includes a non linear dependence vs multiplicity (hydro?)

D meson RAA at 2.76 TeV



D meson R_{AA} at 2.76 TeV





Strong suppression in central PbPb events:

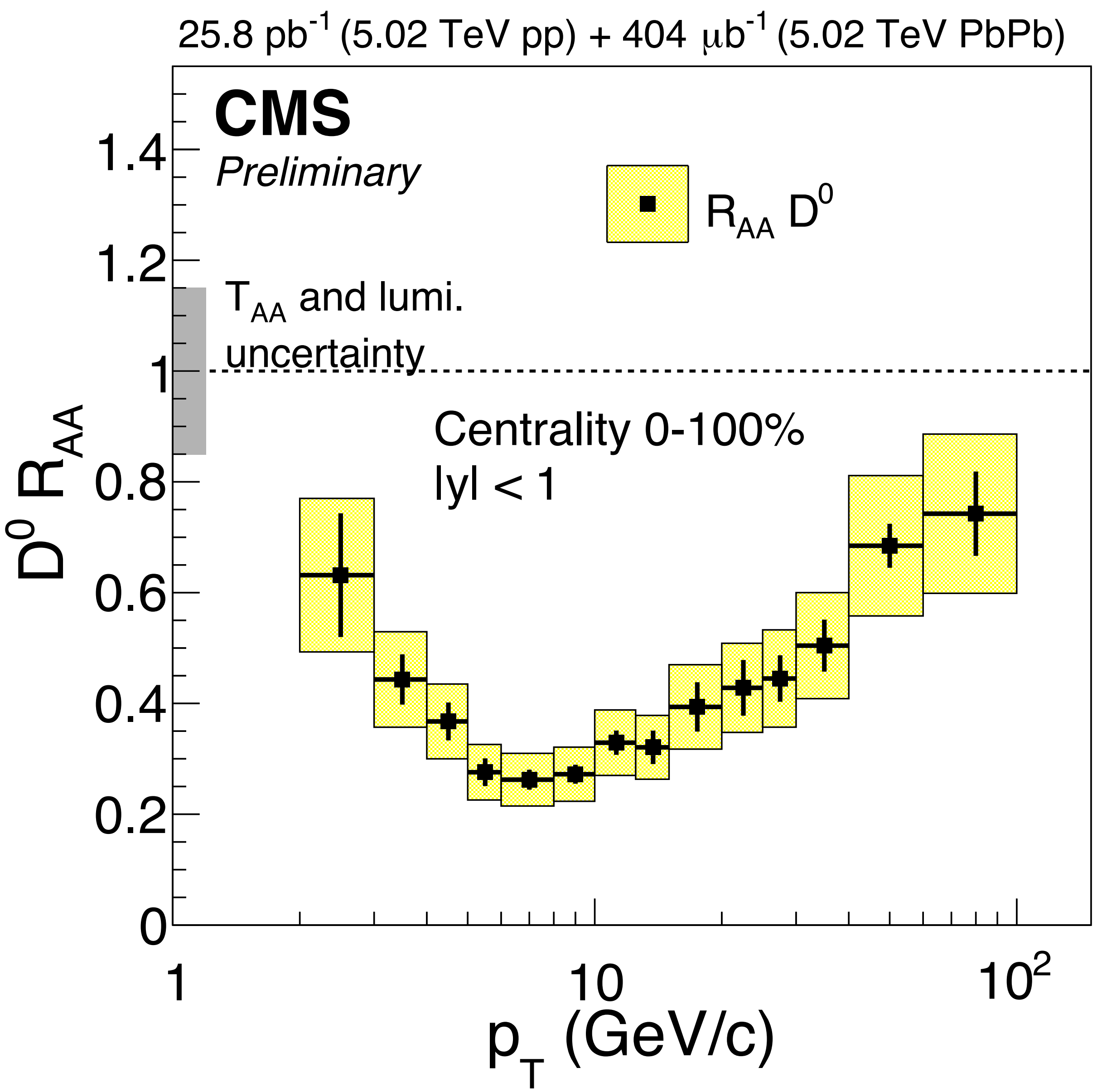
same suppression for D^0,D^+,D^{*+} indicate independence from fragmentation

