QGP France 2021

Heavy Flavor review / overview

« … un petit survol des enjeux… »

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Disclaimer: This ultra short presentation…

- is NOT intended to enter in any technical aspect
- is NOT intended for the specialists in the field (they'd better visit the cliffs)
- is NOT intended to resolve ambiguities or express my personal opinion — Or just a little bit
- is NOT intended to cover all the fascinating topics

I’ll try to cover

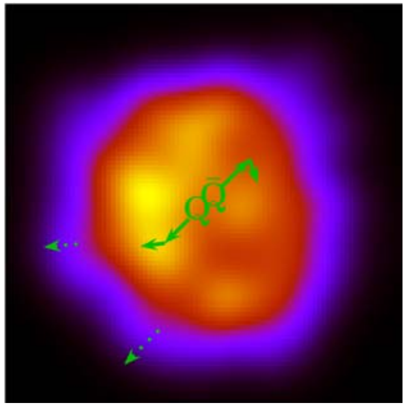
interesting, but I’ll not to cover (look later by yourself between 2 emails)

Hard probing QGP in URHIC with the help of HF ?

1. Φ: Heavy quarks are produced early, number conserved through time evolution (even at LHC) ⇒ signature of early (hot) phase
2. Φ: Weakly affected by late time evolution (heavy, colour transparency)
3. Φ: *Strongly (even too strongly ?) affected by the QGP phase*
4. Theory: Heavy mass -> Allows *some* pQCD calculations for the initial production and annihilation, as well as for the dynamics.
5. Exp: Quarkonia suppression: clear decay channel → leptons

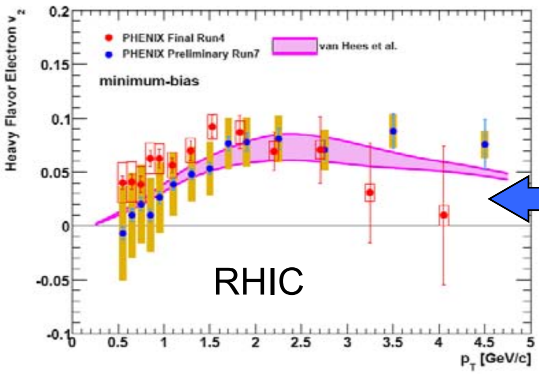
Usually advocated as an ideal *probe* of dense matter

QGP tomography with Q-Qbar pairs



Why open heavy flavors in A-A ?

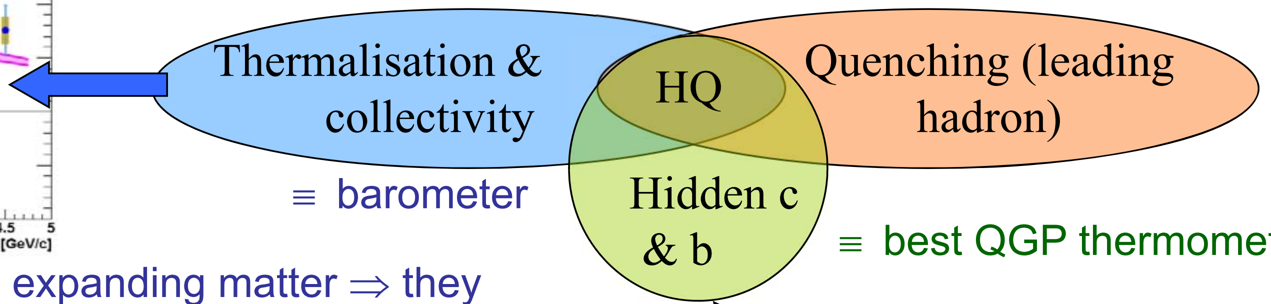
- Those are for sure sensitive to the early stages
- Much simpler then quarkonia and also sensitive to the medium properties (t_{equil} ($\alpha\ M_Q/T^2$) $\Rightarrow$ clear hierarchy for s, c and b).
- Mandatory to understand Q-Qbar evolution in QGP & quarkonia production



HQ are imbedded in expanding matter $\Rightarrow$ they participate to collective motion and gain elliptic flow (v_2:azimutal asymmetry) at finite b… with additional inertia effect

The Trilogy:

≡ densimeter



≡ barometer

≡ best QGP thermometer ???

Quarkonia suppression and Dimuons product; heavy Q thermal production

Challenge:

Description of HQ E-loss / equilibration from fundamental theory. In fact we are at the same time probing the system but also using the results to better understand our probe (and the coupling to QGP) at the same time !

Some open heavy flavor history

74 : Discovery of heavy-flavor

78-80 (Shuryak): Thermal production of c-cbar in QGP. Nice idea; not observed up to now

82 (Rafelski): Thermal production of strangeness

85 (Cleymans & Ray): relativistic Fokker-Planck equation for q

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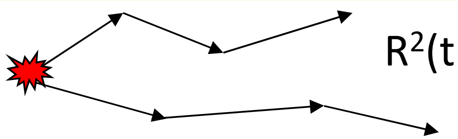
88 (Svetitsky): Fokker Planck equation for HQ (collisional), motivated by consequences for J/Psi: large stochastical localization but « extreme » parameters.



$R^2(t) \alpha\ t$

33 years of J/Psi enhancement !!!

Why Fokker – Planck (AKA Langevin forces) ?

Bona fide answer: because HQ are heavy => long relaxation times => accumulate many collisions before thermalization => the "details" are averaged (central limit theorem) .

μ-model

$$R(\mathbf{p},t) = \frac{1}{2E_\mathbf{p}} \int \frac{d^3\mathbf{q}}{(2\pi)^3 2E_\mathbf{q}} \int \frac{d^3\mathbf{q}'}{(2\pi)^3 2E_{\mathbf{q}'}} \int \frac{d^3\mathbf{p}'}{(2\pi)^3 2E_{\mathbf{p}'}} \times \frac{1}{\gamma_c} \sum |\mathcal{M}|^2 (2\pi)^4 \delta^4 (p+q-p'-q') \times [f(\mathbf{p}')g(\mathbf{q}')\tilde{g}(\mathbf{q}) - f(\mathbf{p})g(\mathbf{q})\tilde{g}(\mathbf{q}')] \,,$$

$$\begin{cases} A_i = \langle\langle (p-p')_i \rangle\rangle \\ \kappa_{i,j} = \langle\langle (p-p')_i (p-p')_j \rangle\rangle \end{cases}$$

mesoscopic model (FP equation)

$$\frac{\partial f}{\partial t} = \vec{\nabla}_p \cdot \left[\vec{A} f + \frac{1}{2} \vec{\nabla}_p (\hat{\kappa} f) \right]$$

distribution f in phase space… which fulfills

$$\frac{d}{dt} \langle \vec{p} \rangle_f = -\langle \vec{A}(T) \rangle_f$$

$$\frac{d}{dt} \langle \vec{p}_i \vec{p}_j \rangle_f = \langle \kappa_{ij}(T) \rangle_f$$

Recovers the averages from the μ-model

… also because it is much easier to solve than sampling the rate !

MC simulation then writes:

$$\Delta \vec{p} = -\vec{A} \Delta t + \vec{\xi}$$ for each Δt

Random force (fluctuations)

Why Fokker – Planck (AKA Langevin forces) ?

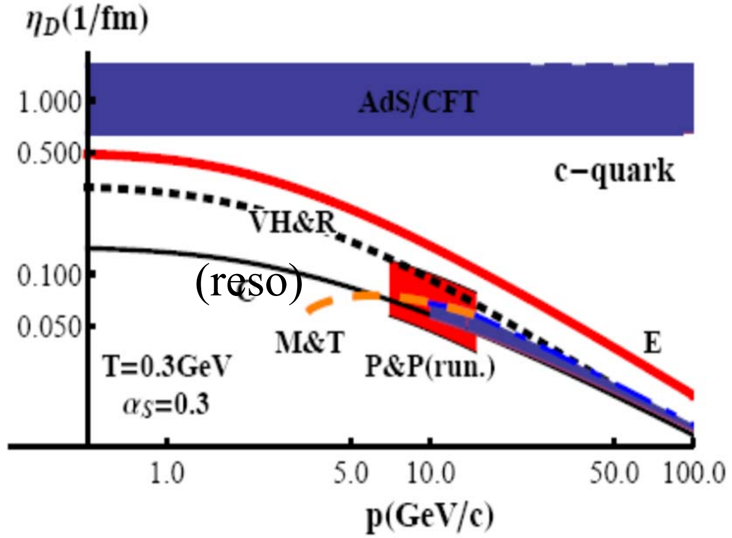
Other transport coefficients:

I) Isotropic medium => $\vec{A}(\vec{p},T) = \eta_D(\vec{p},T) \times \vec{p}$ $\quad \frac{d}{dt}\langle\vec{p}\rangle_f = -\langle\vec{A}(T)\rangle_f$

$$\langle\vec{p}\rangle_f \approx \langle\vec{p}\rangle_f(t=0) \times e^{-\eta_D t}$$

$\eta_D[\mathrm{fm}^{-1}]$: drag (friction) coefficient; relaxation rate

(typical inverse relaxation time)



… also because it allows to access physical quantities of interest more “directly” than in the microscopic model

… also because it is not quite clear what the dof of the QGP are (at large T , QGP is made of Q and G of course)

Why Fokker – Planck (AKA Langevin forces) ?

II) Isotropic medium => $\hat{\kappa}(\vec{p}) = \kappa_L(p)\hat{\Pi}_L(\vec{p}) + \kappa_T(p)\hat{\Pi}_T(\vec{p})$

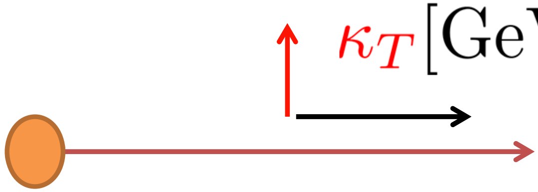
Long. diffusion coefficient (κ_L) — Transverse. diffusion coefficient (κ_T)

with $\left(\hat{\Pi}_L(\vec{p})\right)_{ij} := \frac{p_i p_j}{p^2}$ with $\left(\hat{\Pi}_T(\vec{p})\right)_{ij} := I_{i,j} - \frac{p_i p_j}{p^2}$

$\hat{\Pi}_L$: Projector along HQ instantaneous momentum

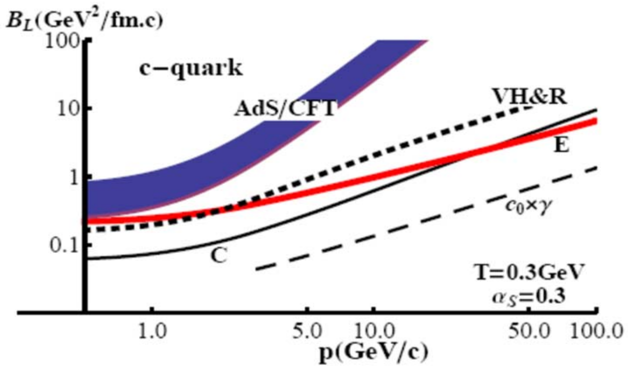
$\hat{\Pi}_T$: Projector ⊥ HQ instantaneous momentum

$\kappa_T\,[\mathrm{GeV}^2\mathrm{fm}^{-1}]$: Transverse diffusion coef. (p space)



Link with well known qhat coefficient

$$\hat{q} = \frac{1}{v}\frac{d\langle p_\perp^2\rangle_f}{dt} \approx 2\kappa_T$$



Some open heavy flavor history

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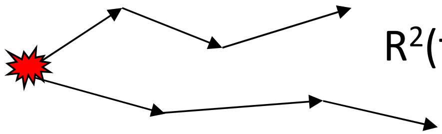


$R^2(t)\ \alpha\ t$

30 years of J/Psi enhancement !!!

94-96 (Vogt et al, Fein et al, Gavin et al): dominant «high-p_T lepton » source comes from heavy flavour decay $\Rightarrow$ HQ will obscure the thermal leptons (HQ = bad guys !)

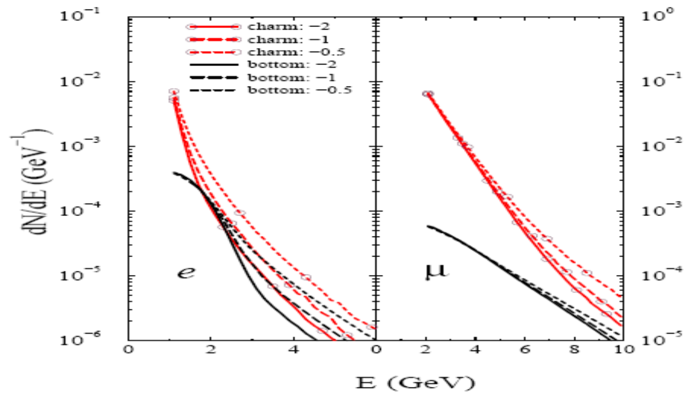
But: No Energy loss !

Some open heavy flavor history

97 (Shuryak): not the dominant (high-p_T) lepton source anymore if one includes a constant dE/dx of 2 GeV/fm (good for thermal leptons)

98 (Lin et al.): "Energy loss effects on charm and bottom production in high energy heavy-ion collisions": first paper on HQ tomography. Idea: access dE/dx via R_{AA}. Mostly «Realistic » ingredients for global scenario. 3 values of energy loss tested: 0.5,1 & 2 GeV/fm

Massless BDMPS (radiative Eloss)

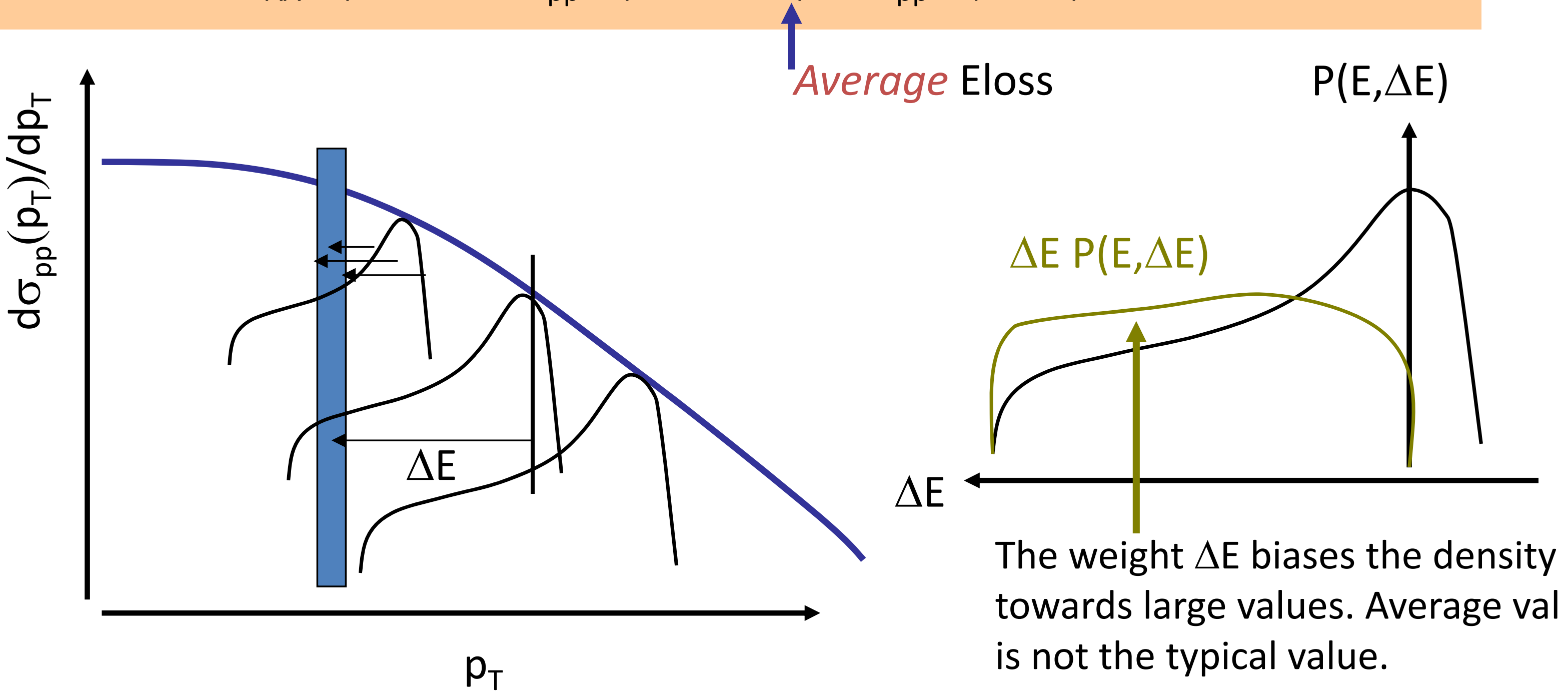


23 years of HQ tomography

98 (Mustafa et al): solves Fokker-Planck equation (with no diffusion, i.e. no fluctuations) with coefficient depending on time dependent fugacity $\lambda(t)$; infinite medium $\Rightarrow$ $\Delta E/E$=10% (RHIC) and 40% (LHC) for charm (α_s=0.3).

Some open heavy flavor history

01 (BDMS): $R_{AA}(p_T)$ is *not* $d\sigma_{pp}(p_T+\Delta E)/dp_T \,/\, d\sigma_{pp}(p_T)/dp_T$



The weight ΔE biases the density P towards large values. Average value is not the typical value.

Eloss Fluctuations do matter ! (beware of FP)

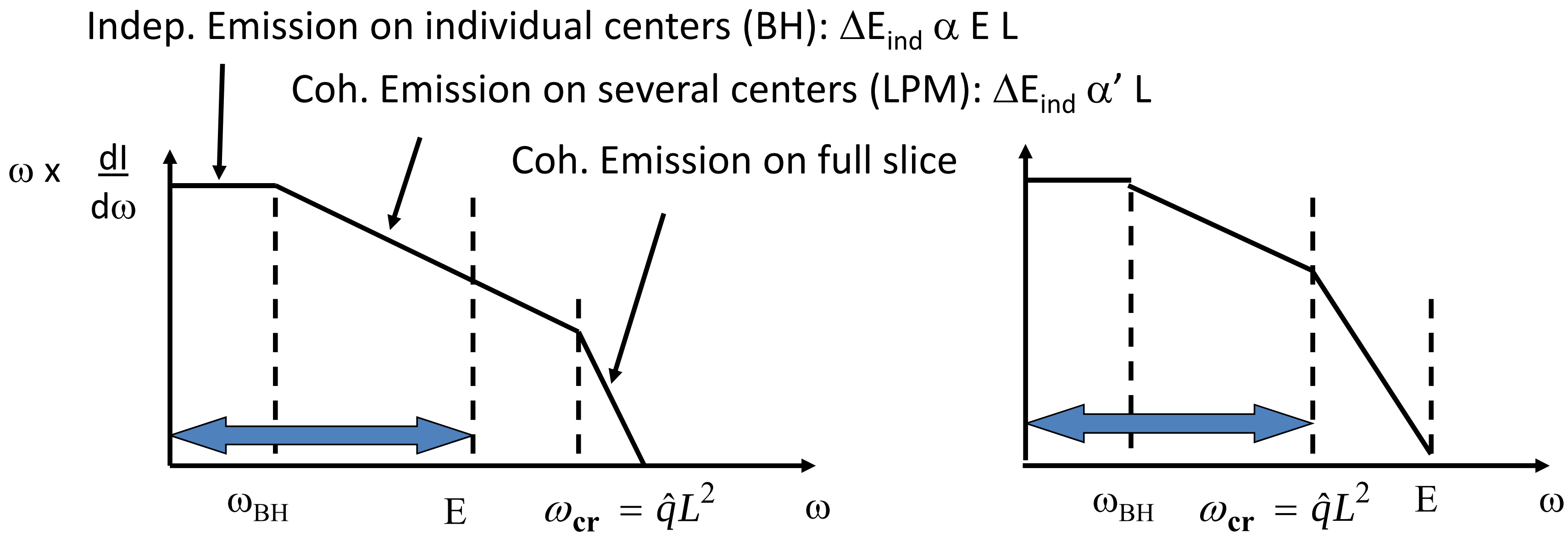
<u>Better</u>: Shift parameter S: $R_{AA}(p_T) = d\sigma_{pp}(p_T+S(n,p_T,\ldots))/dp_T \,/\, d\sigma_{pp}(p_T)/dp_T$

Effective radiation for the quenching: ω from $E \rightarrow E/n$

Some open heavy flavor history

01 (DK): contrarily to previous, HQ induced radiation is suppressed w.r.t. light quark: DEAD CONE EFFECT

gluon radiation from *massless* parton



$$\Delta E_{\rm ind}(L) \propto \sqrt{E\hat{q}}\,L \qquad \Delta E_{\rm ind}(L) \propto \hat{q}L^2$$

Some open heavy flavor history

Soft gluon emission in hard process $\frac{d\theta}{\theta} \to \frac{d\theta}{\theta} \times \frac{1}{\left(1+\left(\frac{M}{E\theta}\right)^2\right)^2}$

gluon radiation from *massive* parton (initial Bremsstrahlung)

Suppression factor DC(θ)

taken at $\theta^2 \to \langle\theta^2\rangle_{\mathrm{BDMPS}} \approx \sqrt{\frac{\hat{q}}{\omega^3}}$ for $t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$

Suppression factor DC(ω)

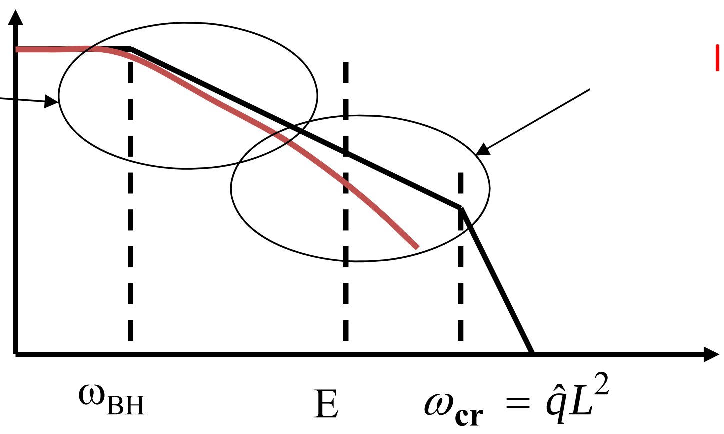
$$\frac{dI}{d\omega} \longrightarrow \frac{dI}{d\omega} \times \mathrm{DC}(\omega)$$

$$\mathbf{DC}(\omega) = \frac{1}{\left(1+\left(\frac{\omega}{\omega_{\mathbf{DC}}}\right)^{3/2}\right)^2}$$

