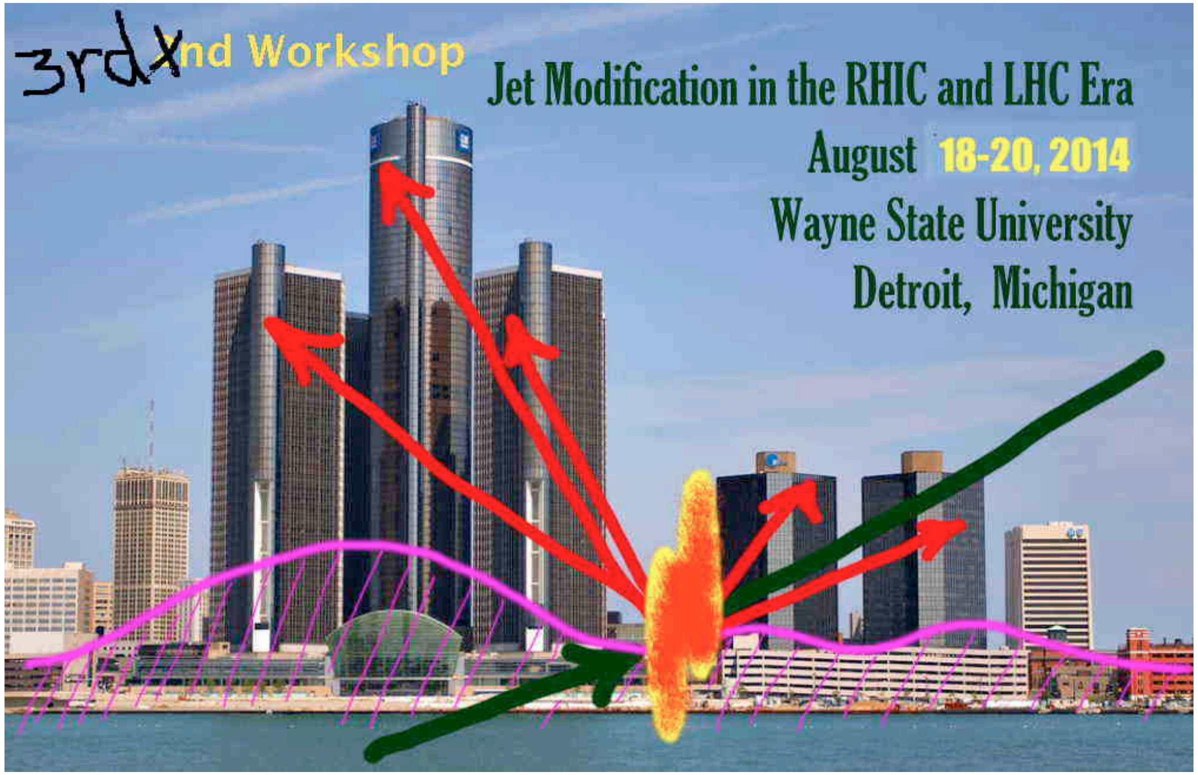
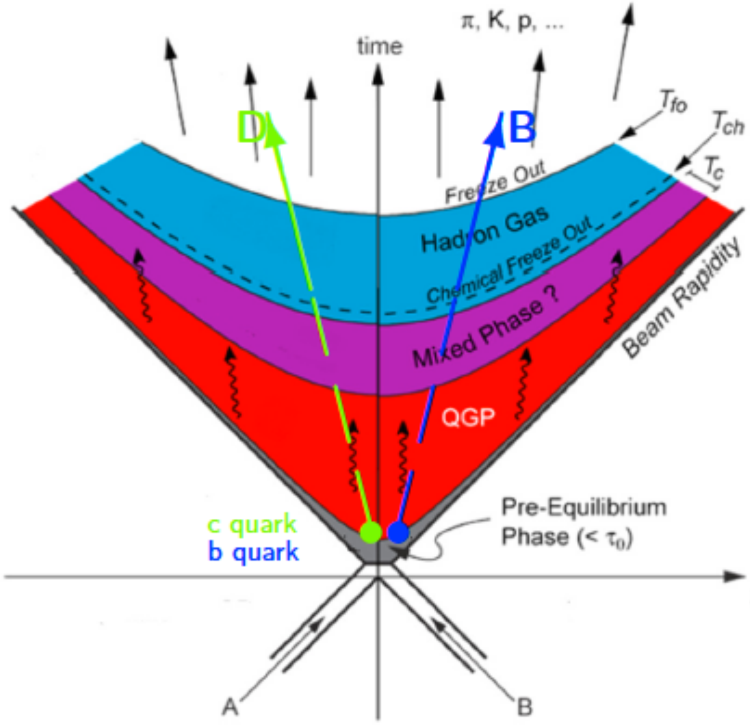


Heavy-flavour and quarkonium production at RHIC and LHC.

Elena Bruna (INFN Torino)

Open heavy-flavours

- tomographic probes of the QGP -



Why Heavy Flavours (charm and beauty)?

Heavy quarks are produced in initial high-Q^2 processes

JHEP 07 (2012) 191
arXiv:1405.4144v1

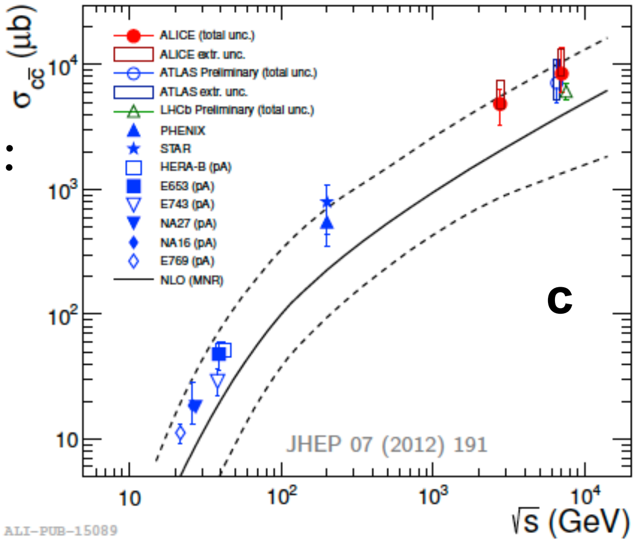
- pp: test for pQCD

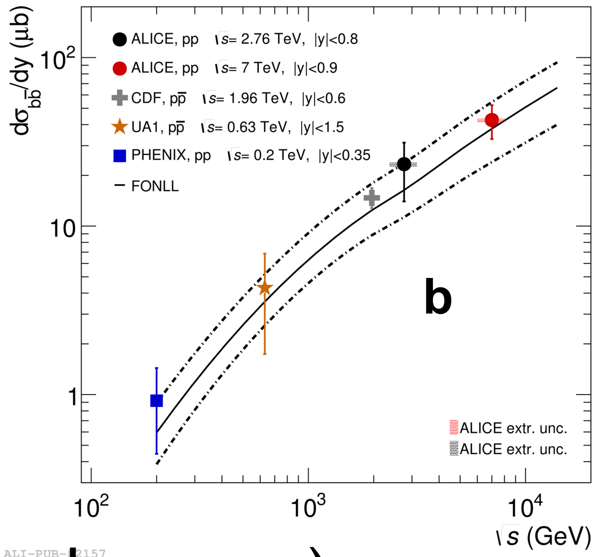
  At LHC, larger cross-section:

  σ_c(LHC)~5-10 σ_c(RHIC)

  σ_b(LHC)~ 50 σ_b(RHIC)

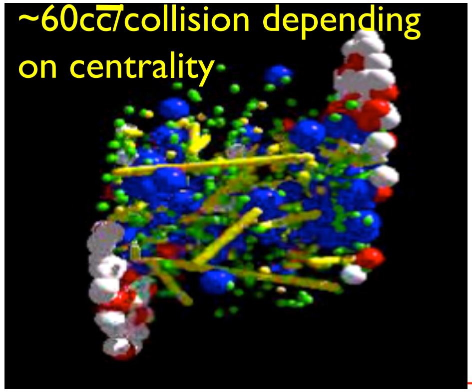
  Reference for pA and AA





- pPb: reference for cold nuclear matter effects (and more…)
- PbPb: "self-generated" probes exposed to the medium evolution.

  Thermal production negligible?



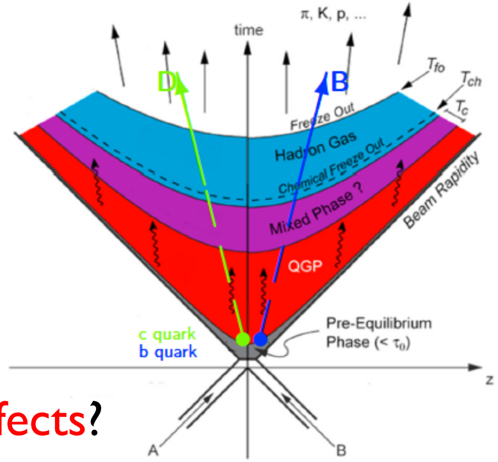
~60$c\bar{c}$/collision depending on centrality

Questions:

How do partons interact with the medium?

How does the energy loss depend on path-length, medium density, parton mass?

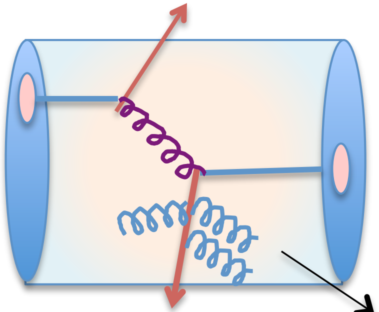
How to disentangle cold from hot nuclear state effects?



Heavy Flavours and Heavy-Ion Collisions

- How do partons interact with the medium?
  - Energy loss mechanism via:

    radiative gluon emission and elastic collisions



energy loss in
the medium

- What does the energy loss depend on?
  - Medium density, path-length
  - Colour-charge, Mass ("dead-cone")

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

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

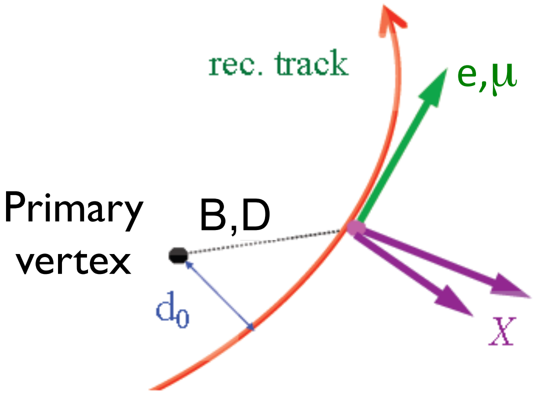
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

- Do heavy flavours participate in collective motion?
  - at low p_T, this gives information on the transport properties of the medium

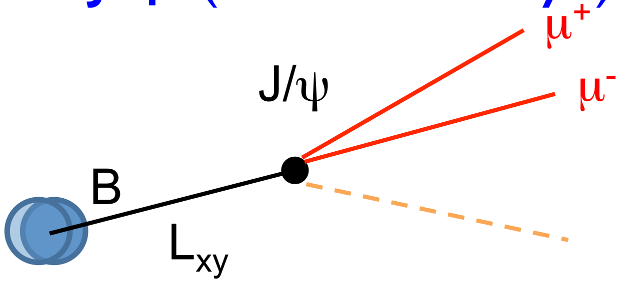
- How to disentangle cold and dense hot nuclear matter effects?
  - PbPb collisions: nuclear matter under extreme conditions of temperature/energy density. From Lattice QCD the phase transition occurs at: $T_c \sim 170$ MeV, $\varepsilon_c \sim 0.6$ GeV/fm^3, these conditions are reached at RHIC and the LHC
  - pPb collisions: control experiment used as reference

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

Semi-leptonic decays (charm,beauty)



Displaced J/ψ (from B decays)



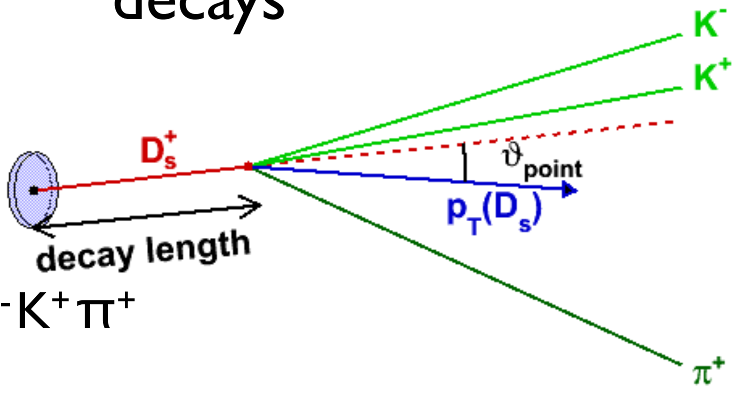
Full reconstruction of D meson hadronic decays

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

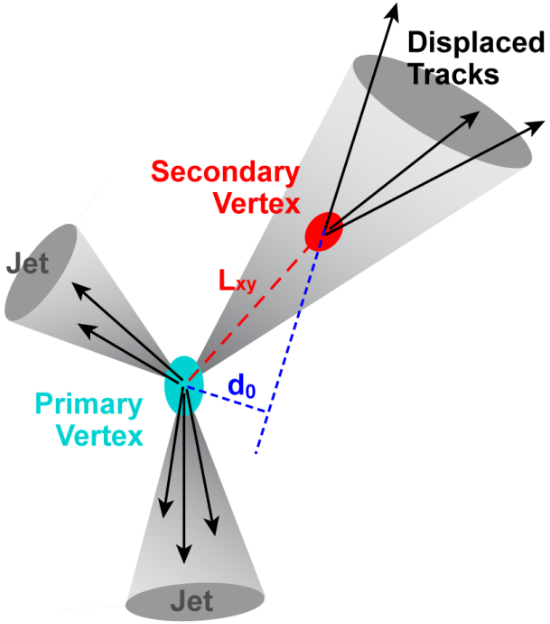
$D^+ \rightarrow K^-\pi^+\pi^+$

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

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

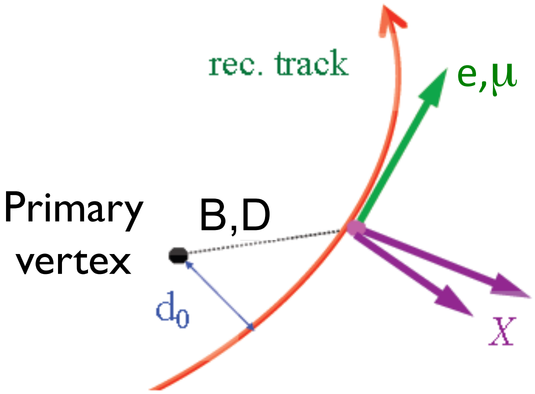


Jet b-tagging

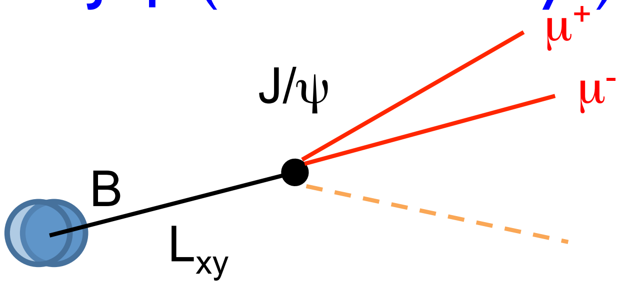


Measurements of Heavy Flavours at RHIC and LHC in A-A (and pp)

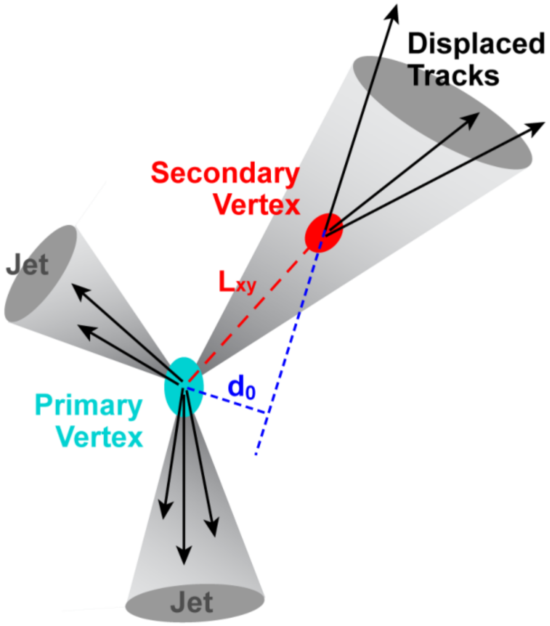
Semi-leptonic decays (charm,beauty)



Displaced J/ψ (from B decays)



Jet b-tagging



Full reconstruction of beauty decays: **B** and **Λ_b** hadrons (**pp**: ATLAS/CMS,LHCb)

$\Lambda_b \rightarrow J/\psi\ \Lambda$

$B^+ \rightarrow J/\psi\ K^+$, $J/\psi\ K\pi$

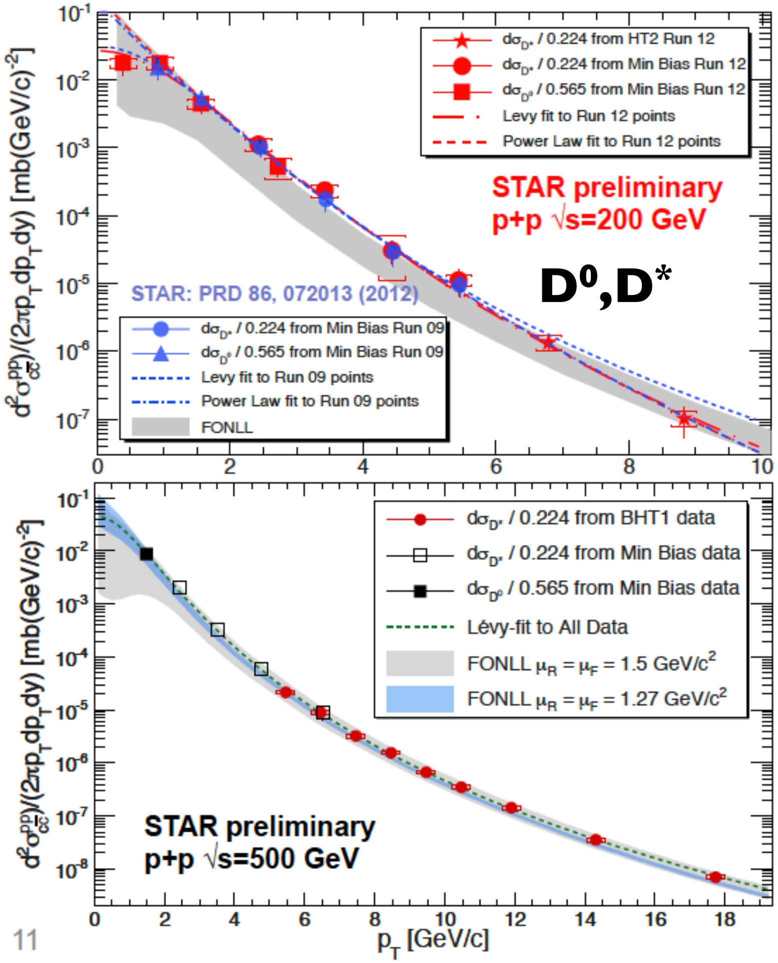
$B^0 \rightarrow J/\psi\ K^0_s$

$B_s^0 \rightarrow J/\psi\ \phi$

pPb (CMS) : $B \rightarrow J/\psi\ K, \pi$

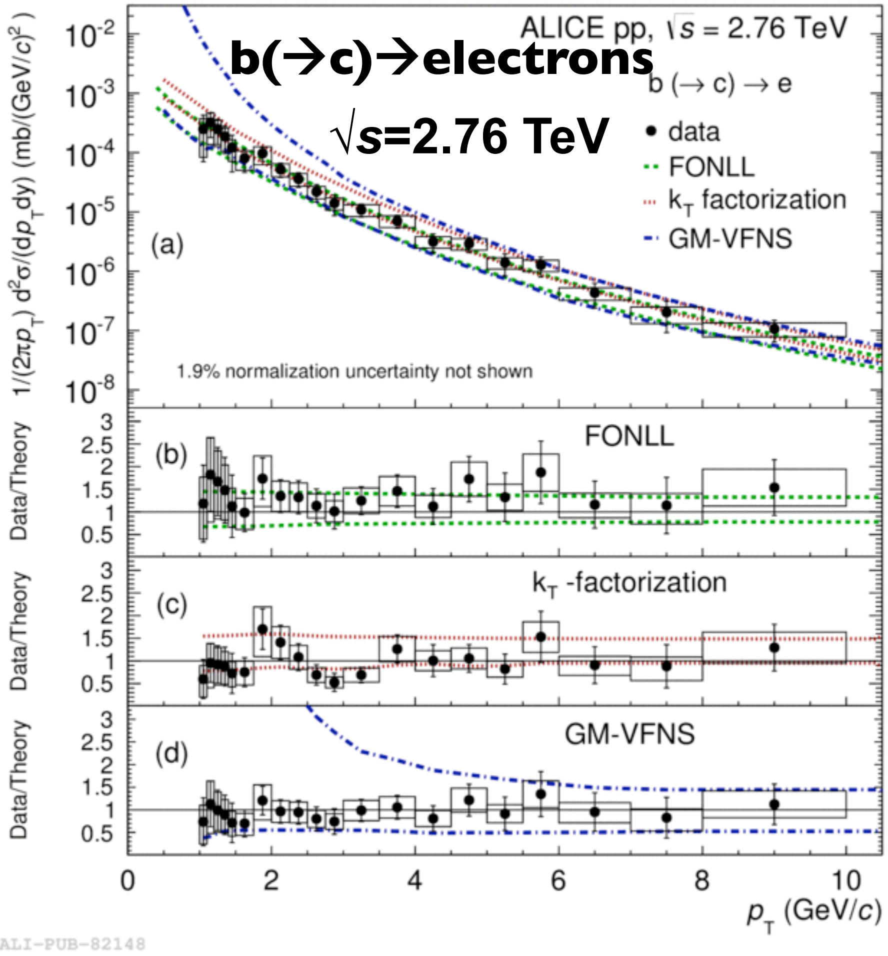
same technique as for D mesons based on displaced vertex topologies

pp: Test for pQCD and reference for pA and AA



D^0,D*

STAR Coll., PRD 86 (2012) 072013



b(→c)→electrons

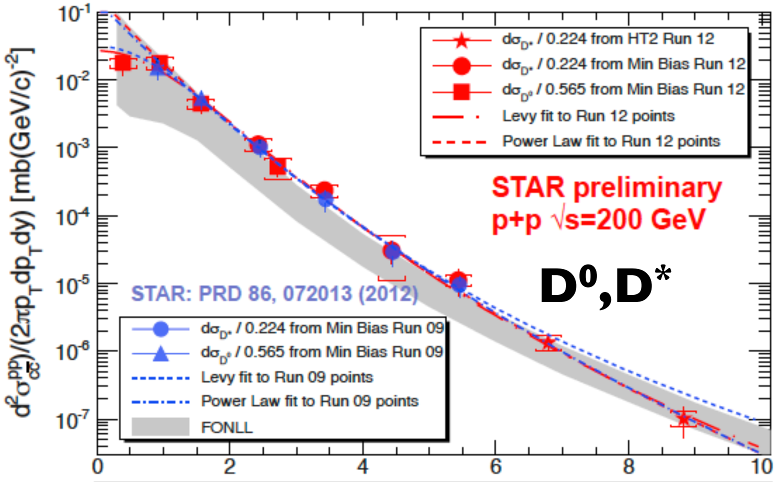
√s=2.76 TeV

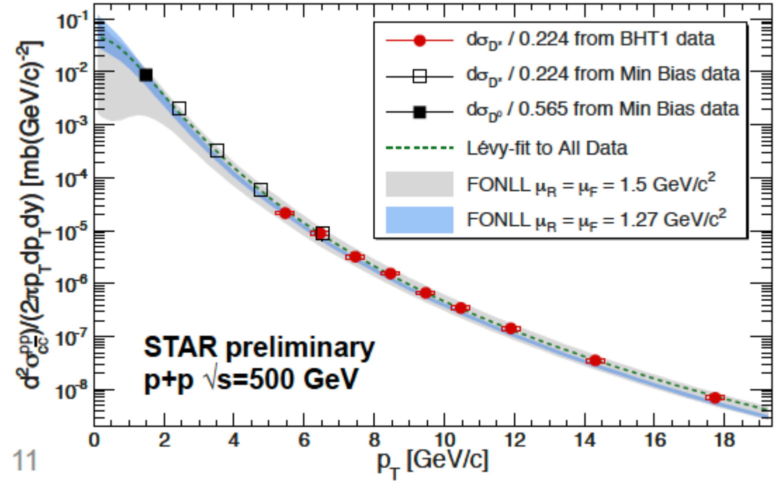
ALICE Coll., arXiv:1405.4117v1

GM-VFNS: Eur.Phys.J., C72(2012)2082
Nucl. Phys. B, 872(2013) 253
k_T factorization: Phys.Rev., D87(2013)094022

