Heavy-quark transport coefficients
Sensitivity to hadronization description

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Outline

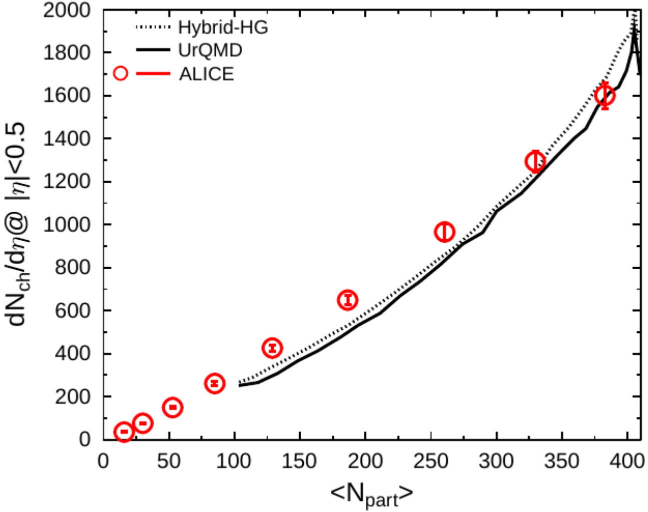
Bulk-medium evolution (e.g., LHC)

- transport (UrQMD) + hydro (SHASTA) hybrid model
- nuclei: Woods-Saxon profile; binary interactions
- string excitation, fragmentation (PYTHIA)
- after $t_{\text{start}} = 0.5\,\text{fm}/c$: particle distributions, momenta, energy density from UrQMD $\rightarrow$ via Gaussian smearing to initial conditions for hydro
- during hydro evolution: HG EoS or chiral DE-EoS
- switch back to transport: Cooper-Frye freezeout at constant τ-hypersurfaces for $\epsilon \lesssim 5\epsilon_0 \simeq 730\,\text{MeV}/\text{fm}^3$

[H. Petersen, Phys.Rev. C **84** (2011) 034912; arXiv:1206.3371 [nucl-th]]

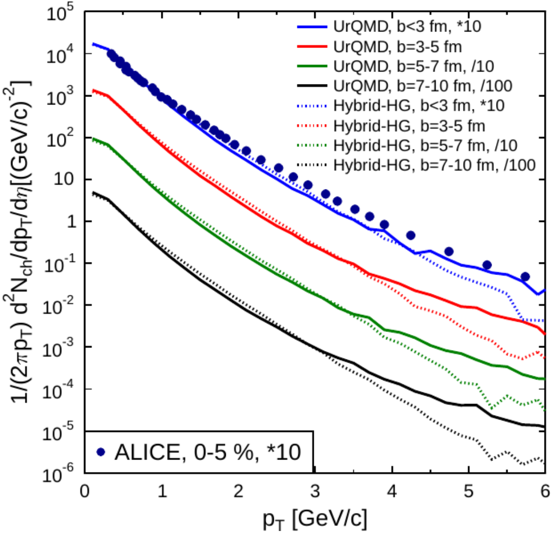
Bulk-medium evolution

- Pb-Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV
- particle multiplicities at mid rapidity $|\eta| < 0.5$



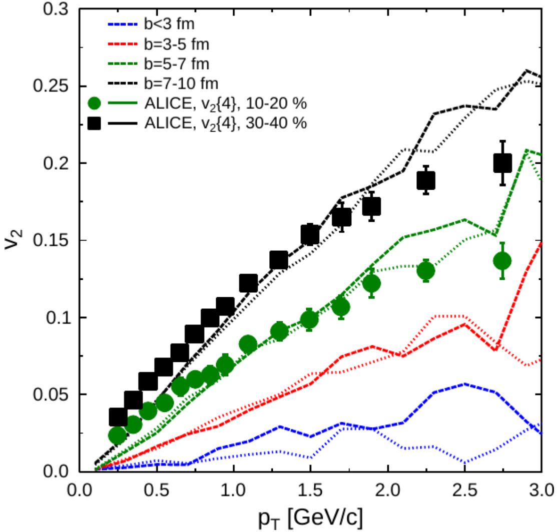
Bulk-medium evolution

- Pb-Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV
- p_T distribution of charged hadrons



