

# ISMD 2017 – Tlaxcala City (Mexico)

Heavy flavors in quark gluon plasma: group chasing of the transport coefficients



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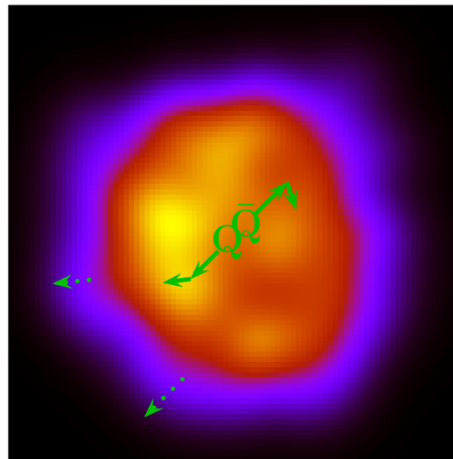
Special thanks to Shanshan CAO and Marlene NAHRGANG

# Why heavy flavors in A-A ?

1. Produced early, number conserved through time evolution (even at LHC)  $\Rightarrow$  signature (hard probes) of early (hot) phase
2. Weakly affected by late time evolution (heavy, colour transparency)
3. *Strongly affected by the QGP phase ... probe the QGP strength in a way that is arguably under better control from the theory view point*
4. Allows *some* pQCD calculations for the production and annihilation,...
5. Clear decay channel of quarkonia in leptons

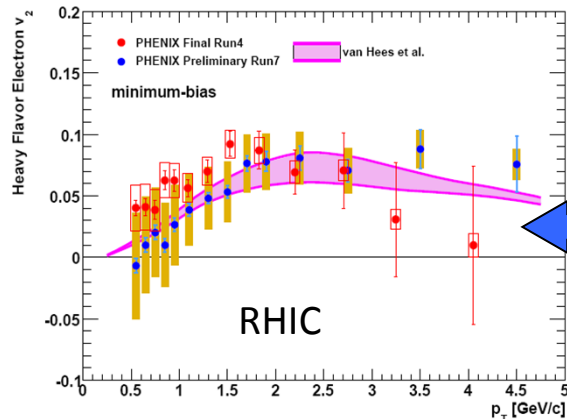
See f.i talk by  
R. Rapp

Seems to be an ideal alternate probe of dense matter as compared to light sector...



# Why open heavy flavors in A-A ?

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



The Trilogy:  $\equiv$  densitometer

Thermalisation & collectivity

$\equiv$  barometer

Quenching (leading hadron)

HQ

Hidden c & b

$\equiv$  thermometer

Quarkonia suppression and Dimuons product; heavy Q thermal production

HQ are imbedded in expanding matter  $\Rightarrow$  they participate to collective motion and gain elliptic flow ( $v_2$ : azimuthal asymmetry) at finite b

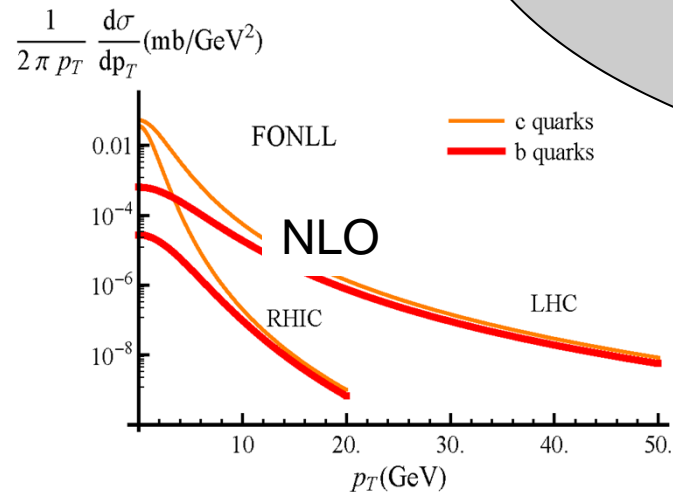
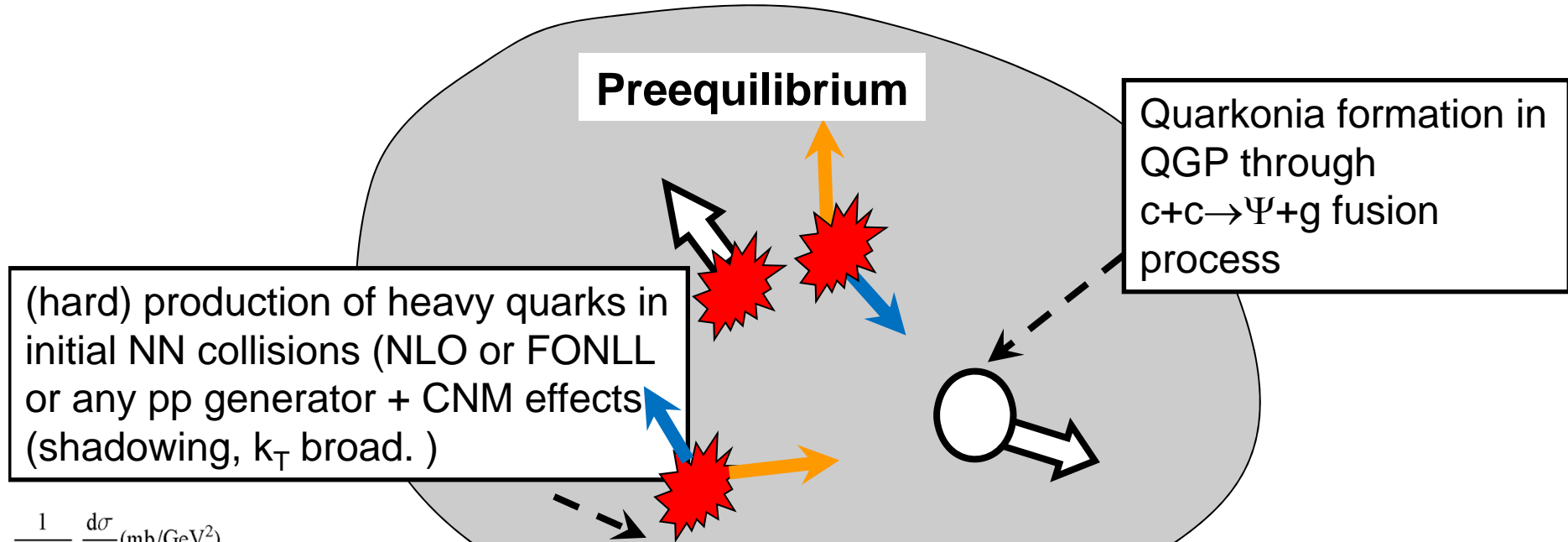
## Challenges:

- Description of HQ E-loss / equilibration from fundamental theory
- Joint  $v_2$ - $R_{AA}$  explanation could help to better constrain free parameters...
- Dual game “probe the medium evolution” vs “understands the force”

# Paradigm of HF evolution in URHIC

For low and intermediate  $p_T$

No force on HQ before thermalization of QGP

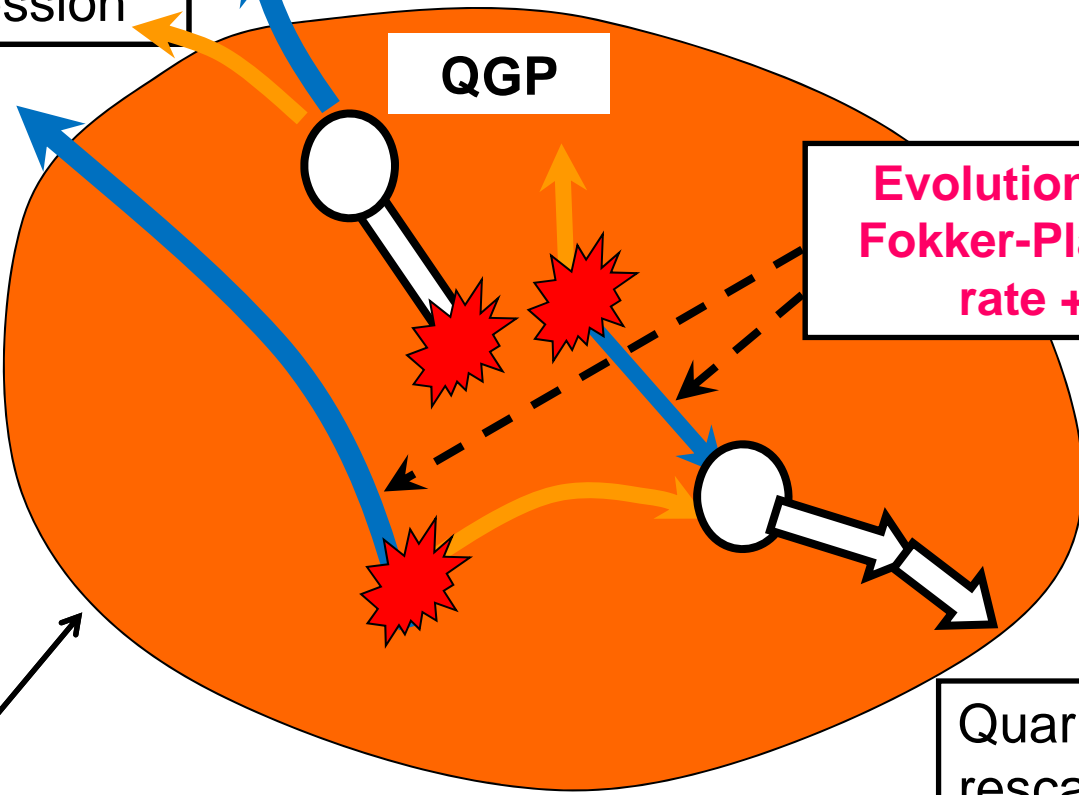


# Paradigm of HF evolution in URHIC

For low and intermediate  $p_T$

**Bulk Evolution: hydro or cascade (Boltzmann,...)**

Quarkonia suppression

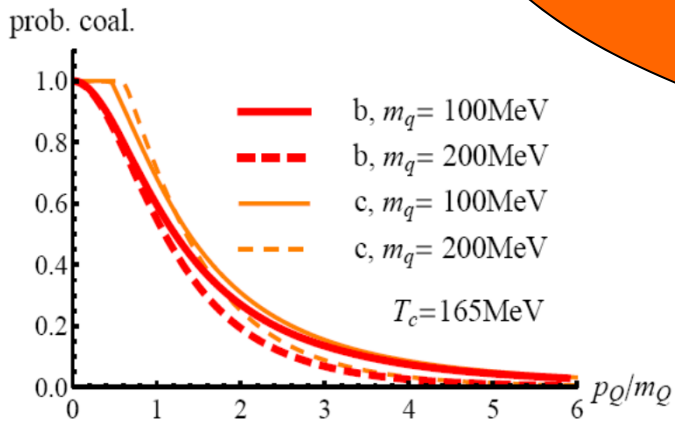
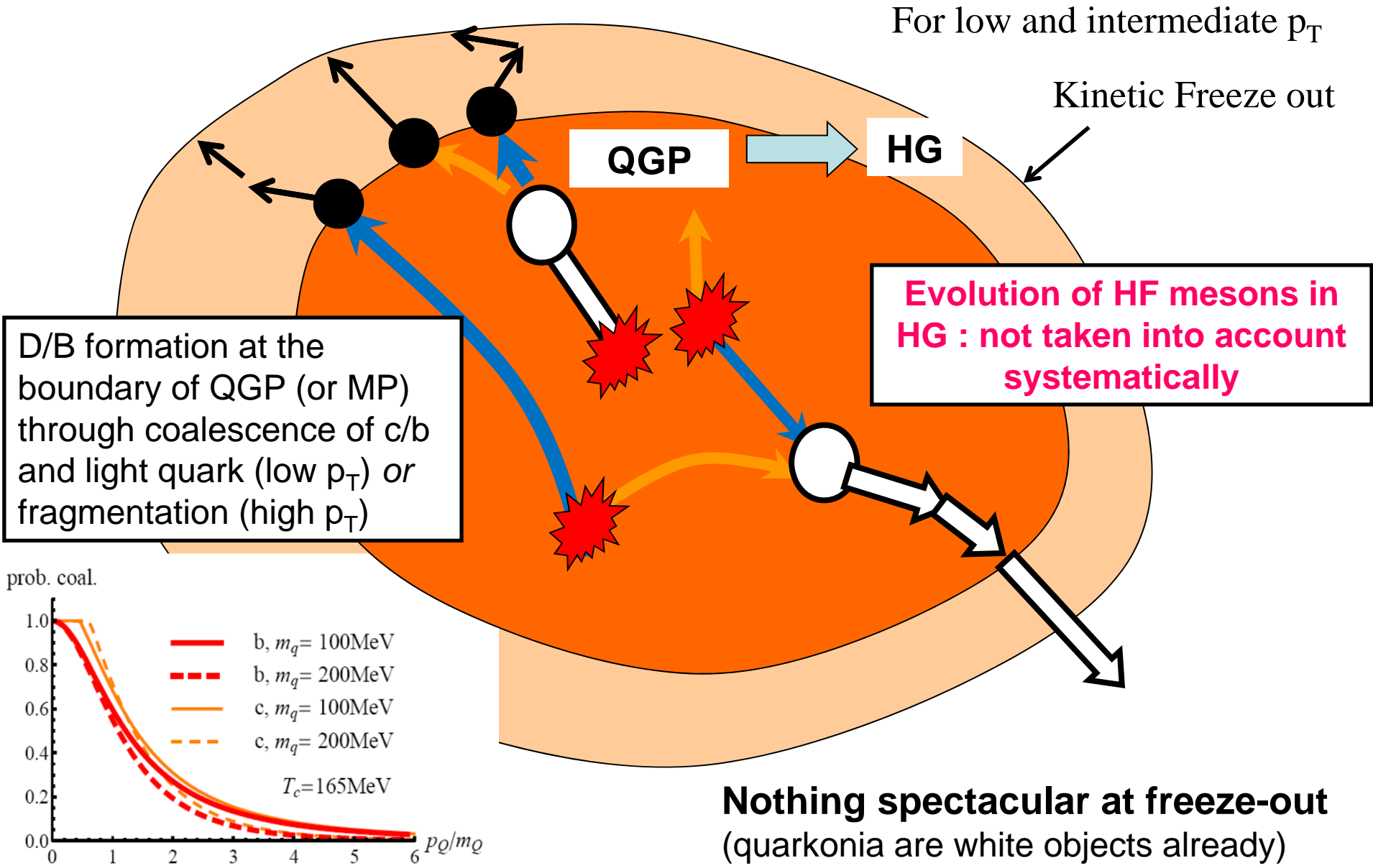


**Evolution of HQ in bulk : Fokker-Planck or reaction rate + Boltzmann**

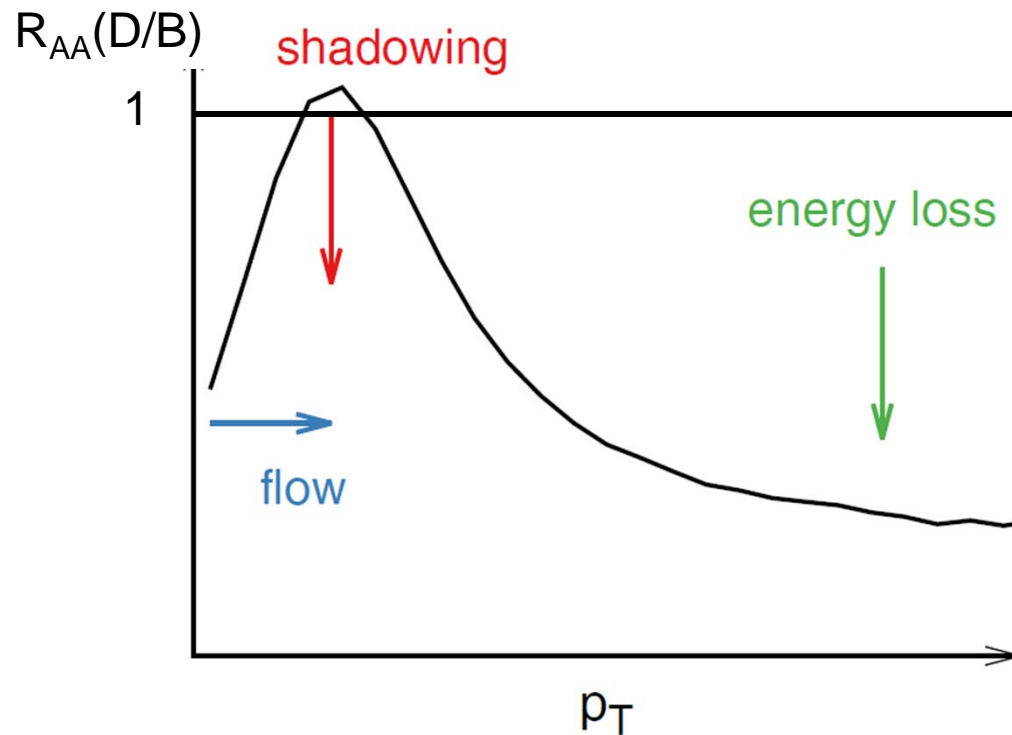
Quarkonia rescattering

Somehow arbitrary  $T_c$  between QGP and hadronic phase

# Paradigm of HF evolution in URHIC



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



**Flow bump:** due to

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

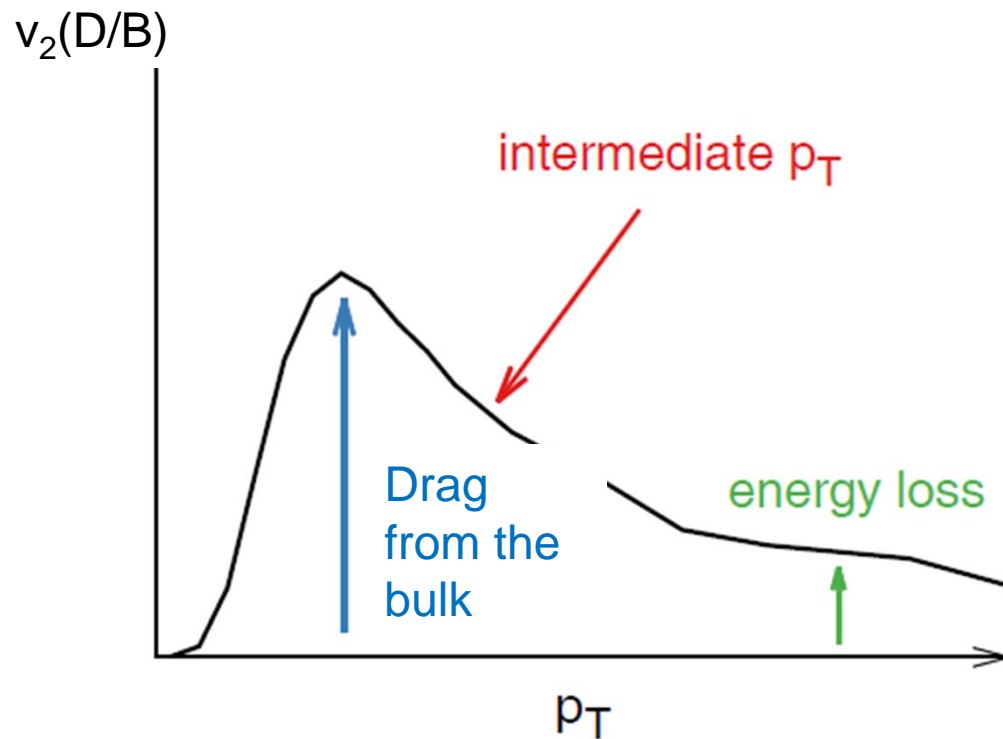
**shadowing:** due to *initial state nuclear effects*

**energy loss:** due to

- *elastic and inelastic scatterings*
- *opacity of the medium*
- *coherence important at larger  $p_T$*

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

# 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.

## 2 Important remarks:

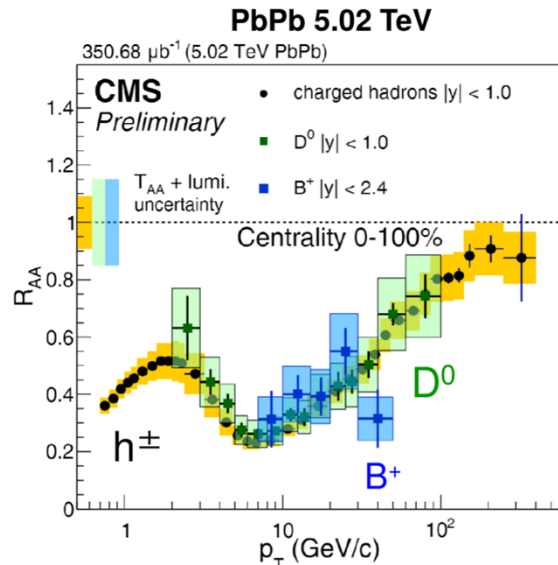
- Any energy loss model, even the roughest one, will generate these typical structures in the  $R_{AA}$  and the  $v_2$ . Getting a correct **quantitative** agreement is much more involved.
- Quantitative predictions also depends on numerous extra ingredients



# Setting the scene: E-Loss and thermalization

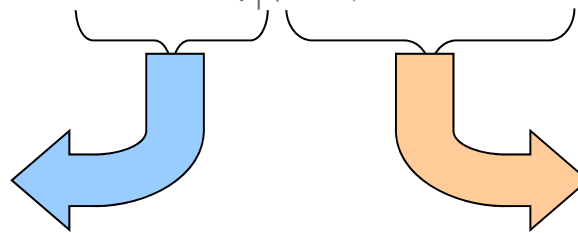
$$(init) P_T \approx m_Q$$

- Bulk part of Q production
- E gain becomes probable
- HQ scatter and can thermalize with the medium
- very  $\neq$  from light quarks
- *Dominated by collisional processes and diffusion*
- Non perturbative effect (small momentum transfert, coalescence with light quark)
- 1 dominant transport parameter



$$(init) P_T \gg m_Q$$

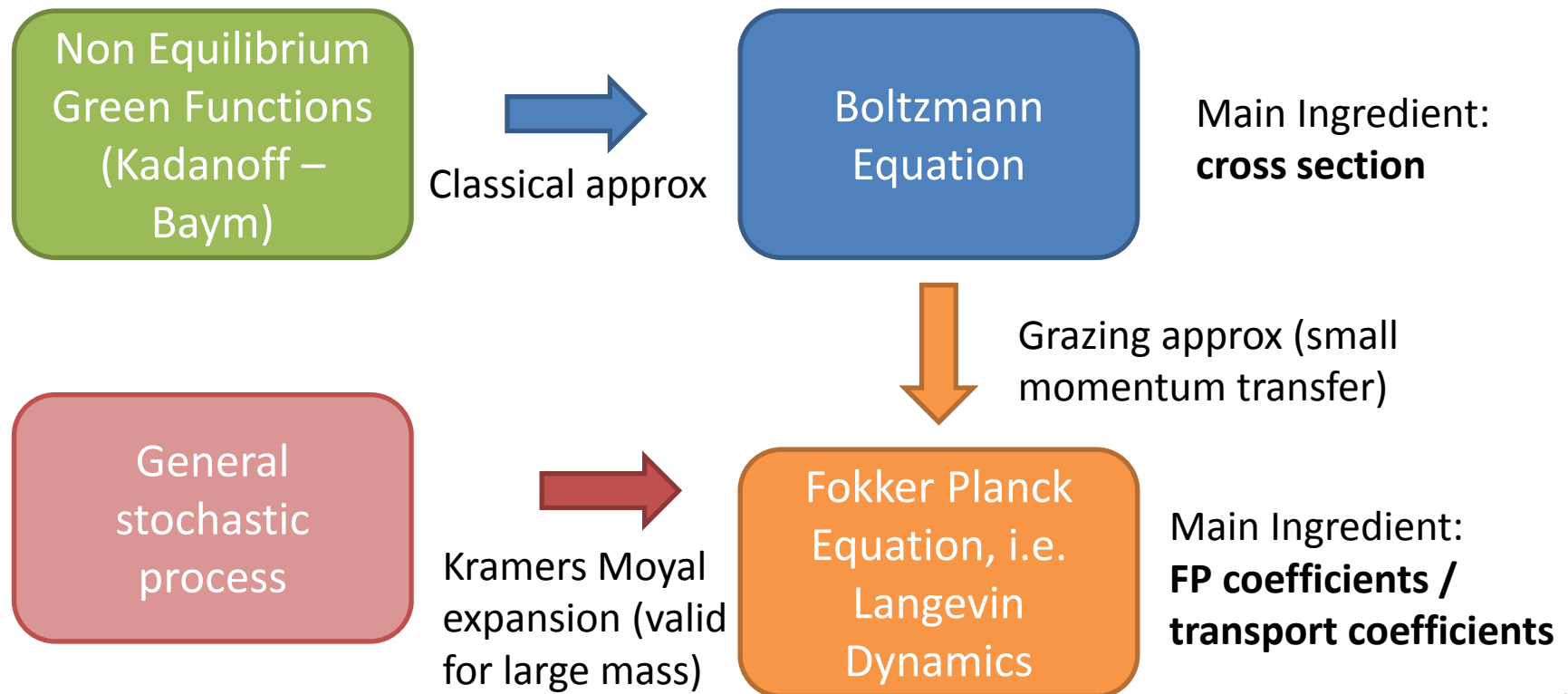
- Rare processes
- Mostly Energy loss
- HQ go on nearly straight lines and probe the opacity of matter. Little thermalization
- *~ light quarks (s.e.p.)*
- *Coherent radiative + collisional processes*
- Good test of pQCD... Theory at work (a priori)
- Several transport coefficients implied ( $dE/dx$ ,  $B_T$ ,...)



