LHCP2017

Open heavy-flavour and Quarkonia in heavy ion collisions

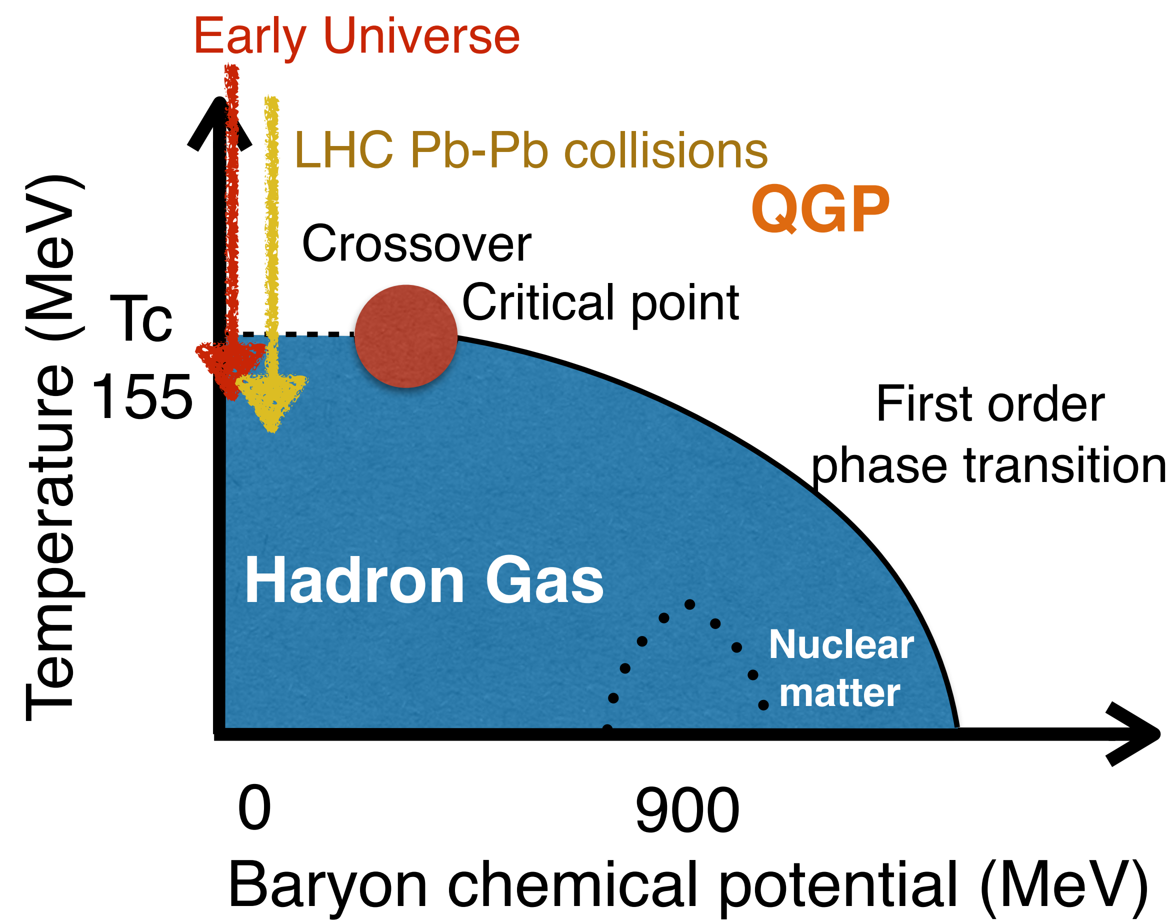
A. Festanti
CERN
On behalf of ALICE, ATLAS, CMS, LHCb

Thanks to: R. Arnaldi, I.Arsene, F.Bossu, E.Bruna, A.Dainese, A.Rossi, B.Schmidt, P.Steinberg

Introduction

- Quark-Gluon Plasma (QGP): state of strongly-interacting matter where quarks and gluons are deconfined

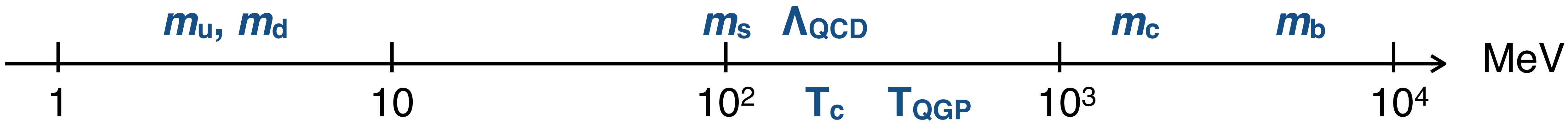
- Focus on a selection of the most recent LHC results for:



Open heavy flavours —> probe the opacity of the QGP

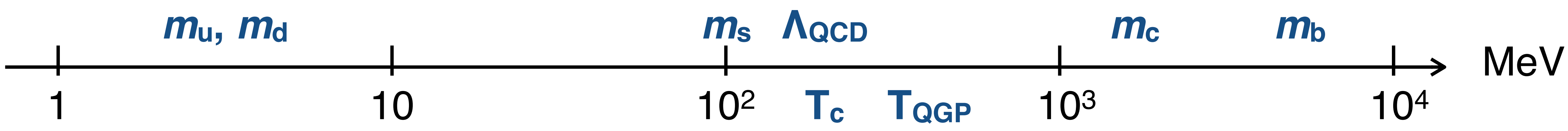
Quarkonia —> sensitive to the temperature of QGP

Probing QGP with heavy flavours



- Early production in hard-scattering processes with high Q^2 (m_c, m_b >> T_{QGP})
- Production cross section calculable with pQCD (m_c, m_b >> Λ_{QCD})
- Experience the entire evolution of the medium
- Strongly interacting with QGP

Probing QGP with heavy flavours



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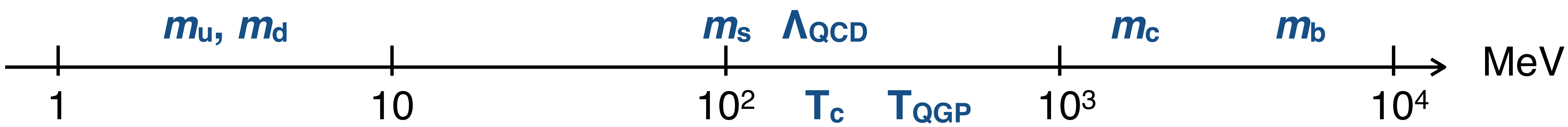
- **energy loss via radiative and collisional processes**
  - path length and medium density
  - color charge (Casimir factor)
  - quark mass (dead cone effect)

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Observable: nuclear modification factor

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \, d\sigma_{pp}/dp_T}$$

Probing QGP with heavy flavours



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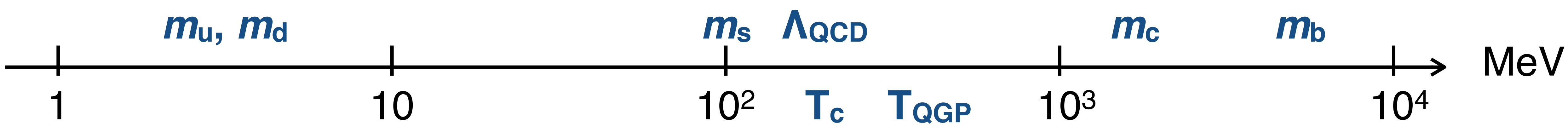
  - **energy loss via radiative and collisional processes**
  - **medium modification to HF hadron formation**
    - hadronisation via quark coalescence

Probing QGP with heavy flavours



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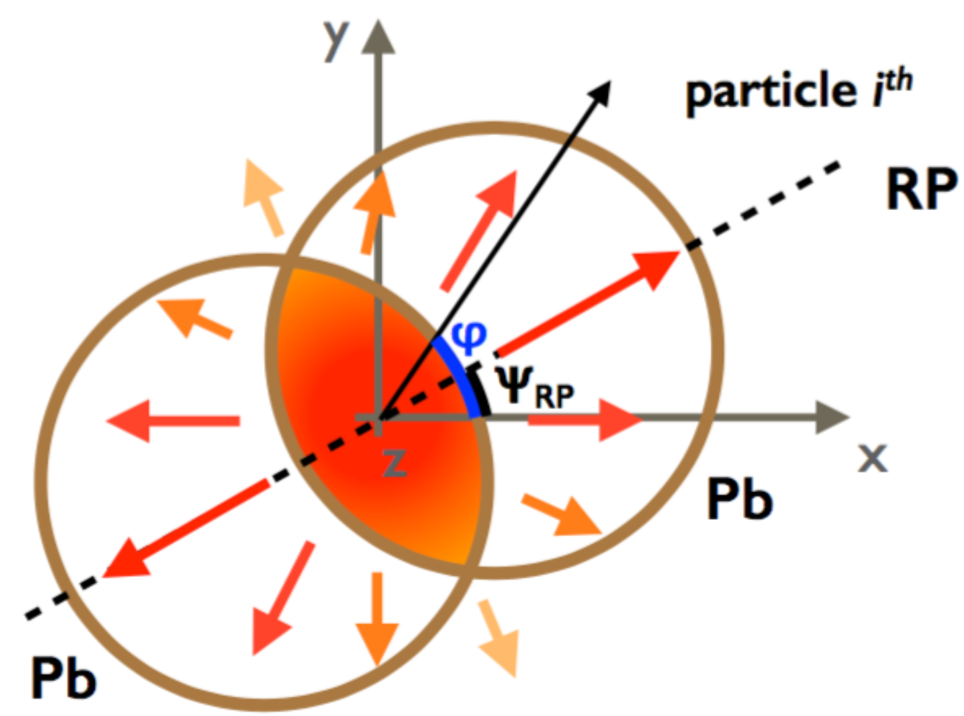
- **energy loss via radiative and collisional processes**
- **medium modification to HF hadron formation**
- **participation in the collective motion**
  - azimuthal anisotropy of produced particles

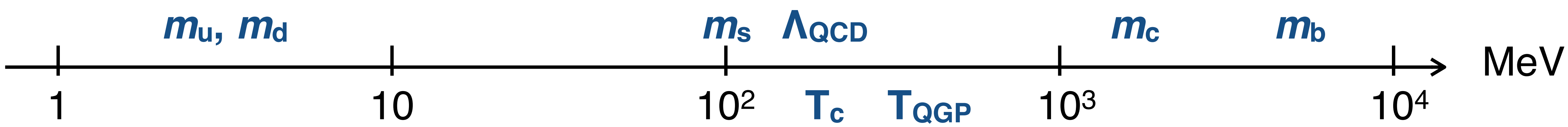


Observable: elliptic flow v_2

$$v_2 = \langle \cos 2(\varphi - \psi_2) \rangle$$

Second coefficient of the Fourier expansion of the azimuthal distribution of D w.r.t. to RP

Probing QGP with heavy flavours



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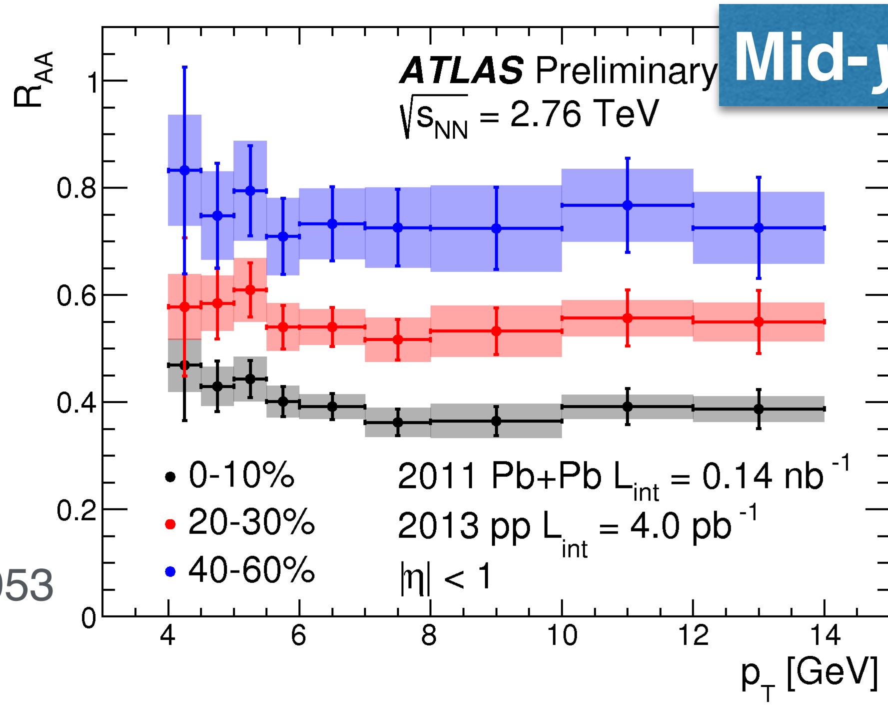
- Strongly interacting with QGP
  - **energy loss via radiative and collisional processes**
  - **medium modification to HF hadron formation**
  - **participation in the collective motion**
- Cold Nuclear Matter (CNM) effects (not due to QGP formation) that can modify heavy-flavour production in nuclear collisions studied in p-Pb collisions —> nuclear modification factor R_{pPb}

Heavy-flavour decay muons

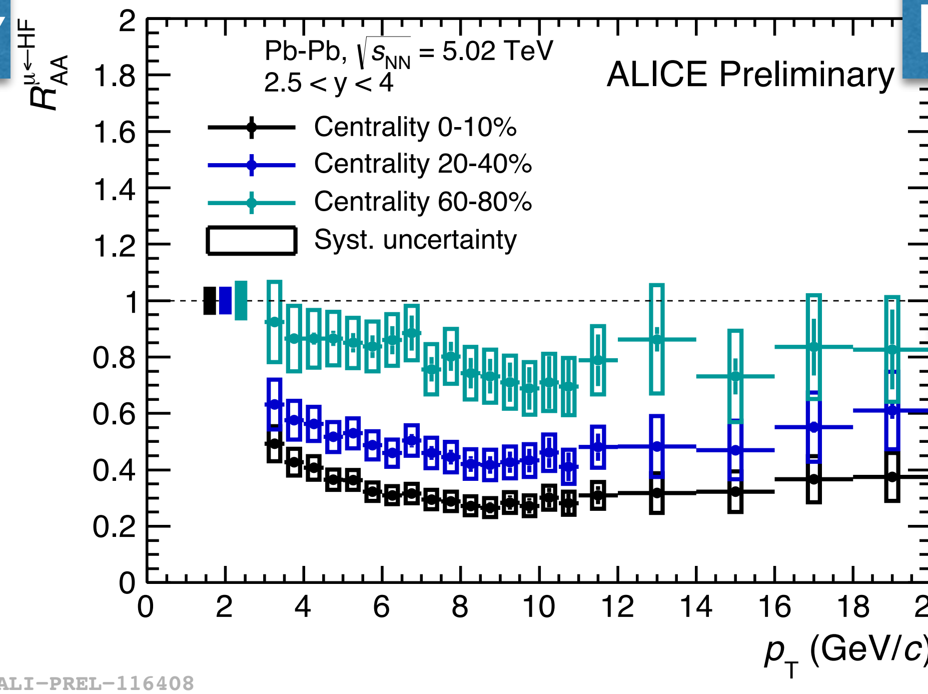
- Suppression of heavy-flavour decay muons increasing with centrality at mid and forward rapidity (no strong dependence on $\sqrt{s_{NN}}$ observed)

Pb-Pb



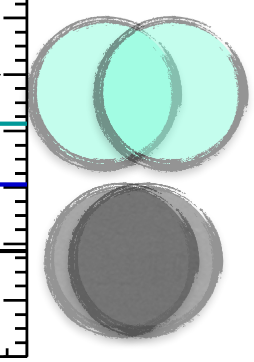
Mid-*y*

ATLAS-CONF-2015-053



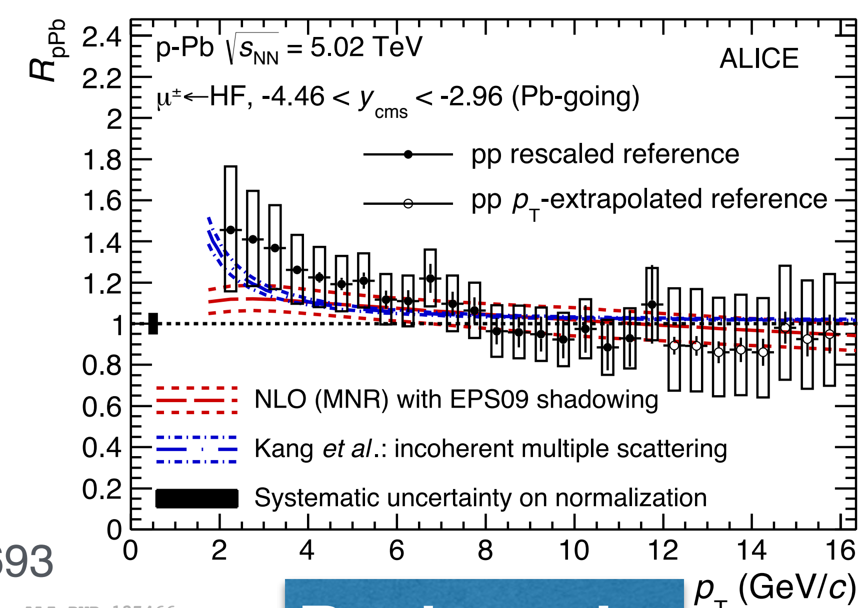
ALI−PREL−116408

Forward-*y*



- R_{pPb} consistent with unity —> suppression in Pb-Pb collisions due to hot nuclear matter effects

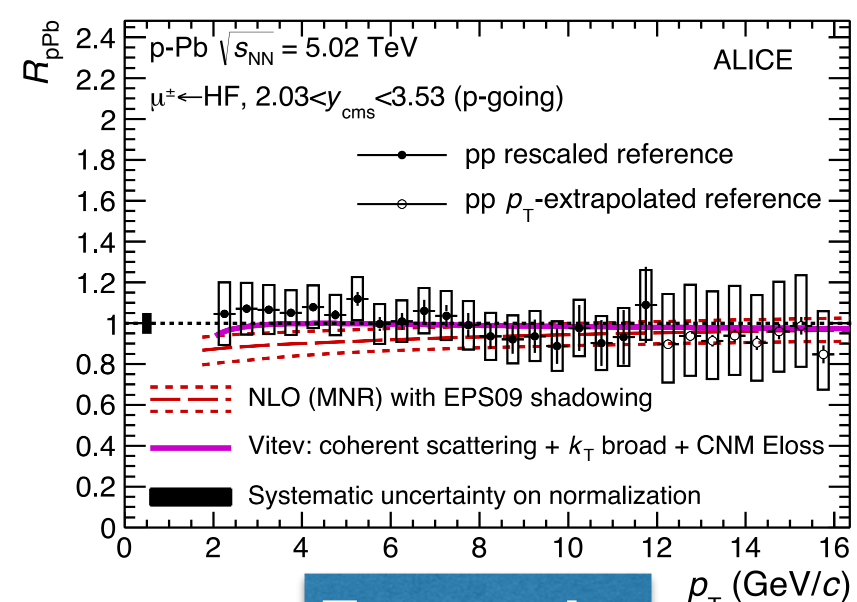
p-Pb



PLB (2017) 0370-2693

ALI−PUB−127466

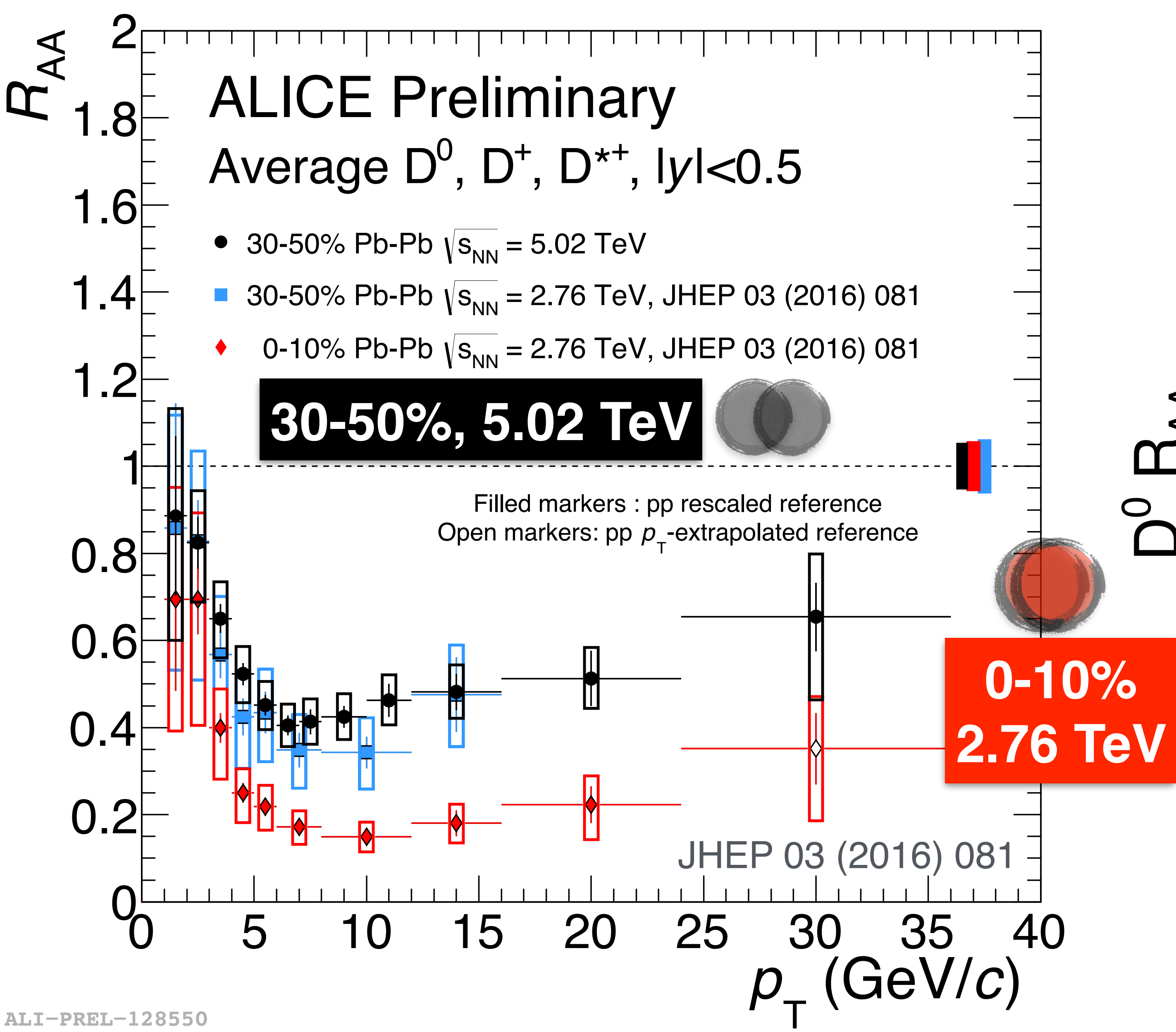
Backward-*y*

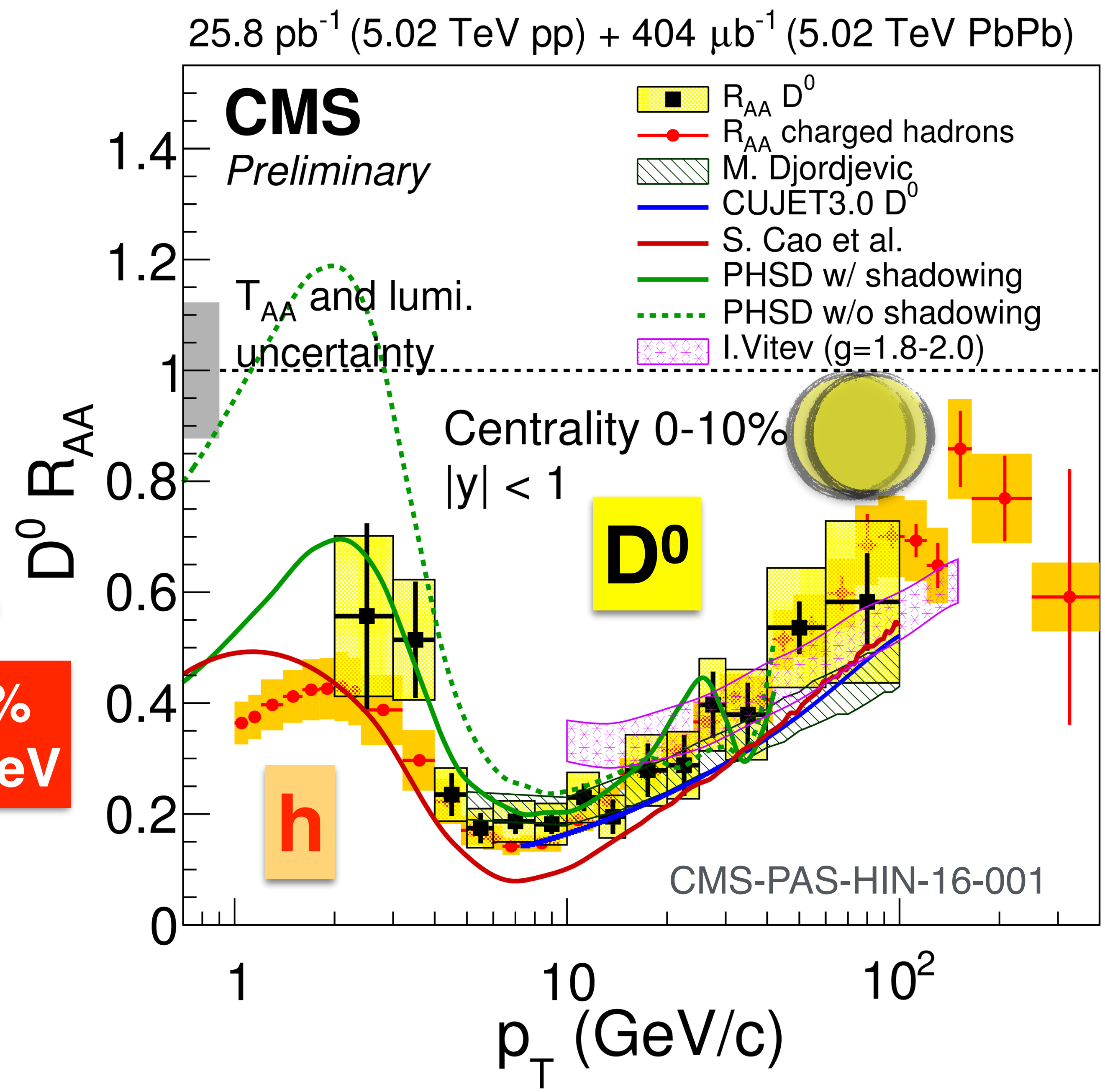


ALI−PUB−127462

Forward-*y*

Charm suppression

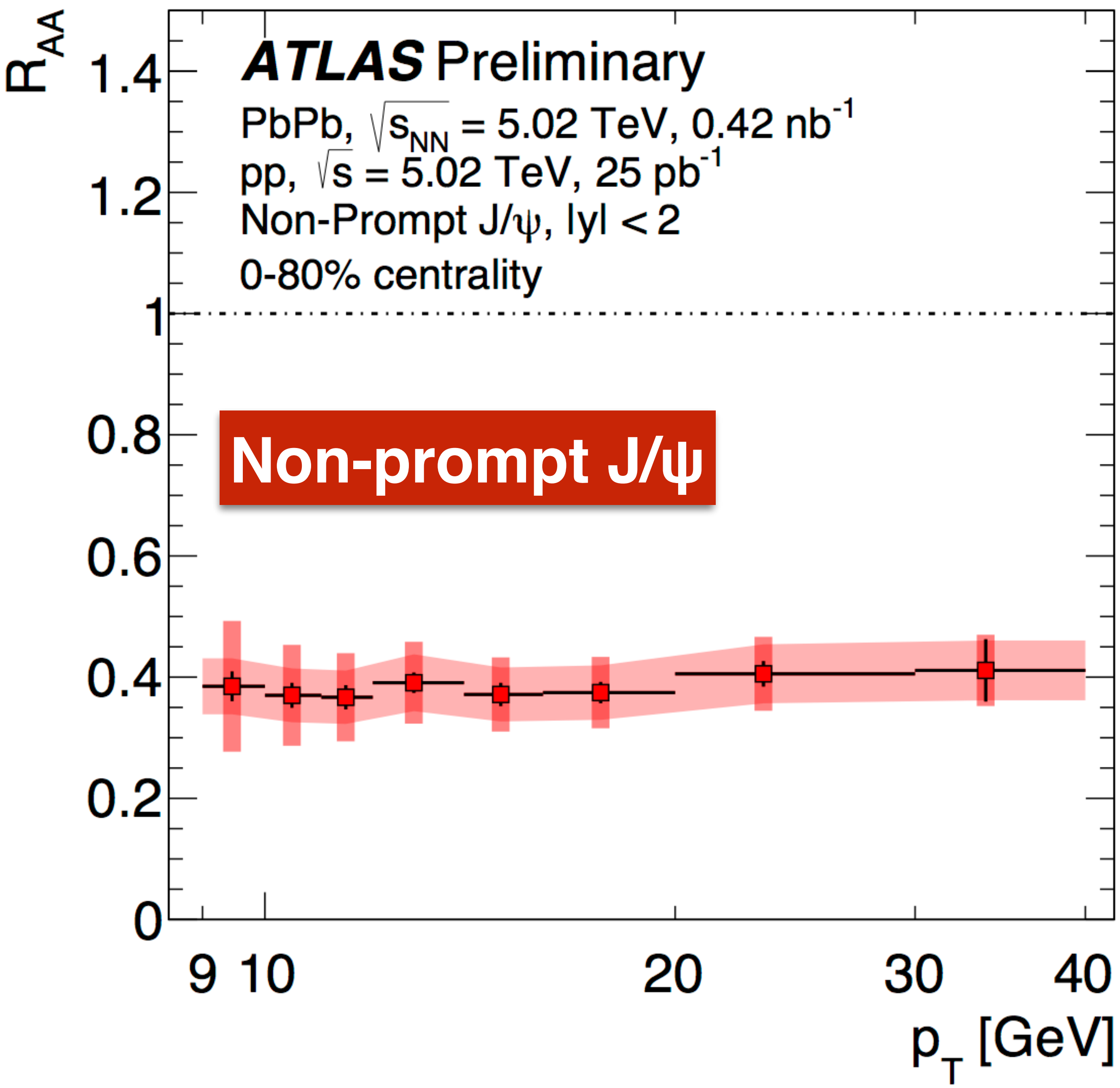




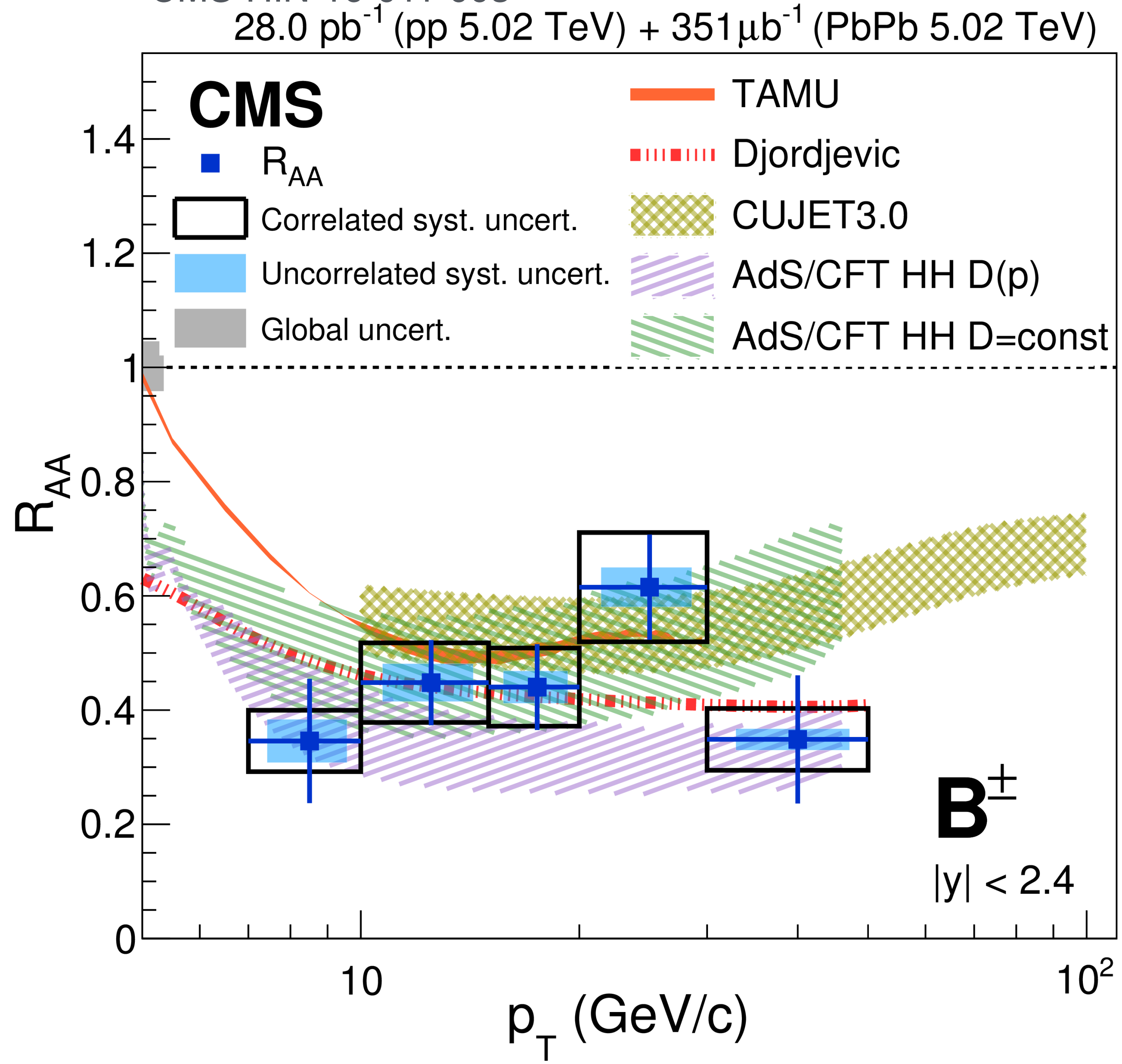
- Strong suppression of D-meson R_{AA} in central Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV
- Similar suppression in semi-central events at different energies
- R_{AA}(D) ~ R_{AA}(h) for p_T > 4 GeV/c

