D-meson propagation in hadronic matter and consequences on heavy-flavor observables in heavy-ion collisions

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in collaboration with

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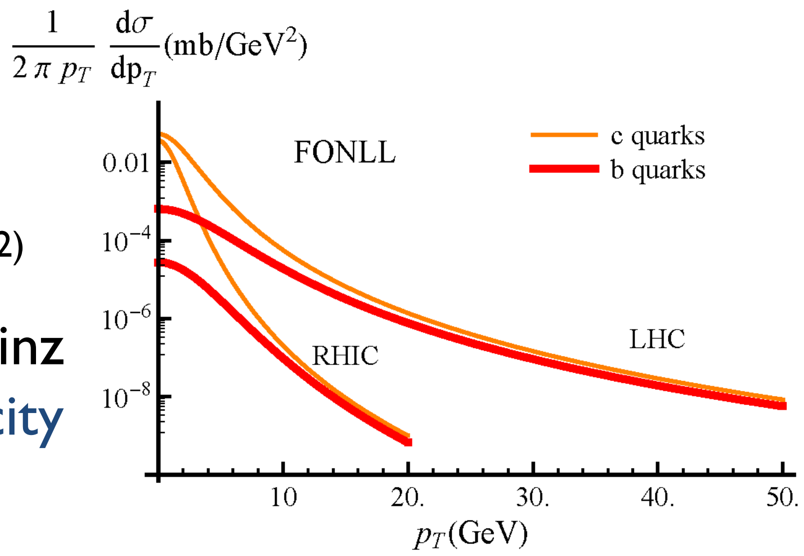
NeD Symposium, 13 June 2014

Hersonissos, Crete, Greece

„Monte Carlo @ Heavy Quark“ generator

- **production** of heavy quarks at the original NN scattering points according to the FONLL spectra

  M.Cacciari et al., Phys. Rev. Lett. **95** (2005), JHEP **1210** (2012)



- **bulk evolution:** non-viscous Kolb-Heinz hydro; provides temperature and velocity fields

  P.F.Kolb, J.Sollfrank, U.Heinz, Phys. Rev. **C62,** 054909 (2000)

- **evolution of HQ** in the bulk: the Boltzmann equation

- **hadronization of HQ:** coalescence (low p_T) and fragmentation (high p_T)

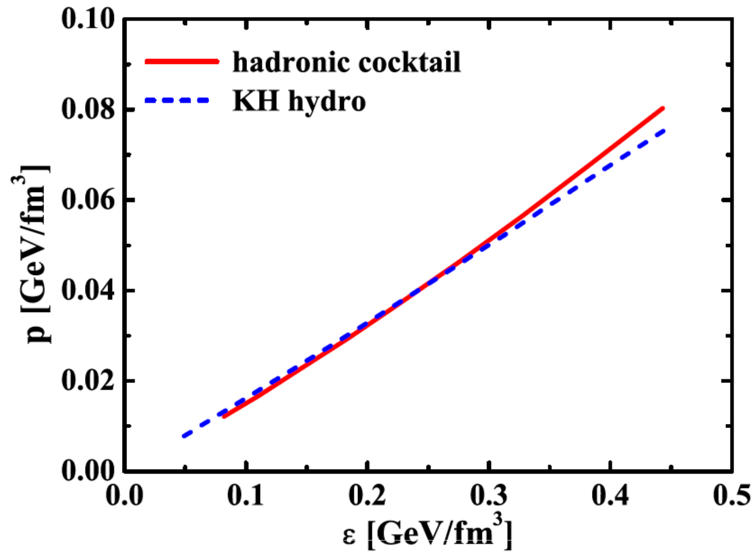
$$T_c = 165 \text{ MeV}, \quad \varepsilon_c = 0.45 \text{ GeV/fm}^3$$

- **D-meson propagation** in hadronic matter: the Fokker-Planck equation

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

Hadronic cocktail

- Hadron gas **composition:**
  - light mesons (up to masses 1.285 GeV)
  - strange mesons (K, K*,K_1)
  - nucleons
  - nuclear and Δ-resonances (up to masses 1.7 GeV)



Thermal equilibrium + effective chemical potentials

- Employ a **specific entropy** of S/N_B = 250 (characteristic value for collisions at top RHIC energy) R.Rapp, Phys. Rev. **C66**, 017901 (2002)

- **Freeze-out** point: $$T_{\rm fo}^{\rm ch} = 170\ {\rm MeV},\quad \mu_{\rm B}^{\rm ch} = 28.3\ {\rm MeV}$$ $$\varepsilon \approx 0.45\ {\rm GeV/fm^3}$$

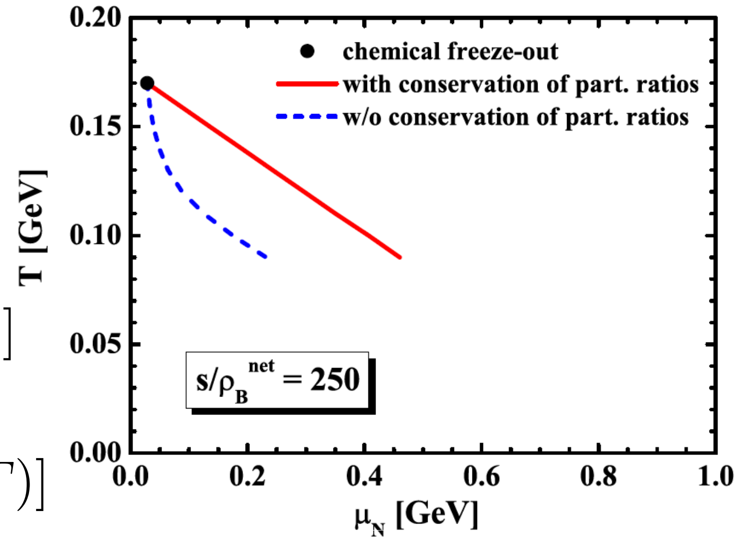
Thermodynamic trajectories

- **Thermodynamic trajectory** keeping a specific entropy fixed:

$$s/\rho_B^{\rm net} = 250$$

$$s = \mp \sum_i d_i \int \frac{d^3k}{(2\pi)^3}[\pm f \ln f + (1 \mp f)\ln(1 \mp f)]$$

$$\rho_B^{\rm net} = \sum_{B_i} d_{B_i} \int \frac{d^3k}{(2\pi)^3}[f^{B_i}(\mu_{B_i}, T) - f^{\bar{B}_i}(\mu_{\bar{B}_i}, T)]$$



- Keep a **ratios** of effective stable particle numbers to effective antibaryon number constant in a hadronic evolution:

R.Rapp, Phys.Rev. **C66**, 017901 (2002)

$$\frac{N_B^{\rm eff}}{N_{\bar{B}}^{\rm eff}}, \frac{N_\pi^{\rm eff}}{N_{\bar{B}}^{\rm eff}}, \frac{N_\eta^{\rm eff}}{N_{\bar{B}}^{\rm eff}}, \frac{N_K^{\rm eff}}{N_{\bar{B}}^{\rm eff}}, \frac{N_\omega^{\rm eff}}{N_{\bar{B}}^{\rm eff}}, \frac{N_{\eta'}^{\rm eff}}{N_{\bar{B}}^{\rm eff}}, \frac{N_\phi^{\rm eff}}{N_{\bar{B}}^{\rm eff}}$$

$$N_{\bar{B}}^{\rm eff} = V_{FB} \sum_{\bar{B}_i} n_{\bar{B}_i}(T, \mu_{\bar{B}_i})$$

$$N_\pi^{\rm eff} = V_{FB} \sum_i N_\pi^{(i)} n_i(T, \mu_i)$$

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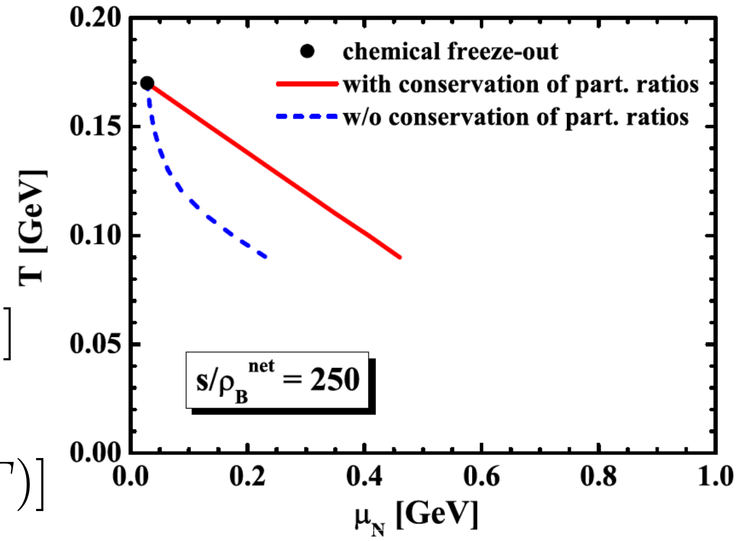

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$$N_\pi^{\text{eff}} = V_{FB} \sum_i N_\pi^{(i)} n_i(T, \mu_i)$$

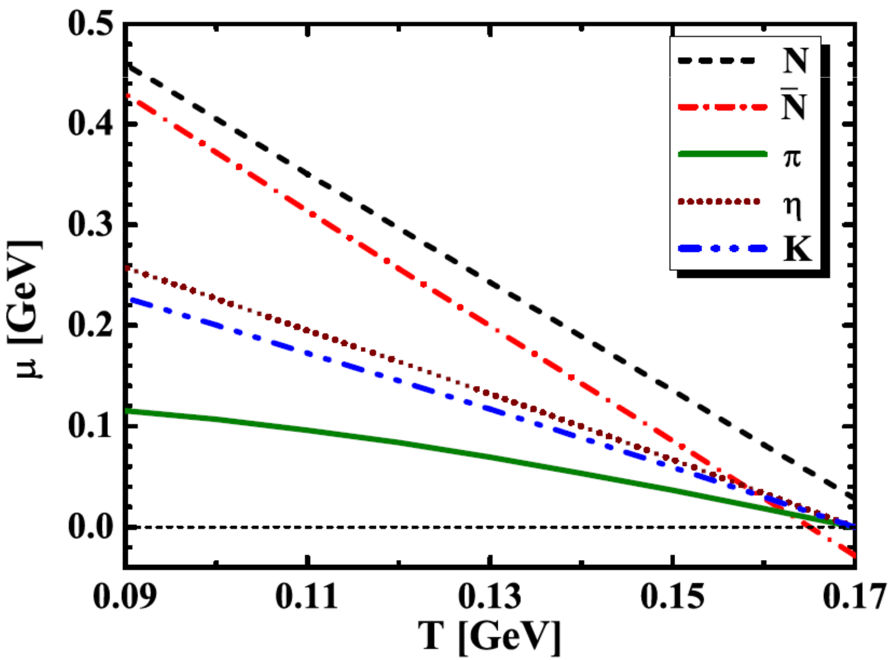
$$N_\pi^{(\rho)} = 2, N_\pi^{(\Delta)} = 1, N_\pi^{(N(1520))} = 0.55 * 1 + 0.45 * 2$$

