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

- 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)

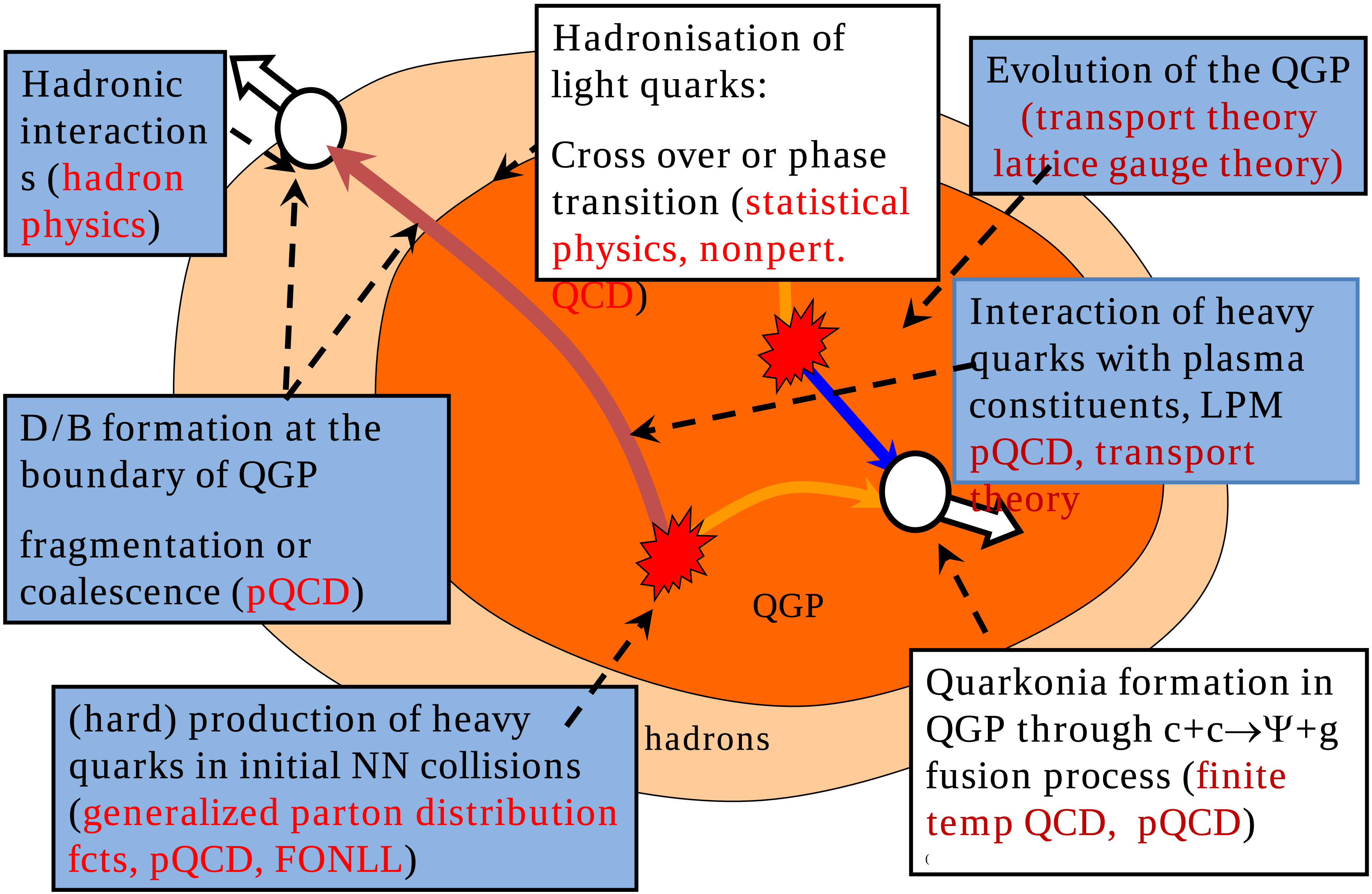
- high p_T: no equilibrium with plasma particles (information about the early state of the plasma)

- 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 :



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 :

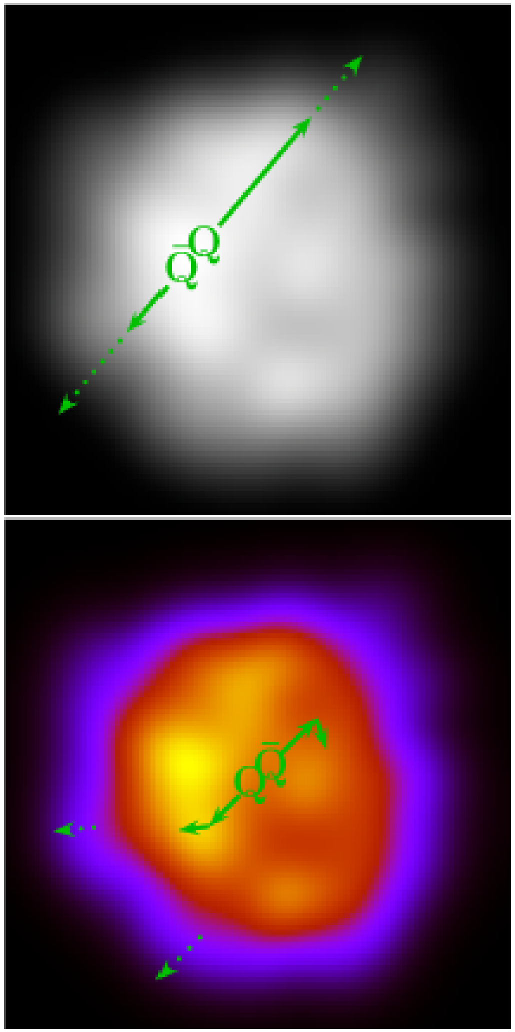
We want to

- 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)

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

Details of the approach: PB Gossiaux , Saturday 11h

Heavy-quark propagation in the QGP



Production:

- FONLL
  $\Rightarrow$ inclusive spectra, no information about correlations $\rightarrow$ 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
  $\Rightarrow$ exclusive spectra, like $Q\bar{Q}$ correlations

Interaction with the medium

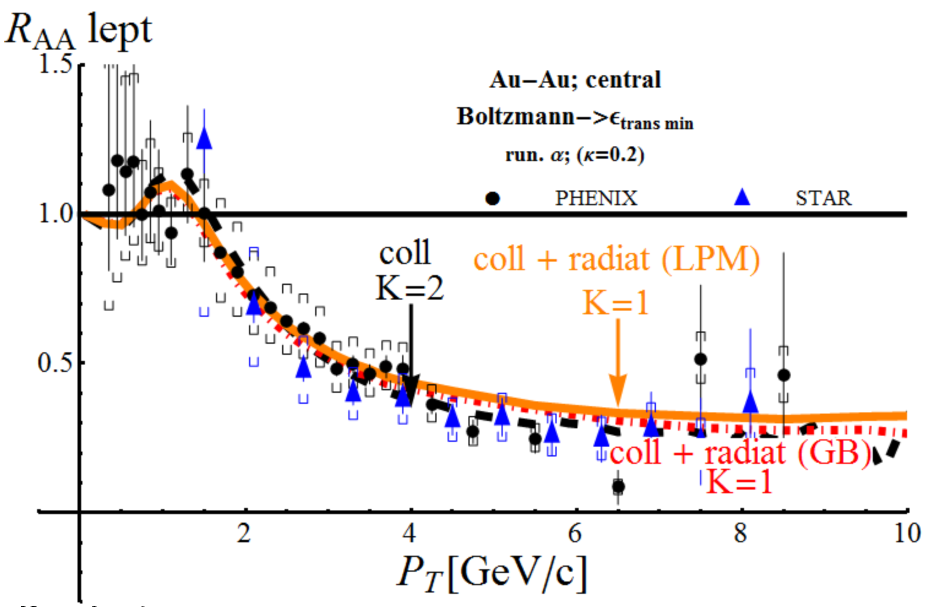
- Energy loss at high transverse momentum.
- Thermalization at low transverse momentum.
- Different interaction mechanisms: purely collisional or **collisional+radiative (+LPM)**.
- Longitudinal vs. transverse dynamics.

