Correlations and higher-order flow: new heavy-quark observables in relation to the bulk dynamics

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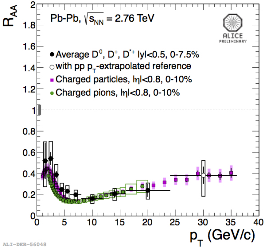
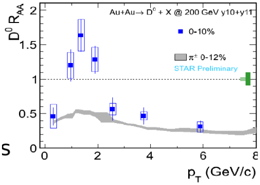
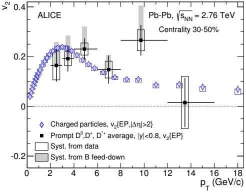
Heavy-quark observables

Traditional heavy-flavor observables (R_{AA} and v_2) show...

- Low p_T: (partial) thermalization of heavy quarks.
- High p_T: elastic collisions + bremsstrahlung $\Rightarrow$ energy loss.





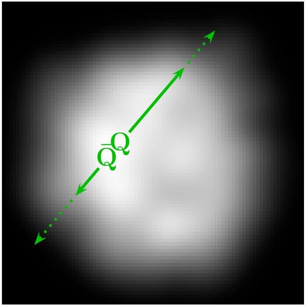


- HF R_{AA} and v_2, are very similar to the light hadron R_{AA} and v_2.
- Motivation: go beyond these observables and study their relation to the bulk event!

ALICE NPA904-905 (2013); PRL **111** (2013); STAR (2014)

Modeling of **heavy-quark dynamics** in the QGP

production interaction with the medium hadronization



- LO pQCD $\Rightarrow$ back-to-back initialization, no information about the azimuthal $Q\bar{Q}$ correlations $\rightarrow$ including resummation of logs: FONLL $\rightarrow$ inclusive spectra

  M. Cacciari et al. PRL**95** (2005), JHEP **1210** (2012)

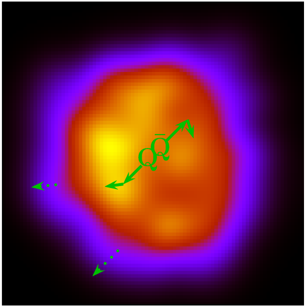
- NLO pQCD matrix elements plus parton shower, e.g. POWHEG or MC@NLO $\Rightarrow$ exclusive spectra, like $Q\bar{Q}$ correlations

  S. Frixione et al. JHEP **0206** (2002), JHEP **0308** (2003)

- Cold nuclear matter effects

Modeling of **heavy-quark dynamics** in the QGP

production | **interaction with the medium** | hadronization

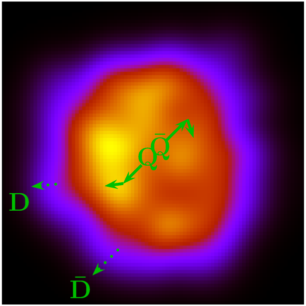


- Collisional (elastic) cross sections $\Rightarrow$ $\Delta E \sim \log(E) L$
- Incoherent radiation (BH regime) $\Rightarrow$ $\Delta E \sim EL/\lambda_{\mathrm{mfp}}$
- Coherent radiation (BDMPS-Z regime) $\Rightarrow$ $\Delta E \sim \sqrt{E} L$
- Dead cone effect reduces radiative eloss for heavy quarks.
- For very energetic partons (fact. regime) $\Rightarrow$ $\Delta E \sim L^2$
- Further radiative effects: finite gluon mass and width

J. D. Bjorken (1982); E. Braaten et al, PRD **44** (1991), PRD **44** (1991); A. Peshier, PRL **97** (2006); S. Peigne et al., PRD **77** (2008) 114017; M. Gyulassy et al, NPB **420** (1994); BDMPS PLB **345** (1995); NPB **483** (1997); ibid. **484** (1997); B. G. Zakharov, JETP Lett. **63** (1996) 952; ibid. **64** (1996) 781; ibid. **65** (1997) 615; ibid. **73** (2001) 49; ibid. **78** (2003) 759; M. Gyulassy et al, PRL **85** (2000); NPB **571** (2000) 197; ibid. **594** (2001); Y. L. Dokshitzer et al., PLB **519** (2001); P. B. Arnold et al., JHEP 0011 (2000), 0305 (2003); N. Armesto et al., PRD **69** (2004); PRCC **72** (2005); B.-W. Zhang et al., PRL **93** (2004); B. Kämpfer et al., PLB **477** (2000); M. Djordjevic et al., PRC **68** (2003) PLB **560** (2003); M. Bluhm et al. PRL **107** (2011)

Modeling of **heavy-quark dynamics** in the QGP

production   interaction with the medium   **hadronization**



- Coalescence – predominantly at small p_T.

