D-meson propagation in hadronic matter and MC@sHQ+EPOS3 results

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in collaboration with

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PRC90, 054909 (2014)

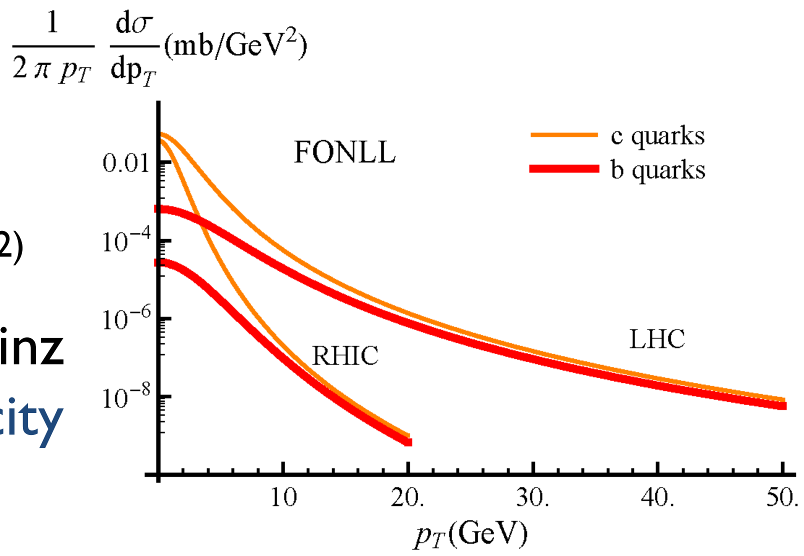
SaporeGravis Workshop, 12.12.2014
Padova, Italy

TOGETHER Project (Region Pays de la Loire)

„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)

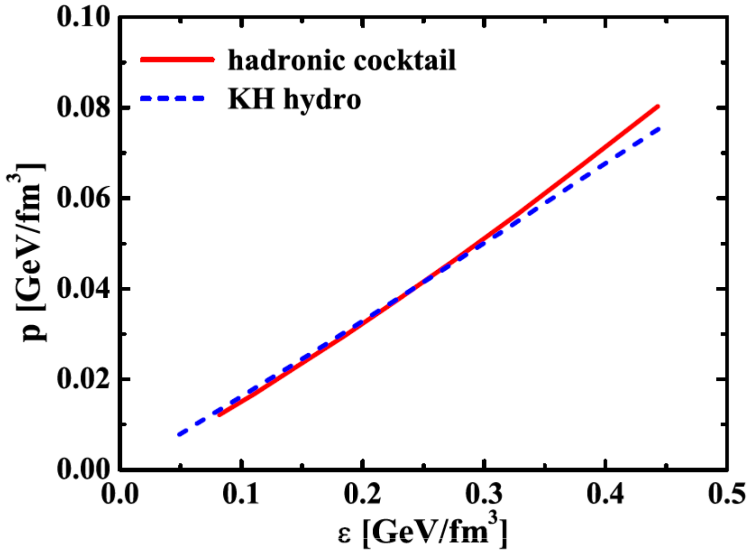
$$T_c = 165\ \mathrm{MeV}, \quad \varepsilon_c = 0.45\ \mathrm{GeV/fm^3}$$

- **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: $T_{\rm fo}^{\rm ch} = 170\ {\rm MeV}, \quad \mu_{\rm B}^{\rm ch} = 28.3\ {\rm MeV}$

$$\varepsilon \approx 0.45\ {\rm GeV/fm^3}$$

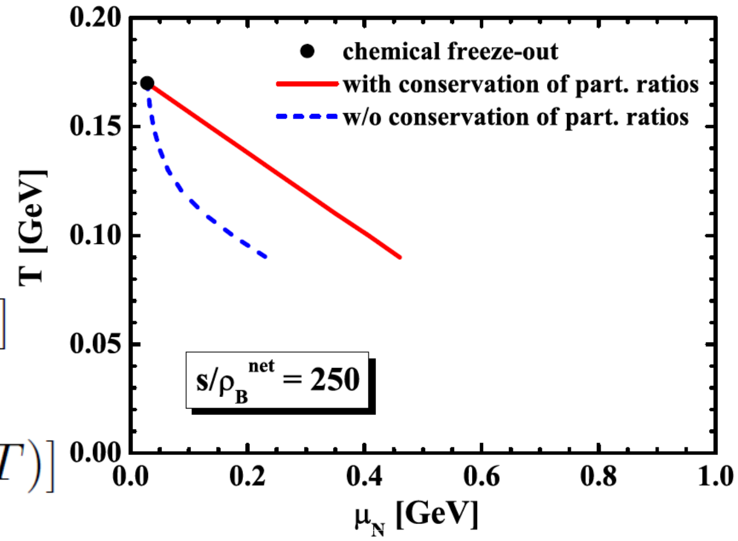
Thermodynamic trajectories

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

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

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

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



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

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

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

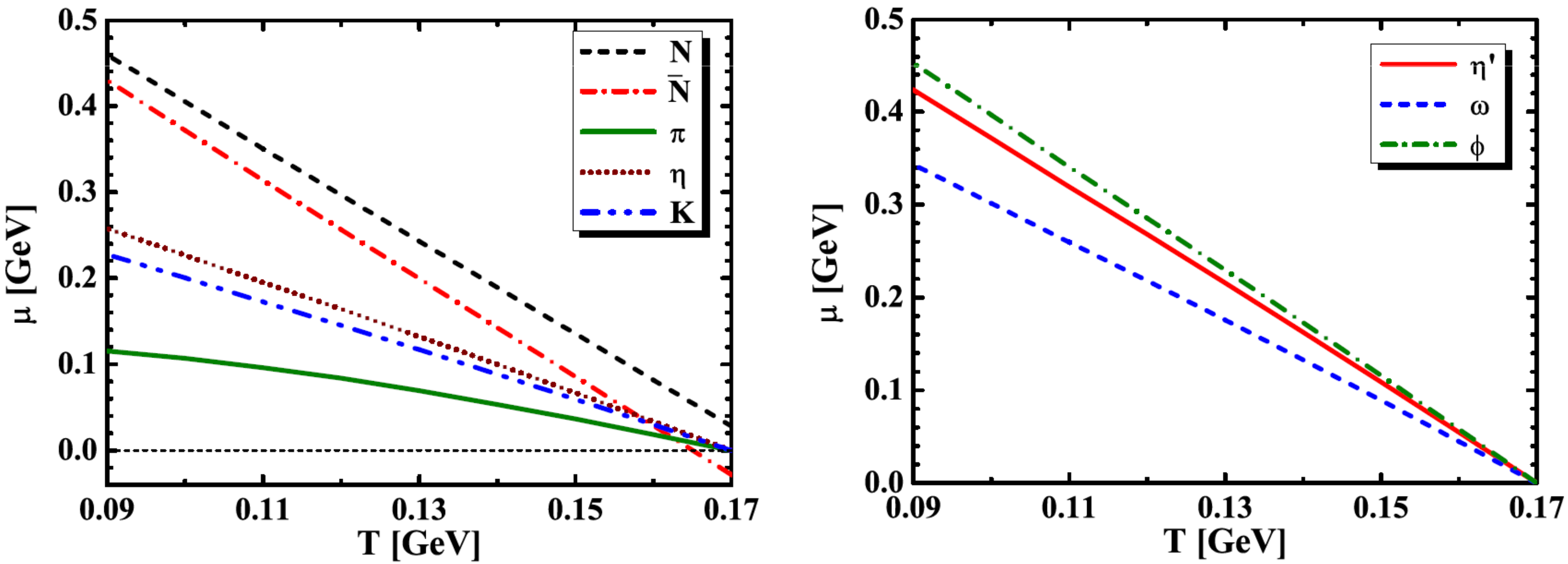
$$N_{\bar{B}}^{\rm eff} = V_{FB} \sum_{\bar{B}_i} n_{\bar{B}_i}(T, \mu_{\bar{B}_i})$$

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

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., $\mu_{\bar{N}} = -\mu_N + \mu_{\bar{B}}^{\mathrm{eff}}$.

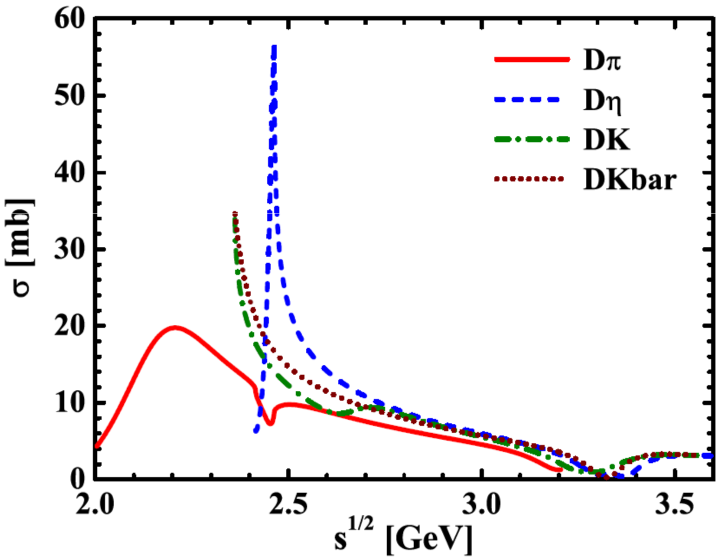
- At chemical freeze-out temperature all meson effective chemical potentials are zero