Bulk-medium evolution

- Pb-Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV
- v_2 of charged hadrons

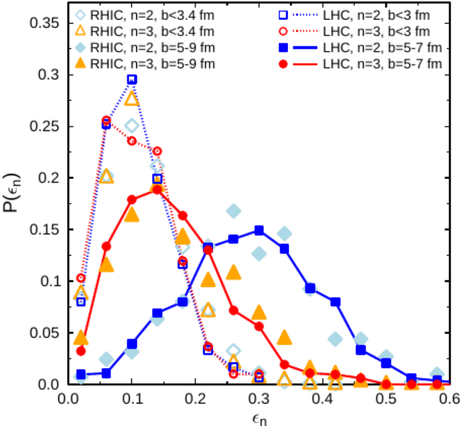


Bulk-medium evolution

- Pb-Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV
- ϵ_2 and ϵ_3 distributions

[H. Petersen, G.-Y. Qin, S. A. Bass, B. Müller, Phys. Rev. C **82**, 041901 (2010); arXiv:1008.0625 [nucl-th]]

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$



Relativistic Langevin process

- Langevin process: friction force + Gaussian random force
- in the (local) rest frame of the heat bath

$$\mathrm{d}\vec{x} = \frac{\vec{p}}{E_p}\mathrm{d}t,$$
$$\mathrm{d}\vec{p} = -A\,\vec{p}\,\mathrm{d}t + \sqrt{2\mathrm{d}t}[\sqrt{B_0}P_\perp + \sqrt{B_1}P_\|]\vec{w}$$

- $\vec{w}$: normal-distributed random variable
- A: friction (drag) coefficient
- $B_{0,1}$: diffusion coefficients
- Einstein dissipation-fluctuation relation $B_1 = E_p T A$.
- flow via Lorentz boosts between “heat-bath frame” and “lab frame”
- A and B_0 from microscopic models for qQ, gQ scattering
- medium: UrQMD → hydro → UrQMD vs. UrQMD/coarse-graining

[R. Rapp, HvH, R. C. Hwa and X. N. Wang (eds.), Quark-Gluon Plasma Vol. IV, World Sientific (2010), arXiv: 0903.1096 [hep-ph]; M. He, HvH, P. B. Gossiaux, R. J. Fries, R. Rapp, Phys. Rev. E **88**, 032138 (2013)]

Free Lagrangian: Particle Content

- Chiral symmetry $\mathrm{SU}_V(2) \otimes \mathrm{SU}_A(2)$ in light-quark sector of QCD

$$\mathscr{L}_D^{(0)} = \sum_{i=1}^{2} [(\partial_\mu \Phi_i^\dagger)(\partial^\mu \Phi_i) - m_D^2 \Phi_i^\dagger \Phi_i] + \text{massive (pseudo-)vectors } D^*$$

- Φ_i: two doublets: pseudo-scalar $\sim \binom{\overline{D^0}}{D^-}$ and scalar
- Φ_i^*: two doublets: vector $\sim \binom{\overline{D^{0*}}}{D^{-*}}$ and pseudo-vector

$$\mathscr{L}_{qc}^{(0)} = \bar{q} \mathrm{i} \not{\partial} q + \bar{c}(\mathrm{i} \not{\partial} - m_c) c$$

- q: light-quark doublet $\sim \binom{u}{d}$
- c: singlet

Interactions

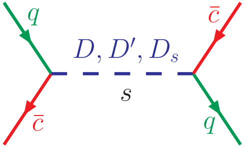
- Interactions determined by chiral symmetry
- For transversality of vector mesons:
  heavy-quark effective theory vertices

