Tomography of the QGP at RHIC and LHC by heavy mesons

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in collaboration with

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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 collisional and radiative?

Results for RHIC and LHC

What makes heavy quarks (mesons) so interesting?

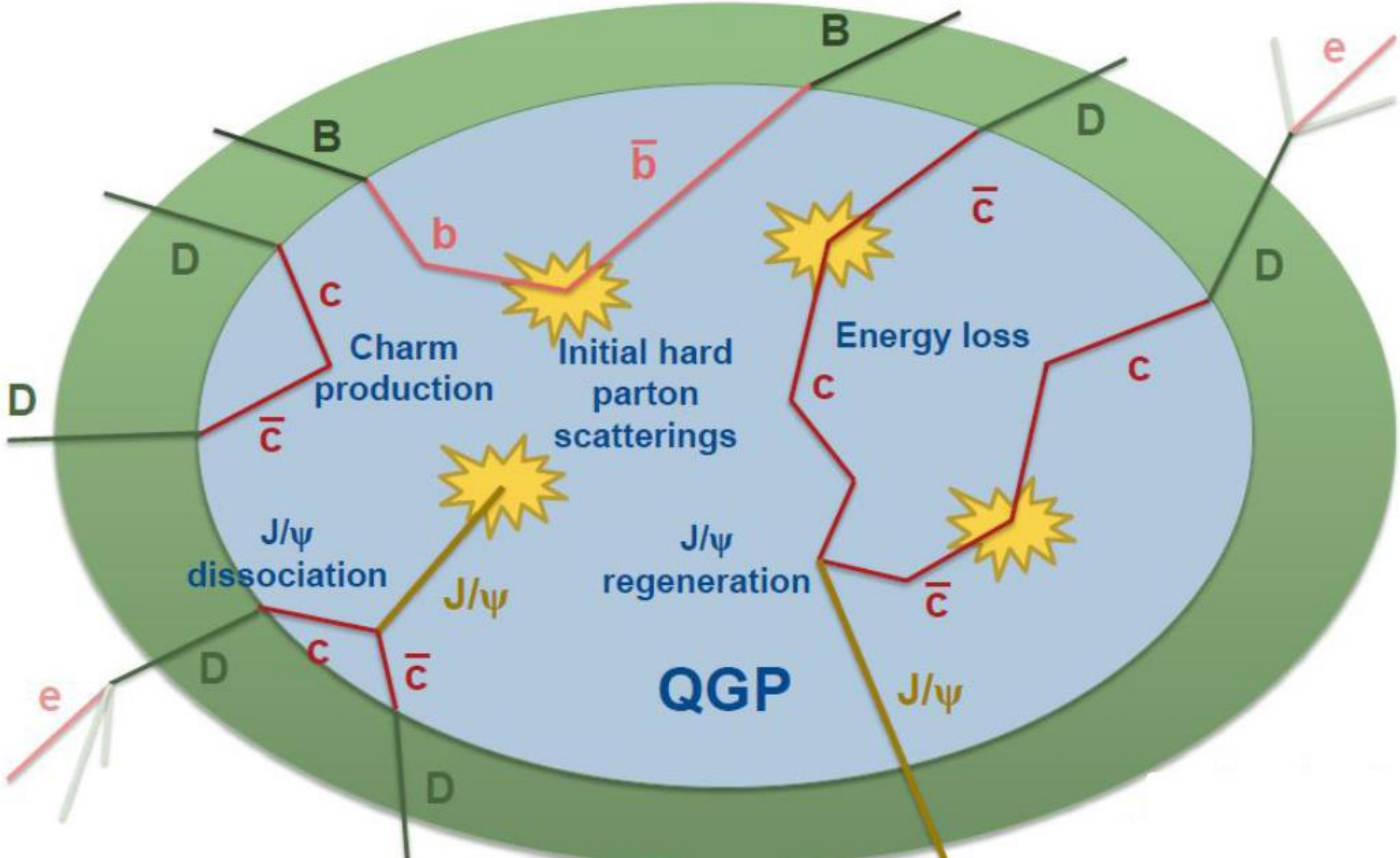
- produced in hard collisions (initial distribution: FONLL confirmed by STAR/Phenix)

