Heavy quarks: a comparison of different theoretical approaches

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- How can we compare the approaches (-> transport coefficients)?
- Influence of elementary HQ-parton interaction, of QGP expansion and of initial condition.
- What can we conclude presently?

Phys. Rev. C99,014902 (19): Yingru Xu, Steffen A. Bass, Pierre Moreau, Taesoo Song, Marlene Nahrgang, Elena Bratkovskaya, Pol Gossiaux, Jorg Aichelin, Shanshan Cao, Vincenzo Greco, Gabriele Coci, Klaus Werner

Phys. Rev. C99,054907 (19): Shanshan Cao, Gabriele Coci , Santosh Kumar Das, Weiyao Ke, Shuai Y.F. Liu, Salvatore Plumari, Taesoo Song, Yingru Xu, Jörg Aichelin, Steffen Bass, Elena Bratkovskaya, Xing Dong, Pol Bernard Gossiaux, Vincenzo Greco, Min He, Marlene Nahrgang, Ralf Rapp, Francesco Scardina, Xin-Nian Wang

At first glance HQs are an ideal probe for a tomography of the QGP

initially created in a hard process → accessible to pQCD calculations

high p_T HQs traverse the QGP without coming to an equilibrium with the QGP
→ preserve memory on the trajectory in the QGP
→ sensitive to the properties of the QGP during the expansion (and not only to its final state)

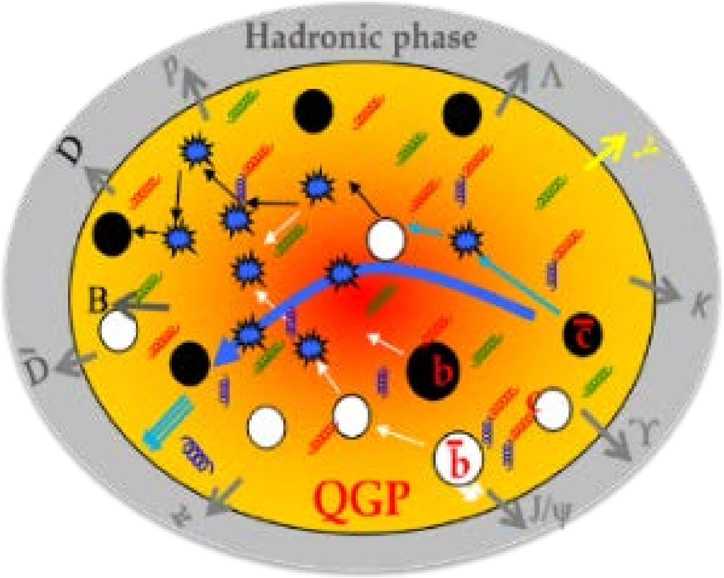
HQs keep their identity while traversing the QGP (in contradistinction to light quark jets)

HQs interact strongly with the QGP (in contradistinction to photons)

HQs are heavy and theory does not predict large changes of their mass in a QGP

But –as usual – the devil is in the details

The details one has to know to explore the information carried by HQs



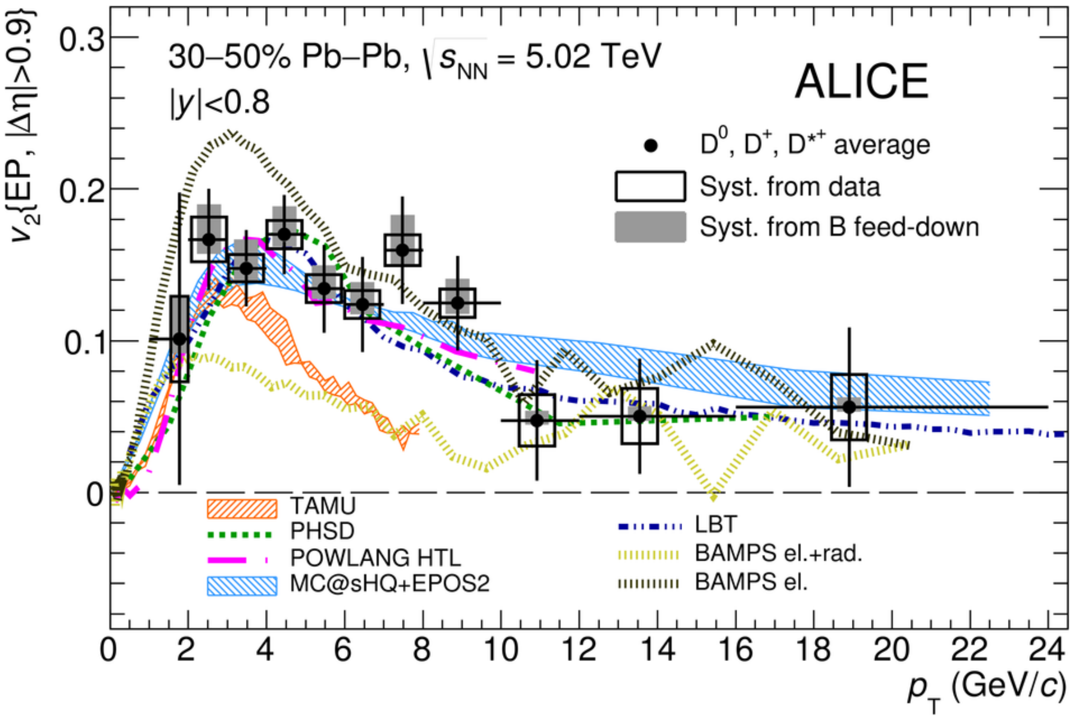
- (p,x) distribution of the hard collisions which produce HQ (FONLL, Glauber)
- Initial (p,x) distribution of the QGP (EPOS, Trento, PHSD, Glasma)
- Formation time of heavy quarks and the QGP (when does the interactions start?)
- Expansion of the QGP ((viscous) hydrodynamics, PHSD)
- Elementary interaction between HQ and the QGP
- Hadronization of HQs to heavy hadrons
- Hadronic scattering of heavy hadrons

In addition there is the question which time evolution equations are appropriate to describe the heavy quarks which travers the QGP. Two presently used:

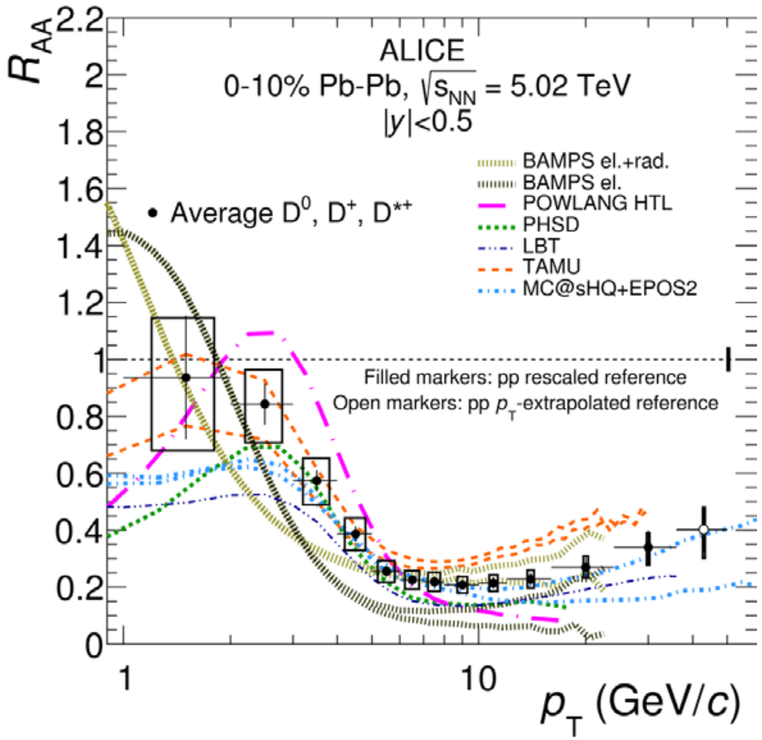
- ❑ Fokker-Planck equation
- ❑ Boltzmann equation

This I cannot cover in this talk

Most of the models reproduce quite reasonable the experimental results !!



Phys. Rev. Lett. 120 (2018)102301



Phys. Rev. C 96 (2017) 034904

More difficult is to answer the question:

What tells us this agreement?

What can we take home?

Participants:

Catania (Santosh Das)
Duke (Yingrou Xu)
Frankfurt (PHSD) (Taesoo Song)
CCNU-LBNL (Shanshan Cao)
Nantes (PB. Gossiaux, M. Nahrgang)
TAMU (Min He)

Some key features of the participating programs:

	Catania	Duke	Frankfurt(PHSD)	LBL	Nantes	TAMU
Initial HQ (p)	FONLL	FONLL	pQCD	pQCD	FONLL	
Initial HQ (x)	binary coll.	binaryy coll.	binary coll.	binary coll.		binary coll.
Initial QGP	Glauber	Trento	Lund		EPOS	
QGP	Boltzm.	Vishnu	Boltzm.	Vishnu	EPOS	2d ideal hydro
partons	mass	m=0	m(T)	m=0	m=0	m=0
formation time QGP	0.3 fm/c	0.6 fm/c	0.6 fm/c (early coll.)	0.6 fm/c	0.3 fm/c	0.4 fm/c
formation time HQ	1/(2m)	0	0	0	0.	0.4 fm/c
interactions in between	HQ-glasma	no	HQ-preformed plasma	no		no

GOAL: To study how the different model ingredients influence the final result by replacing the specific ingredient of a model by a common standard

- for the expansion of the QGP
- for the elementary interaction between QGP partons and HQs
- for the initial condition

How to compare the different approaches?

A Boltzmann equation can be (under certain conditions) converted into a Fokker-Planck equation which can be solved by a stochastic differential equation, the Langevin eq.

→ Langevin eq. for the heavy quarks is the lowest common denominator of all approaches

$$
\begin{aligned}
dx_i &= \frac{p_i}{E} dt \\
dp_i &= -\eta_D(\vec{p}, T)\; p_i\; dt + \xi_i dt
\end{aligned}
$$

ξ_i = Gaussian random variable

$$< \xi_i(t) \xi_j(t') >= (\kappa_T(\vec{p}, T)\; p_{ij}^T + \kappa_{||}(\vec{p}, T)\; p_{ij}^{||}) \delta(t - t')$$

$$< \xi_i >= 0$$

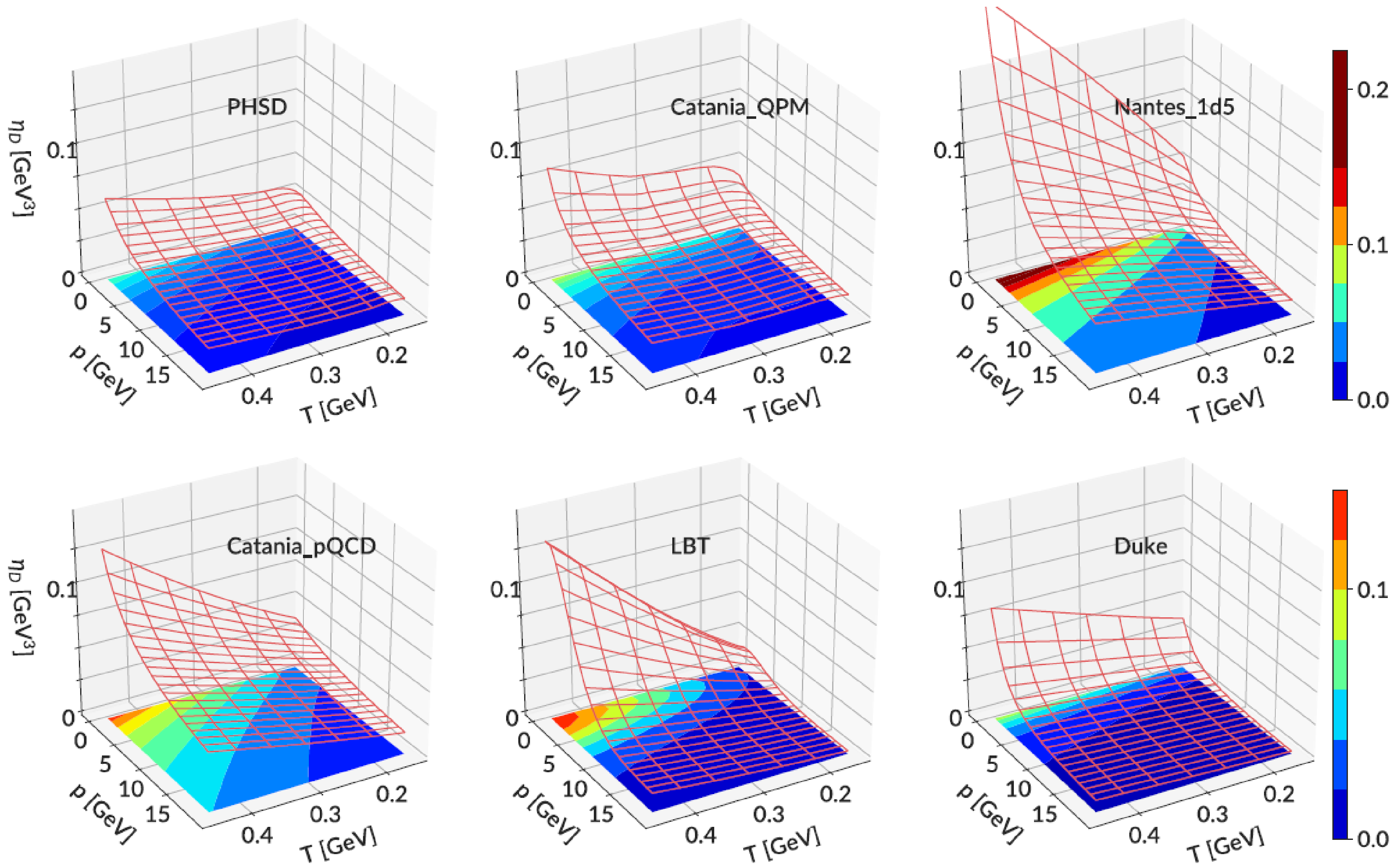
$$p_{ij}^T = \delta_{ij} - \frac{p_i p_j}{p^2} \; ; \; p_{ij}^{||} = \frac{p_i p_j}{p^2}$$