Beauty suppression

ATLAS-CONF-2016-109

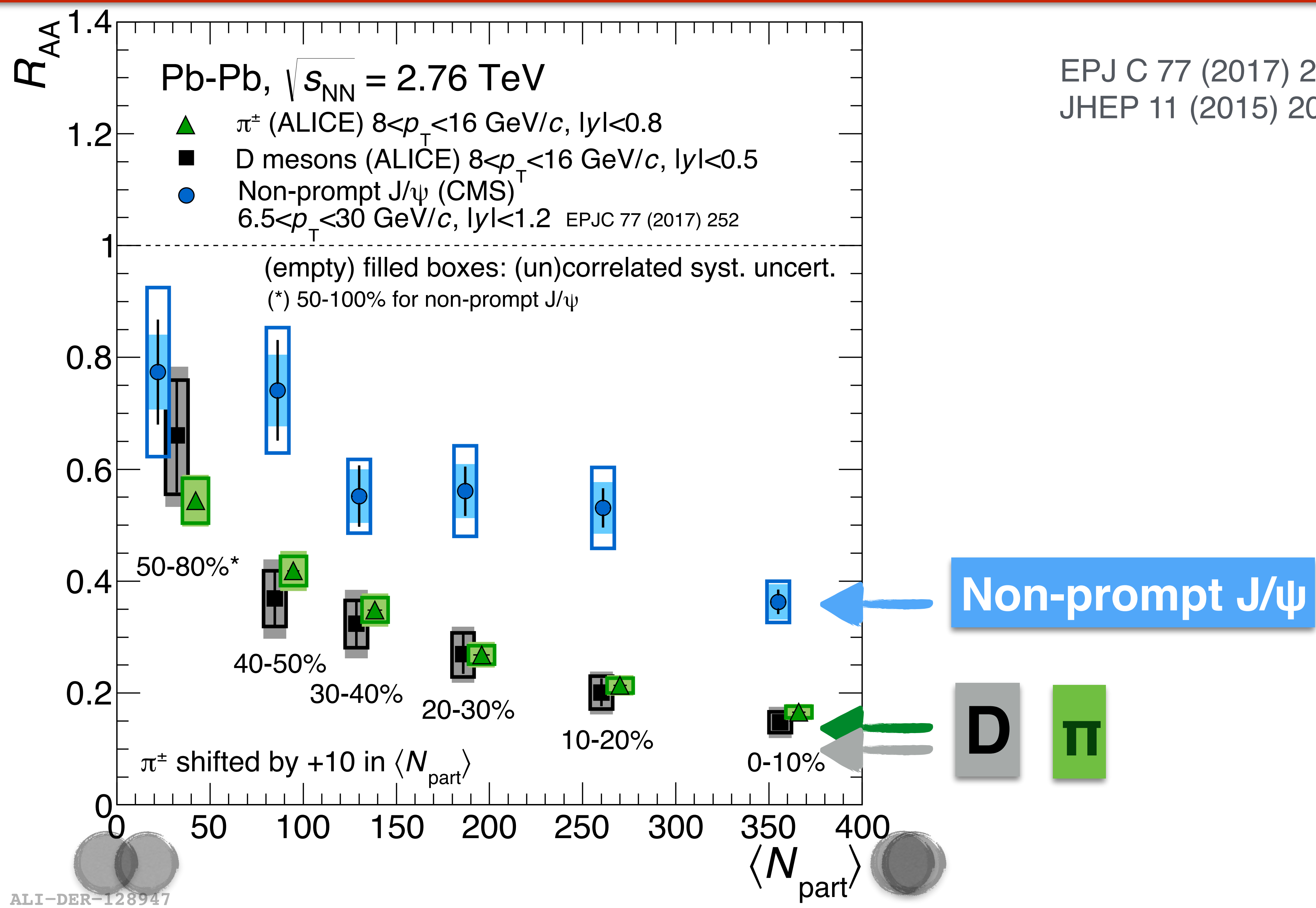


CMS-HIN-16-011-003



- Similar suppression ($R_{AA} \sim 0.4$) for non-prompt J/ψ and B± for $p_T > 10$ GeV/c observed in wide centrality class (0-80% for non-prompt J/ψ and 0-100% for B±)

Charm and beauty suppression



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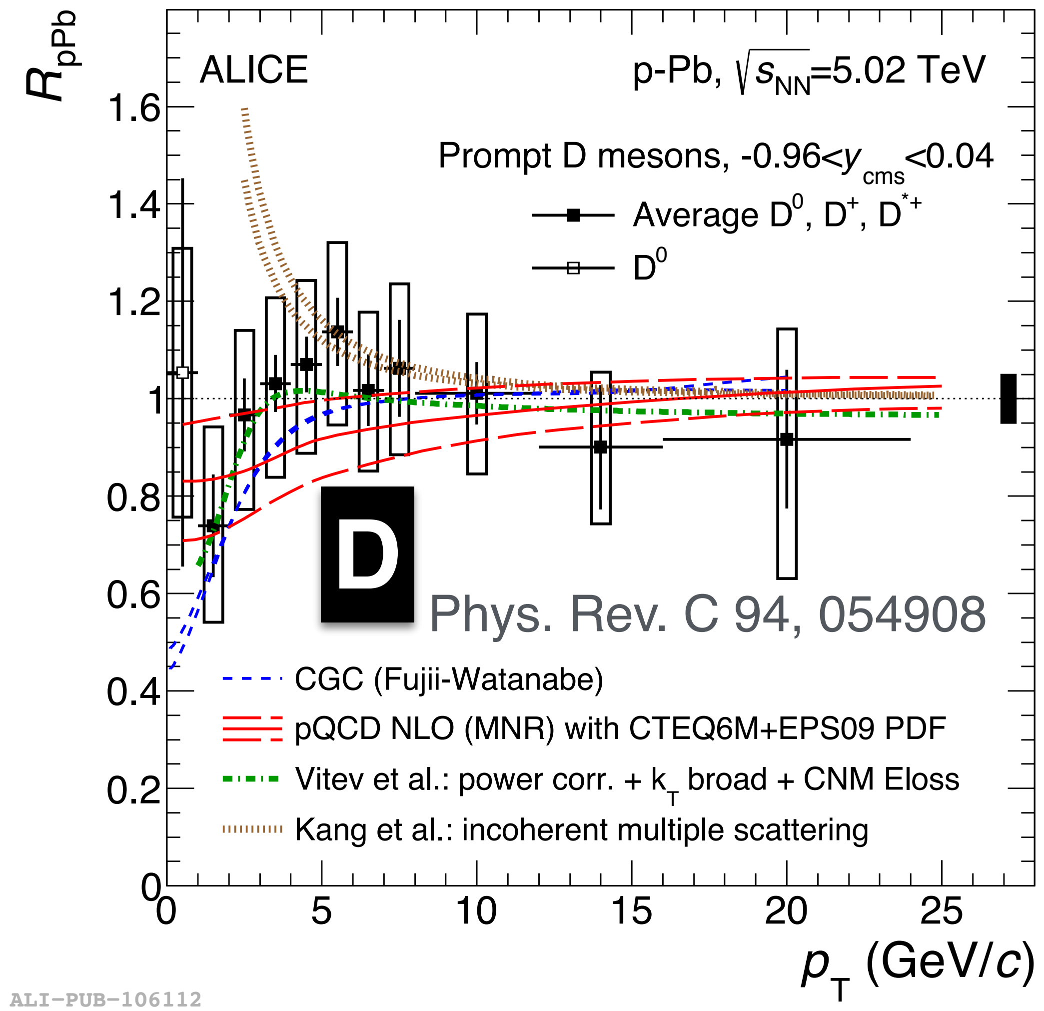
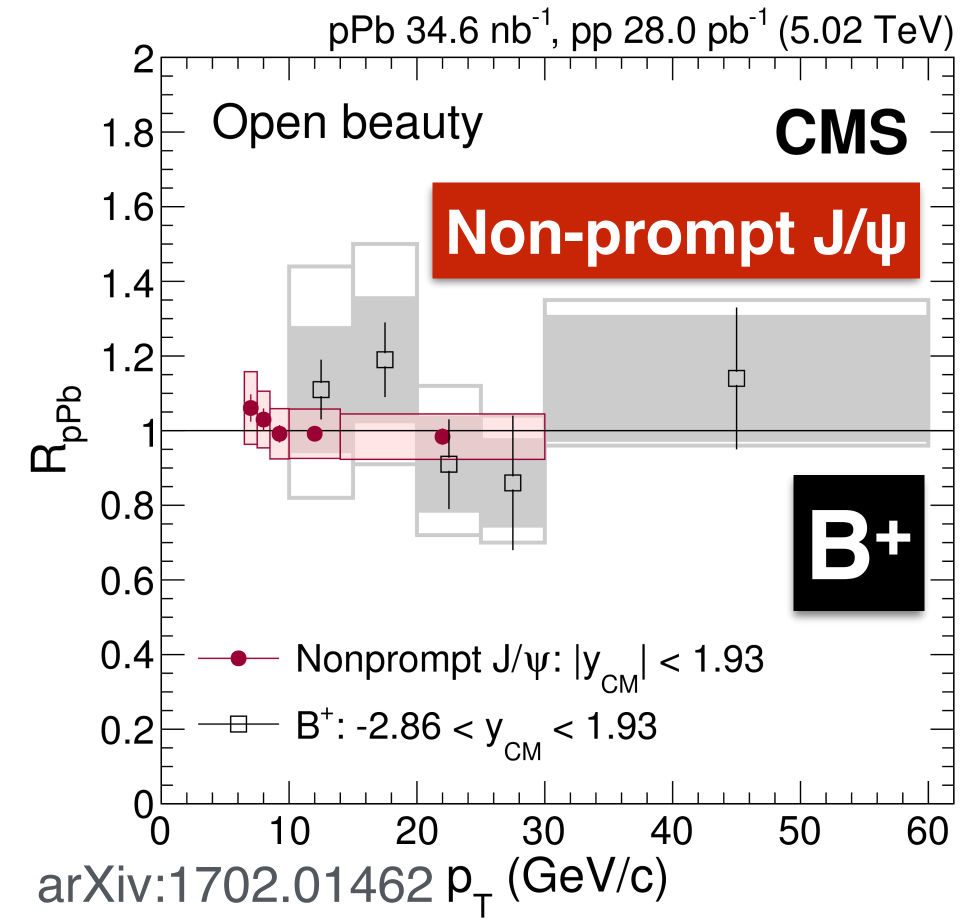
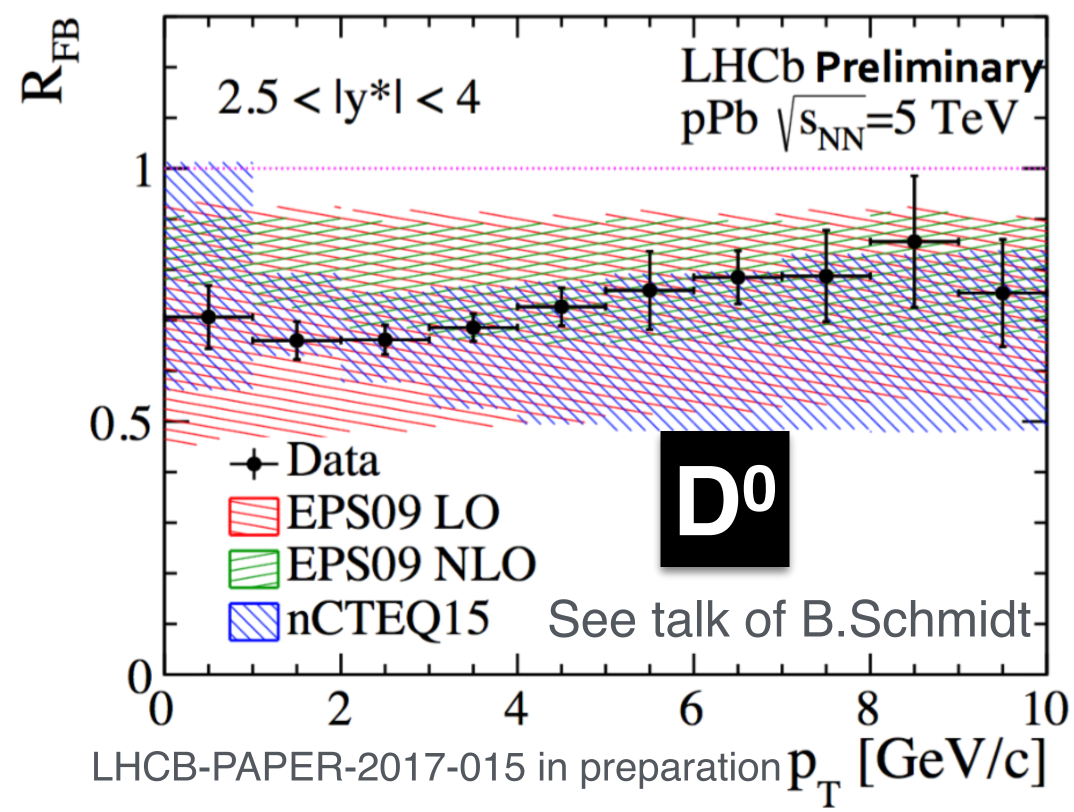
JHEP 11 (2015) 205

- D-meson R_{AA} significantly smaller than the R_{AA} of non-prompt J/ψ in central collisions —> indication of mass dependent suppression for charm and beauty
- R_{AA}(D) ~ R_{AA}(π) —> different vacuum fragmentation of charm vs. light quarks and light/heavy quark p_T spectrum are relevant in the R_{AA} comparison

Charm and beauty in p-Pb collisions

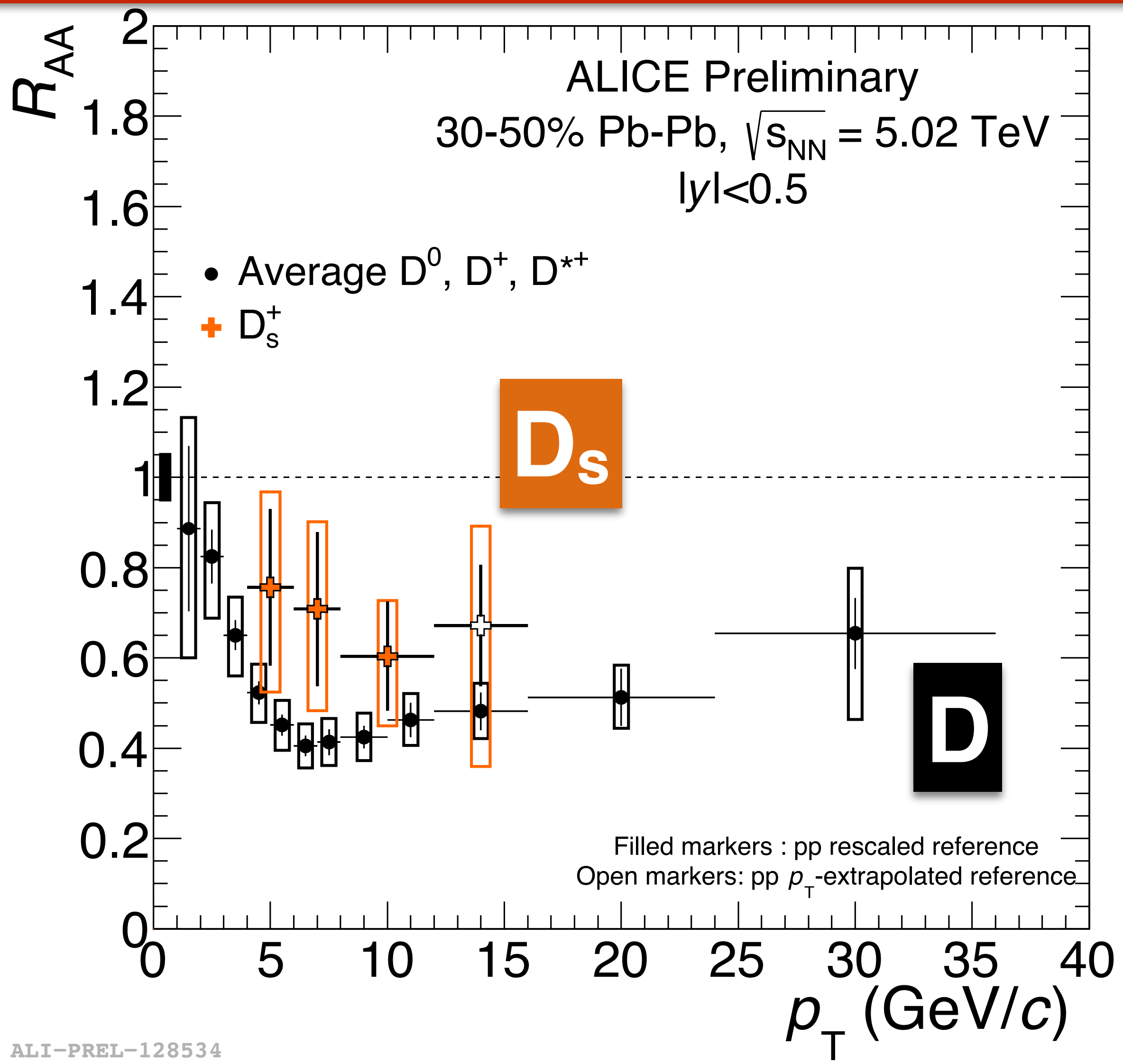


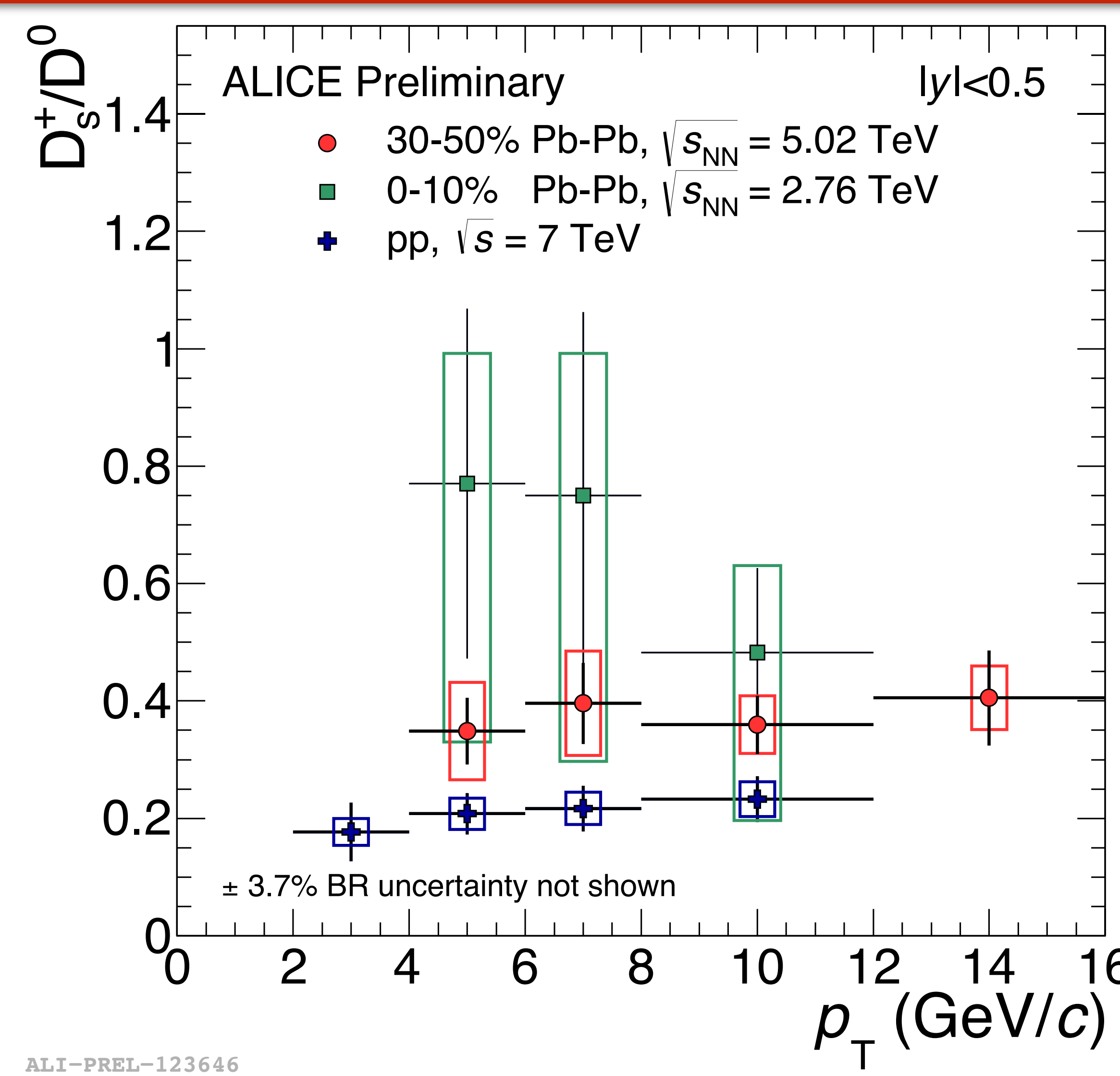




- D-meson, non-prompt J/ψ and B^+ R_{pPb} compatible with unity
  - Strong suppression observed in central Pb-Pb collisions due to hot nuclear matter effects
- Models based on pQCD and including Cold Nuclear Matter effects describe D-meson R_{pPb} at mid-rapidity and forward/backward asymmetry

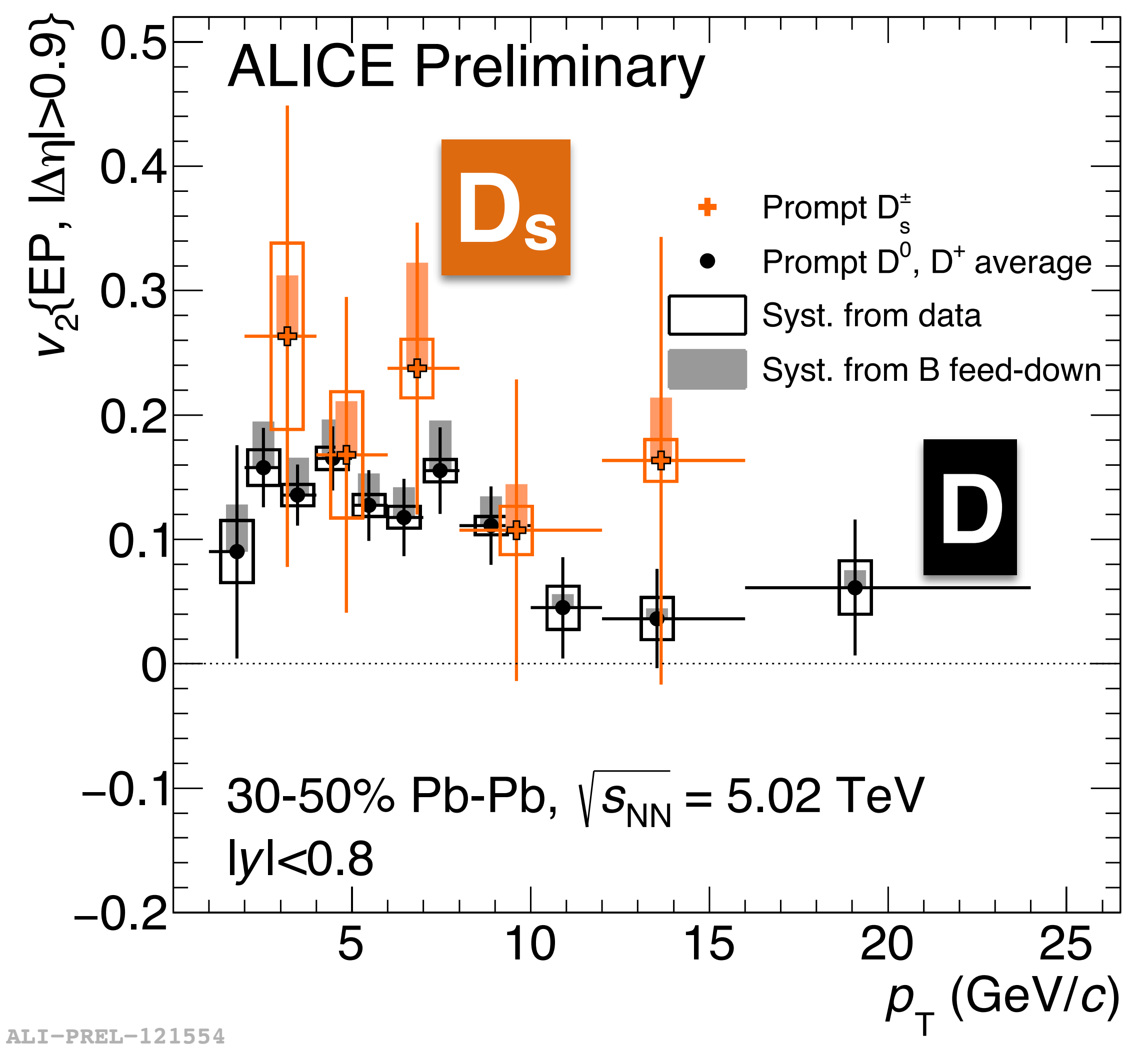
D_s production in Pb-Pb collisions

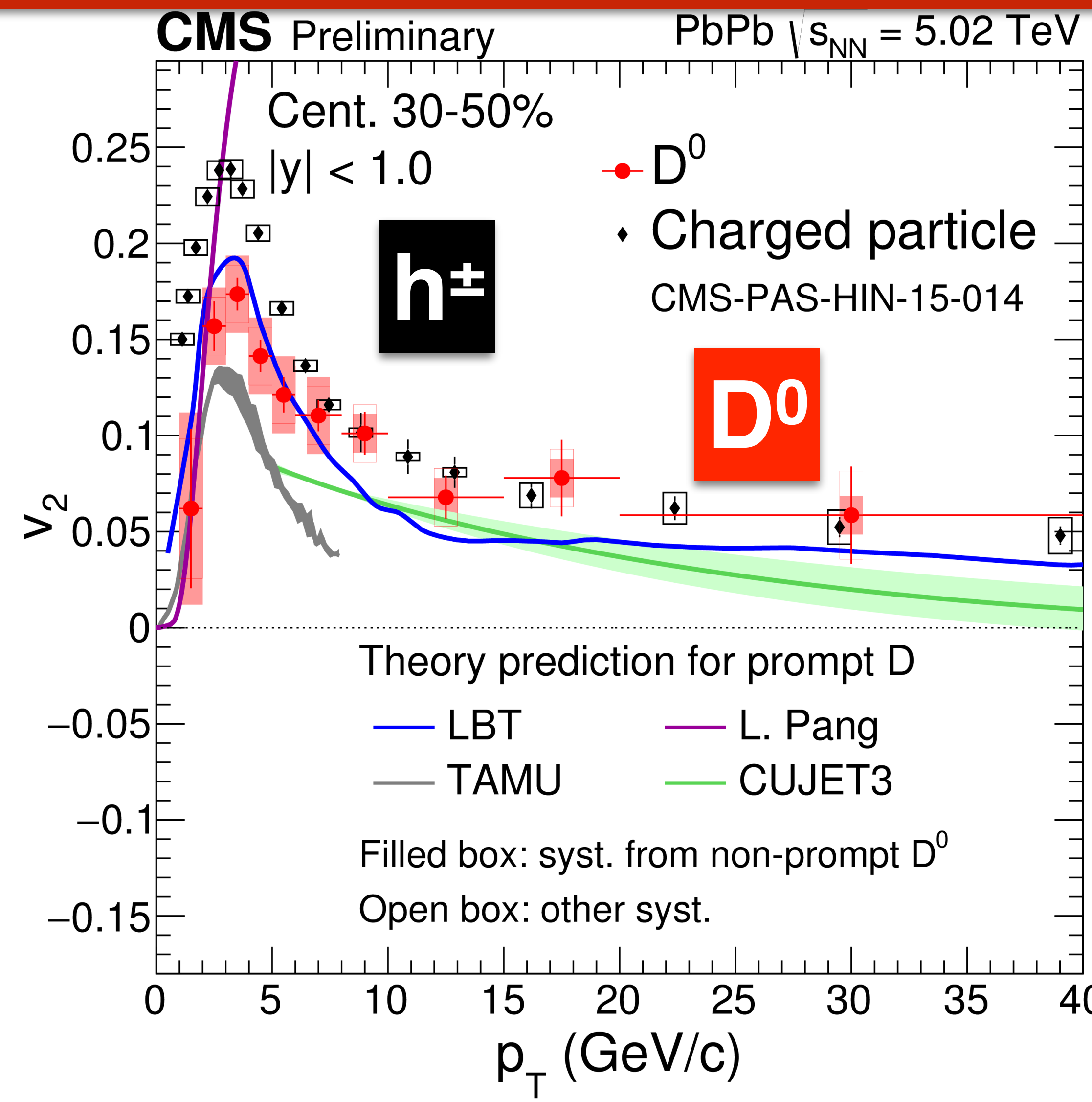




- Enhanced production of quark s in Pb-Pb collisions with respect to pp collisions—> expected larger D_s yields than non-strange D mesons at low p_T (coalescence)
- Hint of $R_{AA}(D_s) > R_{AA}(D)$ in semi-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (still large uncertainties to draw conclusions)
- D_s/D^0 ratio increasing going from **pp**, to **semi-central** and **central** Pb-Pb collisions (large uncertainties in central collisions)
- Support contribution from coalescence for hadronisation

D-meson v_2

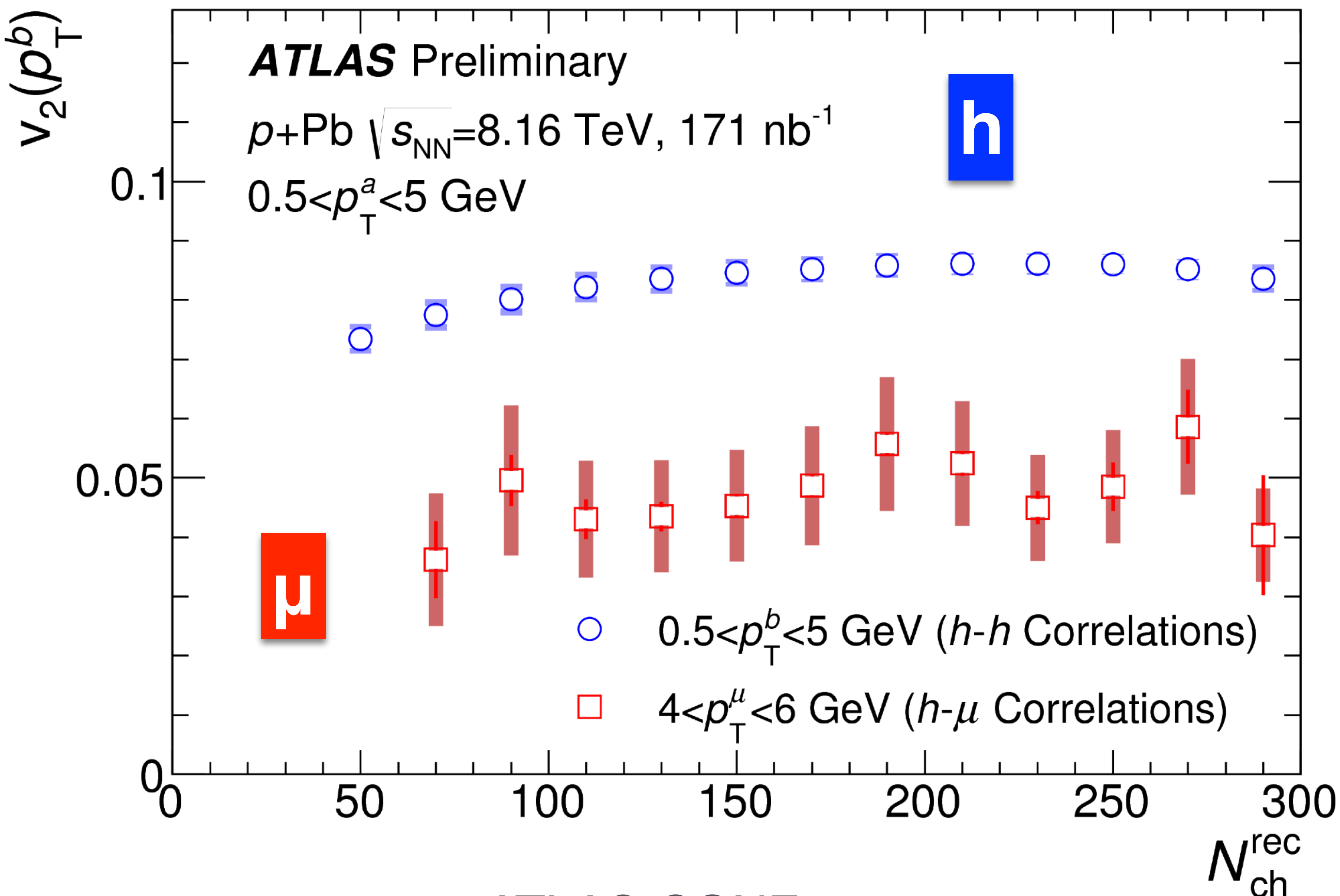




- Significant D-meson v_2 measured in semi-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- First measurement of D_s v_2 at LHC
- D-meson v_2 has similar values as charged-particle v_2
- Strong interaction of charm quark with medium constituents
  - low p_T: charm takes part in the collective expansion of the system
  - high p_T: path-length dependence of energy loss