# Various approaches to modeling

## 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



# Various approaches to modeling: Langevin Dynamics

- FP equation for the HQ distribution

$$\frac{\partial}{\partial t} f_Q(\mathbf{p}, t) = \nabla_i [A^i f_Q(\mathbf{p}, t) + \nabla_j (B_{ij} f_Q(\mathbf{p}, t))]$$

with (in local isotropic medium):

$$A^i(\mathbf{p}, T) = \underbrace{\eta(p, T)}_{\text{Friction (drag) coefficient; relaxation rate}} p^i \quad \text{and}$$

Friction (drag) coefficient; relaxation rate

Longitudinal and transverse projectors

$$\hat{B} = B_1 \hat{P}_L + B_0 \hat{P}_T$$

Longitudinal and transverse diffusion coefficients

- $\Leftrightarrow$  Langevin Dynamics for each individual HQ:  $\frac{d\mathbf{p}}{dt} = -\eta(p)\mathbf{p} + \hat{\xi}$

with  $\langle \xi_i(t) \xi_j(t') \rangle = 2B_{ij} \delta(t - t')$

- In most implementations: Einstein relation imposed in order to obtain asymptotic Boltzmann – Jüttner distributions :

$$B_1 (= B_0) = \eta E_Q T \quad (\text{in post point Ito; no systematic prescription})$$

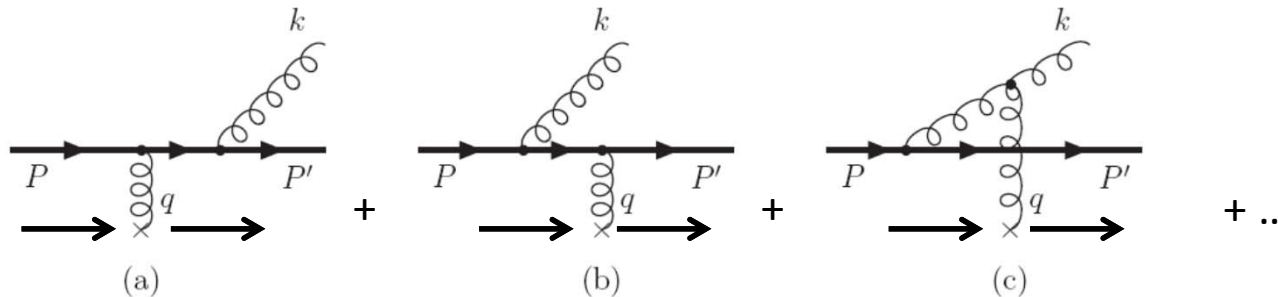
# pQCD inspired models (f.i. Nantes)

## Collisional component

- One-gluon exchange model: reduced IR regulator  $\lambda m_D^2$  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

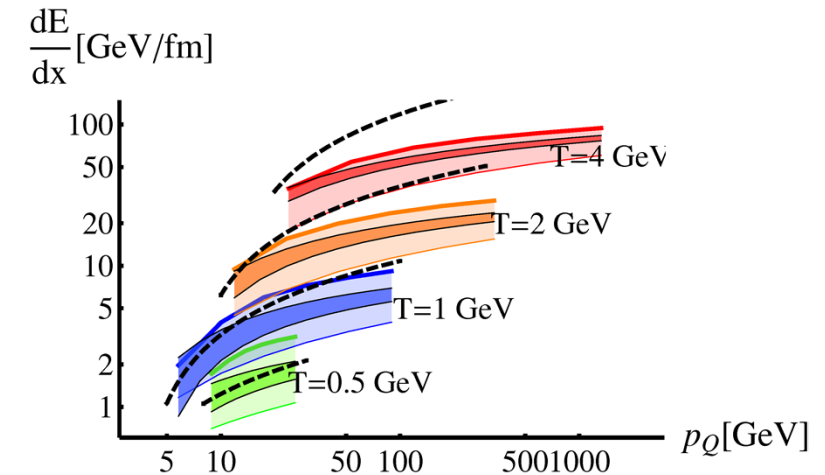


- Extension of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass  $m_Q$  distribution of induced gluon radiation per collision ( $\Delta E_{\text{rad}} \propto E L$ ):

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

- LPM effect for moderate gluon energy

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



# 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)

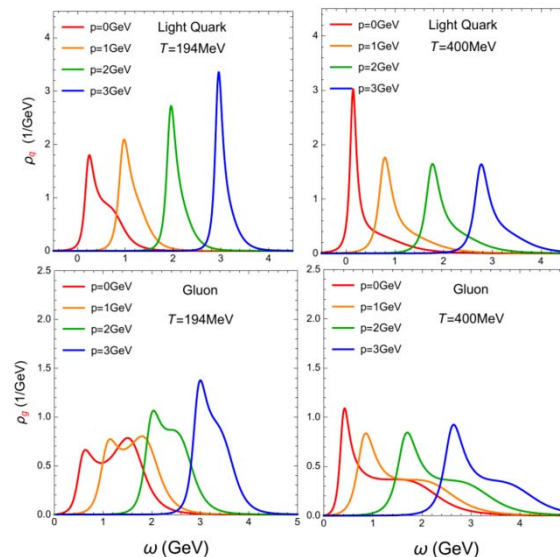
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

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

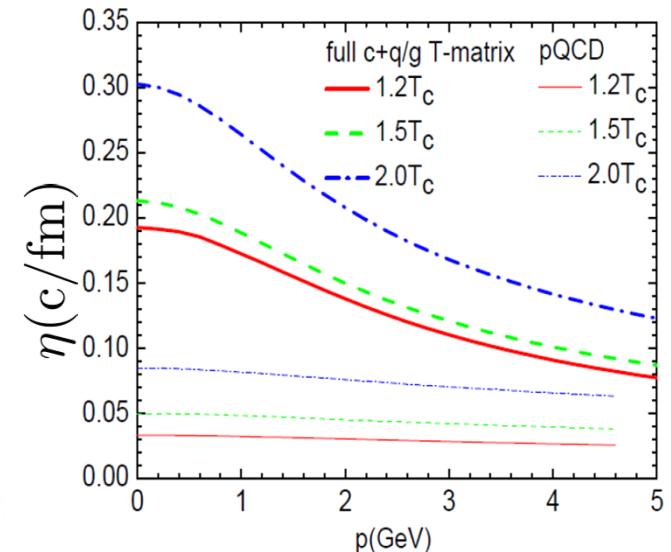
- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near  $T_c$  from the same underlying interactions!

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  $p_Q$  13

# 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)

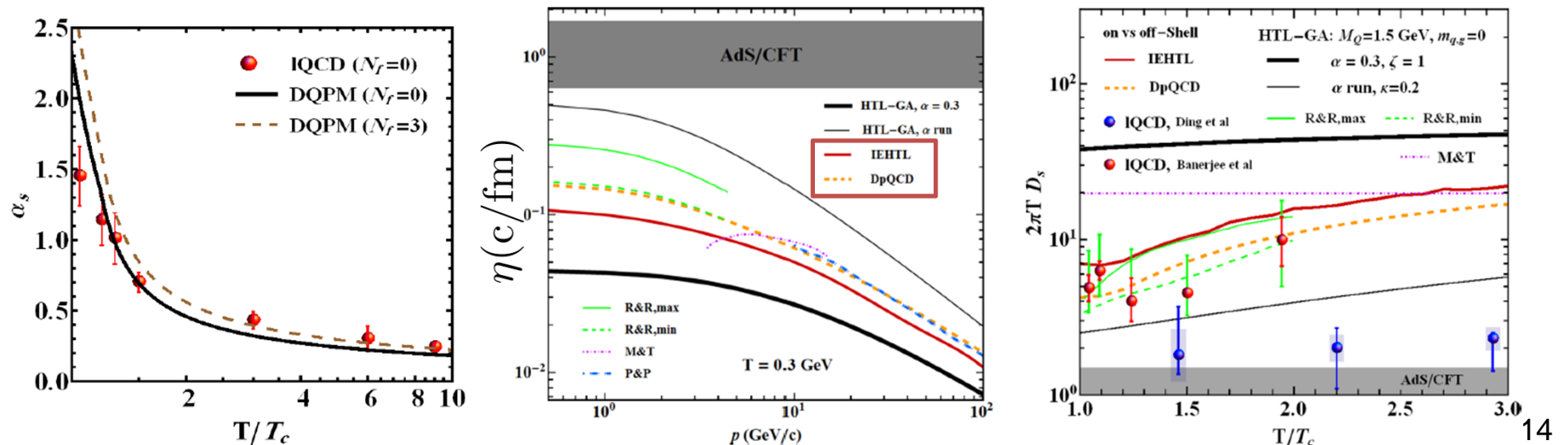
- Relaxation rates larger than in pQCD for all  $T$  relevant for QGP, slightly smaller than the ones from TAMU

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

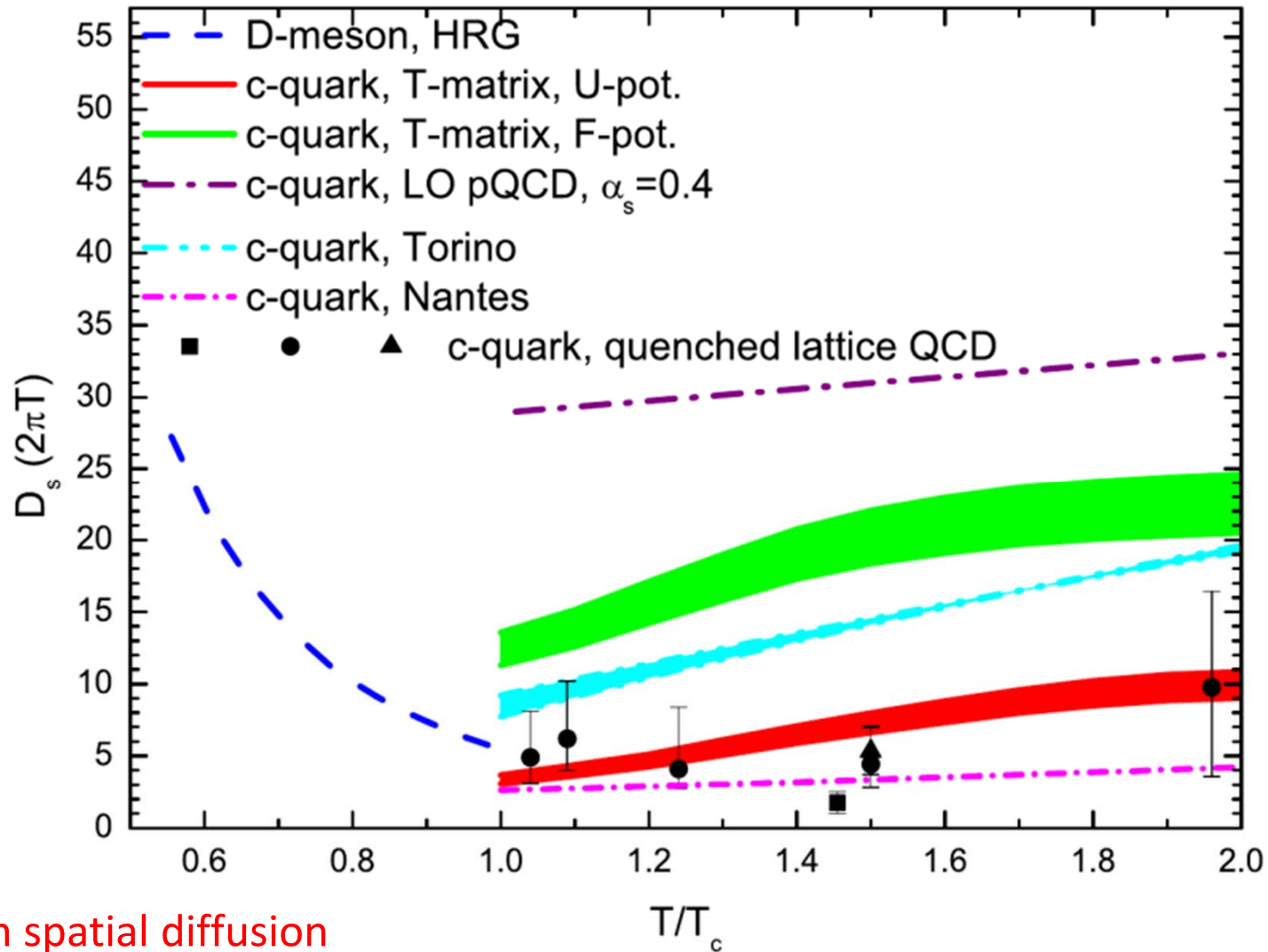
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilibrium transport).

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

**But also CATANIA**



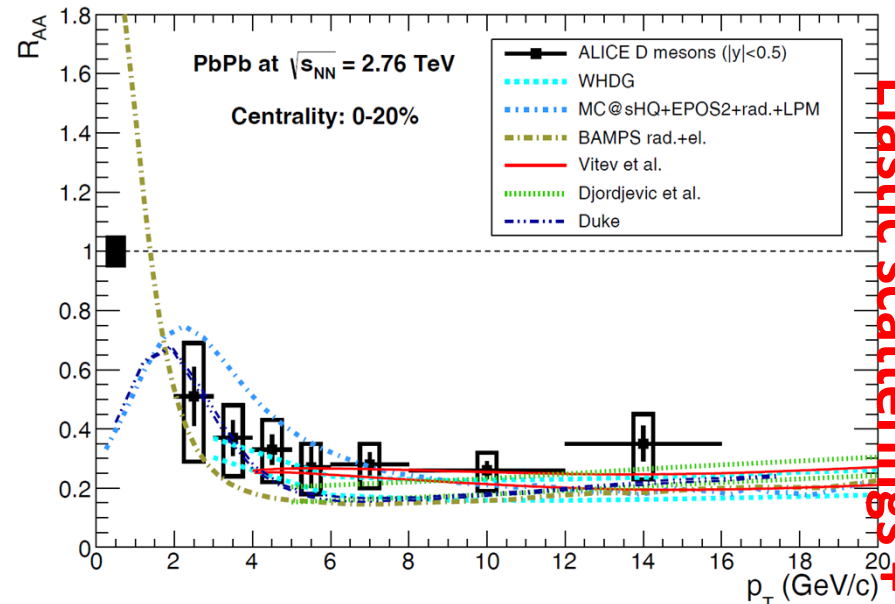
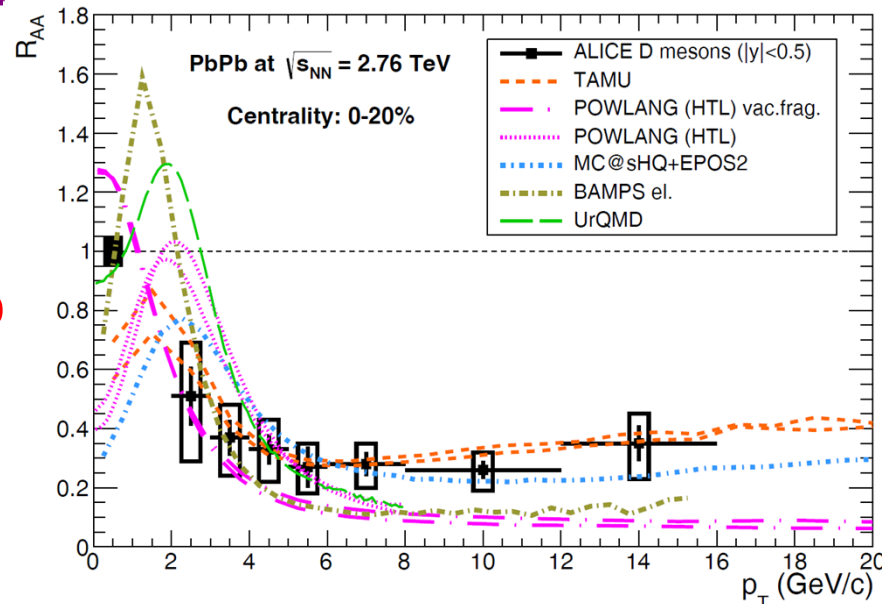
# Various models... with various coupling strength of heavy quarks to the QGP !



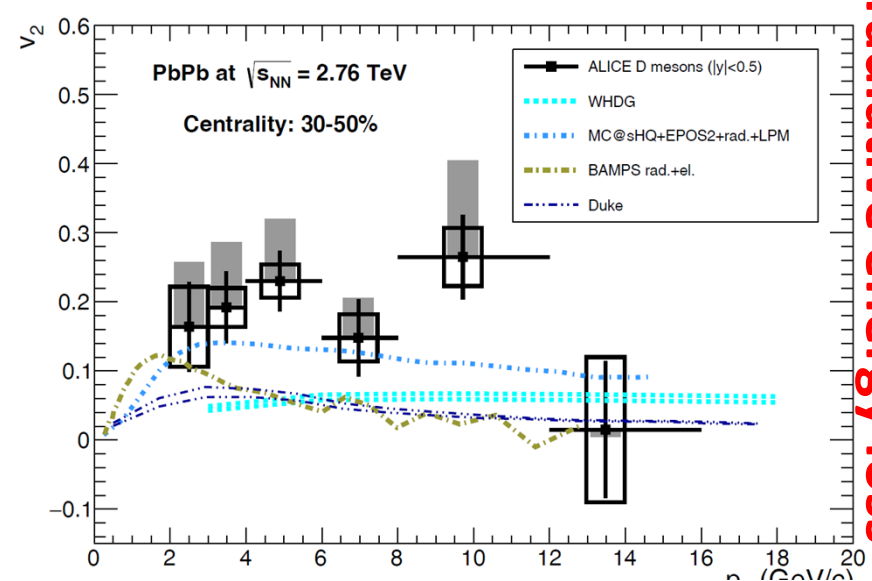
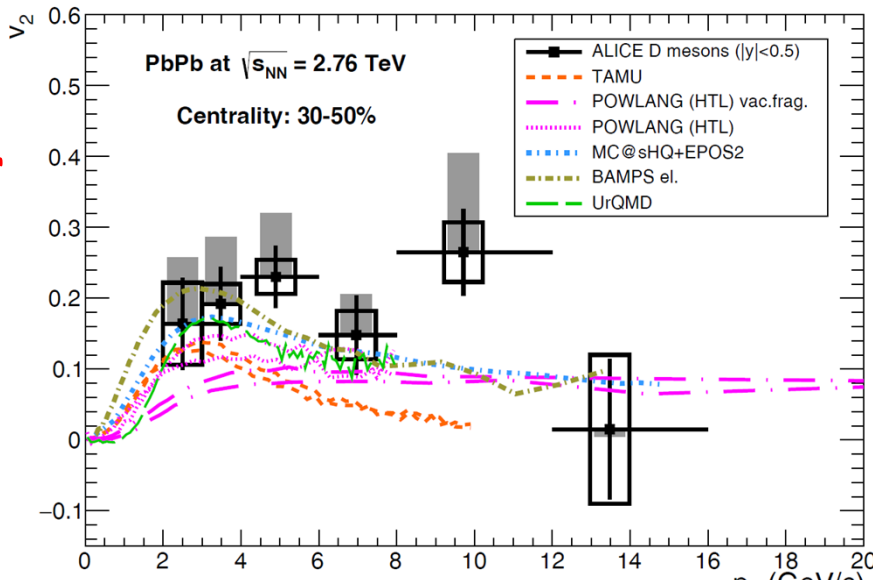
charm spatial diffusion  
coefficient