New scale $\omega_{\mathbf{DC}} = \left(\frac{E^4\hat{q}}{M^4}\right)^{1/3}$

Moderate for quenching

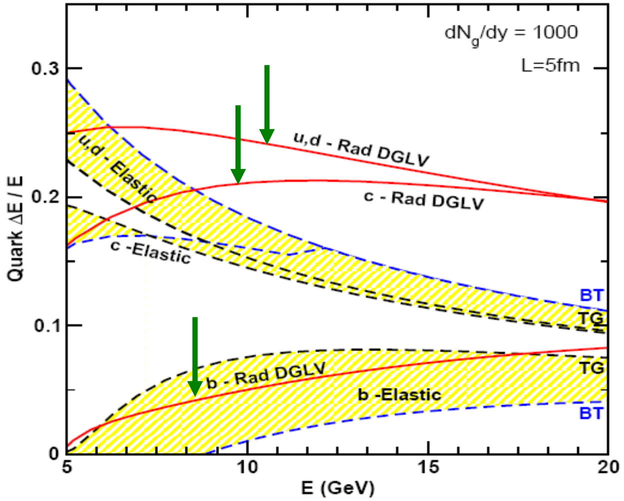
Important for ΔE

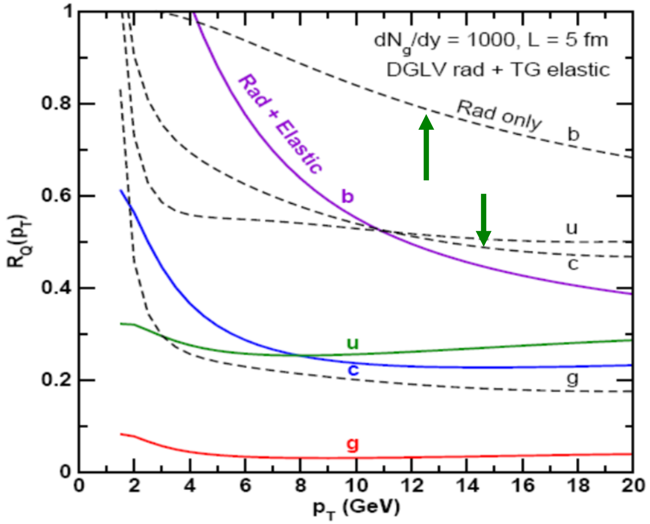


Some open heavy flavor history

More rigorous implementations

WHDG 07

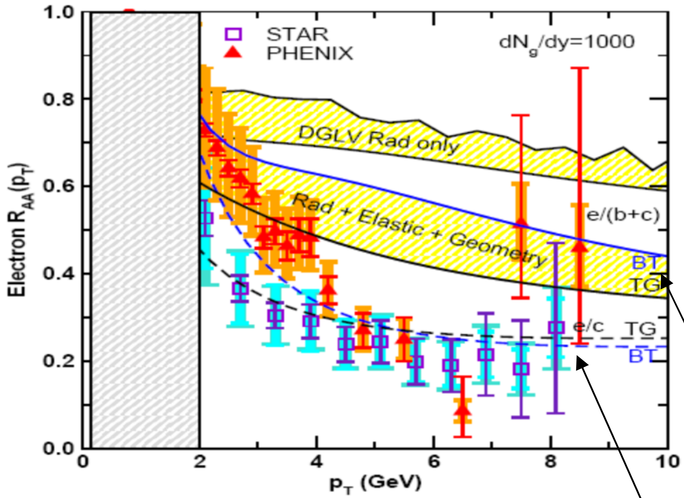


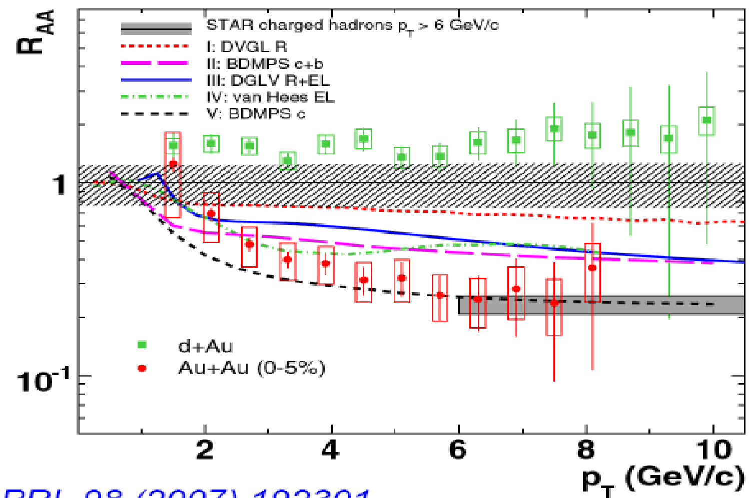


Mass hierarchy in radiative energy loss

… but it is also present in the « usual » elastic energy loss

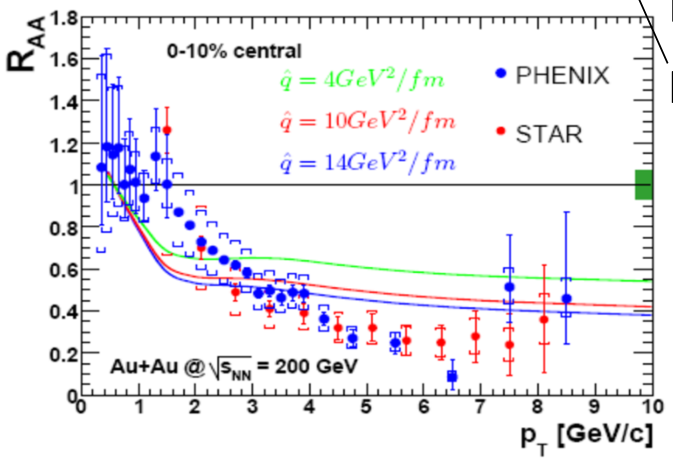
… more Eloss than expected from pQCD, even adding elastic part (often neglected up to then)



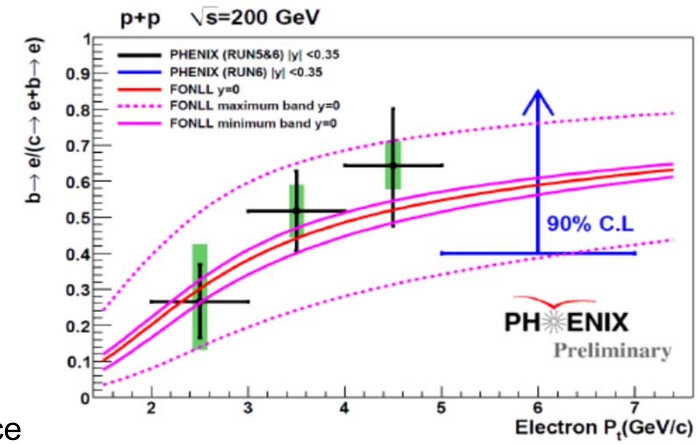


PRL 98 (2007) 192301

Elastic Eloss strikes back (Mustafa 05, Dutt Mazumber 05)



b quark is the puzzle and is definitively there:

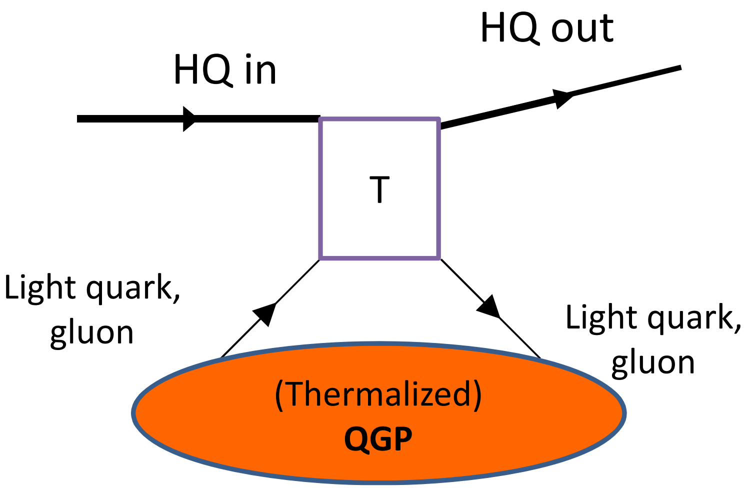


Meanwhile: $dN/dy(y\approx0)$ scales like N_{bin}

Collisional (elastic) vs Radiative

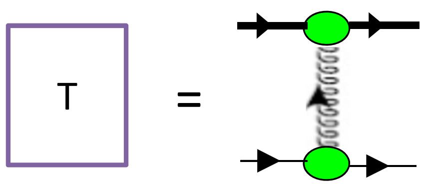
Strictly speaking: Both terms apply to pQCD processes (small and moderate coupling), or to pQCD-inspired processes for which quasi-particles still exists

Collisional (elastic): 2 $\rightarrow$ 2

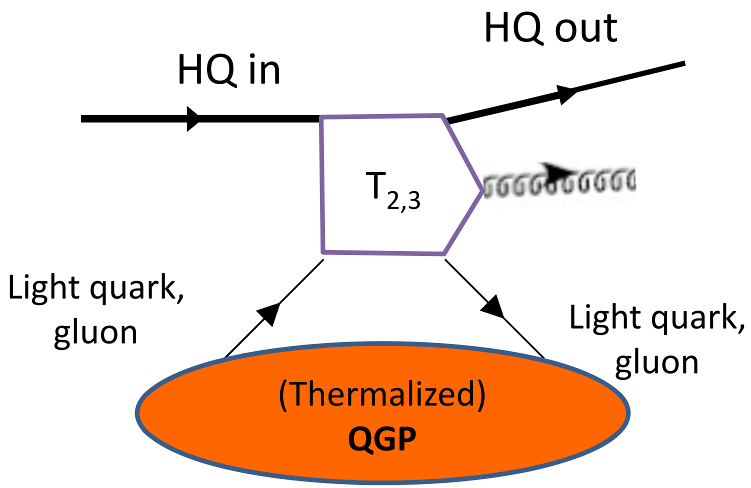


Energy flows from HQ $\leftrightarrow$ medium

e.g. :

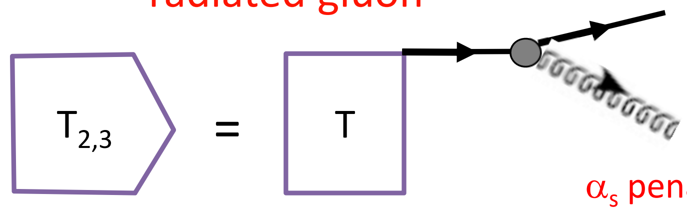


Radiative : 2 $\rightarrow$ 3



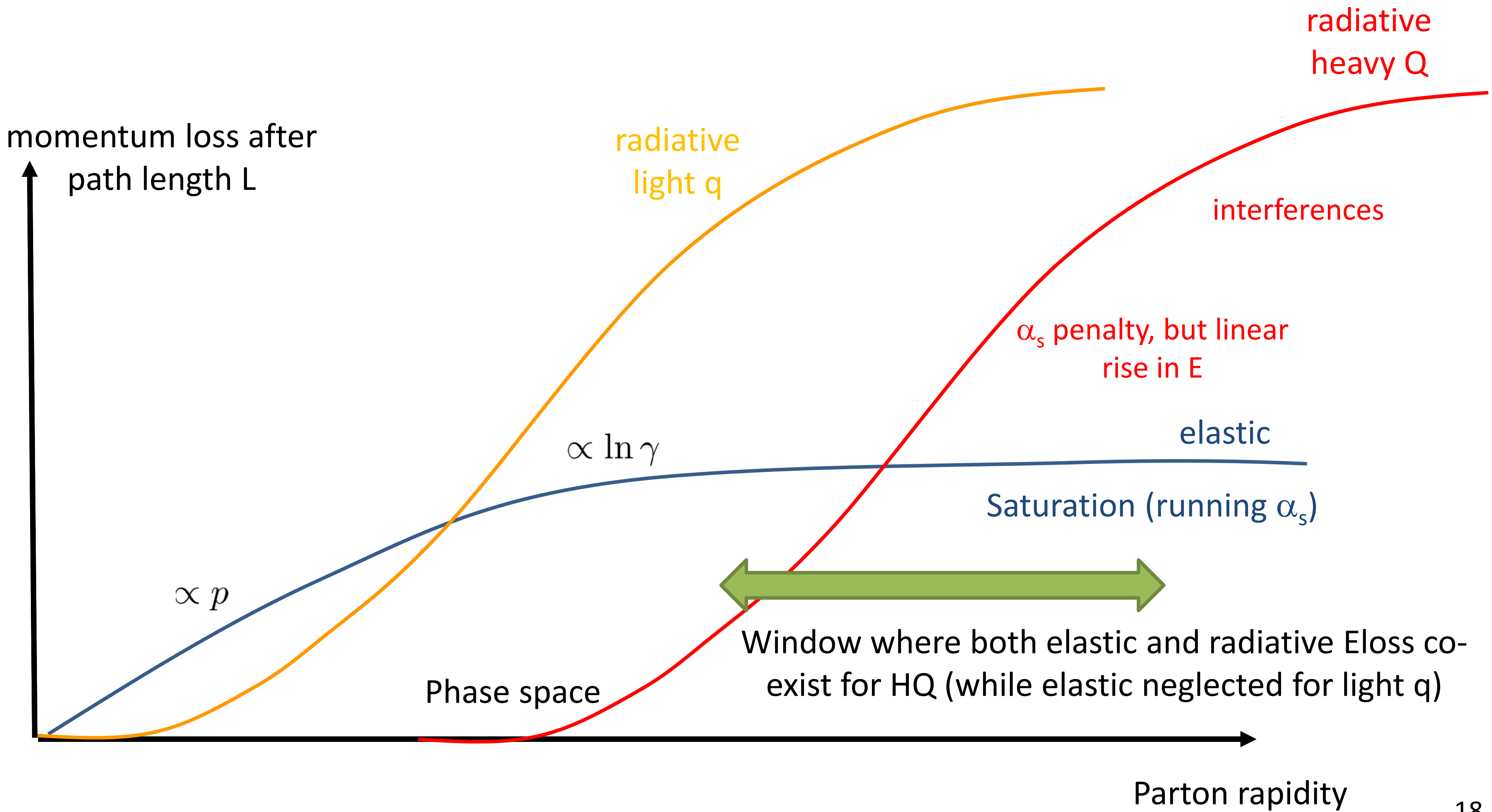
Most of energy flows from HE HQ $\rightarrow$ radiated gluon

e.g. :

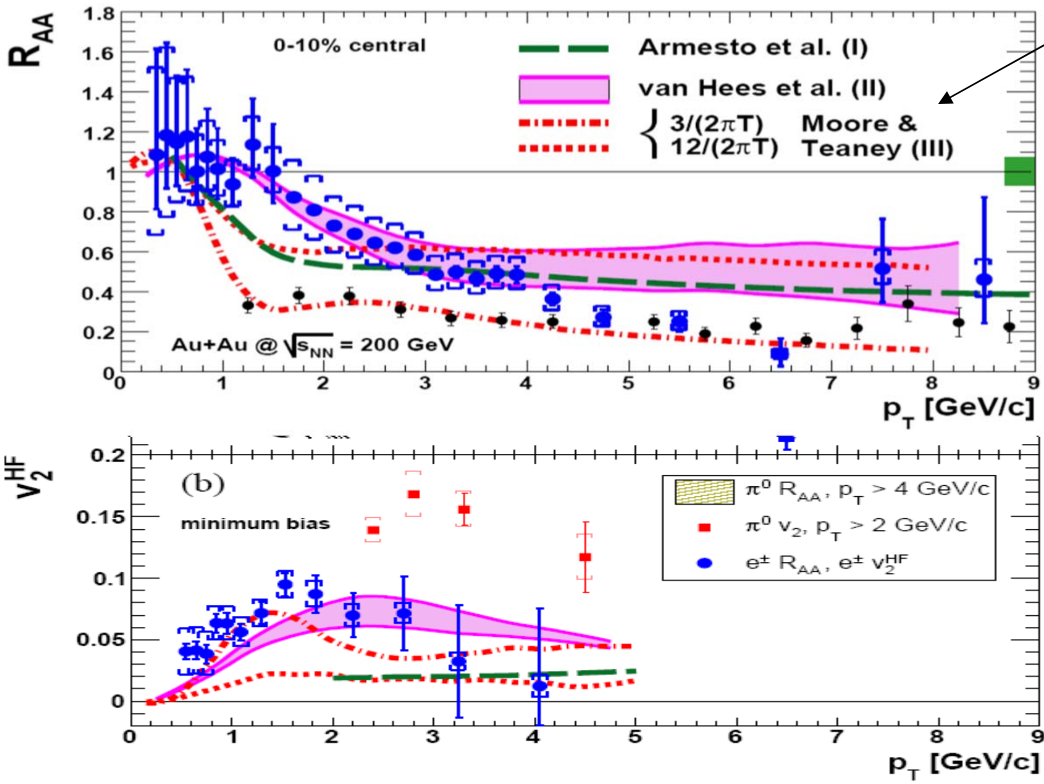


α_s penalty

Collisional (elastic) vs Radiative



more thermalisation than expected from pQCD, some ways out

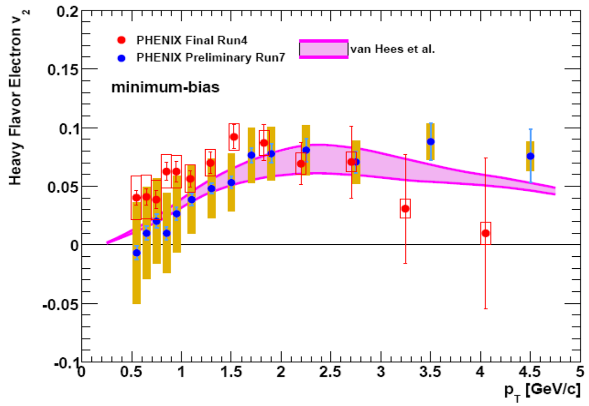


D: spatial diffus coeff (fm²/fm/c)

pQCD: $$D \approx \frac{6}{2\pi T}\left(\frac{0.5}{\alpha_s}\right)^2$$

$\approx 24/(2\pi T)$

Charm flows !!!

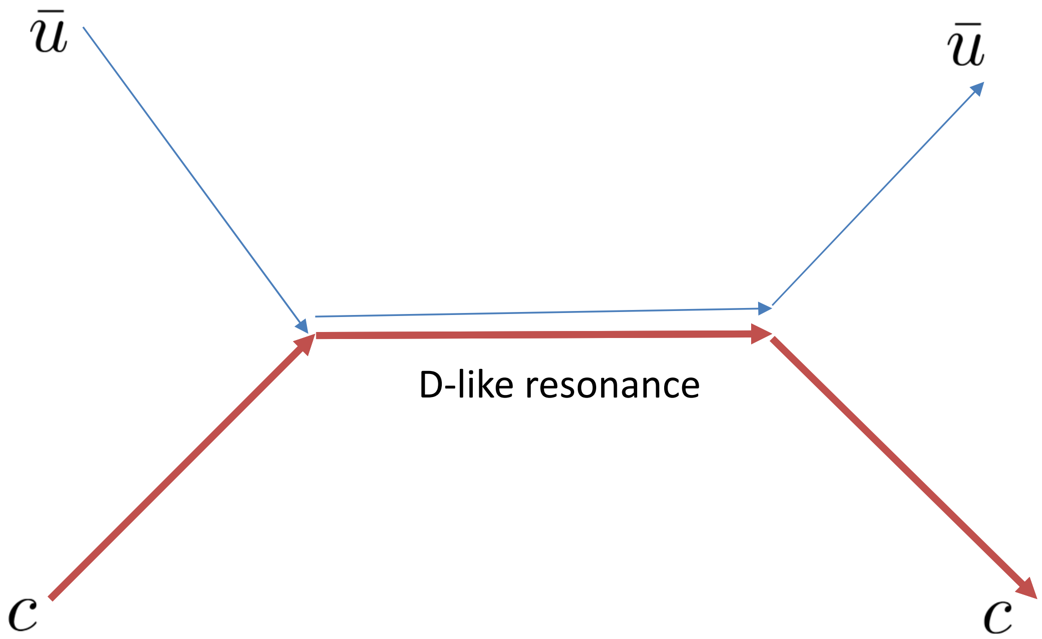


Intermediate-p_T Q marginally lie in the pQCD regime, but this is the bulk of production. For the time, we deal with phenomenology: Strategy: *Reproduce* maximum of existing experimental data with models (transport theory) *inspired* from QCD containing at less ingredients as possible… and make predictions for others

more *thermalisation* than expected from pQCD, some ways out

- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states, resorting to Langevin Dynamics

$$\Delta\vec{p} = -\vec{A}\Delta t + \underbrace{\vec{\xi}}_{\text{Random force (fluctuations)}} \quad \text{for each } \Delta t$$



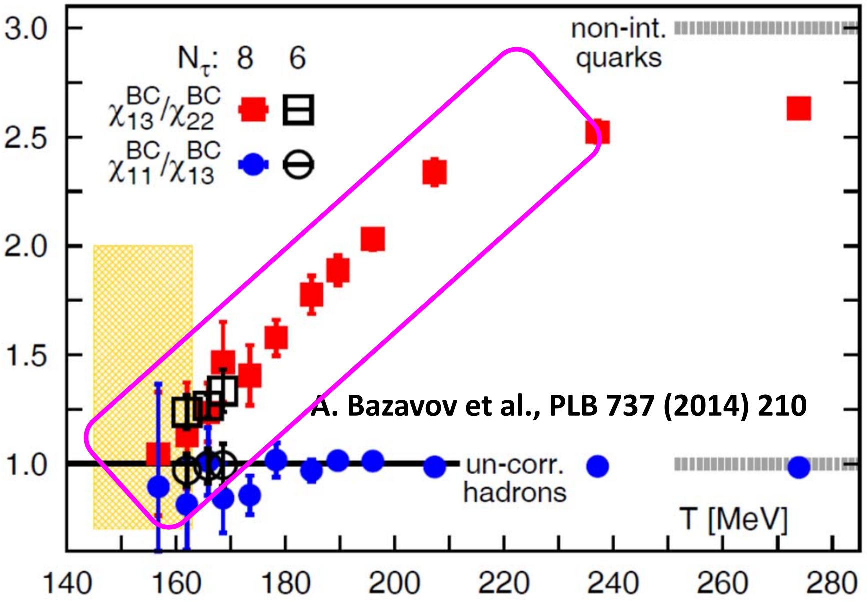
lQCD calculation => Physical Picture around T_{pc}

- Several indications that charm is not weakly interacting around Tc (screening masses, correlators,…)
- Quark susceptibilities on the lattice :

$$\chi^{BC}_{mn} = \frac{\partial^{m+n} p(T,\mu_B,\mu_C)}{\partial \hat{\mu}_B^m \partial \hat{\mu}_C^n}\Big|_{\mu_B=\mu_C=0}$$