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

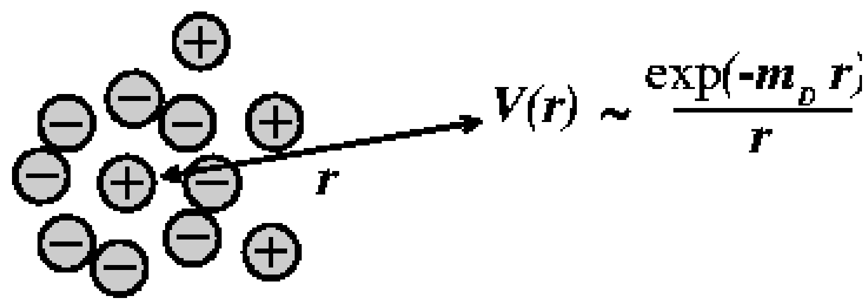
Our Approach

pQCD cross section like qQ -> qQ   in a medium has 2 parameters:

a) Running coupling constant

$$\frac{d\sigma}{dt} = \frac{16\pi\alpha_s^2}{(s-M^2)^2}\left[\frac{(s-m^2)^2}{(t-\kappa m_D^2)^2} + \frac{s}{t-\kappa m_D^2} + \frac{1}{2}\right]$$

b) Infrared regulator



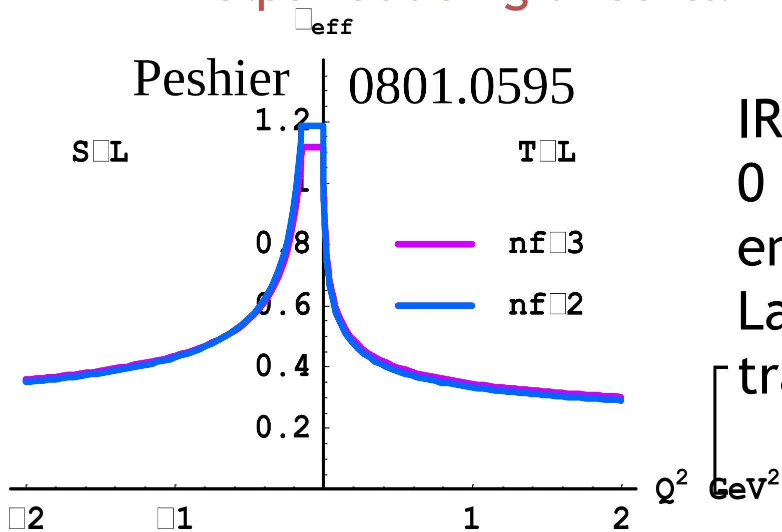
m_D regulates the long range behaviour of the interaction

Neither α_S nor $\kappa\ m_D^2$ are well determined
standard: α_S = constant or $\alpha_S\ (2\pi T)$
with κ =1 and **α** =.3: large K-factors (≈ 10) are necessary to describe data