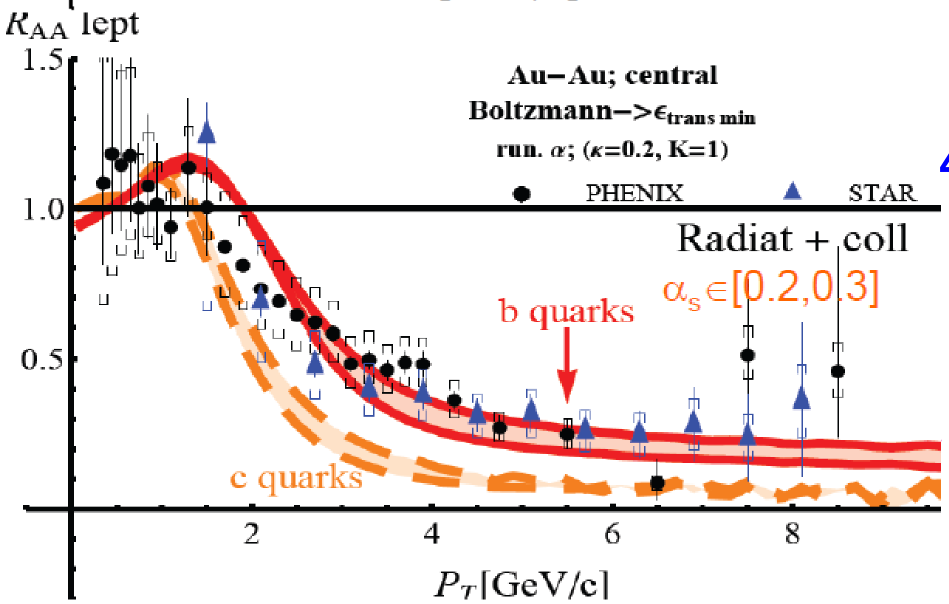
Hadronization:

- 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

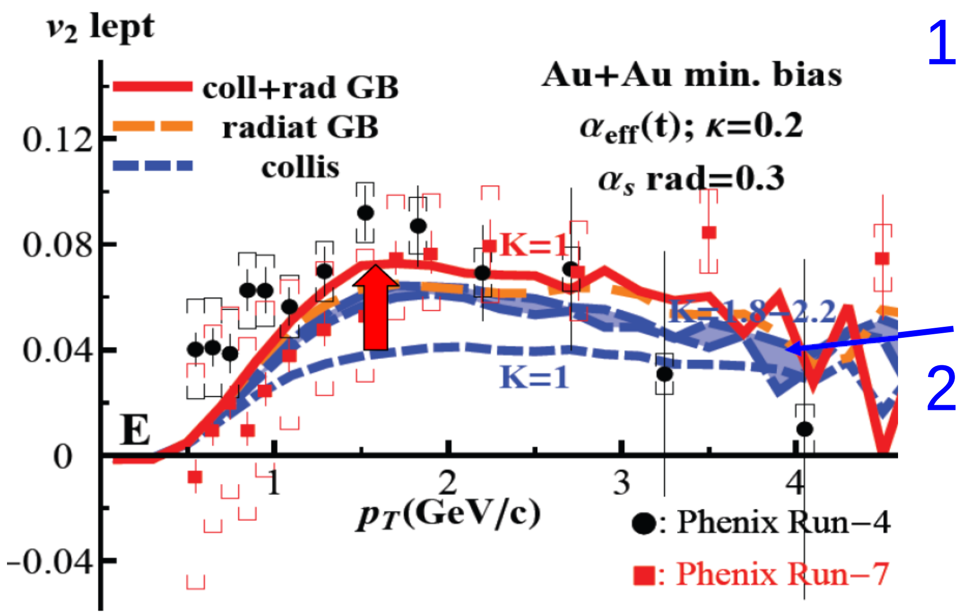




1. Coll:too little quenching (but very sensitive to freeze out) -> K=2
2. Radiative Eloss indeed as important as the collisional one
3. Flat experimental shape is well reproduced
4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC)

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

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

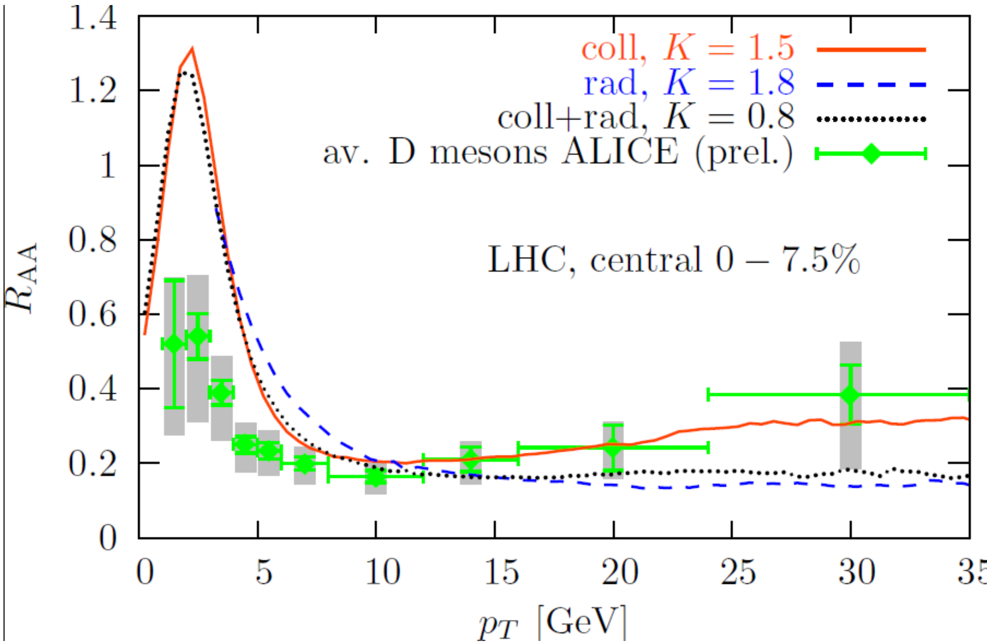
EPOS:

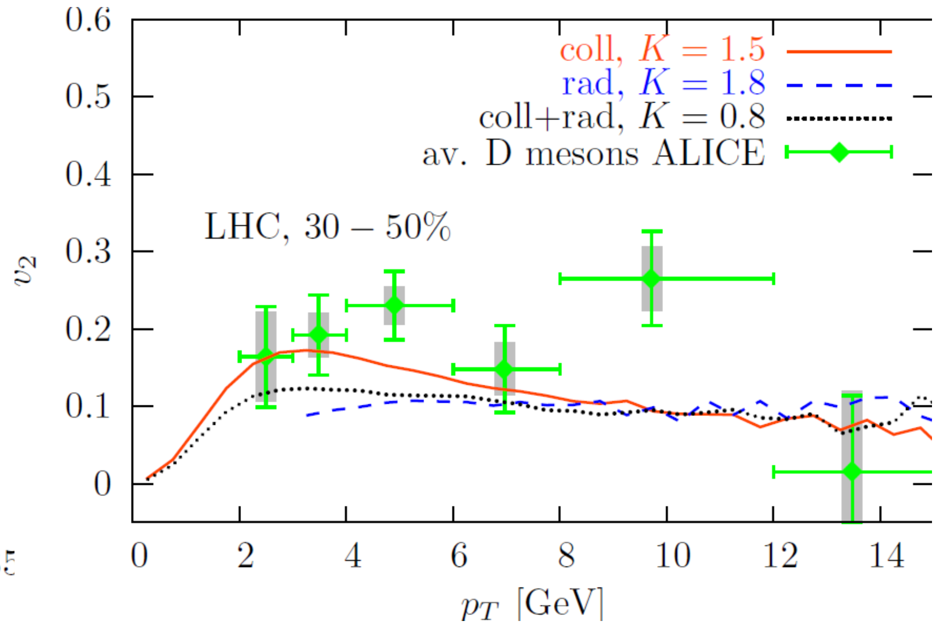
- Initial conditions from a flux tube approach to multiple scattering events.
- $3+1$ d ideal fluid dynamics.
- Including a parametrization of the equation of state from lattice QCD.
- Finite initial radial velocity.
- Event-by-event fluctuating initial conditions.

