Tomography of the QGP at RHIC and LHC by heavy mesons

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in collaboration with

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(A. Peshier)

Why heavy quarks are interesting?

Interaction of heavy quarks with the plasma
- collisional
- radiative
- Landau Pomeranschuk Migdal (LPM) effect
- and if gluons get absorbed...
- difference between coliisional and radiative?

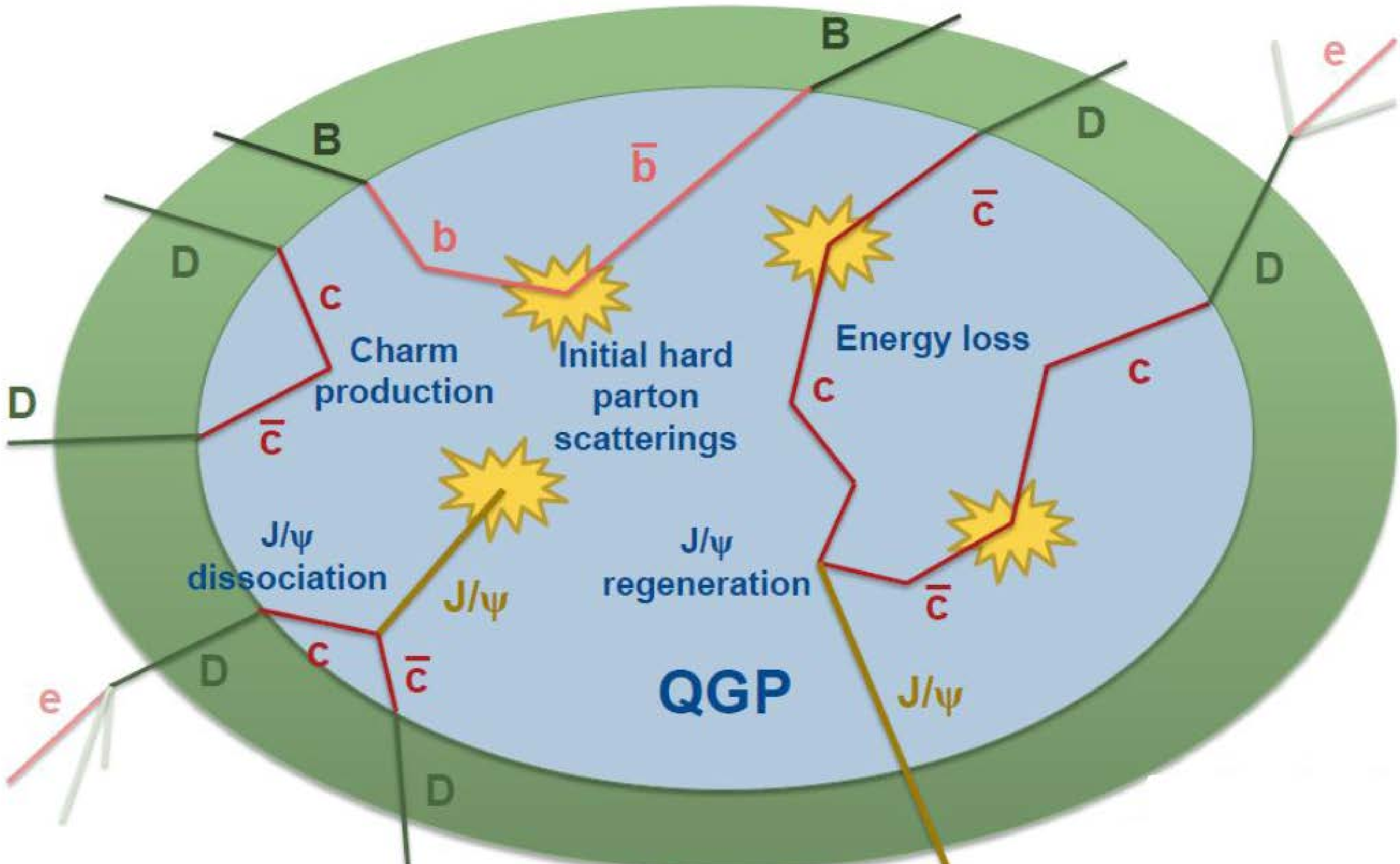
Results for RHIC and LHC

What makes heavy quarks (mesons) so interesting?

- produced in hard collisions (initial distribution: FONLL confirmed by STAR/Phenix)
- 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**)


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

E.Scomparin

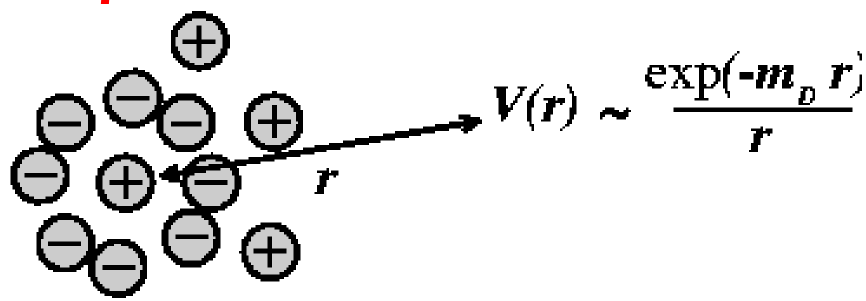
Nantes approach: Elastic heavy quark – q(g) collisions

Key ingradients: pQCD cross section like qQ -> 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

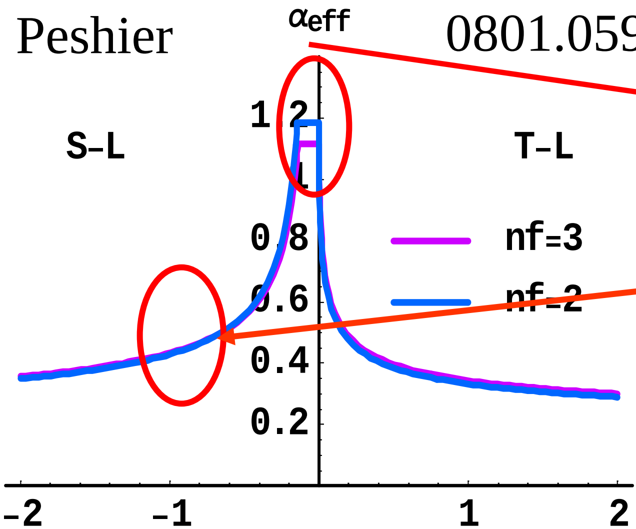
Neither $g^2 = 4\pi\,\alpha(t)$ nor $\kappa\, m_D^2$= are well determined
standard: $\alpha(t)$ =is taken as constant or as $\alpha(2\pi T)$
κ =1 and α =.3: large K-factors (≈ 10) are necessary to describe data

A) Running coupling constant

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

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

Peshier 0801.0595

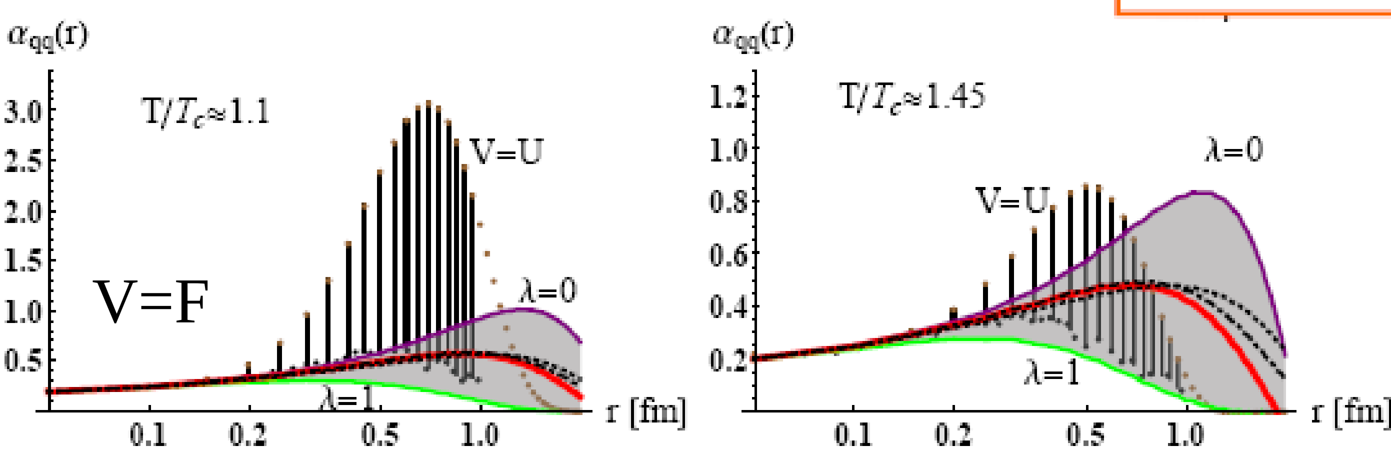


IR safe. The detailed form very close to $Q^2 = 0$ is not important does not contribute to the energy loss

Large values for intermediate momentum-transfer

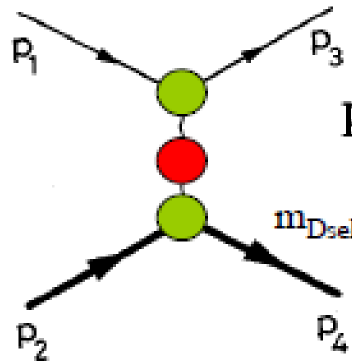
Comp w lattice results PRD71,114510

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



B) Debye mass

PRC78 014904, 0901.0946



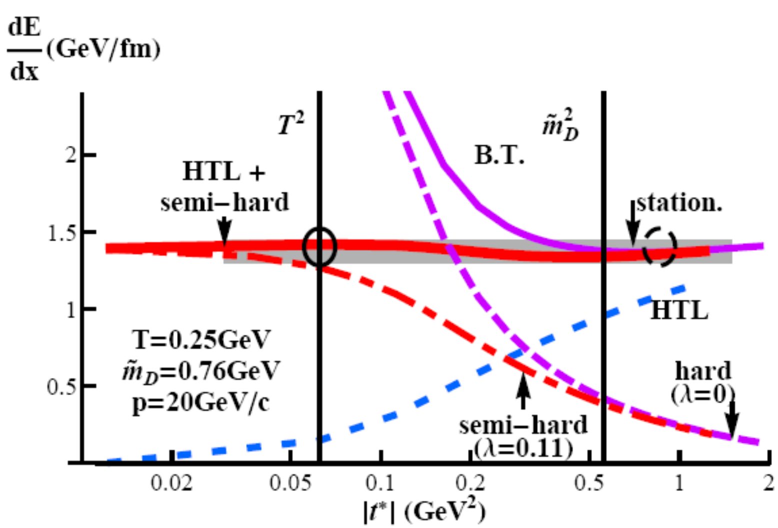
$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{Dself}(T)}$$

