COST THOR Working Group I & II & GDRI Meeting
Lisboa 2018, May 11-14

Open Heavy Flavors in MC: an overview

Outline

- Introduction and structuration
- Understanding the $R_{AA} - v_2$
  - From a low p_T perspective: transport coefficients
  - From a high p_T perspective: pQCD
- Higher flow harmonics
- Lessons from recent collective initiatives (bulk, hadronization,transport,…)
- Prospects and future strategies (including other observables)
- Conclusions

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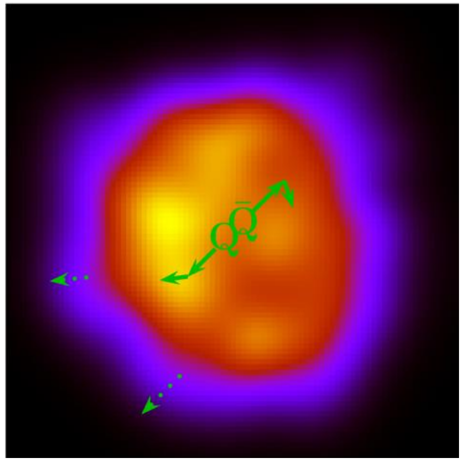
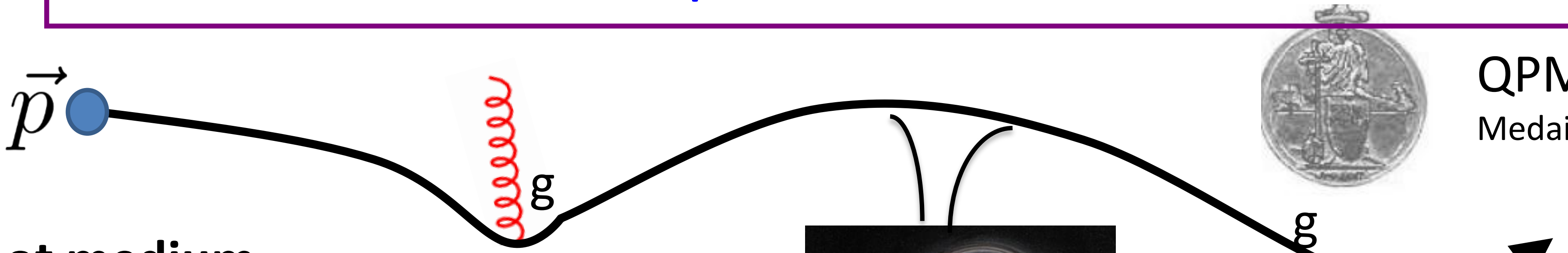
Why open heavy flavors in A-A ?



1. Φ: Produced early, number conserved through time evolution (even at LHC) ⇒ signature (hard probes) of early (hot) phase
2. Φ: *Strongly affected by the QGP phase (up to factor 5 in the final spectrum)*
3. Φ: Weakly affected by late time evolution (heavy, colour transparency)
4. Interpretation: Allows physical picture based on physical scales ($t_{relax} \propto m_Q/T^2 \Rightarrow$ clear hierarchy for s, c and b)
5. Theory: Allows *some* pQCD calculations for the initial production and annihilation,…
6. Theory: …

Usually advocated as an ideal *probe* of dense matter

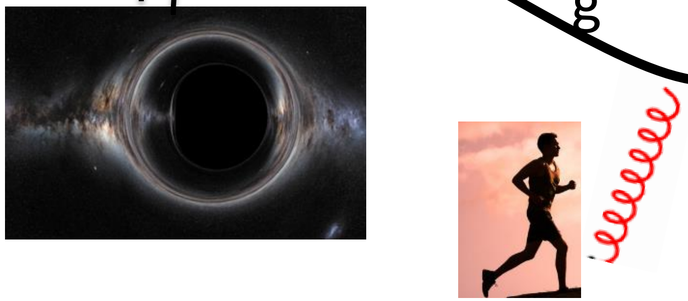
Transport coefficients



QPM (Queen's Police Medail)

HQ in hot medium…

… interacting with various objects



Quasi random process =>

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

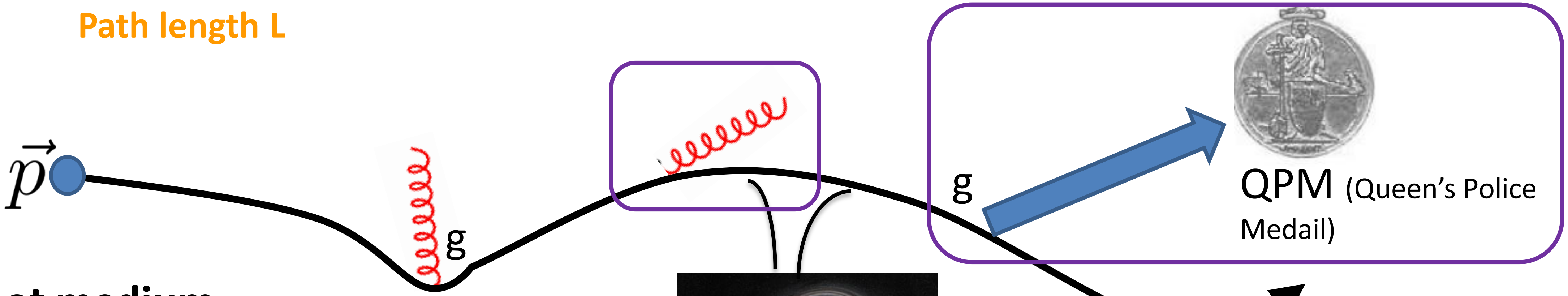
$$\frac{d}{dt}\langle\vec{p}_{T,i}\vec{p}_{T,j}\rangle = \kappa_T(\vec{p},T)\delta_{i,j} \qquad \kappa_T[\mathrm{GeV}^2\mathrm{fm}^{-1}]:$$ Transverse diffusion coef. (p space) ; $\boxed{\hat{q} = 2\kappa_T = 4B_0}$

Similar in longitudinal direction $\qquad \kappa_L[\mathrm{GeV}^2\mathrm{fm}^{-1}]:$ Longitudinal diffusion coef.

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

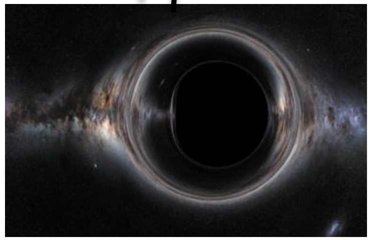
Transport coefficients and inelastic processes

Path length L



HQ in hot medium…

… interacting with various objects…

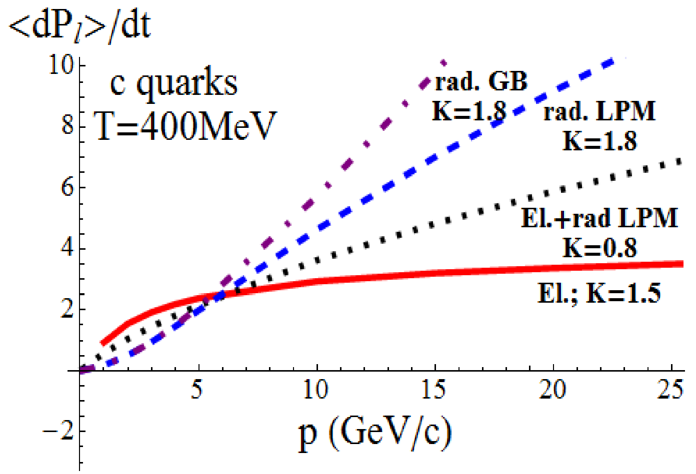


… and emitting some objects

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

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

Seeked ransport coeff.



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

Transport coefficients at low momentum p≈m_Q

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

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

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

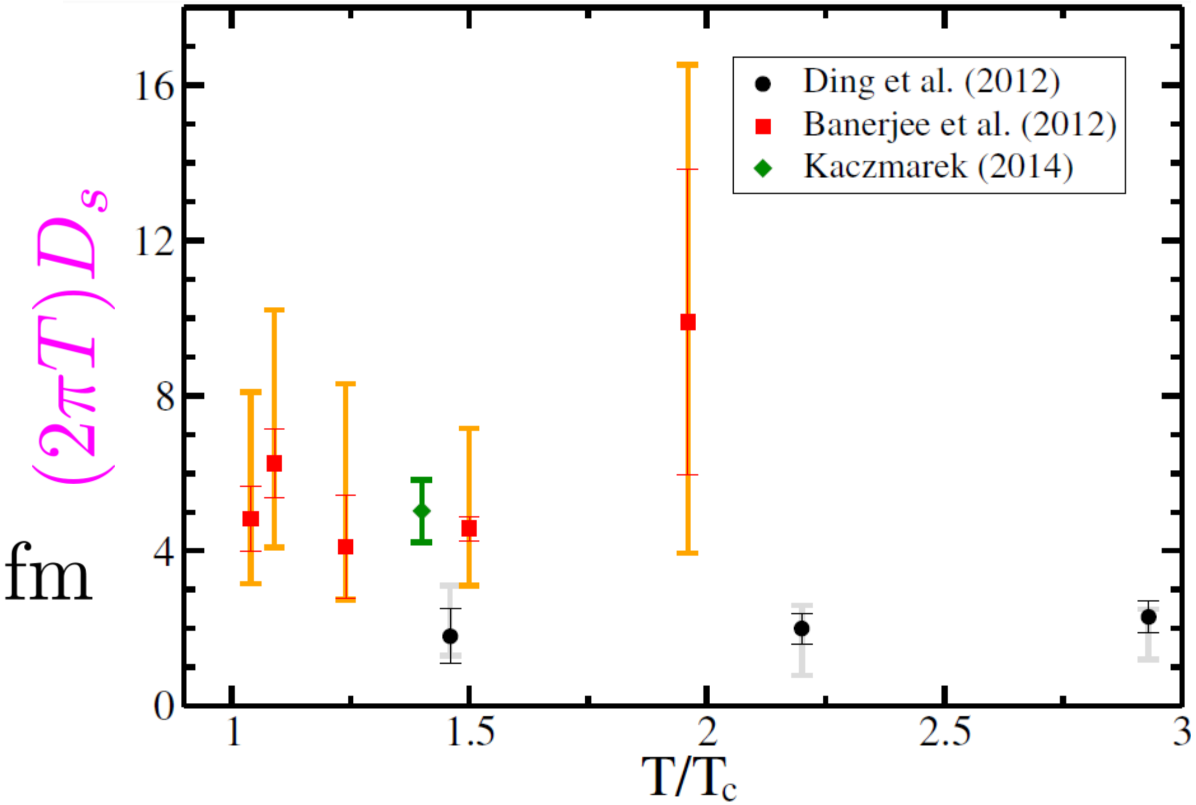
$$(2\pi T)D_s = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q\eta_D} \Rightarrow \tau_{\rm relax} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$$

Gauge for the coupling strength

lQCD results

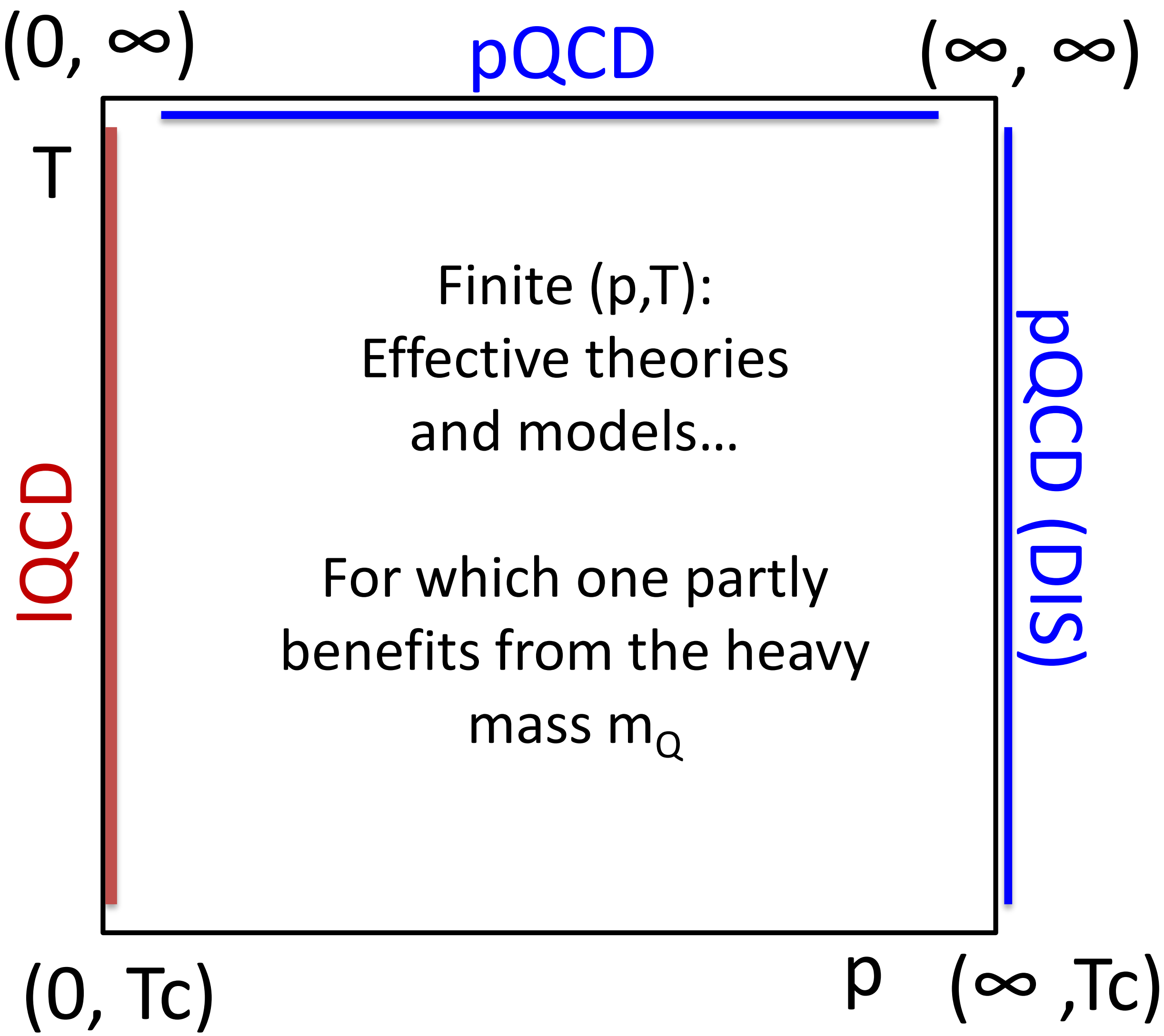
The sole direct rigorous calculation of the transport coeff to my knowledge

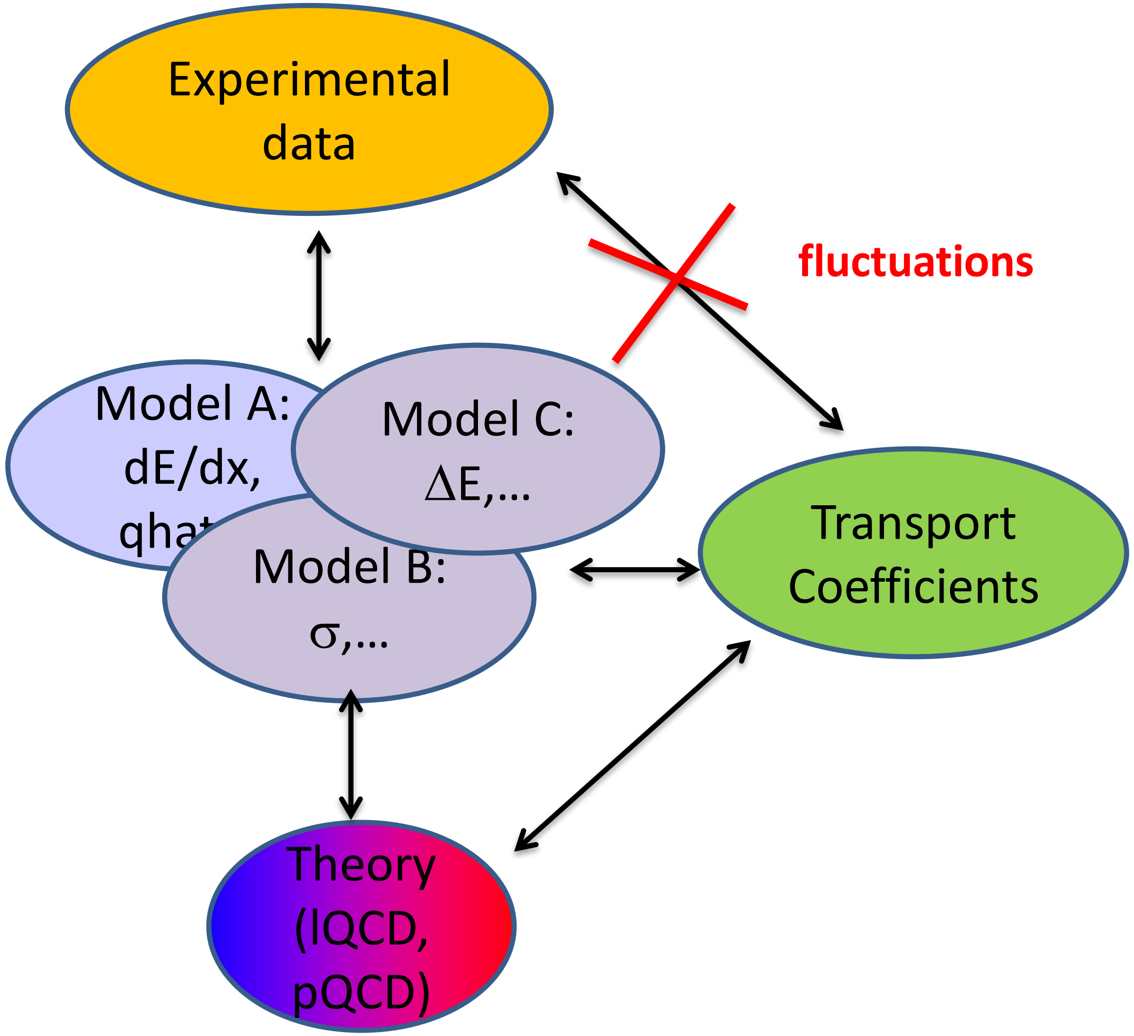
$$\tau_{\rm relax}(T_c) \approx m_Q[\mathrm{GeV}] \times (3 \pm 1.5)\ \mathrm{fm}$$



Lanscape of HF theory and modeling in URHIC

Transp. coeff. $\eta_D, \kappa_T, \kappa_L$

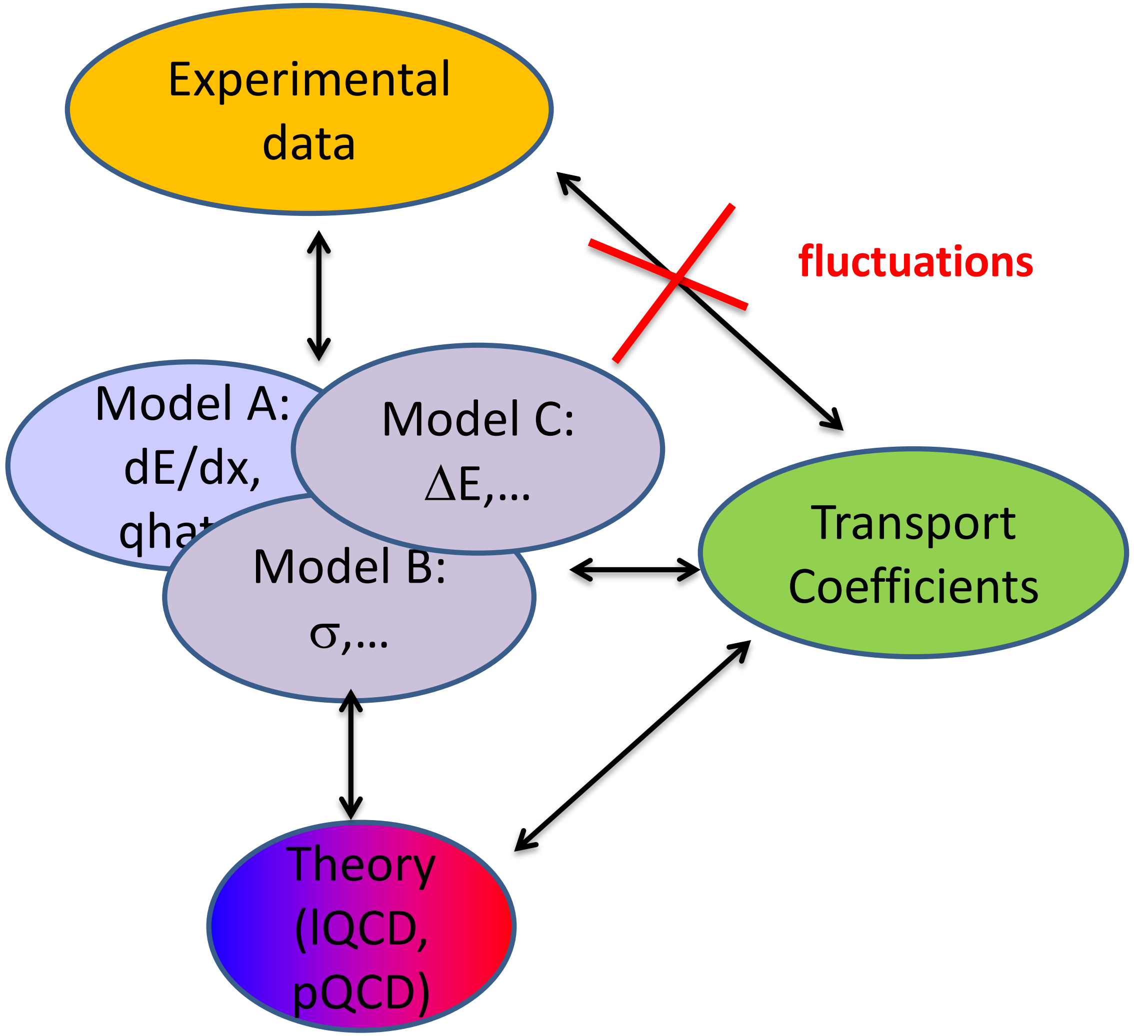




Today Stakes and Motivation

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

Big motivations for this talk



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

A bit of structure

HQ propagation in QM & URHIC…

Effects and consequence in various systems

See Fabio’s talk

Core ingredients:

HQ – (local) Coupling to hot matter

Transport of HQ in medium

Hadronization process at FO

Transport coefficients

Effective lagrangian,
Effective potential,
Effective DOF
…

Transport equation,
Path integrals,…

See Elena’s talk

Theoretical understanding of other QGP aspects

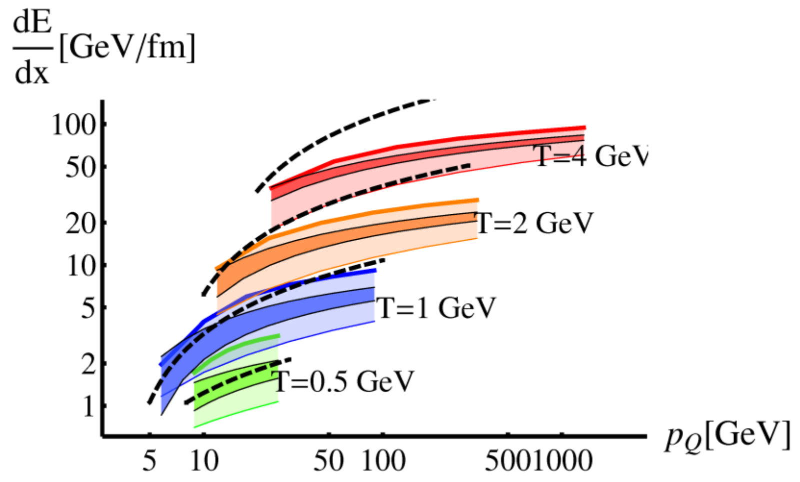
lQCD

pQCD inspired models (f.i. Nantes)

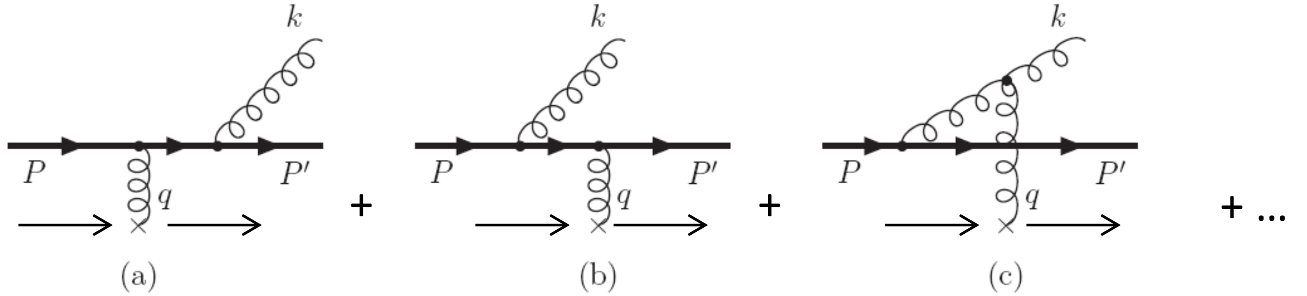
Colisional component

- 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,…

Quasi particle models (f.i DQPM)

- Nonperturbative effects near Tc are captured by αs (T), leading to thermal masses/widths, determined from fits to lQCD EoS.

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

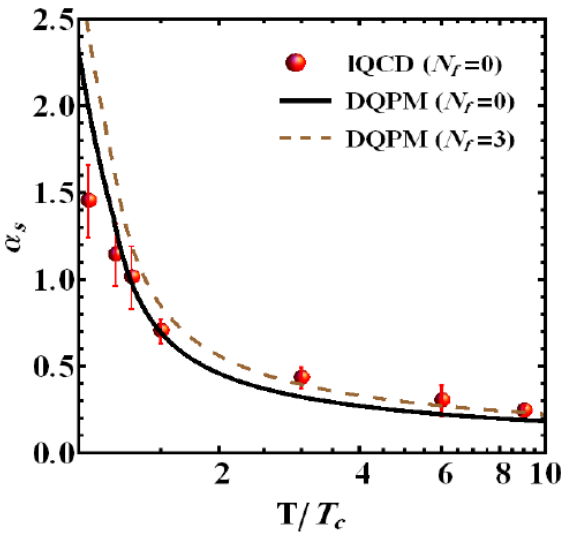
- Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

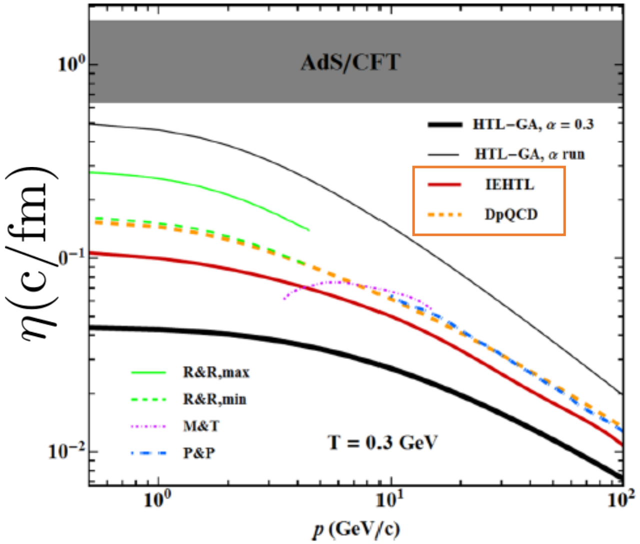
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

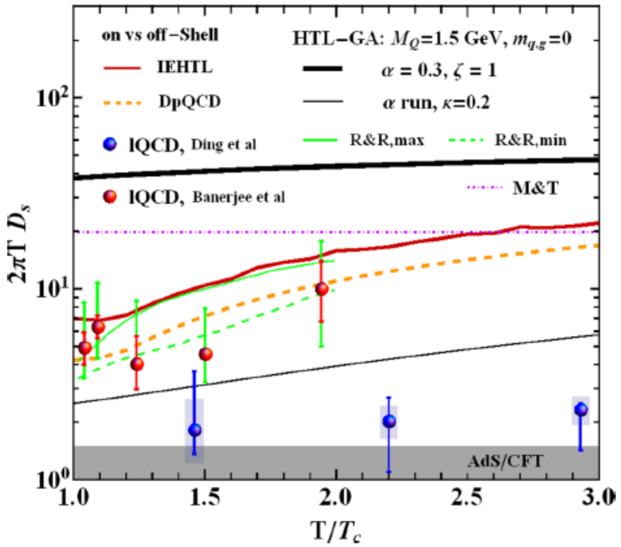
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

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

But also CATANIA







Potential models (TAMU)

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

D. Cabrera, R. Rapp PRD 76 (2007); H. van Hees, M. Mannarelli, V. Greco, R. Rapp PRL 100 (2008)

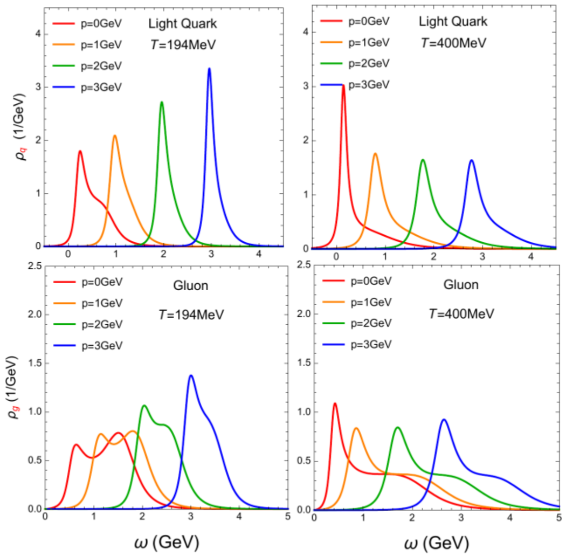
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

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

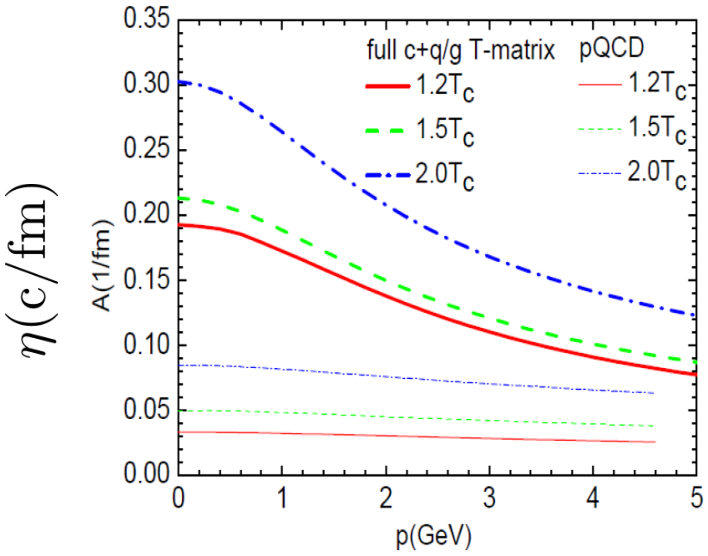
- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions!

