Heavy Quarks in an expanding QPG Plasma

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Subatech/Nantes

Why: Heavy quarks (heavy mesons) are one of the few observables which carry information of the plasma interior

most of the light quark observables are described by hydrodynamics
-> compatible with the assumption that local equilibrium is reached

-> contain mostly information of a locally equilibrated system at the phase transition temperature

Goal: Explain the Nantes scenario and give a summary where we are

The idea:

c and b quarks are created in hard processes

-> the initial p_t distribution can be calculated by pQCD calculations presently available : FONLL (first order next to leading log)

-> no interaction with QGP: final heavy meson p_T distribution close to the initial heavy quark p_T distribution

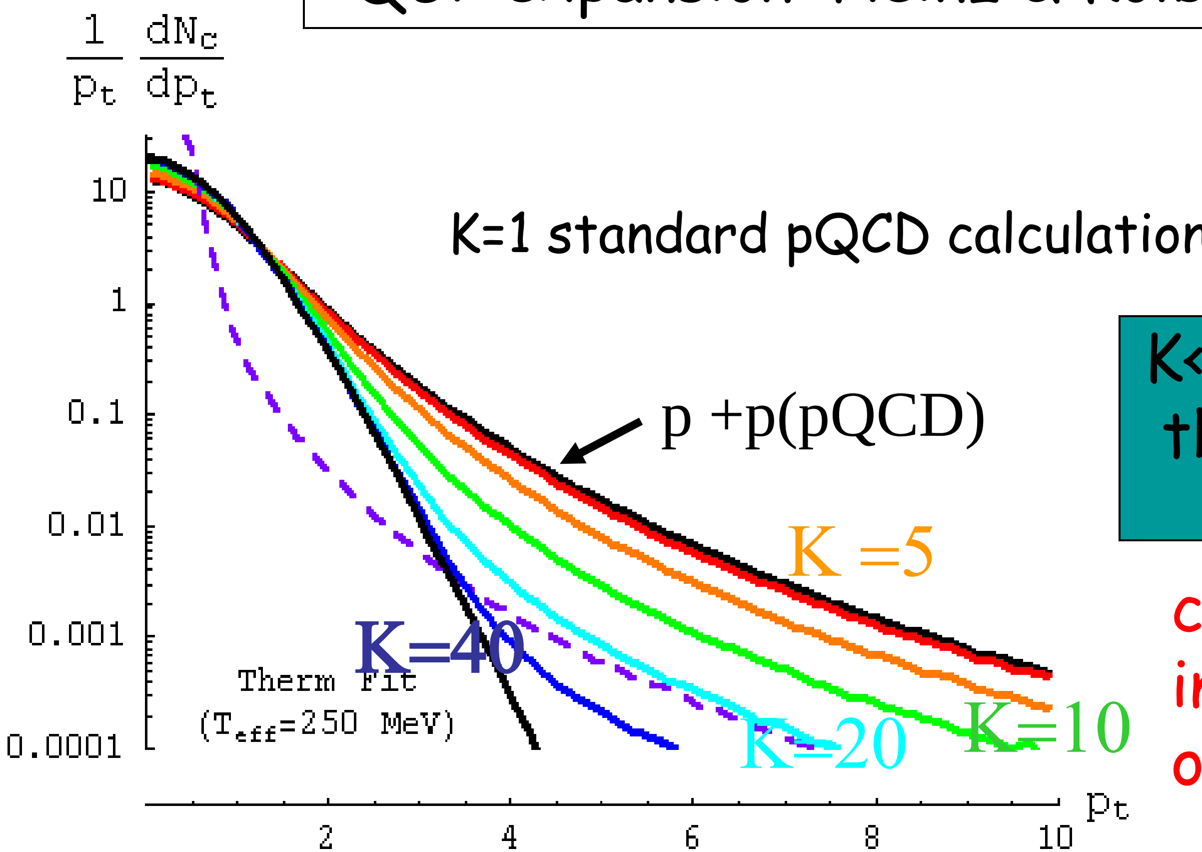
-> interaction: distribution of heavy mesons approaches thermal distribution

-> if there is a large difference between initial and thermal distribution the degree of approach to a thermal distribution reflects the interaction with the plasma particles

-> the final heavy meson distribution depends then on the expansion of the plasma but is difficult to nail down from the data this scenario

Interaction of c and b with the QGP

QGP expansion: Heinz & Kolb's hydrodynamics



K< 40: plasma does not thermalize the c or b:

c and b carry direct information on the QGP

This may allow for studying plasma properties using pt distribution, v_2 transfer, back to back correlations etc

The lever arm is sufficient to study the interaction

but

what we can compare with experiment is a combination of two effects

- the elementary interaction of the heavy quark with a plasma particle (well studied)

- the expansion of the plasma which determines the number and energy of the heavy quark plasma interaction (not really addressed)

which we want to separate

Whether this is possible we will study later

The Nantes approach

to the interaction of heavy quarks with the plasma

The plasma expansion is described by the hydro dynamical model of Heinz and Kolb
-> reproduces many light quark observables

The interaction between heavy quarks and plasma:

elastic collisions
radiative collisions
Landau Pomerantschuk Migdal effect

all based on perturbative QCD but with improvements compared to standard approaches

Weak points of the existing calculations of coll energy loss

R_{AA} or energy loss is determined by the elementary elastic scattering cross sections.

$$\frac{d\sigma^{qq\to qq}}{dt} = \frac{4}{9}\frac{\pi\alpha_s(t)^2}{s^2}\frac{s^2+u^2}{t^2+\kappa m_D^2}$$

neither $\alpha(t)$ nor κm_D^2= are well determined

$\alpha(t)$ =is taken as constant [$0.2 < \alpha < 0.6$] or $\alpha(2\pi T)$

$m_{Dself}^2(T) = (1+n_f/6)\, 4\pi\alpha_s(m_{Dself}^2) \times T^2$ (Peshier hep-ph/0607275)

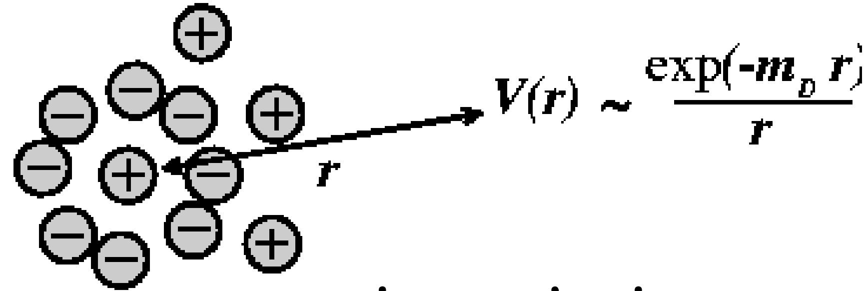
But which κ is appropriate?

