

QM 2018 – Venezia (Italy)

Open Heavy Flavors (in Nuclear Collisions): Theory (and model) 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,...)
- Prospects and future strategies (including other observables)
- Conclusions

P.B. Gossiaux

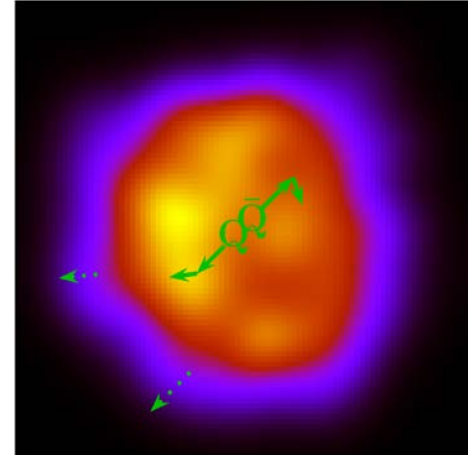
SUBATECH, UMR 6457

Université de Nantes, IMT Atlantique, IN2P3/CNRS

Why open heavy flavors in A-A ?

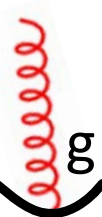
1. Φ : Produced early, number conserved through time evolution (even at LHC) \Rightarrow signature (hard probes) of early (hot) phase
2. Φ : *Strongly affected by the QGP phase (up to factor 5 in the final spectrum)*
3. Φ : Weakly affected by late time evolution (heavy, colour transparency)
4. Interpretation: Allows physical picture based on physical scales ($t_{\text{relax}} \propto m_Q/T^2 \Rightarrow$ 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

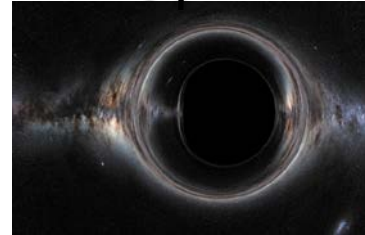


Transport coefficients

\vec{p}



g



QPM (Queen's Police Medall)

g



HQ in hot medium...

... interacting with various objects

Quasi random process =>

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

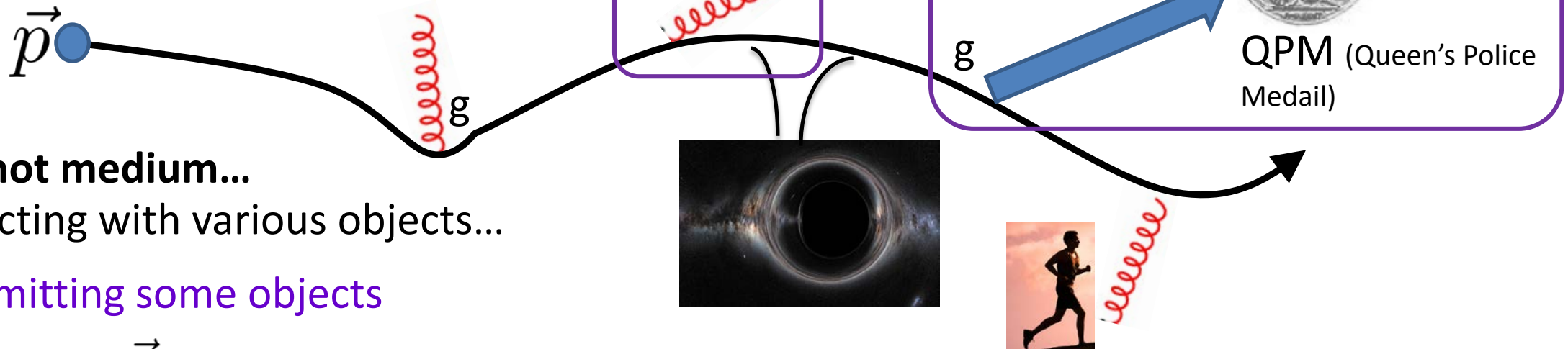
$$\frac{d}{dt} \langle \vec{p}_{T,i} \vec{p}_{T,j} \rangle = \kappa_T(\vec{p}, T) \delta_{i,j} \quad \kappa_T [\text{GeV}^2 \text{fm}^{-1}] : \text{Transverse diffusion coef. (p space)}; \quad \hat{q} = 2\kappa_T = 4B_0$$

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

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...

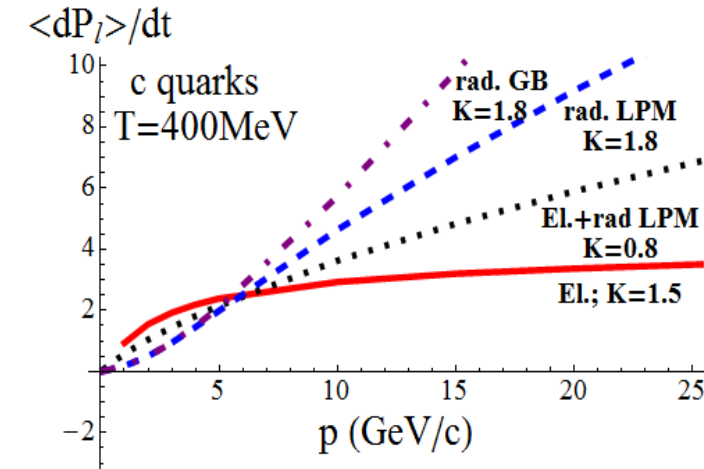
... interacting with various objects...

... and emitting some objects

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

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

Sought transport coeff.



!!! In this case, the relaxation rate $< (<<) \eta_D$

Transport coefficients at low momentum $p \approx m_Q$

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

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

For historical reasons, physics displayed as a function of $2\pi T$ x the spatial diffusion coefficient

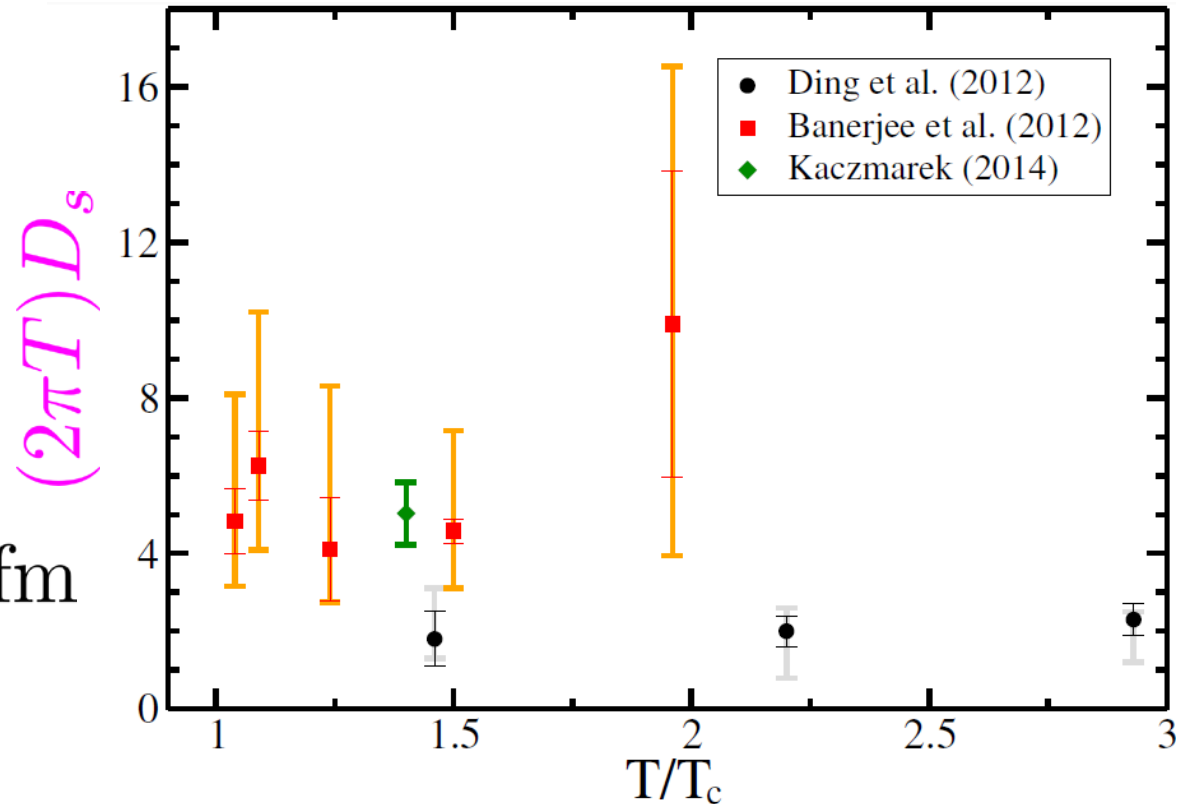
$$\underbrace{(2\pi T)D_s}_{\text{Gauge for the coupling strength}} = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q\eta_D} \quad \Rightarrow \quad \tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$$

Gauge for the coupling strength

IQCD results

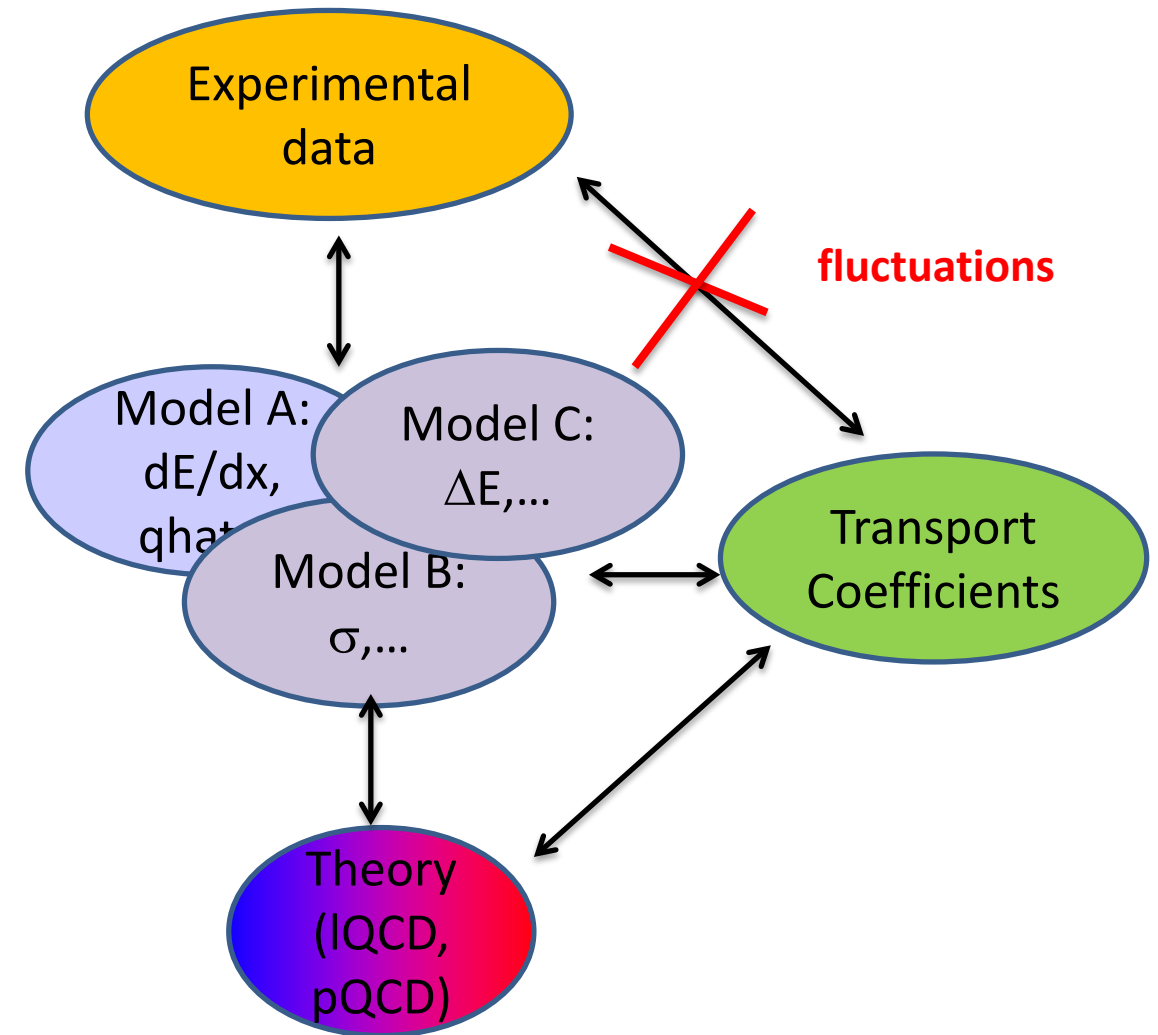
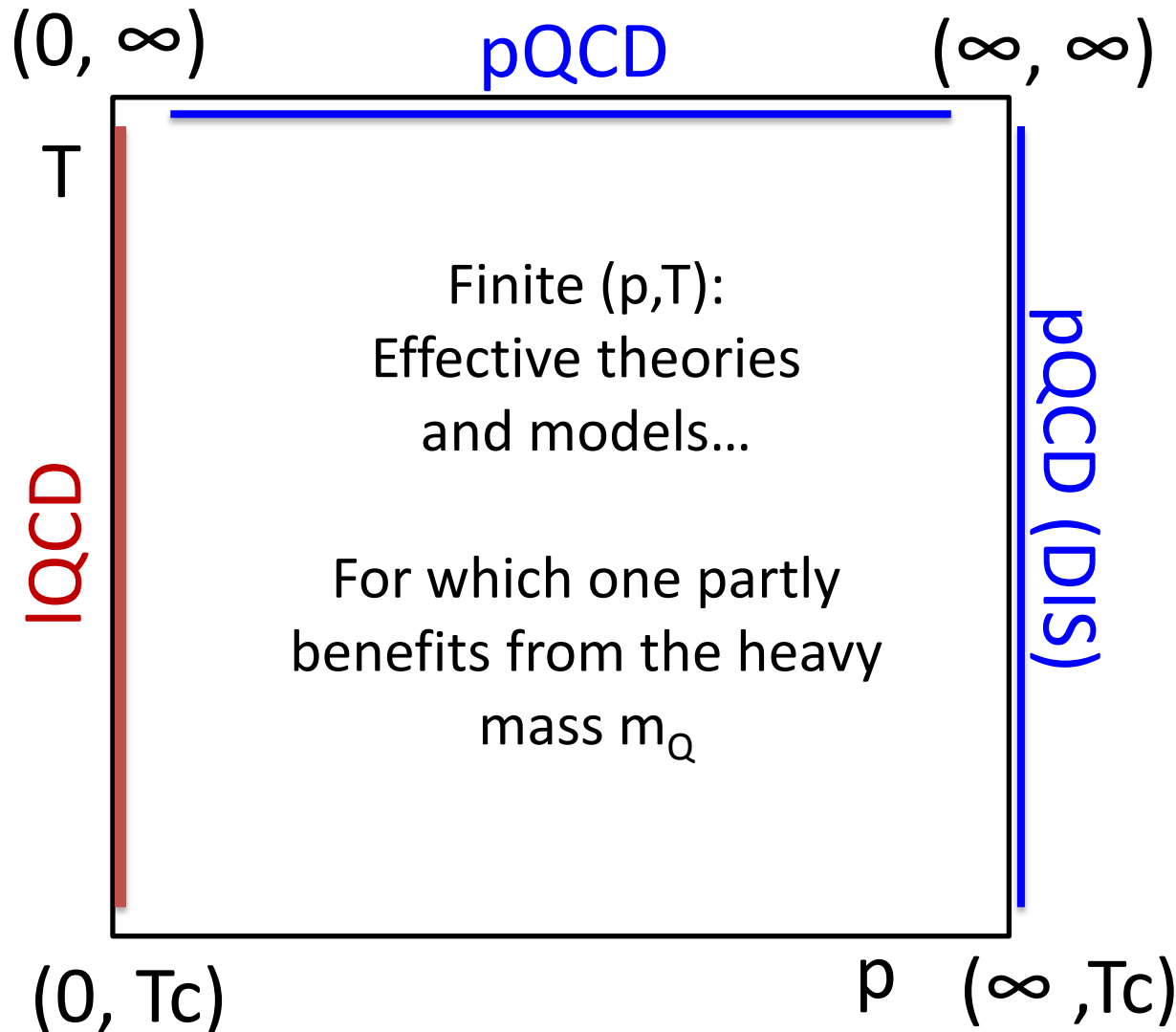
The sole direct rigorous calculation of the transport coeff to my knowledge

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



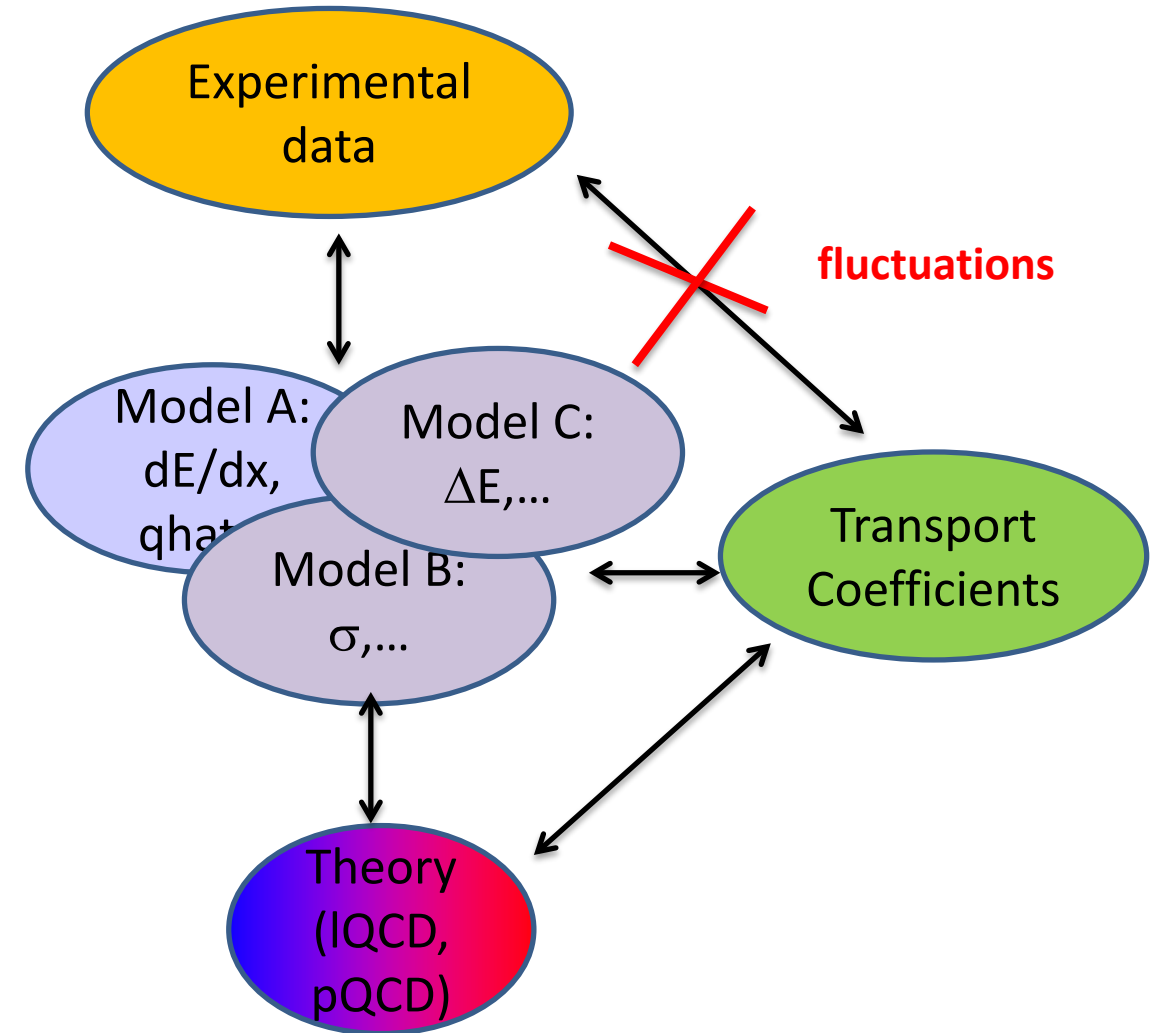
Landscape of HF theory and modeling in URHIC

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



Today Stakes and Motivation

- Very subtle 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 « reasonable » precision ?
 - => What is the impact of various « extra » ingredients ?
 - Do we agree on what « reasonable » means (x 2 ? 50% ?, 10% ?)
- **Need to intercompare the approaches.**



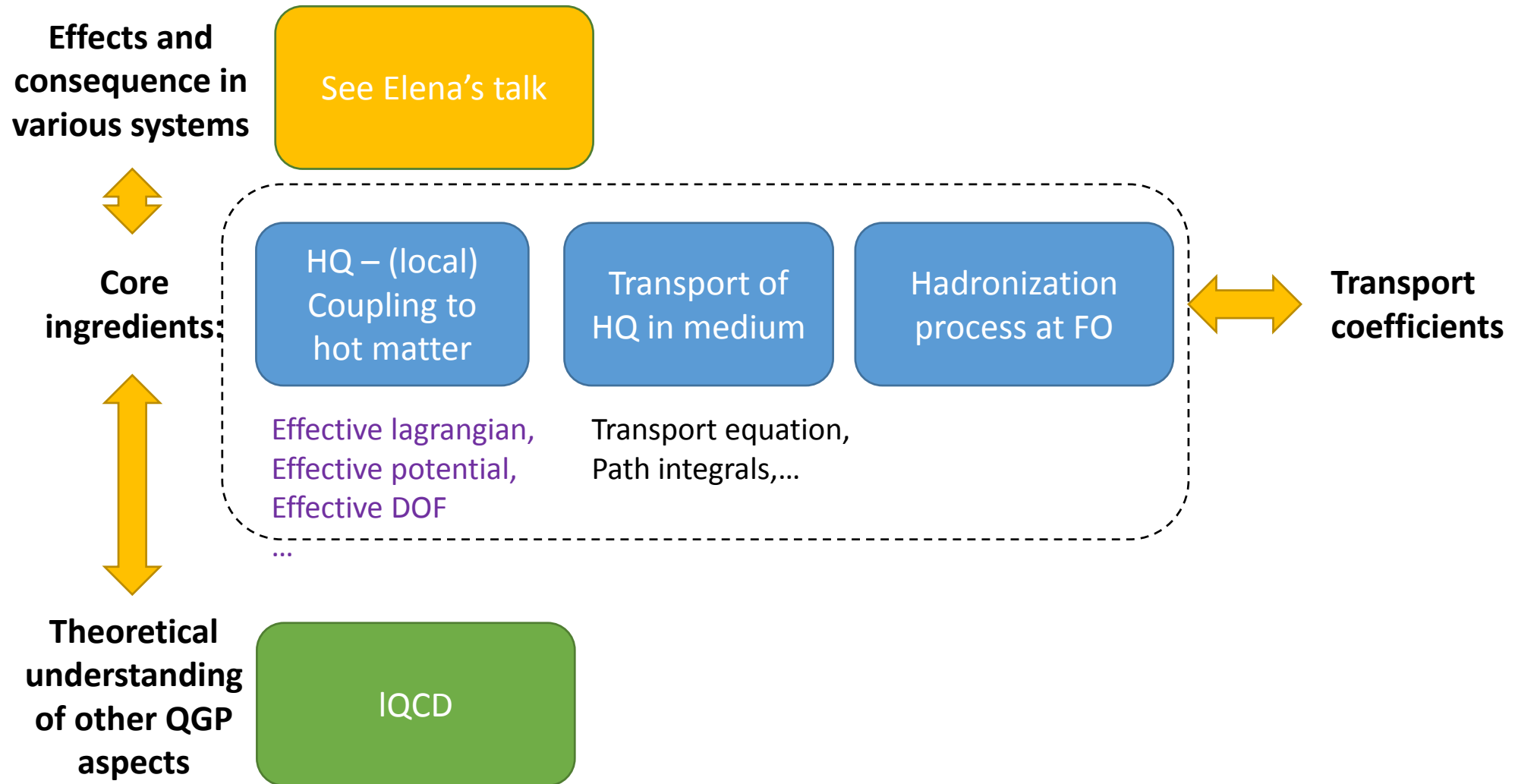
Big motivations for this talk

See Andrea Rossi at student day:

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

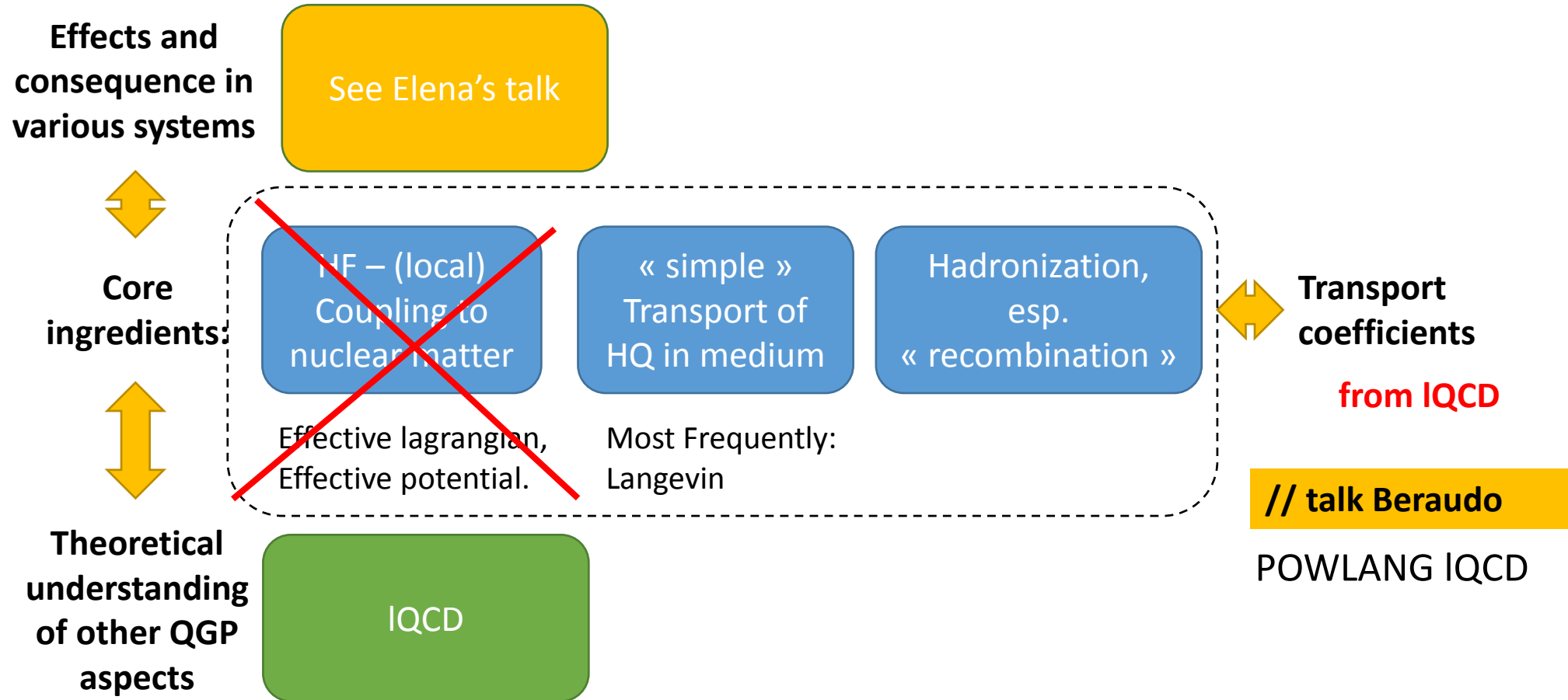
A bit of structure

HQ propagation in QM & URHIC...



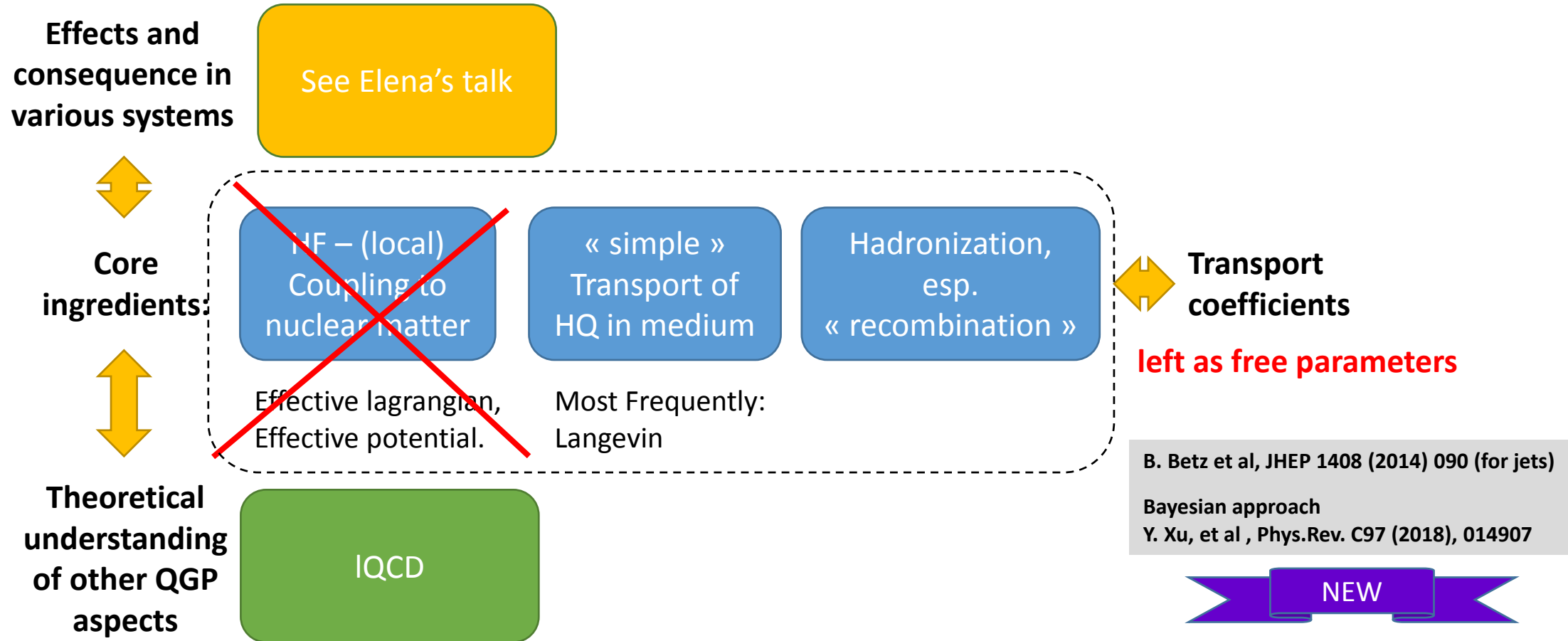
A bit of structure

No Model approach



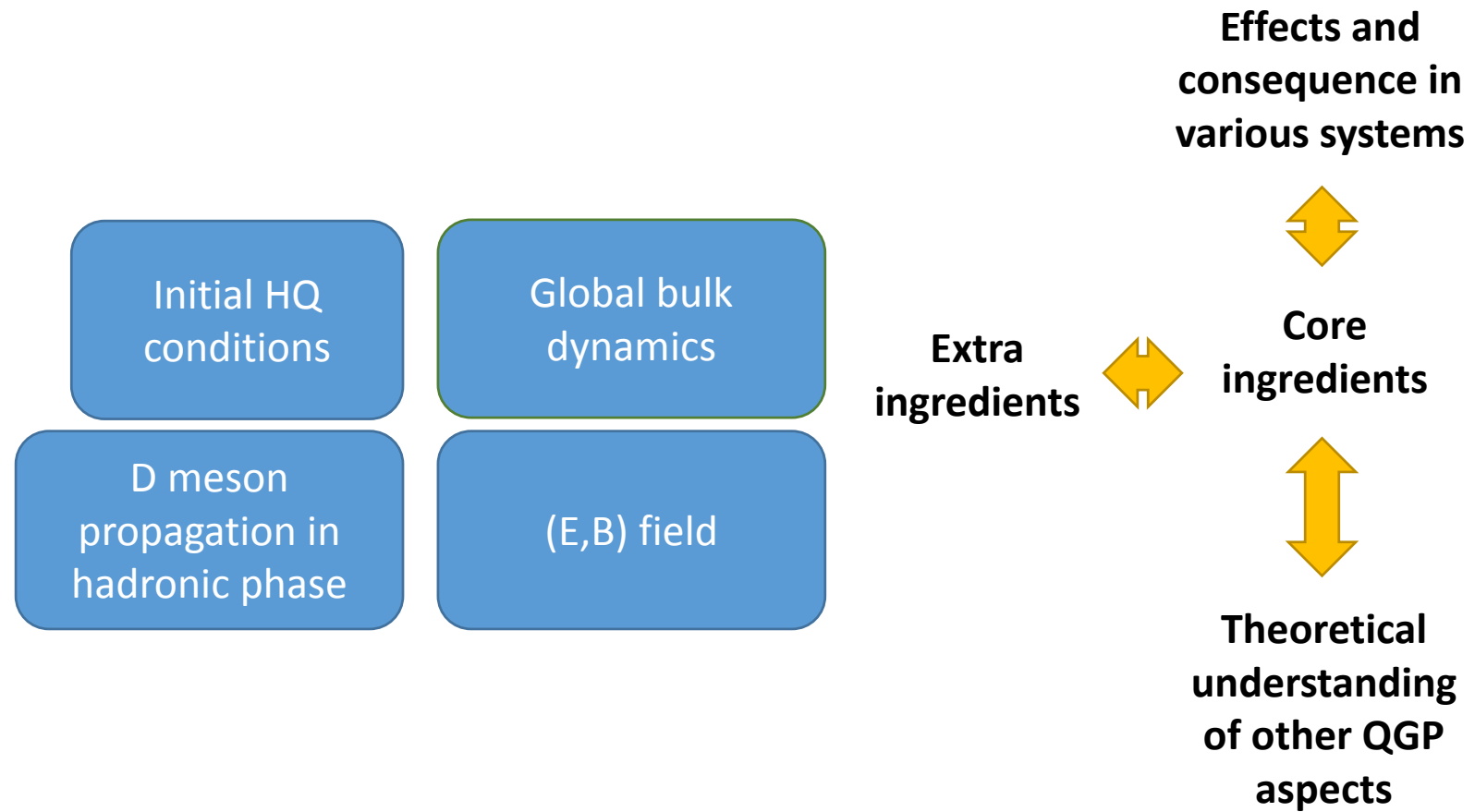
A bit of structure

No Model approach



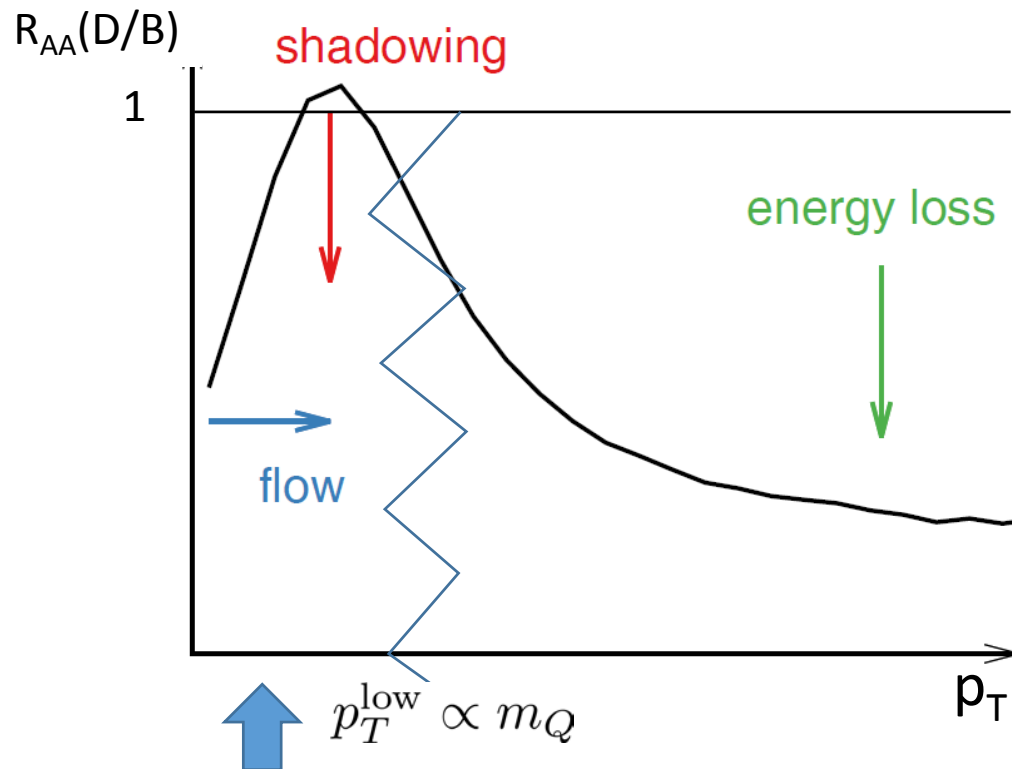
A bit of structure

HQ propagation in QM & URHIC...



