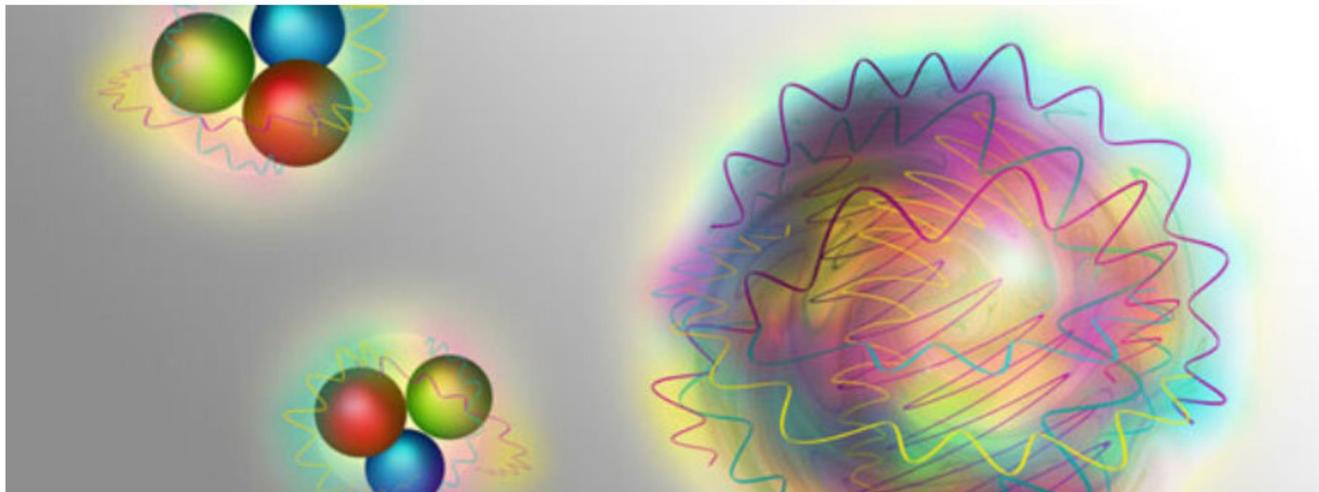


Heavy quark diffusion in QGP

HEAVY-FLAVOR TRANSPORT IN QCD MATTER



26 April 2021 — 30 April 2021 Virtual/Online

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(On behalf of Catania Group)

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Salvatore Plumari
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OUTLINE OF MY TALK.....

□ Heavy quark diffusion in QGP

I) Quasiparticle Model

II) Constrained by lattice QCD

III) Relation to bulk medium

Boltzmann Kinetic equation

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

➤ The plasma is uniform ,i.e., the distribution function is independent of \mathbf{x} .

➤ In the absence of any external force, $\mathbf{F}=\mathbf{0}$

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

$$\omega(p, k) = g \int \frac{d^3 q}{(2\pi)^3} f'(q) v_{q,p} \sigma_{p,q \rightarrow p-k, q+k} \longrightarrow \text{is rate of collisions which change the momentum of the charmed quark from } p \text{ to } p-k$$

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

$$\frac{\partial \mathbf{f}}{\partial t} = \frac{\partial}{\partial \mathbf{p}_i} \left[\mathbf{A}_i(\mathbf{p}) \mathbf{f} + \frac{\partial}{\partial \mathbf{p}_j} [\mathbf{B}_{ij}(\mathbf{p}) \mathbf{f}] \right]$$

B. Svetitsky PRD 37(1987)2484

where we have defined the kernels

$$\mathbf{A}_i = \int d^3 \mathbf{k} \omega(\mathbf{p}, \mathbf{k}) \mathbf{k}_i \quad \rightarrow \text{Drag Coefficient}$$

$$\mathbf{B}_{ij} = \int d^3 \mathbf{k} \omega(\mathbf{p}, \mathbf{k}) \mathbf{k}_i \mathbf{k}_j \quad \rightarrow \text{Diffusion Coefficient}$$