Running α_s

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

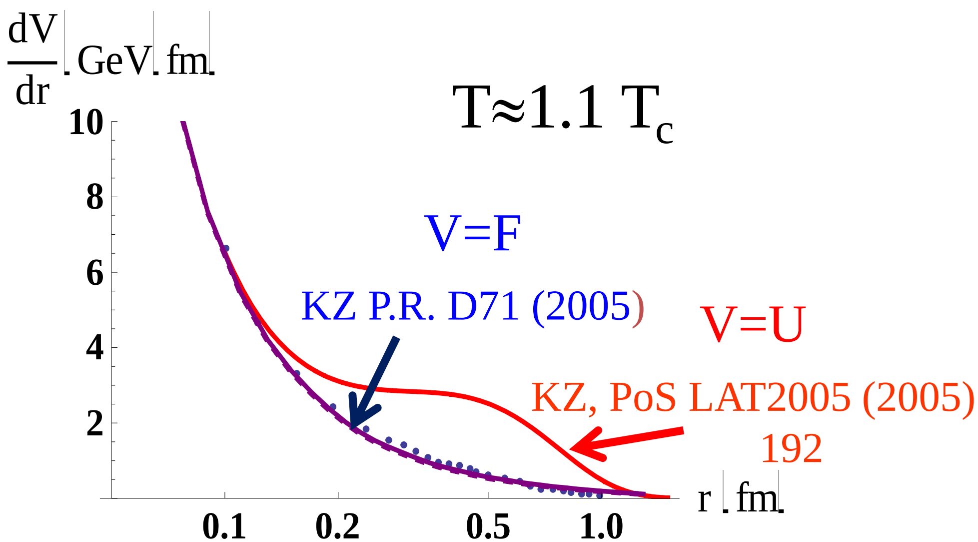
$$\frac{1}{Q_u}\int_{|Q^2|\le Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$

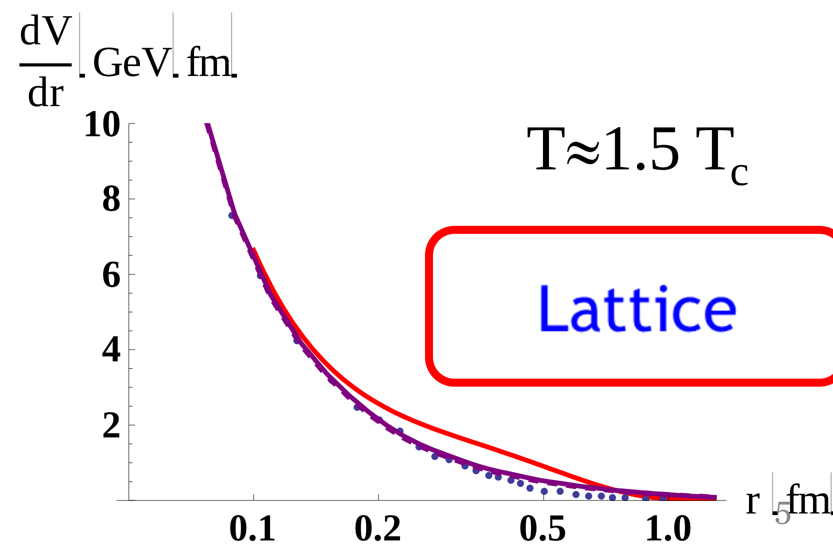


IR safe. The detailed form very close to Q^2 = 0 is not important does not contribute to the energy loss

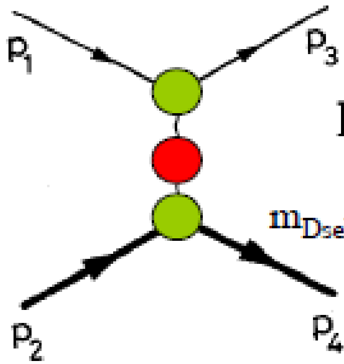
Large values for intermediate momentum-transfer

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





Infrared Regulator



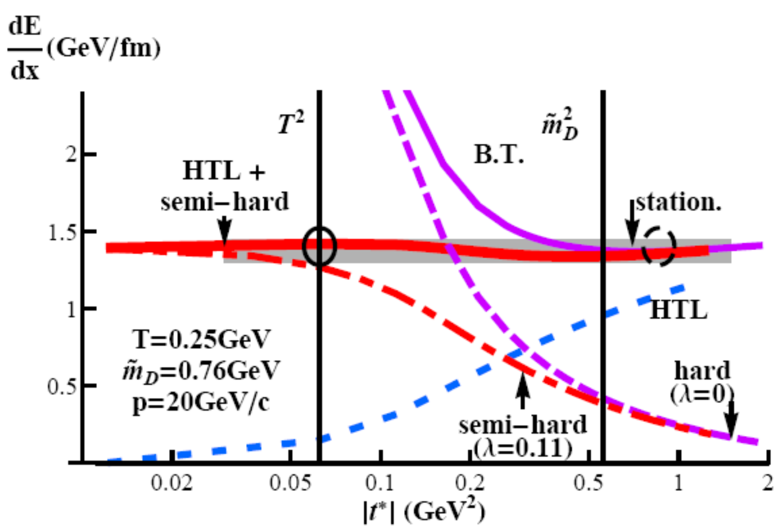
$$\text{prop} \propto \frac{1}{q^2 - \kappa m^2_{\mathrm{Dself}}(T)}$$