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

The pattern seen in the data



- Dominated by elastic interactions
- $m_Q \gg T \Rightarrow$ 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

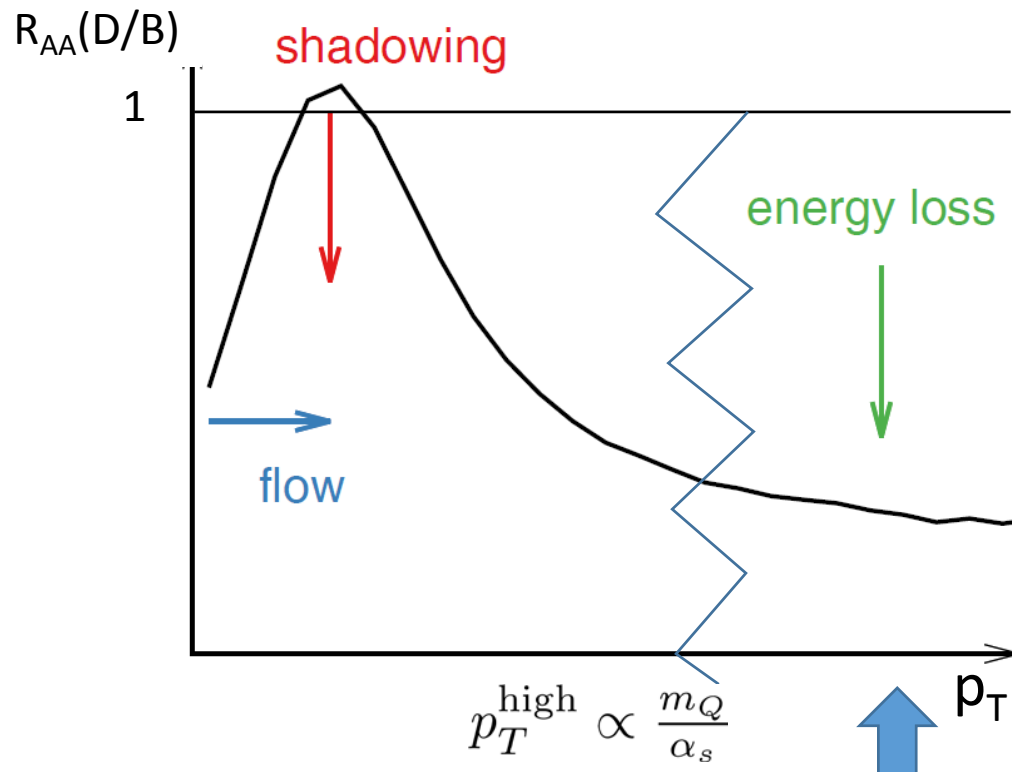
Quenching & energy loss: due to

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

Italic: extrinsic 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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Flow bump: due to

- (radial) flow of the medium and coupling at small p_T
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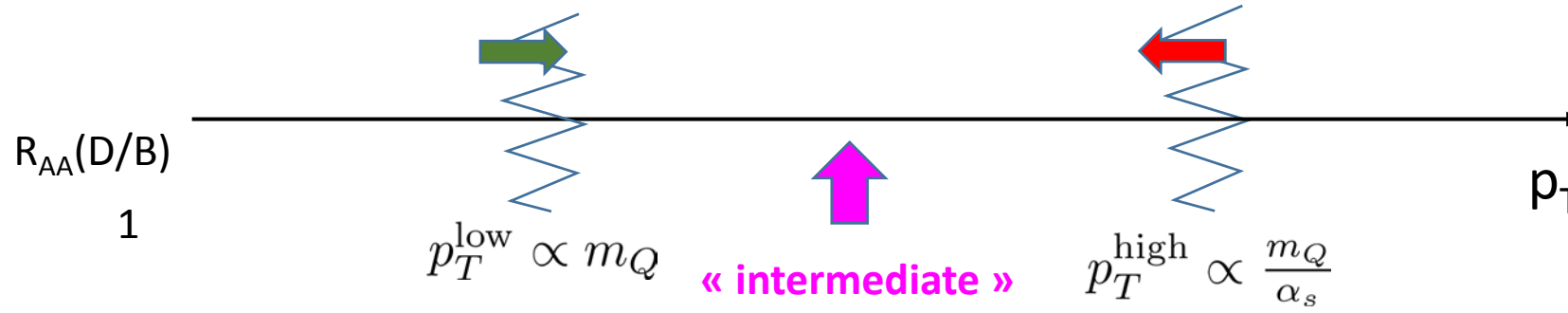
shadowing: due to initial state nuclear effects

Quenching & energy loss: due to

- elastic and inelastic scatterings
- opacity of the medium

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

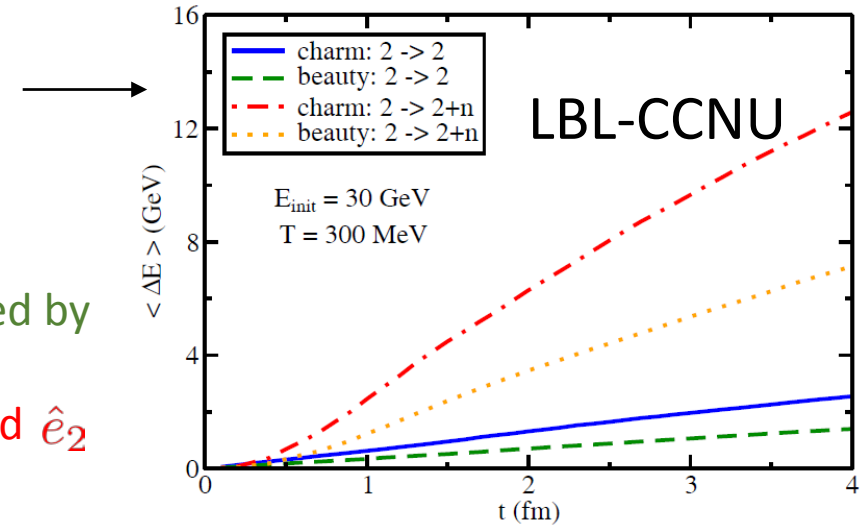
Basic Consequences of HQ interaction with QGP for the R_{AA}



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



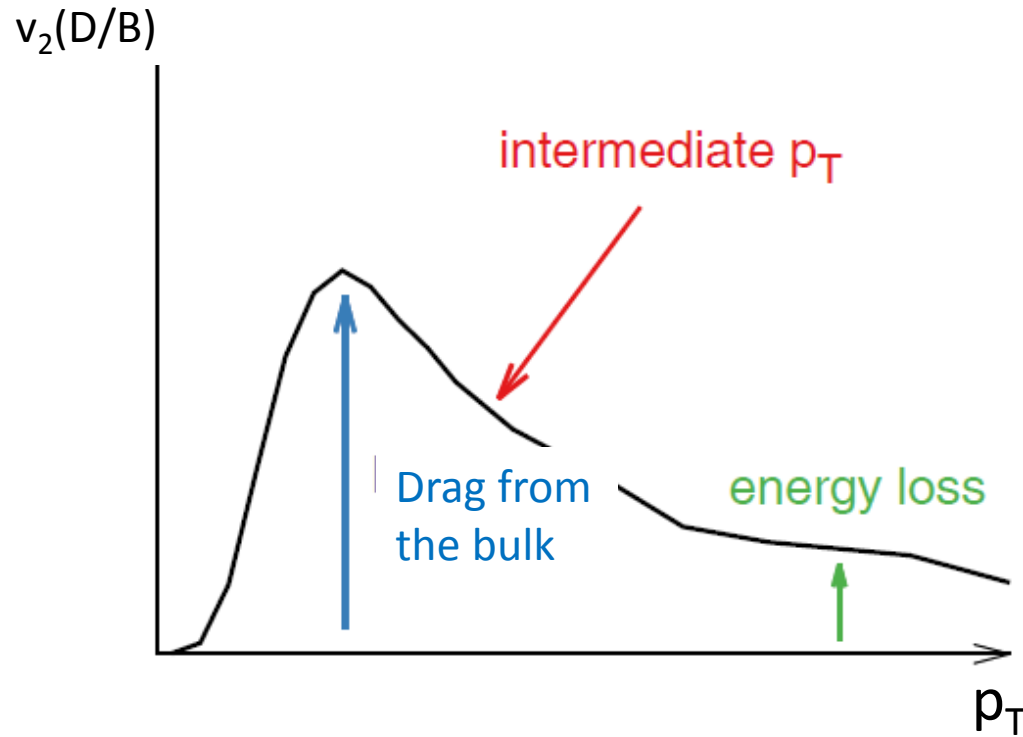
$$\frac{dN_g}{dy dl_{\perp}^2 d\tau} = 2 \frac{\alpha}{\pi} P(y) \frac{1}{l_{\perp}^4} \left(\frac{1}{1+\chi} \right)^4 \sin^2 \left(\frac{l_{\perp}^2}{4l^-(1-y)} (1+\chi) \tau \right) \times \left[\left\{ \left(1 - \frac{y}{2} \right) - \chi + \left(1 - \frac{y}{2} \right) \chi^2 \right\} \hat{q} +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



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

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

Basic Consequences of HQ interaction with QGP for the v_2



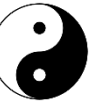
Small p_T : height of v_2 at low p_T sensitive to:

- 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 mechanism » characterized by a large v_2 component stemming from $N_{\text{coll}} \approx 1$



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 »

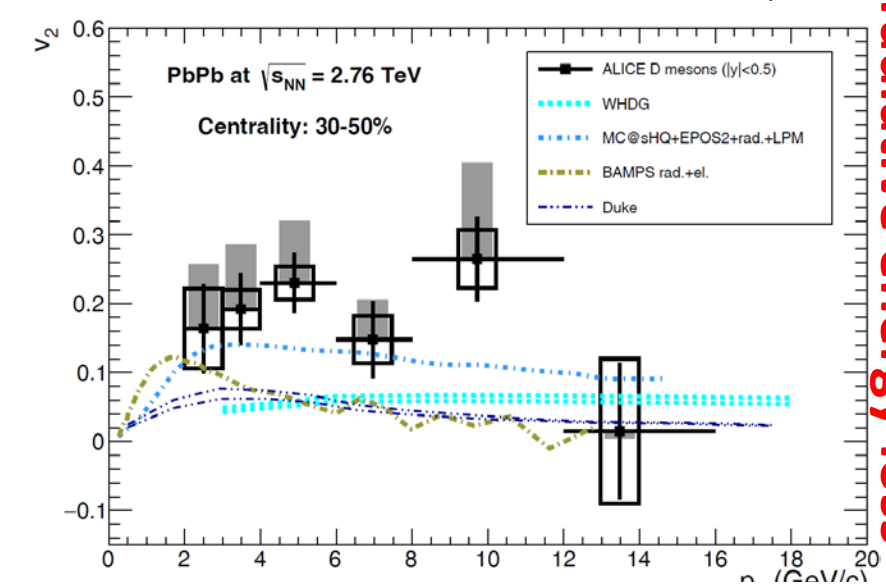
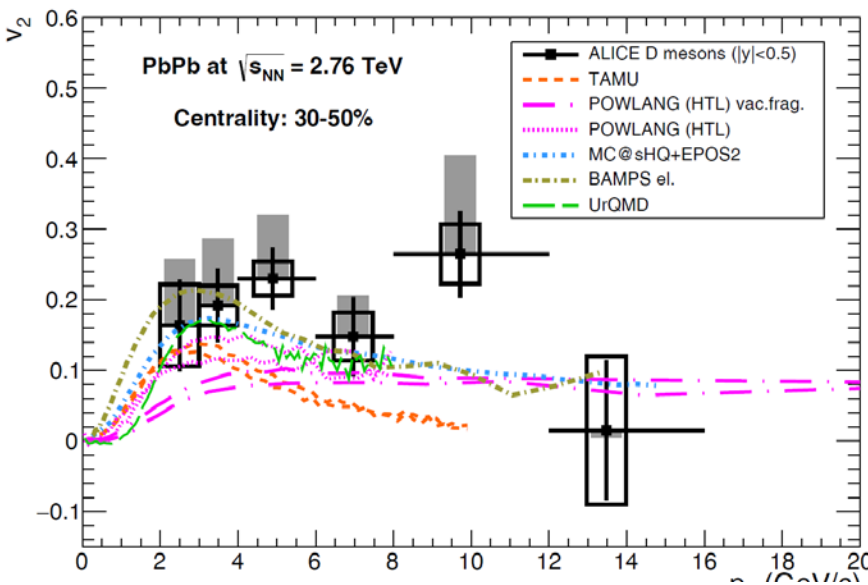
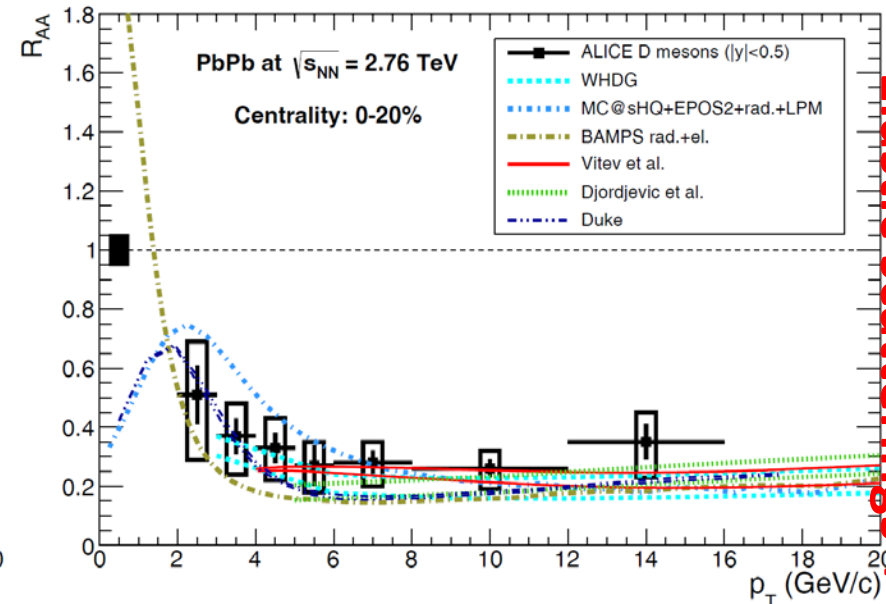
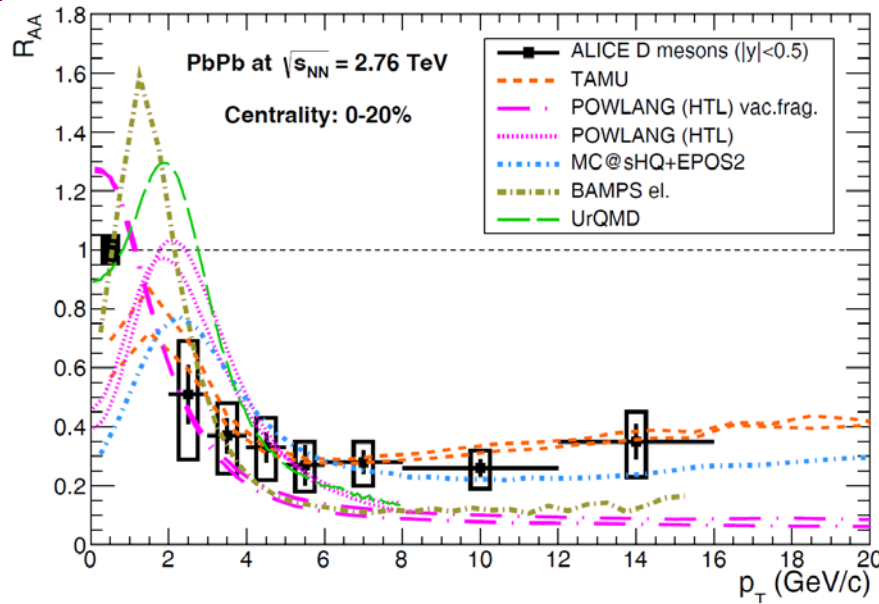
Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coeff based (LV,...)	TAMU POWLANG HTL Catania LV	Duke	ASW	ADS/CFT POWLANG IQCD <i>DABMOD</i> (poster R. Katz) <i>S. Li et al, arXiv:1803.01508</i>
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 <i>LIDO</i> (DUKE; poster W. Ke)	SCET _{G,M}	

Red: Transport models

Models vs DATA at LHC (Saporo Gravis Report compilation)

Purely elastic scatterings

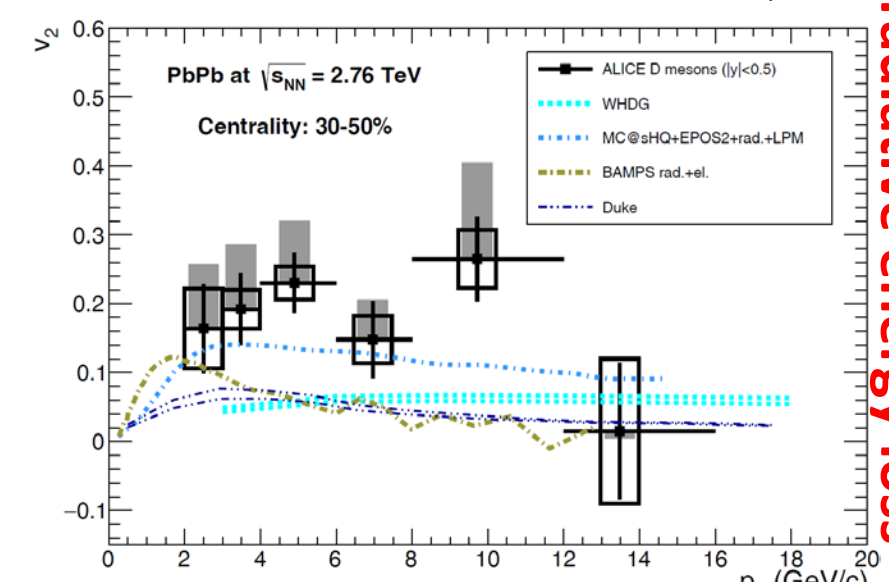
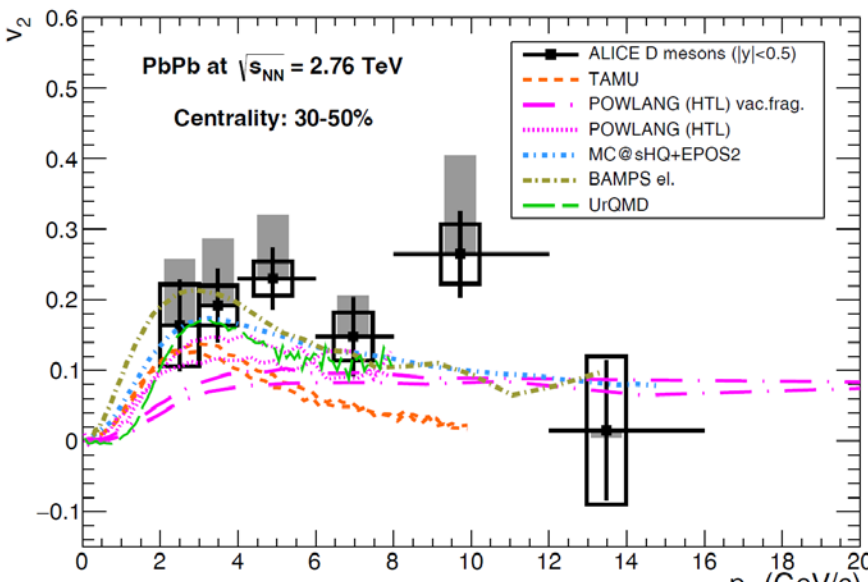
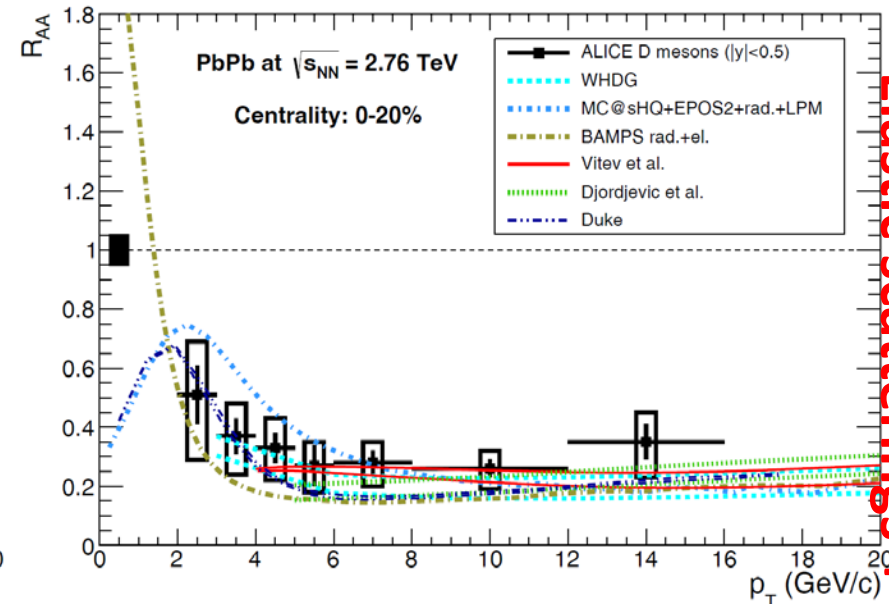
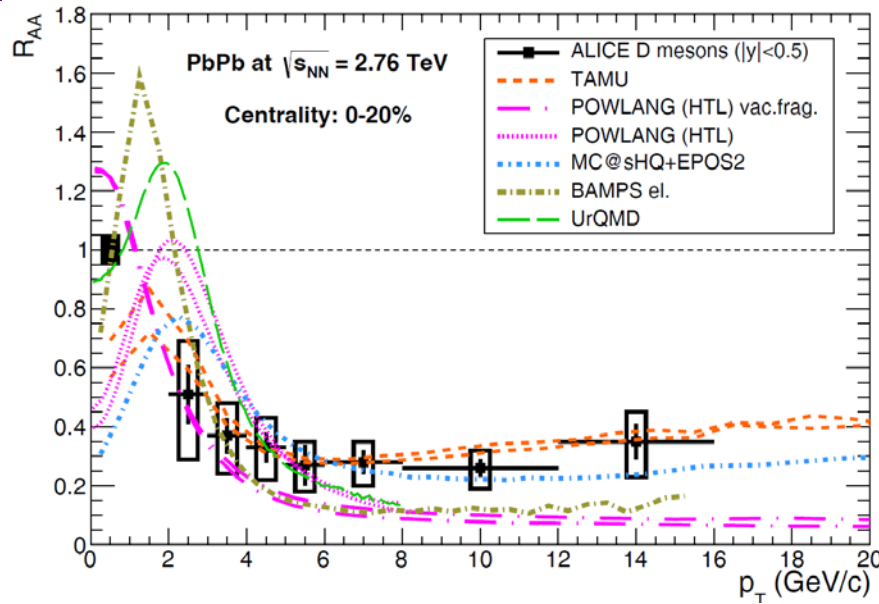


Elastic scatterings + radiative energy loss

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

Models vs DATA at LHC (Saporo Gravis Report compilation)

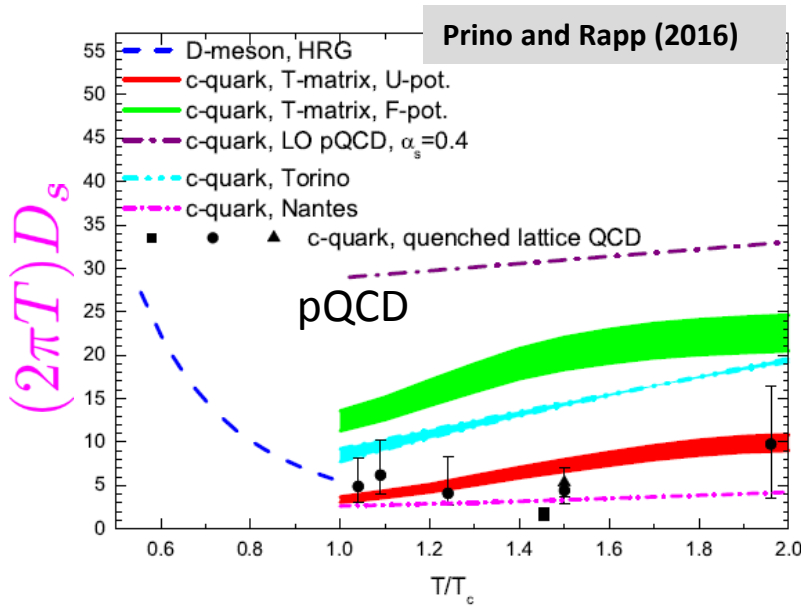
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Elastic scatterings + radiative energy loss

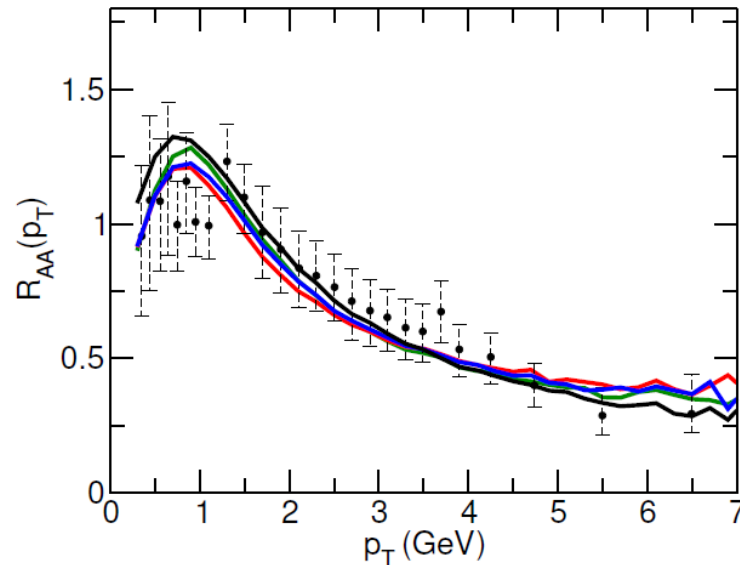
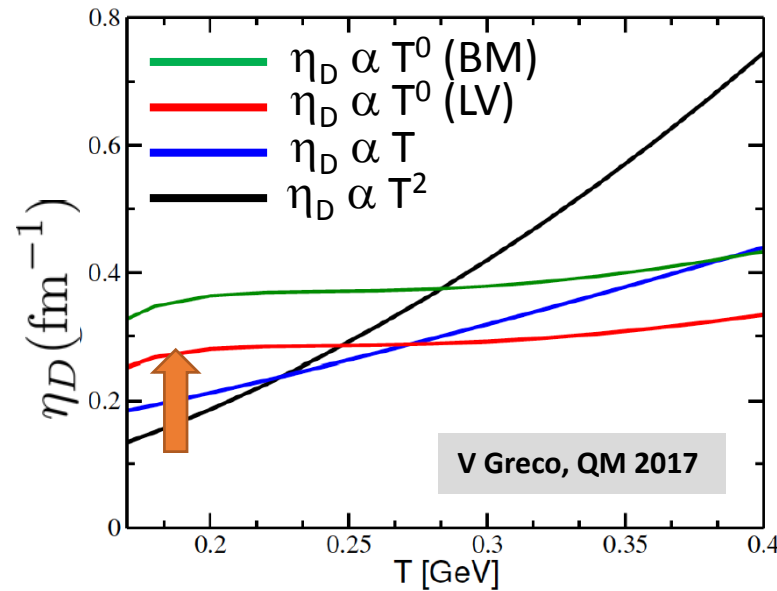
Some advocated tension between R_{AA} and v_2

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



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

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

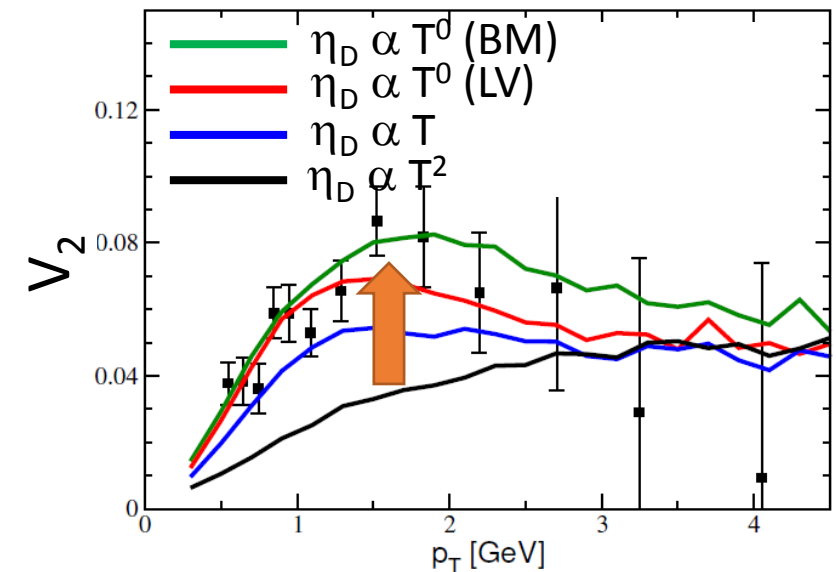


$\eta_D \propto T^2$: pQCD (fixed α_s), AdS/CFT

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

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

Tuned to reproduce $R_{AA} \Rightarrow$ Larger coupling with the bulk near T_c (when the hydro v_2 has fully developed) \Rightarrow Larger v_2



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

Extra increase from LV => Boltzmann dynamics

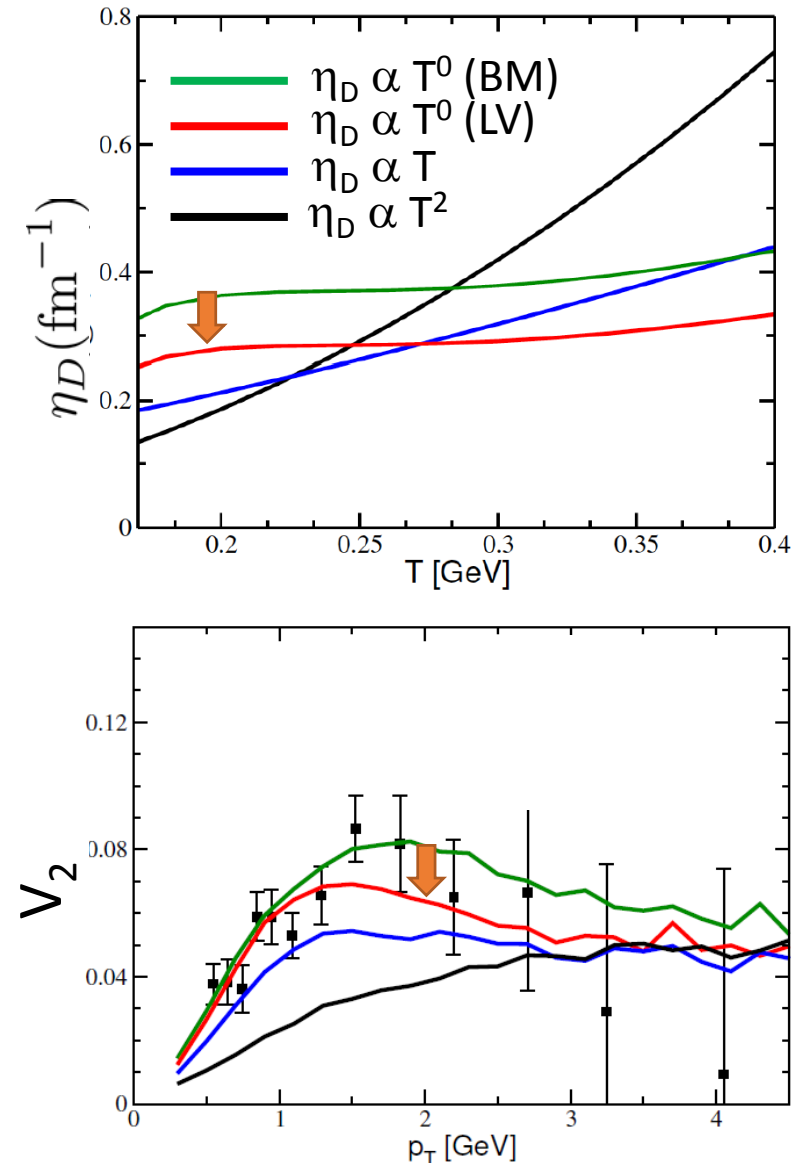
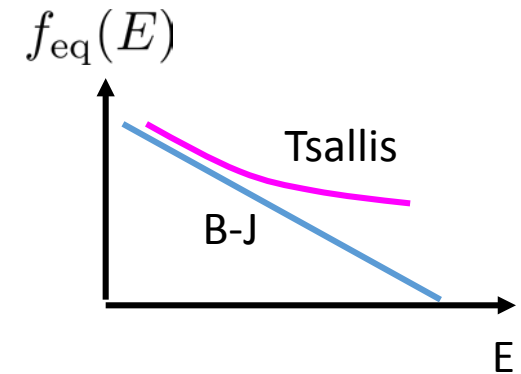
Should be seen as a *decrease* passing from Boltzmann => LV

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

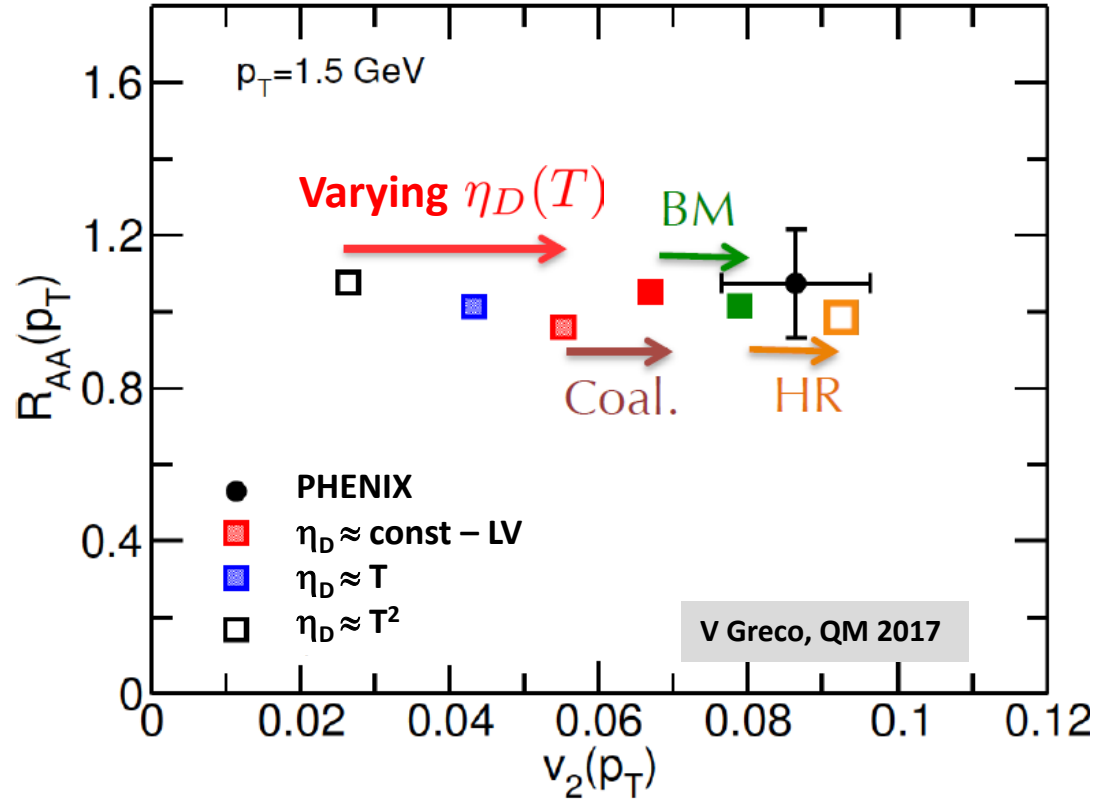
=> Encoding the physics into Langevin scheme, we do not describe properly the fluctuations at large momentum (as seen f.i. in the Tsallis like eq. Asymtotic distribution).