The whole dynamics is there casted into 3 momentum and temperature dependent functions which describe the interaction between HQ and the QGP

η_D = drag coefficient
κ = diffusion coefficients (transversal and longitudinal)

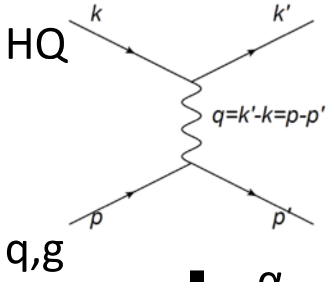
For every transport approach these coefficients, which contain the elementary interaction between heavy quarks and partons, have been calculated and made available for the comparison.

The drag coefficient η_D of the different models (standard version to describe the data)



All drag coefficients η_D increase with p and T but absolute values differ by large factors

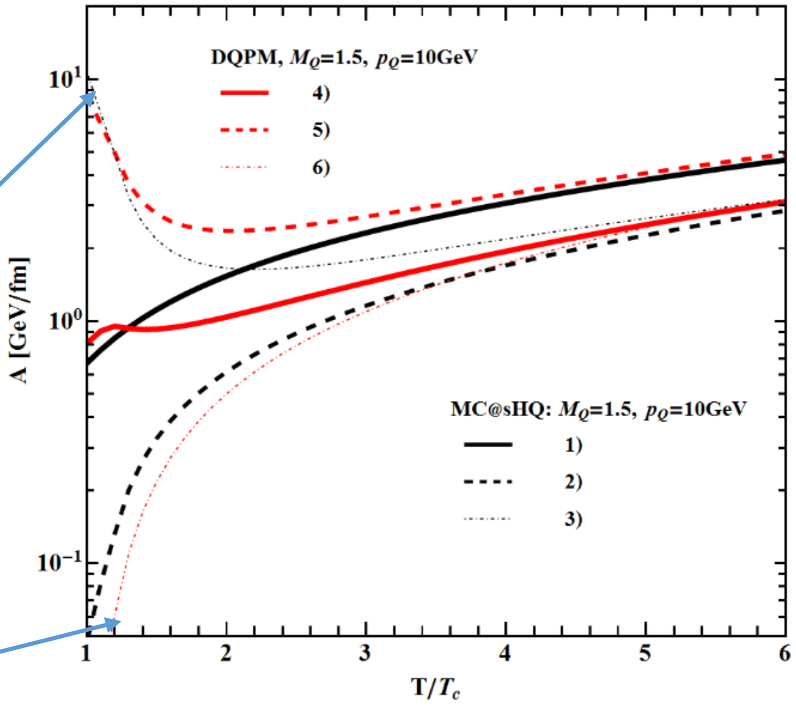
How can this happen if the if the cross sections q(g)Q -> q(g)Q are calculated in leading order pQCD?



Take a simple t-channel elastic scattering
For the calculation one has to fix:

- α_S , α_S (T), α_S (Q^2)
- masses of the incoming/outgoing QGP partons
- mass of the exchanged gluons (m_D)

		coupling	mass in gluon propagator	mass in external legs
Nantes	1)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
	2)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = m_{q,g}^{DQPM}$
	3)	$\alpha(T)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
Frankfurt PHSD	4)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$
	5)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = 0$
	6)	$\alpha(Q^2)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$



H. Berrehrah et al. 1604.02343,
T. Song et al. PRC 92 (2015), PRC 93 (2016)

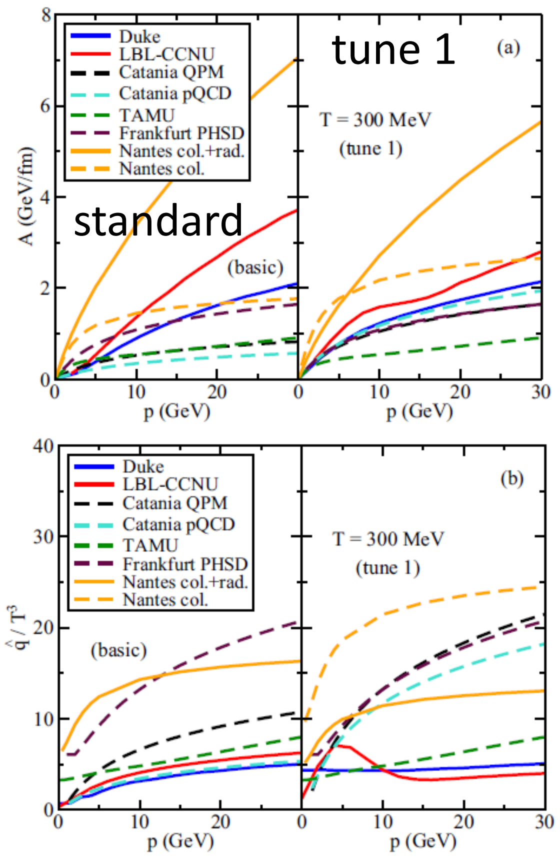
Different choices chance the drag A for p_{HQ} = 10 GeV/c by
a factor of 100 close to T_C
a factor of 2 for 4 T_C

