Open heavy-flavour production in heavy-ion collisions

Elena Bruna (INFN Torino)

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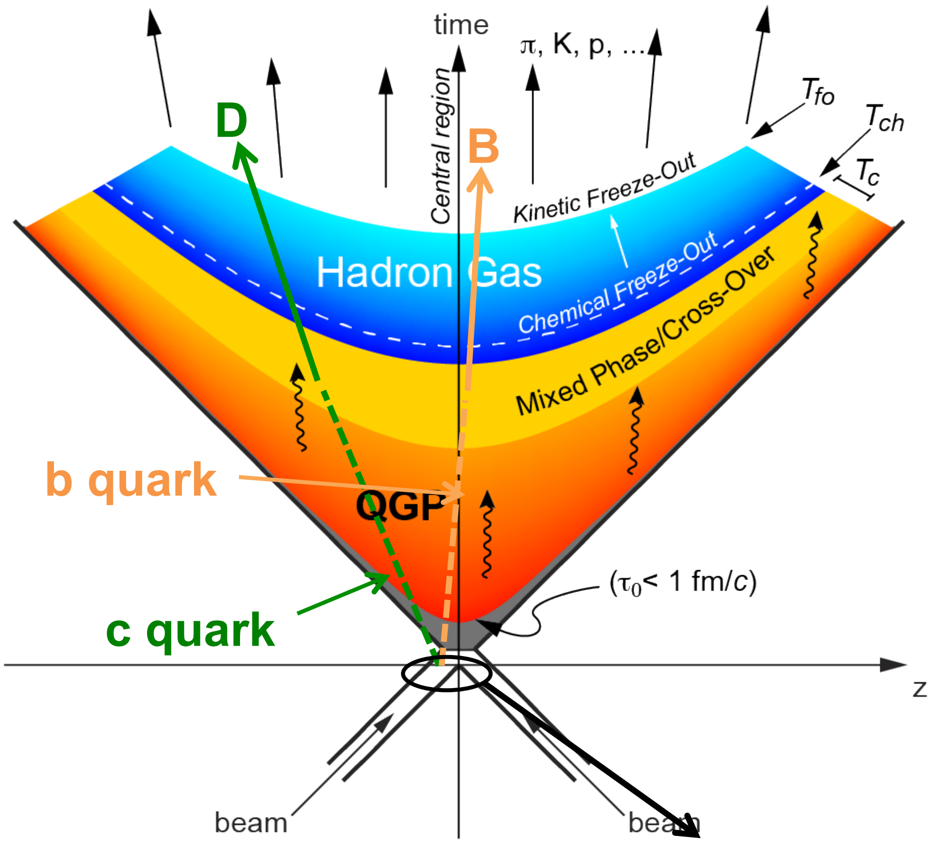
Ecole Polytechnique

Heavy Flavours: unique probes

- Produced in initial high-Q^2 processes → calculable with pQCD
- Large mass → short formation time → experience medium evolution
  - $1/2m_c$ (~0.07 fm/c) < QGP formation time (~0.1-1fm/c) << QGP life time (10 fm/c)
- Expected small rate of thermal production in the QGP ($m_{c,b}$ >> T)



Collision evolution stages probed by heavy quarks:

Initial stages:
- test pQCD
- probe nPDF

QGP/partonic phase:
- energy loss: radiative vs collisional
- collectivity

Hadronization:
- fragmentation
- recombination

Different collision systems to gain insight in these evolution stages !

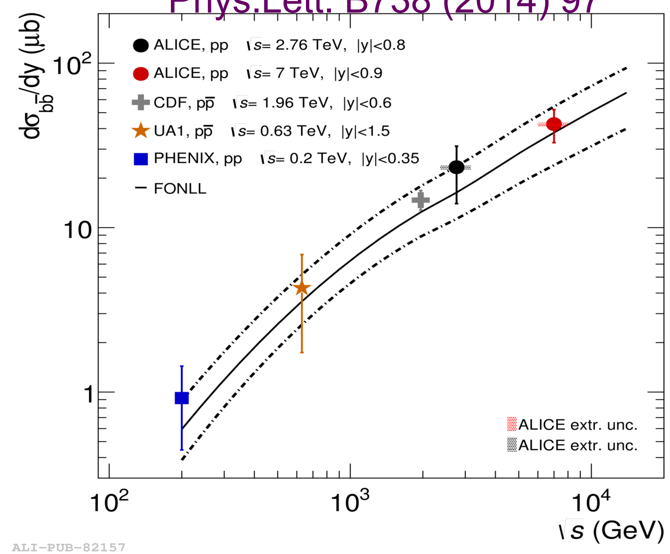
Heavy Flavours in small collision systems

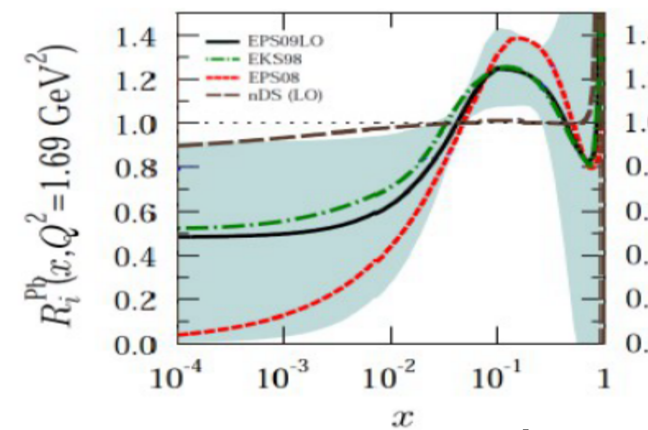
- **pp:**
  - test for pQCD
  - reference for pA and AA
  - role of Multi Parton Interactions (MPI)

- **p-Pb:**
  - reference for cold nuclear matter (CNM) effects
  - initial/final-state effects
    - nPDF, saturation and more effects

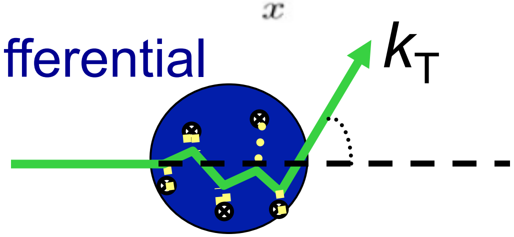
      (k_T broadening, energy loss)
  - role of collision geometry/multiplicity density
  - collective effects in small systems?

Phys.Lett. B738 (2014) 97



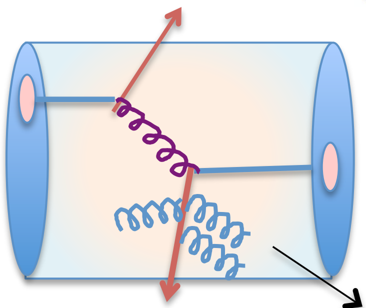


→ Experimentally: inclusive cross sections, multiplicity differential measurements and heavy-flavour correlations



Heavy Flavours in Pb-Pb collisions

- **Energy loss** of heavy-quarks in the medium:
  - modifies phase-space distribution of HQ
  - mechanisms: gluon radiation, elastic collisions
  - depends on:
    - Medium density, path-length
    - Colour-charge, Mass



$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

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

"dead-cone" effect in radiative energy loss
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

- Heavy-flavour **azimuthal anisotropy**
  - at low p_T → information on the transport properties of the medium, collectivity and thermalization of HQ
  - at high p_T → information on path-length dependent energy loss

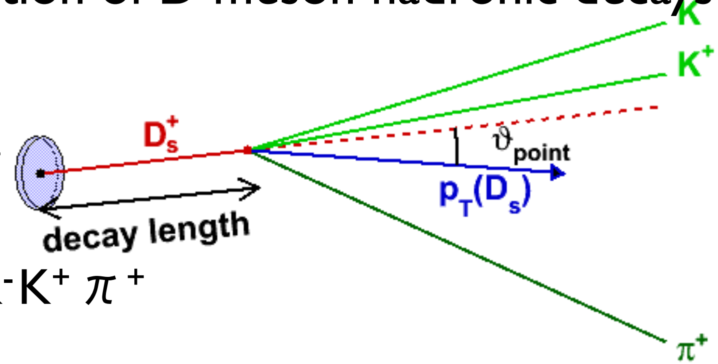
- **Hadronization** mechanism
  - role of coalescence of HQ with low-p_T light quarks in the medium

→ Experimentally: differential measurements toward a quantitative picture: charm vs beauty R_{AA} and v_2, correlations and jets, baryons vs mesons

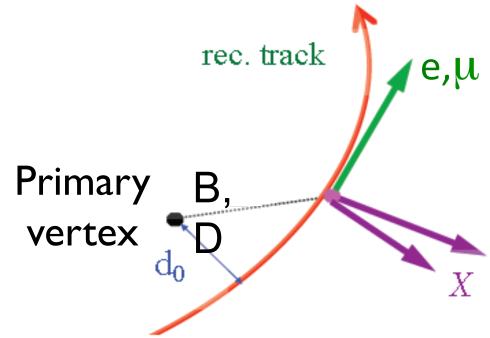
Measurements of Heavy Flavours at RHIC and LHC in A-A (and pp, pA)

Full reconstruction of D meson hadronic decays

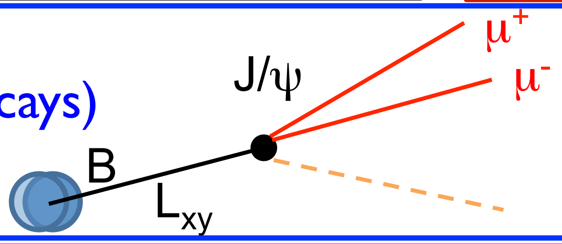
$D^0 \to K^- \pi^+$
$D^+ \to K^- \pi^+ \pi^+$
$D^{*+} \to D^0 \pi^+$
$D_s^+ \to \phi\pi^+ \to K^-K^+ \pi^+$



Semi-leptonic decays (charm,beauty), electrons from b



Displaced J/ψ (from B decays)

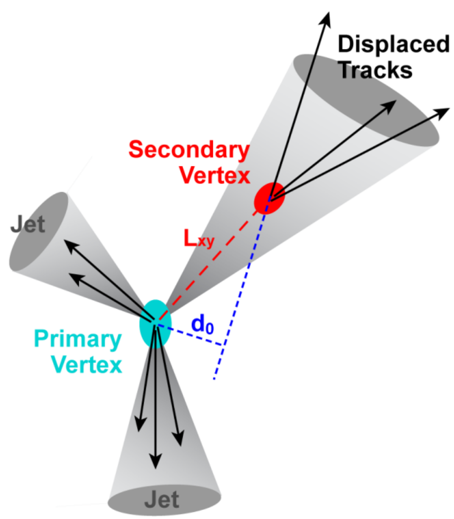


Full reconstruction of beauty decays: **B** and **Λ_b**

$\Lambda_b \to J/\psi\ \Lambda$
$B^+ \to J/\psi\ K^+$, $J/\psi\ K\ \pi$
$B^0 \to J/\psi\ K^0_s$
$B_s^0 \to J/\psi\ \phi$
pp: ATLAS/CMS,LHCb
pPb (CMS) : $B \to J/\psi\ K, \pi$

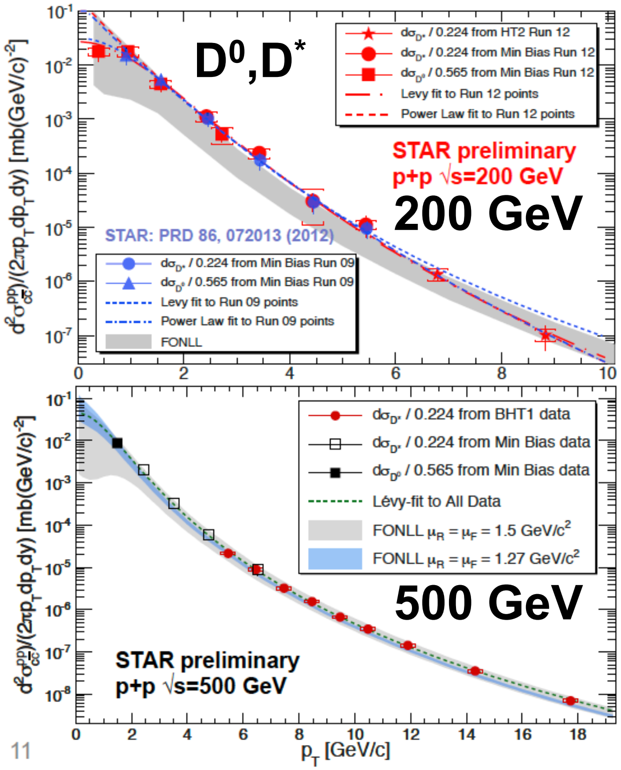
same technique as for D mesons based on displaced vertex topologies

Jet b-tagging

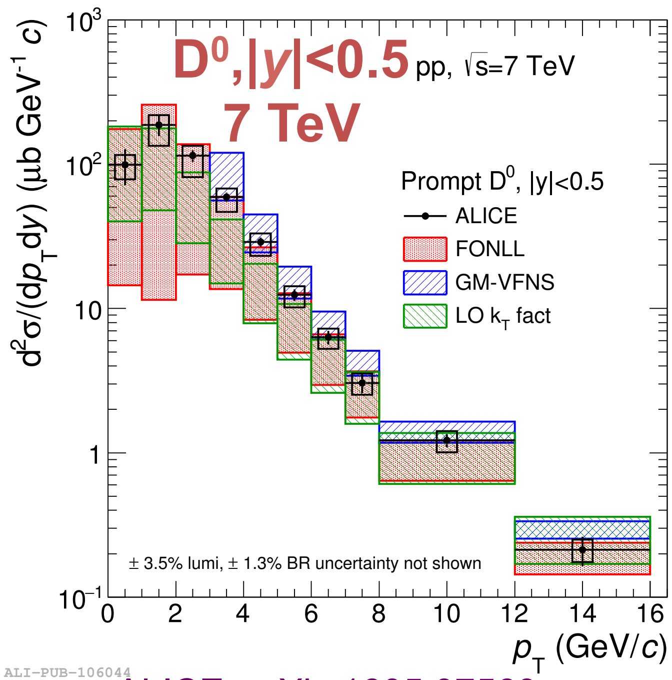


Heavy-flavour results in pp collisions

Charm in pp: Test for pQCD and reference for pA and AA



STAR, PRD 86 (2012) 072013



ALICE, arXiv:1605.07569

JHEP 1201 (2012) 128

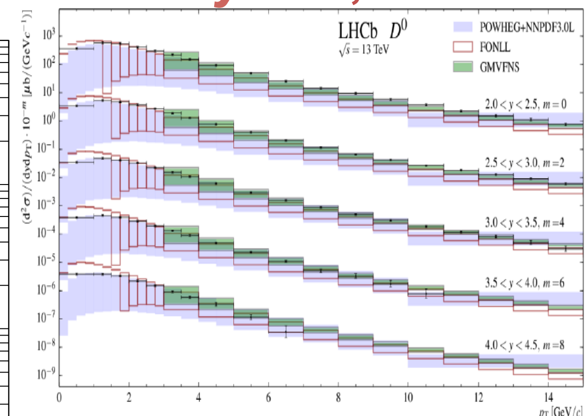
FONLL: JHEP, 1210 (2012) 137

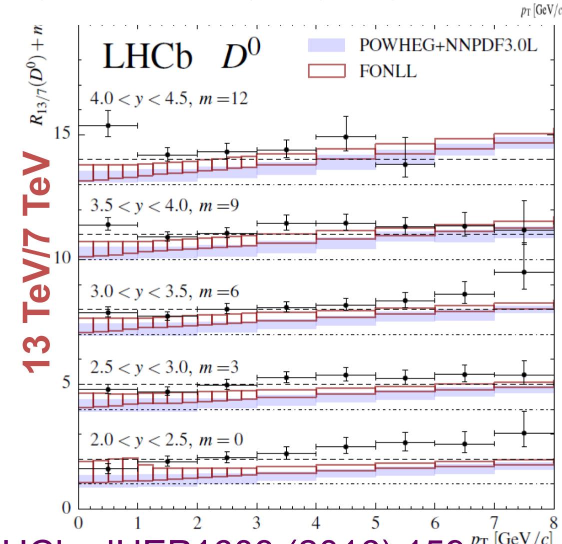
GM-VFNS: Eur.Phys.J., C72(2012)2082

Nucl. Phys. B, 872(2013) 253

LO k_T fact: Phys.Rev., D87 (2013) 094022

D^0 $2<y<4.5$, 13 TeV



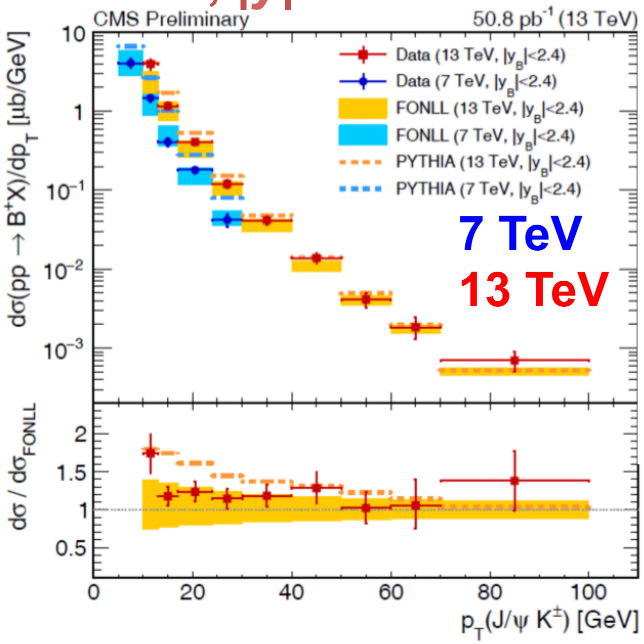


LHCb, JHEP1603 (2016) 159

Cross sections at both RHIC and LHC energies well described by pQCD predictions. Charm cross-section on the upper side of the FONLL uncertainty band at both RHIC and LHC

Beauty in pp: Test for pQCD and reference for pA and AA

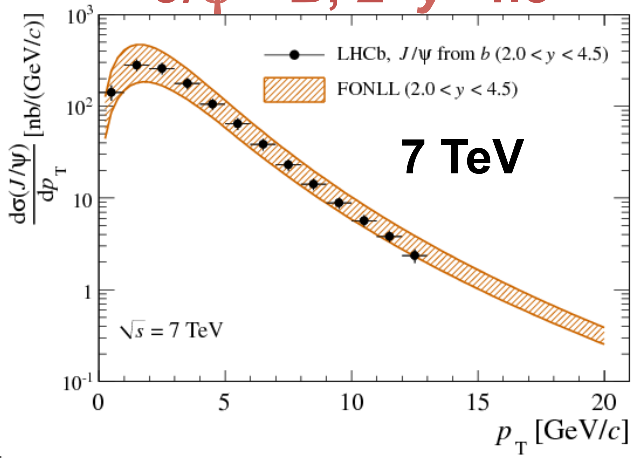
B^+, $|y|<2.4$

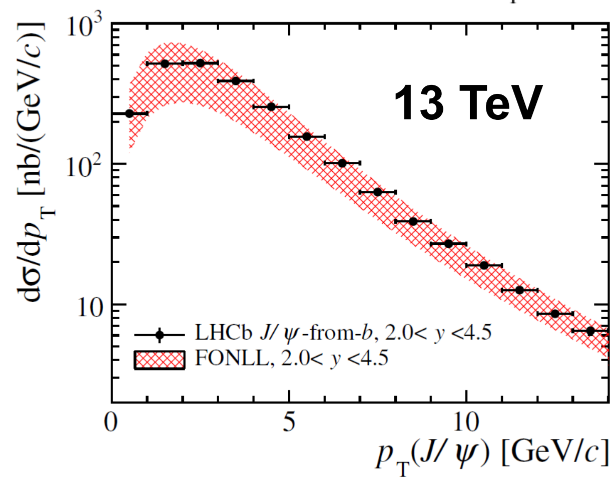


CMS, PRL 106 (2011) 112001
CMS-PAS-BPH-15-004

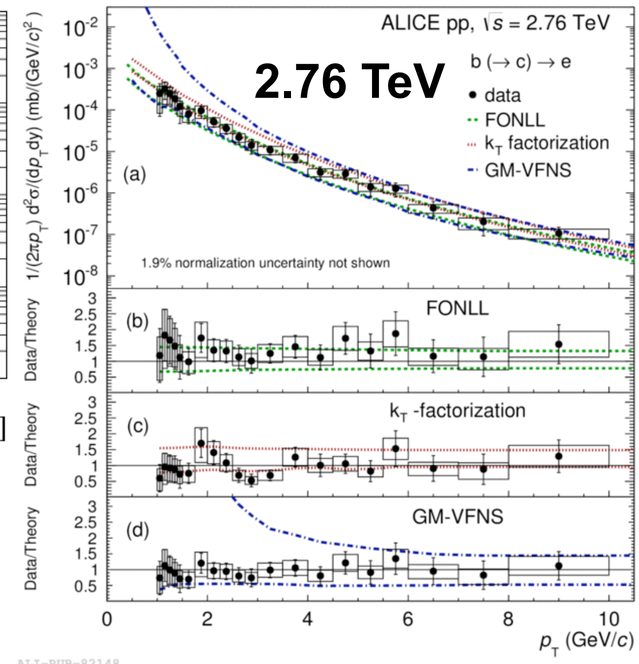
Λ_b:
CMS: PLB 714 (2012) 136
ATLAS: PRD 87 (2013)3, 032002

