Open heavy-flavor production in pA and AA at LHC

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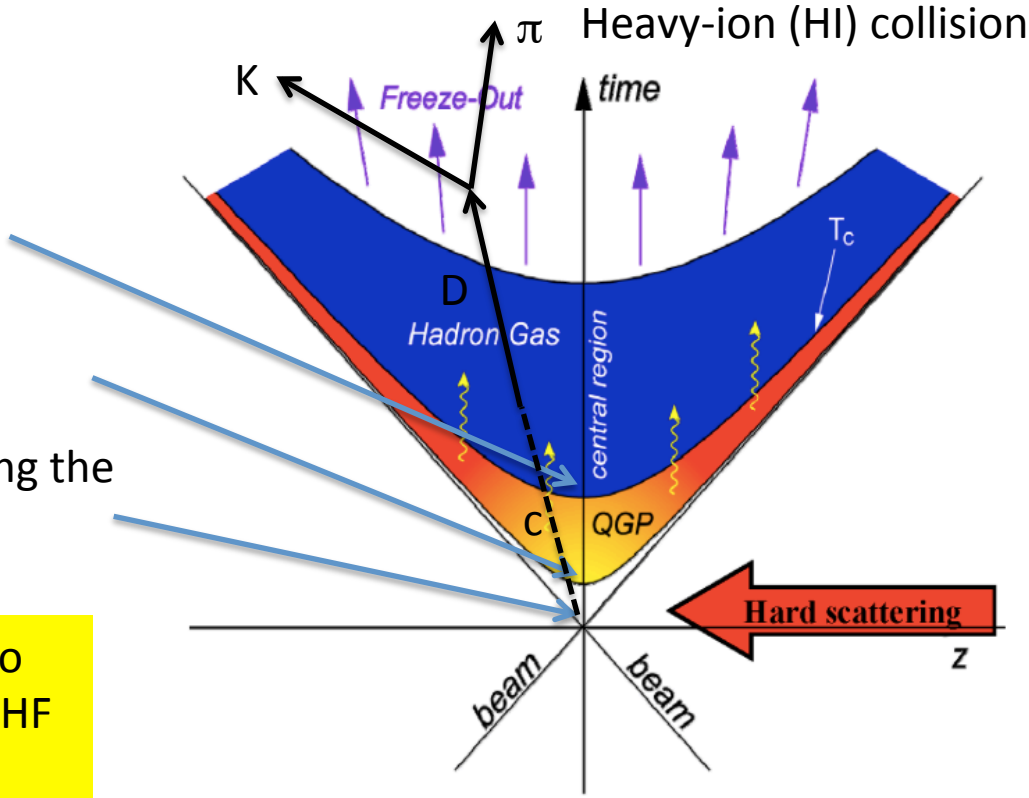
Physics motivation

t

Lifetime of QGP ≈ 10 fm/*c*

Formation time of the QGP ≤ 0.1 fm/*c*

heavy-flavor (HF) early production during the collision: $1/2m_c = 0.08$ fm/*c*



a probe of the medium from production to observation that gives a unique access to HF interactions in the QGP.

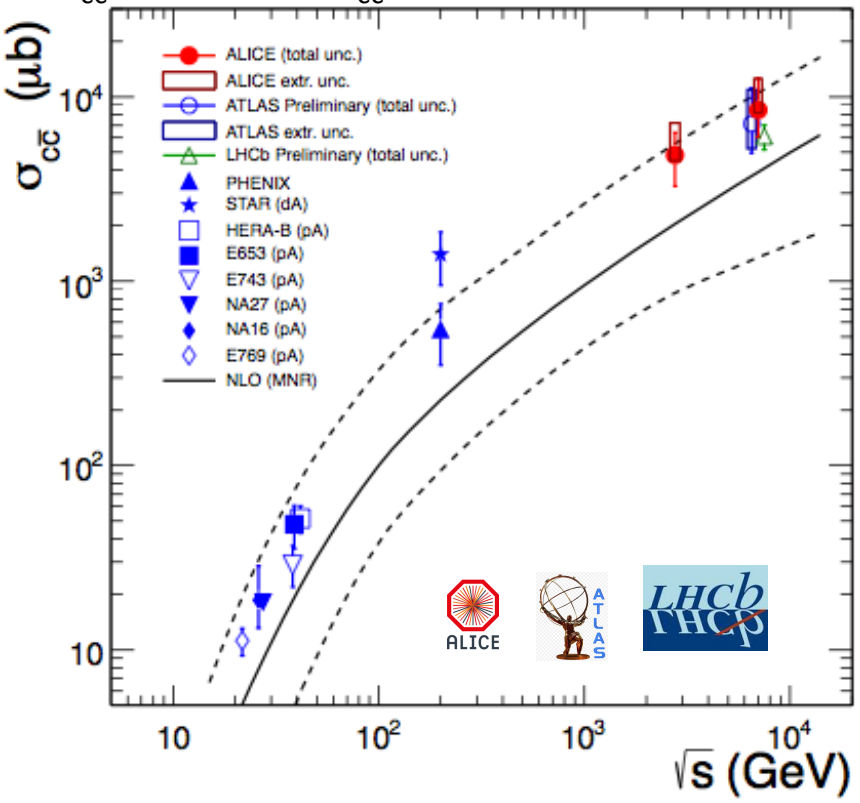
production cross sections (hard scattering) calculable with perturbative QCD

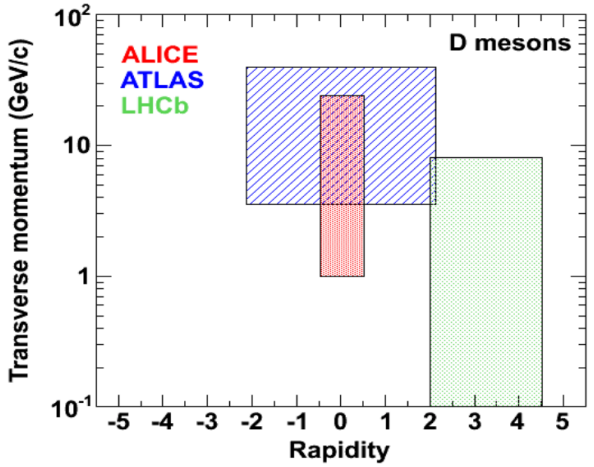
We can investigate:

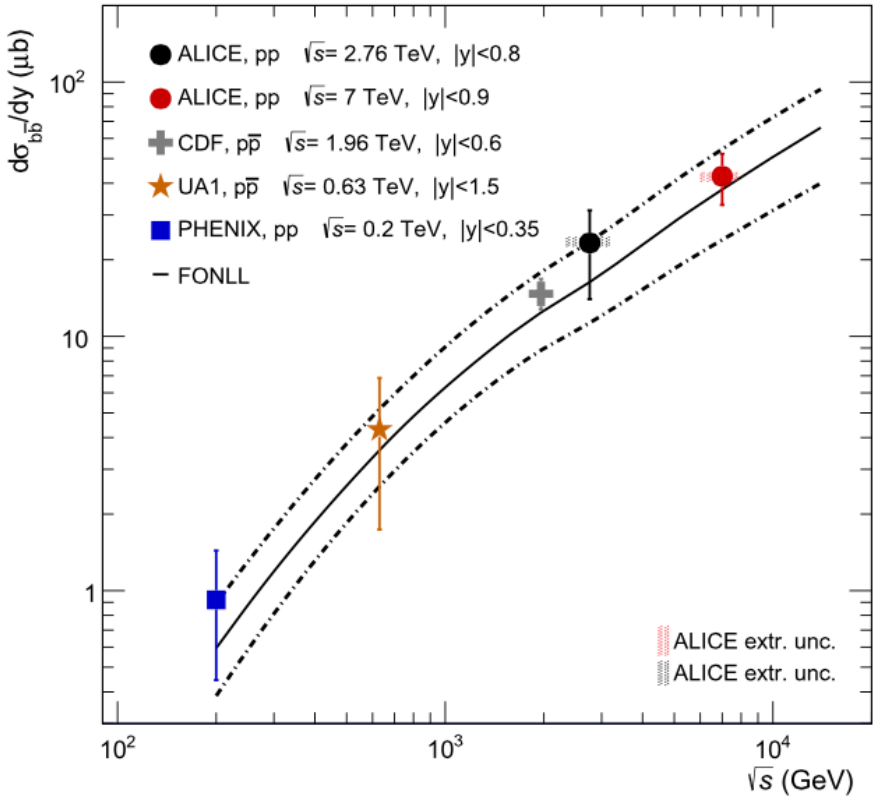
1. Parton energy loss in the QGP
2. Participation of heavy quarks in the collective expansion of the medium

The baseline: HF production in pp

- for charm production there is fair agreement among the LHC experiments and all points populate the upper side of the theoretical prediction
- Reference for p-Pb and Pb-Pb collisions
- $\sigma_{c\bar{c}}$(LHC) ~ 10 $\sigma_{c\bar{c}}$ (RHIC) (factor 50 for $b\bar{b}$)





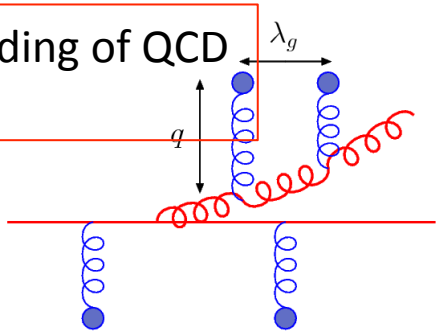


ALICE, Phys. Lett. B738 (2014) 97

ALICE, JHEP 1207 (2012) 191 JHEP 1207 (2012) 191
ATLAS, ATLAS-PHYS-PUB-2011-012 (2011)
LHCb, Nucl. Phys. B 871 (2013)