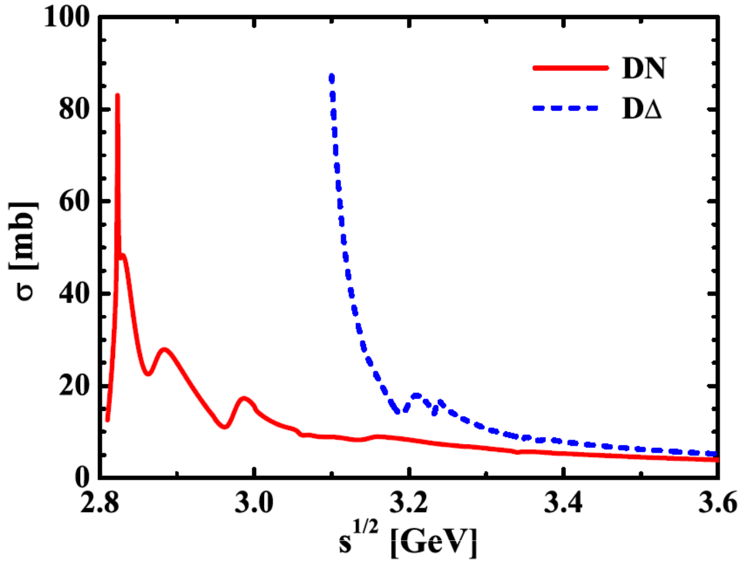


Elastic cross sections

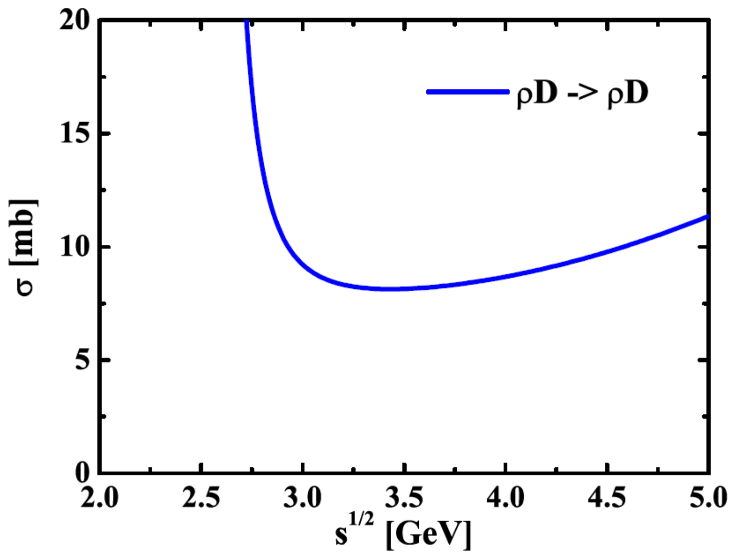
- Implement the **cross sections** (as in the vacuum) for the interaction of a D-meson with hadrons (effective models):

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:**

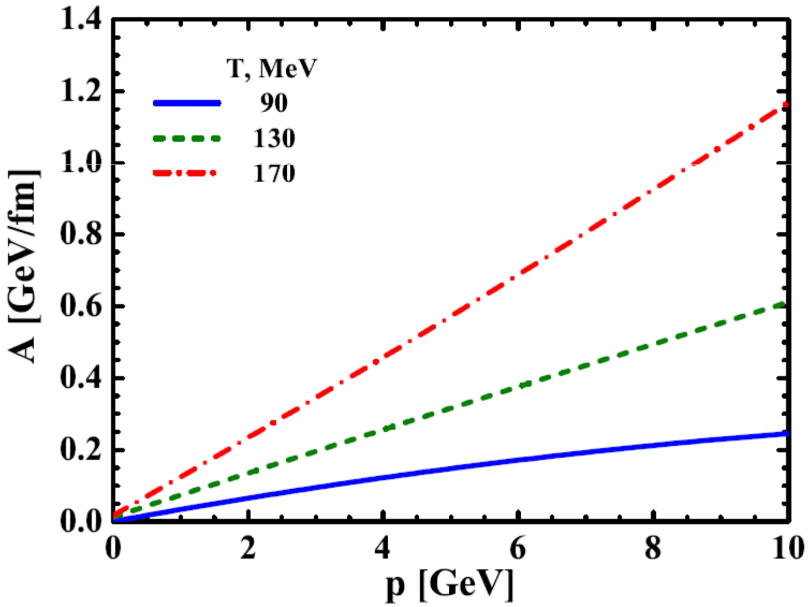
$$Dm \rightarrow Dm \Rightarrow \sigma = 10 \text{ mb}$$

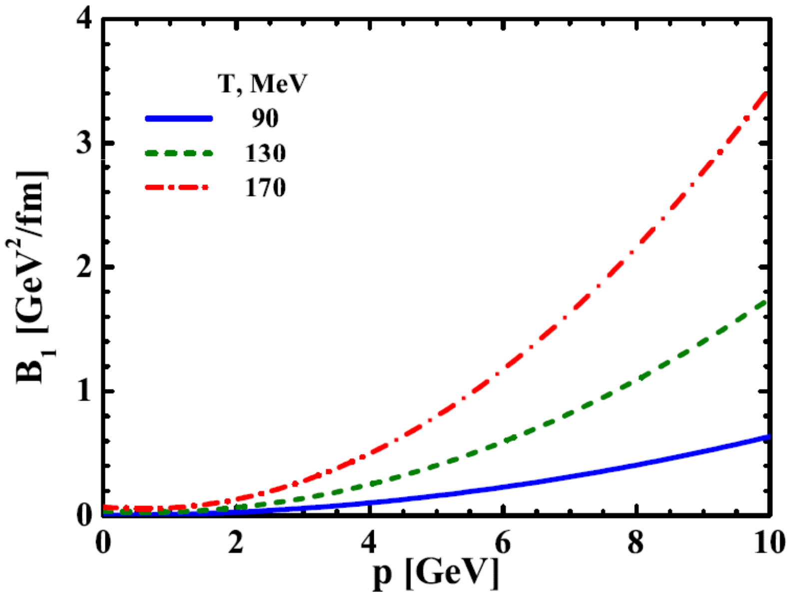
$$DB(\bar{B}) \rightarrow DB(\bar{B}) \Rightarrow \sigma = 15 \text{ mb}$$

D-meson transport coefficients

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

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





- 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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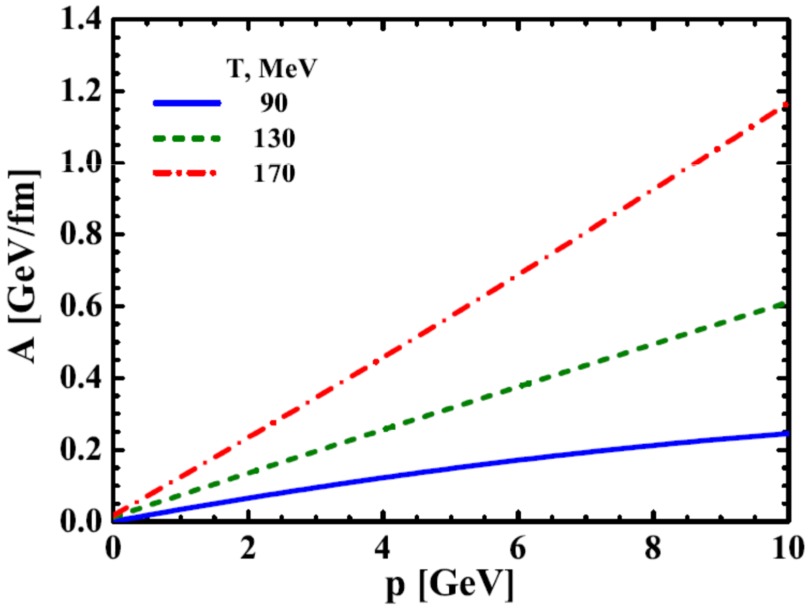

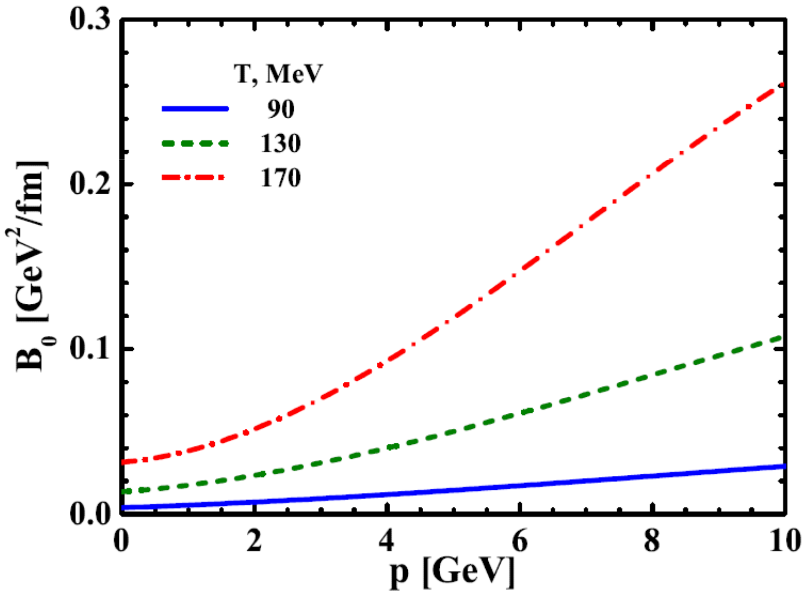

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in the **static limit:**

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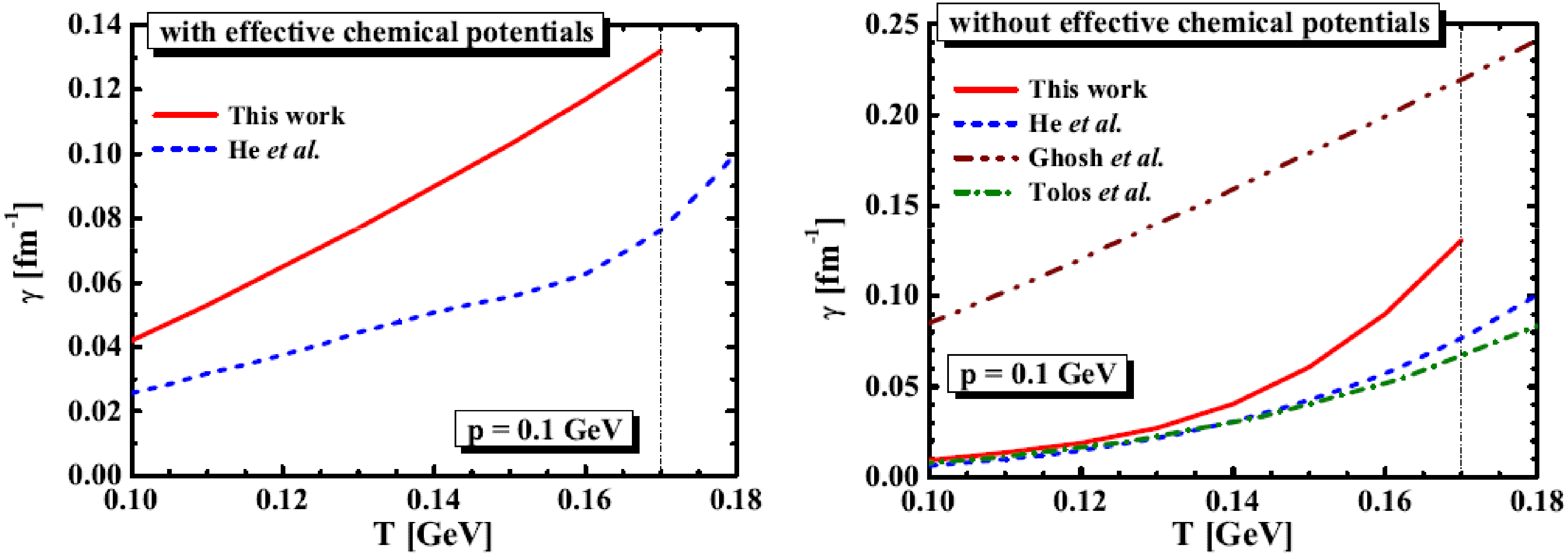
D-meson thermal relaxation time

