3rd Heavy Flavor Meet
Indore 2019, March 18-20

(more or less) Recent topics in (open) heavy-flavor production

Outline

- Introduction and structuration
- « Understanding » the $R_{AA} - v_2$
- Lessons from recent collective initiatives (bulk, hadronization,transport,…)
- New observables
- More lessons from recent collective initiatives
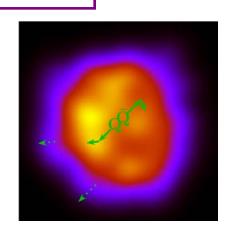- The role of transport
- A word on small systems
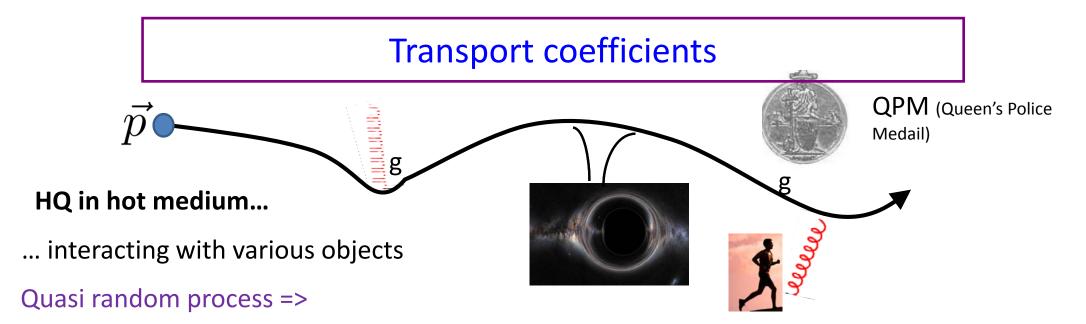- Conclusions

P.B. Gossiaux

SUBATECH, UMR 6457

Université de Nantes, IMT Atlantique, IN2P3/CNRS

Why open heavy flavors in A-A ?

1. Φ: Produced early, number conserved through time evolution (even at LHC) $\Rightarrow$ signature (hard probes) of early (hot) phase

2. Φ: *Strongly affected by the QGP phase (up to factor 5 in the final spectrum)*

3. Φ: Weakly affected by late time evolution (heavy, colour transparency)

4. Interpretation: Allows physical picture based on physical scales ($t_{relax} \, \alpha \, m_Q/T^2 \Rightarrow$ clear hierarchy for s, c and b)

5. Theory: Allows *some* pQCD calculations for the initial production and annihilation,…

6. Theory: …
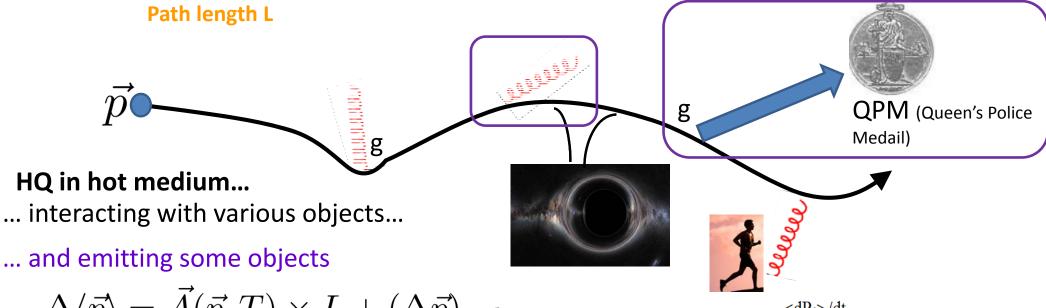
   Usually advocated as an ideal *probe* of dense matter

Transport coefficients

$\vec{p}$ ●

HQ in hot medium…

… interacting with various objects

g

g

QPM (Queen's Police Medail)

Quasi random process =>

$$-\frac{d}{dt}\langle\vec{p}\rangle = \vec{A}(\vec{p},T) = \eta_D(\vec{p},T)\times\vec{p} \quad \eta_D[\mathrm{fm}^{-1}]: \quad \text{Relaxation rate}$$

$$\frac{d}{dt}\langle\vec{p}_{T,i}\vec{p}_{T,j}\rangle = \kappa_T(\vec{p},T)\delta_{i,j} \quad \kappa_T[\mathrm{GeV}^2\mathrm{fm}^{-1}]: \quad \text{Transverse diffusion coef. (p space)}; \quad \boxed{\hat{q} = 2\kappa_T = 4B_0}$$

$$\kappa_L[\mathrm{GeV}^2\mathrm{fm}^{-1}]: \quad \text{Longitudinal diffusion coef.}$$

Similar in longitudinal direction

In general, no relation between these coefficients except $\kappa_T = \kappa_L$ for p=0.
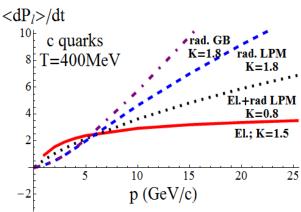
3

Transport coefficients and inelastic processes

Path length L

$$\vec{p}$$

HQ in hot medium…

… interacting with various objects…

… and emitting some objects

g

g

QPM (Queen's Police Medail)

$$\Delta\langle\vec{p}\rangle = \vec{A}(\vec{p},T) \times L + \underbrace{(\Delta\vec{p})_{\mathrm{rad}}}$$

- contribution from « radiated » part
- In most of existing schemes: $(\Delta\vec{p})_{\mathrm{rad}} = \mathcal{F}(\underbrace{\eta_D, \kappa_T, \kappa_L}, p, L)$

Seeked ransport coeff.

!!! In this case, the relaxation rate < (<<) η_D

$\langle dP_l\rangle/dt$

c quarks
T=400MeV

rad. GB
K=1.8

rad. LPM
K=1.8

El.+rad LPM
K=0.8

El.; K=1.5

p (GeV/c)

4

Transport coefficients at low momentum p≈m_Q
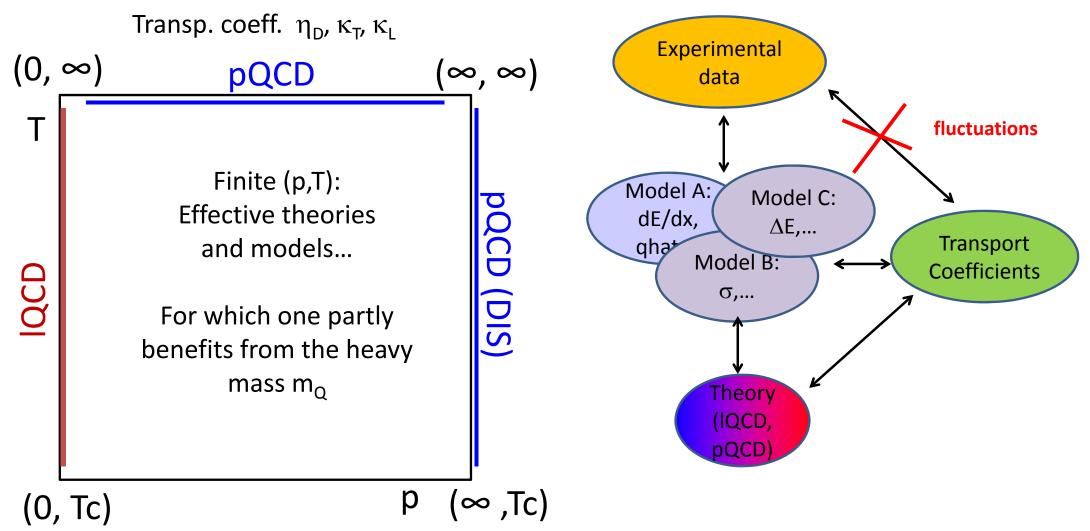
Langevin regime => Einstein relation: $\kappa = 2TE_Q\eta_D$

$$D_s = \left(= \frac{1}{6}\lim_{t\to\infty}\frac{\langle(\mathbf{x}(t) - \mathbf{x}(0))^2\rangle}{t}\right)$$

For historical reasons, physics displayed as a function of 2πT x the spatial diffusion coefficient

$$(2\pi T)D_s = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q\eta_D} \quad\Rightarrow\quad \tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$$

Gauge for the coupling strength

lQCD results

The sole direct rigorous calculation of the transport coeff to my knowledge

$$\tau_{\text{relax}}(T_c) \approx m_Q[\text{GeV}] \times (3 \pm 1.5)\,\text{fm}$$

Improvement Required

5
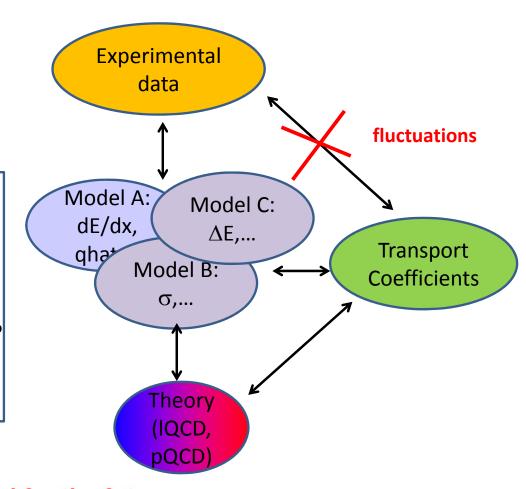
Today Stakes and Motivation

- Very subttle interplay between fundamental theory and experimental data to build and calibrate / constrain the models in order to better understand HF – QGP interaction (including QGP constituents)
- Then maybe one day: probing the bulk !
- On a more phenomenological and data driven level: Are we able to constrain / extract the in – medium transp. coefficients with a « reasonnable » precision ?
  - => What is the impact of various « extra » ingredients ?
  - Do we agree on what « reasonnable » means (x 2 ? 50% ?, 10% ?)
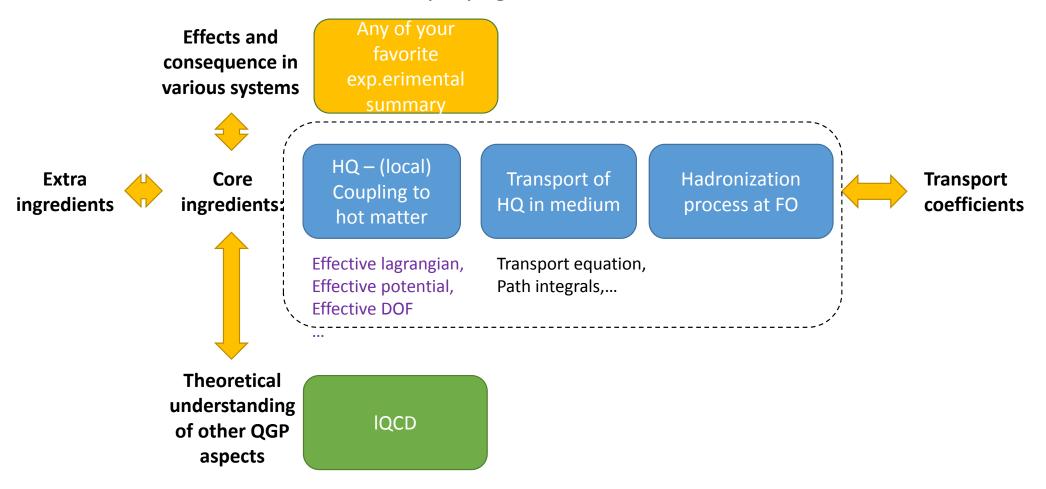- Need to intercompare the approaches.

Big motivation of OHF community

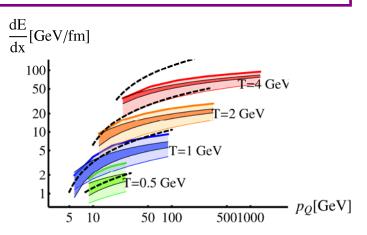Major goal for the future:
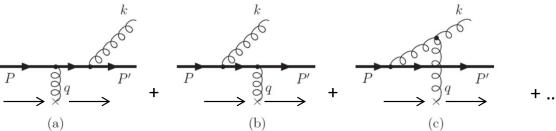from indication to real quantification!

pQCD inspired models (f.i. Nantes)

Colisional component

- One-gluon exchange model: reduced IR regulator $\lambda\, m^2_D$ in the hard propagator, fixed on HTL Energy loss
- Running coupling α_{eff} (t) and self consistent Debye mass

$$m_{Dself}{}^2\,(T) = (1+n_f/6)\,4\pi\alpha_{eff}(m_{Dself}{}^2)T^2$$

$\dfrac{dE}{dx}$[GeV/fm]

T=4 GeV
T=2 GeV
T=1 GeV
T=0.5 GeV

p_Q[GeV]

Radiative component

- Extention of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision ($\Delta E_{rad}\ \alpha\ E\ L$):

$$P_g(x, \mathbf{k}_\perp, \mathbf{q}_\perp, m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2 + xm_Q^2} - \frac{\mathbf{k}_\perp - \mathbf{q}_\perp}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + xm_Q^2}\right)^2$$

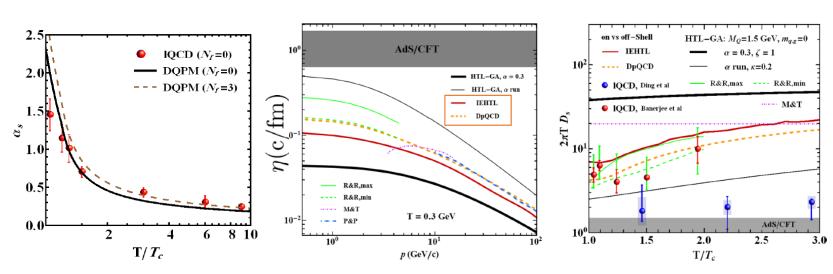- LPM effect for moderate gluon energy

Implemented in MC@HQ + EPOS2(3) through Boltzmann dynamics

But also BAMPS, LBL-CCNU, Duke,…   9

Quasi particle models (f.i DQPM)

- Non perturbative effects near Tc are captured by $\alpha_s(T)$, leading to thermal masses/widths, determined from fits to lQCD EoS.

A. Peshier et al. PLB 337 (1994), PRD 70 (2004); M. Bluhm et al. EPJC 49 (2007); W. Cassing et al. NPA 795 (2007)

- Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

T. Song et al. PRC 92 (2015), PRC 93 (2016)

But also CATANIA

10

Potential models (TAMU)

- Thermodynamic T-matrix approach, $T = V + VGT$, given by a two-body driving kernel V, estimated from the lQCD internal/free energy for a static Q-Qbar pair; increase of coupling with QGP at small momentum

D. Cabrera, R. Rapp PRD 76 (2007); H. van Hees, M. Mannarelli, V. Greco, R. Rapp PRL 100 (2008)
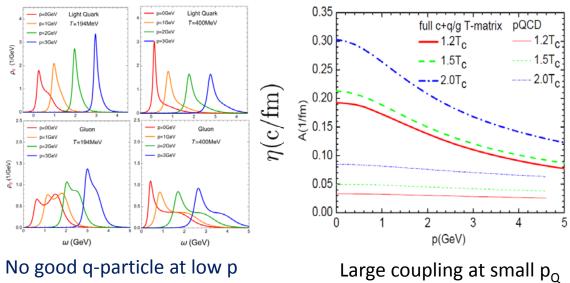
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

F. Riek, R. Rapp PRC 82 (2010); S. Liu, R. Rapp arxiv:1612.09138

- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions!
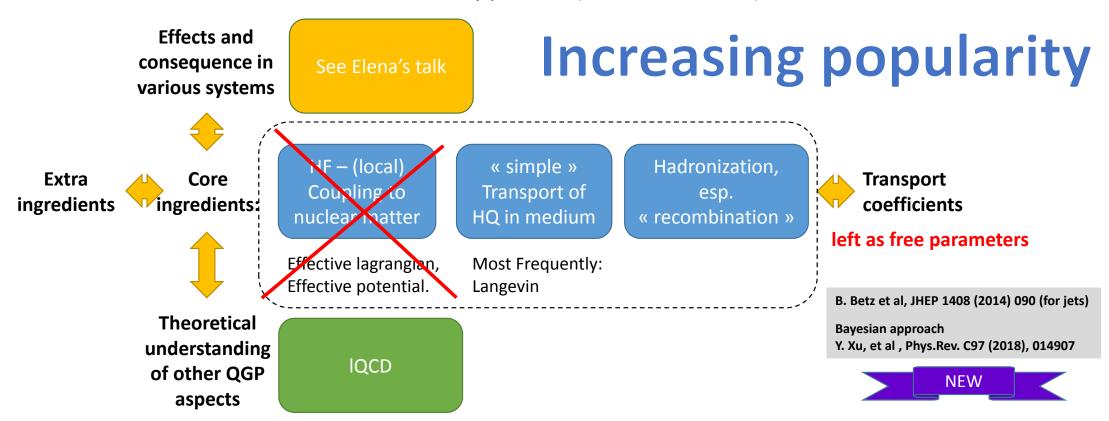
M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)

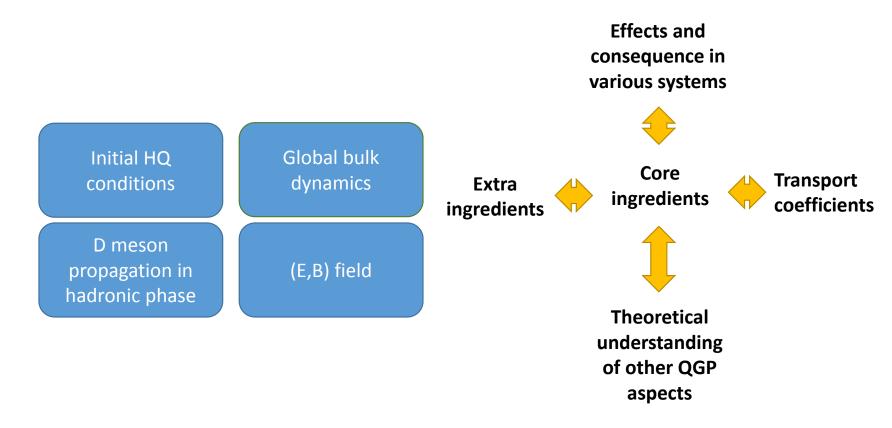- Implemented through Langevin dynamics in hydro evolution or in URQMD

No good q-particle at low p

Large coupling at small p_Q

A bit of structure

No-Model approach (« data driven »)

Effects and consequence in various systems

See Elena's talk

Increasing popularity

Extra ingredients

Core ingredients:

HF – (local) Coupling to nuclear matter

« simple » Transport of HQ in medium

Hadronization, esp. « recombination »

Transport coefficients

left as free parameters

Effective lagrangian, Effective potential.