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?

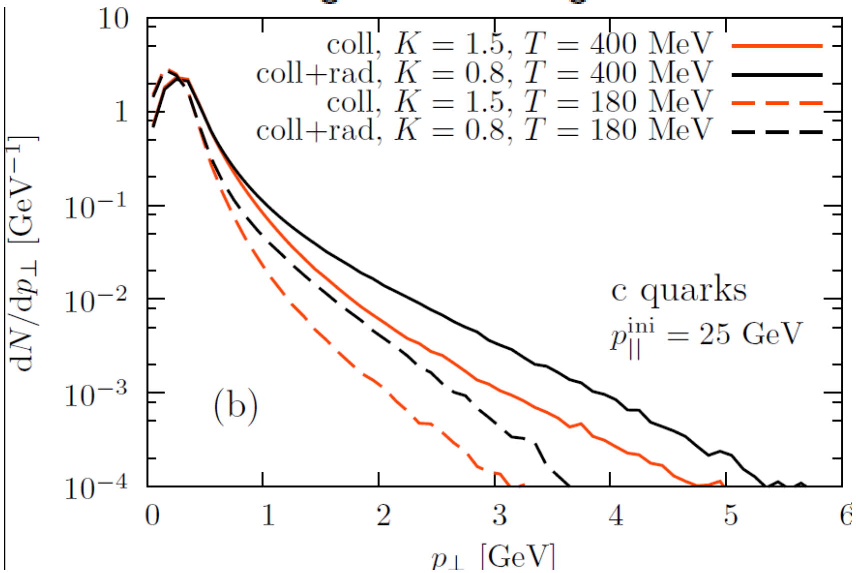
Possible candidate: heavy flavor correlations

They may be sensitive to

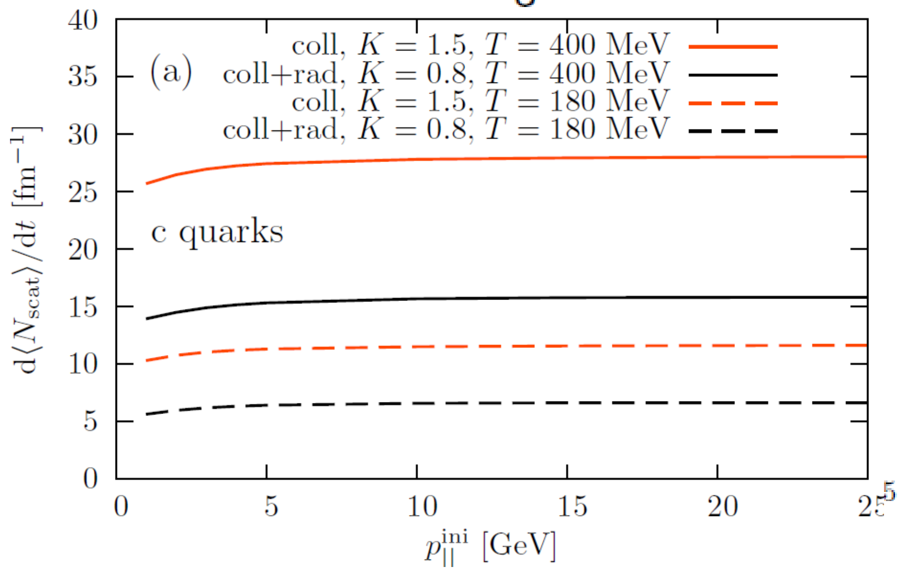
- Properties of the energy loss model: path length dependence? Parton mass dependence?
- Properties of the interaction inside a medium: drag coefficient, jet quenching parameter?

WHY?

Single scattering:



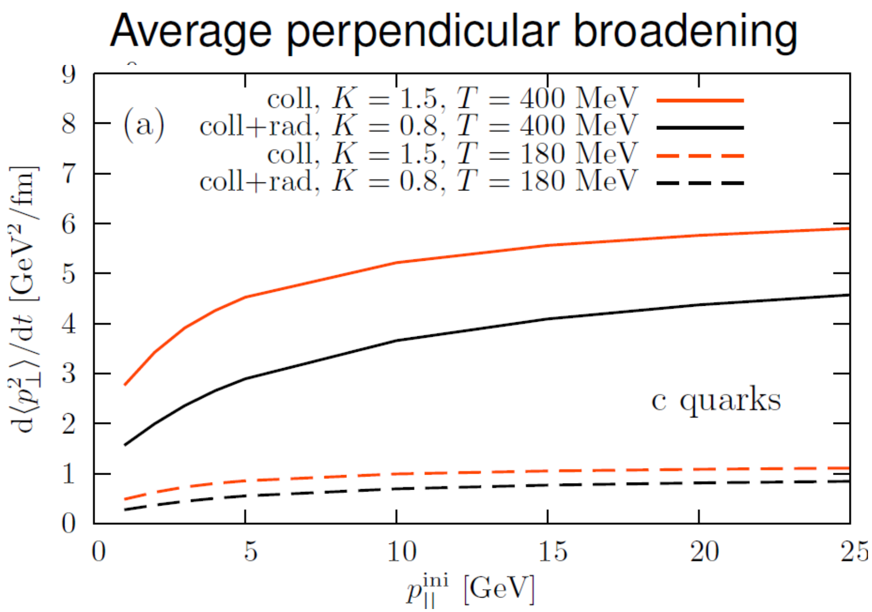
Scattering rate:

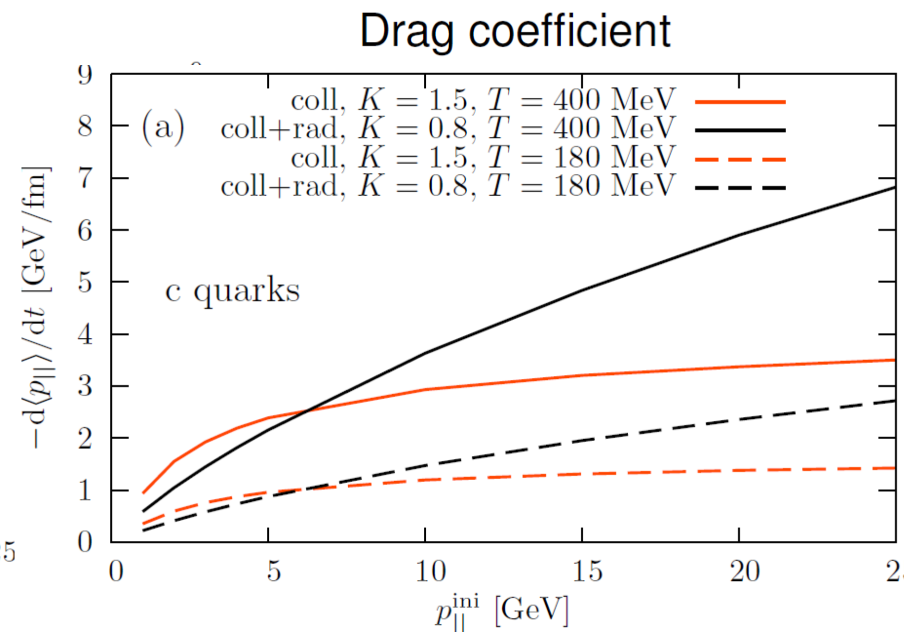


- p_T-distribution in a single scattering: larger $\langle p_T \rangle$ for **coll+rad ($K = 0.7$)**.
- Scattering rate is larger for coll ($K = 1.5$)!