  C. B. Dover, U. W. Heinz, E. Schnedermann, J. Zimanyi PRC **44** (1991)

- Fragmentation – predominantly at large p_T.

  M. Cacciari, P. Nason, R. Vogt PRL **95** (2005)

Modeling of heavy-quark dynamics in the **QGP**

production interaction with the medium hadronization

medium description coupling medium - HF sector

- Model the QGP: a locally thermalized medium provides the scattering partners.
- Input from a fluid dynamical description of the bulk QGP medium: temperatures and fluid velocities.
- Consistent coupling of heavy quarks to the fluid.
- Use a fluid dynamical description which describes well the bulk observables!

MC@sHQ + EPOS

MC@sHQ - heavy flavor

- Evolution by the Boltzmann transport equation.
- Elastic cross sections from the pQCD Born approximation with HTL+semi-hard propagators.
- Including a running coupling ⇒ selfconsistently determined Debye mass.
- Radiative energy loss including suppression due to coherent radiation.

coupling

+

consistent

EPOS - light flavor

- 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 velocities.
- Event-by-event fluctuating initial conditions.

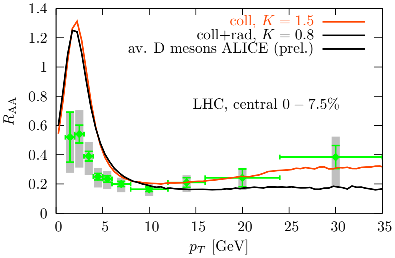
For calibration a global rescaling of the cross sections by a K-factor is required!

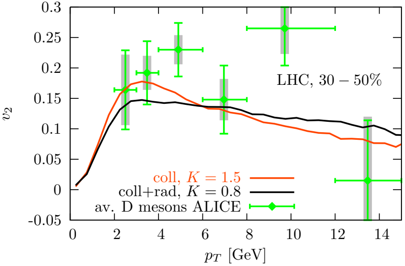
MN, J. Aichelin, P. B. Gossiaux, K. Werner PRC **89** (2014);
K. Werner, I. .Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, PRC **85** (2012)
P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. G **37** (2010); P. B. Gossiaux and J. Aichelin, PRC **78** (2008)

The traditional observables: R_{AA} and v_2 at LHC

Strategy: require a reasonable agreement of the D-meson R_{AA}

$\Rightarrow$ fix the K-factor once and for all!



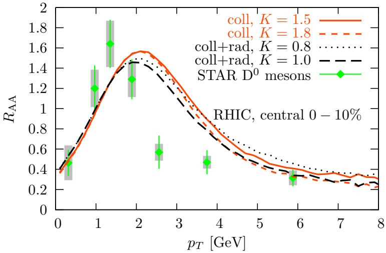


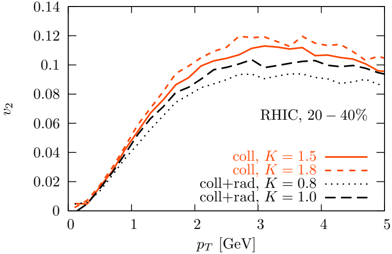
ALICE Nucl. Phys. A904-905 (2013); PRL **111** (2013)

- Reasonable agreement for the R_{AA} for D mesons above $p_T > 5$ GeV.
- At low p_T: sensitive to details of the medium + need to include shadowing.
- The description is slightly better for purely collisional energy loss scenarios!
- Reasonable agreement for the v_2 of D mesons.
- v_2 between $1 - 5$ GeV enhanced by $10 - 20\%$ in purely collisional over **collisional+radiative(+LPM)** energy loss mechanism.

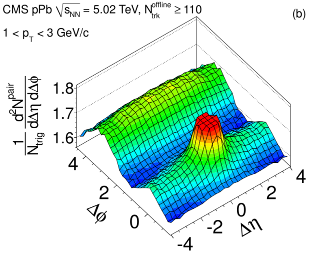
The traditional observables: R_{AA} and v_2 at RHIC

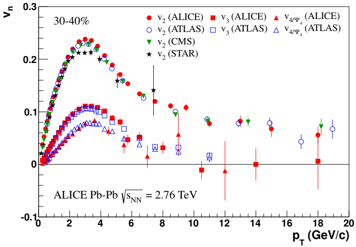
Do we need to adapt the K-factor? $\Rightarrow$ Difficult to say in the current p_T range...



