Heavy quarks thermalization in URHIC :

Elastic vs. Radiative

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I) Model

II) Results for R_{AA}

III) Results for v_2

IV) Azimutal correlations

V) Conclusions

Heavy quarks in QGP (or in strongly interacting matter)

• Starting point: For heavy quarks, relaxation time >> collision time ; at large momentum (as for all quarks) but also at low momentum (thanks to inertia)

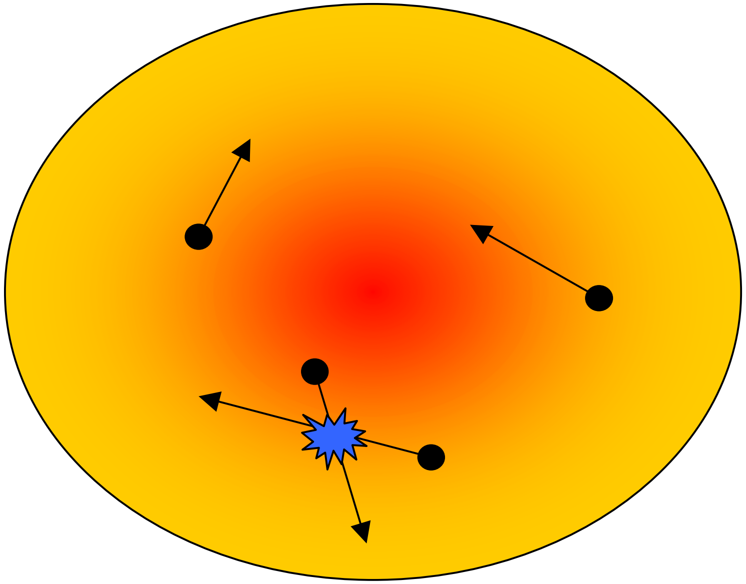
• Heavy quarks behave according to Brownian motion / Langevin forces ⇔ c quarks distribution evolves according to Fokker – Planck equation

$$\frac{\partial f}{\partial t} = \vec{\nabla}_p \left[\vec{A} f + \vec{\nabla}_p \left(\overleftrightarrow{B} f \right) \right]$$

N.B.: What is the best model (if any) ? FP or Boltzmann equation ?

Heavy quarks in QGP (or in strongly interacting matter)

• The physics : a couple of heavy quarks, a medium (+ transport coefficients) and some hidden charm and beauty mesons.



• Ideally : measure the transport coefficients and compare their value with theory (Lattice; cf. talk by Petreczky).

A few words on the transport coefficients

$$\frac{d}{dt} < \vec{p} >_f = < -\vec{A} >_f$$

with $\vec{A}(\vec{p}) = \tilde{A}(p)\ \vec{p}$

• drag coefficient $\tilde{A}(p)$ is thus the proportion of momentum lost per unit of time

• At high energy, one has (assuming f is peaked):

$$\frac{d<E>}{dt} = <\vec{\beta} \cdot \frac{d\vec{p}}{dt}> \approx \vec{\beta} \cdot < \frac{d\vec{p}}{dt} > \approx -\vec{\beta} \cdot <\vec{A}> \approx -\beta\ \tilde{A}\ p$$

$\Rightarrow$ A(p) and the energy loss per unit of length are the same quantities

• At low energy, not true any more: On the average, particles can gain/loose energy without gaining or loosing momentum.

A few words on the transport coefficients (II)

$$\frac{d}{dt} \langle \Delta p_i \, \Delta p_j \rangle_f = 2 \langle B_{ij} \rangle_f$$

with $\Delta\vec{p} := \vec{p} - \langle \vec{p} \rangle_f$

• Diffusion (in momentum space); not to be confused with diffusion in "normal" space (D).

• In isotropic media, $\overleftrightarrow{B}$ admits a (longitudinal,transverse) decomposition $\Rightarrow$ only 2 independent coefficients.

• Essentially a markovian process

A few words on the transport coefficients (III)

How well / precisely do we know these transport coefficients (in the case of heavy quarks) ?

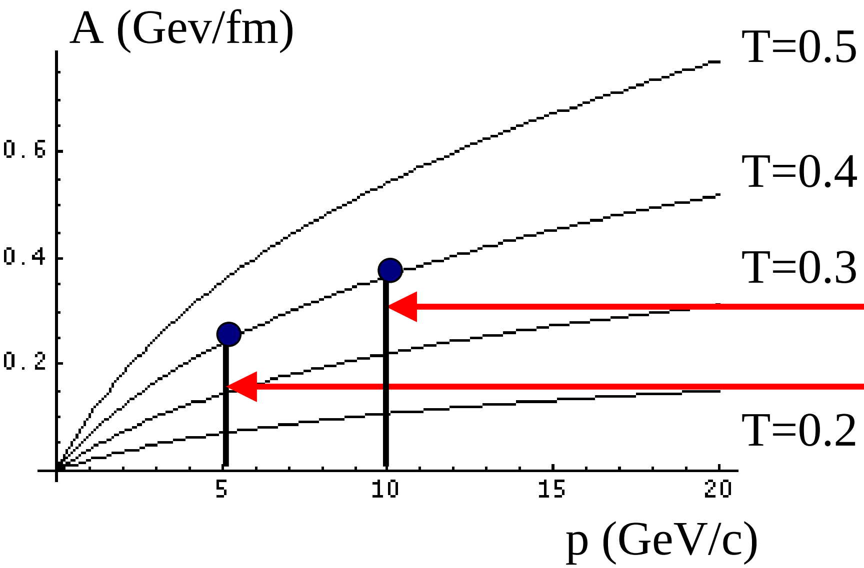
Start from a more « fundamental » theory

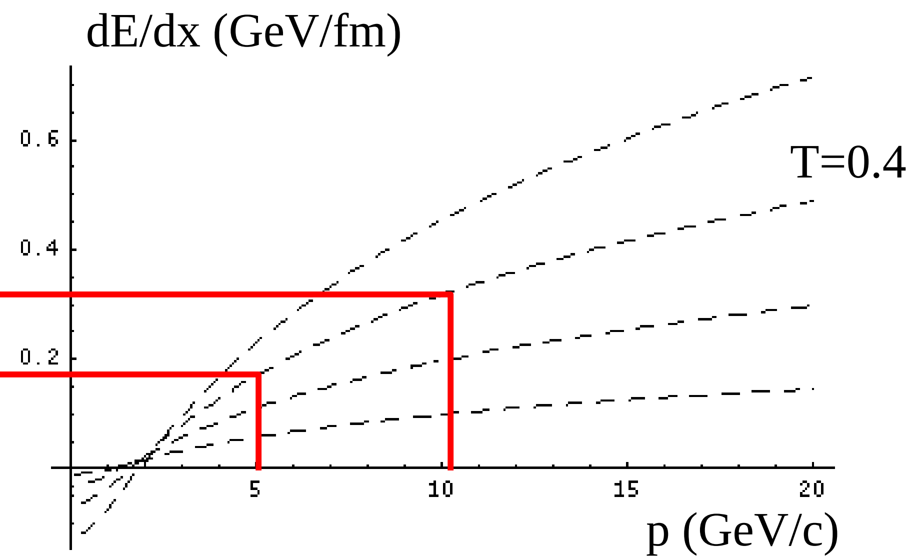
(for instance, Boltzmann equation, assuming – although not mandatory – that surrounding medium is thermalized)

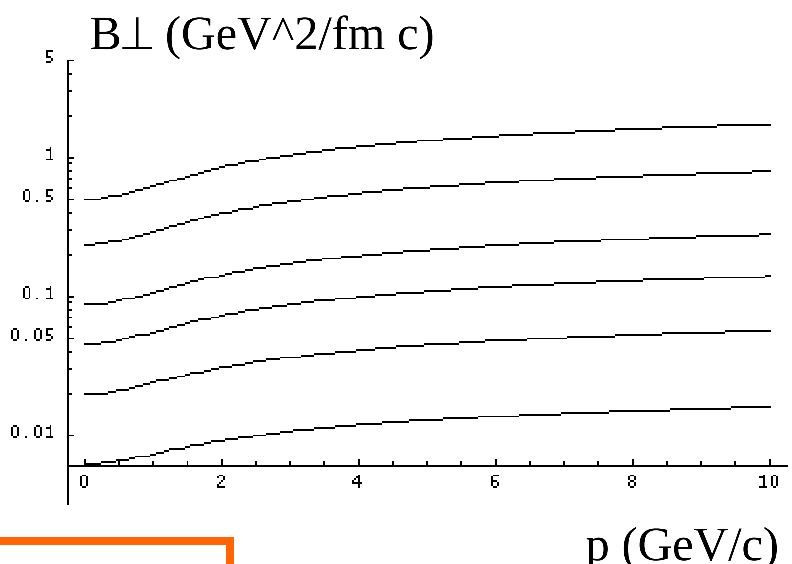
• In case of collisions (2 $\rightarrow$2 processes): Pioneering work of Cleymans (1985), Svetitsky (1987), extended later by Mustafa, Pal & Srivastava (1997). The FP coefficients are expressed as moments of the differential cross section.