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

hep-ph/0607275

If t is small (<<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



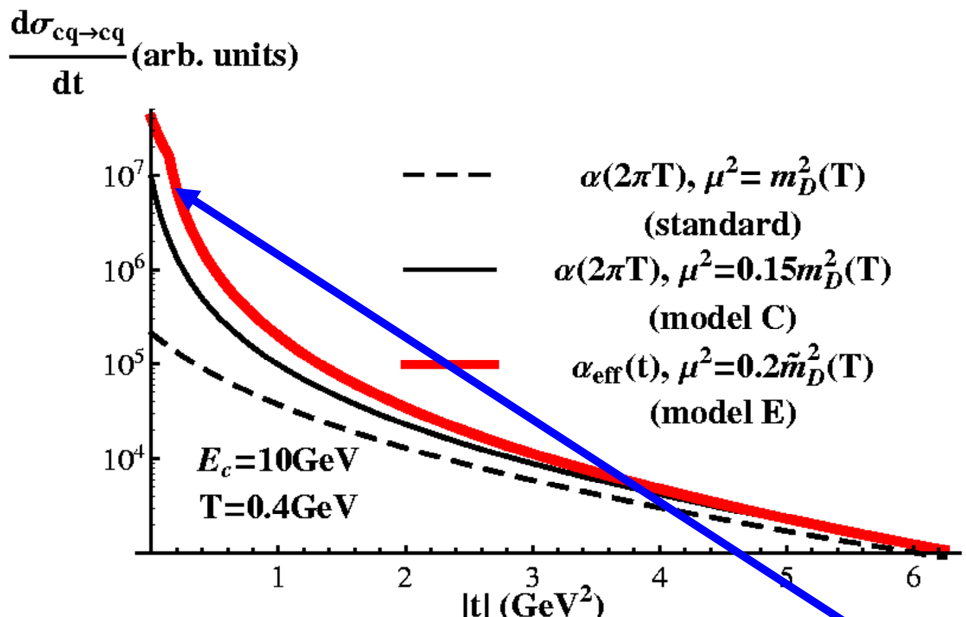
We do the same for QCD (a bit more complicated)
Phys.Rev.C78:014904
Result:

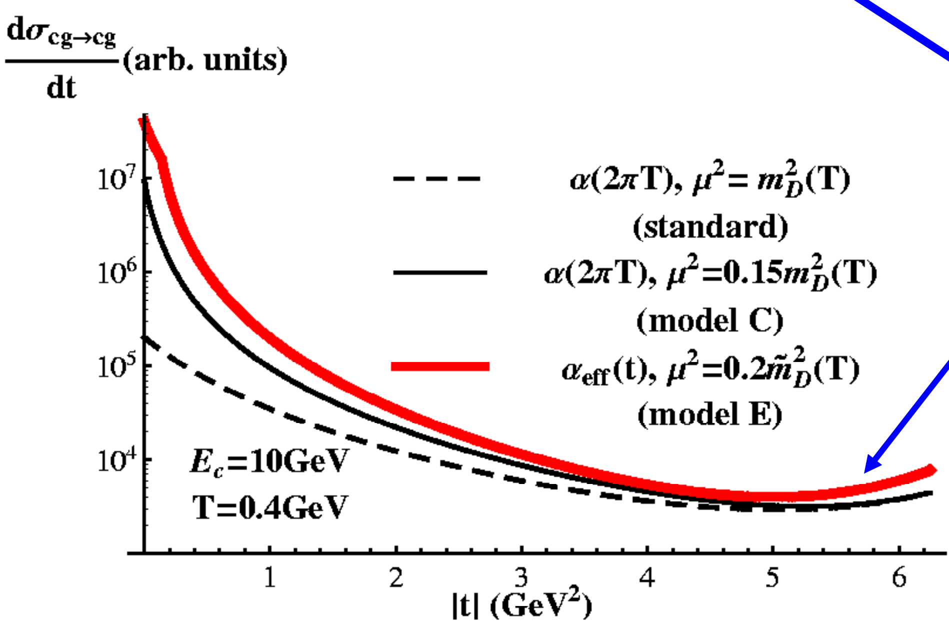
$\kappa \approx 0.2$

much lower than the standard value

$$\frac{d\sigma_F}{dt} = \frac{g^4}{\pi(s-M^2)^2}\left[\frac{(s-M^2)^2}{(t-\mu)^2} + \frac{s}{t-\mu} + \frac{1}{2}\right]$$

Consequences for cross sections





Large enhancement of cross sections at small t

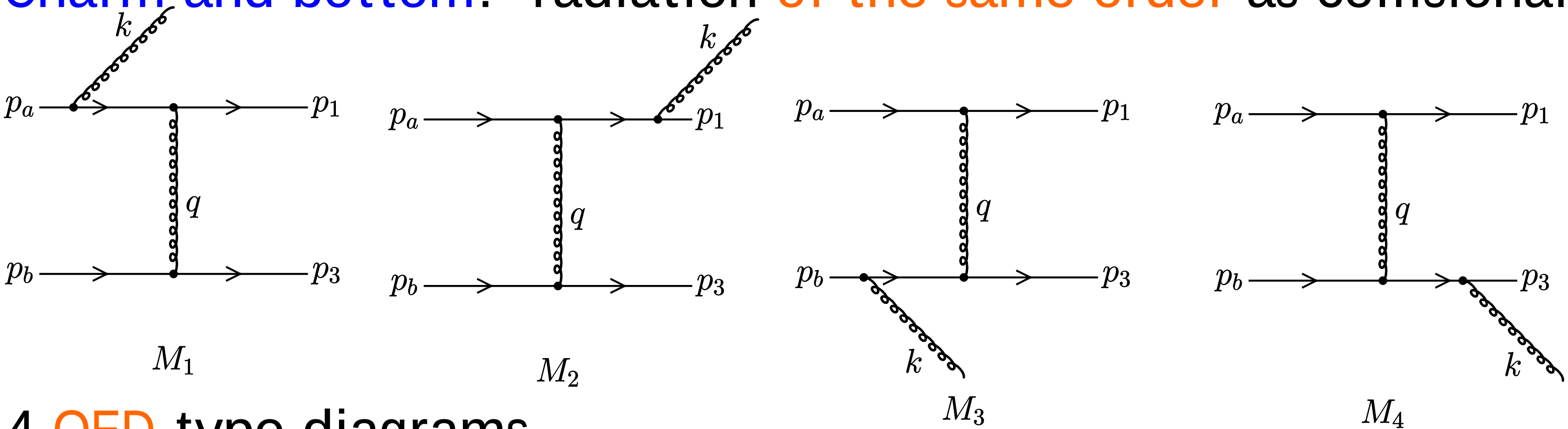
Little change at large t

Largest energy transfer from u-channel gluons

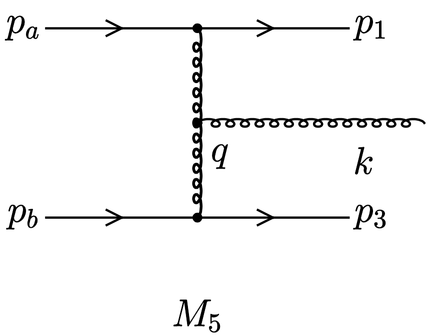
Inelastic Collisions

Low mass quarks : radiation dominantes 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

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

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

M_{QCD} dominates the radiation

M^{SQCD} in light cone gauge

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

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

k_t , ω = 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

leading order: no emission from light q

heals colinear divergences

m=0 -> Gunion Bertsch

Energy loss:

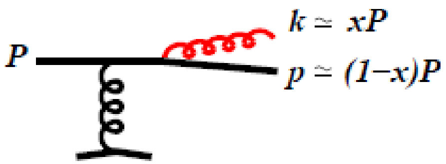
$$\frac{\omega d^4 \sigma^{rad}}{dx d^2 k_t dq_t^2} = \frac{N_c \alpha_s}{\pi^2} (1 - x) \cdot \frac{d\sigma^{el}}{dq_t^2} \cdot P_{rad}$$

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

Subatech

Landau Pomeranschuk Migdal Effekt (LPM)

reduces energy loss by gluon radiation



Heavy quark radiates gluons

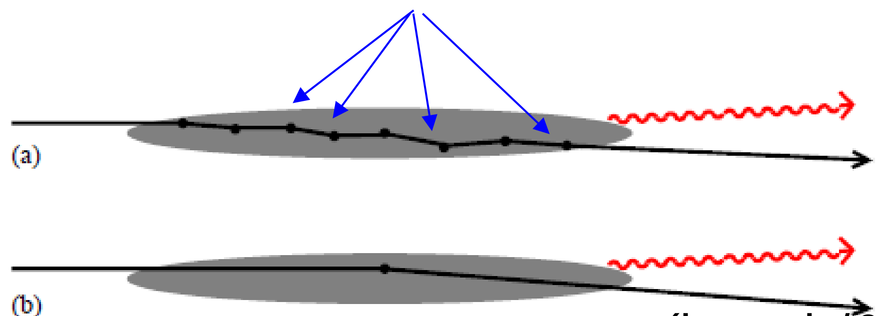
gluon needs time to be formed

Collisions during the formation time

do not lead to emission of a second gluon

emission of one gluon

(not N as Bethe Heitler)



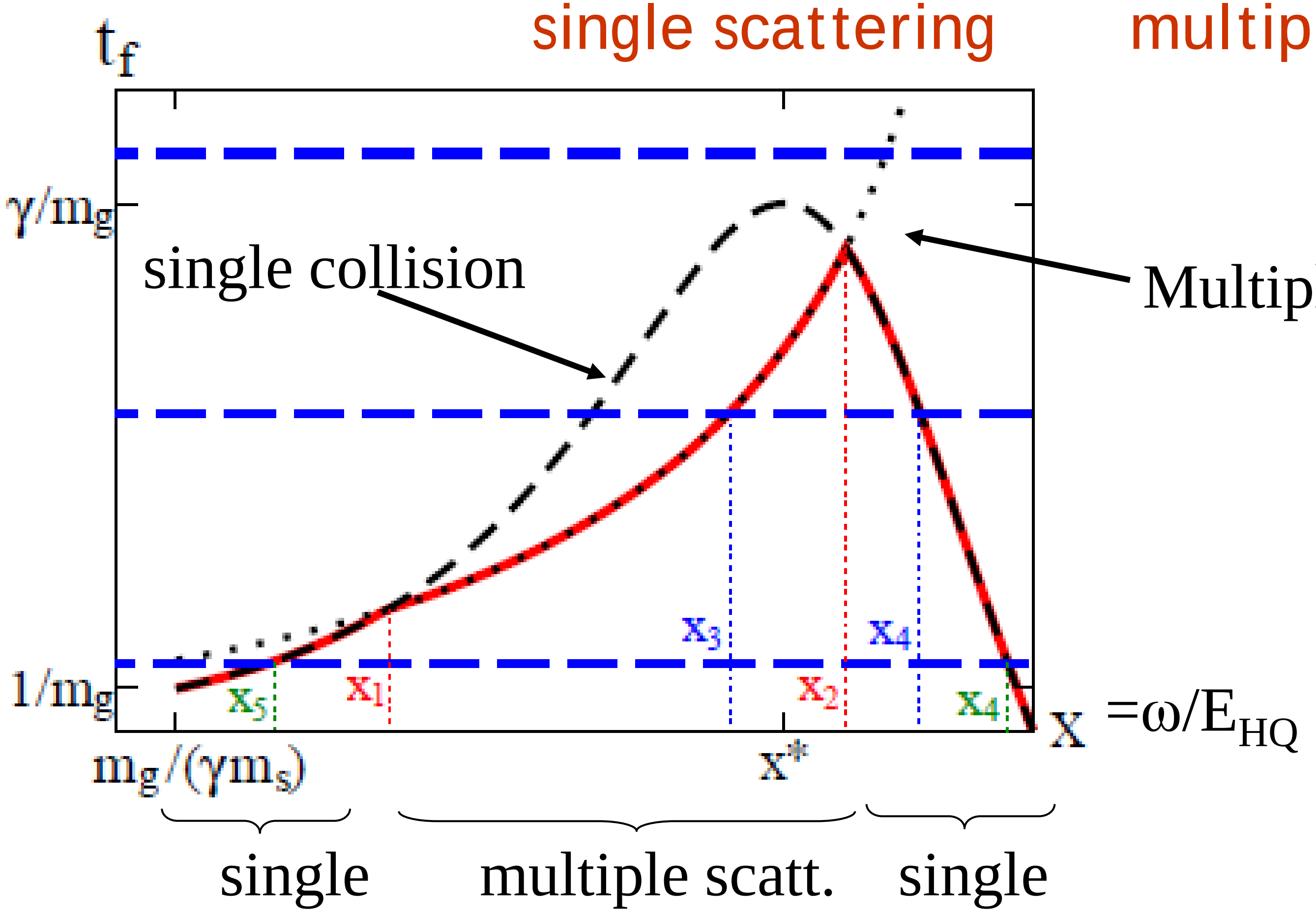
(hep-ph/0204343)