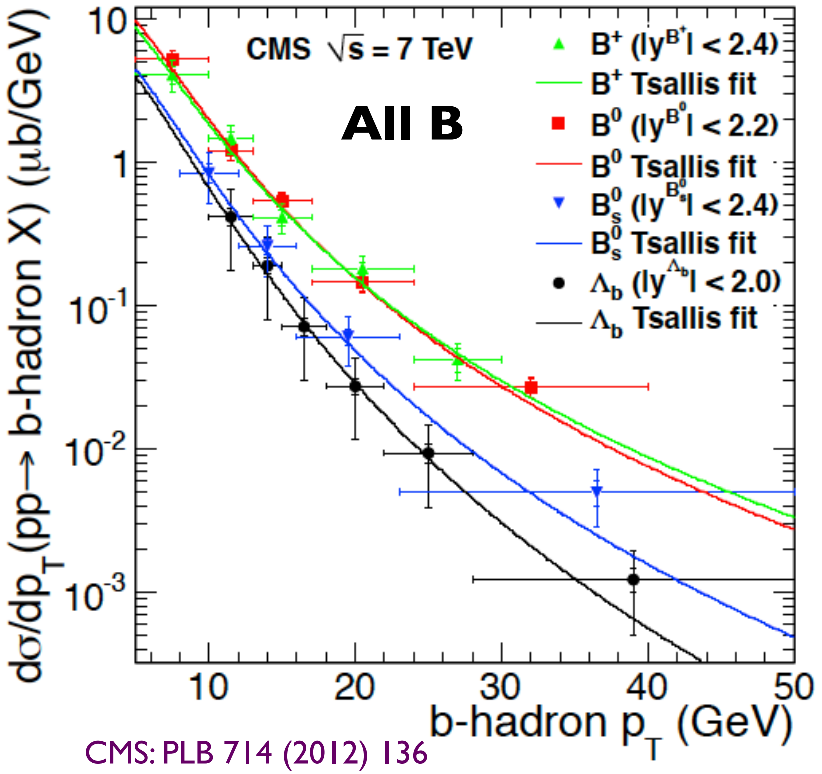
Cross sections at both RHIC and LHC energies well described by pQCD predictions

pp: Test for pQCD and reference for pA and AA





STAR Coll., PRD 86 (2012) 072013

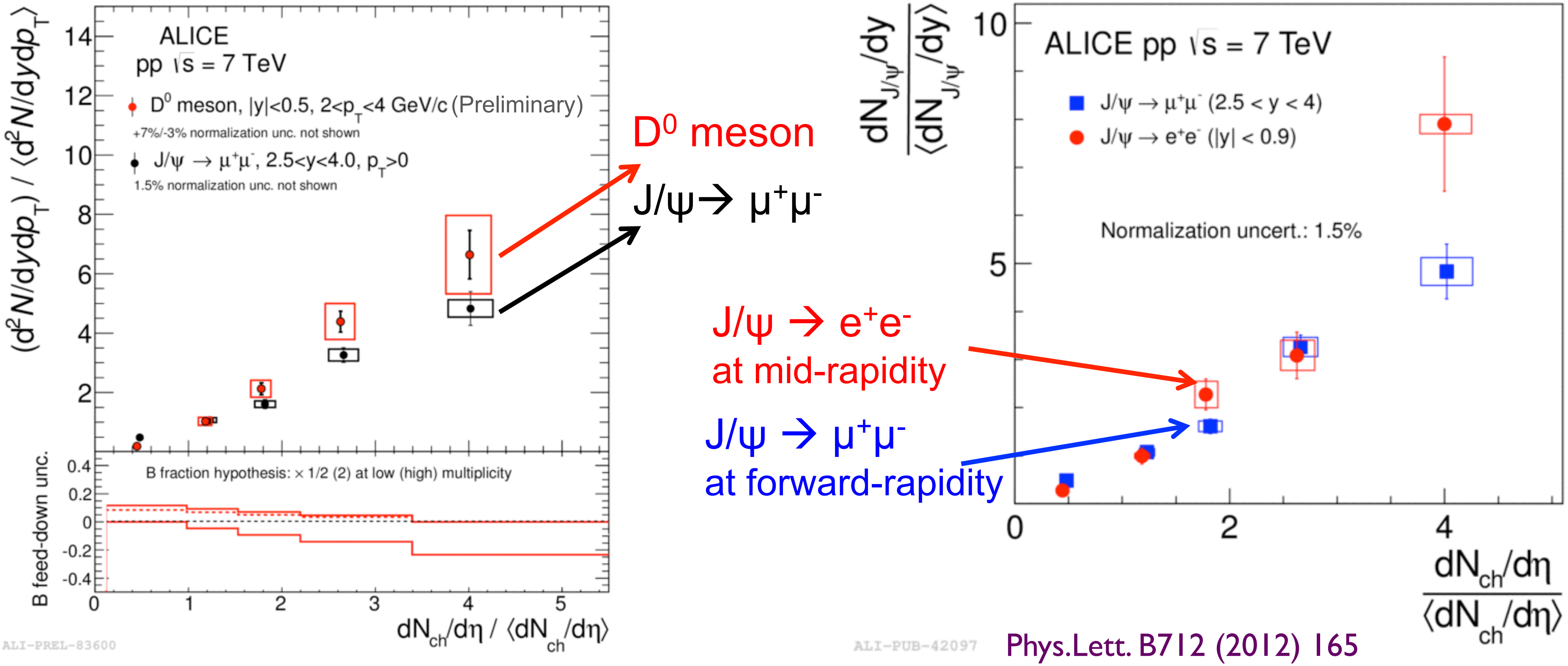


CMS: PLB 714 (2012) 136

ATLAS: arXiv: 1207.2284

pp: D-meson and J/ψ yields vs event multiplicity

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



D^0 meson

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

$J/\psi \rightarrow e^+e^-$ at mid-rapidity

$J/\psi \rightarrow \mu^+\mu^-$ at forward-rapidity

Phys.Lett. B712 (2012) 165

Caveat: different rapidity and p_T intervals for D and J/ψ measurements

More on Υ in the next slides…
CMS Coll., JHEP 04 (2014) 103

Increasing trend with multiplicity for both D mesons and J/ψ in pp collisions
→ MPI are dominating the high-multiplicity events and affecting heavy-flavour production

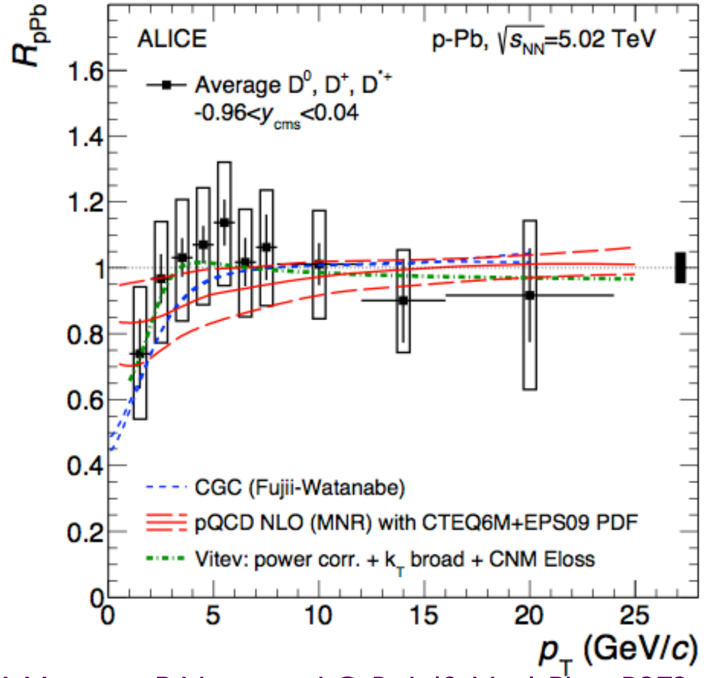
pA: control experiment (and more…)

$$R_{pPb} = \frac{(d\sigma/dp_T)_{pPb}}{A \times (d\sigma/dp_T)_{pp}}$$

Mid-rapidity - LHC

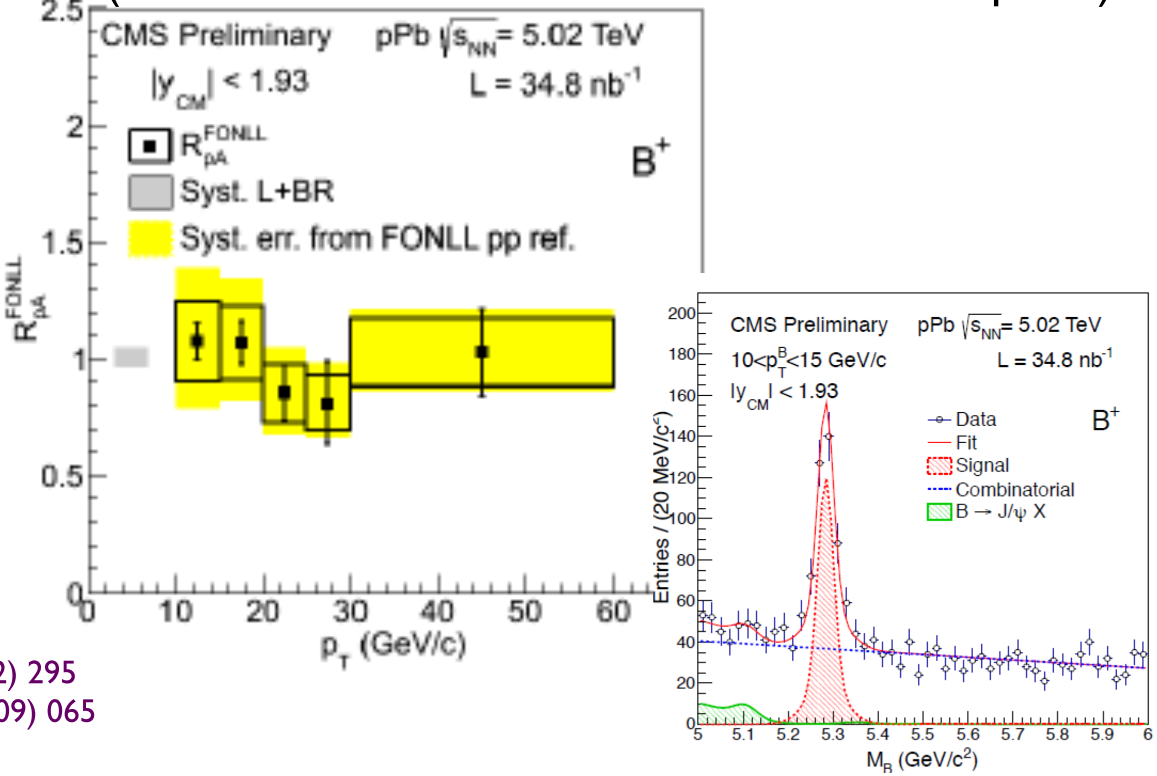
D mesons

ALICE Coll., arXiv:1405.3452



B mesons

(exclusive reconstruction for first time in p-Pb)



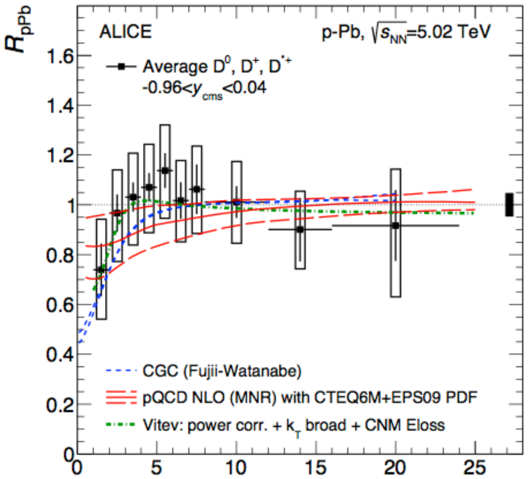
M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009) 065
R. Sharma, I. Vitev, B. Zhang, Phys. Rev. C 80 (2009) 054902
Fujii - Watanabe, private communication

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

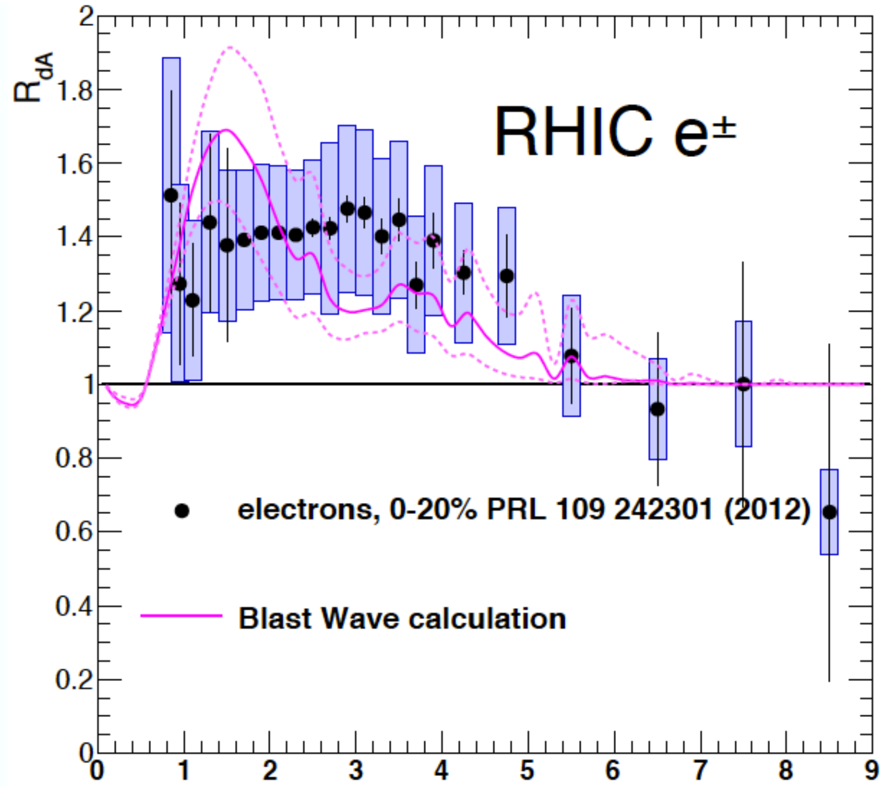
pA: control experiment (and more…)

$$R_{pPb} = \frac{(d\sigma/dp_T)_{pPb}}{A \times (d\sigma/dp_T)_{pp}}$$

Mid-rapidity - RHIC



ALICE Coll., arXiv:1405.3452



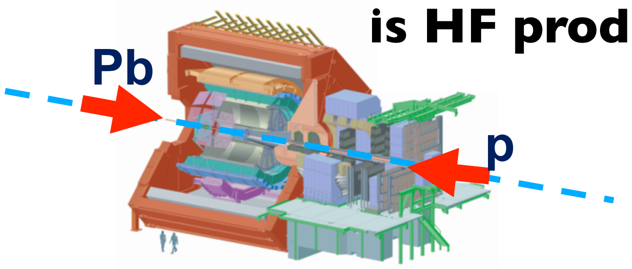
PHENIX Coll., PRL 109 (2012) 242301

RHIC: R_{dAu}>1 for electrons from heavy-flavours at low p_T. Compatible with radial flow?

LHC: smaller effect could be due to harder initial spectrum

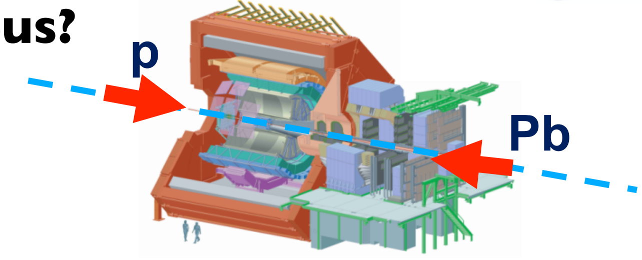
pA: control experiment (and more…)

is HF production affected by the nucleus?

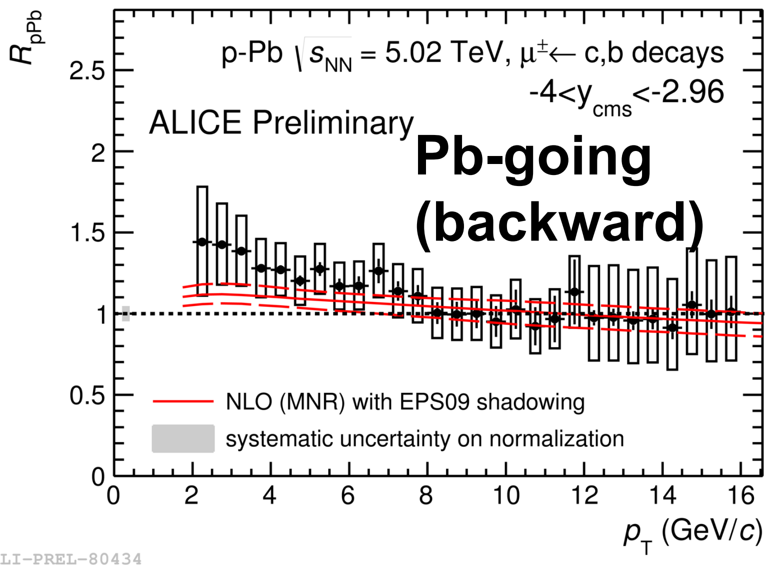


$-4.46<y_{\mathrm{CMS}}<-2.96$
$10^{-2}<x<5\cdot10^{-2}$

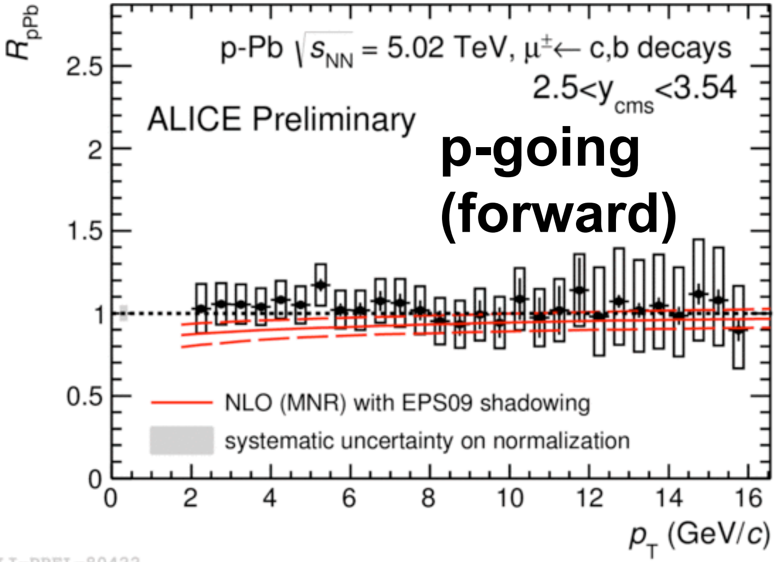
Forward and backward rapidity at the LHC



$2.03<y_{\mathrm{CMS}}<3.53$
$10^{-5}<x<8\cdot10^{-5}$



ALI-PREL-80434



ALI-PREL-80422

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

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

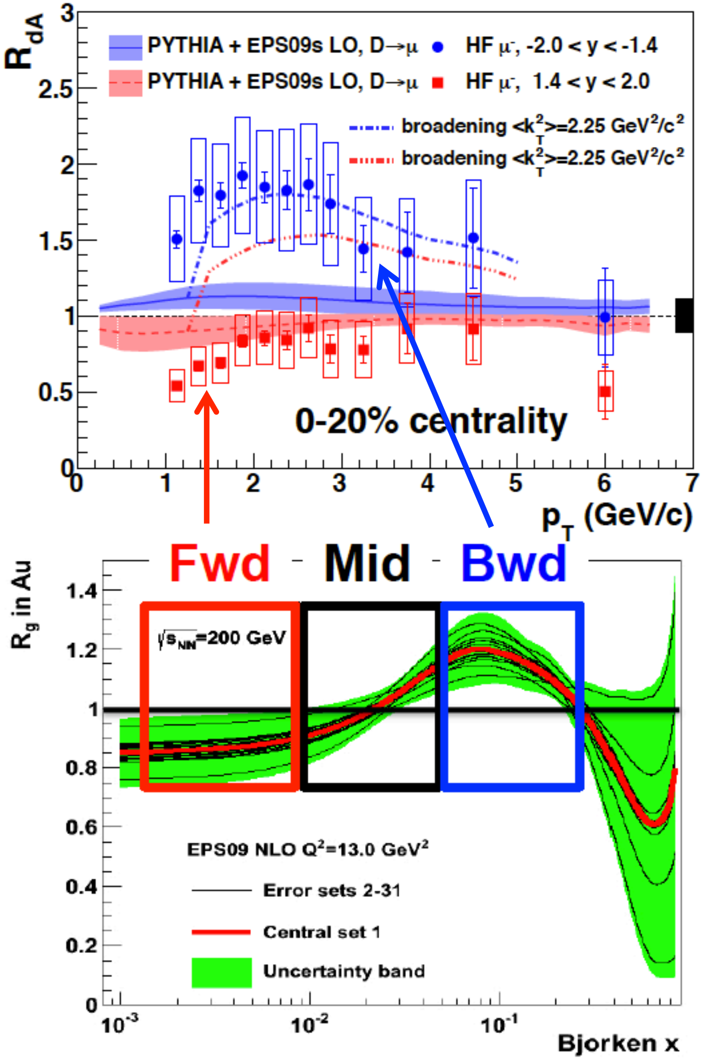
Data described within uncertainties by different models of initial state effects

pA: control experiment (and more...)

is HF production affected by the nucleus?

