UNIVERSITÉ DE NANTES

D-meson observables in pPb and PbPb collisions at LHC with MC@sHQ+EPOS3 model

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in collaboration with

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Quy Nhon, Vietnam

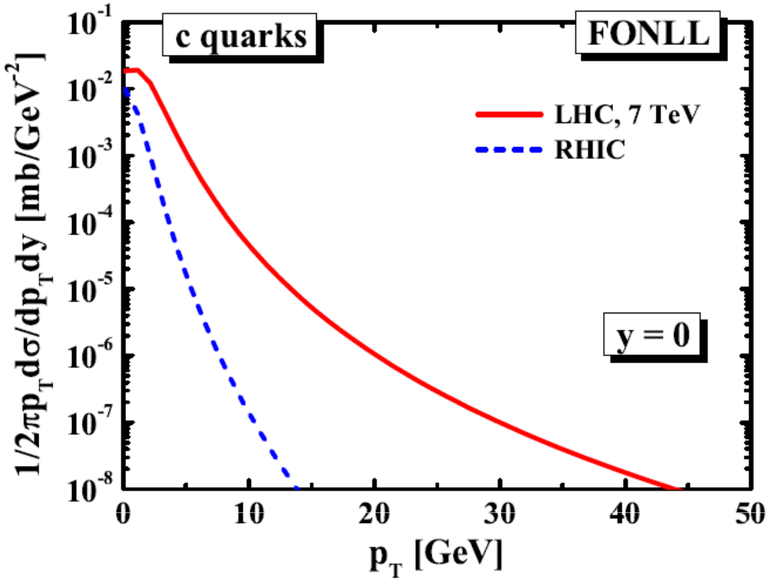
TOGETHER Project (Region Pays de la Loire)

MC@sHQ+EPOS2 results

MC@sHQ+EPOS2 model

- **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:** 3+1d ideal hydro stemming from **EPOS2** initial conditions; provides **temperature** and **velocity** fields

  K.Werner et al., Phys. Rev. C **82**, 044904 (2010)

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

- **interaction of HQ** in the bulk: by either **elastic** or **radiative** collisions

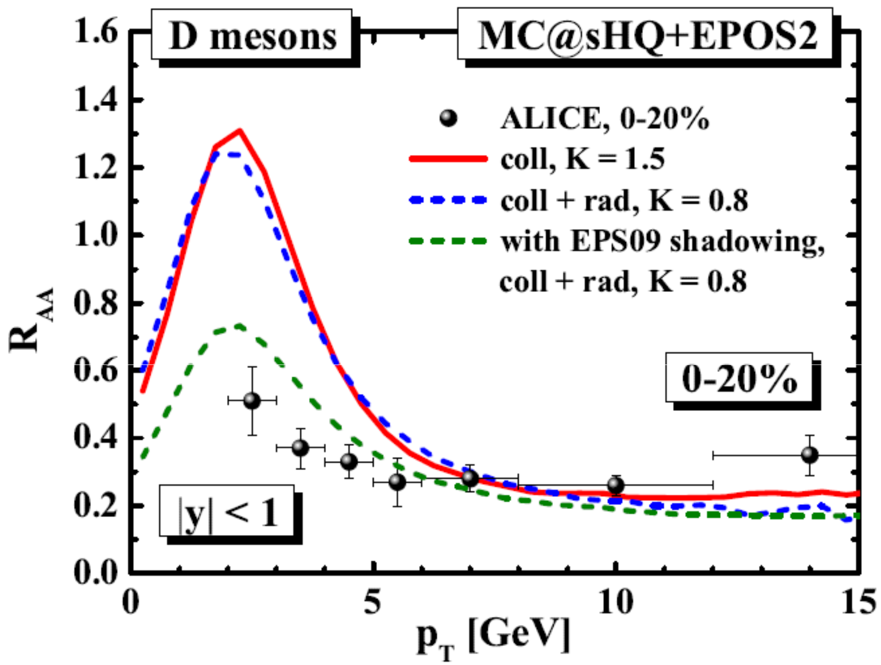
- **hadronization of HQ: coalescence** (low p_T) and **fragmentation** (high p_T)

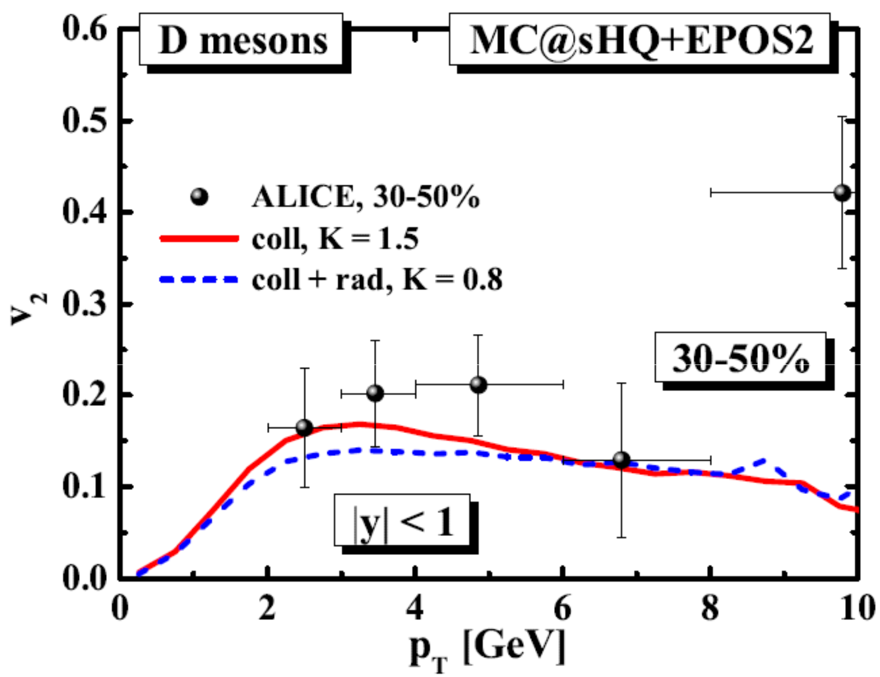
$$T_c = 155 \text{ MeV}$$

MC@sHQ+EPOS2 results (R_{AA} and 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** for the R_{AA} of D mesons at **p_T > 5 GeV**;
- at **low p_T**: sensitive to the medium – **good agreement** with **EPS09 shadowing**;
- **reasonable agreement** for the v_2 of D mesons.

MC@sHQ+EPOS3 results

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.

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

❑ 3d+1 **viscous** hydrodynamical evolution, **eta/s = 0.08**;

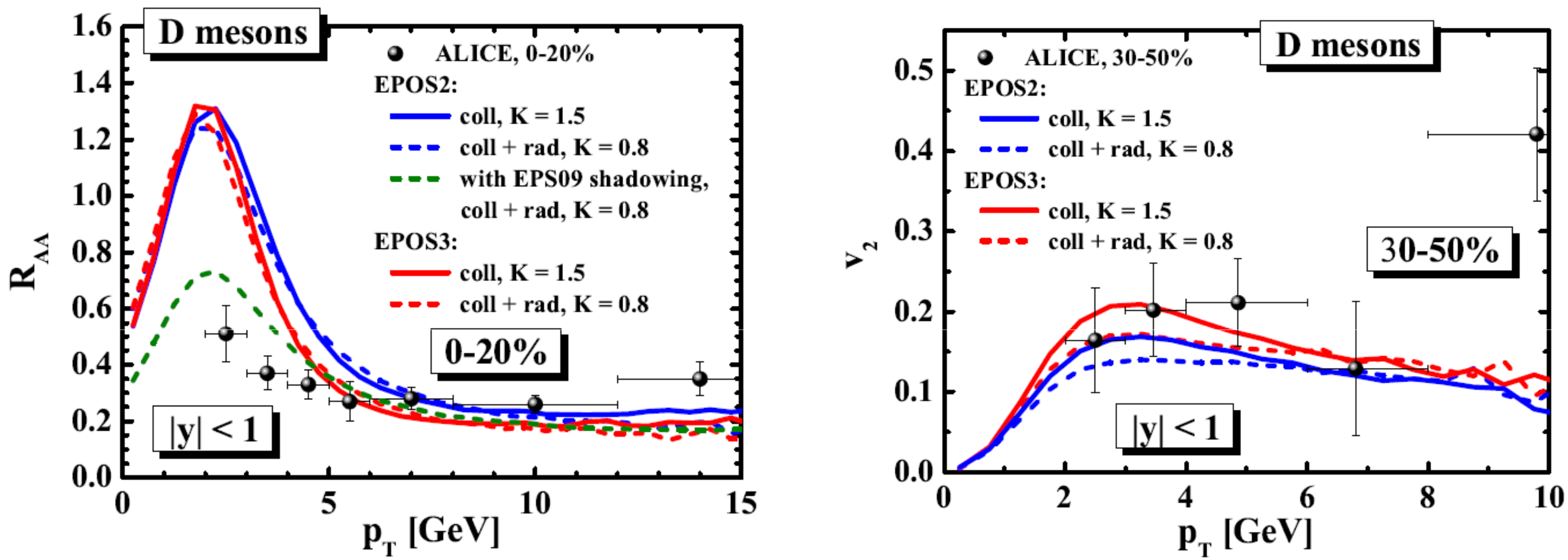
❑ **more sophisticated** treatment of nonlinear effects in the parton evolution by considering **individual (per Pomeron) saturation scales**;

❑ **changes** in **core-corona** procedure

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

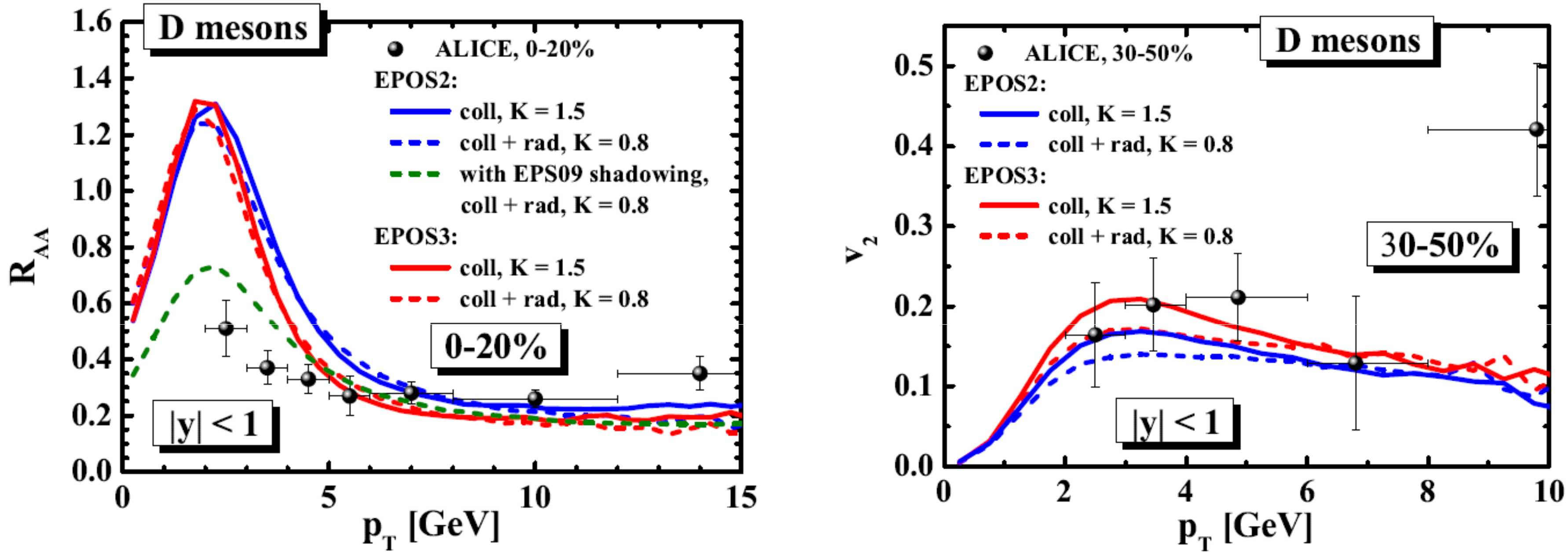


- **reasonable agreement** for the R_{AA} of D mesons at **p_T > 5 GeV**;
- **larger suppression** for MC@sHQ+EPOS3 results at **intermediate p_T**;
- at **low p_T**: sensitive to the medium – **good agreement** with **EPS09 shadowing**;