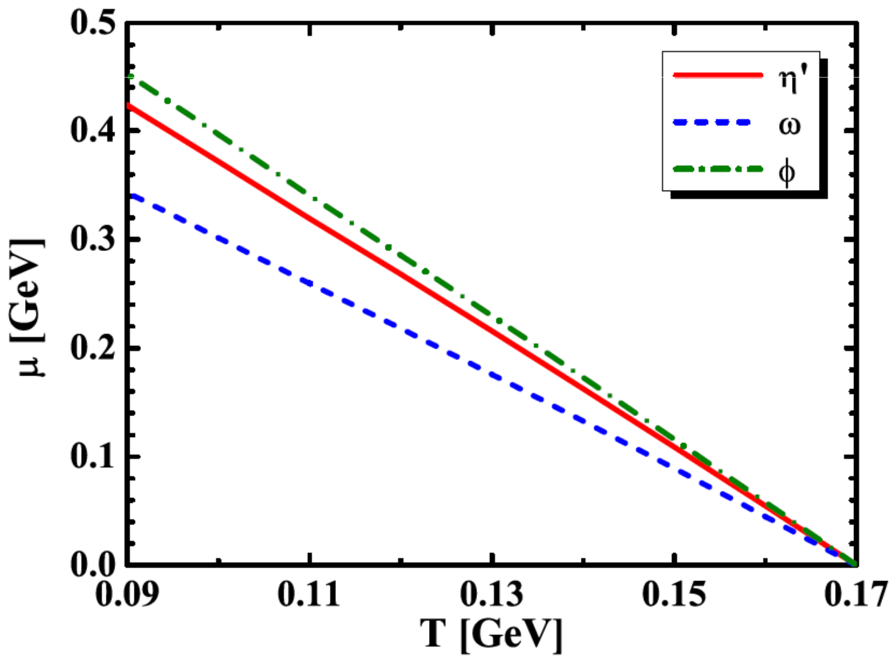
$$\Rightarrow \mu_\rho = 2\mu_\pi, \mu_\Delta = \mu_N + \mu_\pi, \mu_{N(1520)} = \mu_N + 1.45\mu_\pi$$

Effective chemical potentials

❑ To conserve the ratio of effective baryon to antibaryon number we introduce **antibaryon effective ch. potential**, $\mu_{\bar{B}}^{\mathrm{eff}}$, e.g., $\mu_{\bar{N}} = -\mu_N + \mu_{\bar{B}}^{\mathrm{eff}}$.

❑ At chemical freeze-out temperature all meson effective chemical potentials are zero

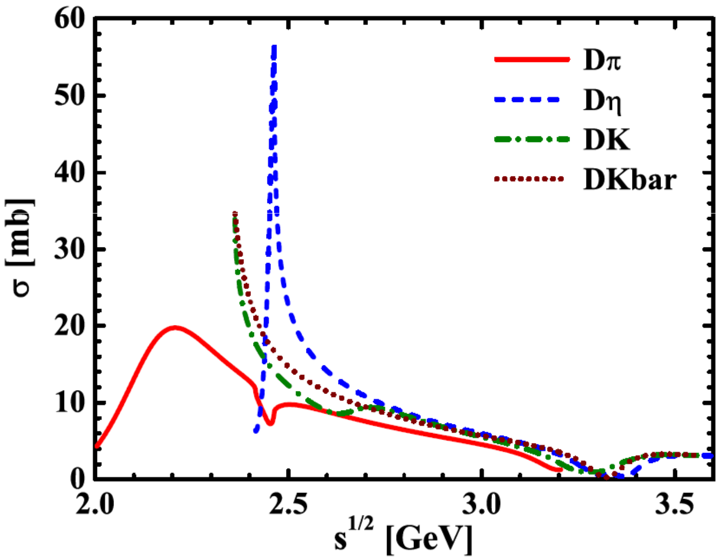


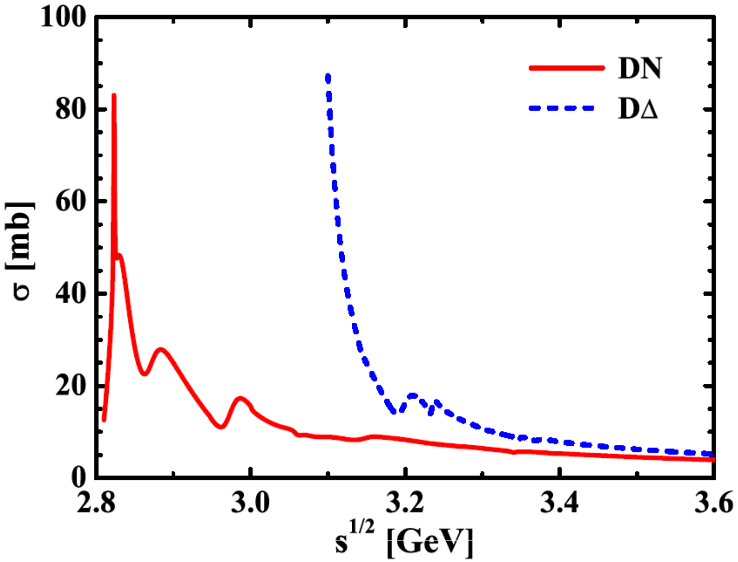


Elastic cross sections (scenario A)

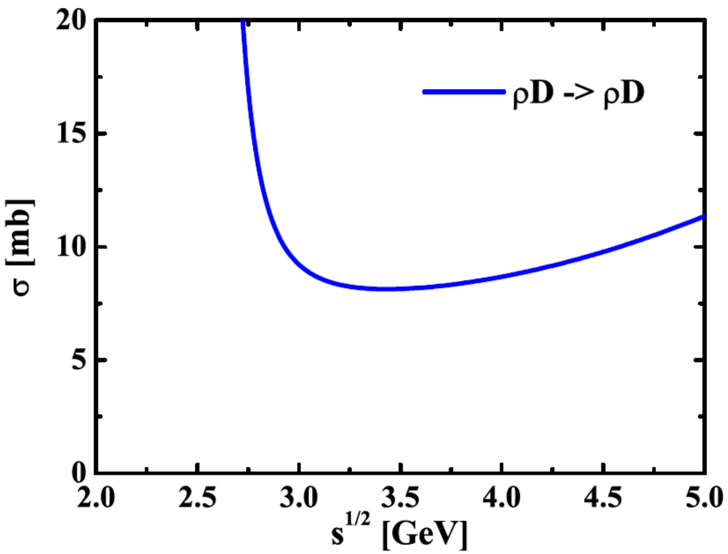
- Implement the **cross sections** (as in the vacuum) for the interaction of a D-meson with hadrons (effective models):

L.Tolos, J.M.Torres-Rincon, Phys. Rev. **D88**, 074019 (2013)





Z.Lin, T.G.Di, C.M.Ko, Nucl. Phys. **A689**, 965 (2001)



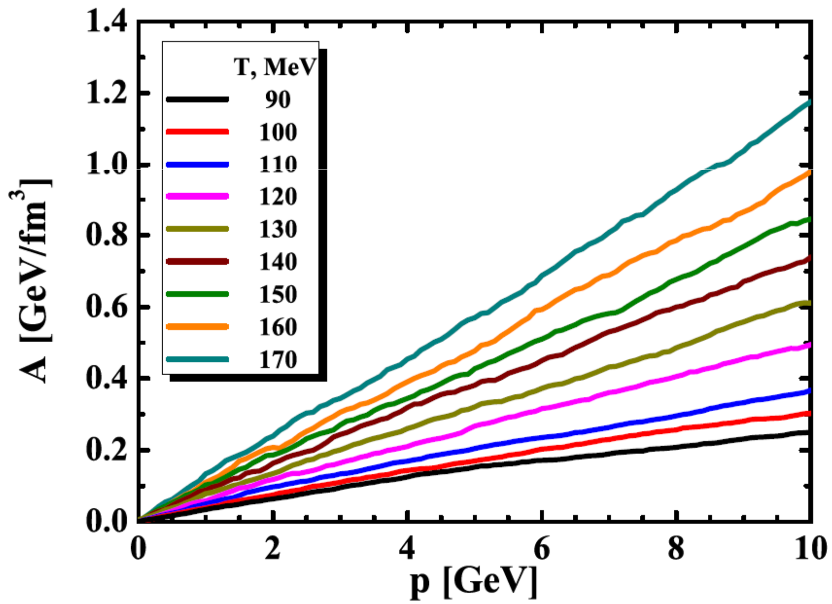
- Other **elastic processes:**

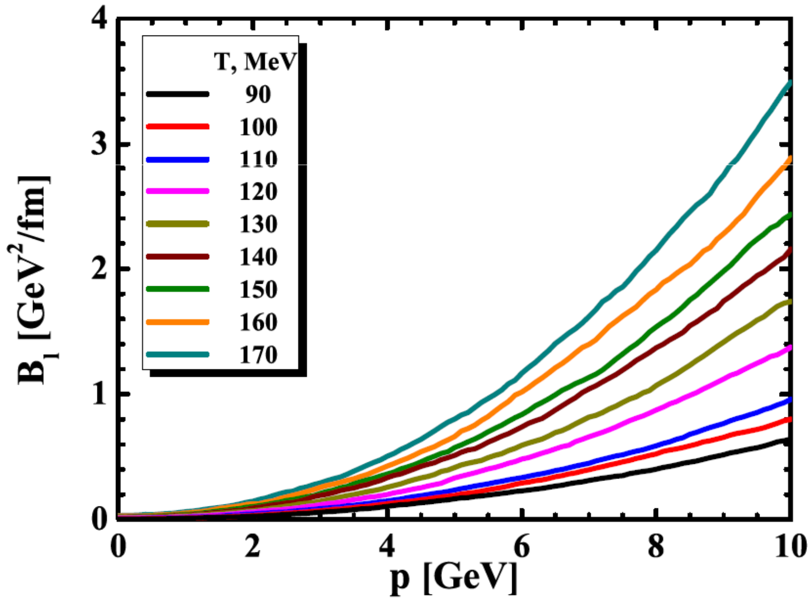
$$Dm \to Dm \Rightarrow \sigma = 10 \text{ mb}$$
$$DB(\bar{B}) \to DB(\bar{B}) \Rightarrow \sigma = 15 \text{ mb}$$

D-meson transport coefficients

❑ Calculate the following average quantities, which can be related to the **drag, longitudinal and transverse diffusion coefficients:**

$$A = -\left\langle \frac{dp_z}{dt} \right\rangle, \;\; B_l = \frac{1}{2} \frac{d(\langle p_z^2 \rangle - \langle p_z \rangle^2)}{dt}, \;\; B_T = \frac{1}{4} \left\langle \frac{dp_T^2}{dt} \right\rangle$$





