The Physics of Heavy Quarks in AA collisions

Why heavy quarks are interesting ?

Interaction of heavy quarks with the plasma

- our model (elastic and inelastic collisions, LPM)
- comparison with data
- how far we are with our understanding

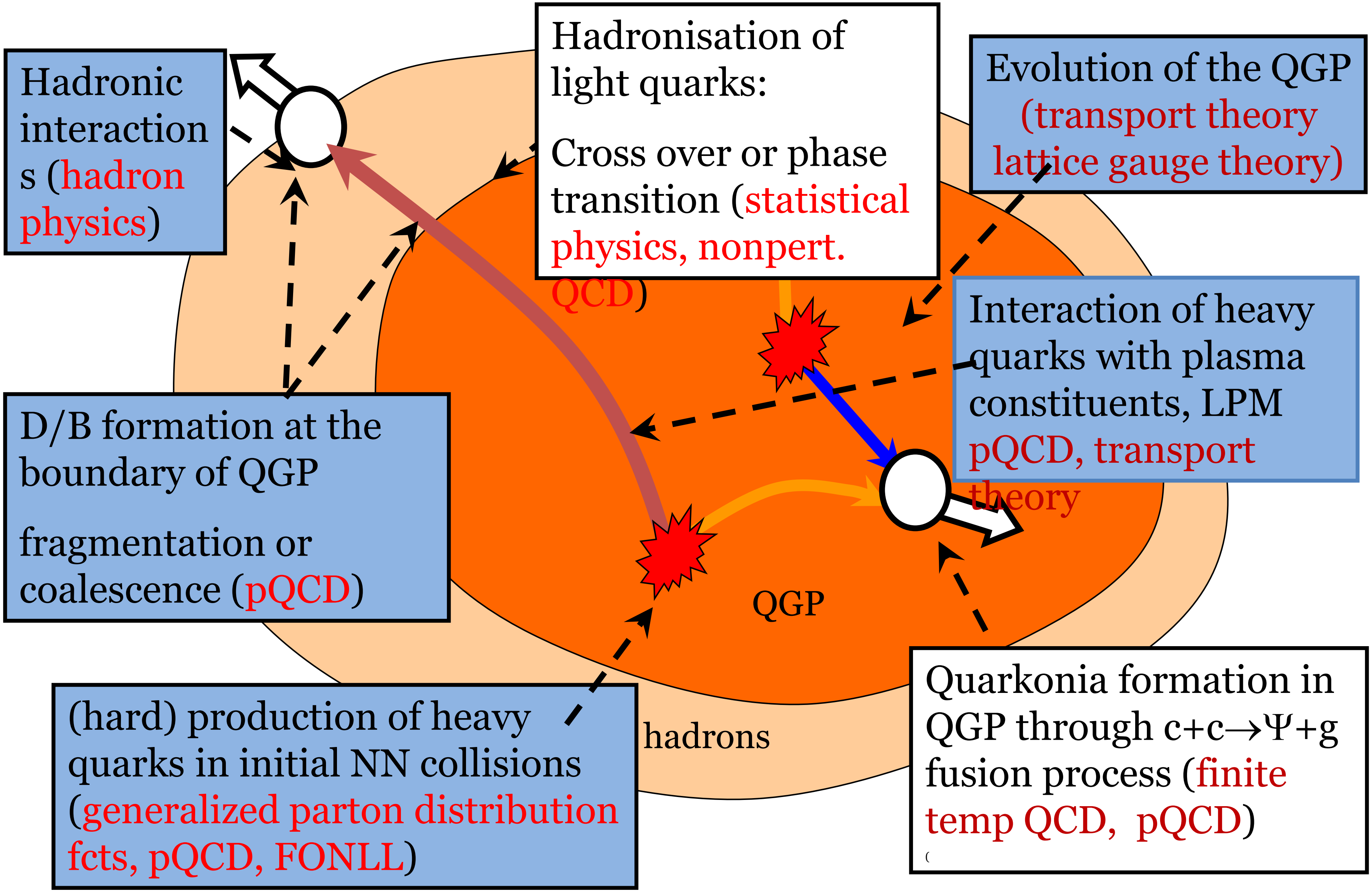
What makes heavy quarks (mesons) so interesting?

- produced in hard collisions (initial distribution: FONLL confirmed by STAR/Phenix)
- high p_T: no equilibrium with plasma particles (information about the early state of the plasma)
- not very sensitive to the hadronisation process

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))
difficult to separate (**arXiv:1102.1114**)

Complexity of heavy quark physics in a nutshell :



Hadronic interactions (hadron physics)

Hadronisation of light quarks:

Cross over or phase transition (statistical physics, nonpert. QCD)

Evolution of the QGP (transport theory lattice gauge theory)

Interaction of heavy quarks with plasma constituents, LPM pQCD, transport theory

D/B formation at the boundary of QGP

fragmentation or coalescence (pQCD)

(hard) production of heavy quarks in initial NN collisions (generalized parton distribution fcts, pQCD, FONLL)

Quarkonia formation in QGP through $c+c\rightarrow\Psi+g$ fusion process (finite temp QCD, pQCD)

(

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 Fokker Planck approx
- 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

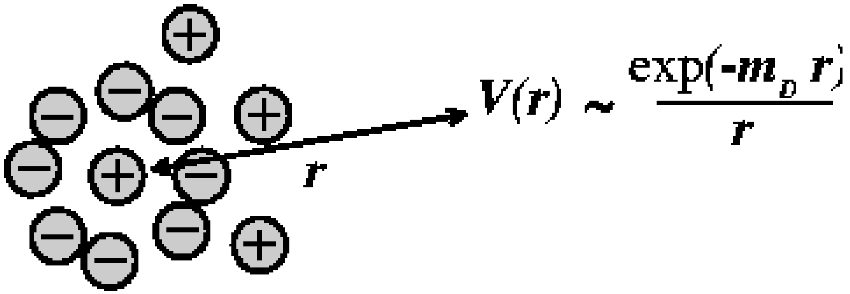
Nantes approach: Elastic heavy quark – q(g) collisions

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

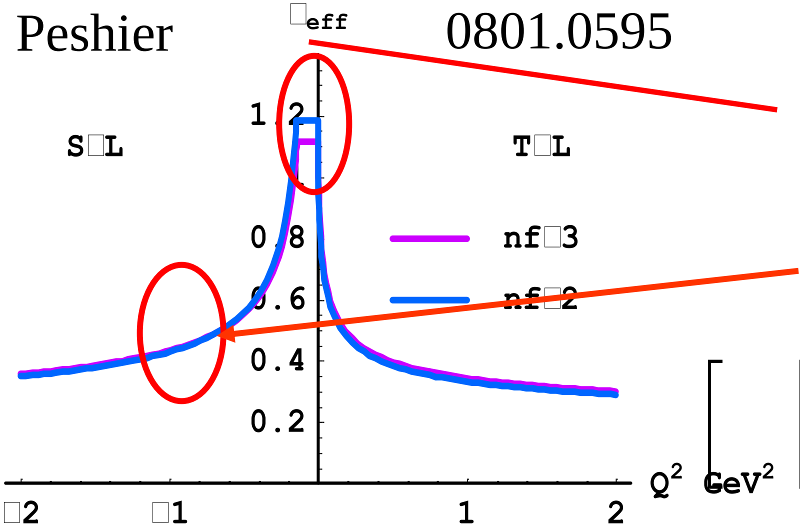
Neither $g^2 = 4\pi\,\alpha(t)$ nor $\kappa\, m_D^2$= are well determined
standard: $\alpha(t)$ =is taken as constant or as $\alpha(2\pi T)$
κ =1 and α =.3: large K-factors (≈ 10) are necessary to describe data

A) Running coupling constant

“Universality constraint” (Dokshitzer 02) helps reducing uncertainties:

