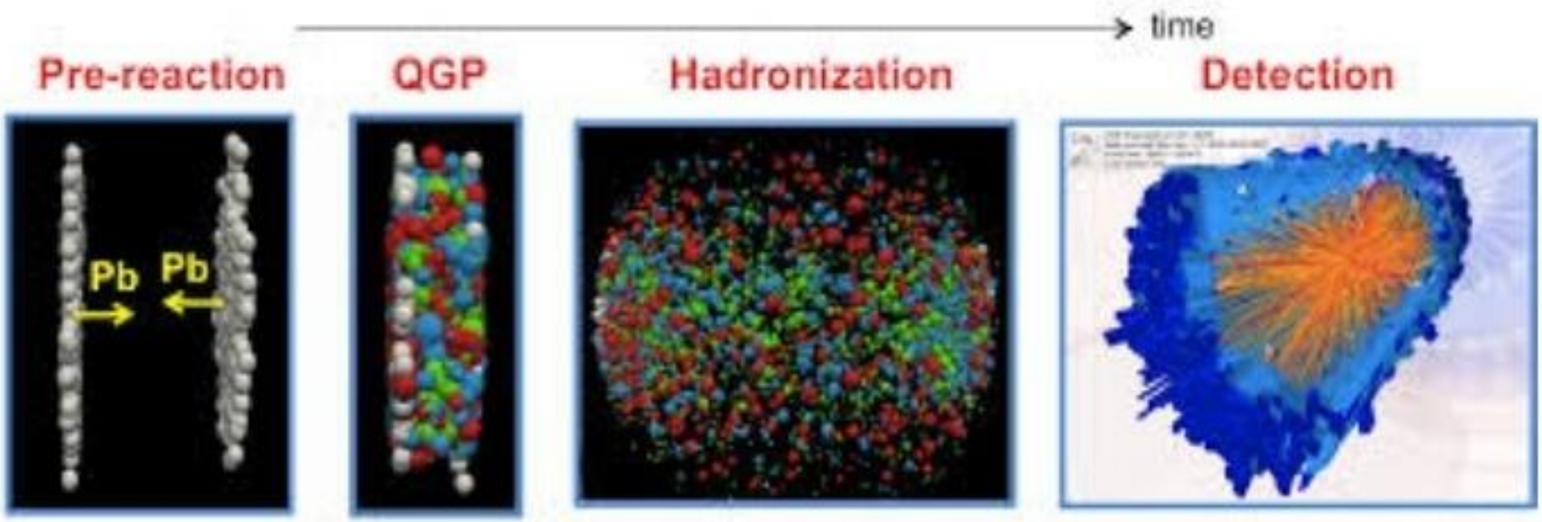
Theory Overview on open Heavy Flavor



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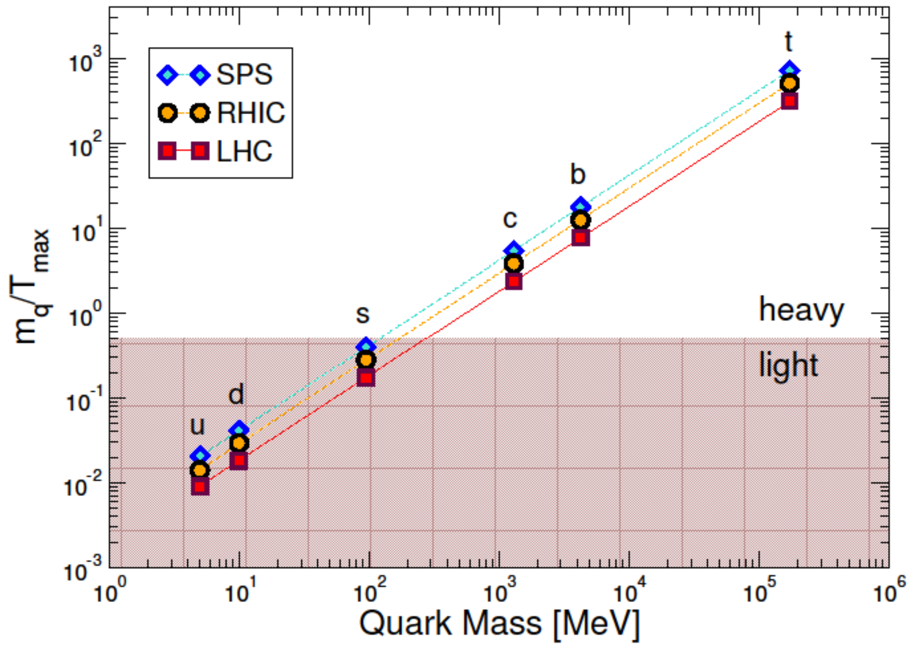
Goa, India

Exploring High-MuB Matter with rare Probes
11-15 October 2021, ECT* - Trento

OUTLINE ....

- Introduction
- Heavy quark diffusion in QGP
- Heavy meson diffusion in hadronic matter
- Impact of hadronic phase on heavy quark observables
- Possible impact of pre-equilibrium phase
- Summary and outlook

Heavy Quark & QGP



SPS to LHC

$\sqrt{s} = 17.3 GeV\ to\ 2.76 TeV$ **~100 times**

$T_i = 200\ MeV\ to\ 600\ MeV$ **~3 times**

$$M_{c,b} >> \Lambda_{QCD}$$

Produced by pQCD process (before equilibrium)
(Early production)

$$\tau_{c,b} >> \tau_{QGP}$$

They go through all the QGP life time

$$M_{c,b} >> T_0$$

No thermal production

Boltzmann Kinetic equation

$$\left(\frac{\partial}{\partial t} + \frac{P}{E}\frac{\partial}{\partial x} + \mathrm{F}.\frac{\partial}{\partial p}\right) f\left(x, p, t\right) = \left(\frac{\partial f}{\partial t}\right)_{col}$$

- The plasma is uniform ,i.e., the distribution function is independent of x.
- In the absence of any external force, F=0

$$\boxed{R(p,t) = \left(\frac{\partial f}{\partial t}\right)_{col} = \int d^3k\left[\omega(p+k,k) f(p+k) - \omega(p,k) f(p)\right]}$$

$$\omega(p,k) = g\int \frac{d^3q}{(2\pi)^3} f'(q) v_{q,p}\sigma_{p,q\to p-k,q+k}$$

$\longrightarrow$ is rate of collisions which change the momentum of the charmed quark from p to p-k

$$\omega(p+k,k) f(p+k) \approx \omega(p,k) f(p) + k.\frac{\partial}{\partial p}(\omega f) + \frac{1}{2}k_i k_j \frac{\partial^2}{\partial p_i \partial p_j}(\omega f)$$

$$\boxed{\frac{\partial \mathbf{f}}{\partial \mathbf{t}} = \frac{\partial}{\partial \mathbf{p_i}}\left[\mathbf{A_i}(\mathbf{p})\mathbf{f} + \frac{\partial}{\partial \mathbf{p_j}}\left[\mathbf{B_{ij}}(\mathbf{p})\mathbf{f}\right]\right]}$$

B. Svetitsky PRD 37(1987)2484

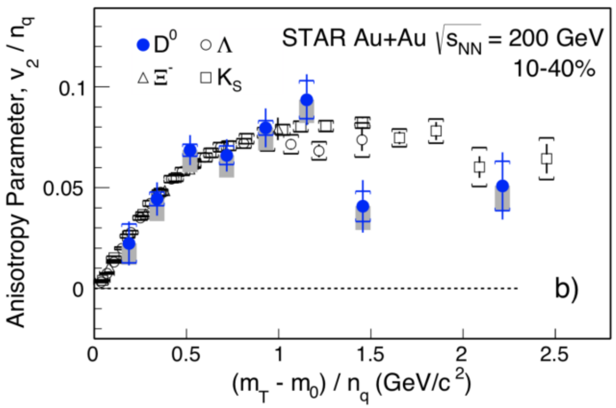
where we have defined the kernels

$$\mathbf{A_i} = \int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i} \quad \rightarrow \textbf{Drag Coefficient}$$

$$\mathbf{B_{ij}} = \int \mathbf{d^3k}\,\omega(\mathbf{p},\mathbf{k})\mathbf{k_i}\mathbf{k_j} \quad \rightarrow \textbf{Diffusion Coefficient}$$