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

$$\gamma = \lim_{p \to 0} \frac{A}{p}$$

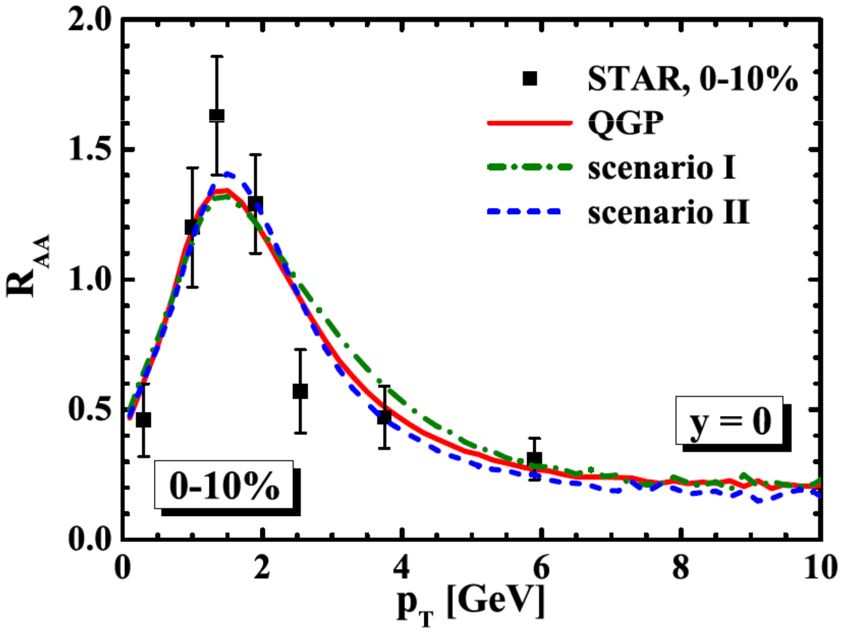
M.He, J.Fries, R.Rapp, Phys. Lett **B701**, 445 (2011)

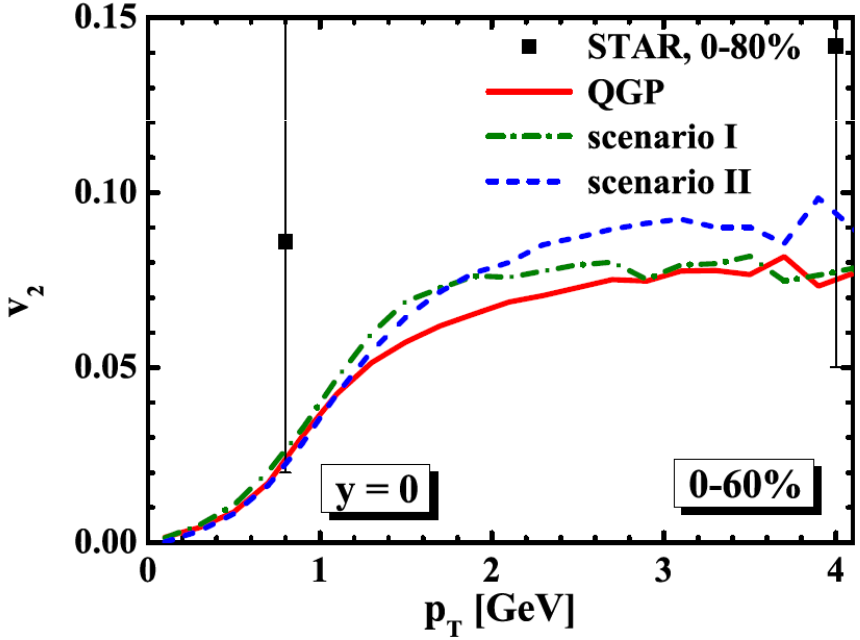


- ❑ **Increase by a factor of 2** of the thermal relaxation time due to the different hadronic cocktail and different cross sections

R_{AA} and v_2 of D-meson at RHIC

- Implement the **obtained results** to "MC@sHQ" 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 at RHIC

- Implement the **obtained results** to “MC@sHQ” generator
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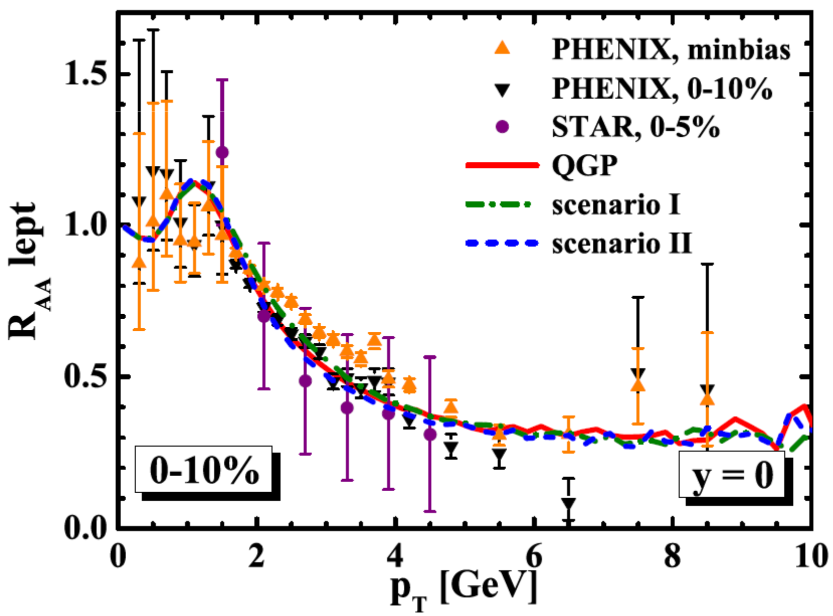

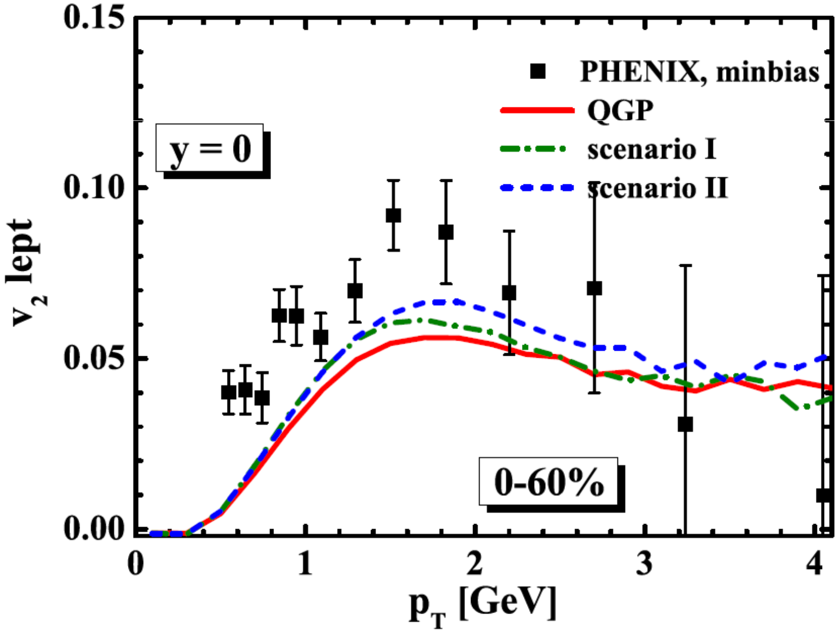

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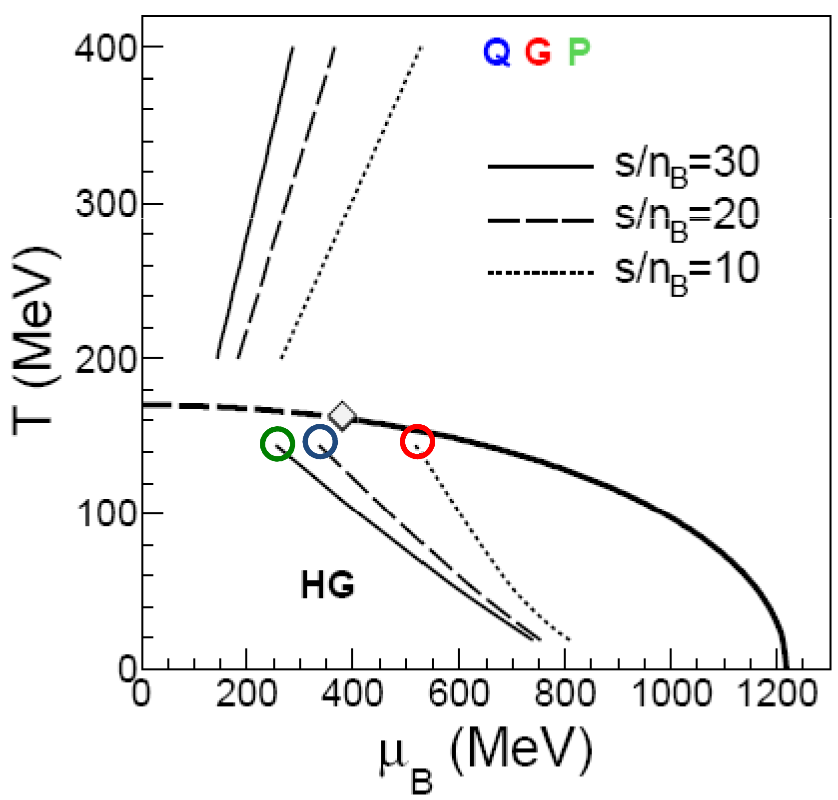
Moderate effect on v_2, but systematic