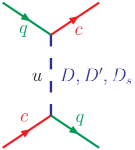
$$\begin{aligned}\mathscr{L}_{\text{int}} = &- G_S \left(\bar{q} \frac{1+\slashed{v}}{2} \Phi_1 c_v + \bar{q} \frac{1+\slashed{v}}{2} \mathrm{i}\gamma^5 \Phi_2 c_v + h.c. \right) \\ &- G_V \left(\bar{q} \frac{1+\slashed{v}}{2} \gamma^\mu \Phi_{1\mu}^* c_v + \bar{q} \frac{1+\slashed{v}}{2} \mathrm{i}\gamma^\mu \gamma^5 \Phi_{2\mu}^* c_v + h.c. \right)\end{aligned}$$

- v: four velocity of heavy quark
- in HQET: spin symmetry $\Rightarrow G_S = G_V$

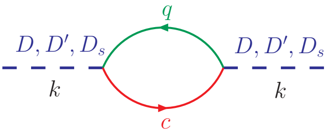
Non-perturbative interactions: Resonance Scattering

- General idea: Survival of D- and B-meson like resonances above T_c
- model based on chiral symmetry (light quarks) HQ-effective theory
- elastic heavy-light-(anti-)quark scattering





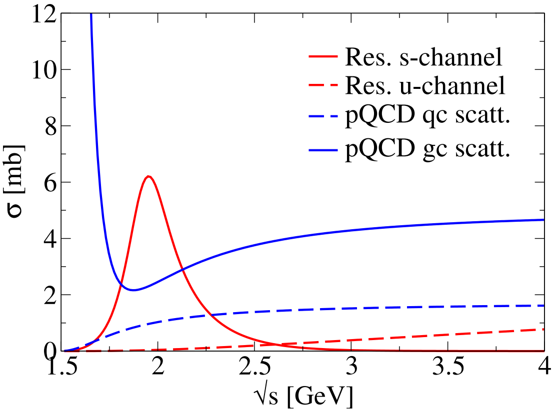
- D- and B-meson like resonances in sQGP



- parameters
  - $m_D = 2\,\text{GeV}$, $\Gamma_D = 0.4 \ldots 0.75\,\text{GeV}$
  - $m_B = 5\,\text{GeV}$, $\Gamma_B = 0.4 \ldots 0.75\,\text{GeV}$

[HvH, R. Rapp, Phys. Rev. C **71**, 034907 (2005); HvH, V. Greco, R. Rapp, Phys. Rev. C 73, 034913 (2006)]

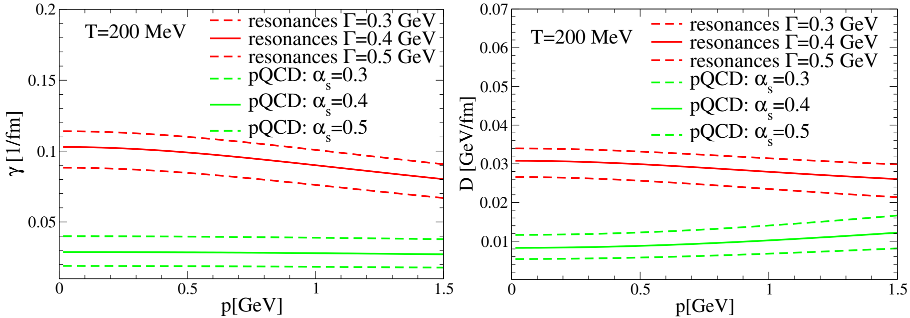
Cross sections



- total pQCD and resonance cross sections: comparable in size
- BUT pQCD forward peaked ⟷ resonance isotropic
- resonance scattering more effective for friction and diffusion

