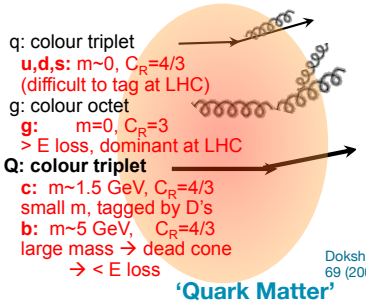
Experimental Data on
Open Heavy Flavour and Quarkonia

MinJung Kweon
Inha University
HIM
June 20, 2014

What's special about heavy quarks

- Large mass ($m_q \gg \Lambda_{QCD}$) → produced in the early stages of the HI collision with short formation time($t_{charm} \sim 1/m_c \sim 0.1$ fm/c << $\tau_{QGP} \sim O(10$ fm/c)), traverse the medium interacting with its constituents
  - ➡ natural probe of the hot medium created in HI interactions
- Interactions with QGP don't change flavour identity
- Uniqueness of heavy quarks: cannot be destroyed/created in the medium
  - ➡ transported through the full system evolution



q: colour triplet
u,d,s: m~0, C_R=4/3
(difficult to tag at LHC)
g: colour octet
g: m=0, C_R=3
> E loss, dominant at LHC
Q: colour triplet
c: m~1.5 GeV, C_R=4/3
small m, tagged by D's
b: m~5 GeV, C_R=4/3
large mass → dead cone
→ < E loss

'Quark Matter'

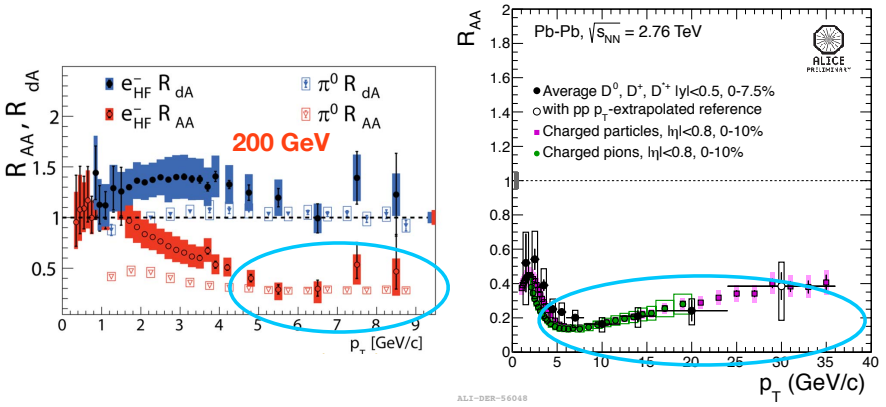
Parton Energy Loss by
→ medium-induced gluon radiation
→ collisions with medium constituents

$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

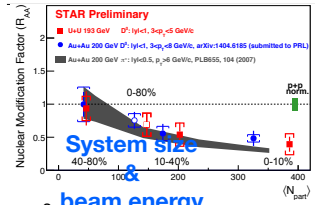
Prediction: $\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$

Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

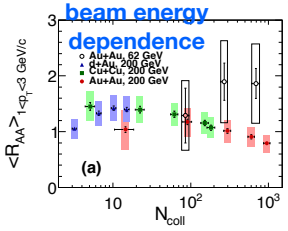
At both RHIC and LHC: suppressed as much as ...

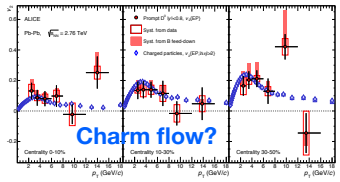


Suppressed → Answers to more differential questions

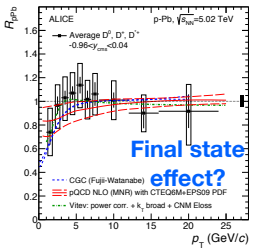


System size & beam energy dependence

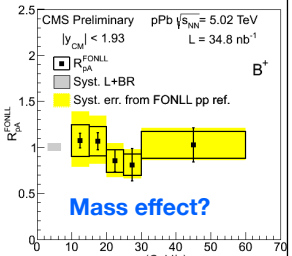




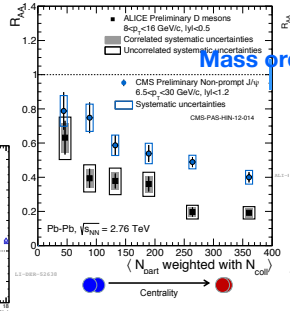
Charm flow?



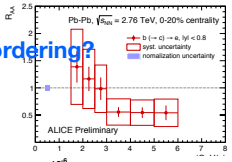
Final state effect?

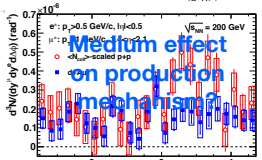


Mass effect?



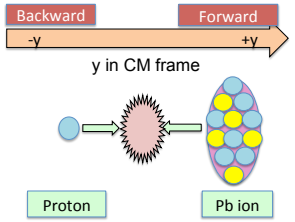
Mass ordering?





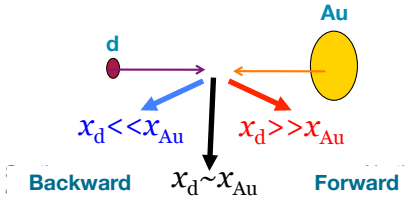
Medium effect on production mechanism?

LHC



y_{CMS} = 0.465 in the p-beam direction

RHIC



p-A collisions at √s = 0.2 and 5.02 TeV

d-Au, p-Pb
Cold nuclear matter effect

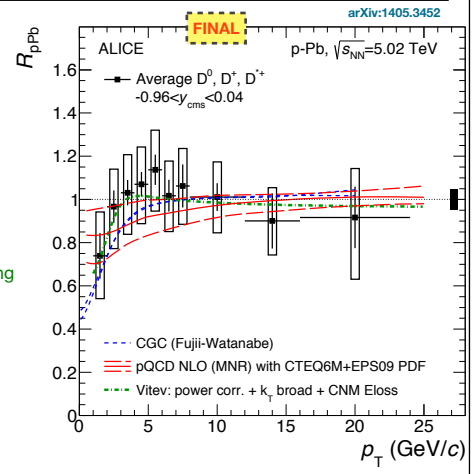
$$\frac{dN^{D}_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^{c}}{dp_T} \otimes P(\Delta E) \otimes D_{c\to D}(z)$$

Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE

- D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

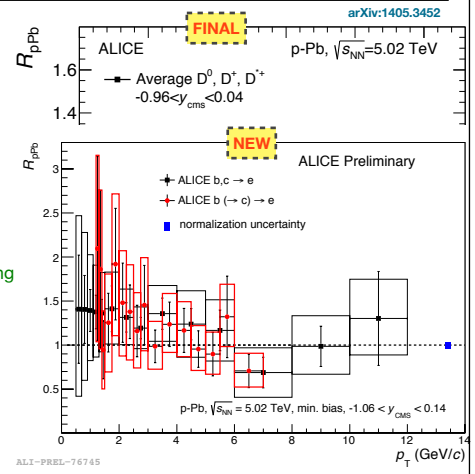


Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

ALICE ◉ c,b→e & b→e (mid rapidity)



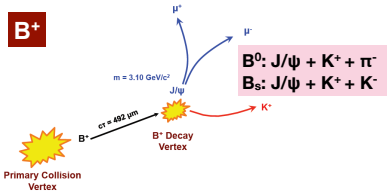
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

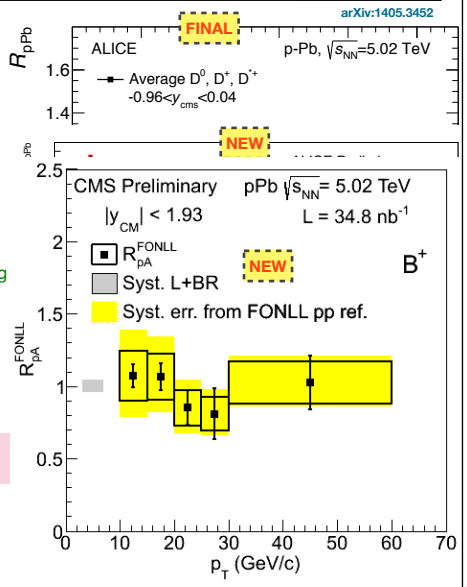
ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

ALICE ◉ c,b→e & b→e (mid rapidity)

CMS ◉ B^+, B^0, B_s (mid rapidity): FONLL expectation as a pp reference



B^0: J/ψ + K^+ + π^-
B_s: J/ψ + K^+ + K^-



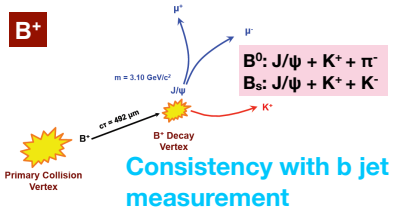
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadenir

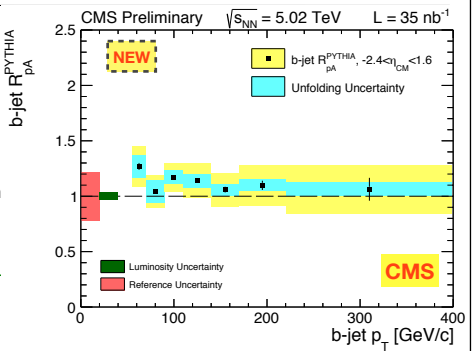
ALICE ◉ c,b→e & b→e (mid rapidity)

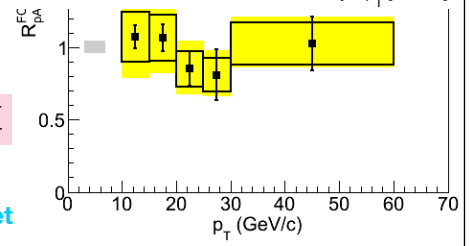
CMS ◉ B^+, B^0, B_s (mid rapidity): FONLL expectation as a pp reference



B^0: J/ψ + K^+ + π^-
B_s: J/ψ + K^+ + K^-

Consistency with b jet measurement



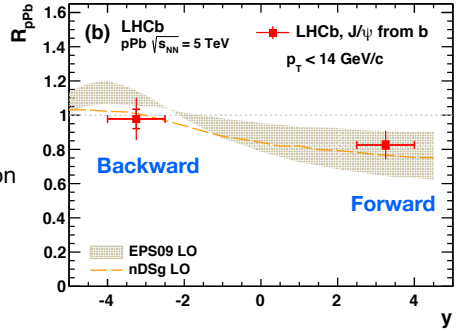


Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- Slight rapidity dependence

LHCb ◉ non-prompt J/ψ:

- at forward, modest suppression
- at backward, consistent with unity within uncertainties



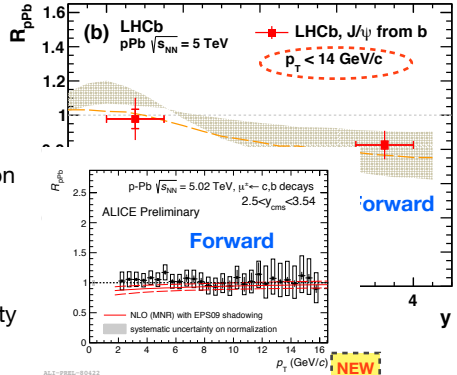
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- Slight rapidity dependence

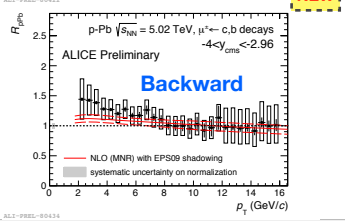
LHCb
- non-prompt J/ψ:
  - at forward, modest suppression
  - at backward, consistent with unity within uncertainties
- c,b→μ:
  - at forward, consistent with unity within uncertainties
  - at backward, slightly larger than unity in 2<p_T<4 GeV

ALICE

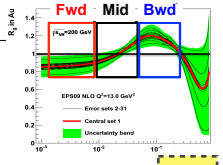
Within uncertainties, data can be described by pQCD calculations with EPS09 parameterization of shadowing