Isentropic trajectories (FAIR facility)

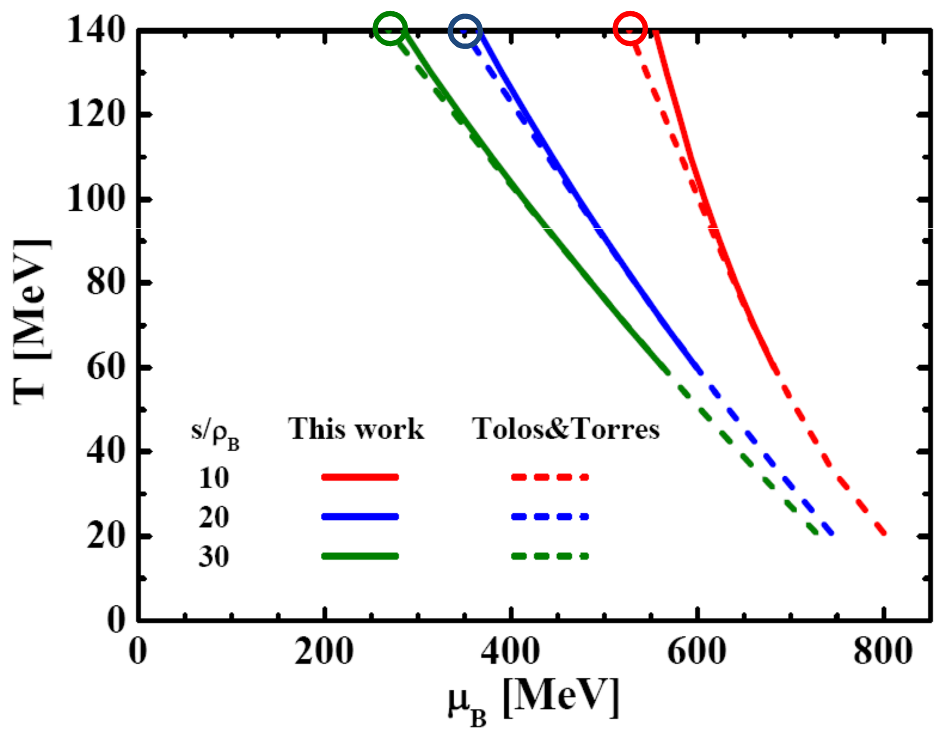
- Assume a **constant specific entropy** (entropy per net baryon) for **FAIR physics:**

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

Juan Torres FAIRNESS 2013



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

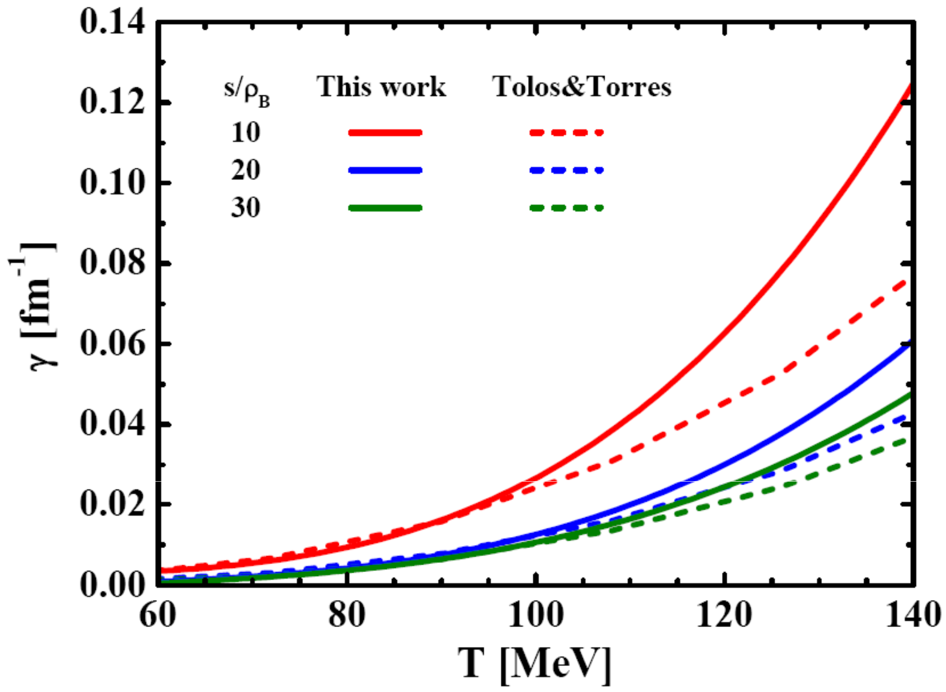


Small deviation due to the higher states in our hadronic cocktail

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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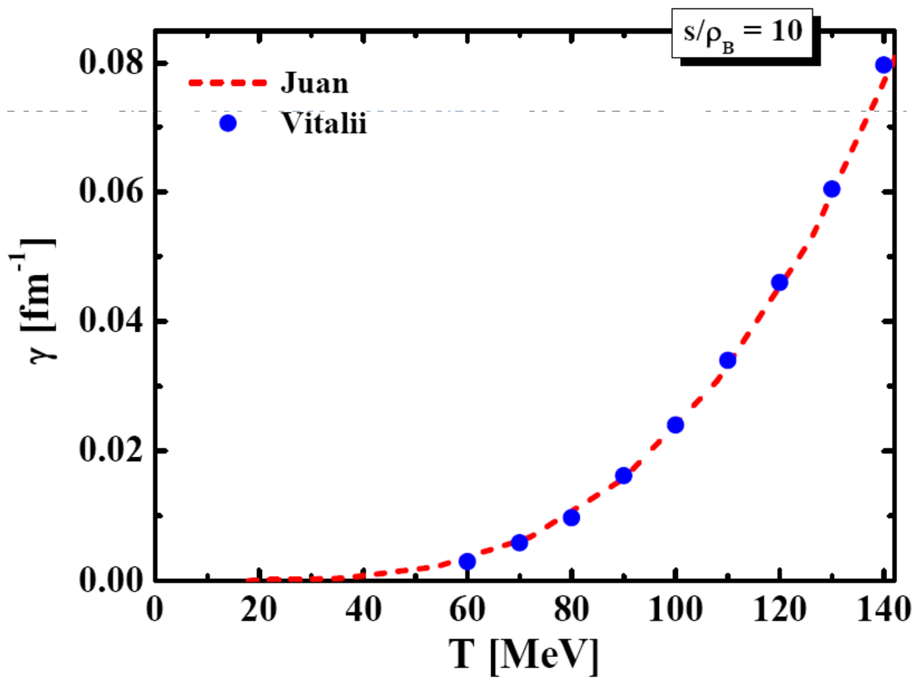
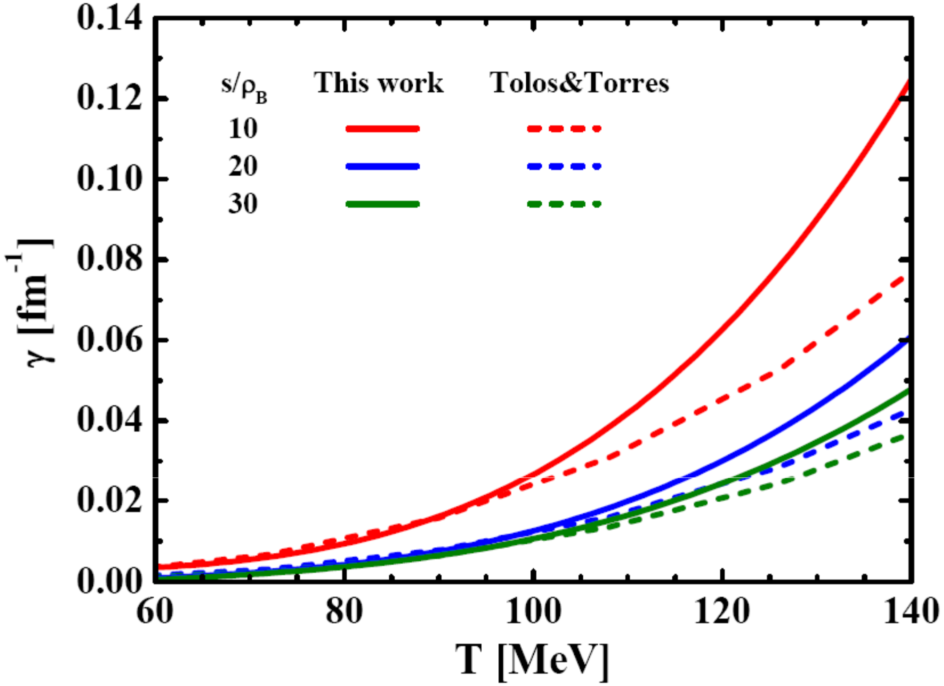


L.Tolos, J.M.Torres-Rincon, Phys. Rev. **D88**, 074019 (2013)