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

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



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



Nice guideline but need:

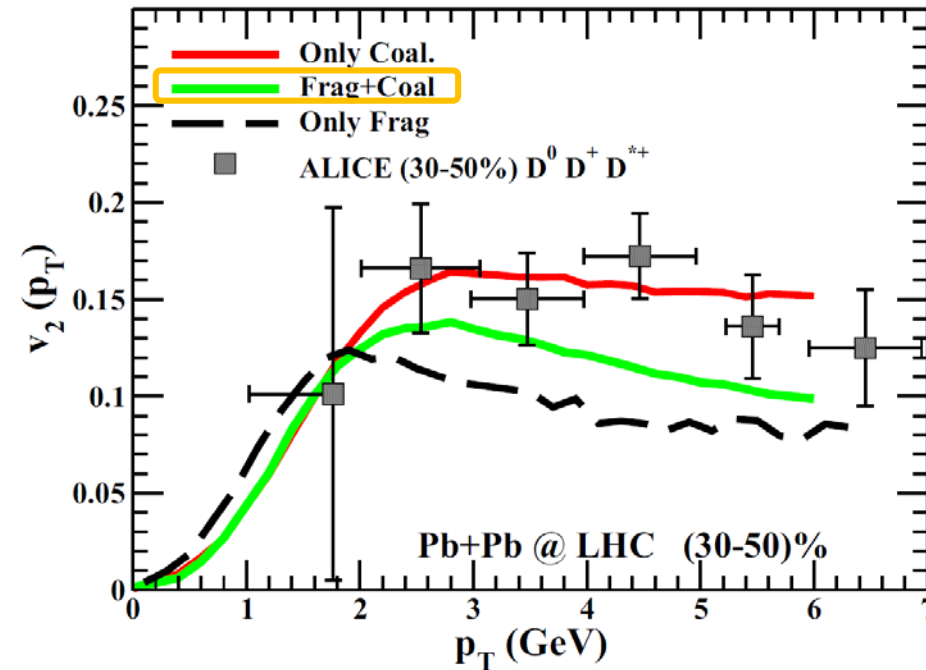
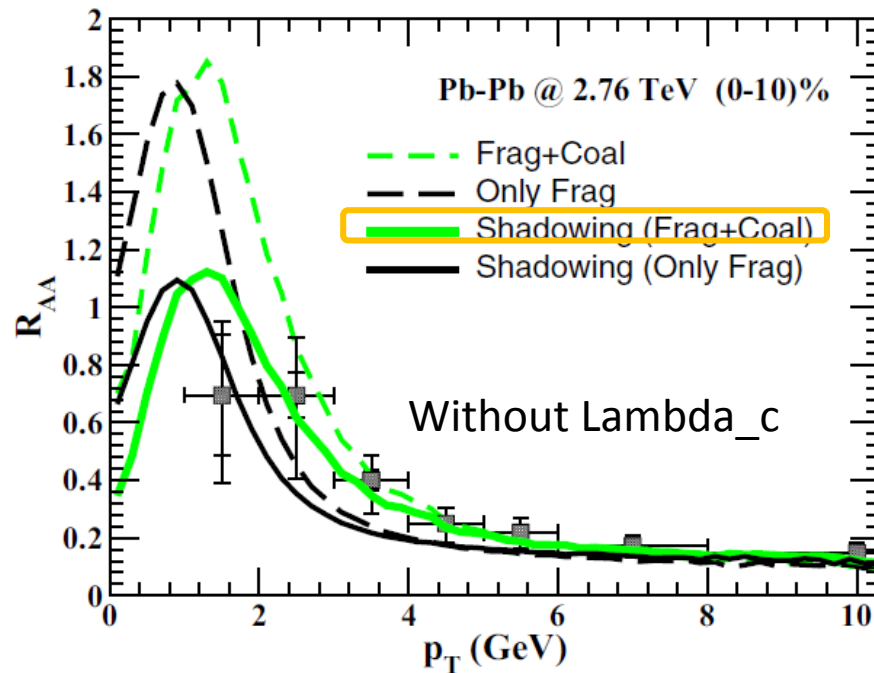
- To consider extra ingredients (bulk, initial v_2, \dots)
- To assess the uncertainties on « Coal » and « HR »
- ... before one can think of ruling out other trends for η_D .

- Nonperturbative effects near T_c are captured by $\alpha_s(T)$, determined from fits to IQCD pressure and interaction 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



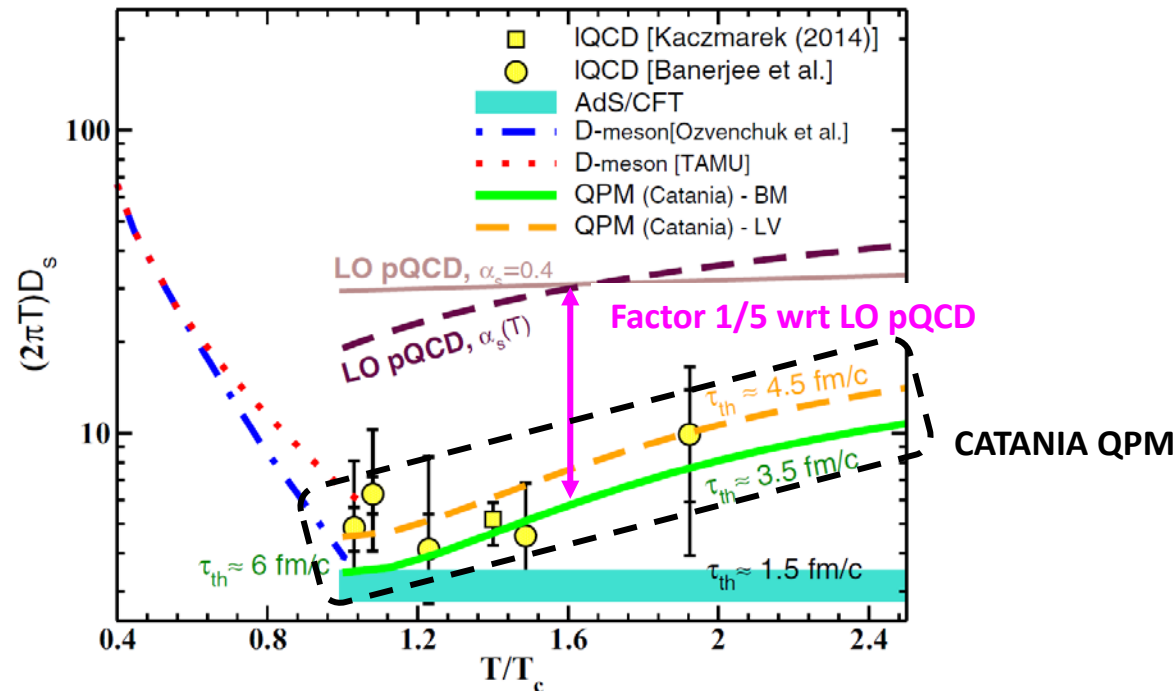
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- Hadronization performed through (local) coalescence + fragmentation
- Good description of R_{AA} and v_2
- ... Leading to an indirect extraction of the D_s coefficient... in the bulk of IQCD calculations

...and slowly increasing -> LO pQCD



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

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

Higher twist

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

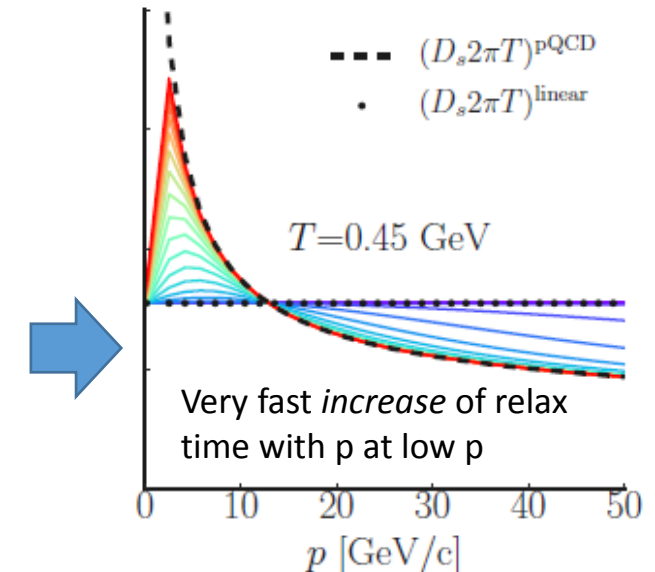
+ coal / frag hadronization and hadronic rescattering

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

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

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

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”

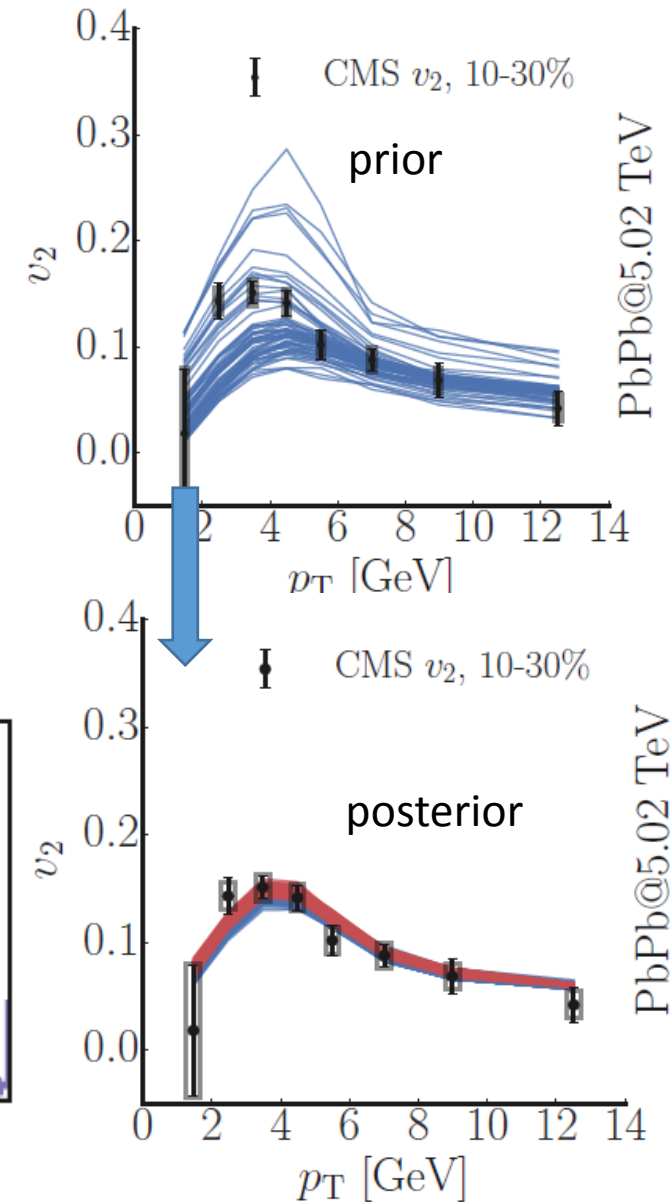
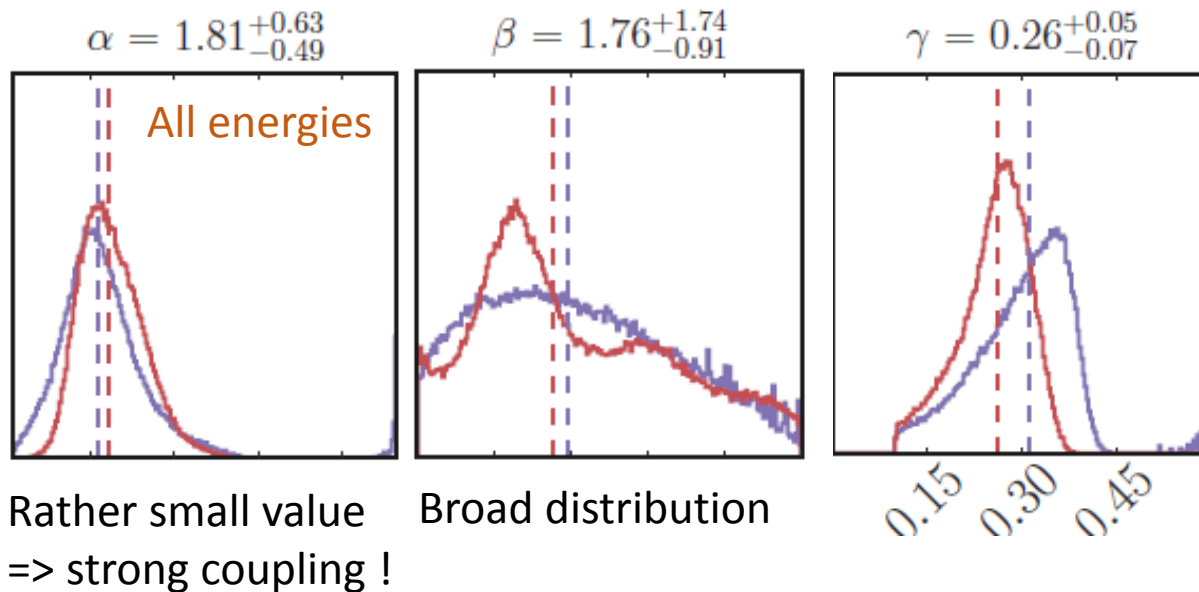
- Choice of 60 « prior » for which the physical observables are calculated
- Gaussian emulator to build a fast surrogate of physics
- Random walk throughout parameter space, with acceptance and rejection according to likelihood (with all uncertainties assumed to be uncorrelated).

Let the data
speak

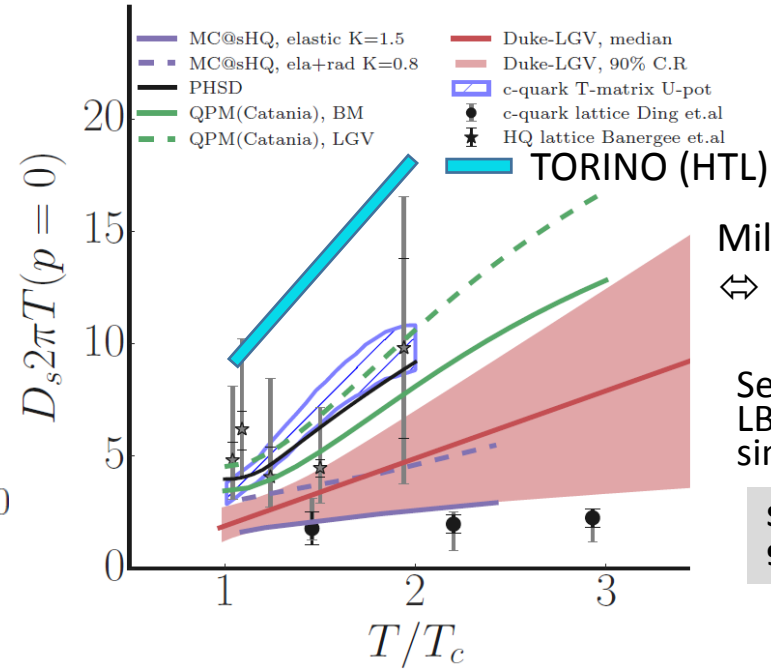
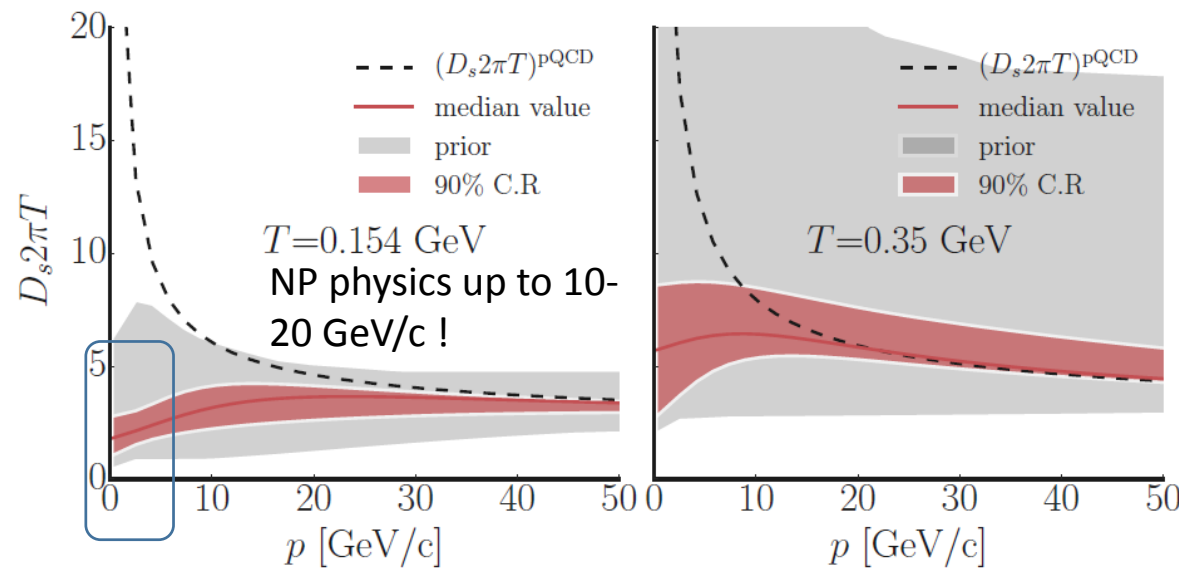


$$(D_s 2\pi T)^{\text{linear}} = \alpha \cdot (1 + \beta(T/T_c - 1))$$

RESULTS



Duke “Bayesian approach” vs models



Mild Lin. increase of $2\pi D_s T \dots$
 \Leftrightarrow physics beyond pQCD.

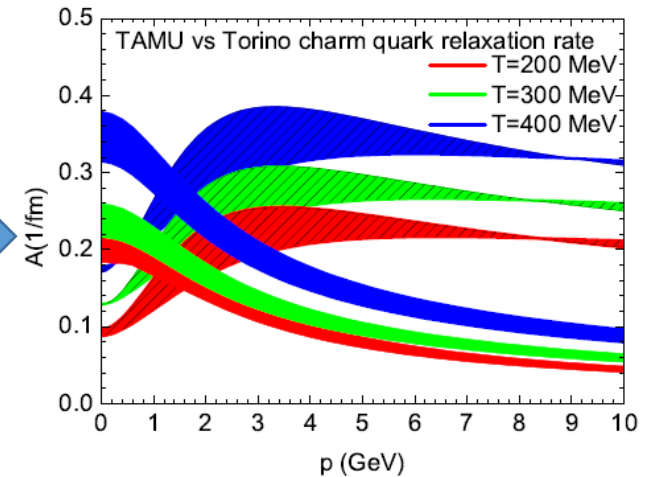
See as well analysis in the
 LBL-CCNU model with
 similar conclusions

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

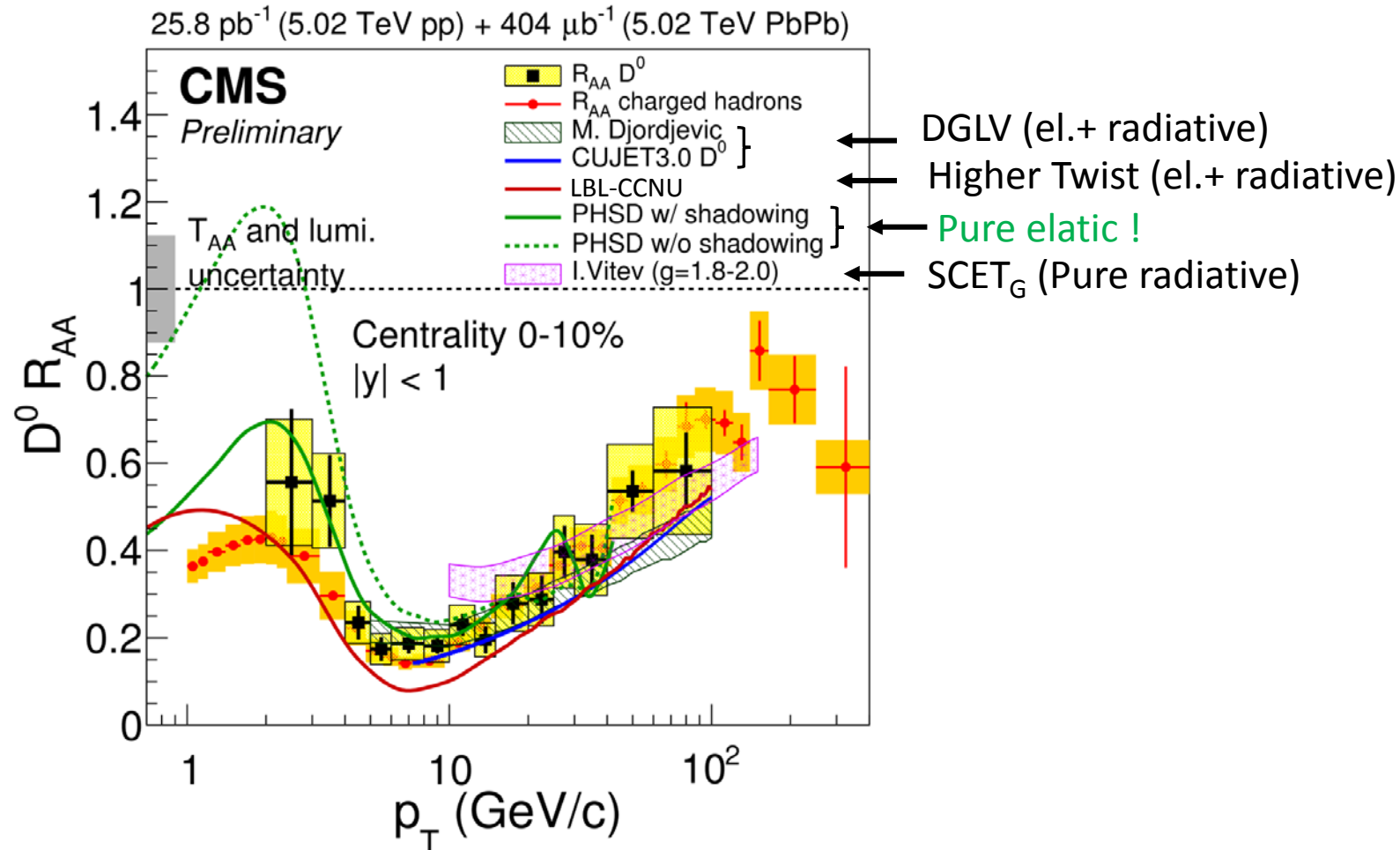
- Does not mean that all models inhold the same physics...
- $D_s(p=0)$ does not represent the full physics (different momentum dependences)
- D_s (finite p) in Duke's el + rad approach should not be compared to the same quantity in purely elastic models (additional contribution to energy loss due to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

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



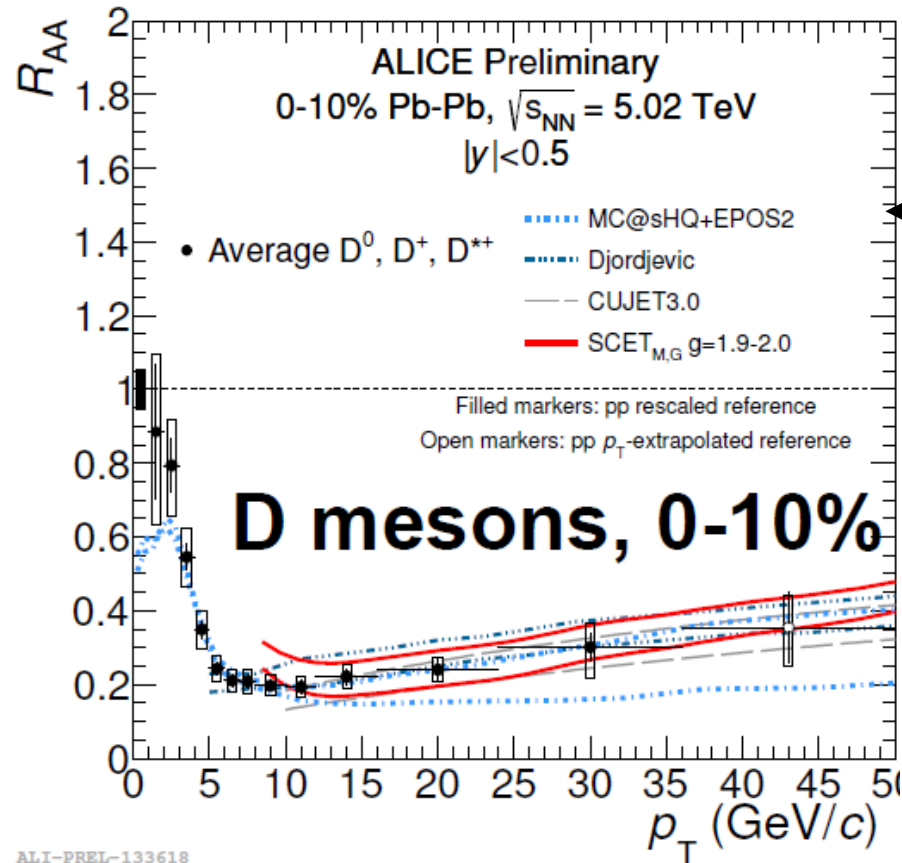
Status of high p_T HQ

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

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

B Blagojevic et al,
arXiv:1804.07593v1

- Recently released soft gluon approximation
- Path length fluctuations
- Model evolution according to Bjorken picture leading to better agreement for the v_2

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

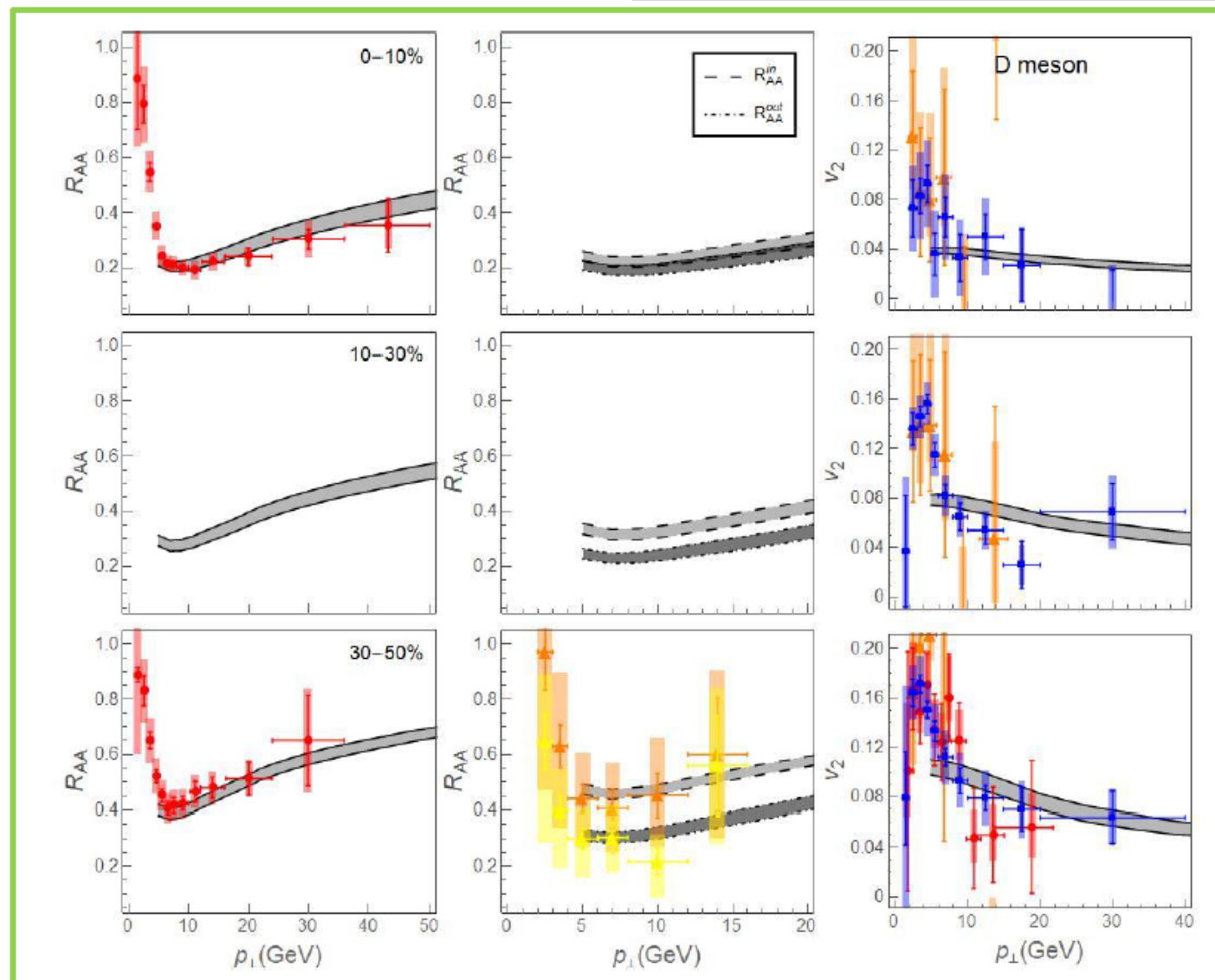
Direction: more realistic **evolving medium**.