Properties of the interaction

arXiv: 1305.3823
1310.2218



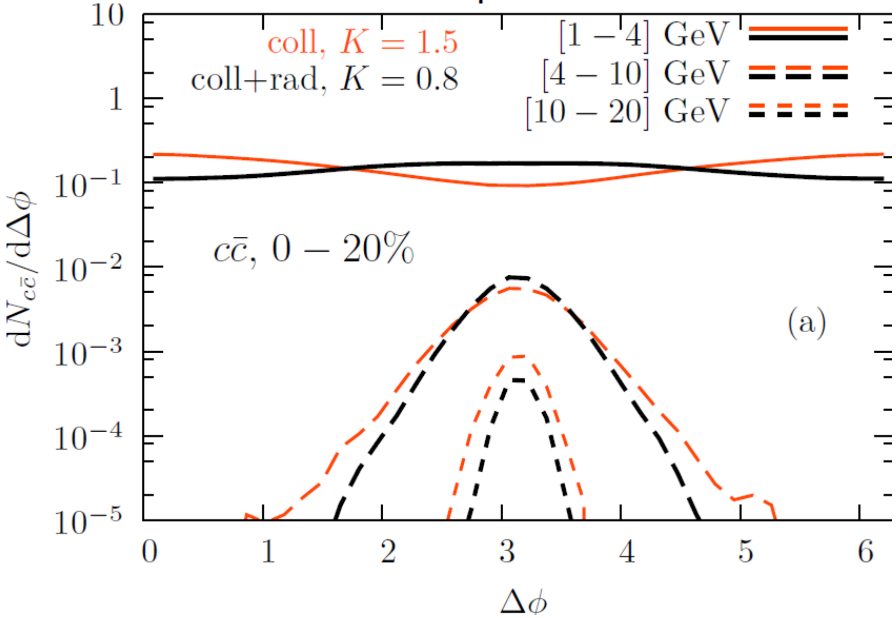


- The purely collisional scatterings lead to a larger average $\langle p_\perp^2 \rangle$ than the **radiative** corrections.
- The final $p_\perp$ also depends indirectly on the drag coefficients.
- The drag coefficients increases faster for the **collisional+radiative** interaction scenario $\Rightarrow$ 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.

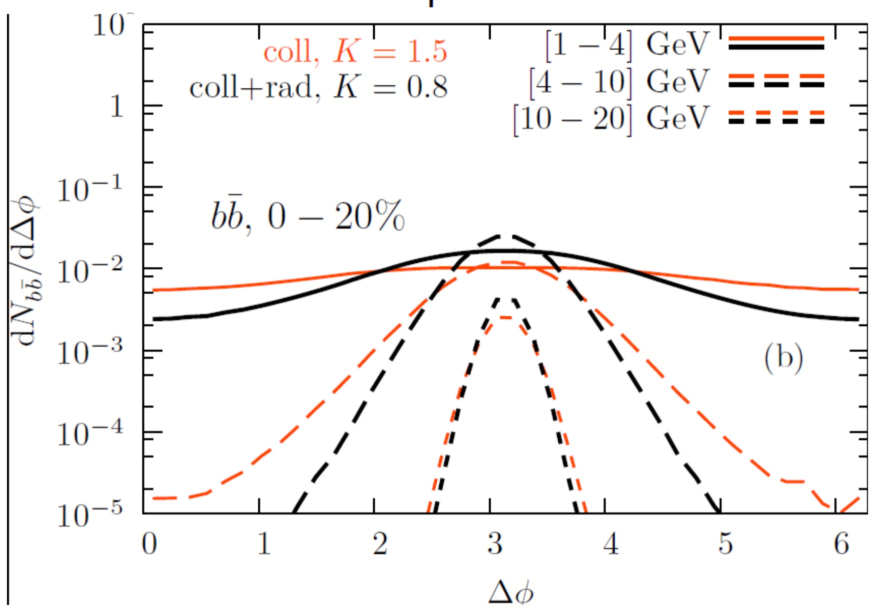
Heavy-quark azimuthal correlations

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

charm quarks



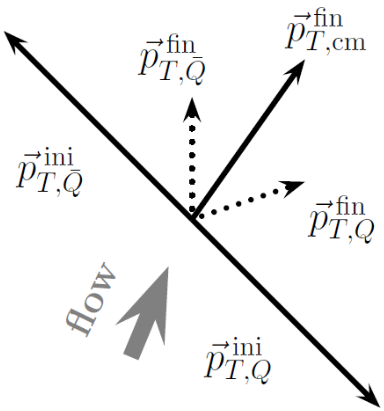
bottom quarks



- 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.

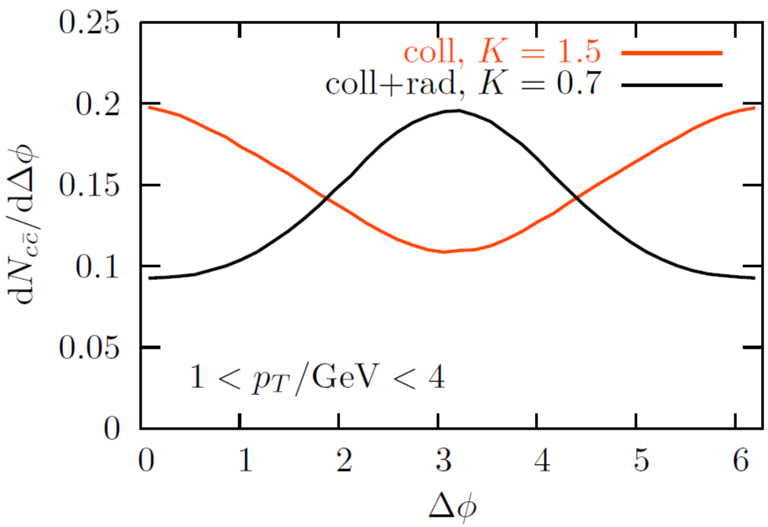
“Partonic wind” effect

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!



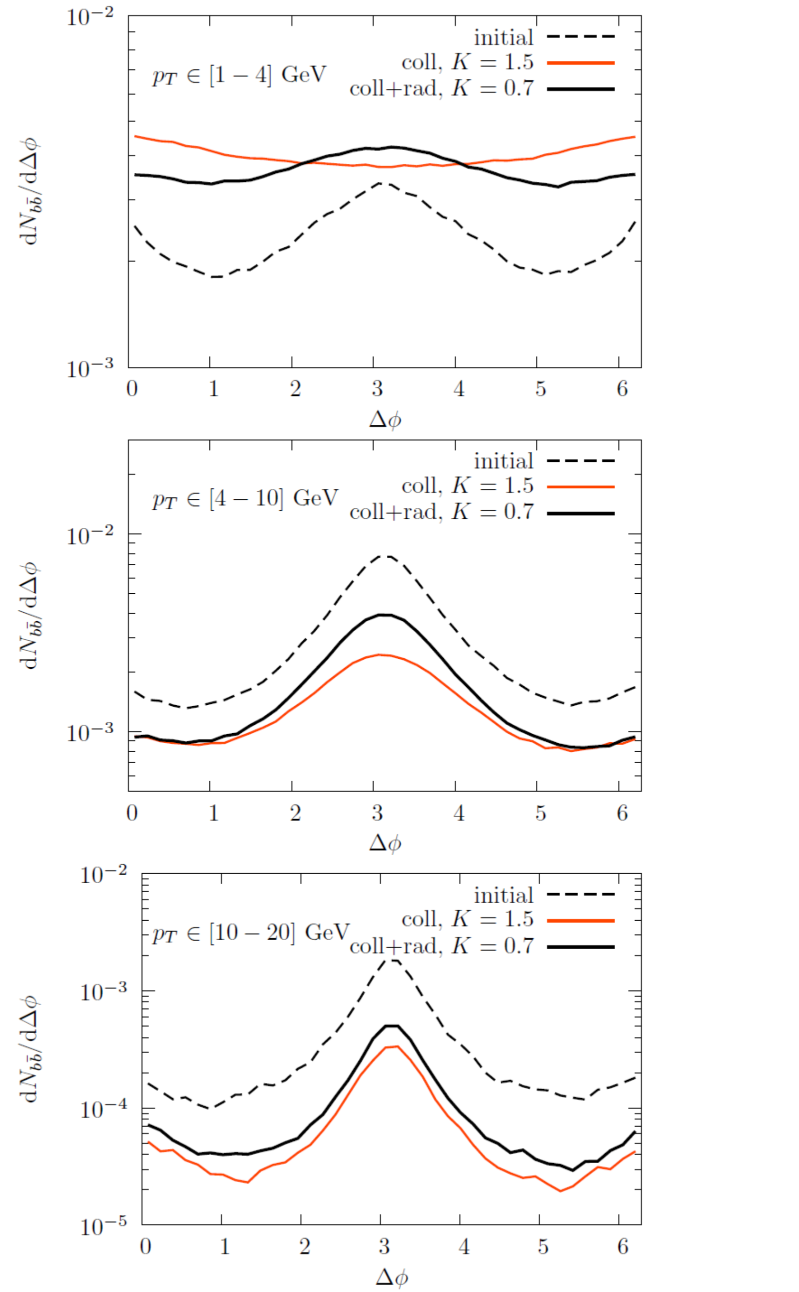
Realistic initial $b\bar{b}$ distributions - MC@NLO