Transport coefficients: pQCD vs. resonance scattering

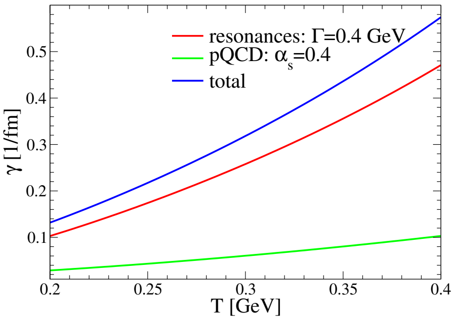
- three-momentum dependence

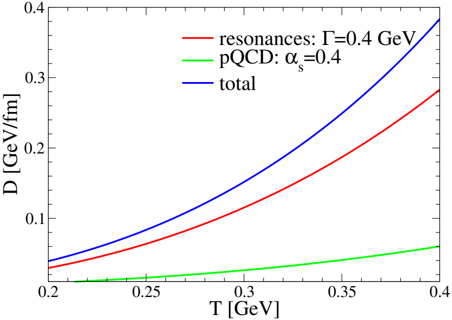


- resonance contributions factor $\sim 2 \ldots 3$ higher than pQCD!

Transport coefficients: pQCD vs. resonance scattering

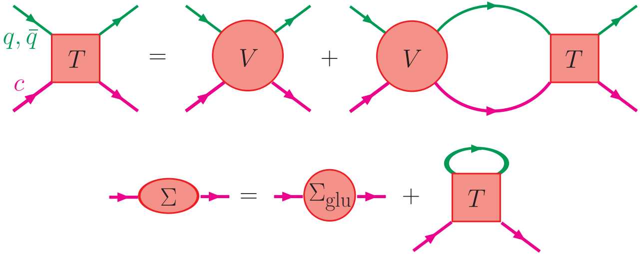
- Temperature dependence





T-matrix

- Brueckner many-body approach for elastic Qq, $Q\bar{q}$ scattering

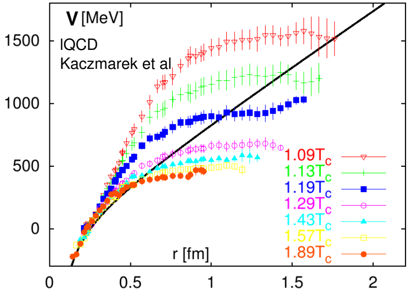


- V: static $q\bar{q}$ potential from lattice QCD (F and U)
- reduction scheme: 4D Bethe-Salpeter → 3D Lipmann-Schwinger
- S- and P waves
- Relation to invariant matrix elements

$$\sum |\mathcal{M}(s)|^2 \propto \sum_q d_a \left(|T_{a,l=0}(s)|^2 + 3|T_{a,l=1}(s)|^2 \cos\theta_{\text{cm}}\right)$$

[HvH, M. Mannarelli, V. Greco, R. Rapp, Phys. Rev. Lett. **100**, 192301 (2008)]

Static heavy-quark potentials from lattice QCD



- color-singlet free energy from lattice → internal energy

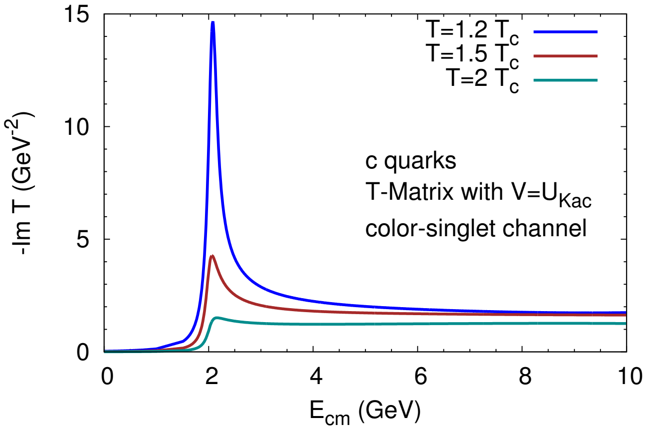
$$U_1(r,T) = F_1(r,T) - T\frac{\partial F_1(r,T)}{\partial T},$$

$$V_1(r,T) = U_1(r,T) - U_1(r\to\infty,T)$$

- Casimir scaling of Coulomb part for other color channels; confining part color blind [F. Riek, R. Rapp, Phys. Rev. C **82**, 035201 (2010)].