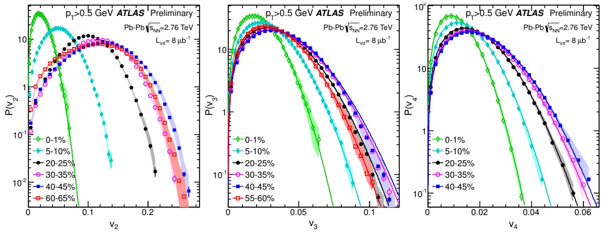


- Probably a reasonable agreement for the R_{AA} for D mesons above $p_T > 5$ GeV.
- Finite D meson v_2 but lower than at the LHC!
- Not possible to distinguish between the energy loss mechanisms with the available data.



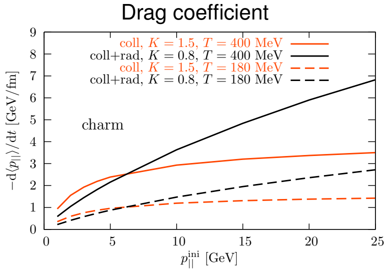


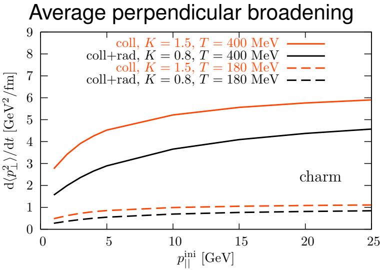
- Correlations in the light hadron sector have revealed astonishing structures $\Rightarrow$ e.g. the ridge!
- Higher flow coefficients of light hadrons have helped to better understand the initial conditions and η / s of the QGP.
- Recent high-precision measurements can study event-by-event v_n distributions!



CMS (2013); ALICE PLB**179** (2013); ATLAS (2013)

Properties of the interaction



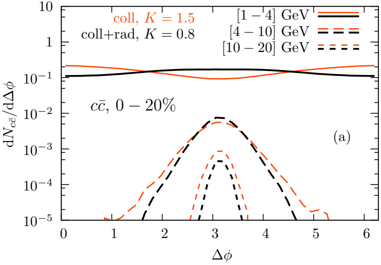


- Clearly different p_T dependence of the drag coefficient, stronger increase for **collisional+radiative(+LPM)** energy loss.
- At low p_T the drag coefficient is larger for collisional energy loss.
- Purely collisional scatterings lead to a larger average $\langle p_\perp^2 \rangle$ than **collisional+radiative(+LPM)**.
- Expectation: initial correlations are broadened more effectively by a purely collisional interaction mechanism.

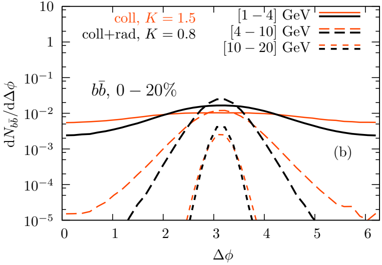
Heavy-quark azimuthal correlations at LHC energies

(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(+LPM)** interaction mechanism
- Variances in the intermediate p_T-range:
  0.22 vs. **0.13** (charm) and 0.3 vs. **0.14** (bottom)
- Initial correlations survive the propagation in the medium at higher p_T.
- At low p_T initial correlations are almost washed out: small residual correlations remain for the **collisional+radiative(+LPM)** mechanism, "partonic wind" effect for a purely collisional scenario.

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

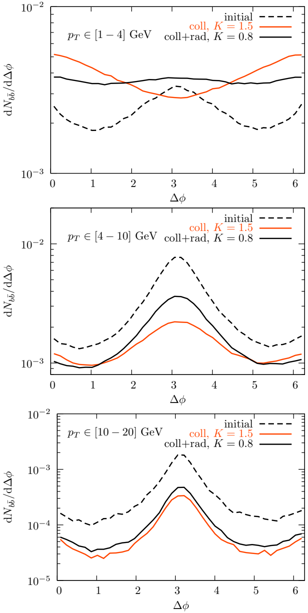
NLO QCD matrix elements coupled to parton shower evolution: MC@NLO+Herwig.

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

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

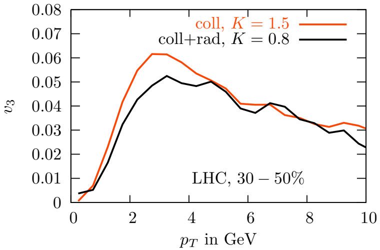
- Higher-order processes lead to an initial broadening around $\Delta\phi \approx \pi$ and an enhancement of the correlations at $\Delta\phi \approx 0$.
- For intermediate p_T: increase of the variances from initial to final by $\sim 20\%$ for the purely collisional mechanism and $\sim 10\%$ for **collisional+radiative(+LPM)**.
- Correlations at large p_T seem to be dominated by the initial correlations.
- Large differences between NLO+parton shower approaches on charm quark production!
- Very important: need a reliable pp reference for $\Delta\phi$ distributions!

