Azimuthal correlations and hadronic rescattering of heavy quarks in AA collisions

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in collaboration with

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Why heavy quarks are interesting?

Interaction of heavy quarks with the plasma
- different approaches
- our model (elastic and inelastic collisions, LPM)

- is there more than R_{AA} and v_2
- correlations between quarks and antiquarks
- hadronic rescattering

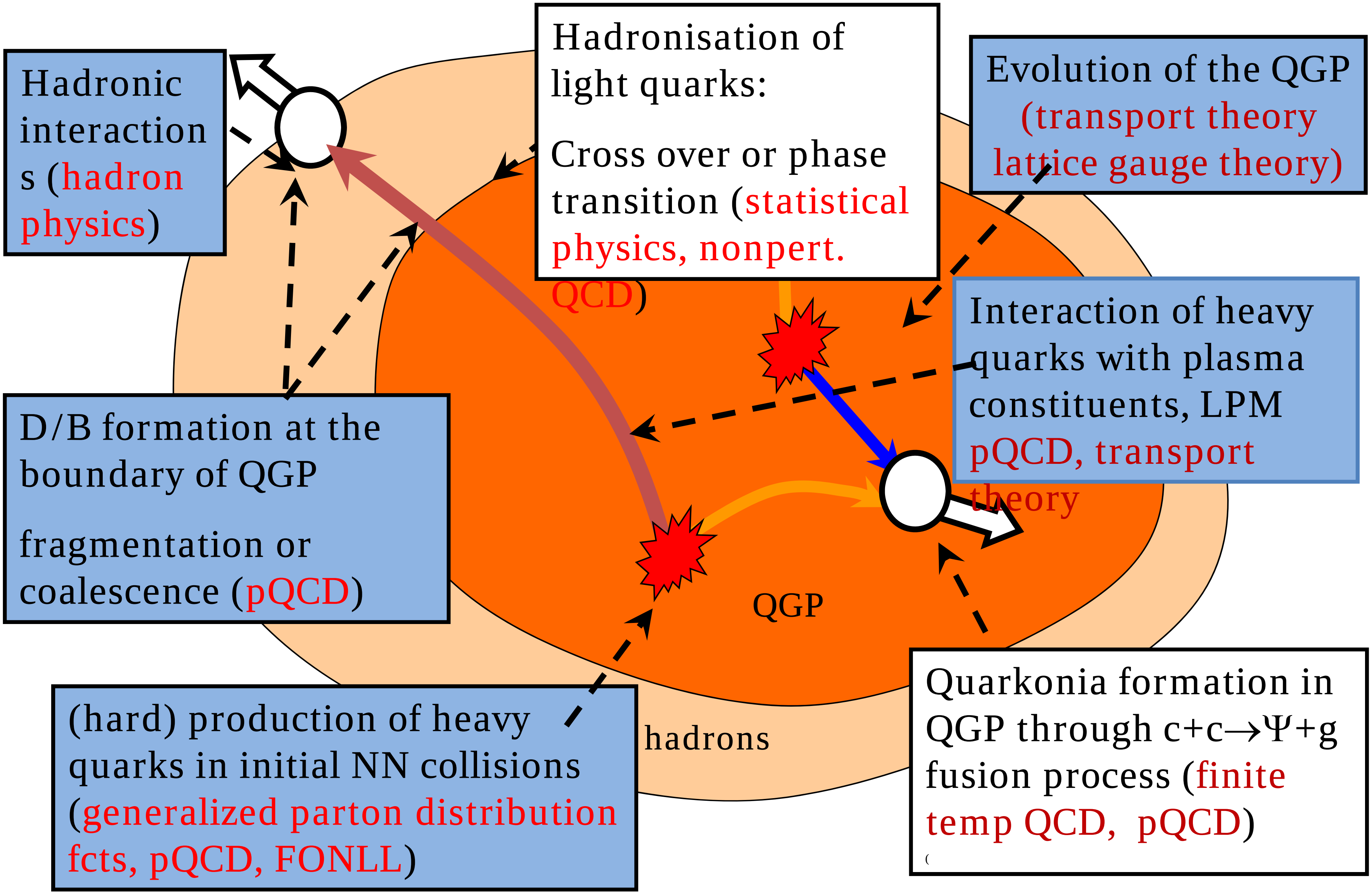
What makes heavy quarks (mesons) so interesting?

- 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→Ψ+g fusion process (finite temp QCD, pQCD)

Presently the 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 tests the late stage of the expansion

Many models on the market which describe these observables reasonably well

Mostly based on Fokker Planck approaches

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

which need only a drag A_i and a diffusion B_{ij} coefficients

Both related by Einstein correlation (or not)

At most qualitative predictions possible (LPM, elementary cross sections..)

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

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

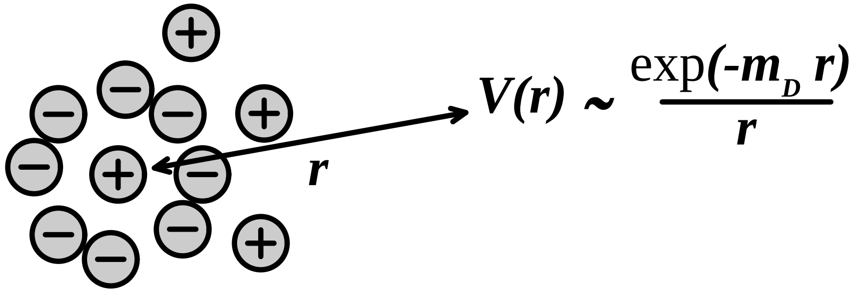
Nantes approach: Elastic heavy quark – q(g) collisions

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

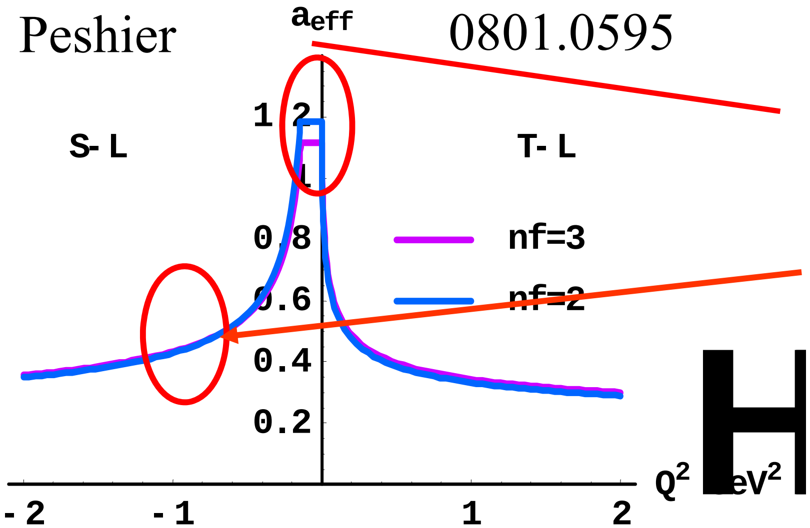
Neither $g^2 = 4\pi\,\alpha(t)$ nor $\kappa\, m_D^2 =$ are well determined
standard: α(t) =is taken as constant or as α(2πT)

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:

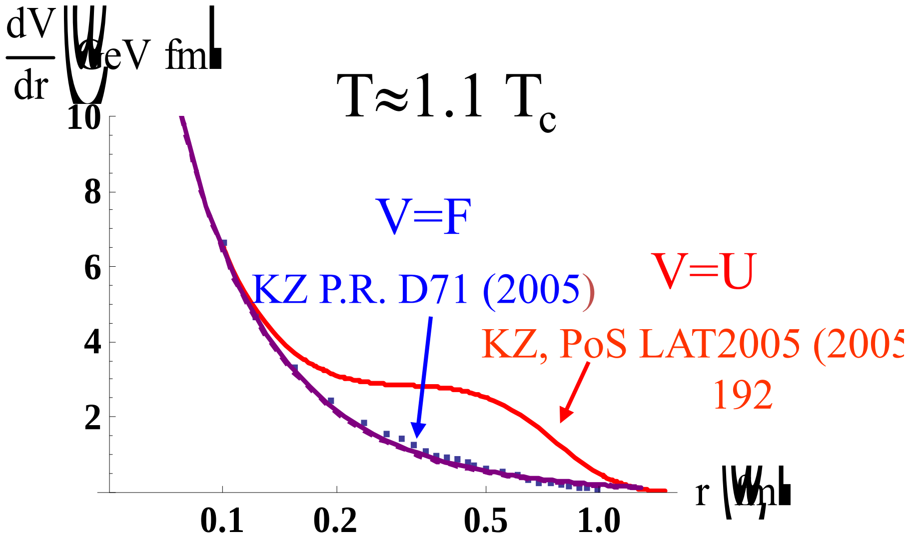
$$\frac{1}{Q_u}\int_{|Q^2|\leq Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$

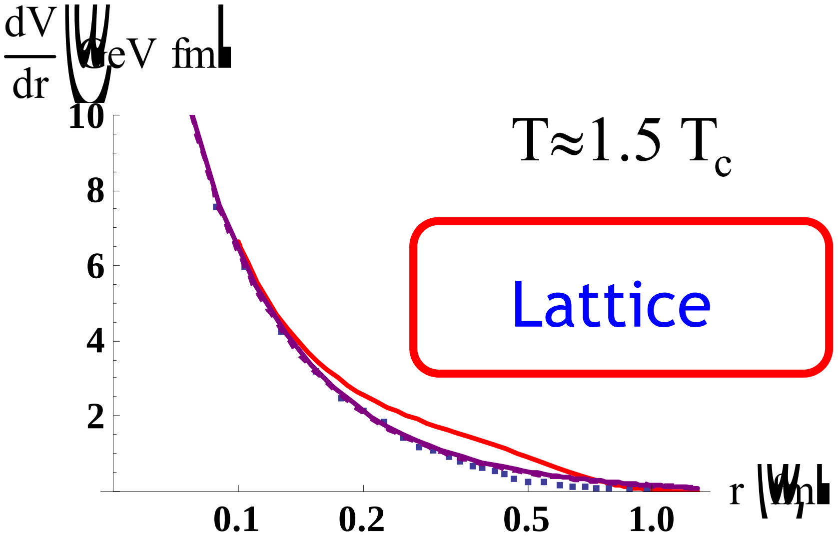


IR safe. The detailed form very close to $Q^2 = 0$ is not important does not contribute to the energy loss

Large values for intermediate momentum-transfer

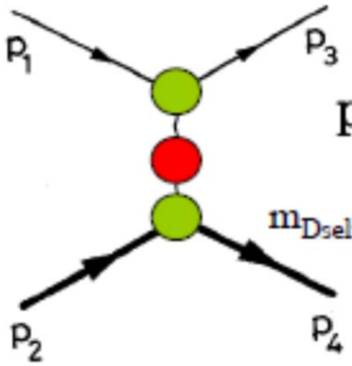
$$\alpha_{qq}(r) \equiv \frac{3}{4} r^2 \frac{dV(r)}{dr}$$





B) Debye mass

PRC78 014904, 0901.0946



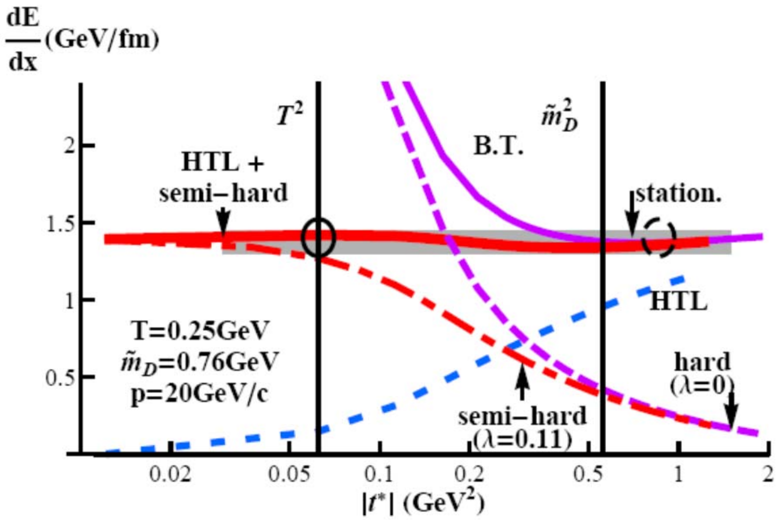
$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\text{Dself}}(T)}$$

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

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:

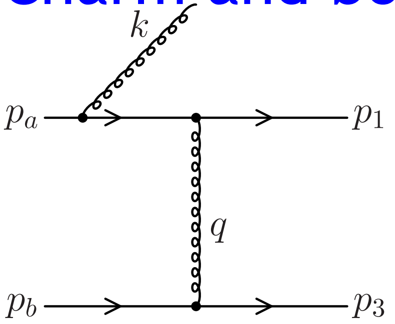
$$\kappa \;\approx 0.2$$

much lower than the standard value

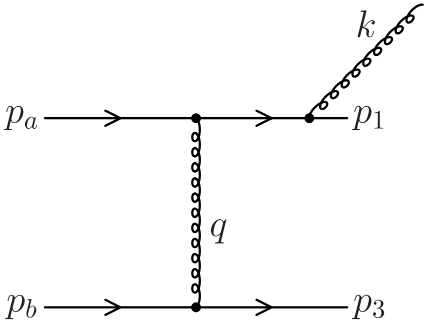
C) Inelastic Collisions

Low mass quarks : radiation dominantes energy loss

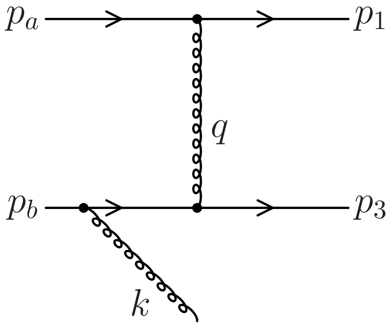
Charm and bottom: radiation of the same order as collisional



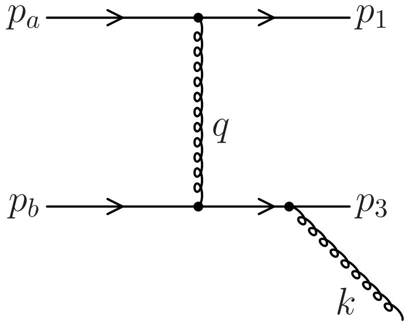
M_1



M_2

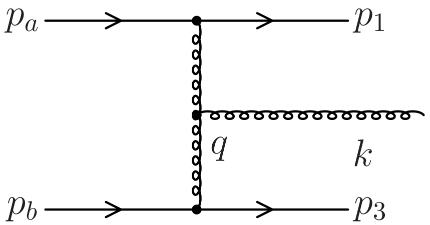


M_3



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 $\sqrt{s} \rightarrow \infty$ the radiation matrix elements factorize in

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

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:

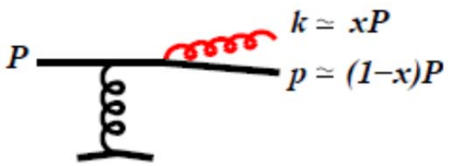
$$\frac{\omega d^4\sigma^{rad}}{dx d^2k_t dq_t^2} = \frac{N_c\alpha_s}{\pi^2}(1-x)\cdot\frac{d\sigma^{el}}{dq_t^2}\cdot P_{rad}$$

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

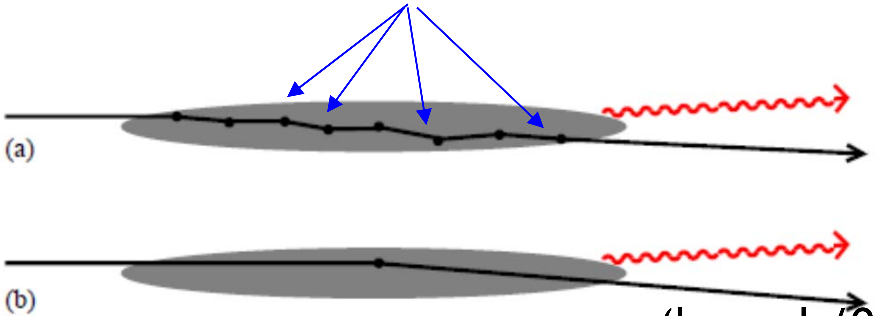


Heavy quark radiates gluons

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)

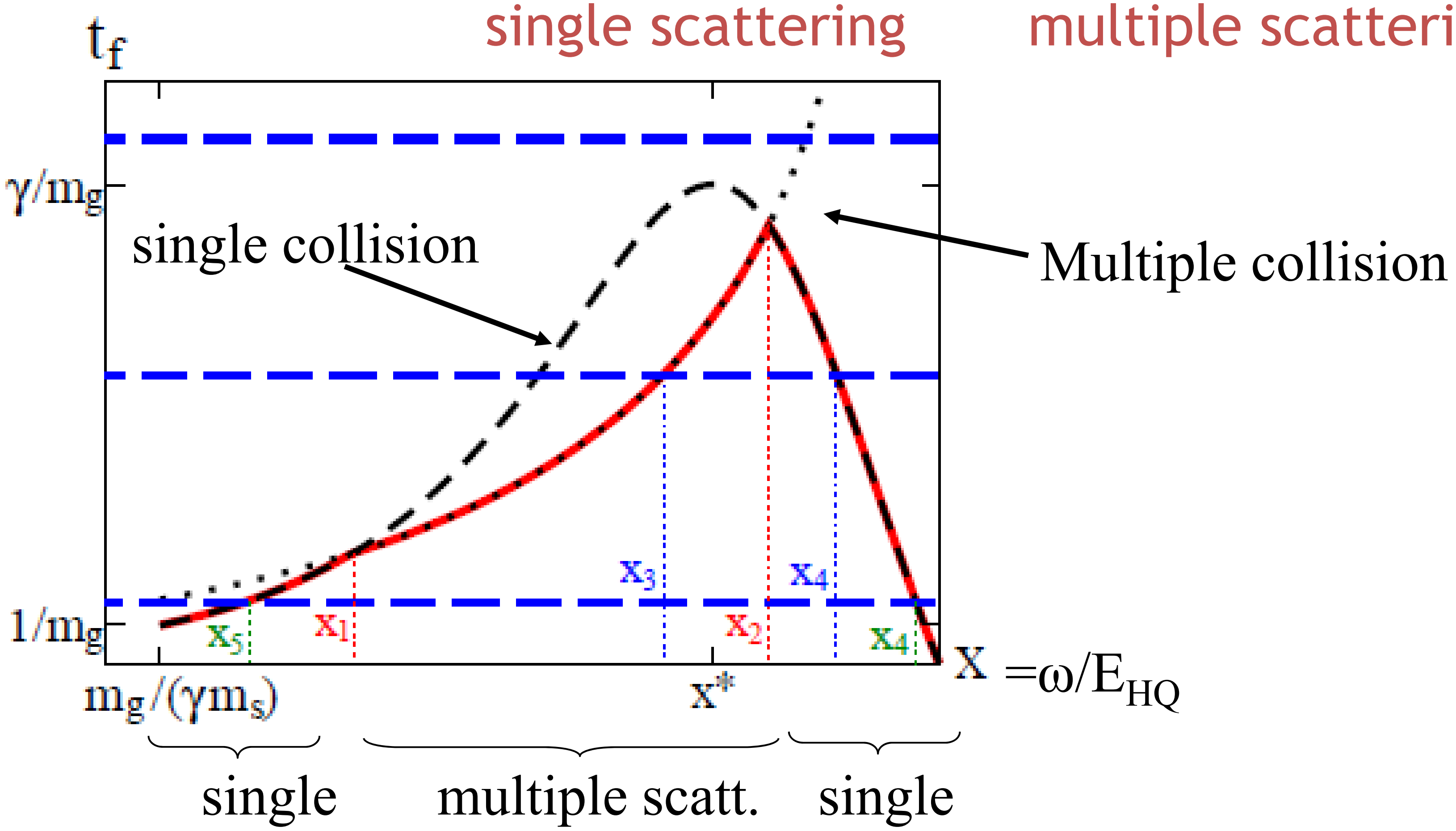
(hep-ph/0204343)

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

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

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

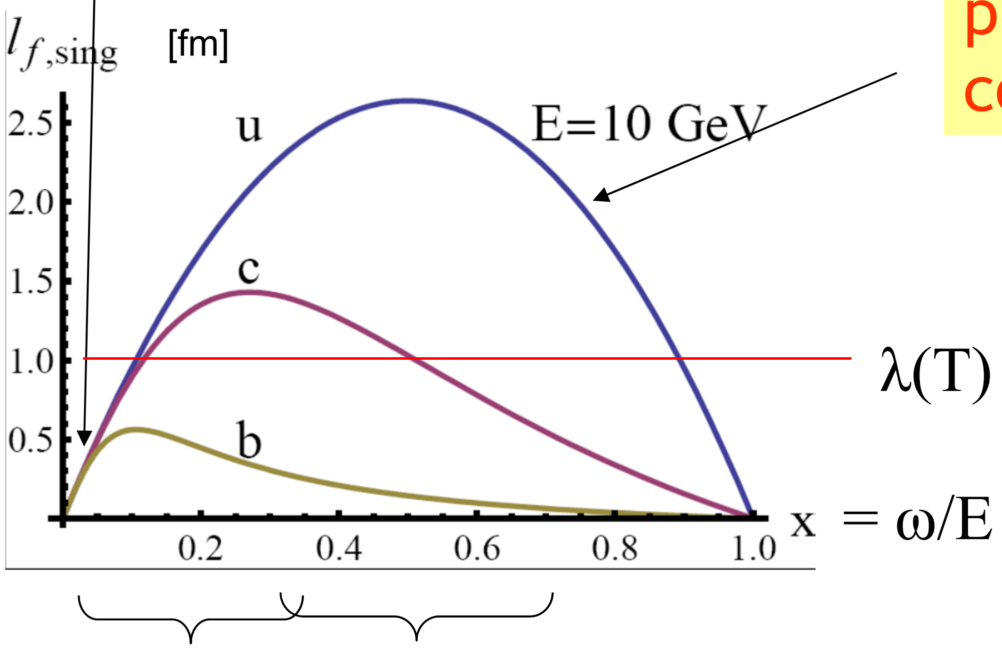
$$\underbrace{t_f \frac{x}{2E}\left[\frac{m_s^2}{(1-x)}+\frac{m_g^2}{x^2}\right]}_{\text{single scattering}} + \underbrace{t_f^2 \frac{x\hat{q}_s}{2E(1-x)}}_{\text{multiple scattering}} \simeq 1\,.$$



At intermediate gluon energies formation time is determined by multiple scattering

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.

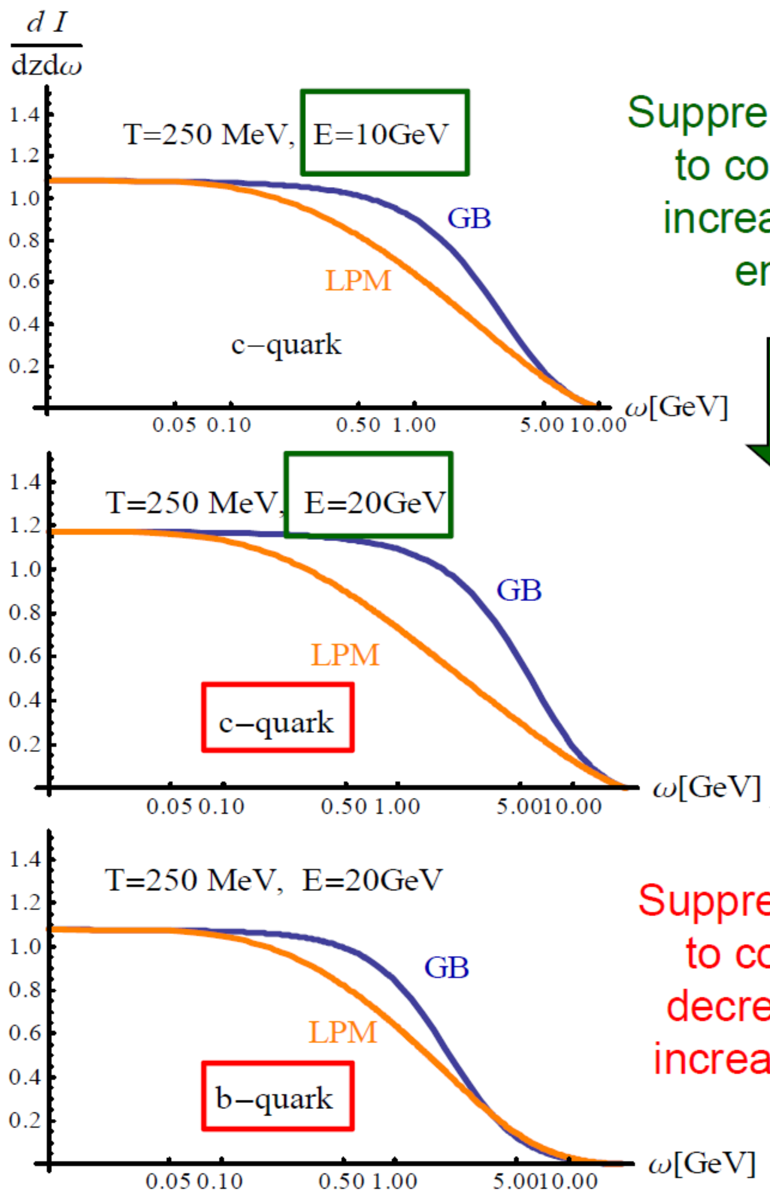


Most of the collisions $\frac{d\sigma}{dx}$

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

LPM important for intermediate x where formation time is long

Consequences of LPM on the energy loss



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

.. and if the medium is absorptive (PRL 107, 265004)

$$-\frac{d^2W}{dz\,d\omega} \simeq -\frac{2\alpha}{3\pi}\frac{\hat q}{E^2}\int_0^\infty \underbrace{d\bar t\,\omega\cos(\omega\bar t\,)\sin\left[\omega|n_r|\beta\bar t\left(1-\frac{\hat q\bar t}{6E^2}\right)\right]}_{\text{Ter-Mikaelian}}\underbrace{\mathcal{F}(\bar t\,)}_{\text{damping}}$$