# Models vs DATA at LHC: Sapore Gravis Report

Purely elastic scatterings



Elastic scatterings + radiative energy loss



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



# Models vs DATA at LHC: Sapore Gravis Report

Sapore Gravis I3HP Network (Led by G. Martinez) => comprehensive report

Eur. Phys. J. C (2016) 76:107  
DOI 10.1140/epjc/s10052-015-3819-5

THE EUROPEAN  
PHYSICAL JOURNAL C



Review

## Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions

A. Andronic<sup>1</sup>, F. Arleo<sup>2,3</sup>, R. Arnaldi<sup>4</sup>, A. Beraudo<sup>4</sup>, E. Bruna<sup>4</sup>, D. Caffarri<sup>5</sup>, Z. Conesa del Valle<sup>6</sup>, J. G. Contreras<sup>7</sup>, T. Dahms<sup>8</sup>, A. Dainese<sup>9</sup>, M. Djordjevic<sup>10</sup>, E. G. Ferreira<sup>11</sup>, H. Fujii<sup>12</sup>, P.-B. Gossiaux<sup>13</sup>, R. Granier de Cassagnac<sup>2</sup>, C. Hadjidakis<sup>6</sup>, M. He<sup>14</sup>, H. van Hees<sup>15</sup>, W. A. Horowitz<sup>16</sup>, R. Kolevatov<sup>13,17</sup>, B. Z. Kopeliovich<sup>18</sup>, J.-P. Lansberg<sup>6</sup>, M. P. Lombardo<sup>19</sup>, C. Lourenço<sup>5</sup>, G. Martinez-Garcia<sup>13</sup>, L. Massacrier<sup>6,13,20,a</sup>, C. Mironov<sup>2</sup>, A. Mischke<sup>21,22</sup>, M. Nahrgang<sup>23</sup>, M. Nguyen<sup>2</sup>, J. Nystrand<sup>24</sup>, S. Peigné<sup>13</sup>, S. Porteboeuf-Houssais<sup>25</sup>, I. K. Potashnikova<sup>18</sup>, A. Rakotozafindrabe<sup>26</sup>, R. Rapp<sup>27</sup>, P. Robbe<sup>20</sup>, M. Rosati<sup>28</sup>, P. Rosnet<sup>25</sup>, H. Satz<sup>29</sup>, R. Schicker<sup>30</sup>, I. Schienbein<sup>31</sup>, I. Schmidt<sup>18</sup>, E. Scomparin<sup>4</sup>, R. Sharma<sup>32</sup>, J. Stachel<sup>30</sup>, D. Stocco<sup>13</sup>, M. Strickland<sup>33</sup>, R. Tieulent<sup>34</sup>, B. A. Trzeciak<sup>7</sup>, J. Uphoff<sup>35</sup>, I. Vitev<sup>36</sup>, R. Vogt<sup>37,38</sup>, K. Watanabe<sup>39,40</sup>, H. Wochri<sup>5</sup>, P. Zhuang<sup>41</sup>

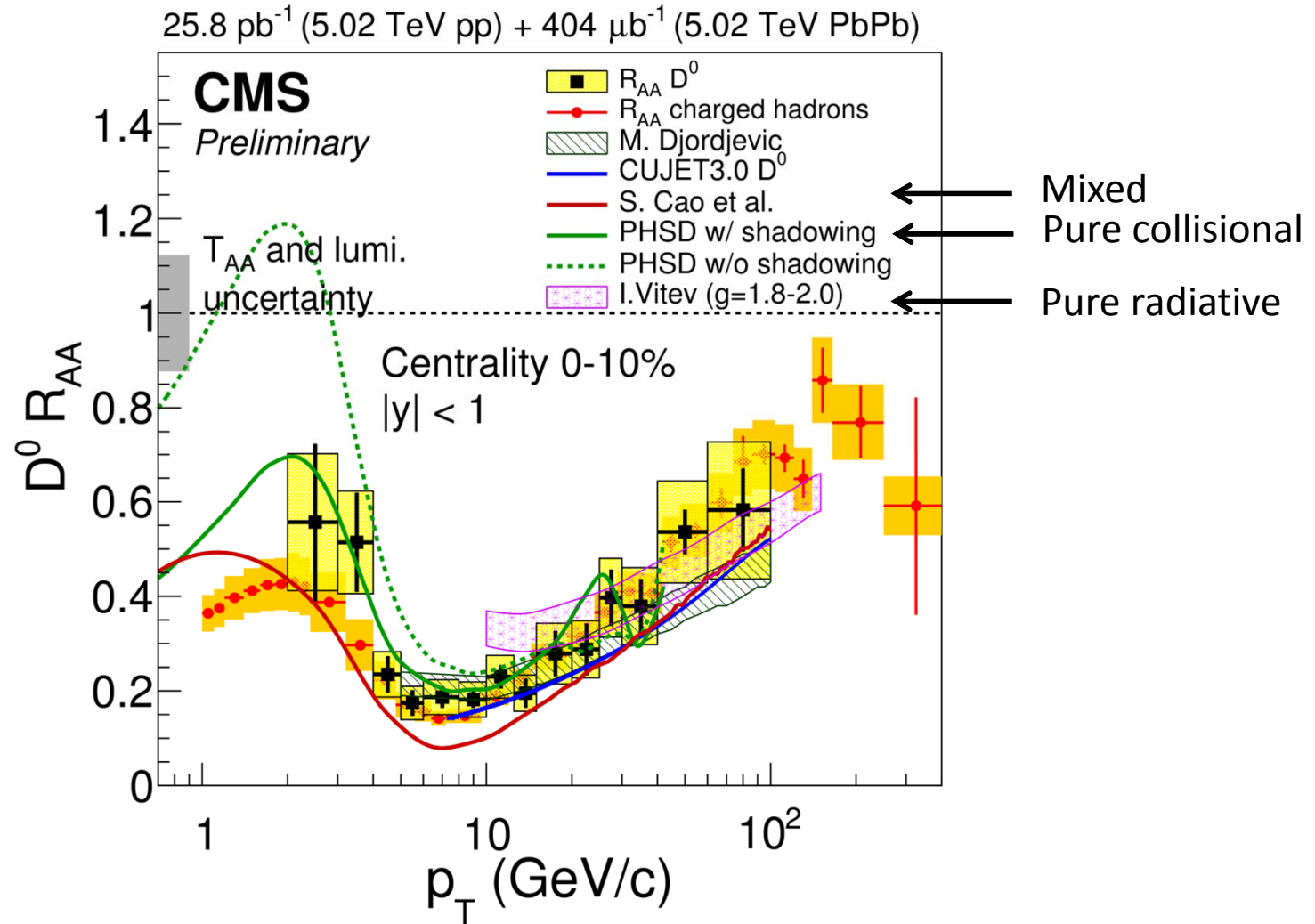
- Compilation of all existing (published) experimental results vs a large number of models
- Explicitation of these models on the same footing (as much as possible)
- (partial) compilation of « Fokker Plank coefficients » (drag & diffusionS)

# Models vs DATA at LHC: Sapore Gravis Report

The models considered  
In SG. New ones in the  
meanwhile (pHSD, CCNU,  
Catania)

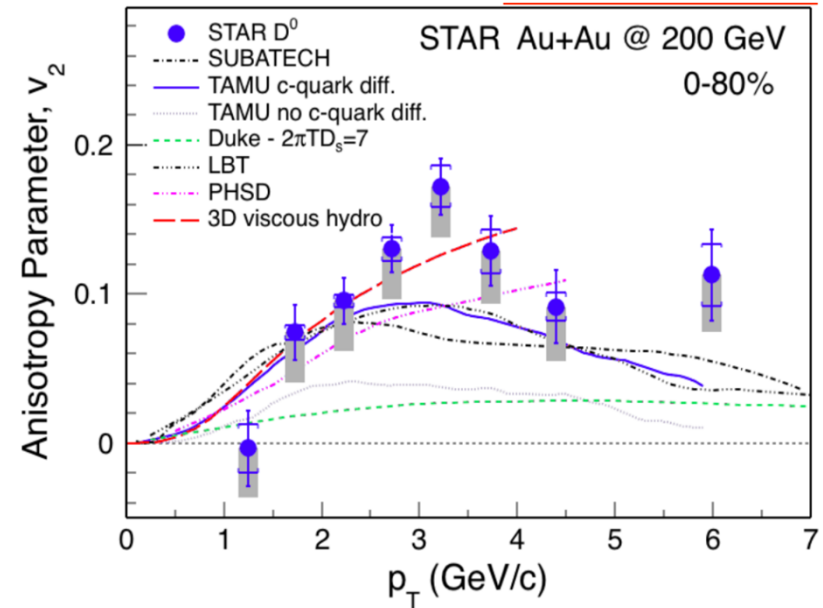
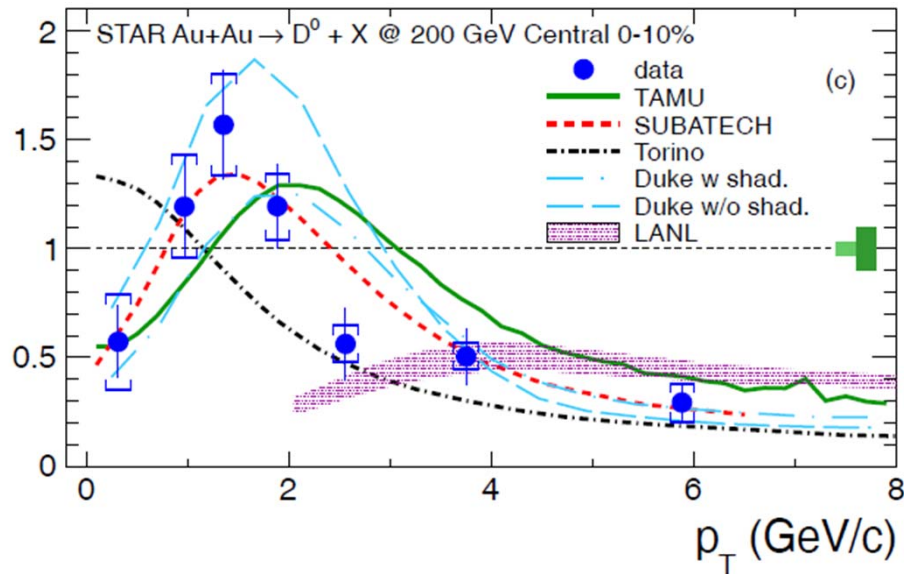
Model	Heavy-quark production	Medium modelling	Quark-medium interactions	Heavy-quark hadronisation	Tuning of medium coupling (or density) parameter(s)
Djordjevic et al. [511–515]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	Rad. + coll. energy loss finite magnetic mass	Fragmentation	Medium temperature fixed separately at RHIC and LHC
WHDG [459,519]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	Rad. + coll. energy loss	Fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$ )
Vitev et al. [422,460]	Non-zero-mass VFNS no PDF shadowing	Glauber model nuclear overlap ideal fl. dyn. 1 + 1d Bjorken expansion	Radiative energy loss in-medium meson dissociation	Fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$ )
AdS/CFT (HG) [624, 625]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	AdS/CFT drag	Fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$ )
POWLANG [507–509,585,586]	POWHEG (NLO) EPS09 (NLO) PDF shadowing	2 + 1d expansion with viscous fl. dyn. evolution	Transport with Langevin eq. collisional energy loss	Fragmentation recombination	Assume pQCD (or l-QCD $U$ potential)
MC@ <sub>s</sub> HQ+EPOS2 [528–530]	FONLL EPS09 (LO) PDF shadowing	3 + 1d expansion (EPOS model)	Transport with Boltzmann eq. rad. + coll. energy loss	Fragmentation recombination	QGP transport coefficient fixed at LHC, slightly adapted for RHIC
BAMPS [537–540]	MC@NLO no PDF shadowing	3 + 1d expansion parton cascade	Transport with Boltzmann eq. rad. + coll. energy loss	Fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$ )
TAMU [491,565, 606]	FONLL EPS09 (NLO) PDF shadowing	2+1d expansion ideal fl. dyn.	Transport with Langevin eq. collisional energy loss diffusion in hadronic phase	Fragmentation recombination	Assume l-QCD $U$ potential
UrQMD [608–610]	PYTHIA no PDF shadowing	3+1d expansion ideal fl. dyn.	Transport with Langevin eq. collisional energy loss	fragmentation recombination	Assume l-QCD $U$ potential
Duke [587,628]	PYTHIA EPS09 (LO) PDF shadowing	2+1d expansion viscous fl. dyn.	Transport with Langevin eq. rad. + coll. energy loss	Fragmentation recombination	QGP transport coefficient fixed at RHIC and LHC (same value)

# Extended $p_T$ measurement by CMS...



... can hardly permit to discriminate btwn models !

# Models vs DATA at RHIC



**Which information / properties to extract from all of this ?**

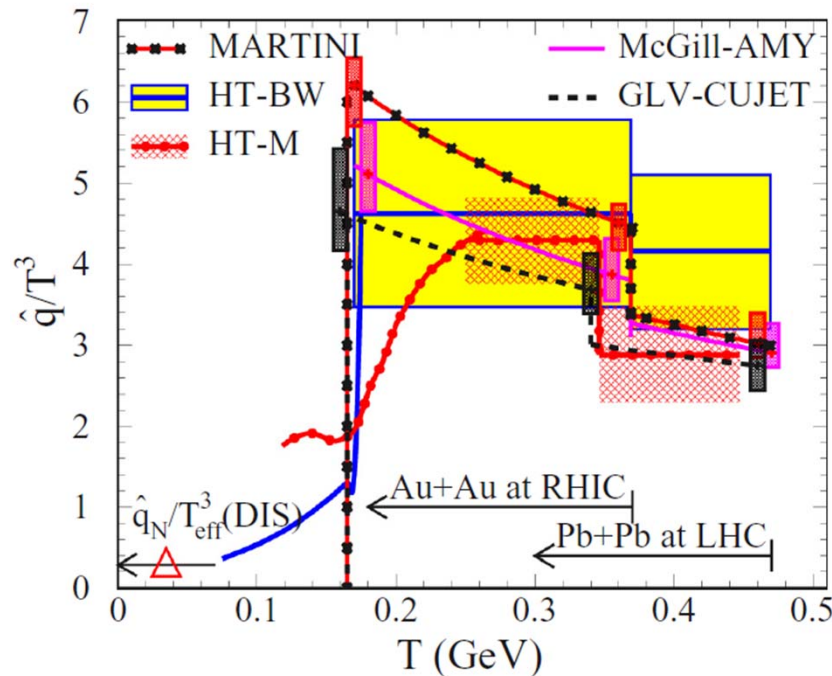
**Some people are confident they can...**

# Inspiration from the JET Collaboration

PHYSICAL REVIEW C **90**, 014909 (2014)

## Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions

Karen M. Burke,<sup>1</sup> Alessandro Buzzatti,<sup>2</sup> Ningbo Chang,<sup>3</sup> Charles Gale,<sup>4</sup> Miklos Gyulassy,<sup>5</sup> Ulrich Heinz,<sup>6</sup> Sangyong Jeon,<sup>4</sup> Abhijit Majumder,<sup>1</sup> Berndt Müller,<sup>7</sup> Guang-You Qin,<sup>1,3</sup> Björn Schenke,<sup>7</sup> Chun Shen,<sup>6</sup> Xin-Nian Wang,<sup>2,3,\*</sup> Jiechen Xu,<sup>5</sup> Clint Young,<sup>8</sup> and Hanzhong Zhang<sup>3</sup>  
(JET Collaboration)



$$\hat{q} = \left\langle \frac{\Delta p_T^2(L)}{L} \right\rangle$$

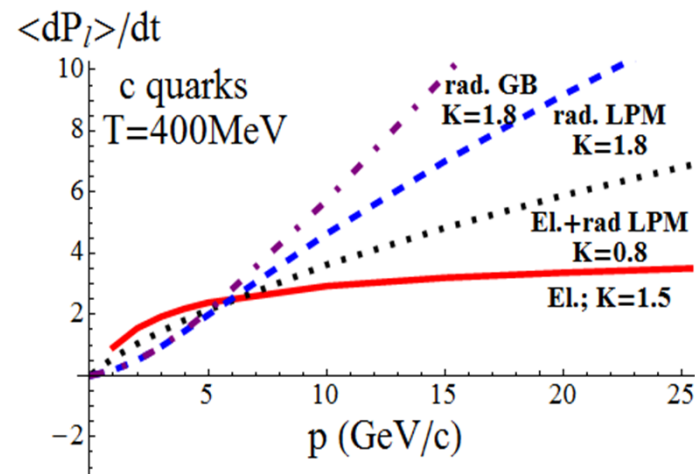
$\sim 4 \times B_0$  FP Coefficient in the case of HQ

See talk by A. Majumder

# Which relevant quantity to measure with HQ ?

Reminder: The JET collaboration calibrated their transport coefficient on the quenching :  $\Delta E = F(E, L, \hat{q}, \dots)$

For Heavy Flavor at small and intermediate  $p_T$ , the link between  $\Delta E$  and  $\hat{q}$  is more intricate => « extract »  $\langle dP \rangle / dt$  ?



Several issues:

- Non-trivial momentum dependence
- No prediction from IQCD

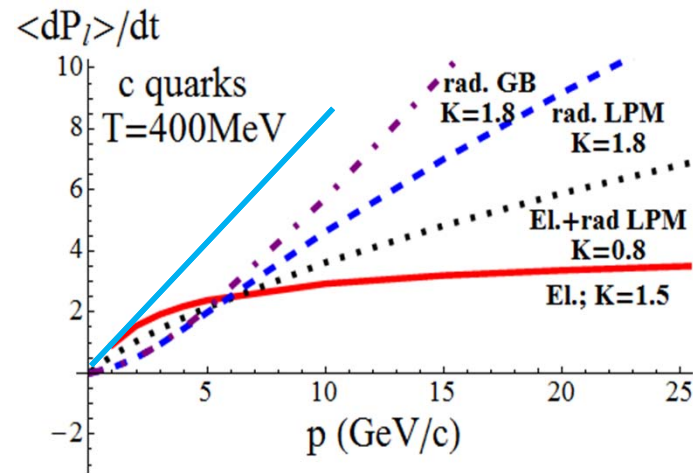
# Which relevant quantity to measure with HQ ?

At  $p_T \approx 0$  : All FP coefficients are equivalent and measure the (long wave) coupling strength to the medium :

$$B_1 = B_0 = B = \eta m_Q T$$



Slope of  $\langle dP \rangle / dp$  at  $p \rightarrow 0$



Most often recatch into the spatial diffusion coefficient  $D_s$   $\left( = \frac{1}{6} \lim_{t \rightarrow \infty} \frac{\langle (\mathbf{x}(t) - \mathbf{x}(0))^2 \rangle}{t} \right)$

$$D_s = \left. \frac{B}{m_Q^2 \eta^2} \right|_{p \approx 0} = \frac{T}{m_Q \eta} = \frac{T^2}{B}$$

Small  $D_s \Leftrightarrow$  large  
relaxation  $\Leftrightarrow$  large  
fluctuations

Good News: Lattice QCD calculation for  $D_s$

# 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  $\kappa$  of stochastic forces (a transport coefficient;  $\kappa = 2 \times B$ ) from the slope of spectral function  $\rho_E$  at  $\omega = 0$ :

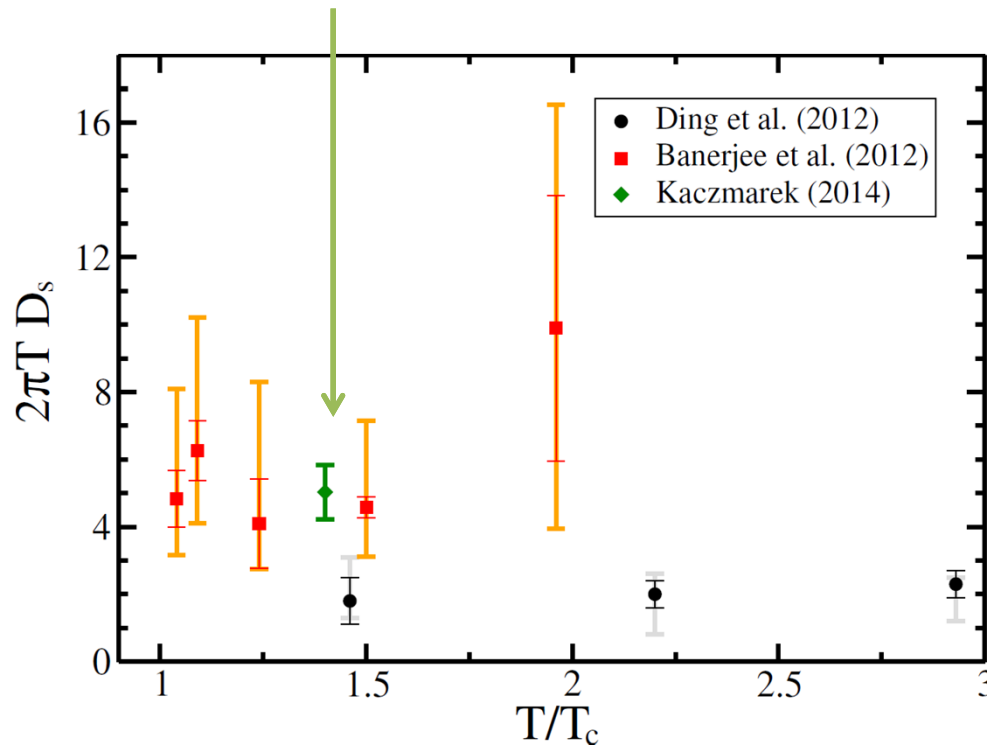
$$\kappa \equiv \lim_{\omega \rightarrow 0} \frac{2T \rho_E(\omega)}{\omega} \quad \text{with } \rho_E \text{ extracted from } G_E(\tau) = \int_0^\infty \frac{d\omega}{\pi} \rho_E(\omega) \frac{\cosh[\omega(\frac{\beta}{2} - \tau)]}{\sinh[\frac{\omega\beta}{2}]}$$

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



# IQCD Calculation of $D_s$

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



World data on IQCD calculation of  $D_s$

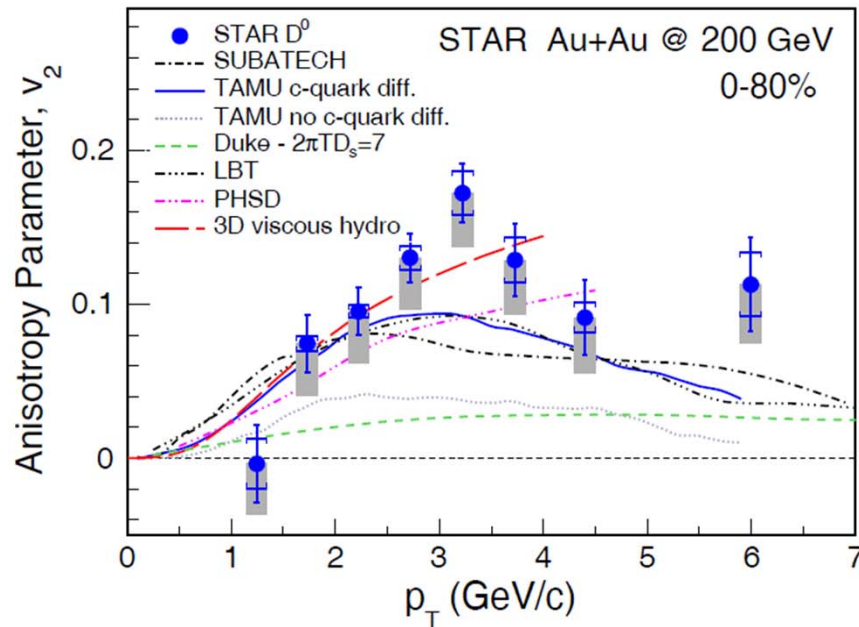
- Still drastic approximations/limitations: quenched QCD, heavy quark vs. charm quark, (no) continuum extrapolation,...

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

# Model + Exp. Constrains on $D_s$

- F.i., recent STAR study:

STAR Collab. PRL 118 (2017)



compare with	$2\pi T D_s$	$\chi^2/\text{NDF}$	$p$ -value
SUBATECH [11]	2–4	15.2 / 8	0.06
TAMU c quark diff. [13]	5–12	10.0 / 8	0.26
<del>TAMU no c quark diff. [13]</del>	<del>-</del>	<del>29.5 / 8</del>	<del><math>2 \times 10^{-4}</math></del>
Duke [14]	7	35.7 / 8	$2 \times 10^{-5}$
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  $\chi^2/\text{NDF}$  and the  $p$ -value (the probability of observing a  $\chi^2$  that exceeds the current measured  $\chi^2$  by chance).  $2\pi T D_s$  values quoted are in the range of  $T_c$  to  $2T_c$ .  $\chi^2/\text{NDF}$  is calculated in the  $p_T$  range wherever the model calculation is available.

