Some open heavy flavor history

Soft gluon emission in hard process

$$\frac{d\theta}{\theta} \rightarrow \frac{d\theta}{\theta} \times \frac{1}{\left(1+\left(\frac{M}{E\,\theta}\right)^2\right)^2}$$

gluon radiation from *massive* parton (initial Bremsstrahlung)

Suppression factor DC(θ)

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

Suppression factor DC(ω)

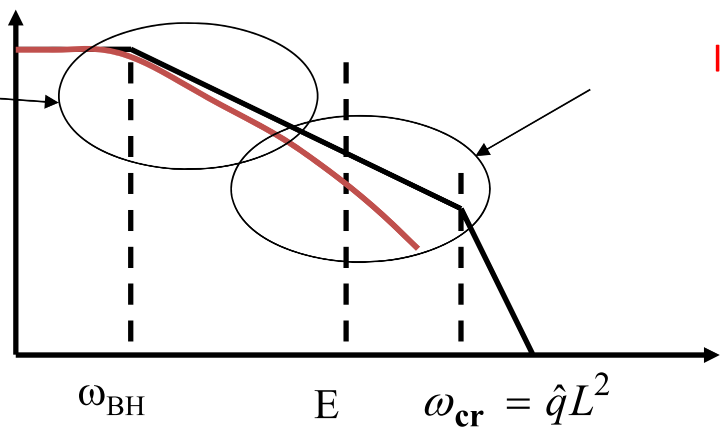
$$DC(\omega) = \frac{1}{\left(1+\left(\frac{\omega}{\omega_{DC}}\right)^{3/2}\right)^2}$$

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

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

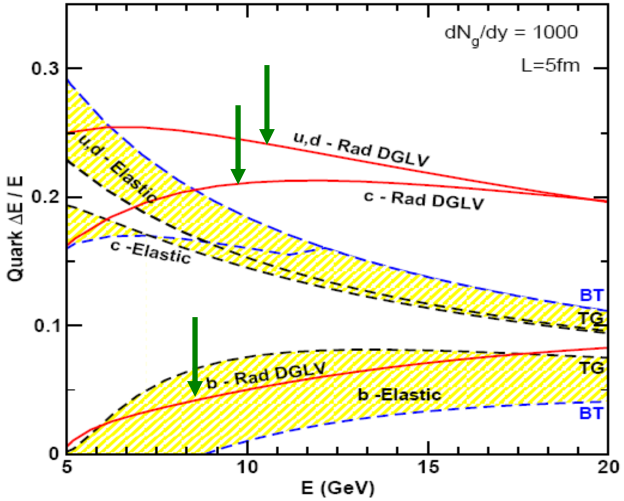
Moderate for quenching

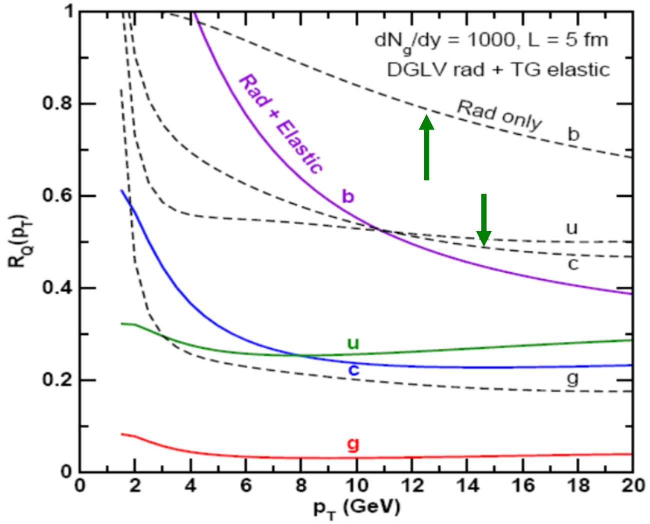
Important for ΔE



Some open heavy flavor history

WHDG 07

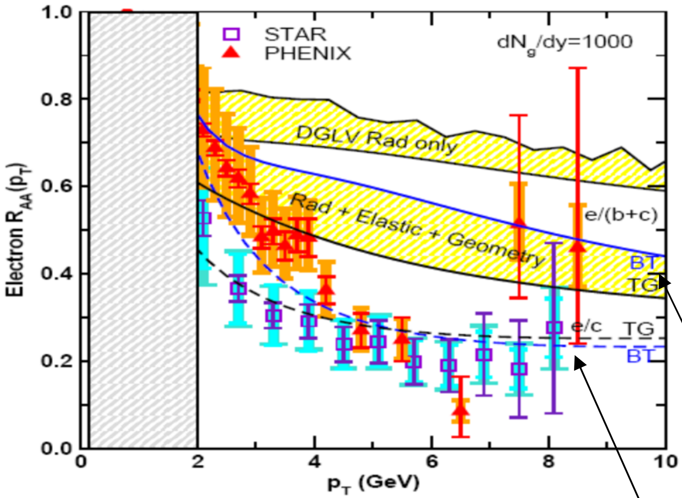


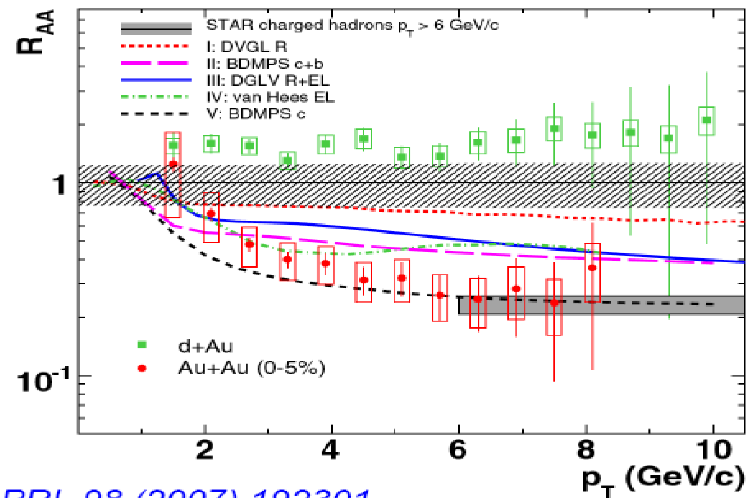


Mass hierarchy in radiative energy loss

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

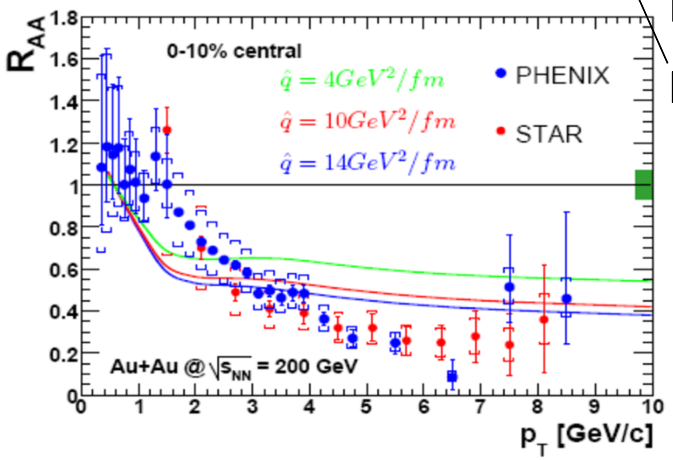
… more Eloss than expected from pQCD, even adding elastic part (often neglected up to then)



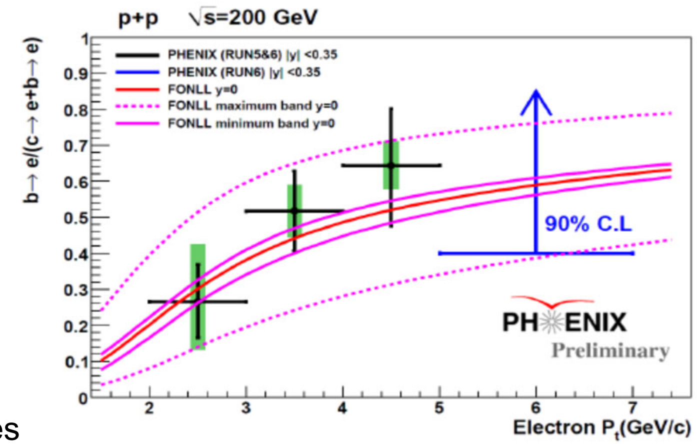


PRL 98 (2007) 192301

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

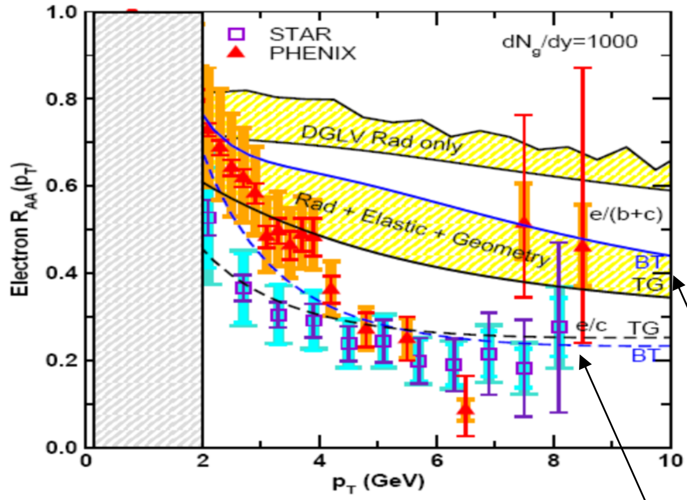


b quark is the puzzle and is definitively there:



Meanwhile: dN/dy(y≈0) scales like N_{bin}

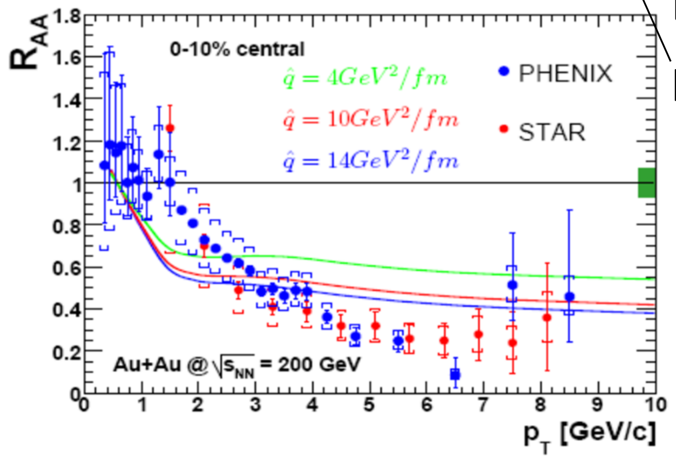
... more Eloss than expected from pQCD, even adding elastic part (often neglected up to then)

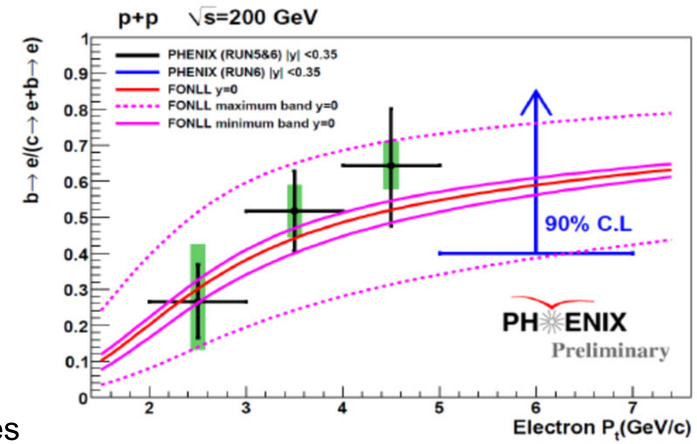


In the meanwhile, several improvements in the theoretical framework => the DGLV approach based on pQCD can reproduce the "high pT" data (see recent works by M. Djordjevic and collaborators)

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

b quark is the puzzle and is definitively there:



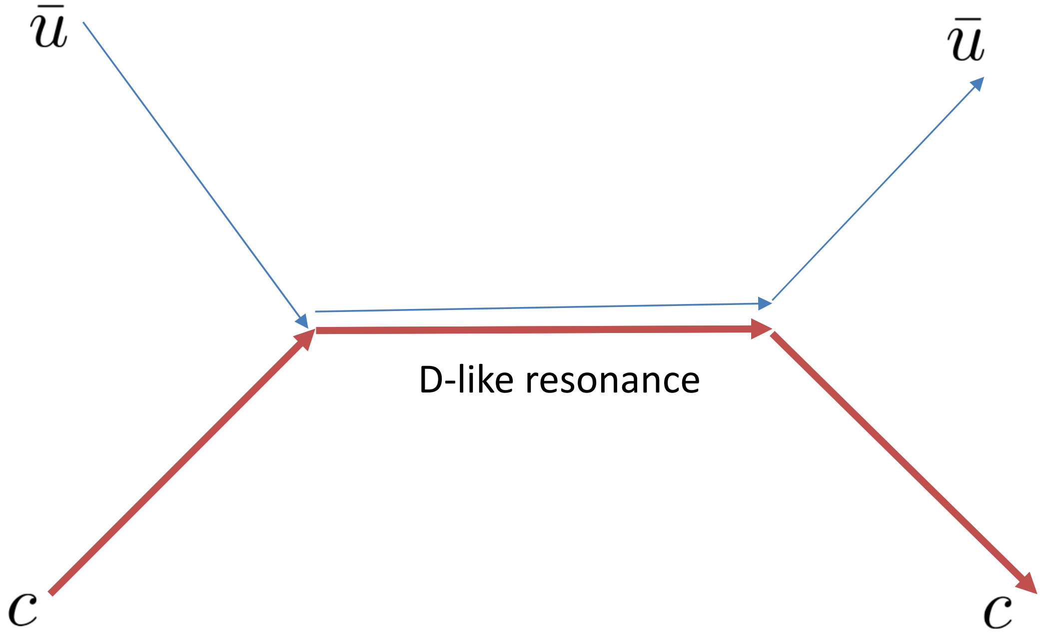


Meanwhile: dN/dy(y≈0) scales like N_{bin}

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

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



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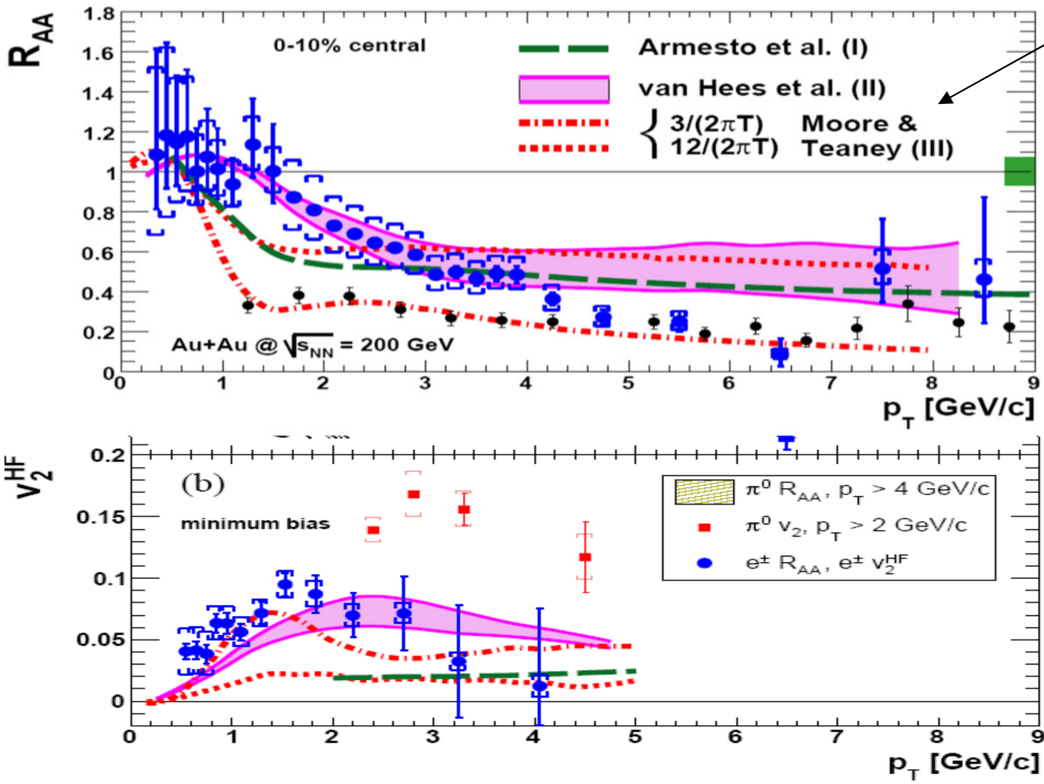
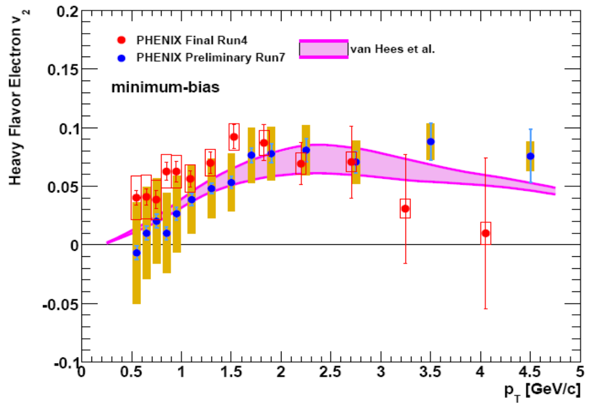


D: spatial diffus coeff ($fm^2/fm/c$)

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

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

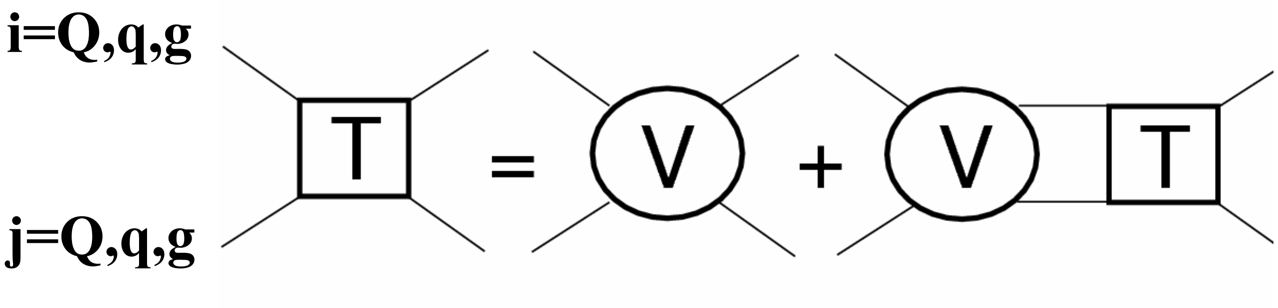
Charm flows !!!



