Open Charm at FAIR energies - what do we need/want to know?

HIC for FAIR workshop: heavy flavor physics with CBM

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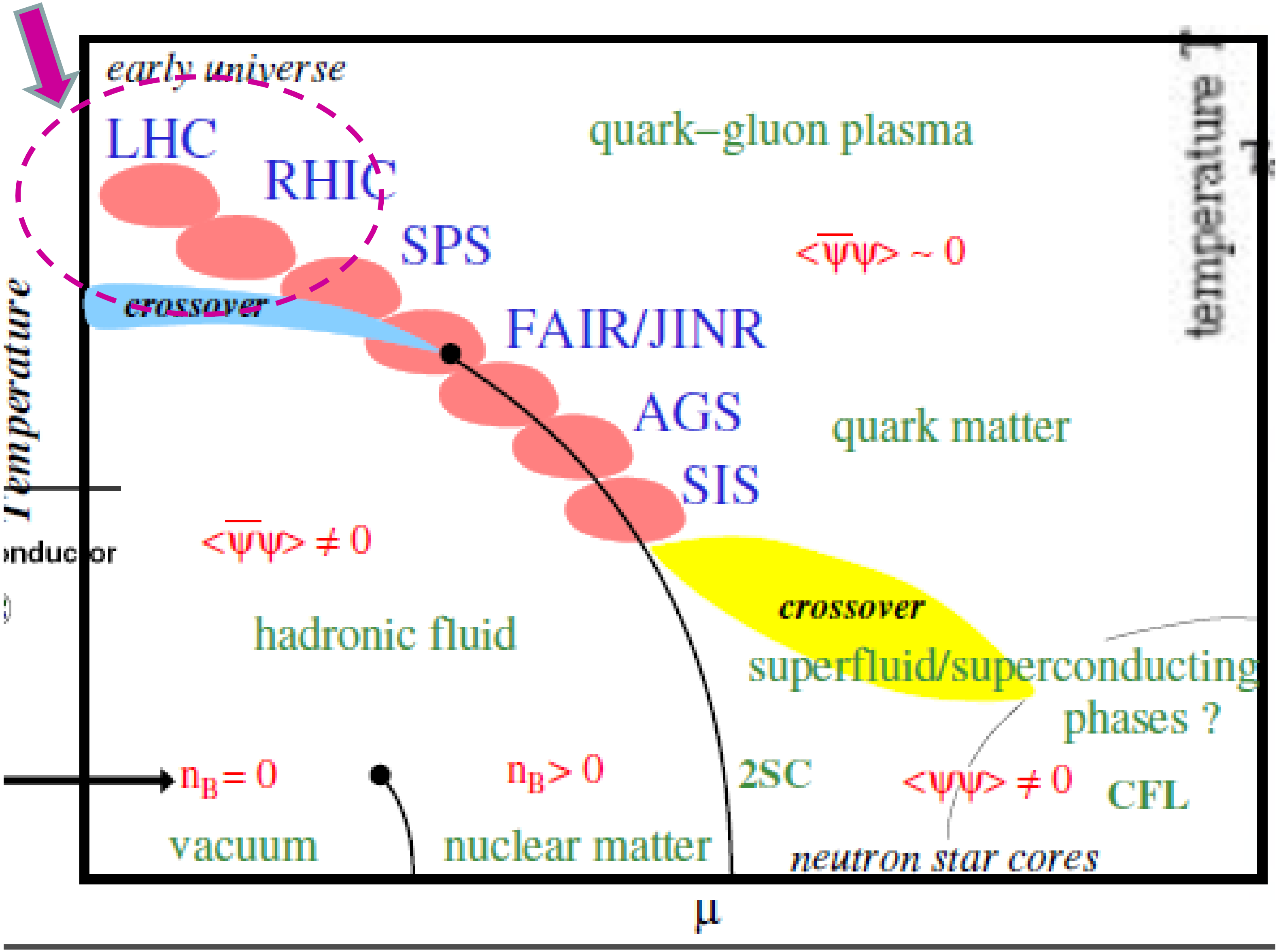
My HQ life up to now



Model in a Nutshell: HQ Interaction with the bulk

- No force on HQ before thermalization of QGP
- Hydro evol => macroscopic parameters T(t,h,xT), **v**(t,h,xT), μ(t,h,xT),
- In QGP: heavy quarks are assumed to interact with partons of type "i" (massless quarks and gluons) with local 2→2 collisional rate:

$$R_i = \frac{1}{2E_p}\int\frac{d^3k}{(2\pi)^3 2k}\int\frac{d^3k'}{(2\pi)^3 2k'}\int\frac{d^3p'}{(2\pi)^3 2E'}$$
$$n_i(k)\times(2\pi)^4\delta^{(4)}(P+K-P'-K')\sum|\mathcal{M}_i|^2$$

Φ inside

…depends on the QGP macroscopic parameters at a given 4-position (t,x).

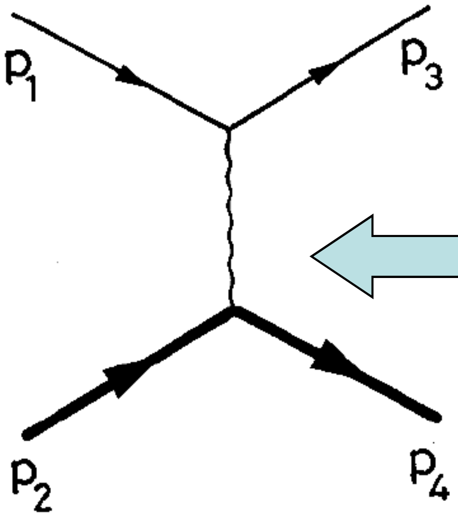
We follow the hydro evolution and sample the rates R_i "on the way", performing the Qq→Q'q' & Qg→Q'g' collisions according to Boltzmann:

Monte Carlo approach

- In mixed phase: Rate = $\varepsilon/\varepsilon_{\text{end QGP}}$ x Rate at end of QGP
- No D (B) interaction in hadronic phase

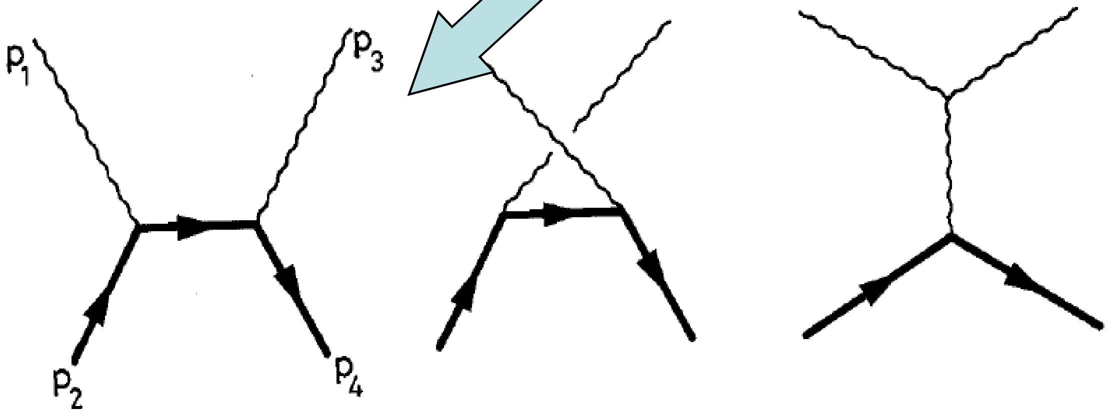
Cross sections

Starting from Combridge (79) as a basis:



$$\sum |\mathcal{M}|^2 = \frac{64\pi^2\alpha^2(Q^2)}{9}\,\frac{(M^2-u)^2+(s-M^2)^2+2M^2t}{t^2}$$

$$\sum |\mathcal{M}|^2 = \pi^2\alpha^2(Q^2)\Big[\frac{32(s-M^2)(M^2-u)}{t^2}+\frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(s+M^2)}{(s-M^2)^2}$$
$$+\frac{64}{9}\frac{(s-M^2)(M^2-u)+2M^2(M^2+u)}{(M^2-u)^2}+\frac{16}{9}\frac{M^2(4M^2-t)}{(s-M^2)(M^2-u)}$$
$$+16\frac{(s-M^2)(M^2-u)+M^2(s-u)}{t\,(s-M^2)}-16\frac{(s-M^2)(M^2-u)-M^2(s-u)}{t\,(M^2-u)}\Big]$$



However, t-channel is IR divergent

=> modelS

$$\frac{1}{t} \to \frac{1}{t-\mu^2(T)}$$

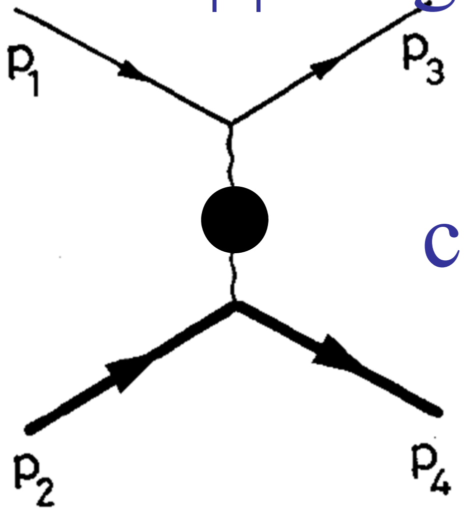
Naïve pQCD (f.i. Svetitsky 89)

Braaten-Thoma:

(Peshier – Peigné)

HTL: convergent kinetic
(matching 2 regions)

Low |t|: large distances



HTL:
collective
modes

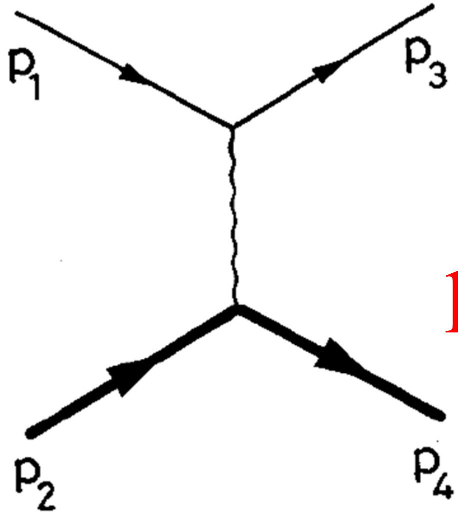
$$G_{\mu\nu}(Q) = \frac{-\delta_{\mu 0}\delta_{\nu 0}}{q^2 + \Pi_{00}} + \frac{\delta_{ij} - \hat{q}_i \hat{q}_j}{q^2 - \omega^2 + \Pi_T}$$

$$\frac{dE_{soft}}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{t^*}}{m_D/\sqrt{3}}\right) + \ldots$$

$|t^*|$

+

Large |t|: close coll.



Bare
propagator

$$G_{\mu\nu}(Q) = \frac{-\delta_{\mu\nu}}{q^2 - \omega^2}$$

$$\frac{dE_{hard}}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{ET}}{\sqrt{t^*}}\right) + \ldots$$

SUM: $$\frac{dE}{dx} = \frac{2}{3}\alpha\, m_D^2 \ln\left(\frac{\sqrt{ET}}{m_D/\sqrt{3}}\right)$$

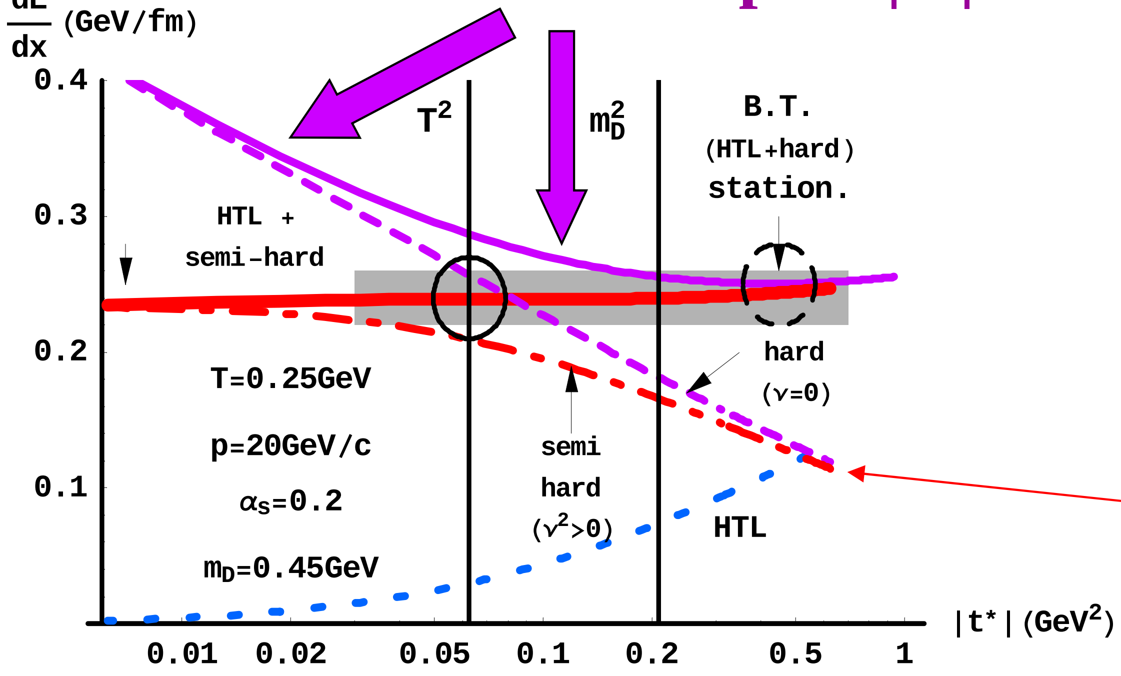
Indep. of |t*| !

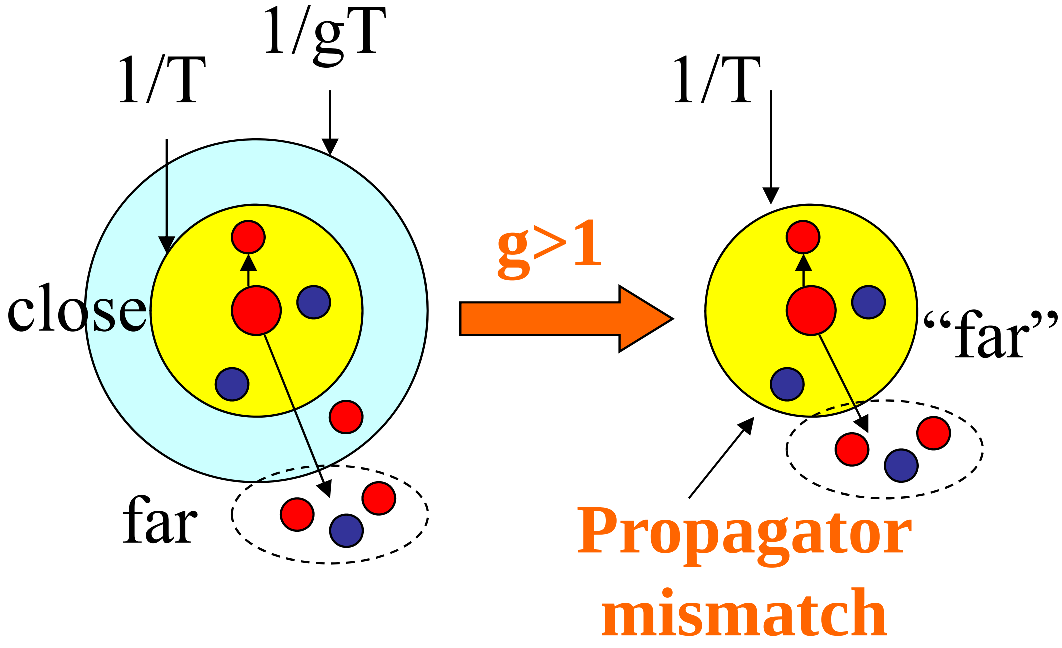
(provided $g^2T^2 \ll |t^*| \ll T^2$)

HTL at finite (not small) coupling

In QGP: $g^2T^2 > T^2$!!!

BT: Not Indep. of |t*| !





Our solution: Introduce a semi-hard propagator $1/(t-\nu^2)$ for $|t|>|t^*|$ to attenuate the discontinuities at t^* in BT approach.

Prescription: ν^2 in the semi-hard prop. is *chosen* such that the resulting E loss is maximally $|t^*|$-independent.

This allows a matching at a sound value of $|t^*| \approx T$

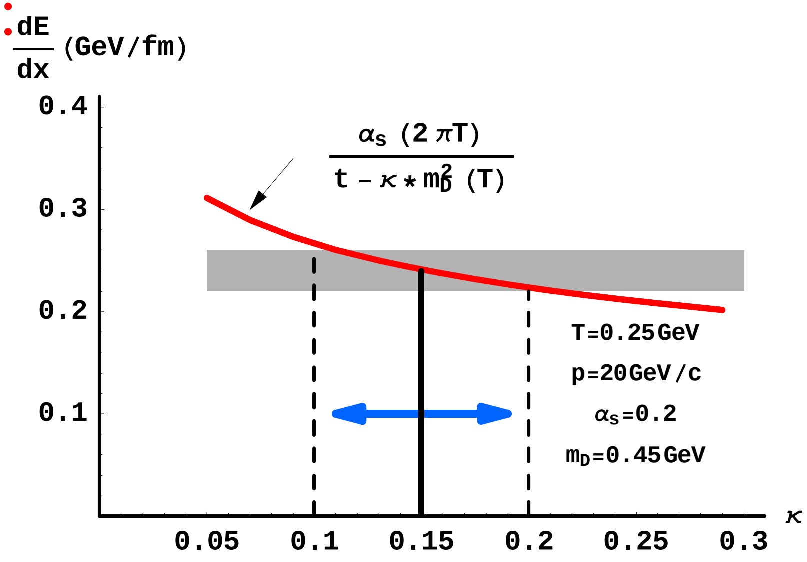
OBE Model at fixed α_s: optimal μ^2

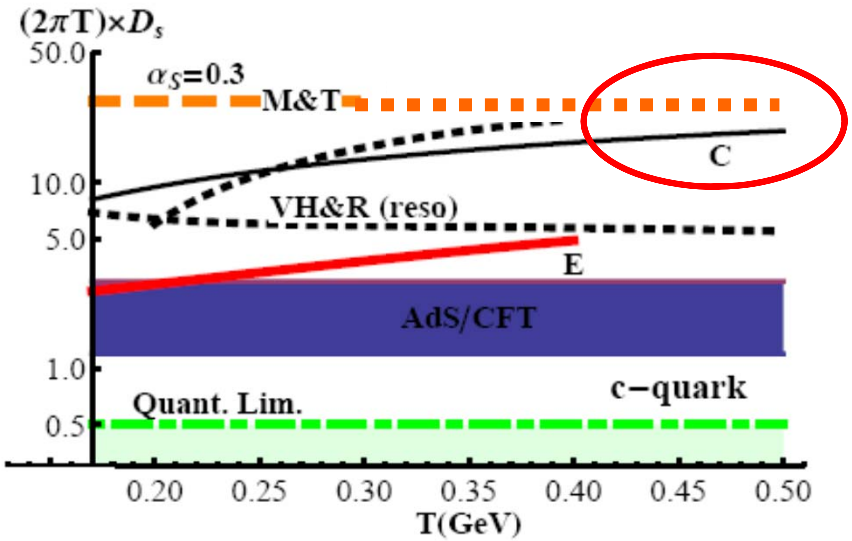
THEN: Optimal choice of μ in our OBE model:

$$\frac{\alpha_s(2\pi T)}{t-\mu^2}$$

$$\mu^2(T) \approx 0.15\ m_D^2(T)$$

with $m_D^2 = 4\pi\alpha_s(2\pi T)(1+3/6)xT^2$





Convergence with "pQCD" at high T

Running α_s …

Motivation: Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant has been "forgotten/neglected" in most of approaches

…asymptotic freedom and infrared slavery

<u>Strategy</u>

1. Effective $\alpha_{eff}(Q^2)$
2. "generalized BT" / convergent-kinetic => dE/dx
3. Fix the optimal IR regulator in propagator i.e. in t-channel, fix the optimal κ

$$\frac{\alpha_{eff}(t)}{t - \kappa \tilde{m}_D^2(T)}$$

$\mu^2(T)$

Self consistent m_D (Peshier hep-ph/0607275)

$m_{Dself}^2(T) = (1+n_f/6)\, 4\pi\alpha_s(m_{Dself}^2)\, xT^2$

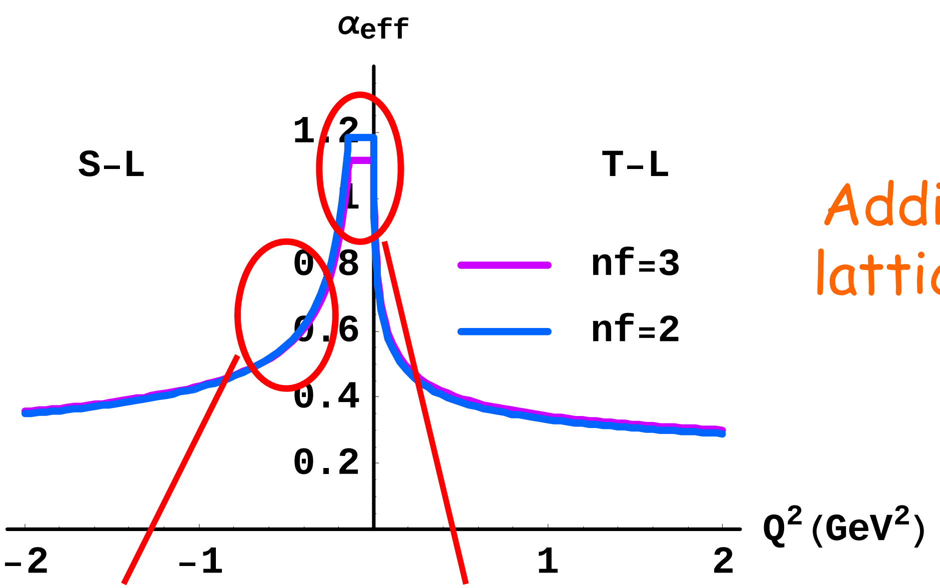
Model E : running α_s AND optimal μ^2

- Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)

Observable = T-L effective coupling * Process dependent fct

"Universality constrain" (Dokshitzer 02) helps reducing uncertainties:

$$\frac{1}{Q_u}\int_{|Q^2|\le Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$



Additional inputs (from lattice) could be helpful

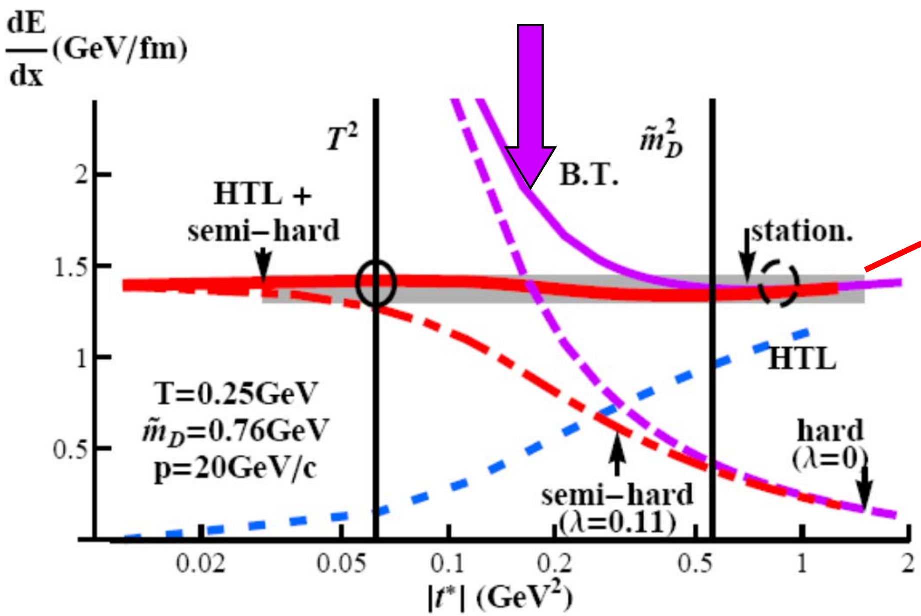
Large values for intermediate momentum-transfer

IR safe. The detailed form very close to $Q^2=0$ is not important does not contribute to the energy loss

Model E : running α_s AND optimal μ^2

• Bona fide "running HTL": $\alpha_s \to \alpha_s(Q^2)$

Brute BT: Not Indep. of |t*| !