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

- Implemented through Langevin dynamics in hydro evolution or in URQMD



No good q-particle at low p



Large coupling at small p_Q

A bit of structure

No Model approach

Effects and consequence in various systems

See Elena's talk

Core ingredients:

~~HF – (local) Coupling to nuclear matter~~

~~Effective lagrangian, Effective potential.~~

« simple » Transport of HQ in medium

Most Frequently: Langevin

Hadronization, esp. « recombination »

Transport coefficients

from lQCD

POWLANG lQCD

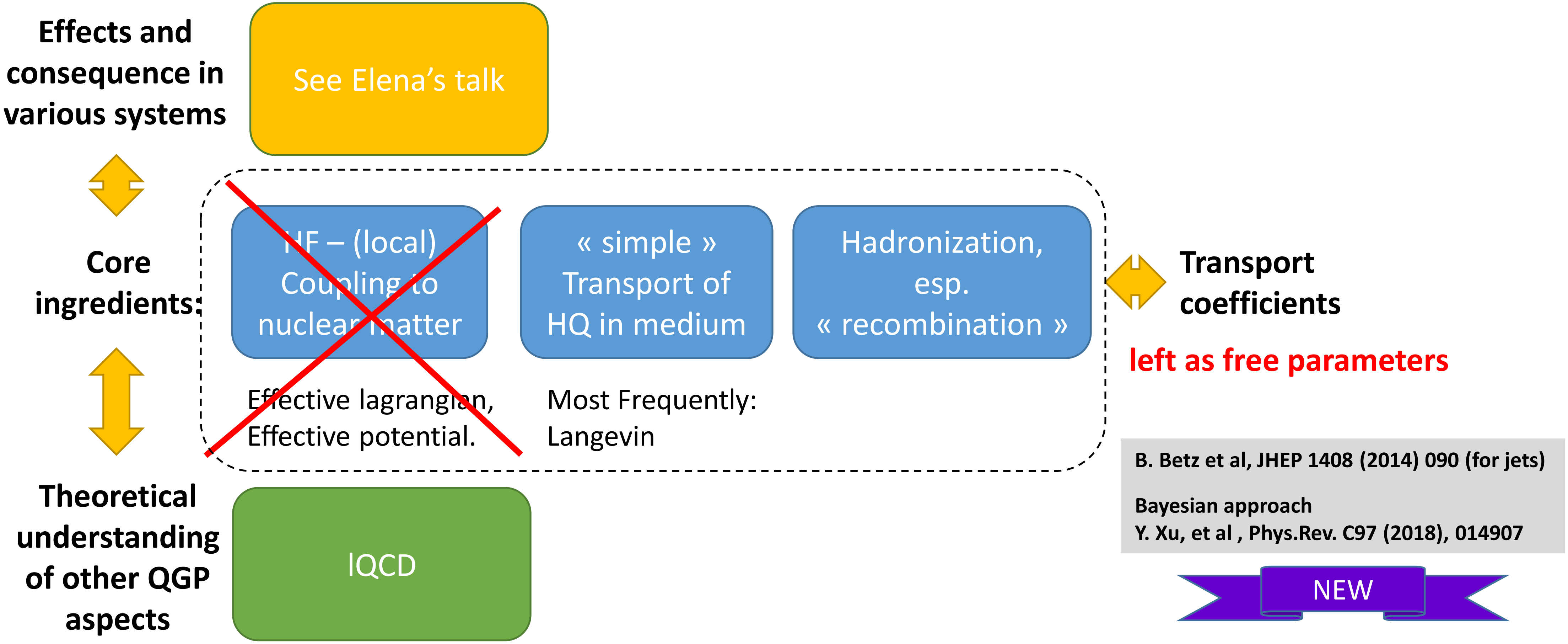
Beraudo, QM 2018

Theoretical understanding of other QGP aspects

lQCD

A bit of structure

No Model approach



A bit of structure

HQ propagation in QM & URHIC…

Effects and consequence in various systems

Initial HQ conditions

Global bulk dynamics

D meson propagation in hadronic phase

(E,B) field

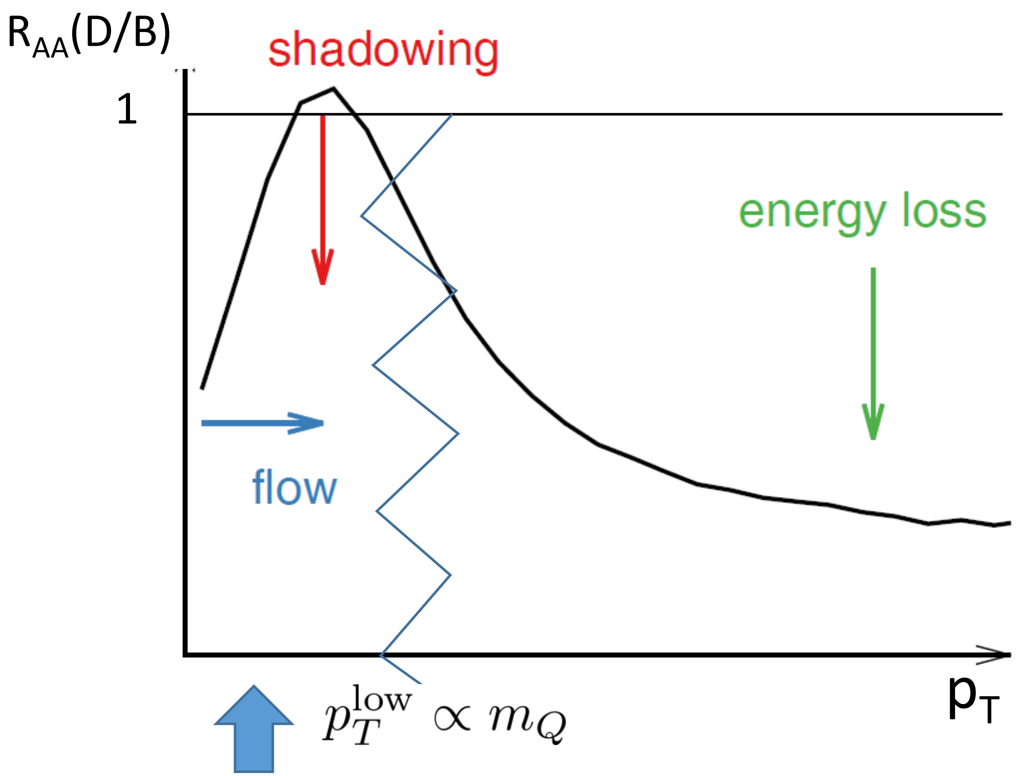
Extra ingredients

Core ingredients

Theoretical understanding of other QGP aspects

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*

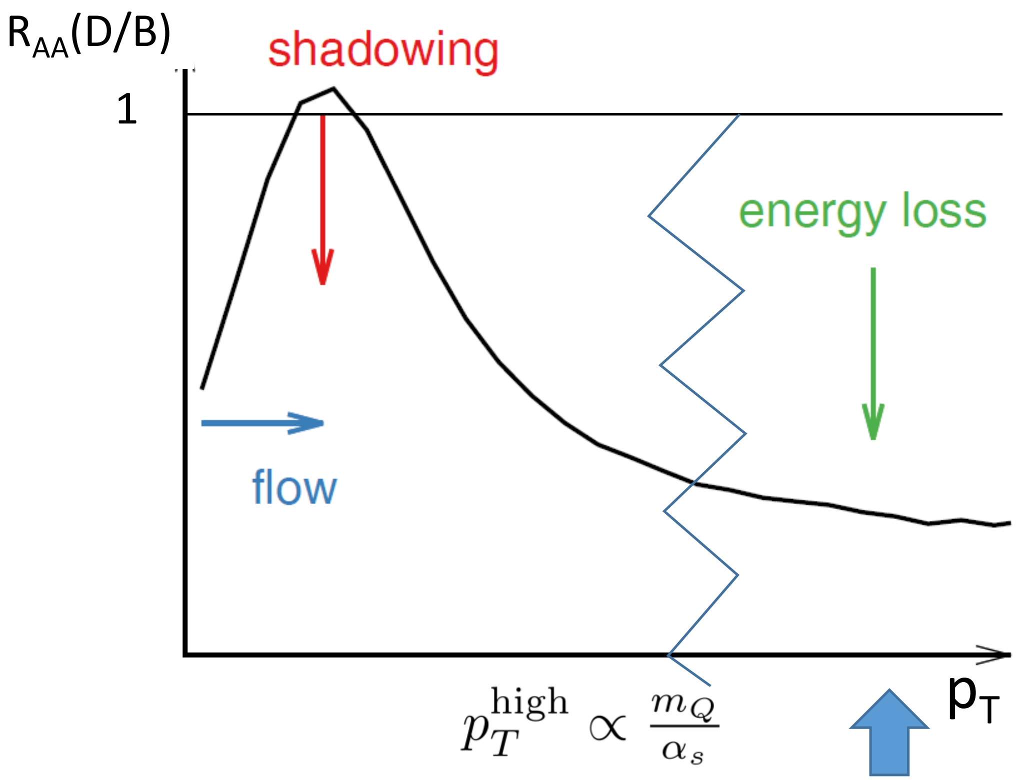
Quenching & energy loss: due to

- 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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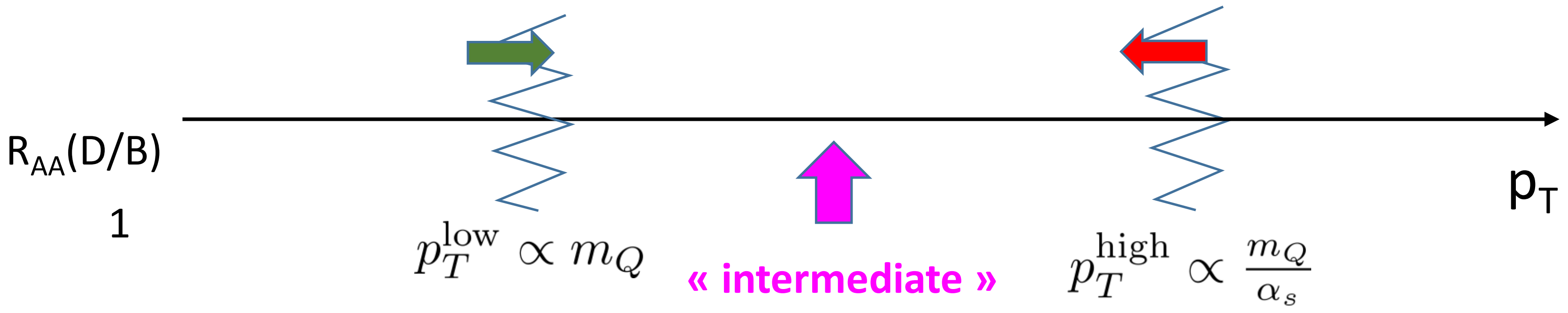
shadowing: due to *initial state nuclear effects*

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

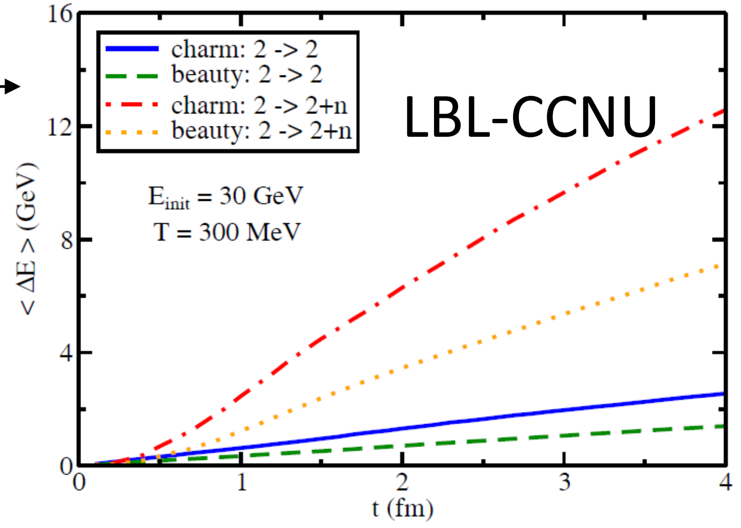
- Dominated by radiative energy loss (with important coherence effects: $\Delta E_{\rm rad} \propto C_A \hat{q} L^2$)
- Eikonal regime (propagation along straight lines)
- 1 single transport coefficient dominates the whole physics: $\hat{q} \propto \kappa_T$
- HQ do not equilibrate with the medium
-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

See François's talk

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 $\hat{e}_2$



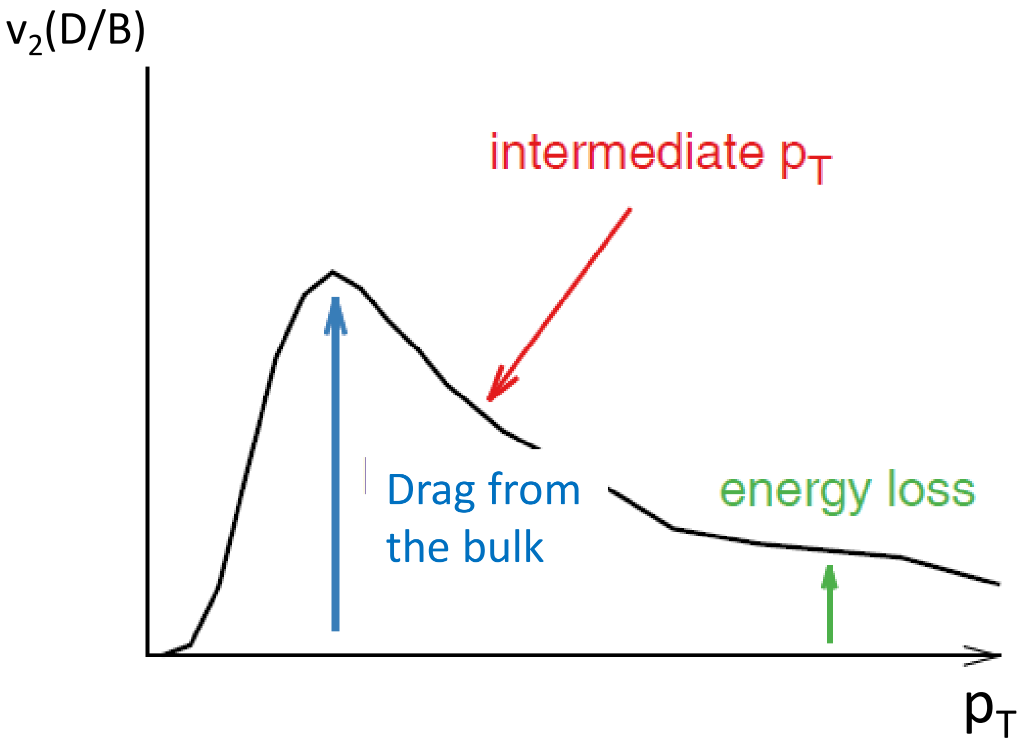
S. Cao et al, Phys. Rev. C 94, 014909 (2016)

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

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 »

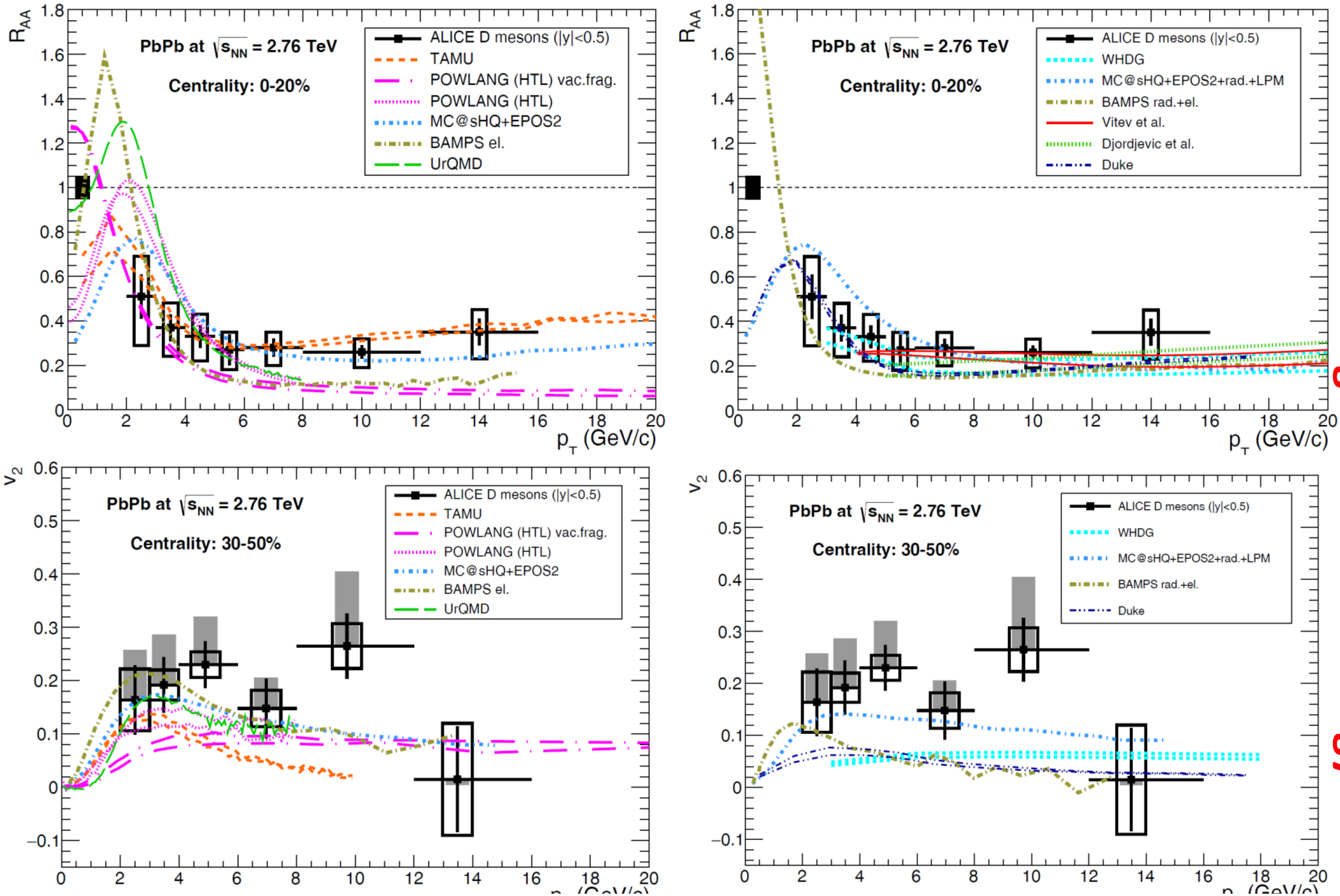
Models & Effective Theories

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

Red: Transport models

Models vs DATA at LHC (Sapore Gravis Report compilation)

Purely elastic scatterings

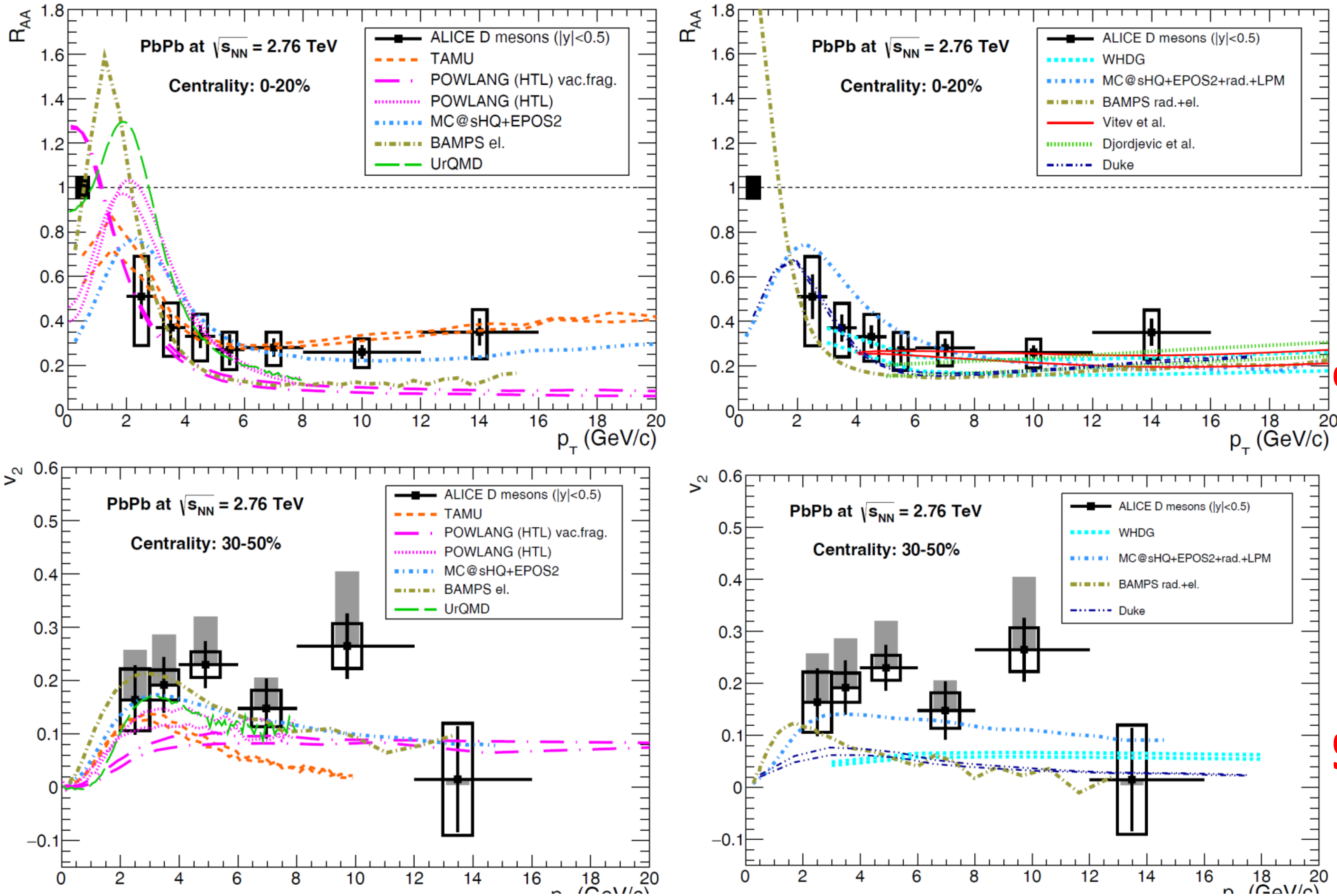


Elastic scatterings + radiative energy loss

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

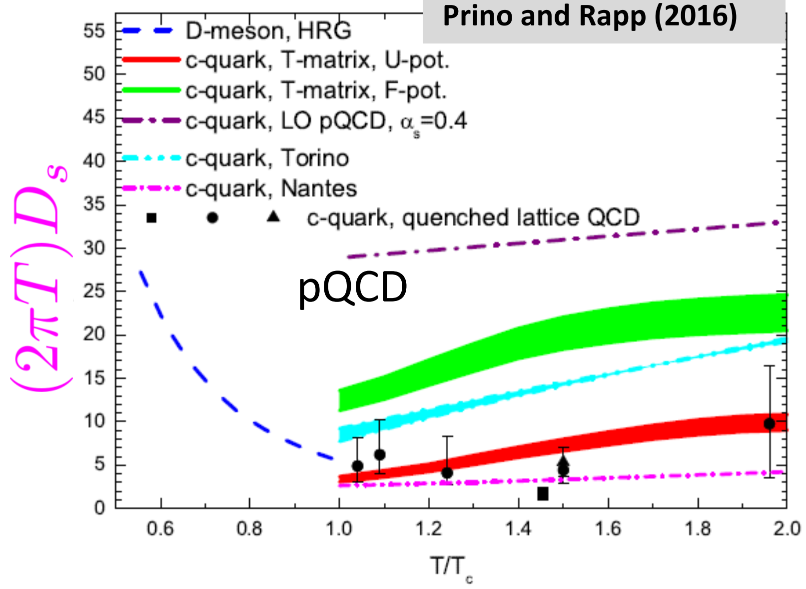


Elastic scatterings + radiative energy loss

Some advocated tension between R_{AA} and v_2

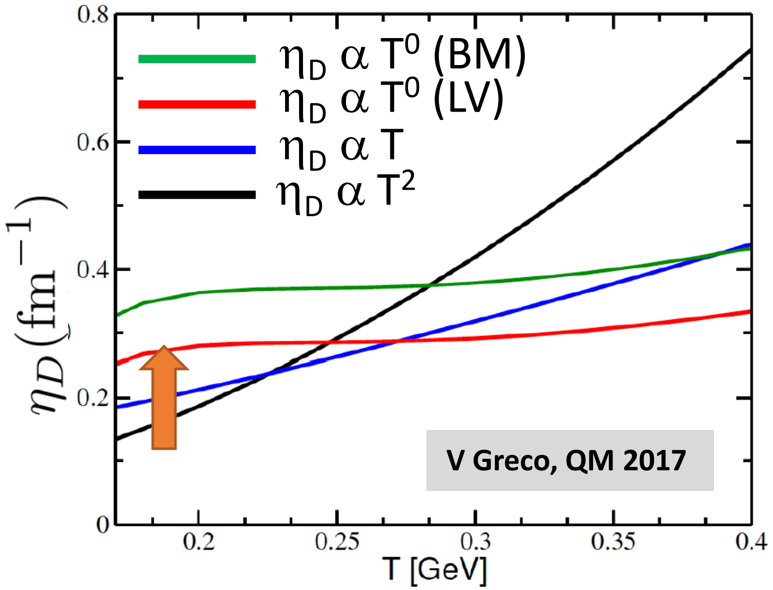
Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

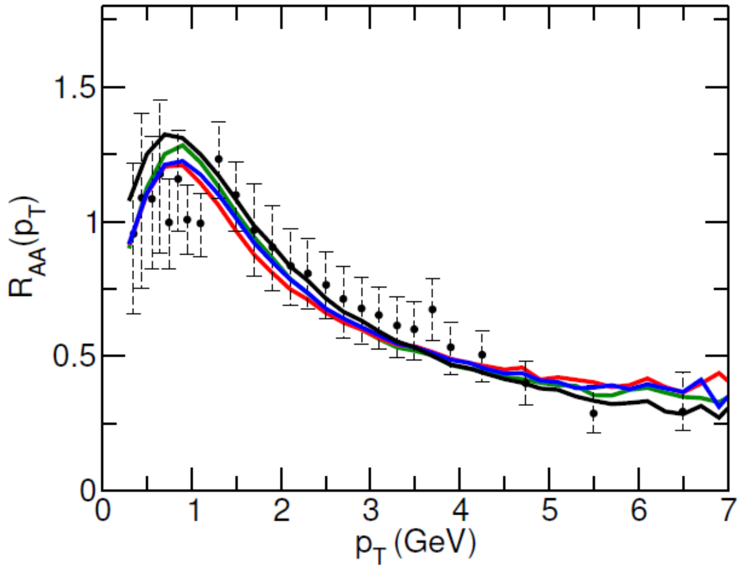
Prino and Rapp (2016)

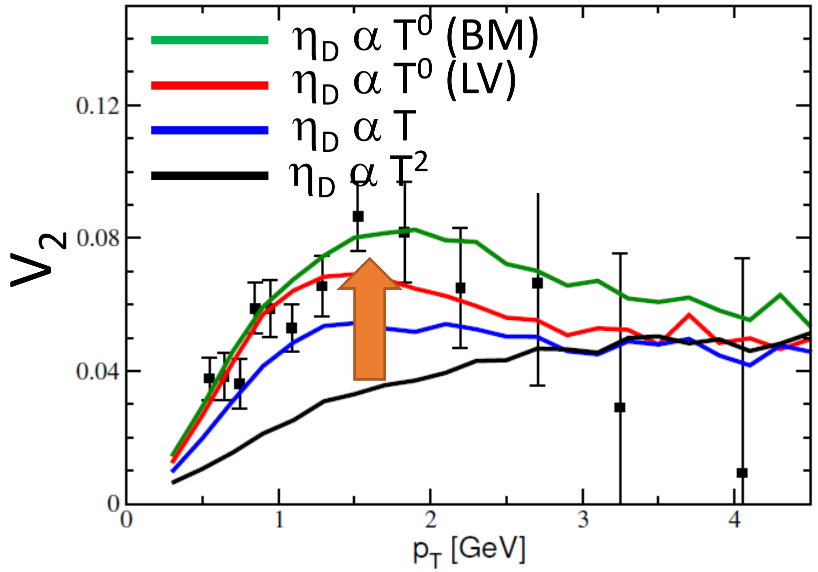


$$\tau_{\text{relax}} = \eta_D^{-1} = (2\pi T) D_s \times \frac{m_Q}{2\pi T^2}$$

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







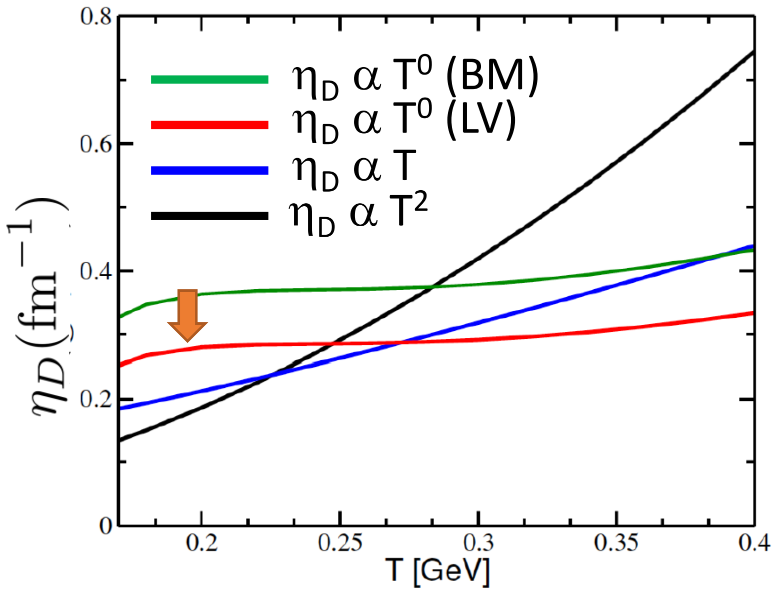
$\eta_D \propto T^2$: pQCD (fixed α_s), AdS/CFT

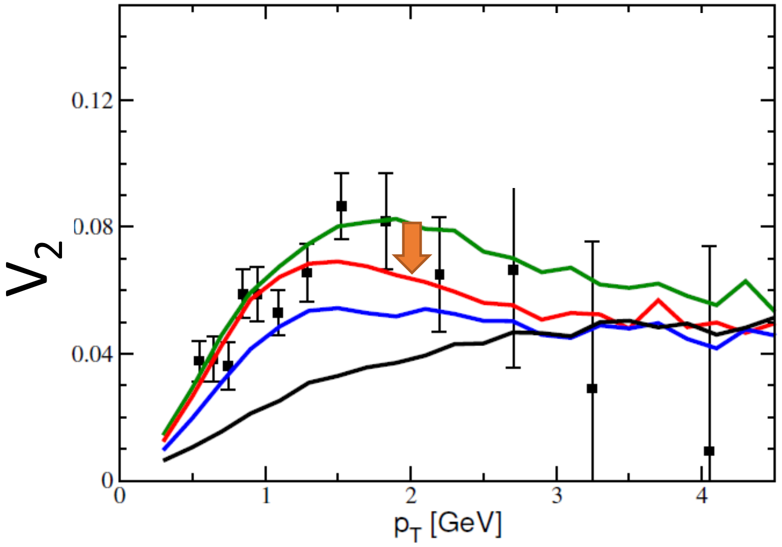
$\eta_D \propto T$: pQCD (running α_s)

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

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





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

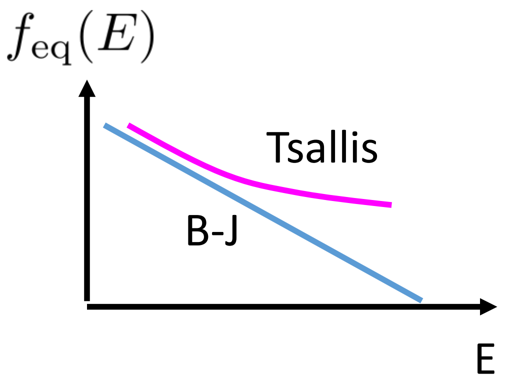
Extra increase from LV => Boltzmann dynamics

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

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

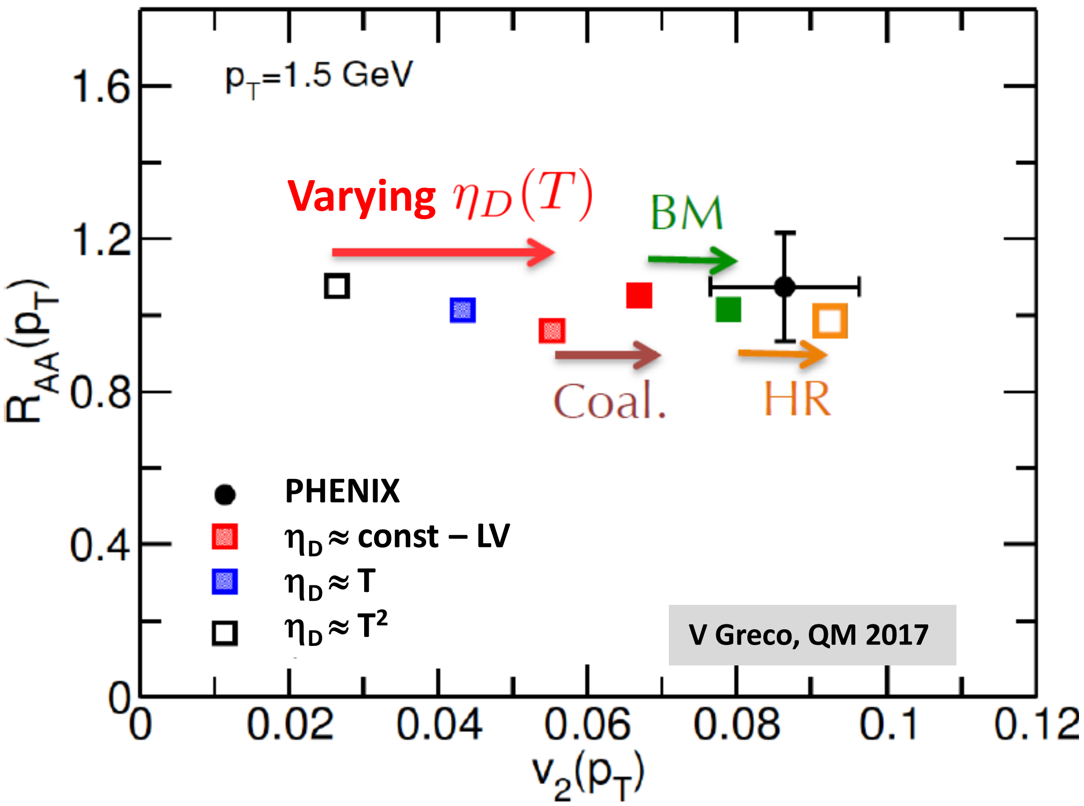
=> Encoding the physics into Langevin scheme, we do not describe properly the fluctuations at large momentum (as seen f.i. in the Tsallis like asymtotic distribution).

=> 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.

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.

NEW

Results from QPM

Francesco Scardina et al., PHYS REV. C 96, 044905 (2017)

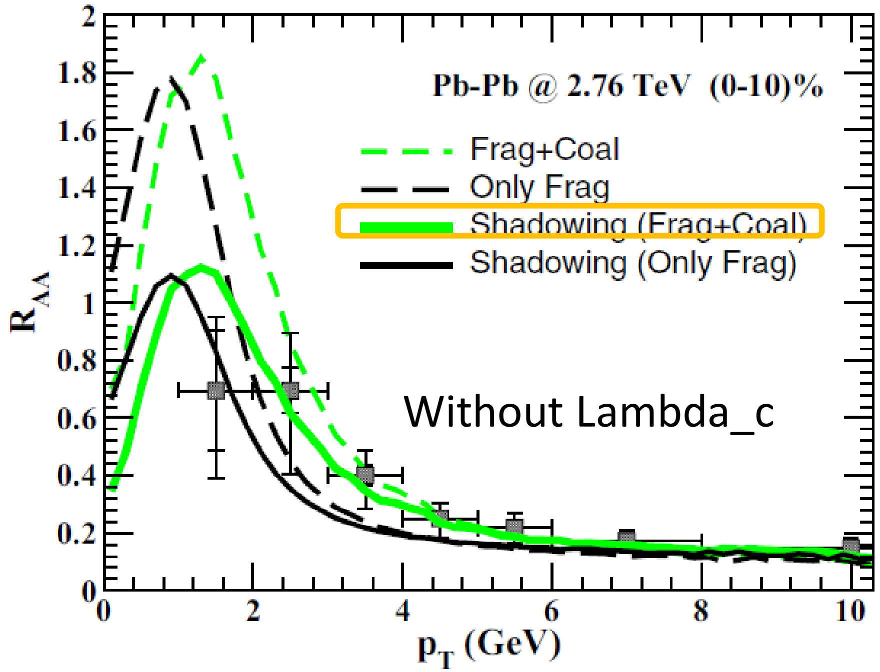
Plumari, QM 2018

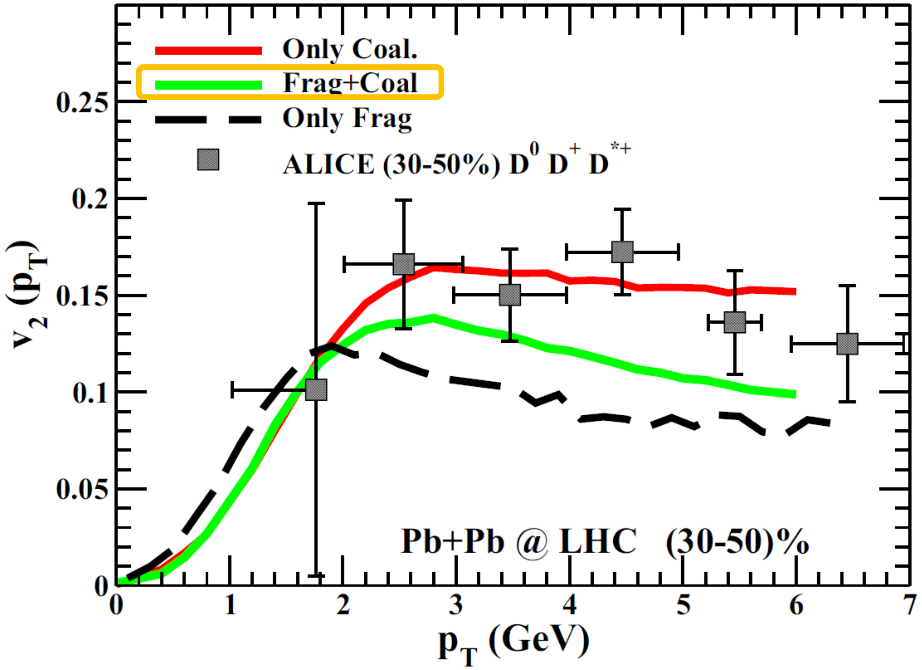
- Nonperturbative effects near Tc are captured by α_s (T), determined from fits to lQCD pressure and interation measure and leading to pretty large thermal masses.
- Bulk of massive partons described by Boltzmann dynamics, with gain and loss term is tuned to a fixed $\eta/s(T)$

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

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

- Hadronization performed through (local) coalescence + fragmentation
- Good common description of R_{AA} and v_2