MC@sHQ+EPOS3 results (R_{AA} and v_2 at LHC)

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

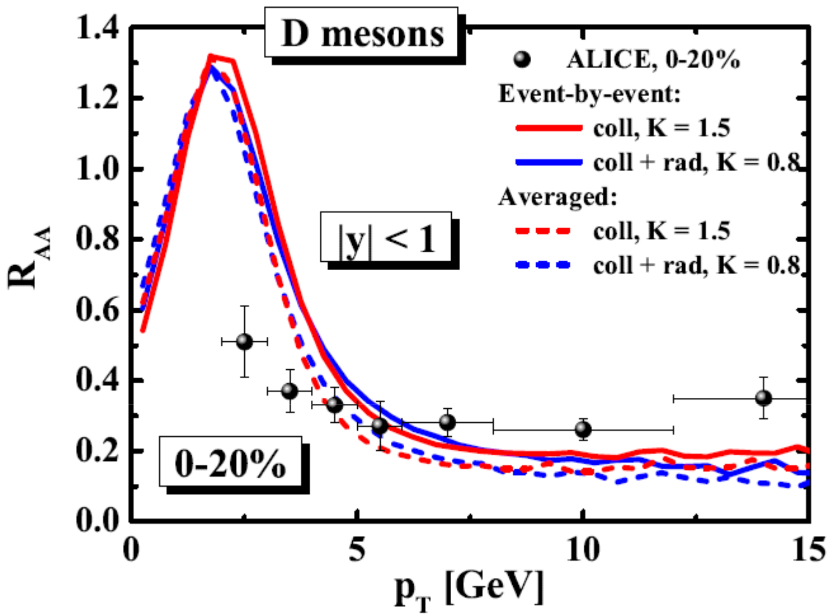
MC@sHQ+EPOS2 results: M.Nahrgang *et al*, Phys. Rev. **C89**, 014905 (2014)

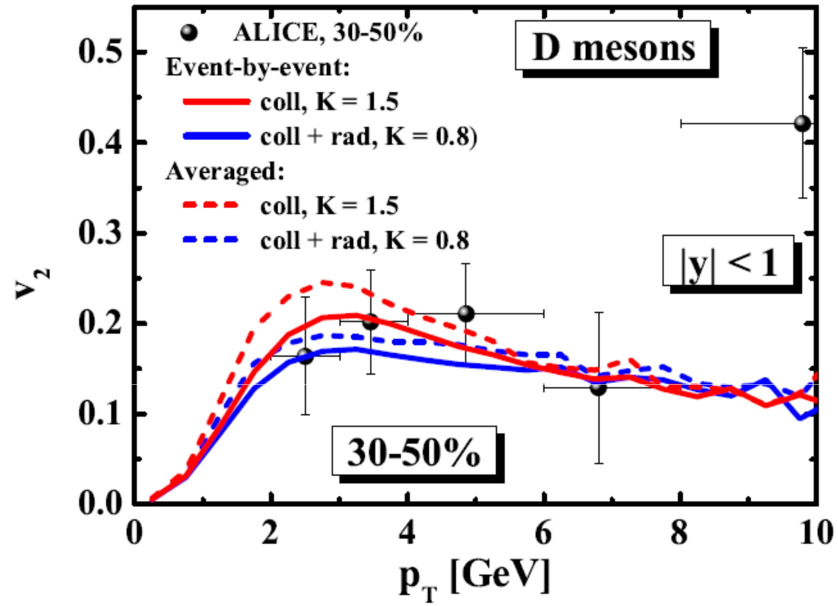


- **reasonable agreement** for v_2 of D mesons;
- **enhancement** for MC@sHQ+EPOS3 results at **intermediate p_T**;
- need to include **hadronic contribution** *(work in progress…)*

Event-by-event vs. AIC

- we average over **400 EPOS3** events



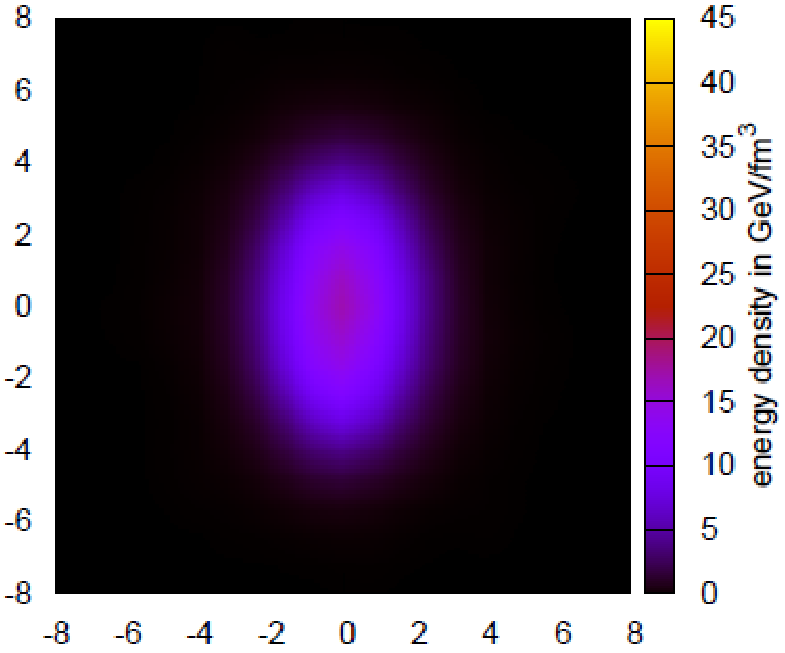


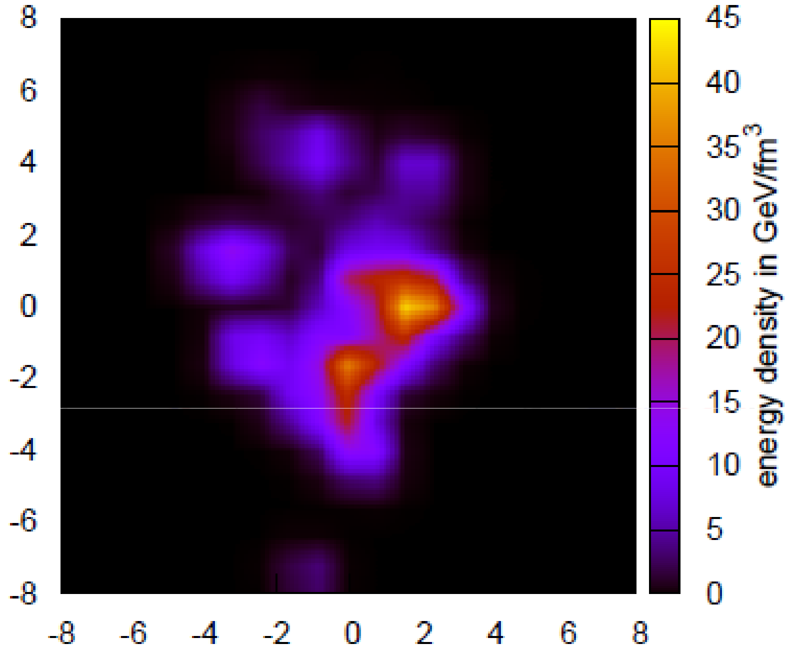
- **for R_{AA}: larger quenching** for averaged than for fluctuating initial conditions

- **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





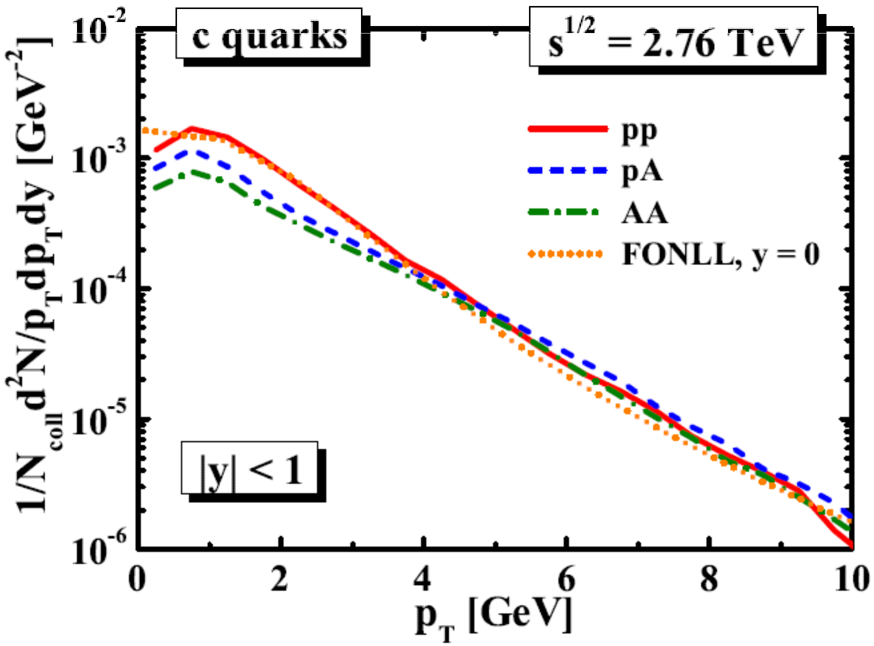
- **for R_{AA}:** the hot spots in FIC lead to an **enhanced** energy loss

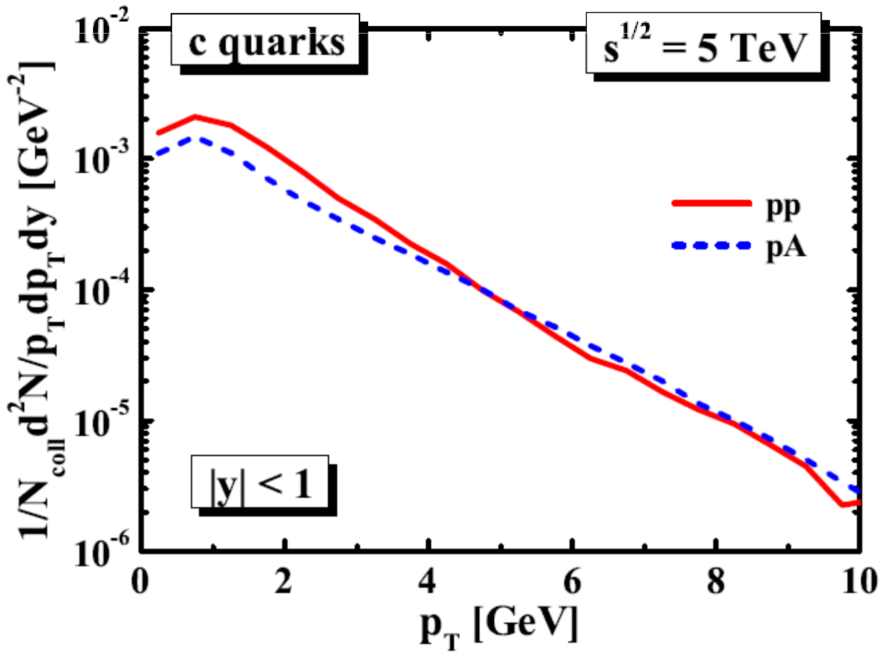
- **for v_2:** the hot spots are rather **spherical,** which reduces the spatial anisotropy; local pressure gradients produce an **azimuthally isotropic** expansion