Pb-Pb interactions: testing parton energy loss

heavy flavour: testing our understanding of QCD energy loss in the medium



$$\Delta E \propto \alpha_s C_R \bar{q} L^2$$

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

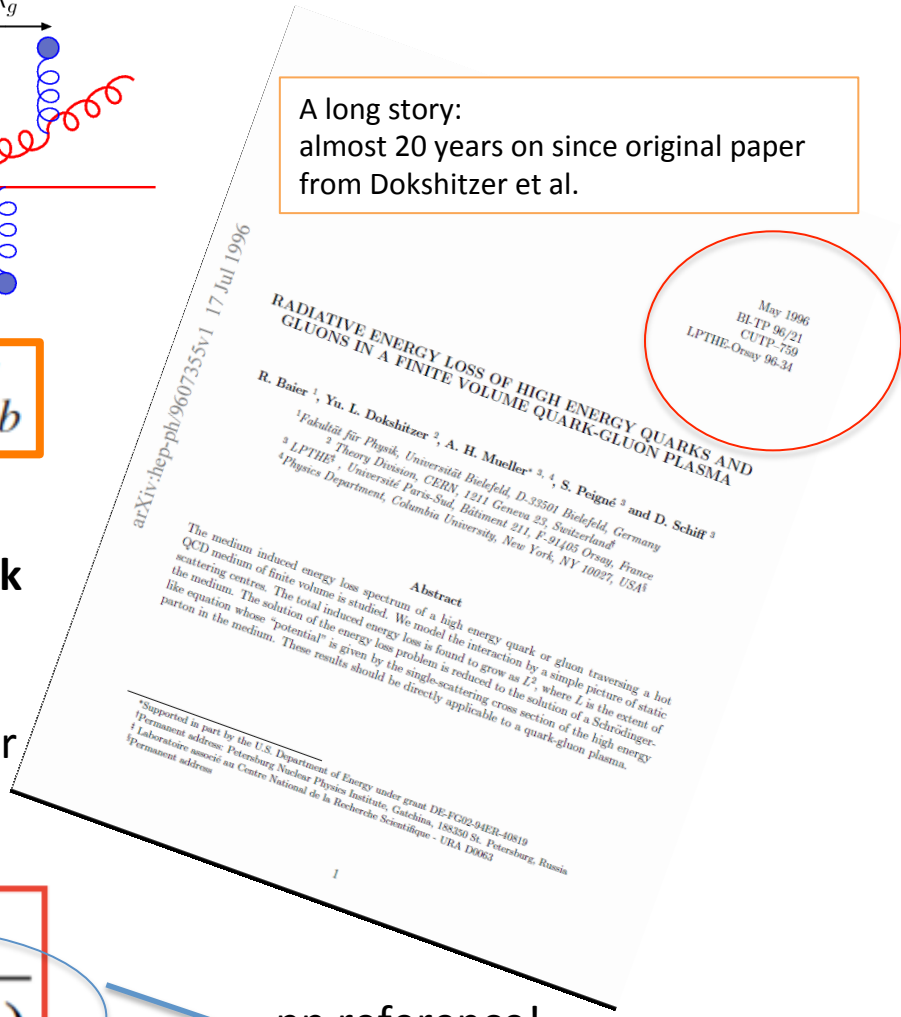
Casimir factors and dead-cone effect: **gluon/quark hierarchy** and **mass hierarchy**

This is tested/quantified via the study of nuclear modification factor

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{COLL} \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

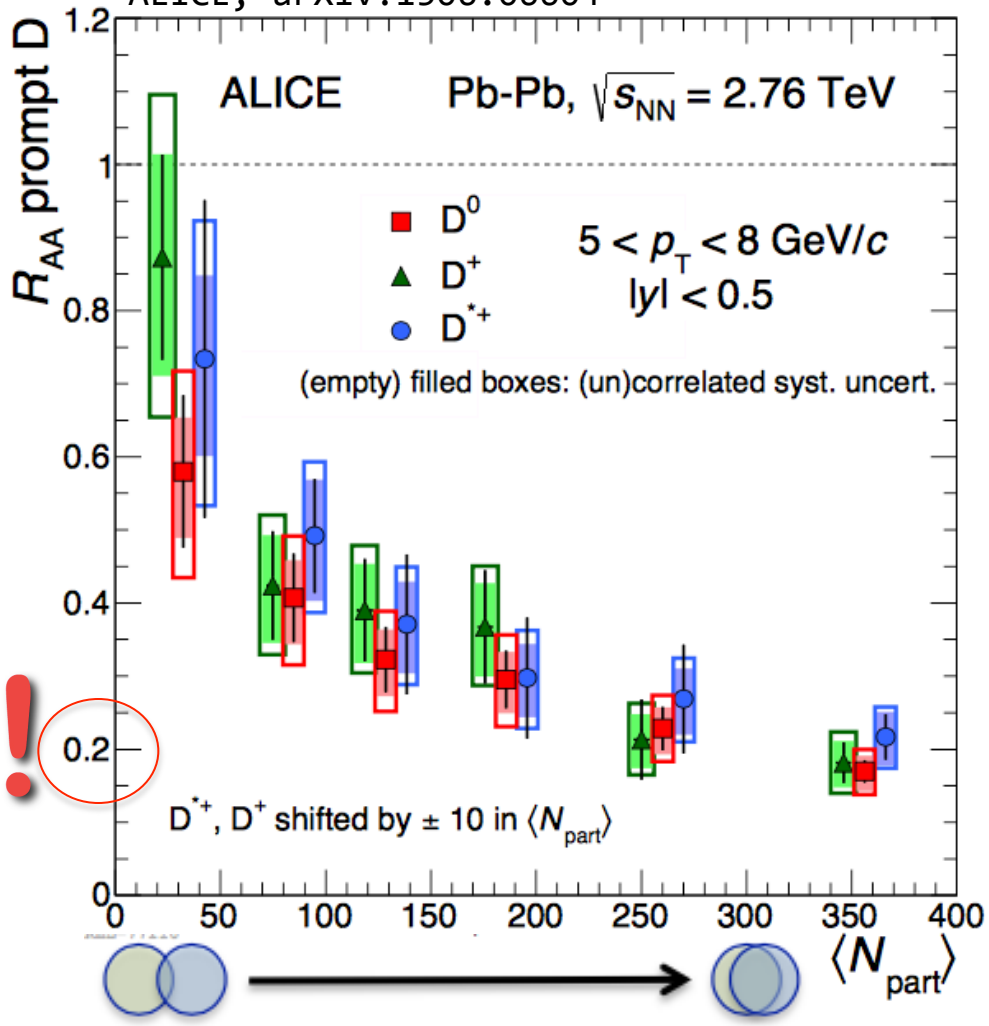
pp reference!

A long story:
almost 20 years on since original paper from Dokshitzer et al.



R_{AA} of D mesons (I)

