

Review of heavy-flavour production in heavy-ion collisions

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EPS-HEP
Vienna, 22 – 29 July 2015

- Not a comprehensive review: rather a selection of results at RHIC and LHC
- For further reading, see e.g. [arXiv:1506.03981](https://arxiv.org/abs/1506.03981)

Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions

A. Andronic^{a,1}, F. Arleo^{b,c,1}, R. Arnaldi^{d,1}, A. Beraudo^d, E. Bruna^d, D. Caffarré^e, Z. Conesa del Valle^{d,1}, J.G. Conteras^{e,1}, T. Dahms^{d,1}, A. Dainese^{d,1}, M. Djordjević^f, E.G. Ferreiro^{d,1}, H. Fujii^g, P.-B. Gossiaux^{m,1}, R. Granier de Cassagnac^h, C. Hadjidakis^{i,1}, M. He^j, H. van Hees^k, W.A. Horowitz^l, R. Kolevato^{m,1}, B.Z. Kopeliovich^l, J. P. Lansberg^{d,1}, M.P. Lombardo^{d,1}, C. Lourenço^o, G. Martínez-García^{m,1}, L. Massacrier^{m,n,l,s}, C. Mironov^o, A. Mischke^{o,w}, M. Nahrgang^s, M. Nguyen^o, J. Nystrand^{d,1}, S. Peigneⁿ, S. Porteboef-Houssais^{d,1}, I.K. Potashnikova^o, A. Rakotocafindraibe^d, R. Rapp^o, P. Robbe^{m,1}, M. Rosati^o, P. Rosnet^{d,1}, H. Satz^d, R. Schicker^{a,1}, I. Schienbein^{d,1}, I. Schmidt^o, E. Scomparin^d, R. Sharma^o, J. Stachel^{d,1}, D. Stocco^{m,1}, M. Strickland^{ab}, R. Tieulent^{a,1}, B.A. Trzeciak^{b,1}, J. Uphoff^d, I. Vitev^o, R. Vogt^{l,m}, K. Watanabe^{an,o}, H. Woehr^o, P. Zhuang^p

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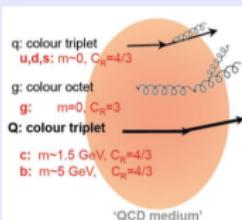
^oDepartment of High Energy Physics, Saint-Petersburg State University Ulyanovskaya 1, Saint-Petersburg, Russia,

^pDepartamento de Física, Universidad Técnica Federico Santa María; and Centro Científico-Tecnológico de Valparaíso , Valparaíso, Chile,

^qINFN, Laboratori Nazionali di Frascati, Frascati, Italy.

- Charm and beauty quarks produced in the initial hard scattering processes with high virtuality \Rightarrow formation time $\Delta t < 1/(2m_Q) \sim 0.1 \text{ fm}/c$
 - production in QGP expected to be negligible [B.W.Zhang, C.M.Ko, W.Liu, PR C 77 (2008) 024901]
- Conserved flavour in QGP interaction
- Exposed to the evolution of the high-energy density medium

Heavy flavours are excellent probes of the medium properties



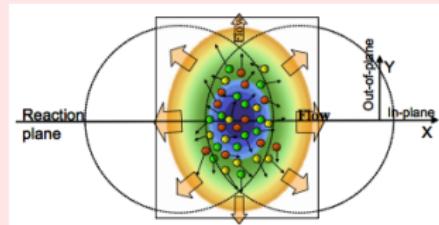
- Colour-charge and mass dependence of in-medium energy loss:

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

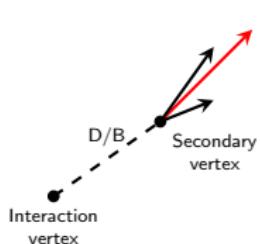
↓

Tested by comparing $R_{AA}(\pi)$, $R_{AA}(D)$, $R_{AA}(B)$

- Interactions with medium constituent can transfer to charm and beauty quarks the collective flow of the medium
 - Large mass: frequent interactions with large coupling needed to build flow \Rightarrow expected $v_2(b) < v_2(c)$
 - HF flow provides information on **transport coefficients**, role of **energy loss mechanisms** and **hadronisation** mechanisms

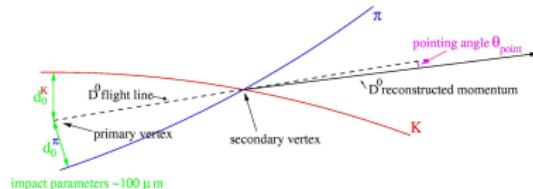


Semi-leptonic decays

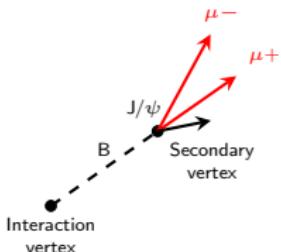


Beauty separation via impact parameter analysis or electron-hadron correlations

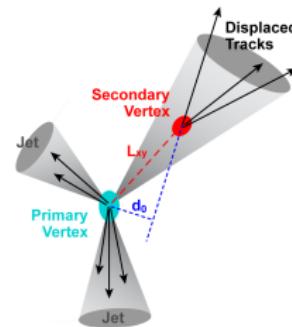
D meson hadronic decays



J/ψ from B decay

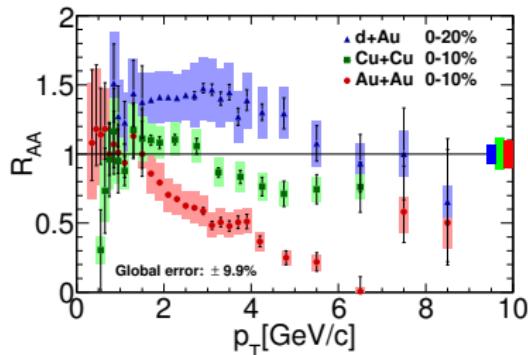


b-tagged jets



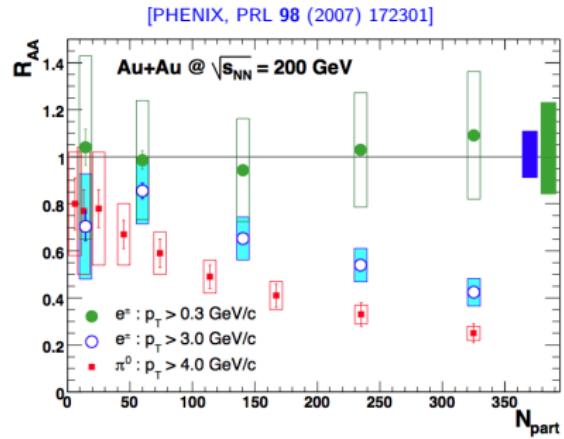
Heavy-flavour electrons at RHIC: suppression at high- p_T