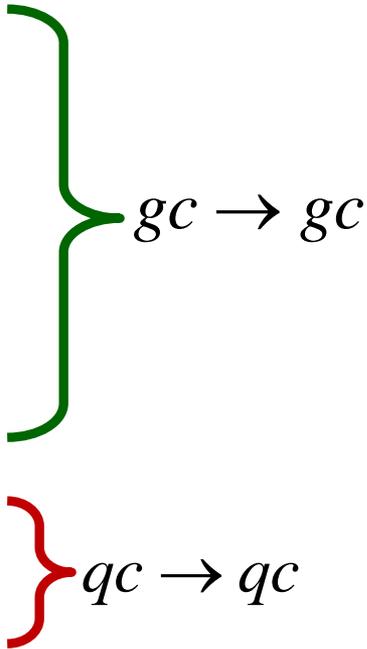
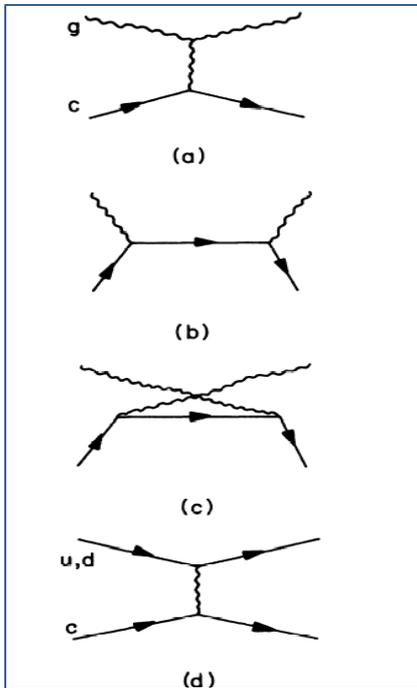
$$\frac{\partial \mathbf{f}}{\partial \mathbf{t}} = \frac{\partial}{\partial \mathbf{p}_i} \left[\mathbf{A}_i(\mathbf{p}) \mathbf{f} + \frac{\partial}{\partial \mathbf{p}_j} [\mathbf{B}_{ij}(\mathbf{p}) \mathbf{f}] \right]$$

For **Collision Process** the \mathbf{A}_i and \mathbf{B}_{ij} can be calculated as following :

$$A_i = \frac{1}{2E_p} \int \frac{d^3 q}{(2\pi)^3 2E_q} \int \frac{d^3 q'}{(2\pi)^3 2E_{q'}} \int \frac{d^3 p'}{(2\pi)^3 2E_{p'}} \frac{1}{\gamma_c} \sum |M|^2 (2\pi)^4 \delta^4(p+q-p'-q') f(q) [(p-p')_i] = \langle\langle (p-p')_i \rangle\rangle$$

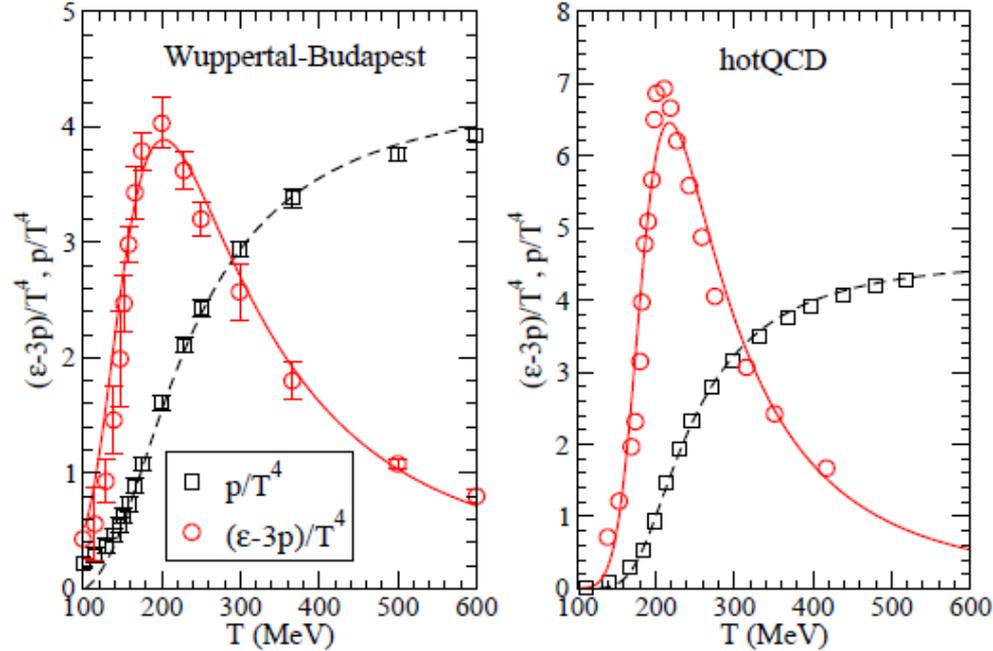
$$B_{ij} = \frac{1}{2} \langle\langle (p-p')_i (p'-p)_j \rangle\rangle$$