Other recent works

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

Poster A. I. Sheikh

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

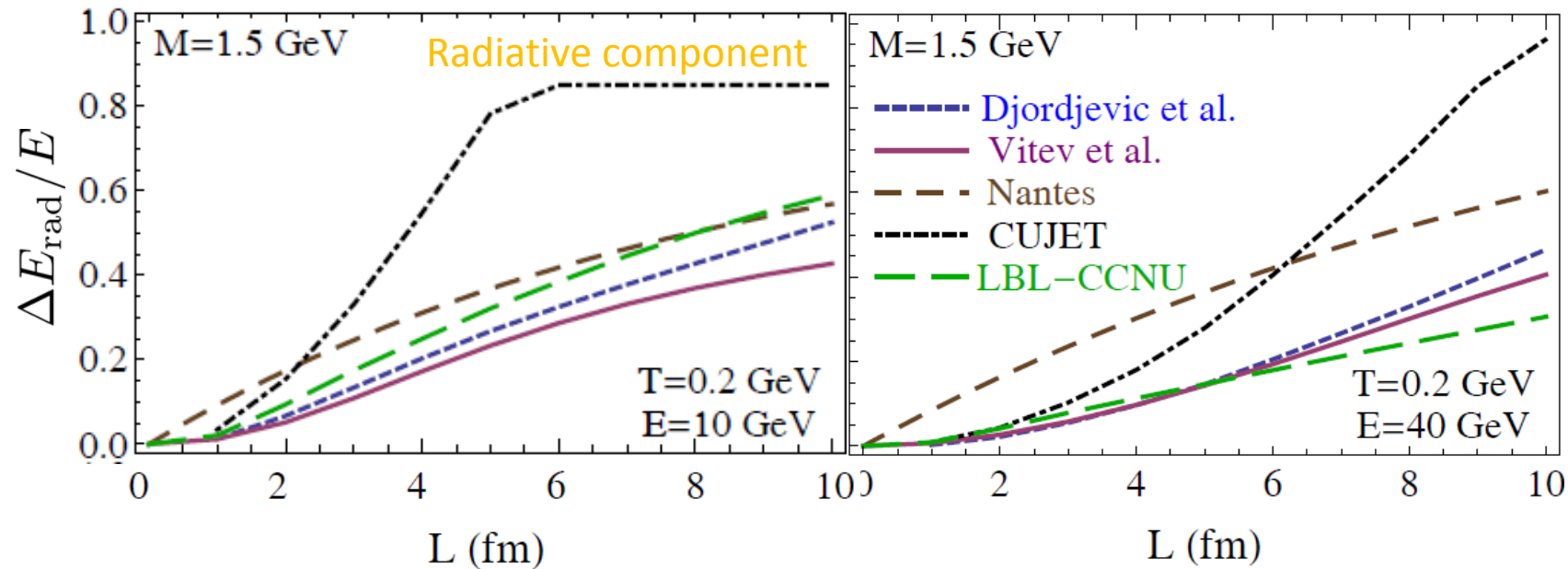


Status of high p_T HQ: prospects

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

Clear case for
b-quark physics

Comparing some calibration curve for main approaches:



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

- Rather good agreement between Djordjevic and 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 p_T (for which it should apply)
- Much increased value for the CUJET3 stemming from the assumption of magnetic monopoles « around » $T_c \Rightarrow$ If all other ingredients are under, offers a unique opportunity to probe the QGP dof with high p_T partons

Status of high p_T HQ: prospects

Other challenges:

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

“Drag Induced Radiation and Multi-Stage Effects in Heavy-Flavor Energy Loss”

S. Cao et al, arXiv:1711.09053

// talk S. Cao

Also poster G-Y Qin

Hard scale $Q=p_T$

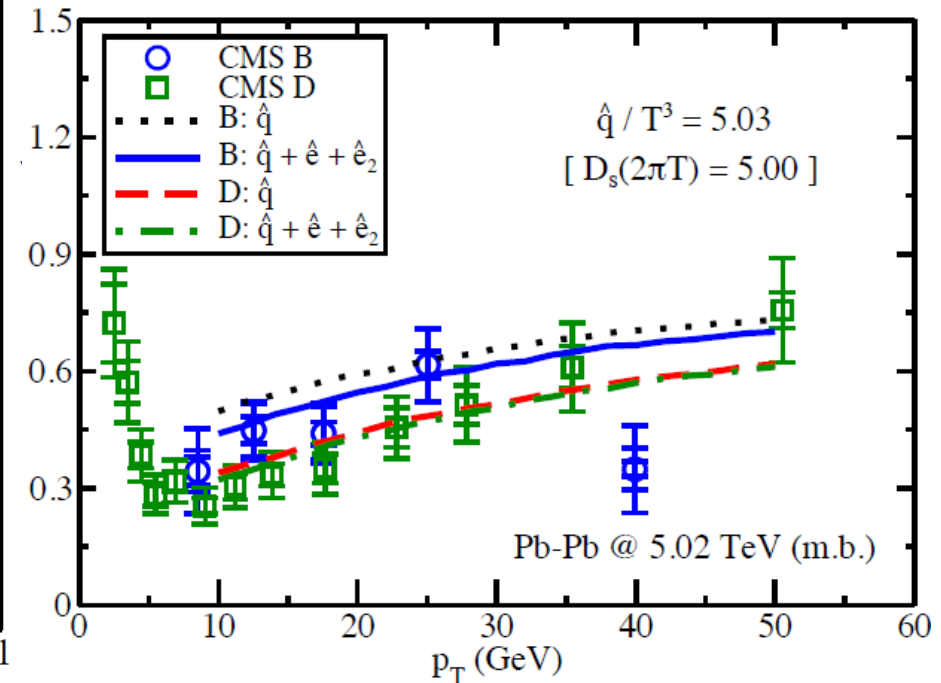
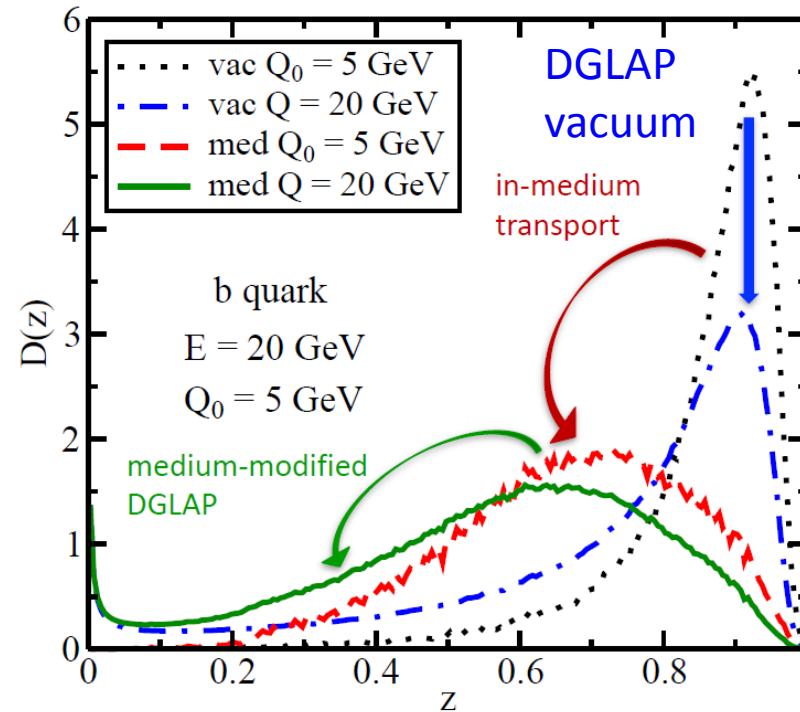


Modified DGLAP evolution
(virtuality ordered)

Low scale $Q_0=m_Q$



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



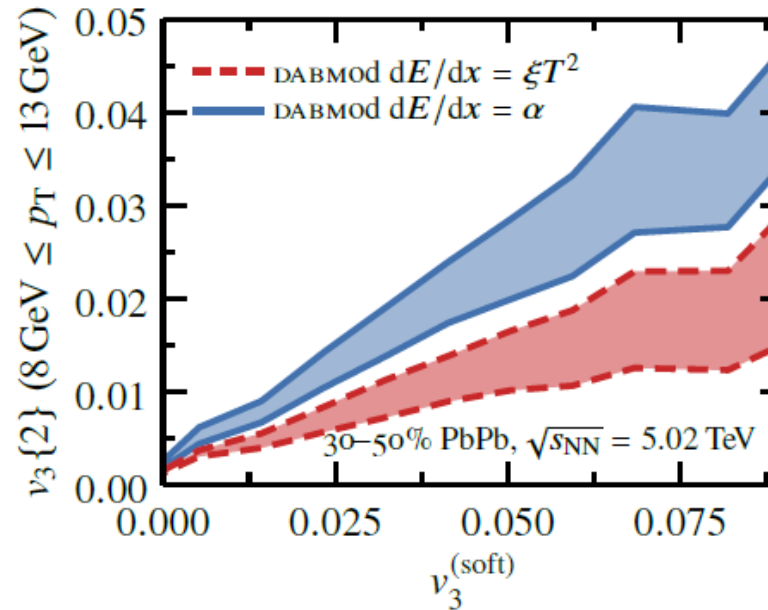
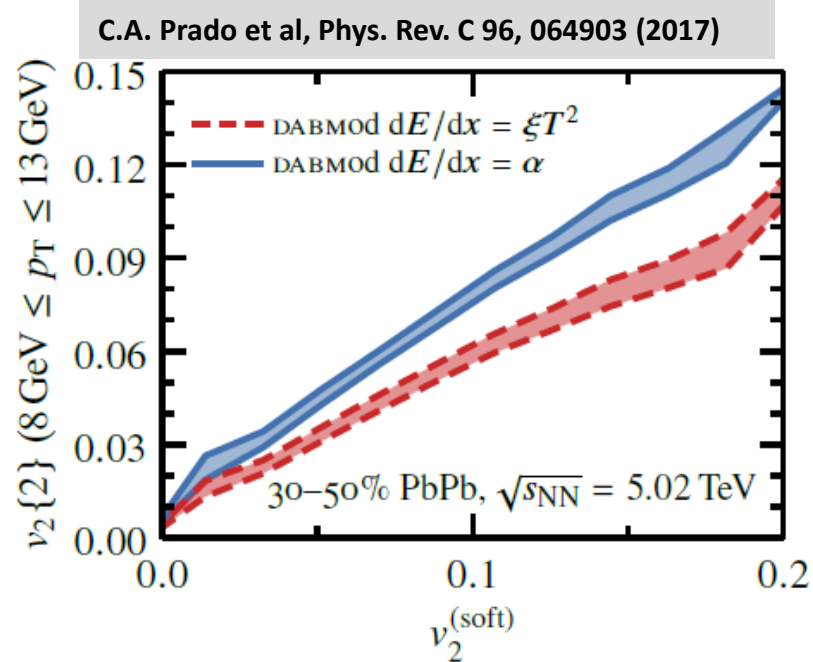
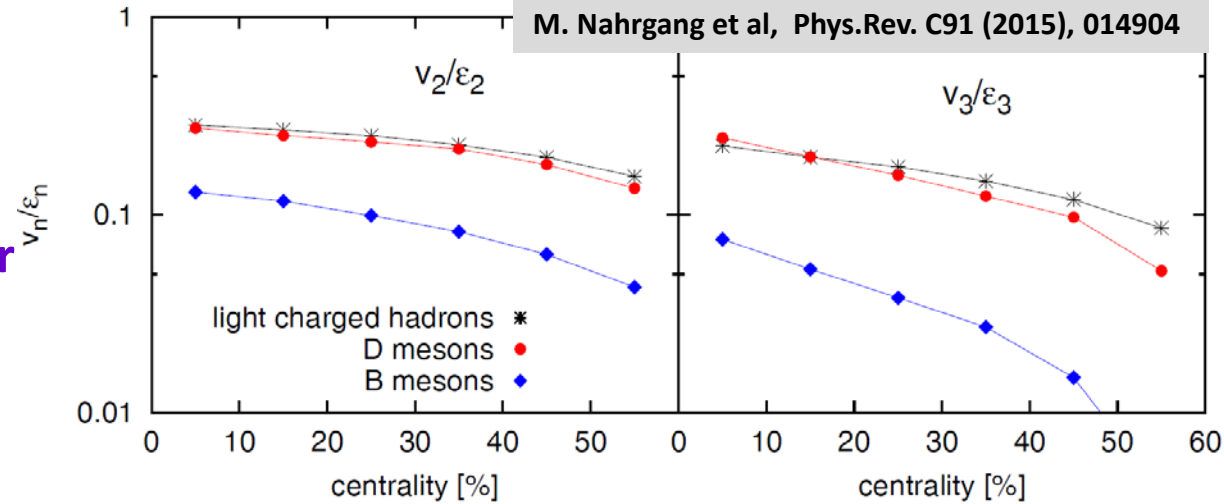
Good agreement with CMS data for D and B, some influence of higher order term at intermediate p_T

More on v_2 and higher flow harmonics

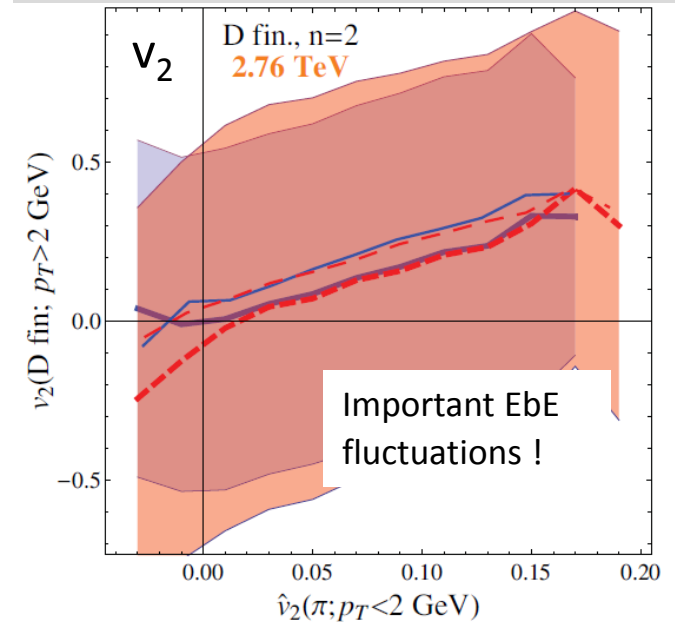
Goal: better understand the **coupling btwn HQ and QGP** by:

- 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 , larger mass and larger centrality...**

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



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

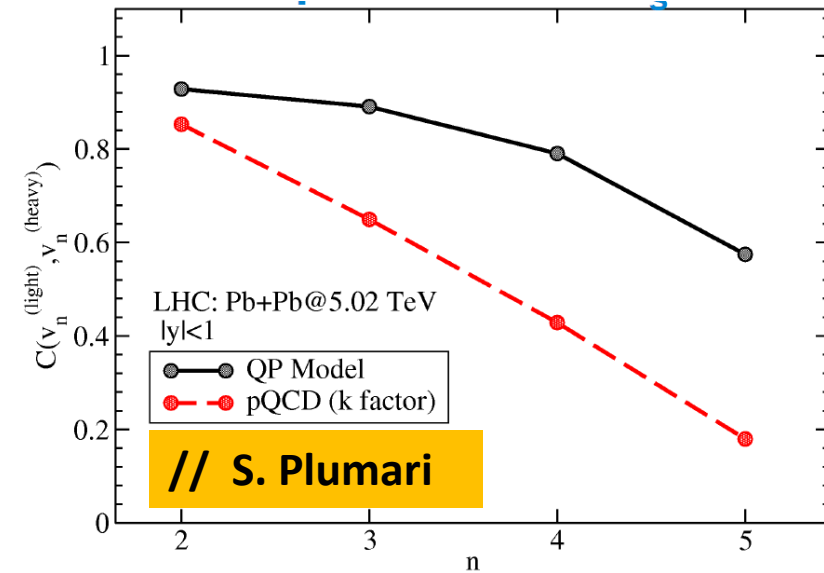


No saturation ./ Linearly BUT larger flow from $\frac{dE}{dx} \propto T^0$ and larger reduction for v_3

More on v_2 and higher flow harmonics

NEW

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

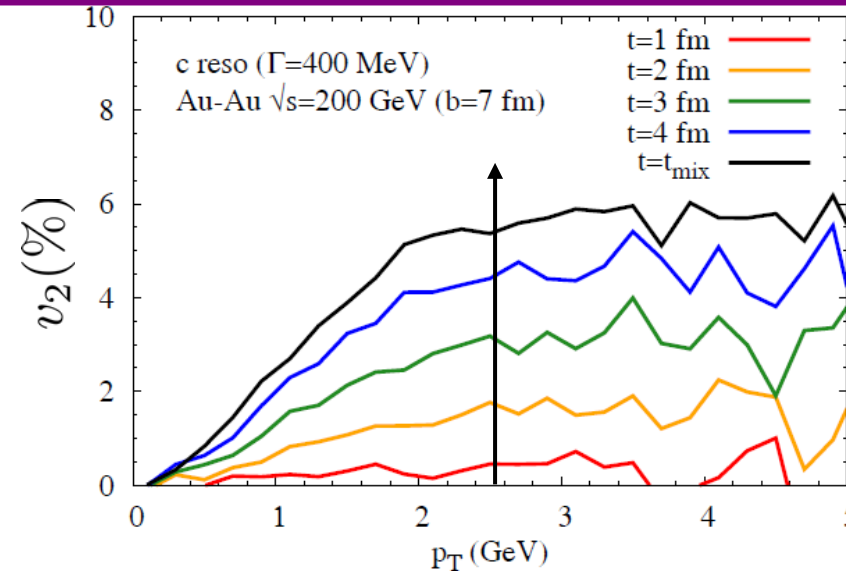


Confirms previous trends up to the 5th moment! No correlation expected for pQCD-like

Poster R. Katz

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

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

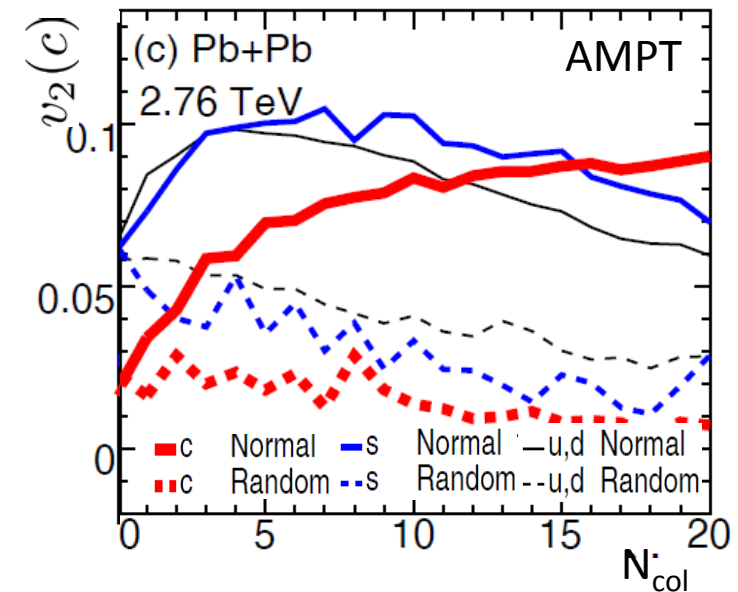
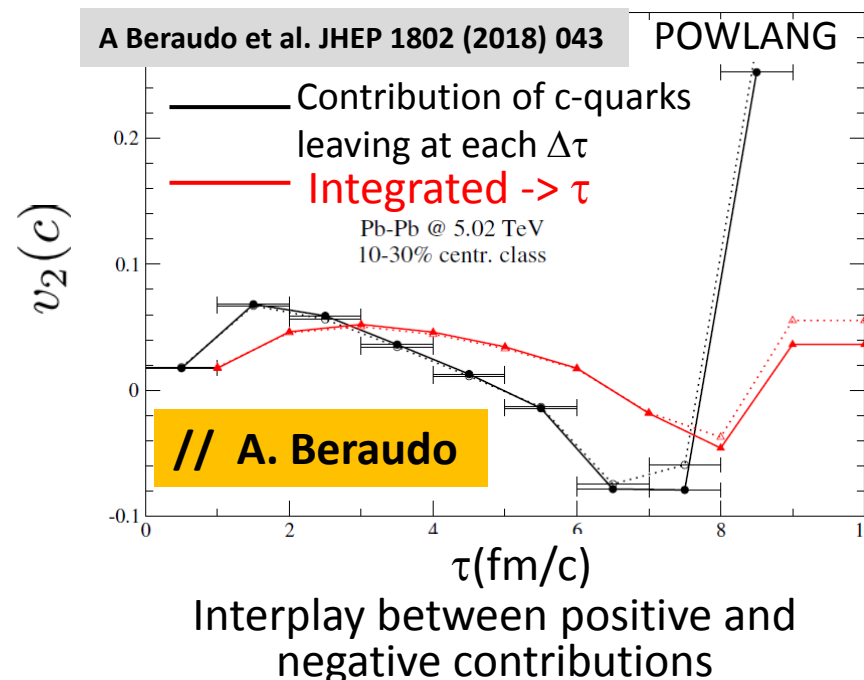


Need to understand the v_2 (time), especially in light of the recently advocated escape mechanism

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

Steady increase of v_2 (all c quarks)

H. Li et al 1804.02681



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

Recent Collective actions beyond Sapore Gravis

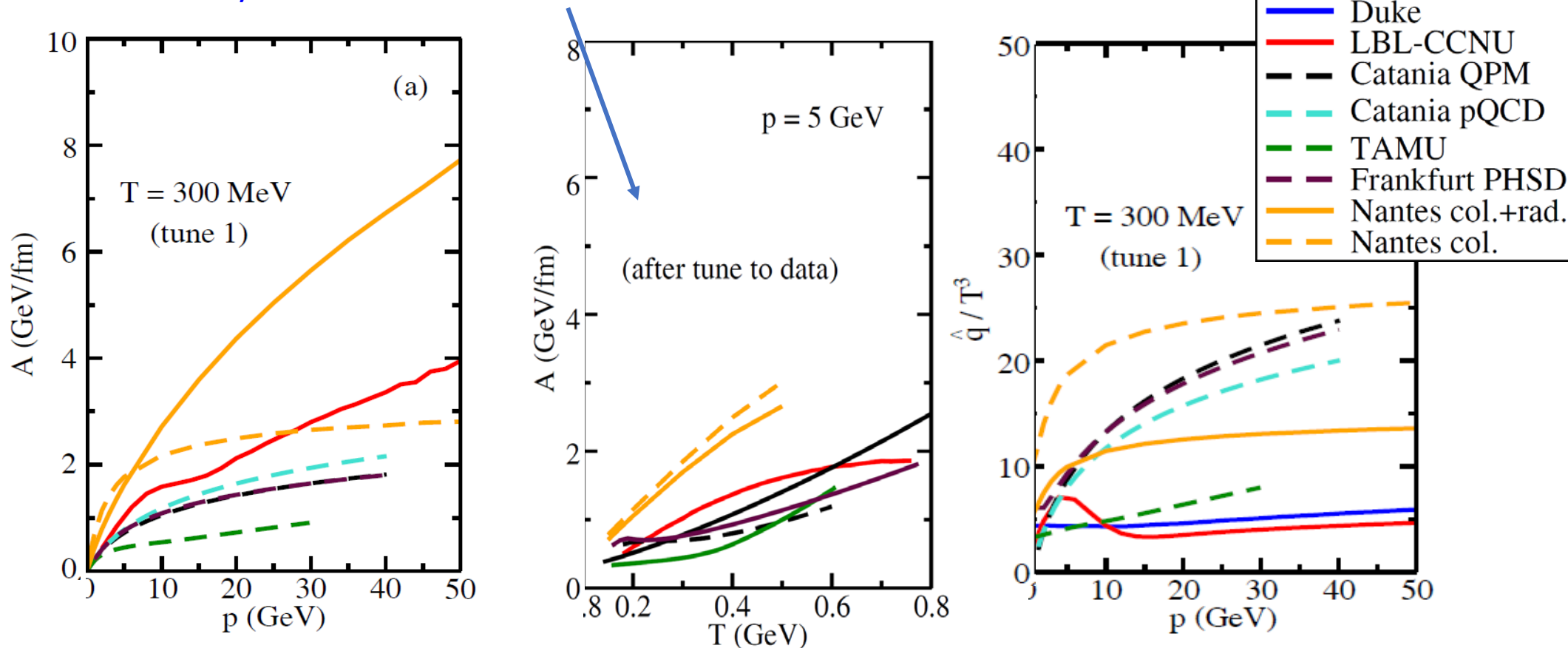
- **Heavy Quark – Working Group** (convener: X-N Wang); in the spirit of the Jet Collaboration, the goal is, in a first stage, to :
 - Collect and compare the transport coefficients from various models,
 - Measure and understand their consequences by first studying a simpler brick problem
 - Estimate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

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 constraints from IQCD
 - 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. Beraudo⁵,
E. Bratkovskaya^{3,6}, P. Braun-Munzinger^{3,7}, S. Cao⁸, A. Dainese⁹, S.K. Das^{10,11},
M. Djordjevic¹², V. Greco^{11,13}, M. He¹⁴, H. van Hees⁶, G. Inghirami^{3,6,15,16}, O. Kaczmarek^{17,18},
Y.-J. Lee¹⁹, J. Liao²⁰, S.Y.F. Liu¹, G. Moore²¹, M. Nahrgang², J. Pawlowski²², P. Petreczky²³,
S. Plumari¹¹, F. Prino⁵, S. Shi²⁰, T. Song²⁴, J. Stachel⁷, I. Vitev²⁵, 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 months since first meeting)

Topics:

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

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

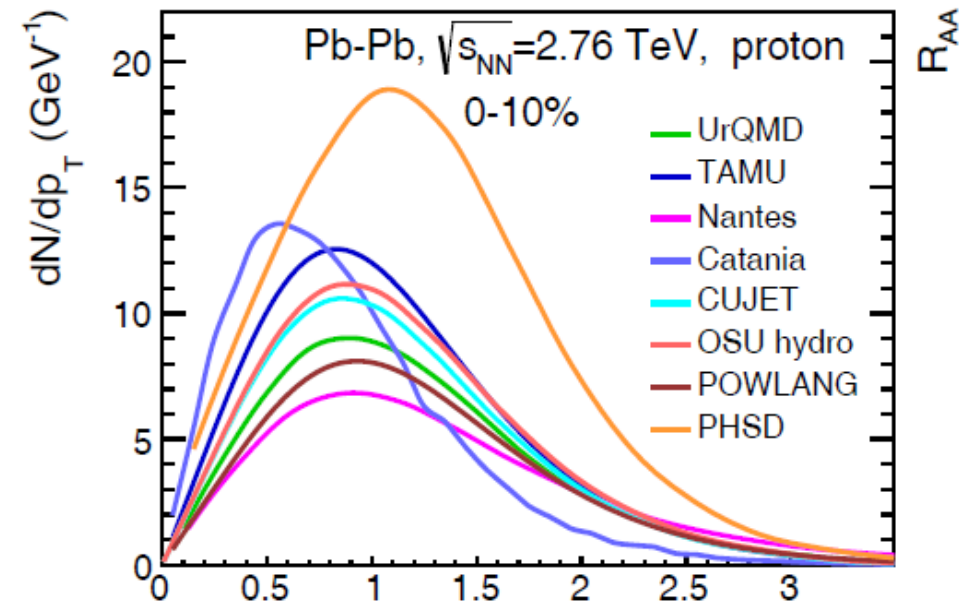
Question: What is the role of the different medium evolution models, and how do different predictions for the bulk cooling and expansion temperature in the current models manifest themselves in HF observables ?

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

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

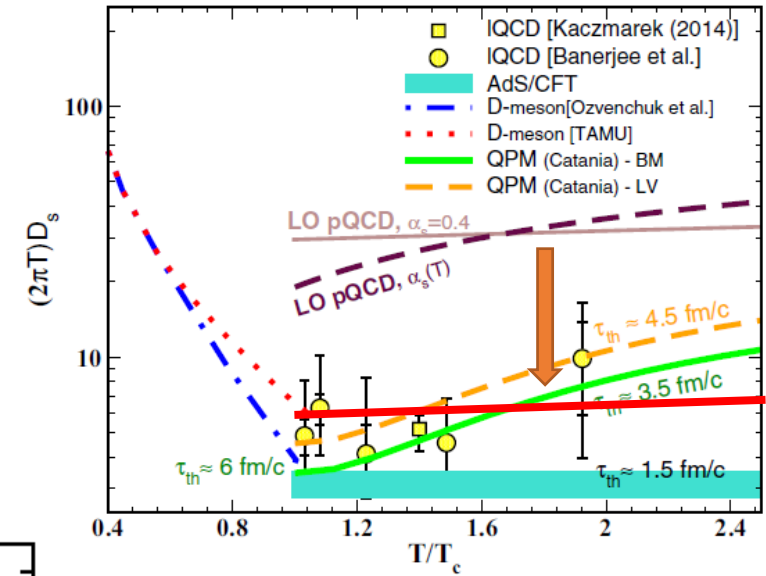
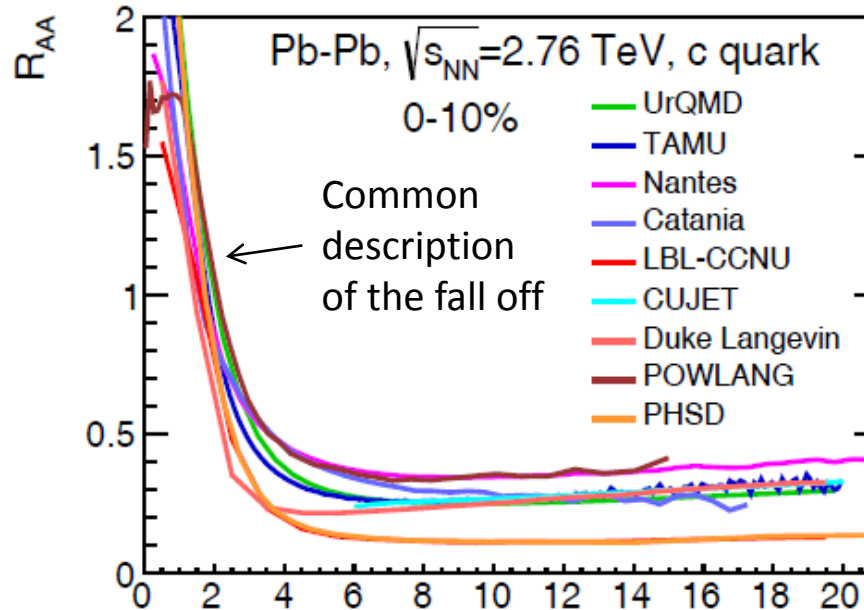
R. Rapp et al, arXiv: 1803.03824

Protons from the bulk at FO



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

c quarks at FO



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

For most bulks:

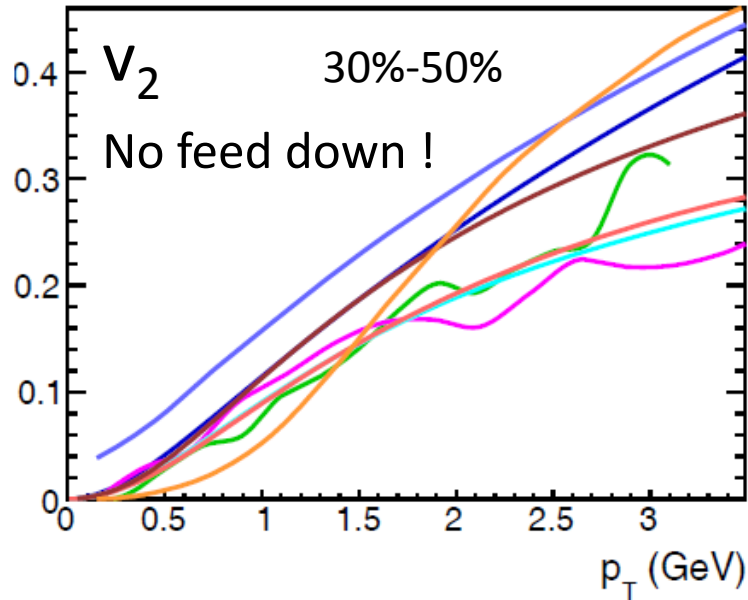
$$R_{AA}(c, 10 \text{ GeV}) \approx 0.3 - 0.4$$

For 30%-50%:

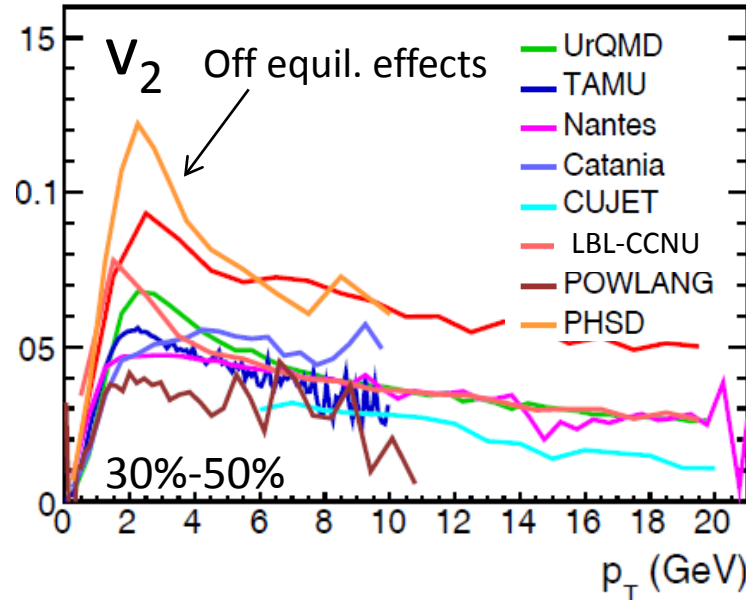
$$R_{AA}(c, 10 \text{ GeV}) \approx 0.4 - 0.6$$

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

Protons from the bulk at FO



c quarks at FO

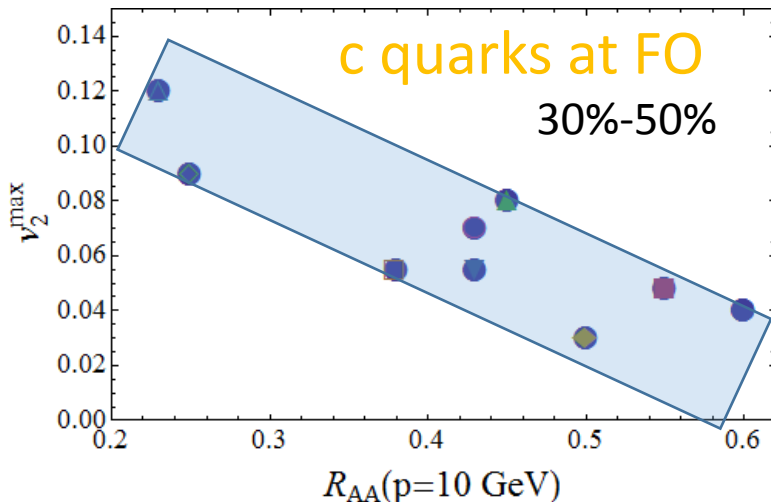


N.B.: LBL-CCNU could not implement scattering on thermal- massive partons

For most bulks:

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

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:

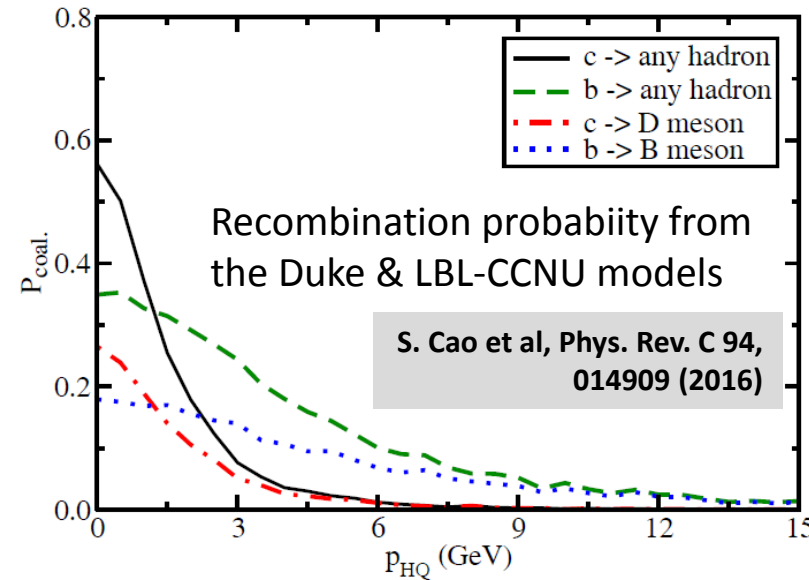
- towards the end of QGP, hadronization of (of equilibrium) HQ can proceed through a **dual mechanism**:

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 reconfinement (?!)
- Crucial to explain the flow bump in $R_{AA}(D)$ and sizable $v_2(D)$ => **large impact.**

Uncertain (and not disputed enough):

- Genuine physical recombination process !



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,...)