MC@sHQ+EPOS3 results
(with HQ from EPOS3 initial conditions)

Heavy quarks from EPOS3

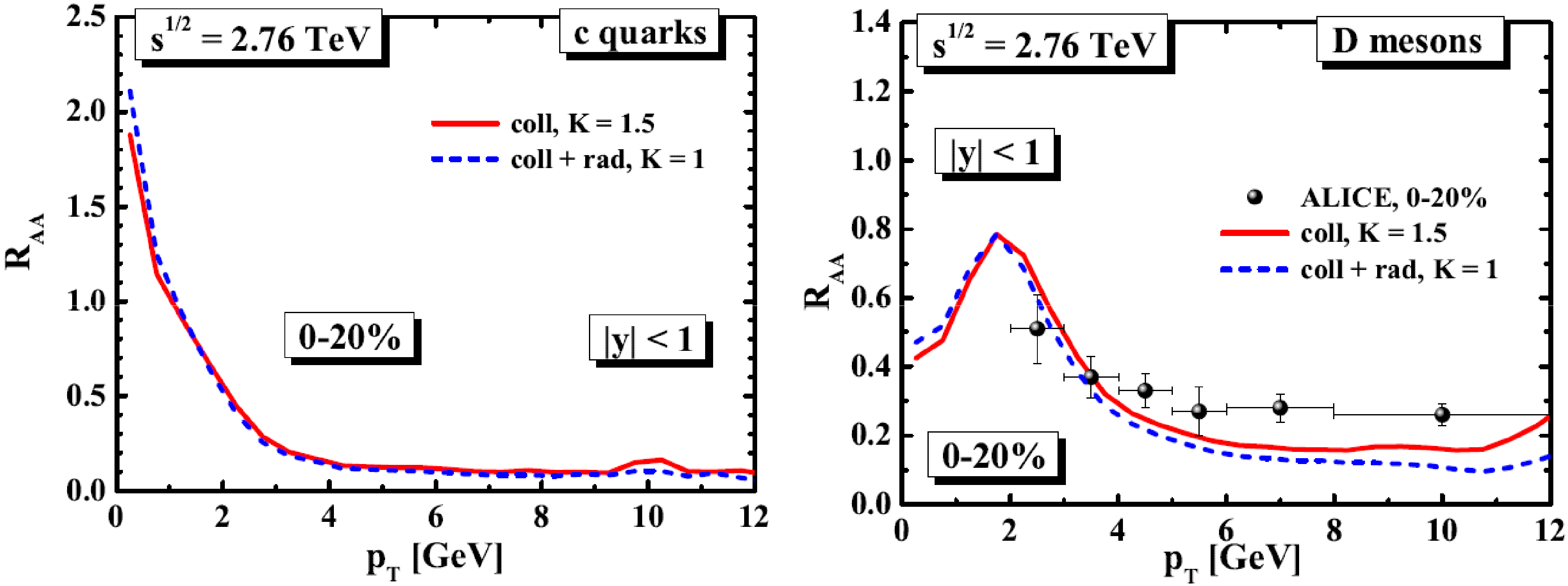
- we implement the **heavy quarks** from **EPOS3** model
- the **heavy quarks** in **EPOS3** can be produced during:
  - spacelike cascade;
  - Born process;
  - partonic shower





R_{AA} of D meson in PbPb@2.76 TeV

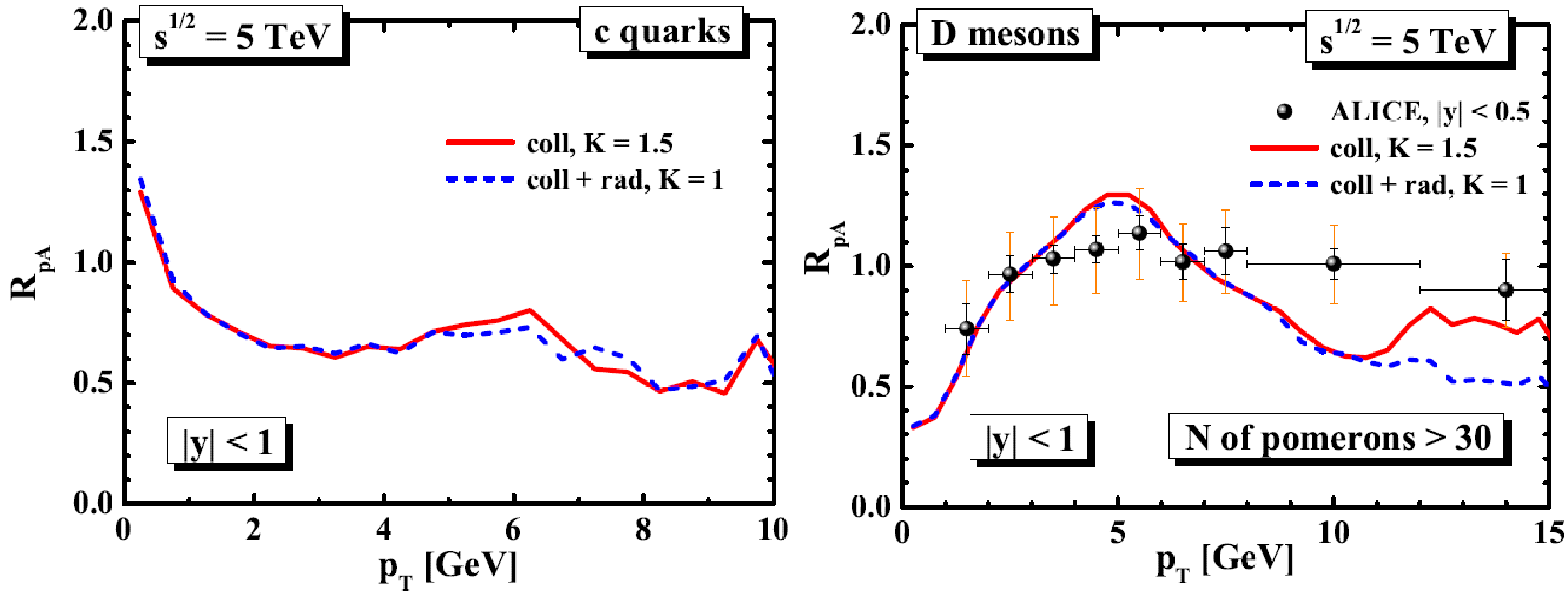
Very preliminary



- ❑ **reasonable agreement** for R_{AA} of D mesons for **whole range of p_T**
- ❑ almost the **same behavior** for two sets of parameters

R_{pA} of D meson in pPb@5 TeV

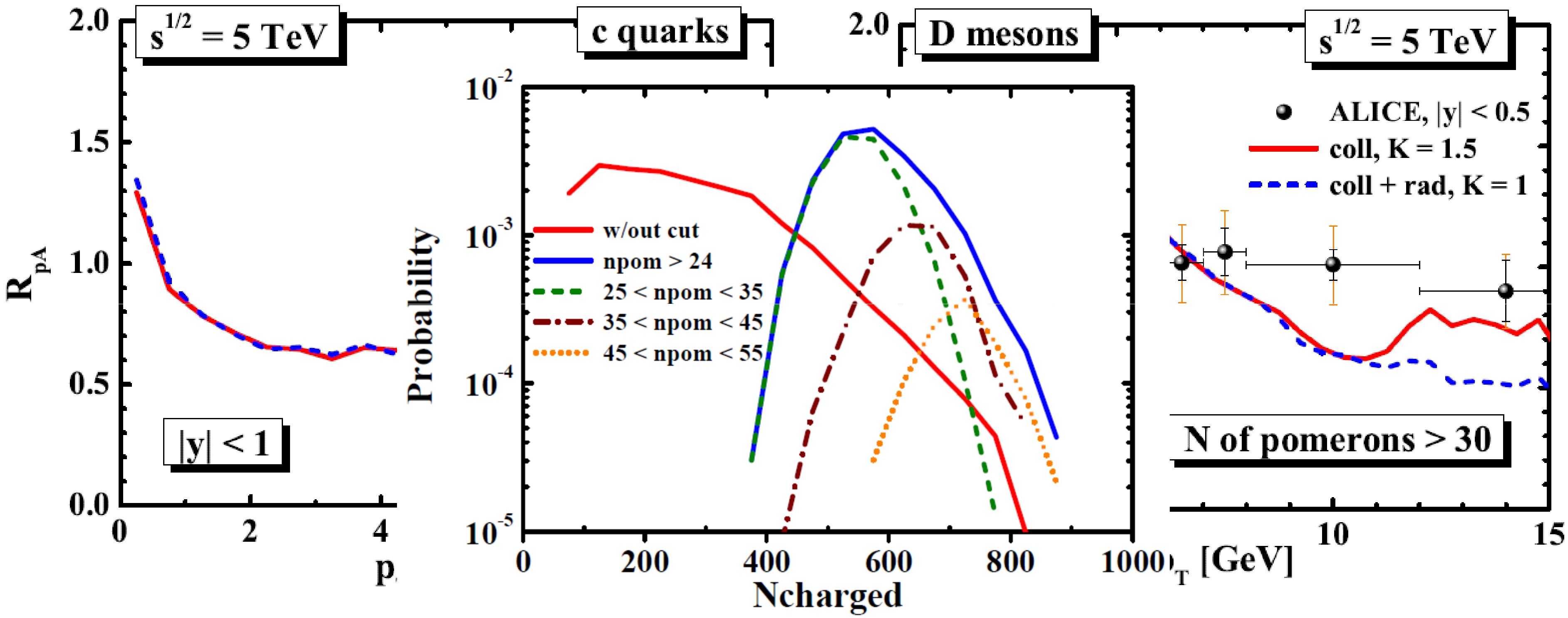
Very preliminary



- **reasonable agreement** for R_{pA} of D mesons at **p_T < 7 GeV**
- **deviation** for R_{pA} of D mesons at **p_T > 7 GeV**

