The Physics of Heavy Quarks in Heavy Ion collisions

How to detect a plasma of quarks and gluons and its degrees of freedom?

Why are heavy quarks interesting ?

Interaction of heavy quarks with the quark gluon plasma
- our model (elastic and inelastic collisions, LPM)
- comparison with data
- interpretation of the results

- state of the art of the transport approaches
- what have we learned and where are the open questions
    - c cbar interaction with the plasma
    - Boltzmann versus Fokker Planck

The existence of a quark gluon plasma and the kind of transition towards the hadronic world

has been predicted by lattice gauge calculations
has been claimed to be seen in experiments (Science)

Why this is still a topic ?
because we want to know the degrees of freedom of the plasma

Light hadrons: their multiplicity follows a gas of T = 158 MeV
Hadronic rescattering spoils spectra ⇒ no info about plasma

Possible probes:
collective variables : ridge, elliptic flow (← hydro, only EOS)

γ, dileptons
jets
heavy quarks (D,B Mesons, J/psi, Υ)

} no equilibrium with plasma

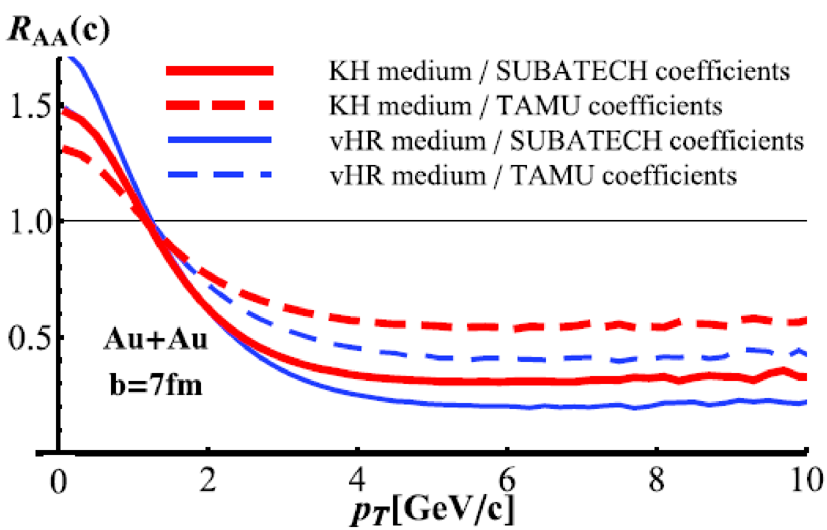
What makes heavy quarks (mesons) so interesting?

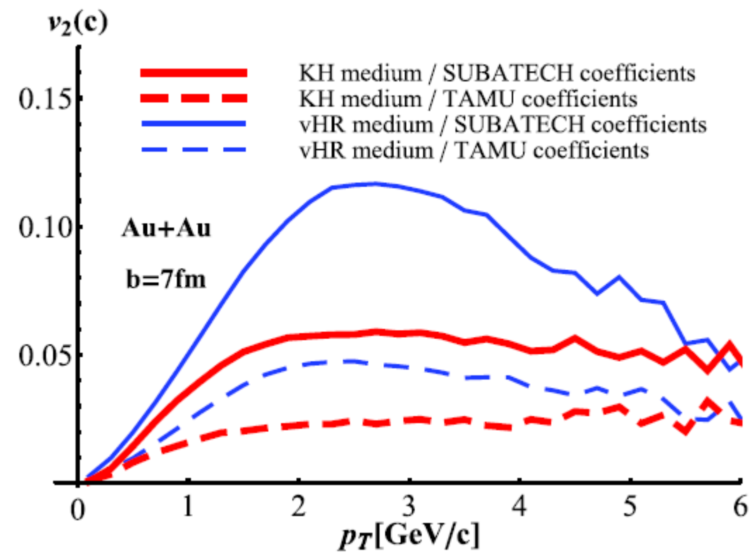
- produced in hard collisions(distribution: FONLL confirmed by STAR)
- high p_T: no equilibrium with plasma particles
- not very sensitive to the hadronisation process at high p_T

Ideal probe to study
properties of the QGP **during** its expansion

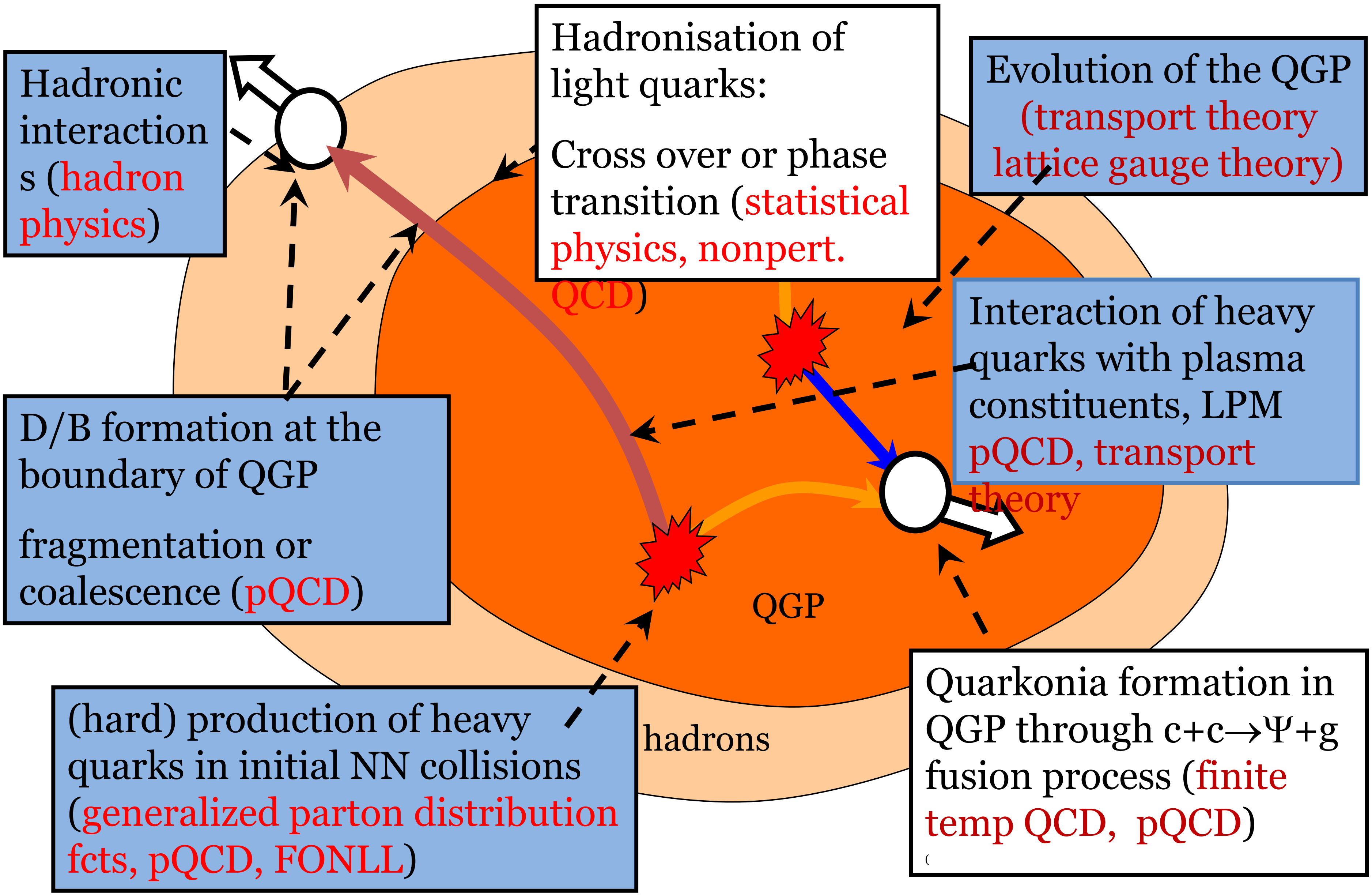
Caveat: two major ingredients: expansion of the plasma AND elementary cross section (c(b)+q(g) ->c(b)+q(g)) (**arXiv:1102.1114**)

Heavy quark physics not decoupled from light quark physics





Complexity of heavy quark physics in a nutshell :



Our approach :

- We assume that pQCD provides the tools to study the processes

We want to
- model the reaction with a minimum of approximations: exact Boltzmann collisions kernel, no probably unrealistic Fokker Planck approx. (1309.7930)
- take into account all the known physics with
- no approximations of scattering processes (coll+ radiative)
- make connection to the light quark sector (v_2 jets particle spectra) by embedding the heavy quarks into EPOS (LHC) (or before Kolb & Heinz (RHIC))

- This serves then as a benchmark
- deviation from data points towards new physics

Problem: at the moment only two obs: R_{AA} and v_2 available

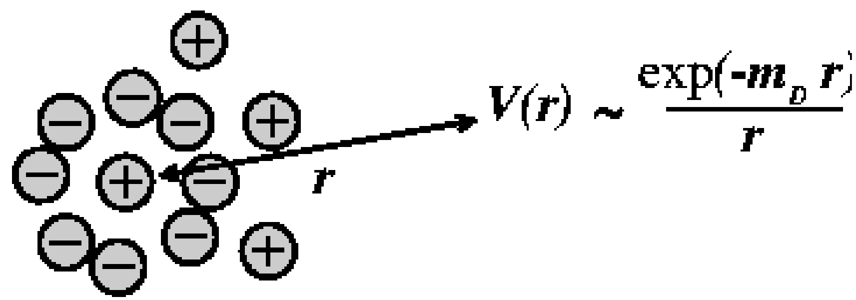
Nantes approach: Elastic heavy quark – q(g) collisions

Key ingradients: pQCD cross section like qQ -> qQ
pQCD cross section in a medium has 2 problems:

a) Running coupling constant

$$\frac{d\sigma_F}{dt} = \frac{g^4}{\pi(s-M^2)^2}\left[\frac{(s-M^2)^2}{(t-\kappa m_D^2)^2} + \frac{s}{t-\kappa m_D^2} + \frac{1}{2}\right]$$

b) Infrared regulator



m_D regulates the long range behaviour of the interaction

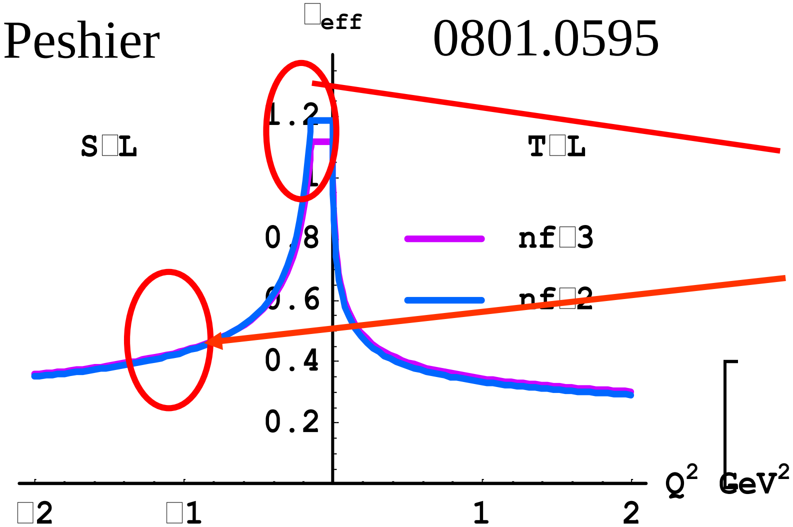
Neither $g^2 = 4\pi\,\alpha(t)$ nor $\kappa\, m_D^2$= are well determined
standard: $\alpha(t)$ =is taken as constant or as $\alpha(2\pi T)$
κ =1 and α =.3: large K-factors ($\approx$ 10) are necessary to describe data

A) Running coupling constant

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

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

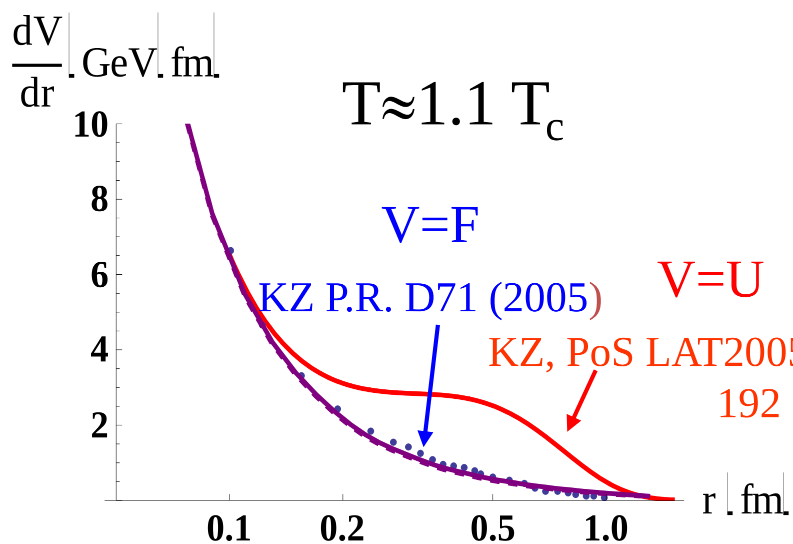
Peshier 0801.0595

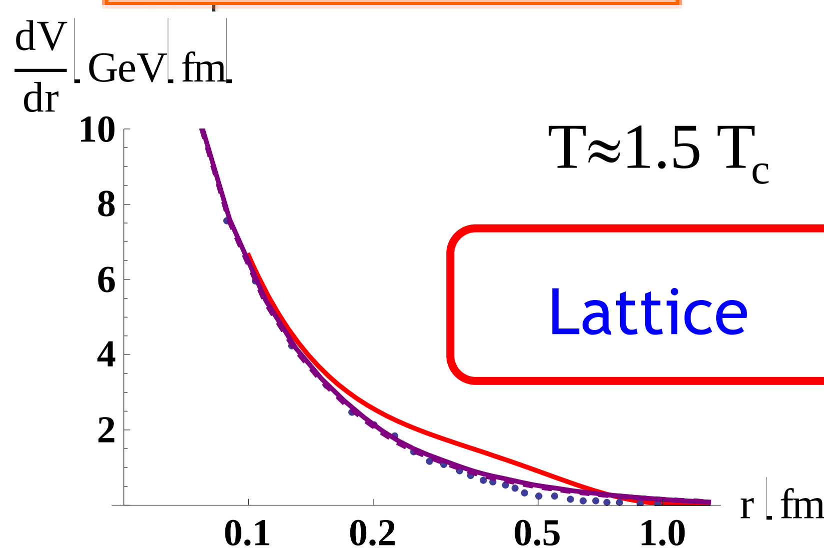


IR safe. The detailed form very close to $Q^2 = 0$ is not important does not contribute to the energy loss