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

Potential models (TAMU)

- Scattering equation

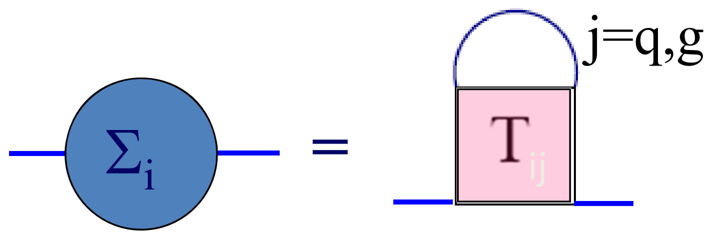


- Ressummation

•Approximation : $q \sim T \ll m_Q \Rightarrow q_{(4)}^2 = q_0^2 - \mathbf{q}^2 \approx -\mathbf{q}^2$

$\Rightarrow$ **3D** reduction of Bethe-Salpeter equation

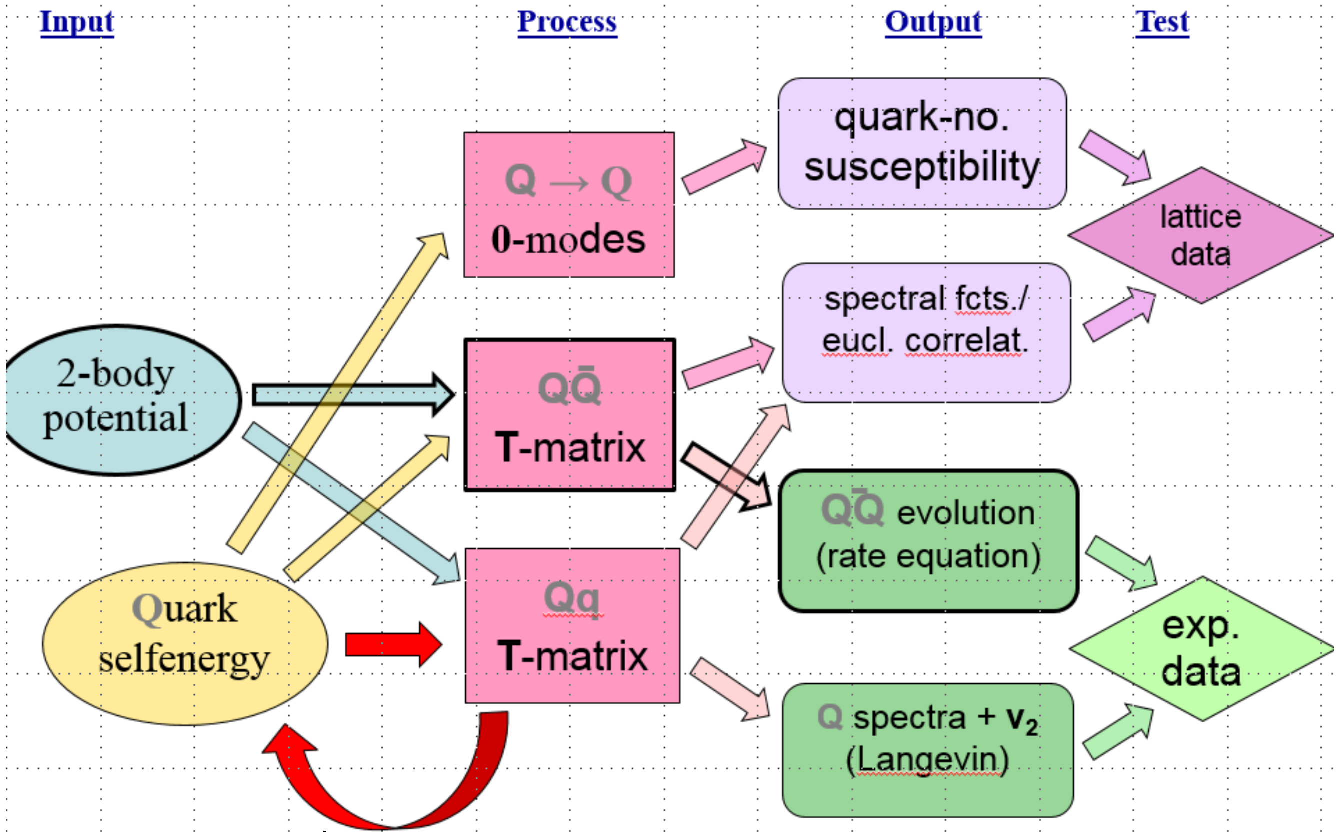
•Parton **self-energies** → **self-consistency**:



- Also di-quarks near Tc (found in lQCD ?)

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



HQ lectures

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)

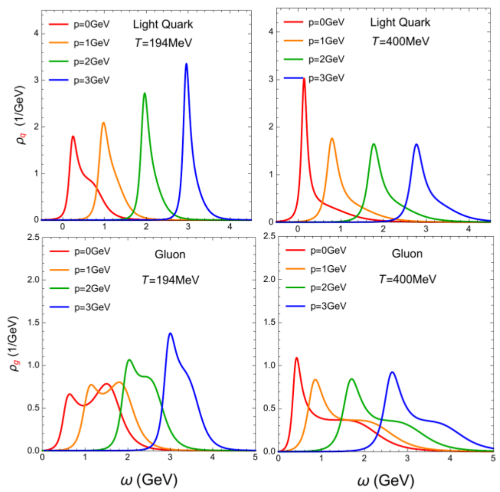
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

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

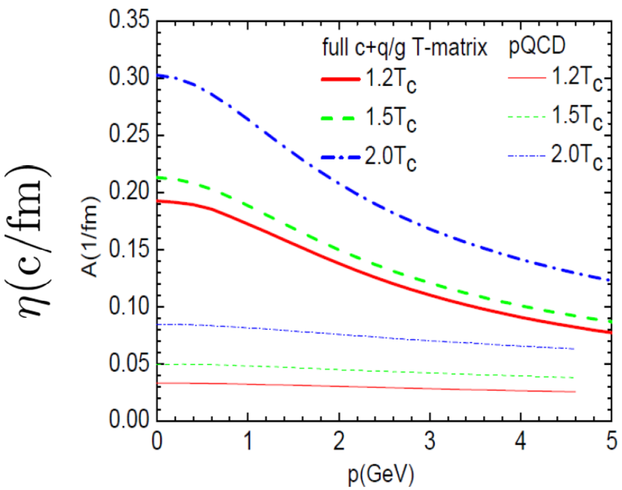
- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions!

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



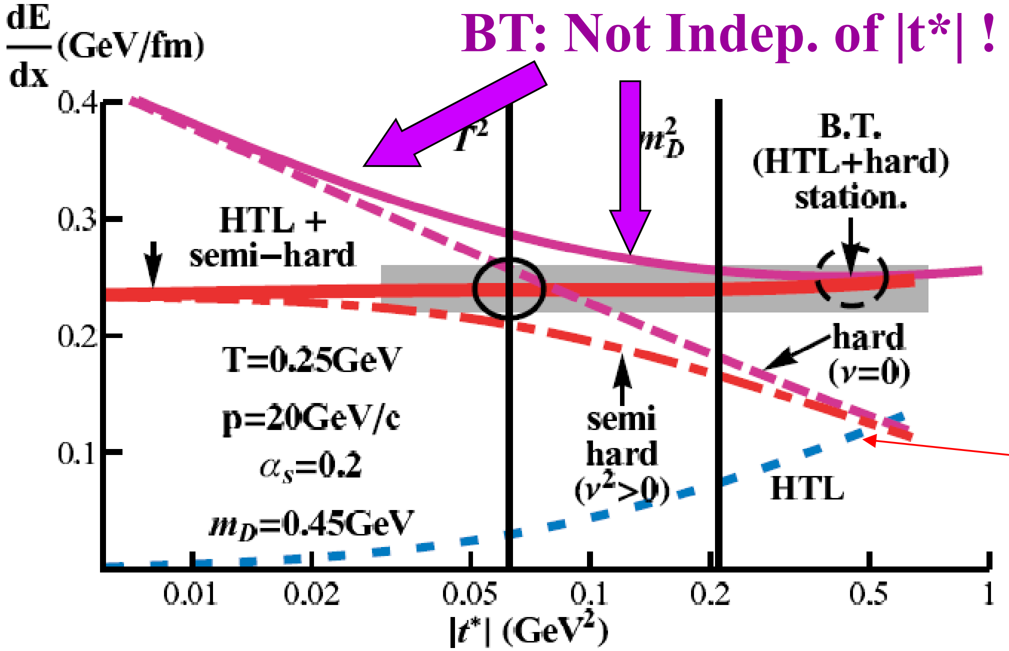
Large coupling at small p_Q

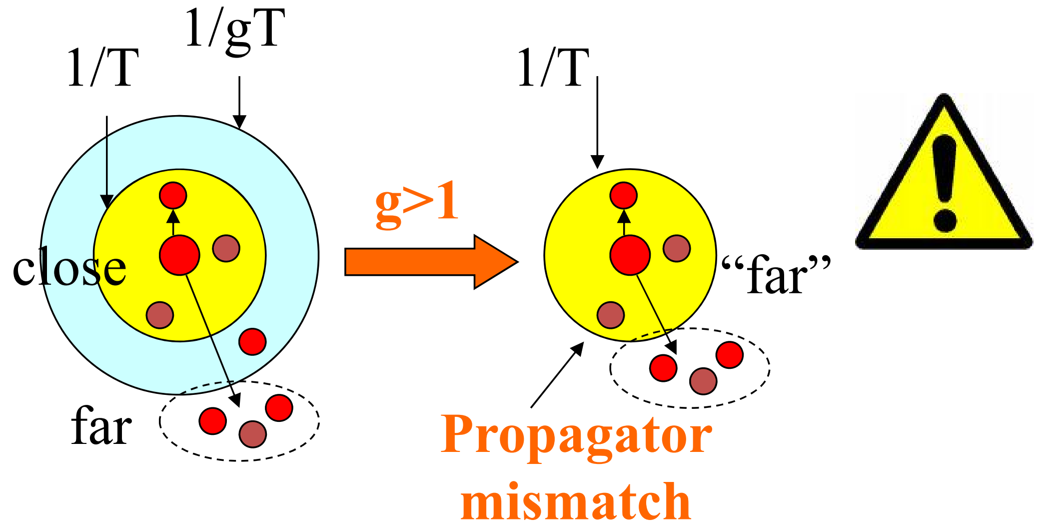
Open question, some ways out

- 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)

In QGP: $g^2T^2 > T^2$!!!





Our proposal: Introduce a semi-hard propagator --$1/(t-\nu^2)$ -- for |t|>|t*| to attenuate the discontinuities at t* in BT approach.

Prescription: ν^2 in the semi-hard prop. is *chosen* such that the resulting E loss is maximally |t*|-independent.

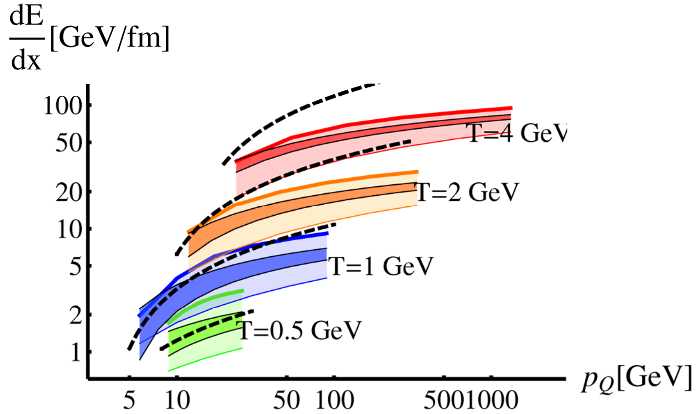
This allows a matching at a natural value of |t*| ≈T... Not an increase wrt Braaten-Thoma

pQCD inspired models (f.i. Nantes)

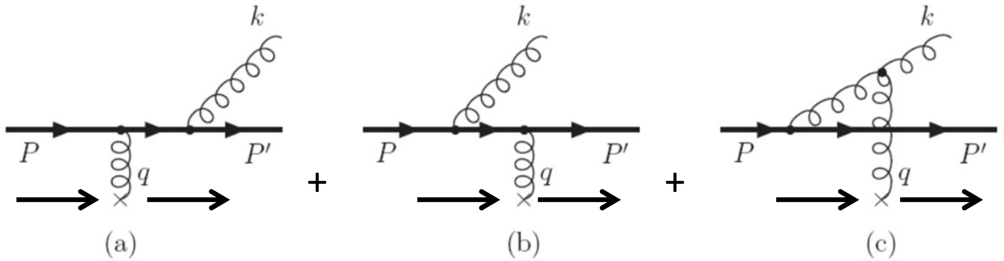
Colisional component

- One-gluon exchange model: reduced IR regulator $\lambda\ m^2_D$ in the hard propagator, fixed on HTL Energy loss at intermediate p_T
- 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 (ΔE_{rad} α 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 dynamics

But also BAMPS, LBL-CCNU, Duke,…

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 (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)

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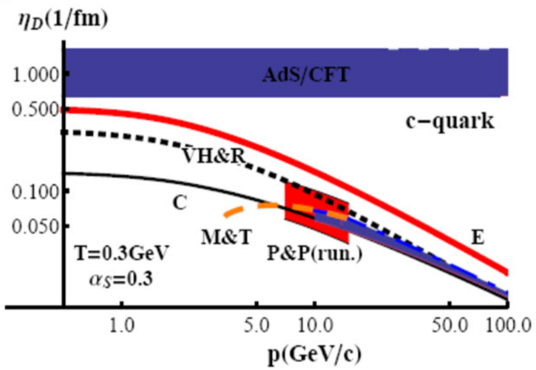
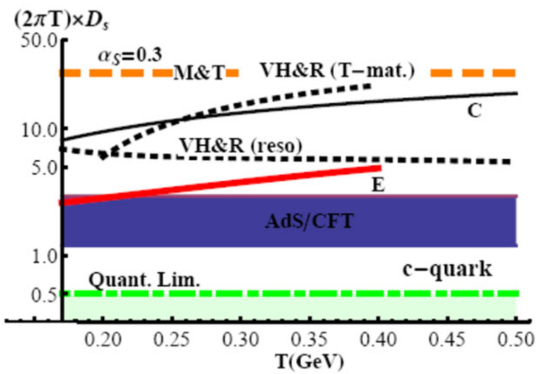
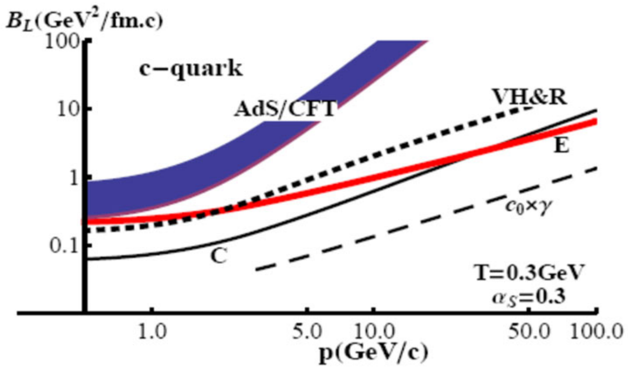
- Leptonic decay through Λ_c (Martinez et Crochet)
-



Drag coefficient



Spatial Diff. coefficient

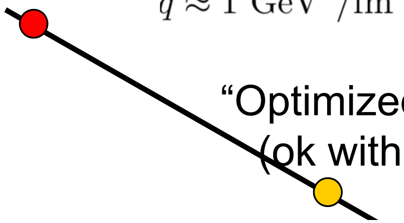


Long. fluctuations

Already 3 classes of models: collisional, radiative, ADS/CFT + genuine theory (lQCD)

The weak to strong axis for HQ

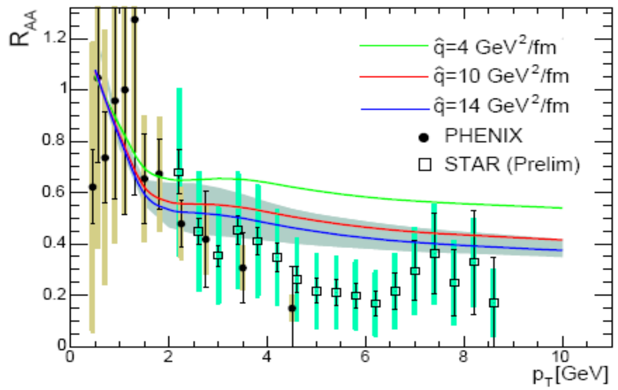
“Naive” pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$



“Optimized” pQCD
(ok with pions)

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

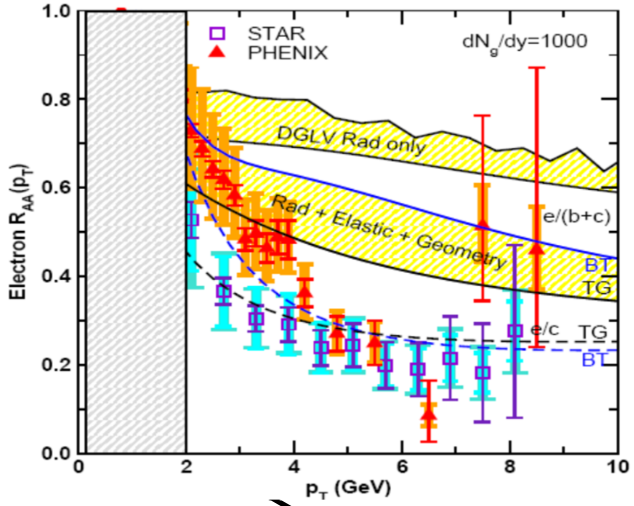
ASW (pure rad. energy loss; extended BDMPS)