$J/\psi \leftarrow B$, $2<y<4.5$





$b \to e$, $0<|y|<0.8$



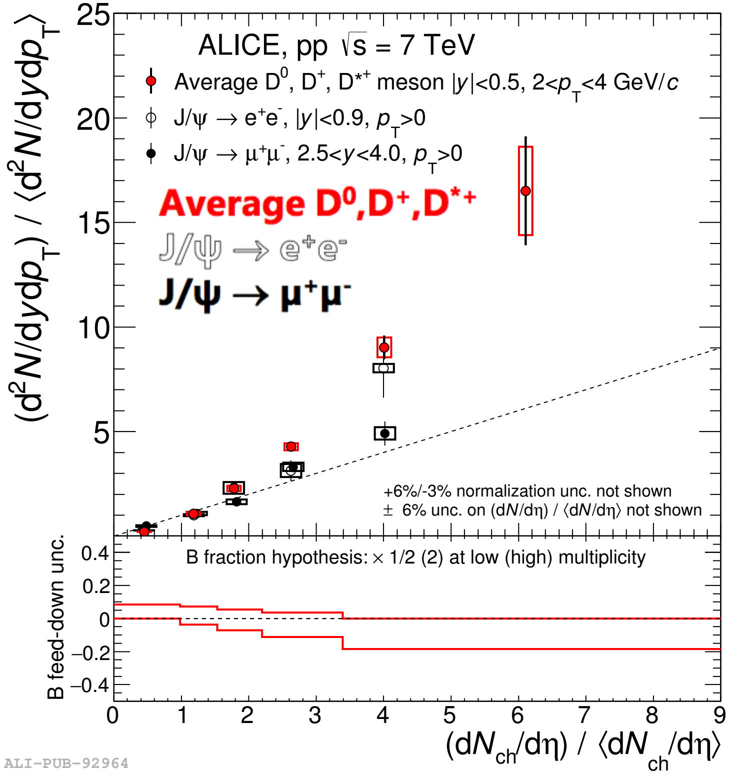
ALICE, PRD 91 (2015) 012001

LHCb, EPJ C71 (2011) 1645
JHEP 1510 (2015) 172

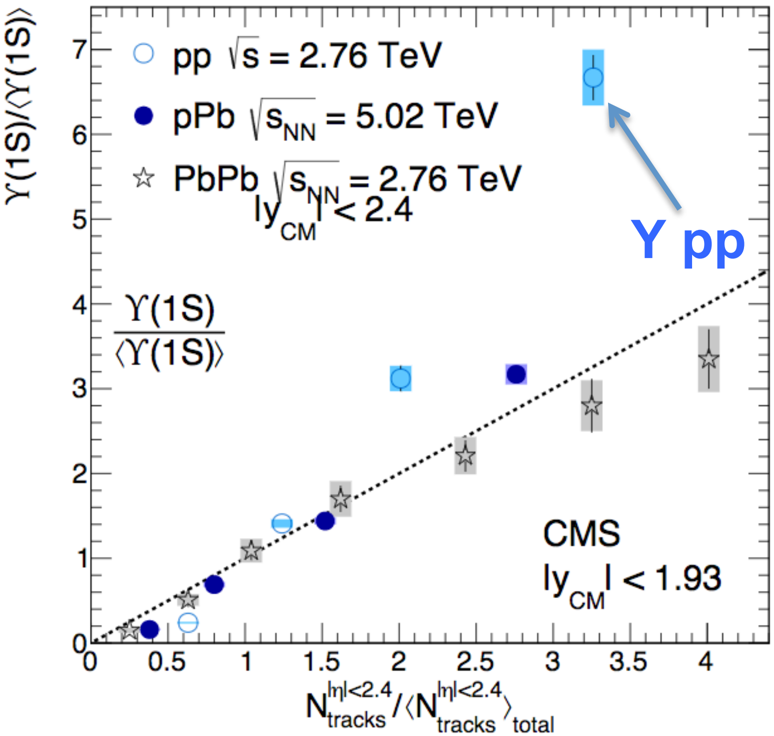
Beauty cross sections at LHC energies well described by pQCD predictions.
The central values of **7 TeV** data better agree with FONLL wrt **13 TeV**

pp: HF yields vs event multiplicity

Study the effect of multi-particle interactions on the hard heavy-flavour scale



ALICE, Phys.Lett. B712 (2012) 165
JHEP 09 (2015) 148



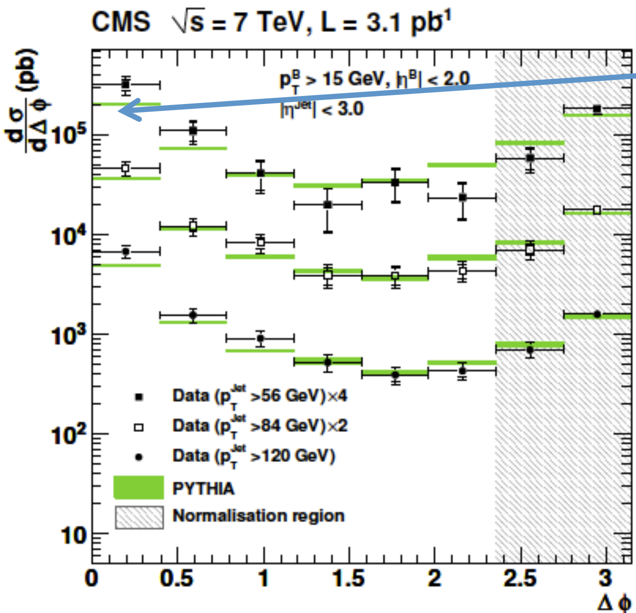
CMS, JHEP 04 (2014) 103

Increasing trend with multiplicity for D mesons, J/ψ and Y in pp collisions:

- Behaviour related to HQ production process rather than to hadronization mechanism
- MPI are dominating the high-multiplicity events and affecting heavy-flavour production

HF correlations in pp at the LHC

Provide constraints to MC generators about HF production mechanisms



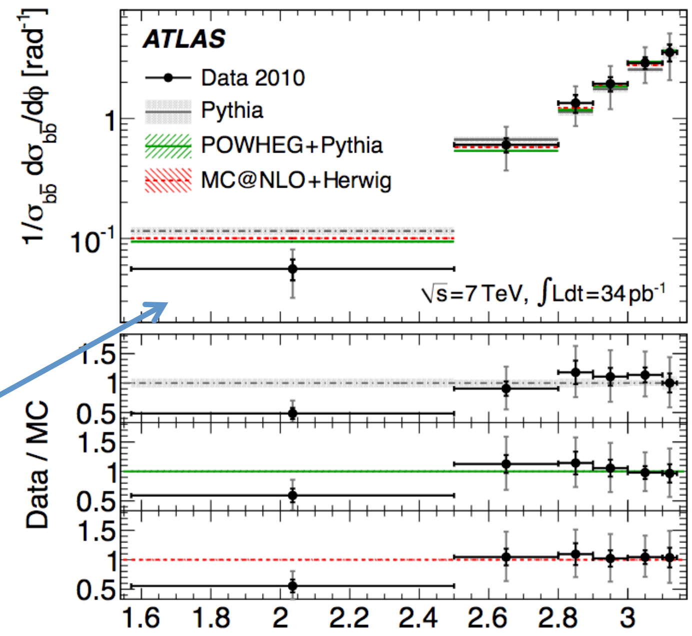
CMS, JHEP 1103:136,2011

B-Bbar correlations

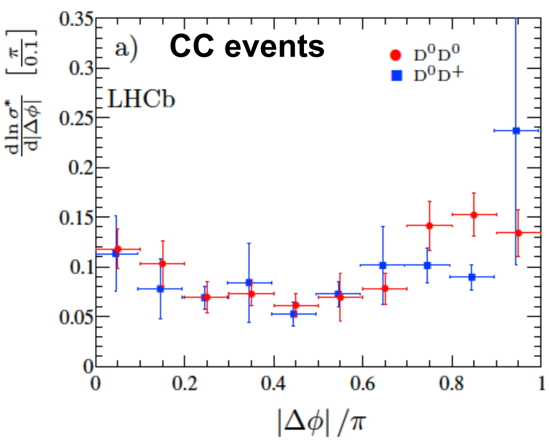
Generators tend to under-predict higher-order contributions (i.e. gluon splitting) in the near side

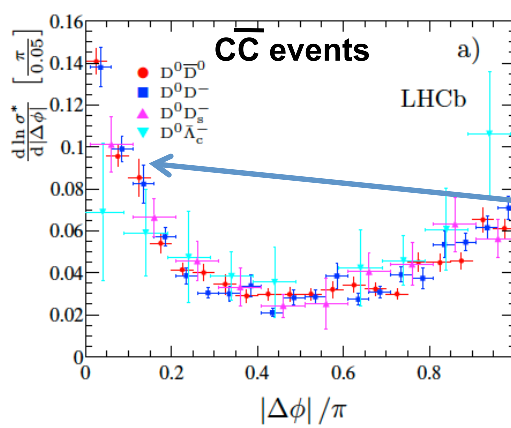
di-b-jet correlations

back-to-back configuration predicted by MC generators



ATLAS,EPJ C 71 (2011) 1846





Azimuthal DD correlations

$C\bar{C}$ events have a clear enhancement at small Δϕ, consistent with gluon splitting

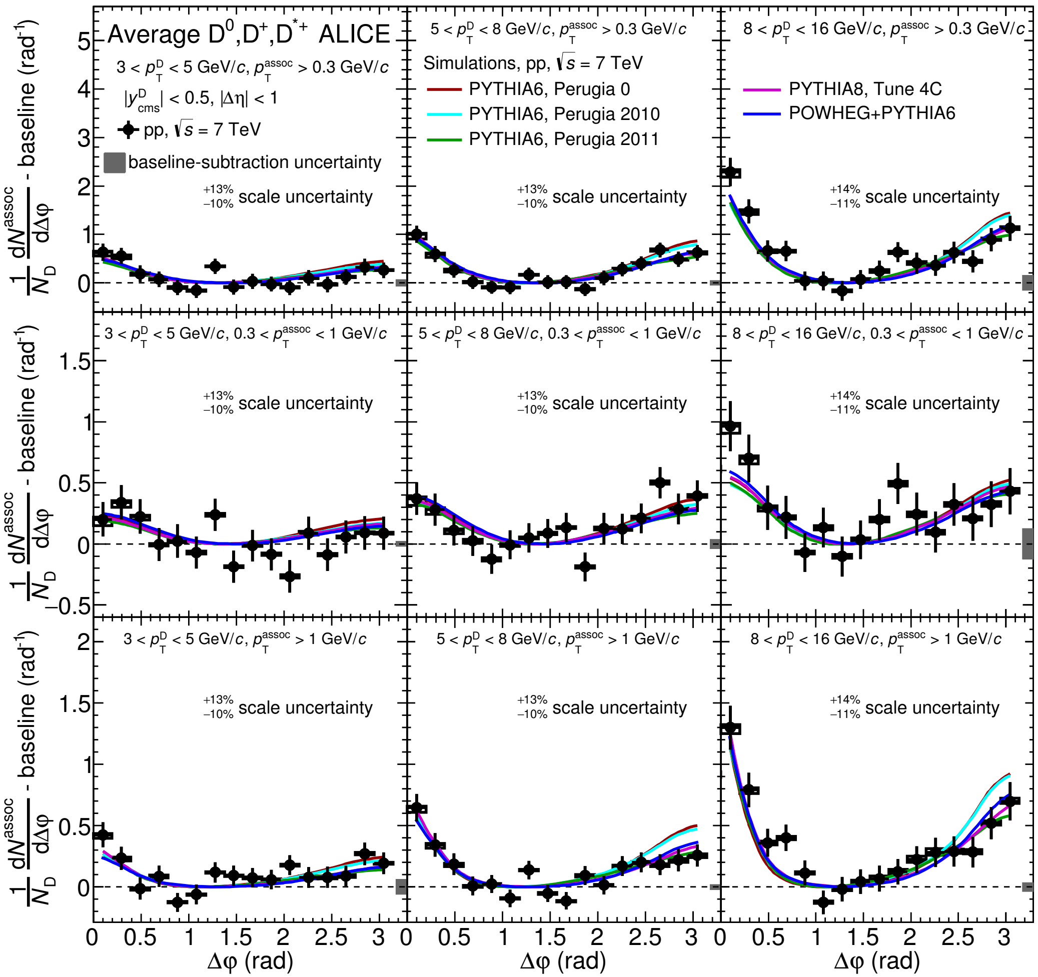
LHCb, JHEP06(2012)141

HF correlations in pp at the LHC

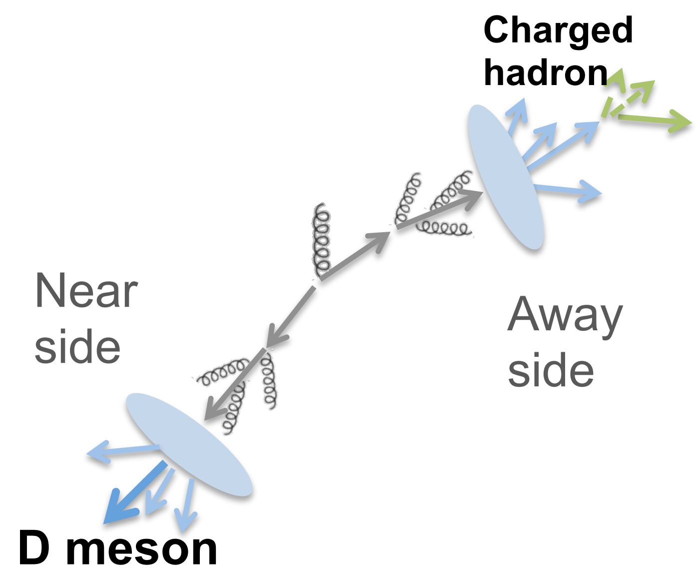
D-meson trigger p_T

3-5 GeV/c | 5-8 GeV/c | 8-16 GeV/c

p_T^{assoc}>0.3 GeV/c | 0.3-1 GeV/c | >1 GeV/c



ALI-PUB-106084



ALICE, arXiv:1605.06963

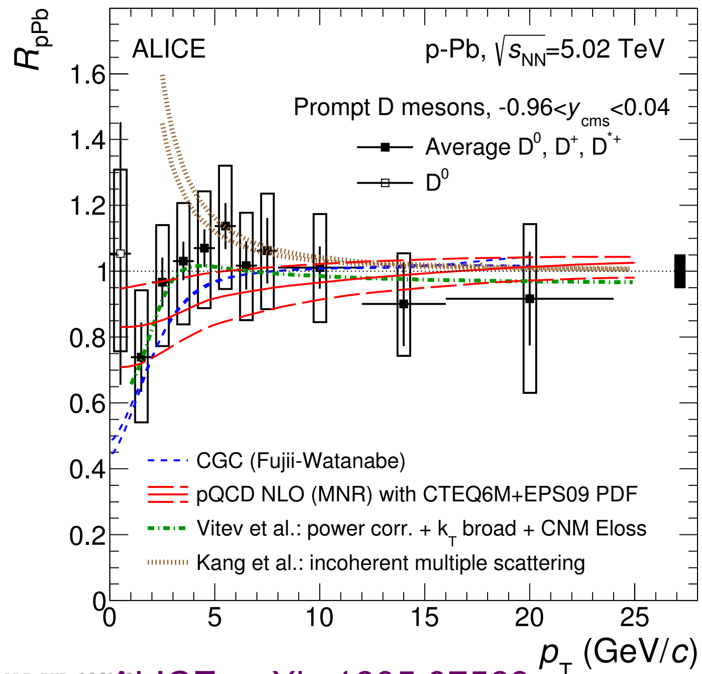
Compatible within uncertainties with expectations from different MC generators and tunes (PYTHIA6, PYTHIA8, POWHEG+PYTHIA) after baseline subtraction

Heavy-flavour results in p-Pb collisions

HF in pA: control experiment

Mid-rapidity - LHC

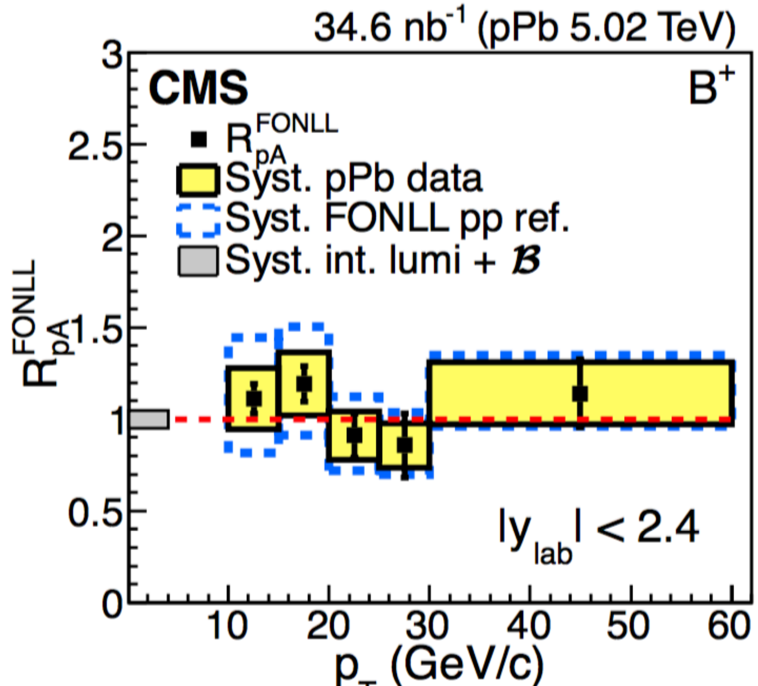
D mesons



ALICE, arXiv:1605.07569
PRL 113 (2014) 232301

H. Fuji et al., Nucl Phys A920 (2013) 78
M. Mangano et al., Nucl. Phys. B373 (1992) 295
K. J. Eskola et al., JHEP 0904 (2009) 065
Vitev et al., Phys. Rev. C 80 (2009) 05490
Z.-B. Kang et al., Phys. Lett.B740 (2015)23

B mesons



CMS, PRL 116 (2016) 032301

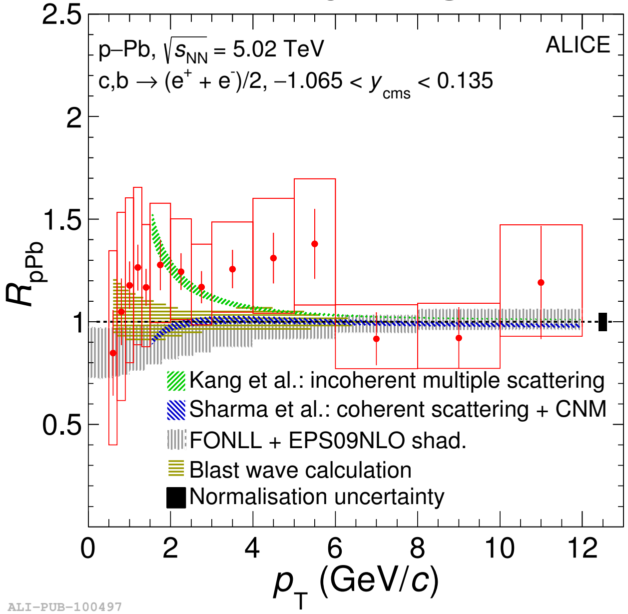
R_{pPb}~1 for D and B mesons in p-Pb collisions
Models with CNM describe the data within the uncertainties

HF in pA: RHIC vs LHC

c,b→electrons

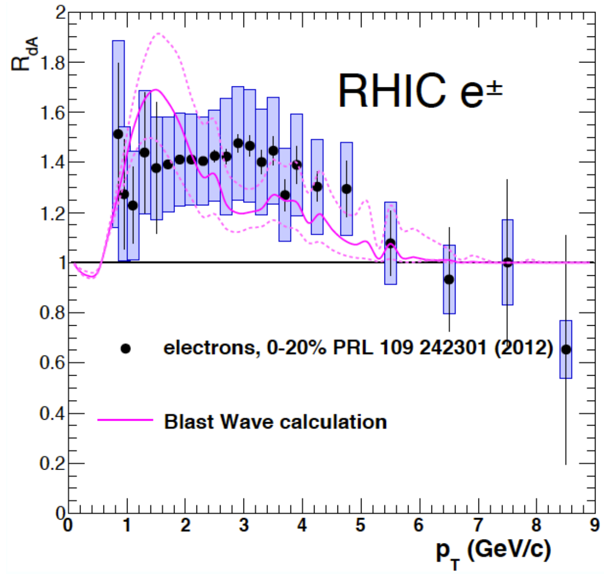
Mid-rapidity: RHIC vs LHC

multiplicity integrated

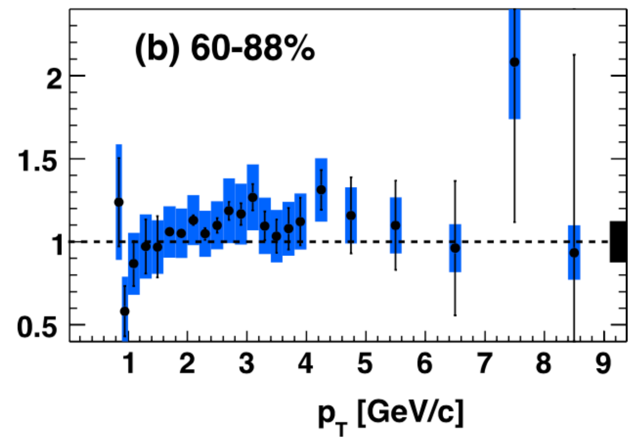


ALICE, Phys. Lett. B 754 (2016) 81

0-20% d+Au



80-80% d+Au



PHENIX, PRL 109 (2012) 242301

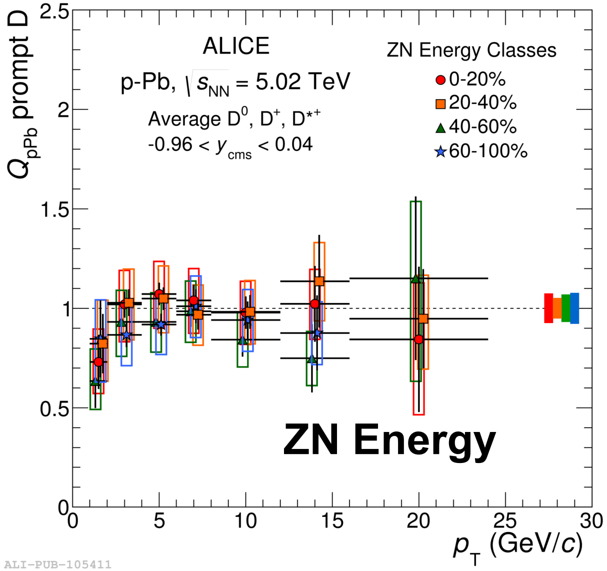
LHC: R_{pPb}~1 for electrons from c/b in p-Pb collisions

RHIC: R_{dAu}>1 for electrons from heavy-flavours at low p_T in central d+Au. Compatible with radial flow? Peripheral: consistent with binary-scaled pp