Large values for intermediate momentum-transfer

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

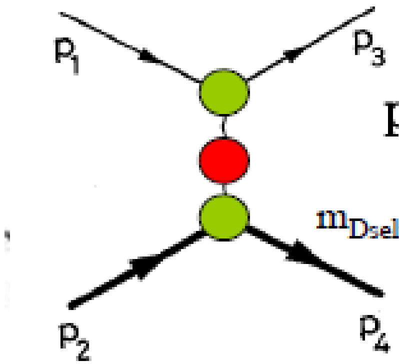




Lattice

B) Debye mass

PRC78 014904, 0901.0946



$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\text{Dself}}(T)}$$

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

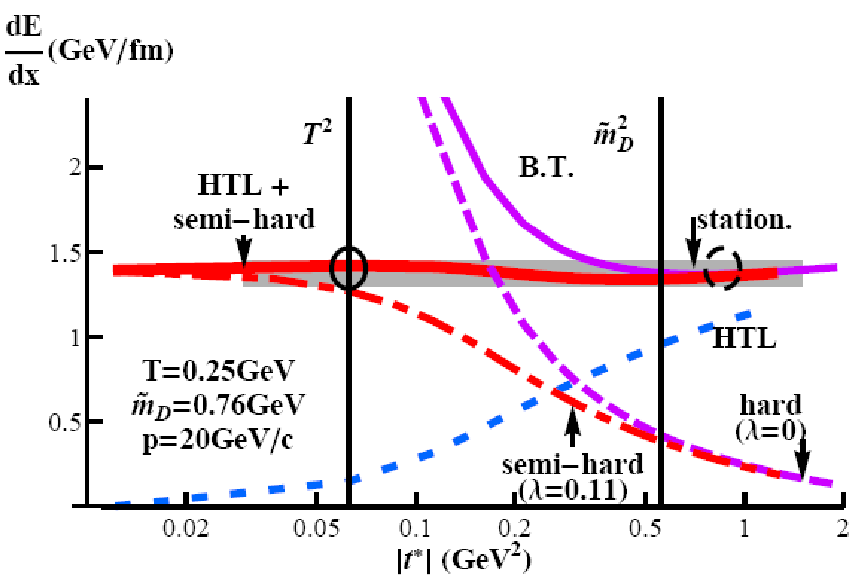
hep-ph/0607275

If t is small (<<T) : Born has to be replaced by a hard thermal loop (HTL) approach

For t>T Born approximation is (almost) ok

(Braaten and Thoma PRD44 (91) 1298,2625) for QED:

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



We do the same for QCD (a bit more complicated)

Phys.Rev.C78:014904

Result:

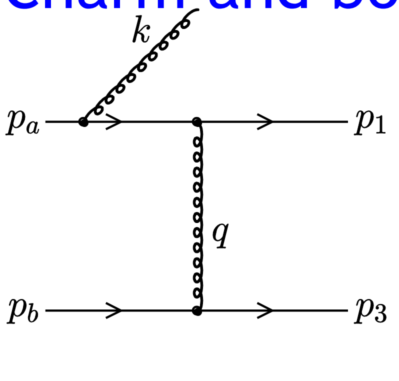
$\kappa \approx 0.2$

much lower than the standard value

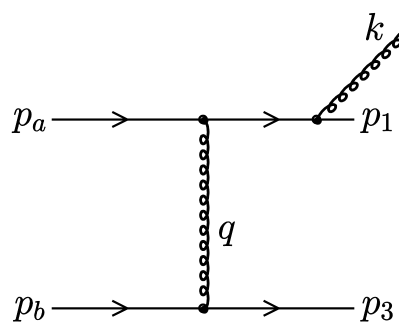
C) Inelastic Collisions

Low mass quarks : radiation dominantes energy loss

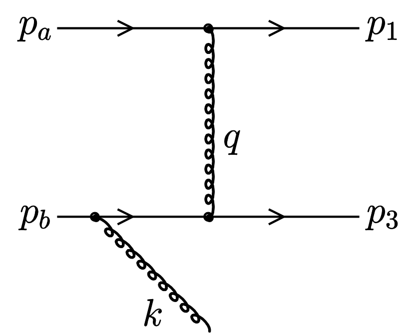
Charm and bottom: radiation of the same order as collisional



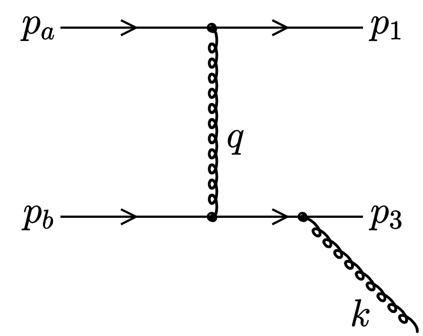
M_1



M_2

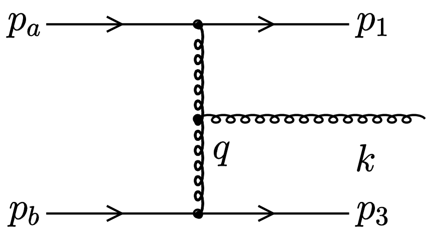


M_3



M_4

4 QED type diagrams



M_5

1 QCD diagram

Commutator of the color SU(3) operators

$$T^b T^a = T^a T^b - i f_{abc} T^c$$

M1-M5 : 3 gauge invariant subgroups

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

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

M_{QCD} dominates the radiation

M^{SQCD} in light cone gauge

In the limit $\sqrt{s} \to \infty$ the radiation matrix elements factorize in

$$M^2_{tot} = M^2_{elast} \cdot P_{rad}$$

k_t , ω = transv mom/ energy of gluon E = energy of the heavy quark

$$P_{rad} = C_A \left(\frac{\vec{k}_t}{k_t^2 + (\omega/E)^2 m^2} - \frac{\vec{k}_t - \vec{q}_t}{(\vec{q}_t - \vec{k}_t)^2 + (\omega/E)^2 m^2} \right)^2$$

Emission from heavy q

Emission from g

leading order: no emission from light q

heals colinear divergences

m=0 -> Gunion Bertsch

Energy loss:

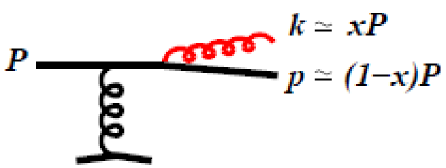
$$\frac{\omega d^4\sigma^{rad}}{dx d^2k_t dq_t^2} = \frac{N_c \alpha_s}{\pi^2}(1-x) \cdot \frac{d\sigma^{el}}{dq_t^2} \cdot P_{rad}$$

x=□/E

$$M_{QCD} = M_{SQCD}\left(1 - \frac{(\omega/E)^2}{(1-\omega/E)^2}\right)$$

Landau Pomeranschuk Migdal Effekt (LPM)

reduces energy loss by gluon radiation



Heavy quark radiates gluons

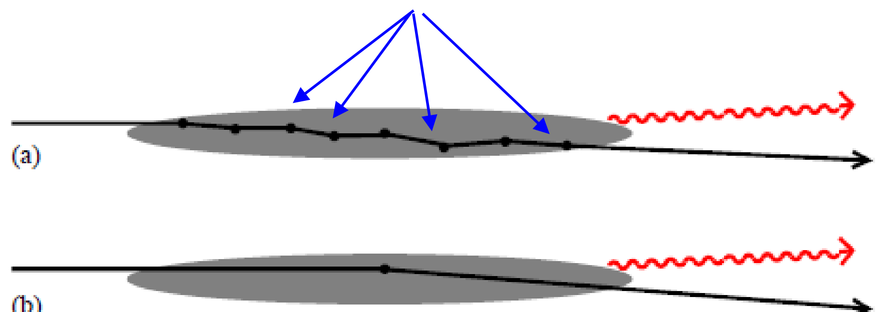
gluon needs time to be formed

Collisions during the formation time

do not lead to emission of a second gluon

emission of one gluon

(not N as Bethe Heitler)



ph/0204343)

$$t_f = \frac{2(1-x)\omega}{(\tilde{k}_\perp - \tilde{q}_\perp)^2 + x^2M^2 + (1-x)m_g^2}$$

Multiple scatt .QCD: ≈ N_{coll} $\langle k_t^2 \rangle = t\, \hat{q}$

single scatt.

dominates x<1   dominates x≈1 dominates x<<1

Calculations for RHIC and LHC

Initialization: FONLL distribution of c and b

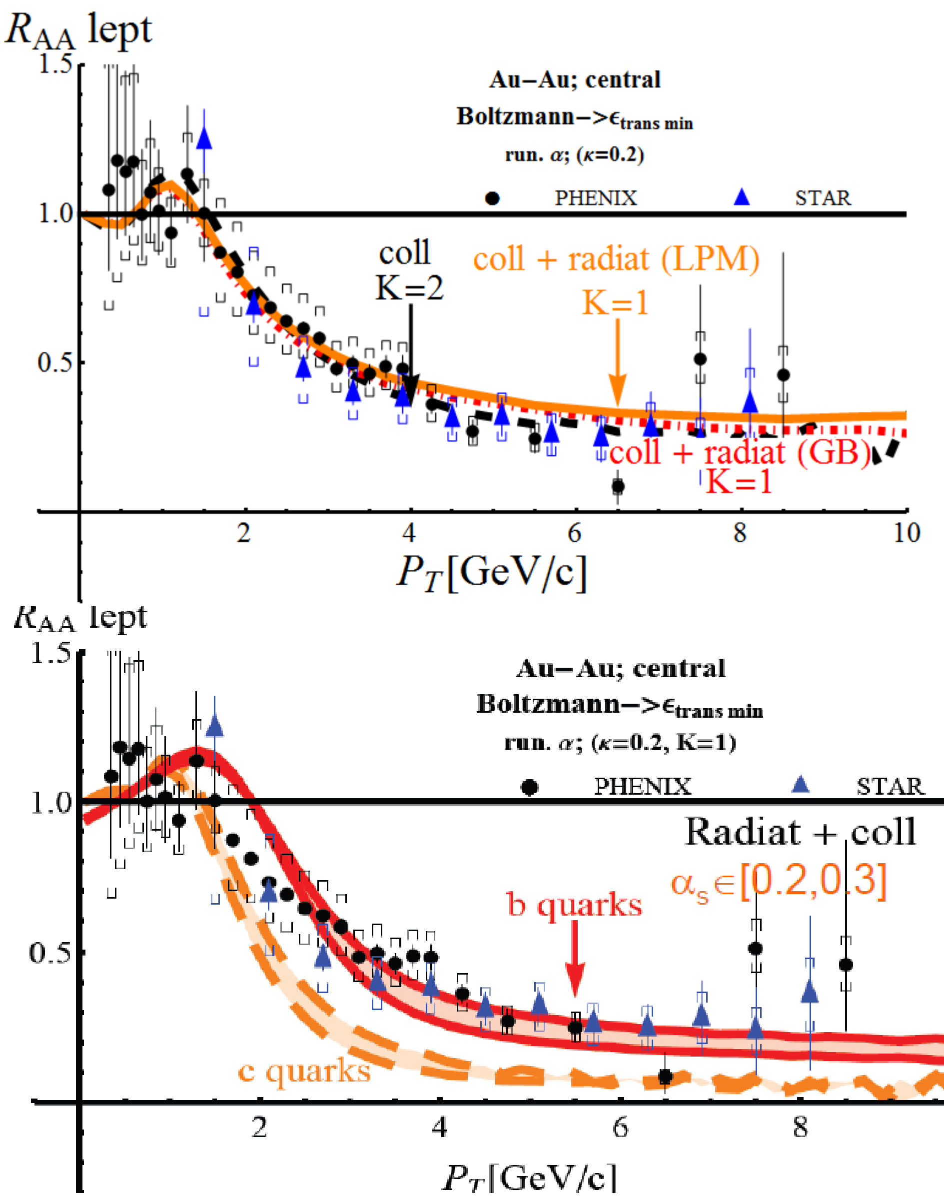
QGP : Hydro Kolb-Heinz for RHIC
EPOS for LHC