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. C 79 (2009) 044905

R. J. Fries, V. Greco, and P. Sorensen, Ann. Rev. Nucl. Part. Sci. 58 (2008) 177

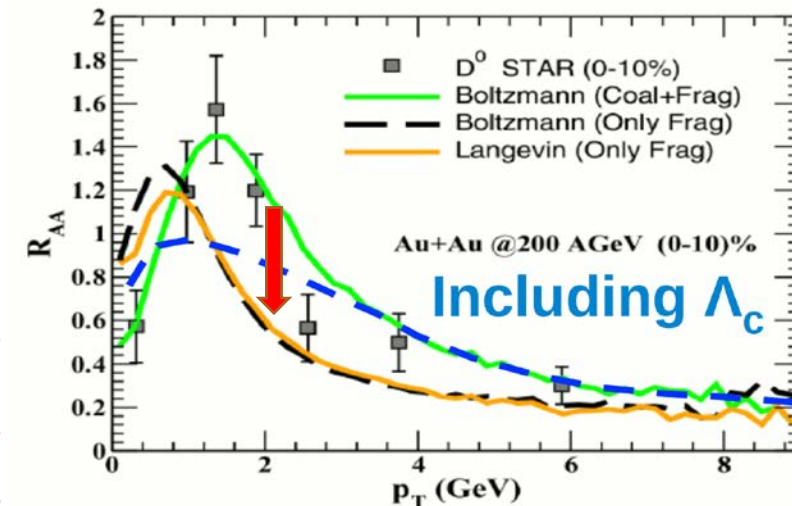
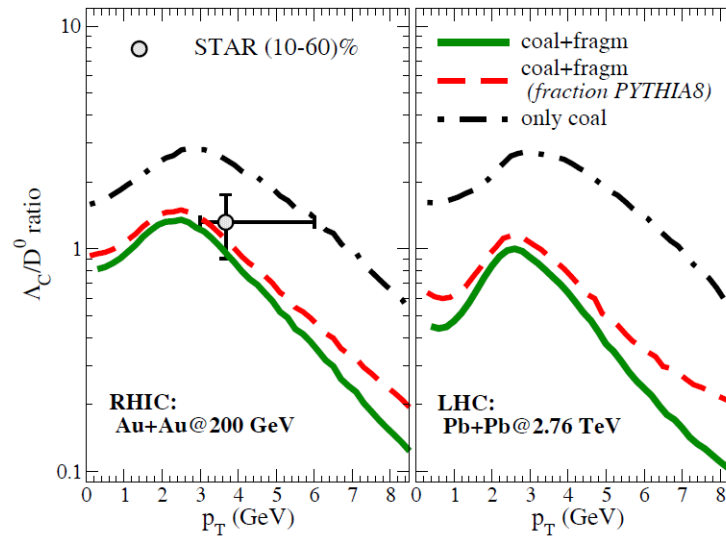
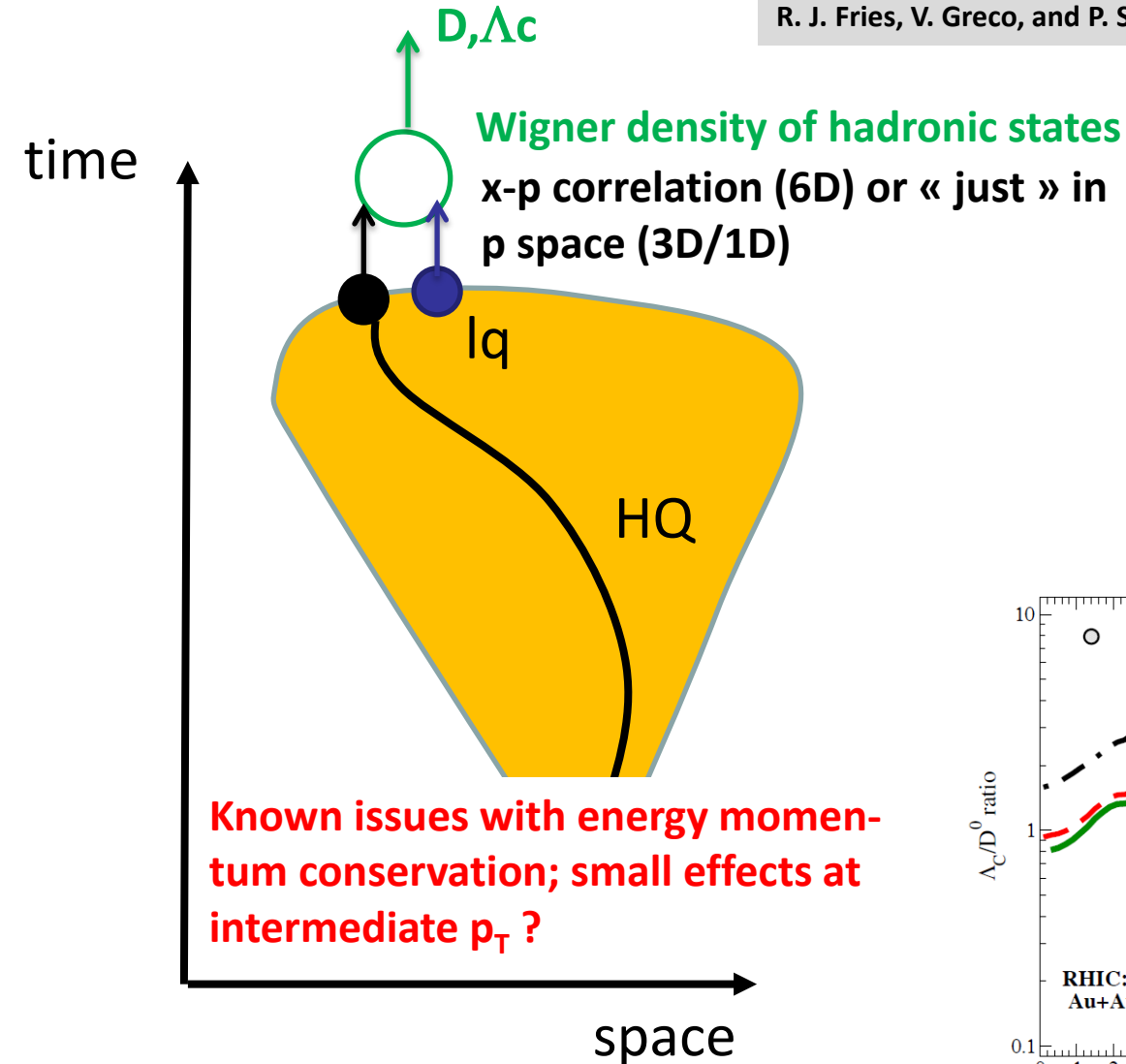
NEW

S Plumari et al. arXiv:1712.00730

Poster V. Minissale

Latest Catania's coalescence model:

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

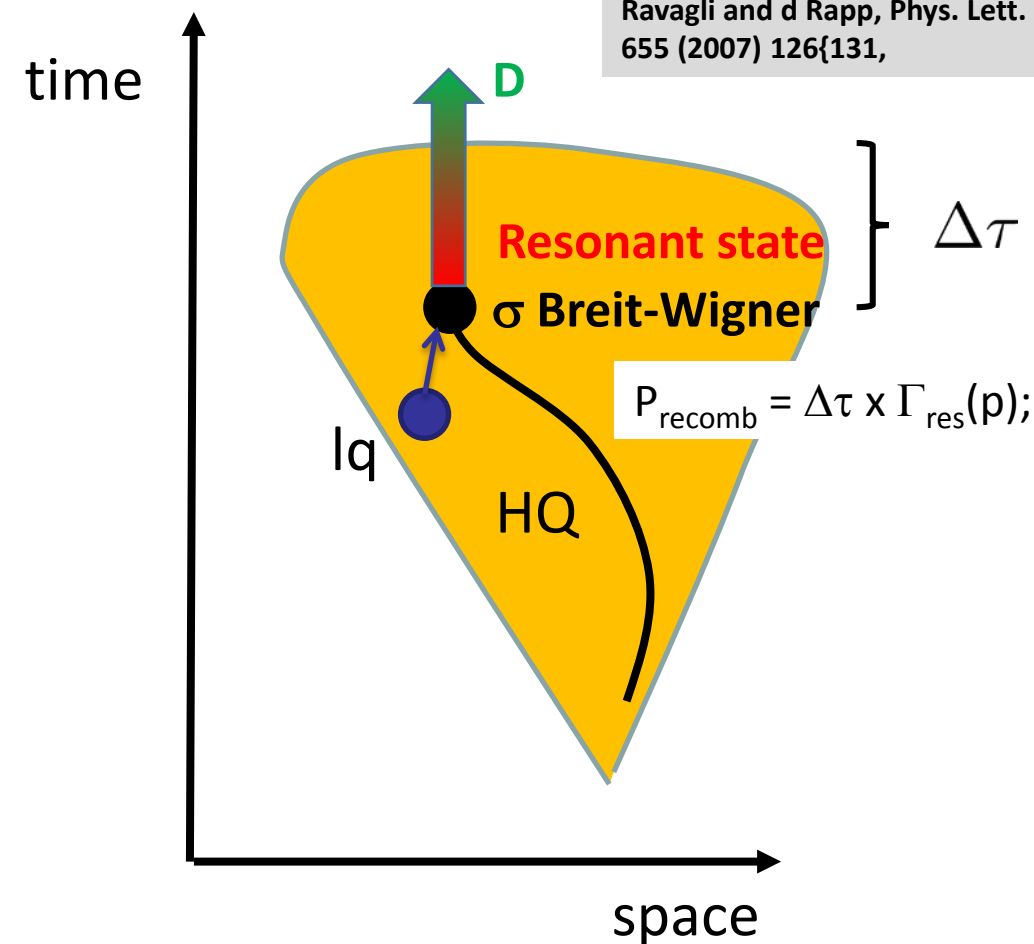


HQ - Recombination

Resonance Recombination Model:

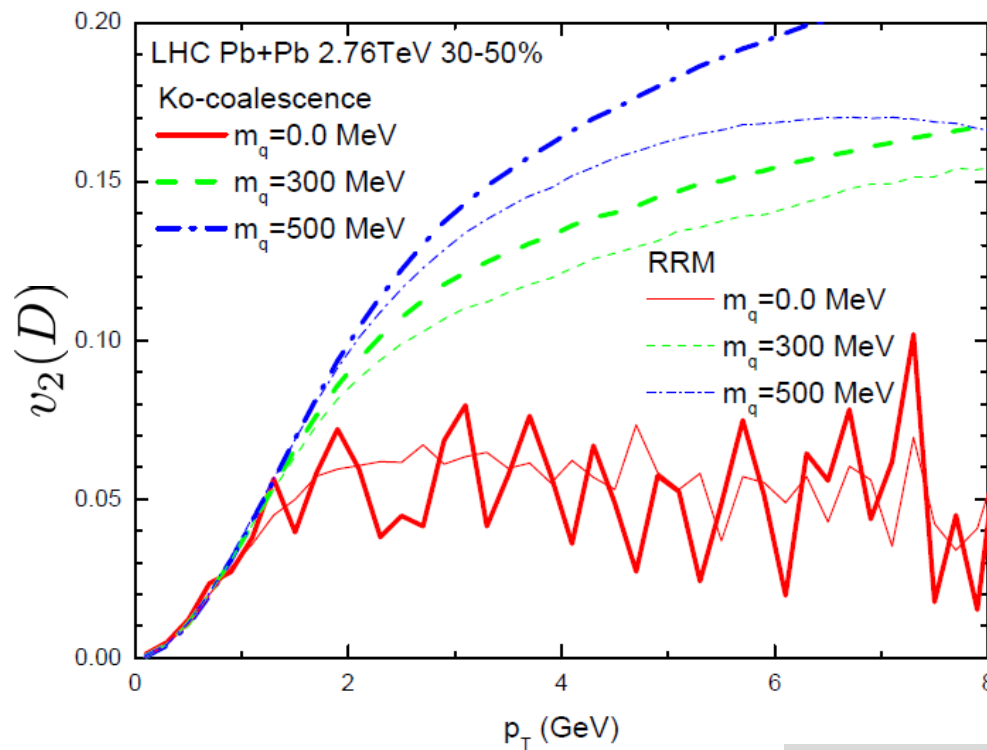
$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \vec{\nabla} \right) F_M(t, \vec{x}, \vec{p}) = -\frac{\Gamma}{\gamma_p} F_M(t, \vec{x}, \vec{p}) + \beta(\vec{x}, \vec{p})$$

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 $T_c \Rightarrow$ natural link with the energy loss model.

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



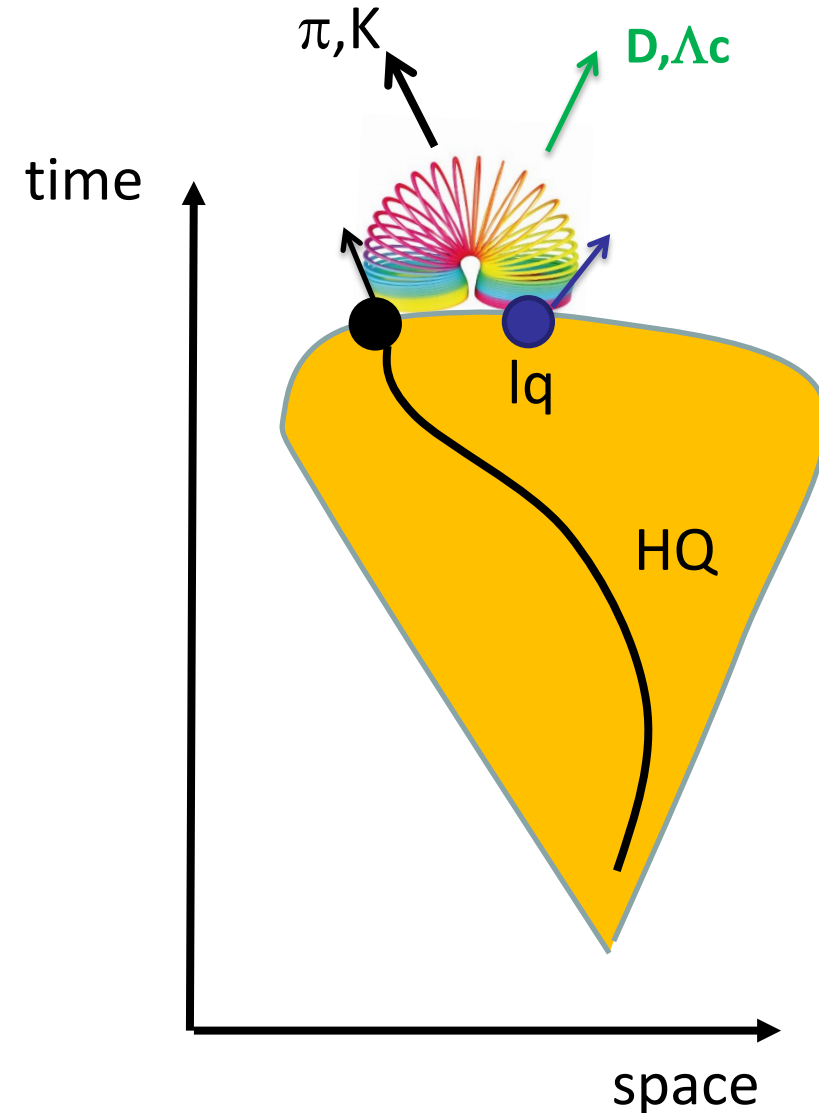
starting from the same bulk and from the same c spectrum

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

HQ - Recombination

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

In-Medium recombination:



- String formed at T_c 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

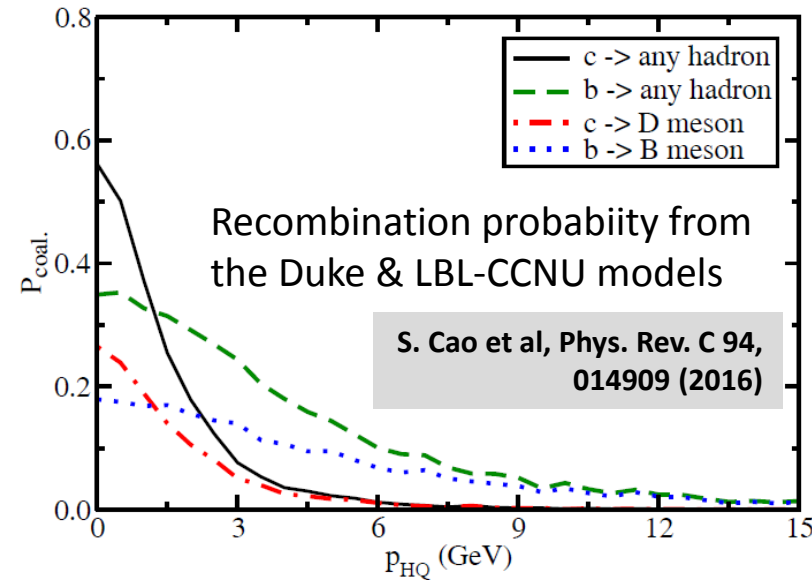
HQ - Recombination

Acknowledged:

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

Low p_T :

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- New specific recombination mechanism; no obvious calibration**
- The footprint of reconfinement (?!)
- 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:
 - 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 $c+q\bar{q} \rightarrow D$; 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

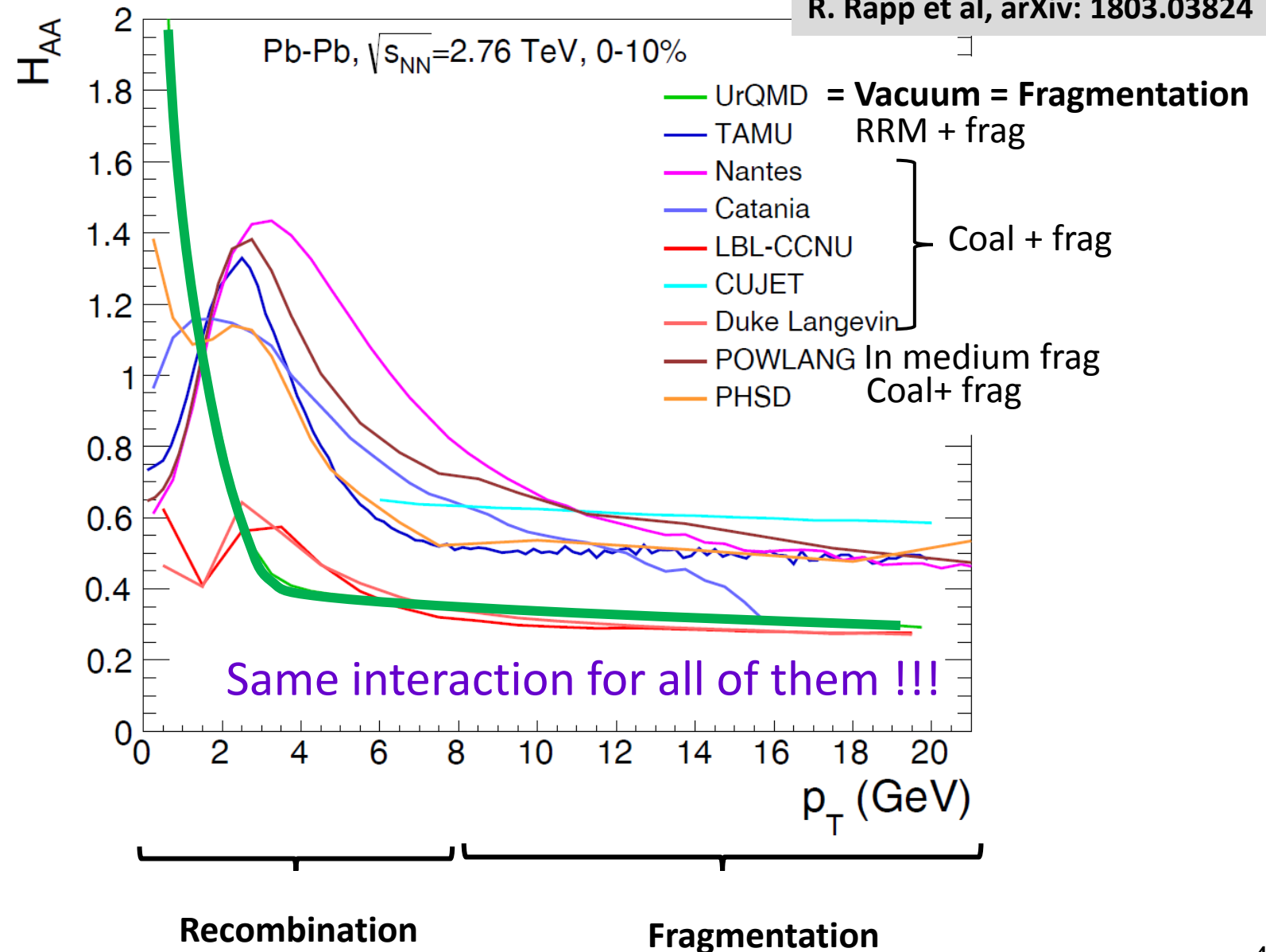
We define and display the H_{AA} quantity

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

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

Significant uncertainties !

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



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

TOP SECRET

TOP SECRET

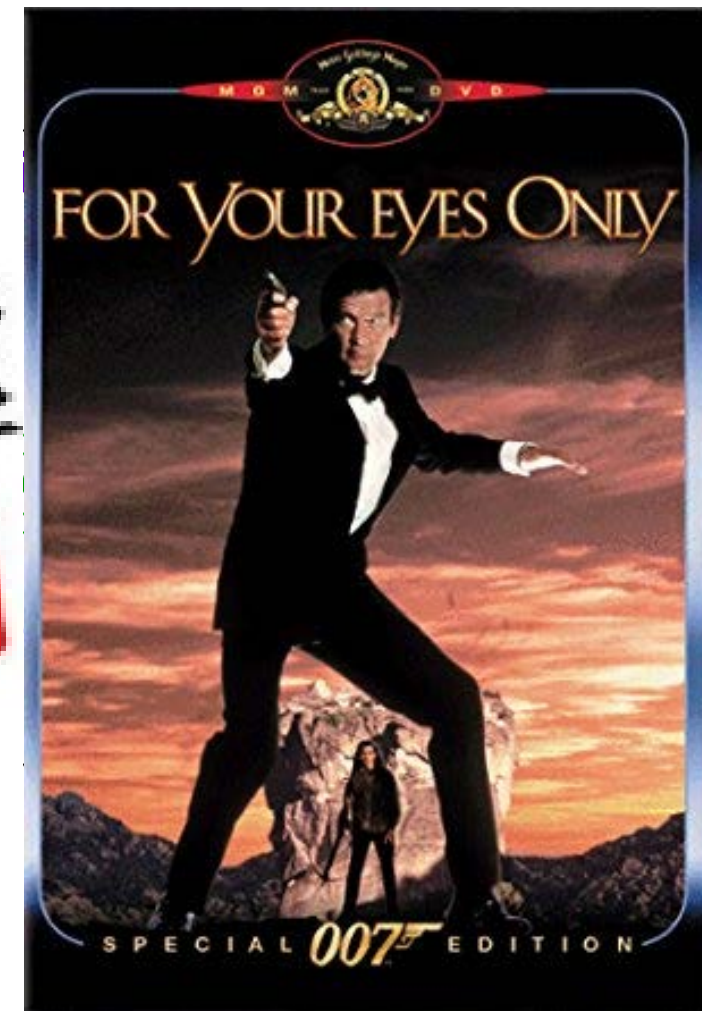
FOR YOUR EYES ONLY

CONFIDENTIAL

CLASSIFIED

FOR YOUR EYES ONLY

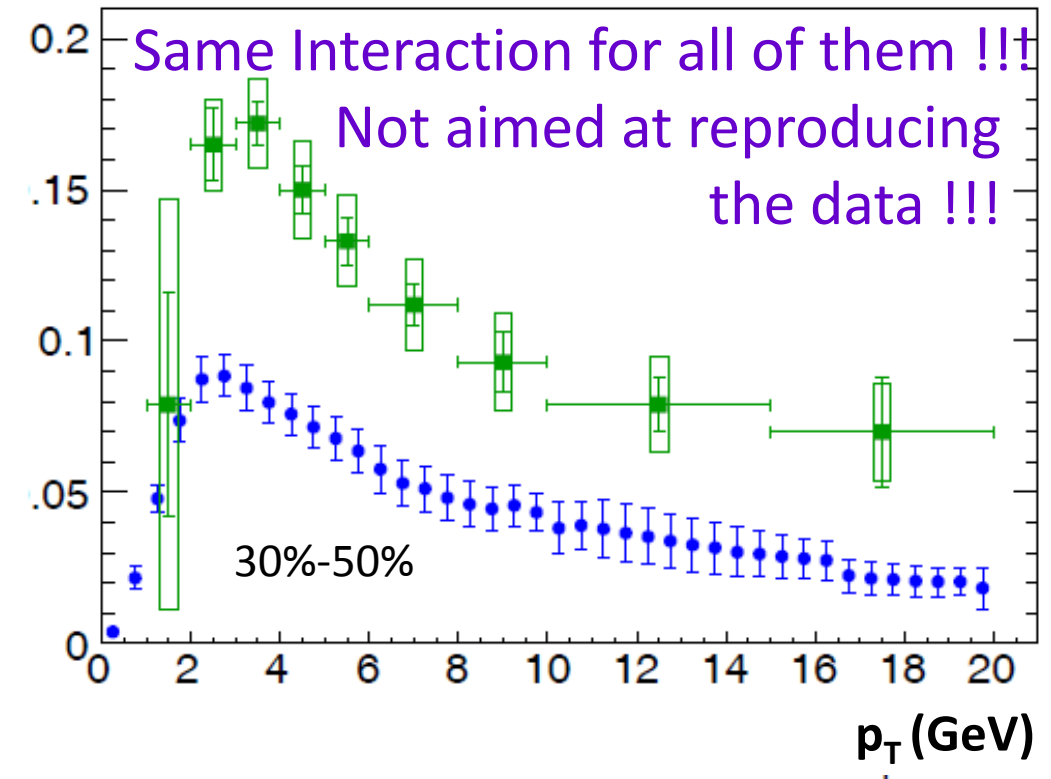
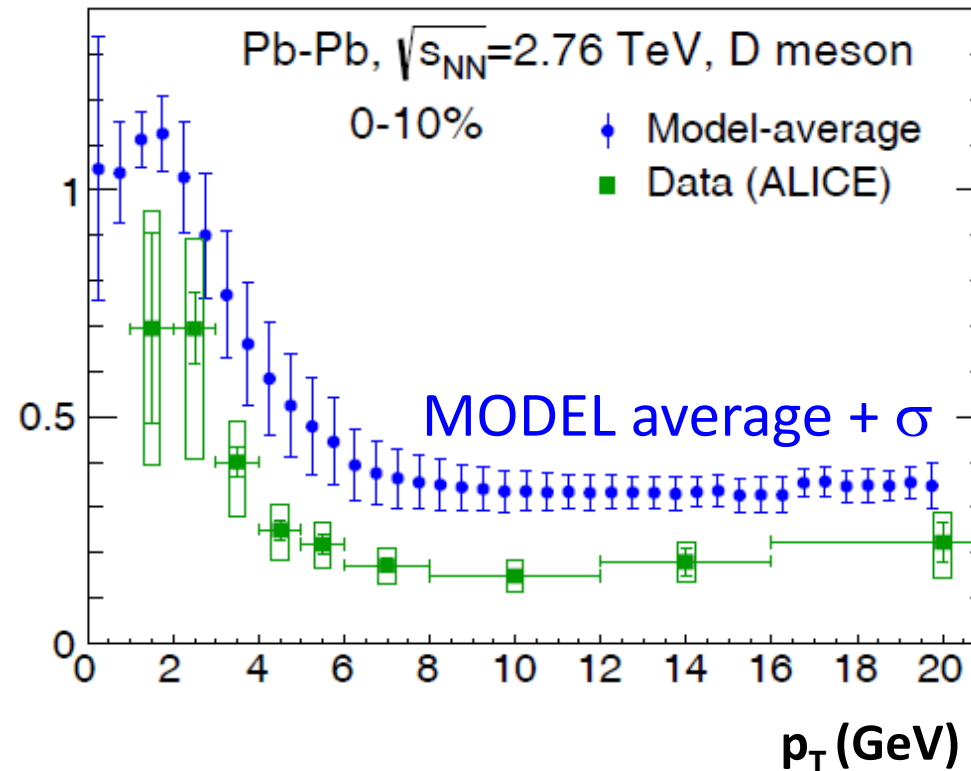
www.shutterstock.com · 576536515



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

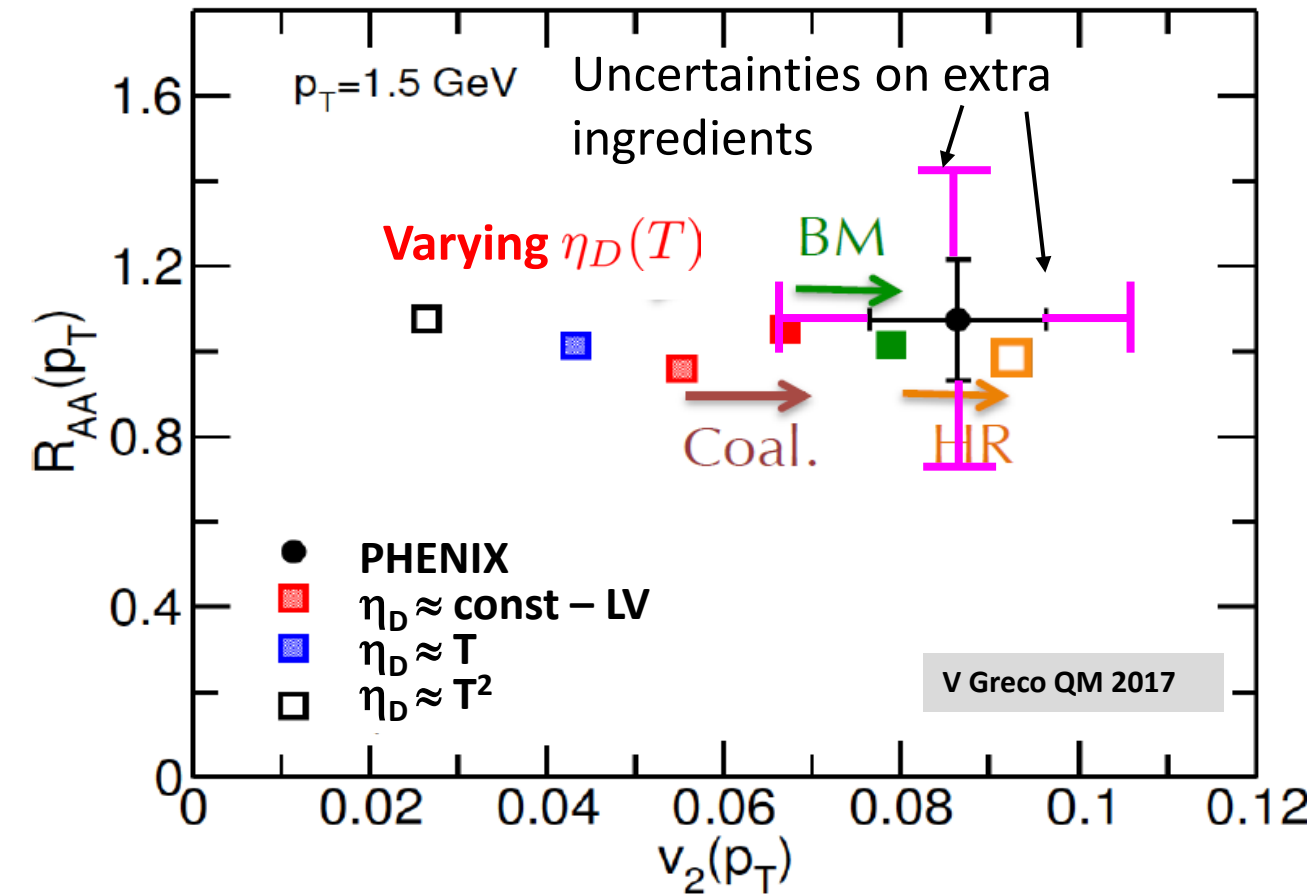
But without shadowing and hadronic rescatterings

R. Rapp et al, arXiv: 1803.03824



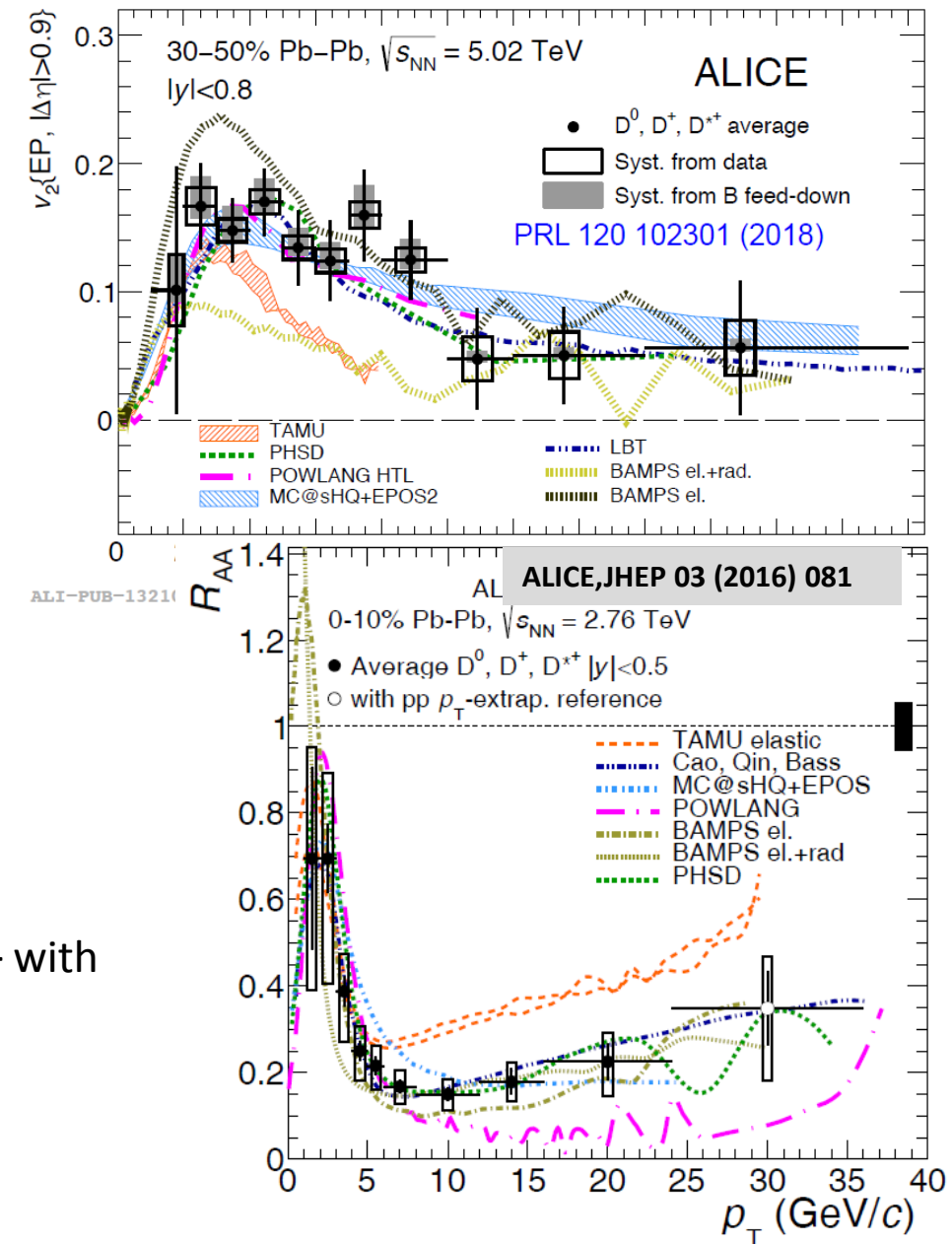
- You asked for it, you got it... « Theory error band »
- At least as large as the experimental one !

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 .