- Not really conclusive;  $\chi^2/\text{NDF}$  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 »

# 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
- **EMMI Rapid Reaction Task Force** (organizers: A. Andronic, R. Averbek, PB Gossiaux, S. Maschicchi, R. Rapp):
  - 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 IQCD
  - Initiate discussions to assess the limitations of some existing models.
- **Lorentz Workshop** on “Tomography of the quark-gluon plasma with heavy quarks”; oct 2016 (organizers: J. Aichelin, R. Granier de Cassagnac, M.P. Lombardo, A. Mischke, N. Xu): The goal of this workshop is to identify common understandings and develop strategies for the upcoming 5 years to achieve a profound knowledge of the dynamical properties of the quark-gluon plasma

# Heavy-Quark Working Group

- 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. Berrehrh)
- Nantes (J. Aichelin, PB Gossiaux, M. Nahrgang)



PHYSICAL REVIEW C ~~90, 014909 (2014)~~  
(2017)

Extracting the ~~jet~~ transport coefficient from ~~jet quenching~~ in high-energy heavy-ion collisions  
 charm Drag coefficient D-meson observables  
 Fluctuation tensor

# Heavy-Quark Working Group



After 3 meetings, footprints of the physics start to emerge... but no firm conclusion yet



For step 1: Compare HQ spectra from different models in static medium with common initial condition

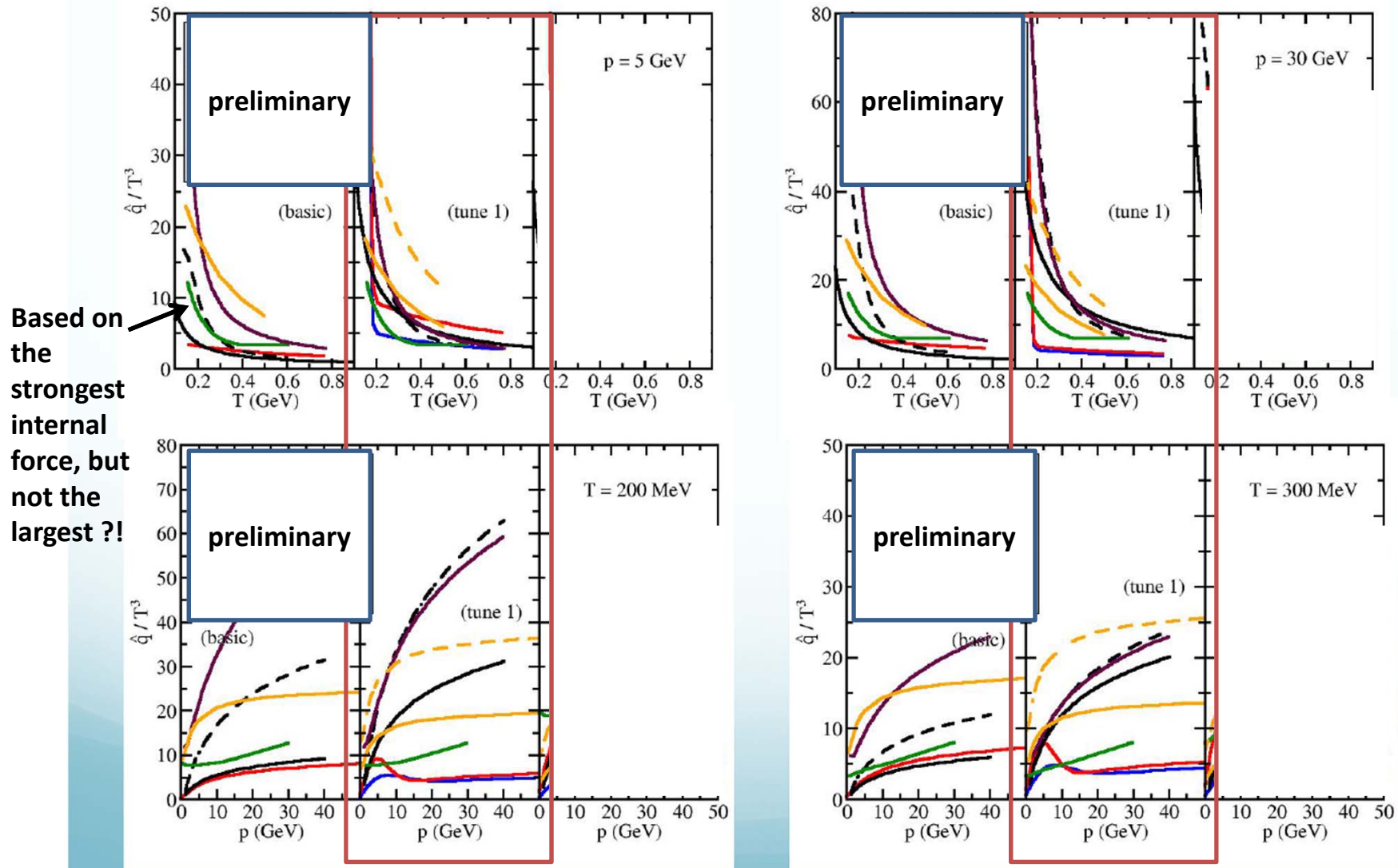
Models	note	basic	tune 1
LBL-CCNU ★	fix $\alpha_s$	$\alpha_s = 0.3$	$\alpha_s = 0.26$
Duke ★	fix $\alpha_s$	$\alpha_s = 0.3$	$\alpha_s = 0.23$
Catania QPM	$\alpha_s(T)$	$K = 1$	$K = 2$
Catania pQCD	$\alpha_s(T)$	$K = 1$	$K = 3.4$
TAMU	$U$ -potential	no tuning	no tuning
Frankfurt PHSD	$\alpha_s(T)$	no tuning	no tuning
Nantes col. + rad. ★	$\alpha_s(q^2)$	$K = 1$	$K = 0.8$
Nantes col. only	$\alpha_s(q^2)$	$K = 1$	$K = 1.5$

★: Radiative included

Basic: original model

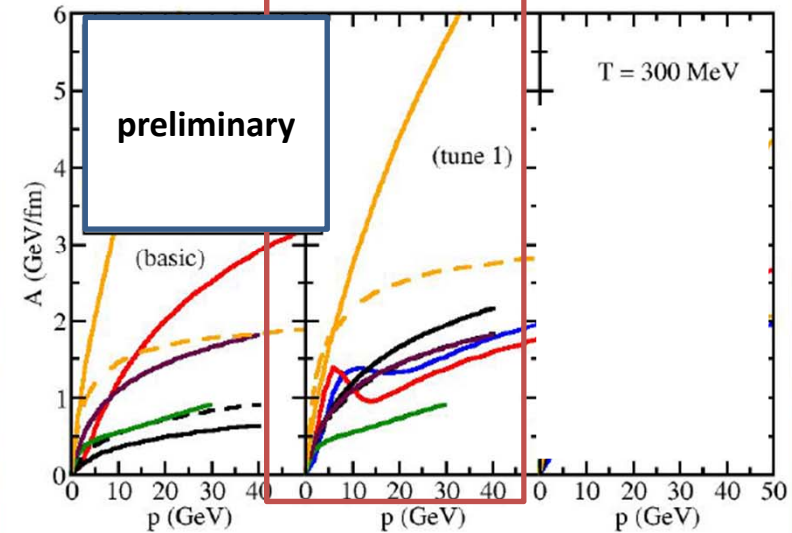
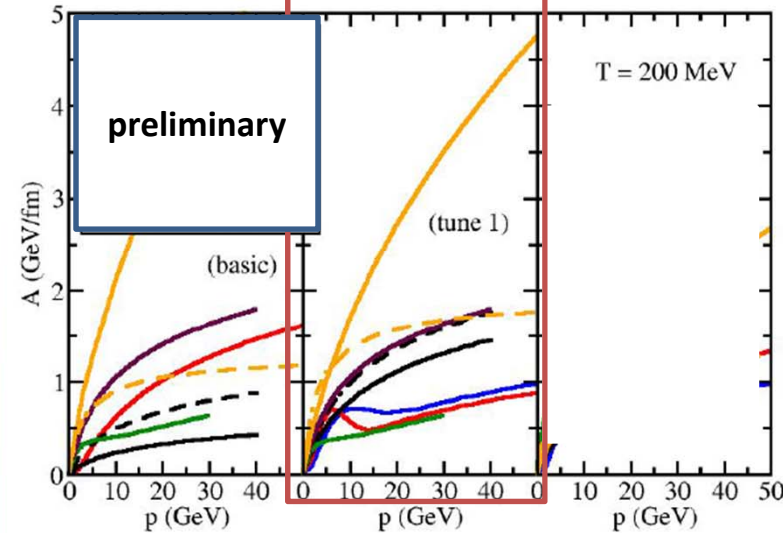
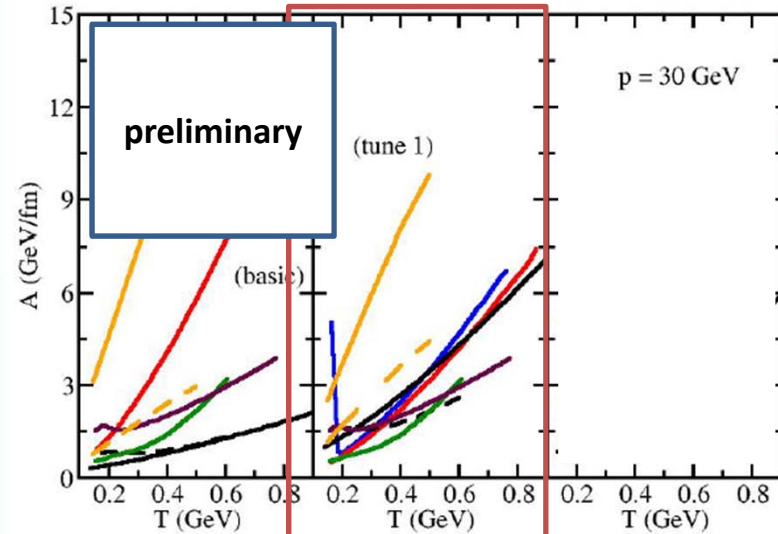
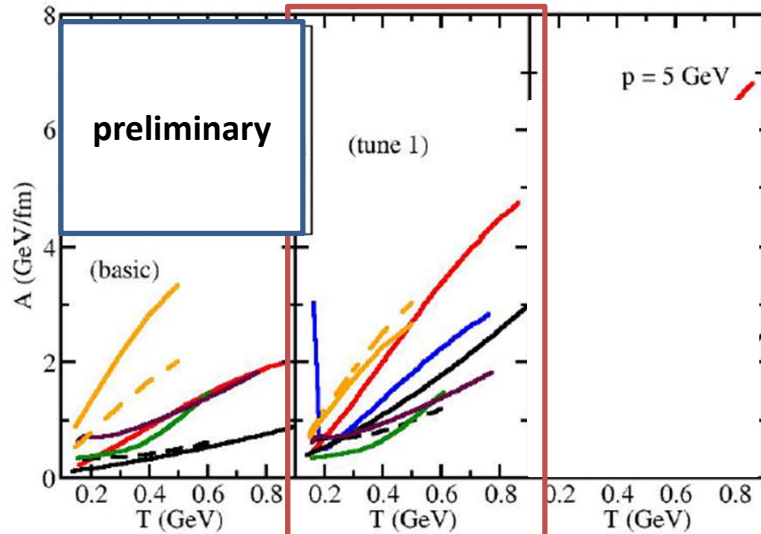
Tune 1: favorite tuning of each group in order to describe  $D$  meson data with their own ingredients (background, hadronization,...) ;  $K$  = rate multiplier

# qhat – momentum broadening per unit time (due to elastic scattering) ONLY



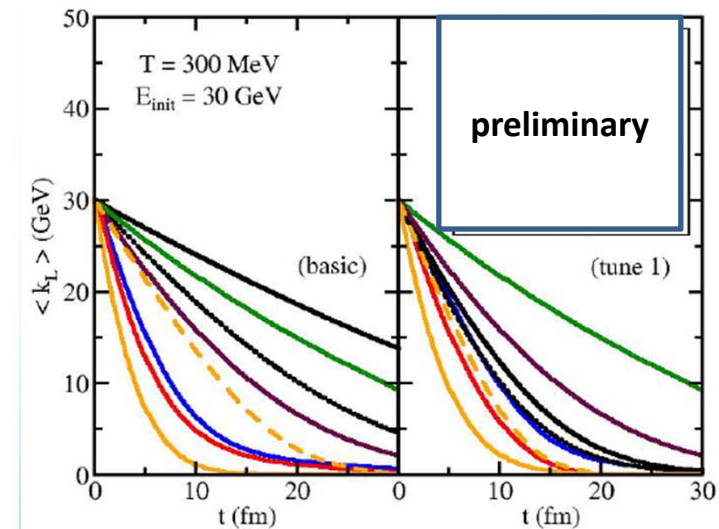
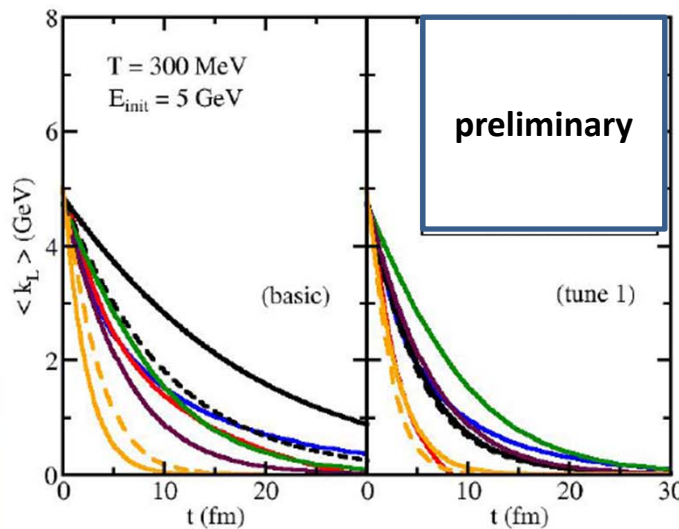
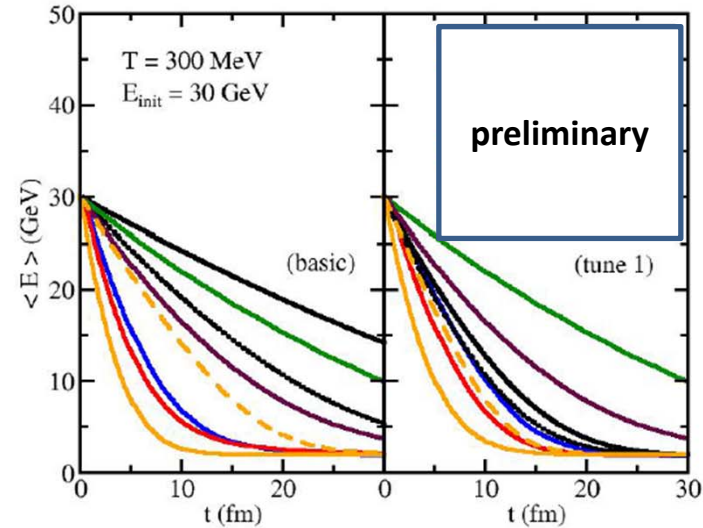
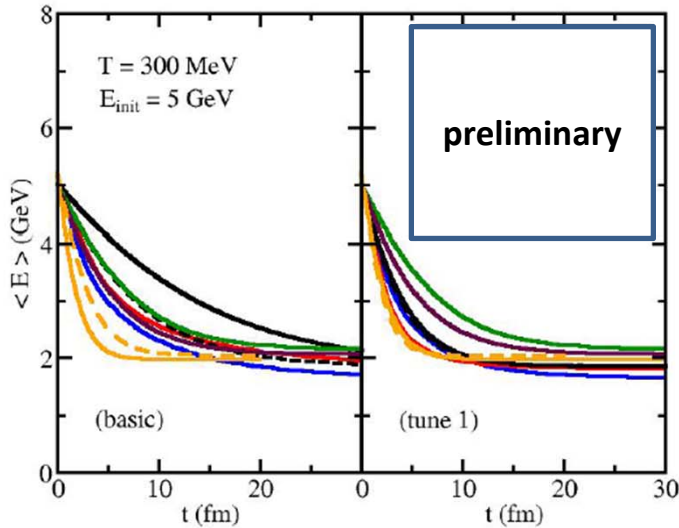
Tune 1 would be the « extraction »... Large « error bands » except at small  $p_T$  !!!  
Nature is maybe not so kind...

# A (drag force) – $p_L$ change per unit time (total)



Tune 1 would be the « extraction »... Large « error bands » as well

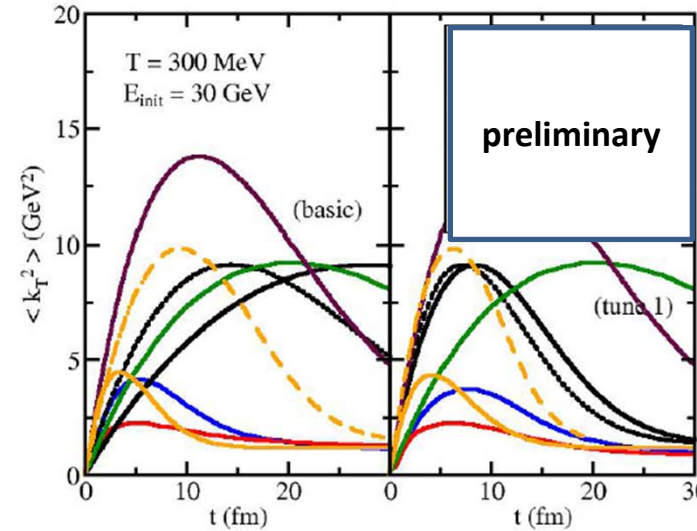
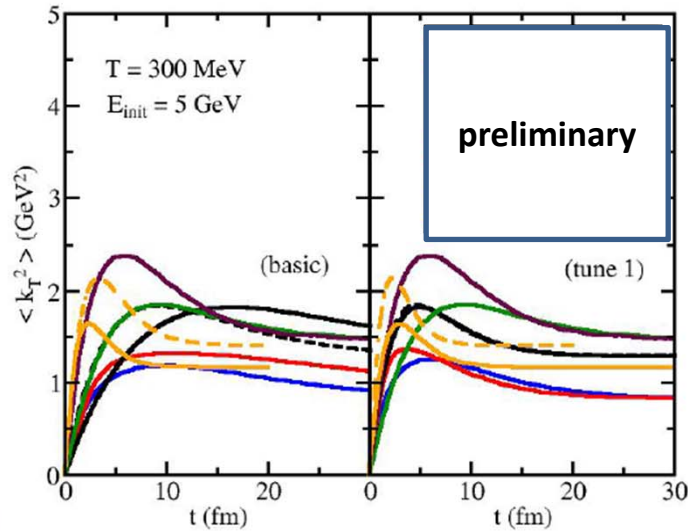
# Time evolution of average quantities (thermalization process)



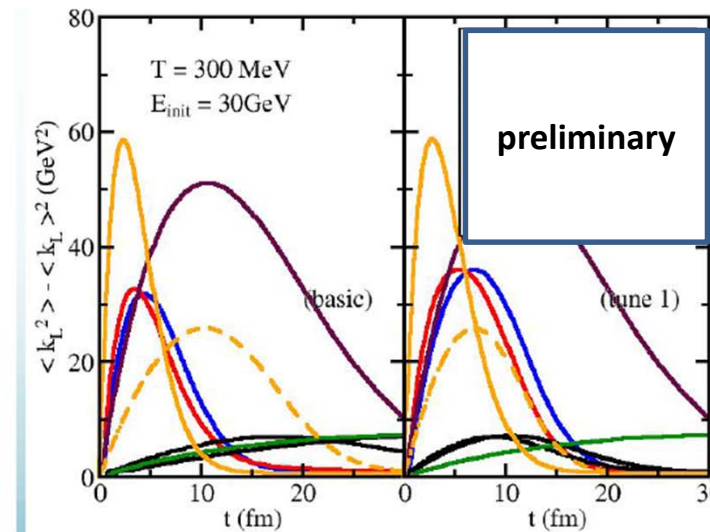
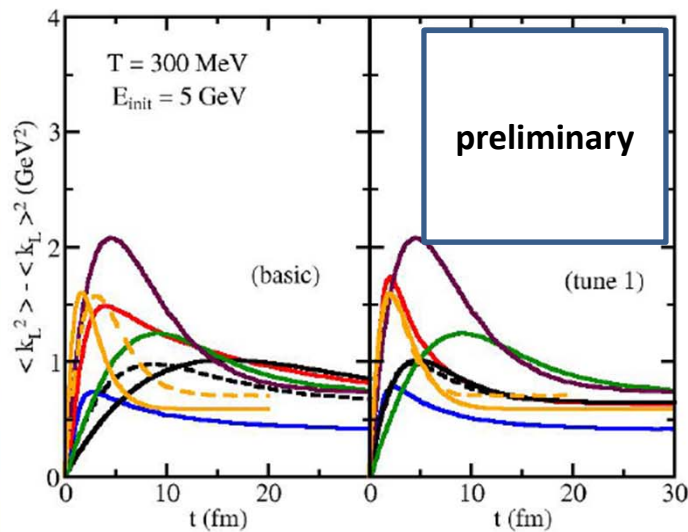
Looking at the evolution in a brick, still large fluctuations observed