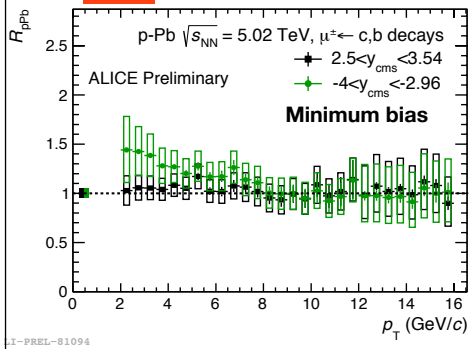
NEW



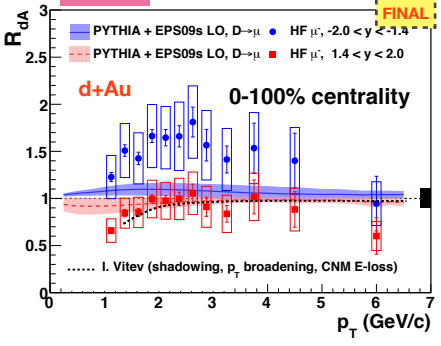
Heavy flavour in pA at LHC and RHIC



ALICE



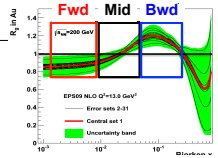
PHENIX



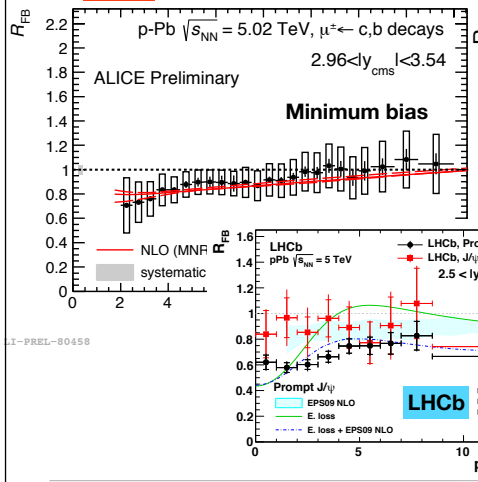
At RHIC, fail to reproduce the data at both rapidity simultaneously

arXiv:1310.1005

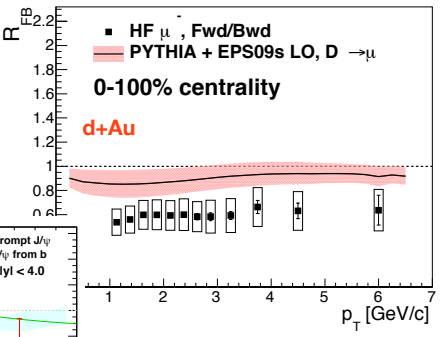
Heavy flavour in pA at LHC and RHIC



ALICE

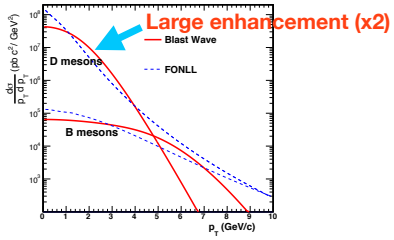


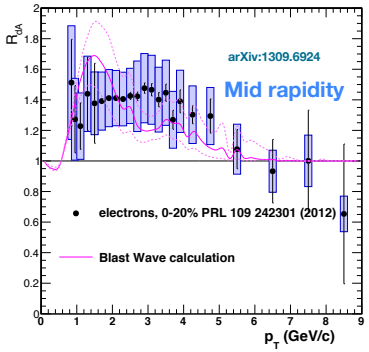
PHENIX



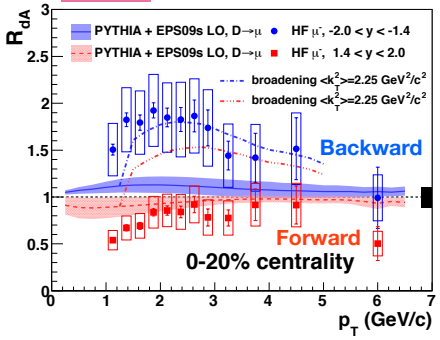
At RHIC, fail to reproduce the data at both rapidity simultaneously

Enhancement in central d+Au





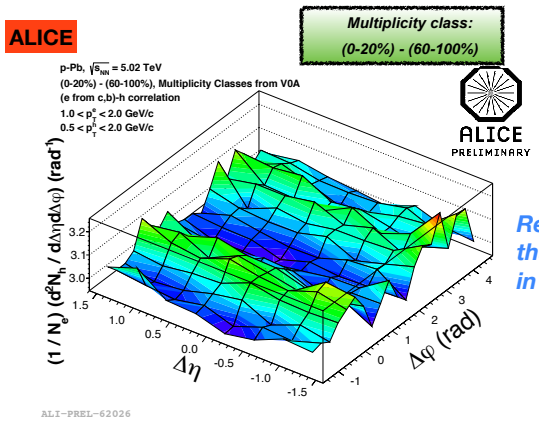
PHENIX



← **Radial flow qualitatively reproduces the data!**

Enhancement at mid- and backward rapidity possibly due to hydrodynamics?

More differential information:
Heavy-flavour electron-hadron correlations



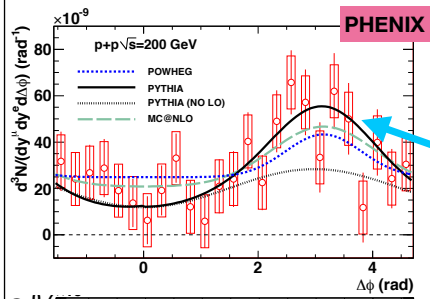
supporting?

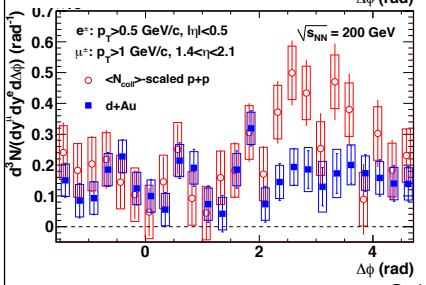
Resembles the structure that in AA is interpreted in terms of collective flow

The double ridge also observed in heavy-flavour sector!

The mechanism (CGC? Hydro?) that generates it affects also HF

More differential information:
Heavy-flavour electron-muon correlation in d+Au





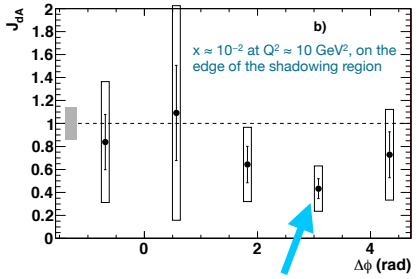
Phys. Rev. C 89, 034915 (2014)

Access to the *g*-PDF?

$\sigma_{c\bar{c}} = 538 \pm 46(\text{stat}) \pm 197(\text{data sys}) \pm 174(\text{model sys})\mu b$

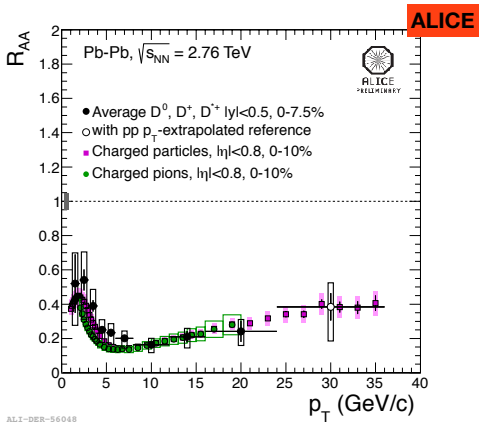
Peak by leading order gluon fusion
Continuum by higher order processes

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



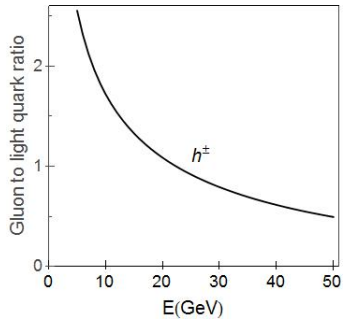
Cold nuclear medium modifies the $c\bar{c}$ correlations

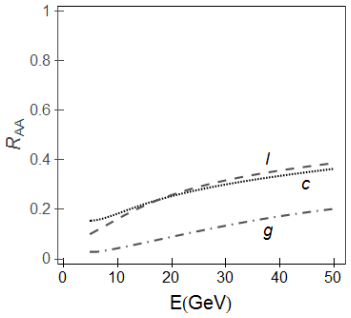
Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$



- Comparable results for π and D mesons suppressions within uncertainties
- Is it consistent with the colour charge dependence picture?

Heavy flavour puzzle at LHC



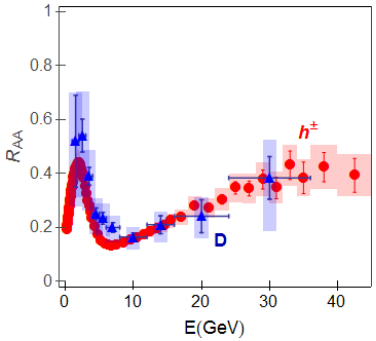


Significant gluon contribution in charged hadrons

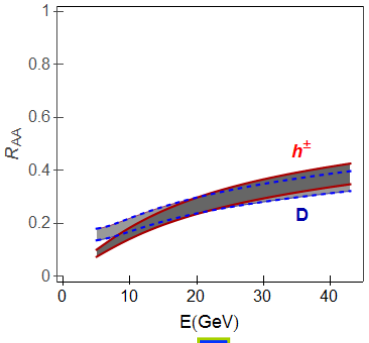
Much larger gluon suppression

$$R_{AA}(h^{\pm}) < R_{AA}(D)$$

Charged hadrons vs D meson R_{AA}



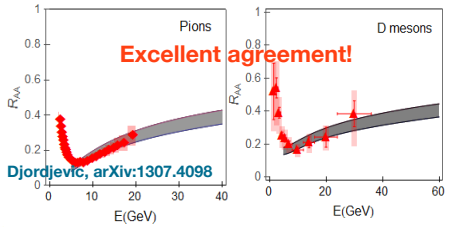
R_{AA} ($h^{\pm}$) = R_{AA} (D)



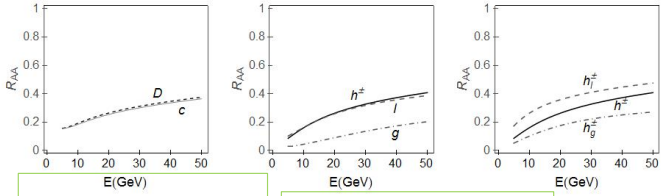
Excellent agreement with the data!

Disagreement with the qualitative expectations!

Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$



Calculation by M. Djordjevic (rad+coll energy loss) can describe both R_{AA}



Shows strong colour charge effect in partonic R_{AA} (g vs. light and c)

R_{AA} (D) = R_{AA} (charm)

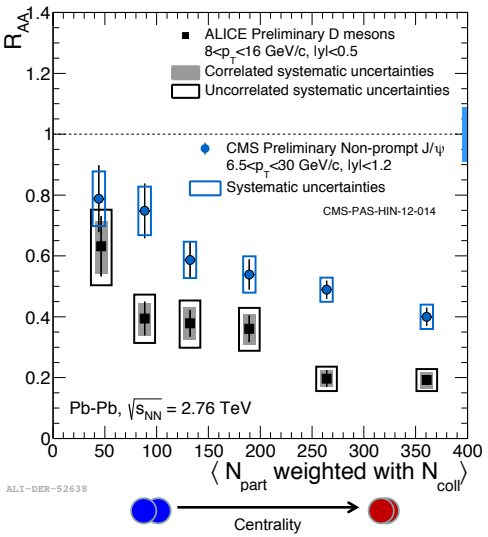
R_{AA} (light quarks) = R_{AA} (charm)

Distortion by fragmentation!

R_{AA} ($h^{\pm}$) = R_{AA} (D)

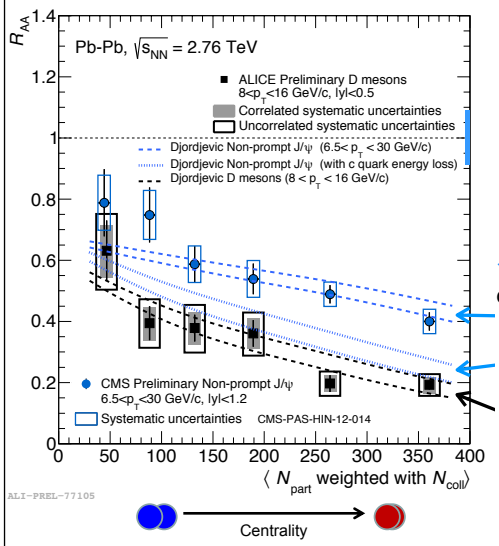
Colour charge effect plays!

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ



- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c
- **Clear indication of a dependence on quark mass : $R_{AA}^B > R_{AA}^D$**

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ



- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c
- **Clear indication of a dependence on quark mass : $R_{AA}^B > R_{AA}^D$**

✓ Djordjevic: non-prompt J/ψ R_{AA} considering for energy loss
- b quark mass
- c quarkmass

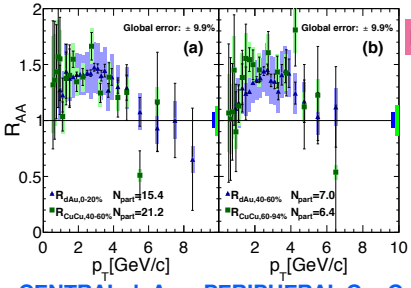
No trivial relation between ΔE and R_{AA}

✓ Djordjevic: D meson R_{AA}

Calculation by M. Djordjevic (including mass-dependent rad+coll energy loss) predict a difference

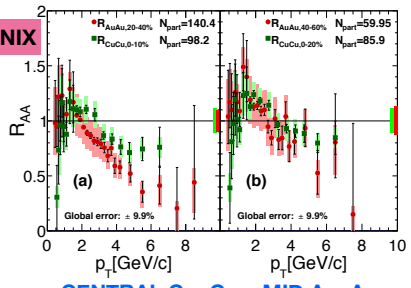
Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).