R_{pA} of D meson in pPb@5 TeV

Very preliminary



❑ **reasonable agreement** for R_{pA} of D mesons at **p_T < 7 GeV**

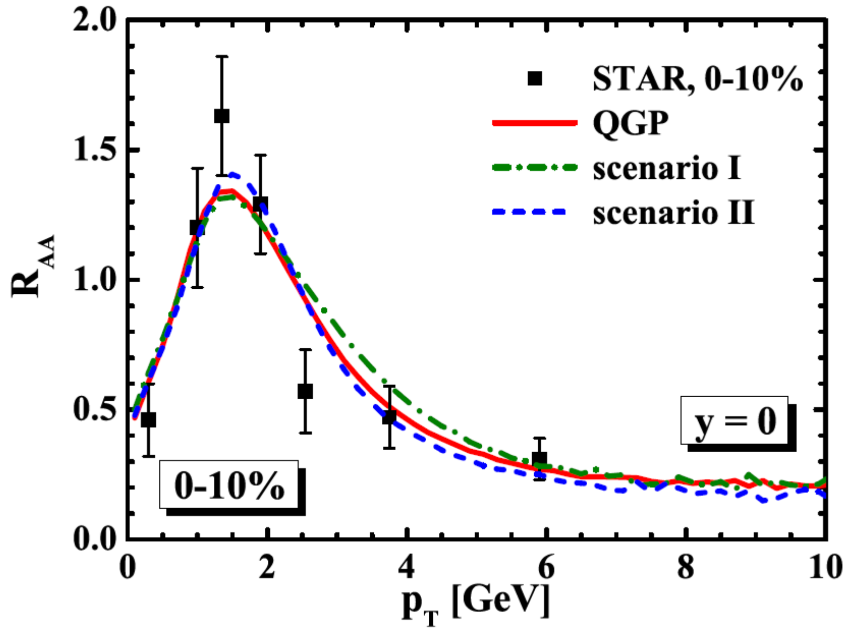
❑ **deviation** for R_{pA} of D mesons at **p_T > 7 GeV** *(need to define centrality classes)*

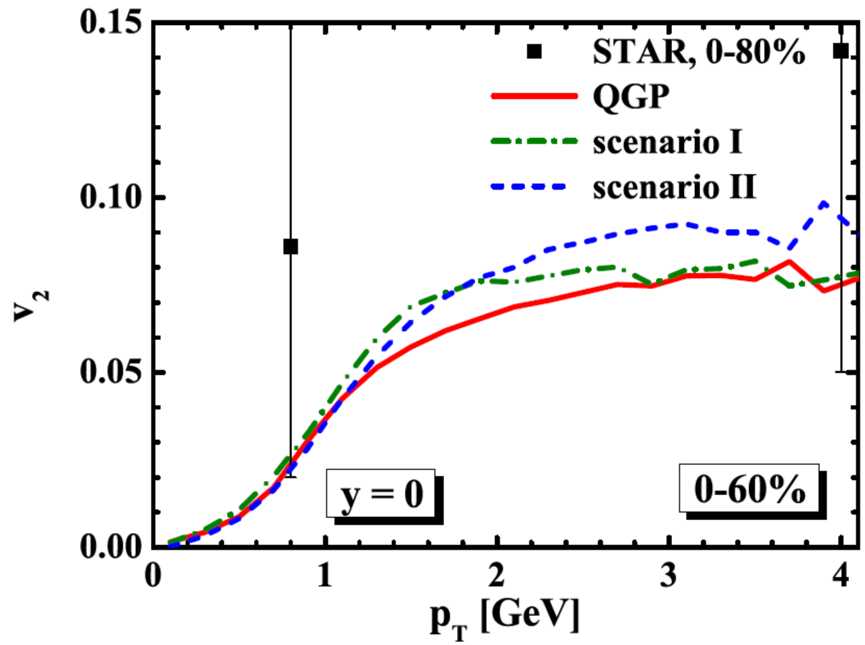
Outlook

- **to define** the **centrality classes** for the pPb collisions

- **to calculate** the **elliptic flow** of D mesons both for PbPb and pPb collisions at LHC within MC@sHQ+EPOS3 with **HQ** from **EPOS3 initial conditions**

- **to include** the **hadronic rescattering** to our model (to couple with UrQMD).





Summary

- **MC@sHQ+EPOS3 model is a powerful tool** to study HQ and HF mesons for **pp**, **pA**, and **AA** collisions.

- Our model shows a **reasonable agreement** both for the **nuclear modification factor** (for the intermediate p_T) and **elliptic flow** of D mesons in PbPb collisions at LHC

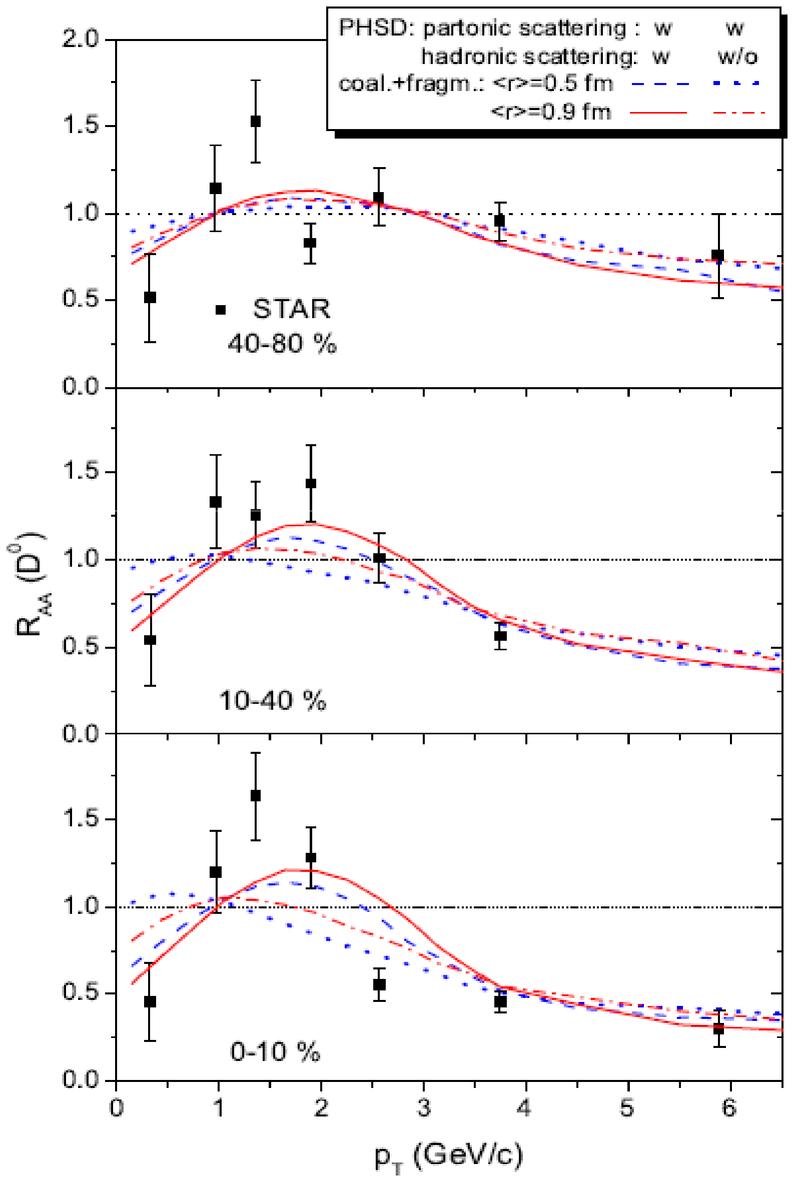
- The introduction of **HQ** from **EPOS3 IC** to a model leads to the **better description** of the experimental data for the **R_{AA}** of D mesons at **low p_T** in PbPb@2.76 TeV

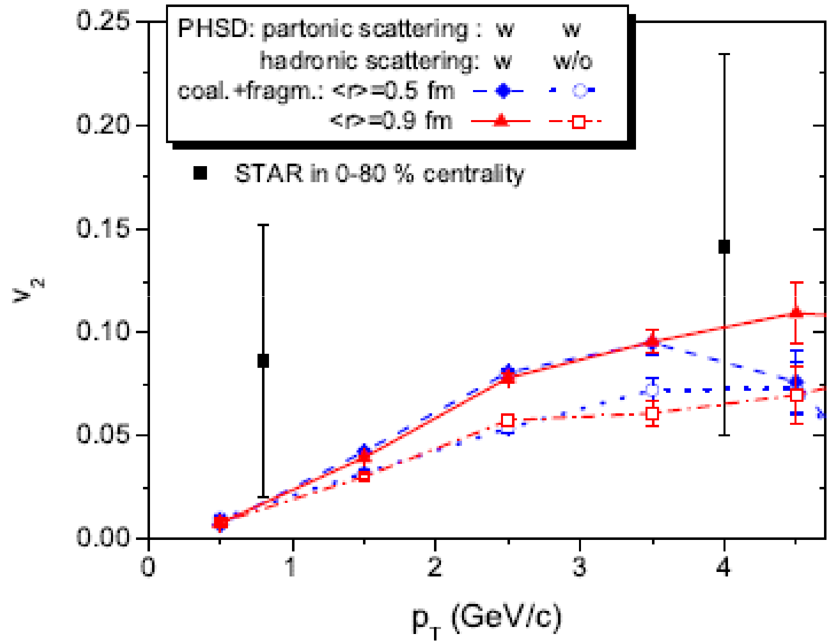
- The **R_{pA}** of D mesons in pPb@5 TeV shows a **suppression** of D-meson yield at **p_T > 7 GeV**

- We need to include the **hadronic interactions** to the calculations at LHC energies

Back up

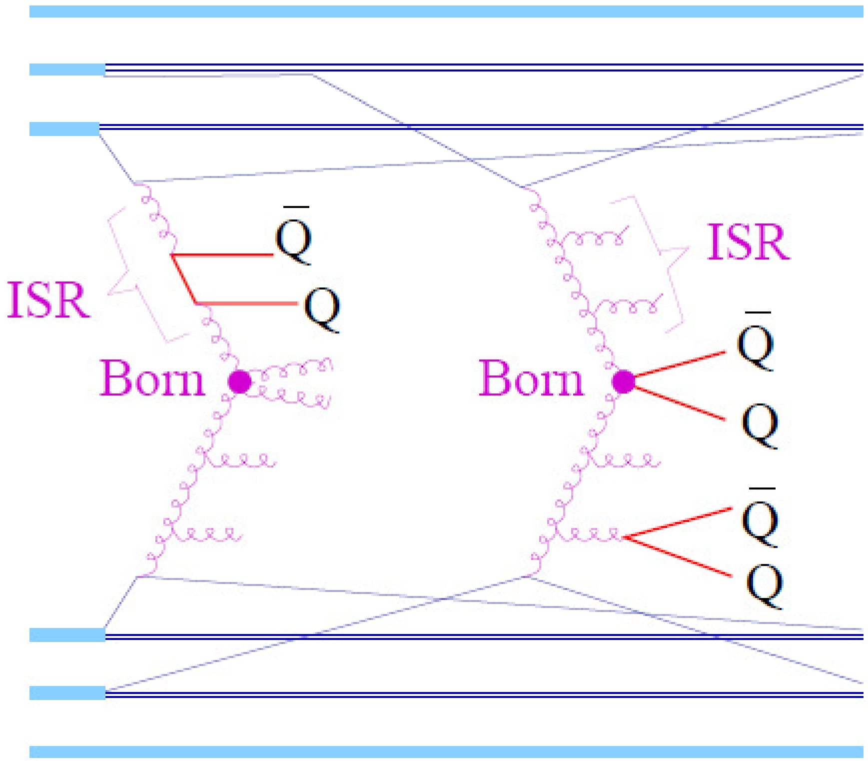
PHSD results for the D-meson observables at RHIC