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

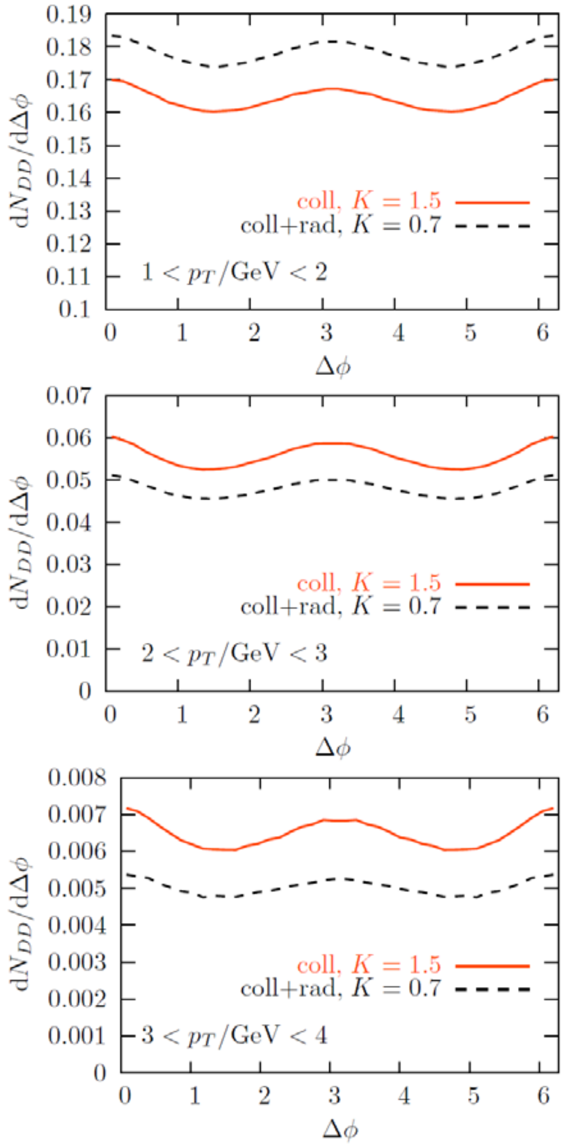
S. Frixione and B. R. Webber, JHEP **0206** (2002)

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!

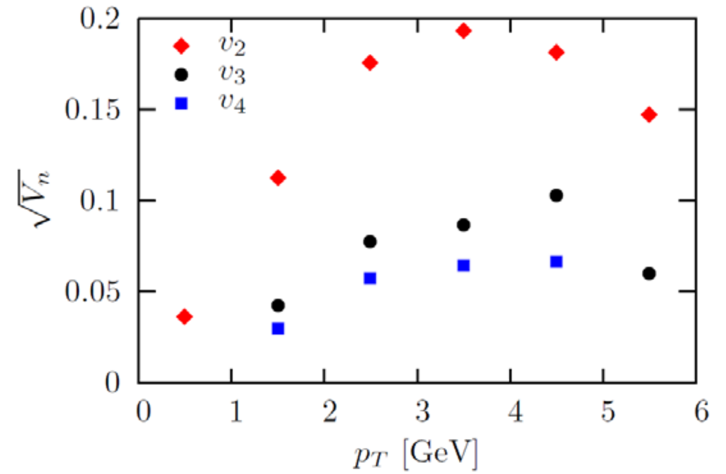


Azimuthal correlations and flow



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

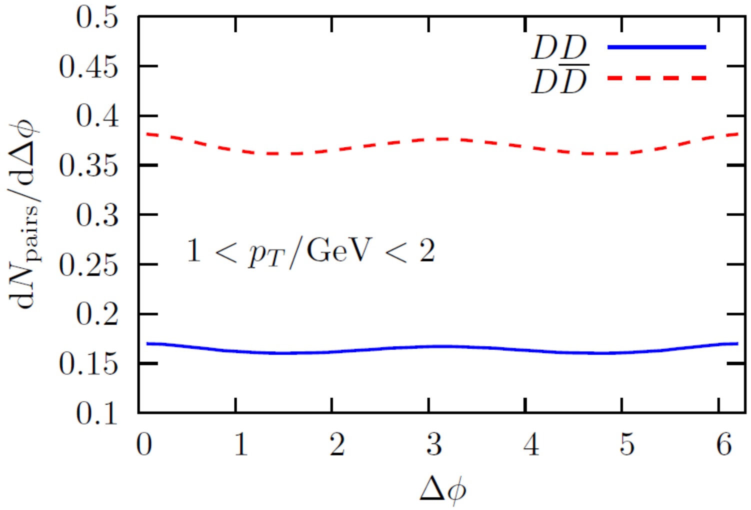
collisional, $K = 1.5$

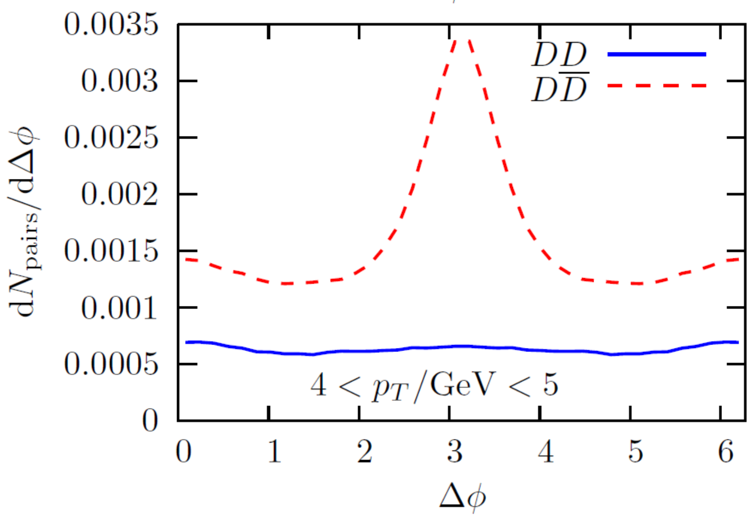


- Similar V_n for both interaction mechanisms at low p_T.
- Nonvanishing higher flow coefficients.