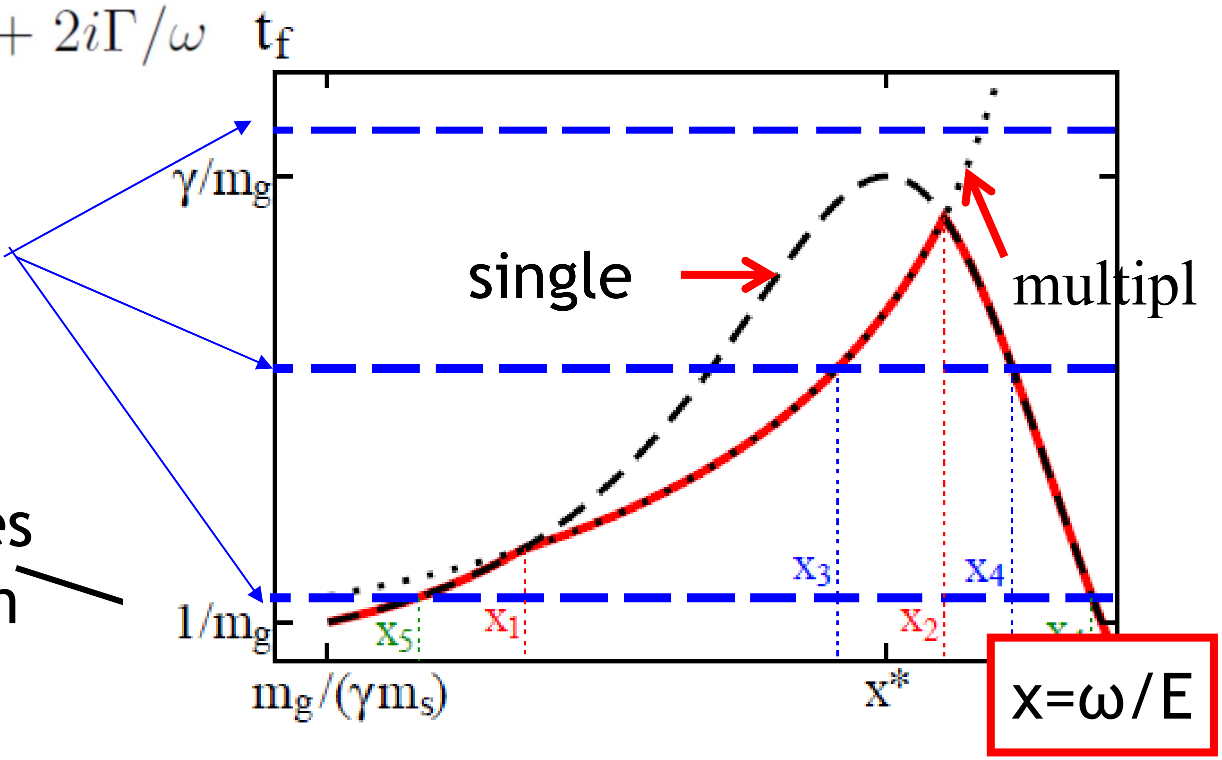
$$\mathcal{F}(t) = \exp[-\omega|n_i|\beta t(1-\hat q t/(6E^2))]$$

with

$$n^2(\omega) = 1 - m^2/\omega^2 + 2i\Gamma/\omega$$

New timescale 1/Γ

damping dominates radiation spectrum



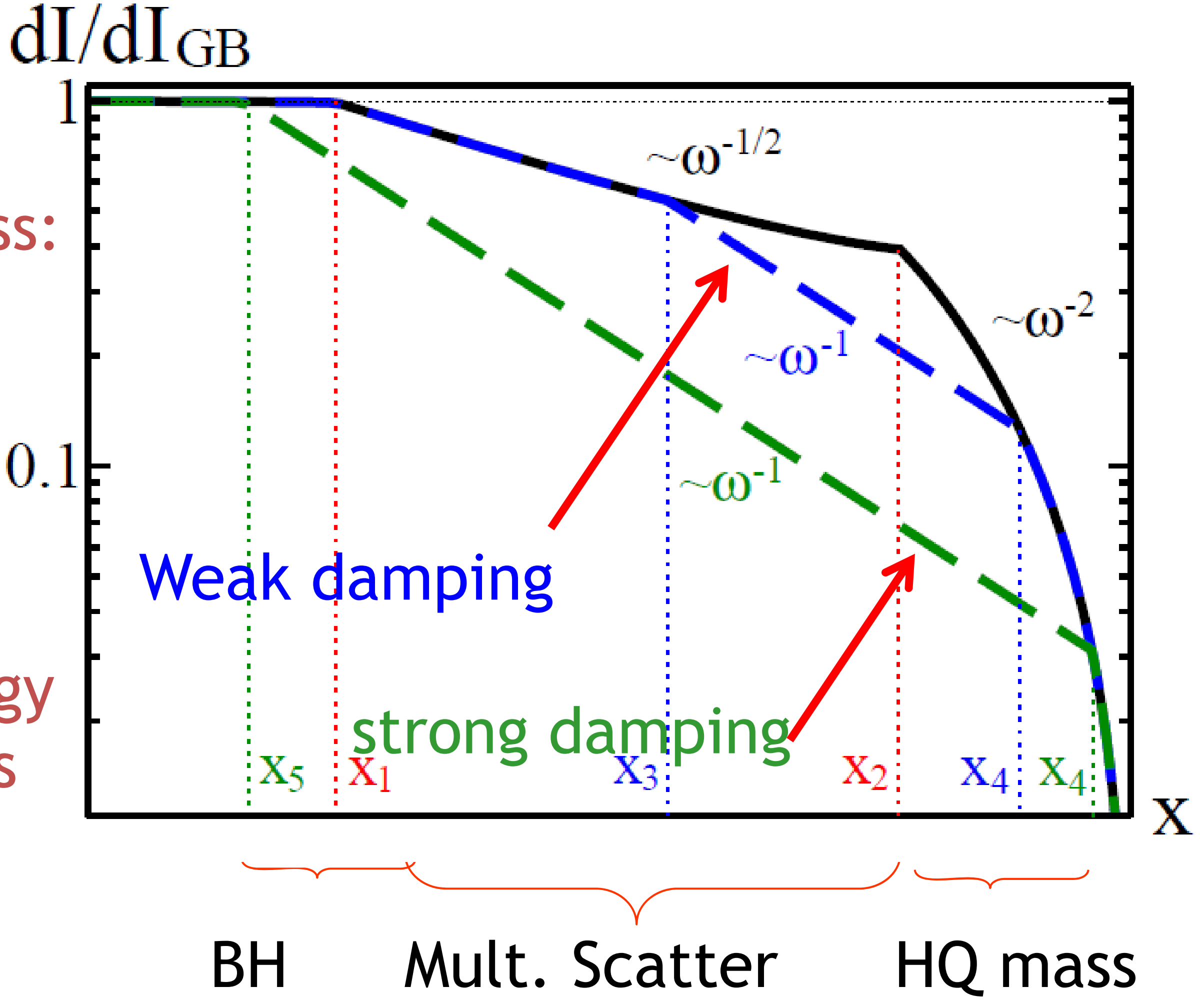
Influence of LPM and damping on the radiation spectra

$$\frac{dI}{dI_{GB}} \simeq \frac{\tilde{t}_f}{t_{GB}}$$

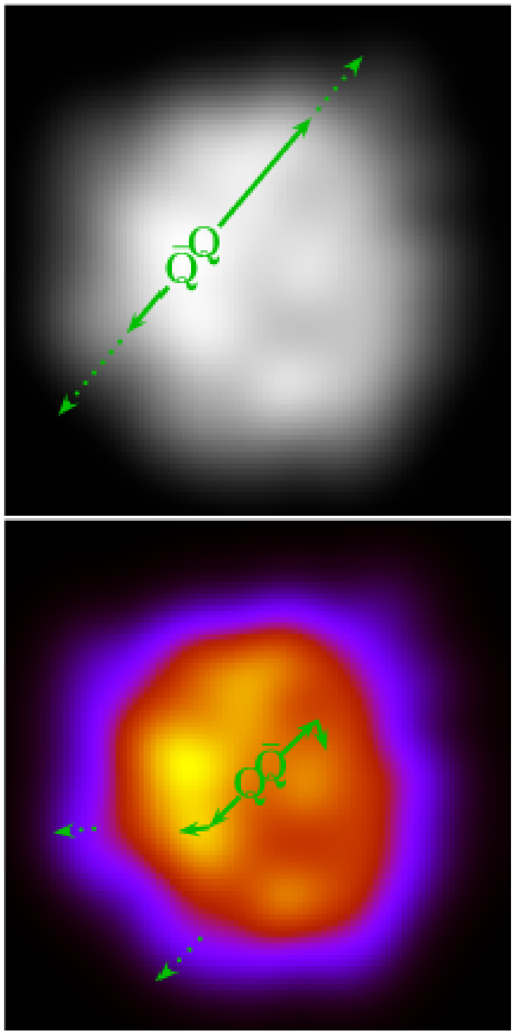
$$\tilde{t} = min\{t^{single}, t^{multiple}, t^{damping}\}$$

LPM, damping, mass:
Strong reduction
of gluon yield
at large ω

LPM:
increase with energy
decrease with mass



Heavy-quark propagation in the QGP



Production:

- FONLL
  ⇒ inclusive spectra, no information about correlations → equivalent to a back-to-back initialization of $Q\bar{Q}$-pairs.
- Next-to-leading order QCD matrix elements plus parton shower evolution, e. g. POWHEG or MC@NLO
  ⇒ exclusive spectra, like $Q\bar{Q}$ correlations

Interaction with the medium

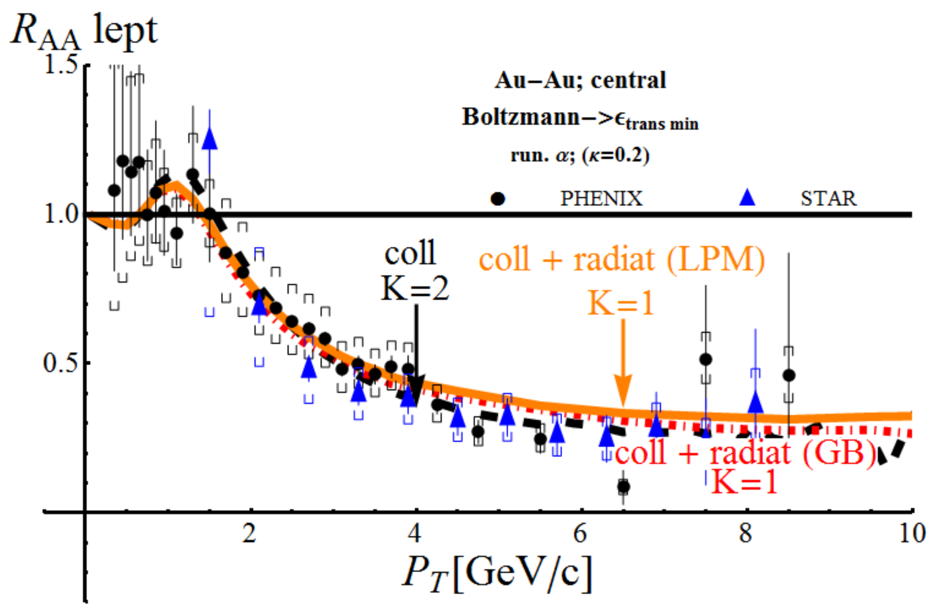
- Energy loss at high transverse momentum.
- Thermalization at low transverse momentum.
- Different interaction mechanisms: purely collisional or **collisional+radiative (+LPM)**.
- Longitudinal vs. transverse dynamics.