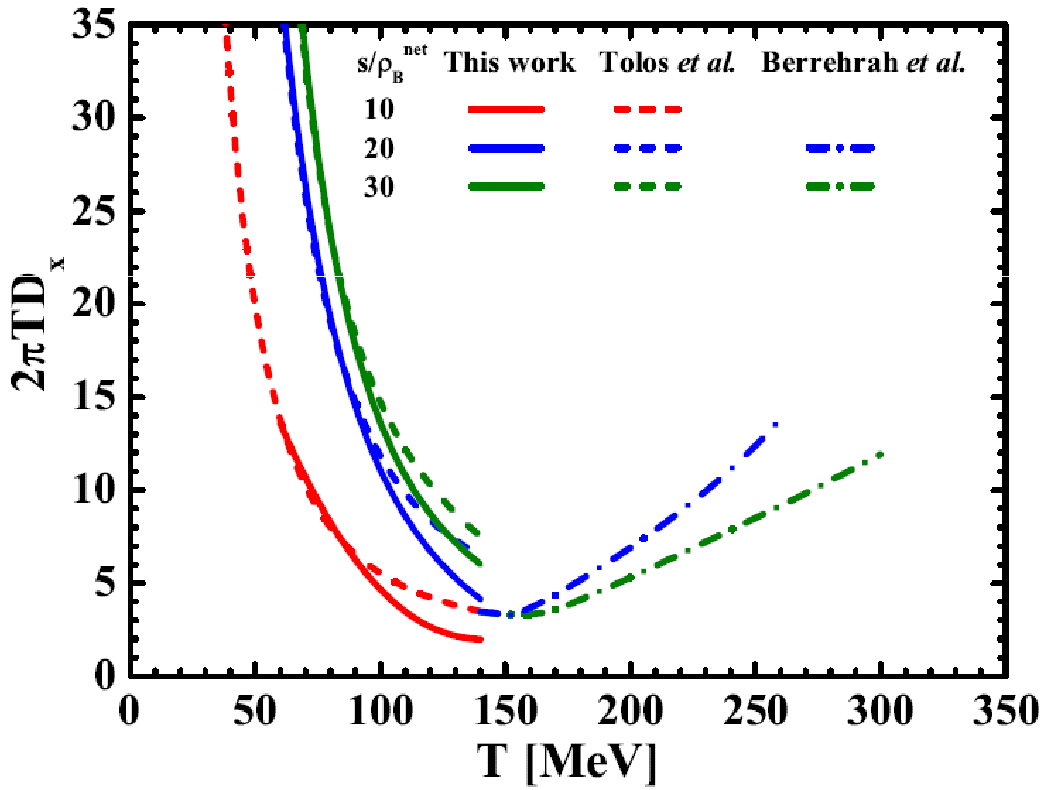
Perfect agreement

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)
H.Berrehrah *et al.*, Phys. Rev. **C90**, 051901 (2014)



perfect matching of results for D mesons and c quarks for s/rho=20

EPOS2 vs. EPOS3

Slide from Marlene's talk

M.Nahrgang *et al*, Phys. Rev. **C89**, 014905 (2014)

MC@sHQ - heavy flavor

- Evolution by the Boltzmann transport equation.
- Elastic cross sections from the pQCD Born approximation with HTL+semi-hard propagators.
- Including a running coupling ⇒ selfconsistently determined Debye mass.
- Radiative energy loss including suppression due to coherent radiation.

consistent + coupling

EPOS2 - light flavor

- Initial conditions from a flux tube approach to multiple scattering events.
- $3 + 1$ d ideal fluid dynamics with viscous effects being mimicked.
- Including a parametrization of the equation of state from lattice QCD.
- Finite initial velocities.
- Event-by-event fluctuating initial conditions.

EPOS2 vs. EPOS3

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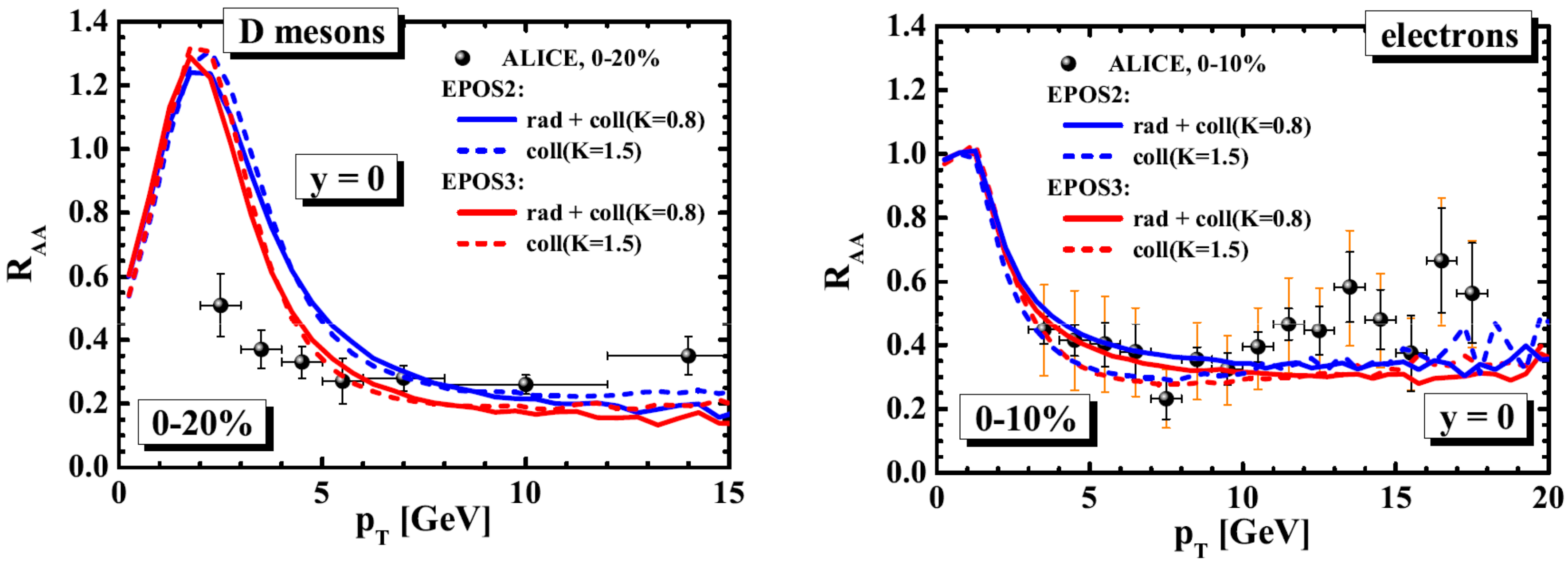
K.Werner *et al*, Phys. Rev. **C89**, 064903 (2014)

- ❑ 3d+1 **viscous** hydrodynamical evolution, eta/s = 0.08;
- ❑ **more sophisticated** treatment of nonlinear effects in the parton evolution by considering individual (per Pomeron) saturation scales;
- ❑ **changes** in core-corona procedure

MC@sHQ+EPOS3 results (R_{AA} at LHC)

- we generate **10000 MC** events for **1 EPOS** event

MC@sHQ+EPOS2 results: M.Nahrgang *et al*, Phys. Rev. **C89**, 014905 (2014)

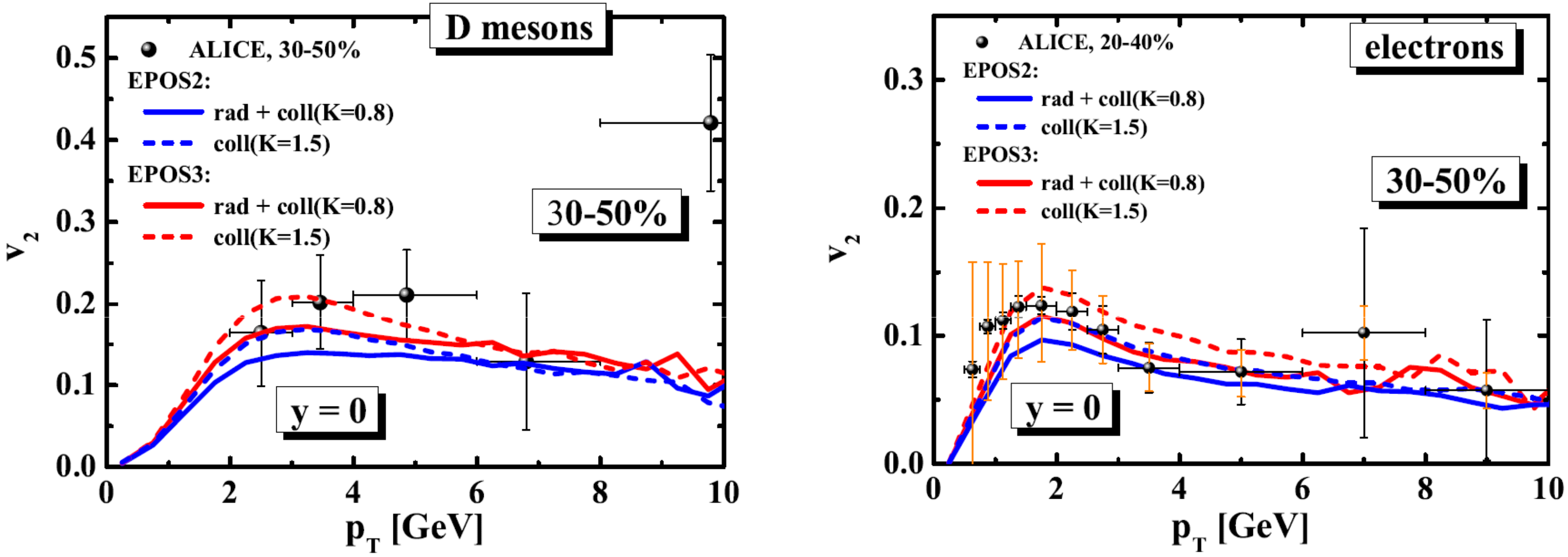


- **reasonable agreement** for the R_{AA} for D mesons at p_T > 5 GeV;
- **larger suppression** for MC@sHQ+EPOS3 results at intermediate p_T;
- at low p_T: sensitive to the medium – need to include **shadowing** *(work in progress…)*

MC@sHQ+EPOS3 results (v_2 at LHC)