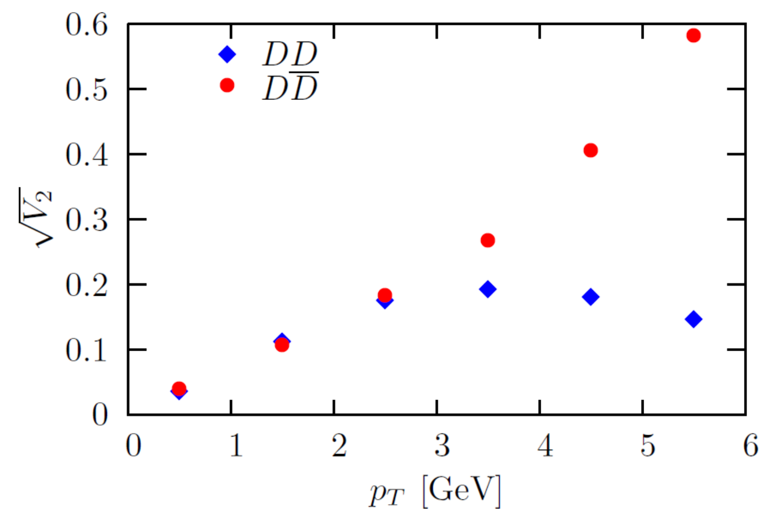
Azimuthal correlations and flow

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.

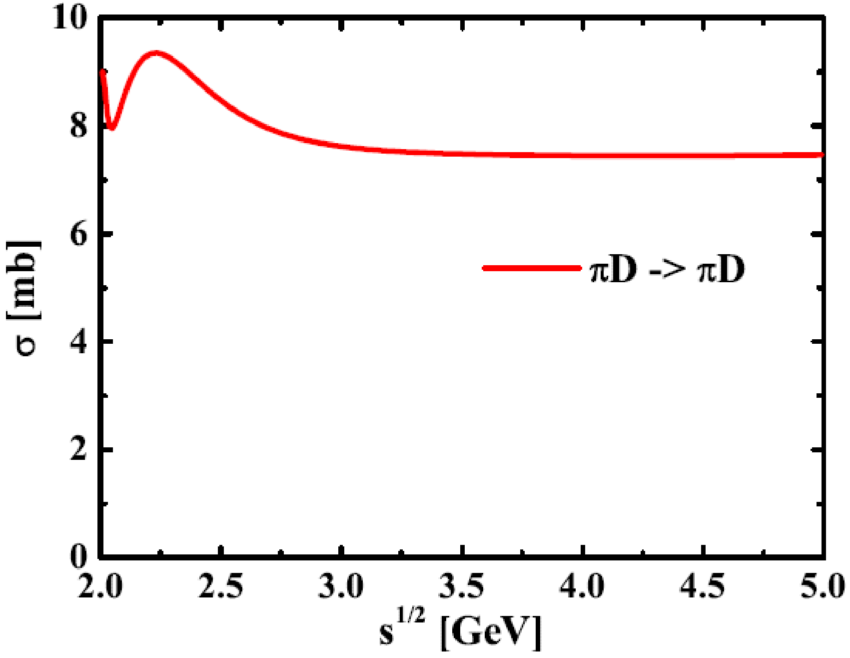


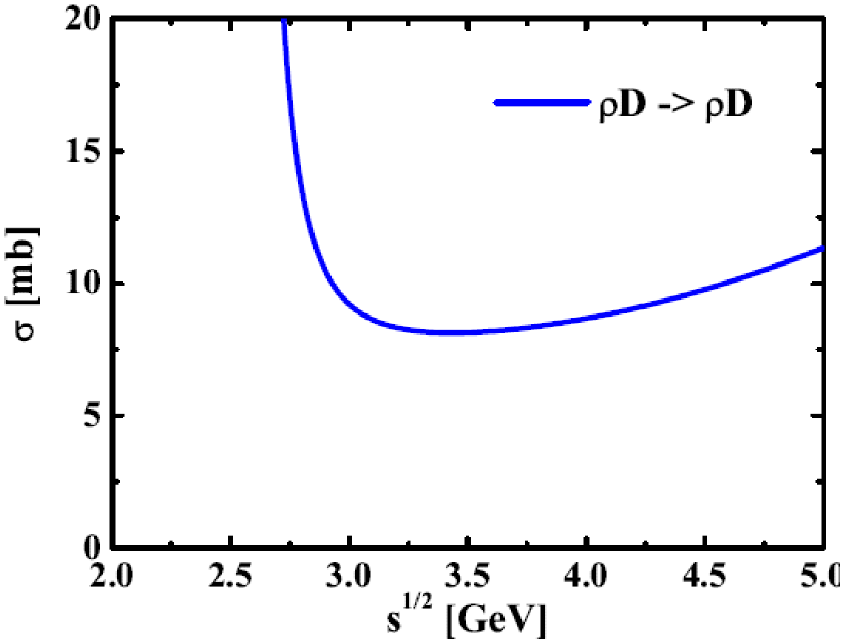
- Similar V_2 for DD and $D\bar{D}$ at low p_T.
- Dominant initial back-to-back correlation in $D\bar{D}$-correlations at higher p_T.

Hadronic rescattering

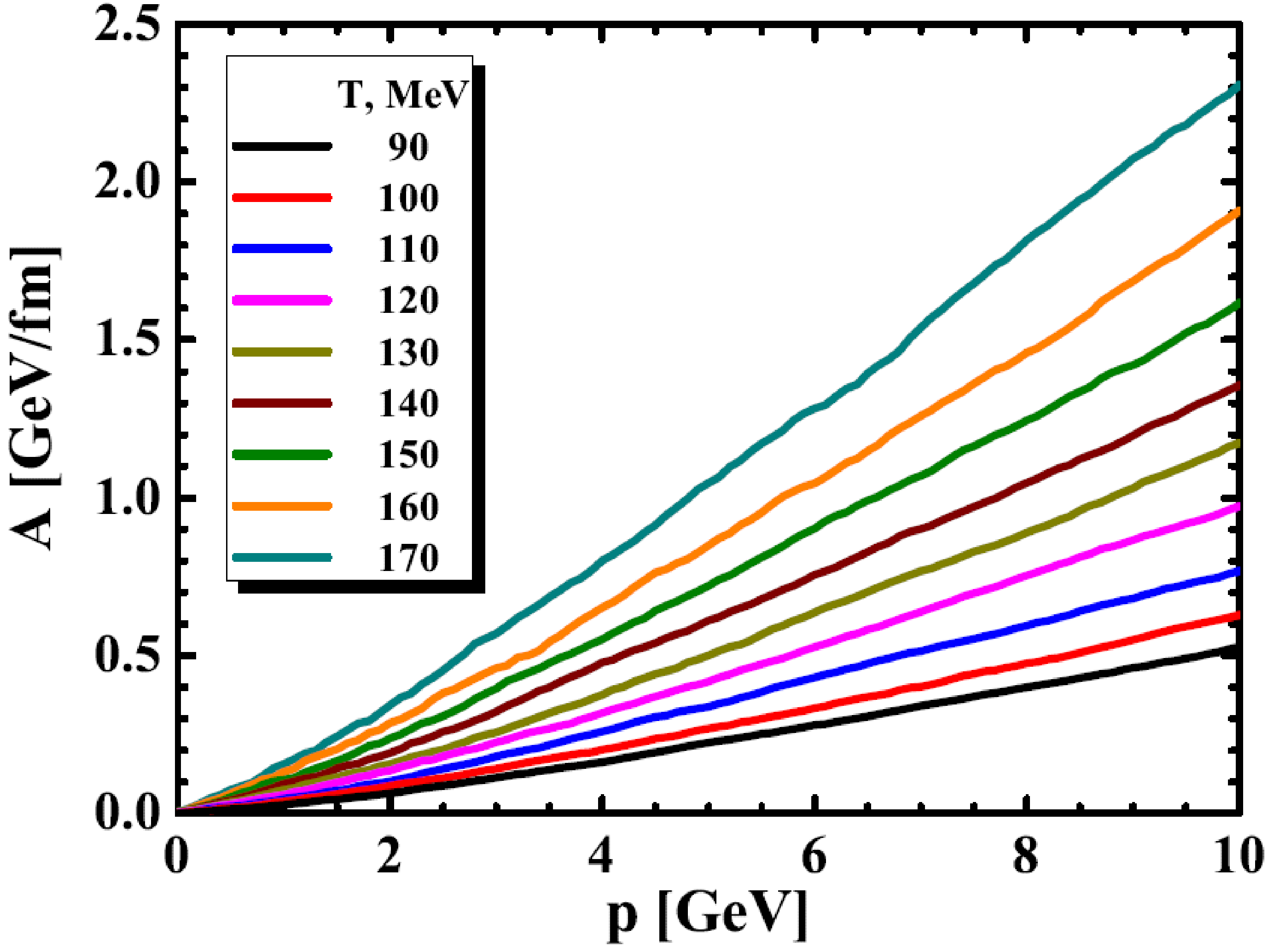
Most advanced cross section of D mesons with hadrons based on next to leading order chiral Lagrangian