Heavy quark physics at different scales

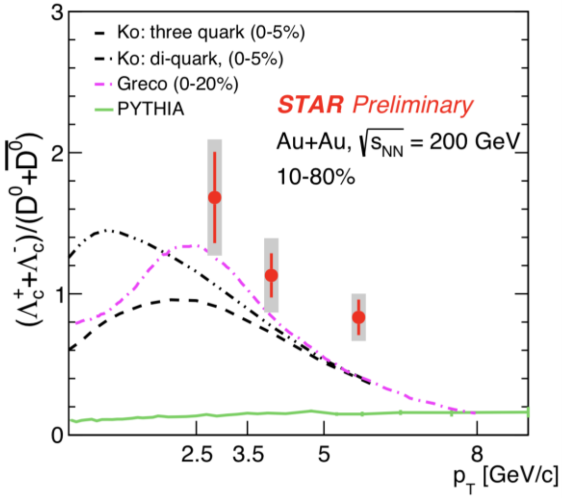
low p_T



Study thermalization process of HQ

Constrain diffusion coefficient D_s

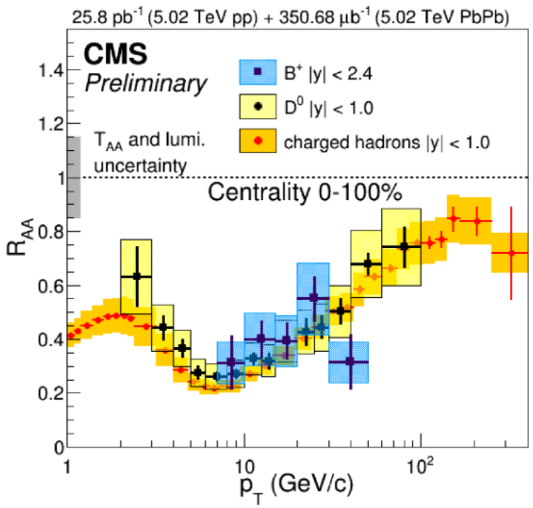
medium p_T



Study hadronization process of HQ

Constrain hadron wave-function

high p_T

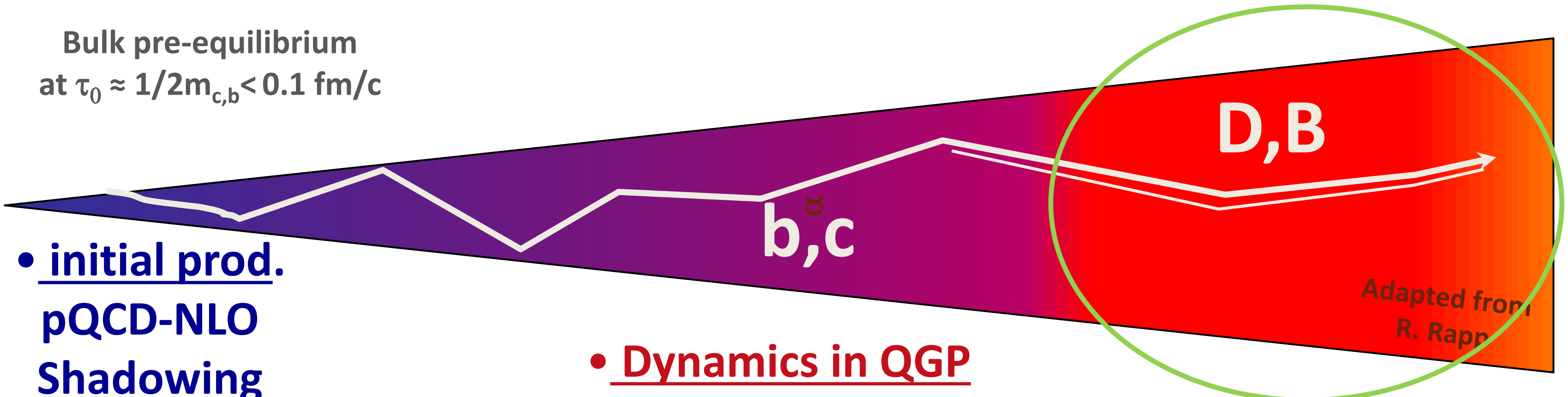


Study parton energy loss and mass effect

Constrain jet transport parameter $\hat{q}$

S. Cao (HP 2018)

Studying the HF dynamics in HIC



- **<u>initial prod</u>.**

pQCD-NLO
Shadowing
Pre-equilibrium Effect/Glasma
Electromagnetic filed

- **<u>Dynamics in QGP</u>**

Heavy quark QGP interaction

Transp. coeff. of QCD matter

-> thermalization ?!

Mass & color in Jet quenching

Heavy quark momentum evol.

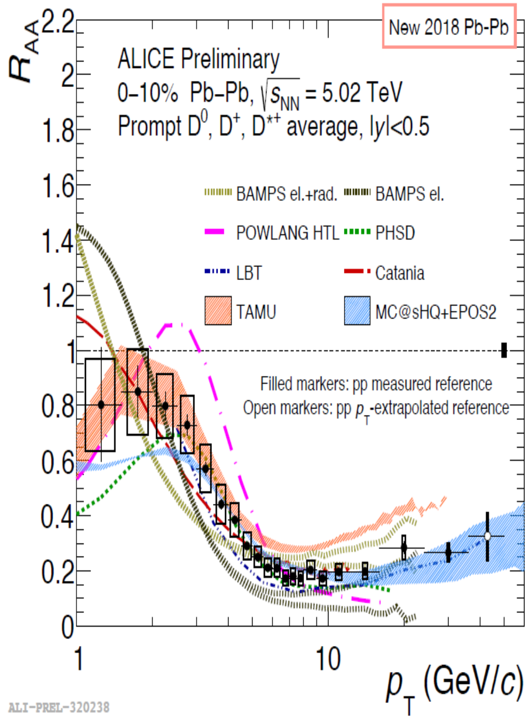
(Langevin/Boltzmann/E. loss model)

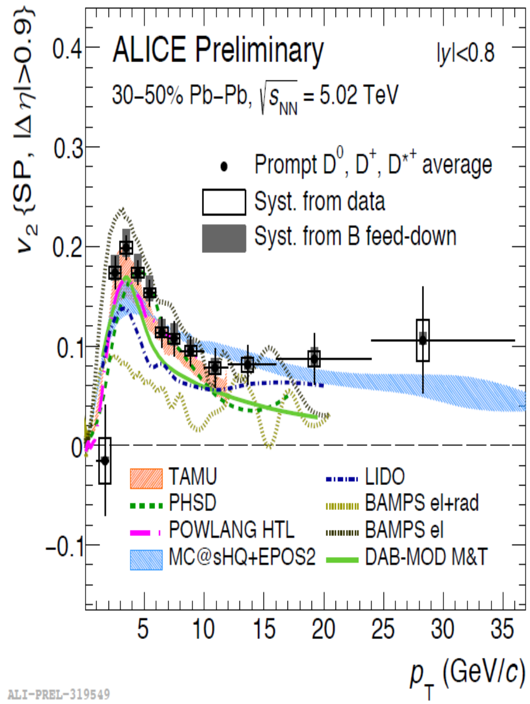
- **<u>hadronization:</u>**

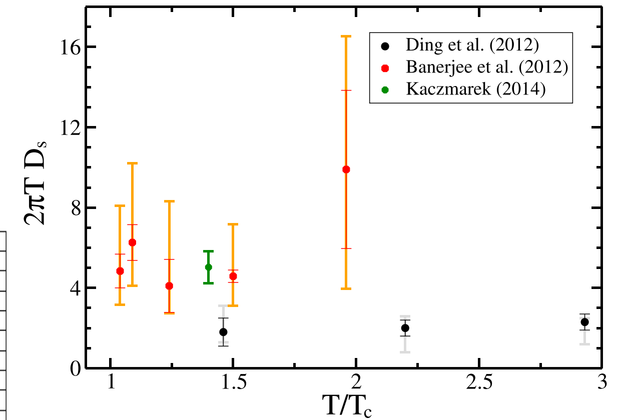
coalescence and/or fragmentation.

Hadronic rescattering

R_{AA} and v_2
Comparison with models





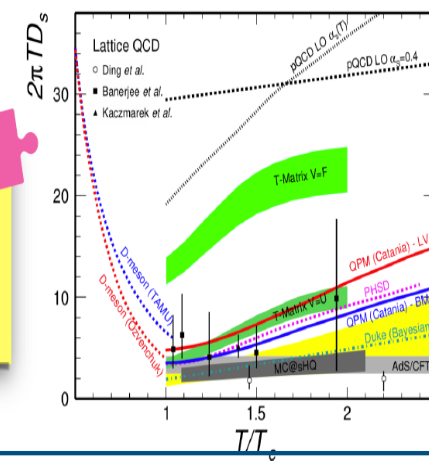


TAMU: PLB 735,445-450(2014), arXiv:1905.09216
PHSD: PRC 92, 014910 (2015)
POWLANG: EPJC 75,121(2015)
MC@sHQ+EPOS2: PRC 89 014905 (2014)
LBT: PLB 777 (2018) 255-259
LIDO: arXiv:1810.08177
BAMPS: JPG 42, 115106 (2016)
Djordevic: PRC 92, 024918 (2015)
CUJETS3.0: JHEP 02 (2016) 169
SCET: JHEP 03 (2017) 146
DAB-MOD: PRC 96 (2017) 064903
Catania: Eur. Phys. J. C (2018) 78: 348

➡ Simultaneous description of R_{AA} and v_2 **is challenging** in the whole measured p_T range!

➡ Experimental measurements start to **provide constraint to the models** for the characterization of the charm and beauty interaction with the medium

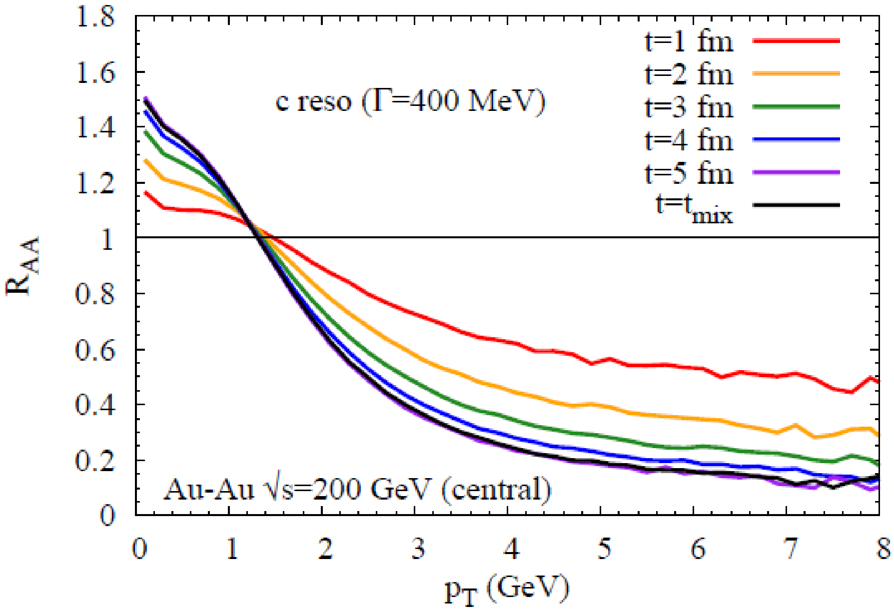
➡**constraints on plasma transport parameters**, such as the heavy-quark diffusion coefficient