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

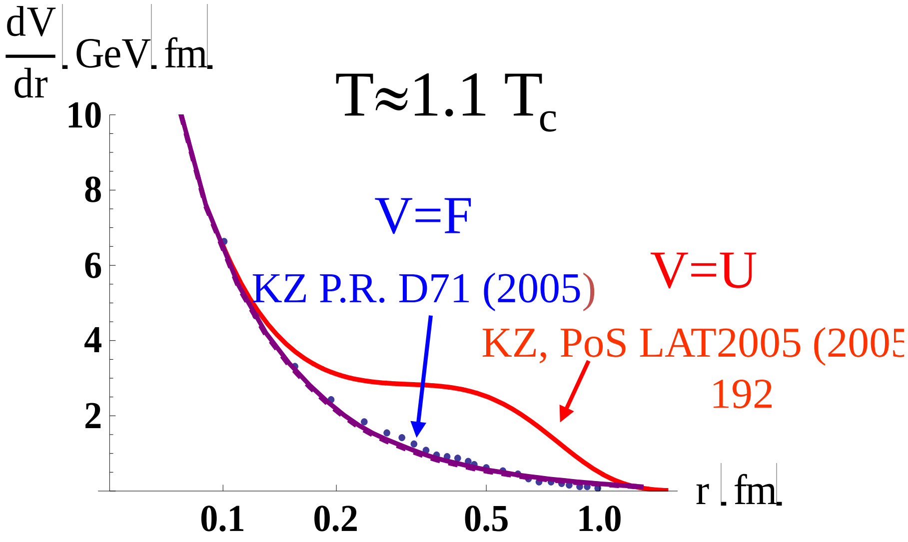
Peshier 0801.0595



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

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



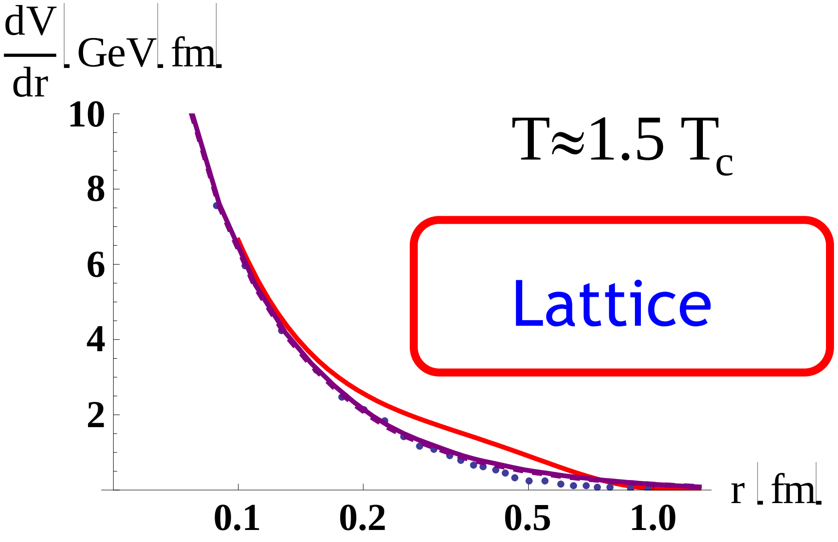
T≈1.1 T_c

V=F

KZ P.R. D71 (2005)

V=U

KZ, PoS LAT2005 (2005) 192

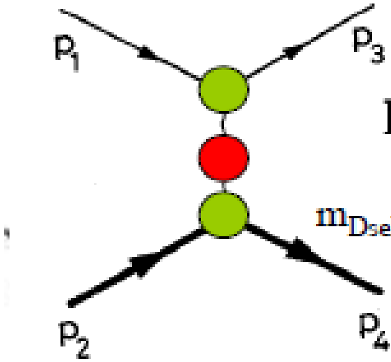


T≈1.5 T_c

Lattice

B) Debye mass

PRC78 014904, 0901.0946



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

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

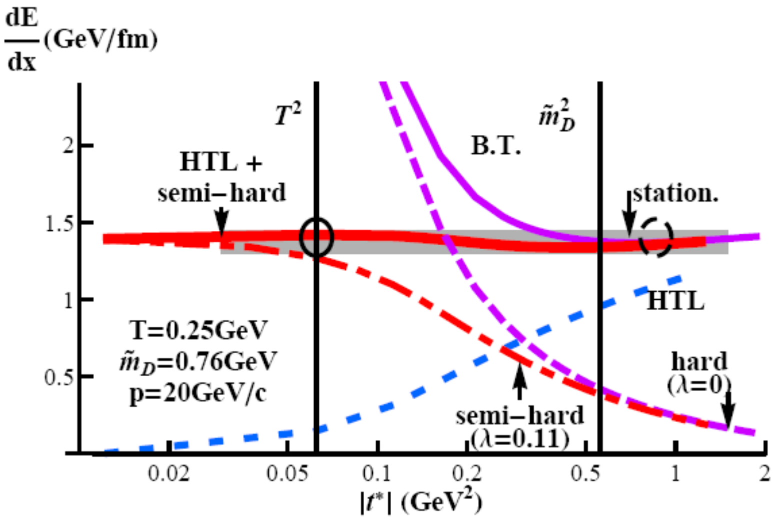
hep-ph/0607275

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:

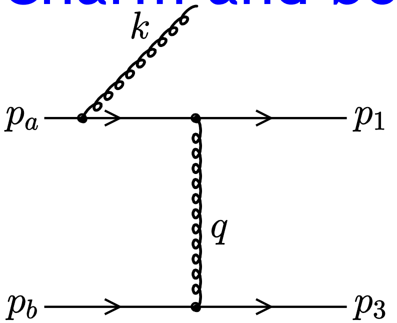
$\kappa \approx 0.2$

much lower than the standard value

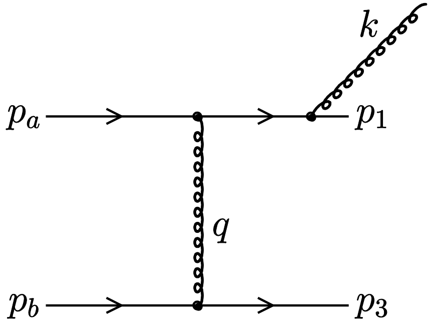
C) Inelastic Collisions

Low mass quarks : radiation dominantes energy loss

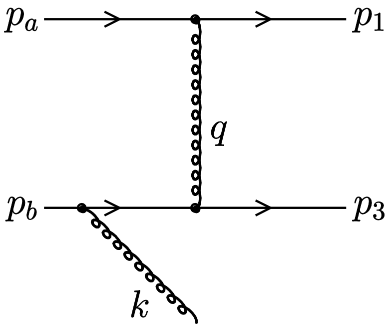
Charm and bottom: radiation of the same order as collisional



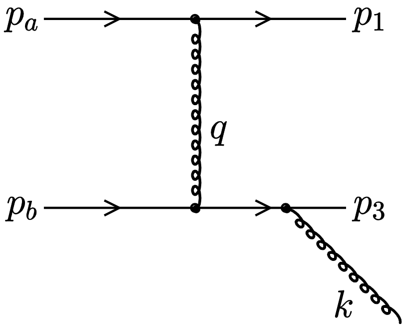
M_1



M_2

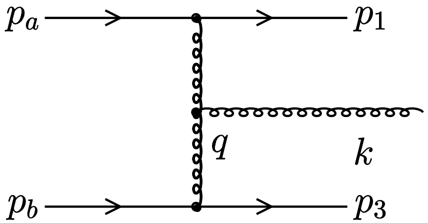


M_3



M_4

4 QED type diagrams



M_5

1 QCD diagram

Commutator of the color SU(3) operators

$$T^bT^a = T^aT^b - if_{abc}T^c$$

M1-M5 : 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

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:

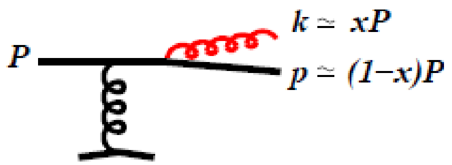
$$\frac{\omega d^4\sigma^{rad}}{dx d^2k_t dq_t^2} = \frac{N_c\alpha_s}{\pi^2}(1-x)\cdot\frac{d\sigma^{el}}{dq_t^2}\cdot P_{rad}$$

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

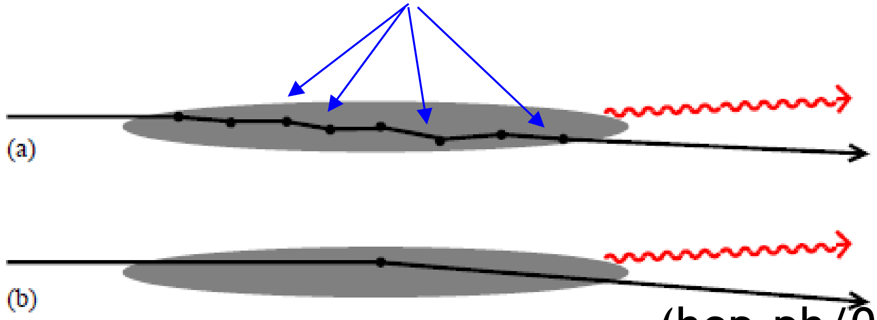


Heavy quark radiates gluons

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)

(hep-ph/0204343)