ALICE, arXiv:1506.06604

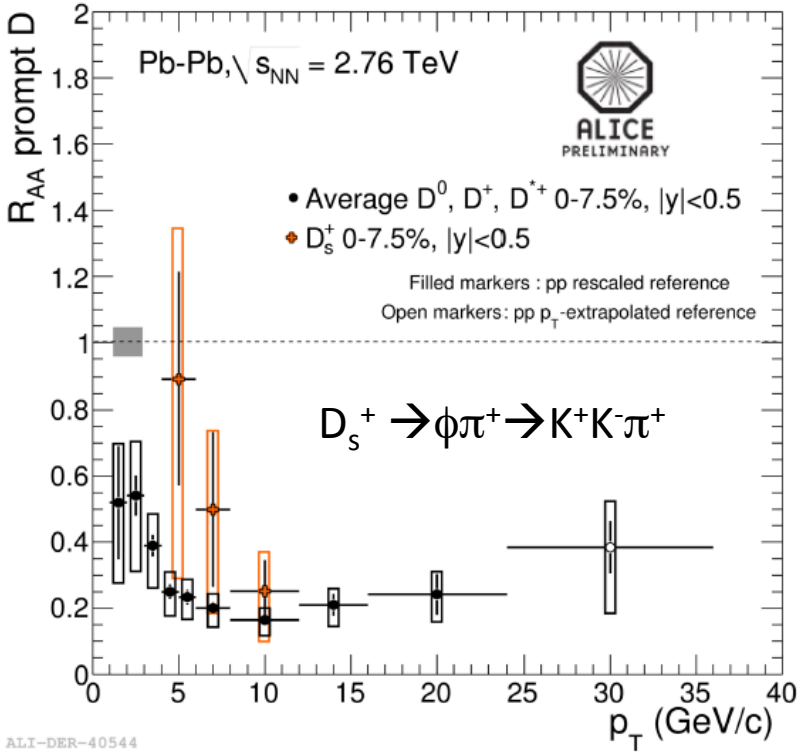


$D^0 \rightarrow K^-\pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

$D^{*+} \rightarrow D^0\pi^+$

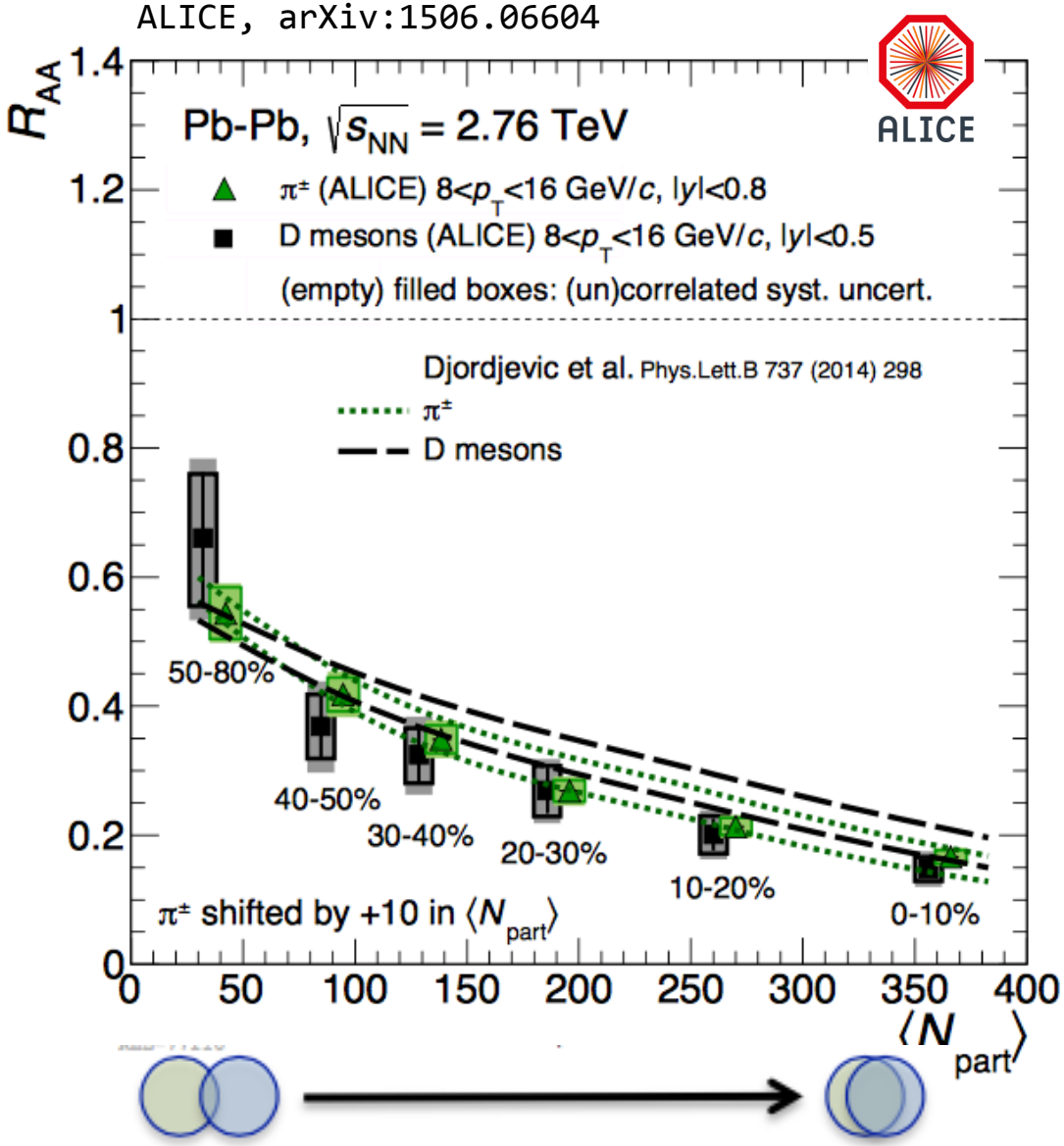
- prompt D mesons
- suppression → effect of the medium



hint of a larger R_{AA} value for D_s at low p_T (expected by strangeness enhancement)

R_{AA} of D mesons (II): color-charge dependence?

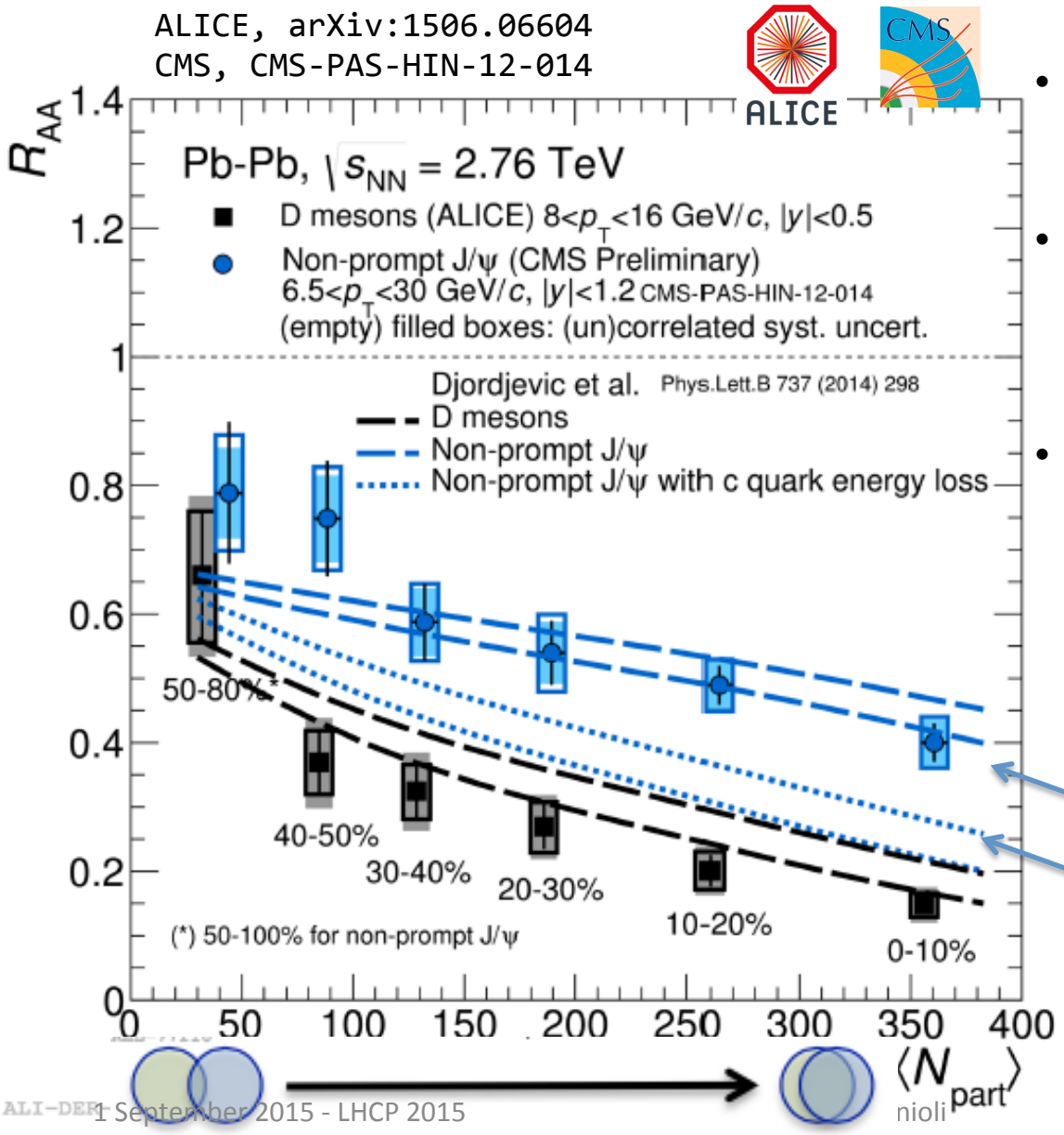
ALICE, arXiv:1506.06604



- comparison between D mesons and charged pions → color-charge dependence
- compensation of the effect due to softer p_T fragmentation and gluons p_T spectrum → similar values of R_{AA} expected
- Djordjevic et al. reproduces exp. results

R_{AA} of D mesons (II): mass dependence?

ALICE, arXiv:1506.06604
CMS, CMS-PAS-HIN-12-014



- comparison between D mesons and non-prompt J/ψ → mass dependence
- non prompt fraction extracted by CMS, fitting simultaneously invariant μ mass pair + pseudo-proper decay length
- similar kinematics $p_T^D \approx p_T^B$

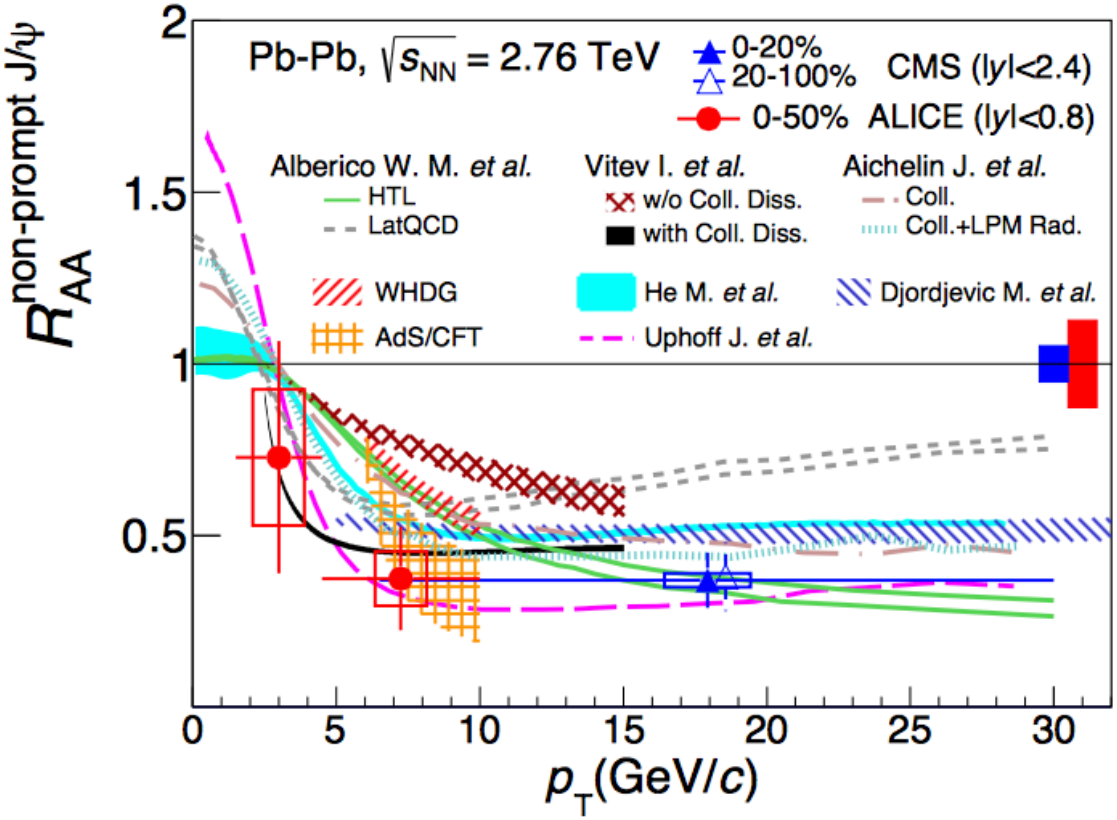
$\Delta E_b < \Delta E_c$

b mass in energy loss computation

c mass in energy loss computation

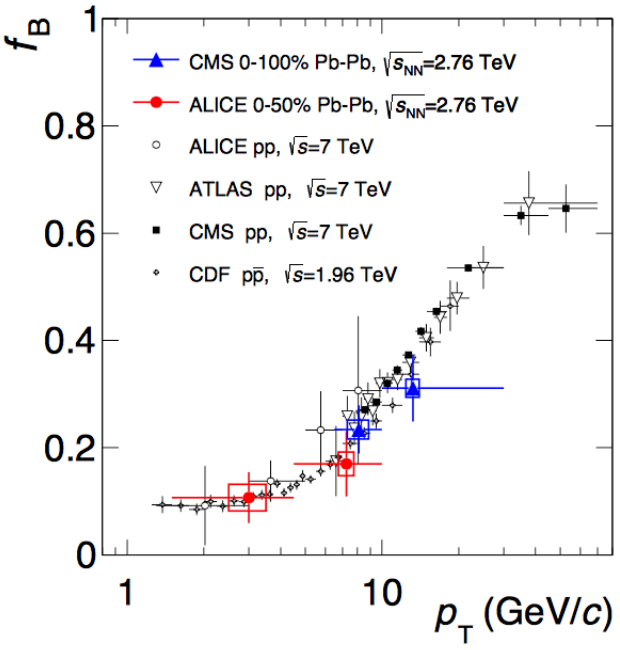
R_{AA} of non-prompt J/ψ: testing models