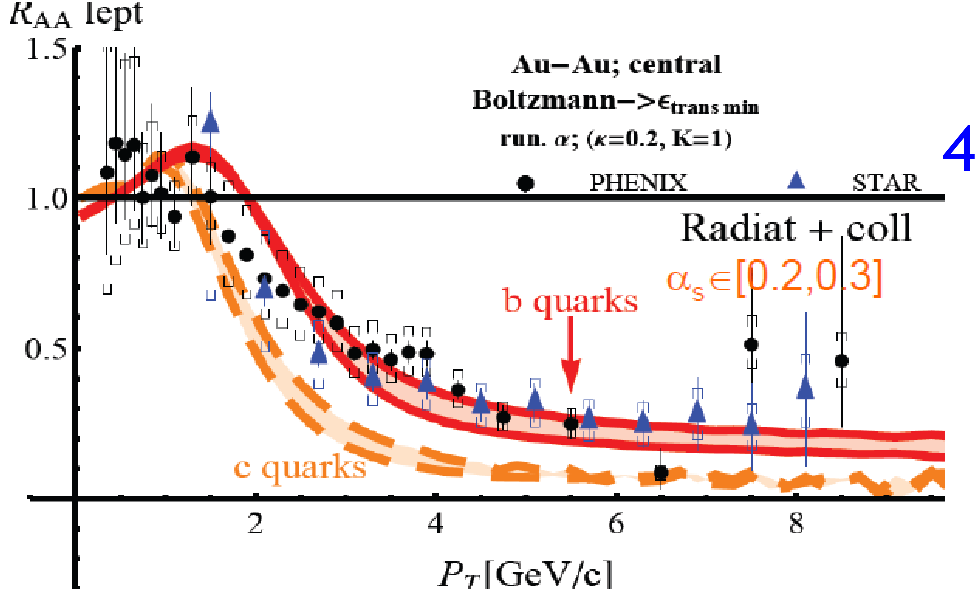
Hadronization:

- Coalescence – predominantly at small p_T.
- Fragmentation – predominantly at large p_T.

X. Zhu et al., PLB 647 (2007); P. B. Gossiaux et al., JPG 32 (2006); X. Zhu et al, PRL 100 (2008); Y. Akamatsu et al, PRC 80 (2009)

RHIC Hydro: Kolb Heinz

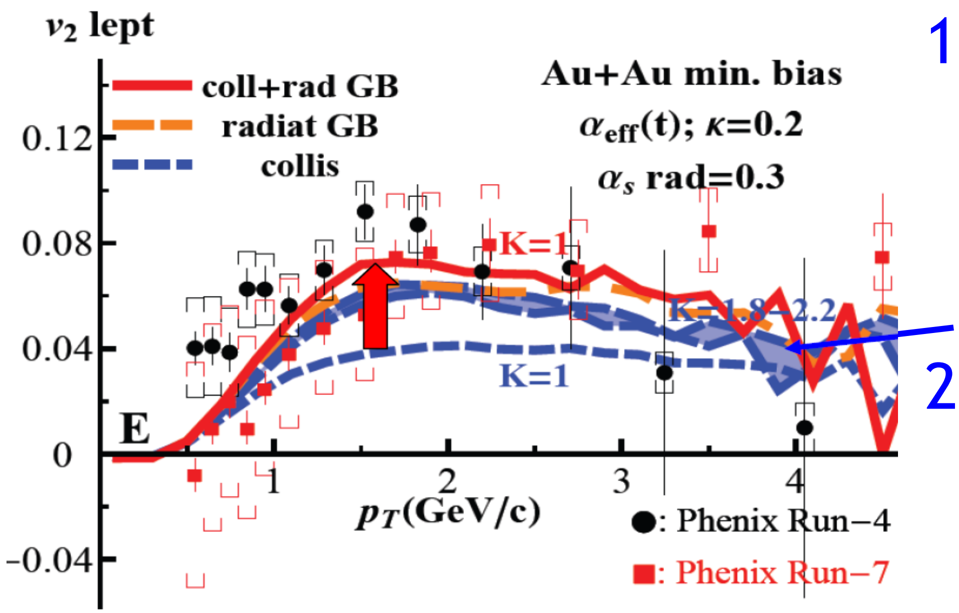




1. Coll:too little quenching (but very sensitive to freeze out) -> K=2
2. Radiative Eloss indeed as important as the collisional one
3. Flat experimental shape is well reproduced
4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC)

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

RHIC

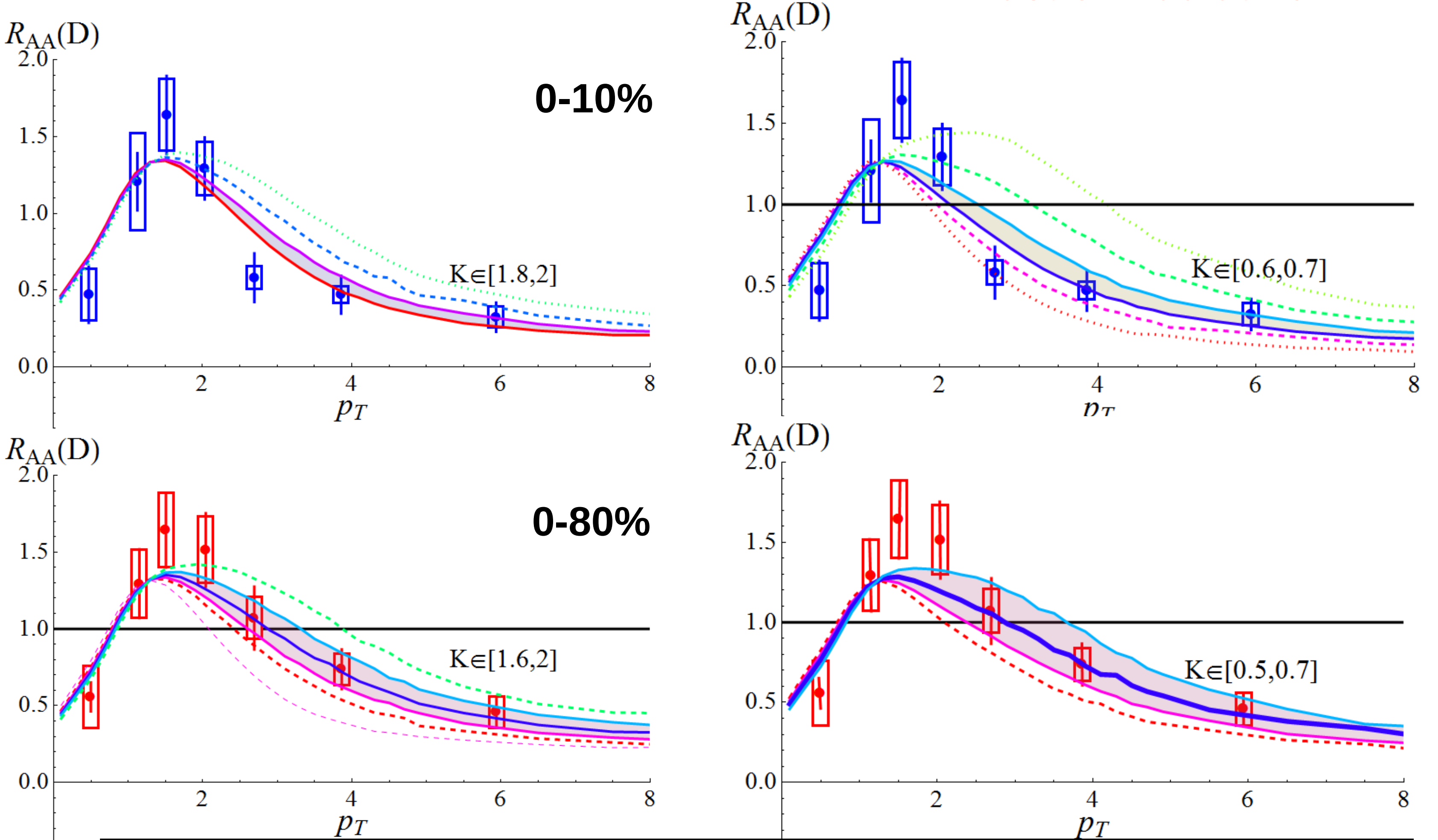


1. Collisional + radiative energy loss + dynamical medium : *compatible* with data
2. To our knowledge, one of the first model using radiative Eloss that reproduces v_2

For the hydro code of Kolb and Heinz:

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

RHIC IV: D mesons



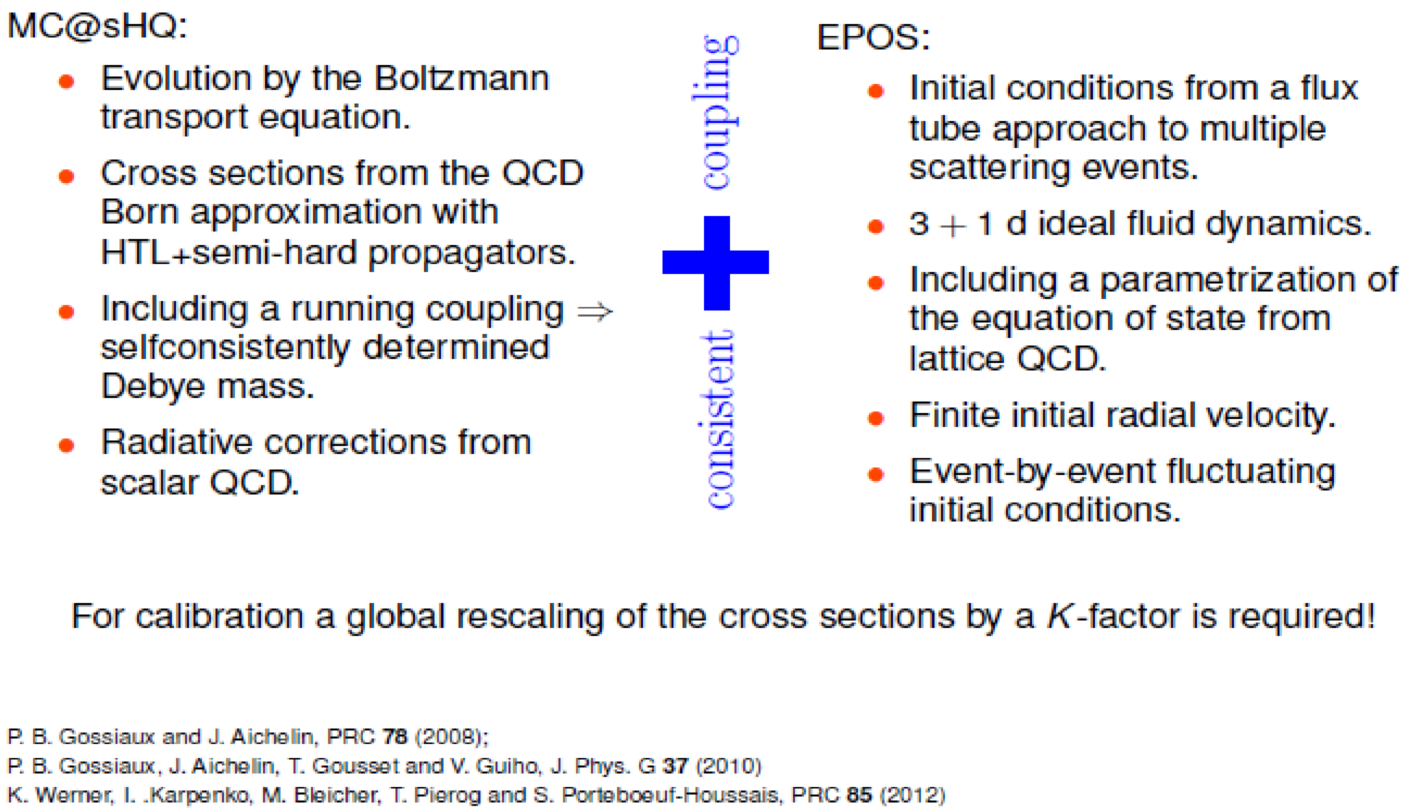
Elastic

Elastic + radiative LPM

No form difference between coll and coll + rad

Hydro Kolb Heinz a bit outdated, to make progress:

Marriage of two large simulation programs MC@sHQ and EPOS



MC@sHQ:

- Evolution by the Boltzmann transport equation.
- Cross sections from the QCD Born approximation with HTL+semi-hard propagators.
- Including a running coupling ⇒ selfconsistently determined Debye mass.
- Radiative corrections from scalar QCD.

consistent + coupling

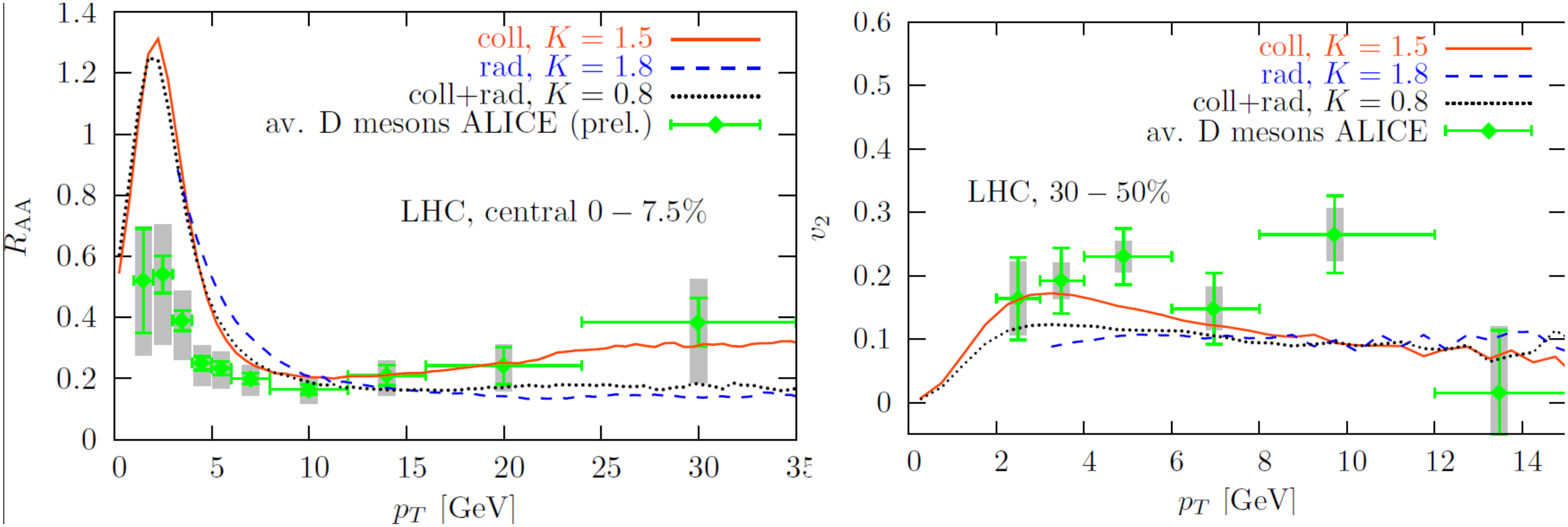
EPOS:

- Initial conditions from a flux tube approach to multiple scattering events.
- 3 + 1 d ideal fluid dynamics.
- Including a parametrization of the equation of state from lattice QCD.
- Finite initial radial velocity.
- Event-by-event fluctuating initial conditions.

For calibration a global rescaling of the cross sections by a K-factor is required!

P. B. Gossiaux and J. Aichelin, PRC **78** (2008);
P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. G **37** (2010)
K. Werner, I. .Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, PRC **85** (2012)

Expanding plasma : EPOS event generator



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

Are there other observables which are sensitive on the interaction mechanism?

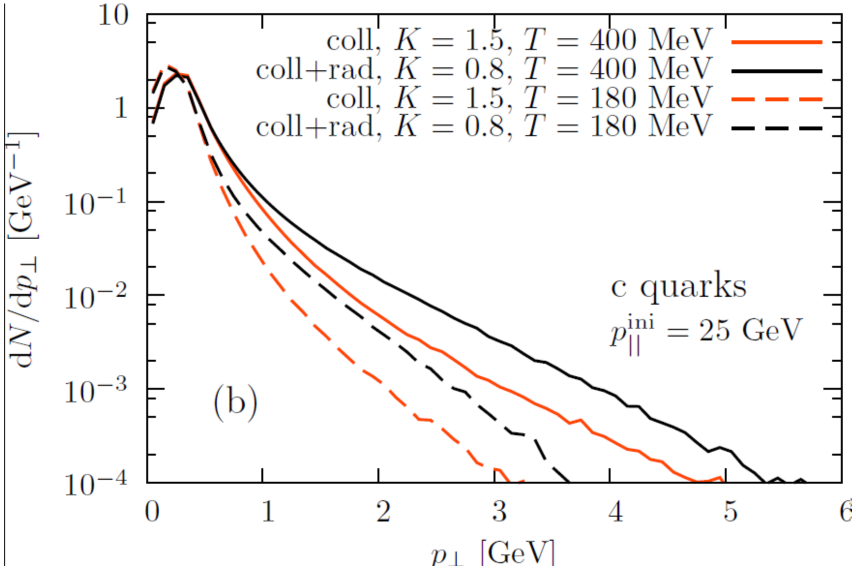
Possible candidate: heavy flavor correlations

They may be sensitive to

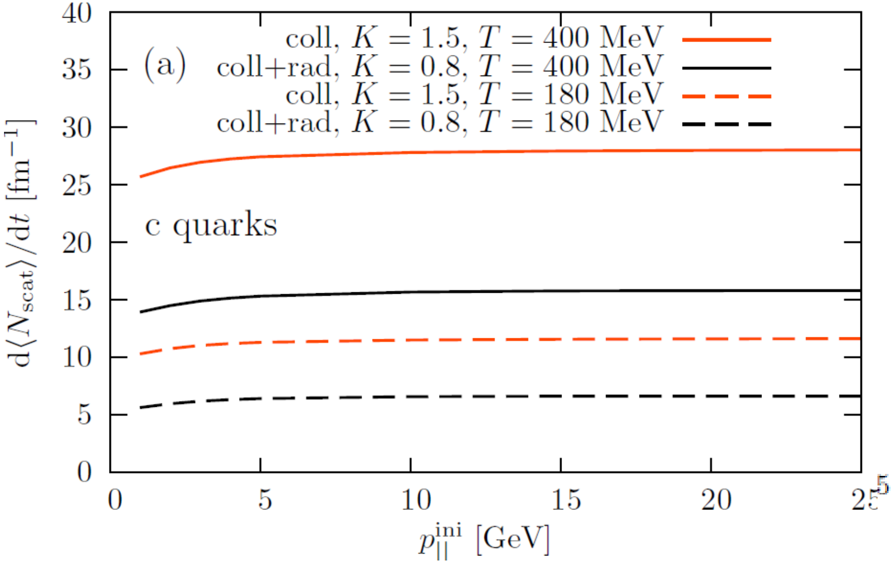
- Properties of the energy loss model: path length dependence? Parton mass dependence?
- Properties of the interaction inside a medium: drag coefficient, jet quenching parameter?

WHY?

Single scattering:



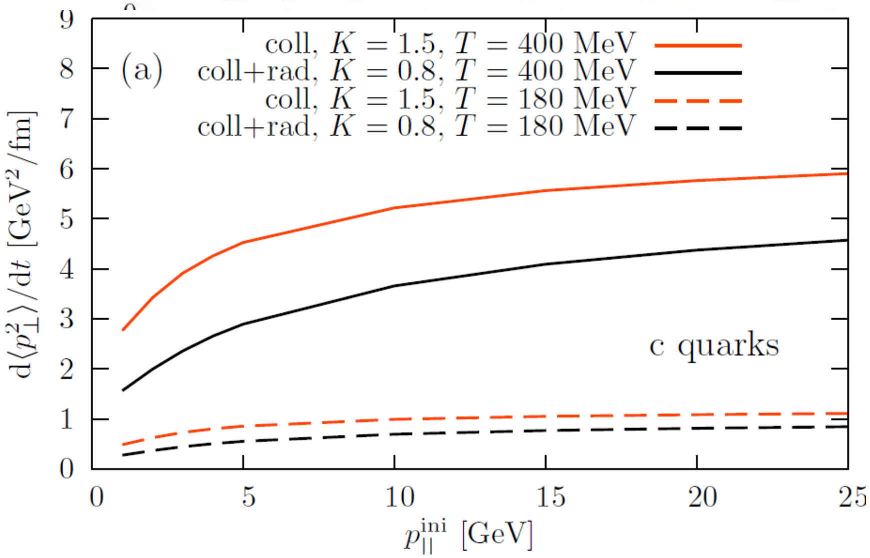
Scattering rate:



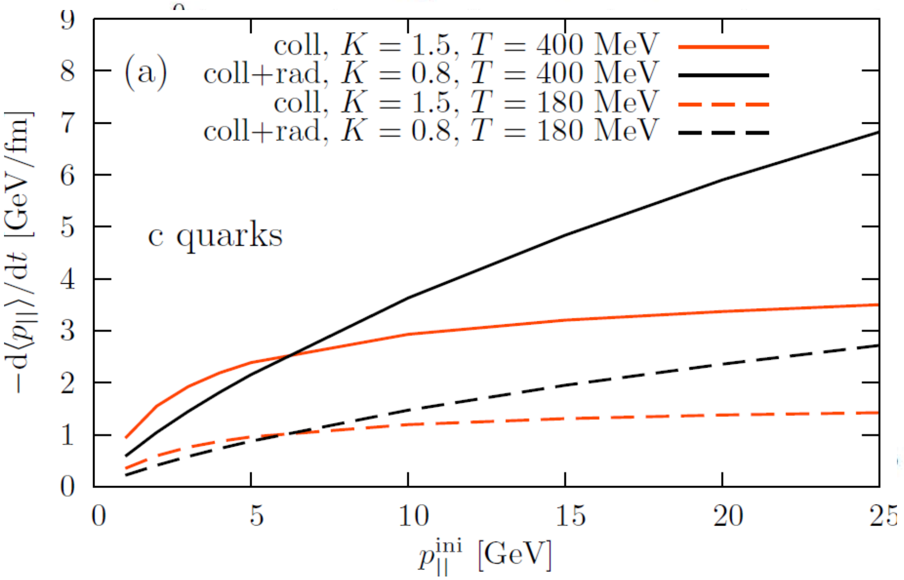
- p_T-distribution in a single scattering: larger $\langle p_T \rangle$ for **coll+rad ($K = 0.7$)**.
- Scattering rate is larger for coll ($K = 1.5$)!

Properties of the interaction

arXiv: 1305.3823
1310.2218



Average perpendicular broadening

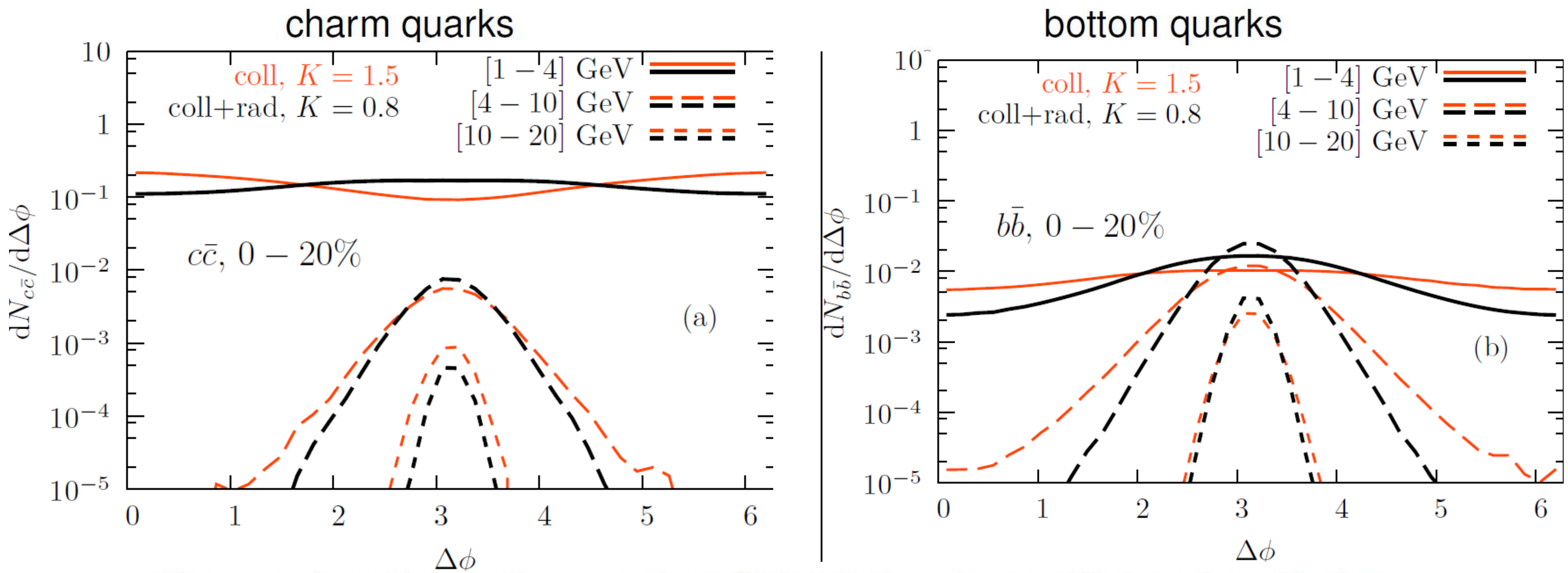


Drag coefficient

- The purely collisional scatterings lead to a larger average $\langle p_\perp^2 \rangle$ than the **radiative** corrections.
- The final $p_\perp$ also depends indirectly on the drag coefficients.
- The drag coefficients increases faster for the **collisional+radiative** interaction scenario $\Rightarrow$ A quick loss in longitudinal momentum leads to less perpendicular momentum broadening.
- Expectation: Initial correlations will be broadened more effectively in a purely collisional interaction mechanism.