HF in pA: RHIC vs LHC

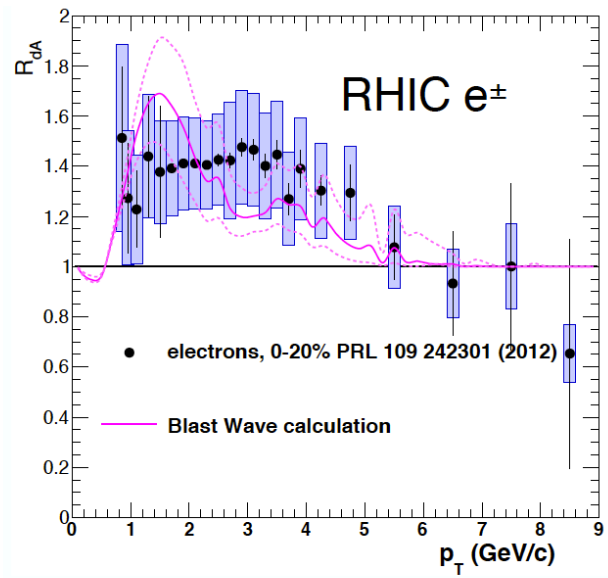
Mid-rapidity: RHIC vs LHC

D mesons vs p-Pb centrality

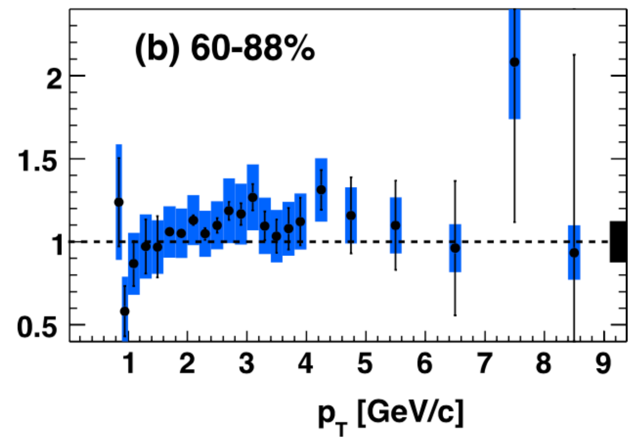


ALICE, arXiv:1605.07569

0-20% d+Au



80-80% d+Au



PHENIX, PRL 109 (2012) 242301

RHIC: R_{dAu}>1 for electrons from heavy-flavours at low p_T in central d+Au. Compatible with radial flow? Peripheral: consistent with binary-scaled pp

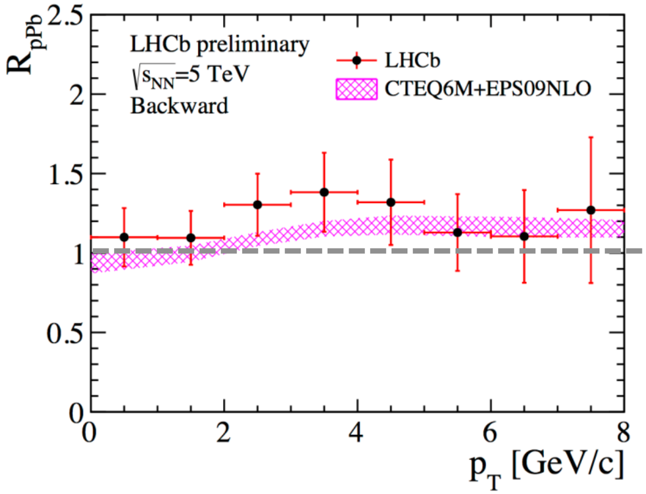
LHC: No multiplicity dependent modification of D-meson production relative to pp collisions within uncertainties.
→ Smaller effect could be due to harder initial spectrum

HF in pA: different rapidities at LHC

D mesons

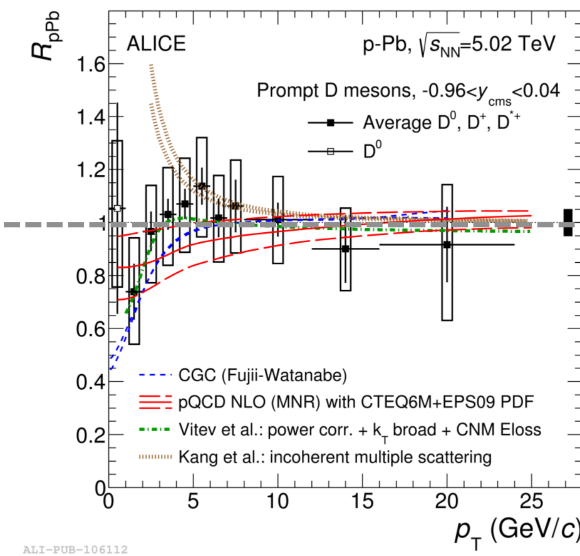
Forward and backward rapidity at LHC

Pb-going (backward)



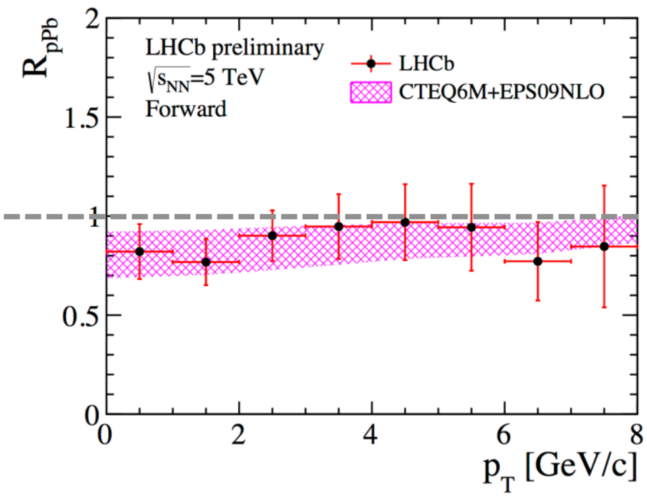
LHCb-CONF-2016-003

mid-rapidity



ALICE, PRL113 (2014), 232301
ALICE, arXiv:1605.07569

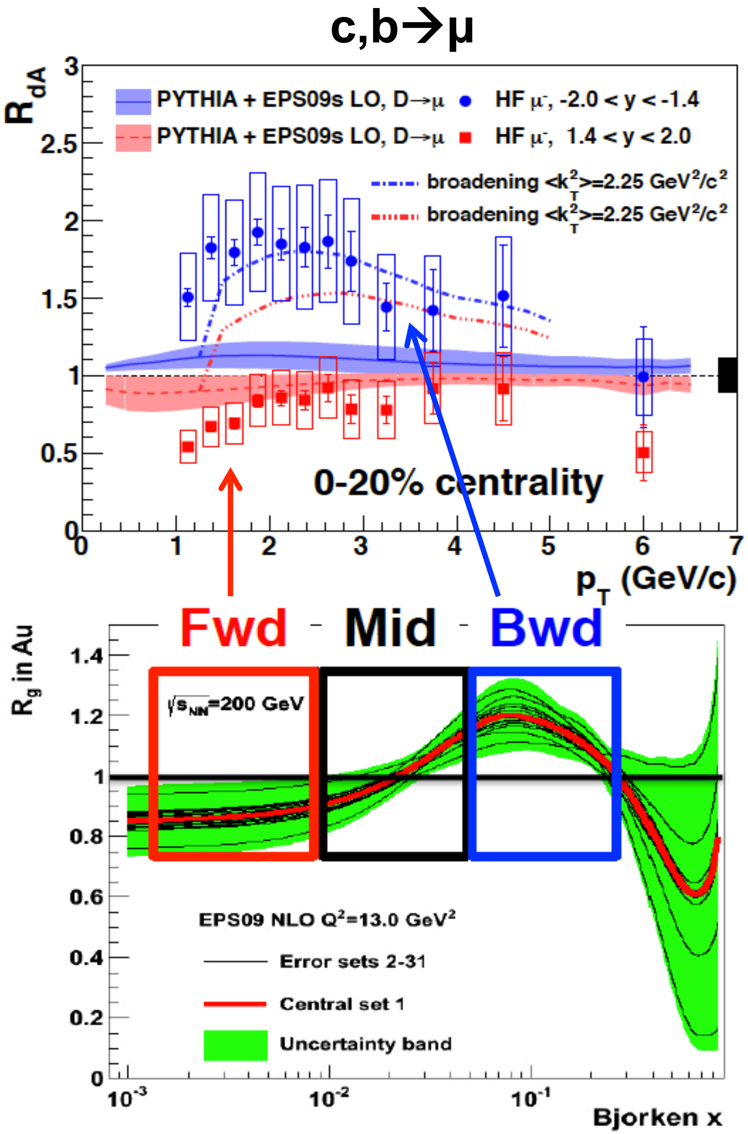
p-going (forward)



Different *x* regimes explored in different rapidity ranges with HF probes
→shadowing/saturation relevant at low p_T at the LHC

Data described within uncertainties by the models with nPDF and other CNM effects

HF in pA: different rapidities at RHIC



Forward and backward rapidity at RHIC

Suppression at forward rapidity

Enhancement at backward rapidity

Models based on different initial-state effects fail to reproduce d+Au data at both forward and backward rapidities at RHIC energies

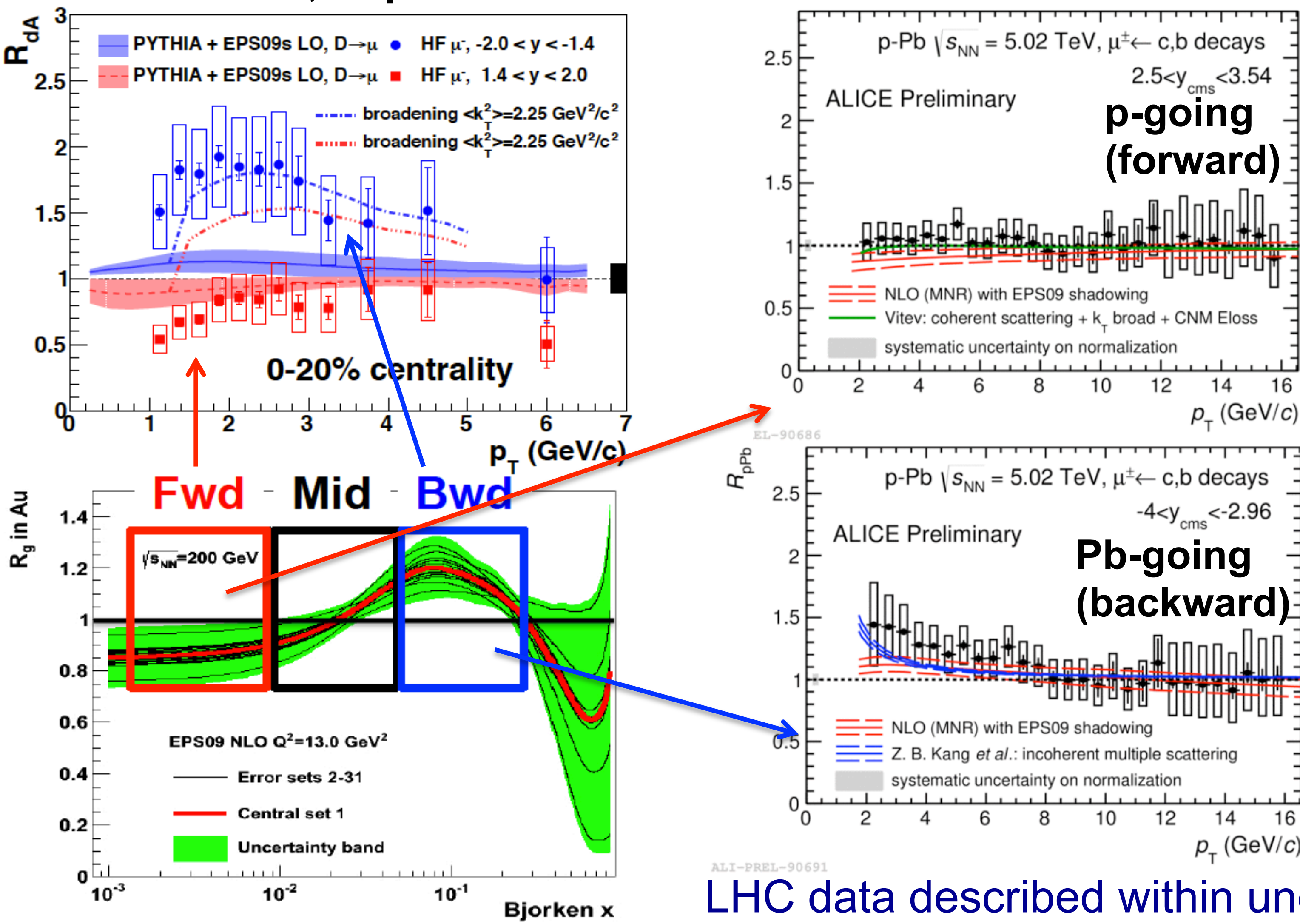
PHENIX, PRL112 (2014) 252301

HF in pA: different rapidities at RHIC vs LHC

Forward and backward rapidity at RHIC and LHC

c,b→μ

c,b→μ



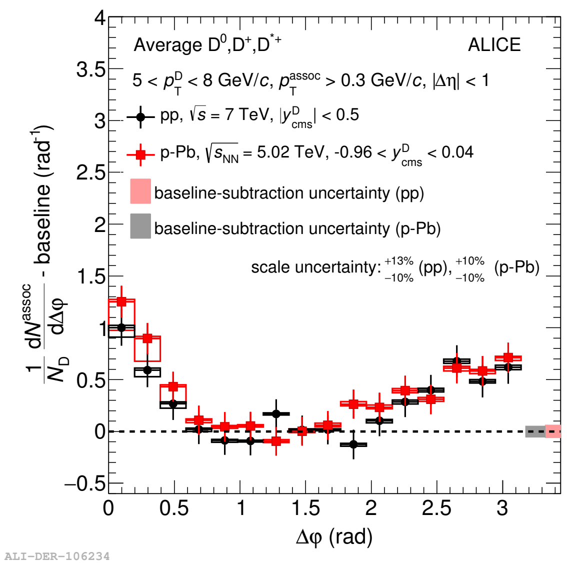
M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009) 065
R. Sharma, I. Vitev et al., PRC 80 (2009) 054902
Z.B. Kang et al., PLB 740 (2015) 23

PHENIX, PRL112 (2014) 252301

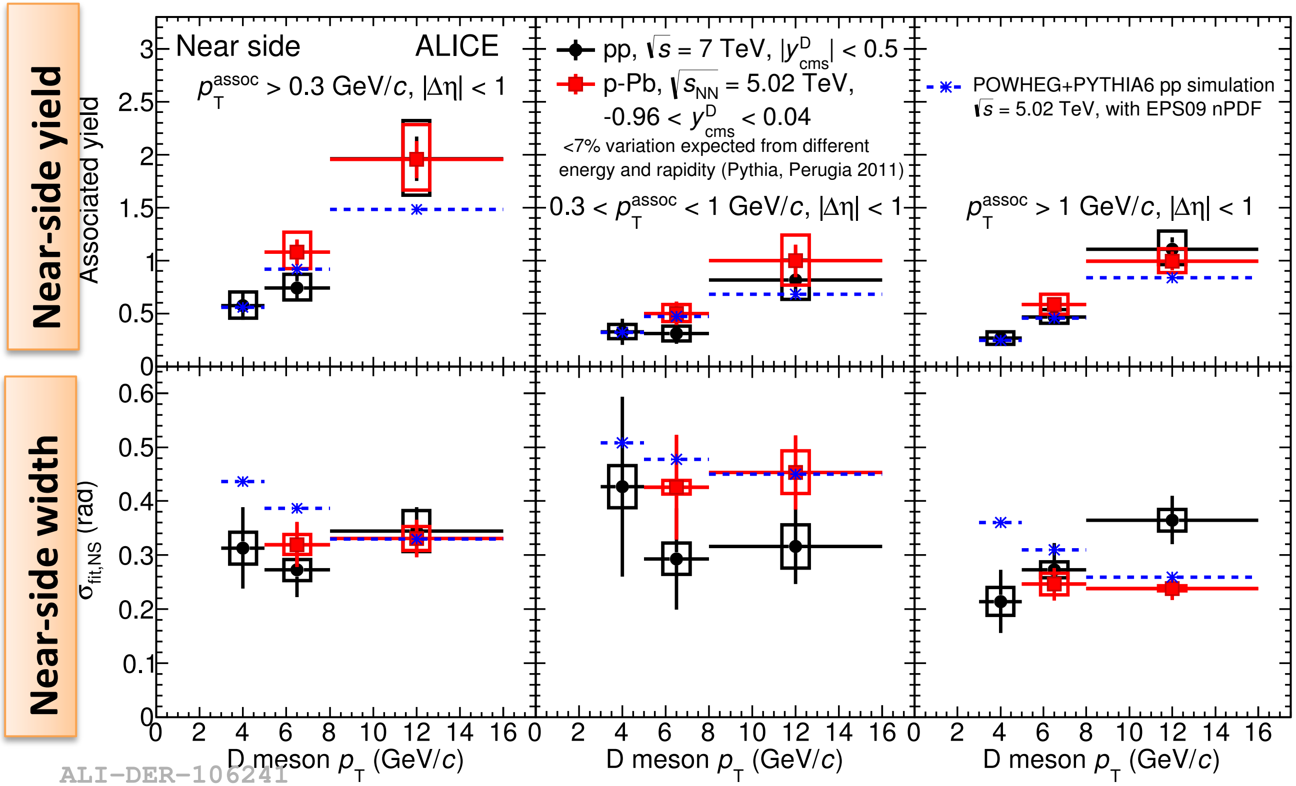
LHC data described within uncertainties by the models with CNM effects

D-h correlations in pp and p-Pb

5<p_T^D<8 GeV/c, p_T^{assoc}>0.3 GeV/c



ALICE, arXiv:1605.06963

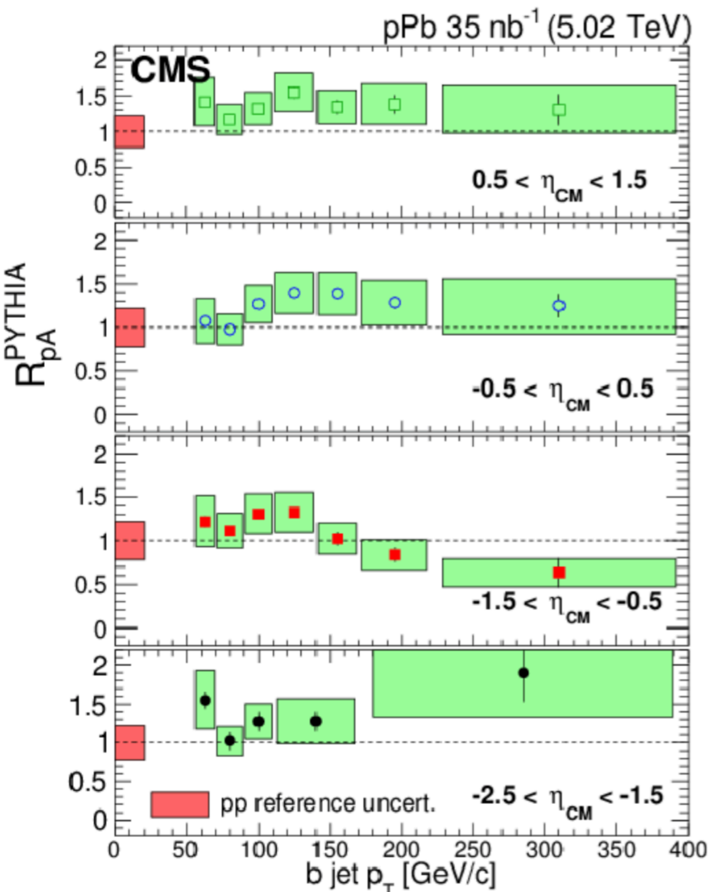


Compatibility within uncertainties between **pp collisions at √s = 7 TeV** and **p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV** after baseline subtraction

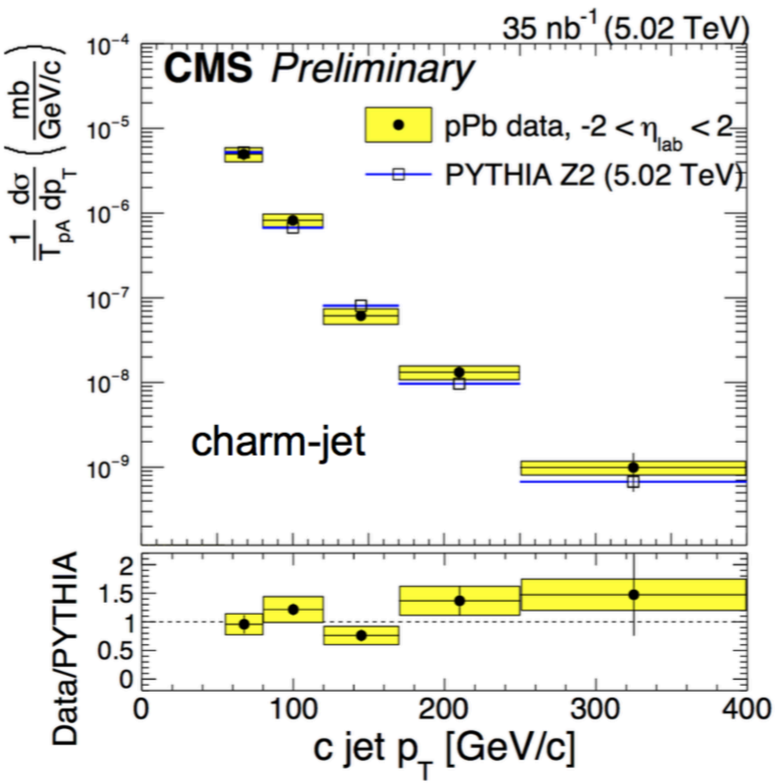
Near-side yields and widths compatible in data and simulations within uncertainties.