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

Multiple scatt .QCD: $\approx N_{coll} \langle k_t^2 \rangle = t_f \, \hat{q}$ single scatt.

dominates x<1 dominates x≈1 dominates x<<1

$$\underbrace{t_f \frac{x}{2E}\left[\frac{m_s^2}{(1-x)} + \frac{m_g^2}{x^2}\right]}_{\text{single scattering}} + \underbrace{t_f^2 \frac{x\hat{q}_s}{2E(1-x)}}_{\text{multiple scattering}} \simeq 1\,.$$

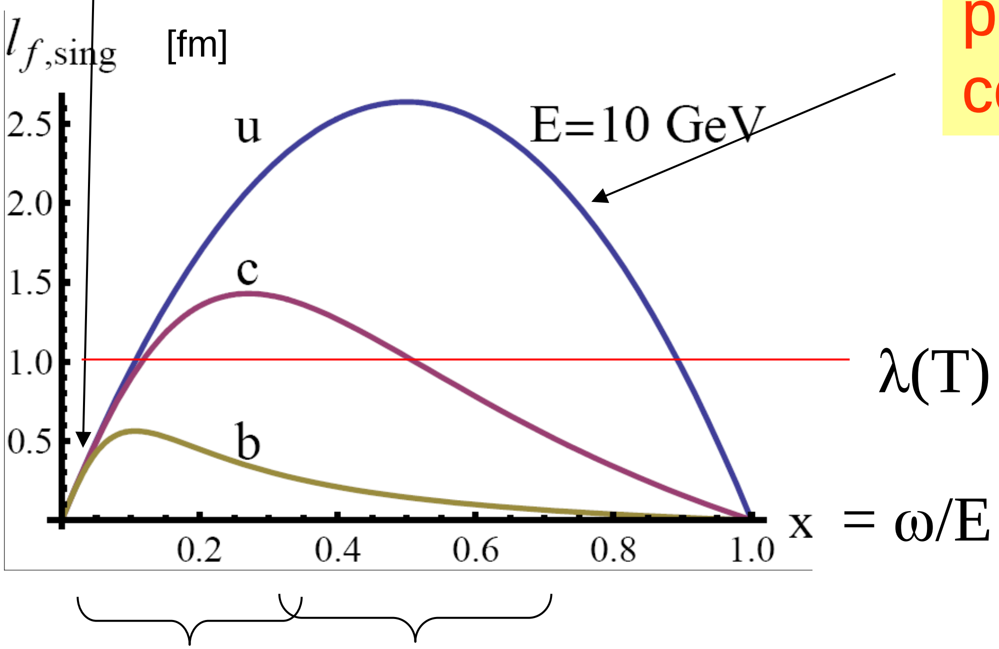


At intermediate gluon energies formation time is determined by multiple scattering

Subatech

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



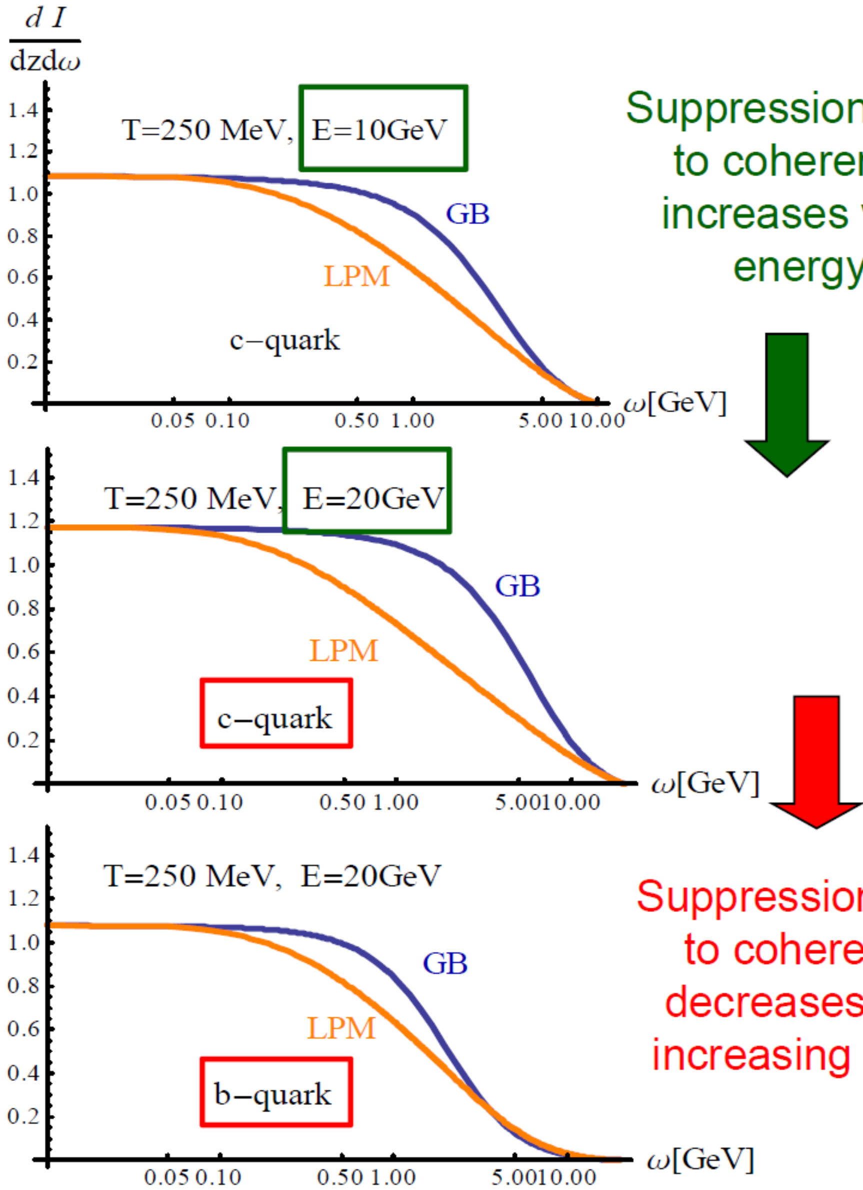
LPM important for intermediate x where formation time is long

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

Dominant region for average E loss $x\frac{d\sigma}{dx}$

Subatech

Consequences of LPM on the energy loss



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

LPM effect

Subatech

.. And if the medium is absorptive (PRL 107, 265004)

$$-\frac{d^2W}{dz\,d\omega} \simeq -\frac{2\alpha}{3\pi}\frac{\hat q}{E^2}\int_0^\infty d\bar t\,\underbrace{\omega\cos(\omega\bar t\,)\sin\left[\omega|n_r|\beta\bar t\left(1-\frac{\hat q\bar t}{6E^2}\right)\right]}_{\text{Ter-Mikaelian}}\underbrace{\mathcal{F}(\bar t\,)}_{\text{damping}}$$