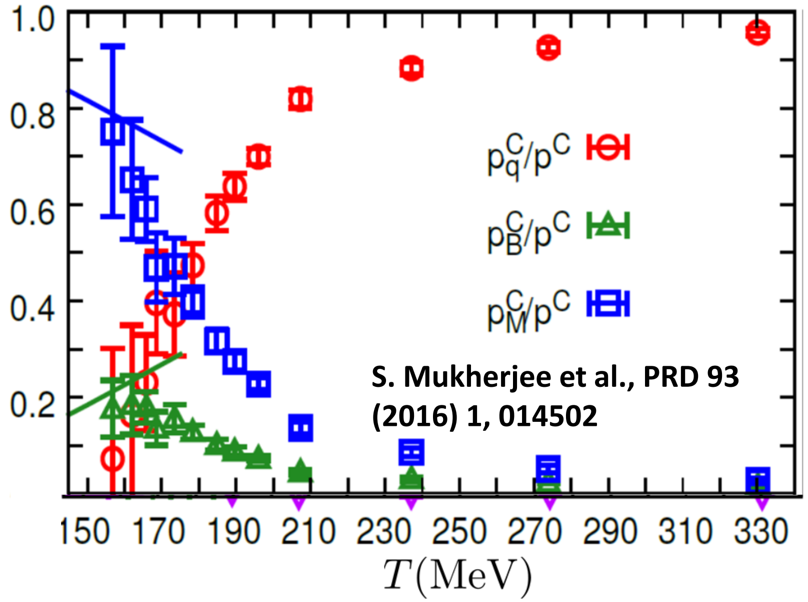
where $\hat{\mu} = \mu/T$

Minimalistic model :
$$P^C = P^C_q(T)\cosh(\hat{\mu}_C + \frac{\hat{\mu}_B}{3}) + P^C_M(T)\cosh(\hat{\mu}_C) + P^C_B(T)\cosh(\hat{\mu}_C + \hat{\mu}_B) + \underbrace{\cdots}_{C>1\ (\text{small})}$$



Gradual transition from hadronic-like -> non interacting quark values

fractional contributions of partial pressures (PP)



PP drop: hadronic resonances become broad at high T and do not contribute

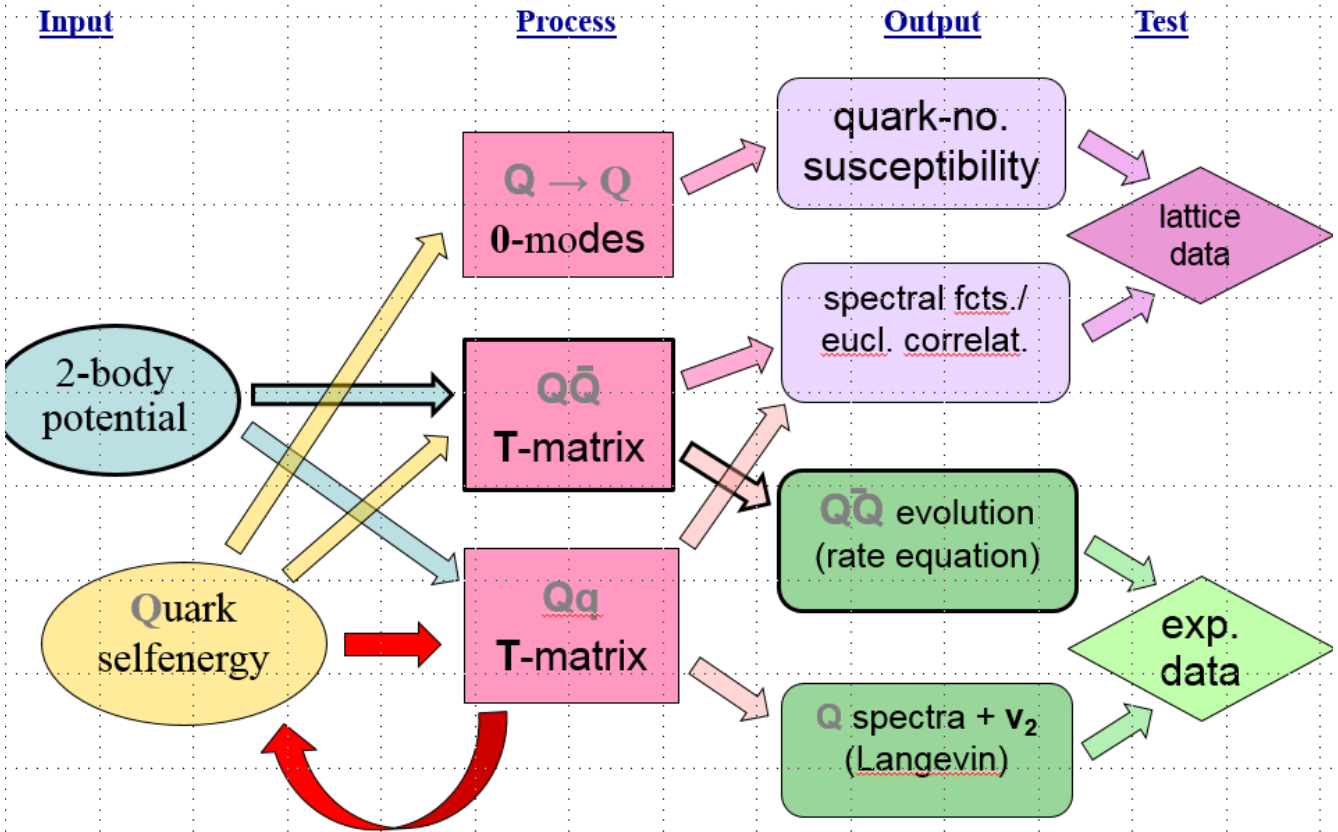
Jakovác, PRD88 (2013), 065012, Biró, Jakovác, PRD(2014)065012

Confirms the resonance picture of Ravagli and Rapp

L. Ravagli and R. Rapp, Phys. Lett. B 655 (2007)

Potential models (TAMU)

- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states; then (2008) systematically developped using the T-matrix resummation of a bona-fide 2 body potential



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)

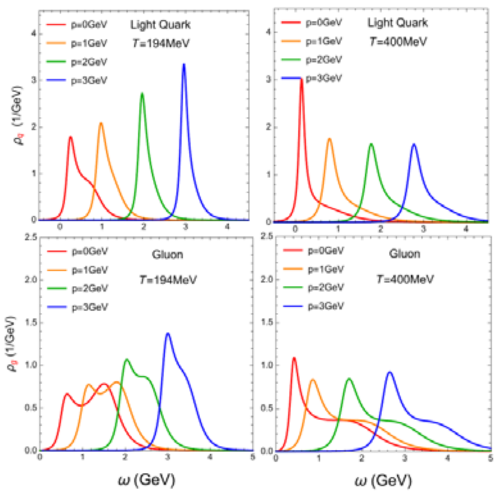
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

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!

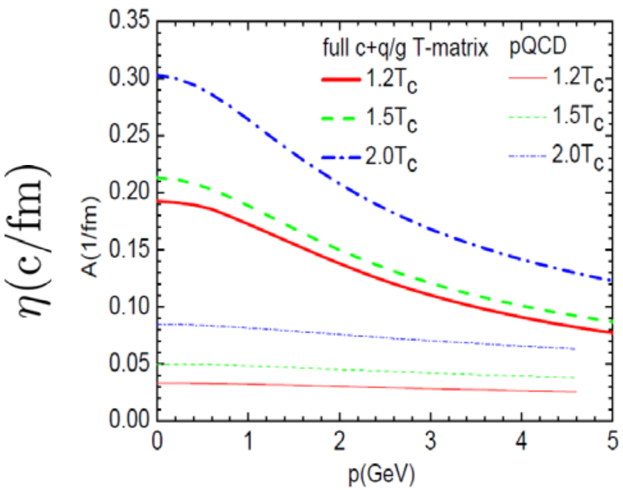
M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)

- Implementation through Langevin dynamics in hydro evolution or in URQMD also corresponds to the disappearance of well defined quasi particles (for which Boltzmann breaks down while Langevin still holds)



No good q-particle at low p

QGP France



Large coupling at small p_Q

Open question, some ways out

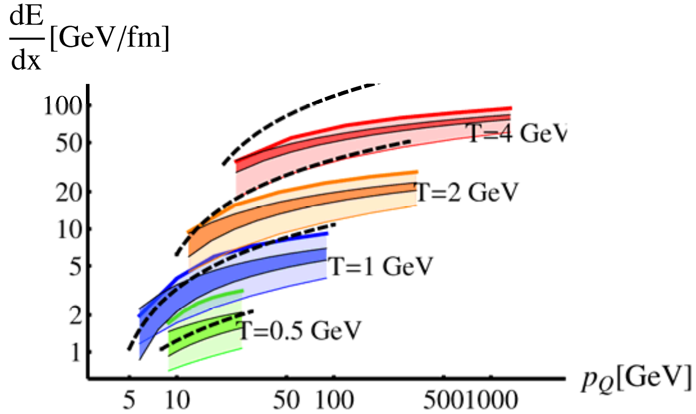
- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states; then (2008) systematically developped using the T-matrix resummation of a bona-fide 2 body potential
- *Running* of α_s could have dramatic consequences (Peshier 06) => effective model and numerical *Boltzmann* implementation by Peshier (2008), Gossiaux & Aichelin (2008), then Uphoff & Greiner)

pQCD inspired models (f.i. Nantes)

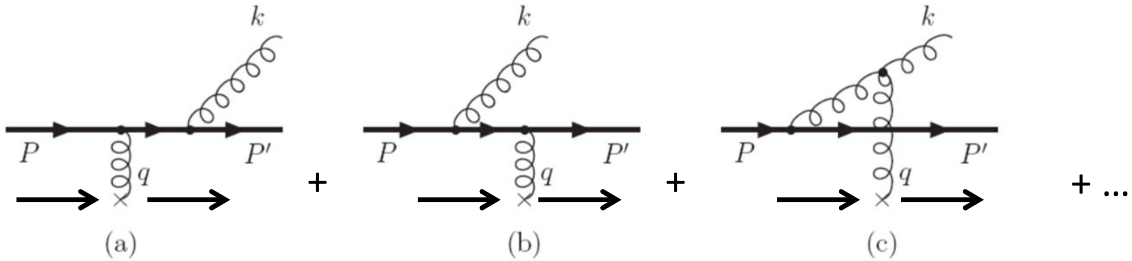
Colisional component

- 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

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



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):

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

- LPM effect for moderate gluon energy

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

But also BAMPS, LBL-CCNU, Duke,…

Open question, some ways out

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- *Running* of α_s (Peshier 06, then Gossiaux & Aichelin 08, then Uphoff & Greiner)
- sQGP: "supersymetric + AdS/CFT" (application to R_{AA} by Horowitz and Gyulassy, later implementation by Akamatsu)

The weak to strong axis for HQ

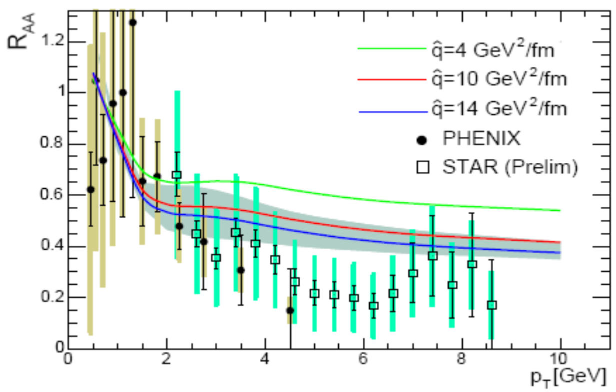
"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

So-called "Failure of pQCD approach" aka "the non photonic single electron puzzle"

"Optimized" pQCD
(ok with pions)

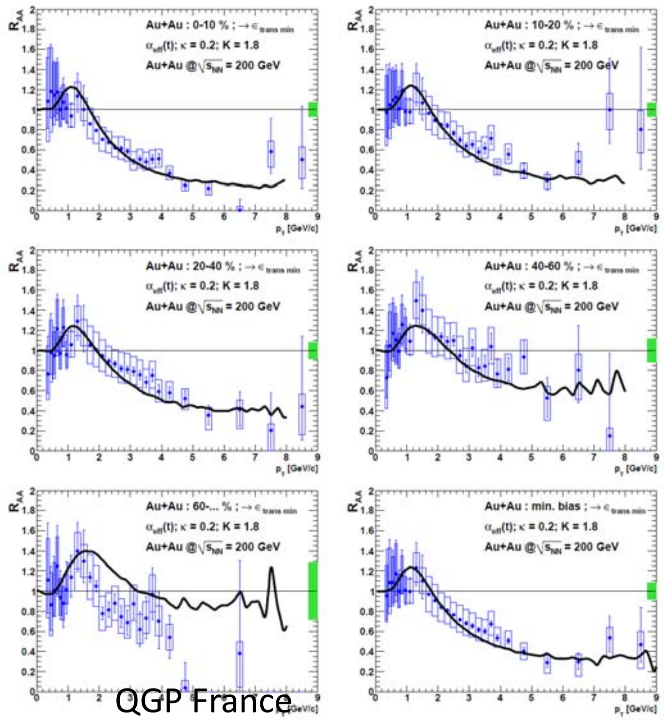
ASW (pure rad. energy loss; extended BDMPS)

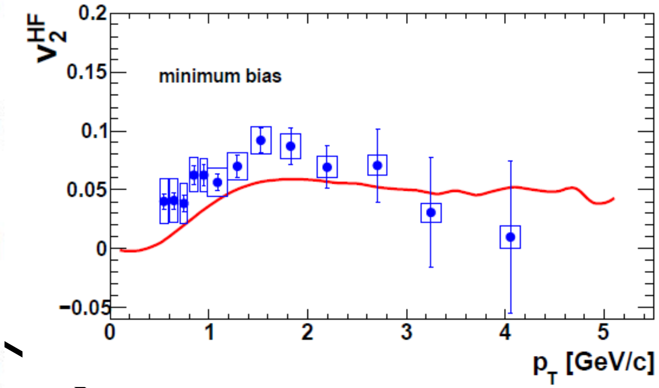
Collisional model with running α_s and optimized gluon propagator (Peshier, Gossiaux and Aichelin, BAMPS)



Armesto et al Dainese, Phys. Rev D (hep-ph/0501225) &
Phys.Lett. B637 (2006) 362-366 hep-ph/0511257

Conclude to rough agreement, subjected to b/c ratio in p-p





The weak to strong axis for HQ

“Naive” pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

So-called “Failure of pQCD approach” aka “the non photonic single electron puzzle”

“Optimized” pQCD

Running α_s (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]

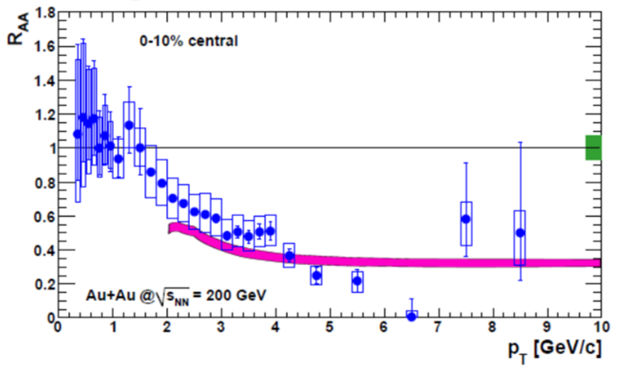


FIG. 41: (Color online) R_{AuAu} in 0–10% centrality class compared with a collisional dissociation model [78] (band) in Au+Au collisions.

The weak to strong axis for HQ

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(WHDG, ASW,…)
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Distorsion (
fragmentat
existence (
R. Sharma
0904.0032

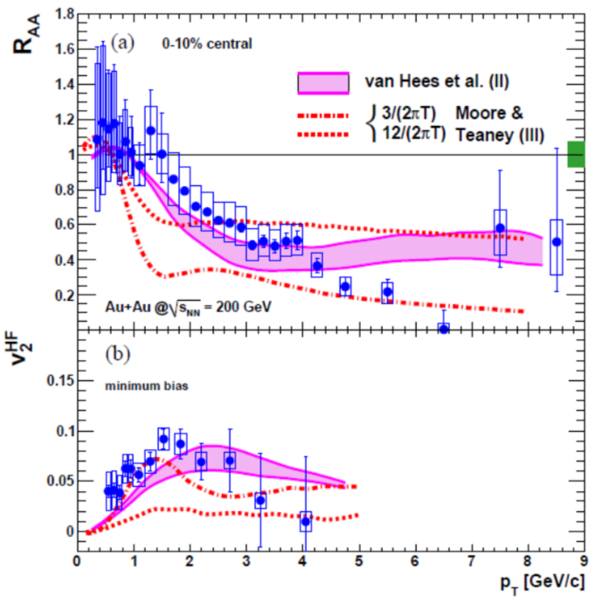


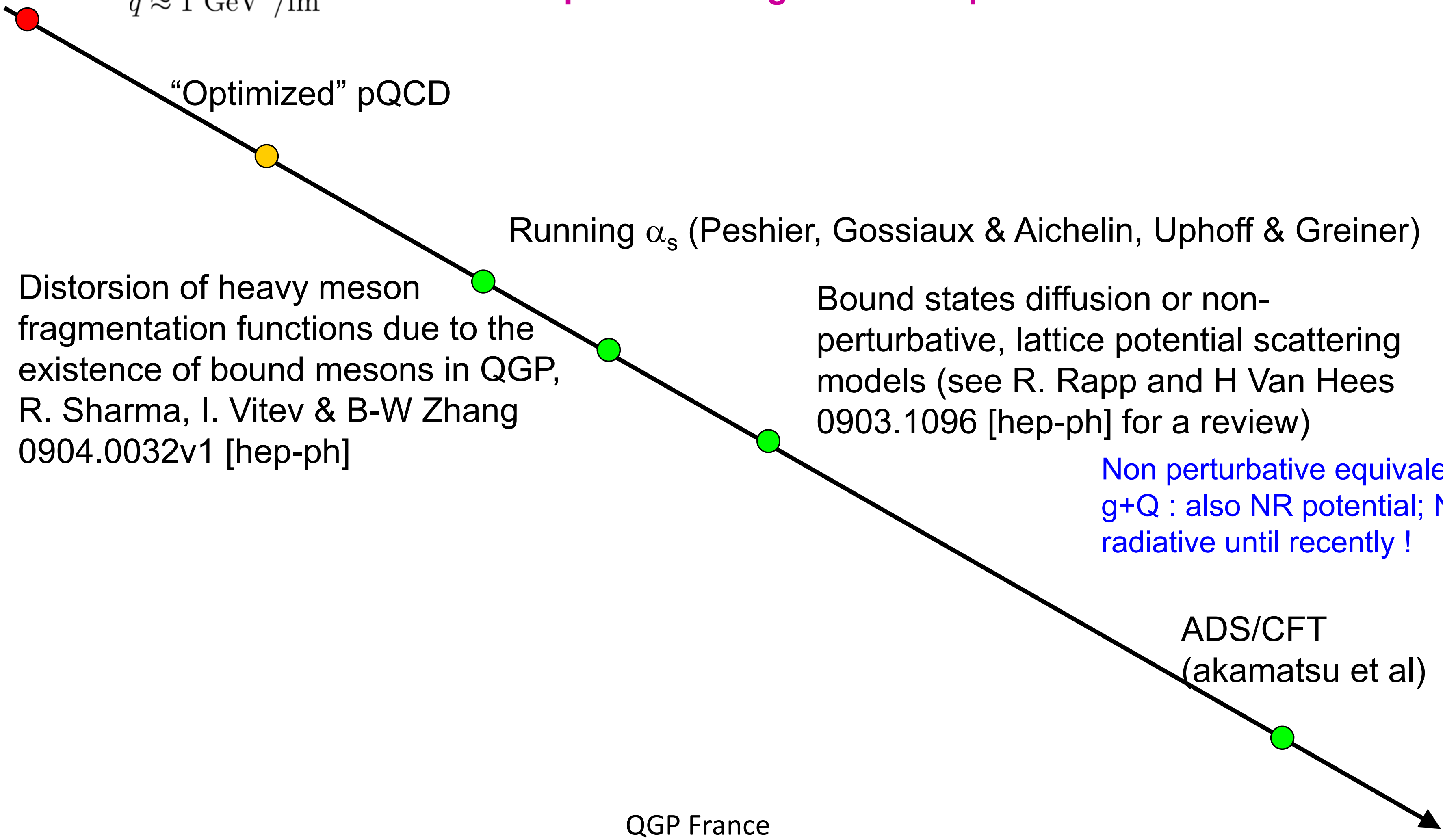
FIG. 40: (Color online) Comparison of Langevin-based models from [74–76] to the heavy flavor electron R_{AuAu} for 0–10% centrality and v_2 for minimum-bias collisions.

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

Non perturbative equivalent for g+Q ?
No radiative !

The weak to strong axis for HQ

So-called "Failure of pQCD approach" aka "the non photonic single electron puzzle"



The weak to strong axis for HQ

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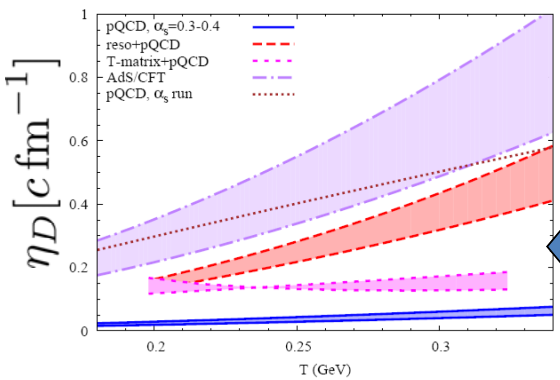
Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

Non perturbative equivalent for g+Q : also NR potential; No radiative until recently !



from Rapp & Van Hees 0903.1096

Lesson n°1 (pre LHC):

Several models containing either non perturbative features or tunable parameters are able to reproduce the HQ data, but many questions remain… and how to reconcile them all stays a challenge

ADS/CFT (akamatsu et al)

The LHC Era: 2010 -> Now

- Huge data from LHC constraining the models (at high p_T as well as in the b sector)
- A last class of model: Quasi Particle Model
- Constrains from the fundamental theory : lQCD estimates
- The way towards more collective work in the theory community
- Alternate observables (correlations)
- HQ-jets
- HQ in small systems
- ....