Most Frequently: Langevin

B. Betz et al, JHEP 1408 (2014) 090 (for jets)

**Bayesian approach
Y. Xu, et al , Phys.Rev. C97 (2018), 014907**

NEW

Theoretical understanding of other QGP aspects

lQCD

A bit of structure

HQ propagation in QM & URHIC…
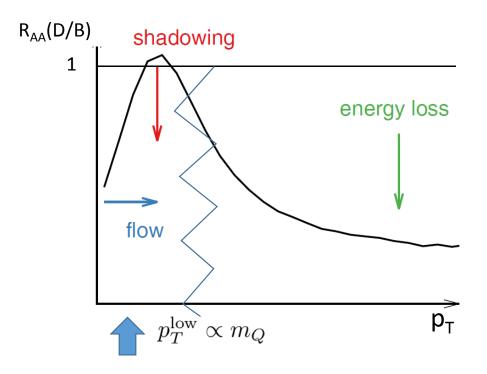
Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coefficient based (LV,...)	TAMU POWLANG HTL Catania LV	Duke	ASW	ADS/CFT POWLANG lQCD *DABMOD* (poster QM R. Katz) *S. Li et al,* arXiv:1803.01508
Cross section (or $|M|^2$) based (Boltzmann,...)	AMPT MC@sHQ el URQMD PHSD Catania BM	Djordjevic et al MC@sHQ el + rad BAMPS CUJET3 HYDJET++ Abir and Mustafa LBL-CCNU VNI/BMS *LIDO* (poster QM W. Ke)	$SCET_{G,M}$	

Red: Transport models

Basic Consequences of HQ interaction with QGP for the R_{AA}

The pattern seen in the data

R_{AA}(D/B)

shadowing

energy loss

flow

$p_T^{low} \propto m_Q$

p_T

The acknowledged effects

Flow bump: due to
- *(radial) flow of the medium* and coupling at small p_T
- *recombination with light quarks*

shadowing: due to *initial state nuclear effects*
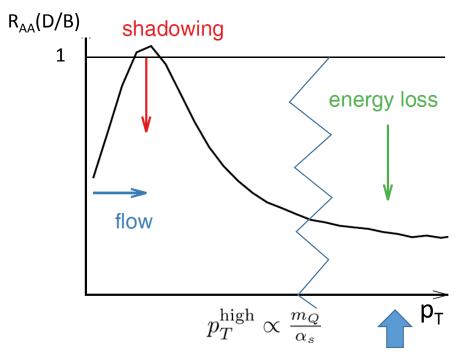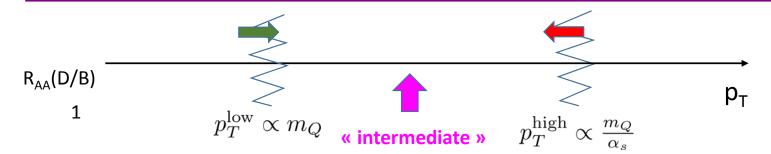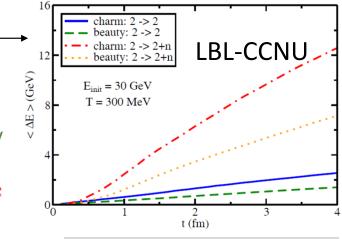
Quenching & energy loss: due to
- elastic and *inelastic* scatterings
- *opacity of the medium*

Italic: extrinsinc to the HF coupling with QGP AKA « energy loss model»

- Dominated by elastic interactions
- m_Q >> T => needs « many » collisions to equilibrate
- Physics close to « Langevin »

15

Basic Consequences of HQ interaction with QGP for the R_{AA}

The pattern seen in the data

The acknowledged effects

R_{AA}(D/B)

1

shadowing

energy loss

flow

$$p_T^{\mathrm{high}} \propto \frac{m_Q}{\alpha_s}$$

p_T

Flow bump: due to
- *(radial) flow of the medium* and coupling at small p_T
- *recombination with light quarks*

shadowing: due to *initial state nuclear effects*

Quenching & energy loss: due to
- elastic and *inelastic* scatterings
- *opacity of the medium*

- Dominated by radiative energy loss (with important coherence effects: $\Delta E_{\mathrm{rad}} \propto C_A \hat{q} L^2$)
- Eikonal regime (propagation along straight lines)
- 1 single transport coefficient dominates the whole physics: $\hat{q} \propto \kappa_T$
- HQ do not equilibrate with the medium
- m_Q becomes a subscale of the physics ($m_Q \ll p_T$)

16

$R_{AA}(D/B)$

1

$$p_T^{\text{low}} \propto m_Q \qquad \text{« intermediate »} \qquad p_T^{\text{high}} \propto \frac{m_Q}{\alpha_s}$$

p_T

- Interplay between elastic and radiative interactions…
- … whose dominance depends on the path length
- Fluctuations need to be taken properly into account
- Elastic component: Not clear that Langevin regime still applies (harder and harder collisions)
- 3 transport coefficients in momentum space (η, κ_L, κ_T) are « only » constrained by Fluc. Dissip. Th.
- Radiative component acquires NLO in m_Q/p and starts being sensitive to $\hat{e}$ and $\hat{e}_2$

LBL-CCNU

S. Cao et al, Phys. Rev. C 94, 014909 (2016)
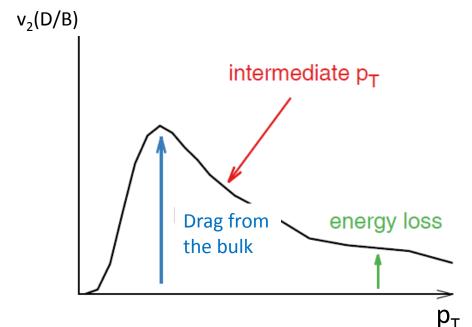
$$\frac{dN_g}{dy dl_\perp^2 d\tau} = 2 \; \frac{\alpha}{\pi} \; P(y) \; \frac{1}{l_\perp^4} \left(\frac{1}{1+\chi} \right)^4 \; \sin^2 \left(\frac{l_\perp^2}{4 l^-(1-y)} (1+\chi) \, \tau \right)$$
$$\times \left[\left\{ \left(1 - \frac{y}{2}\right) - \chi + \left(1 - \frac{y}{2}\right)\chi^2 \right\} \hat{q} + \frac{l_\perp^2}{l^-} \chi (1+\chi)^2 \; \hat{e} + \frac{l_\perp^2}{(l^-)^2} \chi \left(\frac{1}{2} - \frac{11}{4}\chi \right) \hat{e}_2 \right]$$

Abir and Majumder, Phys. Rev. C 94, 054902 (2016)

See as well Aichelin, Gossiaux & Gousset, PRD (2013)

17

Basic Consequences of HQ interaction with QGP for the v_2

v_2(D/B)

intermediate p_T

Drag from the bulk

energy loss

p_T

Small pT: height of v2 at low p_T sensitive to:
- *Bulk anisotropy, mostly at the late times*
- The drag force acting locally on HF

high p_T non-0 v_2 is due to anisotropic Eloss (same ingredients as for the RAA + *geometrical anisotropy of initial distribution of matter*)

intermediate p_T : onset and offset of many competing effects.

!!! Alternative pointed out recently within transport model (AMPT & MPC) study: so-called « escape mechanim » characterized by a large v_2 component stemming from $N_{coll} \approx 1$

L. He et al, Physics Letters B753 (2016) 506
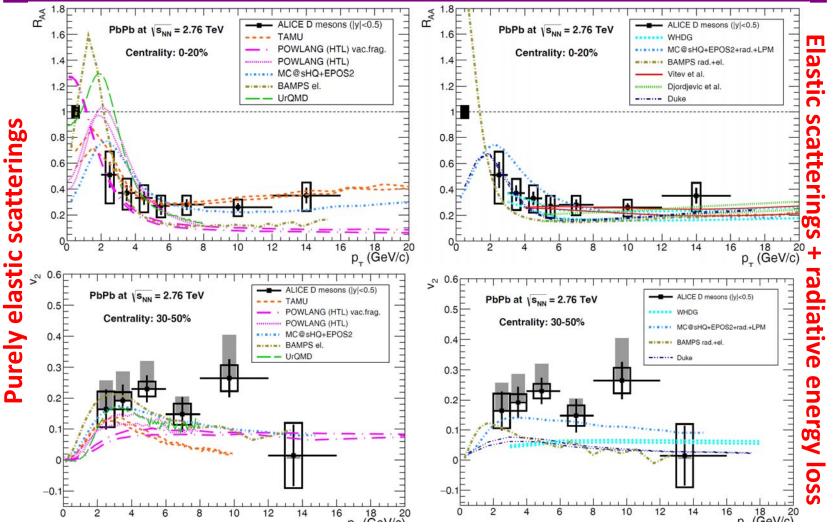
2 Important remarks:
- Any energy loss model, even the roughest one, will generate these typical structures in the R_{AA} and the v_2. Getting a correct **quantitative** agreement is much more involved.
- Quantitative predictions also depends on those « extra ingredients »

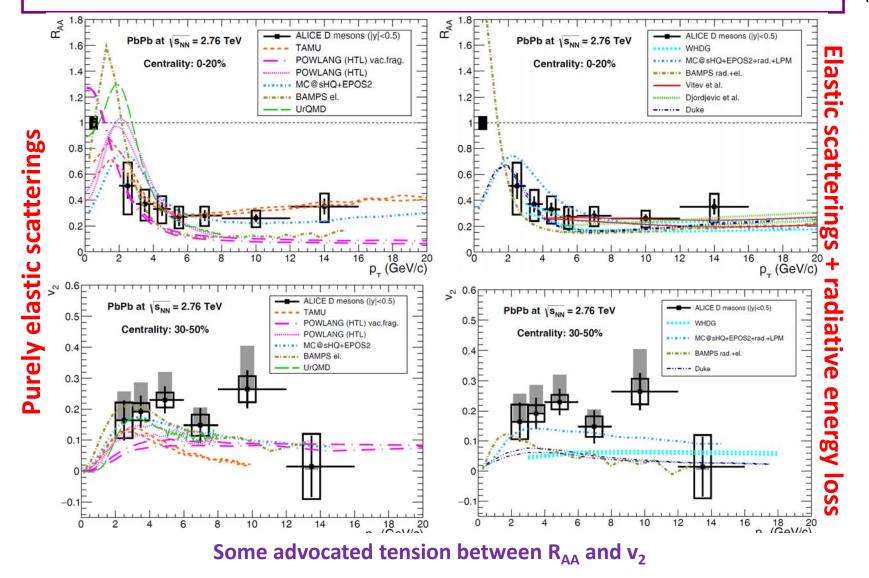**Purely elastic scatterings**
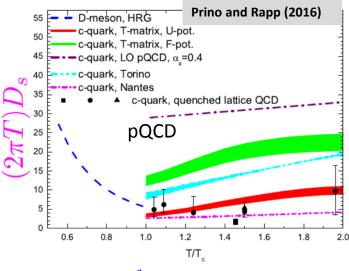
Elastic scatterings + radiative energy loss

Despite various prescriptions for Energy loss, a lot of models can cope with the data

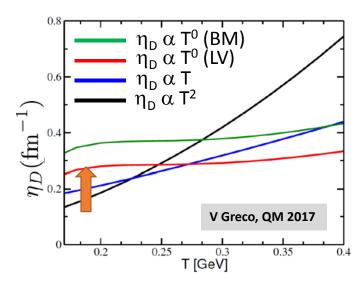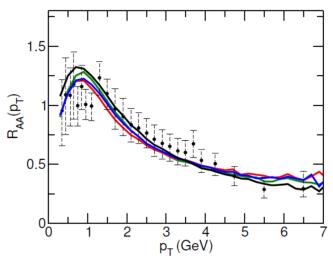# Models vs DATA at LHC (Sapore Gravis Report compilation)

Purely elastic scatterings

Elastic scatterings + radiative energy loss

Some advocated tension between R_{AA} and v_2

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

Prino and Rapp (2016)

pQCD

$(2\pi T)D_s$

$$\tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{m_Q}{2\pi T^2}$$
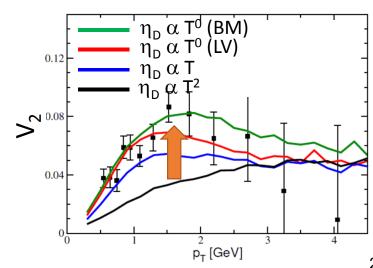
S.K. Das et al, Physics Letters B747 (2015) 260

V Greco, QM 2017

$\eta_D \, \alpha \, T^2$: pQCD (fixed α_s), AdS/CFT
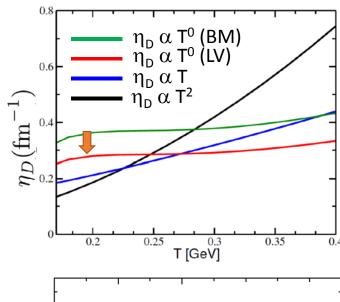
$\eta_D \, \alpha \, T$: pQCD (running α_s)

$\eta_D \, \alpha \, T^0$: QPM, DQPM, U potential (TAMU)

Tuned to reproduce R_{AA} => Larger coupling with the bulk near T_c (when the hydro v_2 has fully developped) => Larger v_2

21

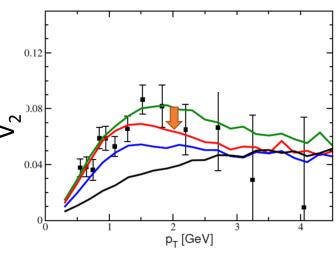# Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

Extra increase from LV => Boltzmann dynamics

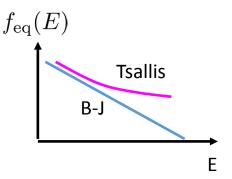**Should be seen as a *decrease* passing from Boltzmann =>LV**

In models considering $\gamma \propto T^0$ like QPM, DQPM, TAMU: microscopic $d\sigma/d\theta$ generate more diffusion at large angles

=> Encoding the physics into Langevin scheme, we do not describe properly the fluctuations at large momentum (as seen f.i. in the Tsallis like asymtotic distribution).
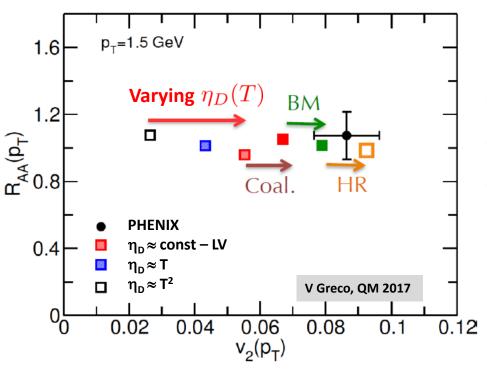

=> For dynamical evolution, one needs to crank down the interaction and the FP coefficients in order to reproduced a « given » R_{AA}

=> Smaller « extracted » coefficients ($\approx$ -20%) & smaller v_2.

S.K. Das et al, Physics Letters B747 (2015) 260

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

$p_T = 1.5$ GeV

Varying $\eta_D(T)$ BM

Coal.   HR

$R_{AA}(p_T)$
$v_2(p_T)$

- PHENIX
- $\eta_D \approx$ const – LV
- $\eta_D \approx T$
- $\eta_D \approx T^2$
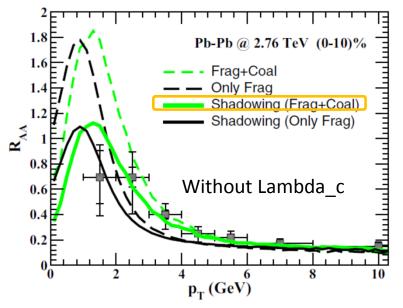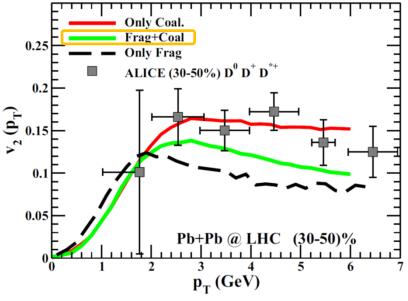
V Greco, QM 2017

Nice guideline but need:

- To consider extra ingredients (bulk, initial v_2,..)

- To assess the uncertainties on « Coal » and « HR »

- ... before one can think of ruling out other trends for η_D.

Results from QPM

Plumari, QM 2018

- Nonperturbative effects near Tc are captured by α_s (T), determined from fits to lQCD pressure and interation measure and leading to pretty large thermal masses.

