

# The Physics of Heavy Quarks in AA collisions

Why heavy quarks are interesting ?

Interaction of heavy quarks with the plasma

- our model (elastic and inelastic collisions, LPM)
- comparison with data
- how far we are with our understanding

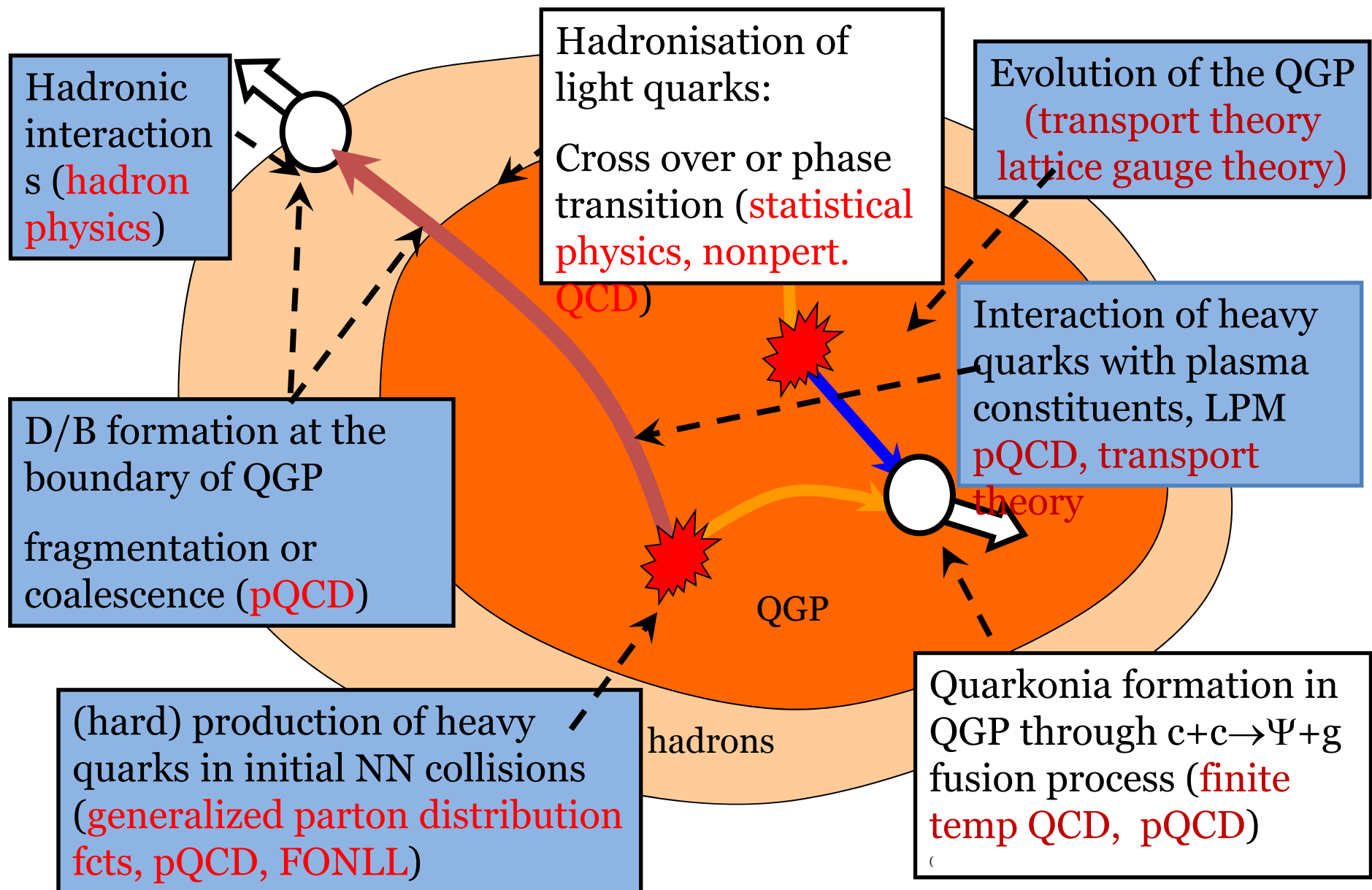
# What makes heavy quarks (mesons) so interesting?

- 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 ( $c(b)+q(g) \rightarrow c(b)+q(g)$ )  
difficult to separate (arXiv:1102.1114 )

# Complexity of heavy quark physics in a nutshell :



Presently the analysis/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  $v_2$  
$$\frac{dN}{d\Phi} = \frac{1}{2\pi} (1 + 2v_1 \cos \Phi + 2v_2 \cos 2\Phi \dots)$$

tests the late stage of the expansion

# 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 (LHC)  
(or before Kolb & Heinz (RHIC))
- This serves then as a benchmark
- **deviation from data points towards new physics**

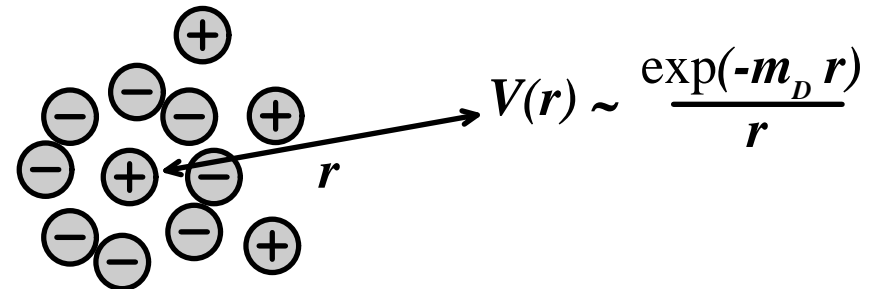
## Nantes approach: Elastic heavy quark – q(g) collisions

Key ingredients: pQCD cross section like  $qQ \rightarrow qQ$   
 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

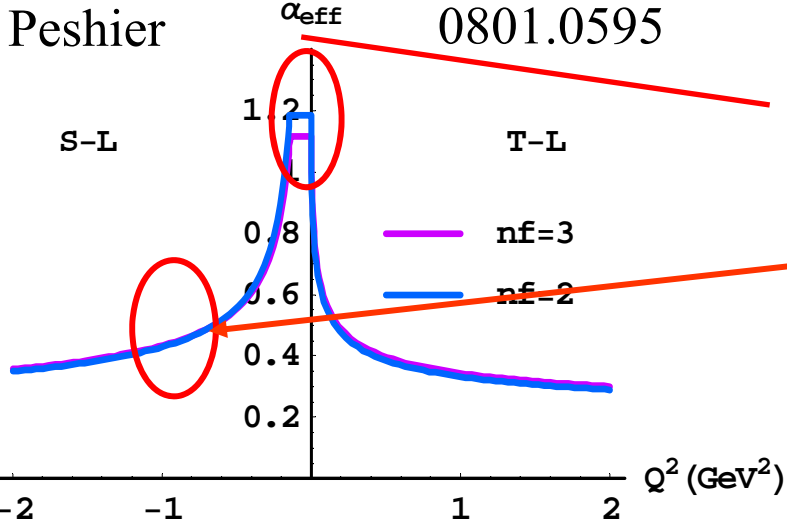
standard:  $\alpha(t)$  is taken as constant or as  $\alpha(2\pi T)$

$\kappa = 1$  and  $\alpha = .3$ : large K-factors ( $\approx 10$ ) are necessary to describe data