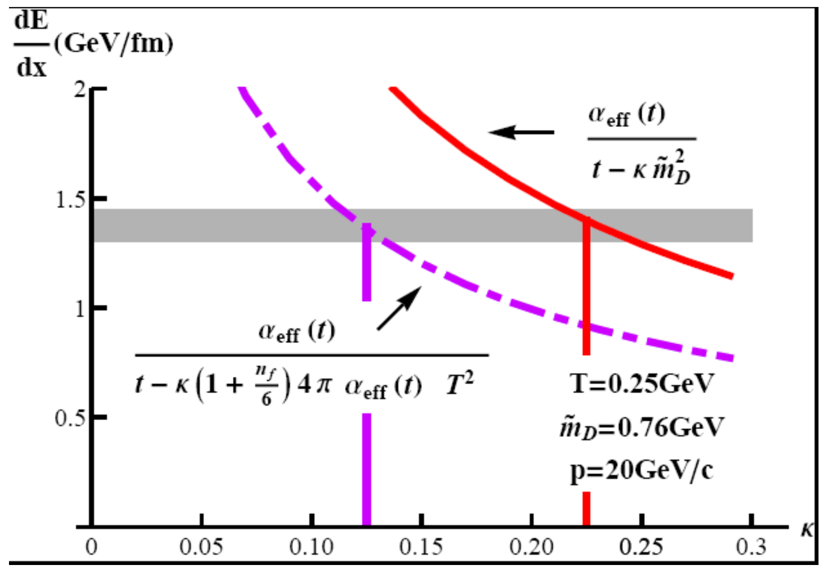
Introducing semi-hard propag…

$$\frac{\alpha_{\rm eff}(t)}{t} \longrightarrow \frac{\alpha_{\rm eff}(t)}{t-\lambda m_D^2(T,t)}$$

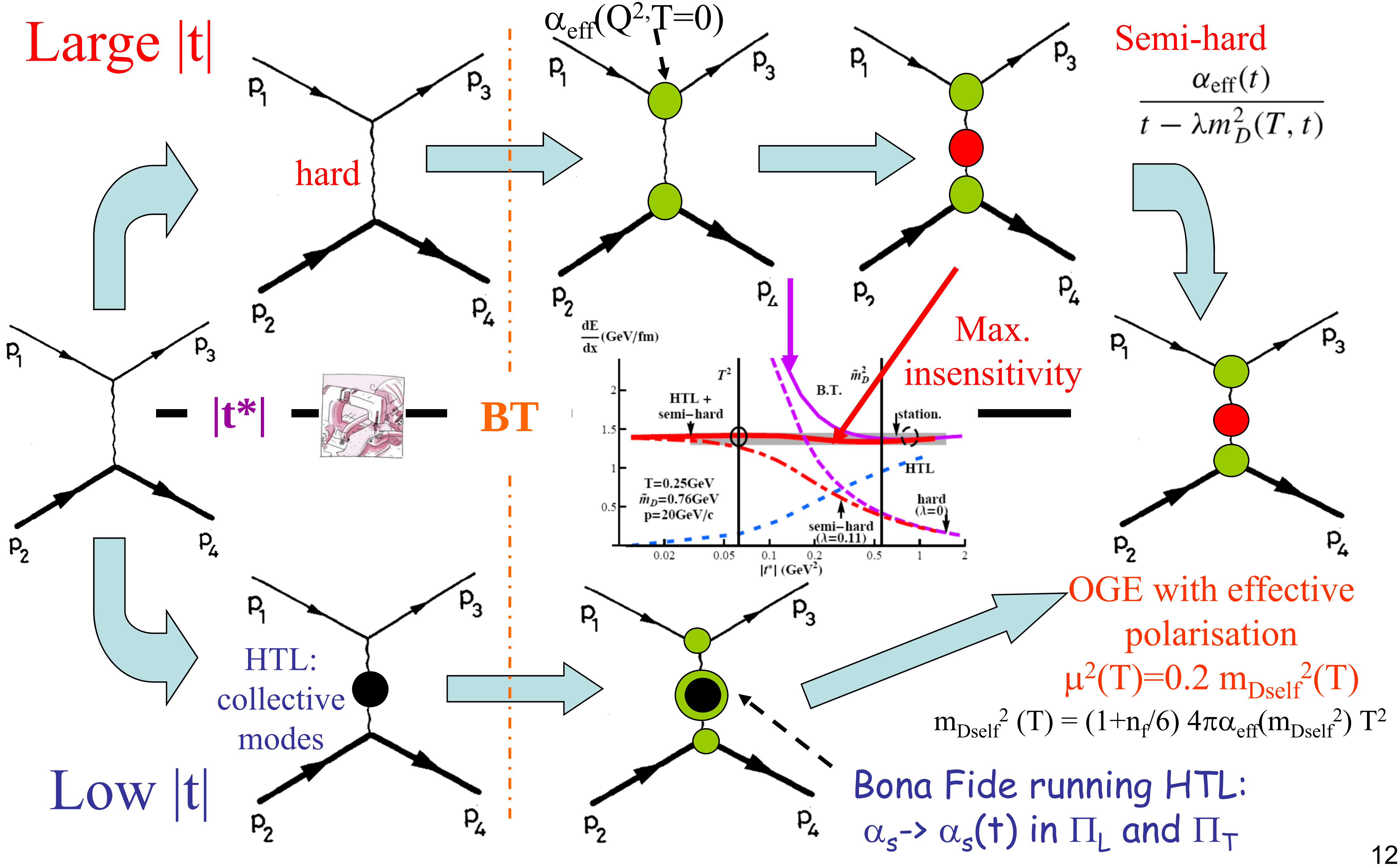
…leads to stationary results

• Optimal regulator:

$$\mu^2(T) \approx 0.2\ m_{\rm Dself}^2(T)$$



μ-local-model: medium effects at finite T in t-channel



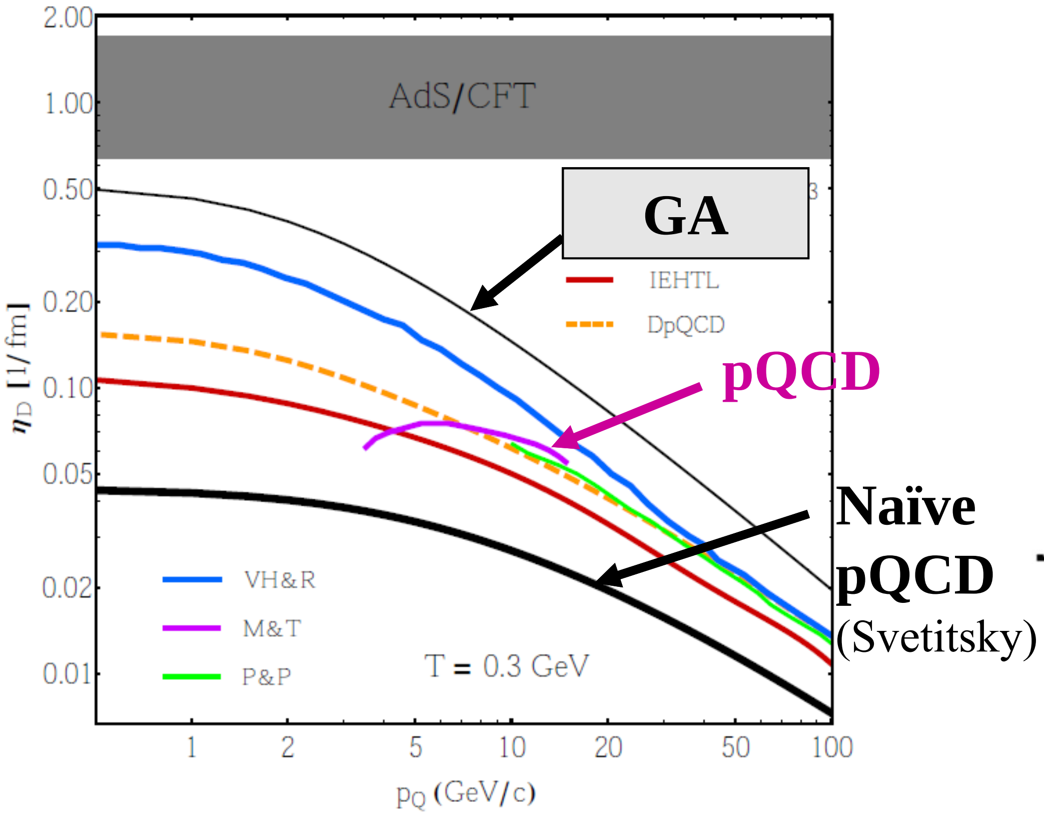
Running α_s : some Energy-Loss values

$$\frac{dE_{coll}(c/b)}{dx}$$

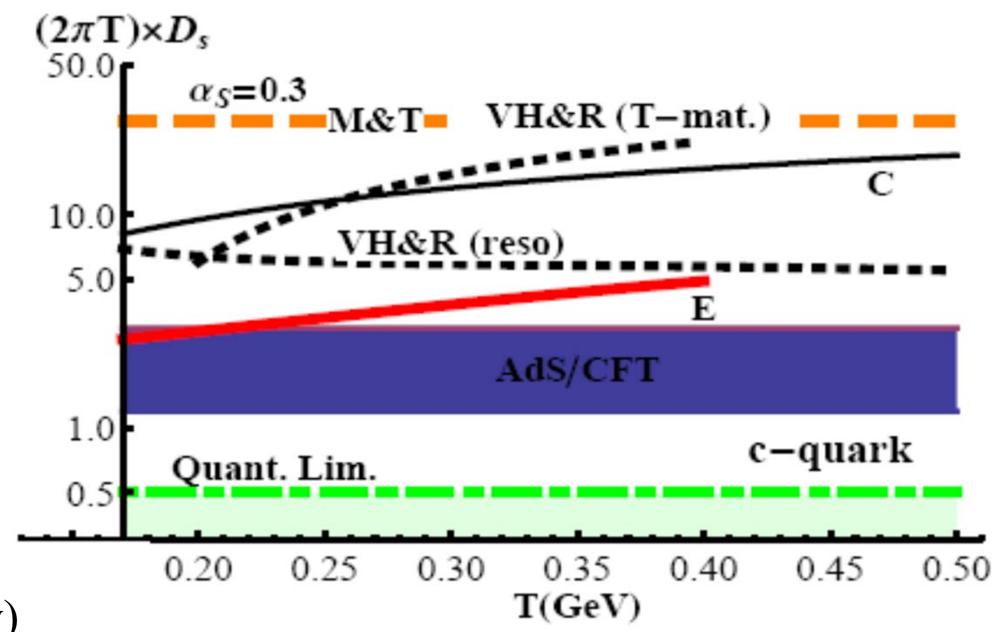
T(MeV) \p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

≈ 10 % of HQ energy

Drag coefficient (inverse relax. time)



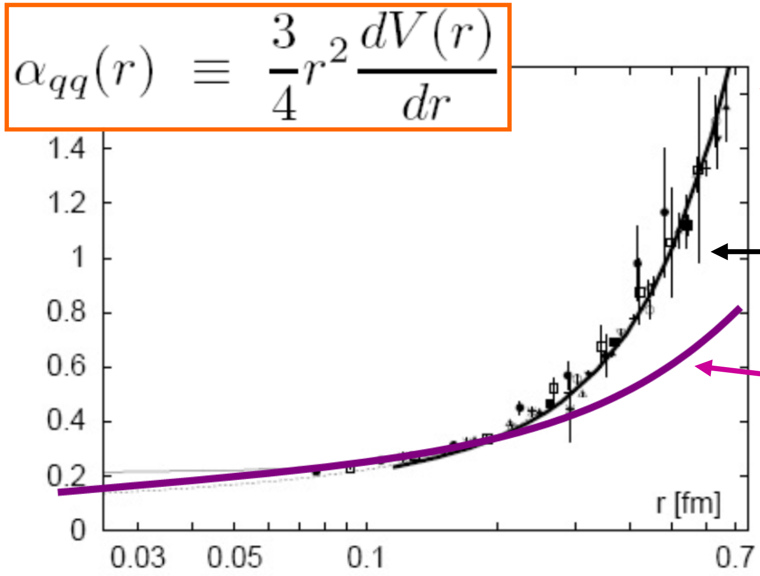
Diffusion coefficient



μ-local-model: Eff. Running α_s vs lQCD

T=0

$$\alpha_{qq}(r) \equiv \frac{3}{4} r^2 \frac{dV(r)}{dr}$$



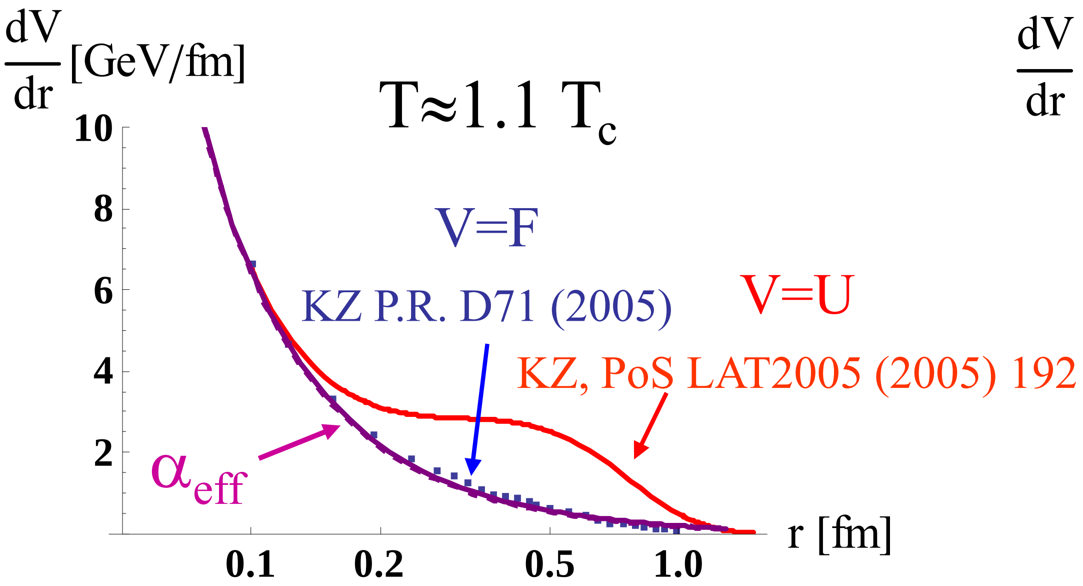
O. Kaczmarek & F. Zantow (KZ) (n_f=2 QCD), P.R.D71 (2005) 114510

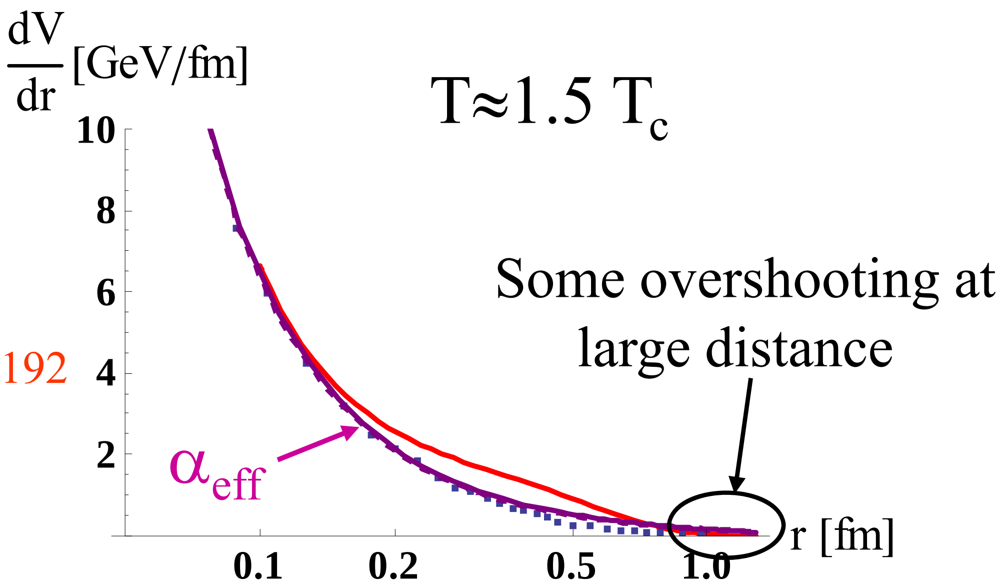
Genuine non-pert (flux tube)

optimal μ, running α_{eff}

V:ω=0 sector; dE/dx: finite ω

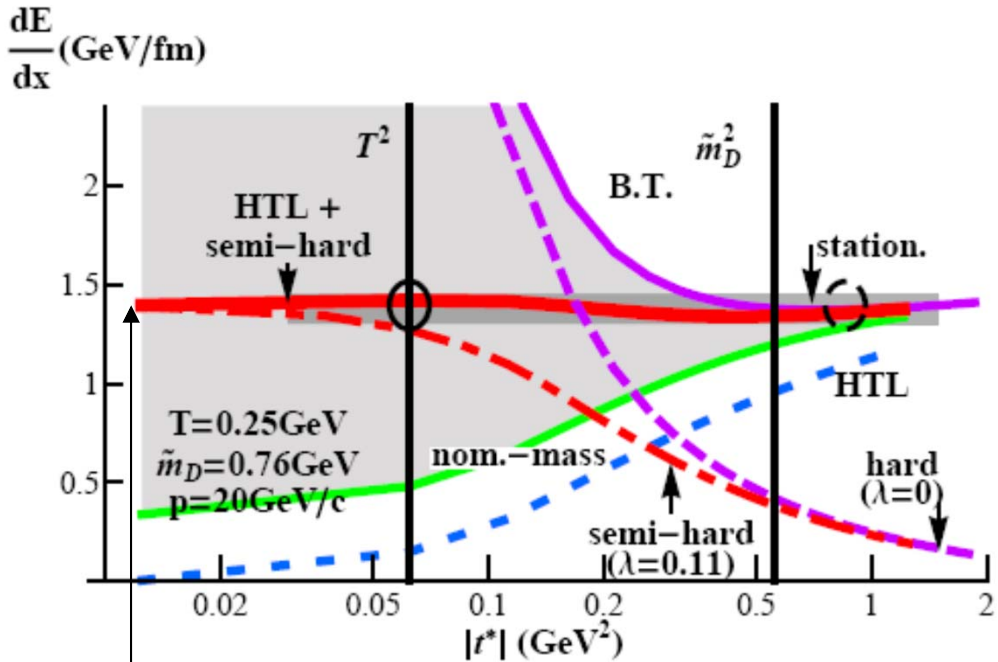
Finite T



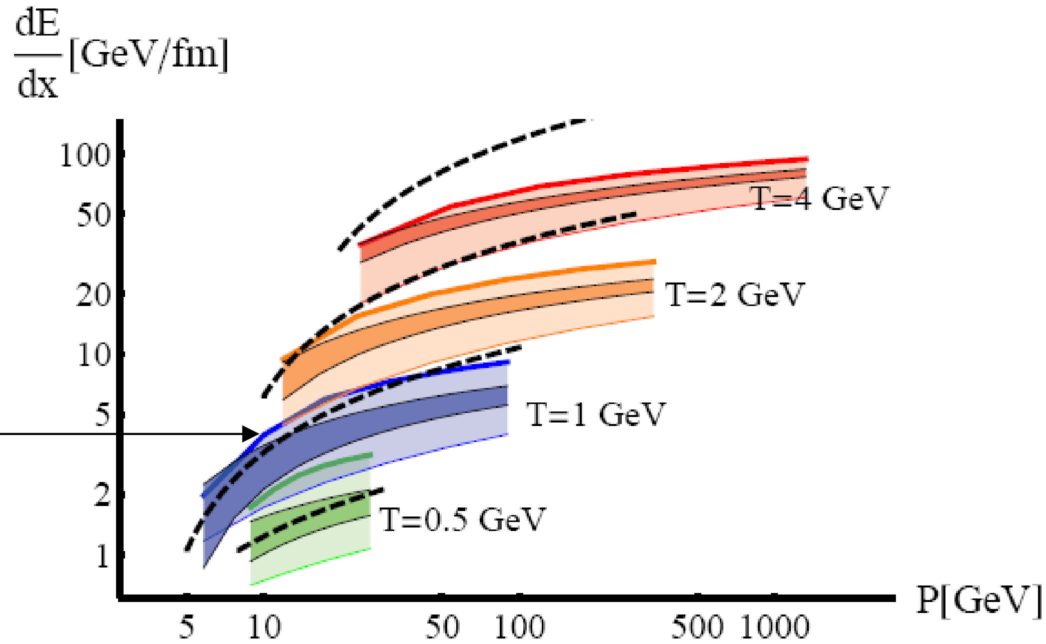


Merging at ≈2 T_c

Running α_s : theoretical uncertainties

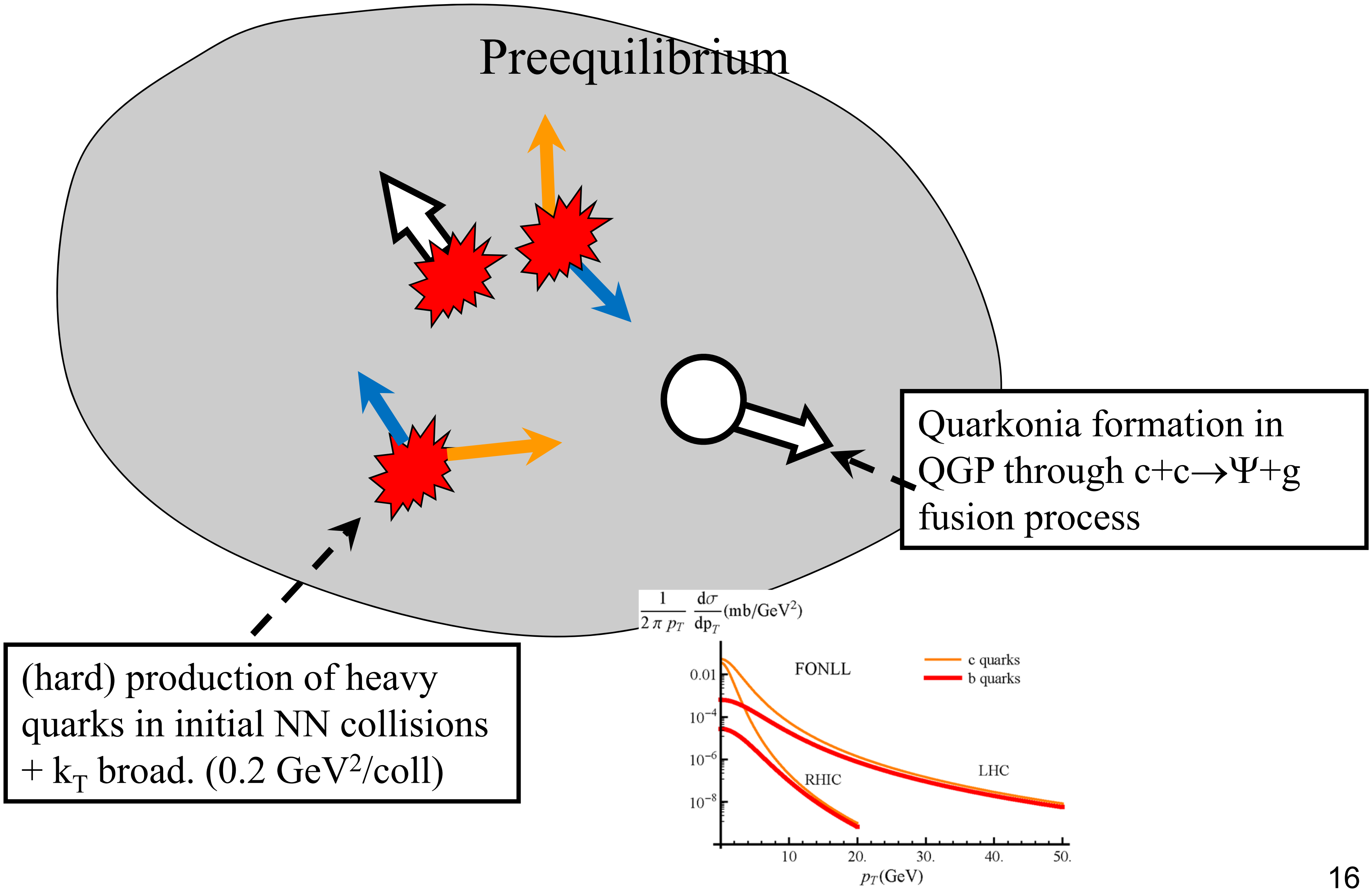


E: optimal μ, running α_{eff}

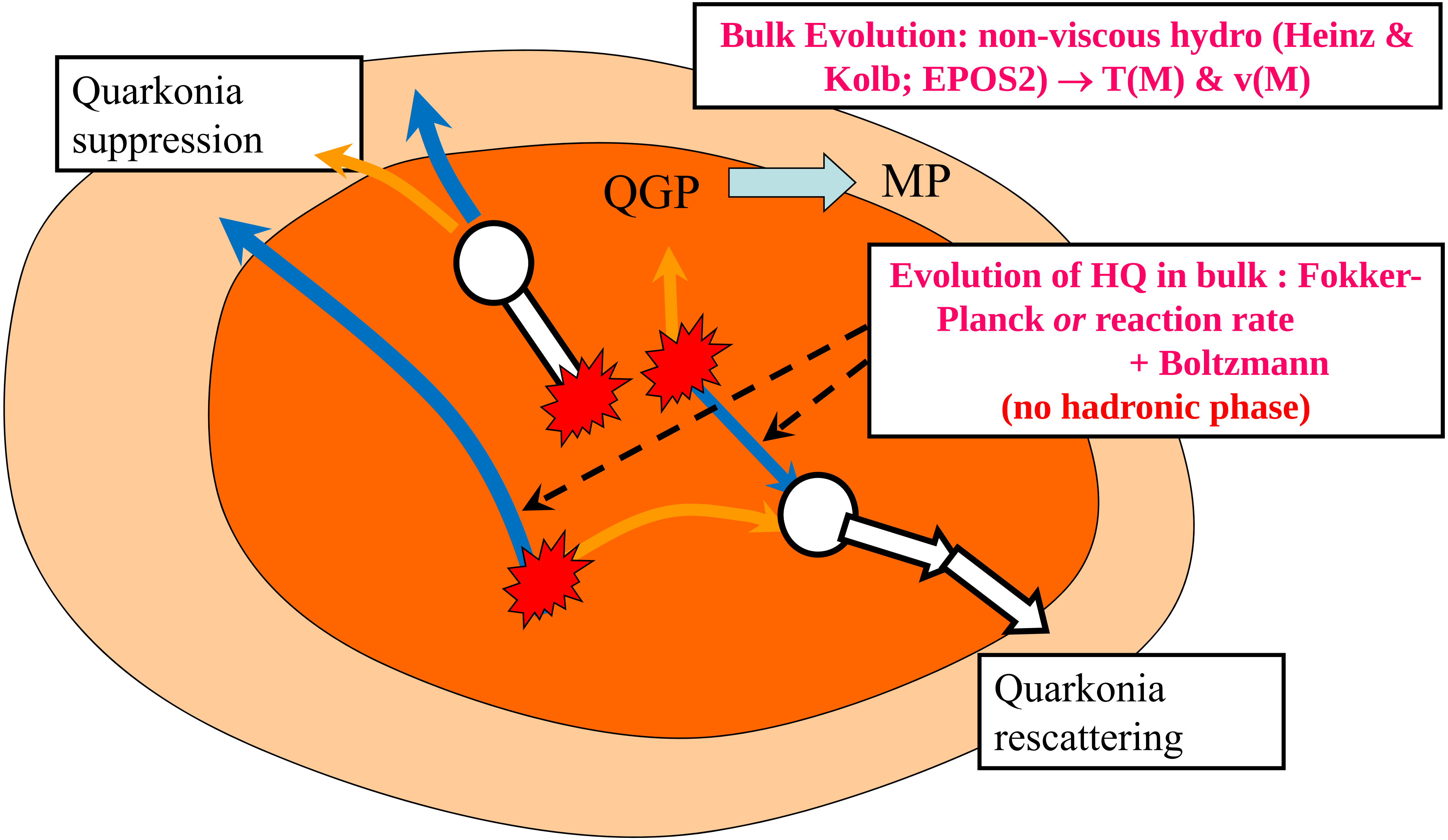


Dark zones: Peshier & Peigné

Schematic view of « Monte Carlo @ Heavy Quark » generator

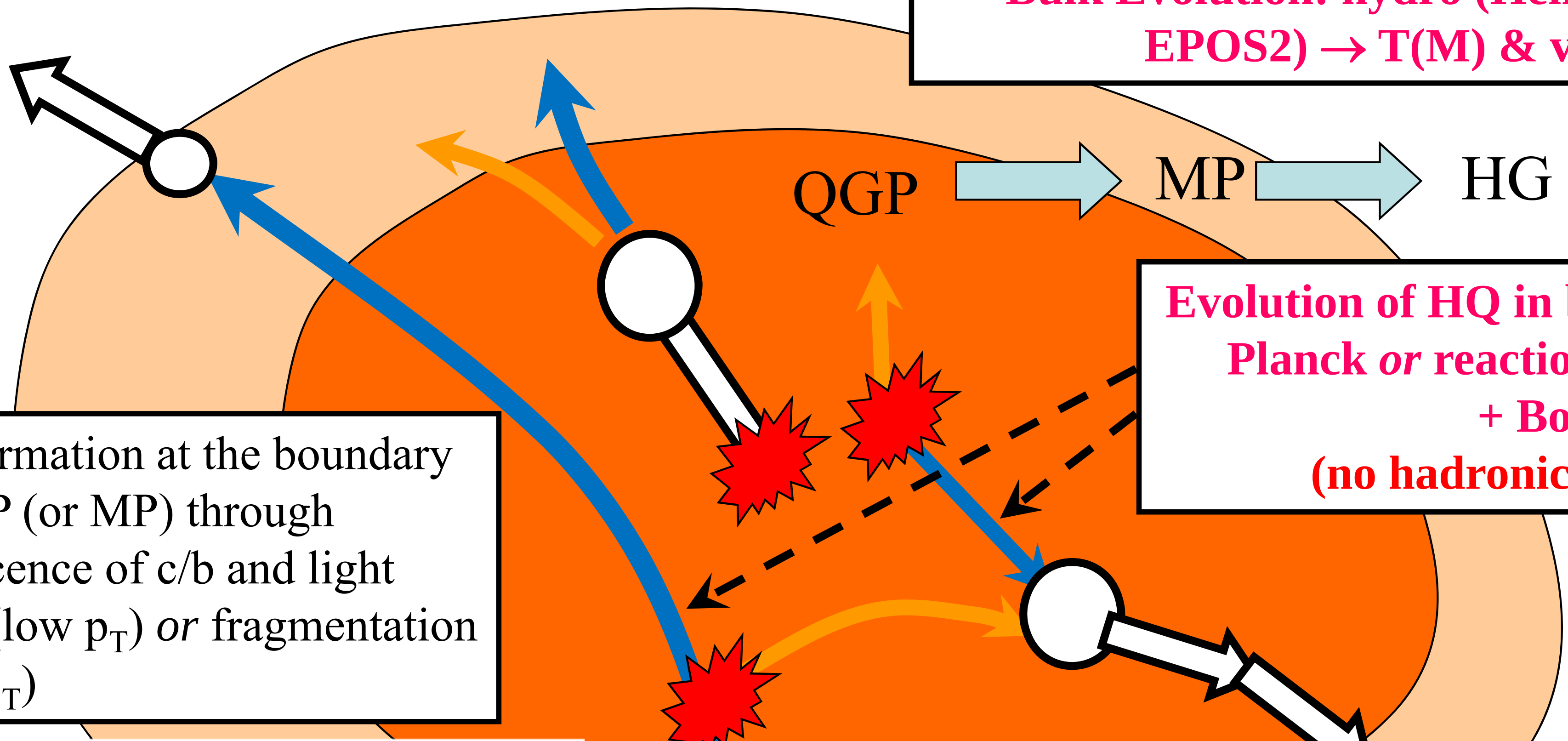


Schematic view of « Monte Carlo @ Heavy Quark » generator



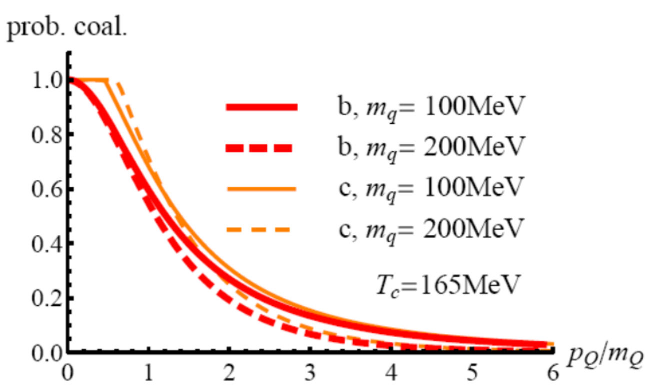
Schematic view of « Monte Carlo @ Heavy Quark » generator