Heavy quarks from EPOS3

Heavy quark production in EPOS multiple scattering framework



as light quark production

In any of the ladders via

- ☐ **splitting during ISR**
- ☐ **splitting during FSR**
- ☐ **$Q\bar{Q}$ in Born**

but m_Q non-zero

$(m_c = 1.3,\ m_b = 4.2)$

Heavy quarks from EPOS3

The virtuality of the TL parton is assumed to be m_Q^2, so

$$q^2 = k^2 - 2pk = -Q^2 + \frac{Q^2 + k_t^2}{x} = m_Q^2 \; (\text{using } \mathrm{Q}^2 = -\mathrm{k}^2)$$

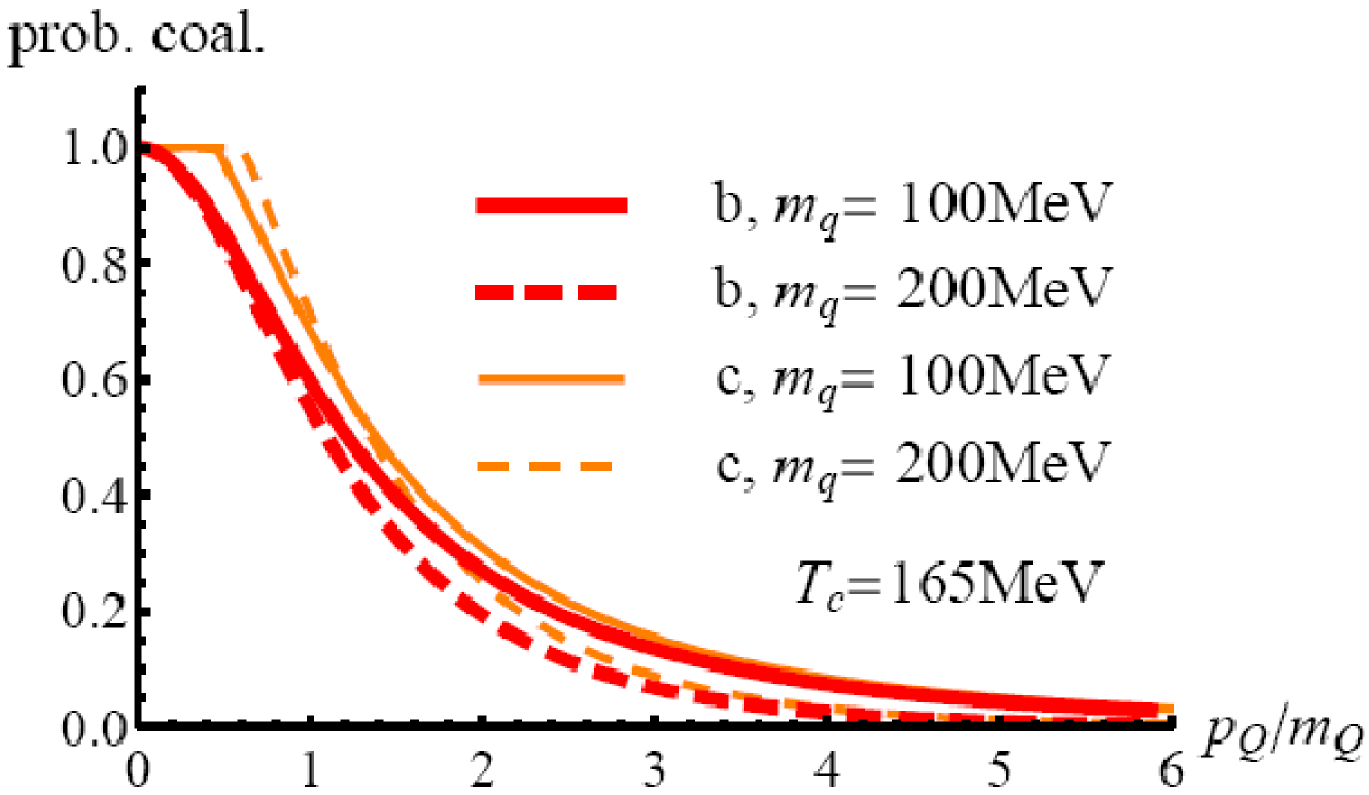
$$\rightarrow -k_t^2 = Q^2 - xQ^2 - xm_Q^2 > 0$$

which implies

$$\boxed{x < \frac{Q^2}{Q^2 + m_Q^2},}$$

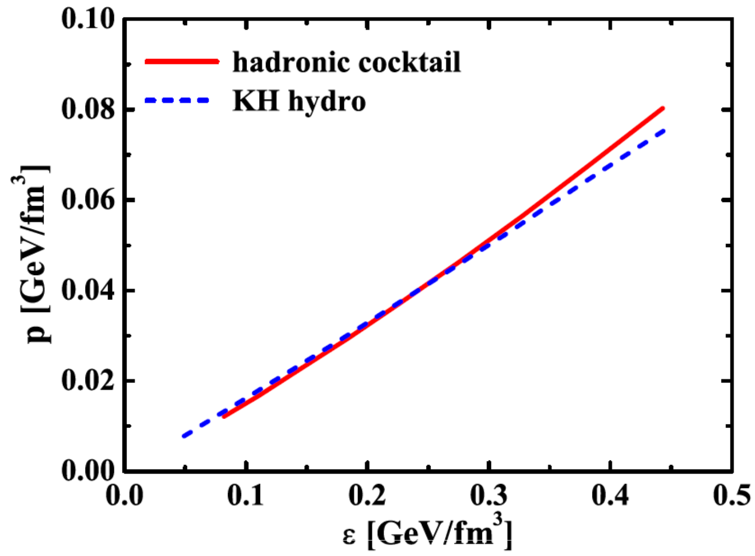
suppressing large x.

Hadronization of HQ



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)

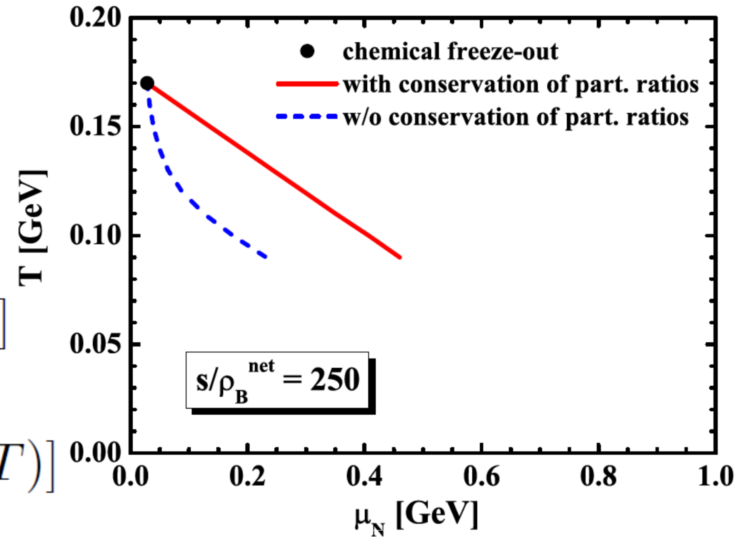
- **Freeze-out** point: $T_{\rm fo}^{\rm ch} = 170\ {\rm MeV}, \quad \mu_{\rm B}^{\rm ch} = 28.3\ {\rm MeV}$

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

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)

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

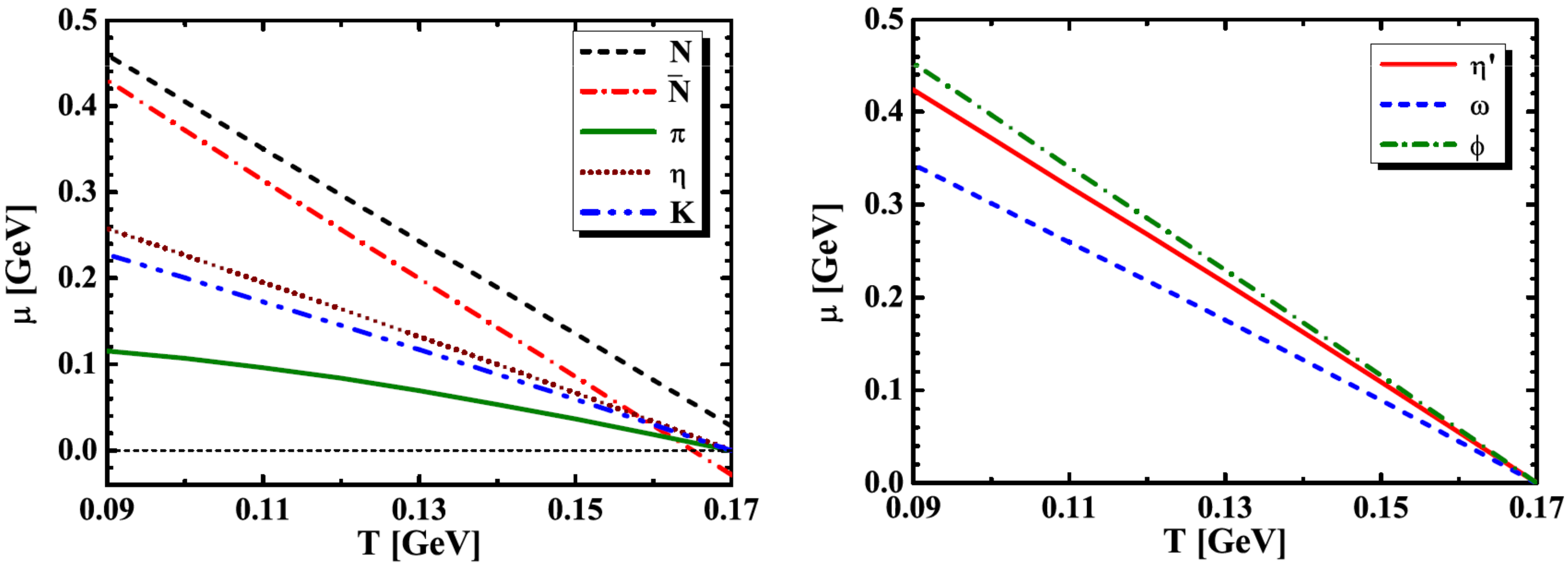
$$N_{\bar{B}}^{\rm eff} = V_{FB} \sum_{\bar{B}_i} n_{\bar{B}_i}(T, \mu_{\bar{B}_i})$$

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

Effective chemical potentials

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

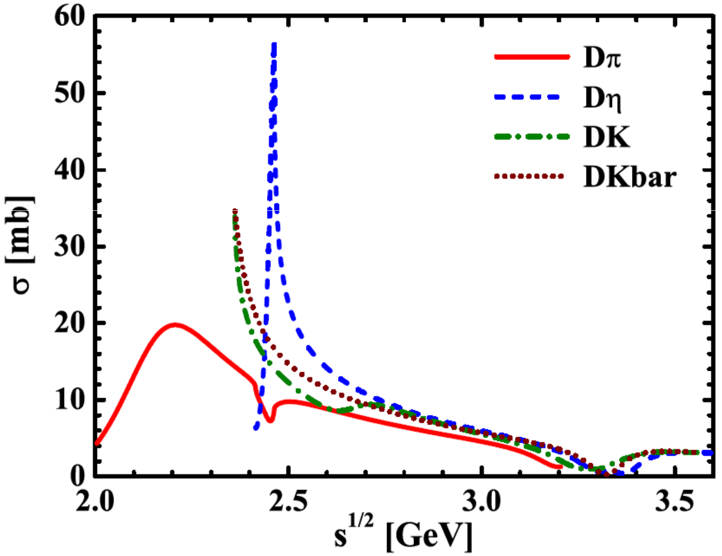
- At chemical freeze-out temperature all meson effective chemical potentials are zero