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

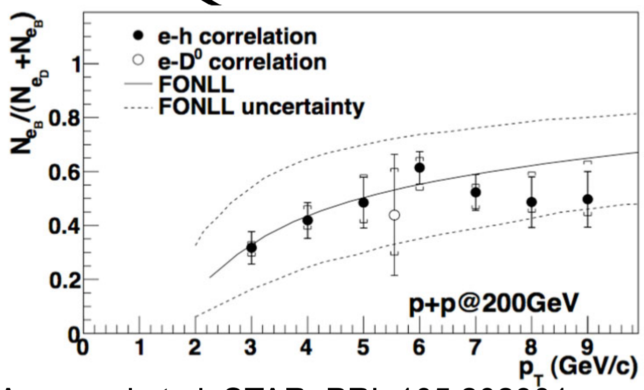
Conclude to rough agreement, subjected to b/c ratio in p-p

coll Eloss (BT and TG) + radiative Eloss



WHDG

Beauty is the problem… but beauty is found to contribute



M Aggarwal et al, STAR, PRL 105 202301

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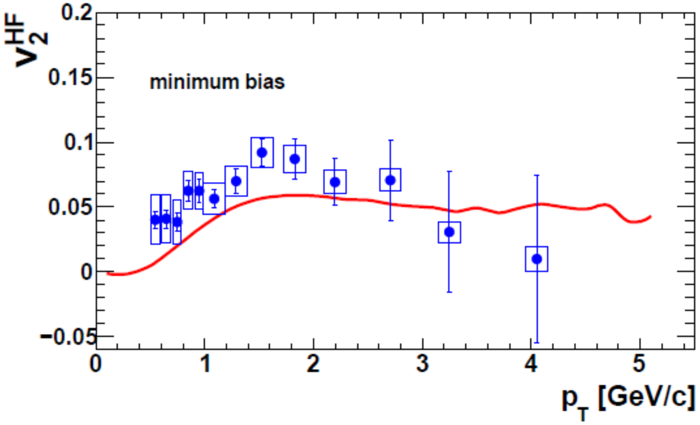
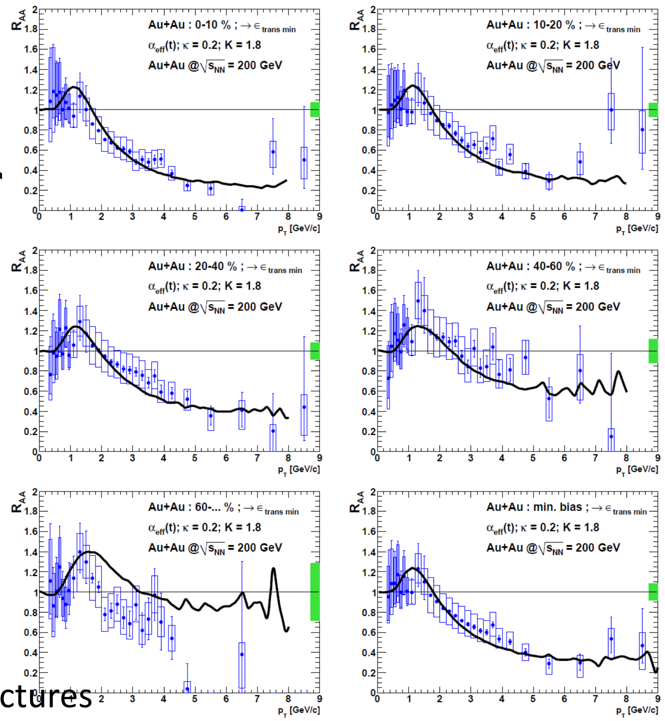
“Optimized” pQCD
(ok with pions)

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





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$\hat{q} \approx 1 \text{ GeV}^2/\text{fm}$

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]

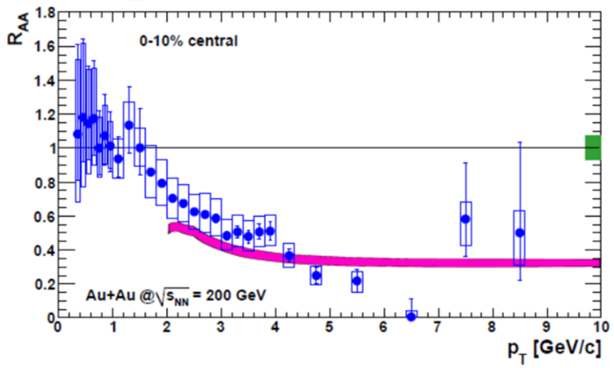

FIG. 41: (Color online) R_{AuAu} in 0–10% centrality class compared with a collisional dissociation model [78] (band) in Au+Au collisions.

The weak to strong axis for HQ

"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"

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

Distorsion
fragmentat
existence
R. Sharma
0904.0032

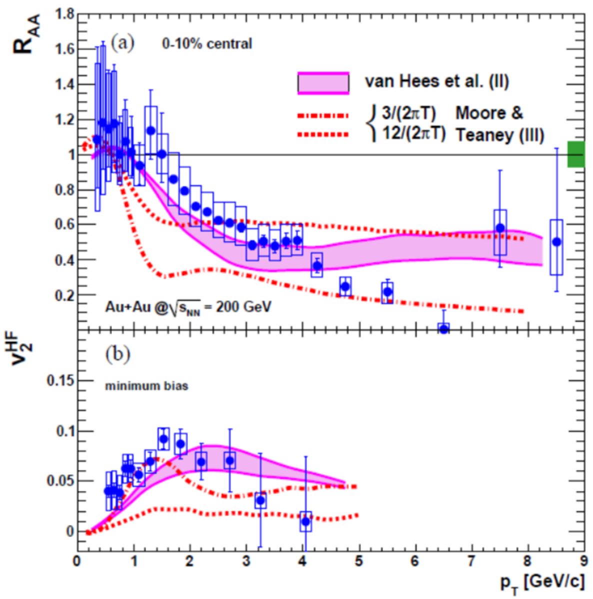
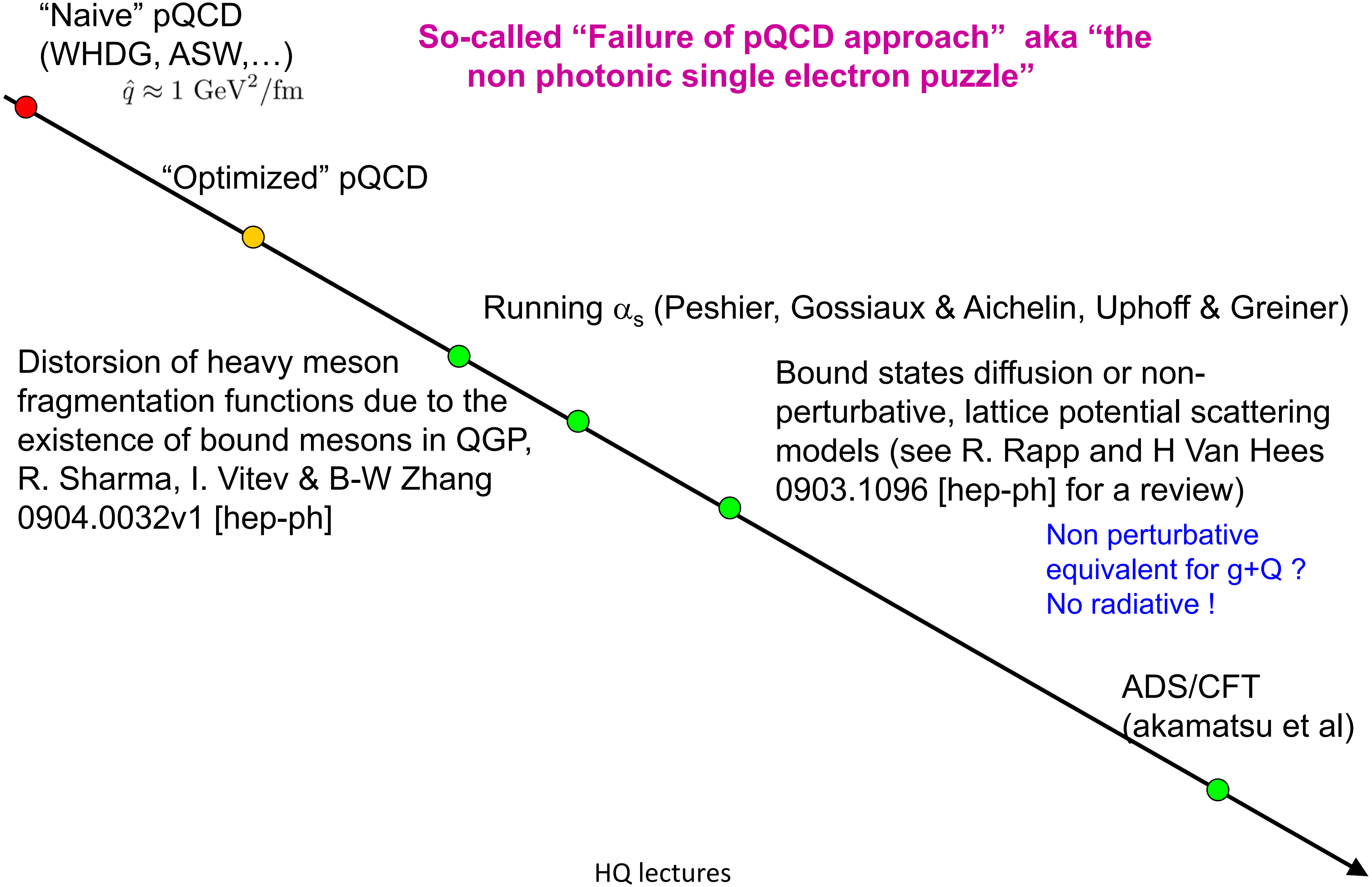


FIG. 40: (Color online) Comparison of Langevin-based models from [74–76] to the heavy flavor electron R_{AuAu} for 0-10% centrality and v_2 for minimum-bias collisions.

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



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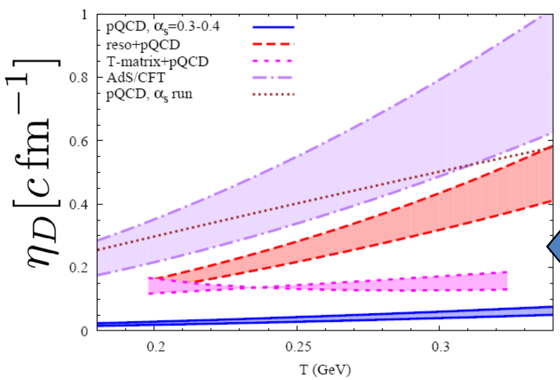


from Rapp & Van Hees 0903.1096

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 pT as well as in the b sector)
- Constrains from the fundamental theory : lQCD estimates
- A last class of model: Quasi Particle Model
- Alternate observables (correlations)
- The way towards more collective work in the theory community
- HQ-jets
- HQ in small systems
- Early stage : Glasma + magnetic field
- ….

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)

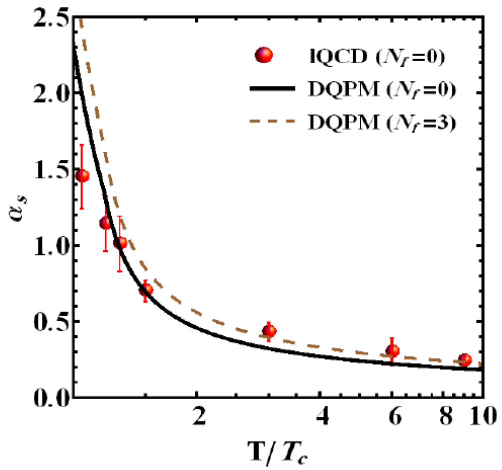
- Coupling between the effective DOF is then taken as $\alpha_s(T)$=> Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

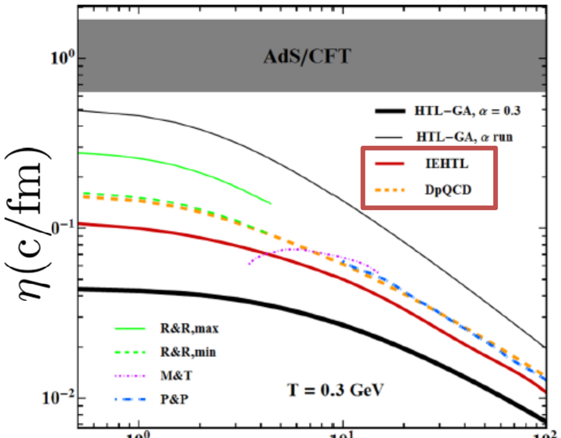
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

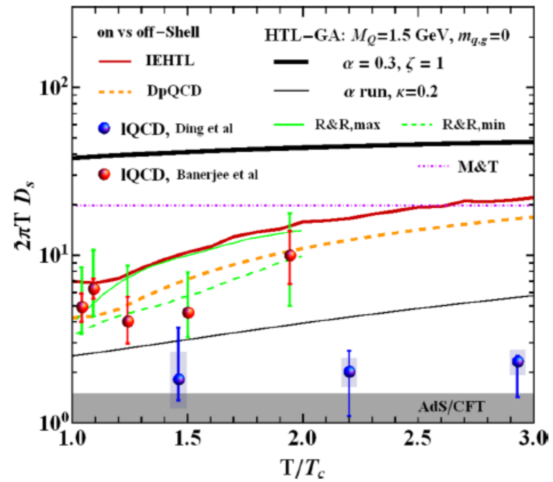
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

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

But also CATANIA







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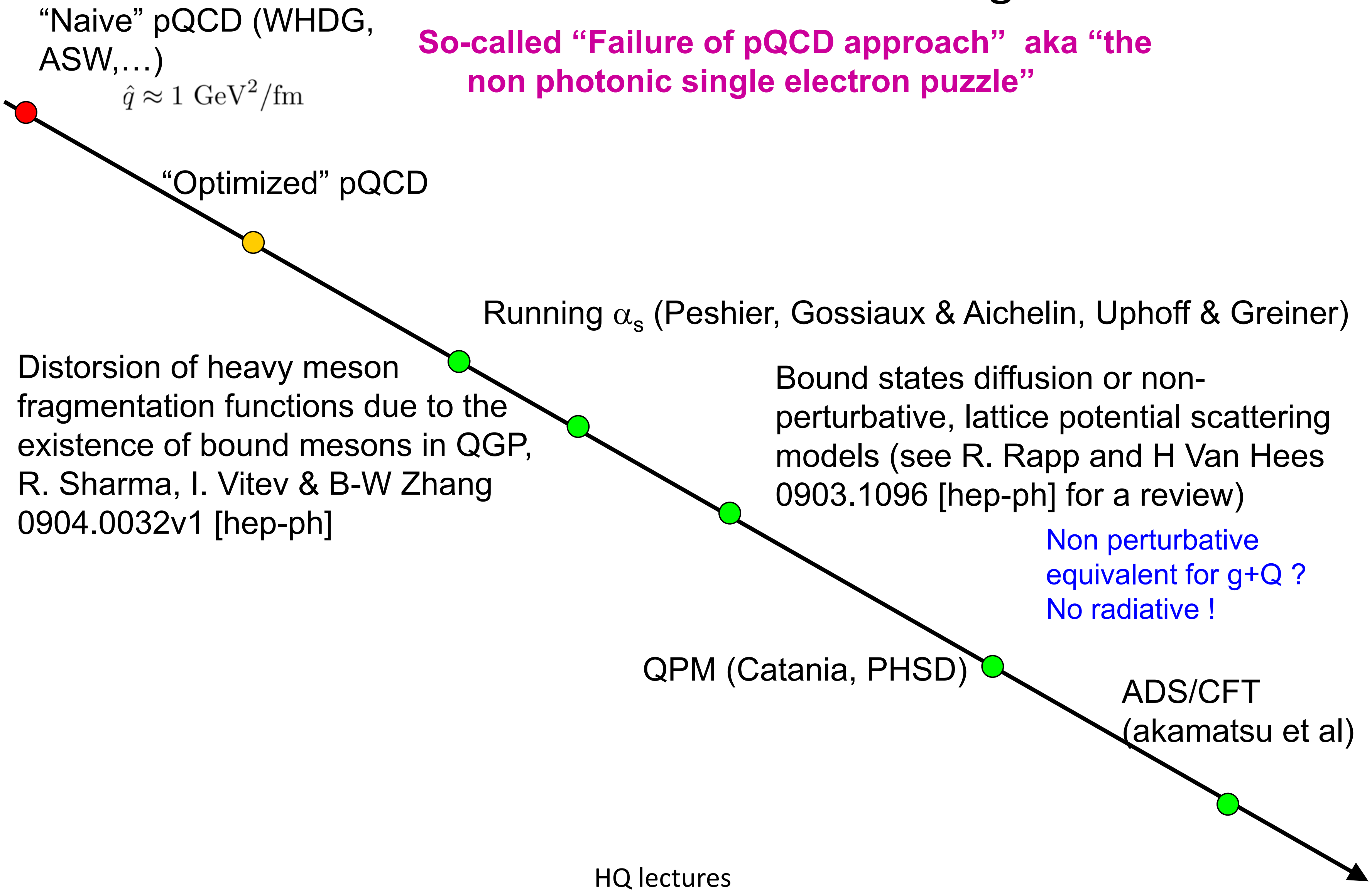
So-called “Failure of pQCD approach” aka “the non photonic single electron puzzle”



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- ....

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

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

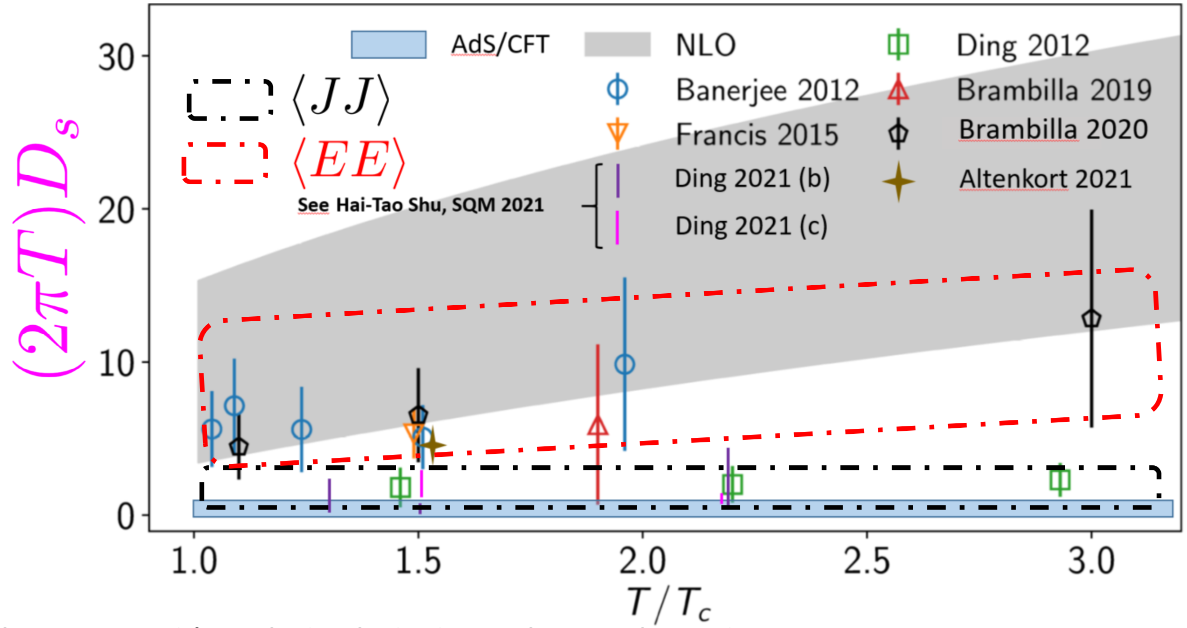
Gauge for the coupling strength

lQCD results

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

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

Still not conclusive



2 possible methods : direct current – current correlator (diffusion peak) or field-field benefitting from large m_Q. Tension between the two approaches ?