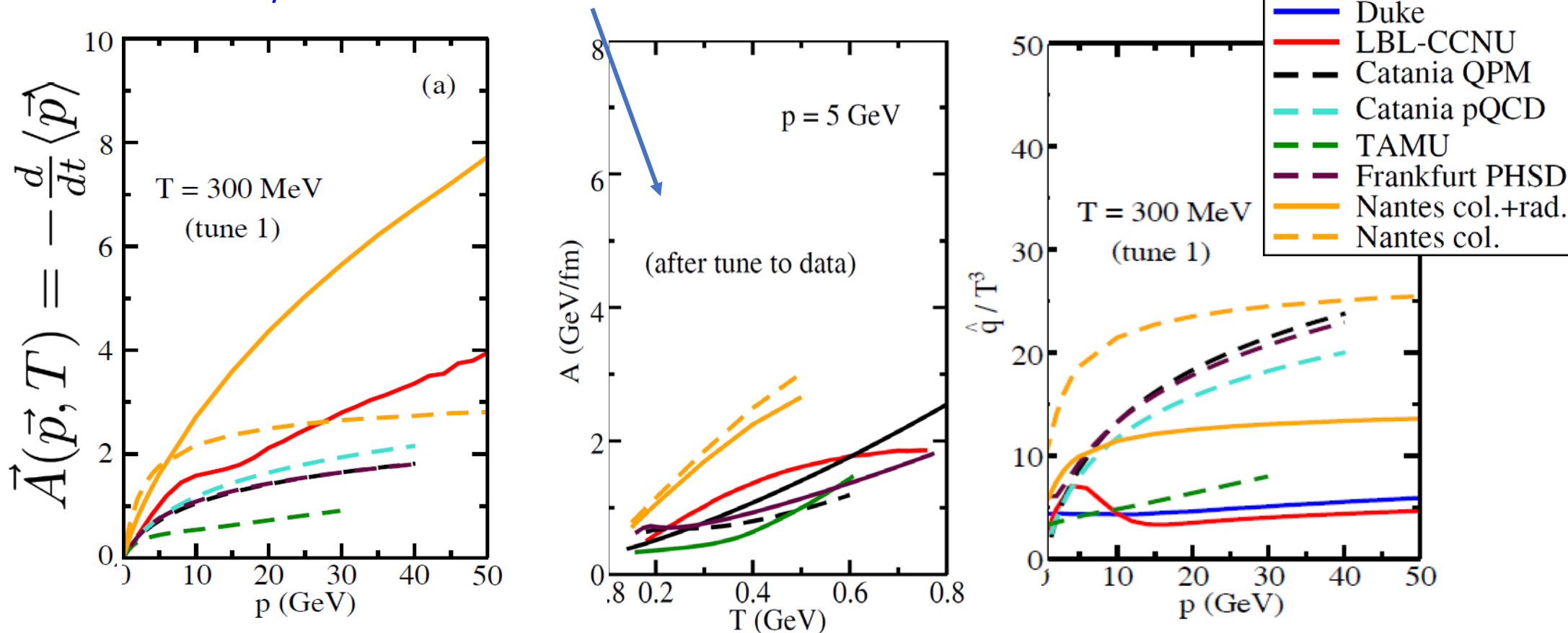
- What should we do next ?



HQ Working Group

- 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 !!!

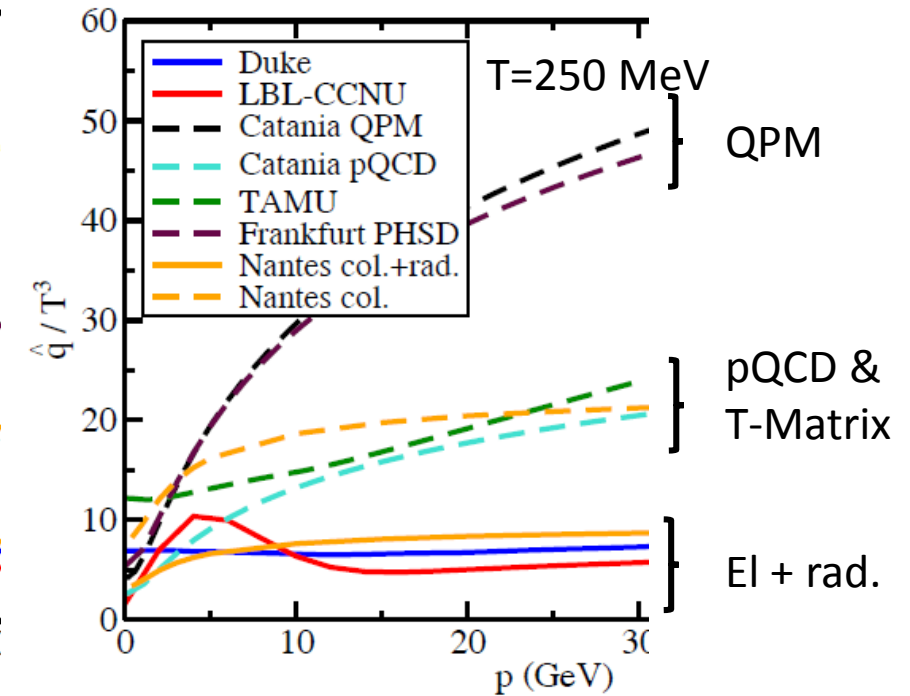
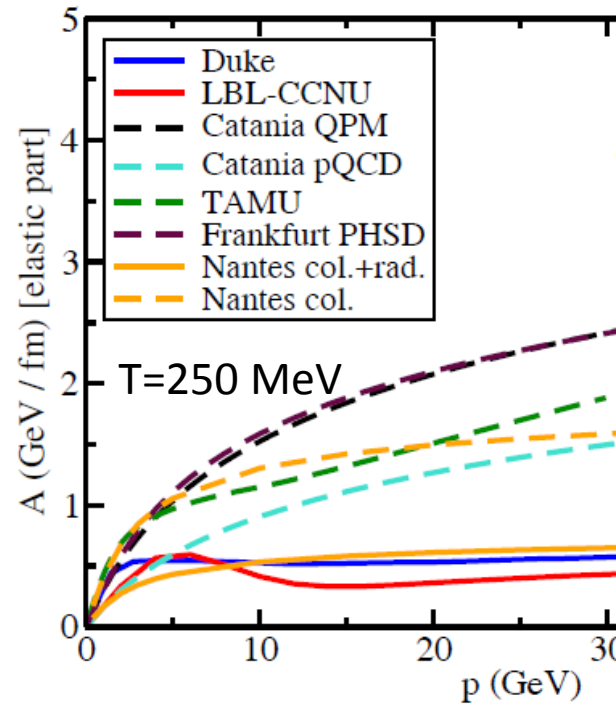
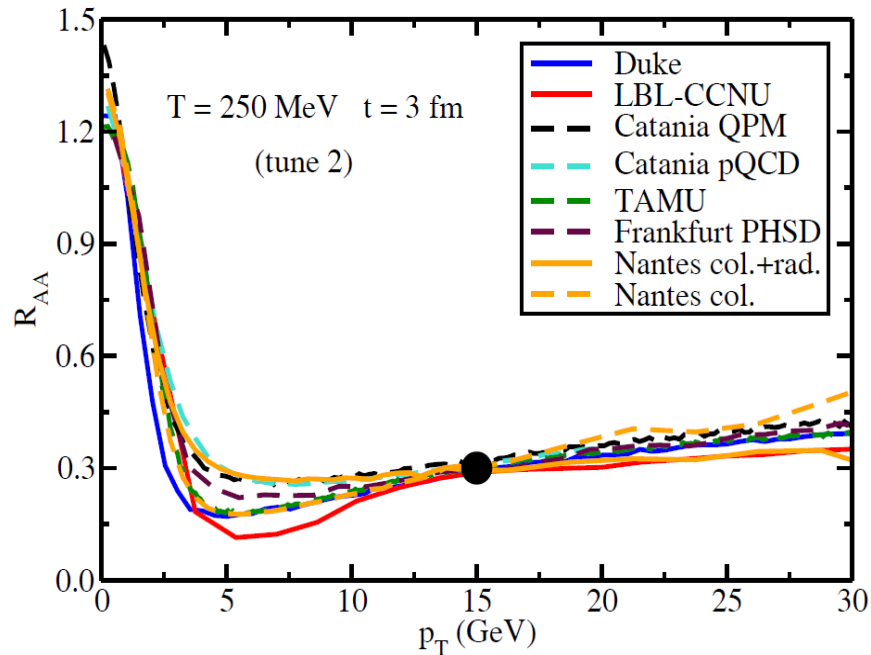
HQ-Working Group (convener: X-N Wang)

- 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 controlled 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

Mid term strategies



The beginning of the film was captivating... What do we need for a good ending ?

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

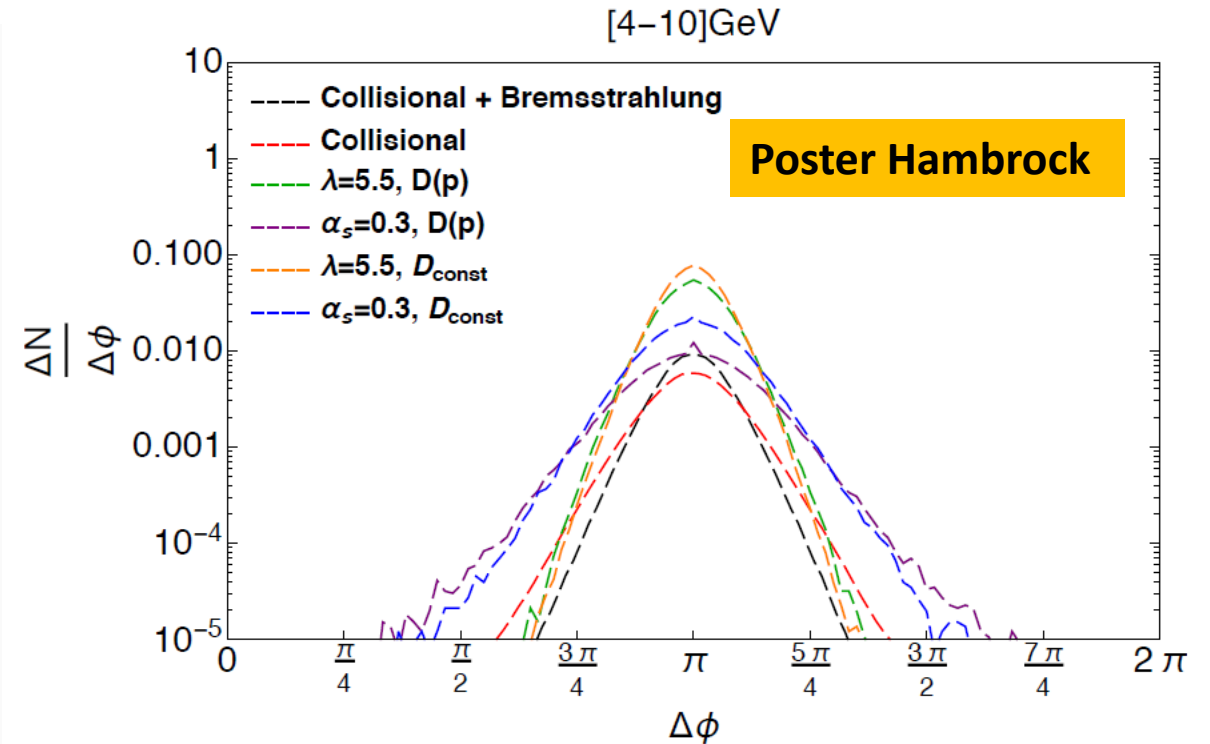
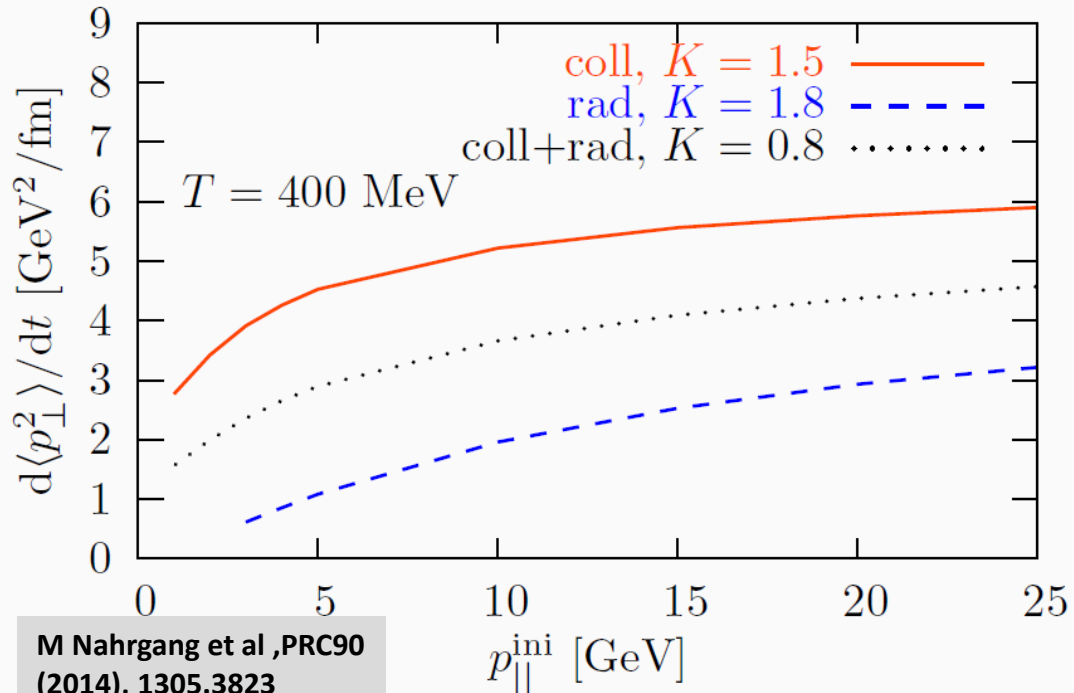
- We should as well rely more intensively and systematically on modern methods like Bayesian analysis, which allow a better quantitative contact with the experimental community

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 // Djordjevic
- The larger “collinearity” found in radiative collisions, which could be seen in azimuthal correlations...



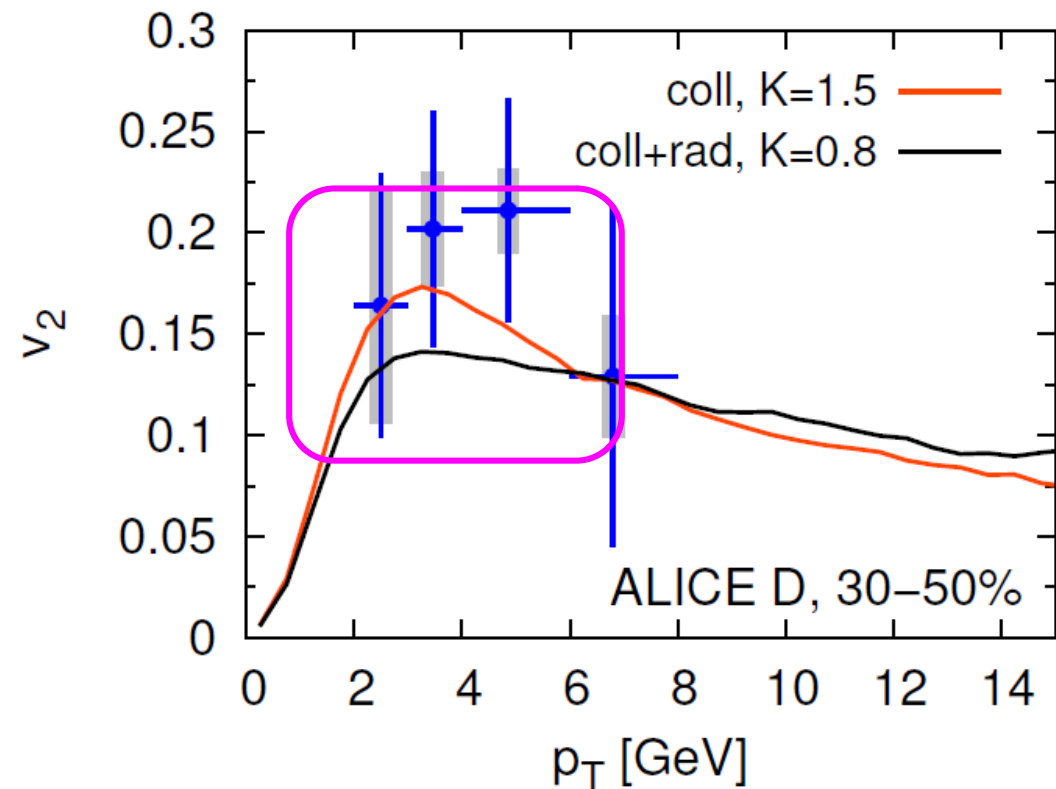
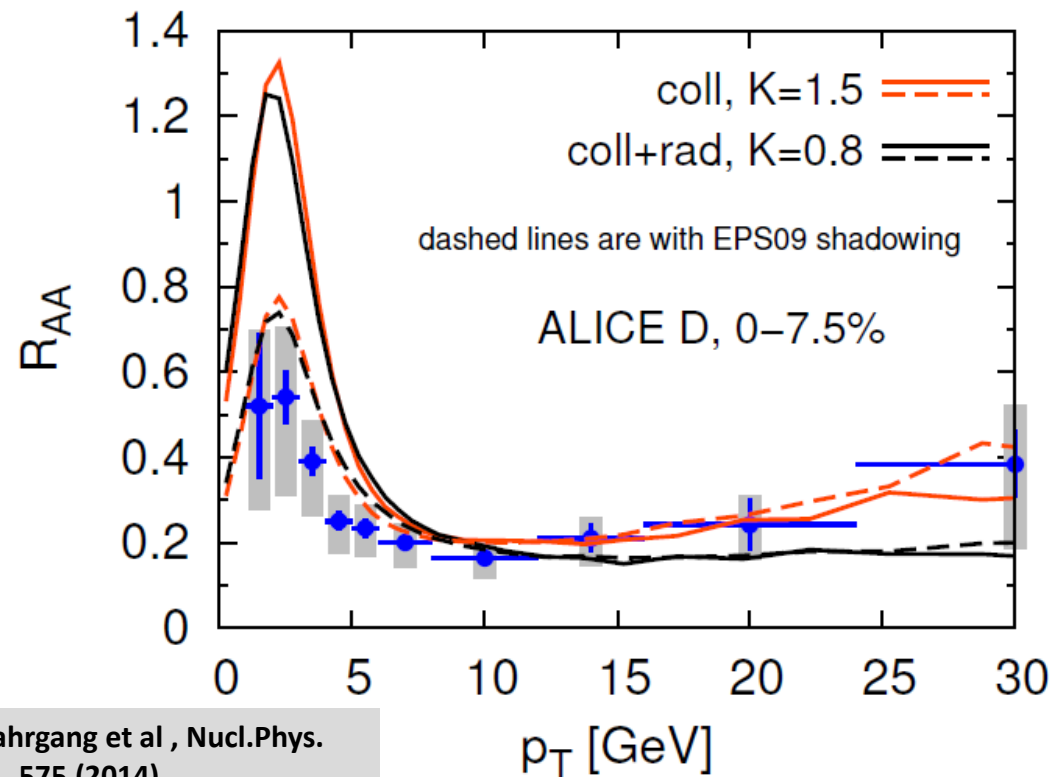
... But not “short term” !!! WE NEED VERY GOOD MEASUREMENTS ON THIS

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 // Djordjevic
- 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



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

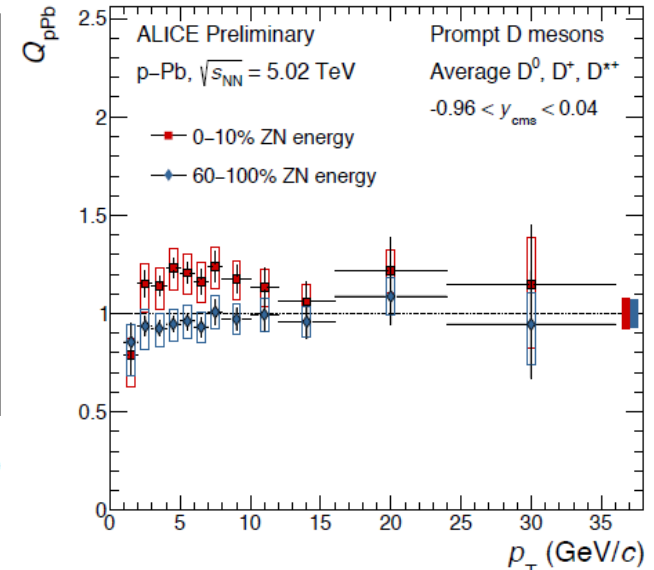
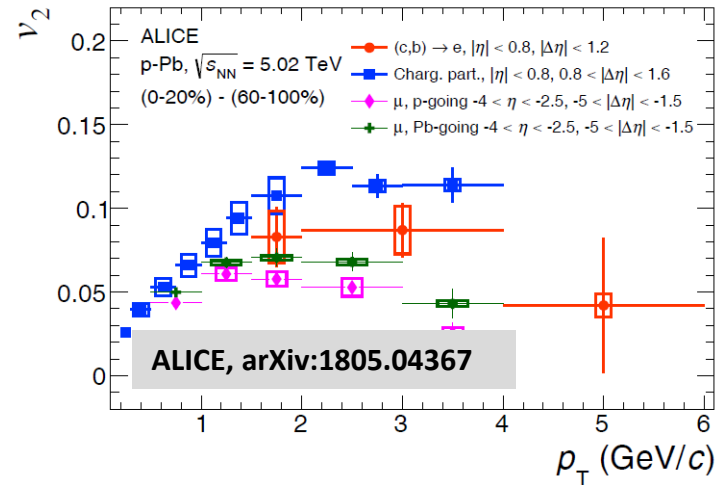
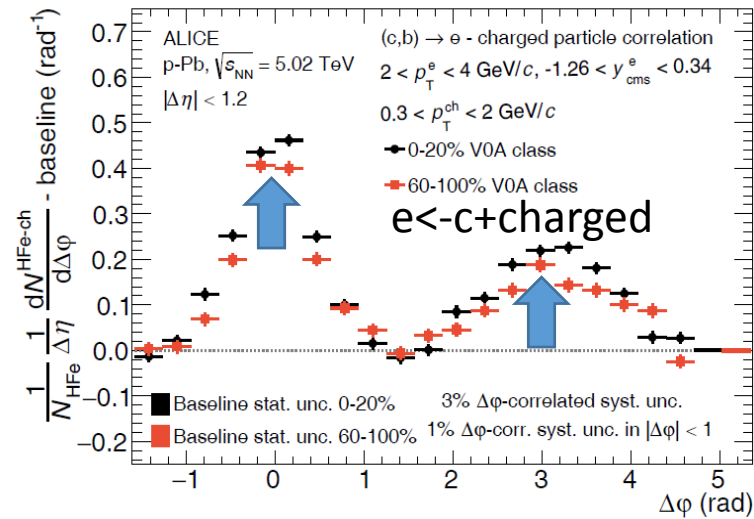
- Analysis of the path length dependence // Djordjevic
- The larger “collinearity” found in radiative collisions, which could already be seen in the Bayesian analysis !

New Observables are coming

Short term, mid-term, long term,...

What	Good for ?	Caviat
Event shape engineering	Strength and T dependence of the interaction	Might be sensitive to the bulk and initial stage => play collective
Heavy light - correlations	b/c-jet substructure, nature of the interaction Poster Rohmoser	Might be sensitive to various HF creation in pp, to be calibrated Poster Vermunt
$\Lambda_c, D_s, B_s, \dots$	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 IQCD probably needed
$v_1(y)$ // 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 ?

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

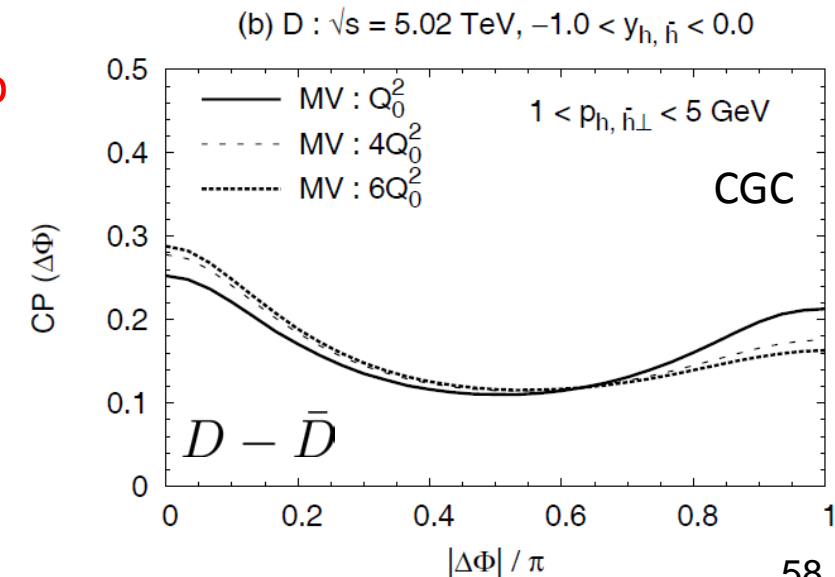


- Finite v_2 seen in p-Pb data but no significant difference in the spectrum ?
- It seems to me that we get similar modifications from both the 0th and 2nd order harmonic (to be checked)
- Physical origin ?
- Both coupling to hydro **and** CGC lead to azimuthal correl. for HF in p-Pb

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

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

both $v_2 \approx 4\%$



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 ?

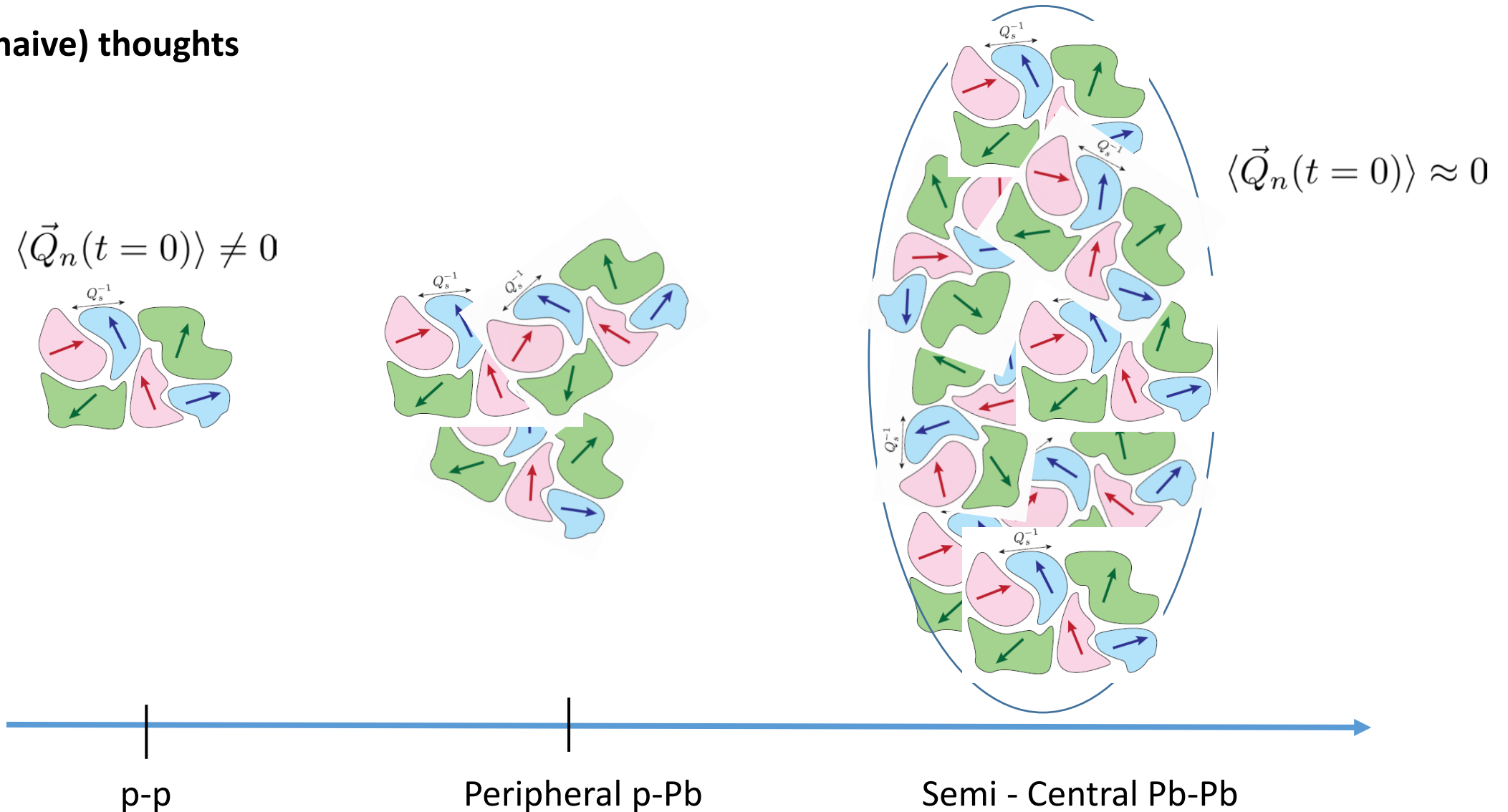
favor CGC	disfavor CGC	Pro hydro	disfavor hydro
Effect deeply rooted in the production mechanism	?	Other indications of collectivity in p-Pb	Theoretical status of hydro in p-Pb unclear (see M. Strickland's talk)
K Watanabe: « From the CGC view point, heavy mesons should be more correlated than light 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: $v_2(B) < v_2(D) < v_2(\pi)$

- It might well be that the mass ordering differs between the mechanisms. Need further study
- 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 further (naive) thoughts



Gradual transition from CGC -> geometry ?

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**

(is it big enough, Andrea ?)

Mid-term strategies

But also, from the theory view point:

- Get more insights and constraints from IQCD (transport coefficient at finite p ?)...

See discussions f.i. in

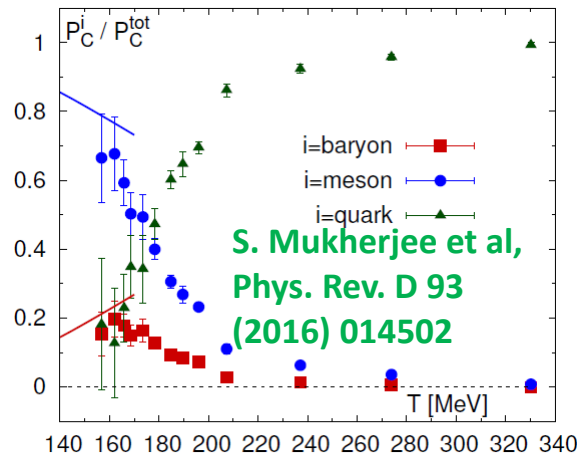
G. Aarts et al, Eur. Phys. J.A 53, no. 5, 93 (2017)

(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 T_c -- should be evaluated in the existing and future models and compared with the IQCD results

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

// S. Y.F. Liu



- Develop models which span the low p – intermediate – 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:

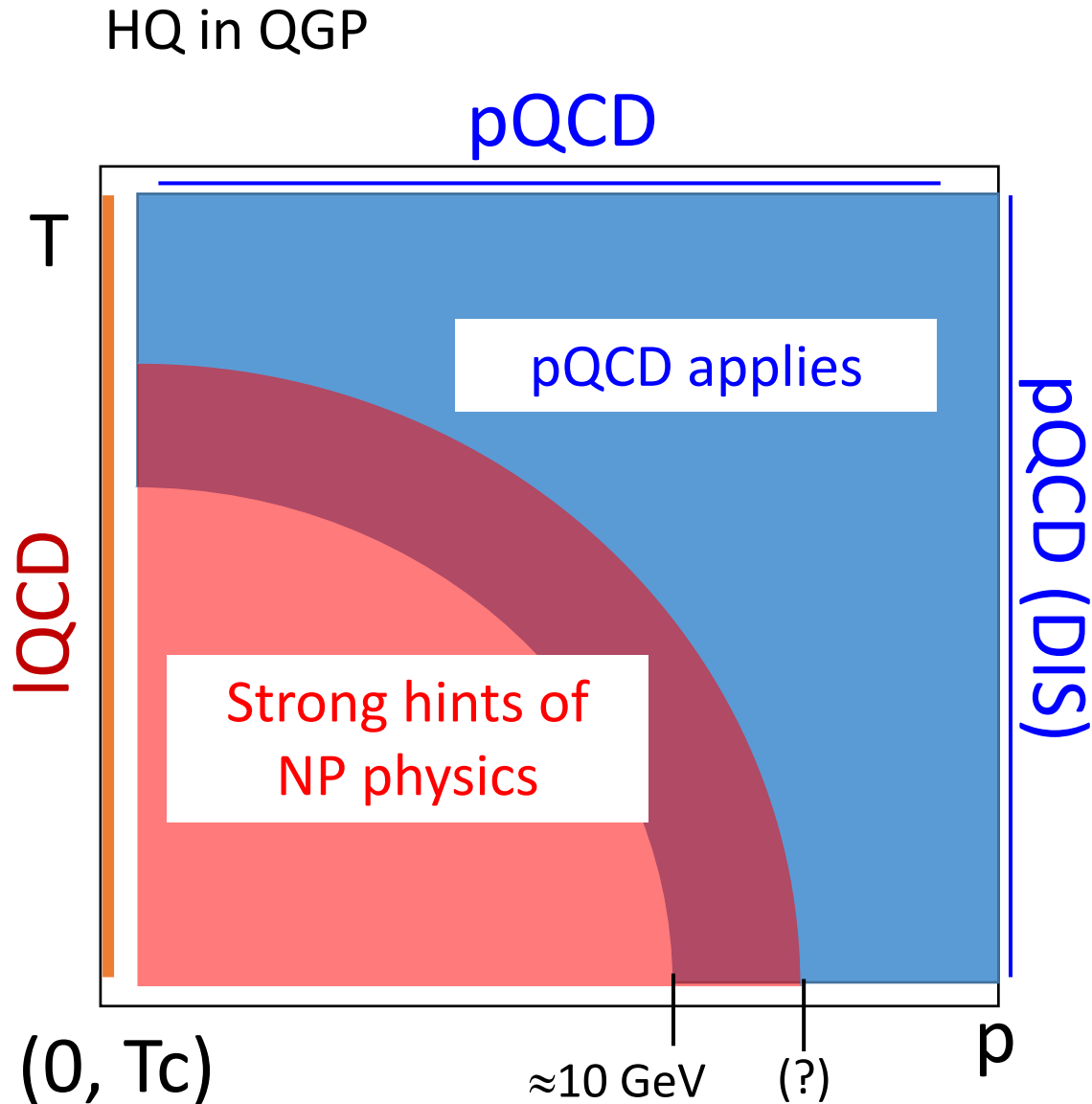
- Develop transport theories beyond the classical approximation (and don't be afraid by numerical work, even if tedious)
- Assess the role of non-equil. QGP effects in QGP on HF (including in the initial stage).
- Achieve a rigorous implementation of radiative energy loss in realistic bulks.
- Strutinize the consequences of other effects usually discarded
 - Evolution in turbulent plasma
 - Fluctuation of chromoelectric field
 - ...