System size dependence of R_{AA}



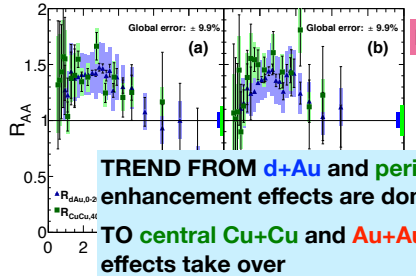
CENTRAL d+Au ≈ PERIPHERAL Cu+Cu

PHENIX

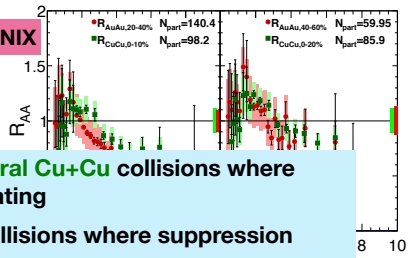


CENTRAL Cu+Cu ≈ MID Au+Au

System size dependence of R_{AA}

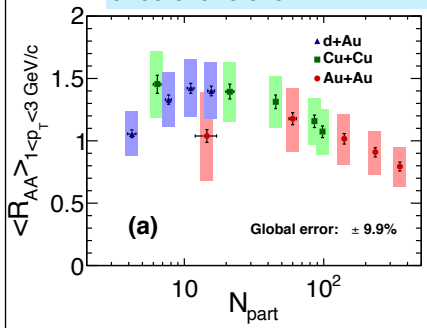


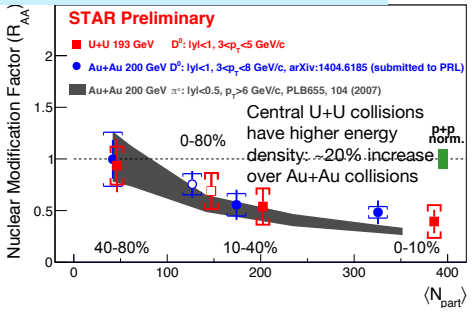
PHENIX



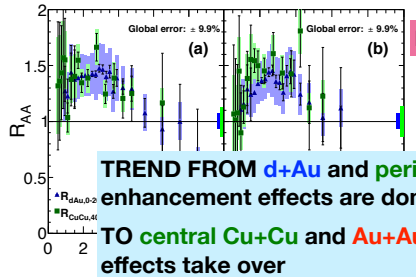
TREND FROM d+Au and peripheral Cu+Cu collisions where enhancement effects are dominating

TO central Cu+Cu and Au+Au collisions where suppression effects take over

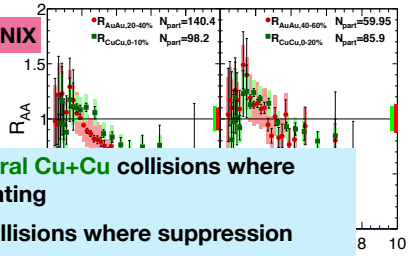




System size dependence of R_{AA}

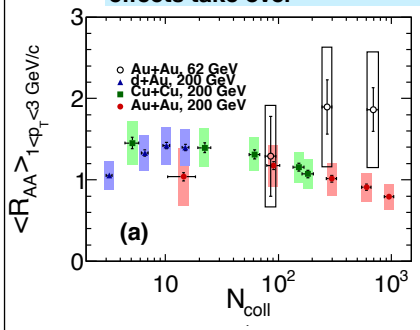


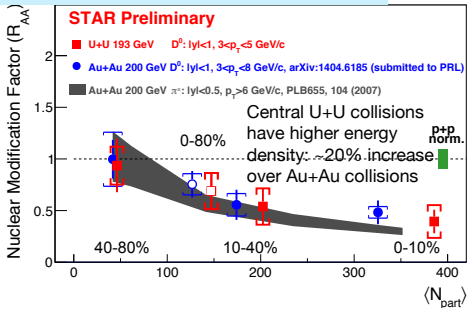
PHENIX



TREND FROM d+Au and peripheral Cu+Cu collisions where enhancement effects are dominating

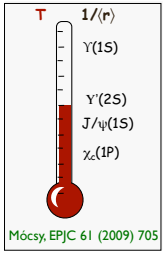
TO central Cu+Cu and Au+Au collisions where suppression effects take over

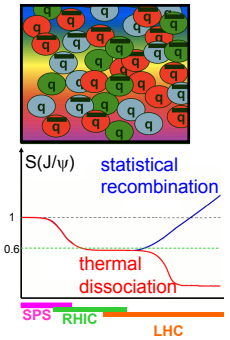




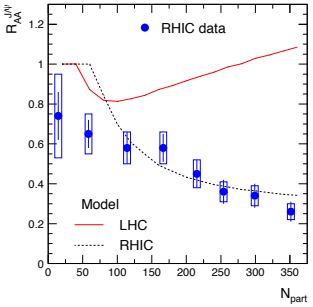
What's special about Quarkonia

What happens in QGP to the Quarkonia?
→ Suppression by color screening (disappearance of specific quarkonium states signals)
→ Regeneration by statistical recombination?





Matsui, Satz, PLB178 (1986) 416
Digal et al., PRD64 (2001) 094015
Braun-Munzinger, Stachel, PLB 490 (2000) 196 40



What is so different at LHC?
(compared to RHIC)
$\sigma_{c\bar{c}}$: ~10x, Volume: 2.2-3x

AA et al., PLB 652 (2007) 259

Latest from experiments on Quarkonia

A.Andronic@GSI.de

STAR

Suppression of Υ Production in d+Au and Au+Au Collisions at $\sqrt{s_{\rm NN}} = 200$ GeV arXiv:1312.3675

PHENIX

Measurement of Υ(1S+2S+3S) production in p+p and Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV arXiv:1404.2246

Nuclear matter effects on J/ψ production in asymmetric Cu+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV arXiv:1404.1873

Nuclear modification of ψ', χ_c and J/ψ production in d+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV arXiv:1305.5516

CMS

Event activity dependence of $\Upsilon(nS)$ production in $\sqrt{s_{\rm NN}} = 5.02$ TeV pPb and $\sqrt{s} = 2.76$ TeV pp collisions arXiv:1312.6300

ALICE

Suppression of $\Upsilon(1S)$ production at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV arXiv:1405.4493

Suppression of $\psi(2S)$ production in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV arXiv:1405.3796

Centrality, rapidity and transverse momentum dependence of J/ψ suppression in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV arXiv:1311.0214

J/ψ production and nuclear effects in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV arXiv:1308.6726

J/ψ elliptic flow in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV arXiv:1303.5880

LHCb

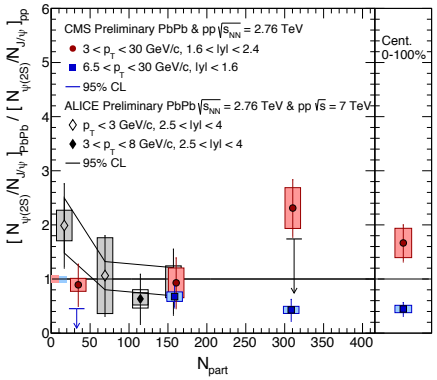
Study of Υ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV arXiv:1405.5152

Study of J/ψ production and cold nuclear effects in pPb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV arXiv:1308.6729

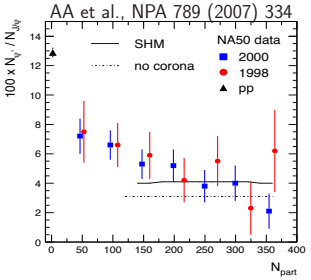
$\psi(2S)$ production at the LHC

A.Andronic@GSI.de

$$R = \frac{N^{\psi(2S)}_{\mathrm{Pb-Pb}}/N^{J/\psi}_{\mathrm{Pb-Pb}}}{N^{\psi(2S)}_{\mathrm{pp}}/N^{J/\psi}_{\mathrm{pp}}} = \frac{R^{\psi(2S)}_{\mathrm{AA}}}{R^{J/\psi}_{\mathrm{AA}}}$$



(light) "discrepancy" ALICE / CMS ? mind diff. p_T, y ranges (thanks, Raphaël:)

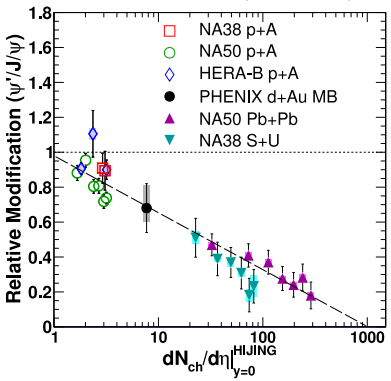


at SPS: $R \simeq 0.24$ (p_T-integrated)
...evidence against sequential dissociation

Charmonium in p(d)-A collisions

A.Andronic@GSI.de

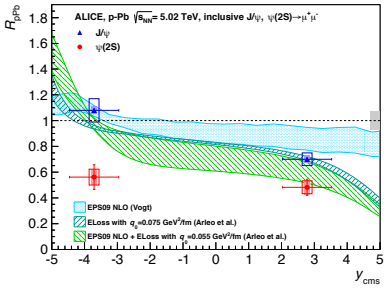
PHENIX, arXiv:1305.5516 (Durham, HF 5)



abs. cross sect. depends on time spent in the nucleus

(McGlinchey et al., PRC 87 (2013) 054910)

ALICE, arXiv:1405.3796 (Arnaldi, HF 5)



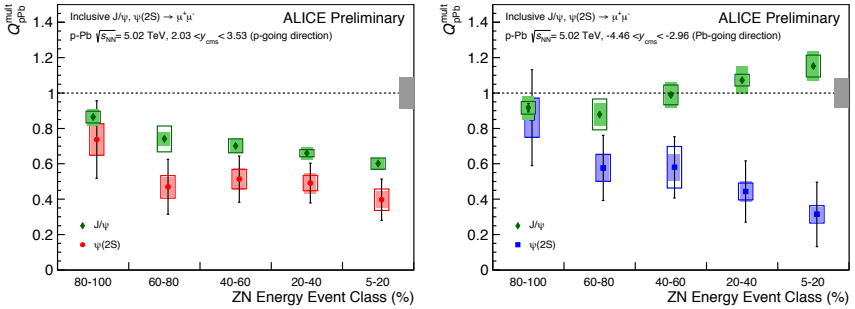
at the LHC, the strong $\psi(2S)$ suppression in Pb-side remains puzzling

indication for final-state effects?

Charmonium prod. vs. event activity in p-Pb collisions

A.Andronic@GSI.de

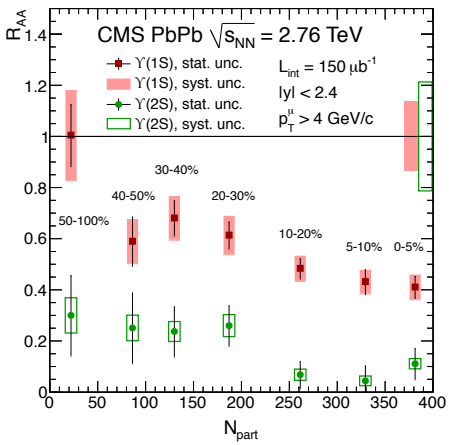
ALICE (Arnaldi, HF 5, Lakomov, F-26)



different suppression pattern on Pb-side

Bottomonium at the LHC

A.Andronic@GSI.de



CMS, PRL 109 (2012) 222301

interpreted as effect of (<u>almost</u>:) full dissoc. of $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b

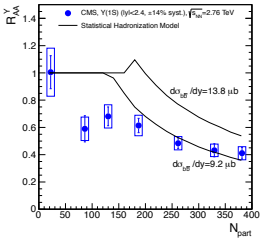
Transport models:

Emerick et al./TAMU, EPJA 48 (2012) 72

Zhuang, HF 6

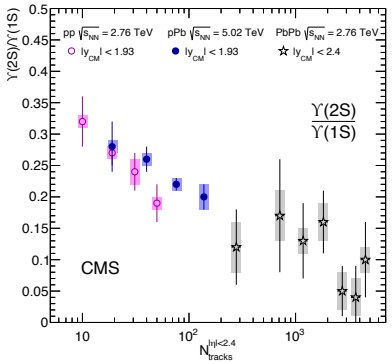
(re)gen. component small ($\lesssim$10%),

Stat. Hadr. model



Bottomonium ratios in p-Pb collisions

A.Andronic@GSI.de



approximate scaling with multiplicity

thermal model:
$\Upsilon(2S)/\Upsilon(1S)$=0.033
(and again against sequential dissoc.)