Interaction QGP-heavy quarks:
elastic collisions (collisional energy loss) ($K \approx 2$)
elastic collisions + and gluon emission (radiative energy loss)
+LPM

Hadronisation:
Coalescence for low pt heavy quarks
Fragmentation for high pt heavy quarks

Hadronic rescattering is small

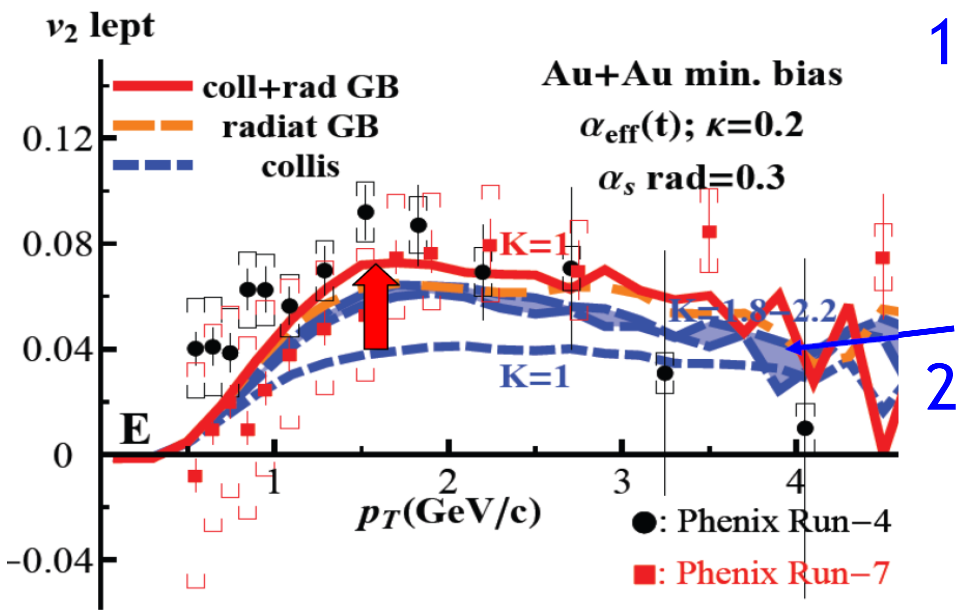
RHIC Hydro: Kolb Heinz



1. Coll:too little quenching (but very sensitive to freeze out) -> K=2
2. Radiative Eloss indeed as important as the collisional one
3. Flat experimental shape is well reproduced
4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC)

separated contributions e **from** D and e **from** B.

RHIC



1. Collisional + radiative energy loss + dynamical medium : *compatible* with data

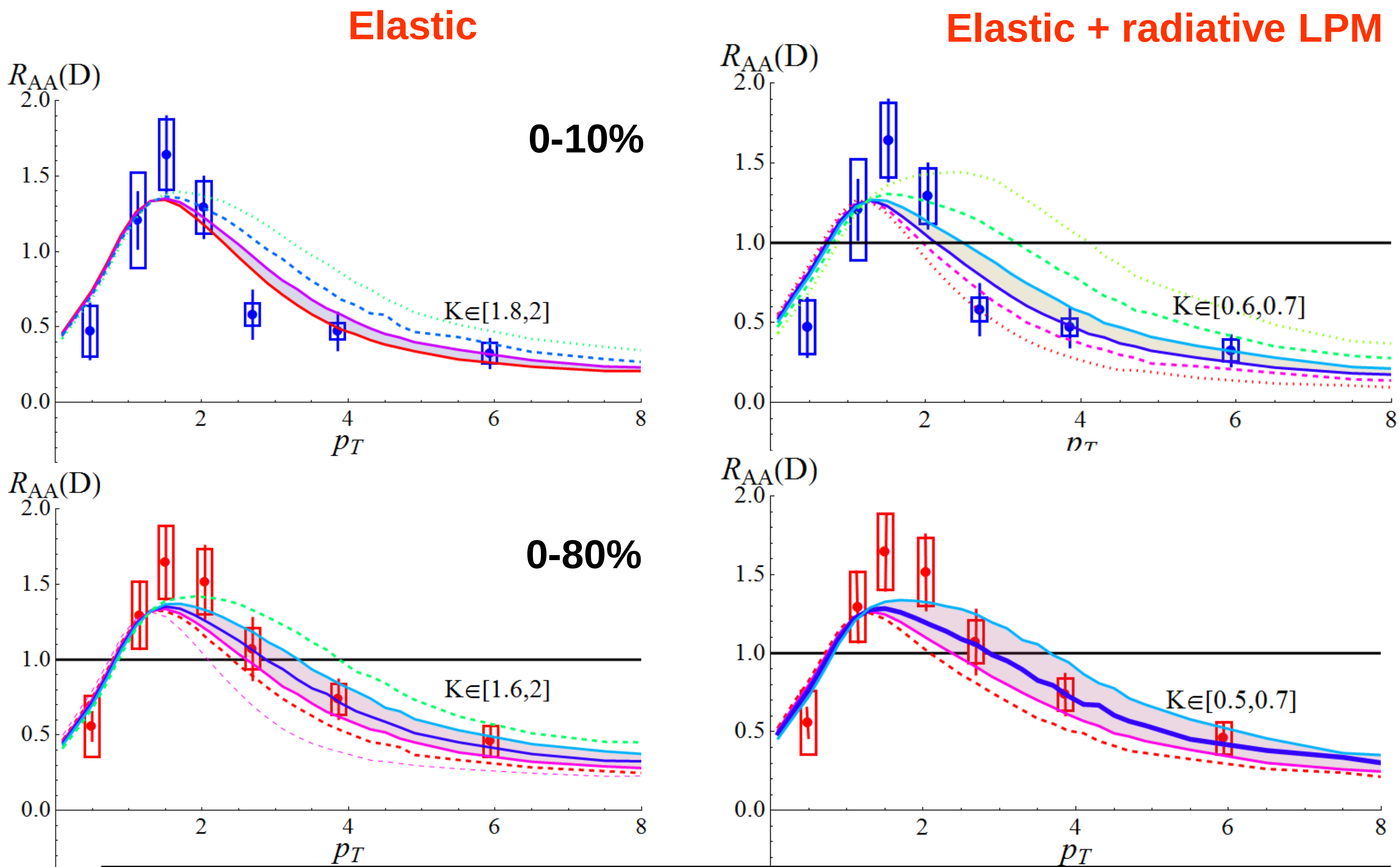
2. To our knowledge, one of the first model using radiative Eloss that reproduces v_2

For the hydro code of Kolb and Heinz:

K = 1 compatible with data
K = 0.7 best description – remember influence of expansion

RHIC: D mesons

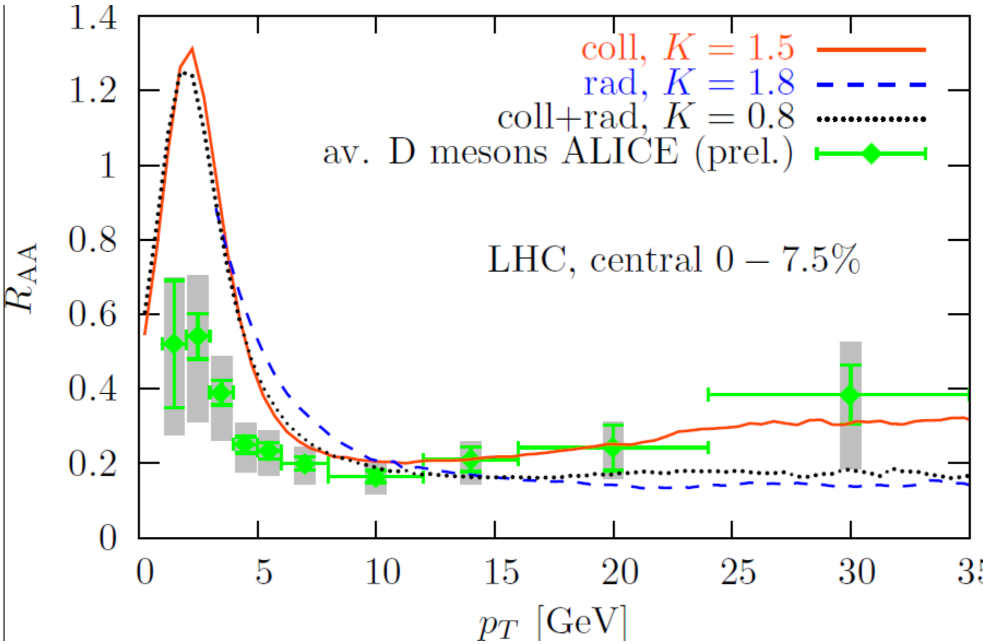
Energy loss tests the initial phase of the expansion



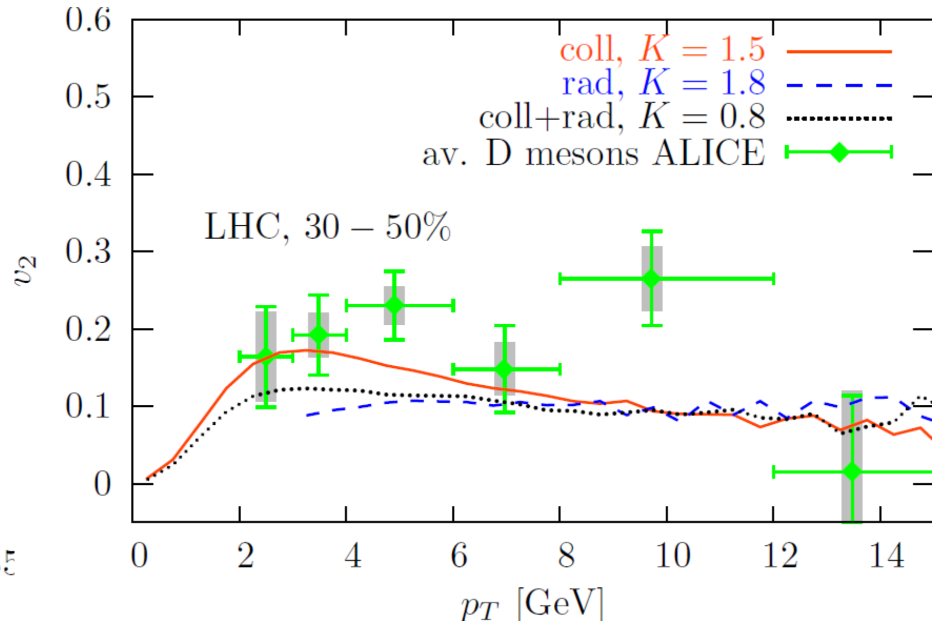
No form difference between coll and coll + rad

LHC : EPOS event generator

Energy loss tests the initial phase of the expansion



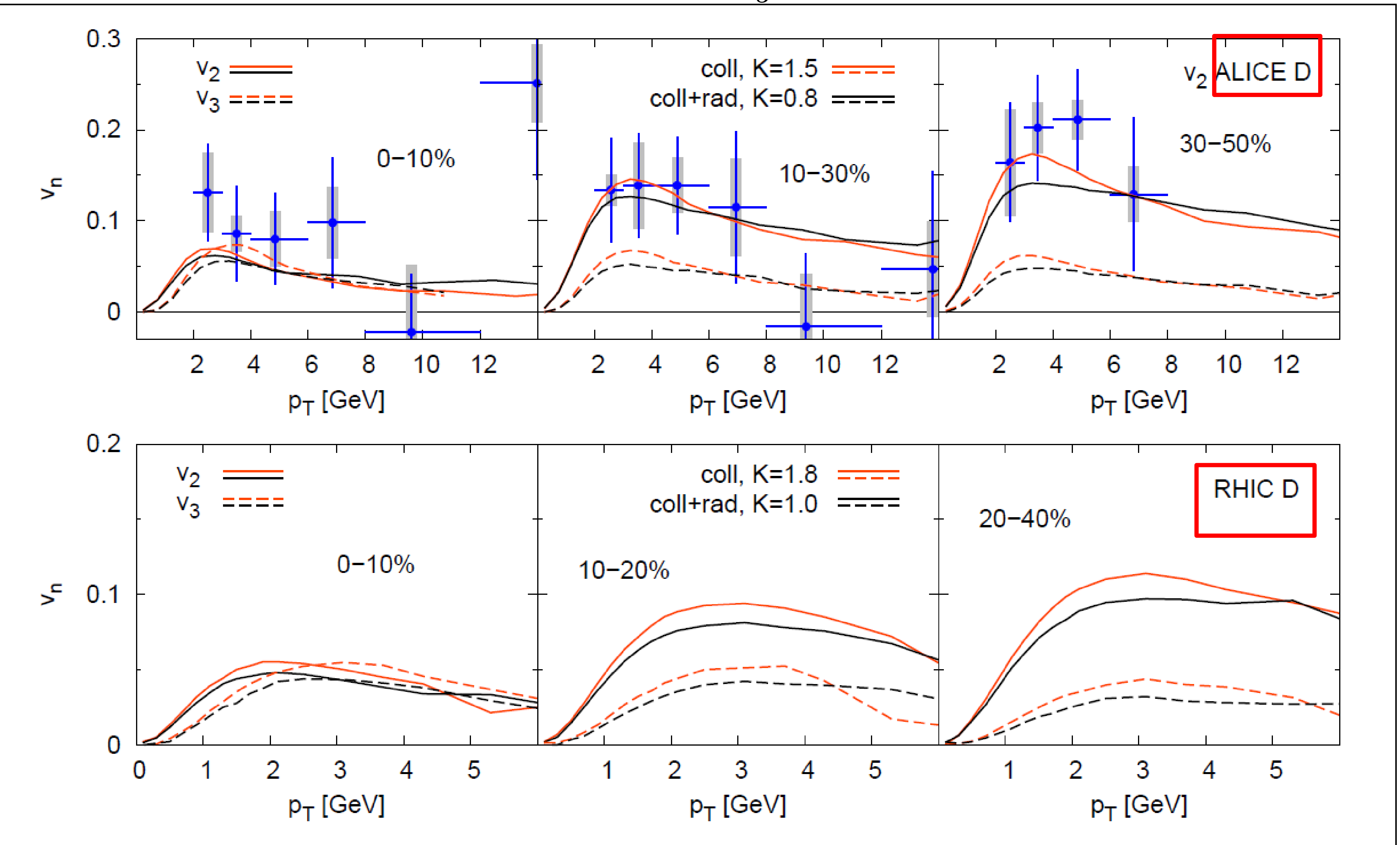
v_2 tests the late stage of the expansion