Bulk Evolution: hydro (Heinz & Kolb; EPOS2) → T(M) & v(M)



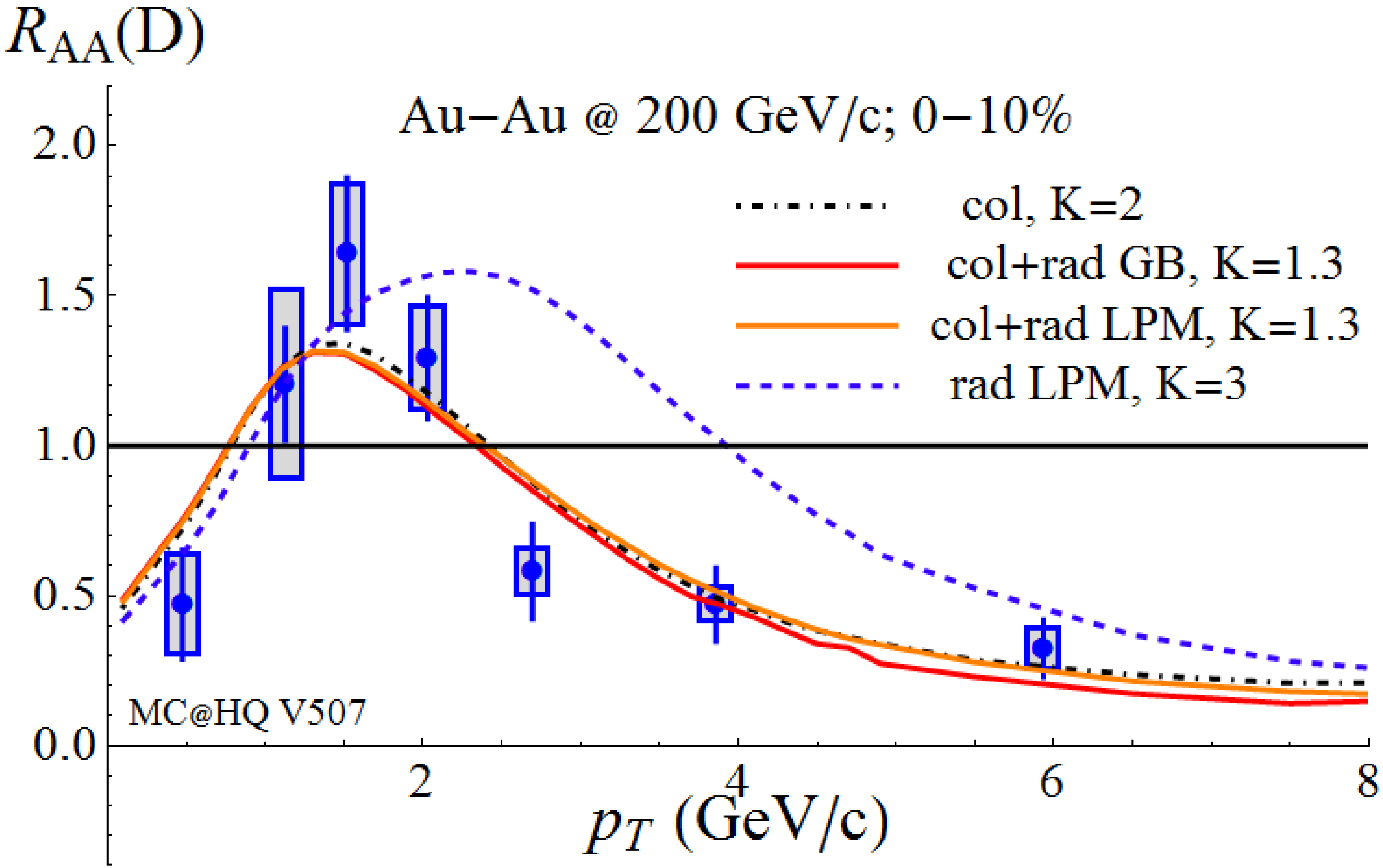
Evolution of HQ in bulk : Fokker-Planck *or* reaction rate + Boltzmann
(no hadronic phase)

D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low p_T) *or* fragmentation (high p_T)



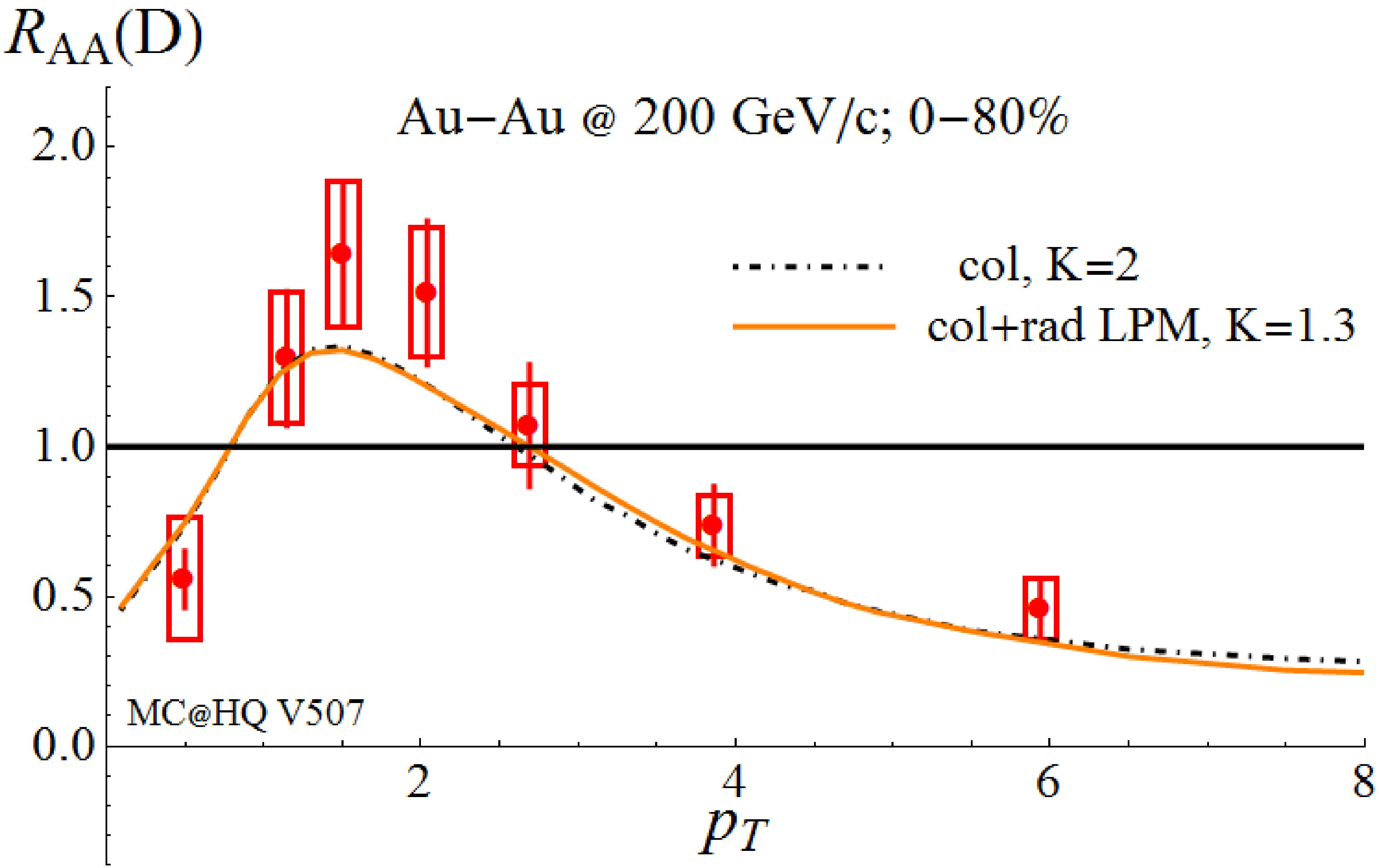
{Radiative + Elastic} vs Elastic for D mesons @ RHIC

=> Allow for some global rescaling of the rates: "K" fixed on experiment

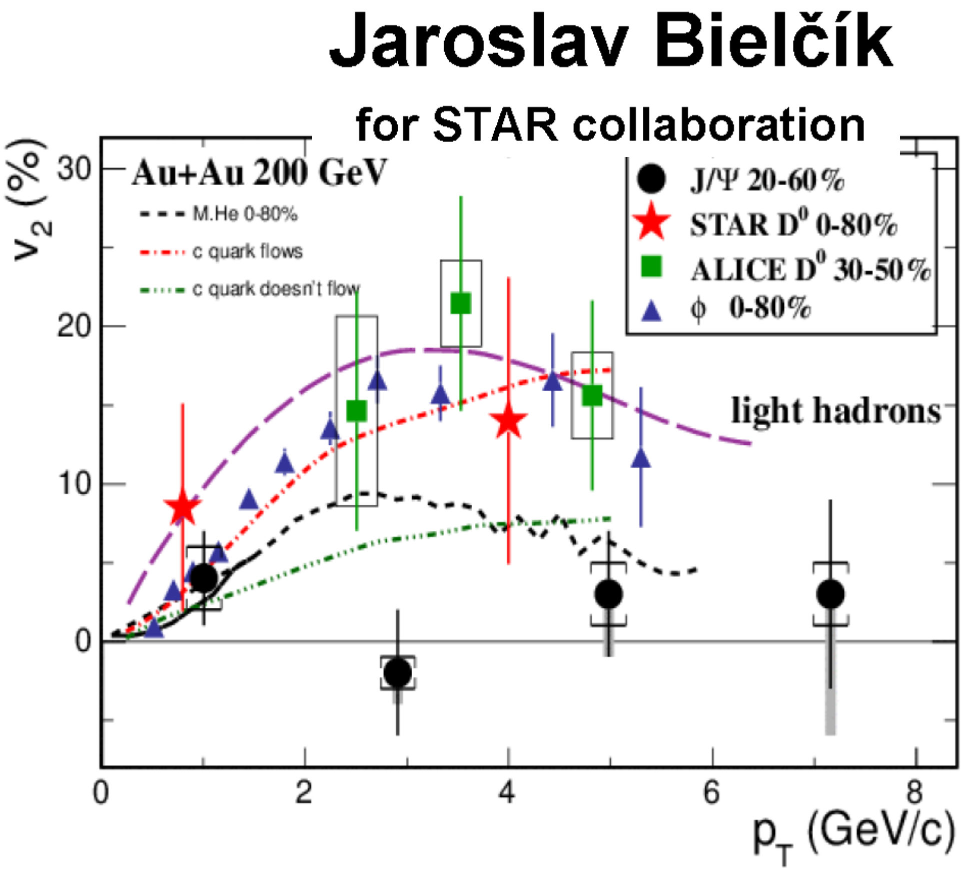


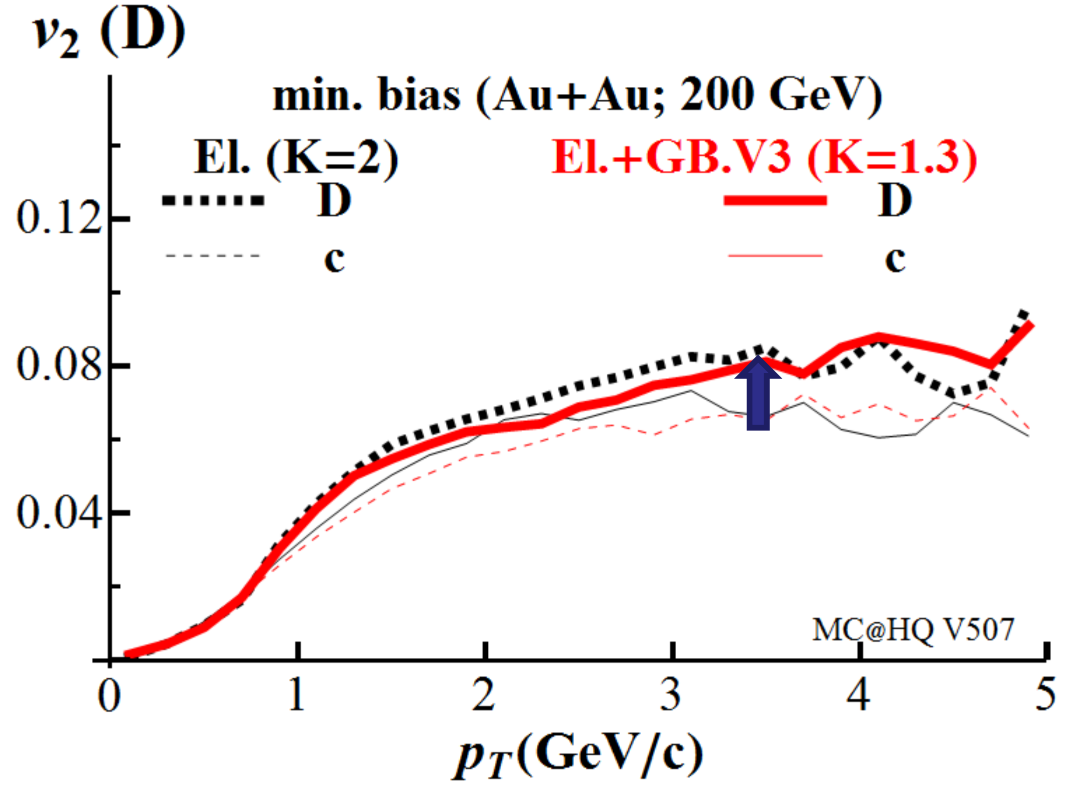
K coming closer to unity if radiation included

{Radiative + Elastic} vs Elastic for D mesons @ RHIC



{Radiative + Elastic} vs Elastic for D mesons @ RHIC





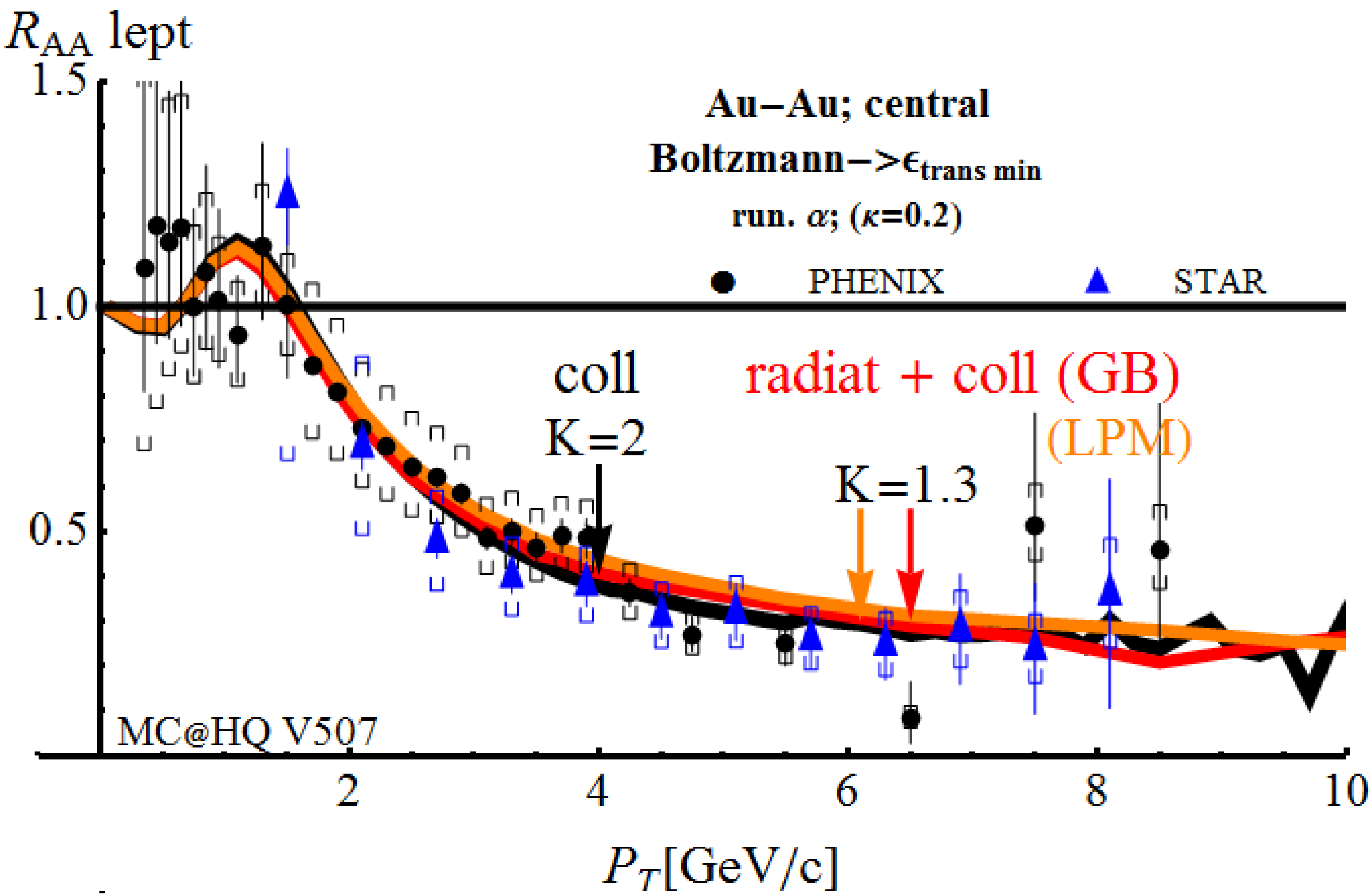
Rather little contribution from the light quark in our treatment… but conclusion may depend on the parameters (m_q, wave function)

Coalescence according to extended Dover framework

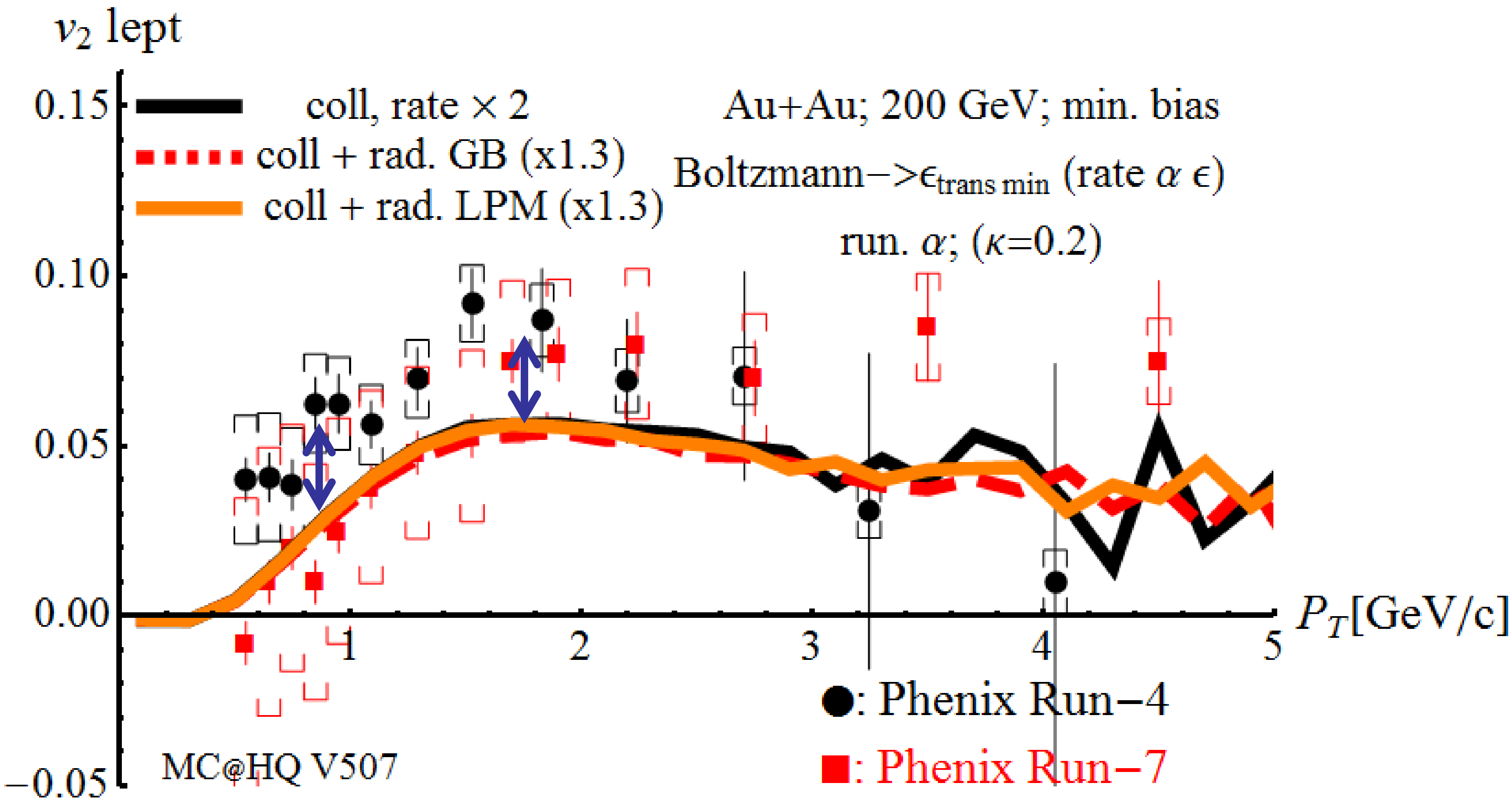
(PRC 79 044906)

$$N_\Phi = \int \frac{d^3 p_q}{(2\pi\hbar)^3 E_q} \frac{p_q \cdot d\hat{\sigma}}{u_Q \cdot d\hat{\sigma}} f_q(x_Q, p_q)(\sqrt{2\pi} R_c)^3 \times F_\Phi(p_Q, p_q),$$

{Radiative + Elastic} vs Elastic for leptons @ RHIC



{Radiative + Elastic} vs Elastic for leptons @ RHIC

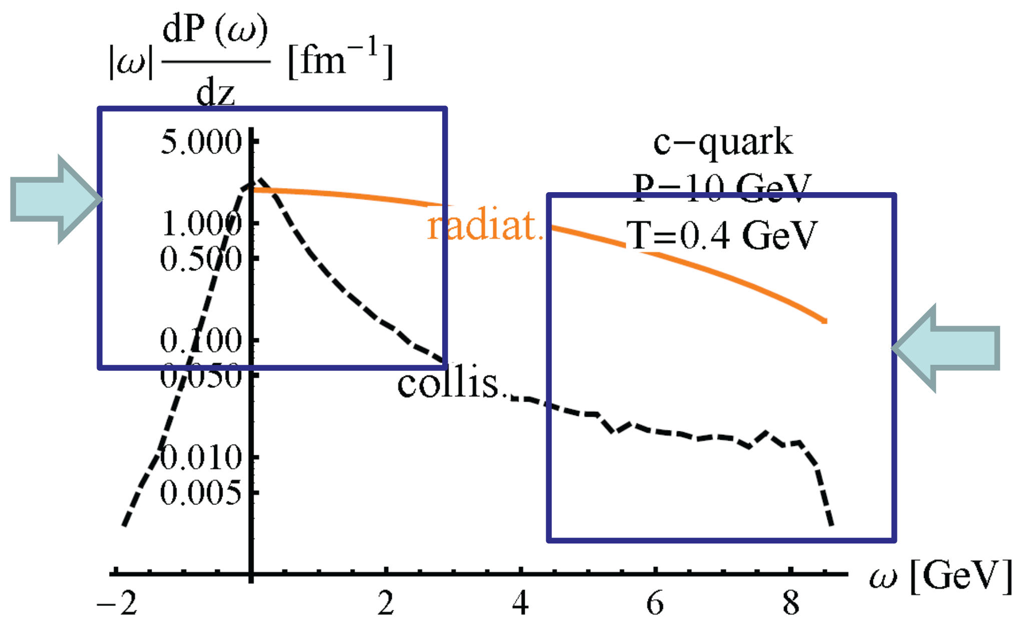


El. + rad: No lack of elliptic flow wrt pure (rescaled) elastic processes (!?)