CMS, arXiv:1312.6300 (Valiyavalappil Kizhakkepura, HF 6)

Backup

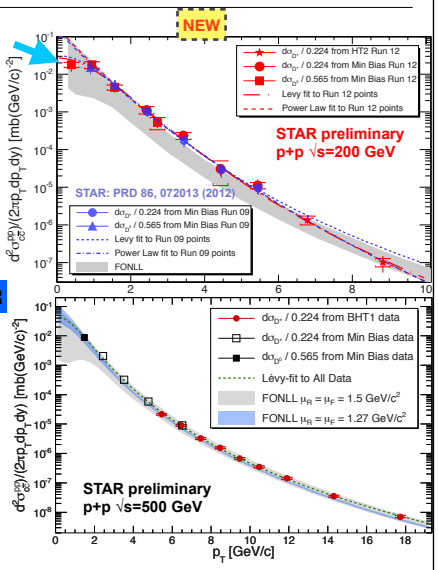
pp collisions at $\sqrt{s}$ = 0.2, 0.5, 2.76 and 7 TeV

Baseline for AA, pA
Test pQCD: more differentially...

p_T-differential cross sections in pp collisions

- Heavy flavour cross section measurements: **extended kinetic reaches, beam energy dependences**

- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
  - D^0, D^{*+} (mid rapidity, down to p_T~0.4 GeV/c at 200 GeV) at **200 & 500 GeV** **STAR**

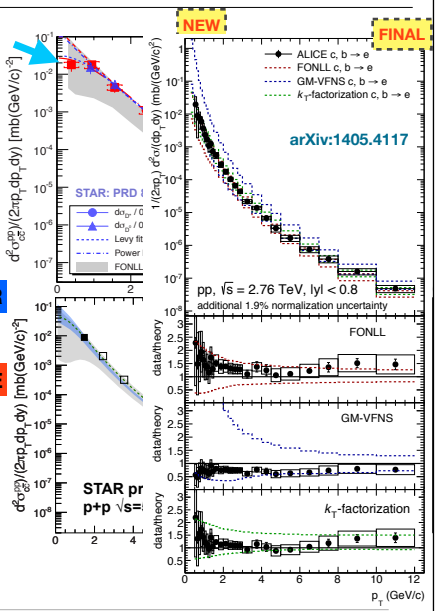


FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082,
k_T factorisation: arXiv:1301.3033

p_T-differential cross sections in pp collisions

- Heavy flavour cross section measurements: **extended kinetic reaches, beam energy dependences**

- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
  - D^0, D^{*+} (mid rapidity, down to p_T~0.4 GeV/c at 200 GeV) at **200 & 500 GeV** **STAR**
  - D^0, D^+, D^{*+} mesons (mid rapidity) at 2.76 & 7 TeV
  - c,b→e (mid rapidity, down to p_T~0.5 GeV/c) at **2.76** & 7 TeV **ALICE**
  - c,b→μ (forward rapidity) at 2.76 & 7 TeV

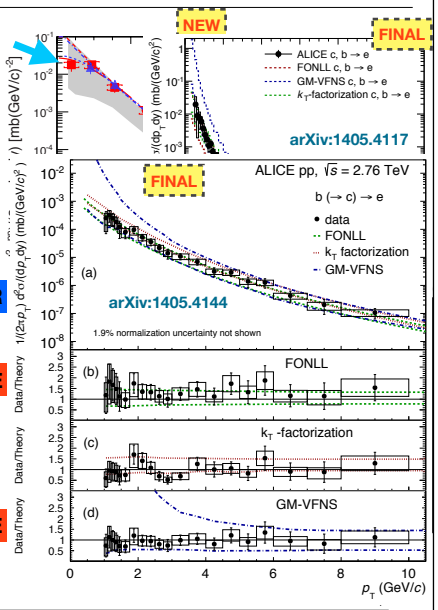


FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082,
k_T factorisation: arXiv:1301.3033

p_T-differential cross sections in pp collisions

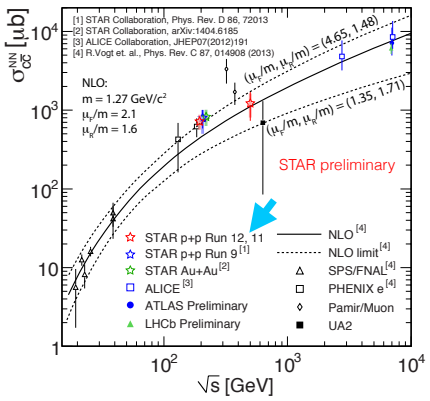
- Heavy flavour cross section measurements: **extended kinetic reaches, beam energy dependences**

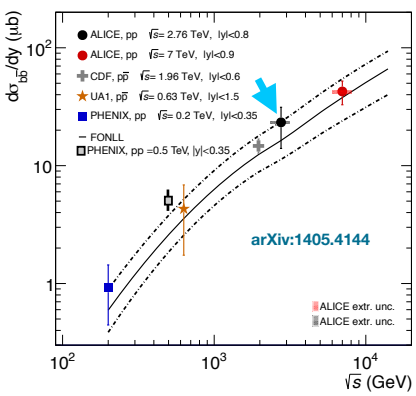
- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
  - D^0, D^{*+} (mid rapidity, down to p_T~0.4 GeV/c at 200 GeV) at **200 & 500 GeV** **STAR**
  - D^0, D^+, D^{*+} mesons (mid rapidity) at 2.76 & 7 TeV
  - c,b→e (mid rapidity, down to p_T~0.5 GeV/c) at **2.76** & 7 TeV **ALICE**
  - c,b→μ (forward rapidity) at 2.76 & 7 TeV
  - b→e (mid rapidity, down to p_T~1 GeV/c) at **2.76** & 7 TeV **ALICE**



FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082,
k_T factorisation: arXiv:1301.3033

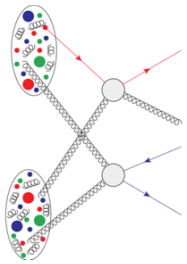
Heavy flavour production cross sections





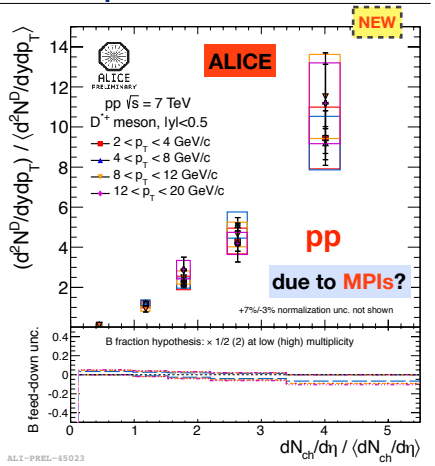
- Calculation based on pQCD (ex. FONLL) describes consistently energy dependence of total cross sections
- Charm (beauty) x~10 (~100) from RHIC (200 GeV) to LHC

More on production mechanism:
Multiplicity dependences of charm production



Particle production in pp collisions at LHC shows **better agreement with models including MPIs**

Eur. Phys. J. C 73 (2013) 2674



For heavy flavours:

- LHCb: double charm production agrees better with models including double parton scattering

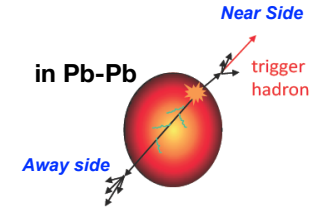
J. High Energy Phys., 06 (2012) 141

MPIs involving only light quarks and gluons?

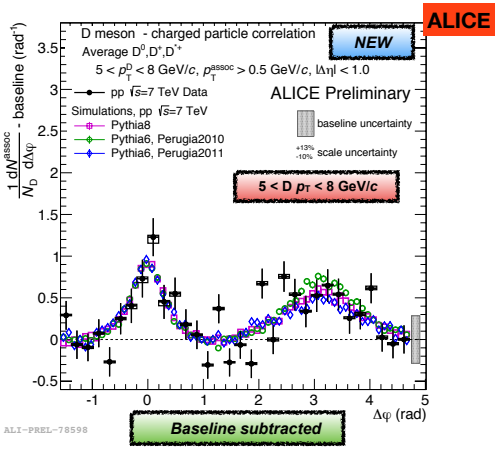
- D-meson yields increase with charged-particle multiplicity
→ presence of MPI and contribution on the a harder scale?

More differential information:
Heavy flavour correlations

Heavy flavour jet properties

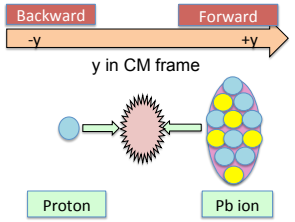


Path length dependence



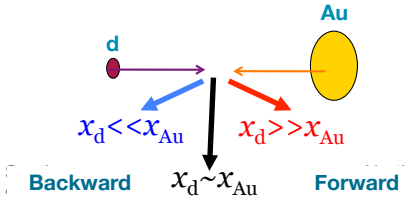
- D-hadron correlations in pp show good agreement with expectations from Pythia (different tunes)

LHC



y_{CMS} = 0.465 in the p-beam direction

RHIC



p-A collisions at √s = 0.2 and 5.02 TeV

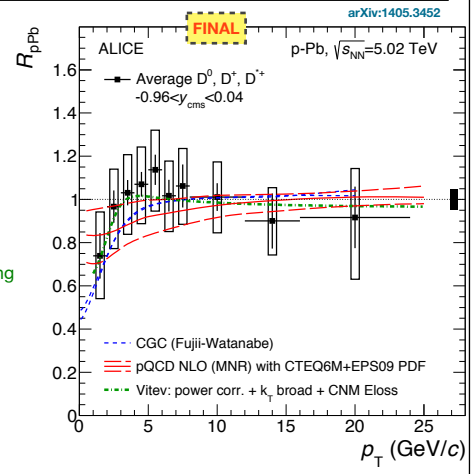
d-Au, p-Pb
Cold nuclear matter effect

$$\frac{dN^{D}_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^{c}}{dp_T} \otimes P(\Delta E) \otimes D_{c\to D}(z)$$

Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

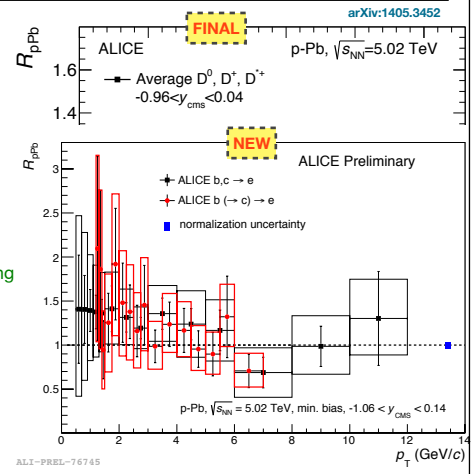


Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

ALICE ◉ c,b→e & b→e (mid rapidity)



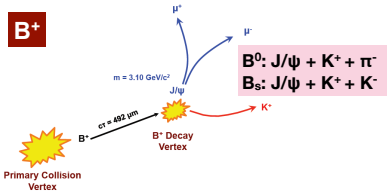
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

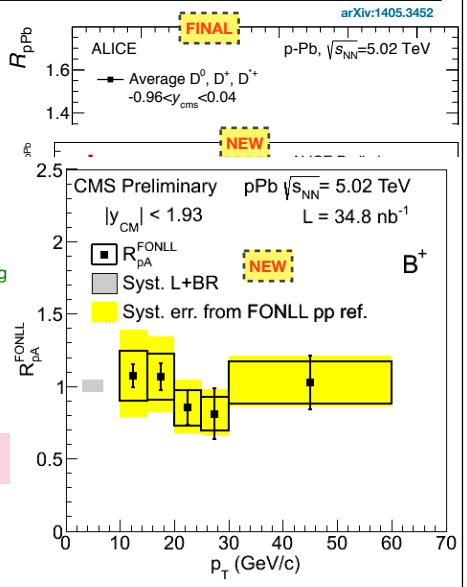
ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

ALICE ◉ c,b→e & b→e (mid rapidity)

CMS ◉ B^+, B^0, B_s (mid rapidity): FONLL expectation as a pp reference



B^0: J/ψ + K^+ + π^-
B_s: J/ψ + K^+ + K^-



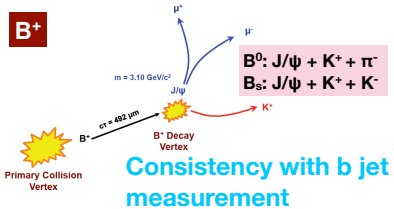
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadenir

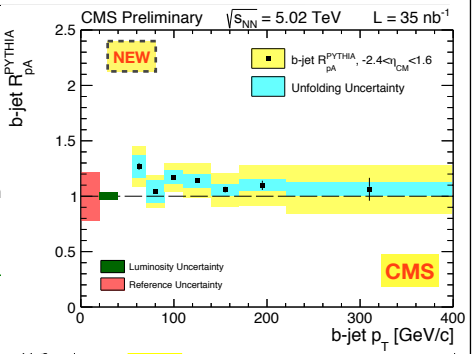
ALICE ◉ c,b→e & b→e (mid rapidity)