Three options : Collisions only K factor = 1.5
Collision and radiation K = 0.8
Radiation only K= 1.8

R_{AA} and v_2 for coll and coll + radiative about the same

Heavy quarks show also a finite v_3 and finite higher moments



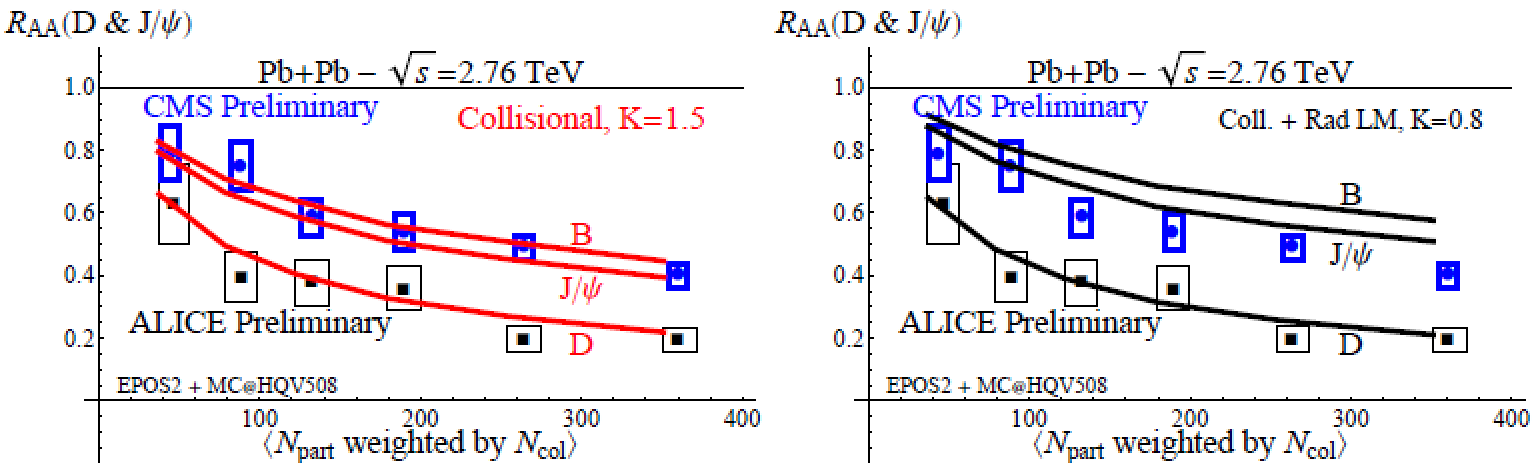
What can one learn from these results?

v_2 decreases with centrality -> understandable with the decrease of ϵ_2

v_3 independent of centrality -> fluctuations

Analysis of the results

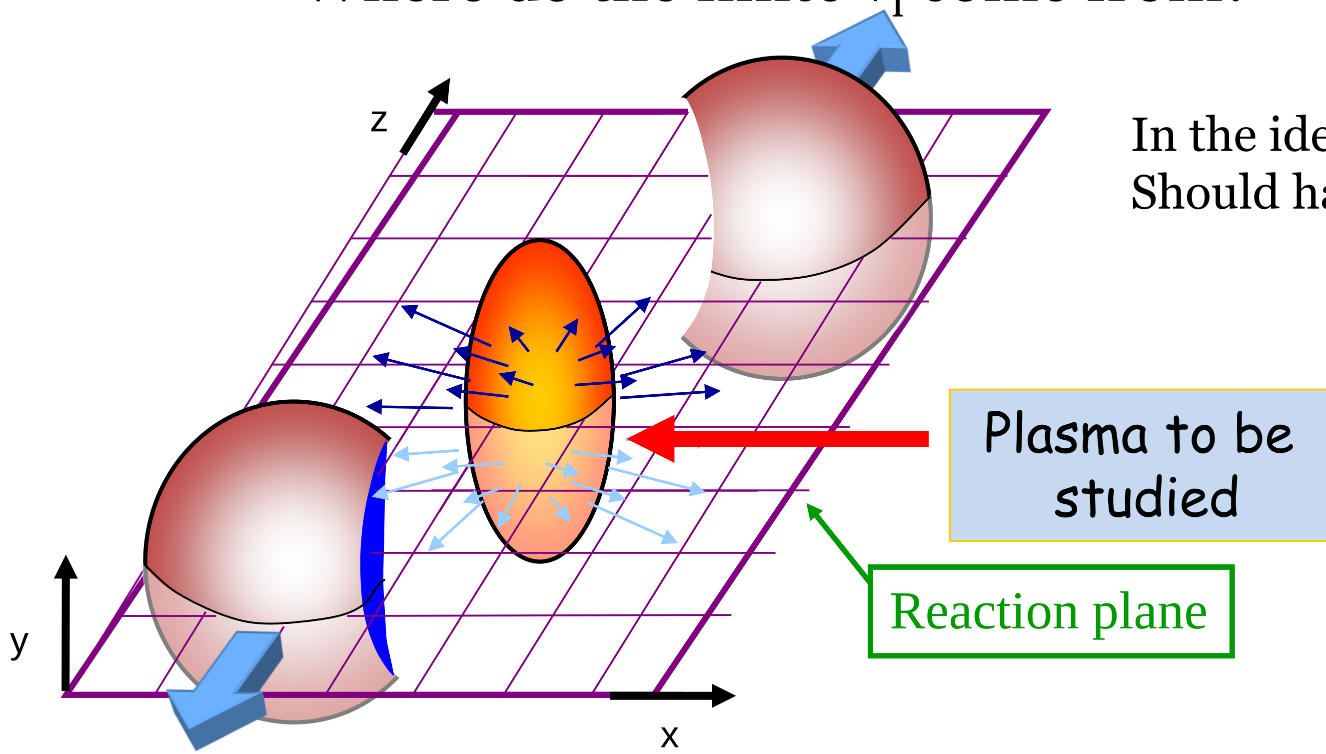
The different R_{AA} of D and B mesons seem to be verified experimentally (by comparing two different experiments)



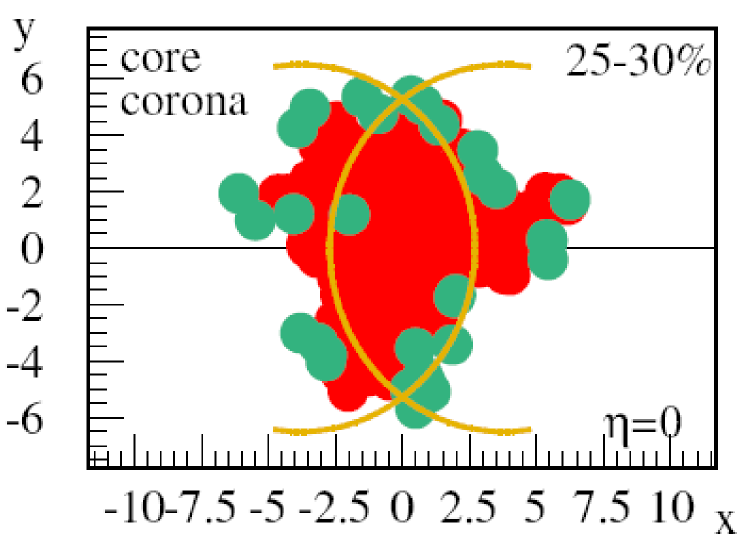
ALICE D meson R_{AA}, $6<p_T<12$ GeV/c, $|y|<0.5$

CMS Preliminary Non-prompt J/ψ R_{AA}, $6.5<p_T<30$ GeV/c $|y|<1.2$

Where do the finite v_i come from?



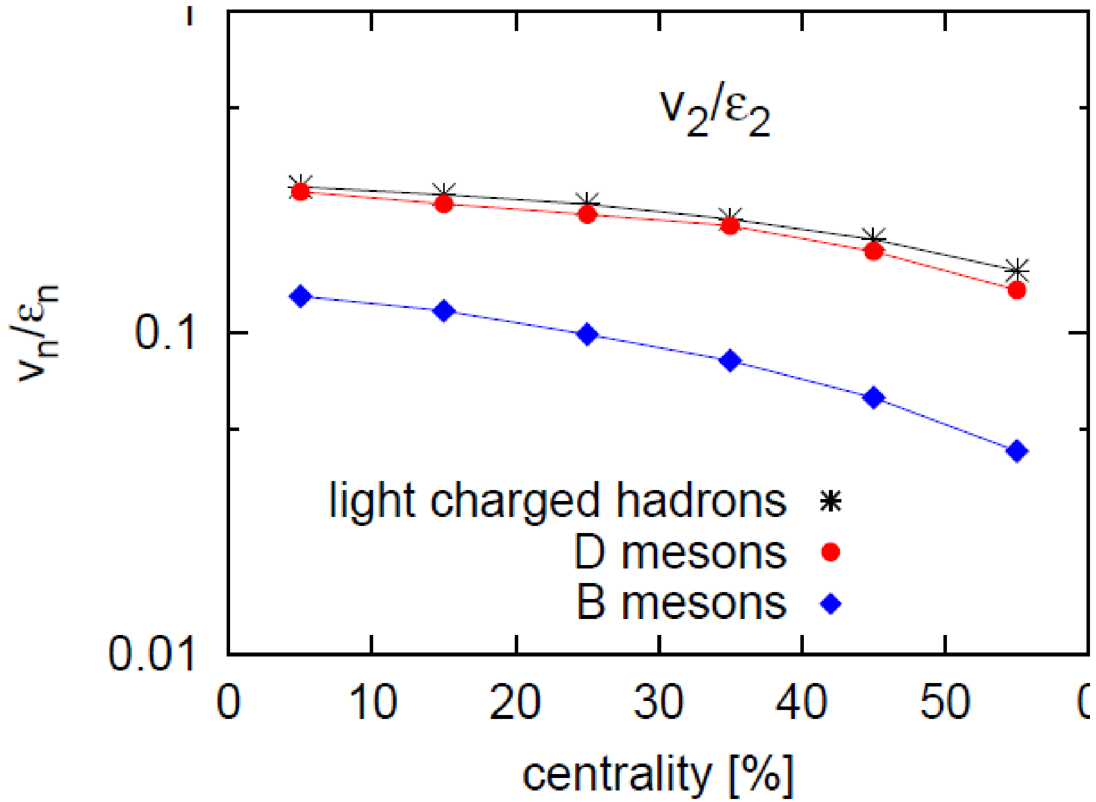
In the ideal world the plasma
Should have only v_2