No modifications due to CNM effects in p-Pb seen within uncertainties

b- and c- jets in p-Pb collisions



CMS, PLB 754 (2016) 59



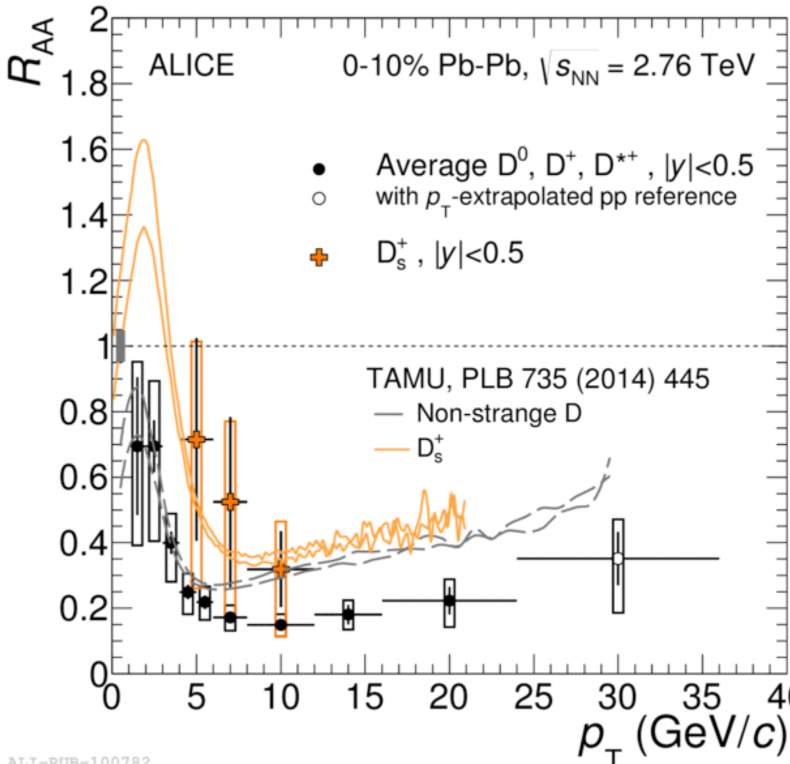
CMS-PAS-HIN-15-012

High-p_T jets tagged with charm and beauty quarks
No significant CNM effects for jet p_T>50 GeV/c

Heavy-flavour results in Pb-Pb collisions

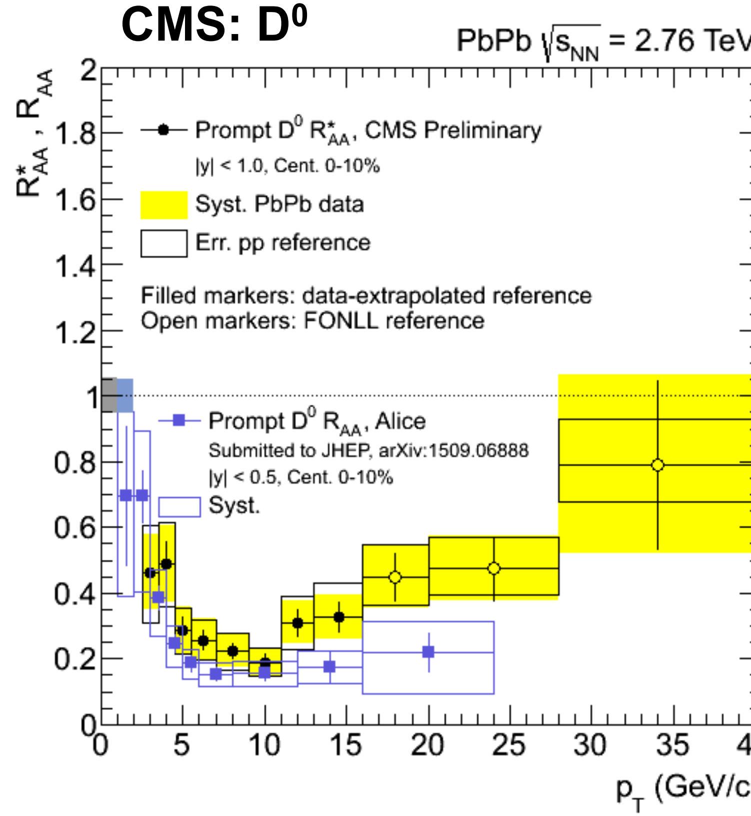
AA: D-meson R_{AA} at LHC

ALICE: D^0,D^+,D^{*+},D_s^+



ALICE, JHEP1603 (2016) 081
JHEP1603 (2016) 082

CMS: D^0

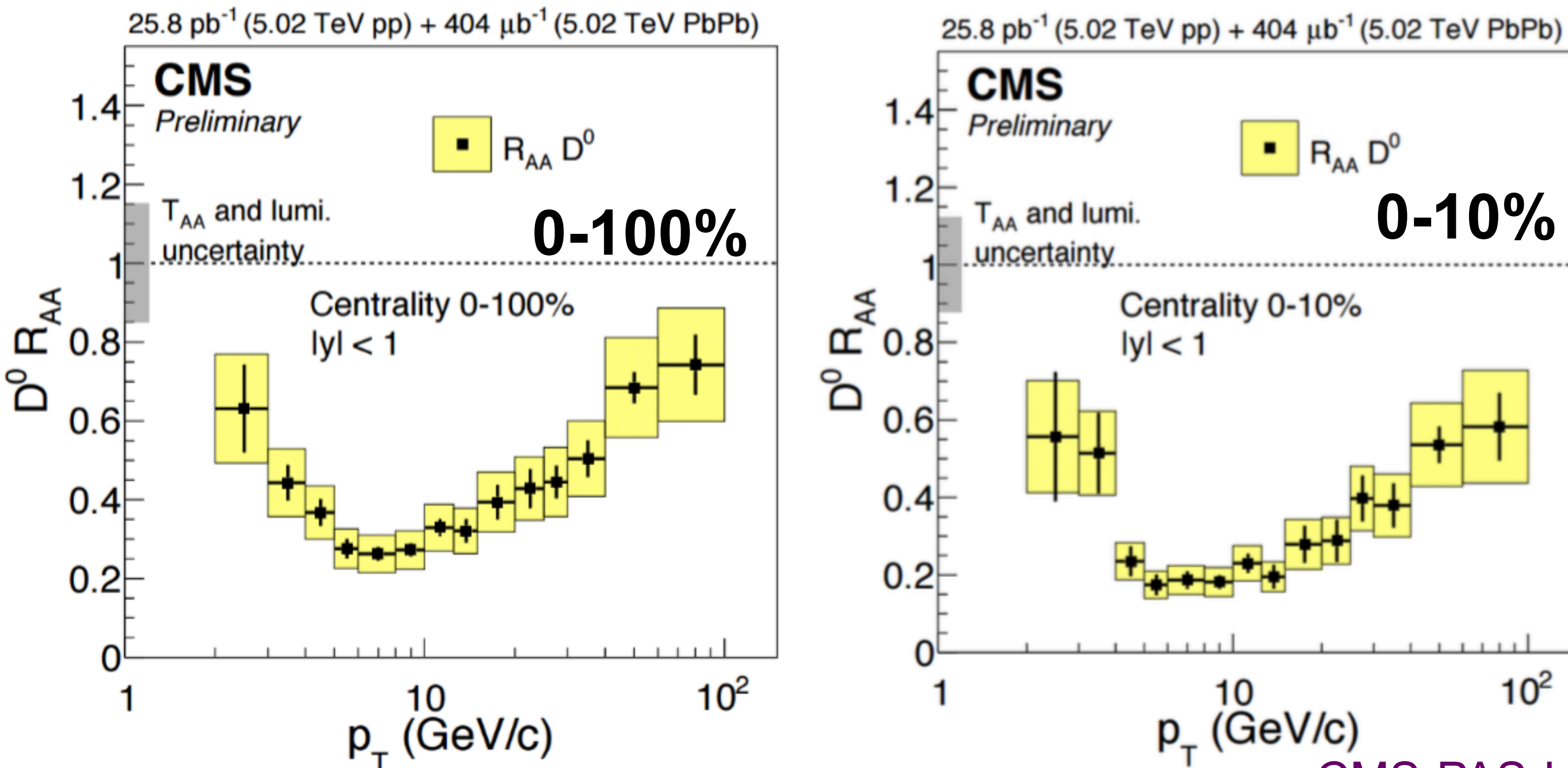


CMS-PAS-HIN-15-005

Strong suppression of prompt D-meson yield in central Pb-Pb collisions
- up to a factor of 5 at p_T~10 GeV/c

Hint for less suppression of D_s^+ than non-strange D at low p_T
- expected if recombination plays a role in charm hadronization

AA: D-meson R_{AA} at LHC in Run 2



CMS-PAS-HIN-16-001

Strong suppression of D^0 mesons in Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV

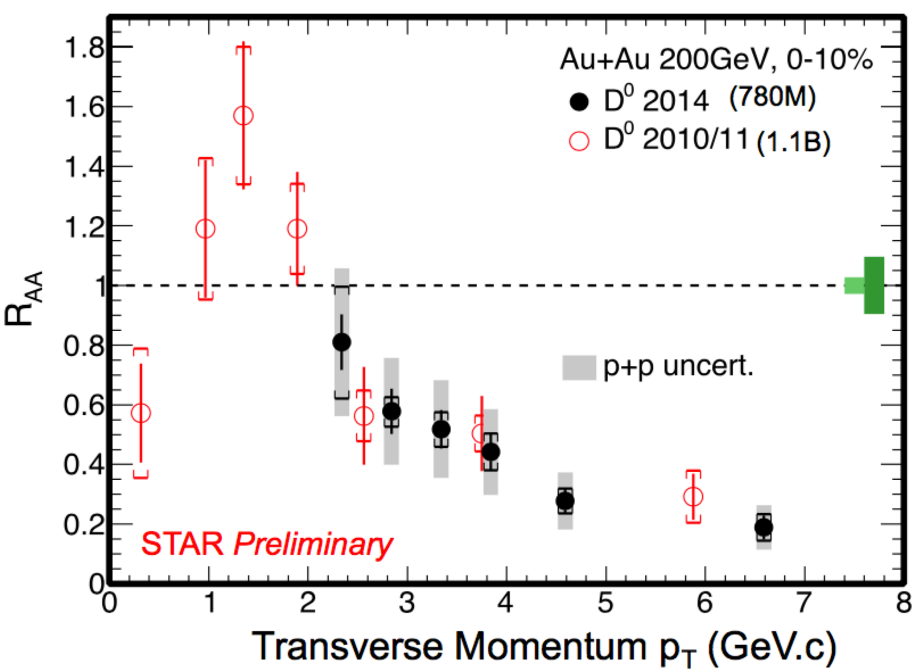
→ ~factor 5 at p_T=10 GeV/c

Similar suppression as in in Pb-Pb at **$\sqrt{s_{NN}}$=2.76 TeV**

At high p_T > 10 GeV: D^0 R_{AA} **increases** as a function of D^0 p_T

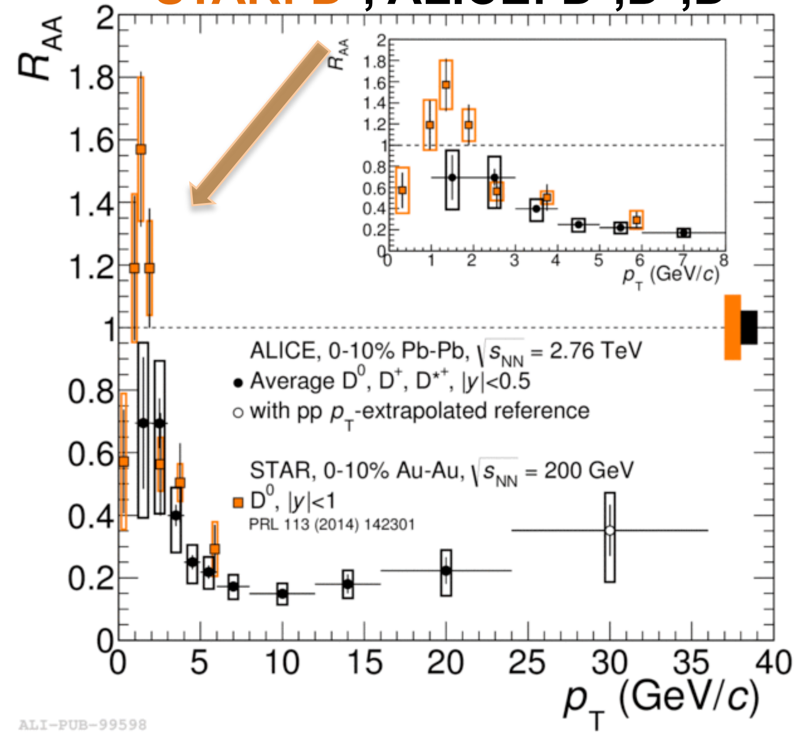
AA: comparison to RHIC

STAR: D^0



STAR: PRL 113 (2014) 142301
PLB 655 (2007) 104

STAR: D^0, ALICE: D^0,D^+,D^{*+}



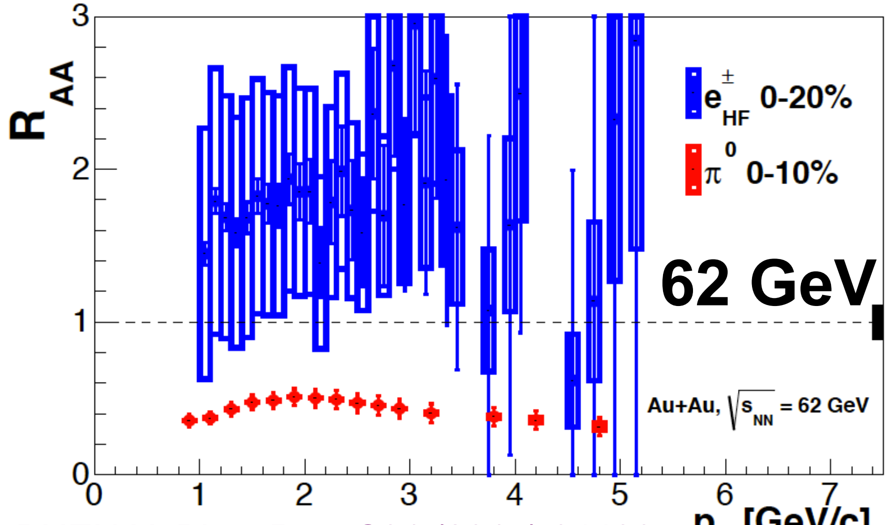
STAR, PRL113 (2014) 142301
ALICE, JHEP1603 (2016) 081

Similar suppression in central A-A collisions at high p_T

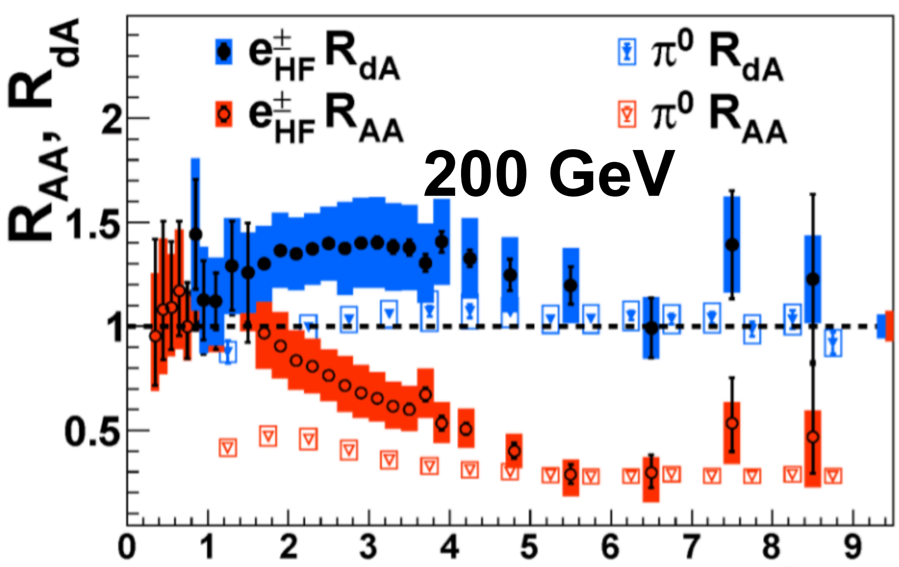
Differences at low p_T: radial flow? Shadowing? Recombination?

Crucial to go to $p_T \sim 0$ at the LHC

Leptons from HF at RHIC



PHENIX, Phys.Rev. C91 (2015) 044907



PHENIX, PRL 109 (2012) 242301

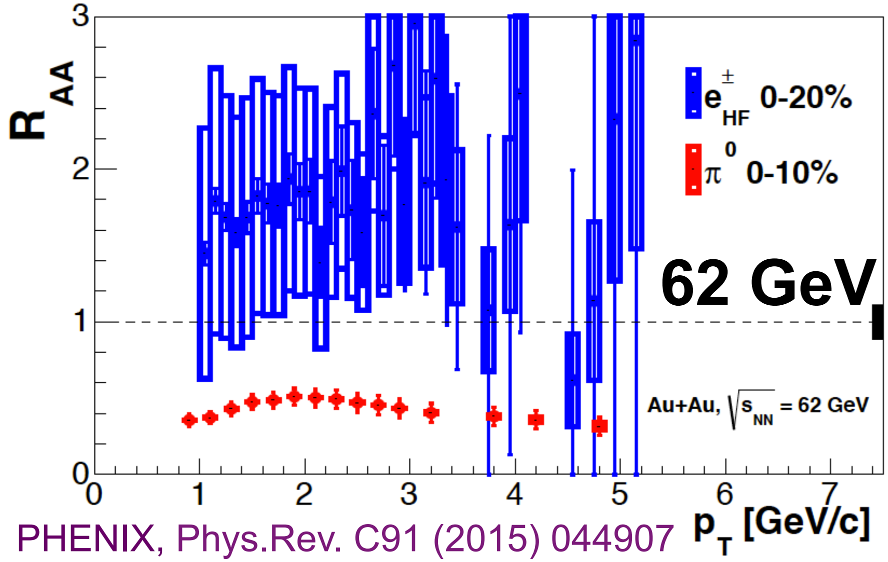
c,b→electrons

Different suppression trend at $\sqrt{s_{NN}}$=62 and 200 GeV.

Different effects at two energies: interplay between initial-state k_t-broadening, final-state flow and energy loss

Note: 62 GeV pp reference comes from ISR. More data at 62 GeV

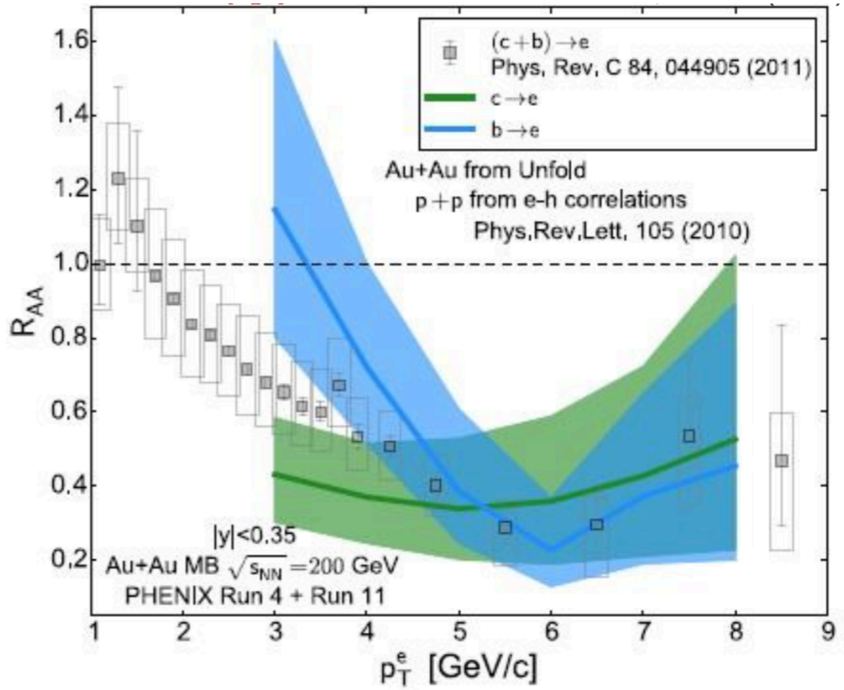
Leptons from HF at RHIC



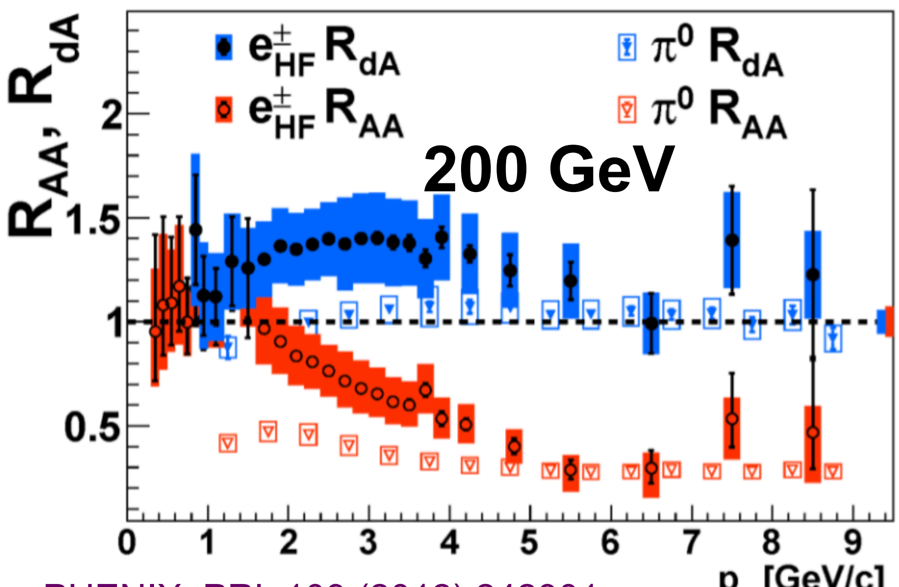
PHENIX, Phys.Rev. C91 (2015) 044907

c,b→electrons

Charm and beauty separation



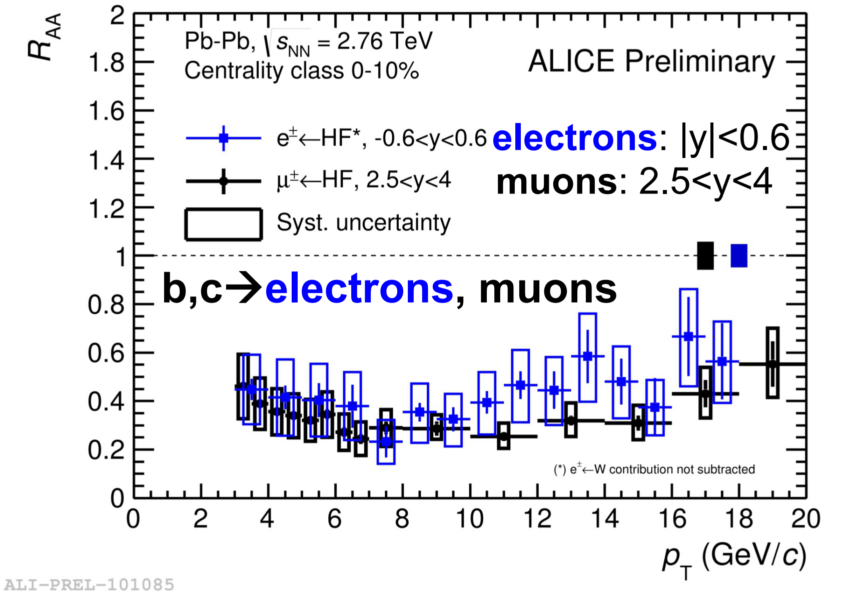
PHENIX, PRC 93 (2016) 034904



PHENIX, PRL 109 (2012) 242301

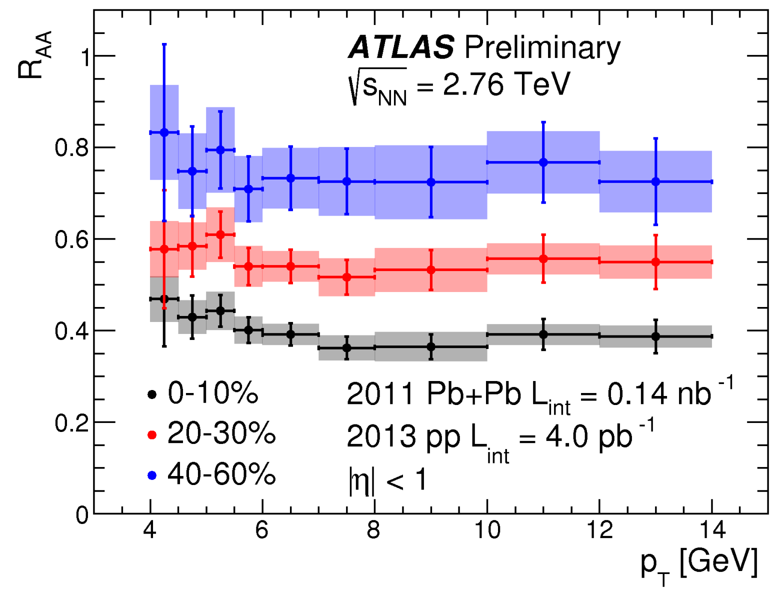
From 2011 Au-Au data
→ Expected improvement from 2014 run with x10 statistics