Conclusions from RHIC

- Good consistency between NPSE and D mesons (10% difference in K values)…
- … within a model with mass hierarchy
- ΔE radiative < ΔE elastic
- Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) ⇒ Not sensitive to the large-ω tail of the Energy-loss probability (thanks to initial HQ distribution)

“Fokker Planck” regime

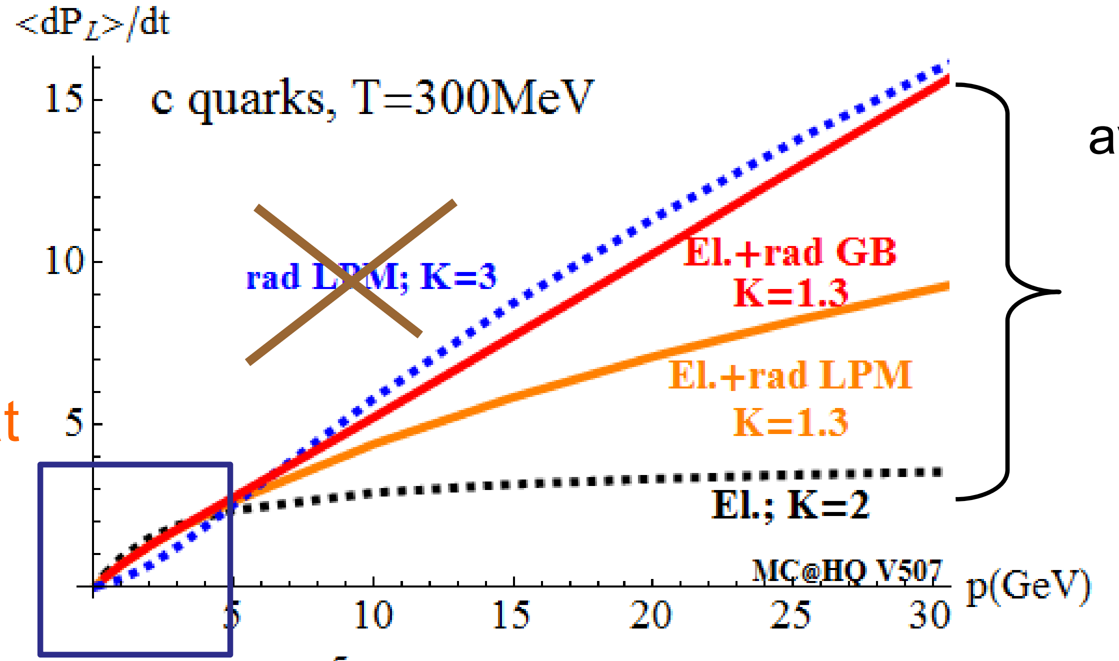


“hard scattering” regime

QGP properties from HQ probe at RHIC

Gathering all *rescaled* models (*coll. and radiative*) compatible with RHIC R_{AA}:

Similar diffusion coefficient at low p



the drag coefficient reflects the average momentum loss (per unit time) => large weight on $x \sim 1$

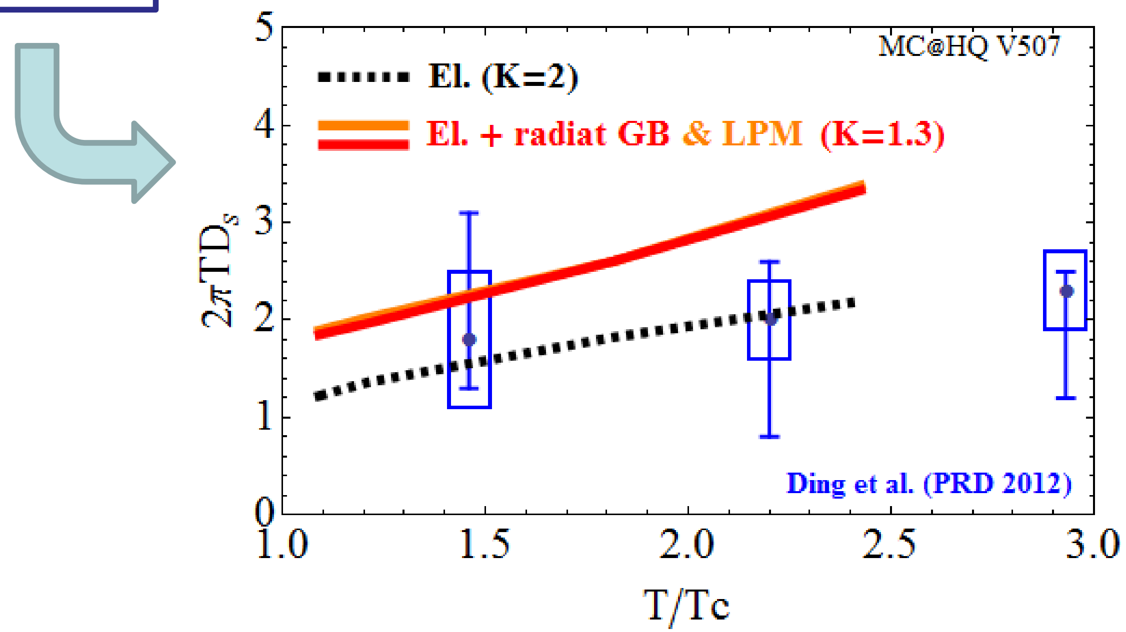
Present RHIC experiments cannot resolve between those various trends

Hope that LHC can do !!!

We extract it from data

(starting from SQM 2008)

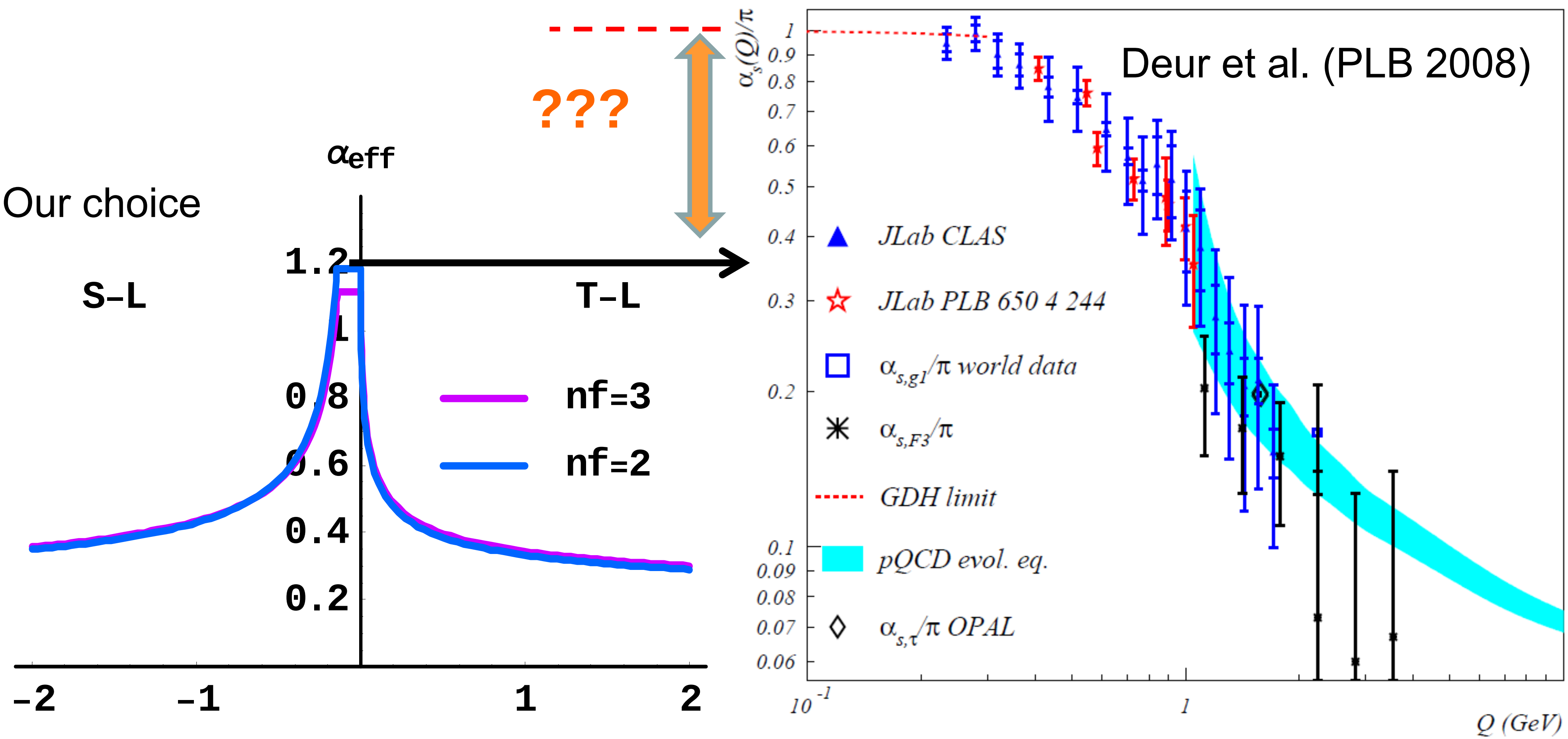
We compare with recent lattice results



Main message

It is possible to reveal some fundamental property of QGP using HQ probes

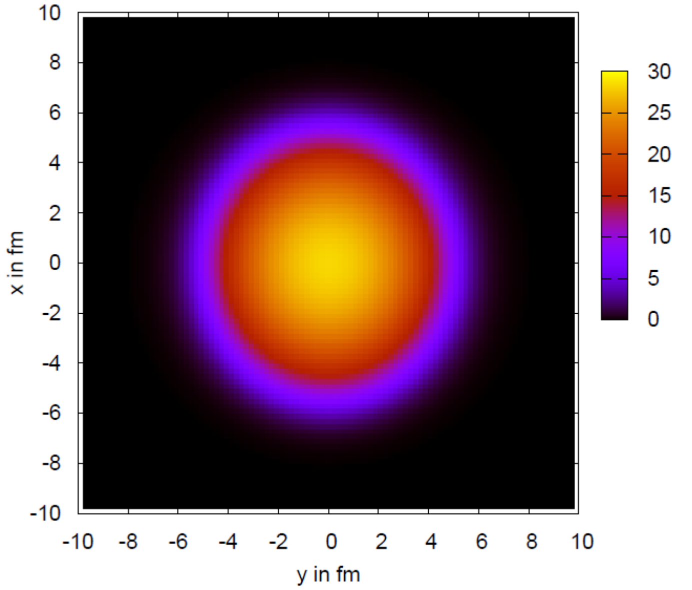
“Motivation” for a large K factor

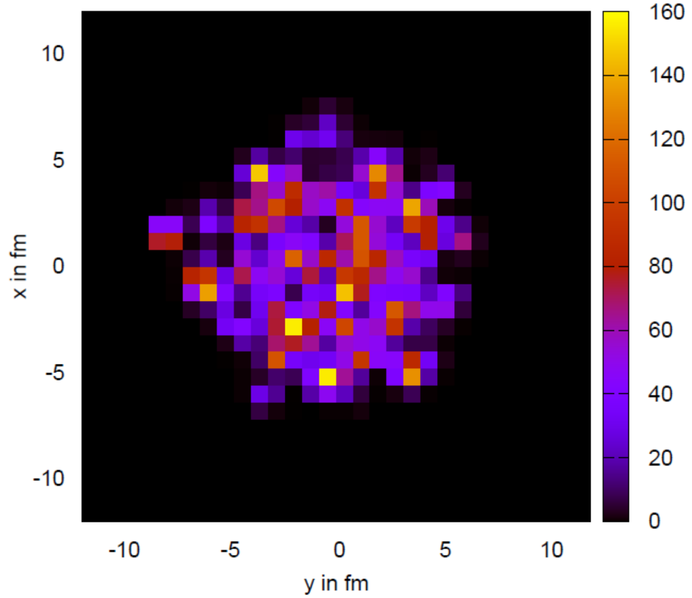


EPOS as a background for MC@sHQ

EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density @ RHIC (central Au-Au)





Beware: ≠ color scales

Kolb Heinz (used previously)

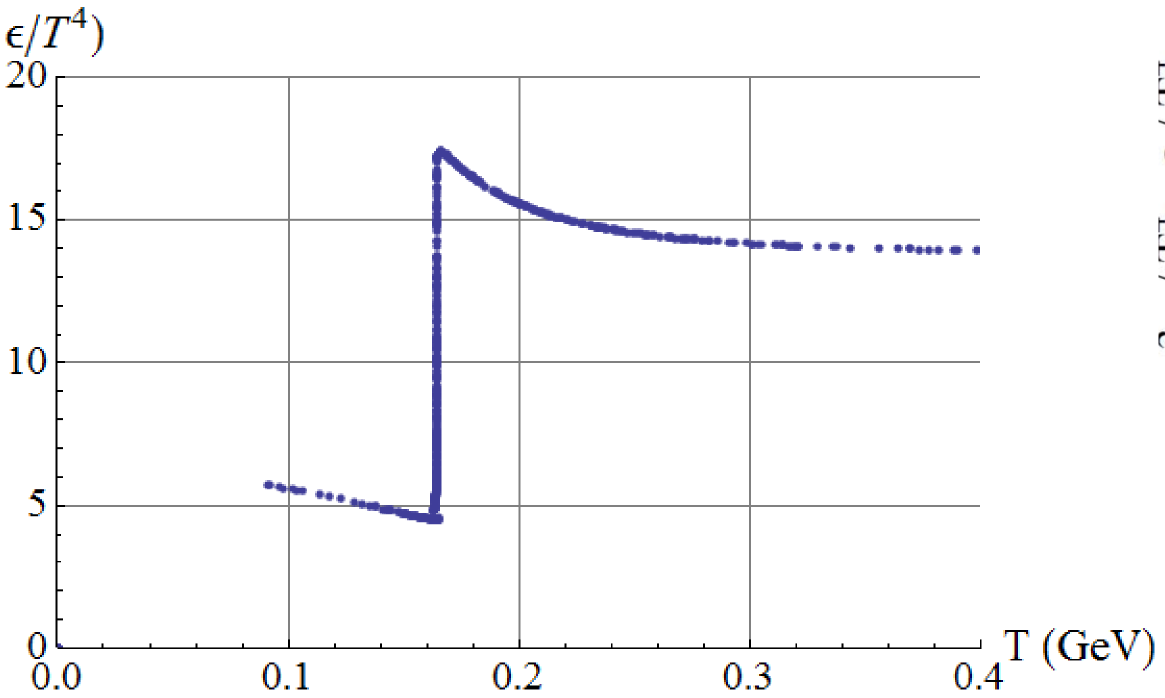
EPOS

More realistic hydro and initial conditions => original HQ studies such as:

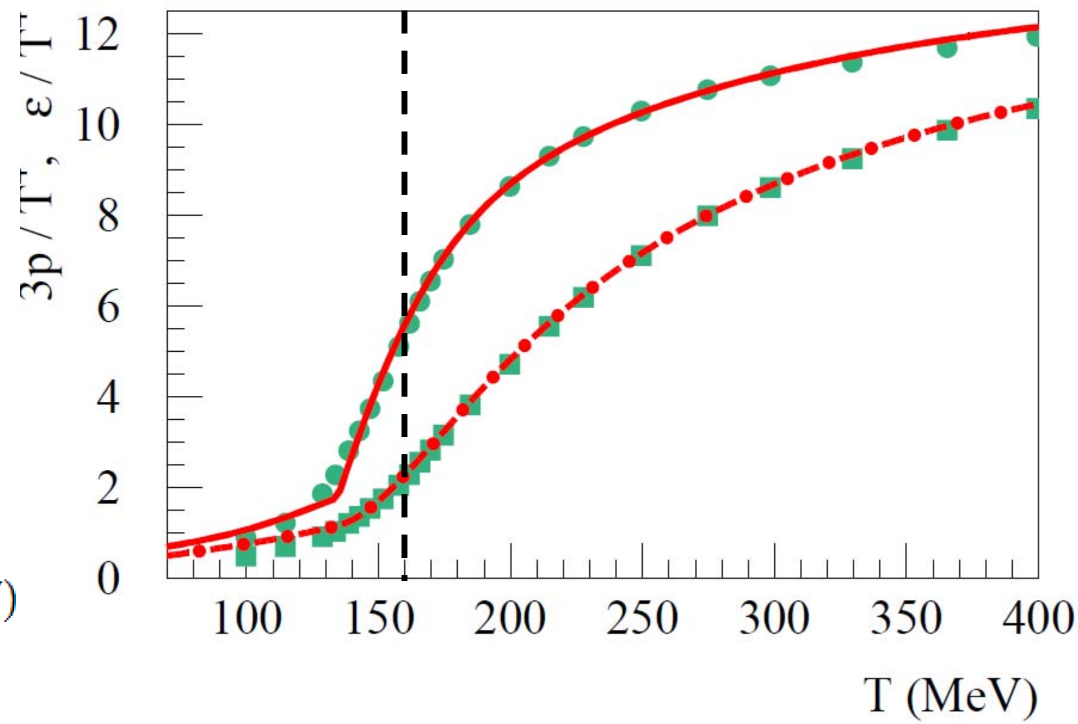
1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)

2) correlations between HF and light hadrons

Large differences in the EOS !



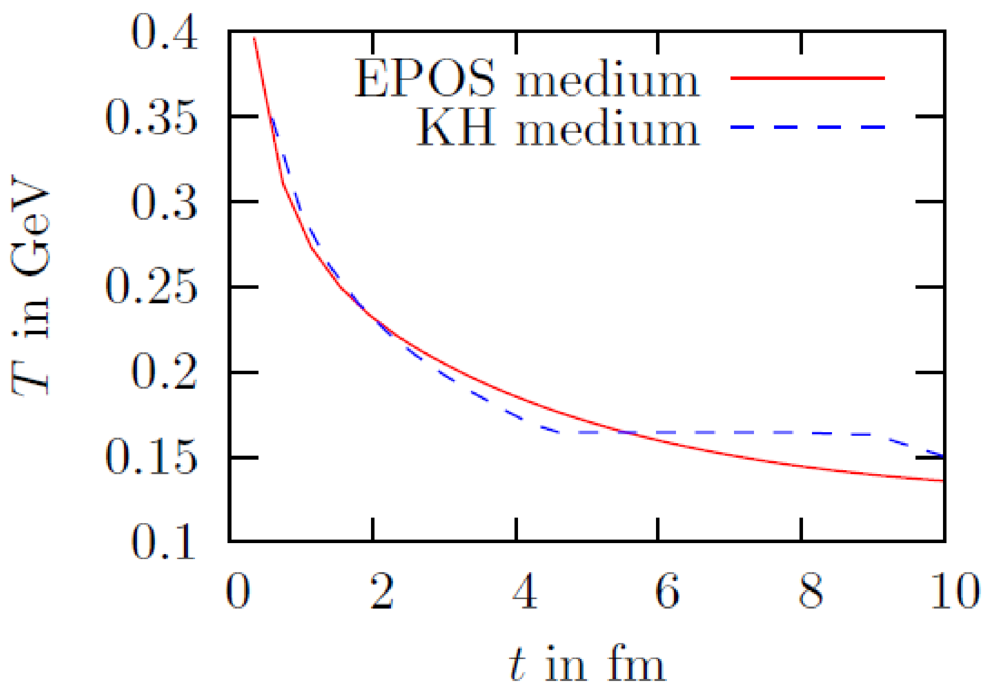
c-quark FO: 155 MeV

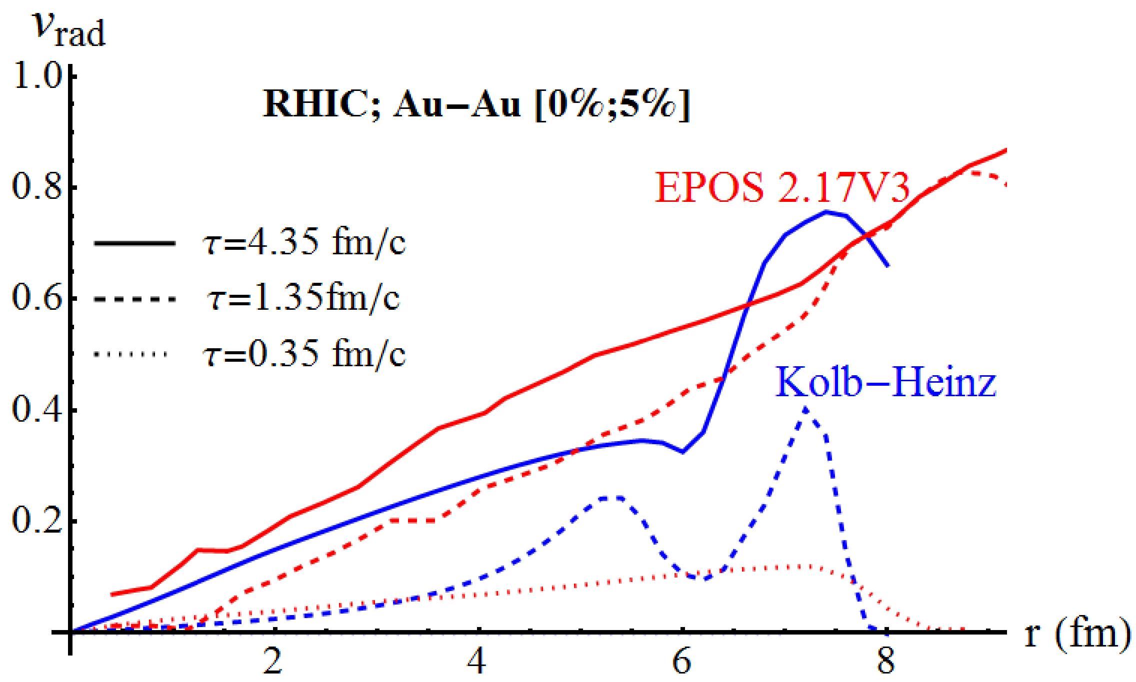


Kolb Heinz: bag model (1rst order transition btwn hadronic phase and massless partons)

EPOS2: fitted on the lattice data from the Wuppertal-Budapest collaboration

Medium comparison at RHIC



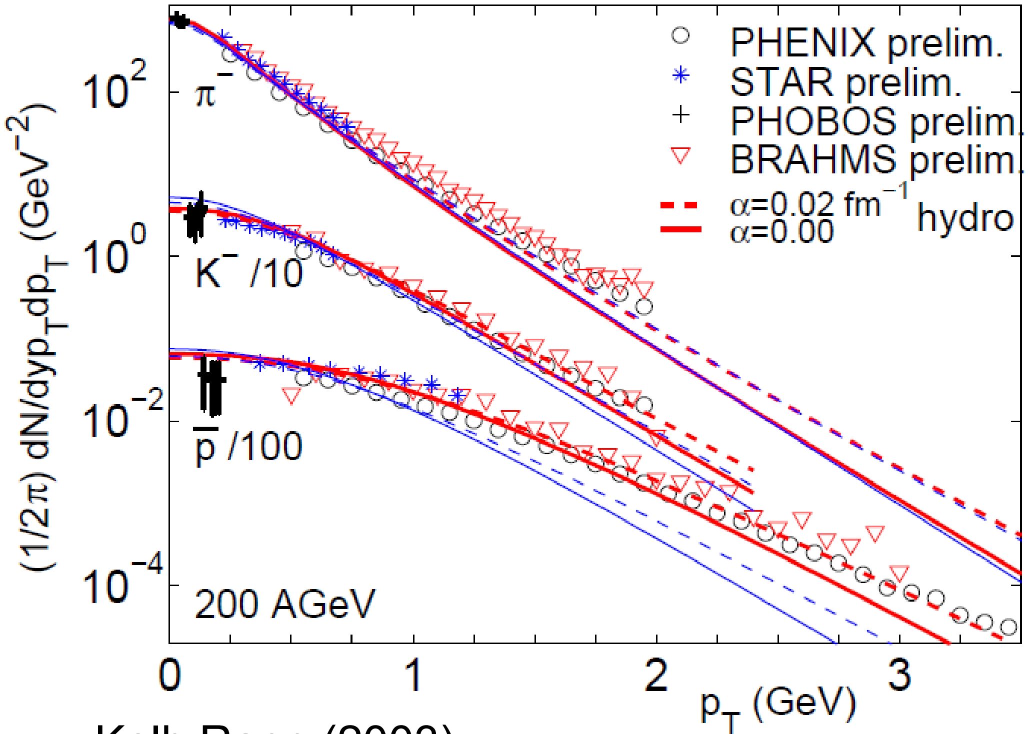


Gross features of T-evolution are identical in the « plasma » phase (T>200 MeV)

Radial velocities differ significantly, starting from the earliest times in the evolution

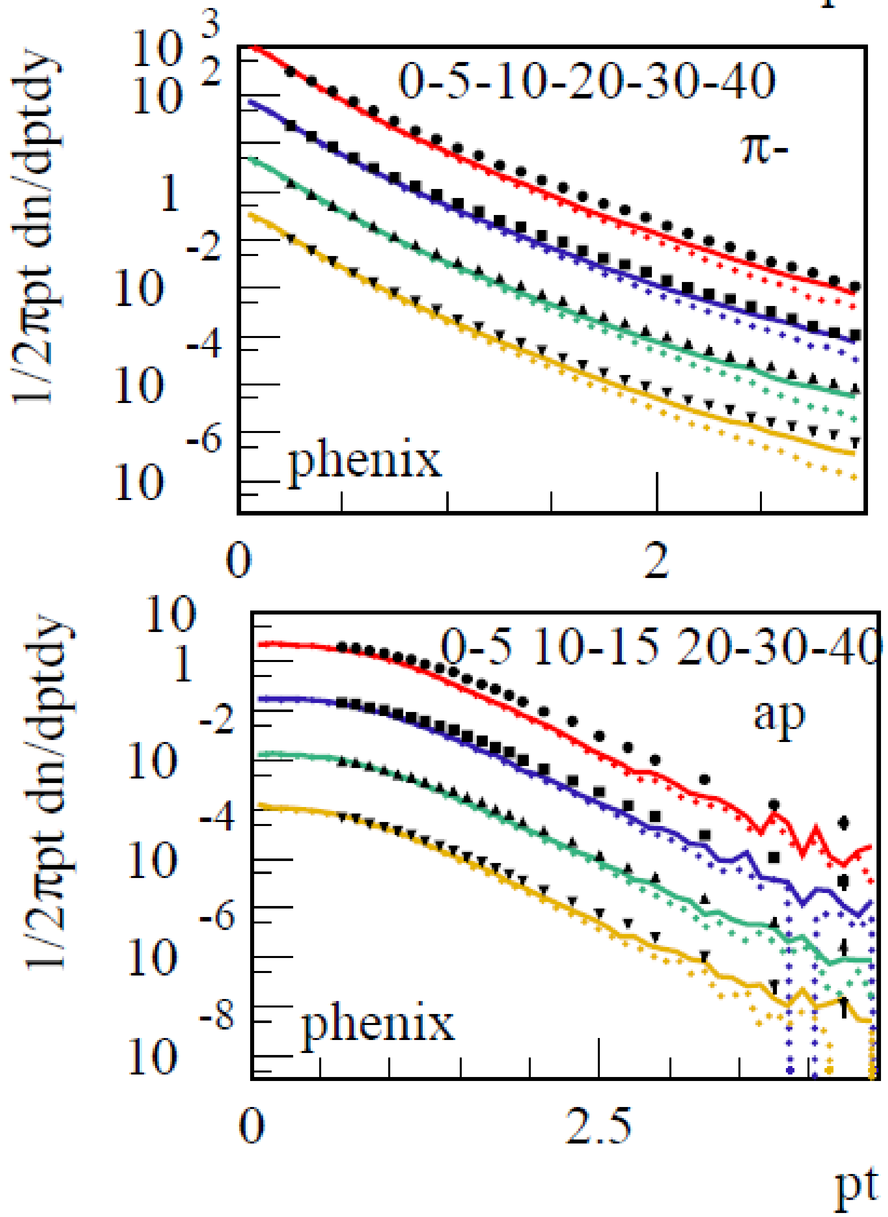
Identified particles spectra at RHIC

Kolb-Heinz



Kolb Rapp (2003)