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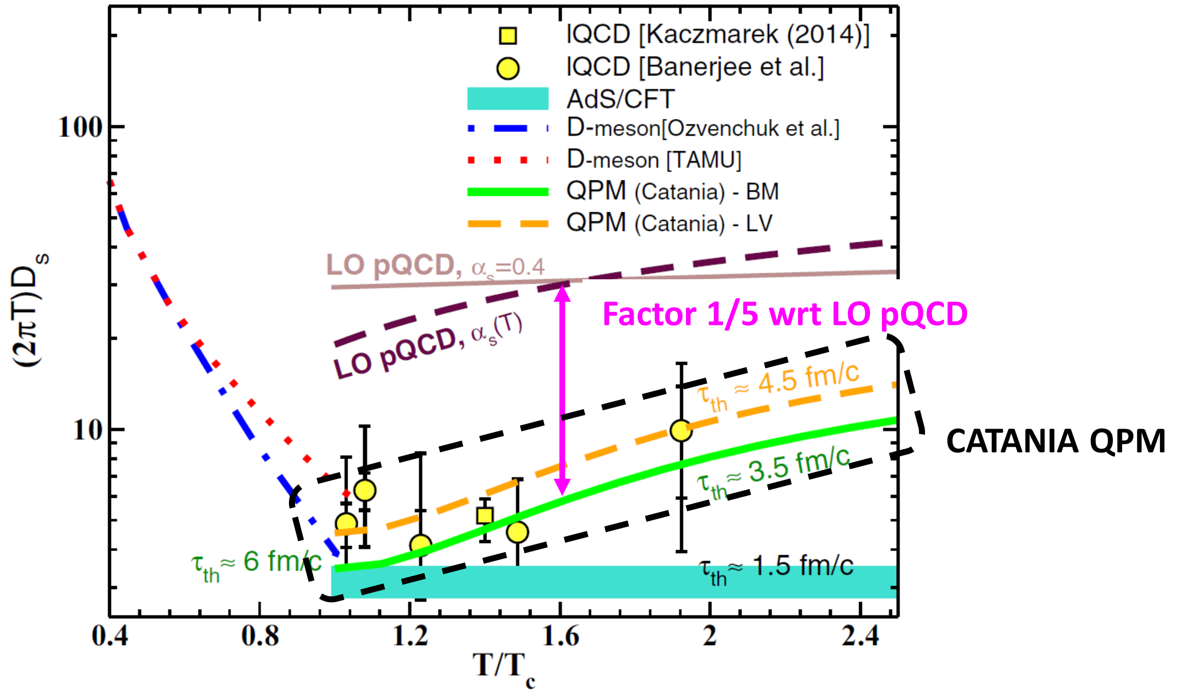
- Bulk of massive partons described by Boltzmann dynamics, with gain and loss term is tuned to a fixed $\eta/s(T)$

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

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

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

…and slowly increasing -> LO pQCD



Data driven extraction of transport coefficients

NEW

Y. Xu et al
arXiv:1710.00807v1

Poster Y. Xu, QM 2018

« 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 $\kappa = \frac{2T^2}{D_s}$

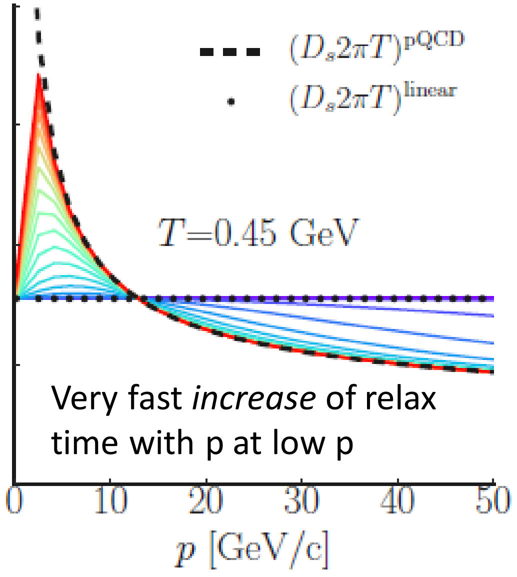
+ coal / frag hadronization and hadronic rescattering

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

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

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

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



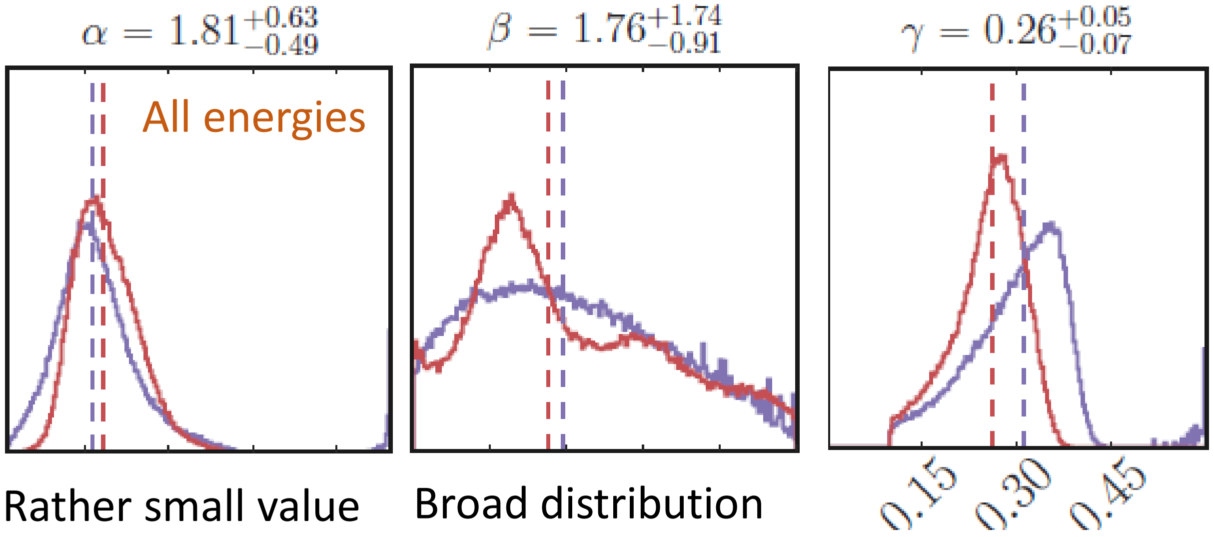
Duke "Bayesian approach"

- 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

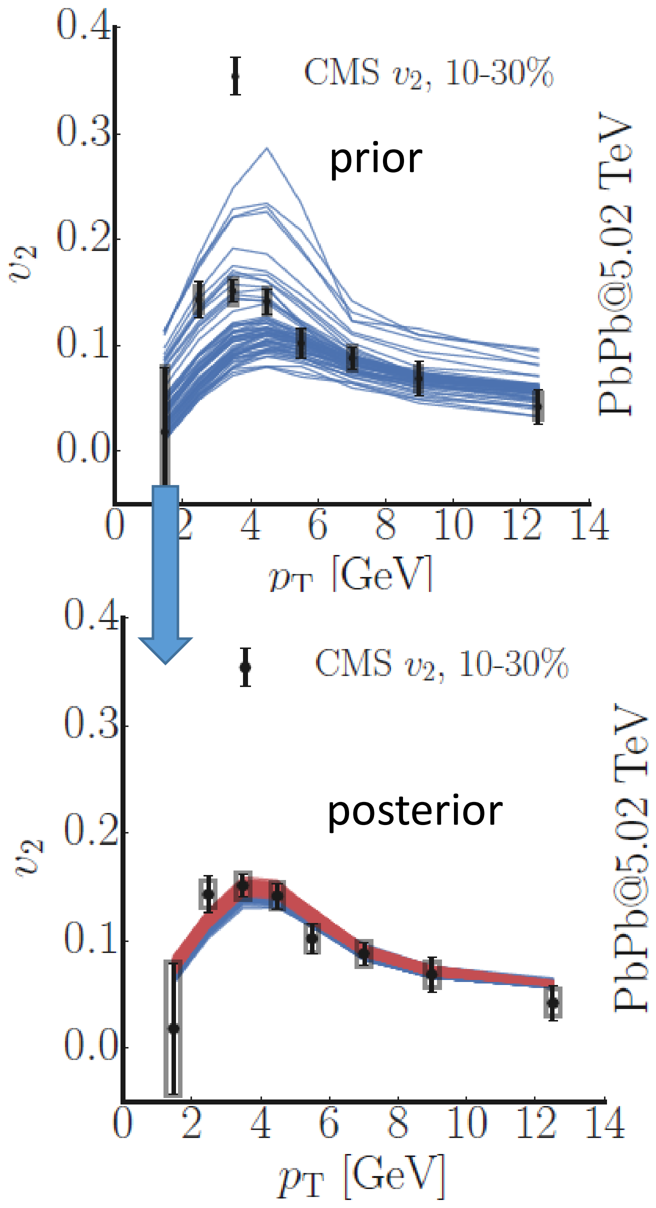
$$(D_s 2\pi T)^{\text{linear}} = \alpha \cdot (1 + \beta (T/T_c - 1))$$

RESULTS

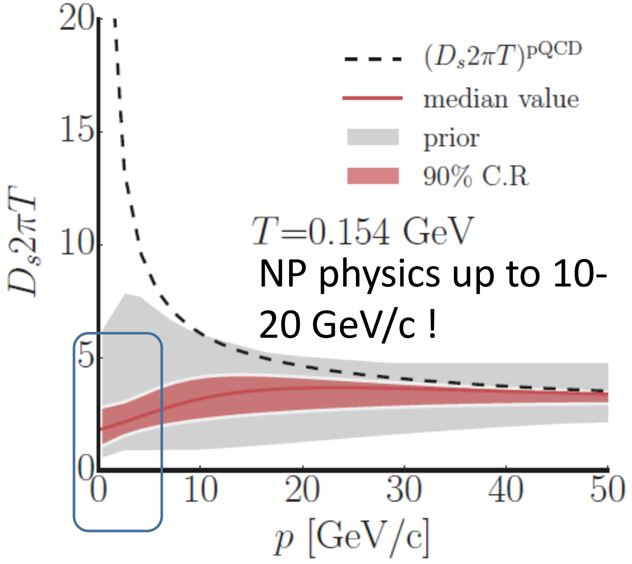


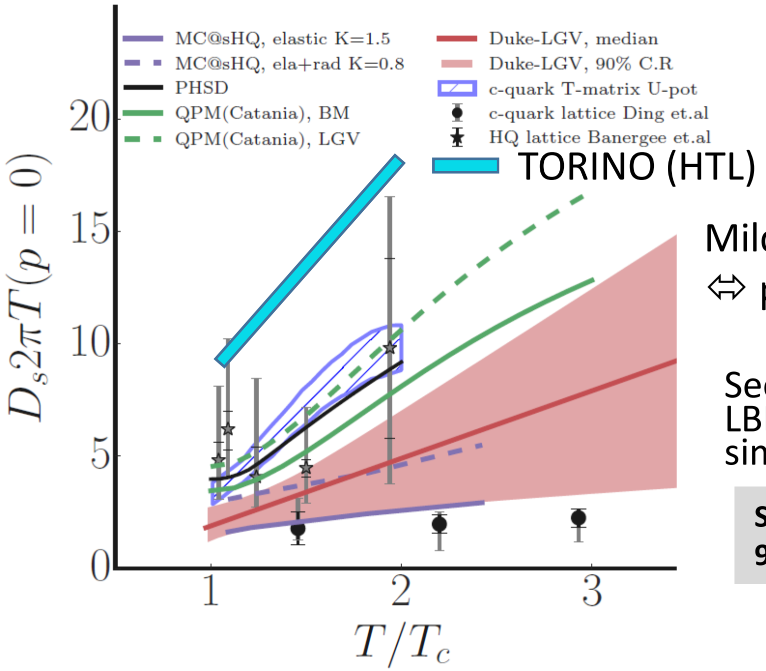
Rather small value
=> strong coupling !

Broad distribution



Duke “Bayesian approach” vs models





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

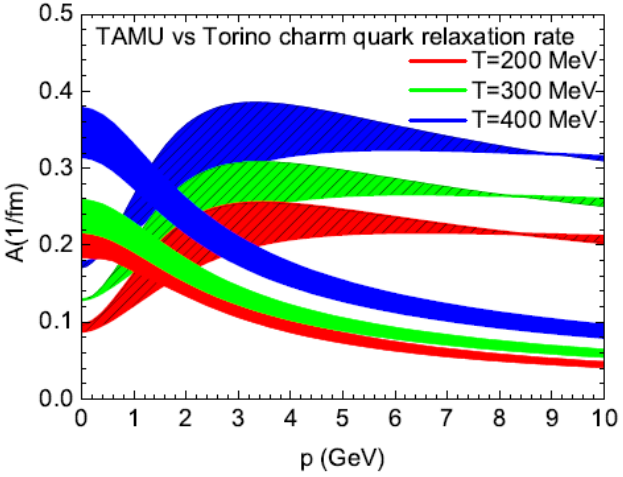
See as well analysis in the LBL-CCNU model with similar conclusions

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

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

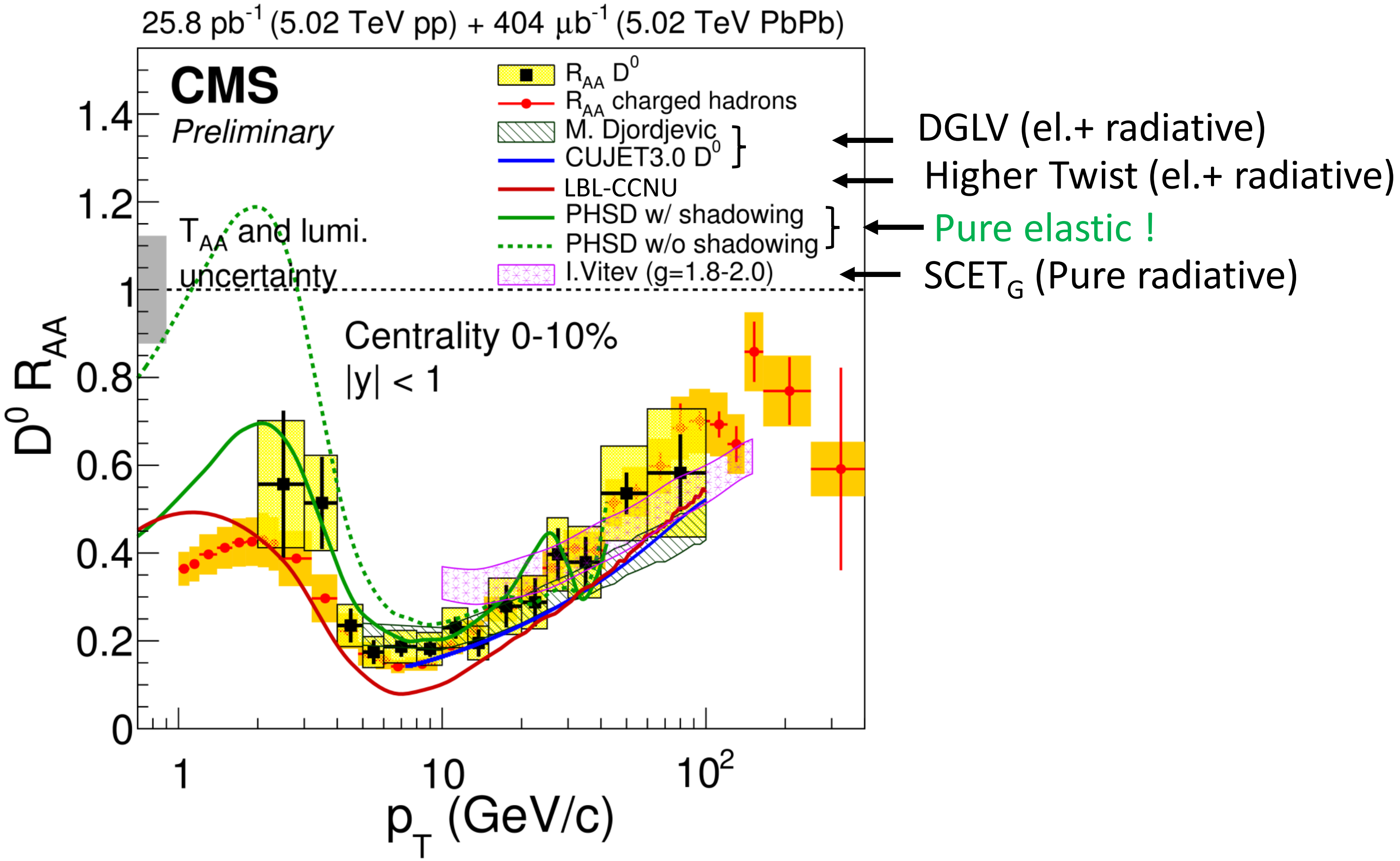
- Does not mean that all models inhold the same physics…
- D_s (p=0) does not represent the full physics (different momentum dependences)
- D_s (finite p) in Duke’s el + rad approach should not be compared to the same quantity in purely elastic models (additional contribution to energy loss due to the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

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



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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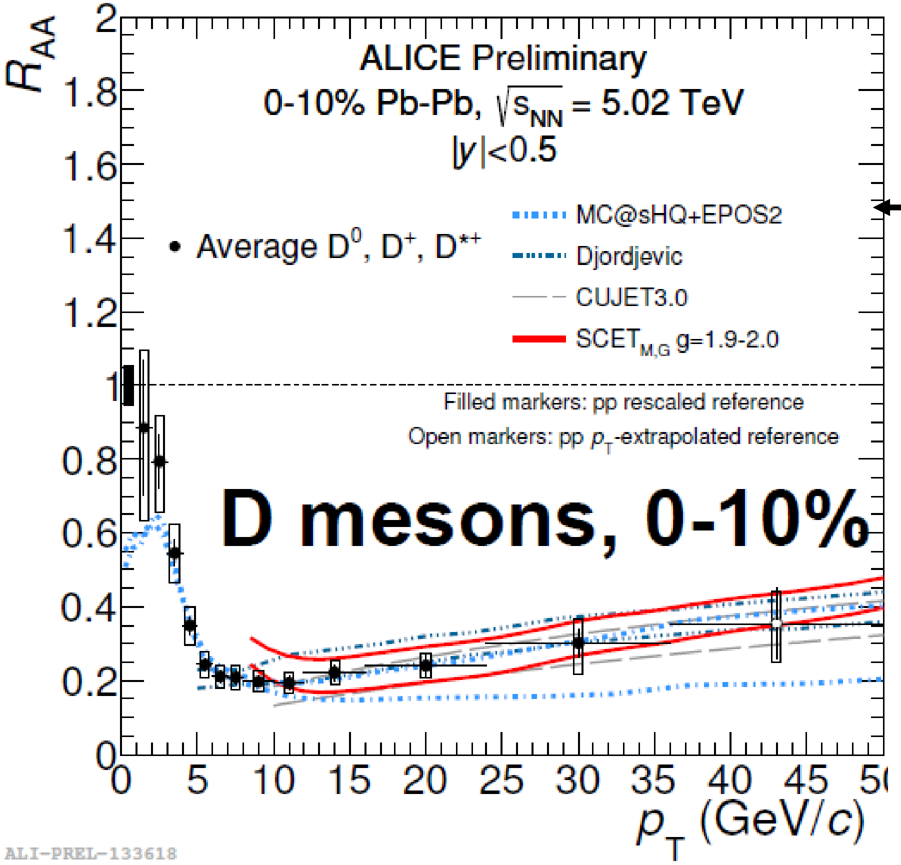


← BDMPS (« infinite » path length regime)

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

M. Djordjevic, QM 2018

As a state of the art representative:

Dynamical Energy Loss:

- dynamical scattering centers,
- finite size QCD medium,
- radiative and collisional energy loss,
- finite magnetic mass,
- running coupling,
- multi gluon emission
- Recently released soft gluon approximation
- Path length fluctuations
- Model evolution according to Bjorken picture leading to better agreement for the v_2

B Blagojevic et al, arXiv:1804.07593v1

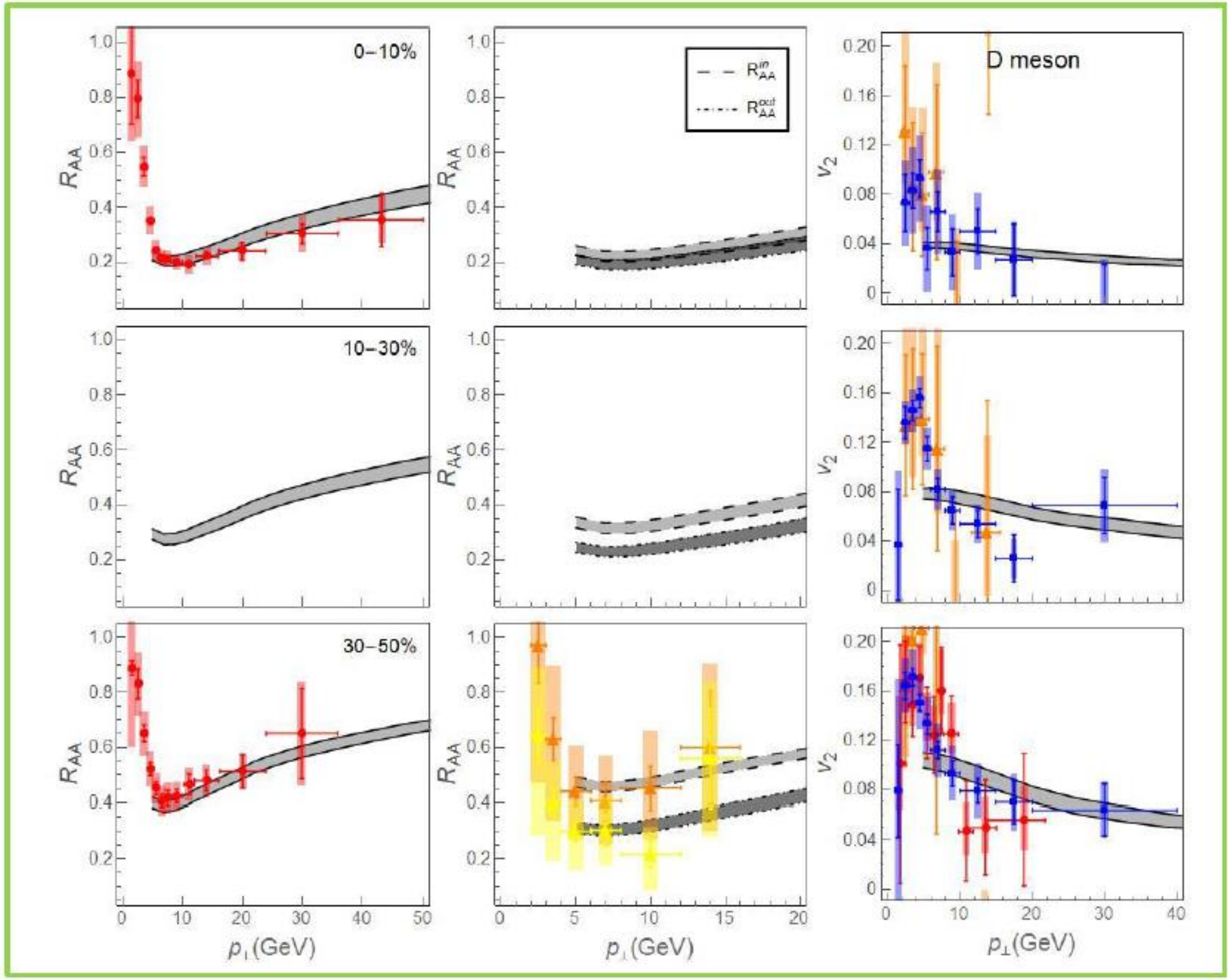
Noticable success in explaining R_{AA} and v_2 of both charged particles AND HF mesons for all centralities

Direction: more realistic evolving medium.

Other recent works

- **Vitev et al: arXiv:1801.00008, JHEP 1703 (2017) 146,…**
- **A. I. Sheikh arXiv:1711.06245**
- **….**

D. Zigic et al, arXiv:1805.03494 and refs therein

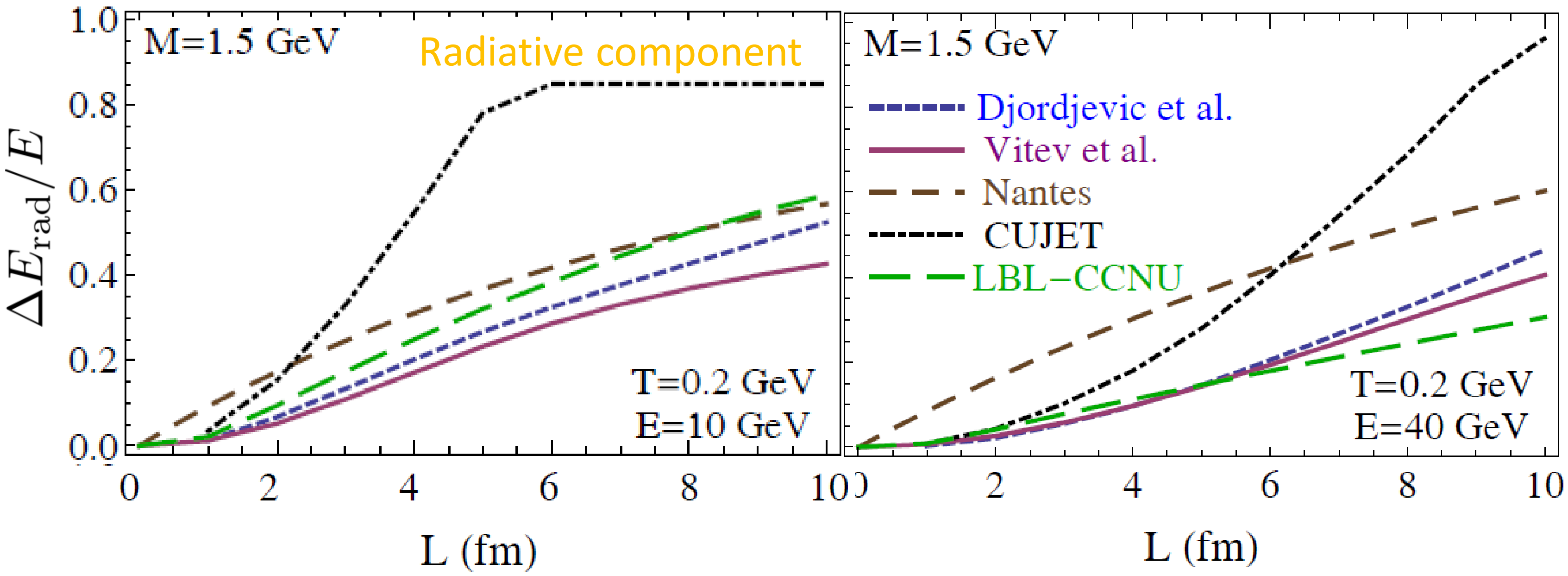


Status of high p_T HQ: prospects

… 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

Status of high p_T HQ: prospects

<u>Other challenges:</u>

- Better understanding of heavy mass effect and medium properties in the radiation (especially on the coherence effects)
- Embedding in a realistic medium
- In a « jetty » picture: Combination of induced Eloss affecting the « initial » DGLAP evolution and the final « on shell » HQ

<u>"Drag Induced Radiation and Multi-Stage Effects in Heavy-Flavor Energy Loss"</u>

S. Cao et al, arXiv:1711.09053

S. Cao, QM 2018

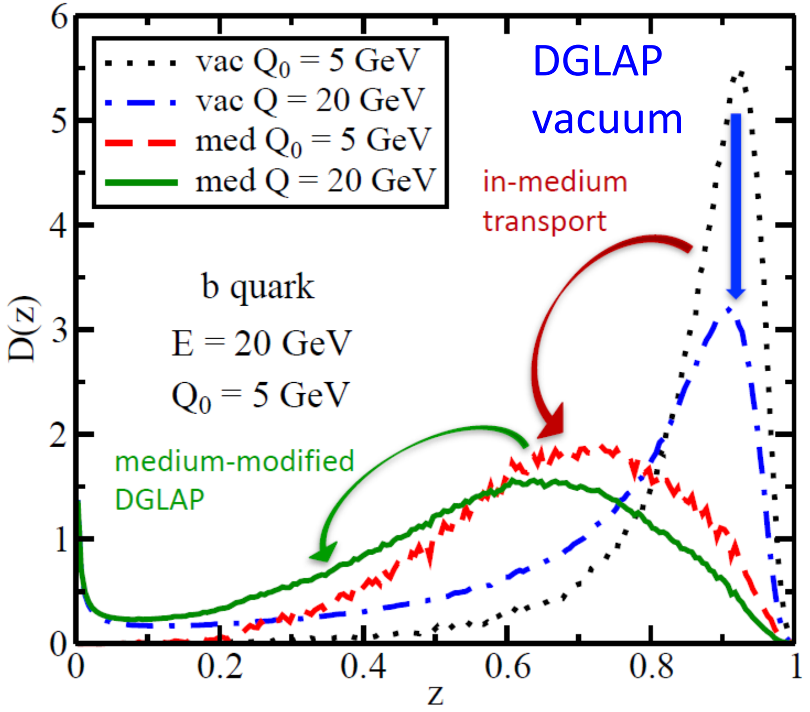
Also poster G-Y Qin

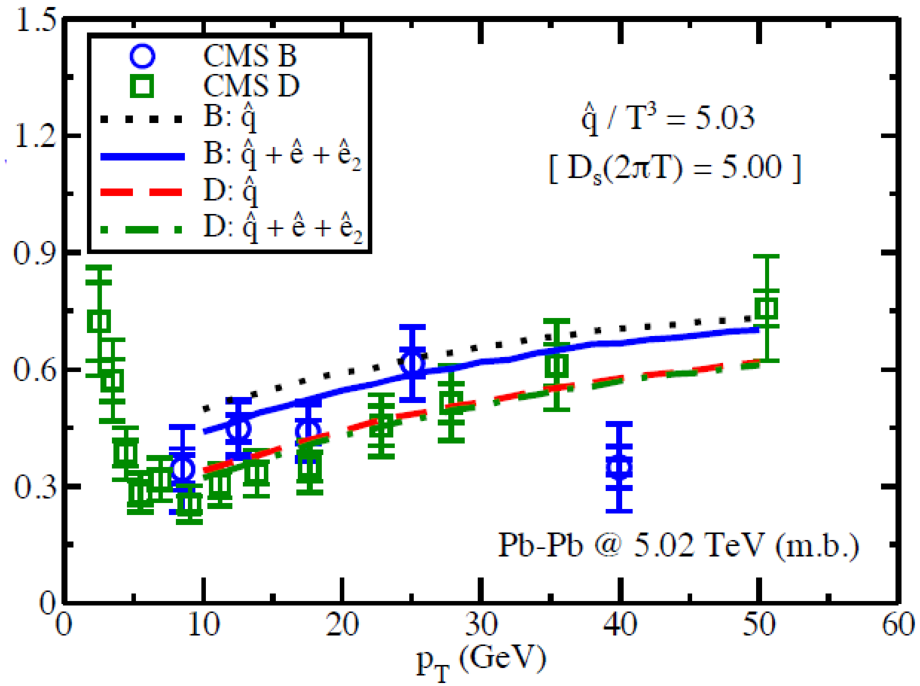
Hard scale $Q=p_T$

Modified DGLAP evolution (virtuality ordered)

Low scale $Q_0=m_Q$

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





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

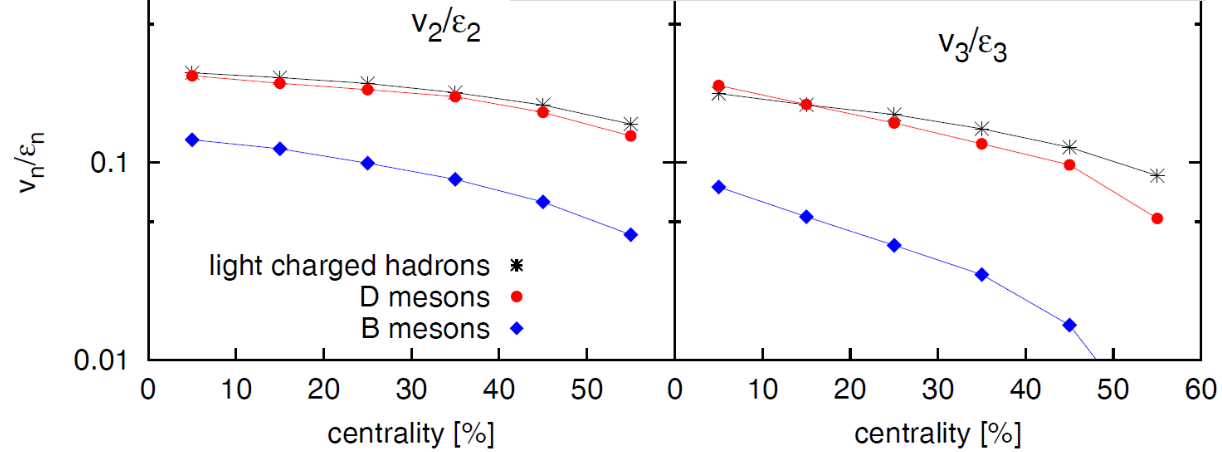
More on v_2 and higher flow harmonics

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

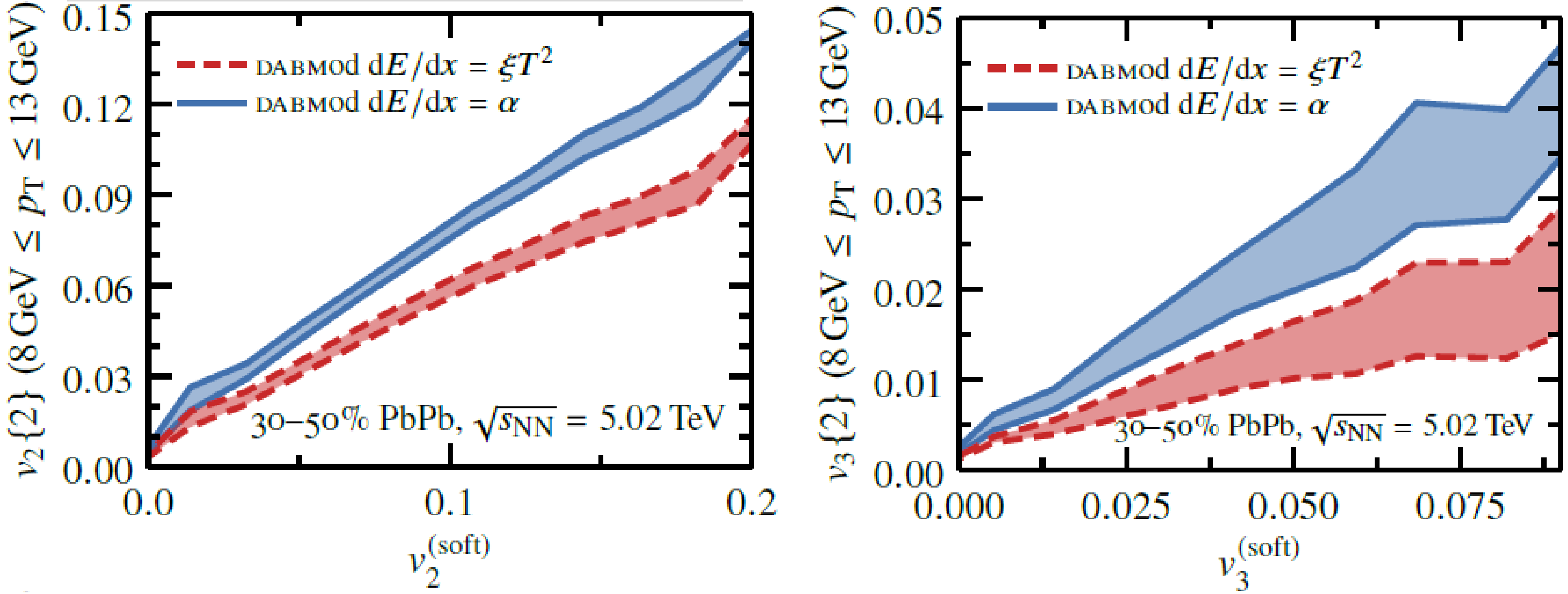
- departing from the nearly equilibrated regime
- exploring the consequences of inertia due to large m_Q
- Our observation: **reduction of v_n/ε_n for a) larger n, b) larger mass and c) larger centrality…**

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

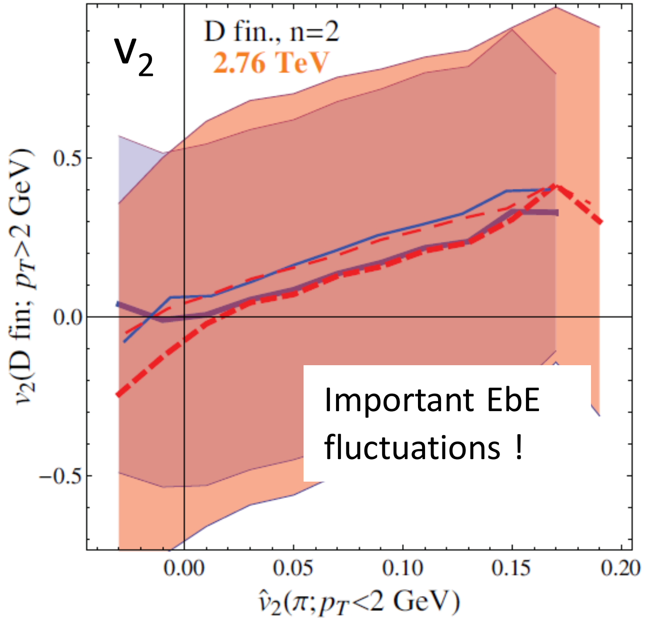
M. Nahrgang et al, Phys.Rev. C91 (2015), 014904