# Time evolution of average quantities (thermalization process)

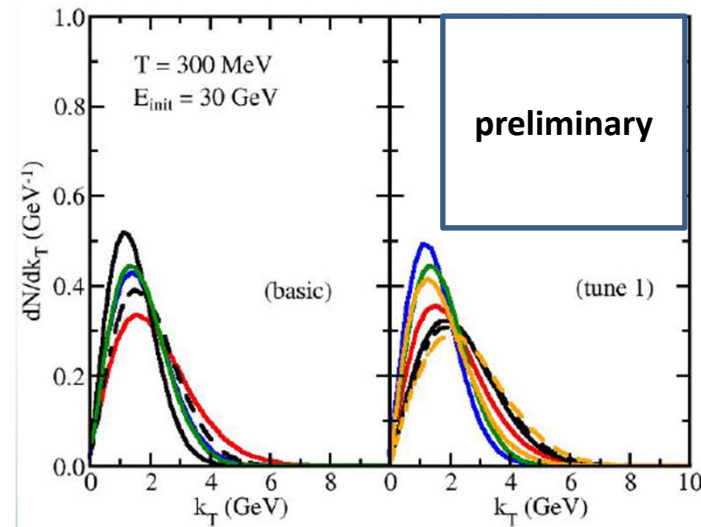
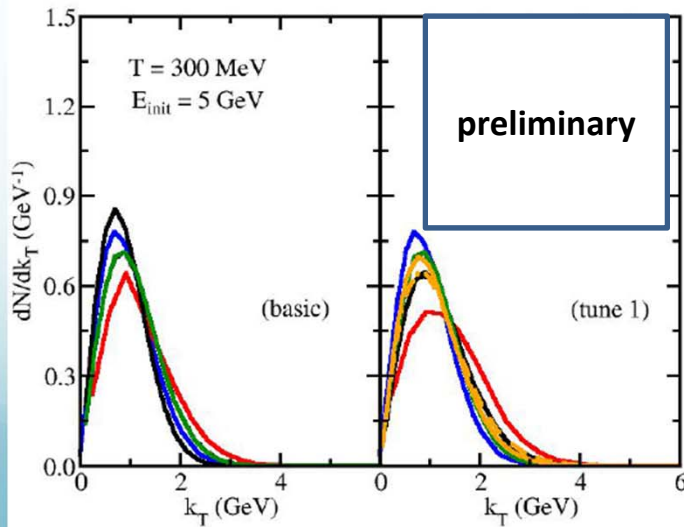
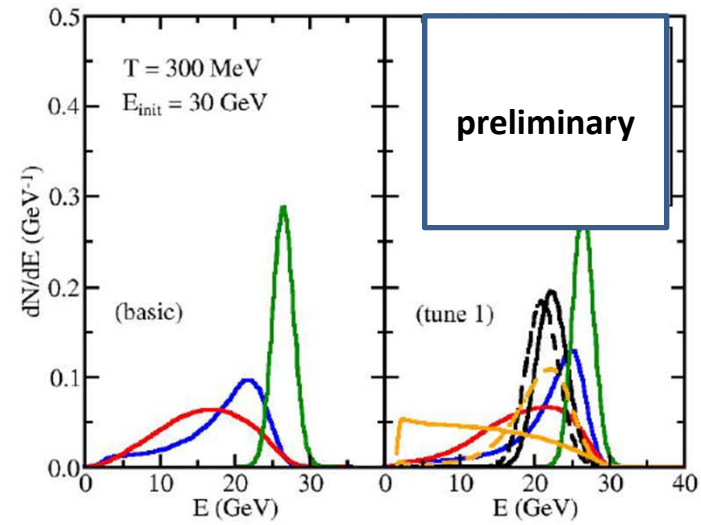
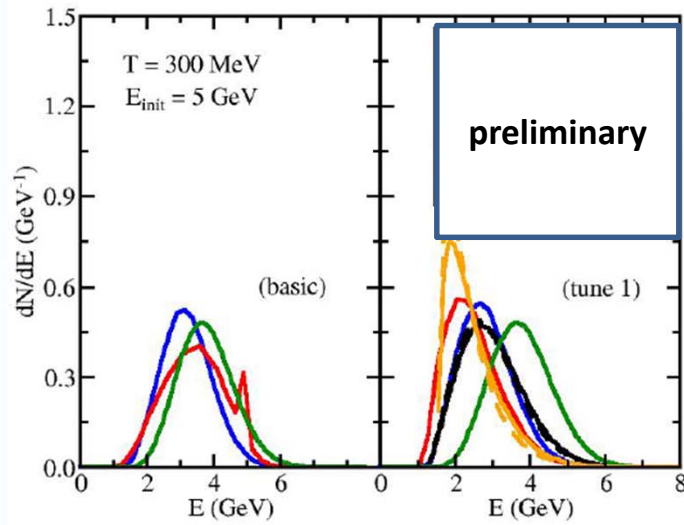
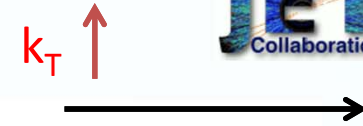


**Models without radiation => larger transverse broadening at large momentum**



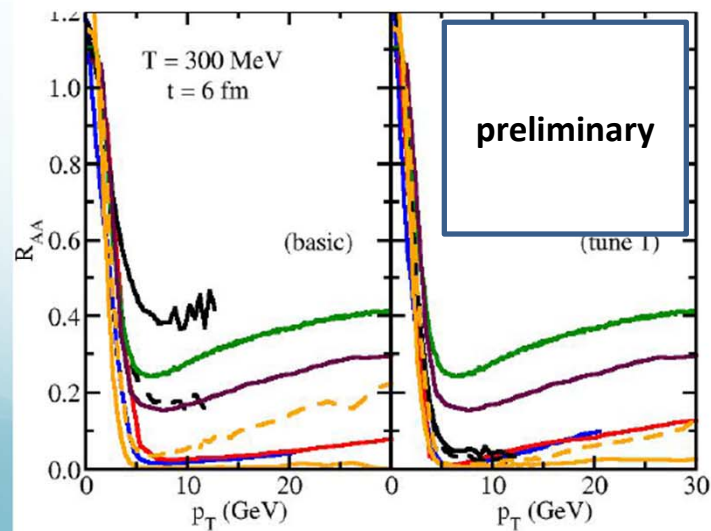
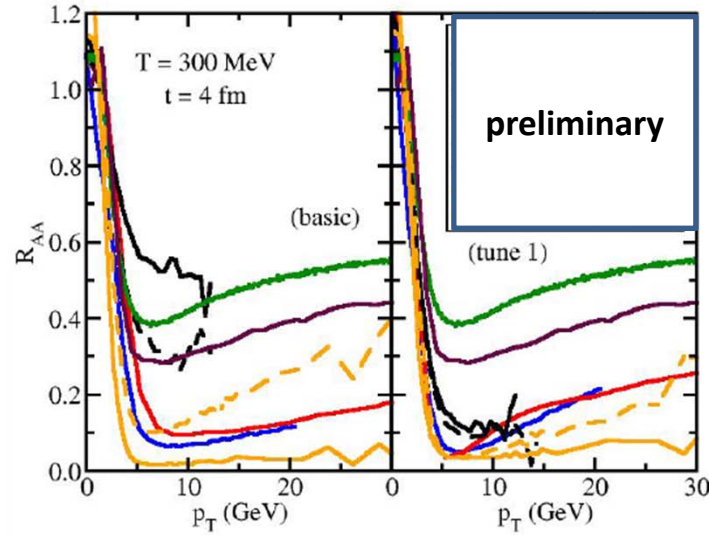
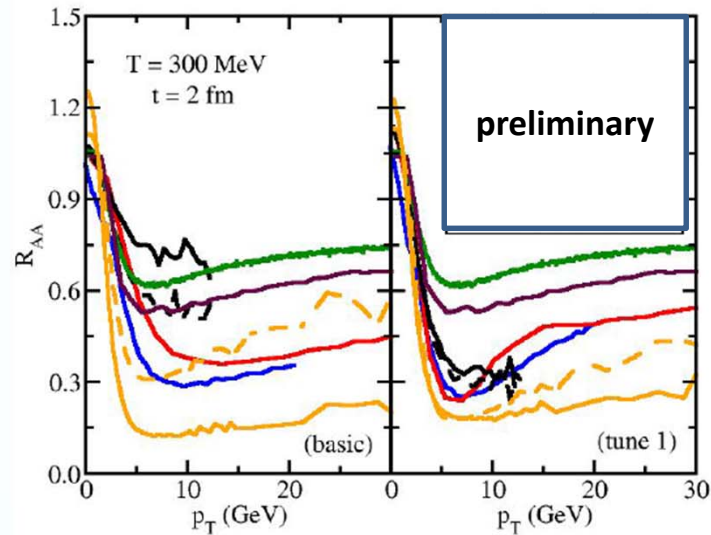
Looking at the evolution in a brick, still large fluctuations observed

# $E$ and $k_T$ distribution at 4 fm



Looking at the outcome of the evolution in a brick, still large fluctuations observed, especially in long direction -> seek for more exclusive variables !!!

# $R_{AA}$ of $c$ -quark in static medium

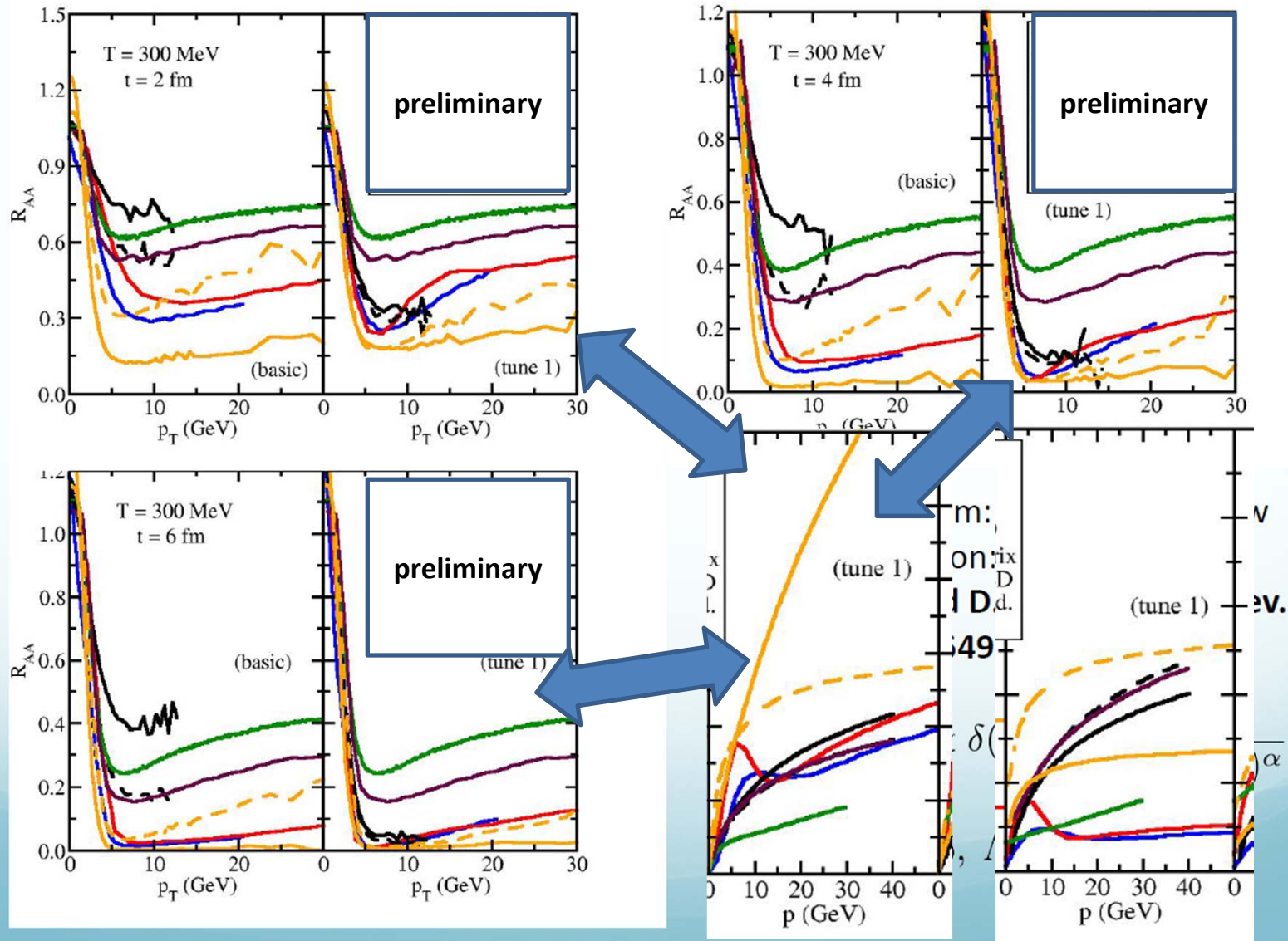


Initial spectrum: simple power-law parametrization:  
**G. Moore and D. Teaney, Phys. Rev. C71 (2005) 064904. Eq. 5.12**

$$\frac{dN}{dyd\eta d^2p_T} \propto \delta(y - \eta) \frac{1}{(p_T^2 + \Lambda^2)^\alpha}$$

$$\alpha = 3.5, \Lambda = 1.849 \text{ GeV}$$

# $R_{AA}$ of c-quark in static medium



... but rather good hierachical ordering as comp. to  $A$  (not so clear with  $\hat{q}/T^3$ )

## Heavy-Quark Working Group: preliminary conclusions

Previous studies suggest that the other « ingredients » play a crucial role in each prediction and prevent accurate extraction of Fokker Planck coefficient from the URHIC data...

.... assuming it makes sense otherwise !

=> Difficult to extract physics out of the variety of {tune 1}; **conclusion reinforced by this study**

=> **Method and further work: Use the brick configuration and some « Gedanken Experiment » to provide information on the smallest achievable ERROR-BAND WIDTH (and not on the absolute values of the FP coefficients)**

Stay tuned !

# EMMI RRTF

Thanks to the generosity of EMMI !!!

1<sup>st</sup> meeting: 18-22 July 2016; GSI (Germany)

2<sup>nd</sup> 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)

# EMMI RRTF

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

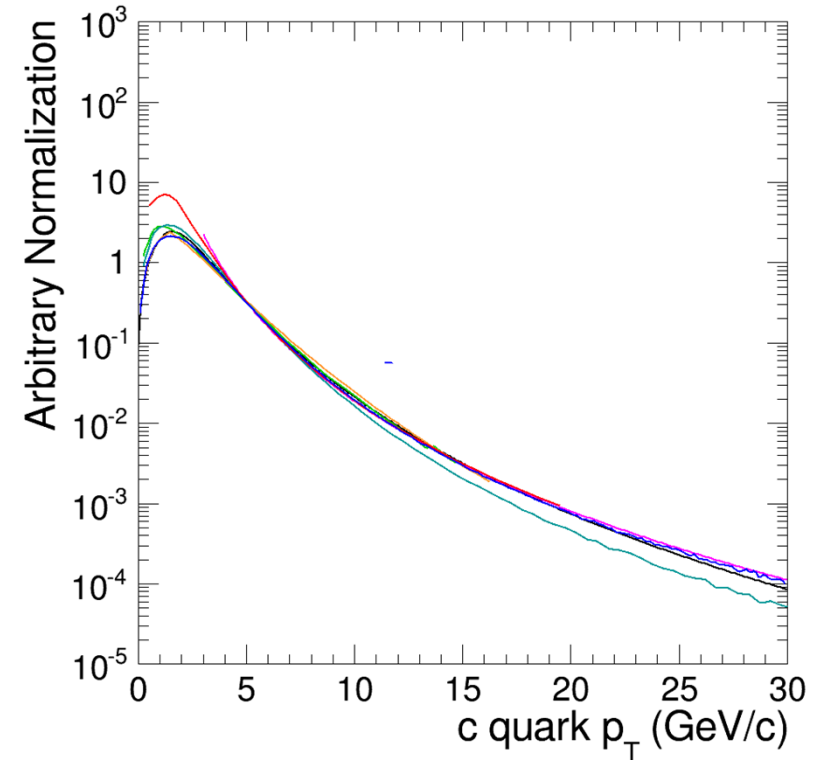
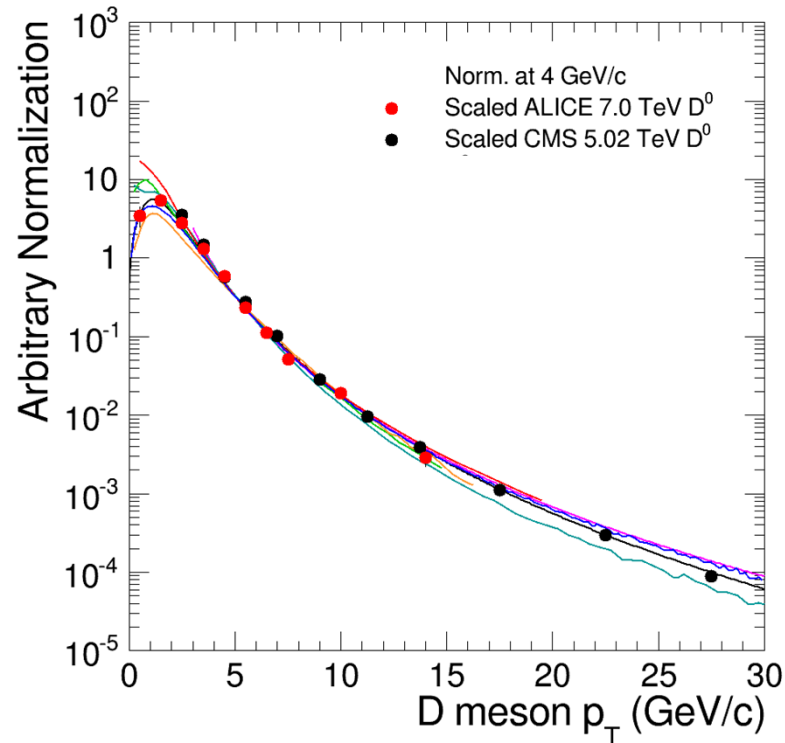
Topics:

- 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.

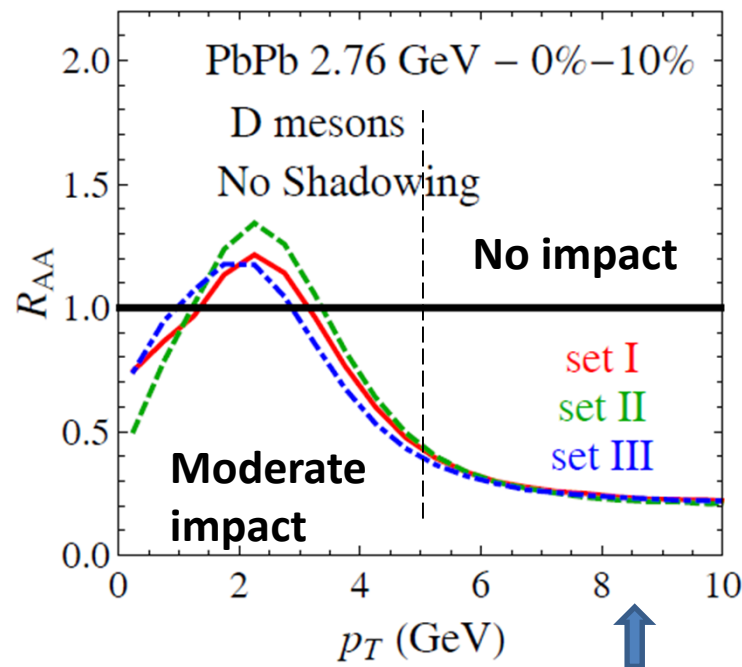
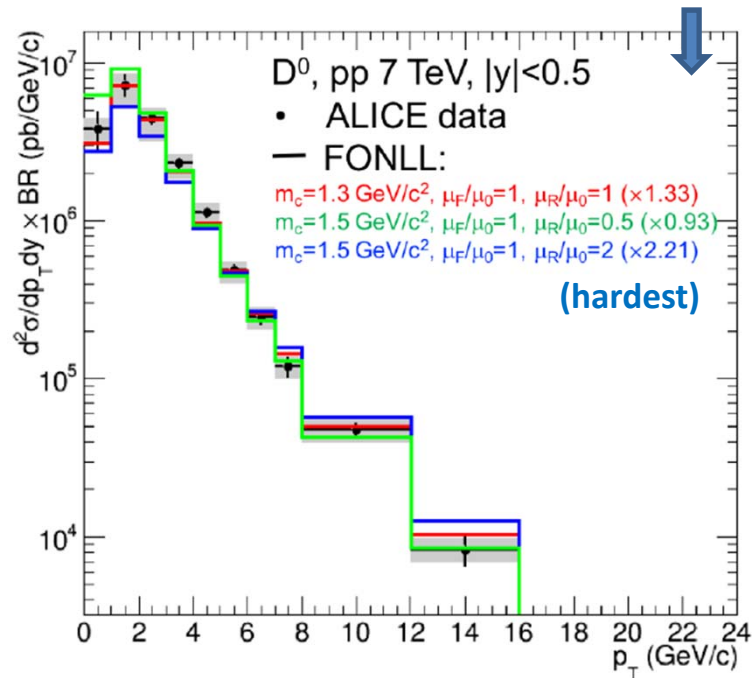
« We all do FONLL / GM - VFNS » ... yes, but with slightly different parameters !



# EMMI RRTF : Initial HF spectra and shadowing

Right now: data better than uncertainty band in theory:

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

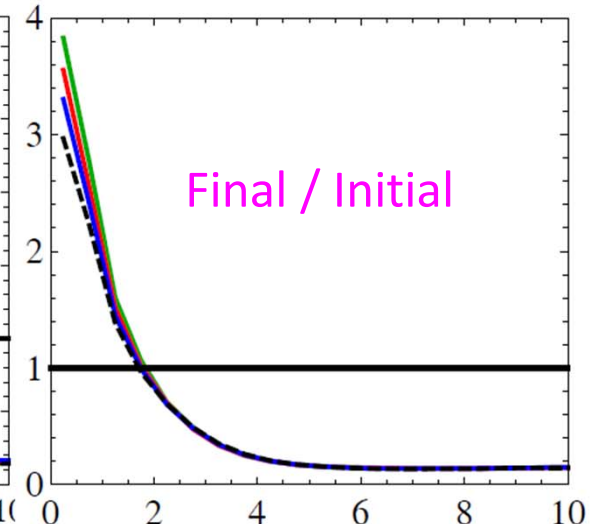
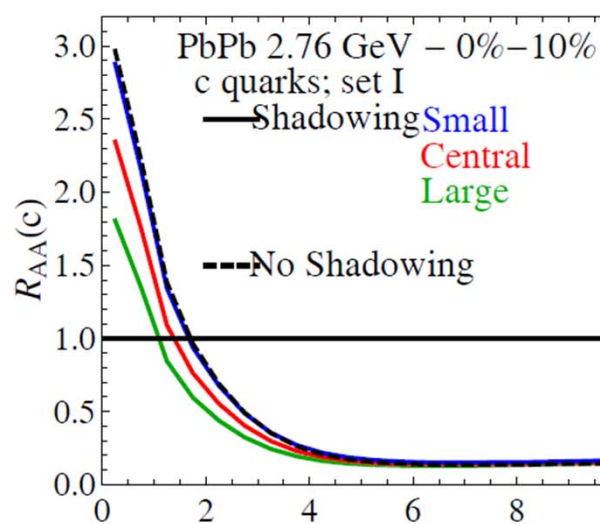
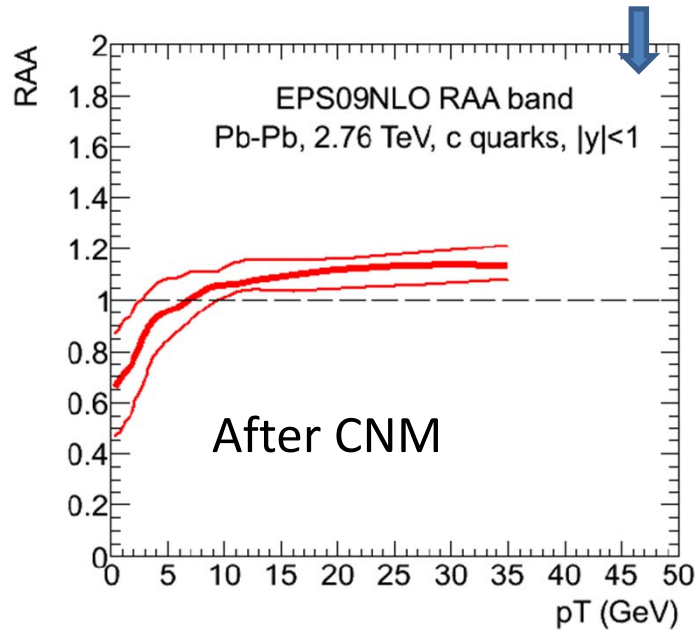


Consequence of the baseline on the RAA of D mesons in the Nantes Model (thermalisation at small  $p_T \Rightarrow$  the initial profile has a large impact in the ratio)

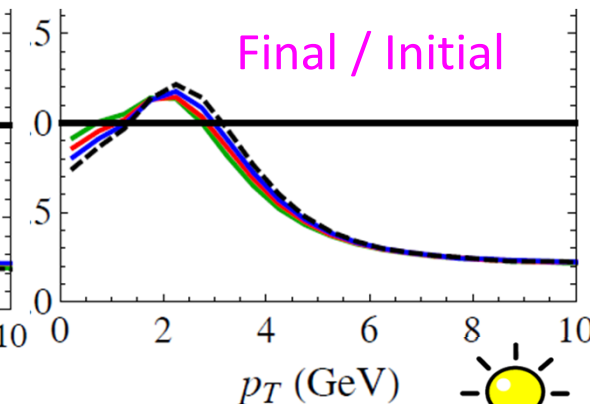
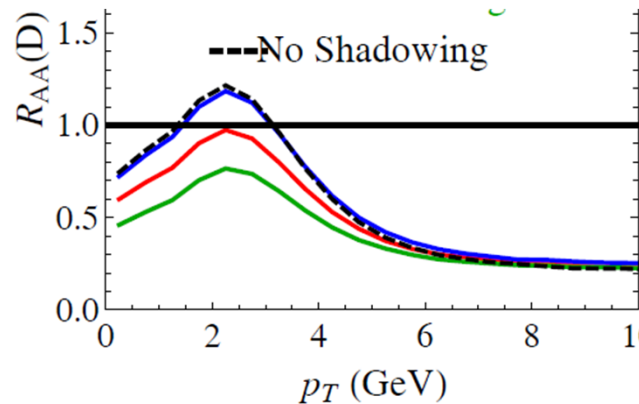
Consequence for the collective chase: ideally, all models should adopt the baseline; minimal action: check that the  $\chi^2$  with their own production model is at least as small as the one found in the baseline (rejection if  $\chi^2/NDF > 2$ ).