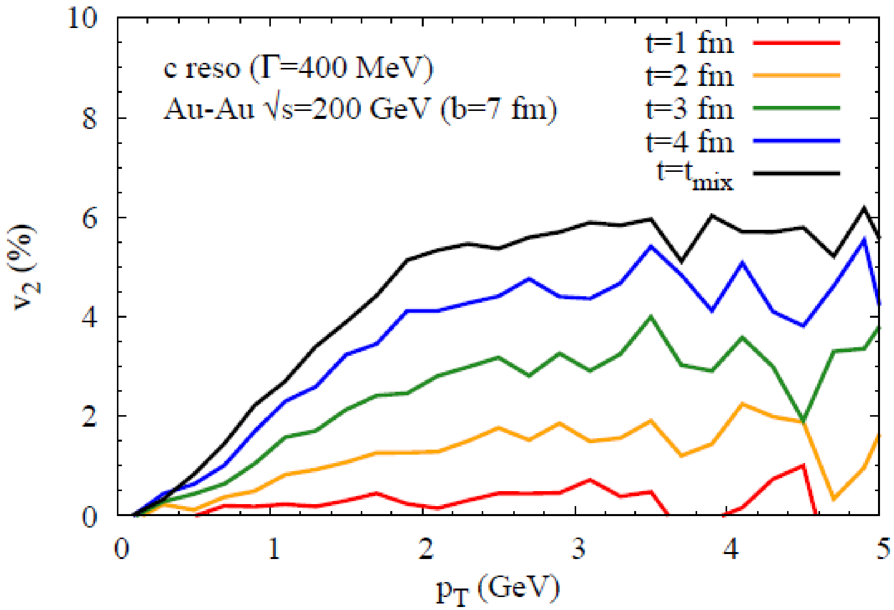


Terrevoli (SQM 2019)

Time evolution of Heavy quarks observables

R_{AA} can be "generated" faster than v_2



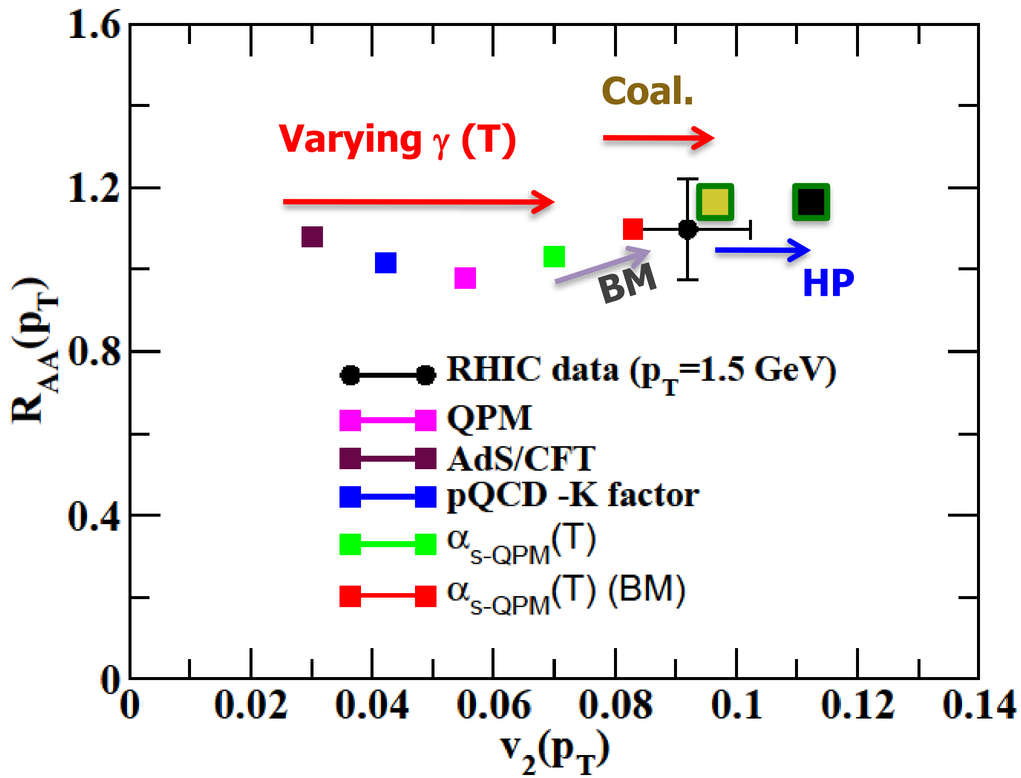


Rapp & Hees, arxiv:0803.0901

R_{AA} developed during the early stage of the evolution

V_2 developed duringing the later stage of the evolution

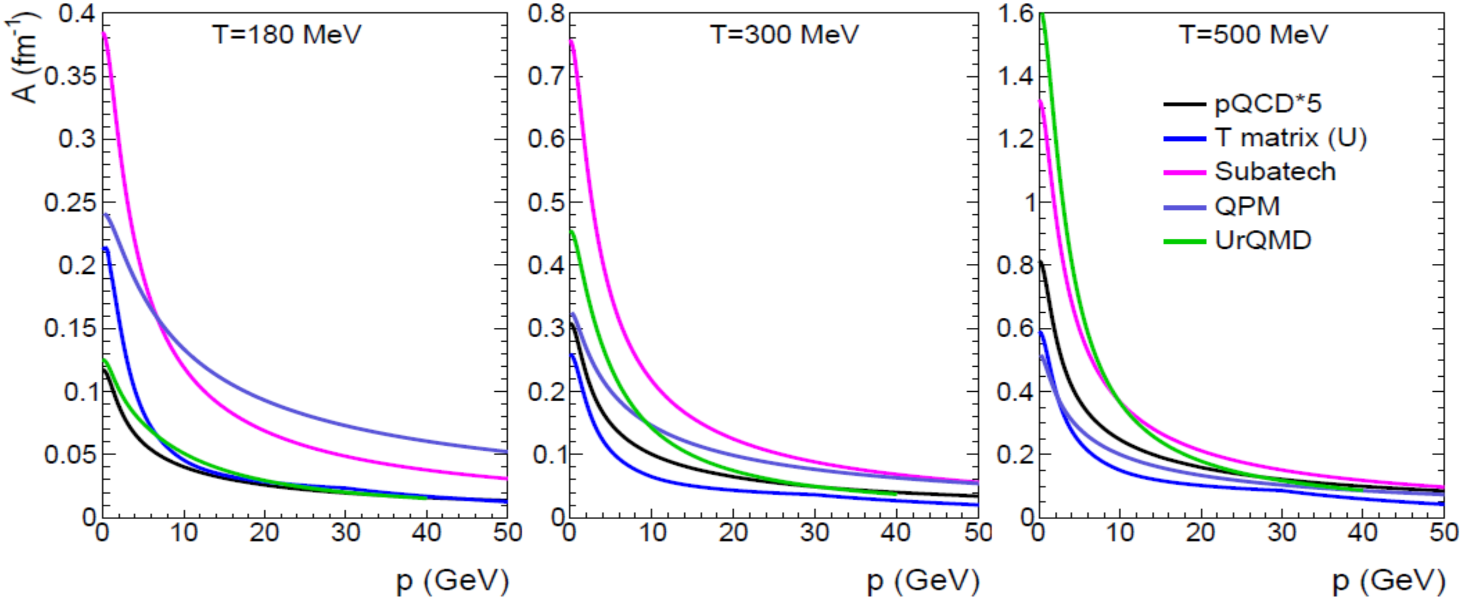
Summary on the build-up of v_2 at fixed R_{AA}



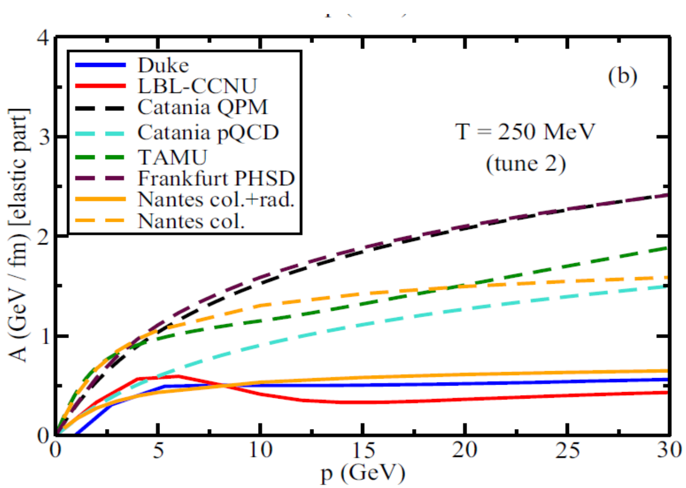
Das, Scardina, Plumari, Greco
PLB,747 (2015) 260

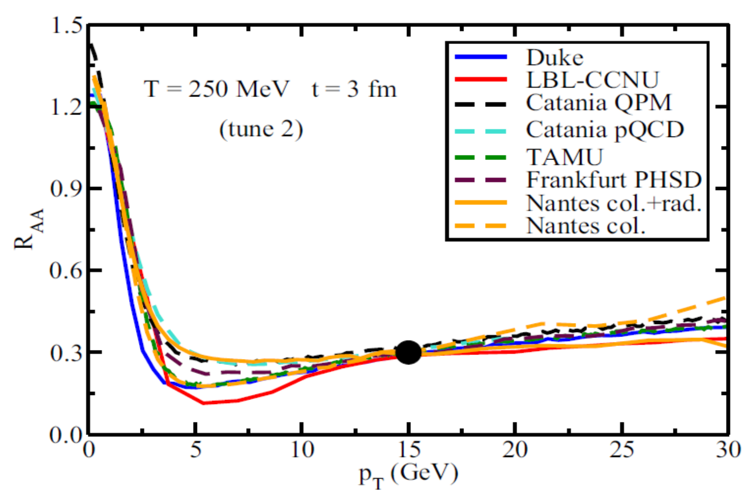
R_{AA} and V_2 are correlated but still one can have
R_{AA} about the same while V_2 can change up to a factor 2-3
γ(T) + Boltzmann dynamics+ hadronization+ hadronic phase

A systematic attempts are going on within the EMMI-RRTF and "JET-HQ" working groups to find a common agreement between different groups:



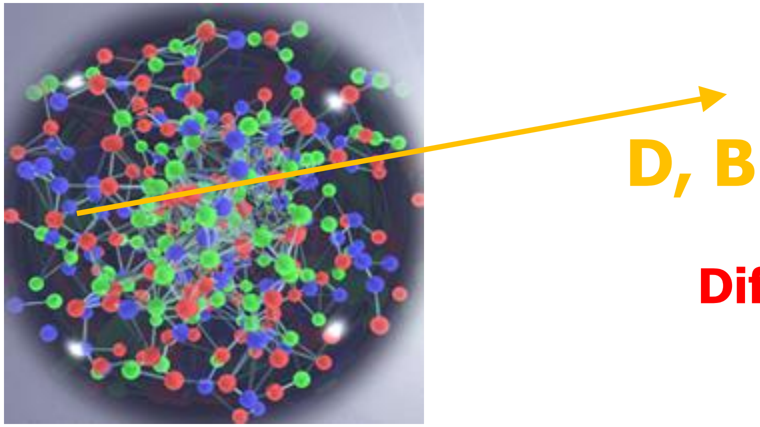
R. Rapp et.al NPA 979 (2018) (EMMI-RRTF)





S. Cao et. al PRC 99, 054907 (2019) (JET-HQ)

Heavy meson transport coefficient in hadronic phase



Different models at work:

Heavy meson chiral perturbation Theory

Low temperature: 30 MeV < T< 80 MeV

M. Laine, JHEP 04 (2011) 124.

Phenomenological model

Empirical scattering amplitudes of D/D* off $\pi, K, \eta, \rho, \varpi, K^*, N, \Delta$

He, Fries, Rapp, PLB 701, 445 (2011).

Effective Lagrangian

Also model based on scattering lengths

Ghosh, Das, Sarkar, Alam, PRD 84, 011503 (2011)

Das, Ghosh, Sarkar, Alam, PRD 85, 074017 (2012).

Unitarized heavy meson chiral perturbation theory

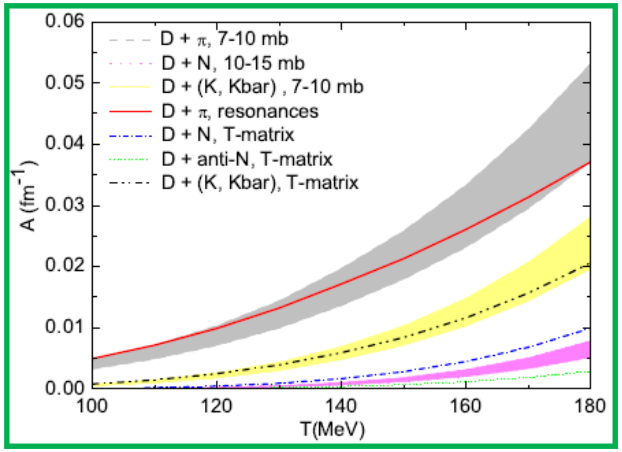
Abreu, Cabrera, Llanes-Estrada, Torres-Rincon, Ann. Phys. 326, 2737 (2011).

Abreu, Cabrera, Torres-Rincon, PRD 87, 034019 (2013).

Tolos, Torres-Rincon, PRD, 88, 074019, (2013)

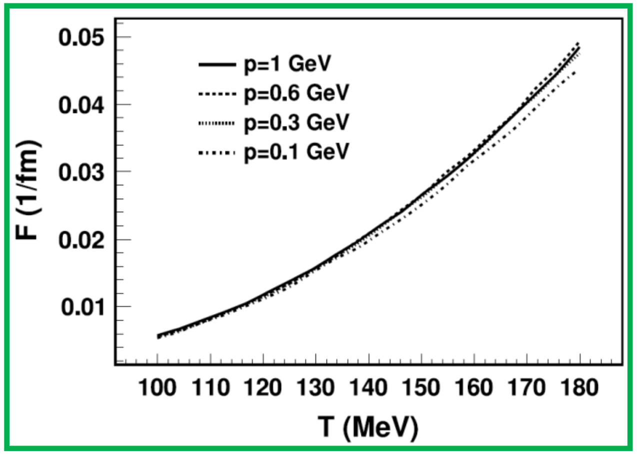
D-meson drag coefficient in hadronic phase

Phenomenological



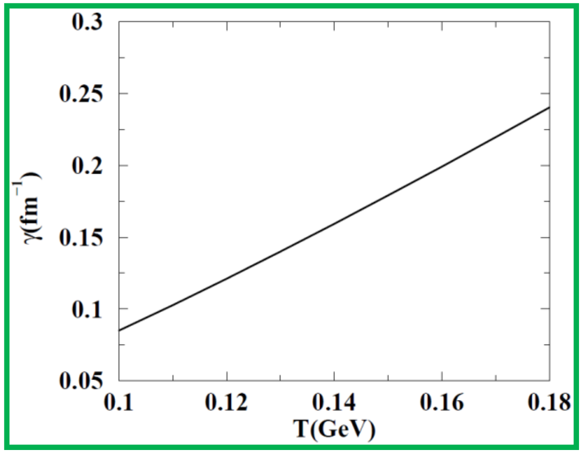
He, Fries, Rapp,
PLB 701, 445 (2011)

Unitarized HMChPT



Abreu, Cabrera, Llanes-Estrada,
Torres-Rincon, Ann. Phys. 326, 2737 (2011).

Effective Lagrangian

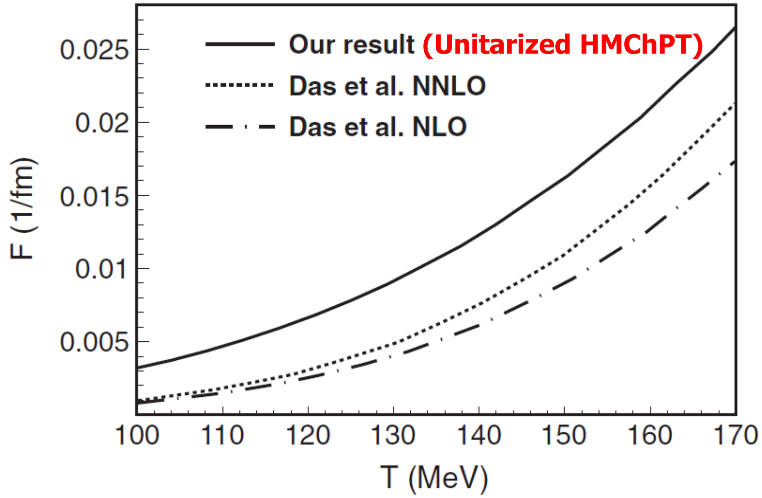


Ghosh, Das, Sarkar, Alam,
PRD 84, 011503 (2011)

Value of the drag coefficient at $p \to 0$ and $T = 100$ MeV.

Authors	F (fm^{-1})
Laine	0.05
He, Fries, Rapp	5×10^{-3}
Ghosh et al.	0.11
This work (Abreu et. al)	$\mathbf{3.5 \times 10^{-3}}$

Heavy hadron transport coefficients in hadronic phase



Model based on scattering lengths

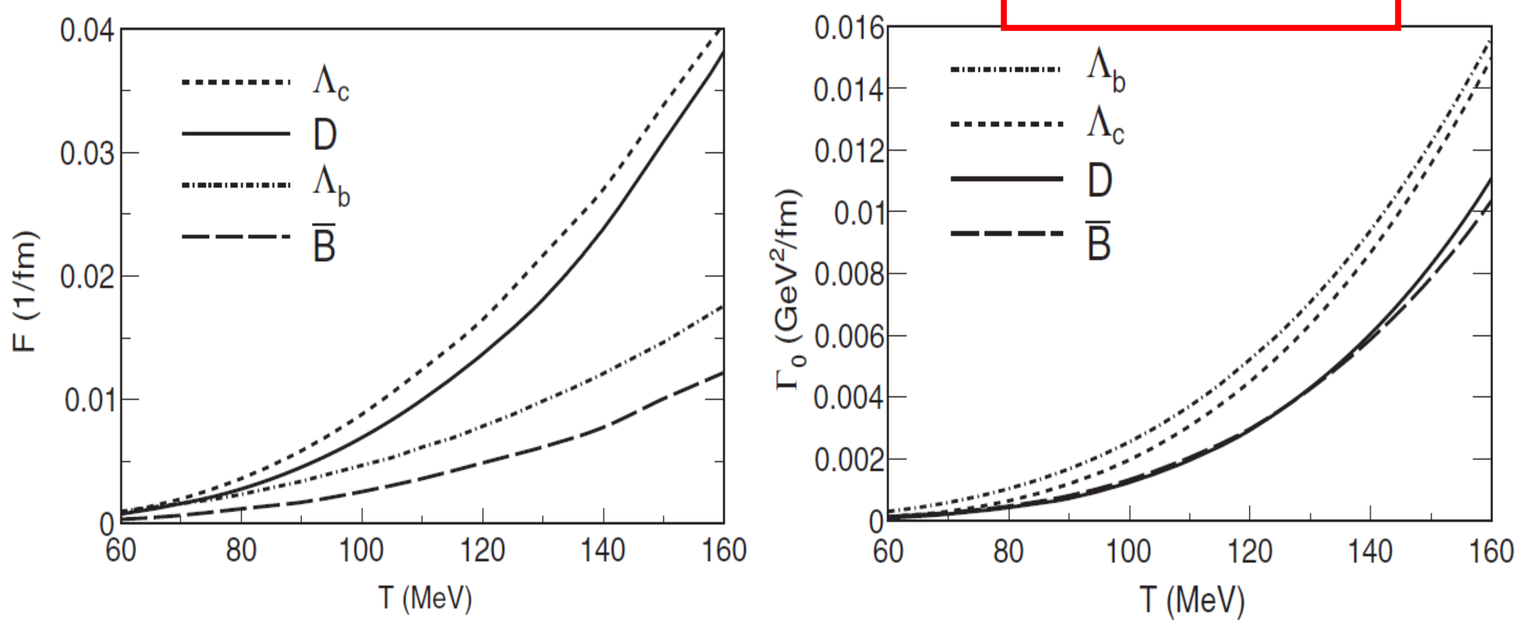
Das, Ghosh, Sarkar, Alam, PRD 85, 074017 (2012).