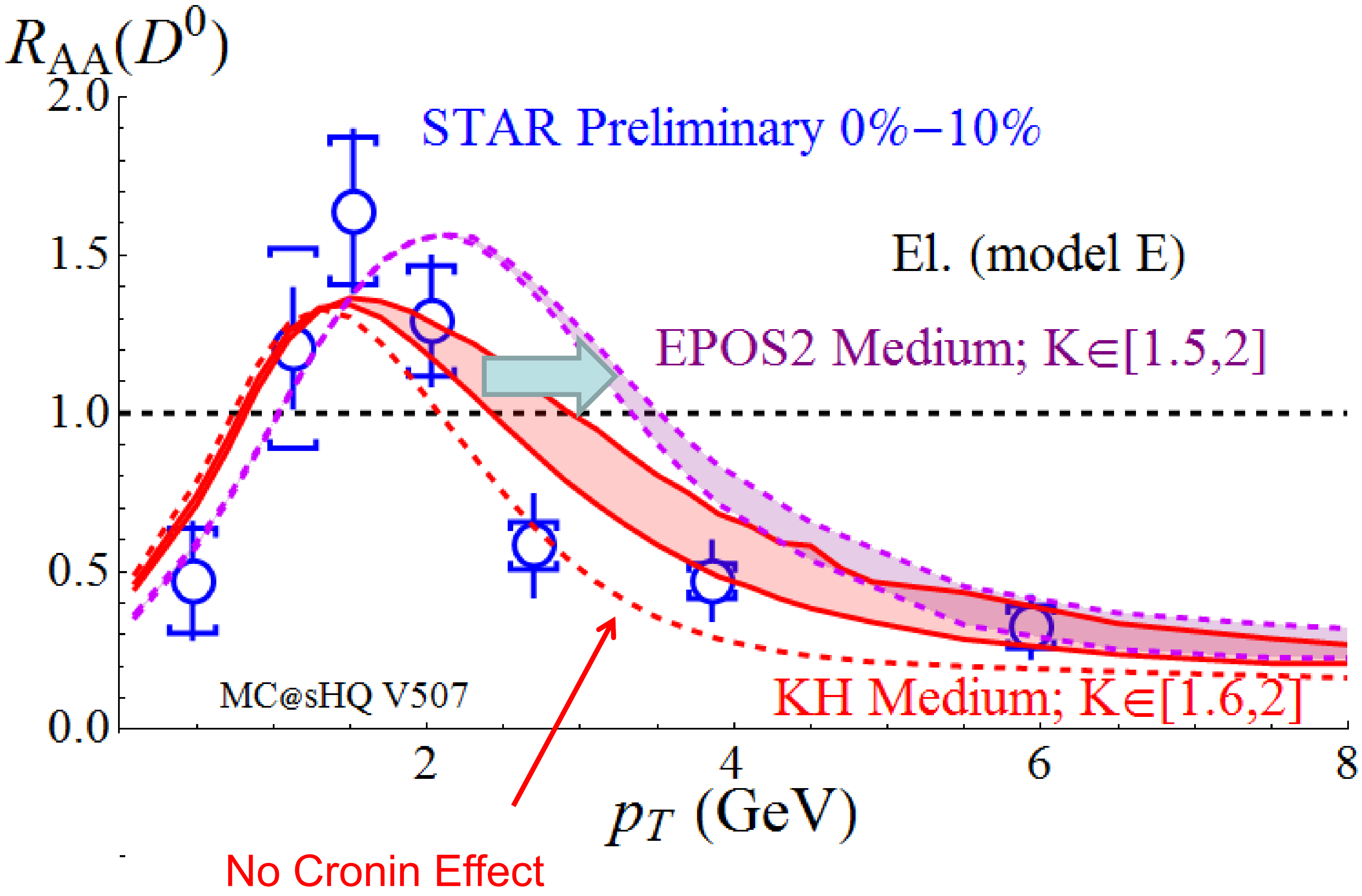
EPOS2.17V3



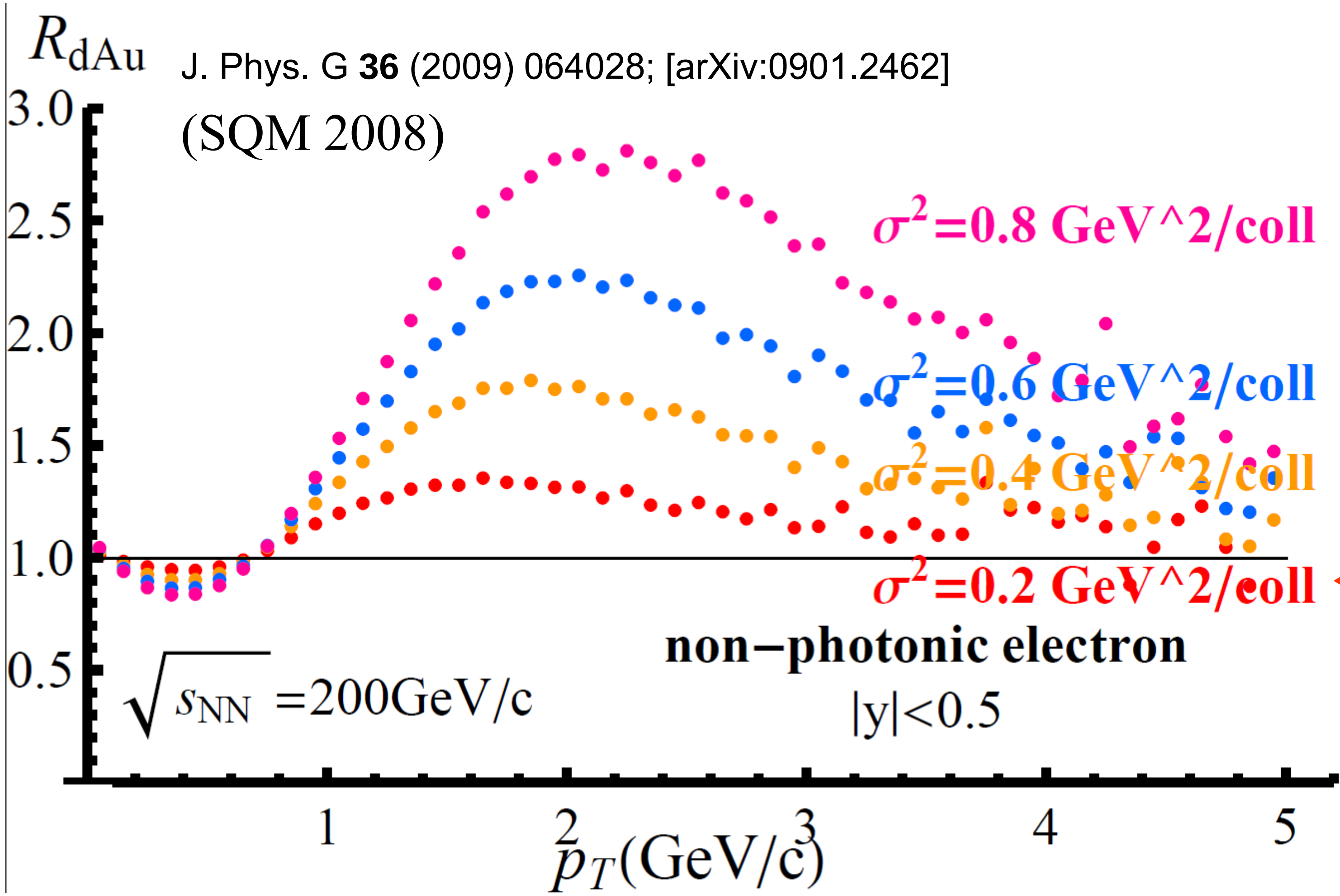
better agreement if
initial flow (vr=tanh(0.02 r))

Elastic D mesons @ RHIC

=> Allow for some global rescaling of the rates: "K" fixed on experiment

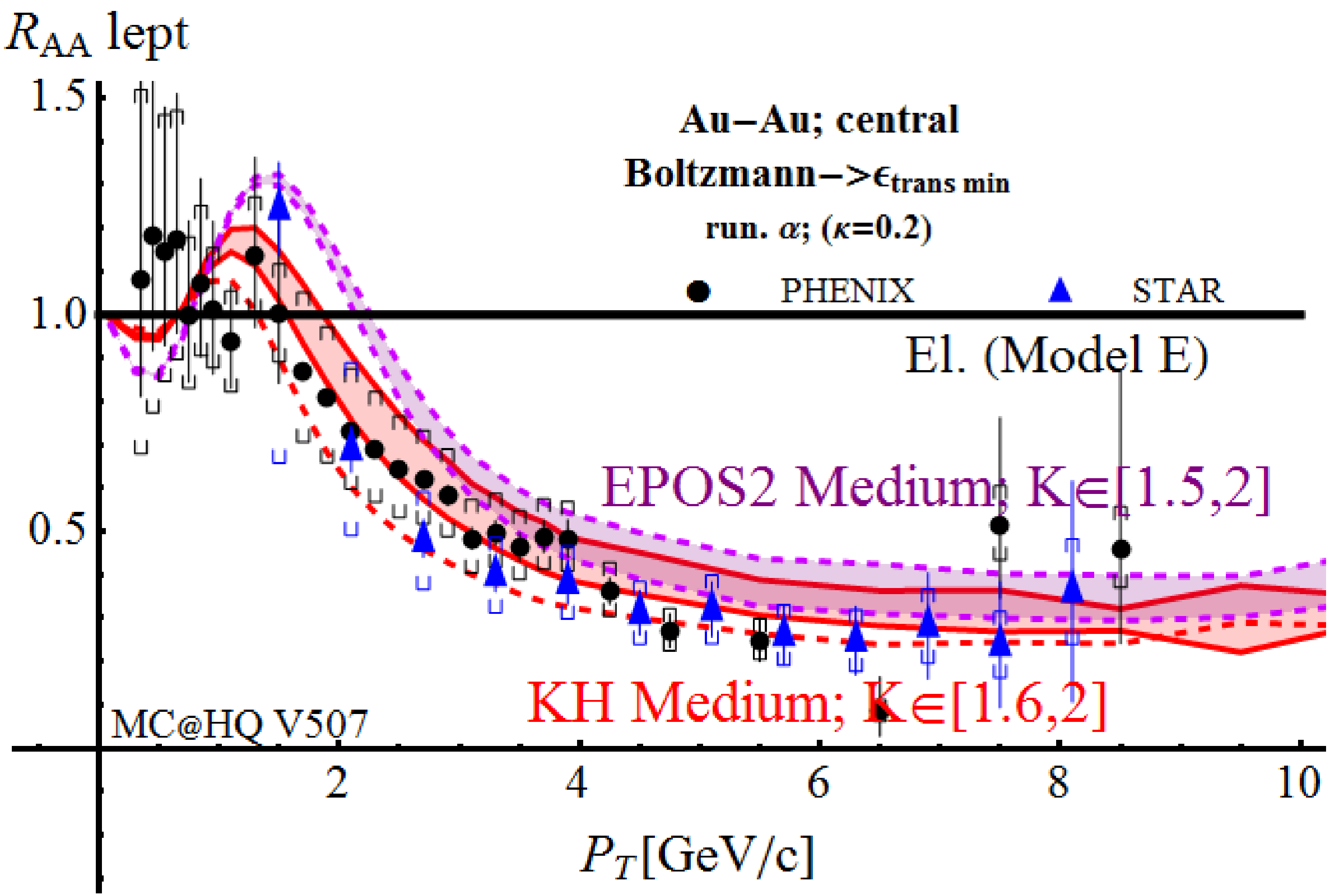


CNM effects

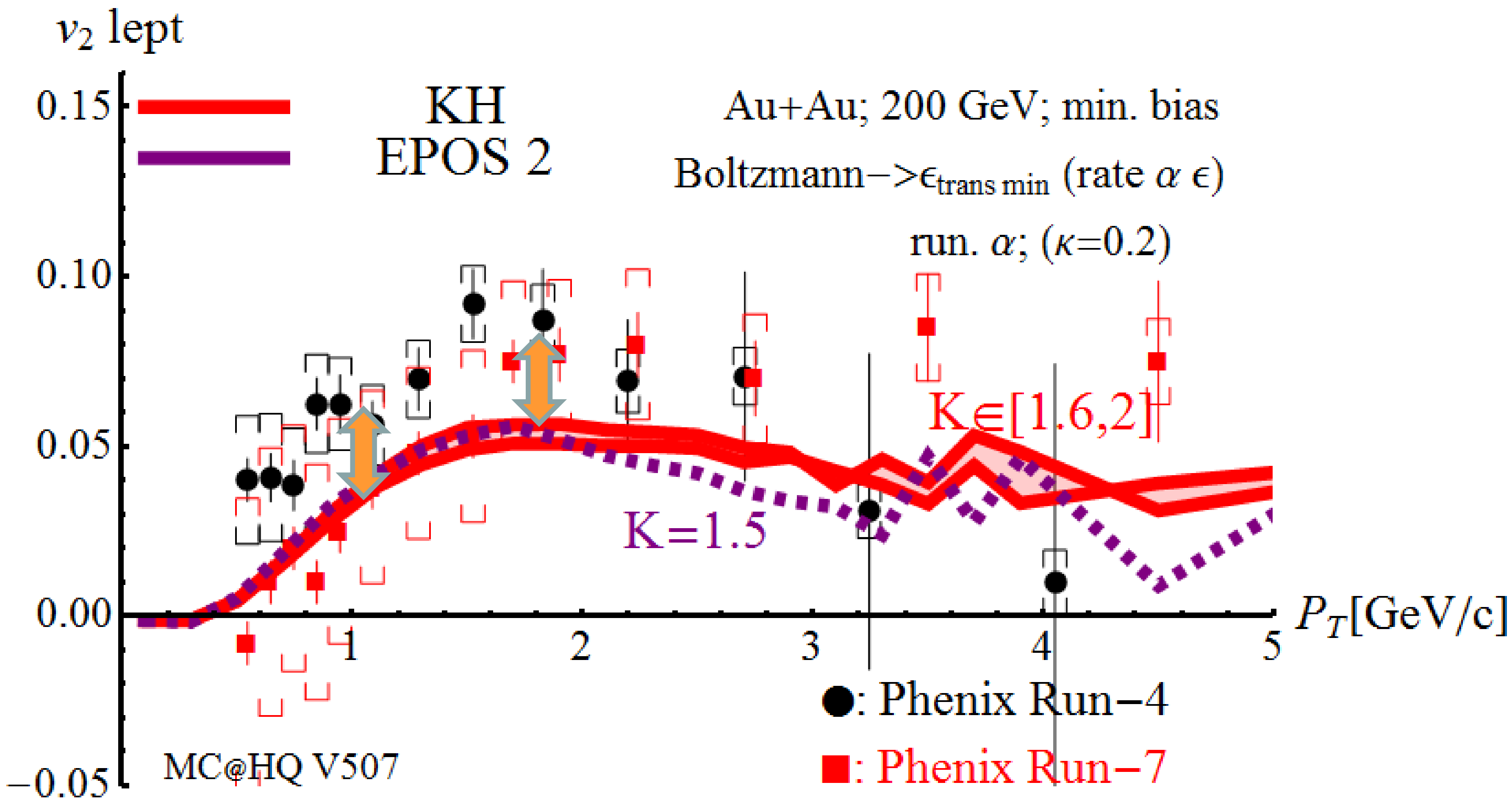


← Selected values; rough agreement with recent RHIC measurement, but physical origin remains unclear

Elastic for leptons @ RHIC



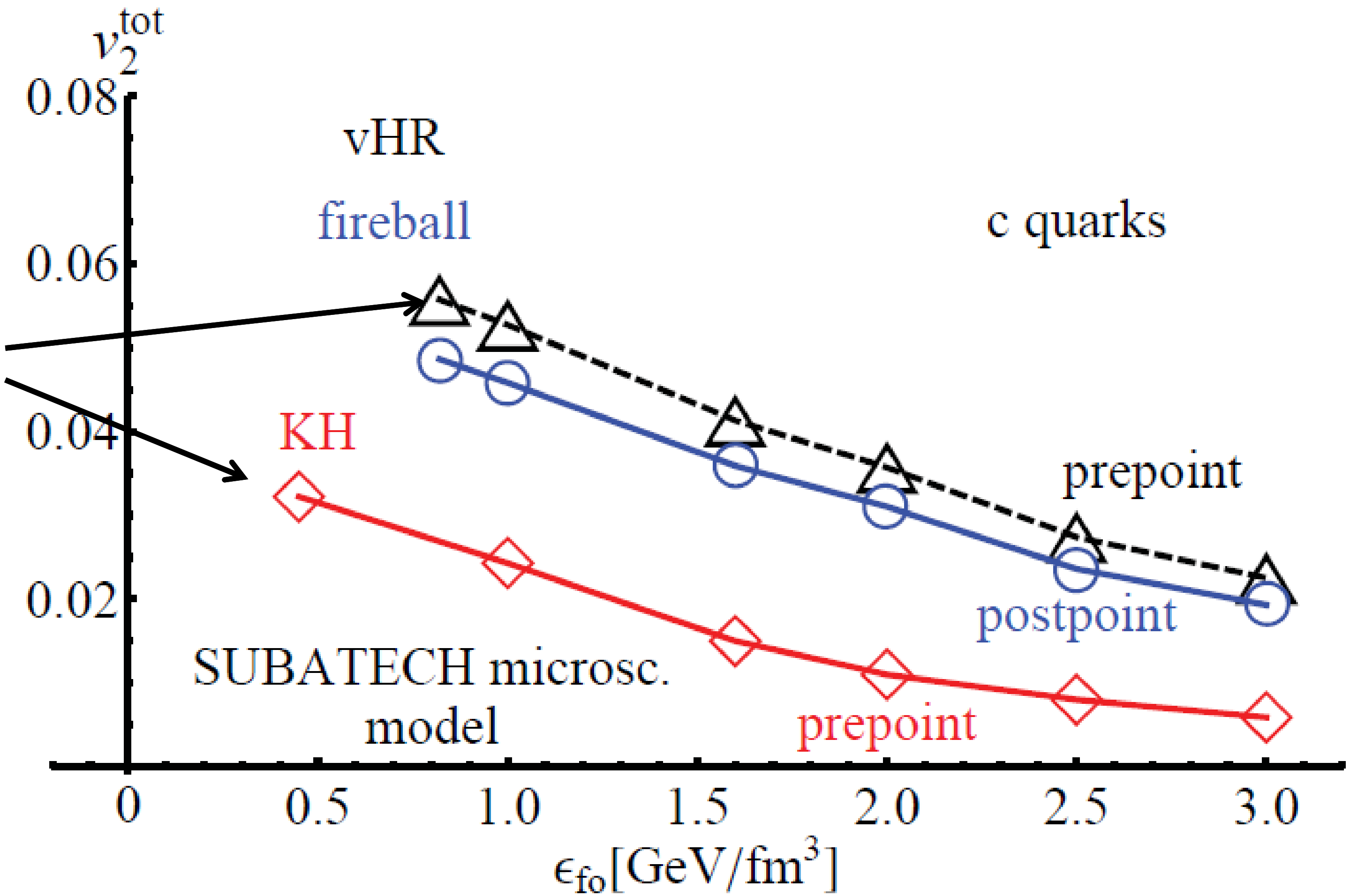
{Radiative + Elastic} vs Elastic for leptons @ RHIC



Rather systematic underestimation of the v2… sign for a significant D mesons rescattering in hadronic matter ?

{Radiative + Elastic} vs Elastic for leptons @ RHIC

V2 builds continuously with time (large inertia) => support the need for studying the D-mesons interactions in hadronic matter



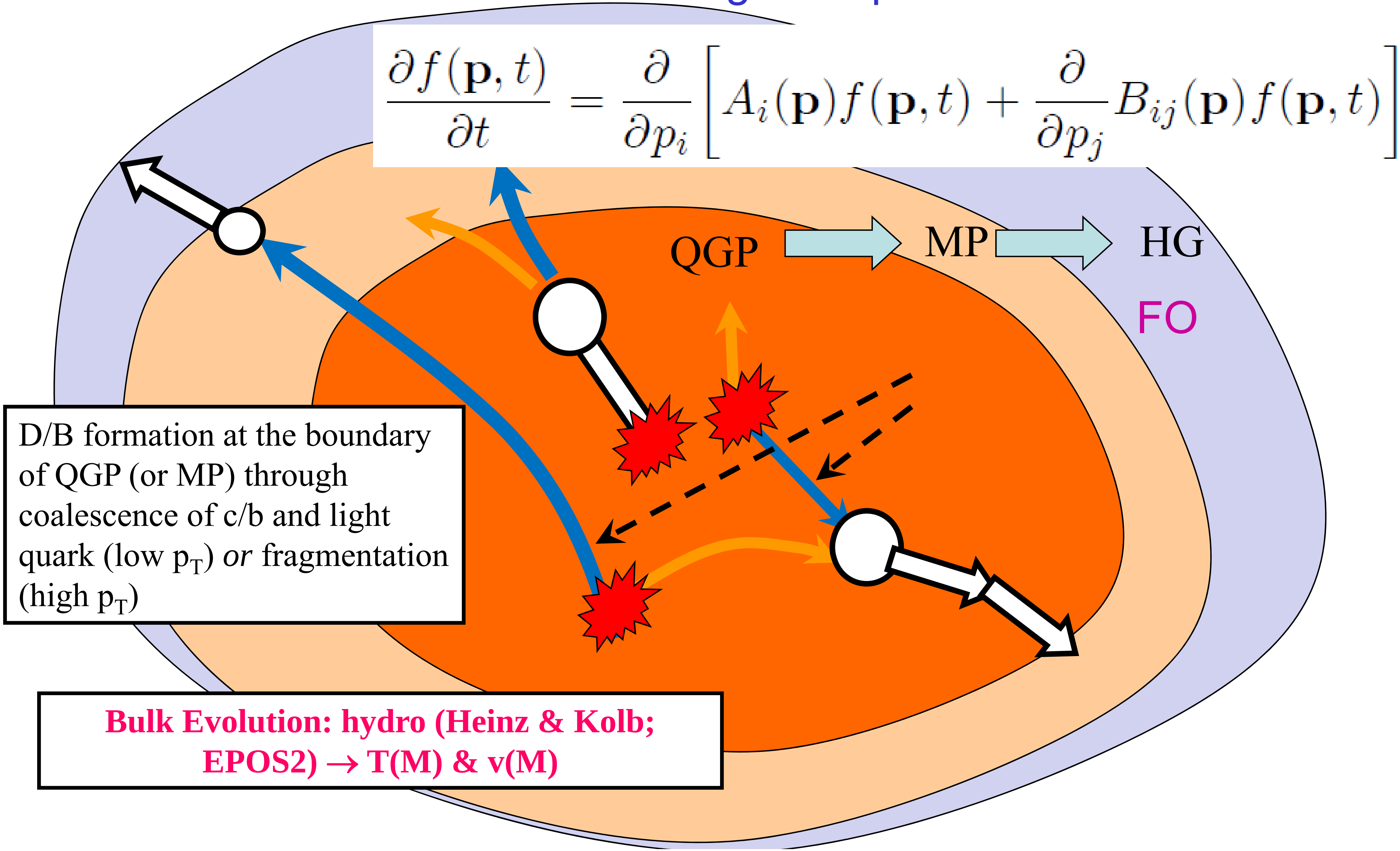
Alternative "exotic" explanation: early v2 => fundamental issue of initial state conditions in AA collisions

Having the hadronic sector under control (FAIR) will help constraining the "exotic" explanation => important cross-talk between FAIR & RHIC-LHC

D mesons rescattering in hadronic matter

D mesons assumed to evolve along FP equation after chemical FO

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

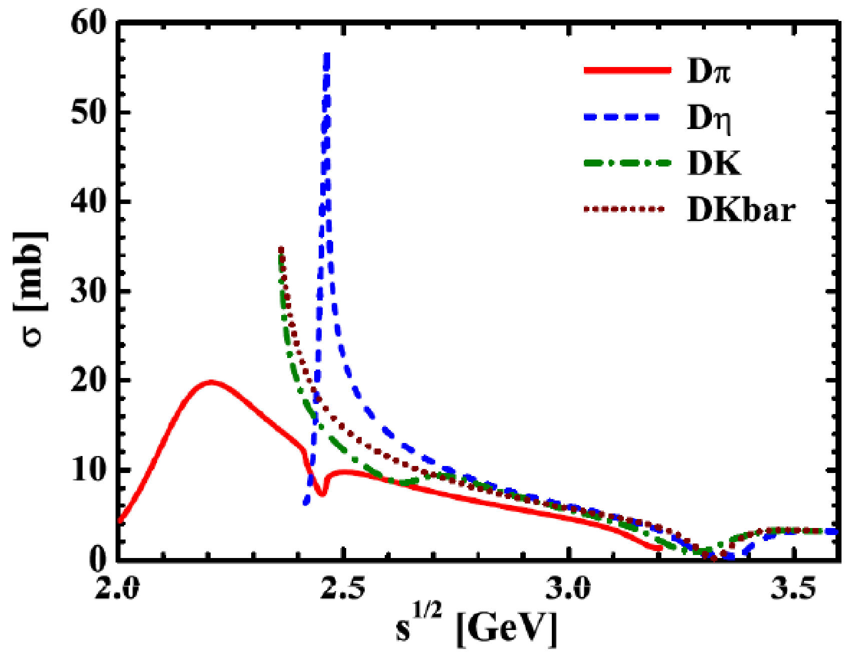


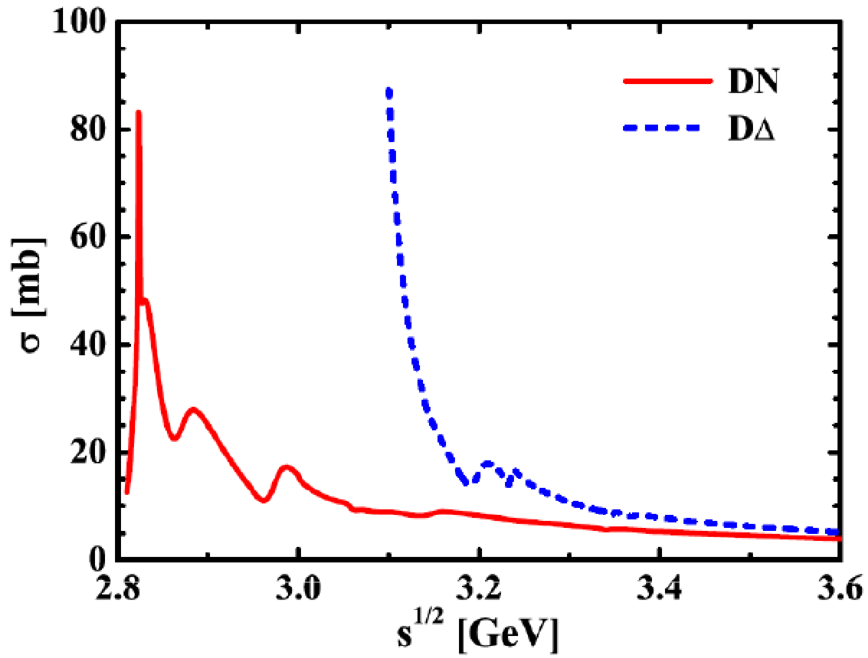
The cross sections

Drag (A) and diffusion coefficients (B) from:

a) most advanced cross section of D mesons with hadrons, based on SU (3),

Tolos and Torres –Rincon Phys.Rev. D88 (2013) 074019





- $D\rho \rightarrow D\rho$ is taken from Z.Lin, T.G.Di, and C.M.Ko, Nucl. Phys. **A689**, 965 (2001)
- $Dm \rightarrow Dm \Rightarrow \sigma = 10$ mb
- $DB(\bar{B}) \rightarrow DB(\bar{B}) \Rightarrow \sigma = 15$ mb