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



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

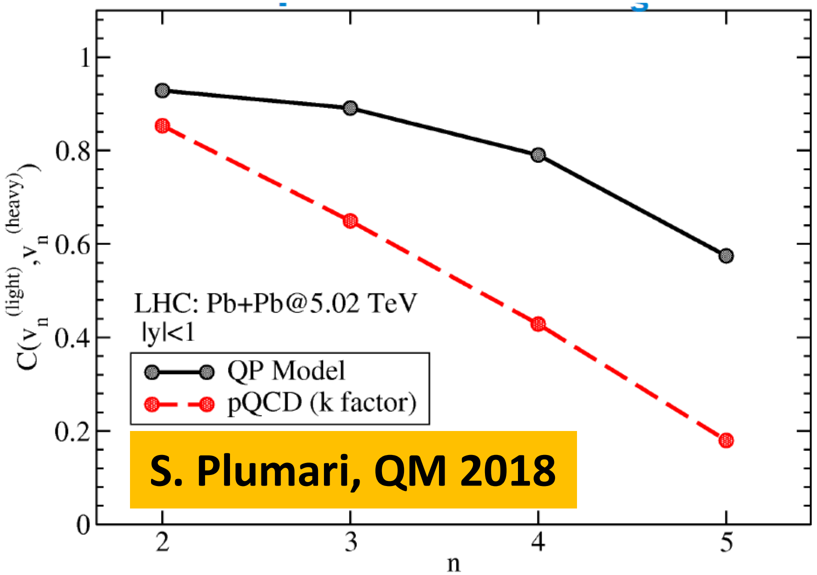


No saturation ./. Linearity BUT larger flow from $\frac{dE}{dx} \propto T^0$ and larger reduction for v_3

More on v_2 and higher flow harmonics

NEW

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



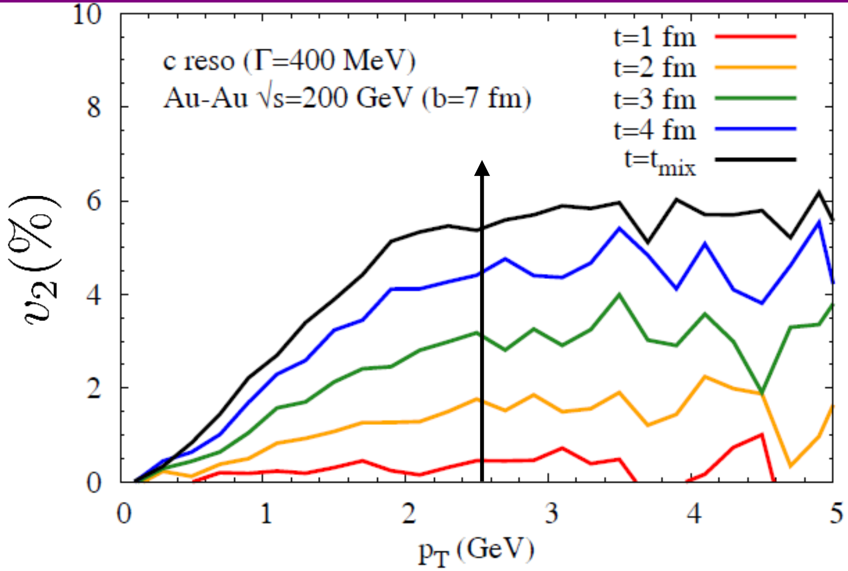
S. Plumari, QM 2018

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

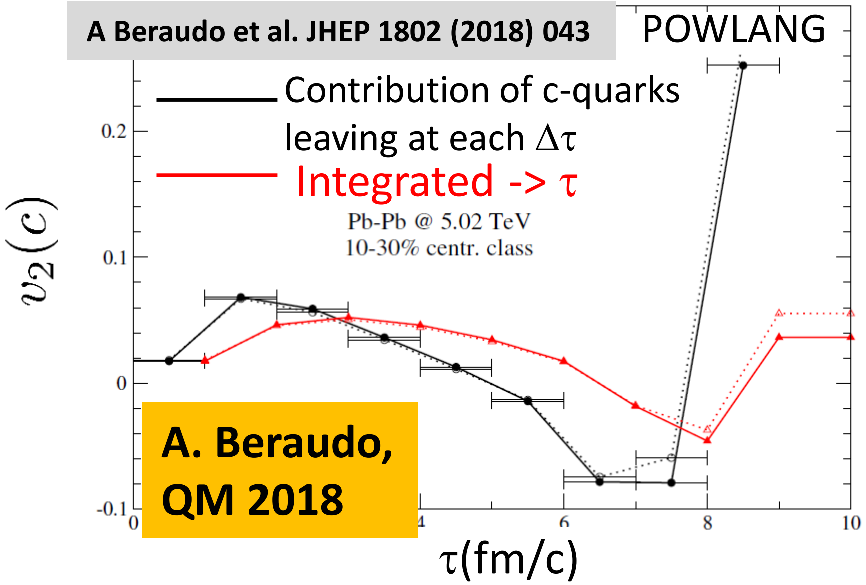
Poster R. Katz, QM 2018

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

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



A Beraudo et al. JHEP 1802 (2018) 043



A. Beraudo, QM 2018

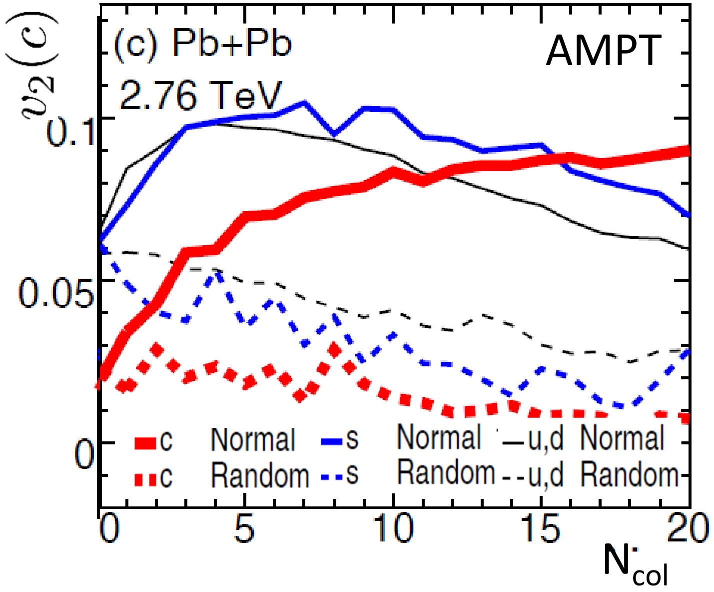
Interplay between positive and negative contributions

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

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

Steady increase of v_2 (all c quarks)

H. Li et al1804.02681



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

Recent Collective actions beyond Sapore Gravis

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

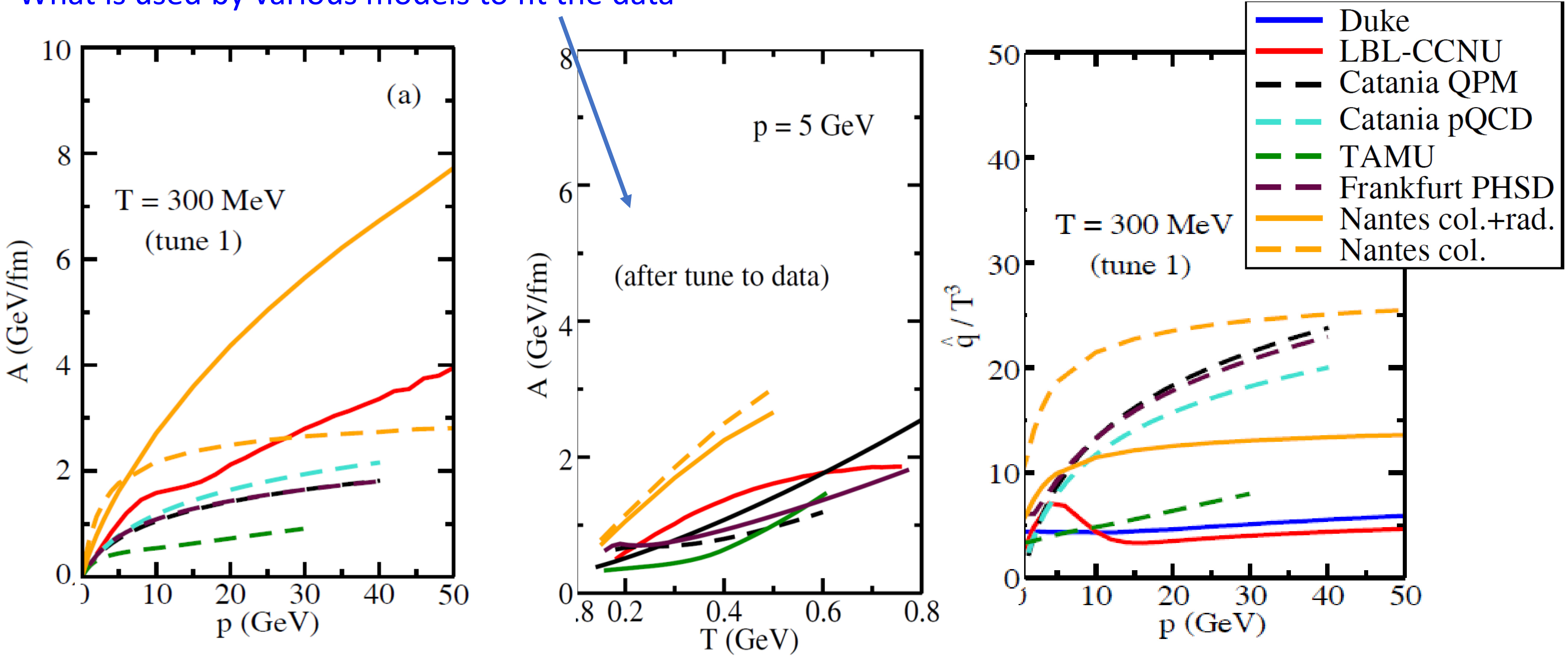
- LBL-CCNU (XN Wang, S. Cao)
- Duke (S. Bass , S. Cao, M. Nahrgang, Y. Xu)
- Catania (V. Greco, S. Das, S. Plumari, F. Scardina)
- TAMU (R. Rapp, M. He)
- Frankfurt pHSD (E. Bratkovskaya, T. Song, H. Berrehrah)
- Nantes (J. Aichelin, PB Gossiaux, M. Nahrgang)

HQ Working Group

- Collect and compare the transport coefficients from various models:

c-quarks

What is used by various models to fit the data



- Obviously not satisfying (from many perspectives) !
- Larger dispersion than the predictions for concrete observables… WHY ?
- Because of « extra ingredients », chosen differently in each model !!!

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

(20 monthes since first meeting)

EMMI RRTF

Topics:

- Initial spectra and shadowing
- Bulk evolution and consequence on HF observables
- Transport implementation
- Hadronization
- Microscopic models for HF energy loss and constrains from QCD at low and high momentum
- Future observables

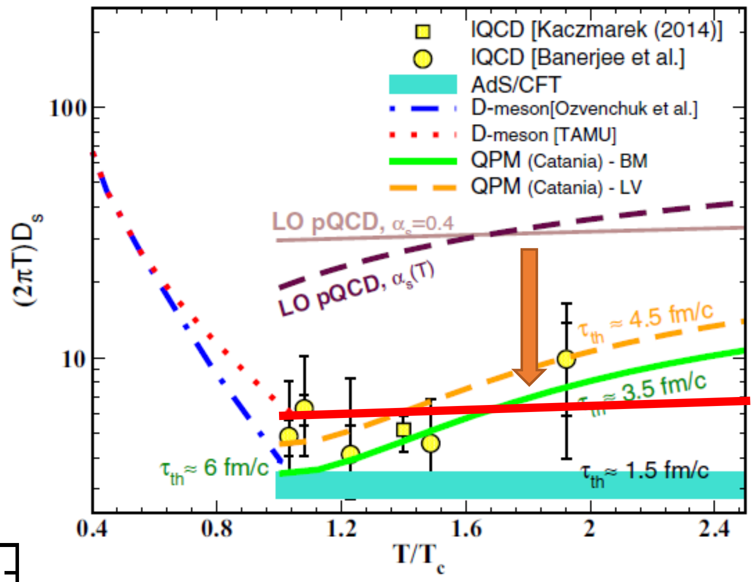
EMMI RRTF : Consequences from the **bulk choice** **(and partly transport)**

<u>Question</u>: 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 ?

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

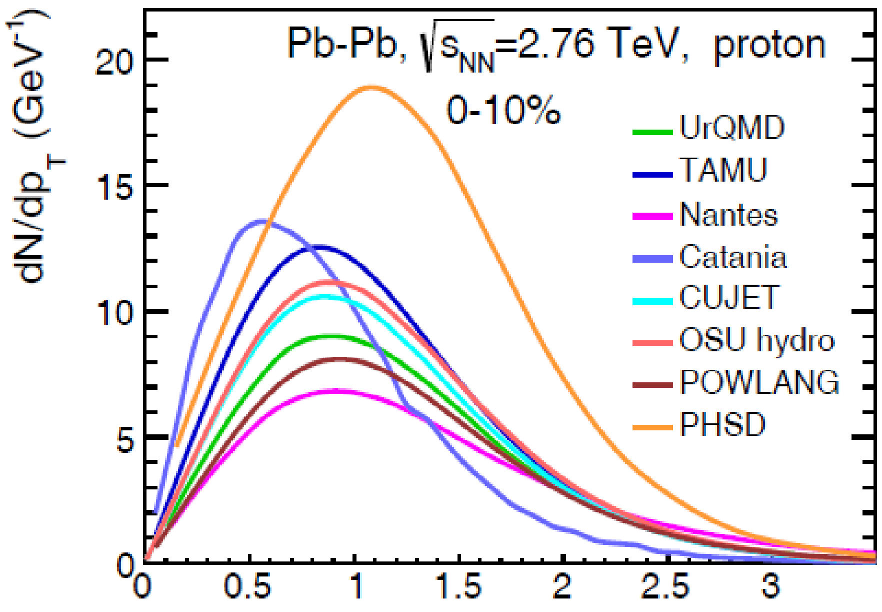
One Interaction for all of them; not aimed at reproducing the data !!!

R. Rapp et al, arXiv: 1803.03824

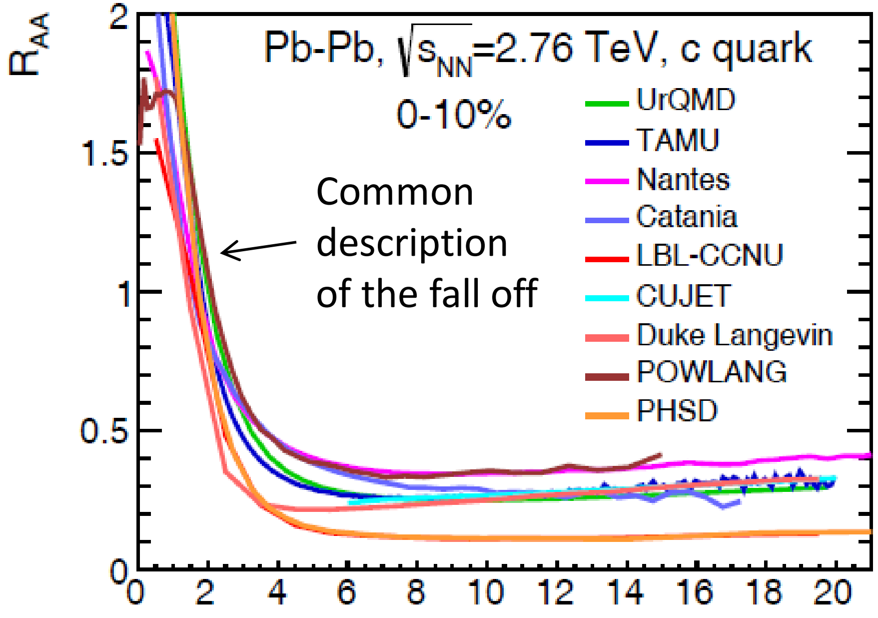


This allows to probe the effect of the bulk with a mechanism that has a D_s roughly similar to the one extracted from lQCD

Protons from the bulk **at FO**



c quarks **at FO**



For most bulks:

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

For 30%-50%:

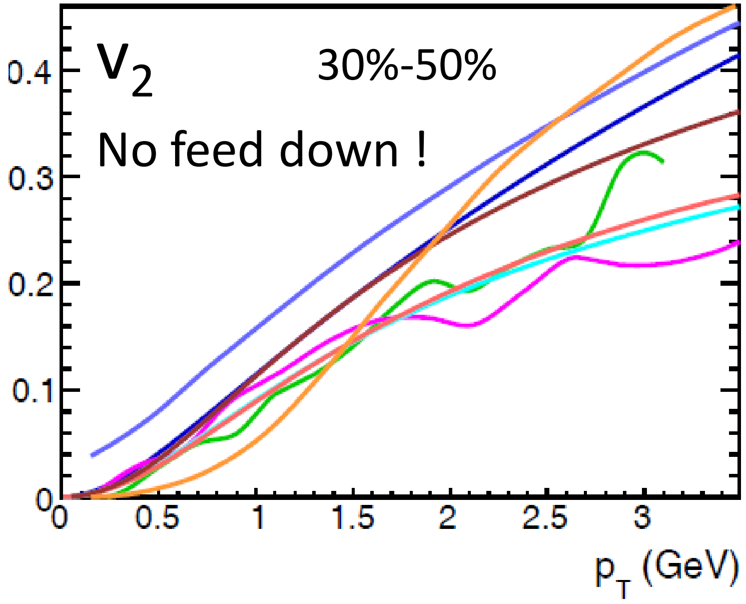
$$R_{AA}(c, 10\,\mathrm{GeV}) \approx 0.4 - 0.6$$

No feed down !

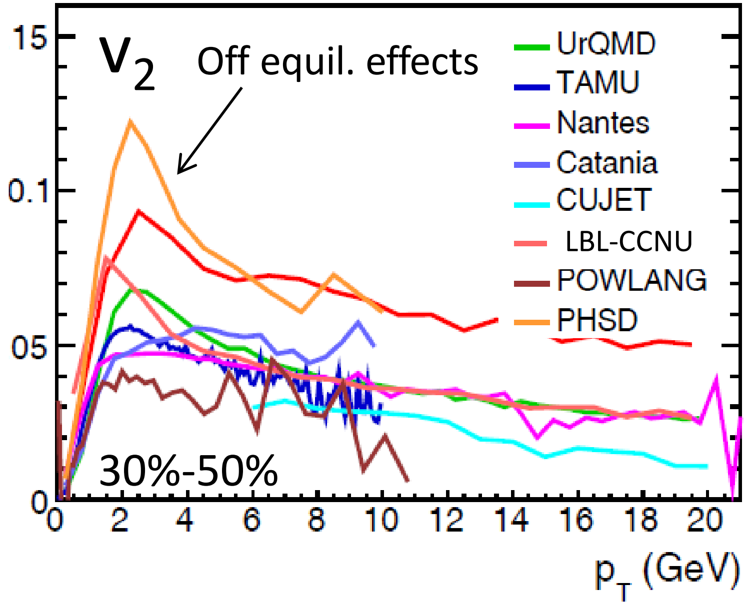
Some correlation between dN(p) and R_{AA}(c) but not systematic

EMMI RRTF : Consequences from the **bulk choice**

Protons from the bulk at FO



c quarks at FO

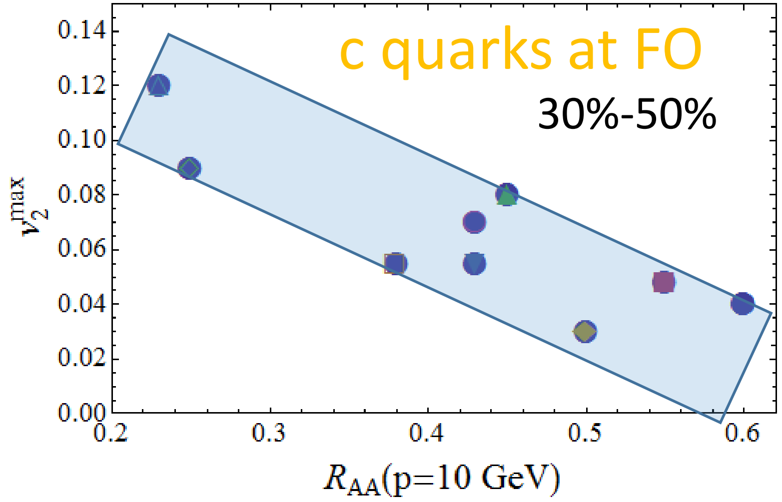


N.B.: LBL-CCNU could not implement scattering on thermal- massive partons

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 bulks » would permit to shrink the residuals in the « extraction » of the optimal transport coefficients.

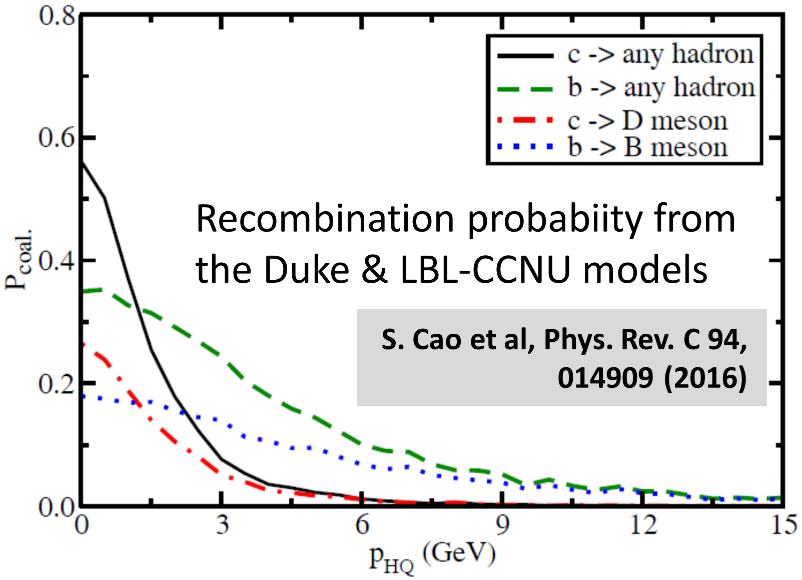
HQ-Hadronization (would deserve a full talk)

Acknowledged:

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

Low p_T :

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



High p_T :

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

Uncertain (and not disputed enough):

- Genuine physical recombination process !

HQ - Recombination

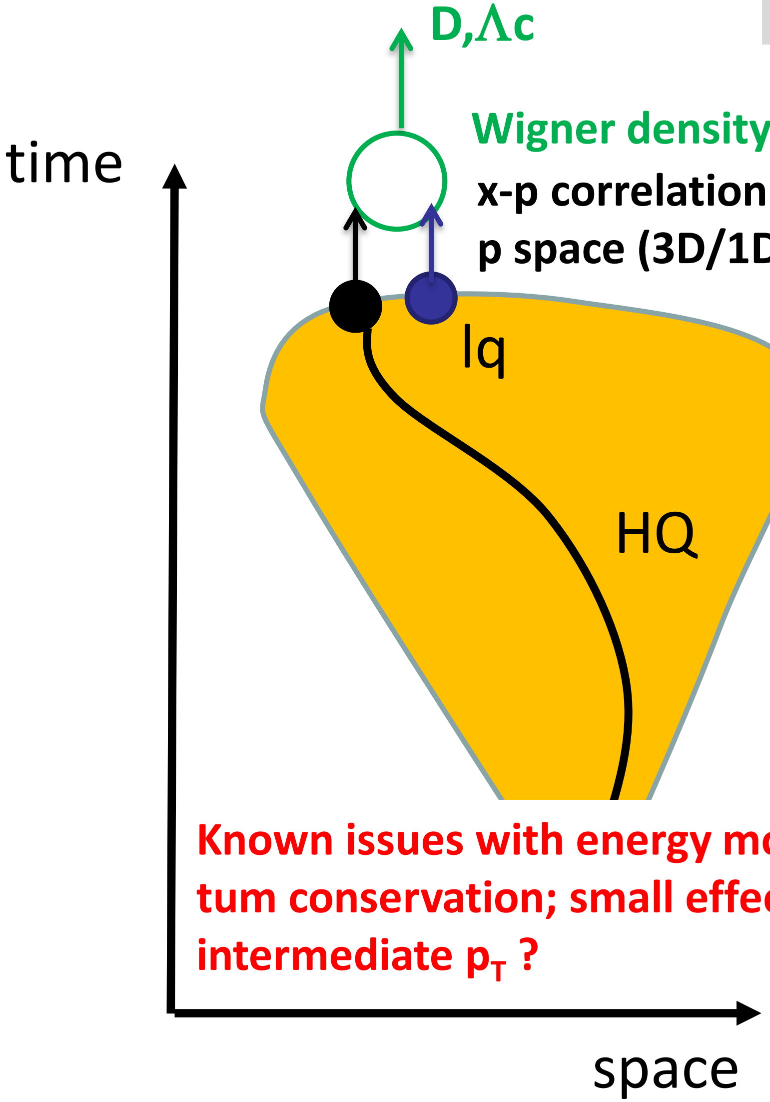
Instantaneous coalescence:

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

NEW

S Plumari et al. arXiv:1712.00730

Poster V. Minissale, QM 2018



Wigner density of hadronic states

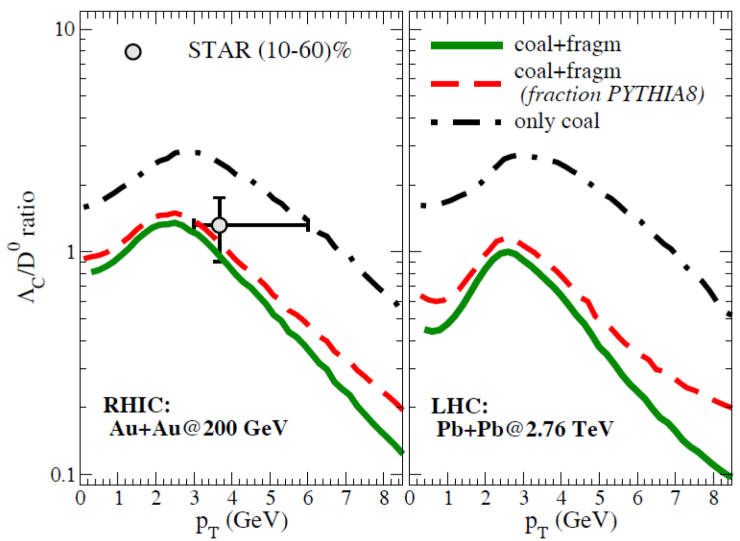
x-p correlation (6D) or « just » in p space (3D/1D)

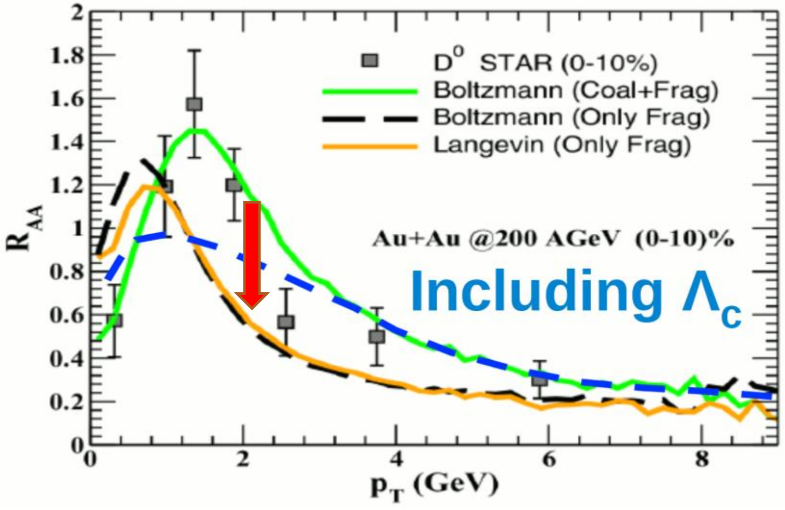
Known issues with energy momentum conservation; small effects at intermediate p_T ?

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.

// S. Plumari, QM 2018



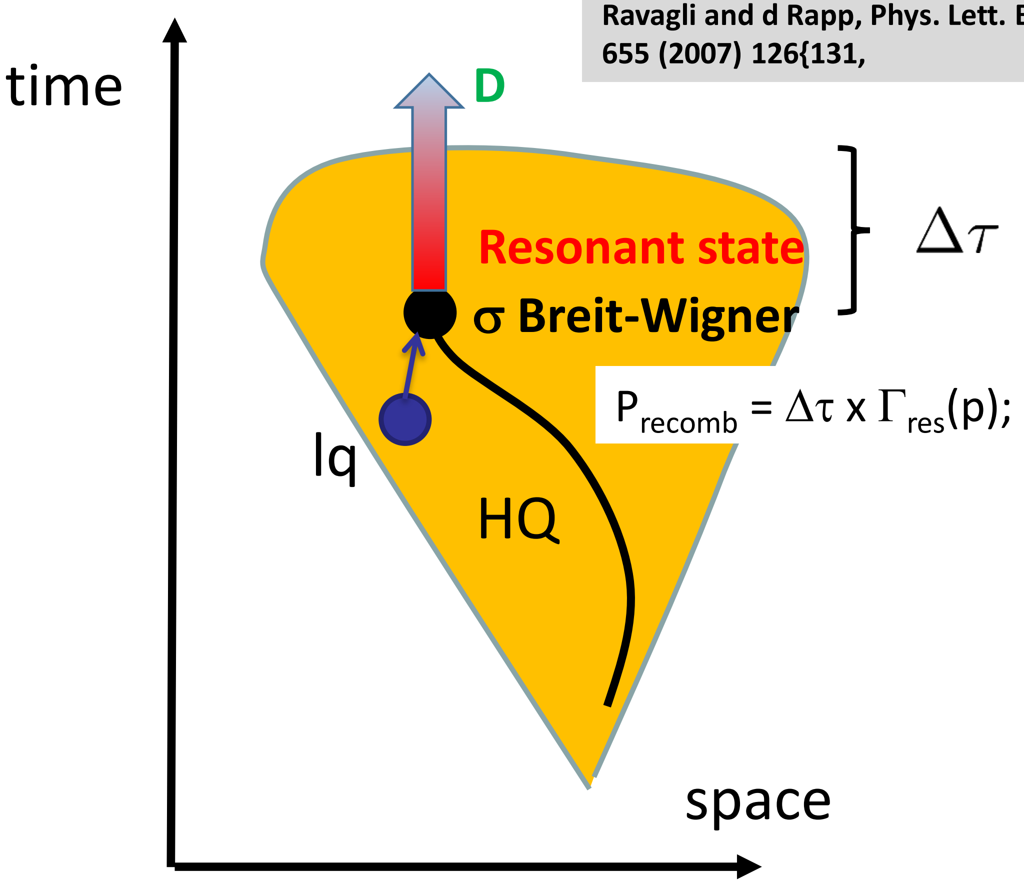


HQ - Recombination

Resonance Recombination Model:

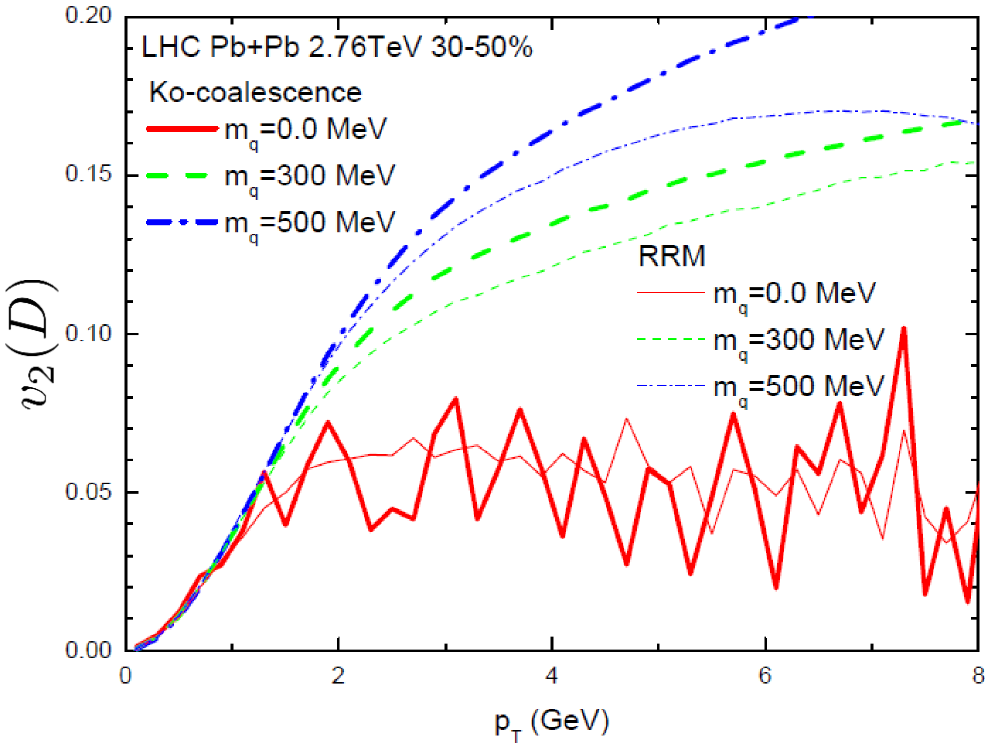
$$\left(\frac{\partial}{\partial t} + \vec{v}\cdot\vec{\nabla}\right) F_M(t,\vec{x},\vec{p}) = -\frac{\Gamma}{\gamma_p} F_M(t,\vec{x},\vec{p}) + \beta(\vec{x},\vec{p})$$

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



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

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



starting from the same bulk and from the same c spectrum

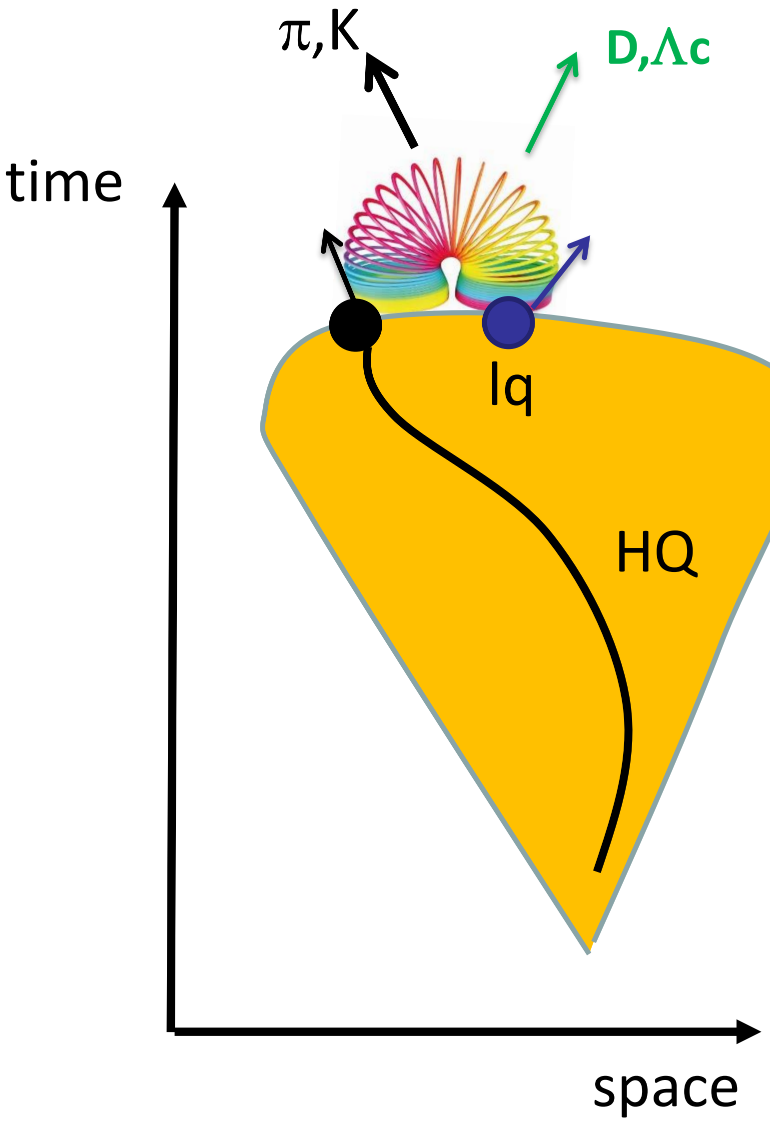
Significant differences found both for D meson p_T spectrum and v_2.

