From the R_{AA} to azimuthal correlations: what can we learn from heavy-quark observables?

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SUBATECH, Nantes & Duke University, Durham & FIAS, Frankfurt

Strangeness in Quark Matter, July 2013, Birmingham UK

MN, J. Aichelin, P. B. Gossiaux, K. Werner, arXiv:1305.3823

thanks to: TOGETHER & "Van Gogh project" with Utrecht Univ.

Heavy-quark observables

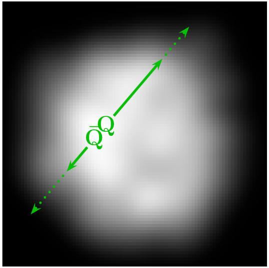
- Nuclear modification factor: $R_{\mathrm{AA}} = \frac{\mathrm{d}\sigma_{\mathrm{AA}}/\mathrm{d}p_T}{N_{\mathrm{bin}}\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_T}$.
- Low p_T: (partial) thermalization of heavy quarks.
- High p_T: elastic collisions + bremsstrahlung $\Rightarrow$ energy loss.
- v_2 from p_T-broadening and flow of the medium.

$\Rightarrow$ Too many models describe R_{AA} and v_2 fairly well!

Heavy-flavor correlations:

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

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)

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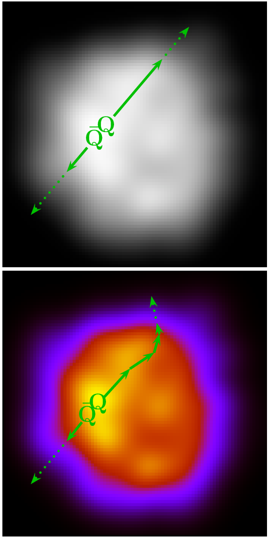

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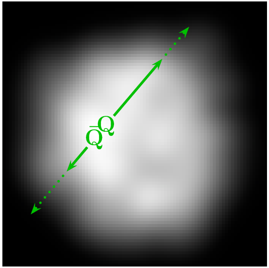

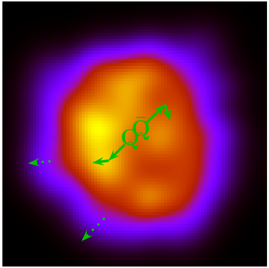

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MC@sHQ + EPOS

More details on our model: talk by PB Gossiaux, Fri 26/07, 2:40pm!

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.

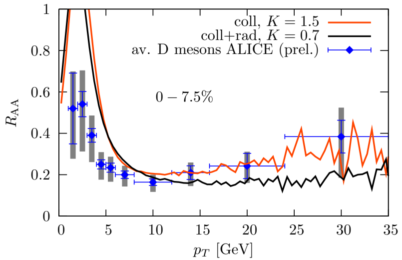
For calibration a global rescaling of the cross sections by a K-factor is required!

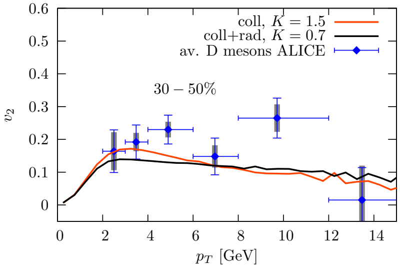
P. B. Gossiaux and J. Aichelin, PRC **78** (2008);
P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. G **37** (2010)
K. Werner, I. .Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, PRC **85** (2012)

The traditional observables: R_{AA} and v_2

Strategy:

Require a reasonable agreement of the D-meson $R_{\mathrm{AA}} \Rightarrow$ fix the K-factor once and for all and study other observables, like the v_2.





- Reasonable agreement for the R_{AA} for D mesons above $p_t > 5$ GeV.
- Reasonable agreement for the v_2 of D mesons.
- Need to include shadowing in the low p_T region.
- The agreement is slightly better for purely collisional energy loss scenarios!