κ =1 and α =.3: large K-factors are necessary to describe data

pQCD not correct?

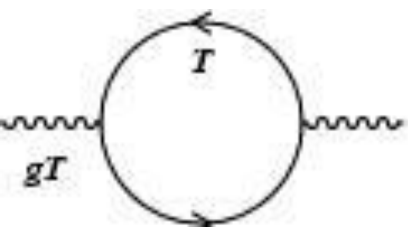
Is there a way to get a handle on α and κ ?

A) Debye mass



PRC78 014904, 0901.0946

m_D **regulates the long range behaviour of the interaction**



Loops are formed

If t is small (<<T) : Born has to be replaced by a hard thermal loop (HTL) approach like in QED: (Braaten and Thoma PRD44 (91) 1298,2625)

For t>T Born approximation is ok

QED: the energy loss (ω = E-E')

$$-\frac{dE}{dx} = \frac{1}{2Ev}\int \frac{d^3k}{(2\pi)^3 2k}\int \frac{d^3k'}{(2\pi)^3 2k'}\int \frac{d^3p'}{(2\pi)^3 2E'} \times (2\pi)^4 \delta^{(4)}(p+k-p'-k') \sum \frac{n_i(k)}{d_i} |\mathcal{M}_i|^2\, \omega\,.$$

Energy loss indep. of the artificial scale t* which separates the 2 regimes

Extension to QCD

HTL in QCD cross sections is too complicated for simulations

Idea: - Use HTL ($t<t^*$) and Born ($t>t^*$) amplitude to calculate dE/dx make sure that result does not depend on t^*

- use the cross section in Born approximation

$$\frac{d\sigma^{qq\to qq}}{dt} = \frac{4}{9}\frac{\pi\alpha_s(t)^2}{s^2}\frac{s^2+u^2}{t^2+\kappa m_D^2}$$

and determine κm_D in that way that HTL calculation and Born approximation give the same energy loss

Constant coupling constant -> Analytical formula -> Phys.Rev.C78:014904
Running -> numerically

B) Running coupling constant

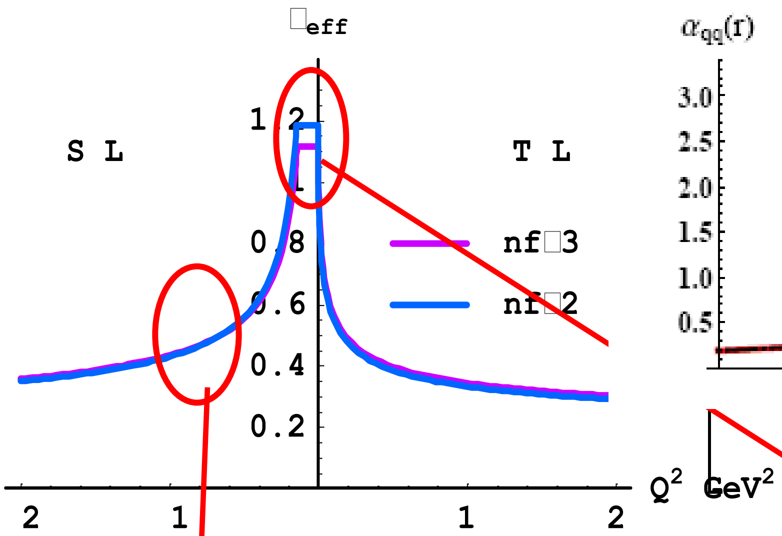
- Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)

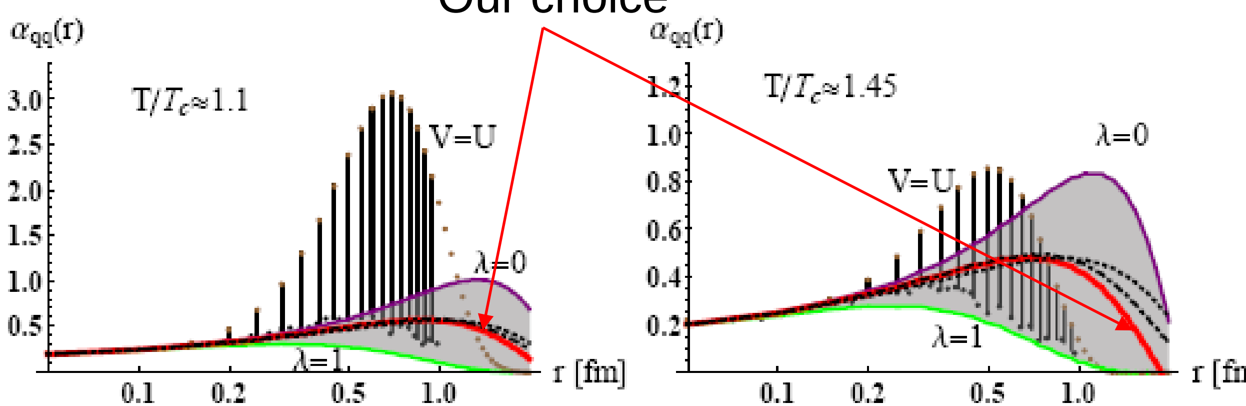
Observable = effective coupling * Process dependent fct