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



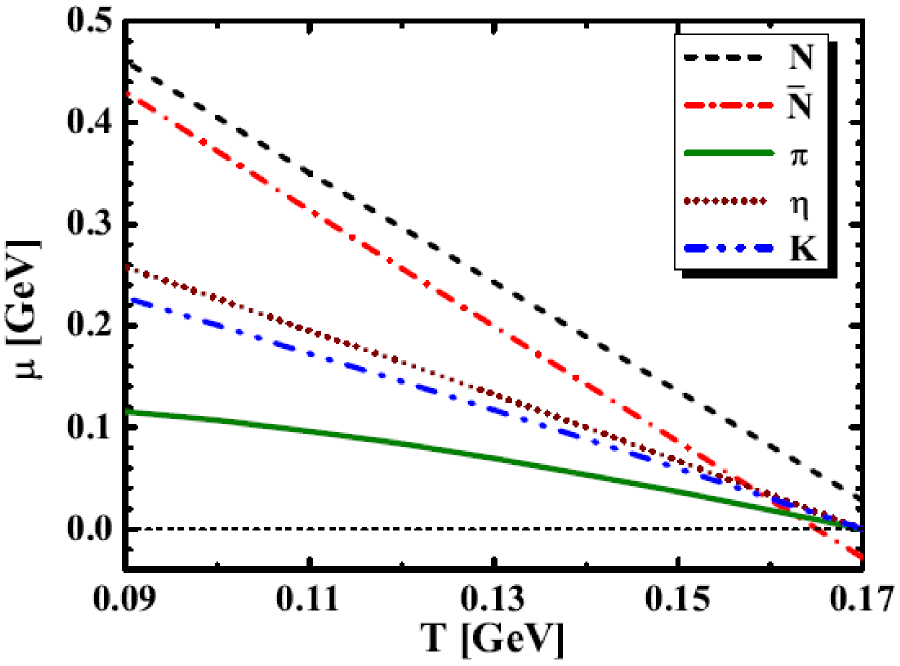


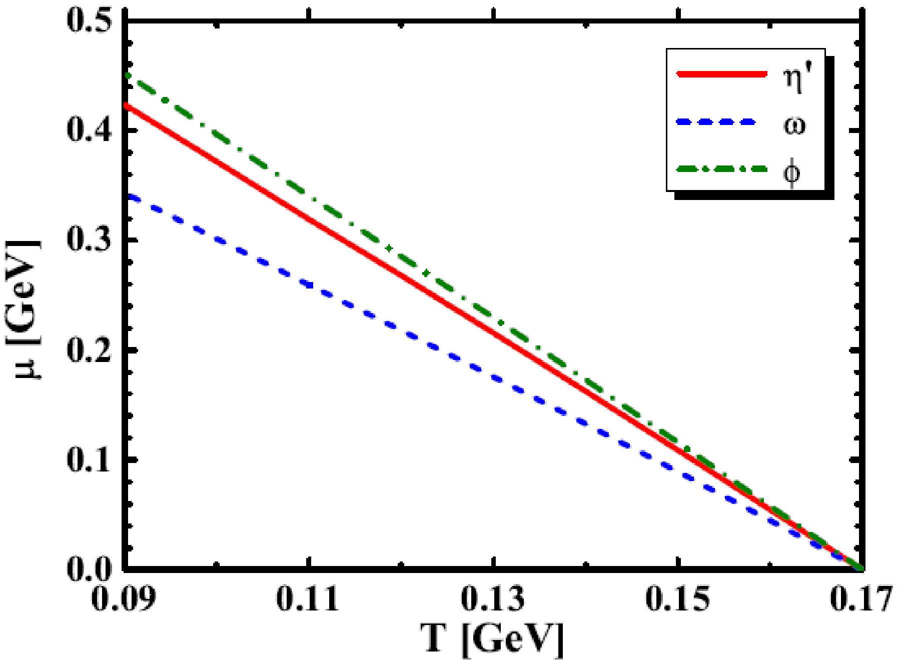
We obtain drag coefficients

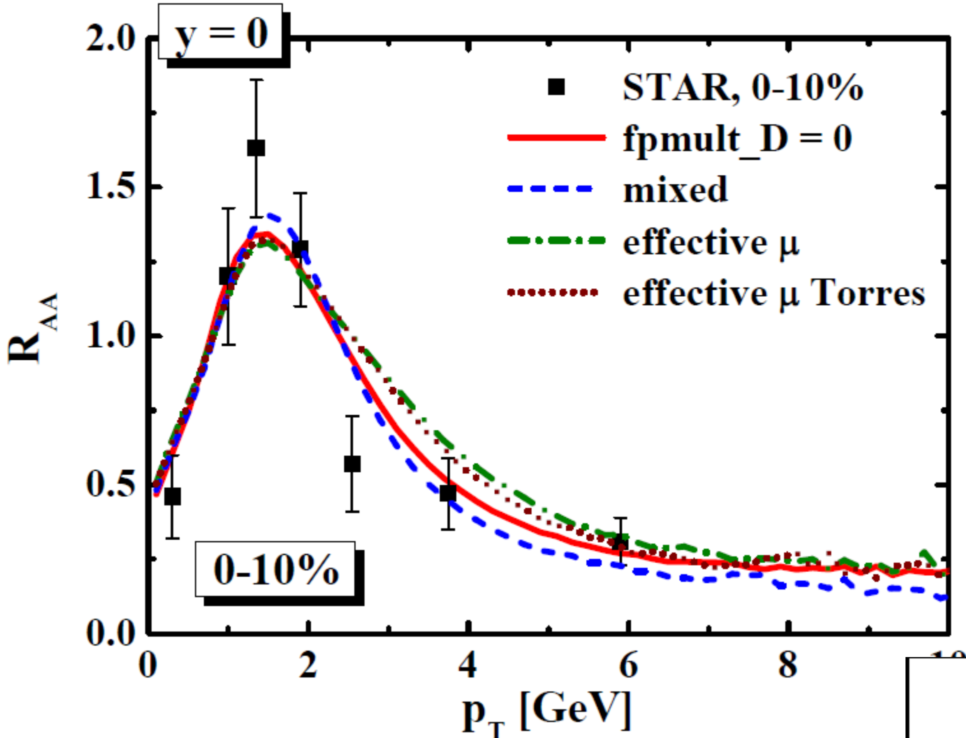


Chemical freeze out at ϵ = 0.5 GeV/fm^3
kinetic freeze out at T = 100 MeV

Modeled by effective chemical potentials (Rapp PRC66 017901)