Thanks to Daniel Cabrera and Juan Torres-Rincon for their precious help

Hadron resonance gas

Drag (A) and diffusion coefficients (B) from:

a) most advanced cross section of D mesons with hadrons, based on SU (3),

b) 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

(method introduced by Rapp PRC66 017901)

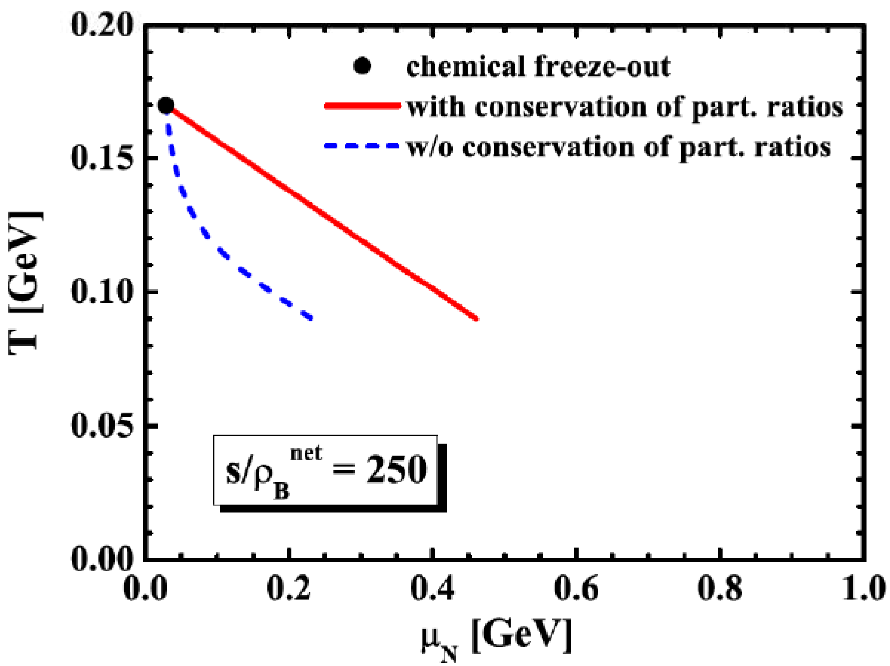
Effective chemical potentials

- Employ a specific entropy (i.e., entropy pet net baryon density) of S/N$_B$ = 250 (characteristic value for collisions at top RHIC energy)

- Freeze-out point:

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

- Construct a thermodynamic trajectory in μ_N-T plane keeping a specific entropy fixed (blue dashed line):



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

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

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

Chemical freeze out at ϵ = 0.5 GeV/fm^3 kinetic freeze out at T = 100 MeV

Effective chemical potentials

- In addition, we keep a ratios of effective stable particle numbers to effective antibaryon number constant in a hadronic evolution (red solid line):

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

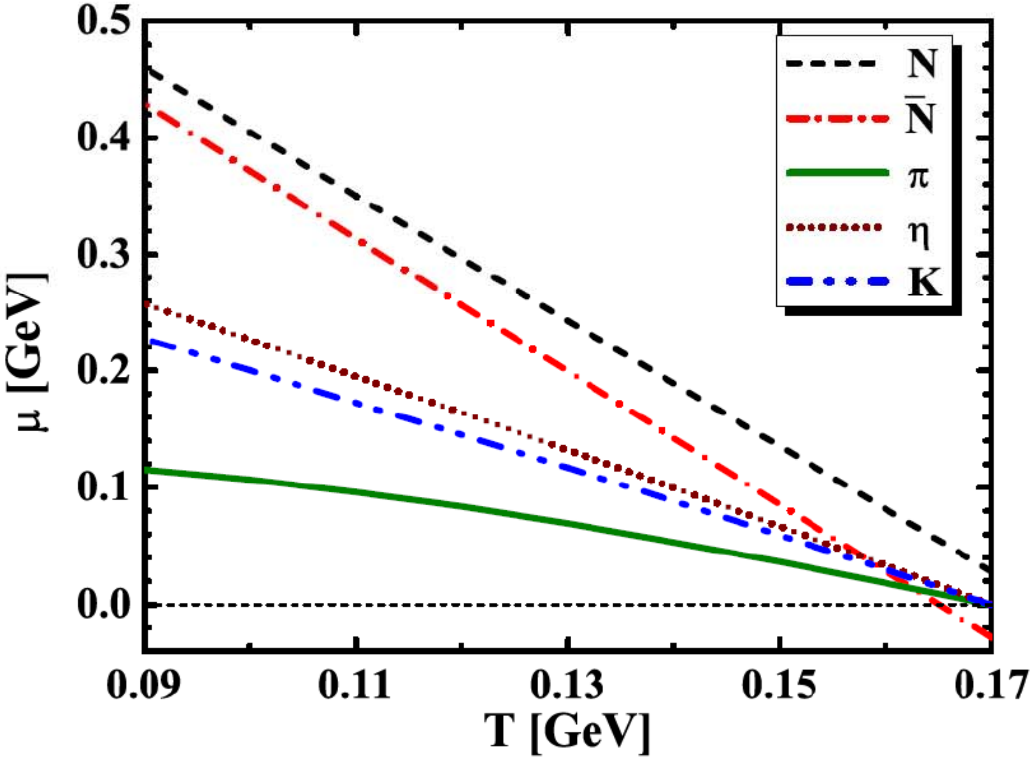
$$N_{\bar{B}}^{\rm eff} = V_{FB}\sum_{\bar{B}_i} n_{\bar{B}_i}(T,\mu_{\bar{B}_i})$$

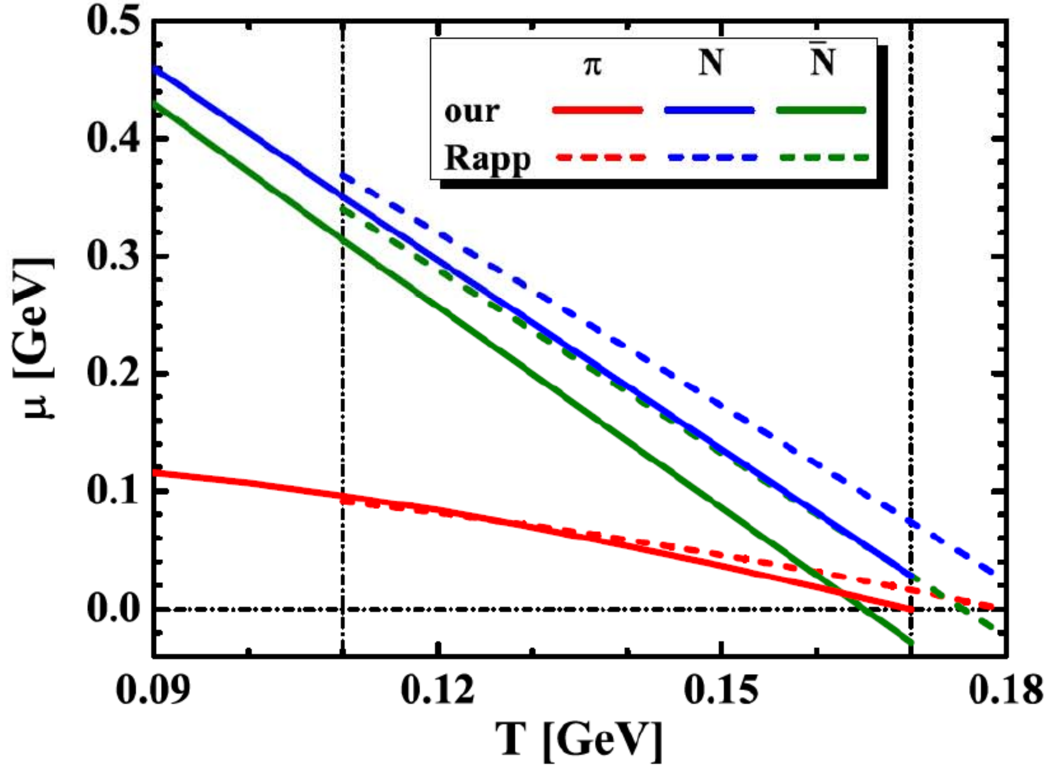
$$N_\pi^{\rm eff} = V_{FB}\sum_i N_\pi^{(i)} n_i(T,\mu_i)$$

Assumption of local chemical equilibrated for all meta-stable hadrons

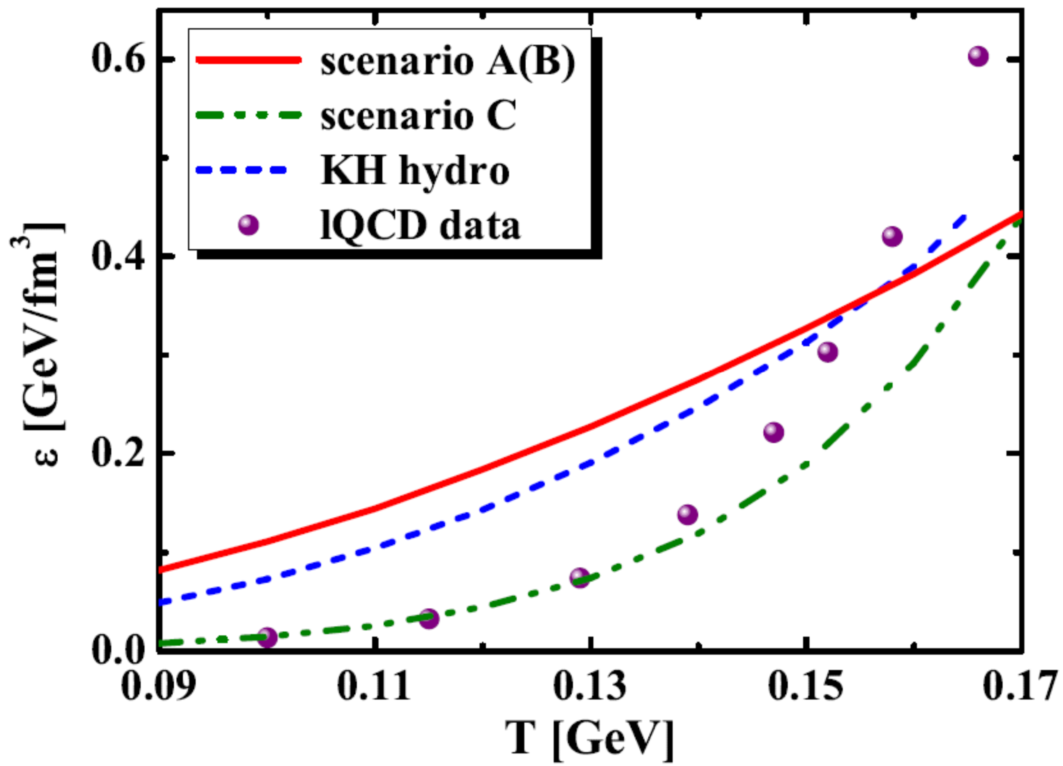
Effective chemical potentials

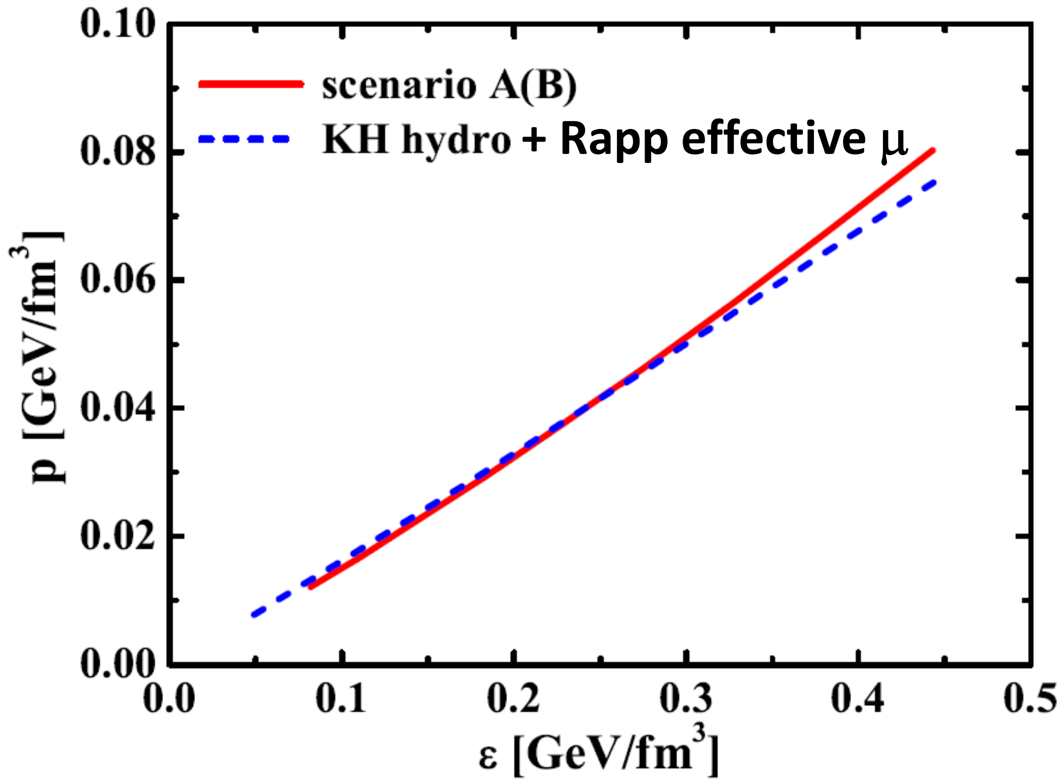
- To conserve the ratio of effective baryon to antibaryon number we introduce antibaryon effective chemical potential, $\mu_{\bar{B}}^{\text{eff}}$, e.g., $\mu_{\bar{N}} = -\mu_N + \mu_{\bar{B}}^{\text{eff}}$.





Effective EOS





Good mapping with hydro EOS => use hydro evolution in the HG as well

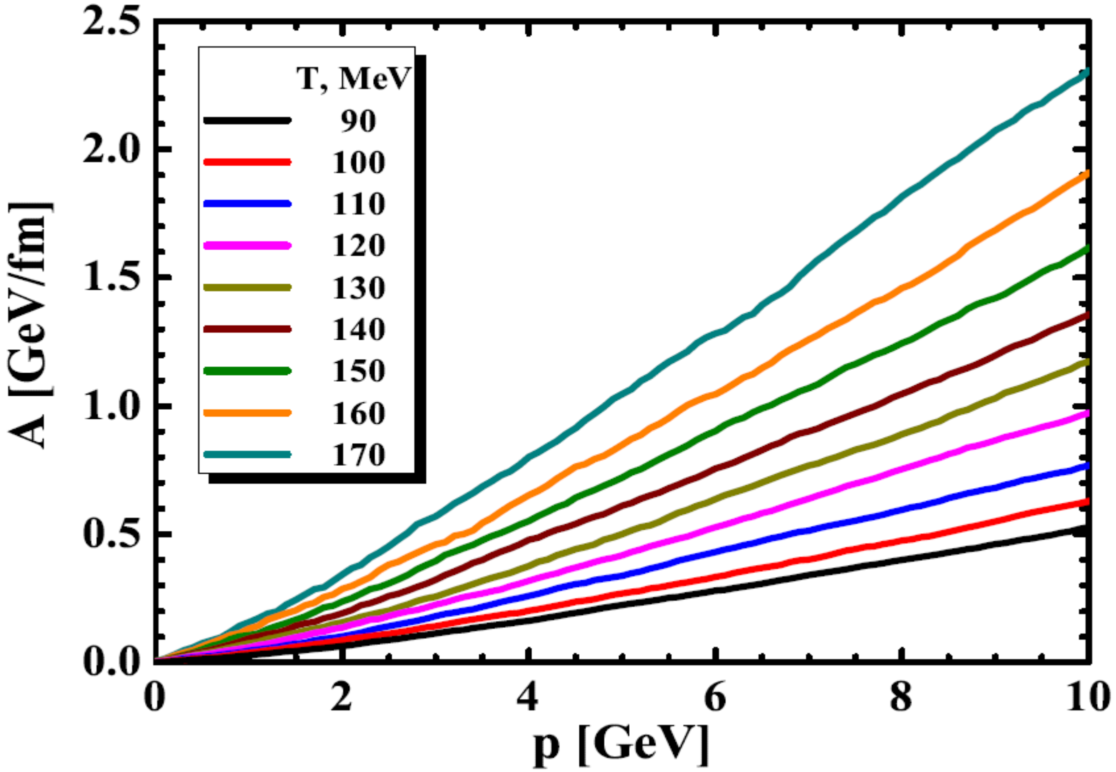
A) scenario discussed above

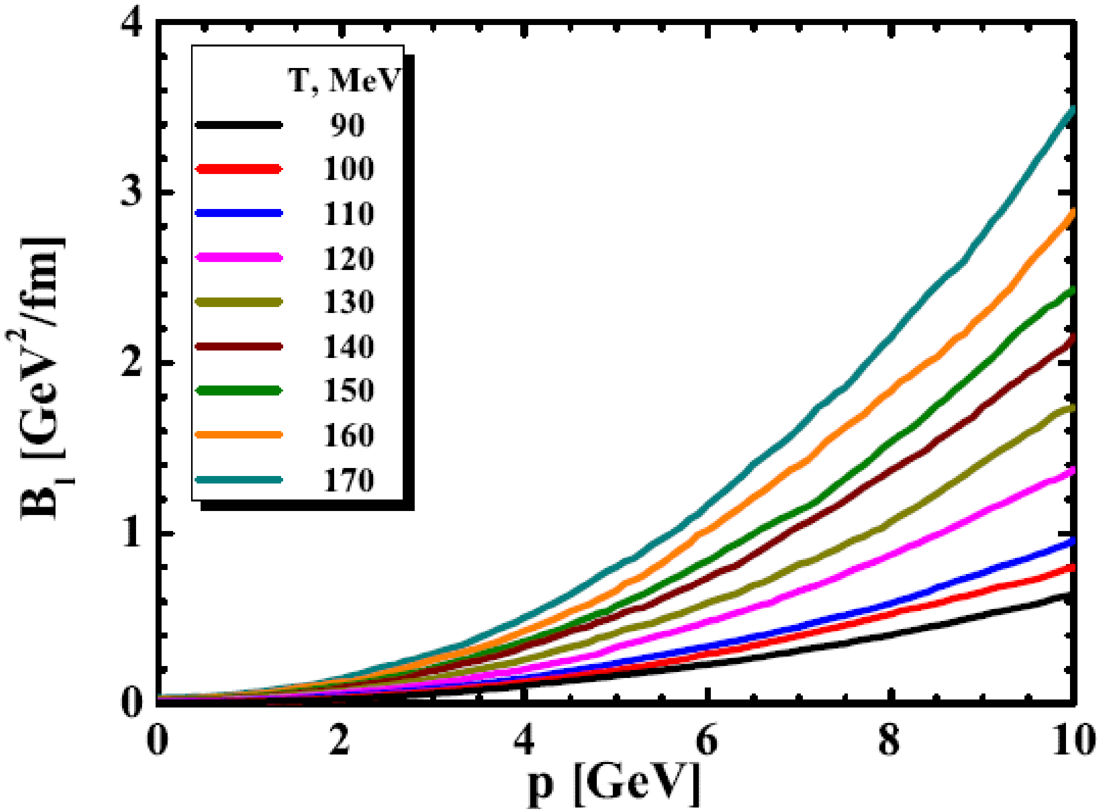
B) Simpler cross sections

C) As A but with no effective potential (should coincide with lattice)

Drag and Diffusion

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

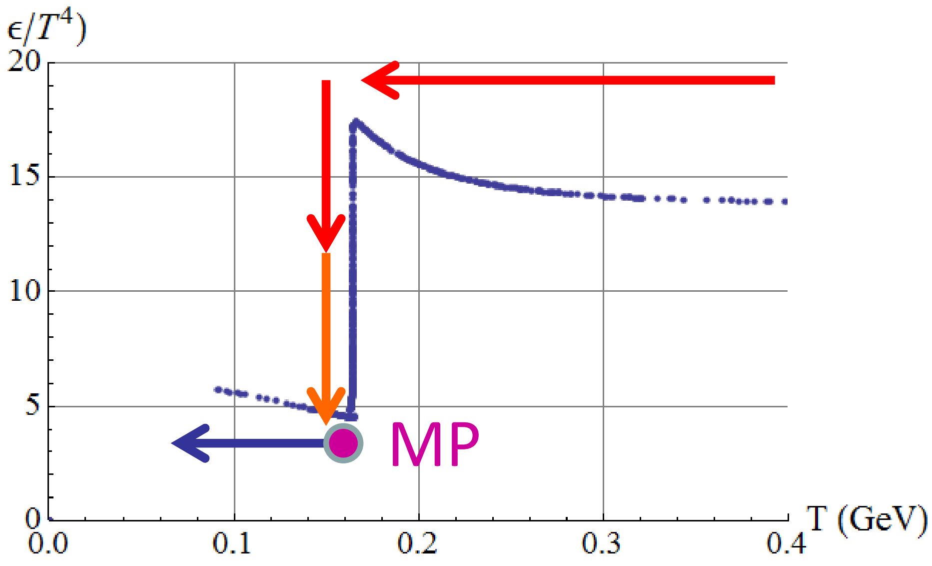


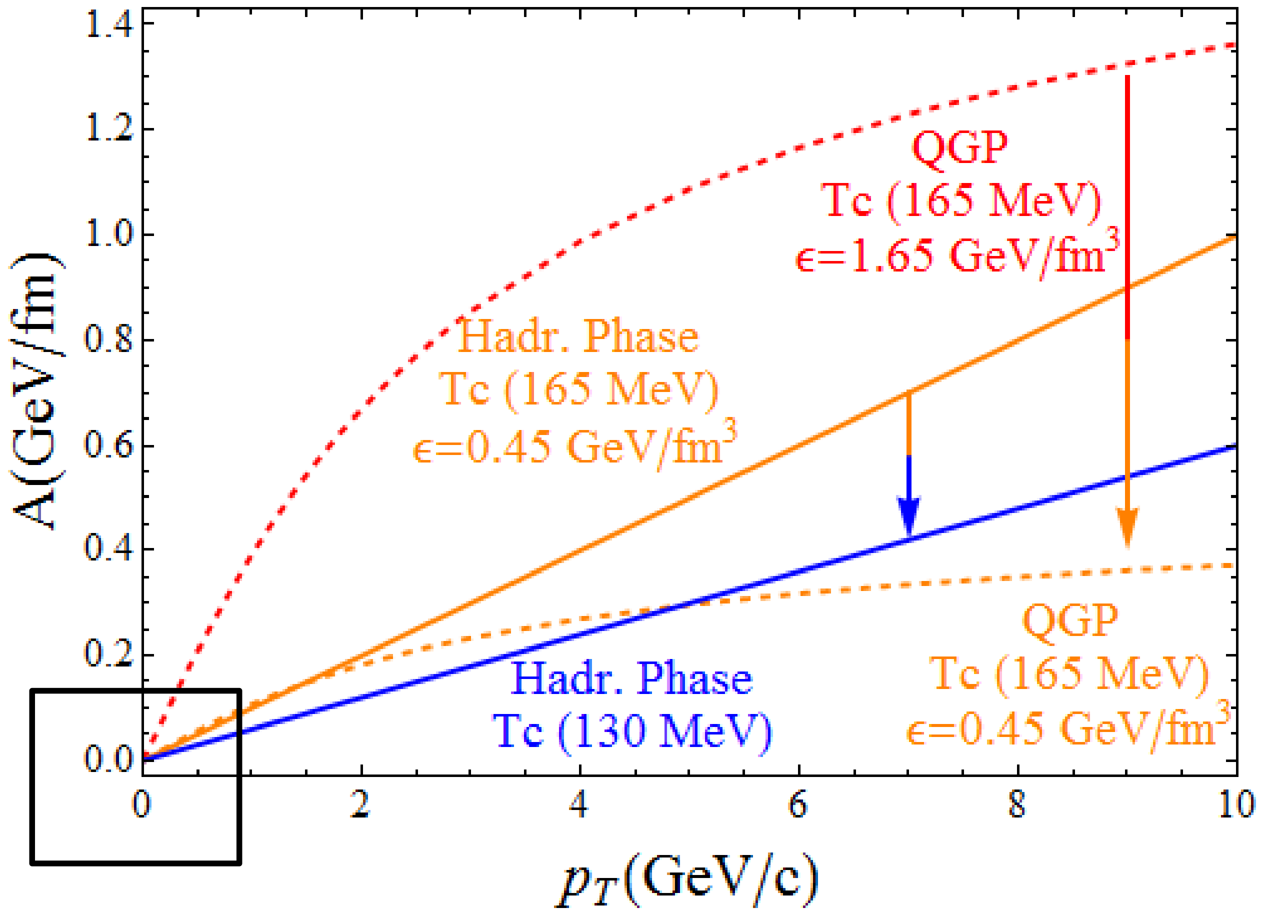


Artificial **linear rise stems from isotropic cross section**

One recovers B_L=B_T at p=0

… compared to HQ (assumed) in plasma

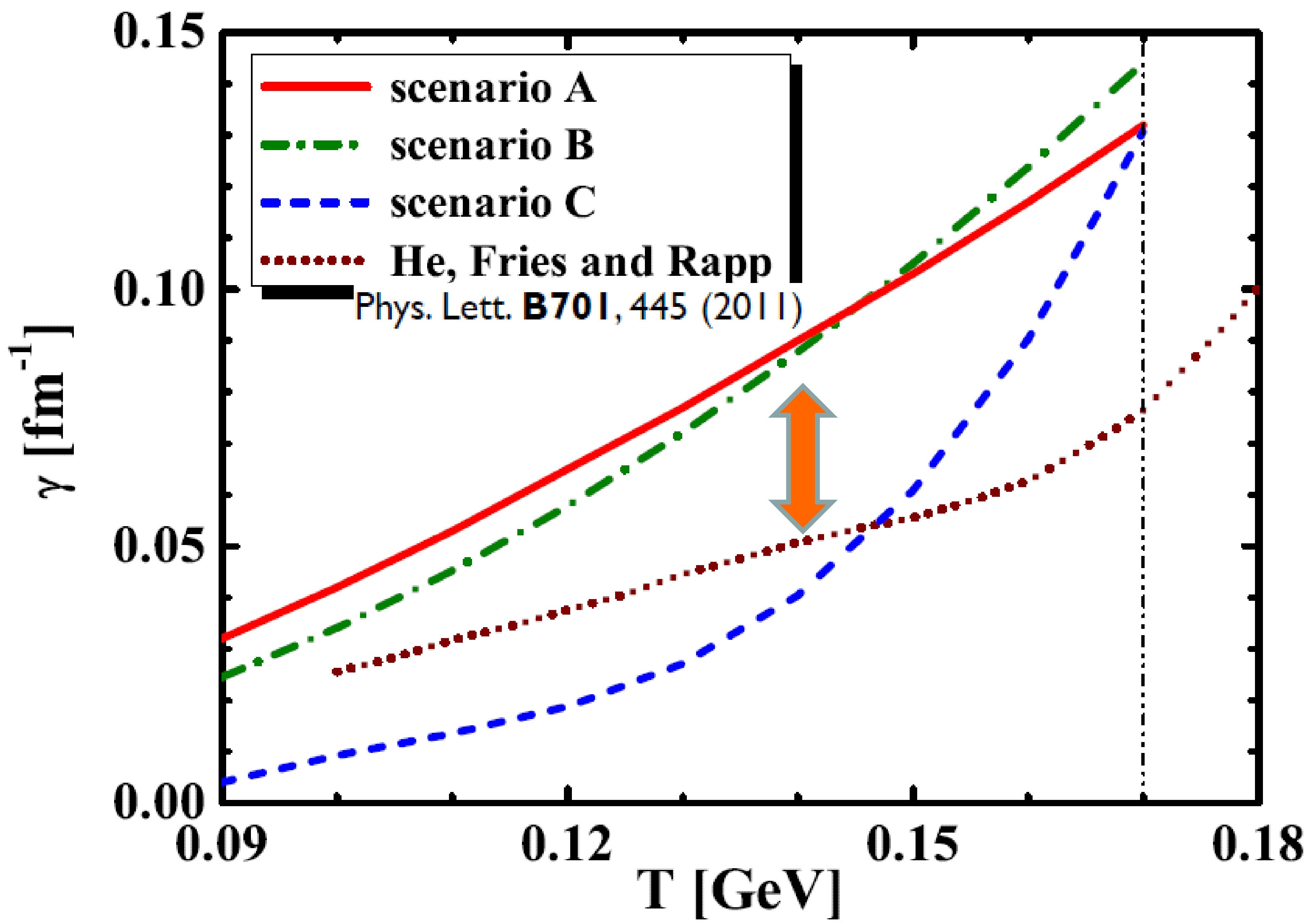




Relaxation times at the matching point (MP) fairly agrees (≈ 10 fm/c)