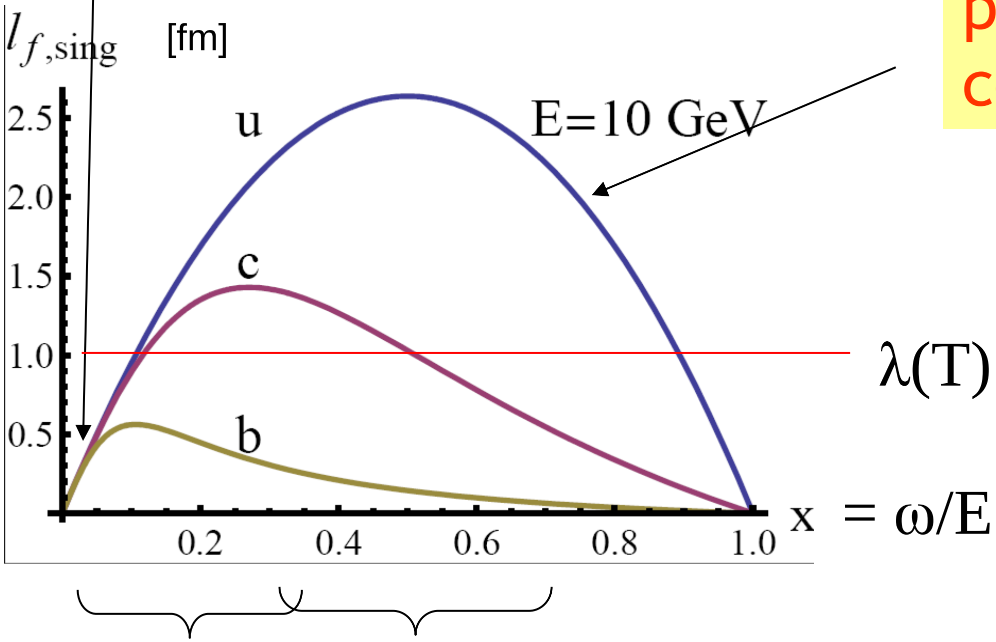
$$t_f \approx \frac{2(1-x)\omega}{\boxed{\underbrace{(\vec{k}_\perp - \vec{q}_\perp)^2}} + \boxed{\underbrace{x^2M^2 + (1-x)m_g^2}}}$$

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

dominates $x<1$ dominates $x\approx1$ dominates $x<<1$

For $x<x_{cr}=m_g/M$, basically no mass effect in gluon radiation

For $x>x_{cr}=m_g/M$, gluons radiated from heavy quarks are resolved in less time then those from light quarks and gluons => radiation process less affected by coherence effects.



LPM important for intermediate x where formation time is long

Most of the collisions $\frac{d\sigma}{dx}$

Dominant region for average E loss $x\frac{d\sigma}{dx}$

Calculations for RHIC and LHC

Initialization: FONLL distribution of c and b

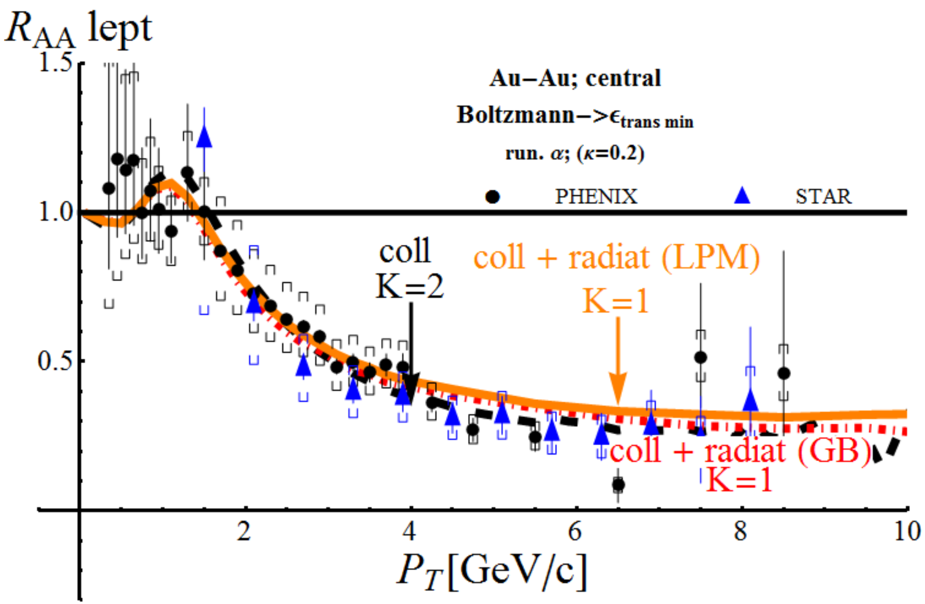
QGP : Hydro Kolb-Heinz for RHIC
EPOS for LHC

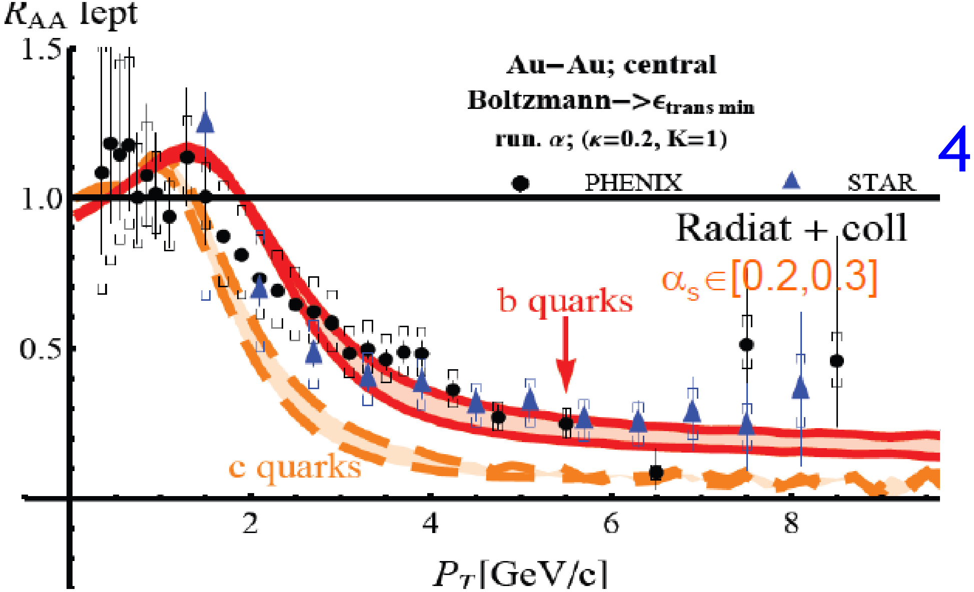
Interaction QGP-heavy quarks:
elastic collisions (collisional energy loss) (K ≈ 1.7)
elastic collisions + and gluon emission (radiative energy loss)
+LPM (K ≈ .7)

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

Hadronic rescattering is small

RHIC   Hydro: Kolb Heinz



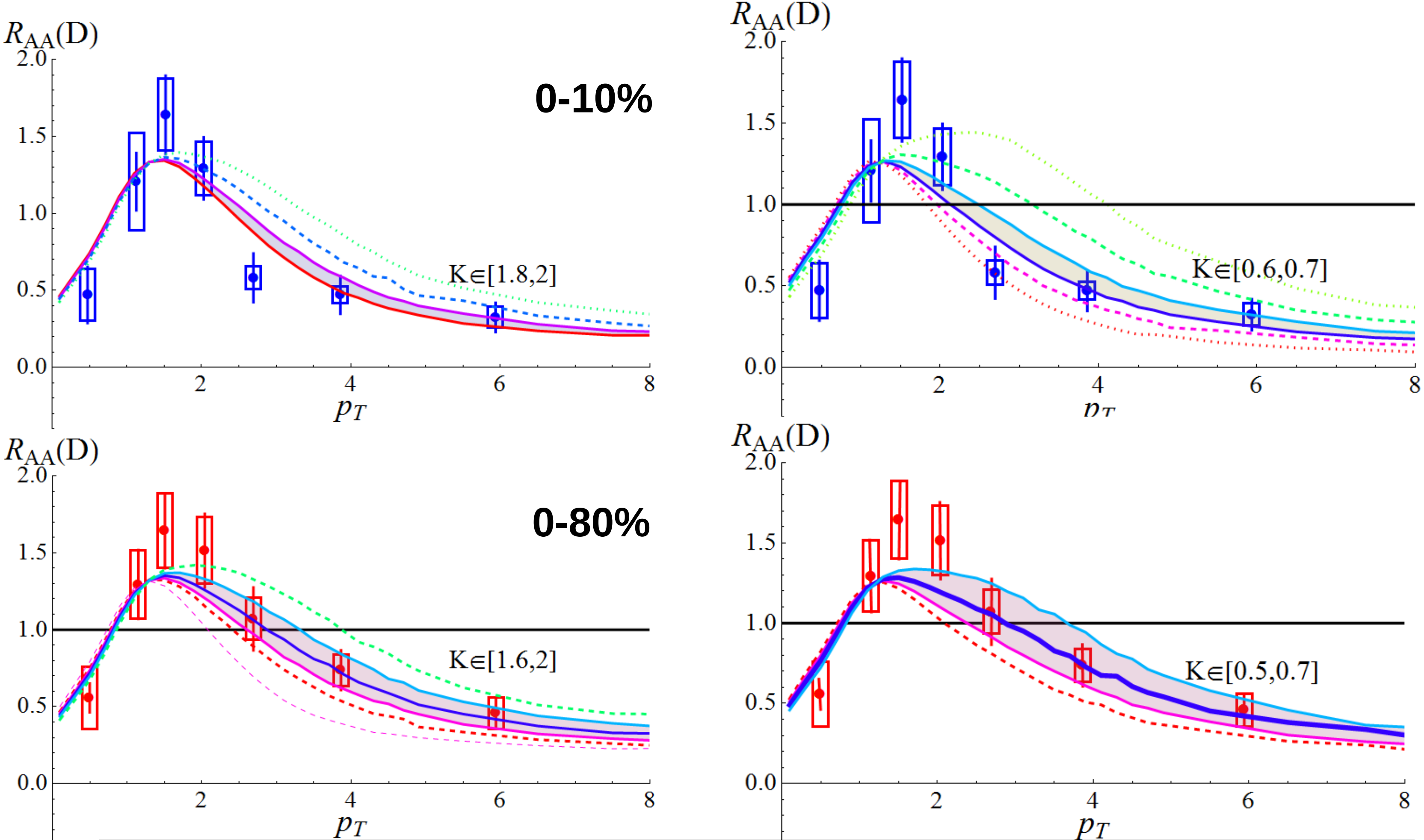


1. Coll:too little quenching (but very sensitive to freeze out) -> K=2
2. Radiative Eloss indeed as important as the collisional one
3. Flat experimental shape is well reproduced
4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC)