Elastic processes



**Inputs: Scattering matrix, Coupling
Debye Screening mass
Light quarks and gluon mass**

Quasi-Particle-Model (fit to IQCD ϵ, P)



$$\epsilon_{qp}(T) = \epsilon_{\text{lattice}}(T).$$

$$g_{QP}^2(T) = \frac{48\pi^2}{(11N_c - 2N_f) \ln \left[\lambda \left(\frac{T}{T_c} - \frac{T_s}{T_c} \right) \right]^2}$$

$$\lambda=2.6$$

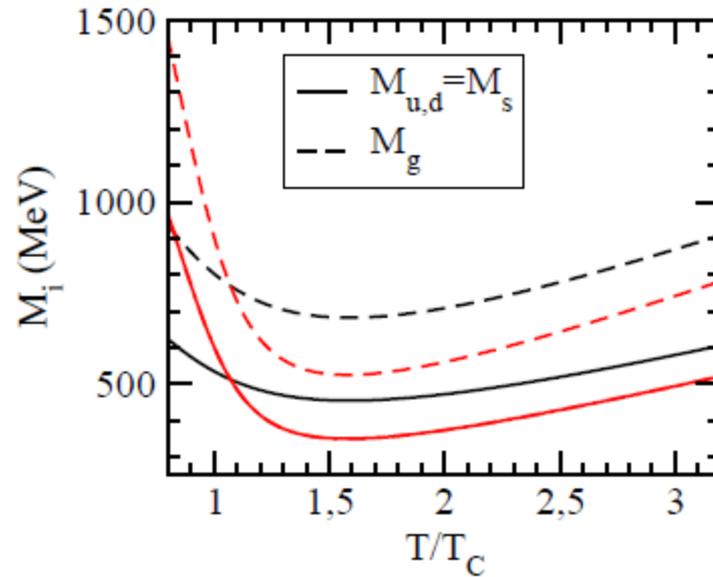
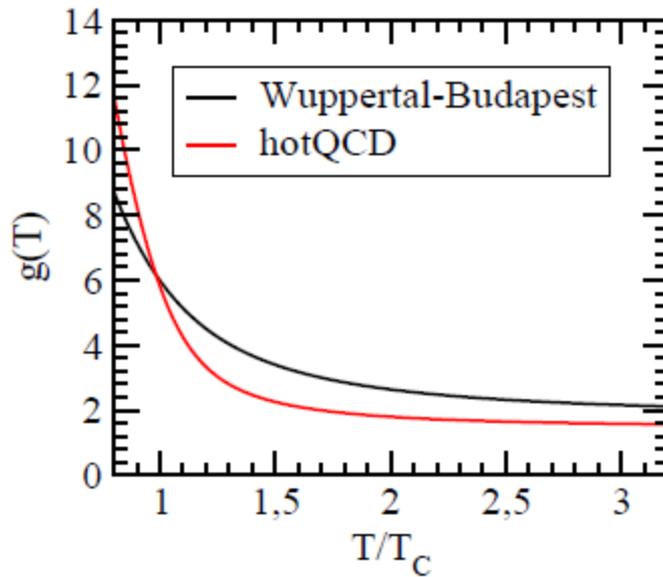
$$T_s=0.57$$

$$m_g^2 = \frac{1}{6} \left(N_c + \frac{1}{2} N_f \right) g^2 T^2$$

$$m_q^2 = \frac{N_c^2 - 1}{8N_c} g^2 T^2$$

Plumari et. al. PRD, 84, 094004 (2011)

Quasi-Particle-Model (fit to IQCD ε, P)



$$g_{QP}^2(T) = \frac{48\pi^2}{(11N_c - 2N_f) \ln \left[\lambda \left(\frac{T}{T_c} - \frac{T_s}{T_c} \right) \right]^2}$$

$$\lambda = 2.6$$

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On-shell vs off-shell dynamics

Sambataro et al.
EPJC 80 (2020) 12, 1140

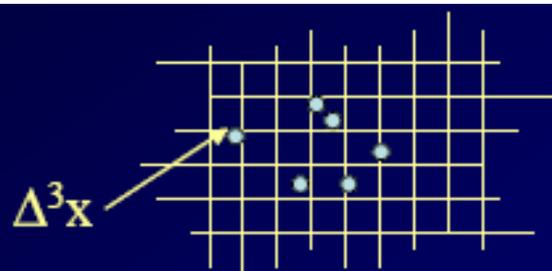
Plumari et al. PRD, 84, 094004 (2011)

Transport theory

$$p^\mu \partial_\mu f(x, p) = C_{22}$$

We consider two body collisions

$$C_{22} = \frac{1}{2E_1} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{1}{\nu} \int \frac{d^3 p'_1}{(2\pi)^3 2E'_1} \frac{d^3 p'_2}{(2\pi)^3 2E'_2} f'_1 f'_2 |\mathcal{M}_{1'2' \rightarrow 12}|^2 (2\pi)^4 \delta^{(4)}(p'_1 + p'_2 - p_1 - p_2) \\ - \frac{1}{2E_1} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{1}{\nu} \int \frac{d^3 p'_1}{(2\pi)^3 2E'_1} \frac{d^3 p'_2}{(2\pi)^3 2E'_2} f_1 f_2 |\mathcal{M}_{12 \rightarrow 1'2'}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p'_1 - p'_2)$$



$$\Delta t \rightarrow 0$$

$$\Delta^3 x \rightarrow 0$$



**Exact
solution**

Collision integral is solved with a **local stochastic sampling**

Das, Scardina, Plumari and Greco
Phys. Rev. C, 90, 044901 (2014)

$$P_{22} = \frac{\Delta N_{\text{coll}}^{2 \rightarrow 2}}{\Delta N_1 \Delta N_2} = v_{\text{rel}} \sigma_{22} \frac{\Delta t}{\Delta^3 x}$$