Quasi particle models (f.i DQPM)

- Nonperturbative 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)

- Coupling between the effective DOF is then taken as $\alpha_s(T)$=> Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

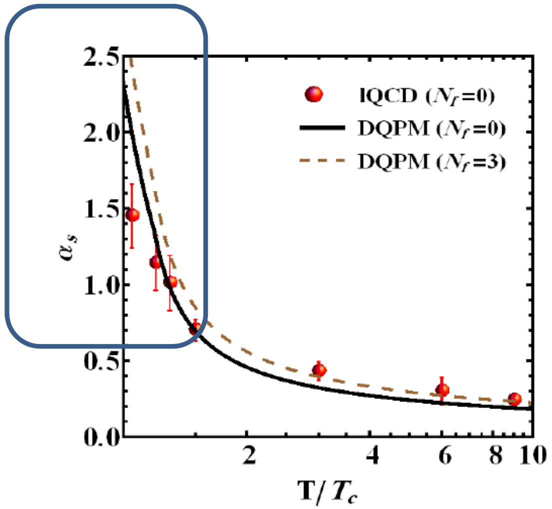
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

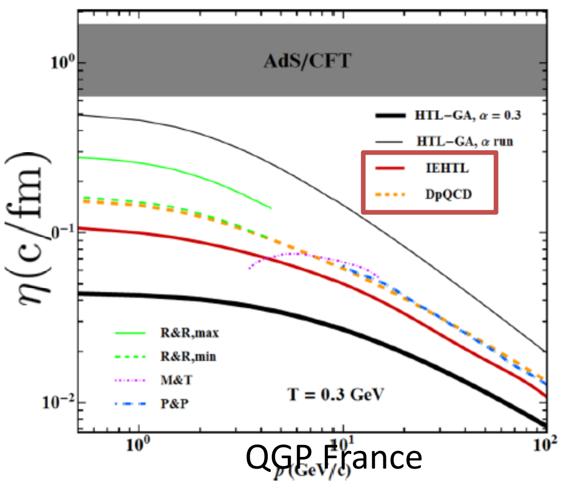
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

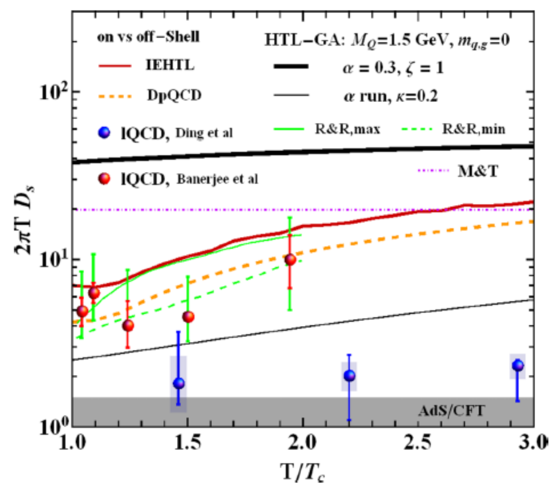
T. Song et al. PRC 92 (2015), PRC 93 (2016)

But also CATANIA

Huge !!!







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- HQ-jets
- HQ in small systems
- ….

Transport coefficients at low momentum p≈m_Q

Langevin regime => Einstein relation: $\kappa = 2TE_Q\eta_D$

$$\langle r^2(t)\rangle = 2dD_s t$$

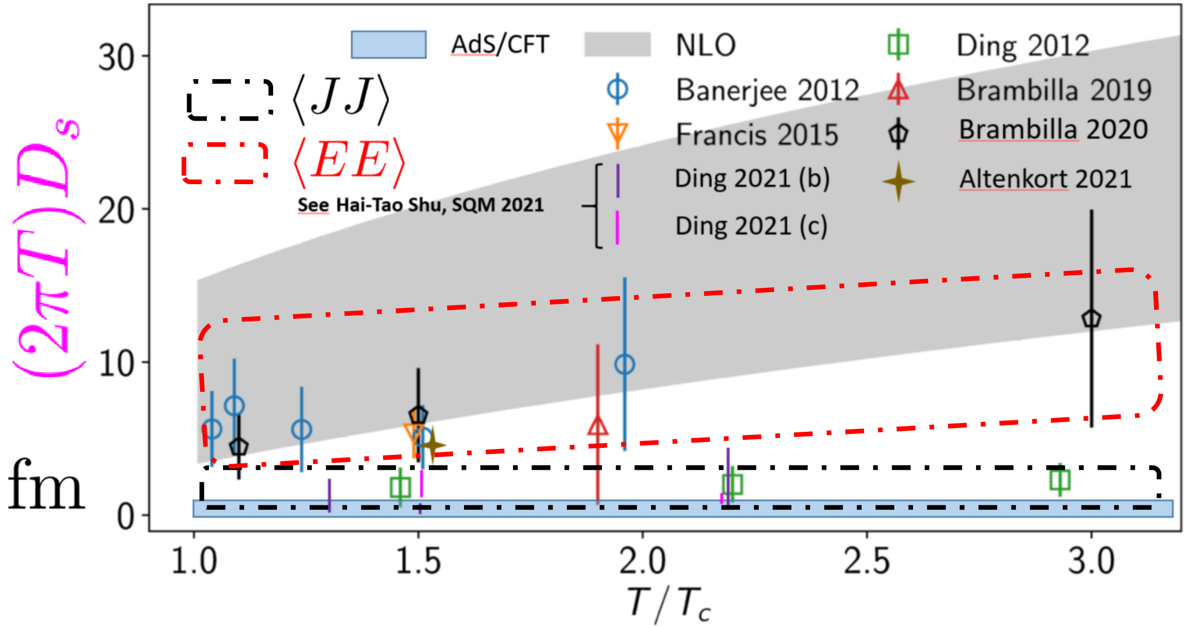
For historical reasons, physics displayed as a function of 2πT x the spatial diffusion coefficient

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

Gauge for the coupling strength

lQCD results

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

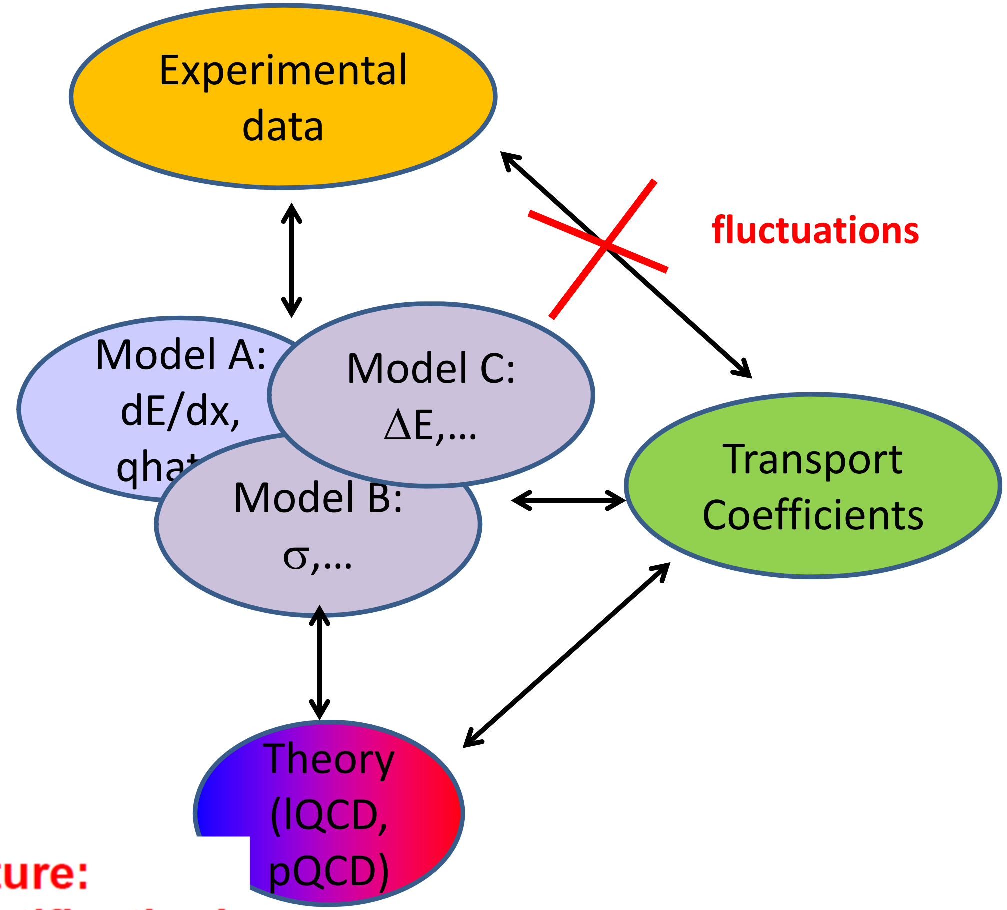


$$\tau_{\rm relax}(T_c) \approx m_Q[\mathrm{GeV}] \times (3 \pm 1.5)\ \mathrm{fm}$$

For b: Indeed a hard probe !

Today Stakes and Motivation

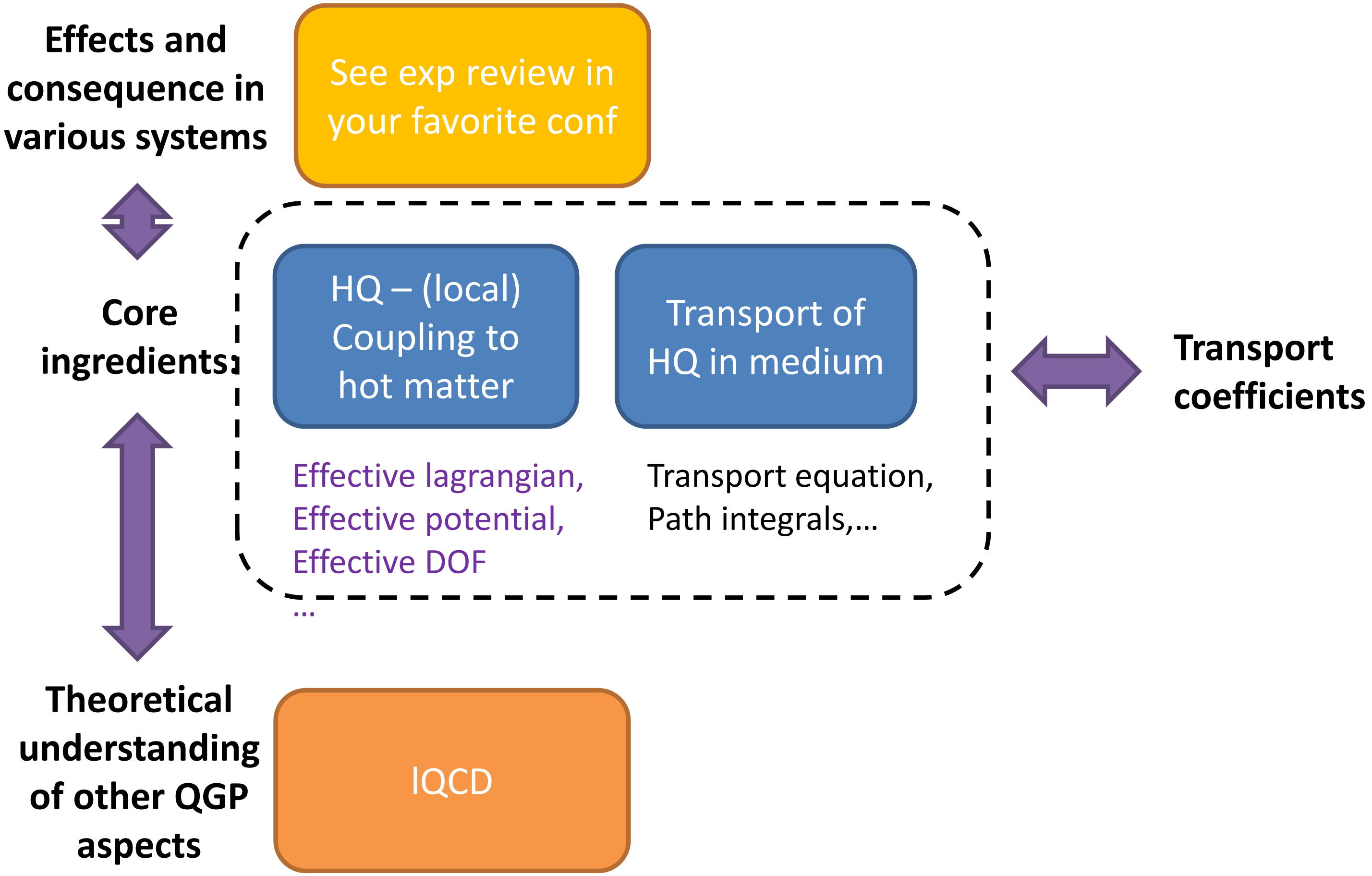
- Very subttle interplay between fundamental theory and experimental data to build and calibrate / constrain the models in order to better understand HF – QGP interaction (including QGP constituents)
- Then maybe one day: probing the bulk !
- On a more phenomenological and data driven level: Are we able 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.



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

A bit of structure

- HQ propagation in QM & URHIC…



A bit of structure

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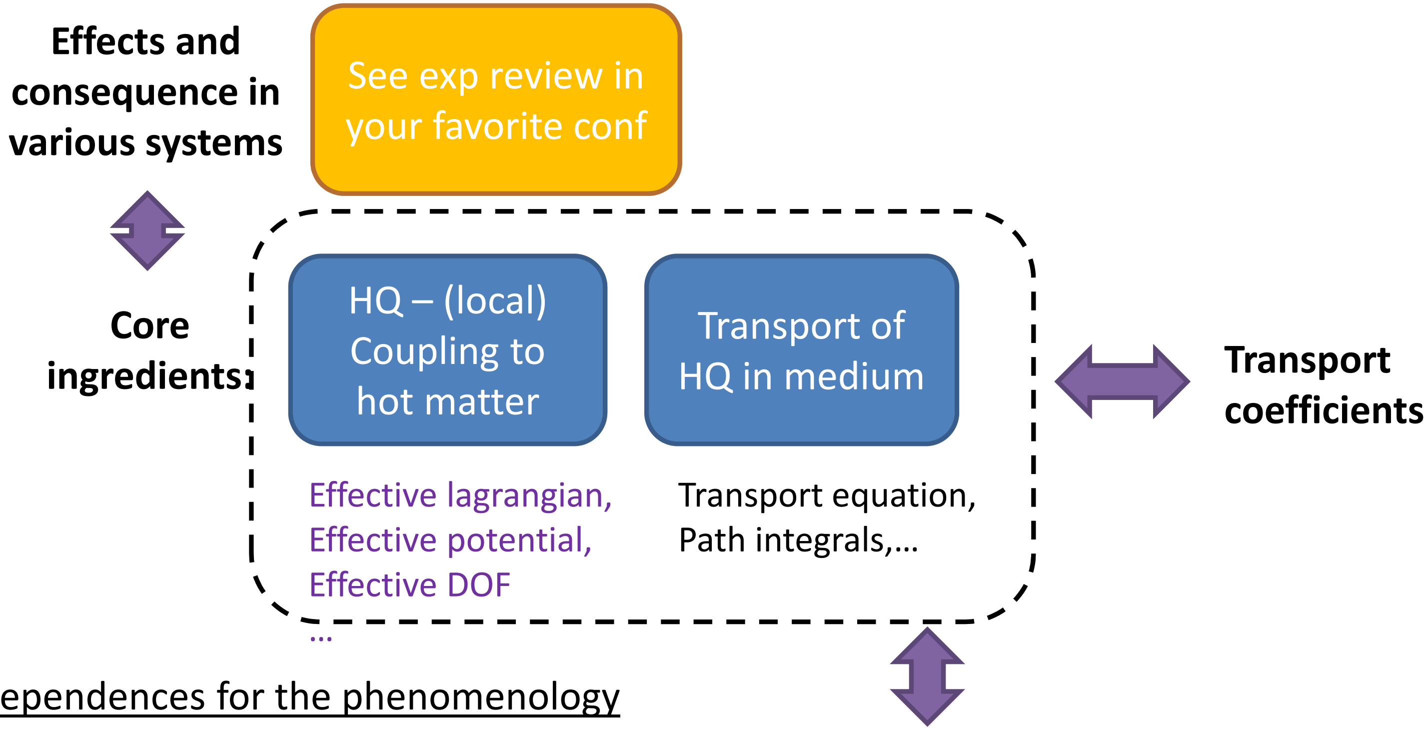
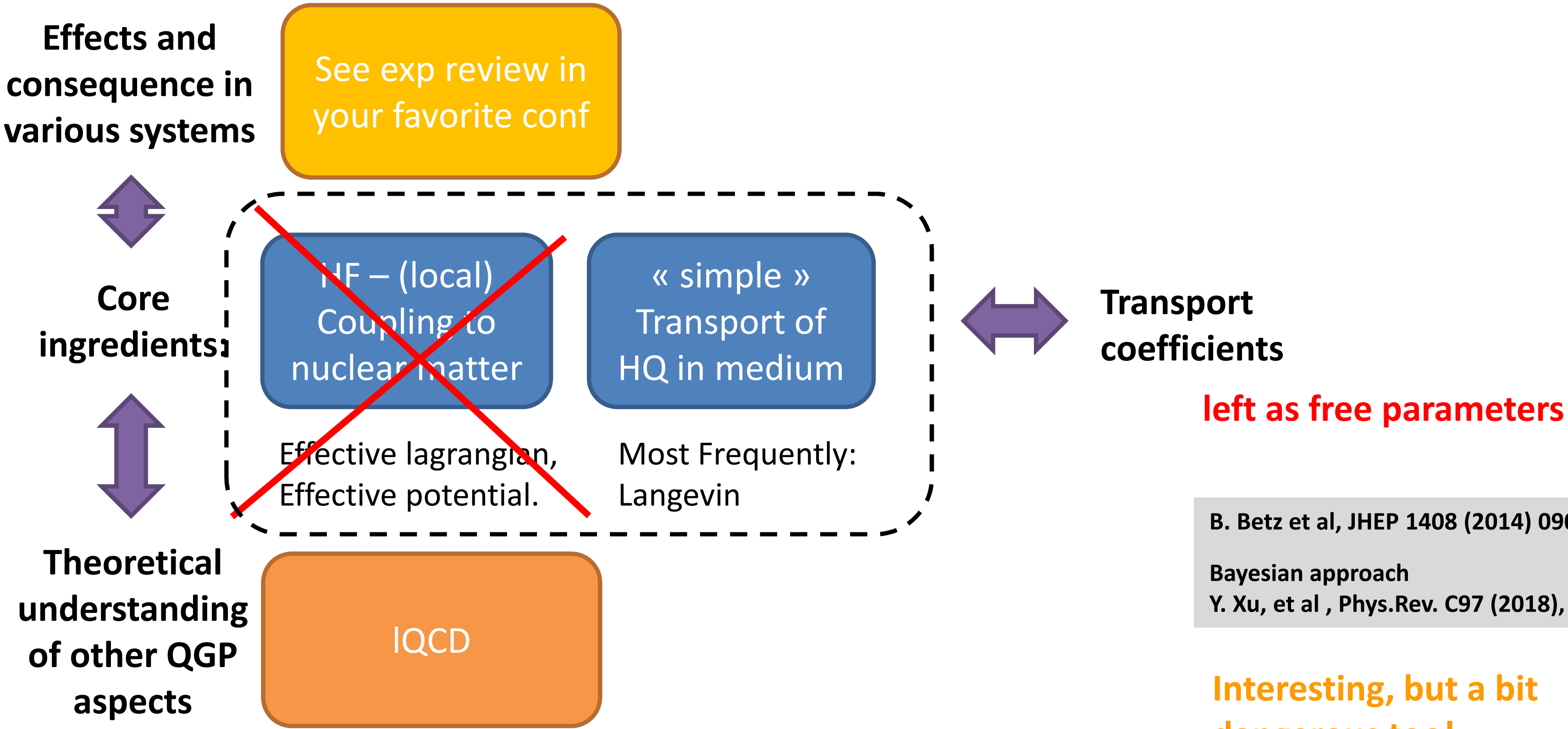


<u>4 important dependences for the phenomenology</u>

- Energy dependence : the saturation at large E explain the restoration -> 1 at large p_T
- Mass dependence => less thermalization for b quarks
- T dependence weigths differently the initial stage and the late evolution (for which flows have developped)
- Path length dependence => makes it more transparent to the radiative in small systems ($\Delta E_{rad} \alpha L^2$)

A bit of structure

- No Model approach



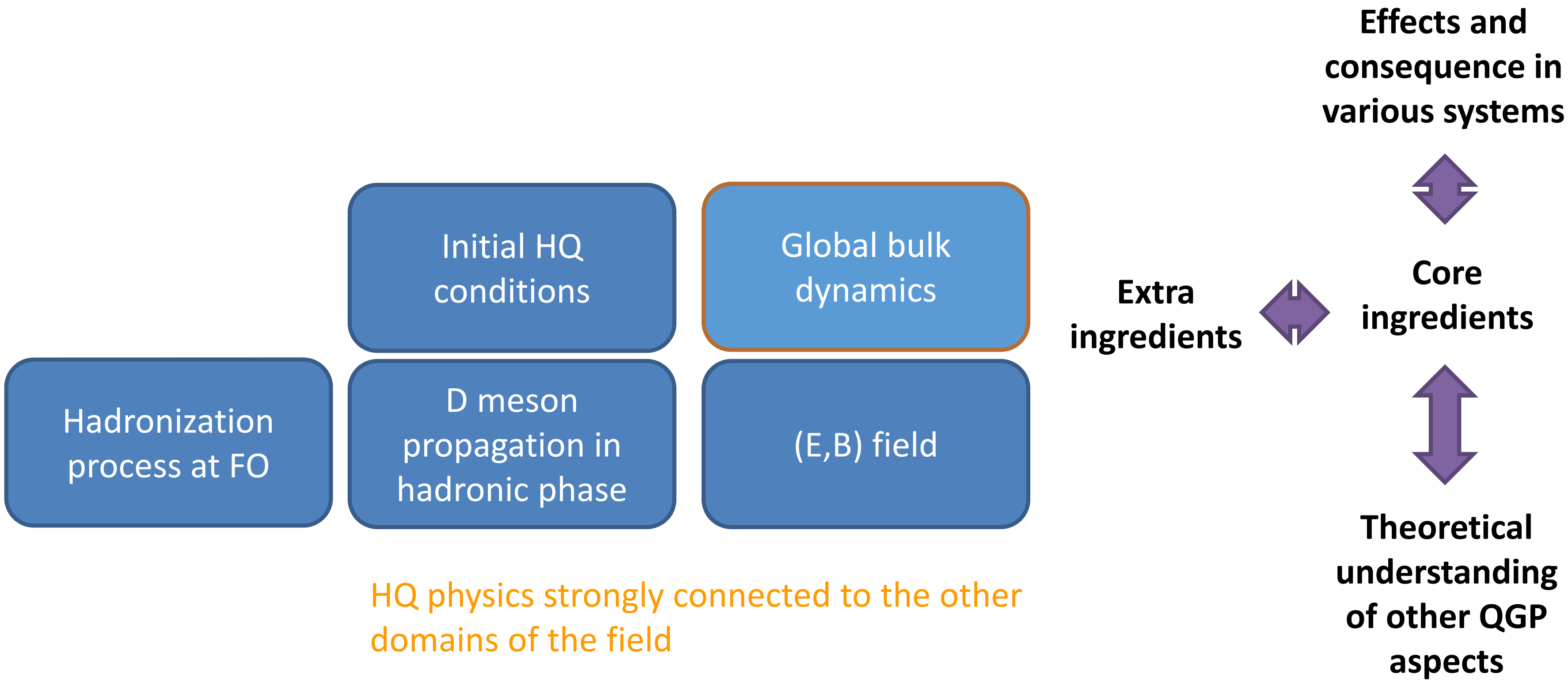
B. Betz et al, JHEP 1408 (2014) 090 (for jets)

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

Interesting, but a bit dangerous too!