R. Rapp et al, arXiv: 1803.03824

HQ - Recombination

In-Medium recombination:

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



- 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

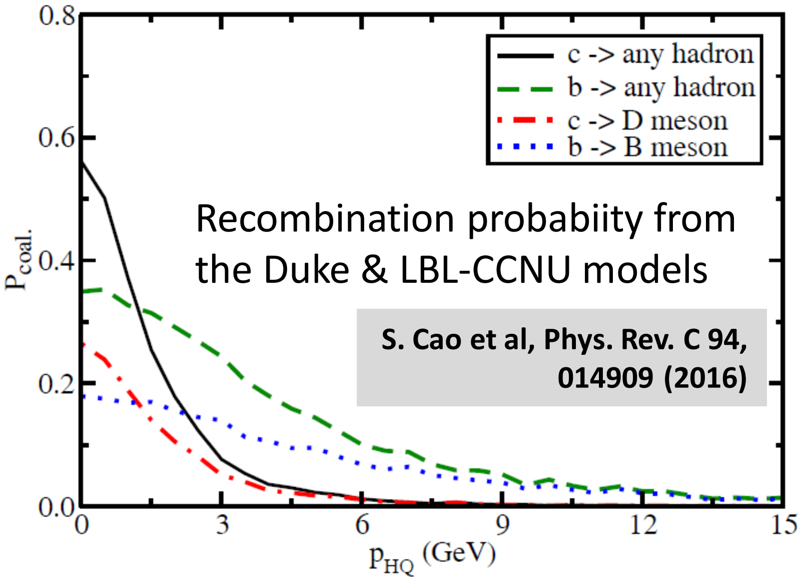
HQ - Recombination

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

EMMI RRTF : Consequences from various **Hadronization Mechanisms**

We define and display the H_{AA} quantity

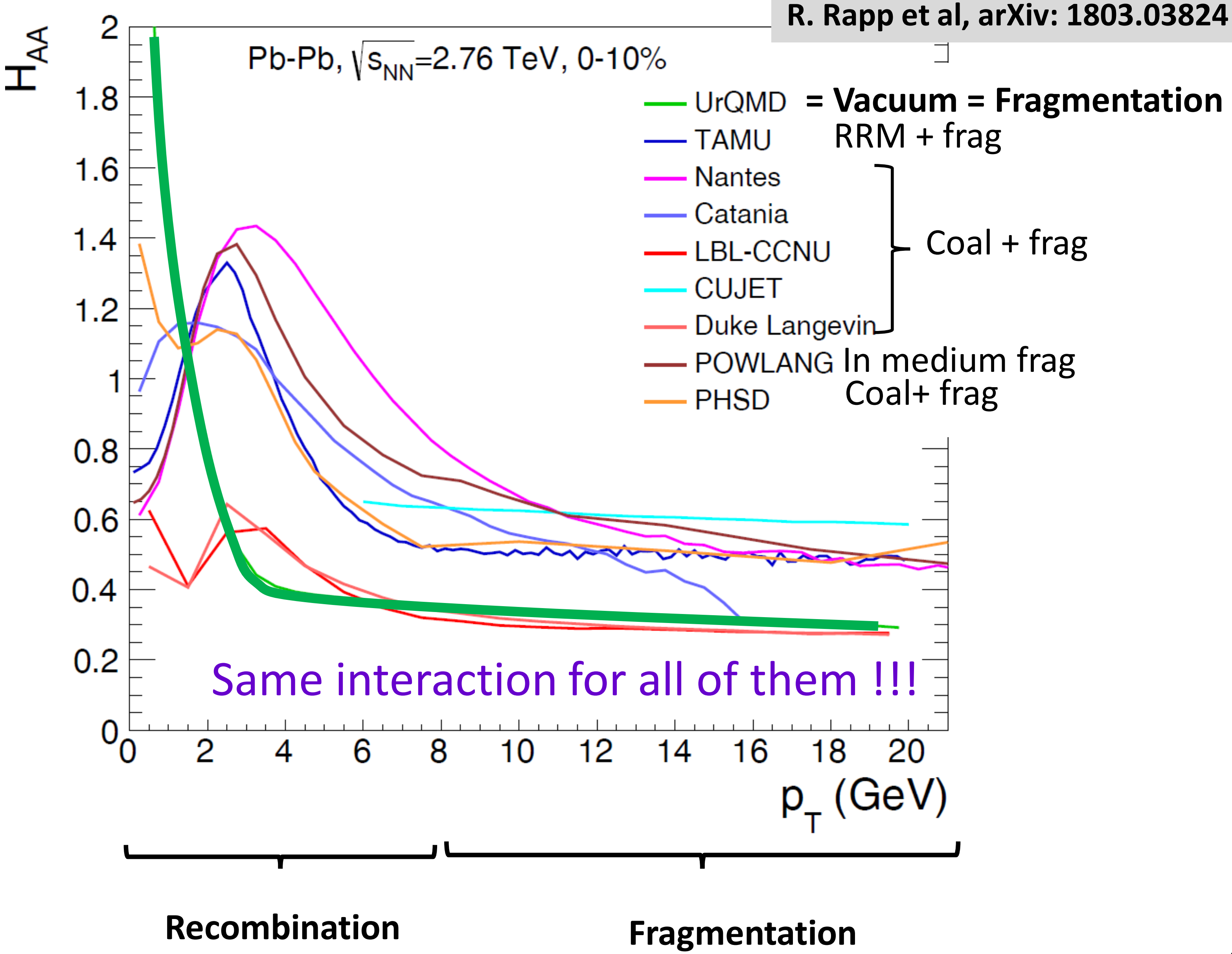
$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ final}}{dp_T}}$$

…which exhibits at best the specific effects of hadronization :

Significant uncertainties !

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

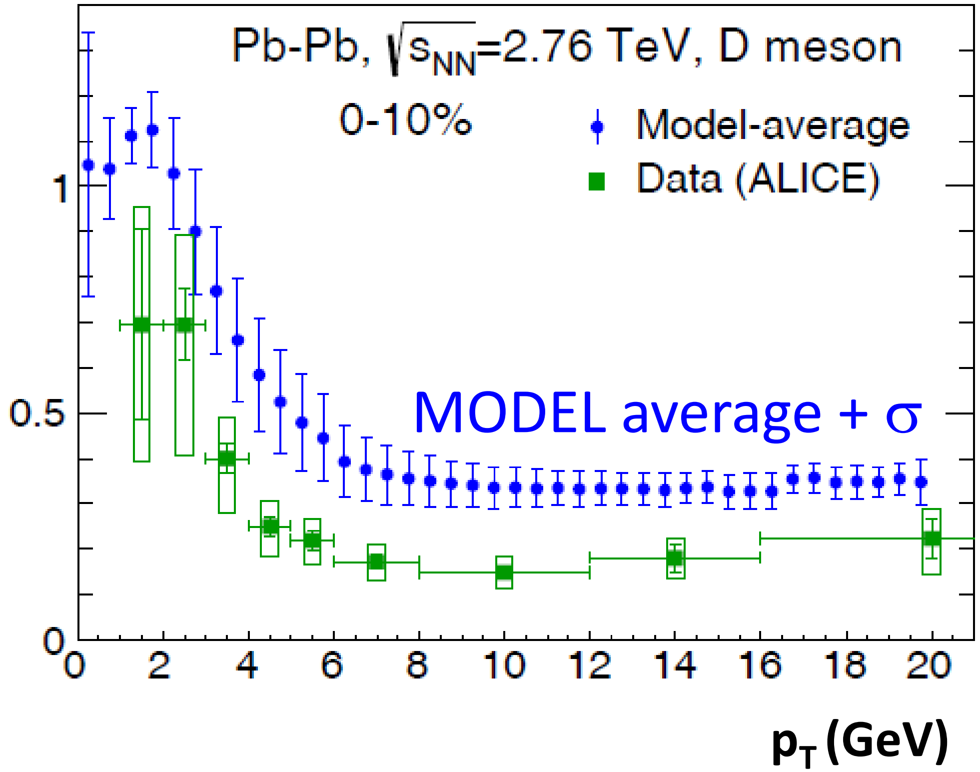
R. Rapp et al, arXiv: 1803.03824

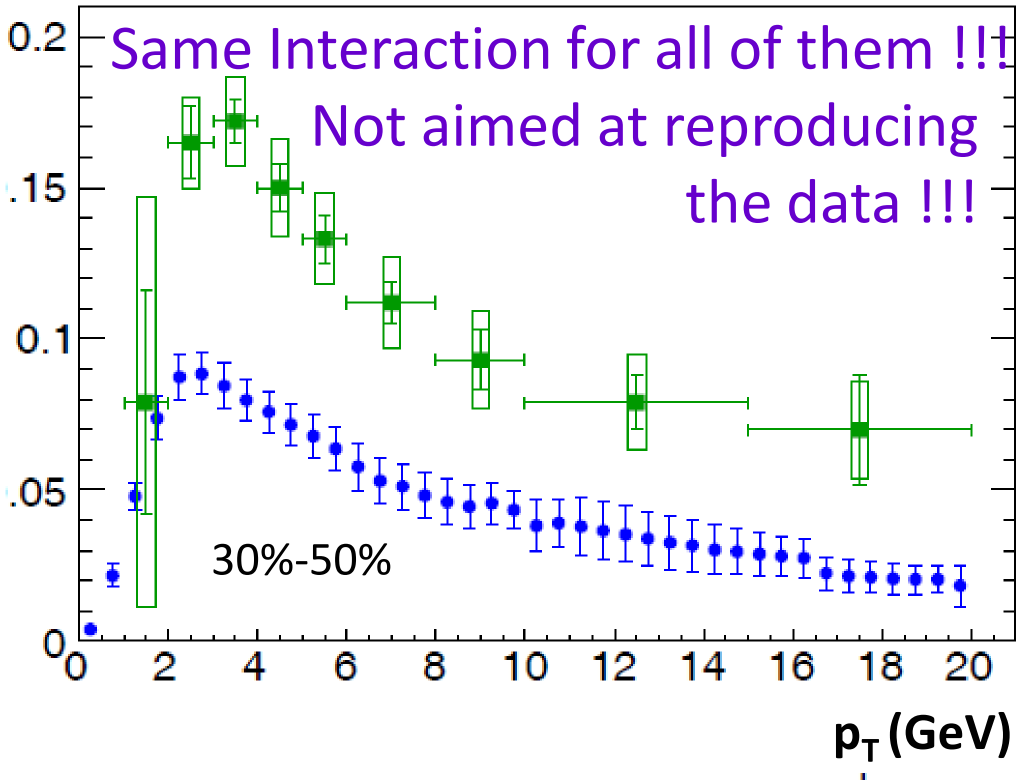


Consequences from the choice for Bulk, Hadronization and init. Spectrum

But without shadowing and hadronic rescatterings

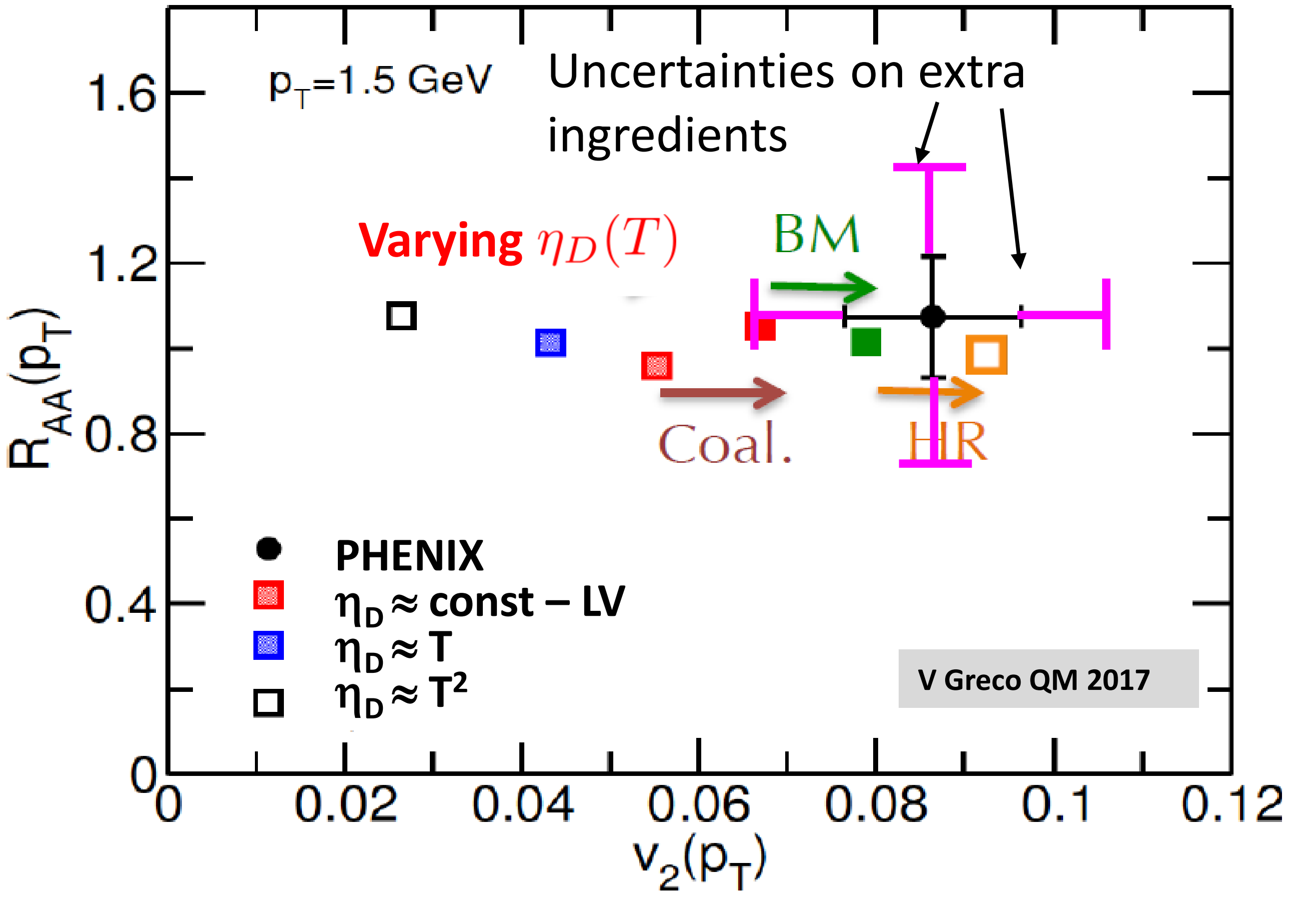
R. Rapp et al, arXiv: 1803.03824

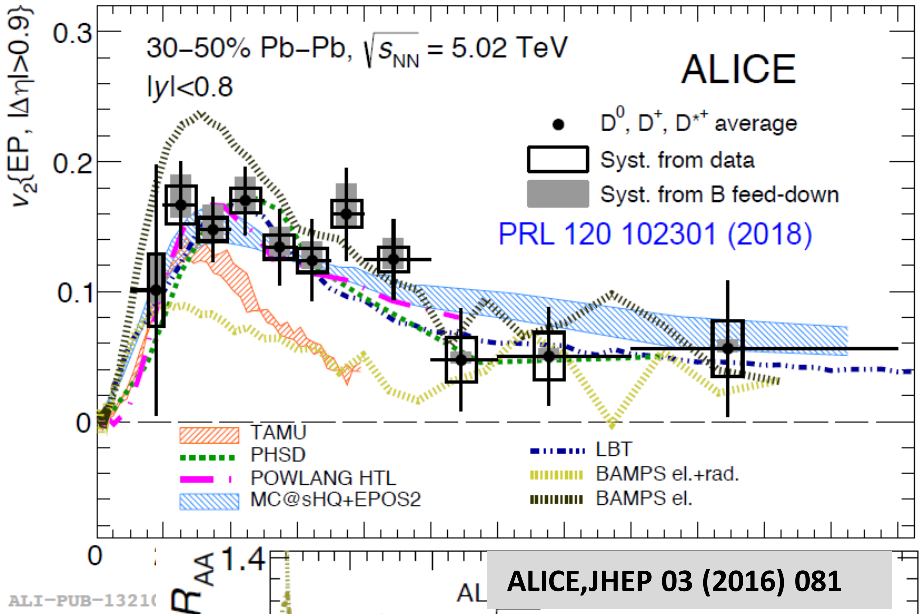


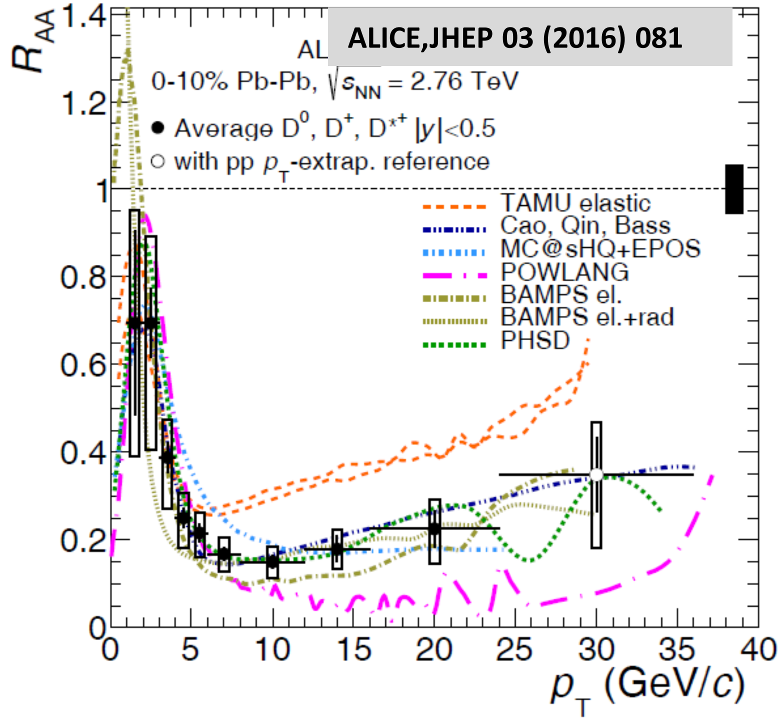


- You asked for it, you got it… « Theory error band »
- At least as large as the experimental one !

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







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

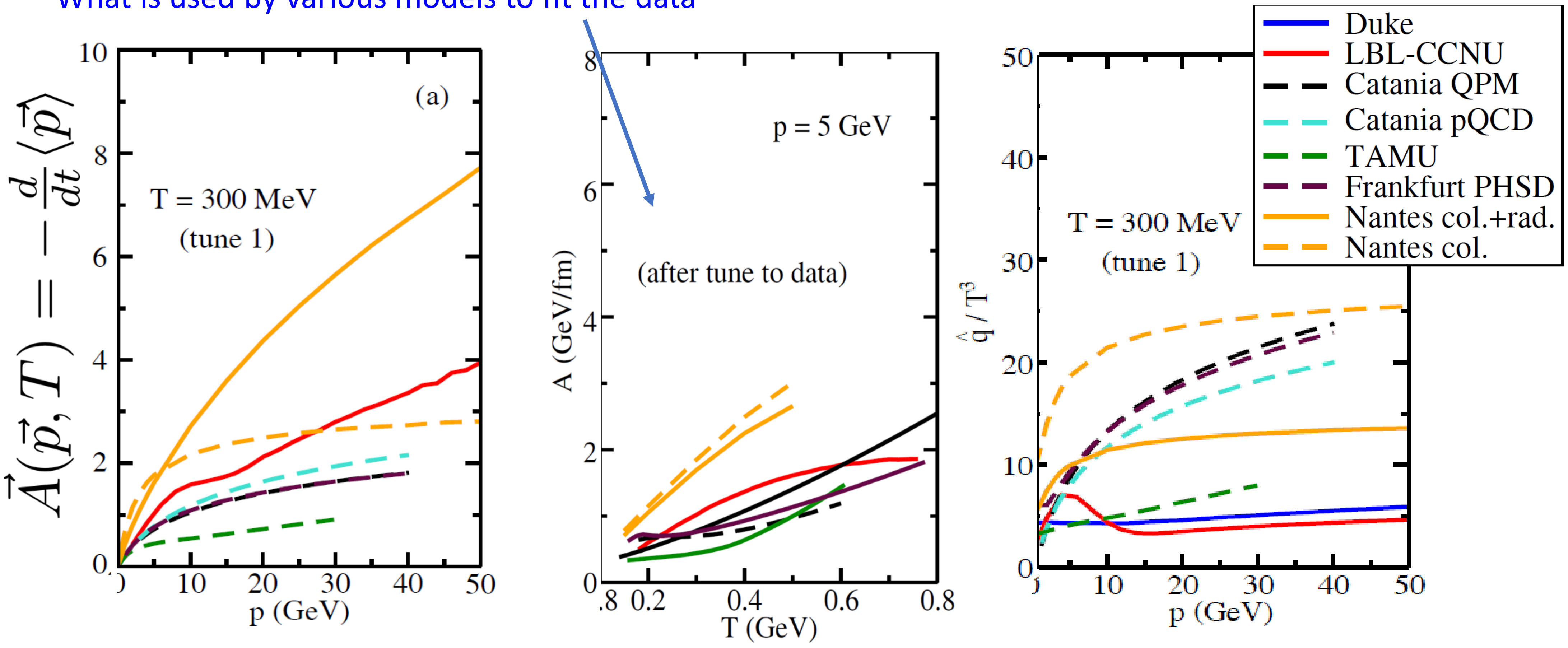
- What should we do next ?

HQ Working Group

c-quarks

- Collect and compare the transport coefficients from various models:

What is used by various models to fit the data



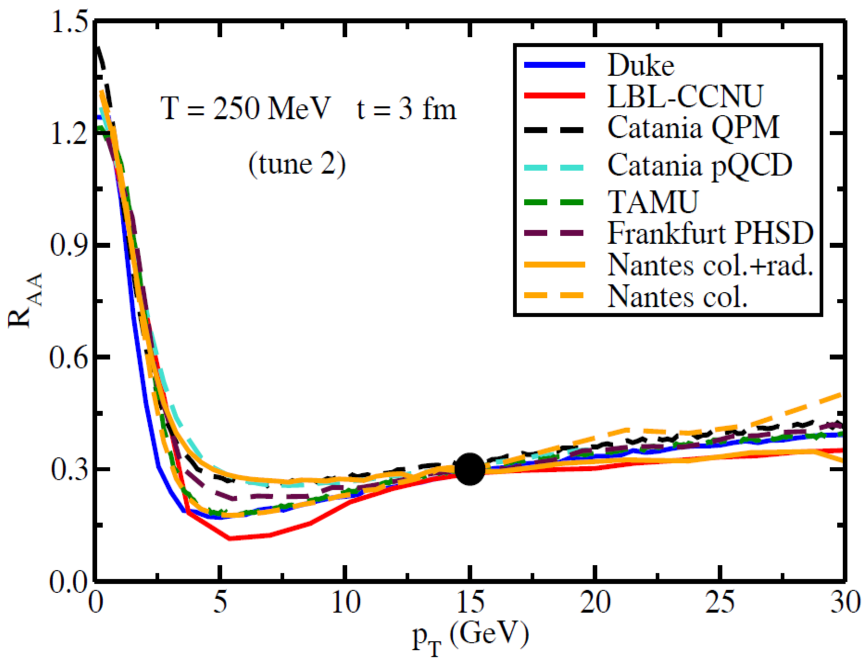
- Obviously not satisfying (from many perspectives) !
- Larger dispersion than the predictions for concrete observables… WHY ?
- Because of « extra ingredients », chosen differently in each model !!!

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

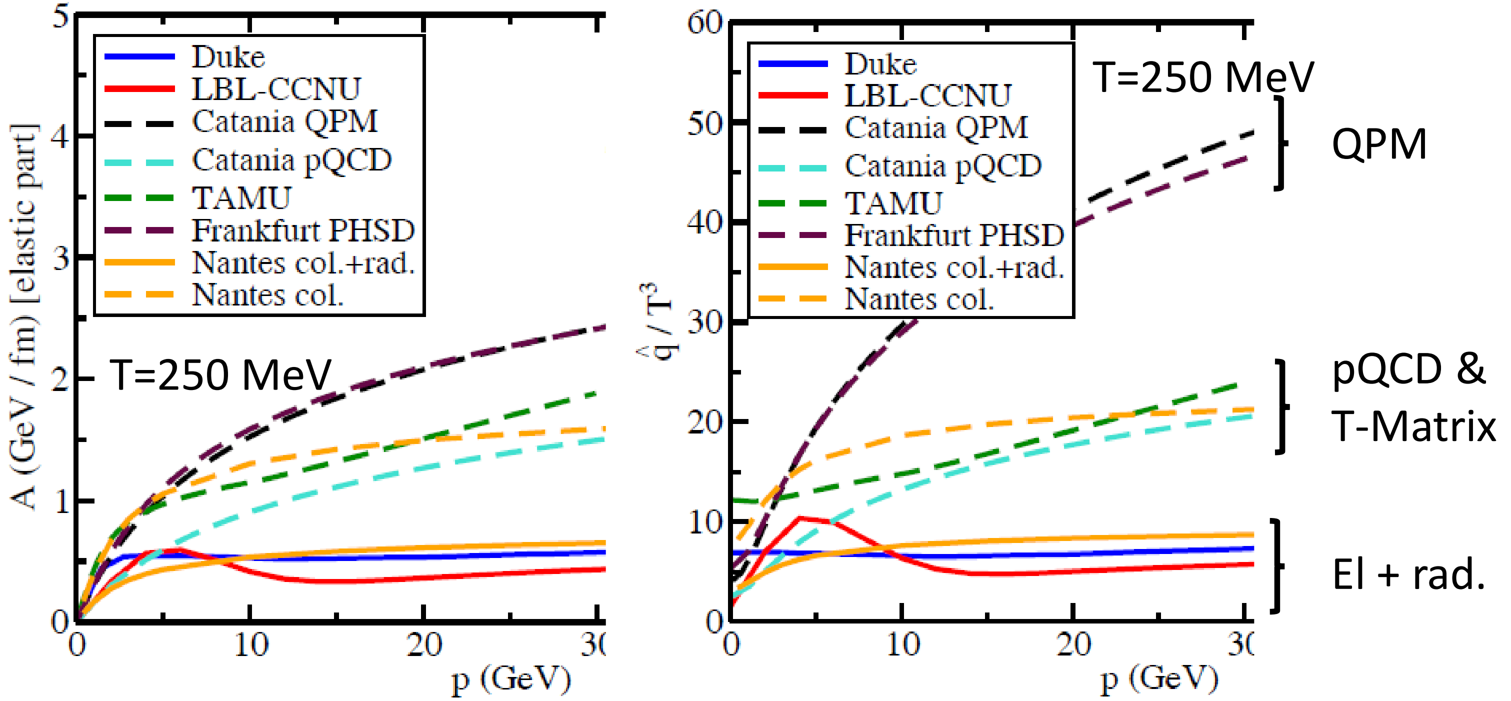
The goal is to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
- Estimate some systematics + uncertainties

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

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



2) Compare them !

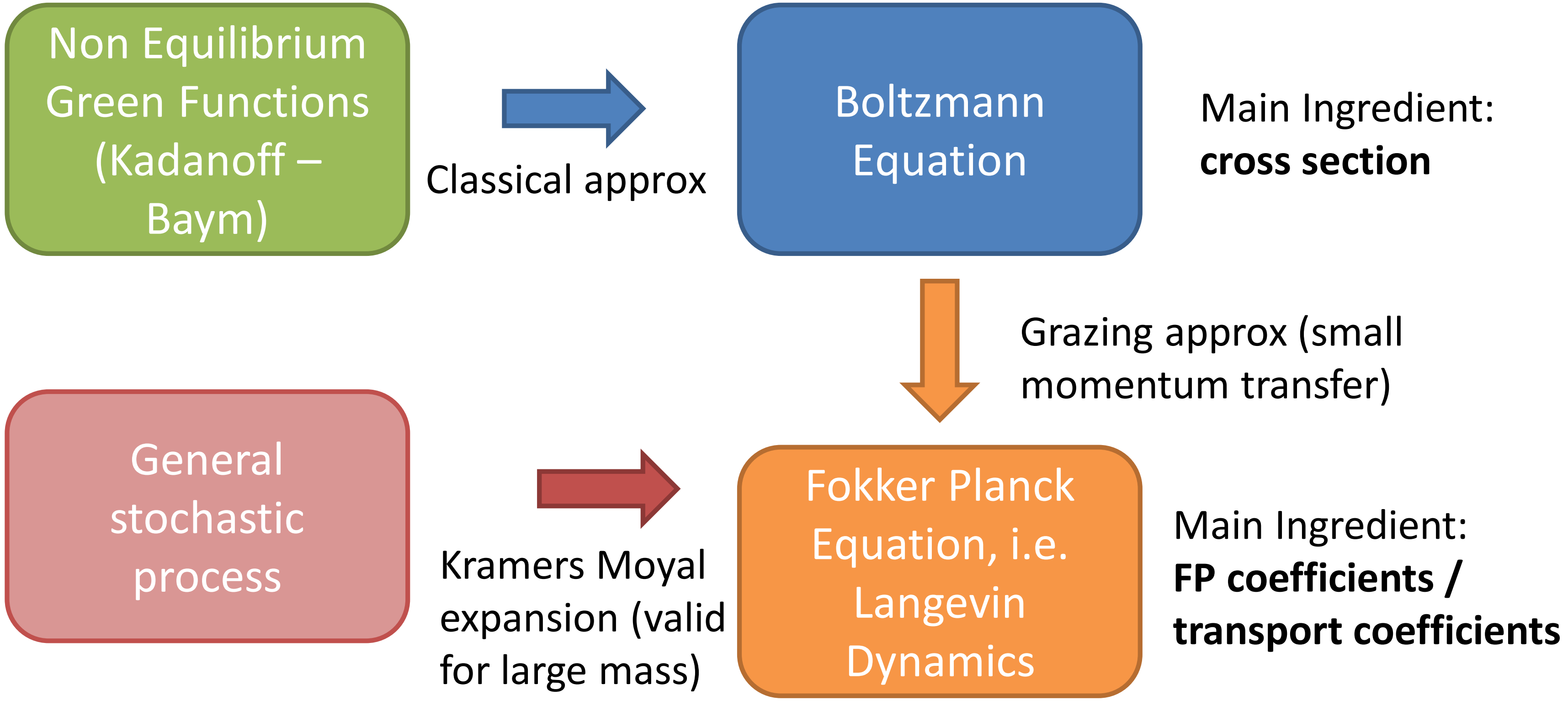


Main result: Nice structuration of the transport coefficients in different classes. For each class, the work illustrates the maximal accuracy reachable for each class once all other ingredients are either fixed or chosen commonly

Various approaches to transport

Bottom-up schemes (microscopic -> mesoscopic):

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



Boltzmann vs Langevin Dynamics

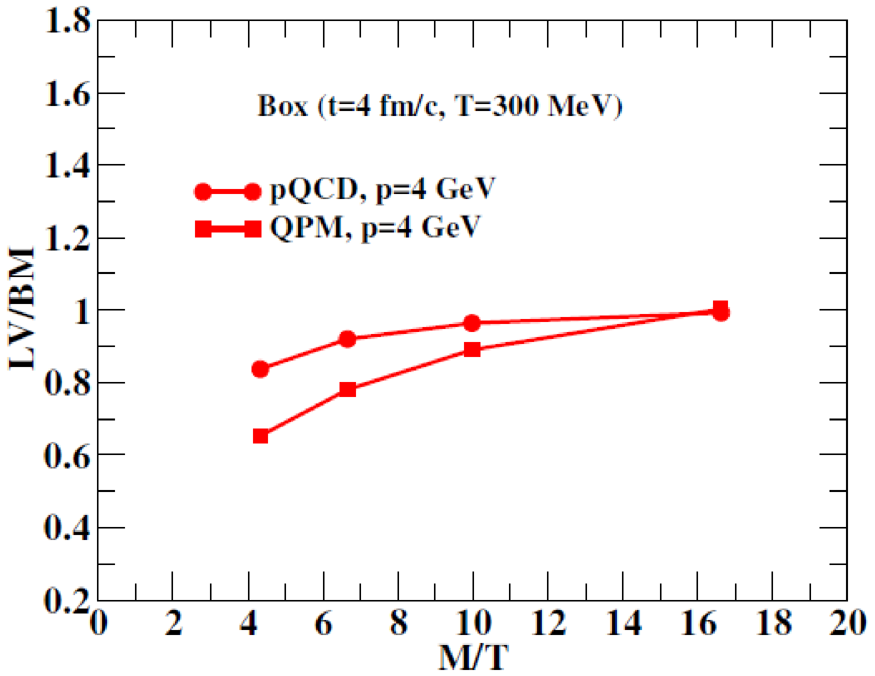
Langevin from Boltzmann view point:

- In general, not possible to accommodate all fluctuations as well as the asymptotic distribution (at a fixed T)
- Requires to impose some Einstein – relation / fluctuation – dissipation theorem between the drag coefficient and the diffusion coefficients
- Lesson 1 (from comparison to Boltzmann benchmark): The most conservative way to implement FDT is to preserve η_D and κ_T and to adapt κ_L.