Transport coefficients at low momentum p≈m_Q

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

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

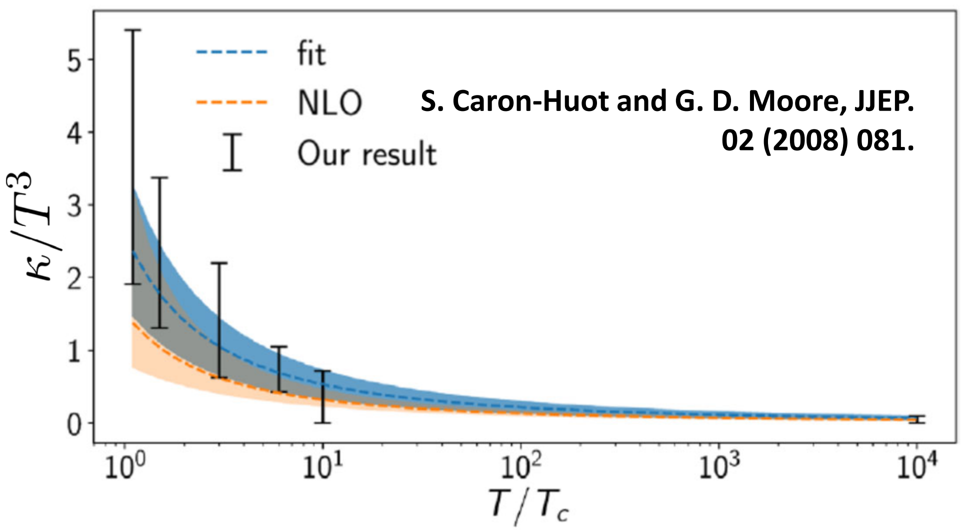
For historical reasons, physics displayed as a function of 2πT x the spatial diffusion coefficient

$$\underbrace{(2\pi T)D_s}_{\text{Gauge for the coupling strength}} = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q\eta_D} \Rightarrow \tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$$

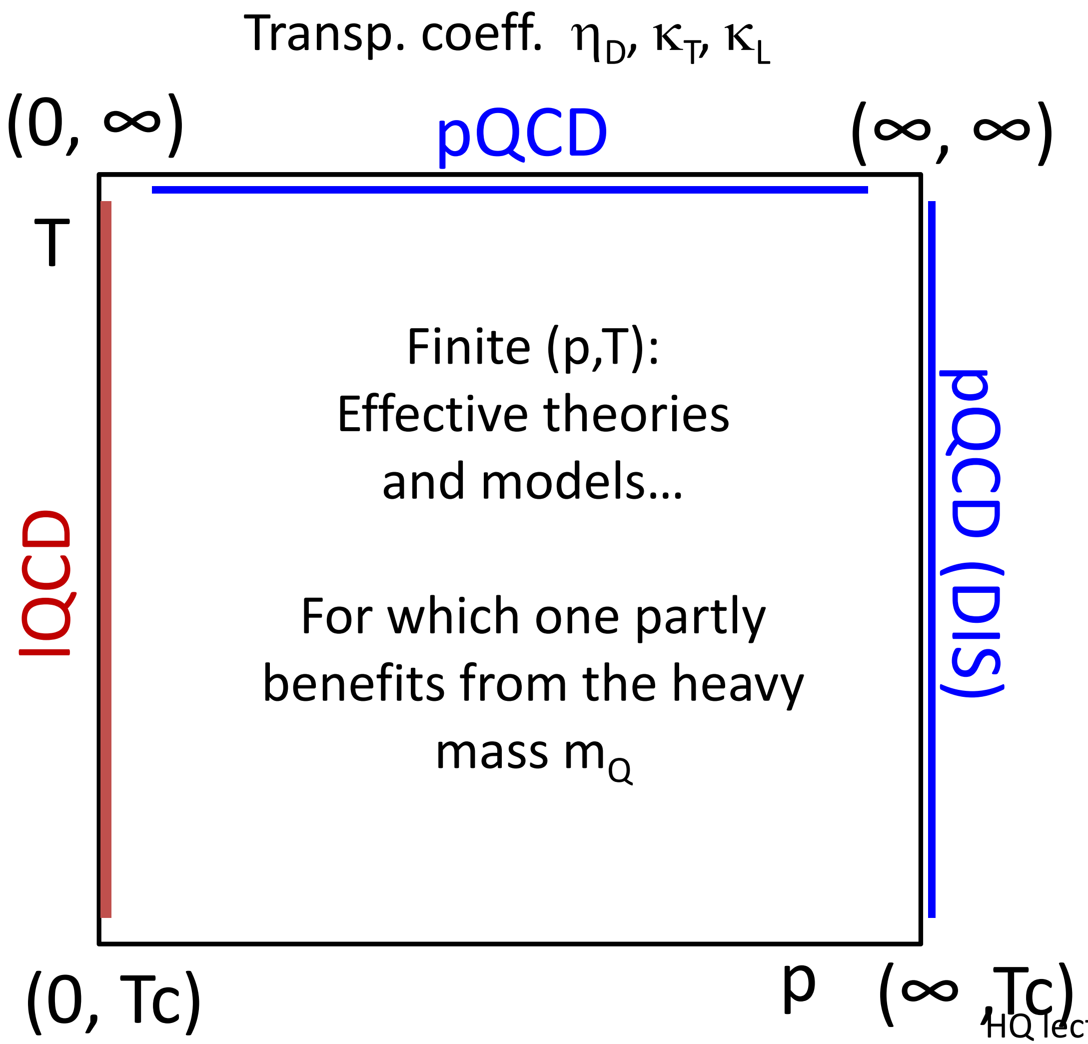
Gauge for the coupling strength

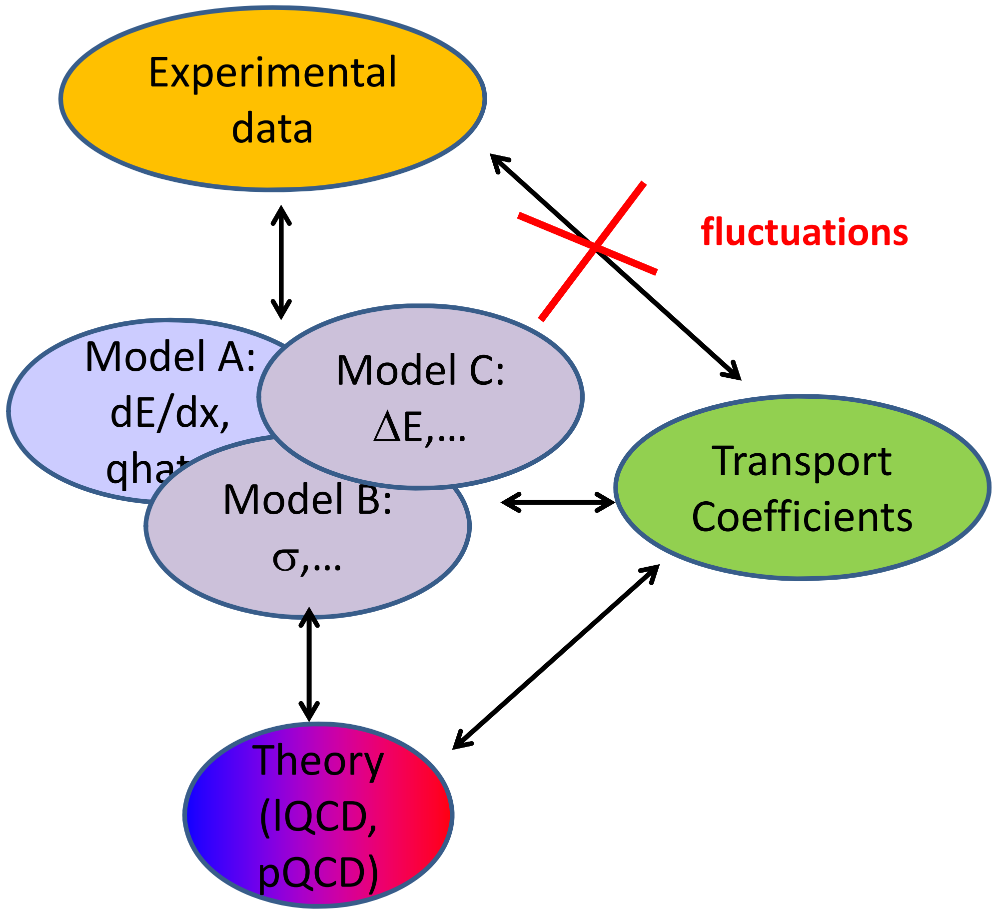
- Large corrections observed from LO -> NLO calculation of κ
- NLO calculation appears to be nearly compatible with lQCD calculations
- The T dependence appears to be in quite good agreement and even serves to design optimal fits

Brambilla et al, PRDD 102, 074503 (2020)



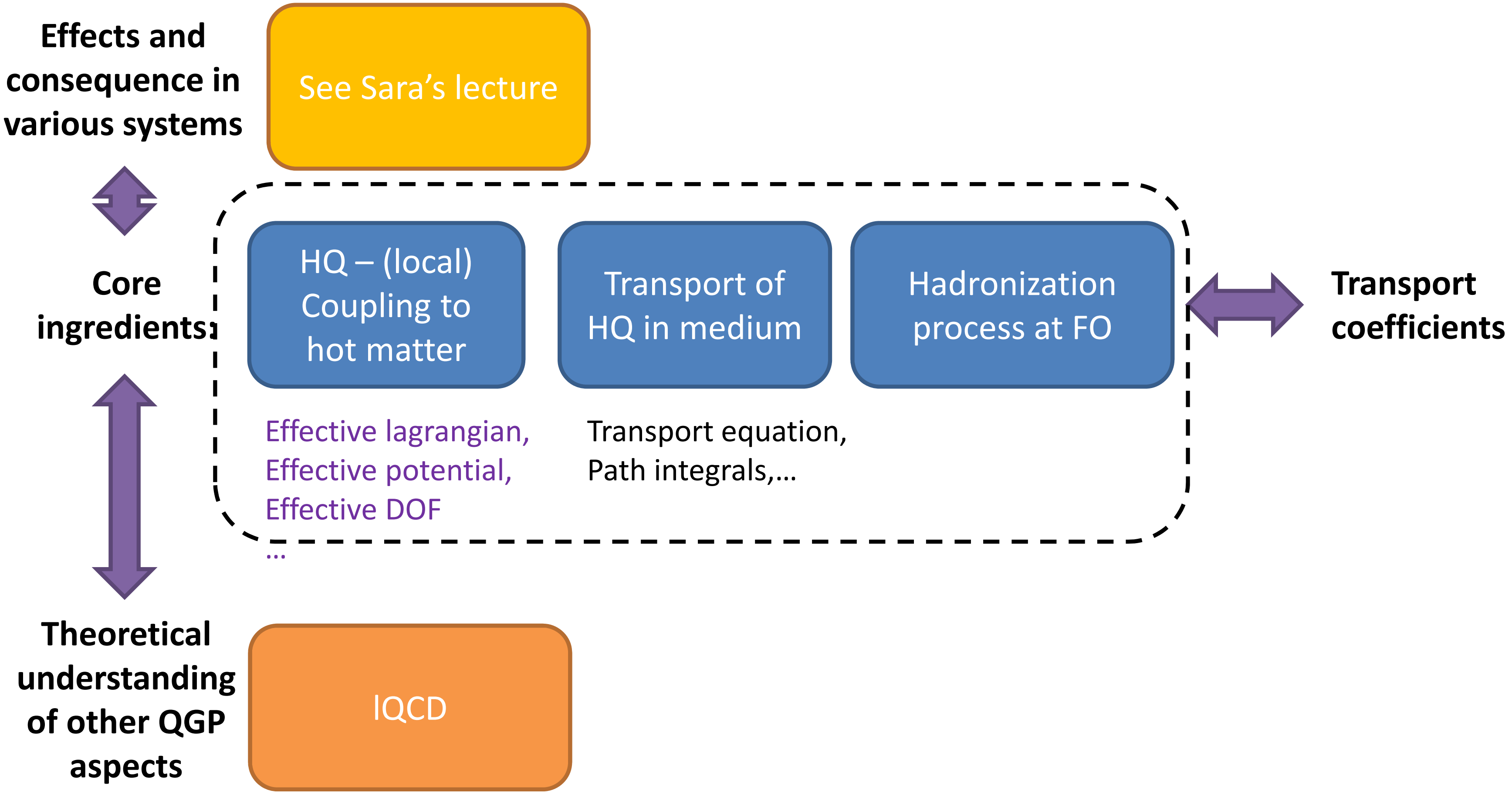
Lanscape of HF theory and modeling in URHIC





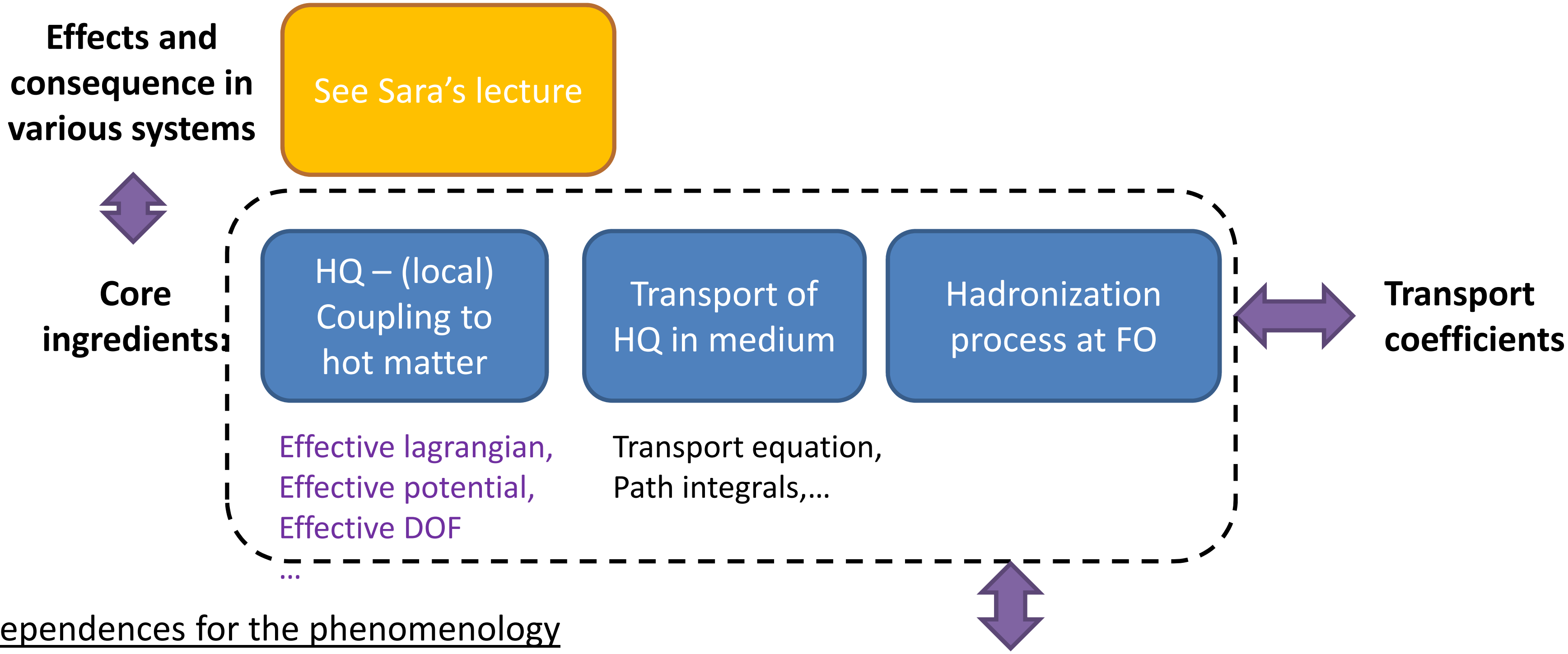
A bit of structure

- HQ propagation in QM & URHIC…



A bit of structure

- HQ propagation in QM & URHIC…

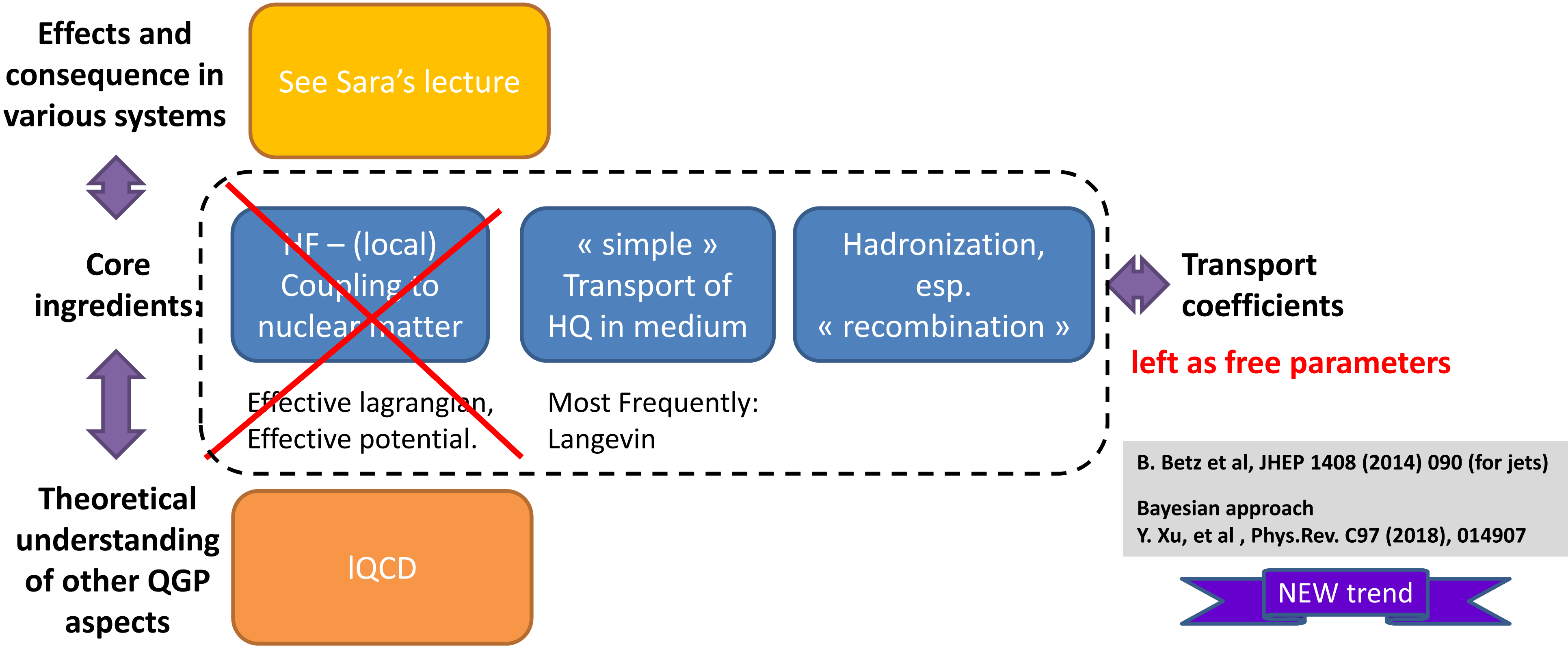


<u>4 important dependences for the phenomenology</u>

- 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 ($\Delta E_{rad} \propto L^2$)