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

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

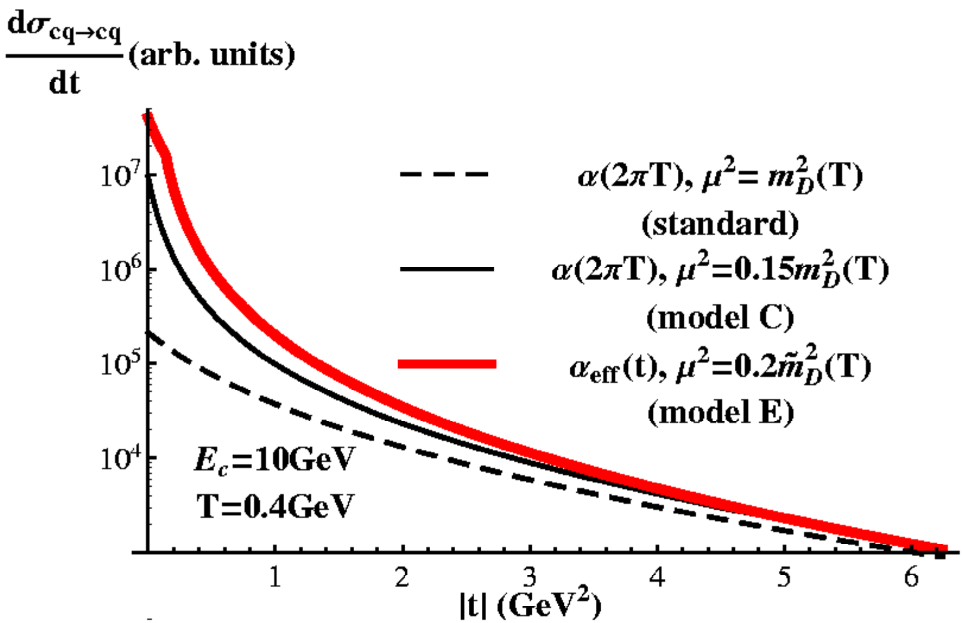


We do the same for QCD
(a bit more complicated)
Phys.Rev.C78:014904
Result:

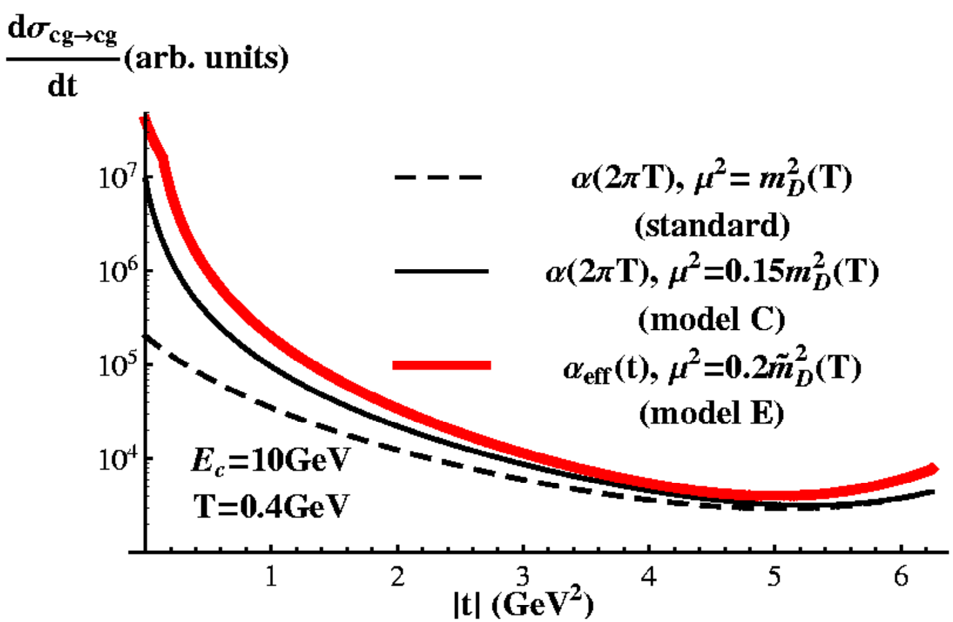
$$\boxed{\kappa \approx 0.2}$$

much lower than the standard value

Consequences for the Cross Section



$$\frac{d\sigma}{dt} = \frac{16\pi\alpha_s^2}{(s-M^2)^2}\left[\frac{(s-m^2)^2}{(t-\mu)^2} + \frac{s}{t-\mu} + \frac{1}{2}\right]$$