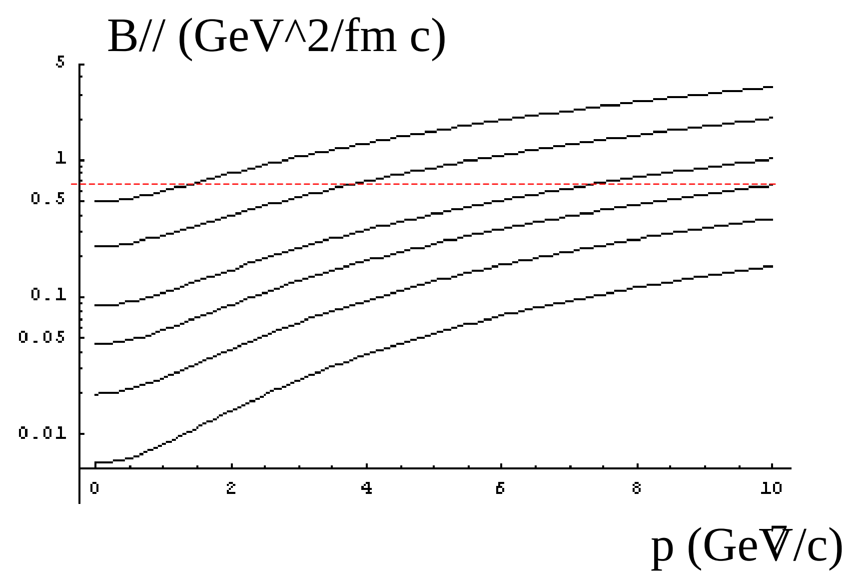
• For radiation: Numerous works on energy loss; very little seems to have been done on diffusion coefficients

A few words on the transport coefficients: The case of charm

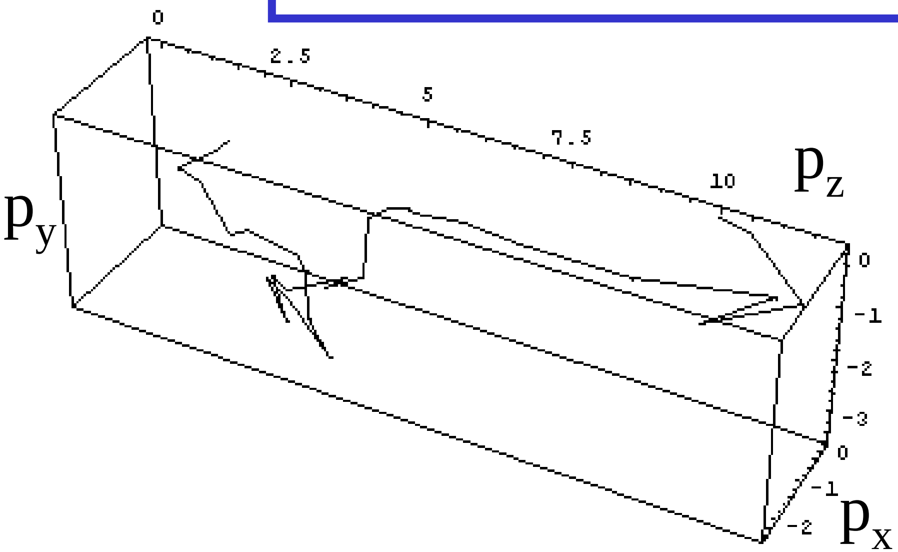








From Fokker-Planck coefficients → Langevin forces



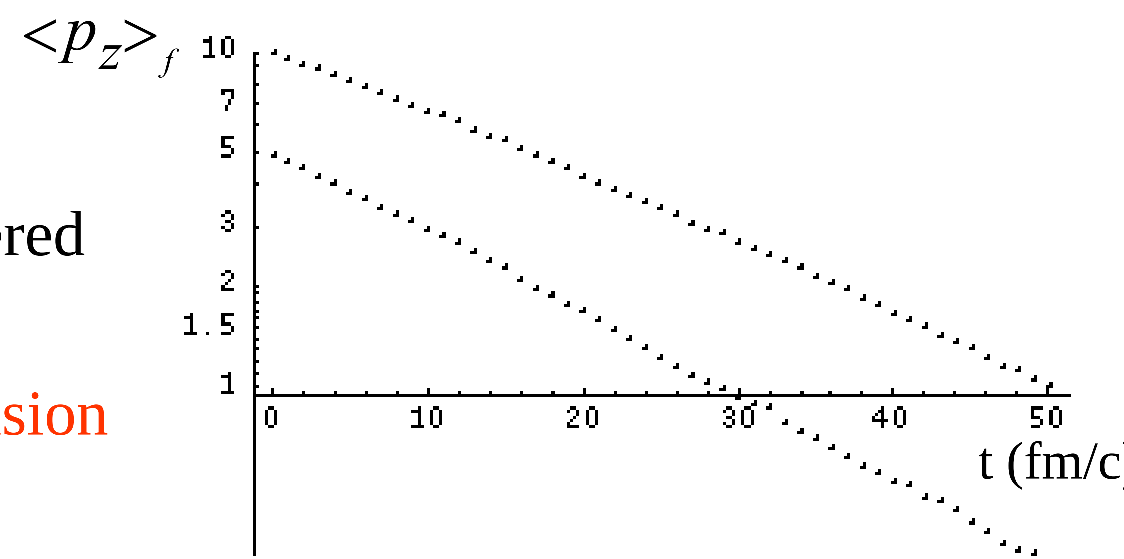
Evolution of one c quark inside a $\mu=0$ -- T=400 MeV QGP.

Starting from p=(0,0,10 GeV/c).

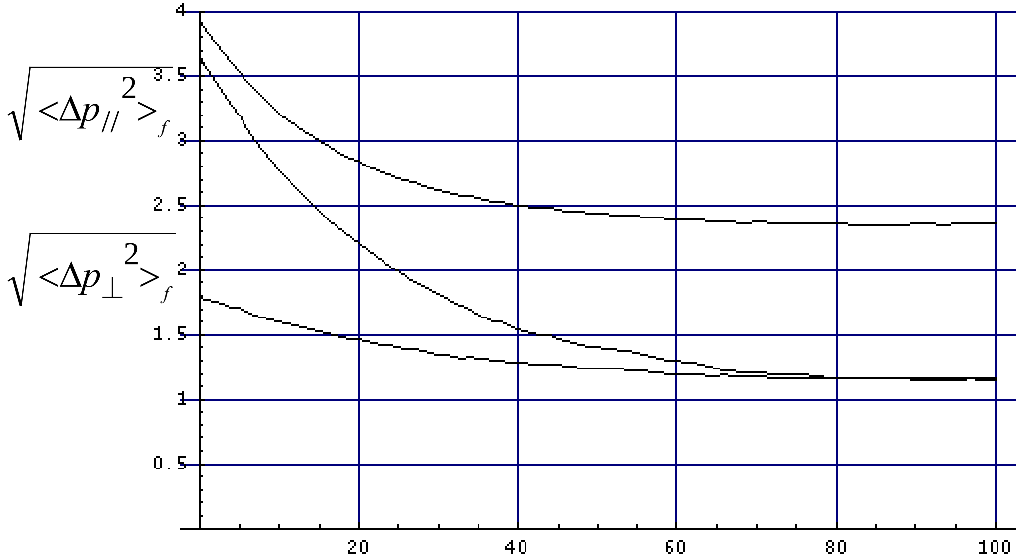
Evolution time = 30 fm/c

… looks a little less « erratic » when considered on the average:

Relaxation time >> collision time : self consistent



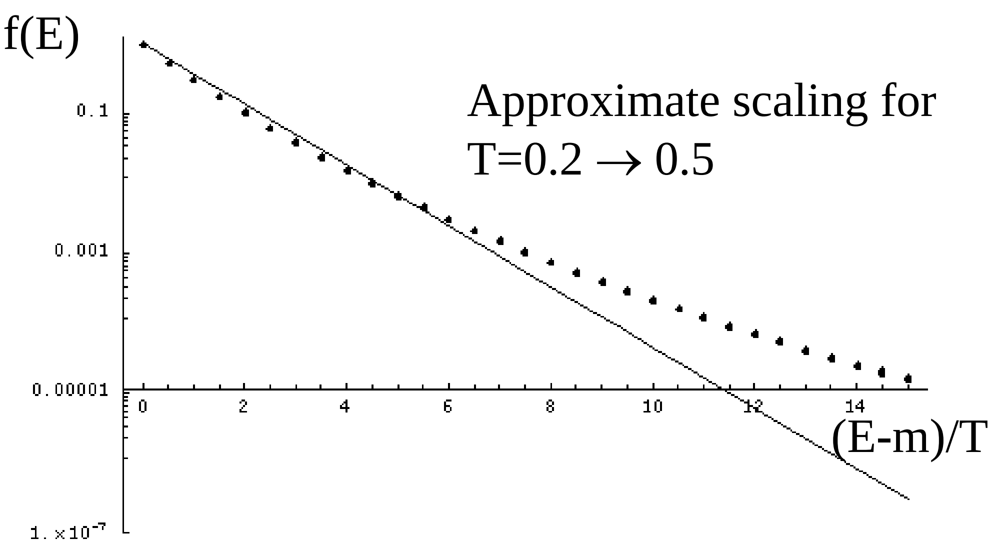
First results on c-quark evolution



Relaxation of <E>, of $\sqrt{<\Delta p_{\perp}^2>_f}$ and of $\sqrt{<\Delta p_{//}^2>_f}$ for c-quarks produced in 200 GeV p-p collisions (Δy=2).