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

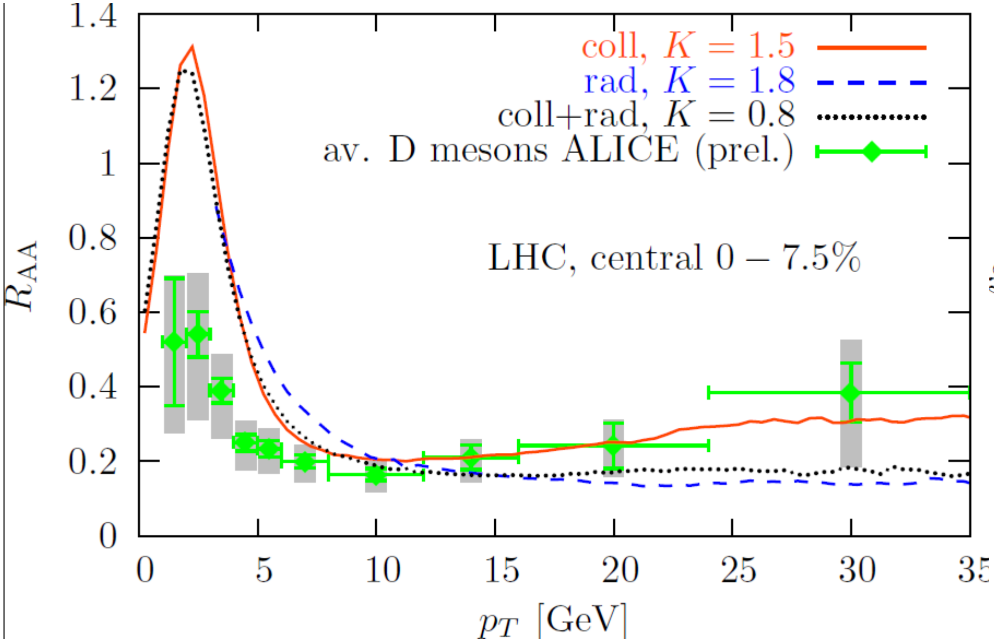
RHIC: D mesons

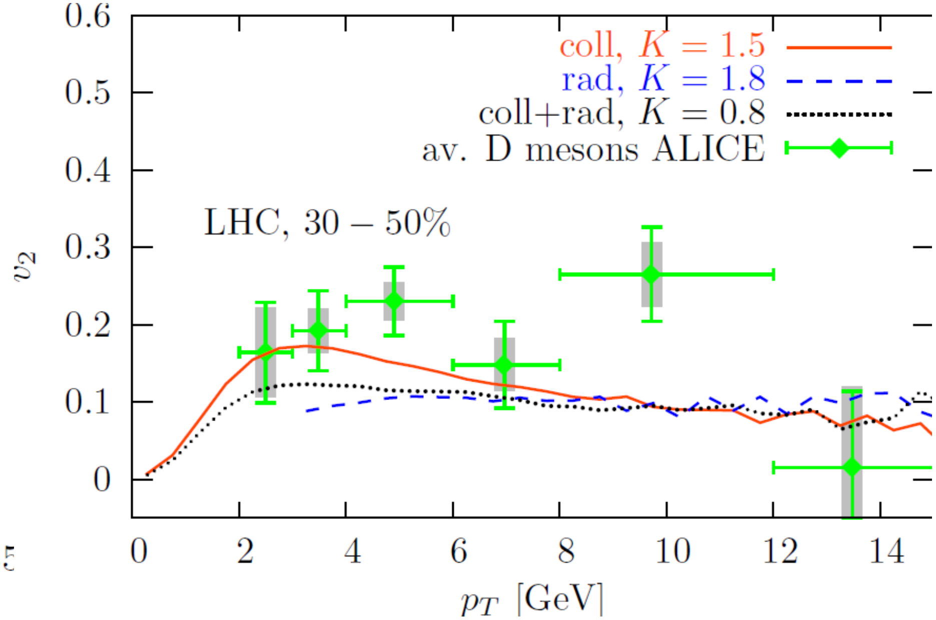
Elastic **Elastic + radiative LPM**



No form difference between coll and coll + rad

LHC : EPOS 2 event generator



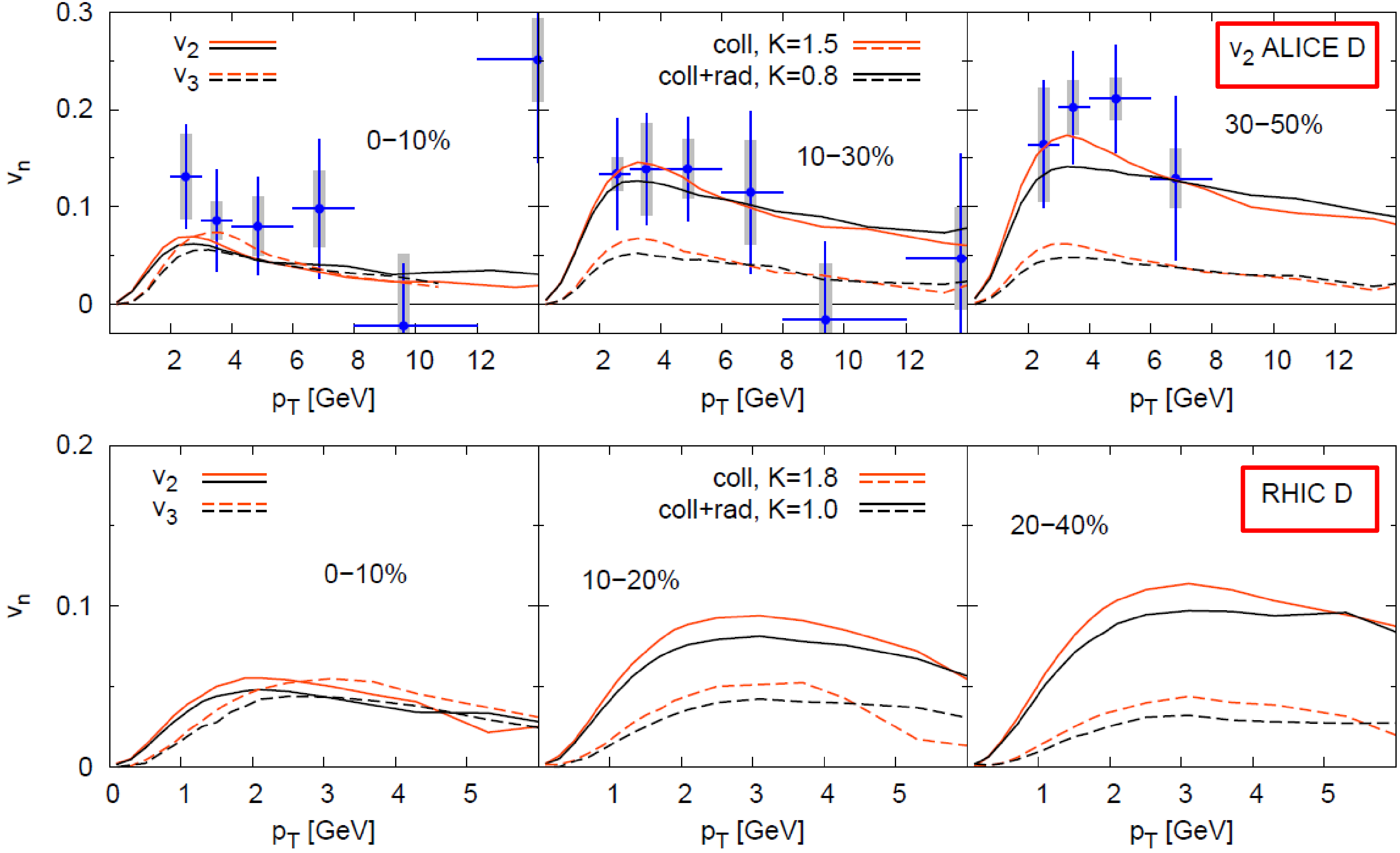


Three options : Collisions only K factor = 1.5
Collision and radiation K = 0.8
Radiation only K= 1.8