Heavy-quark azimuthal correlations

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



charm quarks

bottom quarks

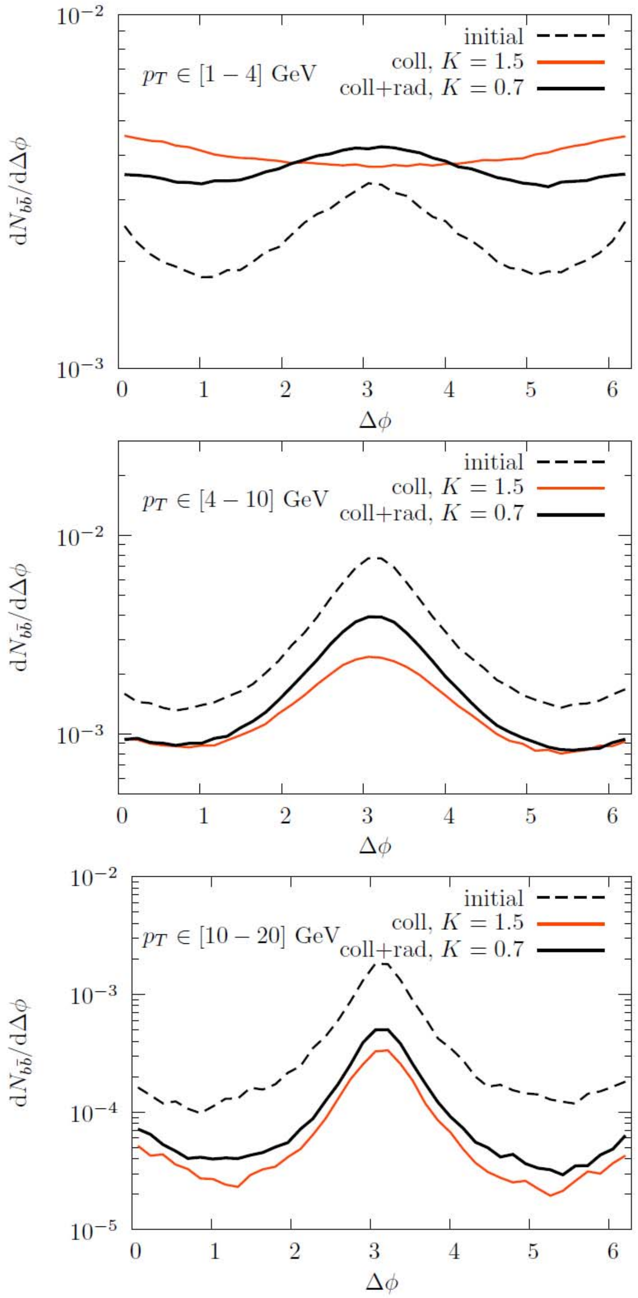
- Stronger broadening in a purely collisional than in a **collisional+radiative** interaction mechanism
- Variances in the intermediate p_T-range: 0.18 vs. **0.094** (charm) and 0.28 vs. **0.12** (bottom)
- At low p_T initial correlations are almost washed out: small residual correlations remain for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

Realistic initial $b\bar{b}$ distributions - MC@NLO

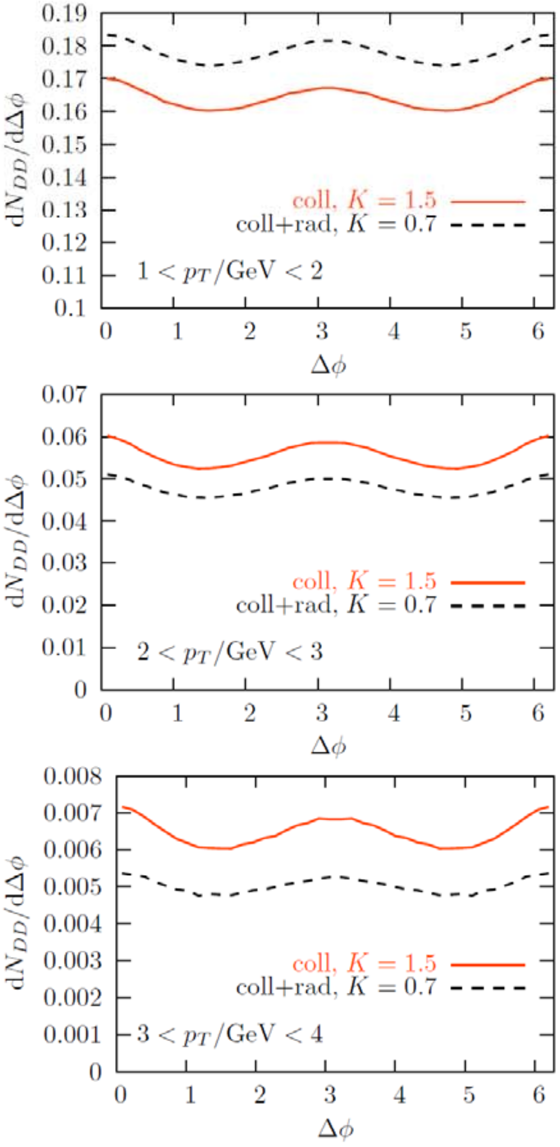
Next-to-leading order QCD matrix elements coupled to parton shower (HERWIG) evolution: MC@NLO.

S. Frixione and B. R. Webber, JHEP **0206** (2002)
S. Frixione, P. Nason and B. R. Webber, JHEP **0308** (2003)

- Gluon splitting processes lead to an initial enhancement of the correlations at $\Delta\phi \approx 0$.
- For intermediate p_T: increase of the variances from 0.43 (initial NLO) to 0.51 ($\sim$ 20%) for the purely collisional mechanisms and to 0.47 ($\sim$ 10%) for the interaction including **radiative** corrections.
- Correlations at large p_T seem to be dominated by the initial correlations.
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production!

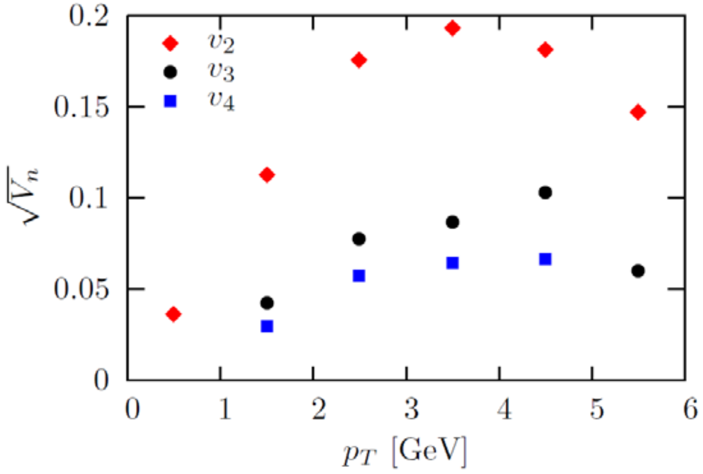


Azimuthal correlations and flow



- DD correlations, 30-50% central.
- Flow harmonics from 2-particle correlation functions $\propto \frac{N}{2\pi}(1 + 2\sum V_n \cos(n\Delta\phi))$.

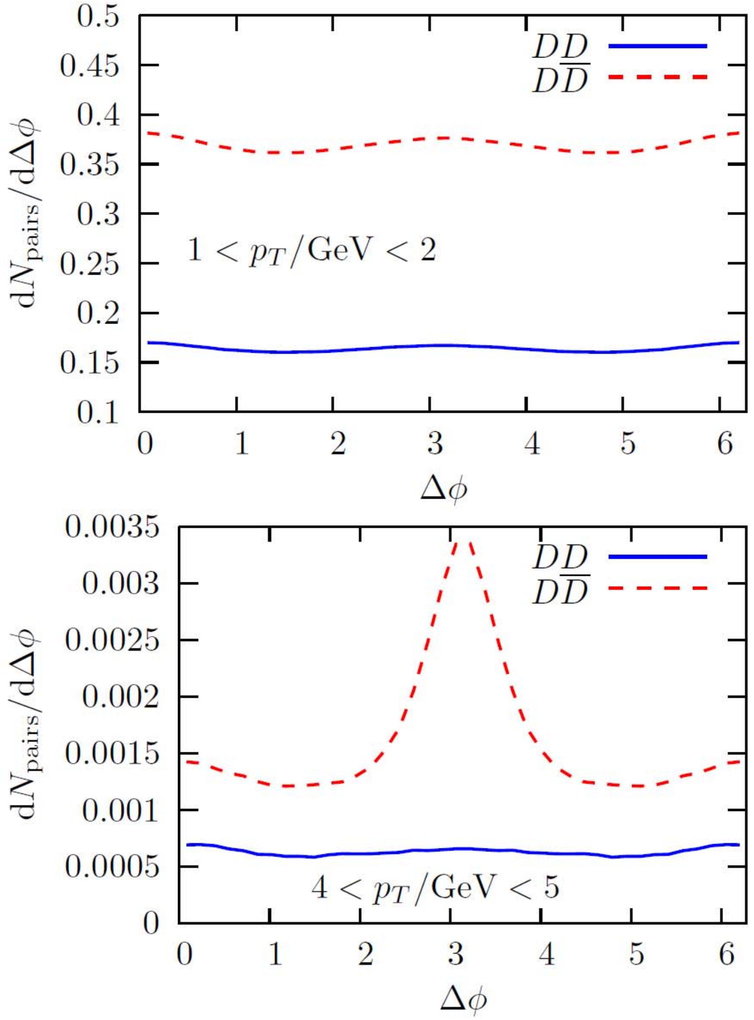
collisional, $K = 1.5$



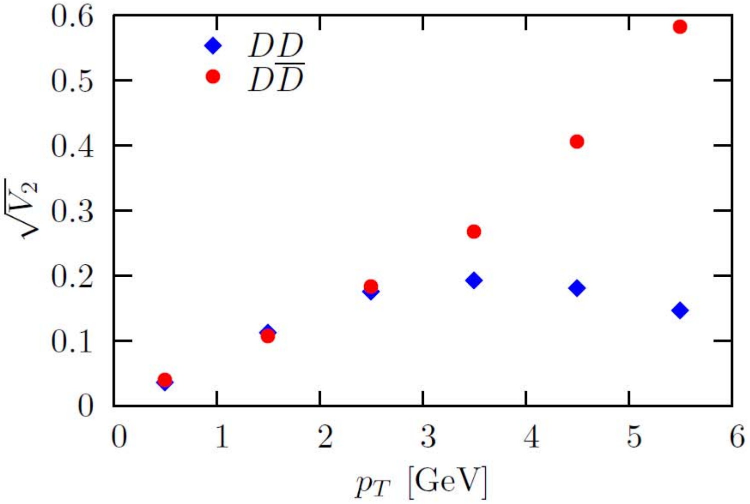
- Similar V_n for both interaction mechanisms at low p_T.
- Nonvanishing higher flow coefficients.

Azimuthal correlations and flow

as an example collisional, $K = 1.5$



- Compare DD correlations to $D\bar{D}$ correlations to learn about the flow contribution and the degree of isotropization of $D\bar{D}$ pairs.



- Similar V_2 for DD and $D\bar{D}$ at low p_T.
- Dominant initial back-to-back correlation in $D\bar{D}$-correlations at higher p_T.