$$\mathcal{F}(t) = \exp[-\omega|n_i|\beta t(1-\hat q t/(6E^2))]$$

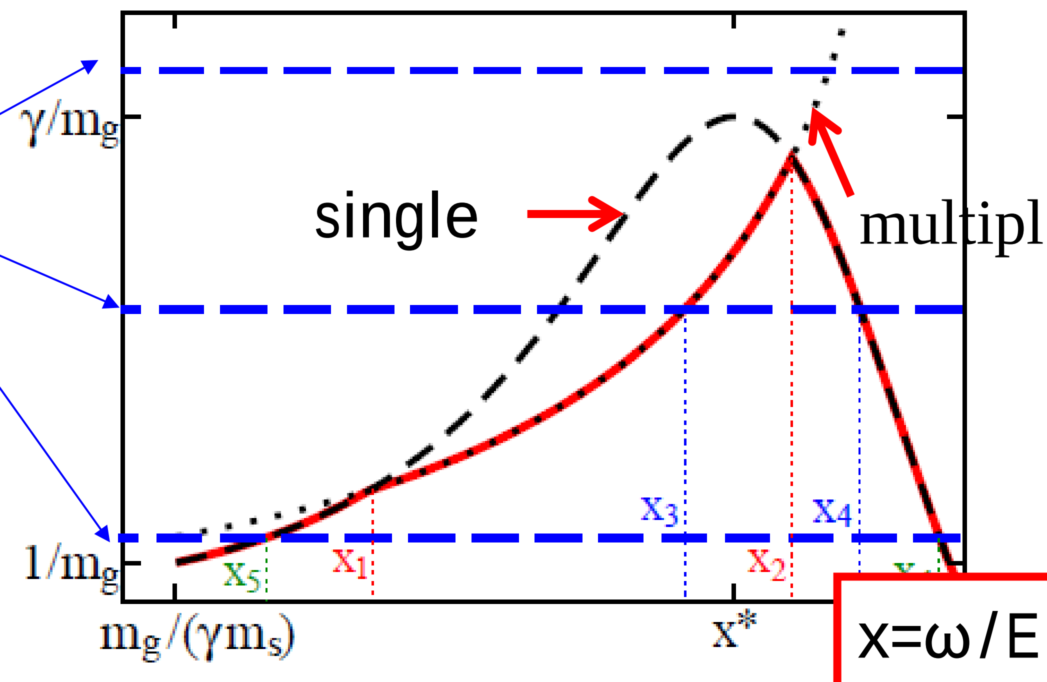
with

$$n^2(\omega) = 1 - m^2/\omega^2 + 2i\Gamma/\omega$$

t_f

New timescale $1/\Gamma$

damping dominates radiation spectrum



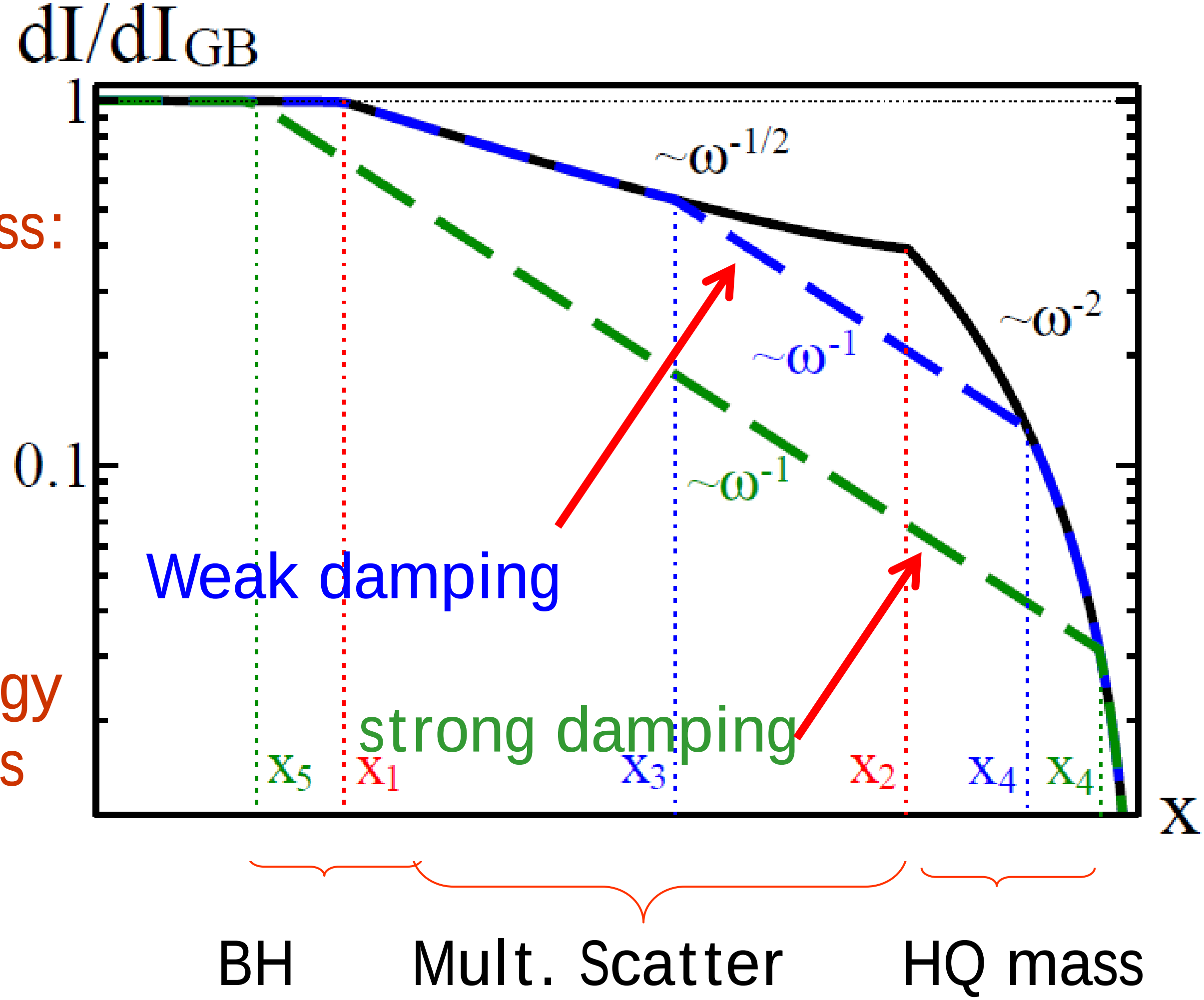
Subatech

Influence of LPM and damping on the radiation spectra

$$\frac{dI}{dI_{GB}} \simeq \frac{\tilde{t}_f}{t_{GB}} \qquad \tilde{t} = min\{t^{single}, t^{multiple}, t^{damping}\}$$

LPM, damping, mass:
Strong reduction
of gluon yield
at large ω

LPM:
increase with energy
decrease with mass



RHIC 200 AGeV and LHC 2.76 TeV

. c,b-quark transverse-space distribution according to Glauber

• c,b-quark transverse momentum distribution as in d-Au (STAR)… very similar to p-p (FONLL) □ Cronin effect included.

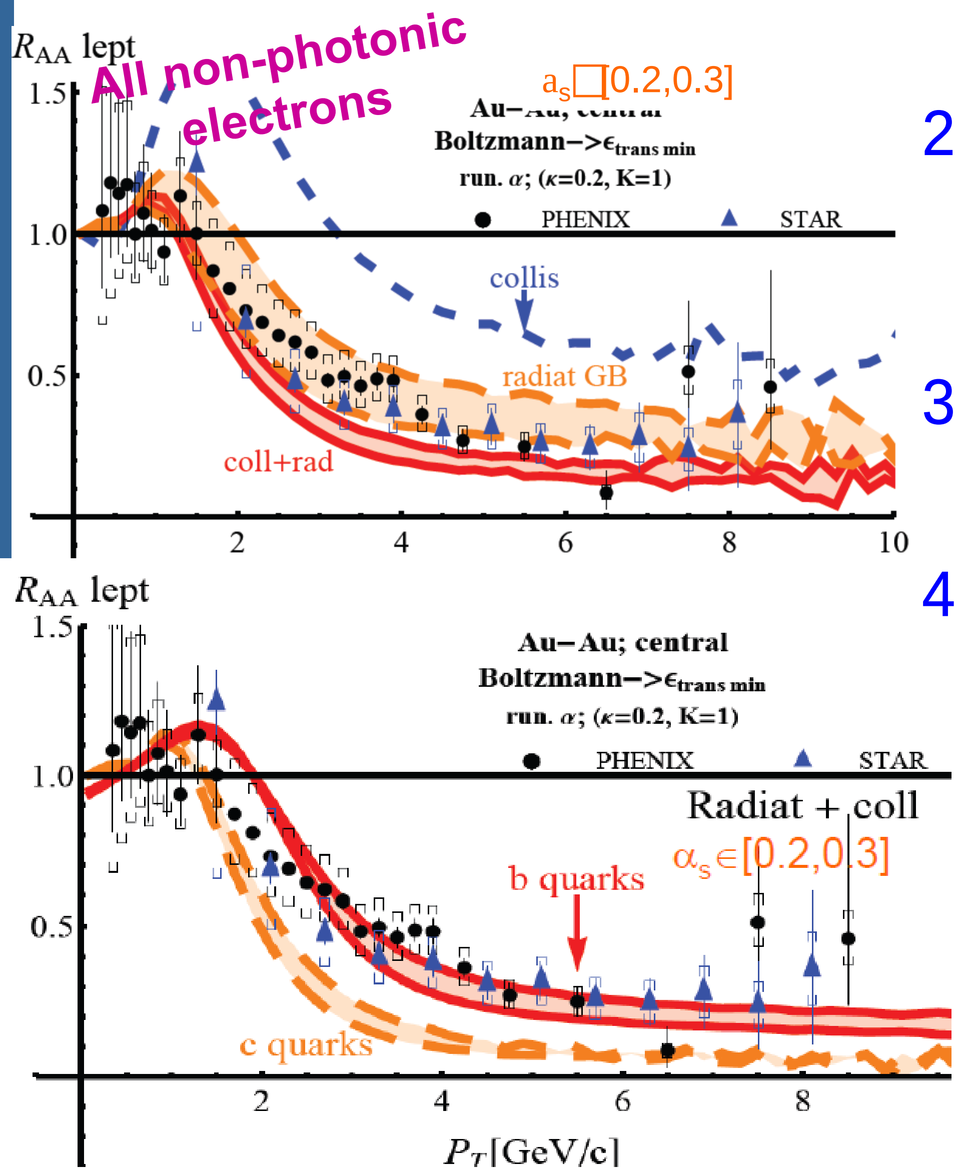
• c,b-quark rapidity distribution according to R.Vogt (Int.J.Mod.Phys. E12 (2003) 211-270) and priv comm.

• QGP evolution: 4D / Need local quantities such as T(x,t) □ taken from hydro dynamical evolution (Heinz & Kolb)

•D meson produced via coalescence mechanism. (at the transition temperature we pick a u/d quark with the a thermal distribution) but other scenarios possible.

•No damping yet

Results RHIC I

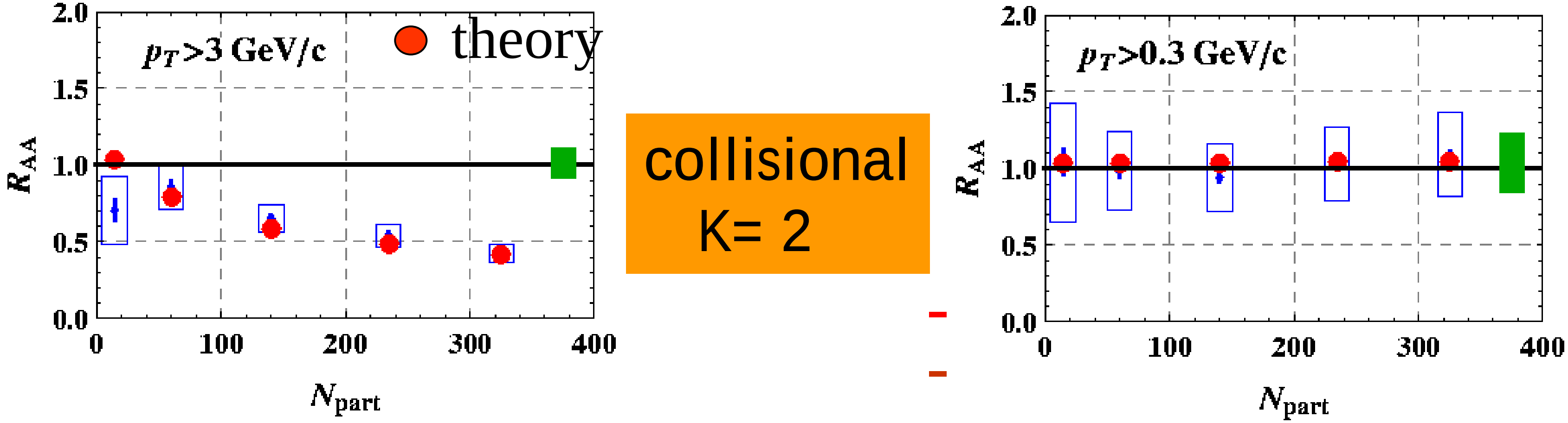


1. Too large quenching (but very sensitive to freeze out)
2. Radiative Eloss indeed dominates the collisional one
3. Flat experimental shape is well reproduced
4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC)

separated contributions e **from** D and e **from** B.

Results RHIC II

arXiv 1005.1627 (PHENIX)