- we generate **10000 MC** events for **1 EPOS** event

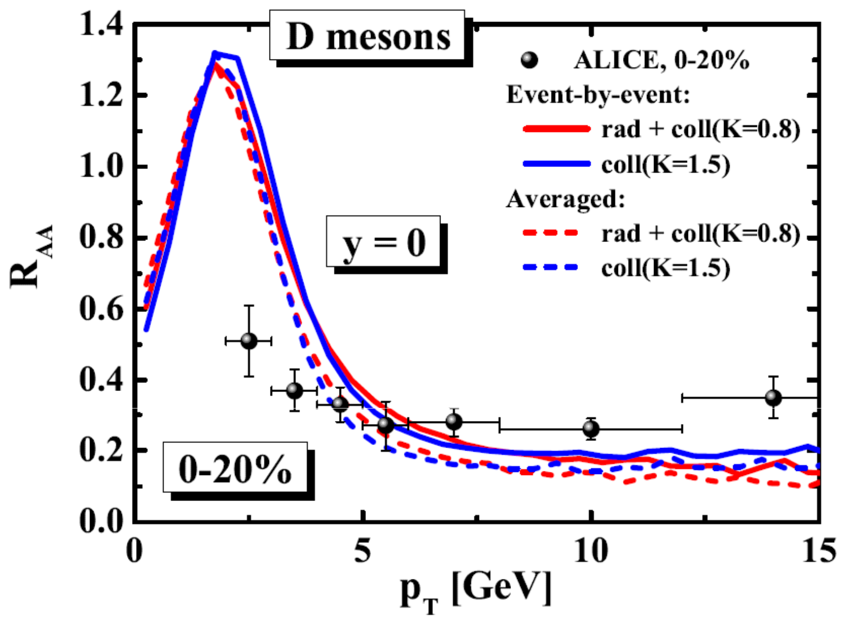
MC@sHQ+EPOS2 results: M.Nahrgang *et al*, Phys. Rev. **C89**, 014905 (2014)

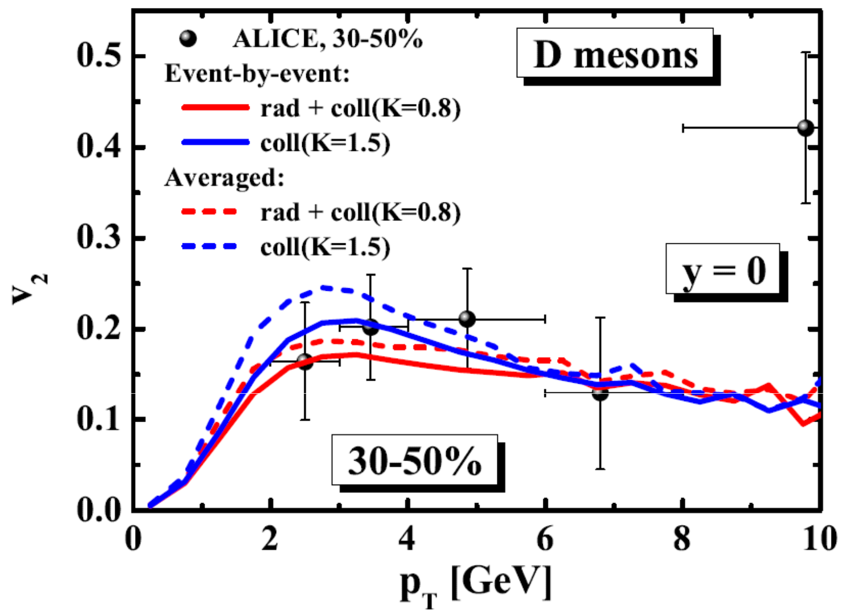


- **reasonable agreement** both for D mesons and HF electrons;
- **enhancement** for MC@sHQ+EPOS3 results at intermediate p_T;
- need to include **hadronic contribution** *(work in progress…)*

Event-by-event vs. AIC

- we average over **400 EPOS** events



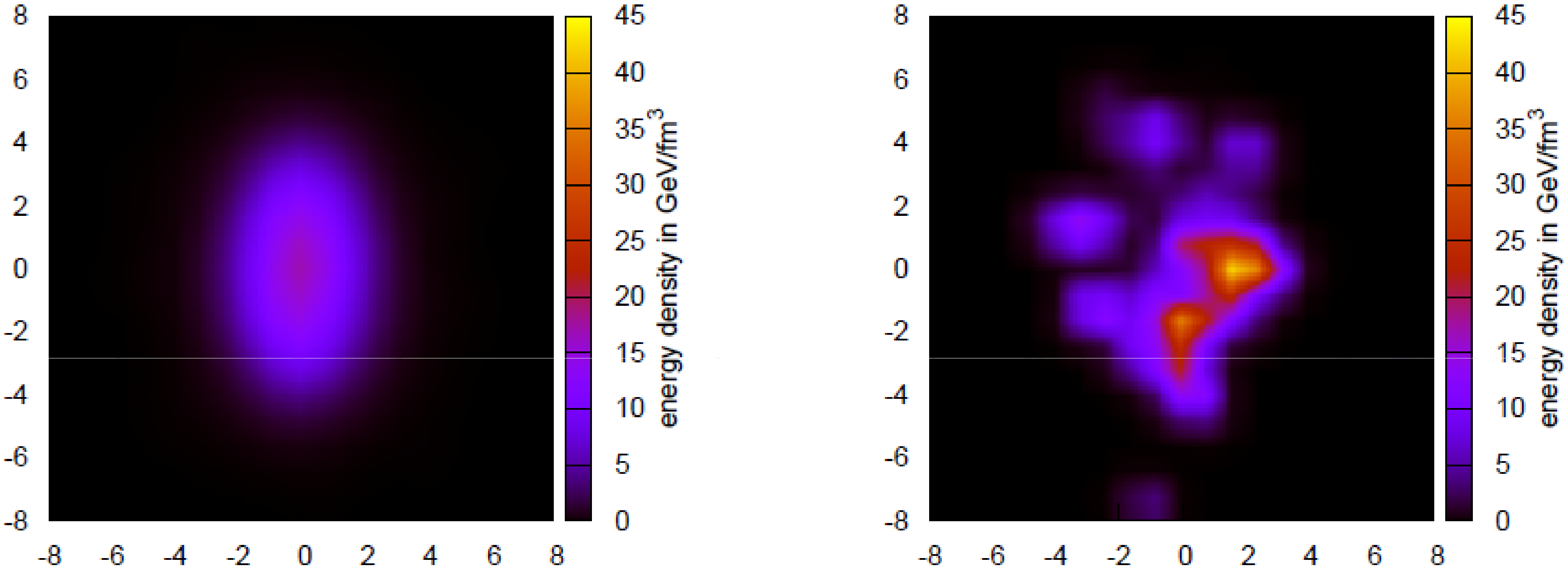


- for R_{AA}: **larger quenching** for averaged than for fluctuating initial conditions

- for v_2: at low p_T the AIC lead to a **larger v_2** than the FIC
  at high p_T path-length difference should be the main contribution

Event-by-event vs. AIC

M.Nahrgang, J.Aichelin, P.B.Gossiaux, K.Werner, arXiv: 1405.0938



- for R_{AA}: the hot spots in FIC lead to an **enhanced** energy loss

- for v_2: the hot spots are rather **spherical,** which reduces the spatial anisotropy; local pressure gradients produce an **azimuthally isotropic** expansion

Summary

❑ 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 electrons originating from the decays of heavy mesons

❑ We extend our calculations to the finite chemical potential (**FAIR** and **NICA**); there is a **perfect matching** for **s/rho=20** of our results for the **spatial diffusion coefficient** with the results for **c quarks** propagating in the partonic matter

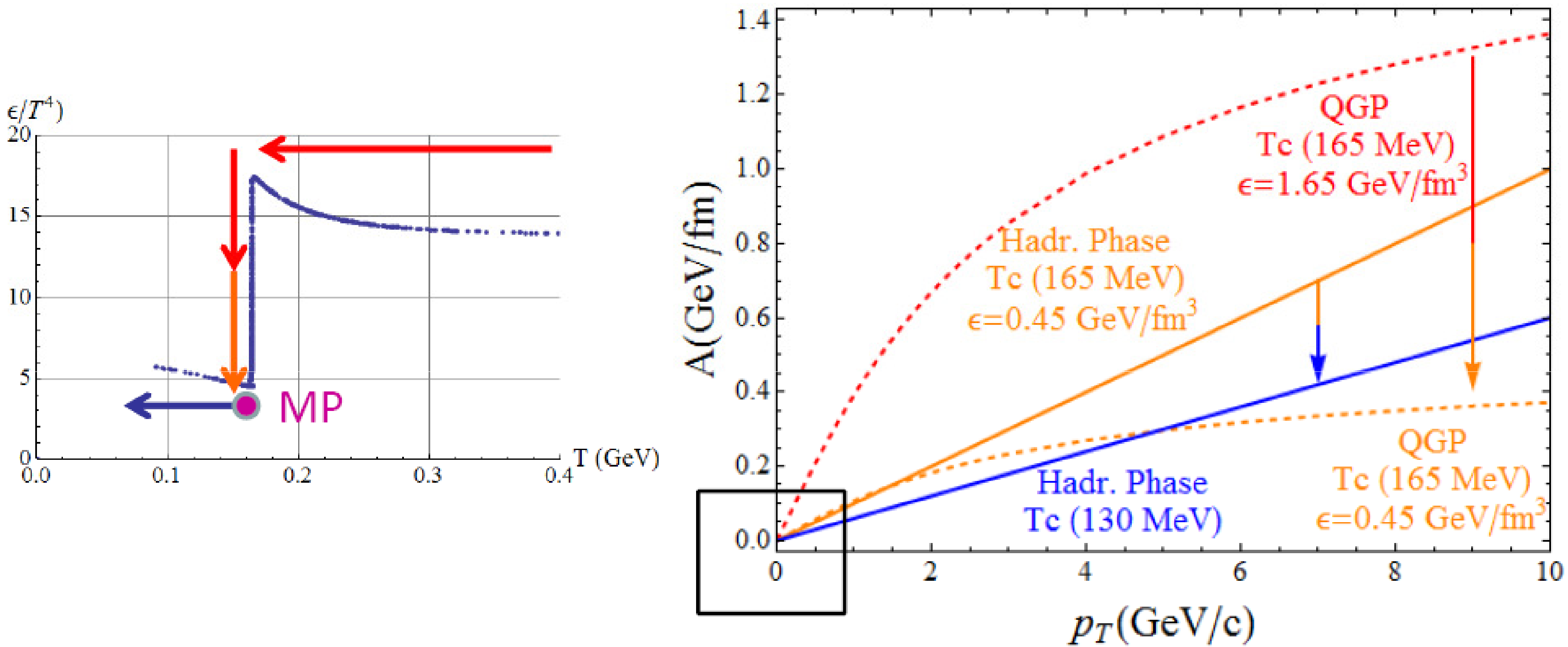
❑ **MC@sHQ+EPOS3 results:**

- **reasonable agreement** for R_{AA} and v_2 at LHC
- need to include **shadowing** and **hadronic interactions**
- **powerful tool** to study HQ and HF mesons for **pp**, **pA**, and **AA** collisions