Langevin Equation

The Fokker-Planck equation can be recast to Langevin equation:

$$\frac{dp}{dt} = -\gamma(p)p + \zeta \quad \text{with} \quad \langle \zeta_i(t)\zeta_k(t') \rangle = D\delta(t-t')\delta_{jk}$$

where γ is the deterministic friction (drag) force

ζ is stochastic force

Das, Scardina, Plumari, Greco
Phys. Lett. B 747 (2015)260-264

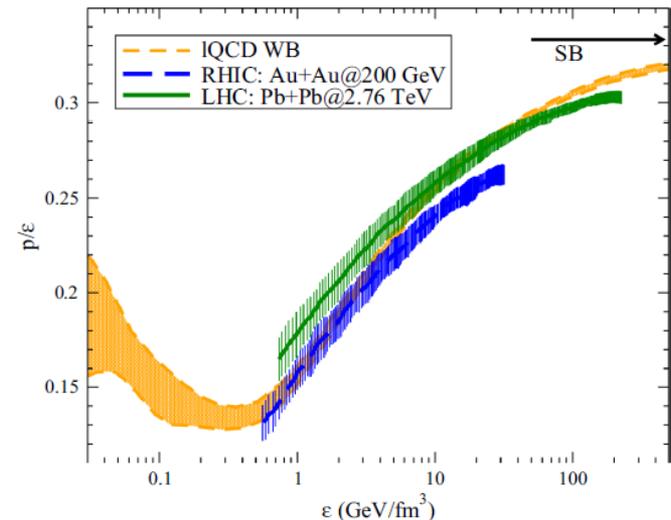
For the numerical implementation of Langevin dynamics we use pre-point Ito discretization.

Bulk evolution:

Transport bulk
Light quark and gluon are massive
Able to reproduce the bulk spectra and v_2

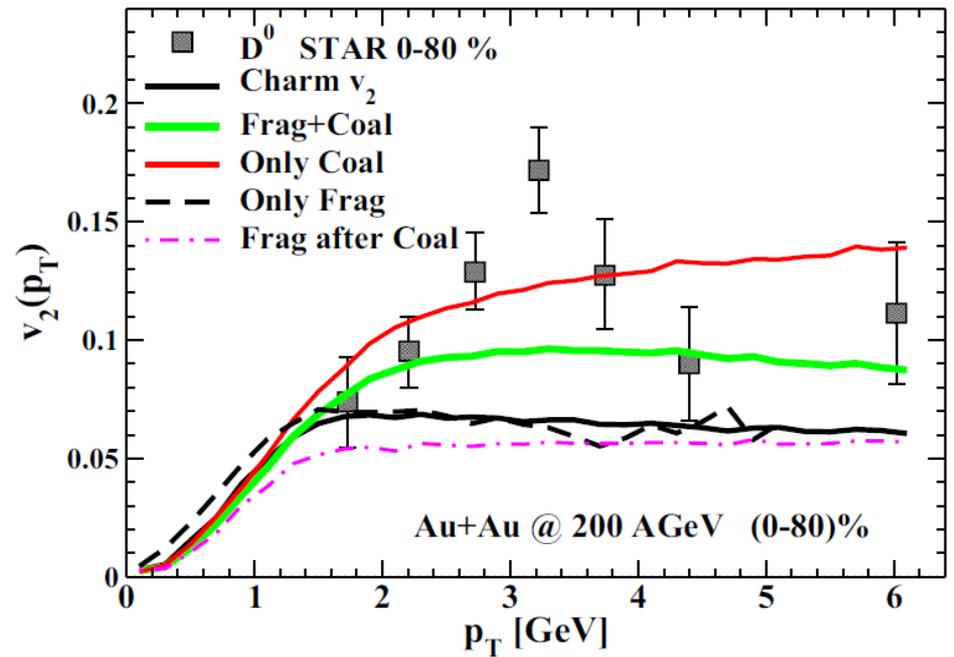
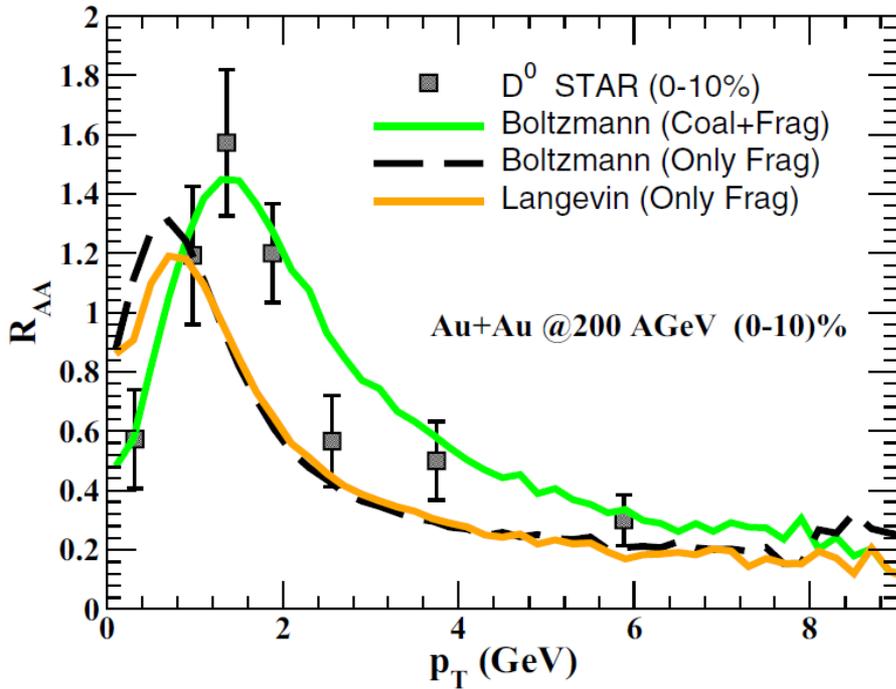
Ruggieri, Scardina, Plumari, Greco
PRC, 89, 054914 (2014)