Heavy-flavour v_2 in p-Pb collisions

- Strong interaction of charm quark with medium constituents in Pb-Pb collisions —> coupling to the azimuthal anisotropy of the system
- Investigate azimuthal anisotropy in small systems like p-Pb collisions



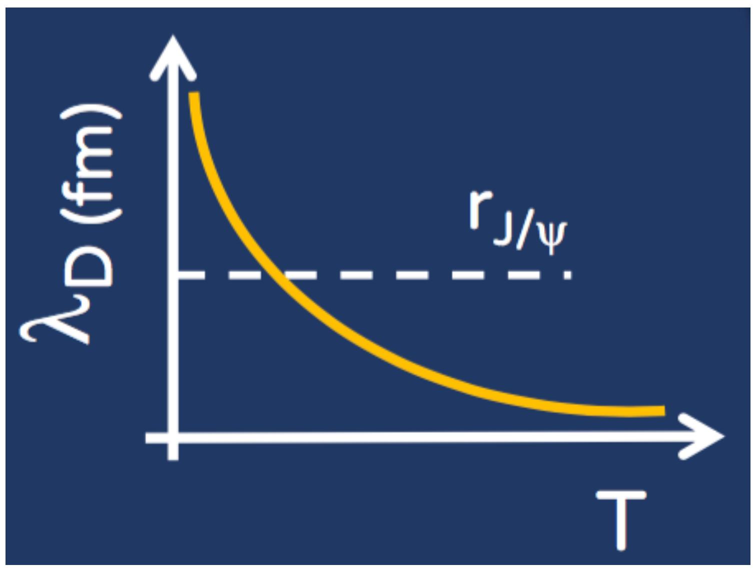
ATLAS-CONF-2017-006

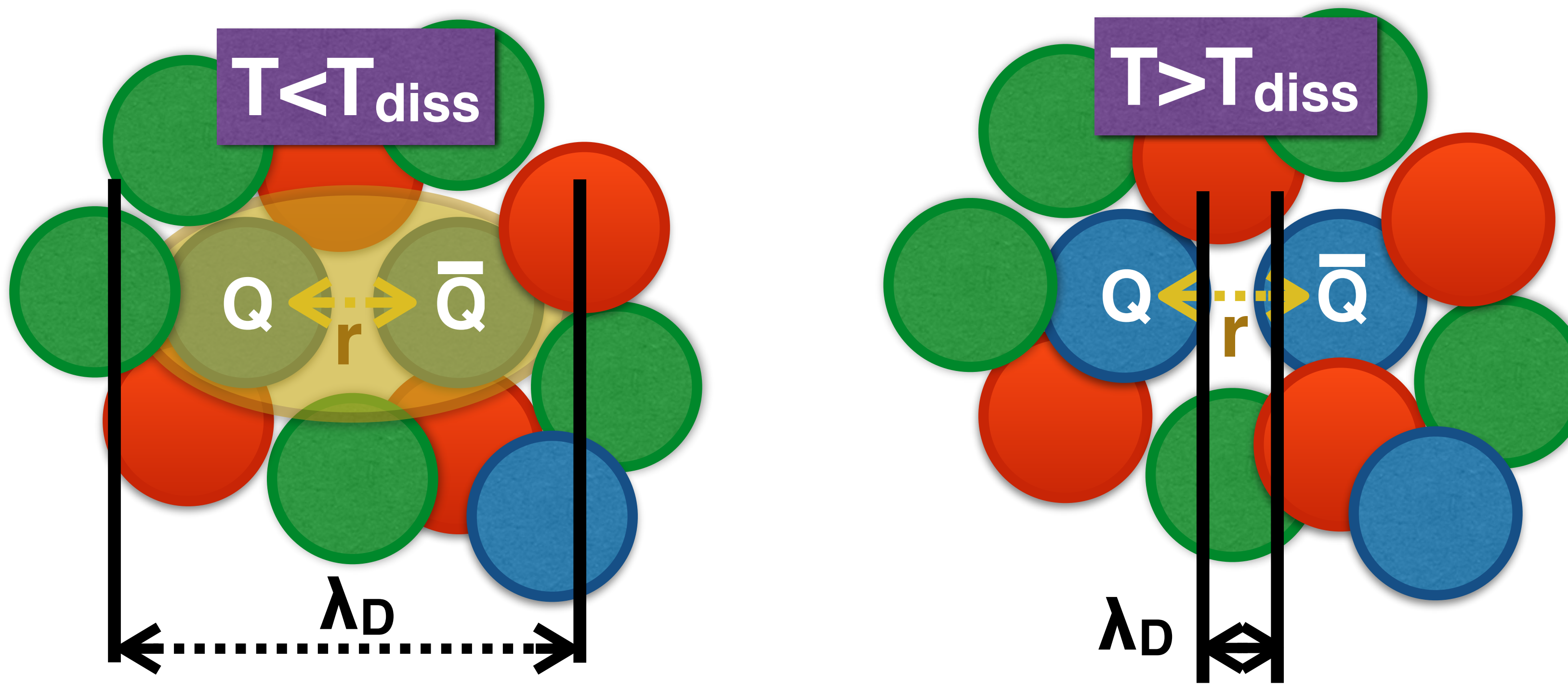
- ATLAS measured heavy-flavour decay muons v_2 in p-Pb collisions at 8.16 TeV
- Significant v_2 (~0.6 hadron v_2) observed for heavy-flavour decay muons for multiplicities > 60

Quarkonium suppression

Color Screening

- Quarkonium production suppression due to color screening in the QGP

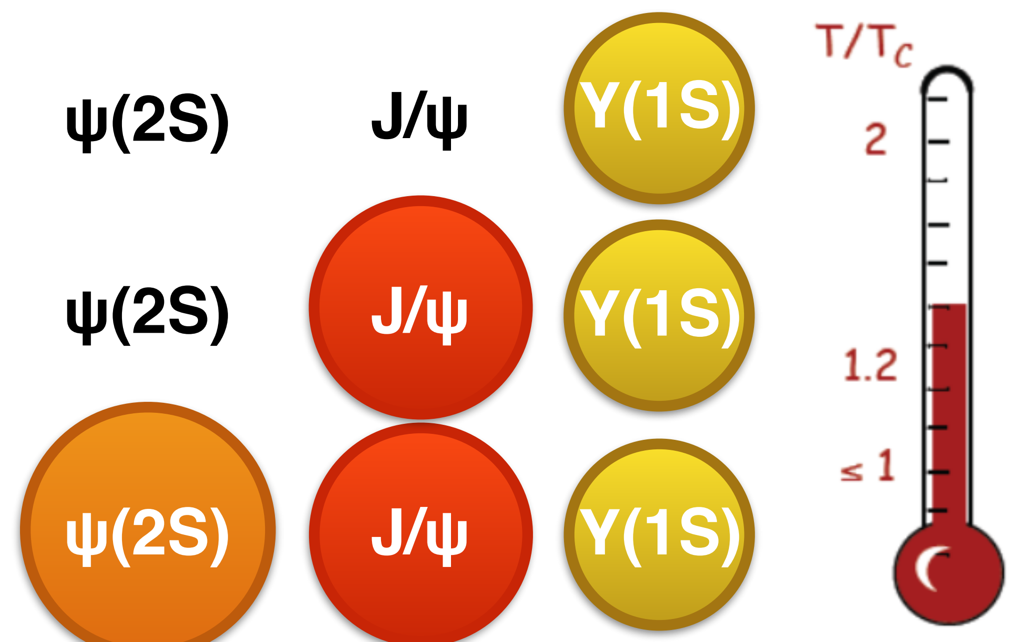




T.Matsui and H.Satz, PLB178 (1986) 416

Sequential melting

- Different states with different binding energies (sizes)
- Sequential melting with increasing temperature



Quarkonium recombination

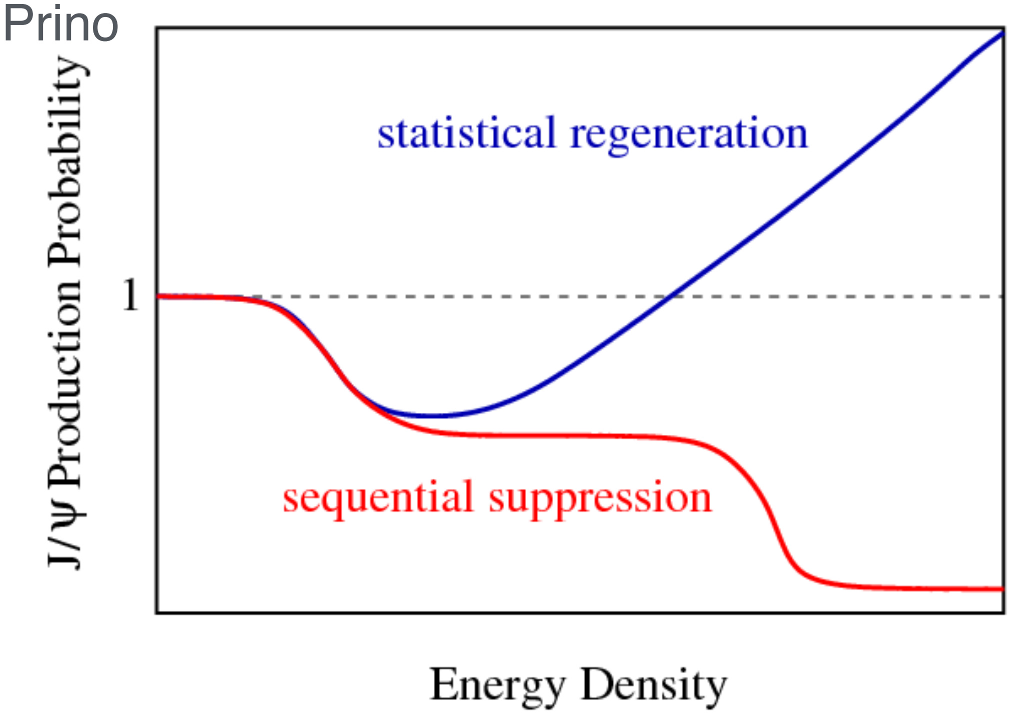
(Re)combination

- Increasing the collision energy the $c\bar{c}$ pair multiplicity increases

Central AA collisions	$N_{c\bar{c}}$ / event	$N_{b\bar{b}}$ / event
SPS, 20 GeV	~0.2	-
RHIC, 200GeV	~10	-
LHC, 2.76TeV	~85	~2
LHC, 5.02 TeV	~115	~3

Private communication R.Arnaldi, A.Dainese, F.Prino

- Enhanced quarkonium production via (re)combination at hadronisation or during the QGP phase
- Negligible recombination contribution for bottomonia even at LHC energies

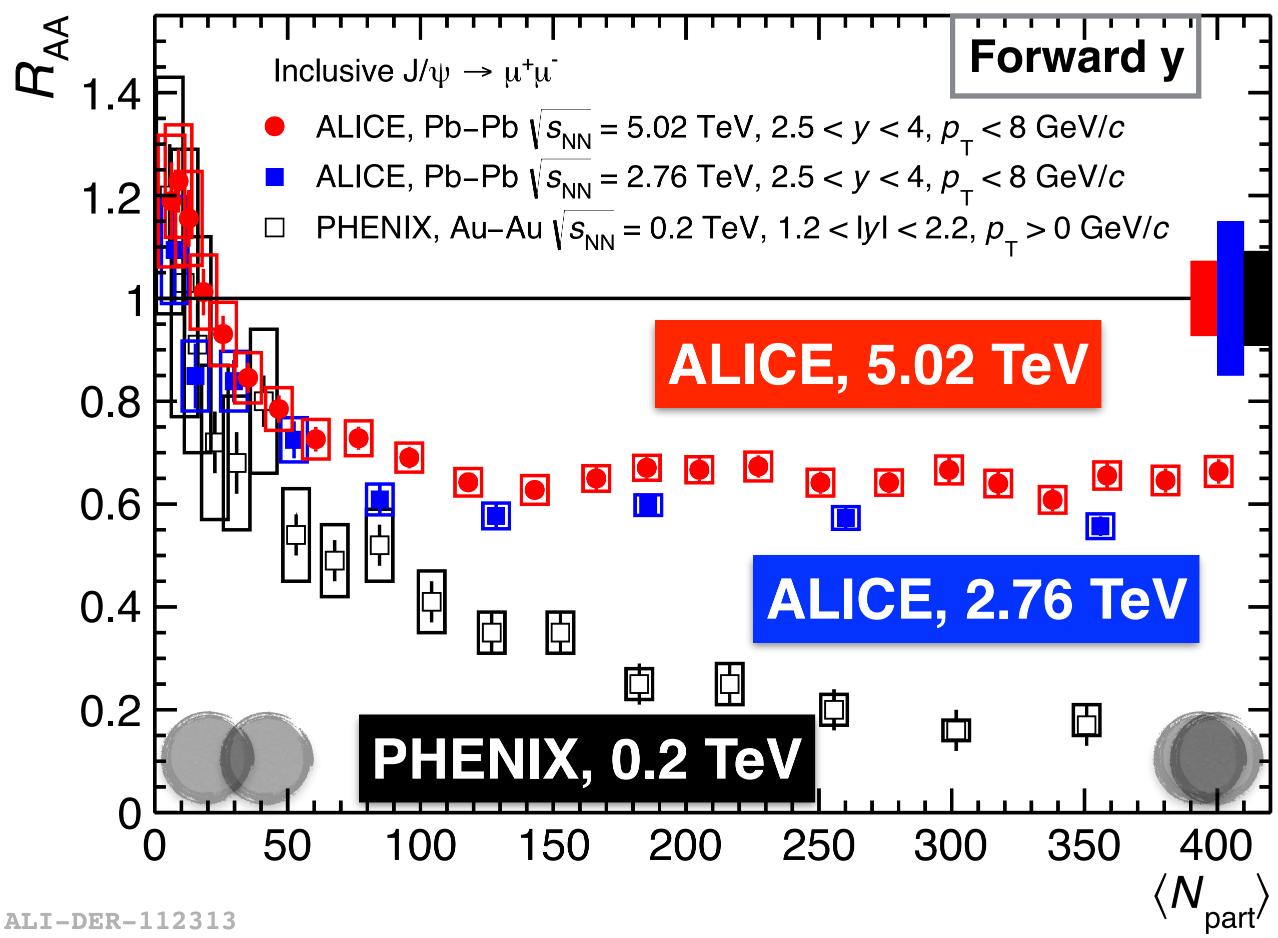


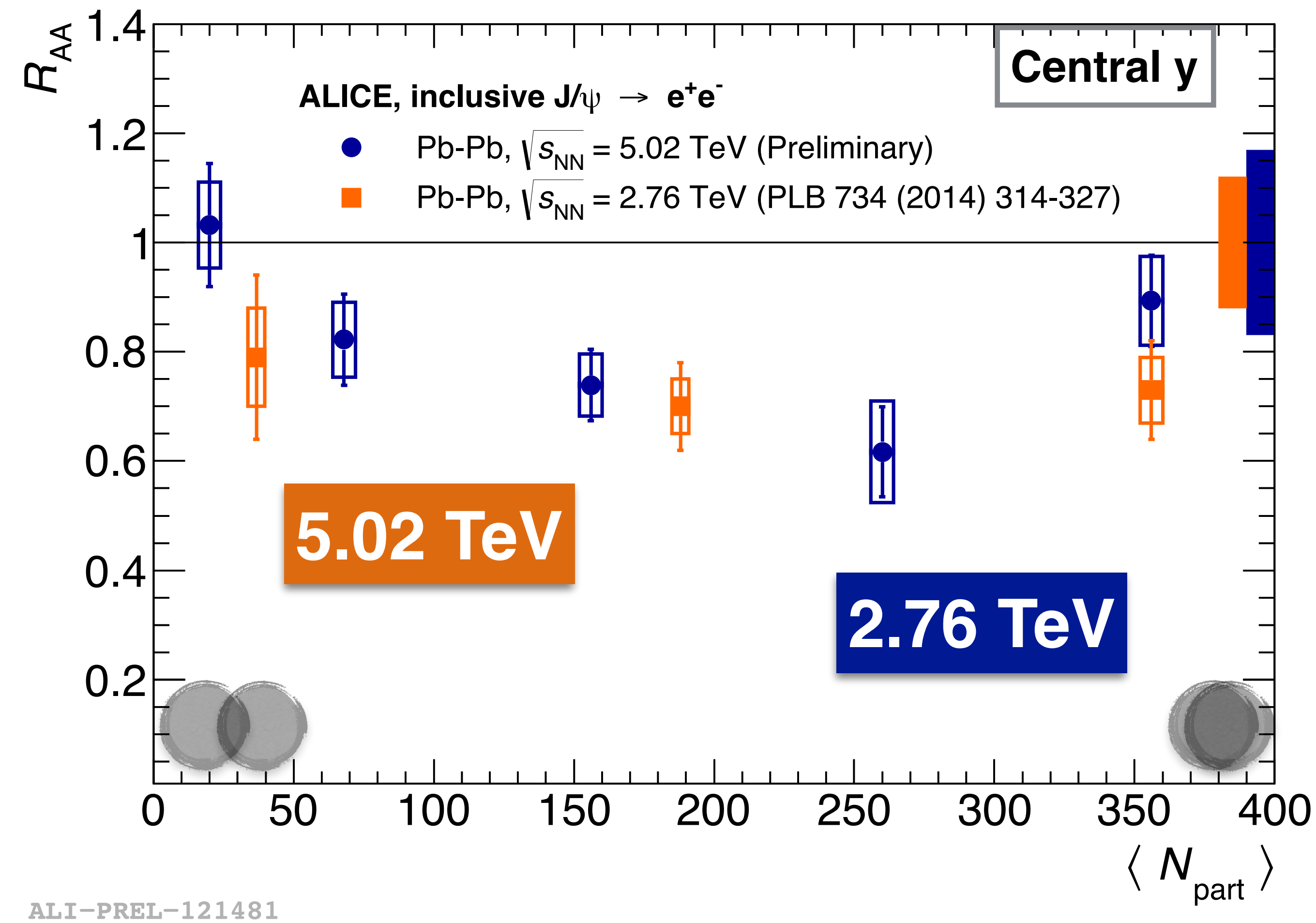
P. Braun-Muzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)

Cold nuclear matter effects

- On top of hot matter mechanisms, the effects related to cold nuclear matter (CNM) might affect quarkonium production —> addressed with p-Pb collisions

Low p_T J/ψ





- Clear J/ψ suppression with almost no centrality dependence for N_{part} > 100 in ALICE
- Stronger J/ψ suppression vs centrality at RHIC than at LHC, despite the larger energy density
- No significant $\sqrt{s_{NN}}$ dependence of R_{AA} (2.76 vs 5.02 TeV) at central and forward-*y* within uncertainties
- Important role of recombination at LHC energies

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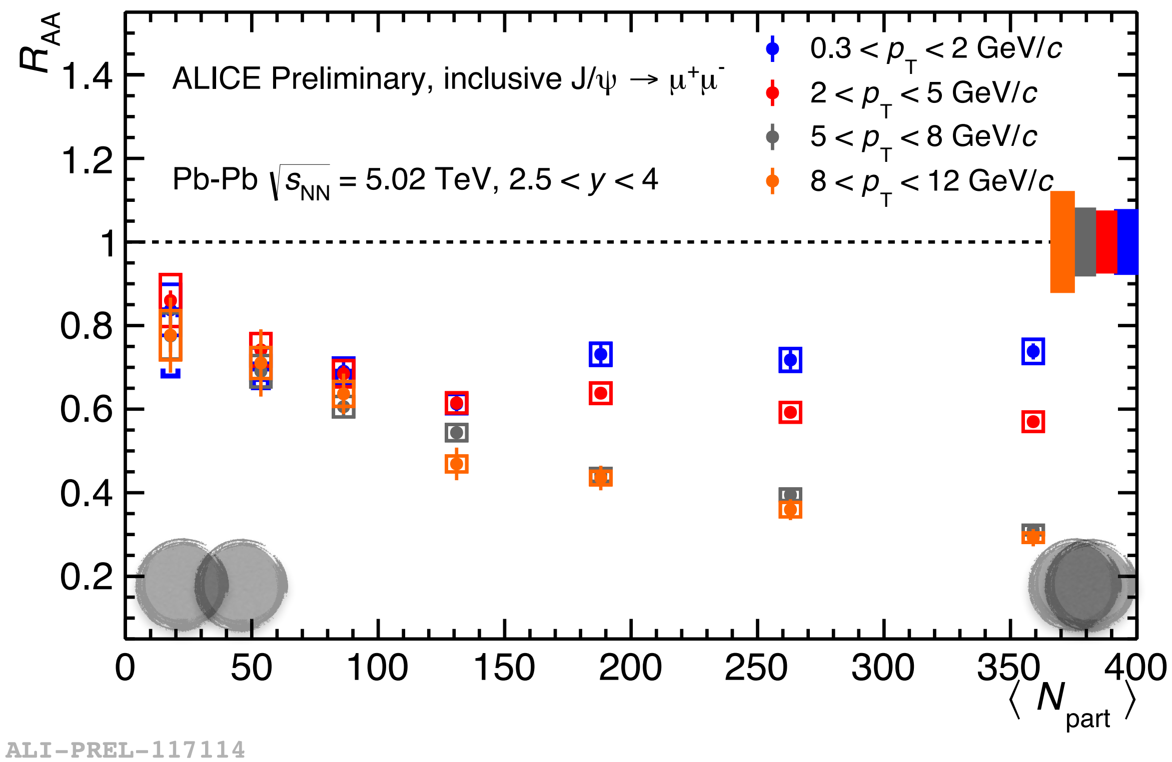
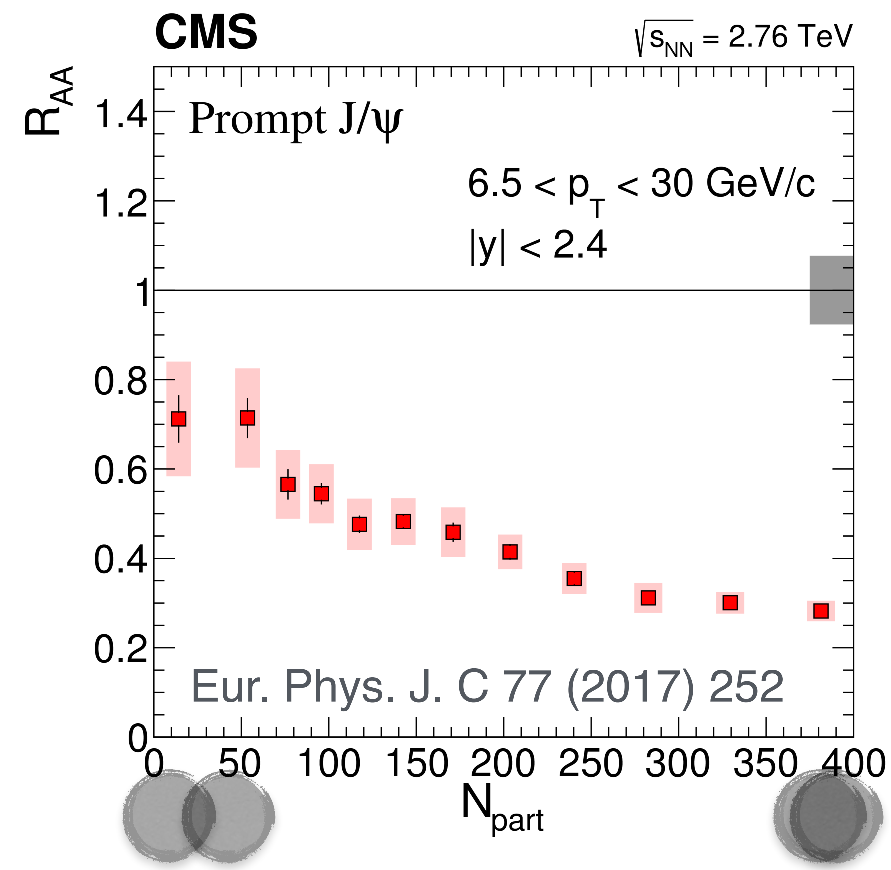
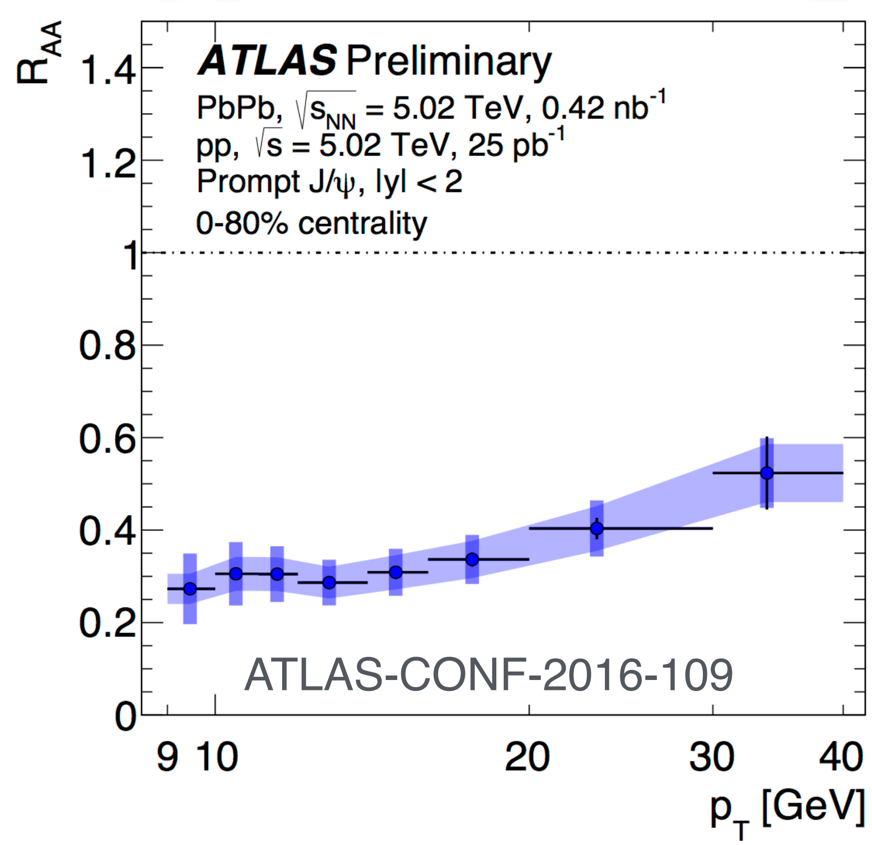
PLB 734 (2014) 314
PRL 109 (2012) 072301

High p_T J/ψ



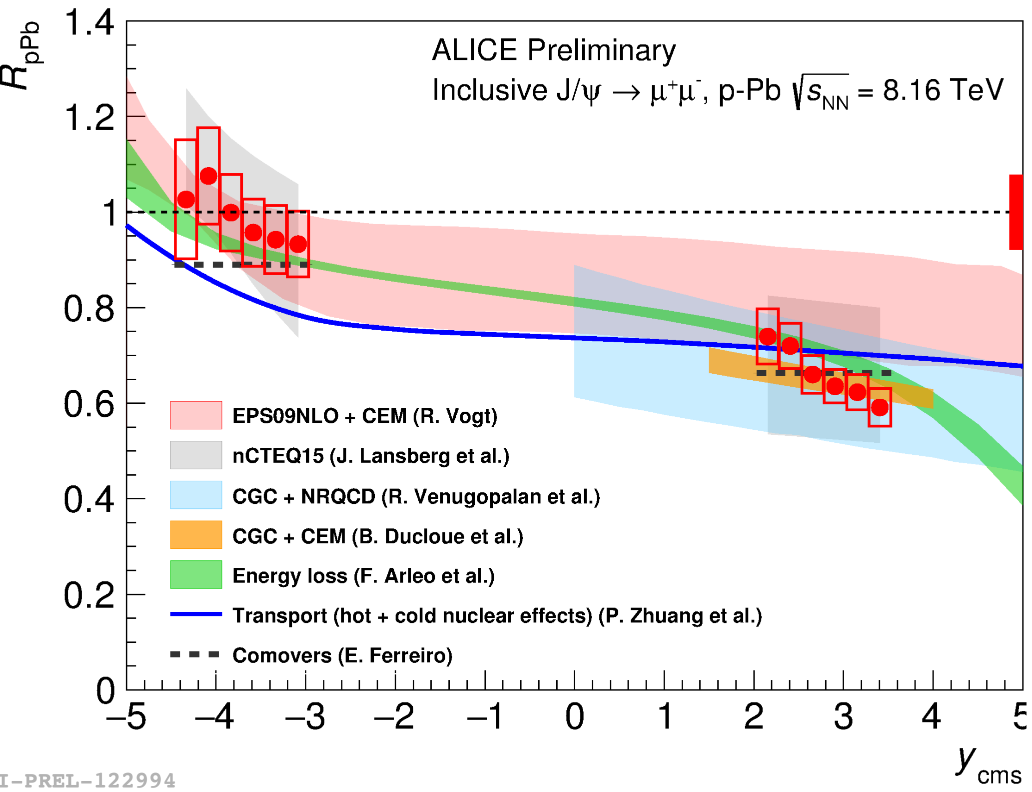




- Suppression increasing with centrality for high p_T J/ψ —> down to $R_{AA} \sim 0.3$
- R_{AA} increases for p_T > 20 GeV/c —> energy loss effect (rather than dissociation)?