ALICE, arXiv:1504.07151
CMS, JHEP 1205 (2012) 063

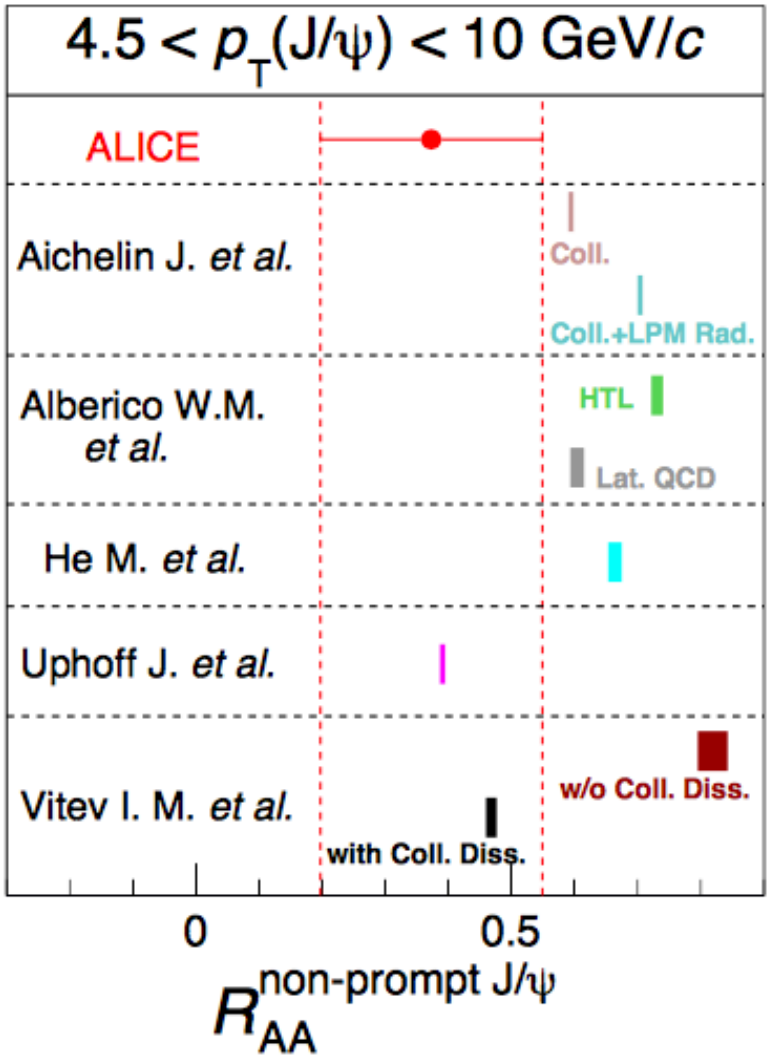


- R_{AA} seems overestimated by most of the models in the 4.5 < p_T< 10 GeV/c range
- We need more precise data!

ALICE non prompt J/ψ at mid-rapidity studied in e^+e^- channel → p_T complementarity with CMS



Comparing models....

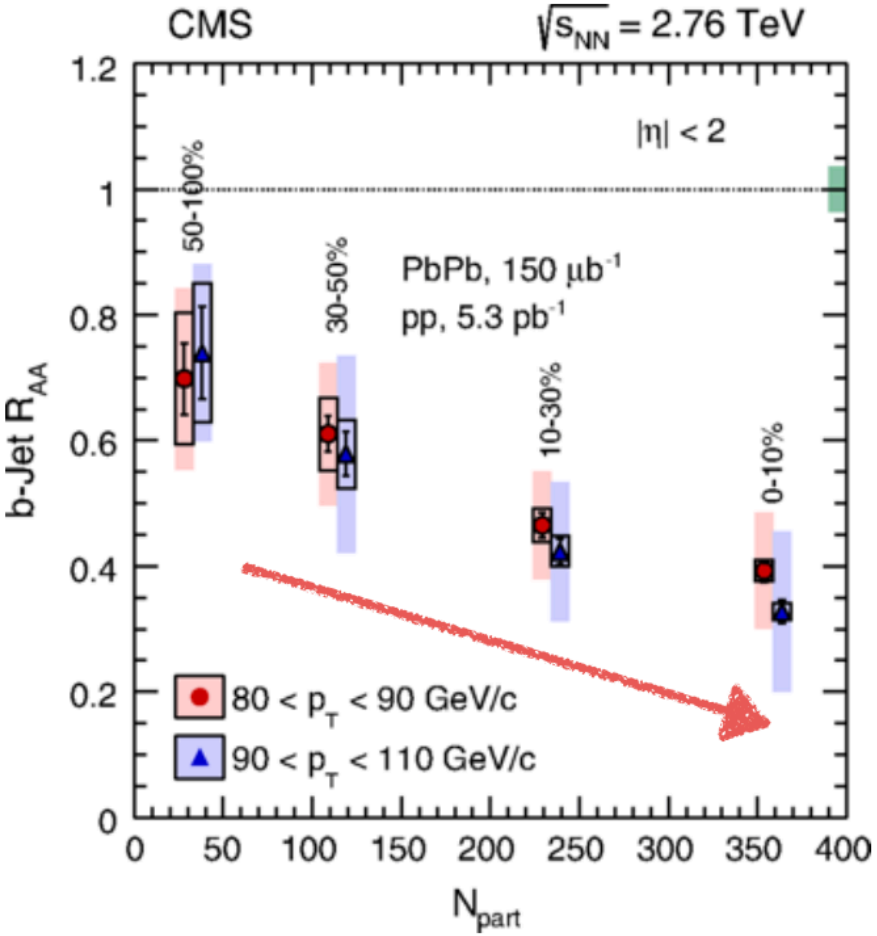


- Aichelin et al. (PRD 89 (2014) 074018) : radiative gluon emission in the interactions between light/heavy quarks
- Alberico et al. (EPJC 73 (2013) 2481): relativistic Langevin equation, R_{AA} p_T dependence highly dependent on parameters
- He et al. (PLB 735 (2014) 445): non perturbative interactions for heavy quarks, no radiative process
- Uphoff et al. (PLB 717 (2012) 430: transport Boltzmann based, no radiative process for quarks
- Vitev et al. (PRC 87 (2013) 044905): modified beauty quark PDF and fragmentation function / collisional dissociation important for suppression

Too many models (and parameters), not yet enough data precision

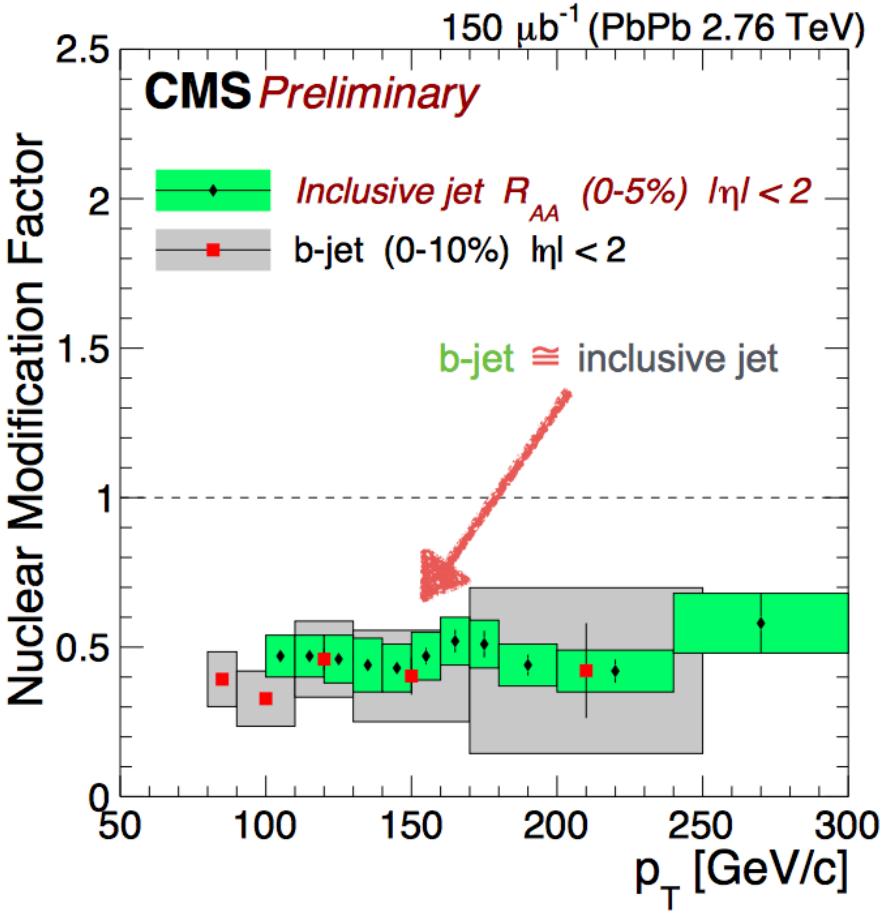
R_{AA}: b-jet tagging

CMS, Phys. Rev. Lett. 113, 132301 (2014)