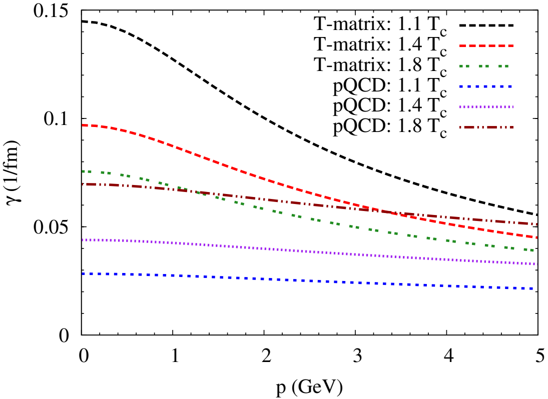
$$V_{\bar{3}} = \frac{1}{2}V_1, \quad V_6 = -\frac{1}{4}V_1, \quad V_8 = -\frac{1}{8}V_1$$

T-matrix results



- resonance formation at lower temperatures $T \simeq T_c$
- melting of resonances at higher T
- model-independent assessment of elastic Qq, $Q\bar{q}$ scattering!

Transport coefficients



- T-matrix resonance-scattering coefficients: decrease with T
- from non-pert. interactions reach $A_{\text{non-pert}} \simeq 1/(7\,\text{fm}/c) \simeq 4 A_{\text{pQCD}}$
- results for free-energy potential, F considerably smaller

Hadronization

- Coalescence [Greco, Ko, Rapp, Phys. Lett. B **595**, 202 (2004)]

$$P_{\text{coa}} = \exp\left\{\left[(\Delta p^0)^2 - \sum_{i=1}^{3}(\Delta p^i)^2 - (\Delta_m)^2\right]\sigma^2\right\}, \quad \sigma^2 = \frac{8}{3} r_{\text{D}}^2$$

- Petersen fragmentation (z: momentum fraction $\text{c} \rightarrow \text{D}$)

$$D(z) = \frac{H}{z[1-(1/z)-\epsilon_p/(1-z)]^2}.$$

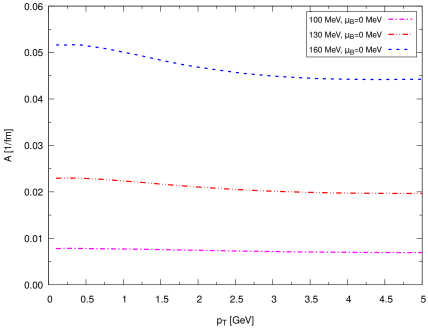
Hadronic transport coefficients

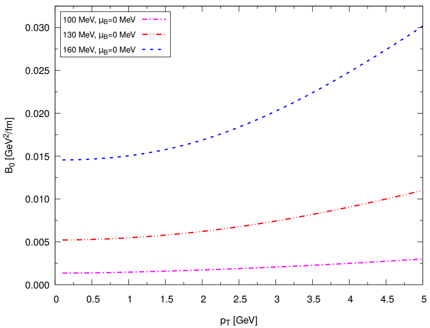
- based on unitarized chiral HQ model

  [Abreu et al, Ann. Phys. **326**, 2737 (2011); PRD **87**, 034019 (2013); Tolos, Torres-Rincon, PRD **88**, 074019 (2013)]
- coupled channel T-matrix approach with pseudo-Goldstone mesons (π, η, K) and baryons (N, $\bar{N}$, Δ, $\bar{\Delta}$)
- D-meson scattering cross sections used for HQ drag and diffusion coefficients