remember : Different hydro scenario give different K- factores

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

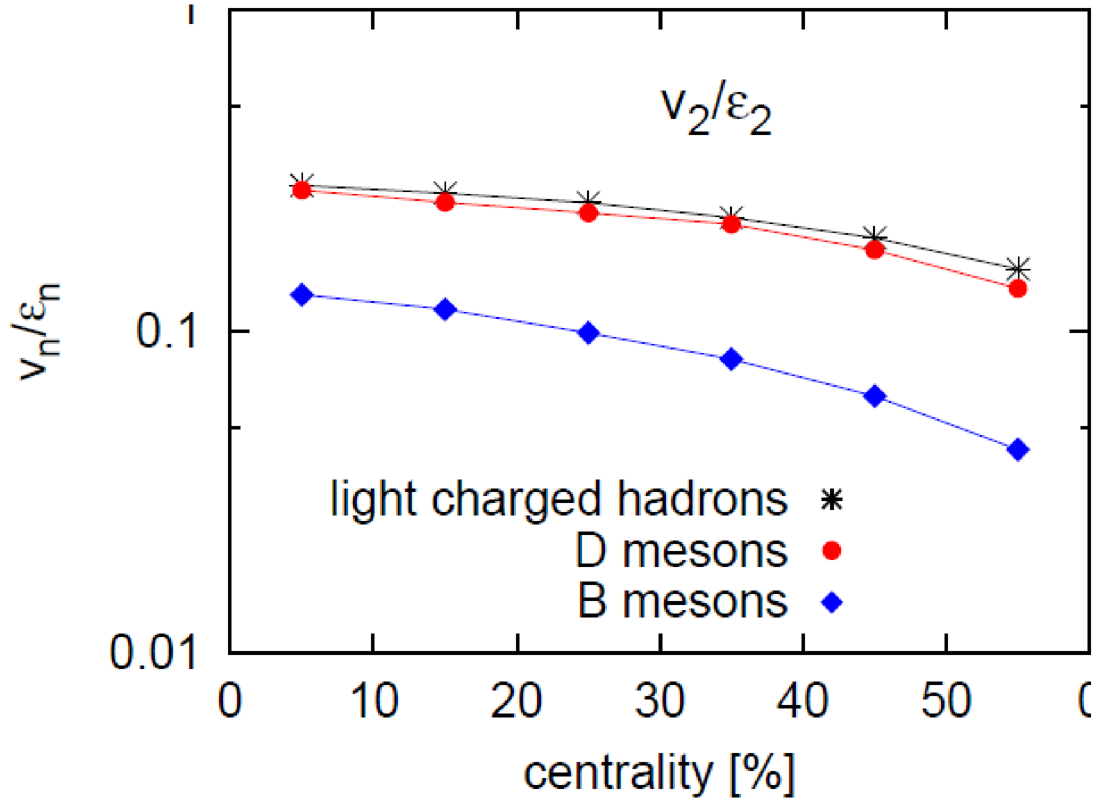


What can one learn from these results?

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

v_3 independent of centrality -> fluctuations

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

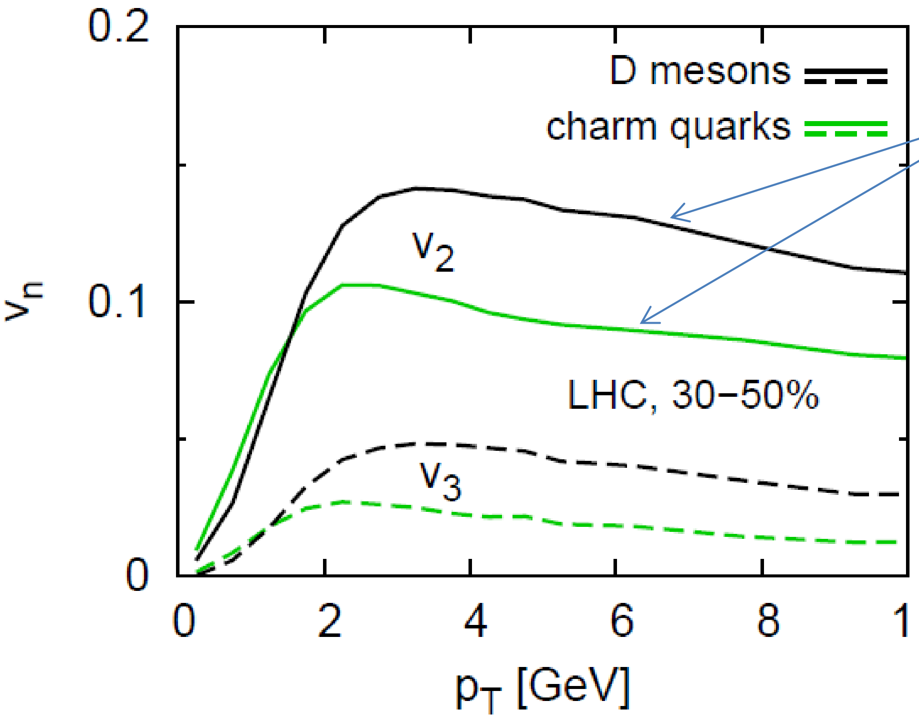
Heavy quarks: No initial v_2 (hard process)

v_2 only due to interaction with q and g

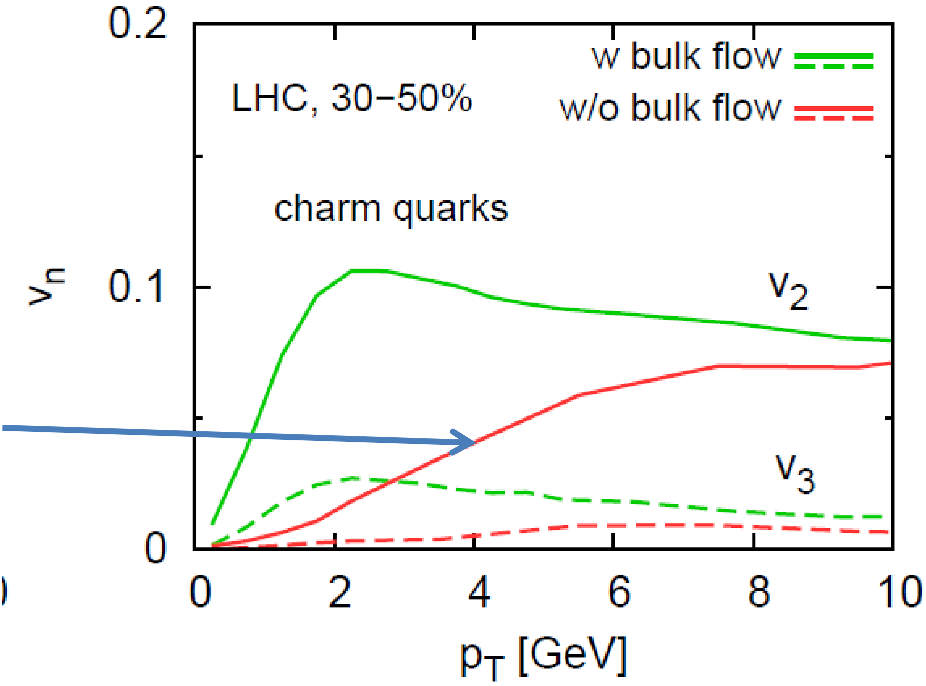
v_2 of heavy quarks is created later measures the interaction time

Bottom quarks are to heavy to follow

More detailed analysis of the flow



20% of v_2 due to the hadronisation uncertainty
whether fragmentation
or coalescence is not essential for v_2