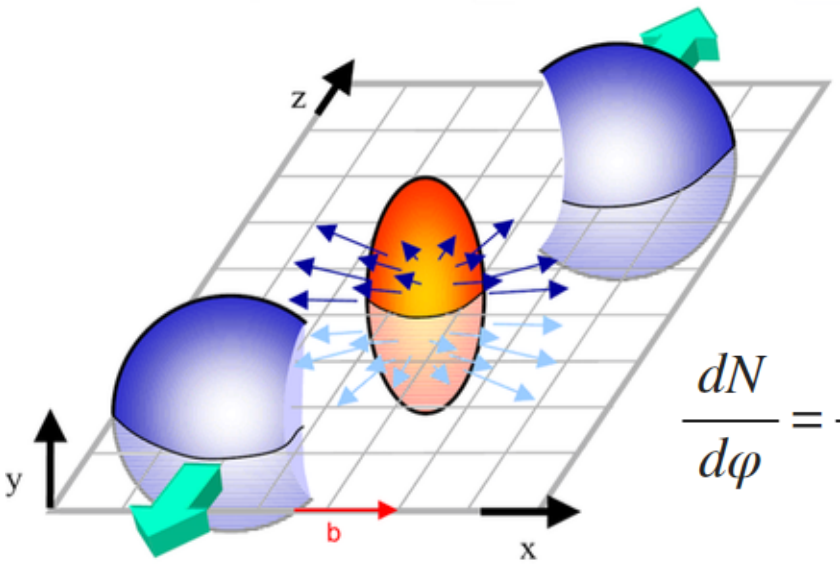
Evidence of increased suppression in most central collisions

CMS, CMS-PAS-HIN-12-004



No clear dependence of R_{AA} on b-jet p_T observed

Heavy-flavor: collectivity?

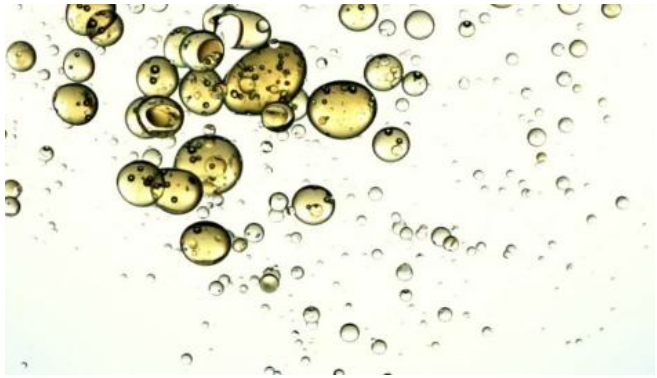


initial space anisotropy of the collision → anisotropy of particles in momentum space

Fourier expansion in azimuthal angle with respect to reaction plane

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_1)+2v_2\cos(\varphi-\Psi_2)+\ldots\right)$$

a "smoking gun" for collectivity of the medium created



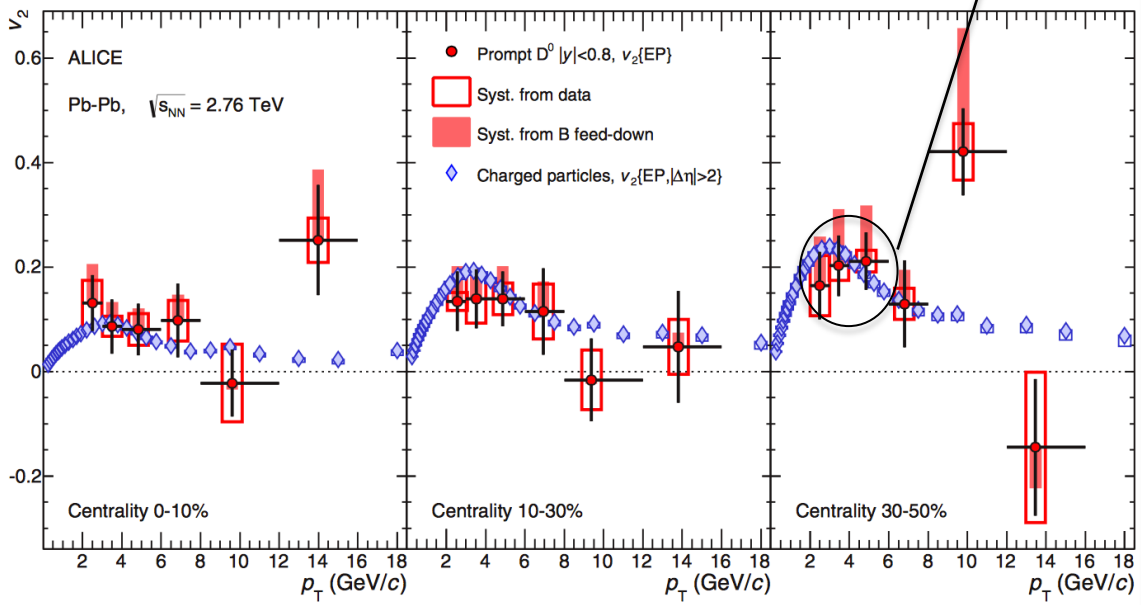
heavy quarks: heavy probes which can be easily tagged moving in a collective liquid

low p_T → $v_2 > 0$ for charm = participation of charm in collective motion
high p_T → path-length dependence → energy loss

D mesons: elliptic flow

5.7 σ effect for $2 < p_T < 6$ GeV/c

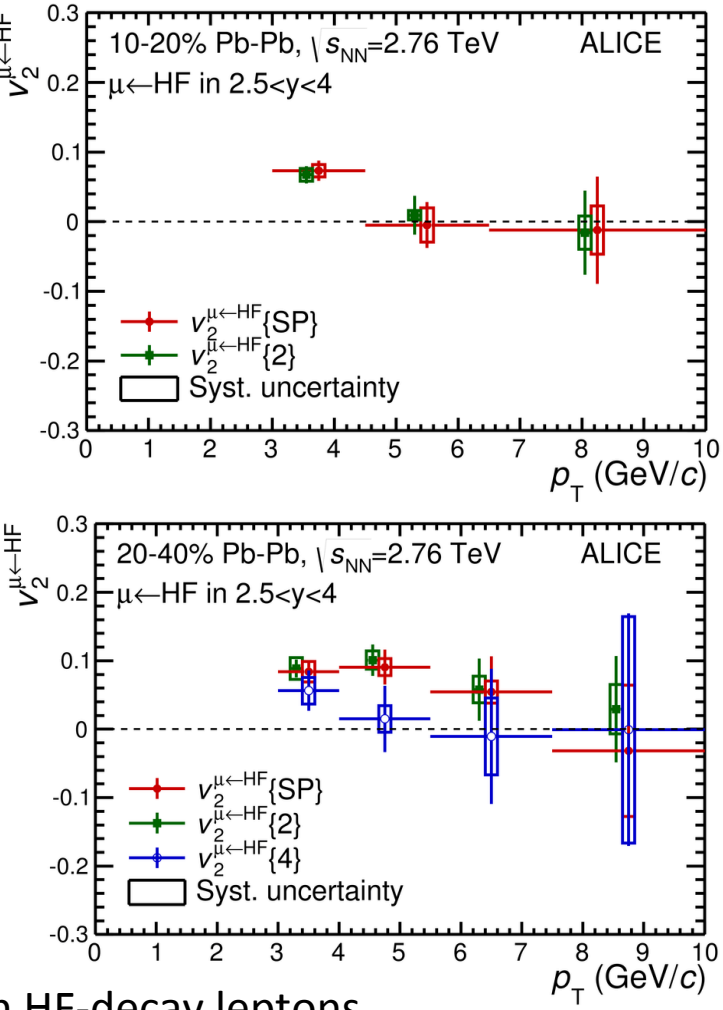
ALICE, PRC 90 (2014) 034904



- positive v_2 and similar to charged particles → charm is part of collective expansion
- hint for an increase of v_2 from central to semi-central
- more data needed for high p_T