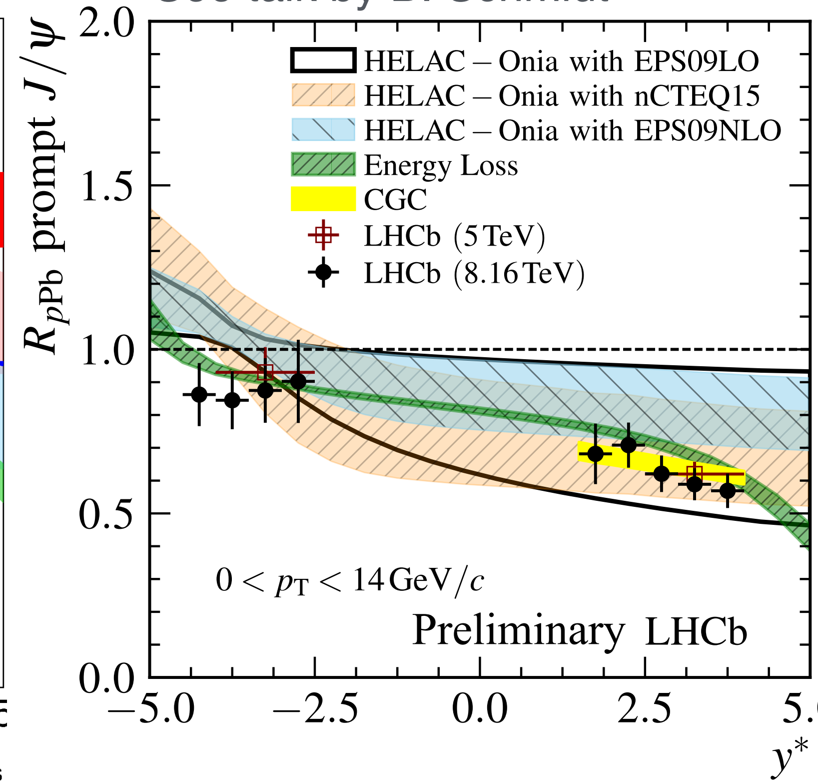
J/ψ in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

- Extended kinematic coverage (p_T = 20GeV/c)
- R_{pPb} in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV and 5.02 TeV are compatible

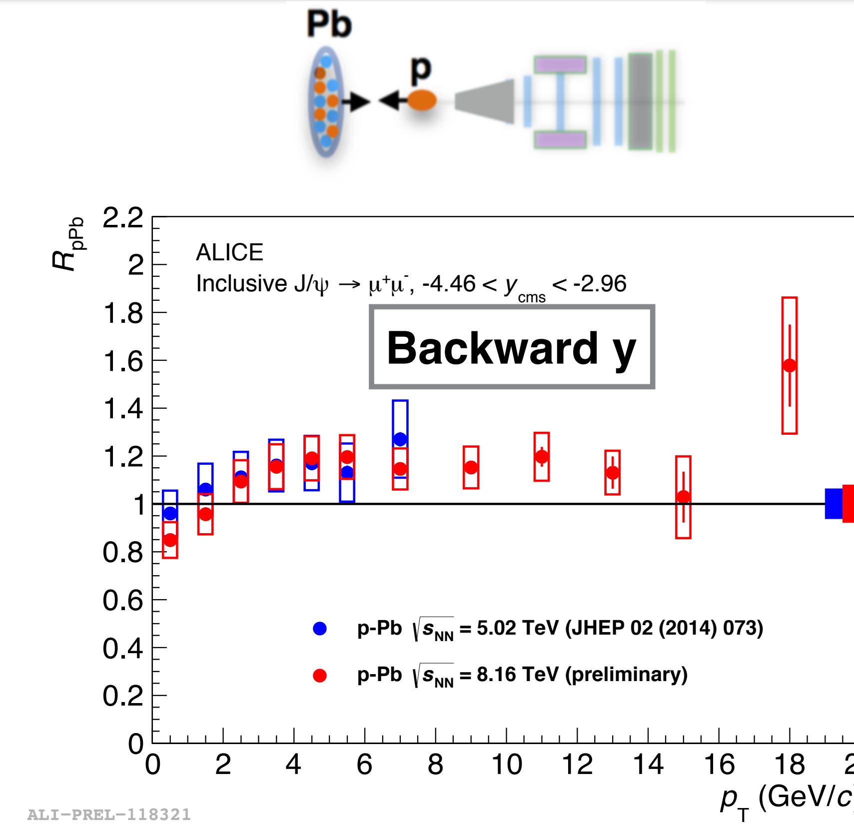


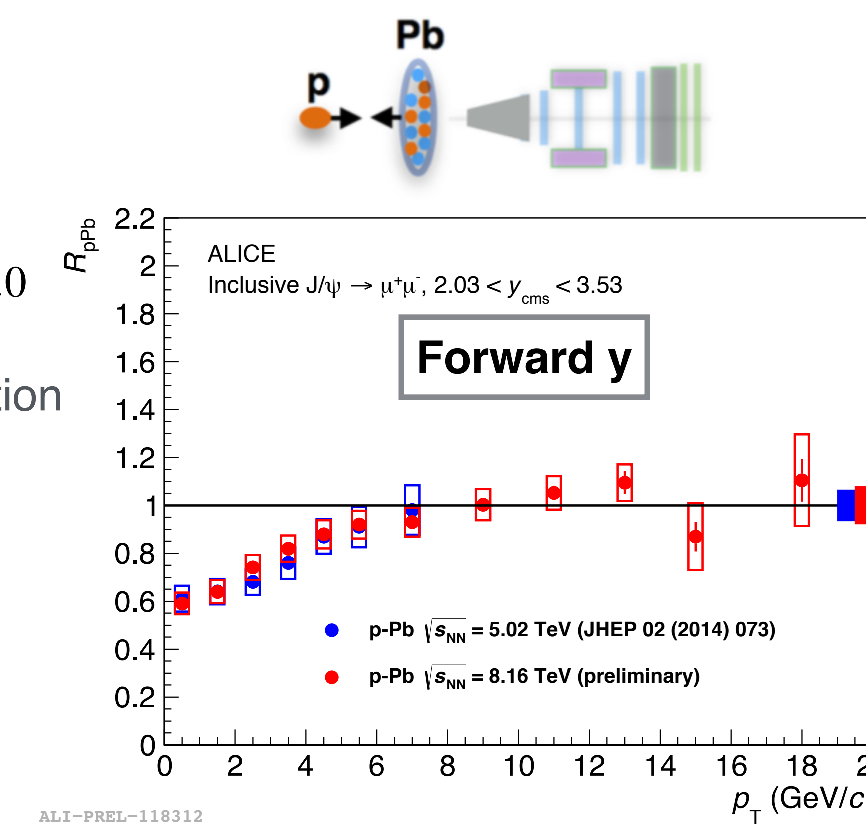
CERN-ALICE-PUBLIC-2017-001

See talk by B. Schmidt



LHCB-PAPER-2017-014 in preparation

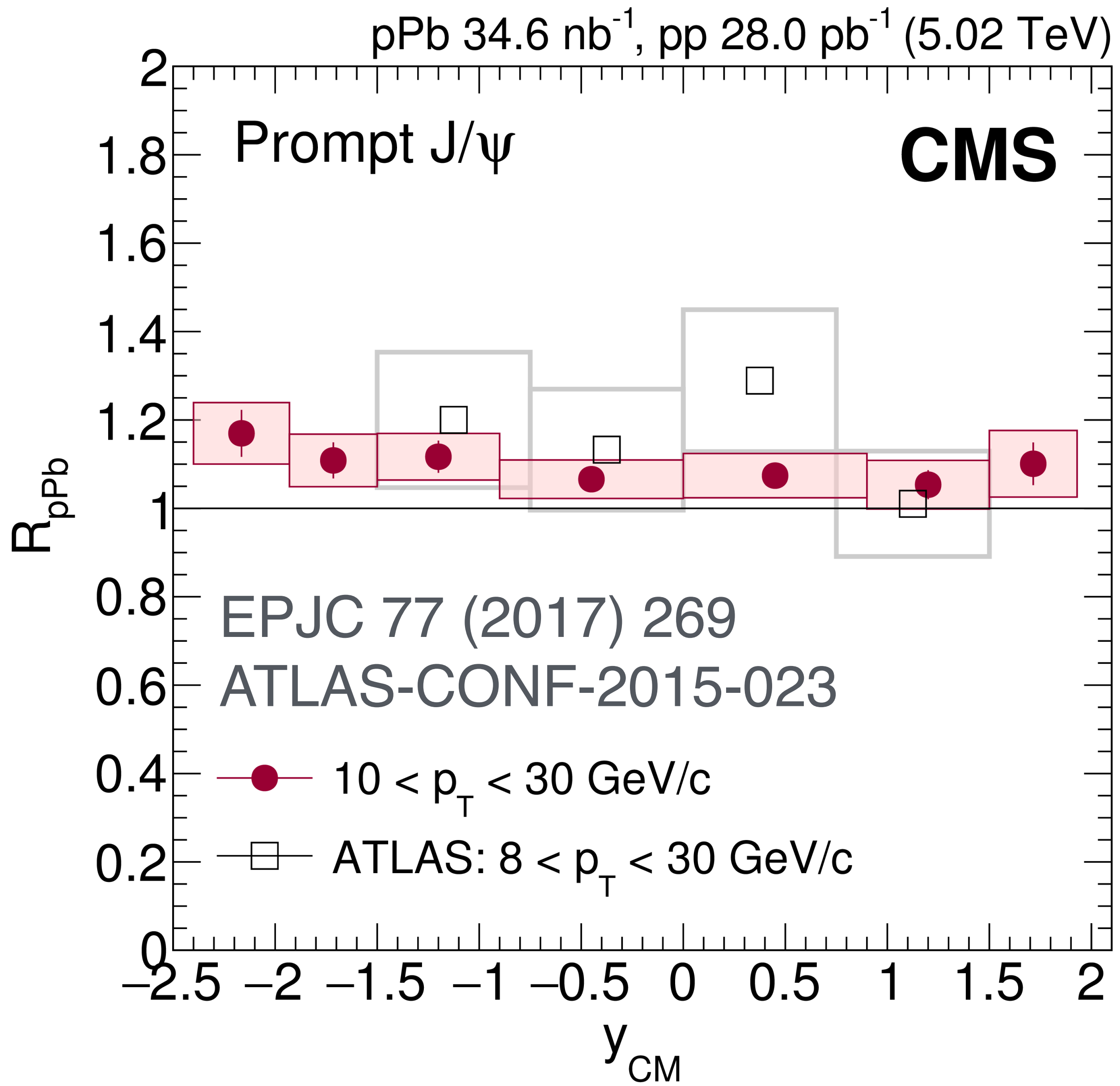


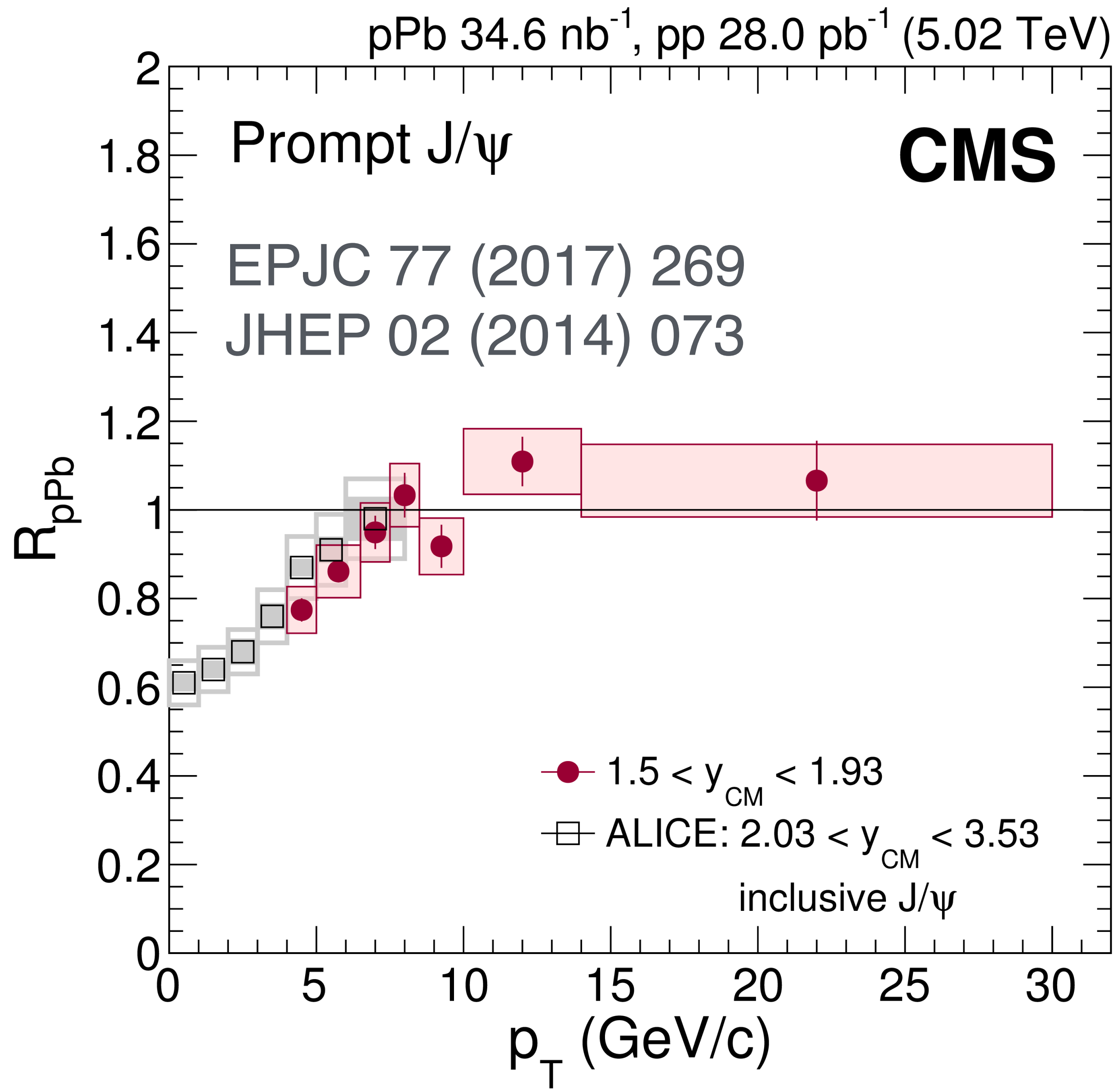


JHEP 02 (2014) 073

- R_{pPb} compatible with unity at backward rapidity while clear suppression at forward rapidity
- Described by models including CNM effects

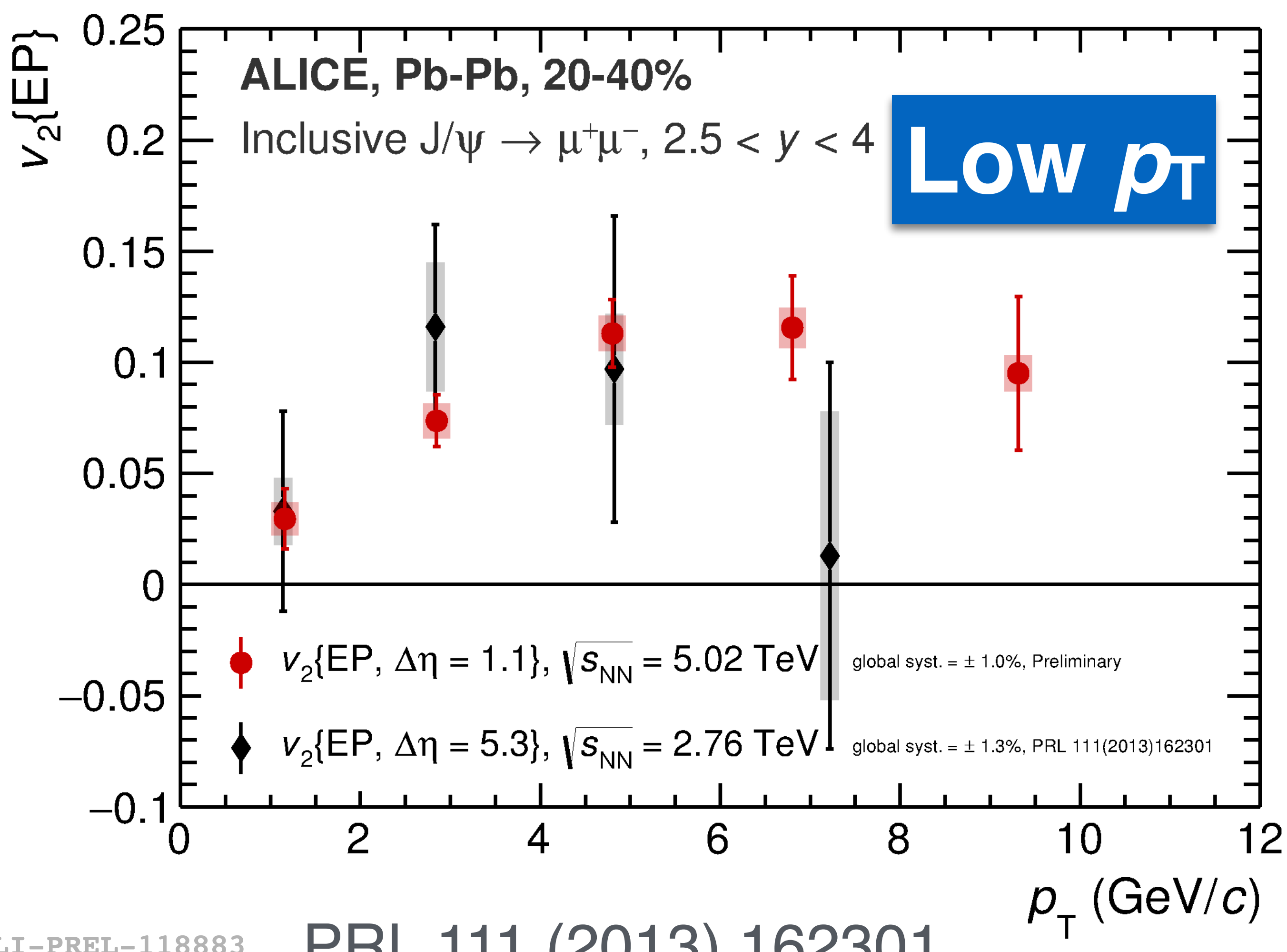
J/ψ in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV



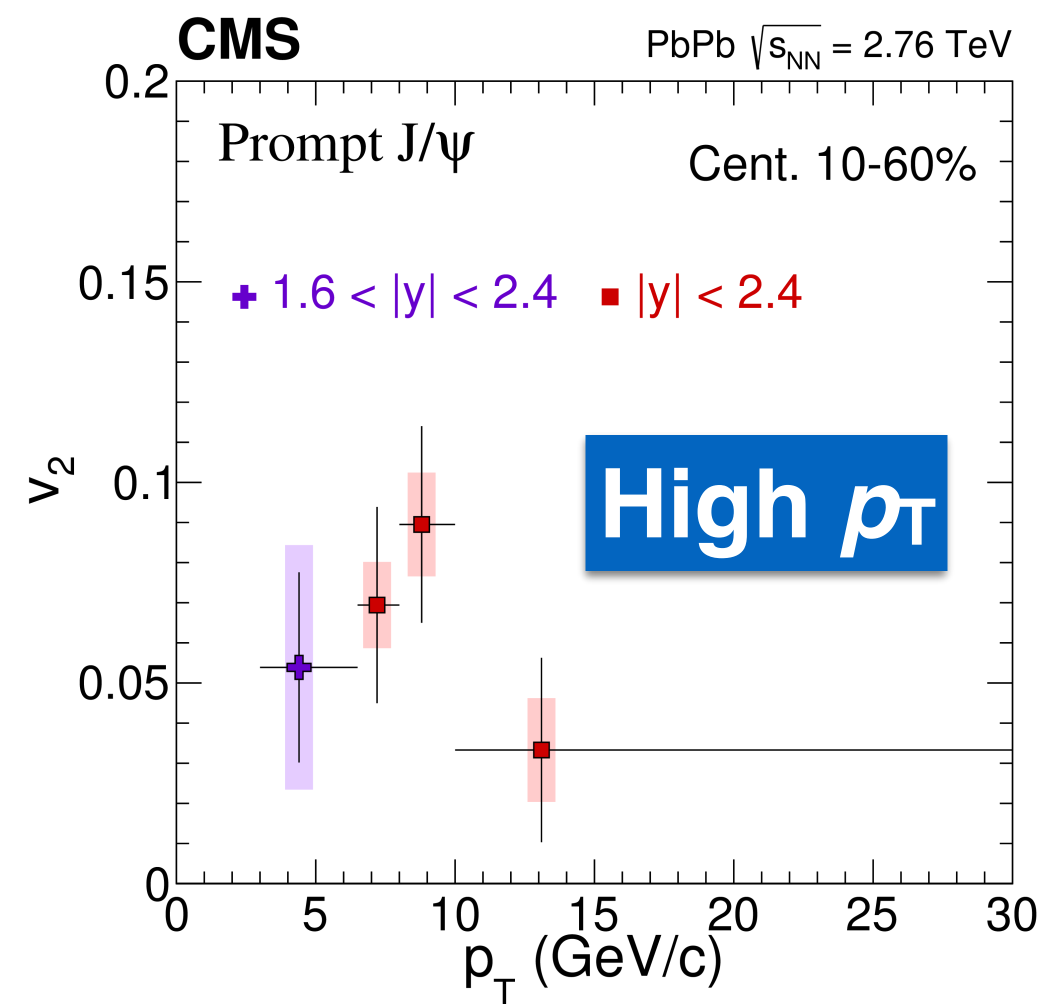


- Weak CNM effects at high p_T
- R_{pPb} compatible in the common y and p_T intervals between ALICE, ATLAS and CMS
- Strong J/ψ suppression observed at high p_T in central Pb-Pb collisions is not due to CNM effects

J/ψ elliptic flow in Pb-Pb



PRL 111 (2013) 162301



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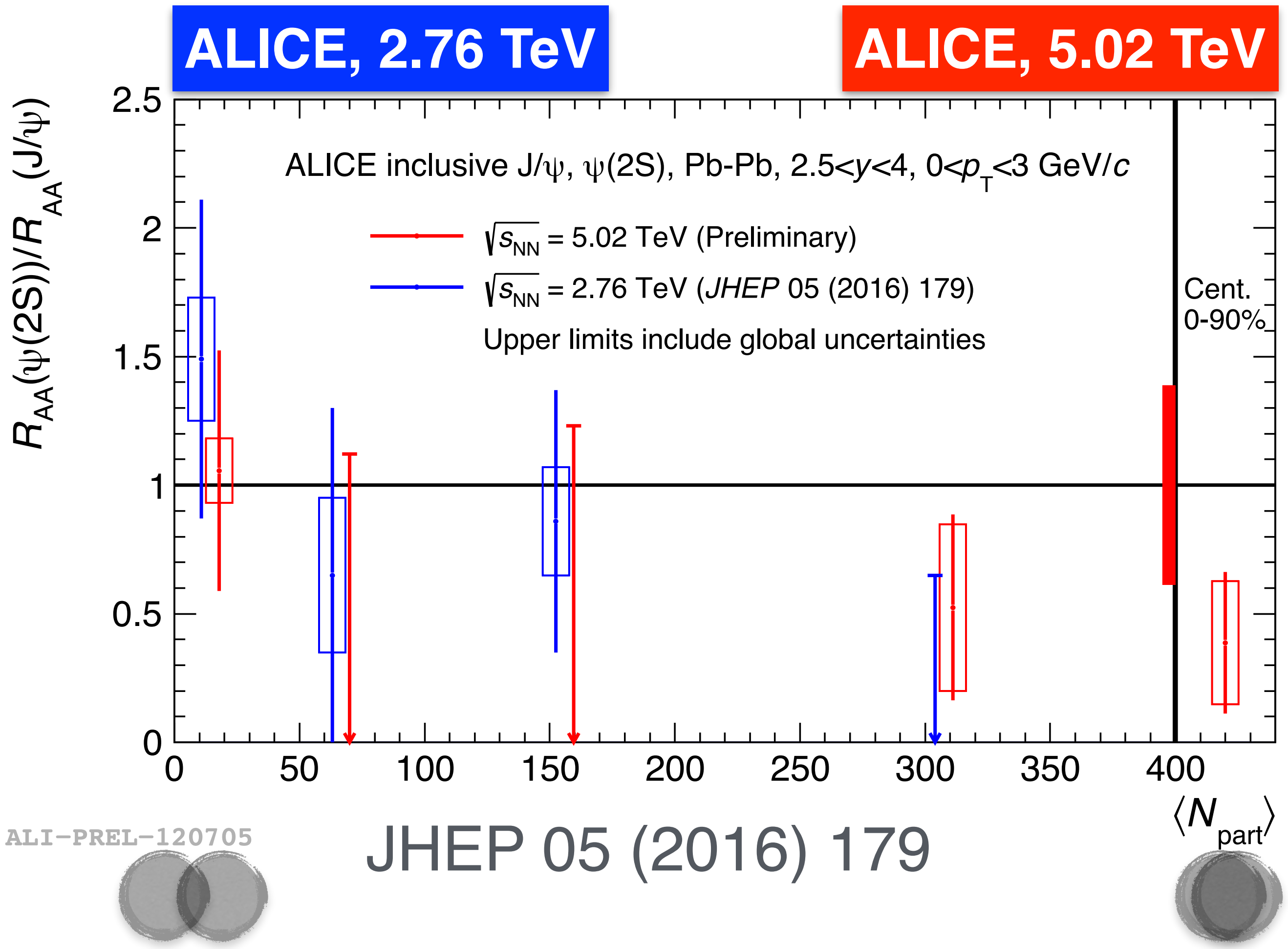
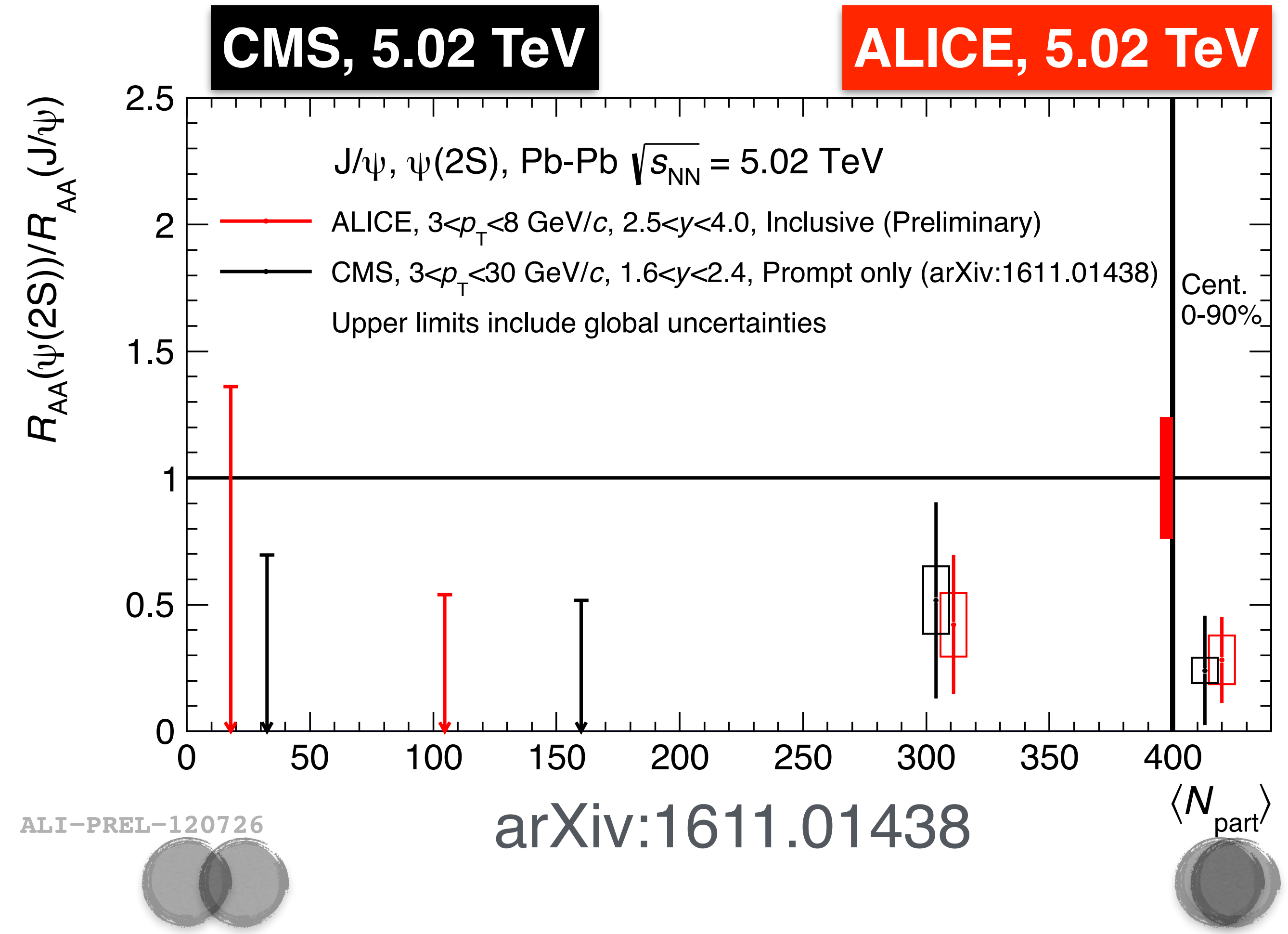
- J/ψ from (re)combination could lead to an elliptic flow at LHC energies —> hint observed in Run1 results
- Evidence for a positive J/ψ v_2 in Run2 data —> a significant fraction of observed J/ψ comes from charm quarks thermalised in the QGP
- v_2 remains significant at high p_T where (re)combination contribution should be negligible —> energy loss path-length dependence

ψ(2S) R_{AA}

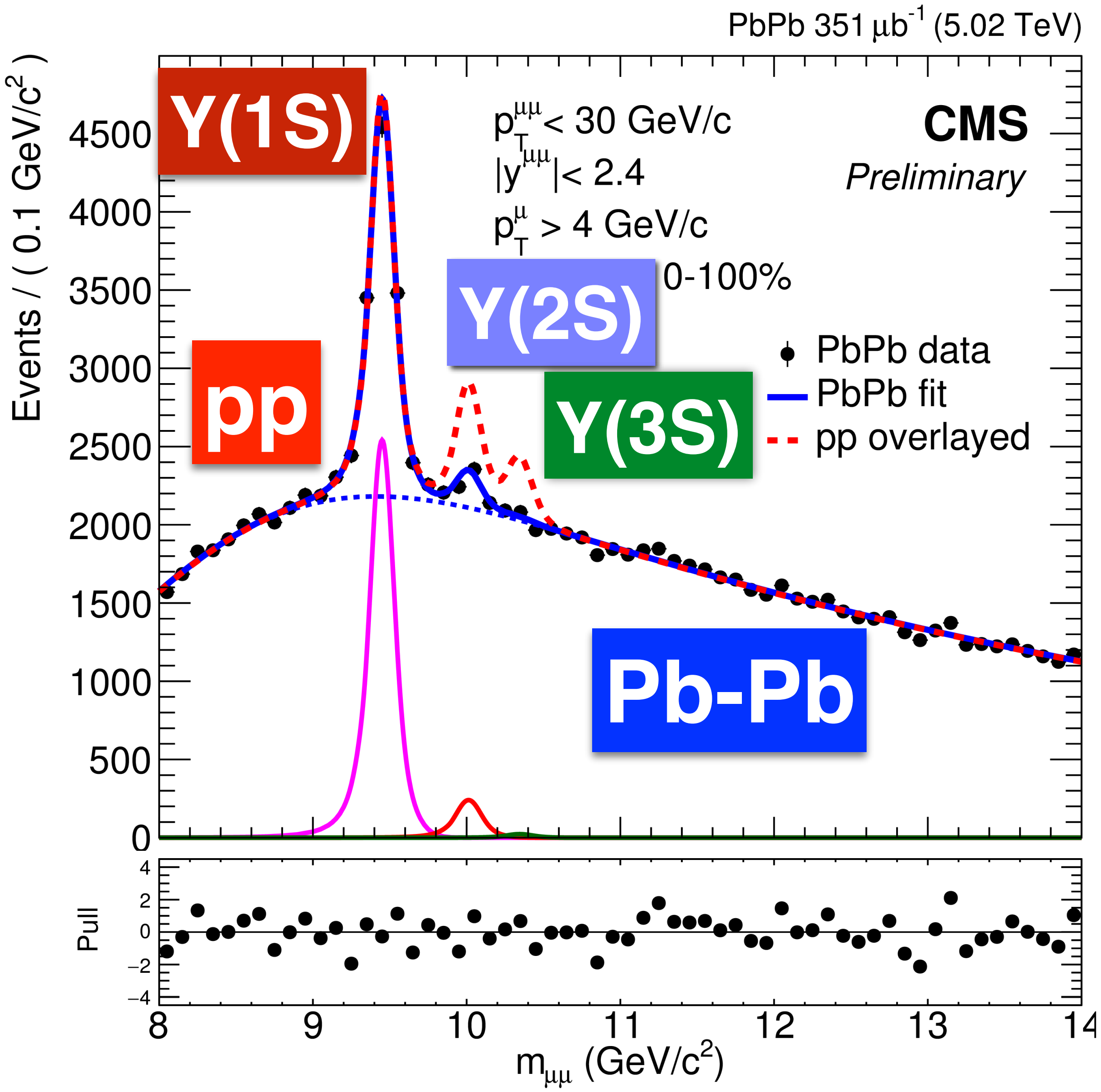
- Binding energy: ψ(2S) ~ 60 MeV vs. J/ψ ~ 640 MeV —> much stronger dissociation effect expected