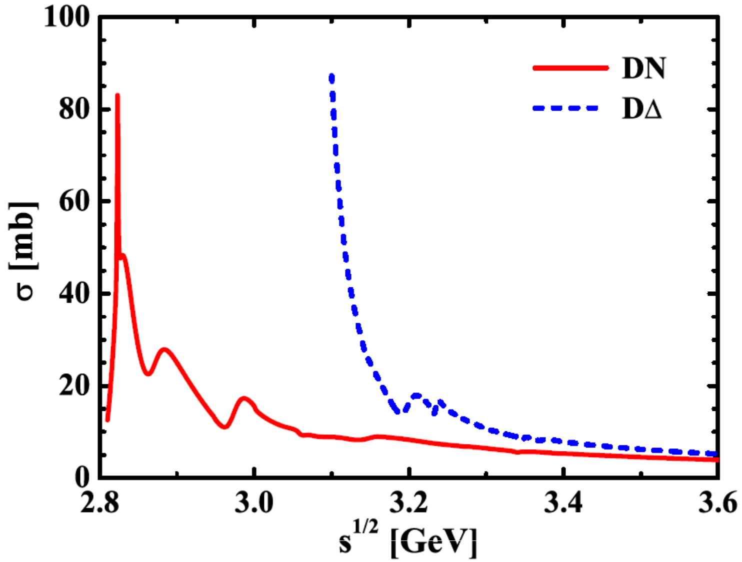


Elastic cross sections

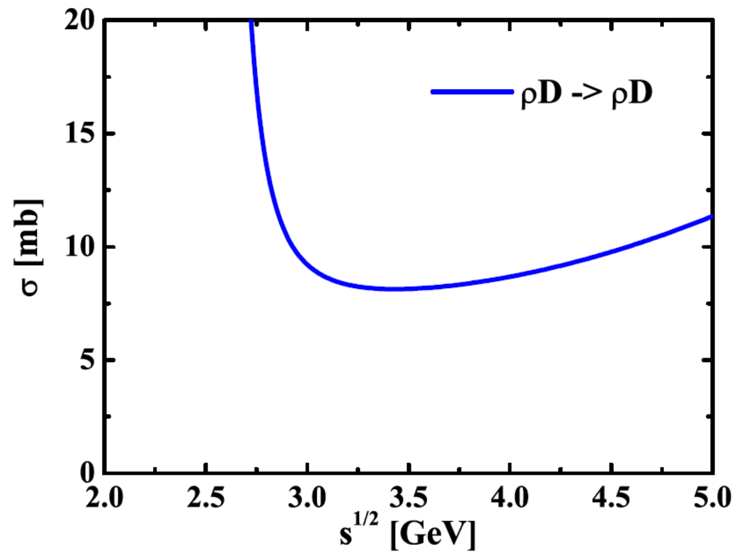
- Implement the **cross sections** (as in the vacuum) for the interaction of a D-meson with hadrons (effective models):

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





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



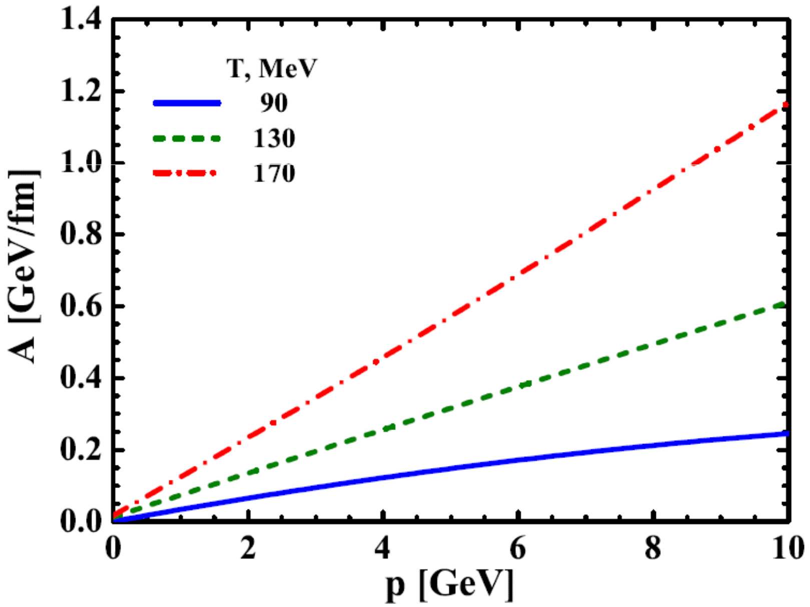
- Other **elastic processes:**

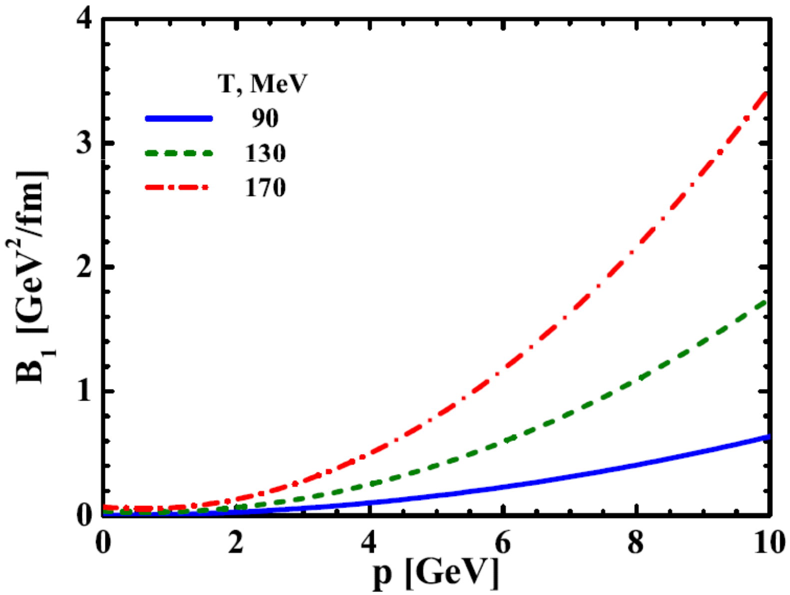
$$Dm \rightarrow Dm \Rightarrow \sigma = 10 \text{ mb}$$
$$DB(\bar{B}) \rightarrow DB(\bar{B}) \Rightarrow \sigma = 15 \text{ mb}$$

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:**

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

D-meson transport coefficients

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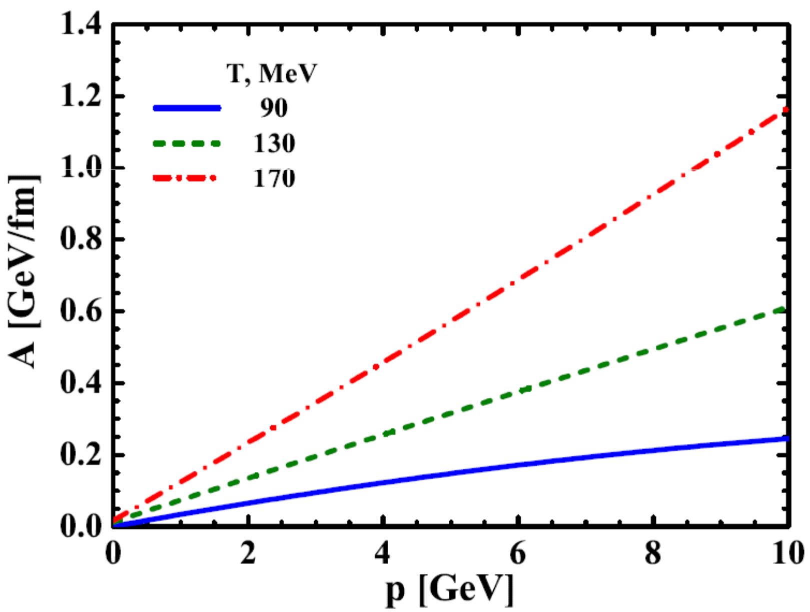

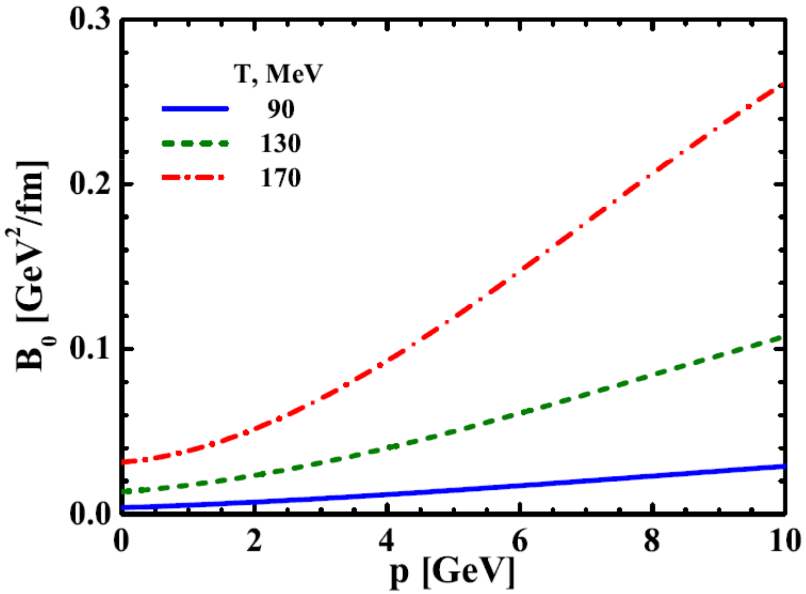

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in the **static limit:**

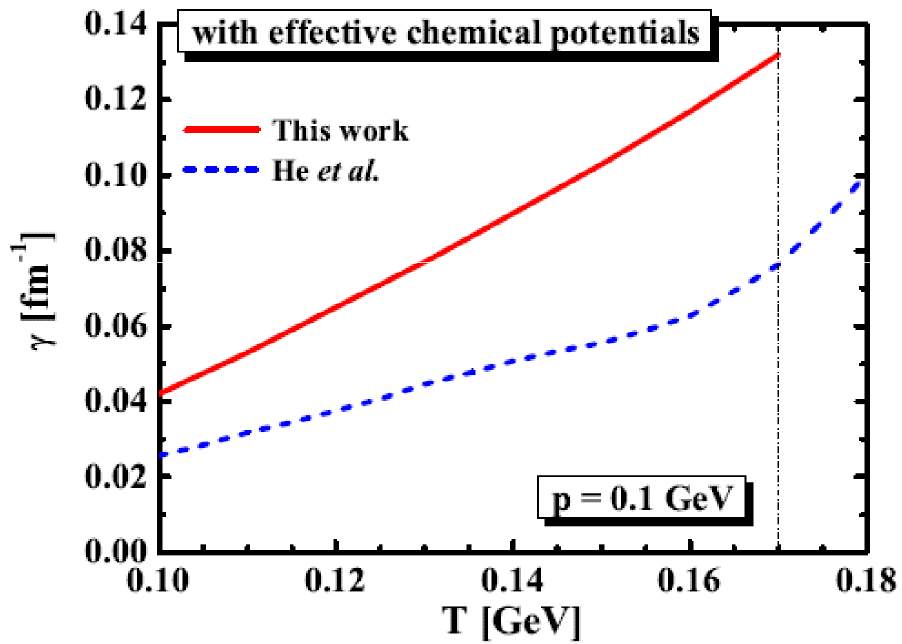
$$\lim_{p \to 0} [B_l(p) - B_T(p)] = 0$$