- almost **linear rise** with the momentum;
- contributions from heavier hadrons become **important** at higher temperatures

in the **static limit:**

$$\lim_{p \to 0} [B_l(p) - B_T(p)] = 0$$

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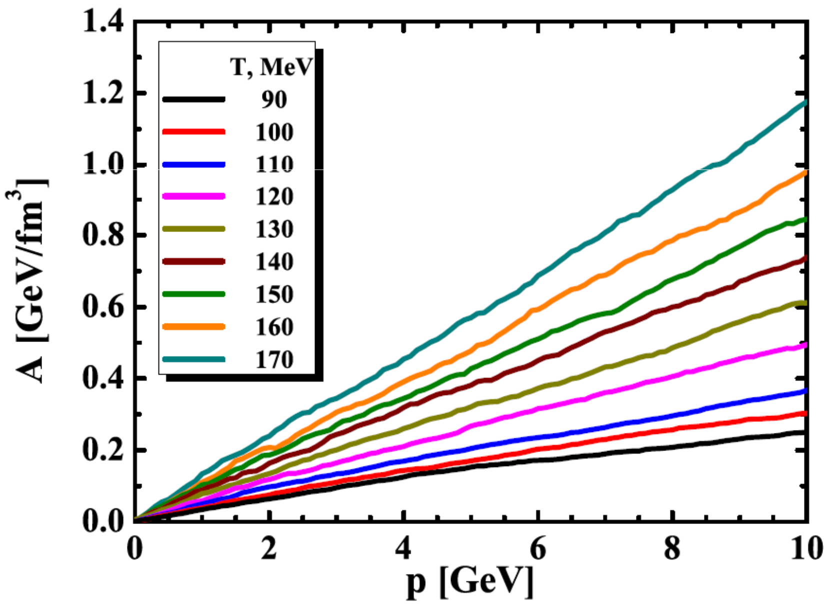

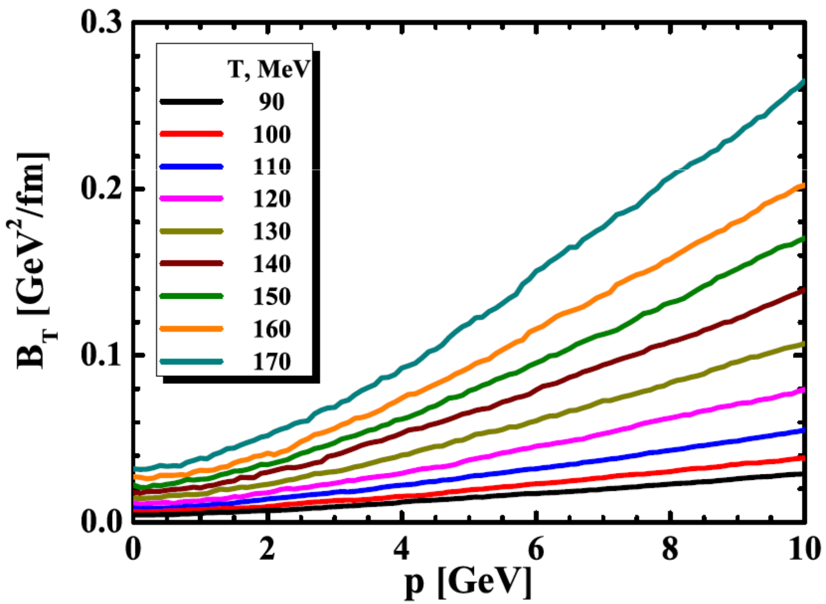

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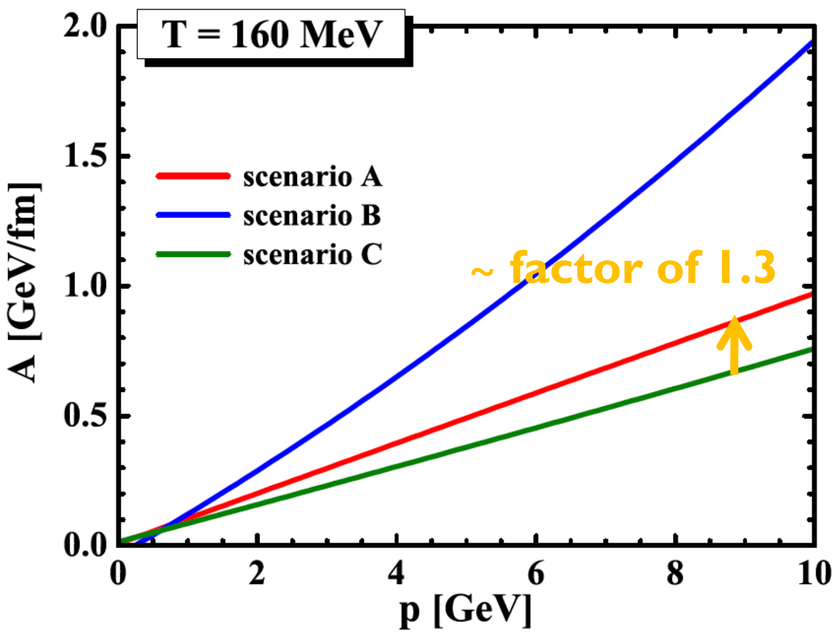
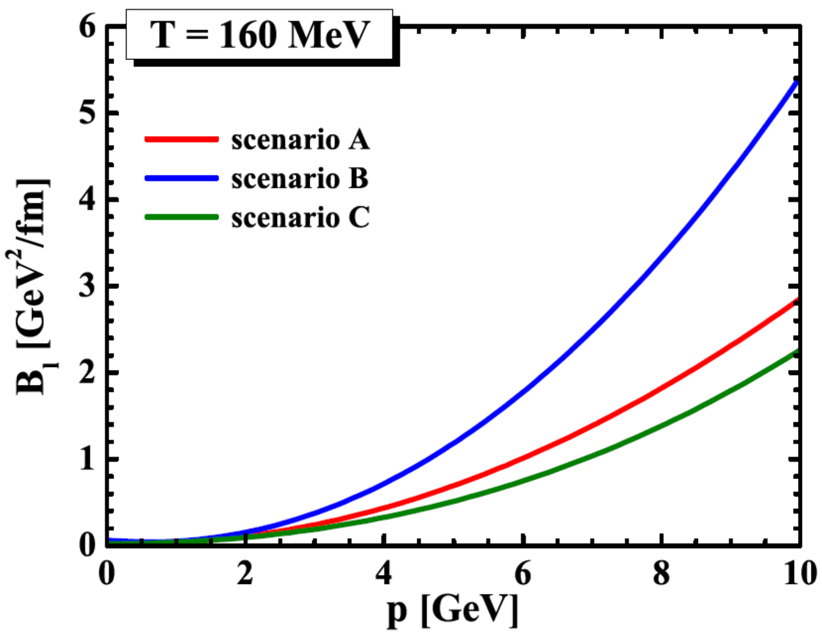
Other scenarios

- ***Scenario A*** – discussed above…
- ***Scenario B*** – use constant cross sections + effective chemical potentials:

$$Dm \rightarrow Dm \Rightarrow \sigma = 10 \text{ mb}, \quad DB(\bar{B}) \rightarrow DB(\bar{B}) \Rightarrow \sigma = 15 \text{ mb}$$

- ***Scenario C*** – do not implement effective chemical potentials: $\mu_i^{\text{eff}}(T) = 0$





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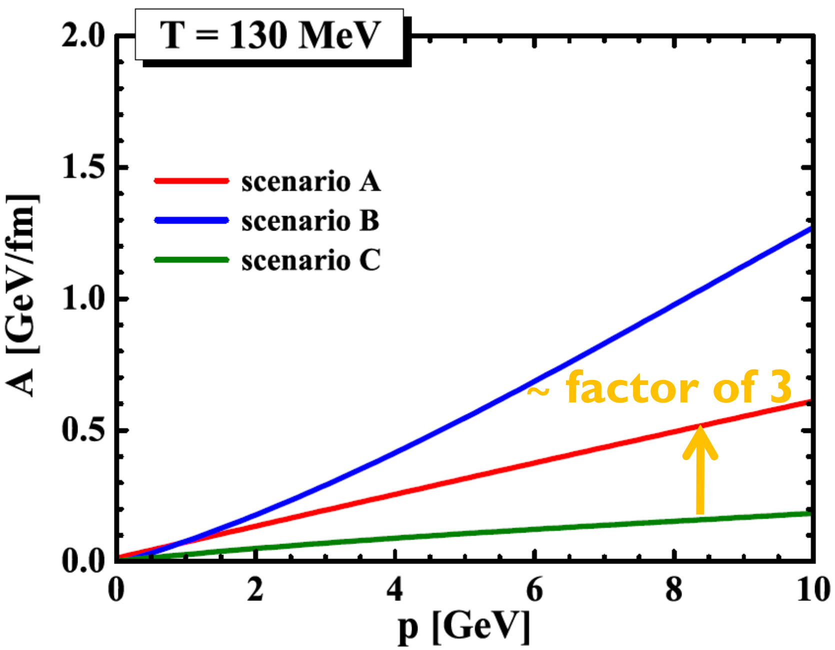