In the real world (EPOS) the plasma has all kinds of moments v_i the v_i impair are fluctuations

v_3 corresponds to a Mercedes Star

Very surprising : v_2/ϵ_2 : same for light hadrons and D mesons



Light quarks: hydro-dynamical pressure caused by spatial eccentricity

v_2/ϵ_2 const for ideal hydro, centrality dependent for viscous hydro

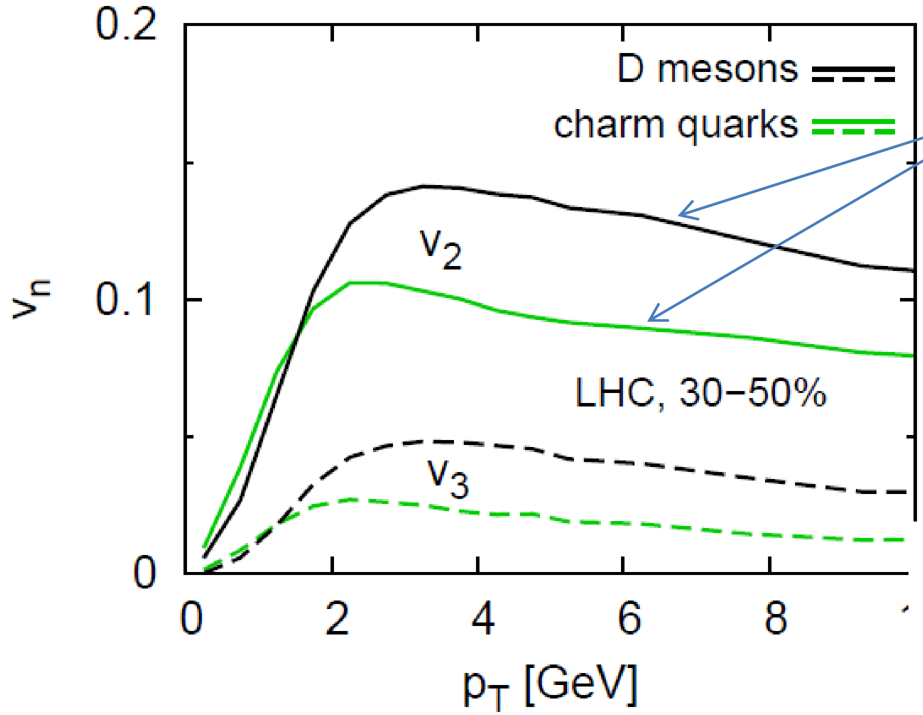
Heavy quarks: No initial v_2 (hard process)

v_2 only due to interaction with q and g

v_2 of heavy quarks is created later, measures the interaction time

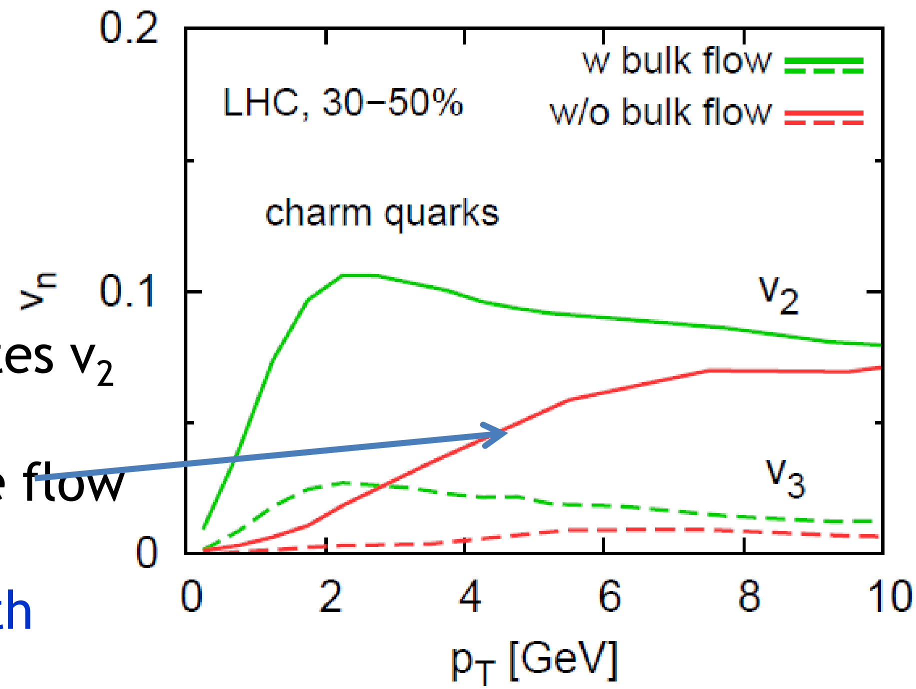
Bottom quarks are too heavy to follow

More detailed analysis of the flow



20% of v_2 due to the hadronisation uncertainty

fragmentation or coalescence



Verification that collective flow creates v_2

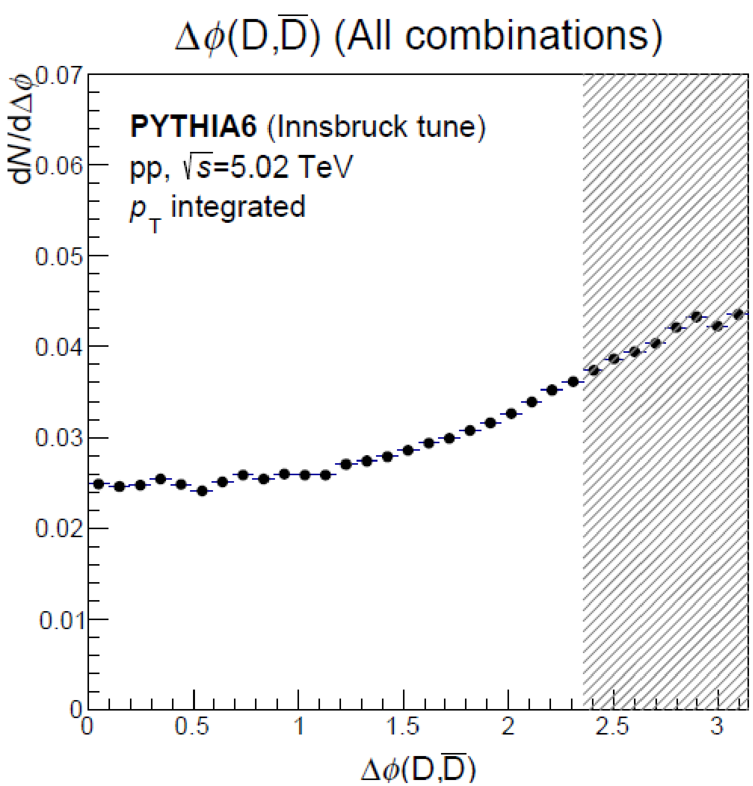
Artificial elimination of the collective flow

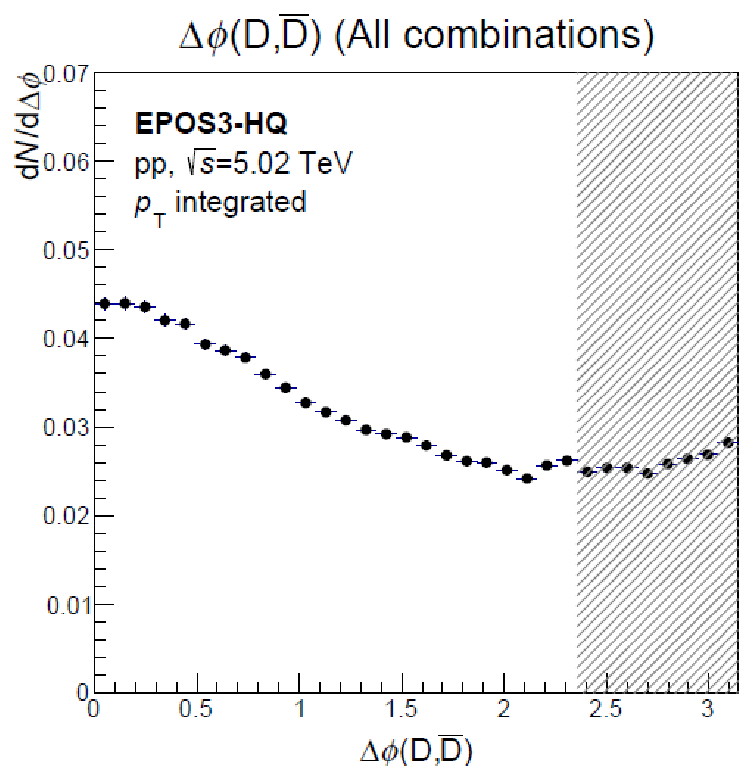
High momentum: different path length in and out of plane

Can we measure the final state radiation of heavy quarks (dead cone effect)?

Idea:

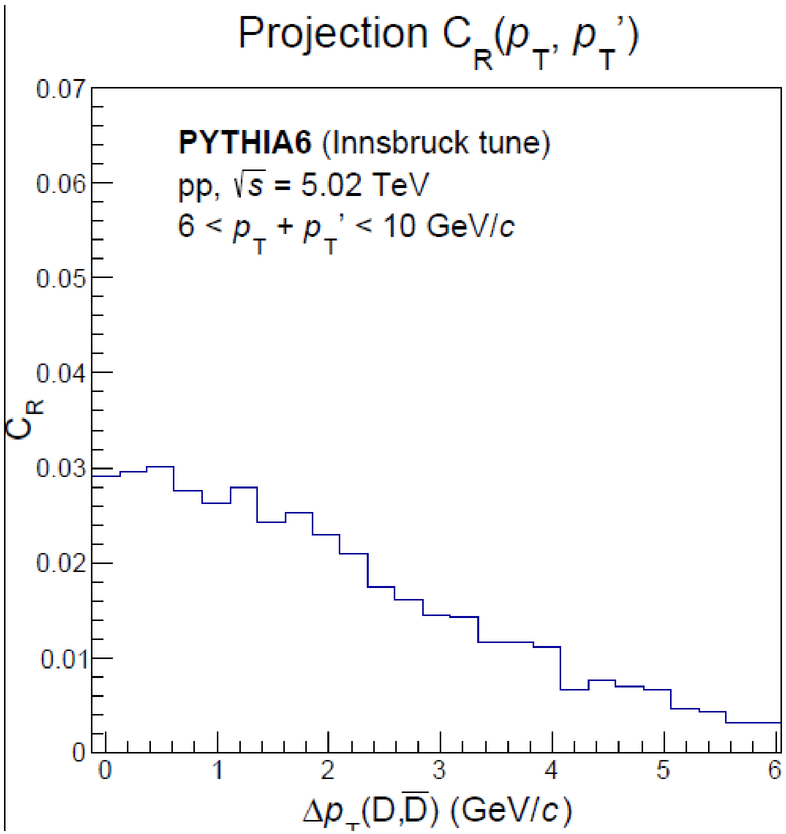
- select experimentally and theoretically
  c cbar pairs emitted under 180° -> sensitive to leading order pQCD
- measure la difference in p_T
- compare with different event generators

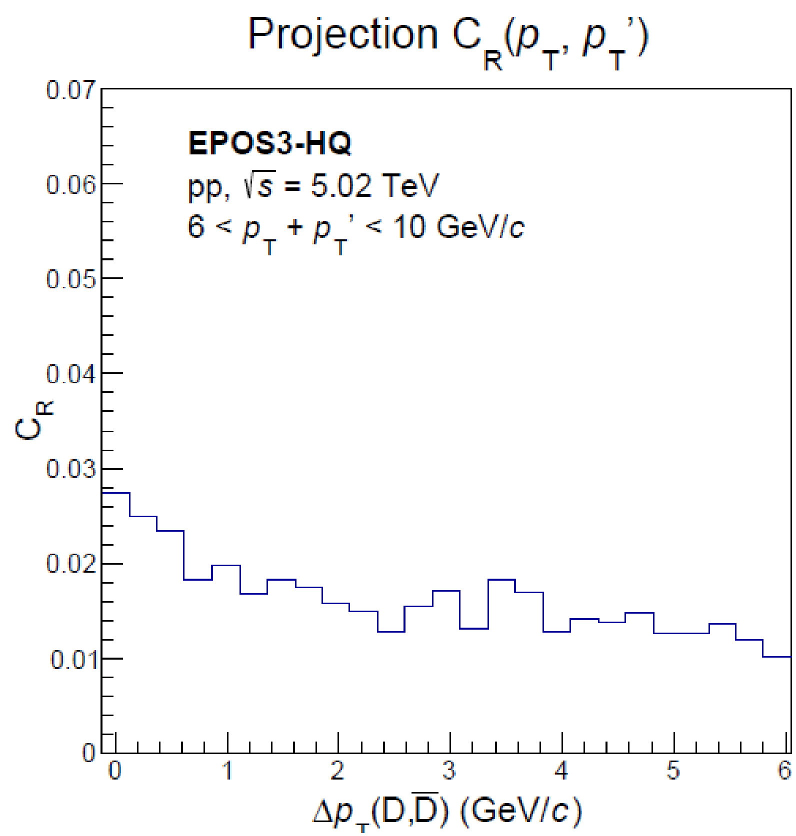




Calculate the correlation function of D Dbar pairs

$$C_R(p_{\mathrm{T}}, p_{\mathrm{T}}') = \frac{\mathrm{d}^2 N(p_{\mathrm{T}}, p_{\mathrm{T}}')}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}'} \Big/ \sqrt{\frac{\mathrm{d}N(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}} \frac{\mathrm{d}N(p_{\mathrm{T}}')}{\mathrm{d}p_{\mathrm{T}}'}}$$