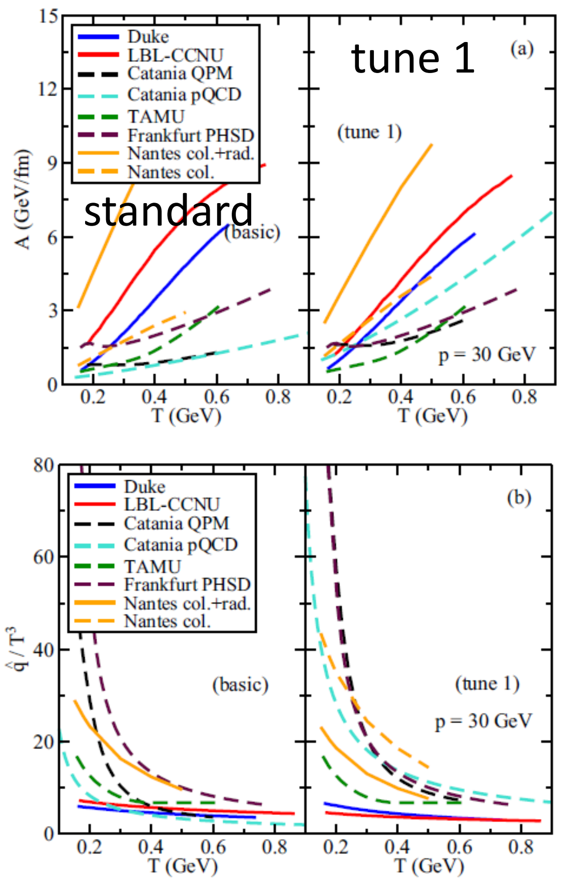
First step for the comparison:

tune the models for best agreement for R_{AA} in PbPb (2.76 ATeV) 2 GeV/c < p_T < 15 GeV/c (tune 1)

$$A = dp_L/dt, \quad \hat{q} = dp_T^2/dt$$ (for elastic collisions only)

standard version



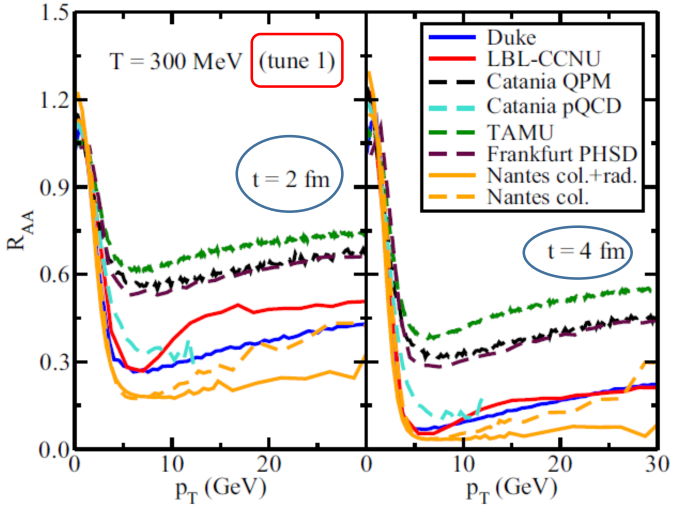


Solid lines elast coll + rad
Dashed lines elast coll

tune 1 does not really narrow the differences

Second step: R_{AA} of charm quarks in a brick

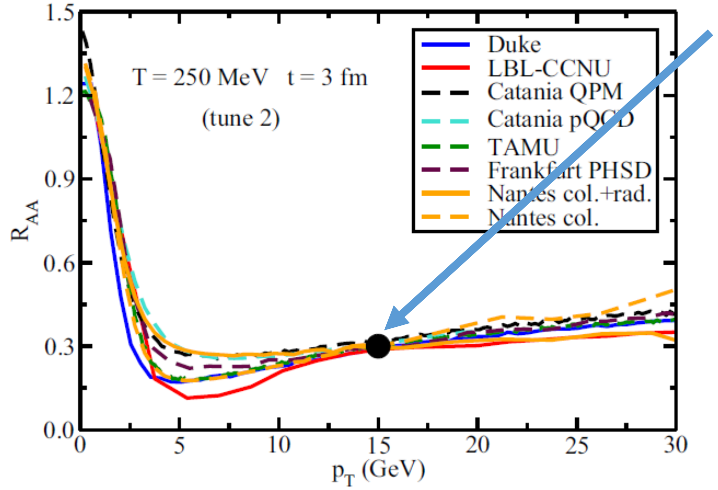
R_{AA} in static brick after 2 and 4 fm/c