Large enhancement of cross sections at small t

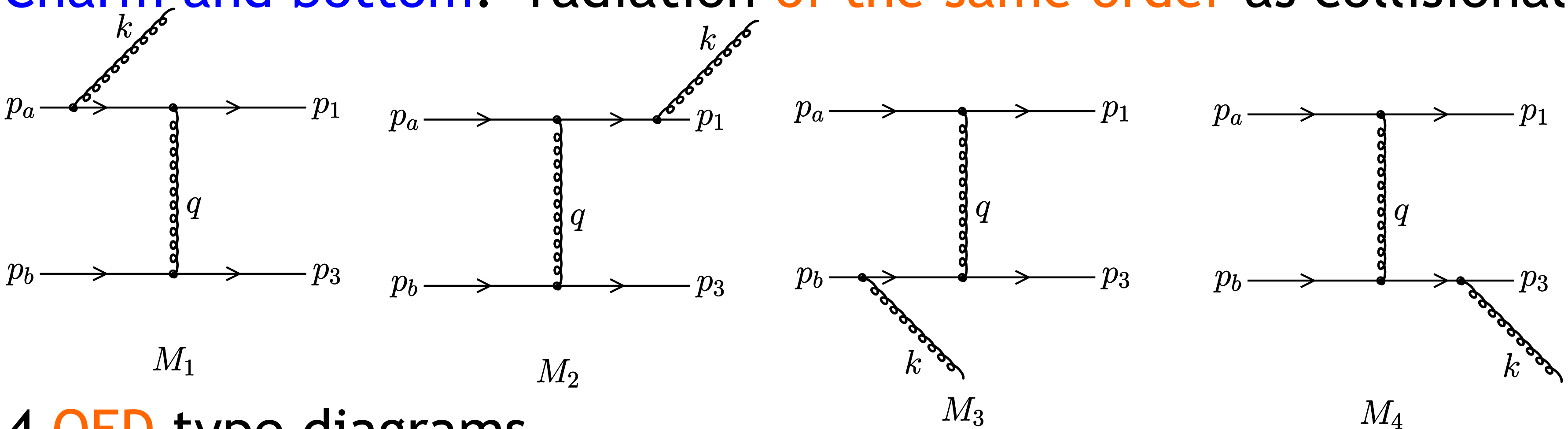
Little change at large t

Largest energy transfer from u-channel gluons

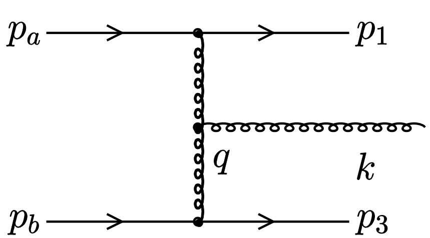
Inelastic Collisions

Low mass quarks : radiation dominantes energy loss

Charm and bottom: radiation of the same order as collisional



4 QED type diagrams



M_5

1 QCD diagram

Commutator of the color SU(3) operators

$$T^bT^a = T^aT^b - if_{abc}T^c$$

M1-M5 : 3 gauge invariant subgroups

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

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

M_{QCD} dominates the radiation

Inelastic collisions in SQCD

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

$$P_{rad} = C_A\left(\frac{\vec{k}_t}{k_t^2+(\omega/E)^2m^2} - \frac{\vec{k}_t-\vec{q}_t}{(\vec{q}_t-\vec{k}_t)^2+(\omega/E)^2m^2}\right)^2$$

Emission from heavy q

Emission from g

leading order: no emission from light q

heals colinear divergences

m=0 -> Gunion Bertsch

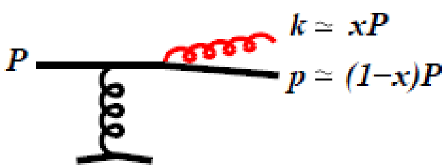
Energy loss:

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

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

Landau Pomeranschuk Migdal Effect (LPM)

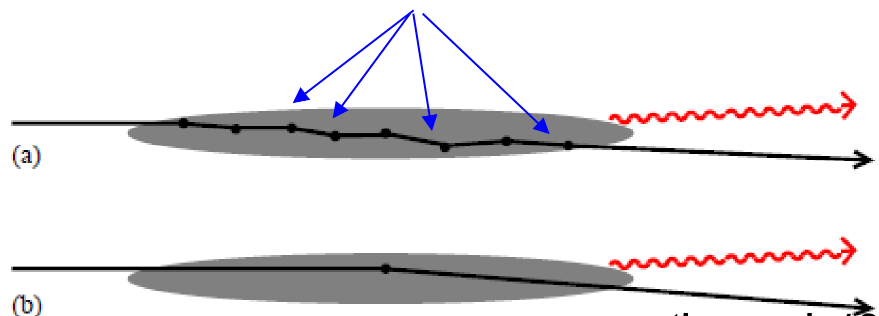
reduces energy loss by gluon radiation



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)