Forward and backward rapidity at RHIC

PHENIX Coll., arXiv:1310.1005



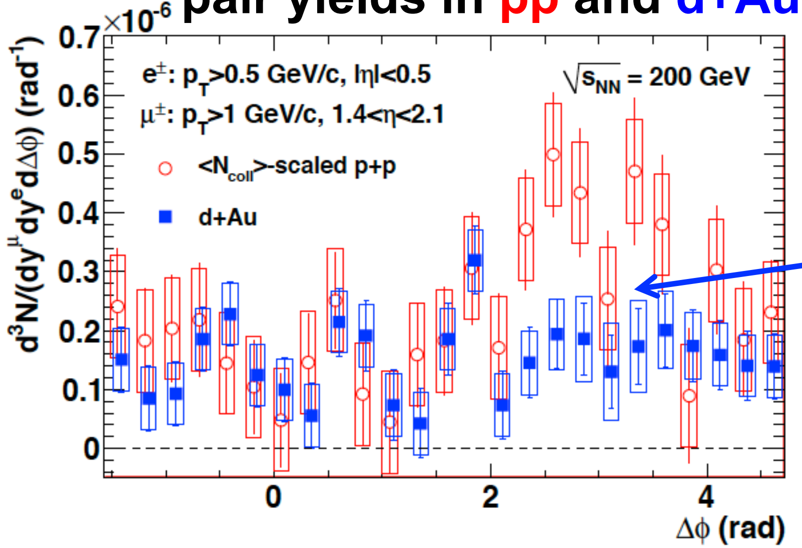
Models based on different initial-state effects fail to reproduce d+Au data at both forward and backward rapidities at RHIC energies

pA: more differential measurements

PHENIX: e-μ correlations

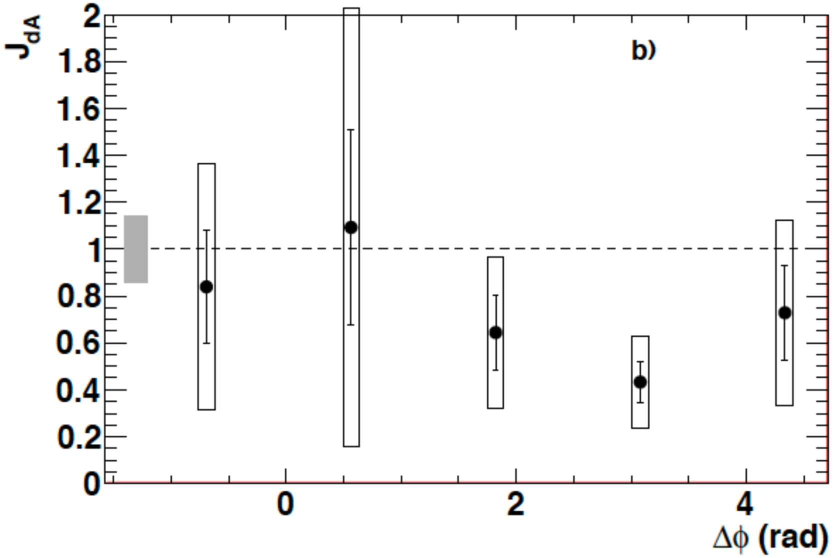
mid-rapidity electrons (from HF) – forward-rapidity muons (from HF)

pair yields in pp and d+Au



peak at π is suppressed in d+Au compared to p+p

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



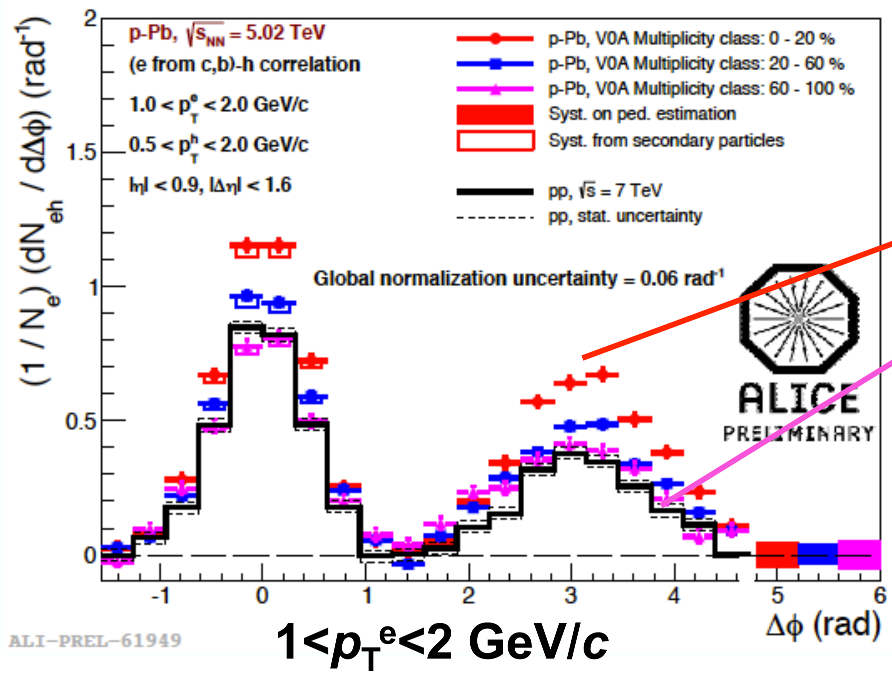
Suppression in d+Au:

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 Coll.: arXiv:1311.1427v1

pA: more differential measurements



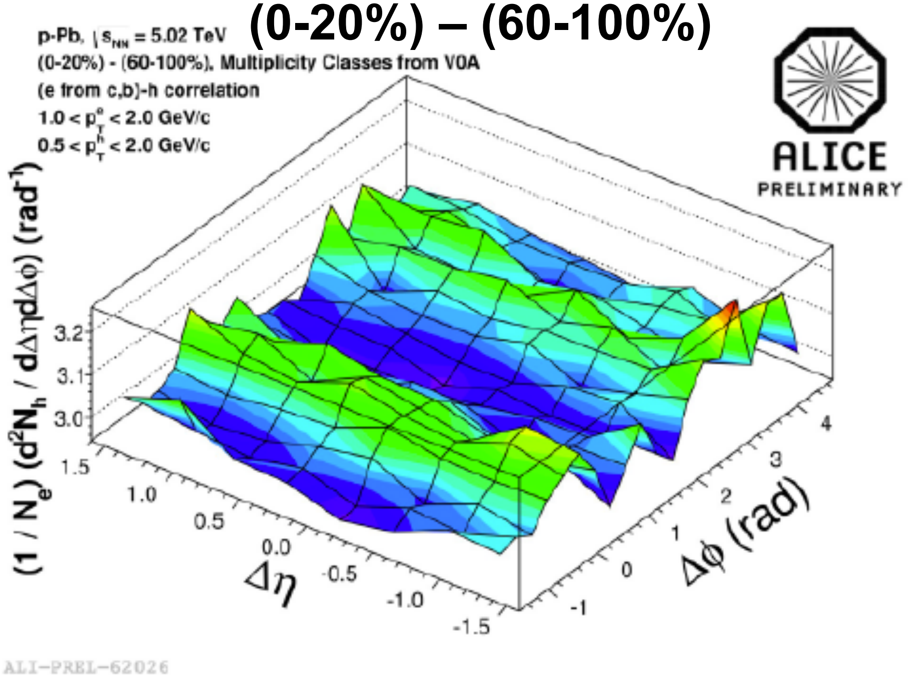
$1<p_T^e<2$ GeV/*c*

ALICE: e-h correlations

p-Pb collisions in two multiplicity ranges:
0-20% (high multiplicity)
60-100% (low multiplicity)

Jet contribution reduced by subtracting low-multiplicity events

(0-20%) – (60-100%)



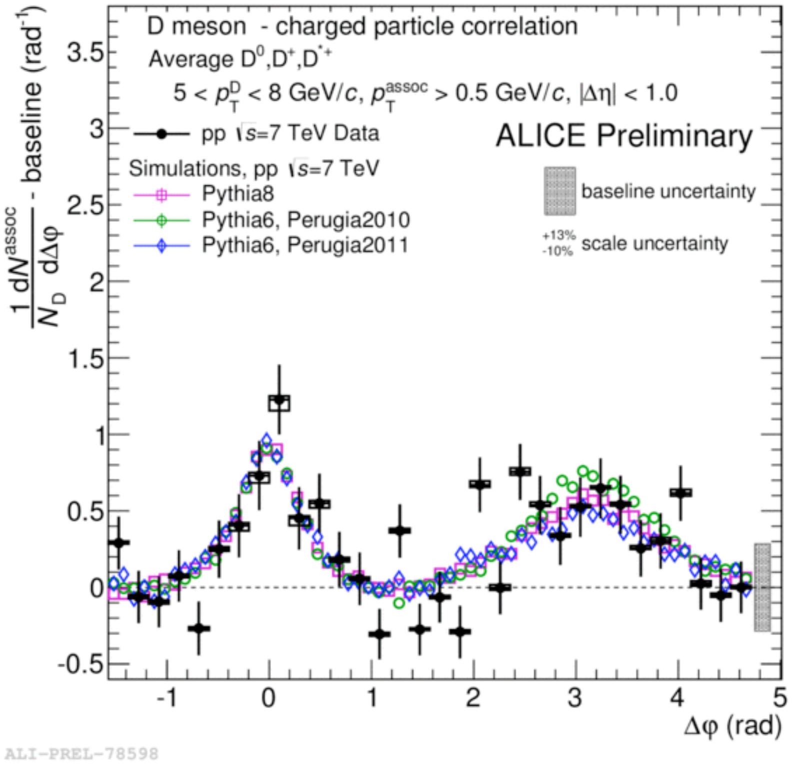
Indications for long-range correlations in Δη for two-particle correlations triggered by heavy-flavour decay electrons.

Similar to what was observed for light particles. Same mechanism (CGC/hydro) for light and heavy flavours?

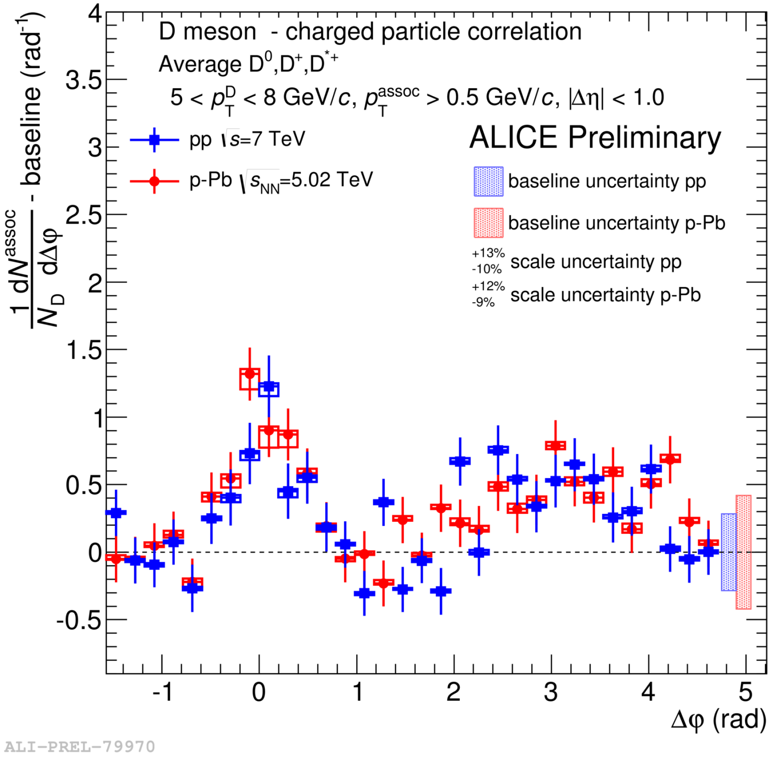
B. Arbuzov et al, Eur.Phys.J. C71 (2011) 1730
K. Dusling and R. Venugopalan, arXiv:1302.7018.
S. Alderweireldt and P. Van Mechelen, arXiv:1203.2048
K. Werner et al, P.R.L. 106 (2011) 122004

pp and pPb: D-h correlations

pp: 5<p_T^D<8 GeV/*c*, p_T^{assoc}>0.5 GeV/*c*



pp&pPb: 5<p_T^D<8 GeV/*c*, p_T^{assoc}>0.5 GeV/*c*

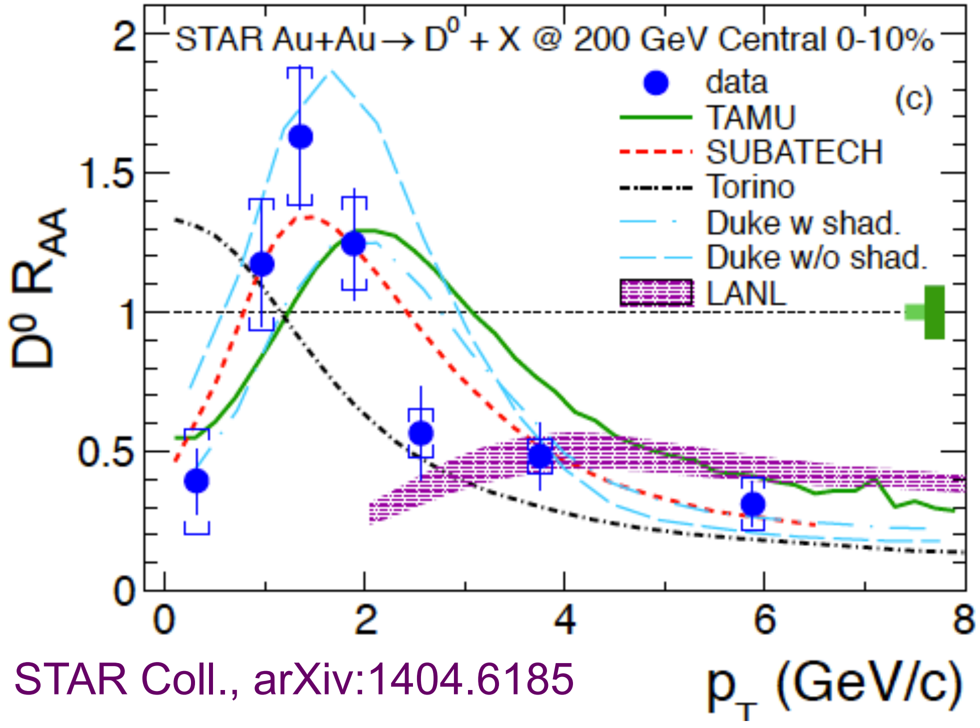


pp: compatible within uncertainties with expectations from different Pythia tunes

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

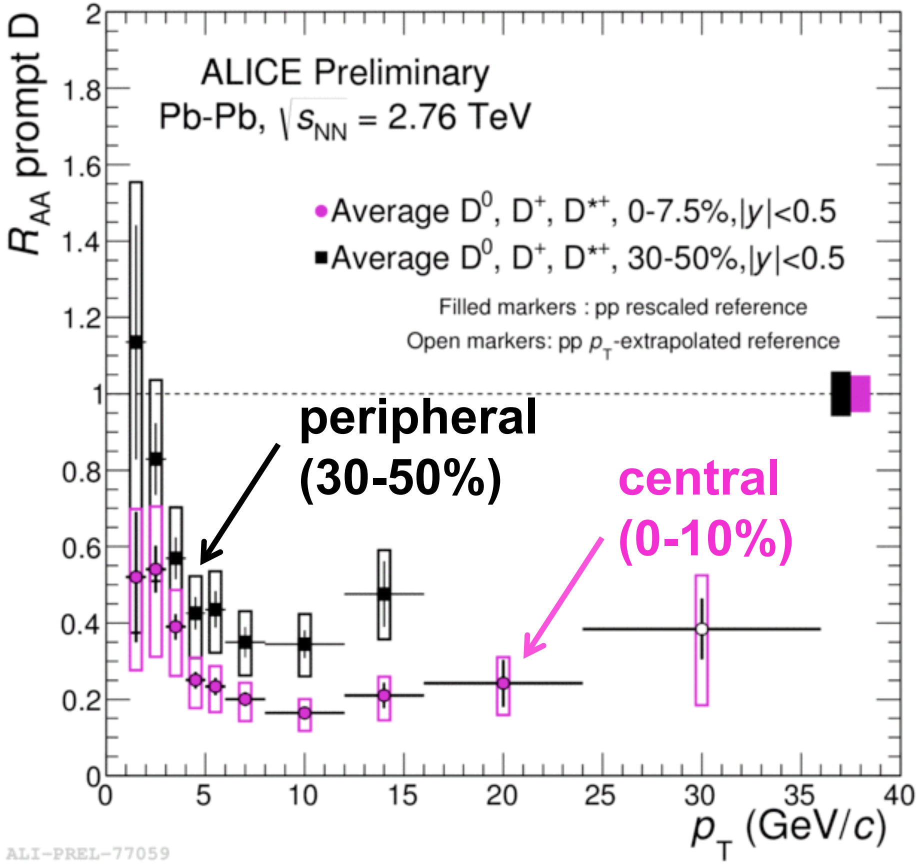
AA: D-meson R_{AA} at RHIC and LHC

STAR: D^0



STAR Coll., arXiv:1404.6185

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

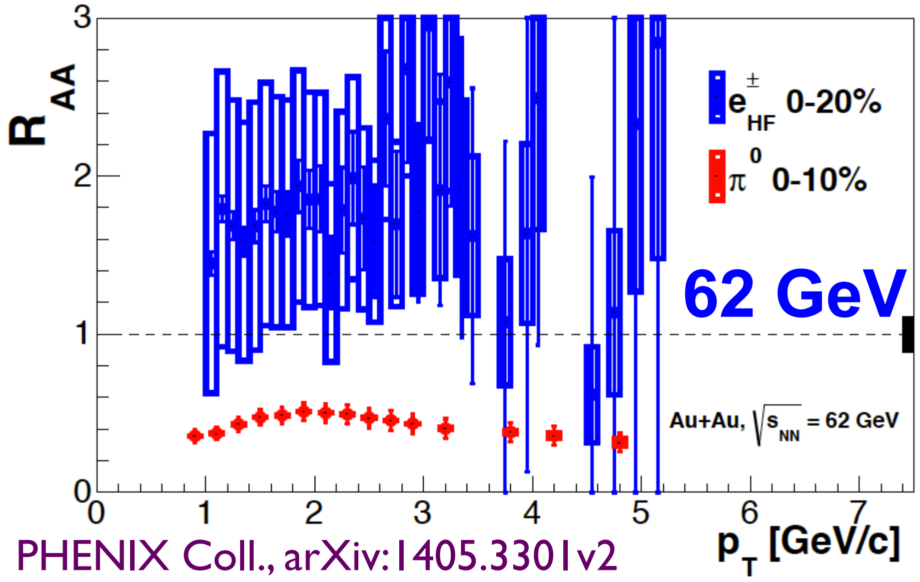


Similar suppression in central A-A collisions at high p_T

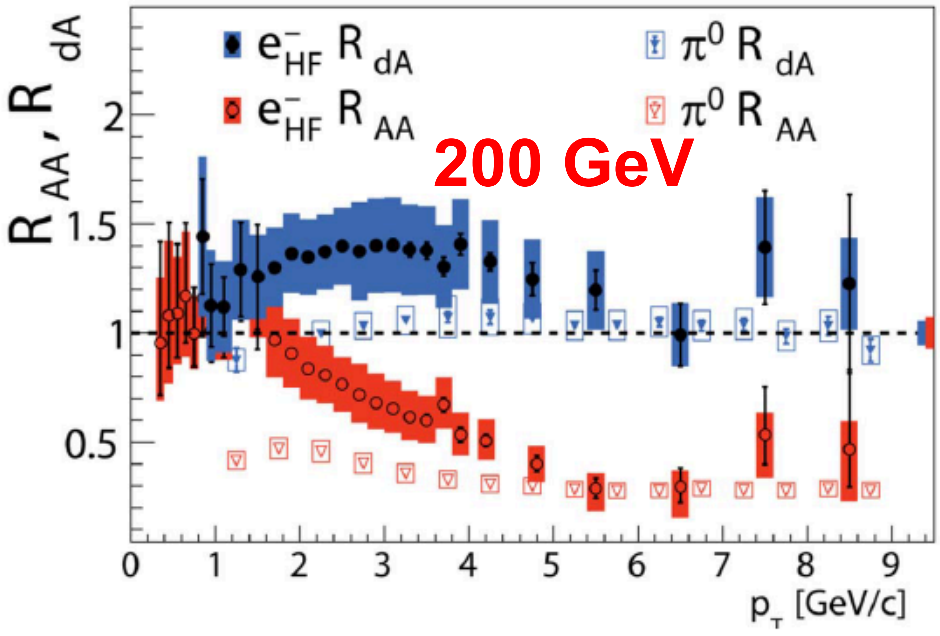
Differences at low p_T: radial flow? Shadowing? Recombination?

Crucial to go to p_T~0 at the LHC

Leptons from HF at RHIC



PHENIX Coll., arXiv:1405.3301v2

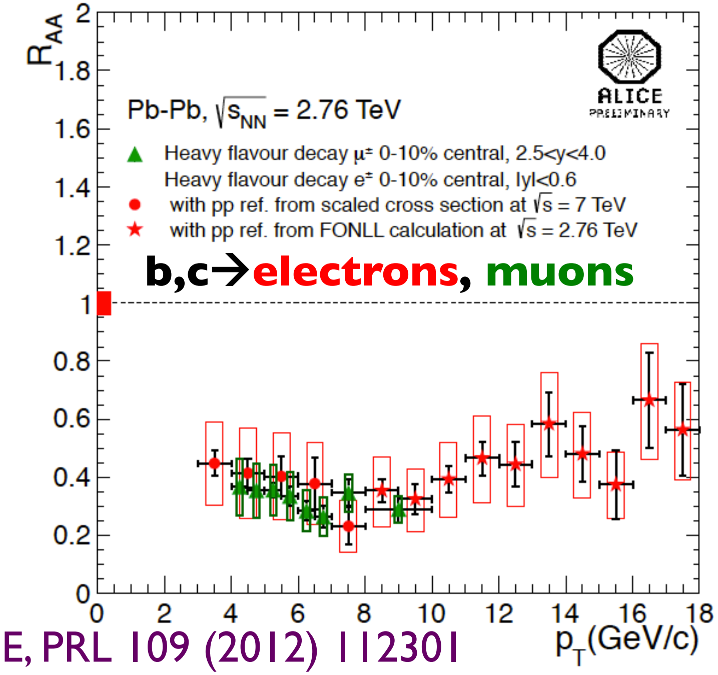


Different suppression trend at 62 and 200 GeV.