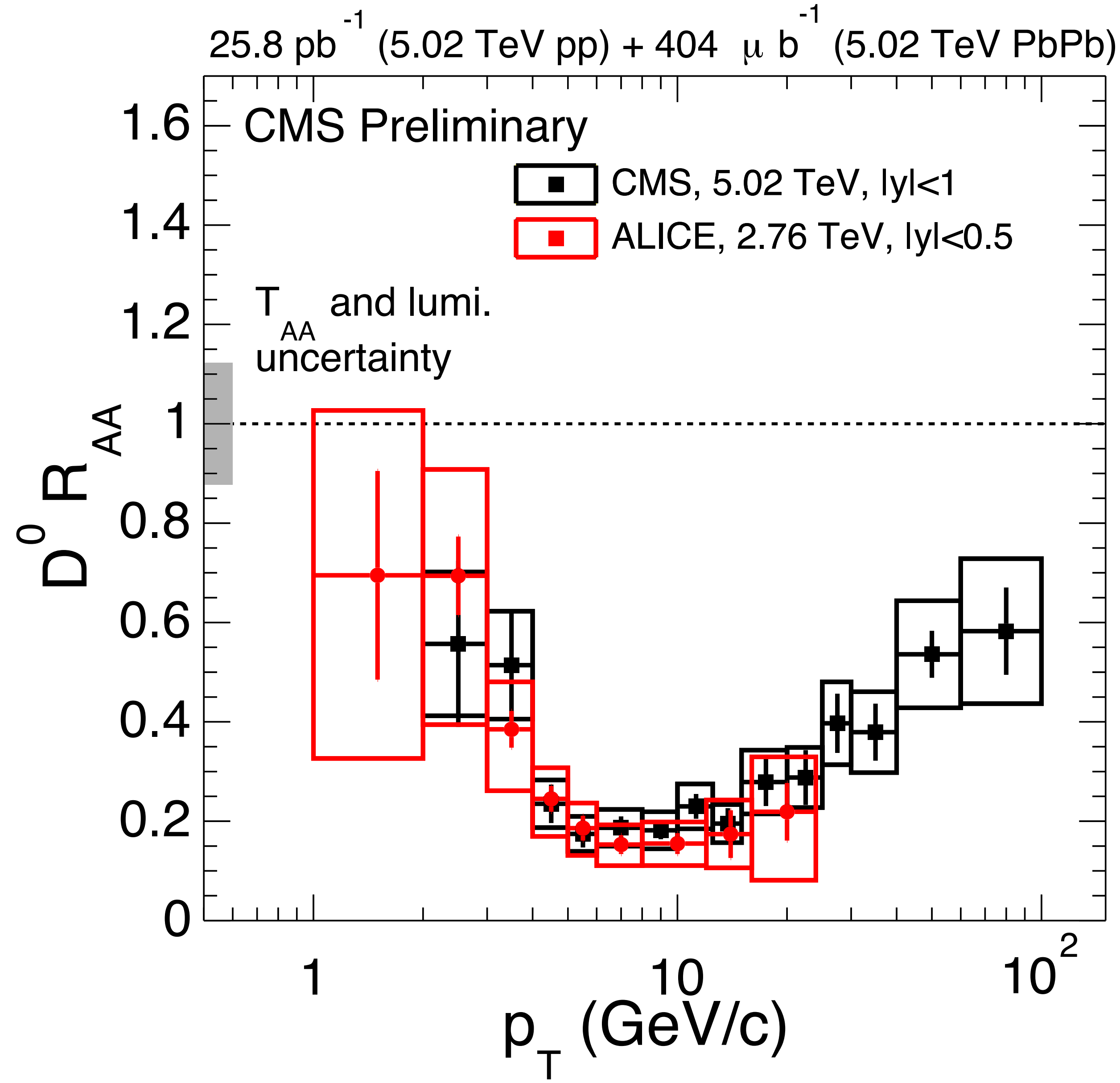
ALICE and CMS in good agreement

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





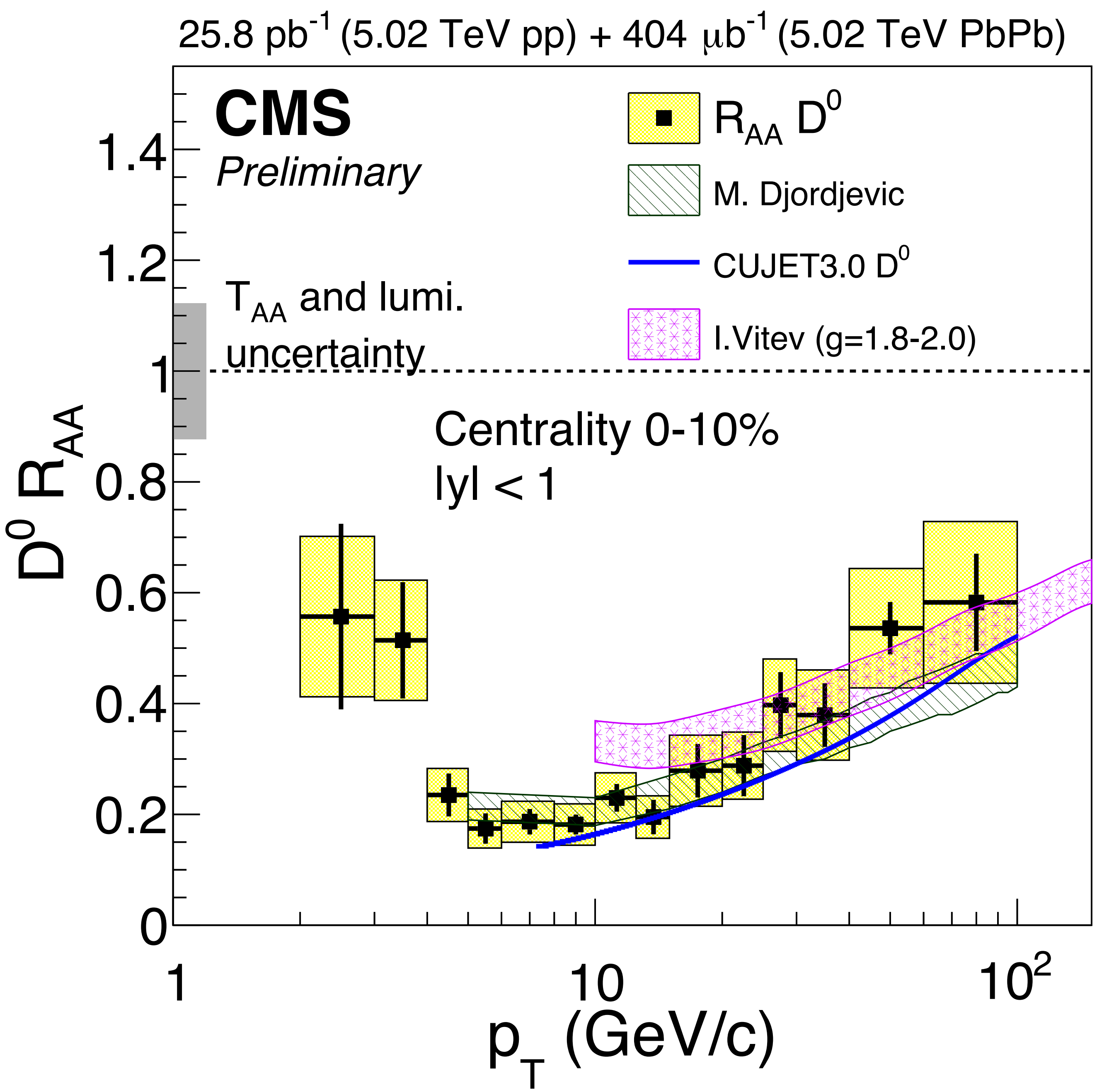
Strong suppression observed at 5.02 TeV

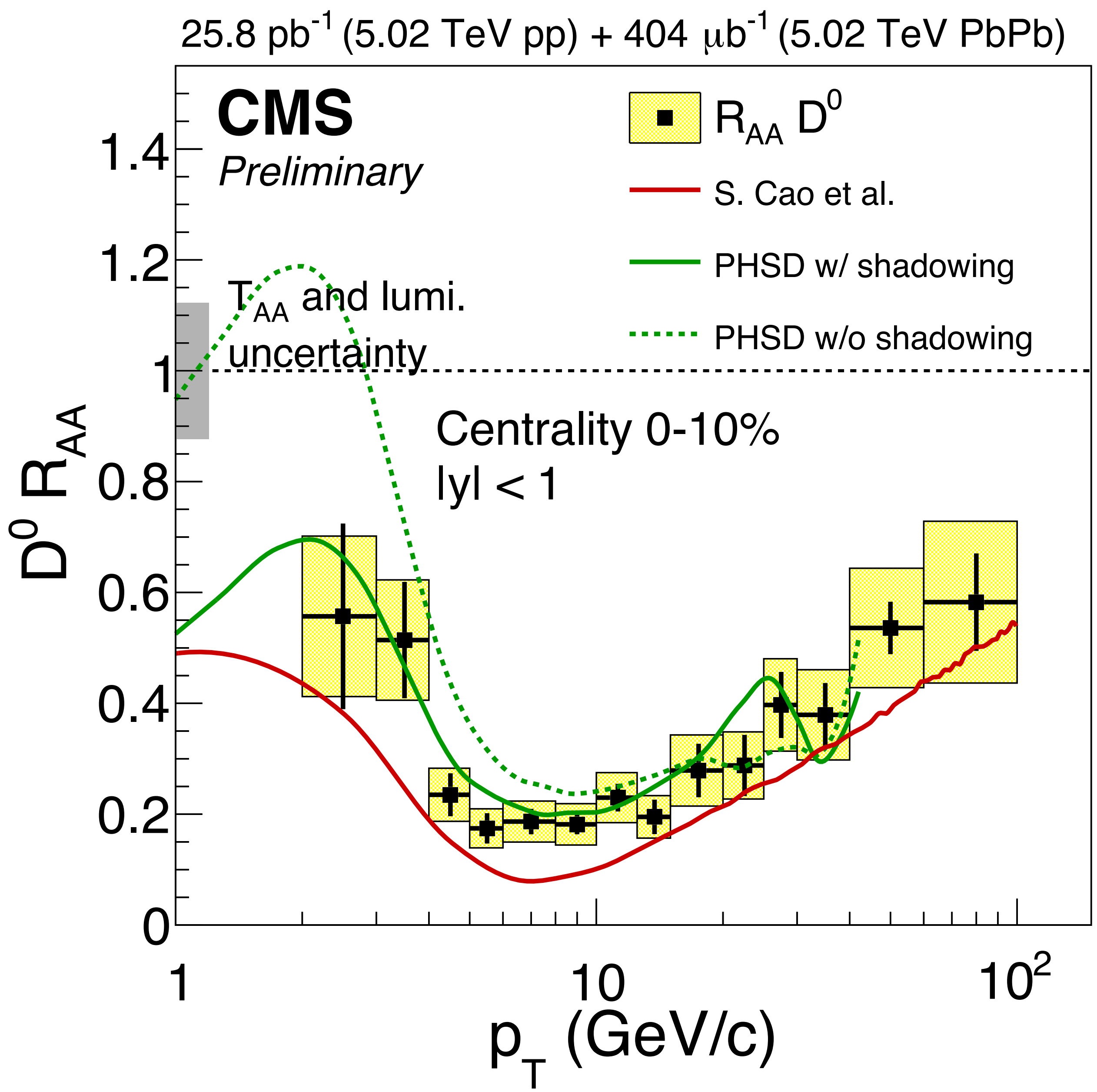
Rising trend observed when going to high p_T