Conclusions I

All experimental midrapidity data are compatible with the assumption that

pQCD describes energy loss and elliptic flow v_2

of heavy quarks.

RHIC and LHC described by same program (hydro ini is diff)

Special features running coupling constant
adjusted Debye mass
Landau Pomeranschuk Migdal

Description of the expansion of the medium (freeze out, initial cond.) can influence the results by at least a factor of 2 (**1102.1114**)

Conclusions II

The present heavy quark data are do not allow discriminate between radiative and collisional energy loss

Correlations of c and cbar offer more possibilities:

They show that
low pt heavy quarks equilibrate with the plasma (isotropic azimuthal distribution)
high pt heavy quarks do not equilibrate. Widening in pt depends on the reaction mechanism.

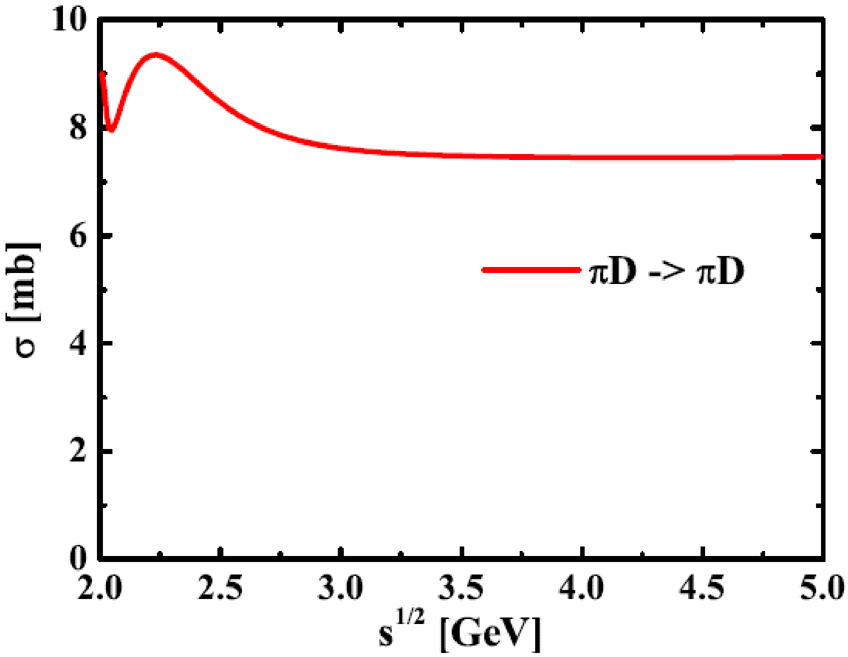
There is hope that this can be measured.

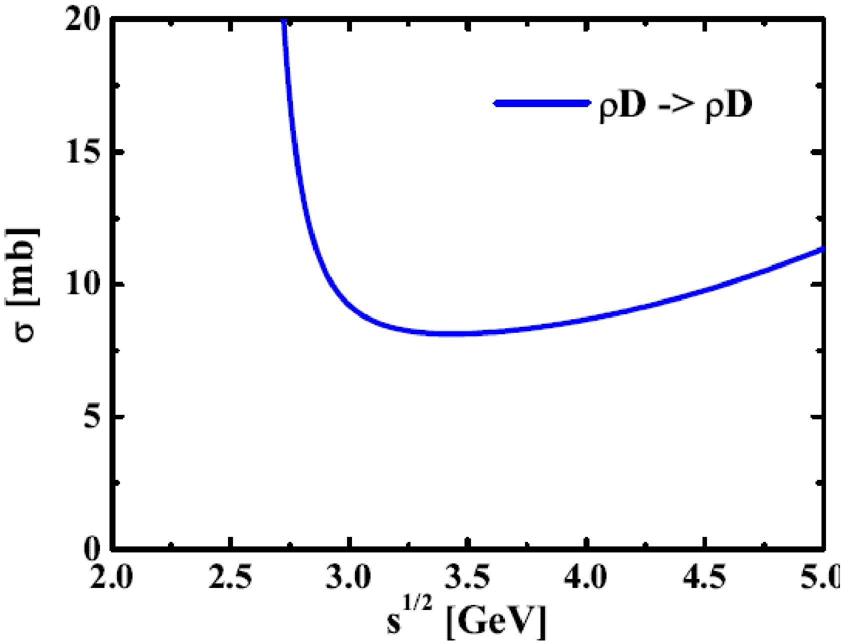
Hadronic rescattering has little influence on R_{AA} and v_2.

Hadronic rescattering

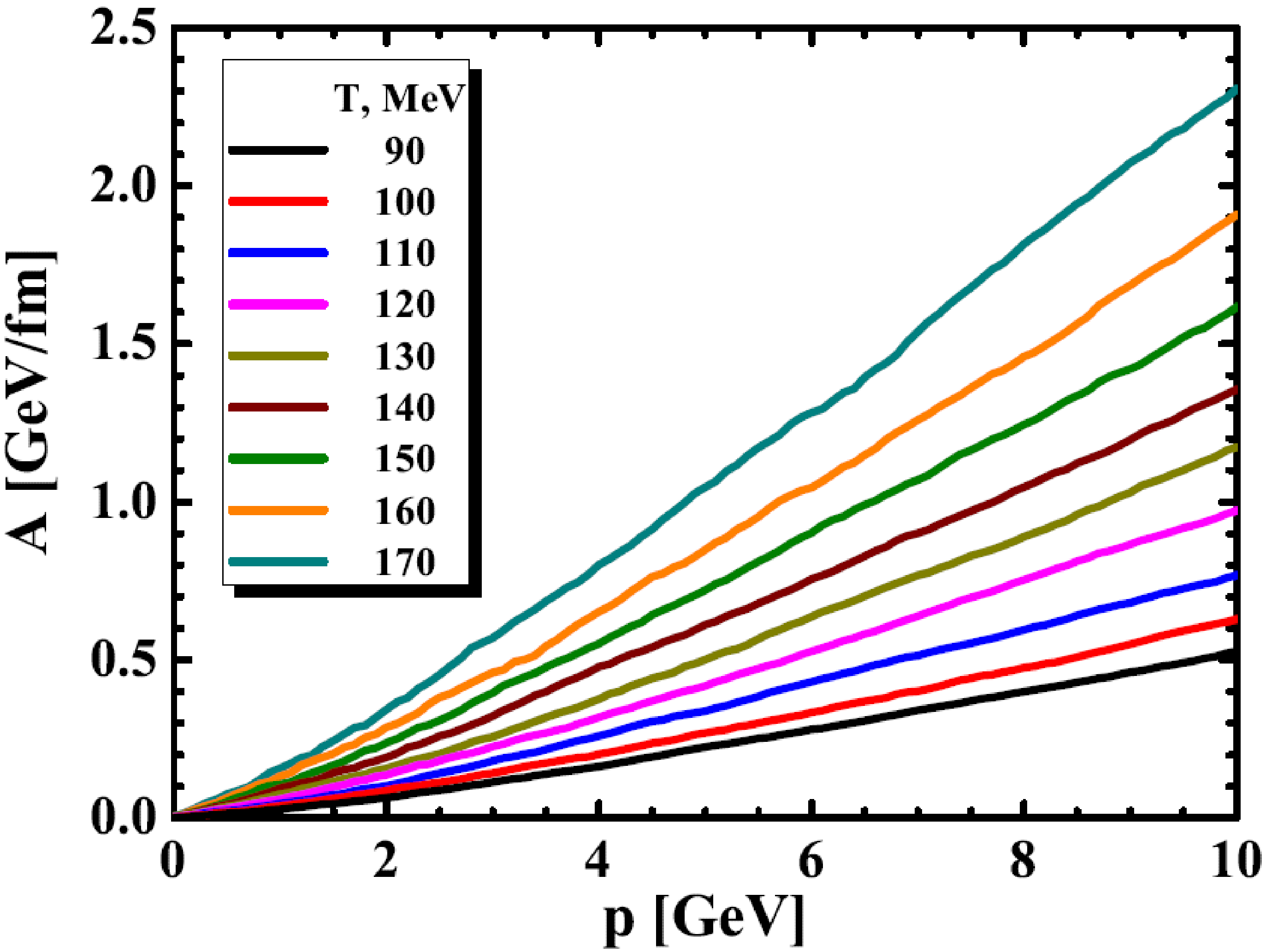
Most advanced cross section of D mesons with hadrons based on next to leading order chiral Lagrangian