Hadronic transport coefficients

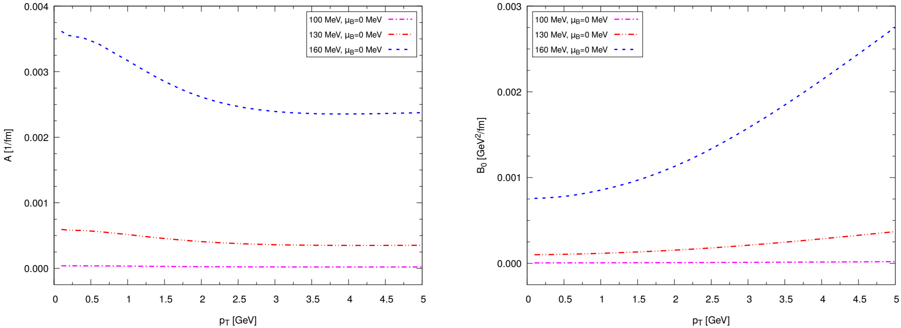
- drag and diffusion coefficients for D from mesonic interactions





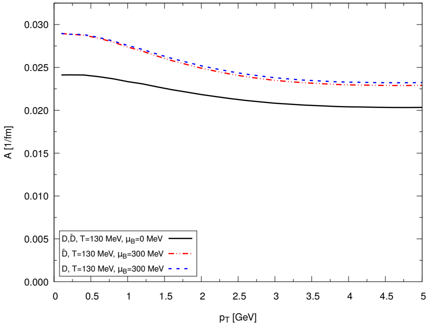
Hadronic transport coefficients

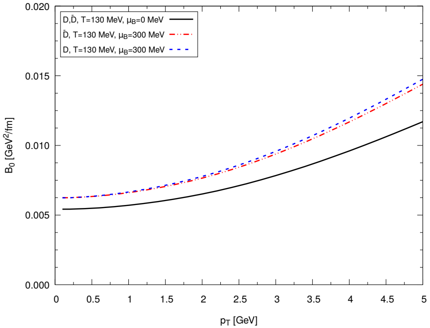
- drag and diffusion coefficients for D from baryonic interactions



Hadronic transport coefficients

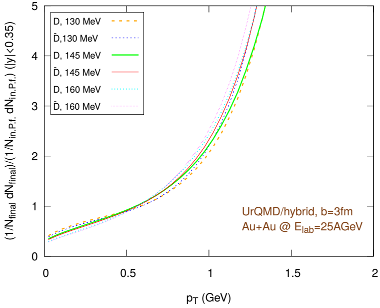
- drag and diffusion coefficients for D at finite μ_B

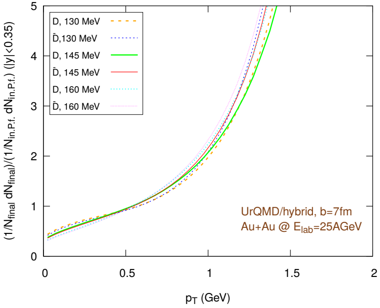




D-mesons at FAIR

- $E_{\text{kin}} = 25A\text{GeV}$
- bulk-medium evolution: UrQMD-hydro hybrid vs. UrQMD coarse graining
- QQP HQ transport coefficients from resonance model
- influence of hadronization description: sensitivity to
  - hadronization temperature
  - coalescence vs. fragmentation (dependence on r_{D}, ϵ_{P})





- strong rise in R_{AA} due to energy constraint in pp ($p_{\text{T}} \lesssim 2.5\,\text{GeV}$)

[Inghirami, HvH, Endres, Torres-Rincon, Bleicher, Eur. Phys. J. 79:52 (2019)]

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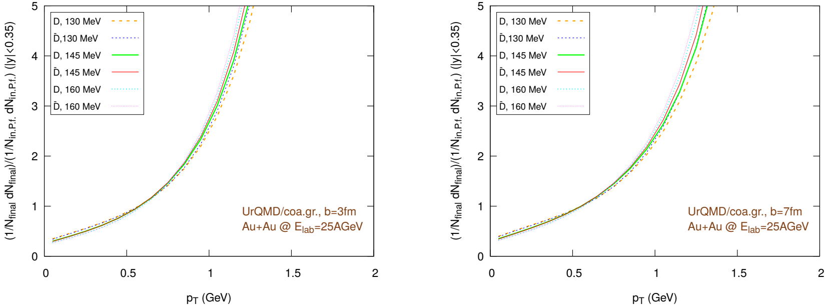