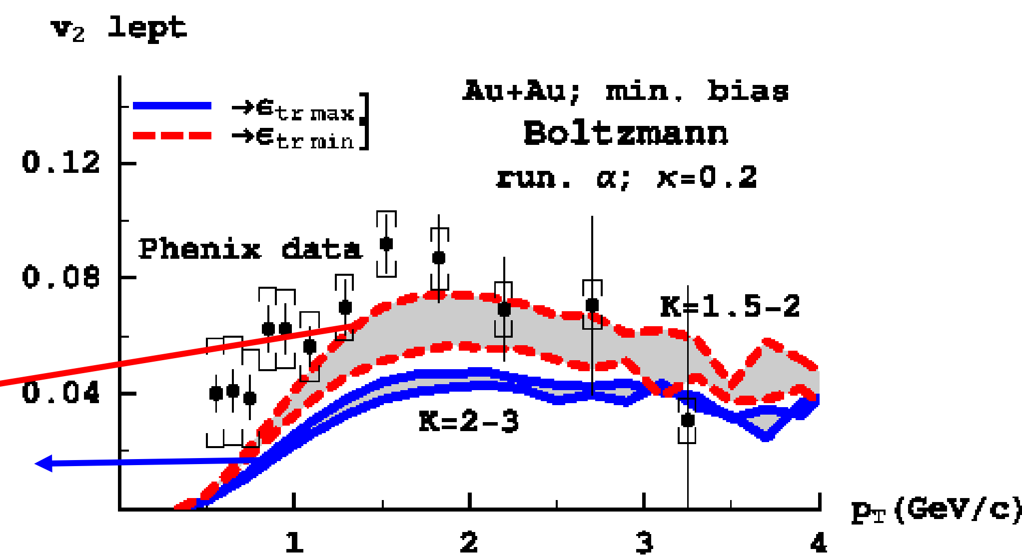
collisional
K= 2

R_{AA} centrality dependence (PHENIX) well reproduced

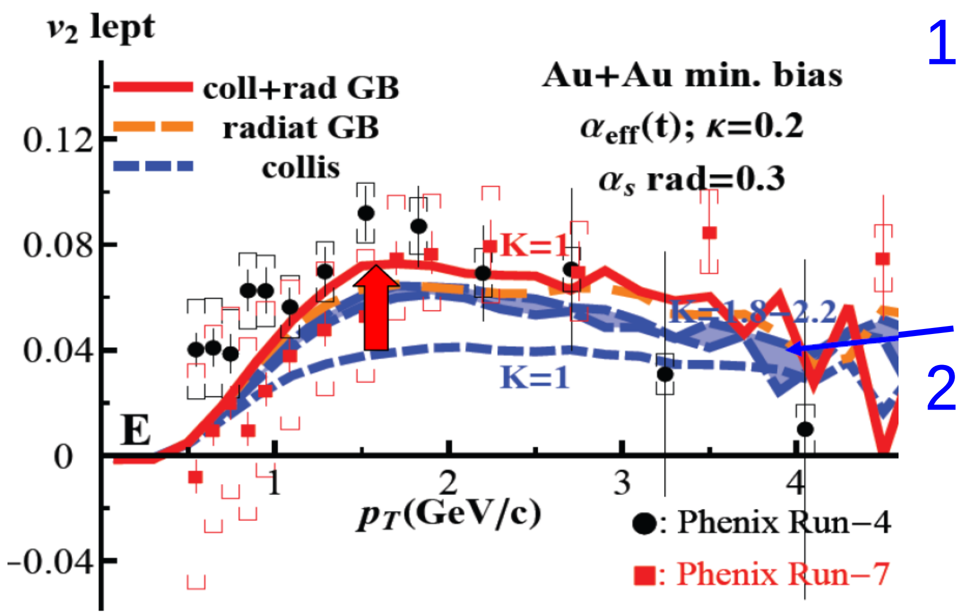
v_2 of heavy mesons depends on where fragmentation/ coalescence takes place

end of mixed phase

beginning of mixed phase



Results RHIC III

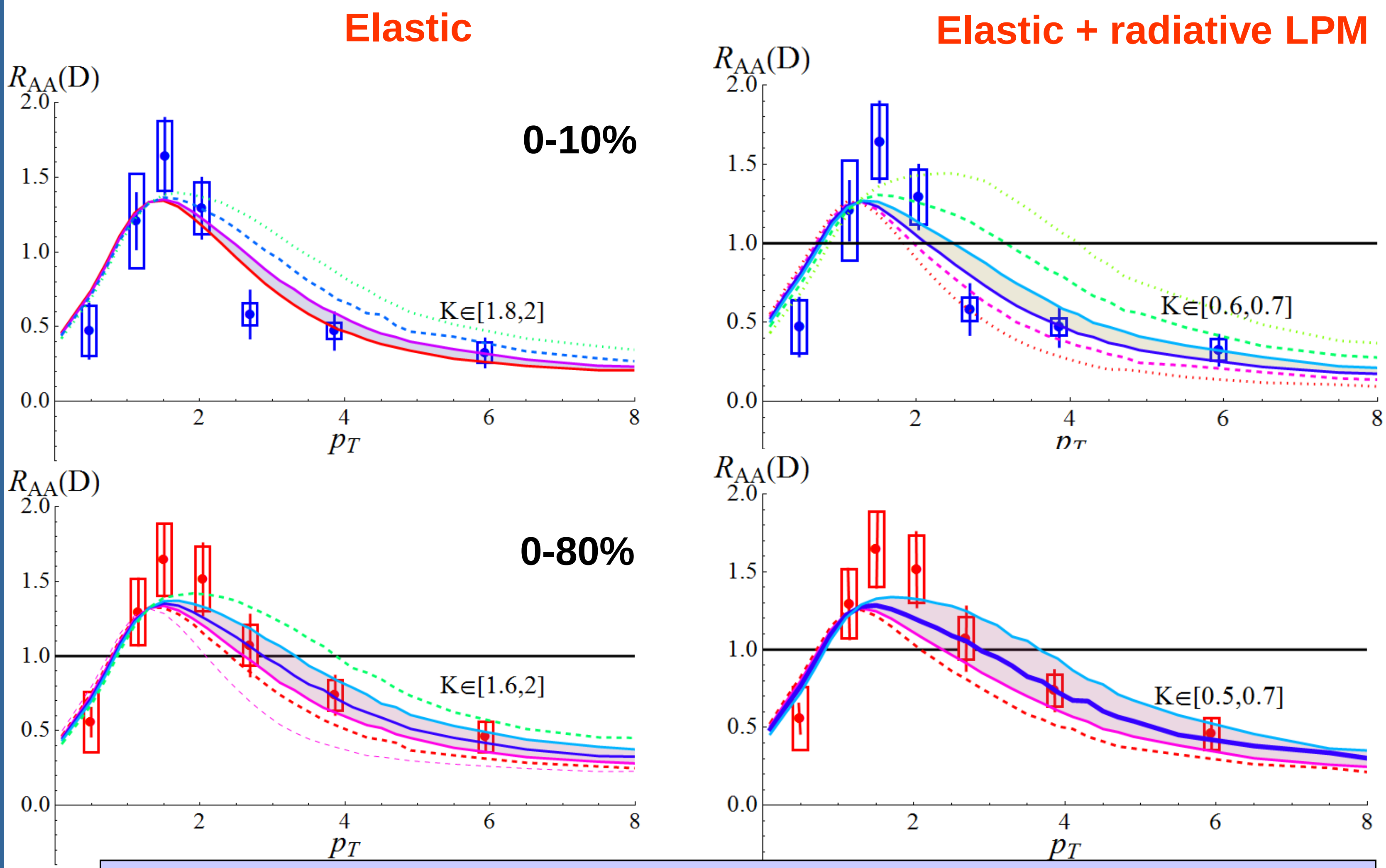


1. Collisional + radiative energy loss + dynamical medium : *compatible* with data
2. To our knowledge, one of the first model using radiative Eloss that reproduces v_2

For the hydro code of Kolb and Heinz:

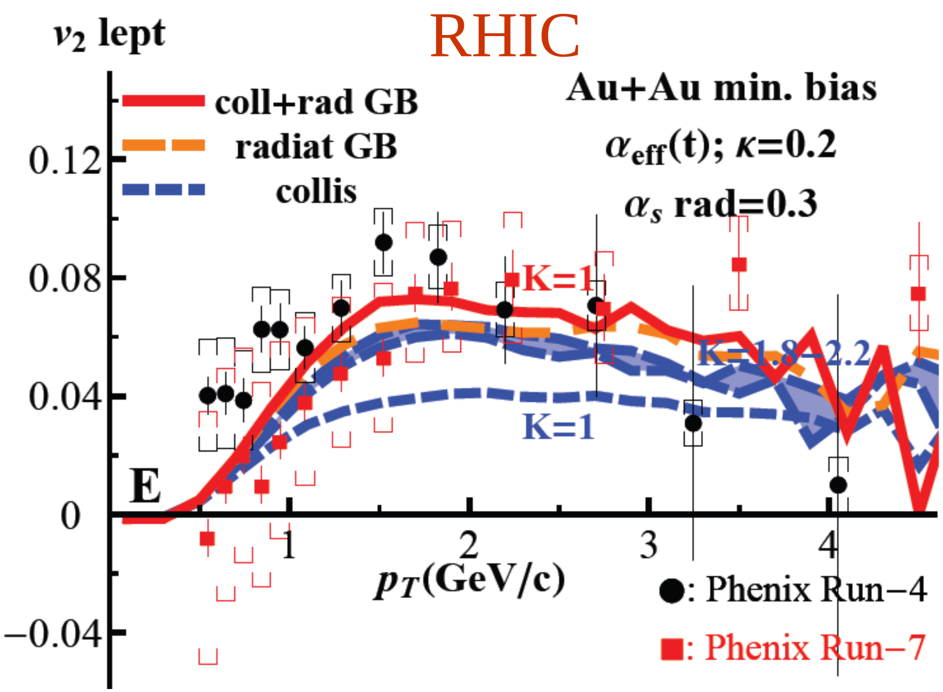
K = 1 compatible with data
K = 0.7 best description

Results RHIC IV: D mesons

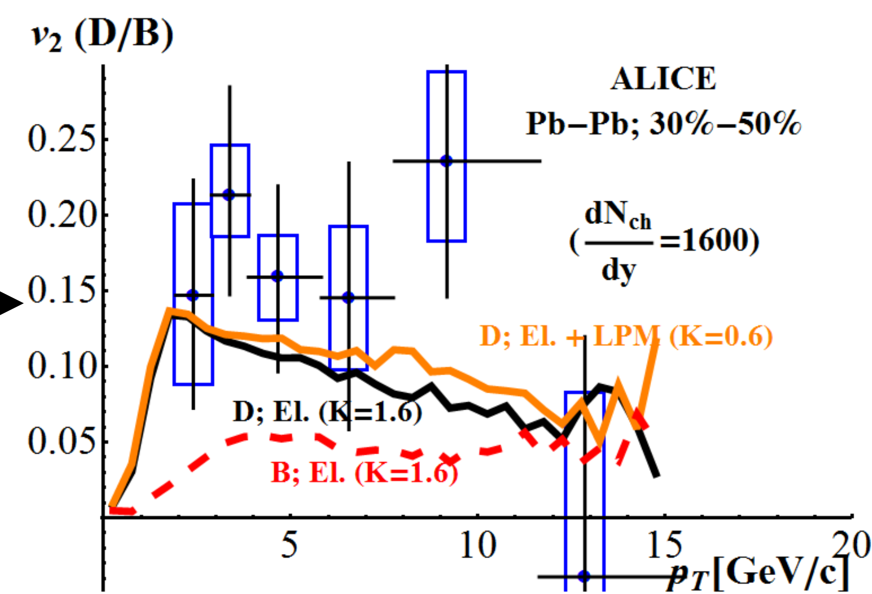


No form difference between coll and coll + rad

Results LHC I

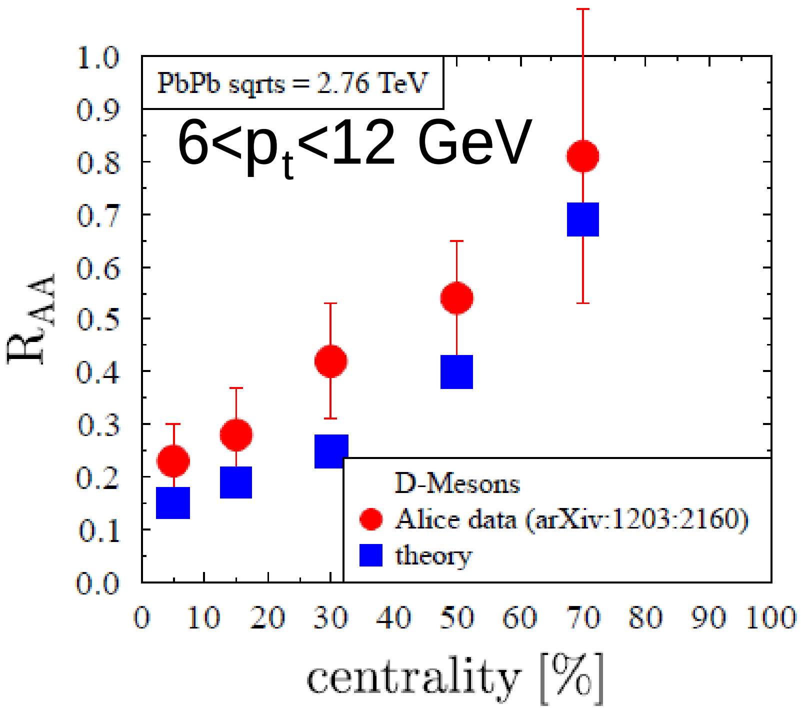


v_2 very similar at RHIC and LHC
B and b flow identical
D and c 20% difference (hadronization)