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

Caveat: different rapidities

Comparison with theoretical calculations





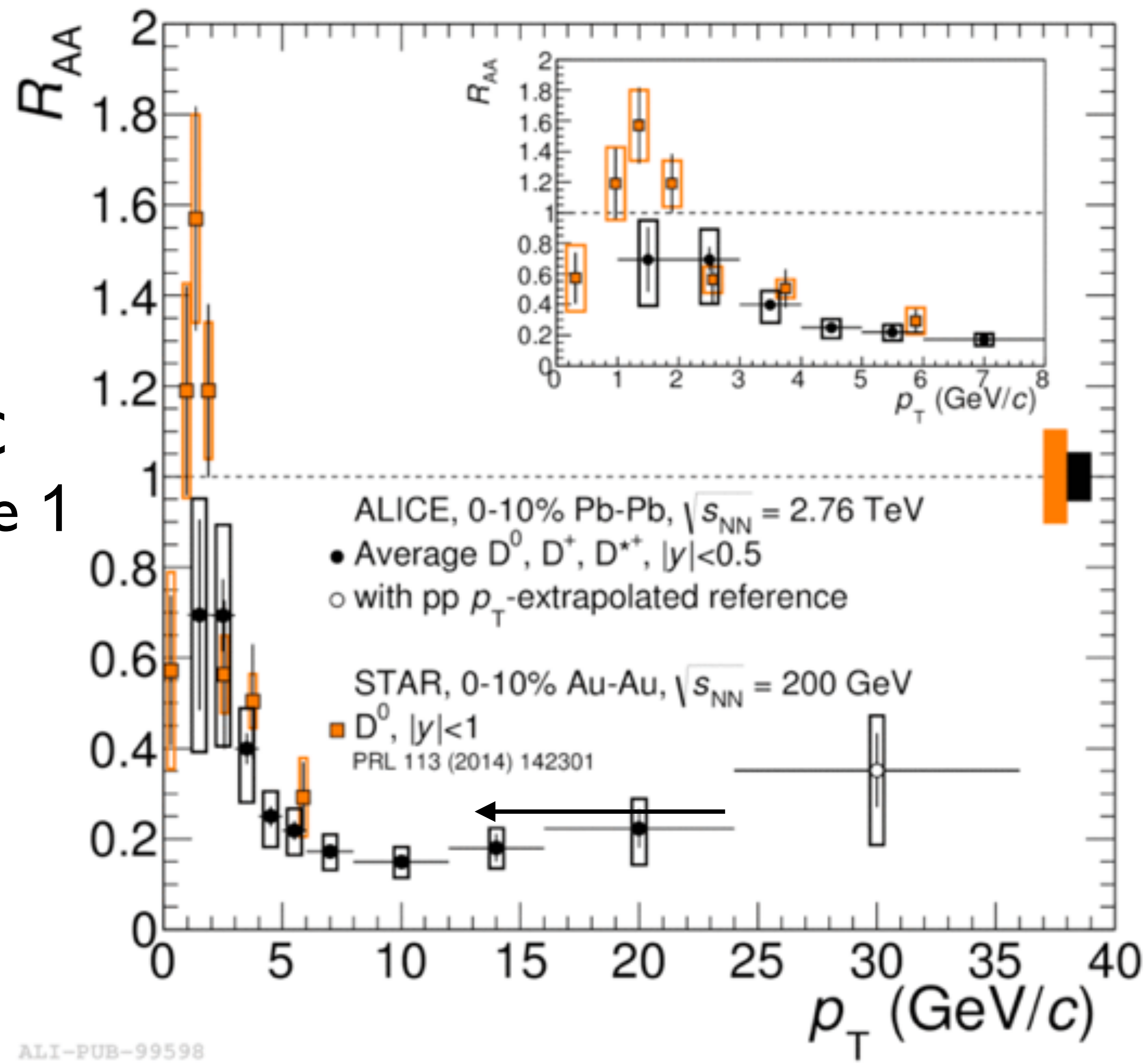
To describe D^0 R_{AA} in the full p_T range, models have to include:

- both collisional and radiative energy loss
- shadowing

Comparison with RHIC

At lower $p_{T,}$ RHIC D^0 R_{AA} goes above 1

PRL113 (2014) 142301
JHEP1603 (2016) 081

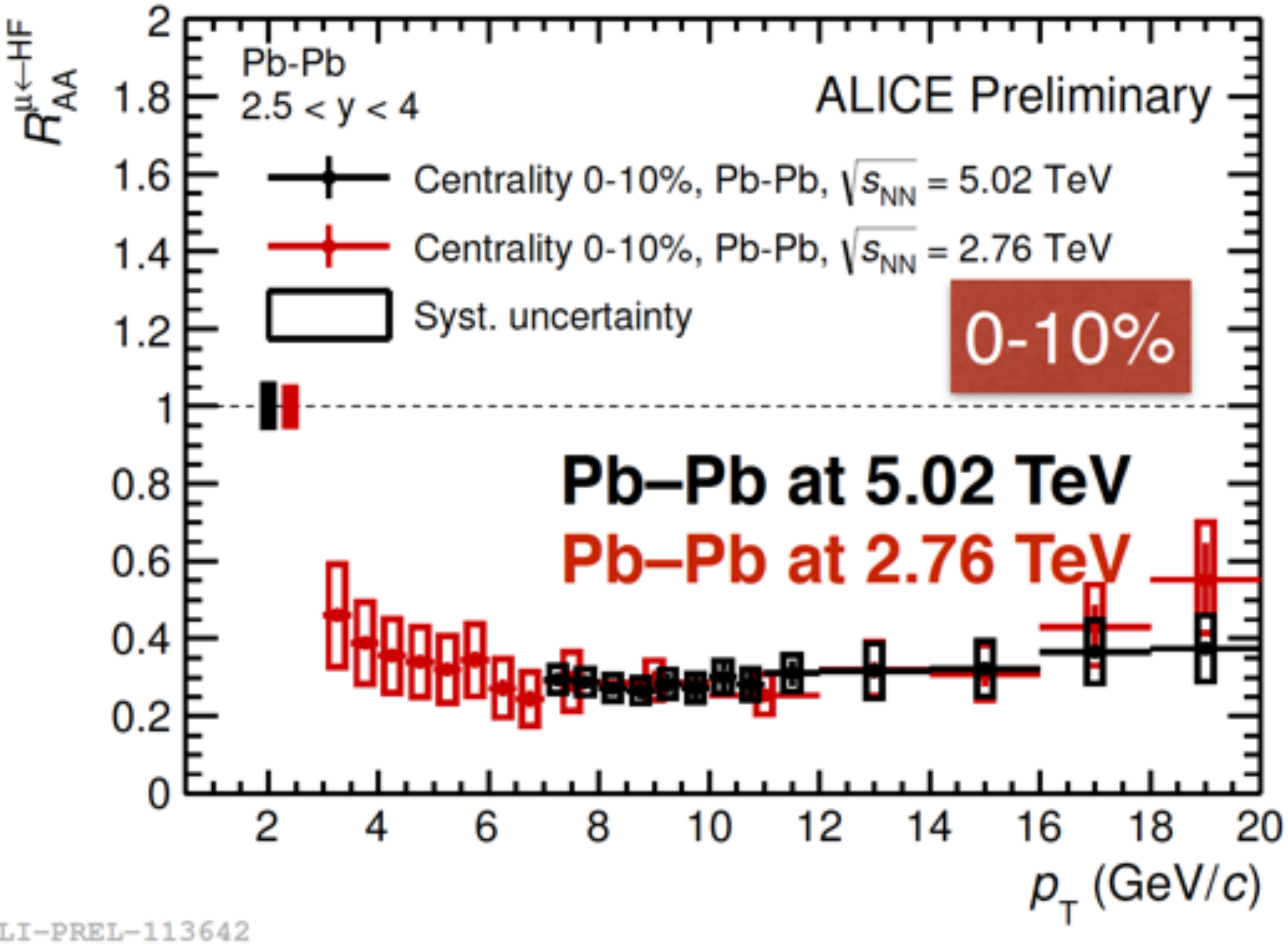


Smaller suppression at RHIC can be a consequence of different magnitude of the shadowing at RHIC vs. LHC energies

x_{BJ} (200 GeV) ~ 10^{-2} , x_{BJ} (2.76 TeV) ~ $8 \cdot 10^{-4}$

R_{AA} of heavy flavour muons

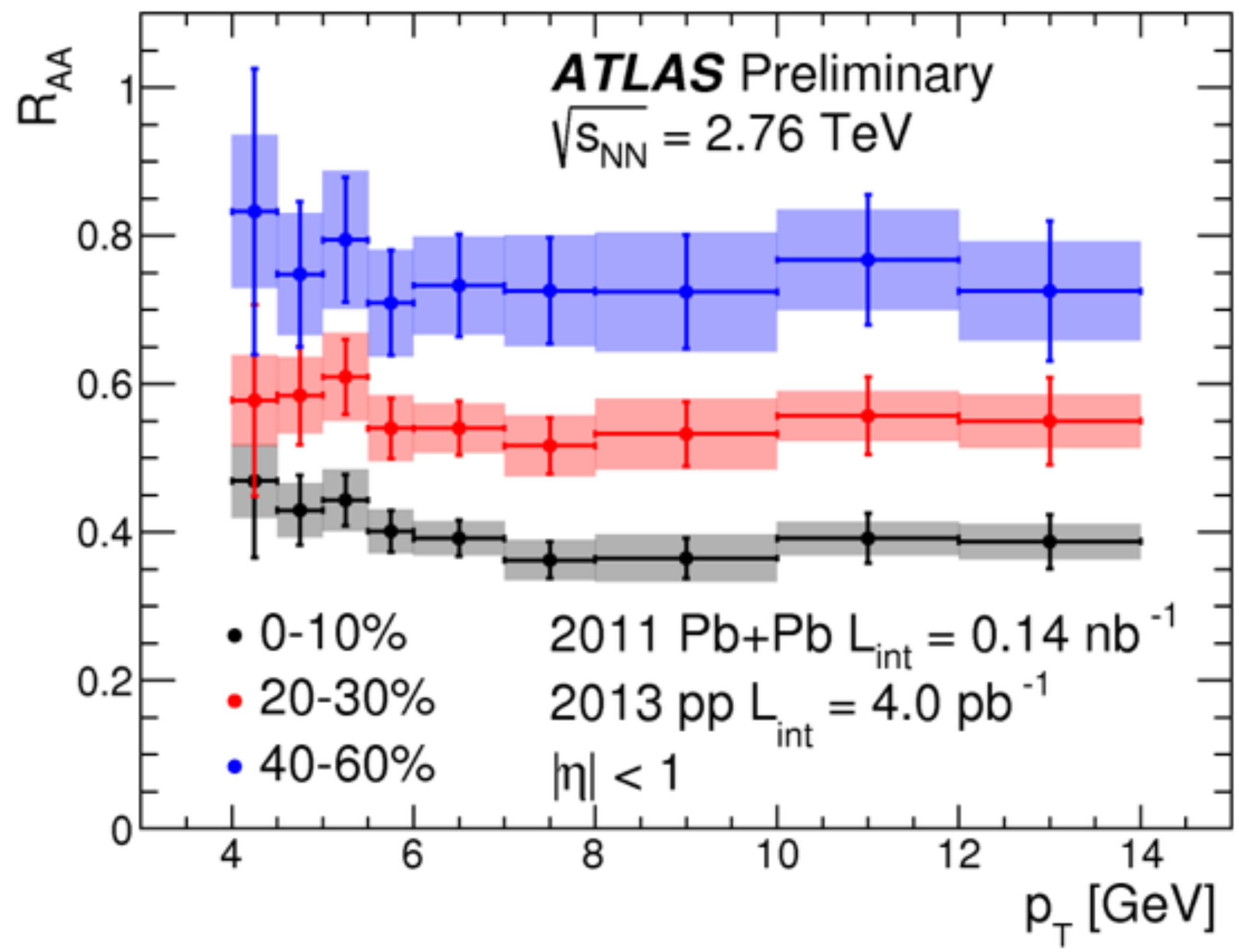
ALICE R_{AA} of heavy-flavour muons at 2.76 TeV and 5.02 TeV