Plumari, EPJC (2019) 79



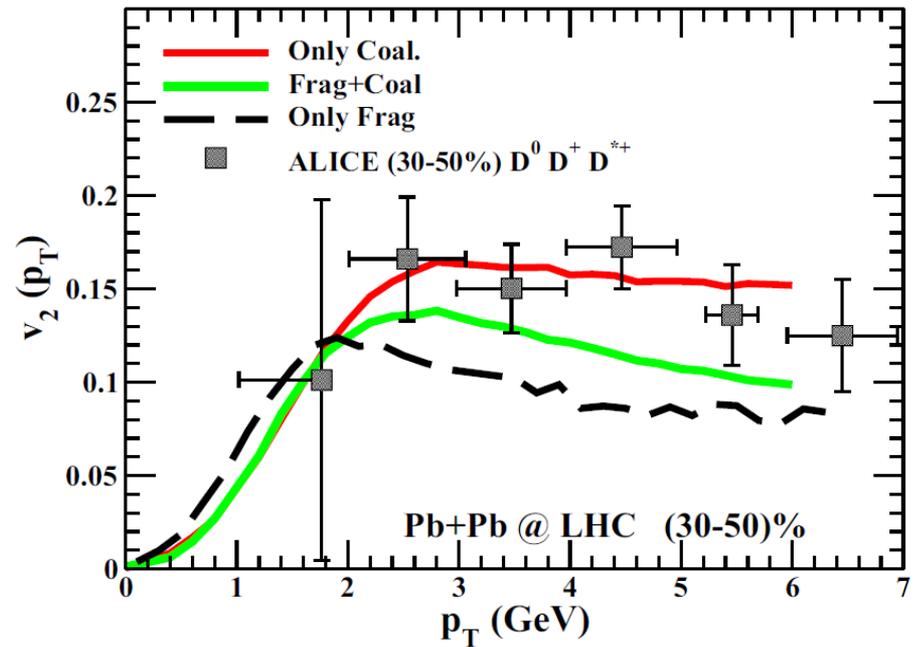
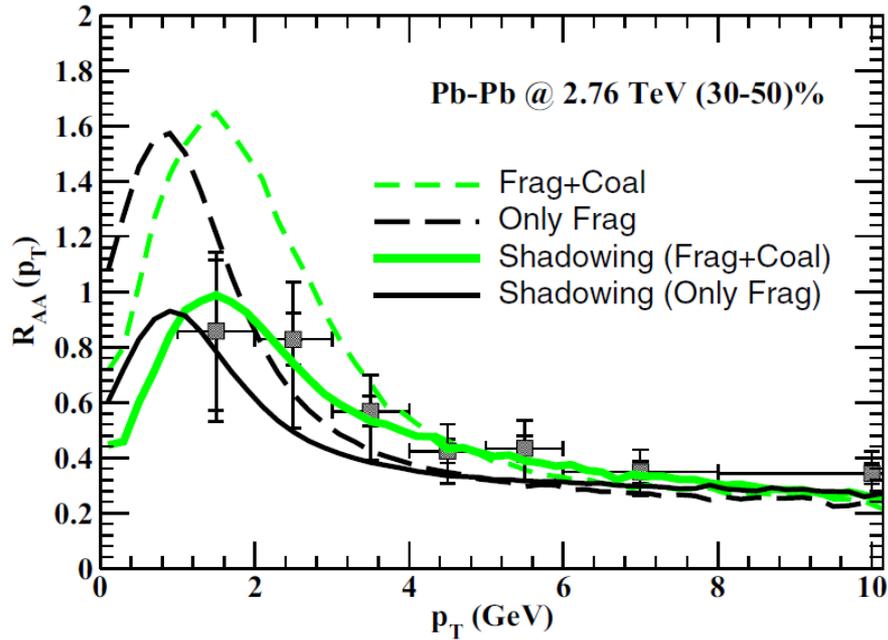
EoS obtained within the transport approach