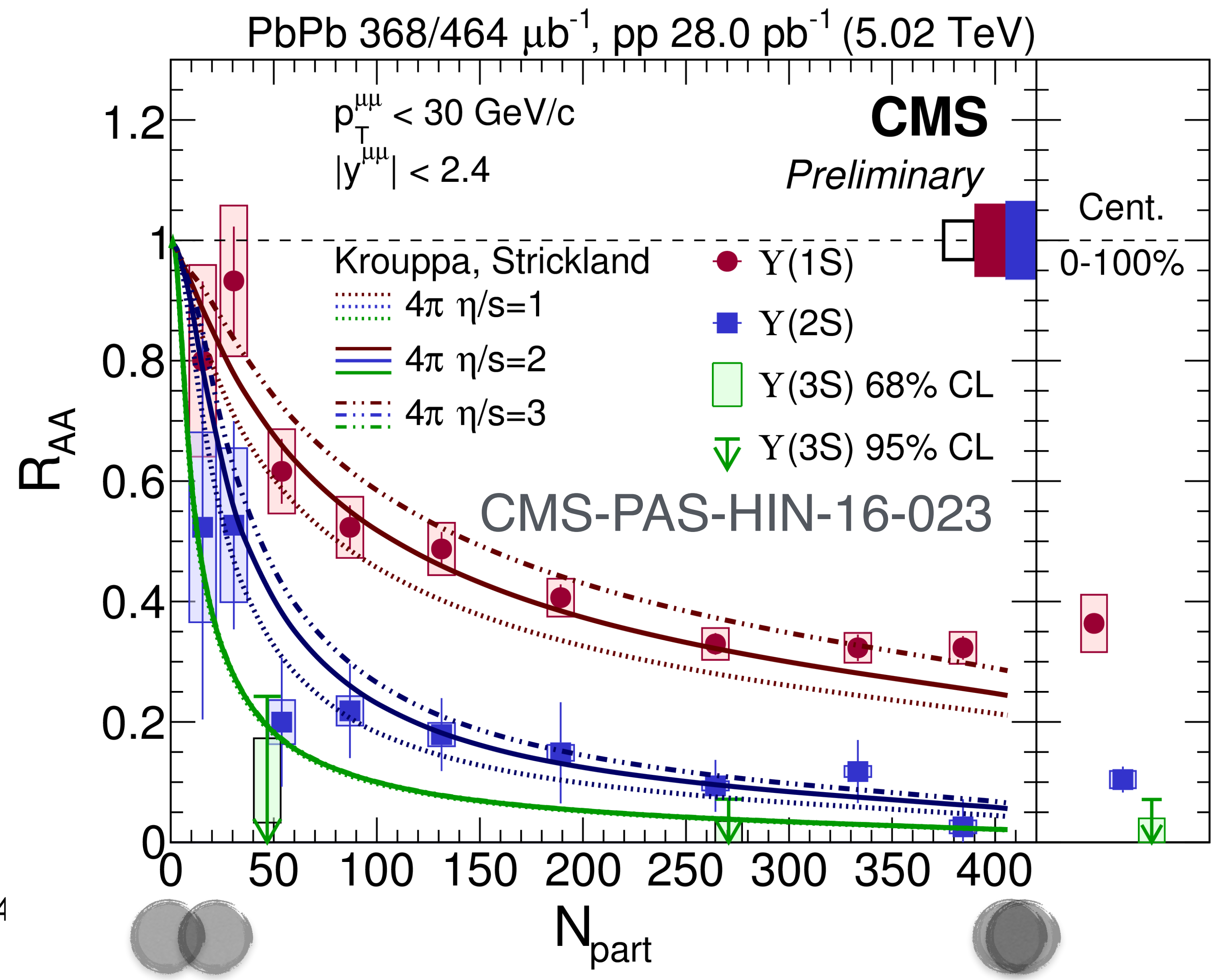




- ψ(2S) shows a stronger suppression in central collisions than J/ψ
- Results at $\sqrt{s_{NN}}$ = 5.02 TeV are compatible with the ones at 2.76 TeV
- Good compatibility between ALICE and CMS results $\sqrt{s_{NN}}$ = 5.02 TeV in a similar kinematic range

Bottomonium sequential suppression





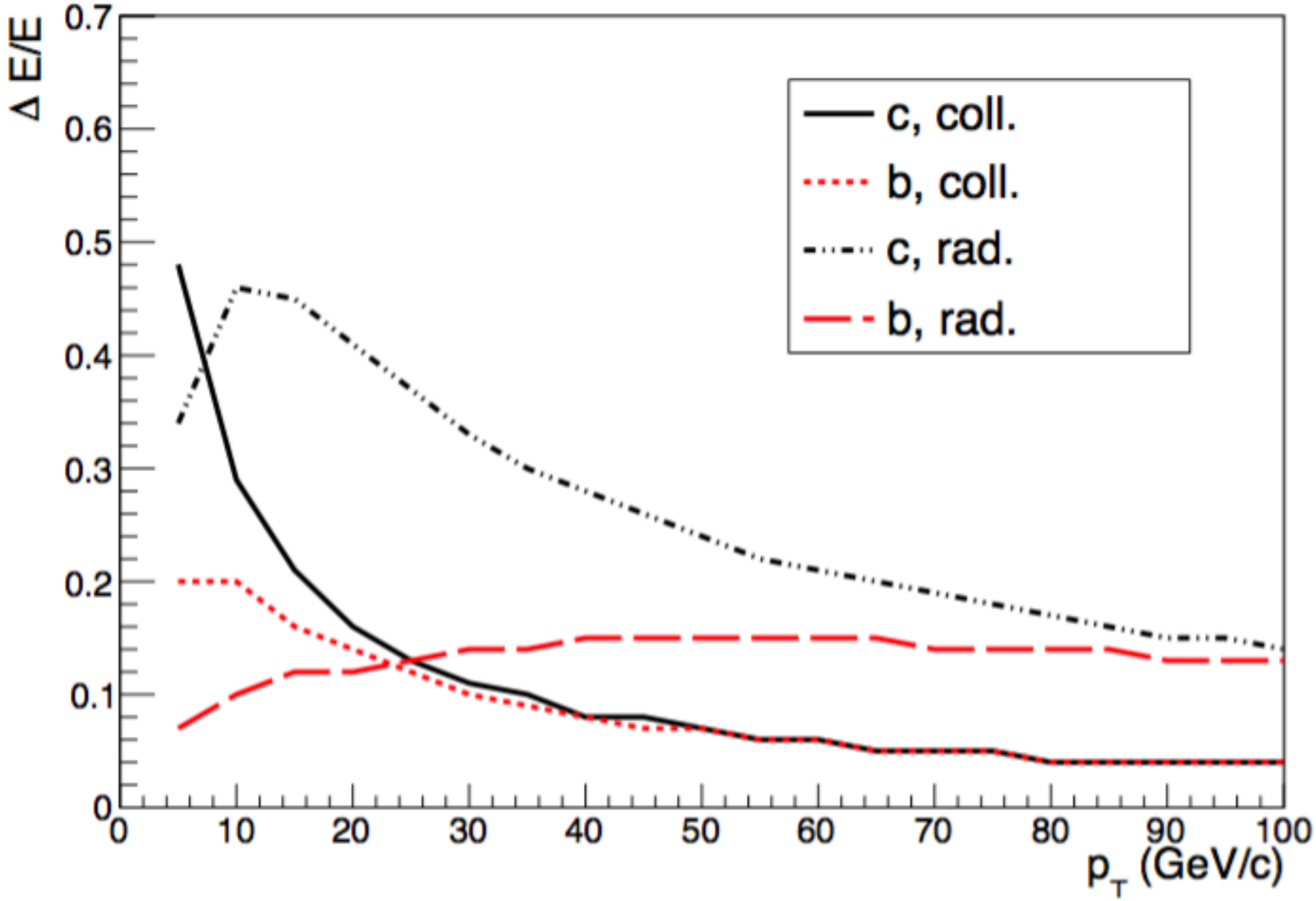
- Y(1S) (E_b ~ 1100 MeV), Y(2S) (E_b ~ 500 MeV) and Y(3S) (E_b ~ 200 MeV) have very different sensitivity to the medium
- Strong suppression of Y(2S, 3S) with respect to Y(1S) increasing with centrality (already observed at $\sqrt{s_{NN}}$ = 2.76 TeV)

Summary

- Complete set of results from LHC Run1 and already many results at Run2 energies are available
- **Heavy quarks**/**quarkonia** —> privileged probes for the study of the Quark-Gluon Plasma
  - **open charm/beauty mesons**
    - energy loss pattern, including mass-dependent effects, in agreement with theoretical calculations
    - significant v_2 —> participation of charm quarks in the collective expansion of the QGP (low p_T) + path-length dependence of parton energy loss (high p_T)
    - indication of a modification of the charm quark fragmentation (hint of less suppressed D_s w.r.t. non-strange D mesons)
  - **quarkonium**
    - charmonium —> suppression plus (re)generation (low p_T)
    - bottomonium —> sequential suppression as expected from color screening
- Most of the heavy quarks/quarkonia related observables will benefit from the incoming additional Run2 data and from the experiment upgrades

Backup

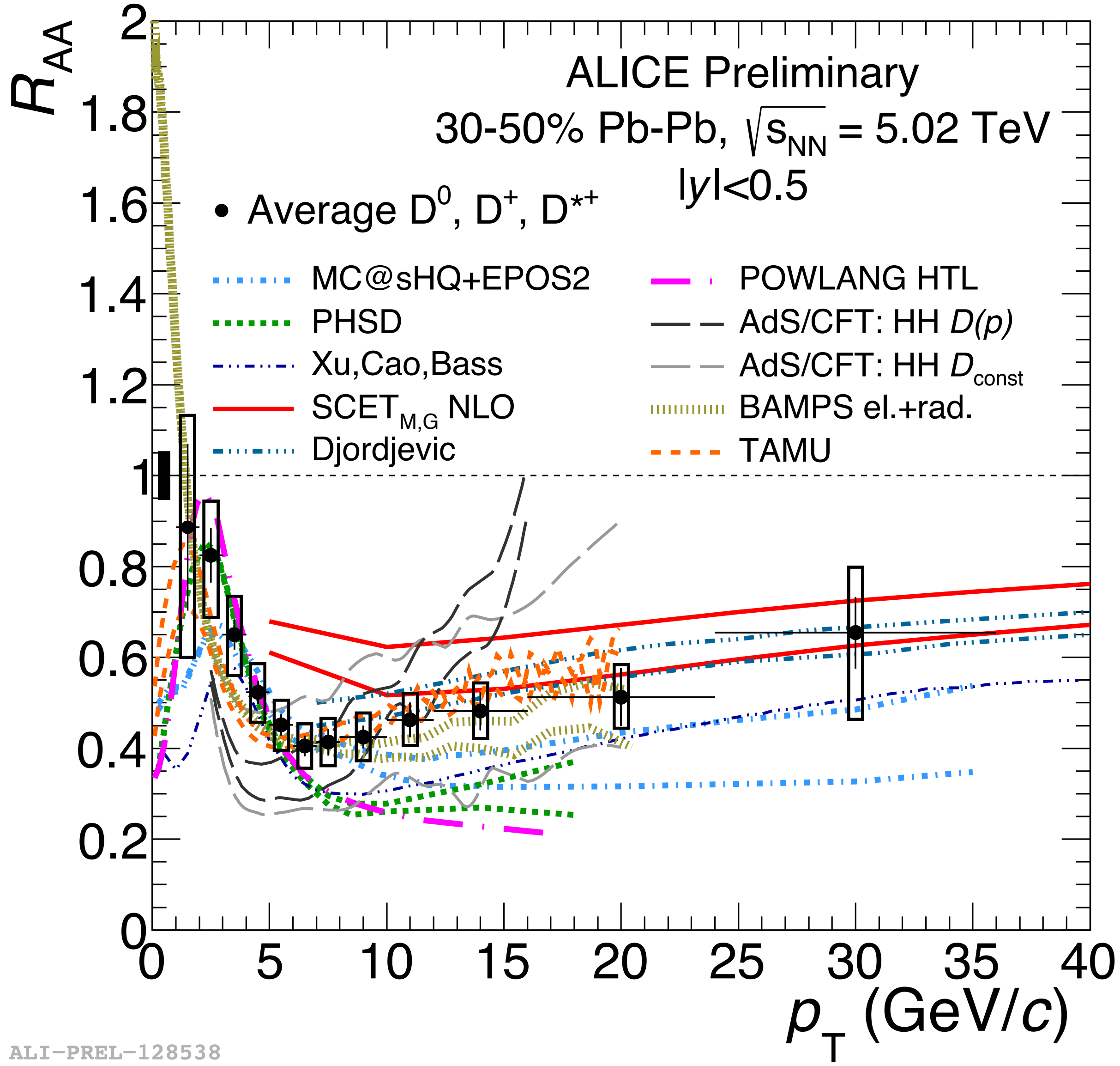
Heavy quarks energy loss

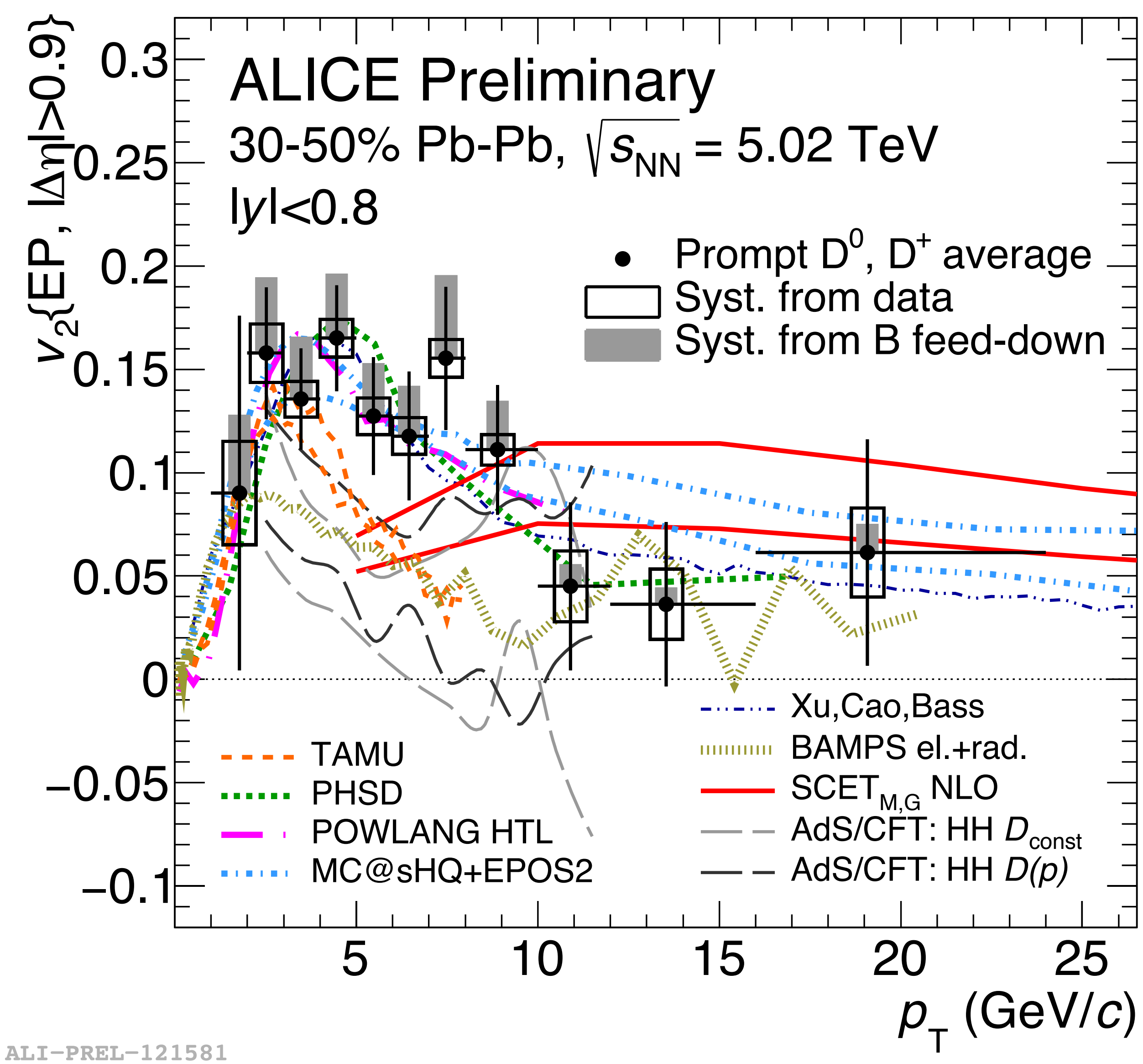


Andronic, A., Arleo, F., Arnaldi, R. et al.
Eur. Phys. J. C (2016) 76: 107

Comparison with models

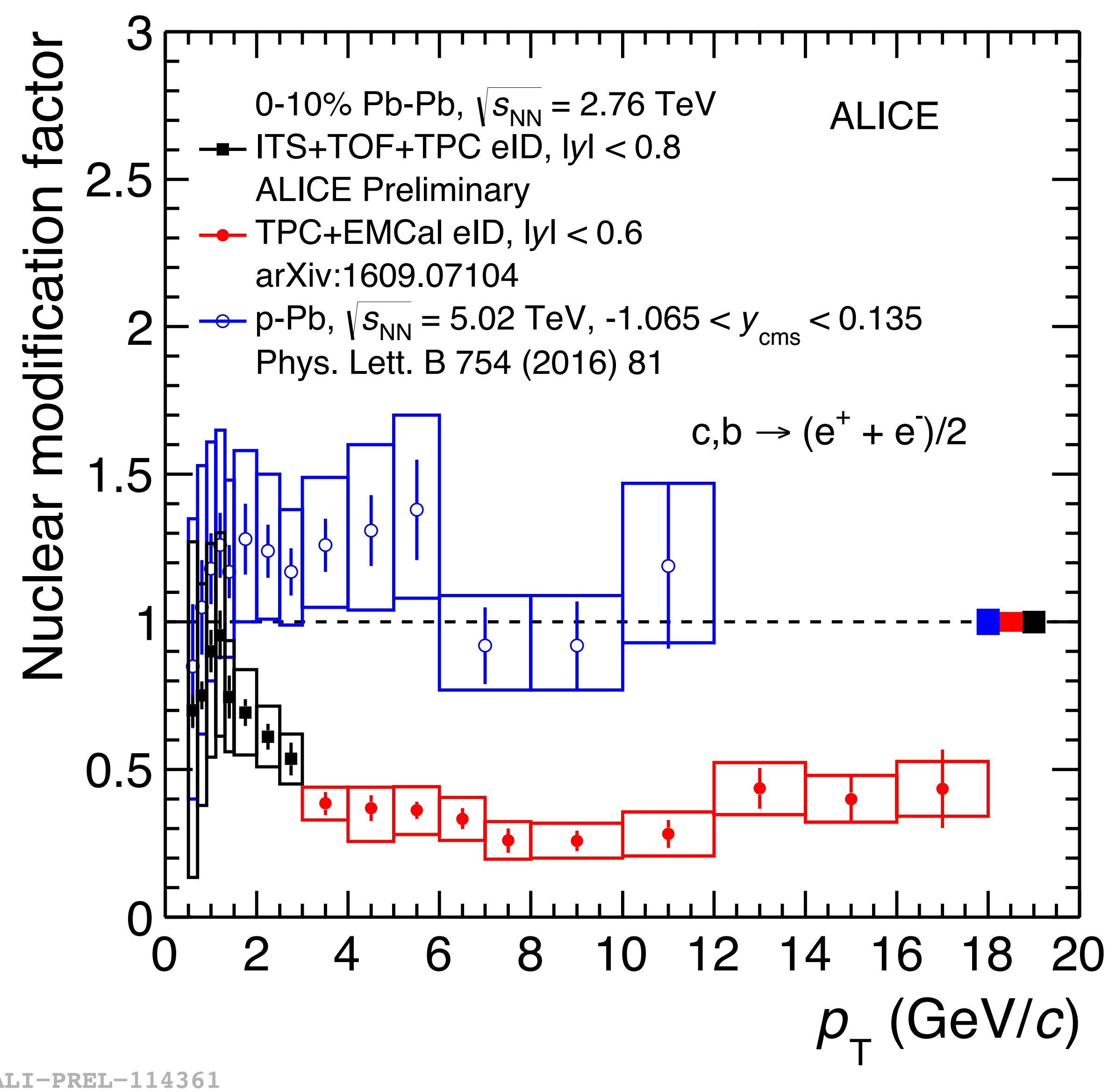
- Simultaneous comparison of different observables with theoretical models —> constrain heavy-quark transport coefficient of the medium

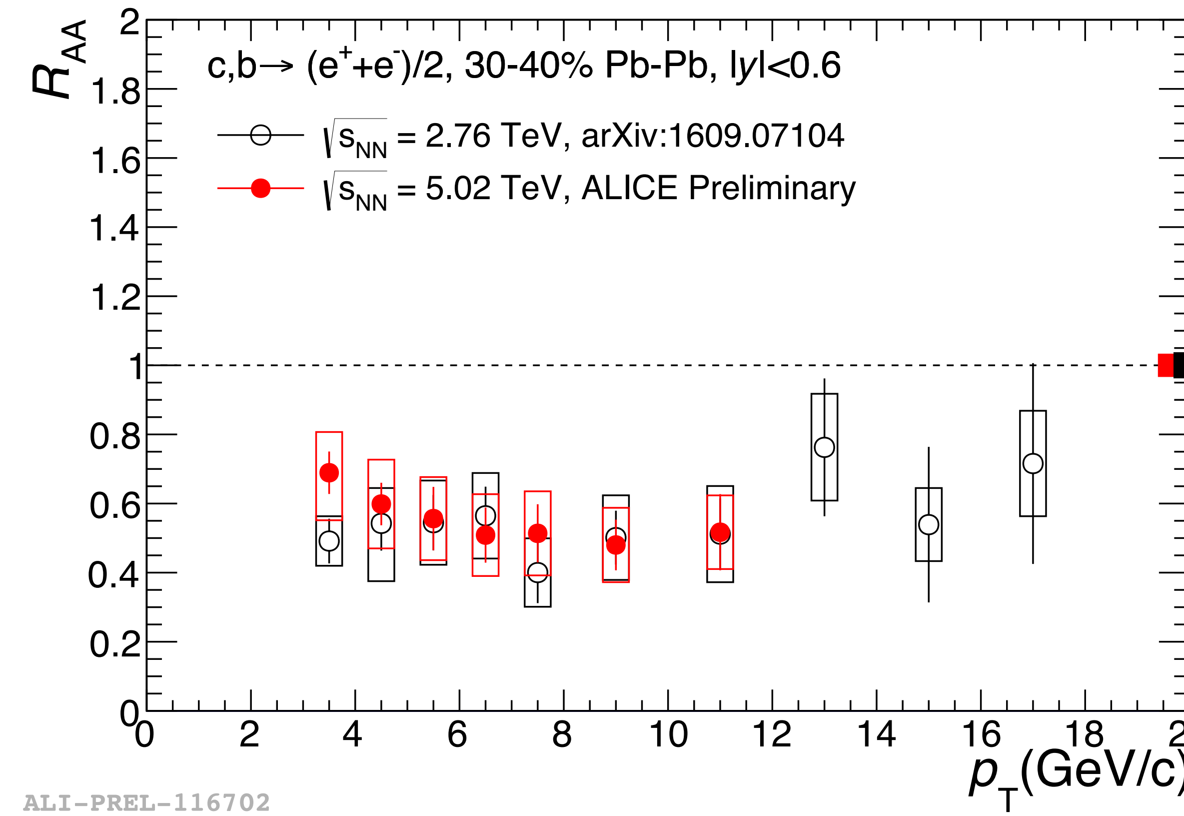




Heavy-flavour electrons

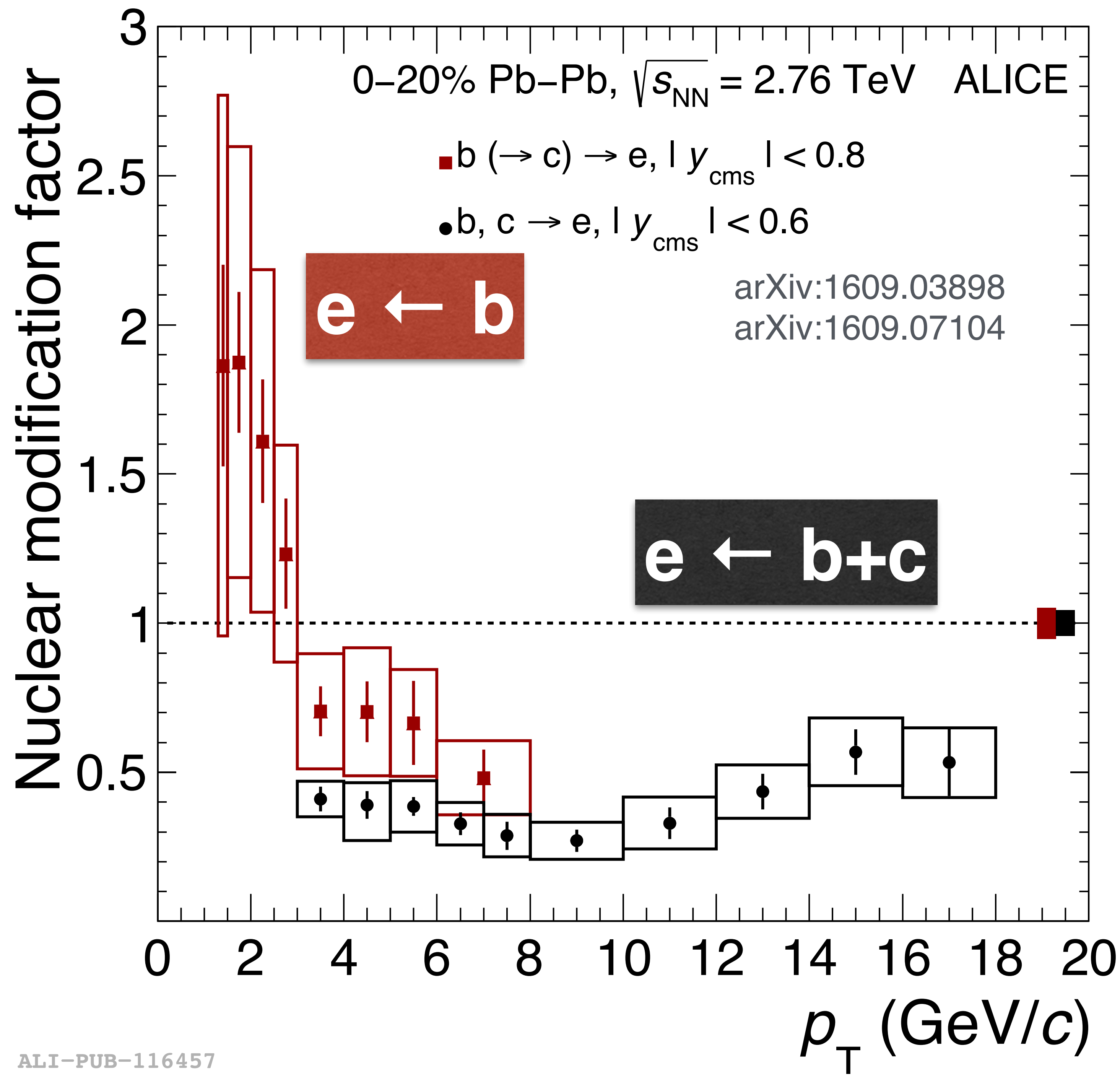
PLB 754 (2016) 81
arXiv:1609.07104





- Suppression of heavy-flavour decay electrons at low p_T in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- No strong modification of the electron spectrum in p-Pb with respect to pp collisions
- Similar suppression observed at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV

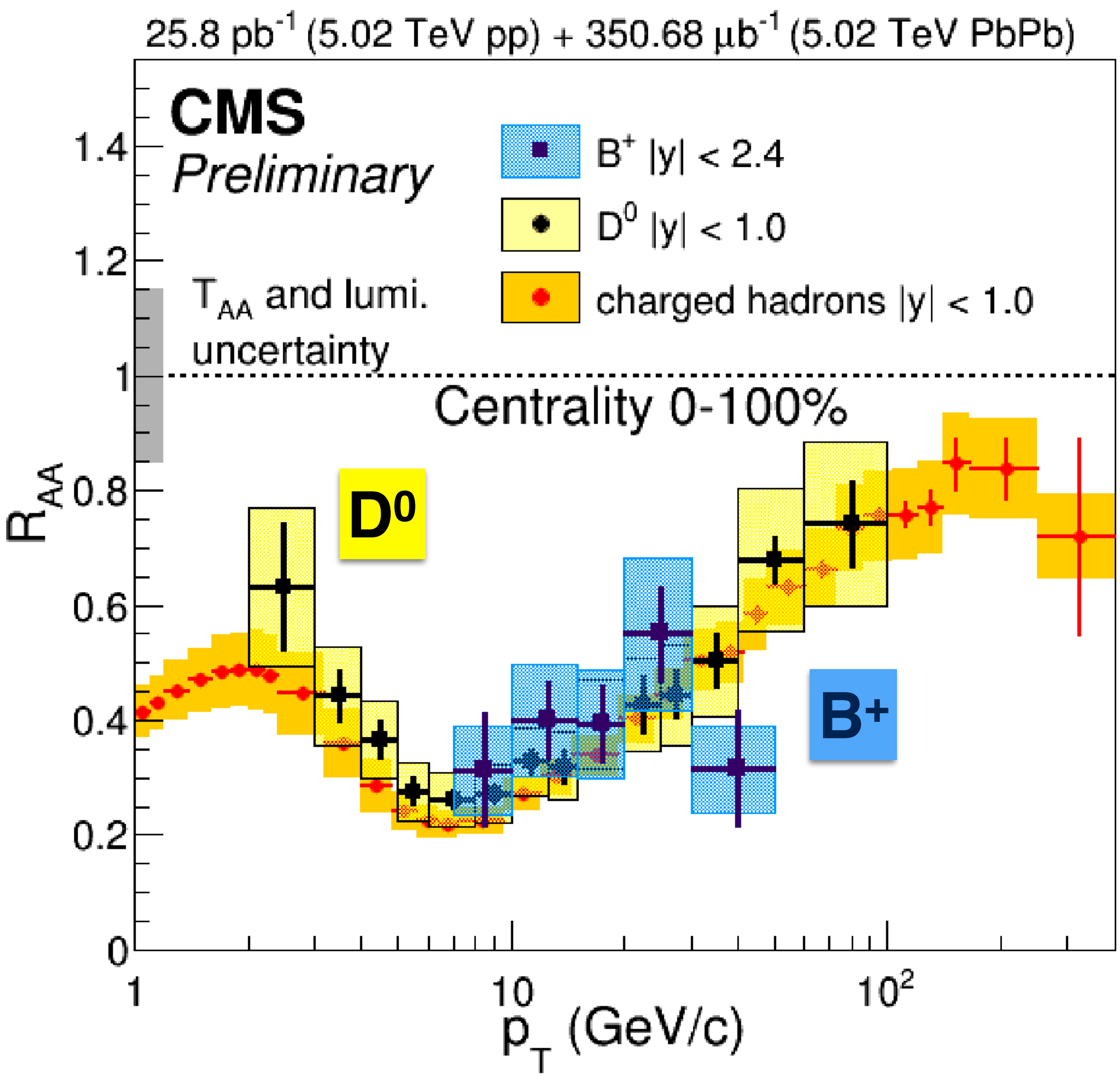
Charm and beauty suppression



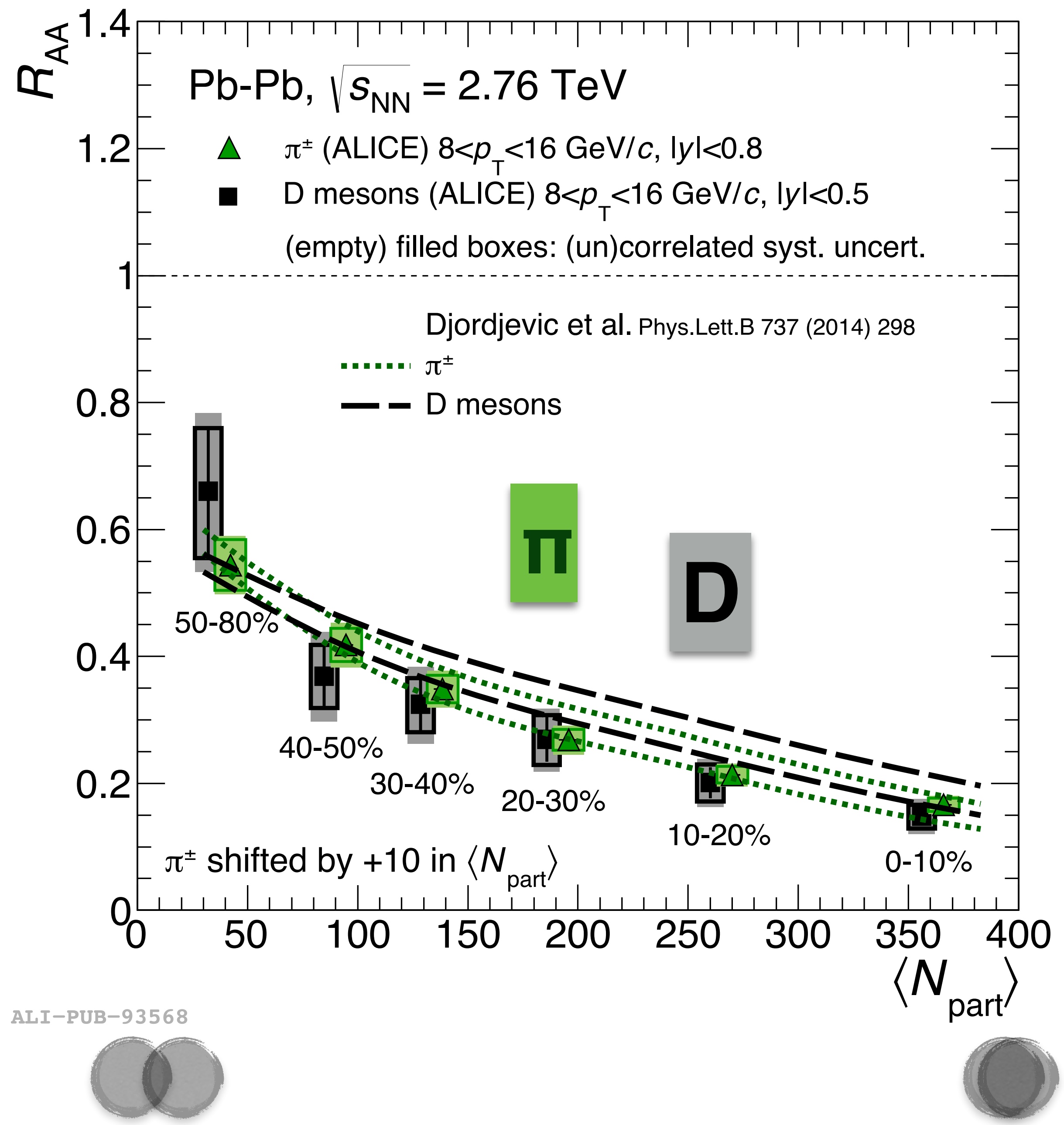
- Hint of R_{AA}(e ← b) > R_{AA}(e ← b+c) in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