A bit of structure

- No Model approach



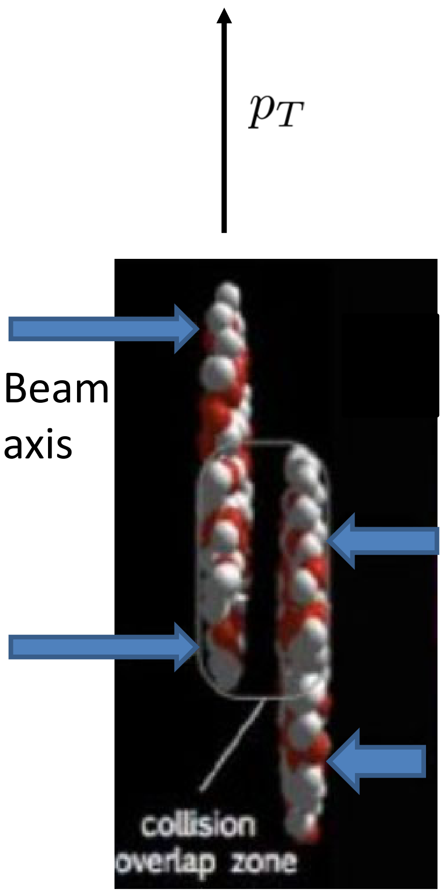
Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coefficient based (LV,…)	TAMU POWLANG HTL Catania LV	Duke, TAMU w rad.	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	DREENA MC@sHQ el + rad BAMPS CUJET3 HYDJET++ Abir and Mustafa LBL-CCNU VNI/BMS LIDO	$SCET_{G,M}$	

Red: Transport models

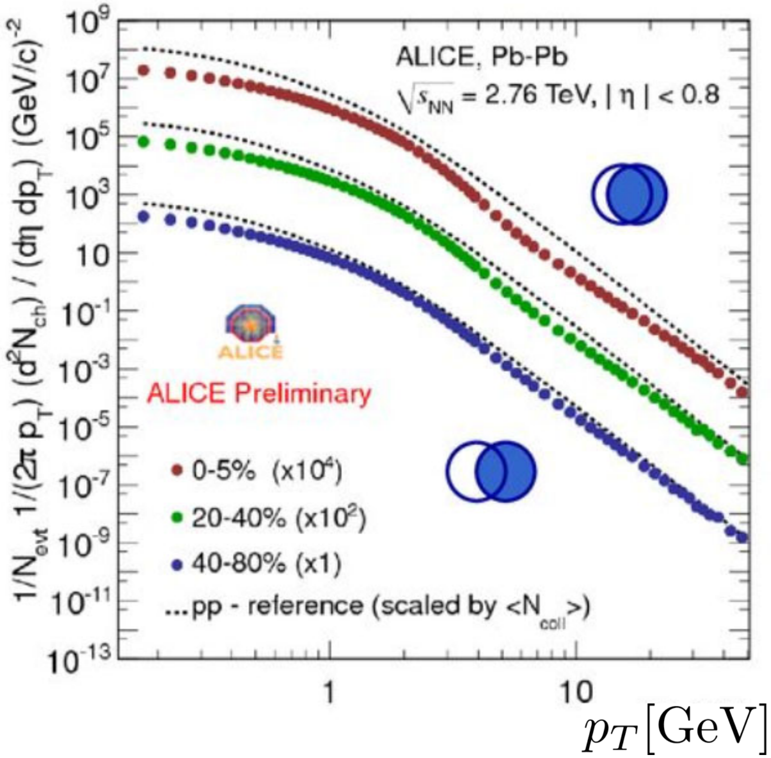
Disclaimer : If your advisor/team model does not appear here, please forgive me and contact me for completion

Observable 1: Nuclear modification factor



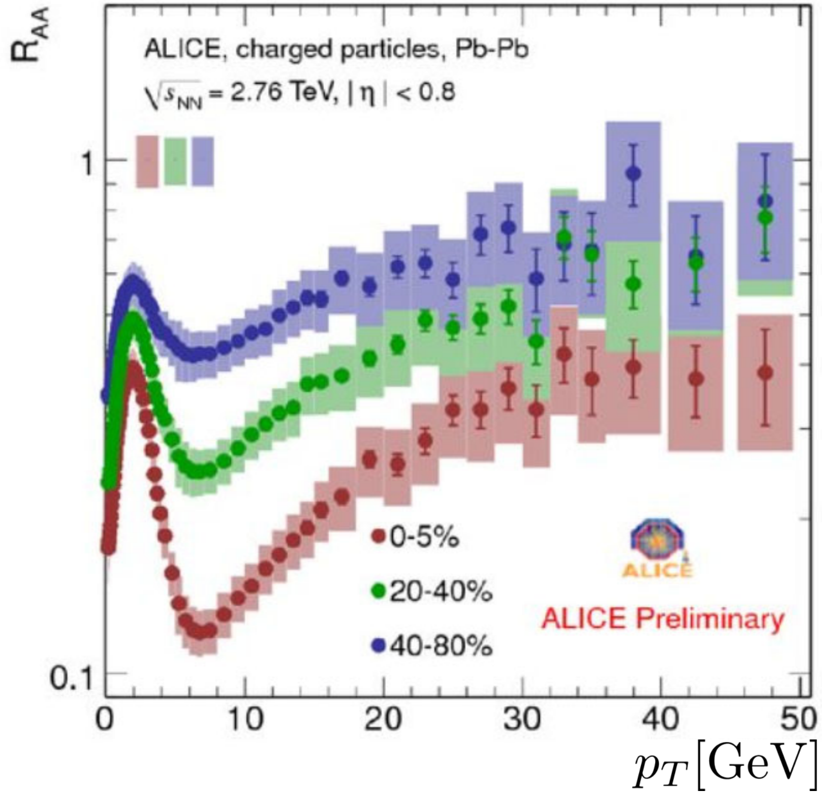
Equivalent number of pp collisions in the overlap: N_{coll}

Charged hadrons p_T spectra



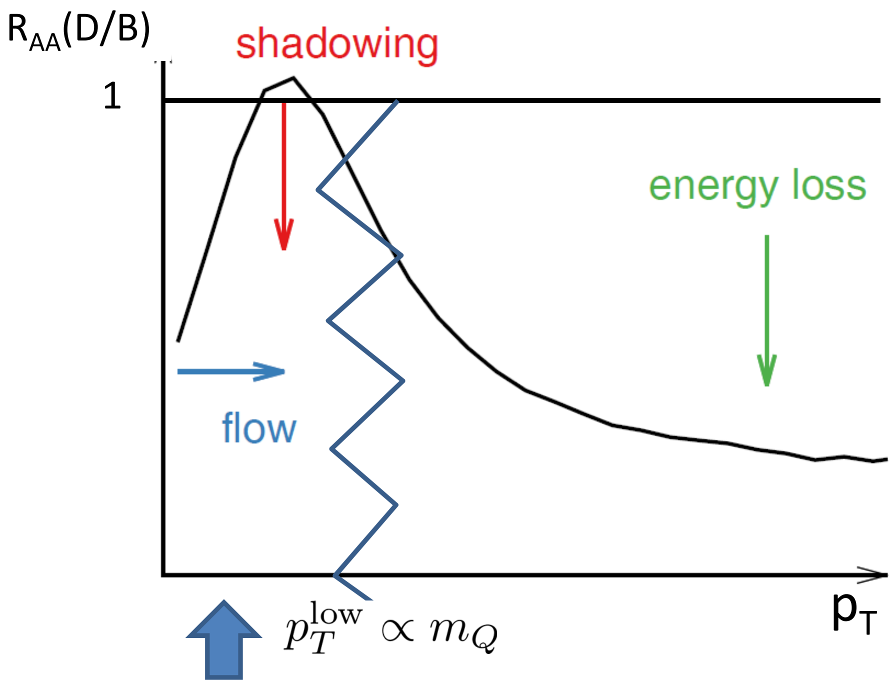
Nuclear modification factor

$$R_{AA}(X) = \frac{\left.\frac{dN^X}{dp_T}\right|_{AA}}{N_{\rm coll}\left.\frac{dN^X}{dp_T}\right|_{pp}}$$



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*

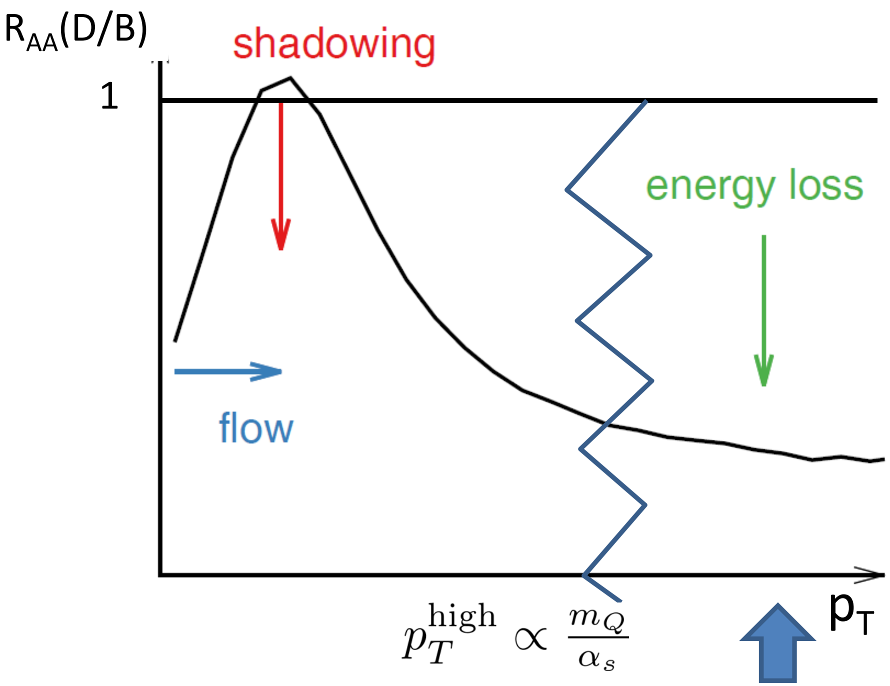
Quenching & energy loss: due to

- 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



The acknowledged effects

Flow bump: due to

- *(radial) flow of the medium* and coupling at small p_T
- *recombination with light quarks*

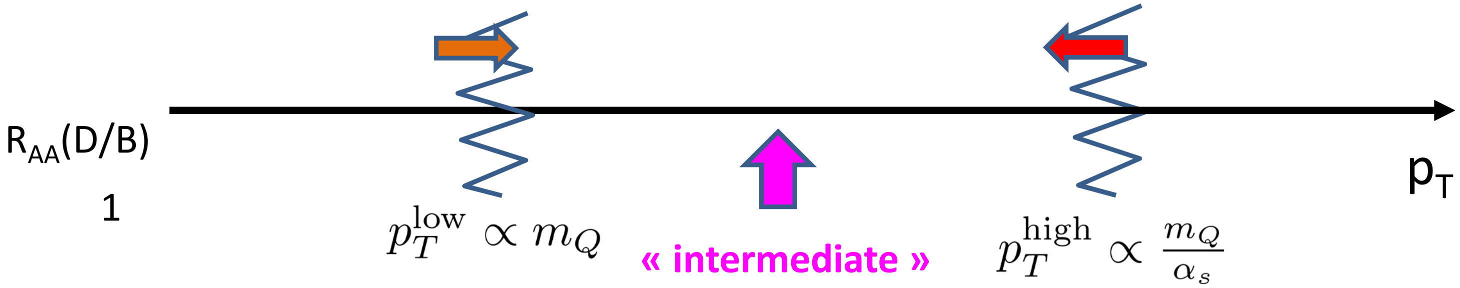
shadowing: due to *initial state nuclear effects*

Quenching & energy loss: due to

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

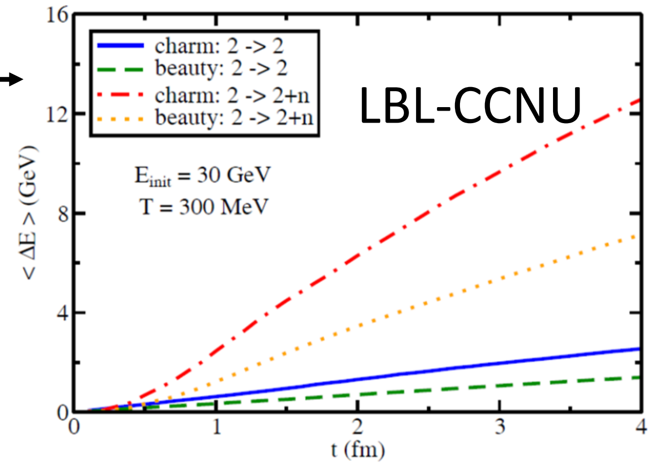
- Dominated by radiative energy loss (with important coherence effects: $\Delta E_{\mathrm{rad}} \propto C_A \hat{q} L^2$)
- Eikonal regime (propagation along straight lines)
- 1 single transport coefficient dominates the whole physics: $\hat{q} \propto \kappa_T$
- HQ do not equilibrate with the medium
- m_Q becomes a subscale of the physics (m_Q << 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 $\hat{e}_2$

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



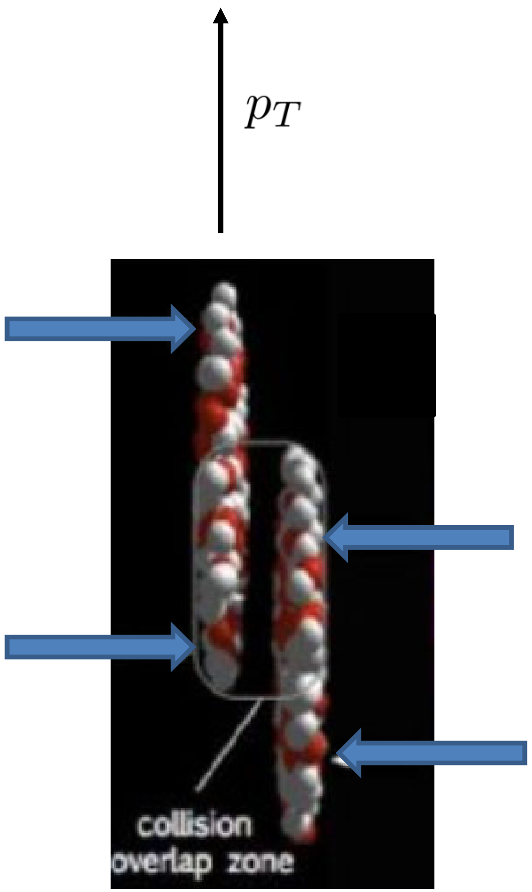
S. Cao et al, Phys. Rev. C 94, 014909 (2016)

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

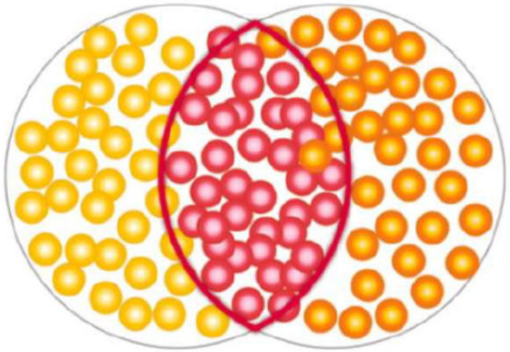
See as well Aichelin, Gossiaux & Gousset, PRD (2013)

Observable 2: azimuthal flows

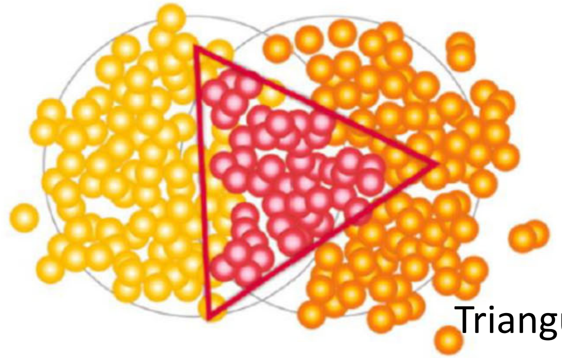
Beam axis (Oz)



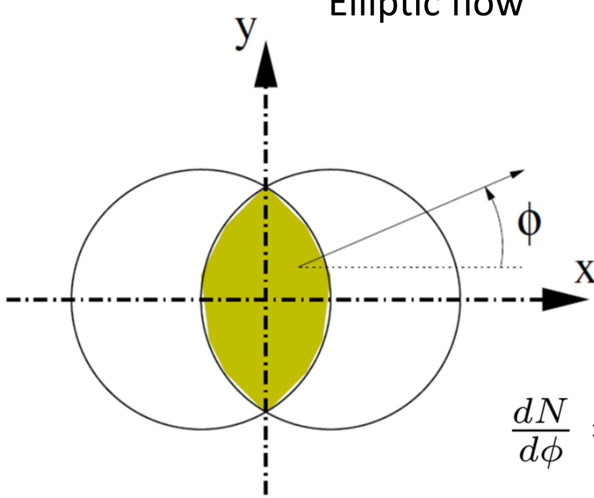
Initial stage of the collisions seen in the transverse plane: Non spherical initial spatial distribution due to eccentricity + fluctuations



Elliptic flow



Triangular flow



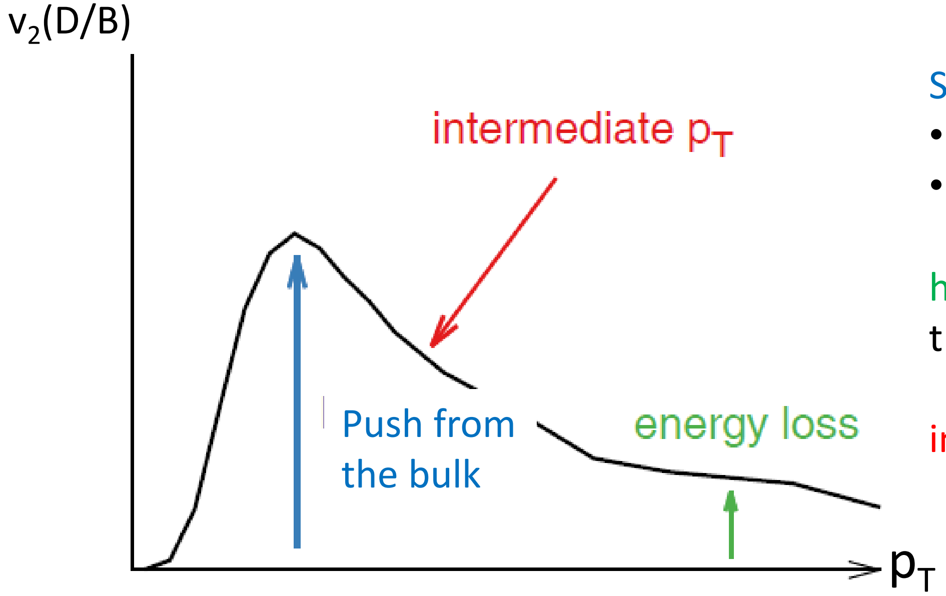
... later on converted in anisotropies due to the fluid dynamics evolution.

anisotropies in the final hadrons azimuthal distributions (Fourier series)

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2v_2 \cos[2(\phi - \psi_{\mathrm{RP}})] + \cdots\right)$$

$$v_2 = \langle \cos[2(\phi - \psi_{\mathrm{RP}})] \rangle$$

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.