RAA and v_2 @ RHIC



Scardina, Das, Minissale, Plumari, Greco
PRC,96, 044905 (2017)

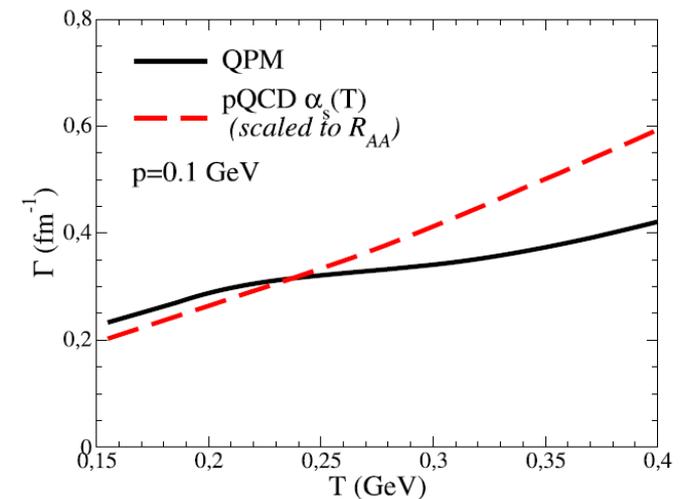
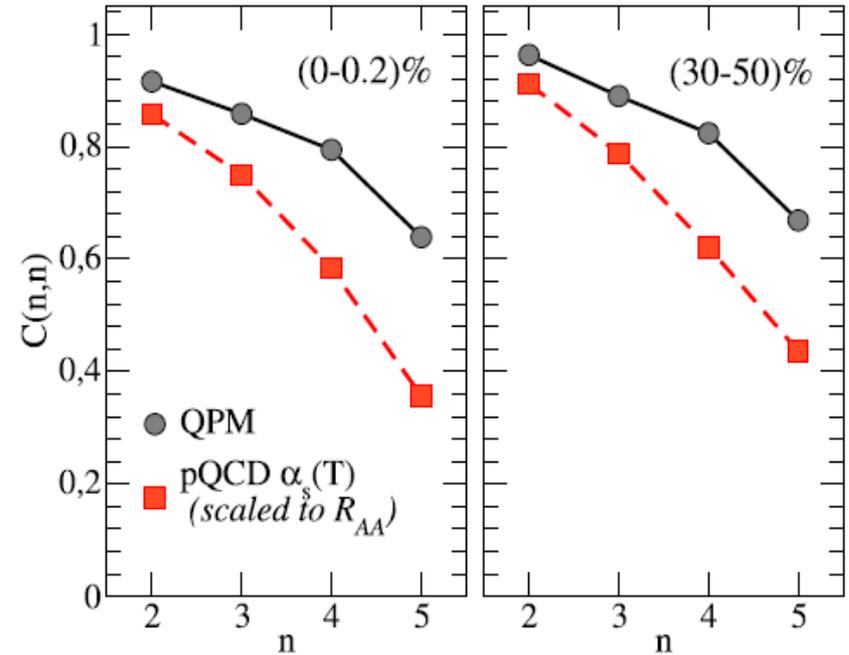
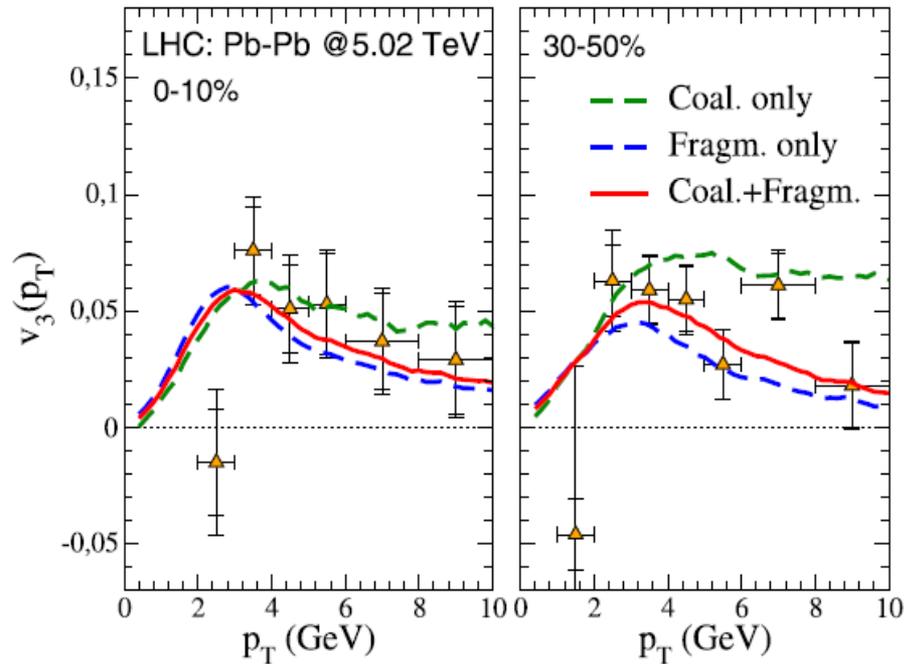
RAA and v_2 @ LHC