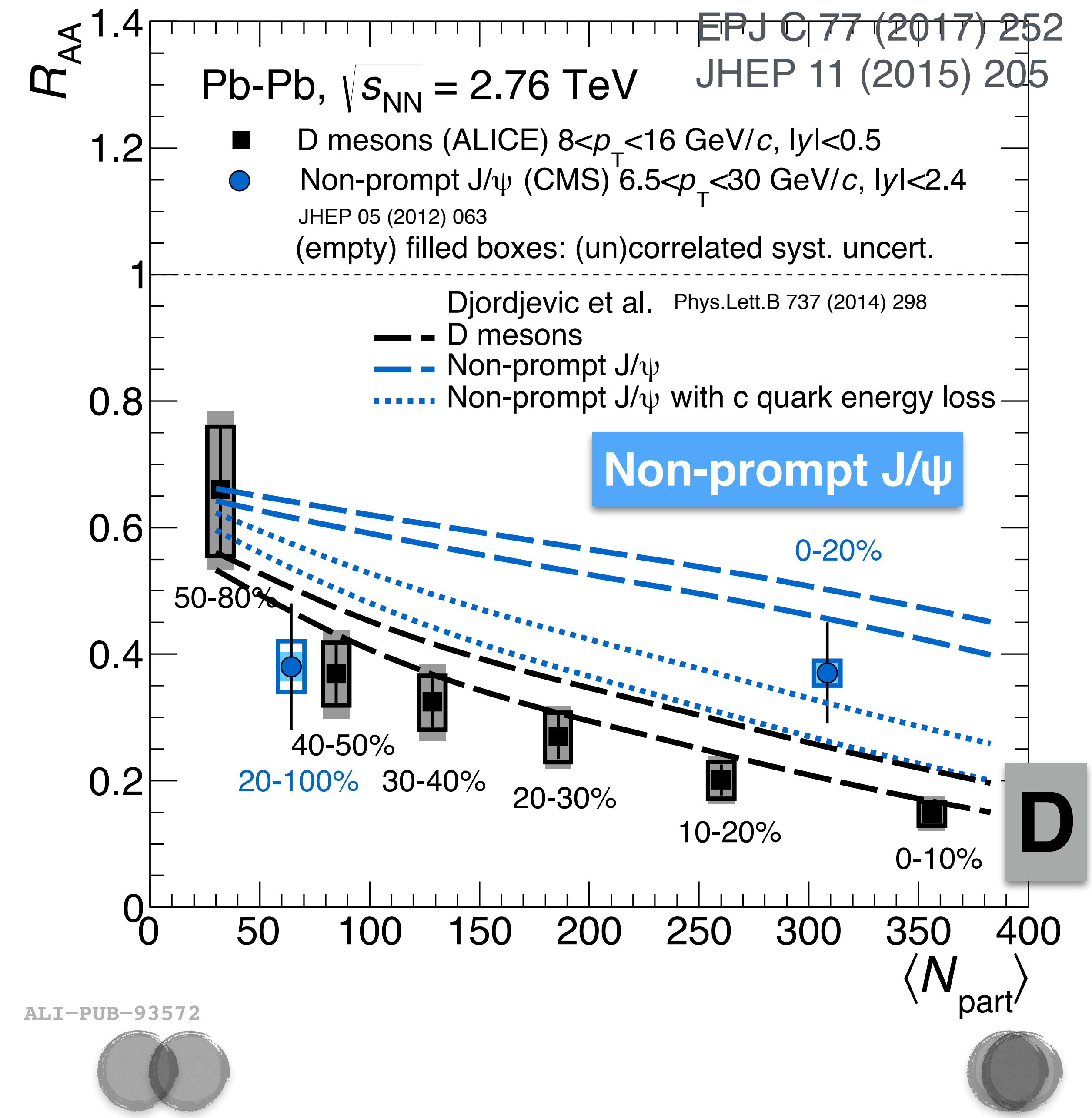
Beauty suppression

CMS-PAS-HIN-16-011



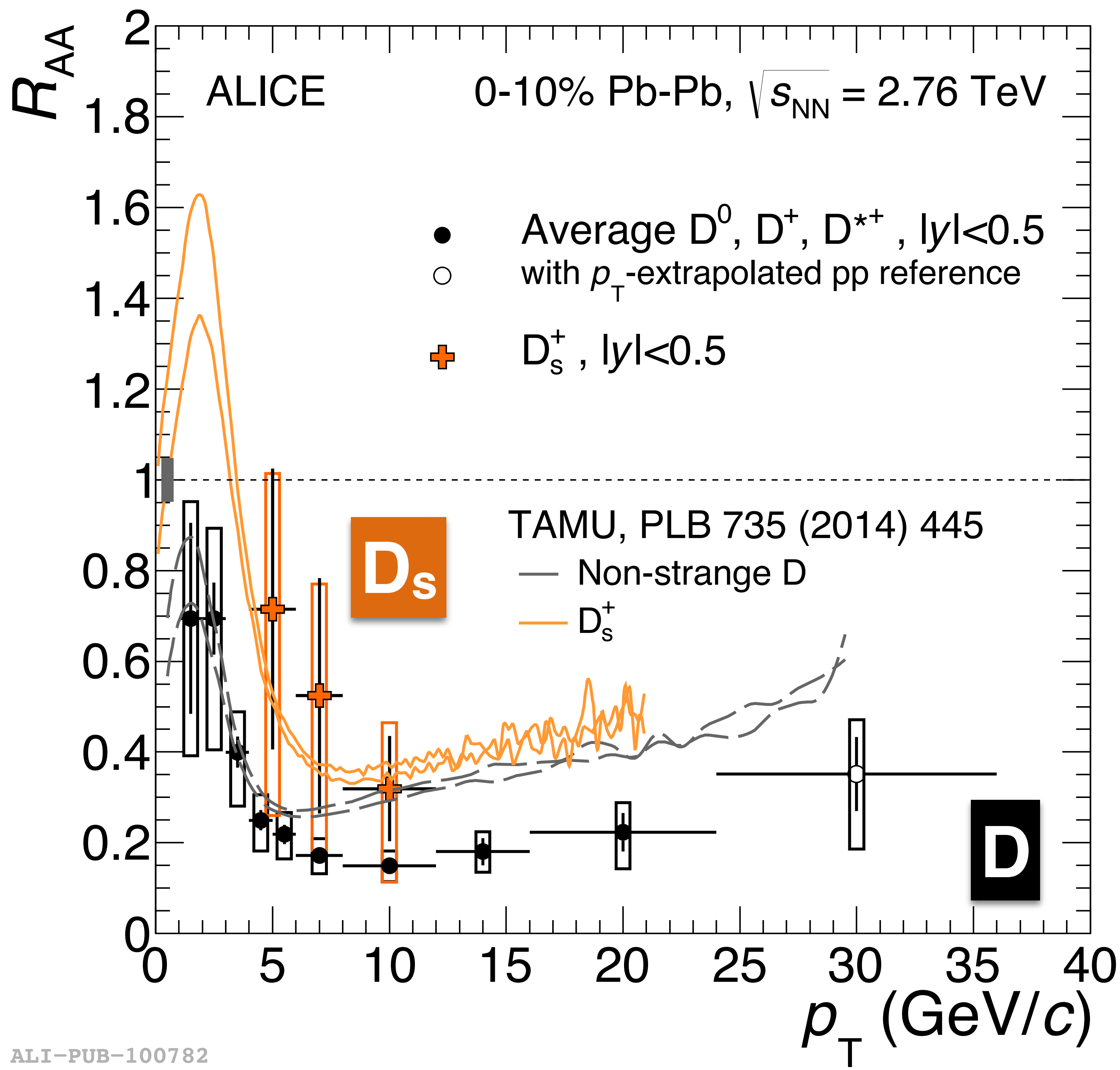
Charm and beauty suppression



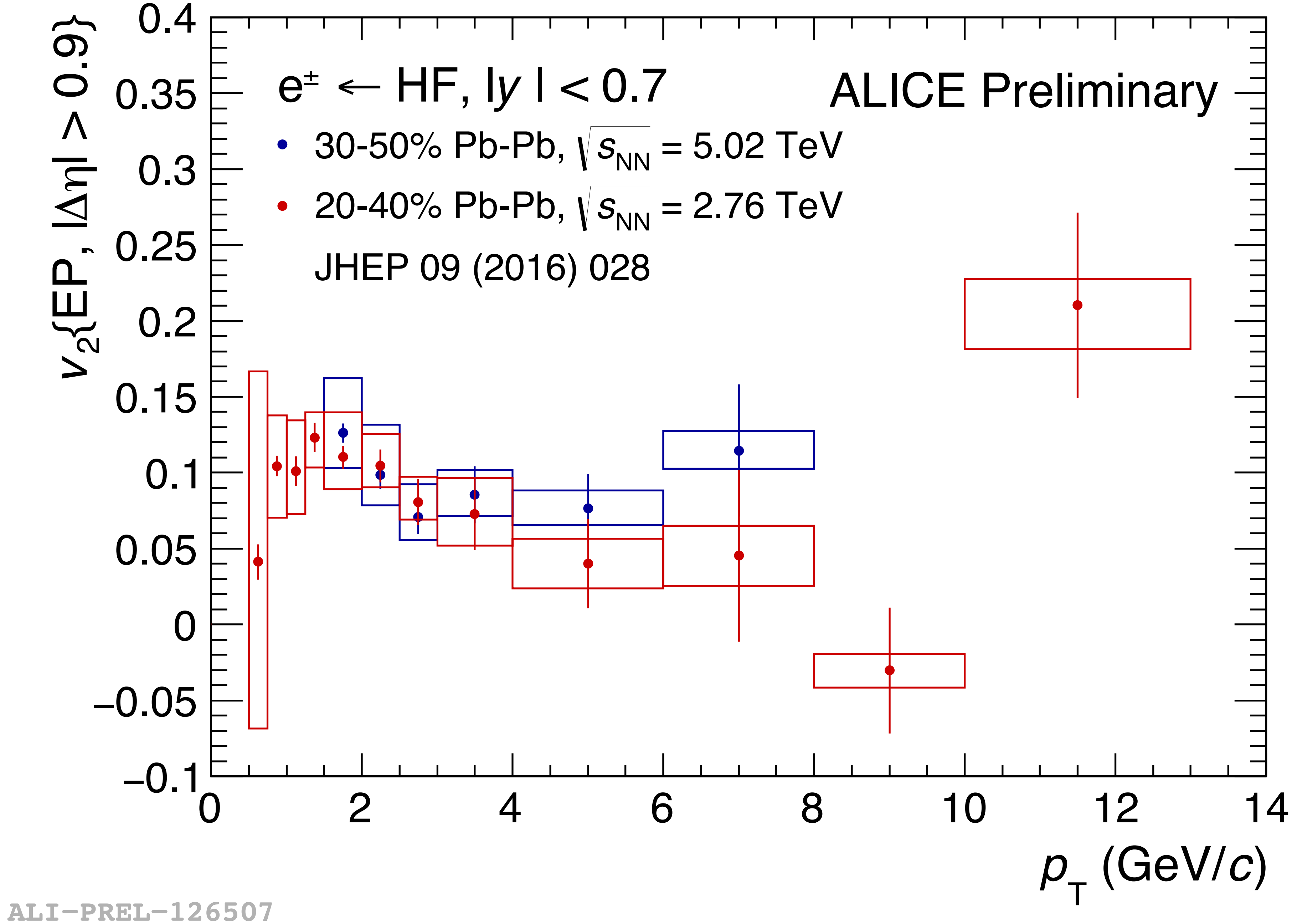


- D-meson R_{AA} significantly smaller than the R_{AA} of non-prompt J/ψ in central collisions —> indication of mass dependent suppression for charm and beauty
- R_{AA}(D) ~ R_{AA}(π) —> different vacuum fragmentation of charm vs. light quarks and light/heavy quark p_T spectrum are relevant in the R_{AA} comparison

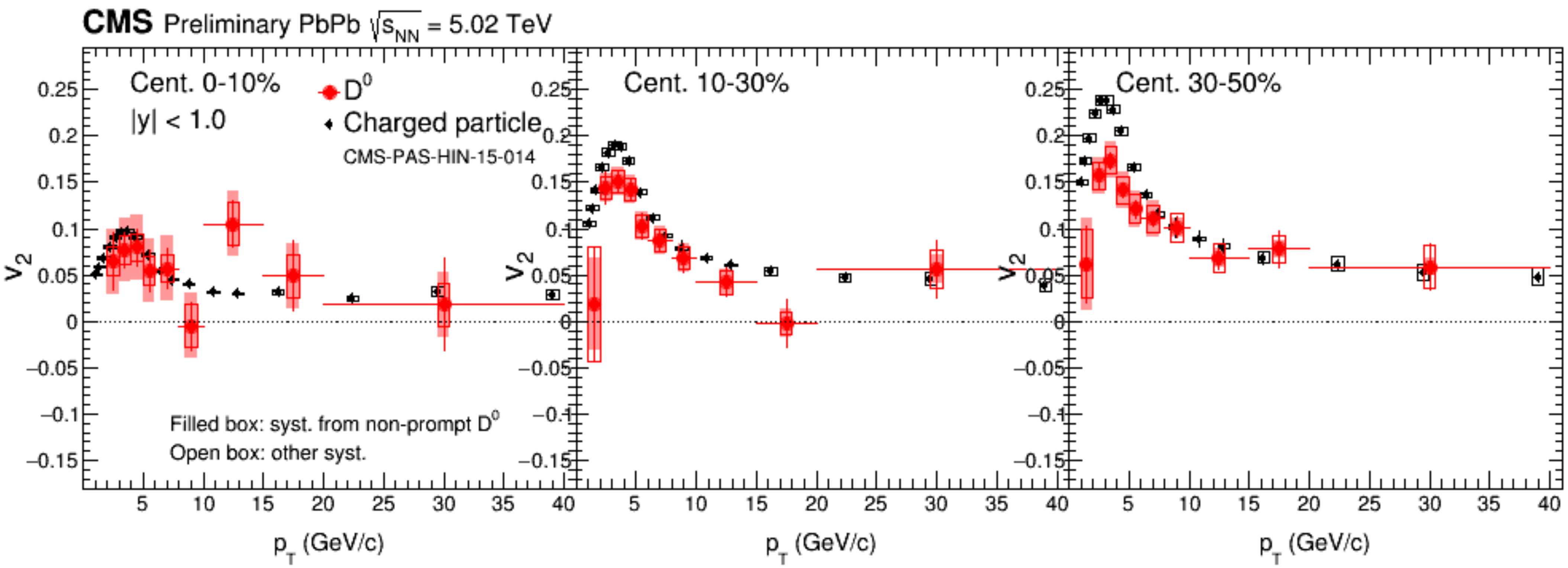
D_s production in Pb-Pb collisions



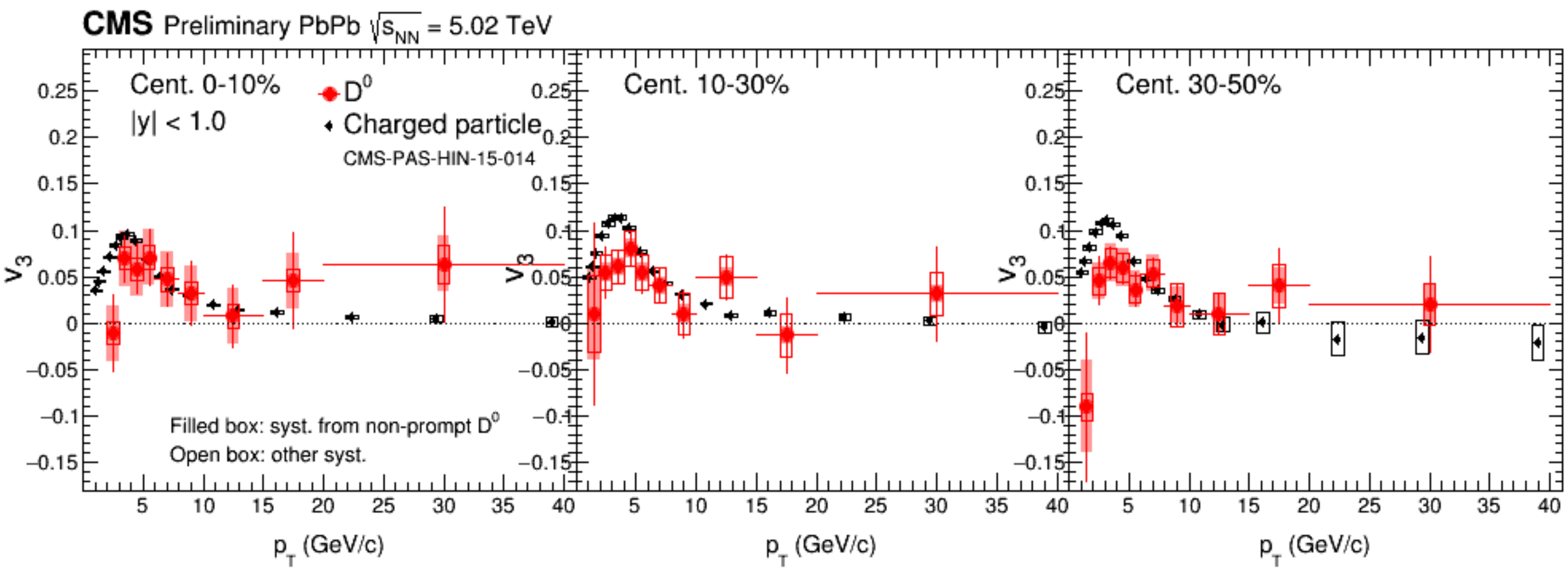
HF electrons v_2



D^0 v_2 and v_3



CMS Preliminary PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Cent. 0-10%
|y| < 1.0
D^0
Charged particle
CMS-PAS-HIN-15-014
Filled box: syst. from non-prompt D^0
Open box: other syst.
Cent. 10-30%
Cent. 30-50%
v_2
p_T (GeV/c)



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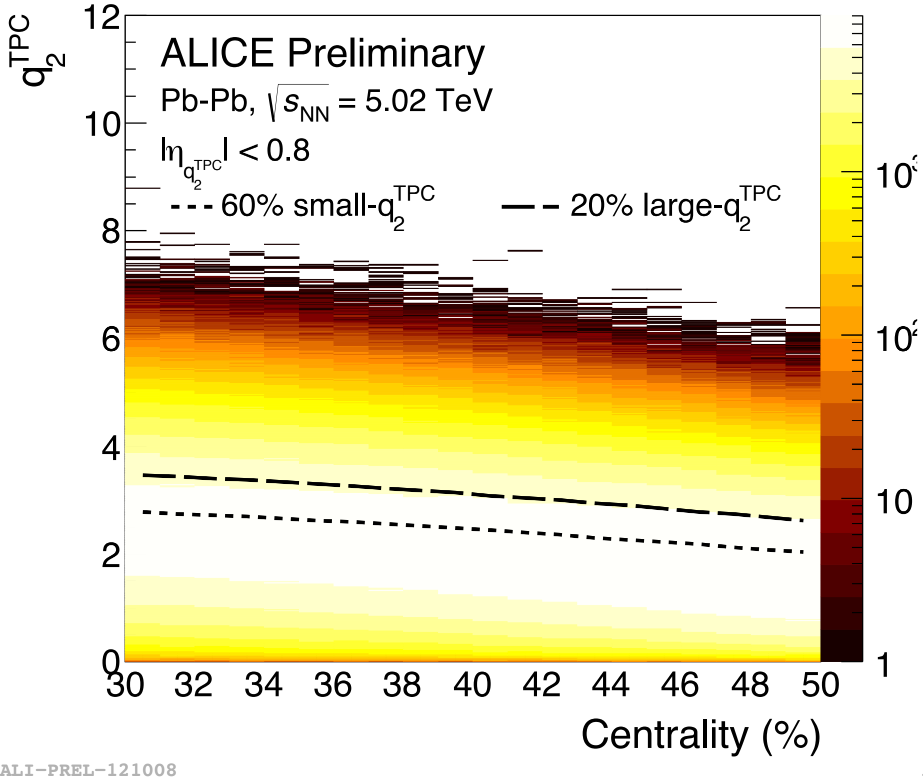
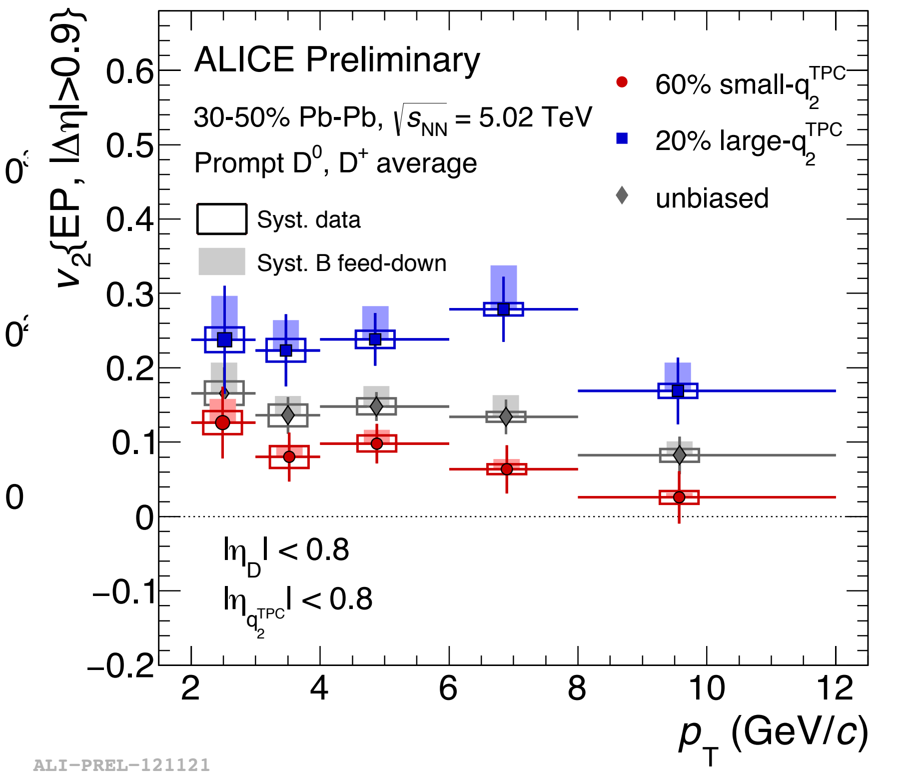
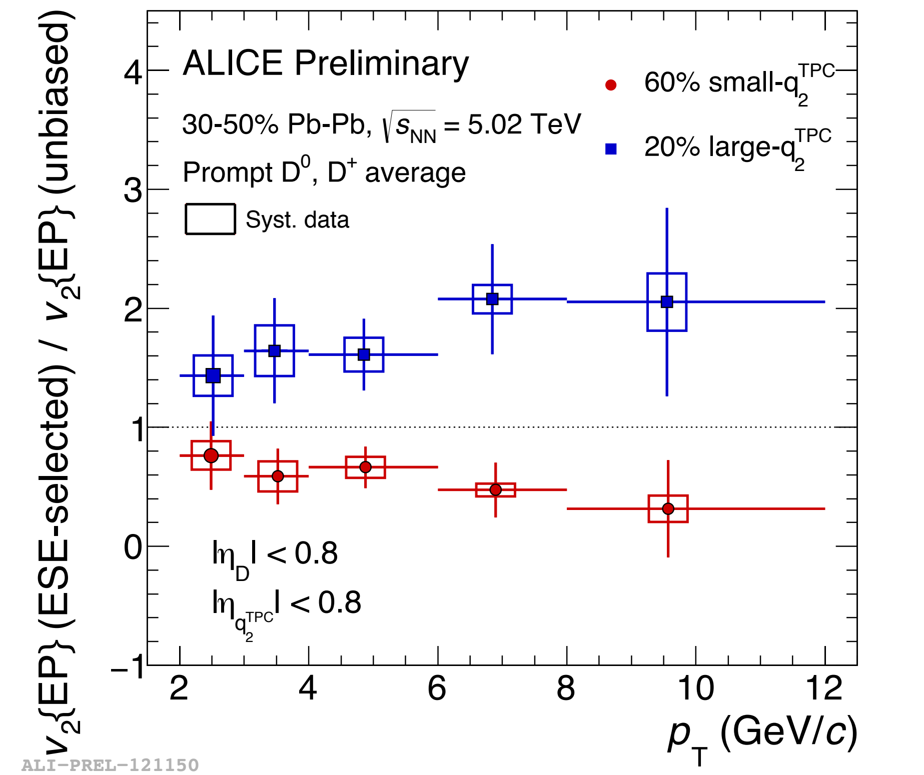
Filled box: syst. from non-prompt D^0
Open box: other syst.
Cent. 10-30%
Cent. 30-50%
v_3
p_T (GeV/c)

D-meson v_2 - Event Shape Engineering Analysis







- q_2, second order reduced flow vector, defined as: $q_2 = \frac{|\boldsymbol{Q}_2|}{\sqrt{M}}$

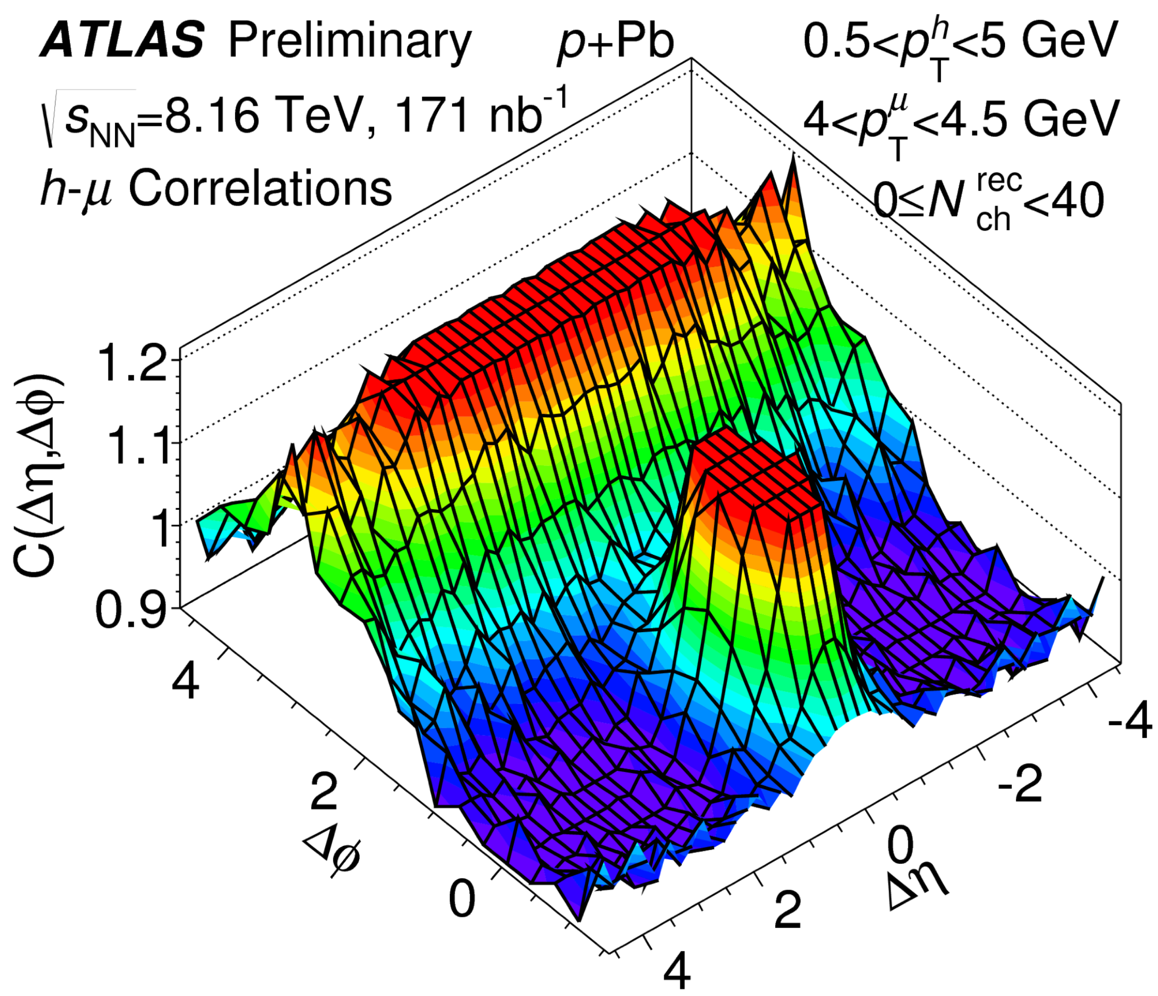
M: multiplicity

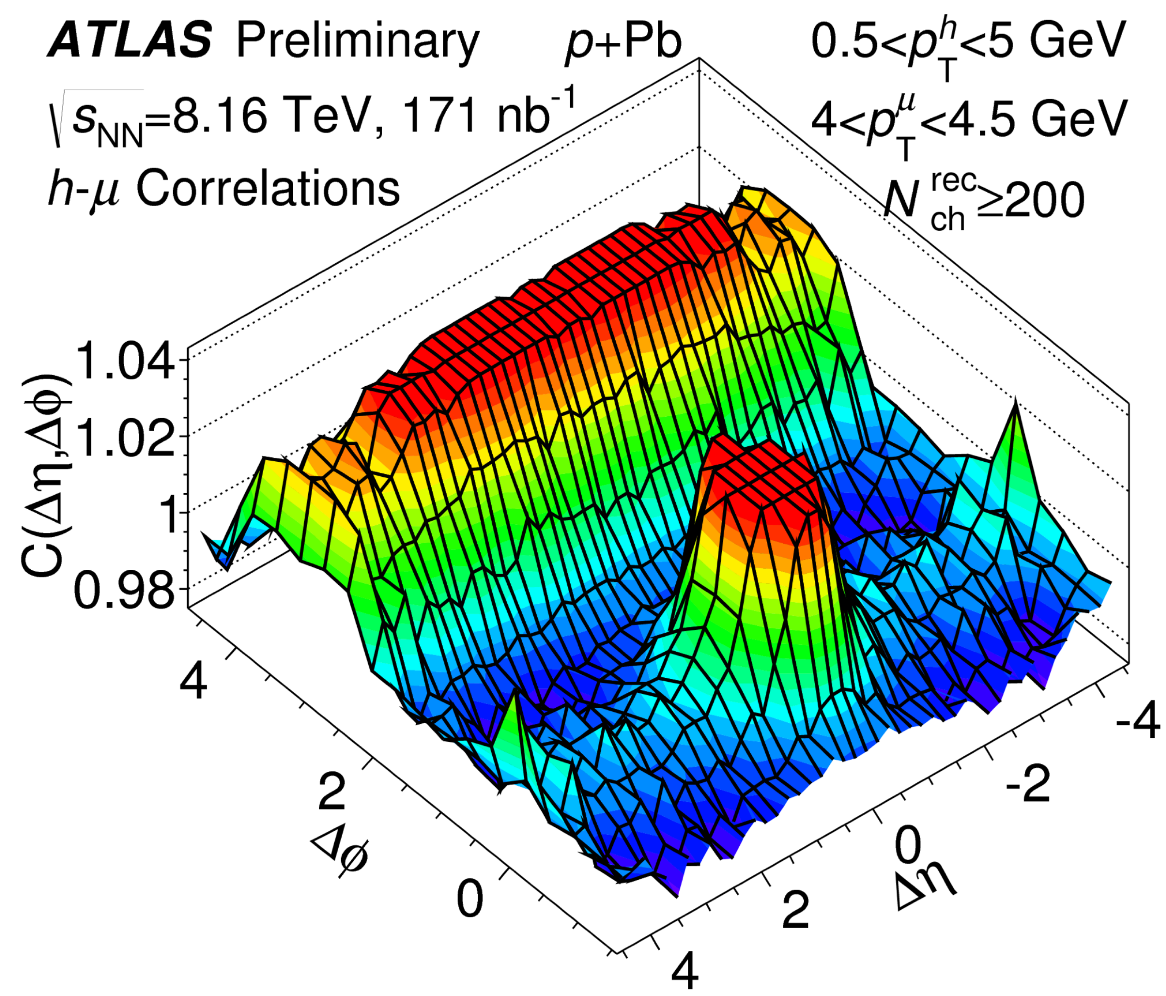
$$|\boldsymbol{Q}_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$$

$$Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i \, , \; Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$