- Bulk of massive partons described by Boltzmann dynamics, with gain and loss term is tuned to a fixed $\eta/s(T)$

$$g^2(T) = \frac{48\pi^2}{(11N_C - 2N_f)\ln\left[\lambda\left(\frac{T}{T_C} - \frac{T_S}{T_C}\right)\right]^2}$$

- Hadronization performed through (local) coalescence + fragmentation

- **Good common description of R_{AA} and v_2**
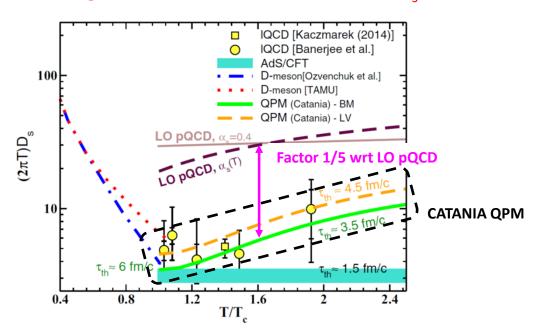
Results from QPM

Plumari, QM 2018

- Nonperturbative effects near Tc are captured by α_s (T), determined from fits to lQCD pressure and interation measure and leading to pretty large thermal masses.
- Bulk of massive partons described by Boltzmann dynamics, with gain and loss term is tuned to a fixed $\eta/s(T)$

$$g^2(T) = \frac{48\pi^2}{(11 N_C - 2 N_f) \ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}.$$

M. Ruggieri et al., Phys. Rev. C 89, 054914 (2014).

- Hadronization performed through (local) coalescence + fragmentation
- Good description of R_{AA} and v_2
- … Leading to an indirect extraction of the D_s coefficient… in the bulk of lQCD calculations

…and slowly increasing -> LO pQCD

Data driven extraction of transport coefficients

NEW

« Minimal model approach » : Bayesian analysis by the Duke group

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \quad \leftarrow \quad \frac{dN_g}{dx\,dk_\perp^2\,dt} = \frac{2\alpha_s P(x)\hat{q}_g}{\pi k_\perp^4}\sin^2\left(\frac{t - t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$
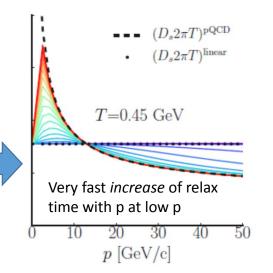
Higher twist
(no freedom
except qhat)

Usual Langevin $\langle \xi_i(t)\xi_j(t')\rangle = \kappa\delta_{ij}\delta(t-t')$ with $\kappa = \frac{2T^2}{D_s}$

+ coal / frag hadronization and hadronic rescattering

$$D_s(T, p) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{lin}}(T; \alpha, \beta)$$
$$+ \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{pQCD}}(T, p)$$

$$(D_s 2\pi T)^{\mathrm{pQCD}} = 8\pi/(\hat{q}/T^3)$$

$$(D_s 2\pi T)^{\mathrm{linear}} = \alpha \cdot (1 + \beta(T/T_c - 1))$$

Encodes possible Non Perturbative Effects around T_c
through parameters α (magnitude), β (slope) and γ (inverse
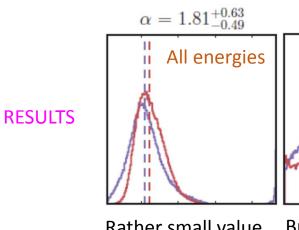momentum range of NP effects)

- - - $(D_s 2\pi T)^{\mathrm{pQCD}}$
· $(D_s 2\pi T)^{\mathrm{linear}}$

$T = 0.45$ GeV

Very fast *increase* of relax
time with p at low p

p [GeV/c]
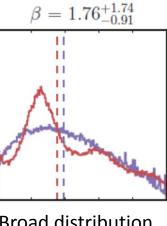
26

Duke "Bayesian approach"

- Choice of 60 « prior » for which the physical observabes are calculated
- Gaussian emulator to build a fast surrogate of physics
- Random walk throughout parameter space, with acceptance and rejection according to likelihood (with all uncertainties assumed to be uncorrelated).
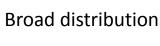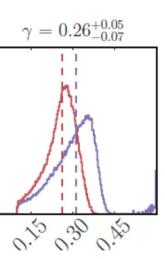
Let the data speak

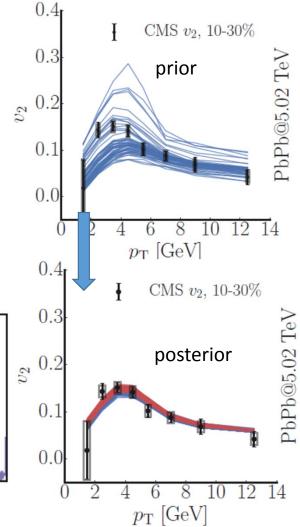$$(D_s 2\pi T)^{\text{linear}} = \alpha \cdot (1 + \beta(T/T_c - 1))$$

RESULTS

$\alpha = 1.81^{+0.63}_{-0.49}$ $\beta = 1.76^{+1.74}_{-0.91}$ $\gamma = 0.26^{+0.05}_{-0.07}$

All energies

0.15   0.30   0.45

Rather small value => strong coupling !   Broad distribution
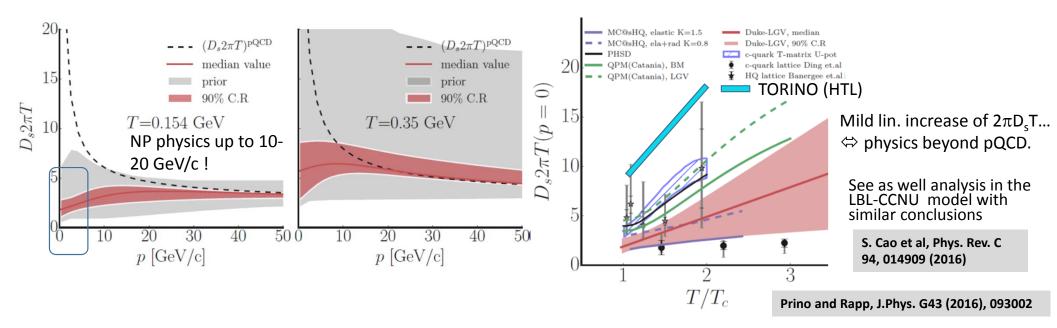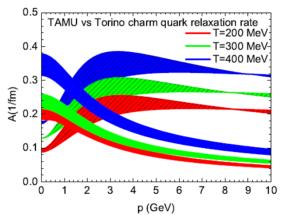
Duke "Bayesian approach" vs models

T=0.154 GeV
NP physics up to 10-20 GeV/c !

T=0.35 GeV

Mild lin. increase of $2\pi D_s T$…
⇔ physics beyond pQCD.

See as well analysis in the LBL-CCNU model with similar conclusions

S. Cao et al, Phys. Rev. C 94, 014909 (2016)

Prino and Rapp, J.Phys. G43 (2016), 093002
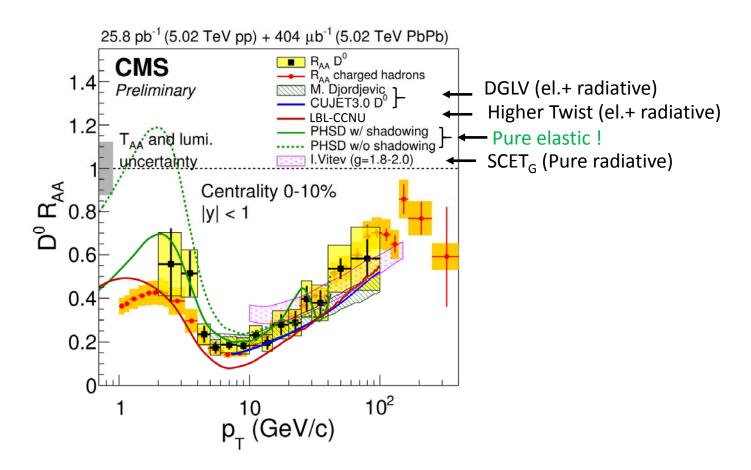
All together (lQCD, Bayesian analysis and most recent models) make a strong case for NP physics « around T_c » and at «low» p_T … needs to be precised in the future

- Does not mean that all models inhold the same physics…
- D_s (p=0) does not represent the full physics (different momentum dependences)
- D_s (finite p) in Duke's el + rad approach should not be compared to the same quantity in purely elastic models (additional contribution to energy loss due to the rad. part)
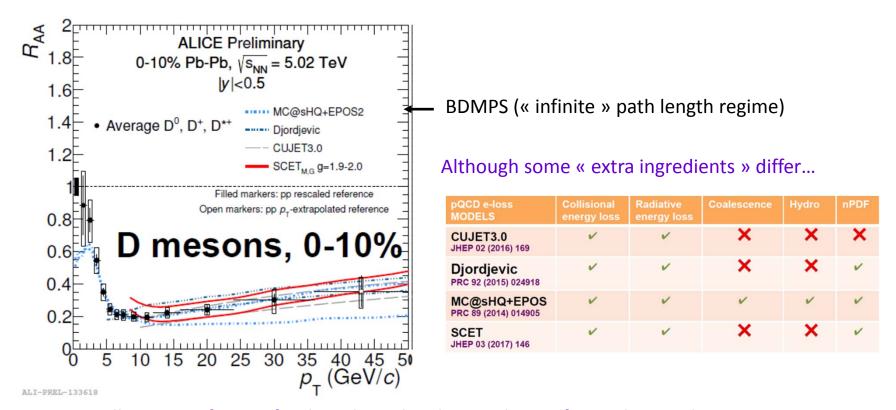
28

Over the past years, steady development of several sophisticated pQCD-based radiative Energy loss schemes in order to cope with the radiation of energetic partons: BDMPSZ, AMY, higher twist, DGLV, SCET... some of them leading to successful comparison with the data in their numerical implementation...

DGLV (el.+ radiative)

Higher Twist (el.+ radiative)

Pure elastic !

$SCET_G$ (Pure radiative)

29

Status of high p_T HQ

Over the past years, steady development of several sophisticated pQCD-based radiative Energy loss schemes in order to cope with the radiation of energetic partons: BDMPSZ, AMY, higher twist, DGLV, SCET... some of them leading to successful comparison with the data in their numerical implementation...

BDMPS (« infinite » path length regime)

Although some « extra ingredients » differ...

pQCD e-loss MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro	nPDF
CUJET3.0 JHEP 02 (2016) 169	✔	✔	✖	✖	✖
Djordjevic PRC 92 (2015) 024918	✔	✔	✖	✖	✔
MC@sHQ+EPOS PRC 89 (2014) 014905	✔	✔	✔	✔	✔
SCET JHEP 03 (2017) 146	✔	✔	✖	✖	✔

... Overall success of pQCD for describing the gluon radiation from a hot medium.
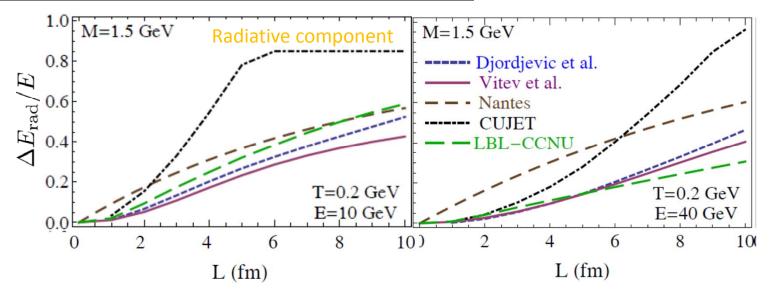
Beware : $\hat{q}$ is « just » an indirect result in some of those formalisms

30

Status of high p_T HQ: prospects

… Overall success of pQCD for describing the gluon radiation from a hot medium…. However, in a regime where m/p_T is small => The genuine mass ordering has still to be quantified and scrutinized more precisely between various approaches

Clear case for b-quark physics

Comparing some callibration curve for main approaches:

R. Rapp et al,
Nuclear Physics A 979 (2018) 21–86
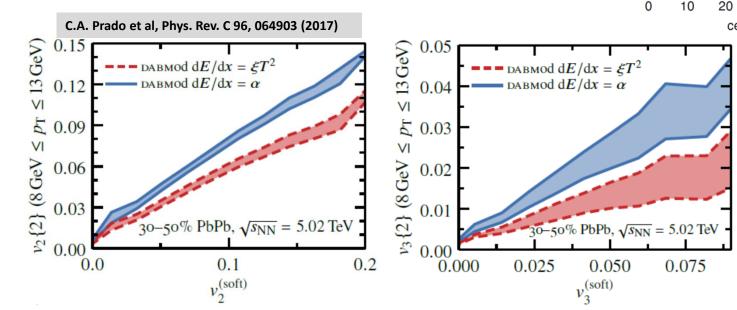arXiv: 1803.03824
EMMI Task Force

- Rather good agreement between Djordjevic ans SCET$_G$ (same α_s=), and also with LBL-CCNU (although smaller value of α_s.
- Trend reproduced by Nantes implementation of BDMPS for intermediate pT (for which it should apply)
- Much increased value for the CUJET3 stemming from the assumption of magnetic monopoles « around » Tc => If all other ingredients are under control, offers a unique opportunity to probe the QGP dof with high p_T partons
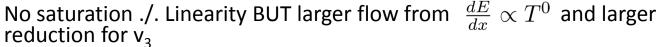
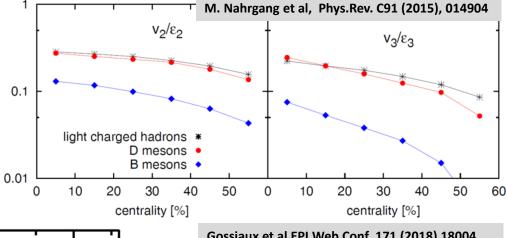31

More on v_2 and higher flow harmonics

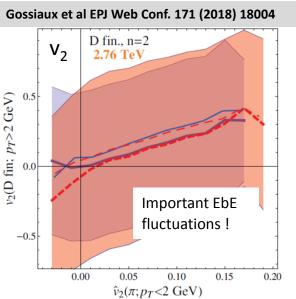Goal: better understand the coupling btwn HQ and QGP by:

- departing from the nearly equilibrated regime

- exploring the consequences of inertia due to large m_Q

- Our observation: **reduction of v_n/ε_n for a) larger n, b) larger mass and c) larger centrality…**

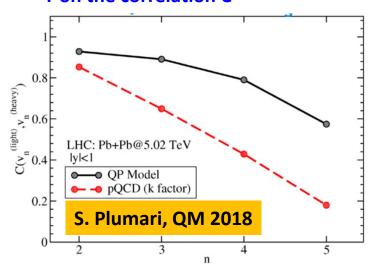Does the HQ flow follows the light sector ? => EbE analysis

M. Nahrgang et al, Phys.Rev. C91 (2015), 014904

C.A. Prado et al, Phys. Rev. C 96, 064903 (2017)

Gossiaux et al EPJ Web Conf. 171 (2018) 18004

Important EbE fluctuations !

No saturation ./. Linearity BUT larger flow from $\frac{dE}{dx} \propto T^0$ and larger reduction for v_3

32

More on v_2 and higher flow harmonics

Impact of T-dependence of Ds on T on the correlation C
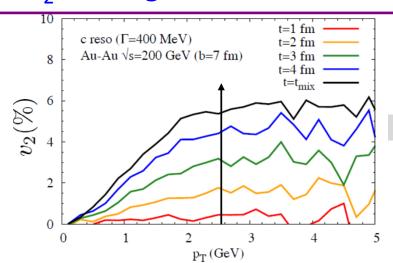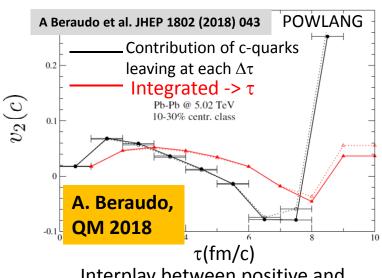

S. Plumari, QM 2018

Confirms previous trends up to the 5th moment! No correlation expected for pQCD-like

Poster R. Katz, QM 2018

DABMOD: extension of the Eloss scenarios considered: same trend!

Seems promising, but systematic study needs to be performed on an ensemble of bulks + initial fluctuations

c reso (Γ=400 MeV)
Au-Au √s=200 GeV (b=7 fm)

t=1 fm
t=2 fm
t=3 fm
t=4 fm
t=t_{mix}

A Beraudo et al. JHEP 1802 (2018) 043   POWLANG

Contribution of c-quarks leaving at each $\Delta\tau$
Integrated -> τ
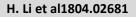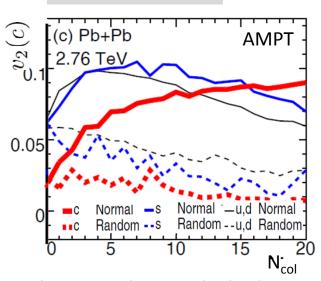Pb-Pb @ 5.02 TeV
10-30% centr. class

A. Beraudo, QM 2018

Interplay between positive and negative contributions

Need to understand the v_2(time), especially in light of the recently advocated escape mechanism

R. Rapp J.Phys. G36 (2009) 064014

Steady increase of v_2 (all c quarks)

H. Li et al1804.02681

(c) Pb+Pb
2.76 TeV   AMPT

c Normal   s Normal — u,d Normal
c Random   s Random — — u,d Random

« charm quarks more hydrodynamic then light quarks » Ok, but need to think twice about it!!!

33

Recent Collective actions beyond Sapore Gravis

- **Heavy Quark – Working Group** (convener: X-N Wang); in the spirit of the Jet Collaboration, the goal is, in a first stage, to :
  - Collect and compare the transport coefficients from various models,
  - Measure and understand their consequences by first studying a simpler brick problem
  - Estimate some systematics + uncertainties

  S. Cao et al, arXiv: 1809.07894

- LBL-CCNU (XN Wang, S. Cao)
- Duke (S. Bass , S. Cao, M. Nahrgang, Y. Xu)
- Catania (V. Greco, S. Das, S. Plumari, F. Scardina)
- TAMU (R. Rapp, M. He)
- Frankfurt pHSD (E. Bratkovskaya, T. Song, H. Berrehrah)
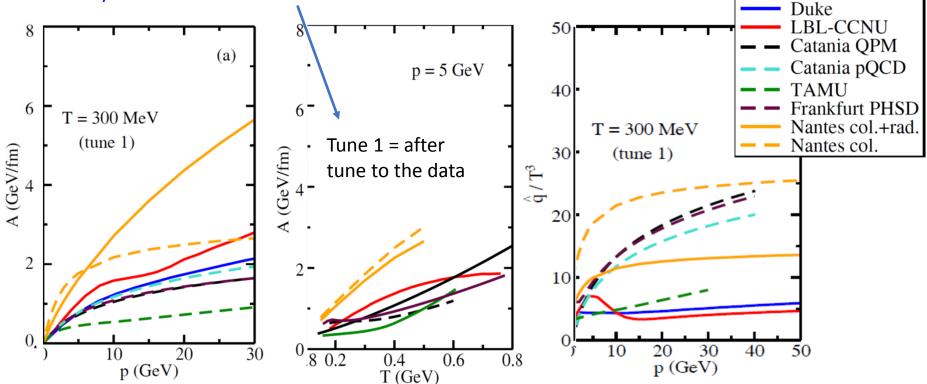- Nantes (J. Aichelin, PB Gossiaux, M. Nahrgang)

- Collect and compare the transport coefficients from various models:

c-quarks

What is used by various models to fit the data

Tune 1 = after tune to the data

Legend:
- Duke
- LBL-CCNU
- Catania QPM
- Catania pQCD
- TAMU
- Frankfurt PHSD
- Nantes col.+rad.
- Nantes col.

- Obviously not satisfying: Larger dispersion than the predictions for concrete observables… WHY ?
- Because of « extra ingredients », chosen differently in each model (partly) !!!
- More complex then for the case of jets (several FP coefficients)

Recent Collective actions beyond Sapore Gravis

- **EMMI Rapid Reaction Task Force** (organizers: R. Rapp, PB Gossiaux, A. Andronic, R. Averbeck,, S. Maschiocchi):
  - Global strategy to extract the diffusion coefficient from the intercomparison between models and data
  - Collect and analyse all ingredients from various models
  - Identify constrains from lQCD
  - Initiate discussions to assess the limitations of some existing models.