Leptons from HF at LHC

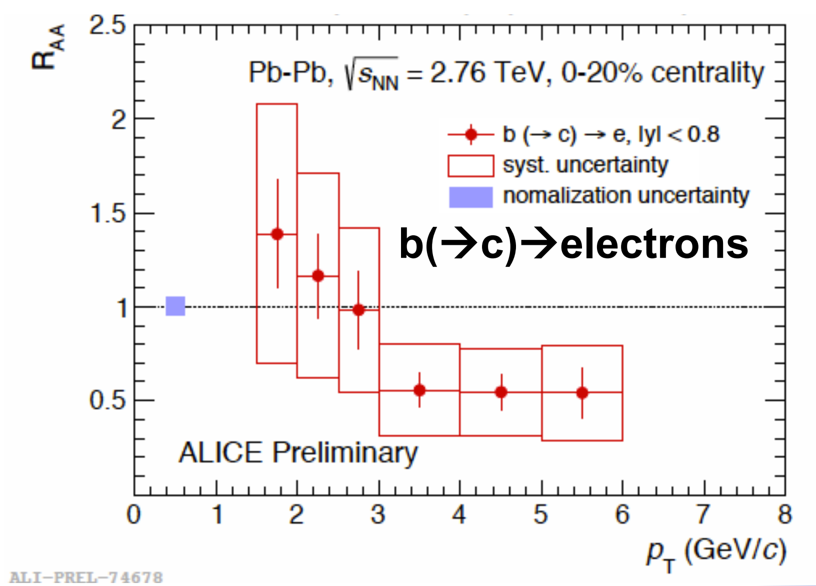


ALICE, PRL 109 (2012) 112301 (HF decay muons)

b,c→muons: |η|<1



ATLAS-CONF-2015-053



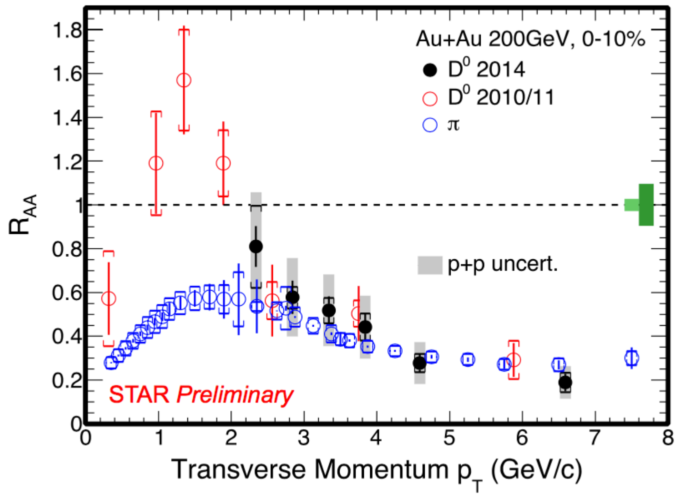
Similar suppression of **electrons and muons from heavy-flavour** hadron decays at the LHC.

Electrons from beauty-hadron decays in Pb-Pb collisions.
Hint for suppression for p_T>3 GeV/c

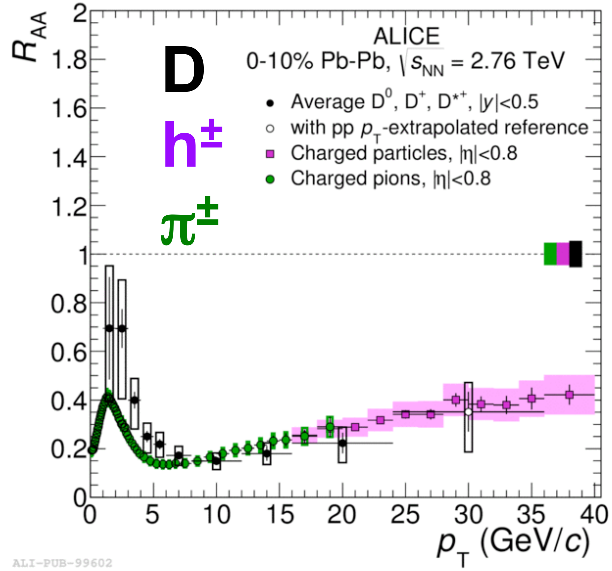
R_{AA}: D mesons and charged hadrons

Mass/colour dependence of energy loss?

200 GeV

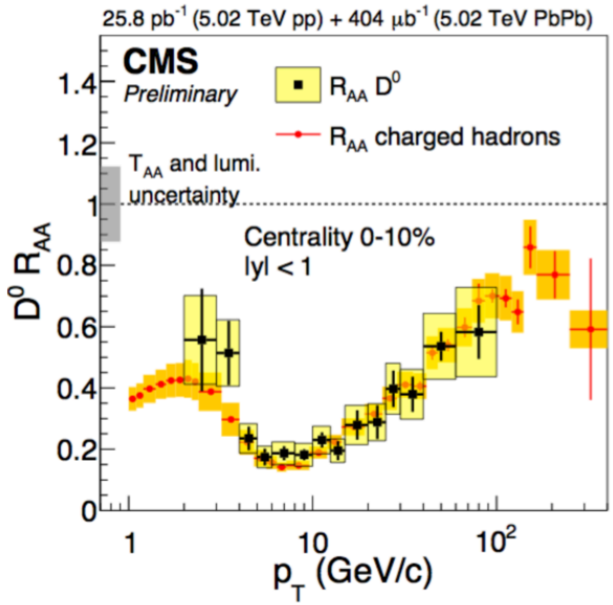


2.76 TeV



ALICE, JHEP1603 (2016) 081

5.02 TeV



$R_{AA}(D) \sim R_{AA}(\pi,h^{\pm})$ in different AA collision energies

What about **$\Delta E(g) > \Delta E(uds) > \Delta E(c) \rightarrow R_{AA}(D) > R_{AA}(\pi,h^{\pm})$** ?

→ Different quark spectra

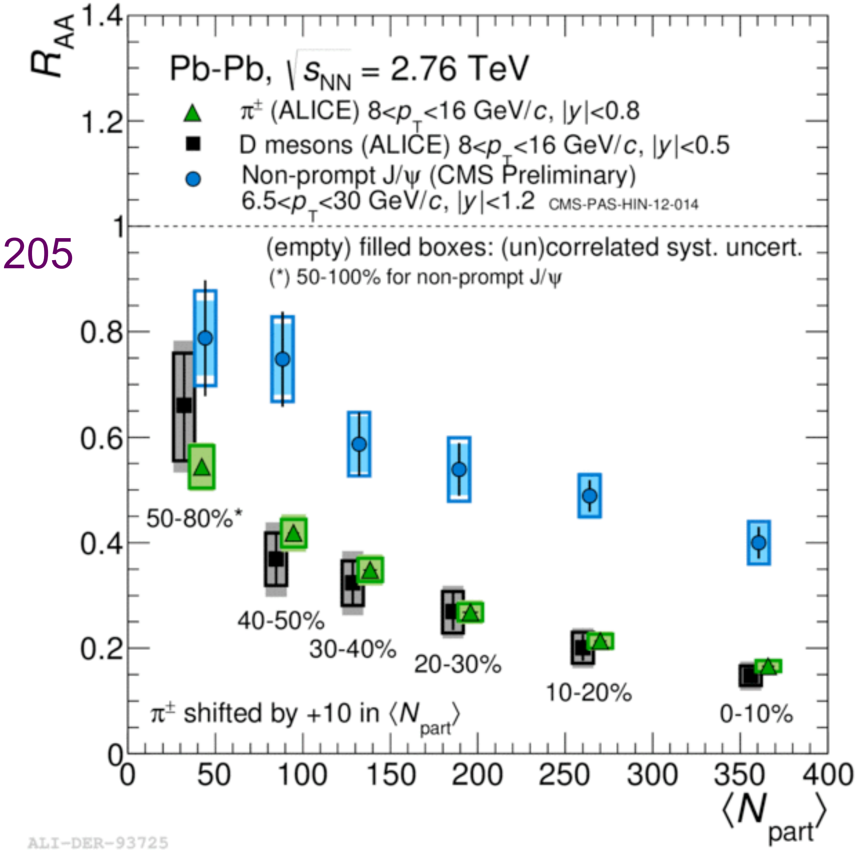
→ $R_{AA}(h)$ affected by fragmentation, $R_{AA}(D) \sim R_{AA}(c)$ because of harder HQ fragmentation

M.Djordjevic, PRL 112, 042302 (2014)

R_{AA}: D mesons and non-prompt J/ψ

Mass dependence of energy loss?

ALICE, JHEP 1511 (2015) 205
CMS, PAS-HIN-12-014

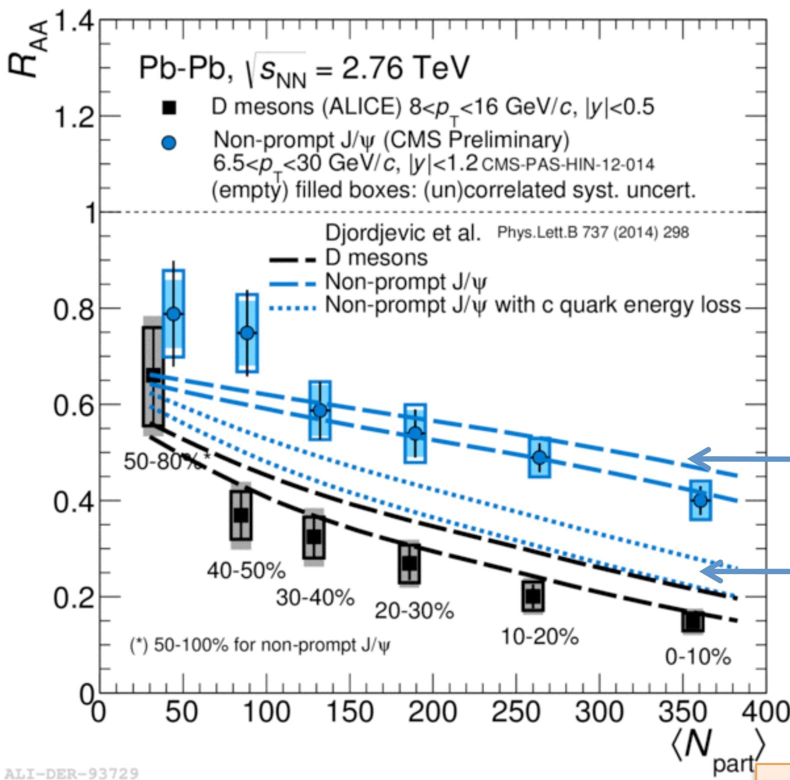


similar kinematics for D and B mesons (**<p_T>~10 GeV/c**)
different y ranges for D and non-prompt J/ψ

Indication of a difference between charm and beauty suppression in central collisions

R_{AA}: D mesons and non-prompt J/ψ

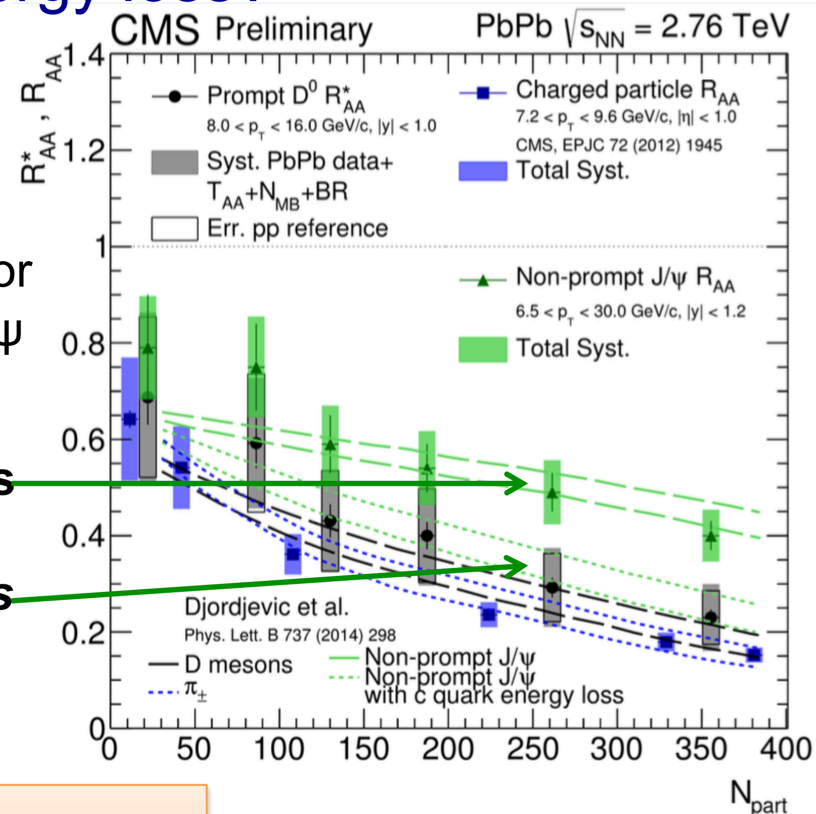
Mass dependence of energy loss?



Theory model (Djordjevic): two mass assumptions for non-prompt J/ψ R_{AA}:

b quark mass

c quark mass



ALICE, JHEP 1511 (2015) 205
CMS, PAS-HIN-12-014

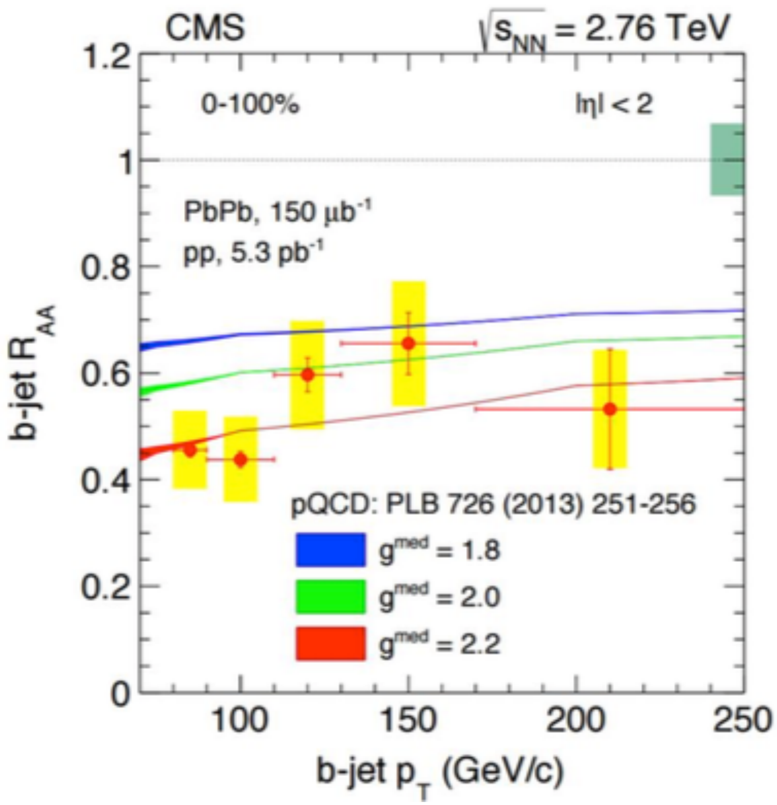
Difference comes from different masses

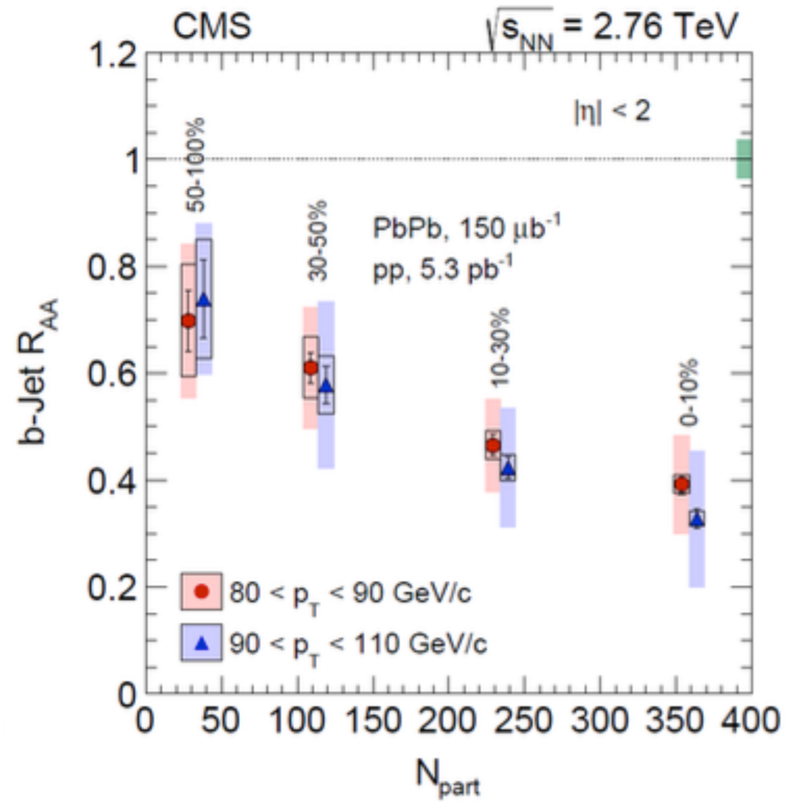
CMS, PAS-HIN-15-005
PAS-HIN-12-014
EPJC 72 (2012) 1945

M.Djordjevic, PRL 112, 042302 (2014)

pQCD in-medium energy loss model based on mass dependent energy loss in agreement with data

Beauty jets in Pb-Pb collisions

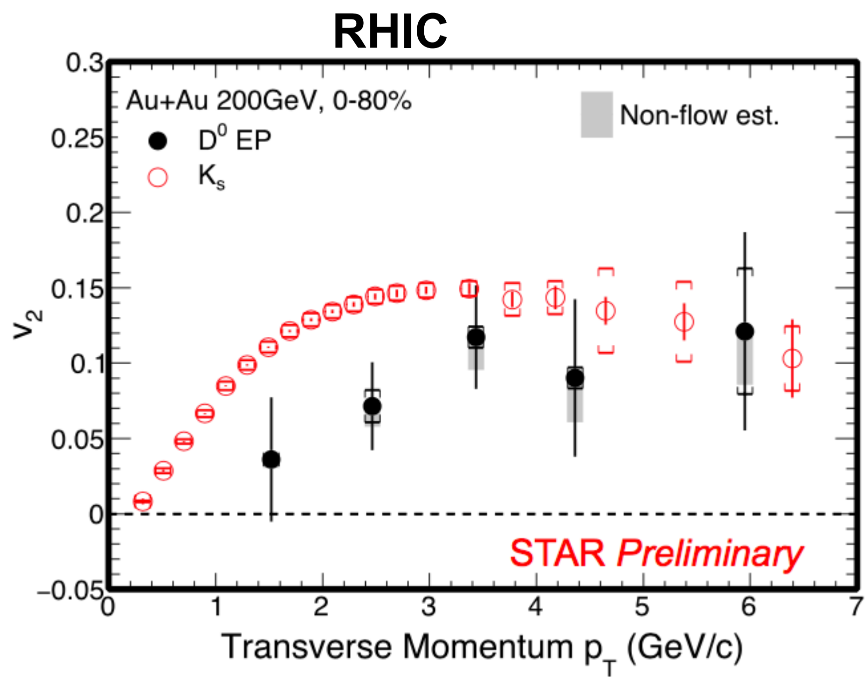


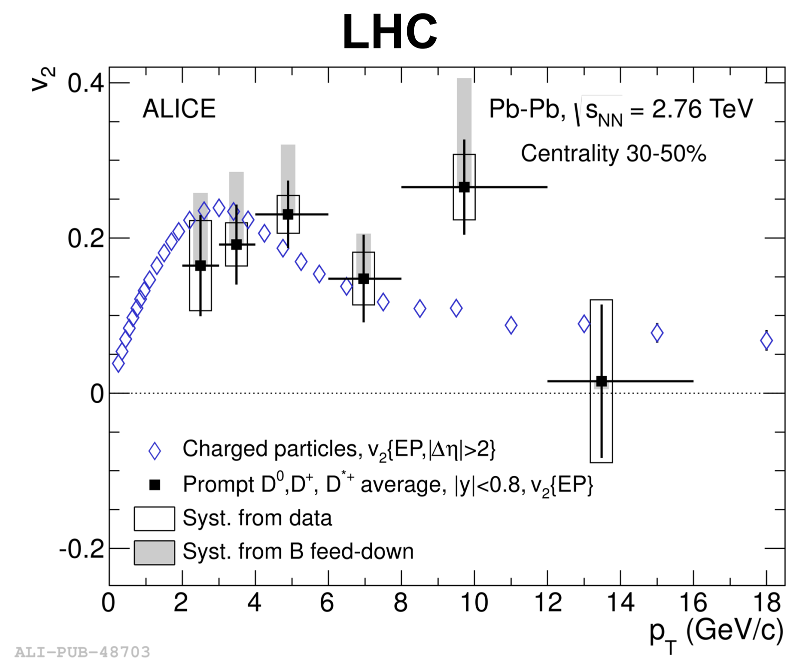


Quark-jets tagged.
B-jet suppression is described by model with strong jet-medium coupling, consistent with inclusive jet suppression.