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

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

Our choice



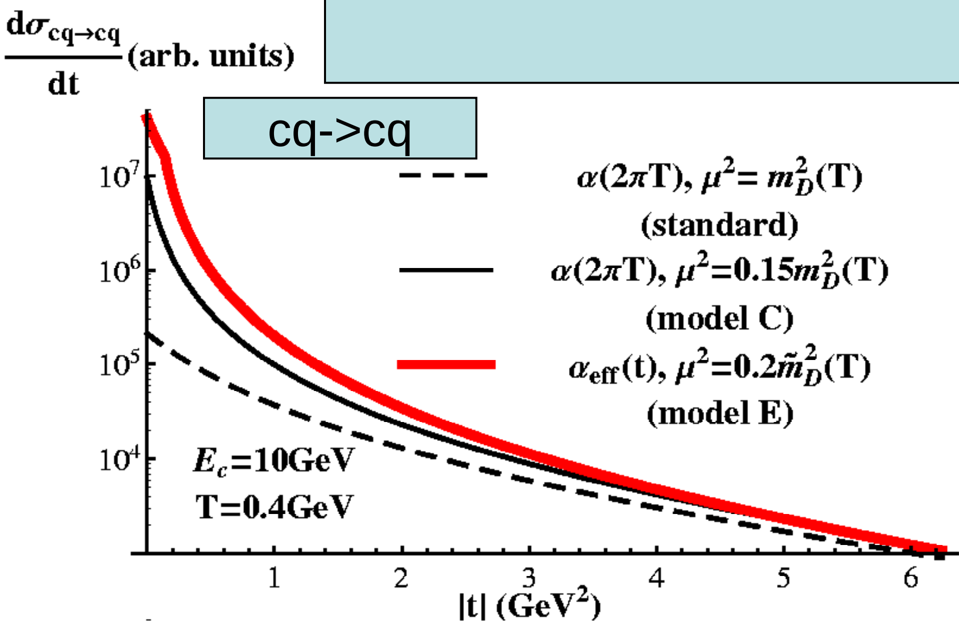


Comp w lattice results PRD71,114510

Large values for intermediate momentum transfer

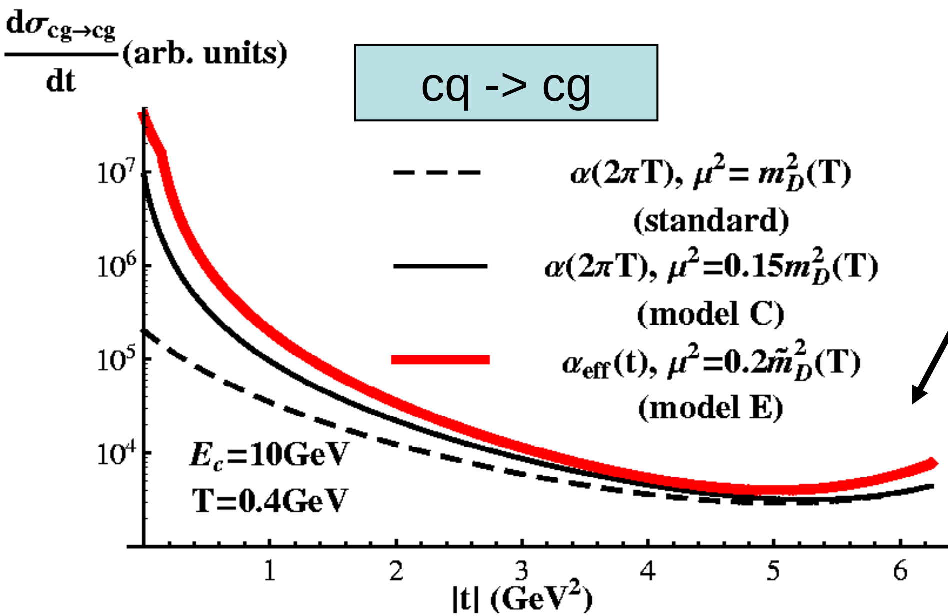
IR safe. The detailed form very close to $Q^2 = 0$ is not important does not contribute to the energy loss

The matching gives **μ=κm$_D$** ≈ 0.2 m$_D$ for running α_S for the Debye mass and **κ** ≈ 0.15 m$_D$ not running!



Large enhancement of cross sections at small t

Little change at large t



Largest energy transfer from u-channel gluons

Au + Au @ 200 AGeV

. c,b-quark transverse-space distribution according to Glauber

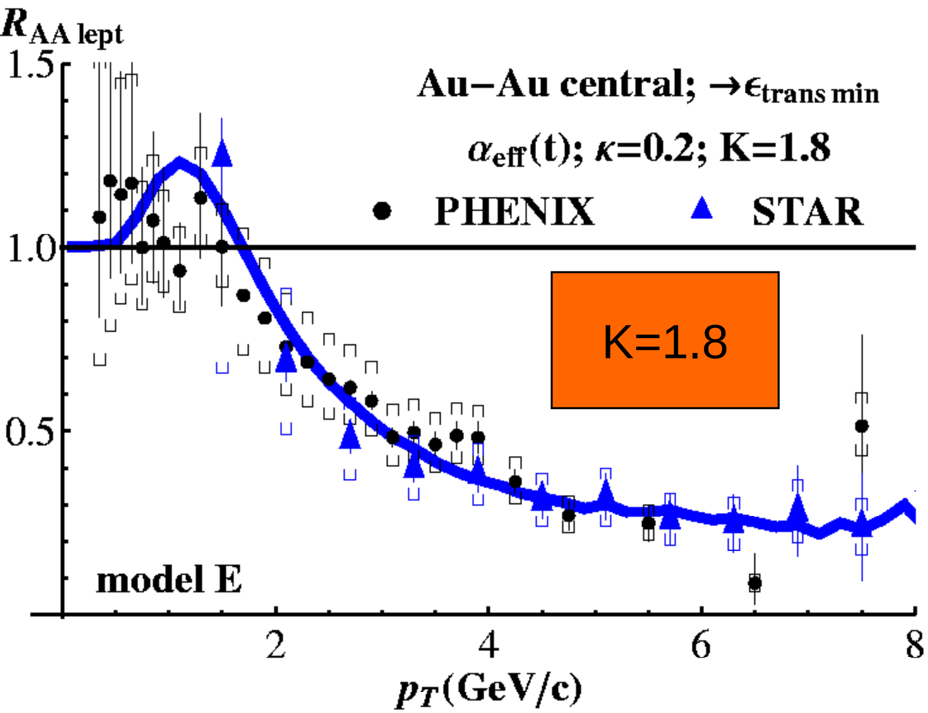
• c,b-quark transverse momentum distribution as in d-Au (STAR)... seems very similar to p-p (FONLL) ⇒ Cronin effect included.

• c,b-quark rapidity distribution according to R.Vogt (Int.J.Mod.Phys. E12 (2003) 211-270).