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

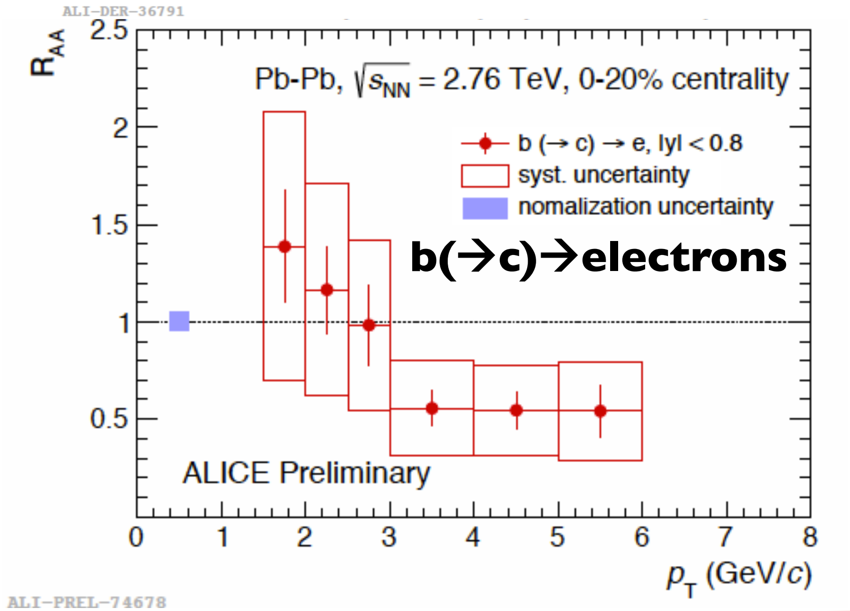
Note: 62 GeV pp reference comes from ISR. More data at 62 GeV

Heavy-flavour leptons at the LHC



ALICE, PRL 109 (2012) 112301

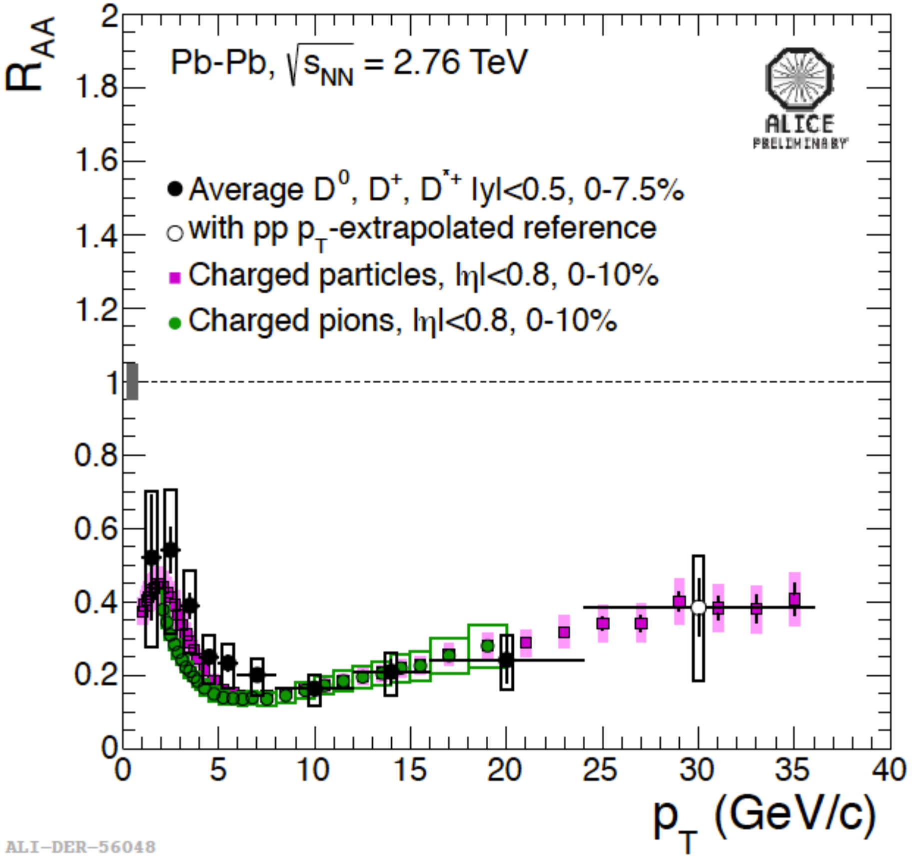
Similar suppression of electrons and muons from heavy-flavour decays at LHC

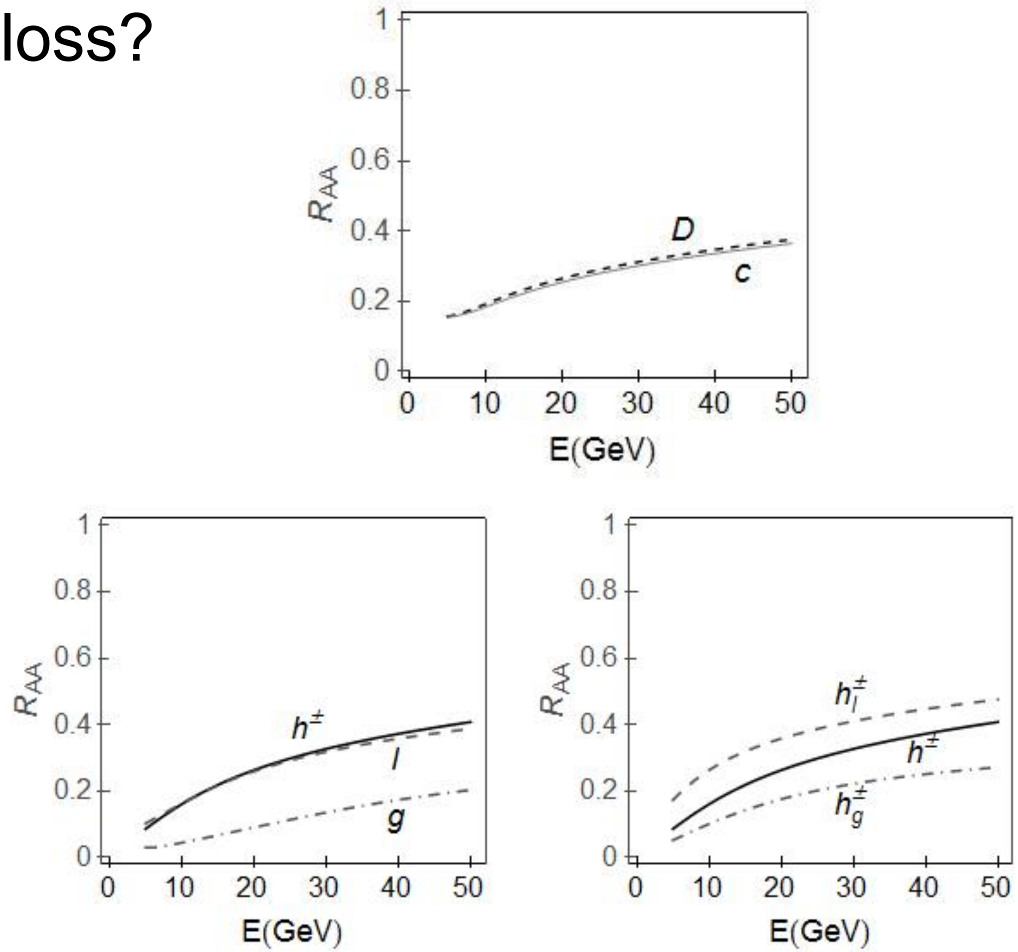


First measurement of electrons from beauty decays in Pb-Pb collisions.
Hint of suppression for p_T>3 GeV/c

R_{AA}: D mesons and charged hadrons

Mass dependence of energy loss?





M.Djordjevic, PRL 112, 042302 (2014)

$R_{AA}(D)\sim R_{AA}(\pi,h^{\pm})$

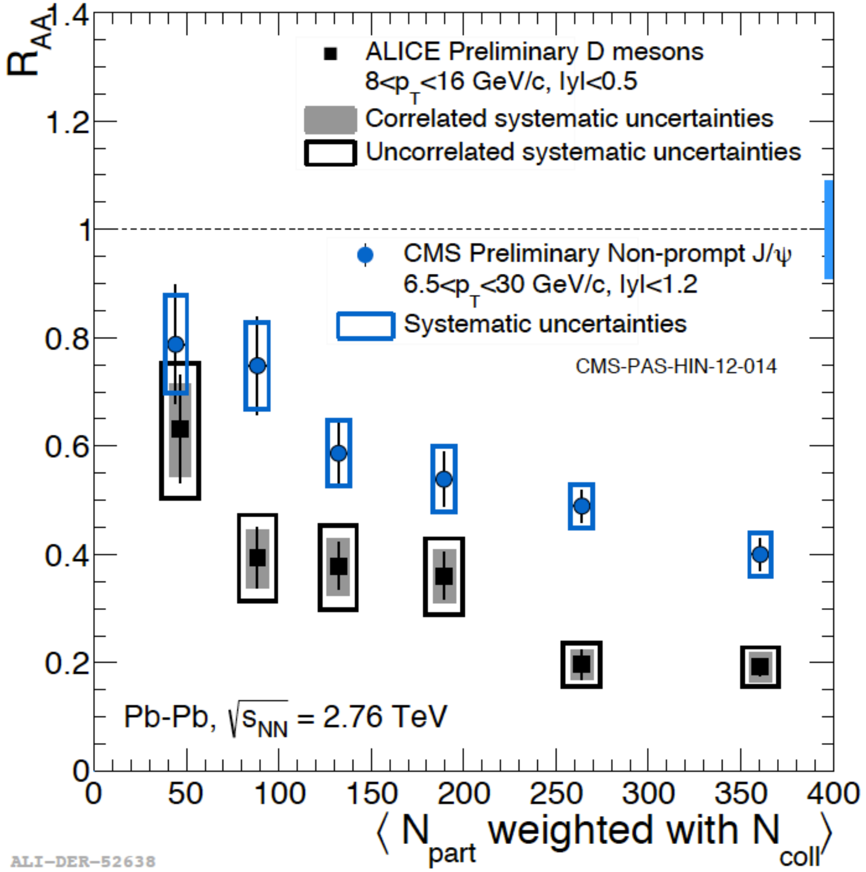
What about $\Delta E(udsg)>\Delta E(c)$? $\rightarrow R_{AA}(D)>R_{AA}(\pi,h^{\pm})$

$\rightarrow$Different quark spectra

$\rightarrow R_{AA}(h)$ affected by fragmentation

R_{AA}: D mesons and non-prompt J/ψ

Mass dependence of energy loss?

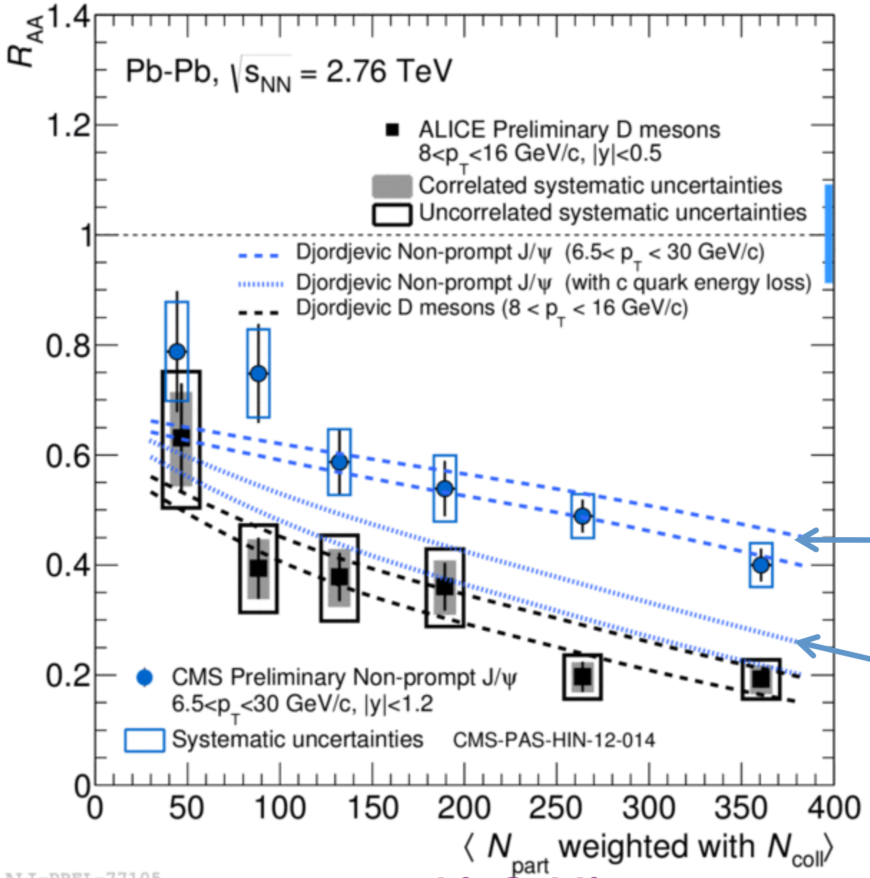


similar kinematics for D and B mesons (**<p_T>~10 GeV/c**)
different y ranges for D and non-prompt J/ψ

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 assumptions on the quark mass in the energy loss to calculate non-prompt J/ψ R_{AA}:

-b quark mass

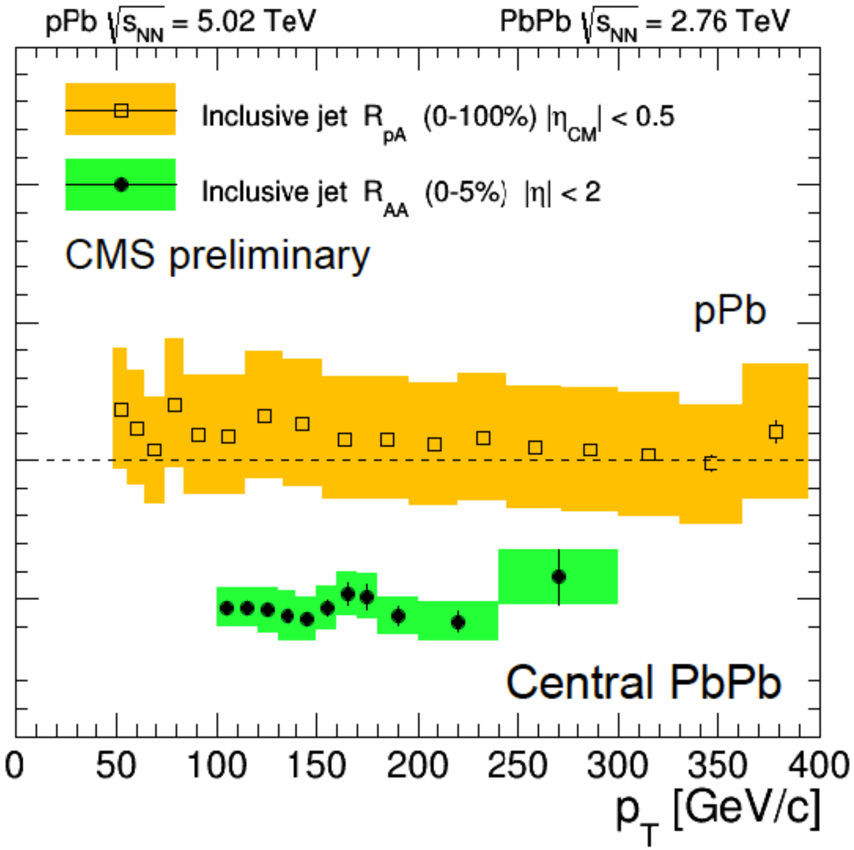
-c quark mass

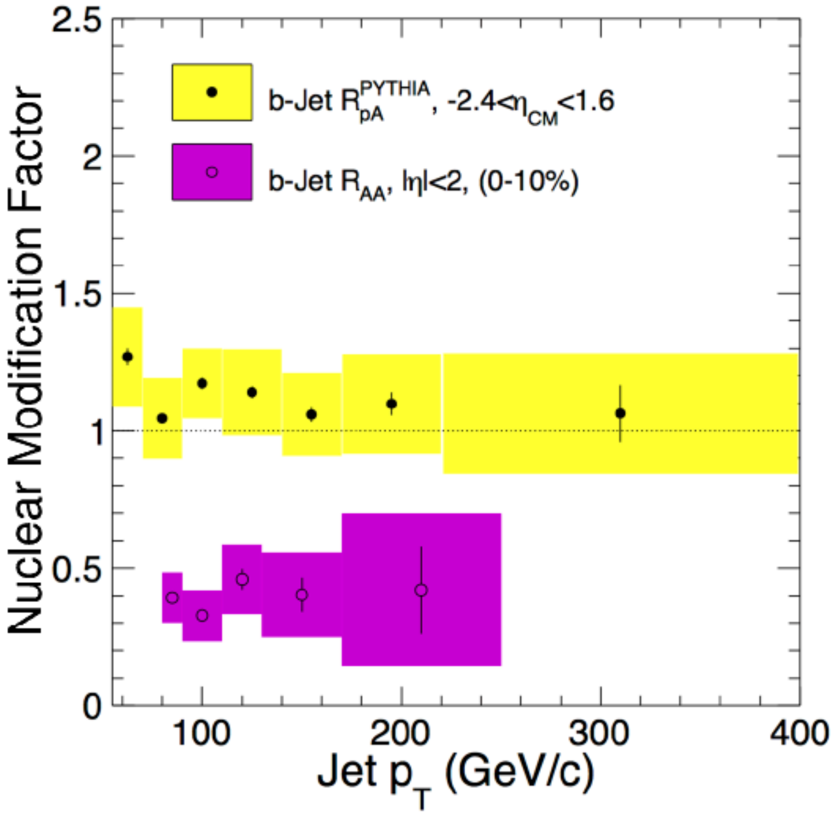
Difference comes from the different masses

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

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

Beauty jets in Pb-Pb collisions



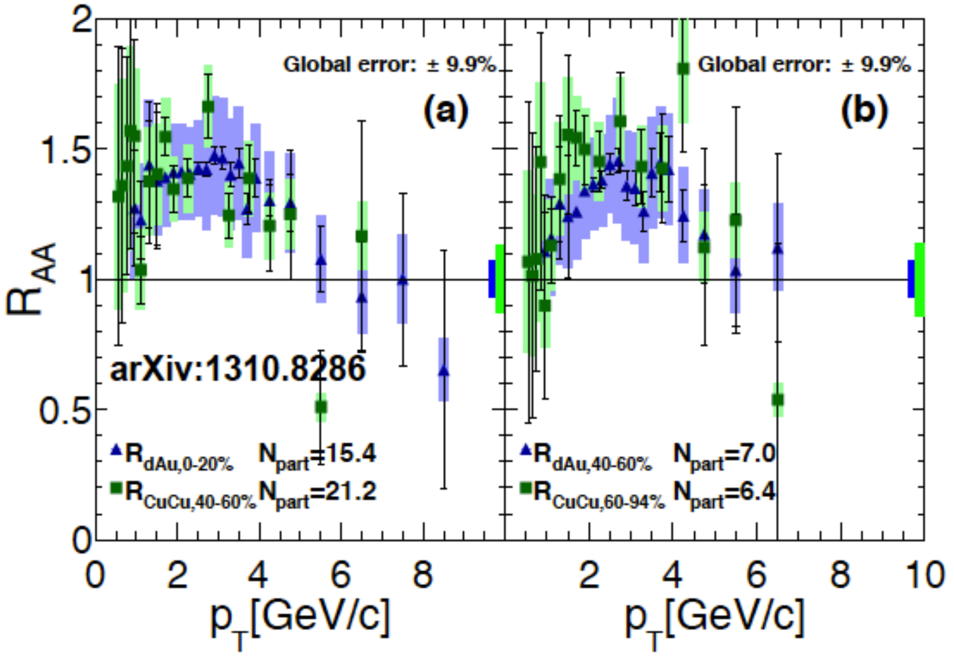


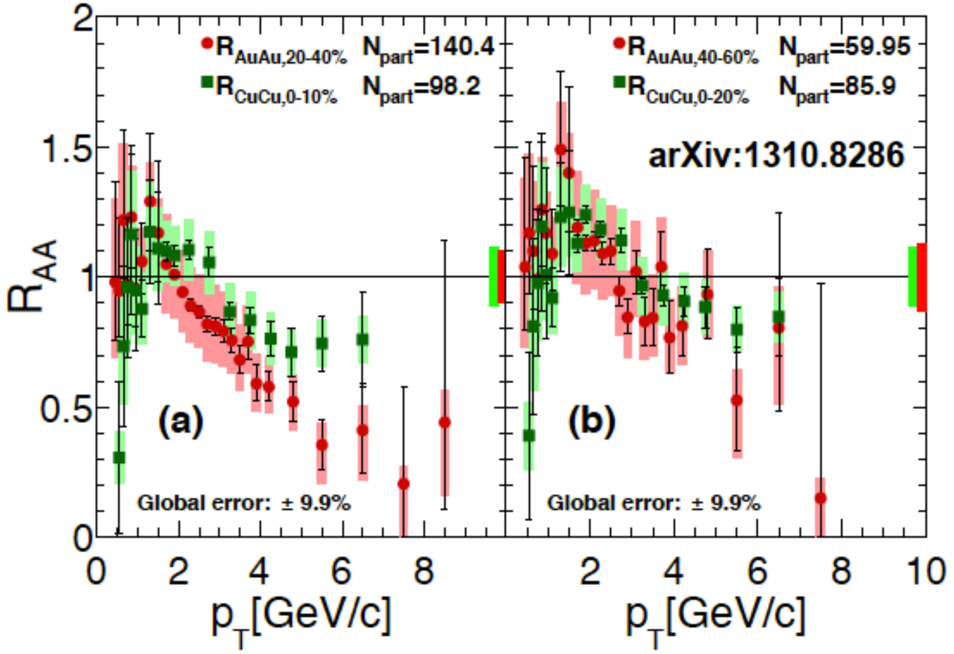
B-jet tagging method based on displaced secondary vertices in jets.
B-jet fraction based on template fits to the invariant mass of secondary vertices.

Quark-jets tagged.
B-jet suppression (0-10%) is consistent with inclusive jet (0-5%) suppression. Quark mass effect negligible at high jet p_T.