R. Rapp[*1], P.B. Gossiaux[*2], A. Andronic[*3,4], R. Averbeck[*3], S. Masciocchi[*3], A. Beraudo[5], E. Bratkovskaya[3,6], P. Braun-Munzinger[3,7], S. Cao[8], A. Dainese[9], S.K. Das[10,11], M. Djordjevic[12], V. Greco[11,13], M. He[14], H. van Hees[6], G. Inghirami[3,6,15,16], O. Kaczmarek[17,18] Y.-J. Lee[19], J. Liao[20], S.Y.F. Liu[1], G. Moore[21], M. Nahrgang[2], J. Pawlowski[22], P. Petreczky[23] S. Plumari[11], F. Prino[5], S. Shi[20], T. Song[24], J. Stachel[7], I. Vitev[25], and X.-N. Wang[26,18]

Goal to attack the problem with a broad view right from the beginning…

R. Rapp et al,
Nuclear Physics A 979 (2018) 21–86
arXiv: 1803.03824
EMMI Task Force

(20 monthes since first meeting)

EMMI RRTF

Topics:

- Initial spectra and shadowing

- Bulk evolution and consequence on HF observables

- Transport implementation

- Hadronization

- Microscopic models for HF energy loss and constrains from QCD at low and high momentum

- Future observables

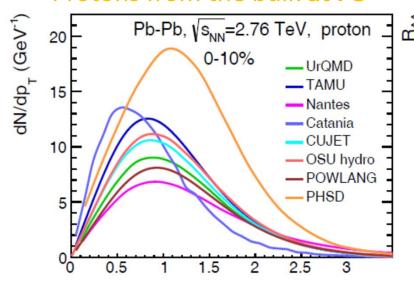# EMMI RRTF : Consequences from the **bulk choice** (and partly transport)

Question: What is the role of the different medium evolution models, and how do different predictions for the bulk cooling and expansion temperature in the current models manifest themselves in HF observables ?

Method: adopt a common α_s=0.4-pQCD x 5 cross section for thermal light partons acting on c-quarks (or associated FP coefficients for models based on FP) in all frameworks.
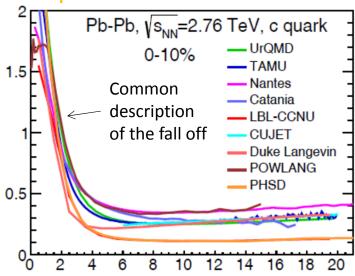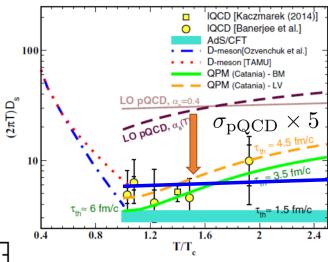
One Interaction for all of them; not aimed at reproducing the data !!!

R. Rapp et al, arXiv: 1803.03824

Protons from the bulk **at FO**   c quarks **at FO**

$\sigma_{\mathrm{pQCD}} \times 5$

This allows to probe the effect of the bulk with a mechanism that has a D_s roughly similar to the one extracted from lQCD

For most bulks:
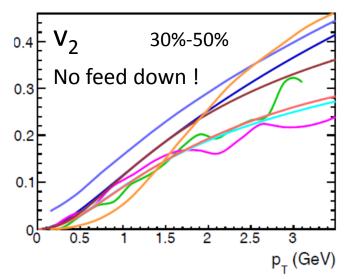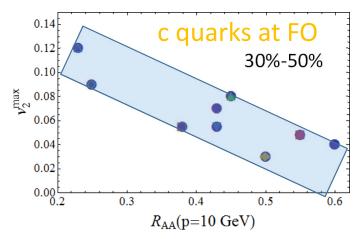$$R_{AA}(c, 10\,\mathrm{GeV}) \approx 0.3 - 0.4$$

For 30%-50%:
$$R_{AA}(c, 10\,\mathrm{GeV}) \approx 0.4 - 0.6$$

Common description of the fall off

No feed down !   Some correlation between dN(p) and R_{AA}(c) but not systematic

Protons from the bulk at FO

v_2 30%-50%

No feed down !

c quarks at FO

v_2 Off equil. effects

- UrQMD
- TAMU
- Nantes
- Catania
- CUJET
- LBL-CCNU
- POWLANG
- PHSD

30%-50%

N.B.: LBL-CCNU could not implement scattering on thermal- massive partons

For most bulks:

$$v_2(c, p_T = 4\,\mathrm{GeV}) \approx 0.4 - 0.6$$

Max v_2 reached between 2 and 4 GeV/c

c quarks at FO

30%-50%

Some correlation between $v_2(p)$ and $v_2(c)$ but not systematic

- Some correlation between $R_{AA}(c)$ and $v_2(c)$ from various bulks, but rather large residuals => Non « scalable » bulkS
- **Adopting a (limited number of) common bulk(s) would permit to shrink the residuals in the « extraction » of the optimal transport coefficients.**
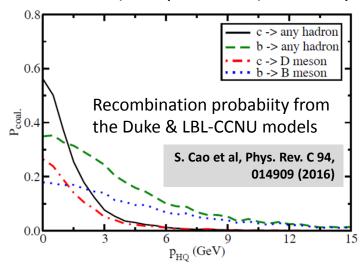
39

HQ-Hadronization (would deserve a full talk)

Acknowledged:
- towards the end of QGP, hadronization of (of equilibrium) HQ can proceed through a dual mechanism:

Low p_T :
- The quark partner(s) are already present in the hot cooling medium
- New specific recombination mechanism; no obvious calibration
- The footprint of reconfinment (?!)
- Crucial to explain the flow bump in R_{AA}(D) and sizable v_2(D) => large impact.

Recombination probabiity from the Duke & LBL-CCNU models

S. Cao et al, Phys. Rev. C 94, 014909 (2016)

High p_T :
- The quark partner(s) needed to create the HF-hadron have to be generated from the vacuum
- « usual » fragmentation calibrated on p+p and $e^+ + e^-$ data (Petersen,…)

Uncertain (and not disputed enough):
- Genuine physical recombination process !

Regained interest in view of the recent Λ_c measurement

HQ - Recombination

Instantaneous coalescence:

Greco, Ko & Levai. Phys. Rev. C 68 (2003) 034904
V. Greco, C. Ko, and R. Rapp, Phys. Lett. B 595 (2004) 202
Y. Oh et al, Phys. Rev. C79 (2009) 044905
R. J. Fries, V. Greco, and P. Sorensen, Ann. Rev. Nucl. Part. Sci. 58 (2008) 177

NEW

S Plumari et al. arXiv:1712.00730

Poster V. Minissale, QM 2018

D, Λc

time

Wigner density of hadronic states

x-p correlation (6D) or « just » in p space (3D/1D)

lq

HQ

space

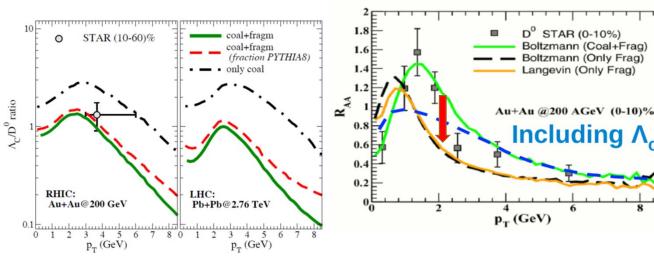**Known issues with energy momentum conservation; small effects at intermediate p_T ?**

Also: one free parameter per resonances

Latest Catania's coalescence model:

- Full 6D coalescence
- New normalization to impose $P_{coal} \rightarrow 1$ for $p_T \rightarrow 0$
- Resonance decay
- Mini jet contribution
- Inclusion of Λ_c baryonic states
  - => reduction of $R_{AA}(D)$ at small p_T
  - => increase of Λ_c/D^0 wrt pp and pPb.
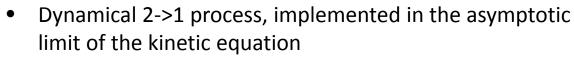
// S. Plumari, QM 2018

41

HQ - Recombination

Resonance Recombination Model:

$$\left(\frac{\partial}{\partial t} + \vec{v}\cdot\vec{\nabla}\right) F_M(t,\vec{x},\vec{p}) = -\frac{\Gamma}{\gamma_p} F_M(t,\vec{x},\vec{p}) + \beta(\vec{x},\vec{p})$$
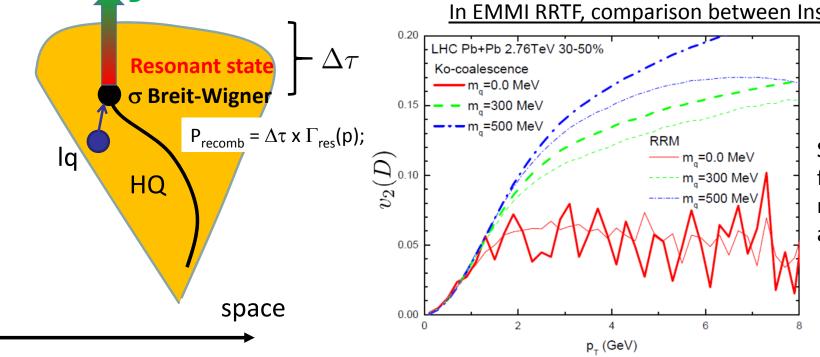
Ravagli and d Rapp, Phys. Lett. B 655 (2007) 126{131,

time

D

Resonant state
σ Breit-Wigner

$\Delta\tau$

$P_{recomb} = \Delta\tau \times \Gamma_{res}(p);$

lq

HQ

space

- Dynamical 2->1 process, implemented in the asymptotic limit of the kinetic equation
- A possible way to solve energy-momentum conservation
- Process governed by the interaction of HQ with QGP around T_c => natural link with the energy loss model.

In EMMI RRTF, comparison between Instant. Coal. & RRM

LHC Pb+Pb 2.76TeV 30-50%
Ko-coalescence
m_q=0.0 MeV
m_q=300 MeV
m_q=500 MeV
RRM
m_q=0.0 MeV
m_q=300 MeV
m_q=500 MeV

starting from the same bulk and from the same c spectrum

Significant differences found both for D meson p_T spectrum and v_2.
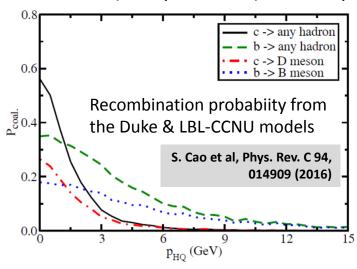
R. Rapp et al, arXiv: 1803.03824

HQ - Recombination

Acknowledged:

- towards the end of QGP, hadronization of (of equilibrium) HQ can proceed through a dual mechanism:

Low p_T :

- The quark partner(s) are already present in the hot cooling medium
- New specific recombination mechanism; no obvious calibration
- The footprint of reconfinment (?!)
- Crucial to explain the flow bump in $R_{AA}(D)$ and sizable $v_2(D)$ => large impact.

Recombination probabiity from the Duke & LBL-CCNU models

S. Cao et al, Phys. Rev. C 94, 014909 (2016)

High p_T :

- The quark partner(s) needed to create the HF-hadron have to be generated from the vacuum
- « usual » fragmentation calibrated on p+p and $e^+ + e^-$ data (Petersen,…)

But also energy density dependent (PHSD) !!!

Uncertain (and not disputed enough):

- Genuine physical recombination process:
  - Instantaneous Parton Coalescence with local (x,p) correlations (Greco, Ko & Levai 2003), Xor in momentum space (Oh et al 2009): known violation of energy-momentum conservation, advocated to have small effects at finite p_T
  - Resonance Recombination Model (Ravagli and Rapp, 2009): kinetic c+qbar -> D; spirit of dynamical recombination around T_c ($P_{recomb} = \Delta\tau \times \Gamma_{res}(p)$; a way to solve the energy-momentum conservation issue
  - In medium Fragmentation (Beraudo et al., 2015) : string from HQ + thermal light
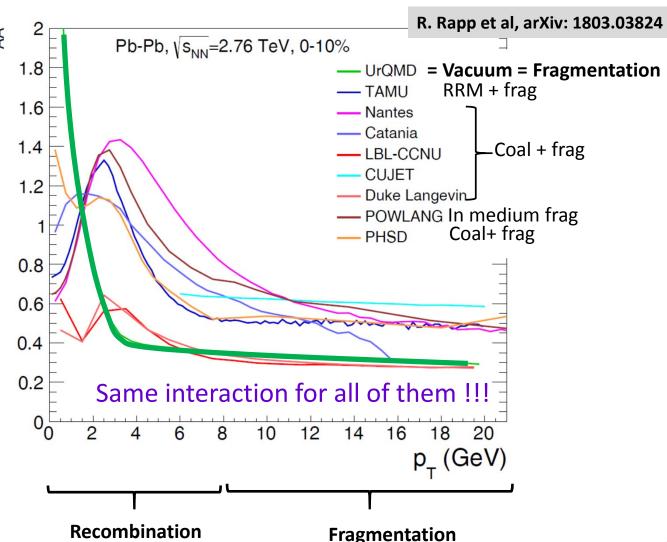- Differences in the « technical implementations » , e.g. normalisation

We define and display the H_{AA} quantity

$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ final}}{dp_T}}$$

...which exhibits at best the specific effects of hadronization :

Significant uncertainties !

=> Yes, one can for sure put more constrains with D_s and Λ_c, but probably one has also to converge on more robust schemes for « basic » D mesons

R. Rapp et al, arXiv: 1803.03824

Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV, 0-10%

- UrQMD **= Vacuum = Fragmentation**
- TAMU   RRM + frag
- Nantes
- Catania
- LBL-CCNU   Coal + frag
- CUJET
- Duke Langevin
- POWLANG In medium frag
- PHSD   Coal+ frag

Same interaction for all of them !!!

Recombination   Fragmentation

44

Consequences from the choice for Bulk, Hadronization and init. Spectrum
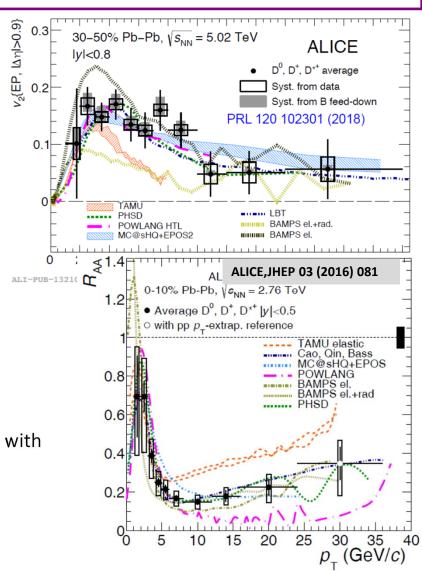
But without shadowing and hadronic rescatterings
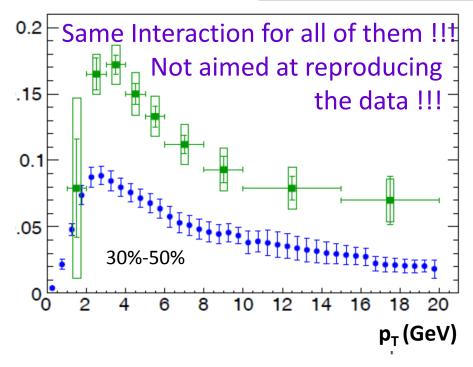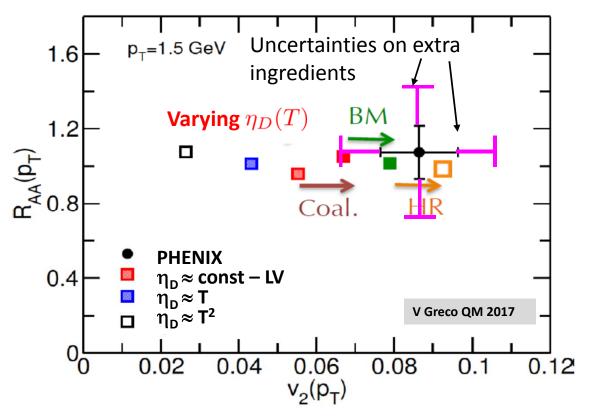
- You asked for it, you got it… « Theory error band »

- At least as large as the experimental one !

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail completed

V Greco QM 2017

PRL 120 102301 (2018)

ALI-PUB-1321(

ALICE,JHEP 03 (2016) 081

- Probably one of the reasons why some models – like EPOS2+MC@sHQ – with NOT (const. η_D) can cope both with R_{AA} and v_2.
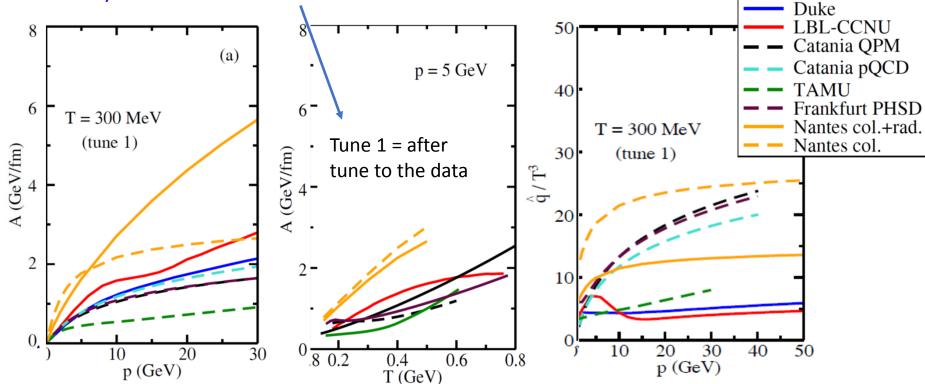
- What should we do next ?

- Collect and compare the transport coefficients from various models:

  c-quarks

  What is used by various models to fit the data

Tune 1 = after
tune to the data

Legend:
- Duke (blue solid)
- LBL-CCNU (red solid)
- Catania QPM (black dashed)
- Catania pQCD (cyan dashed)
- TAMU (green dashed)
- Frankfurt PHSD (purple dashed)
- Nantes col.+rad. (orange solid)
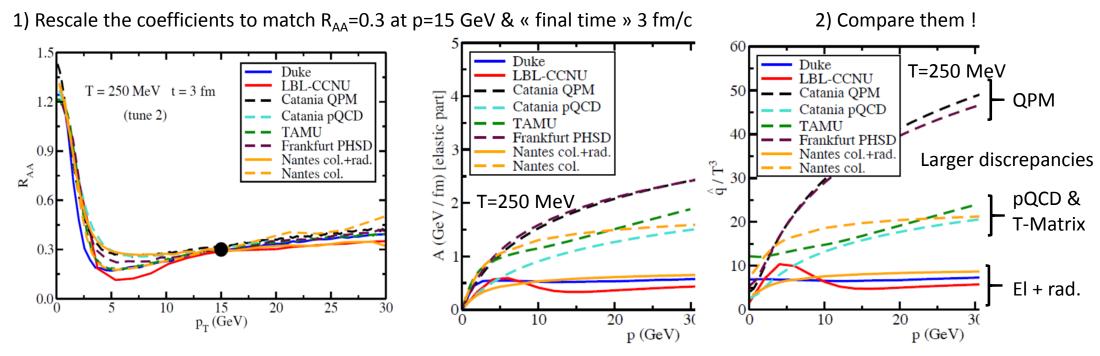- Nantes col. (orange dashed)

- **Obviously not satisfying: Larger dispersion than the predictions for concrete observables... WHY ?**
- Because of « extra ingredients », chosen differently in each model (partly) !!!
- More complex then for the case of jets (several FP coefficients)

47

The goal is to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
- Estimate some systematics + uncertainties

Best controled QGP ever: uniform fixed temperature for all models (with same initial condition FONLL-like @ RHIC)

1) Rescale the coefficients to match $R_{AA}=0.3$ at p=15 GeV & « final time » 3 fm/c

2) Compare them !