A bit of structure

- HQ propagation in QM & URHIC…



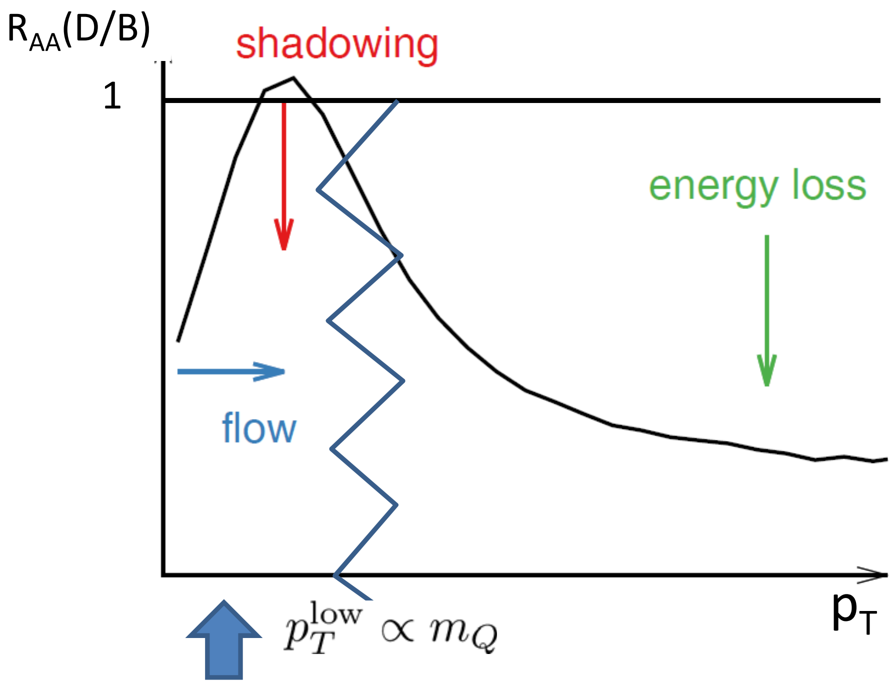
Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coefficient based (LV,…)	TAMU POWLANG HTL Catania LV	Duke	ASW	ADS/CFT POWLANG lQCD *DABMOD* *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*	$SCET_{G,M}$	

Red: Transport models

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

The pattern seen in the data



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

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*

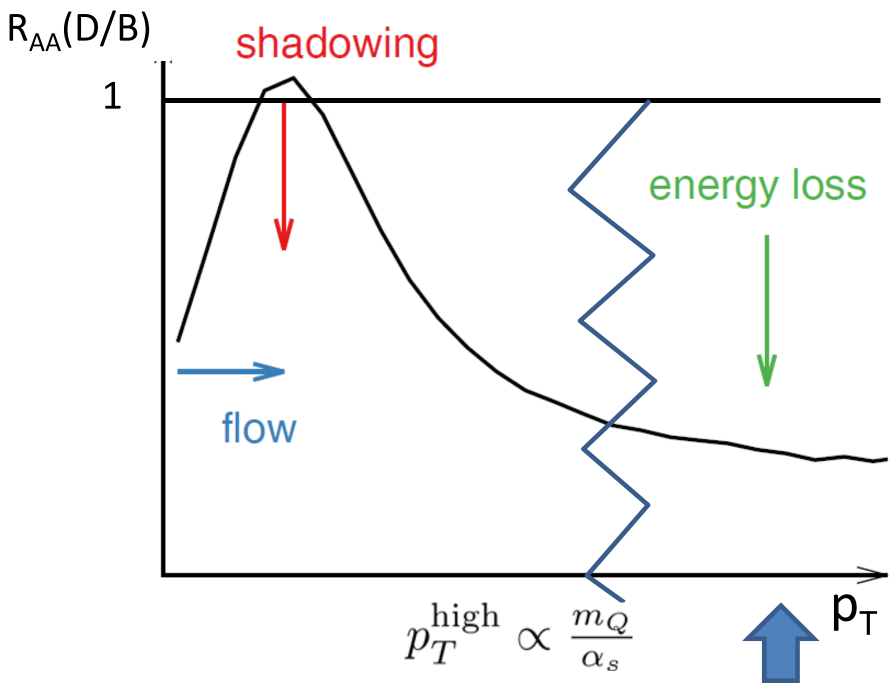
Quenching & energy loss: due to

- elastic and *inelastic* scatterings
- *opacity of the medium*

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

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

The pattern seen in the data



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- *recombination with light quarks*

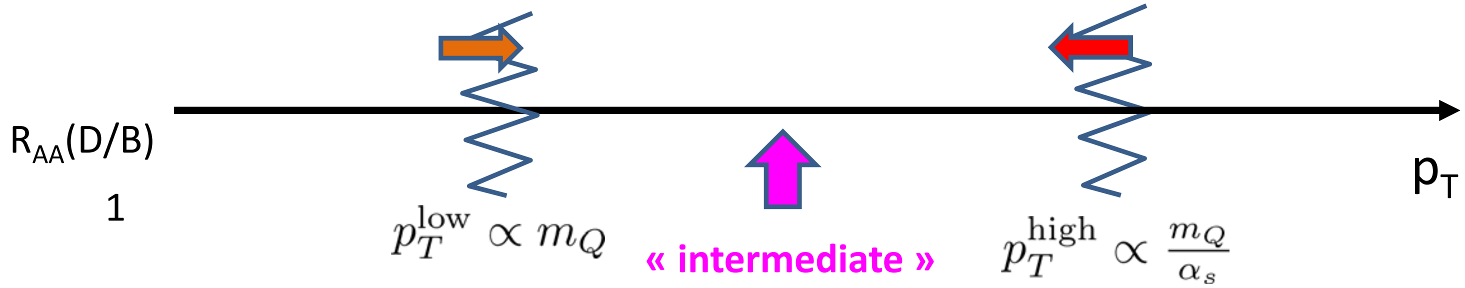
shadowing: due to *initial state nuclear effects*

Quenching & energy loss: due to

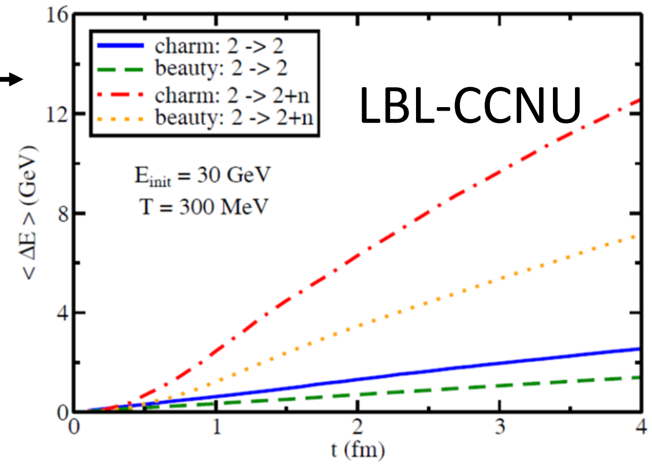
- elastic and *inelastic* scatterings
- *opacity of the medium*

- 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 ($m_Q \ll p_T$)

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



- 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 $\hat{e}_2$



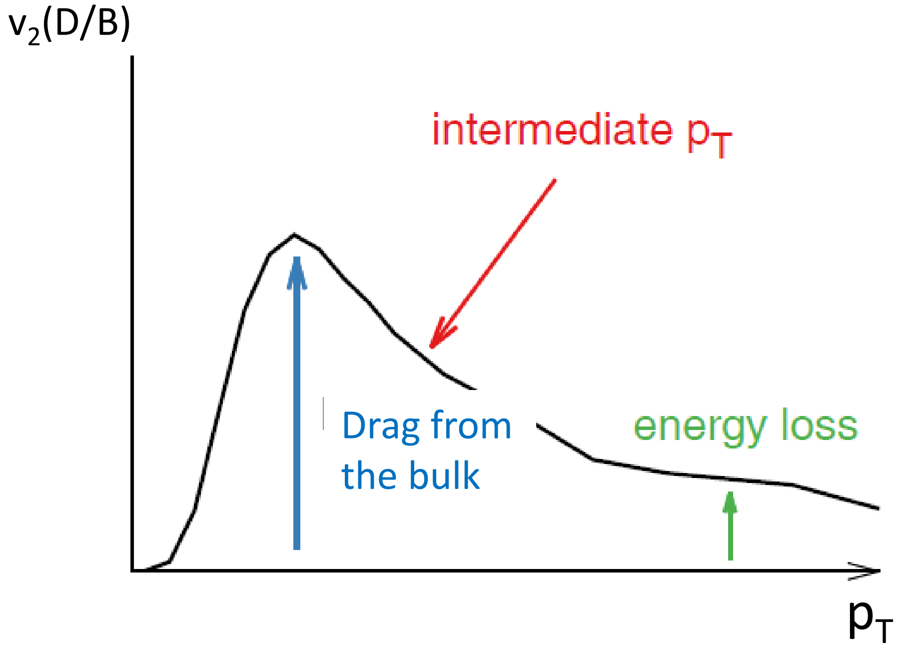
S. Cao et al, Phys. Rev. C 94, 014909 (2016)

$$\frac{dN_g}{dy\,dl_\perp^2\,d\tau} = 2\,\frac{\alpha}{\pi}\,P(y)\,\frac{1}{l_\perp^4}\left(\frac{1}{1+\chi}\right)^4 \sin^2\left(\frac{l_\perp^2}{4l^-(1-y)}(1+\chi)\,\tau\right)$$
$$\times\left[\left\{\left(1-\frac{y}{2}\right)-\chi+\left(1-\frac{y}{2}\right)\chi^2\right\}\hat{q}+\frac{l_\perp^2}{l^-}\chi(1+\chi)^2\,\hat{e}+\frac{l_\perp^2}{(l^-)^2}\chi\left(\frac{1}{2}-\frac{11}{4}\chi\right)\hat{e}_2\right]$$

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

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

Basic Consequences of HQ interaction with QGP for the v_2



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 $N_{coll} \approx 1$

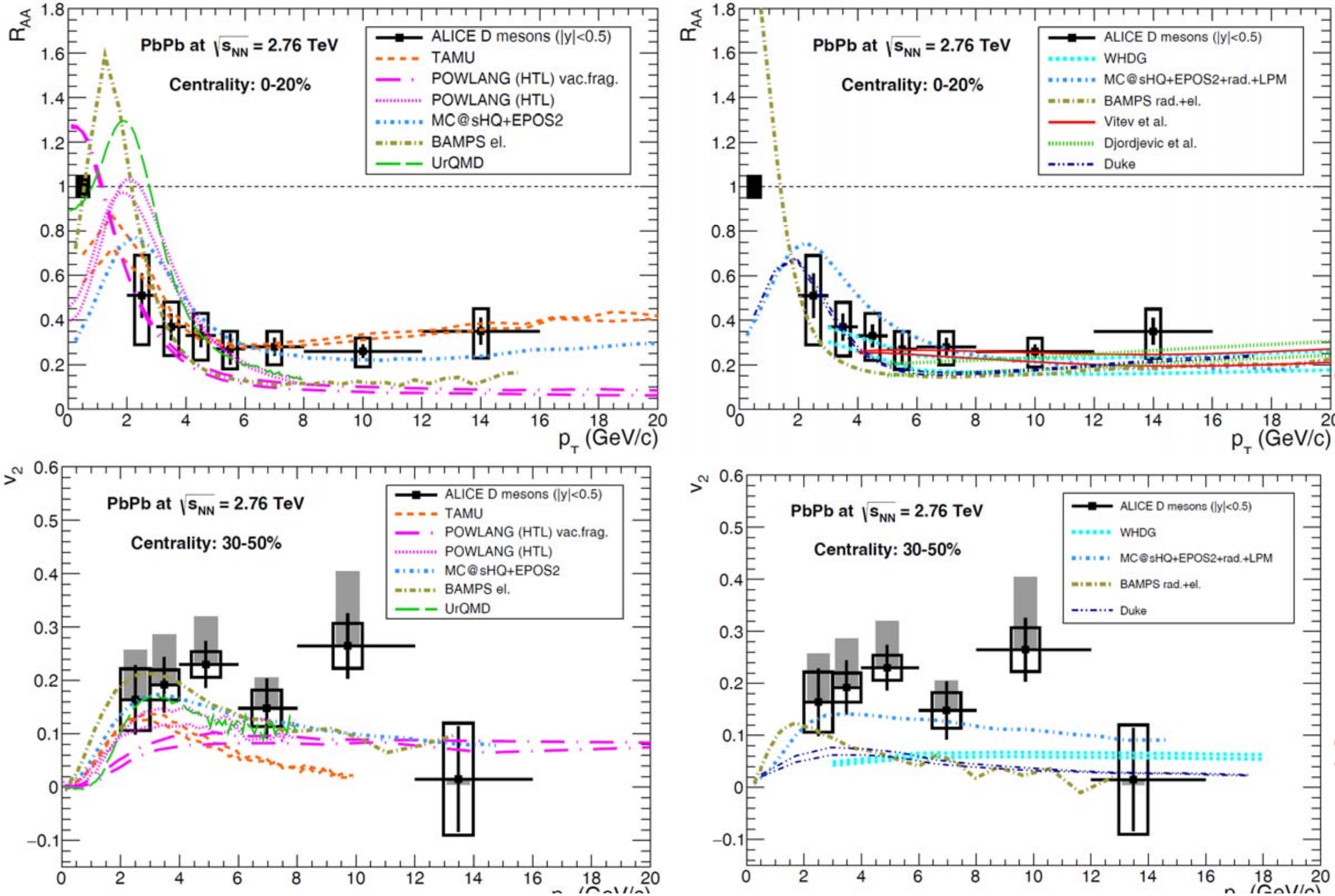
L. He et al, Physics Letters B753 (2016) 506

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 »

Models vs DATA at LHC (Sapore Gravis Report compilation)

Purely elastic scatterings

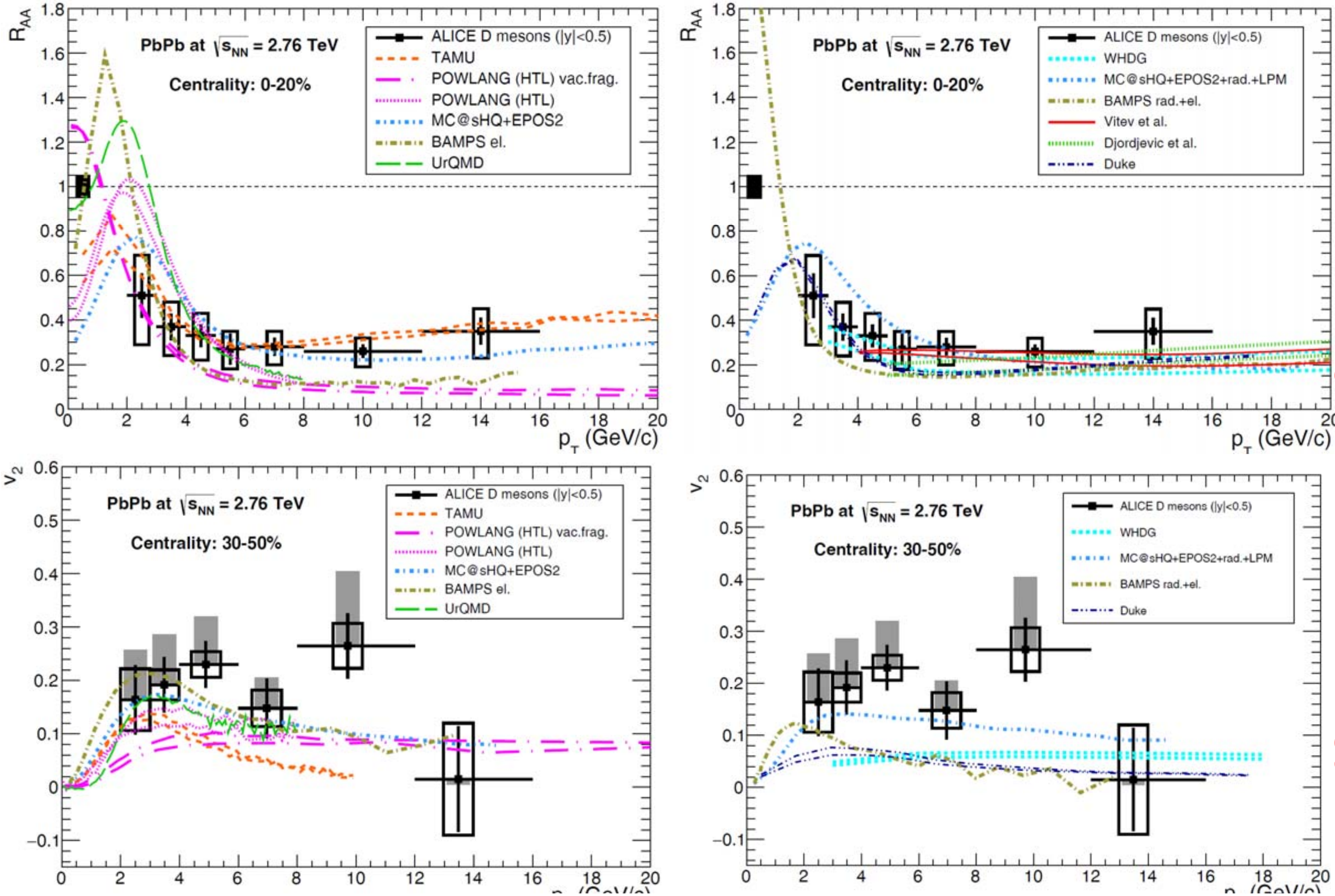


Elastic scatterings + radiative energy loss

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

Models vs DATA at LHC (Sapore Gravis Report compilation)

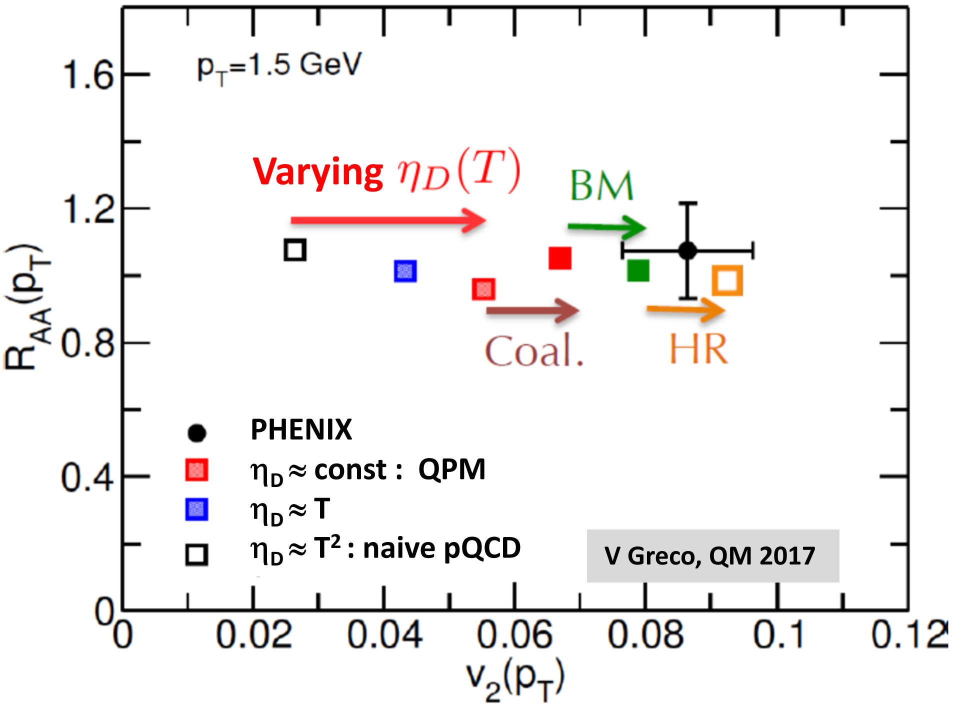
Purely elastic scatterings



Elastic scatterings + radiative energy loss

Some advocated tension between R_{AA} and v_2

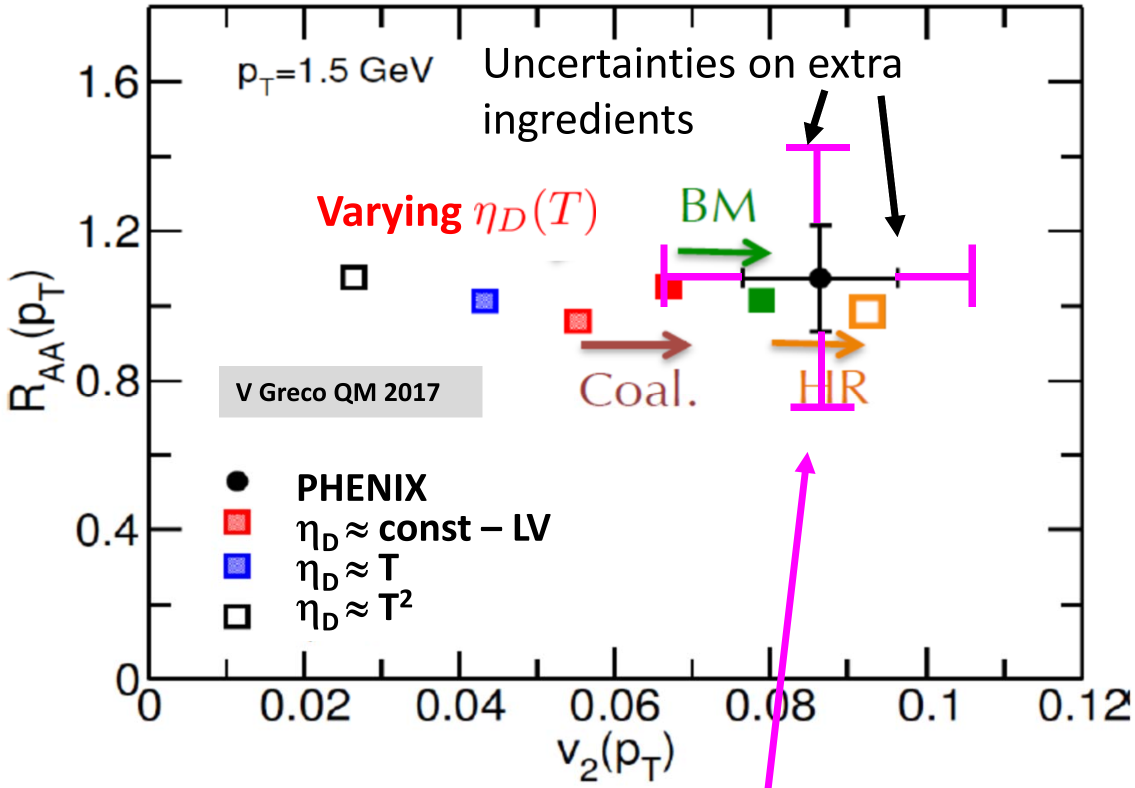
Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