3 Important remarks:

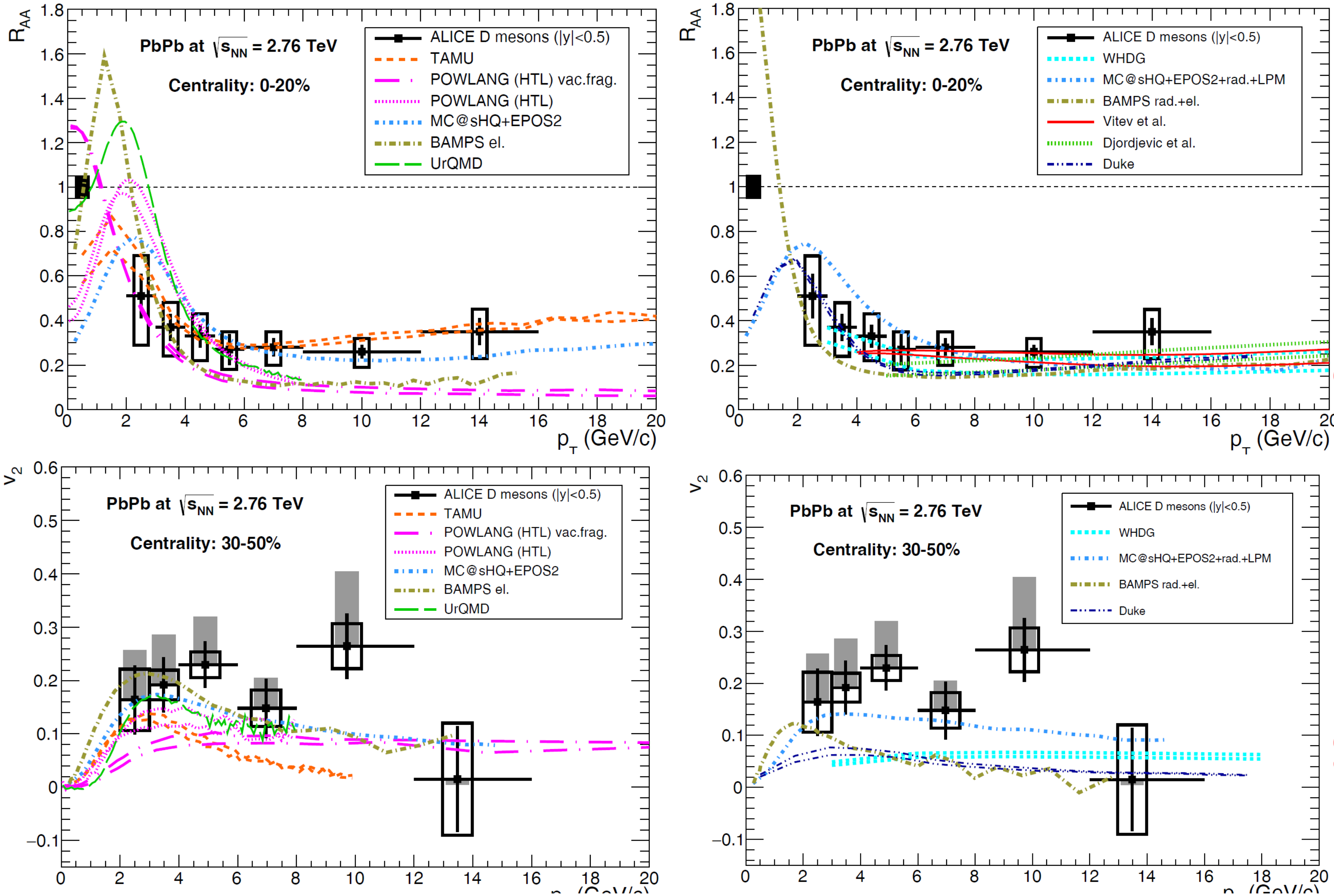
- Any energy loss model, even the crudest one, will generate these typical structures in the R_{AA} and the v_2. Getting a correct **quantitative** agreement is much more involved.
- Quantitative predictions also depends on some « extra ingredients » (bulk, hadronisation,…)
- **While R_{AA} develops early, v_n is sensitive to later stages of the evolution** => quite sensitive to physical mechanisms near Tc.

!!! 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

Models vs DATA at LHC (Sapore Gravis Report compilation)

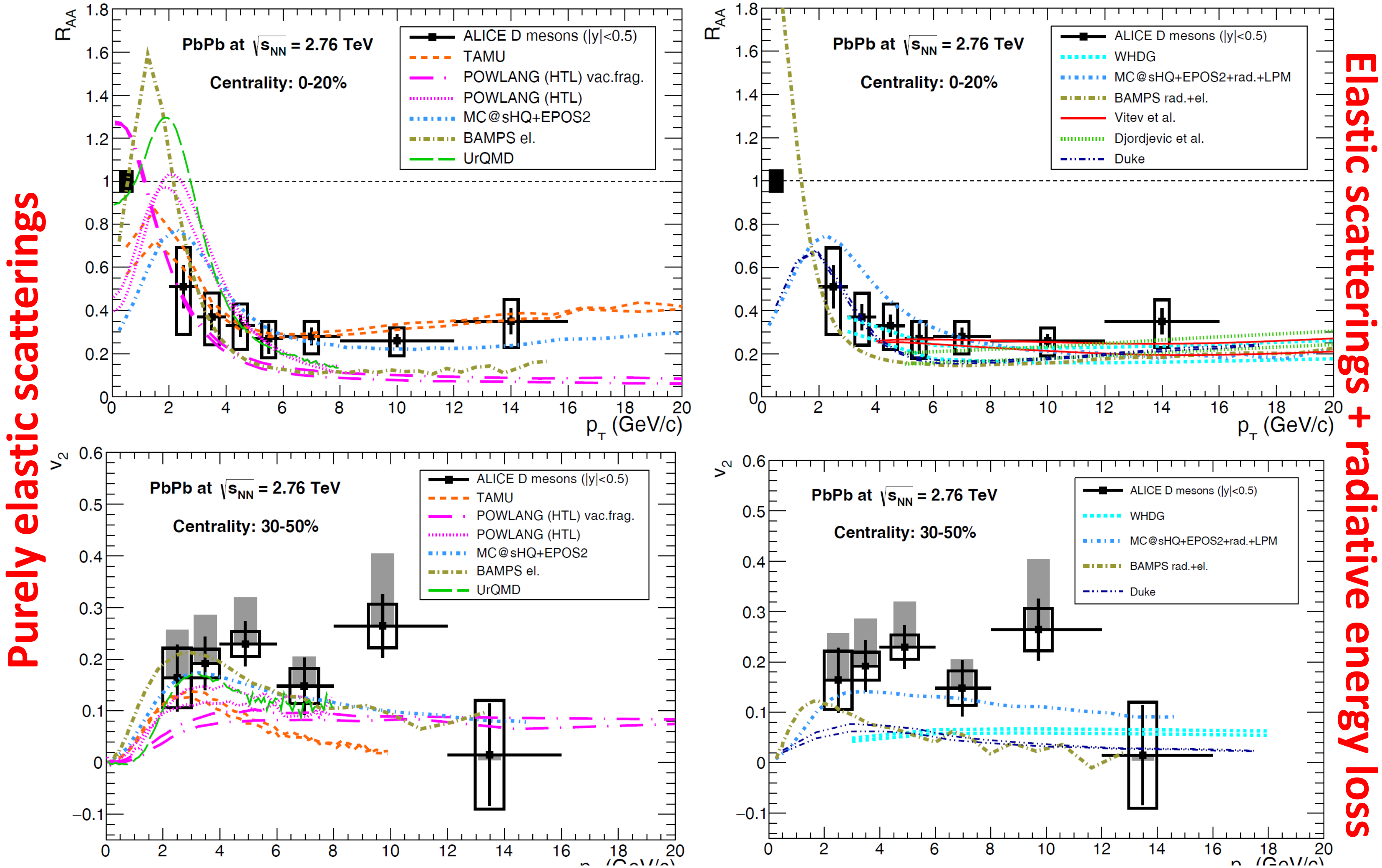
Purely elastic scatterings



Elastic scatterings + radiative energy loss

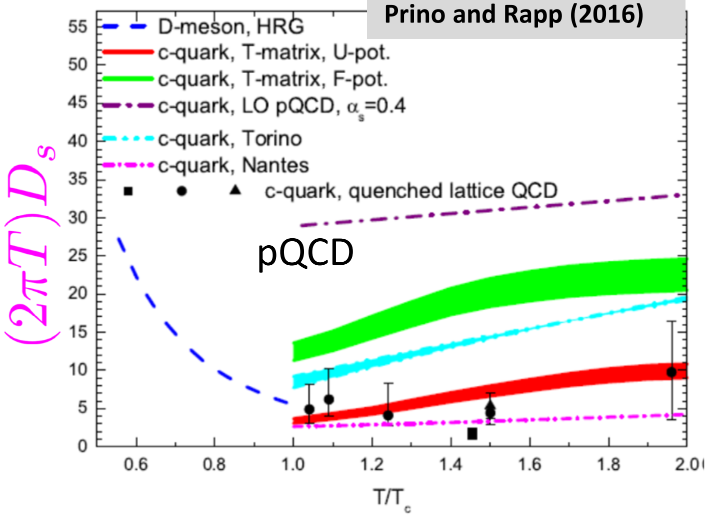
Despite various prescriptions for Energy loss, a lot of models can cope with the data

Models vs DATA at LHC (Sapore Gravis Report compilation)



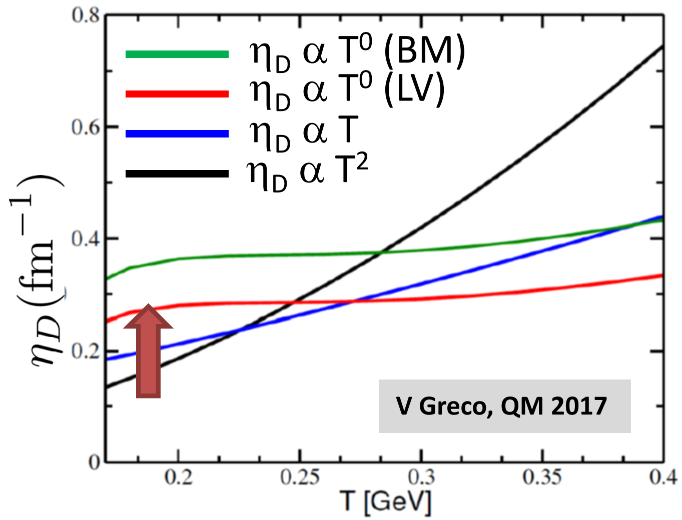
Some advocated tension between R_{AA} and v_2

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



$$\tau_{\rm relax} = \eta_D^{-1} = (2\pi T)D_s \times \frac{m_Q}{2\pi T^2}$$

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

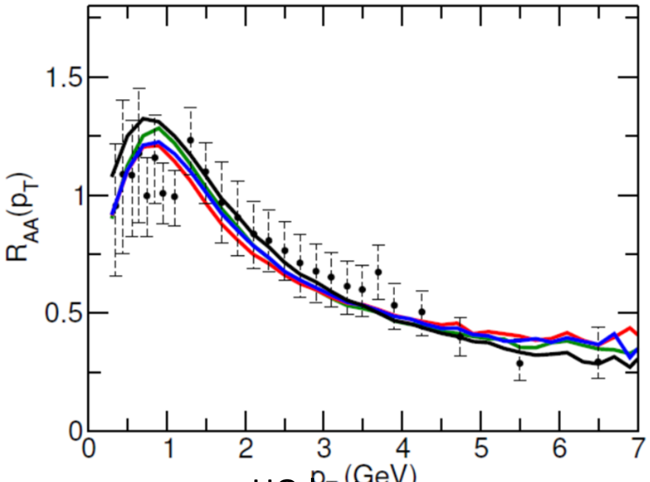


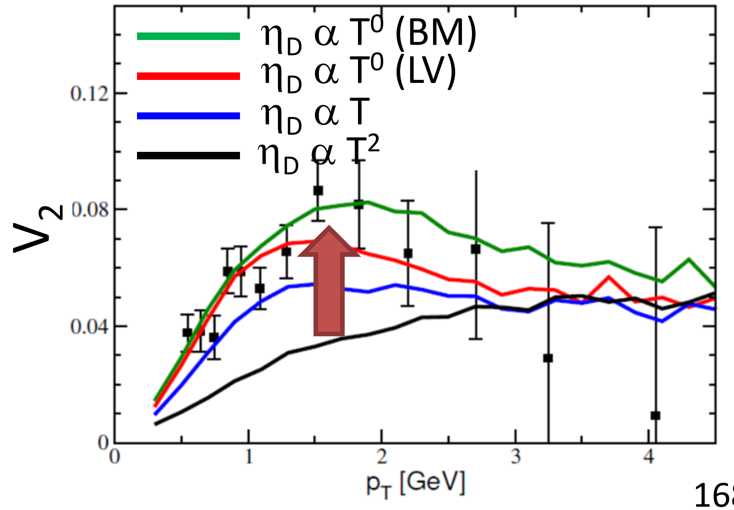
η_D α T^2: pQCD (fixed α_s), AdS/CFT

η_D α T: pQCD (running α_s)

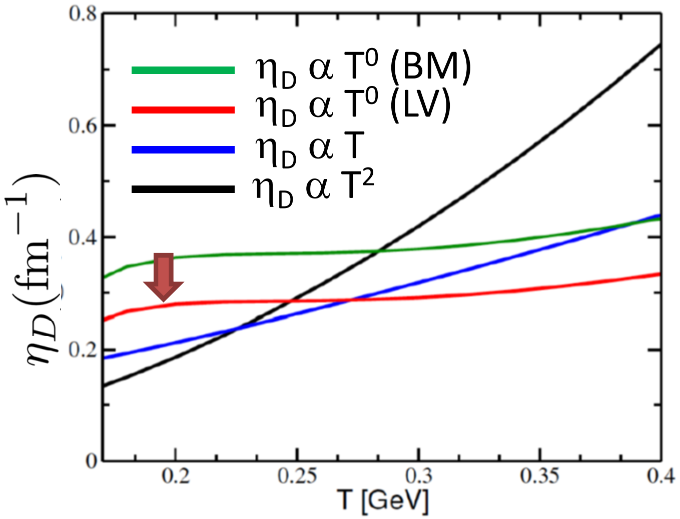
η_D α T^0: QPM, DQPM, U potential (TAMU)

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





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

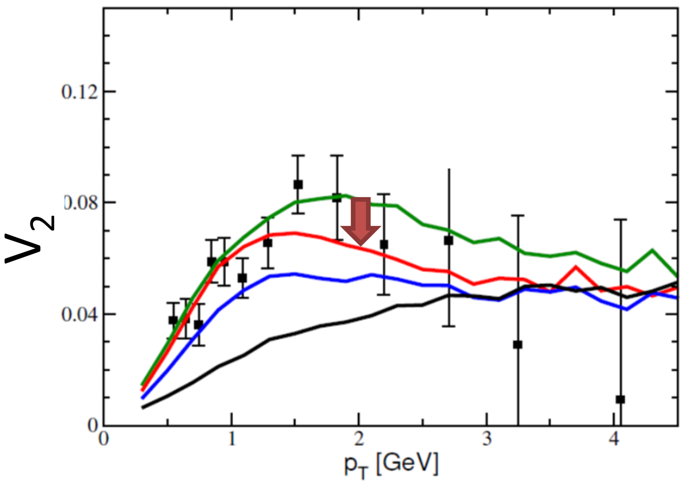


Extra increase from LV => Boltzmann dynamics

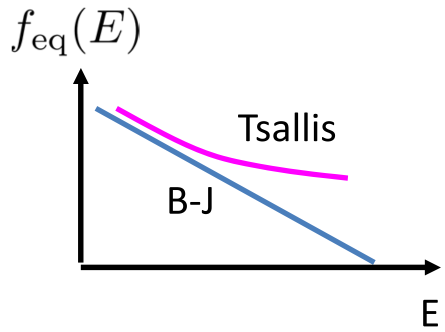
Should be seen as a *decrease* passing from Boltzmann =>LV

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).