# 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  $v_2$



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

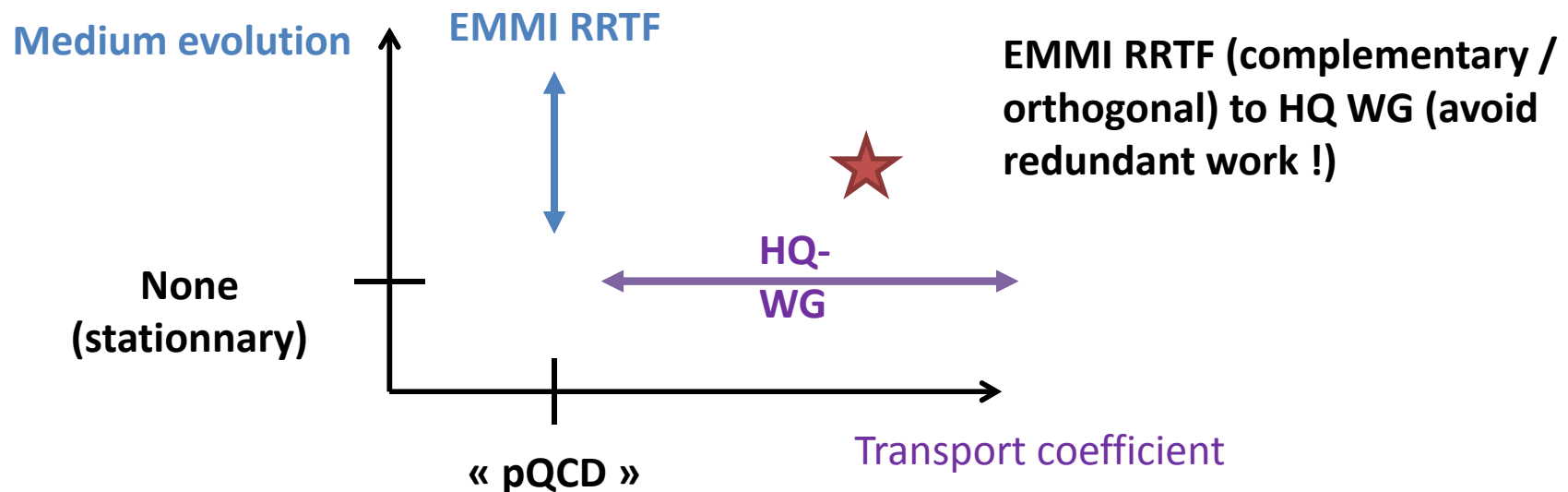
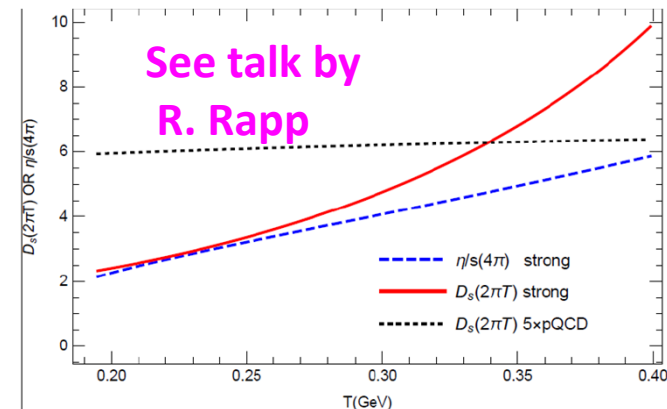
Shadowing seems to act in a nearly multiplicative way

# EMMI RRTF : Consequences from the bulk choice

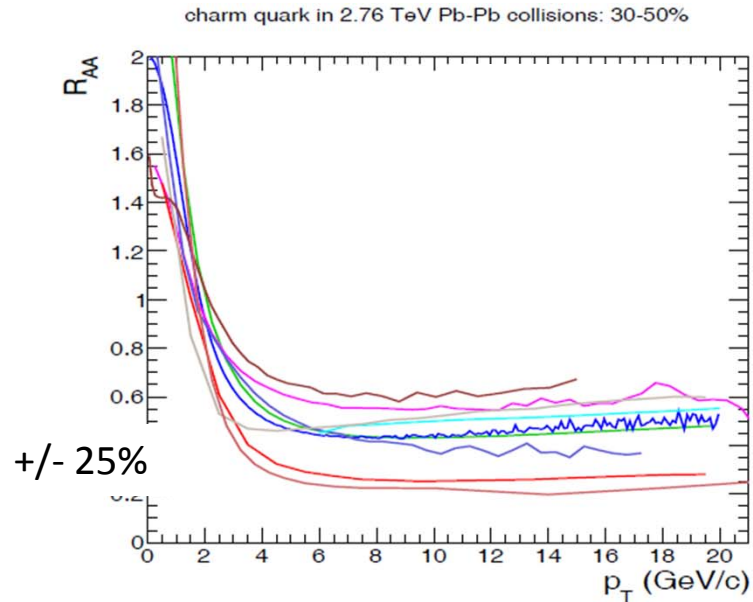
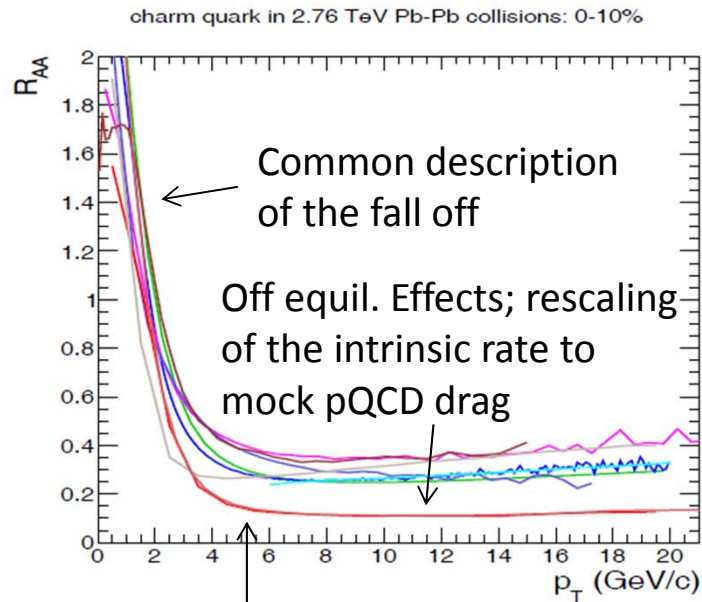
Question: What is the role of the different medium evolution models, and how do different predictions for the bulk cooling and expansion temperature in the current models manifest themselves in HF observables ?

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.

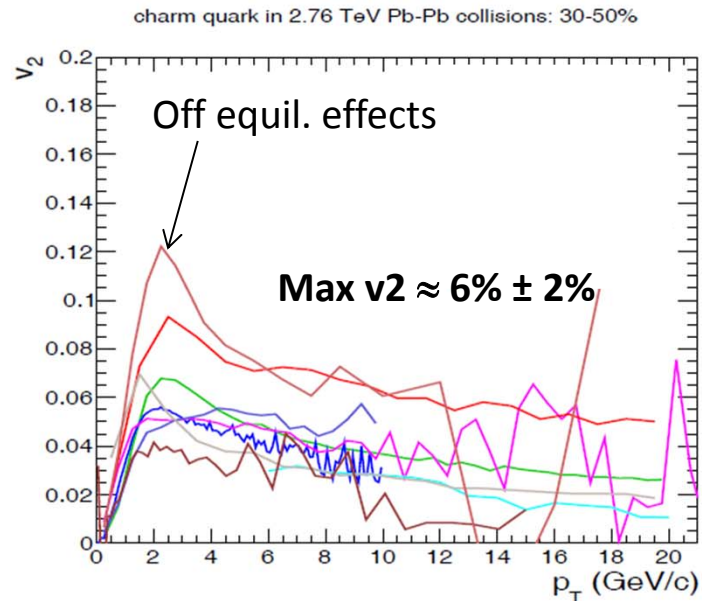
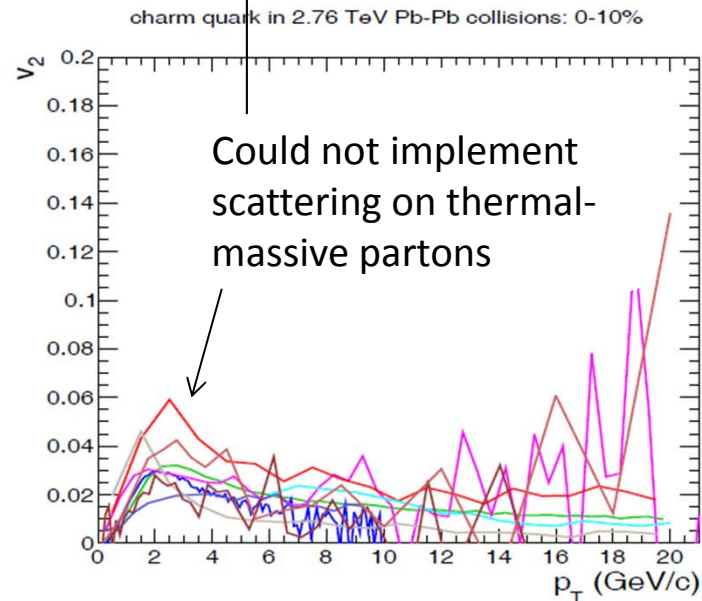
This allows to probe the effect of the bulk with a mechanism that has a  $D_s$  roughly similar to the one extracted from IQCD  
(caution: of course the weighting in the  $T(t)$  might differ a bit)



# Consequences from the bulk choice on c-quarks



More dispersion due to larger fluctuations

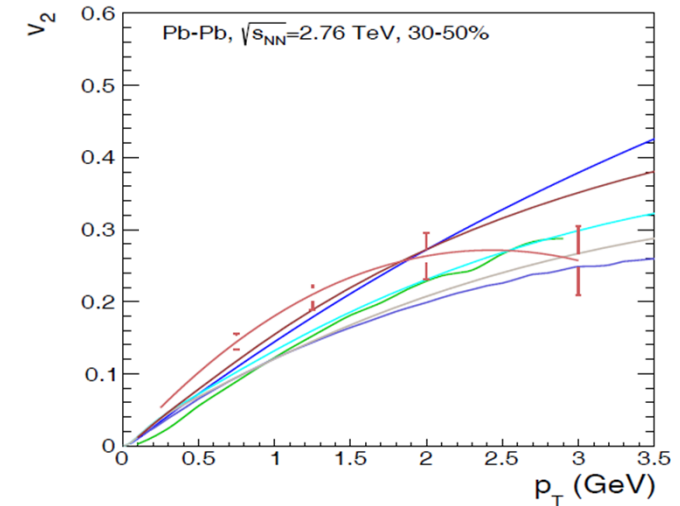


# EMMI RRTF : Consequences from the **bulk choice**

Under work: comparison of genuine bulk quantities (spectra and  $v_2$  of hadrons at freeze out) in order to establish some systematics

## Conclusions:

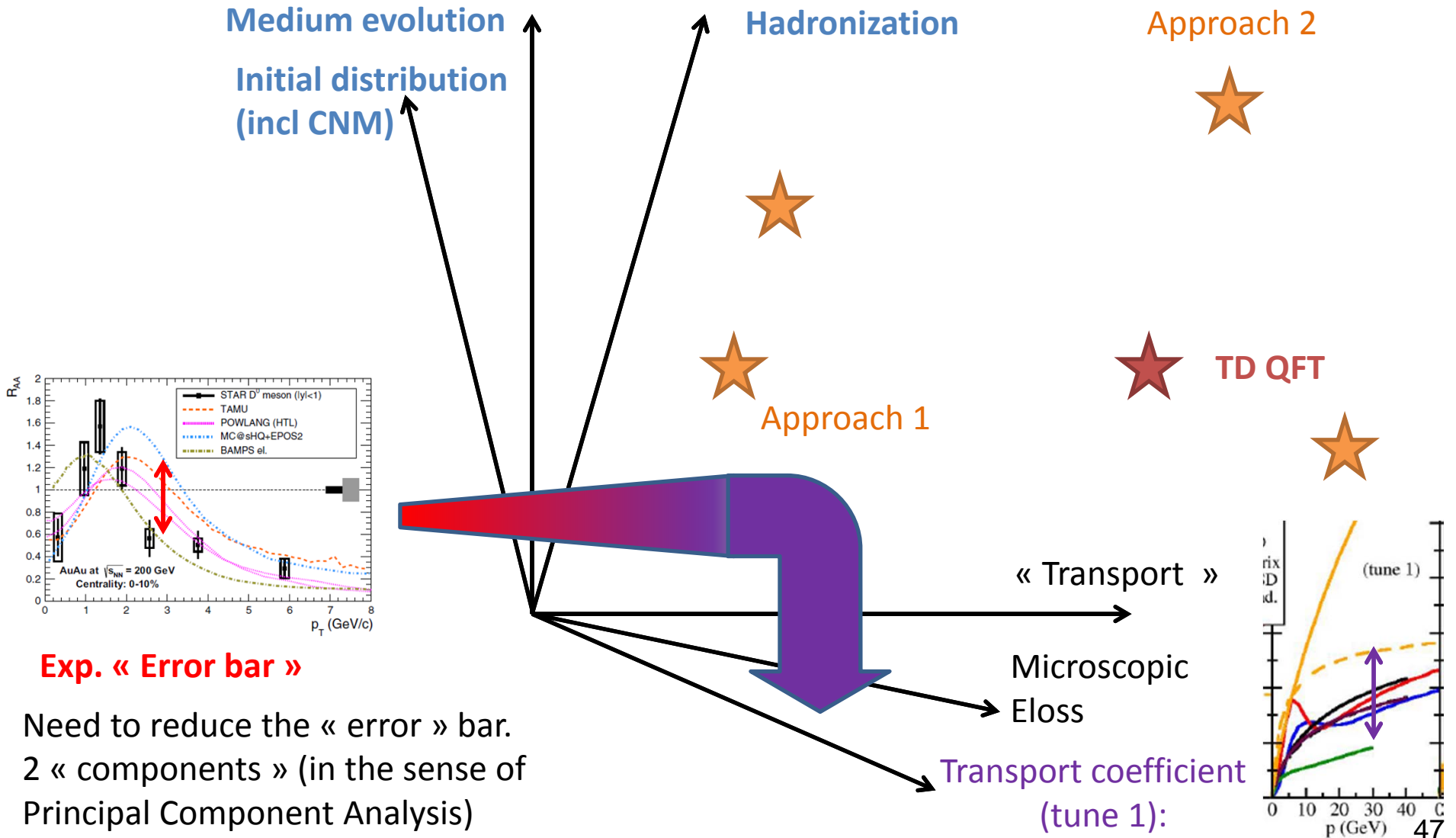
- (Even state of the art) **Bulk evolution can have significant consequences on the HF observables** ( $v_2$ :  $\approx \pm 33\%$  for most of them but can be more in some case)
- Off equilibrium effects present in Boltzman and Kadanoff-Baym modeling of the bulk must be understood in order to provide a reliable estimation of the transport coefficients from the data.
- For all frameworks relying on fluid dynamics to describe the bulk evolution, adopting a **limited number of « common hydro »** would permit to shrink the residuals.
- In //: need for a more precise study of the quantitative bulk characteristics that impact the HF observables



# Global Extraction

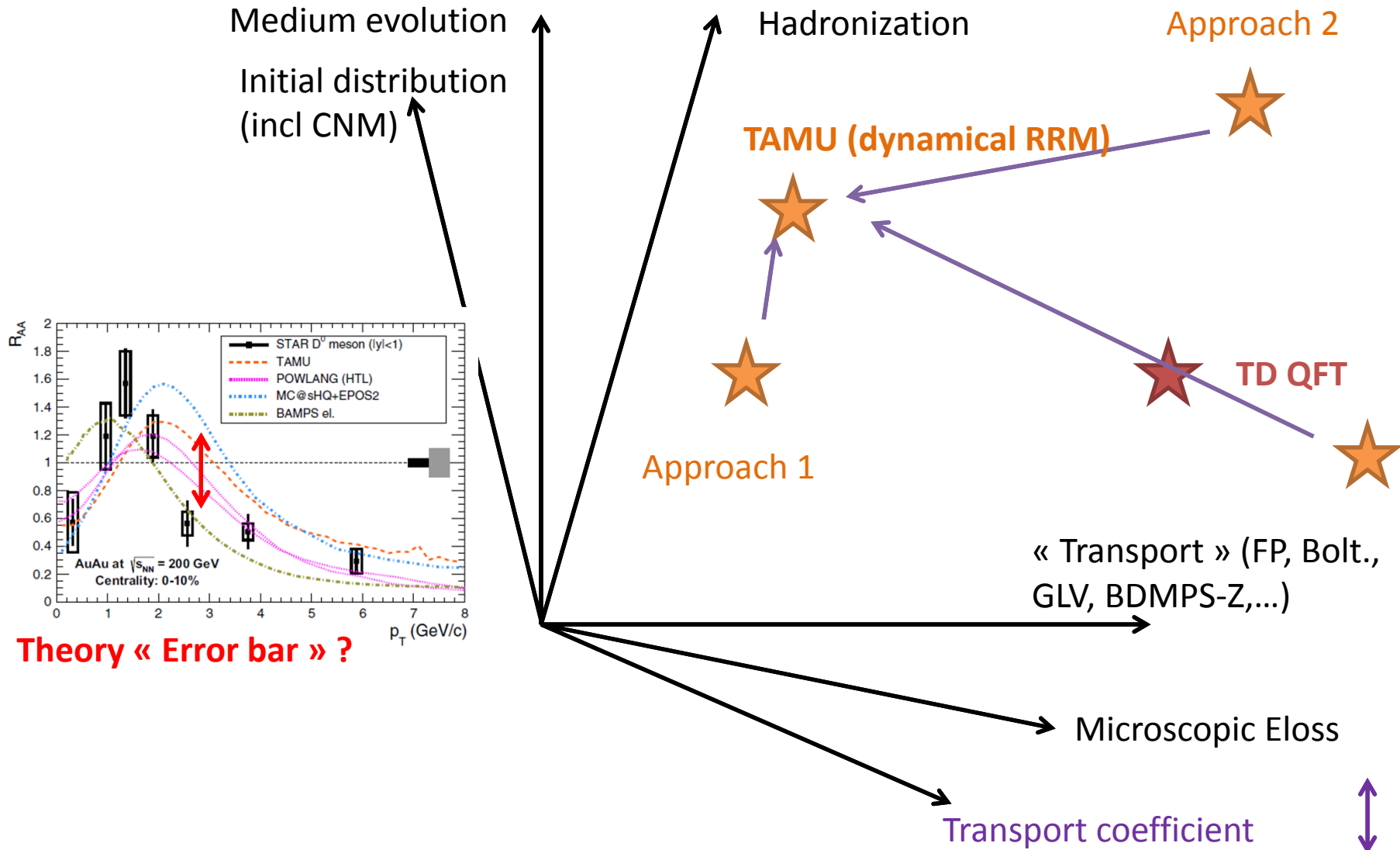
Theory « Error bar » ?

Where we stand...



# Understanding the role of various ingredients

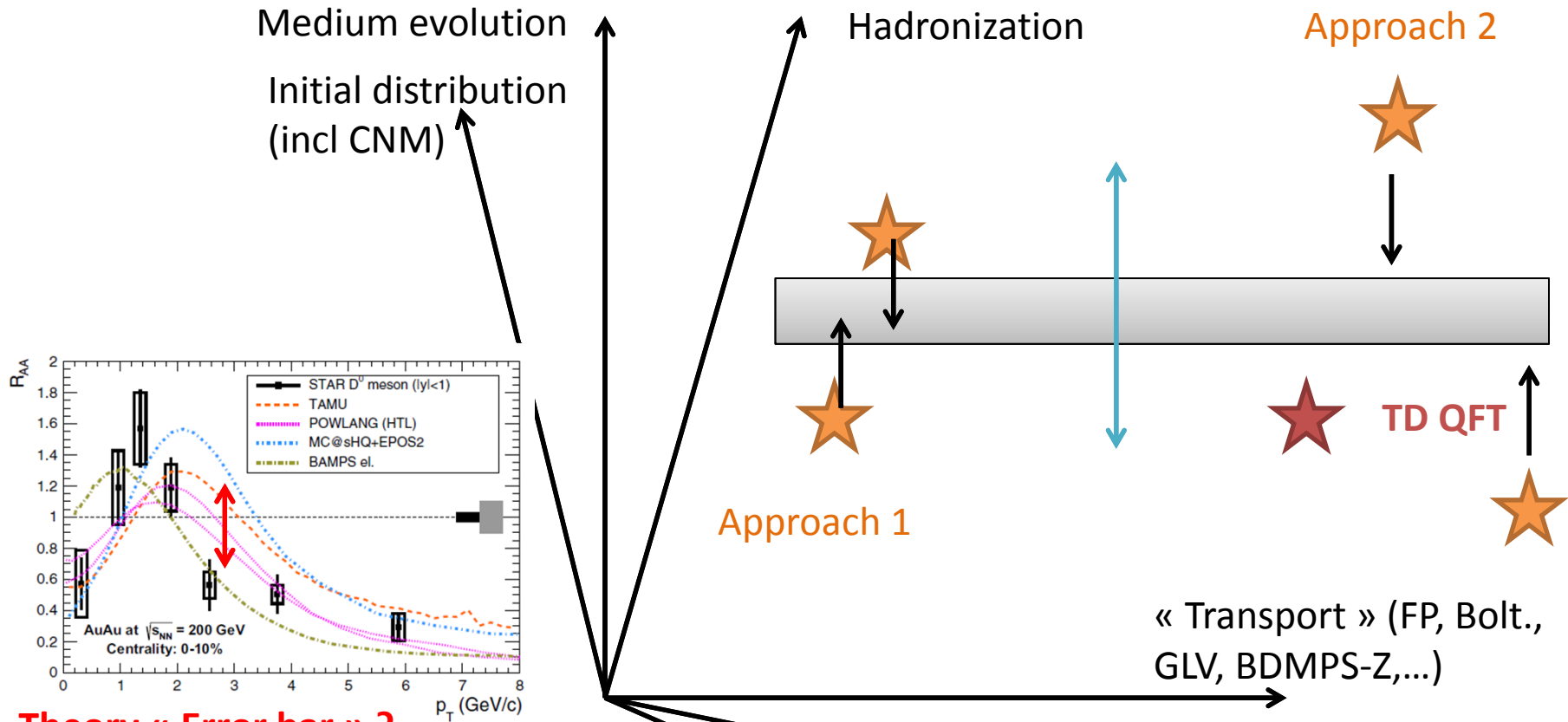
Method : One group collects one given ingredient of all others and proceed to systematic comparison





# Global Extraction

Suggested method once the role of each component is understood: adopt common bona fide ingredients (for some « standard component »)... Collective => need some consensus



Theory « Error bar » ?