ALICE Nucl. Phys. A904-905 (2013); arXiv:1305.2707

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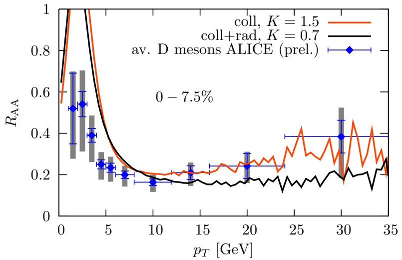

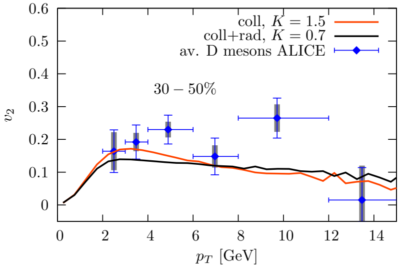

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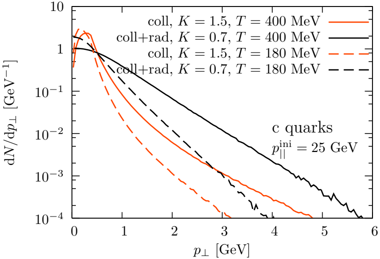
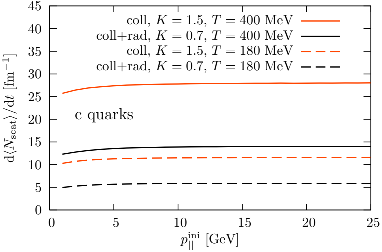
Properties of the interaction

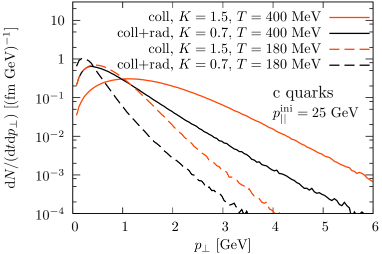
Single scattering:



Evolution in a medium:

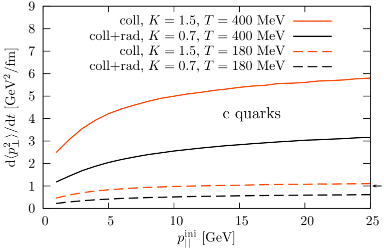


- p_T-distribution in a single scattering: larger $\langle p_T \rangle$ for **coll+rad ($K = 0.7$)**.
- Initialize in a static, infinite medium at temperature T with a given longitudinal momentum, evolve according to the Boltzmann equation for $\Delta t = 0.4$ fm.
- Scat. rate is larger for coll ($K = 1.5$)!
- p_T-distribution after evolution in a static medium: larger $\langle p_T \rangle$ for coll ($K = 1.5$)!

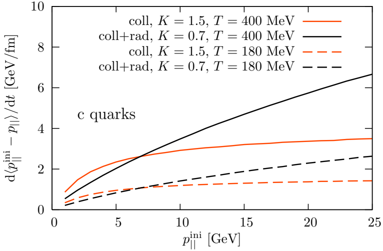


Properties of the interaction

Average perpendicular broadening



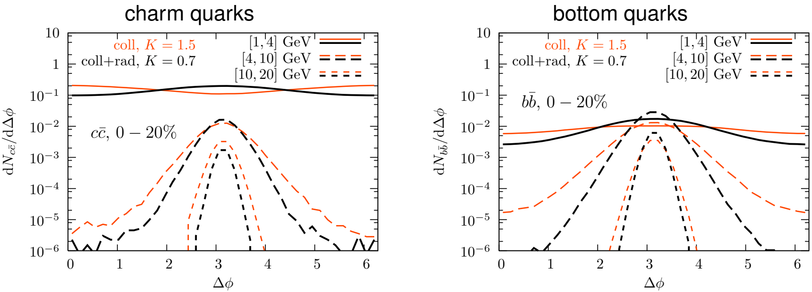
Drag coefficient



- 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

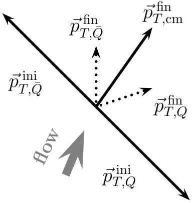
central collisions, back-to-back initialization, no background from uncorrelated pairs



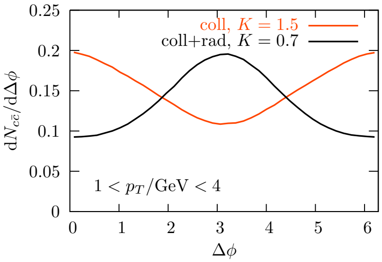
- Stronger broadening in a purely collisional than in a **collisional+radiative** interaction mechanism
- Variances in the intermediate p_T-range: 0.18 vs. **0.094** (charm) and 0.28 vs. **0.12** (bottom)
- At low p_T initial correlations are almost washed out: small residual correlations remain for 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!