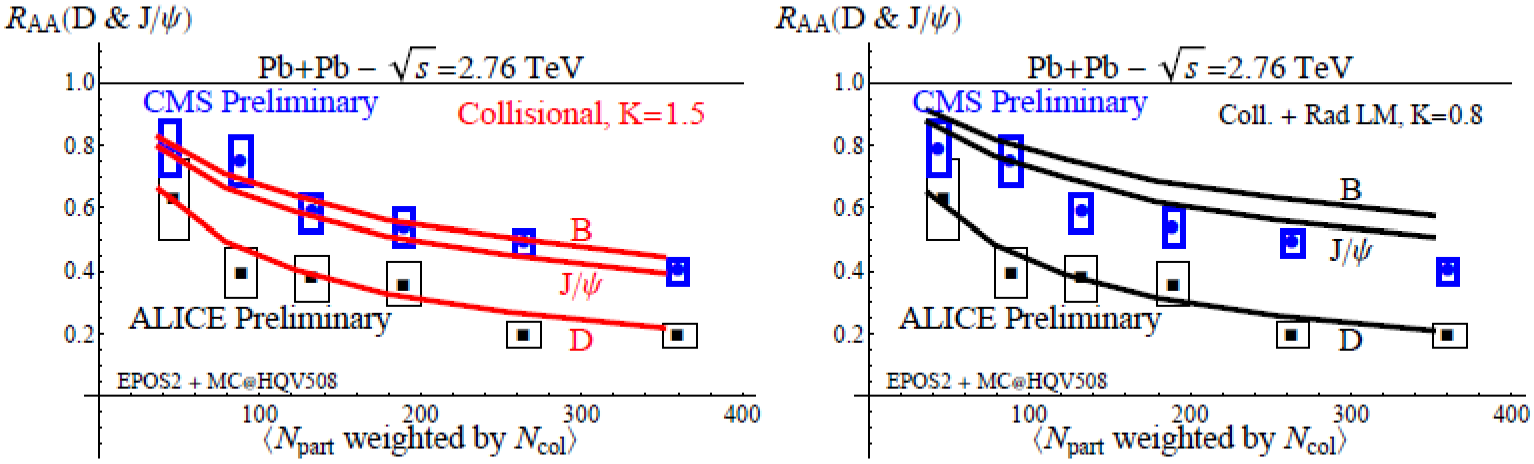


Verification that collective flow creates v_2

Artificial elimination of the collective flow

High momentum: different path length
in and out of plane

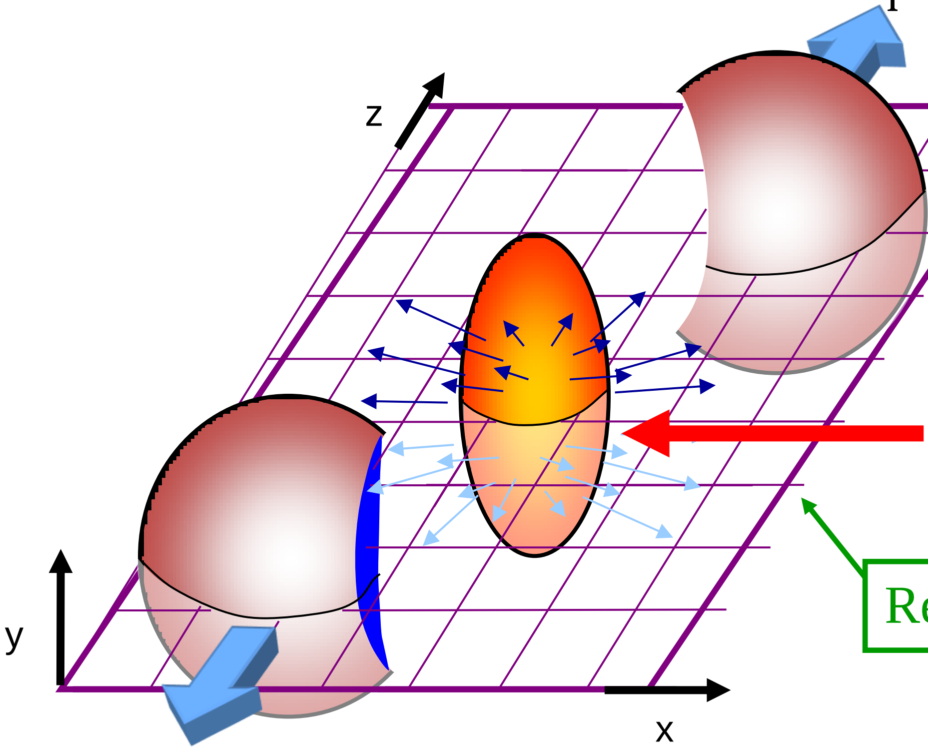
The different R_{AA} of D and B mesons seems to be verified experimentally (by comparing two different experiments)



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 $|y|<1.2$

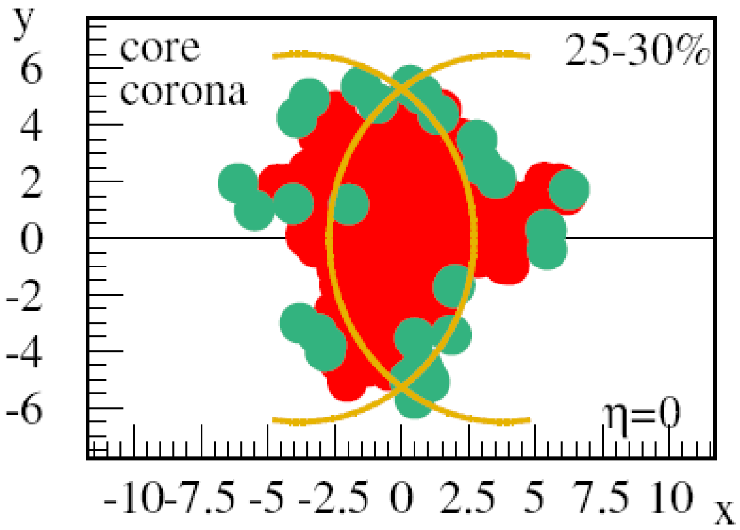
Where do the finite v_i come from?



Plasma to be studied

Reaction plane

In the ideal world the plasma
Should have only v_2

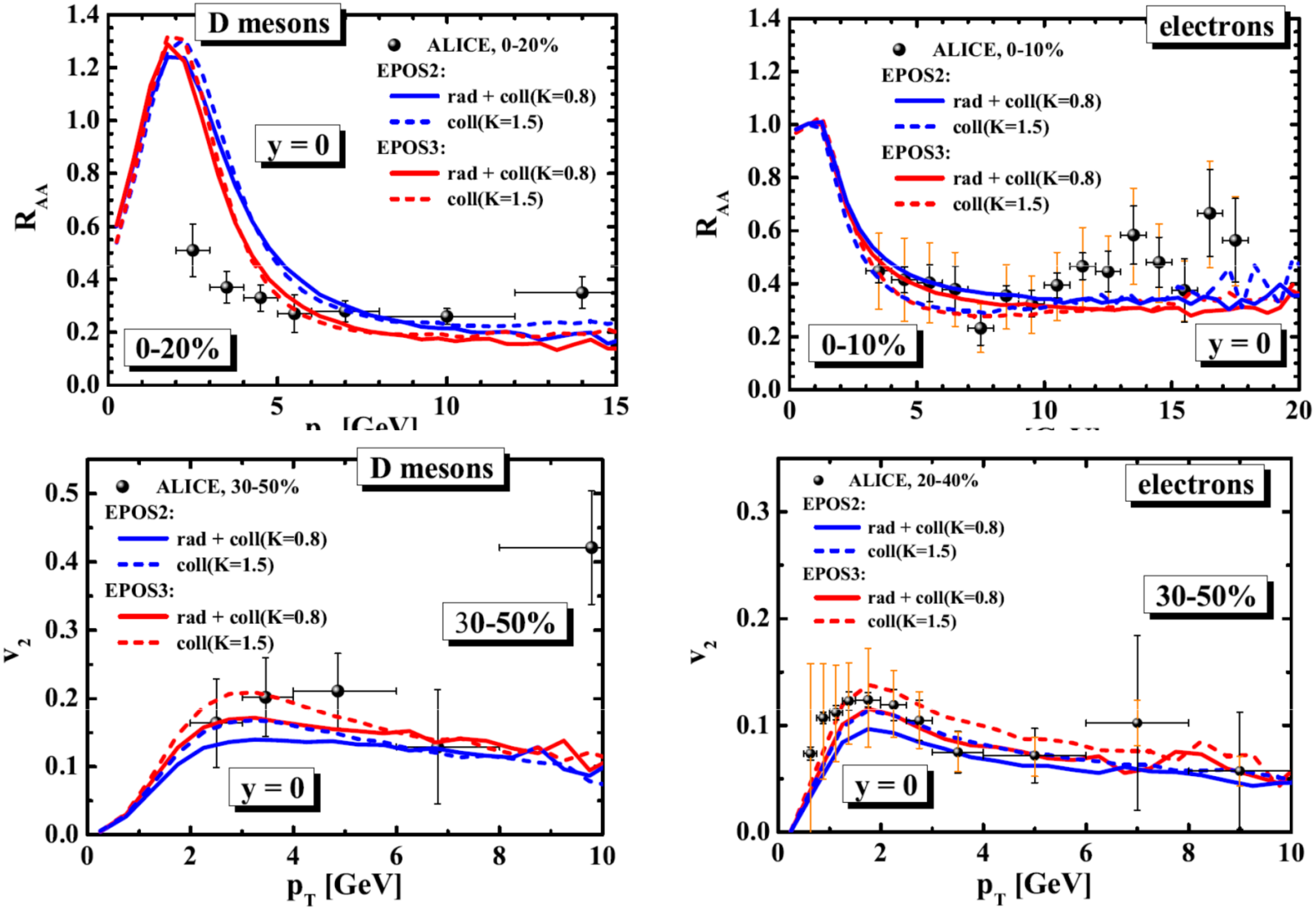


In the real world (EPOS) the
plasma has all kinds of moments v_i
the v_i impair are fluctuations