Back up

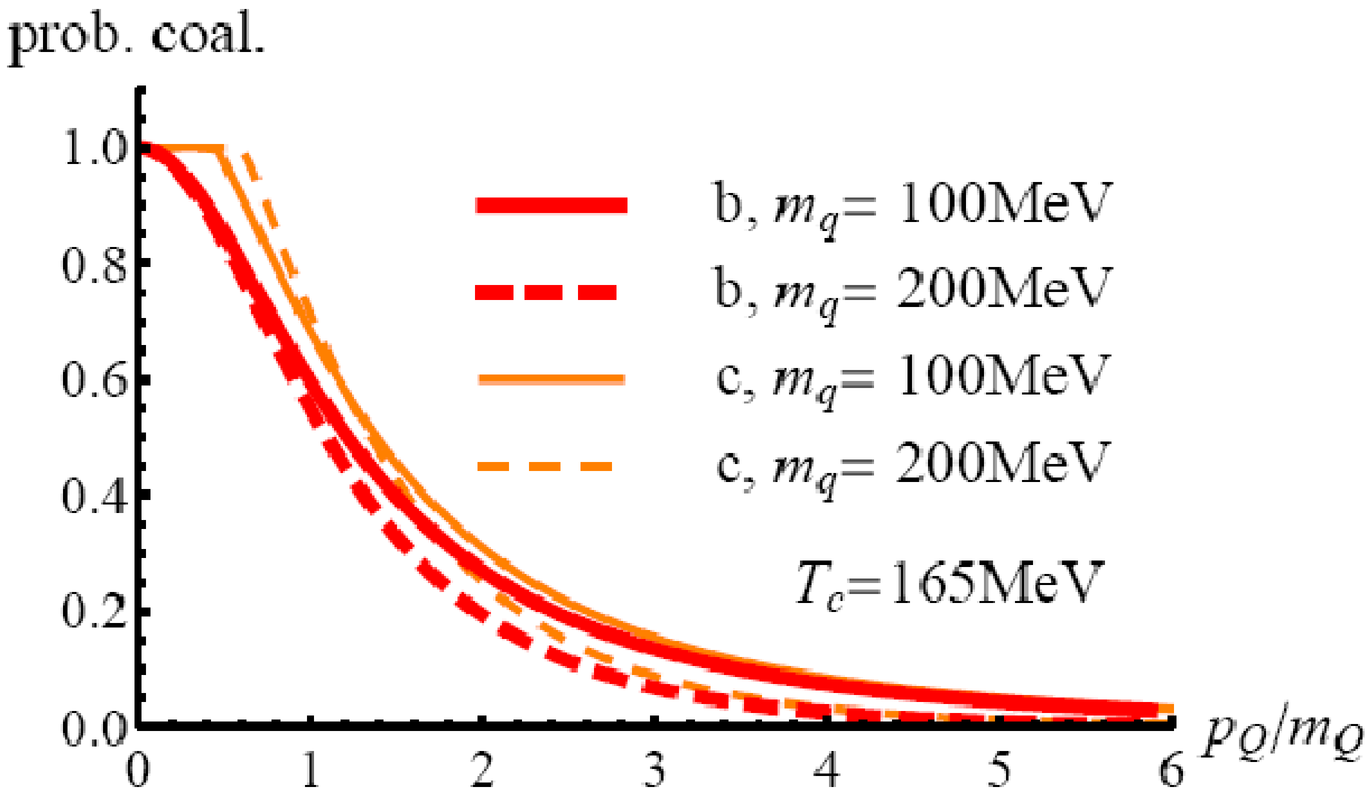
Comparison to HQ in plasma

Slide from Pol's talk

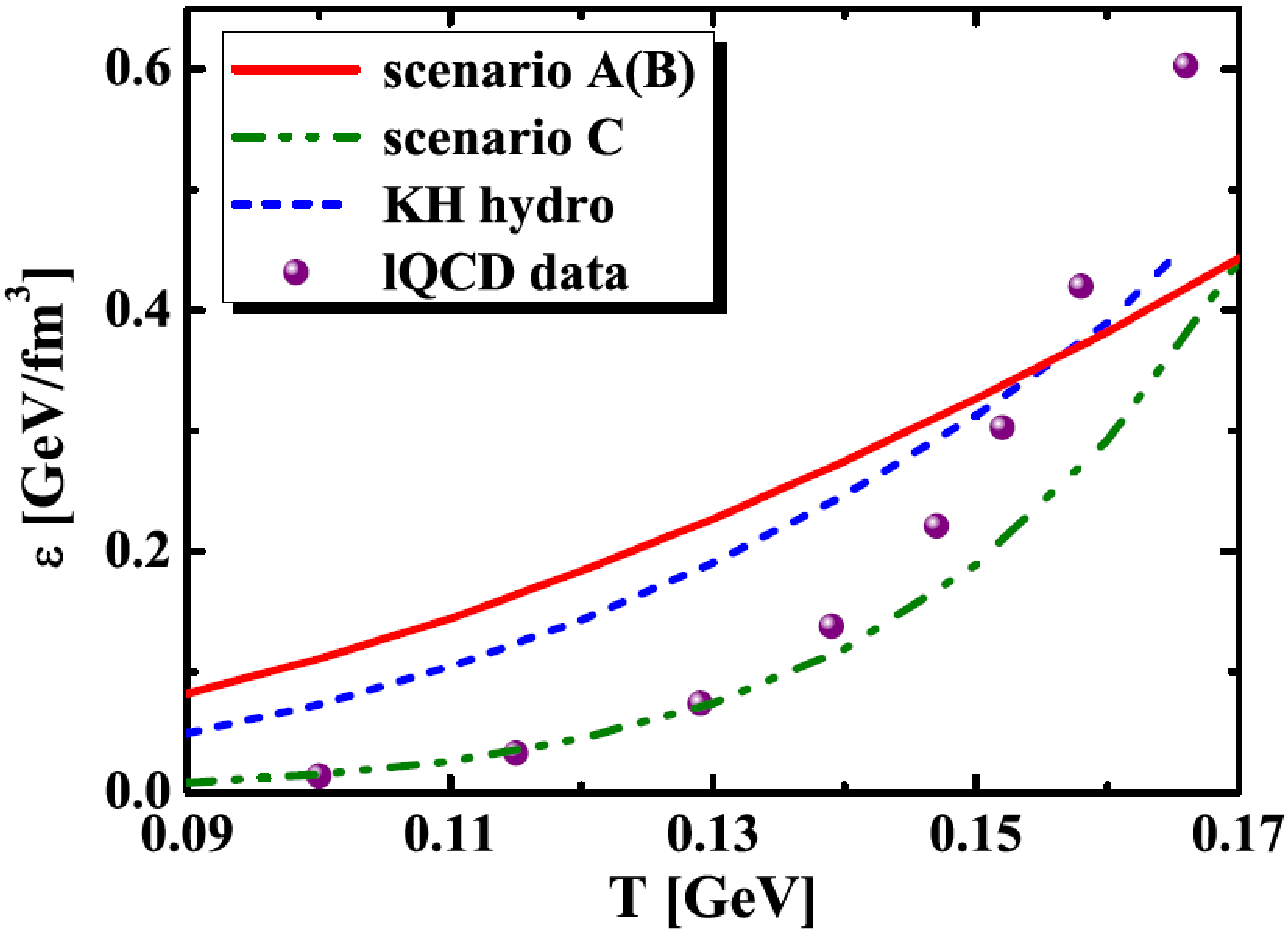


- ❑ **Relaxation times** at the **MP** fairly agrees (≈ 10 fm/c) – it satisfies the "crossover" constrain
- ❑ **p_T dependences** disagree (isotropic cross sections in the HG)