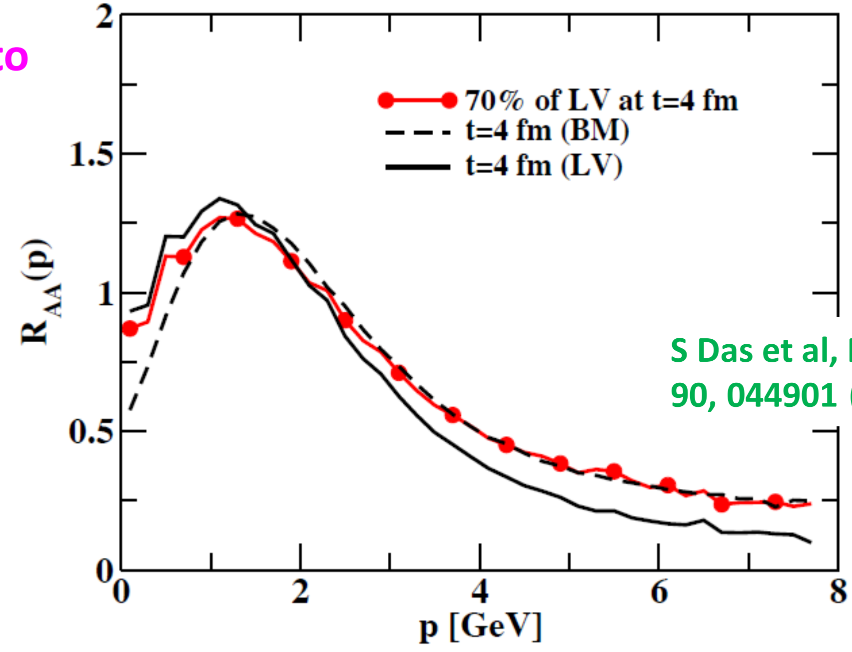
Boltzmann vs Langevin Dynamics

Langevin from Boltzmann view point:

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



Differences up to 40% found in QPM model



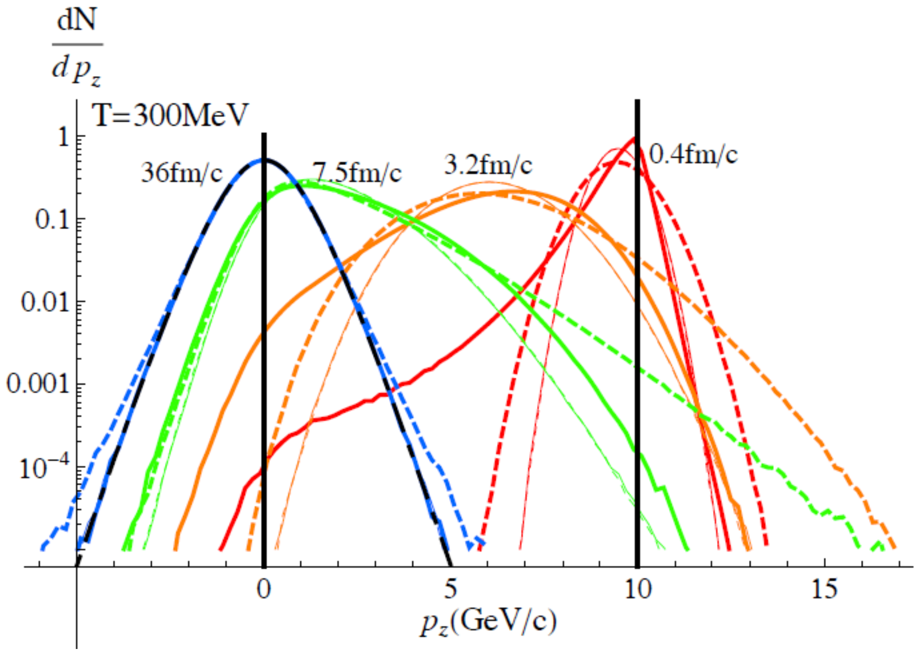
S Das et al, Phys. Rev. C 90, 044901 (2014)

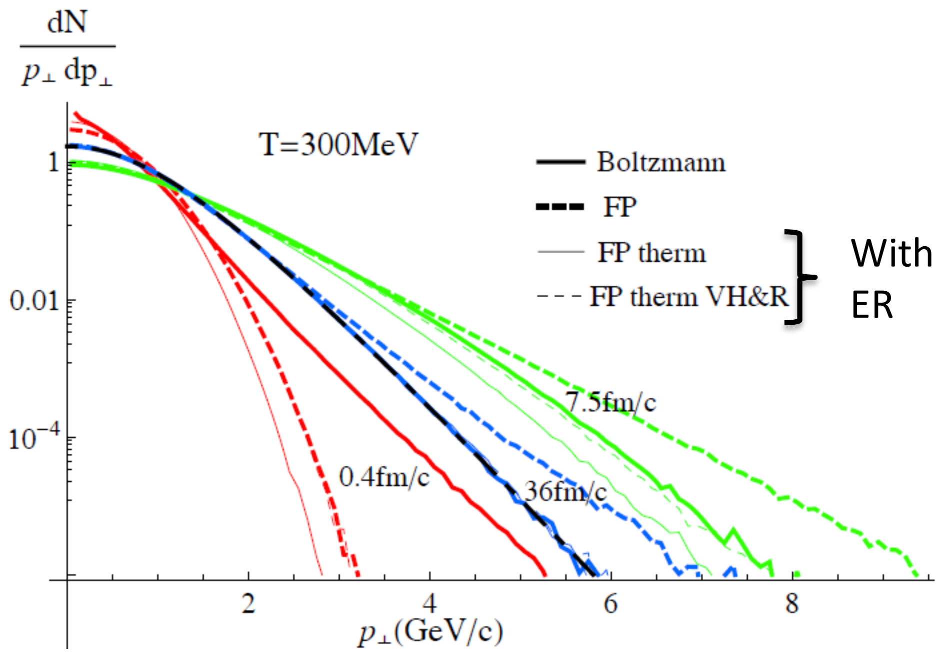
- For $m_D = g\,T \approx 2\,T$ found f.i. in the Quasi Particle Model, extra coupling is found for the R_{AA} using LV, which can be suppressed by reducing the FP coefficients by ≈ 30 %

Boltzmann vs Langevin Dynamics

Langevin from Boltzman view point:

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



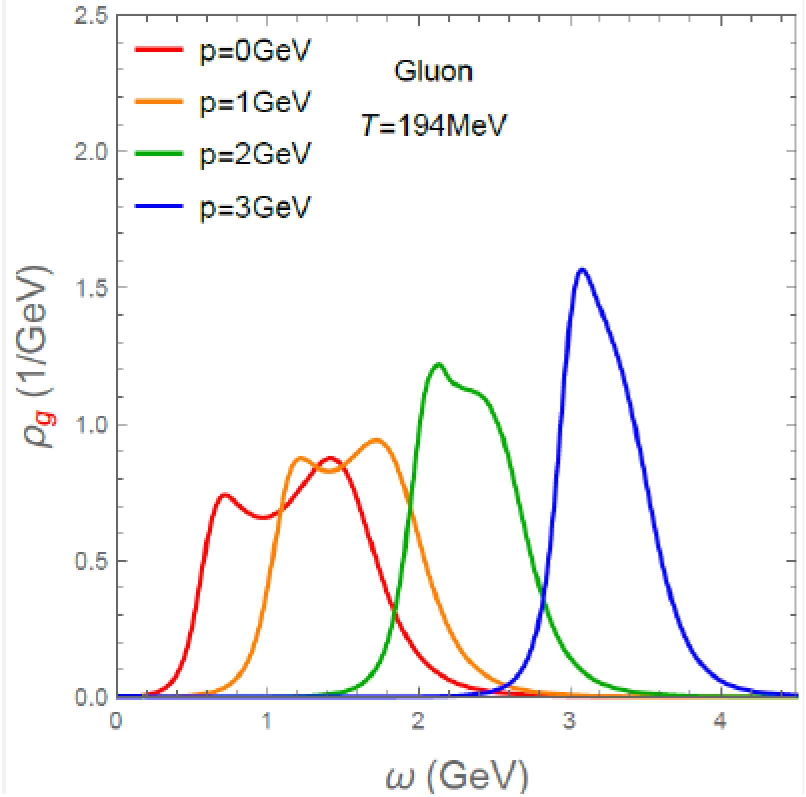


- These differences should me seen in observables like g-HQ correlations

Boltzmann vs Langevin Dynamics

Boltzmann from Langevin view point:

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



Gluon spectral functions (Liu & Rapp 2016)

Short term strategies

Collectivity of the « HQ in URHIC » community

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

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

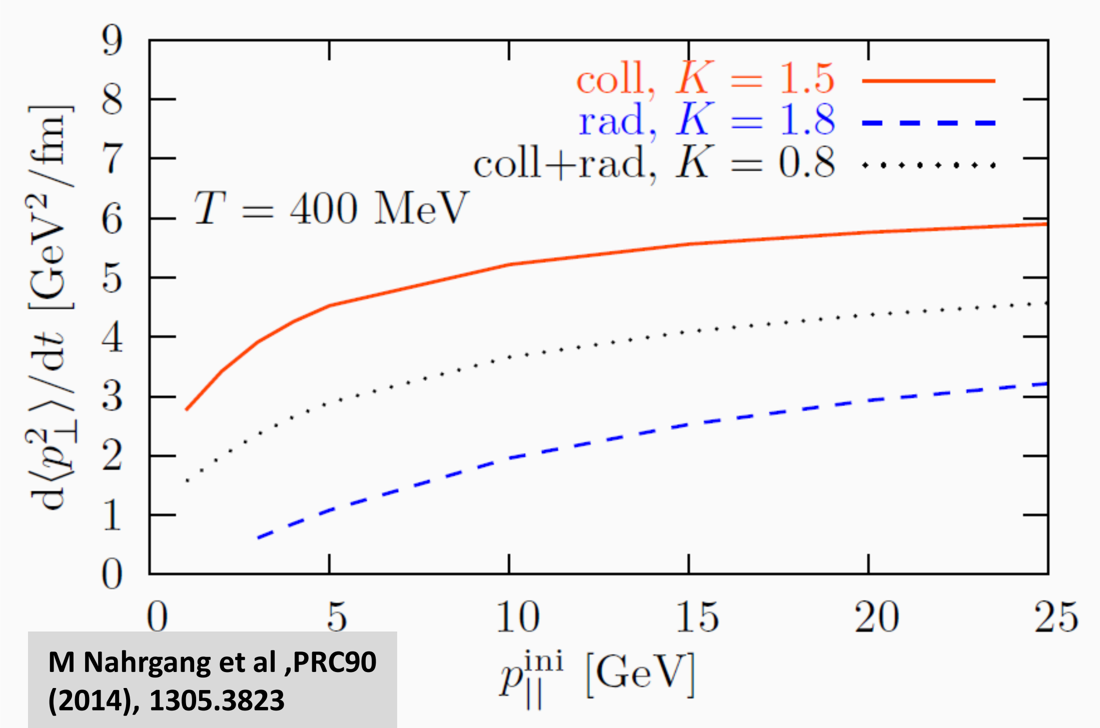
- We should as well rely more intensively and systematically on modern methods like Bayesian analysis, which allow a better quantitative contact with the experimental community

Short term strategies

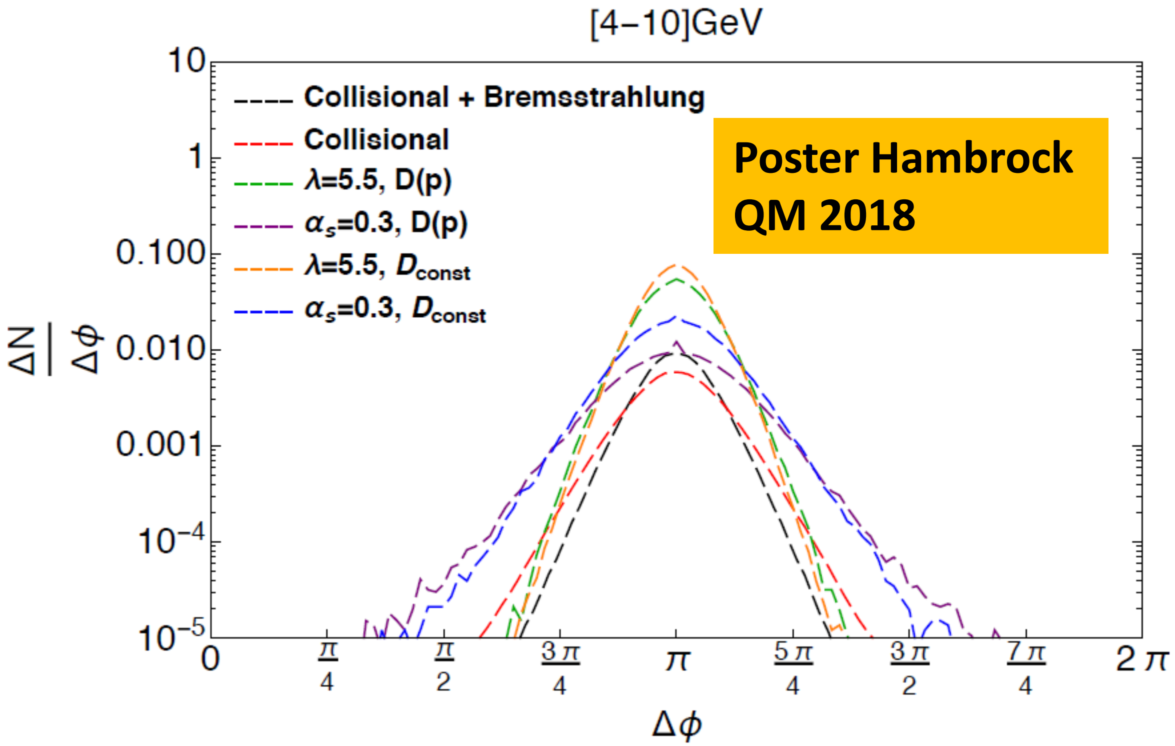
The nature of the interaction (Elastic vs Elastic + Radiative vs AdS/CFT) in the intermediate p_T range

One should exploit both

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



M Nahrgang et al ,PRC90 (2014), 1305.3823



Poster Hambrock QM 2018

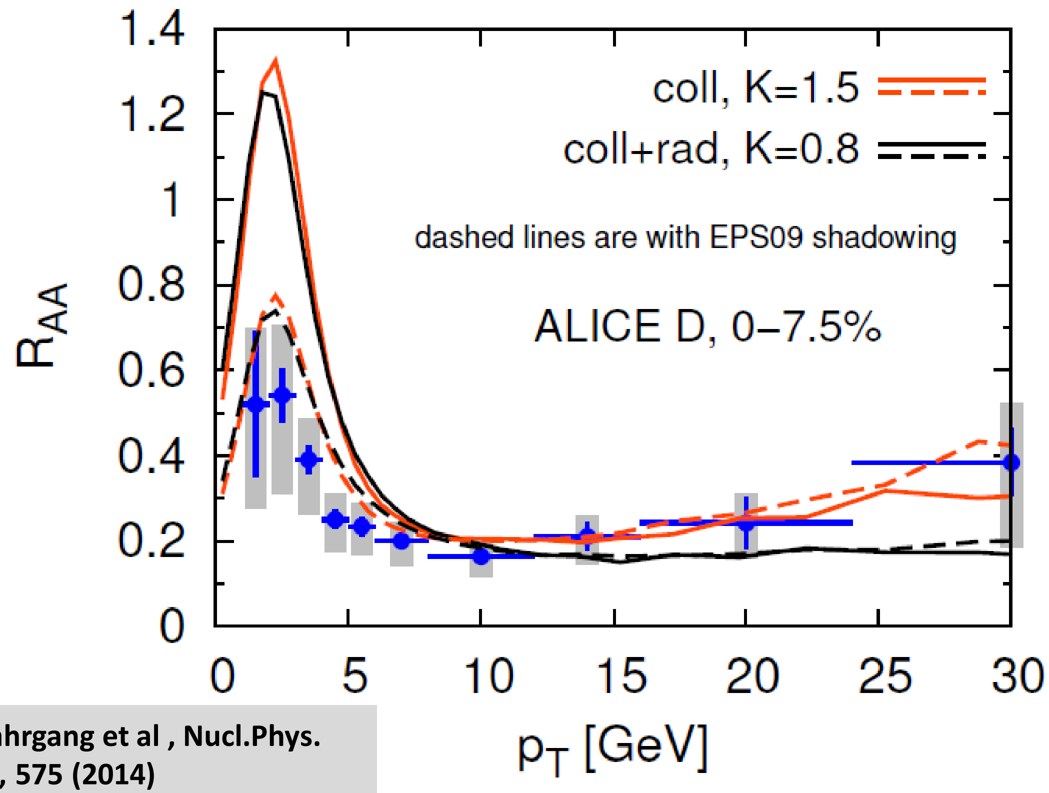
… But not "short term" !!! WE NEED VERY GOOD MEASUREMENTS ON THIS

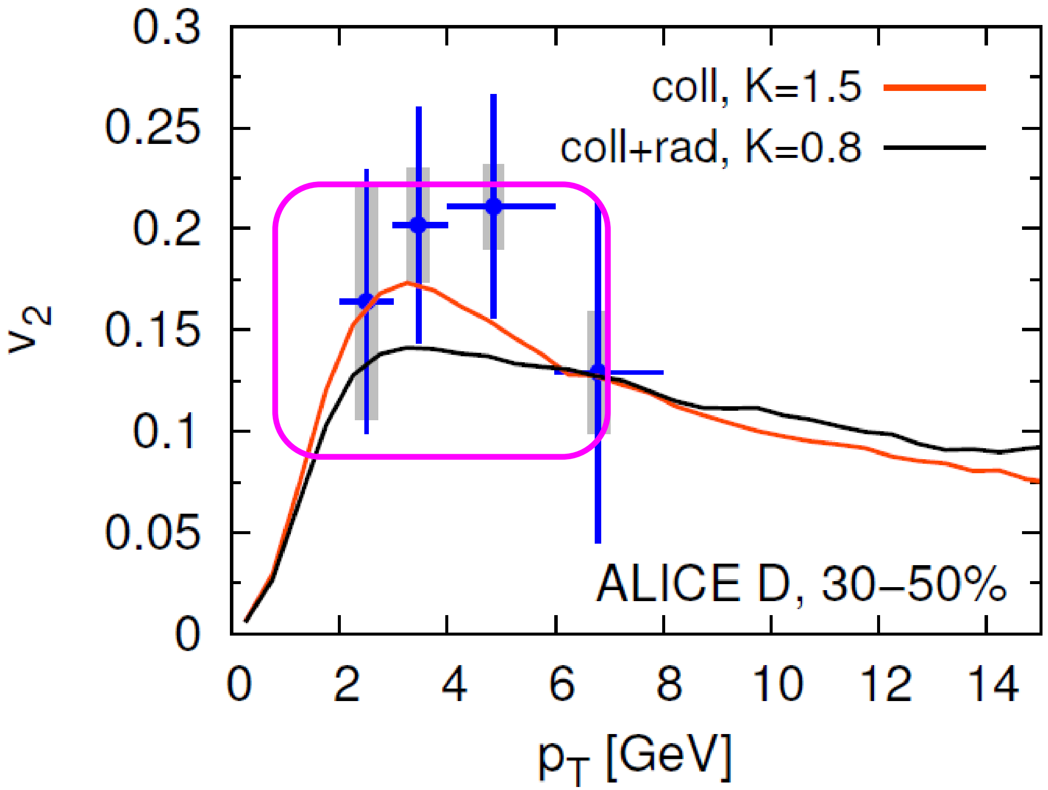
Short term strategies

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

One should exploit both

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





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

New Observables are coming

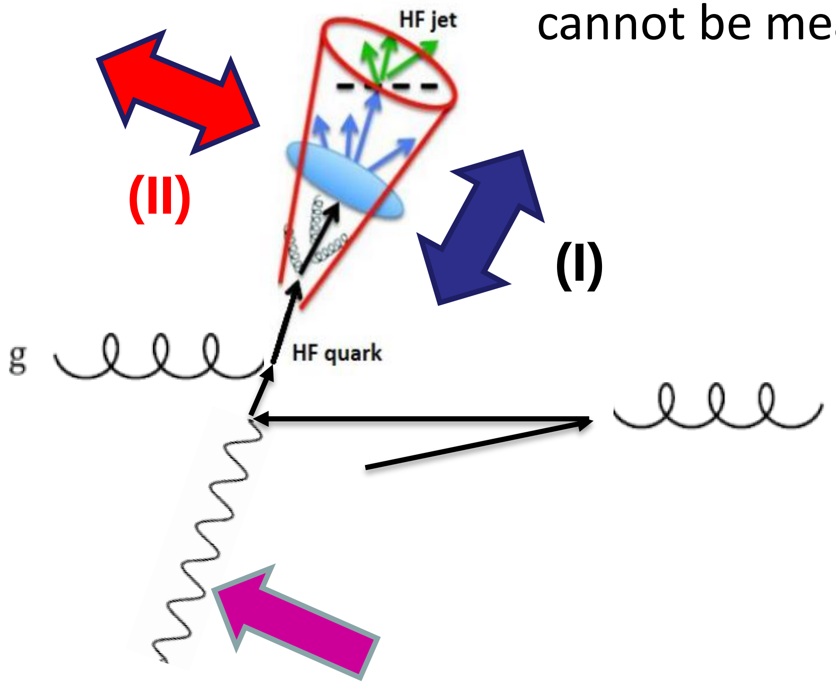
Short term, mid-term, long term,…

What	Good for ?	Caviat
Event shape engineering	Strength and T dependence of the interaction	Might be sensitive to the bulk and initial stage => play collective
Heavy light - correlations	b/c-jet substruture, nature of the interaction **Poster Rohmoser QM 2018**	Might be sensitive to various HF creation in pp, to be calibrated **Poster Vermunt**
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
$v_1(y)$ **QM 2018: // Chatterjee, Poster Coci**	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 ?

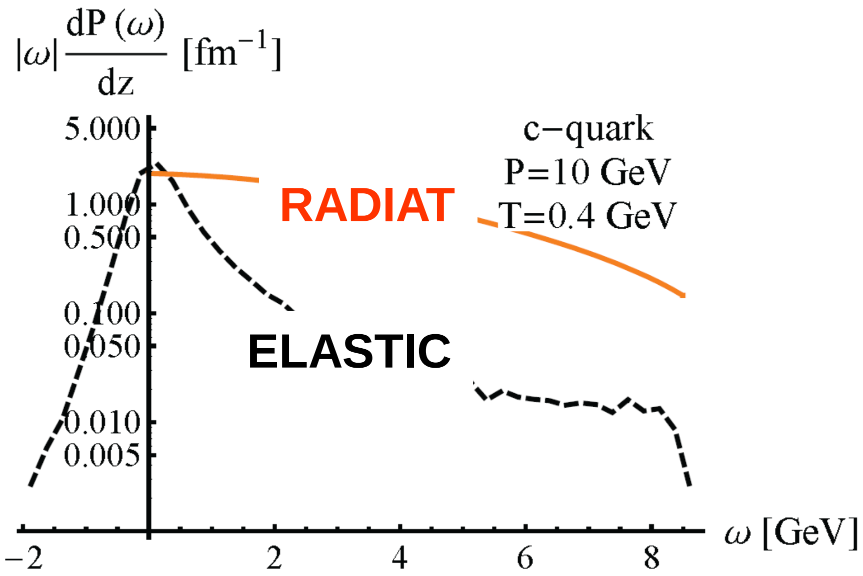
γ - b/c jet: Best HF Correlation ever ?

- 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 $\vec{P}_{HQ}$

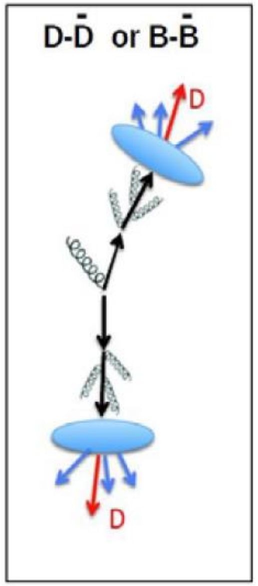


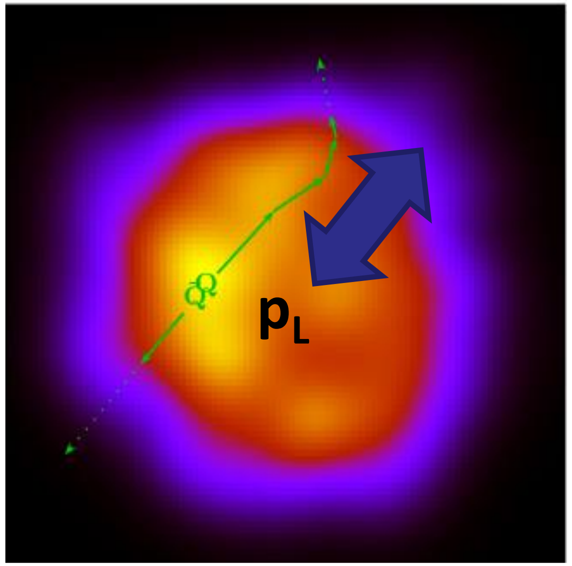
differential probability to loose energy ω per unit time

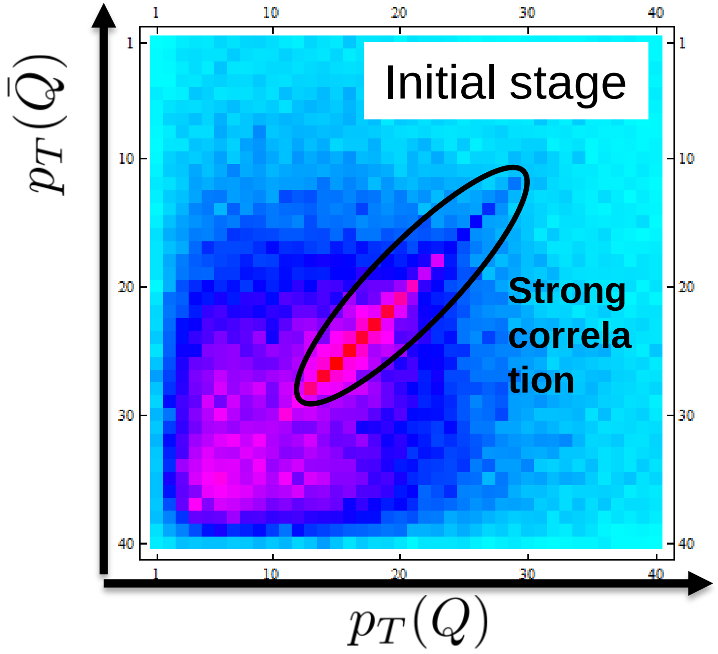
- Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues… RUN3 ? RUN4 ?)

Next best thing: HF-HF correlations

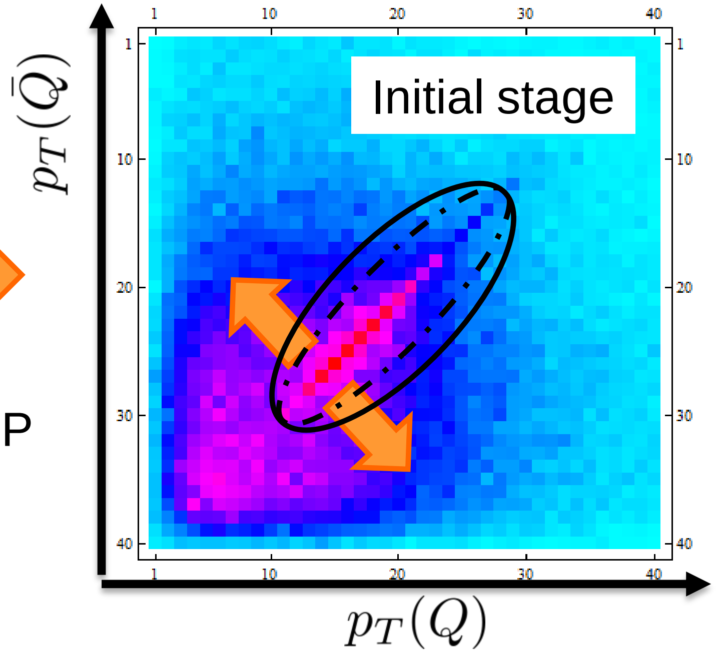
- Back to back D/Dbar or B/Bbar: As compared to γ-D/B: "triggering" itself is affected but symmetry between both particles could limitate the various effects:
- Large number of c-cbar from various NN collisions => large uncorrelated background
- Competing effects due to energy loss: …







Evolution in hot QGP medium

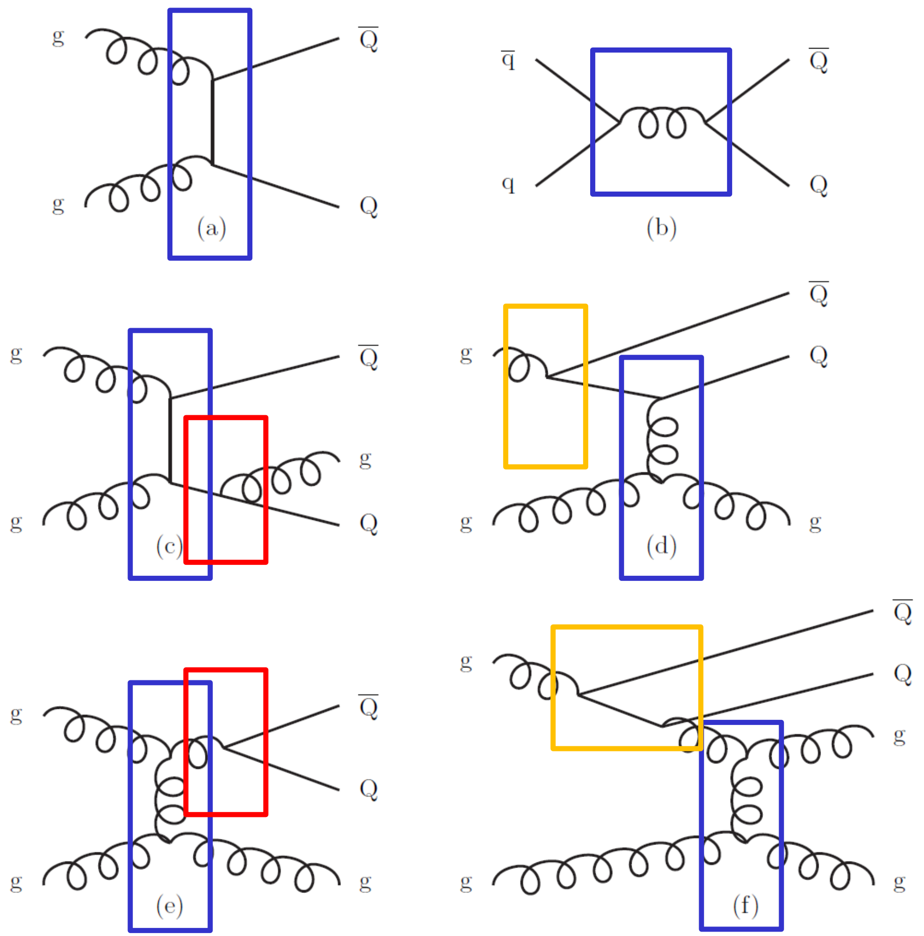


- decorrelation due to various path lengths + fluctuations: reduction

Momentum imbalance: not so naïve approach

L. Vermunt et al.
arXiv:1710.09639

- Goal of the study: investigate whether p_T-p'_T correlations survive NLO effects
- Method for “systematics”: use 2 event generators: PYTHIA (6.4) & EPOS3



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

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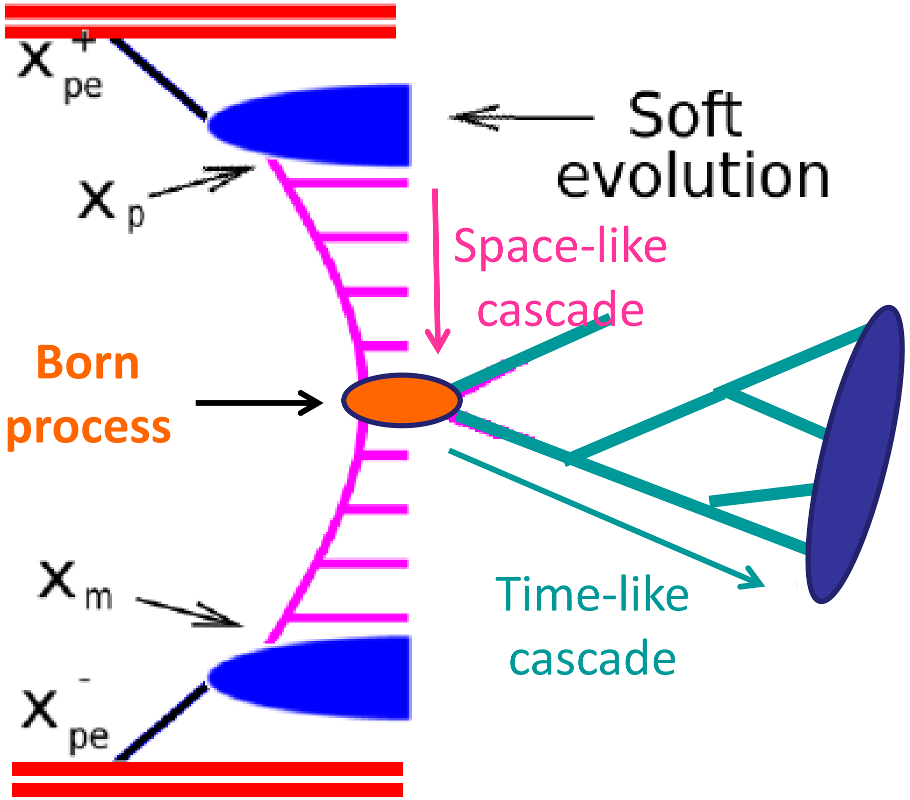

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- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.