System size dependence of R_{AA} at RHIC

electrons from heavy-flavour decays



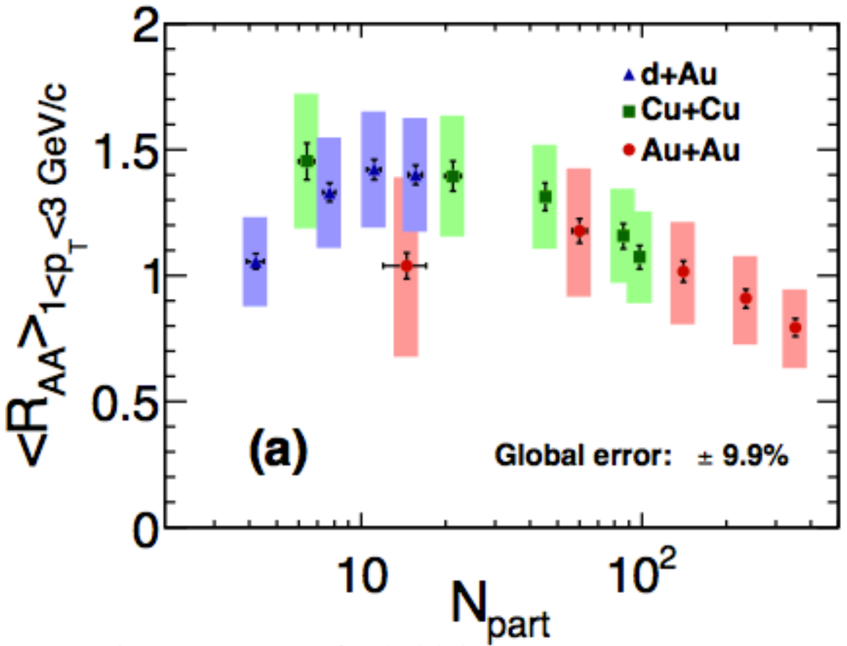


PHENIX Coll., arXiv:1310.8286v1

CENTRAL d+Au ~ PERIPHERAL Cu+Cu

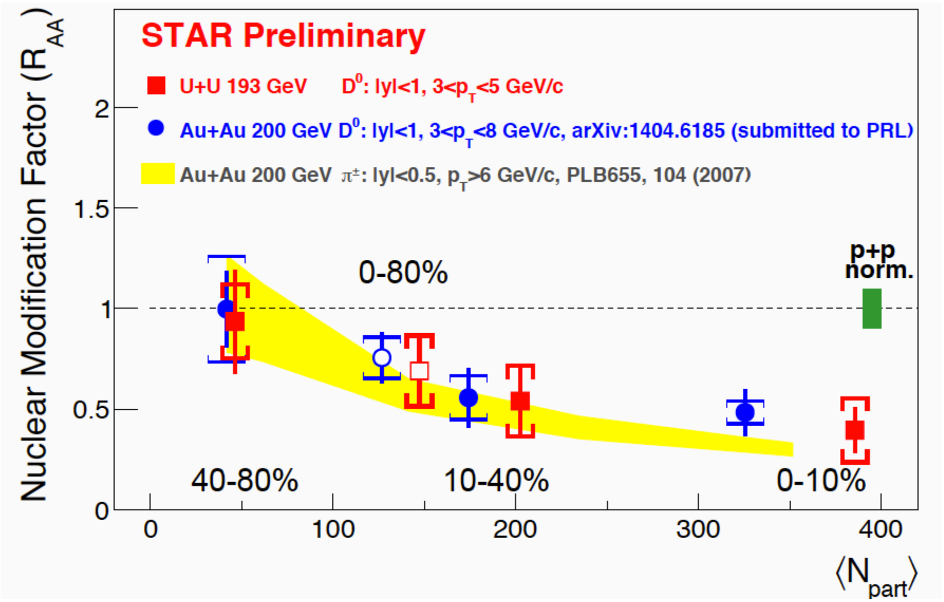
CENTRAL Cu+Cu ~ MID Au+Au

System size dependence of R_{AA} at RHIC



electrons from heavy-flavour decays

PHENIX Coll., arXiv:1310.8286v1



D^0

STAR Coll., arXiv:1404.6185

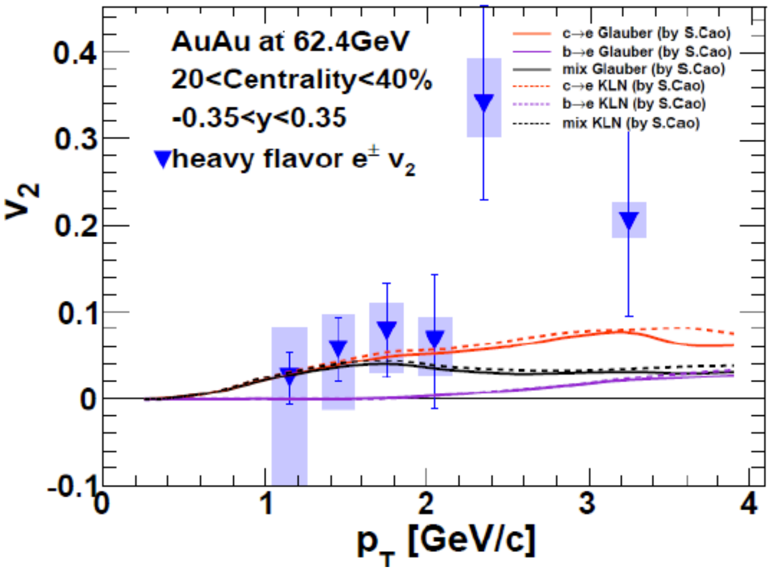
From **d+Au** to **peripheral Cu+Cu**: enhancement effects dominating

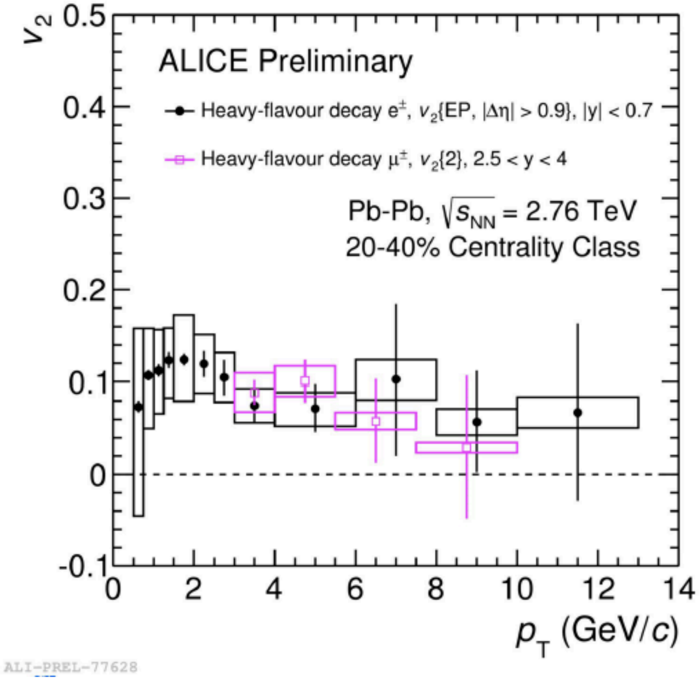
From **Cu+Cu** to **central Au+Au**: suppression dominating

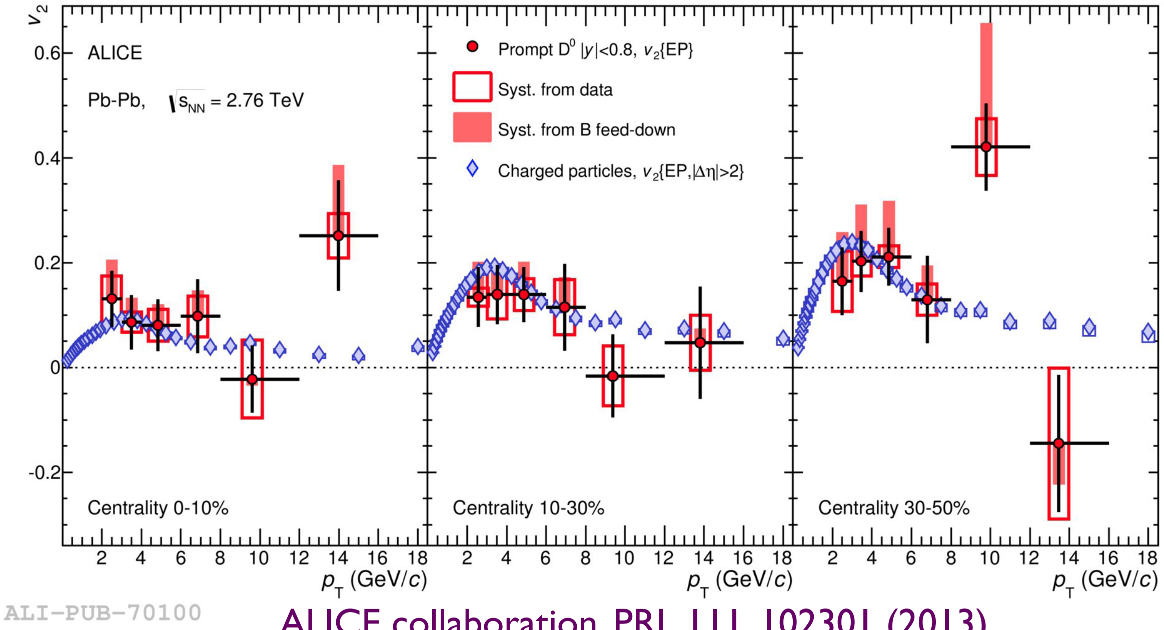
U+U: could have 20% higher energy density than Au+Au
similar D^0 suppression as for Au+Au, extends the trend

Charm collective motion

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





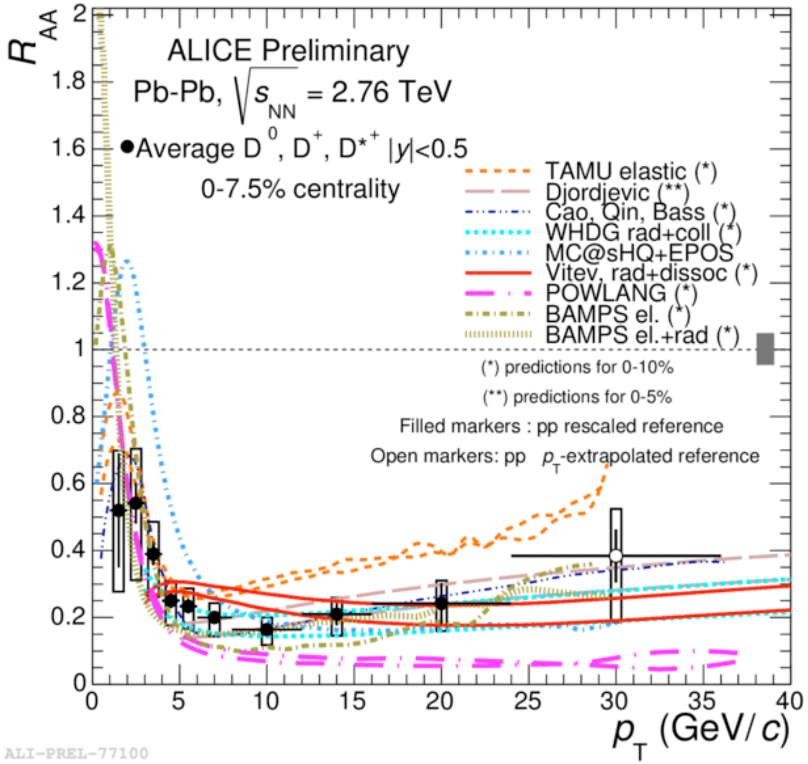


ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001

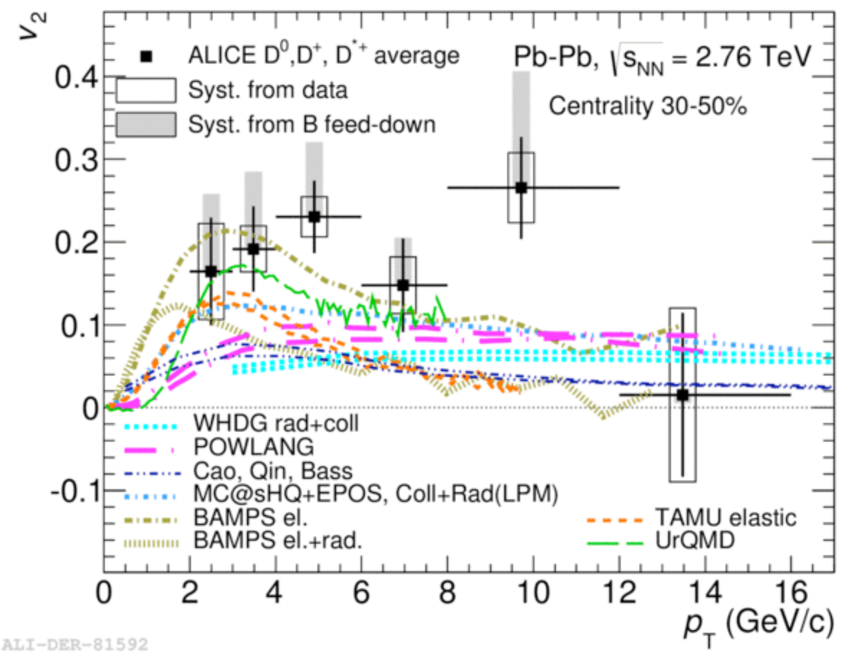
Positive v_2 for D mesons and e/μ from heavy-flavour decays at LHC

Hint for collective motion of charm quarks at low p_T

R_{AA} and v_2: constraints to models



ALICE, PRL 111 (2013) 102301

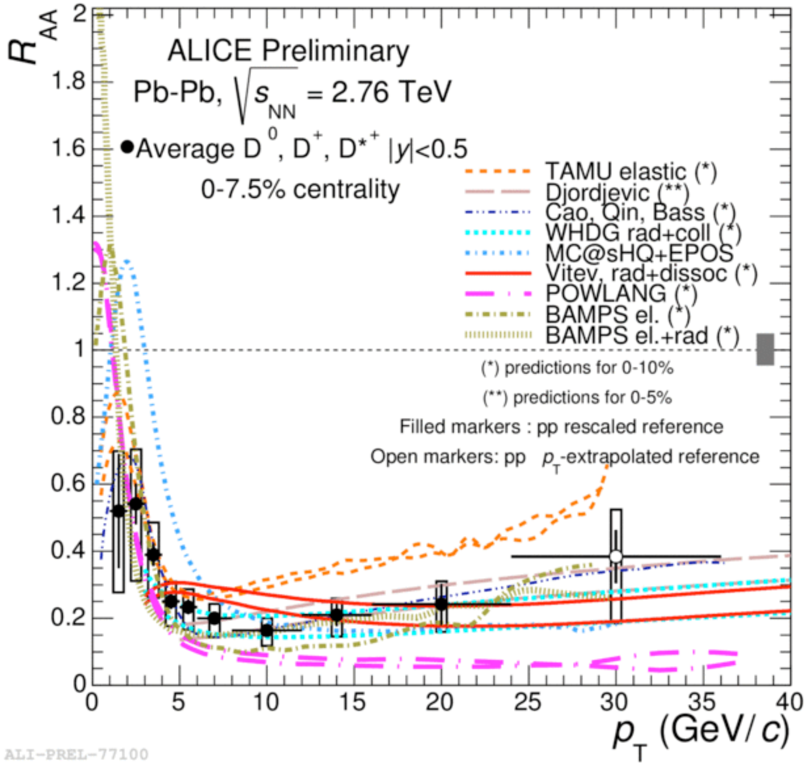


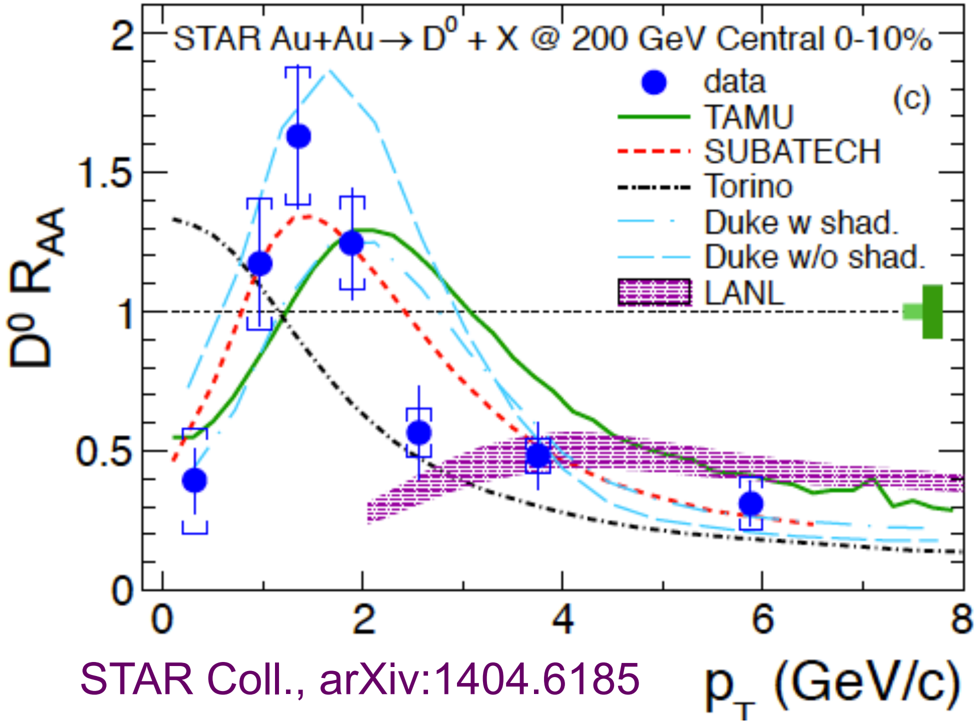
BAMPS: Fochler et al., J. Phys. G38 (2011) 124152
POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666
UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph];
T. Lang et al., arXiv:1212.0696 [hep-ph].
TAMU: Rapp, He et al., Phys. Rev. C 86 (2012) 014903
WHDG: Horowitz et al., JPhys G38 (2011) 124114
Aichelin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

Theoretical models reproduce reasonably well R_{AA} but are challenged by simultaneously reproducing results from heavy-flavour R_{AA} and v_2.

Differential observables needed to constrain models

R_{AA} : constraints to models



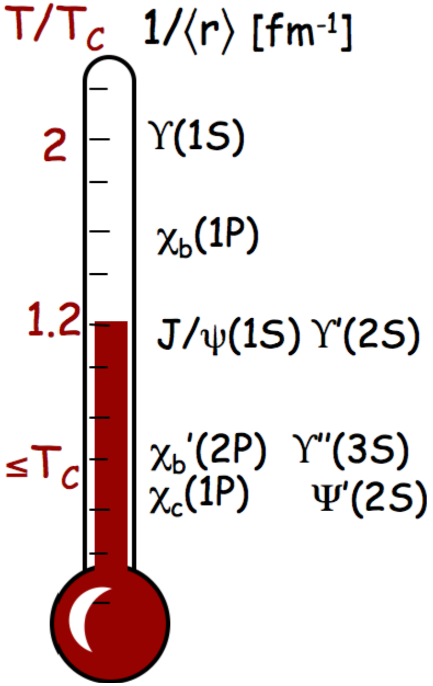


STAR Coll., arXiv:1404.6185

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

Quarkonia

- thermometer of the QGP -



Quarkonium in the QGP

What happens to a $q\bar{q}$ pair in the Quark Gluon Plasma?

The binding of the $q\bar{q}$ pair is subject to the effects of the colour screening

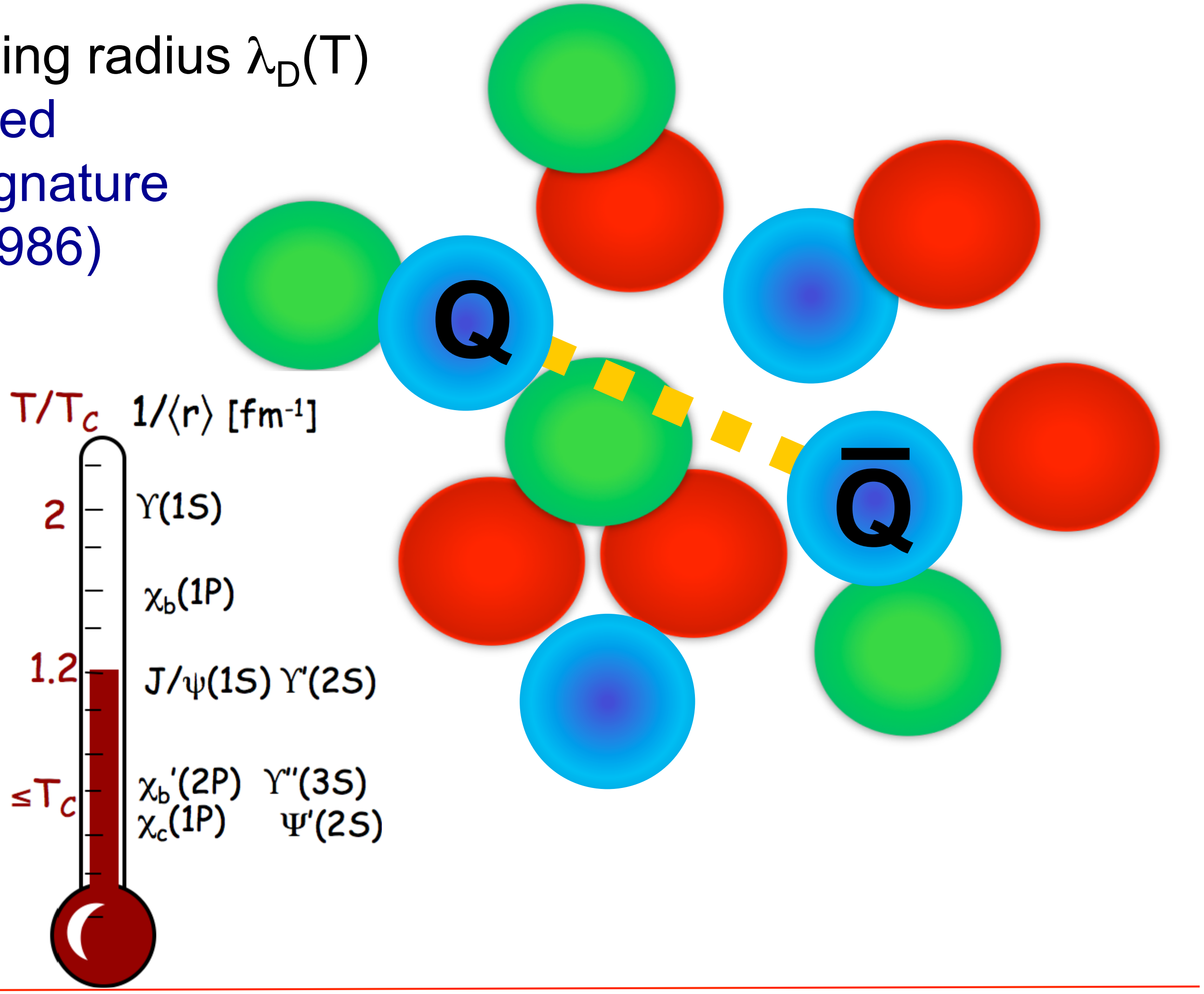
If resonance radius > screening radius $\lambda_D(T)$

→no resonance can be formed

→suppression of J/ψ as a signature for the QGP (Matsui, Satz, 1986)

Differences in the binding energies of $q\bar{q}$ states

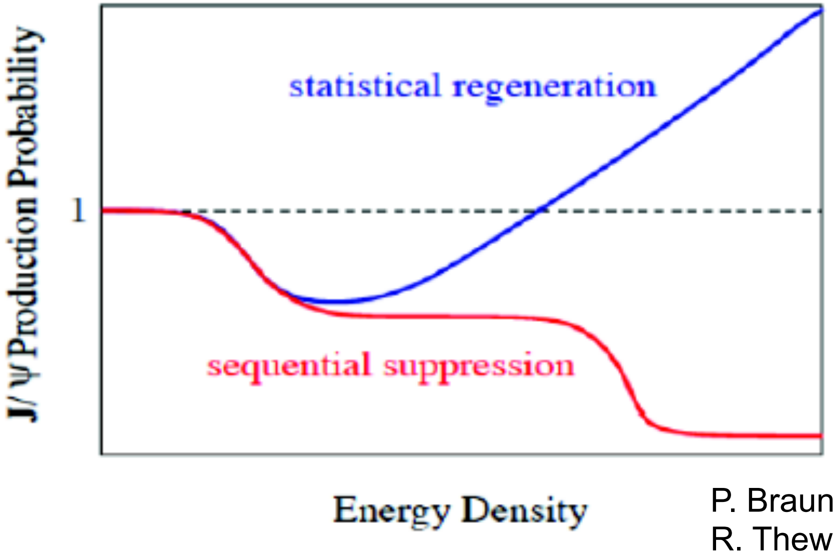
→ sequential suppression of the states with increasing temperature



Quarkonium in the QGP: suppression and/or enhancement?