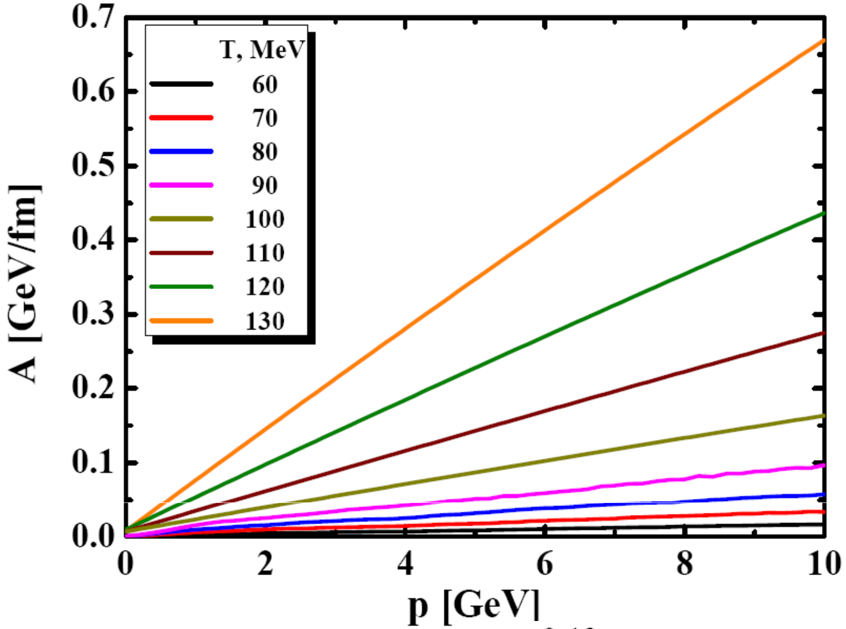
Hadronization of HQ

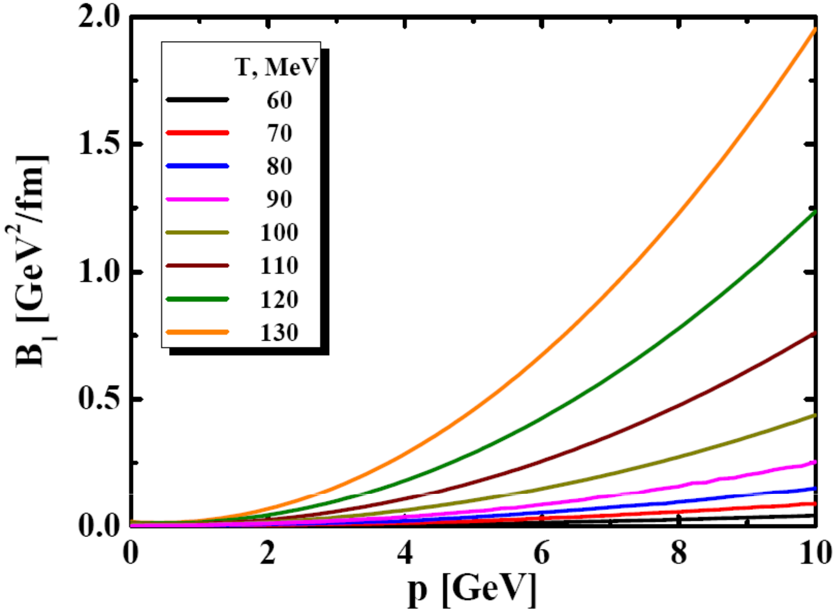


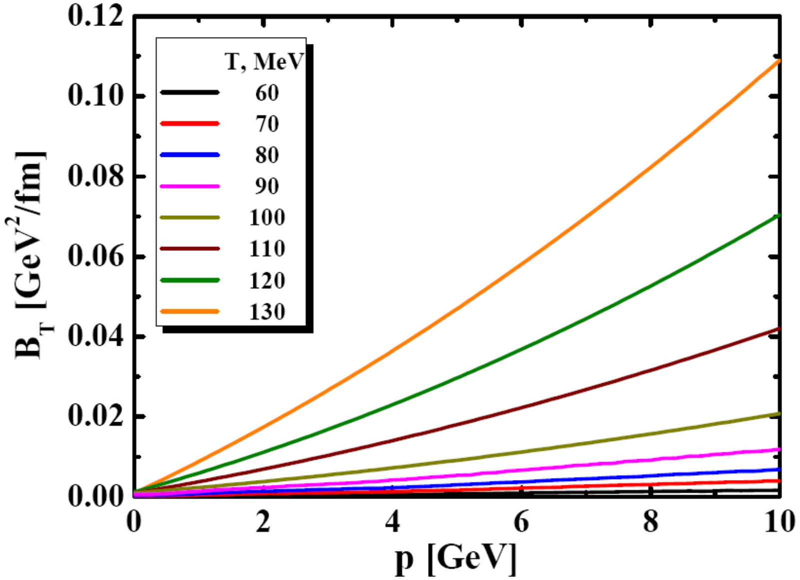
Hadronic equation of state



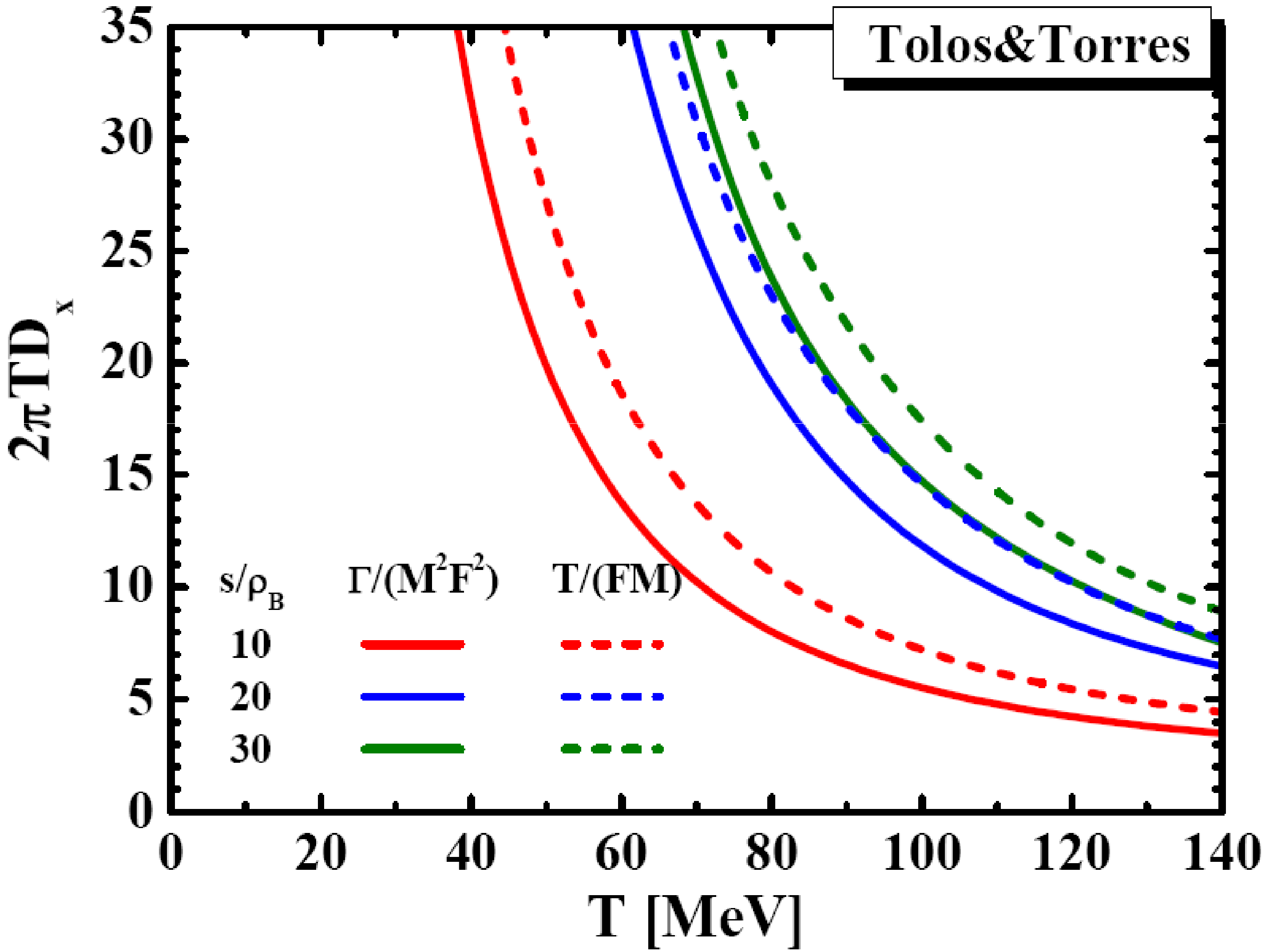
D-meson transport coefficint (s/n_B = 10)



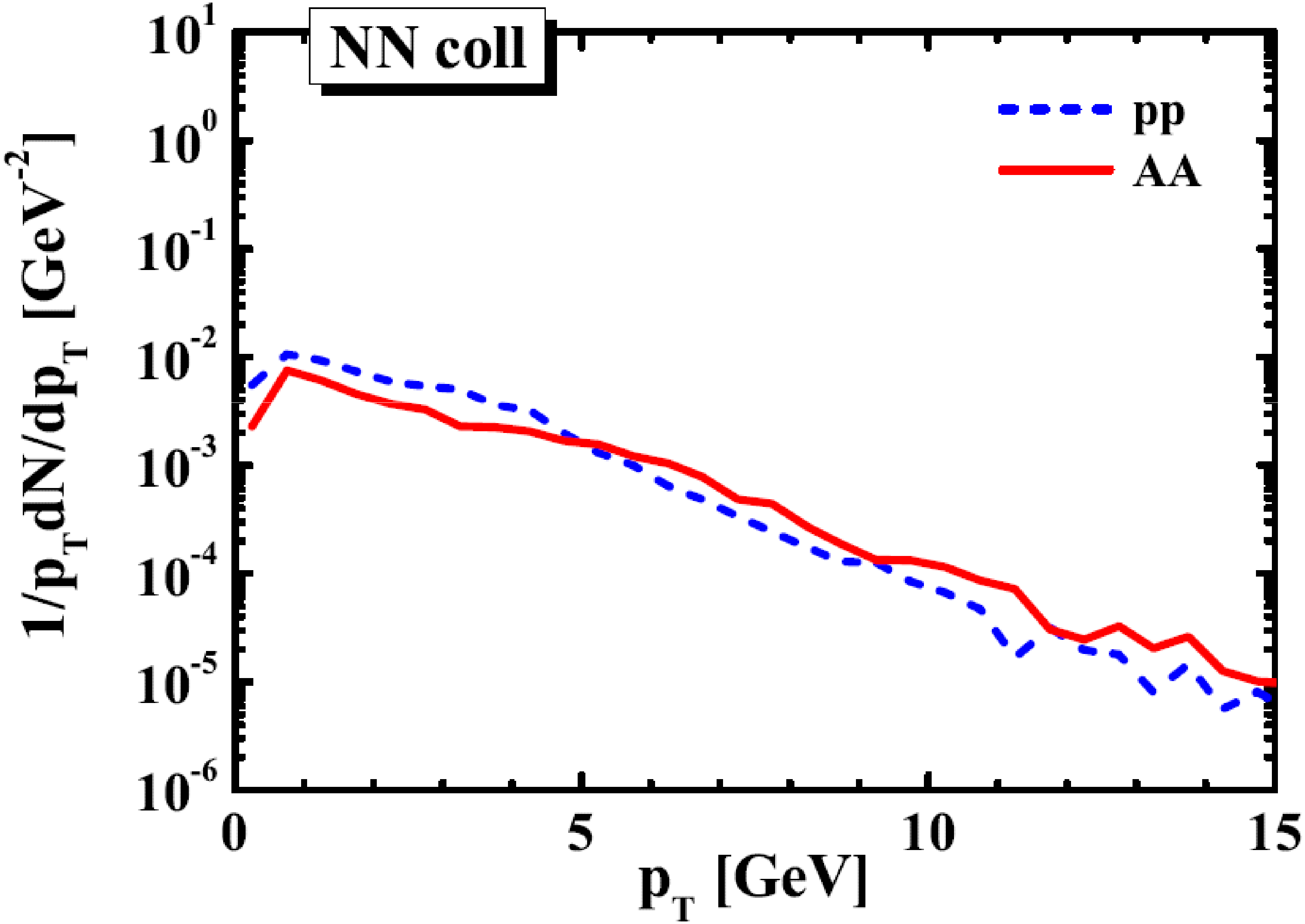




Spatial diffusion coefficient (Juan)



Shadowing (VERY preliminary!!!)



Ratio