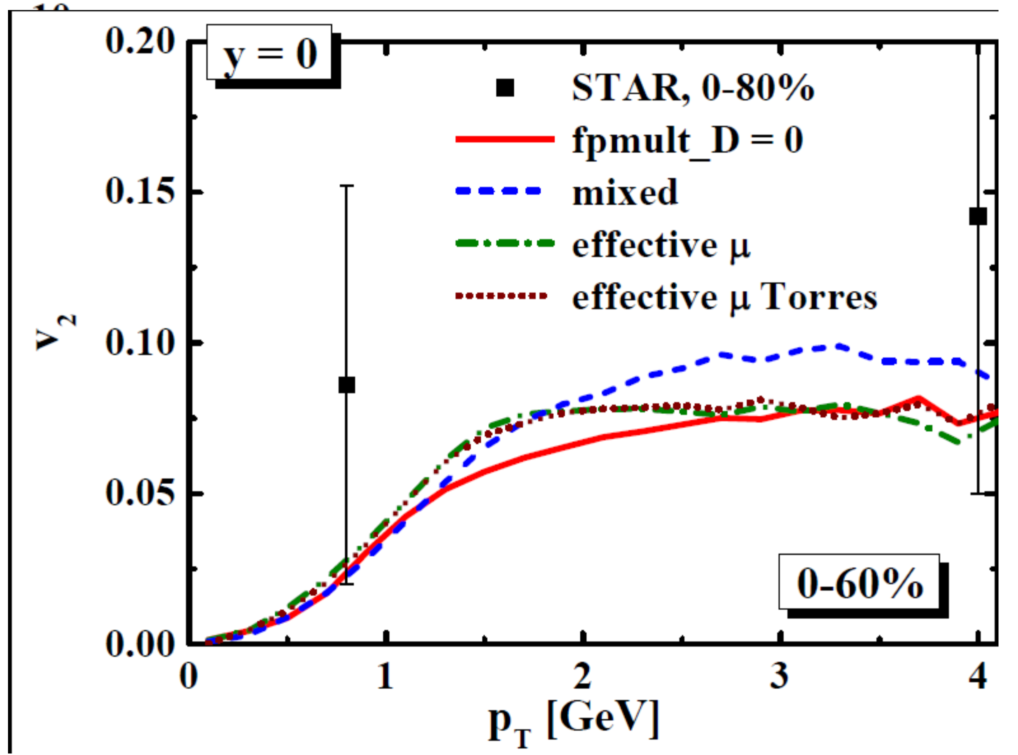




Hadronic rescattering
in the Fokker Planck approach

Little effect for R_{AA} and v_2

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



Conclusions:

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.

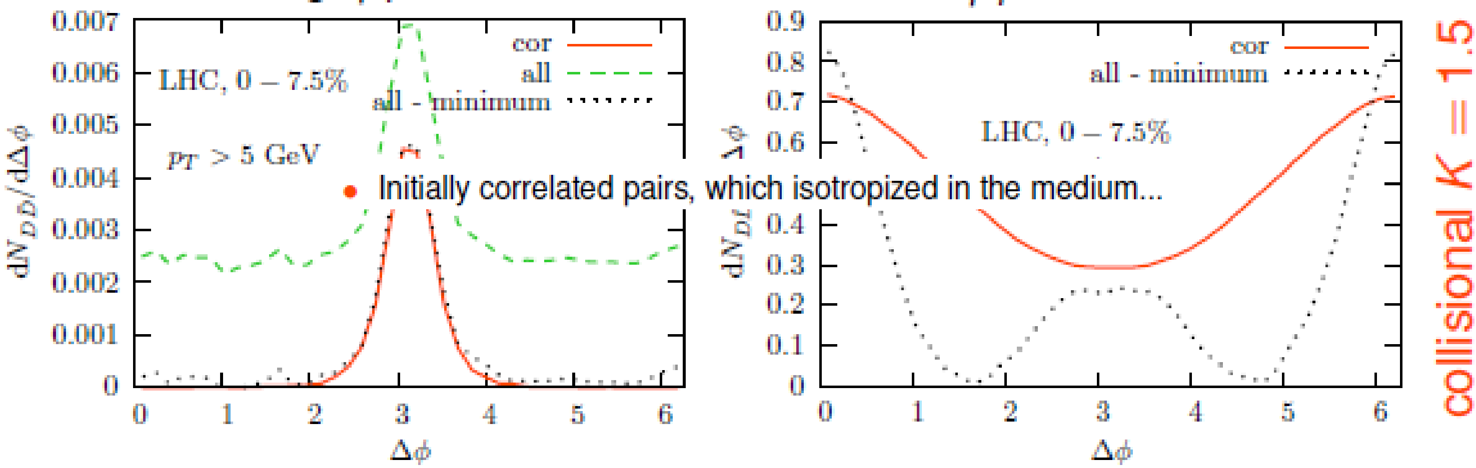
Hadronic rescattering has little influence on R_{AA} and v_2.

Background subtraction

Experimentally impossible to distinguish initially correlated/uncorrelated pairs... $\Rightarrow$ background!

Naiv subtraction via something like ZYAM:

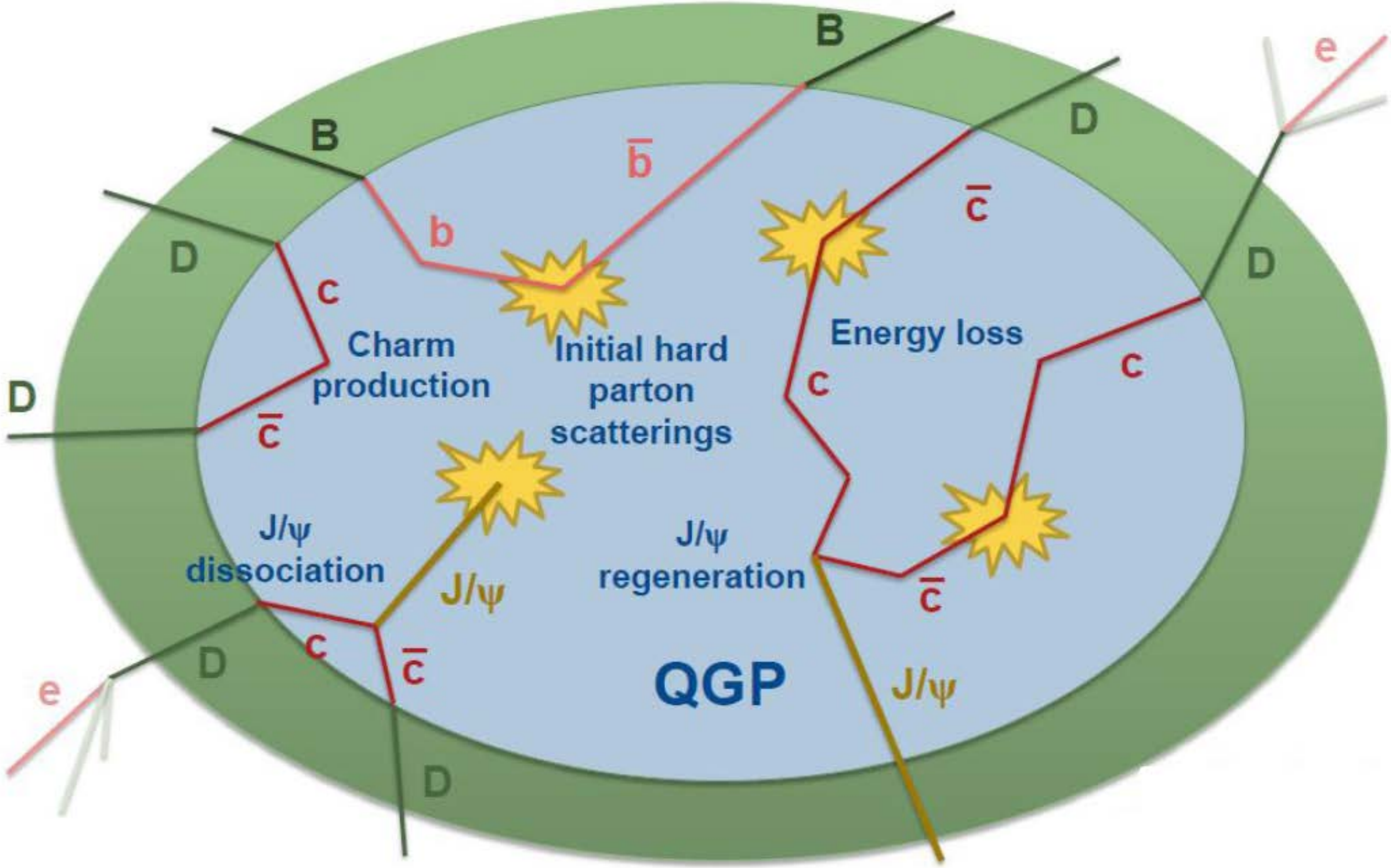
high p_T: low p_T-dominated:



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

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