Main result: Nice structuration of the transport coefficients in different classes. For each class, the work illustrates the maximal accuracy reachable once all other ingredients are either fixed or chosen commonly

48

HQ-Working Group (convener: X-N Wang)

The goal is to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
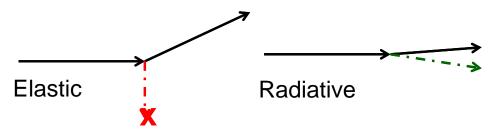- Estimate some systematics + uncertainties

Best controled QGP ever: uniform fixed temperature for all models (with same initial condition FONLL-like @ RHIC)

1) Rescale the coefficients to match $R_{AA}=0.3$ at p=15 GeV & « final time » 3 fm/c   2) Compare them !
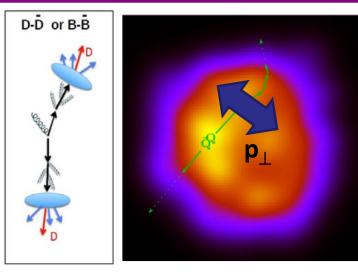

Going beyond: A) radiative energy loss for everyone B) thermal mass of light partons for everyone C) consider alternate observables affording to probe FP coefficients from different perspective D) adopt common ingredients (like common bulk) and (weaker) exchange ingredients between models.
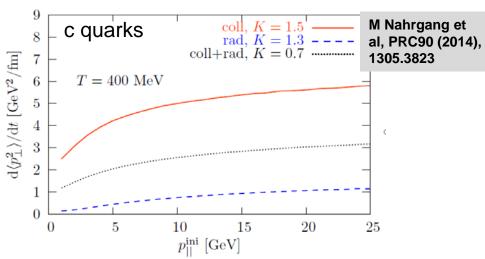
49

Alternate observable: HF-HF correlations

➢ Back to back D/Dbar or B/Bbar: As compared to γ-D/B: "trigger" itself is affected but symmetry between both particles limitates the various effects.

➢ Elastic Eloss vs radiative Eloss: **The purely collisional scatterings lead to a larger average $<p_\perp^2>$ then the radiative "corrections"** (need for large scattering to be efficient)... although both types can give correct agreement with the data at intermediate p_T.

Elastic   Radiative

➢ Expected consequences for azimuthal correlations (probe of B_T: good: **complimentary** to usual RAA and v2)

D-D̄ or B-B̄

$p_\perp$

M Nahrgang et al, PRC90 (2014), 1305.3823

c quarks

coll, $K = 1.5$
rad, $K = 1.3$
coll+rad, $K = 0.7$

$T = 400$ MeV

$d\langle p_\perp^2 \rangle/dt$ [GeV²/fm]

$p_\parallel^{ini}$ [GeV]

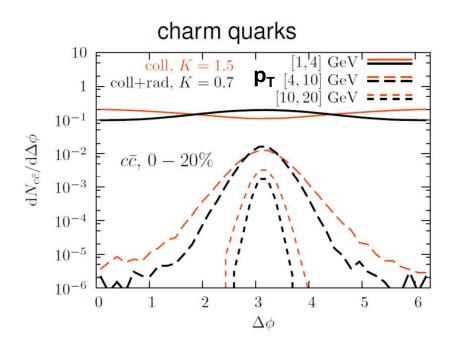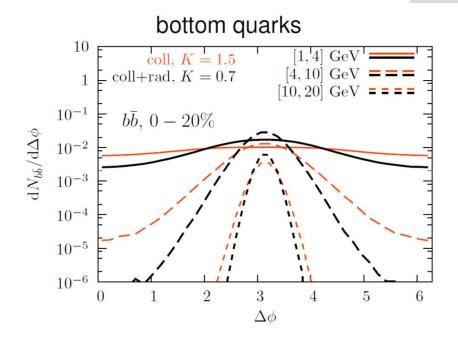**Tuned to reproduce the R$_{AA}$**

50

Alternate observable: HF-HF correlations

➢ Assumption of back 2 back emission of initial QQbar (**naïve LO…**)

charm quarks

bottom quarks
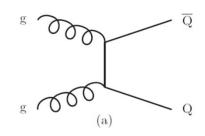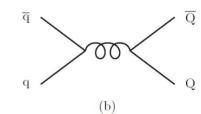
➢ Indeed, rather large differences found for both b and c, and all kind of p_T cuts (… but good to see there is an effect though,…)

➢ For the smallest p_T bin and elastic energy loss, we even find an inversion of the correlation ("hot partonic wind" push; v_0 bulk => v_1 correl; underlying event)
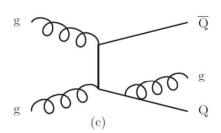
51

Alternate observable: azimuthal correlations
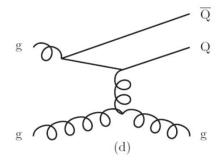
➤ ...but higher orders can have a significant impact:

➤ LO; (a): back to back peak

➤ NLO;

(c): "blurring" of B2B peak
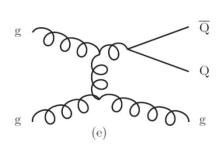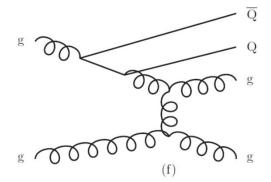
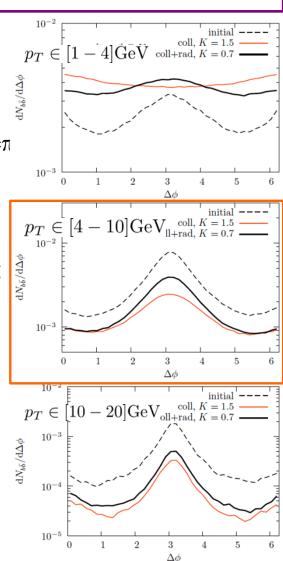(d): "flavor excitation": no strong azimuthal correlation expected

(e): gluon splitting: strong peak around $\Delta\phi=0$

(f): higher order FE; both Q and Qbar in the "remnant" region
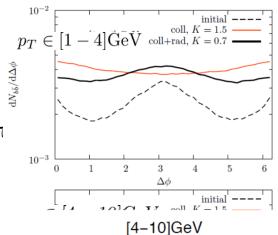
Alternate observable: azimuthal correlations
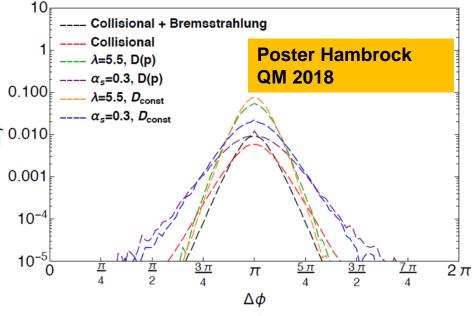
➤ **NLO effect** simulated with MC@NLO + HERWIG (parton shower)

➤ Gluon splitting processes lead to an initial enhancement of the correlations around $\Delta\phi=0$; Strong broadening of the $\Delta\phi=\pi$ peak ("vacuum" radiation is dominant)

➤ For intermediate p_T : increase of the variances due to Eloss from 0.43 (initial NLO) to 0.51 (+20%) for the purely elastic mechanisms and to 0.47 (+10%) for the interaction including **radiative** corrections.

➤ Correlations at large p_T seem to be dominated by the initial correlations. Nothing will be learned on the Eloss mechanisms in this region

➤ Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production

➤ Confirmation by other groups (Duke, CCNU-LBL,…)


53

Alternate observable: azimuthal correlations

➤ **NLO effect** simulated with MC@NLO + HERWIG (parton shower)

➤ Gluon splitting processes lead to an initial enhancement of the correlations around $\Delta\phi=0$; Strong broadening of the $\Delta\phi=\pi$ peak ("vacuum" radiation is dominant)

➤ For intermediate p_T : increase of the variances due to Eloss from 0.43 (initial NLO) to 0.51 (+20%) for the pu mechanisms and to 0.47 (+10%) for the interact **radiative** corrections.

➤ Correlations at large p_T seem to be dominated l correlations. Nothing will be learned on the Elo mechanisms in this region

➤ Different NLO+parton shower approaches agree quark production, differences remain for charm production

➤ Confirmation by other groups (Duke, CCNU-LBL

$p_T \in [1-4]\text{GeV}$

initial - - -
coll, $K=1.5$
coll+rad, $K=0.7$

$dN_{b\bar{b}}/d\Delta\phi$

$\Delta\phi$

[4–10]GeV

initial - - -
coll $K=1.5$

Poster Hambrock QM 2018

- - - - Collisional + Bremsstrahlung
- - - - Collisional
- - - - $\lambda=5.5$, D(p)
- - - - $\alpha_s=0.3$, D(p)
- - - - $\lambda=5.5$, D_{const}
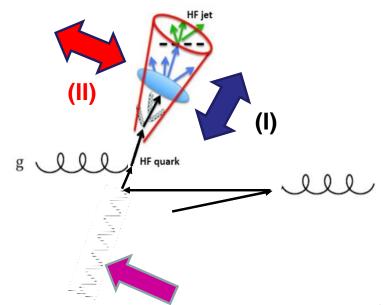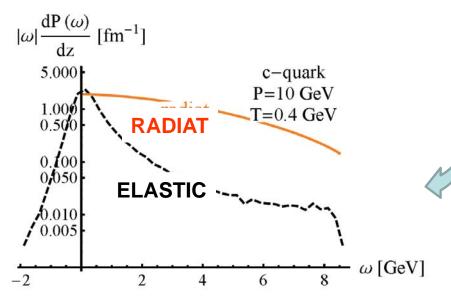- - - - $\alpha_s=0.3$, D_{const}

$\frac{dN}{d\Delta\phi}$

$\Delta\phi$

Alternate observable: momentum imbalance

➢ γ – D/B/c jet /b jet:

In QGP: **Longitudinal fluctuations** of the HQ energy loss crucially depend on the precise mechanism and cannot be measured easily in usual observables like R_{AA} or v_2

(II)

(I)

HF jet

HF quark

g

No E loss => perfect probe of initial $\vec{P}_{HQ}$

$|\omega|\dfrac{dP(\omega)}{dz}$ [fm^{-1}]

RADIAT

ELASTIC

c−quark
P=10 GeV
T=0.4 GeV

ω [GeV]
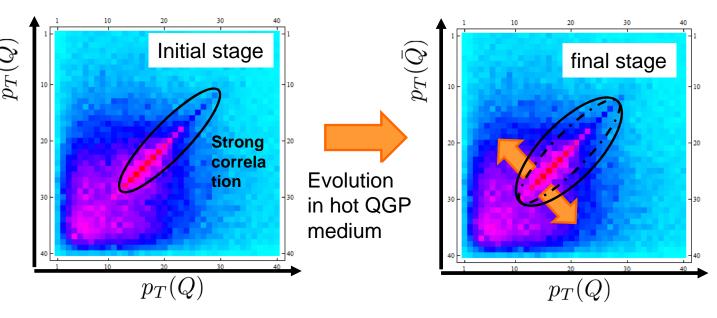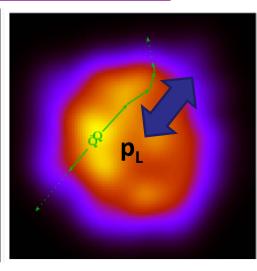
differential probability to loose energy ω per unit time

➢ Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues… RUN3 ? RUN4 ?)

Alternate observable: momentum imbalance

➤ Back to back D/Dbar or B/Bbar: As compared to γ-D/B: "triggering" itself is affected but symmetry between both particles could limitate the various effects:

➤ Large number of c-cbar from various NN collisions => large uncorrelated background

➤ Competing effects due to energy loss: ...

D-D̄ or B-B̄

p_L

$p_T(\bar{Q})$ — Initial stage — Strong correlation

$p_T(Q)$

Evolution in hot QGP medium

$p_T(\bar{Q})$ — final stage

$p_T(Q)$

➤ decorrelation due to various path lengths + fluctuations: reduction

➤ Of course, needs for significant correlations in pp, which is still not quite settled

L. Vermunt et al. arXiv:1710.09639

56

New Observables are coming
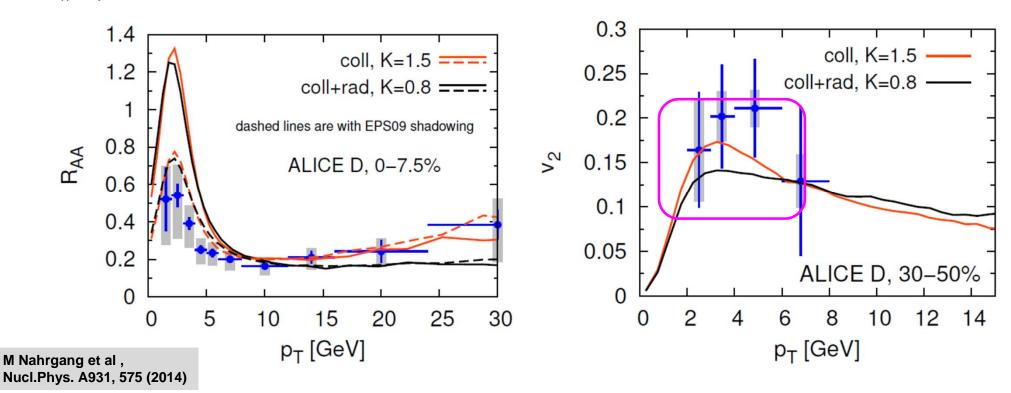
Short term, mid-term, long term,…

What	Good for ?	Caviat
Event shape engineering	Strength and T dependence of the interaction	Might be sensitive to the bulk and initial stage => play collective
Heavy light - correlations	b/c-jet substruture, nature of the interaction	Might be sensitive to various HF creation in pp, to be calibrated
Λ_c, D_s, B_s,…	Understanding hadronization esp. Recombination (if generic enough not to require 1 new free parameter per state) or limits of statistical models	Dynamical treatment of confinement ? Inputs from lQCD probably needed
$v_1(y)$	Constrain (E,B), vorticity, initial tilt of matter initial distribution of HQ in transverse plane	Isn't it a bitt too much for this poor observable ?
….		

…but still a need to better understand old ones !

The nature of the interaction (Elastic vs Elastic + Radiative vs AdS/CFT) in the intermediate p_T range

One should exploit both
- Analysis of the path length dependence
- The larger "collinearity" found in radiative collisions, which could be seen in some structure of the $v_n (p_T)$, to be better understood and studied jointly for B and D

**M Nahrgang et al ,
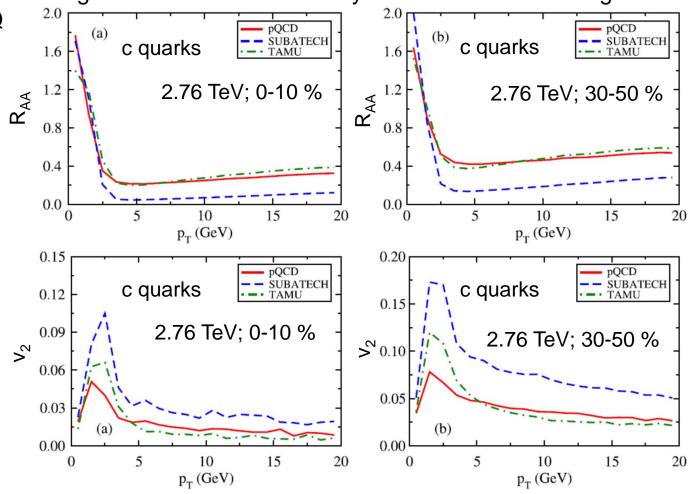Nucl.Phys. A931, 575 (2014)**

Adopting common baseline or exchanging some ingredients

Pioneering work done done by Nantes and Tamu (P. B. Gossiaux et al., arXiv:1102.1114)

- Recent study made by EMMI RRTF using VISHNU 2D+1 viscous hydro as a common background and LANGEVIN dynamics for HQ
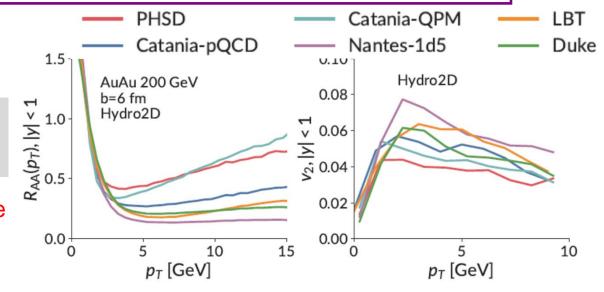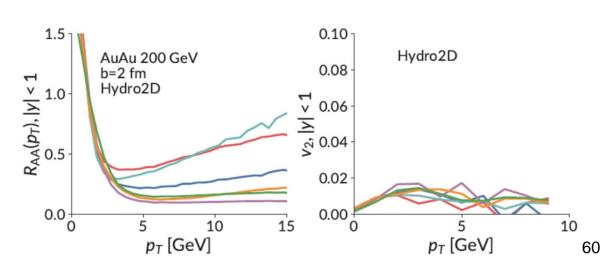
R. Rapp et al,
arXiv: 1803.03824

Adopting common baseline or exchanging some ingredients

- Pioneering work done done by Nantes and Tamu / Recent study made by EMMI RRTF…

  Y. Xu et al,
  Physical Review C99 (2018) **arXiv: 1803. 10734 Catania, Duke, Frankfurt & Nantes**

- Even more recent: 6 HQ Eloss models in the same VISHNU viscous 2D+1 hydro through Langevin dynamics …Confirms the dispersion of results, now after full implementation in bulk evolution

- Others "goodies": impact of initial conditions & impact of Einstein relation.

- Nice work, BUT….