Precise measurement of HF muons at low p_T

Same suppression observed at the two energies

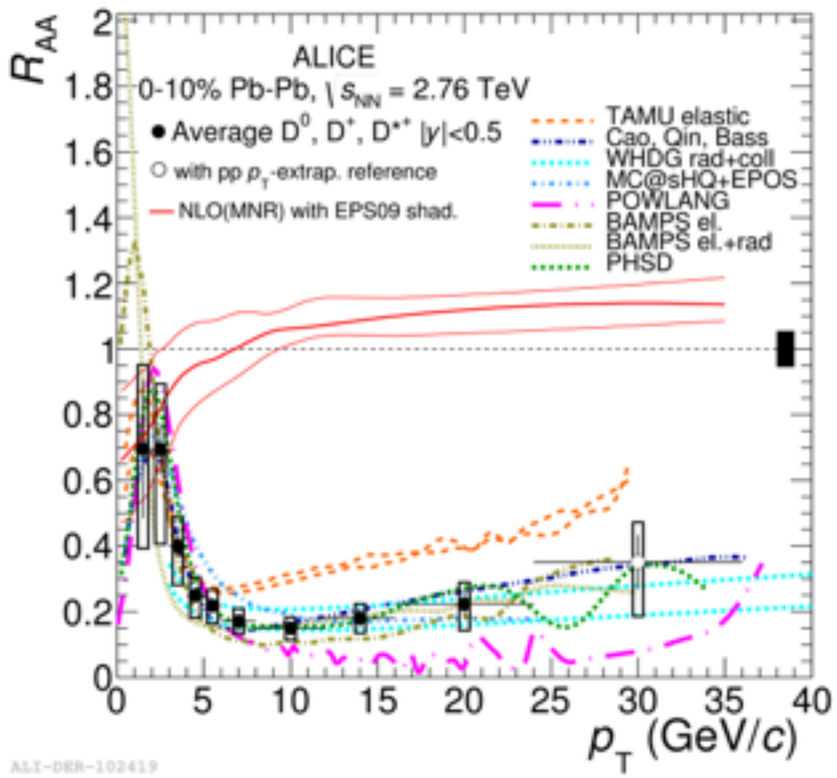
R_{AA} of heavy-flavour muons at 2.76 TeV from ATLAS

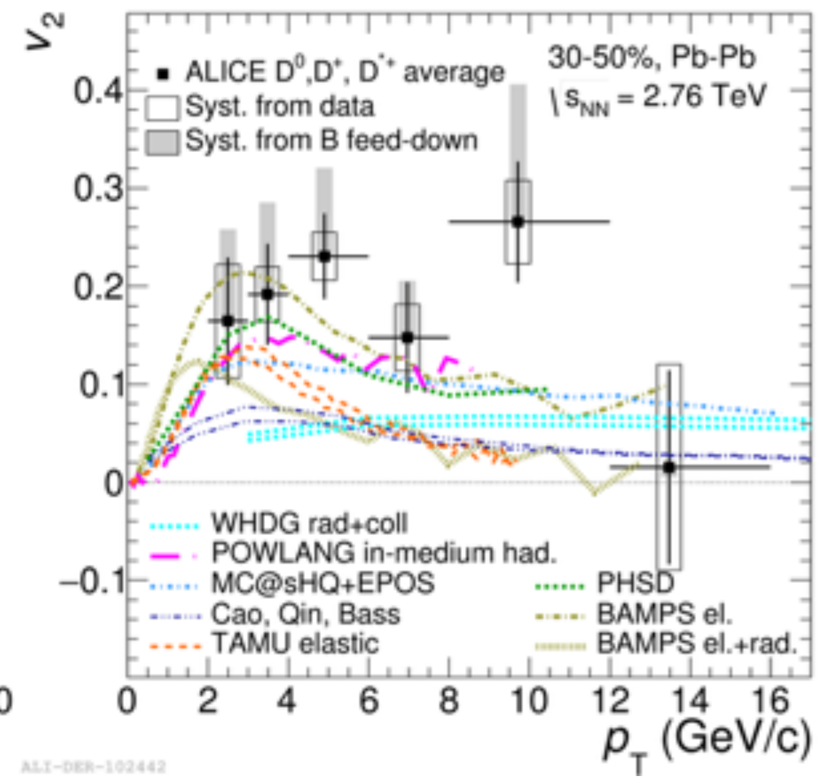


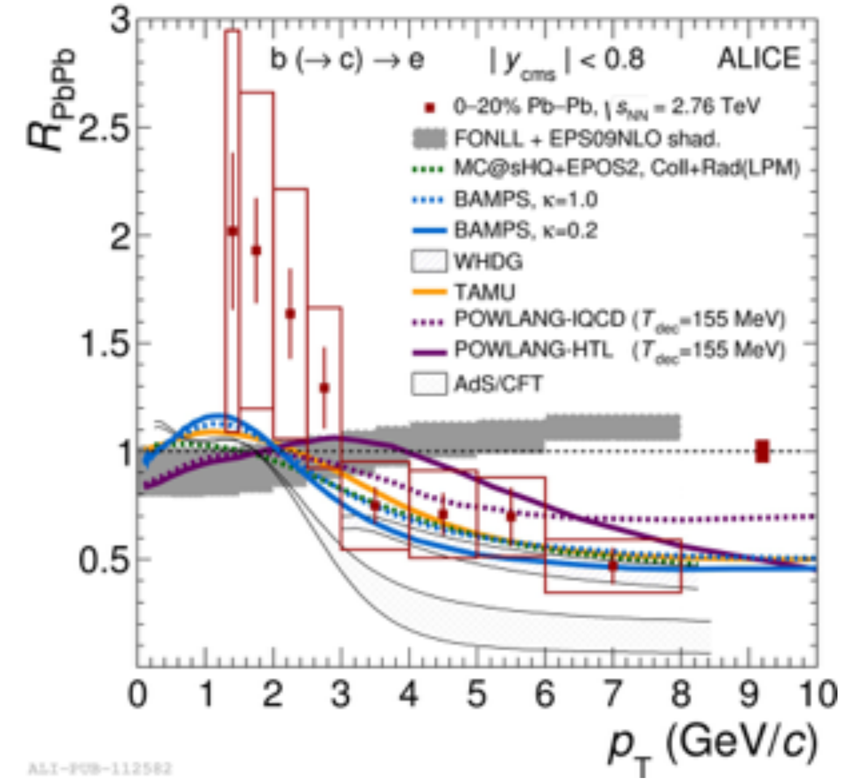
ATLAS-CONF-2015-053

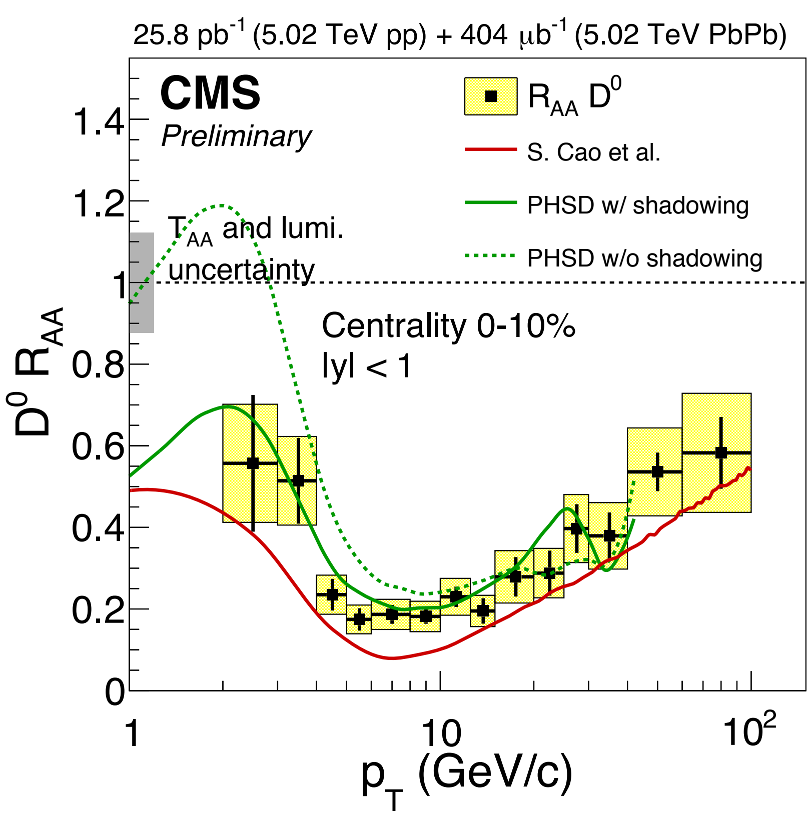
Clear suppression pattern observed as a function of centrality