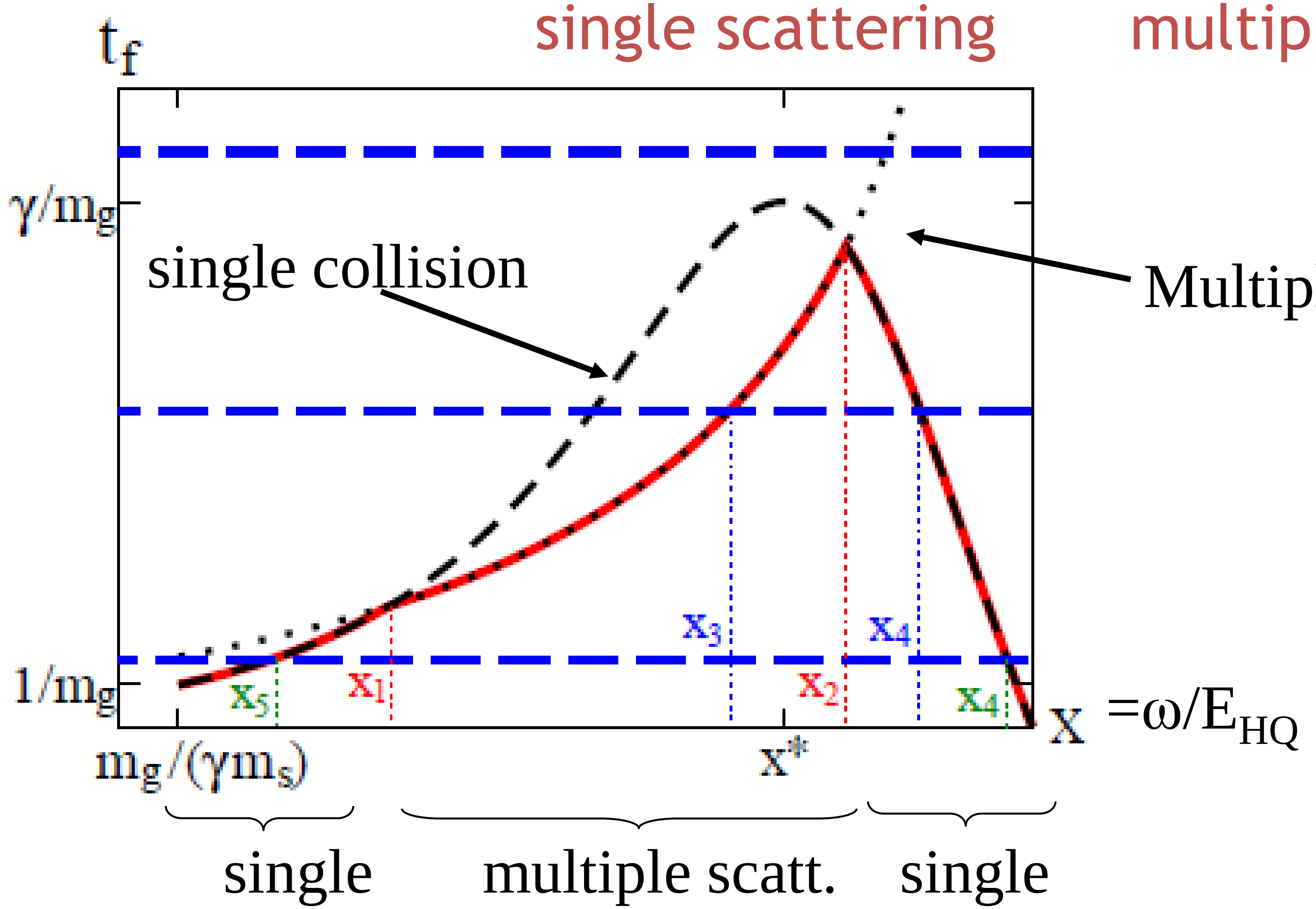
(hep-ph/0204343)

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

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

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

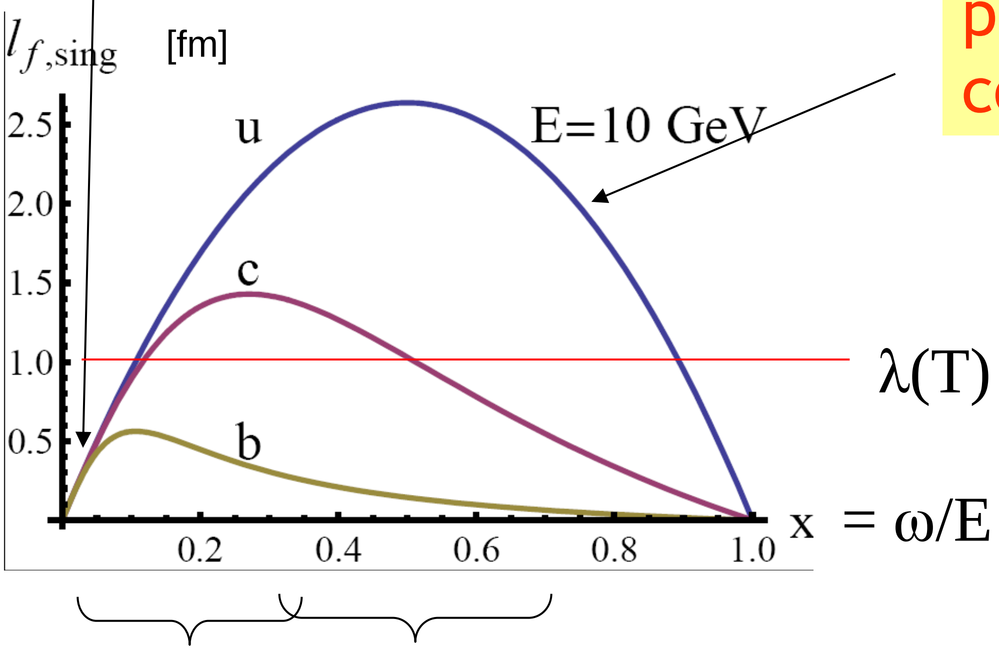
$$\underbrace{t_f \frac{x}{2E}\left[\frac{m_s^2}{(1-x)} + \frac{m_g^2}{x^2}\right]}_{\text{single scattering}} + \underbrace{t_f^2 \frac{x\hat{q}_s}{2E(1-x)}}_{\text{multiple scattering}} \simeq 1\,.$$