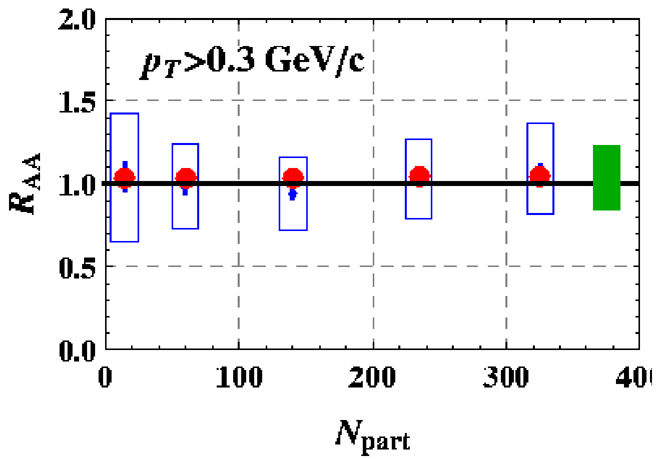
• QGP evolution: 4D / Need local quantities such as T(x,t) ⇒ taken from hydro dynamical evolution (Heinz & Kolb)

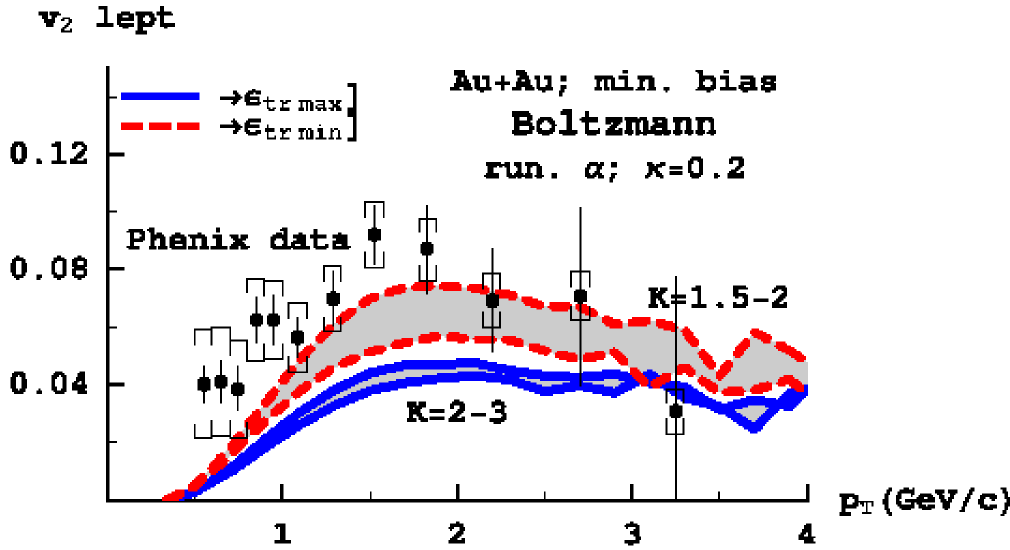
•D meson produced via coalescence mechanism. (at the transition temperature we pick a u/d quark with the a thermal distribution) but other scenarios possible.

RAA=dn/dp$_t$ (AA)/(dn/dp$_t$(pp)* N$_{bin}$)



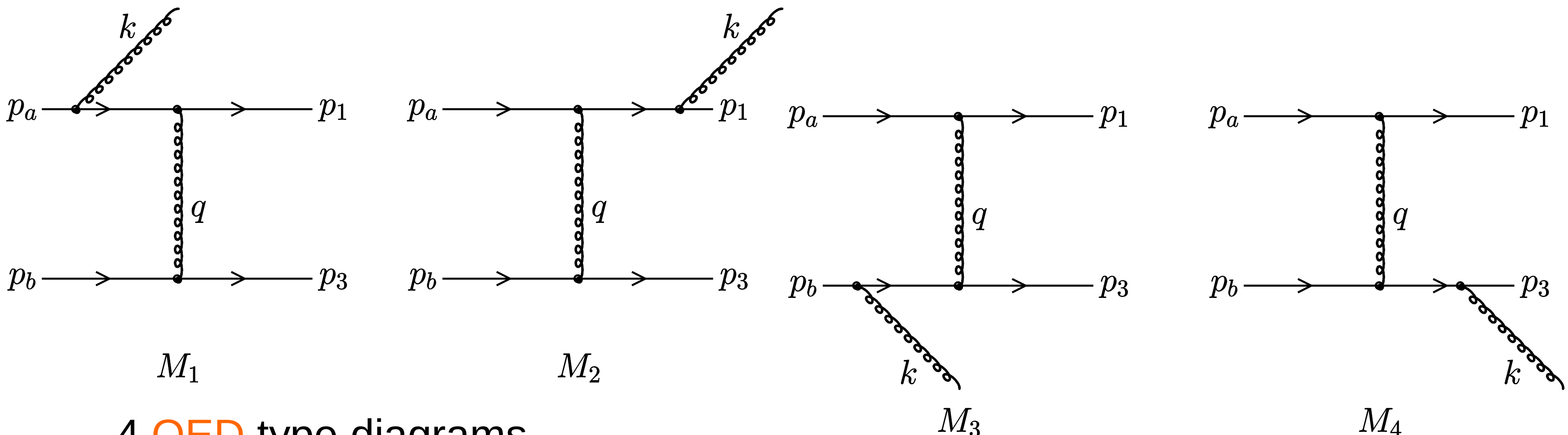
R_{AA}(central), centrality dependence and v_2 described by the same parameters.
The new approach reduces the K- factor
K=12 -> K=2
p_T > 2 bottom dominated!!
more difficult to stop,
compatible with experiment



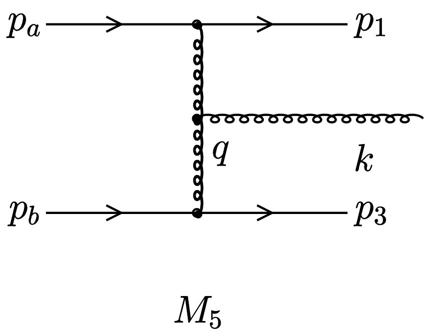


Radiative Energy Loss

Low mass quarks : radiation is the dominant energy loss process
Charm and bottom: radiation should be of the same order as collisional