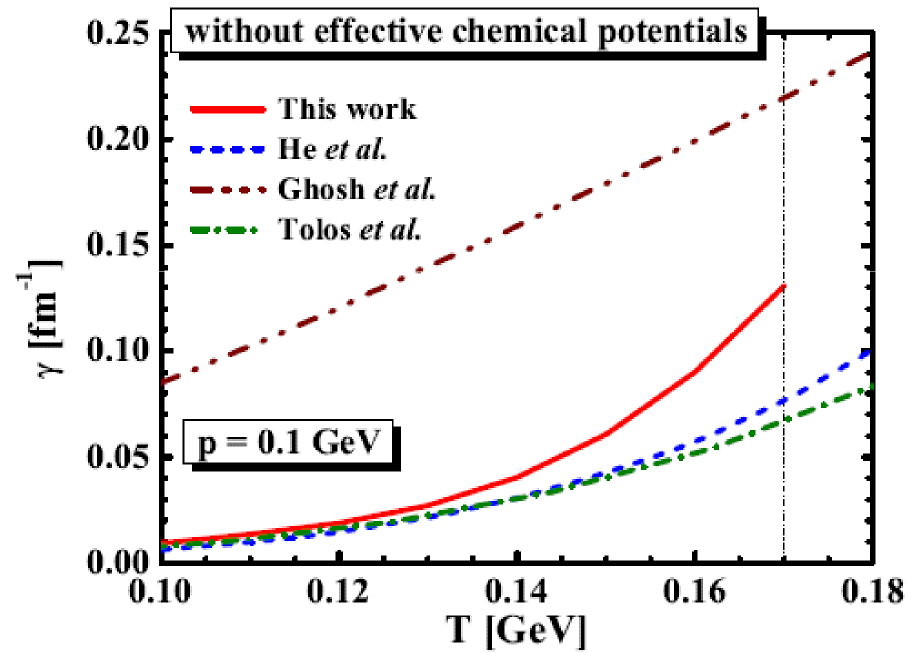
D-meson thermal relaxation time

- 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)

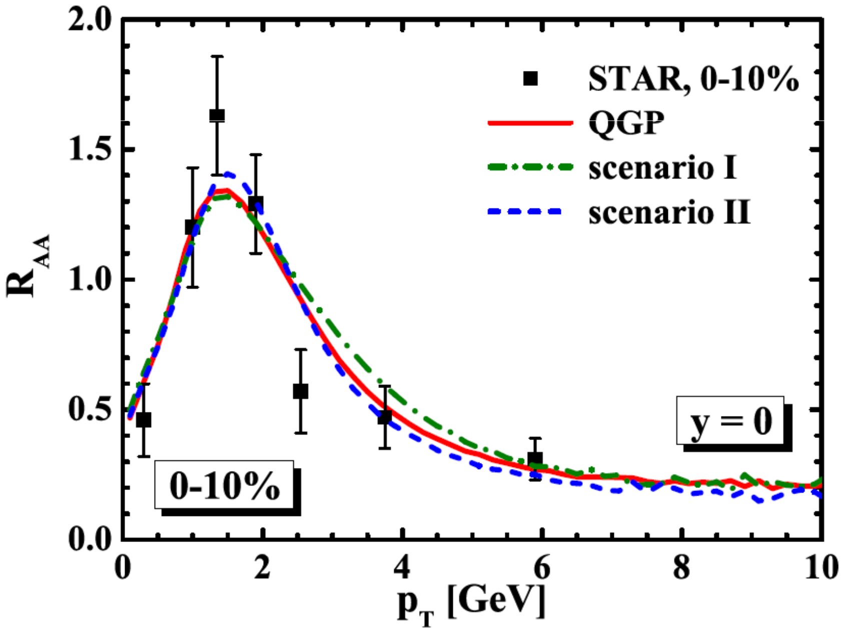




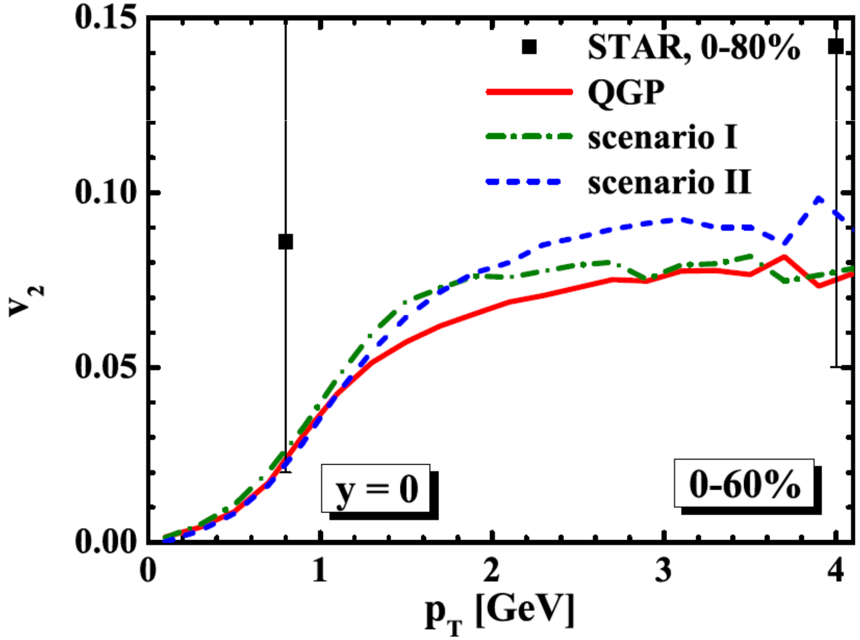
- **Increase by a factor of 2** of the thermal relaxation time due to the different hadronic cocktail and different cross sections

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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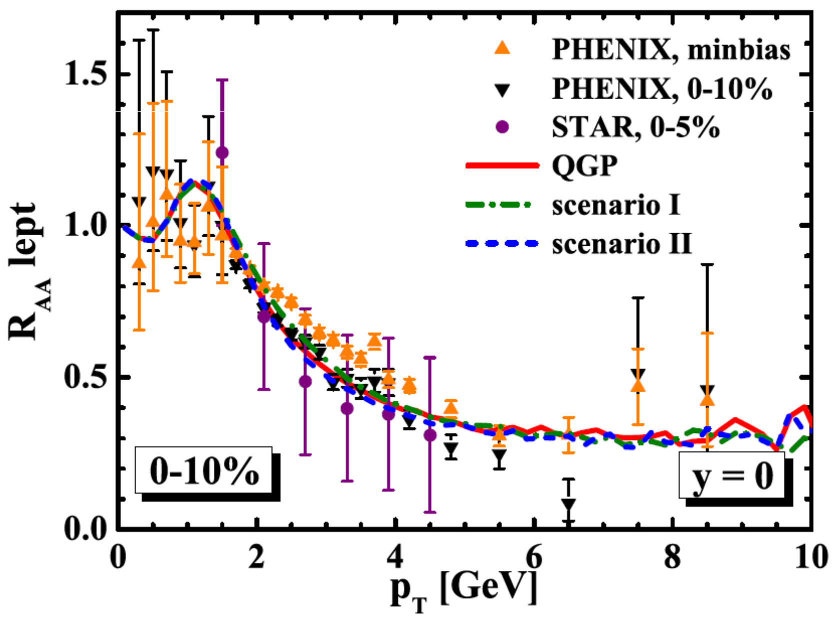
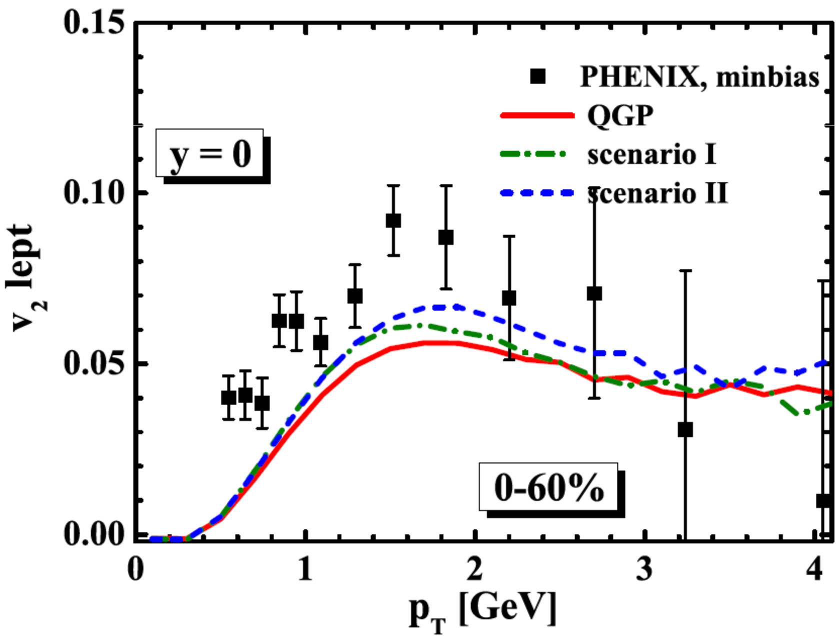




Almost invisible for R_{AA}

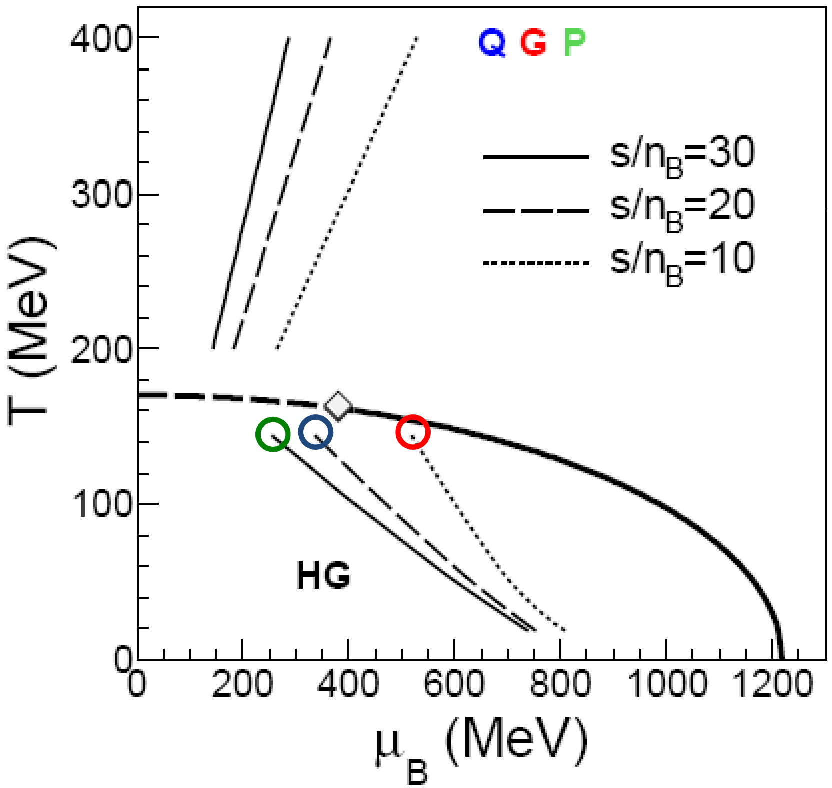
Moderate effect on v_2, but systematic

Isentropic trajectories (FAIR facility)