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

In most central AA collisions	SPS 20 GeV	RHIC 200GeV	LHC 2.76TeV
N_{ccbar}/event	~0.2	~10	~60

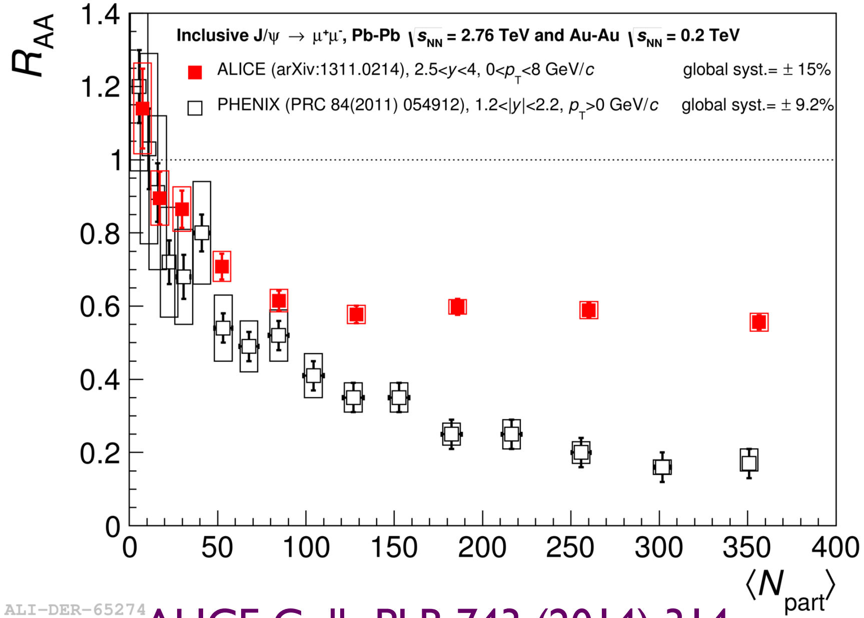


P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196,
R. Thews et al, Phys.Rev.C63:054905(2001)

This mechanism can lead to charmonium enhancement via (re)combination of $c\bar{c}$ pairs at hadronization or during QGP stage

If so, charmonium is no longer a “thermometer” of QGP ...but becomes an observable for the phase boundary

J/ψ R_{AA} at RHIC and LHC



ALICE Coll., PLB 743 (2014) 314

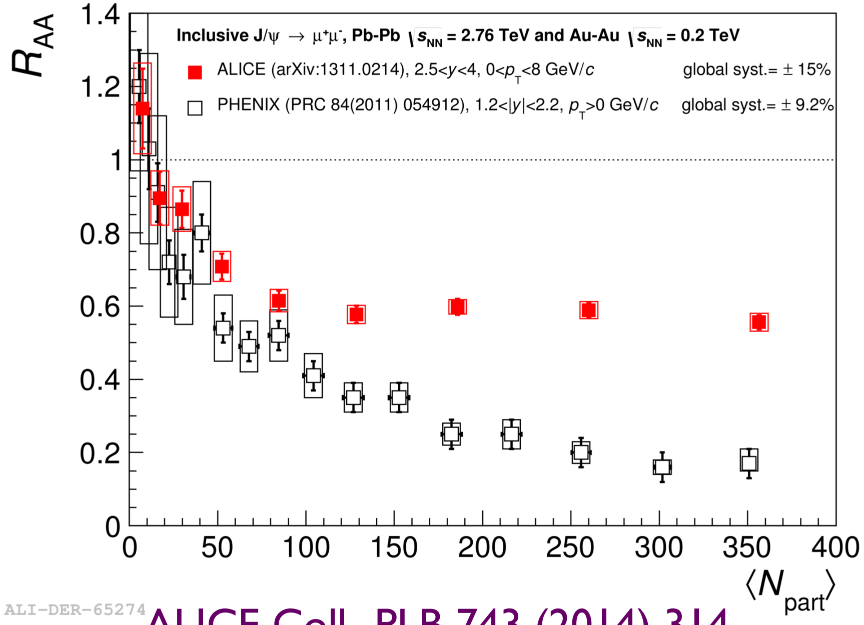
J/ψ less suppressed at LHC than at RHIC.

Could it be (re)combination at LHC energies?

-i.e. quarkonium formed by (re)combination of $c\bar{c}$ quarks close in momentum

-if so, it should be at low p_T

J/ψ R_{AA} at RHIC and LHC



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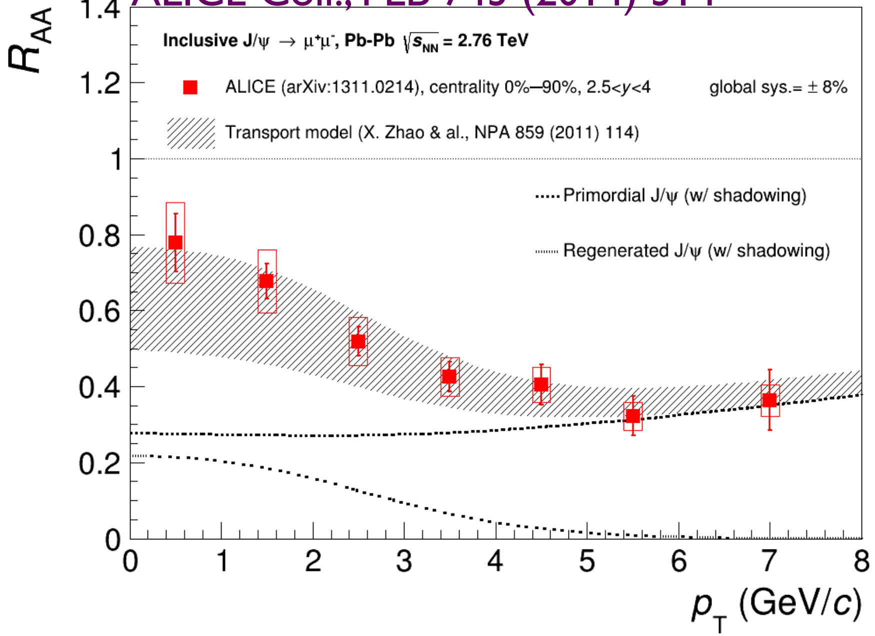
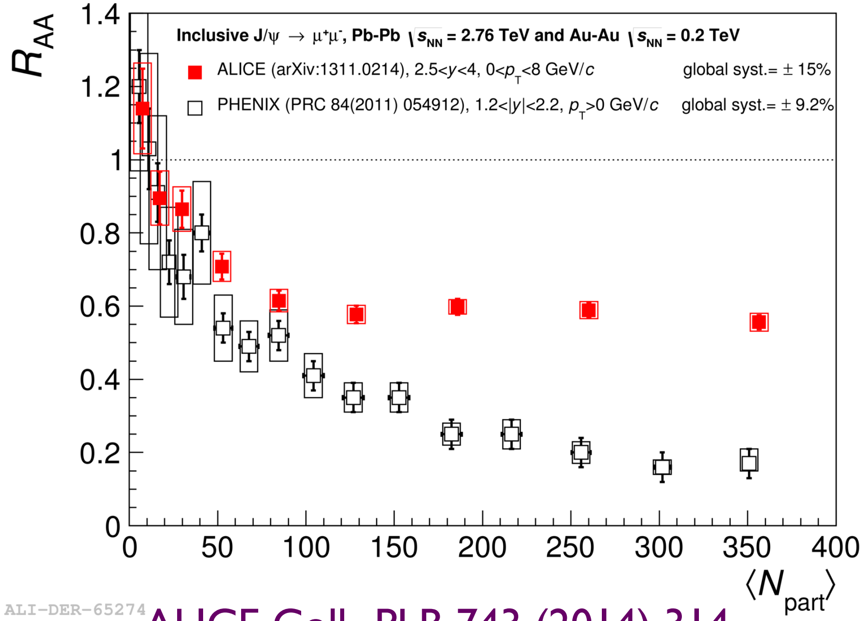
ALICE Coll., PLB 743 (2014) 314



Strong dependence of J/ψ suppression vs p_T!

Models: ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible

J/ψ R_{AA} at RHIC and LHC



ALICE Coll., PLB 743 (2014) 314

J/ψ less suppressed at LHC than at RHIC.

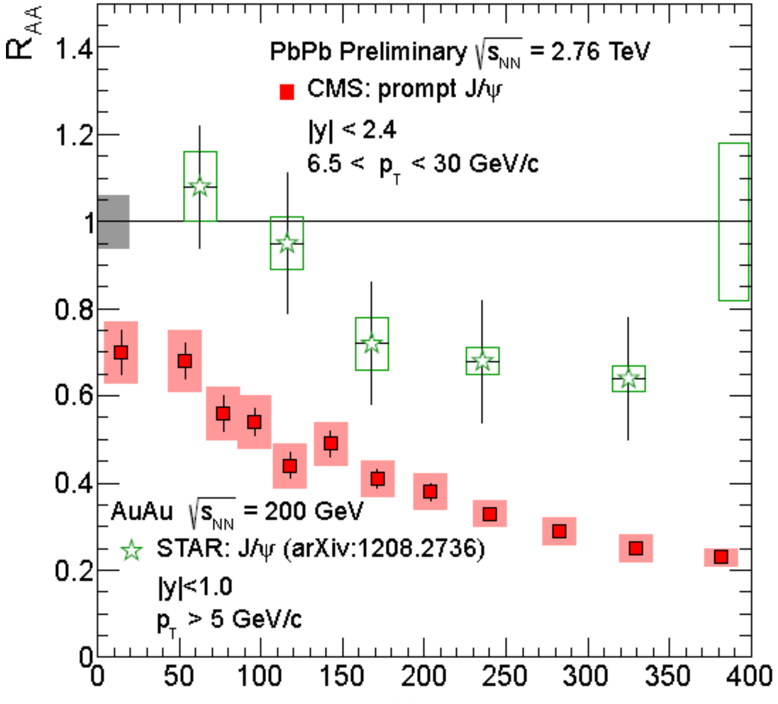
Could it be (re)combination at LHC energies?

-i.e. quarkonium formed by (re)combination of $c\bar{c}$ quarks close in momentum

-if so, it should be at low p_T

At high J/ψ p_T?

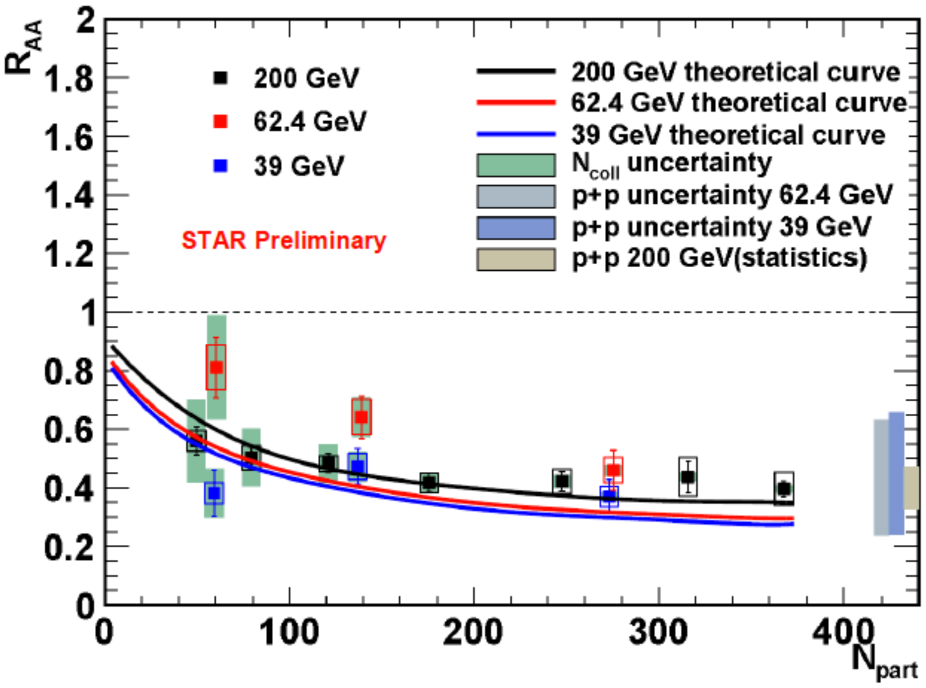
strong J/ψ suppression at LHC (re-combination should not play a role at high p_T)



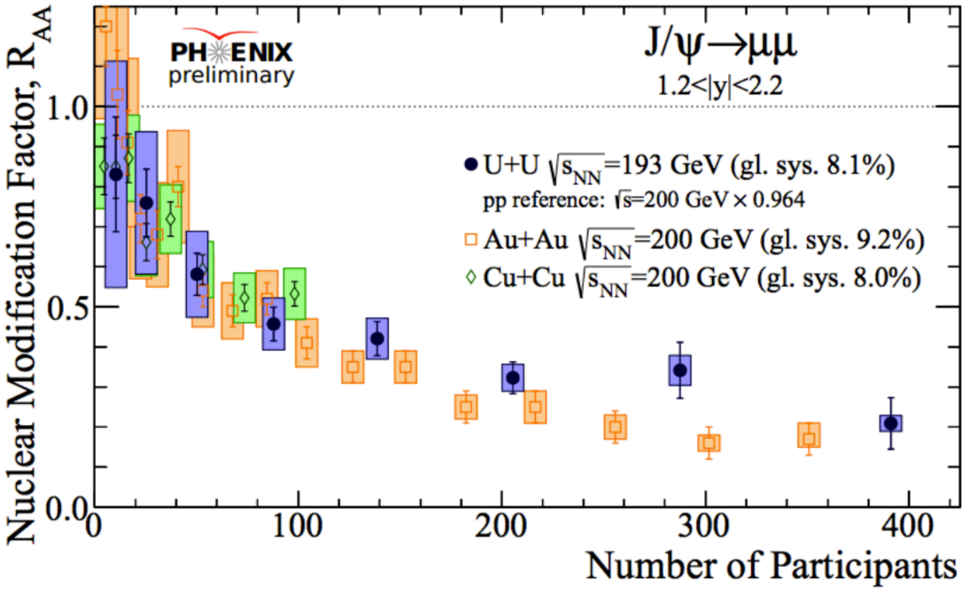
STAR Coll., PLB 722 (2013) 55

J/ψ at RHIC

Beam energy scan



Collision system scan

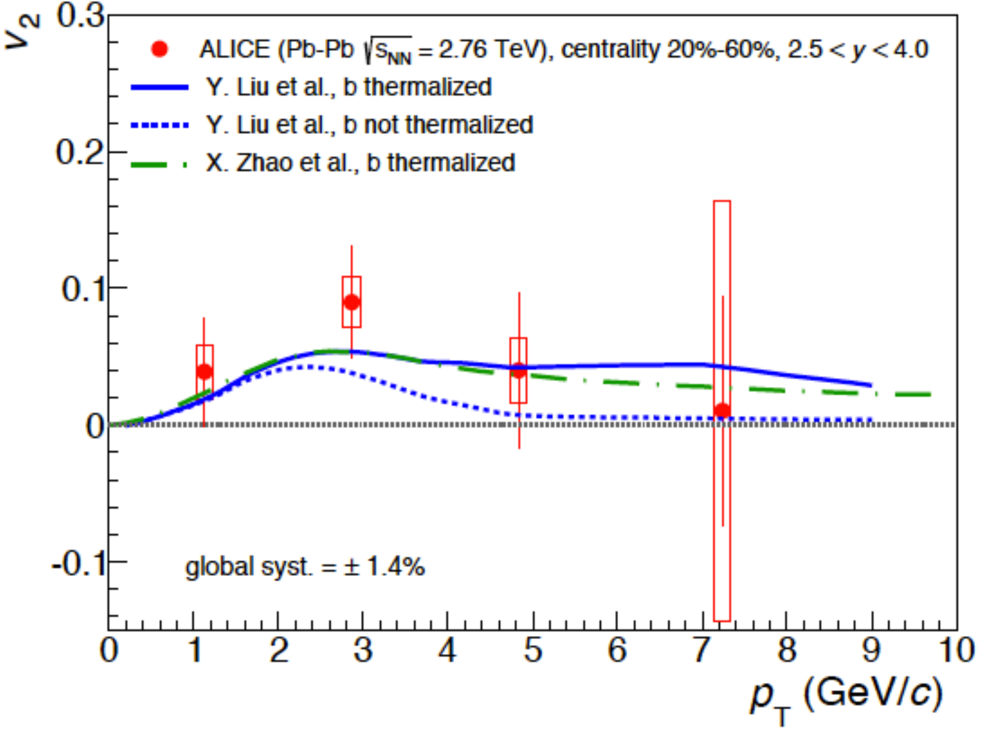


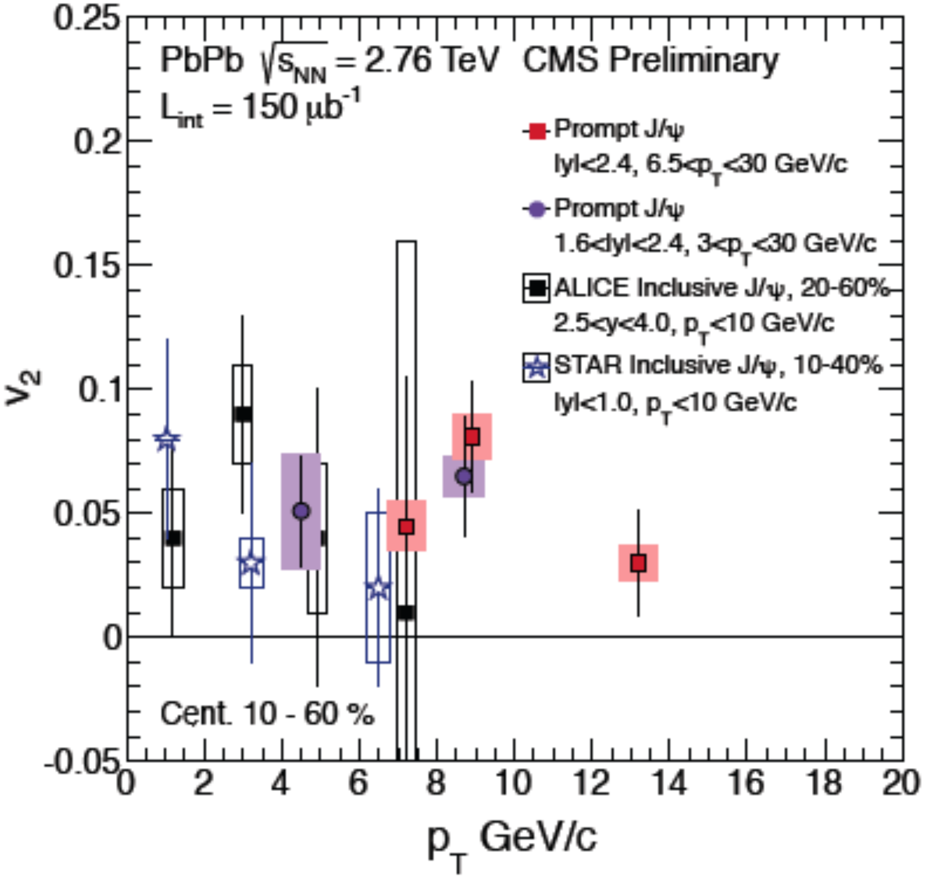
Similar suppression trends for different energies and collision systems at RHIC

Important testing ground to tune models with different energies/systems

J/ψ flow at LHC

ALICE Coll., PRL 111 (2013) 162301



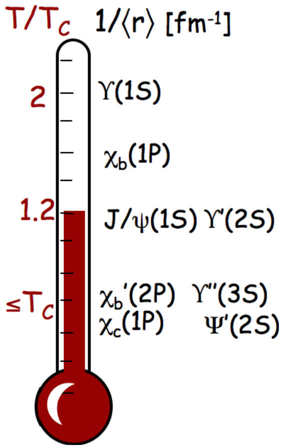


Results support production in QGP or at chemical freeze-out at the LHC

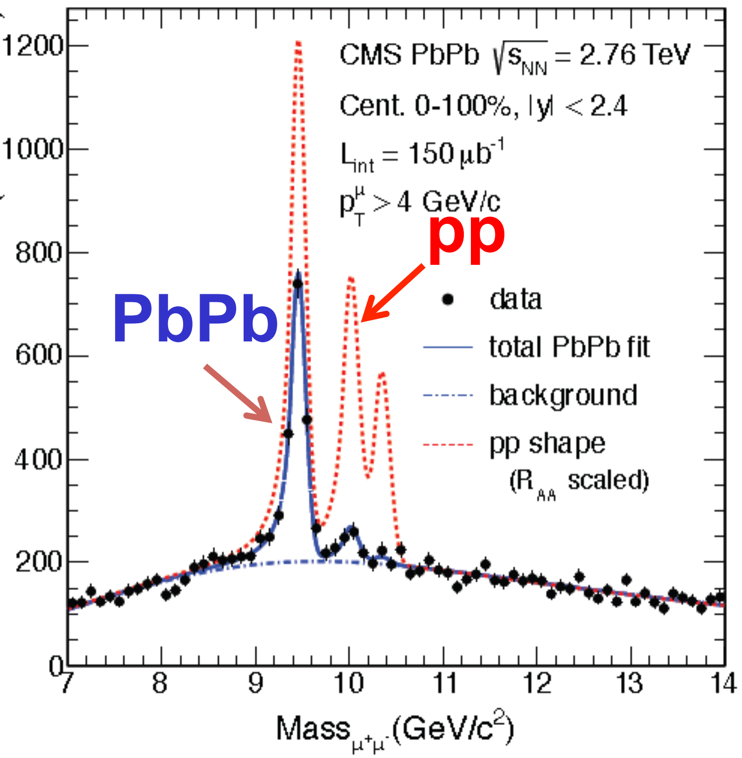
RHIC: compatible with v_2(J/ψ)~0

Wide p_T range explored: from J/ψ regeneration to path-length dependence of charm energy loss

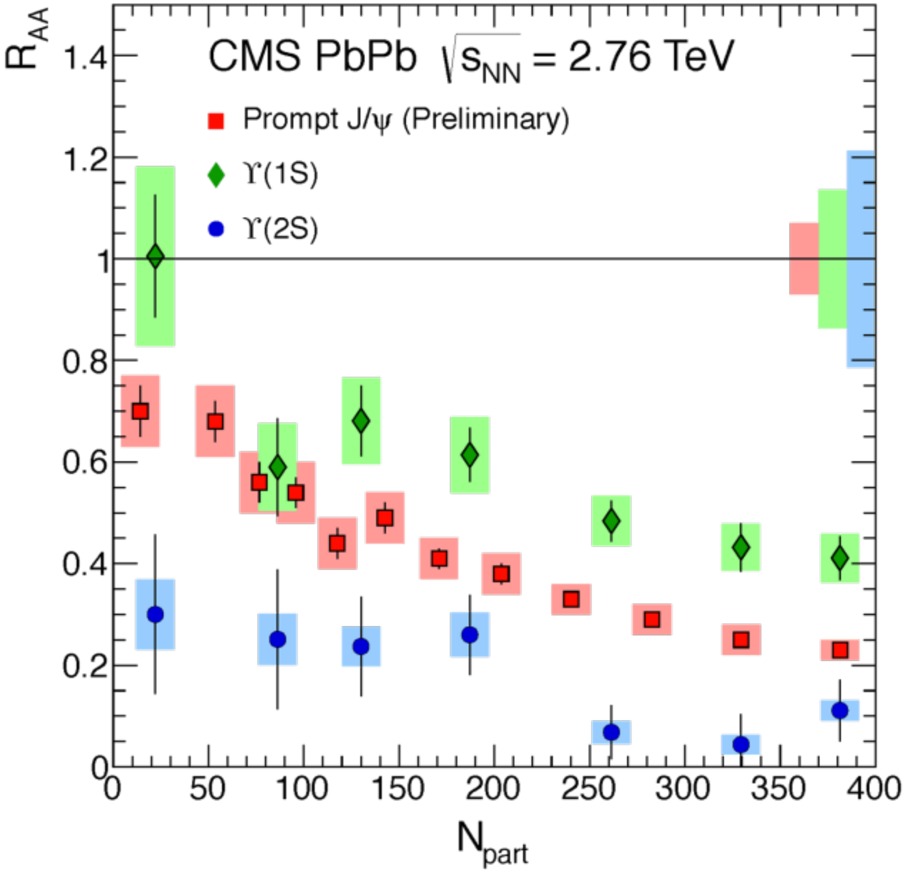
Bottomonium at the LHC



PRL 109, 222301 (2012)



CMS Coll., PRL 109 (2012) 222301



Υ(2S) suppressed more suppressed than Υ(1S) (also in periph.). Υ(3S) melted.