4 QED type diagrams



1 QCD type diagram

Thanks to the commutator rel of the Color SU(3) operators $$T^bT^a = T^aT^b - if_{abc}T^c$$

we can regroup M1-M5 into 3 gauge invariant subgroups

$$M^1_{QED} = T^aT^b(M_1 + M_2) \quad M^2_{QED} = T^aT^b(M_3 + M_4)$$

$$M_{QCD} = if_{abc}T^c(M_1 + M_3 + M_5)$$

M_{QCD} dominates the radiation

radiative energy loss

Energy loss per unit length

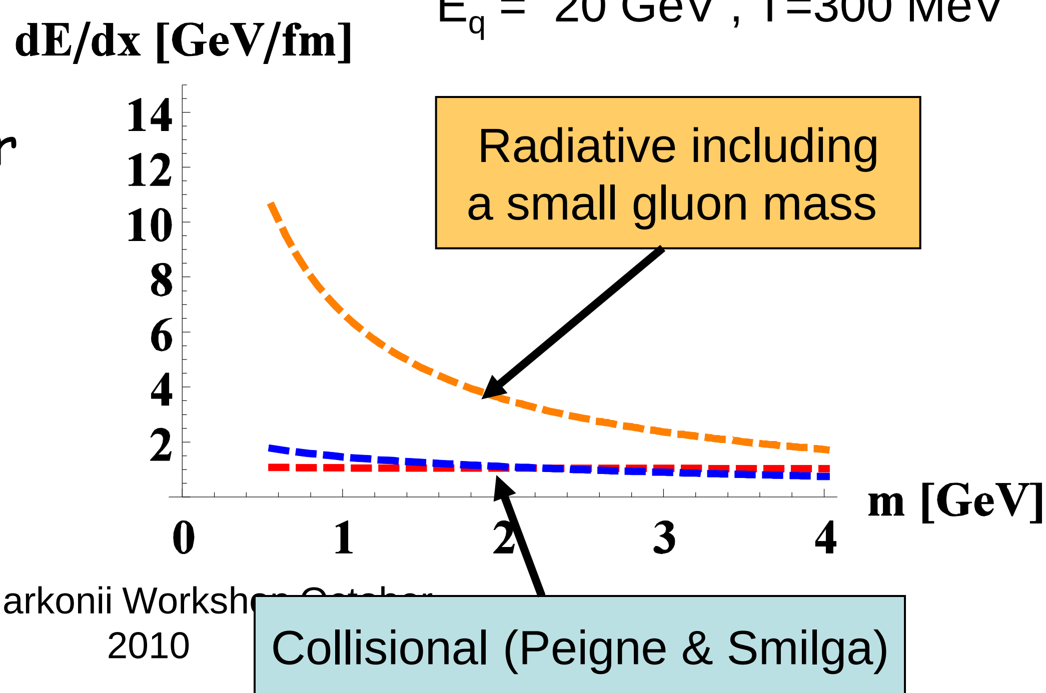
$$\frac{dE}{dz} = \int d^3k\ \rho_k \int \Delta E \frac{d\sigma}{dx}\ dx = \int d^3k\ \rho_k E \int x \frac{d\sigma}{dx}$$

For large q masses:
Collisional and radiative
energy loss of the same order

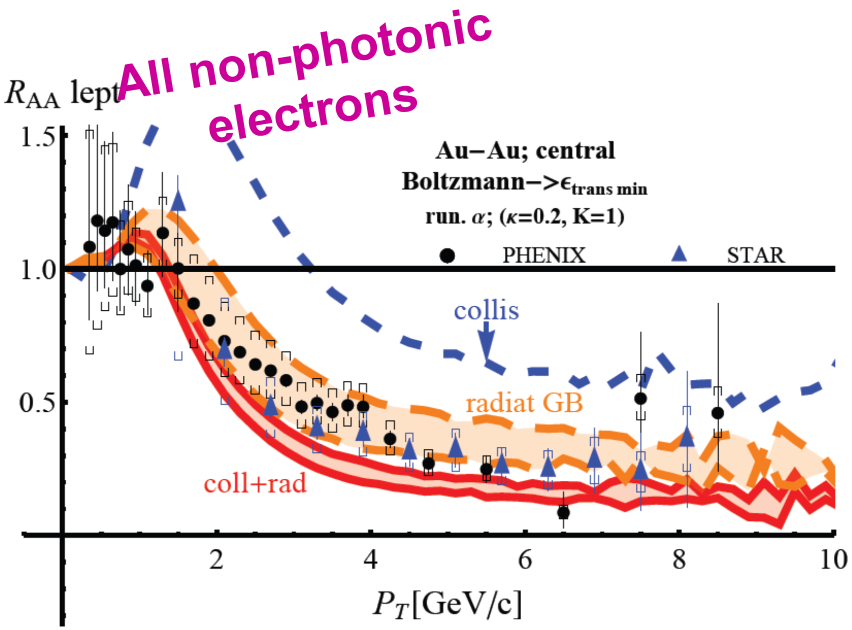
Small q masses:
radiative dominant

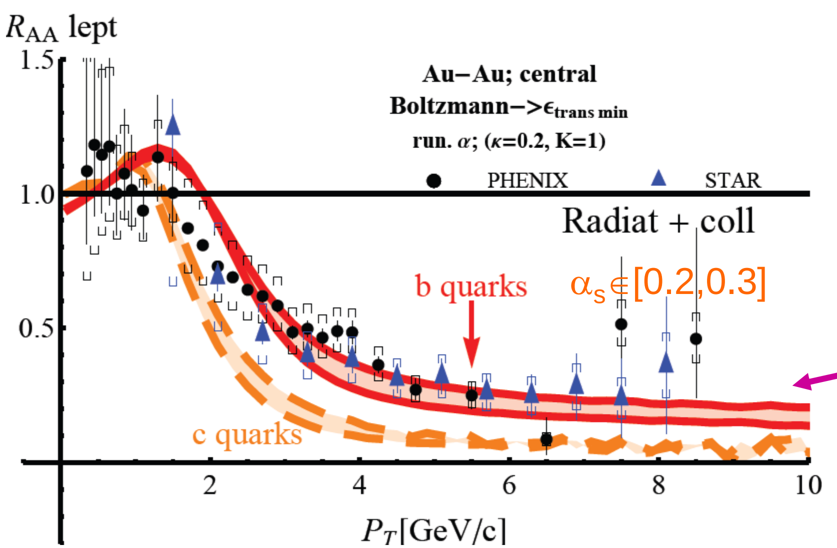
Rad: $\Delta E \propto E$
Coll: $\Delta E \propto \ln E$