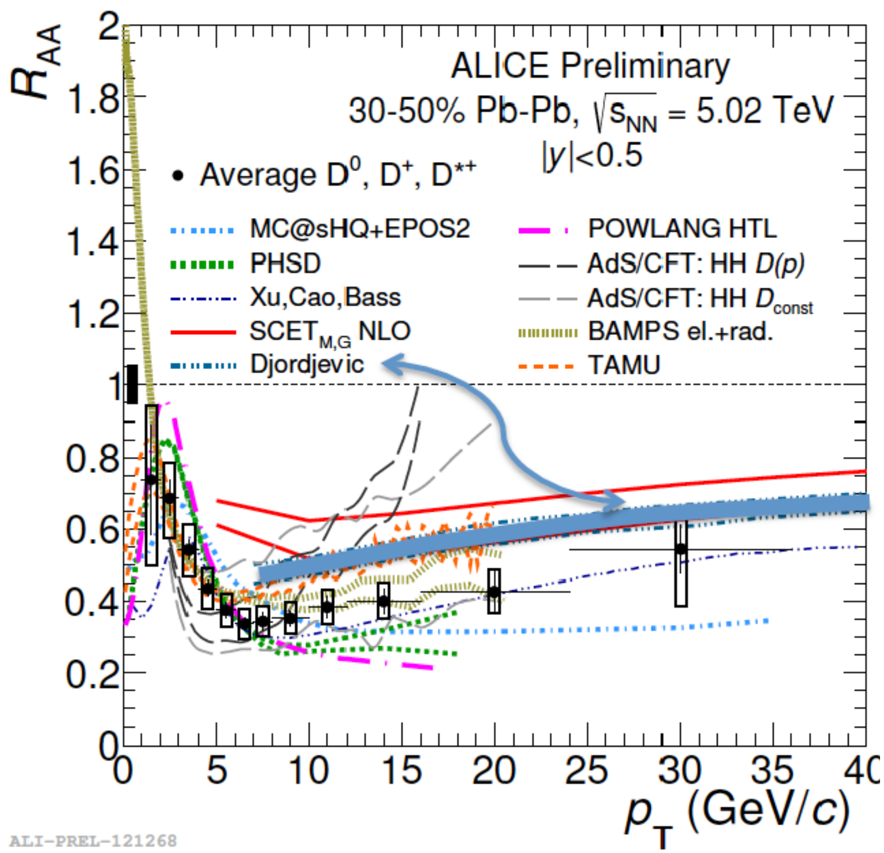


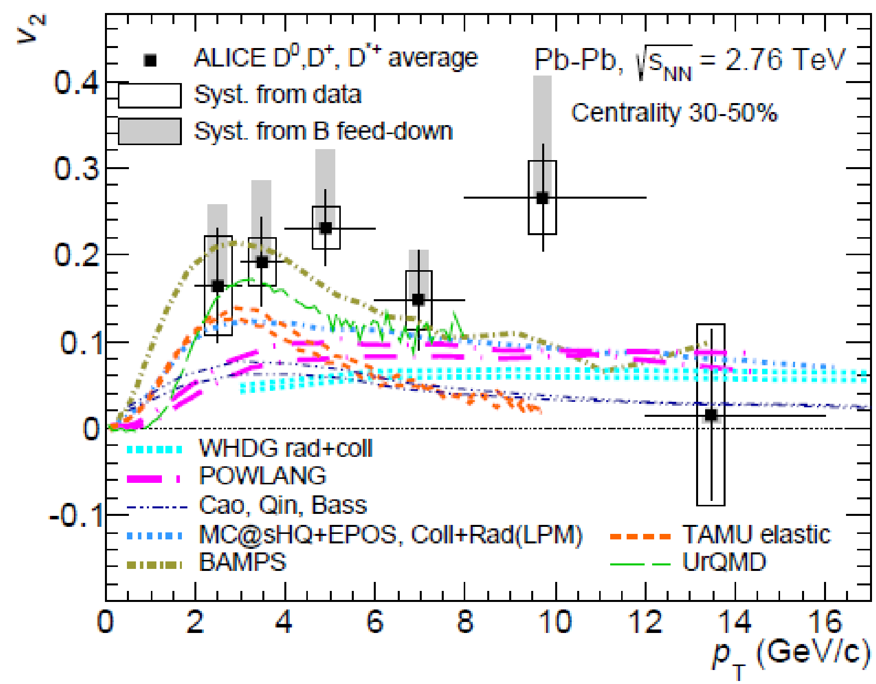
Measurable difference depending on the final state radiation

→ experimentally accessible after upgrate

State of the Art of the Field

Evidently there are many approaches which describe
the two key observables R_{AA} and v_2.
despite of quite different physics input

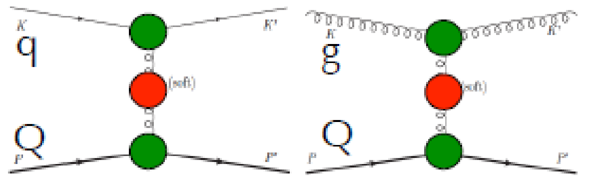




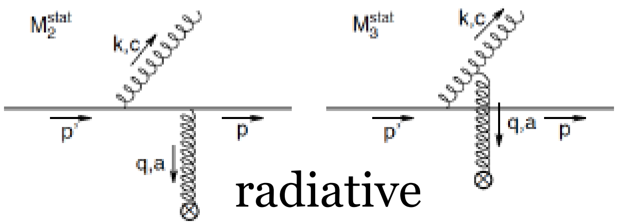
Models studying R_{AA} and v_2 simultaneously
assume that the passage through QPG medium can be modeled by independent collisions (besides LPM)

Born type cross sections and FONLL initial distribution of heavy quarks
but

- ❑ - different cross section (collisional, radiative or both, b and c)



collisional



radiative

- ❑ different coupling constants $\alpha(Q^2)$, $\alpha(T)$, α= const
- ❑ different masses in the propagators (form of the propagators)
- ❑ different masses in exit an entrance channel m_0 , m(T)

- ❑ different initial QGP
- ❑ different expansion scenarios (viscous, ideal hydro, gas of q,g)
- ❑ different hadronization (coalescence, fragmentation)

R_{AA} and v_2 are not sufficient to nail down all these model parameters

All agree on:

- ❑ FONLL is the proper initial condition (shadowing??)
- ❑ pQCD cross sections (α=0.3 , m=m_0) are too small to explain data

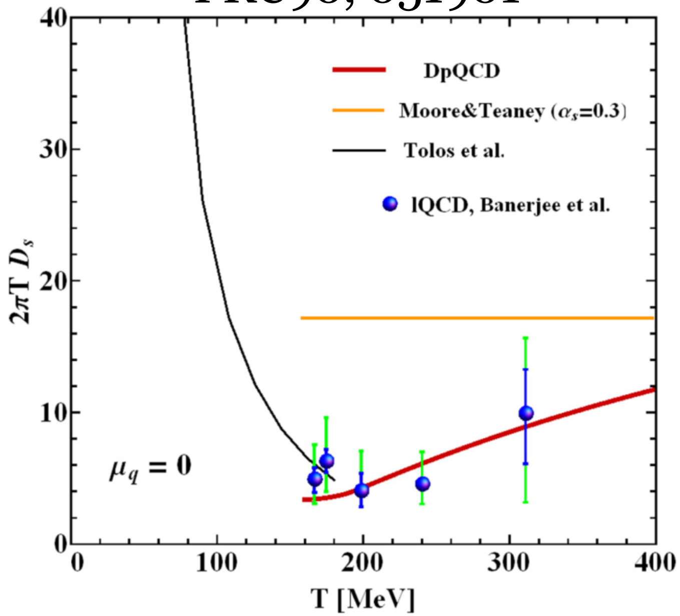
Confirmed by lattice calculations : Spatial diffusion coefficient

$$D_s = \lim_{p_Q \to 0} T/(M_Q \eta_D),$$

$$\eta_D = A/p_Q$$

A= drift coefficient
PRC90,064906

PRC90, 051901



How to compare different approaches and what is the result?

Sequence of meetings:
Berkeley I and II
EMMi/ GSI
Leiden

How to advance to compare very different theories?

As far as collisions are concerned: Start with transport coefficients

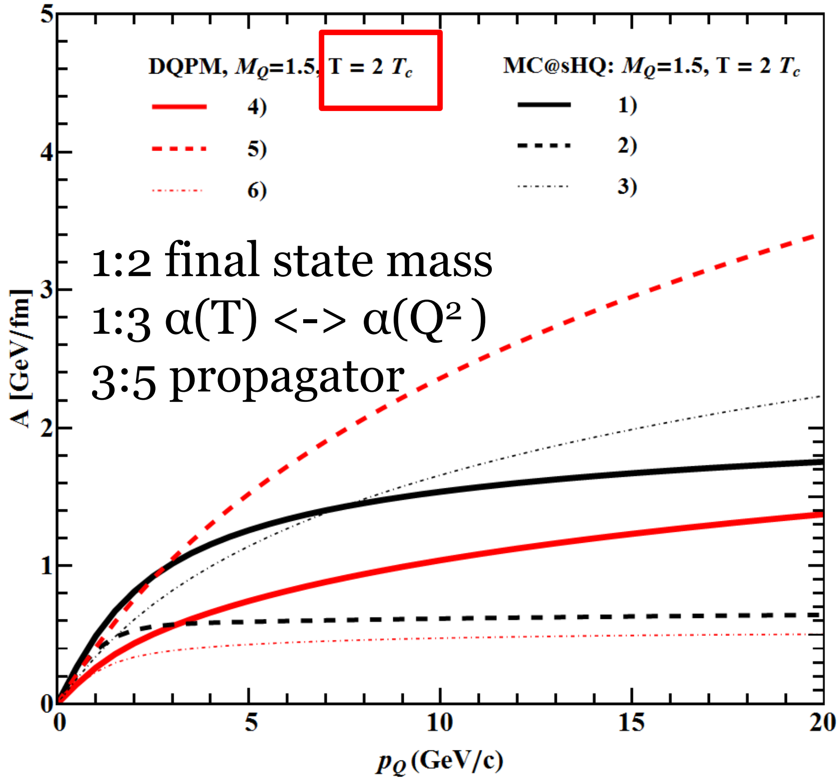
= Reaction of a fast particle on a thermal environment

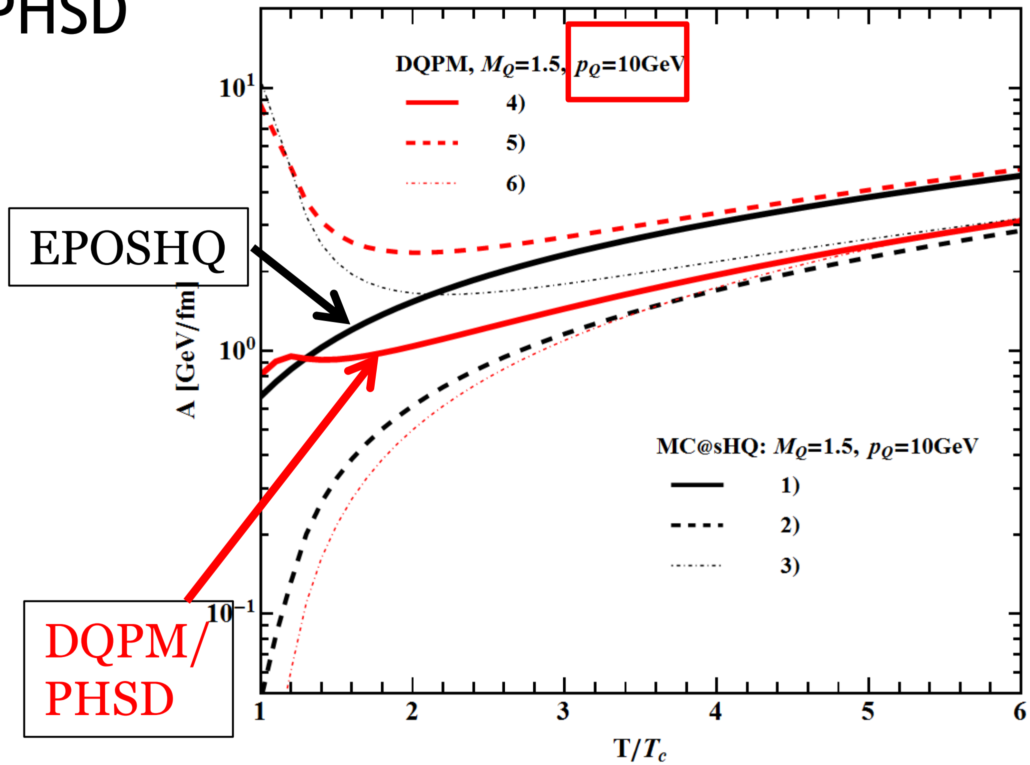
Drag coefficient:

$$A(p,T)_{(\|)} = \boxed{-\frac{\mathrm{d}(p-p')_{\|}}{\mathrm{d}t}} = \frac{1}{2E}\int \frac{d^3k}{(2\pi)^3 2E_k}\int \frac{d^3k'}{(2\pi)^3 2E_{k'}}\int \frac{d^3p'}{(2\pi)^3 2E'} \times \sum \frac{1}{d_i}|\mathcal{M}_{i,2\to 2}|^2\, n_i(k)\,(p-p'_i)_{\|} \times (2\pi)^4\delta^{(4)}(p+k-p'-k'),$$

- ❑ reduces the cross section information to a function of 2 variables: p,T
- ❑ can be calculated for every cross section
  -> makes cross sections comparable

Example : EPOSHQ and PHSD





$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left(\lambda^2(\frac{T}{T_c} - \frac{T_s}{T_c})^2\right)} \quad T > T^\star = 1.19\,T_c,$$

$$g^2(T/T_c) \to g^2(T^\star/T_c)\left(\frac{T^\star}{T}\right)^{3.1} \qquad T < T^\star = 1.19\,T_c.$$

$$M_g^2(T) = \frac{g^2(T/T_c)}{6}\left((N_c + \frac{1}{2}N_f)T^2\right),$$

$$M_q^2(T) = \frac{N_c^2 - 1}{8N_c}g^2(T/T_c)\left(T^2\right),$$

	coupling	mass in gluon propagator	mass in external legs
1)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
2)	$\alpha(Q^2)$	$\kappa = 0.2, m_D$	$m_{q,g} = m_{q,g}^{DQPM}$
3)	$\alpha(T)$	$\kappa = 0.2, m_D$	$m_{q,g} = 0$
4)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$
5)	$\alpha(T)$	m_g^{DQPM}	$m_{q,g} = 0$
6)	$\alpha(Q^2)$	m_g^{DQPM}	$m_{q,g} = m_{q,g}^{DQPM}$