60

Adopting common baseline or exchanging some ingredients
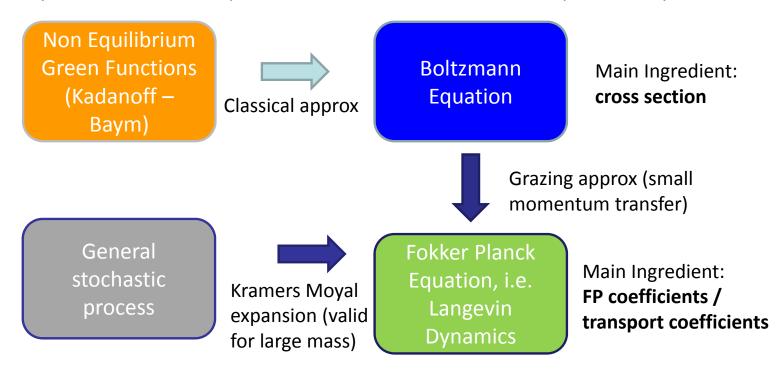
…. Some methodological issues:

- Those comparison can "only" be done for global models relying on external T and velocity fields (provided f.i. by fluid dynamics) while there are a lot of valuable transport models dealing with HF + soft evolution, like PHSD, CATANIA,… (they can always provide such fields by averaging on several events, but not clear it is completely relevant)

- For the time all these comparisons where performed using Langevin forces as a substitute to Boltzmann dynamics (computationally less demanding), although **Y. Xu et al** emit strong doubts whether it is a good way to proceed.

- In some case : comparison of transport coefficient used both in pure elastic processes and in elastic + radiative processes: can lead to some confusion.

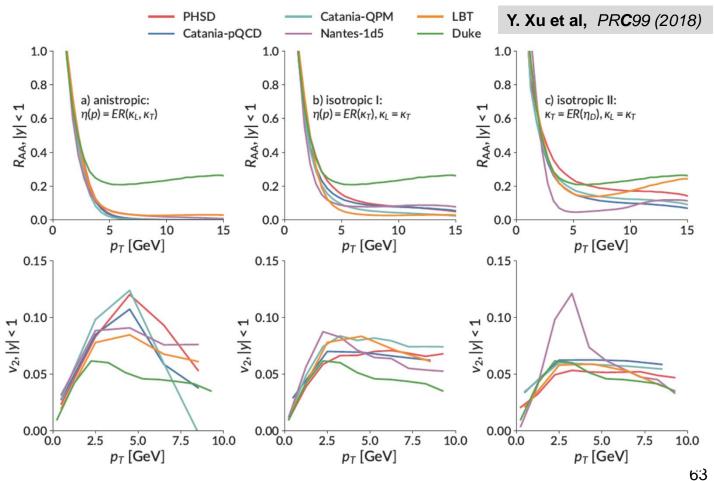=> **Need to think deeper**

Various approaches to transport

Bottom-up schemes (microscopic -> mesoscopic):

- Assume (effective) degrees of freedom and (effective) interactions
- Take insights and constrains from the fundamental QCD theory, but often inholds some free parameter
- Rely on more or less sophisticated realizations of the transport theory

Non Equilibrium Green Functions (Kadanoff – Baym)

Classical approx →

Boltzmann Equation

Main Ingredient: **cross section**

Grazing approx (small momentum transfer)

General stochastic process

Kramers Moyal expansion (valid for large mass) →

Fokker Planck Equation, i.e. Langevin Dynamics

Main Ingredient: **FP coefficients / transport coefficients**
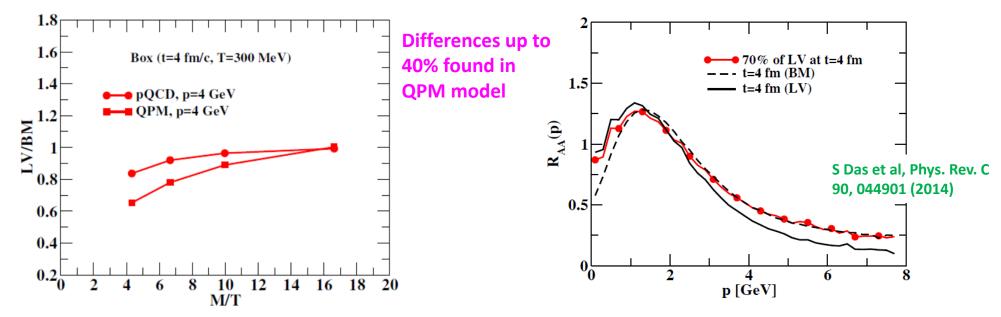
Boltzmann vs Langevin Dynamics

Langevin from <u>Einstein relation (Fluctuation Dissipation Theorem)</u> view point:

- In general, not possible to accommodate all fluctuations as well as the asymptotic distribution (at a fixed T)

- Requires to impose some Einstein – relation / fluctuation – dissipation theorem between the drag coefficient and the diffusion coefficients. Several prescriptions have been tested and lead to various results:

- Lesson 1 : avoid resorting to Langevin just to spare some tedious programming: Going for the microscopic process is more faithfull to physics.

- My personal opinion (from comparison to Boltzmann benchmark): The most conservative way to implement FDT is to preserve η_D and κ_T and to adapt κ_L.

Y. Xu et al, *PRC99 (2018)*

Legend: PHSD, Catania-pQCD, Catania-QPM, Nantes-1d5, LBT, Duke

a) anistropic: $\eta(p) = ER(\kappa_L, \kappa_T)$

b) isotropic I: $\eta(p) = ER(\kappa_T), \kappa_L = \kappa_T$

c) isotropic II: $\kappa_T = ER(\eta_D), \kappa_L = \kappa_T$

Boltzmann vs Langevin Dynamics
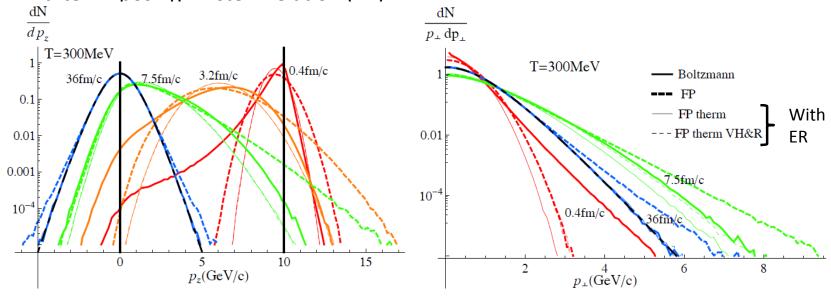
<u>Langevin from Boltzmann view point:</u>

- Lesson 2: For coarse grained observables like the R_{AA} and the v_2, the agreement between the 2 transport schemes essentially depends on the isotropization strength of the cross section (i.e., the Debye mass of the gluon propagator)

Differences up to 40% found in QPM model

Box (t=4 fm/c, T=300 MeV)

pQCD, p=4 GeV
QPM, p=4 GeV

LV/BM

M/T

70% of LV at t=4 fm
t=4 fm (BM)
t=4 fm (LV)

$R_{AA}(p)$

p [GeV]

S Das et al, Phys. Rev. C 90, 044901 (2014)

- For $m_D = g\,T \approx 2\,T$ found f.i. in the Quasi Particle Model, extra coupling is found for the R_{AA} using LV, which can be suppressed by reducing the FP coefficients by ≈ 30 %
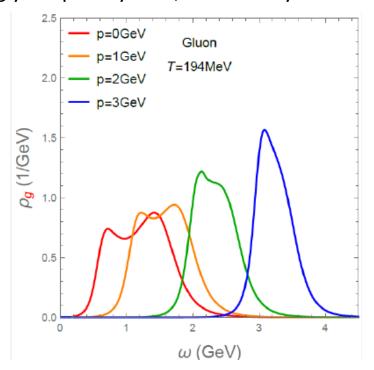
Langevin from Boltzman view point:

- For « exclusive process », momentum distributions differ significantly, even after imposing Einstein relation (ER):

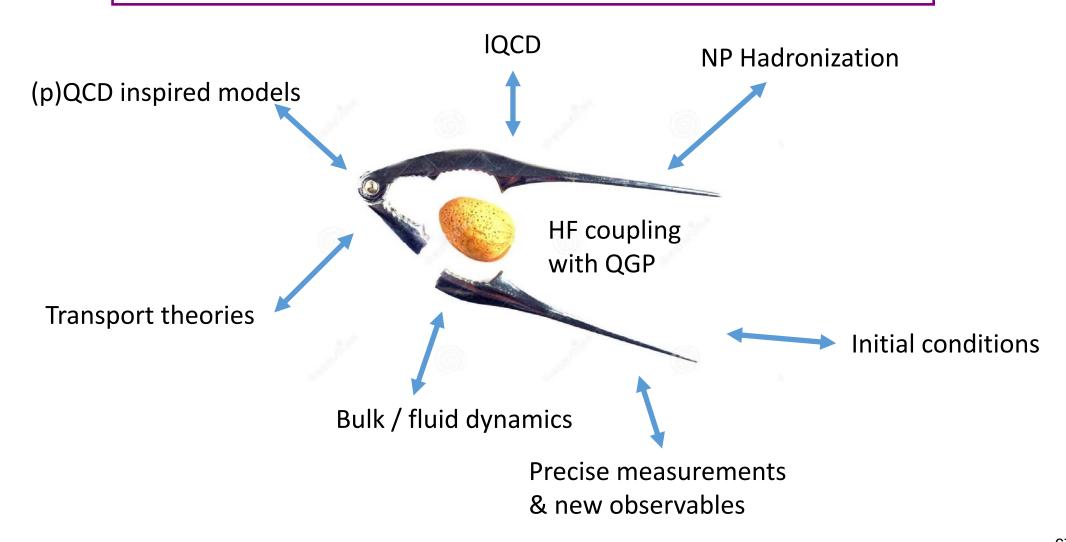- These differences should me seen in observables like g-HQ correlations

Boltzmann vs Langevin Dynamics

Boltzmann from Langevin view point:

- There are a lot of situations where Langevin dynamics applies, but not Boltzmann, thanks to the large mass of the particles.
- It is even a result proven for dynamical systems (conditions on the velocity applies as well)
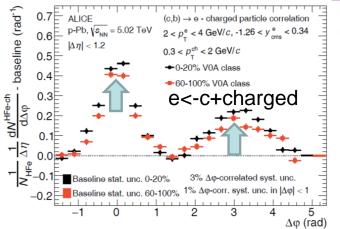- In a dense strongly coupled system, this is likely to be the case !
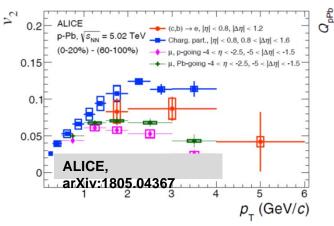

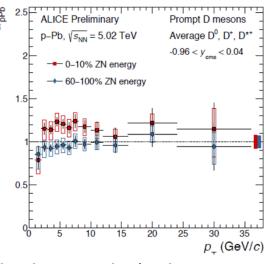**Gluon spectral functions (Liu & Rapp 2016)**

66

Visual summary

lQCD

NP Hadronization

(p)QCD inspired models

HF coupling with QGP

Transport theories

Initial conditions

Bulk / fluid dynamics

Precise measurements & new observables

67

HF in small systems: initial, final (collectivity) or both ?

e<-c+charged

ALICE,
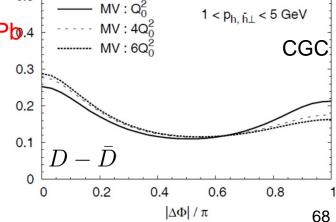arXiv:1805.04367

- Finite v_2 seen in p-Pb data but no significant difference in the spectrum ?
- It seems to me that we get similar modifications from both the 0th and 2nd order harmonic (to be checked)
- Physical origin ?
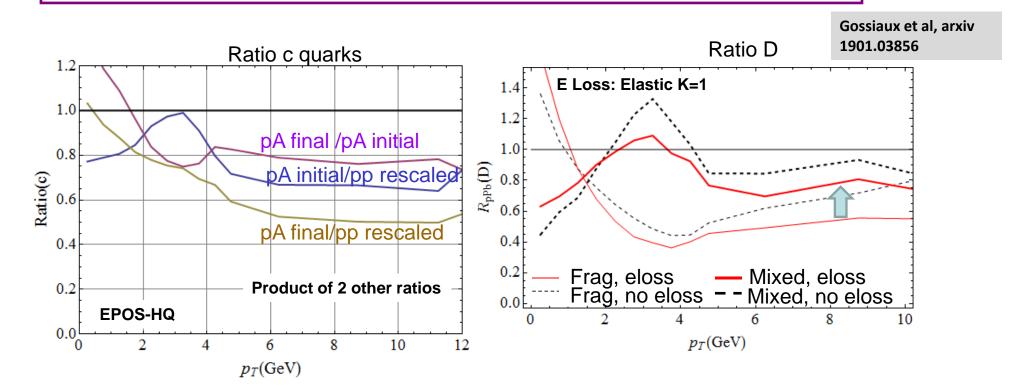- Both coupling to hydro **and** CGC lead to azimuthal correl. for HF in p-Pb

Duke: Y. Xu, Nucl.Part.Phys.Proc. 276-278 (2016) 225
POWLANG: A. Beraudo et al: JHEP 1603 (2016) 123

H. Fujii, K. Watanabe, Nucl.Phys. A920 (2013) 78

both $v_2 \approx 4\%$

(b) D : $\sqrt{s} = 5.02$ TeV, $-1.0 < y_{h,\bar{h}} < 0.0$

CGC

$D - \bar{D}$

68

Recent study using EPOS-HQ (Hard Probes)

Ratio c quarks

pA final /pA initial

pA initial/pp rescaled

pA final/pp rescaled

Product of 2 other ratios

EPOS-HQ

Ratio D

E Loss: Elastic K=1

Frag, eloss — Mixed, eloss
Frag, no eloss — Mixed, no eloss
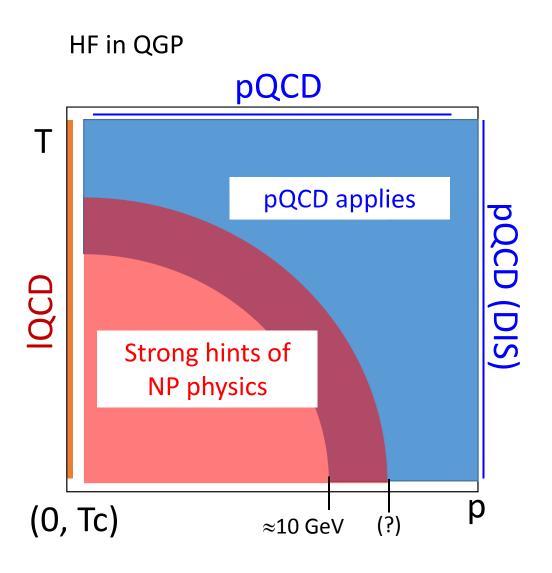
Sensitivity

Saturation	Hadronisation	E Loss
YES	YES	YES

… and chemistry ! Complicated !!!

Our implementation of the coalescence has consequences up to 10 GeV

Conclusions

HF in QGP

- Existing models offer the possibility to describe most of the OHF experimental AA data while being compatible with existing theory constrains…
- … however with unequal precision and no consensus on the physical NP content
- Improvements and quantitative understanding is on their way, but it will still take some time and a lot of efforts => need for ressources, bright (young) people and collective work.
- Open Heavy Flavors are maybe not an ideal probe of QGP yet, but they are quite fascinating and offer bright future for the field, with multiple interconnections.

Back UP

IQCD

lQCD Calculation of D$_s$

- Lattice QCD at finite T is performed in Euclidean space notoriously difficult to calculate dynamical quantities.
- Up to 2014, Ds was evaluated directly through the (narrow) diffusion peak of the spectral function evaluated from current – current correlator (hard)
- From 2014: Use of the field – field correlator in order to obtain a better shaped spectral function:

$$G_{\rm E}(\tau) \equiv -\frac{1}{3}\sum_{i=1}^{3} \frac{\left\langle {\rm Re\, Tr}\left[U(\beta;\tau)\,gE_i(\tau,\mathbf{0})\,U(\tau;0)\,gE_i(0,\mathbf{0})\right]\right\rangle}{\left\langle {\rm Re\, Tr}\left[U(\beta;0)\right]\right\rangle}$$
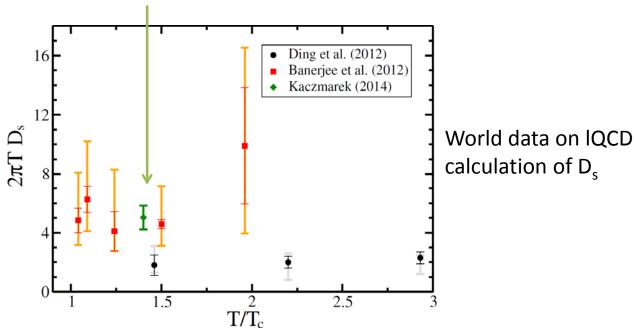
- Then obtain the variance κ of stochastic forces (a transport coefficient; κ = 2 x B) from the slope of spectral function $\rho_{\rm E}$ at ω = 0:

$$\kappa \equiv \lim_{\omega\to 0}\frac{2T\rho_{\rm E}(\omega)}{\omega} \quad \text{with } \rho_{\rm E} \text{ extracted from} \quad G_{\rm E}(\tau) = \int_0^\infty \frac{{\rm d}\omega}{\pi}\,\rho_{\rm E}(\omega)\,\frac{\cosh[\omega(\frac{\beta}{2}-\tau)]}{\sinh[\frac{\omega\beta}{2}]}$$

- Main result : $\kappa/T^3 = 1.8\ldots 3.4$ then convert to D$_s$

- This leads to $2\pi T D_s = 3.7 \dots 6.9$

World data on lQCD calculation of D_s

- Still drastic approximations/limitations: quenched QCD, heavy quark vs. charm quark, (no) continuum extrapolation,…

- Relaxation time $\eta^{-1} = \dfrac{m_Q D_s}{T} = \dfrac{0.59 \dots 1.1\, m_Q}{T^2} \approx 2.5 \dots 5\, \mathrm{fm/c}$

74

High pT

Status of high p_T HQ: prospects

Other challenges:
- Better understanding of heavy mass effect and medium properties in the radiation (especially on the coherence effects)
- Embedding in a realistic medium (for some models)
- In a « jetty » picture: Combination of induced Eloss affecting the « initial » DGLAP evolution and the final « on shell » HQ
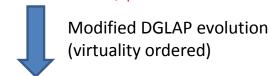
"Drag Induced Radiation and Multi-Stage Effects in Heavy-Flavor Energy Loss"   S. Cao et al, arXiv:1711.09053   **S. Cao, QM 2018**
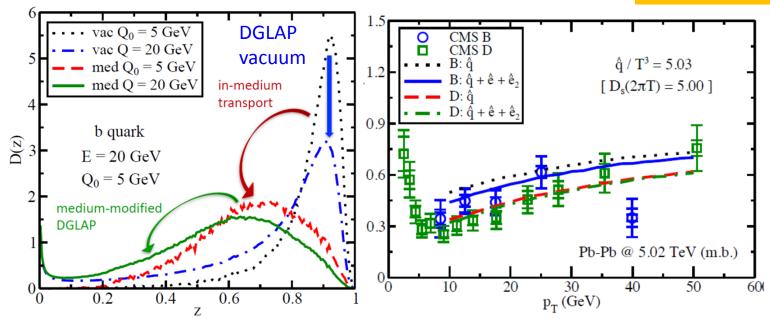
Also poster G-Y Qin