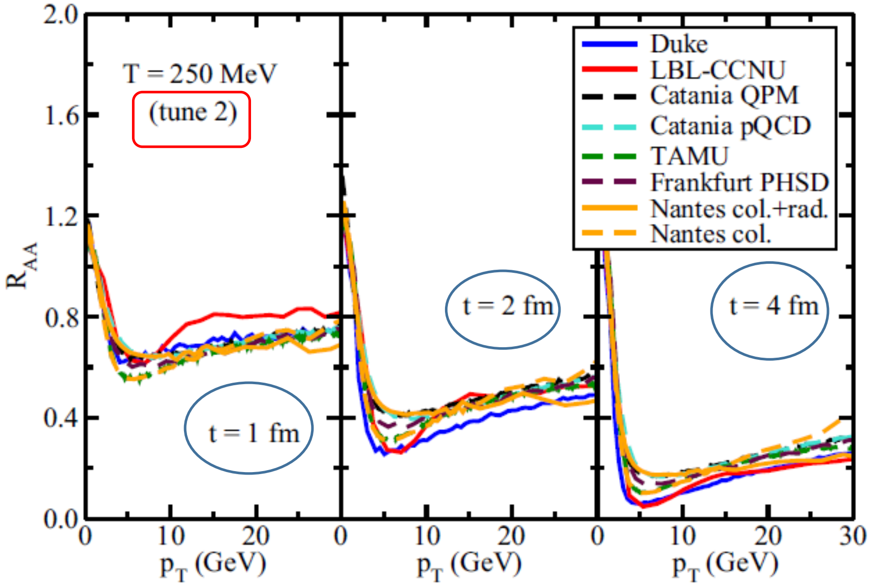


Models do what expected
Large A → small R_{AA}

But differences of more than a factor of two remain

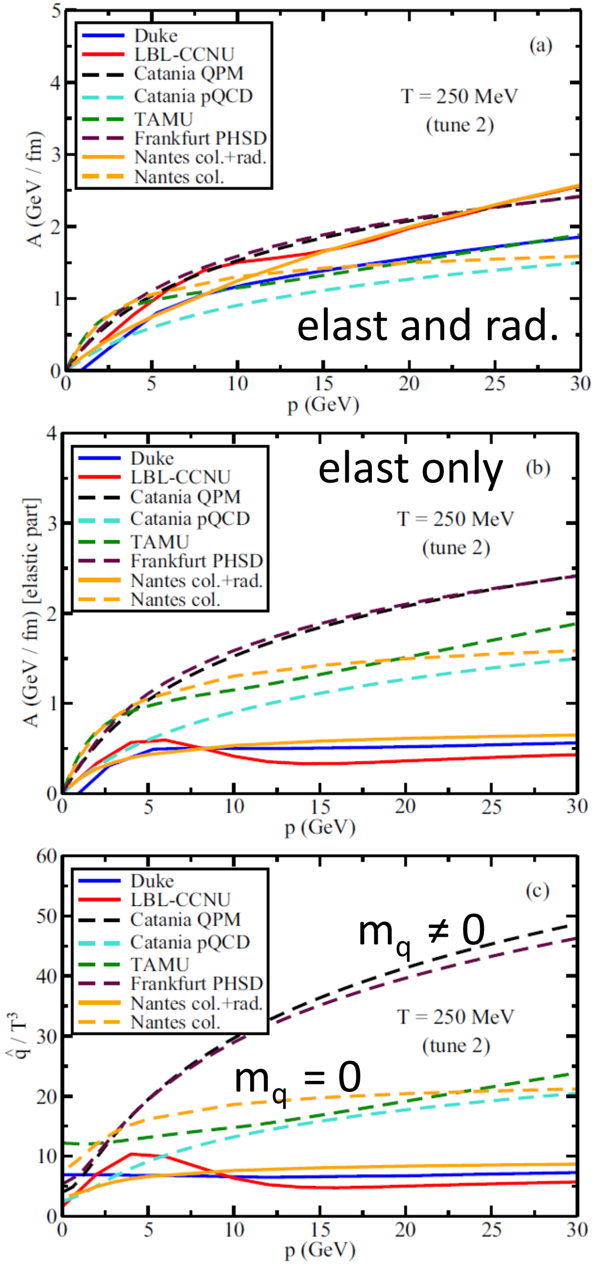
Tune 2: K factors that all models agree for:
T=250 MeV
p=15 GeV/c
at t= 3 fm/c





Narrows down the differences in R_{AA} between the models also at other times.

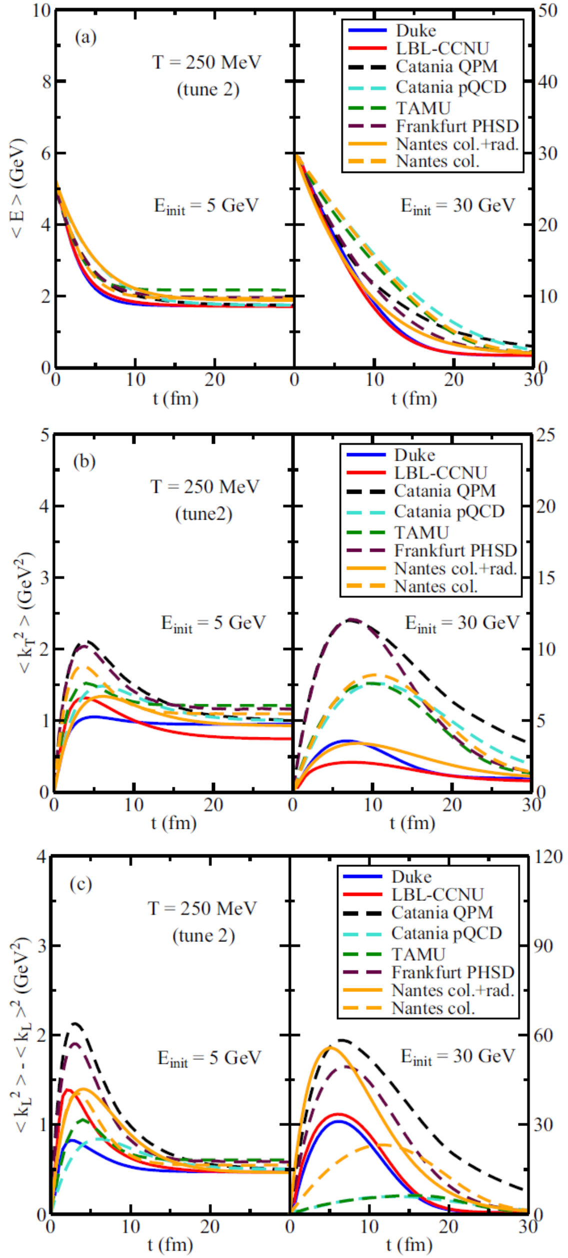
But: does not reduces substantially the difference of drag and diffusion coefficients



drag

drag

qhat



$<E(t)>$

$<k_T^2>$

$<k_L^2> - <k_T^2>$

Conclusions of the brick wall comparison of elementary HQ-parton interact.:

Although all models are internally consistent (checked but not reported here)

different description of the interaction of the HQ with the QGP partons
yield different results for the transport coefficients:

- they vary by up to a factor 2
- this variation is temperature and momentum dependent
- and leads to different energy loss and p_T broadening even in a brick

the difference between different models cannot be removed by a const K-factor
to agree at one common benchmark.

Some of the origins (but not all) of the difference of drag and diffusion coefficients could be identified:

- finite parton masses (to reproduce the lattice Eq. of State)
- radiation in addition to elastic collisions

We have to better understand the interaction between HQ and the QGP. What may help:

- lattice calculations of transport coefficients
- new and better experimental data (correlations)
- modelling of (high multiplicity) small systems (pp)

Can lattice QCD calculation presently help us to fix the transport coefficients?

Lattice:

Spatial diffusion coefficient at p=0 is defined via the spectral function $\sigma(\omega,\vec{p})$ as

$$D_s(\vec{p}=0) = lim(\omega \to 0)\frac{\sigma(\omega,\vec{p}=0)}{\omega\chi_q\pi}$$