Stanislaw Mrowczynski, Eur.Phys.J. A54 (2018) no.3, 43

Poster A. I. Sheikh

Any suggestion welcome !

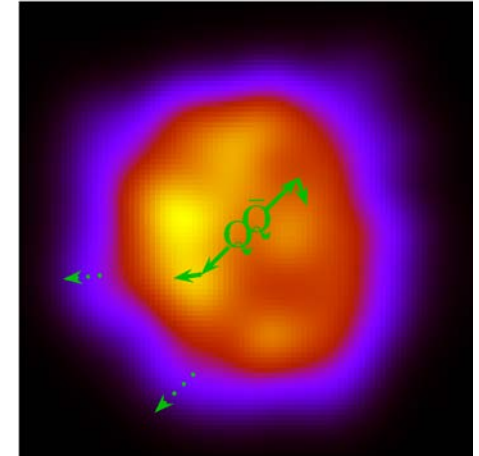
Conclusions



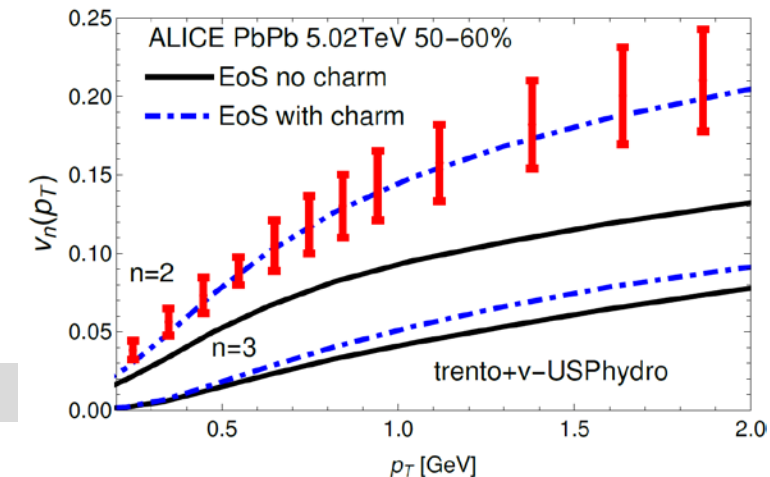
- Existing models offer the possibility to describe most of the OHF experimental AA data while being compatible with existing theory constraints...
- ... however with unequal precision and no consensus on the physical NP content
- Improvements and quantitative understanding is on their way, but it will still take some time and a lot of efforts => need for resources, bright people and collective work.
- Open Heavy Flavours 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 $p_T \gg$ local $T \Rightarrow$ **Hard probe**
- But for $p \approx 0$: $\tau_{\text{relax}} \approx$ QGP lifetime \Rightarrow **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

* Please « Hard Probes » gentle organizers, keep HF on your program

Back UP

IQCD

IQCD Calculation of D_s

- Lattice QCD at finite T is performed in Euclidean space notoriously difficult to calculate dynamical quantities.
- Up to 2014, D_s 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:

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

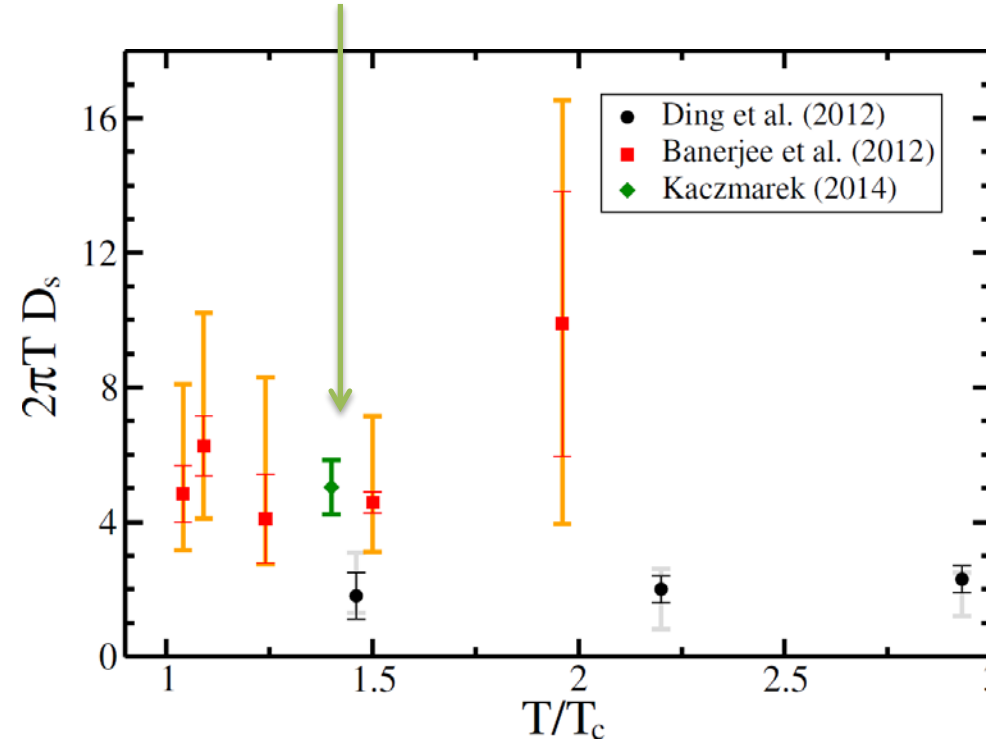
- Then obtain the variance κ of stochastic forces (a transport coefficient; $\kappa = 2 \times B$) from the slope of spectral function ρ_E at $\omega = 0$:

$$\kappa \equiv \lim_{\omega \rightarrow 0} \frac{2T \rho_E(\omega)}{\omega} \quad \text{with } \rho_E \text{ extracted from } G_E(\tau) = \int_0^\infty \frac{d\omega}{\pi} \rho_E(\omega) \frac{\cosh[\omega(\frac{\beta}{2} - \tau)]}{\sinh[\frac{\omega\beta}{2}]}$$

- Main result : $\kappa/T^3 = 1.8 \dots 3.4$ then convert to D_s

IQCD Calculation of D_s

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



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

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

Models

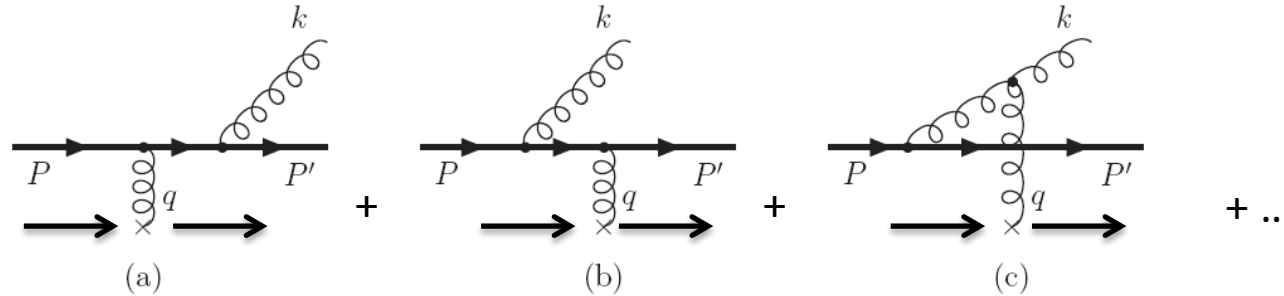
pQCD inspired models (f.i. Nantes)

Collisional component

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

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

Radiative component



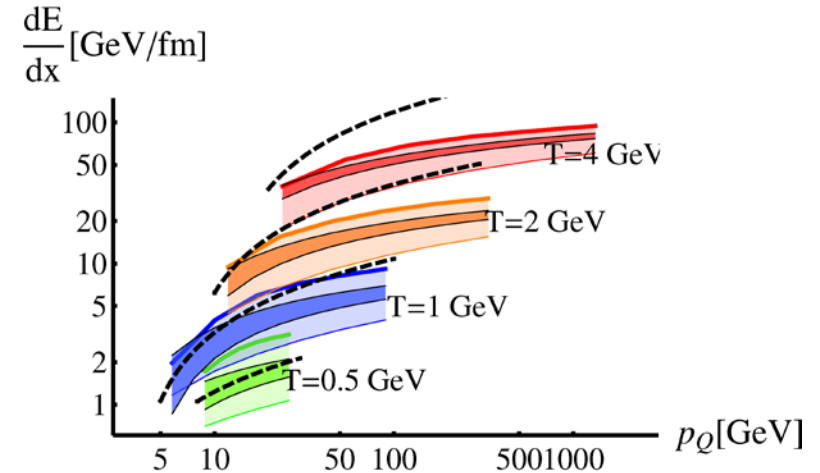
- Extension of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision ($\Delta E_{\text{rad}} \propto E L$):

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

- LPM effect for moderate gluon energy

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

But also BAMPS, LBL-CCNU, Duke,...



Potential models (TAMU)

- Thermodynamic T-matrix approach, $T = V + VGT$, given by a two-body driving kernel V , estimated from the IQCD 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)

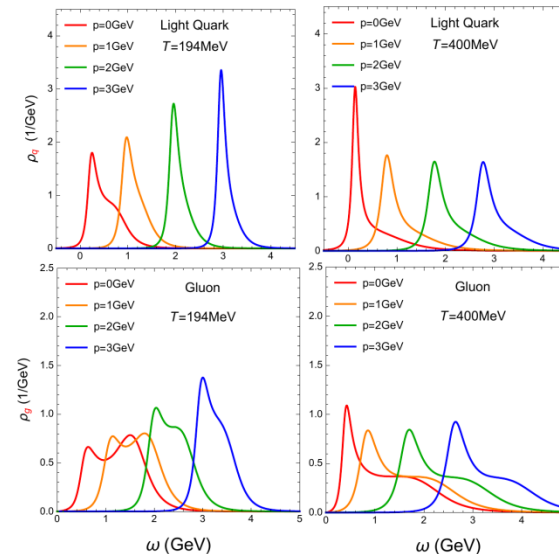
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

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

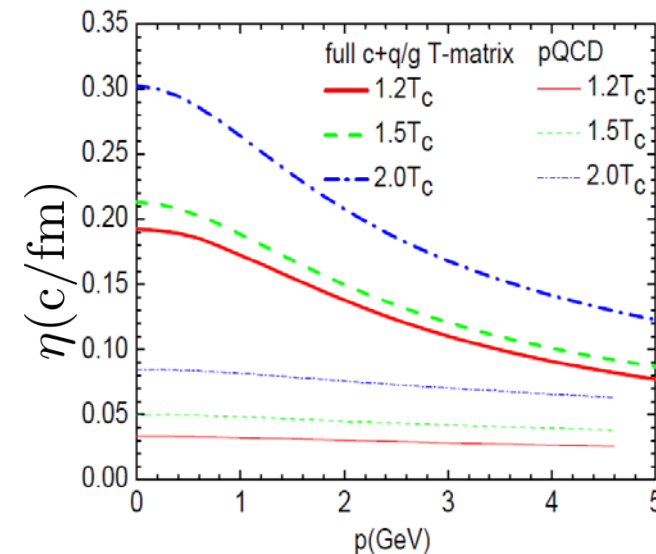
- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions!

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

Quasi particle models (f.i DQPM)

- Nonperturbative effects near T_c are captured by $\alpha_s(T)$, leading to thermal masses/widths, determined from fits to IQCD 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)

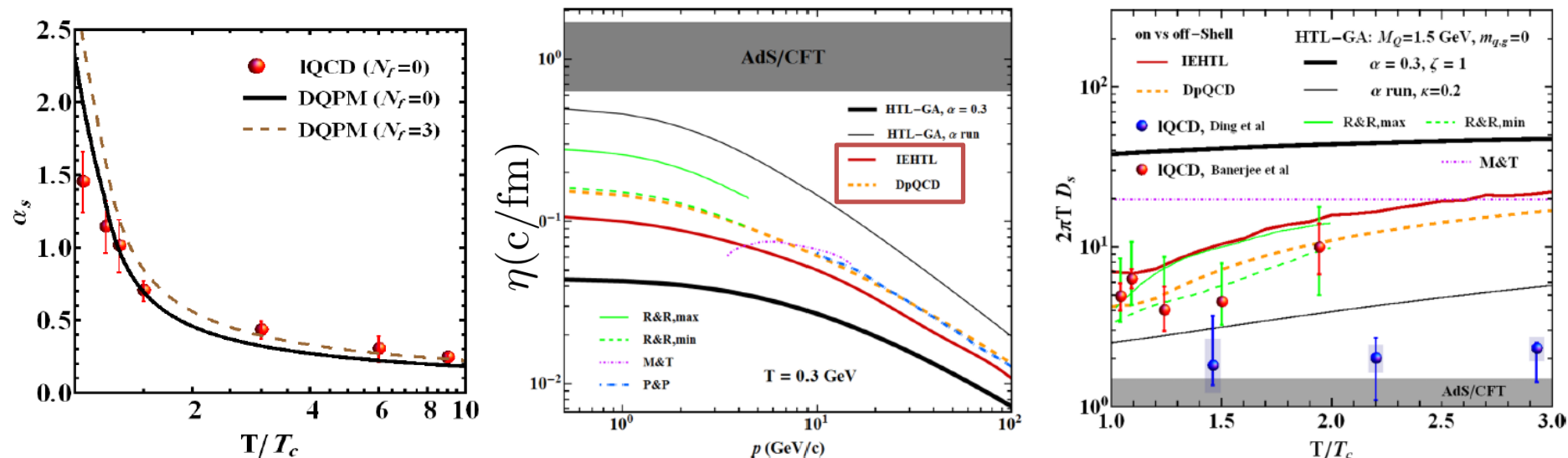
- Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

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

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

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

But also CATANIA

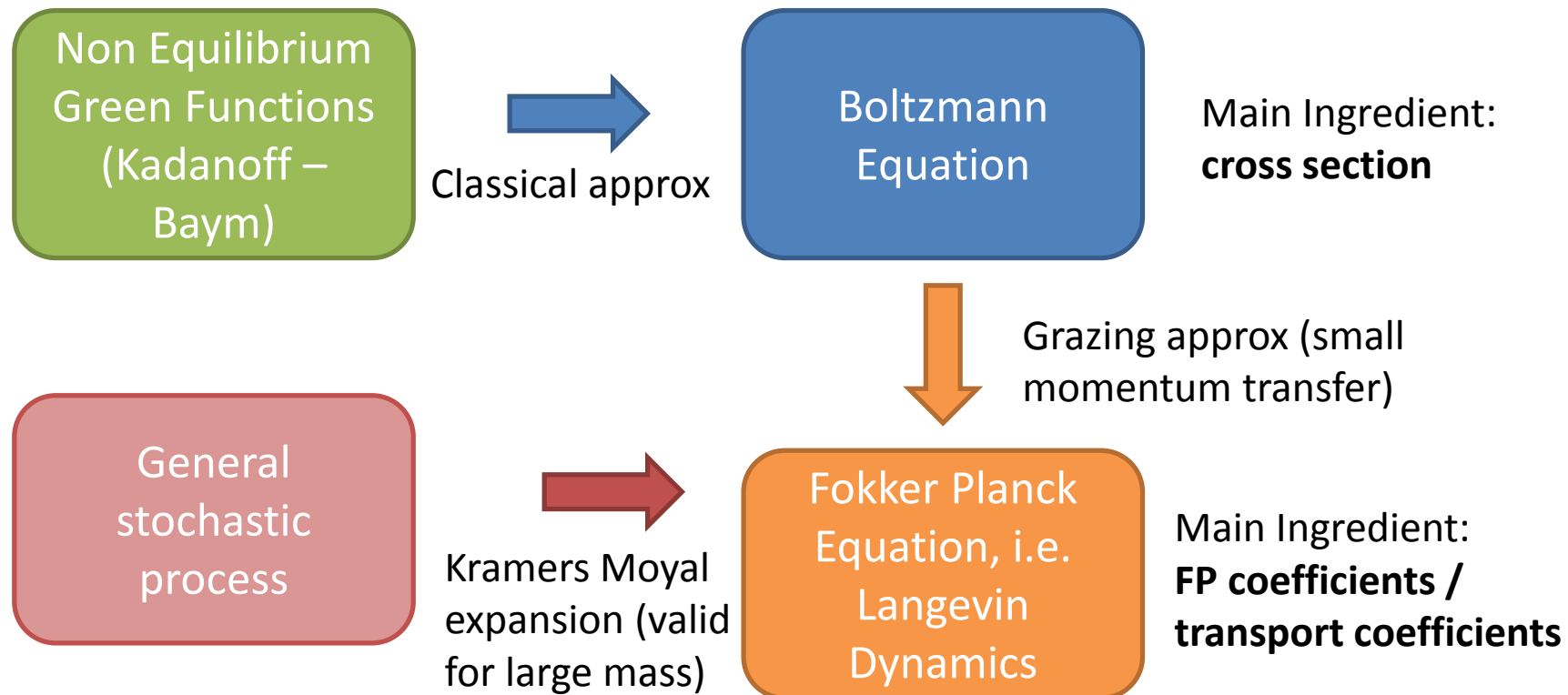


Transport

Various approaches to modeling

Bottom-up schemes (microscopic -> mesoscopic):

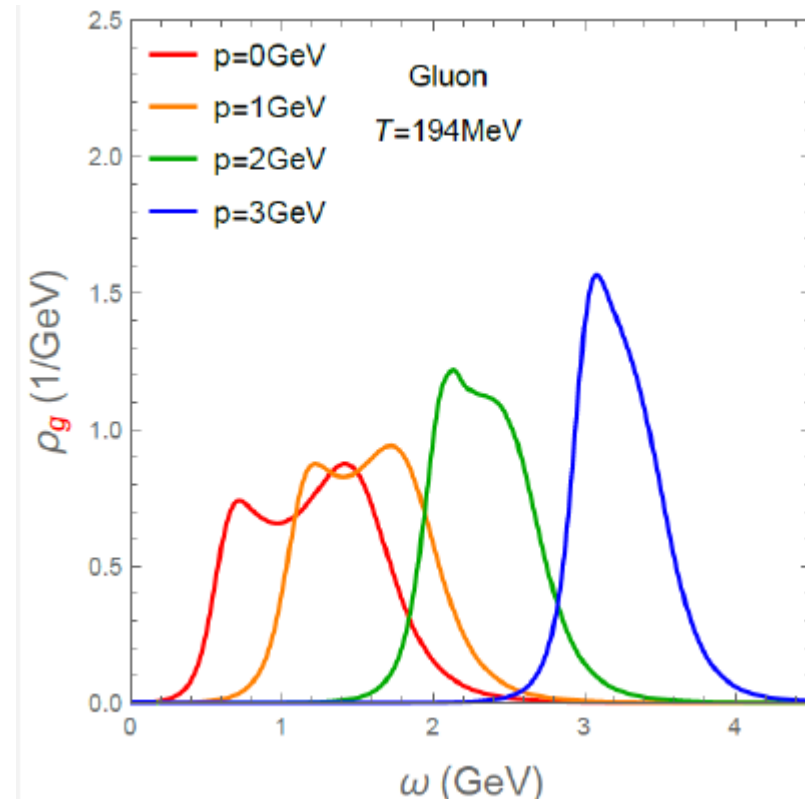
- Assume (effective) degrees of freedom and (effective) interactions
- Take insights and constraints from the fundamental QCD theory, but often inholds some free parameter
- Rely on more or less sophisticated realizations of the transport theory



Boltzmann vs Langevin Dynamics

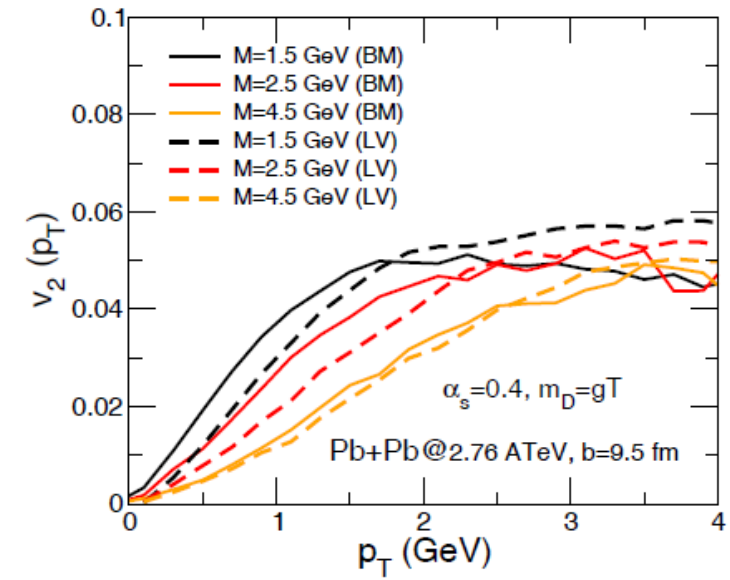
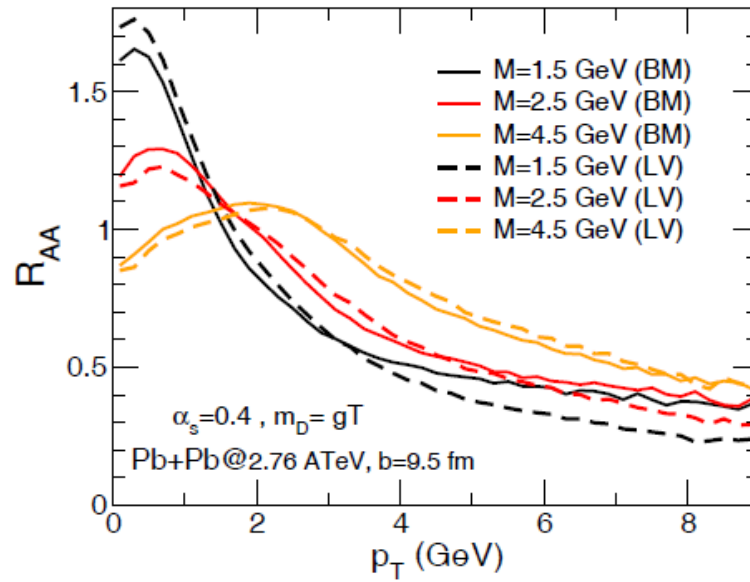
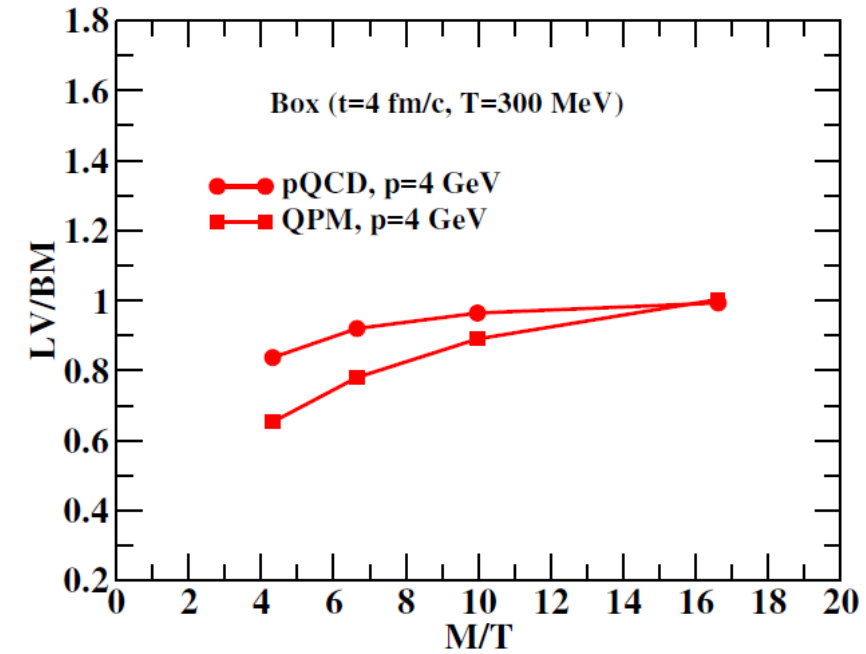
Boltzman from Langevin view point:

- There are a lot of situations where Langevin dynamics applies, but not Boltzmann, thanks to the large mass of the particle.
- 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)

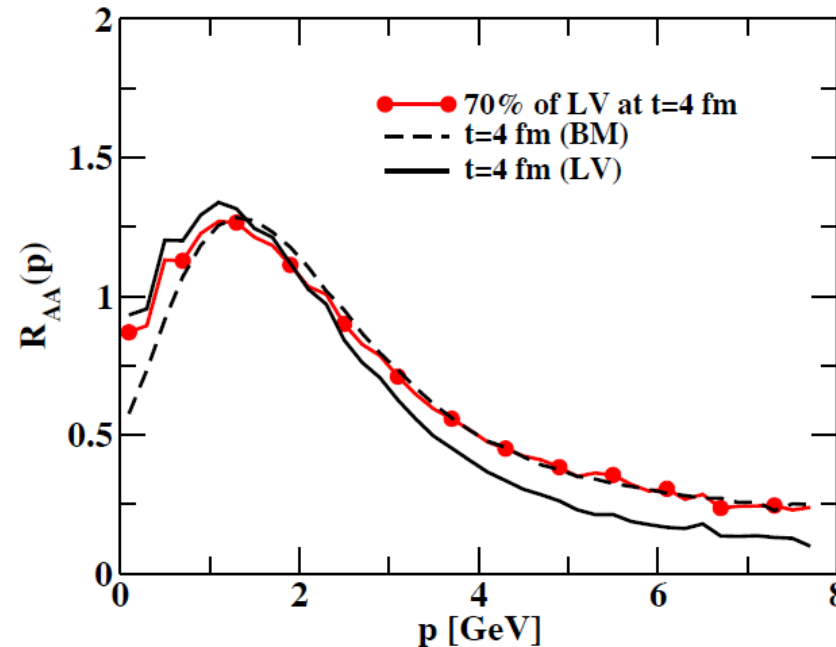
Boltzmann vs Langevin Dynamics



Boltzmann vs Langevin Dynamics

Langevin from Boltzman view point:

- 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)



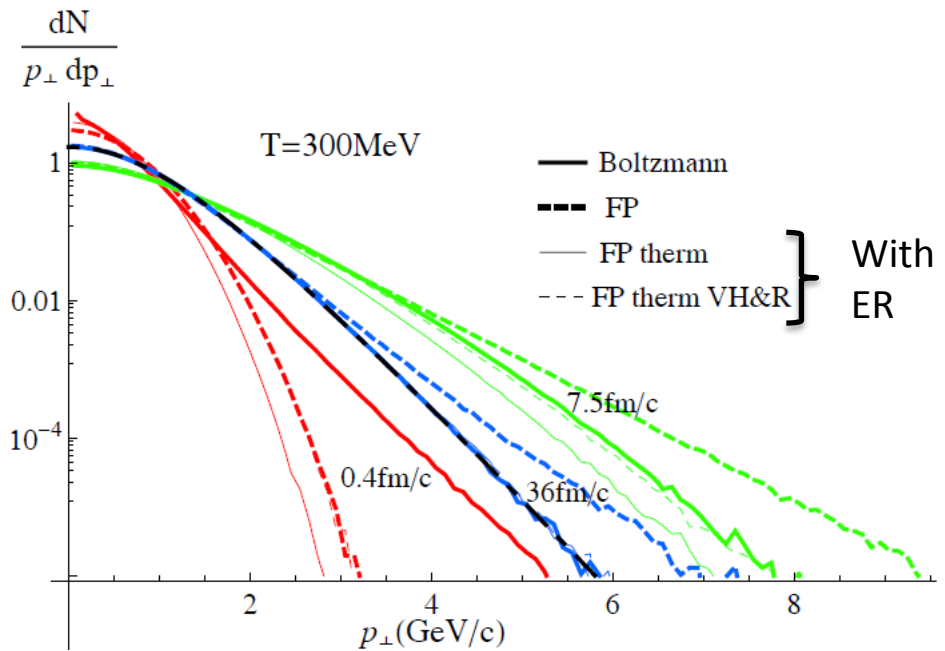
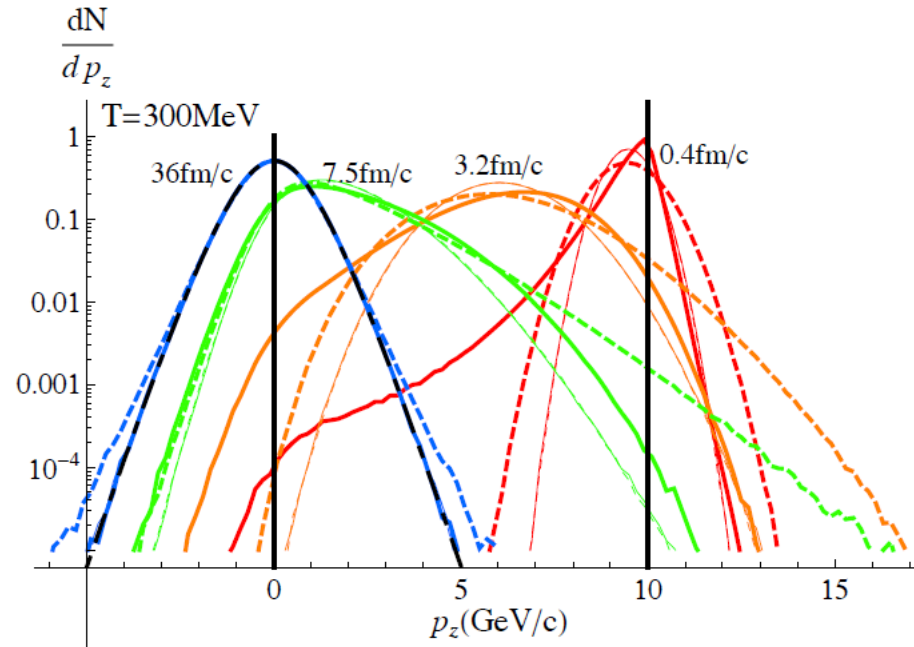
S Das et al, Phys. Rev. C 90,
044901 (2014)

- 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 $\approx 30 \%$

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 be seen in observables like g-HQ correlations

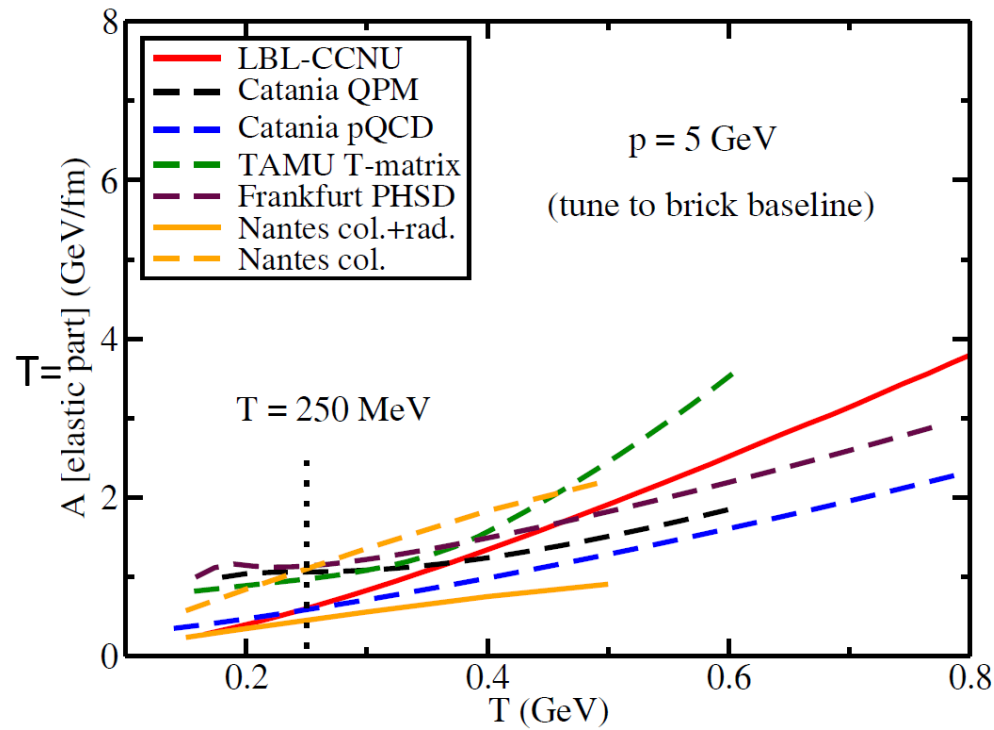
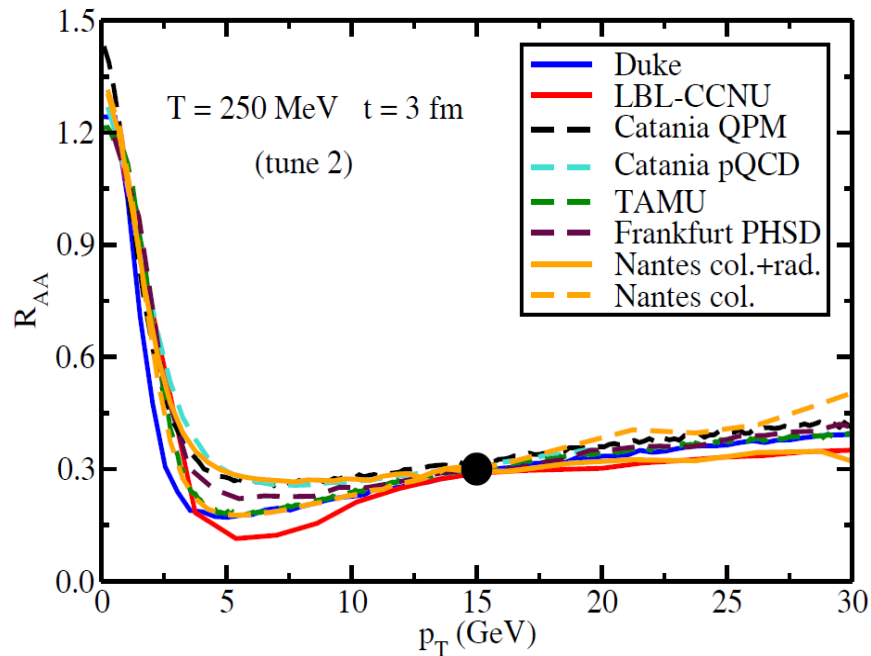
HQ-WG

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 !