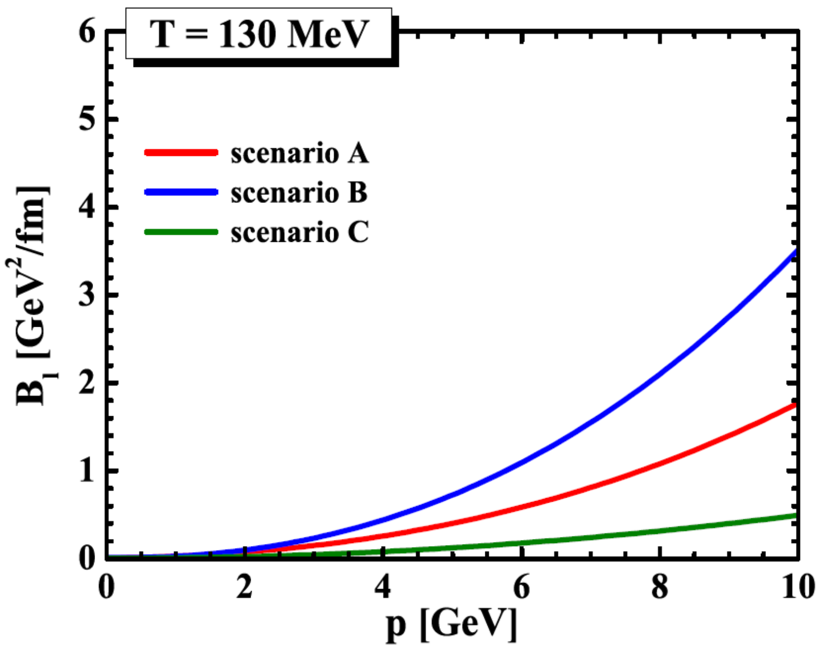

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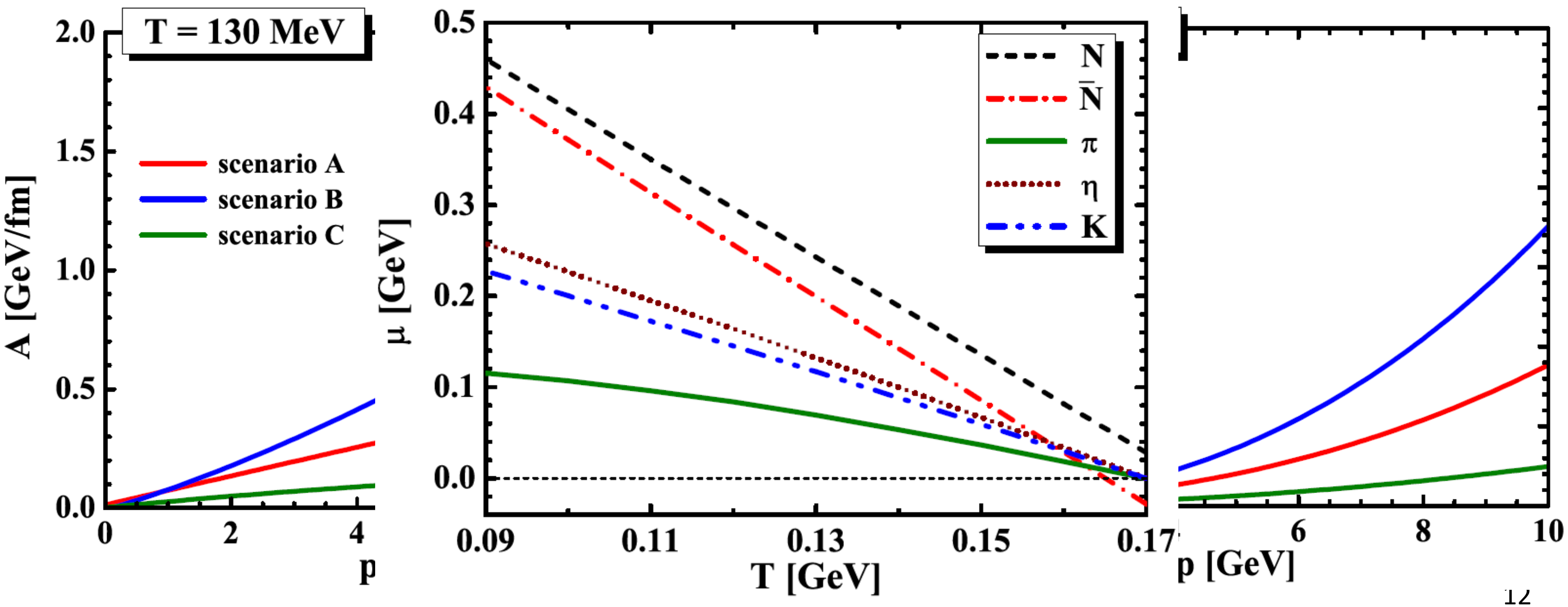
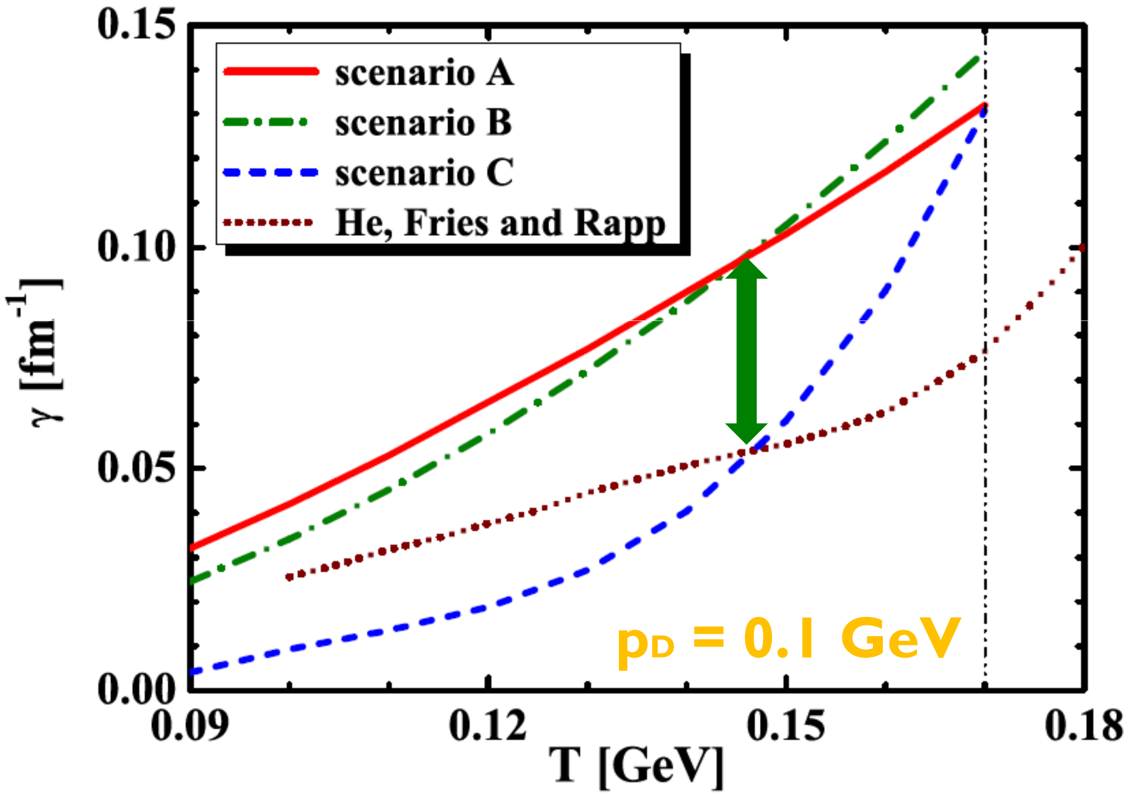


D-meson thermal relaxation time

- Evaluate the **D-meson thermal relaxation time:**

$$\gamma = \frac{A}{p_D} \frac{E_D}{m_D}$$

M.He, J.Fries,R.Rapp, Phys. Lett **B701**, 445 (2011)



- **Increase by a factor of 2** of the thermal relaxation time due to the different hadronic cocktail and different cross sections

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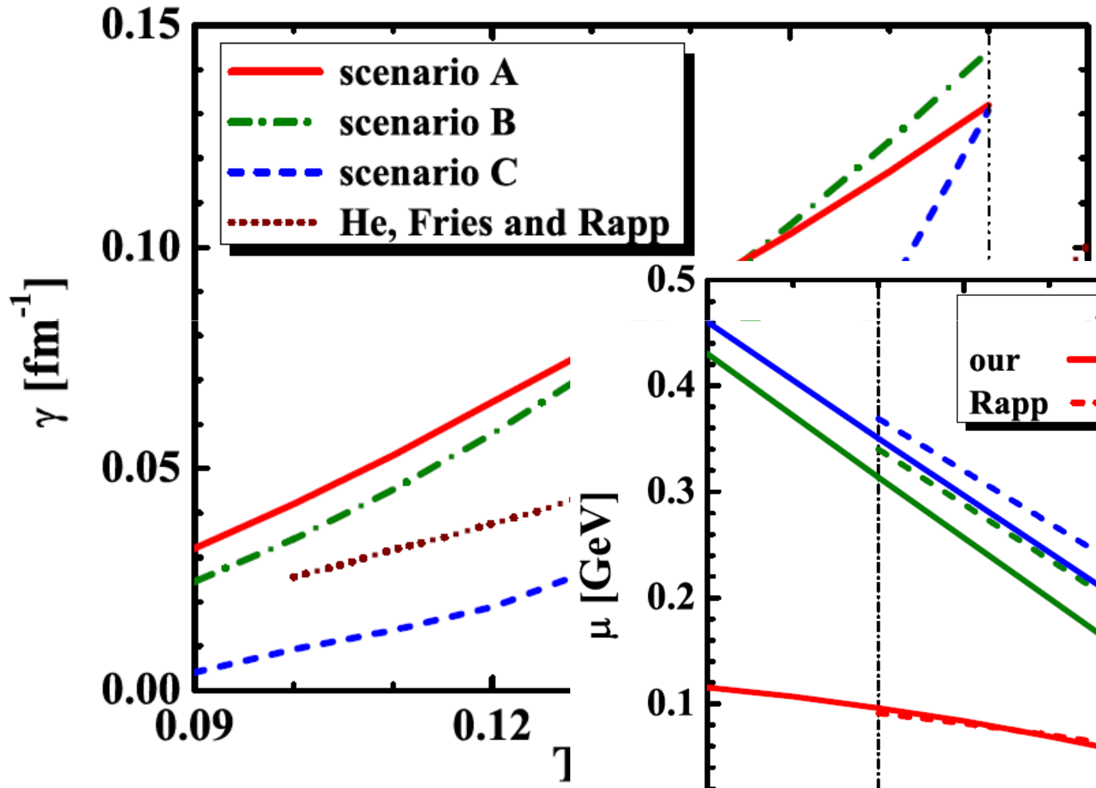
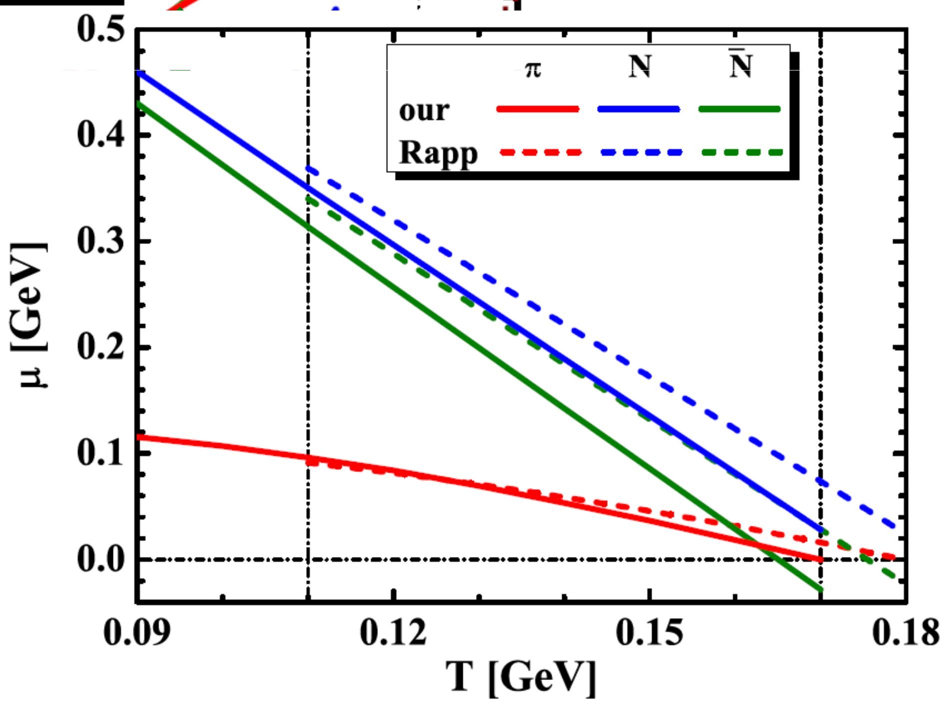