E_q = 20 GeV , T=300 MeV



Results I

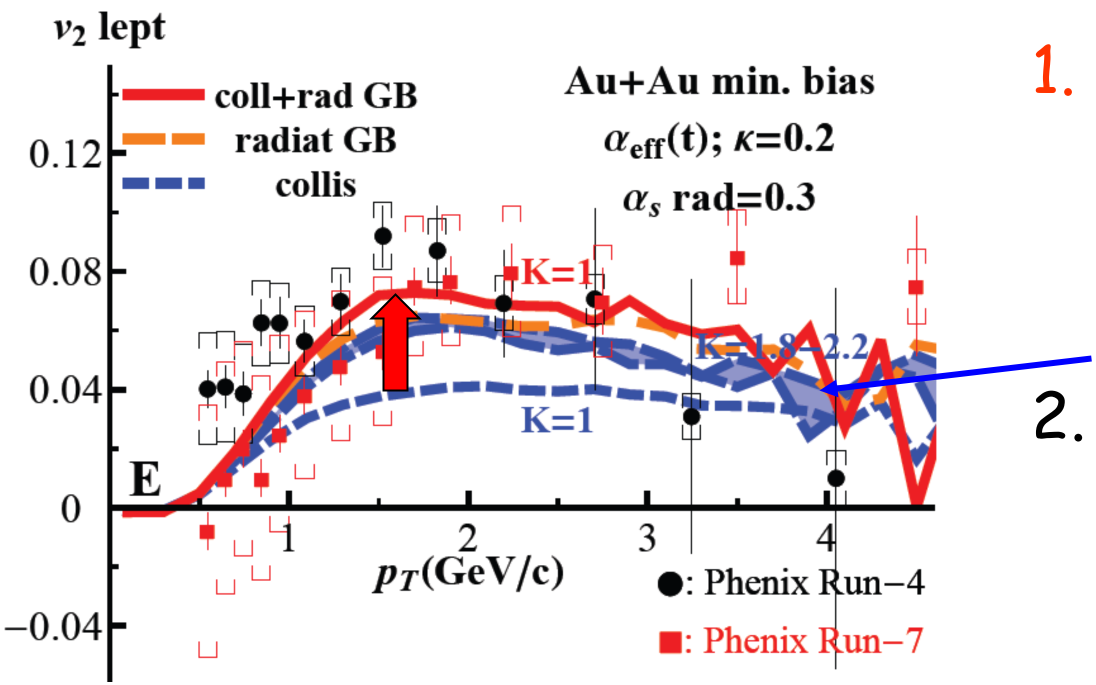




1. Too large quenching (but very sensitive to freeze out)
2. Radiative Eloss indeed dominates the collisional one
3. Flat experimental shape is well reproduced

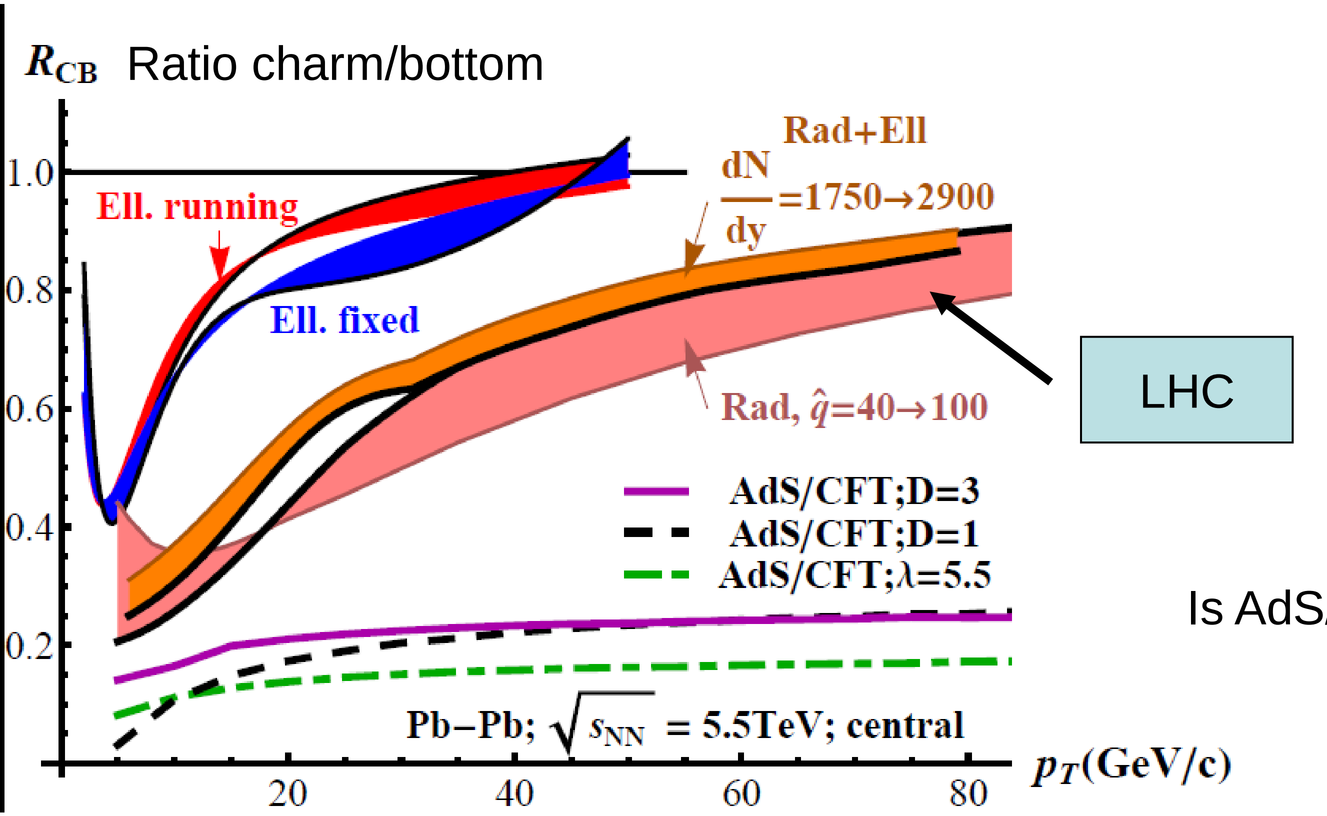
separated contributions e ← D and e ← B.

Results II



1. Collisionnal + radiative energy loss + dynamical medium : *compatible* with data
2. Shape for radiative E loss and *rescaled* collisional E loss are pretty similar
3. To our knowledge, one of the first model using radiative Eloss that reproduces v_2

Predictions



Is AdS/CFT still valid?

So everything seems to be ok. We are close to the data as like other models (for example that of Rapp/van Hees)

Does this mean that we have understood what is going on?