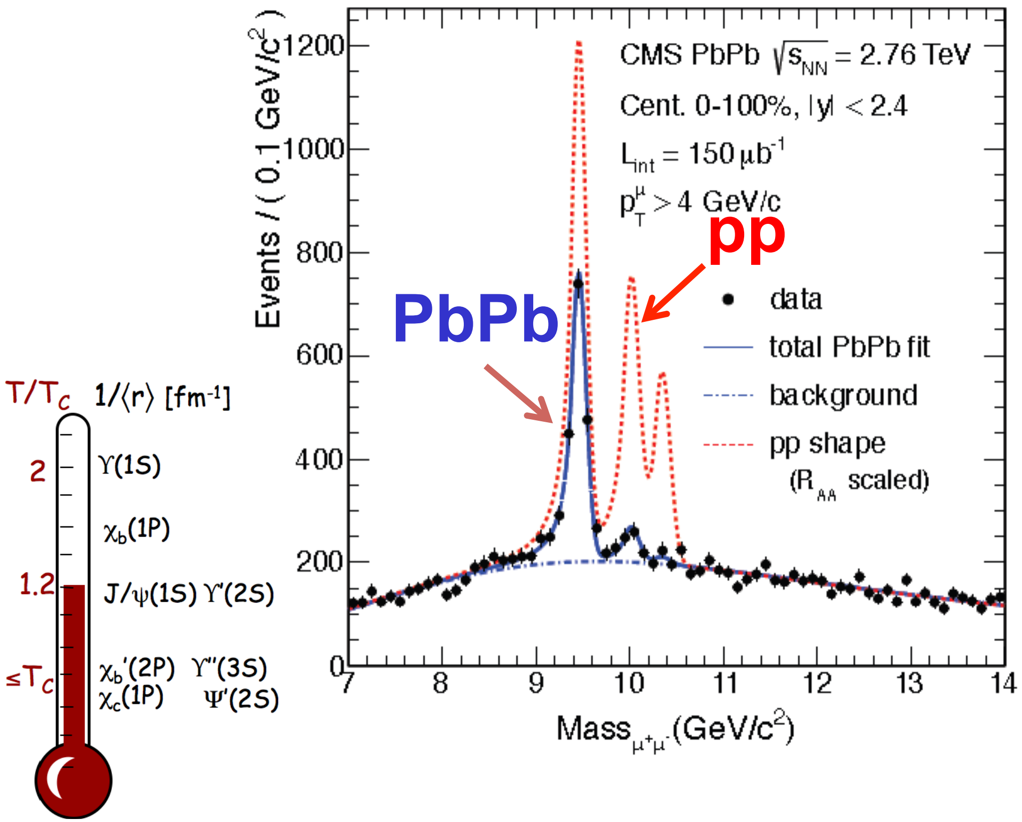
Υ(1S) suppression might be compatible with feed-down suppression (50%).

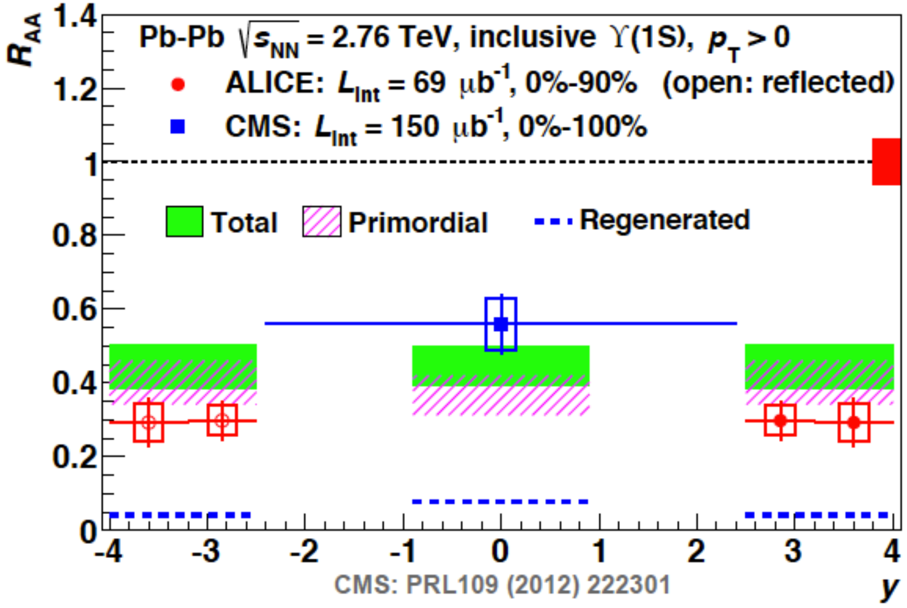
Possibly Υ(1S) dissociation threshold still beyond LHC reach

→ wait for LHC full energy!

Bottomonium at the LHC

PRL 109, 222301 (2012)

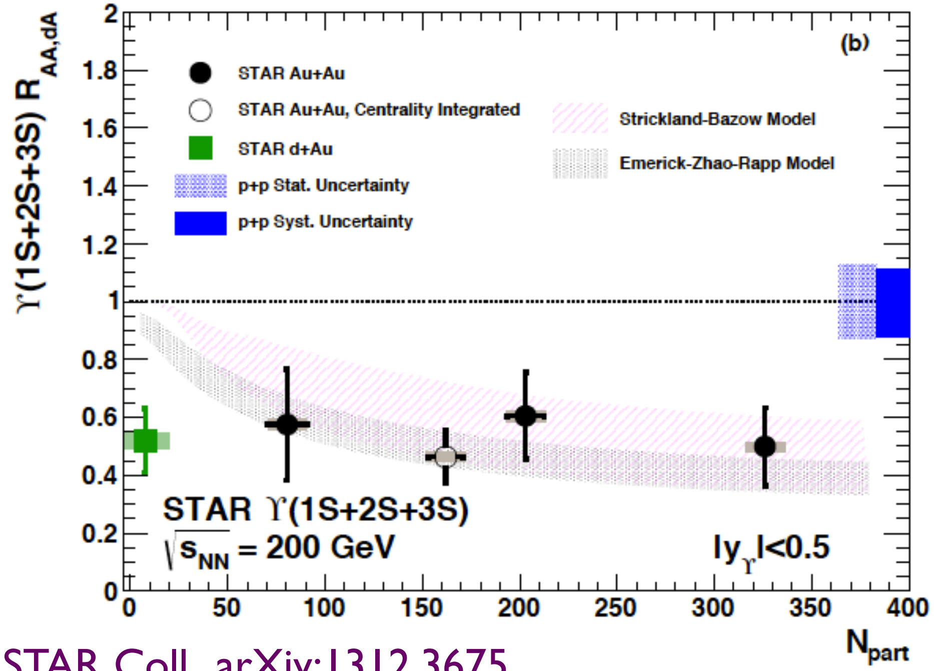




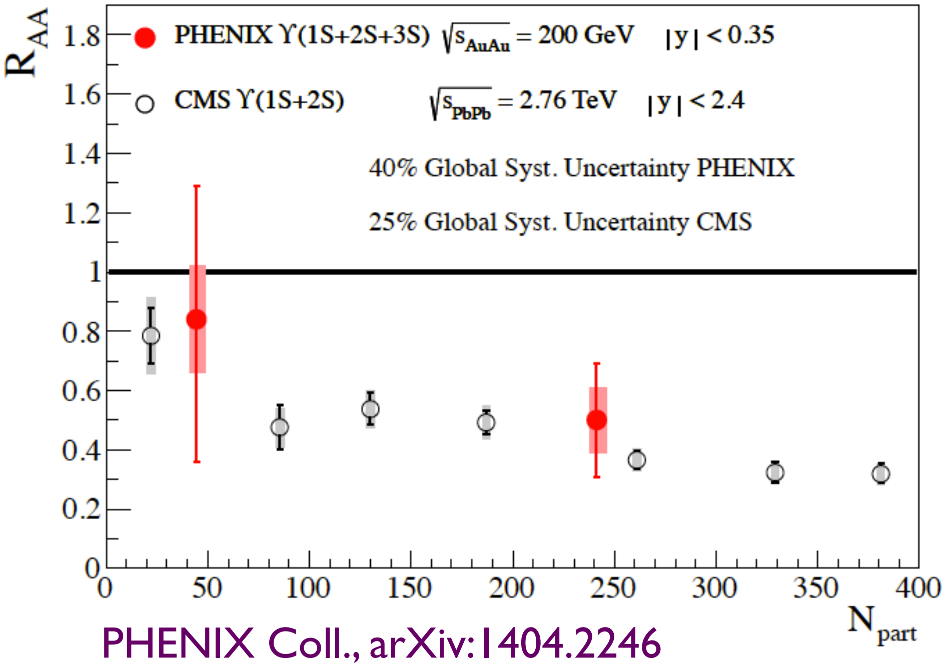
ALICE Coll., arXiv:1405.4493
CMS Coll., PRL 109 (2012) 222301
Transport model:
A. Emerick et al., EPJ A48 (2012) 72

Model does not reproduce the strong rapidity dependence of the R_{AA} and underestimates the Υ(1S) suppression at forward rapidity: Regeneration? CNM?

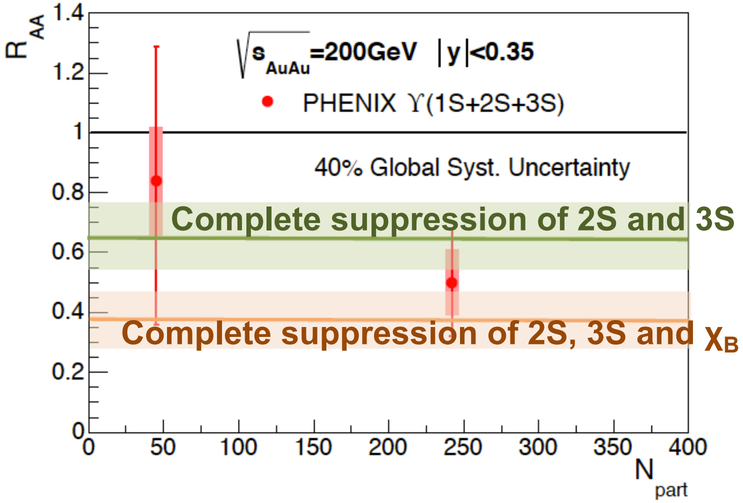
Bottomonium at RHIC



STAR Coll., arXiv:1312.3675



PHENIX Coll., arXiv:1404.2246

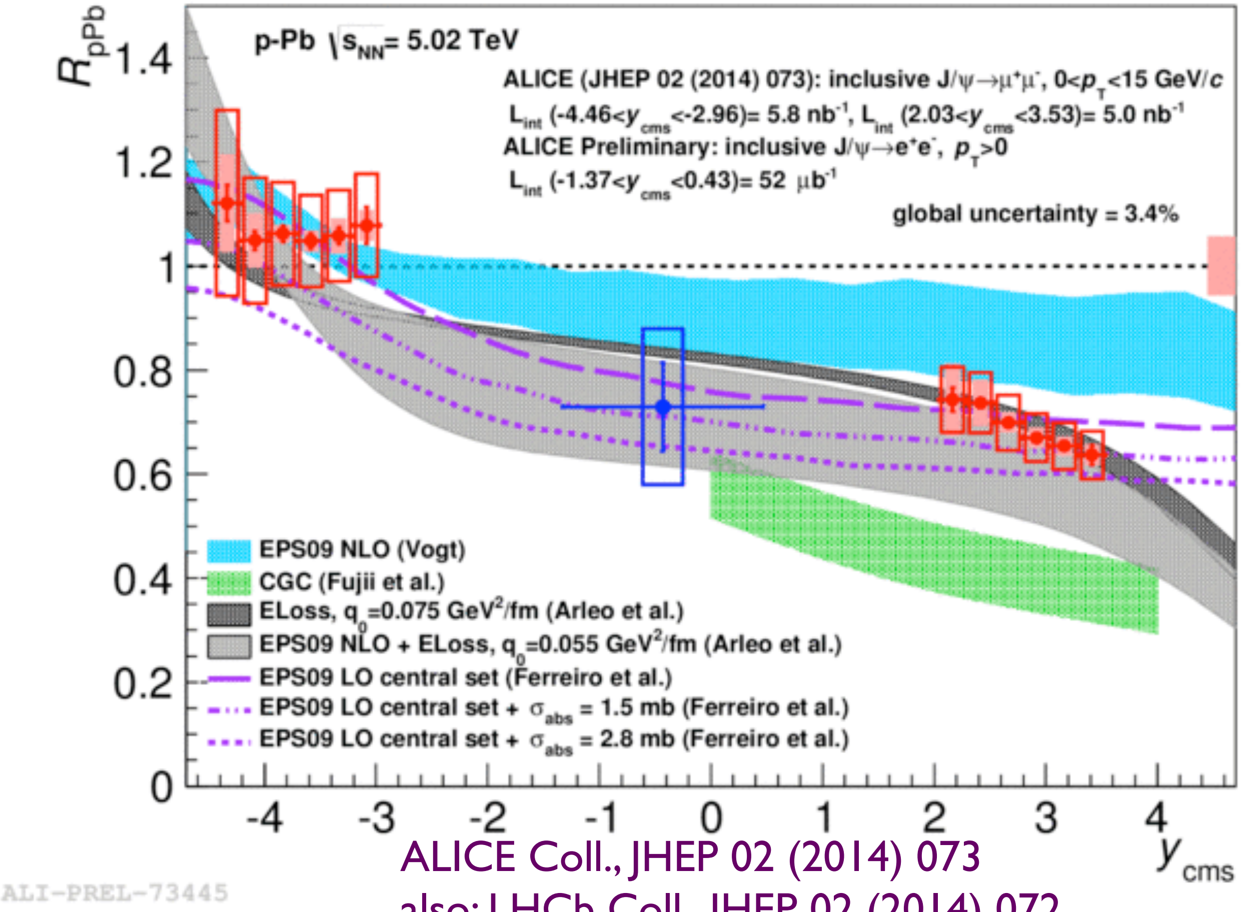


Results compatible at RHIC and LHC

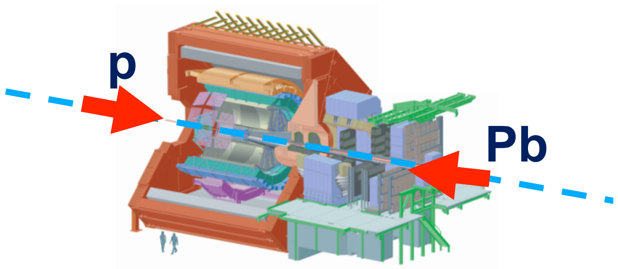
→ more data needed to draw conclusions on different scenarios

→ wait for LHC full energy!

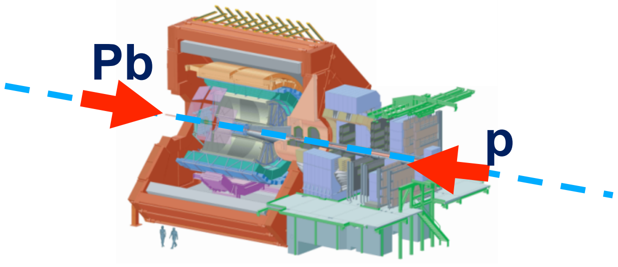
Cold Nuclear Matter effects in quarkonium production



ALICE Coll., JHEP 02 (2014) 073
also: LHCb Coll., JHEP 02 (2014) 072



2.03<y_{CMS}<3.53
10^{-5}<x<$8\cdot10^{-5}$

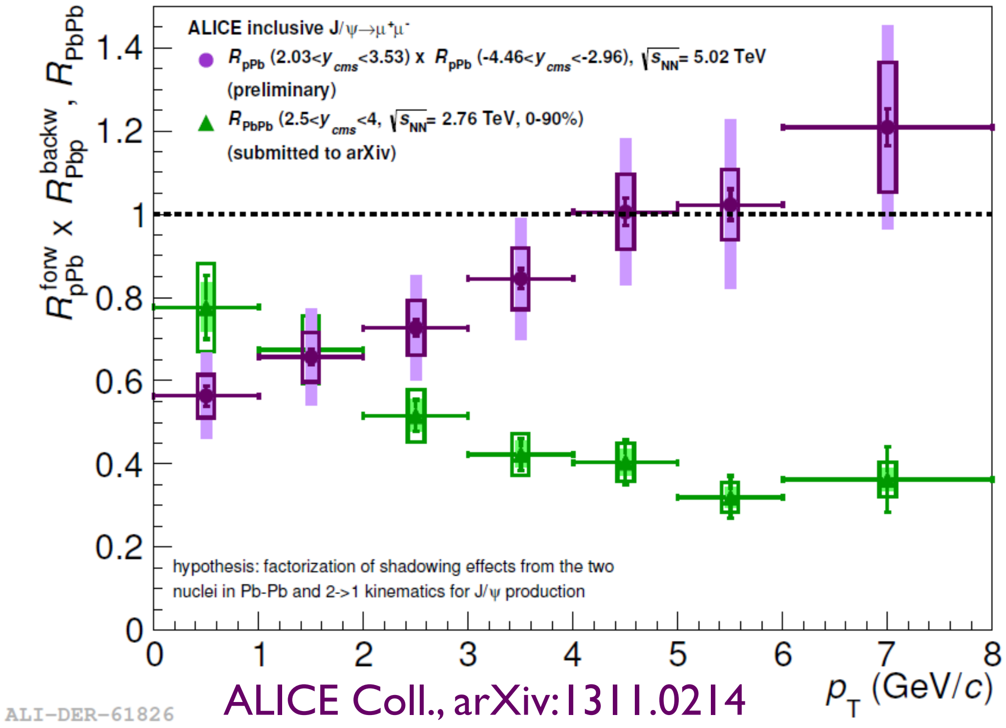


-4.46<y_{CMS}<-2.96
10^{-2}<x<$5\cdot10^{-2}$

J/ψ production is modified also in pA because of CNM effects
Reasonable agreement with theoretical predictions (shadowing/e.loss depends on y)

CNM on J/ψ and ψ(2S)

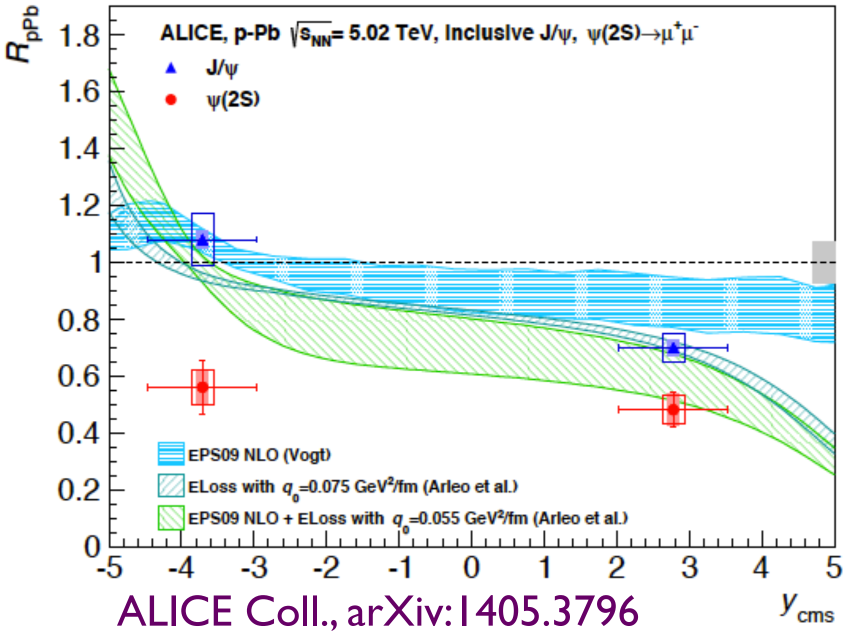
J/ψ $R_{AA(pA)}$ vs p_T



ALICE Coll., arXiv:1311.0214

Contribution of CNM effects in Pb-Pb extrapolated from p-Pb.
Evidence for hot nuclear matter effects.