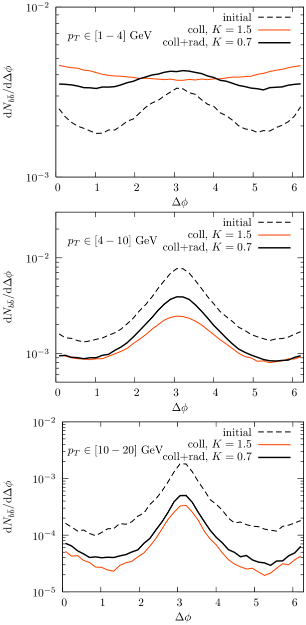
Realistic initial $b\bar{b}$ distributions - MC@NLO

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

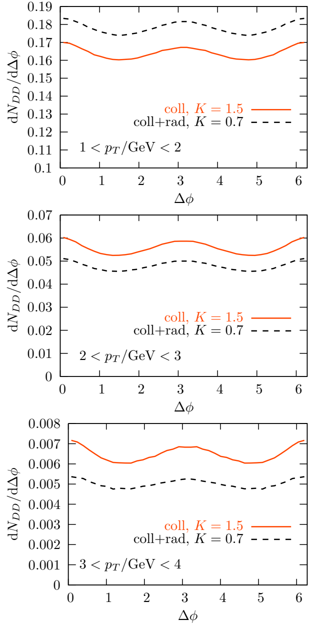
S. Frixione and B. R. Webber, JHEP **0206** (2002)

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!

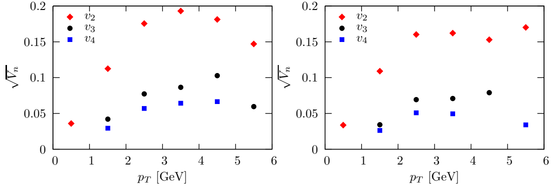


Azimuthal correlations and flow



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

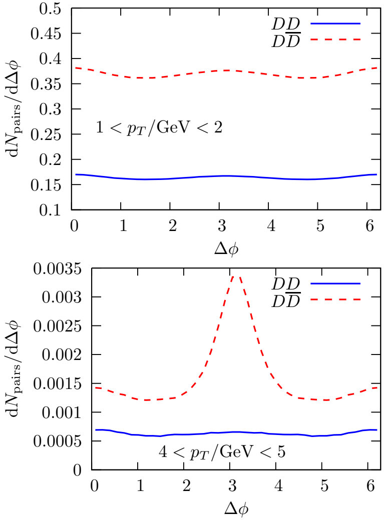
coll., $K = 1.5$ **coll+rad,** $K = 0.7$



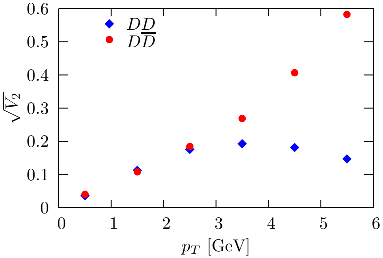
- Similar V_n for both interaction mechanisms at low p_T.
- Nonvanishing higher flow coefficients.

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.

Conclusion

- Monte-Carlo approach to in-medium heavy-quark propagation coupled to EPOS gives a reasonable agreement for the R_{AA} and the v_2 of D mesons at LHC.
- Heavy-quark correlation observables are a promising observable to learn more about the in-medium energy loss:
  - At small p_T: the correlations in $\Delta\phi$ are washed out.
  - At larger p_T: initially correlated $Q\bar{Q}$ pairs show a residual $\Delta\phi \approx \pi$-correlation after propagation in the medium.
  - The peak of the $\Delta\phi$ correlation distribution is broader for the purely collisional interaction mechanism than for the **collisional+radiative** one due to larger average perpendicular broadening.
  - Flow coefficients can be obtained from two-particle correlation functions, higher flow harmonics could further enhance our understanding of flow of heavy quark mesons.
  - Comparison of flow of D-mesons to $D\bar{D}$ correlations shows flow contributions at low p_T.
- Need a reliable proton-proton reference for initial $c\bar{c}$-distributions!
- Study heavy-flavor correlations which are closer to experimental observables!