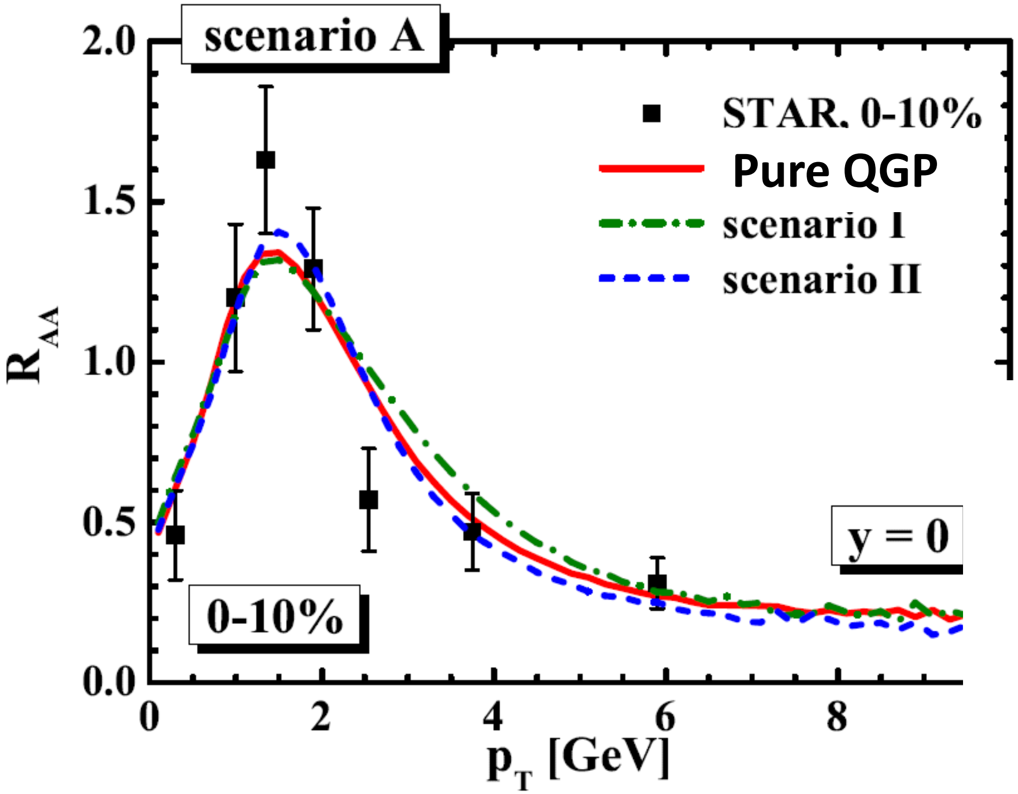
p_T dependences disagree (isotropic cross sections in the HG)

… compared to previous calculations

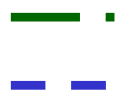


Decrease of a factor ≈2 of the relaxation time, mostly due to the many states included in the HRG model

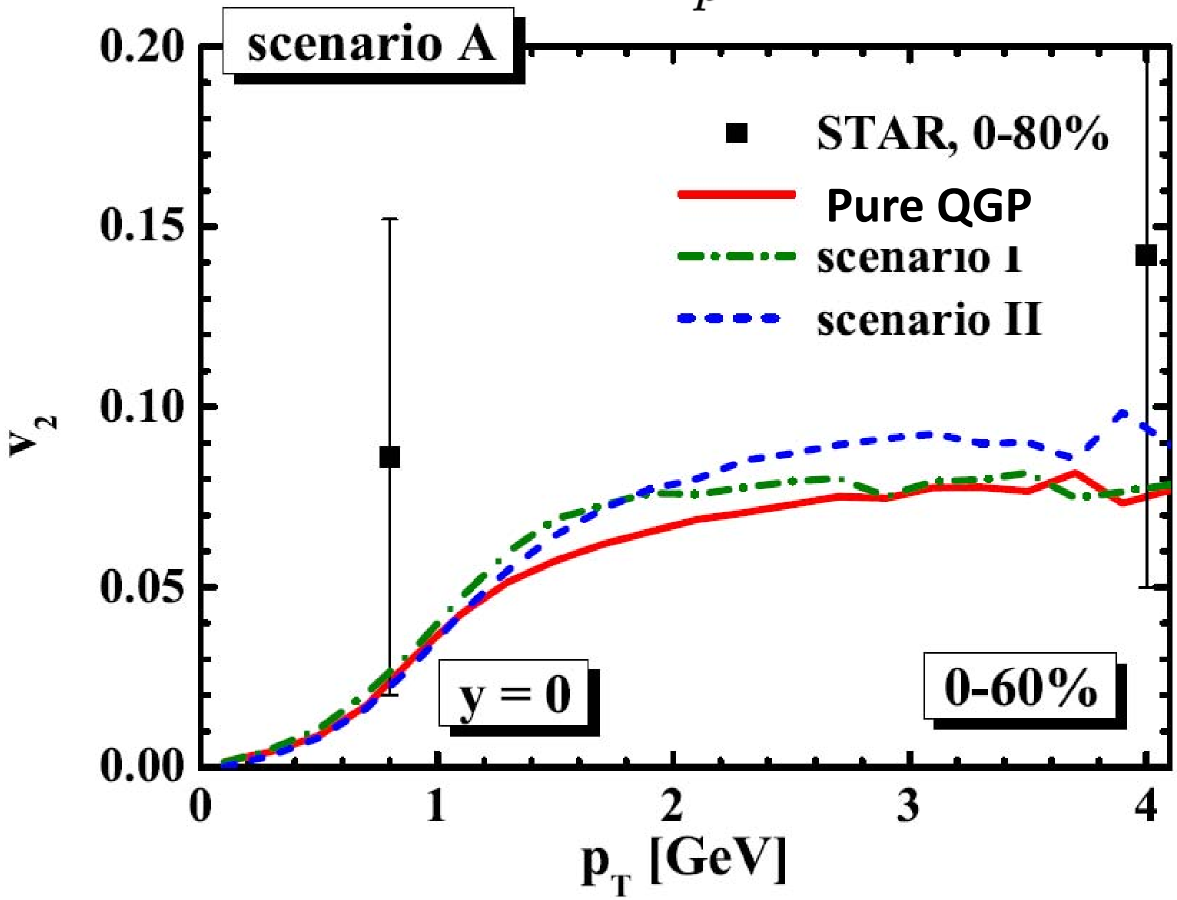
Results (with KH hydro)



assuming the transition between partons and hadrons takes place at ϵ = 0.45 GeV/fm^3



- *A* and *B* as calculated
- *B* taken as $\frac{A}{p} \times TE$



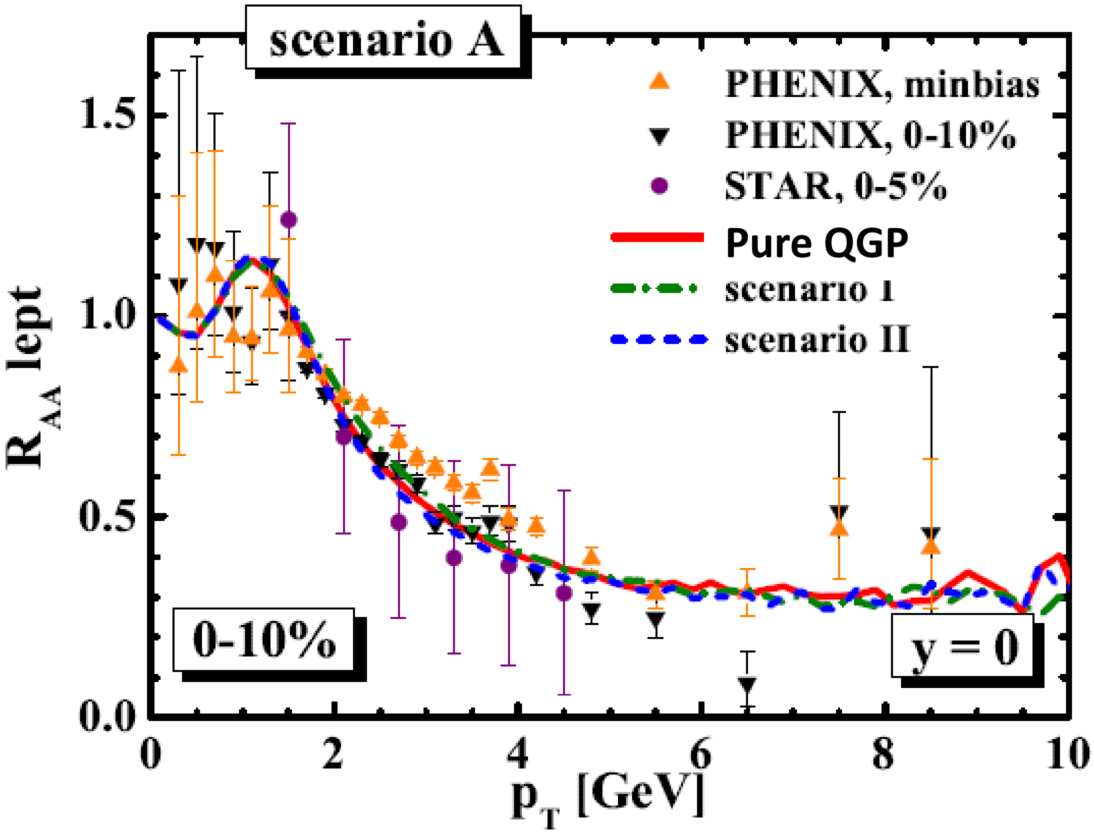
Almost invisible for R_{AA}

(sign depends on transport assumptions)

moderate effect on v_2

(systematic increase)

Results (with KH hydro)



assuming the transition between partons and hadrons takes place at ϵ = 0.45 GeV/fm^3

— · *A* and *B* as calculated

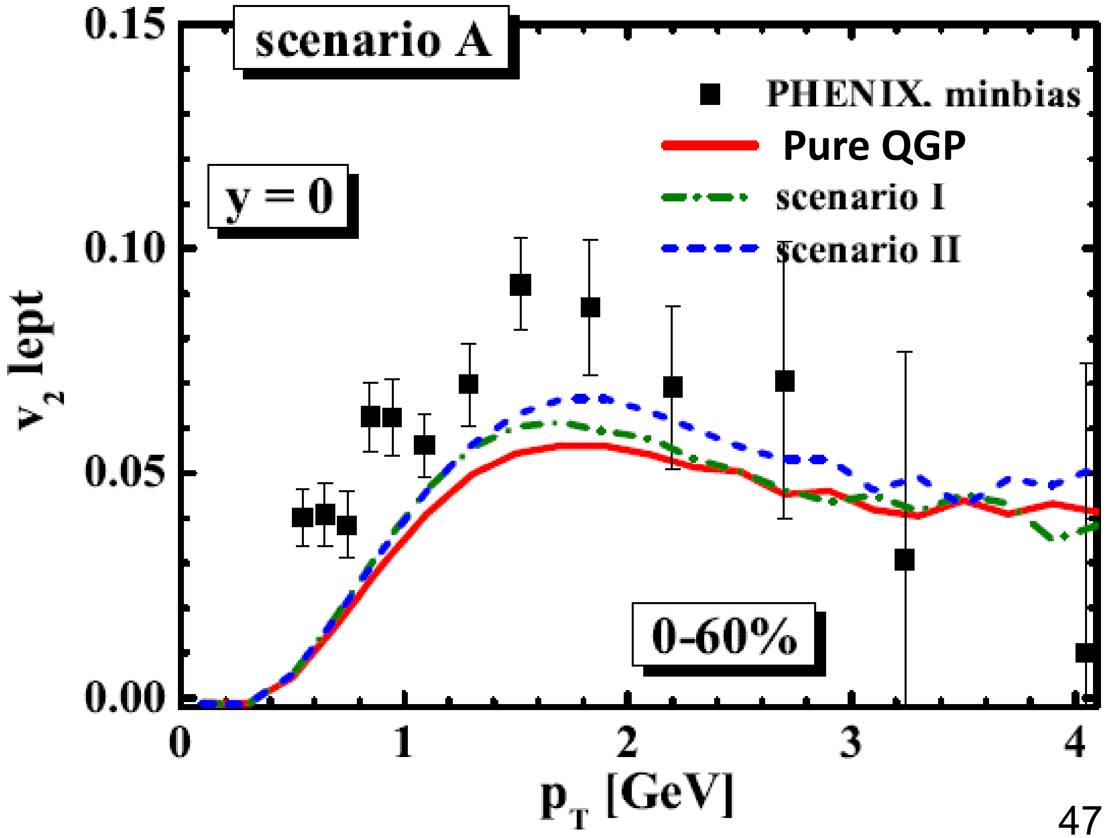
— — *B* taken as $\frac{A}{p} \times TE$

Almost invisible for R_{AA}

(sign depends on transport assumptions)

moderate effect on v_2

(+1%...2% missing)



Conclusions from my RHIC-LHC early life & further studies

- **Inspired pQCD model, in reasonable agreement with RHIC (and LHC) open heavy quark physics (some resummation mandatory)**
- **Hadronization plays an important role (not shown here)**
- **There seems to be a systematic underestimation of the elliptical flows (v_2)**
- **D meson rescattering in HG shows a systematic contribution of 1%-2% to the v_2**
- **Hadronic cocktail plays a large role there (nearly a factor 2 difference)**
- **Yet, some early stage effects in AA are not excluded**

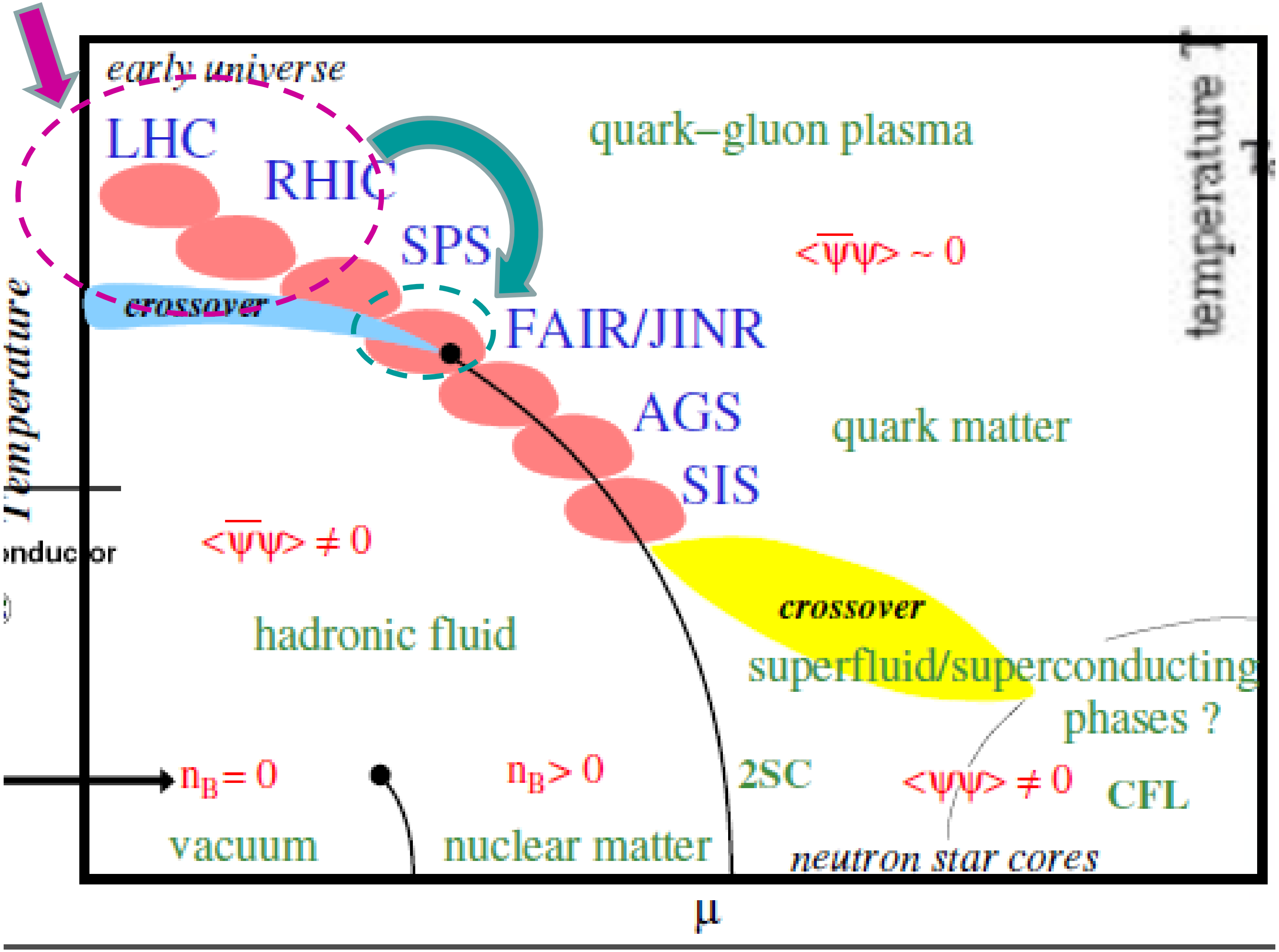
Conclusions from my RHIC-LHC early life & further studies

- **Extend the model to finite m_q and m_g + smooth crossover (see as well Hamza's Berrehrah's talk)**

- **Extend the model to finite μ**

Going Fair

My HQ life up to now

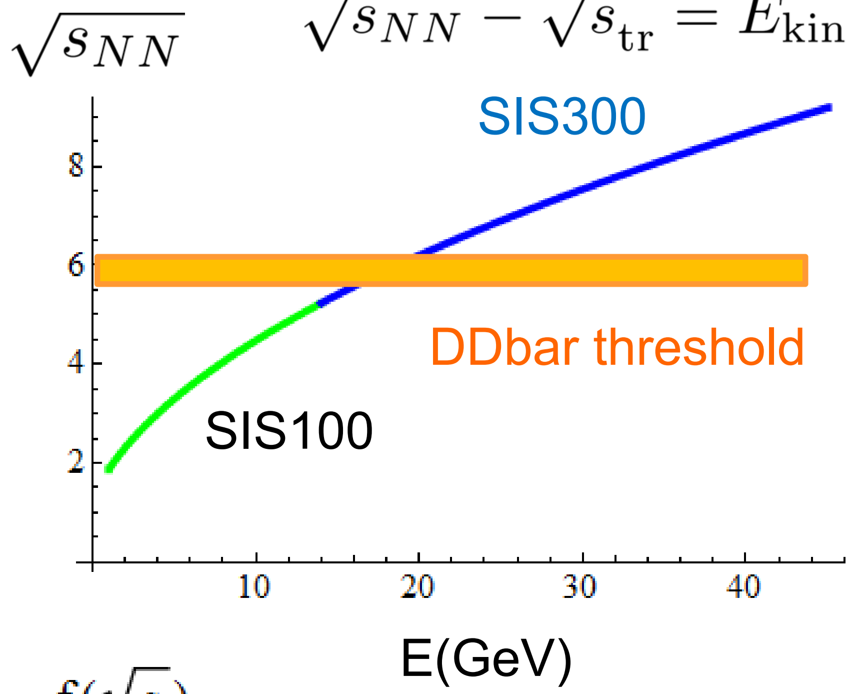


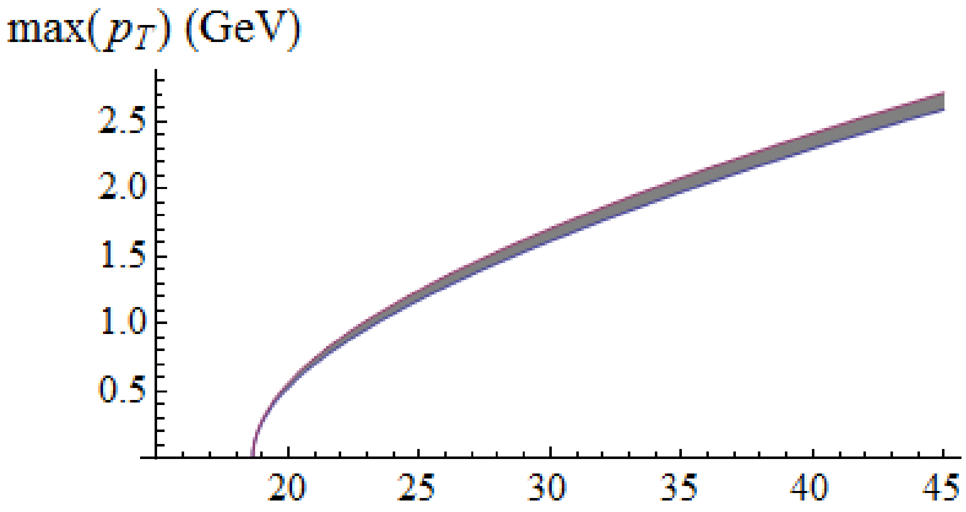
What I'd like…

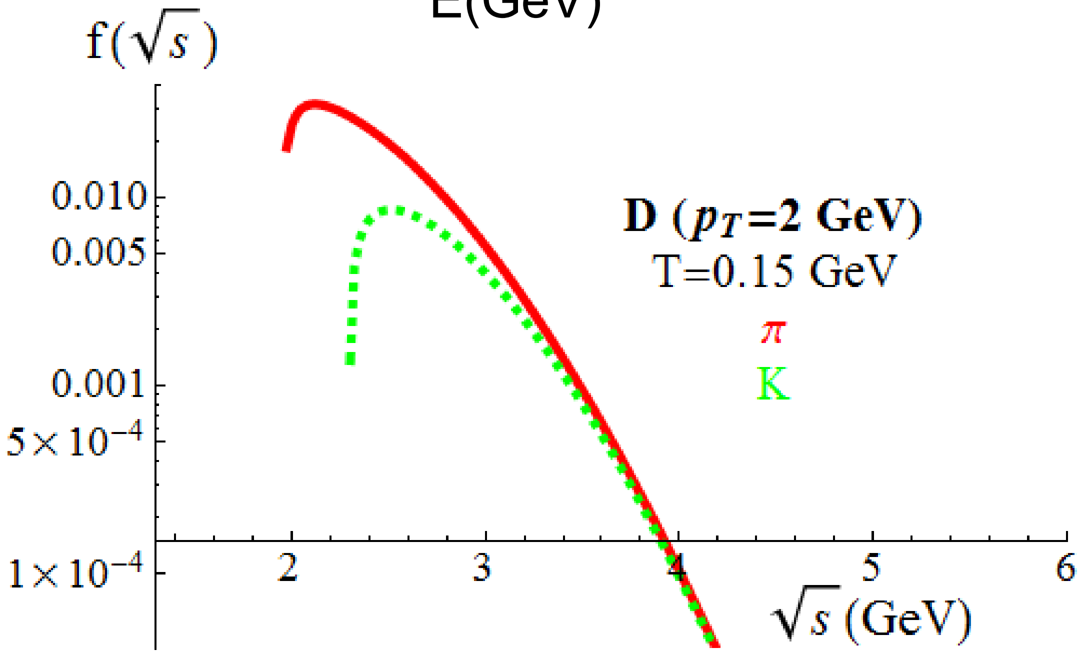
- **Have a better control on D-hardons re-interactions (possibility to study the finite – Ls' in the Dx->Dx*)**
- **Understand whether Fokker-Planck approach is justified at intermediate p_T.**
- **See the sign of a 1rst order transition (?)**
- **Understand what dominates HQ physics (cold nuclear matter effects, QGSoup, hadronic matter)**

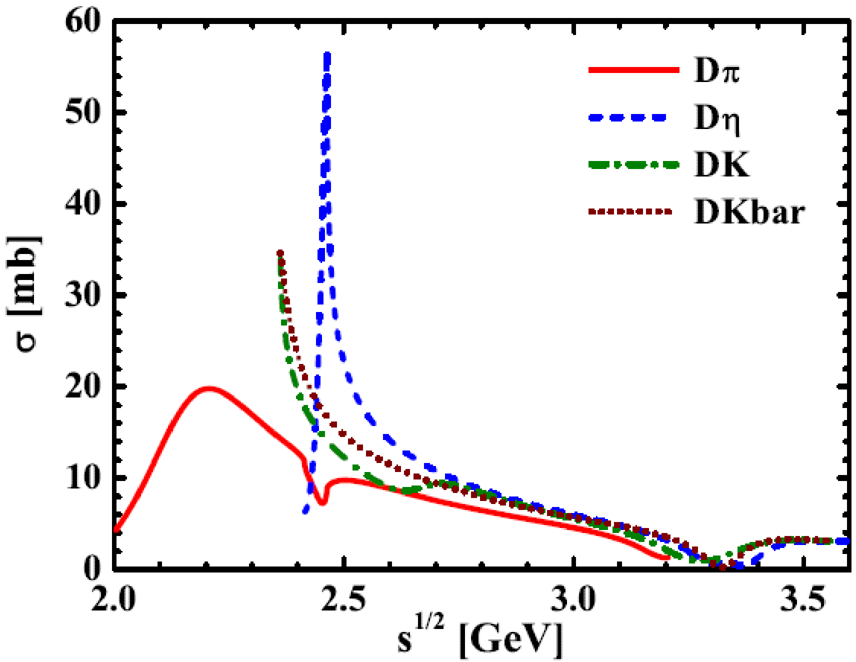
Some simple kinematics

$$\sqrt{s_{NN}} - \sqrt{s}_{\mathrm{tr}} = E_{\mathrm{kin}} = 2\left(\sqrt{p^2 + m_c^2} - m_c\right)$$

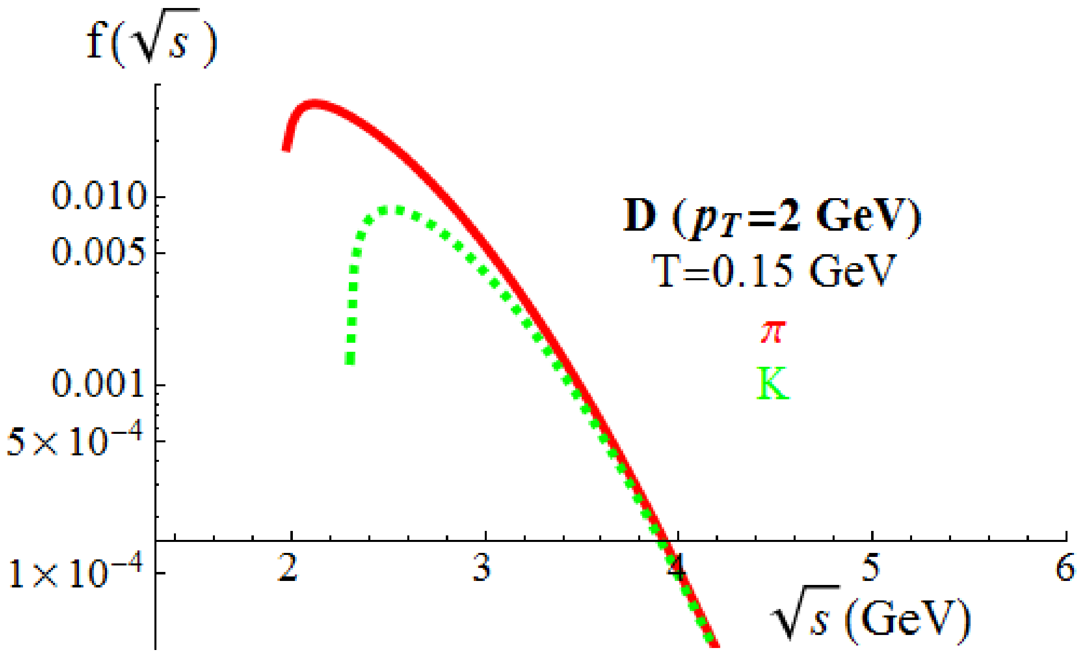


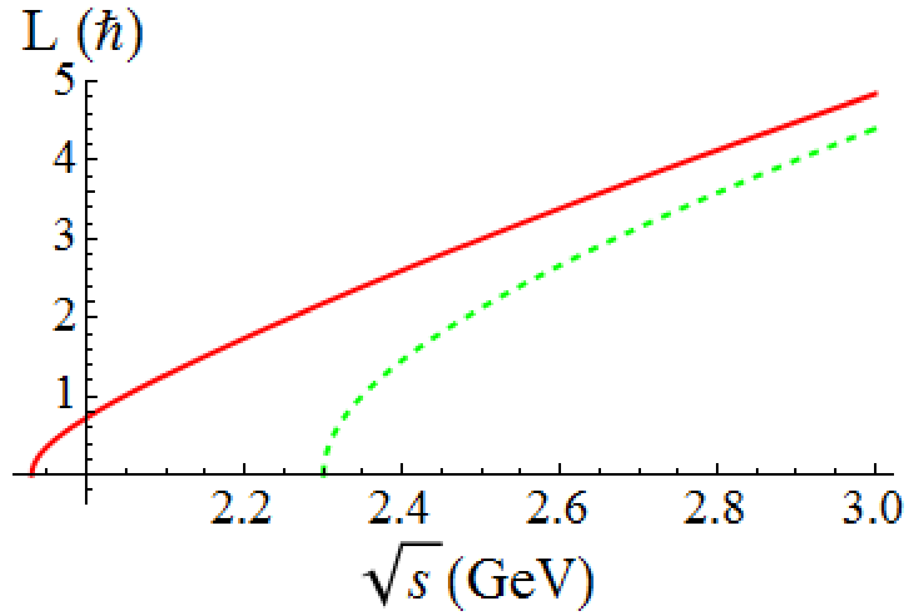






Higher Ls' ?