- q_2 depends on multiplicity and strength of the flow —> connected to event eccentricity
- Measuring v_2 at different q_2 values —> study charm quark coupling to the light hadron bulk
- Significant separation of D-meson v_2 in events with large and small q_2 (autocorrelation and non-flow effects between q_2 determination and D-meson reconstruction not removed)

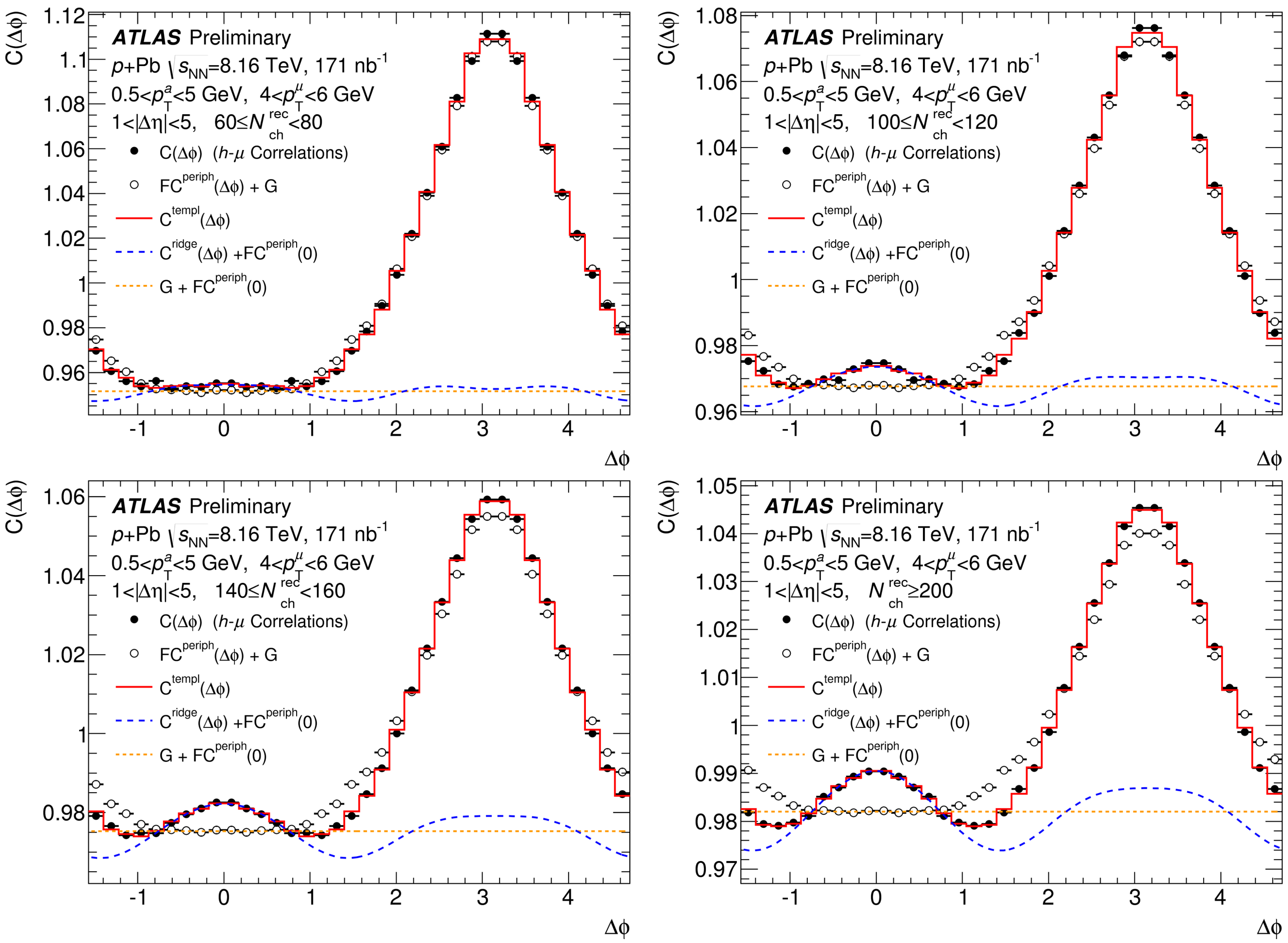
Heavy flavour v_2 in p-Pb collisions





$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

Heavy flavour v_2 in p-Pb collisions



$$C(\Delta\phi) = \frac{\int_1^5 d|\Delta\eta|\, S(|\Delta\eta|,\Delta\phi)}{\int_1^5 d|\Delta\eta|\, B(|\Delta\eta|,\Delta\phi)} \equiv \frac{S(\Delta\phi)}{B(\Delta\phi)}$$

$$C^{\mathrm{templ}}(\Delta\phi) = FC^{\mathrm{periph}}(\Delta\phi) + C^{\mathrm{ridge}}(\Delta\phi)$$

$$C^{\mathrm{ridge}}(\Delta\phi) = G\left(1 + \sum_{n=2}^{\infty} 2v_{n,n}\cos(n\Delta\phi)\right)$$

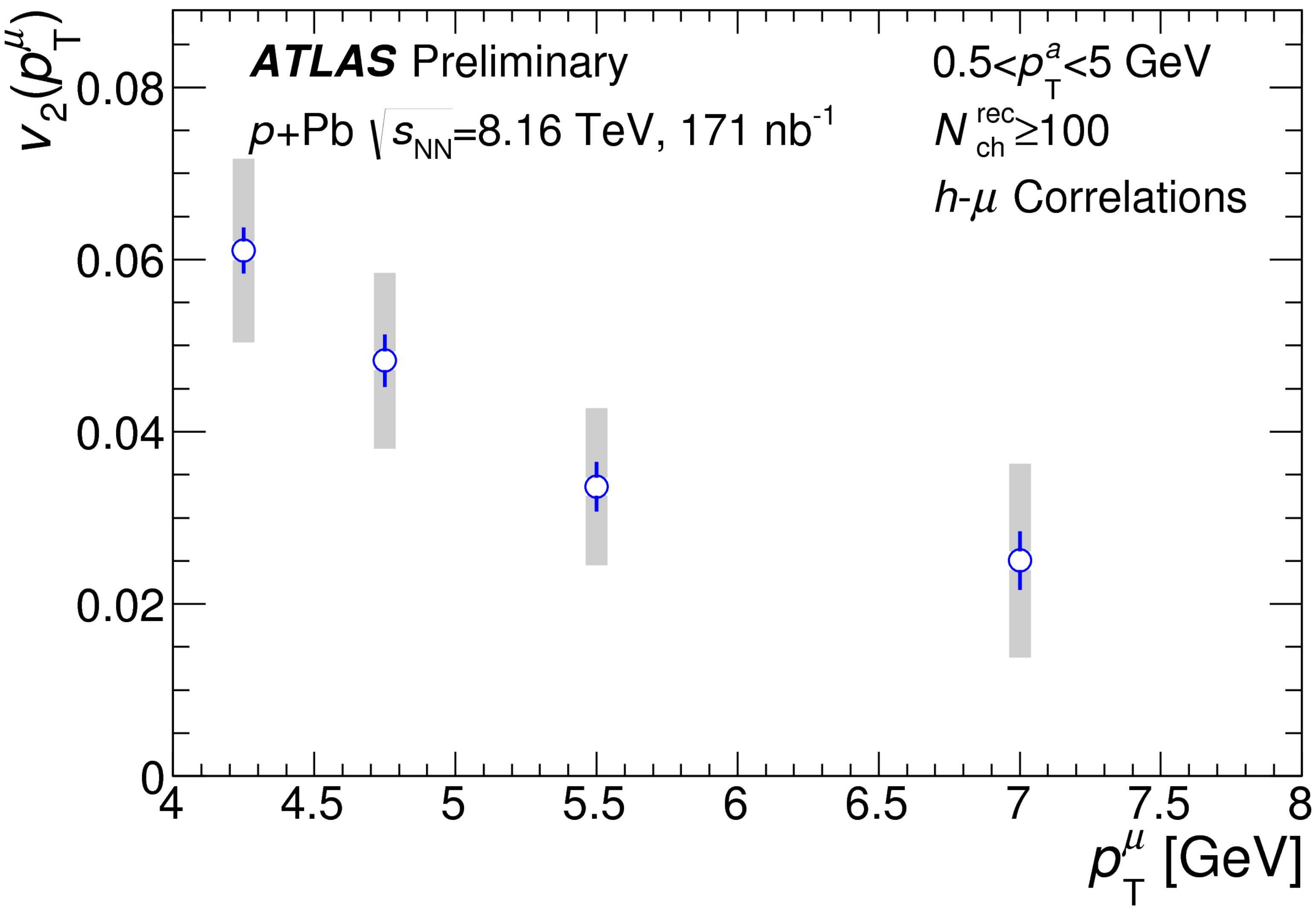
$$v_{n,n}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b) = v_n(p_{\mathrm{T}}^a)v_n(p_{\mathrm{T}}^b)$$

$$v_n(p_{\mathrm{T}}^b) = v_{n,n}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b)/v_n(p_{\mathrm{T}}^a) = v_{n,n}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b)/\sqrt{v_{n,n}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^a)},$$

$$v_{n,n}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^a) = v_n(p_{\mathrm{T}}^a)^2$$

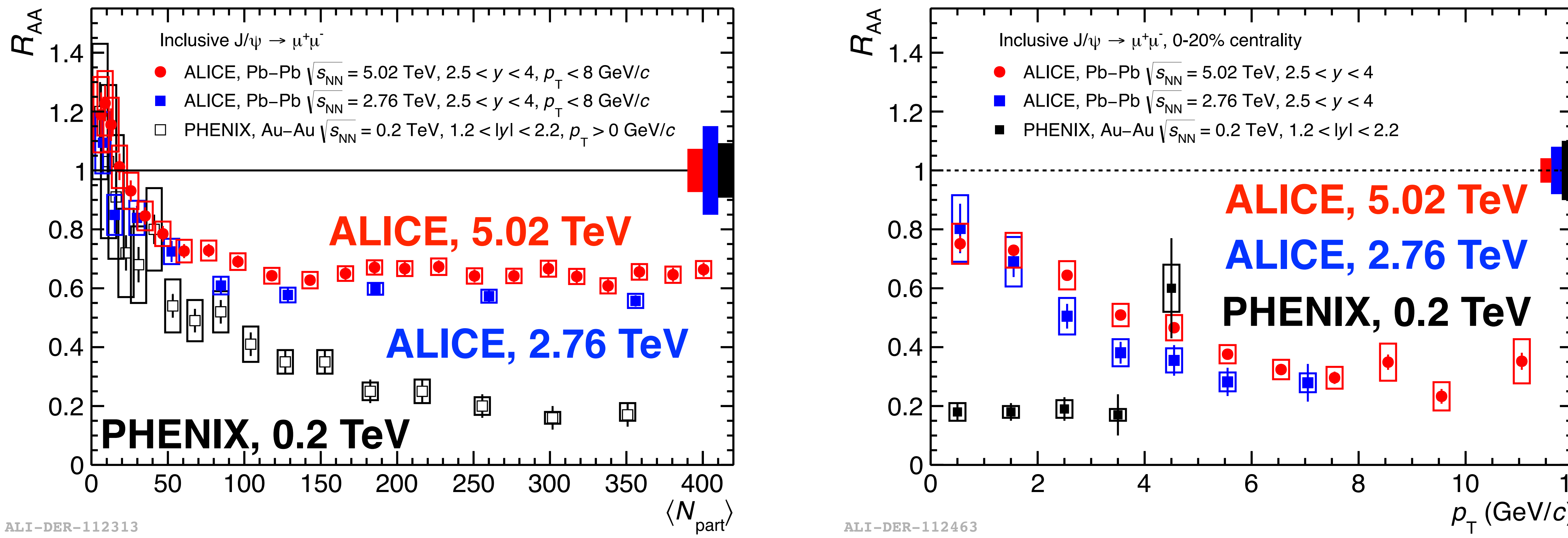
Heavy flavour v_2 in p-Pb collisions

ATLAS-CONF-2017-006



- v_2 decreases with increasing p_T

Low p_T J/ψ



- Clear J/ψ suppression with almost no centrality dependence for N_{part}>100 in ALICE
- Stronger J/ψ suppression vs centrality at RHIC than at LHC, despite the larger energy density
- Weaker low p_T suppression measured at LHC
- No significant $\sqrt{s_{NN}}$ dependence of R_{AA} (2.76 vs 5.02 TeV) at central and forward-*y* within uncertainties
- Important role of recombination at LHC energies

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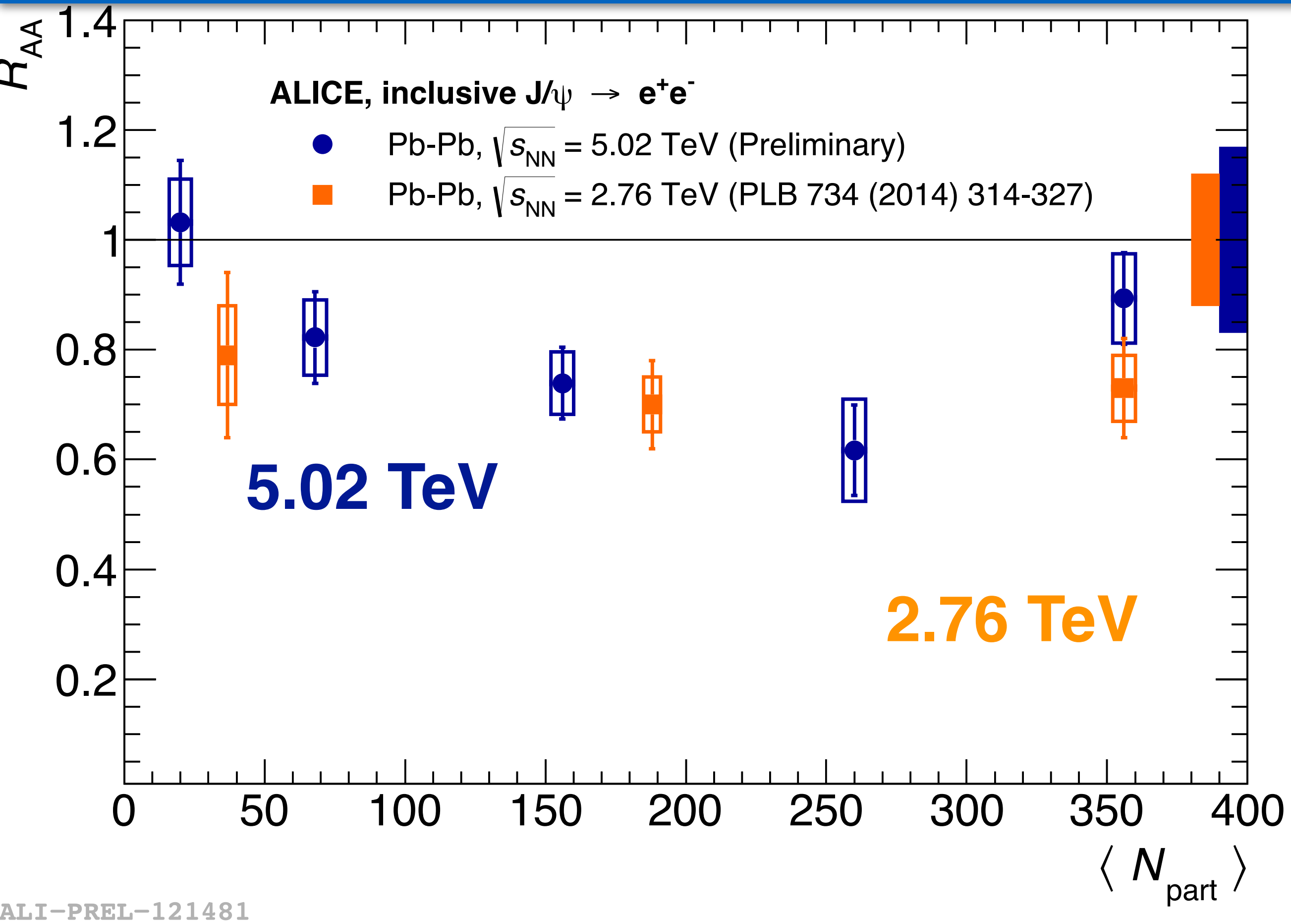
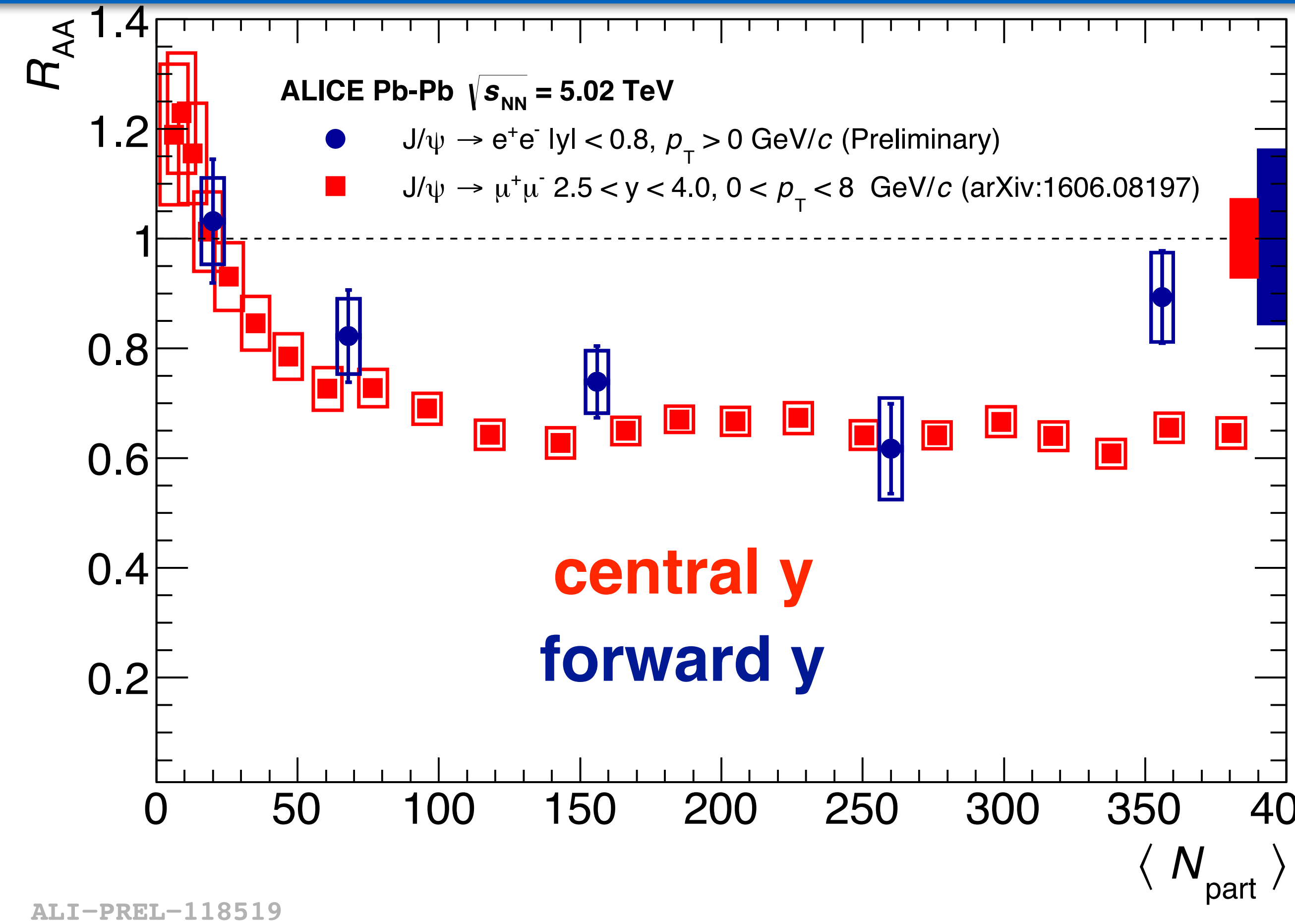
PRL 109 (2012) 072301

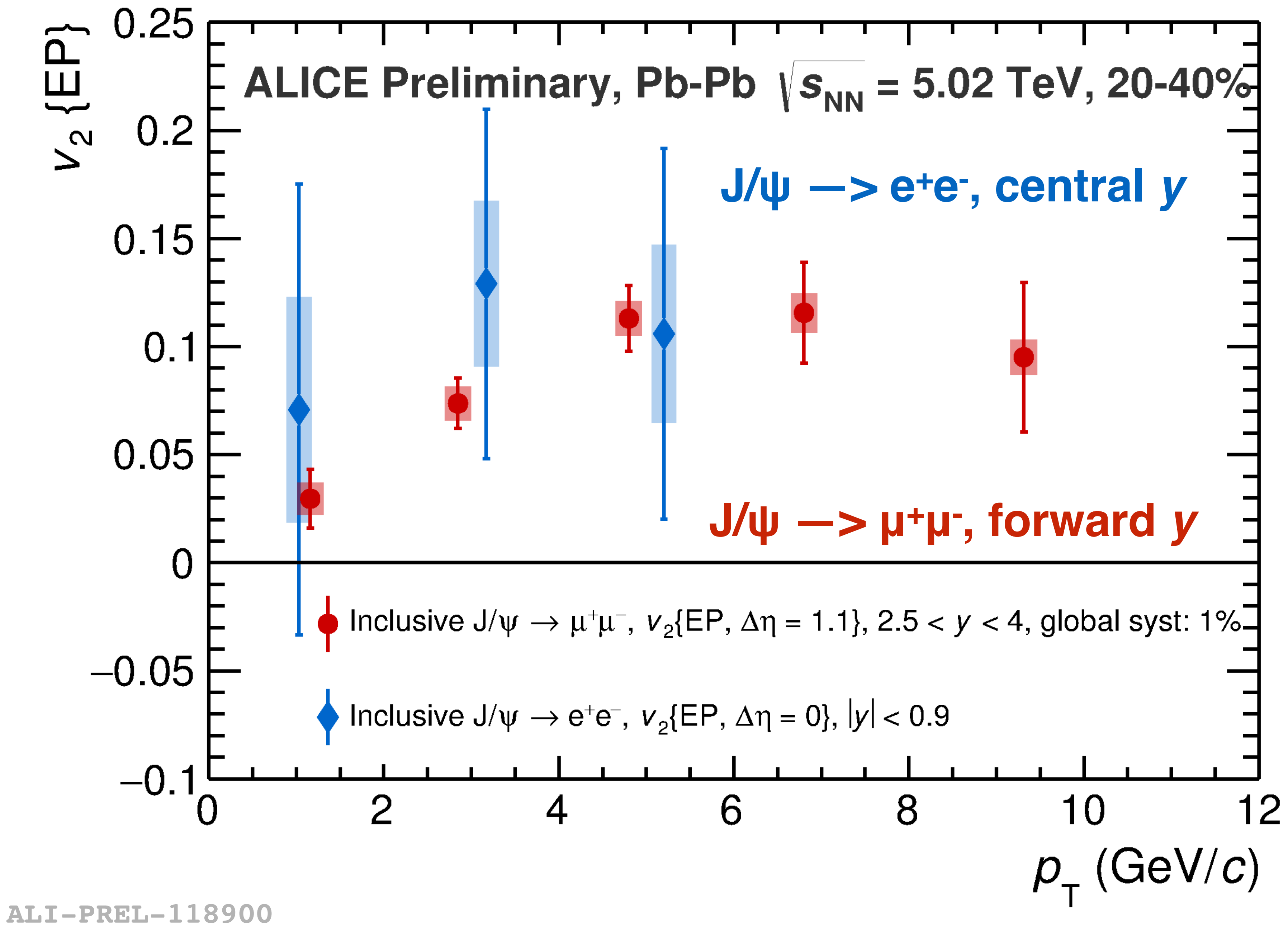
Low p_T J/ψ: central vs. forward y



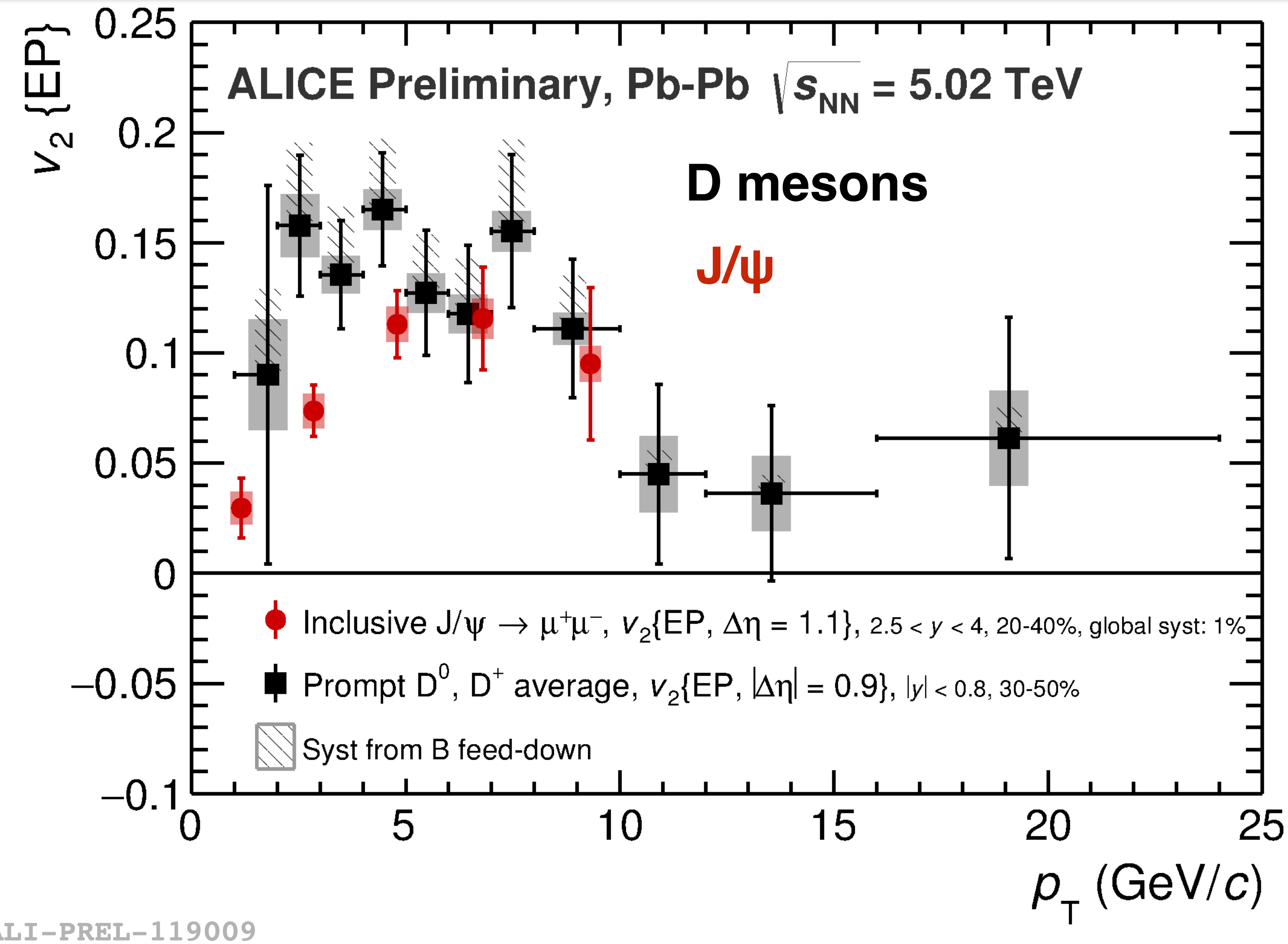


- Hint (<2sigma, only in one centrality class) for a weaker suppression at y~0 with respect to forward-y results in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - expected in a (re)combination scenario (even if fluctuation can not be excluded)
- No significant $\sqrt{s_{NN}}$ dependence of R_{AA} (2.76 vs 5.02 TeV), confirming forward-y observation

J/ψ v_2

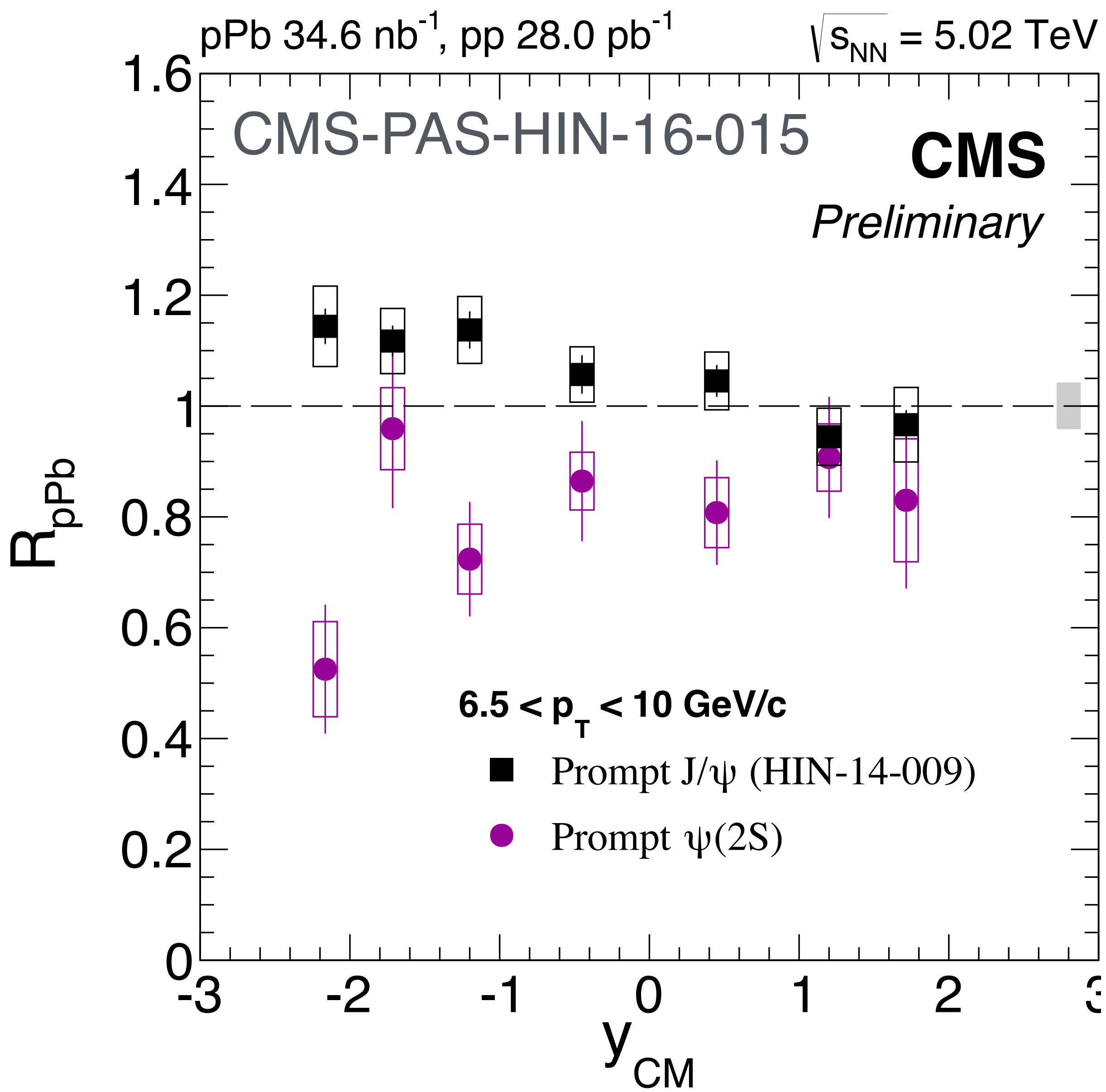


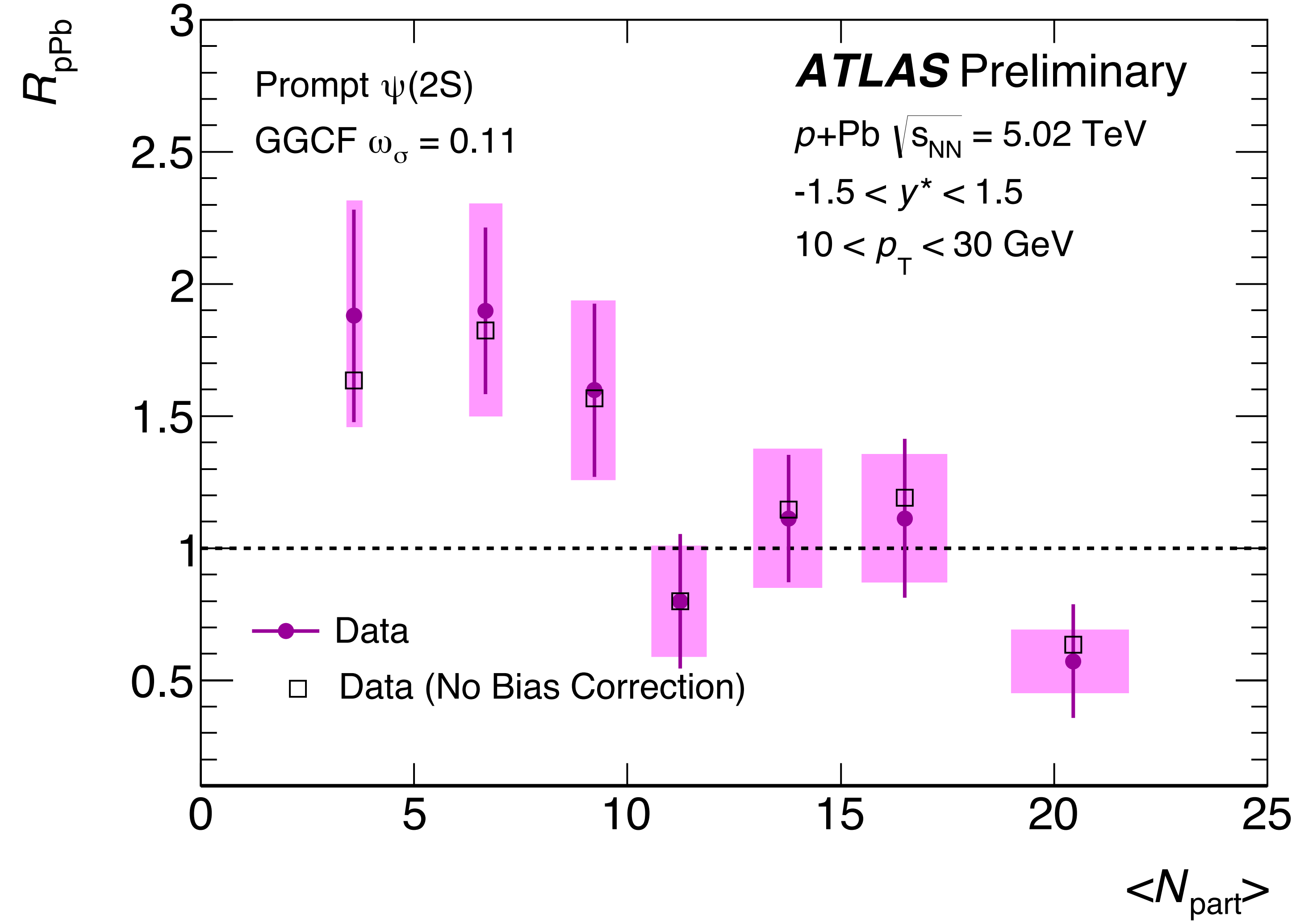
- First ALICE measurement of J/ψ v_2 at mid-rapidity shows agreement with forward-*y* results within uncertainties