Quark mass effect negligible at high jet p_T.

D-meson azimuthal anisotropy





ALICE, PRL 111, 102301 (2013)
ALICE, PRC 90 (2014) 3, 034904

RHIC: D^0 $v_2>0$ for $p_T>2$ GeV/c (0-80%)

- tends to be below light-hadron v_2 at low p_T

LHC: D-meson $v_2>0$ in $2<p_T<6$ GeV/c (with 5.7σ) (30-50%)

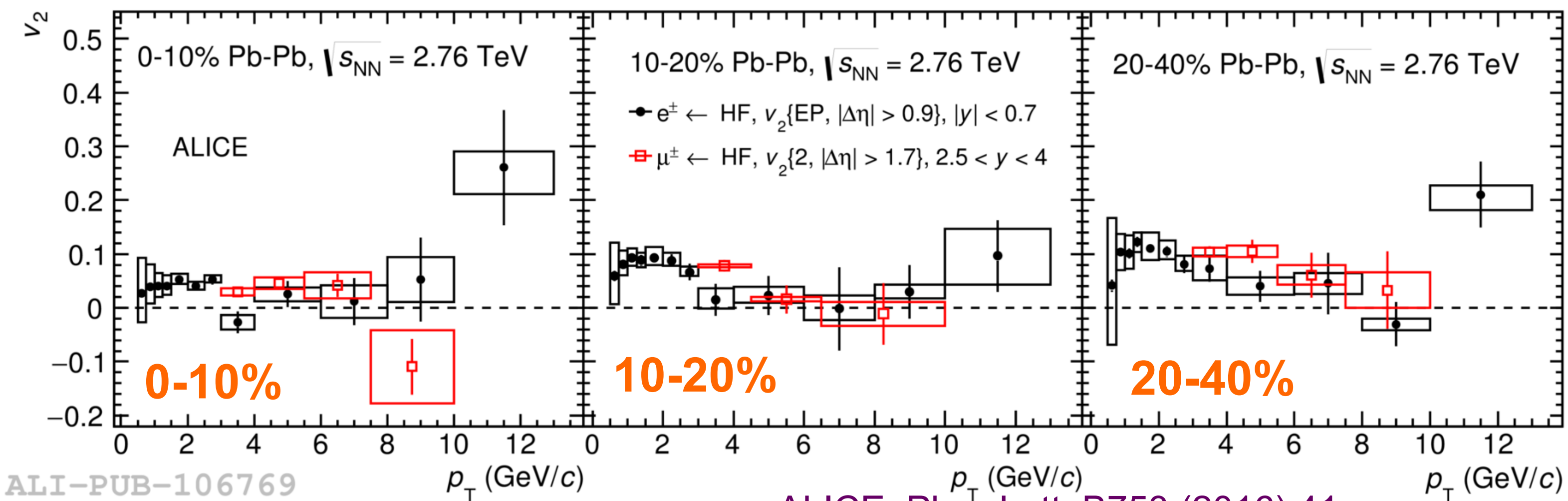
- compatible with v_2 of charged particles

→ more statistics and low-p_T measurements needed to quantify HQ thermalization at RHIC and LHC

HF lepton azimuthal anisotropy

(c,b)→electrons, muons

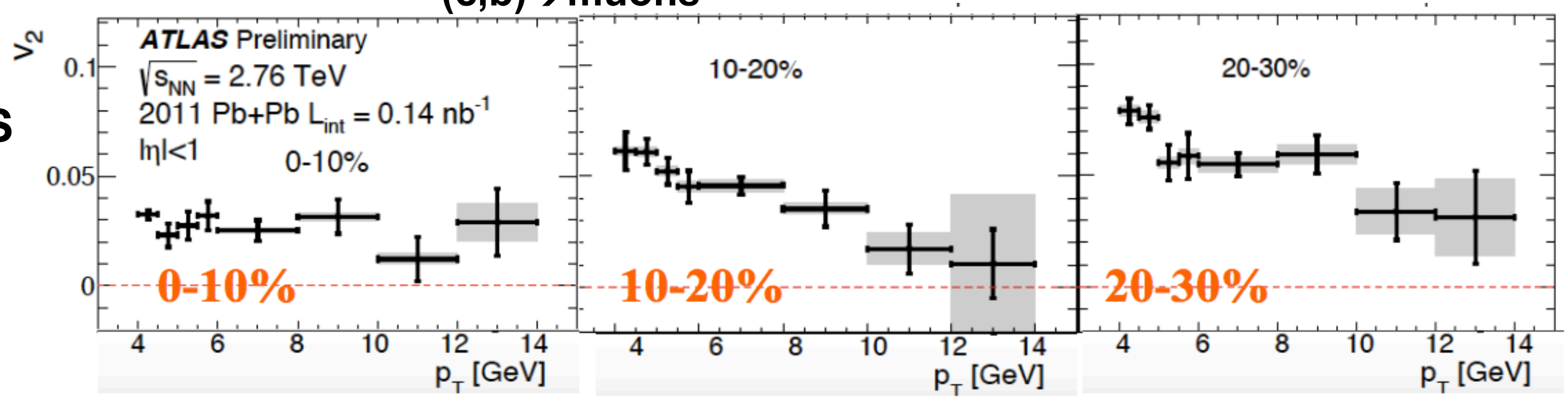
ALICE



ALICE, Phys.Lett. B753 (2016) 41
arXiv:1606.00321

(c,b)→muons

ATLAS



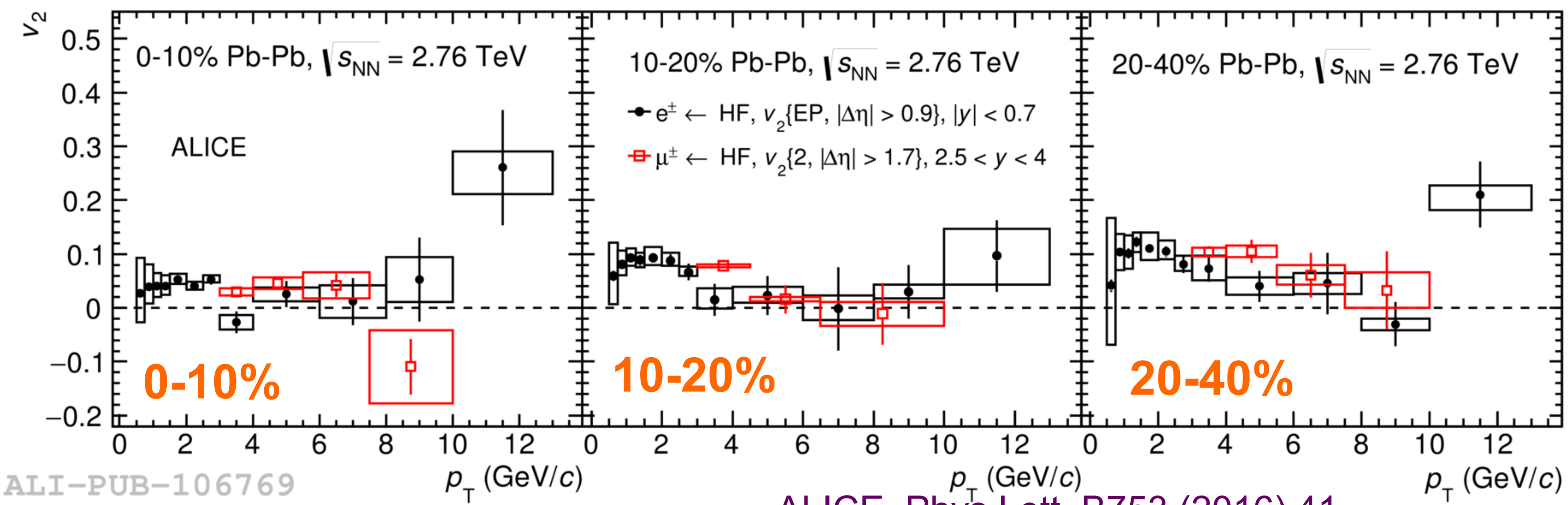
ATLAS-CONF-2015-053

Positive v_2 for e/μ from heavy-flavour decays at LHC

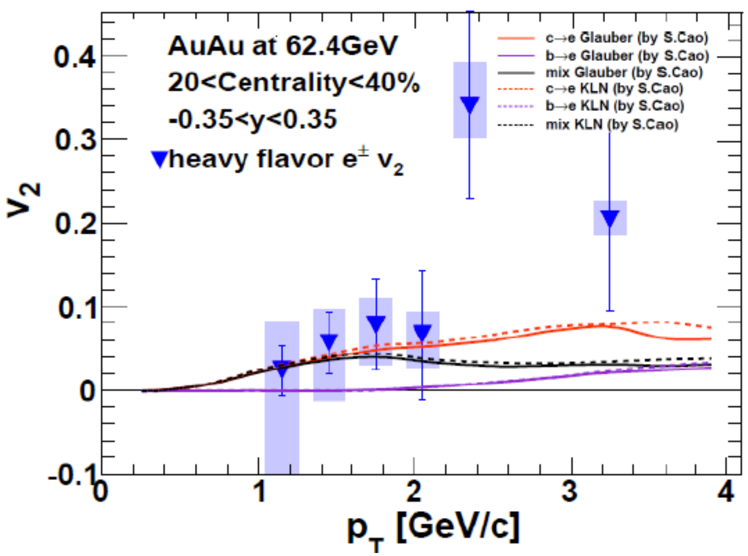
HF lepton azimuthal anisotropy

(c,b)→electrons, muons

ALICE



ALICE, Phys.Lett. B753 (2016) 41
arXiv:1606.00321

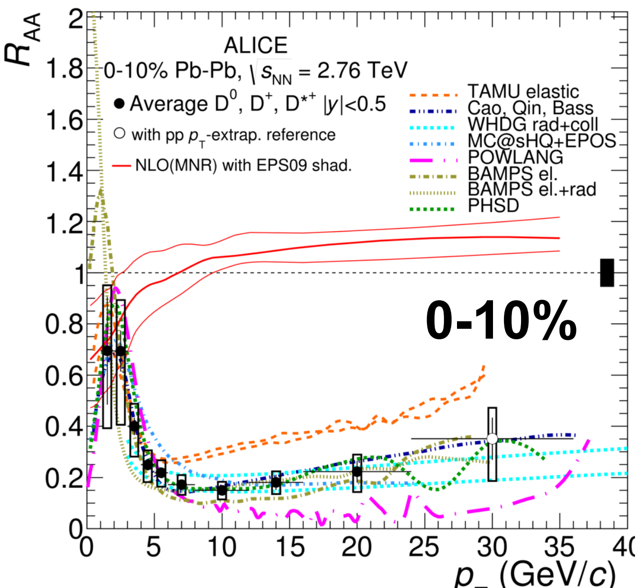


PHENIX, PRC(2015) 044907

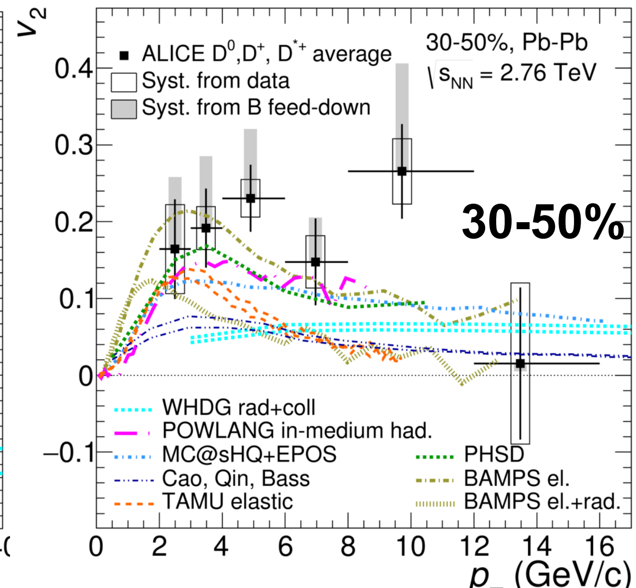
(c,b)→electrons RHIC

Charm v_2 at low energy (62 GeV):
is flowing? is recombination with light quarks?

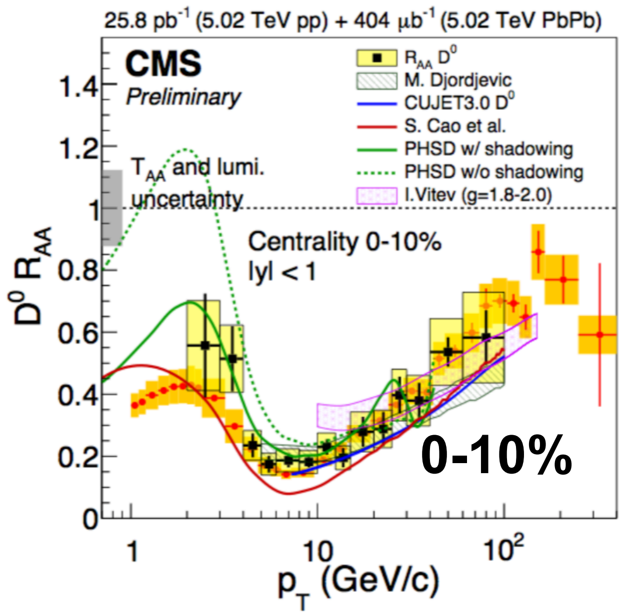
R_{AA} and v_2: constraints to models



ALICE, JHEP1603 (2016) 081

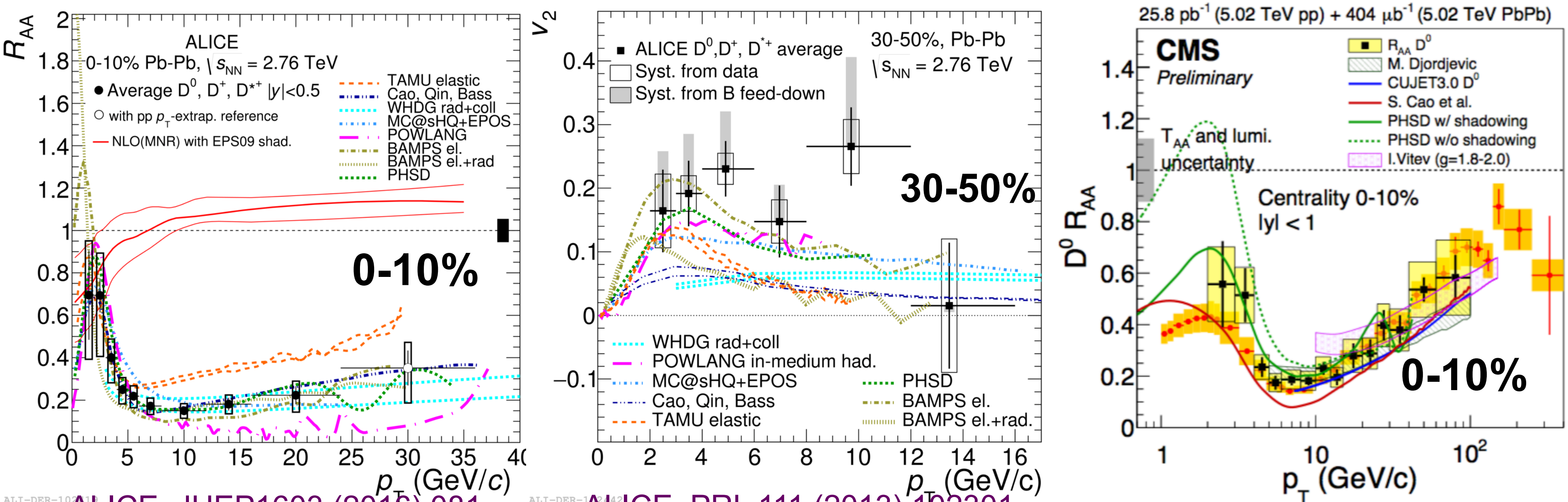


ALICE, PRL 111 (2013) 102301



- **BAMPS** (Boltzman equation with collisional energy loss –and radiative- in expanding QGP): Fochler et al., J. Phys. G38 (2011) 124152, PRC 84 (2011) 024908
- **Cao, Quin, Bass**(Langevin with coll and rad term and recombination+hydro) arXiv:1605.06447v1
- **Djordjevic** (energy loss due to both radiative and collisional
- processes in a finite size dynamical QCD medium) Phys. Rev. C 92 (2015) 024918
- **MC@sHQ+EPOS** (coll and rad e.loss in expanding medium based on EPOS model):Aichelin et al., Phys. Rev. C79 (2009) 044906, J. Phys. G37 (2010) 094019
- **PHSD** (Parton-Hadron-String Dynamics transp0rt approach, coalescence): E. Bratkovskaya et al., PRC 93 (2016) 034906
- **POWLANG** (HQ transport with Langevin equation with collisional energy los and, recombination, viscous hydrodynamic expansion): Alberico et al., Eur.Phys.J C71 (2011) 1666
- **UrQMD** (Langevin equation in UrQMD): T. Lang et al, arXiv:1211.6912 [hep-ph];T. Lang et al., arXiv:1212.0696 [hep-ph].
- **TAMU** (HQ transport with resonant scattering and coalescence+hydro): Rapp, He et al., Phys. Rev. C 86 (2012) 014903
- **Vitev** (in-medium formation and dissociation of D and B, ideal fluid with Bjorken expansion):PLB 639 (2006) 38, PRC 80.5 (2009) 054902
- **WHDG** (pQCD calculation with radiative and collisional energy loss): Horowitz et al., JPhys G38 (2011) 124114

R_{AA} and v_2: constraints to models



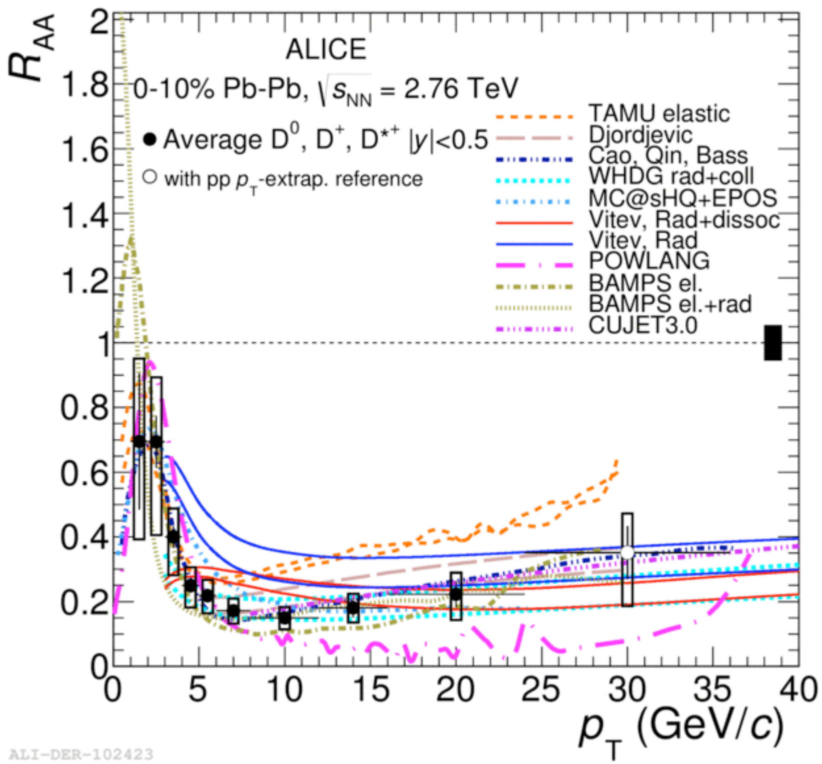
ALICE, JHEP1603 (2016) 081

ALICE, PRL 111 (2013) 102301

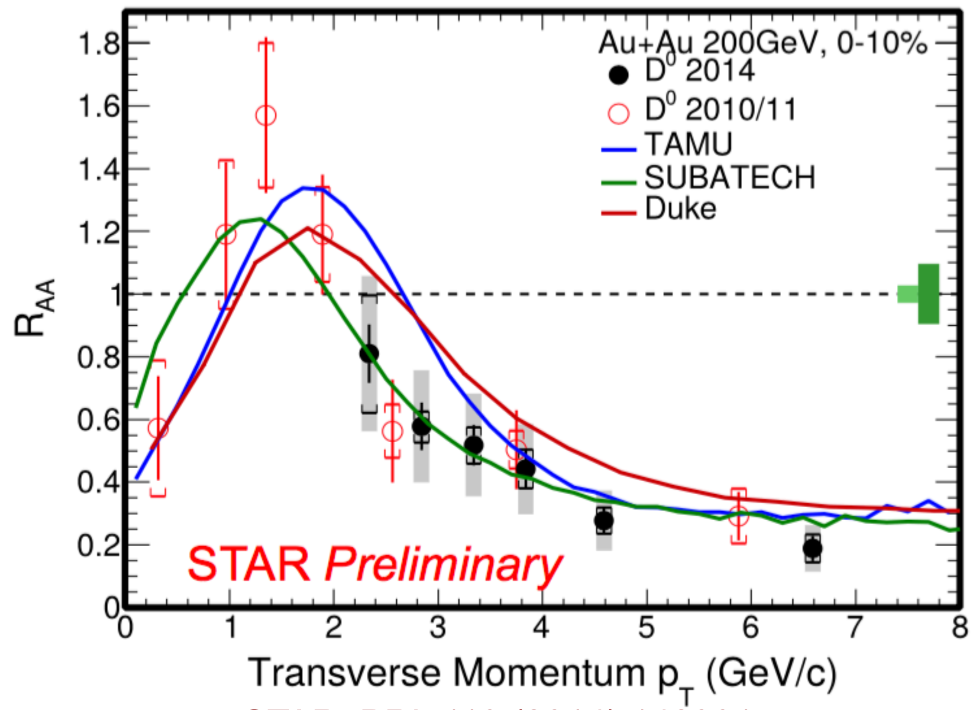
R_{AA} and v_2 results start to provide constraints to models.

Simultaneous description of heavy-flavour R_{AA} and v_2 still challenging.

R_{AA} : constraints to models



ALICE, JHEP1603 (2016) 081

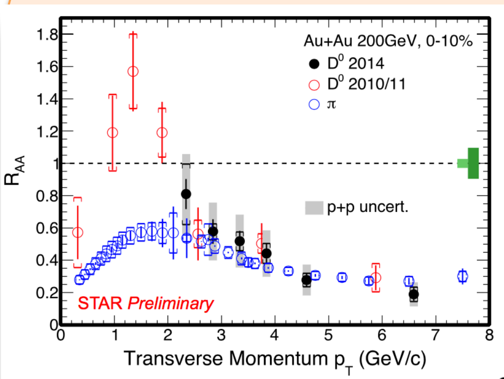


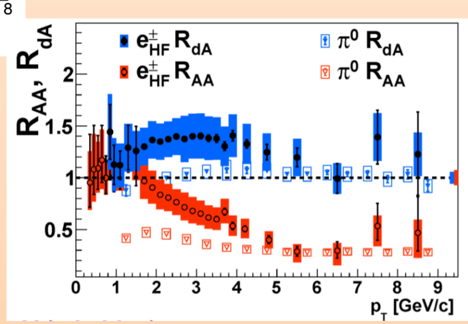
STAR: PRL 113 (2014) 142301
PLB 655 (2007) 104

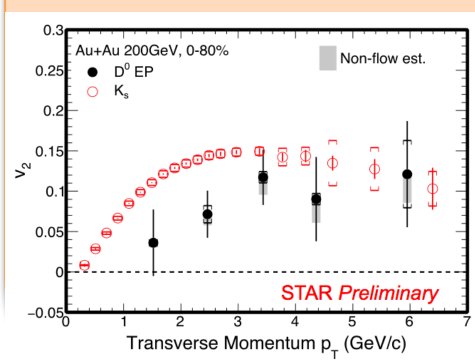
Theoretical models (i.e. TAMU) can reproduce the general R_{AA} trends at both energies in the low p_T range common to both

Current Status: HF at RHIC and LHC

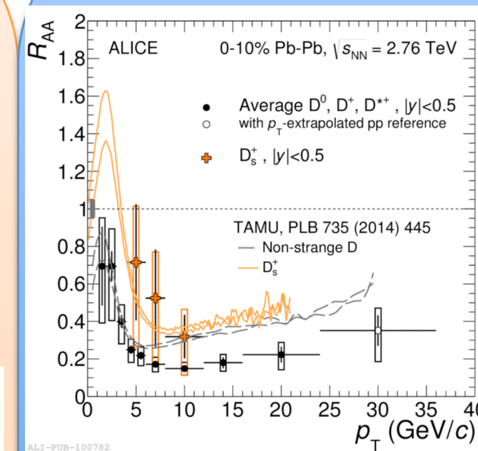
HF at RHIC

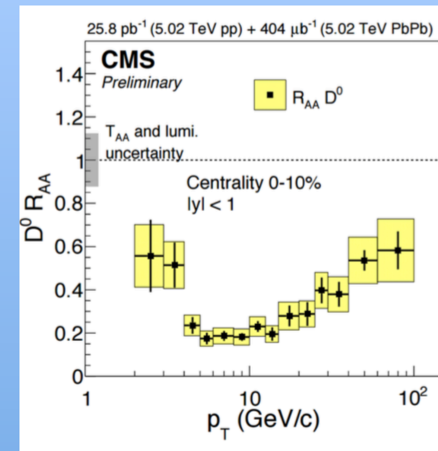


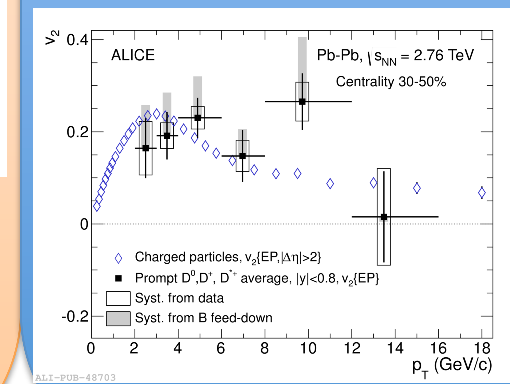


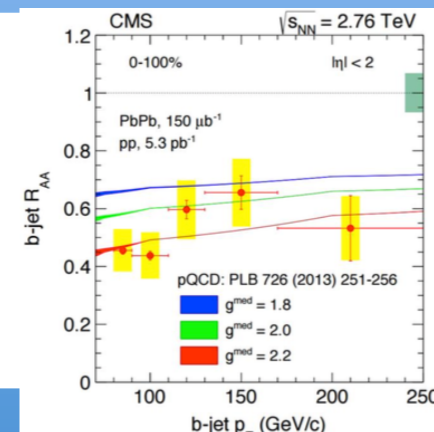


HF at LHC







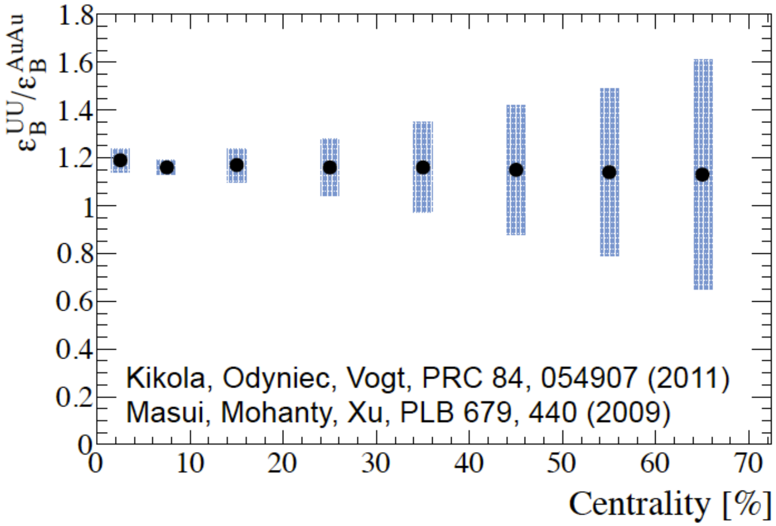


Heavy flavours are unique probes to characterize medium properties at RHIC an LHC energies.

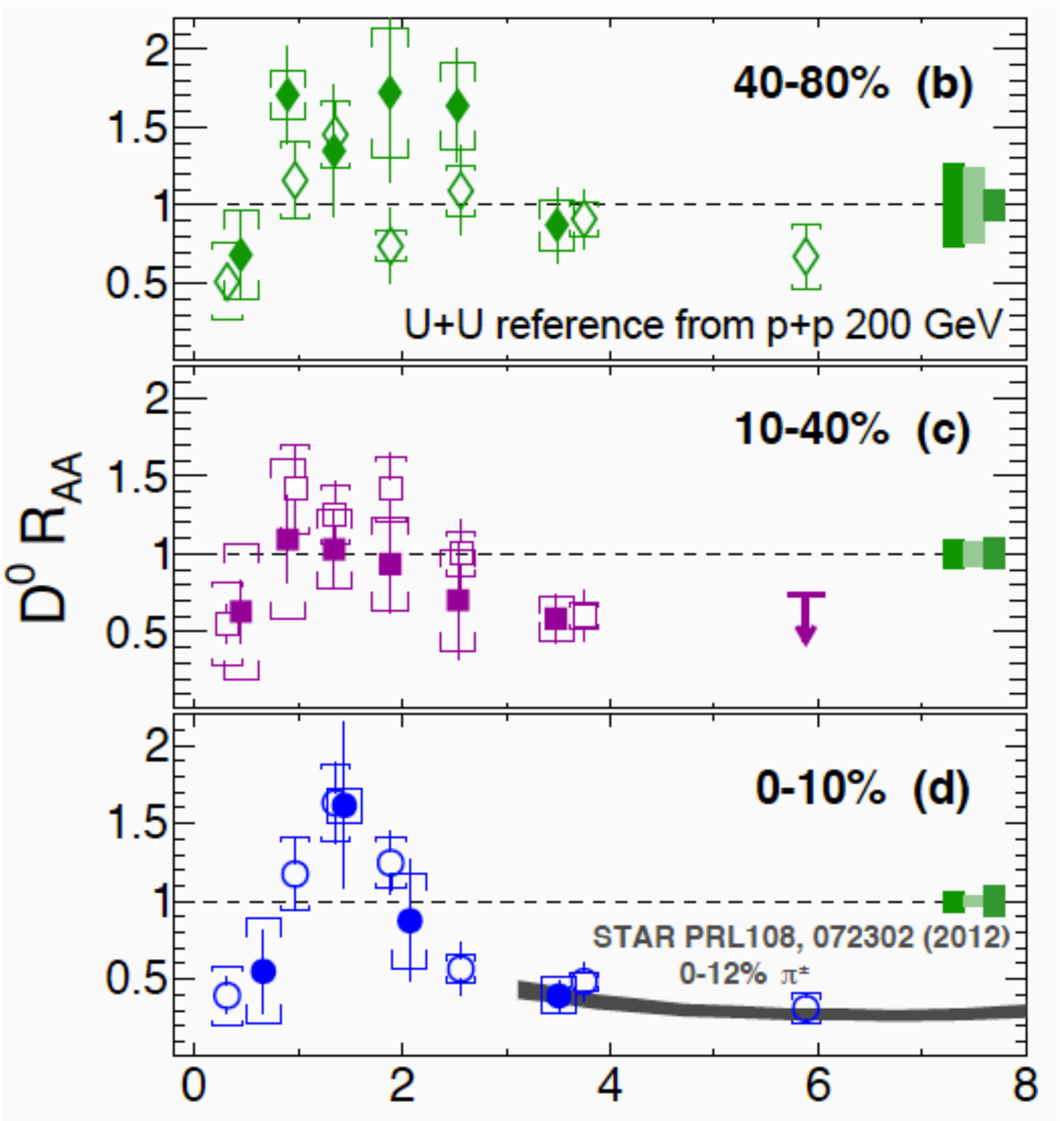
Conclusions

- Large array of heavy flavour measurements at RHIC and LHC
  - **different energies and collision systems**
  - p(d)-A is the system to study **CNM effects**, but also different x regimes and possible collective effects on heavy flavours
- Open charm/beauty strongly affected by the medium
  - from RHIC to LHC: **similar suppression at high p_T**, enhancement at low p_T at RHIC
  - **mass dependence** of suppression trends in agreement with models
  - **positive v_2** suggests collective motion for c quarks at low p_T at RHIC and LHC
- Next: more precise measurements to sharpen the conclusions
  - RHIC, LHC: **new detectors and future upgrades**
  - Smaller uncertainties, new differential measurements will help to **further constrain theory** (and add information on path-length dependence of energy loss, energy loss mechanisms, thermalization, hadronization, …)

U+U at RHIC

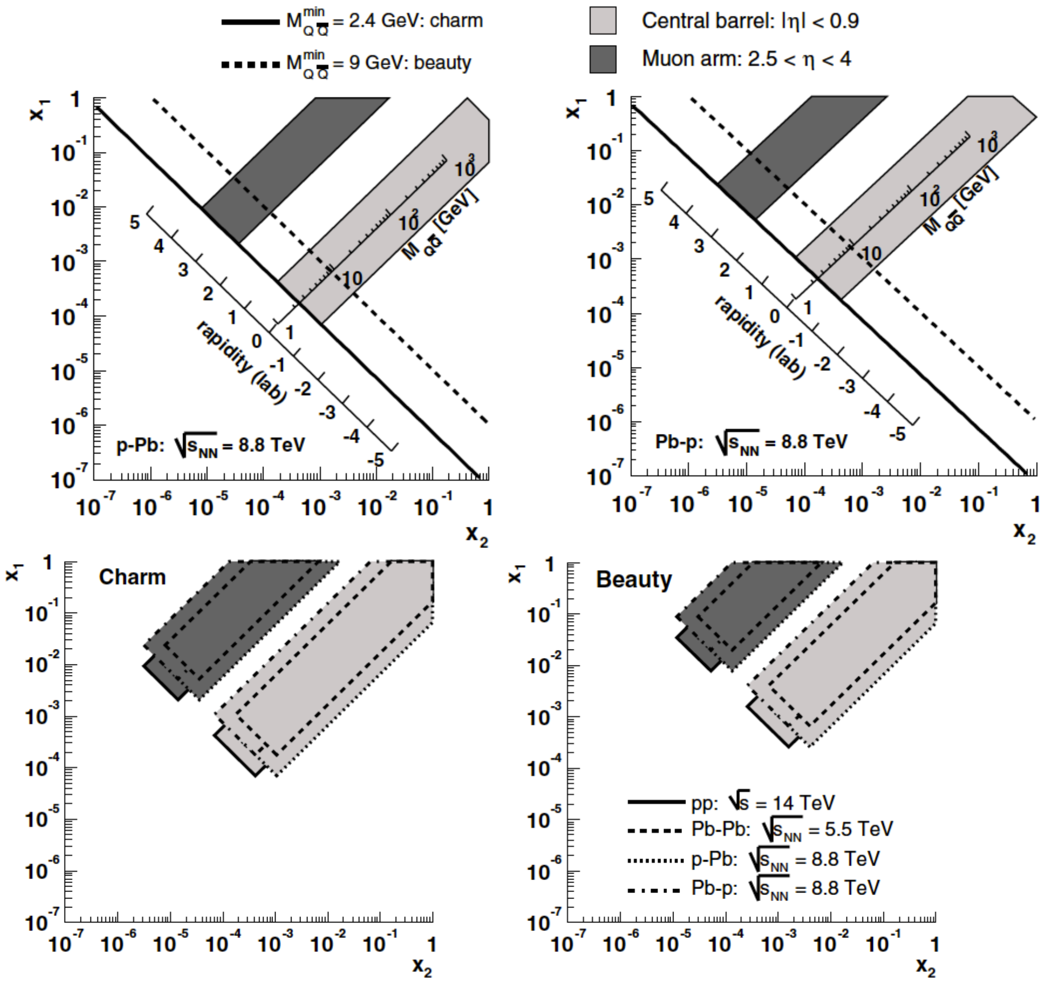


$\varepsilon_B^{UU}/\varepsilon_B^{AuAu}$
Kikola, Odyniec, Vogt, PRC 84, 054907 (2011)
Masui, Mohanty, Xu, PLB 679, 440 (2009)
Centrality [%]



40-80% (b)
U+U reference from p+p 200 GeV
10-40% (c)
0-10% (d)
STAR PRL108, 072302 (2012)
0-12% $\pi^{\pm}$
D^0 R_{AA}

x regimes at the LHC



ALICE Coll.,
J. Phys. G: Nucl. Part. Phys. 32 (2006) 1295–2040

$$x_1 = \frac{A_1}{Z_1} \cdot \frac{M_{Q\overline{Q}}}{\sqrt{s_{pp}}} \exp\left(+y_{Q\overline{Q}}\right)$$

$$x_2 = \frac{A_2}{Z_2} \cdot \frac{M_{Q\overline{Q}}}{\sqrt{s_{pp}}} \exp\left(-y_{Q\overline{Q}}\right)$$

The LHC Probes Smallest x So Far Available

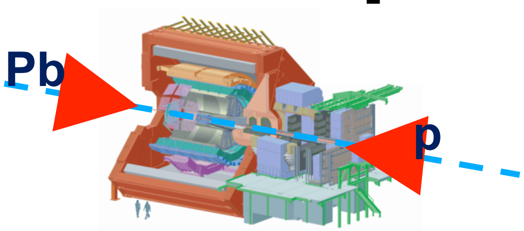
High energy pp and AA colliders probe successively smaller fractional momenta, x, of q, $\bar{q}$ and g for perturbative probes such as dijets, lepton pairs, gauge bosons or quarkonium produced at scale Q

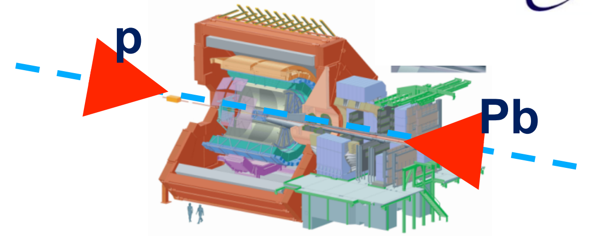
$$x_1 = \frac{Q}{\sqrt{s_{NN}}}\exp(y) \quad \text{“projectile”}$$

$$x_2 = \frac{Q}{\sqrt{s_{NN}}}\exp(-y) \quad \text{“target”}$$

At the LHC, $|y| \leq 8.6 - 9.6$, depending on $\sqrt{s_{NN}}$

HF in pA: different rapidities at LHC

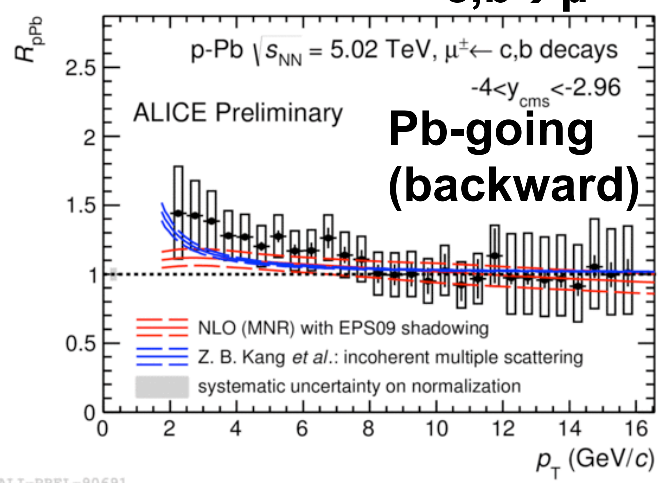




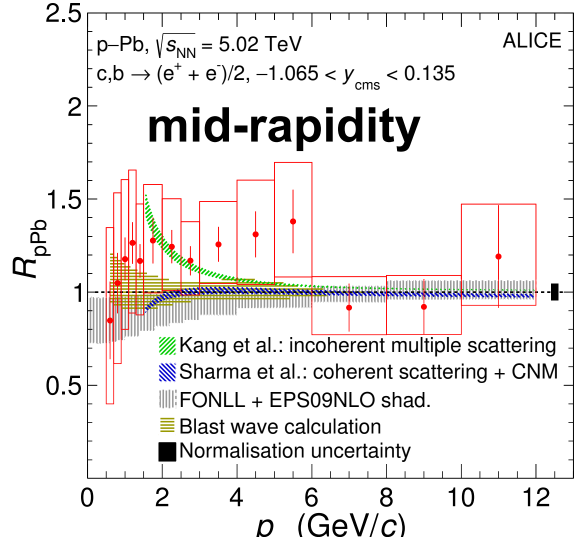
$-4.46<y_{CMS}<-2.96$

$10^{-2}<x<5\cdot10^{-2}$

c,b→μ



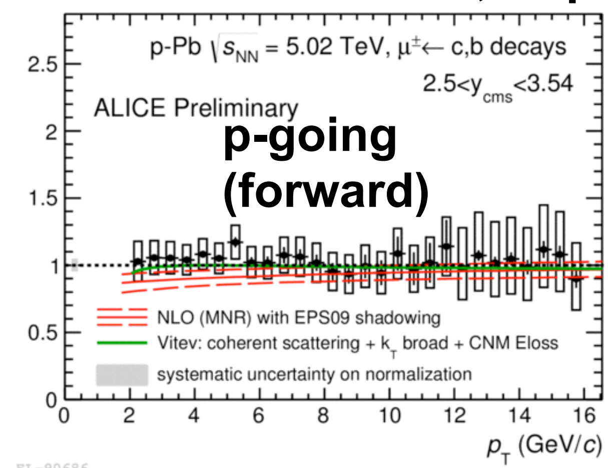
c,b→e



$2.03<y_{CMS}<3.53$

$10^{-5}<x<8\cdot10^{-5}$

c,b→μ



M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009) 065
R. Sharma, I. Vitev et al., PRC 80 (2009) 054902
Z.B. Kang et al., PLB 740 (2015) 23

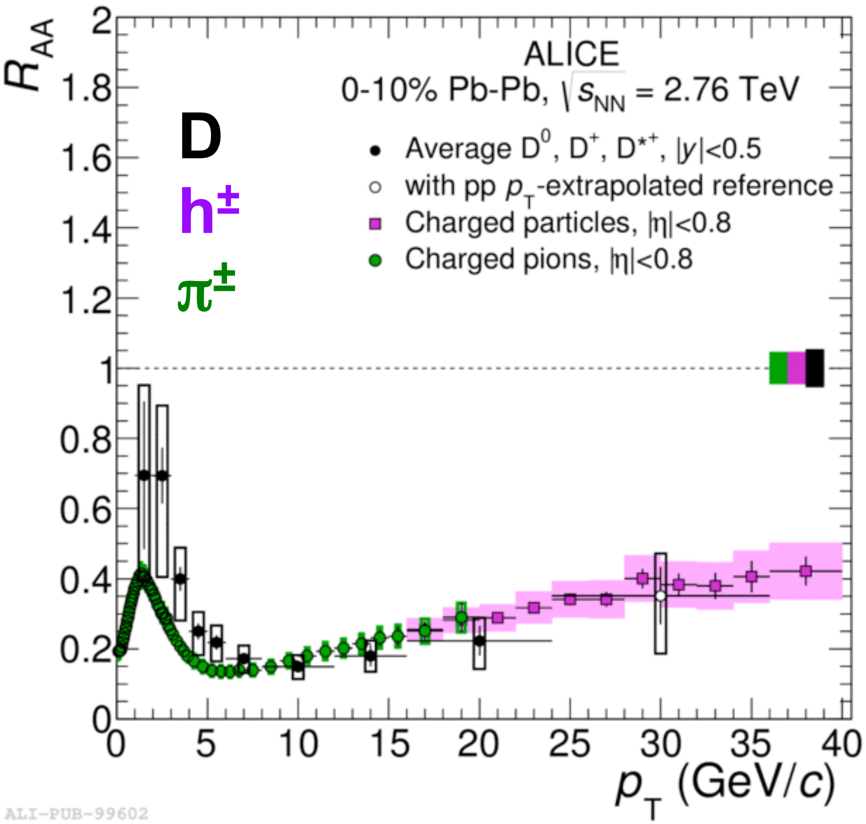
Phys. Lett. B 754 (2016) 81

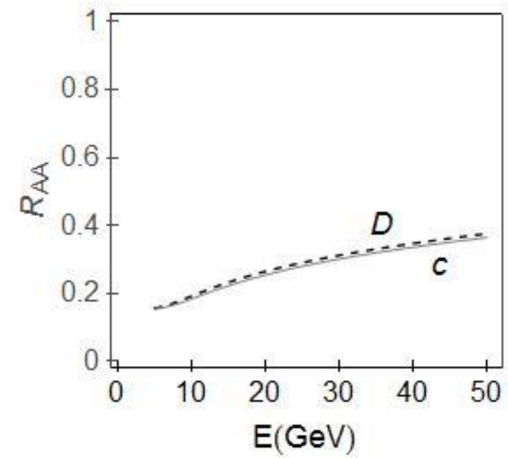
Different *x* regimes explored in different rapidity ranges with HF probes
→shadowing/saturation relevant at low p_T at the LHC

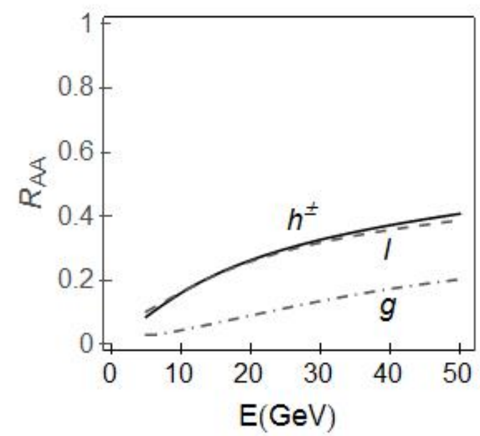
Data described within uncertainties by the models with CNM effects

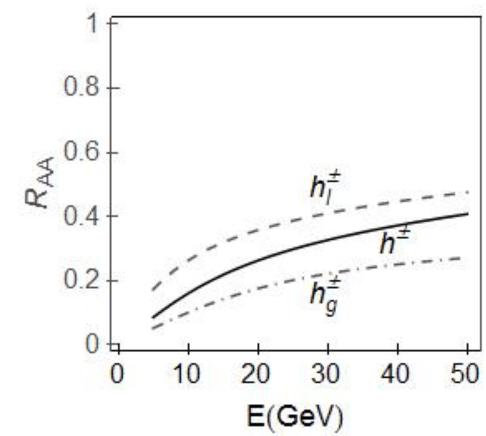
R_{AA}: D mesons and charged hadrons

Mass dependence of energy loss?









M.Djordjevic, PRL 112, 042302 (2014)

R_{AA}(D)~R_{AA}(π,h±)

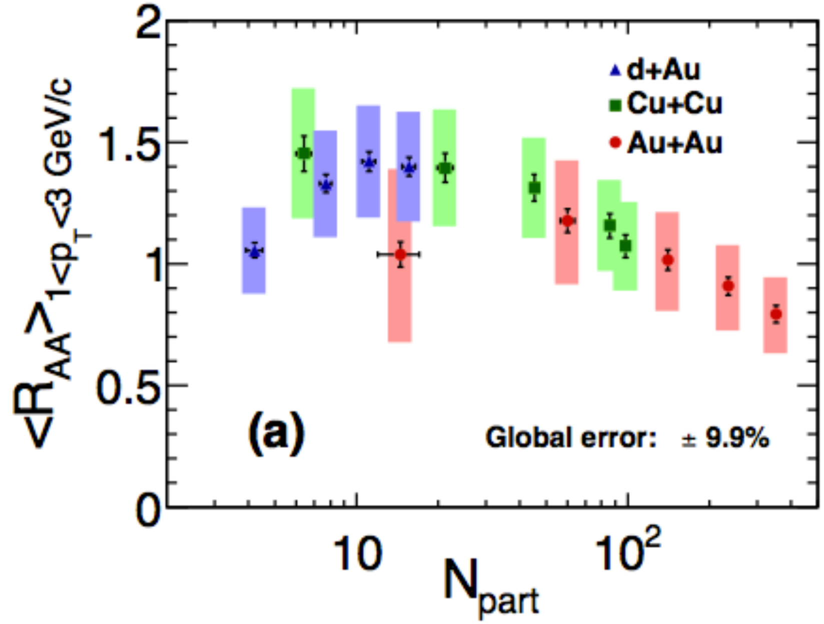
What about ΔE(udsg)>ΔE(c) → R_{AA}(D)>R_{AA}(π,h±) ?

→Different quark spectra

→R_{AA}(h) affected by fragmentation

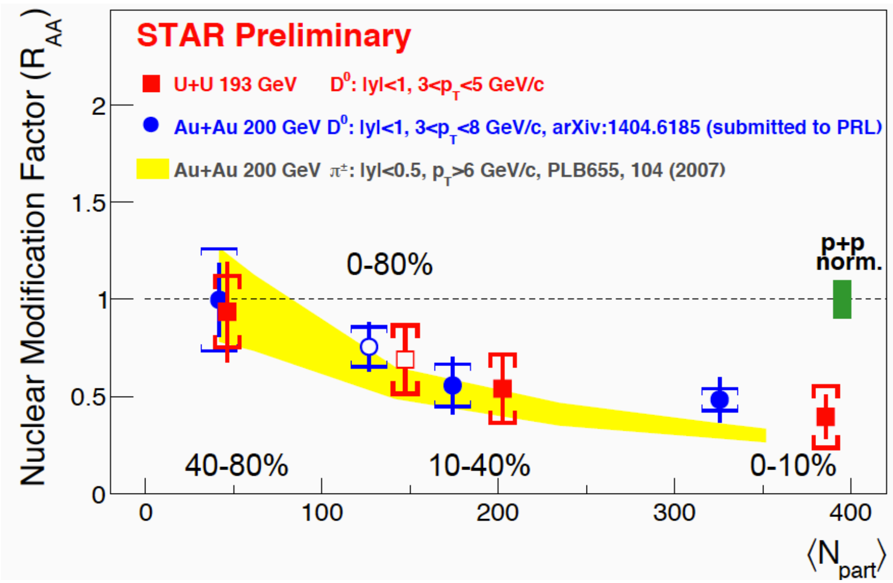
System size dependence of R_{AA} at RHIC

electrons from heavy-flavour decays



PHENIX, PRC 90 (2014) 034903

D^0



STAR, PRL 113 (2014) 142301

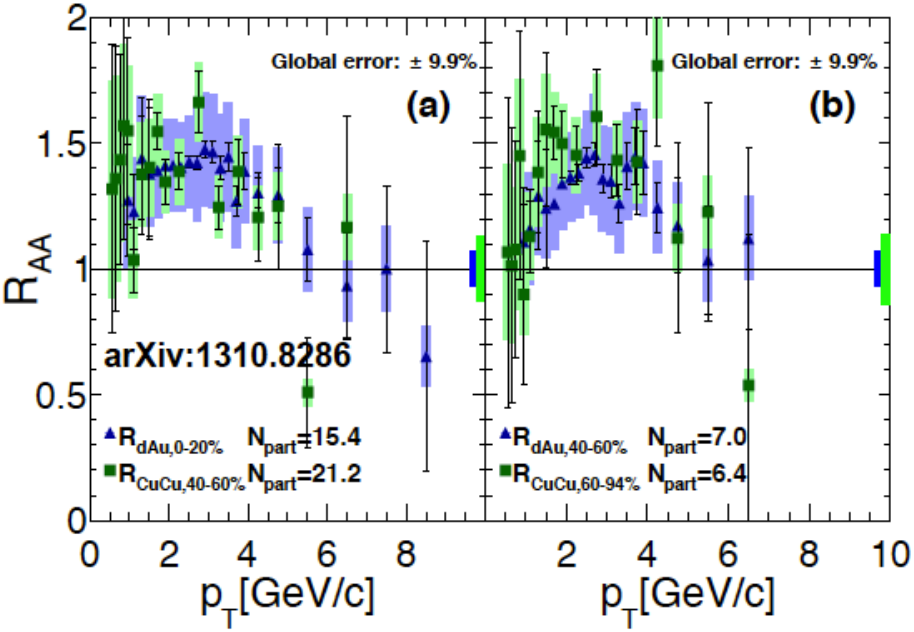
From **d+Au** to **peripheral Cu+Cu**: enhancement effects dominating

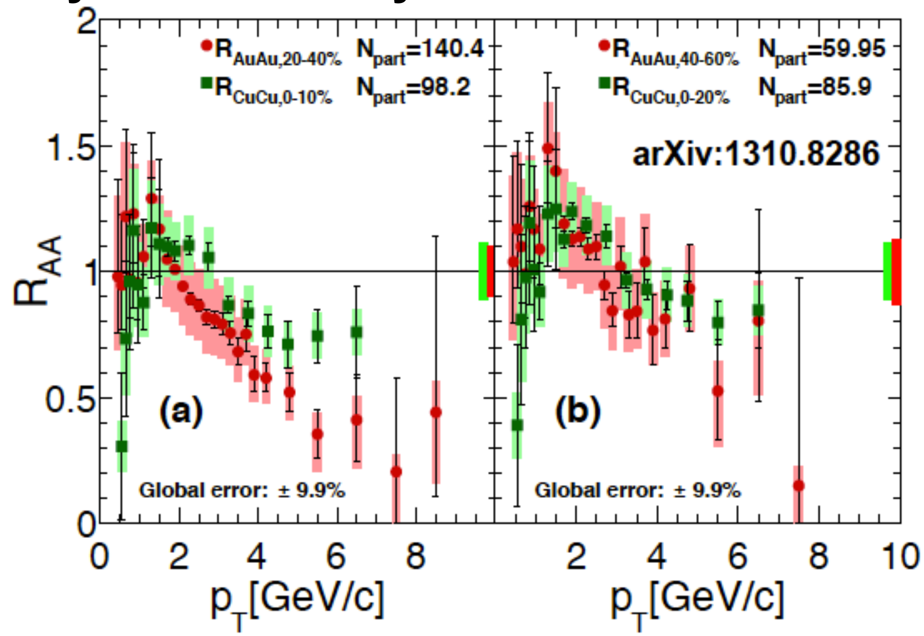
From **Cu+Cu** to **central Au+Au**: suppression dominating

U+U: could have 20% higher energy density than Au+Au
similar D^0 suppression as for Au+Au, extends the trend

System size dependence of R_{AA} at RHIC

electrons from heavy-flavour decays



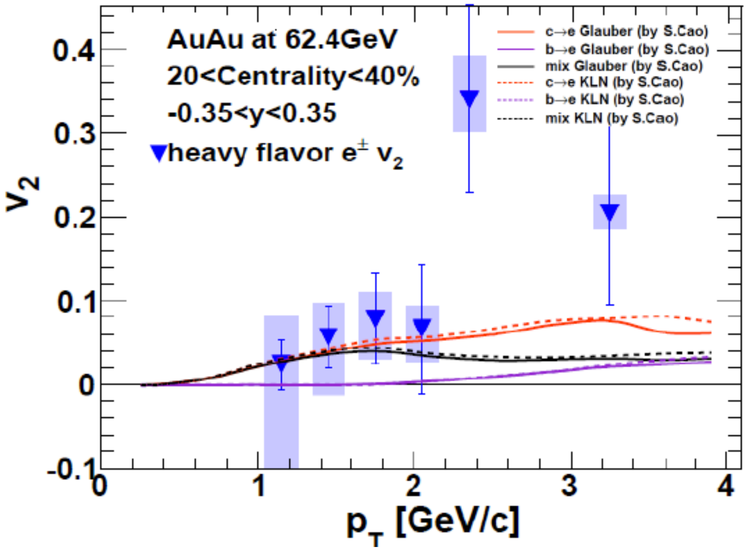


PHENIX, Phys.Rev. C90 (2014) 034903

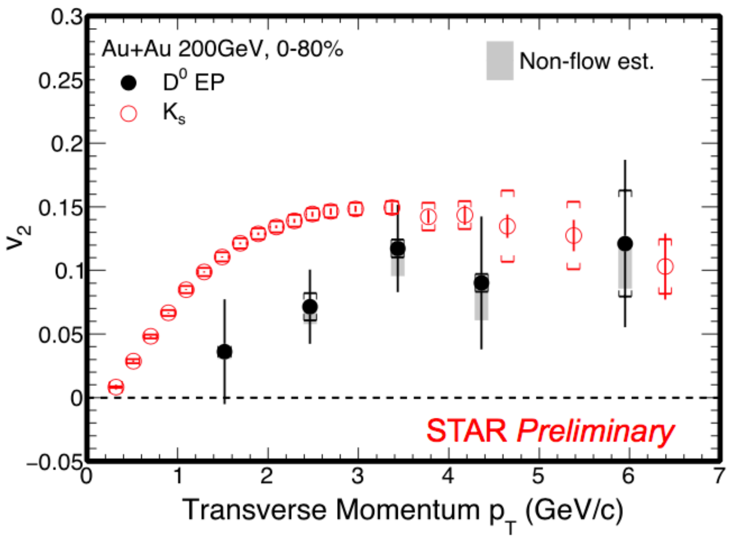
CENTRAL d+Au ~ PERIPHERAL Cu+Cu

CENTRAL Cu+Cu ~ MID Au+Au

Charm collective motion at RHIC

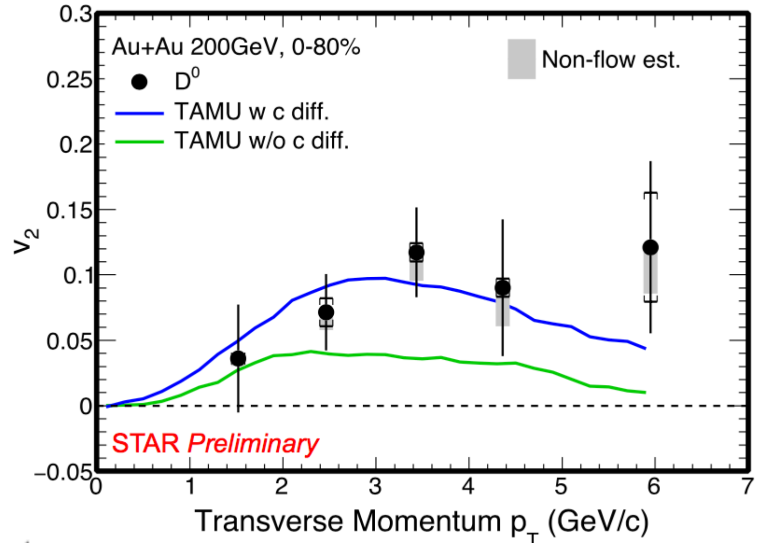


PHENIX, PRC(2015) 044907



Charm v_2 at low energy (62 GeV):

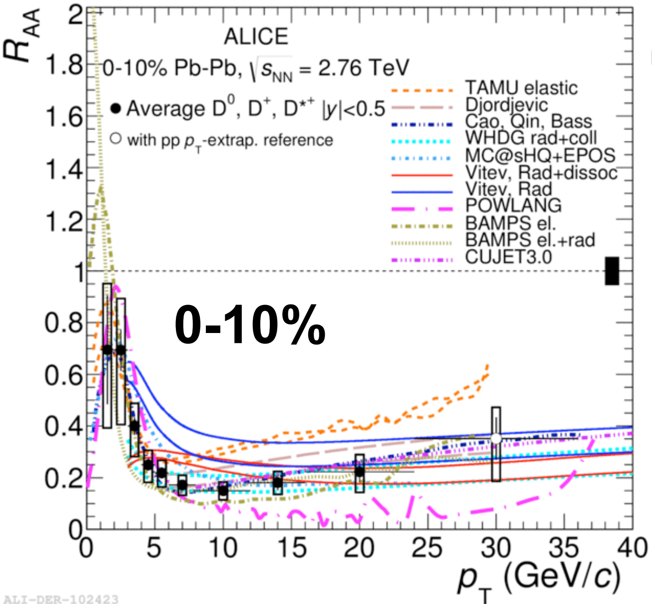
is flowing? is recombination with light quarks?

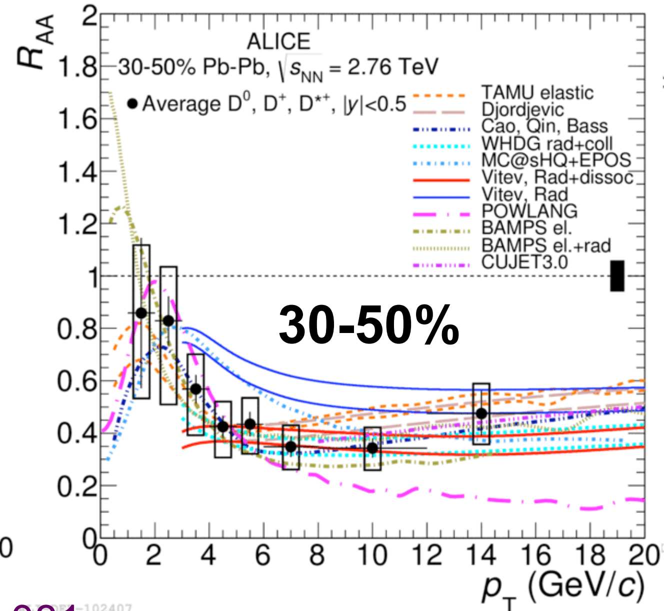


D^0 v_2>0 for p_T>2 GeV/c

- Data favour model including charm quark diffusion in the medium
- Systematically below light-hadron v_2

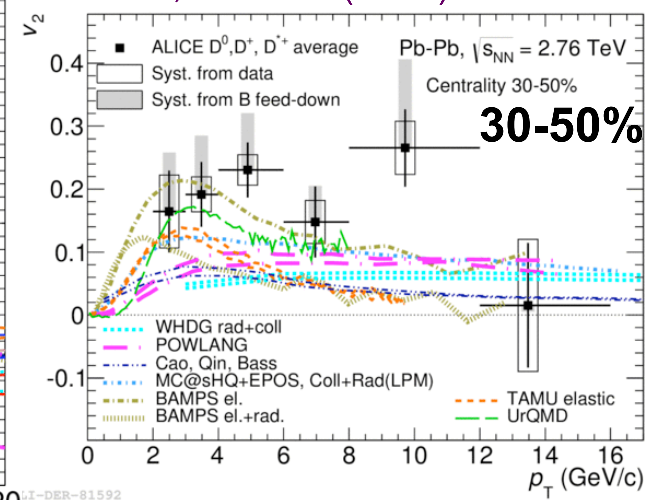
R_{AA} and v_2: constraints to models





ALICE, JHEP1603 (2016) 081

ALICE, PRL 111 (2013) 102301



R_{AA} and v_2 results start to provide constraints to models.

Simultaneous description of heavy-flavour R_{AA} and v_2 still challenging.

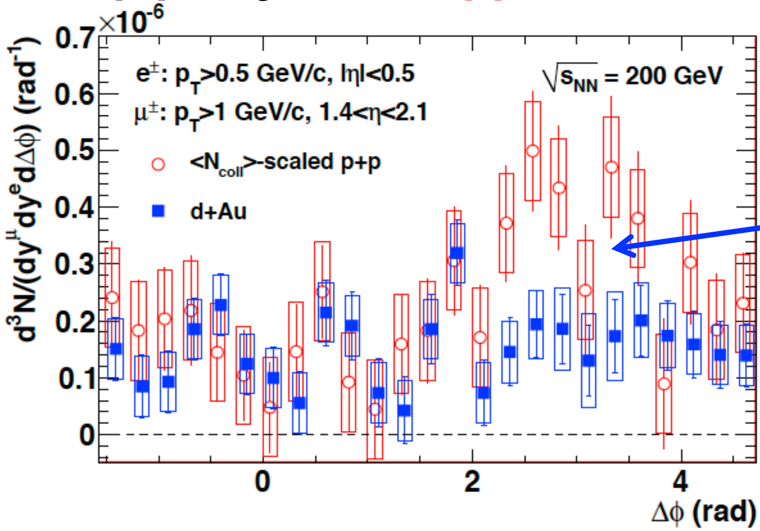
More precise measurements needed to further constrain models

BAMPS: Fochler et al., J. Phys. G38 (2011) 124152
POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666
UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph];
T. Lang et al., arXiv:1212.0696 [hep-ph].
TAMU: Rapp, He et al., Phys. Rev. C 86 (2012) 014903
WHDG: Horowitz et al., JPhys G38 (2011) 124114
Aichelin et al.:Phys. Rev. C79 (2009) 044906
J. Phys. G37 (2010) 094019

HF electron-muon correlations at RHIC

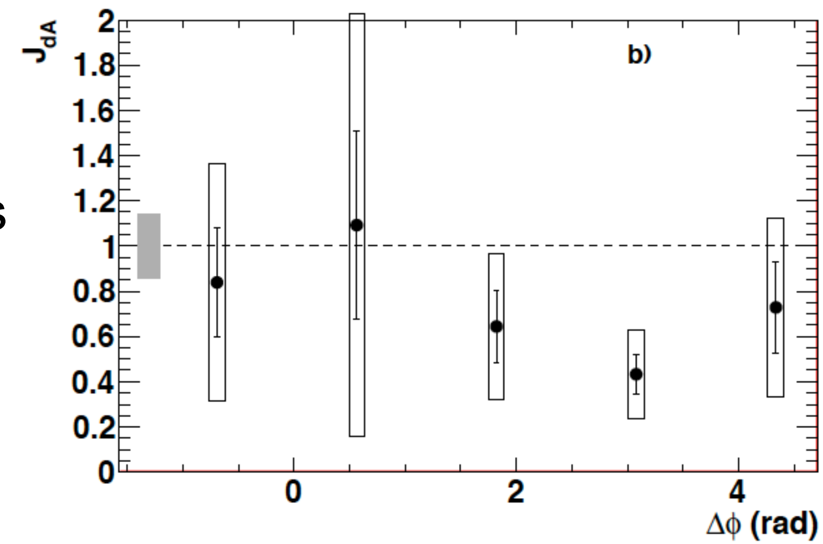
PHENIX: e-μ correlations
- mid-rapidity electrons (from HF) –
- forward-rapidity muons (from HF)

e-μ pair yields in pp and d+Au



peak at π is suppressed in **d+Au** compared to **pp**

$$J_{dA} = \frac{d + \text{Au pair yield}}{\langle N_{\text{coll}} \rangle\ p+p \text{ pair yield}}.$$



Suppression in d+Au:

cold nuclear matter modification of $c\bar{c}$ pairs

(low-x gluons dominating the away side and suffering more shadowing? initial/final state effects ?)

PHENIX, PRC (2014) 034915