Evolution in a μ=0 -- T=400 MeV QGP.

Once again : long relaxation times



Asymptotic energy distribution: no Boltzmann; more like a Tsallis

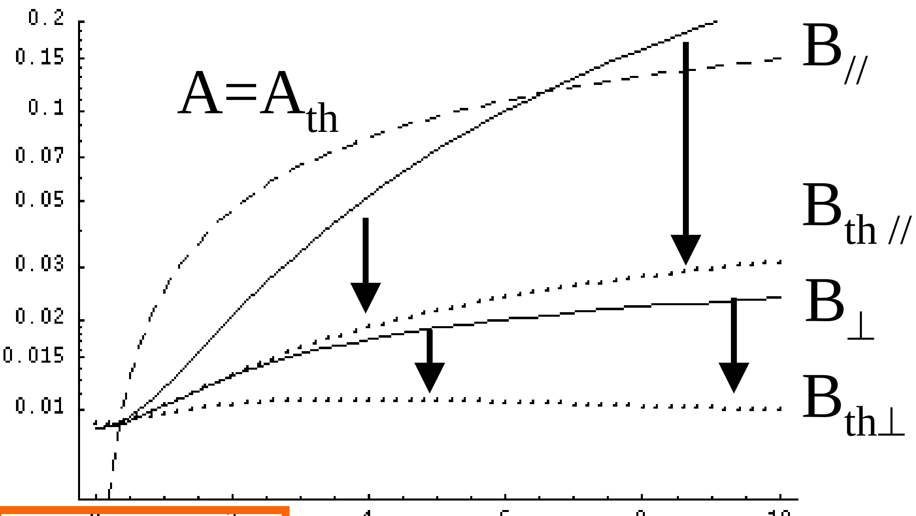
Walton & Rafelski (1999)

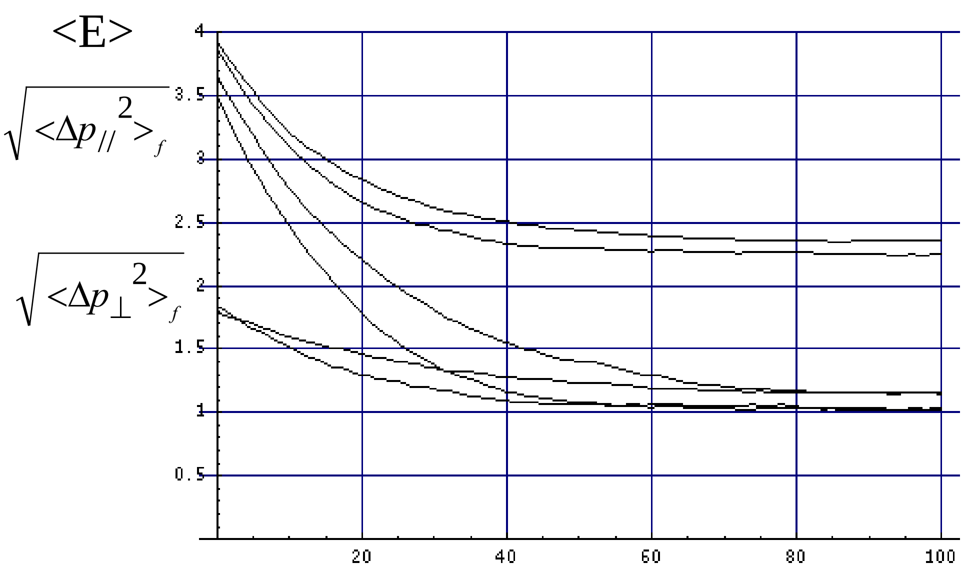
Too much diffusion at large momentum

So what do we do ???

<u>Three sets:</u>

1. FP coefficients deduced by Mustafa, Pal and Srivastava (MPS)
2. Adapt (A,B) → (A_{th} =A,B_{th}) such then the associated f_{asympt} is a Boltzmann distribution, and then → (κ_{col}A, $\kappa_{col}B_{th}$) with κ_{col} varying from 0 → ∞ in order to span from free streaming → instantaneous thermalization.





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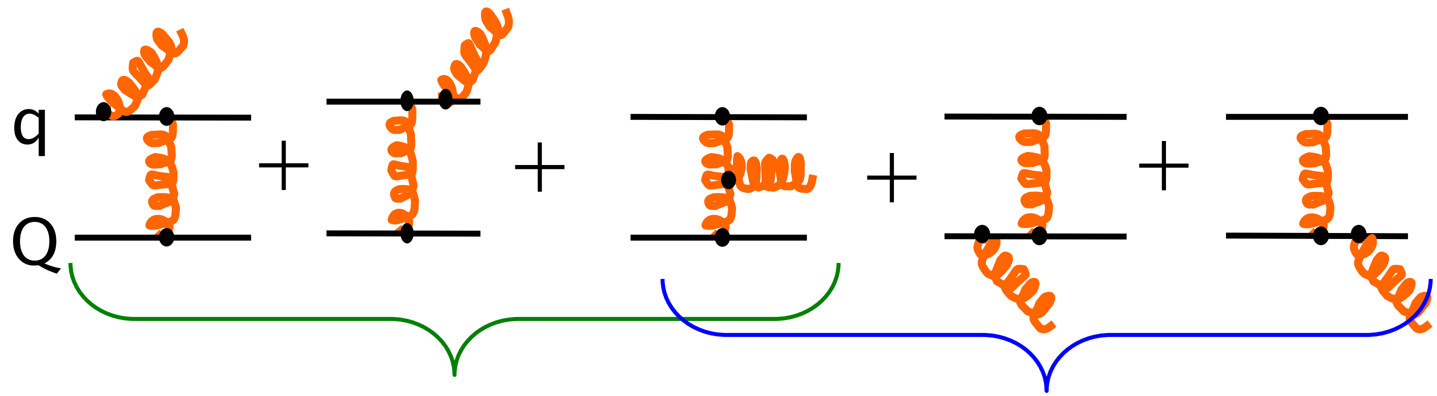
"Radiative" coefficients

MPS + « radiative » coefficients deduced using the Gunion and Bertsch elementary cross section for qQ →qQ+g and its equivalent for gQ →gQ+g in t-channel (u & s-channels are suppressed at high energy).

$\mathcal{M}^{q}{}_{rad} \equiv$

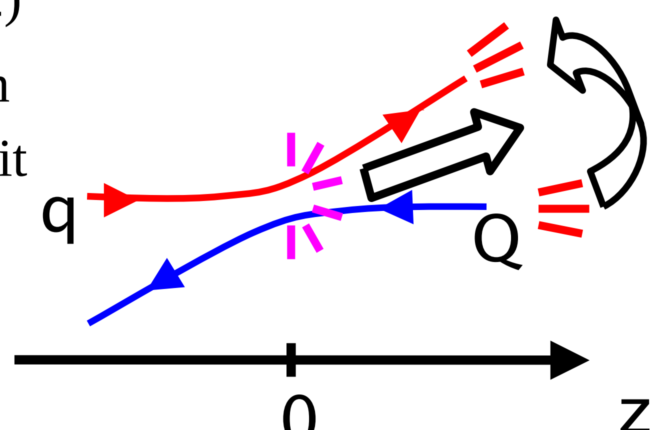


Forward gluon   Backward gluon (dead cone)

<u>At large *s*:</u>

(Gunion & Bertsch ‘82)

ω << E approximation
⇔ ultra-relativistic limit
⇒ In CM, the quarks radiate along q and q' directions :



Factorization:

$$\mathcal{M}^{q}{}_{rad} \propto \mathcal{M}^{q}{}_{col} \times \left[\frac{\vec{k}_T}{k_T^2} + \frac{\vec{l}_T - \vec{k}_T}{\left(\vec{l}_T - \vec{k}_T\right)^2}\right]$$