Unitarized HMChPT

Abreu, Cabrera, Torres-Rincon, PRD 87, 034019 (2013).

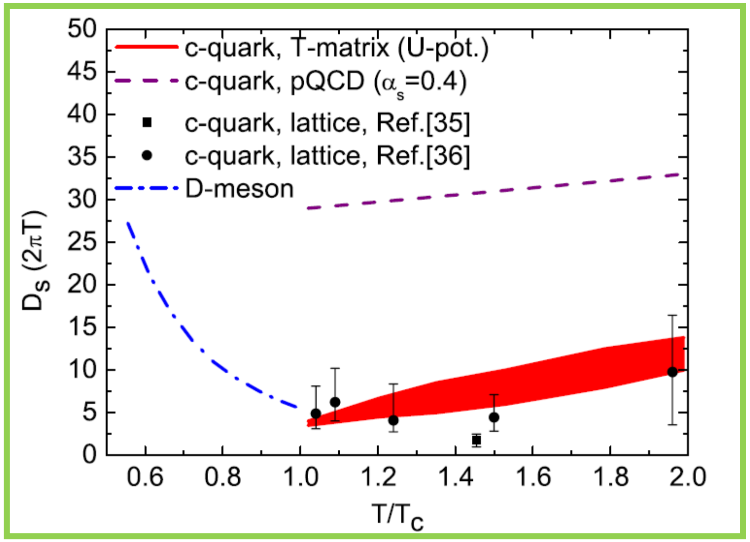
$$F \sim P\sigma\sqrt{\frac{m_l}{T}}\frac{1}{m_H},$$

$$\Gamma \sim P\sigma\sqrt{m_l T}.$$



Tolos, Torres-Rincon, Das, PRD, 034018, 94 (2016)

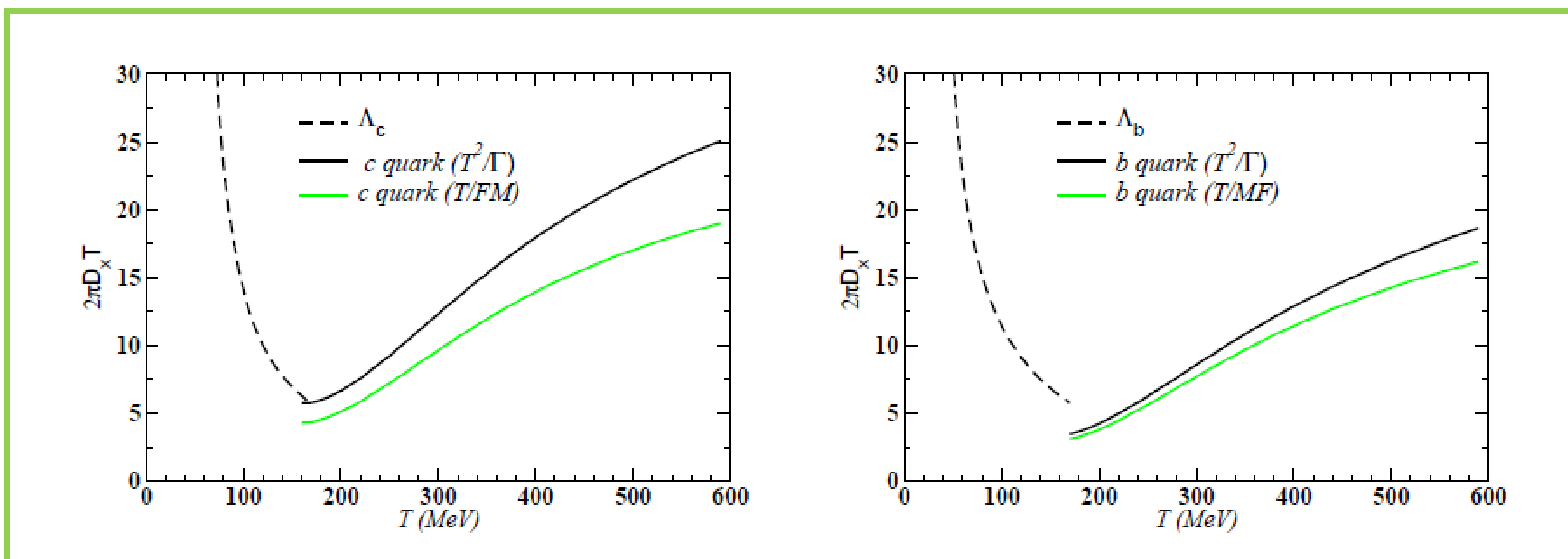
Heavy hadron diffusion in hadronic phase



$$\mathcal{D}_s = T/[m_{c,D} A(p=0,T)]$$

The calculations support a continuous evolution through the transition region with a minimum around Tc.

He, Fries, Rapp, PRL,110, 112301 (2013)

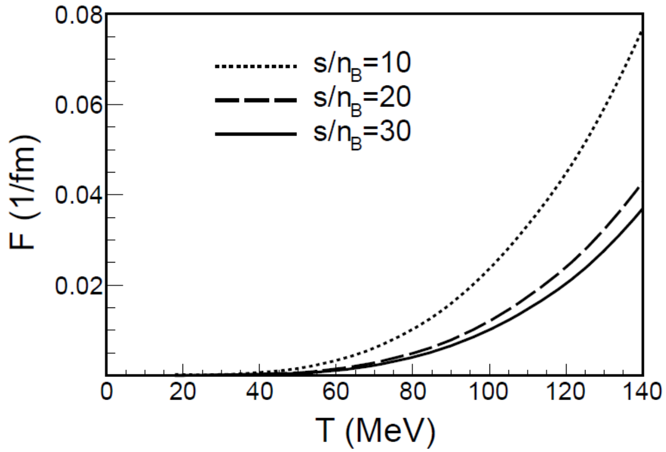


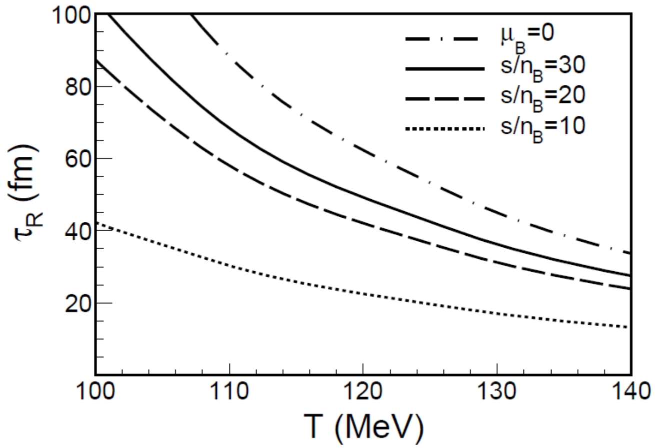
Das, Torres-Rincon, Tolos, Minissale, Scardina, Greco, PRD, 114039, 94 (2016)

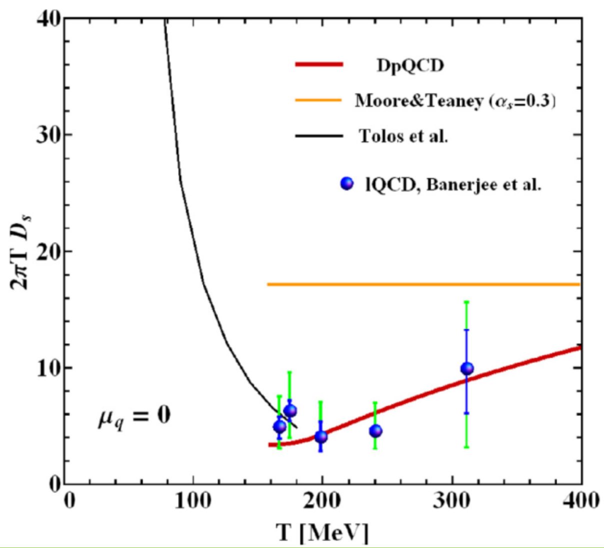
Heavy hadron diffusion at finite chemical potential

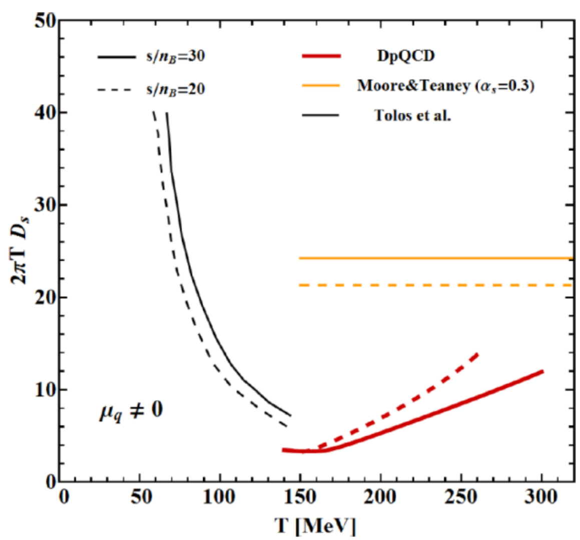
For finite chemical potential the baryon contribution can be large.