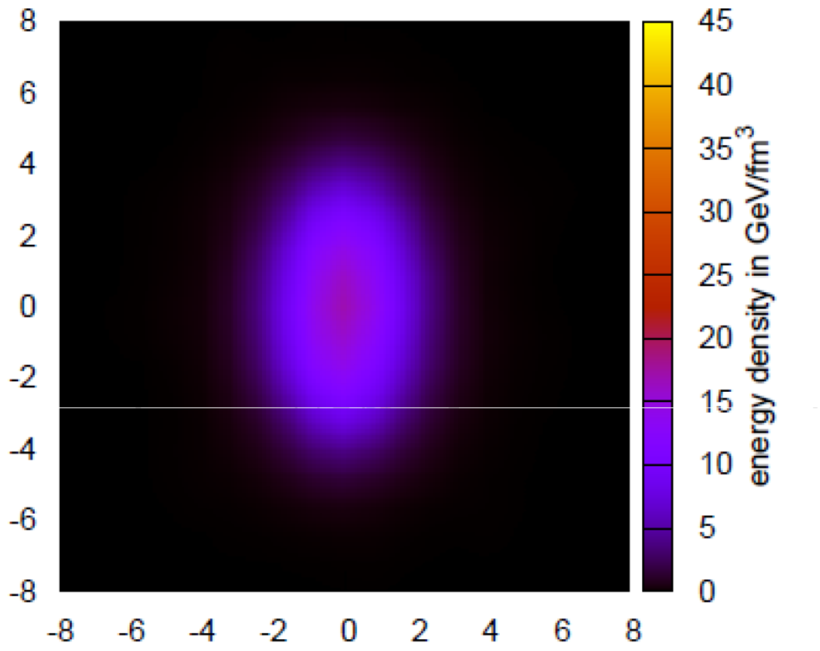
v_3 corresponds to a Mercedes Star

EPOS 2 → EPOS 3 (fluctuating initial condition, viscous hydro, no shadowing)

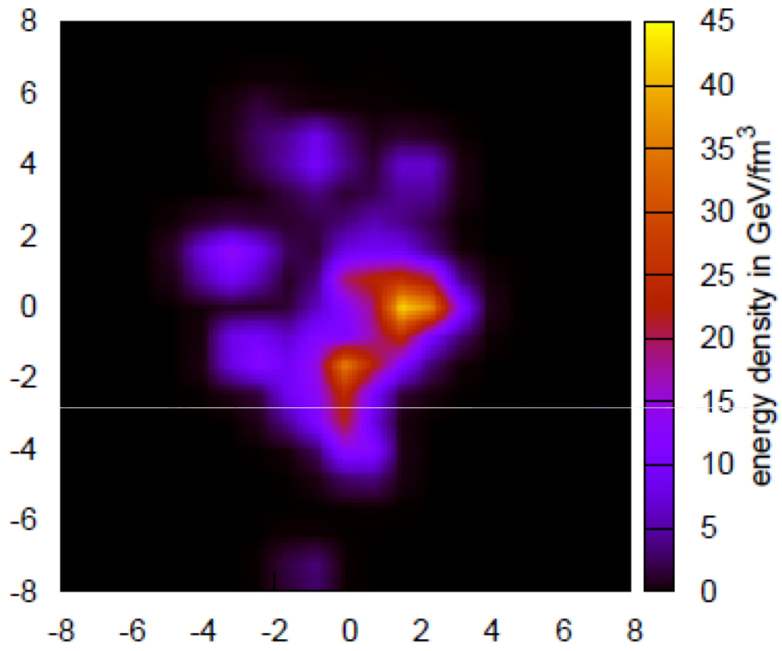
MC@sHQ+EPOS2 results: M.Nahrgang *et al*, Phys. Rev. **C89**, 014905 (2014)



Averaged initial cond.

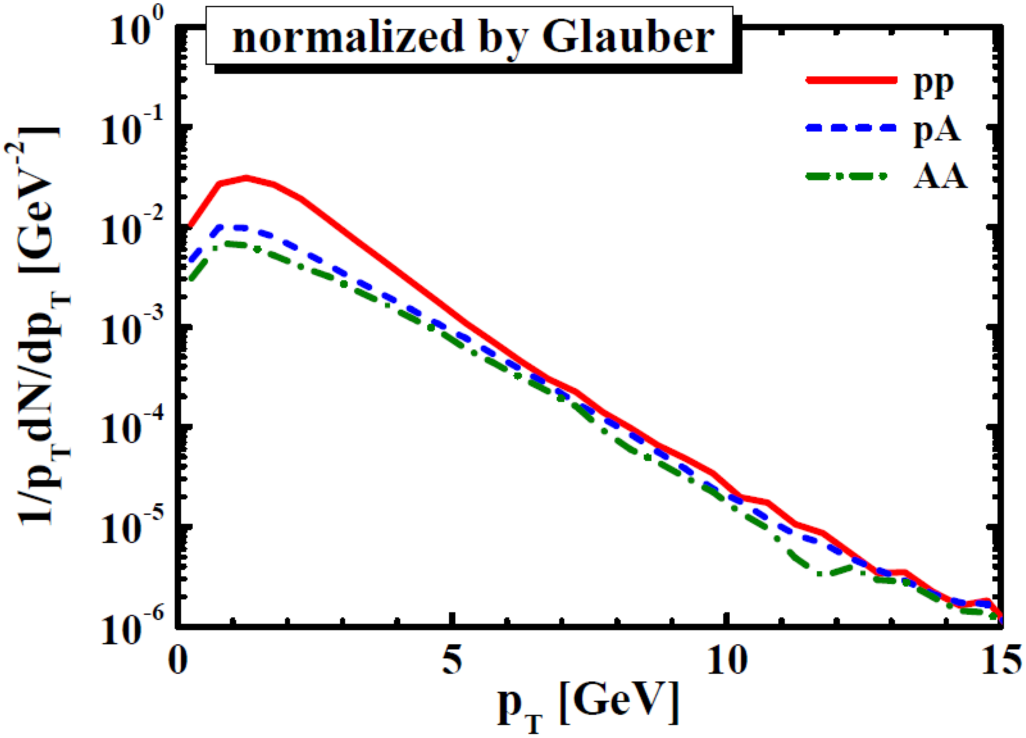


Fluctuation initial cond.



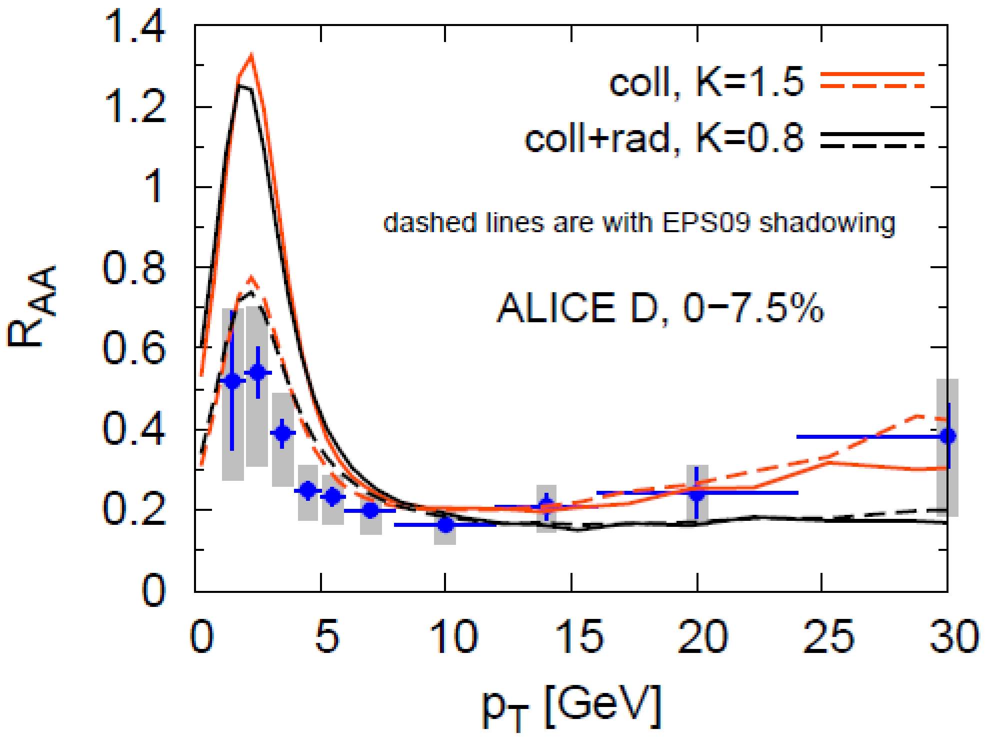
- R_{AA} : spots which create a high energy loss leads to enhanced energy loss
- v_2 : Hot spots rather spherical ->reduces spatial eccentricity

Influence of the shadowing



Discussion of our results

I) R_{AA}



Shadowing effects may suppress strongly the R_{AA} at small p_t
Anti-shadowing visible but not strong at large p_t

Shadowing has little influence on v_i

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.