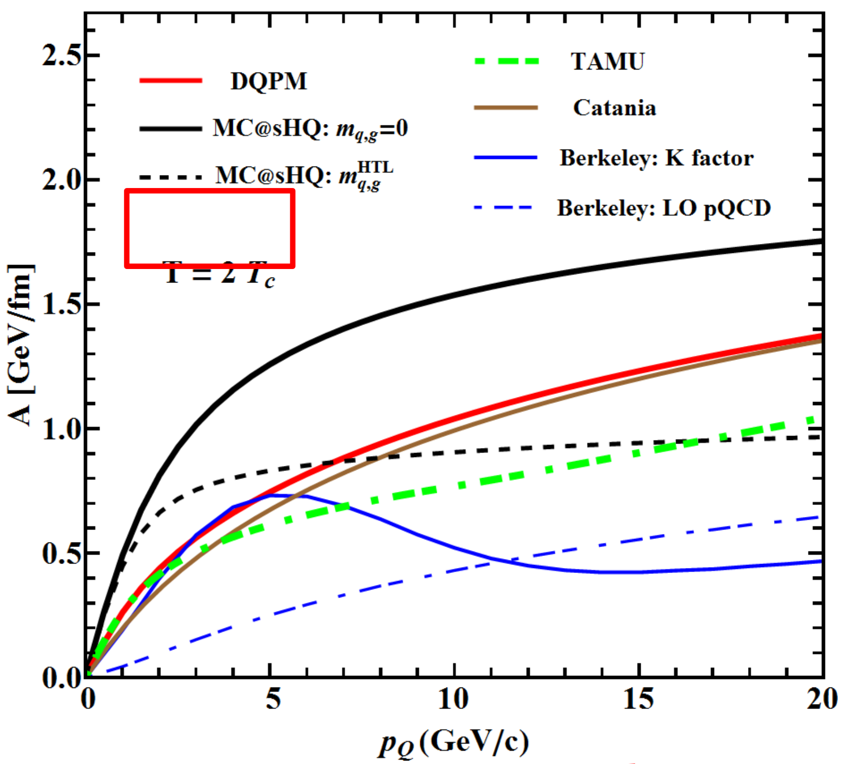
$g^2(T/T_c)$: ⇧ Late energy loss

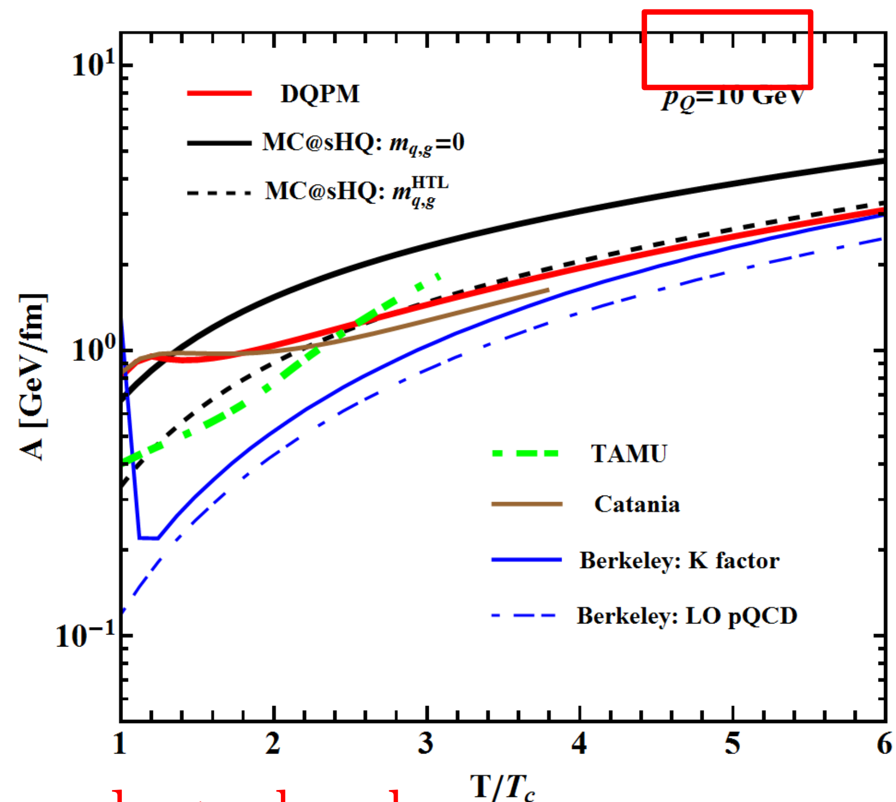
c-quarks reaction to the QGP environment rather differently in the diff. codes

large momentum loss close to T_c like DQPM(PHSD), Catania,Berkeley
large energy loss at $T > T_c$ Nantes, pQCD like ,TAMU

Only the integral over the energy loss can be measured !!

(obviously the same because all describe data)

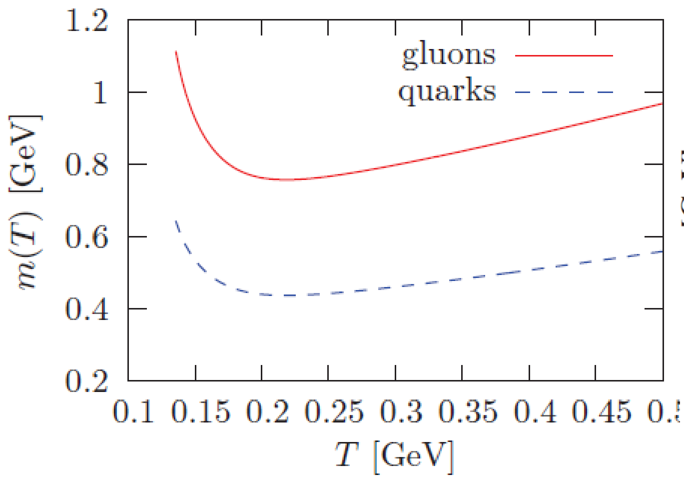




Elastic energy loss and c-quarks only

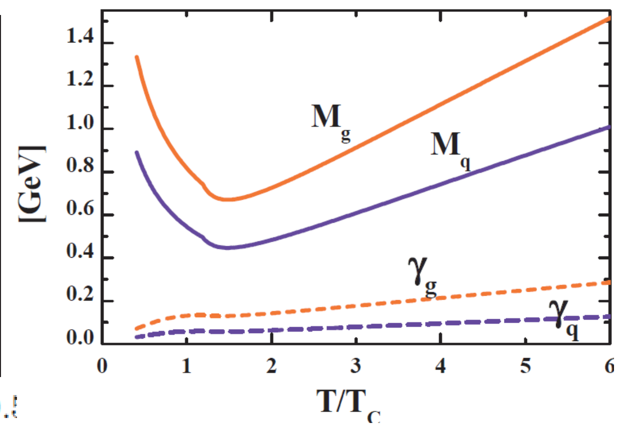
Gives fit of the masses to lQCD results give more insight ?

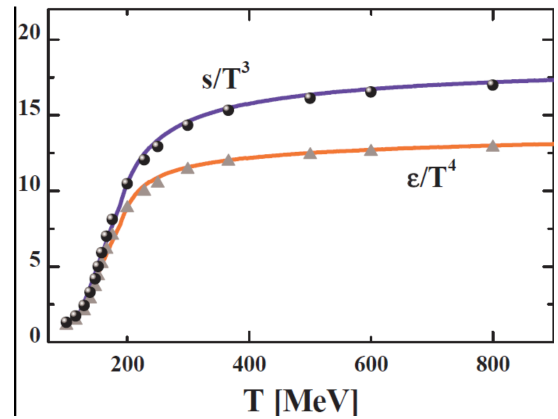
Effective mass model



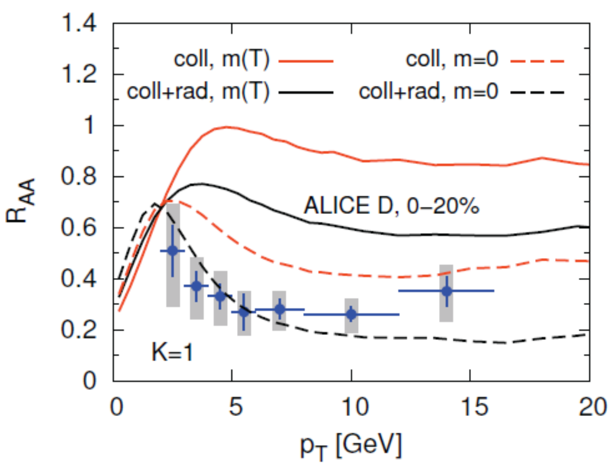
arXiv:1602.03544

PHSD



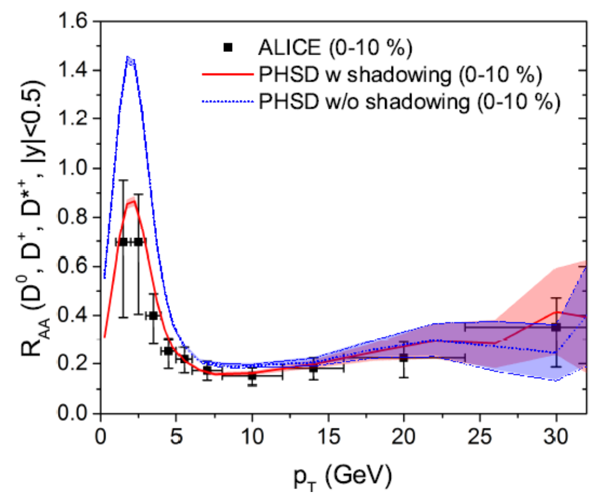


arXiv:1512.00891



NO, masses alone are just one of the ingredients

Effect of finite masses can be compensated by other ingredients



Different descriptions of the c cbar - QGP interaction

Fokker-Planck <-> Boltzmann collision kernel

Different numerical approaches

Fokker-Planck
Langevin
Brownian Motion

Advantage:
- very general approach
- Whole kinematics of HQ is reduced to (mom. dep.) drag and diffusion coefficient
related by the Einstein relation

Drawback:
- Physics very difficult to asses if coeff. not determined from an underlying theory
- Need lattice data, or underlying theory
- otherwise it is a fit

Boltzmann collision integral

Advantage:
- Interaction between HQ and partons is related to the underlying Lagrangian (Feynman diagrams) -> microscopic interpretation possible
- Allows for the calculation of drag and diffusion coeff. independently

Drawback:
- Assumes asympt. free states (low density)
- Presently only effective Lagrangians

Strategy:
Boltzmann type models calculate drag and diffusion coefficients which can be compared with the Langevin approaches

From Boltzmann to Fokker – Planck

One start with the Boltzmann collision term and forms mean values :

$$\frac{d <\mathcal{X}>}{dt} = \sum_{q,g} \frac{1}{(2\pi)^5 2E_Q} \int \frac{d^3q}{2E_q} f(\boldsymbol{q}) \int \frac{d^3q'}{2E_{q'}} \int \frac{d^3p'_Q}{2E'_Q}$$

$$\times \, \delta^{(4)}(P_{in} - P_{fin}) \, \mathcal{X} \, \frac{1}{g_Q g_p} |\mathcal{M}_{2,2}|^2, \qquad ($$

The drag is given by

$$A_i \rightarrow \chi = (p - p'_i)$$

and the diffusion by

$$B_{ij} \rightarrow \chi \rightarrow \frac{1}{2}(p - p'_i)(p - p'_j) \rightarrow B_{||}, B_{\perp}$$

These are the coefficients need for the Fokker-Planck equation

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

4 Observations

a) Whereas the Boltzmann integral brings the heavy quarks for $t \rightarrow \infty$ to a thermal equilibrium, the Fokker Planck equation does this only if

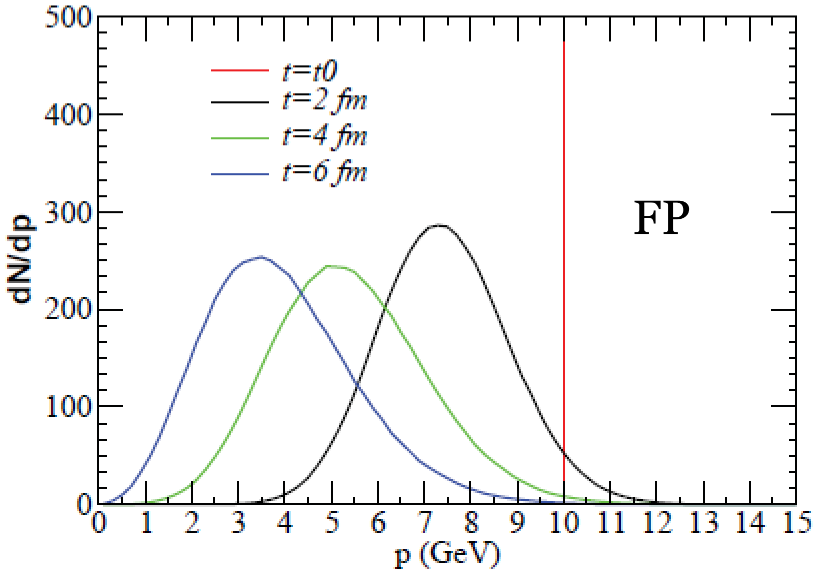
$$B_{\|} = B_{\perp} = B$$ AND A and B related by Einstein relation