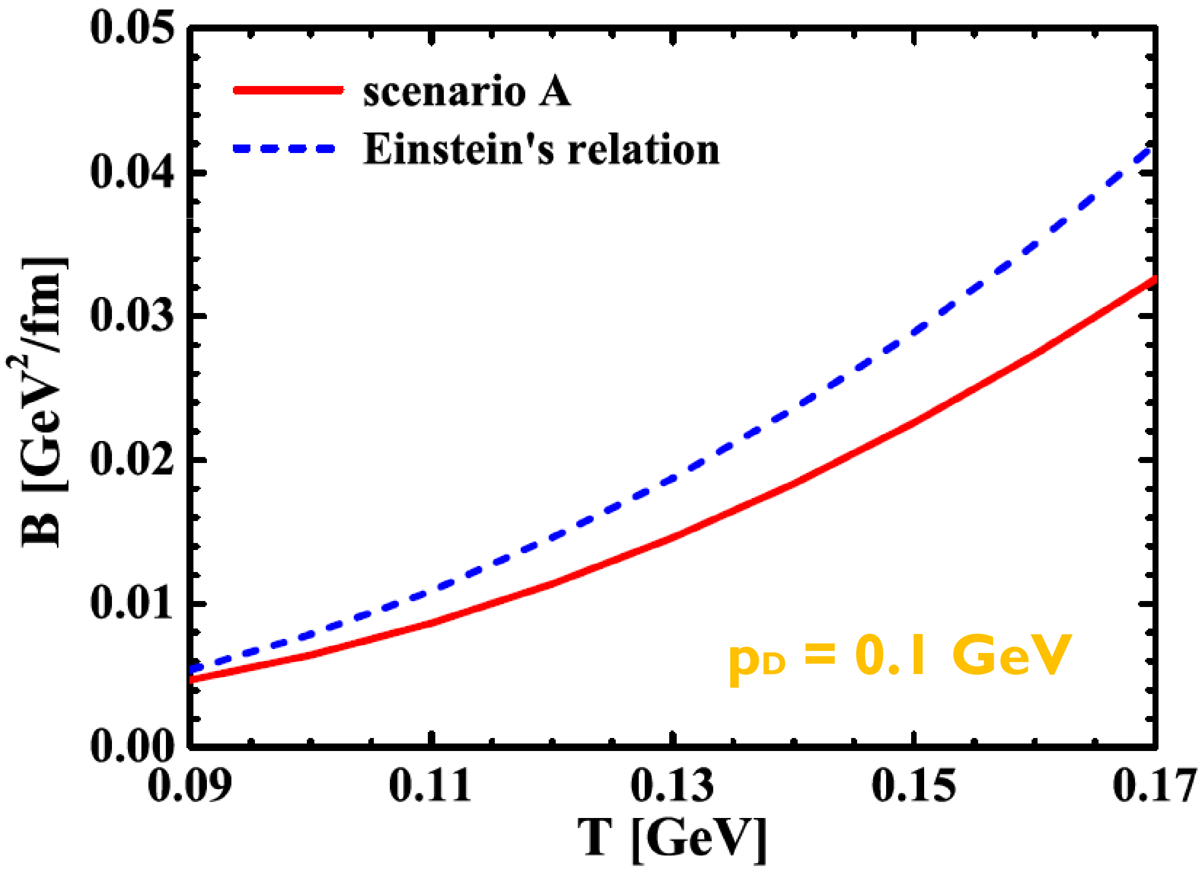
R.Rapp, Phys. Rev **C66**, 017901 (2002)

- **Increase by a factor of 2** of th
different hadronic cocktail and differ

Einstein relation

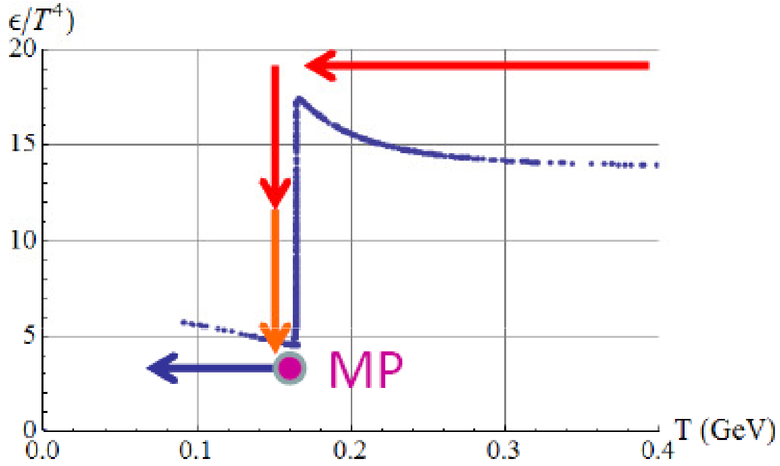
- In the **static limit:** $\lim_{p\to 0}[B_l(p) - B_T(p)] = 0 \quad \Rightarrow \quad B = B_l = B_T$

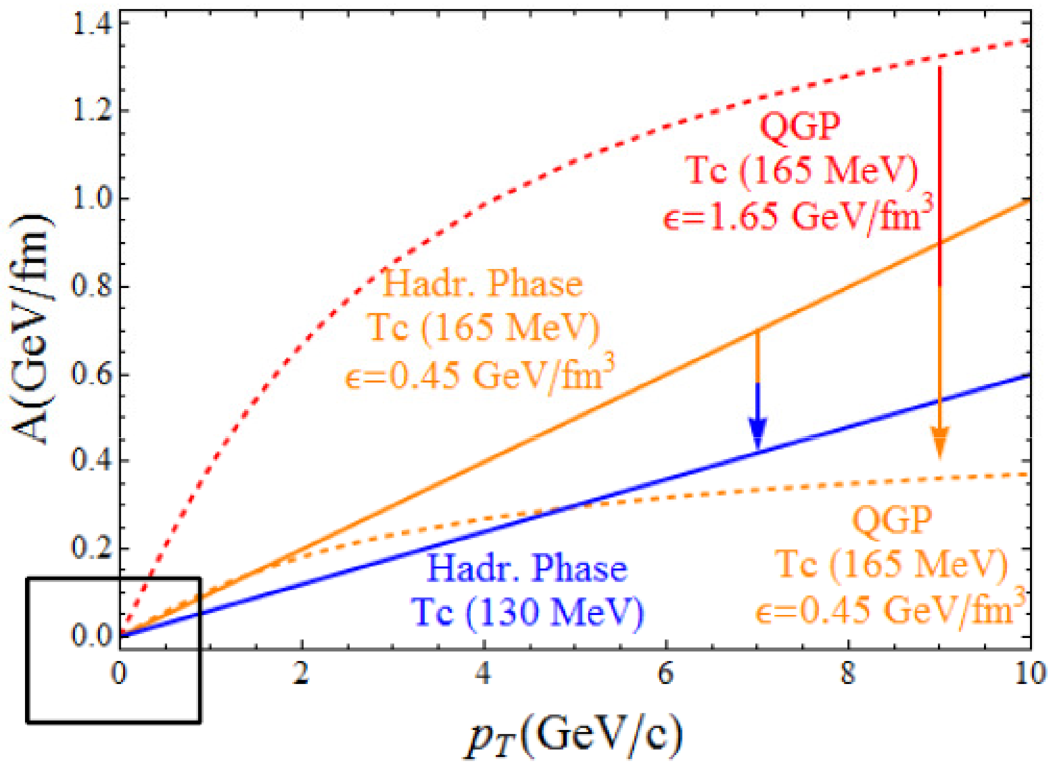
- **Einstein relation:** $\boxed{B = \gamma m_D T}$



Comparison to HQ in plasma

Slide from Pol's talk

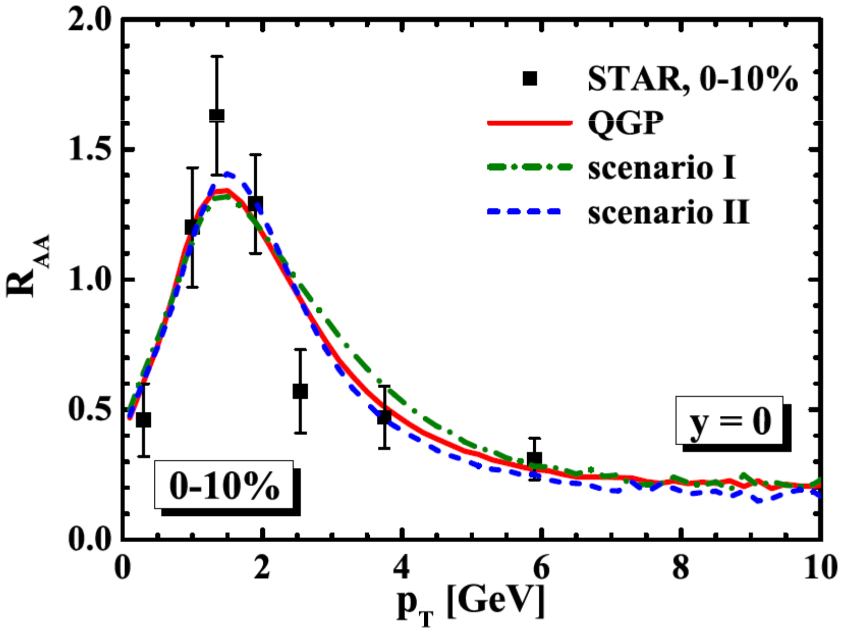


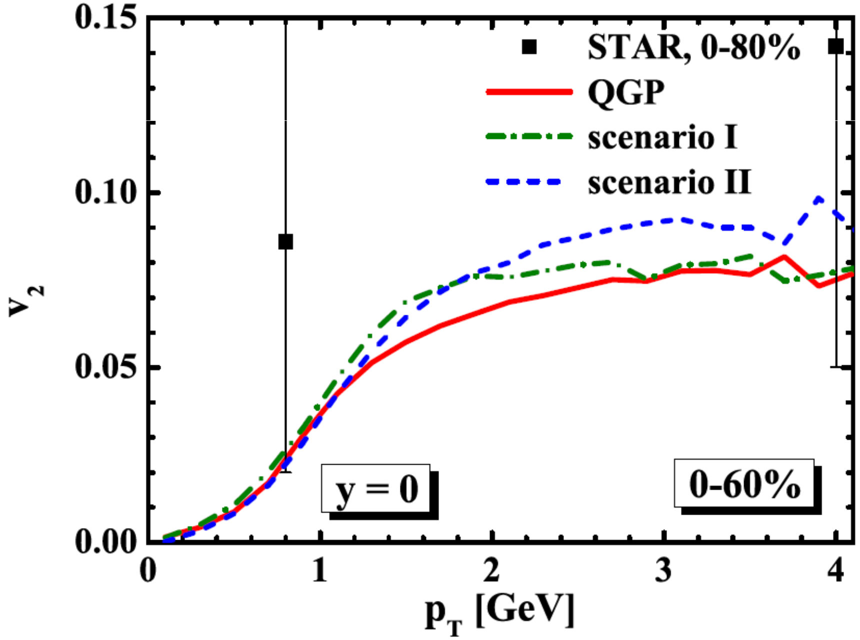


- **Relaxation times** at the **MP** fairly agrees (≈ 10 fm/c) – it satisfies the "crossover" constrain
- **p_T dependences** disagree (isotropic cross sections in the HG)