Scardina, Das, Minissale, Plumari, Greco
PRC,96, 044905 (2017)

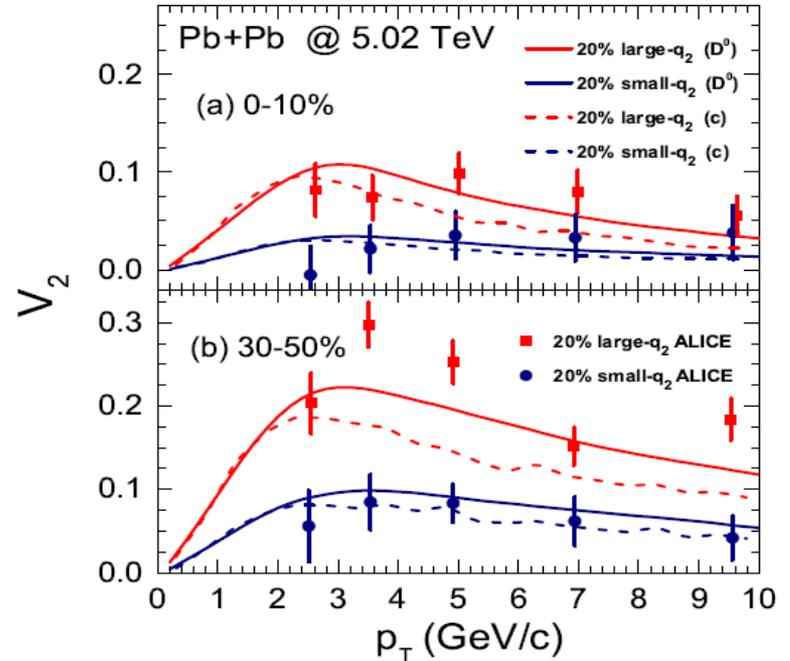
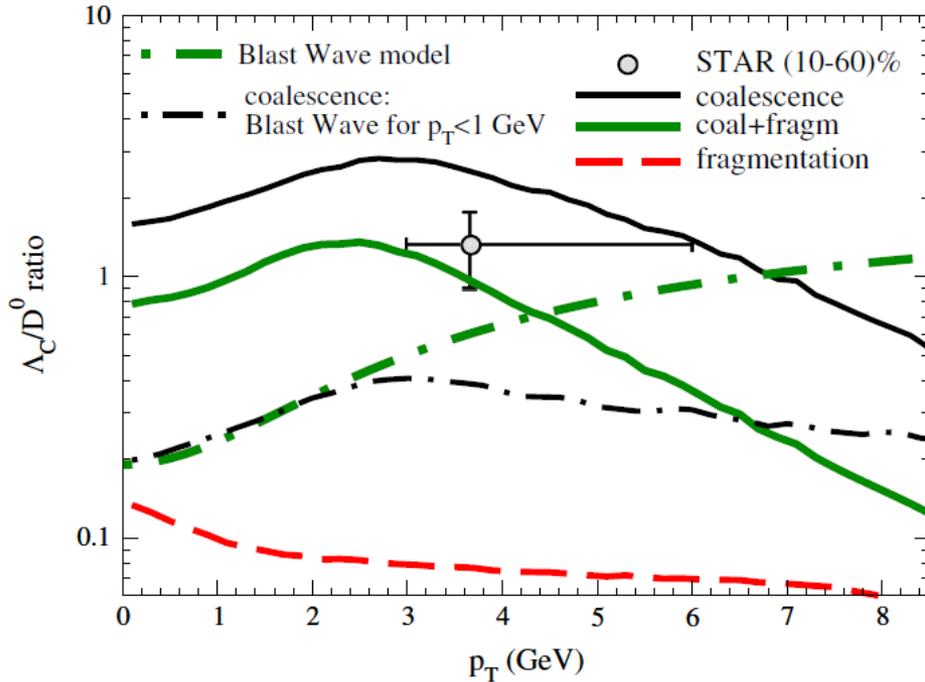
Heavy-light correlation and event-by-event transport

$$C(n, m) = \frac{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)(v_m^{H,i} - \langle v_m^H \rangle)}{\sqrt{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)^2 \sum_i (v_m^{H,i} - \langle v_m^H \rangle)^2}}$$