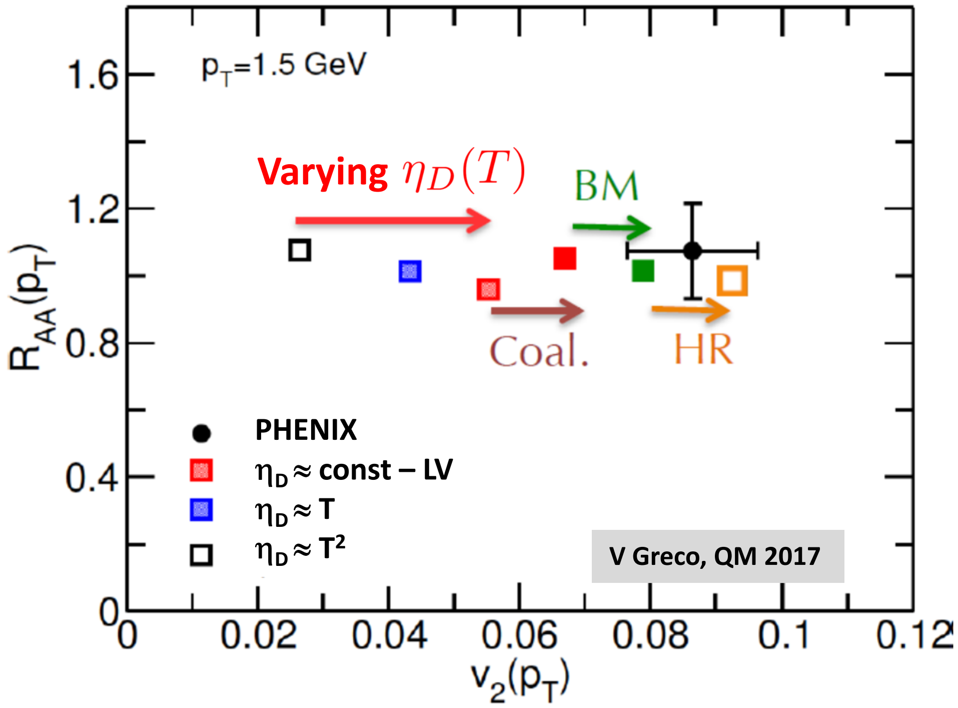
=> For dynamical evolution, one needs to cranck down the interaction and the FP coefficients in order to reproduced a « given » R_{AA}



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

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

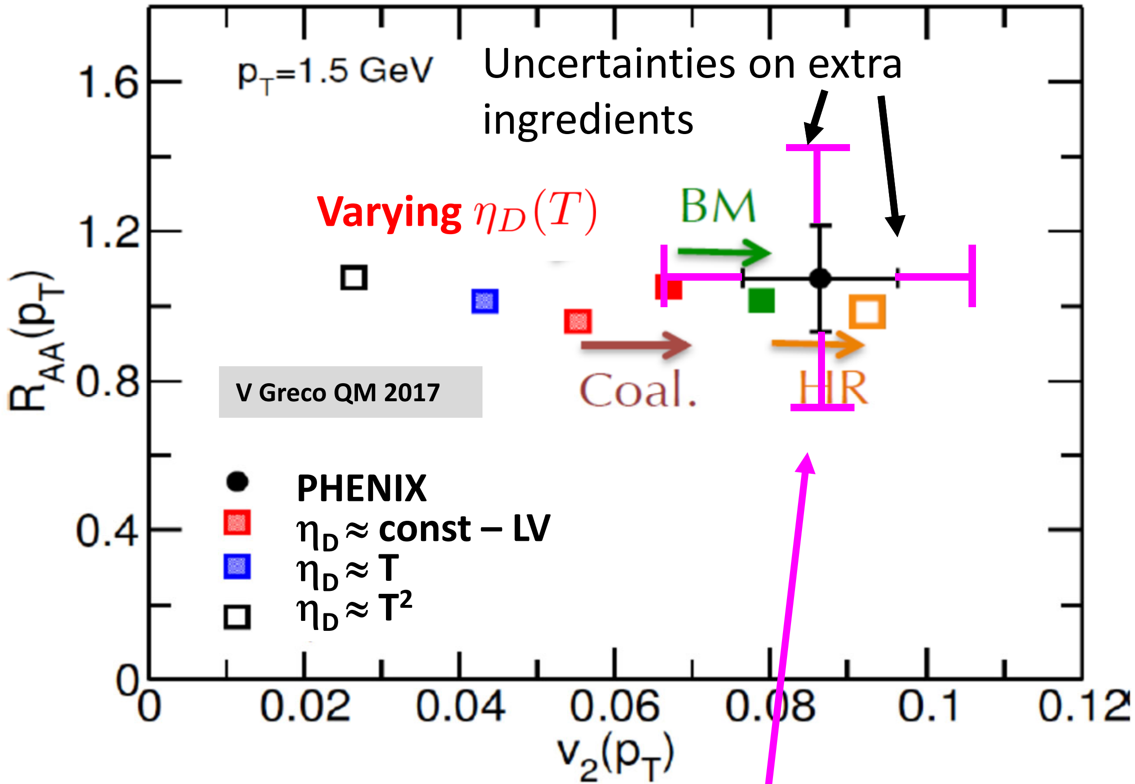
Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

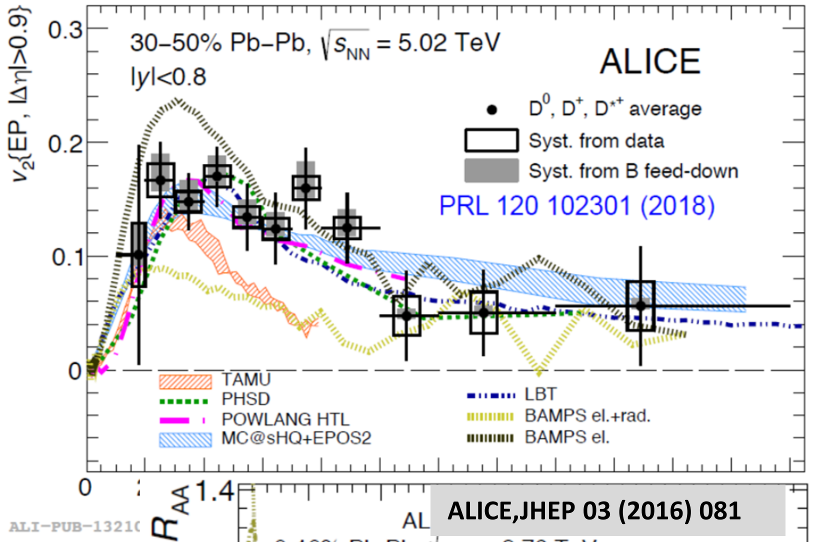


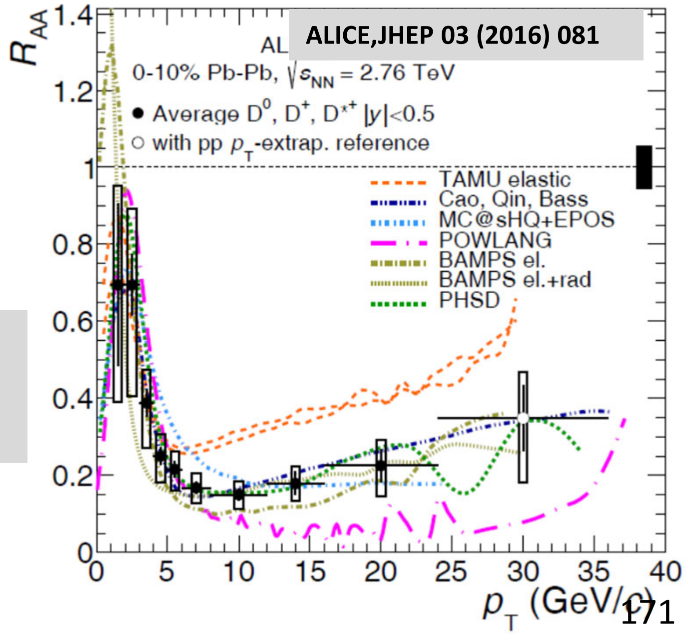
Nice guideline but need:

- 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.

Data driven extraction of transport coefficients

NEW trend

Y. Xu et al
arXiv:1710.00807v1

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

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \leftarrow \frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s P(x)\hat{q}_g}{\pi k_\perp^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$

Higher twist

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

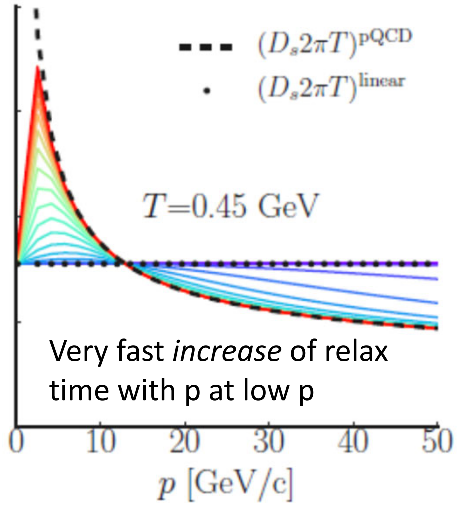
+ coal / frag hadronization and hadronic rescattering

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

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

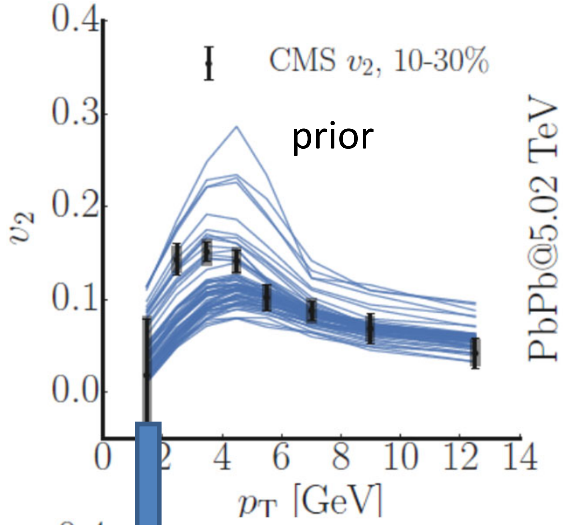
$$(D_s 2\pi T)^{\rm linear} = \alpha\cdot(1+\beta(T/T_c - 1))$$

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



Duke “Bayesian approach”

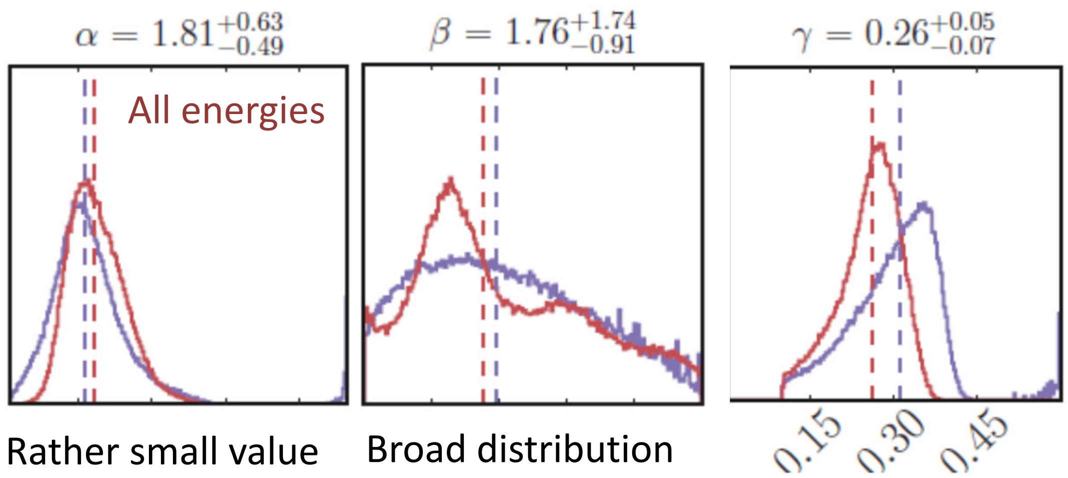
- Choice of 60 « prior » for which the physical observabes are calculated
- Gaussian emulator to build a fast surrogate of physics
- Random walk throughout parameter space, with acceptance and rejection according to likelihood (with all uncertainties assumed to be uncorrelated).



Let the data speak

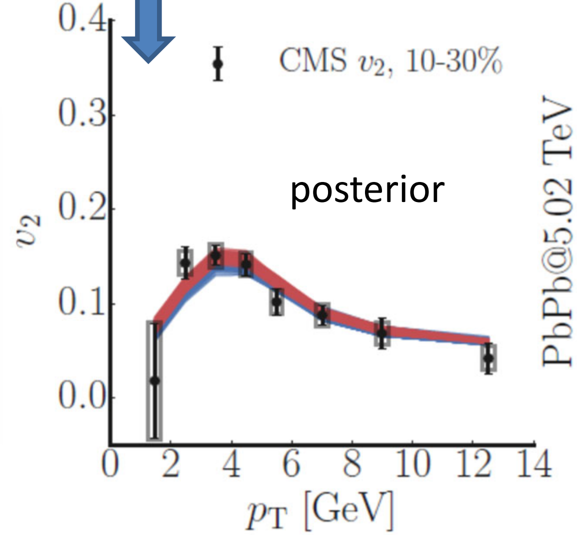
$$(D_s 2\pi T)^{\text{linear}} = \alpha\cdot(1+\beta(T/T_c-1))$$

RESULTS

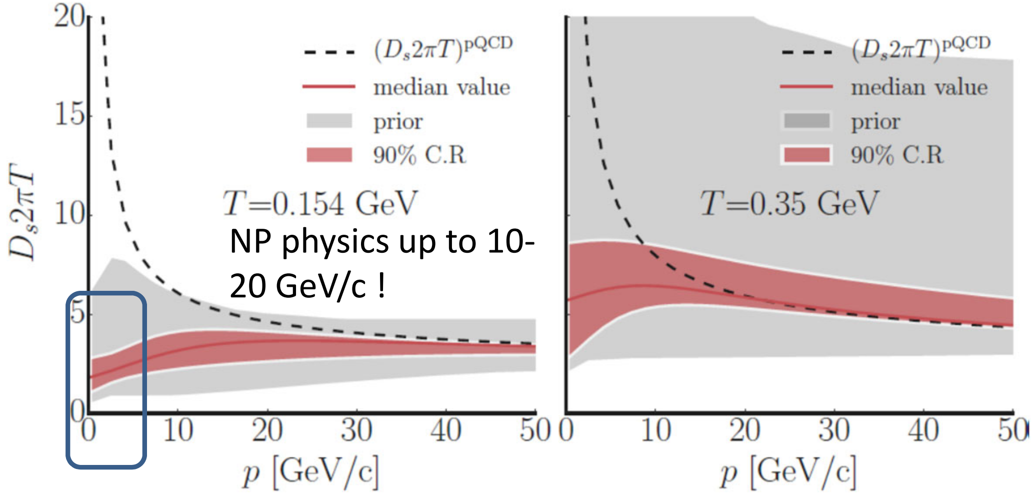


Rather small value => strong coupling !

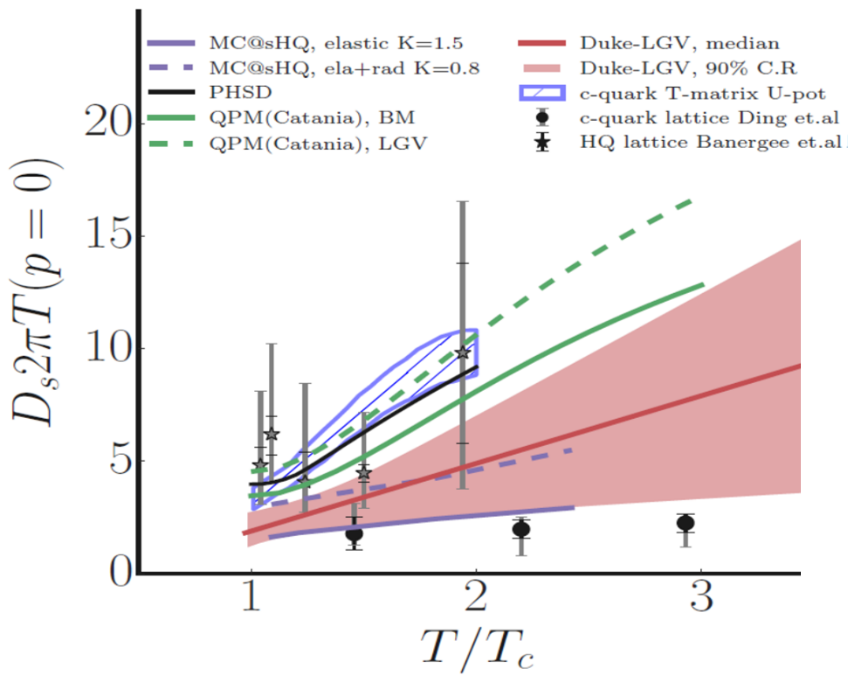
Broad distribution



Duke "Bayesian approach" vs models



Caution: 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)



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

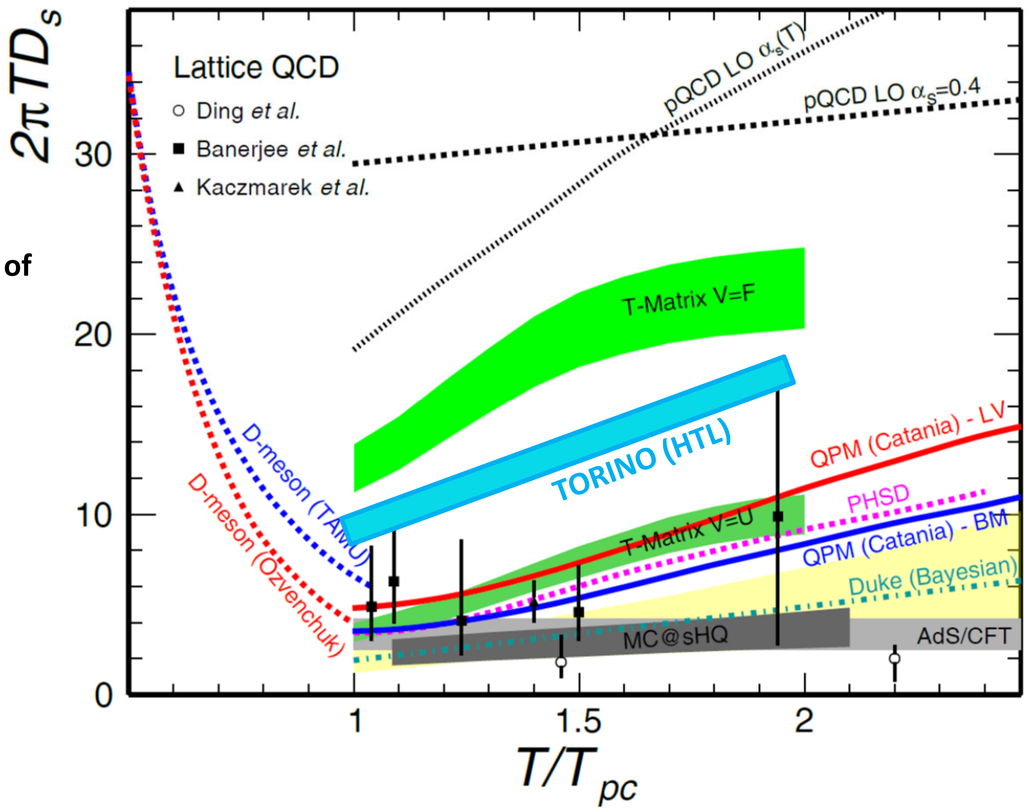
All together (lQCD, Bayesian analysis and most recent models) make a strong case for NP physics « around T_c » and at «low» p_T … needs to be precised in the future

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

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

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).