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

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...)
- IQCD 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)

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

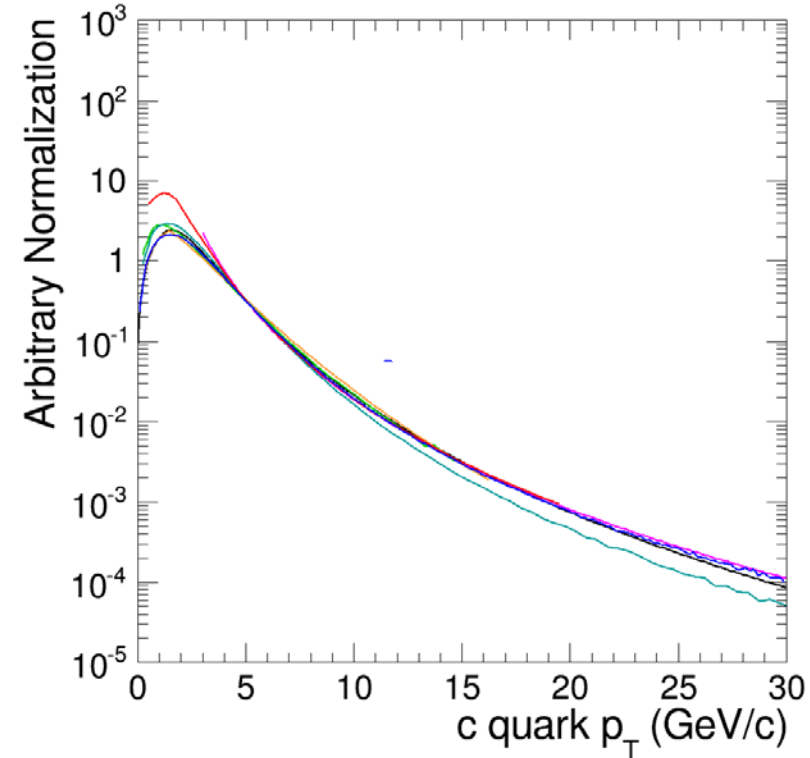
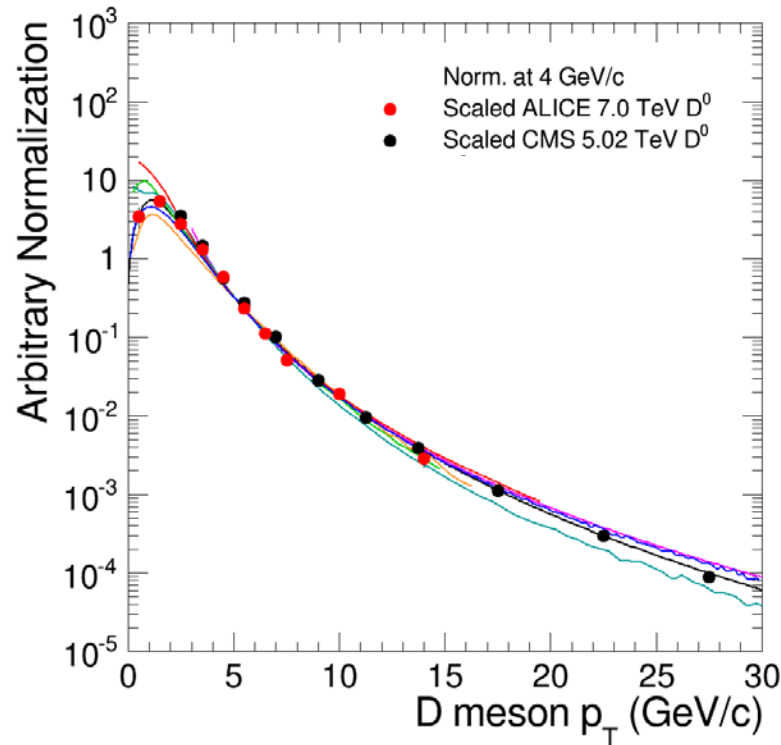
Topics:

- 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:



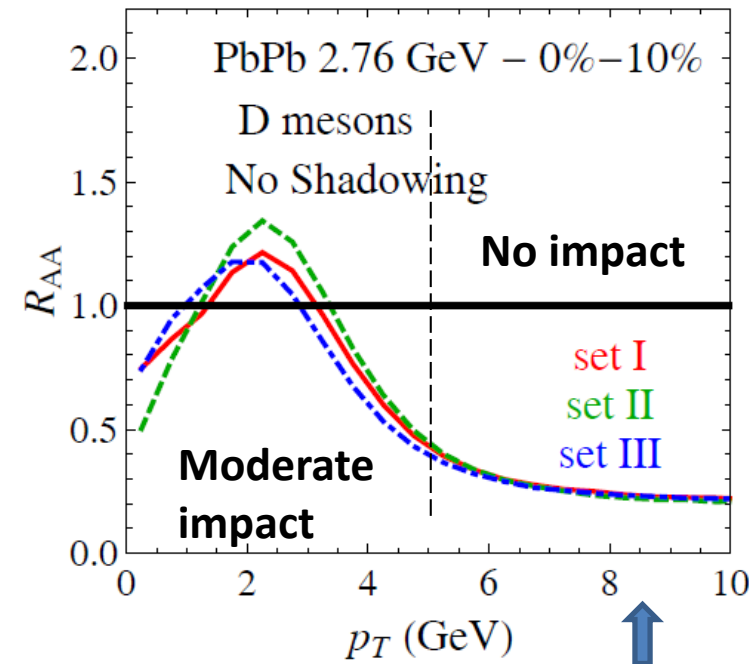
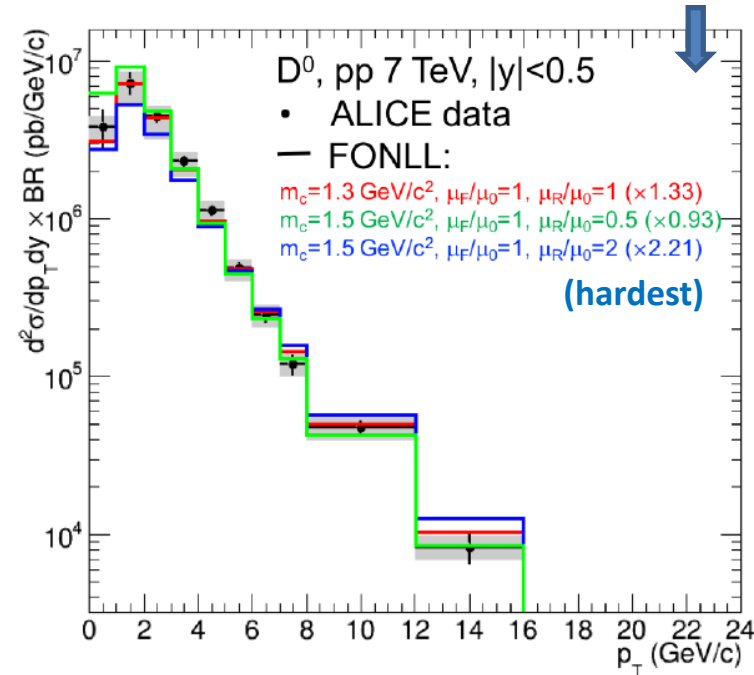
Some « outliers »... Is it acceptable or does it has measurable consequence either on the « extraction » of the transport coefficient (for « tunable » models) or on the agreement with experiment.

« 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)

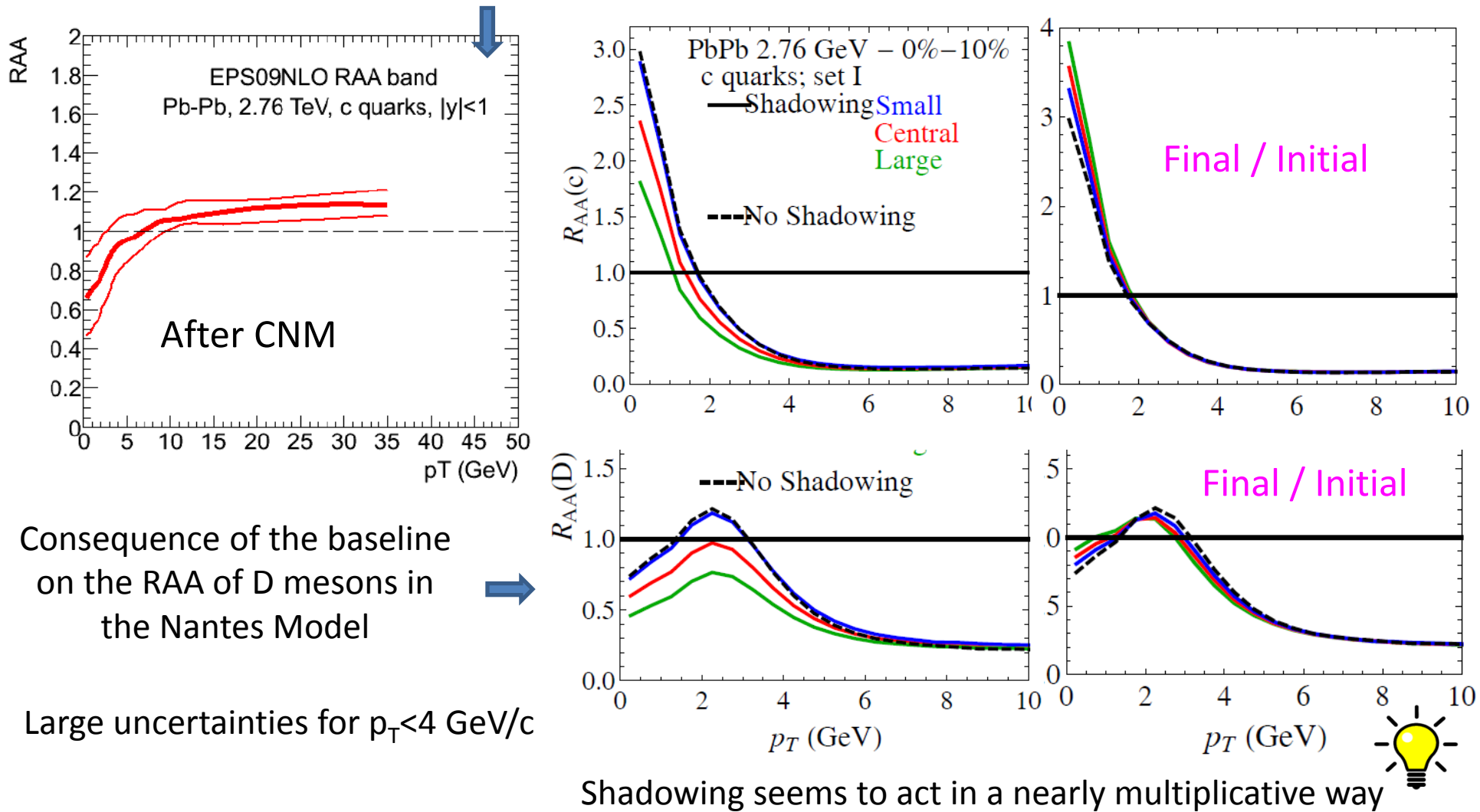


Consequence of the baseline on the RAA of D mesons in the Nantes Model (thermalisation at small $p_T \Rightarrow$ the initial profile has a large impact in the ratio)

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 $\chi^2/NDF > 2$).

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



EMMI RRTF : Initial HF spectra and shadowing

Consequence for the collective chase:

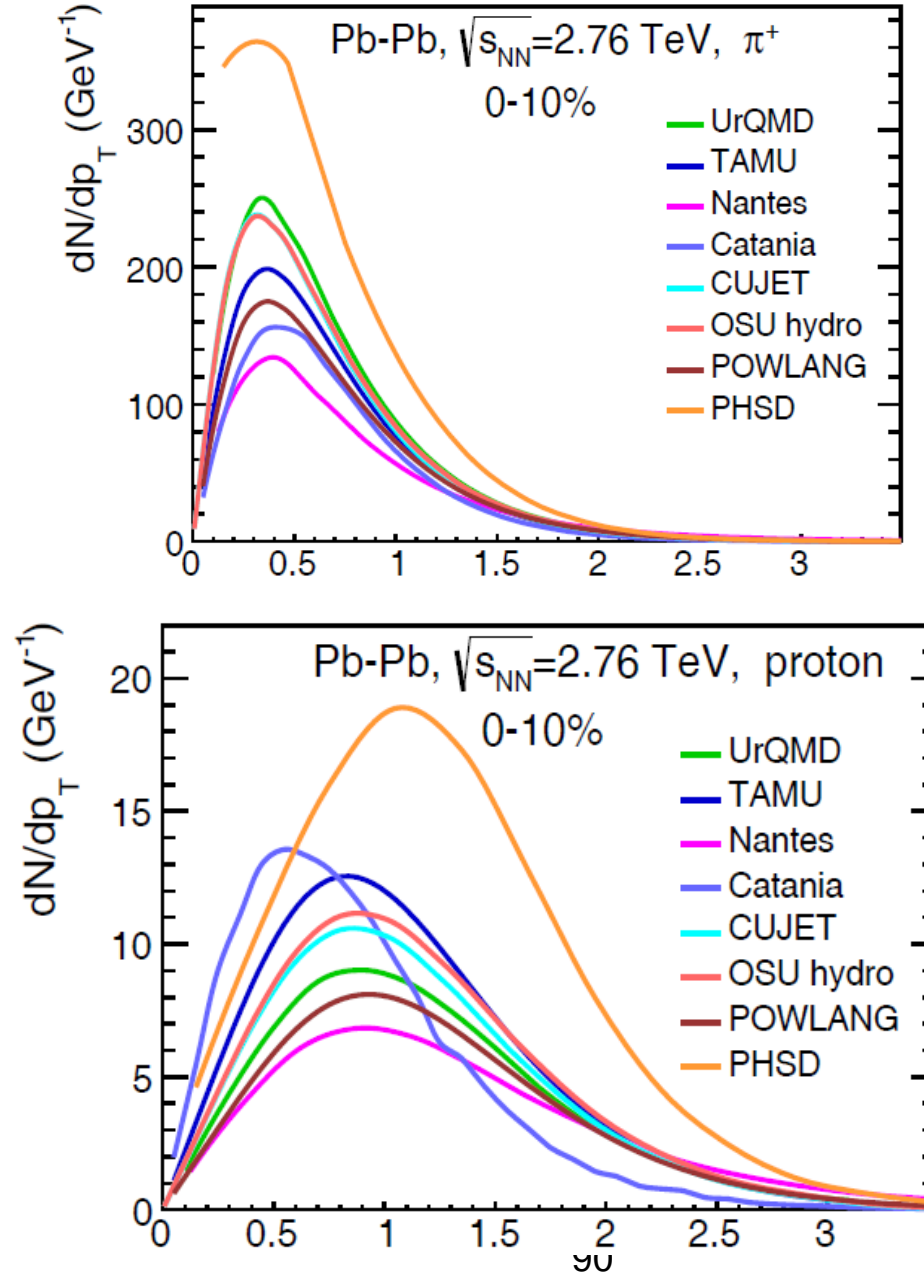
- ideally, all models should adopt the same prescription for shadowing, and the uncertainties on the shadowing should then be recast in a global systematic error on the D_s , *common to all models*
- If some models have an intrinsic theory to evaluate shadowing and are unwilling to modify this for the 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

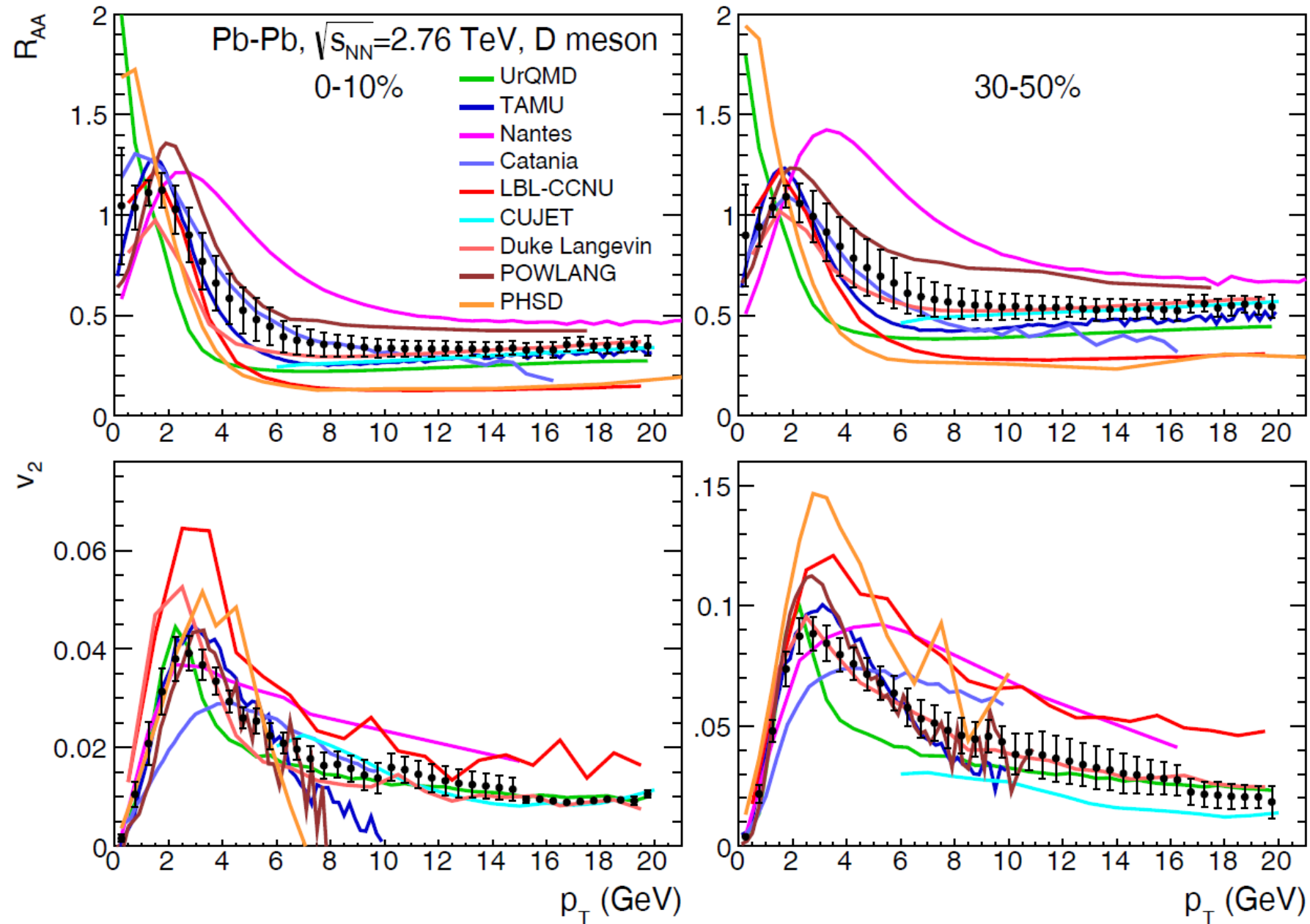
EMMI RRTF : the bulks

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

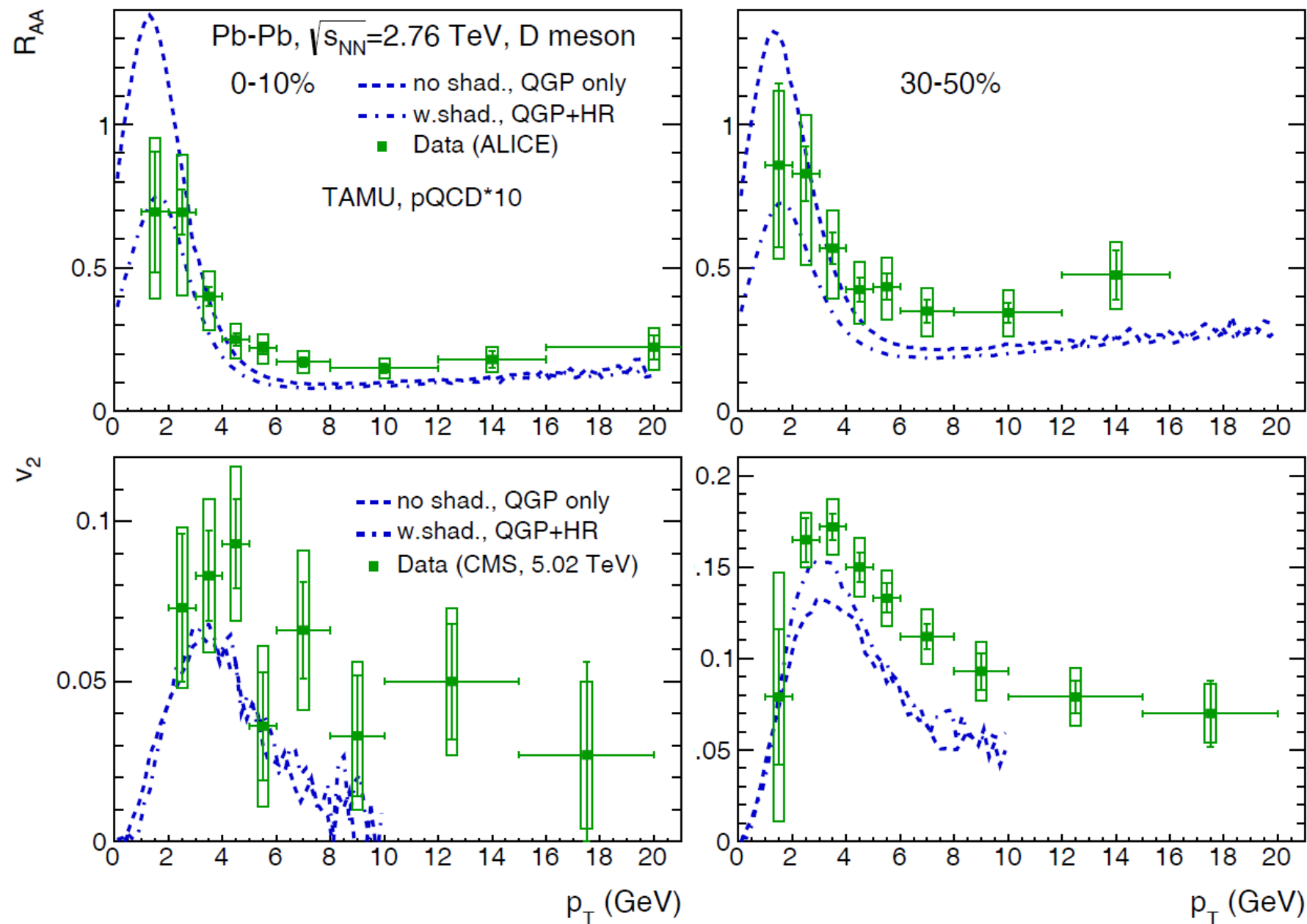
Table 1: Inclusive π^+ and proton numbers (*i.e.*, including strong and electromagnetic feeddown) per unit momentum-space rapidity in Pb-Pb(2.76 TeV) collisions in the various bulk evolution models. Also shown in parentheses are the values for the total entropy per unit space-time rapidity at the end 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

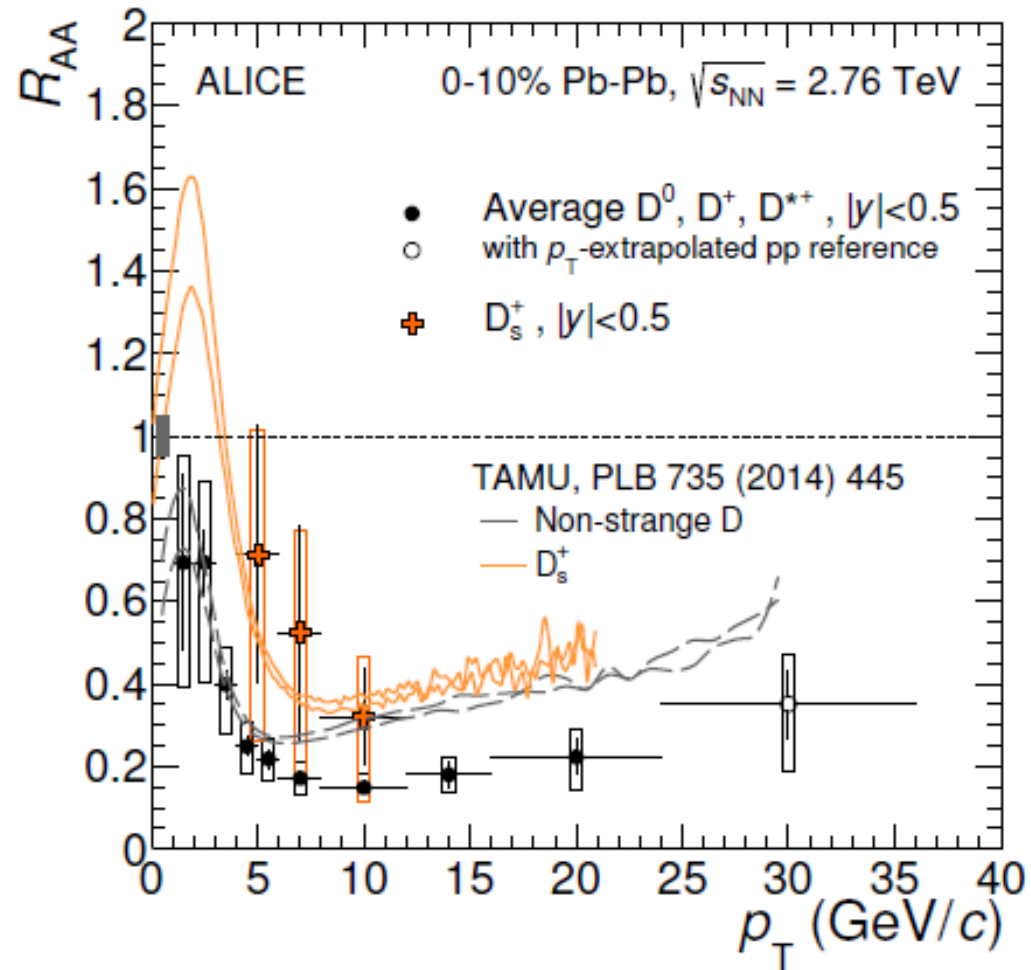


EMMI RRTF : TAMU pQCD x 10



Hadronization

Hadronisation (Ds)



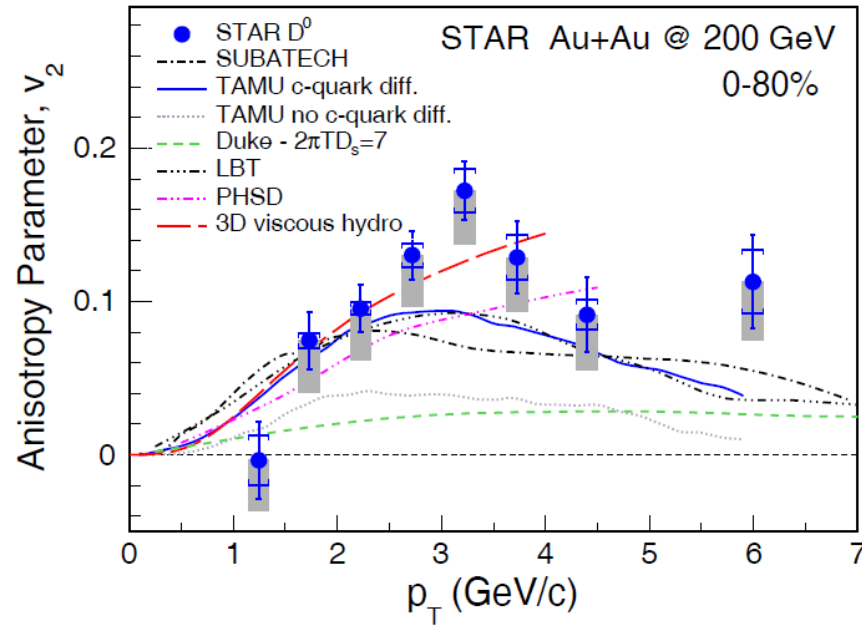
ALICE data for D and Ds mesons (JHEP 1603 (2016) 082) compared with TAMU-model predictions (M- He et al., PLB 735 (2014) 445)

Other constraints

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 »

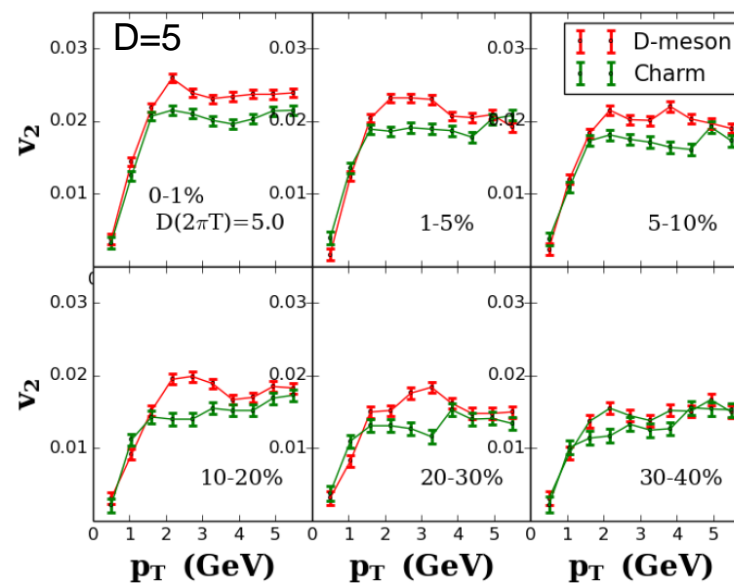
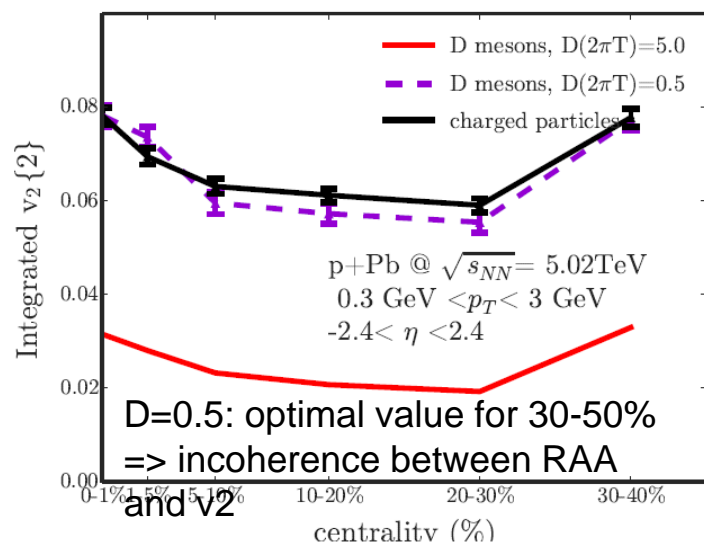
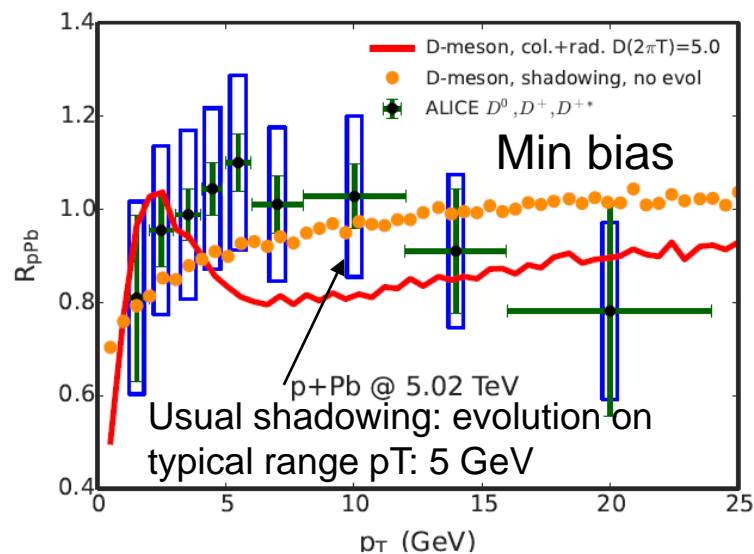
Small systems

p-Pb (Duke)

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

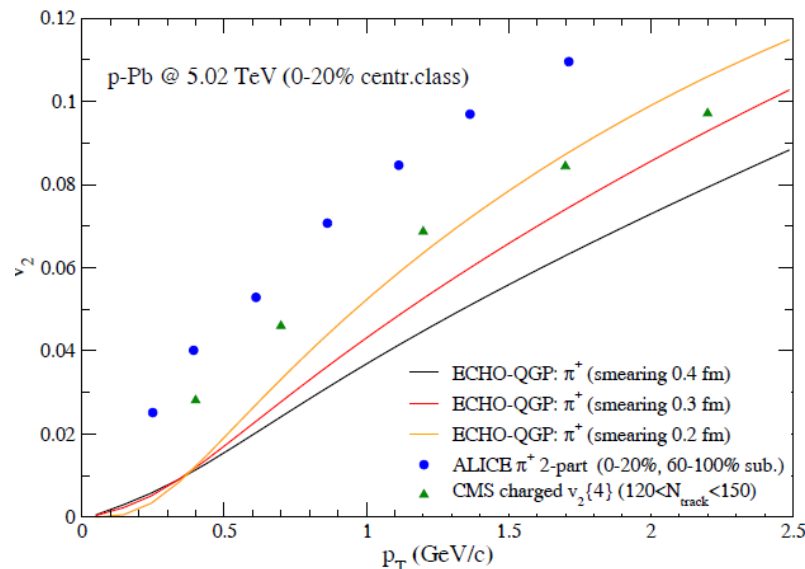
$$\frac{d\vec{p}}{dt} = \underbrace{-\eta_D(p)\vec{p}}_D + \underbrace{\vec{\xi} + \vec{f}_g}_{\hat{q}} \quad D = 4 \frac{T^2}{\hat{q}} \frac{C_A}{C_F}$$

- 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)



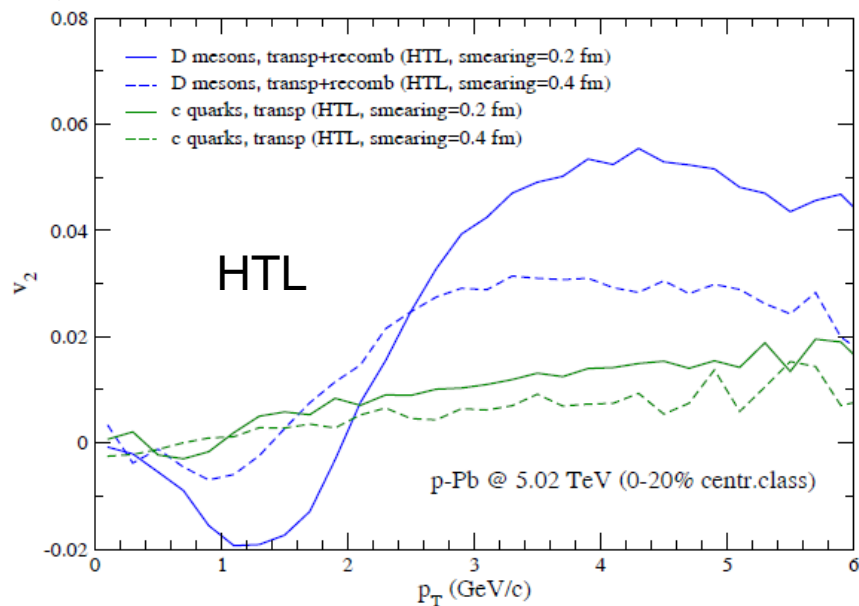
p-Pb (Beraudo et al)

- Arxiv 1512.05186v2: essential role of initial fluctuations (main source of anisotropy) : 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) & IQCD

Major contribution to $v_2(D)$: hadronisation



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