Tolos, Torres-Rincon, PRD, 88, 074019, (2013)





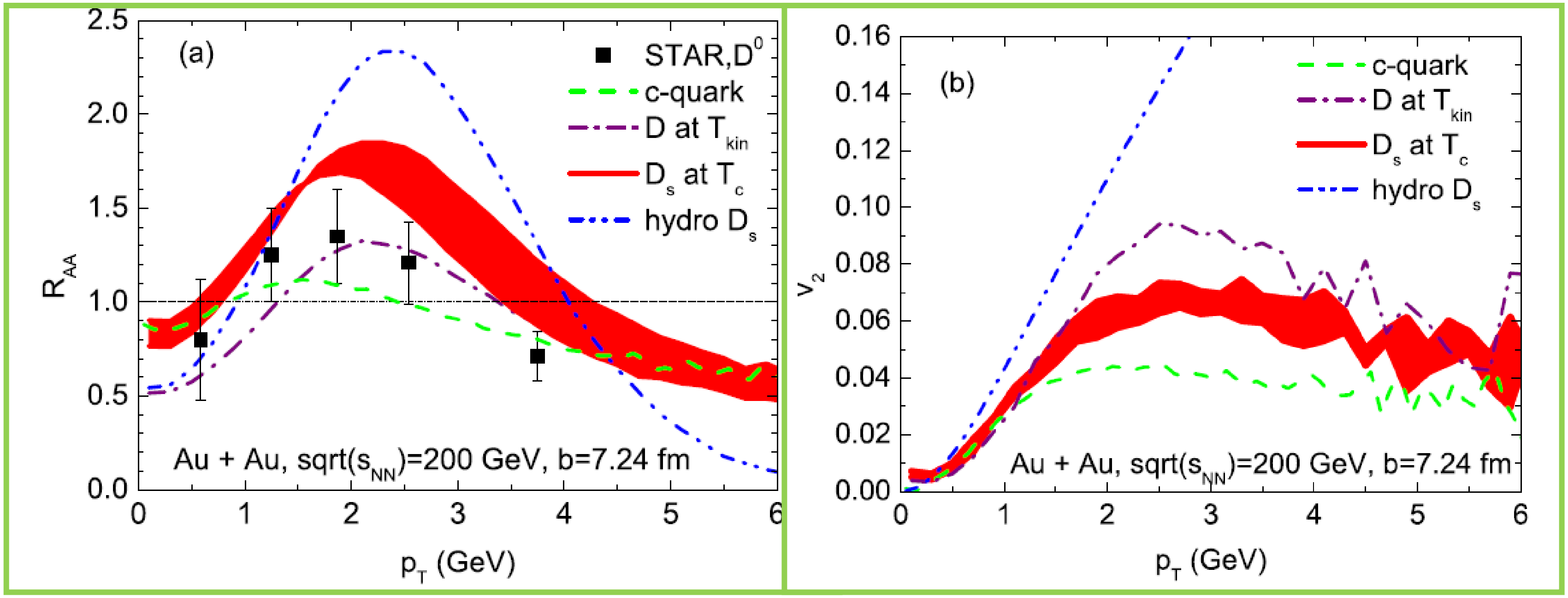




With in DQPM

Berrehrah, Gossiaux, Aichelin, Cassing, Torres-Rincon, and E. Bratkovskaya, PRC,90, 051901(R) (2014)

Impact of hadronic phase on HQ observables at RHIC energy



R_{AA} Difference between D and Ds in gives a quantitative measure of the coalescence effect.

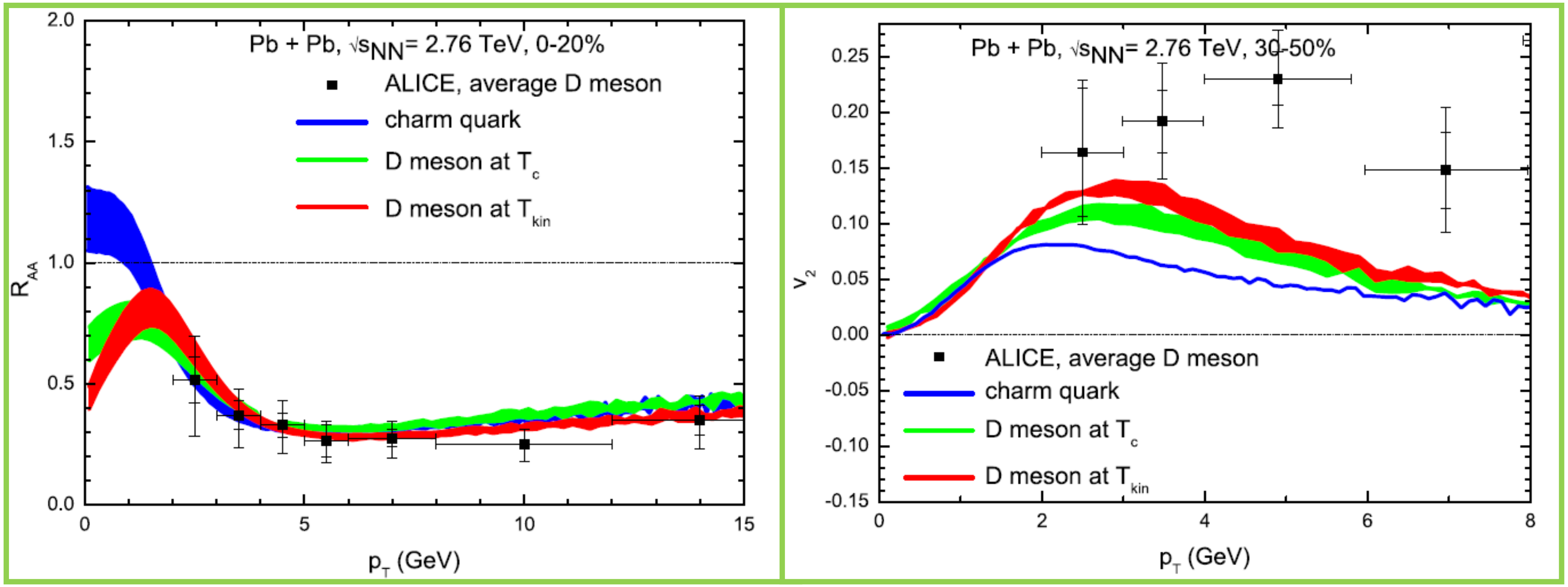
v_2 splitting between D and Ds is a promising measure of the transport properties of the hadronic phase.

The D meson picks up significant additional v_2 from the hadronic phase, which can be quantified by comparing to the Ds-meson v_2 for which hadronic diffusion effects are suppressed.

Impact of hadronic phase on v_2 is about 30%

He, Fries, Rapp, PRL,110, 112301 (2013)

Impact of hadronic phase on HQ observables at LHC energy

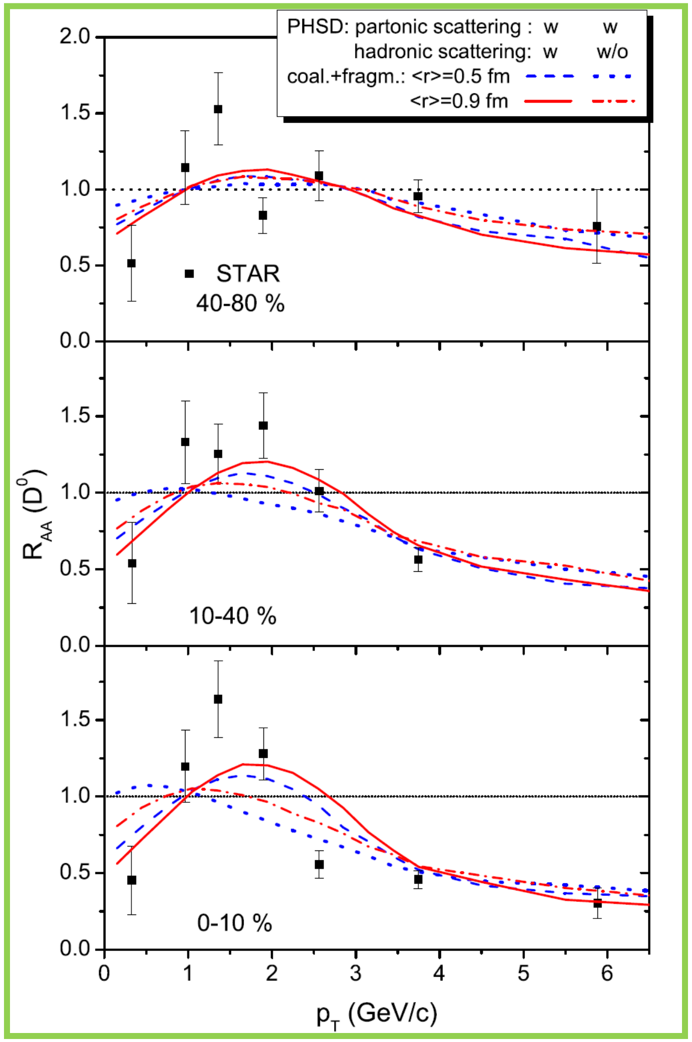


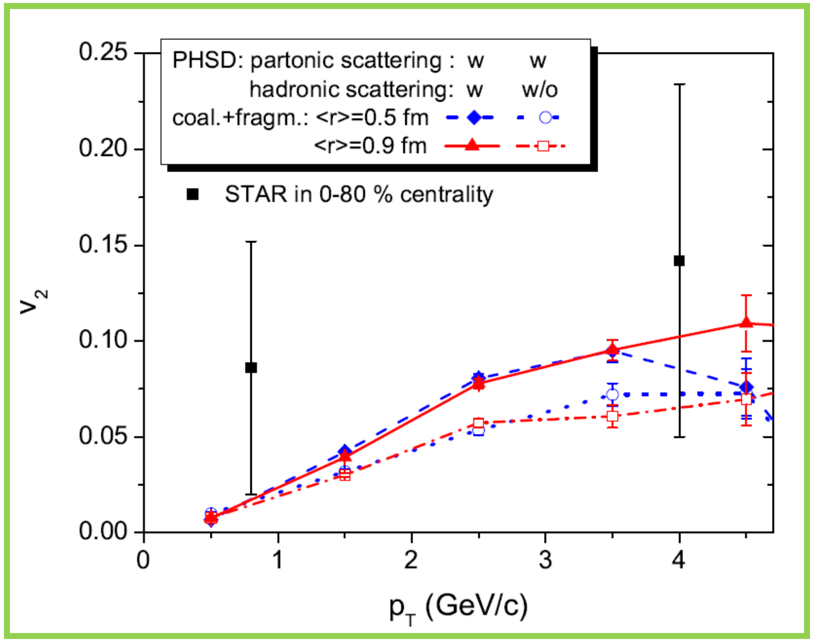
Impact of hadronic phase on v_2 is about 20%

He, Fries, Rapp, PLB, 735, 445 (2014)

This indicates the relative contribution of the hadronic phase may increase with decreasing colliding energy.