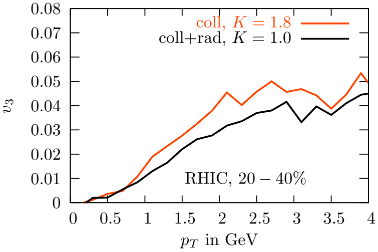
LHC, central $\rightarrow$



The triangular flow at LHC and RHIC

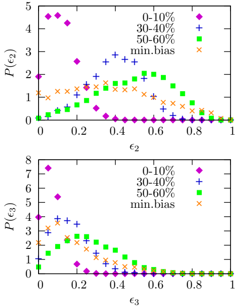
- In the light hadron sector, the higher-order flow coefficients have provided information about the fluid dynamical behavior of the QGP and transport coefficients (viscosity).
- Do heavy quarks show a finite triangular flow? Is it comparable to the light hadron v_3?
- Due to our setup with event-by-event fluctuating initial conditions, we can study the D meson v_3. It is finite!





- $30 - 40\%$ enhancement in collisional over **collisional+radiative(+LPM)** for p_T between 1-3 GeV ($10 - 20\%$ for v_2).

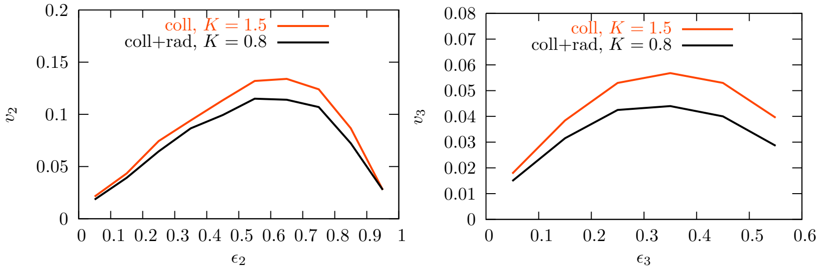
Relation of heavy quark flow to the bulk event



- Bulk flow is driven by the initial elliptic or triangular eccentricity ϵ_2 and ϵ_3

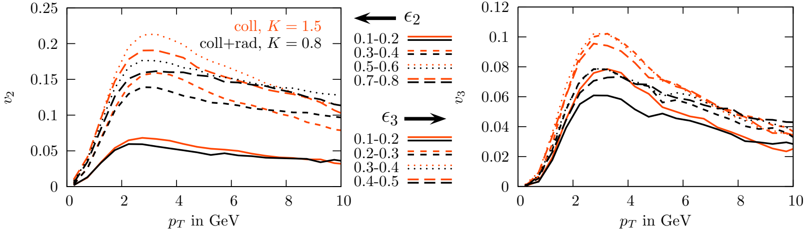
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

- In the light hadron sector the final $v_2 \propto \epsilon_2$ and $v_3 \propto \epsilon_3$, proportionality depends on viscosity.
- v_n distributions have been measured!
- Select events according to the light hadron v_2 and v_3 and look a the D meson v_2 and v_3.



p_T dependence of D meson v_2 and v_3

elliptic flow　　　　　　　　　　triangular flow

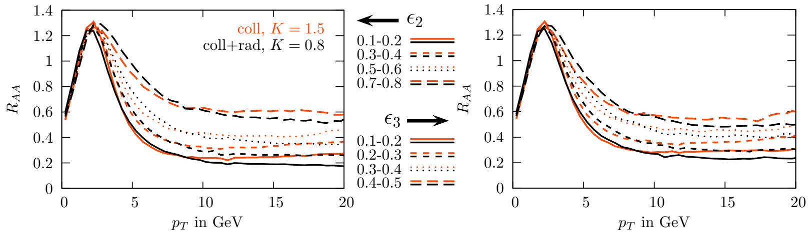


- Events with larger bulk $v_{2,3}$ ($\propto \epsilon_{2,3}$) produce larger D meson $v_{2,3}$ until a maximum is reached.
- At very large $\epsilon_{2,3}$, too little interaction with the medium: D meson $v_{2,3}$ decreases again.