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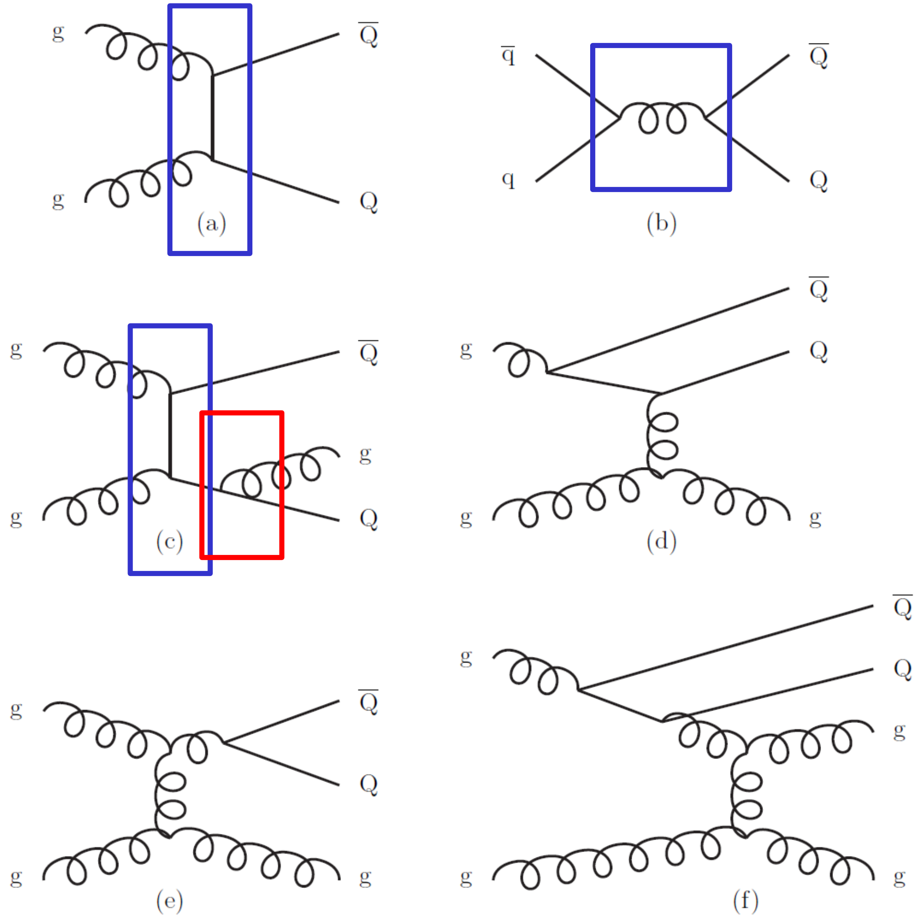

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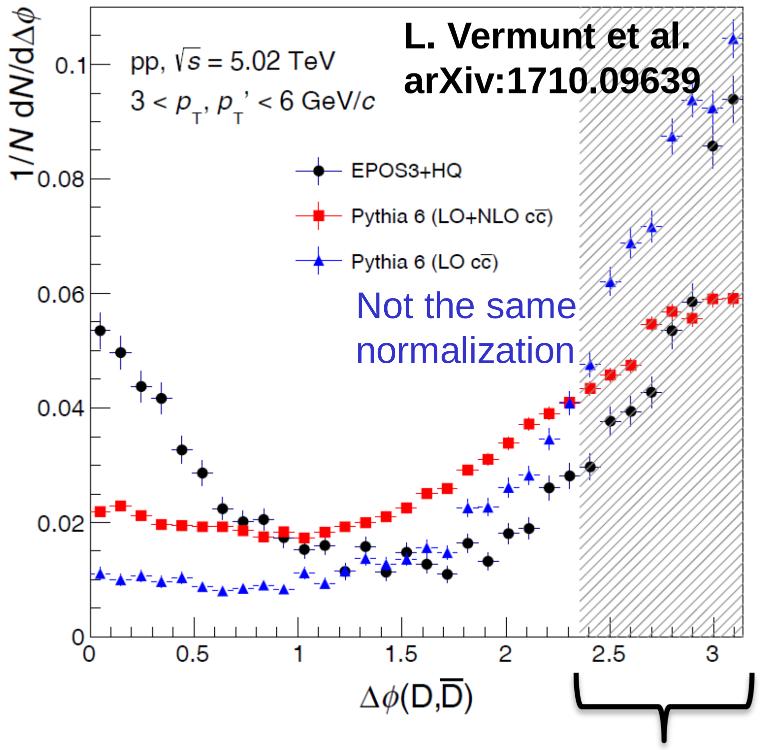
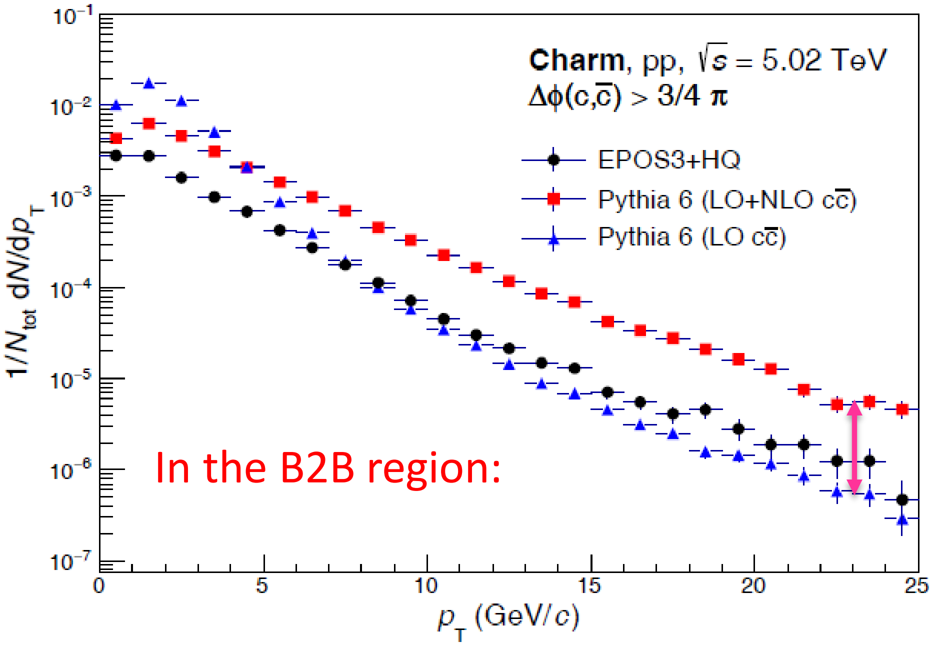
- Same « strategy » in EPOS3, with « semi-hard pomeron » approach (with some soft evolution included), with various LO Born processes.
- In pythia, possibility to restrict to LO ccbar production processes with massive elements (MSEL=1 -> MSEL=4 flag), still switching on the … ISR + FSR … This will be referred to as « LO ccbar »

Momentum imbalance: not so naïve approach

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

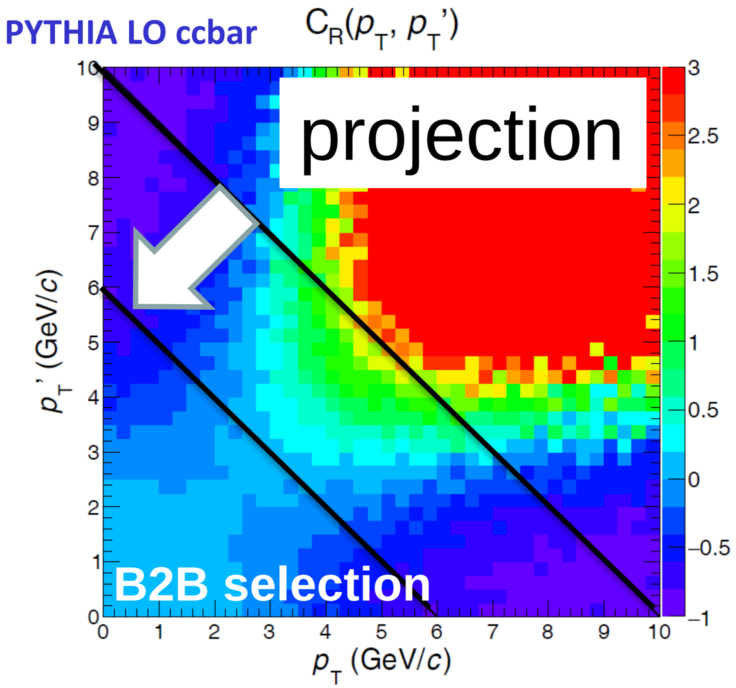




- Good agreement in the normalization for EPOS3 vs PYTHIA « LO » (MSEL=4)
- Large excess PYHTIA « NLO »; shown to be due to flavor excitation like process

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

Momentum imbalance: not so naïve approach



Abolute correlation:

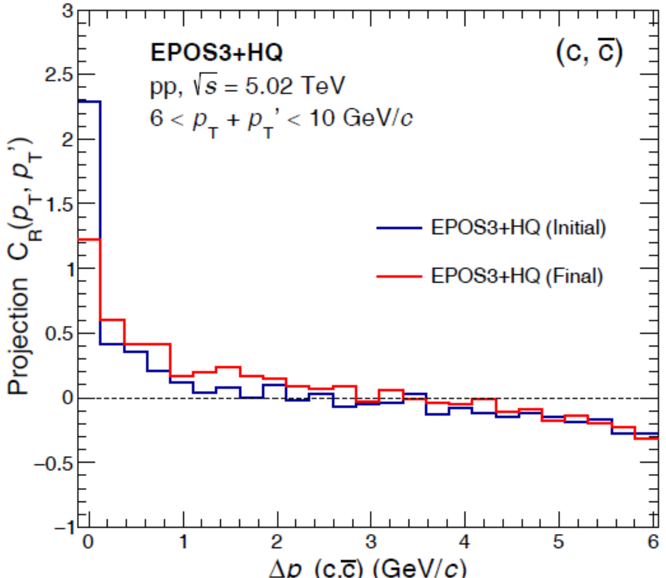
$$C(p_T, p'_T) := \frac{1}{N}\frac{d^2N(p_T, p'_T)}{dp_T dp'_T} - \frac{1}{N}\frac{dN(p_T)}{dp_T} \times \frac{1}{N}\frac{dN(p'_T)}{dp'_T}$$

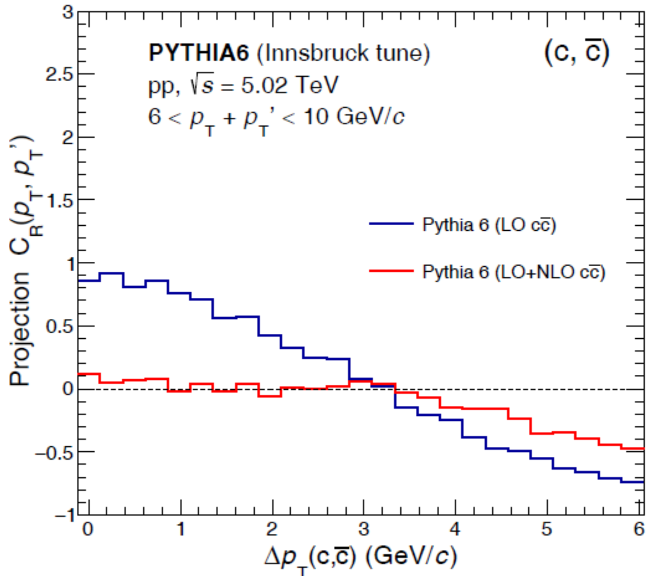
- Vanishes if d^2N factorizes ($d^2N(p,p') = dN(p) \times dN(p')$)
- Satisfies $\int C(p_T, p'_T) dp_T d'_T = 0$

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

- Reveals correlation at finite p_T

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





Mid-term strategies

In order to make progress in our physical understanding and achieve the desired accuracy:

WE NEED GOOD AND PRECISE MEASUREMENTS ON MORE AND MORE SOPHISTICATED OBSERVABLES

Mid-term strategies

But also, from the theory view point:

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

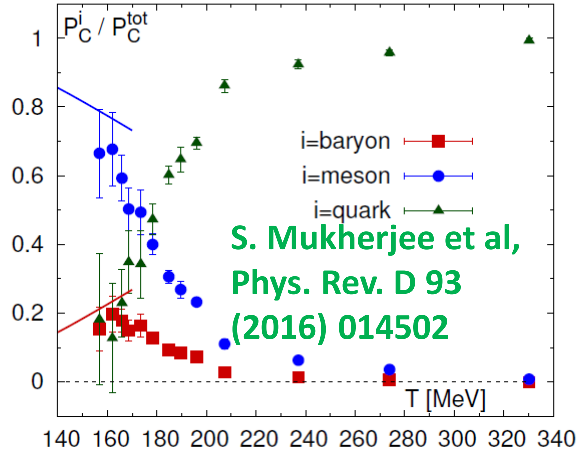
See discussions f.i. in

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

(proc. Lorentz Workshop)

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

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



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

S. Y.F. Liu, QM2018

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

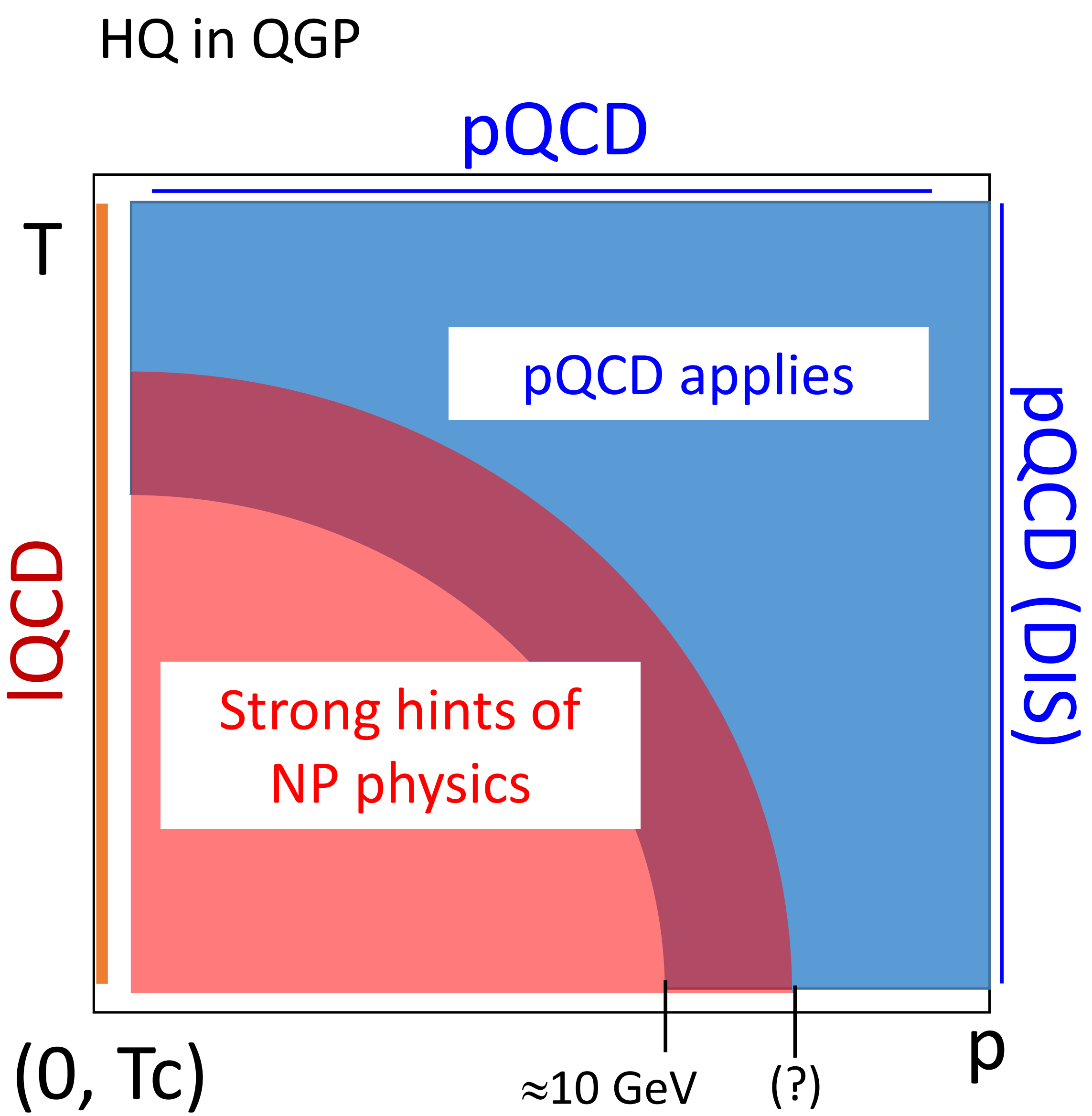
Mid-term strategies

But also, from the theory view point:

- Develop transport theories beyond the classical approximation (and don't be afraid by numerical work, even if redious)
- Assess the role of QGP non-equilibrium effects on HF (including in the initial stage).
- Achieve a rigorous implementation of radiative energy loss in realistic bulks.
- Strutinize the consequences of other effects usually discarded
  - Evolution in turbulent plasma **Stanislaw Mrowczynski, Eur.Phys.J. A54 (2018) no.3, 43**
  - Fluctuation of chromoelectric field **Poster A. I. Sheikh**
  - …

Any suggestion welcome !

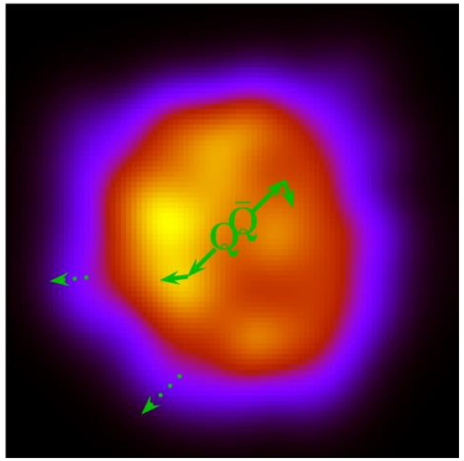
Conclusions



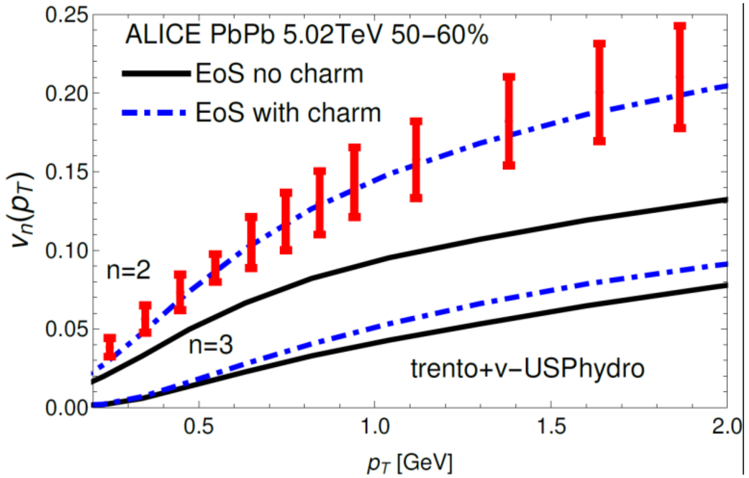
- Existing models offer the possibility to describe most of the OHF experimental AA data while being compatible with existing theory constrains…
- … however with unequal precision and no consensus on the physical NP content
- Improvements and quantitative understanding is on their way, but it will still 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.

Hard or soft probe ?

- Natural thought: m_Q and p_T>> local T => Hard probe
- But for p ≈ 0: τ_{relax} ≈ QGP lifetime = > Soft probe* ?!



- Allows contact with many other fields in Quark Matter and URHIC:
  - Quarkonia
  - Thermalisation of matter
  - Hadronisation
  - Jet physics
  - Small systems
  - CNM
  - MPI
  - Early magnetic field
  - …



J. Noronha-Hostler & Cl. Ratti, arxiv 1804.10661

- This leads to richer physics, but also more complex to scrutinize

Back UP

lQCD

lQCD Calculation of D_s

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

$$G_{\rm E}(\tau) \equiv -\frac{1}{3}\sum_{i=1}^{3} \frac{\Big\langle {\rm Re}\,{\rm Tr}\Big[U(\beta;\tau)\,gE_i(\tau,\mathbf{0})\,U(\tau;0)\,gE_i(0,\mathbf{0})\Big]\Big\rangle}{\Big\langle {\rm Re}\,{\rm Tr}\,[U(\beta;0)]\Big\rangle}$$

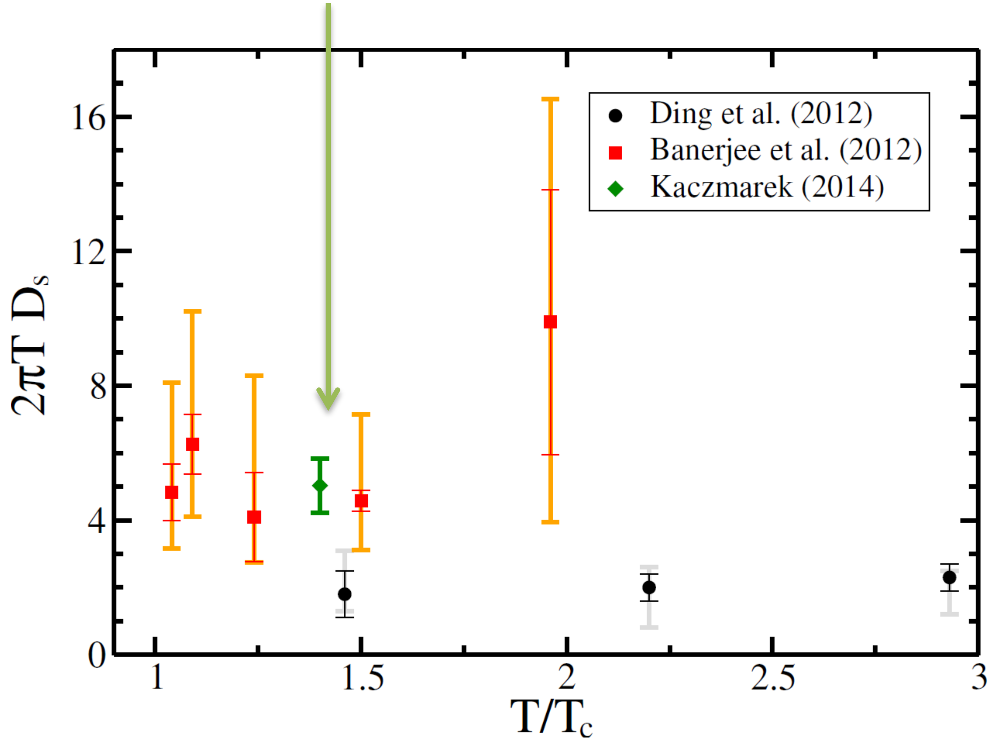
- Then obtain the variance κ of stochastic forces (a transport coefficient; κ = 2 x B) from the slope of spectral function ρ_E at $\omega = 0$:

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

- Main result : $\kappa/T^3 = 1.8\ldots3.4$ then convert to D_s

lQCD Calculation of D_s

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



World data on lQCD calculation of D_s

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

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

HQ-WG

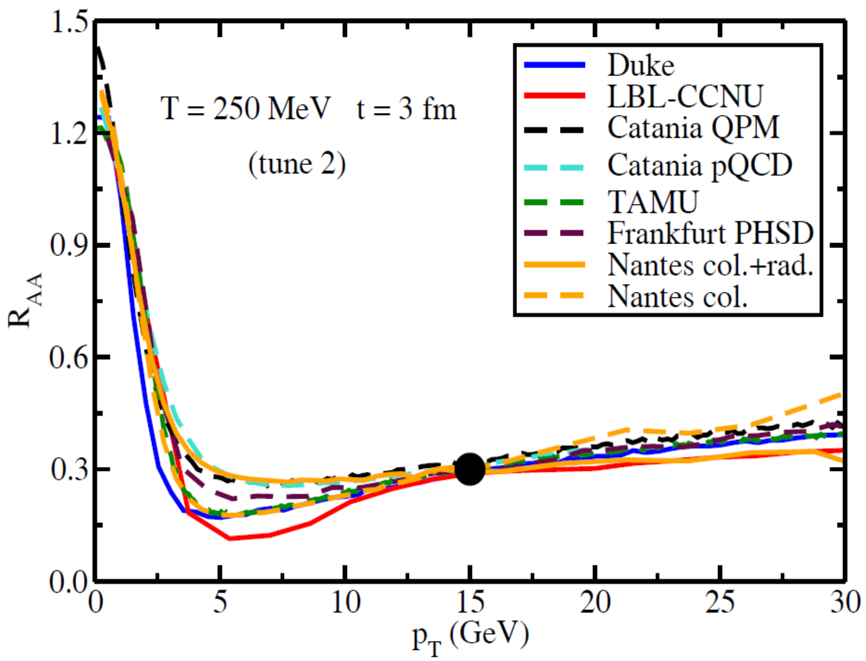
HQ-Working Group (convener: X-N Wang)

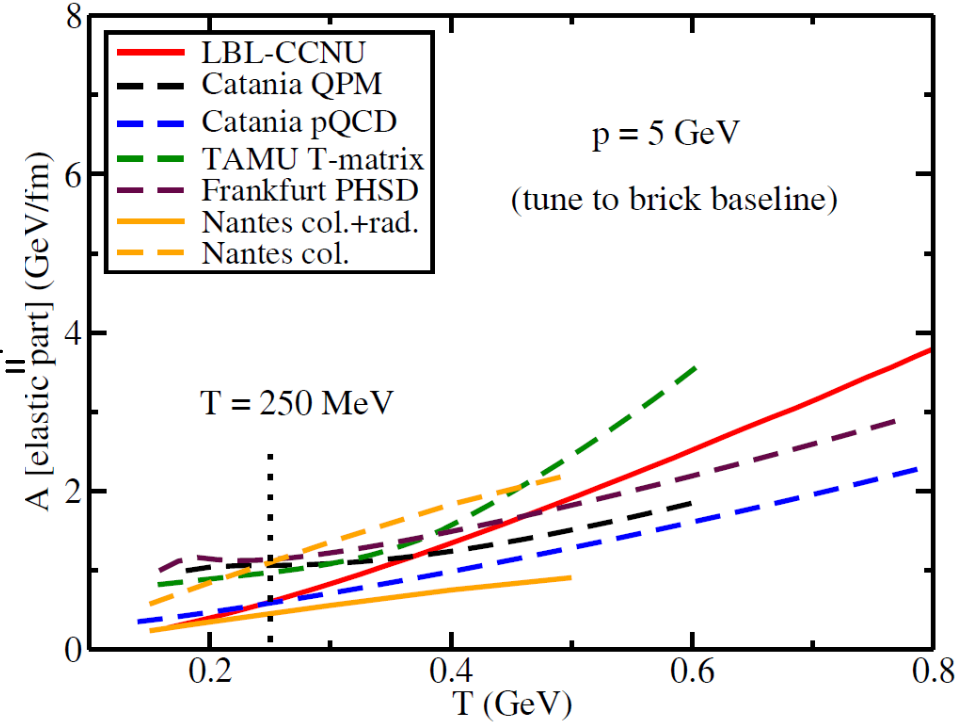
The goal is to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
- Estimate some systematics + uncertainties

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

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

2) Compare them !





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

EMMI - RRTF

EMMI RRTF

Thanks to the generosity of EMMI !!!

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

Researchers involved:

- Organizers
- HQ-WG members
- Other key players in HF – QGP tomography (A. BERAUDO, M. DJORDJEVIC, C. GREINER , G. INGHIRAMI, H. VAN HEES, I. VITEV, CUEJET…)
- lQCD experts (O. KACZMAREK, P. PETRECZKY)
- QCD and EFT experts (G. MOORE , J. PAWLOWSKI)
- Selected experimentalists (J. BIELCIK, P. BRAUN MUNZINGER, E. BRUNA, Z CONESSA, A. DAINESE, YJ LEE, F. PRINO, J. STACHEL)

EMMI RRTF

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

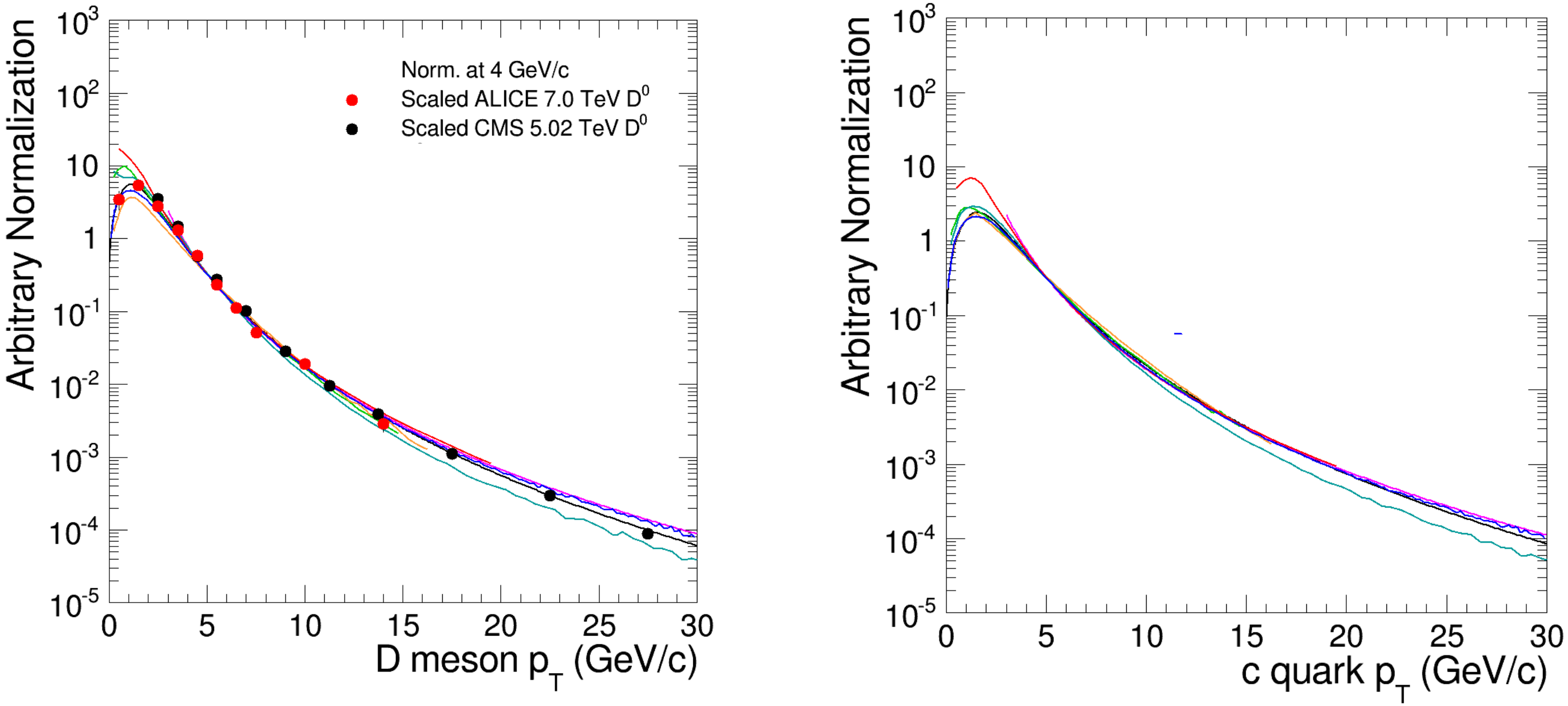
Topics:

- Initial spectra and shadowing
- Bulk evolution and consequence on HF observables
- Transport implementation
- Hadronization
- Microscopic models for HF energy loss and constrains from QCD at low and high momentum
- Future observables

Selected topics presented here

EMMI RRTF : Initial HF spectra and shadowing

Collection of models vs data by Yen-Jie Lee:



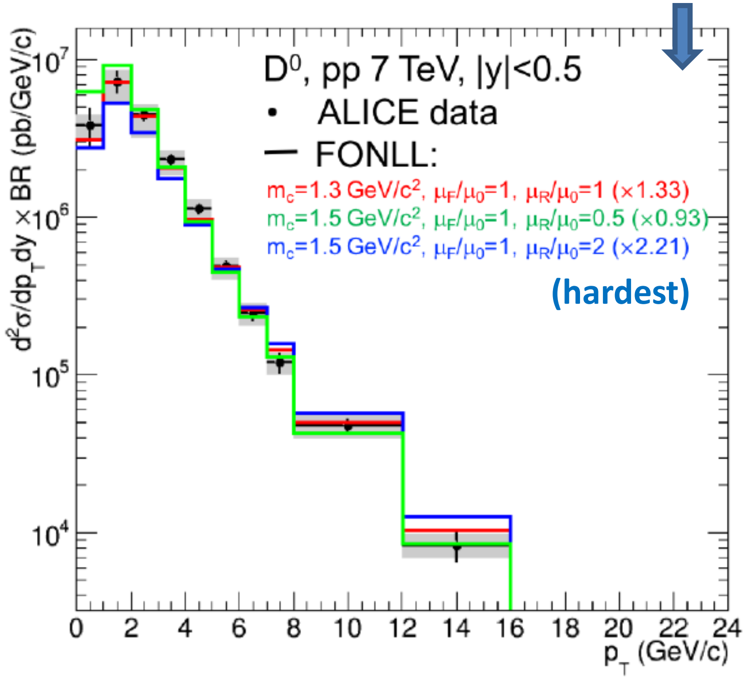
Some « outliers »… Is it acceptable or does it has measurable consequence either on the « extraction » of the transport coefficient (for « tunable » models) or on the agreement with experiment.

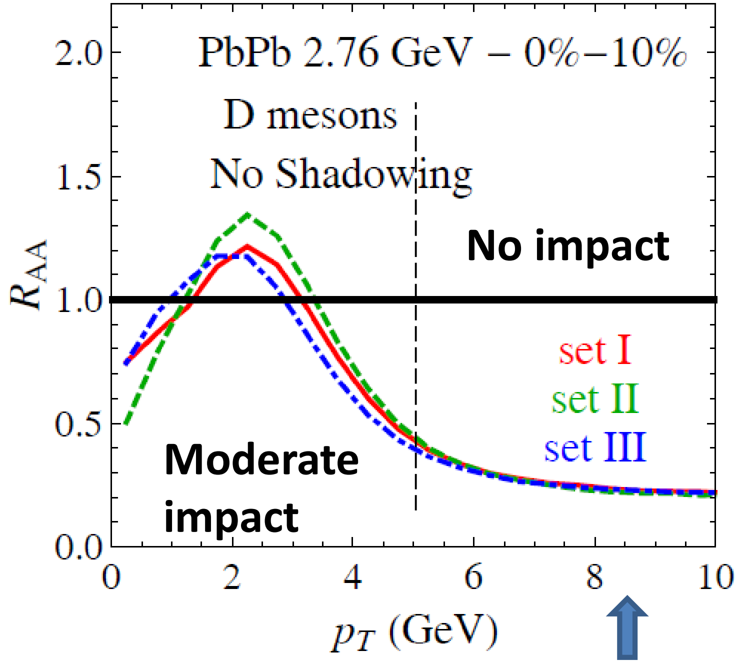
« We all do FONLL / GM - VFNS » … yes, but with slightly different parameters !