Hard scale Q=p_T

Modified DGLAP evolution (virtuality ordered)

Low scale Q_0=m_Q

« Usual » time ordered LBL-CCNU evol. (Higher twist with $\hat{e}$ and $\hat{e}_2$ corrections)

Good agreement with CMS data for D and B, some influence of higher order term at intermediate p_T

33

HQ-WG

Heavy-Quark Working Group

After 3 meetings, footprints of the physics start to emerge... but no firm conclusion yet

For step 1: Compare HQ spectra from different models in static medium with common initial condition

Models	note	basic	tune 1
LBL-CCNU ⭐	fix α_s	$\alpha_s = 0.3$	$\alpha_s = 0.26$
Duke ⭐	fix α_s	$\alpha_s = 0.3$	$\alpha_s = 0.23$
Catania QPM	$\alpha_s(T)$	$K = 1$	$K = 2$
Catania pQCD	$\alpha_s(T)$	$K = 1$	$K = 3.4$
TAMU	U-potential	no tuning	no tuning
Frankfurt PHSD	$\alpha_s(T)$	no tuning	no tuning
Nantes col. + rad. ⭐	$\alpha_s(q^2)$	$K = 1$	$K = 0.8$
Nantes col. only	$\alpha_s(q^2)$	$K = 1$	$K = 1.5$

⭐: Radiative included

Basic: original model

Tune 1: favorite tuning of each group in order to describe *D* meson data with their own ingredients (background, hadronization,...) ; K = rate multiplyer
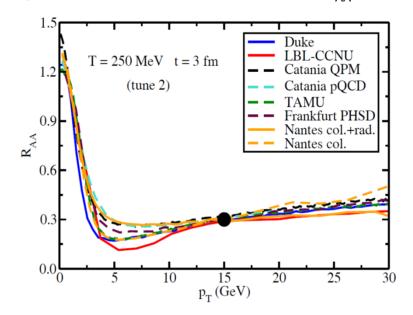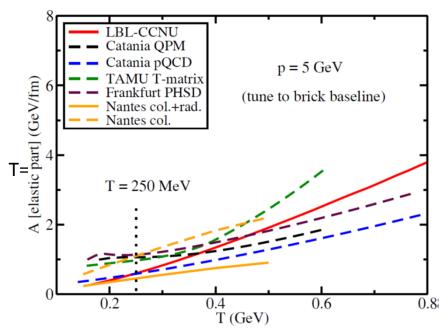
78

The goal is to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
- Estimate some systematics + uncertainties

Best controled QGP ever: uniform fixed temperature for all models (with same initial condition FONLL-like @ RHIC)

1) Rescale the coefficients to match R_{AA}=0.3 at p=15 GeV & « final time » 3 fm/c   2) Compare them !

Main result: Nice structuration of the transport coefficients in different classes. For each class, the work illustrates the maximal accuracy reachable for each class once all other ingredients are either fixed or chosen commonly

79

EMMI - RRTF

EMMI RRTF

Thanks to the generosity of EMMI !!!

1st meeting: 18-22 July 2016; GSI (Germany)
2nd meeting: 12-14 Dec 2016; GSI (Germany)

Researchers involved:

- Organizers

- HQ-WG members

- Other key players in HF – QGP tomography (A. BERAUDO, M. DJORDJEVIC, C. GREINER , G. INGHIRAMI, H. VAN HEES, I. VITEV, CUEJET...)

- lQCD experts (O. KACZMAREK, P. PETRECZKY)

- QCD and EFT experts (G. MOORE , J. PAWLOWSKI)

- Selected experimentalists (J. BIELCIK, P. BRAUN MUNZINGER, E. BRUNA, Z CONESSA, A. DAINESE, YJ LEE, F. PRINO, J. STACHEL)
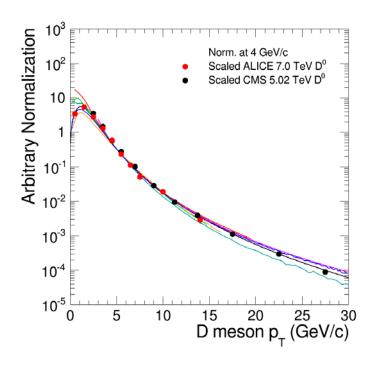
EMMI RRTF

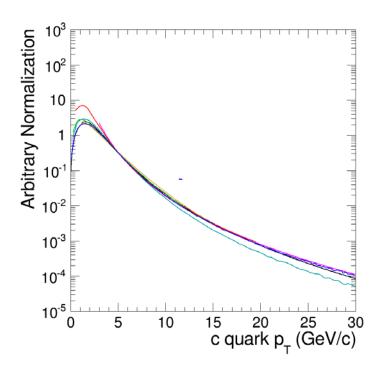**Goal to attack the problem with a broad view right from the beginning…**

Topics:

- Initial spectra and shadowing

- Bulk evolution and consequence on HF observables

- Transport implementation

- Hadronization

- Microscopic models for HF energy loss and constrains from QCD at low and high momentum

- Future observables

Selected topics presented here

EMMI RRTF : Initial HF spectra and shadowing
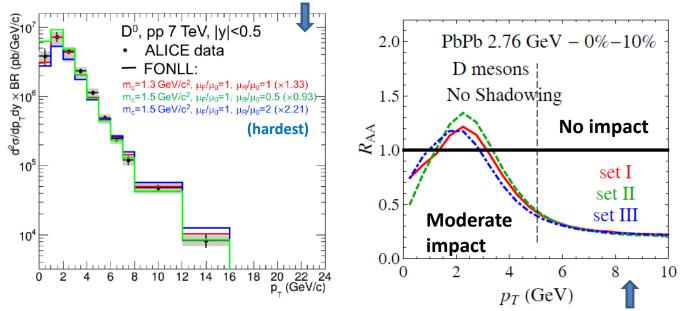
Collection of models vs data by Yen-Jie Lee:

Some « outliers »... Is it acceptable or does it has measurable consequence either on the « extraction » of the transport coefficient (for « tunable » models) or on the agreement with experiment.

« We all do FONLL / GM - VFNS » ... yes, but with slightly different parameters !

EMMI RRTF : **Initial HF spectra** and shadowing

Right now: data better than uncertainty band in theory:
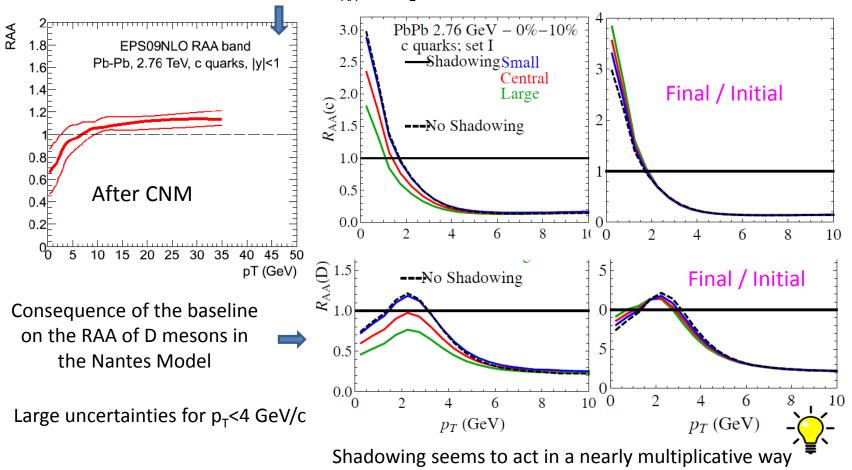
3 best fits extrated from members of the ALICE collaboration, with a fair wish to explore various hardness (BASELINE)

Consequence of the baseline on the RAA of D mesons in the Nantes Model (thermalisation at small p_T => the initial profile has a large impact in the ratio)

Consequence for the collective chase: ideally, all models should adopt the baseline; minimal action: check that the χ^2 with their own production model is at least as small as the one found in the baseline (rejection if χ^2/NDF > 2).

EMMI RRTF : Initial HF spectra and **shadowing**

- RAA for c quarks with MNR+EPS09NLO
- Proposal: multiply the input c-quark p_T spectrum from FONLL by this RAA and use the band to define a band on final R_{AA} and v_2
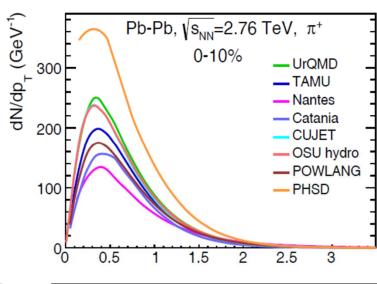

After CNM

Consequence of the baseline
on the RAA of D mesons in
the Nantes Model

Large uncertainties for $p_T < 4$ GeV/c

Shadowing seems to act in a nearly multiplicative way

85

EMMI RRTF : Initial HF spectra and **shadowing**

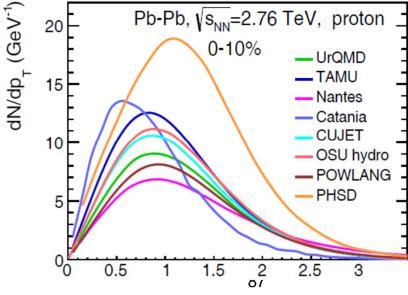Consequence for the collective chase:

- ideally, all models should adopt the same prescription for shadowing, and the uncertainties on the shadowing should then be recast in a global systematic error on the D_s, *common to all models*

- If some models have an intrinsic theory to evaluate shadowing and are unwilling to modify this for the sake of consistency (f.i. EPOS3), the minimal « quality control » should be to implement the common prescription for shadowing and display the consequences on the observables and on their extraction of the transport parameters in order to document the origin of possible differences.

- Perspective (apart from hoping on better control on shadowing):
  - Go for B or to v_2, less sensitive to shadowing
  - Uncertainties on the shadowing may partly factor out if the ratio of R_{AA} at different centralities is considered

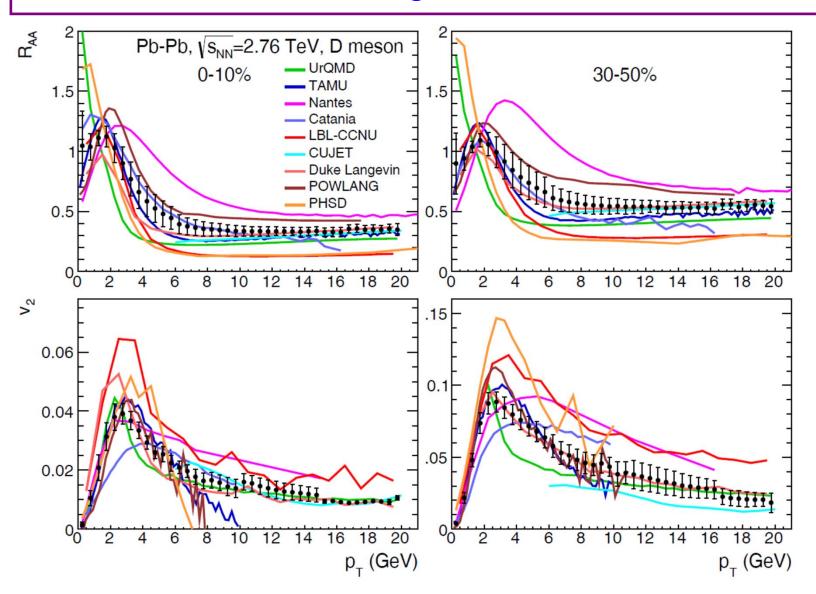Shadowing seems to act in a nearly multiplicative way

EMMI RRTF : the bulkS

Model	dN_{π^+}/dy $(dS/d\eta)$		dN_p/dy	
	0-10%	30-50%	0-10%	30-50%
UrQMD	495	152	34	11
TAMU	682 (12400)	170 (3080)	58	15
Nantes	478	129	38	10
Catania	(14000)	(3700)		
LBL-CCNU/Duke	653 (12600)	160 (3080)		
CUJET	610 (10820)	142 (2610)	45	11
POWLANG	(9100)	(1450)		
PHSD	722	148	31	6
exp.	670±68	163±15	31±4	8±1

Table 1: Inclusive π^+ and proton numbers (*i.e.*, including strong and electromagnetic feeddown) per unit momentum-space rapidity in Pb-Pb(2.76 TeV) collisions in the various bulk evolution models. Also shown in parentheses are the values for the total entropy per unit space-time rapidity at the end of the QGP phase (as available). As a reference the last row shows experimental values from Ref. [51].
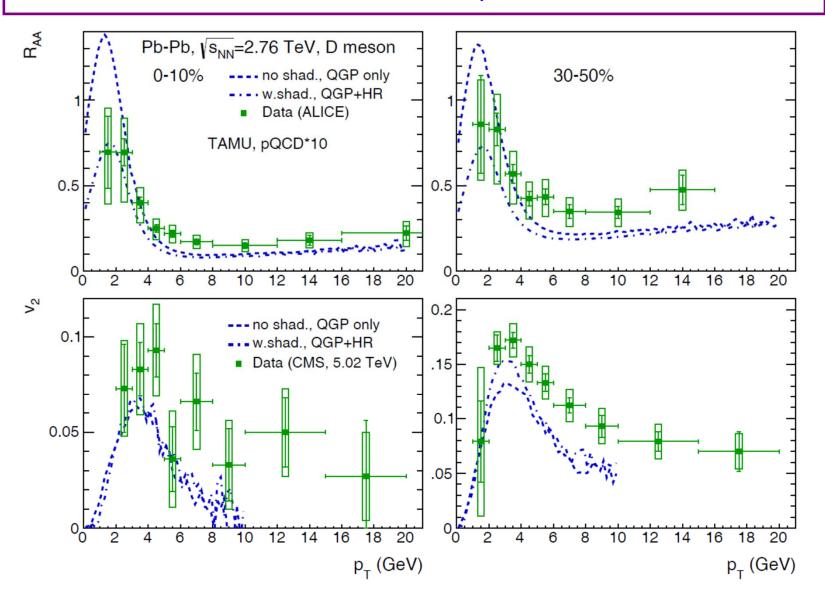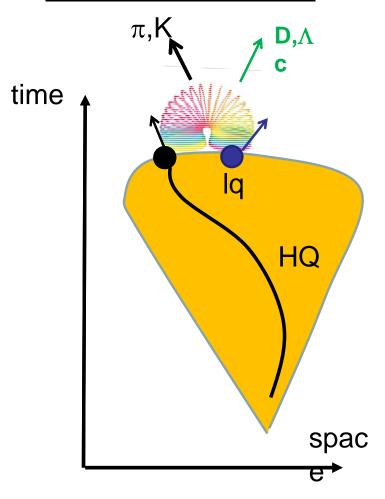
Hadronization

HQ - Recombination
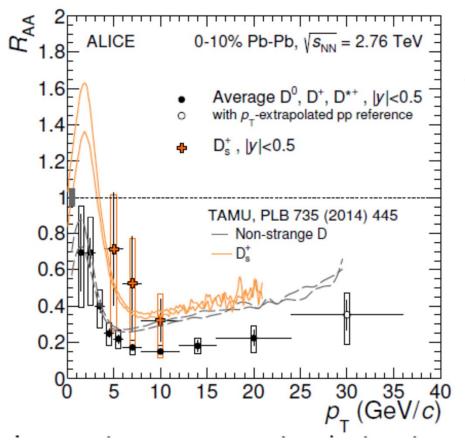
In-Medium recombination:

π, K

D,Λc

time

lq

HQ

space

- String formed at Tc from HQ and light quark sampled out of thermal bath
- Novel mechanism which allows a natural transition from the low p_T to the high p_T
- Also leads to large flow bumps and extra v_2 contribution

43

Hadronisation (Ds)
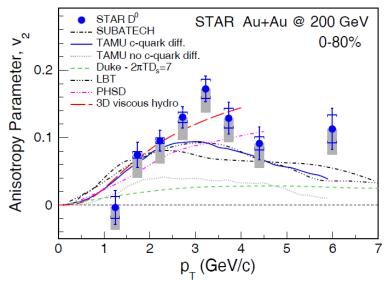

ALICE data for D and Ds mesons (JHEP 1603 (2016) 082) compared with TAMU-model predictions (M- He et al., PLB 735 (2014) 445)

Other constrains

Model + Exp. Constrains on D_s

- F.i., recent STAR study:

compare with	$2\pi T D_s$	χ^2/NDF	p-value
SUBATECH [11]	2−4	15.2 / 8	0.06
TAMU c quark diff. [13]	5−12	10.0 / 8	0.26
TAMU no c quark diff. [13]	-	29.5 / 8	2×10^{-4}
Duke [14]	7	35.7 / 8	2×10^{-5}
LBT [15]	3−6	11.1 / 8	0.19
PHSD [10]	5−12	8.7 / 7	0.28
3D viscous hydro [42]	-	3.6 / 6	0.73

TABLE I. D^0 v_2 in 0–80% centrality Au+Au collisions compared with model calculations, quantified by χ^2/NDF and the p-value (the probability of observing a χ^2 that exceeds the current measured χ^2 by chance). $2\pi T D_s$ values quoted are in the range of T_c to $2T_c$. χ^2/NDF is calculated in the p_T range wherever the model calculation is available.
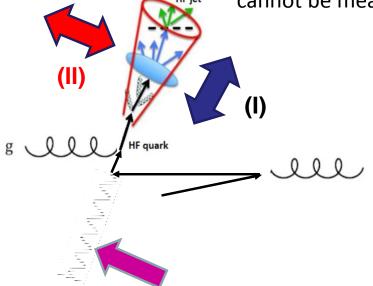
- Not really conclusive; χ^2/NDF is not a smooth function of D_s: large residuals

- Beware: Models are essentially validated at finite $p_{(T)}$; extrapolation at 0 momentum might contain further uncertainties

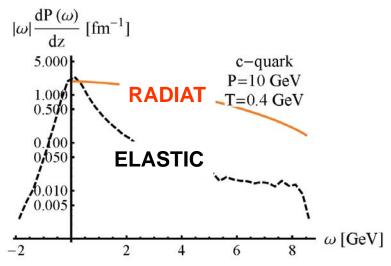- Urgent need for collective actions to better control the « residuals »

Momentum Imbalance

γ - b/c jet: Best HF Correlation ever ?