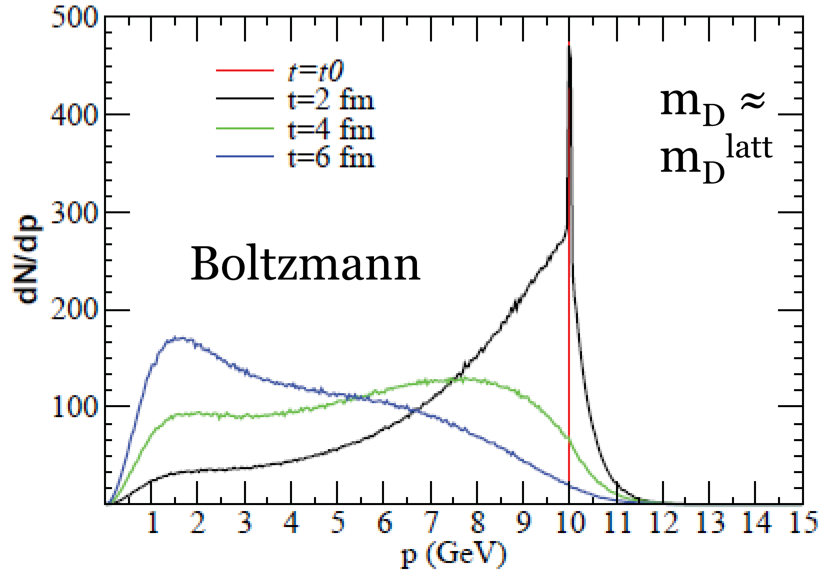
This is (by far) not the case if A and B are calculated from Boltzmann collision Kernel

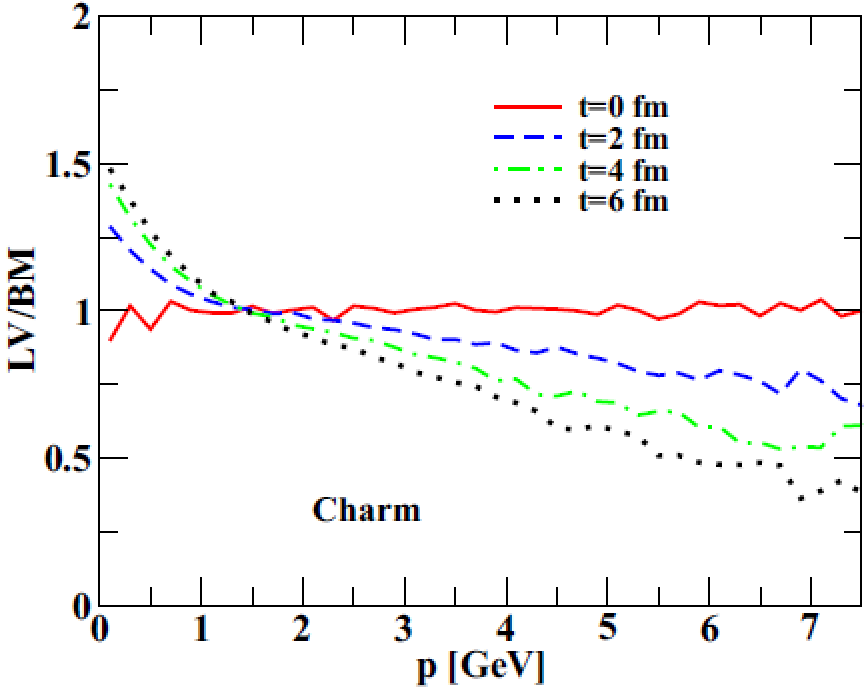
This leaves three options ($B_{\|}, B_{\perp}, A_i$) to relate Fokker Planck to Boltzmann

different choices have been made -> different results

b) Time evolution of f(p,r,t) of c with Fokker Planck is very different as compared to Boltzmann eq. (Das et al. PRC90(14)044901) (here B is used to determine drag)



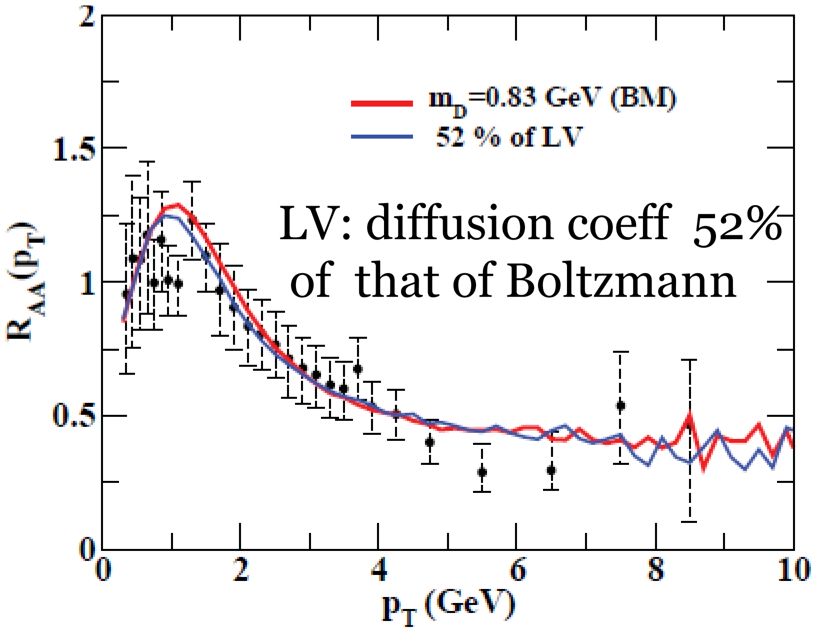


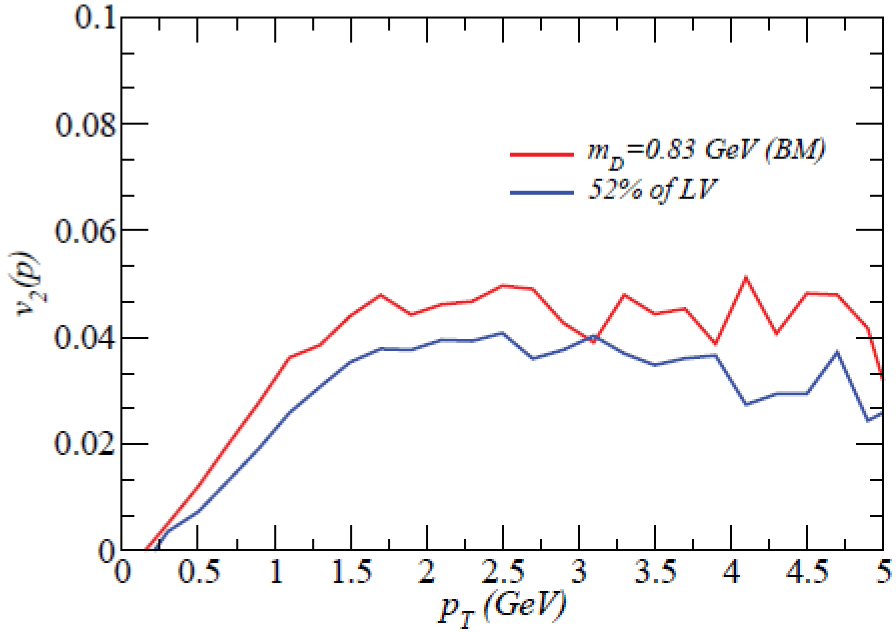


For realistic Debye masses (Kaczmarek et al. (1206.19912))

to reproduce data:

we need by a factor of 2
different drag and diffusion coefficient
Depending on whether we apply
FP or Boltzmann.





Conclusions

All experimental midrapidity RHIC and LHC data are compatible with the assumption that

pQCD describes energy loss and elliptic flow v_2 of heavy quarks.

Special features running coupling constant
adjusted Debye mass
Landau Pomeranschuk Migdal

QGP expansion QGP must be controlled by light hadrons (EPOS)

Data do not allow for discriminating between different pQCD processes: radiative and collisional energy loss

First results about the physics are now possible

- b/c results
- Origin of the flow (p_T)
- Effective degrees of freedom of the QGP

But

There are several approaches which reproduce

R_{AA} and v_2.

the presently only available data.

We measure only integrated energy loss in an expanding QGP

It can be obtain in many ways

lQCD EOS does not help a lot: masses are only one of the ingredients

lQCD spatial diffusion coeff -> pQCD does not work

We have to wait for new observables (identified b, Δφ, high precision v_2 D_S) or more input from lQCD

What transport people can do:

Using for the QGP expansion only models which reproduces data in the light quark sector

Abandon Fokker-Planck approaches and concentrate on the much more demanding Boltzmann collision kernel

Collaborators

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	Pierre Moreau
	Taesoo Song
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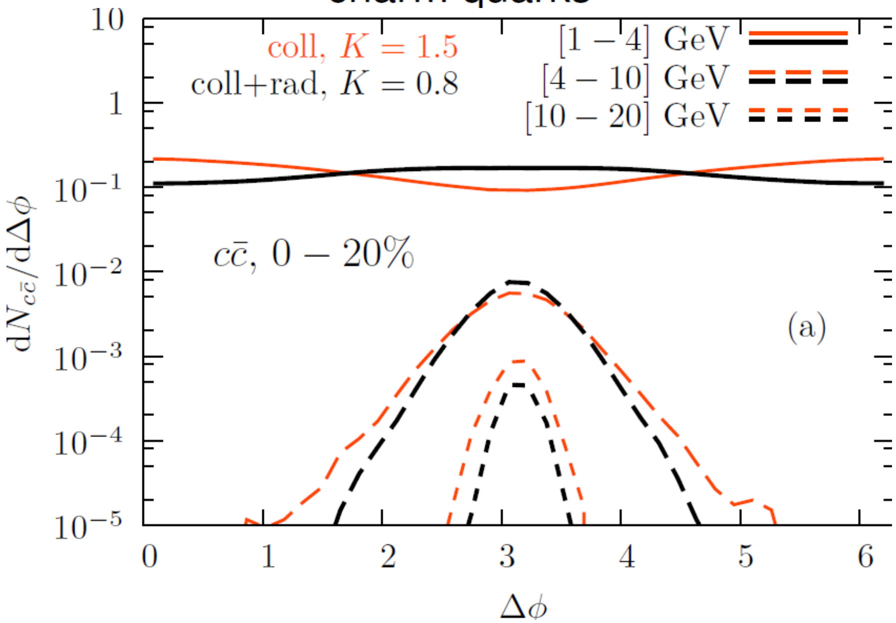
LBL	Shanshan Cao
	Xin-Nian Wang

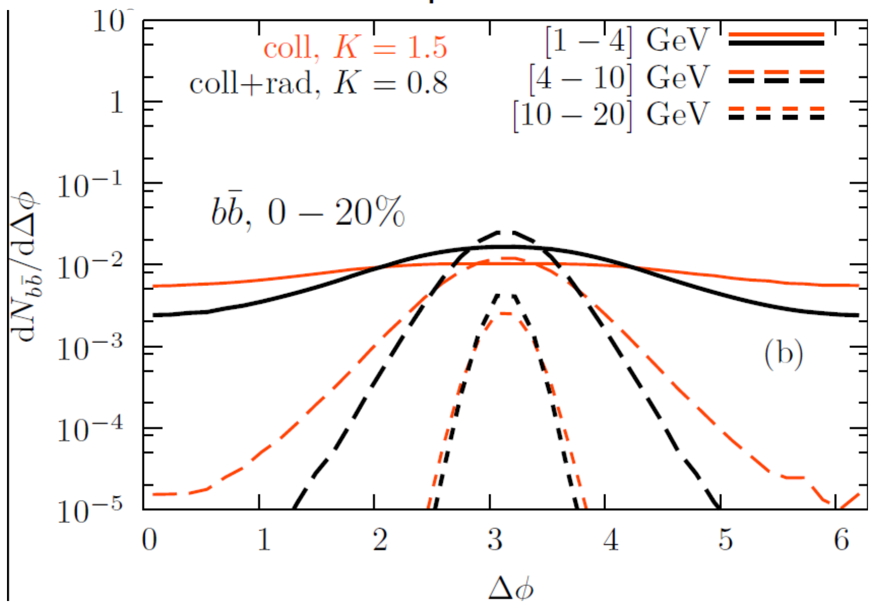
Heavy-quark azimuthal correlations

central collisions, back-to-back initialization, no background from uncorrelated pairs

charm quarks



bottom quarks



- Stronger broadening in a purely collisional than in a **collisional+radiative** interaction mechanism
- Variances in the intermediate p_T-range: 0.18 vs. **0.094** (charm) and 0.28 vs. **0.12** (bottom)
- At low p_T initial correlations are almost washed out: small residual correlations remain for the **collisional+radiative** mechanism, "partonic wind" effect for a purely collisional scenario.
- Initial correlations survive the propagation in the medium at higher p_T.