If yes, both models should give the same for
the elementary quark plasma particle interaction
the expansion of the plasma

Is this the case? Let's try

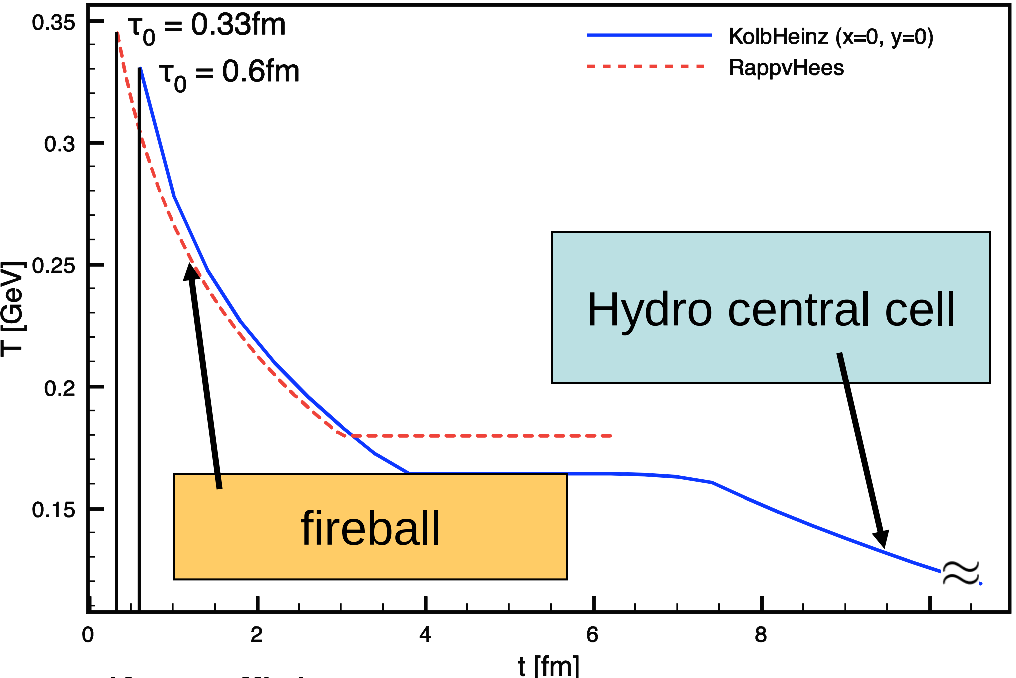
Take the expansion of the plasma of the Rapp/van Hees model and the elementary interaction of the Nantes model

and vice versa

and let's look whether the observables change.

If they do not change, elementary interaction and plasma expansion are separately well understood, if not we have not really understood what is going on and we have to look for other observables to progress.

Comparison of two models which are close to the data



Two expansion scenarios:

Hydrodynamics –local equilibrium
(Heinz and Kolb)
Fireball – global equilibrium
(van Hees/Rapp)

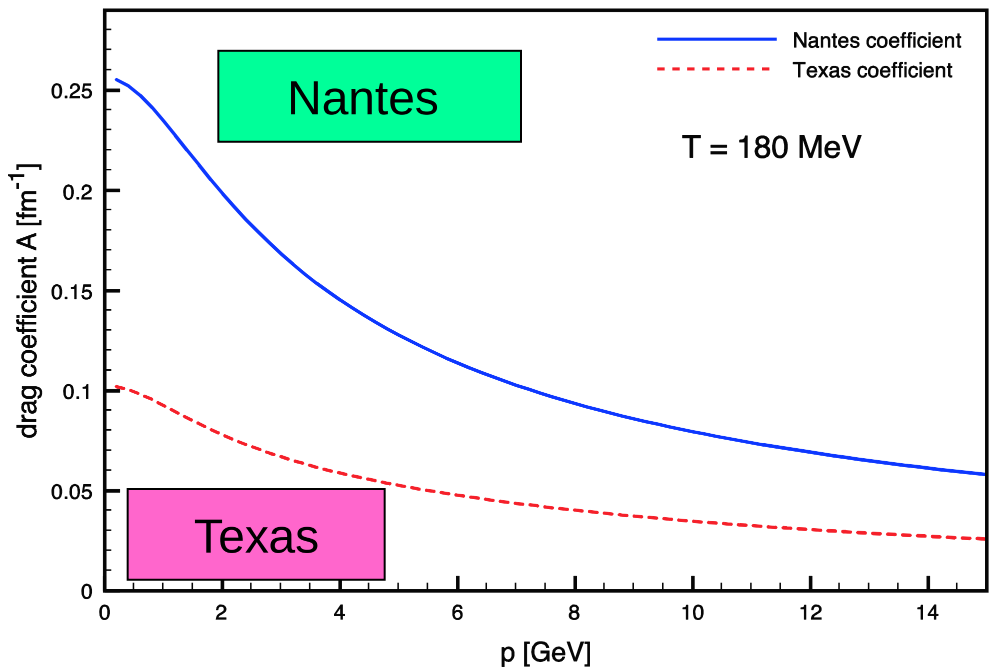
$$T^{hydro}_{central\ cell}(t) \approx T_{FB}(t)$$