Impact of hadronic phase on HQ observables at RHIC energy

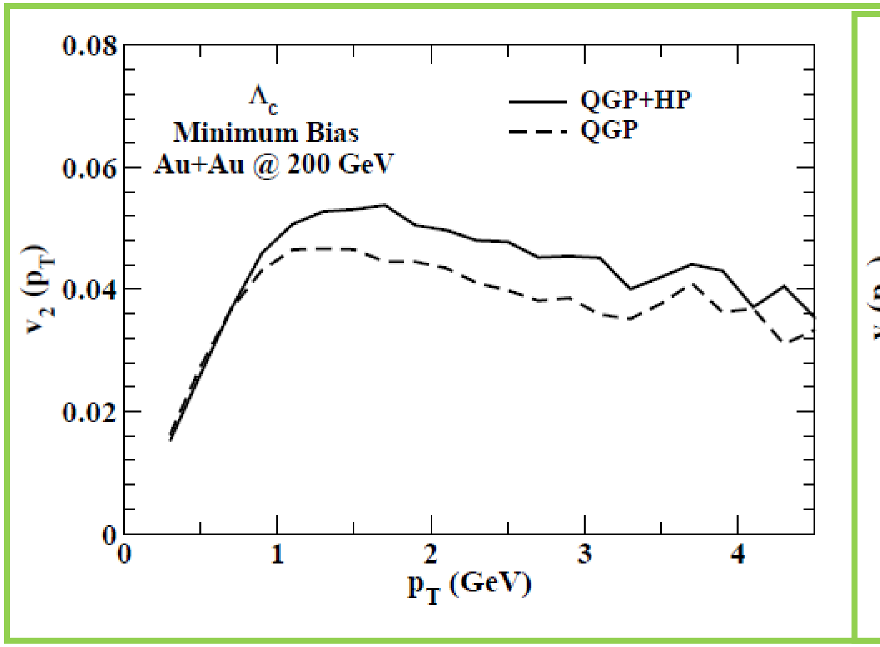


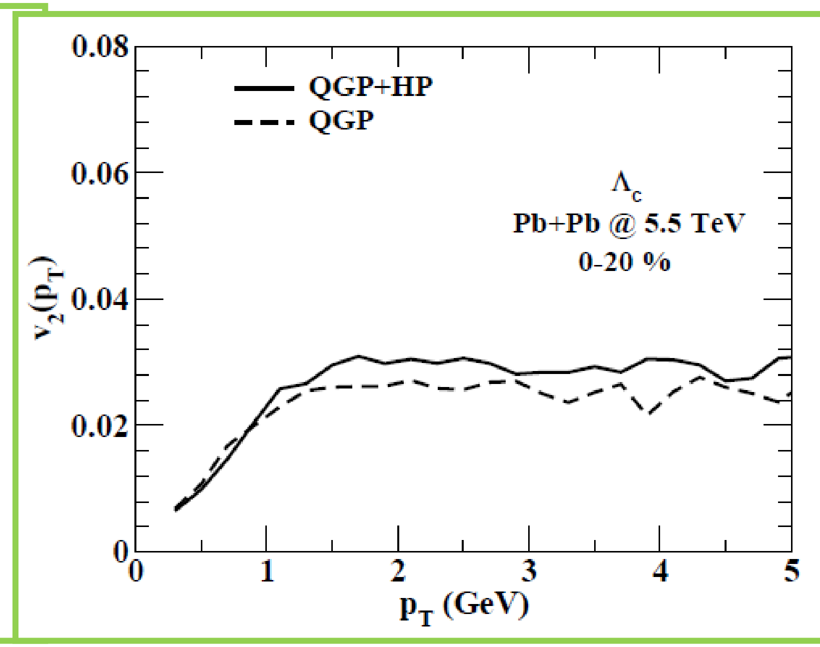


Impact of hadronic phase on v_2 is about 40%

Song, Berrehrah, Cabrera, Torres-Rincon, Tolos, Cassing, Bratkovskaya, PRC, 92, 014910 (2015)

Impact of hadronic phase on HQ observables at RHIC and LHC





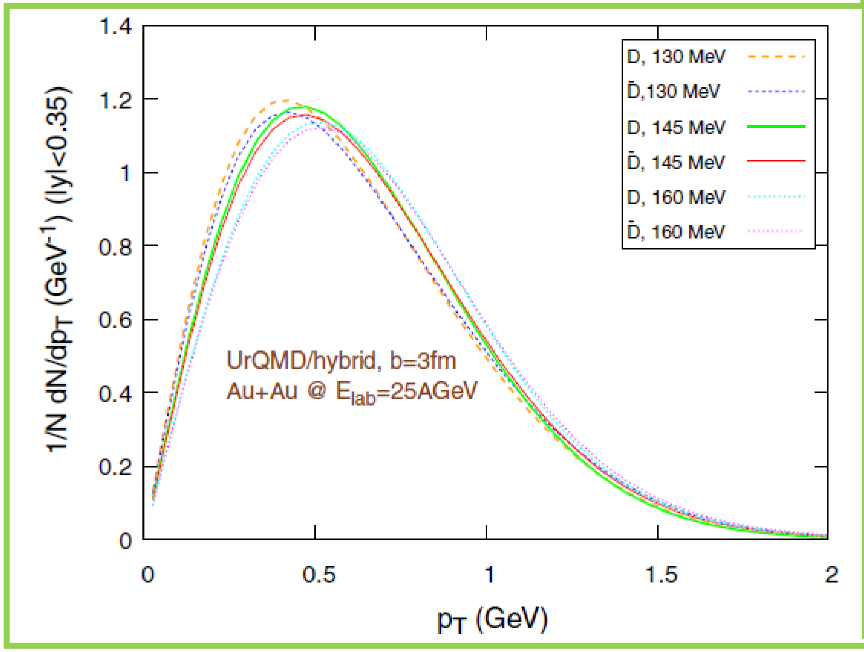
Das, Torres-Rincon, Tolos, Minissale, Scardina, Greco, PRD, 114039, 94 (2016)

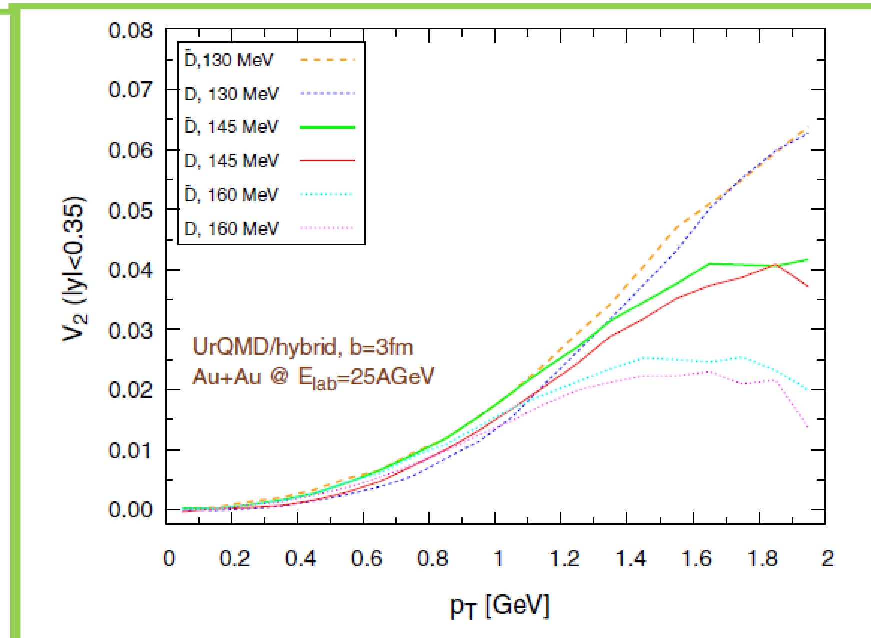
Impact of hadronic phase on v_2 is about 20% at RHIC and about 15% at 5.5 TeV.

All the model calculations indicate at RHIC the hadronic phase contribution to heavy meson v_2 can be: 20-40%

T_c play a significant role to decide the relative contribution of hadronic phase

Heavy quark dynamics at low energy

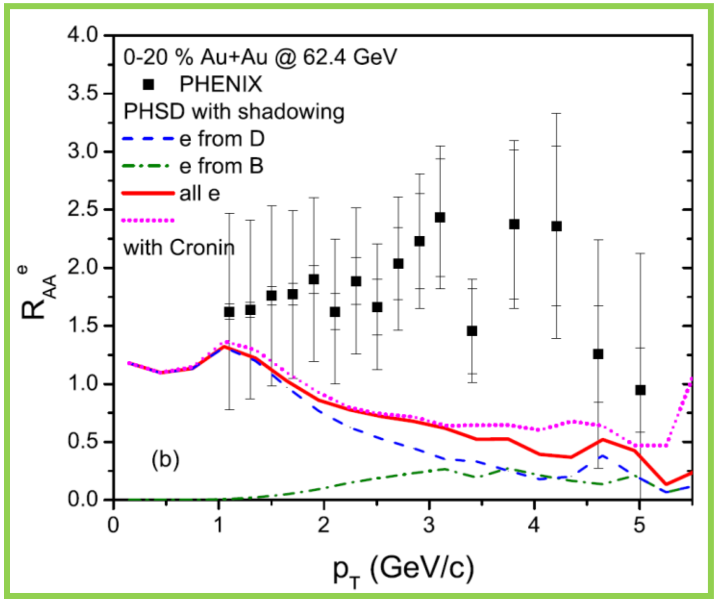




Inghirami, van Hees, Endres, Torres-Rincon, Bleicher, EPJC, 79,52 (2019)

Variation of the decoupling temperature: A lower decoupling temperature leads to an increase of the elliptic flow