➢ γ – D/B/c jet /b jet:

In QGP: **Longitudinal and transverse (qhat) fluctuations** of the HQ, which crucially depend on the Eloss mechanism and cannot be measured in usual observables like R_{AA} or v_2

(II)

(I)

HF jet

HF quark

g

No E loss => perfect probe of initial $\vec{P}_{HQ}$

RADIAT

c−quark
P=10 GeV
T=0.4 GeV

ELASTIC
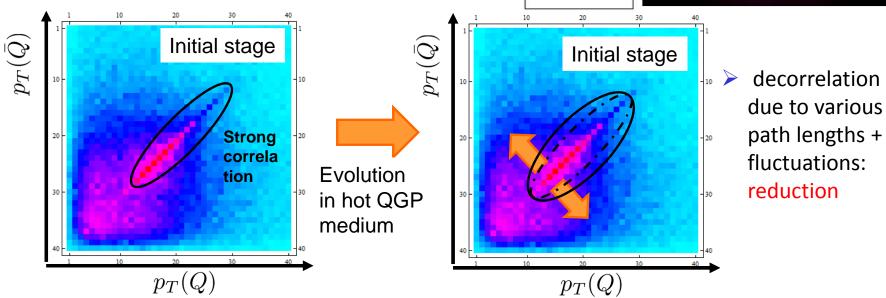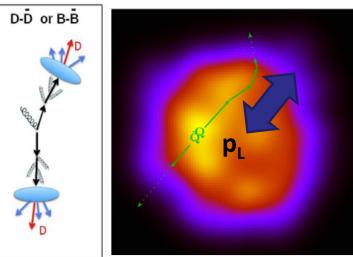
differential probability to loose energy ω per unit time

➢ Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues… RUN3 ? RUN4 ?)

Next best thing: HF-HF correlations

- Back to back D/Dbar or B/Bbar: As compared to γ-D/B: "triggering" itself is affected but symmetry between both particles could limitate the various effects:

- Large number of c-cbar from various NN collisions => large uncorrelated background
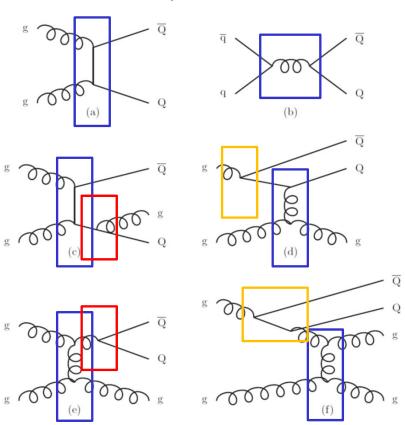
- Competing effects due to energy loss: …

Strong correlation

Initial stage

Evolution in hot QGP medium

Initial stage

- decorrelation due to various path lengths + fluctuations: reduction

Momentum imbalance: not so naïve approach

➢ Goal of the study: investigate whether p_T-p'_T correlations survive NLO effects

L. Vermunt et al. arXiv:1710.09639

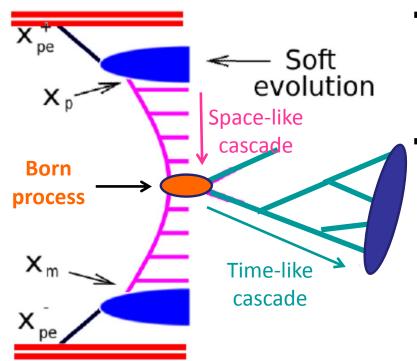➢ Method for "systematics": use 2 event generators: PYTHIA (6.4) & EPOS3

- In pythia, those topologies are generated by coupling LO processes (implying 0,1 or 2 HQ) and ISR + FSR … This will be referred to as « LO + NLO ccbar » (strictly speaking, no NLO !)

98

Momentum imbalance: not so naïve approach

➤ Goal of the study: investigate whether p_T-p'_T correlations survive NLO effects

**L. Vermunt et al.
arXiv:1710.09639**

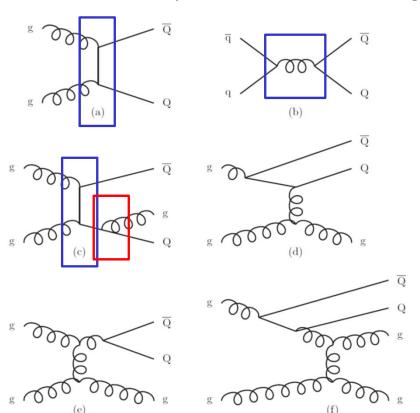➤ Method for "systematics": use 2 event generators: PYTHIA (6.4) & EPOS3

- In pythia, those topologies are generated by coupling LO processes (implying 0,1 or 2 HQ) and ISR + FSR … This will be referred to as « LO + NLO ccbar » (strictly speaking, no NLO !)

- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.

99

Momentum imbalance: not so naïve approach

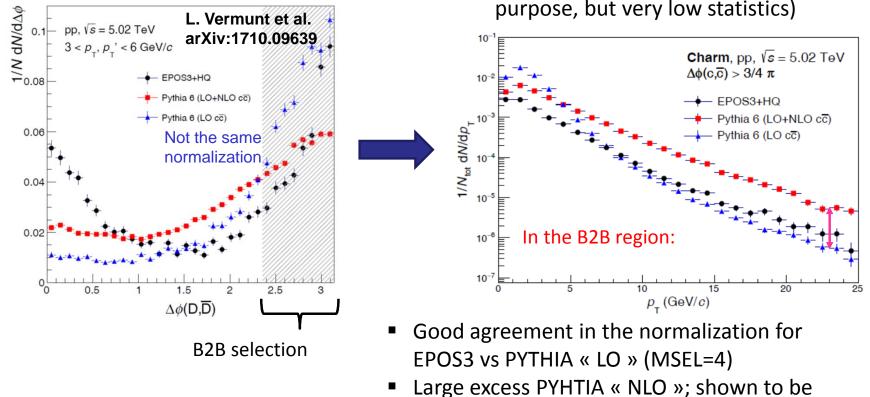➢ Goal of the study: investigate whether p_T-p'_T correlations survive NLO effects

L. Vermunt et al. arXiv:1710.09639

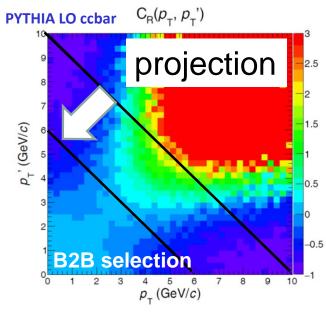➢ Method for "systematics": use 2 event generators: PYTHIA (6.4) & EPOS3

- In pythia, those topologies are generated by coupling LO processes (implying 0,1 or 2 HQ) and ISR + FSR ... This will be referred to as « LO + NLO ccbar » (strictly speaking, no NLO !)

- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.

- In pythia, possibility to restrict to LO ccbar production processes with massive elements (MSEL=1 -> MSEL=4 flag), still switching on the ... ISR + FSR ... This will be referred to as « LO ccbar »

Momentum imbalance: not so naïve approach

➢ Including NLO effects in the charm production (N.B. :beauty would be better for our purpose, but very low statistics)

L. Vermunt et al.
arXiv:1710.09639

Not the same normalization

B2B selection

In the B2B region:

- Good agreement in the normalization for EPOS3 vs PYTHIA « LO » (MSEL=4)
- Large excess PYHTIA « NLO »; shown to be due to flavor excitation like process

N.B.: Pythia MSEL=4: at least 1 ccbar pair un each event => Normalized according to high-p_T LO charm creation in Pythia MSEL=1

Momentum imbalance: not so naïve approach

PYTHIA LO ccbar $C_R(p_T, p_T')$

projection

B2B selection

Abolute correlation:

$$C(p_T, p_T') := \frac{1}{N} \frac{d^2 N(p_T, p_T')}{dp_T dp_T'} - \frac{1}{N} \frac{dN(p_T)}{dp_T} \times \frac{1}{N} \frac{dN(p_T')}{dp_T'}$$

- Vanishes if d²N factorizes (d²N(p,p') = dN(p) x dN(p'))

- Satisfies $\int C(p_T, p_T') dp_T d_T' = 0$

Relative correlation: $C_R(p_T, p_T') := \dfrac{C(p_T, p_T')}{\frac{1}{N} \frac{dN(p_T)}{dp_T} \times \frac{1}{N} \frac{dN(p_T')}{dp_T'}}$

- Reveals correlation at finite p_T

- Different p_T imbalance for 3 production models in pp
- 2 of them show that NLO effects does not completely destroy the perfect correlation found in LO production
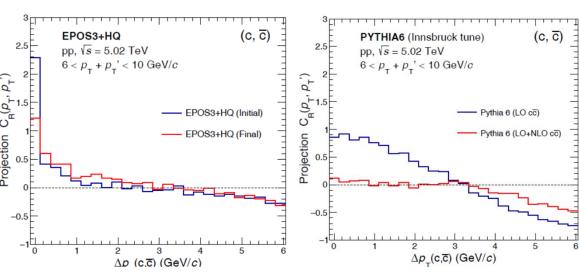- Similar results for DDbar

Guidelines & strategies

Guide lines

Collectivity of the « HQ in URHIC » community

- As theorists, we should maintain and amplify the recent collective efforts in order to
  - Provide more systematic systematical errors from our models as well as "figures of merit" like the Catania cocktail
  - Adopt a reasonable base line for the "extra ingredients" which will make the role of the "core ingredients" more transparent" => possible new "structures" emerging as in the HQ-WG brick study

Good exemple in EMMI RRTF: baseline for c-quark initial spectrum provided by some members of ALICE

- We should as well rely more intensively and systematically on modern methods like Bayesian analysis, which allow a better quantitative contact with the experimental community
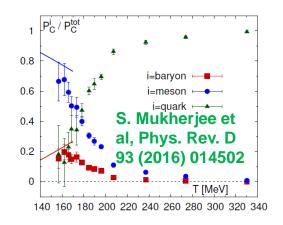
But also, from the theory view point:

- Get more insights and constrains from lQCD (transport coefficient at finite p ?)

  See discussions f.i. in

  G. Aarts et al, Eur. Phys. J.A 53, no. 5, 93 (2017)
  (proc. Lorentz Workshop)

- … and make contact with these in the models. In this respect, charm correlations and charm meson correlators -- which indicate the presence of mesonic dof around Tc -- should be evaluated in the existing and future models and compared with the lCD results

  S. Y.F. Liu and R. Rapp, Phys. Rev. C 97, 034918 (2018)

  S. Y.F. Liu, QM2018

S. Mukherjee et al, Phys. Rev. D 93 (2016) 014502

- Develop models which span the low p – intermediate p – large p & low T – large T range and contain the proper physics in each region

Mid-term strategies

But also, from the theory view point:

- Develop transport theories beyond the classical approximation (and don't be afraid by numerical work, even if redious)

- Assess the role of QGP non-equilibrium effects on HF (including in the initial stage).

- Achieve a rigorous implementation of radiative energy loss in realistic bulks.

- Strutinize the consequences of other effects usually discarded
  - Evolution in turbulent plasma   Stanislaw Mrowczynski, Eur.Phys.J. A54 (2018) no.3, 43
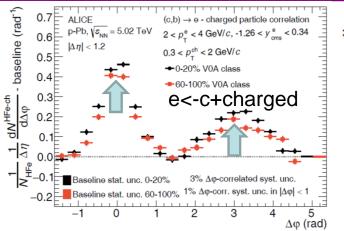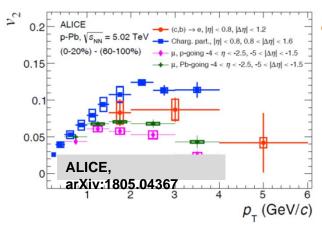 - Fluctuation of chromoelectric field
    QM Poster A. I. Sheikh
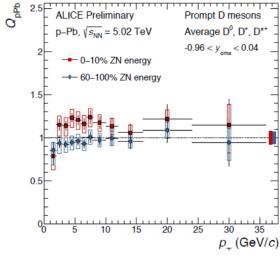 - …

Any suggestion welcome !

Small systems

HF in small systems: initial, final (collectivity) or both ?

e<-c+charged

ALICE,
arXiv:1805.04367

- Finite v_2 seen in p-Pb data but no significant difference in the spectrum ?
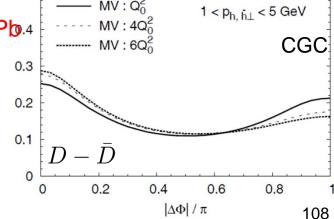- It seems to me that we get similar modifications from both the 0th and 2nd order harmonic (to be checked)
- Physical origin ?
- Both coupling to hydro **and** CGC lead to azimuthal correl. for HF in p-Pb

Duke: Y. Xu, Nucl.Part.Phys.Proc. 276-278 (2016) 225
POWLANG: A. Beraudo et al: JHEP 1603 (2016) 123

H. Fujii, K. Watanabe, Nucl.Phys. A920 (2013) 78

both $v_2 \approx 4\%$

(b) D : $\sqrt{s} = 5.02$ TeV, $-1.0 < y_{h,\bar{h}} < 0.0$

CGC

$D - \bar{D}$

108

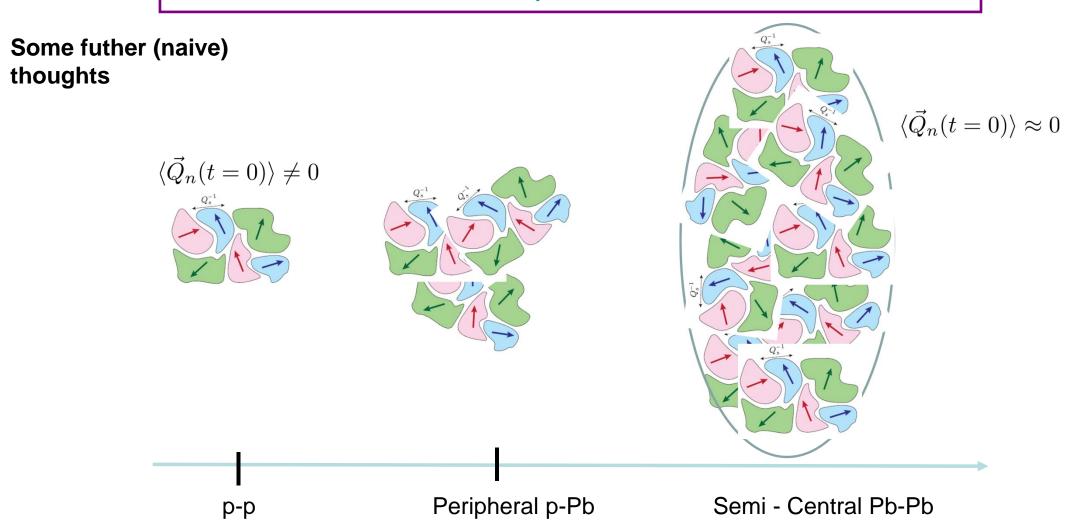# HF in small systems: initial, final (collectivity) or both ?

Some thoughts:

- Very difficult topic, even in the light sector
- What does m_Q bring to the problem ?

favor CGC	disfavor CGC	Pro hydro	disfavor hydro
Effect deeply rooted in the production mechanism	?	Other indications of collectivity in p-Pb	Theoretical status of hydro in p-Pb unclear (see M. Strickland's talk)
K Watanabe: « From the CGC view point, heavy mesons should be more correlated than light hadrons" (reinteraction less efficient).			Recombination in small systems not under control (large differences due to technical implementation)
			Absolute value found up to now too low: v2(B)<v2(D)<v2(π)

-
- In any case studies incorporating both (like the one of M Greif et al. in the light sector) would be interesting.

M. Greif et al, Phys. Rev. D 96, 091504 (2017)

HF: from p-Pb -> Pb-Pb

Some futher (naive) thoughts

$$\langle \vec{Q}_n(t=0)\rangle \neq 0$$

$$\langle \vec{Q}_n(t=0)\rangle \approx 0$$
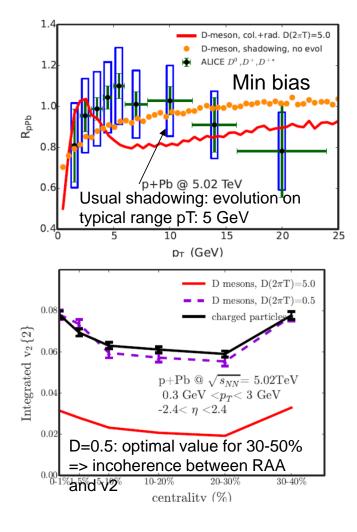

p-p   Peripheral p-Pb   Semi - Central Pb-Pb

Gradual transition from CGC -> geometry ?
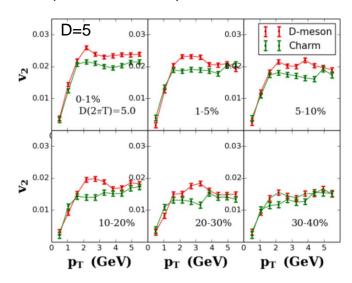
p-Pb (Duke)

- arXiv:1510.07520v2: viscous hydrodynamics model (vHLLE) + improved Langevin + mixed hadronization
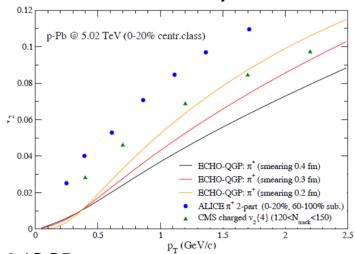

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \qquad D = 4\frac{T^2}{\hat{q}}\frac{C_A}{C_F}$$

$$D \qquad \hat{q}$$

- $D(2\pi T) = 5$ tuned from central PbPb
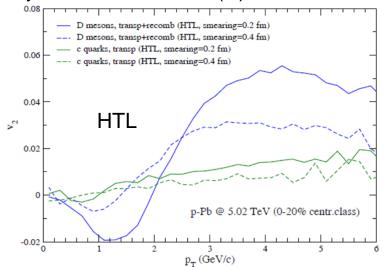- Differential pT (in Hard probes talk) for D=5 saturates at 2% : incomplete coupling with QGP (short lifetime)

p-Pb (Beraudo et al)

- Arxiv 1512.05186v2: essential role of initial flutuations (main source of anosotropy) : MC Glauber + av. init medium cond after psi_2 rotation + PYTHIA + EPS09 shadowing + kt broadening + viscous hydrodynamics (ECHO) + POWLANG + string fragmentation with the light partner taken from finite T medium

Langevin + 2 different Eloss models: HTL (pQCD) & lQCD

Major contribution to v2(D): hadronisation

Some similarity with ALICE mass ordering, (no substraction in Beraudo et al as single part. analysis)