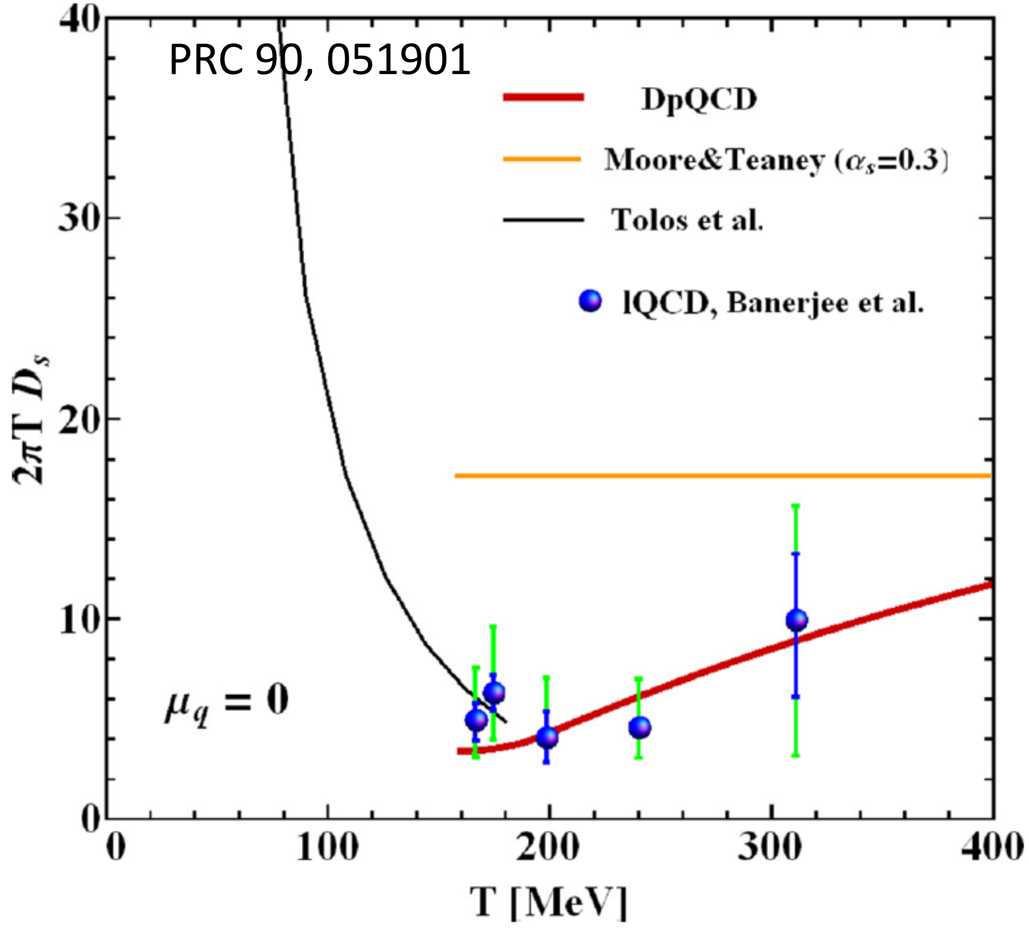
where the spectral function in obtained via the current-current correlator by

$$G(\tau,T) = \int_0^\infty \frac{d\omega}{2\pi}\,\sigma(\omega,T)\;K(\tau,\omega,T)$$

Problems/approximations:

- Euclidian time calculation
- Quenched
- No continuum extrapolation

Does not cover the dynamical range needed in heavy in collisions



Dynamical models:

$$D_s = lim(\vec{p} \to 0)\frac{T}{M\eta_D}$$

η_D = A/p ; A(p,T) = drag force (PRC 71, 064904 PRC 90, 064906)

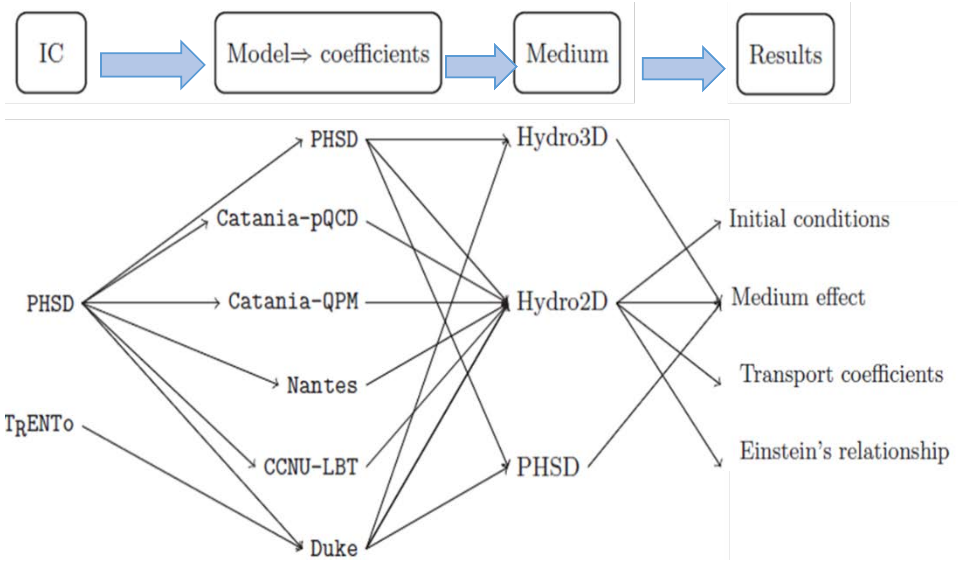
Agreement quite reasonable

Since all models describe the data but the transport coefficients are quite different:
there must be other ingredients in the transport model which compensate for the different transport coefficients.

Possible candidates:

- Initial condition
- time evolution of the QGP
- hadronization

For this a second round of comparisons have been performed



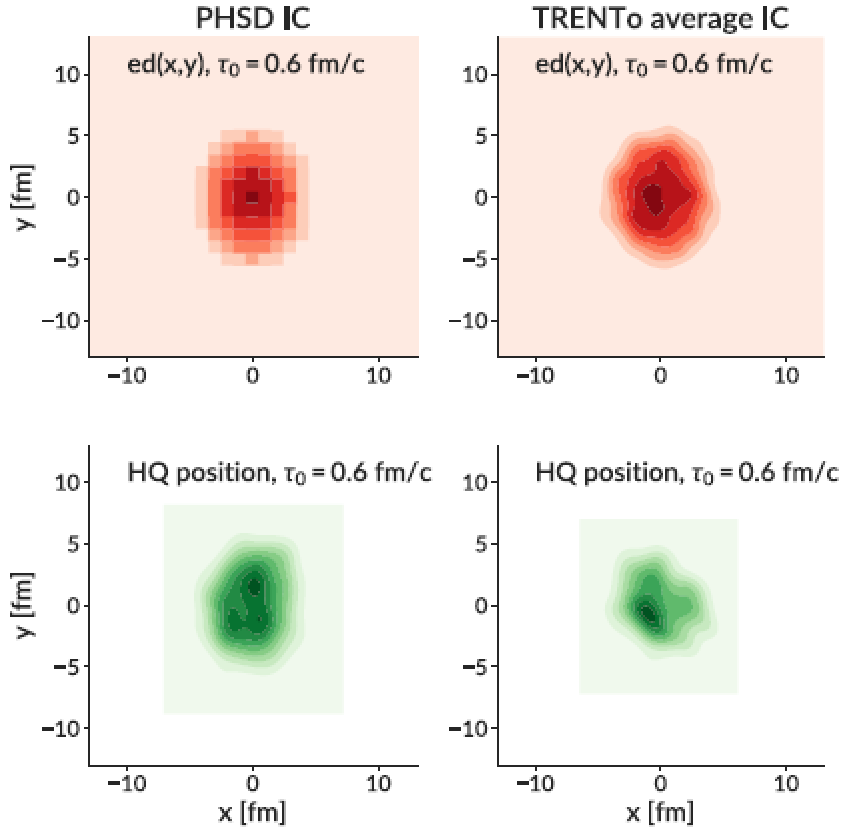
Using the transport coefficients in a Langevin equation we can combine different