Will REDUCE the residuals, but systematic uncertainties

Might constrain FC, with global syst. uncert.

Microscopic Eloss

Transport coefficient

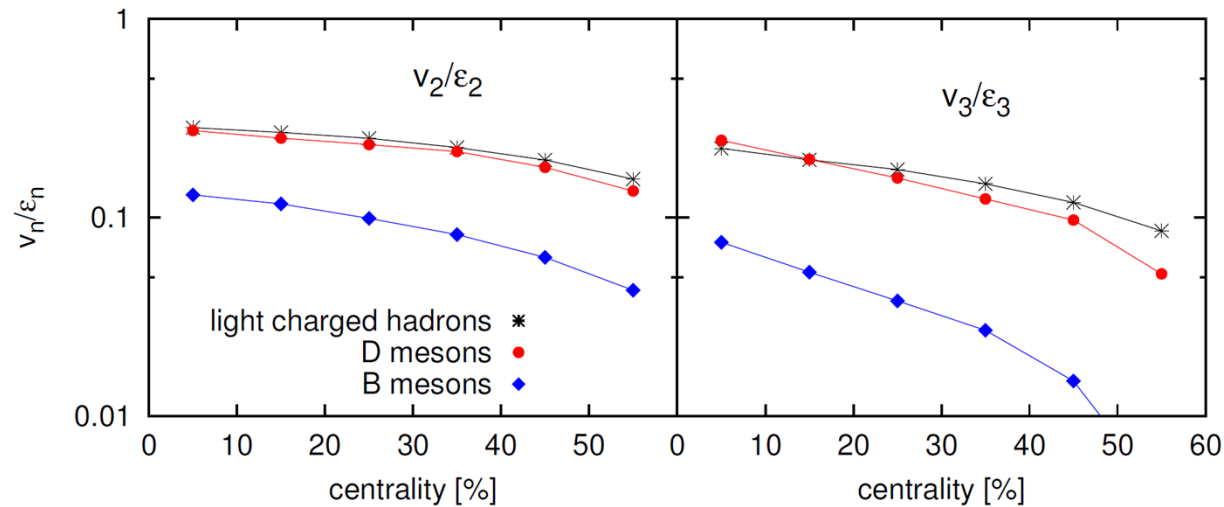


## Preliminary conclusions

- After 10 years of individual work, the open heavy flavour community has moved towards a bit of collectivity.
- Benefits are expected in the upcoming times
- This also implies that some models will be ruled out, while others – whose applicability ranges remain to be settled – will allow a more robust description of QGP probing with heavy flavors...
- ... which is exactly what science should be.

# Mid-term Perspectives

- More sophisticated observables (higher flow components, correlations,... ):

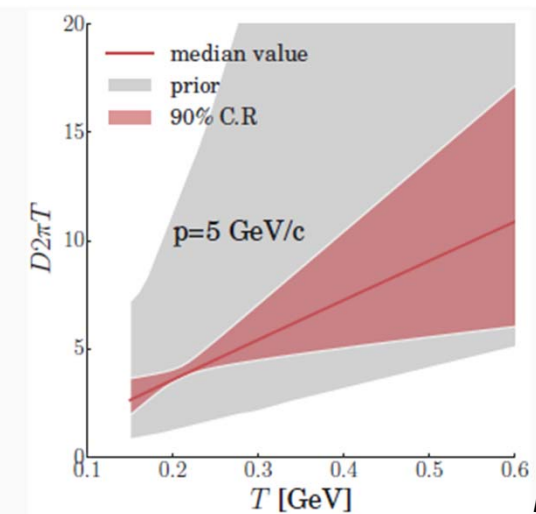
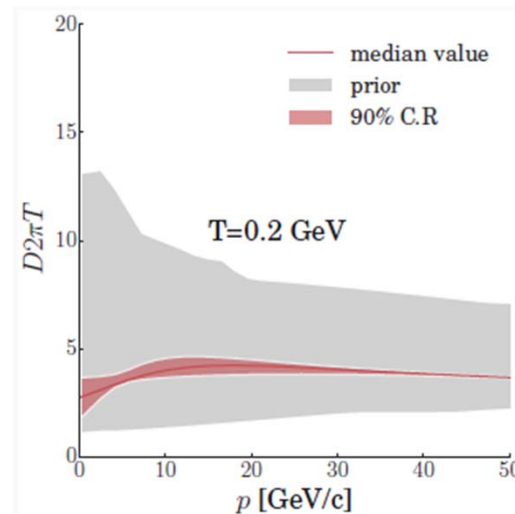


Up to now, no smoking gun => should just be part of the global fit

- « No model approach » : Bayesian analysis pursued by the Duke group

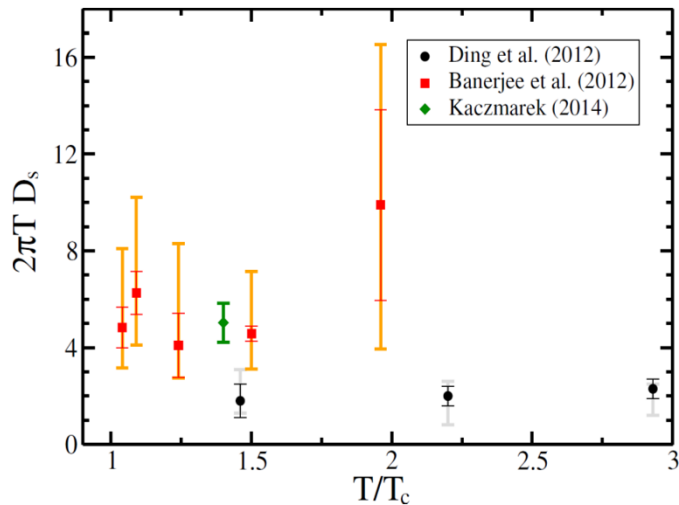
$$D_s(T, p) = \frac{1}{1+(\gamma^2 p)^2} (D_s 2\pi T)^{\text{lin}}(T; \alpha, \beta) + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2} (D_s 2\pi T)^{\text{pQCD}}(T, p)$$

Data

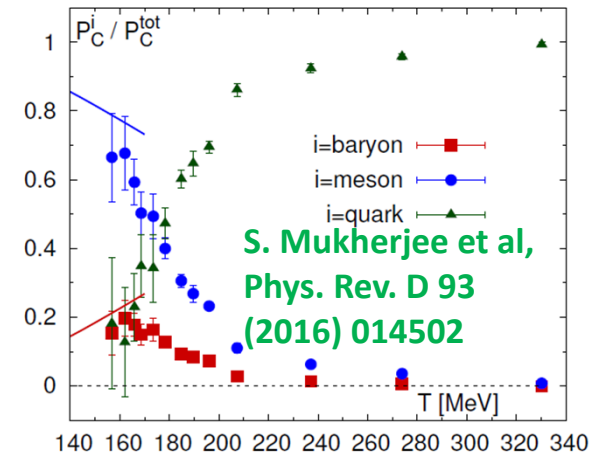


# Mid-term Perspectives

- Each individual model designed to cover the full  $p_T$  range should satisfy « basic constrains » at the phase boundaries (low and high  $p_T$  ; low and high  $T$ )

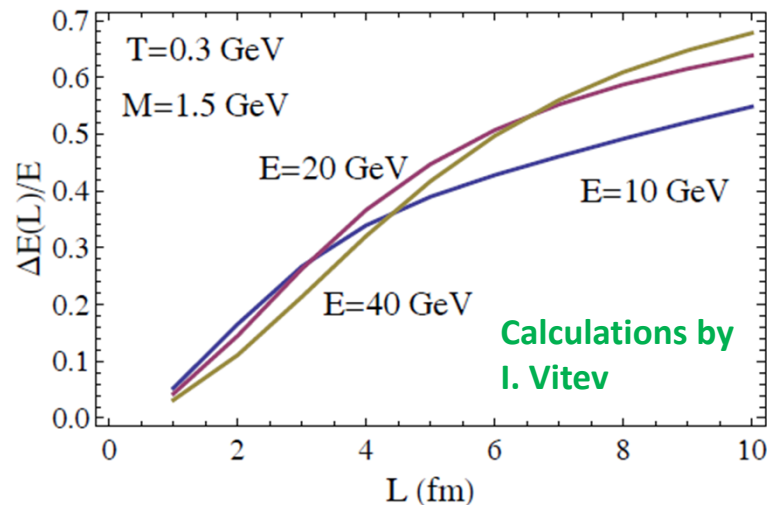


Be in the bulk part of world IQCD data on  $D_s$  at small  $p$



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

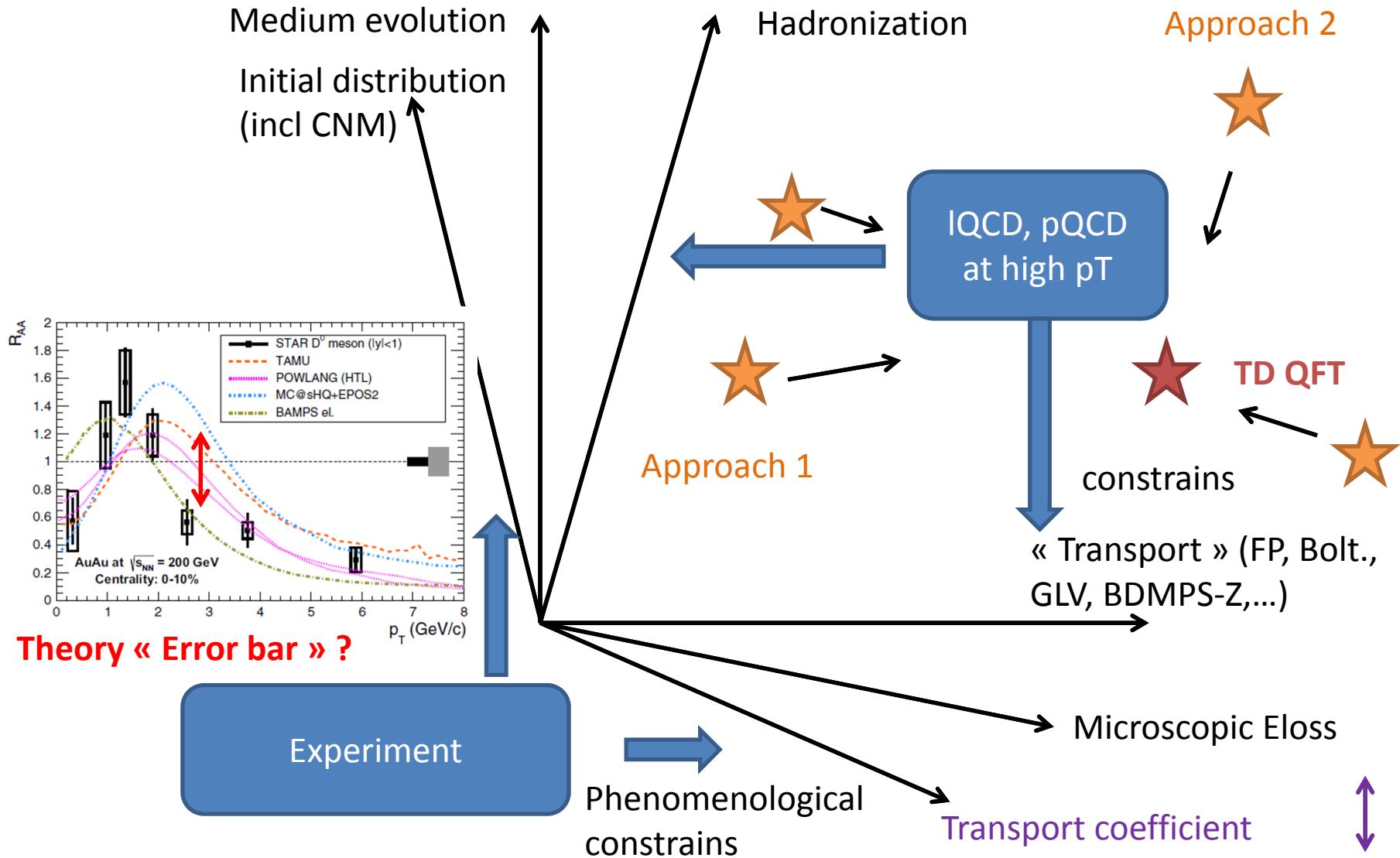
Reproduce the gradual transition from heavy quarks to heavy mesons around  $T_c$



Be compatible with the state of the art multi-gluonic radiative Energy loss at large  $p_T$

# Global Extraction

Method : « use constrains »... collaborative; too generic, exhausts human ressources



## Long-term Perspectives

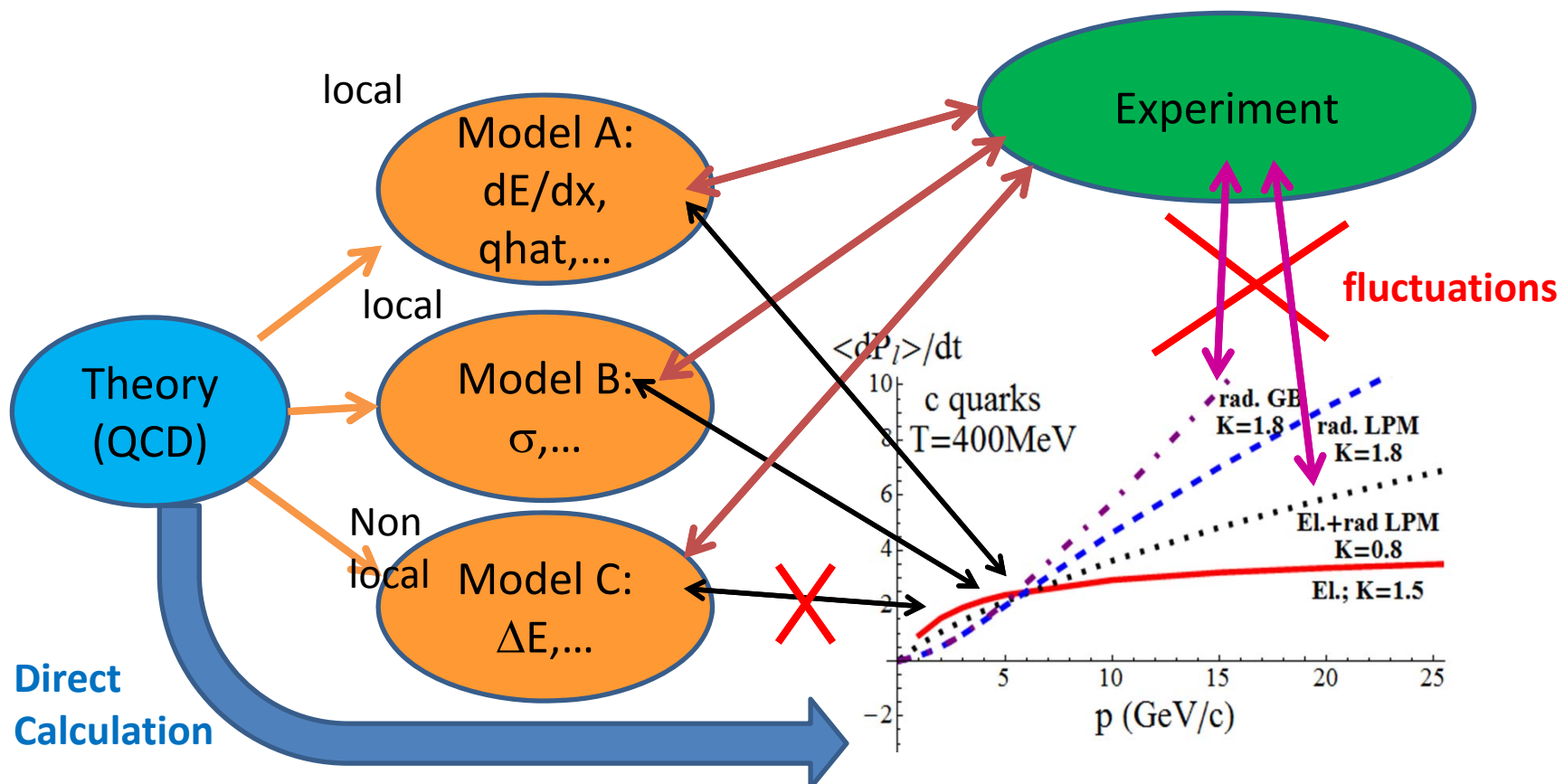
- Input from IQCD at finite heavy quark momentum
- More insight from IQCD on the QGP effective DF and their dynamics
- Schwinger – Dyson at finite temperature

Back UP

# Some thoughts on methodology

2005-2015 was the era of model development for OHF in URHIC (nearly every idea was publishable)... Now it is time to think...

But maybe physics is not so bad with us ... what if some “mesoscopic” coefficients – like f.i. momentum loss per unit time -- have a major influence (nearly) irrespective of the (microscopic) model ?





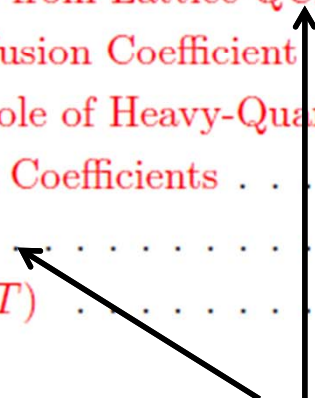
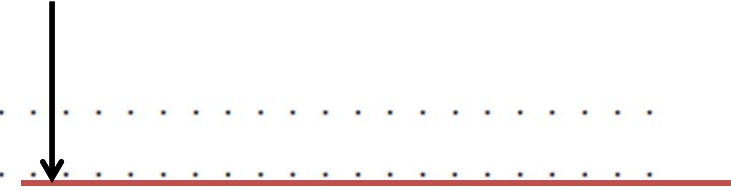
# EMMI RRTF: Some focus

## Transport coefficients

### 4 Transport Coefficients

- 4.1 General Features . . . . .
- 4.2 Comparison of Existing Models . . . . .
- 4.3 Information and Constraints from Lattice QCD . . . . .
  - 4.3.1 Computations of Diffusion Coefficient . . . . .
  - 4.3.2 Susceptibilities and Role of Heavy-Quark Mass . . . . .
- 4.4 Repository of Fokker-Planck Coefficients . . . . .
- 4.5 High- $p_T$  Energy Loss and  $\hat{q}$  . . . . .
- 4.6 "Applicability Chart" in  $(p, T)$  . . . . .

Up to there, we were all good friends..



Consensus on the fact that 2 clear cut regimes:

- Small  $p_T$ , where IQCD should provide strong constrains in the future
- Large  $p_T$ , where all models should converge -> *unique* pQCD with *unique* transp. Coeff.

No Consensus on :

- Room for intermediate  $p_T$
- Whether physics boils down to Fokker Planck & Transport coefficients
- Should we abandon HTL inspired models around  $T_c$
- **What to do with models not fulfilling these constrains ?**
- How to go beyond the present models (not the goal of EMMI RRTF)

Open issues

# EMMI RRTF: Some focus

## Transport coefficients

### 4 Transport Coefficients

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Up to there, we were all good friends..



What is a c « quark » around  $T_c$  ?

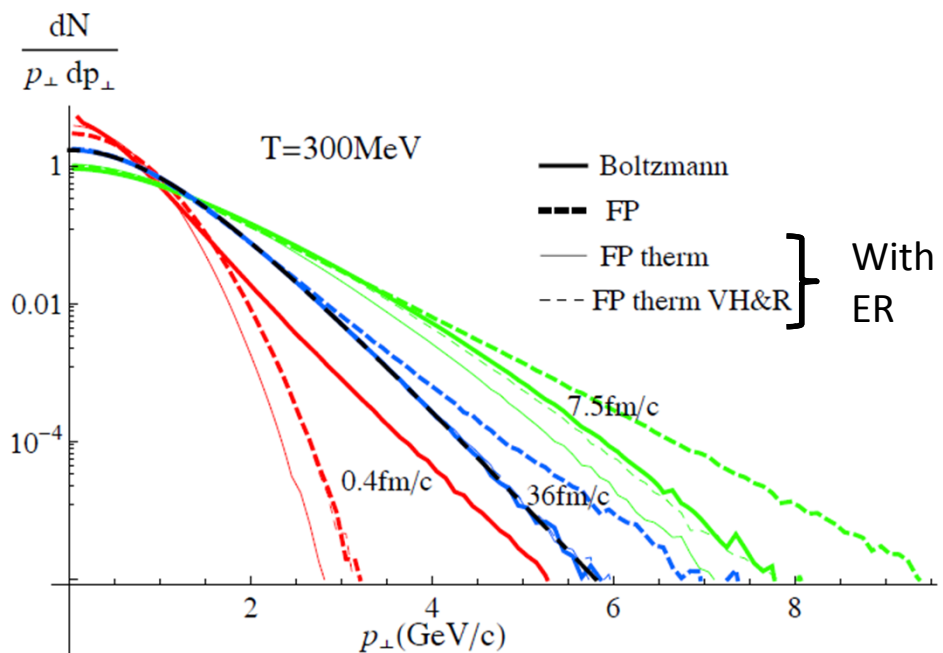
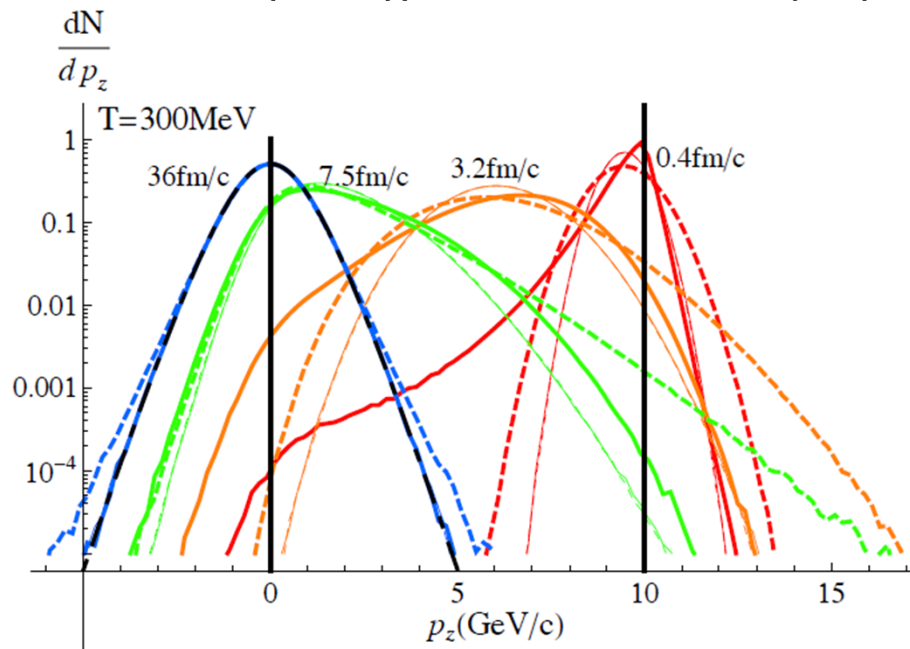
- A quasi particle, as treated by many practitioners ? Seems to be ruled out by IQCD
- A spectral function
- A mix state between c-state and D-state ?