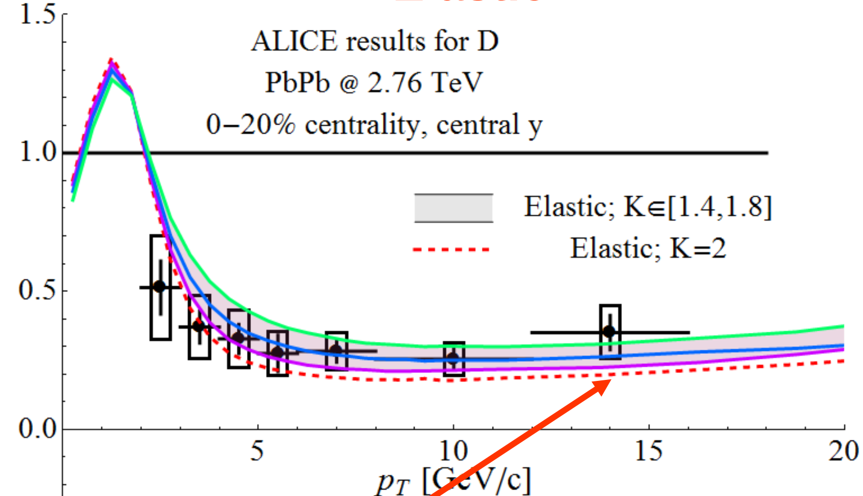
Difference between B and D can validate the model (only difference is the mass)

Results LHC II

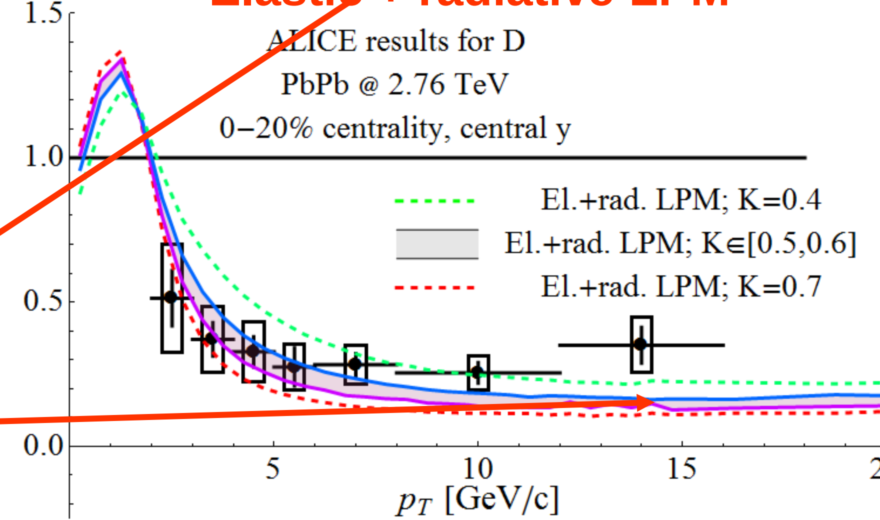


Same calculations as at RHIC
only difference:
initial condition
dN/dy (central) = 1600

Elastic



Elastic + radiative LPM

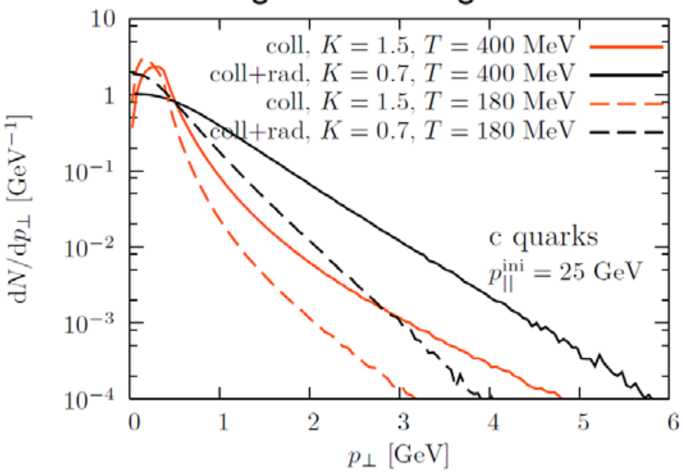


High pt: coll+rad gives
slightly more suppression

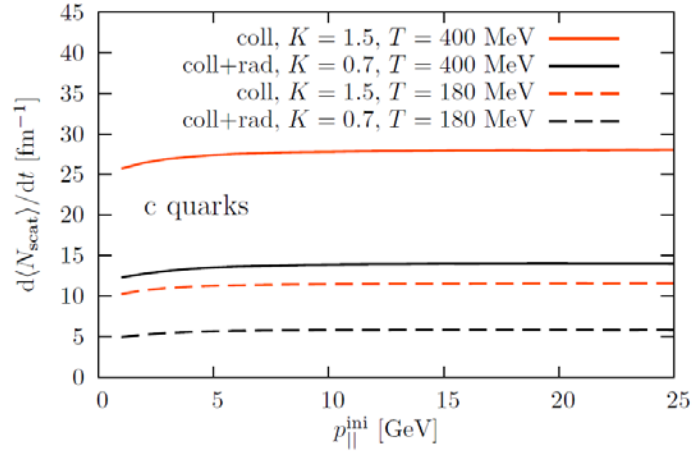
Is there a way to distinguish between radiative and collisional energy loss

Yes: by D-Dbar correlations

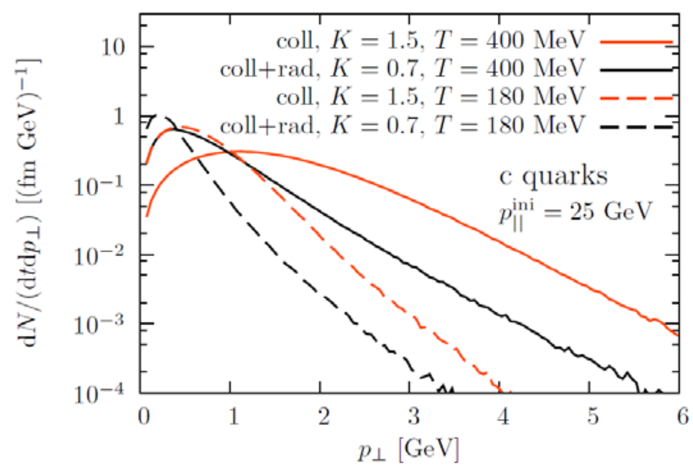
Single scattering:



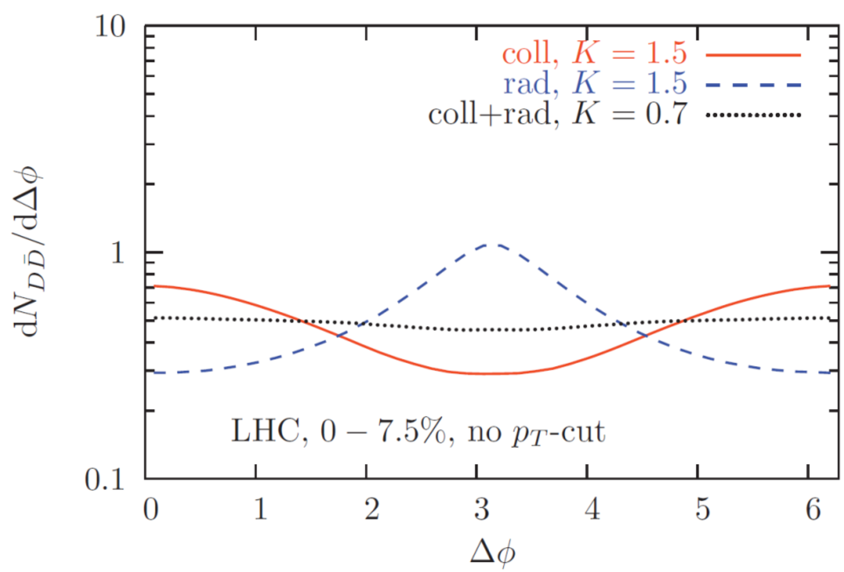
Evolution in a medium:

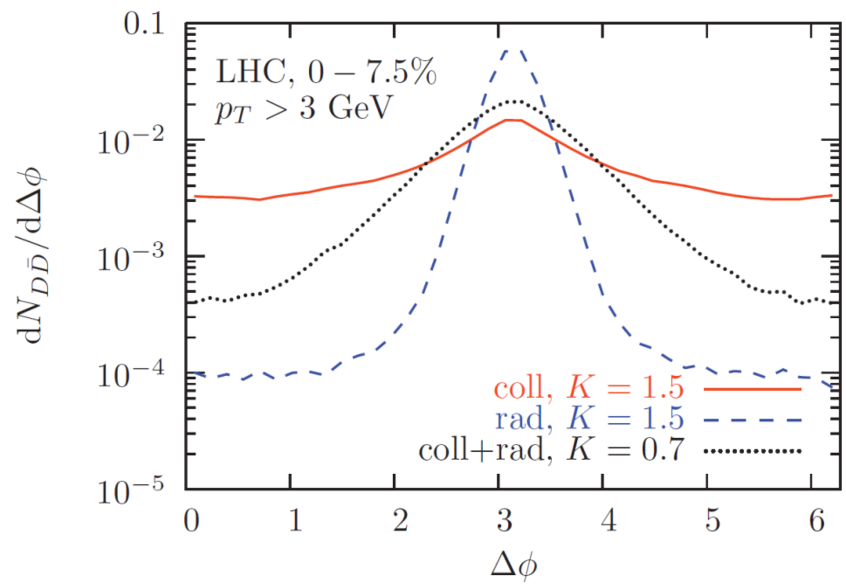


- p_T-distribution in a single scattering: larger $\langle p_T \rangle$ for **coll+rad ($K = 0.7$)**.
- Initialize in a static, infinite medium at temperature T with a given longitudinal momentum, evolve according to the Boltzmann equation for $\Delta t = 0.4$ fm.
- Scat. rate is larger for coll ($K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