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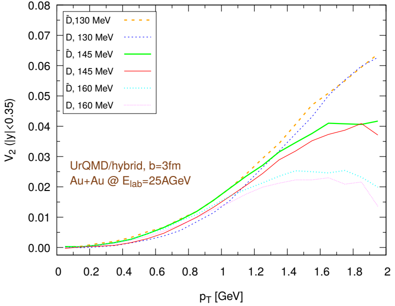

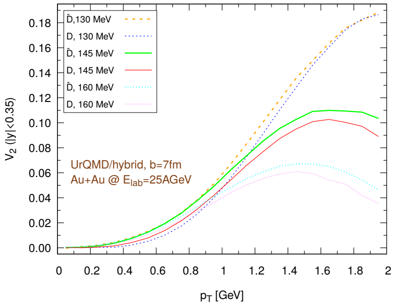

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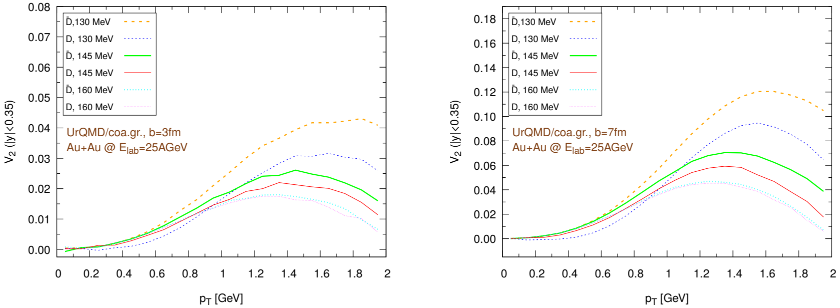

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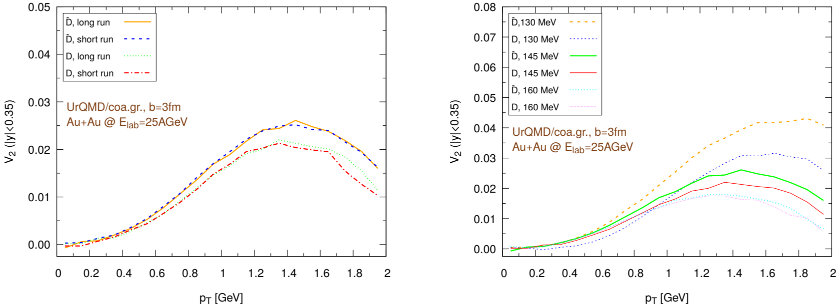

- influence of longer hadronic phase negligible

[Inghirami, HvH, Endres, Torres-Rincon, Bleicher, Eur. Phys. J. 79:52 (2019)]

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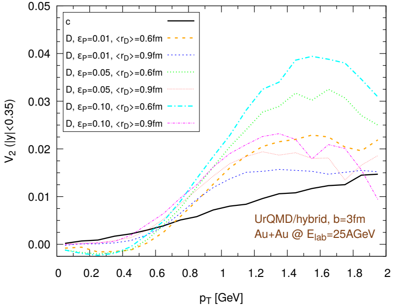

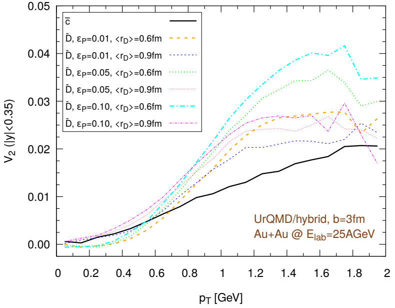

- large influence on hadronization procedure

[Inghirami, HvH, Endres, Torres-Rincon, Bleicher, Eur. Phys. J. 79:52 (2019)]