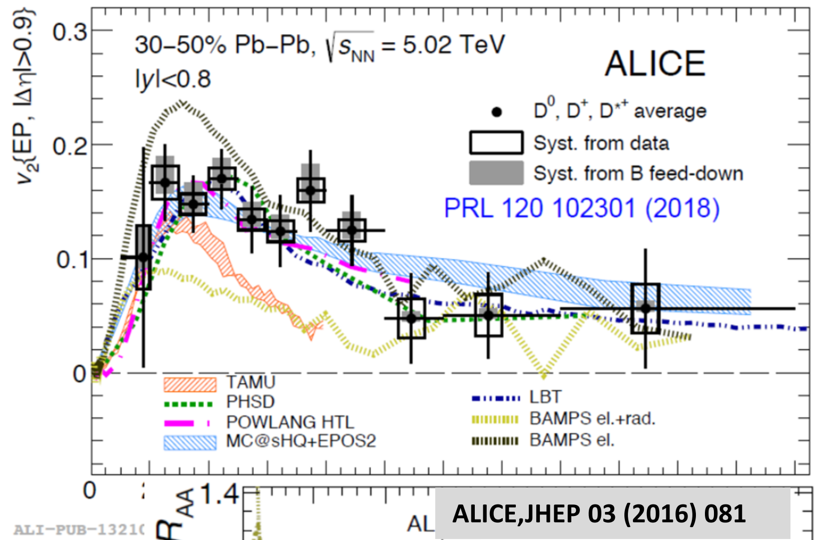


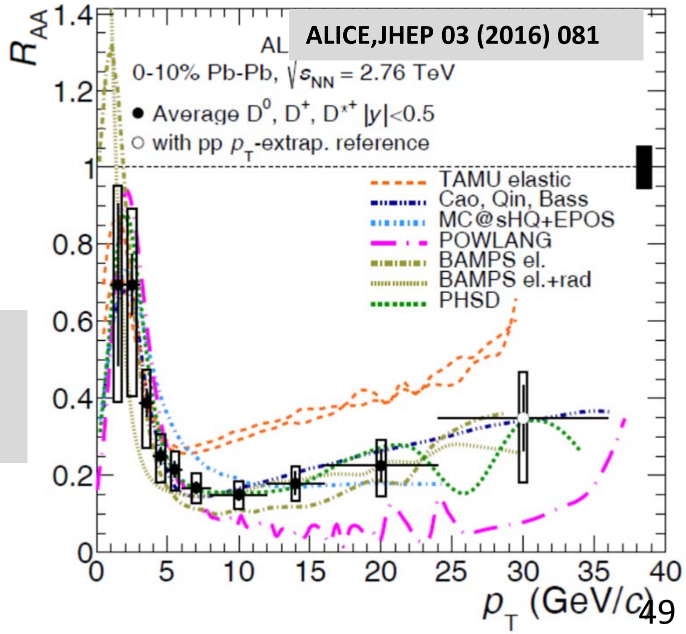
Nice guideline but need:

- 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.

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







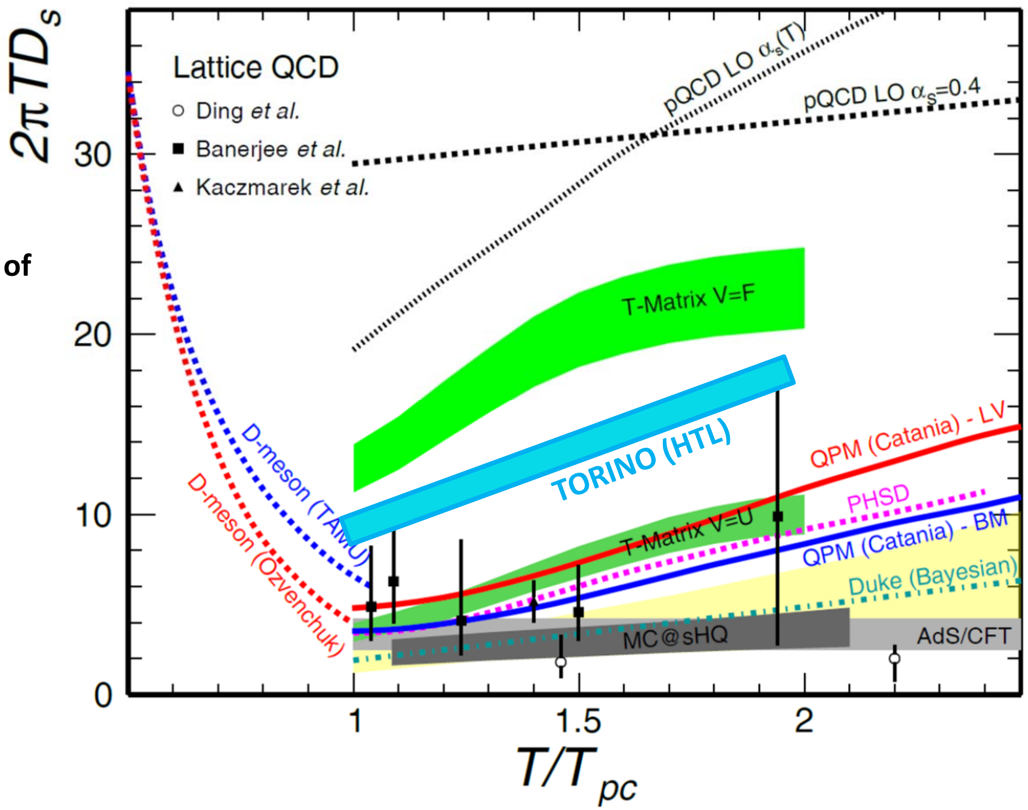
- Extra uncertainties stemming from extra ingredients, analysis in

R. Rapp et al, arXiv: 1803.03824
EMMI Task Force

- 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.

Model summary on $2\pi TD_s$ extraction

X. Dong et al. Annual Review of Nuclear and Particle Science 69:417-445 (2019)



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

$\eta_D \propto T$: pQCD (running α_s)

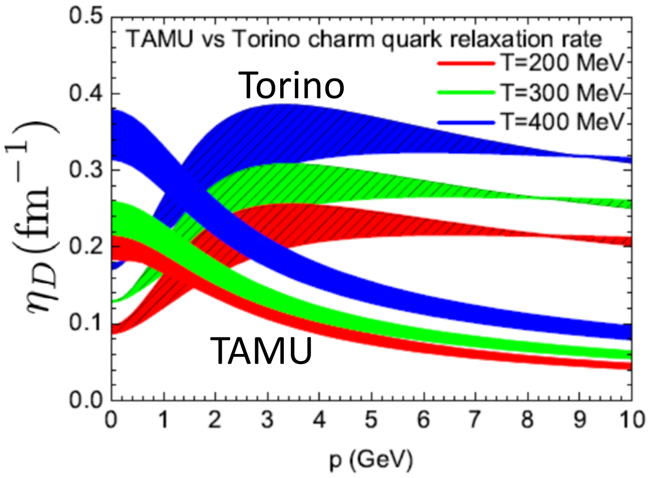
$\eta_D \propto T^0$: QPM, DQPM, U potential (TAMU)

$$(2\pi T)D_s = \frac{2\pi T^2}{E_Q \eta_D}$$

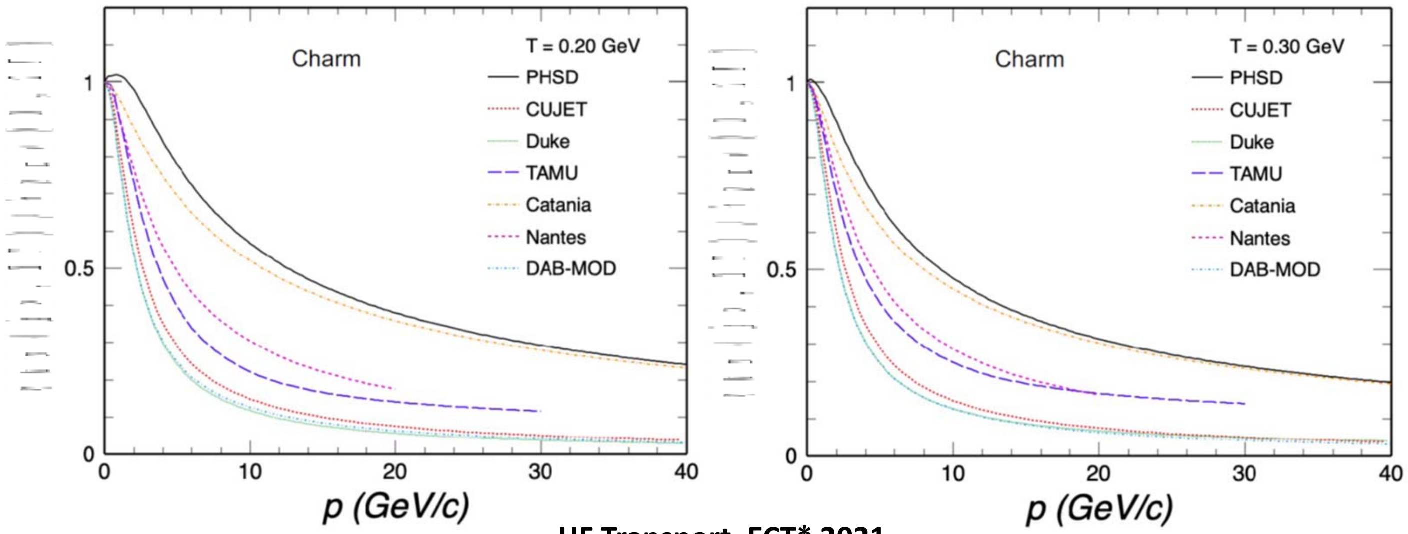
Mild linear increase of $2\pi D_s T$... ⇔ physics beyond pQCD (fixed α_s).

- Most of the values extracted from model comparison with the data are compatible with lQCD calculations !!!
- All together (lQCD, Bayesian analysis and most recent models) make a strong case for physics beyond « weak pQCD LO » around T_c » and at «low» p_T (< 2 GeV/c)
- However, the question whether one needs to include strong non-perturbative features is still debated … needs to be further addressed in the future.

Model summary on $2\pi TD_s$ extraction



Prino and Rapp, J.Phys. G43 (2016), 093002



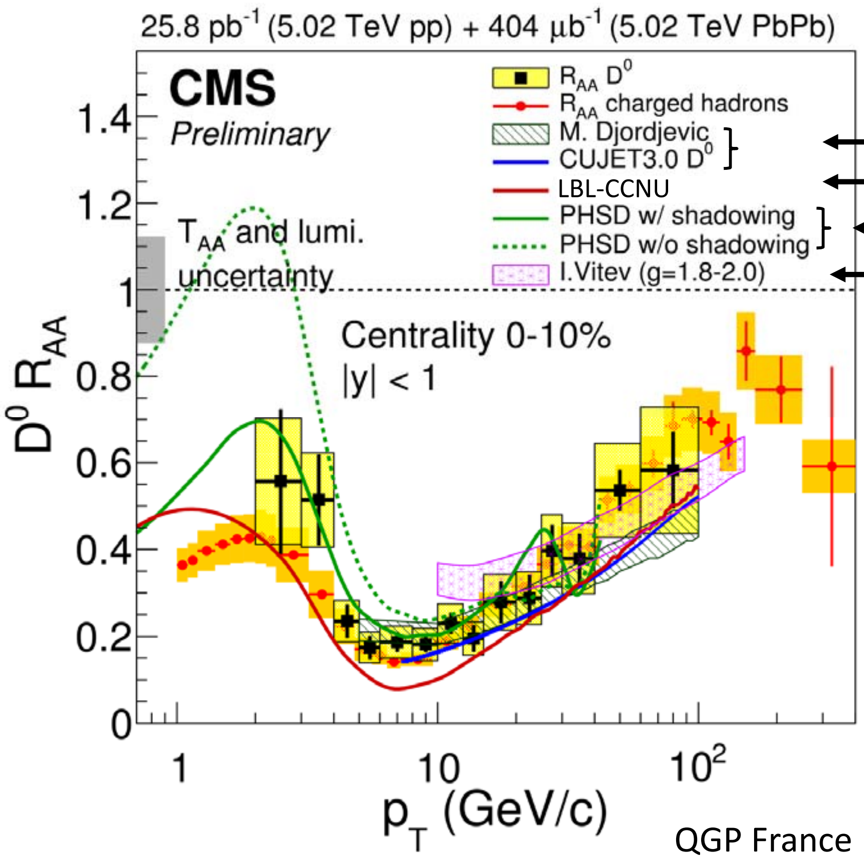
HF Transport, ECT* 2021
https://indico.ectstar.eu/event/98/contributions/1927/

Further thoughts…

- D_s (p=0) does not represent the full physics (different momentum dependences of η_D) … R_{AA} mostly sensitive to energy loss at *finite* momentum (equilibration at low p_T)
- This momentum dependence is the direct footprint of physical dof and interactions => should be better constrained in the future
- Non trivial role of « extra ingredients » (bulk, hadronisation,…)

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…



DGLV (el.+ radiative)

Higher Twist (el.+ radiative)

Pure elastic !

$SCET_G$ (Pure radiative)

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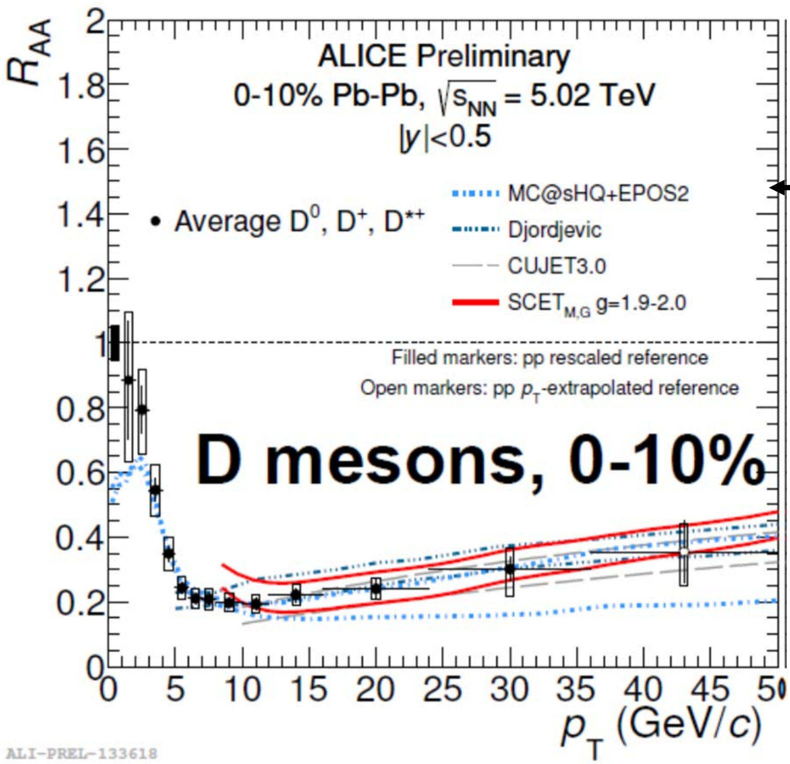


← BDMPS (« infinite » path length regime)

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.

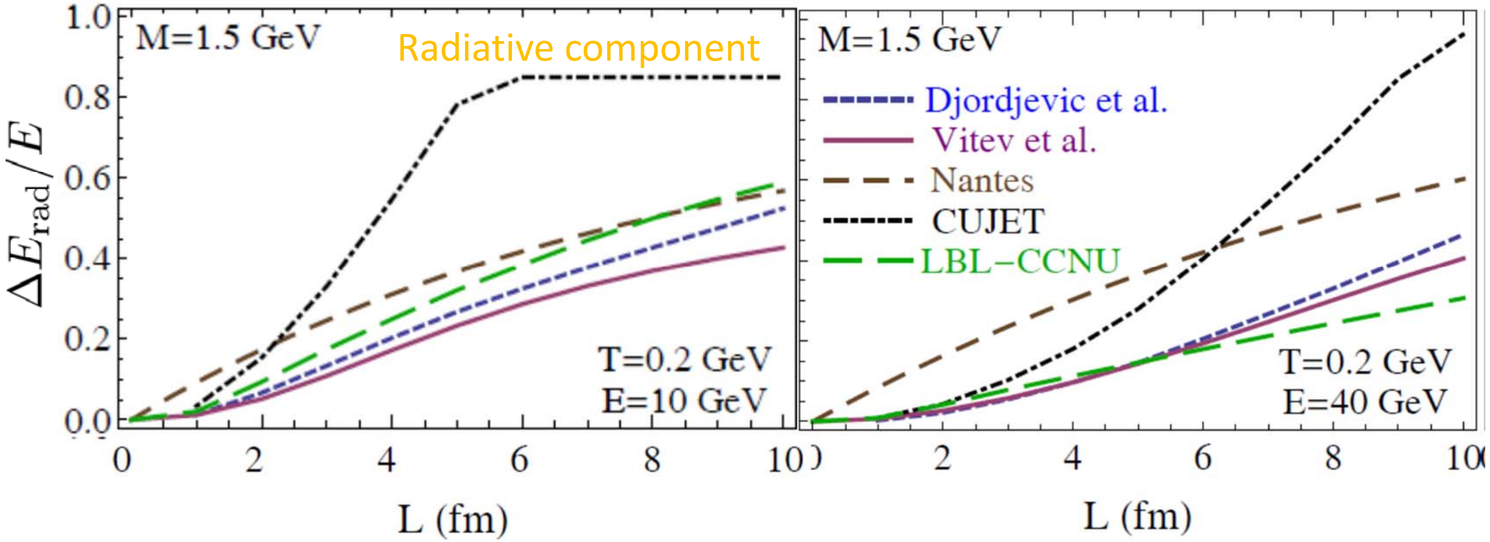
Beware : $\hat{q}$ is « just » an indirect result in some of those formalisms

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, 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

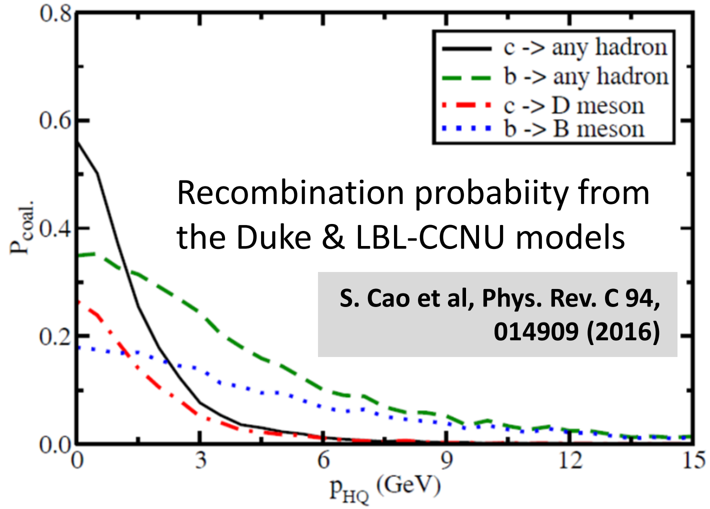
HQ - Recombination

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.



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

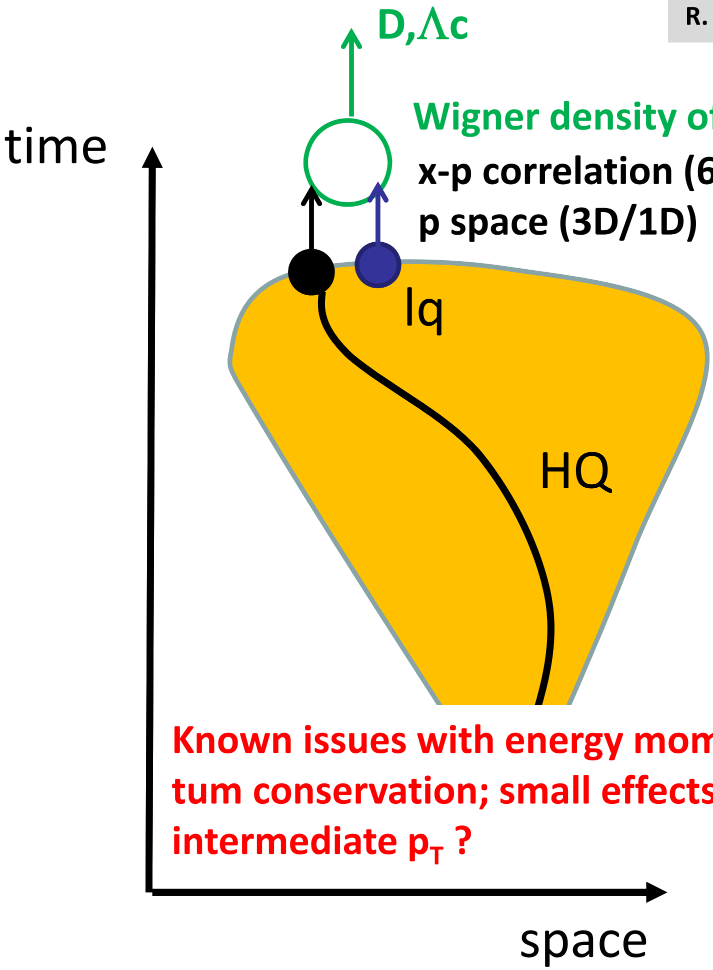
HQ - Recombination

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



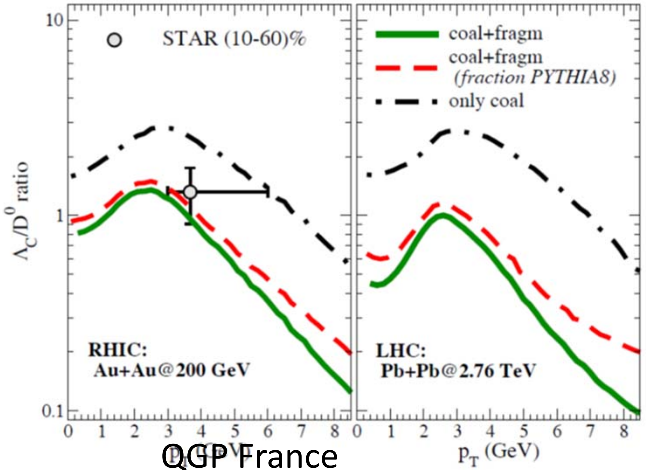
Wigner density of hadronic states

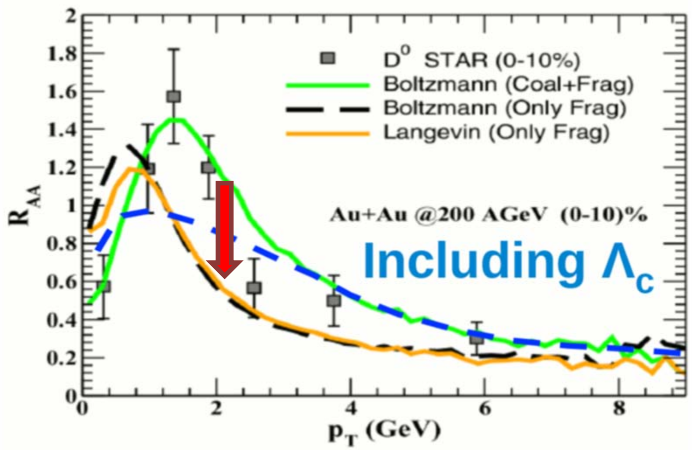
x-p correlation (6D) or « just » in p space (3D/1D)

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

Latest Catania's coalesence model:

- Full 6D coalescence
- New normalization to impose P_{coal} -> 1 for p_T->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.