μ ← HF

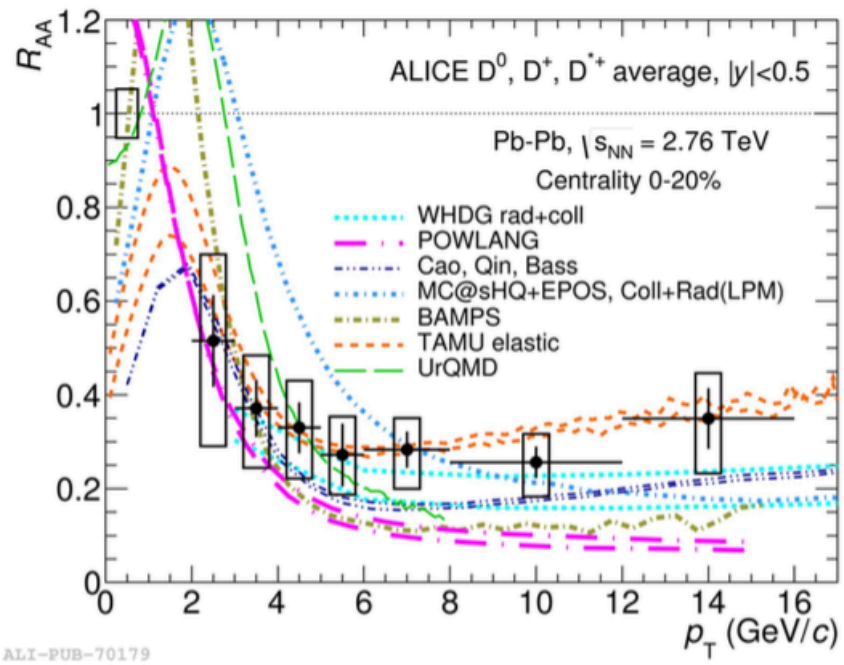
ALICE, arXiv:1507.03134

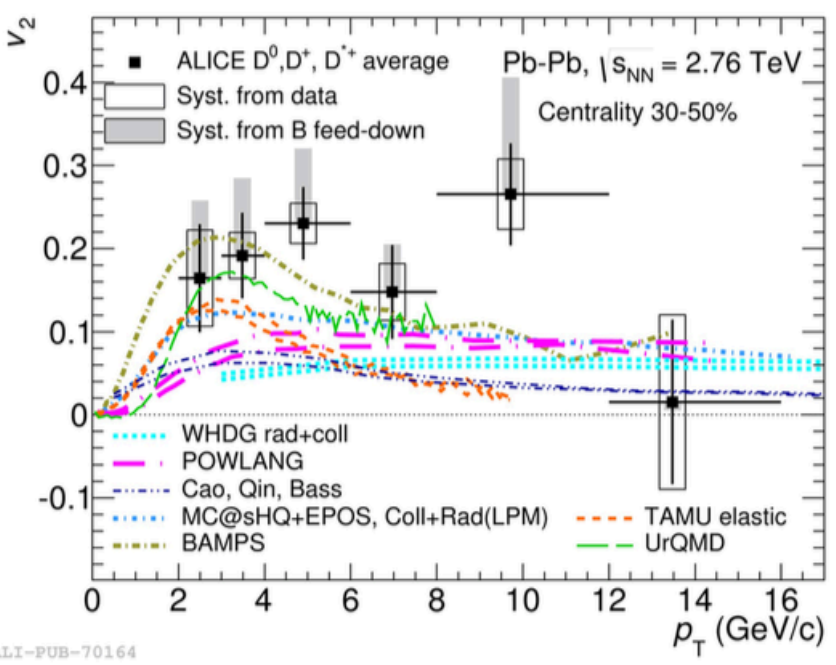


positive v_2 and similar centrality dependence seen also with HF-decay leptons

Use both R_{AA} and v_2 to challenge models

ALICE, PRC 90 (2014) 034904





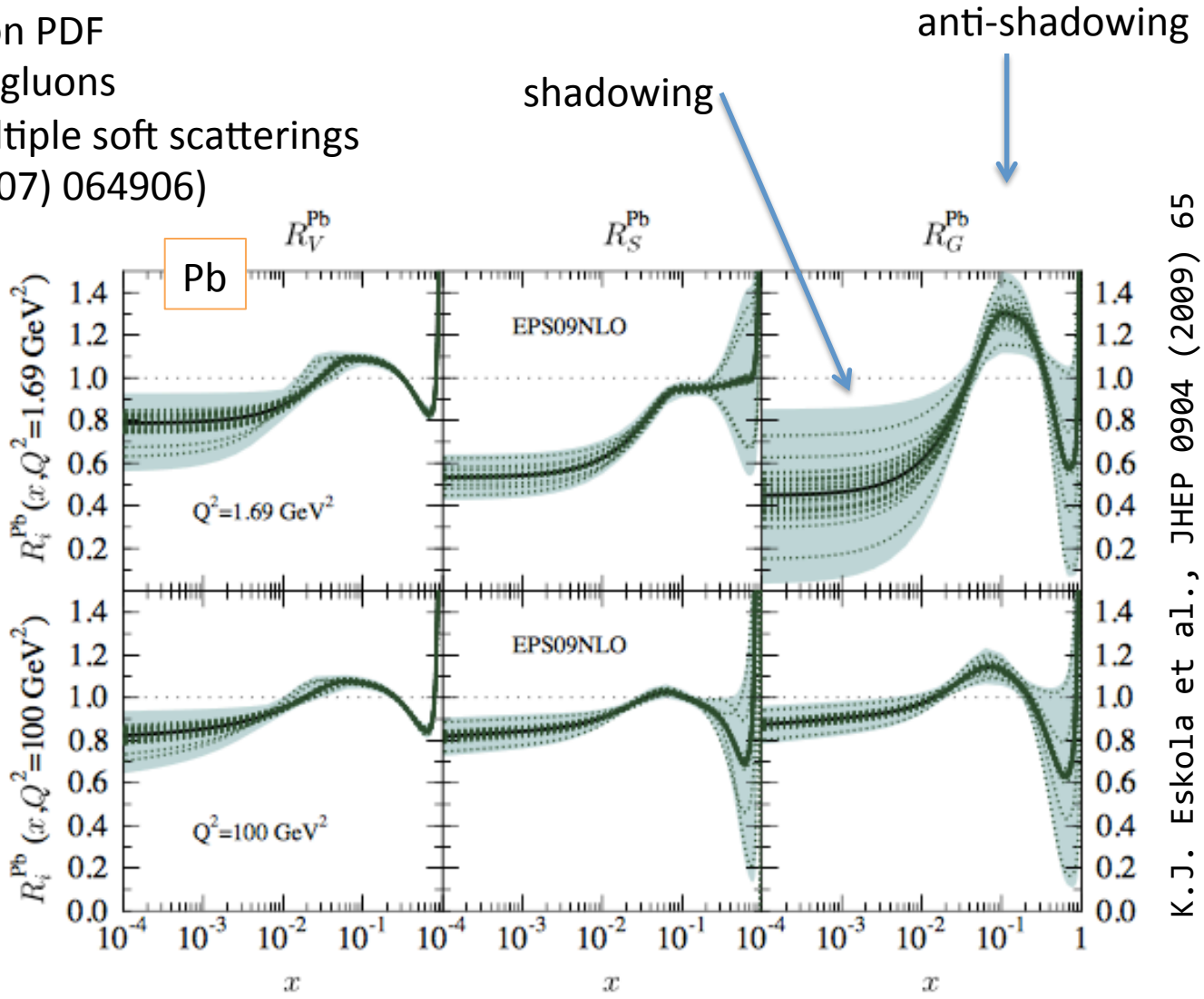
- difficult to fit both simultaneuosly: "R_{AA}-v_2 puzzle"
- we start constraining models with current precision
- anisotropy qualitatively described by models including charm-quark energy loss and collisional mechanisms or resonance scattering (to transfer elliptic flow)
- but... models that describe better R_{AA} tend to underestimate v_2 and viceversa (especially at high p_T)!

p-Pb: is really a QGP effect what we see in Pb-Pb?

p-Pb collisions allows one to study cold nuclear matter (CNM) effects and check their role (if any) in Pb-Pb collisions

- Ratio of nucleus/nucleon PDF
- larger uncertainties for gluons
- k_T broadening from multiple soft scatterings (Vitev et al., PRC 75 (2007) 064906)

p-Pb collisions are a tool to differentiate between initial- and final-state effects



R_{pPb} for D mesons

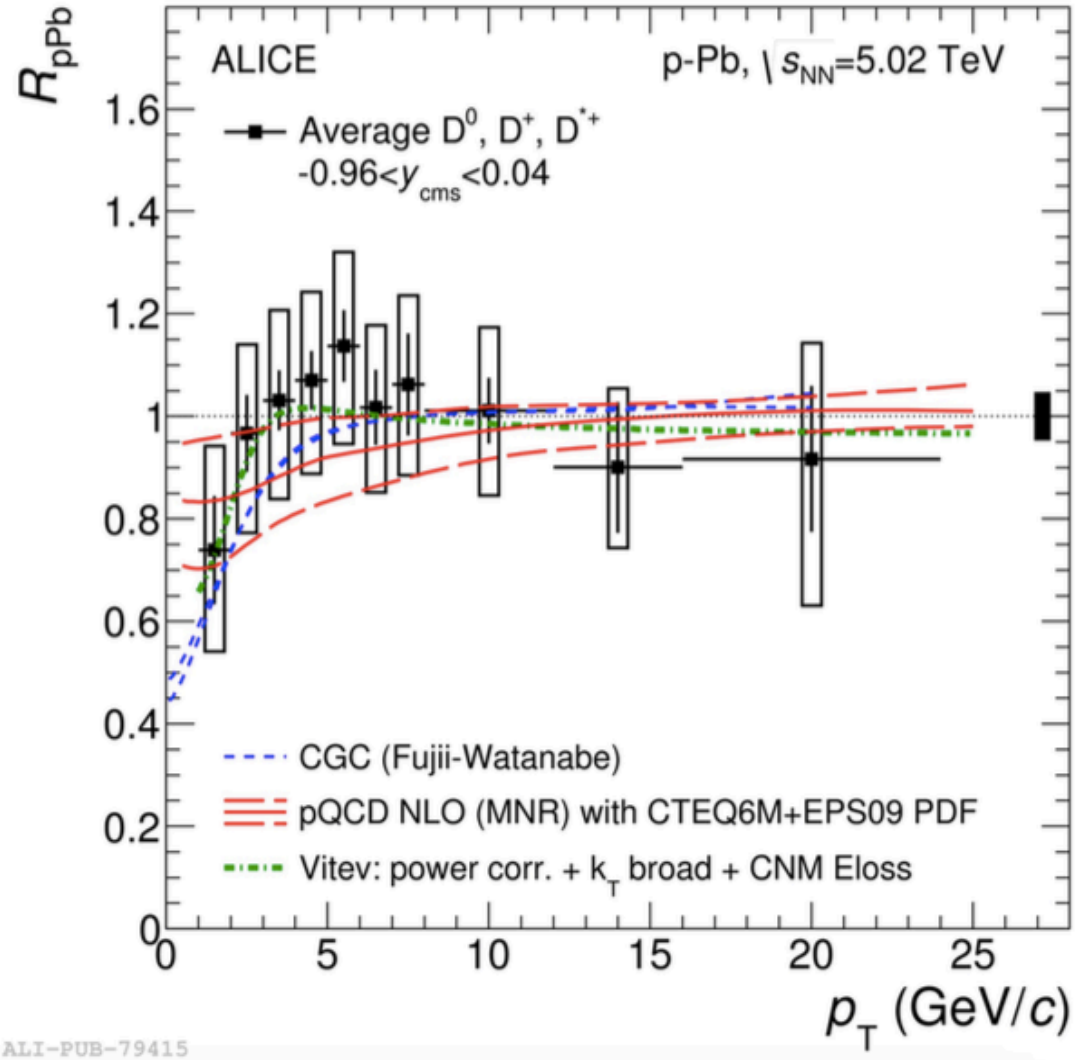
R_{pPb} compatible with unity
→ suppression seen in Pb-Pb is a final-state effect!