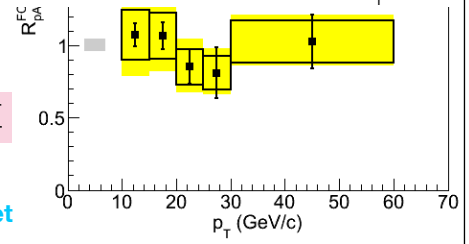
CMS ◉ B^+, B^0, B_s (mid rapidity): FONLL expectation as a pp reference



B^0: J/ψ + K^+ + π^-
B_s: J/ψ + K^+ + K^-

Consistency with b jet measurement



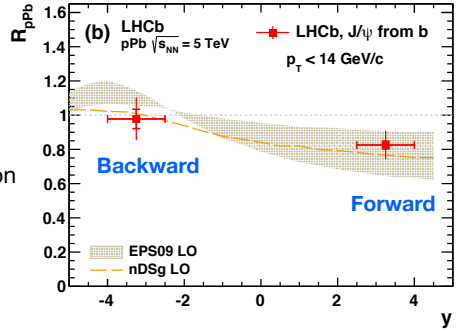


Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- Slight rapidity dependence

LHCb ◉ non-prompt J/ψ:

- at forward, modest suppression
- at backward, consistent with unity within uncertainties



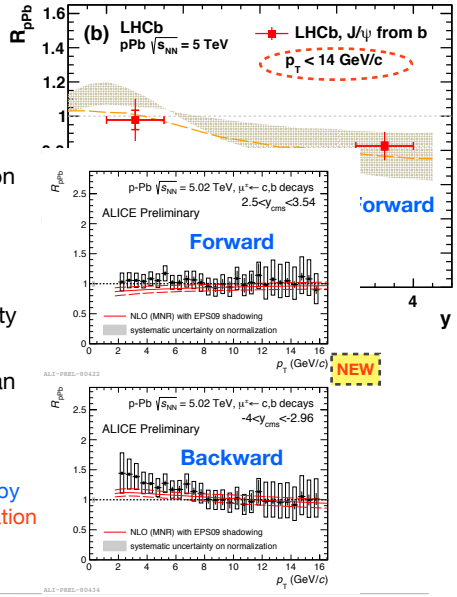
Heavy flavour in p-Pb at LHC (at 5.02 TeV)

- R_{pPb} measured in various channels
- Slight rapidity dependence

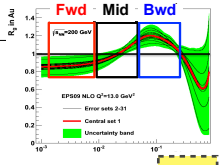
LHCb
- non-prompt J/ψ:
  - at forward, modest suppression
  - at backward, consistent with unity within uncertainties
- c,b→μ:

ALICE
  - at forward, consistent with unity within uncertainties
  - at backward, slightly larger than unity in 2<p_T<4 GeV

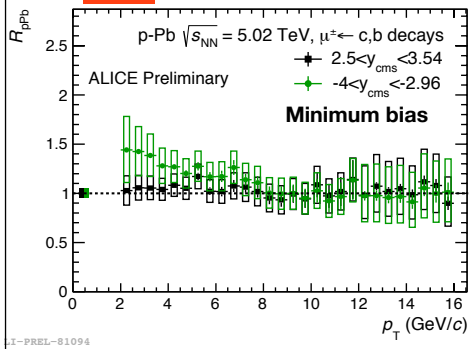
Within uncertainties, data can be described by pQCD calculations with EPS09 parameterization of shadowing



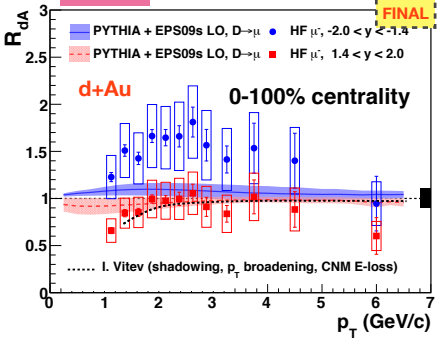
Heavy flavour in pA at LHC and RHIC



ALICE



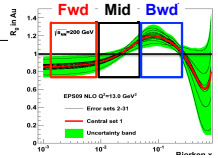
PHENIX



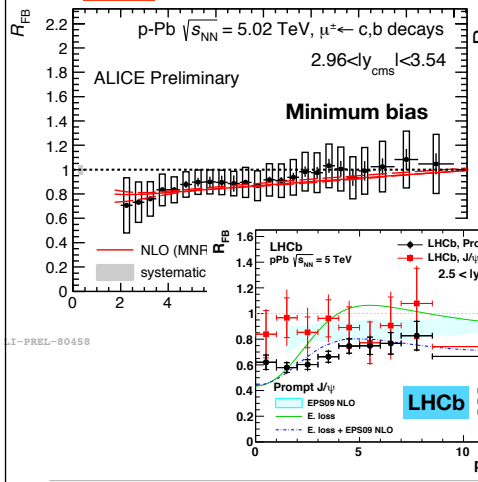
At RHIC, fail to reproduce the data at both rapidity simultaneously

arXiv:1310.1005

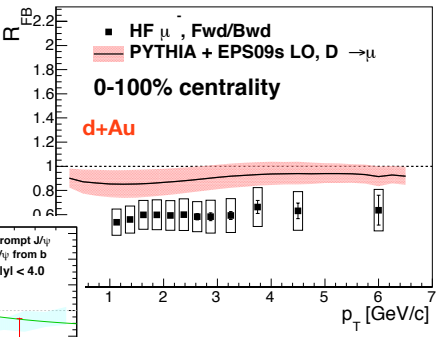
Heavy flavour in pA at LHC and RHIC



ALICE

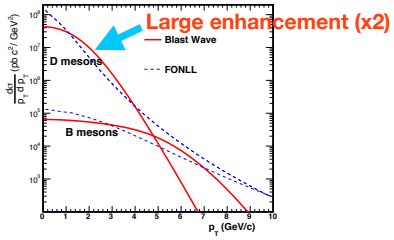


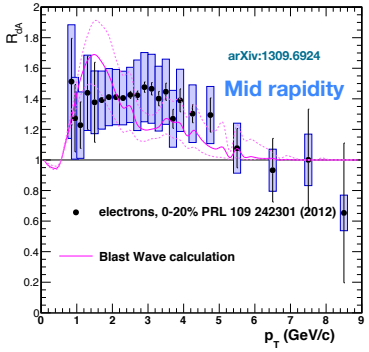
PHENIX



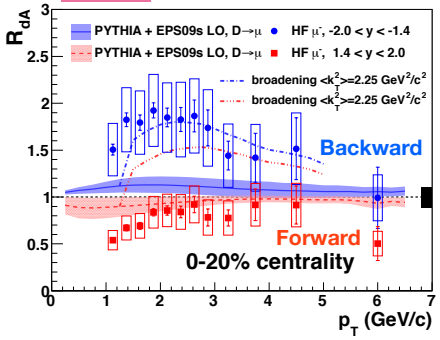
At RHIC, fail to reproduce the data at both rapidity simultaneously

Enhancement in central d+Au





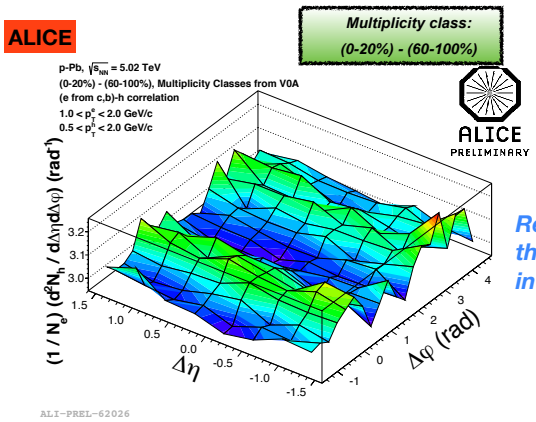
PHENIX



← **Radial flow qualitatively reproduces the data!**

Enhancement at mid- and backward rapidity possibly due to hydrodynamics?

More differential information:
Heavy-flavour electron-hadron correlations



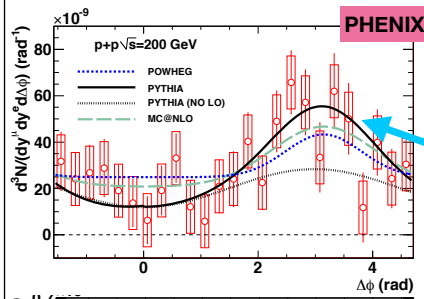
supporting?

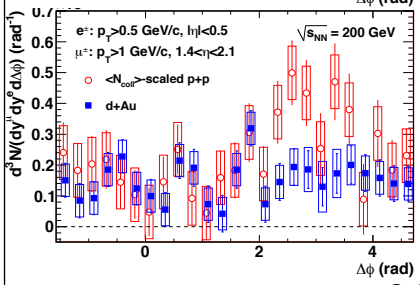
Resembles the structure that in AA is interpreted in terms of collective flow

The double ridge also observed in heavy-flavour sector!

The mechanism (CGC? Hydro?) that generates it affects also HF

More differential information:
Heavy-flavour electron-muon correlation in d+Au





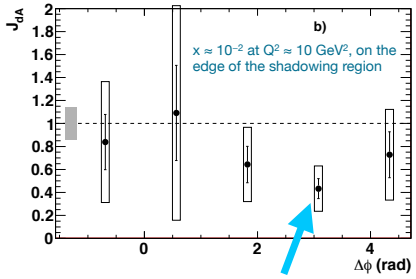
Phys. Rev. C 89, 034915 (2014)

Access to the *g*-PDF?

$\sigma_{c\bar{c}} = 538 \pm 46(\text{stat}) \pm 197(\text{data sys}) \pm 174(\text{model sys})\mu b$

Peak by leading order gluon fusion
Continuum by higher order processes

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



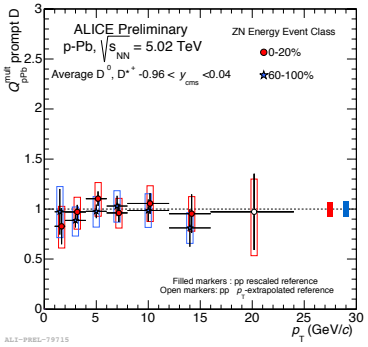
Cold nuclear medium modifies the $c\bar{c}$ correlations

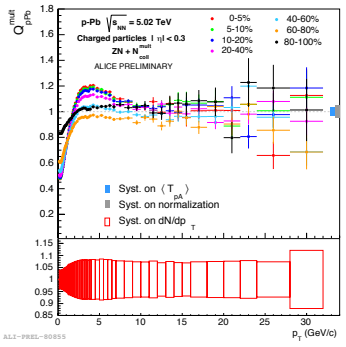
More differential information:
Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

$$Q_{\mathrm{pPb}}^{\mathrm{V0A}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{mult}}^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}^{\mathrm{Glauber}}\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

ALICE





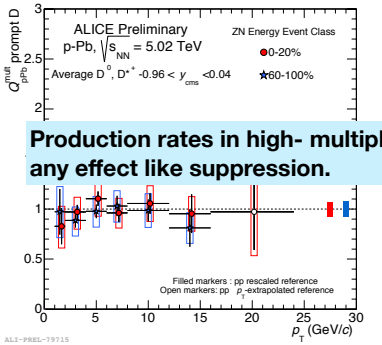
No multiplicity dependent modification of the p_T spectra in p-Pb
Similar pattern for D mesons and high-p_T charged particles

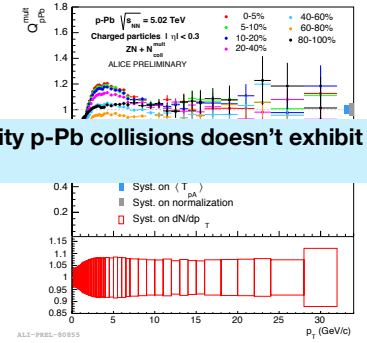
More differential information:
Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

$$Q_{\mathrm{pPb}}^{\mathrm{V0A}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{mult}}^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}^{\mathrm{Glauber}}\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

ALICE

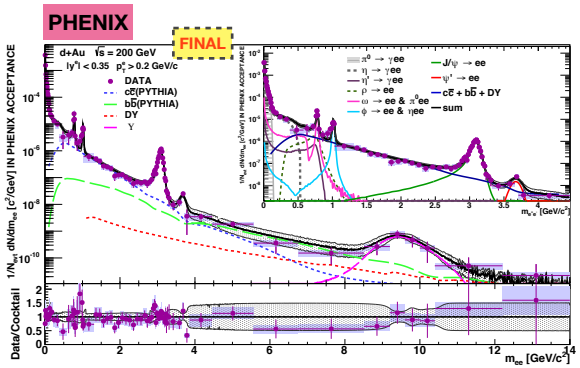




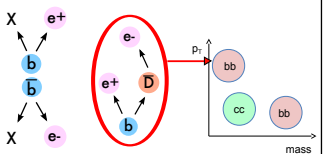
Production rates in high- multiplicity p-Pb collisions doesn't exhibit any effect like suppression.