How to deal consistently with the transport of such object ? Outside the reach of EMMI

# Boltzmann vs Langevin Dynamics

Langevin from Boltzmann view point:

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

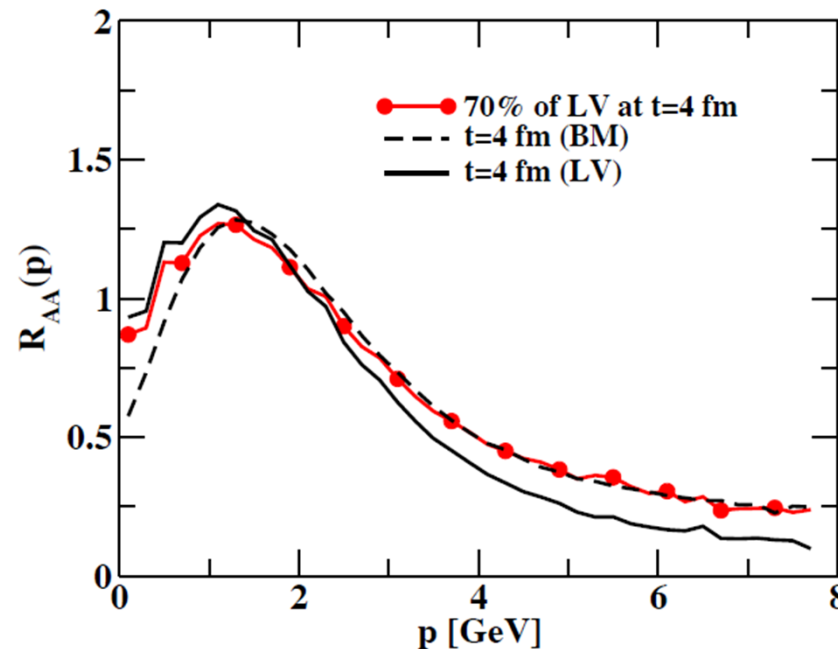


- These differences should be seen in observables like g-HQ correlations

# Boltzmann vs Langevin Dynamics

Langevin from Boltzmann 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)



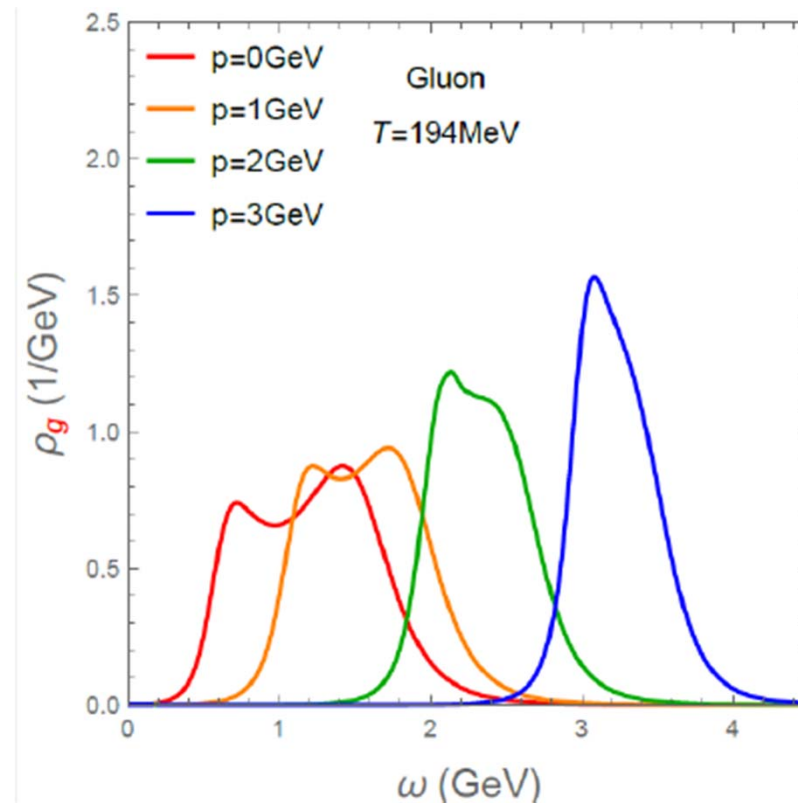
S Das et al, Phys. Rev. C 90,  
044901 (2014)

- 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

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 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)

# Constrains at high $p_T$

- Any reliable Energy loss model should be compatible with the  $D_s$  IQCD world data at small  $p_T$  and with state of the art energy loss calculations at large  $p_T$

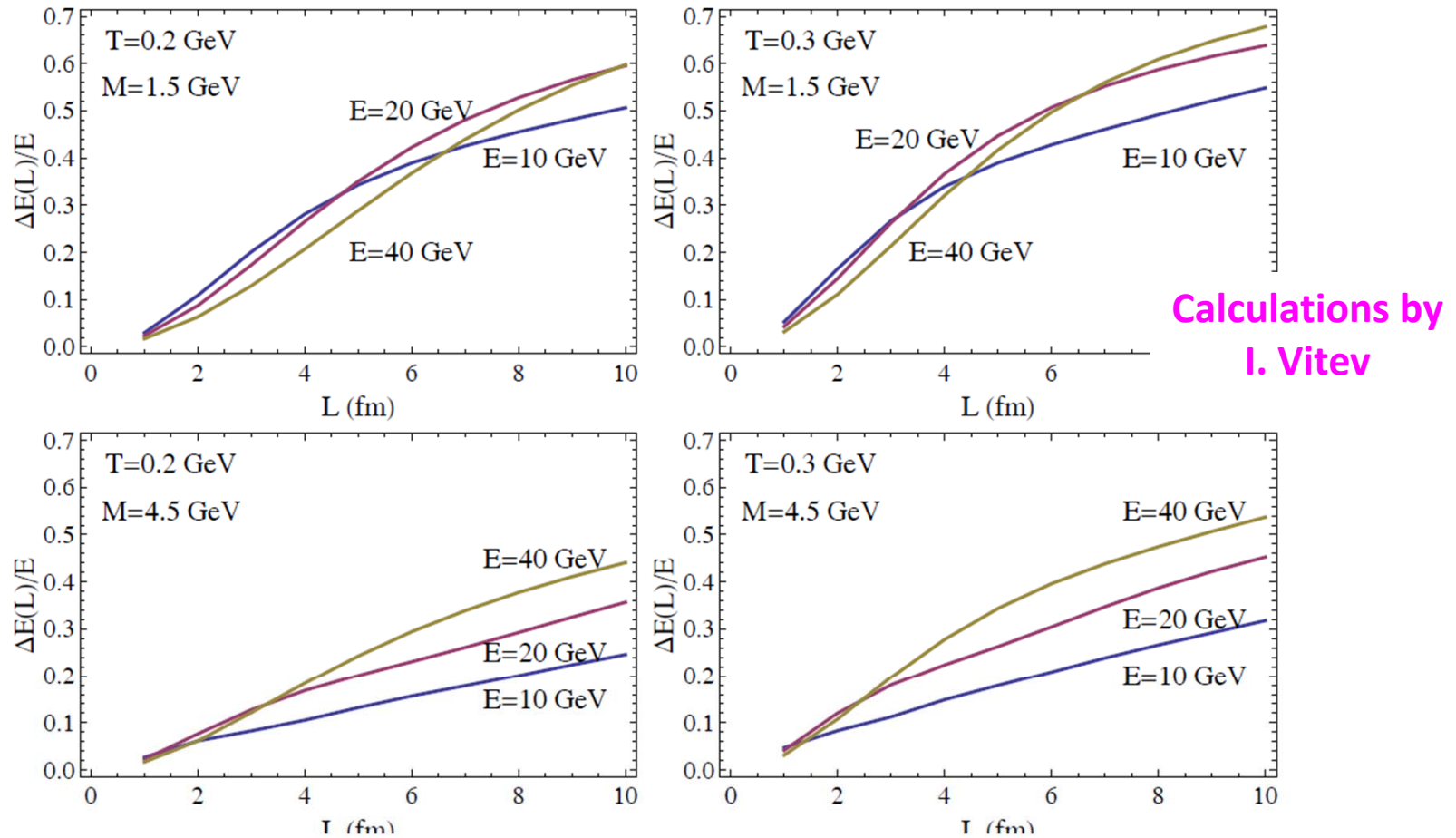


Figure 21: Relative energy loss,  $\Delta E/E$ , of  $c$ -quarks (upper panels) and  $b$ -quarks (lower panels) for the NLO calculation presented in Sec. 5.4, including multi-gluon emission, as a function of the path-length  $L$  for various initial energies,  $E$ , and fixed QGP temperatures of  $T=0.2$  GeV (left panels) and  $T=0.3$  GeV (right panels).

# The weak to strong axis for HQ

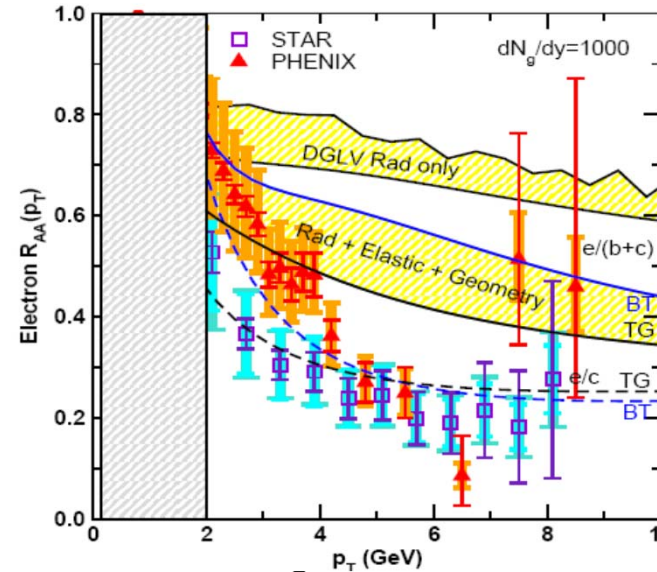
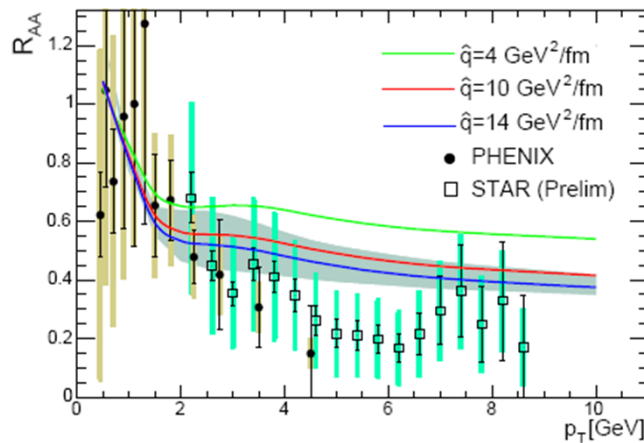
“Naive” pQCD  
(WHDG, ASW,...)  
 $\hat{q} \approx 1 \text{ GeV}^2/\text{fm}$

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

“Optimized”  
pQCD (ok with  
pions)

ASW (pure rad. energy loss;  
extended BDMPS)

coll Eloss (BT and TG) + radiative Eloss

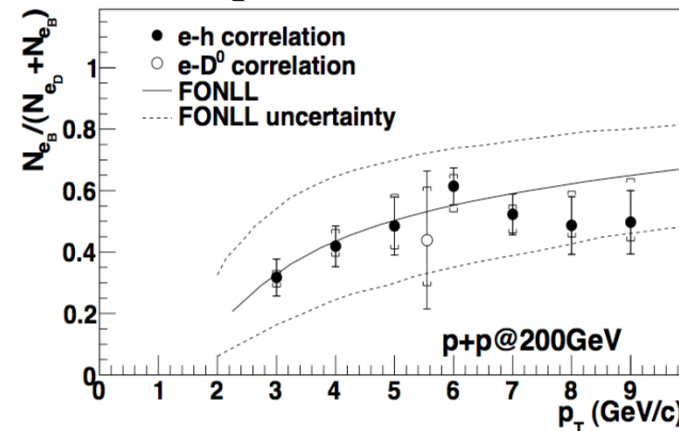


WHDG

Beauty is the problem... but beauty is found to contribute

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

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



M Aggarwal et al, STAR, PRL 105 202301

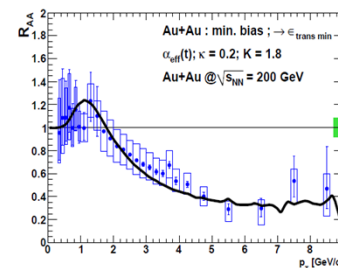
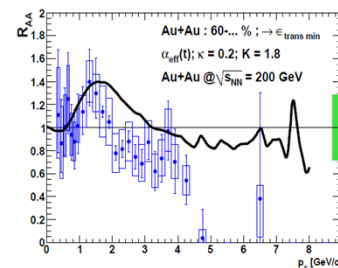
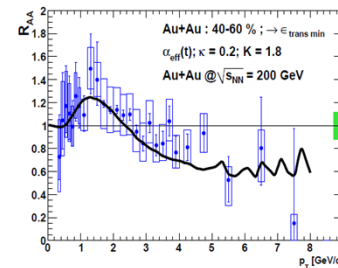
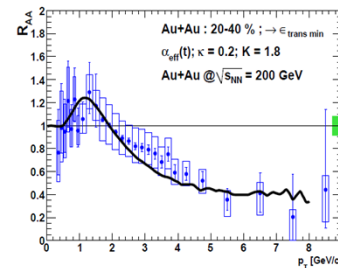
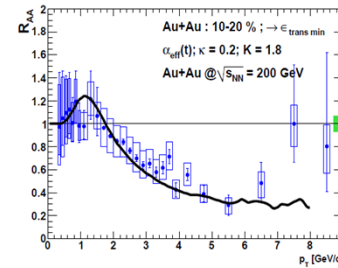
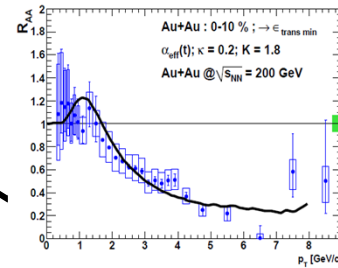
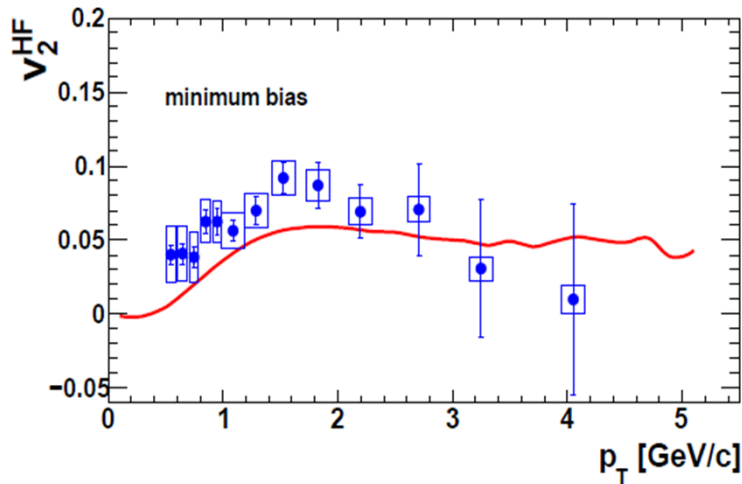
# The weak to strong axis for HQ

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

“Optimized”  
pQCD

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

Collisional model with running  $\alpha_s$  and optimized  
gluon propagator (Peshier, Gossiaux and Aichelin,  
BAMPS)





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Running  $\alpha_s$  (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

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

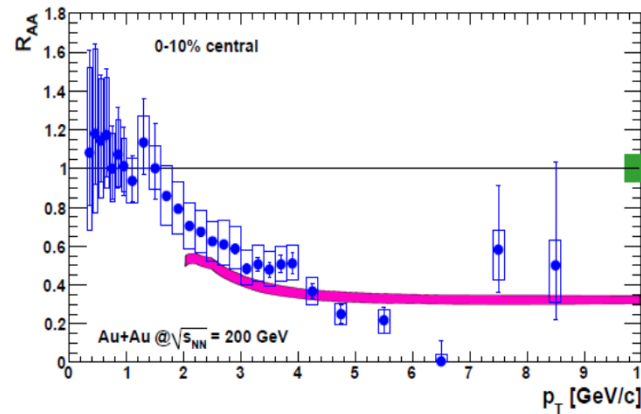


FIG. 41: (Color online)  $R_{\text{AuAu}}$  in 0–10% centrality class compared with a collisional dissociation model [78] (band) in Au+Au collisions.

# The weak to strong axis for HQ

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Distorsion  
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existence  
QGP, R. S  
Zhang 09(

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

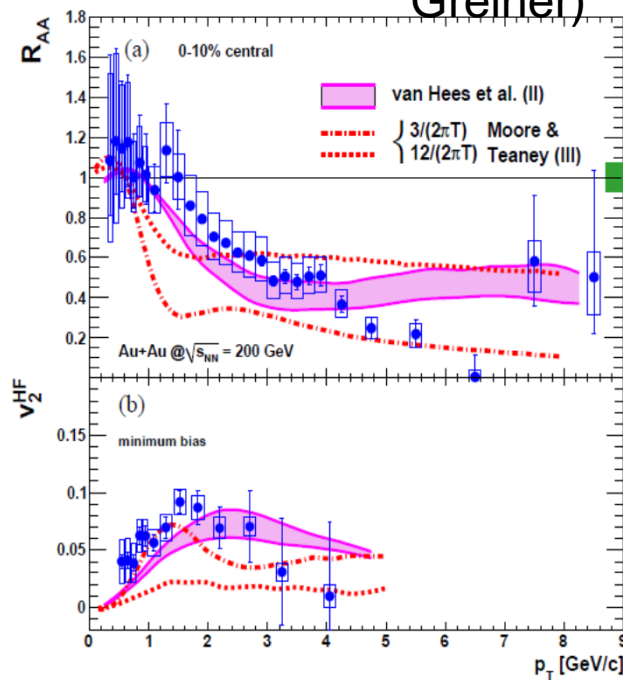


FIG. 40: (Color online) Comparison of Langevin-based models from [74–76] to the heavy flavor electron  $R_{\text{AuAu}}$  for 0–10% centrality and  $v_2$  for minimum-bias collisions.

# The weak to strong axis for HQ

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

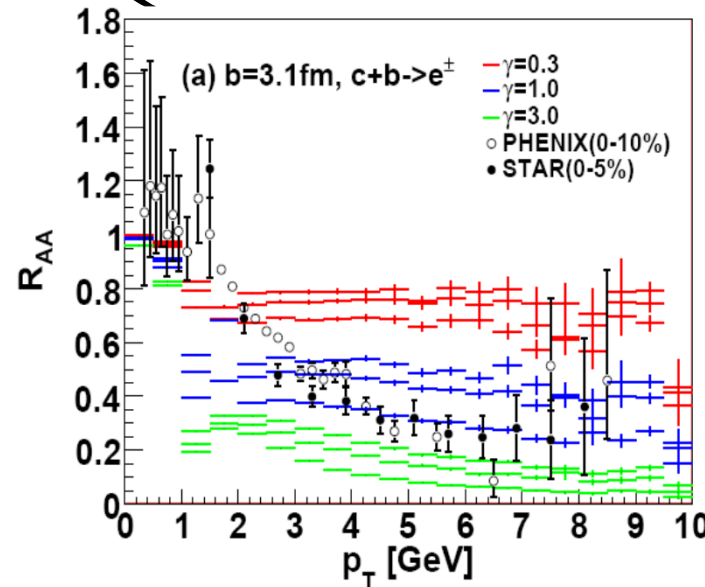
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Bound states diffusion or non-  
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scattering models (see R. Rapp  
03.1096 [hep-



ADS/CFT  
(akamatsu et  
al)

# The weak to strong axis for HQ

“Naive” pQCD (WHDG, ASW,...)

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

So-called “Failure of pQCD approach” aka “the non photonic single electron puzzle” ... recently claimed to be solved by pQCD practitioners

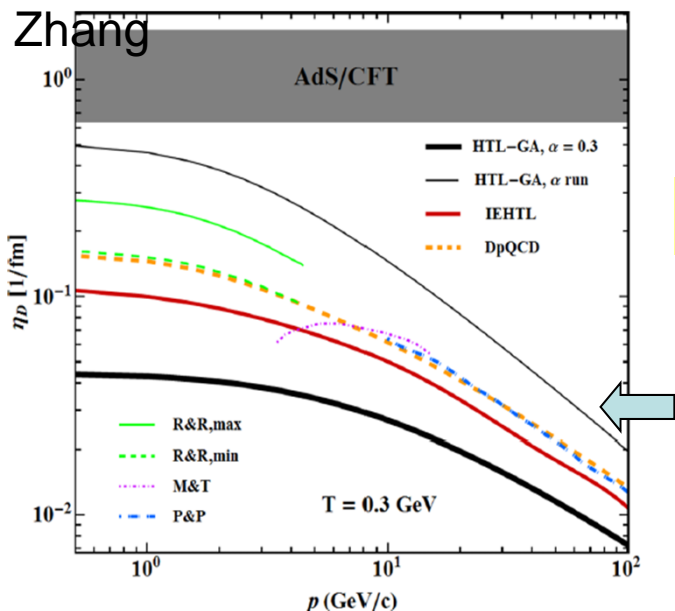
“Optimized” pQCD

Running  $\alpha_s(T)$  and  $m_{q/g}(T)$  (Berrehrach et al. DQPM model Frankfurt)

Running  $\alpha_s$  (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W

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



Big puzzle:

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

ADS/CFT

At LHC