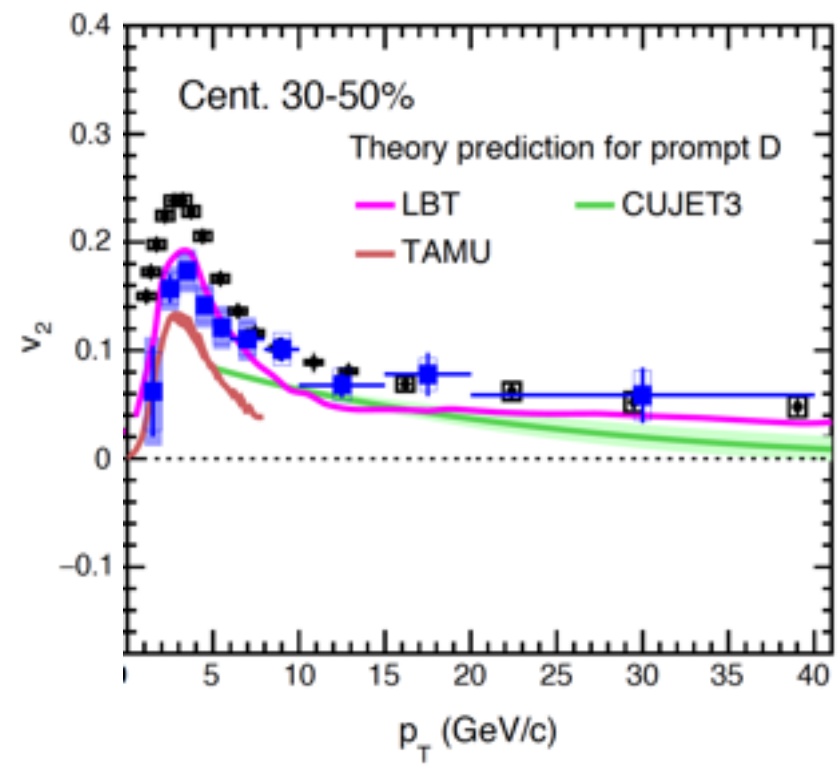
The final picture

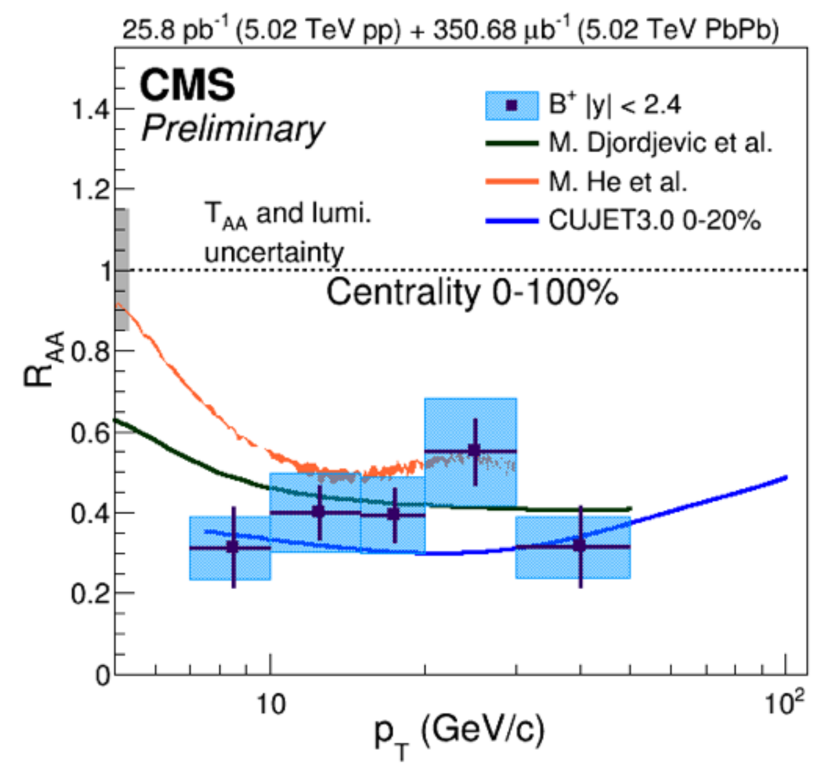




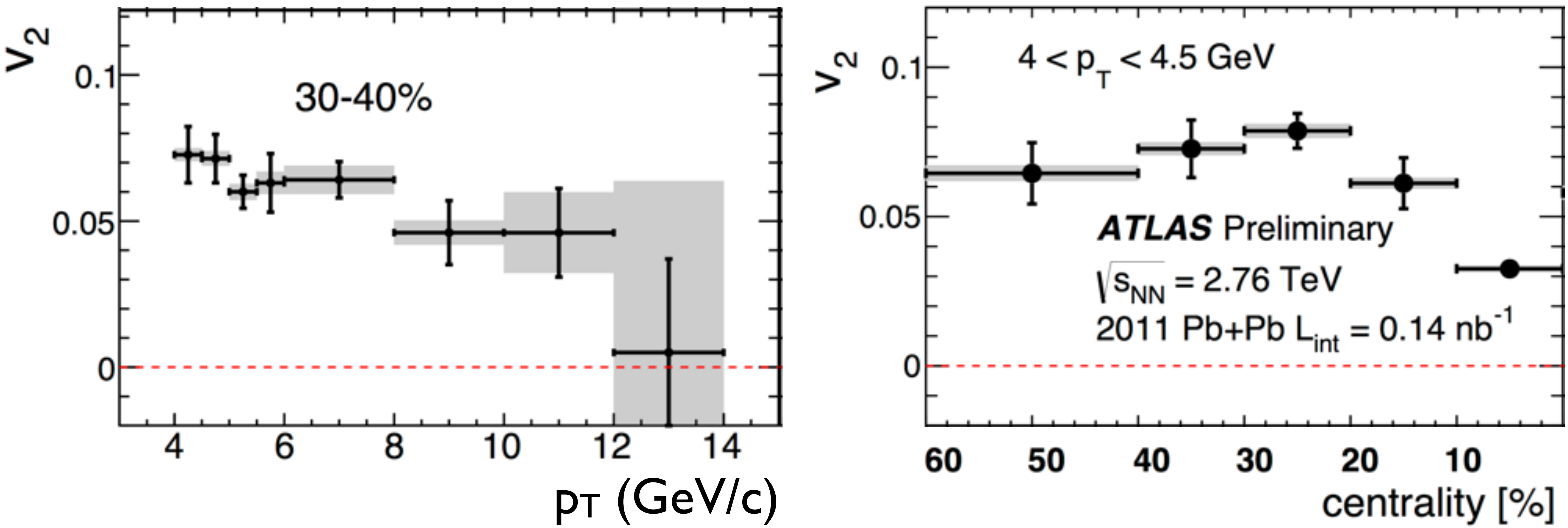








Heavy-flavour muons at 2.76 TeV



ATLAS-CONF-2015-053

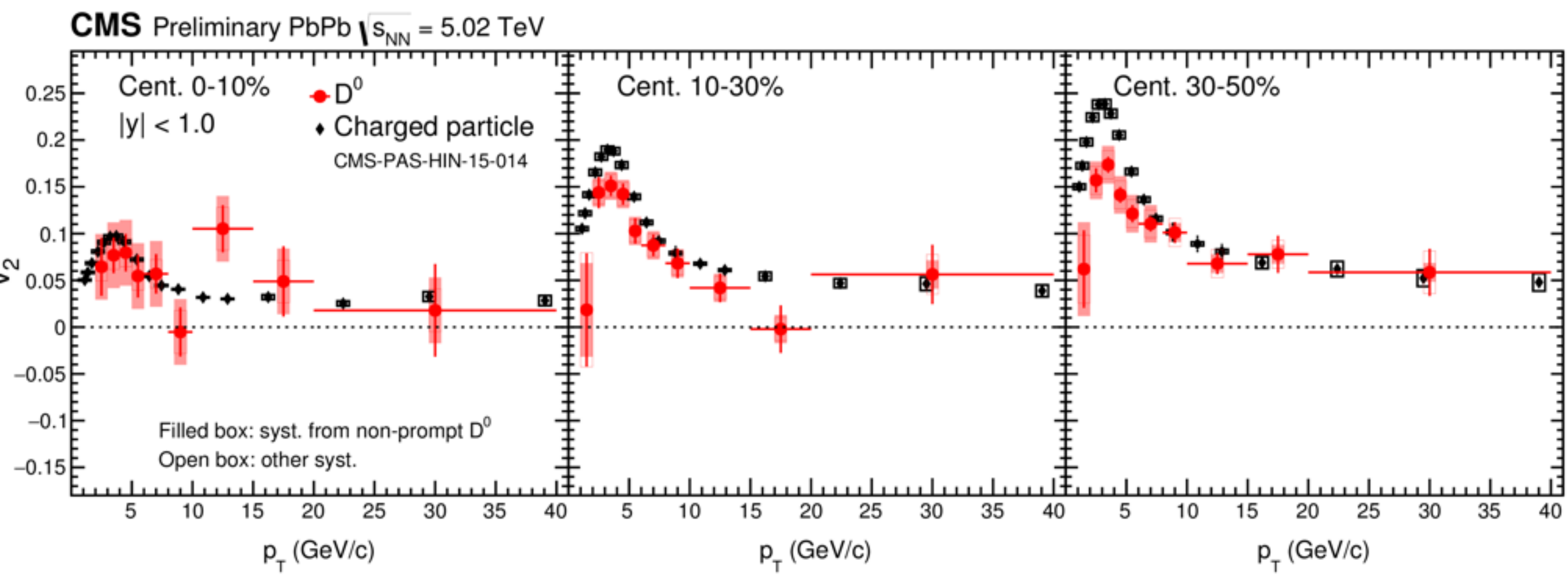
Positive v_2 for muons from heavy-flavour decays (b+c) at LHC:

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