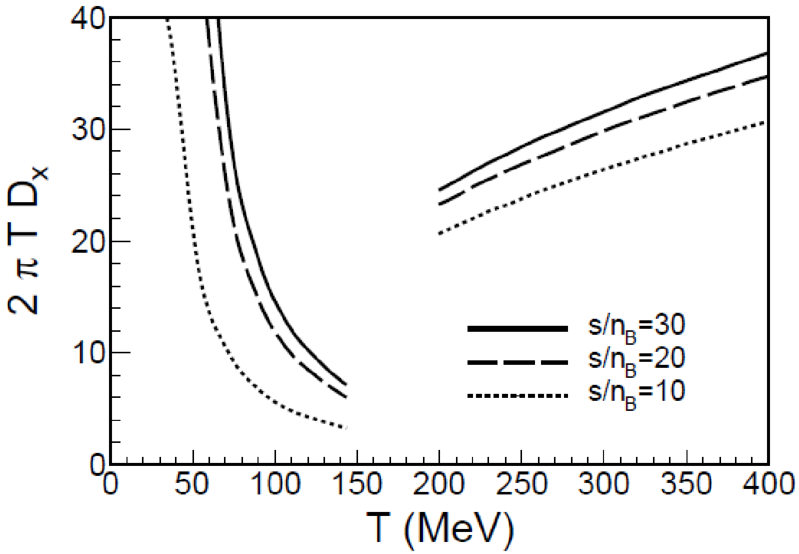


L up to 2 seems achievable at Fair energies

To do: check the consequences by introducing some ansatz in HRG models

Does hadronic world dominate HQ physics ?

Matching with pQCD



Juan Torres (Fairness 2013)

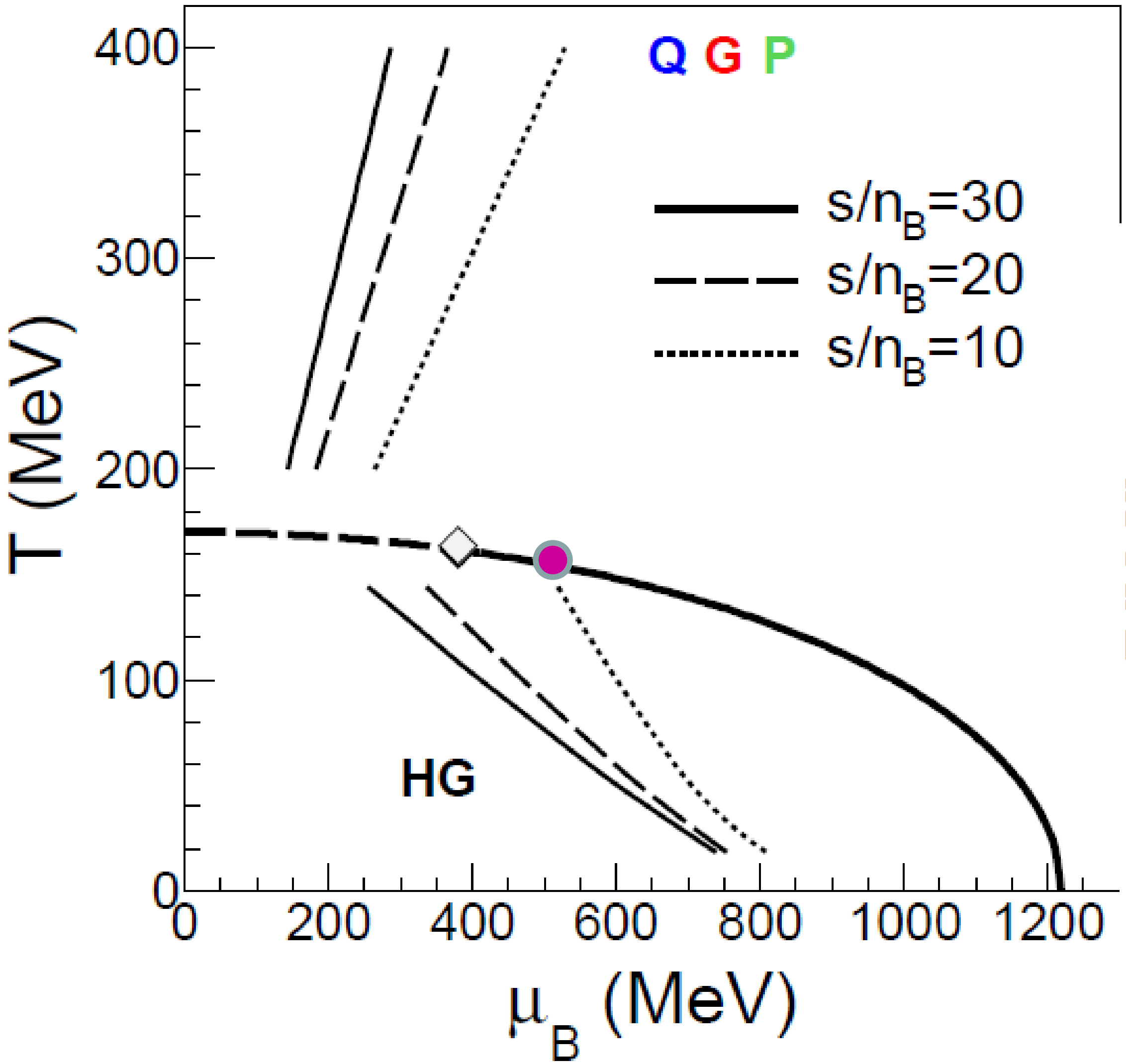
HTL generalized to finite μ (à la Moore & Teaney)

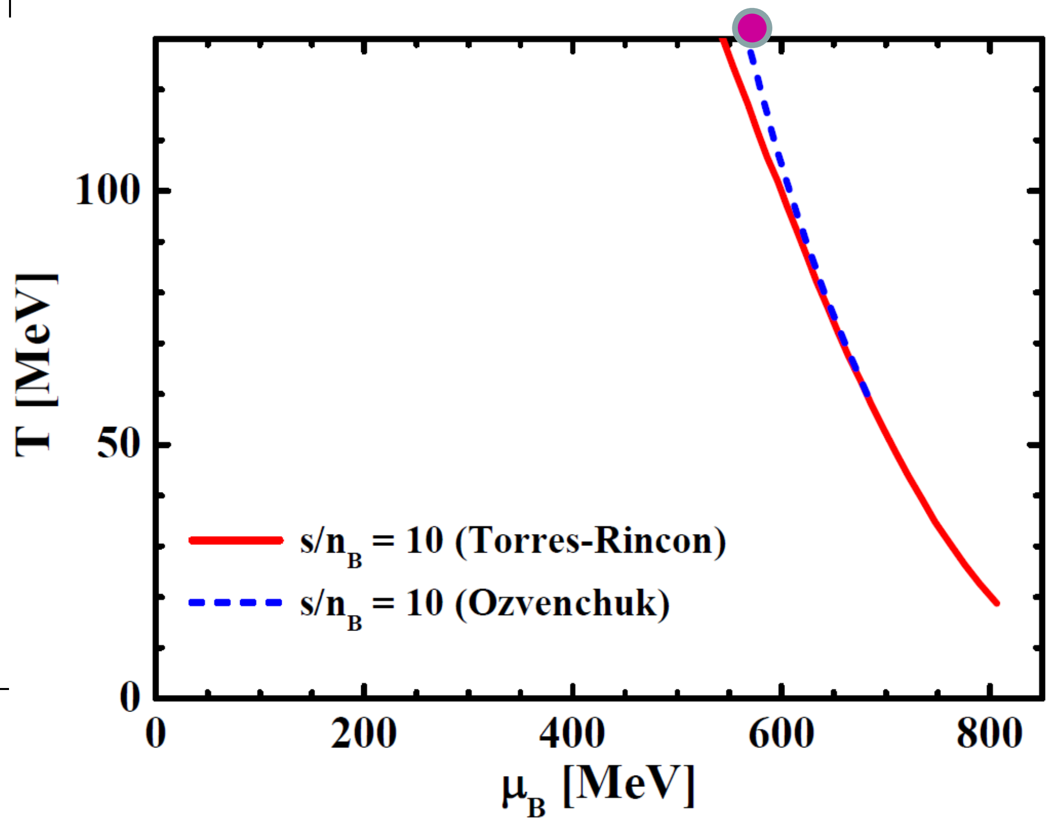
- Similar dependence on nuclear density
- We do NOT expect a continuous matching for two different reasons:
  - Perturbative QCD not valid around T_c (only a crude approximation to gain some insight)
  - Evolution is potentially crossing a first-order transition line: discontinuity in transport coefficients

Let us try to extrapolate our μ=0 study to the finite μ case (and try to provide some tentative answers)

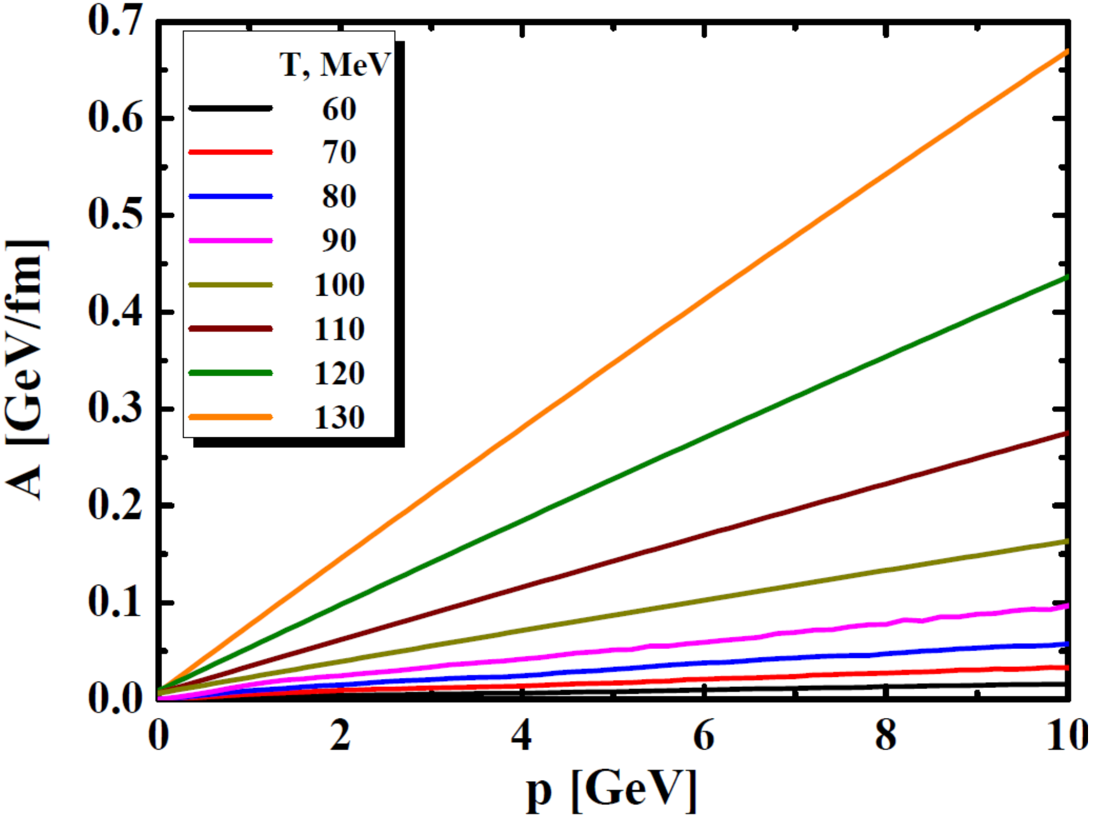
Something we (Vitalii) did…

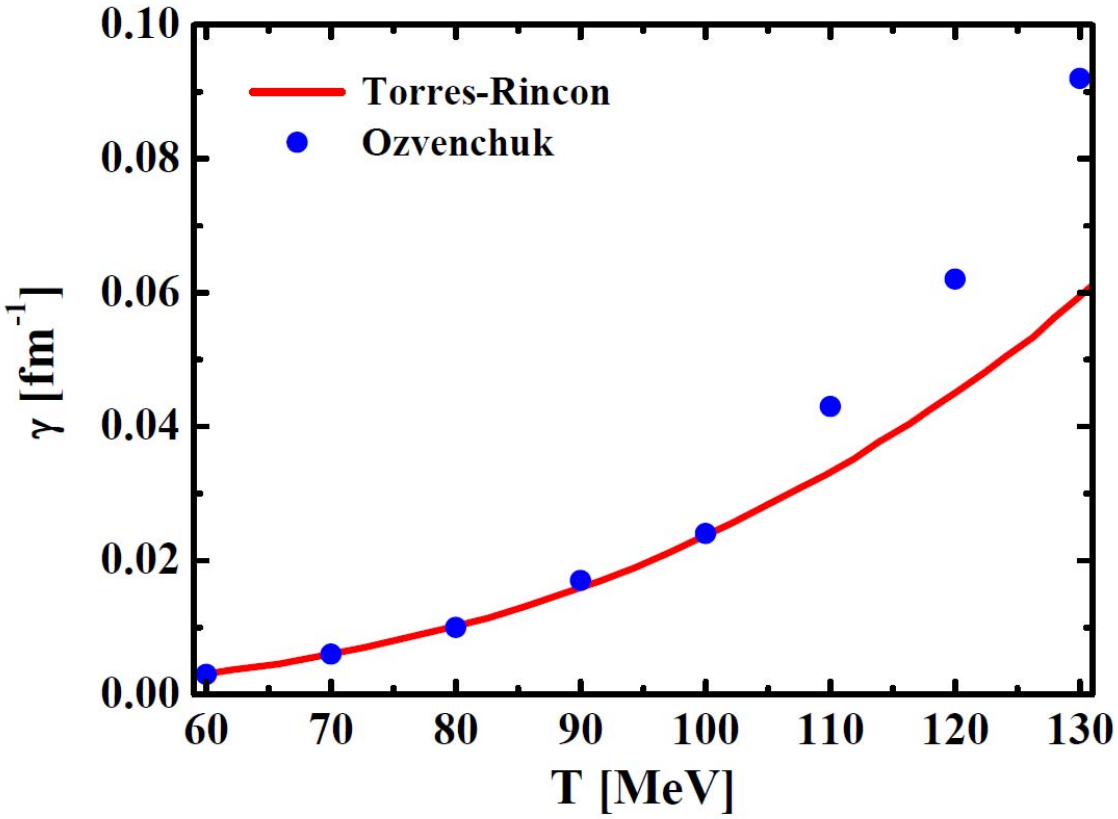
Juan Torres (Fairness 2013)





Something we (Vitalii) did…

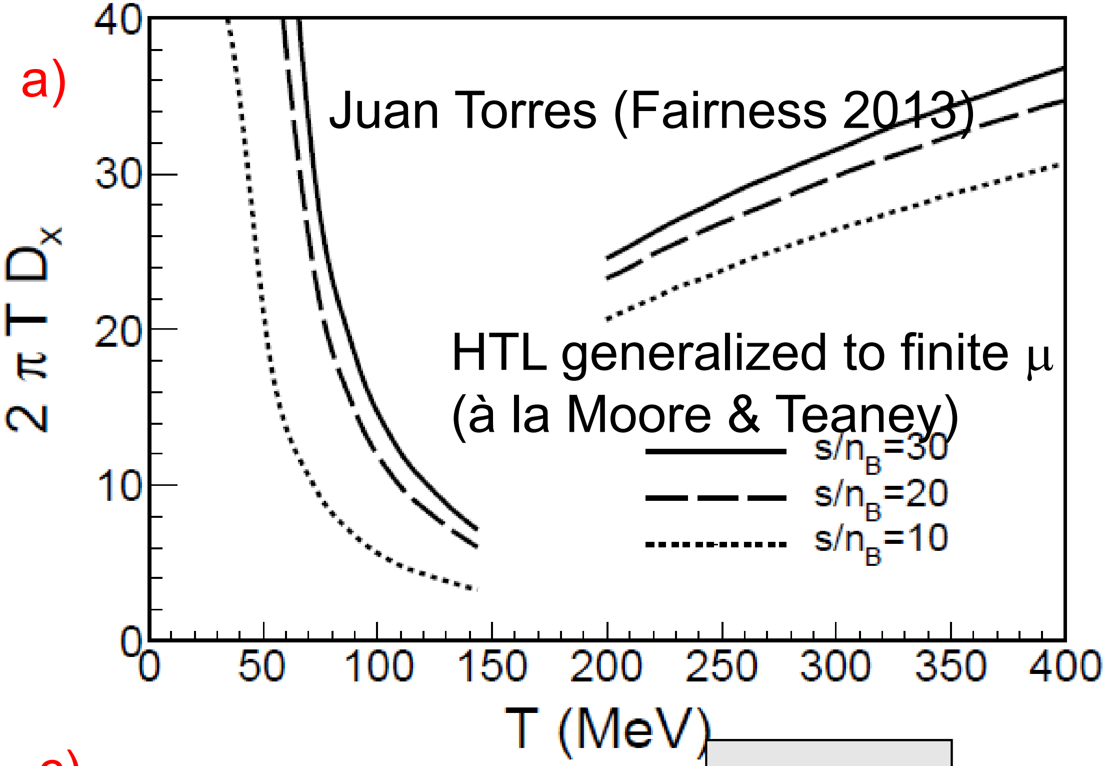




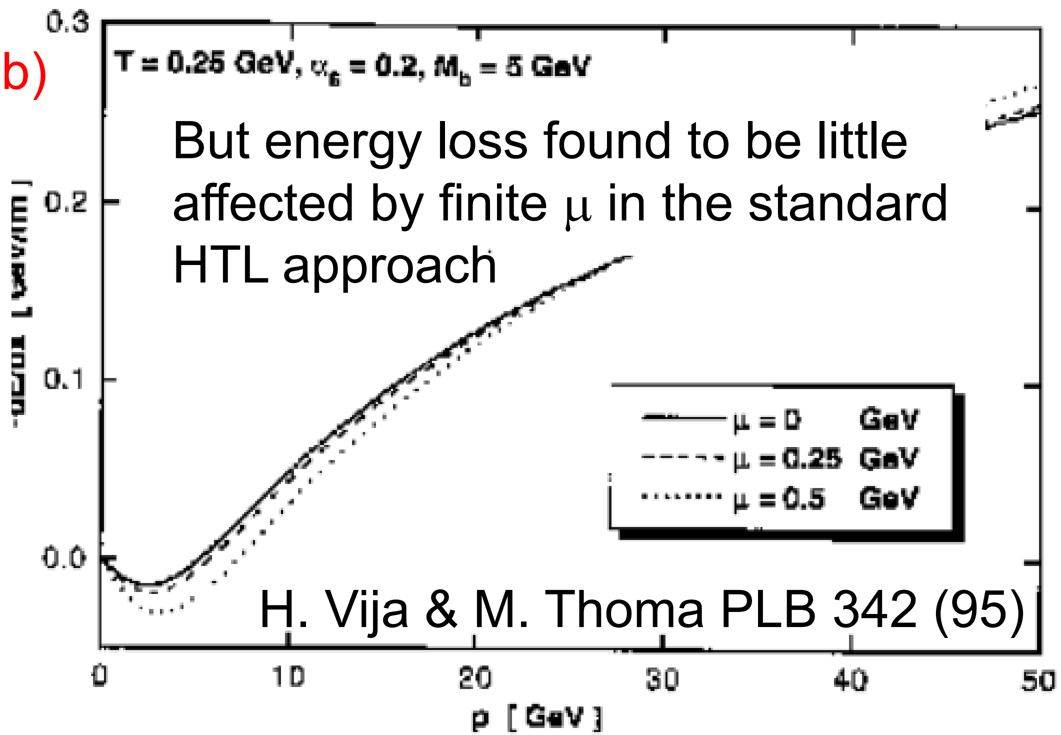
Confirms a) previous calculation of Juan Torres-Rincon & b) excess due to higher states in the HRG model (not seen at smaller T)

Does hadronic world dominate HQ physics ?

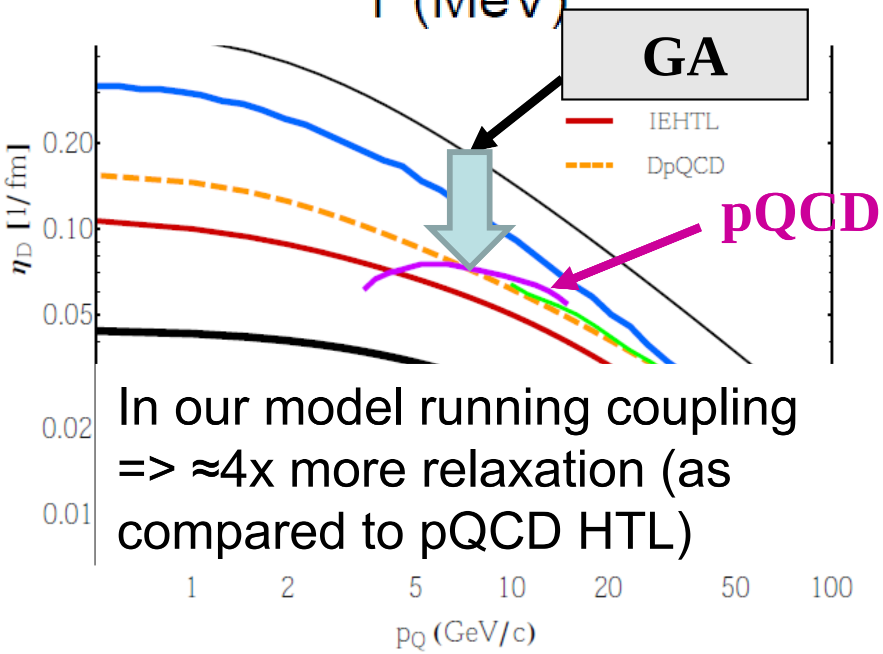
a)



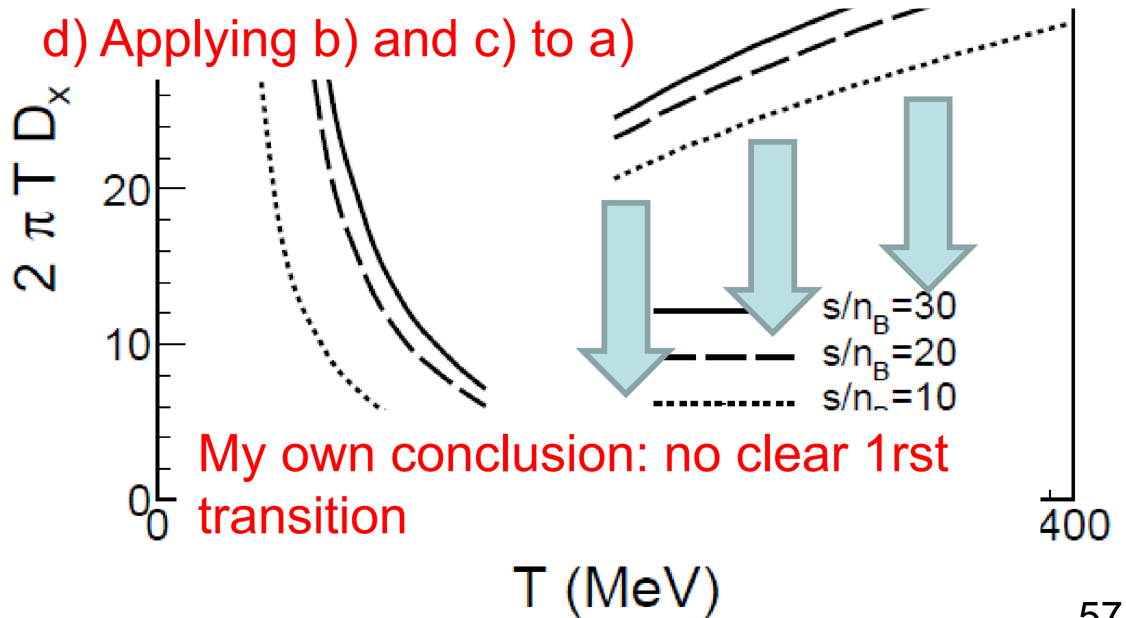
b)



c)



d) Applying b) and c) to a)



Does hadronic world dominate HQ physics ?

- Not clear to me (I would say NO)
- See more on this in Hamza Berrehrah's talk on 28/05/2014