- Observed J/ψ v_2 similar to the one of D mesons
  - Different kinematic range:
    - J/ψ: 2.5<y<4, centrality 20-40%
    - D: |y|<0.8, centrality 30-50%
  - Different p_T of the charm quarks
- Learn about light vs. heavy quark flow

ψ(2S) in p-Pb at √sNN=5.02 TeV

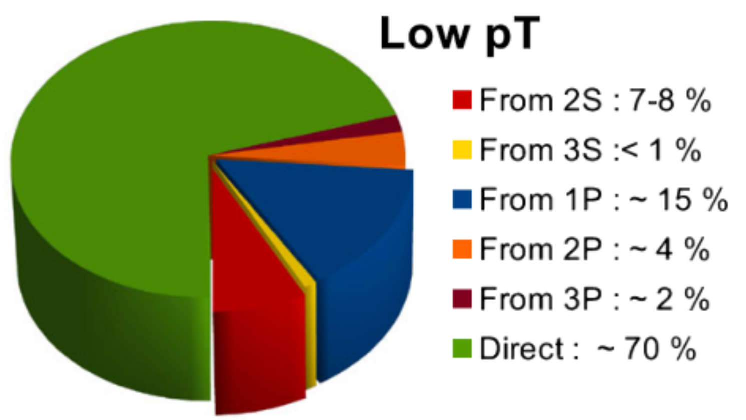


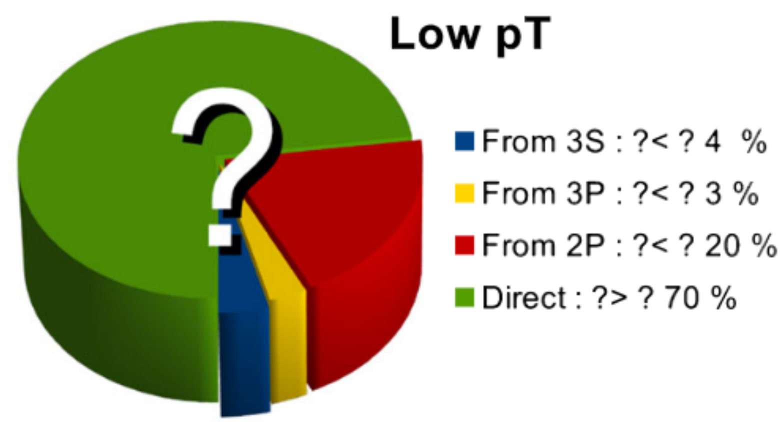


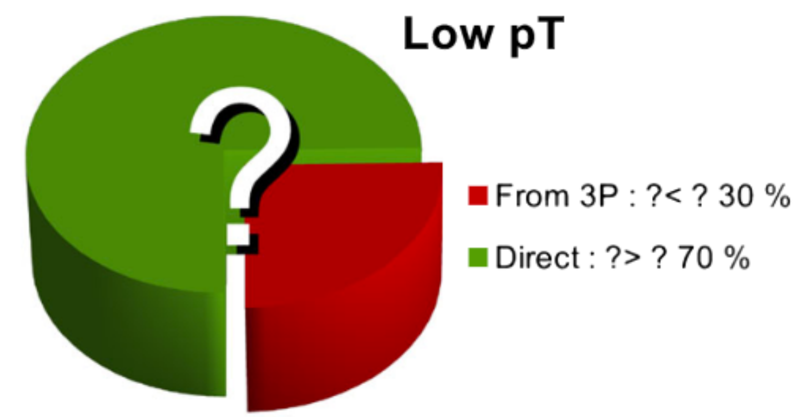
- Suppression of ψ(2S) at backward rapidity observed by CMS (not expected from models including CNM and coherent energy loss effects, it might be consistent with the picture of final state inelastic interactions with the medium produced in pPb collisions)
- Decreasing trend of the ψ(2S) R_{pPb} with increasing centrality

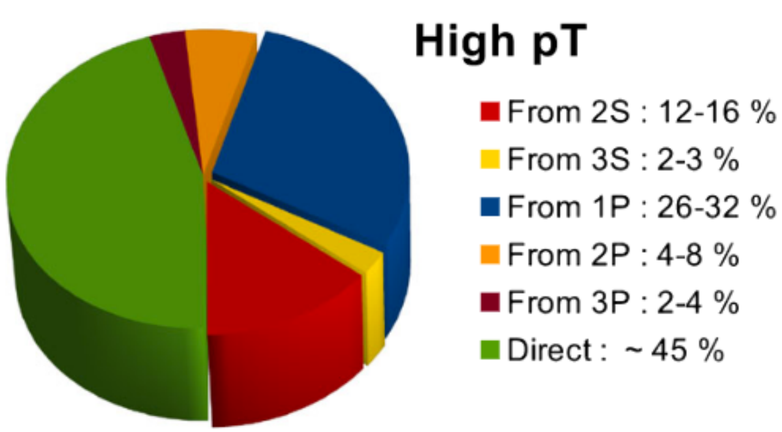
Bottomium feed-down

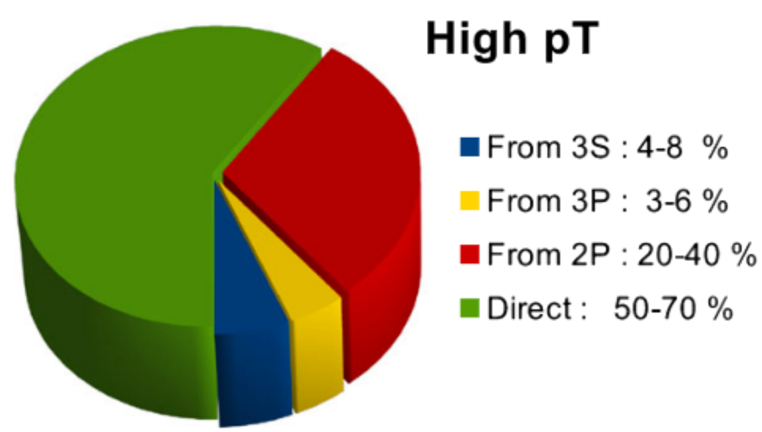
Andronic, A., Arleo, F., Arnaldi, R. et al. Eur. Phys. J. C (2016) 76: 107

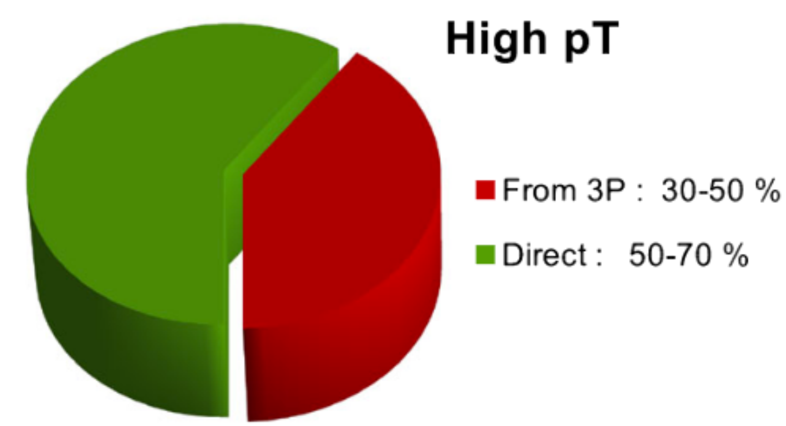










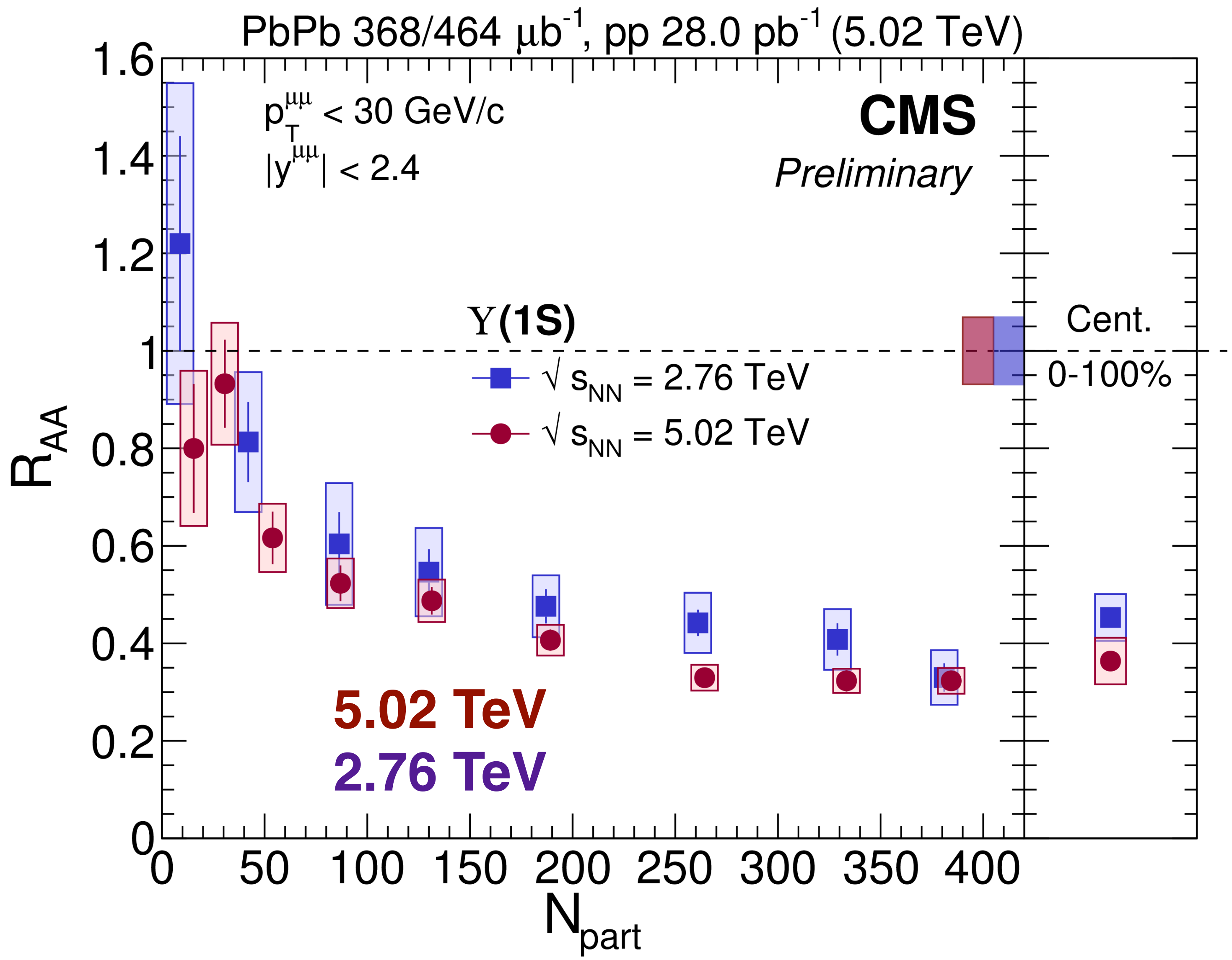


Y(1S) **Y(2S)** **Y(3S)**

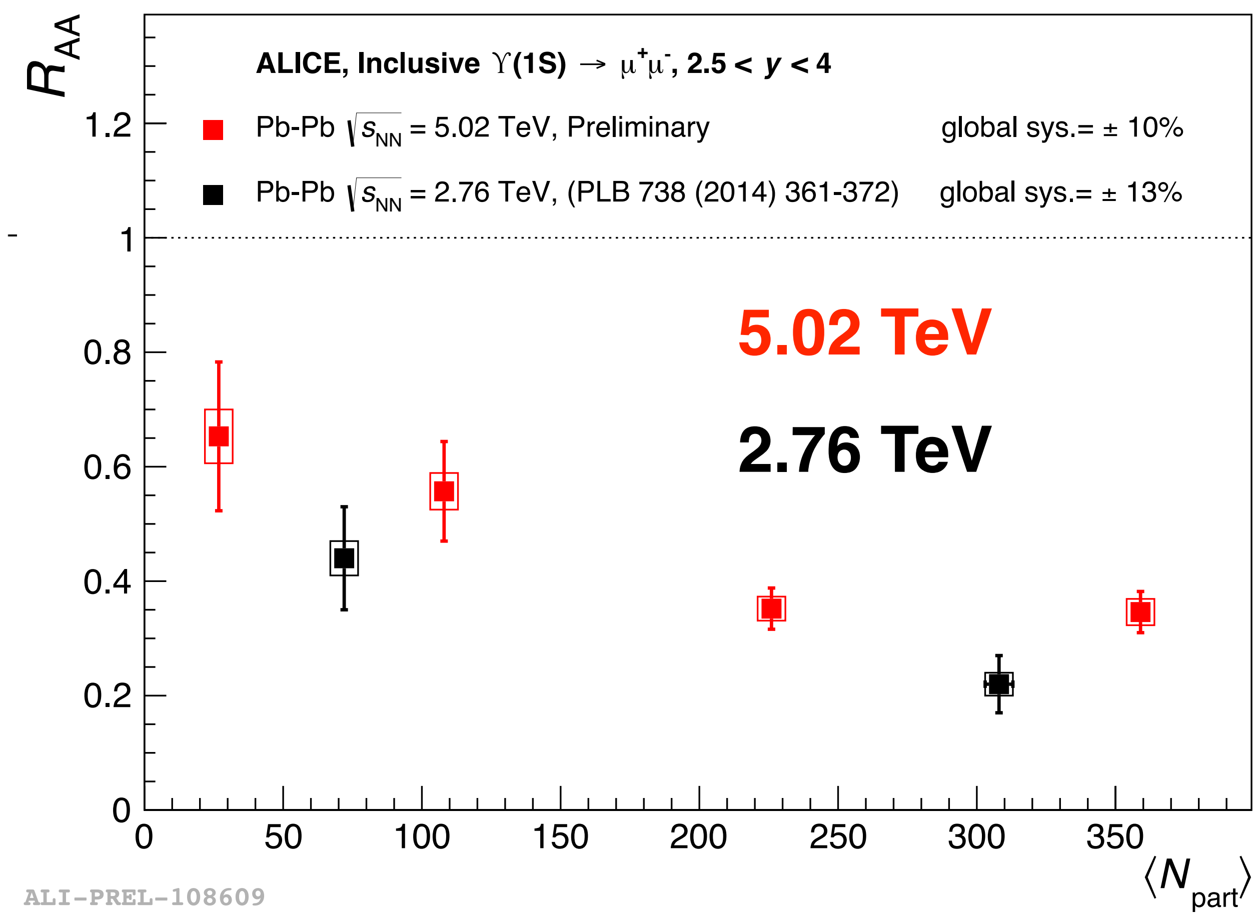
- Prediction on the basis of LHC results

Υ(1S) R_{AA} vs. centrality/energy

CMS-PAS-HIN-16-023

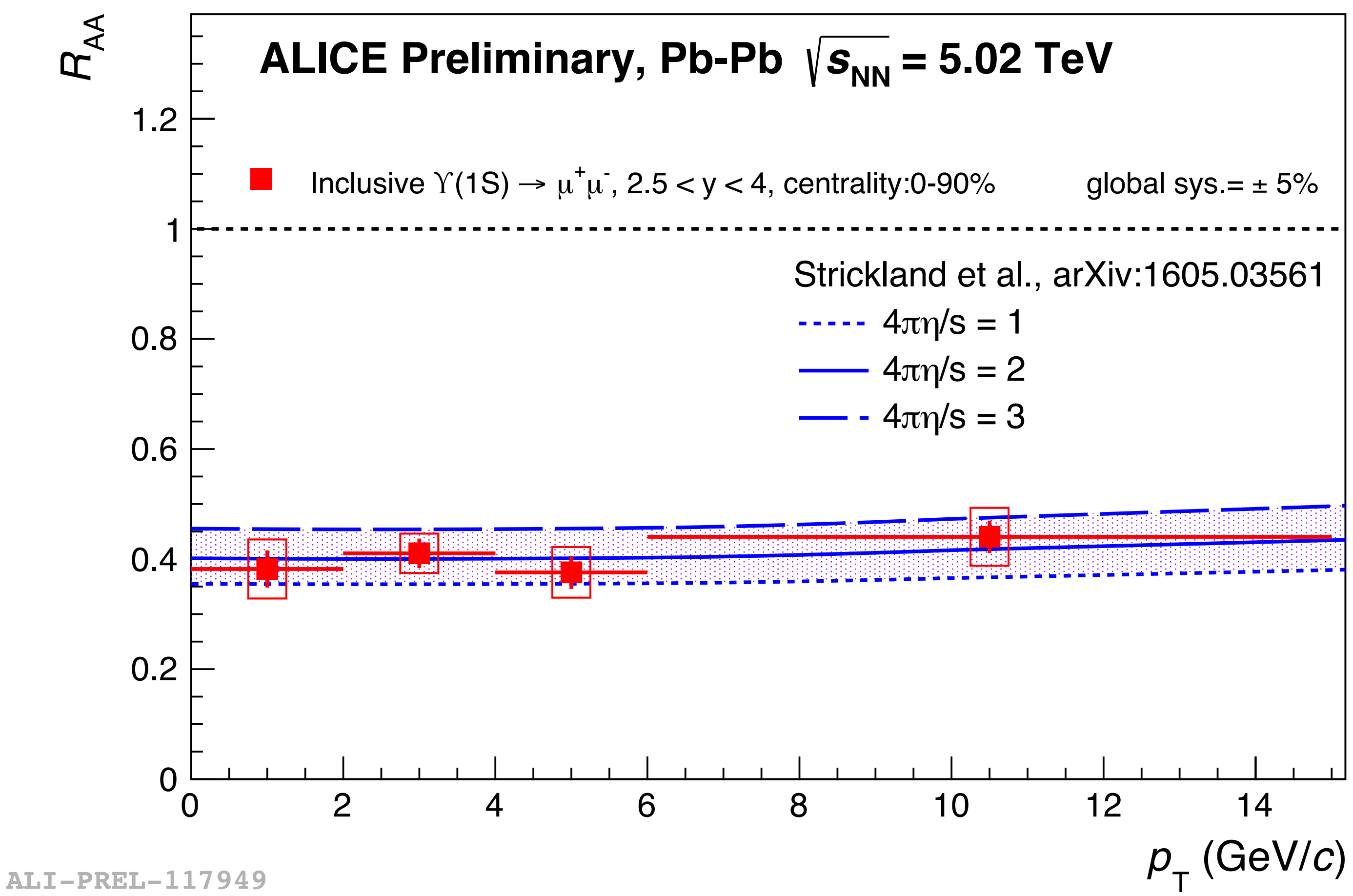


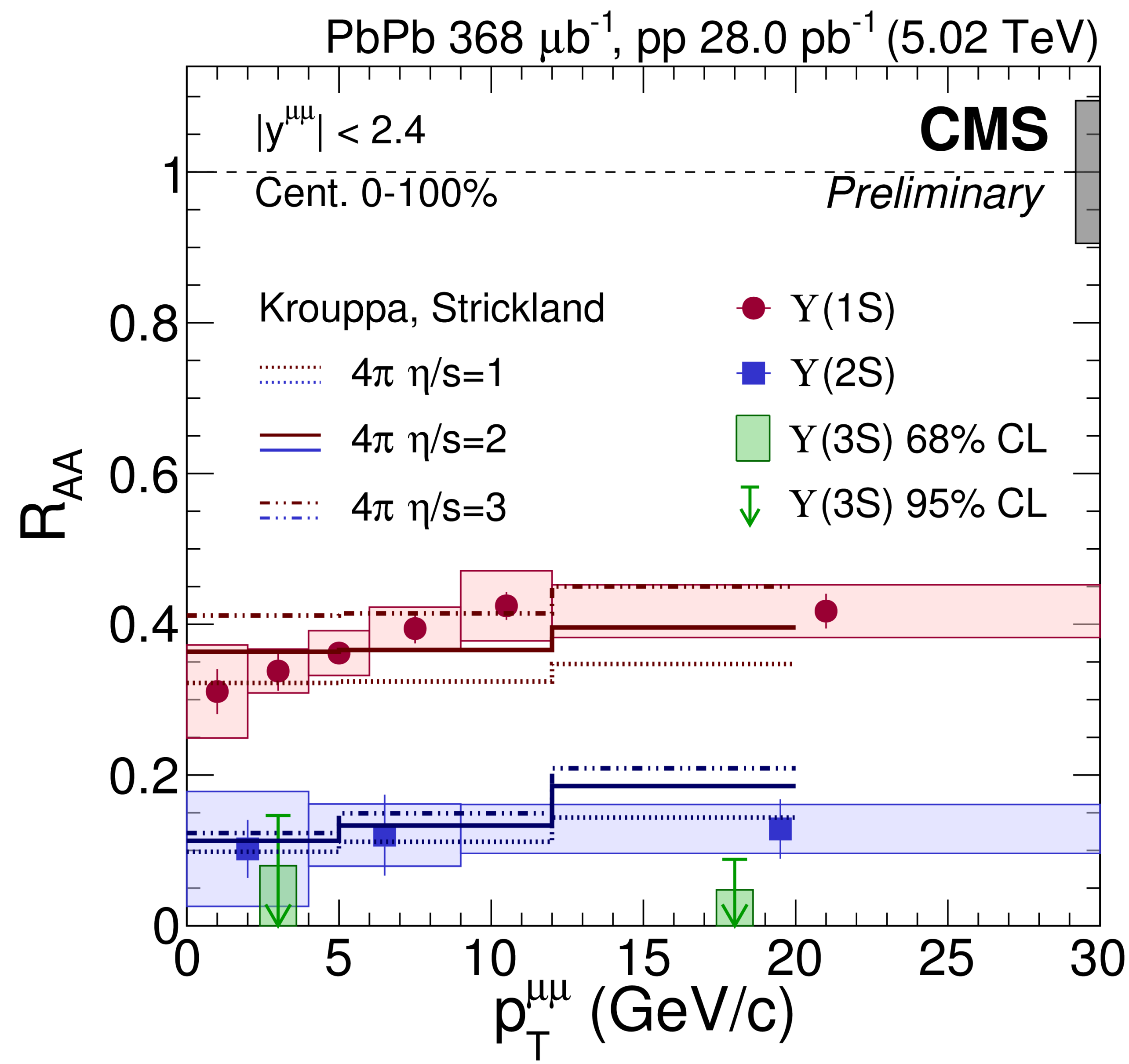
PLB 738 (2014) 361-372



- Hint of larger suppression at $\sqrt{s_{NN}}$ = 5 TeV with respect to 2.76 TeV

Υ(1S) R_{AA} vs. p_T



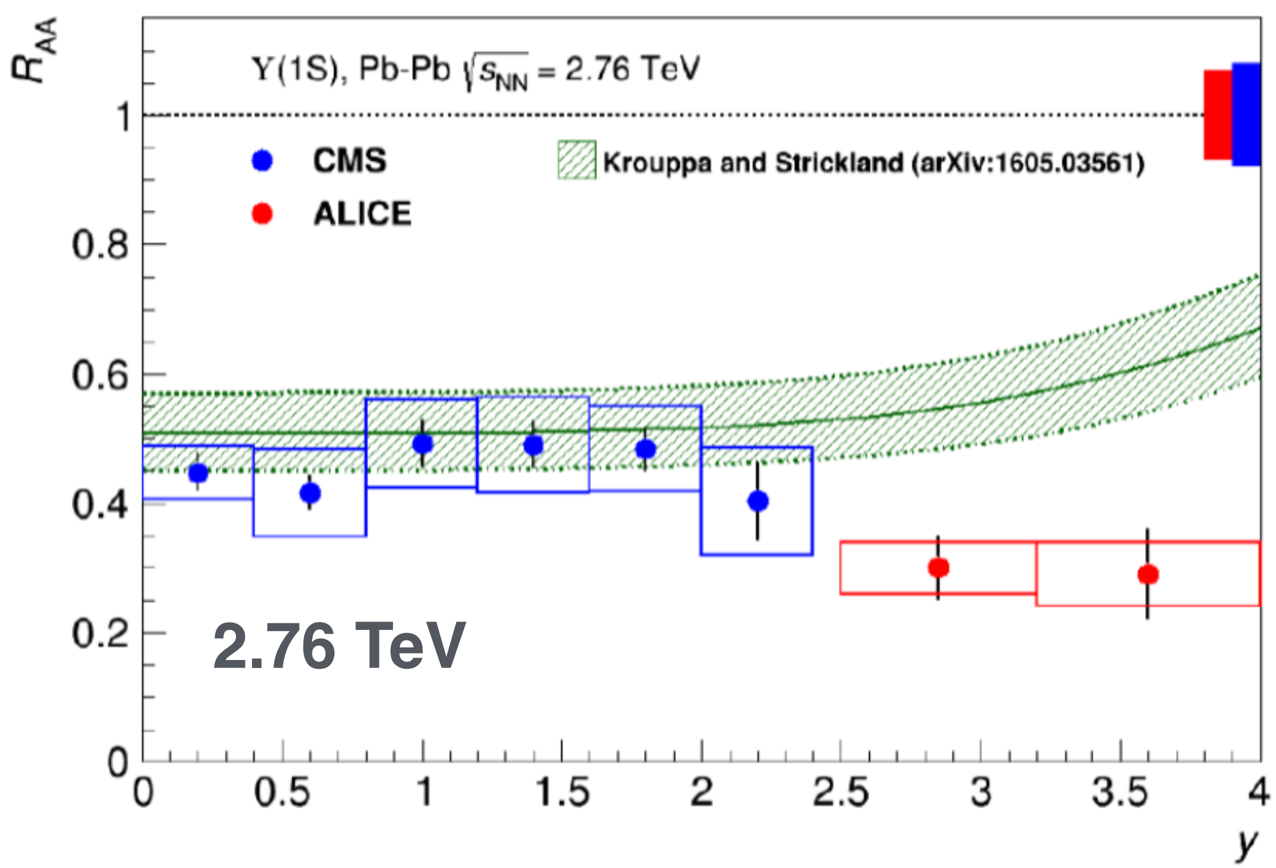


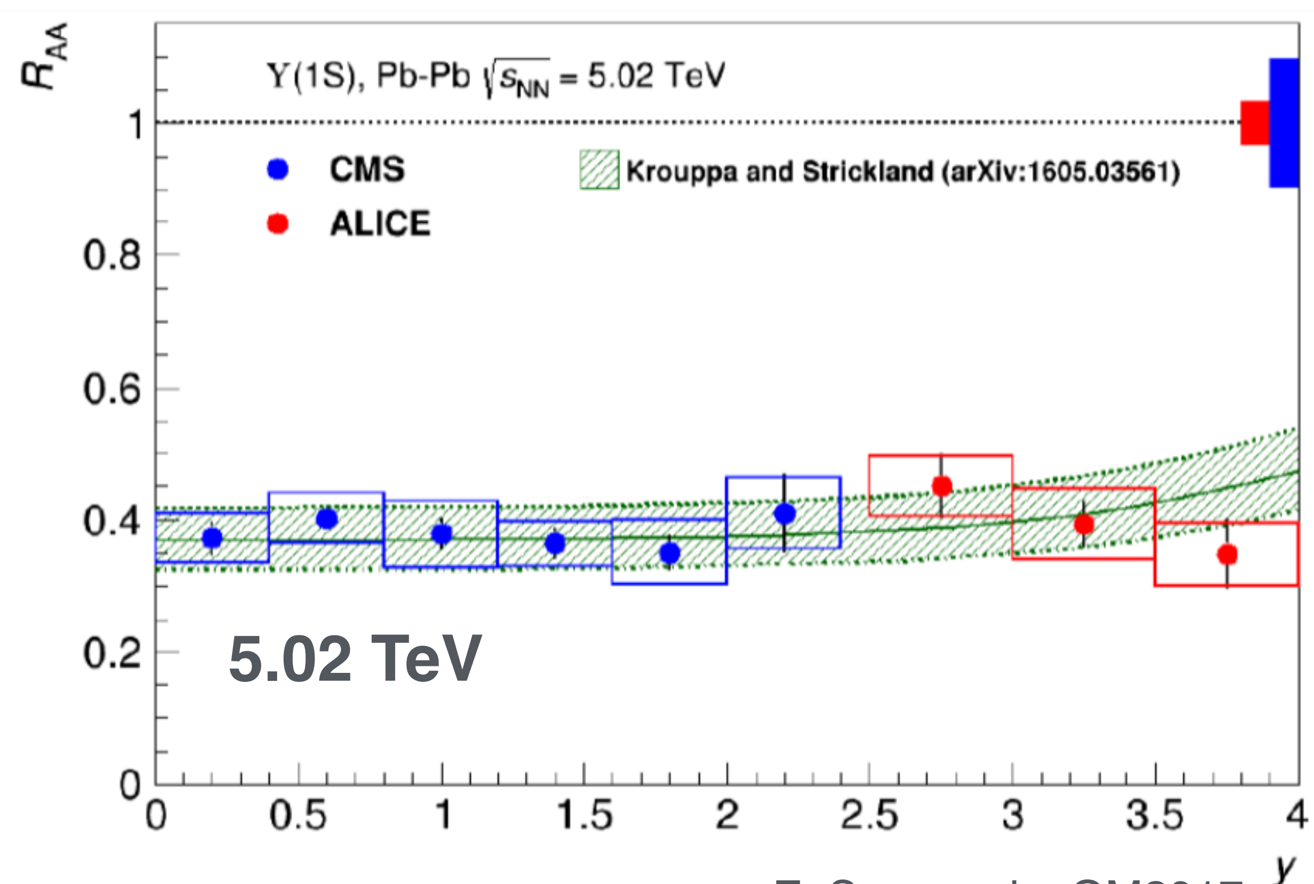
CMS-PAS-HIN-16-023

- Both ALICE and CMS measure mild or no dependence on p_T of the R_{AA}
- Fair agreement with theoretical model

Υ(1S) R_{AA} vs. y

CMS-PAS-HIN-16-023
arXiv:1611.01510





E. Scomparin, QM2017

- Suppression increases with y at $\sqrt{s_{NN}}$ = 2.76 TeV
- Suppression is constant at $\sqrt{s_{NN}}$ = TeV
- Some tension in the R_{AA} evolution vs y with energy, still large uncertainties