No multiplicity dependent modification of the p_T spectra in p-Pb
Similar pattern for D mesons and high-p_T charged particles

Bottom measurement in d+Au via di-electrons



arXiv:1405.4004

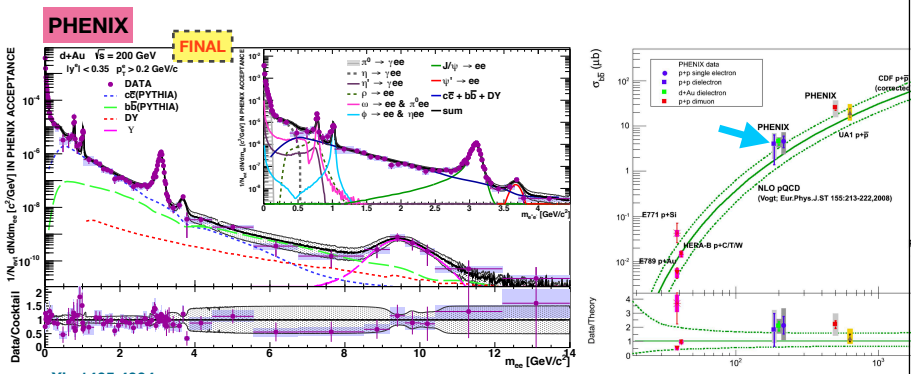


- Low mass, high p_T region is dominated by the decay from a single B meson
- For $m_q \gg p$, less model dependent

p+p equivalent cross sections extracted from PYTHIA and MCNLO as

$$\sigma_{bb} = 3.4 \pm 0.28(stat) \pm 0.46(sys)\mu b$$

Bottom measurement in d+Au via di-electrons



arXiv:1405.4004

p+p equivalent cross sections extracted from PYTHIA and MCNLO as

$\sigma_{bb} = 3.4 \pm 0.28(stat) \pm 0.46(sys)\mu b$

A-A collisions at $\sqrt{s}$ = 0.2 and 2.76 TeV

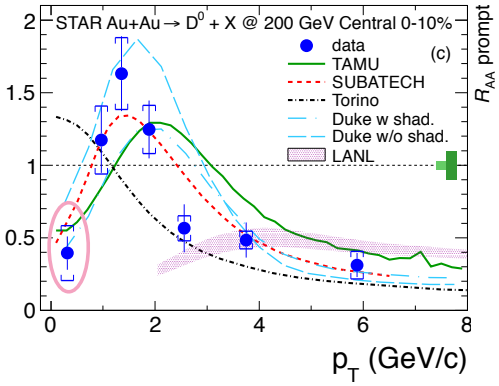
Cu-Cu, Au-Au, Pb-Pb, U-U
Initial & final state effect

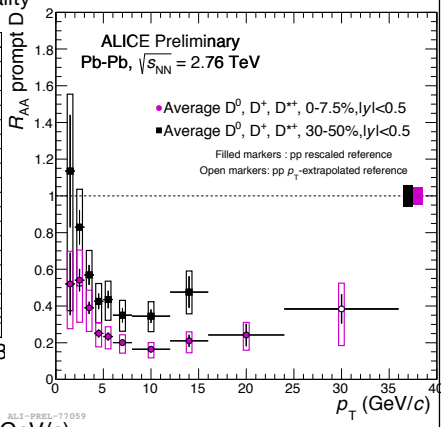
D-meson R_{AA} at LHC and RHIC

- Significant suppression at high p_T

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): 0-7.5 % & 30-50 % centrality

STAR ◉ D^0 mesons (mid rapidity): 0-10 % centrality





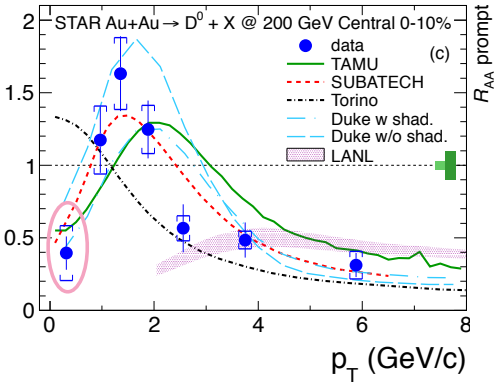
- Similar at high p_T, different at low p_T(1-2 GeV/c)
- Shadowing? recombination? radial flow?

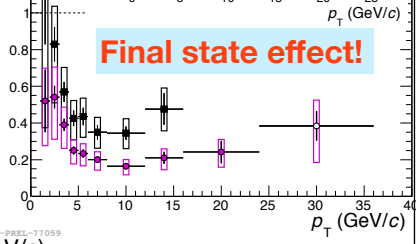
D-meson R_{AA} at LHC and RHIC

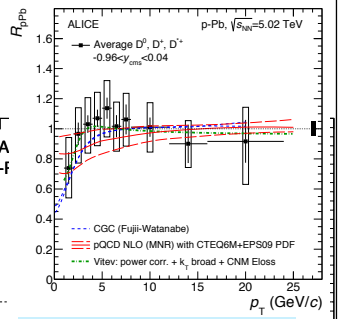
- Significant suppression at high p_T

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): 0-7.5 % & 30-50 % centrality

STAR ◉ D^0 mesons (mid rapidity): 0-10 % centrality







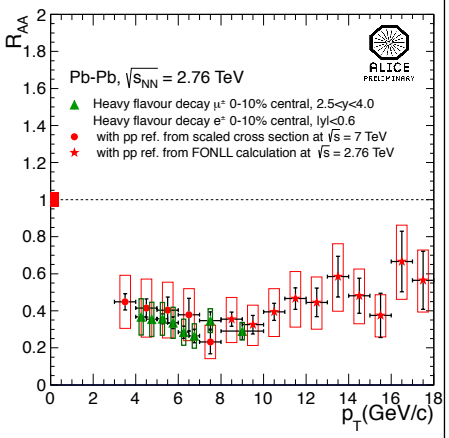
Final state effect!

- Similar at high p_T, different at low p_T(1-2 GeV/c)
- Shadowing? recombination? radial flow?

HF-decay lepton R_{AA} at LHC and RHIC

- Significant suppression at high p_T down to 200 GeV

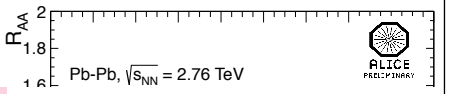
ALICE ◉ c,b→e (mid rapidity) & c,b→μ (forward rapidity)

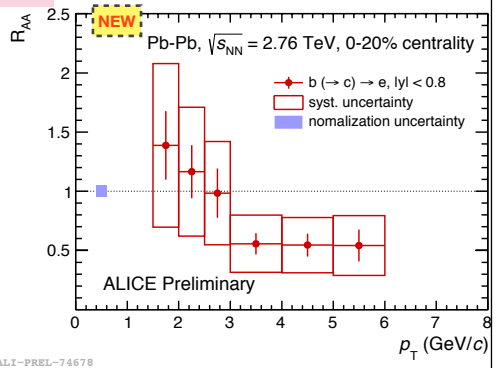


HF-decay lepton R_{AA} at LHC and RHIC

- Significant suppression at high p_T down to 200 GeV

ALICE
- c,b→e (mid rapidity) & c,b→μ (forward rapidity)
- b→e (mid rapidity) **hint of suppression**

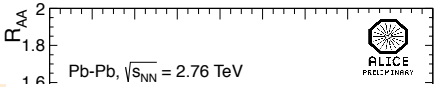


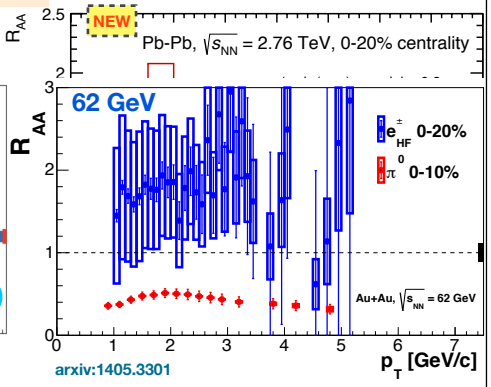


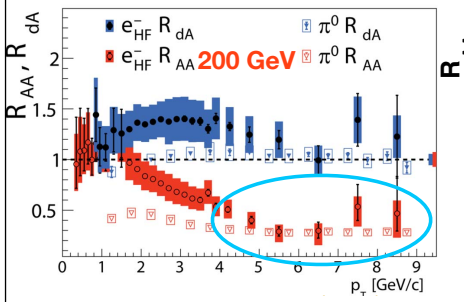
HF-decay lepton R_{AA} at LHC and RHIC

- Significant suppression at high p_T down to 200 GeV

ALICE
- c,b→e (mid rapidity) & c,b→μ (forward rapidity)
- b→e (mid rapidity) **hint of suppression**
- c,b→e (mid rapidity) **PHENIX**

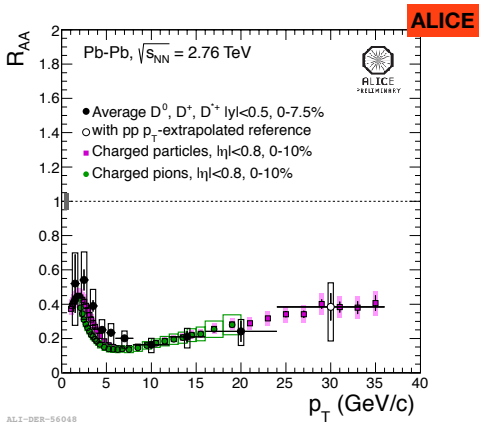






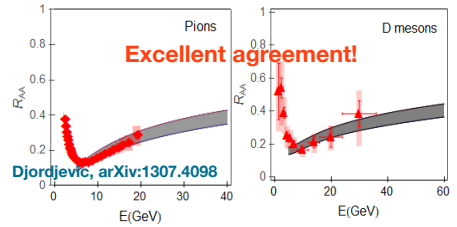
Not the same story for 62 GeV

Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$

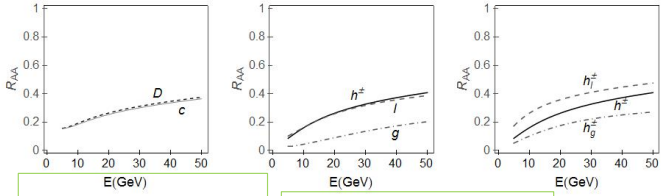


- Comparable results for π and D mesons suppressions within uncertainties
- Is it consistent with the colour charge dependence picture?

Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$



Calculation by M. Djordjevic (rad+coll energy loss) can describe both R_{AA}



Shows strong colour charge effect in partonic R_{AA} (g vs. light and c)

R_{AA} (D) = R_{AA} (charm)

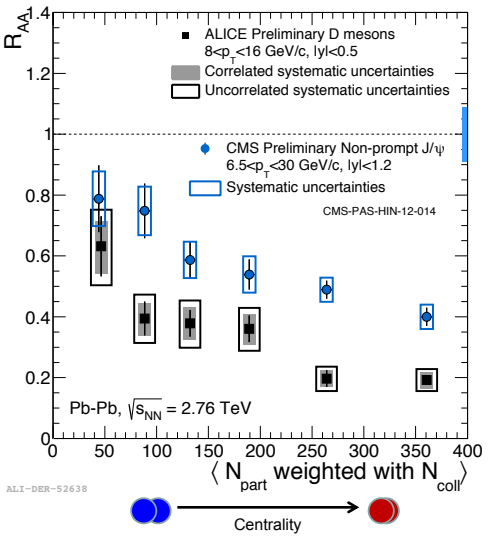
R_{AA} (light quarks) = R_{AA} (charm)

Distortion by fragmentation!

R_{AA} ($h^{\pm}$) = R_{AA} (D)

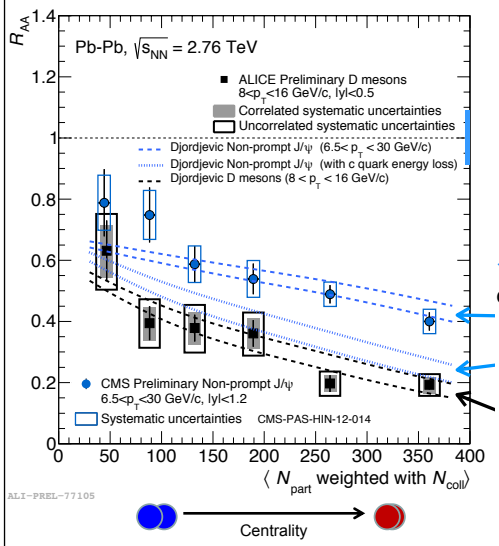
Colour charge effect plays!

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ



- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c
- **Clear indication of a dependence on quark mass : $R_{AA}^B > R_{AA}^D$**

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ



- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c
- **Clear indication of a dependence on quark mass : $R_{AA}^B > R_{AA}^D$**

✓ Djordjevic: non-prompt J/ψ R_{AA} considering for energy loss
- b quark mass
- c quarkmass

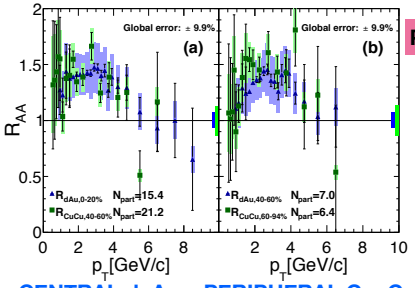
No trivial relation between ΔE and R_{AA}

✓ Djordjevic: D meson R_{AA}

Calculation by M. Djordjevic (including mass-dependent rad+coll energy loss) predict a difference

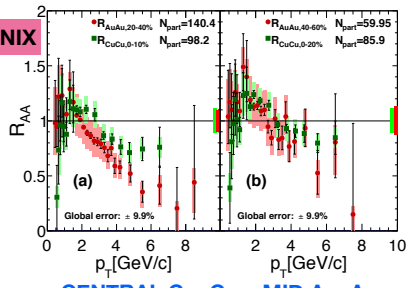
Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).

System size dependence of R_{AA}



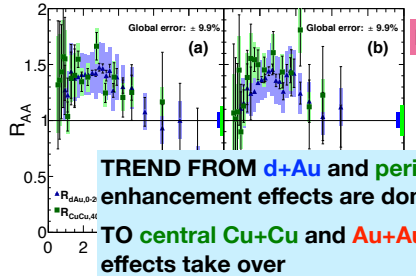
CENTRAL d+Au ≈ PERIPHERAL Cu+Cu

PHENIX

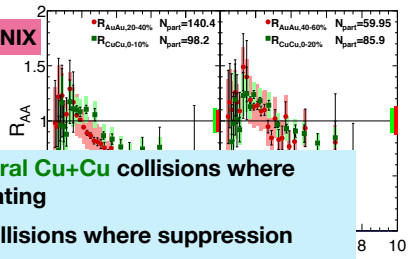


CENTRAL Cu+Cu ≈ MID Au+Au

System size dependence of R_{AA}

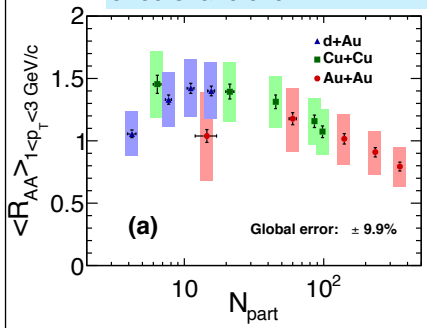


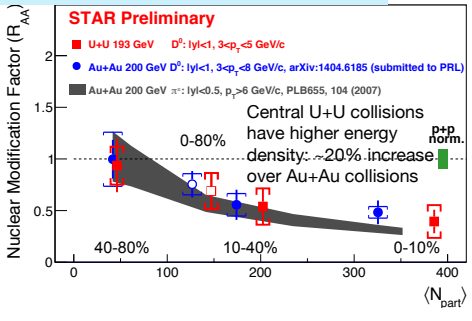
PHENIX



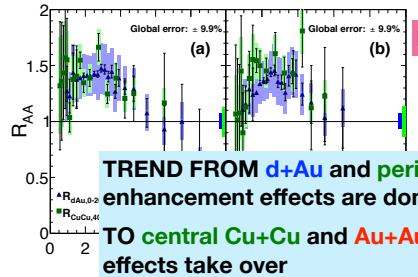
TREND FROM d+Au and peripheral Cu+Cu collisions where enhancement effects are dominating

TO central Cu+Cu and Au+Au collisions where suppression effects take over

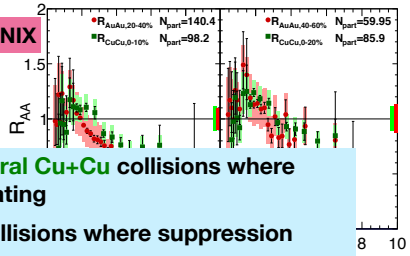




System size dependence of R_{AA}

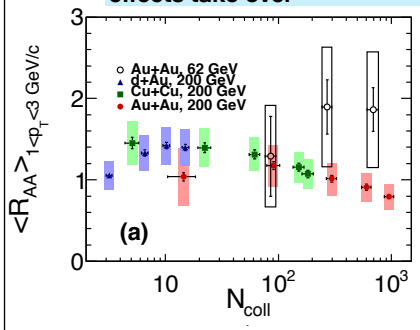


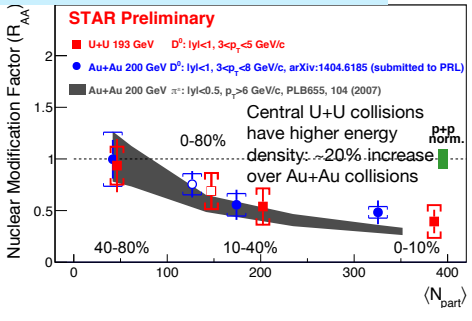
PHENIX



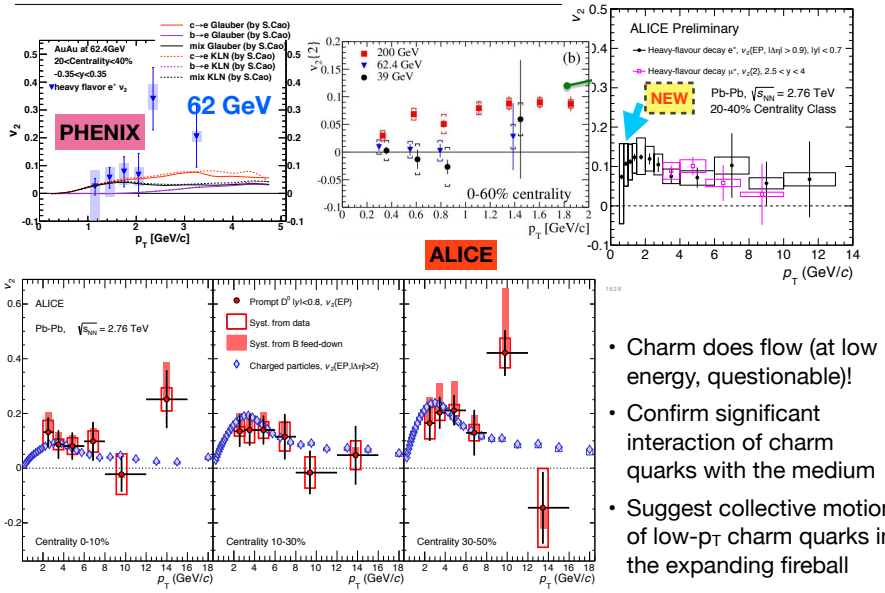
TREND FROM d+Au and peripheral Cu+Cu collisions where enhancement effects are dominating

TO central Cu+Cu and Au+Au collisions where suppression effects take over



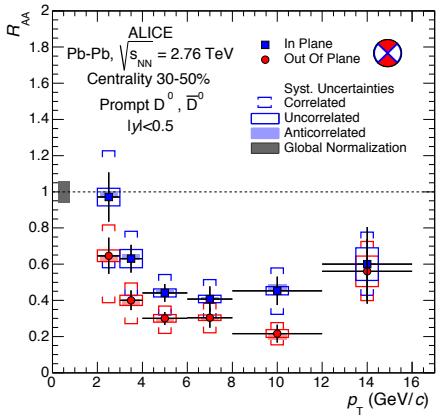


Heavy flavour v_2 at RHIC & LHC



- Charm does flow (at low energy, questionable)!
- Confirm significant interaction of charm quarks with the medium
- Suggest collective motion of low-p_T charm quarks in the expanding fireball

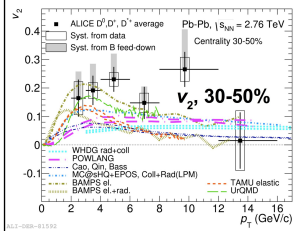
Path length dependence of R_{AA}

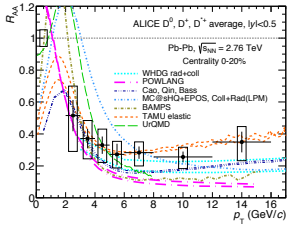


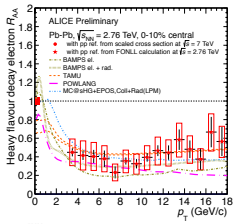
R_{AA} measured in-plane and out-of-plane, sensitive to

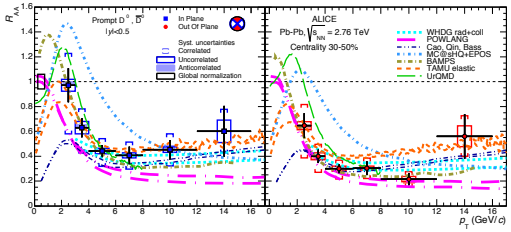
- high p_T: path length dependence of parton energy loss
- low p_T: collectivity

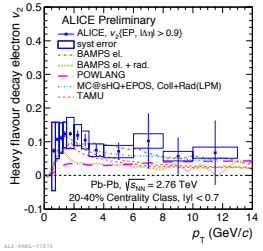
Observables constraining models







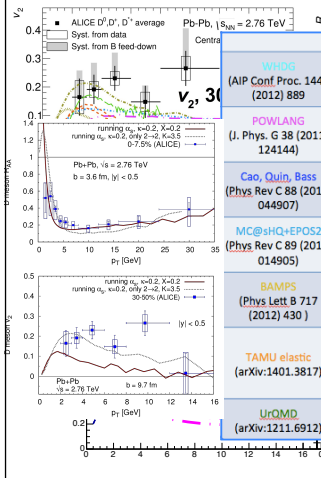


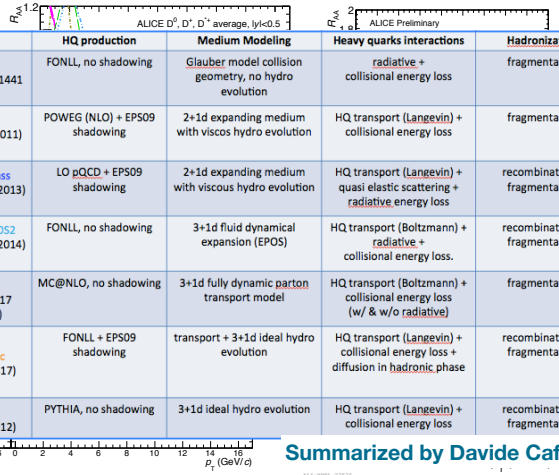


- TAMU elastic: arXiv:1401.3817
- Djordjevic: arXiv:1307.4098
- Cao, Qin, Bass: PRC 88 (2013) 044907
- WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
- MC@sHQ+EPOS: PRC 89 (2014) 014905
- Vitev, rad+dissoc: PRC 80 (2009) 054902
- POWLANG: JPG 38 (2011) 124144
- BAMPS: PLB 717 (2012) 430

Various observables provide constraints for the models

Observables constraining models





	HQ production	Medium Modeling	Heavy quarks interactions	Hadronization
WHDG (AIP Conf Proc. 1441 (2012) 889	FONLL, no shadowing	Glauber model collision geometry, no hydro evolution	radiative + collisional energy loss	fragmentation
POWLANG (J. Phys. G 38 (2011) 124144)	POWEG (NLO) + EPS09 shadowing	2+1d expanding medium with viscos hydro evolution	HQ transport (Langevin) + collisional energy loss	fragmentation
Cao, Quin, Bass (Phys Rev C 88 (2013) 044907)	LO pQCD + EPS09 shadowing	2+1d expanding medium with viscous hydro evolution	HQ transport (Langevin) + quasi elastic scattering + radiative energy loss	recombination + fragmentation
MC@sHQ+EPOS2 (Phys Rev C 89 (2014) 014905)	FONLL, no shadowing	3+1d fluid dynamical expansion (EPOS)	HQ transport (Boltzmann) + radiative + collisional energy loss.	recombination + fragmentation
BAMPS (Phys Lett B 717 (2012) 430)	MC@NLO, no shadowing	3+1d fully dynamic parton transport model	HQ transport (Boltzmann) + collisional energy loss (w/ & w/o radiative)	fragmentation
TAMU elastic (arXiv:1401.3817)	FONLL + EPS09 shadowing	transport + 3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss + diffusion in hadronic phase	recombination + fragmentation
UrQMD (arXiv:1211.6912)	PYTHIA, no shadowing	3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss	recombination + fragmentation

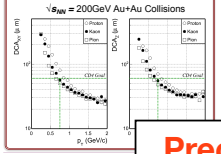
Summarized by Davide Caffarri

TAMU elastic: arXiv:1401.3817
Djordjevic: arXiv:1307.4098
Cao, Qin, Bass: PRC 88 (2013) 044907
WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
MC@sHQ+EPOS: PRC 89 (2014) 014905
Vitev, rad+dissoc: PRC 80 (2009) 054902
POWLANG: JPG 38 (2011) 124144
BAMPS: PLB 717 (2012) 430

Various observables provide constraints for the models

Outlook

Status: Heavy Flavor Tracker



Heavy Flavor Tracker (HFT)

Physics goal: **Precision measurement of heavy quark hadron production in heavy ion collisions**

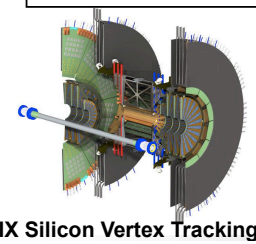
All 3 sub-detectors (PXL, IST, SSD) were completed, installed prior to Run14

PXL – heart of the HFT: state-of-art detector, MAPS technology, first time used at a collider experiment.
Integration time ~ 160μs

Taking data with STAR detector system, on track towards the physics goal

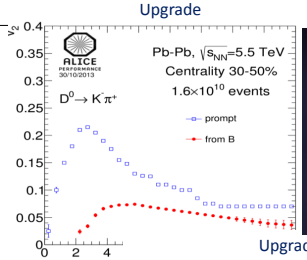
With survey and preliminary alignment, **Kaons at 750 MeV/c: DCA < 60μm**

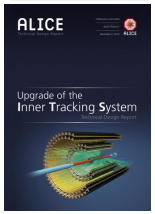
Precision measurements



PHENIX Silicon Vertex Tracking System

Upgrade

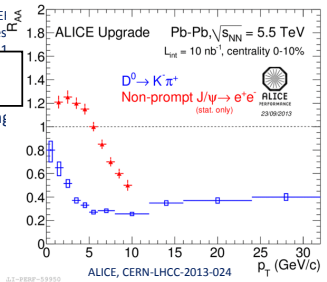




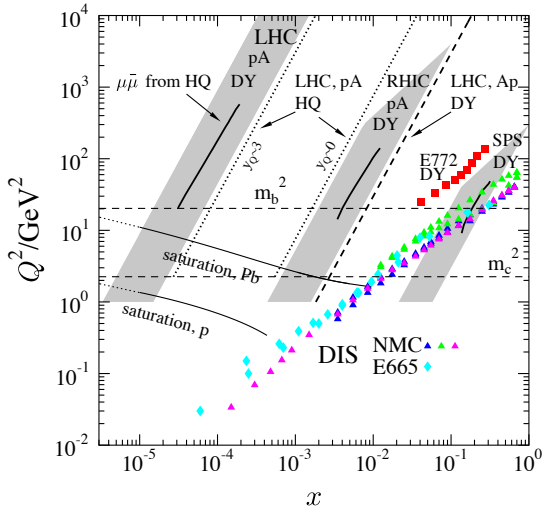
Upgrade

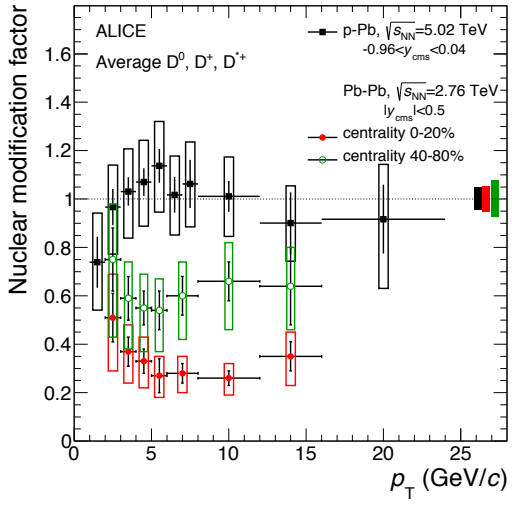
ALICE, CEI
Input values
et al. arXiv:1

p_T~0 using

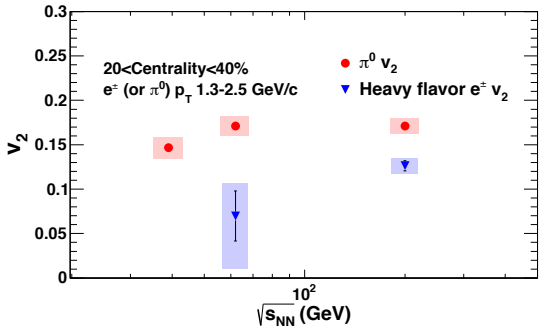


Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ

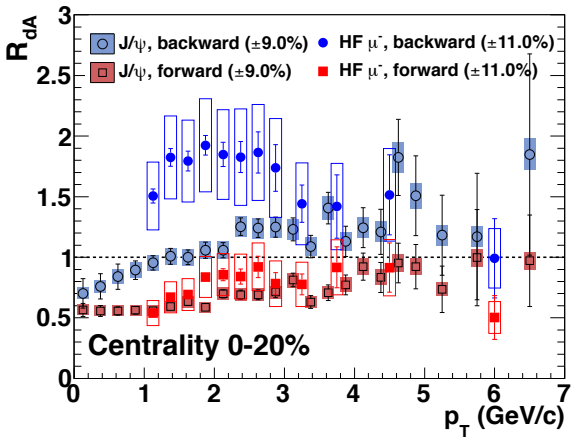

LHC
pA
$\mu\bar{\mu}$ from HQ
DY
LHC, pA
HQ
RHIC
pA
DY
LHC, Ap
DY
SPS
DY
E772
DY
y_0~3
y_0~0
m_b^2
m_c^2
saturation, Pb
saturation, p
DIS
NMC
E665
Q^2/GeV^2
x

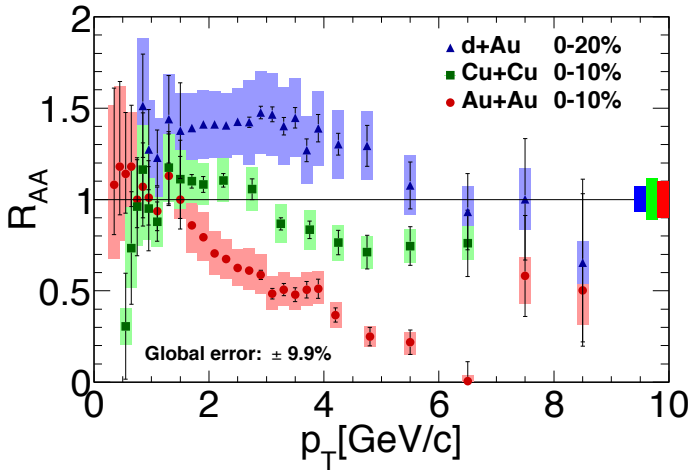

ALICE
Average D0, D+, D*+
p-Pb, √sNN=5.02 TeV
-0.96<ycms<0.04
Pb-Pb, √sNN=2.76 TeV
|ycms|<0.5
centrality 0-20%
centrality 40-80%
Nuclear modification factor
pT (GeV/c)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
5
10
15
20
25

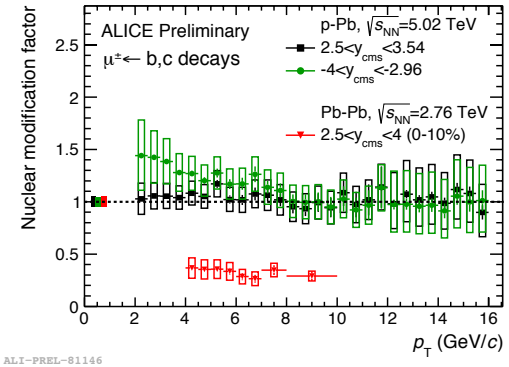
Flow



Is charm actually flowing? or is this v_2 just from recombination with a light quark?


R_{dA}
J/ψ, backward (±9.0%)
HF μ⁻, backward (±11.0%)
J/ψ, forward (±9.0%)
HF μ⁻, forward (±11.0%)
Centrality 0-20%
p_T (GeV/c)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6
7


d+Au 0-20%
Cu+Cu 0-10%
Au+Au 0-10%
Global error: ± 9.9%
R_{AA}
p_T[GeV/c]
0
0.5
1
1.5
2
0
2
4
6
8
10


ALICE Preliminary
μ±← b,c decays
p-Pb, √sNN=5.02 TeV
2.5<ycms<3.54
-4<ycms<-2.96
Pb-Pb, √sNN=2.76 TeV
2.5<ycms<4 (0-10%)
Nuclear modification factor
pT (GeV/c)
ALI-PREL-81146

Heavy Quark Energy Loss in Medium

Radiative energy loss via gluon radiation

Color charge dependence of energy loss

gluon radiation spectrum by the parton propagation in the medium:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$where \quad C_R = 3 \ for\ g, \ \frac{4}{3} \ for\ q$$

Dead Cone Effect

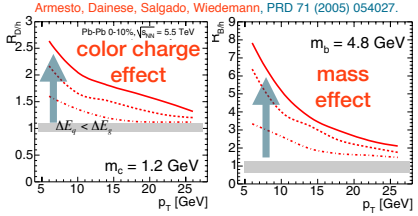
- In vacuum, gluon radiation is suppressed at angles smaller than M_Q/E_Q (ratio of the quark mass to its energy)
- In medium, dead cone implies lower energy loss for massive partons

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B} \qquad R_{AA}(p_T) = \frac{1}{< T_{AA} >} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$R_{D/h}$: R^{D}_{AA}/R^{h}_{AA}

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.



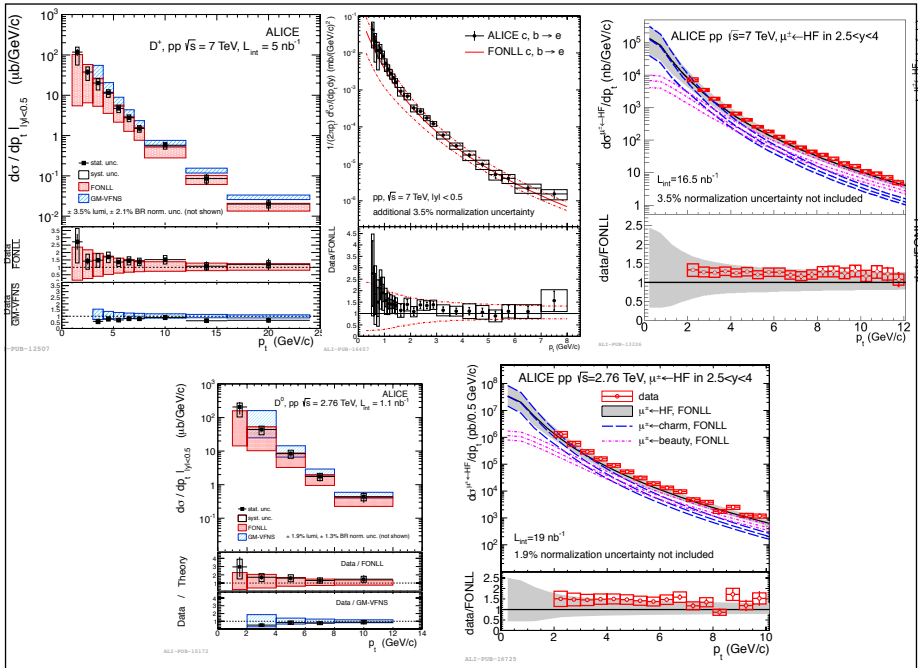
Elastic energy loss is not negligible?

Simon Wicks, William Horowitz, Magdalena Djordjevic, Miklos Gyulassy, Nucl.Phys.A784:426-442,2007

Collisional dissociation probability of heavy mesons in the QGP?

I Vitev, A Adil and H van Hees, J. Phys. G: Nucl. Part. Phys. 34 (2007) S769–S773

Proton-proton collisions: provide important test of pQCD in a new energy domain and heavy ion reference


ALICE
D*, pp √s = 7 TeV, L_int = 5 nb^-1
stat. unc.
syst. unc.
FONLL
GM-VFNS
± 3.5% lumi, ± 2.1% BR norm. unc. (not shown)
Data / FONLL
Data / GM-VFNS
p_t (GeV/c)
ALICE c, b → e
FONLL c, b → e
pp, √s = 7 TeV, |y| < 0.5
additional 3.5% normalization uncertainty
Data/FONLL
ALICE pp √s=7 TeV, μ^±←HF in 2.5<y<4
L_int=16.5 nb^-1
3.5% normalization uncertainty not included
data/FONLL
ALICE
D^0, pp √s = 2.76 TeV, L_int = 1.1 nb^-1
± 1.9% lumi, ± 1.3% BR norm. unc. (not shown)
Data / Theory
Data / FONLL
Data / GM-VFNS
ALICE pp √s=2.76 TeV, μ^±←HF in 2.5<y<4
data
μ^±←HF, FONLL
μ^±←charm, FONLL
μ^±←beauty, FONLL
L_int=19 nb^-1
1.9% normalization uncertainty not included