D meson R_{AA} in events with low and high v_2 and v_3

Nuclear modification factor for minimum bias events classified by

ellipticity triangularity

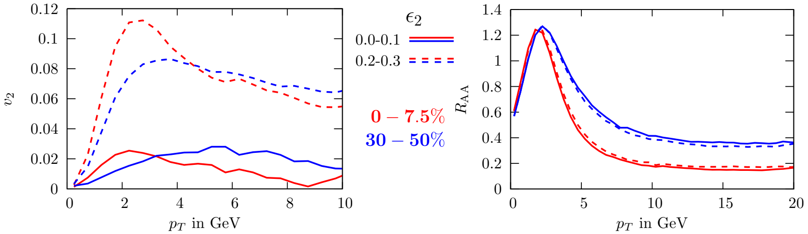


- Events with very small bulk $v_{2,3}$ ($\propto \epsilon_{2,3}$) produce high quenching of D mesons.
- Different way to investigate the centrality dependence of HF R_{AA}!

HF v_2 and R_{AA} in events with low and high v_2

HF observables (**rad+coll, K** $=$ **0.8**) classified by the bulk flow and the centrality:

D meson v_2 D meson R_{AA}



- HF R_{AA} is the very similar for different ϵ_2 in the same centrality class.
- At low p_T central events with a given (moderate) ϵ_2 produce more HF v_2 than midperipheral events with the same ϵ_2 $\Rightarrow$ energy deposition matters!

Conclusion

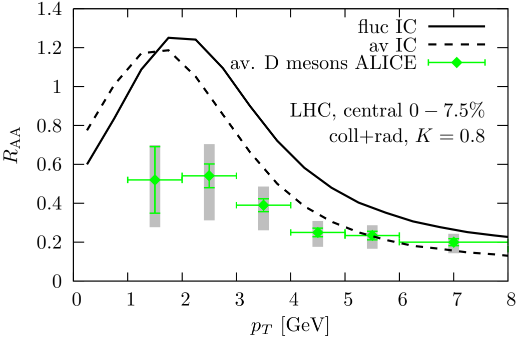
- With the upgrades at STAR (RHIC) and at the experiments at LHC, new promising HF observables become experimentally feasible.
- Azimuthal correlations of HF particles are sensitive to the underlying interaction mechanism: collisional versus **collisional+radiative(+LPM)**.
- MC@sHQ+EPOS yields a finite heavy-flavor v_3, with more relative enhancement for collisional over **collisional+radiative(+LPM)** than found for v_2 (low p_T).
- HF v_2 and v_3 relate to the light hadron v_2 and v_3 of the bulk medium.
- Select events according to properties in the light hadron sector and compare to HF observables!

- Improve on the medium description (viscosity, D-hadron interactions, ...) and the coupling with the upcoming MC@sHQ+EPOS**3**!

backup

Take a closer look at low p_T

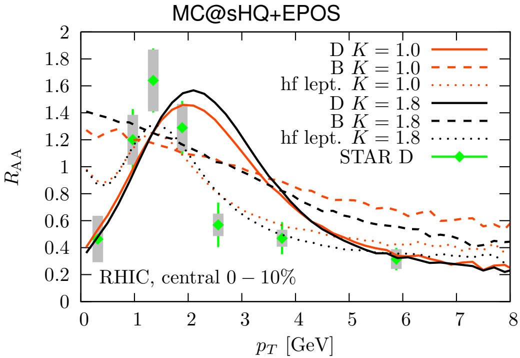
Comparison of fluid dynamics from averaged or fluctuating initial conditions:



- Strong dependence on the details of the description of the QGP in this region!
- Better agreement with averaged initial conditions than with fluctuating event-by-event fluid dynamics (only small difference in v_2).
- Need to include shadowing for smallest p_T.

MN et al. arxiv:1405.0938

D - B - HF lepton $R_{\rm AA}$

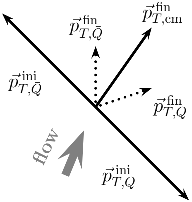


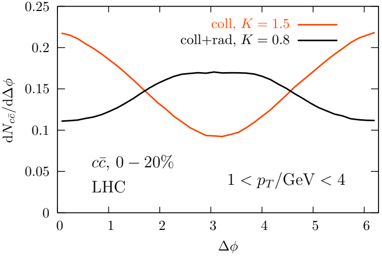
- Measuring D and B meson $R_{\rm AA}$ separately - and as a function of centrality - can help understanding the different energy loss mechanisms, also at RHIC!

“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(+LPM)** interaction mechanism!





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

- Same trend remains: stronger broadening for a purely collisional energy loss mechanism!