→ indirect indication of $v_2(b)<v_2(c)$?

D meson v_2 at 5.02 TeV in PbPb collisions

New CMS measurement of v_2 and v_3 in PbPb collisions at 5.02 TeV in different collision centralities

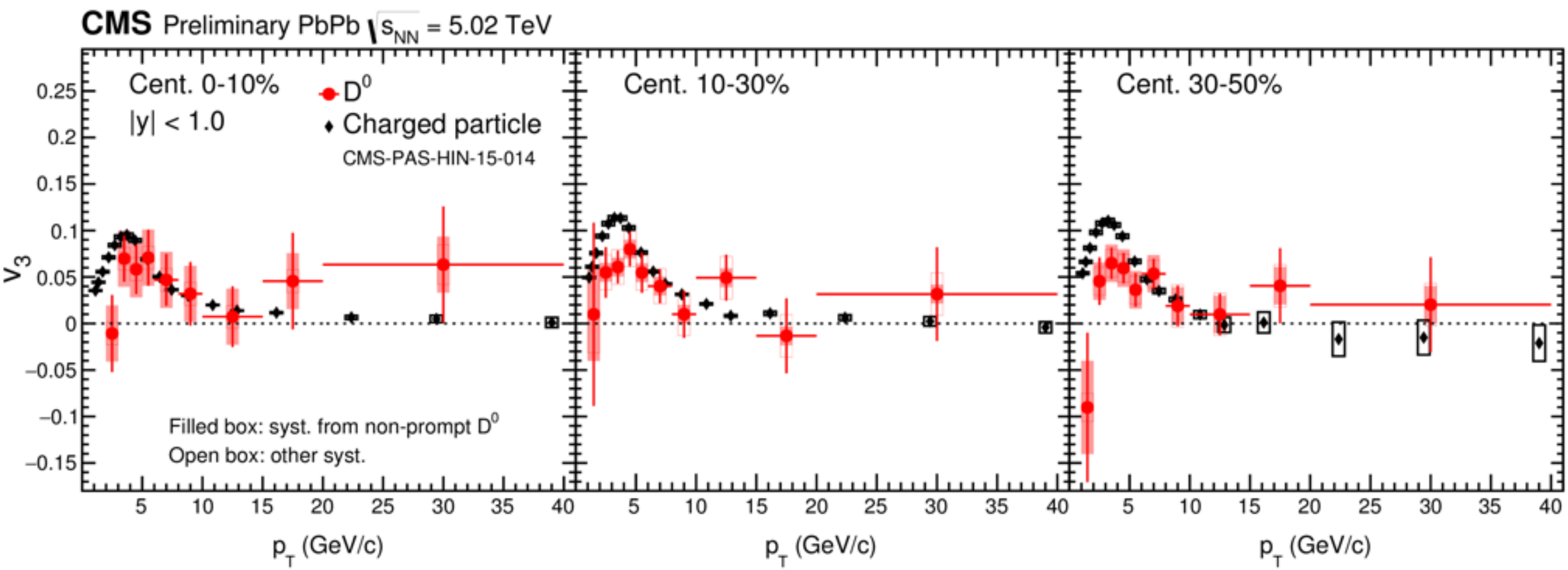


Significant confirmation of v_2>0 for D^0 at 5.02 TeV:

v_2 of D mesons larger than v_2 of charged particles

v_2(0-10%)< v_2(10-30%) ~ v_2(30-50%)