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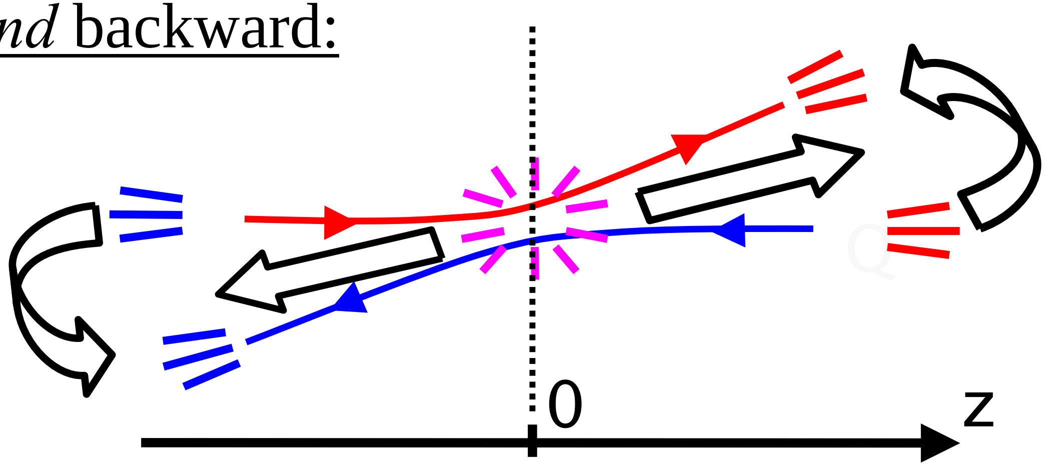
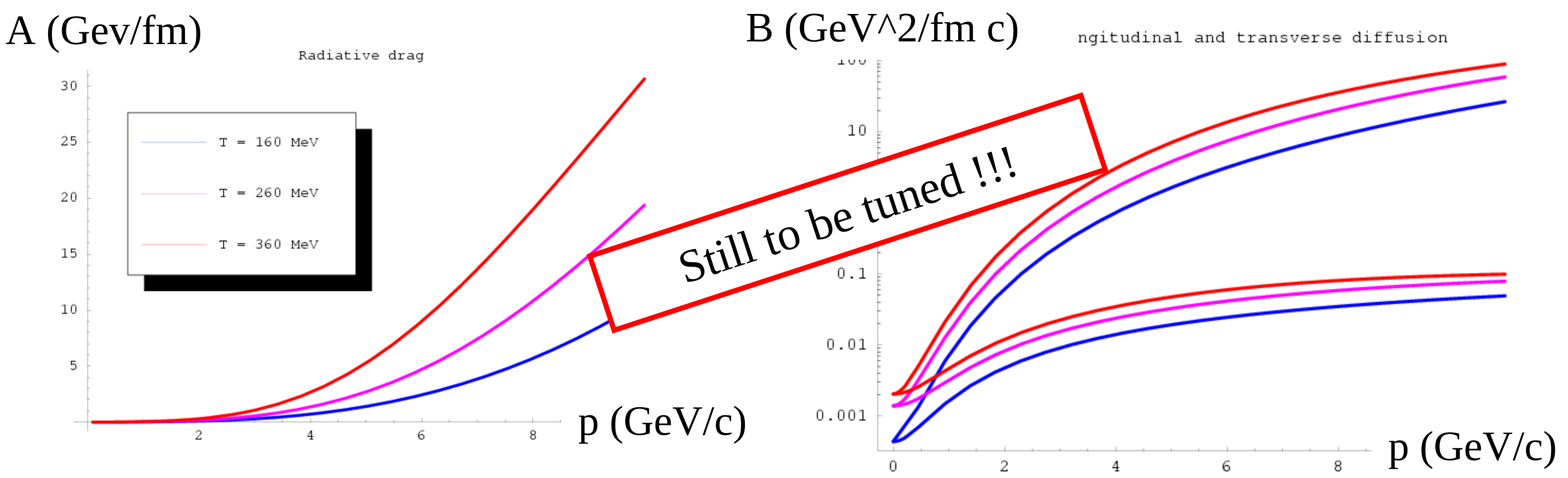
"Radiative" coefficients (II)

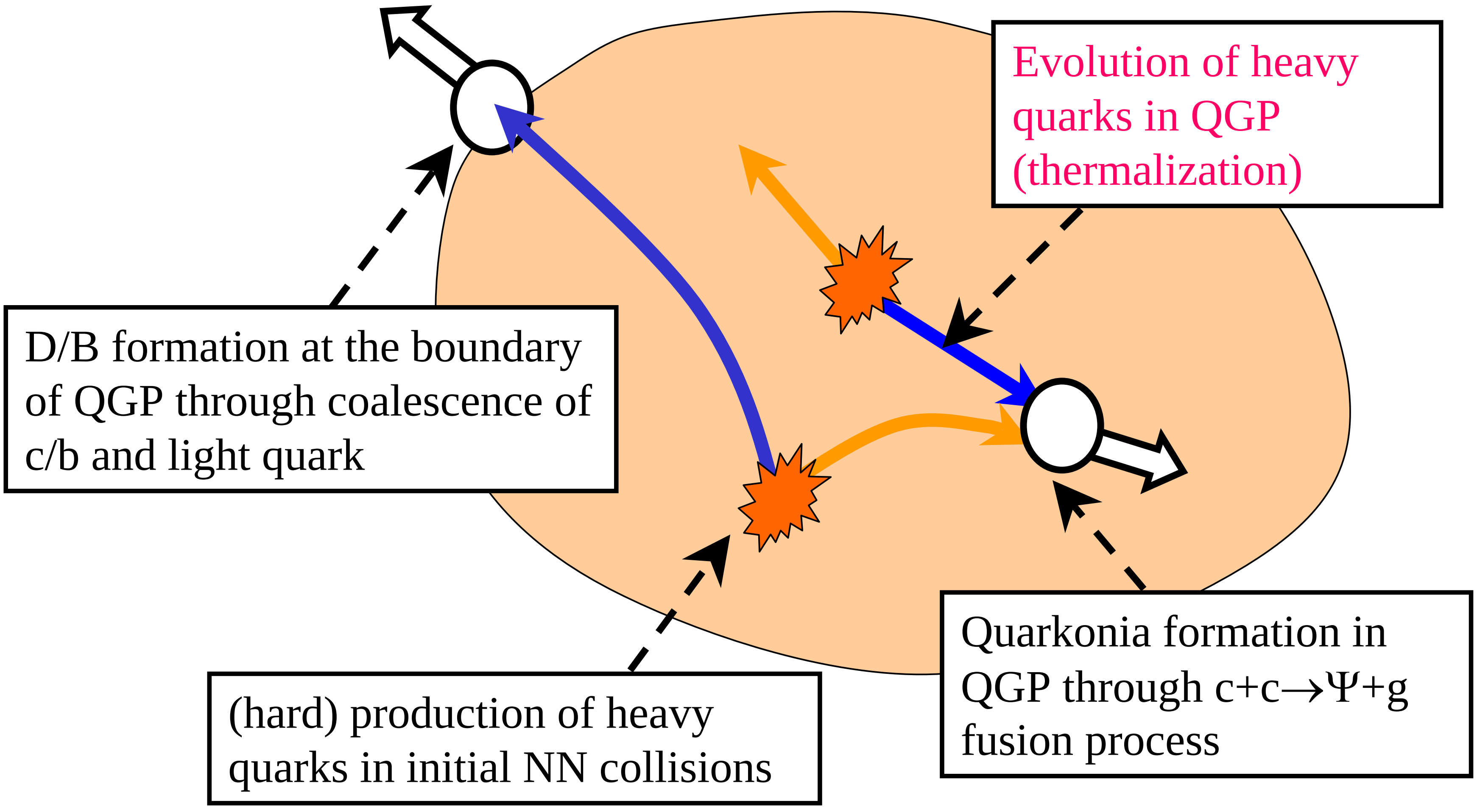
Forward *and* backward:





No LPM for the time ⇒ MPS + κ_{rad} x RAD

Schematic view of our model for hidden and open heavy flavors production in AA collision at RHIC and LHC



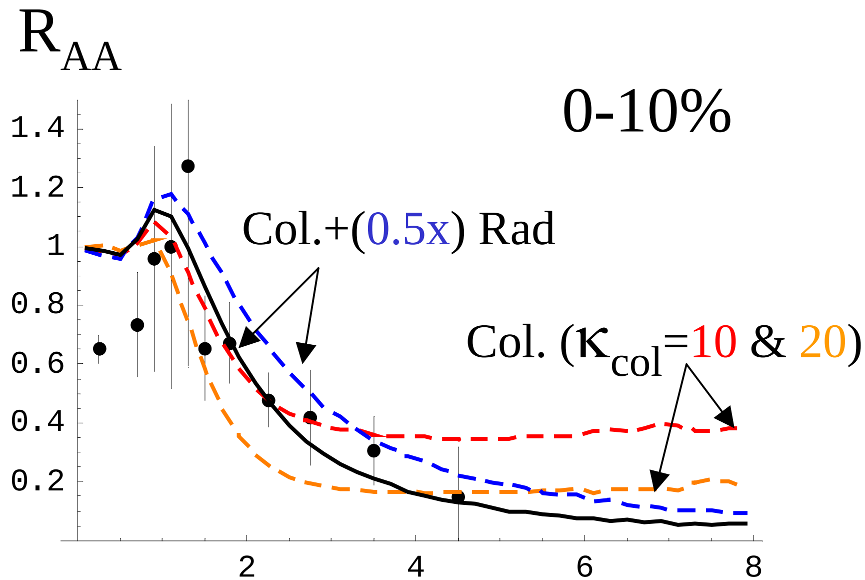
Other hypothesis / ingredients of c-evolution and D production