Initially: back to back

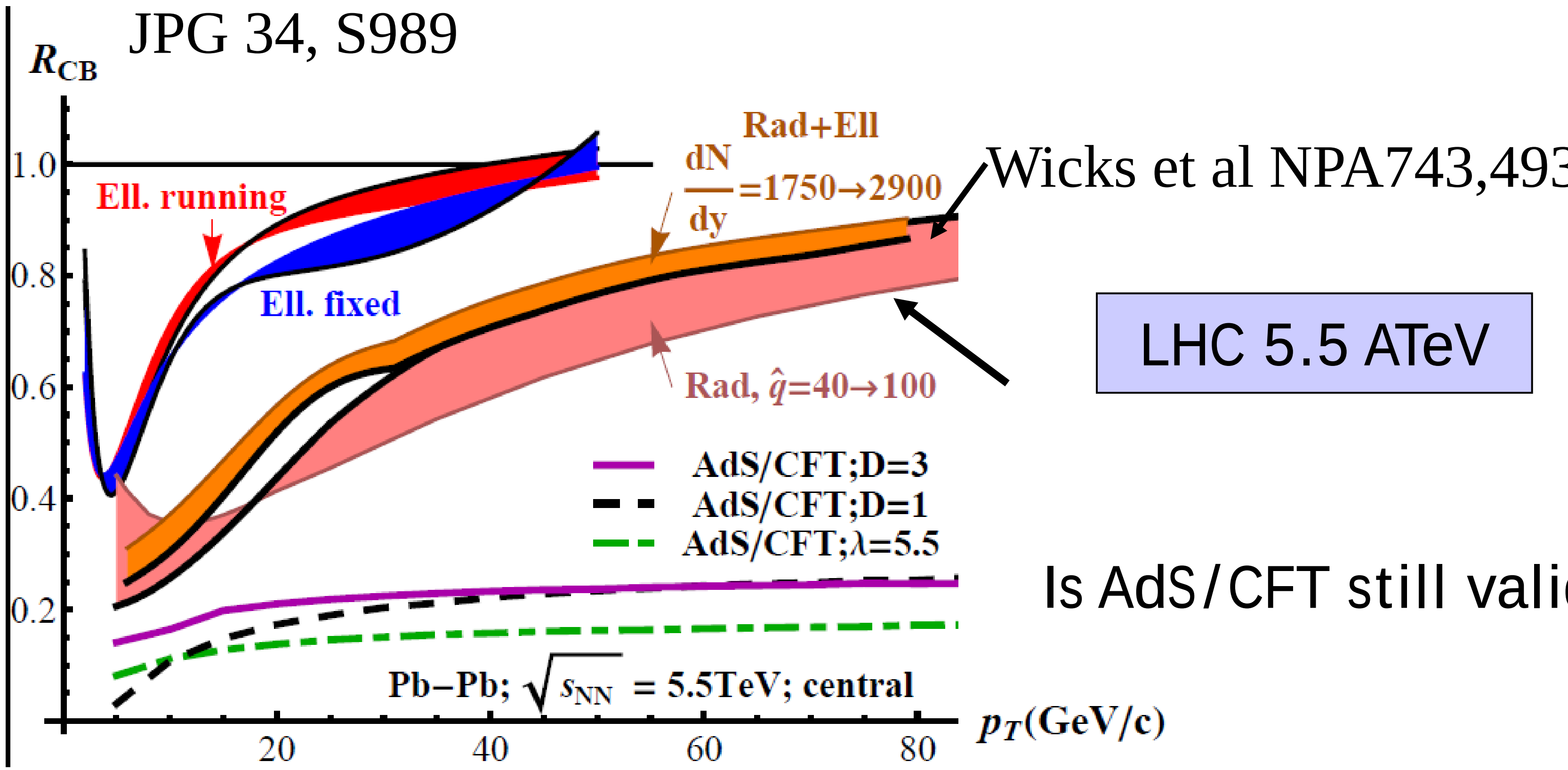




High p_T DDbar most sensitive

Results LHC III

Ratio charm/bottom (Horowitz et al.)



Is AdS/CFT still valid?

Charm/bottom ratio will show whether pQCD or AdS/CFT is the right theory to describe HI reactions

Conclusions

All experimental data are compatible with the assumption that QCD describes

energy loss and elliptic flow v_2

of heavy quarks.

RHIC and LHC described by same program (hydro ini is diff)

Special features running coupling constant

adjusted Debye mass

Landau Pomeranschuk Migdal

Description of the expansion of the medium (freeze out, initial cond.) can influence the results by at least a factor of 2 **(1102.1114)**

Correlations show diff. between collisional and radiative

Refinements still necessary:

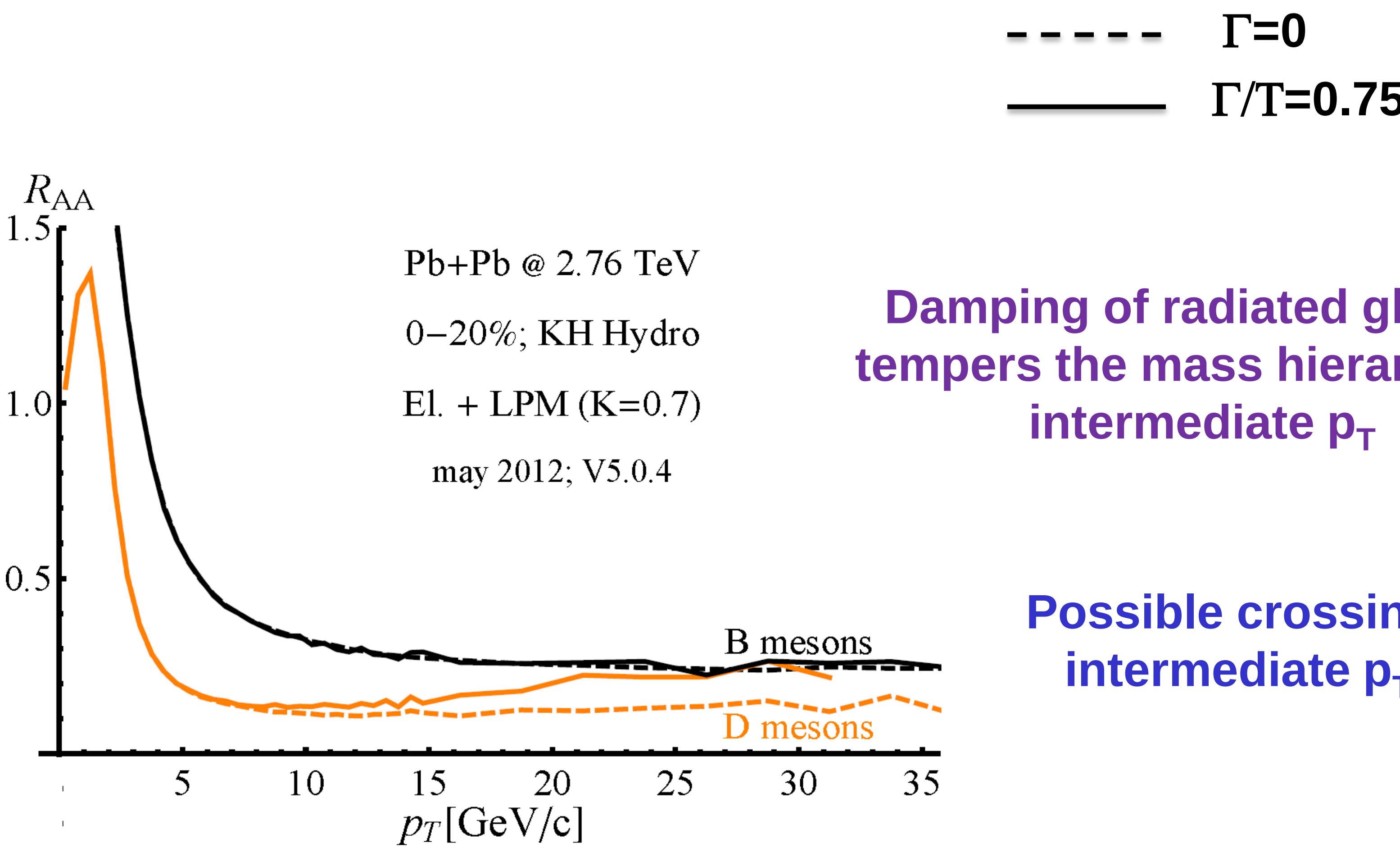
Running coupling constant for gluon emission vertex

gluon absorption and LPM effect improvement

Expansion scenario (fluctuating initial conditions :EPOS)

Absorptive medium influences the spectra at high p_t

RHIC « reference »: no effect seen for Γ=0.75T

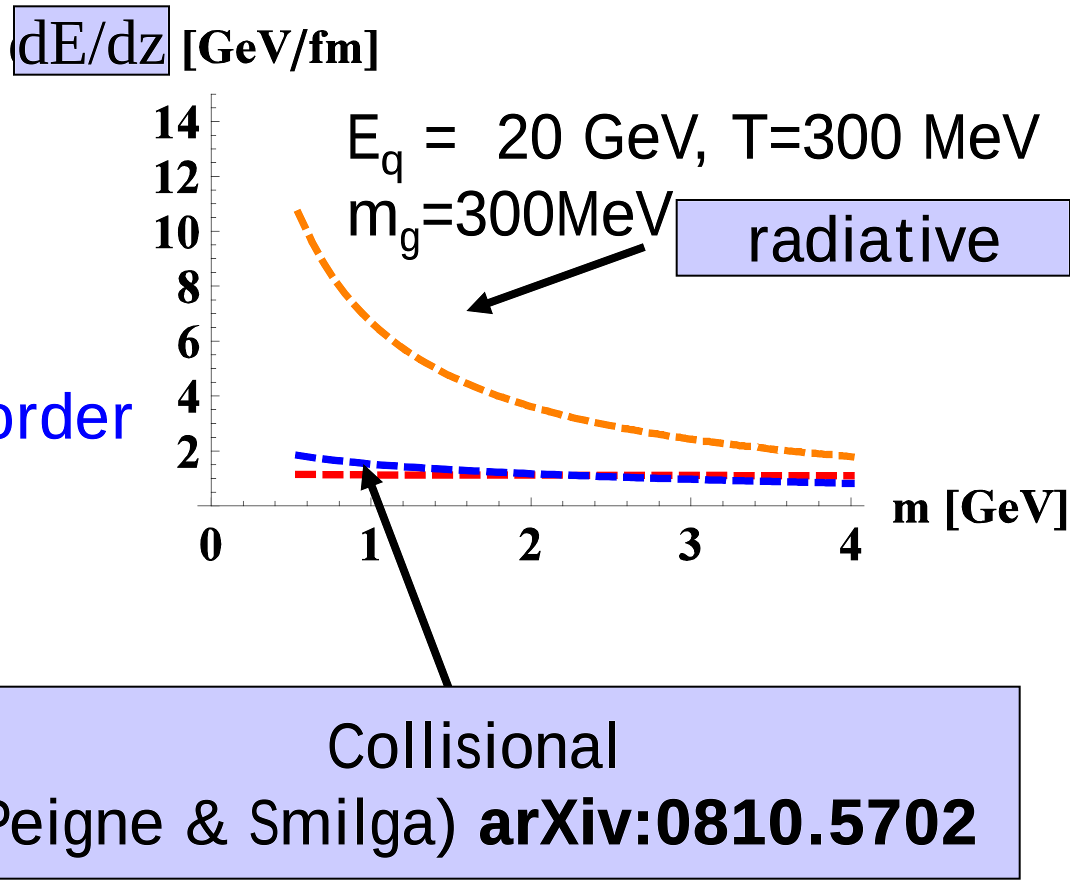


Damping of radiated gluons tempers the mass hierarchy at intermediate p_T

Possible crossing at intermediate p_T ?