D meson v_3 at 5.02 TeV in PbPb collisions

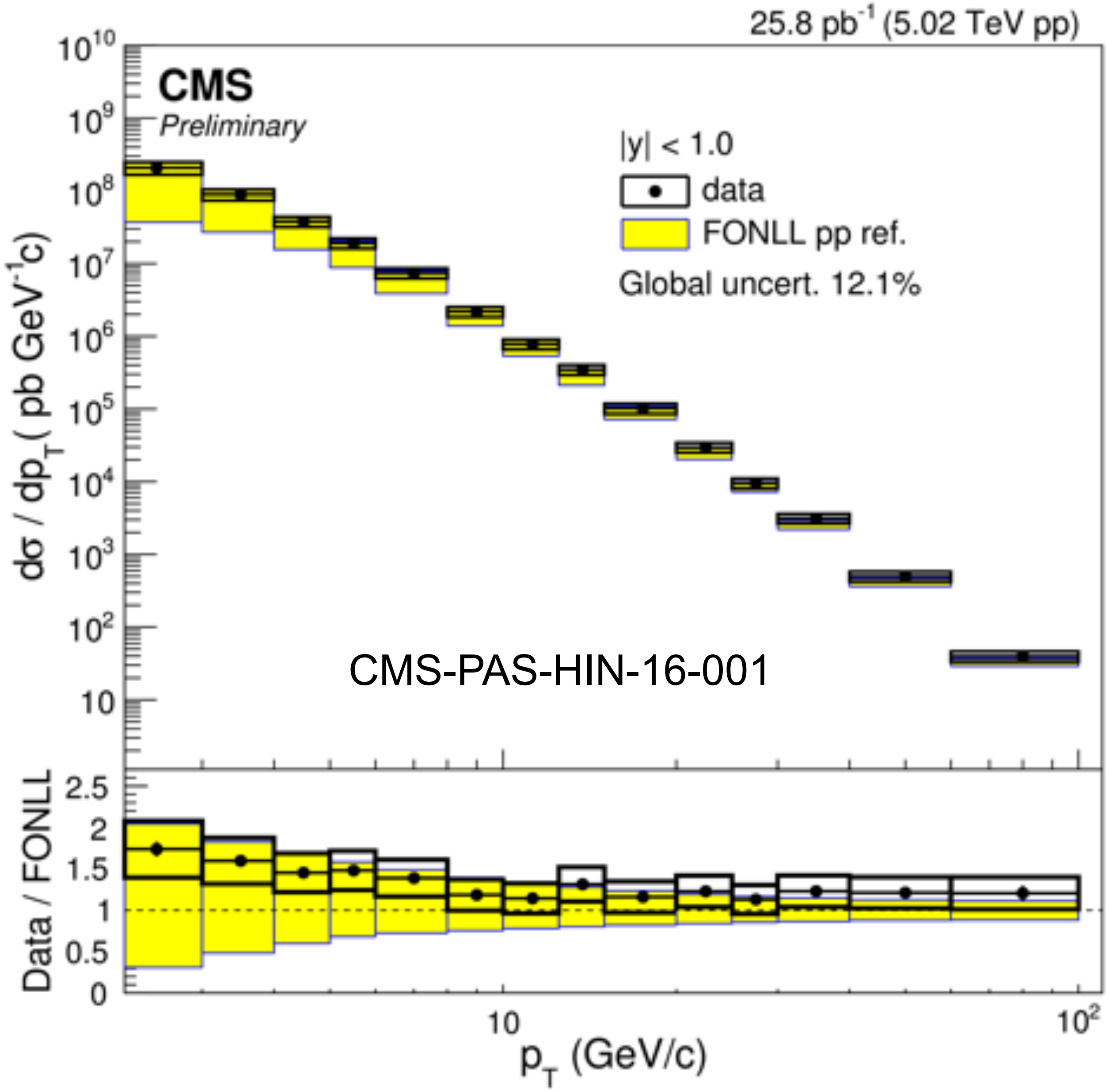


First observation of v_3>0 for charm!

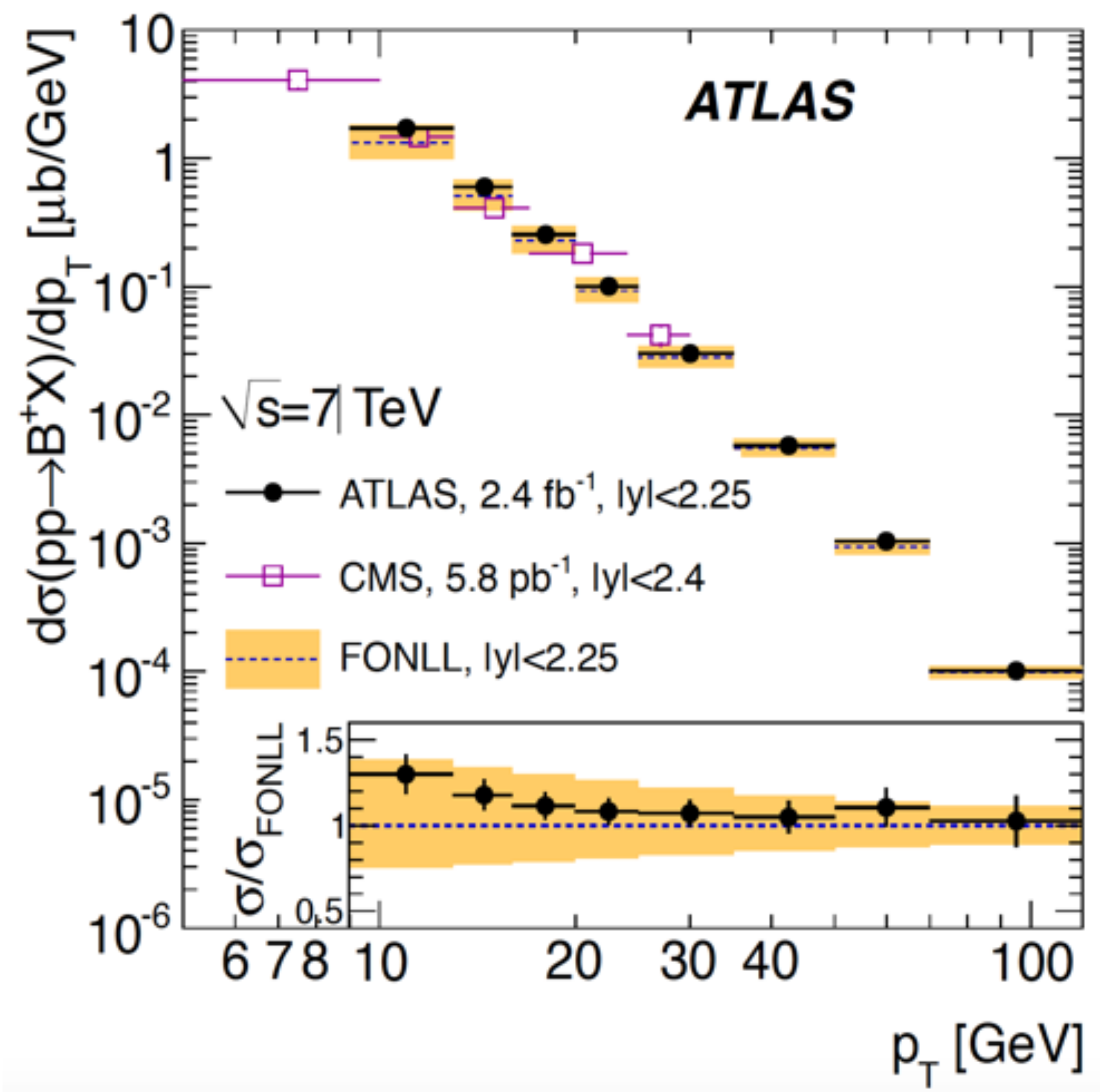
v_3 for charged particle larger that D^0 v_3 although not fully significative given current uncertainties

D and B cross sections at LHC in pp collisions

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



ATLAS B^+ measurement at 7 TeV, |y|<2.25



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*

J.Wang and T.W.Wang's talks, Saturday

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]