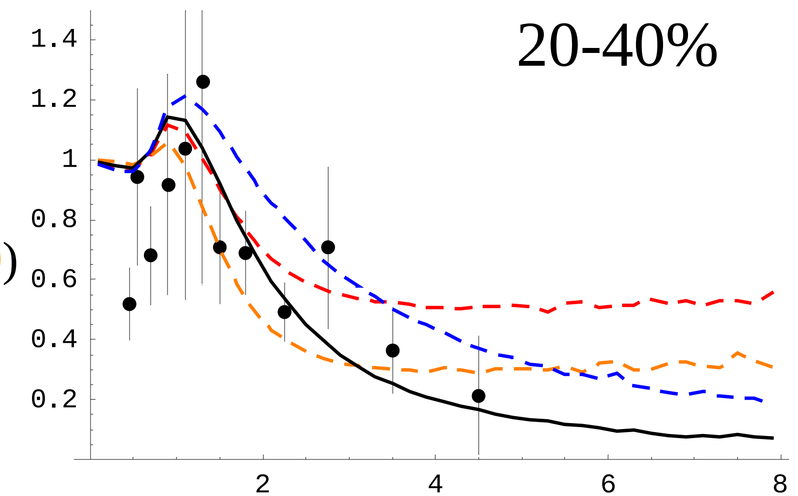
- Au – Au collision at 200 AGeV.
- c-quark transverse-space distribution according to Glauber
- c-quark transverse momentum distribution as in d-Au (STAR)… seems very similar to p-p ⇒ No Cronin effect included; too be improved.
- c-quark rapidity distribution according to R.Vogt (Int.J.Mod.Phys. E12 (2003) 211-270).
- Medium evolution: 4D / Need local quantities such as T(x,t) ⇒ Bjorken (boost invariant with no transverse flow) or various more realistic hydrodynamical evolution (Heinz & Kolb, Huovinen)
- Evolution according to Bjorken time

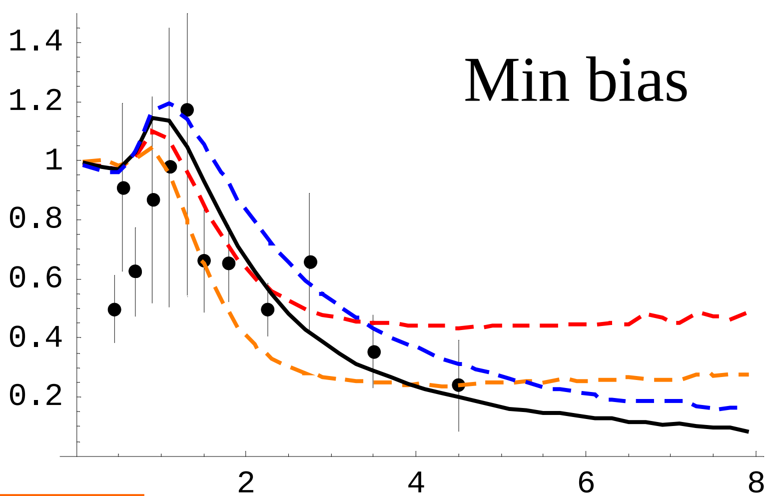
Other hypothesis / ingredients of c evolution and D production

- No force on the c-quarks before thermalization, Langevin force on c-quarks inside QGP and no force on charmed « mesons » during and after transition.
- D & B produced via Coalescence vs. Fragmentation mechanism.
- In fact, no beauty up to now; should be included.

Leptons (← D decay) transverse momentum distribution (y=0)







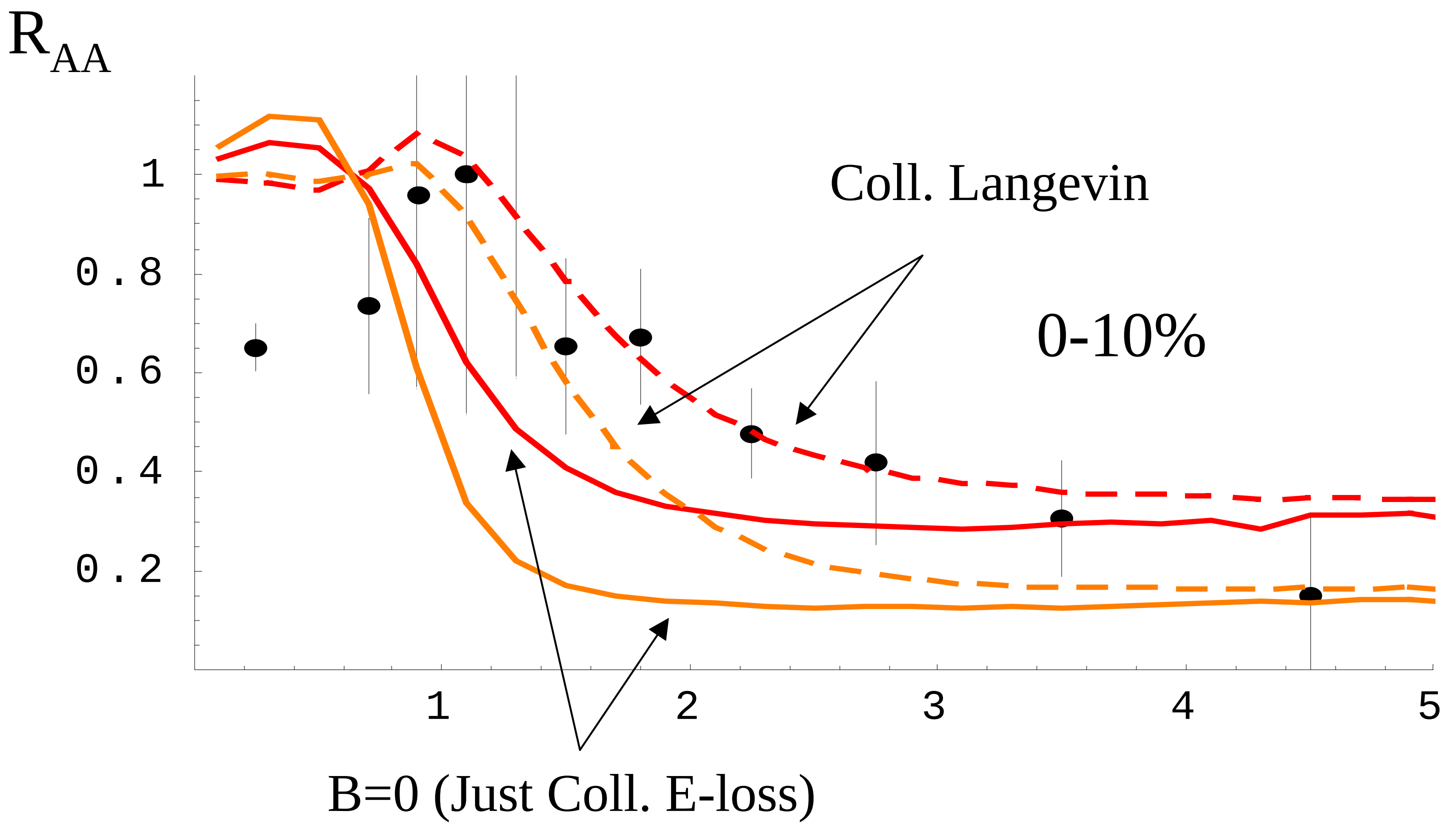
<u>Conclusion I:</u>

One can reproduce the R_{AA} either :

- With cranked up collisional processes

- With « reasonnable » (κ_{rad} not far away from unity) use of radiative processes.

Leptons (← D decay) transverse momentum distribution (y=0)



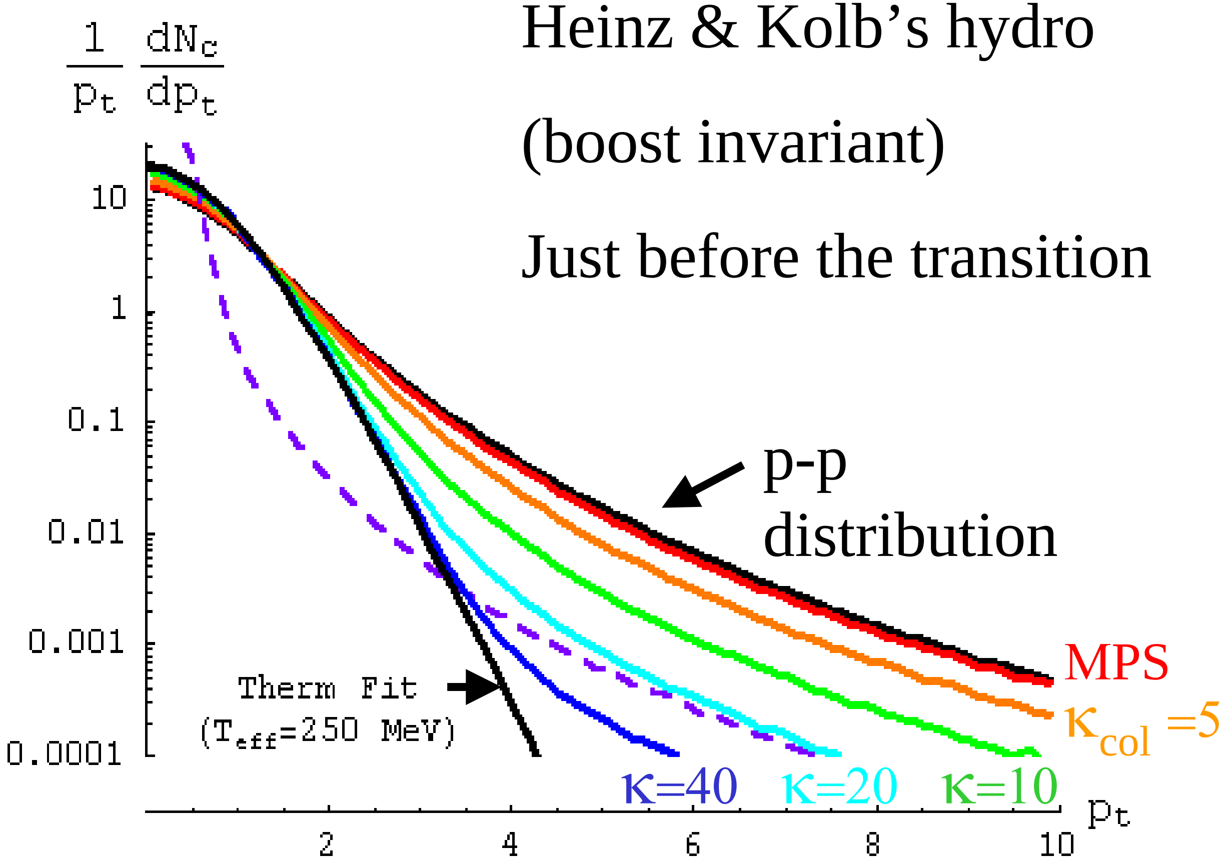
Transition from pure E-loss (high E) towards thermalization regime (intermediate E)

c-quarks transverse momentum distribution (y=0)