- Initial conditions
- QGP evolutions
- HQ-QGP interactions

and explore the cosequences on observables

Influence of the initial condition: here PHSD versus averaged Trento initial condition

RHIC $\sqrt{s}$ =200 AGeV , b= 6fm

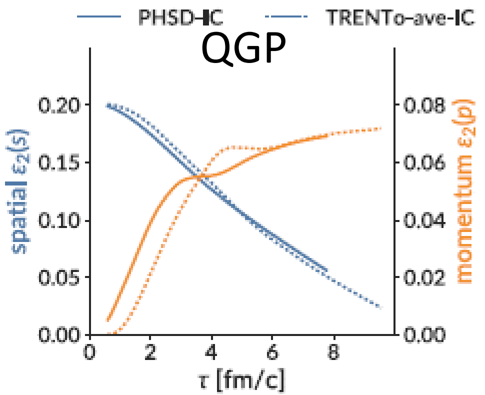


HQ: FONLL

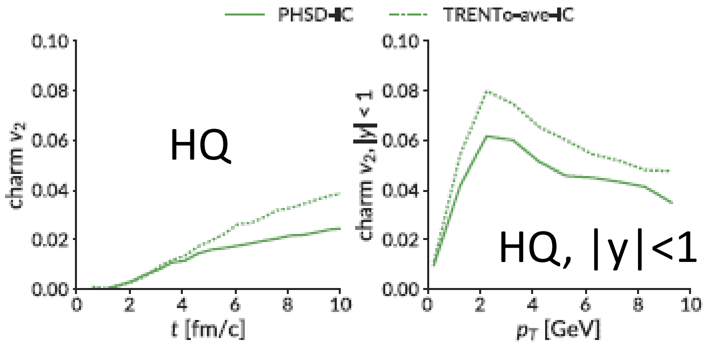
QGP formation time = 0.6 fm/c

QGP evolution: VISHNU

HQ-QGP Duke transport coeff



Spatial and momentum eccentricity little difference



V_2 15-20% difference (v_2 of QGP very similar)

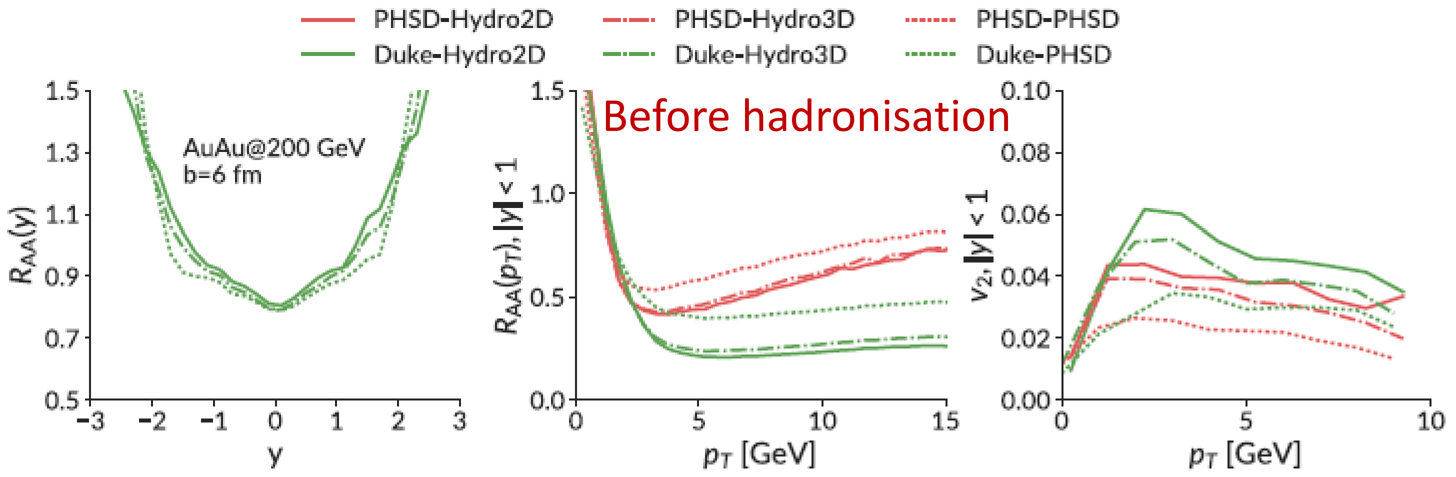
Different initial conditions lead to different values of the HQ observables

Influence of the QGP transport I:

Same transport coeff. , different QGP time evolution (Duke,PHSD, PHSD initial condition)