# A) Running coupling constant

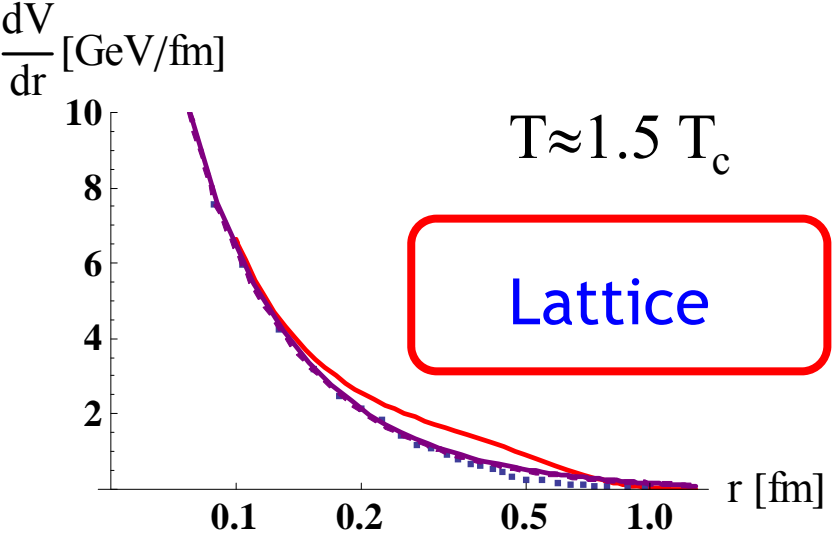
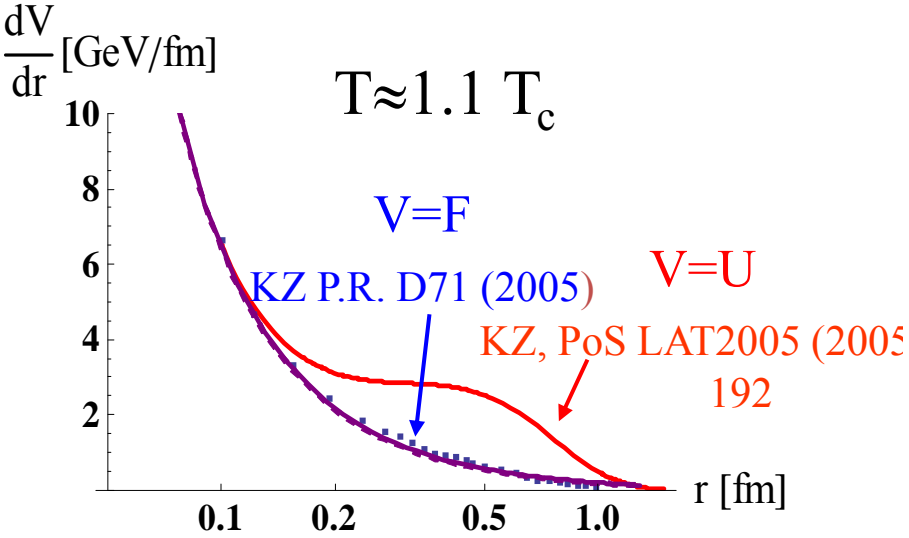
“Universality constraint” (Dokshitzer 02)  
helps reducing uncertainties:

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



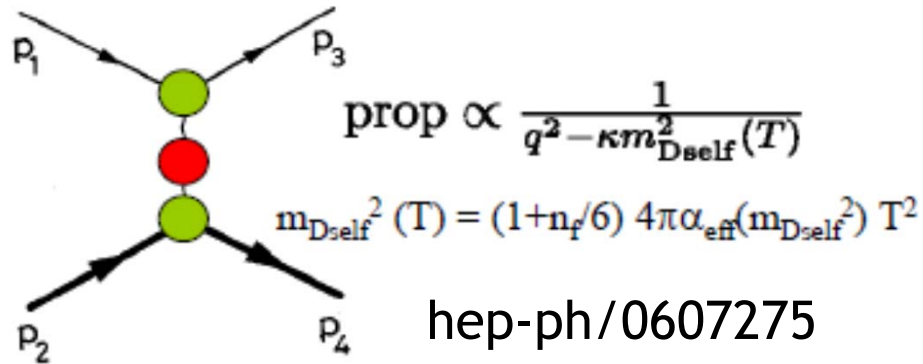
IR safe. The detailed form very close to  $Q^2 = 0$  is not important does not contribute to the energy loss  
Large values for intermediate momentum-transfer

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



## B) Debye mass

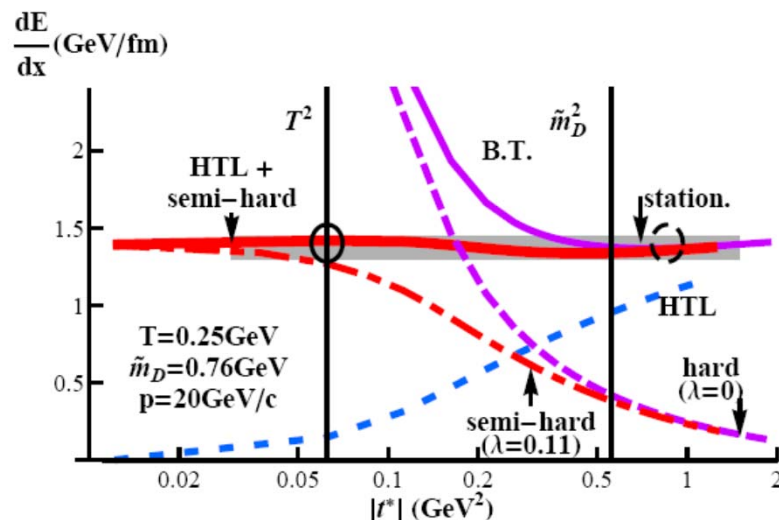
PRC78 014904, 0901.0946



If  $t$  is small ( $\ll T$ ): 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:

$$\kappa \approx 0.2$$

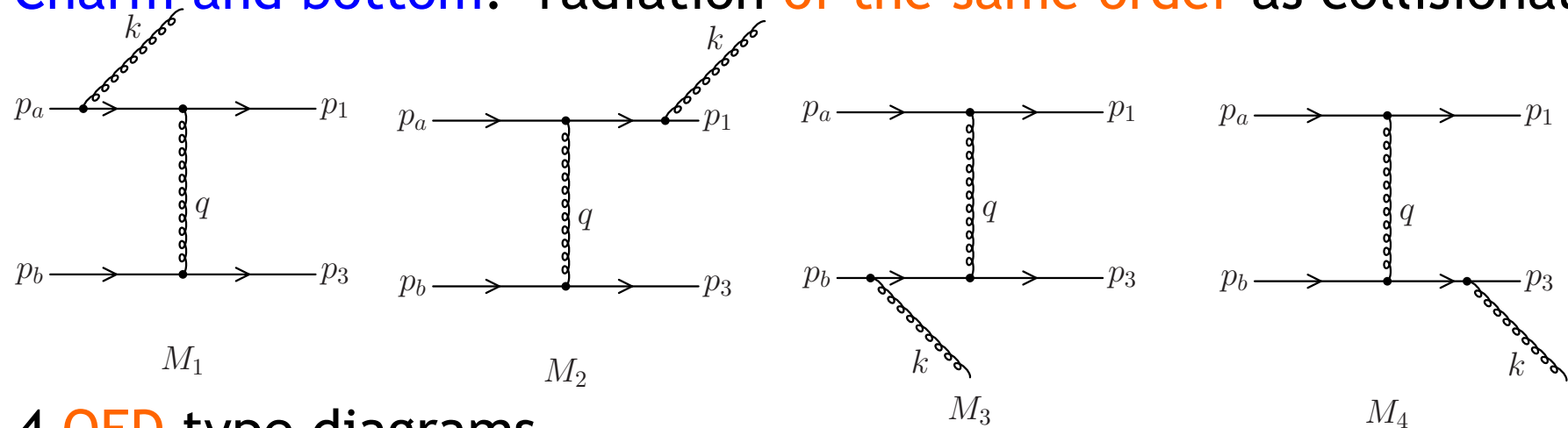
much lower than the standard value



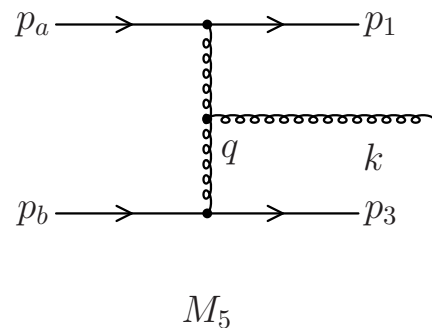
## C) Inelastic Collisions

Low mass quarks : radiation dominates energy loss

Charm and bottom: radiation of the same order as collisional



4 QED type diagrams



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

$$M_{QED}^1 = T^a T^b (M_1 + M_2) \quad M_{QED}^2 = T^a T^b (M_3 + M_4)$$

$$M_{QCD} = i f_{abc} T^c (M_1 + M_3 + M_5)$$

$M_{QCD}$  dominates the radiation

# $M^{\text{SQCD}}$ in light cone gauge

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

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

$k_t, \omega$  = 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

$m=0$  -> Gunion Bertsch  
Energy loss:

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

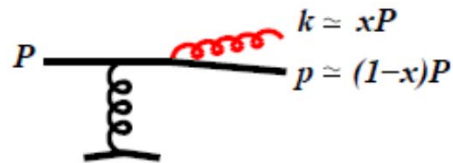
$x = \omega/E$

leading order: no emission  
from light q  
heals collinear divergences

$$M_{QCD} = M_{SQCD} \left( 1 - \frac{(\omega/E)^2}{(1-\omega/E)^2} \right)$$

# Landau Pomeranshuk Migdal Effekt (LPM)

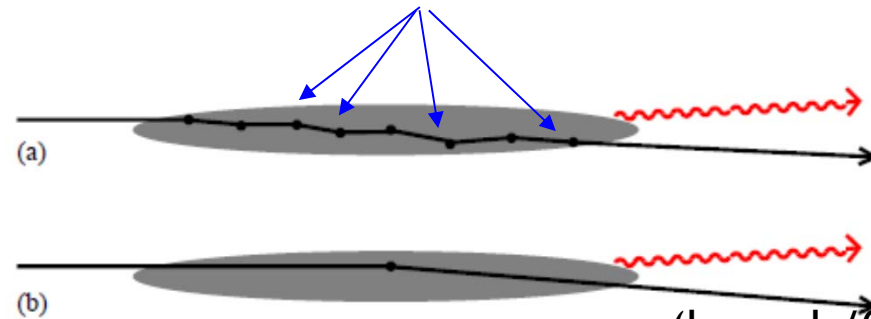
reduces energy loss by gluon radiation



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)

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

Multiple scatt .QCD:  $\approx N_{\text{coll}}$

$$\langle k_t^2 \rangle = t_f \hat{q}$$

single scatt.

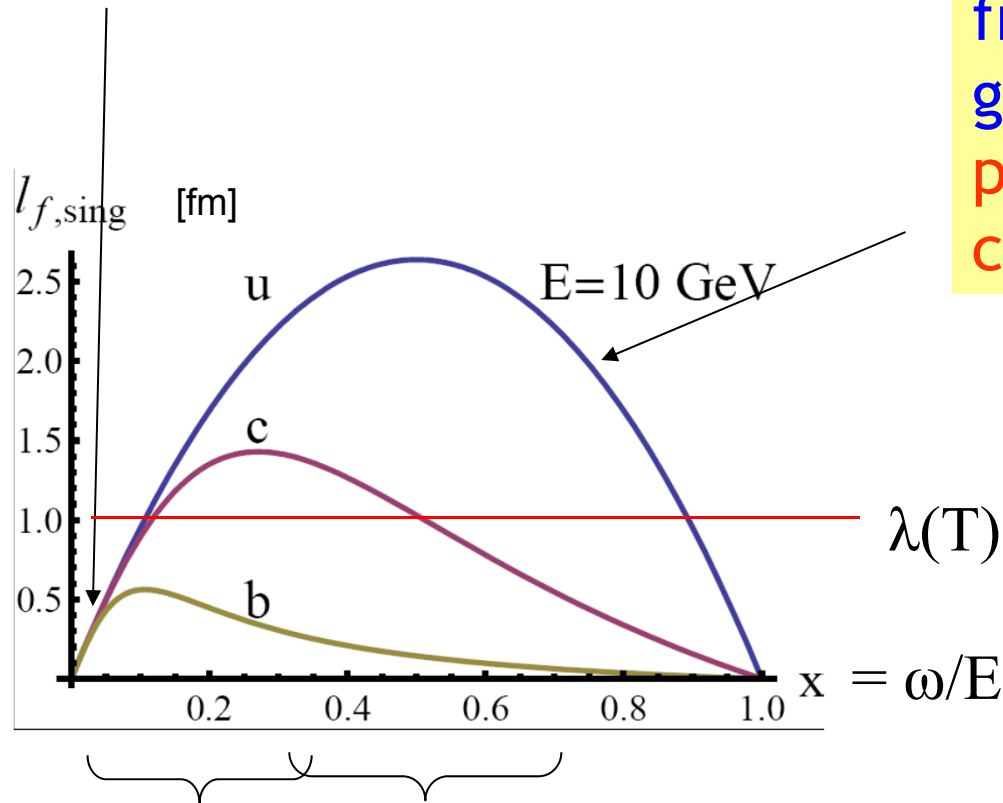
dominates  $x < 1$

dominates  $x \approx 1$

dominates  $x \ll 1$

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 than those from light quarks and gluons => radiation process less affected by coherence effects.

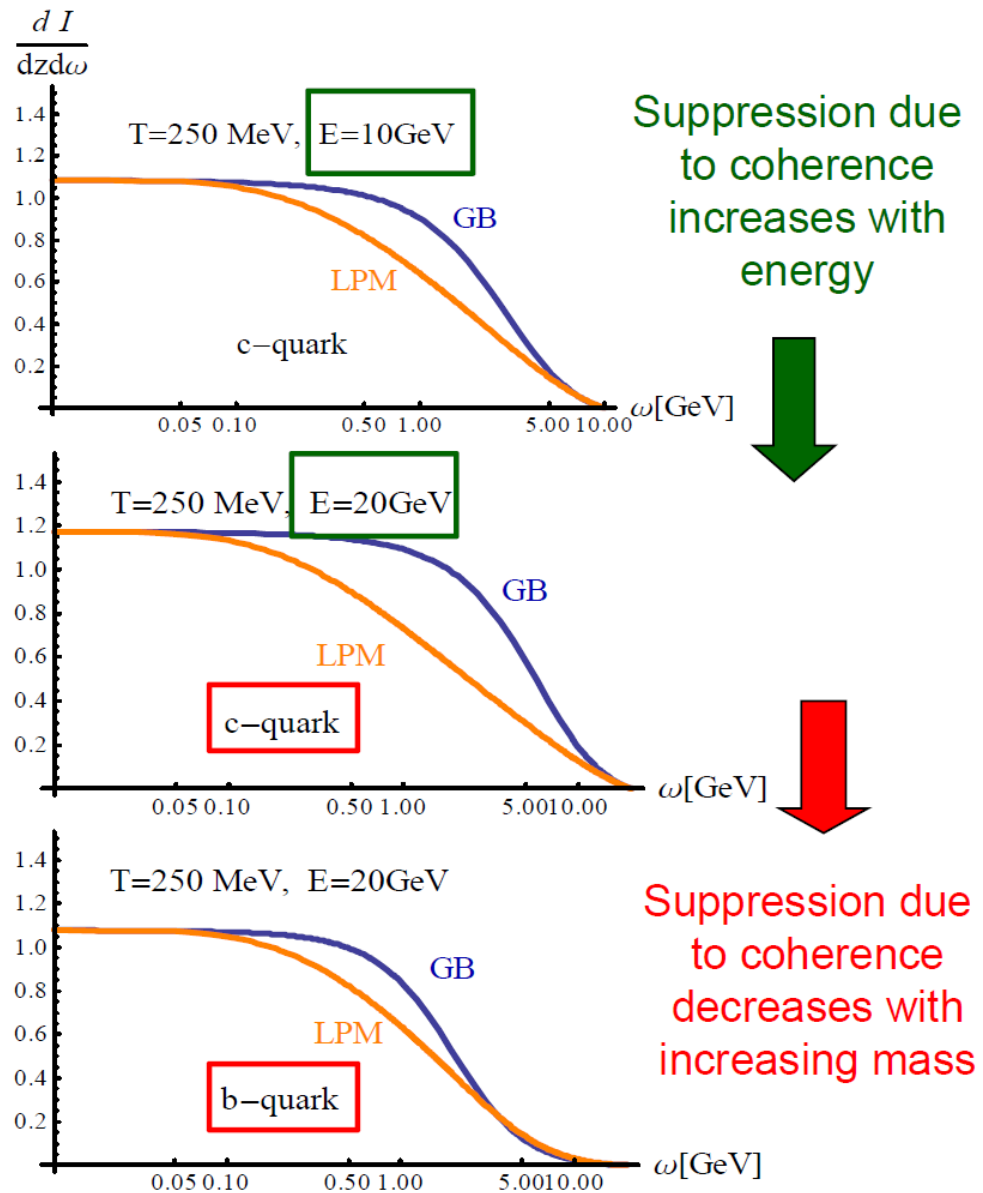


Most of the collisions  $\frac{d\sigma}{dx}$

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



# Calculations for RHIC and LHC

**Initialization:** FONLL distribution of c and b

**QGP :** Hydro Kolb-Heinz for RHIC  
EPOS for LHC

**Interaction QGP-heavy quarks:**

elastic collisions (collisional energy loss) ( $K \approx 2$ )

elastic collisions + and gluon emission (radiative energy loss)  
+LPM

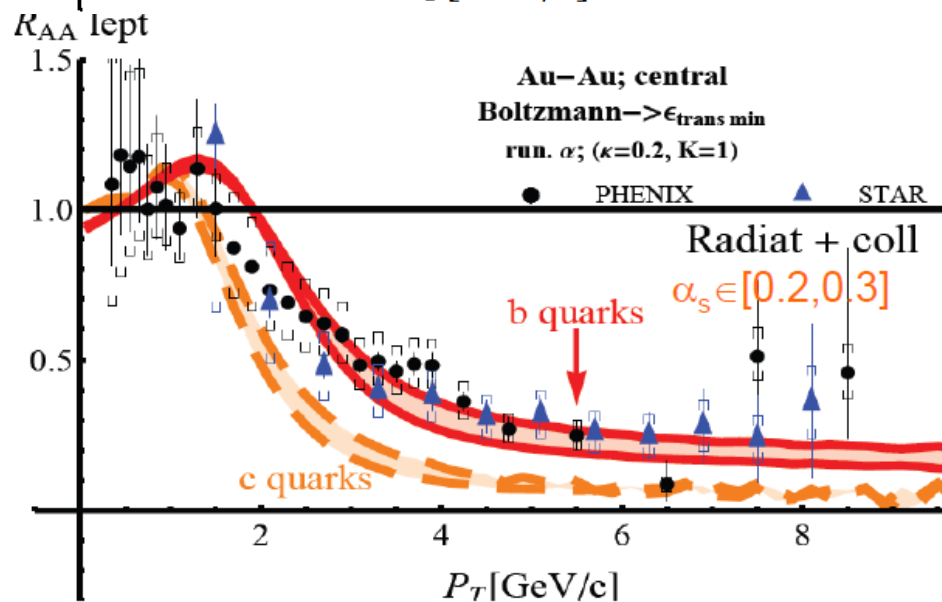
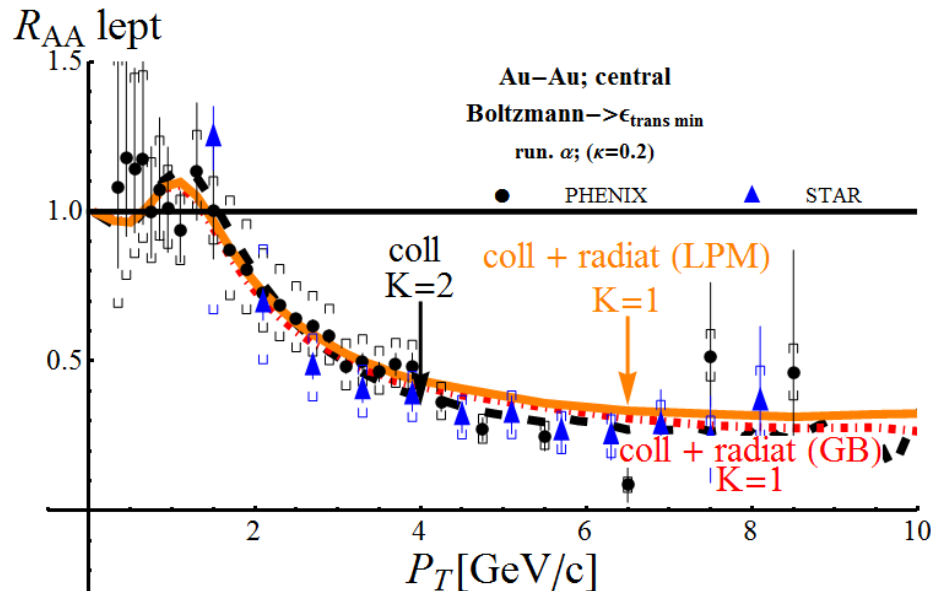
**Hadronisation:**

Coalescence for low pt heavy quarks

Fragmentation for high pt heavy quarks

**Hadronic rescattering** is small

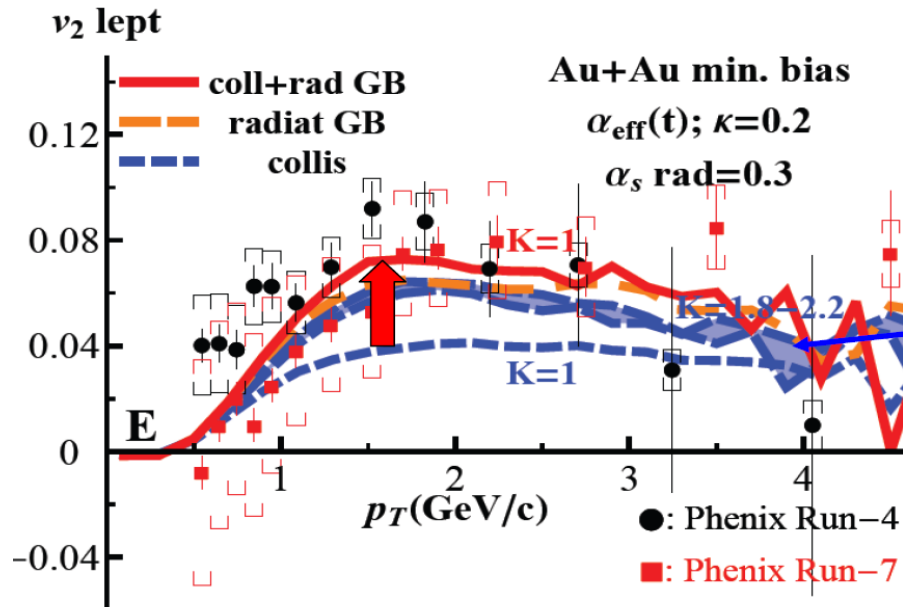
# RHIC Hydro: Kolb Heinz



1. Coll: too little quenching (but very sensitive to freeze out)  $\rightarrow K=2$
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  $v_2$

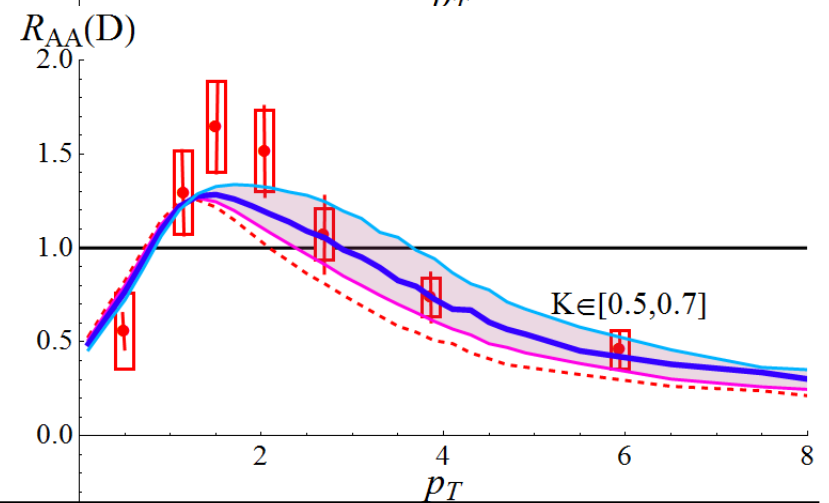
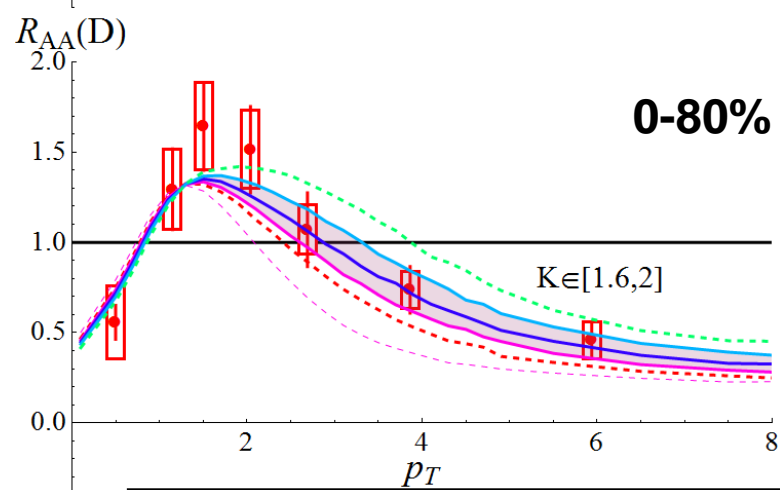
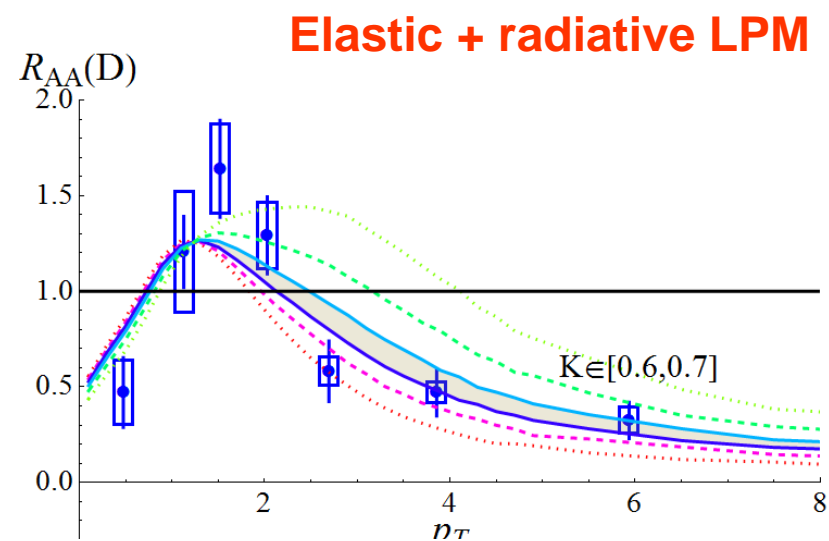
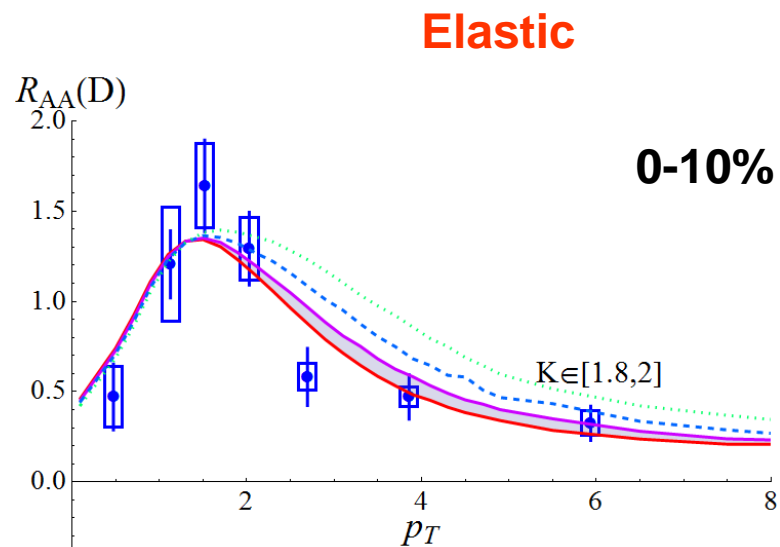
For the hydro code of Kolb and Heinz:

$K = 1$  compatible with data

$K = 0.7$  best description – remember influence of expansion

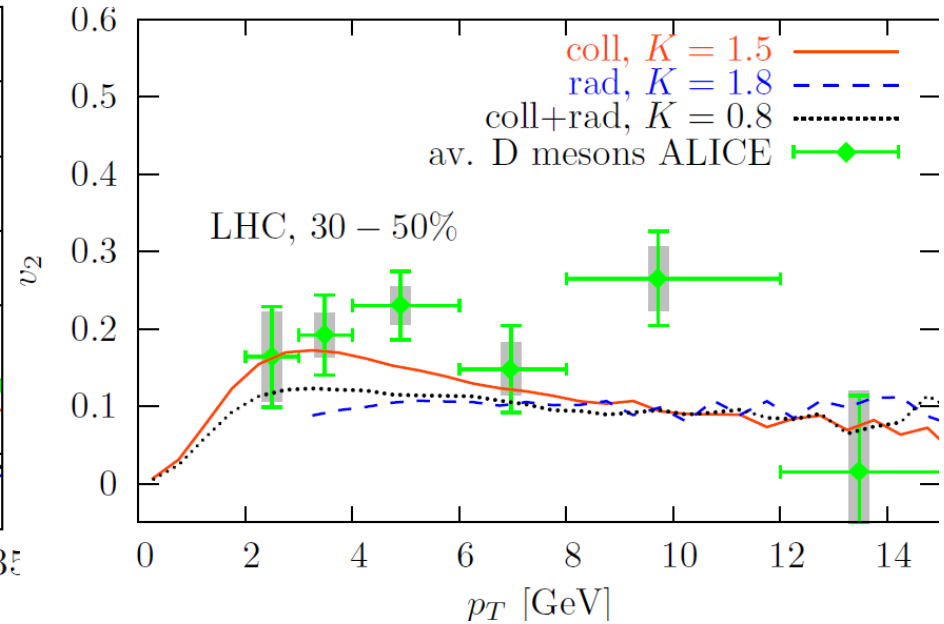
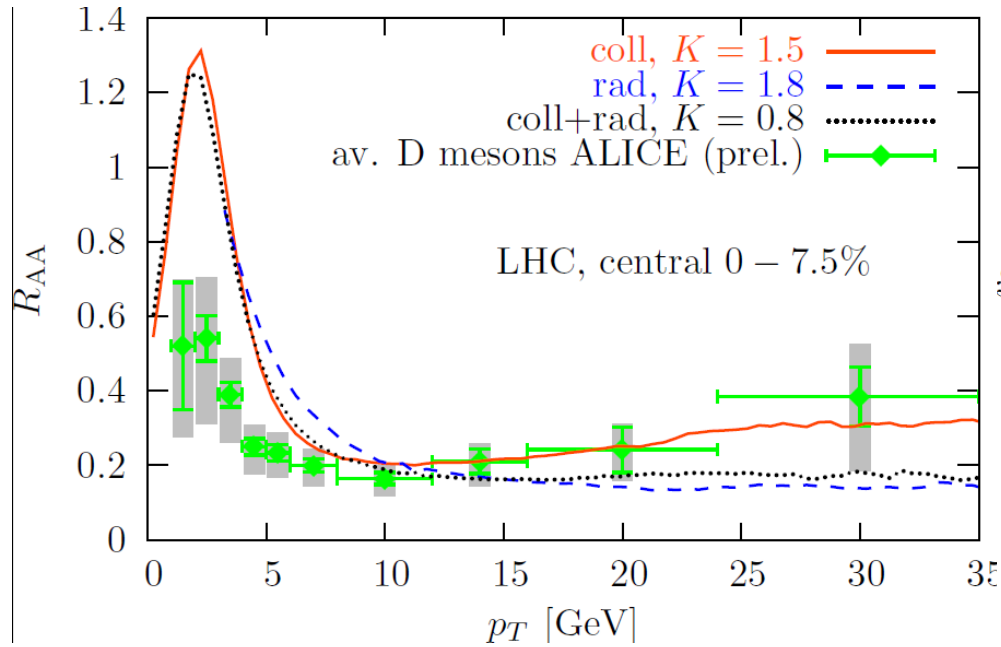


# RHIC IV: D mesons



No form difference between coll and coll + rad

# LHC : EPOS event generator

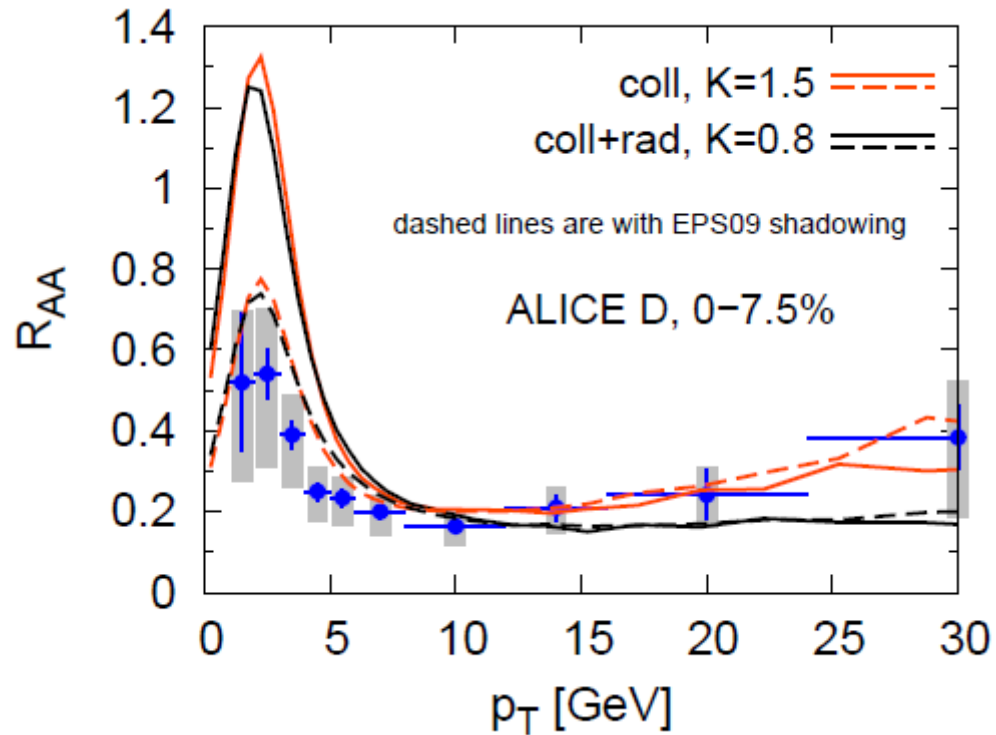


Three options :  
 Collisions only K factor = 1.5  
 Collision and radiation K = 0.8  
 Radiation only K= 1.8

$R_{AA}$  and  $v_2$  for coll and coll + radiative about the same

# Discussion of our results

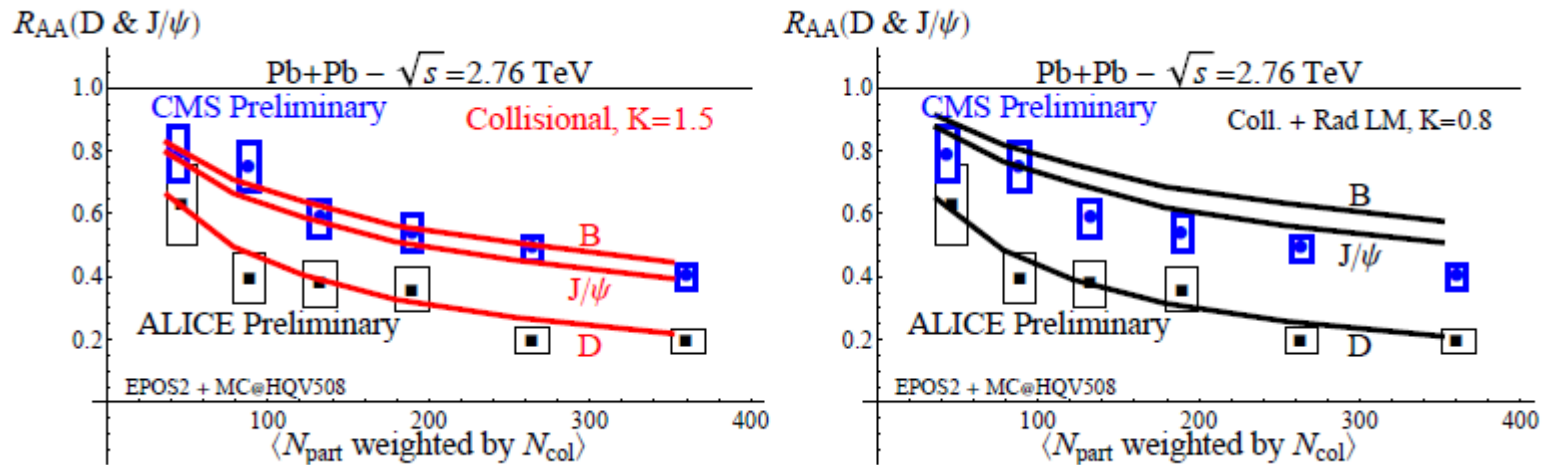
I)  $R_{AA}$



Shadowing effects may **suppress strongly** the  $R_{AA}$  at small  $p_t$   
**Anti-shadowing visible** but not strong at large  $p_t$

Shadowing has little influence on  $v_i$

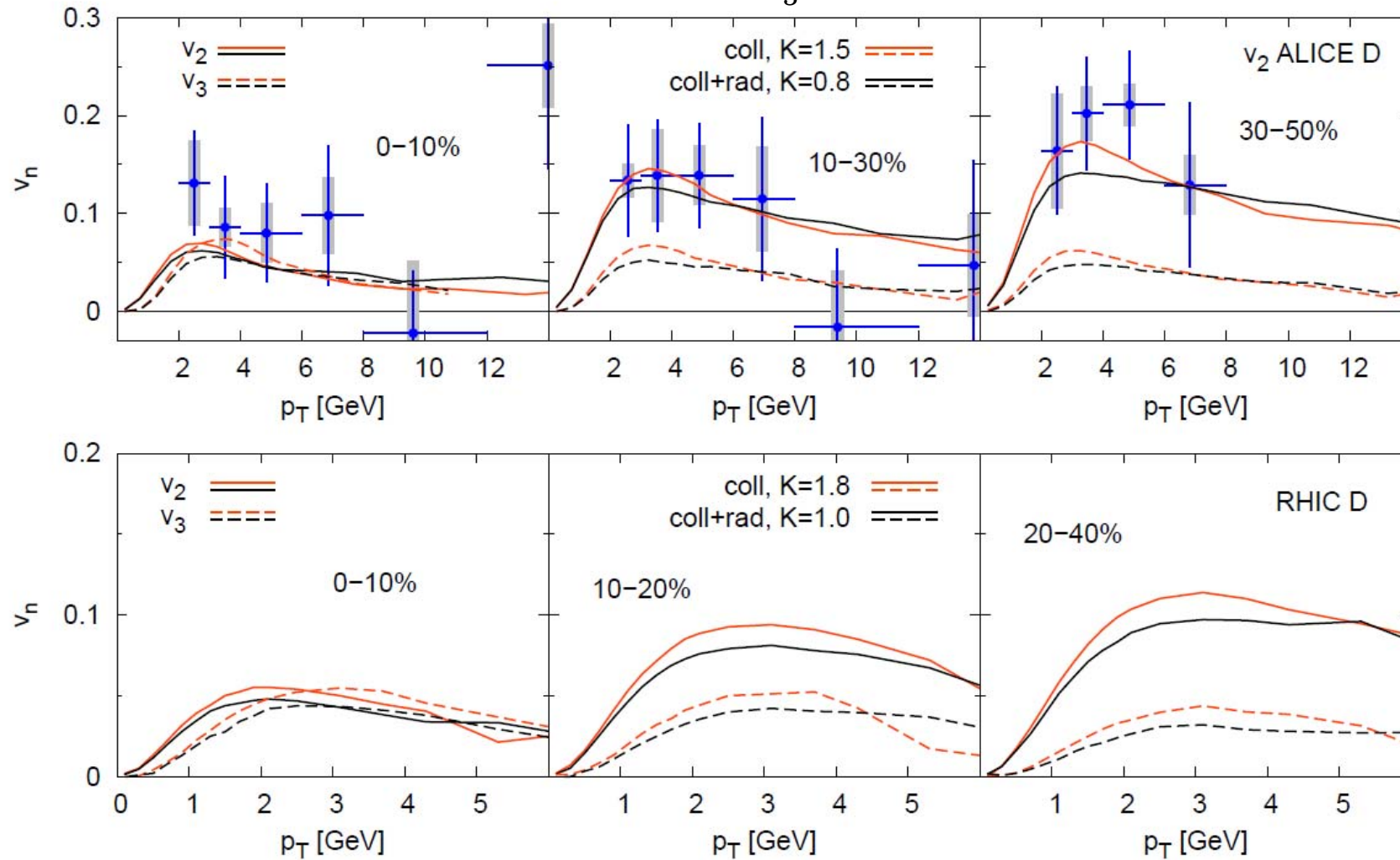
The different  $R_{AA}$  of D and B mesons seem to be verified experimentally (by comparing two different experiments)



ALICE D meson  $R_{AA}$ ,  $6 < p_T < 12$  GeV/c,  $|y| < 0.5$

CMS Preliminary Non-prompt J/ψ  $R_{AA}$ ,  $6.5 < p_T < 30$  GeV/c  $|y| < 1.2$

## Heavy quarks show also a finite $v_3$ and finite higher moments

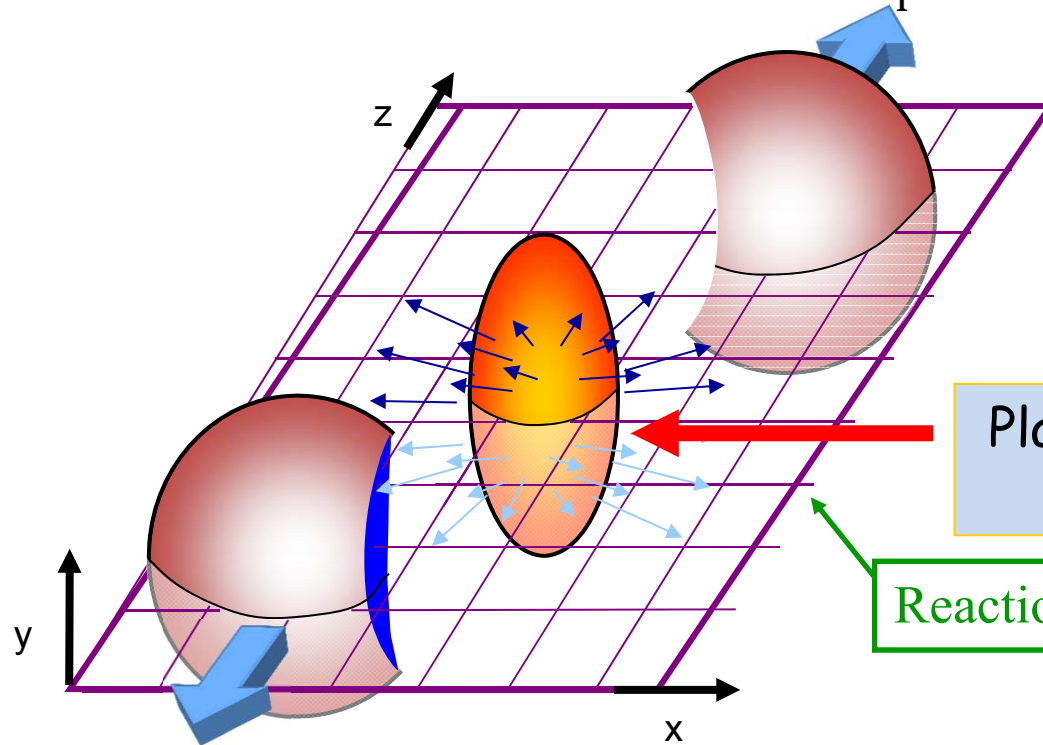


What can one learn from these results?

$v_2$  decreases with centrality -> understandable with the decrease of  $\epsilon_2$

$v_3$  independent of centrality -> fluctuations

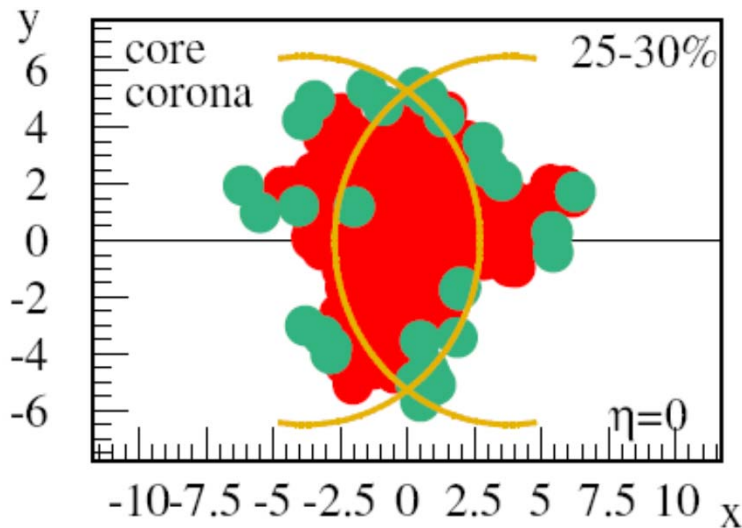
# Where do the finite $v_i$ come from?



In the ideal world the plasma  
Should have only  $v_2$

Plasma to be  
studied

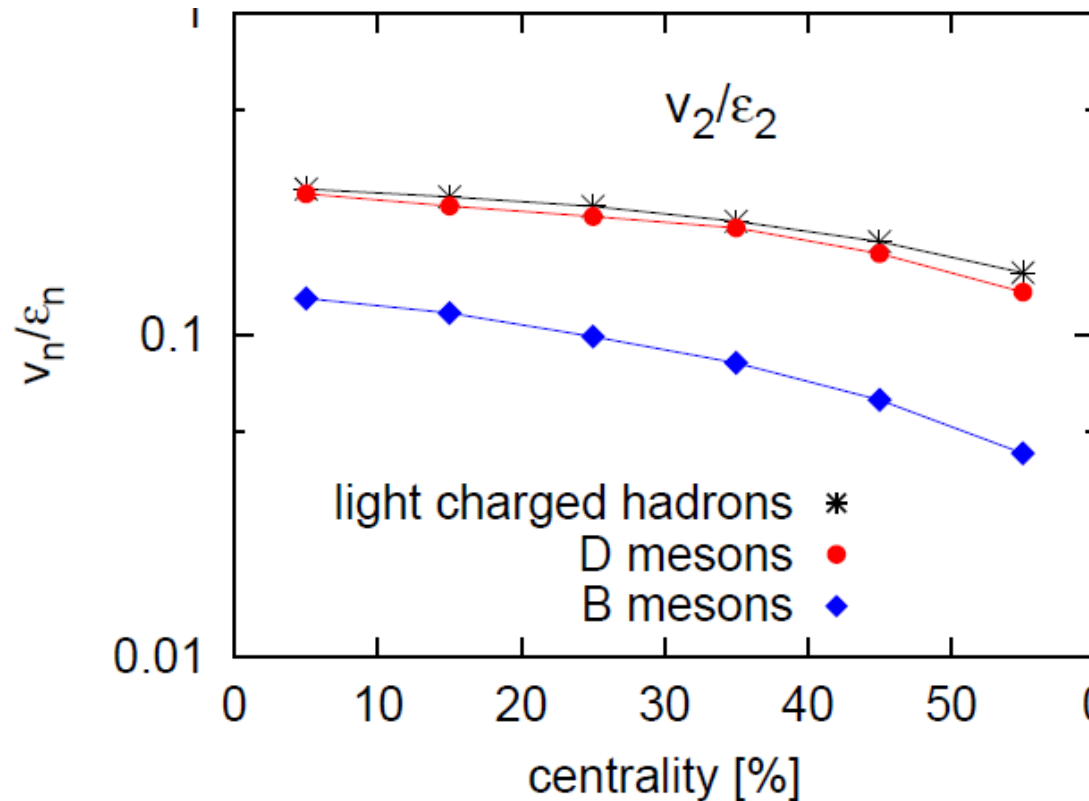
Reaction plane



In the real world (EPOS) the  
plasma has all kinds of moments  $v_i$   
the  $v_i$  impair are fluctuations

$v_3$  corresponds to a Mercedes Star

**Very surprising** :  $v_2/\epsilon_2$  : same for light hadrons and D mesons



Light quarks: **hydro-dynamical pressure** caused by **spatial eccentricity**

$v_2/\epsilon_2$  const for ideal hydro, centrality dependent for viscous hydro

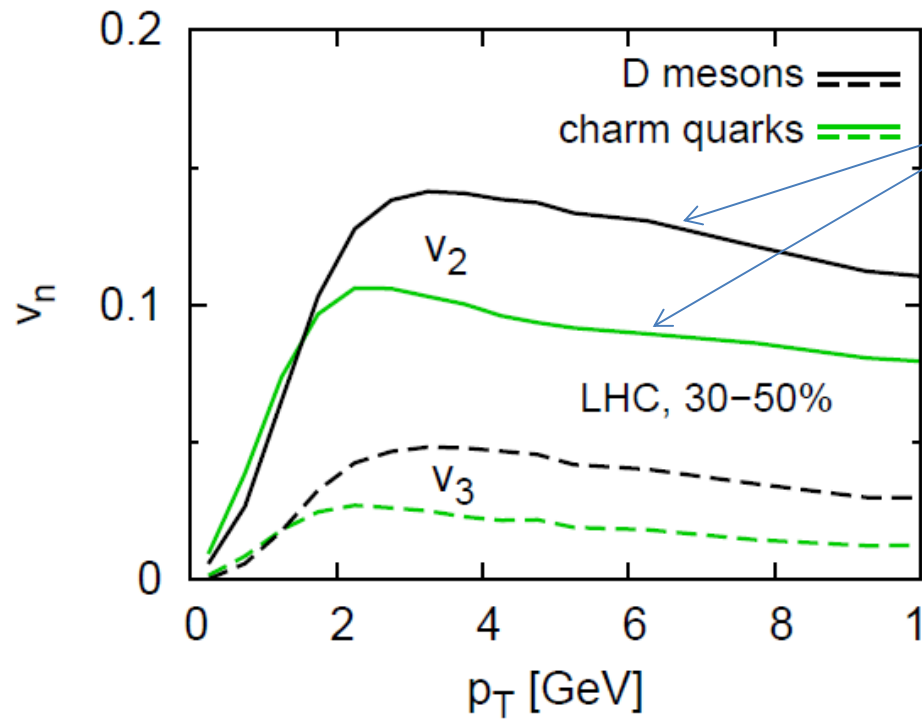
Heavy quarks: **No initial  $v_2$**  (hard process)

$v_2$  only due to interaction with q and g

**$v_2$  of heavy quarks is created later measures the interaction time**

Bottom quarks are too heavy to follow

## More detailed analysis of the flow

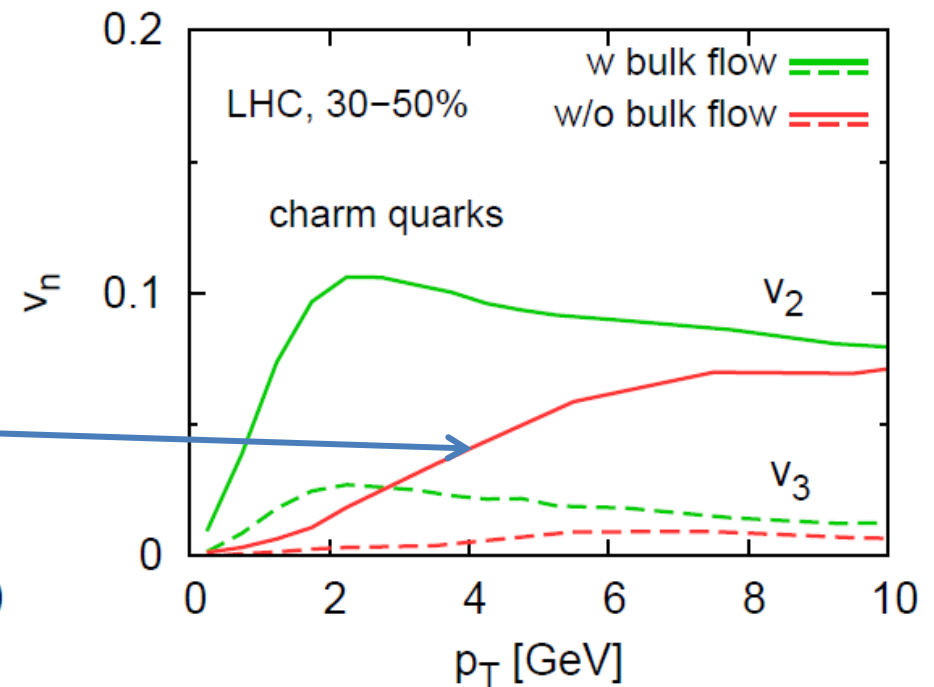


20% of  $v_2$  due to the hadronisation uncertainty  
whether fragmentation or coalescence is not essential for  $v_2$

Verification that collective flow creates  $v_2$

Artificial elimination of the collective flow

High momentum: different path length in and out of plane





## Conclusions

All **experimental midrapidity RHIC and LHC data are compatible** with the assumption that

**pQCD describes energy loss and elliptic flow  $v_2$  of heavy quarks.**

The present heavy quark data are **do not allow to discriminate** between different pQCD processes:  
**radiative and collisional energy loss**

Special features      **running coupling constant**  
                             **adjusted Debye mass**  
                             **Landau Pomeranshuk Migdal**

Description of the **expansion** of the medium (freeze out, initial cond.) has to be controlled by light hadrons (->EPOS)

## Collaborators

### Nantes

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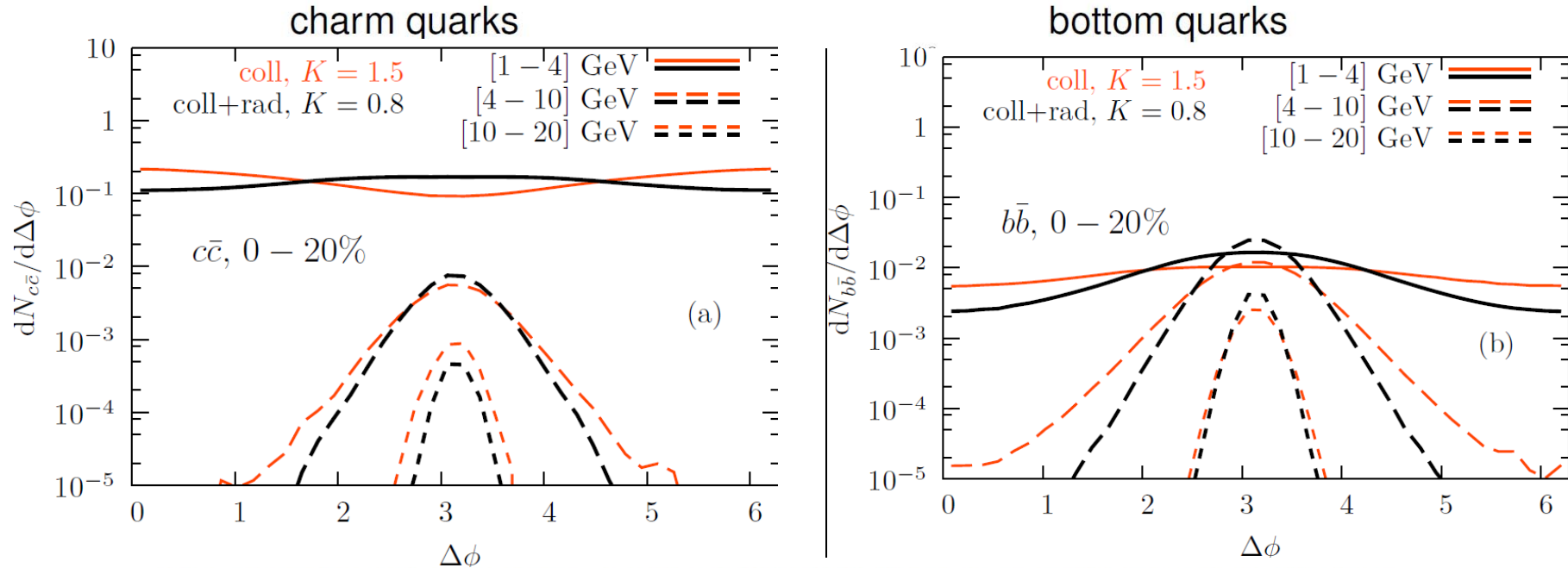
Wolfgang Cassing

### Duke

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Steffen Bass

# 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  $p_T$ .