Heinz & Kolb's hydro

(boost invariant)

Just before the transition



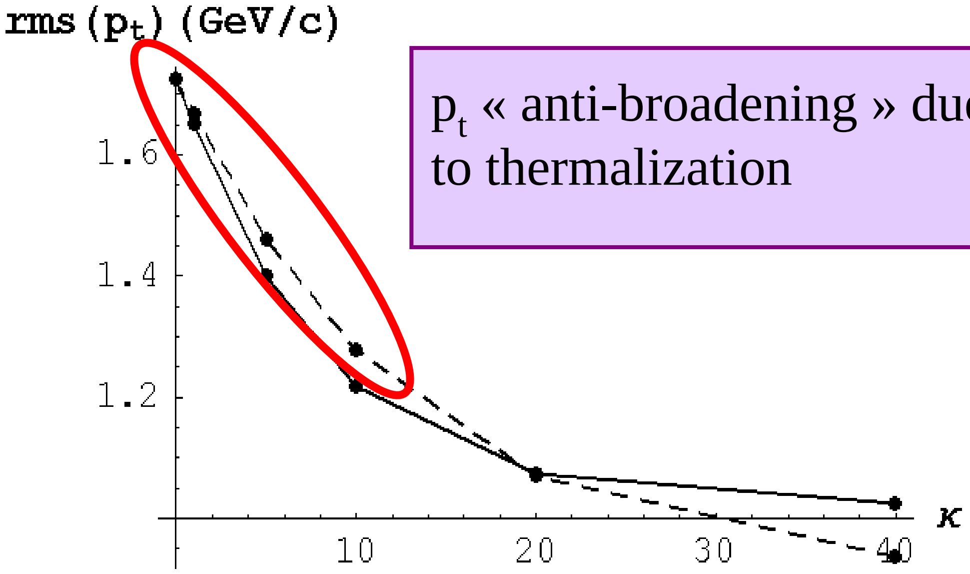
<u>Conclusion II:</u>

κ_{col} =10-20: Still ways to go before thermalization !!!

c-quarks transverse-momentum spectra

Finer Effects:

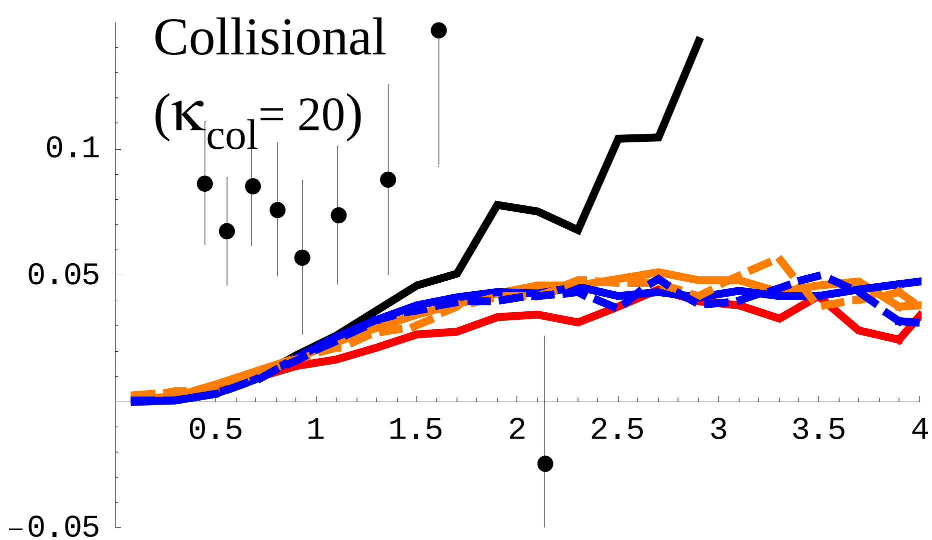
- Effect of radial flow (of QGP) on c-quarks (y=0)
- p_t « antibroadening »:

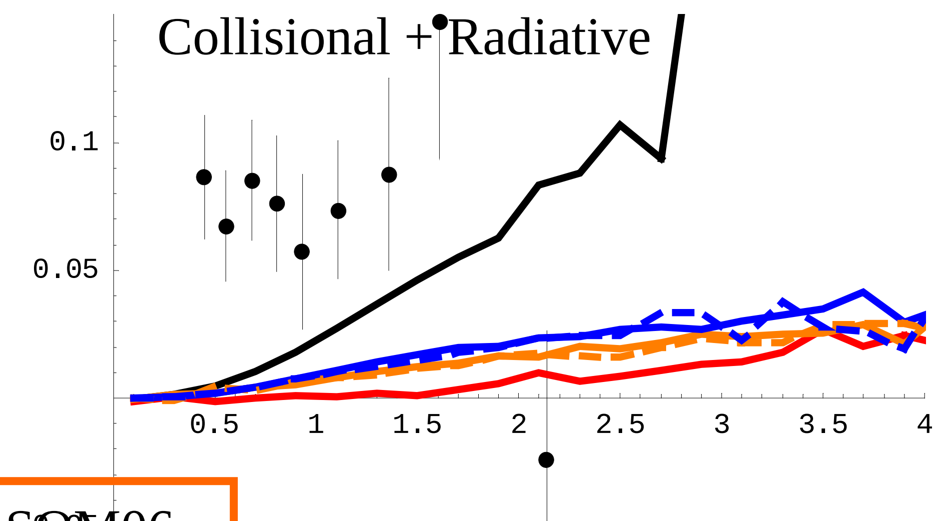


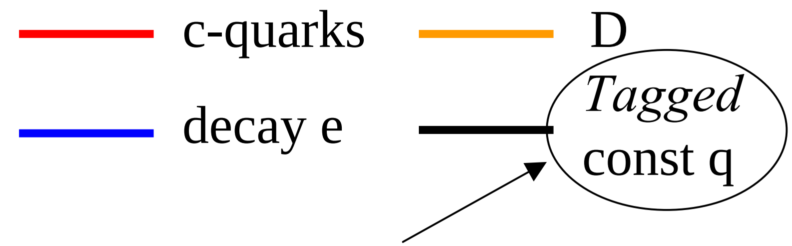
p_t « anti-broadening » due to thermalization

… Might be masked by initial-state interactions

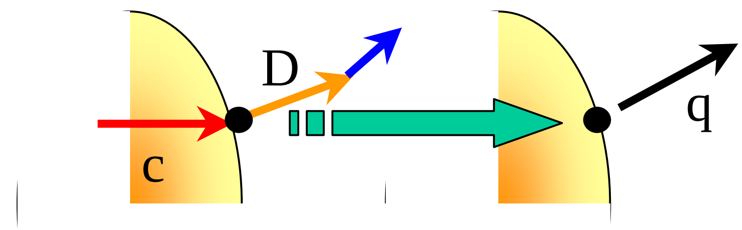
Non-Photonic Electron elliptic-flow at RHIC: comparison with experimental results







Freezed out according to thermal distribution at "punch" points of c quarks through freeze out surface:

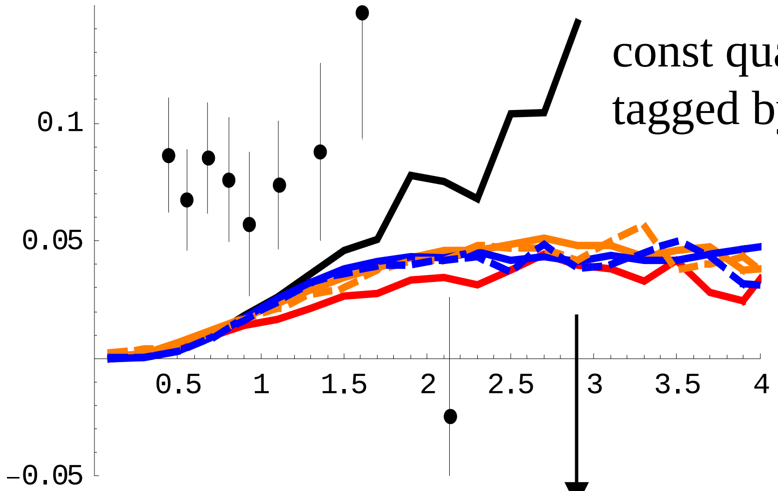


<u>Conclusion III:</u>

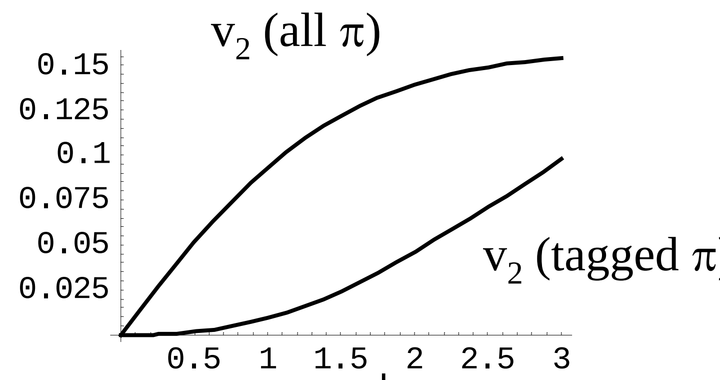
One cannot reproduce the v_2 consistently with the R_{AA}!!!