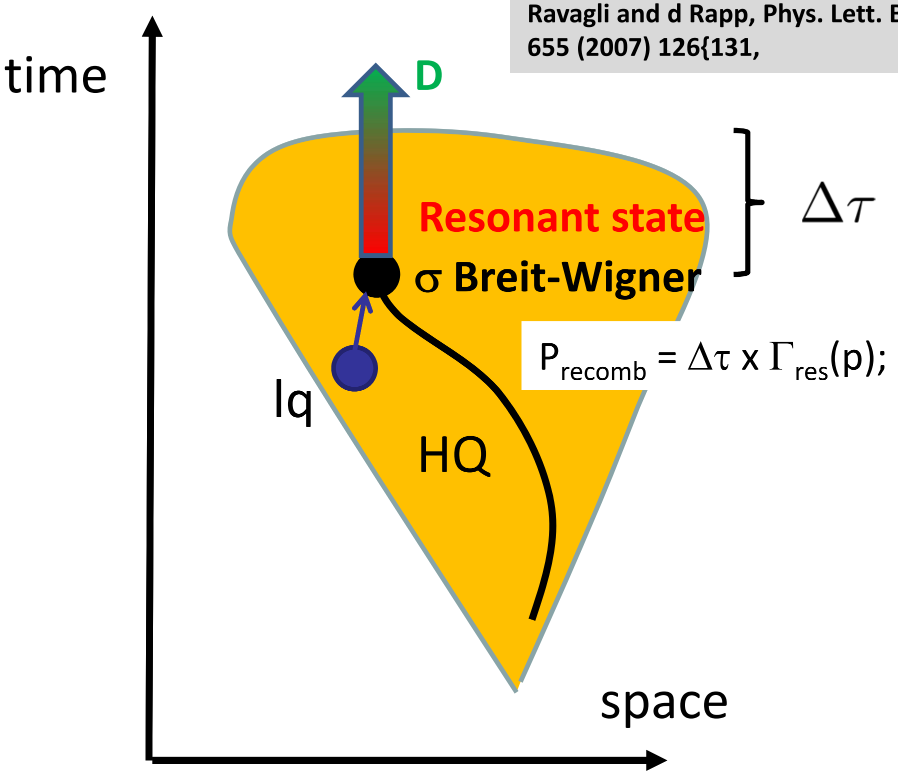


HQ - Recombination

<u>Resonance Recombination Model:</u>

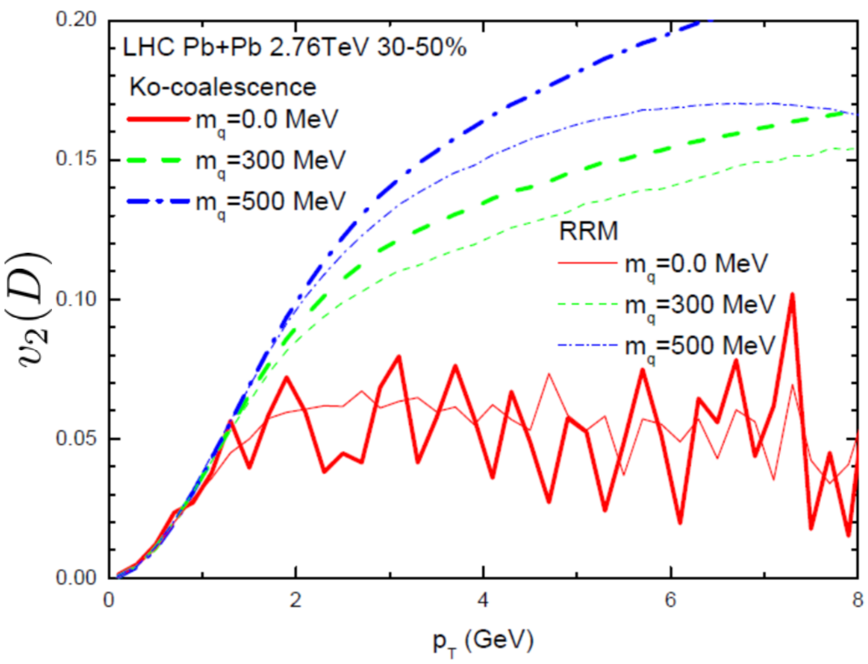
$$\left(\frac{\partial}{\partial t}+\vec{v}\cdot\vec{\nabla}\right)F_M(t,\vec{x},\vec{p})=-\frac{\Gamma}{\gamma_p}F_M(t,\vec{x},\vec{p})+\beta(\vec{x},\vec{p})$$

Ravagli and d Rapp, Phys. Lett. B 655 (2007) 126{131,



- 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.

<u>In EMMI RRTF, comparison between Instant. Coal. & RRM</u>



starting from the same bulk and from the same c spectrum

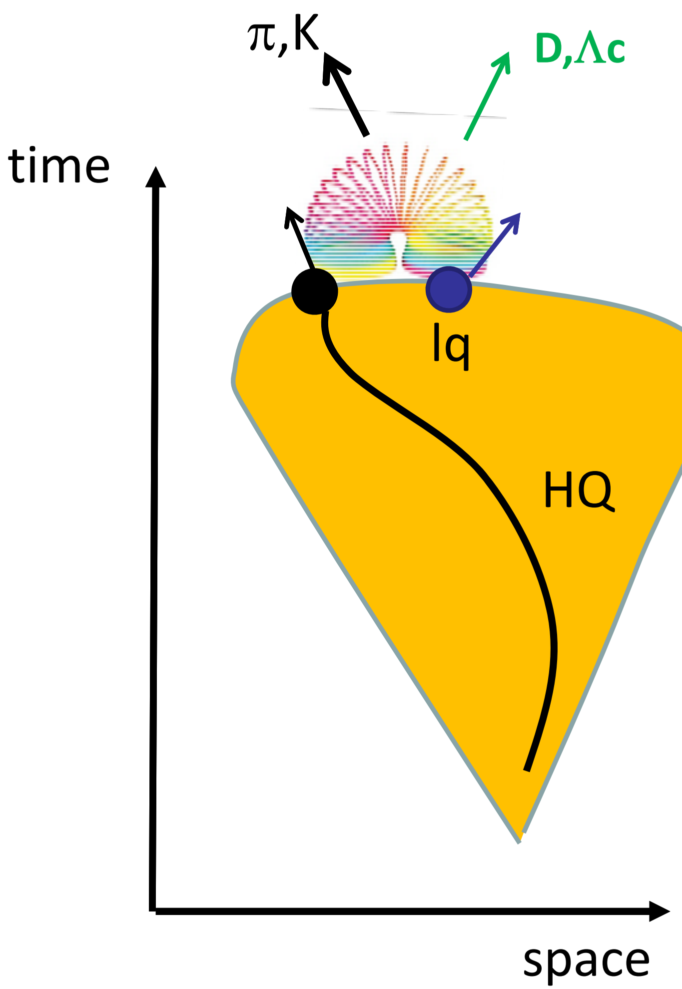
Significant differences found both for D meson p_T spectrum and v_2.

R. Rapp et al, arXiv: 1803.03824

HQ - Recombination

A Beraudo et al., Eur. Phys. J. C75 no. 3, (2015) 121

In-Medium recombination:



- 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

The LHC Era: 2010 -> Now

- Huge data from LHC constraining the models (at high pT as well as in the b sector)
- A last class of model: Quasi Particle Model
- Constrains from the fundamental theory : lQCD estimates
- The way towards more collective work in the theory community
- Alternate observables (correlations)
- HQ-jets
- HQ in small systems
- ….

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, arXiv: 1803.03824
Published in NPA (sept)

(20 monthes since first meeting)

Collective investigation : Consequences from various **Hadronization Mechanisms**

We define and display the H_{AA} quantity

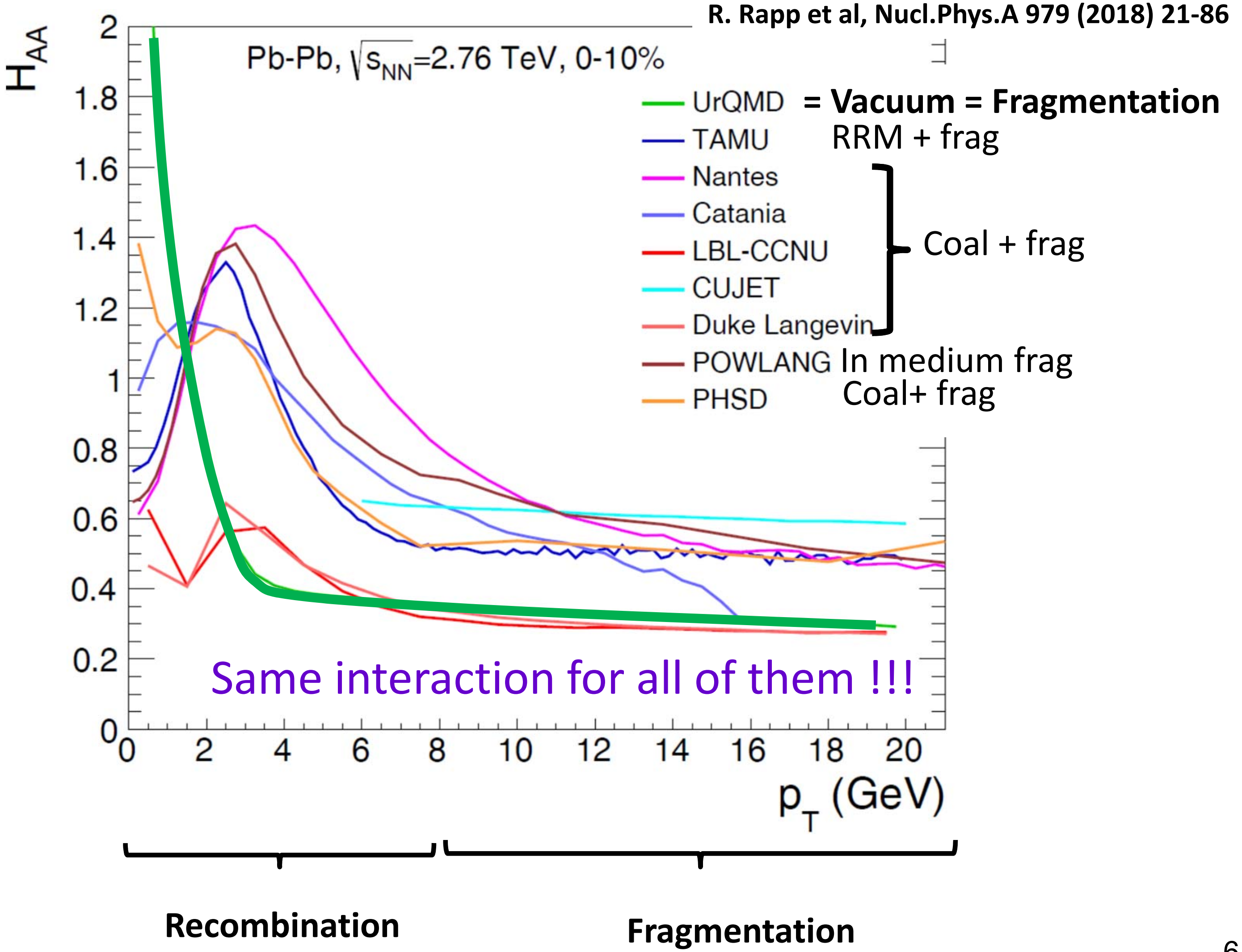
$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ \mathrm{final}}}{dp_T}}$$

…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, Nucl.Phys.A 979 (2018) 21-86



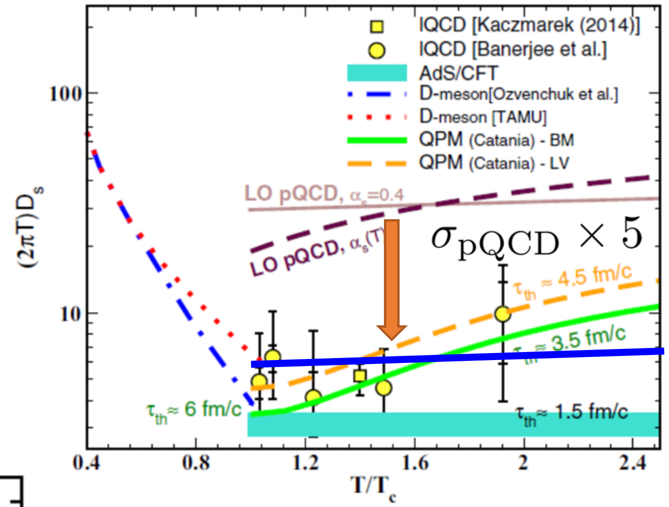
Collective investigation: Consequences from the **bulk choice** (and partly transport)

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 ?

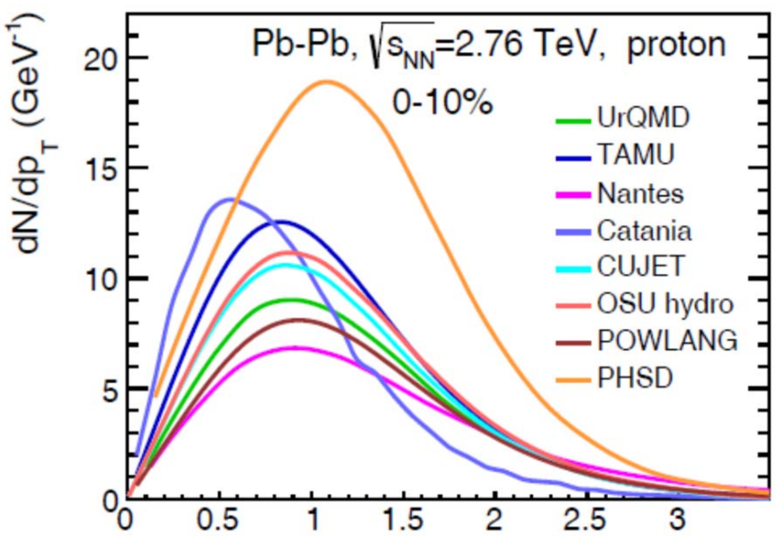
Method: adopt a common α_s=0.4-pQCD x 5 cross section for thermal light partons acting on c-quarks (or associated FP coefficients for models based on FP) in all frameworks.

One Interaction for all of them; not aimed at reproducing the data !!!

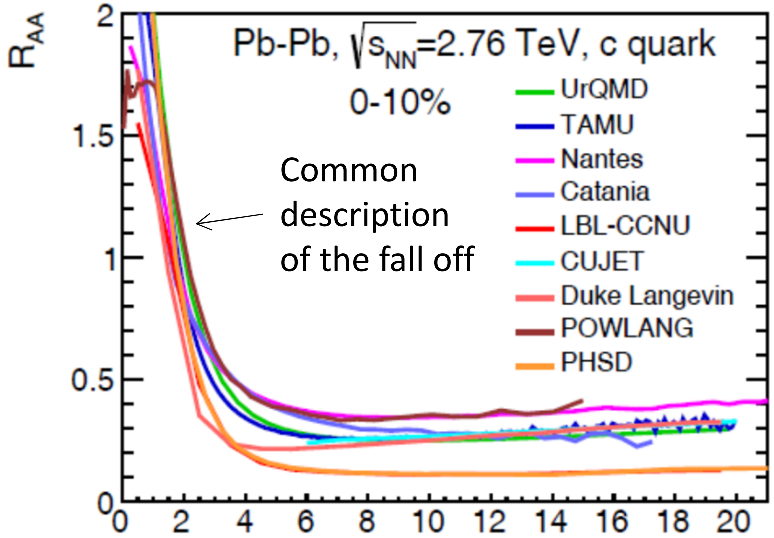
R. Rapp et al, Nucl. Phys.A 979 (2018) 21-86



Protons from the bulk **at FO**



c quarks **at FO**



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%:

$$R_{AA}(c, 10\,\mathrm{GeV}) \approx 0.4 - 0.6$$

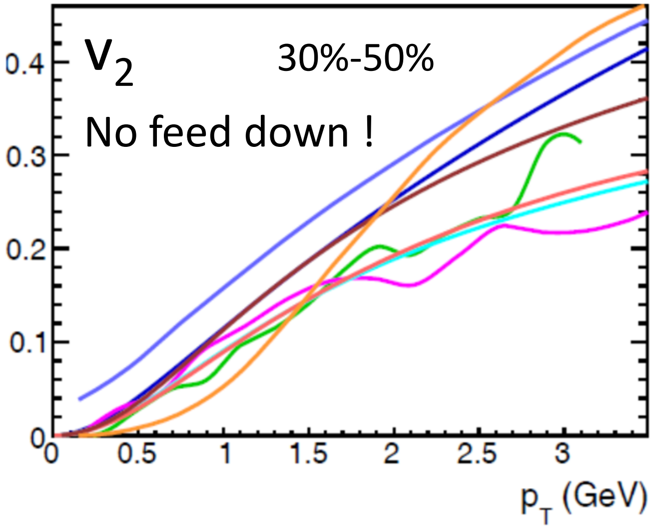
No feed down !

Some correlation between dN(p) and R_{AA}(c) but not systematic

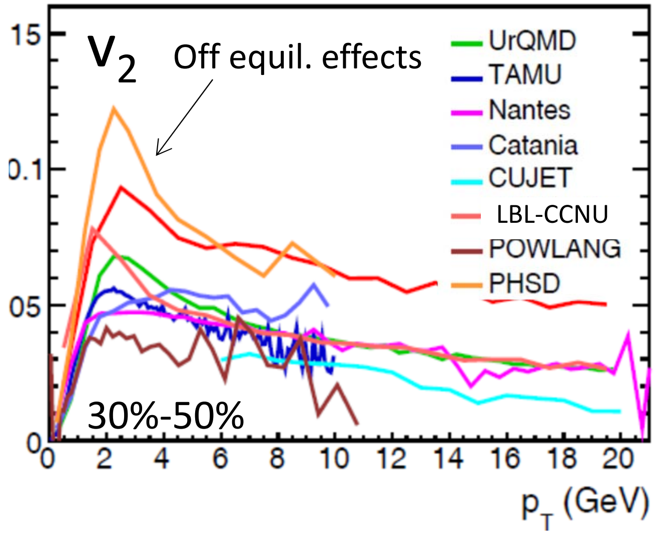
Collective investigation : Consequences from the **bulk choice**

R. Rapp et al, Nucl.Phys.A 979 (2018) 21-86

Protons from the bulk at FO



c quarks at FO

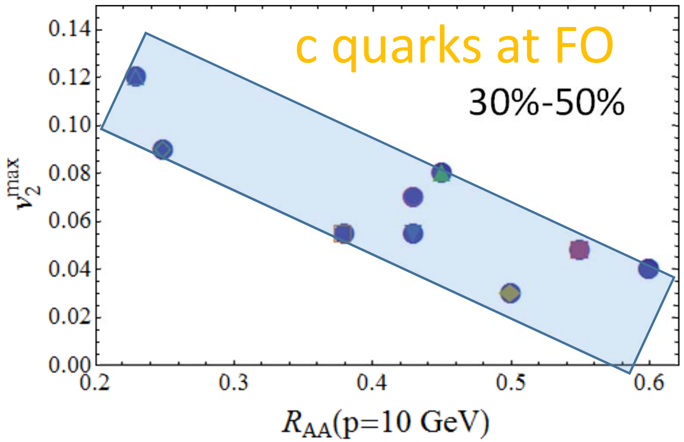


N.B.: LBL-CCNU could not implement scattering on thermal- massive partons

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



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.**

Collective investigation : Study in a QGP brick

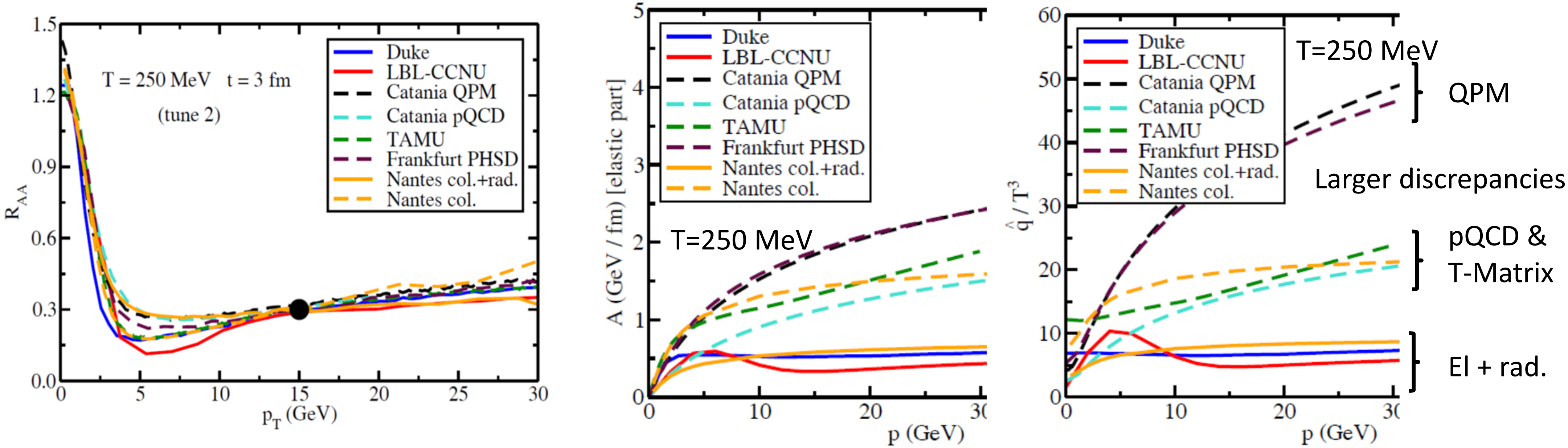
S. Cao et al,
Phys.Rev.C 99 (2019) 5, 054907

The goal was 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

The LHC Era: 2010 -> Now

- Huge data from LHC constraining the models (at high pT as well as in the b sector)
- A last class of model: Quasi Particle Model
- Constrains from the fundamental theory : lQCD estimates
- The way towards more collective work in the theory community
- Alternate observables (correlations,…)
- HQ-jets
- HQ in small systems
- ….