The present heavy quark data are do not allow to discriminate between different pQCD processes:
radiative and collisional energy loss

Special features running coupling constant
adjusted Debye mass
Landau Pomeranschuk Migdal

Description of the expansion of the medium (freeze out, initial cond.) has to be controlled by light hadrons (->EPOS)

Collaborators

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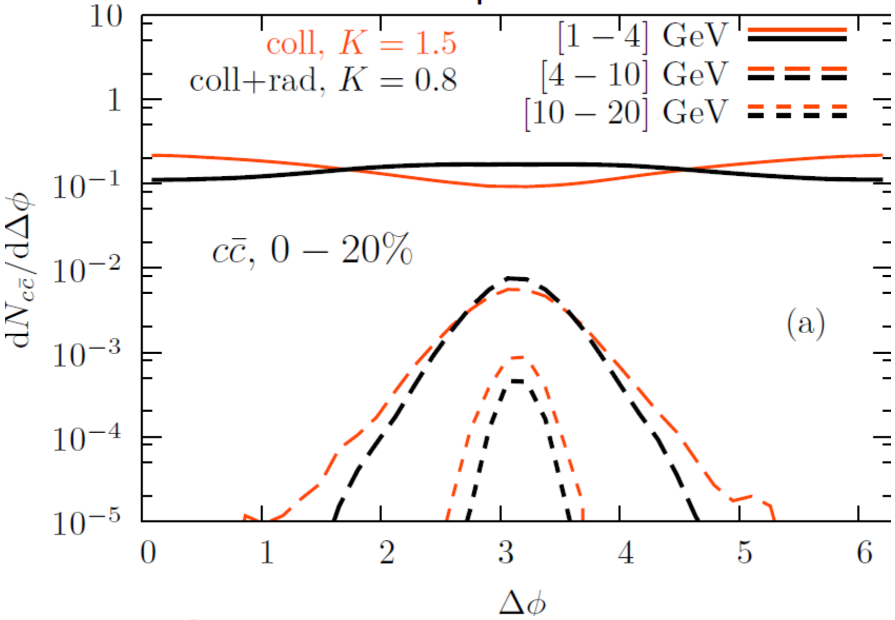
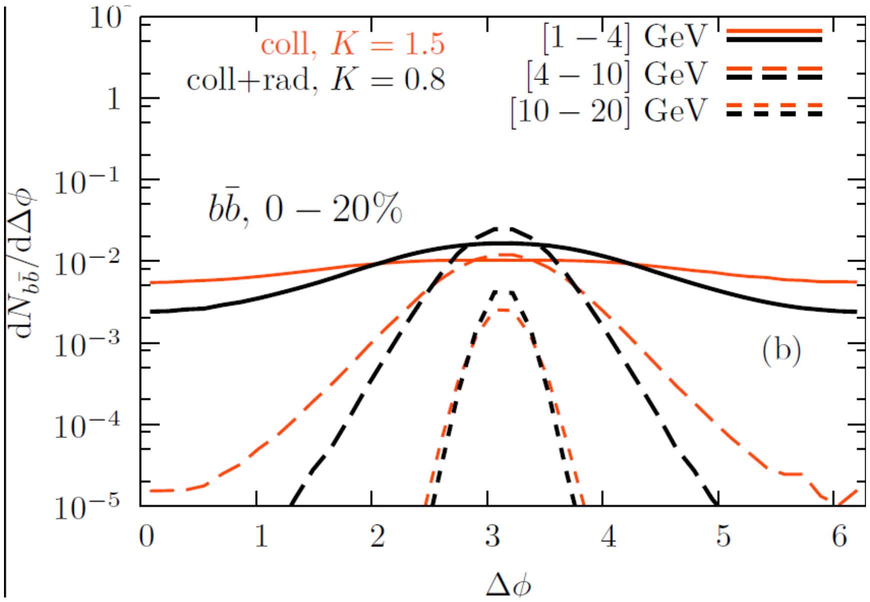
Heavy-quark azimuthal correlations

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

charm quarks

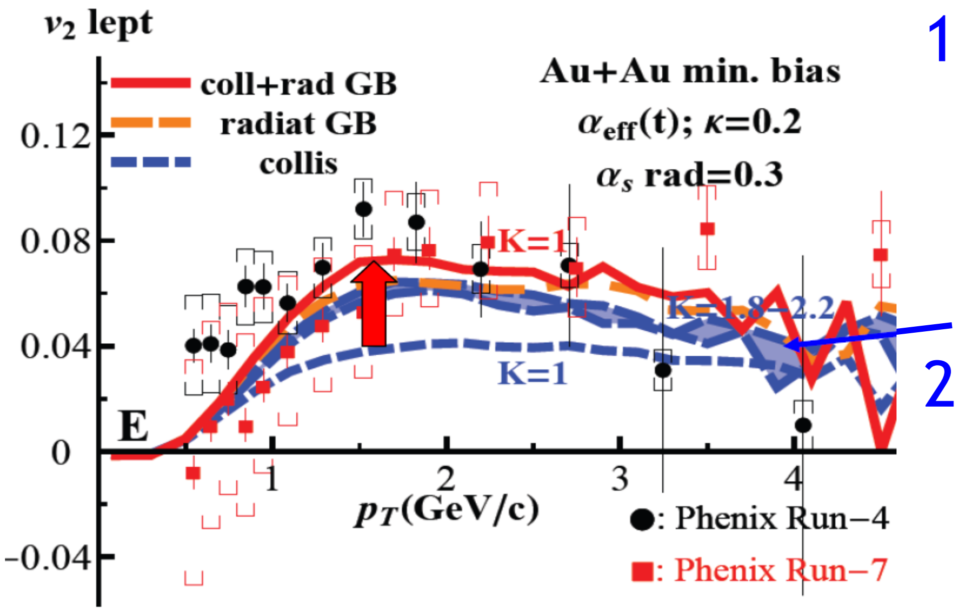


bottom quarks



- 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.

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

Presently the analysis/discussion is centered around
two heavy quark observables:

I)

$$R_{AA} = \frac{d\sigma_{AA}/dp_t}{N_{bin} d\sigma_{pp}/dp_t}$$

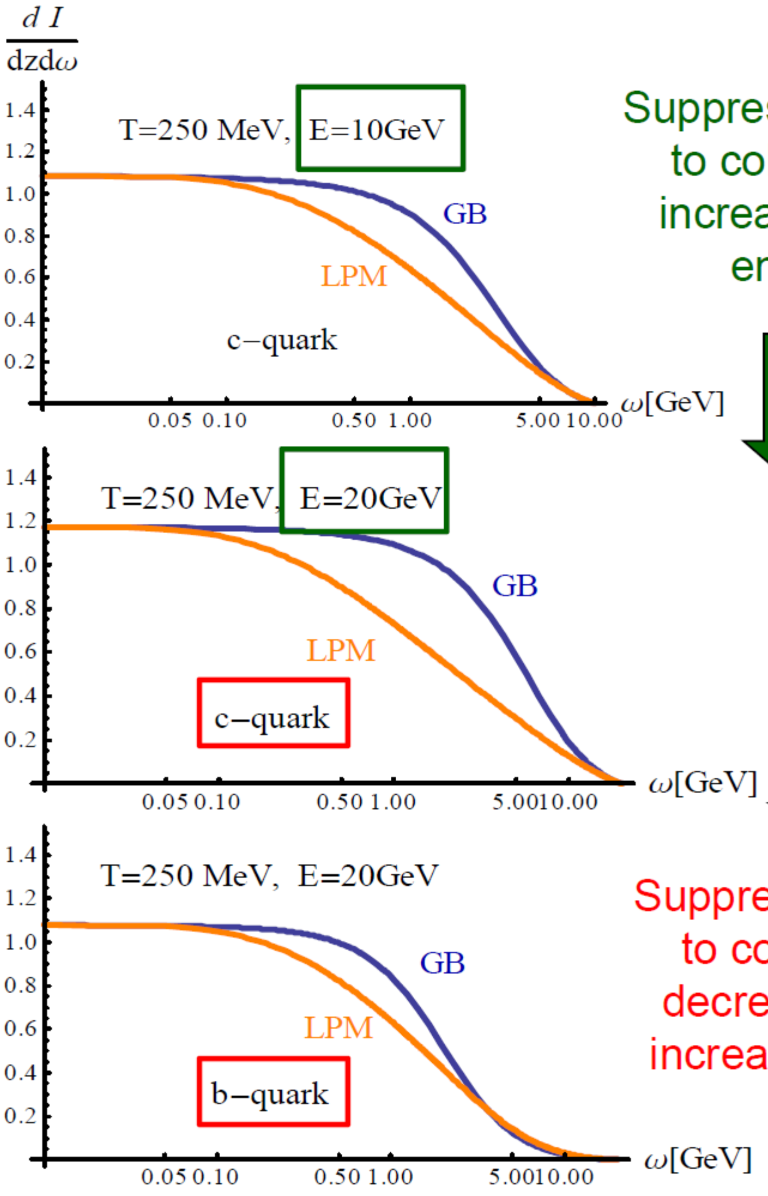
Low p_t partial thermalization
High p_t energy loss due to elastic and radiative collisions
Energy loss tests the initial phase of the expansion

II) Elliptic flow v_2

$$\frac{dN}{d\Phi} = \frac{1}{2\pi}(1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi \ldots.)$$

tests the late stage of the expansion

Consequences of LPM on the energy loss



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass