Azimuthal correlations between high p_T heavy flavour (jets)

9th International workshop on high p_T Physics at LHC

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with

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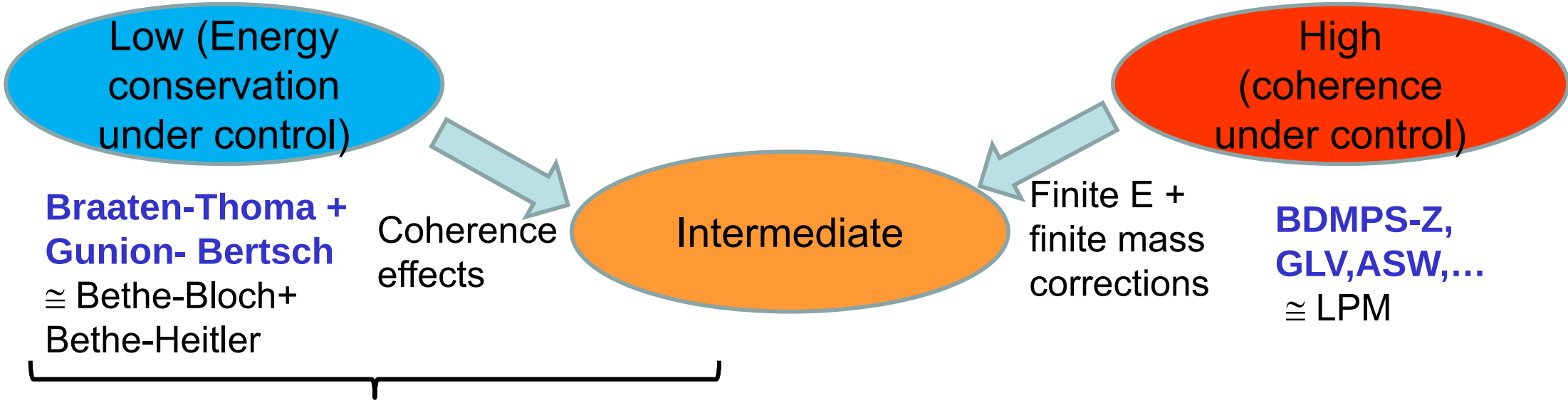
Inspired from arxiv 1305.6544

Motivation and context

- Most of the *interesting* HF observables so far: located at *intermediate* p_T
- Intermediate p_T: hope that pQCD (or pQCD inspired models) apply (as compared to low p_T)
- Intermediate pT: mass effect still present and thus hope to learn something more as compared to large p_T



Approach pursued in our **models…** Unfortunately too many of them

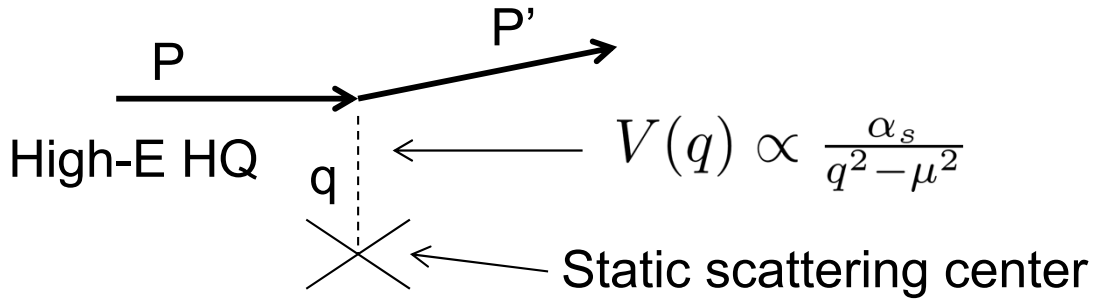
=>Need for falsification (more observables; lQCD): Azimuthal correlations ?

Insufficient control on energy loss theory in QCD

Basic ingredient in the derivation of QED collisional Eloss; transvese force

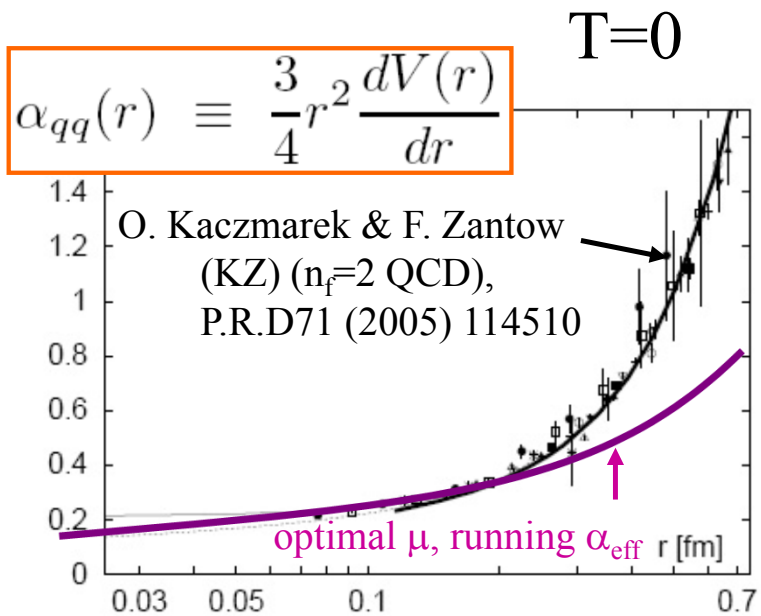
In QCD: non perturbative « corrections » even at large HQ energy

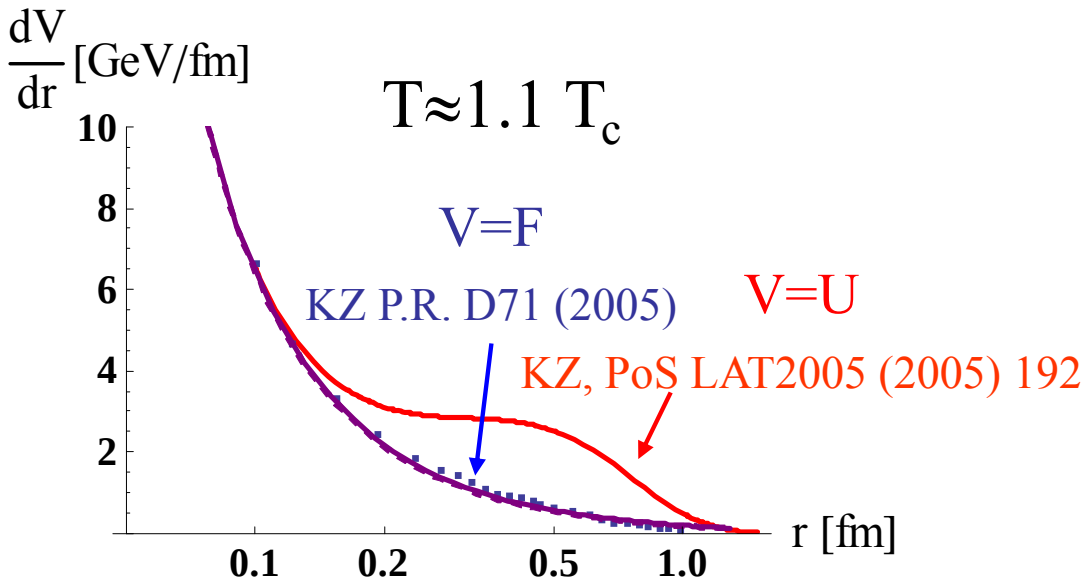
In most models:



Lattice QCD :

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





Significant r-tail in the transverse force acting on the high E HQ

Our basic ingredients for HQ energy loss

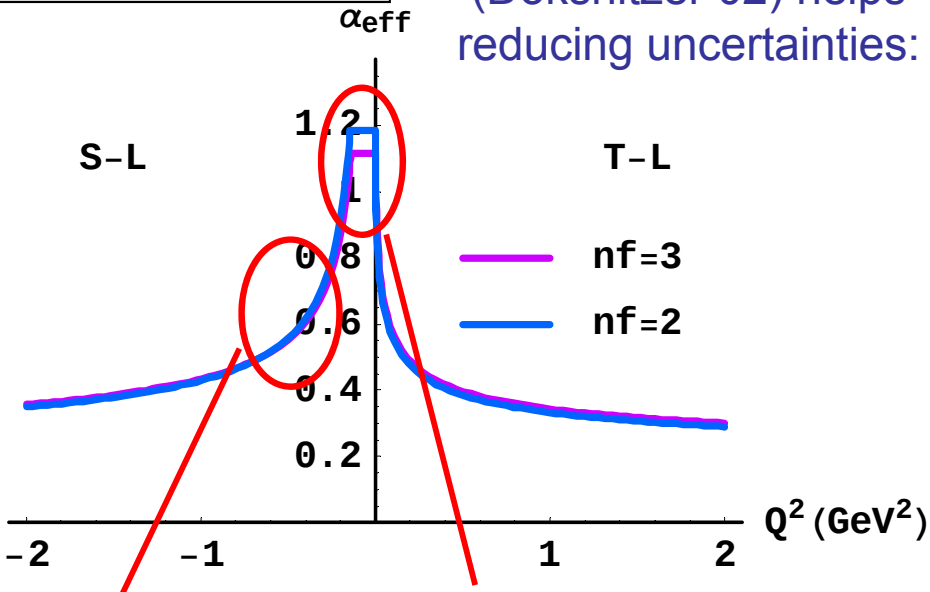
Elastic

Motivation: Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant has been "forgotten/neglected" in most of approaches

Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)

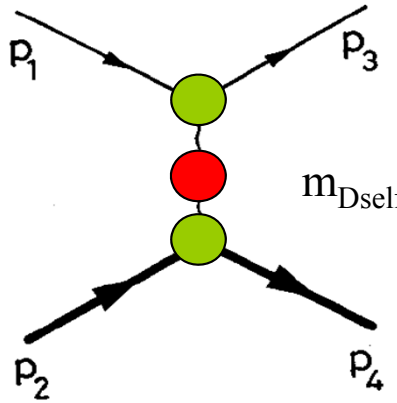
$$\frac{1}{Q_u}\int_{|Q^2|\le Q_u^2} dQ\alpha_s(Q^2) \approx 0.5$$

"Universality constrain" (Dokshitzer 02) helps reducing uncertainties:



IR safe. Q^2 close to 0 does not contribute to Eloss

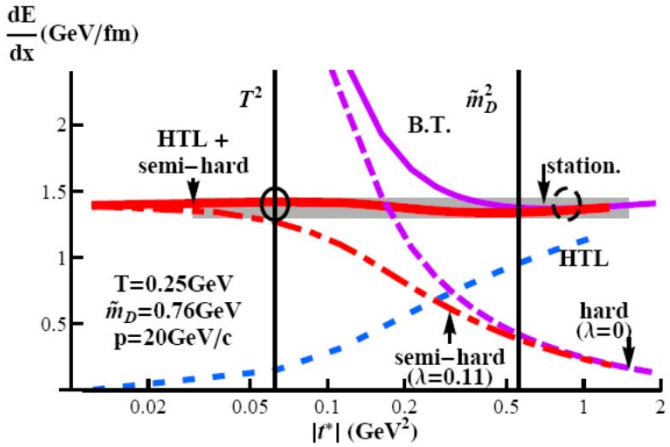
Large values for intermediate momentum-transfer => larger cross section



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

+ u and s channels

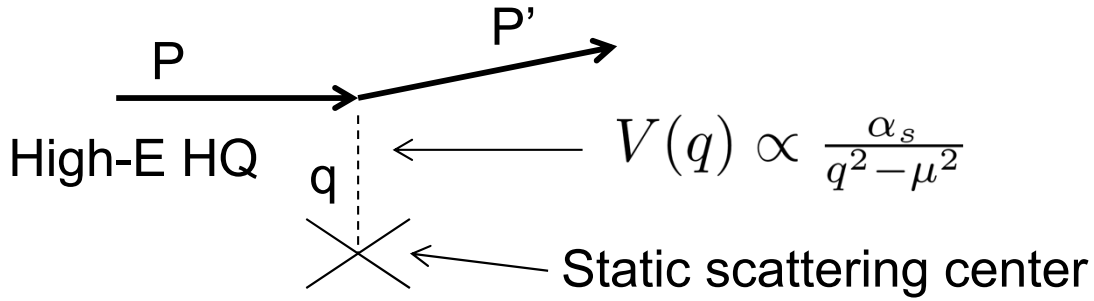
One gluon exchange effective propagator, designed in order to guarantee maximal insensitivity of dE/dx in Braaten-Thomas scheme



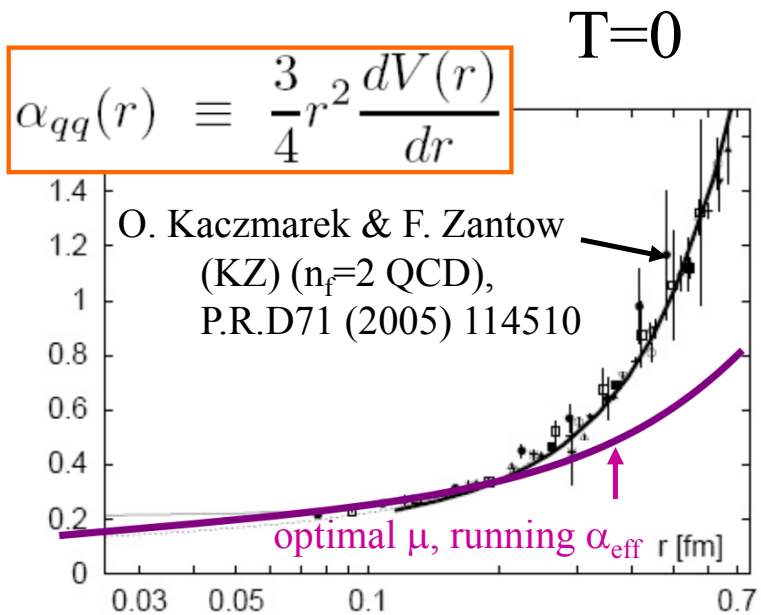
Insufficient control on energy loss theory

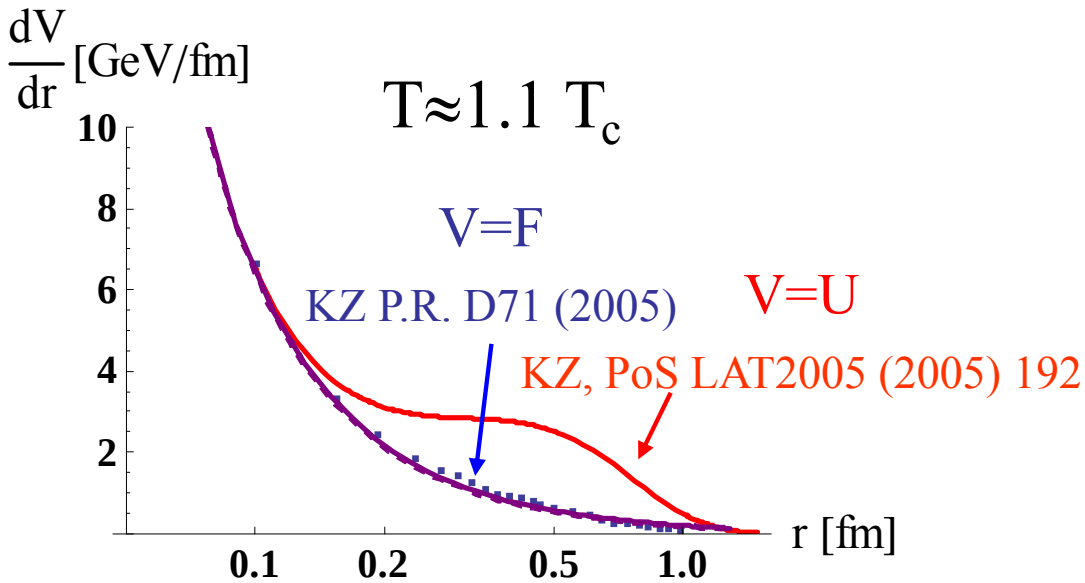
Non perturbative « corrections » even at large HQ energy

In most models:



Lattice QCD :





Our force is close to the one extracted from the free energy as a potential

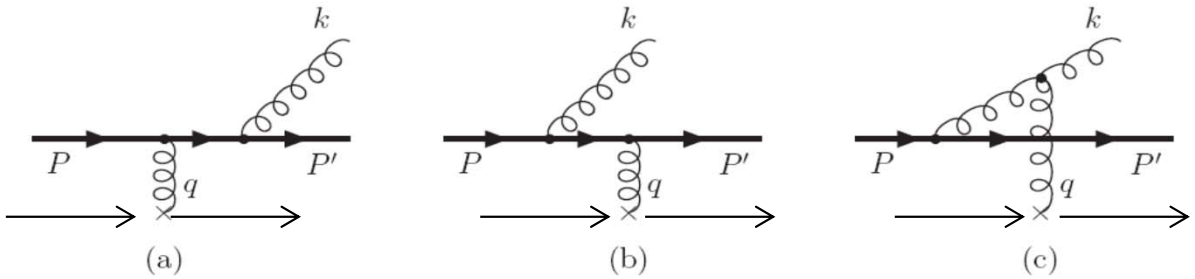
=> Allow for some global rescaling of the rates: "K" fixed on experiment

Our basic ingredients for HQ energy loss

Incoherent Induced Radiative

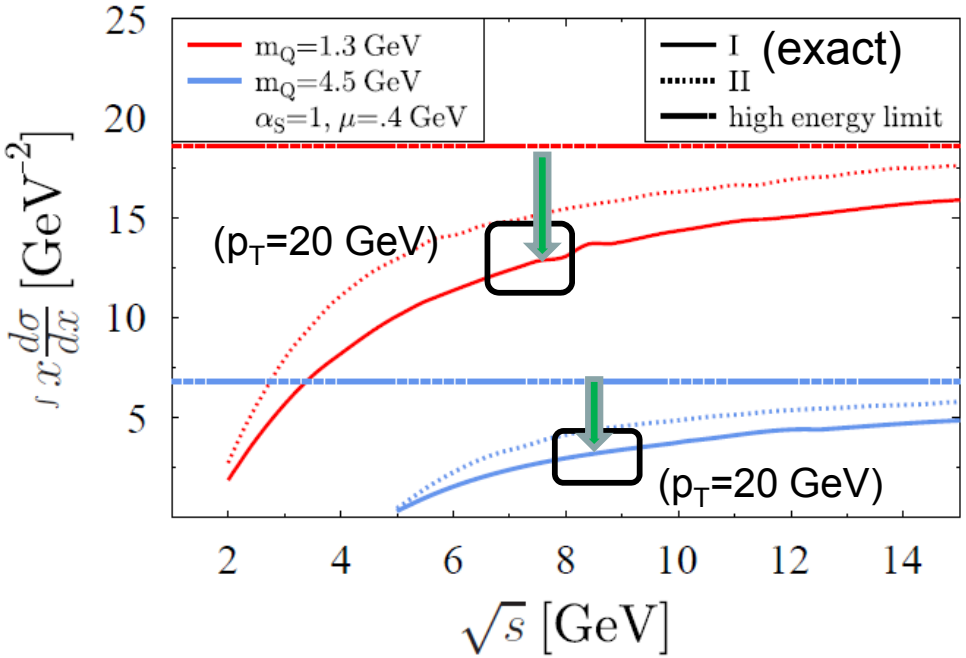
Generalized Gunion-Bertsch for finite mass, finite energy and dynamical light partons

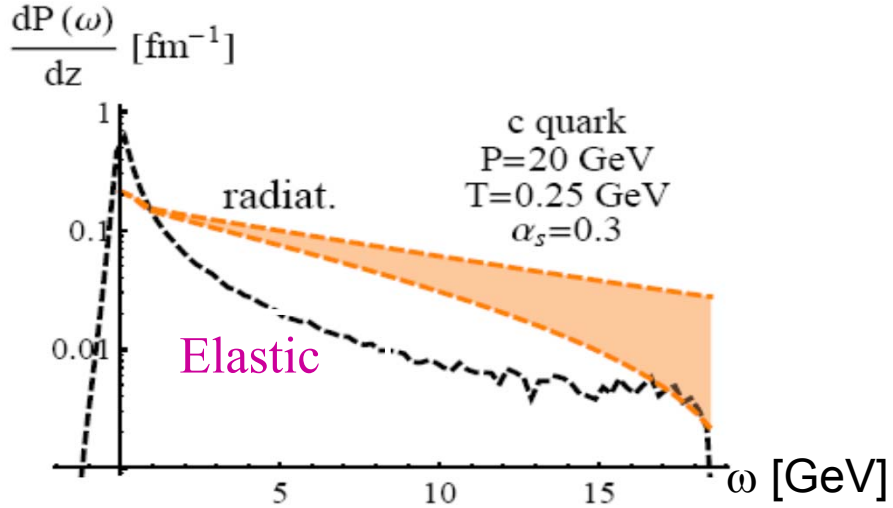
arxiv 1307.5270



$$\omega \frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega d^2k_\perp dq_\perp^2} = \frac{N_c\alpha_s}{\pi^2}(1-x)\times\frac{J^2_{\rm QCD}}{\omega^2}\times\boxed{\frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}}$$

$$\frac{J^2_{\rm QCD}}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2+x^2M^2+(1-x)m_g^2} - \frac{\vec{k}_\perp-\vec{q}_\perp}{\left(\vec{k}_\perp-\vec{q}_\perp\right)^2+x^2M^2+(1-x)m_g^2}\right)^2$$





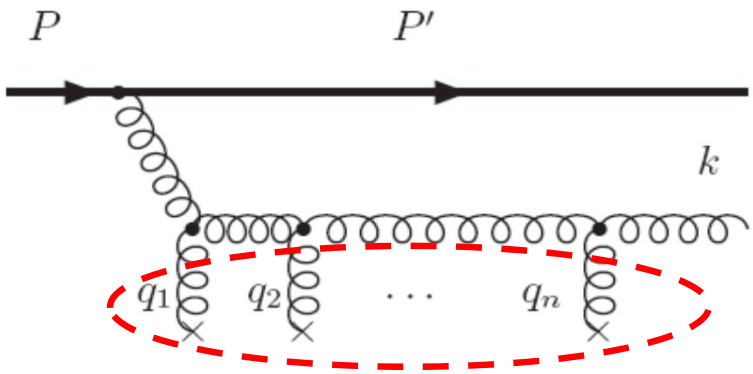
Finite energy lead to strong reduction of the radiative energy loss at intermediate p_T

differential energy loss ω per unit length (T,M,…): big differences between the 2 contributions

Our basic ingredients for HQ energy loss

Coherent Induced Radiative

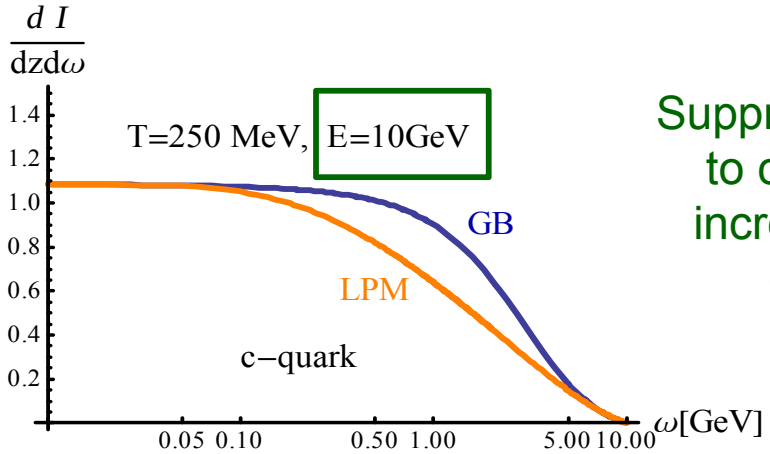
Formation time picture: for $l_{f,mult}>\lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



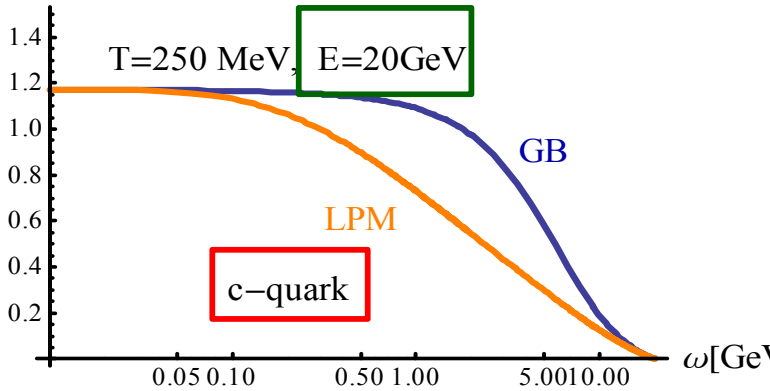
Model: all N_{coh} scatterers act as a single effective one with probability $p_{Ncoh}(Q_\perp)$ obtained by convoluting individual probability of kicks

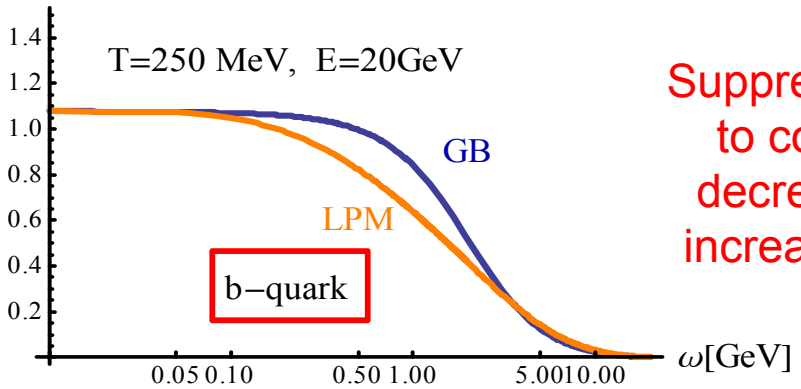
$$\frac{d^2 I_{\rm eff}}{dz\, d\omega} \sim \frac{\alpha_s}{N_{\rm coh}\tilde{\lambda}} \ln\left(1 + \frac{N_{\rm coh}\mu^2}{3\left(m_g^2 + x^2 M^2 + \sqrt{\omega \hat{q}}\right)}\right)$$

[arXiv:1209.0844] (Hard Probes 2012)



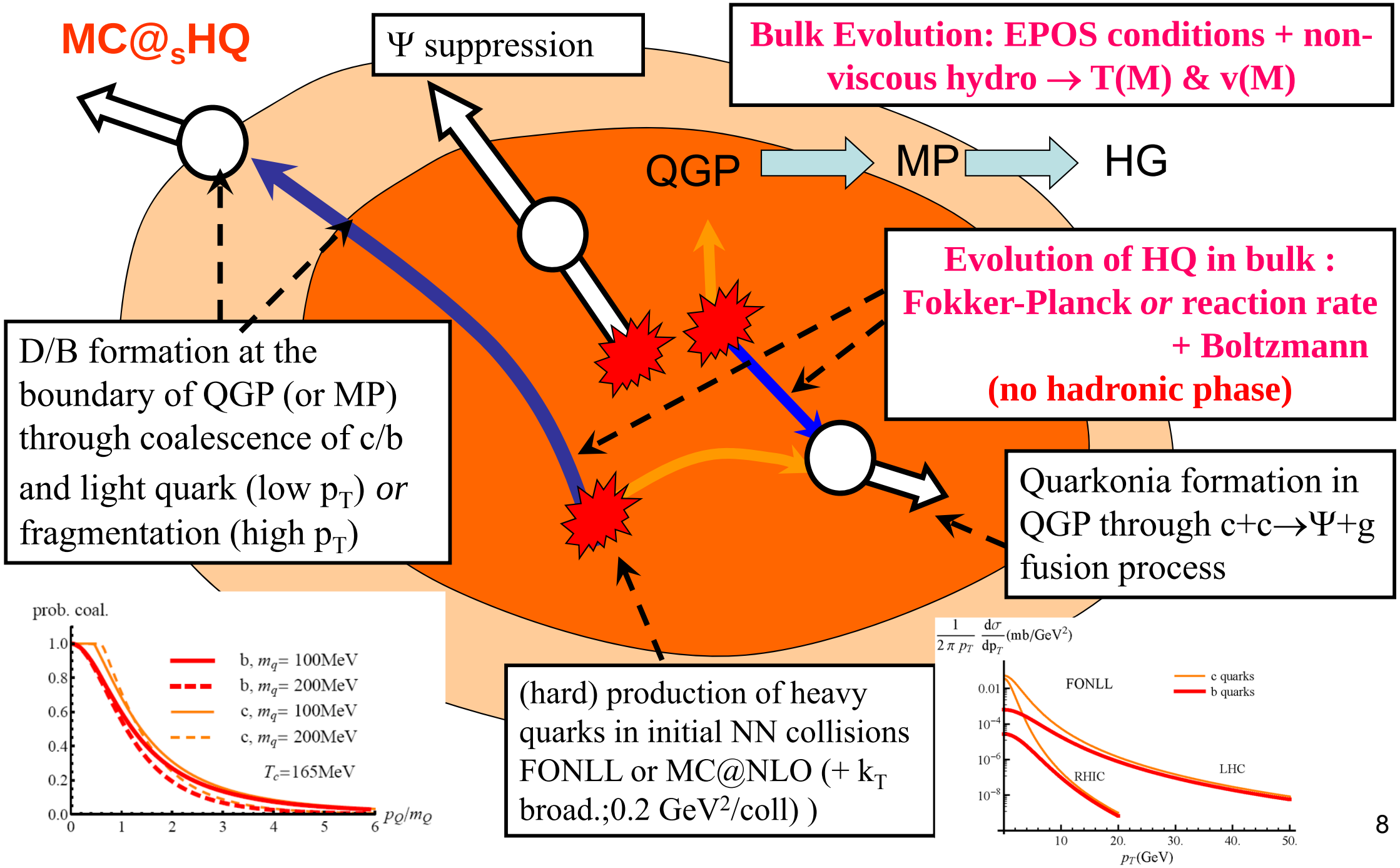
Suppression due to coherence increases with energy





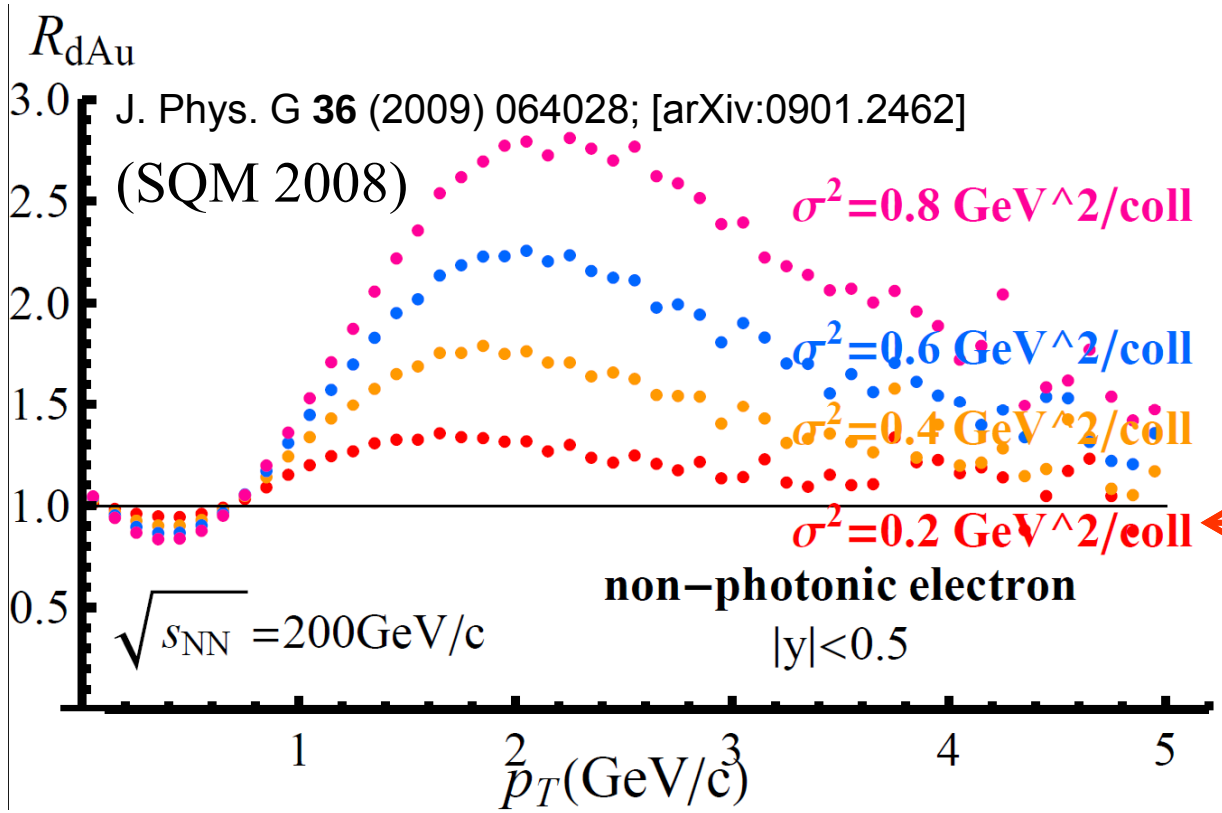
Suppression due to coherence decreases with increasing mass

Schematic view of « Monte Carlo @ Heavy Quark » generator



A Lucky guess for the CNM effects ?

Inserting a phenomenological k_T broadening between HQ FONLL production and fragmentation:

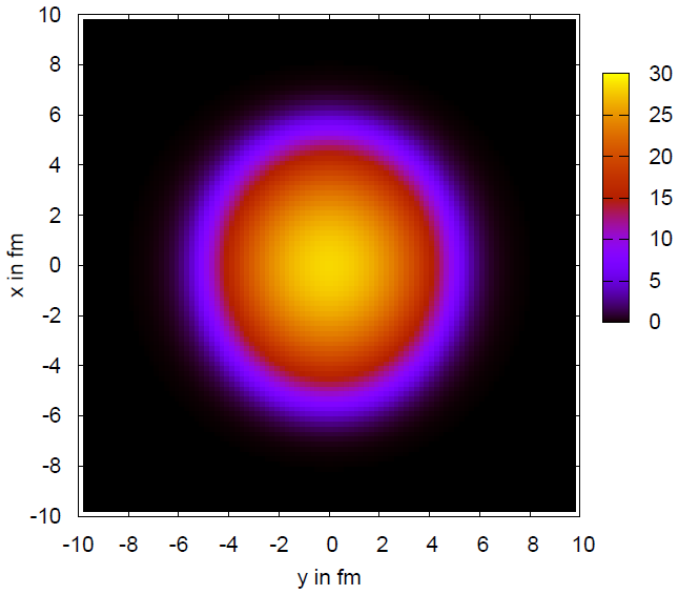


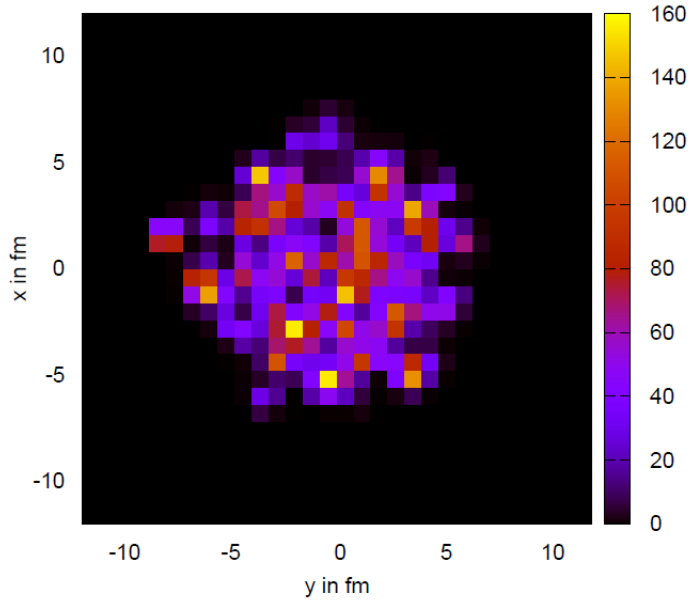
Selected values; good agreement with recent RHIC measurement

EPOS as a background for MC@sHQ

EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density @ RHIC (central Au-Au)





Beware: ≠ color scales

Kolb Heinz (used previously)

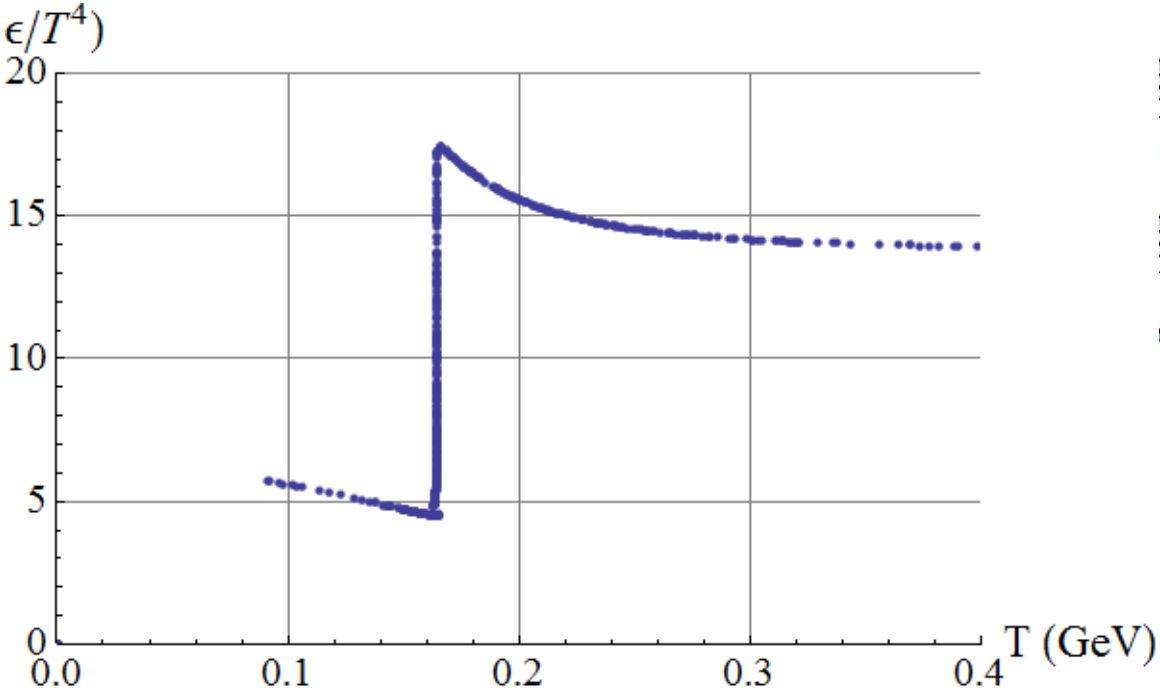
EPOS

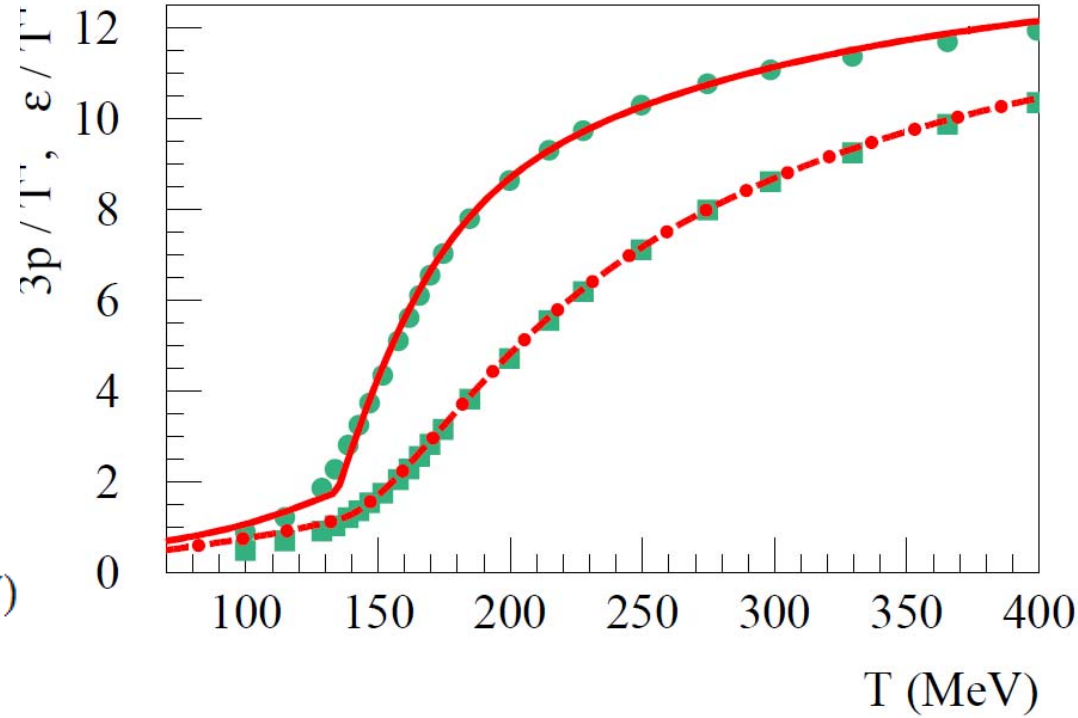
More realistic hydro and initial conditions => original HQ studies such as:

1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)

2) correlations between HF and light hadrons

Large differences in the EOS !

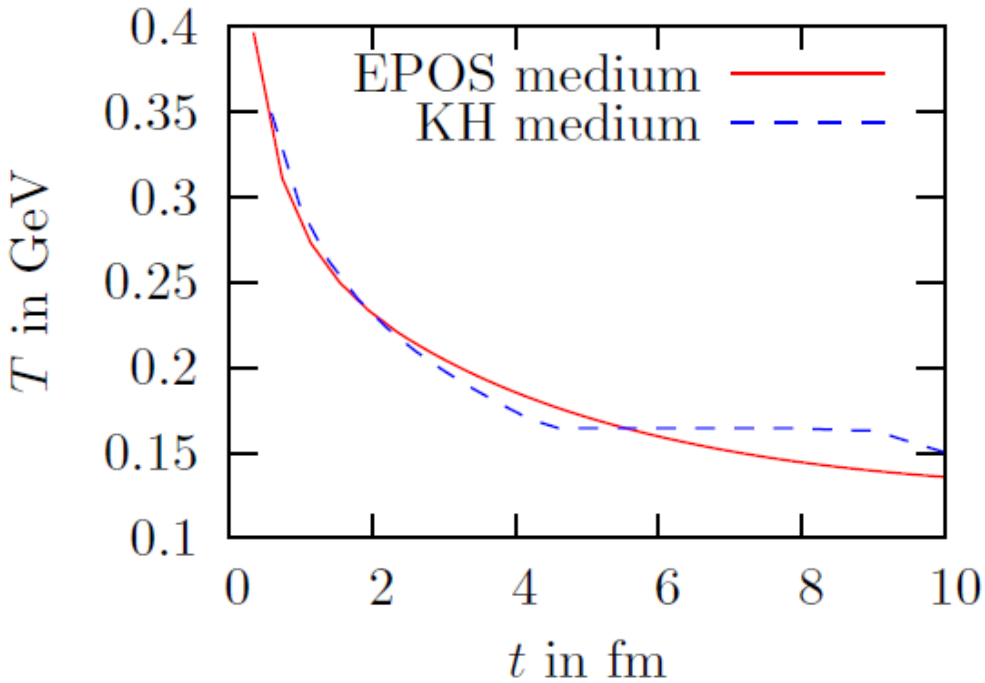


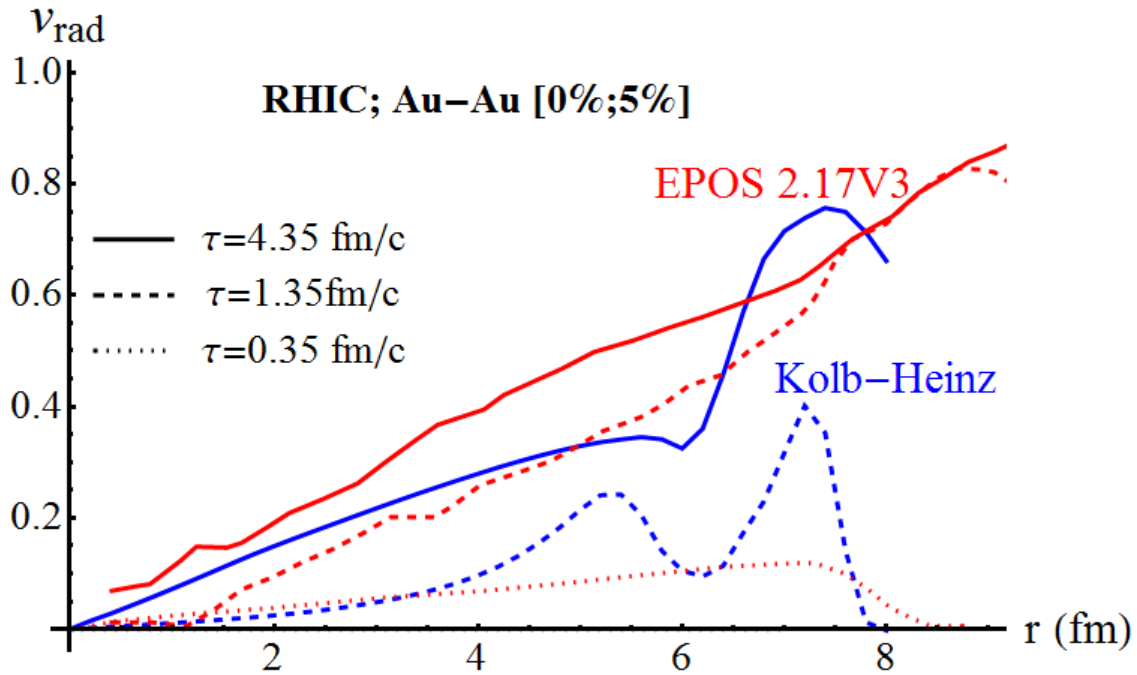


Kolb Heinz: bag model (1rst order transition btwn hadronic phase and massless partons)

EPOS2: fitted on the lattice data from the Wuppertal-Budapest collaboration

Medium comparison at RHIC

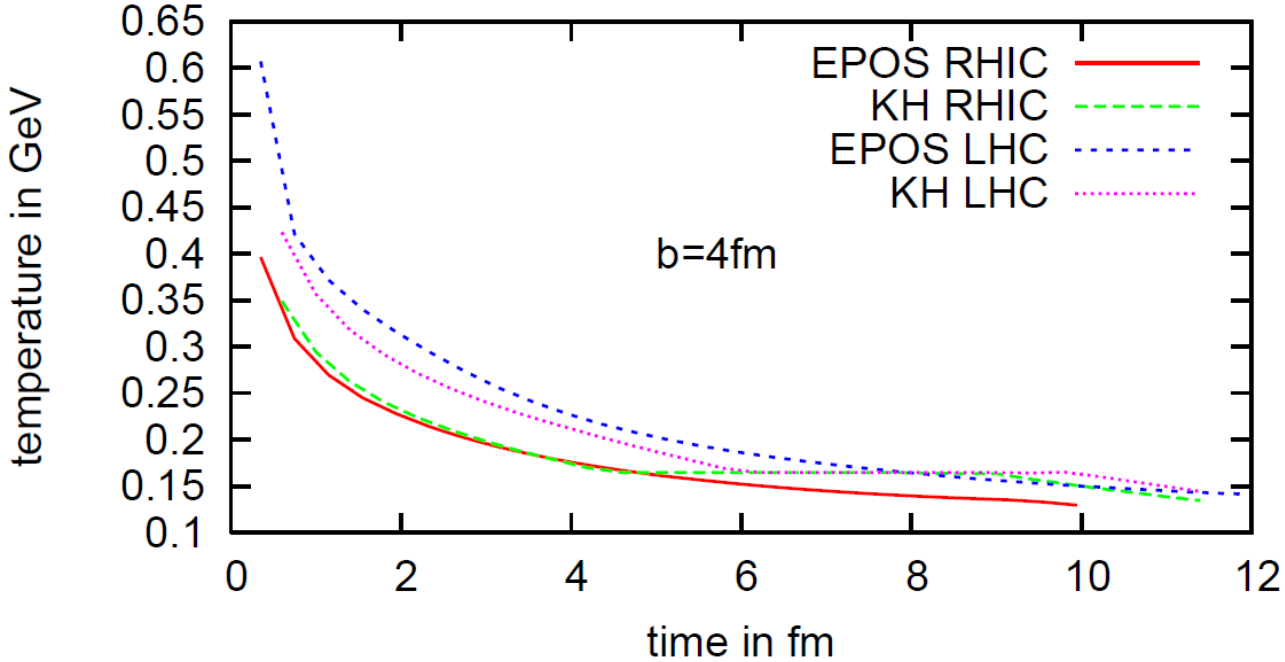


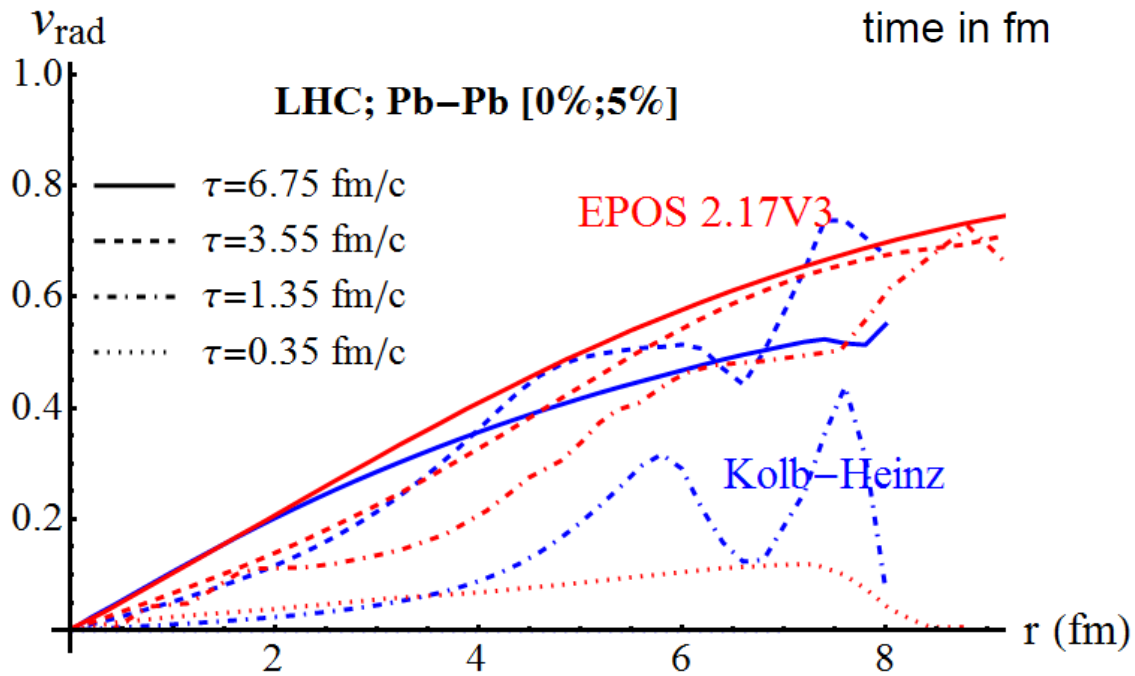


Gross features of T-evolution are identical in the « plasma » phase (T>200 MeV)

Radial velocities differ significantly, starting from the earliest times in the evolution

Medium comparison at LHC



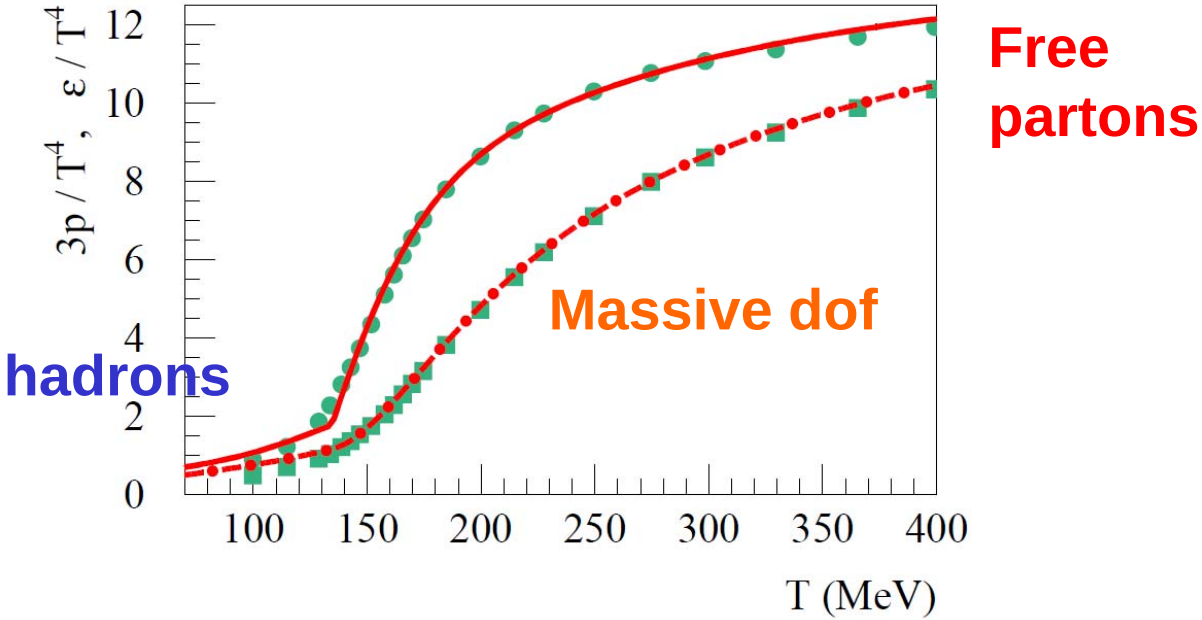


EPOS2 hotter and more explosive than Kolb-Heinz !

Coupling EPOS and MC@$_s$HQ

Two main (physical) issues:

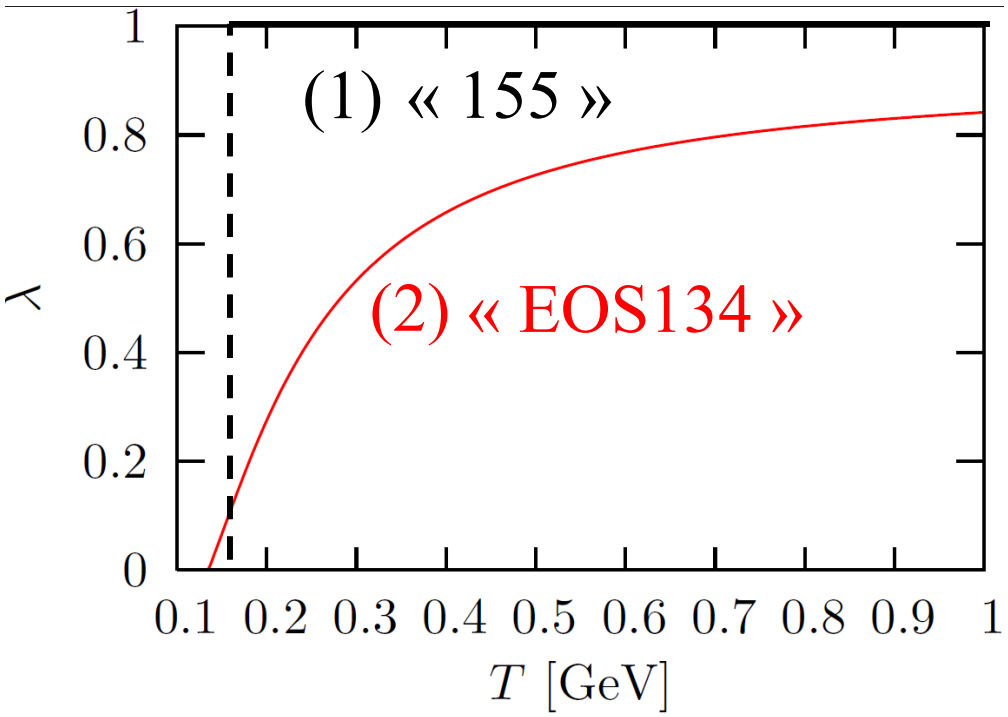
1) Generating initial HQ consistently with the multipartonic approach in EPOS (ongoing project)
2) Dealing properly with the underlying degrees of freedom in a crossover evolution between hadronic phase and QGP.



Coupling EPOS and MC@$_s$HQ

For the time, 2 prescriptions:

1) Interactions as in KH medium (evaluated with masless partons) down to Tc=155MeV (in the bulk of the range for the transition temperatures given from lattice)… most conservative
2) Reduction of effective dof (1->λ) using the EPOS parametrization of the EOS in terms of partonic and hadronic dofs… down to Tc=134MeV (value at which λ=0)

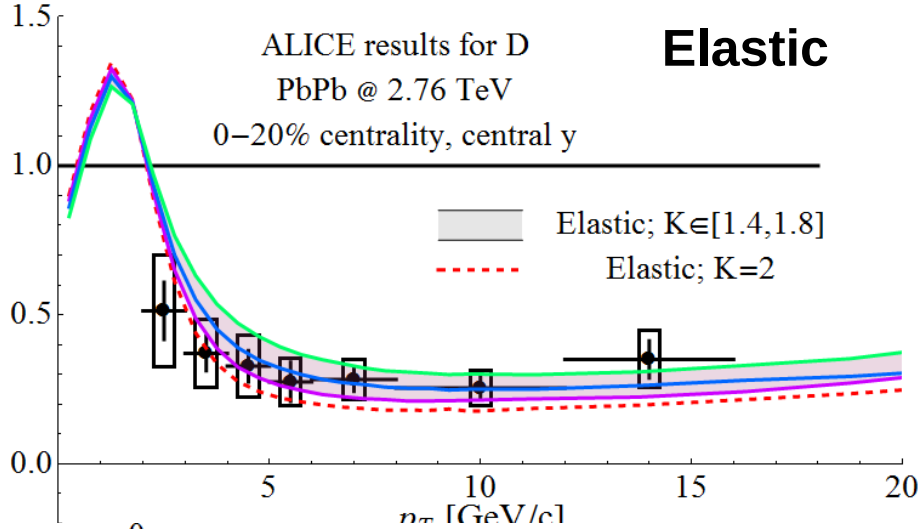


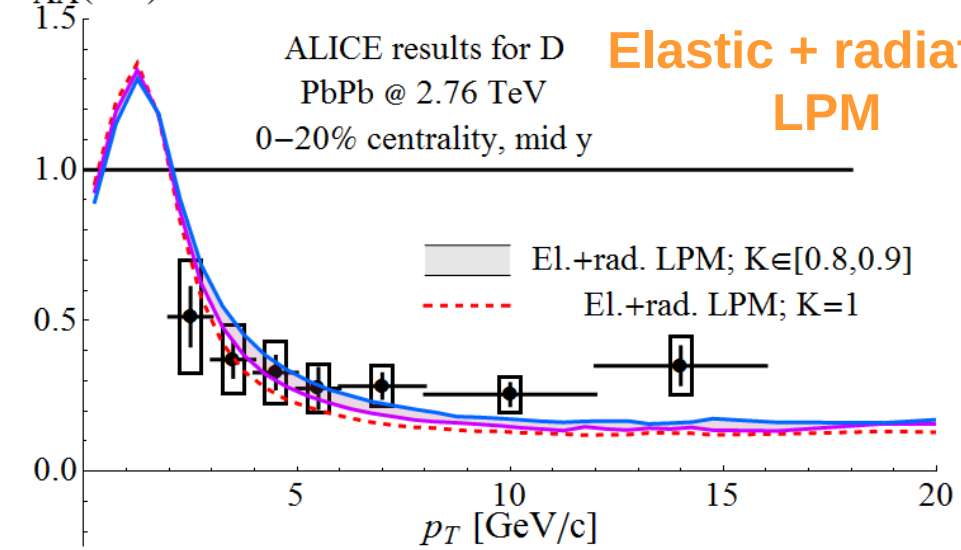
Some EPOS+MC@$_s$HQ results at LHC

NO SHADOWING (yet)

Kolb-Heinz Hydro (dN_{ch}/dy = 1600)

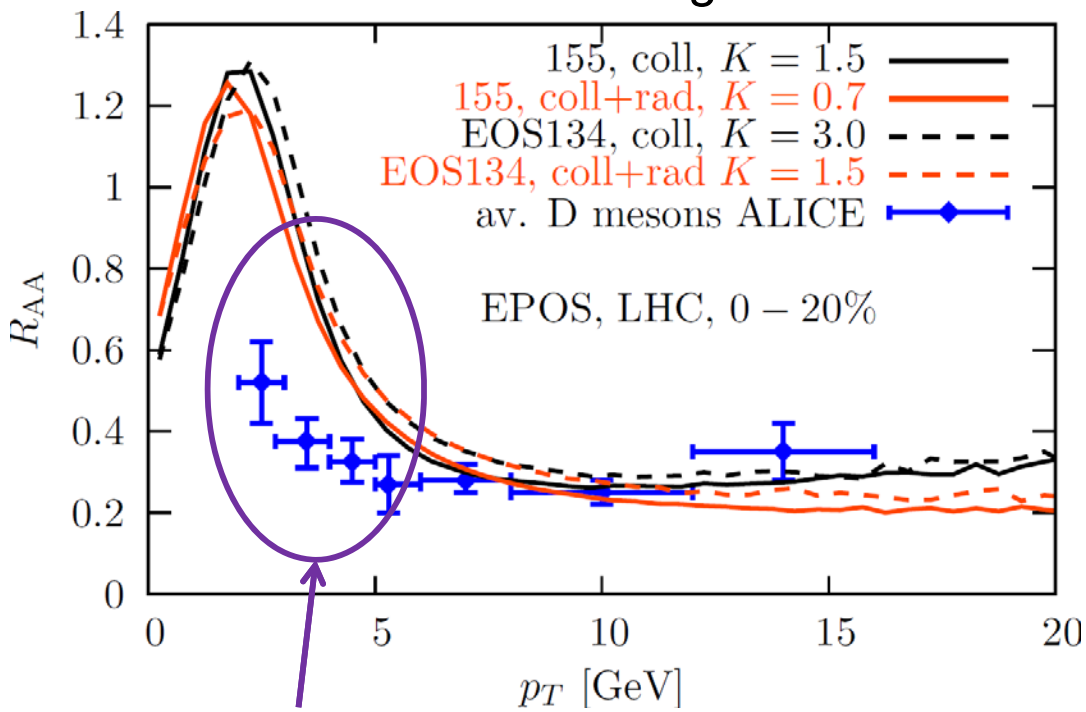
K close to unity if rad + col considered





EPOS background

K values fixed at p_T=10 GeV/c, x2 if reduction of dof according to EOS134 !



Large push from radial flow; discrepancy unlikely to be explained by shadowing alone.

Concern: Need to revisit the model for small p ?

Some EPOS+MC@$_s$HQ results at LHC

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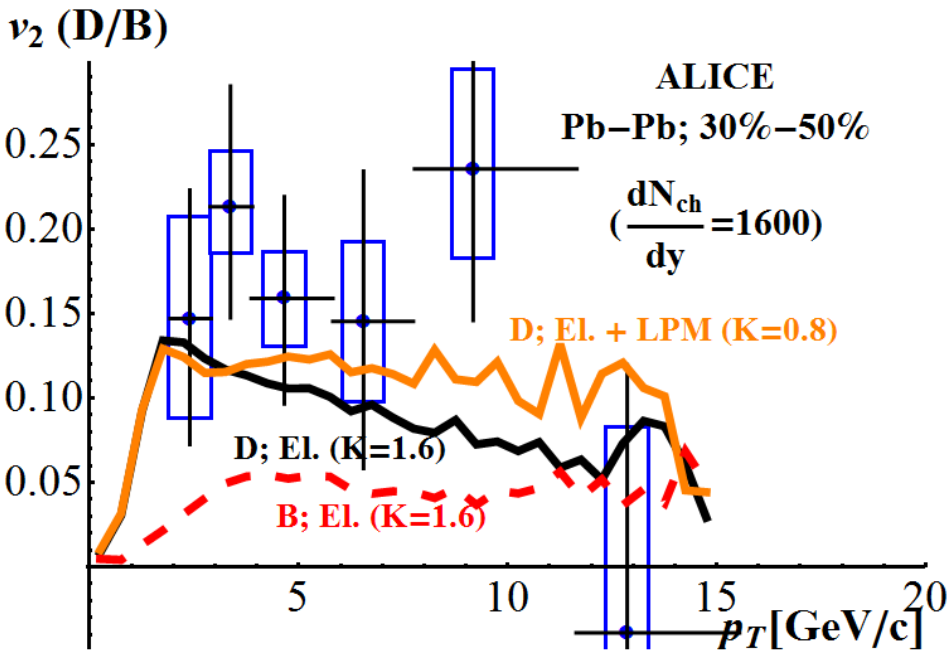

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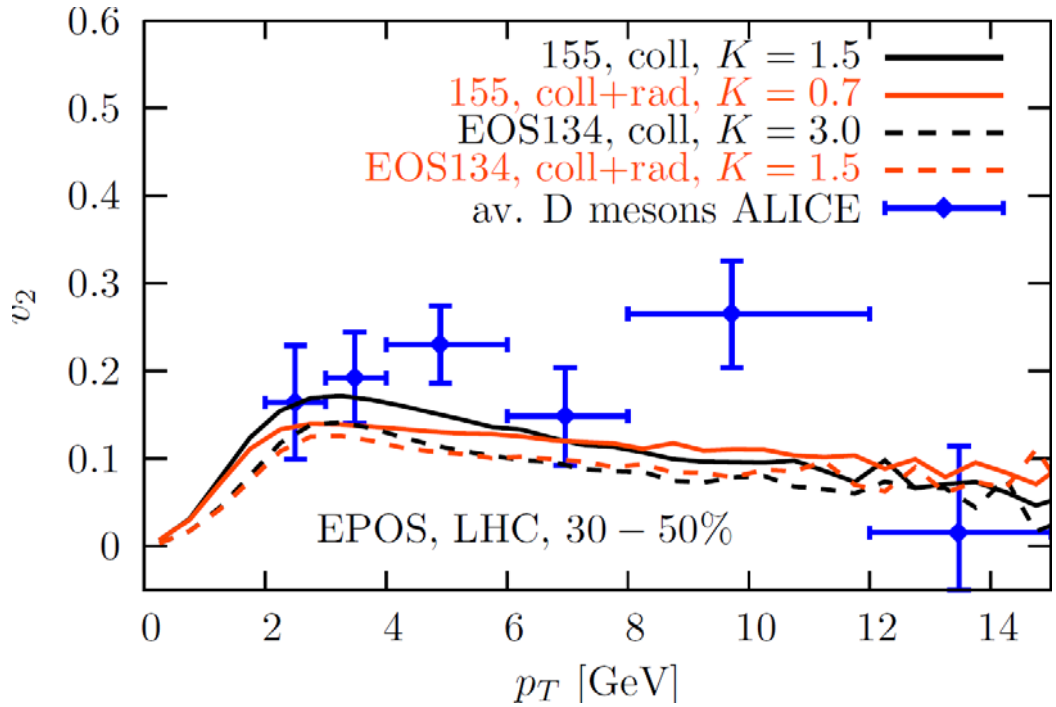
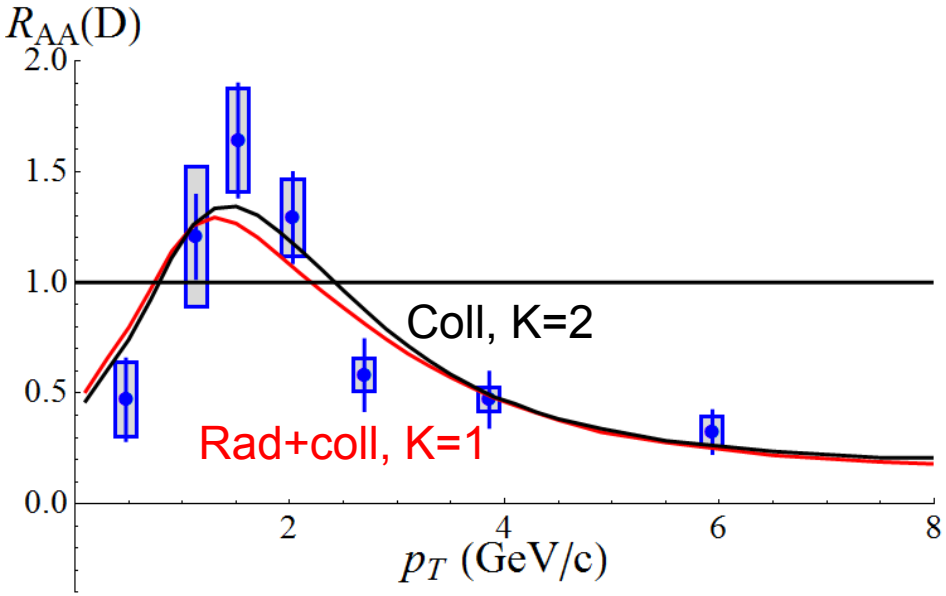


Concerns: Need to revisit the model for small p ?... (Bad) consequences for v2 ?

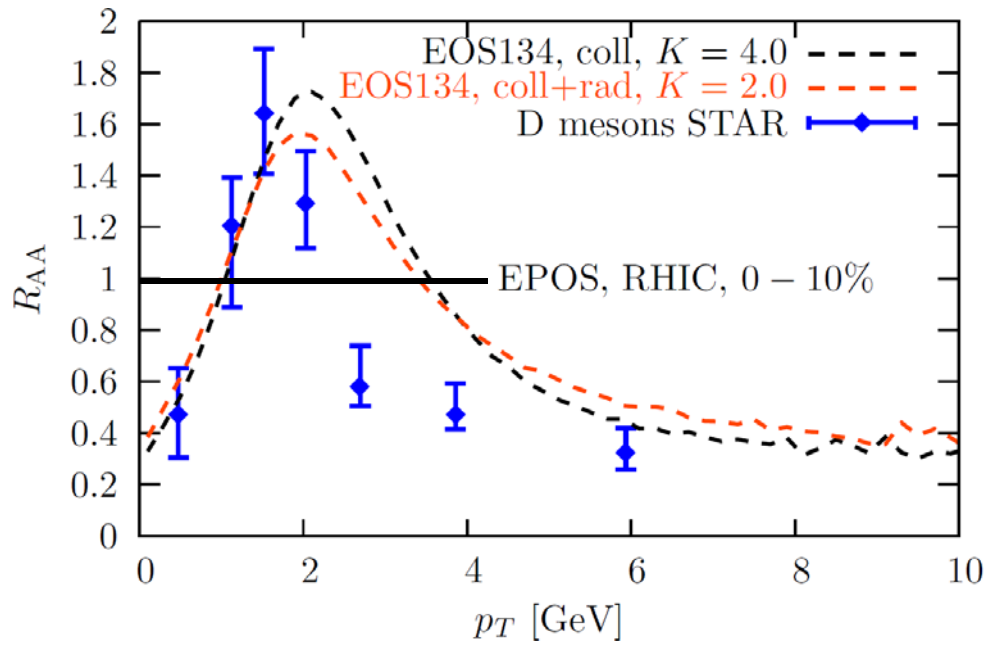
Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together

Some EPOS+MC@$_s$HQ results at RHIC

KH background



EPOS background + reduction of dof



Slightly larger radial flow in EPOS

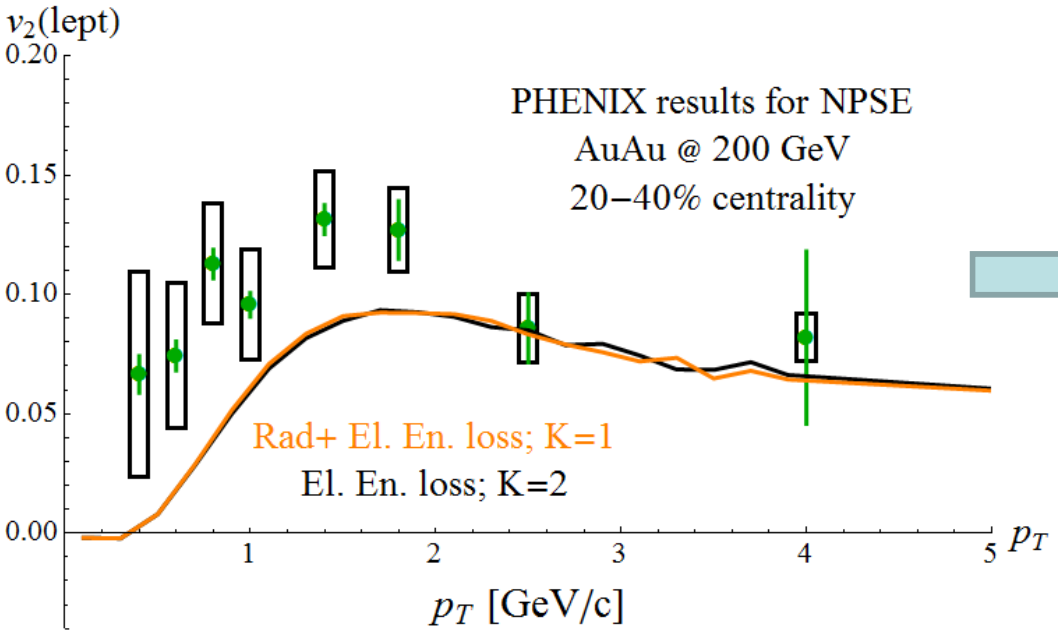
Both « cocktails » (HF energy loss + background + K factor) provide a fair agreement with the data

Data at larger p_T would help a lot !

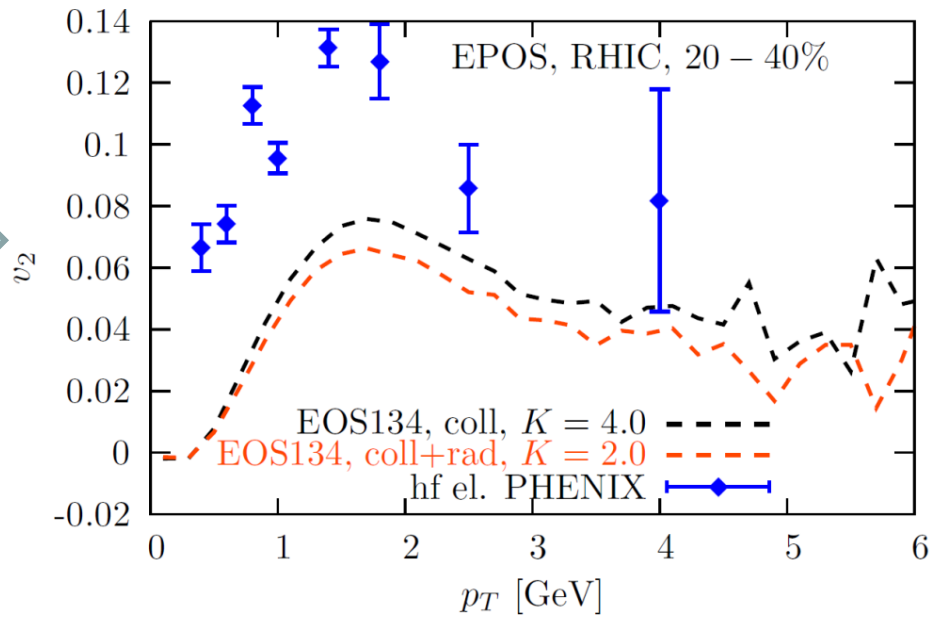
Main message: the models of HF energy loss and the background medium (including its microscopic content) are bound together

Some EPOS+MC@$_s$HQ results at RHIC

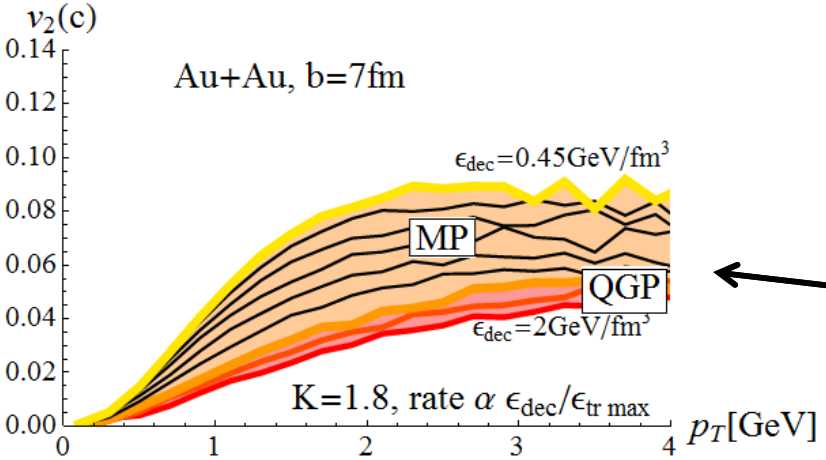
KH background



EPOS background + reduction of dof



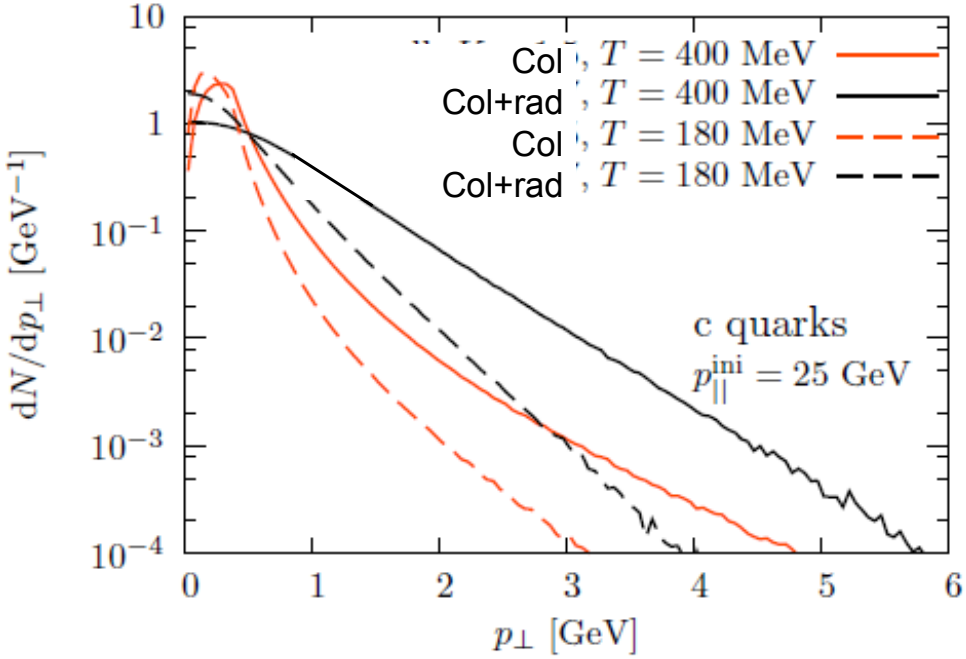
Elliptic flow is reduced by ≈1%



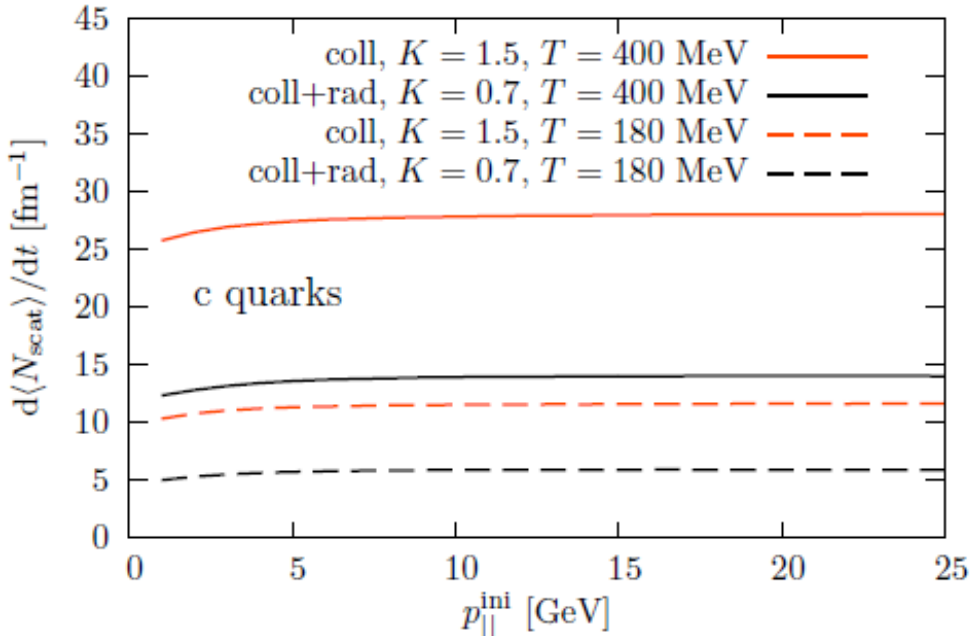
Systematic underprediction of v_2, … which develops continuously in time. Probably need for hadronic afterburner in order to reach experimental values.

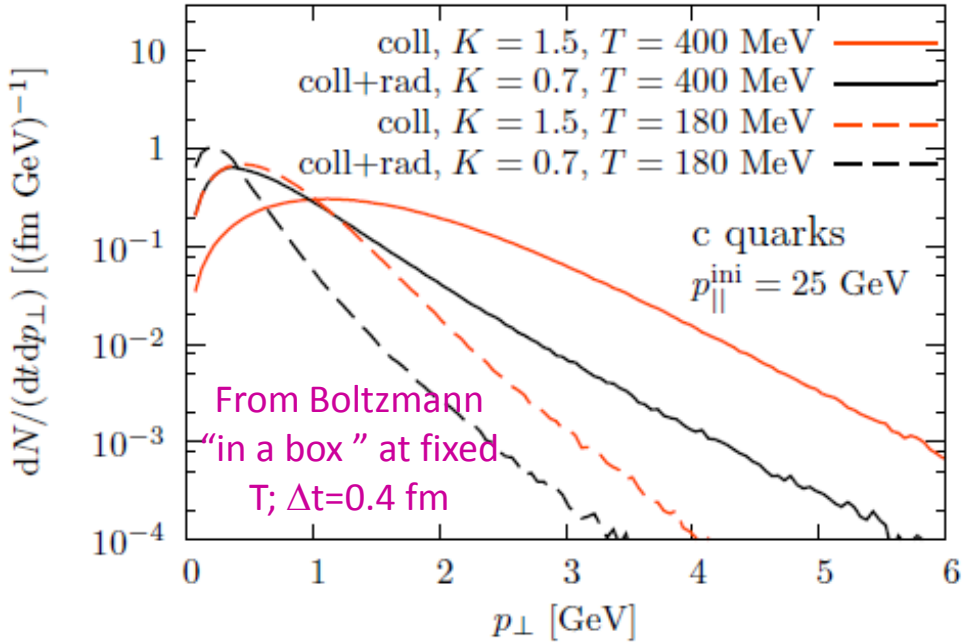
Properties of the interactions

Single scattering:



Evolution in a medium:

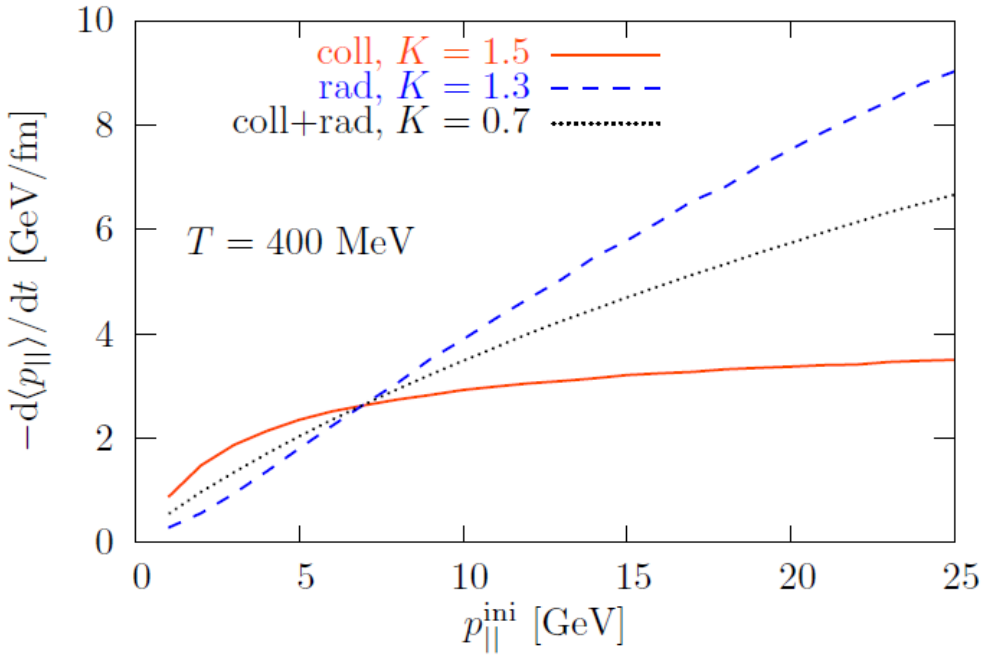




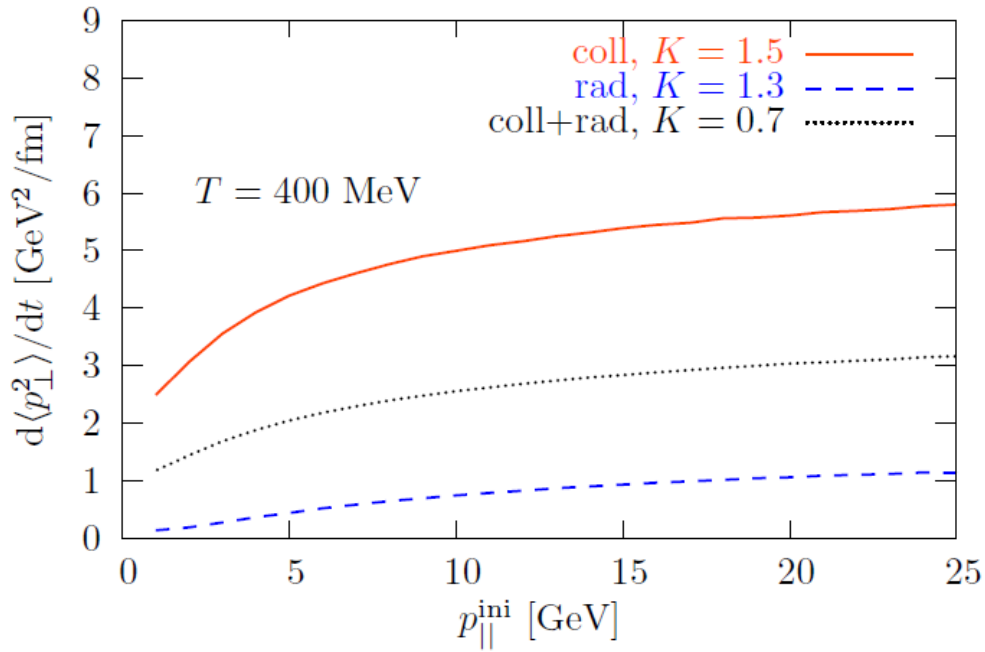
- p_T-distribution in a single scattering: larger $\langle p_T \rangle$ for coll+rad than for col alone
- Scattering rates are much larger for coll (K=1.5)
- Differential broadening per unit time: larger for coll (K=1.5)
- Similar trends for b-quarks

Properties of the interactions

Drag force

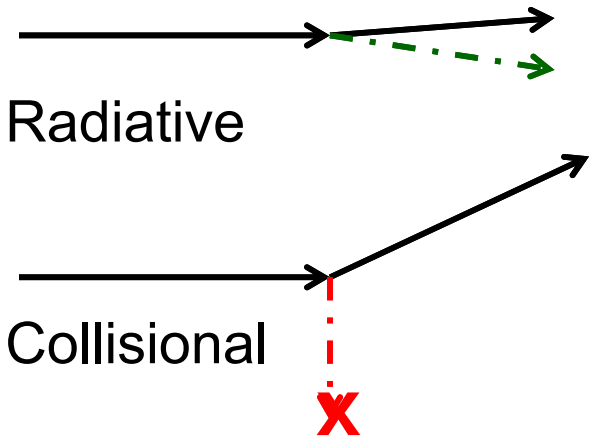


Average perpendicular broadening

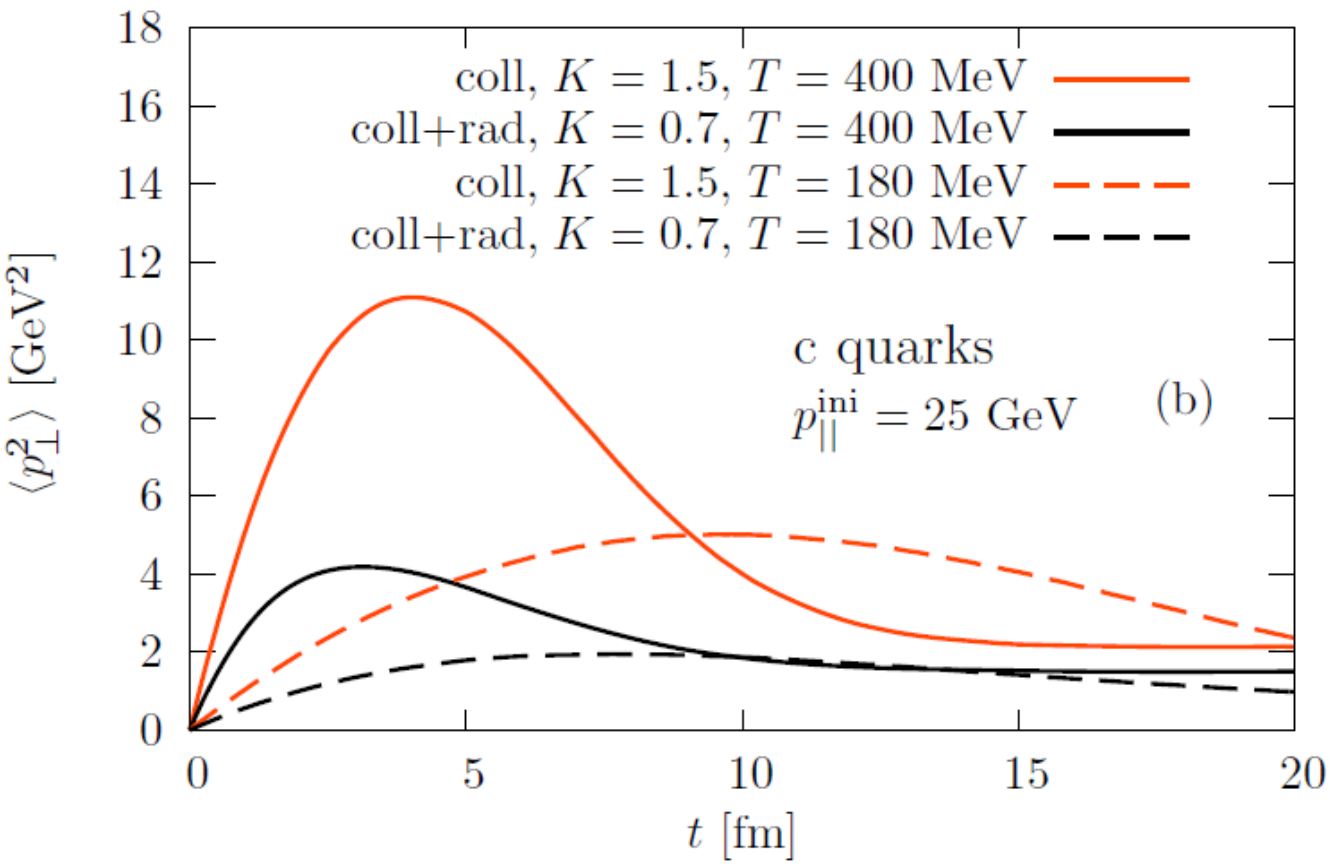


For BK: acceptable description of the data with moderate qhat

- The d<$p_{||}$>/dt (drag force) differ between both models, although correct agreement with the data at intermediate p_T. larger increase of the model with some radiative component.
- The purely collisional scatterings lead to a larger average <p_t^2> then the radiative "corrections" (need for large scattering to be efficient)
- Expectation: Initial correlations will be broadened more effectively in a purely collisional model.



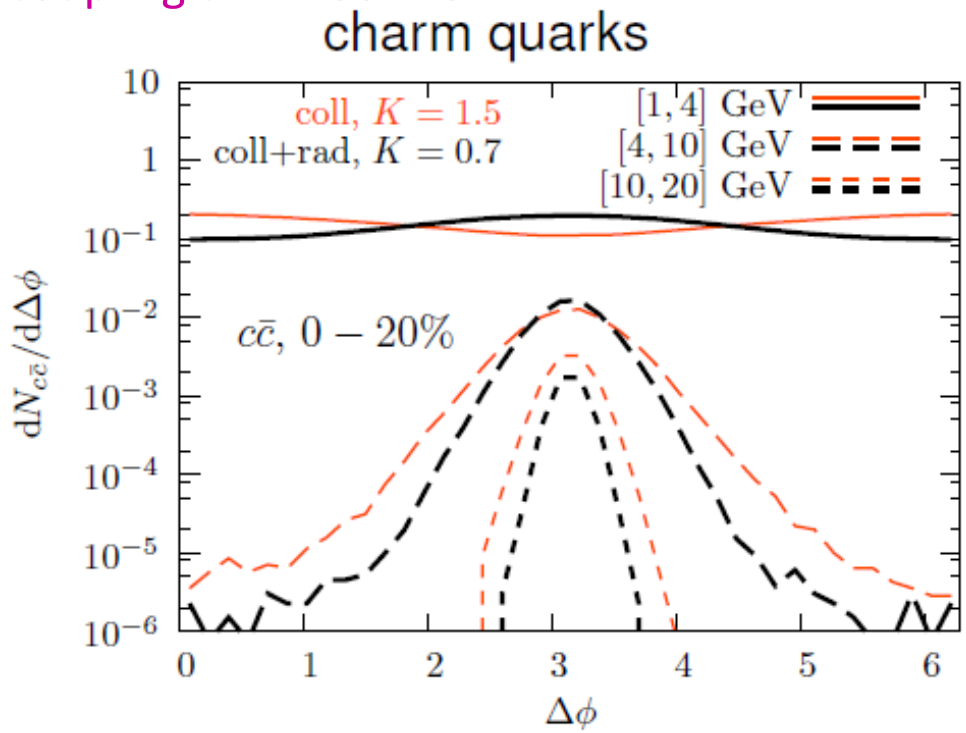
Evolution in a box

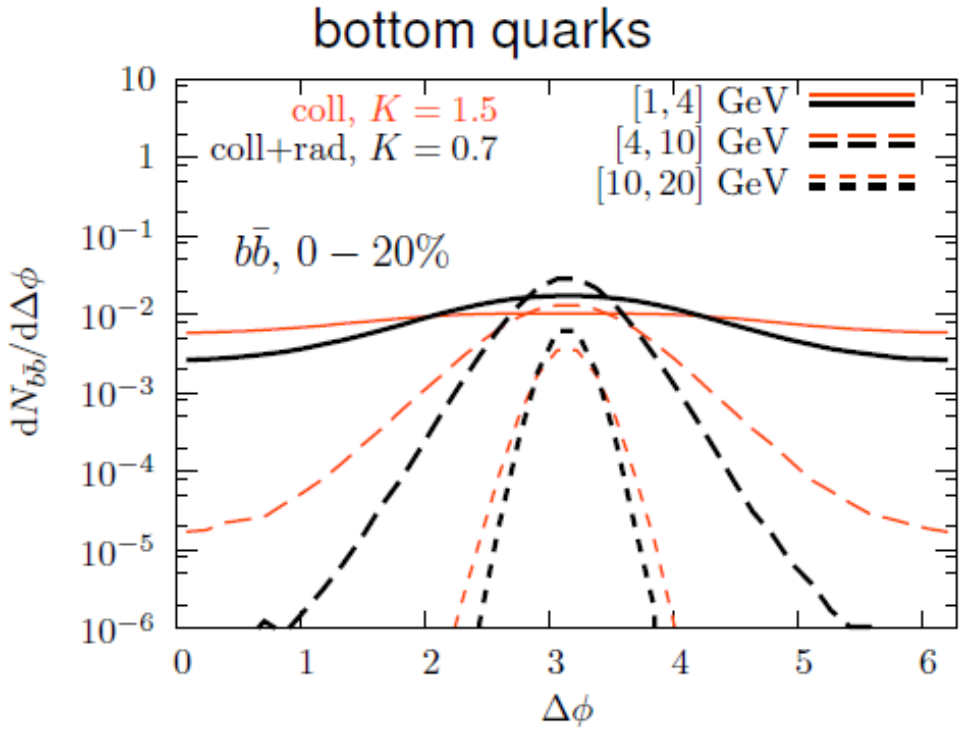


- Linear initial increase, followed by thermalisation at late stage; overshoot at intermediate times… sign of the propagation though hot medium
- Maximum reached at longer times for smaller temperatures (smaller increase, smaller energy loss => smaller thermalisation rate.

Heavy quarks azimuthal correlations: Back-to-back

Pb-Pb at LHC, HQ initialized back-to-back, no background from uncorrelated pairs, eff.deg=1; decoupling at T=155 MeV





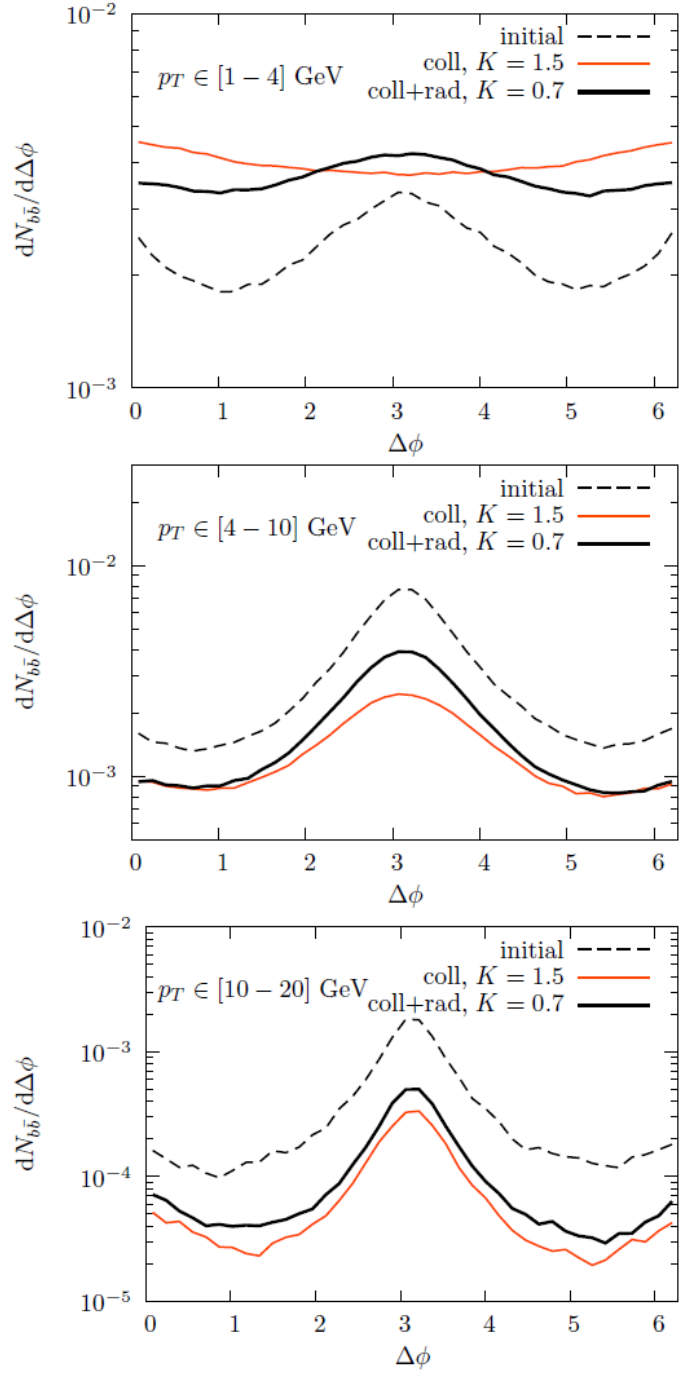
- Stronger broadening in a purely collisional than in a **collisional+radiative** interaction mechanim
- At low pT, initial correlations are almost washed out. Some collectivity seen in the purely collisional scenario
- Variances in the intermediate pT range (4 GeV-10 GeV): 0.18 vs **0.094** (charm) and 0.28 vs **0.12** (bottom)
- At higher pT, initial correlations survive the propagation in the medium

… and with Realistic initial distributions: MC@NLO

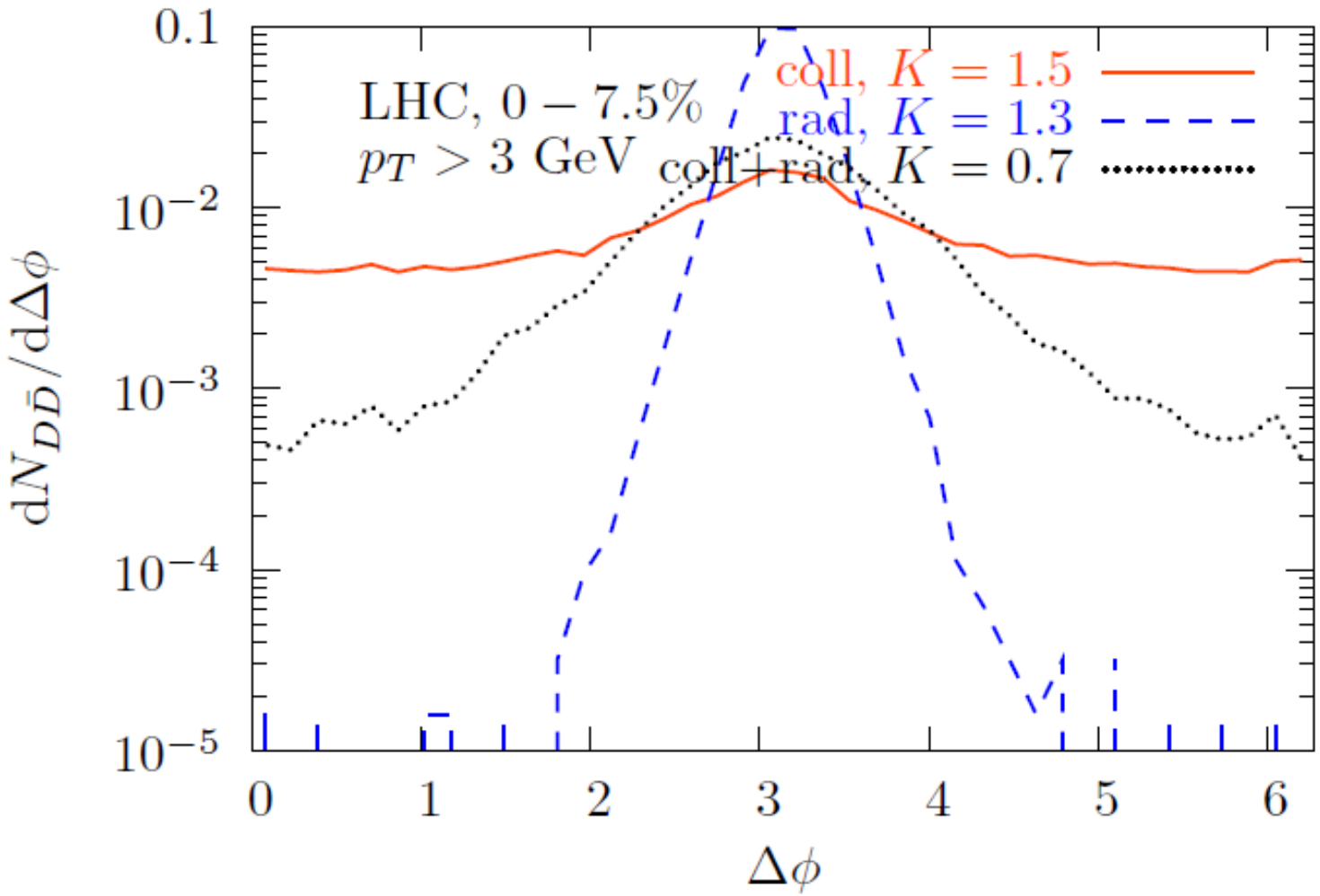
Next-to-leading order QCD matrix elements coupled to parton shower (HERWIG) evolution: MC@NLO

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 pT : increase of the variances from 0.43 (initial NLO) to 0.51 (≈ 20%) for the purely collisional mechanisms and to 0.47 (≈ 10%) for the interaction including **radiative** corrections (no additivity with initial width).
- At larger pT, the deviations from back to back correlations are mostly due to initial NLO corrections.
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production!

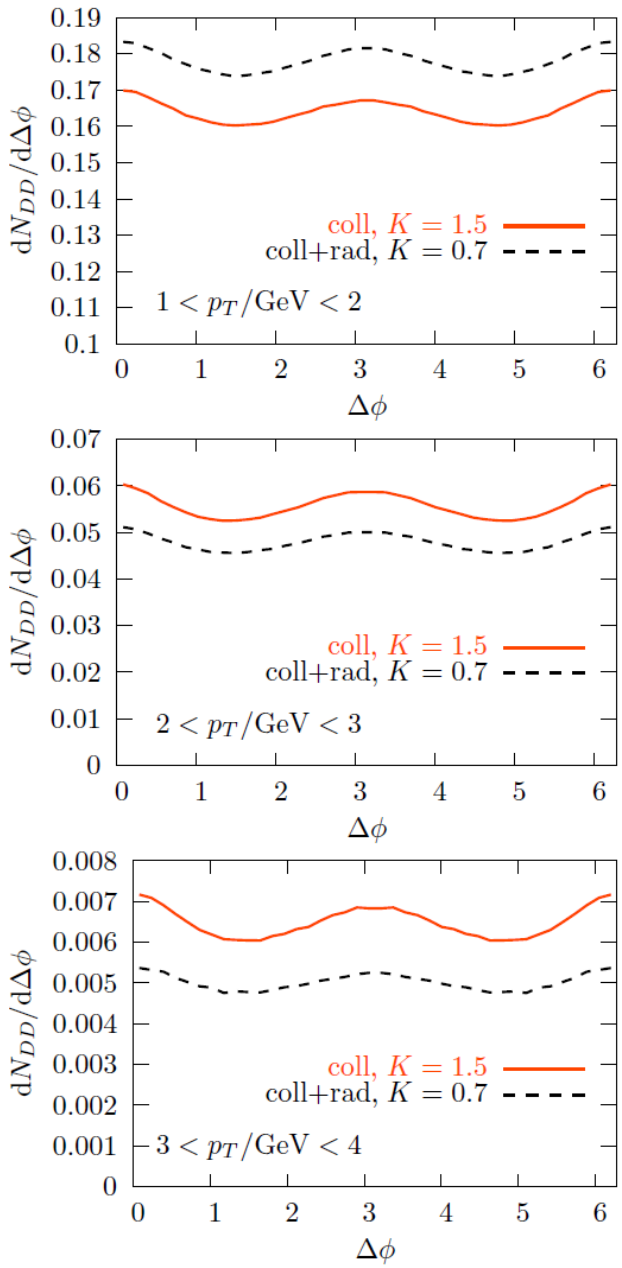


… until then: D mesons with back-to-back ccbar



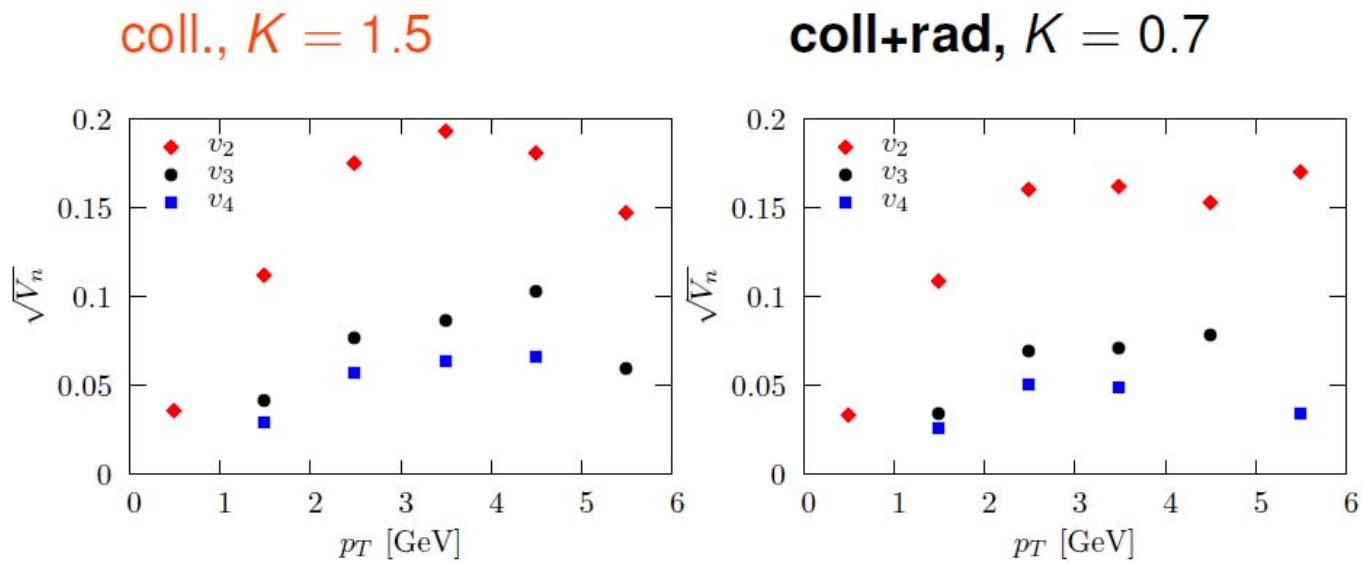
Provide at least some hope that azimuthal correlations could survive the QGP at intermediate pT and help us understand the basic mechanisms at play

Peripheral PbPb: Azimuthal correlations and flow



- 30-50% centrality, DD correlations
- Flow harmonics from 2-particle correlation functions

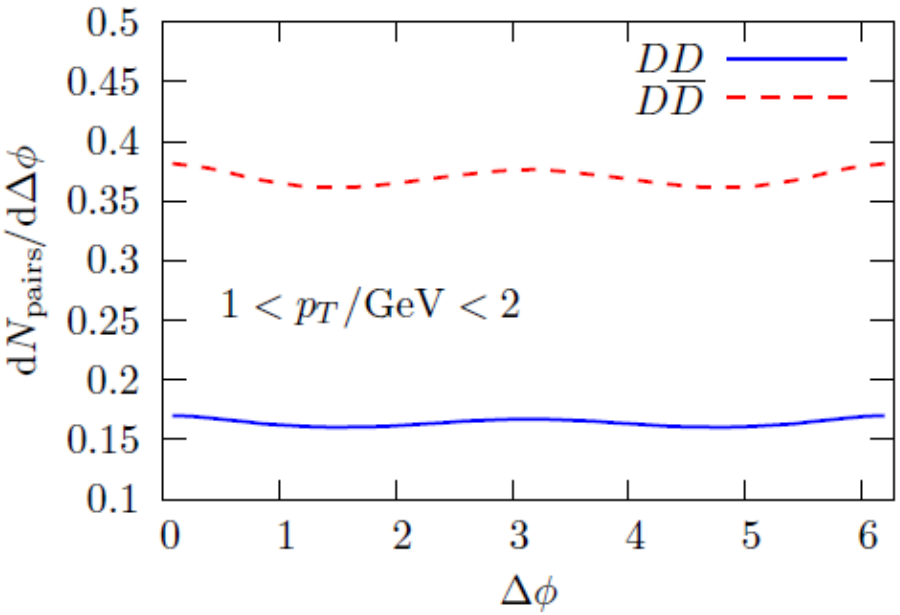
$$\propto \frac{N}{2\pi}\left(1 + 2\sum V_n \cos(n\Delta\phi)\right)$$

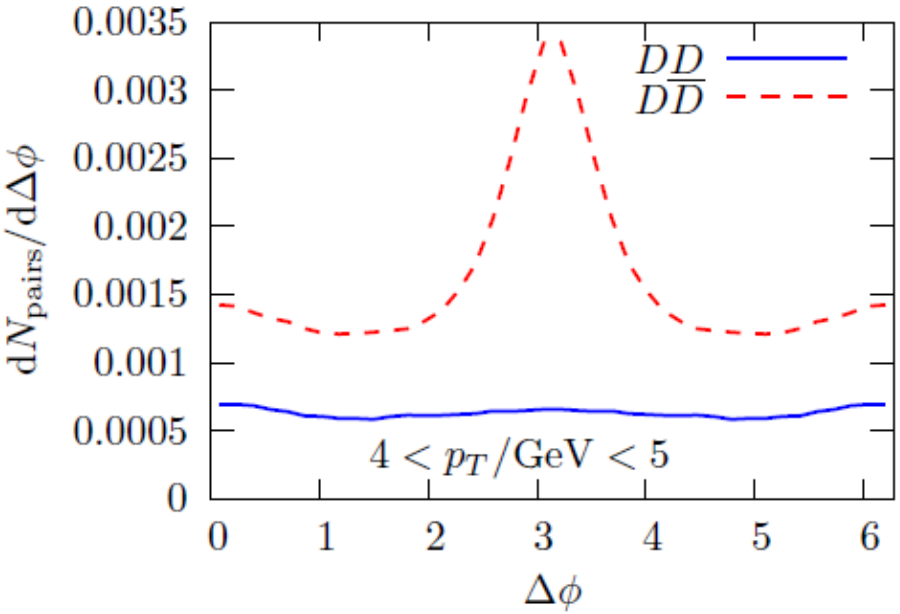


- Similar v_n for both interaction mechanisms at low pT
- Nonvanishing higher flow coefficients

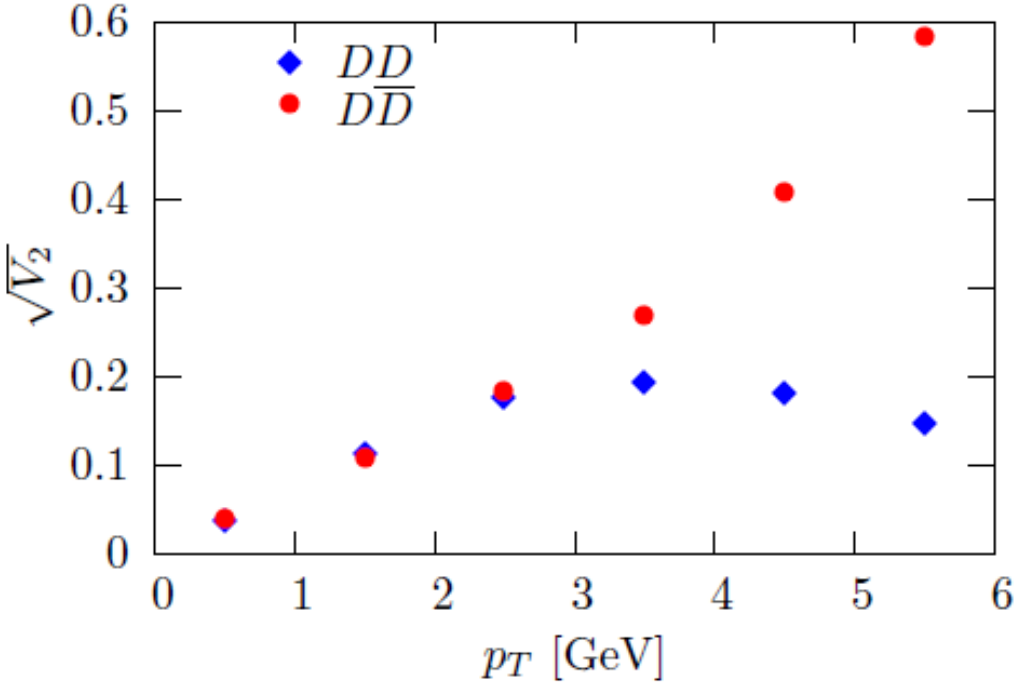
Peripheral PbPb: Azimuthal correlations and flow

as an example collisional, $K = 1.5$





- Compare DD correlations to DDbar correlations to learn about the flow contribution and the degree of isotropization of DDbar pairs



- Similar v2 for both DD and DDbar at small pT
- Dominant initial back-to-back correlation for DDbar at large pT

Conclusions & Perspectives

- Data at intermediate p_T can be reproduced by several model(s).
- D suppression at Large p_T favors collisional energy loss… or suggests improvements are in order for our treatment of radiative energy loss (finite path length, finite gluon width,…)
- Discrepancy at small p_T is increased using a more realistic model of the medium (need to be confirmed using EPOS with viscous hydro).
- Azimuthal correlations of HF mesons at intermediate pT may help constraining the models, but initial NLO distributions need to be better controlled for c-quarks, as well as possible CNM effects (not included here)
- To do: predictions for correlations including the decay chains.

Based on

- *Towards an understanding of the single electron data measured at the BNL Relativistic Heavy Ion Collider (RHIC)*, P.B. Gossiaux & J. Aichelin, Phys. Rev. C **78**, 014904 (2008); [arXiv:0802.2525]
- *Tomography of quark gluon plasma at energies available at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC)*, P.B. Gossiaux, R. Bierkandt & J. Aichelin, Physical Review C **79** (2009) 044906; [arXiv:0901.0946]
- *Tomography of the Quark Gluon Plasma by Heavy Quarks*, P.-B. Gossiaux & J. Aichelin, J. Phys. G **36** (2009) 064028; [arXiv:0901.2462]
- *Energy Loss of Heavy Quarks in a QGP with a Running Coupling Constant Approach*, P.B. Gossiaux & J. Aichelin, Nucl. Phys. A **830** (2009), 203; [arXiv:0907.4329]
- *Competition of Heavy Quark Radiative and Collisional Energy Loss in Deconfined Matter*, P.B. Gossiaux, J. Aichelin, T. Gousset & V. Guiho, J. Phys. G: Nucl. Part. Phys. **37** (2010) 094019; [arXiv:1001.4166]
- *Plasma damping effects on the radiative energy loss of relativistic particles*, M. Bluhm, P. B. Gossiaux, & J. Aichelin, Phys. Rev. Lett. 107 (2011) 265004 [arXiv:1106.2856]
- *Theory of heavy quark energy loss*, P.B. Gossiaux, J. Aichelin, T. Gousset, [arXiv:1201.4038v1]

Based on

- Radiative and Collisional Energy Loss of Heavy Quarks in Deconfined Matter *Radiative*, J. Aichelin, P.B. Gossiaux, T. Gousset, [arXiv:1201.4192v1]
- On the formation of bremsstrahlung in an absorptive QED/QCD medium, M. Bluhm, P. B. Gossiaux, T. Gousset & J. Aichelin, [arXiv:1204.2469v1]
- … other recent publications all available on arxiv
- **Azimuthal correlations of heavy quarks in Pb+Pb collisions at LHC (**$\sqrt{s}$ = 2.76 **TeV),** Marlene Nahrgang,Jorg Aichelin, Pol Bernard Gossiaux, and Klaus Werner [arxiv 1305.6544]