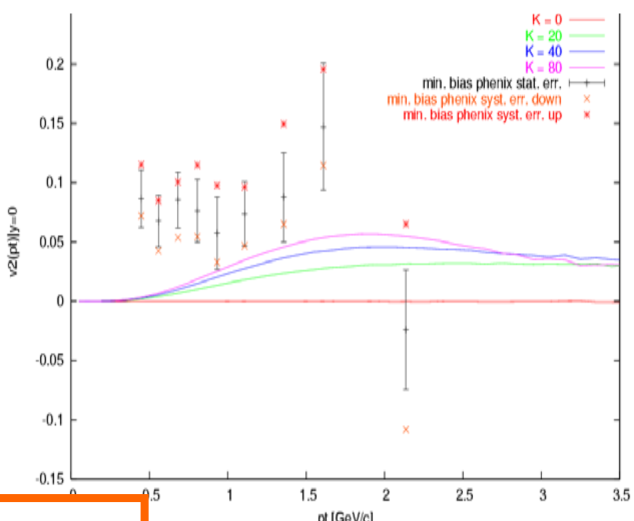
Contribution of light quarks to the elliptic flow of D mesons is small

Non-Photonic Electron elliptic-flow at RHIC: Looking into the bits…



const quark
tagged by c





C-quark does not see the « average » const quark… Why ?

Bigger coupling helps… a little but at the cost of R_{AA}

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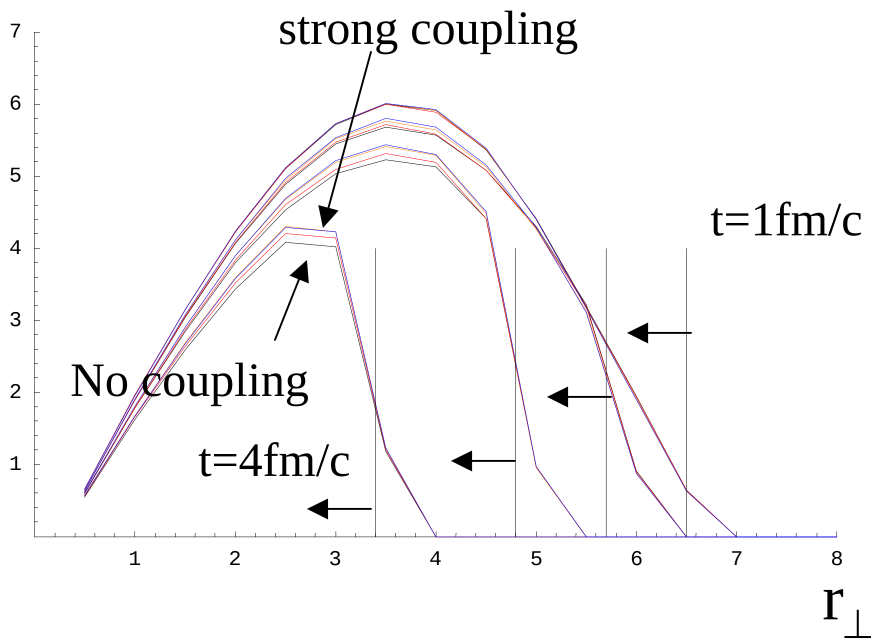
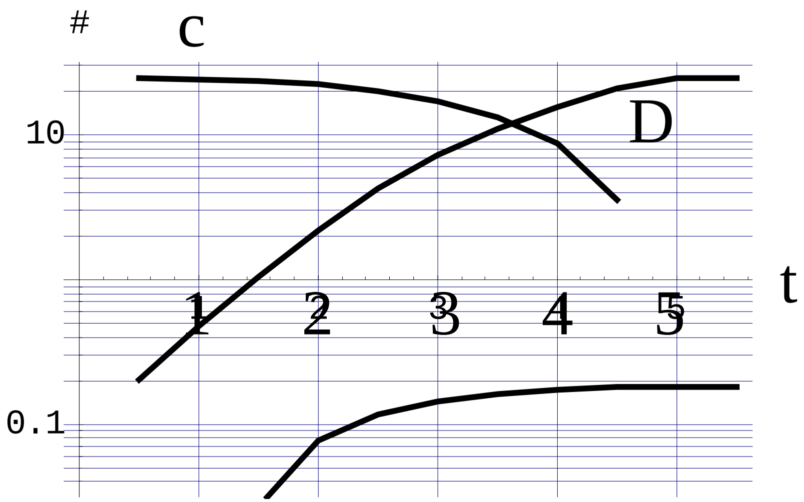
Non-Photonic electron elliptic-flow at RHIC: …and the bites (ouch)

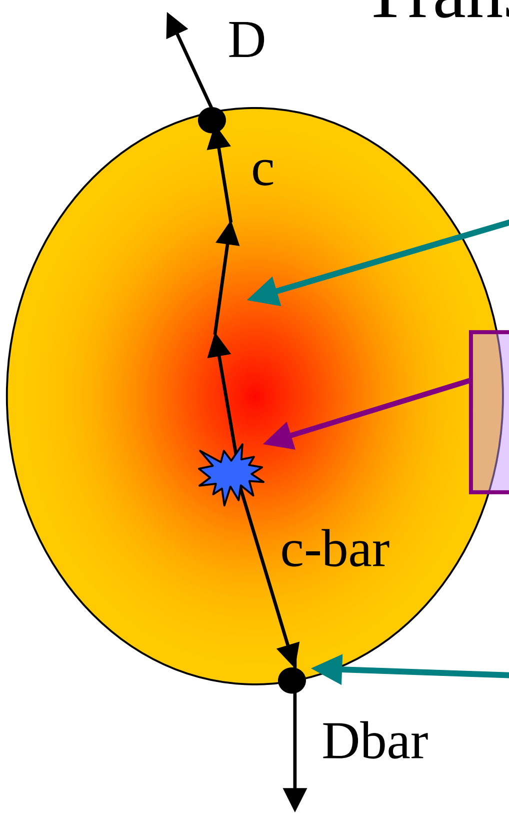




Spatial transverse-distribution might play some role as c-quarks are *not* from the beginning "on" the freeze out surface.

Azimutal Correlations for Open Charm

Transverse plane



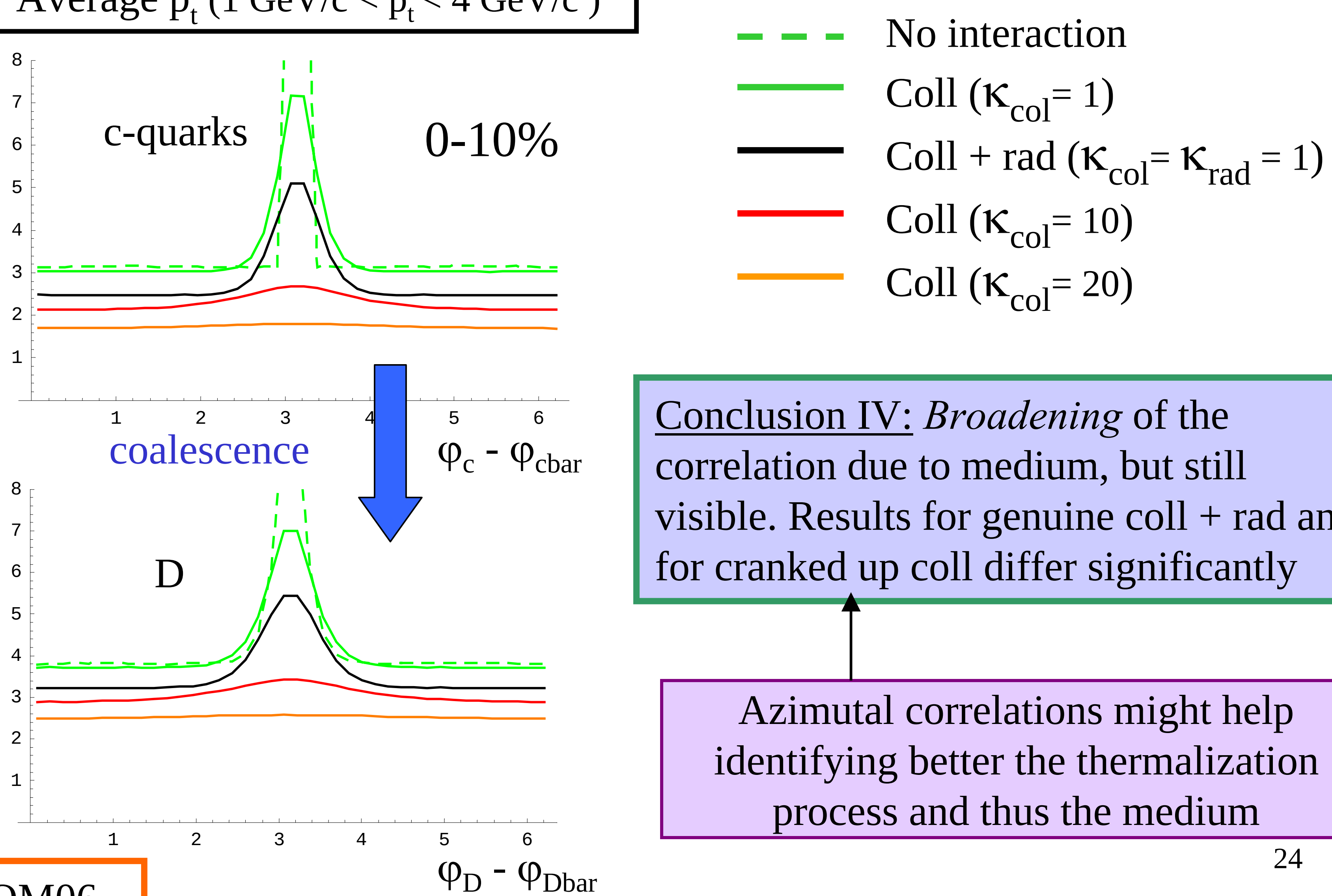
What can we learn about "thermalization" process from the correlations remaining at the end of QGP ?

Initial correlation (at RHIC); supposed back to back here

How does the coalescence - fragmentation mechanism affects the "signature" ?

Azimutal Correlations for Open Charm

Average p_t (1 GeV/c < p_t < 4 GeV/c)

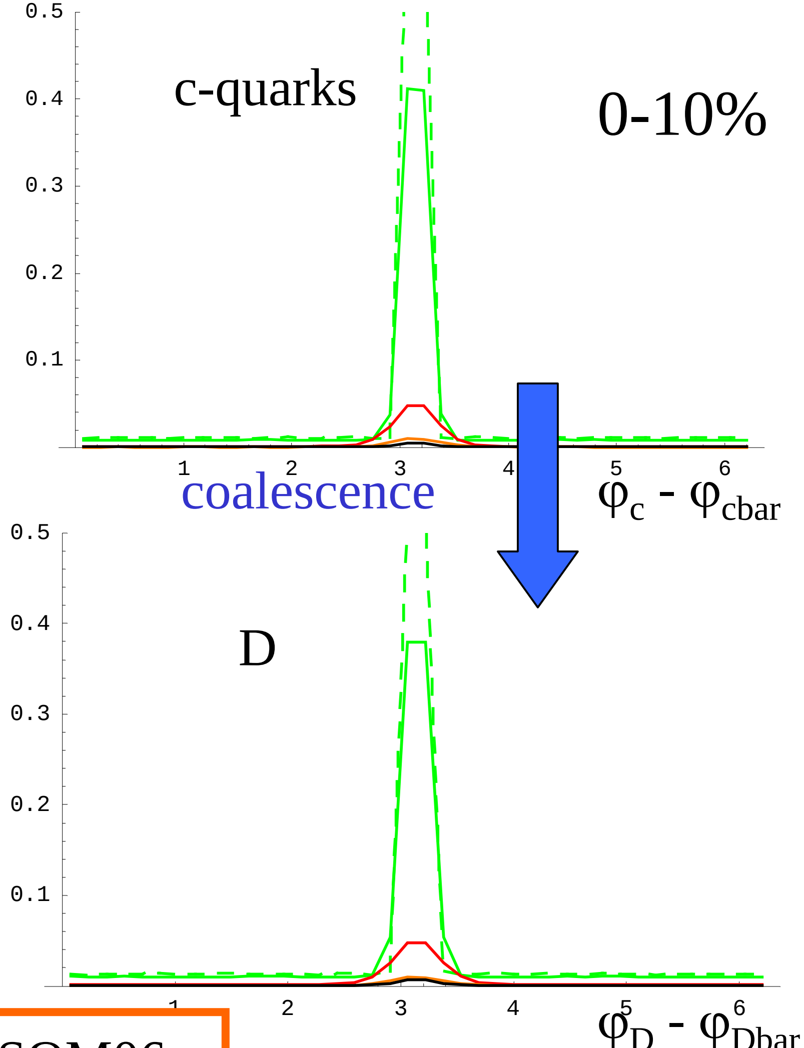


Conclusion IV: *Broadening* of the correlation due to medium, but still visible. Results for genuine coll + rad and for cranked up coll differ significantly

Azimutal correlations might help identifying better the thermalization process and thus the medium

Azimutal Correlations for Open Charm

Large p_t (1 GeV/c < p_t < 4 GeV/c)



- - - No interaction
Coll (κ_{col}= 1)
Coll + rad (κ_{col}= κ_{rad} = 1)
Coll (κ_{col}= 10)
Coll (κ_{col}= 20)

Large reduction but small broadening for increasing coupling with the medium; compatible with corona effect

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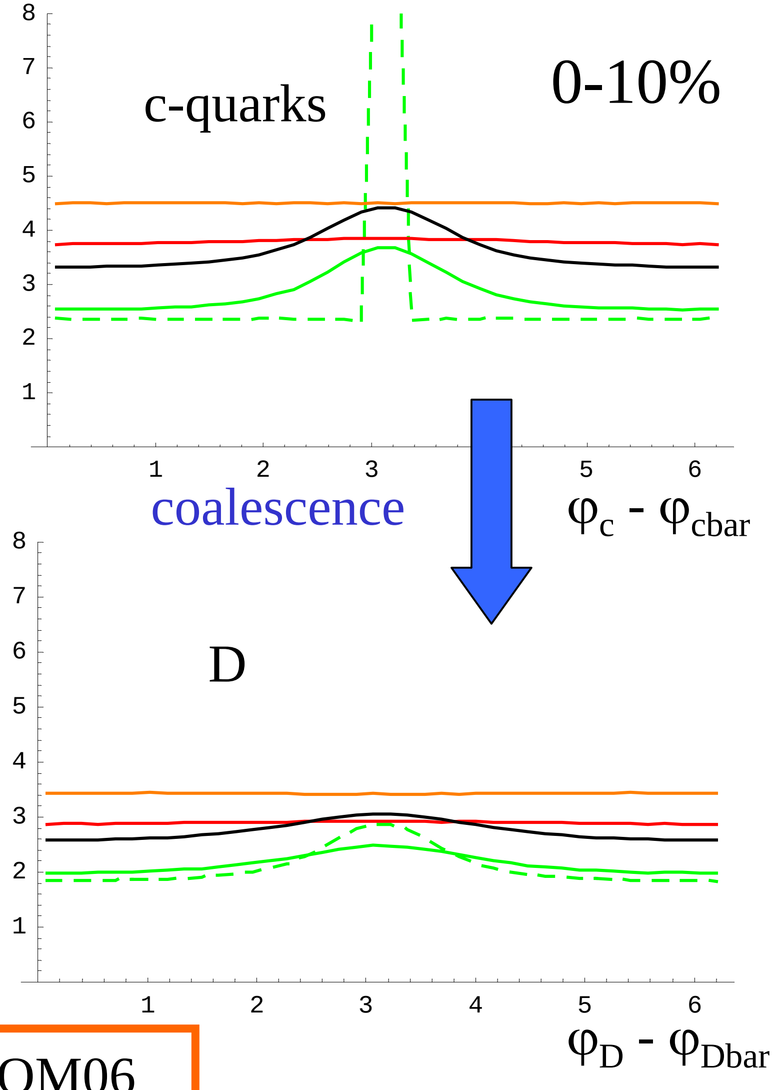
Azimutal Correlations for Open Charm

Small p_t ($p_t < 1 GeV/c$)



No interaction

Coll (κ_{col}= 1)

Coll + rad (κ_{col}= κ_{rad} = 1)

Coll (κ_{col}= 10)

Coll (κ_{col}= 20)

Small correlations at small $p_{t,}$, mostly washed away by coalescence process.

Conclusions

- Experimental data point towards a significant (although not complete) thermalization of c quarks in QGP, which should result in some p_t anti-broadening (beware of Cronin, however)
- The model seems able to reproduce experimental R_{AA}, at the price of a large rescaling κ-factor (especially at large p_t), of the order of $\kappa=10$ or including radiative processes.
- Still a lot to do in order to understand for the v_2. Possible explanations for discrepencies are:

1) Role of the spatial distribution of initial c-quarks
2) Part of the flow is due to the hadronic phase subsequent to QGP ???
3) Caveat of Langevin approach

- Azimutal correlations could be of great help in order to identify the nature of thermalizing mechanism.