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



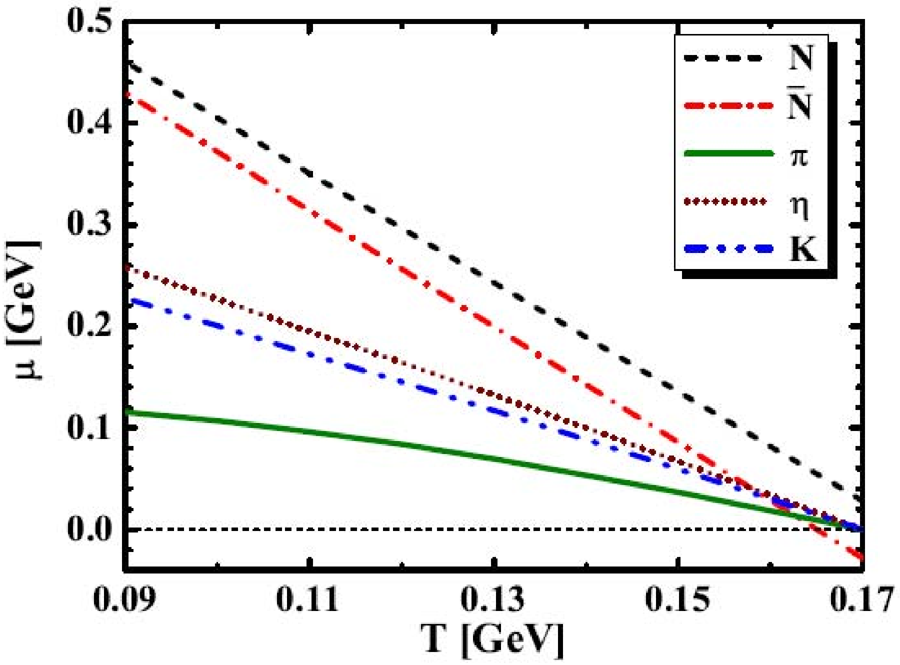


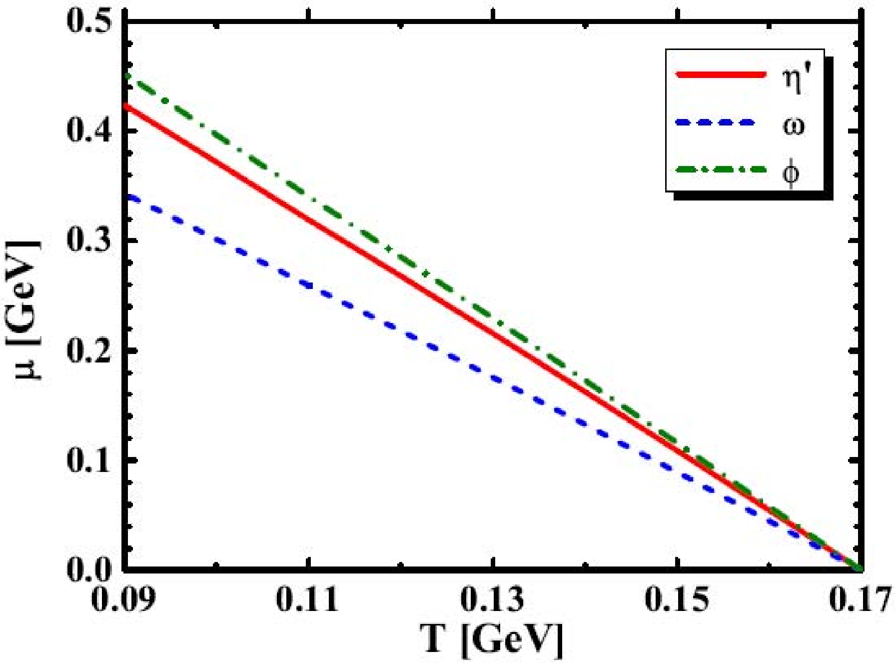
We obtain drag coefficients

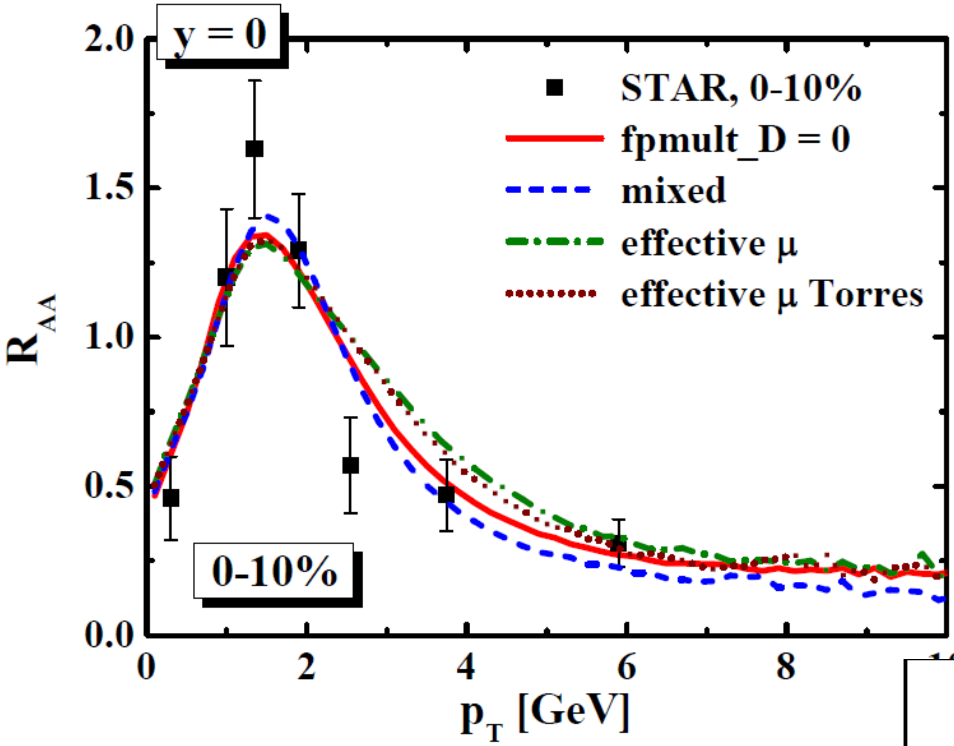


Chemical freeze out at ϵ = 0.5 GeV/fm^3
kinetic freeze out at T = 100 MeV

Modeled by effective chemical potentials (Rapp PRC66 017901)

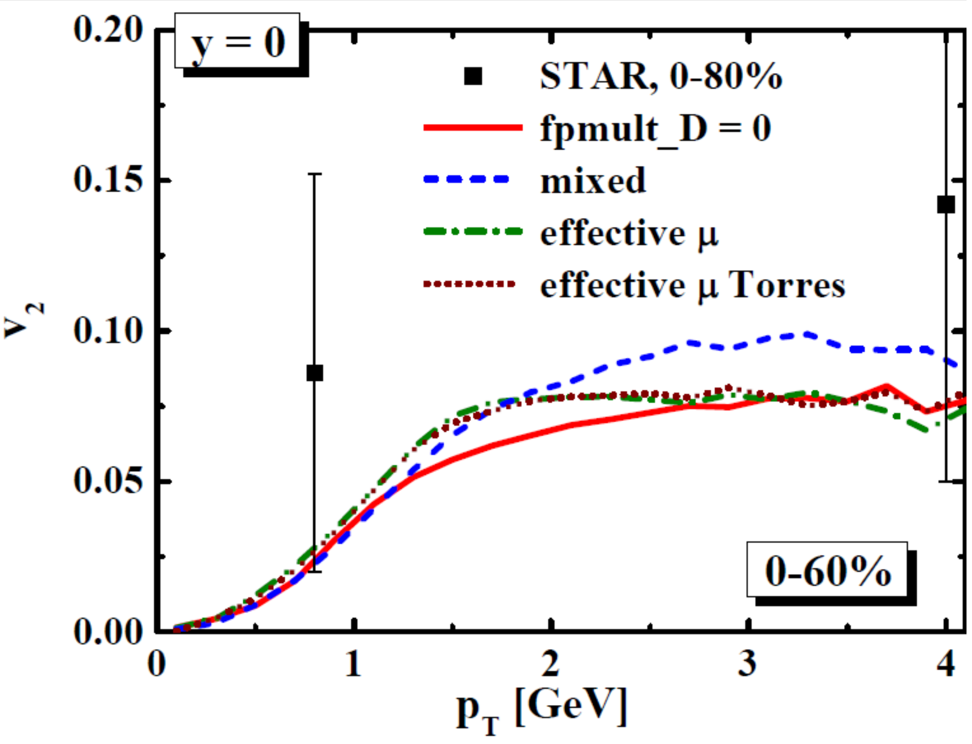






Hadronic rescattering in the Fokker Planck approach

Little effect for R_{AA} and v_2



If the transition between partons and hadrons takes place at ϵ = 0.5 GeV/fm^3

Conclusions

All experimental data are compatible with the assumption that QCD describes

energy loss and elliptic flow v_2

of heavy quarks.

RHIC and LHC described by same program (hydro ini is diff)

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adjusted Debye mass
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There is hope that this can be measured.

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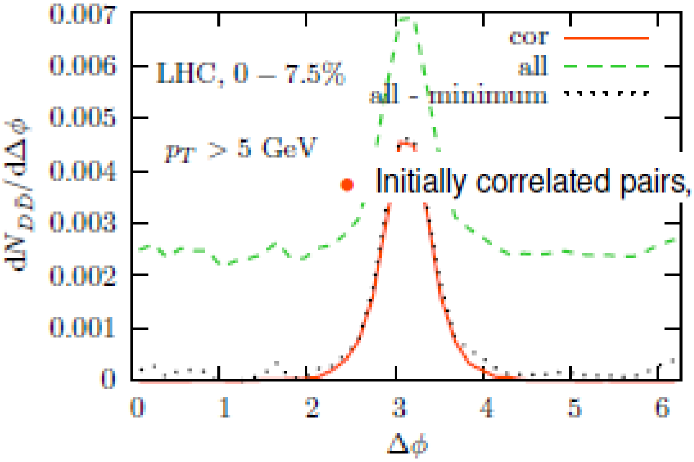
Background subtraction

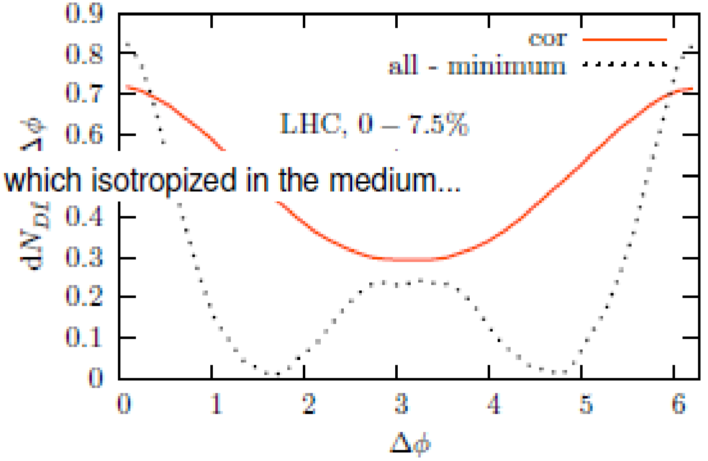
Experimentally impossible to distinguish initially correlated/uncorrelated pairs... ⇒ background!

Naiv subtraction via something like ZYAM:

high p_T:



low p_T-dominated:



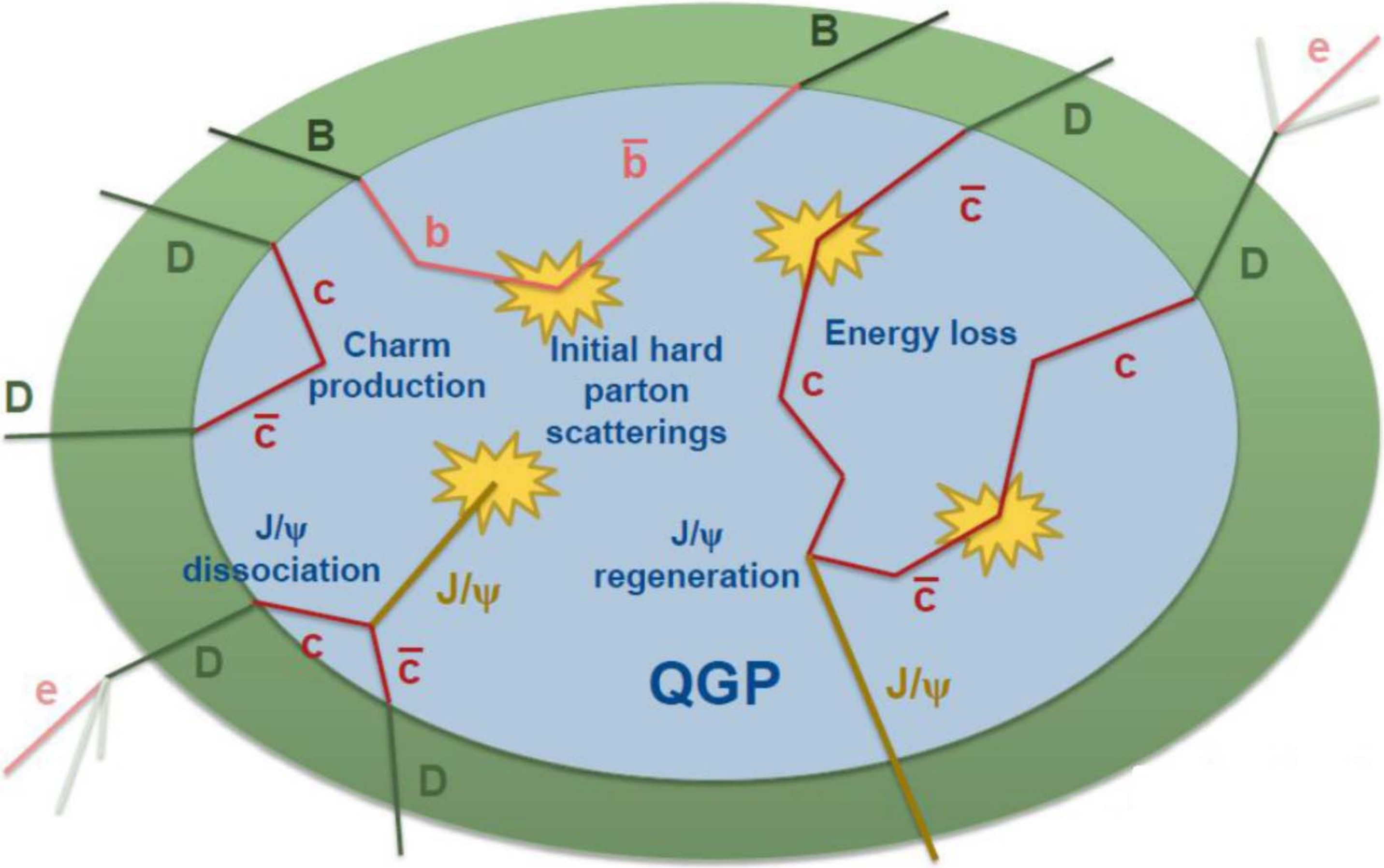
- Initially correlated pairs, which isotropized in the medium...

collisional $K = 1.5$

Background consists of:

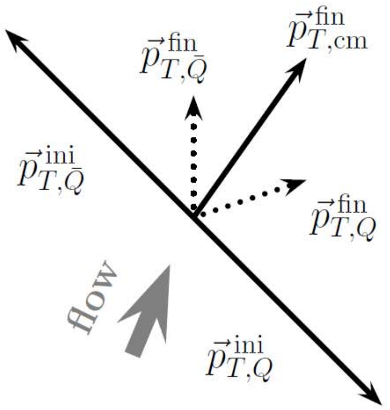
- Initially uncorrelated pairs - uninteresting! Can be removed by mixed-event or like-sign, *DD* correlations?

- Initially correlated pairs, which isotropized in the medium...


B
B
$\bar{b}$
b
D
D
D
c
$\bar{c}$
Charm production
Initial hard parton scatterings
Energy loss
c
c
$\bar{c}$
e
D
J/ψ dissociation
J/ψ
J/ψ regeneration
$\bar{c}$
c
$\bar{c}$
D
e
D
QGP
J/ψ
D

“Partonic wind” effect

X. Zhu, N. Xu and P. Zhuang, PRL **100** (2008)



- Due to the radial flow of the matter low-p_T $c\bar{c}$-pairs are pushed into the same direction.
- Initial correlations at $\Delta\phi \sim \pi$ are washed out but additional correlations at small opening angles appear.

- This happens only in the purely collisional interaction mechanism!
- No “partonic wind” effect observed in **collisional+radiative** interaction mechanism!