[PHENIX, PRC 90 (2014) 3, 034903]

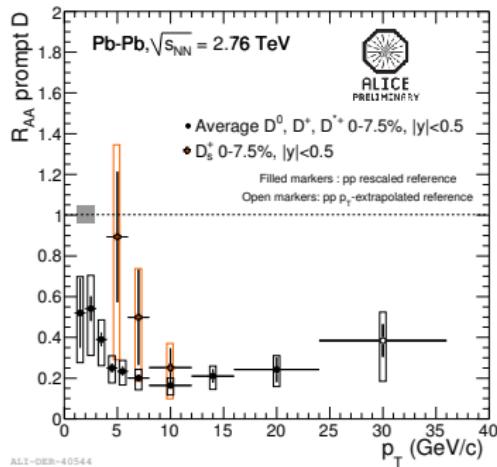


- Strong suppression of HF yields at intermediate and high- p_T
 - final state effect by comparing with d-Au results

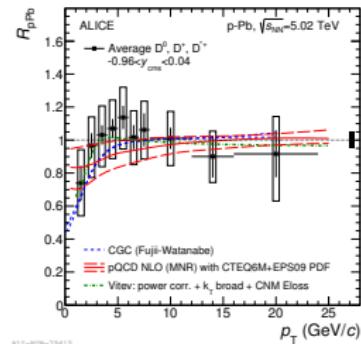
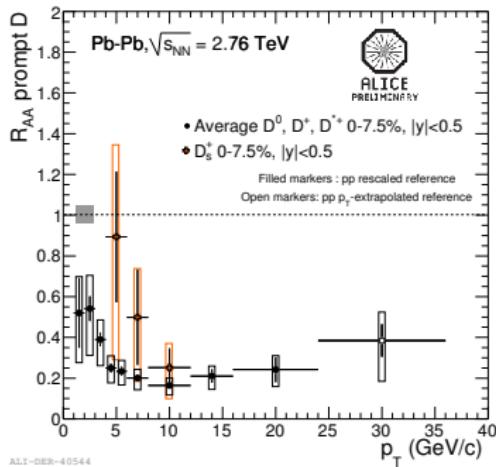
- $R_{AA} \sim 1$ when integrating down to $p_T = 0.3$ GeV/c \Rightarrow Binary scaling of the total HF yields
- NB: measurement of the total HF yields can provide a natural normalisation for quarkonia studies



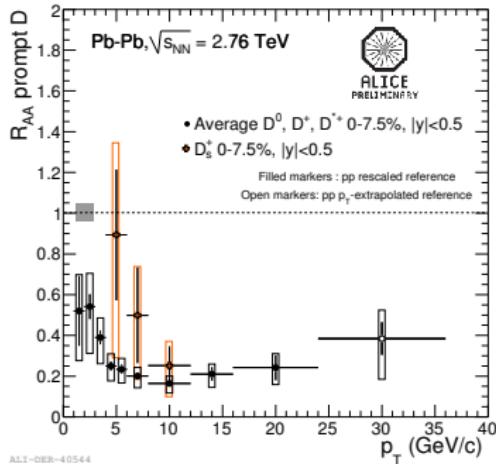
Charm measurements



- D mesons measured in Pb-Pb collisions at 2.76 TeV : suppression by factor ~ 5 at $p_T > 10 \text{ GeV}/c$

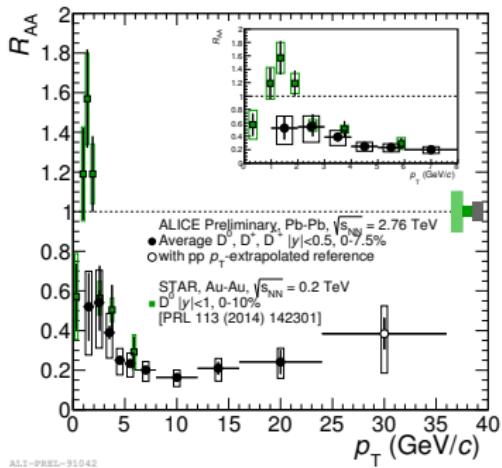


- D mesons measured in Pb–Pb collisions at 2.76 TeV: suppression by factor ~ 5 at $p_T > 10$ GeV/c
 - $R_{pPb} \sim 1$ at high p_T at LHC \Rightarrow final state effect



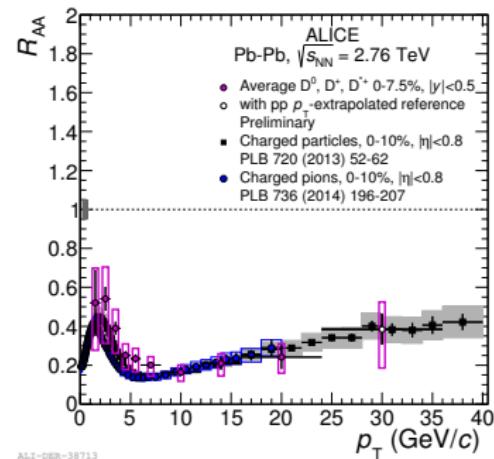
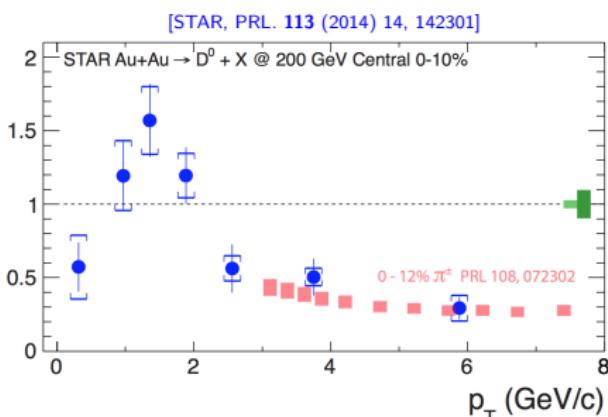
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 - D_s : interesting trend at low p_T . Possible effect of coalescence? More data needed

[STAR, PRL 113 (2014) 14, 142301]



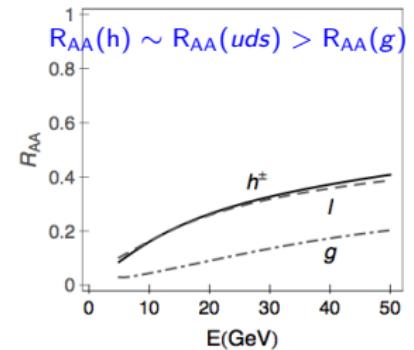
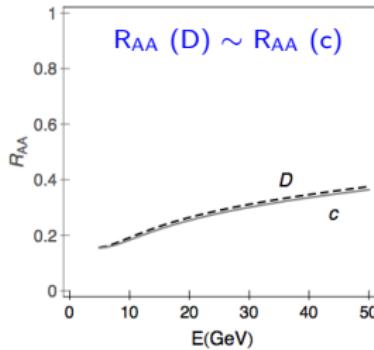
- D mesons measured in Pb–Pb collisions at 2.76 TeV: suppression by factor ~ 5 at $p_T > 10$ GeV/c
 - $R_{pPb} \sim 1$ at high p_T at LHC \Rightarrow final state effect
 - D_s^- : interesting trend at low p_T . Possible effect of coalescence? More data needed
- D^0 measured in Au–Au coll. at 200 GeV
 - at high p_T : suppression similar to LHC
 - at low p_T : $R_{AA} > 1$ (radial flow/coalescence?). Feature not observed at LHC (harder p_T distribution, gluon shadowing) \Rightarrow need for LHC measurements down to $p_T = 0$

Charm & light hadrons



- $R_{AA}(D) \sim R_{AA}(\pi)$ both at RHIC and at the LHC

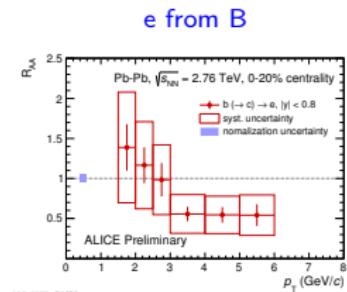
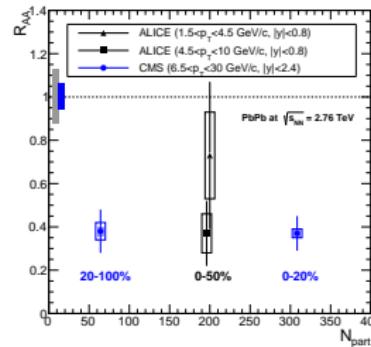
- Interplay between different momentum spectra of charm, light quarks and gluons and different fragmentation functions



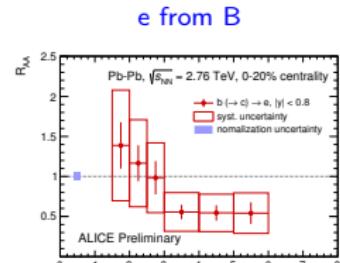
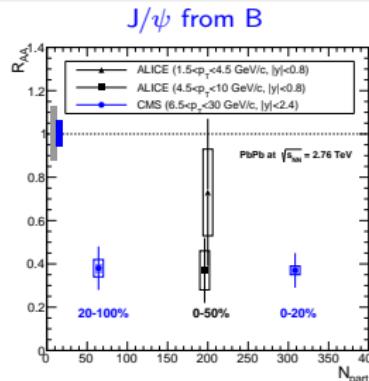
[M. Djordjevic, PRL 112 (2014) 4, 042302]

J/ψ from B

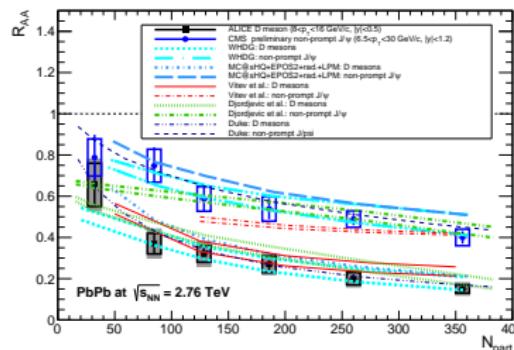
- Beauty production measured at the LHC in the J/ψ decay channel [CMS, PRL 113 (2014) 13, 132301, ALICE, arXiv:1504.07151] and in the electronic decay channel \Rightarrow suppression at high p_T observed



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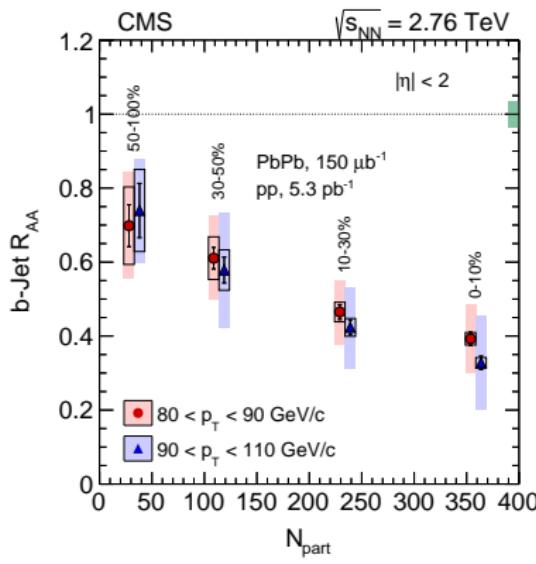


- ALICE D mesons [ALICE, arXiv:1506.06604] and CMS non-prompt J/ψ [CMS, PAS-HIN-12-014] measured in a p_T range tuned to have $\langle p_T(D) \rangle \sim \langle p_T(B) \rangle \sim 10 - 11$ GeV/c



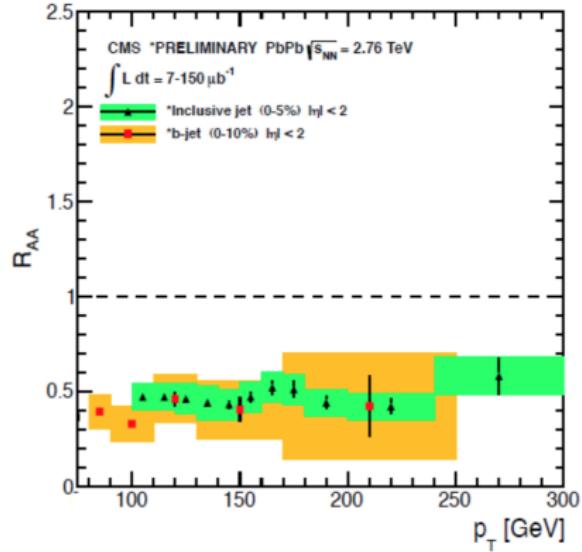
- $R_{AA}(D) < R_{AA}(\text{non-prompt } J/\psi)$ observed
- Results described by all models implementing a quark-mass dependence

[CMS, PRL 113 (2014) 13, 132301]



[CMS, PRL 113 (2014) 13, 132301]

[CMS, PAS-HIN-12-004]

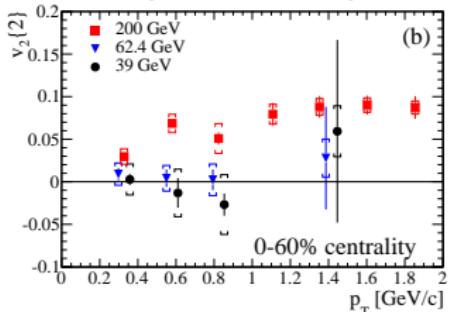


- Significant suppression of b -jets at high- p_T
- Suppression depends on centrality
- R_{AA} of b -jets with $p_T > 100$ GeV/c is consistent with R_{AA} of inclusive jets within uncertainties \Rightarrow mass dependence of energy loss is small for $p_T \gg m_b$
 - NB: at high- p_T significant contribution of gluon splitting expected \Rightarrow a significant part of in-medium path length could be traversed by parent gluons

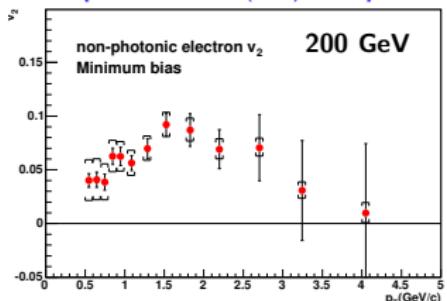
Heavy-flavour leptons v_2

Au–Au

[STAR, arXiv:1405.6348]

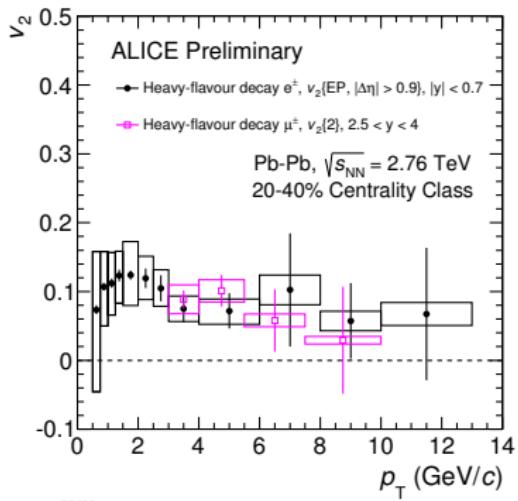


[PHENIX, PRC 84 (2011) 044905]



Pb–Pb, $\sqrt{s_{NN}} = 2.76$ TeV

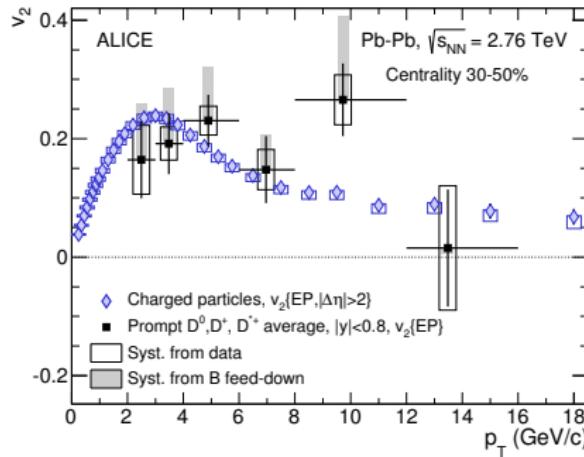
[ALICE, arXiv:1507.03134]



- Heavy flavour lepton v_2 measured at RHIC and LHC:

- v_2 of heavy flavour electrons compatible with 0 at $\sqrt{s_{NN}} = 39$ and 62.4 GeV
- positive v_2 observed in Au–Au collisions at 200 GeV
- positive v_2 observed in Pb–Pb collisions at 2.76 TeV at both forward and mid-rapidity

[ALICE, PRL 111 (2013) 102301]



- Positive D meson v_2 in Pb–Pb collisions at 2.76 TeV
- Compatible with the one of charged particles

 \Downarrow

- Low- p_T charm quarks participating to the **collective motion** of the system?
- Coalescence** with light quarks in the medium?
- More precise measurements of v_2 needed
 - at high- p_T also useful to determine the path length dependence of the energy loss

Interaction with the partonic constituents

Different approaches:

- Perturbative treatment:
 - inelastic (medium-induced gluon radiation)
 - elastic (collisional)
- Strongly-coupled approach (AdS/CFT)

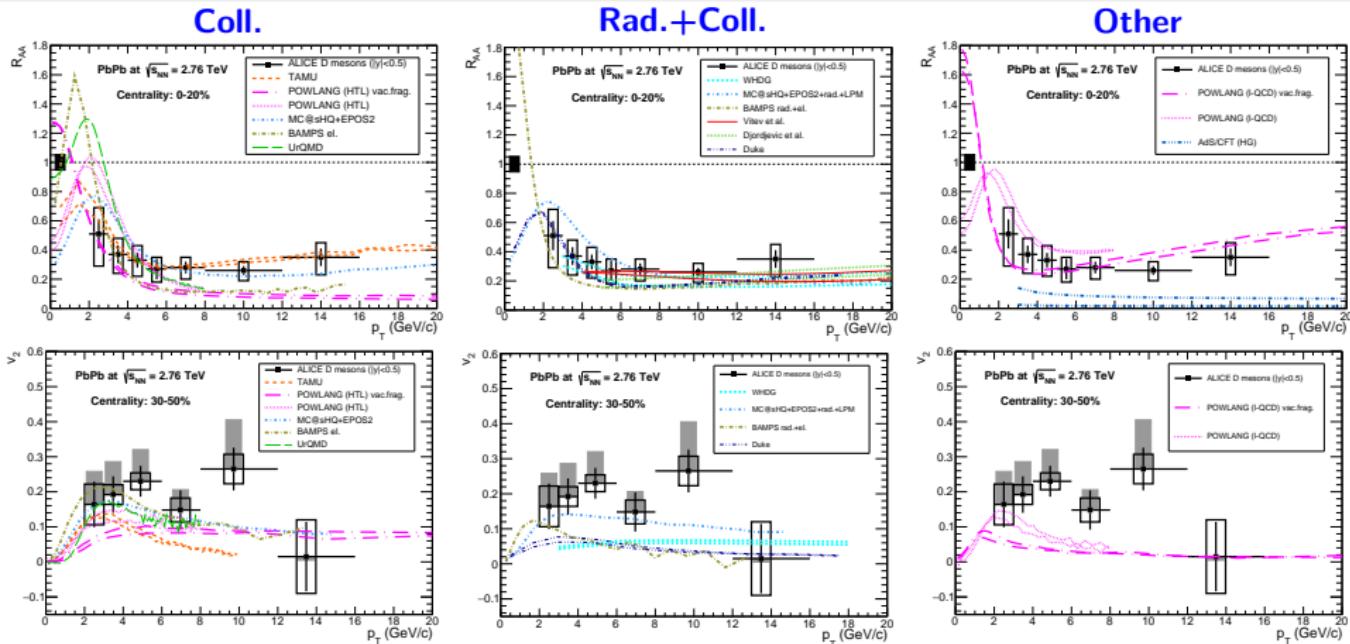
Main ingredients:

- Mean free path
- Debye mass
- Transport coefficients

Medium modelling and medium-induced modification of heavy-flavour production

- Initial production of heavy-flavours
- QGP evolution
- In-medium hadronization
- Interaction of charm and beauty hadrons with the hadronic matter

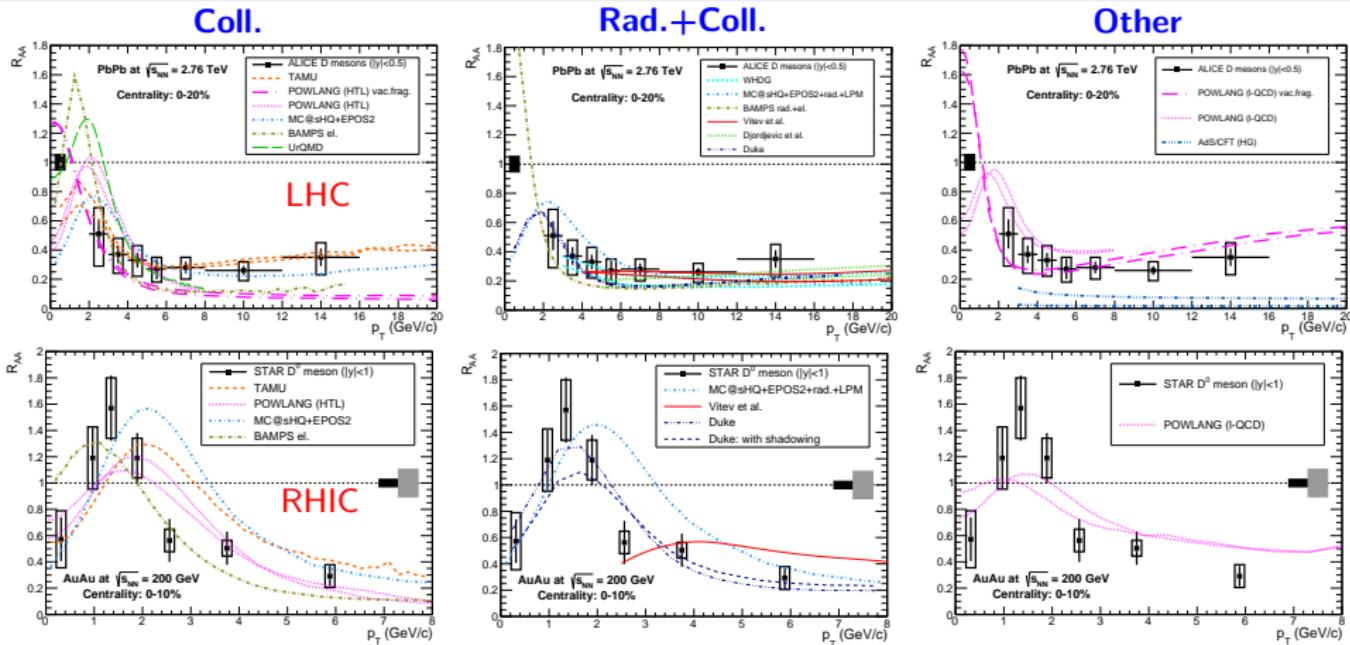
Comparison with data: D mesons



- Models without interaction in an *expanding* medium underestimate v_2 (WHDG)
- Coll. processes more effective than rad.+coll. in building v_2 (see e.g. BAMPS)
- Hadronisation via recombination also effective in building v_2 (see e.g. POWLANG)
- v_2 better reproduced by models including coll. interactions in a fluid-dynamic expanding medium (e.g. BAMPS, TAMU, MC@_sHQ, UrQMD, POWLANG). Most of them include a component of recombination.

[Models refs: see arXiv:1506.03981]

Comparison with data: D mesons

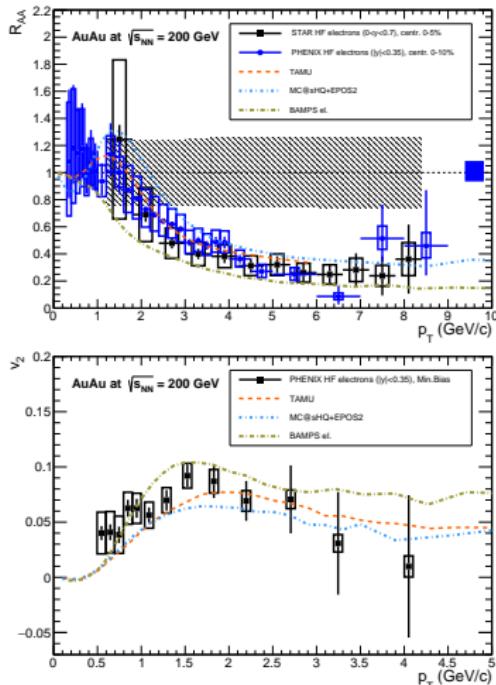


- Models with coll. interactions in a fluid-dynamic expanding medium (e.g. **TAMU**, **MC@HQ**, **POWLANG**, **Duke**, **BAMPS**) reproduce qualitatively the “bump” in the low- p_T R_{AA} at RHIC
- Models not including shadowing (**BAMPS**, **UrQMD**) show $R_{AA} > 1$ at LHC (disfavoured by preliminary meas. down to $p_T = 1$ GeV/c)

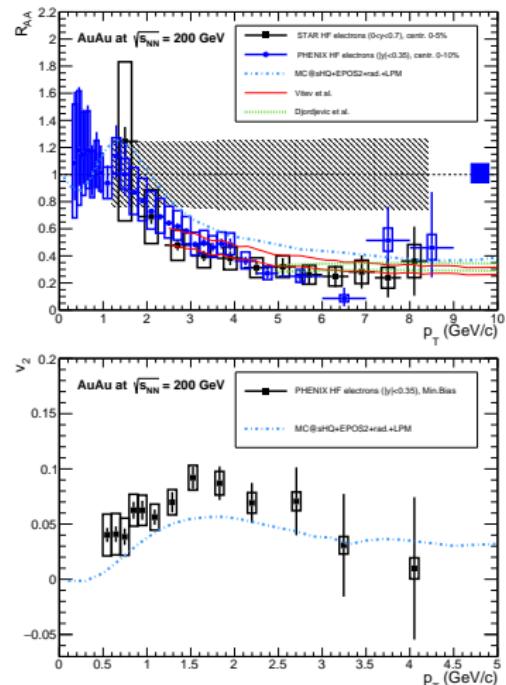
[Models refs: see arXiv:1506.03981]

Comparison with data: heavy flavour decay leptons

Coll.



Rad.+Coll.



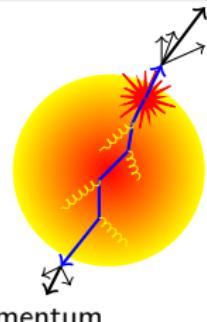
- R_{AA} well reproduced by all models
 - CAVEAT: the parameters of some models are tuned at RHIC (e.g. [Vitev et al.](#), [BAMPS](#))

[Models refs: see arXiv:1506.03981]

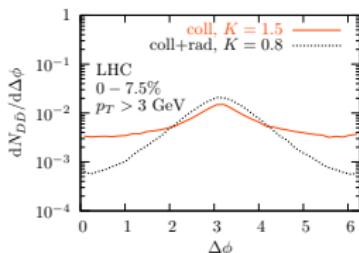
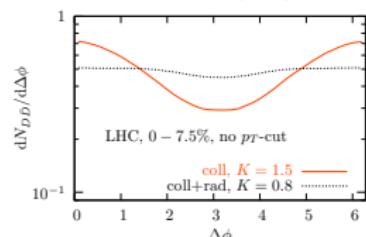
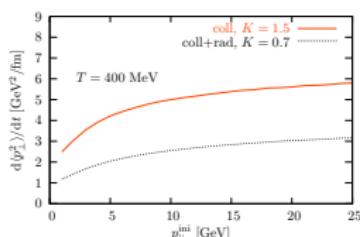
A powerful tool: angular correlations with heavy flavours

Unique features:

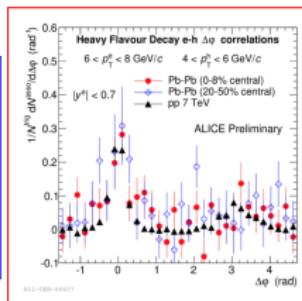
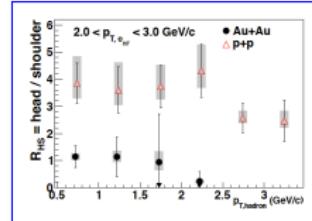
- Trigger particle defined by identity not by momentum range as in hadron-hadron correlations
- Different fragmentation and biases than light quarks and gluons
- Further constrain energy loss mechanism since it is sensitive to:
 - path length ($\Delta E \propto L$ for coll. $\Delta E \propto L^2$ for rad.)
 - momentum broadening in the direction perpendicular to quark momentum



[M.Nahrgang et al., PRC 90 (2014) 2, 024907]



[PHENIX, PRC 83, (2011), 044912]



- e-h correlations measured at **RHIC** and **LHC**... but larger statistics needed

- Heavy-flavour production accessible both at RHIC and LHC in a wide kinematic range and different decay channels

Heavy quark in-medium energy loss

- Large suppression in A–A collisions in all channels at $p_T > 5 \text{ GeV}/c$. Not observed in p–A or d–A ⇒ final state effect
- $R_{AA}(D) \sim R_{AA}(\pi)$ ⇒ described by charge-dependent energy loss (accounting for different p_T distribution and fragmentation of gluons, charm and light quarks)
- $R_{AA}(D) < R_{AA}(J/\psi \leftarrow B)$ with $\langle p_T(D) \rangle \sim \langle p_T(B) \rangle$ ⇒ described by mass-dependent energy loss
- $R_{AA}(b\text{-jets}) \sim R_{AA}(\text{inclusive jets})$ at $p_T > 100 \text{ GeV}/c$ ⇒ negligible effect of quark mass at these scales (CAVEAT: part of path length could be traversed by parent gluon)

In-medium dynamics

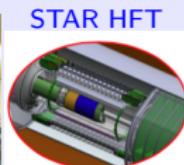
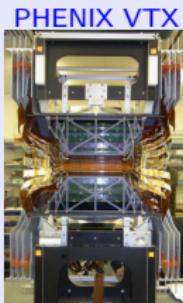
- Positive v_2 measured in non-central collisions for HF decay leptons at RHIC and LHC and for D mesons at LHC ⇒ suggests that collisional processes in a collective medium and maybe coalescence play a role at low/intermediate p_T
- Pronounced maximum of $R_{AA}(D)$ at low p_T at RHIC ⇒ supports the above scenario

Some questions still open:

- **Binary scaling** for total charm production at LHC? \Rightarrow precise measurements of charm and beauty down to $p_T = 0$
- **Experimental evidence of colour-charge dependence of e-loss?** \Rightarrow precise comparison of D meson and pions at intermediate p_T
- Charm quark **thermalisation?** \Rightarrow precise v_2 (and higher harmonics) meas. at low- p_T
- In-medium **hadronisation mechanism?** (fragmentation vs. coalescence) \Rightarrow meas. of HF hadrons with different quark composition (e.g. D_s , Λ_c , B_s , Λ_b)
- Relative **contribution of the energy loss mechanisms?** \Rightarrow simultaneous meas. of R_{AA} and v_2 and comparison with theory; heavy-flavour correlations

Work in progress to address them....

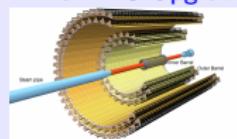
Online



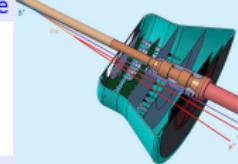
- STAR MTD

Upgrades

ALICE ITS Upgrade



ALICE MFT



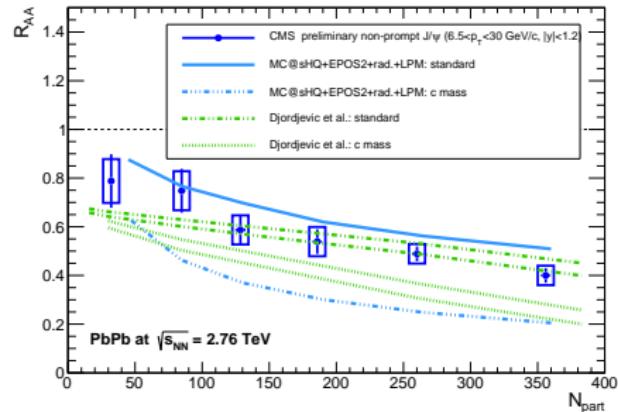
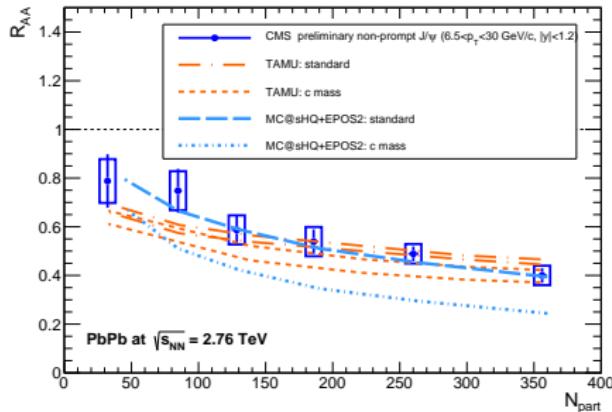
- sPHENIX
- ATLAS
- CMS
- LHCb

Thanks!

Backup slides

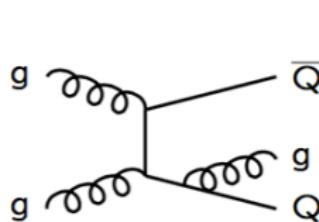
Quark-mass dependence of energy loss

- J/ ψ from B decays in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ [CMS, PAS-HIN-12-014]

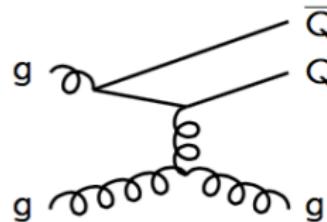


- Quark-mass dependence of energy loss tested by using two values for the b mass:
 - standard b mass
 - c mass
- Stronger suppression expected when setting the mass of the b quark to the value of the c mass

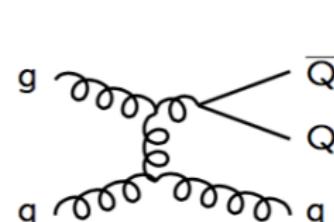
Flavour creation (FCR)



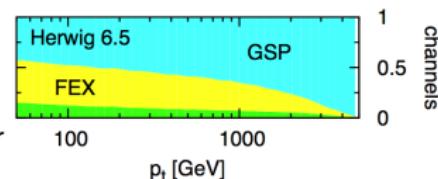
Flavour excitation (FEX)



Gluon splitting (GSP)



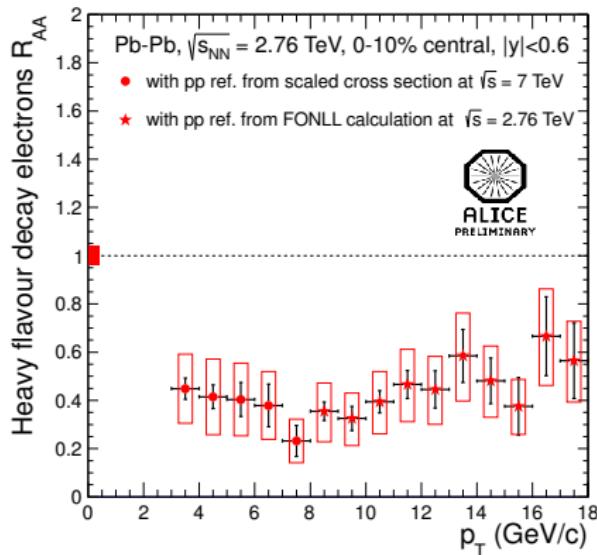
- FCR, FEX: coherence time $\Delta\tau \sim 1/Q$. $Q > 2m_{c,b}$.
 - charm: $\Delta\tau \sim 0.07 \text{ fm}/c$
 - beauty: $\Delta\tau \sim 0.02 \text{ fm}/c$
- GSP: enhancement due to Lorentz boost $E_g/(2m_{c,b}) \sim E_{c,b}/m_{c,b} \Rightarrow \Delta\tau \sim E_{c,b}/2m_{c,b}^2$.
 - charm: $\Delta\tau \sim 1 \text{ fm}/c$ at $p_T = 15 \text{ GeV}/c$
 - beauty: $\Delta\tau \sim 1 \text{ fm}/c$ at $p_T = 150 \text{ GeV}/c$
- Charm: moderate GSP contribution ($\sim 10 - 20\%$) [A.H.Mueller, P.Nason, Phys.Lett.B **157** (1985) 226]
- Beauty: larger GSP contribution $\sim 50\%$ but smaller formation time [A.Banfi, G.P.Salam, G. Zanderighi, JHEP **0707** (2007) 026]



Reasonably, heavy flavours probe heavy-quark in-medium interaction for $p_T \lesssim 50 \text{ GeV}/c$

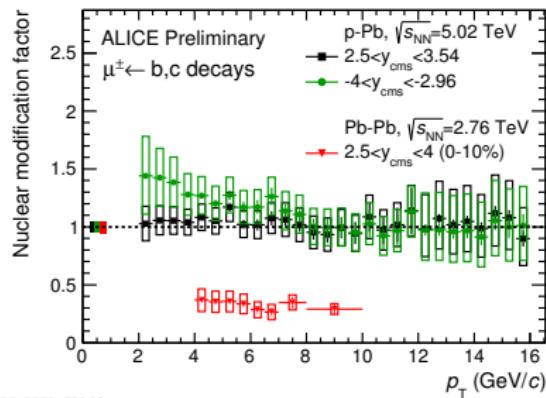
Heavy flavour decay lepton R_{AA} at the LHC

HF electrons, $|y| < 0.6$



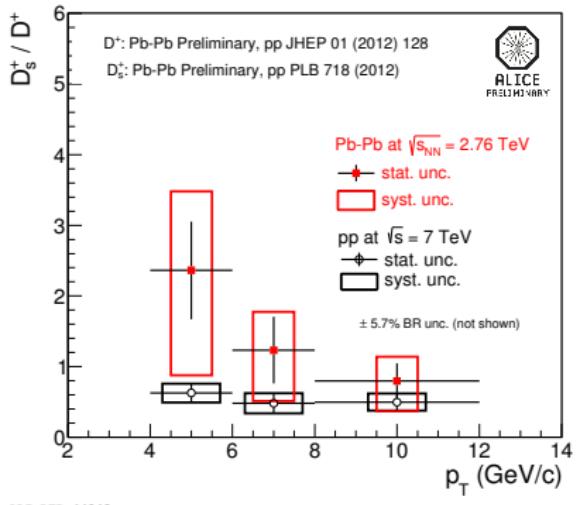
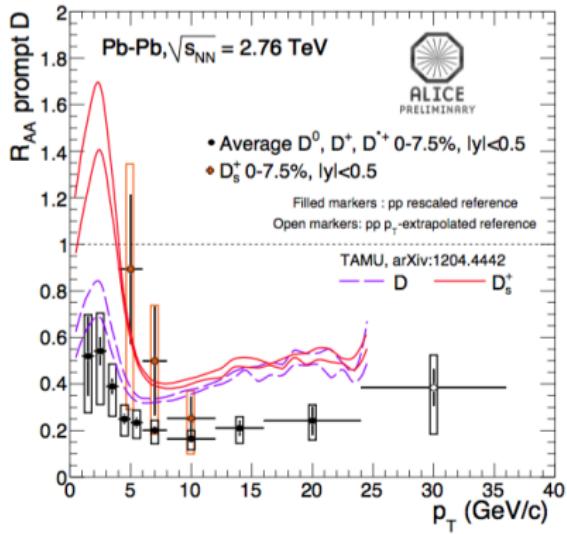
ALI-PREL-31917

HF muons, $2.5 < y < 4$



- Comparable suppression of HF decay leptons at high p_T in central Pb–Pb collisions at central and forward rapidity
 - NB: p_T spectrum dominated by beauty decay at high p_T
- Effect not observed in p–Pb collisions \Rightarrow final state effect

Further info on hadronization mechanism



- D_s measurement at low/intermediate p_T sensitive to hadronisation via recombination in medium
 - current results do not allow to conclude on an enhanced ratio of D_s/D mesons yields in $Pb-Pb$ compared to pp collisions \Rightarrow better precision needed!
- Heavy-flavour baryon to meson ratios are sensitive to coalescence as well

Models overview

Comparative overview of modes for heavy quark energy loss or transport in the medium

<i>Model</i>	<i>Heavy-quark production</i>	<i>Medium modelling</i>	<i>Quark-medium interactions</i>	<i>Heavy-quark hadronisation</i>	<i>Tuning of medium-coupling (or density) parameter(s)</i>
Djordjevic et al.	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss finite magnetic mass	fragmentation	Medium temperature fixed separately at RHIC and LHC
WHDG	FONLL	Glauber model no fl. dyn. evolution	rad. + coll. energy loss	fragmentation	RHIC
Vitev et al.	non-zero-mass VFNS no PDF shadowing	Glauber model nuclear overlap ideal fl. dyn. 1+1d Bjorken expansion	radiative energy loss in-medium meson dissociation	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
AdS/CFT (HG)	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	AdS/CFT drag	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
POWLANG	POWHEG (NLO) EPS09 (NLO) PDF shadowing	2+1d expansion with viscous fl. dyn. evolution	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume pQCD (or I-QCD U potential)
MC@HQ+EPOS2	FONLL EPS09 (LO) PDF shadowing	3+1d expansion (EPOS model)	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at LHC, slightly adapted for RHIC
BAMPS	MC@NLO no PDF shadowing	3+1d expansion parton cascade	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
TAMU	FONLL EPS09 (NLO) PDF shadowing	2+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss diffusion in hadronic phase	fragmentation recombination	assume I-QCD U potential
UrQMD	PYTHIA no PDF shadowing	3+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume I-QCD U potential
Duke	PYTHIA EPS09 (LO) PDF shadowing	2+1d expansion viscous fl. dyn.	transport with Langevin eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at RHIC and LHC (same value)

[A. Andronic et al., arXiv:1506.03981]