R_{pPb} described by:

- CGC – color glass condensate
- MNR pQCD calculation with EPS09 parameterisation of shadowing
- Vitev – coherent scattering, k_T broadening and energy loss in cold nuclear matter

NPA 920 (2013) 78
NPB 373 (1992) 295, JHEP 0904 (2009
PRC 75 (2007) 064906

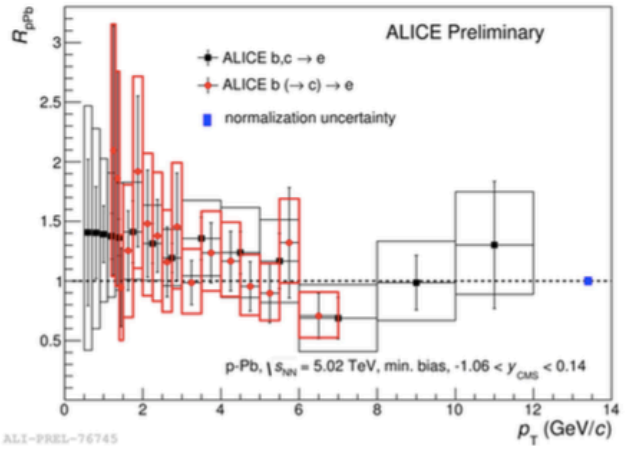
ALICE, PRL 113 (2014) 232301



HF lepton decays

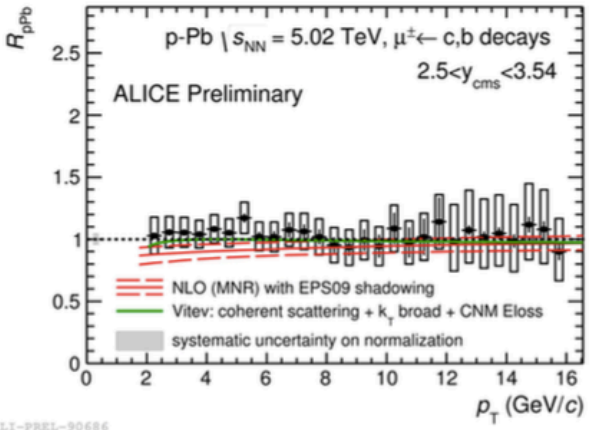
Mid rapidity

Heavy-flavor decay electrons
Beauty-decay electrons



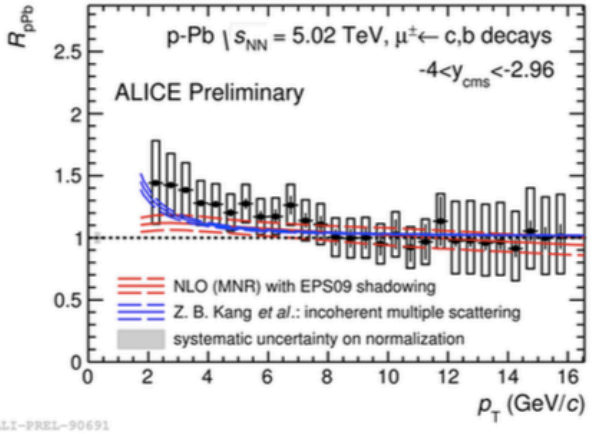
Forward rapidity

Probe low Bjorken x
$x \approx 10^{-4}$
Heavy-flavor decay muons



Backward rapidity

Probe high Bjorken x
$x \approx 0.1$
Heavy-flavor decay muons



- Within measured p_T range covered by ALICE, cold nuclear matter effects don't bring significant suppression
- Within uncertainties, models which include CNM effects describe data (Z. B. Kang et al.: incoherent multiple scattering PLB 740 (2015) 23, Vitev and MNR/EPS09 see previous slide)

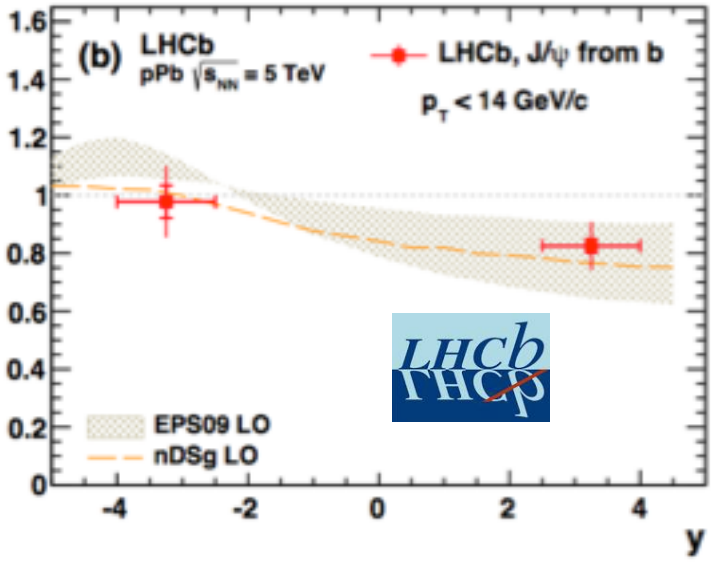
and non-prompt J/ψ

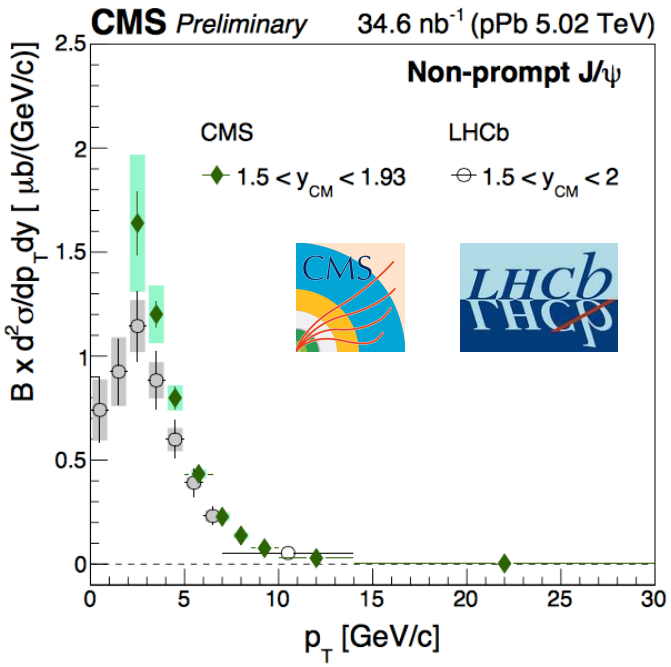
- The good agreement of CNM models with data indicate we need to include them to then interpret HI data
- The measurement indicates that cold nuclear matter effects are less pronounced for J/ψ mesons from b-hadron decays than for prompt J/ψ mesons
- Similar results from ALICE (JHEP 02 (2014) 073) (inclusive J/ψ) and ATLAS (arXiv: 1505.08141)