R_{AA} and v_2 of D-meson

- Implement the **obtained results** to "MC@HQ" generator
- Calculate the D-meson **nuclear modification factor and elliptic flow** for two different scenarios:
  - ***scenario I:*** transport coefficients, drag and diffusion, directly from the simulation
  - ***scenario II:*** drag – simulation, diffusion – Einstein relation





Almost invisible for R_{AA}

Moderate effect on v_2, but systematic

R_{AA} and v_2 of single nonphotonic leptons

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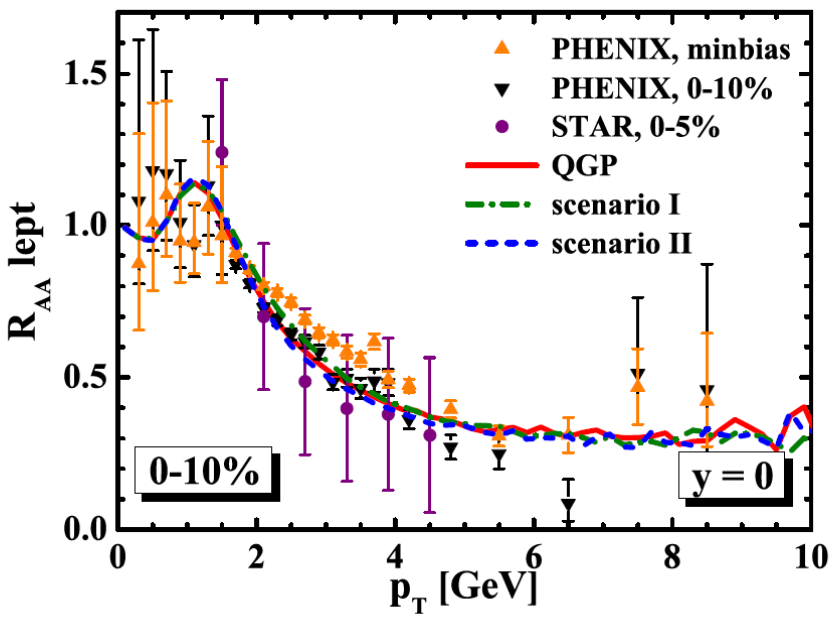

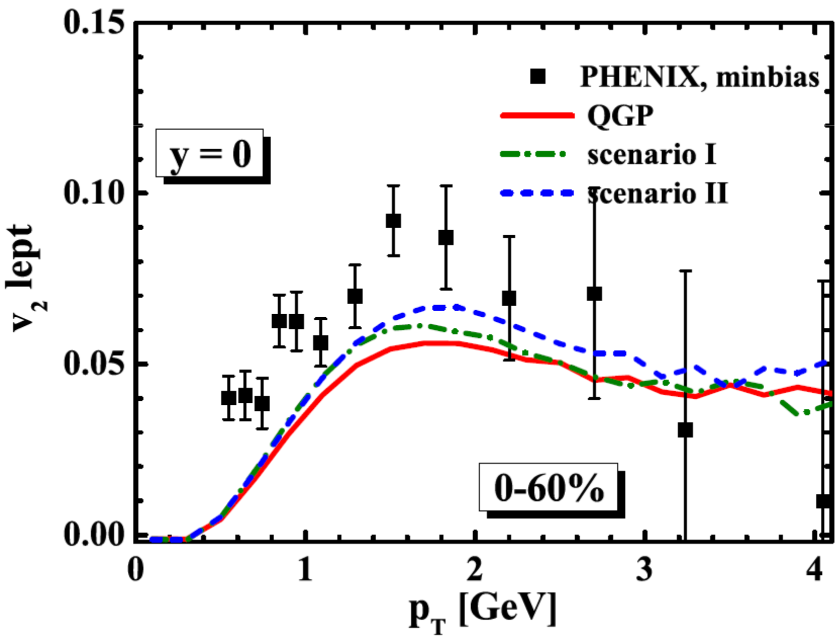

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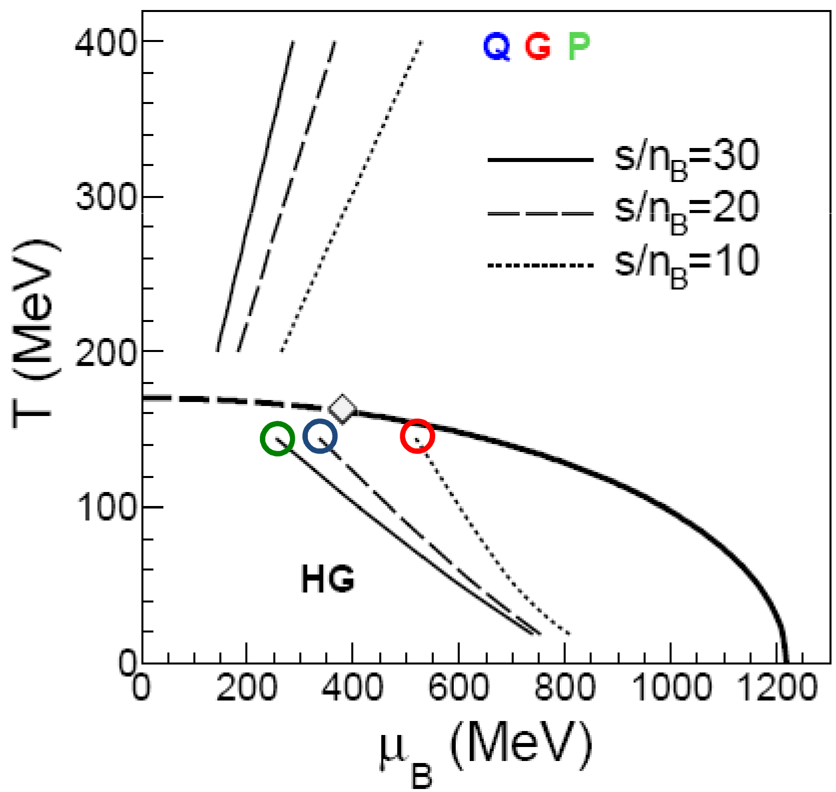
Isentropic trajectories (FAIR facility)

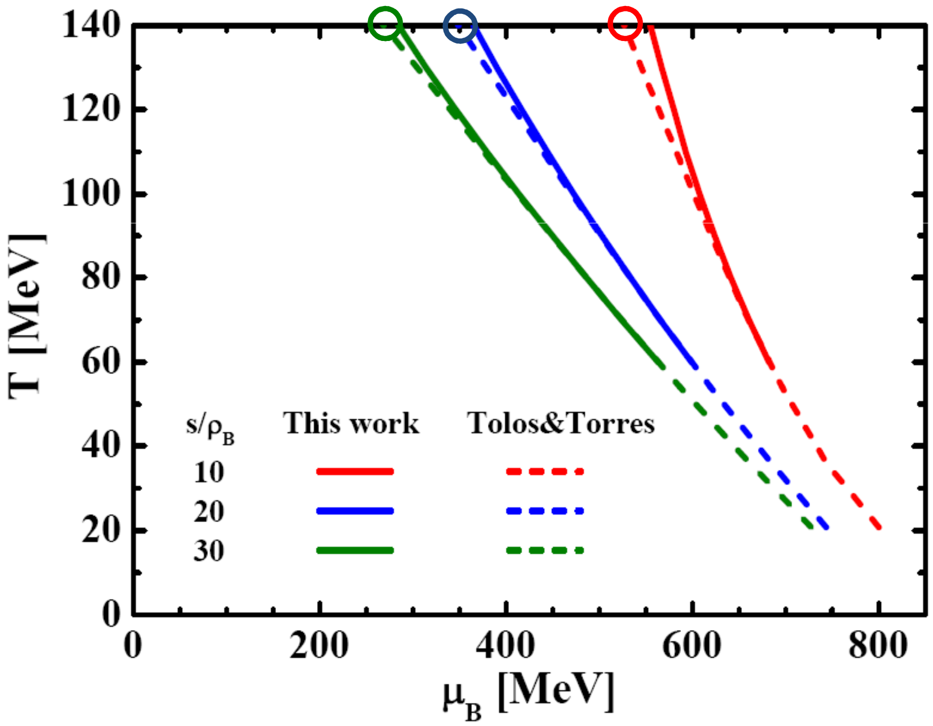
❑ Assume a **constant specific entropy** (entropy per net baryon) for **FAIR physics:**

$$\sqrt{s} = 5 - 40\ AGeV \Leftrightarrow s/n_B = 10 - 30$$

Juan Torres FAIRNESS 2013



L. Tolos, J.M. Torres-Rincon, Phys. Rev. **D88**, 074019 (2013)



Small deviation due to the higher states in our hadronic cocktail

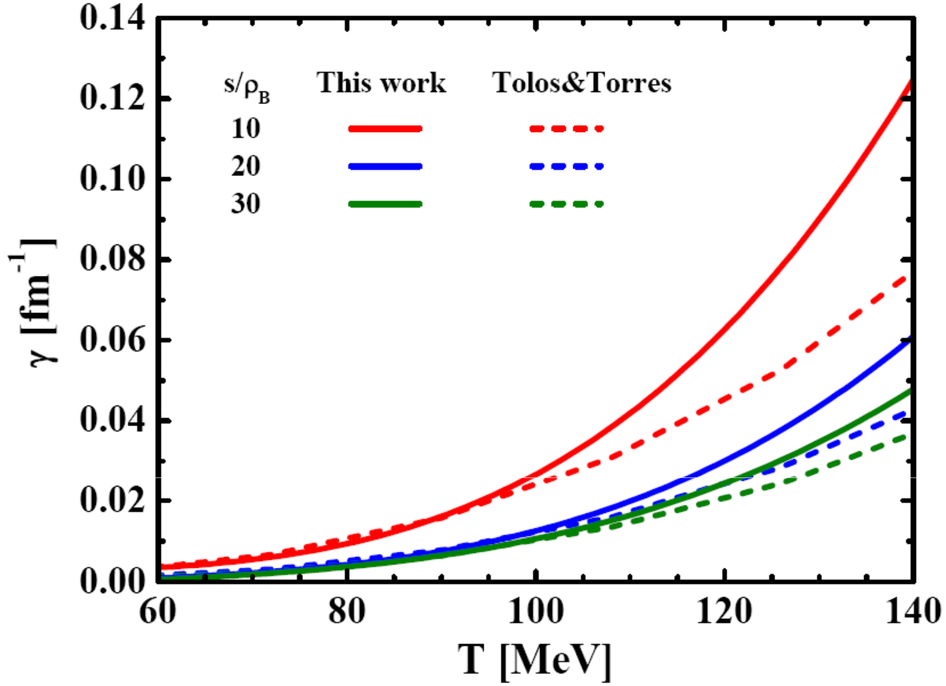
Thermal relaxation rate (FAIR facility)