(HQ-jets, HQ in small systems:) No time to cover.

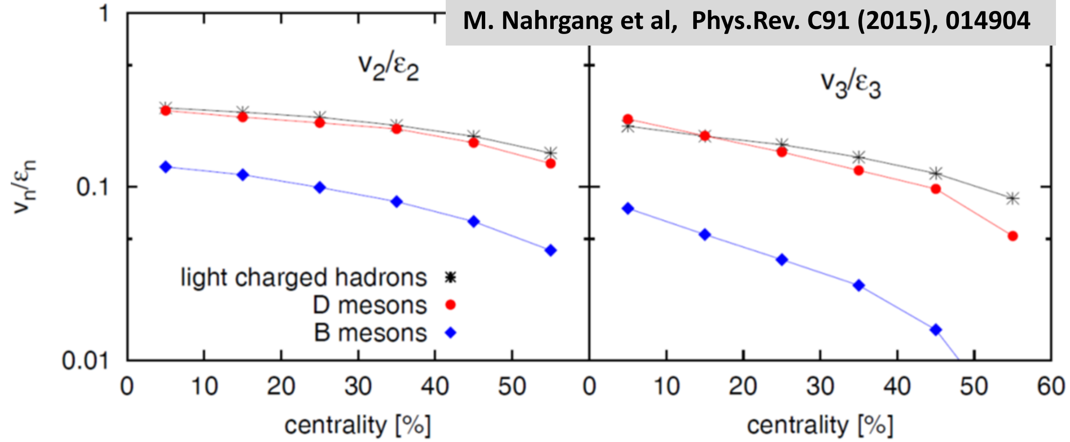
More on v_2 and higher flow harmonics

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

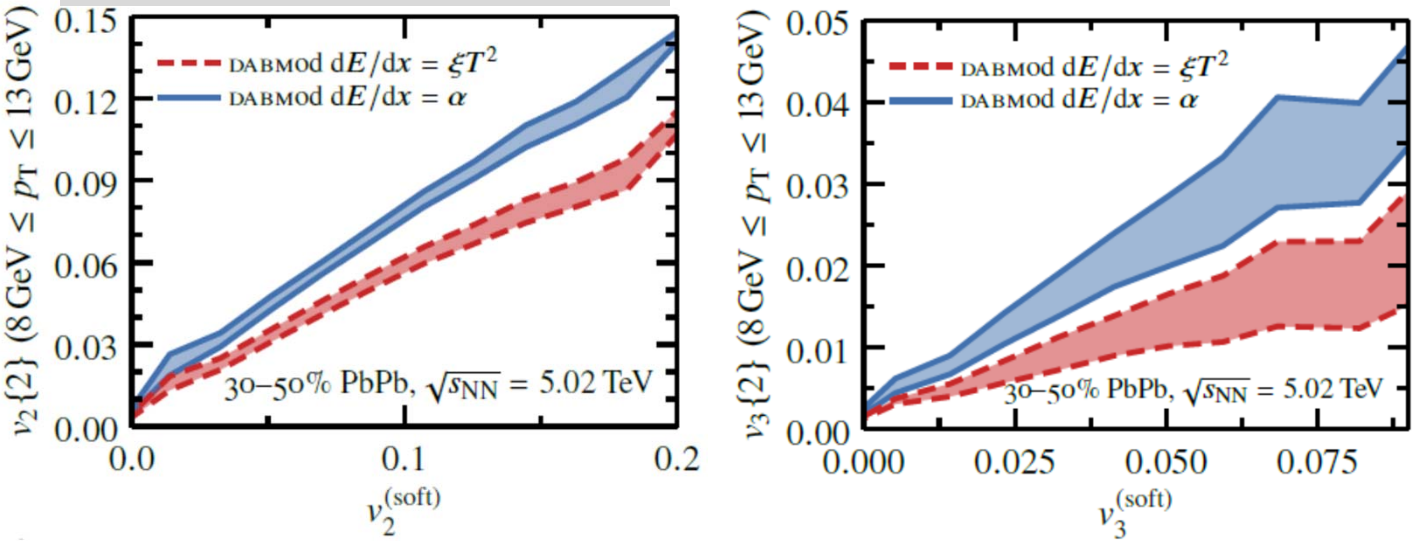
- departing from the nearly equilibrated regime
- exploring the consequences of inertia due to large m_Q
- Our observation: **reduction of v_n/ε_n for a) larger n, b) larger mass and c) larger centrality…**

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

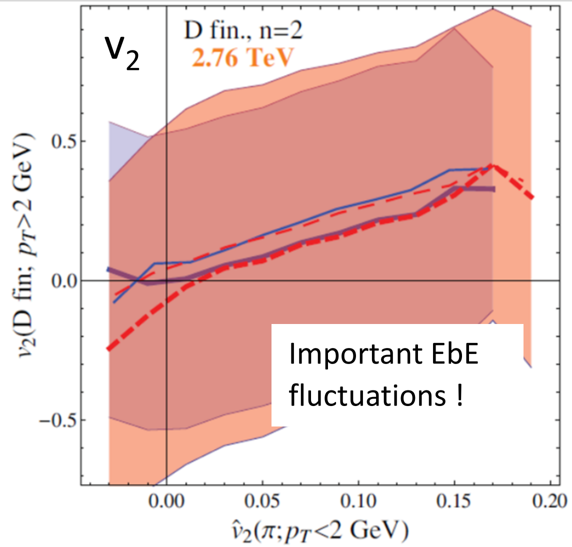
M. Nahrgang et al, Phys.Rev. C91 (2015), 014904



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



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



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

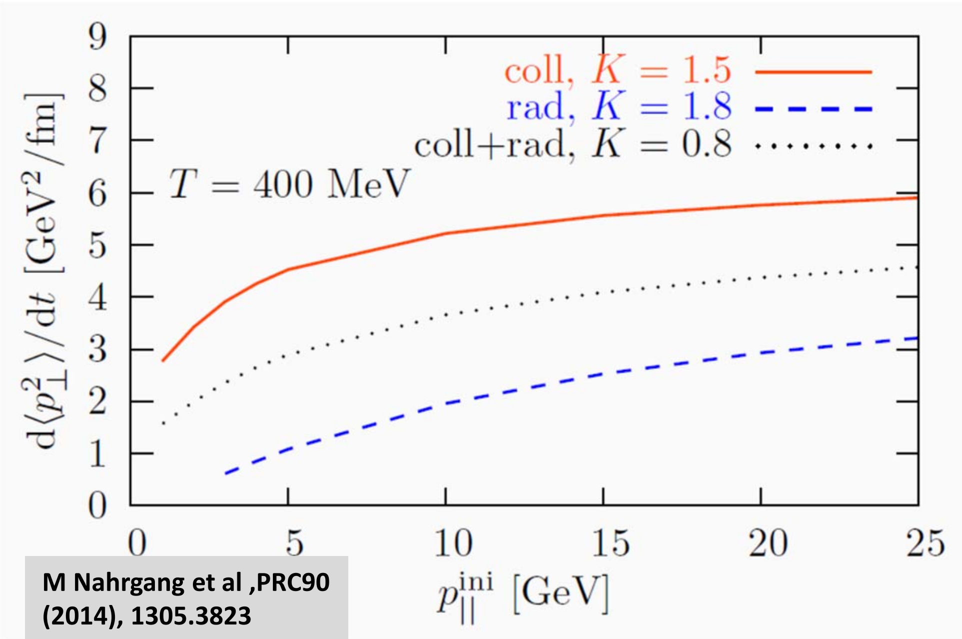
Alternate observables

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

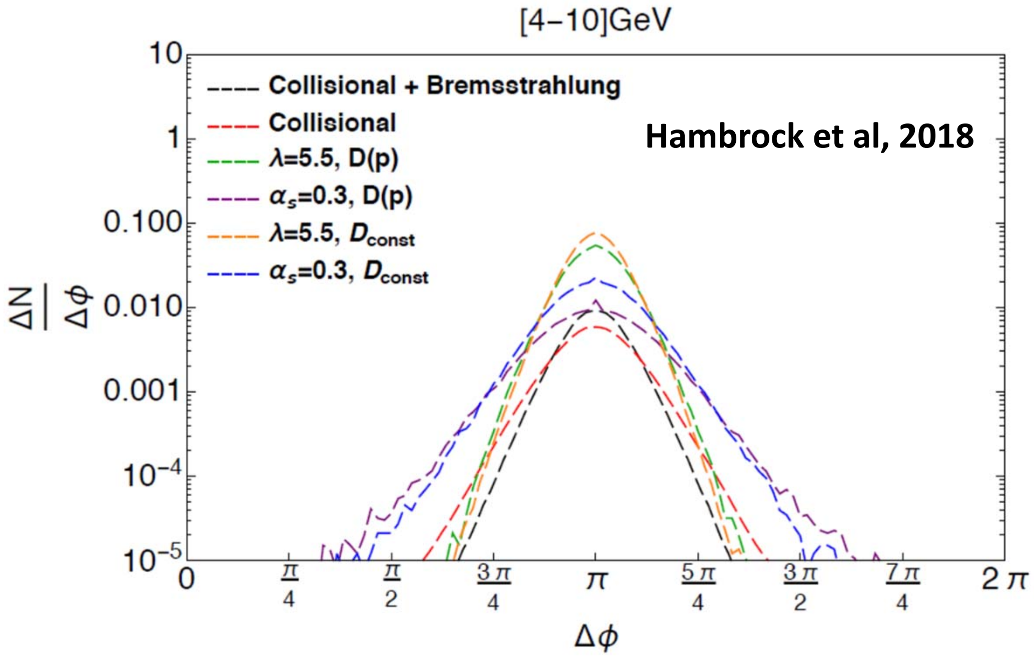
One should exploit both

- Analysis of the path length dependence
- The larger "collinearity" found in radiative collisions, which could be seen in azimuthal correlations…

Much sensitive to $\hat{q}$



M Nahrgang et al ,PRC90 (2014), 1305.3823



… But not "short term" !!! WE NEED VERY GOOD MEASUREMENTS ON THIS

New Observables are coming

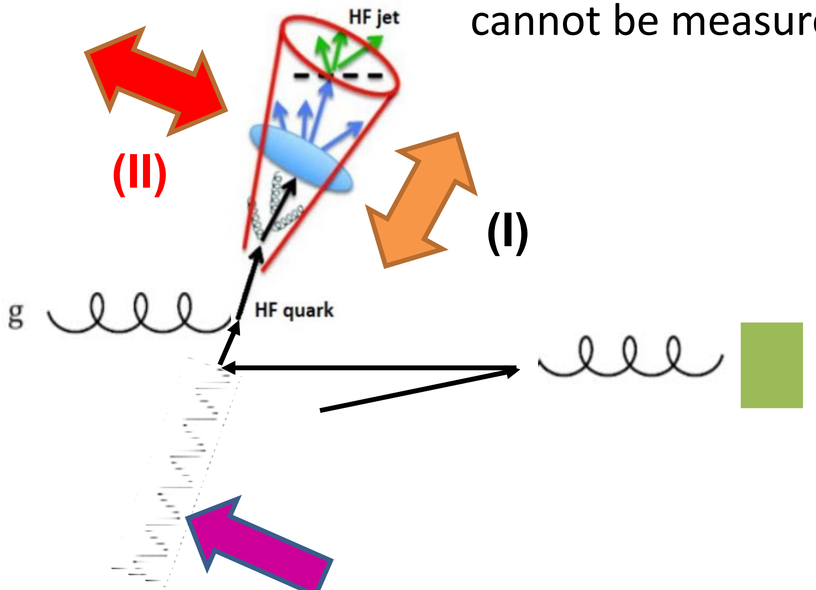
Short term, mid-term, long term,…

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 substructure, nature of the interaction	Might be sensitive to various HF creation in pp, to be calibrated
Heavy - photon	Longitudinal fluctuations coefficients	Need very good baseline in pp
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 ?

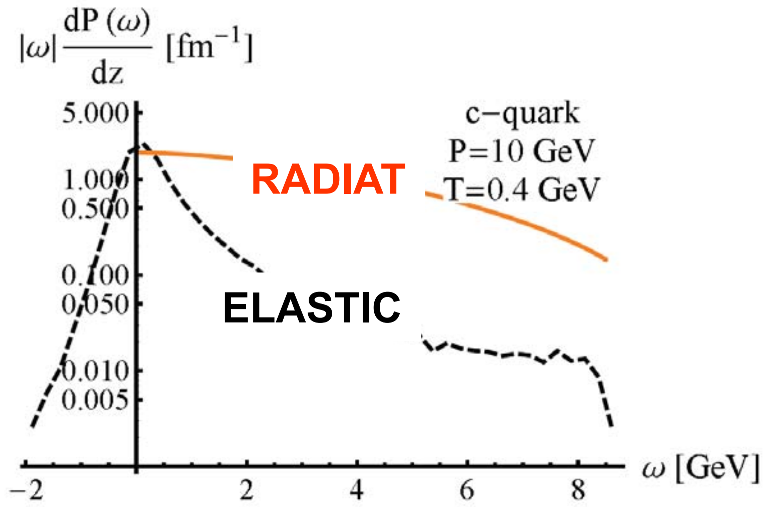
γ - b/c jet: Best HF Correlation ever ?

- 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



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



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 ?)

Recent progresses and future directions

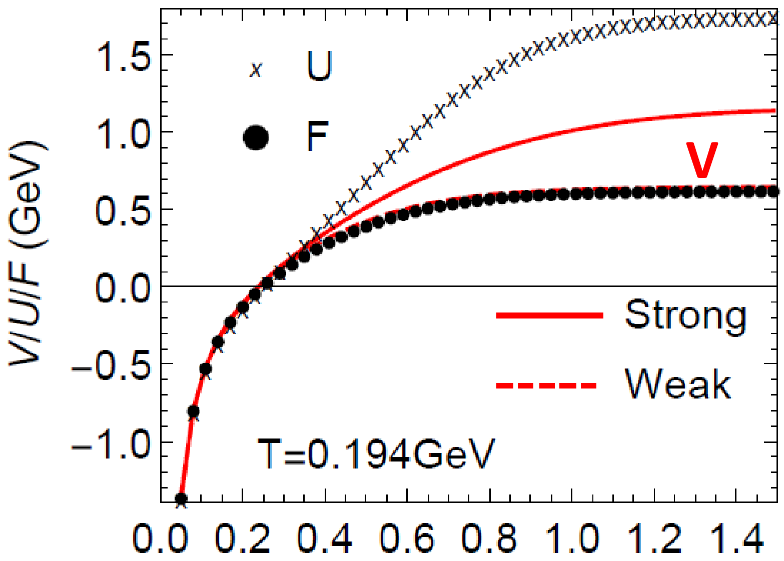
(Selected) Recent trends :

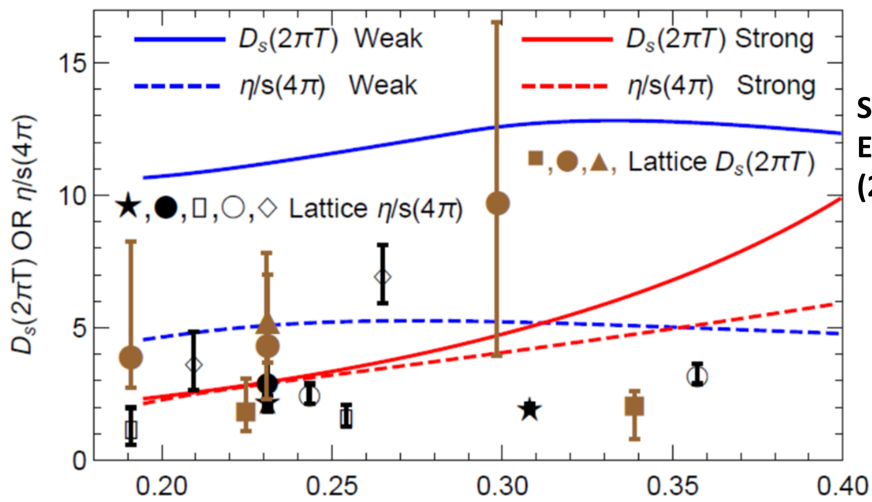
- Generalization of the treatment of (thermal) QGP constituents in the calculation of the transport coefficient :
  - Thermal mass (calibrated on the EOS): **QLBT: https://indico.cern.ch/event/792436/contributions/3548981/, MC@HQ: Nahrgang et al Phys.Rev.C 93 (2016) 4, 044909**
  - Off shell effects (re)considered by the use of spectral function more faithfull to the quantum treatment): **TAMU: Shuai Y.F. Liu et al, Phys. Rev. C 99, 055201 (2019), CATANIA: ML Sambataro et al. Eur. Phys. J. C 80 (2020) 1140**
- Inclusion of radiative energy loss: **TAMU: Shuai Y.F. Liu & R. Rapp JHEP 08 (2020) 168**
- Effect of initial stages on HF evolution (glasma, B field, vorticity): **S. Chatterjee and P. Bozek. PRL120(2018)192301; Y. Sun et al. PLB768(2017) 260-264. PLB 816 (2021) 136271; S. Chen et al Phys.Rev.C 103 (2021) 3; L031902, M. Kurian et al., PRD 101,094024 (2020)**
- …

See as well recent plenary talk of Min He at « Strangeness in Quark Matter » or « Heavy-Flavor Transport in QCD Matter » at ECT* (https://indico.ectstar.eu/event/98/overview)

Recent progresses and future directions

- **Deeper rooting with theory** : TAMU strategy: **S. Y.F. Liu and R. Rapp, PRC97 (2018) 034918**
  - o Hamiltonian formulation of a non relativistic effective theory based on a 2-body potential
  - o Included in the Luttinger-Ward-Baym formalism -> description of the **equation of state** (EoS)
  - o EOS is not enough => evaluation of the **free energy** (./. introduction of Q-Qbar pair) + **quarkonium correlators** ...
  - o Allows to self-consistently derive 2 optimal solutions for the potential by calibration on the equivalent lQCD quantities (one « weak » close to the free energy and one « strong » with remnants of the long range forces… non spectral light quarks and spectral densities





S. Y.F. Liu and R. Rapp Eur. Phys. J. A 56, 44 (2020)

Further comparison with diffusion coefficient favors the « strong » potential

Recent progresses and future directions

Future directions :

Internal « theory » improvement (can discard some models)

- TAMU approach in making the contact with QCD thanks to lQCD calculation and solving of many body theory is a strong incentive for other models to perform an equivalent rooting.
- Calibration on the EOS is a good starting point but other quantities more directly connected to HQ physics should be considered as well (correlators, imaginary potential,…)
- Models based on one (effective) gluon exchange should consider ladder ressummation
- Efforts should be maintained from lQCD community to evaluate quantities as close possible to the Fokker-Planck coefficients at finite momentum (easier contact with phenomenology)
- Need for a better connection between hadronisation of heavy quark at the end of the QGP phase, dynamical models, modern understanding of confinement.

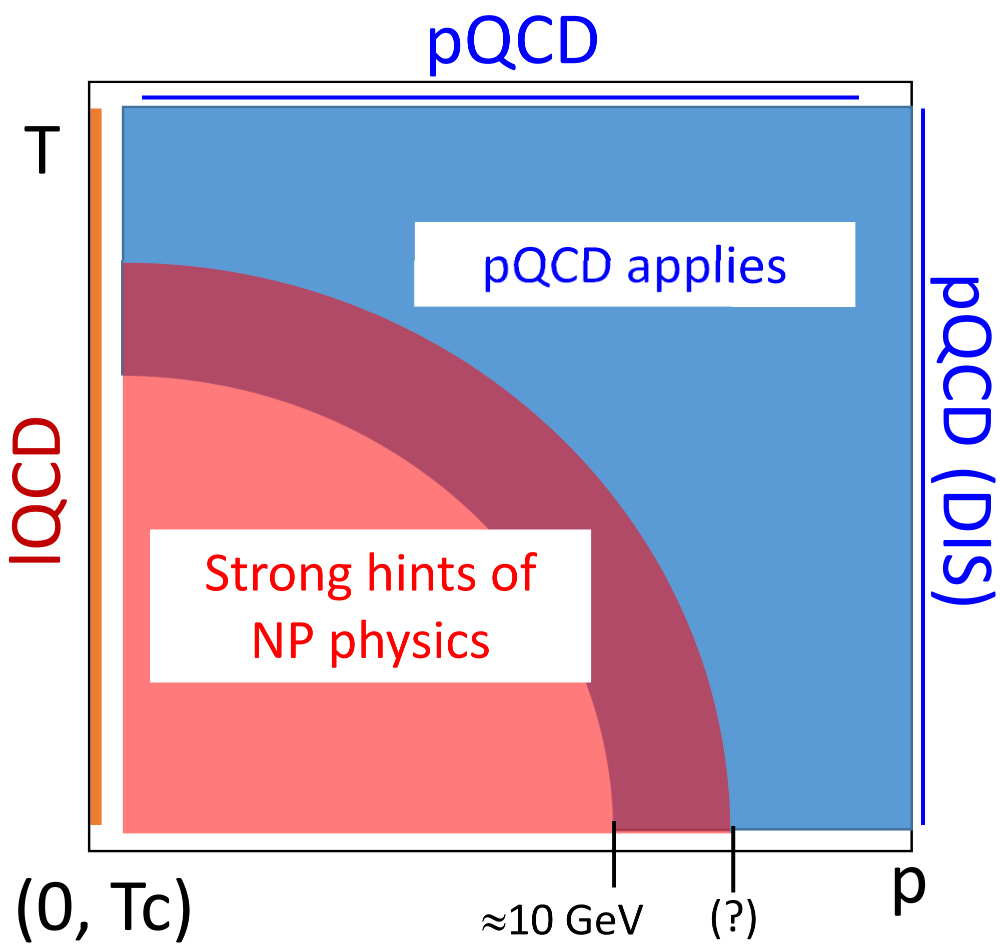
… Hand in hand with experiment

- Need for a systematic reduction of the systematic « errors » affecting the predictions => link with precision data
- new observables (correlations)

Reliable application of the methods to small systems (QGP + CGC initial condition for HQ)

Until then ...

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 (see next slide).