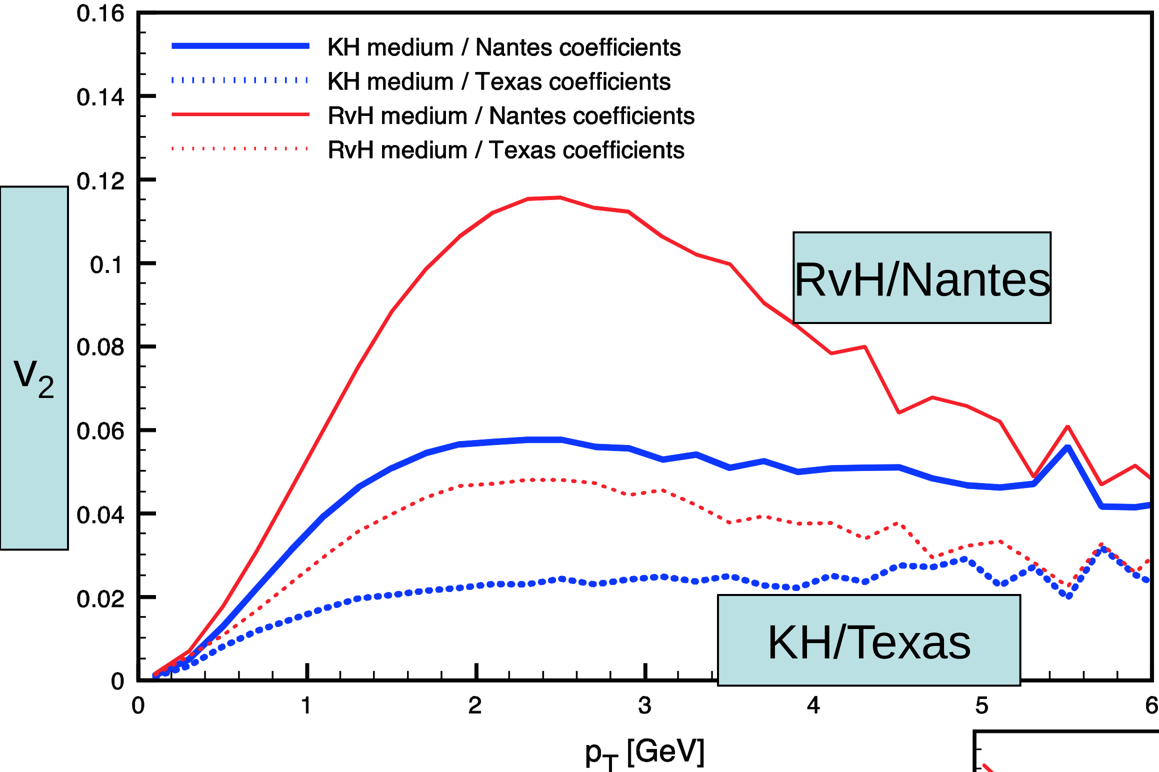
Drift coefficient A

$$\boxed{\dot{p} = \xi(t) - Ap}$$

$$< \xi(t)\xi(t') >= \kappa\delta(t - t')$$

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





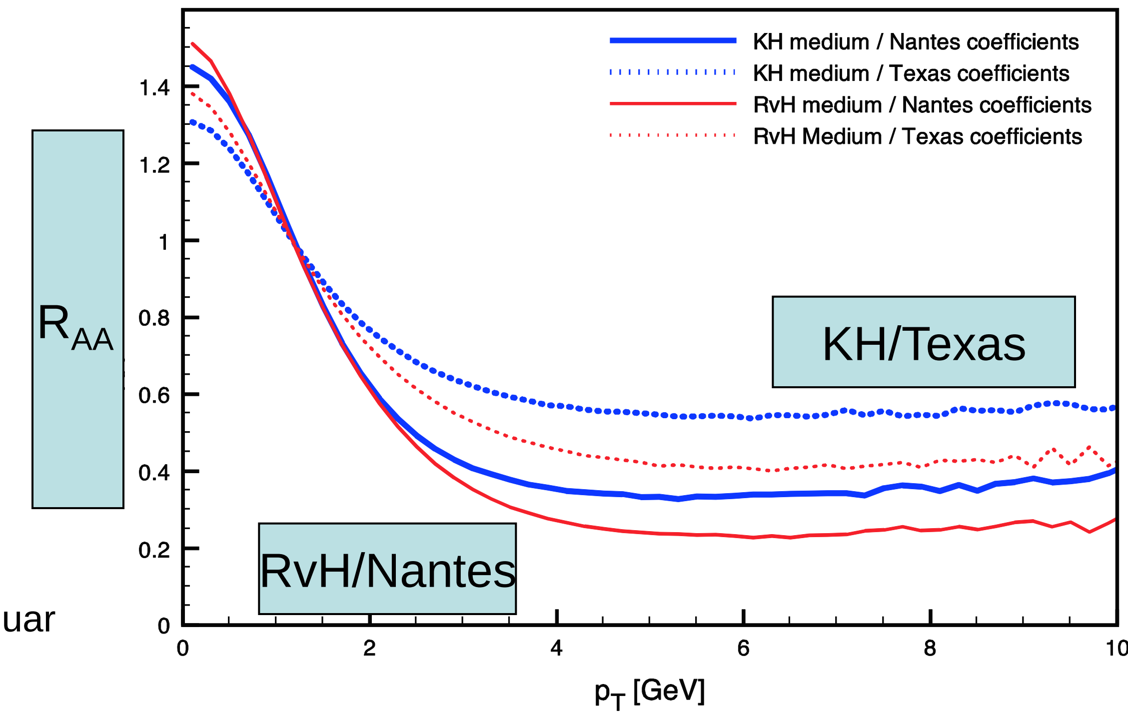
Lead to two very different results for

V_2

R_{AA}

Small drift coeff and many coll
= Large drift coeff and few coll
but
Small drift coeff and few coll
$\neq$ large drift coeff and many coll

Consequence:
Expansion scenario is for heavy quark physics as important as the elementary heavy quark-q(g) cross section



Rete Quar

Is there a possibility to test the expansion scenario independent from heavy quark physics?

Yes: It affects light meson production

But: additional problem: Freeze out
Hydrodynamics: Cooper Frye (PRD 10, 186)

$$E\frac{dN}{d^3p} = \int_\sigma f_{eq}(x,p)p^\mu d\sigma_\mu$$

$$dN = \int (\underbrace{\mathbf{v}dt}_{passing\ surface} - \underbrace{\mathbf{dx}}_{movement\ of\ surface})\hat{\mathbf{n}}S_\perp f_{eq}(x,p)$$

Cooper Frye yields v_2 = 10% for Rapp van Hees and v_2 = 5% for Kolb Heinz so there is in principle a possibility to distinguish between the theories

But there also other possibilities to describe hadronisation.

Therefore only an extensive comparison with the light meson sector may resolve this enigme

Conclusions

All experimental data are compatible with the assumption that pQCD describes

energy loss and elliptic flow v_2

observed in heavy ion collisions. AdS/CFT seems to be possible but only LHC data will show which predictions are realized in nature

Different approaches use different descriptions of the expansion of the plasma and of the elementary interaction. The final result is sensitive to both.

Light mesons may give additional information on the expansion but extensive comparisons between data and predictions are necessary Before conclusions can be drawn

A lot of work is awaiting us before the physics of heavy quarks is understood

Radiation Matrix element in light cone gauge

In the limit $\sqrt{s} \to \infty$, using light cone gauge and scalar QCD (SQCD) (≈ QCD for ω/E_Q -> 0) the radiation matrix element factorizes

$$|M_{SQCD}|^2 = |M_{elast}|^2 D^{QCD} g^2 4(1-x)^2 \left(\frac{\vec{k}_t}{k_t^2+(\omega/E)^2m^2} - \frac{\vec{k}_t-\vec{q}_t}{(\vec{q}_t-\vec{k}_t)^2+(\omega/E)^2m^2}\right)^2$$

Emission from heavy q

Emission from g

k_t , ω = transv mom/ energy of gluon
E = energy of the heavy quark
D^{QCD} = color factor

no emission from light q
m=0 -> Gunion Bertsch
M_{QED}: $q_t \to \omega/E \cdot q_t$

$$x\frac{d\sigma}{dx} = (\omega/E)\frac{d\sigma}{d(\omega/E)} \approx \frac{4C_F\alpha_S^3}{3}\frac{log(\frac{3x^2m^2}{m_d^2})}{x^2m^2}$$