All identical besides

- transport coefficients
- Time evolution of the QGP



Duke transport coeff
Frankfurt (PHSD) transport coeff

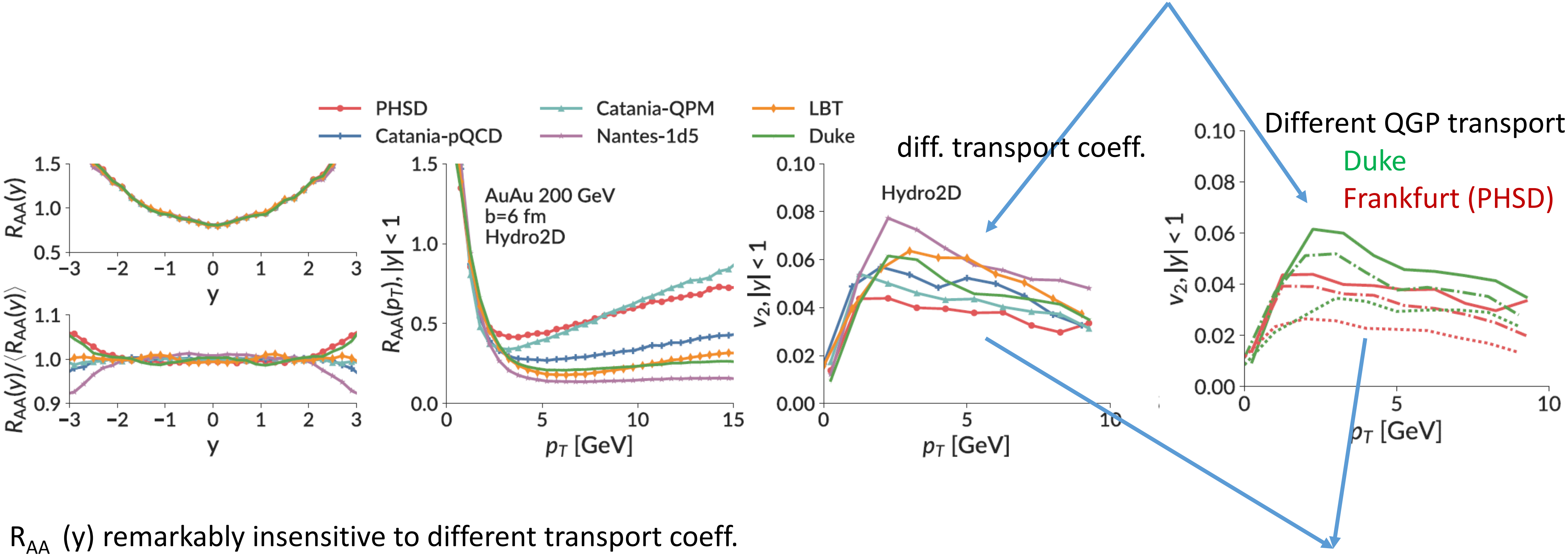
- Rapidity distribution little affected
- 2d hydro and 3d hydro give similar results for R_{AA} but a visible difference for v_2 at $|y|<1$
- v_2 (Hydro) and v_2 (PHSD) differ by 20%

Influence of the QGP transport II:

Same QGP evolution, different transport coeff.

(Vishnu, same initial condition: PHSD)

For comparison:



R_{AA} (y) remarkably insensitive to different transport coeff.

R_{AA} (p_T) shows for large p_T large differences (already expected from brick wall study)

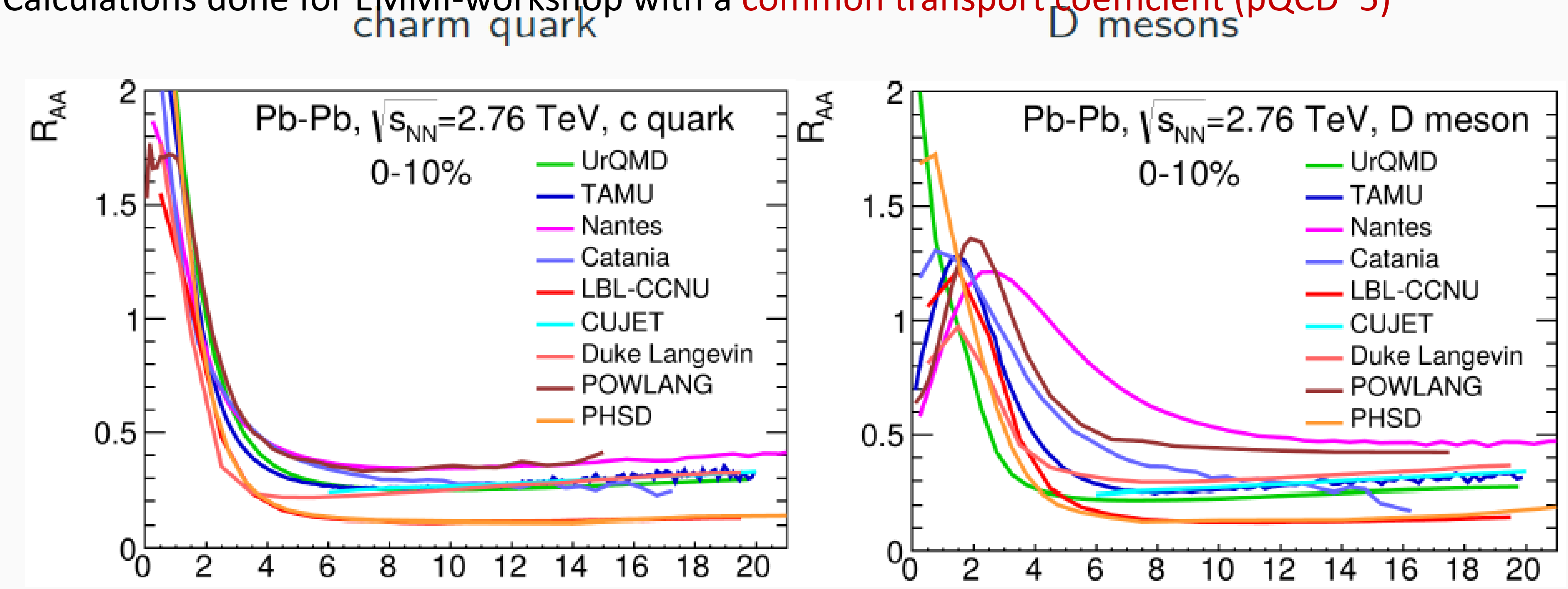
v_2 30% difference between for the transport coefficients of different codes

Both modifications of the same order

Influence of the hadronization on final observables has just started:

Different hadronization mechanisms yield different v_2

Calculations done for EMMI-workshop with a common transport coefficient (pQCD*5)



EMMI
NPA 979, 21

- Common fall off of $v_2\,(p_T)$ of HQs transformed into a variety of different curves.
- Most of the approaches create a maximum of $v_2\,(p_T)$ by hadronization (exception PHSD and UrQMD)

Conclusions

Analyzing models for the evolution of the heavy quark distribution which agree quite well with experiments we see:

HQ observables are a very useful probe to study the QGP properties

they retain information from the initial condition up to the last stage of the HI collision

they are sensitive to the HQ-parton interaction

they are sensitive to the expansion of the QGP

but

with the present data it is impossible to disentangle the different processes which are encoded in the HQ distr.
different assumptions on QGP expansion, initial condition, HQ-QGP interactions vary the results by up to 50%
but compensate each other in the numerical different programs

Our studies allowed to see the influence of different assumptions about the sub-processes
all influence the final distribution on the level of 20-50%

Two major factors for differences could be identified

mass of the QGP partons

the inclusion of radiative energy loss.

others may still be hidden in the transport coefficients.

More data are needed and a lot of work has to be invested to nail down the physics encoded in the HQ observables