Does not mean that all models inhold the same physics…

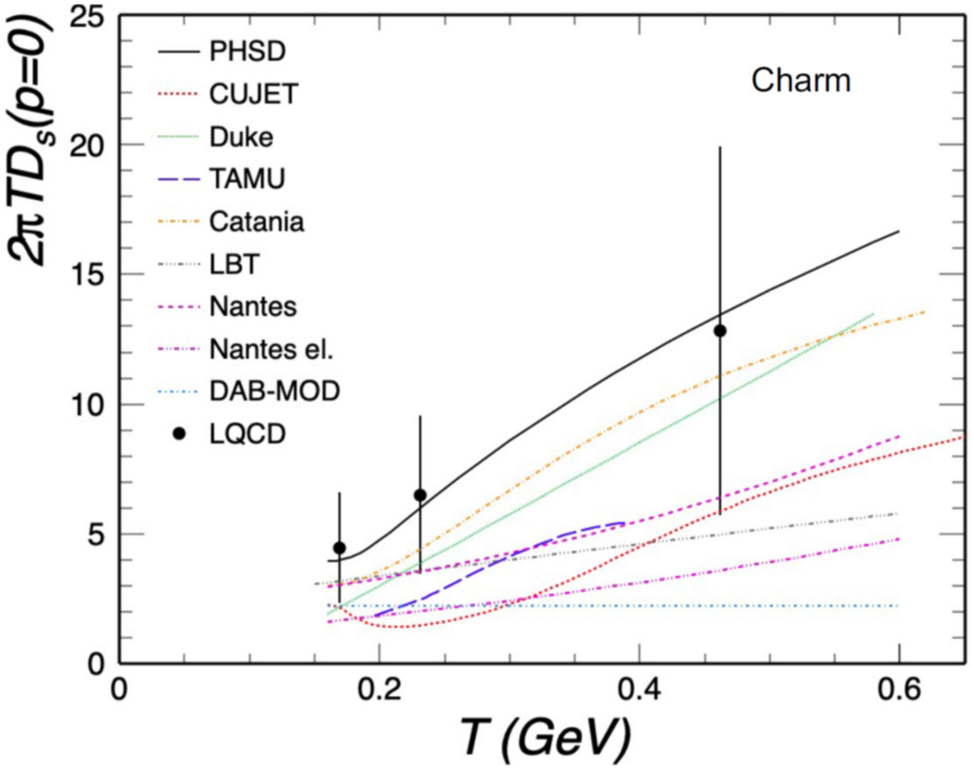
- Most of the values extracted from model comparison with the data are compatible with lQCD calculations !!!
- All together (lQCD, Bayesian analysis and most recent models) make a strong case for physics beyond « weak pQCD LO » around T_c » and at «low» p_T
- However, the question whether one needs to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

Model summary on $2\pi TD_s$ extraction

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

Latest update : https://indico.ectstar.eu/event/98/contributions/1927/

(HF Transport, ECT* 2021)



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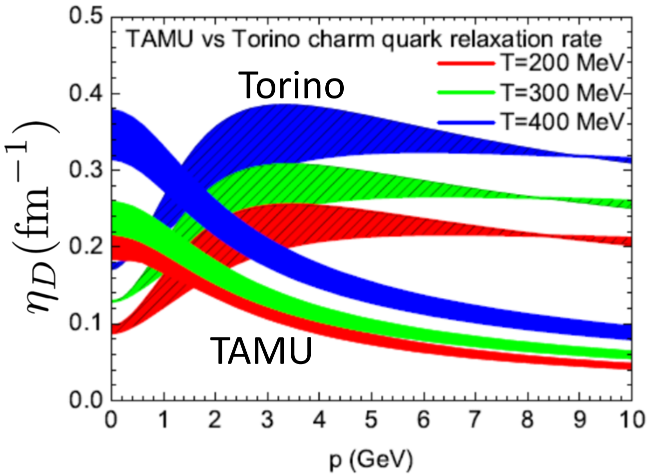
$$(2\pi T) D_s = \frac{2\pi T^2}{E_Q \eta_D}$$

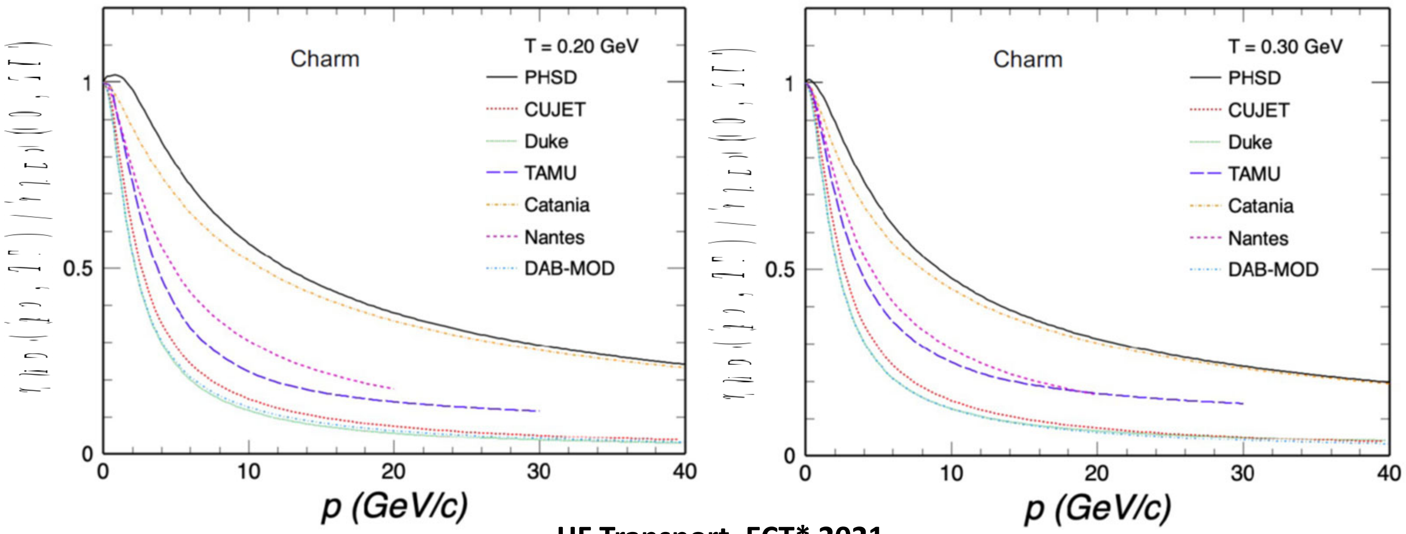
Mild linear increase of $2\pi D_s T$… ⇔ physics beyond pQCD (fixed α_s).

- 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 $2\pi T D_s$ extraction



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



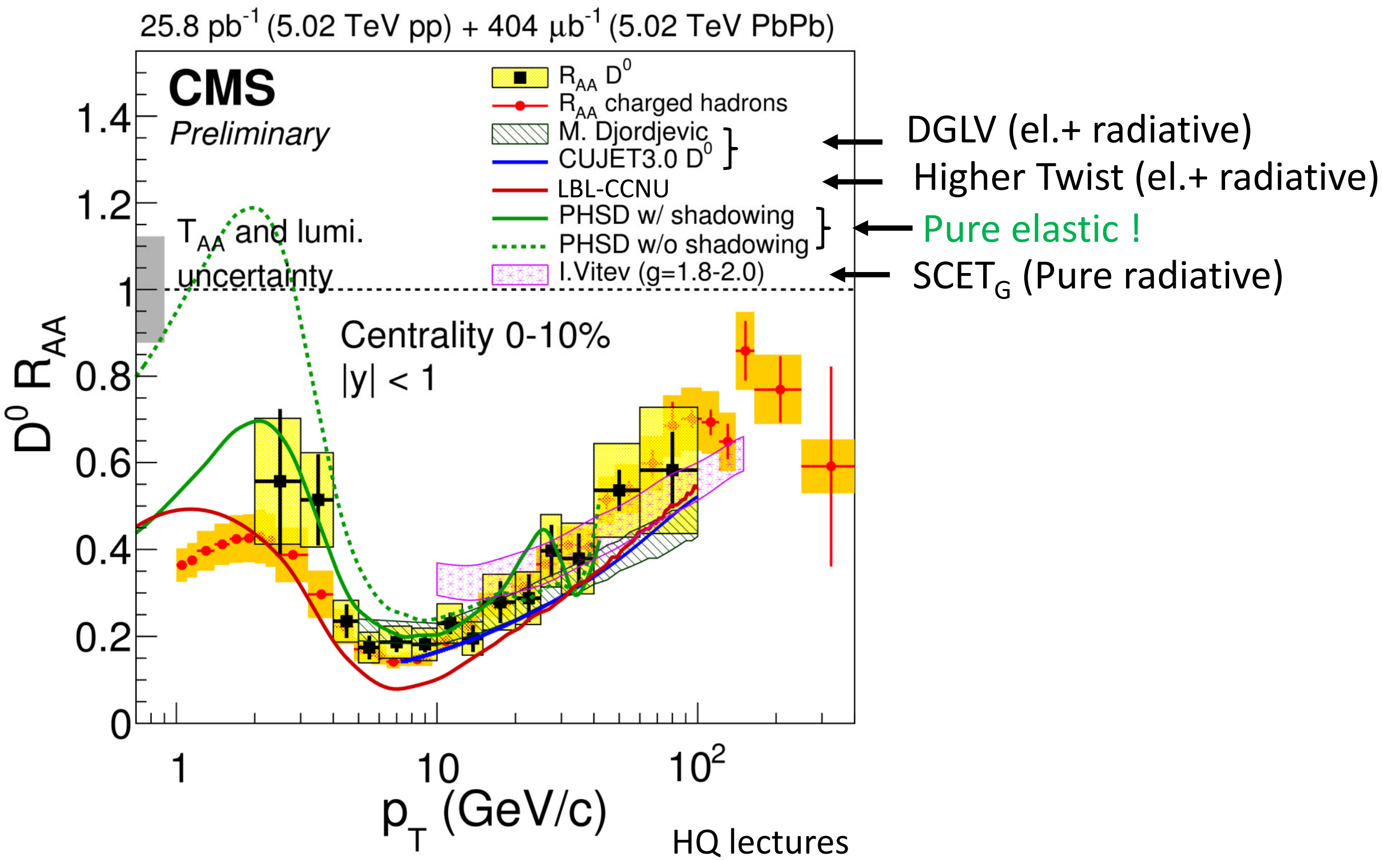
HF Transport, ECT* 2021
https://indico.ectstar.eu/event/98/contributions/1927/

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…



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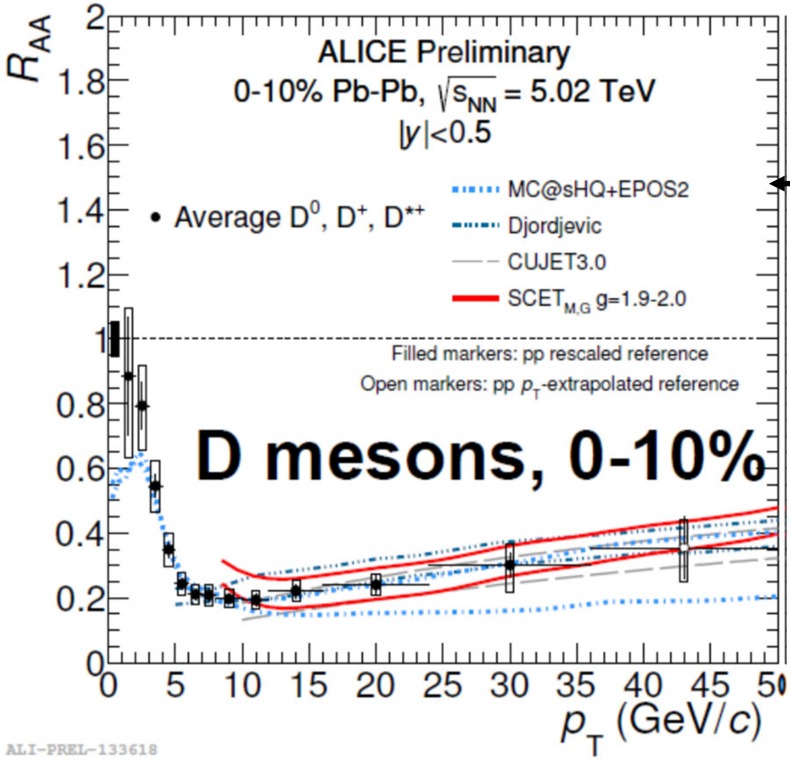


BDMPS (« infinite » path length regime)

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.

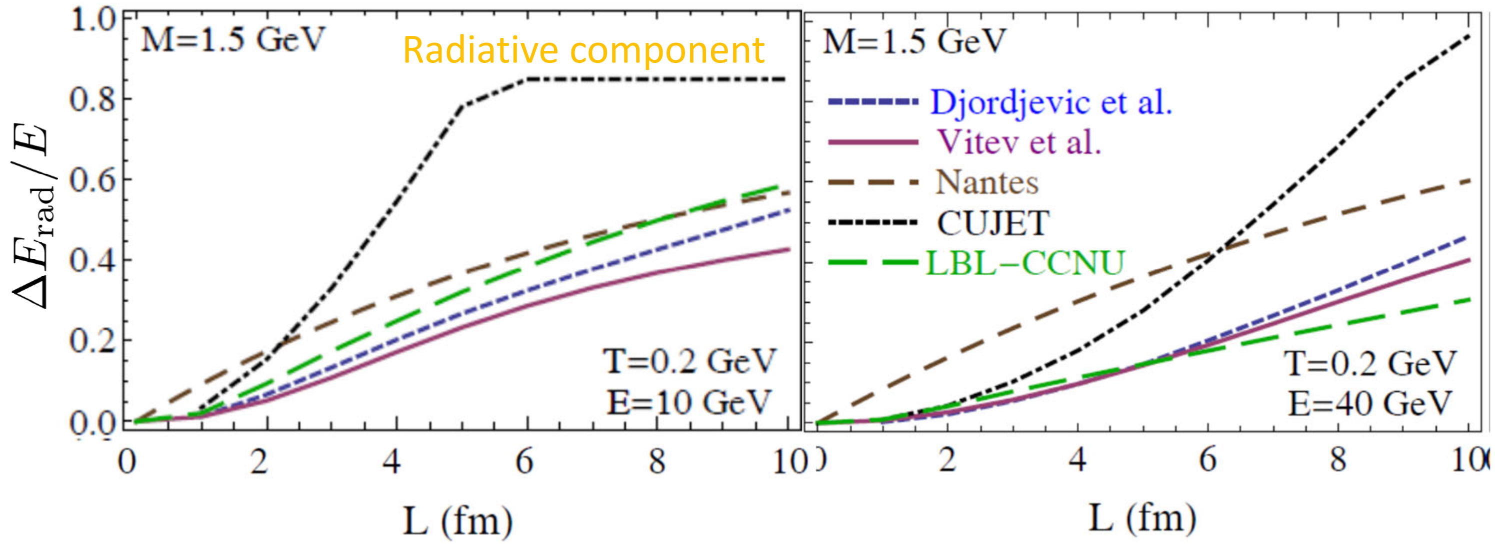
Beware : $\hat{q}$ is « just » an indirect result in some of those formalisms

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

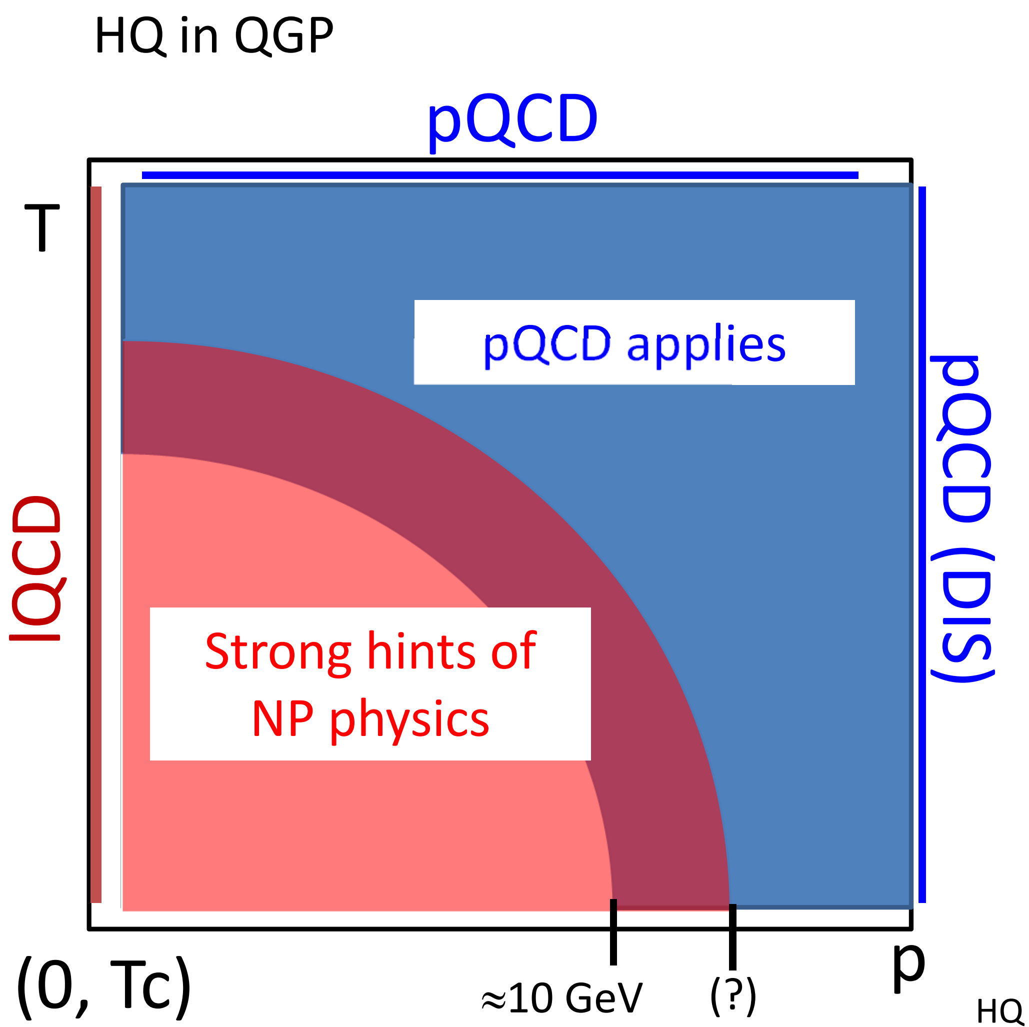
Comparing some callibration curve for main approaches:



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

Conclusions for Open Heavy Flavors



- 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 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.