ψ(2S) R_{pA} vs y



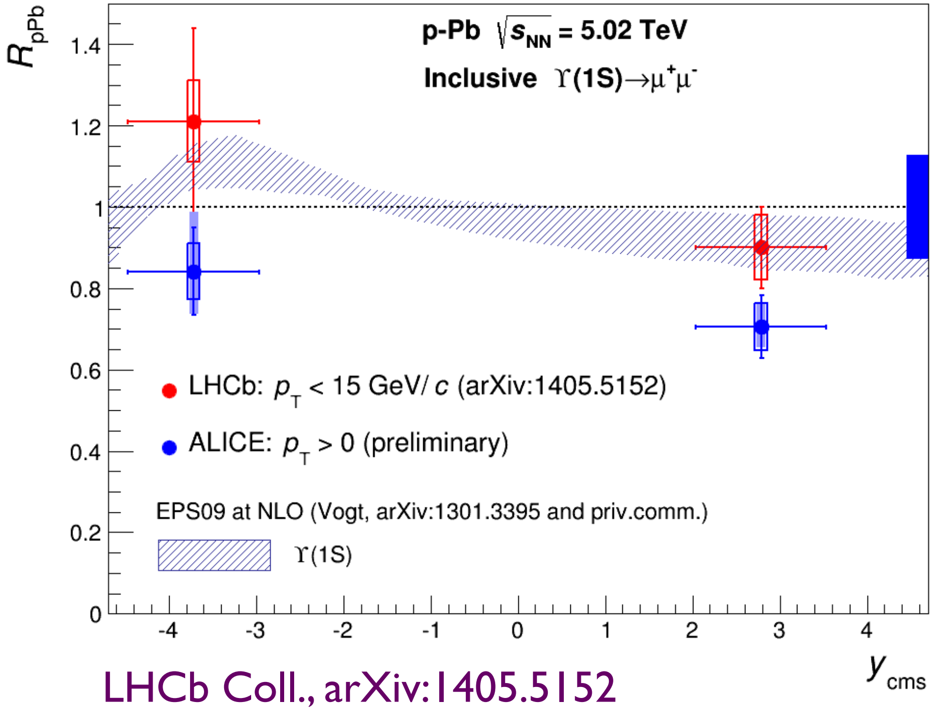
ALICE Coll., arXiv:1405.3796

ψ(2S) suppression is stronger than the one of **J/ψ**

Same initial state CNM effects for J/ψ and ψ(2S)

Other mechanisms needed to explain ψ(2S) behaviour?

CNM for ϒ



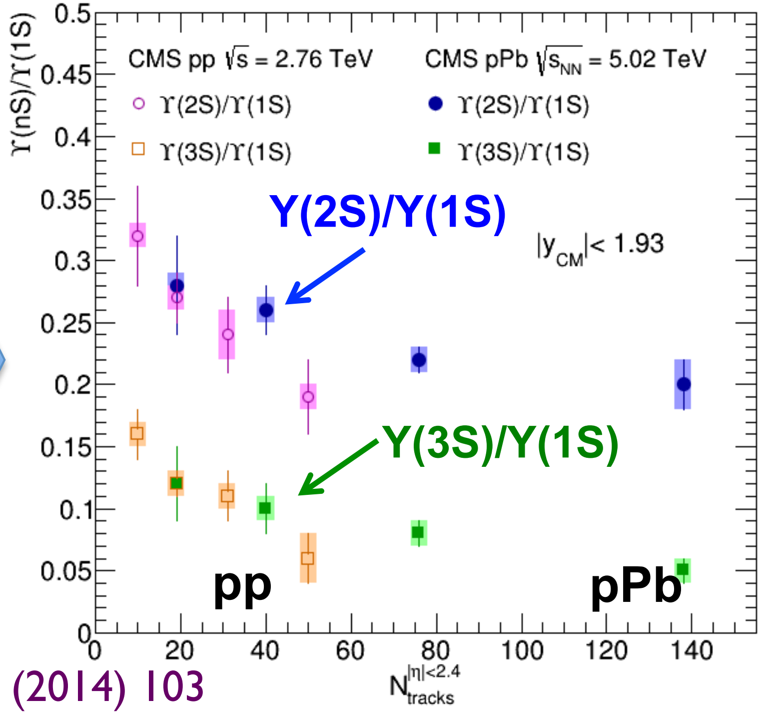
LHCb Coll., arXiv:1405.5152

Hint of ϒ suppression at forward rapidities

Qualitative agreement with models within the uncertainties.

ϒ in pPb vs event multiplicity:

Excited/ground state ratio seems to vary wrt to event multiplicity (at midrapidity) in pPb and pp

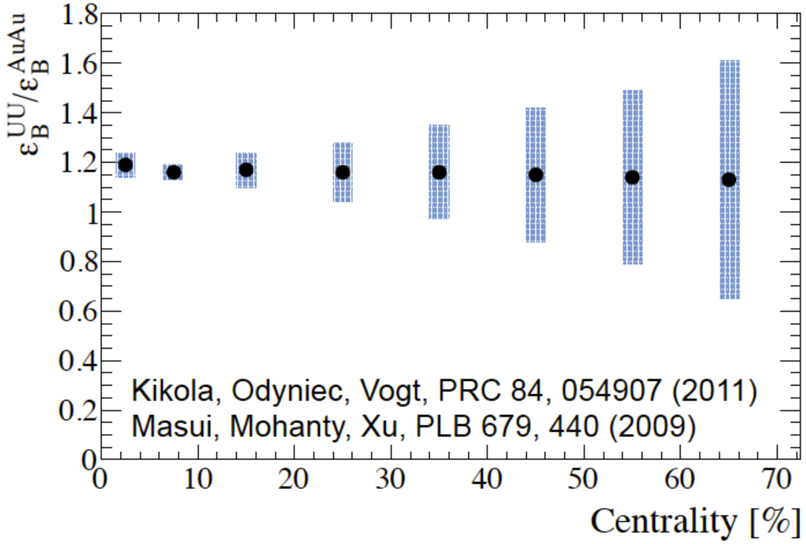


CMS Coll., JHEP 04 (2014) 103

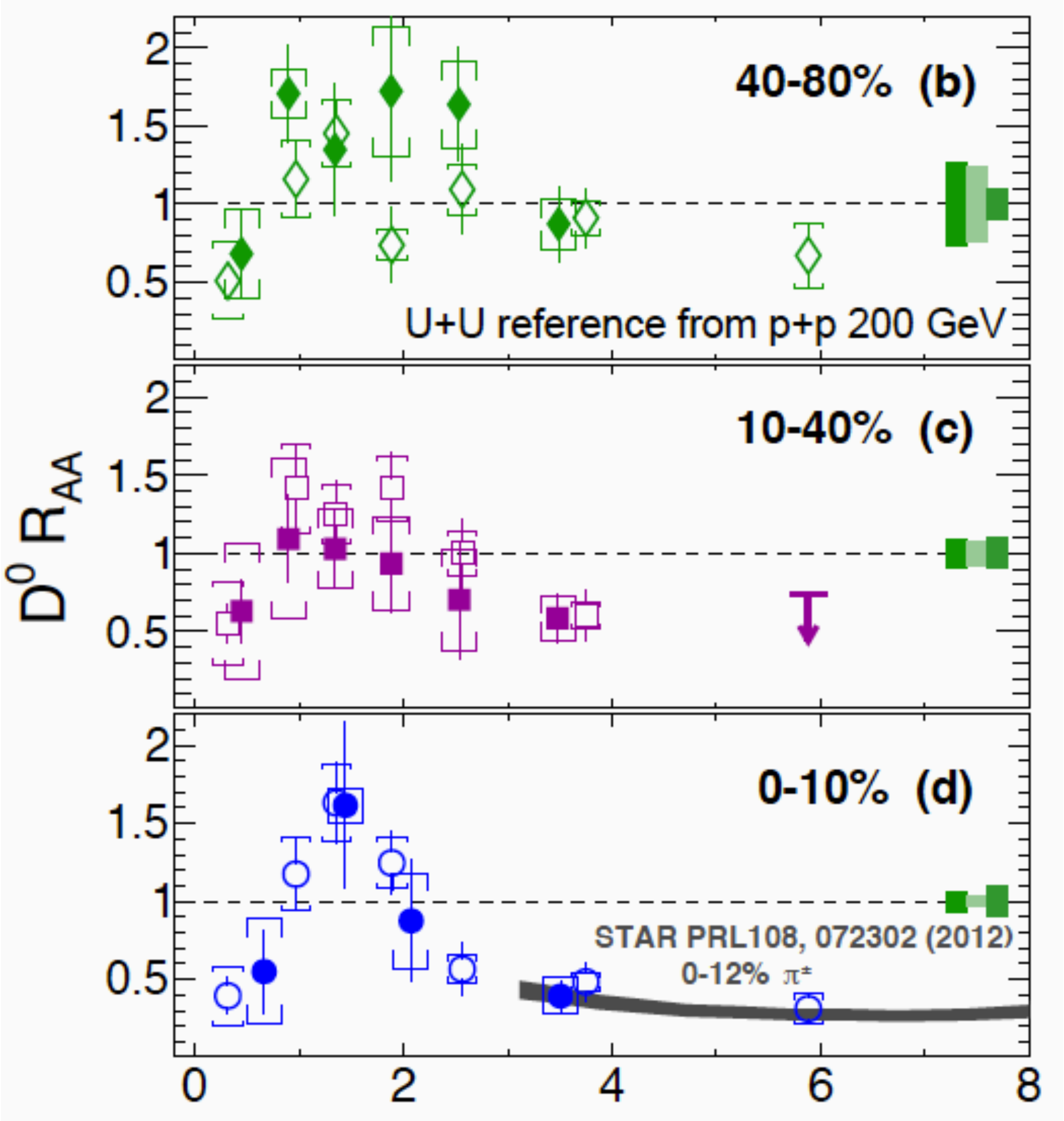
Conclusions

- 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 the LHC
- Quarkonia
  - from RHIC to LHC : J/ψ (re)combination effects at LHC, less relevant at RHIC?
  - ϒ hierarchy in suppression according to their binding energies
- Next: more precise measurements to sharpen the conclusions
  - RHIC: High-statistics runs, new detectors and future upgrades
  - LHC: Run 2 and detectors/machine upgrades

U+U at RHIC



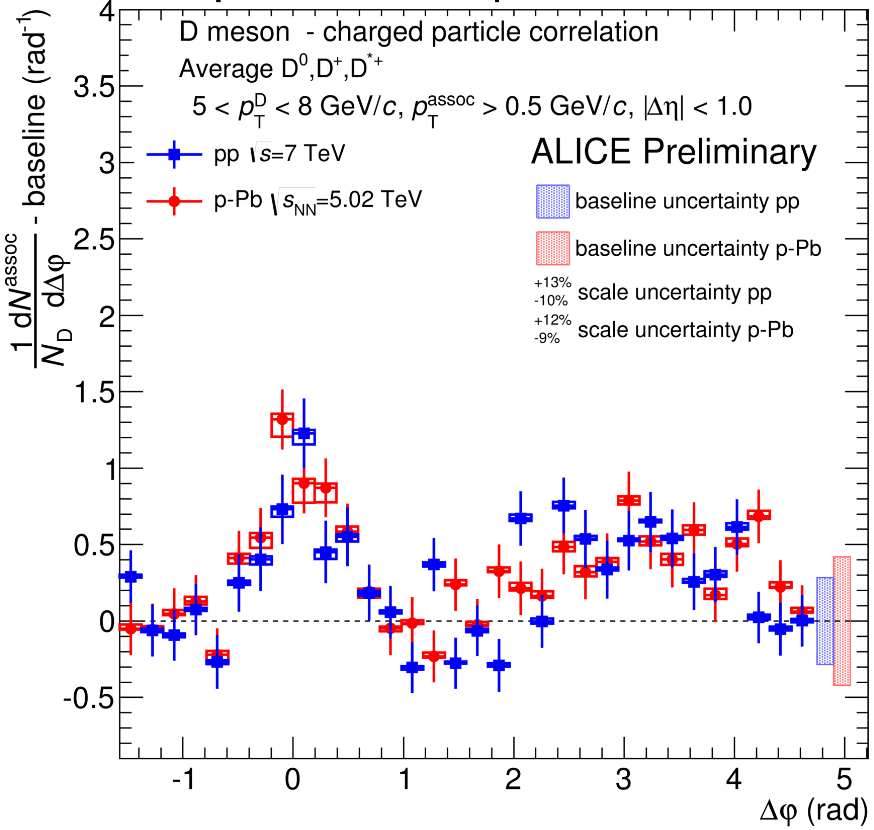
Kikola, Odyniec, Vogt, PRC 84, 054907 (2011)
Masui, Mohanty, Xu, PLB 679, 440 (2009)



STAR PRL108, 072302 (2012)
0-12% $\pi^{\pm}$

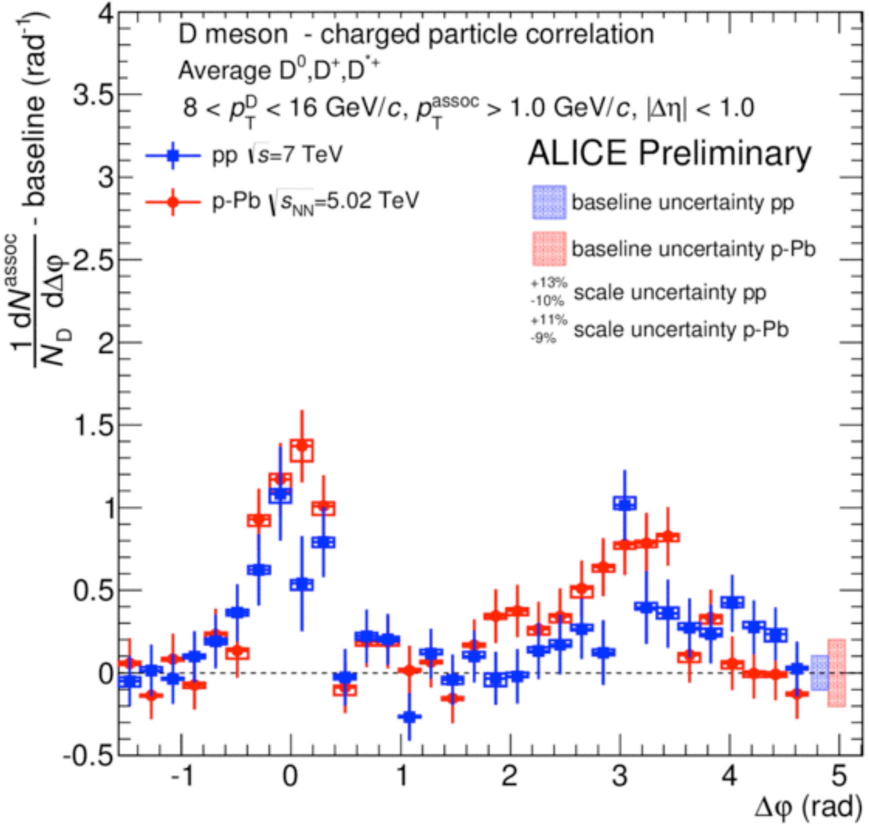
D- hadron azimuthal correlations: pp vs p-Pb

$5<p_T^D<8$ GeV/c, $p_T^{assoc}>0.5$ GeV/c



ALI-PREL-79970

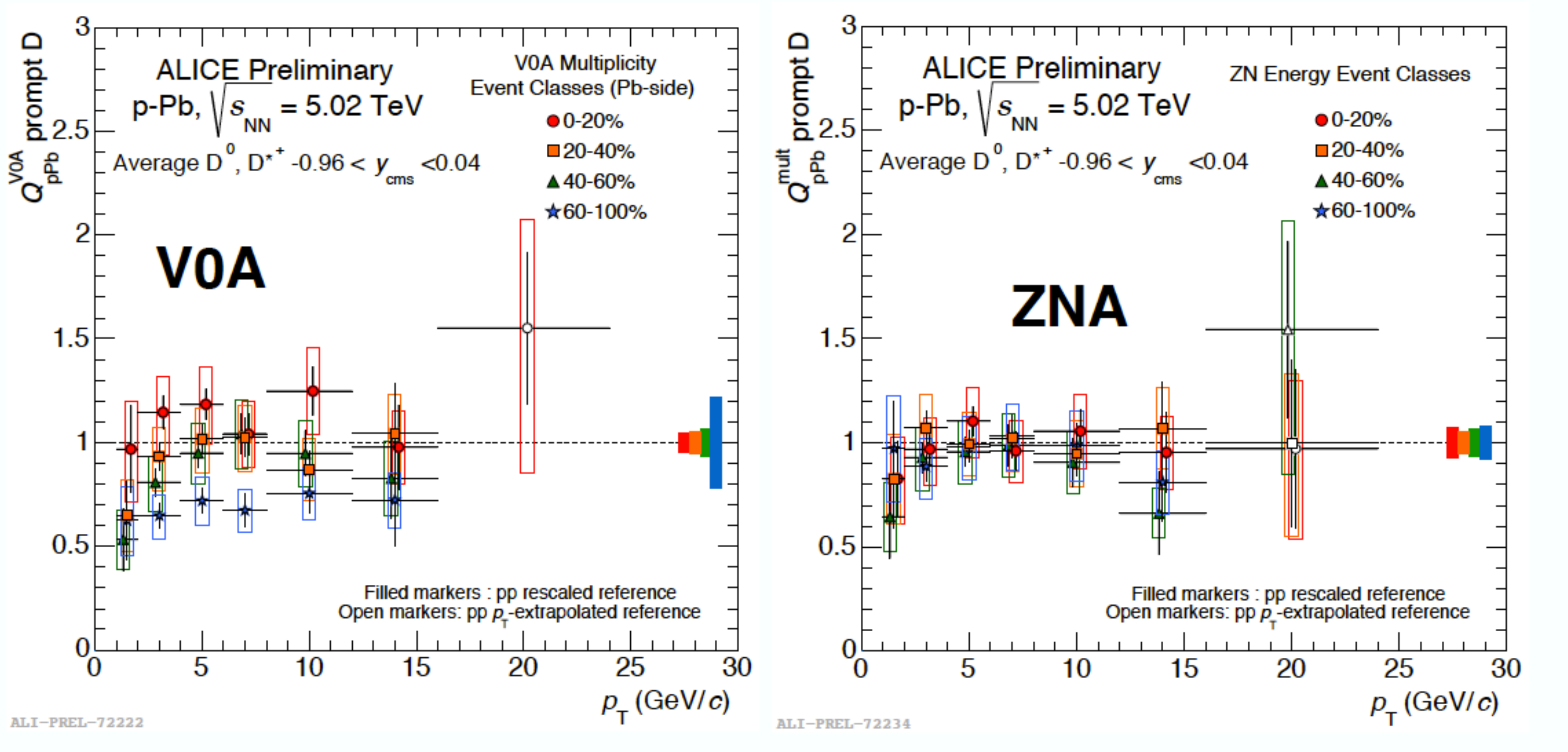
$8<p_T^D<16$ GeV/c, $p_T^{assoc}>1$ GeV/c



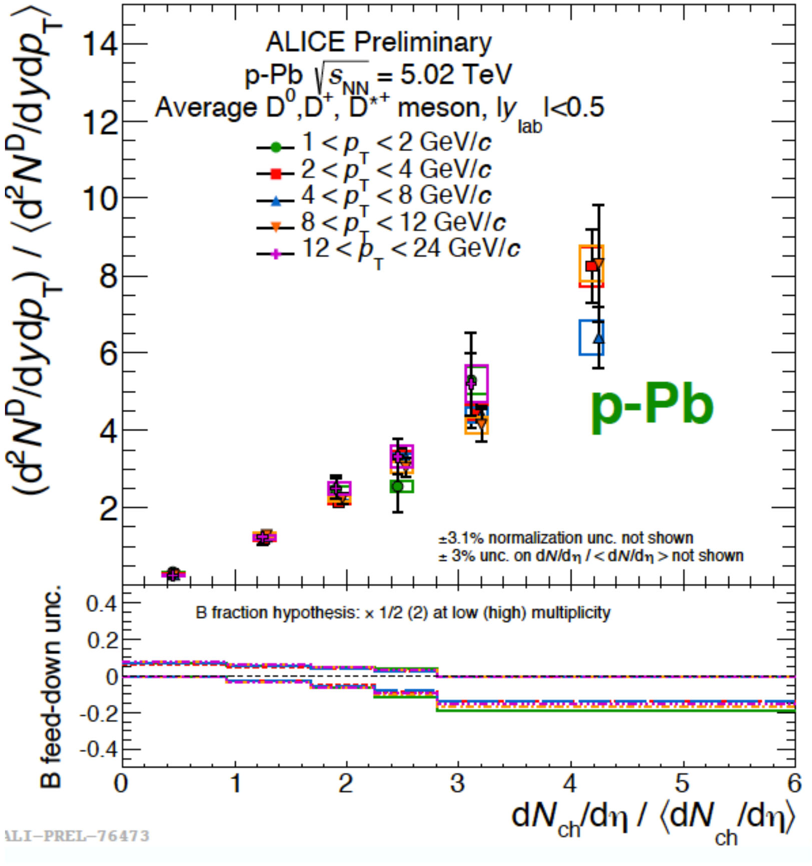
ALI-PREL-79884

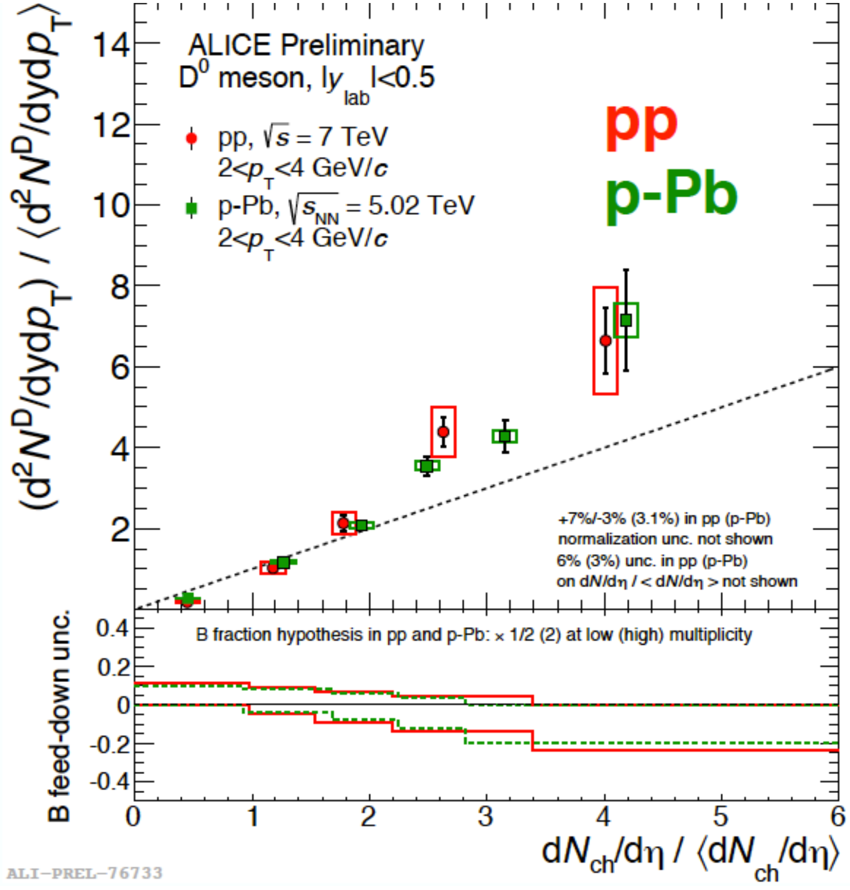
Compatibility within uncertainties between pp collisions at $\sqrt{s}$ = 7 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV after baseline subtraction

QpPb for D mesons



D mesons vs multiplicity in p-Pb





RpPb: ALICE and LHCb