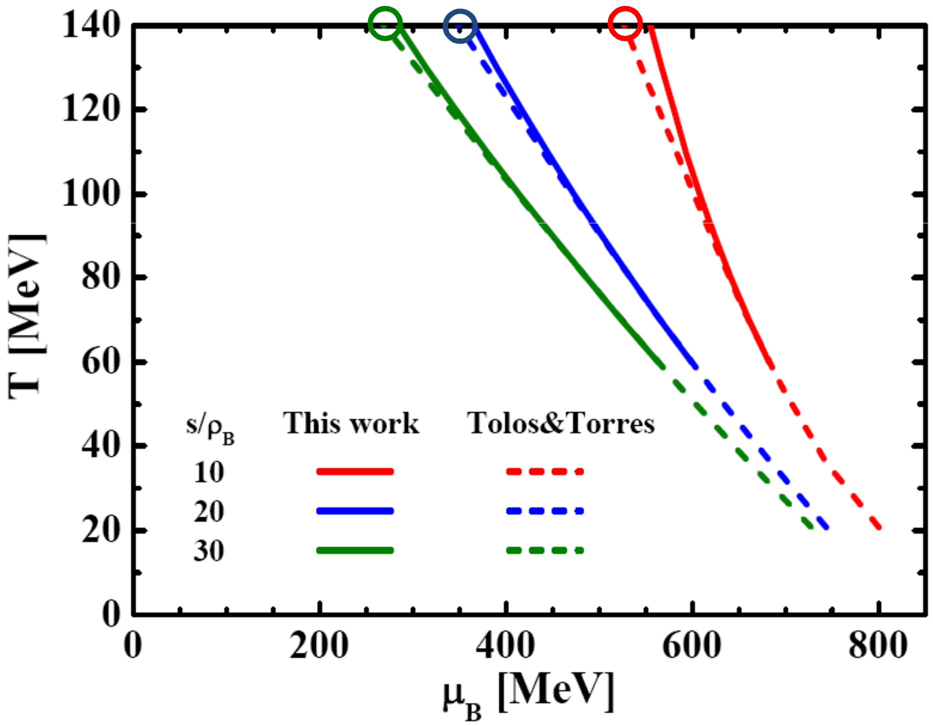
- Assume a **constant specific entropy** (entropy per net baryon) for **FAIR physics:**

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

Juan Torres FAIRNESS 2013



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

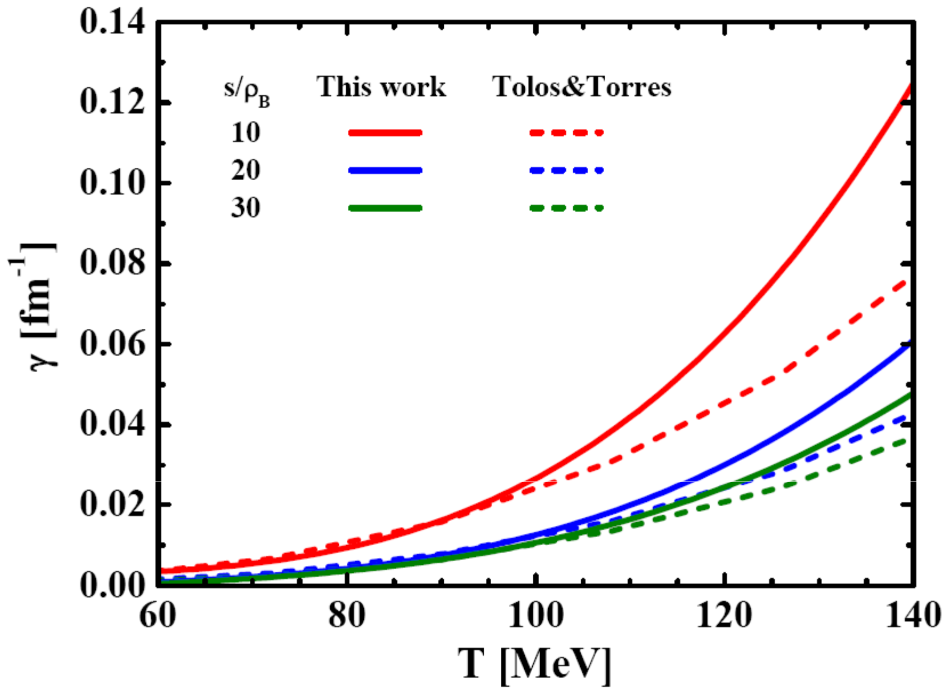


Small deviation due to the higher states in our hadronic cocktail

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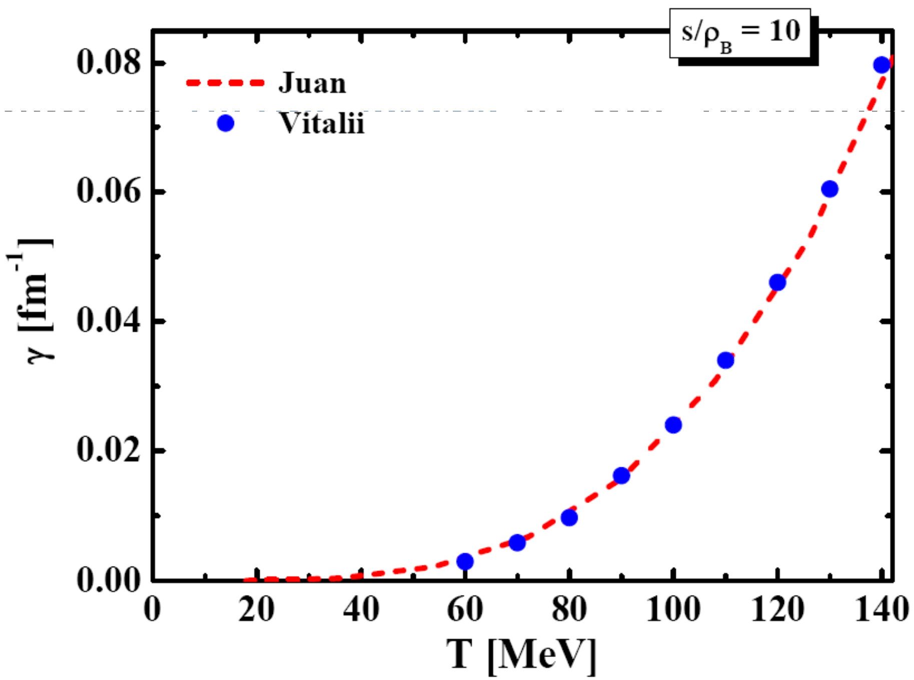
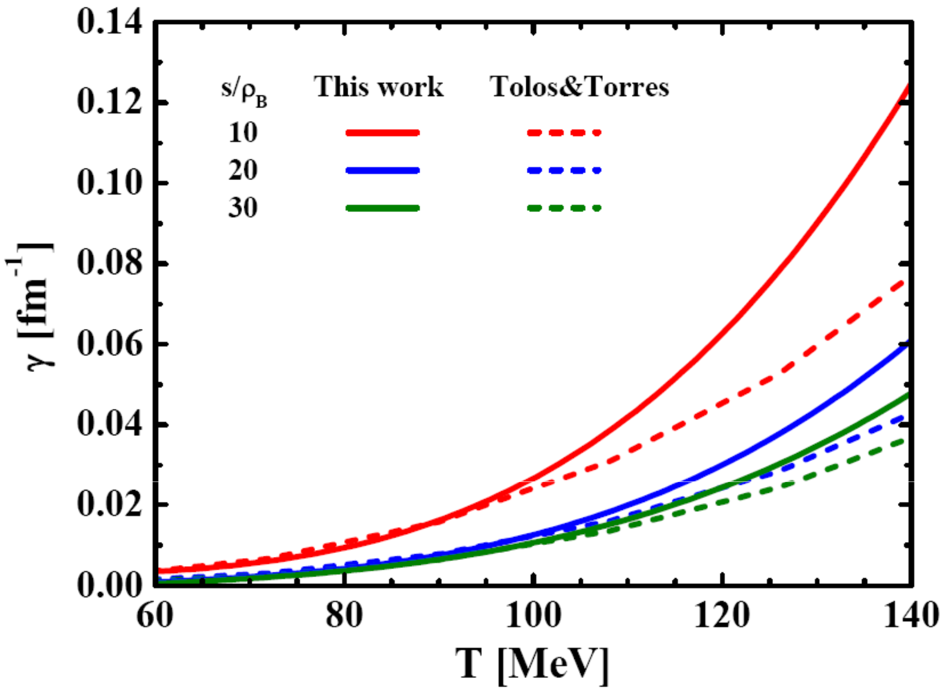
- ❑ **baryons** contribute **significantly** for finite baryochemical potential

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





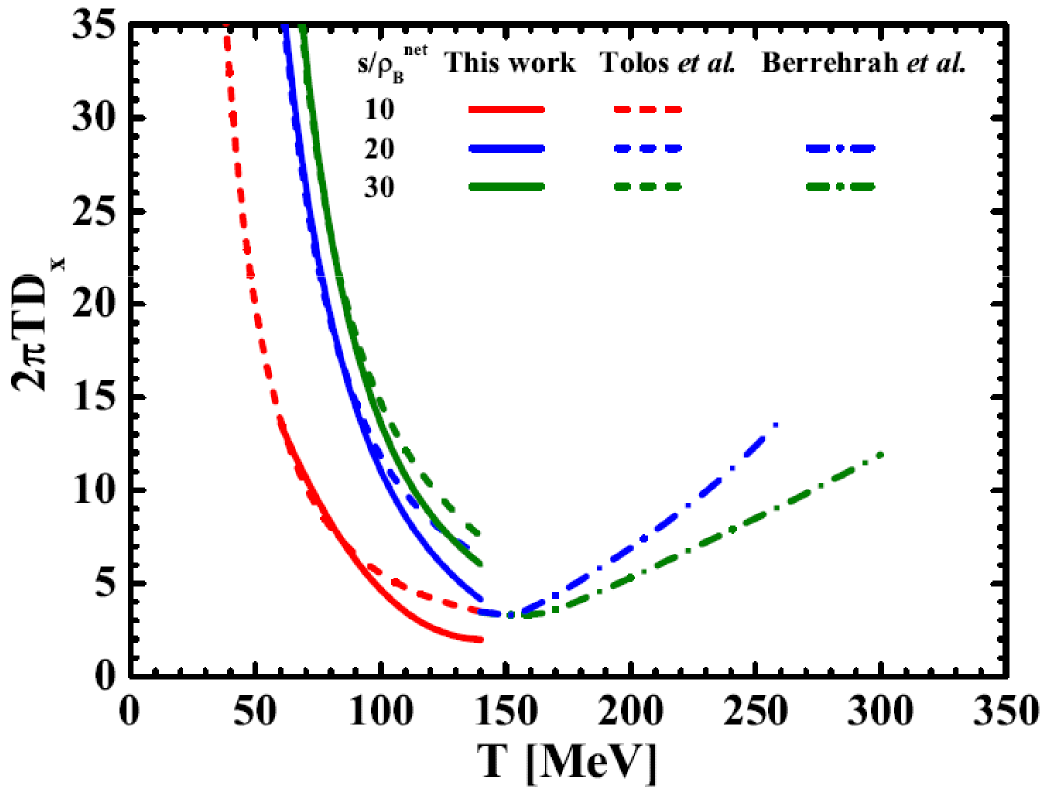
Perfect agreement

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