- **strong dependence** on the isentropic trajectory

- **baryons** contribute **significantly** for finite baryochemical potential

- **deviation** at higher temperatures due to higher states in our hadronic cocktail

L.Tolos, J.M.Torres-Rincon, Phys. Rev. **D88**, 074019 (2013)



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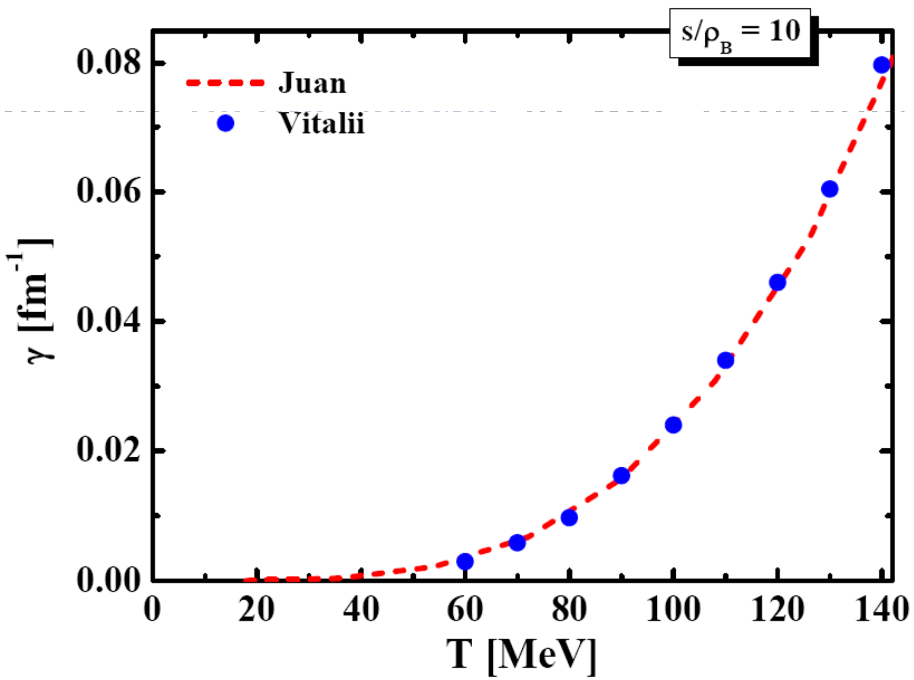
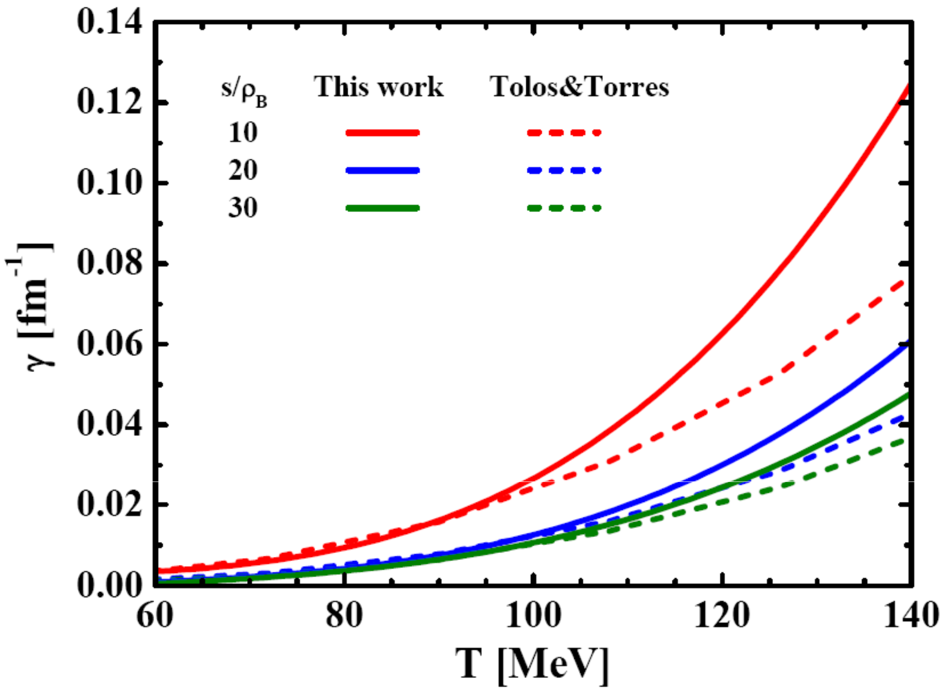


L.Tolos, J.M.Torres-Rincon, Phys. Rev. **D88**, 074019 (2013)

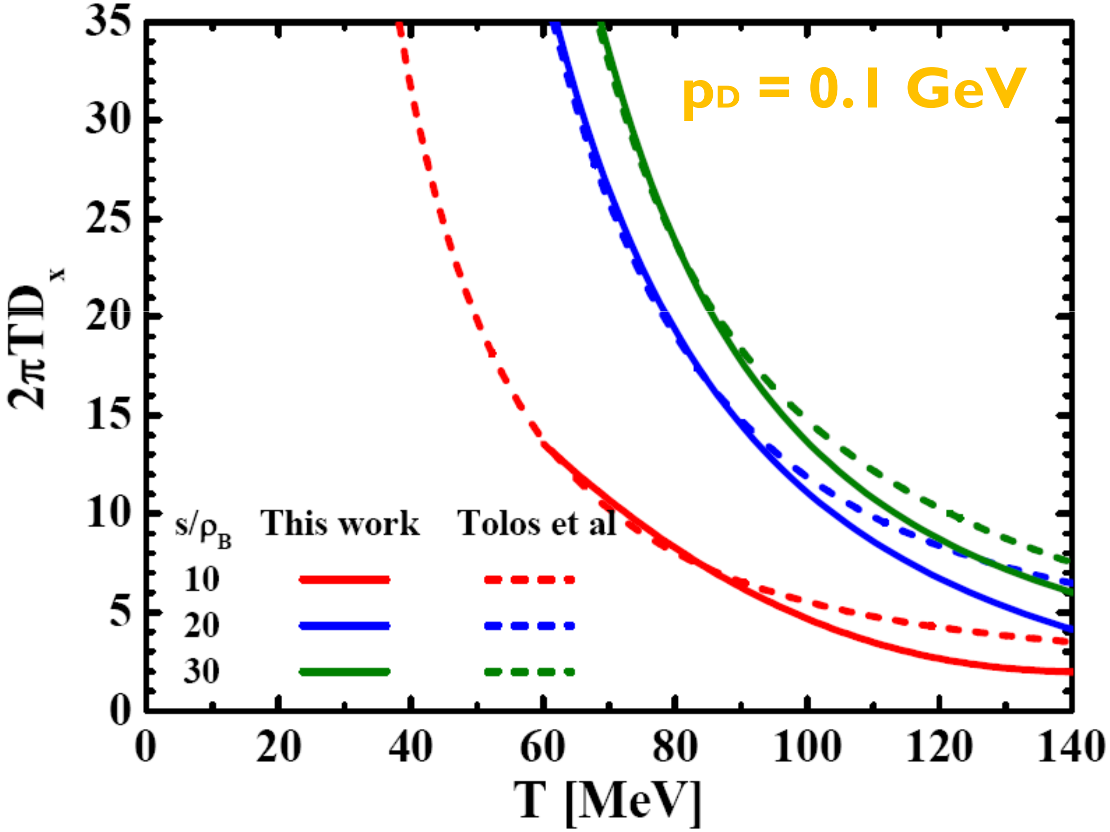


Perfect agreement

Spacial diffusion coefficient (FAIR facility)

- **Spatial diffusion coefficient:** $$D_x = \lim_{p \to 0} \frac{B}{m_D^2 \gamma}$$

L. Tolos, J.M. Torres-Rincon, Phys. Rev. **D88**, 074019 (2013)



the higher states are **important,** but less known

Summary

- Introduce the **effective chemical potentials** for all **hadron species** that are subject to strong decays

- Calculate the **D-meson transport coefficients** as functions of **momentum** and **temperature** for three scenarios

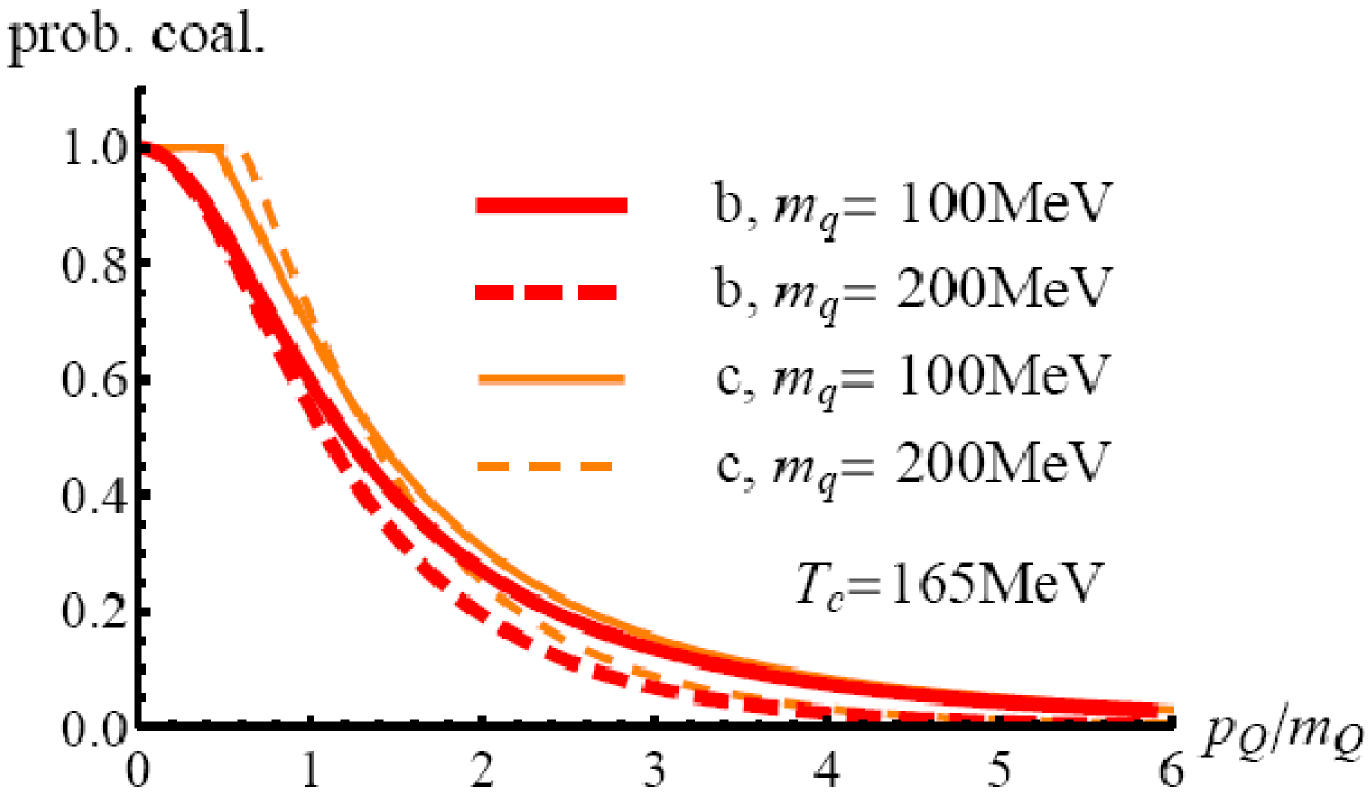
- The **presence** of D-meson rescattering in HG is **almost invisible** for the R_{AA}, but shows a **systematic contribution of 1%-2%** to the v_2 of D-meson and of single nonphotonic leptons originating from the decays of heavy mesons