Heavy quark dynamics at low energy

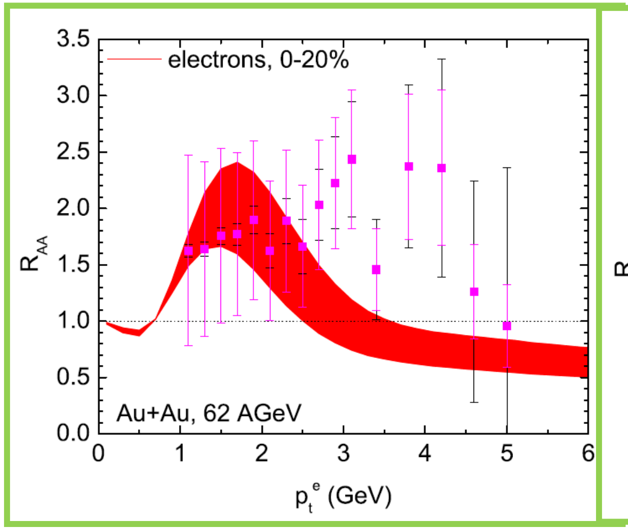


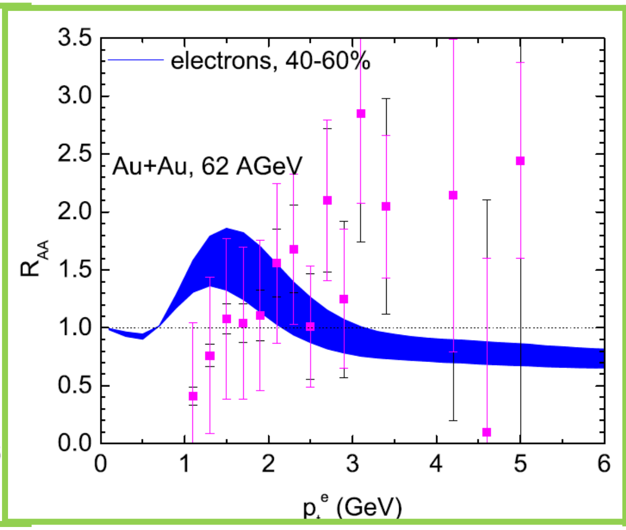
R_{AA} puzzle @ 62.4 GeV

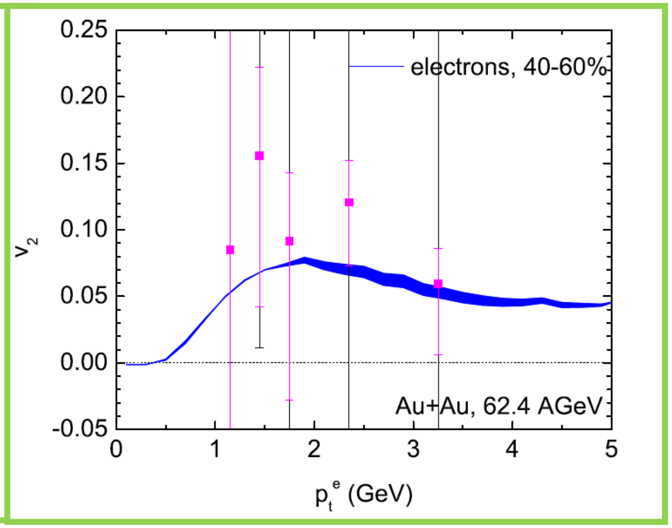
Are we missing something ?

(Pre-equilibrium phase)

Song, Berrehrah, Torres-Rincon, Tolos, Cabrera, Cassing, Bratkovskaya, PRC, 92, 014910 (2015)

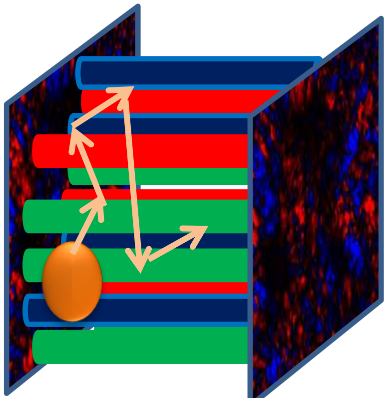






He, Fries, Rapp, PRC, 91, 024904 (2015)

Impact of the initial Glasma



(Adapted from M. Ruggieri)

S. Mrowczynski, EPJA 54 (2018) 3, 4
Ruggieri and Das PRD, 98, 094024 (2018)

$$\frac{dx_i}{dt} = \frac{p_i}{E}, \qquad E = \sqrt{\boldsymbol{p}^2 + m^2}$$

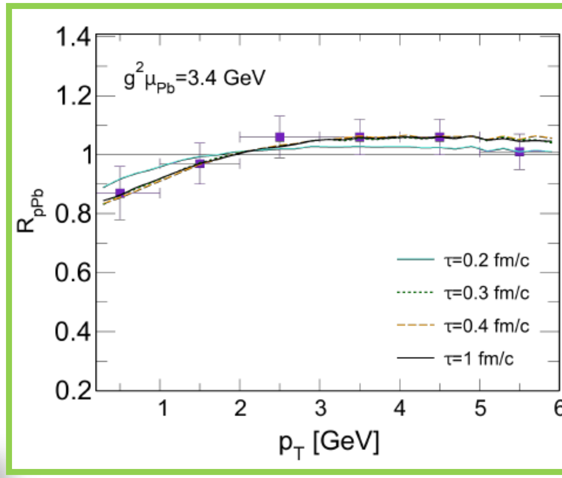
$$E\frac{dp_i}{dt} = gQ_a F^a_{i\nu} p^\nu,$$

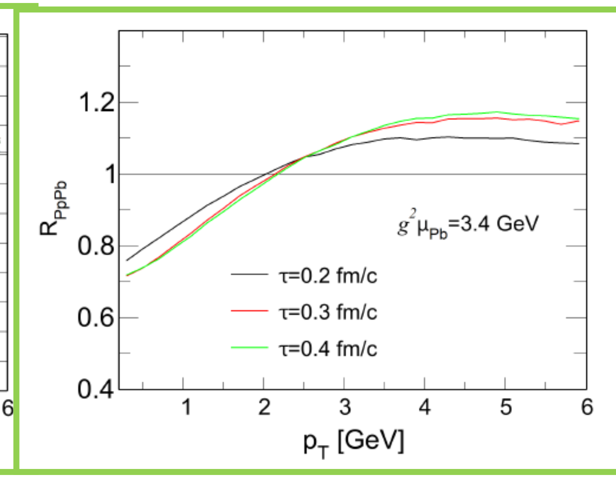
$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p};$$

Wong (1979)

Sun, Coci, Das, Plumari, Ruggieri, Greco
PLB, 798 (2019) 134933

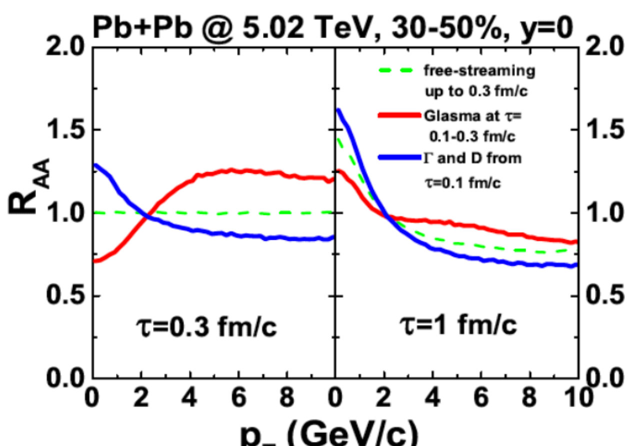
HQs can probe the very early evolution of the Glasma fields

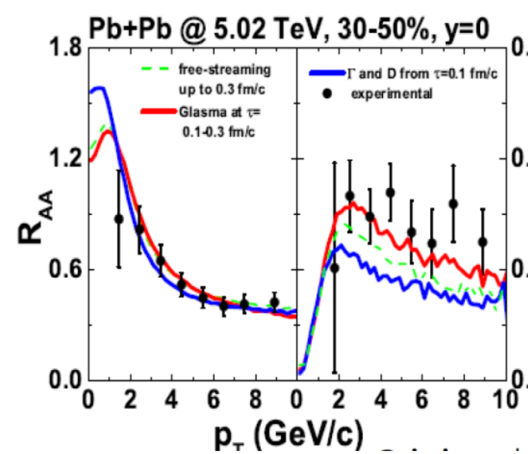




Liu, Plumari, Das, Greco, Marco, PRC, 102, 044902 (2020)

Impact on observables at AA collisions





Few recent works on heavy quark diffusion in pre-equilibrium phase

Energy loss and momentum broadening of heavy quarks in a Glasma.

M. Carrington et al. NPA 1001 (2020) 121914

Heavy quark diffusion within correlator method. They observed an initial rapid rise in the heavy quark momentum broadening in the non-equilibrium gluon plasma.

K. Boguslavski at. al. JHEP 09 (2020) 077

Diffusion of charm quark in Glasma is in a ballistic regime.

Liu, Das, Greco, Marco, PRD, 103, 034029 (2021)

Heavy quark energy loss far from equilibrium in a strongly coupled collisions

Chesler, Lekaveckar, Rajagopal, JHEP 10(2013)013

Within Kinetic Theory:

S. K. Das et al. JPG, 44 (2017) 095112

T. Song et al. PRC, 101 (2020), 044901

Pre-equilibrium phase may play a significant role at low colliding energy.

Conclusions and Perspectives:

- **Open Heavy Flavor will act as an excellent probe of high μ_B matter.**

  (it will open new window to explore QCD matter)

- **Provides unique opportunity to characterize the hadronic phase**

  (v2 splitting between D and Ds, RAA - v2)

- **At low colliding energy the pre-equilibrium phase may play a significant role**

- **R_{AA} @ 62.4 GeV: Already giving some hints on what lie ahead**

- **More precision data and New Observables**


Thank You . . . .