ALICE ATLAS

CMS / LHCb complementarity: key to measure p_T going down to 0

LHCb, JHEP02 (2014) 072



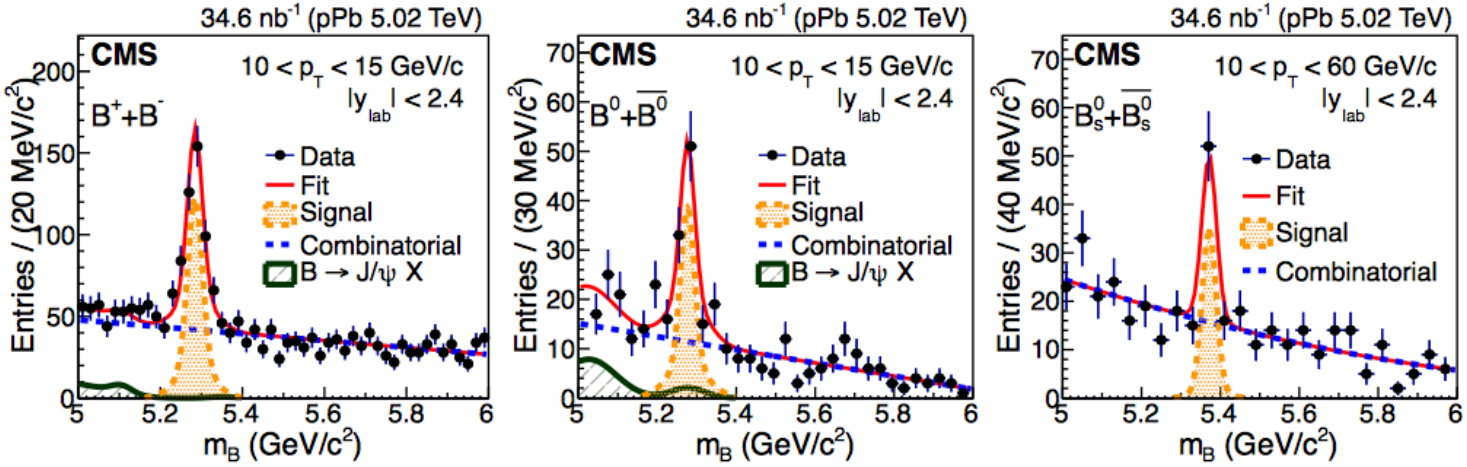


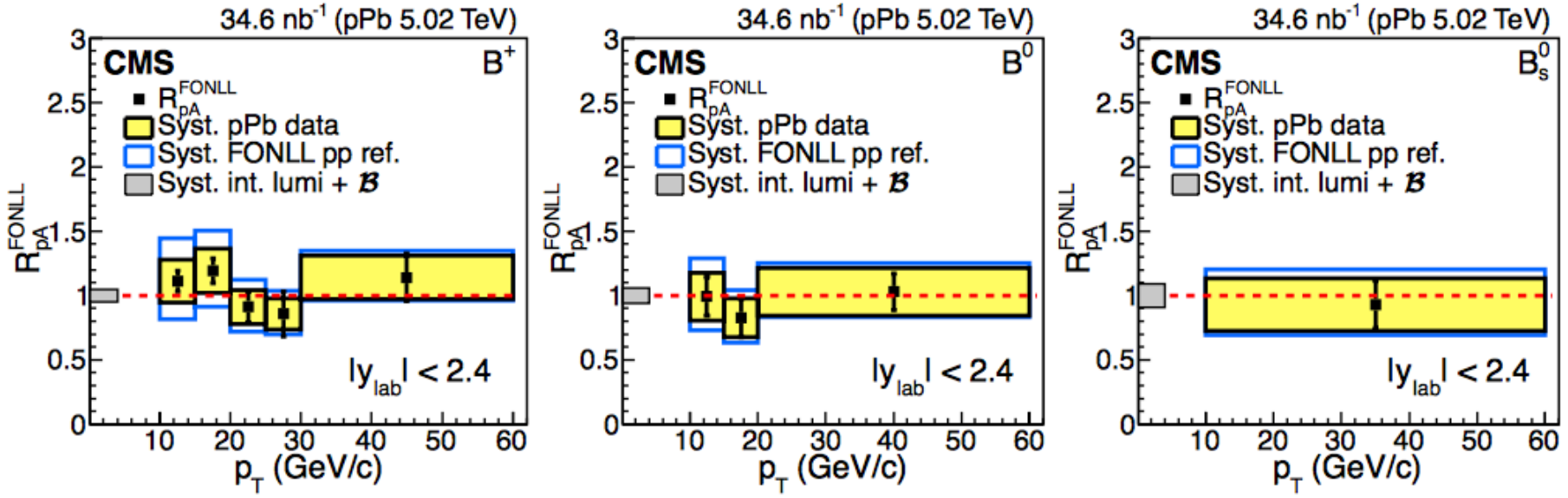
CMS -HIN-14--009

After the D mesons, the B are coming…

$B^+ \rightarrow J/\psi\ K^+$
$B^0 \rightarrow J/\psi\ K^*(892)$
$B^0_s \rightarrow J/\psi\ \phi$

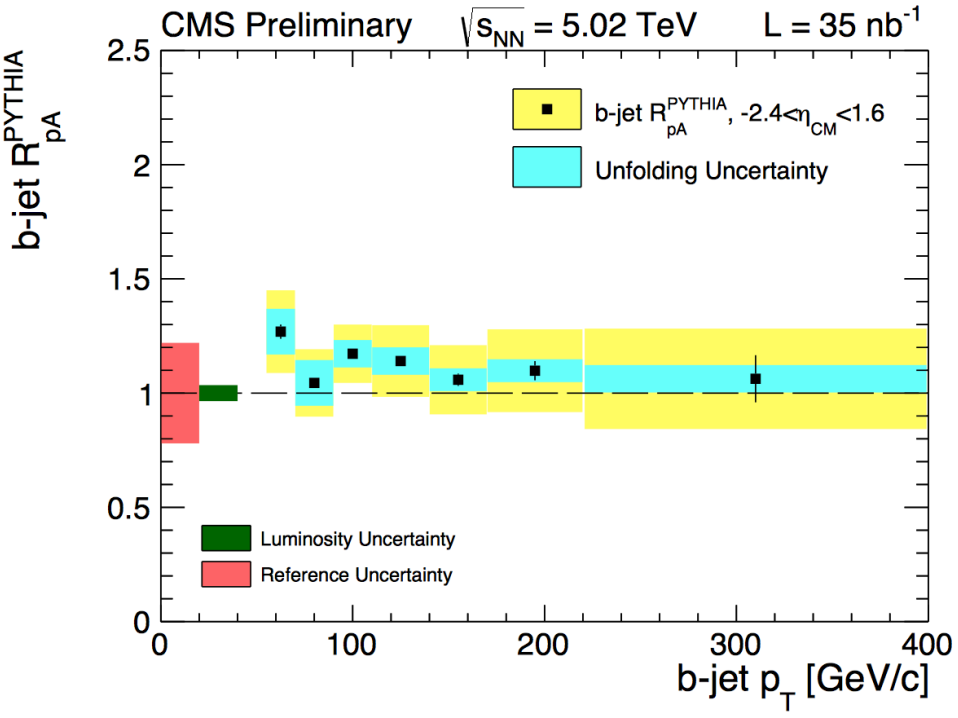
arXiv:1508.06678





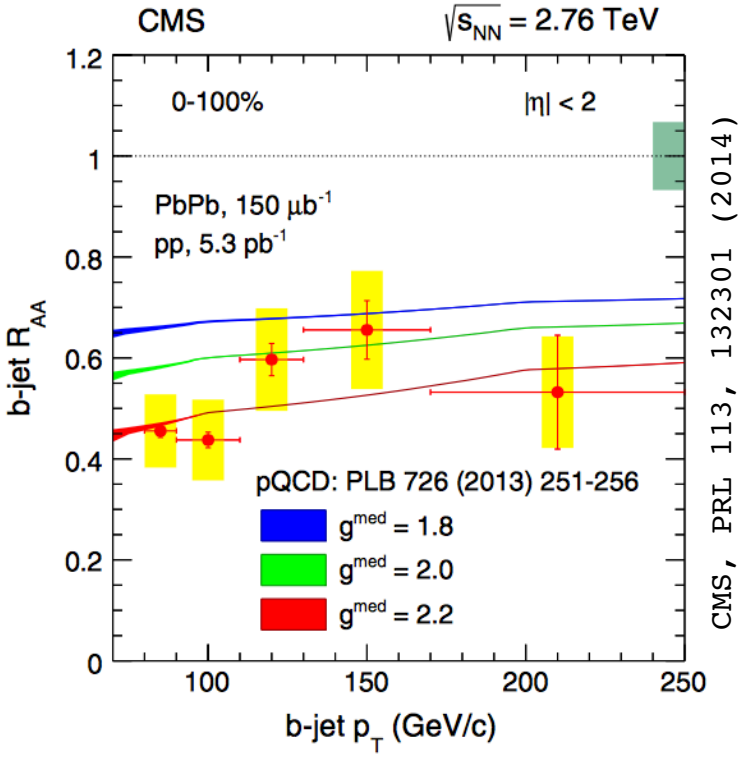
R_{pPb} compatible with unity within stat/sys uncertainties.
Important baseline for the studies of B-meson suppression and b-quark energy loss in HI

R_{pPb} for b-jet



- b-jet cross sections compared to a pp cross section obtained with PYTHIA simulation
- consistent with unity (may show slight enhancement due to CNM)

To be compared with results obtained by CMS in Pb-Pb previously mentioned

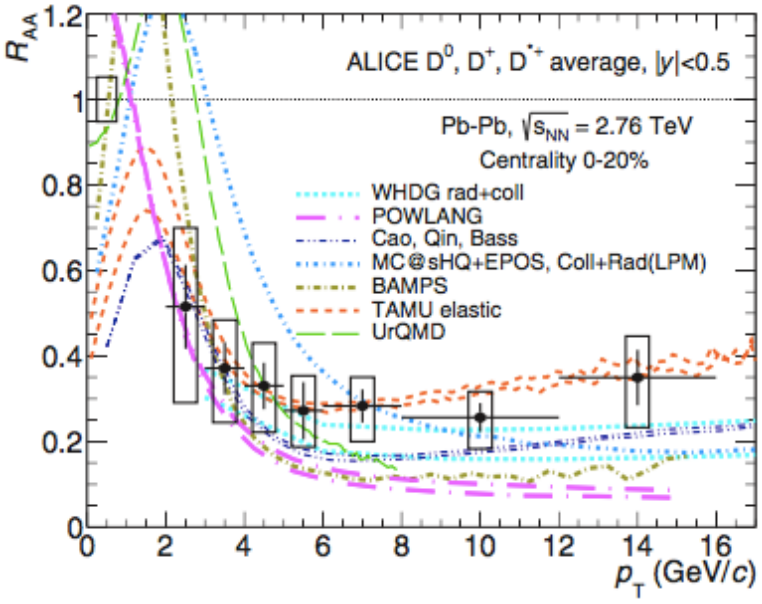


Summary and outlook

- LHC allows to study open heavy flavor production in different ways
  - In heavy-ion collision (Pb-Pb and p-Pb) with D mesons and non prompt J/ψ for b (+ CMS now directly measuring B mesons also in p-Pb)
  - HF semi-leptonic decays are also intensively studied.
  - LHCb indicated prospects for nucleus-nucleus collisions.
- ALICE, CMS, LHCb, ATLAS contributed to measure/evaluate pp reference where **detector complementarity** is particularly visible (PID vs high p_T vs rapidity interval)
- With Run 1 Pb-Pb data we were able to test our basic understanding of energy loss in the medium (**parton energy loss and transport properties of the QGP**): mass hierarchy and collectivity signals
- p-Pb data allowed to study cold nuclear matter effects and claim suppression observed in Pb-Pb results is due to final-state effects
- **More data precision** is now needed to constrain models and solve some tensions emerged (simultaneous description of R_{AA} and v_2). Run 2 will extend p_T range (down to 0 and at higher p_T). Promising results expected from azimuthal correlations, beauty and heavy flavor in jets.

Backup

R_{AA} and v_2: tested models



WHDG (S. Wicks et al., Nucl. Phys A 784 (2007) 426): parton energy loss (rad+coll) no hydro

POWLANG (W. Alberico et al., Eur. Phys. J. C71 (2011) 1666) collisional processes + Langevin + relat. hydro dynamics

Cao, Qin, Bass (S. Cao et al., PRC 88 (2013) 044907) Langevin + coll. + radiative energy loss (gluon radiation as additive force term).

MC@sHQ+EPOS, Coll+Rad(LPM) (M. Nahrgang et al, PRC 89 (2014) 014905) collisional and radiative energy loss mechanisms for heavy quarks. Fluid dynamics with EPOS + heavy quark recombination.

BAMPS (J. Uphoff et al, PRC 84 (2011) 024908) Boltzmann approach + collisional for heavy quarks. Radiative energy loss computed via corr. factor tuned on RHIC data.

TAMU (M. He et al, PLB 735 (2014) 445) collisional energy loss only. Hydro evolution constrained by light-flavor data + recombination

UrQMD (Lang T. et al, arXiv:1211.6912) Langevin approach with UrQMD. Heavy quarks transport with resonance model tuned on RHIC data.