- Transport coefficients **strongly depend** on the isentropic trajectory

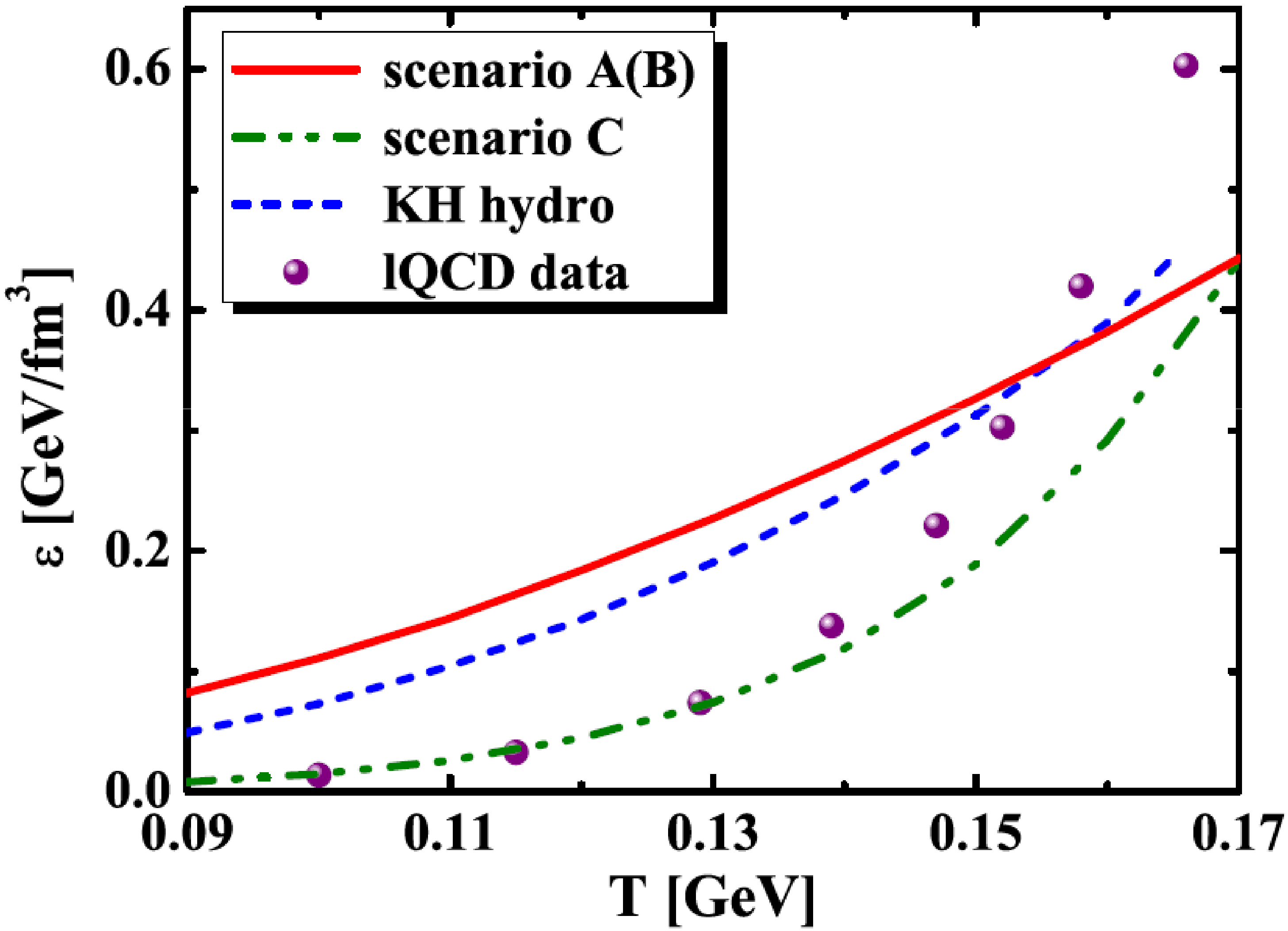
- The **spatial diffusion coefficient** is **sensitive** to the higher states in the HG at higher temperature (extension of the calculations to **FAIR** case)

Back up

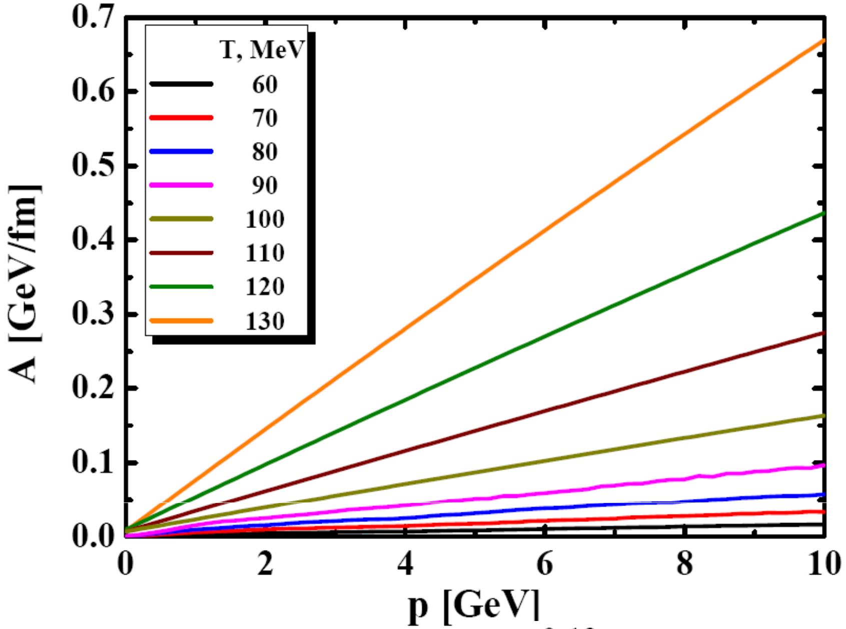
Hadronization of HQ

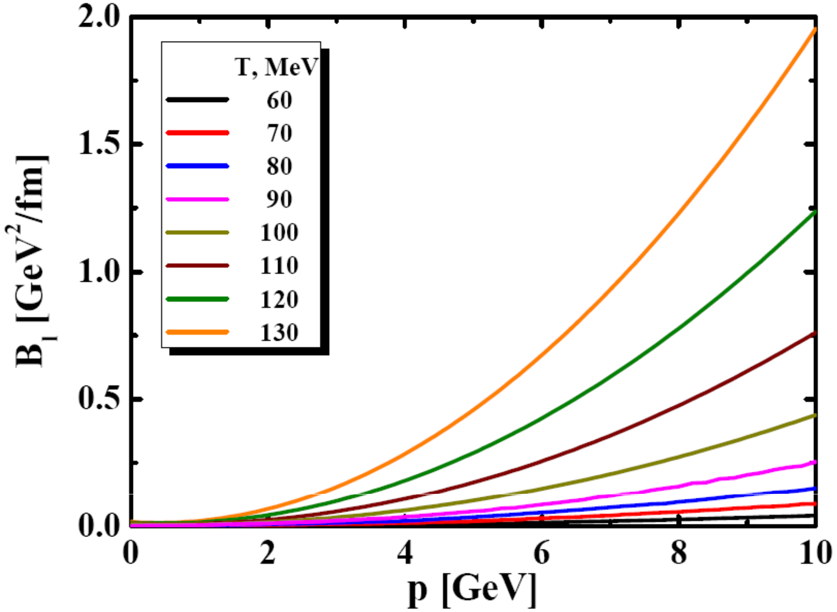


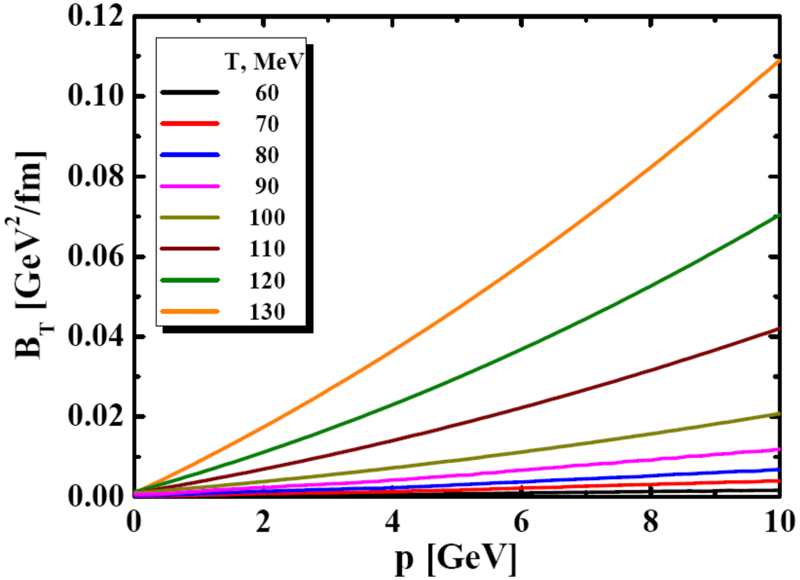
Hadronic equation of state



D-meson transport coefficint (s/n$_B$ = 10)







Spatial diffusion coefficient (Juan)