Plumari, Coci, Minissale, Das, Sun, Greco
PLB, 805 (2020) 135460

Heavy baryon to meson ratio

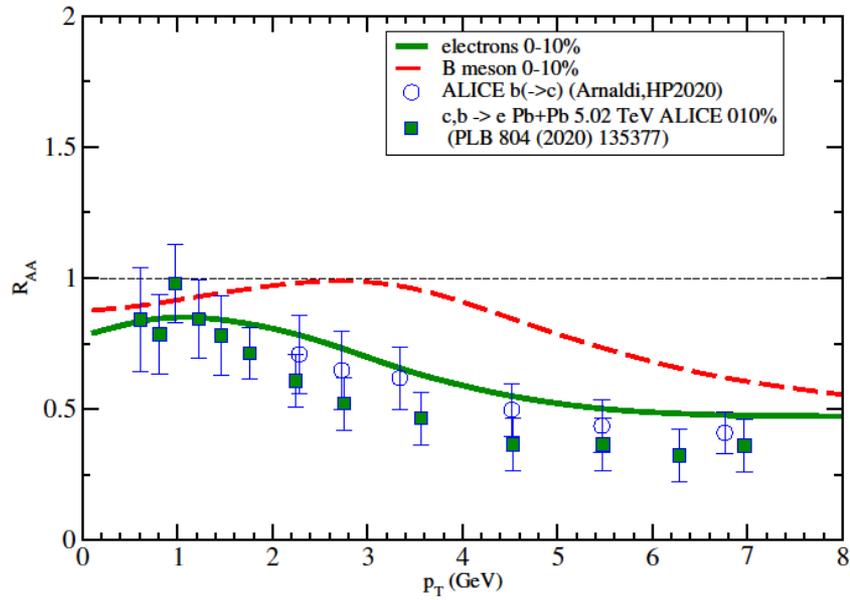


Event shape Engineering

Plumari, Minissale, Das, Coci, Greco
 EPJC, 78, 348 (2018)

Sun et. al

B-meson RAA ALICE



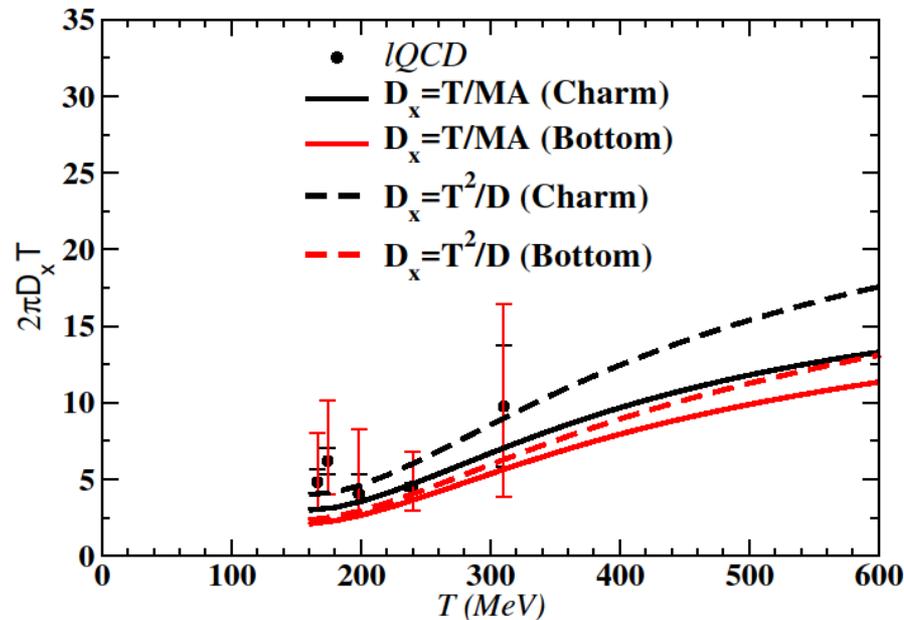
Including Lambda_b

M.L. Sambaturo, V. Minissale et. al

Heavy quark diffusion coefficient

One can compute D_x ($p \rightarrow 0$):

$D_x = T/MA$, M =mass of the heavy quark, A is the drag coefficient
 $D_x = T^2/D$, D is the diffusion coefficient



For the working group comparison we have computed the D_x starting from the drag coefficients (solid line)

Thank You



Impact of 2 dN/dp_T well within FONNL