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

Right now: data better than uncertainty band in theory:

3 best fits extrated from members of the ALICE collaboration, with a fair wish to explore various hardness (BASELINE)



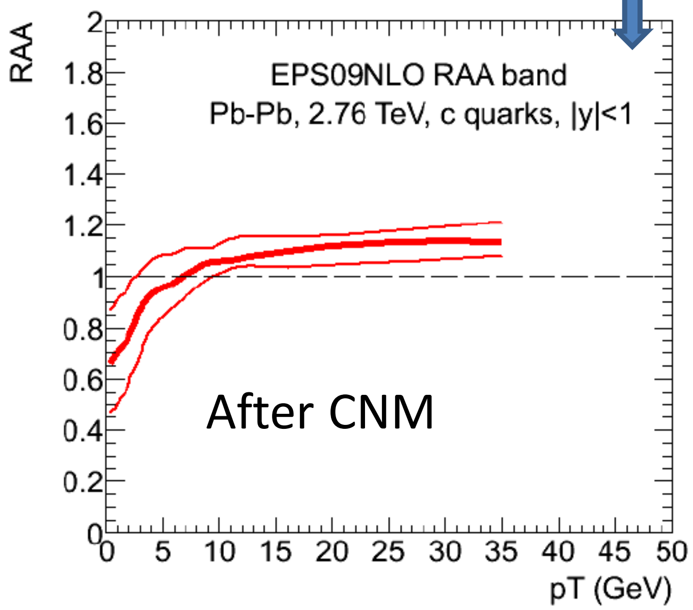


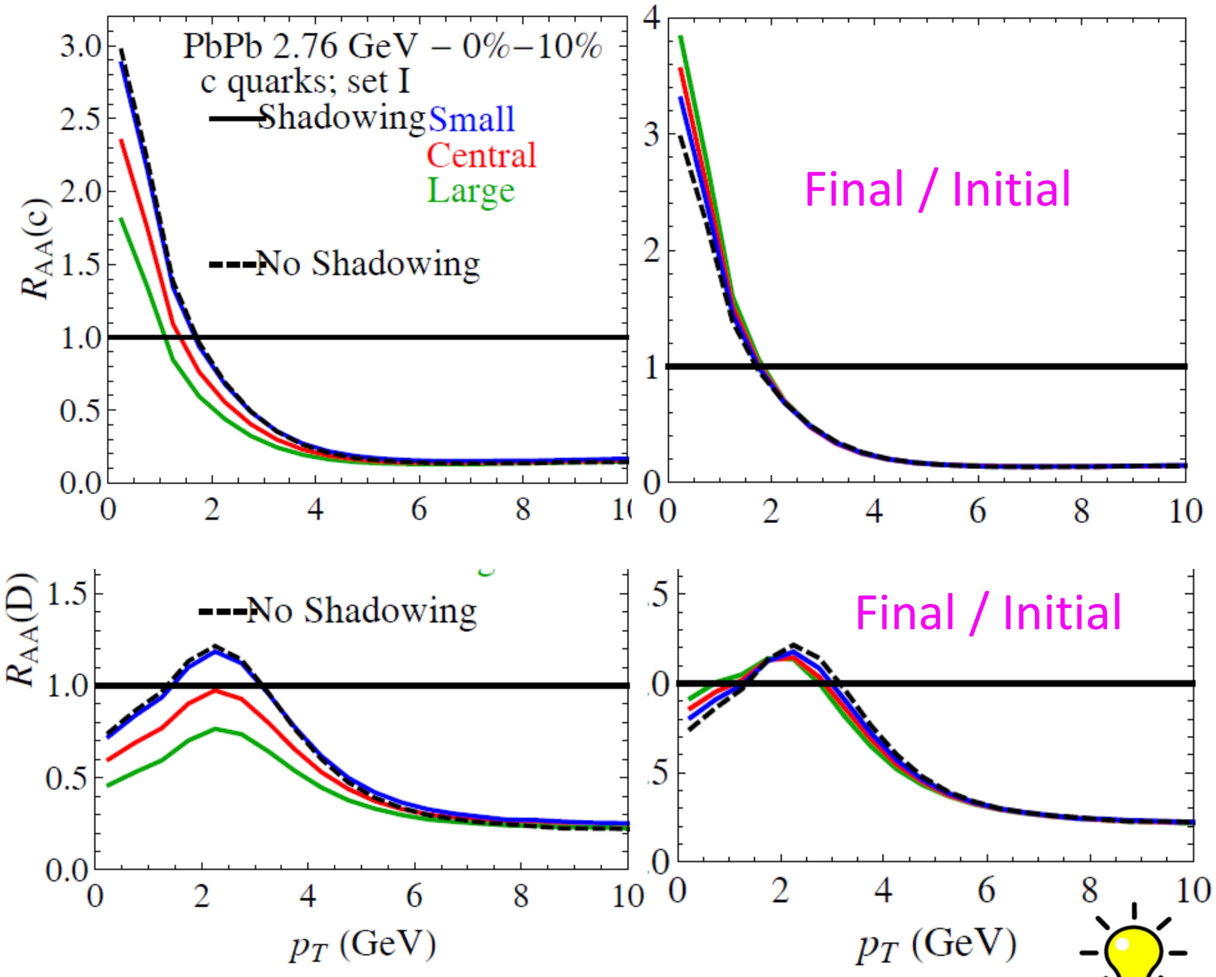
Consequence of the baseline on the RAA of D mesons in the Nantes Model (thermalisation at small p_T => the initial profile has a large impact in the ratio)

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

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

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





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

Large uncertainties for p_T<4 GeV/c

Shadowing seems to act in a nearly multiplicative way

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

Consequence for the collective chase:

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

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

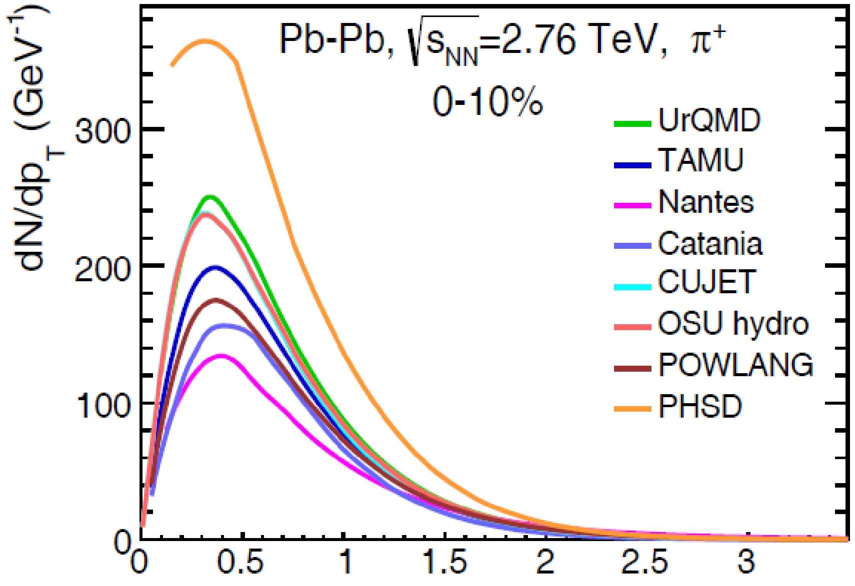
- Perspective (apart from hoping on better control on shadowing):
  - Go for B or to v_2, less sensitive to shadowing
  - Uncertainties on the shadowing may partly factor out if the ratio of R_{AA} at different centralities is considered

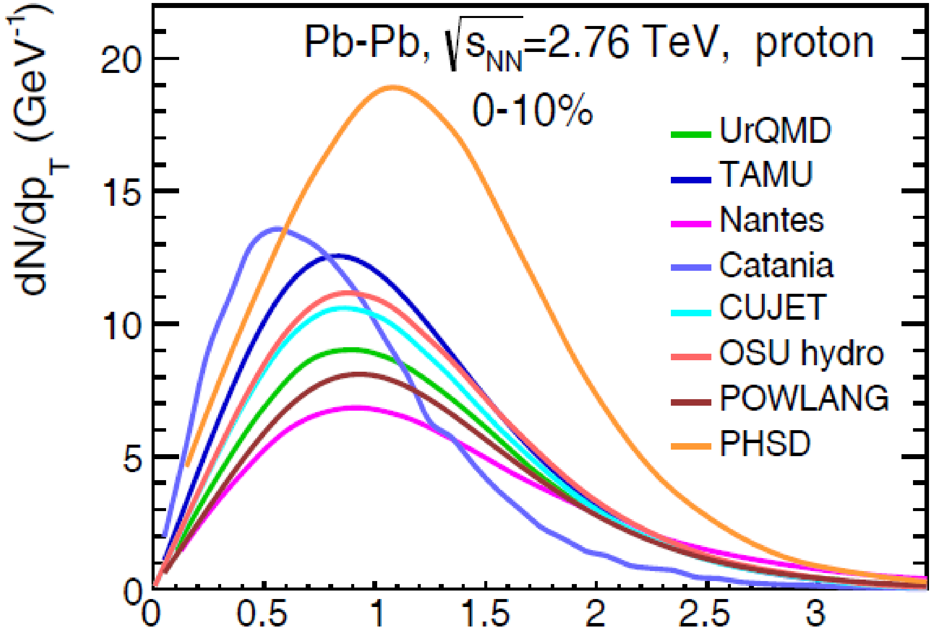
Shadowing seems to act in a nearly multiplicative way

EMMI RRTF : the bulkS

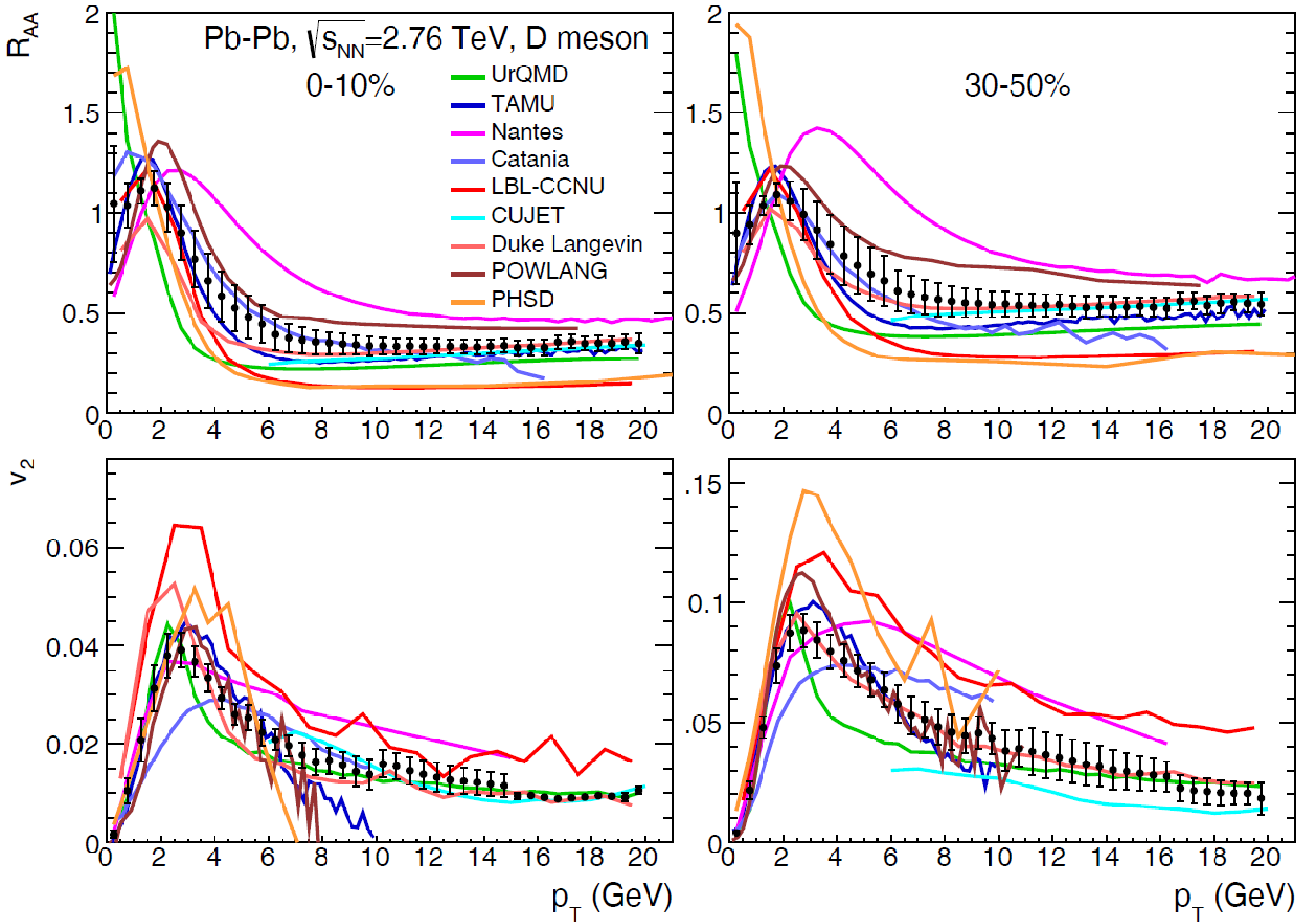
Model	dN_{π^+}/dy $(dS/d\eta)$		dN_p/dy	
	0-10%	30-50%	0-10%	30-50%
UrQMD	495	152	34	11
TAMU	682 (12400)	170 (3080)	58	15
Nantes	478	129	38	10
Catania	(14000)	(3700)		
LBL-CCNU/Duke	653 (12600)	160 (3080)		
CUJET	610 (10820)	142 (2610)	45	11
POWLANG	(9100)	(1450)		
PHSD	722	148	31	6
exp.	670±68	163±15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

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

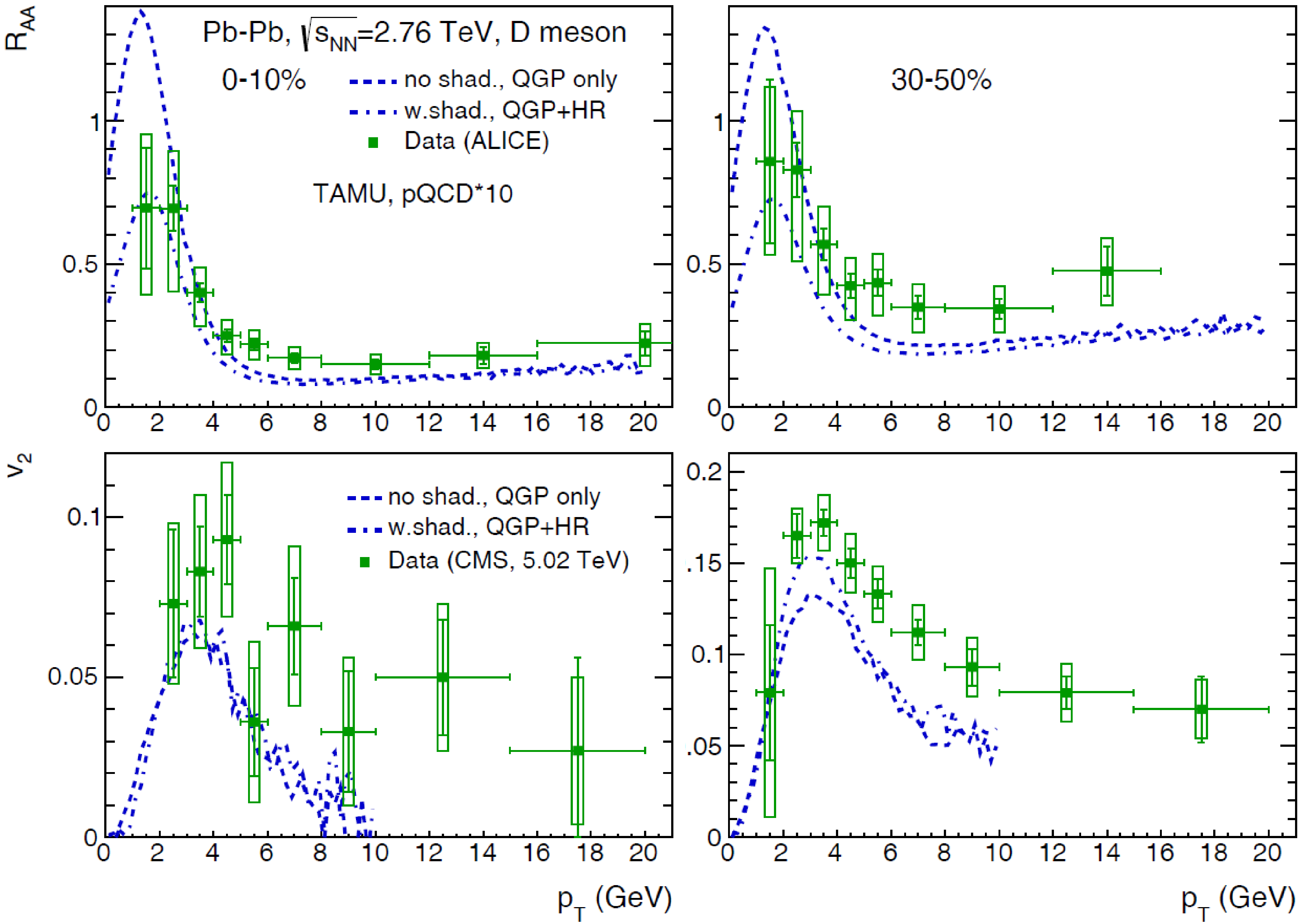




EMMI RRTF : the average vs the various models

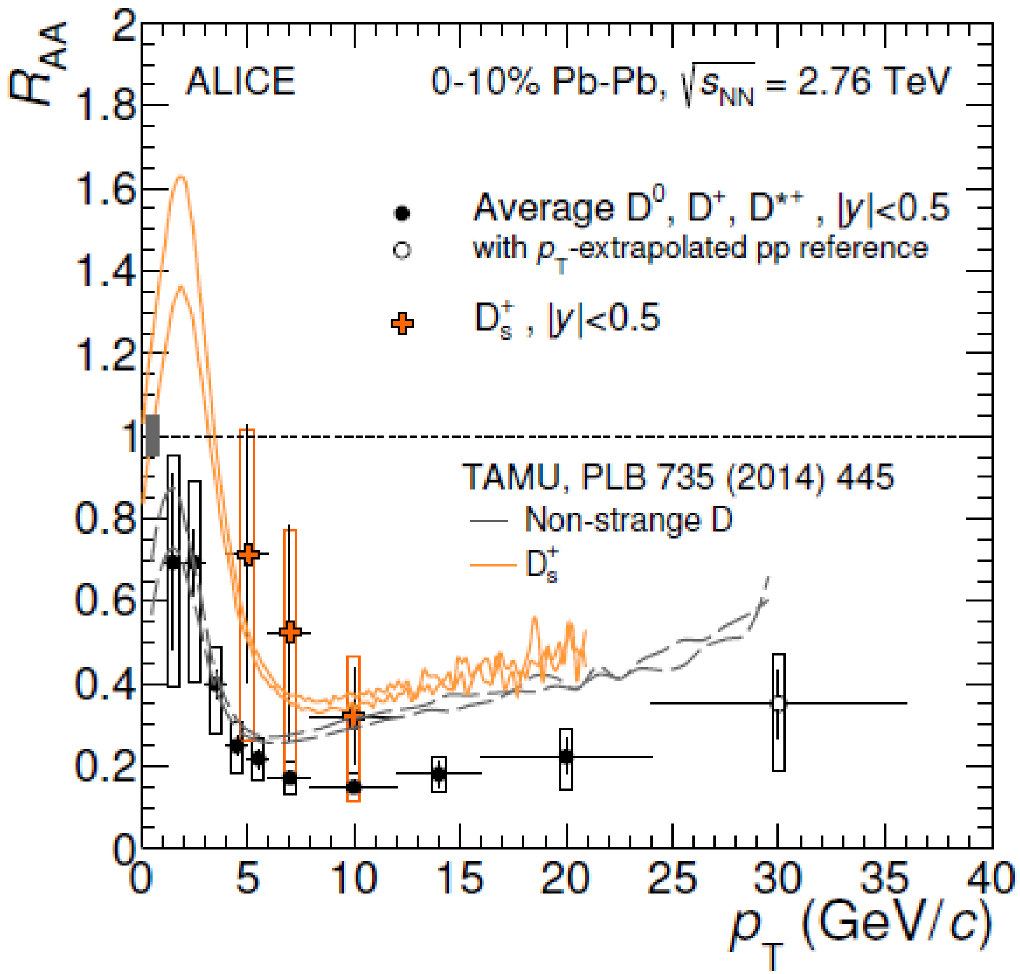


EMMI RRTF : TAMU pQCD x 10



Hadronization

Hadronisation (Ds)

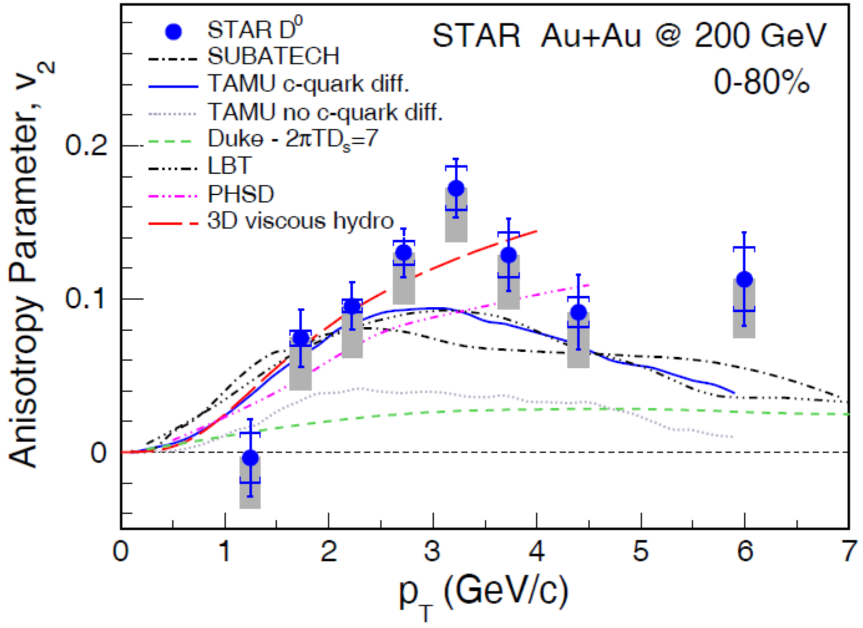


ALICE data for D and Ds mesons (JHEP 1603 (2016) 082) compared with TAMU-model predictions (M- He et al., PLB 735 (2014) 445)

Other constrains

Model + Exp. Constrains on D_s

- F.i., recent STAR study: **STAR Collab. PRL 118 (2017)**



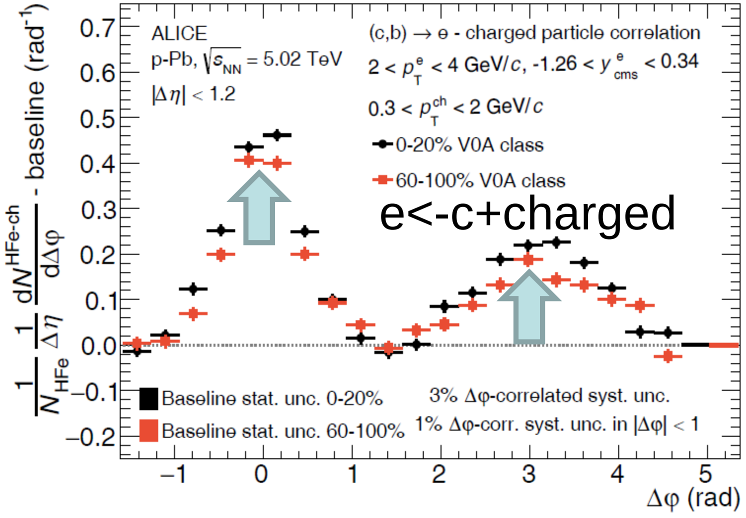
compare with	$2\pi T D_s$	χ^2/NDF	p-value
SUBATECH [11]	2–4	15.2 / 8	0.06
TAMU c quark diff. [13]	5–12	10.0 / 8	0.26
~~TAMU no c quark diff. [13]~~	~~-~~	~~29.5 / 8~~	~~2×10^{-4}~~
Duke [14]	7	35.7 / 8	2×10^{-5}
LBT [15]	3–6	11.1 / 8	0.19
PHSD [10]	5–12	8.7 / 7	0.28
3D viscous hydro [42]	-	3.6 / 6	0.73

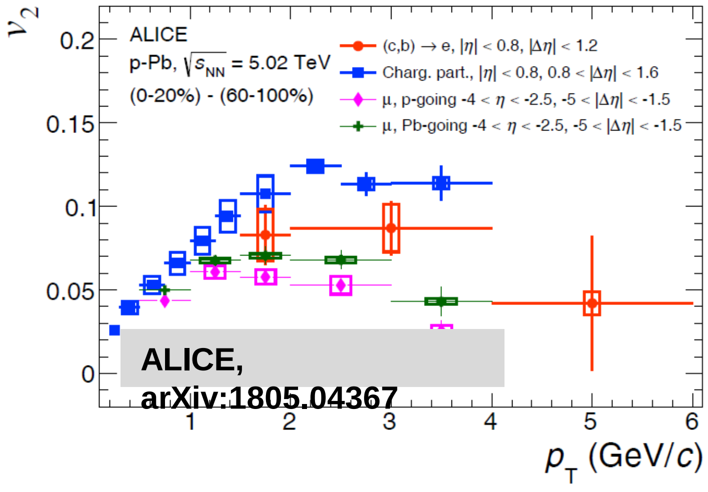
TABLE I. D^0 v_2 in 0–80% centrality Au+Au collisions compared with model calculations, quantified by χ^2/NDF and the p-value (the probability of observing a χ^2 that exceeds the current measured χ^2 by chance). $2\pi T D_s$ values quoted are in the range of T_c to $2T_c$. χ^2/NDF is calculated in the p_T range wherever the model calculation is available.

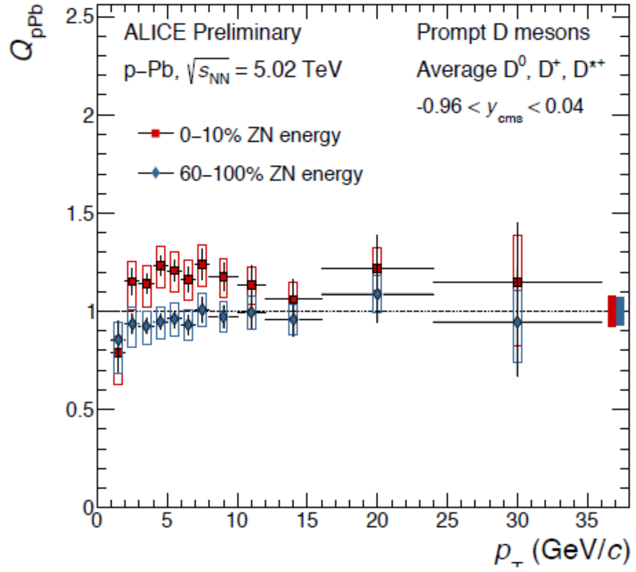
- Not really conclusive; χ^2/NDF is not a smooth function of D_s: large residuals
- Beware: Models are essentially validated at finite $p_{(T)}$; extrapolation at 0 momentum might contain further uncertainties
- Urgent need for collective actions to better control the « residuals »

Small systems

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





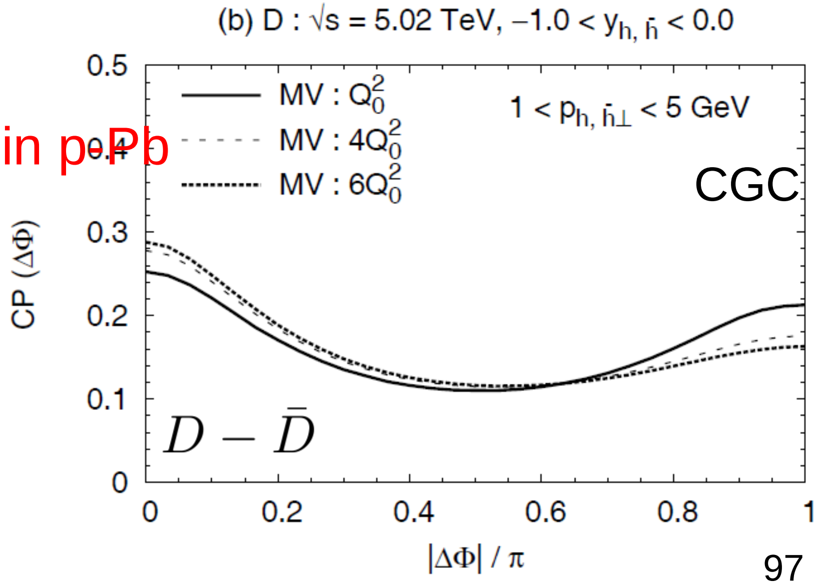


- Finite v_2 seen in p-Pb data but no significant difference in the spectrum ?
- It seems to me that we get similar modifications from both the 0^{th} and 2^{nd} order harmonic (to be checked)
- Physical origin ?
- Both coupling to hydro **and** CGC lead to azimuthal correl. for HF in p-Pb

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

both $v_2 \approx 4\%$

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



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

Some thoughts:

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

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

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

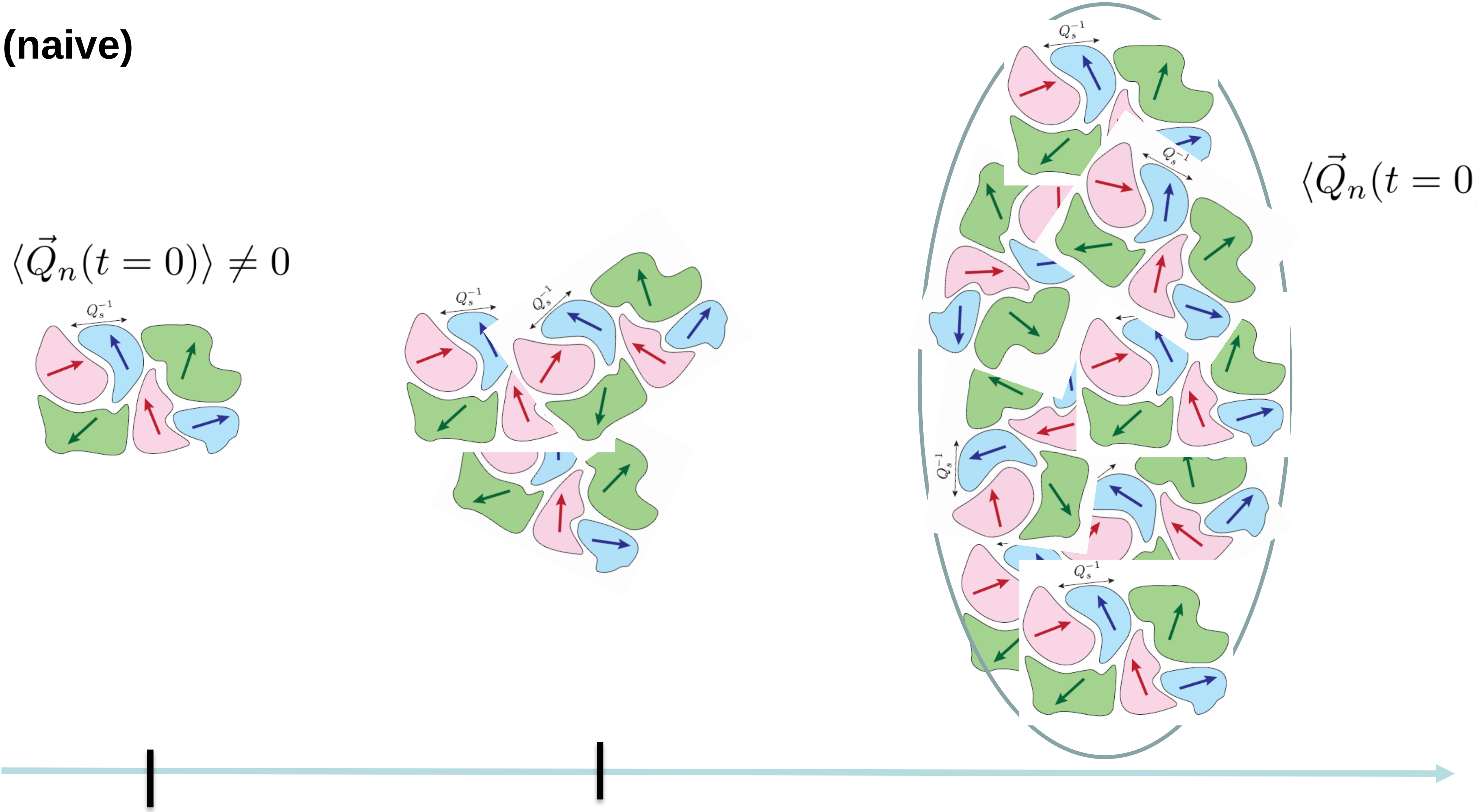
M. Greif et al, Phys. Rev. D 96, 091504 (2017)

HF: from p-Pb -> Pb-Pb

Some futher (naive) thoughts

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

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



p-p

Peripheral p-Pb

Semi - Central Pb-Pb

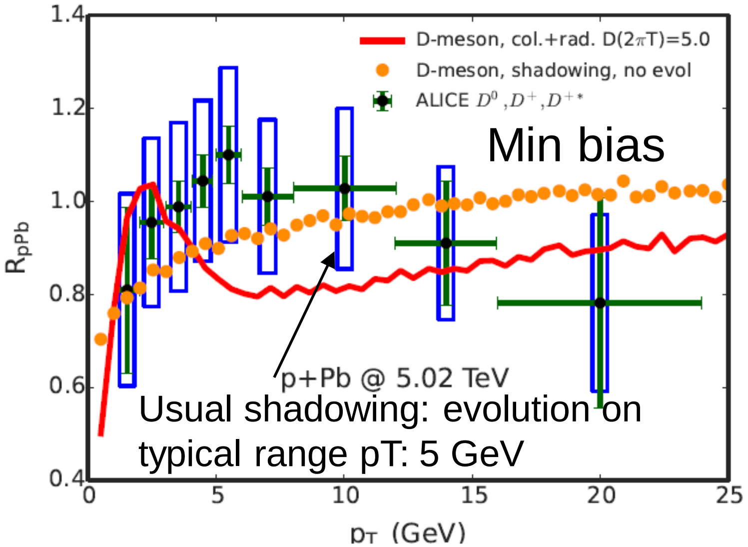
Gradual transition from CGC -> geometry ?

p-Pb (Duke)

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

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

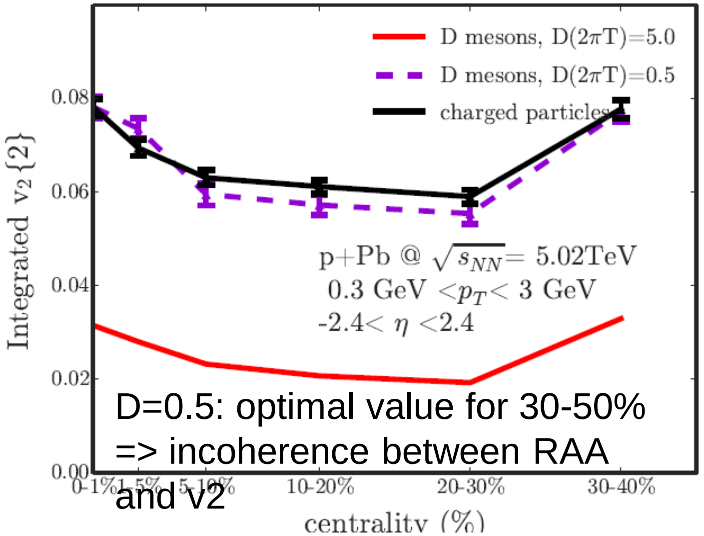
D $\qquad \hat{q}$



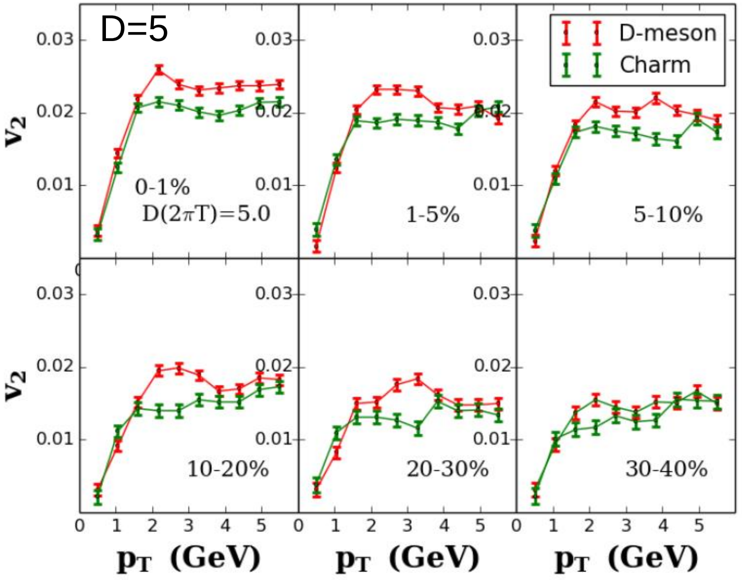
Min bias

Usual shadowing: evolution on typical range pT: 5 GeV

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

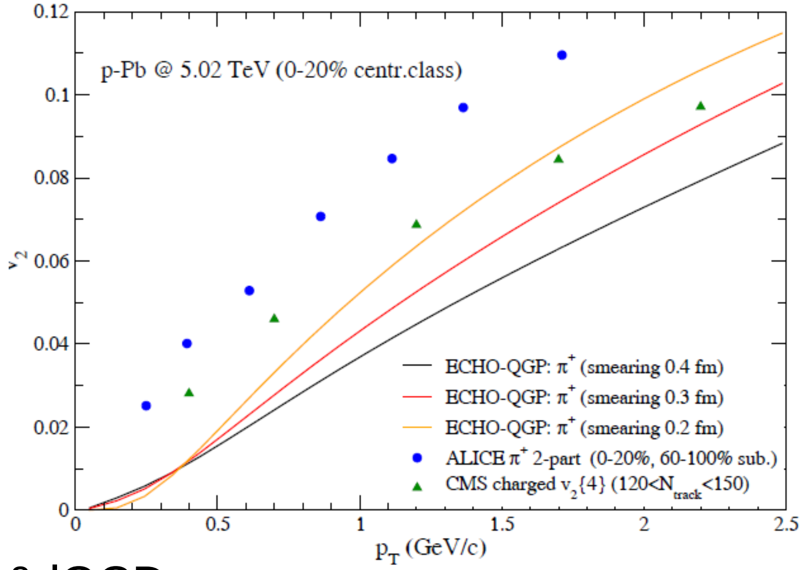


D=0.5: optimal value for 30-50% => incoherence between RAA and v2



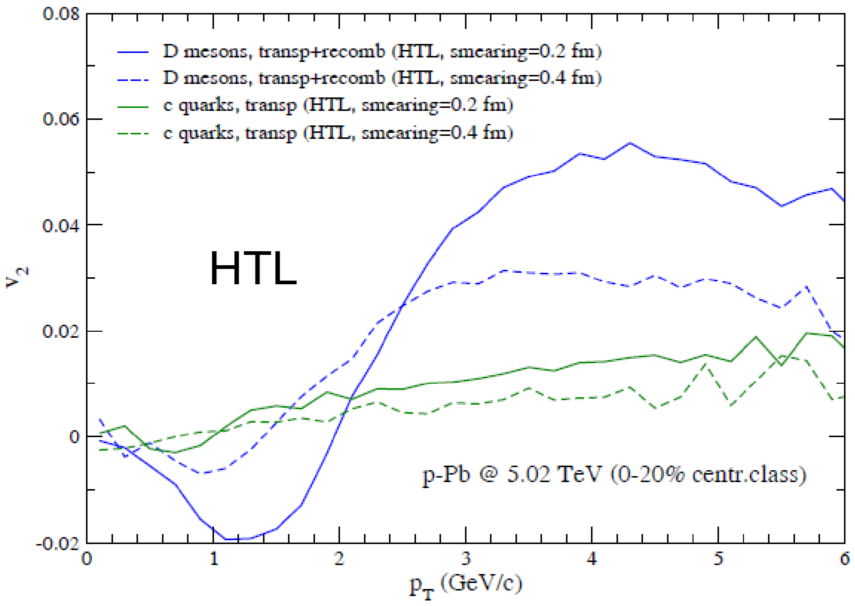
p-Pb (Beraudo et al)

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



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

Major contribution to v2(D): hadronisation



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