Energy loss per unit length:

$$\frac{dE}{dz} = \int d^3k \ \rho_k \int \Delta E \frac{d\sigma}{dx} \ dx = \int d^3k \ \rho_k E \int x \frac{d\sigma}{dx} dx$$



For large quark masses:
Collisional and radiative energy loss of the same order

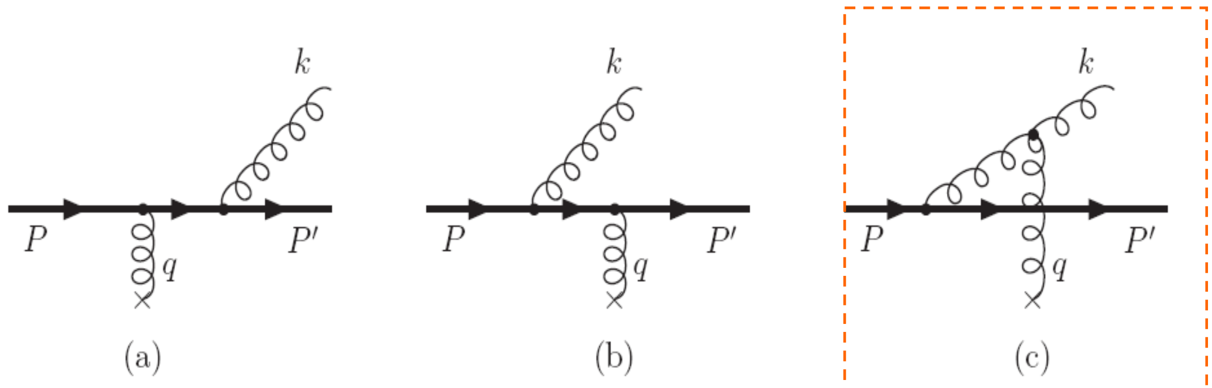
Small q masses:
radiative dominante

Rad: $\Delta E \propto E$

Coll: $\Delta E \propto \ln E$

Landau Pomeranschuk Migdal (LPM) Effect:

A second gluon can only be emitted after the first is formed



In leading order no gluon emission from light quarks

Formation time for a single collision

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

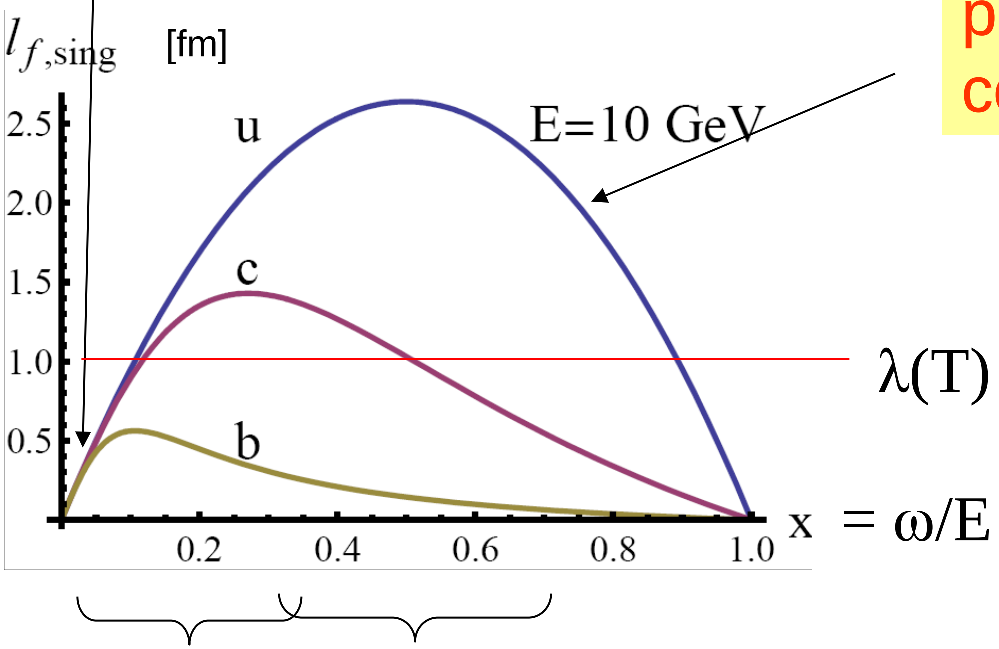
x=ω/E

At $q_t = k_t = 0$:

$$l_{f,\mathrm{sing}} \approx \frac{2x(1-x)E}{m_g^2 + x^2 M^2}$$

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



LPM important for intermediate x

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

Dominant region for average E loss $x\frac{d\sigma}{dx}$

Presumably at RHIC and LHC a plasma (QGP) is formed which is, however, not directly visible. One has to conclude on its existence from decay products

This is all but easy:

- The multiplicity of almost all particles coincides with the expectation of a statistical model

  for given $\mu \approx 0$ and $T \approx 160$ MeV $= T_c$

  Consequence: loss of memory of the history of the QGP

  may measure simply freeze out condition

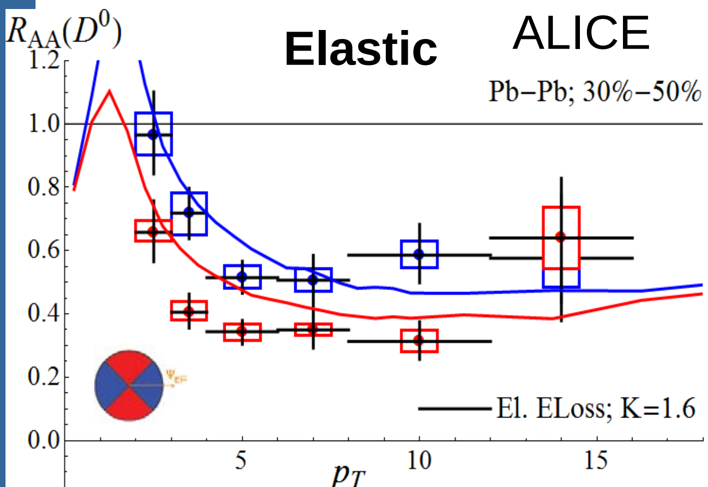
-Spectra distorted by final state hadronic interactions

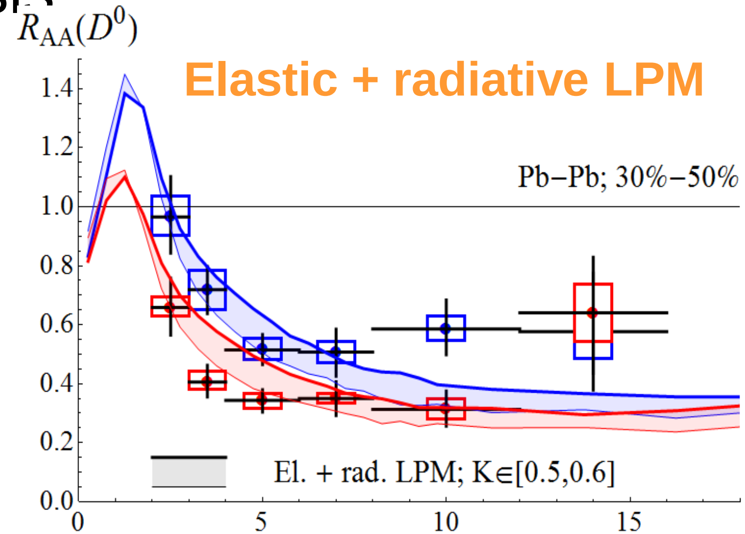
-> most of single particle obs. do not elucidate the enigma

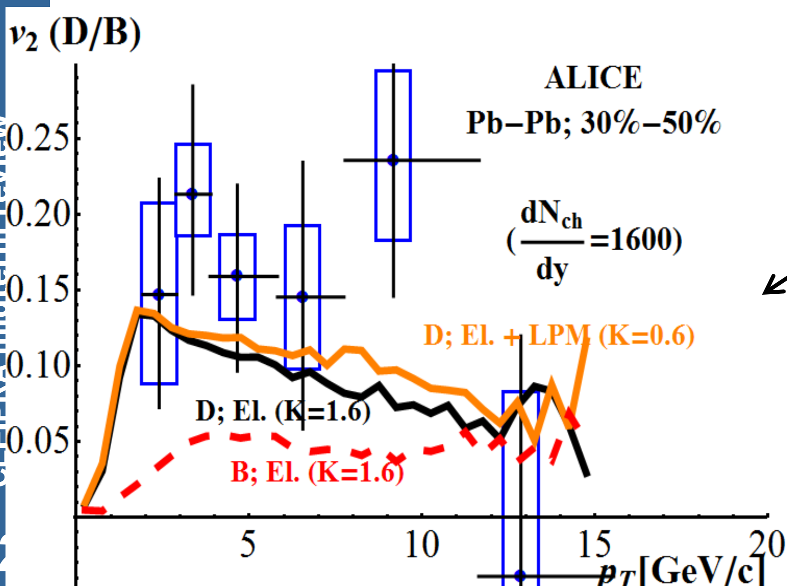
- collective variables
- Jets
- heavy mesons (containing a c or b quark and which do not come to equilibrium)

D mesons at LHC (more differential observables)

"in plane" – "out of plane" analysis





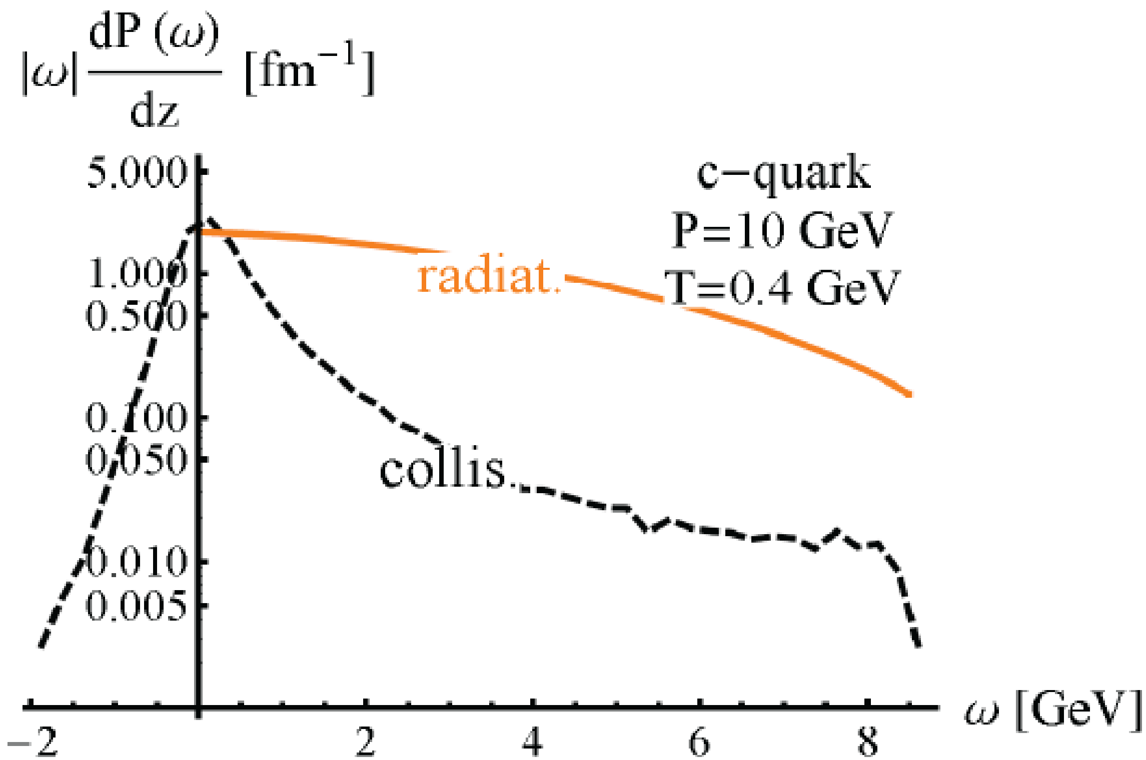


Some systematic trends: el. + rad. LPM shows more coupling… sensitive to larger x in the radiation spectra

Late build up of the flow □Possible contribution from the hadronic phase (neglected in our approach) at intermediate p_T ?

Energy loss in elast. and radiat. collisions is different

Probability P of energy loss ω per unit length (T,M,...):



Radiative energy loss stronger than collisional