At intermediate gluon energies formation time is determined by multiple scattering

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.

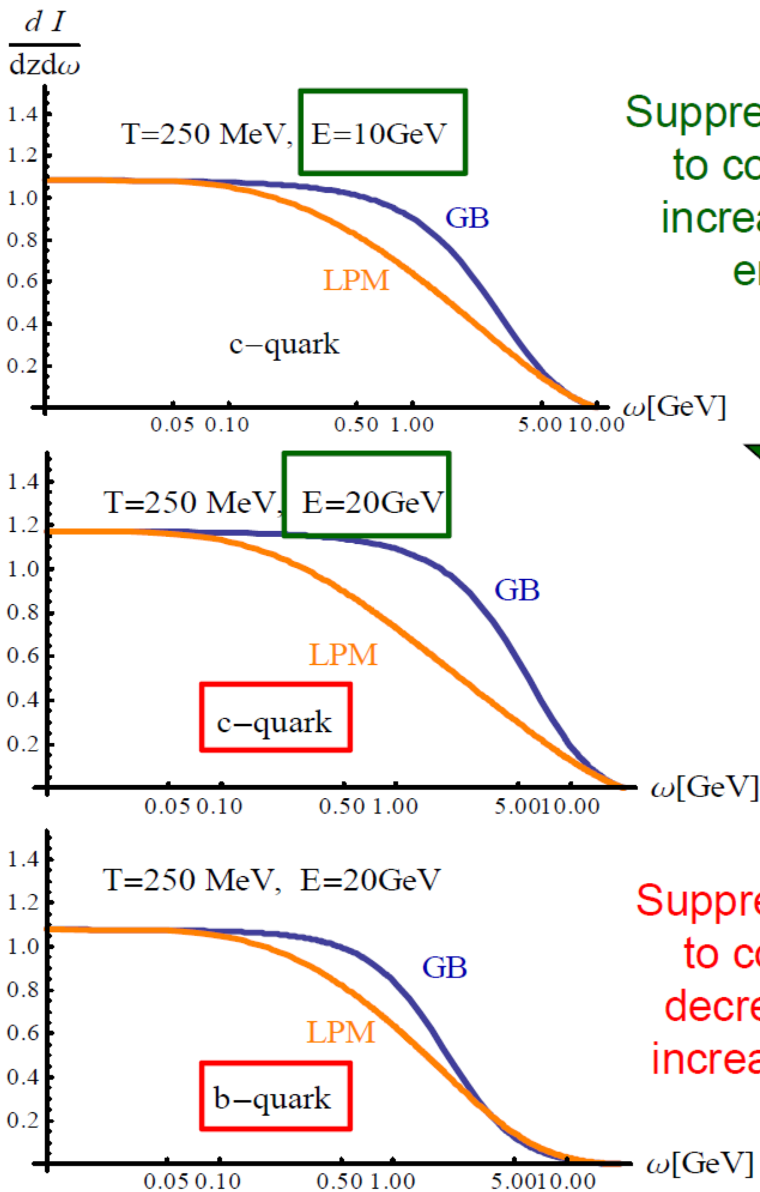


LPM important for intermediate x where formation time is long

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

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

Consequences of LPM on the energy loss



Suppression due to coherence increases with energy

Suppression due to coherence decreases with increasing mass

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

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

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

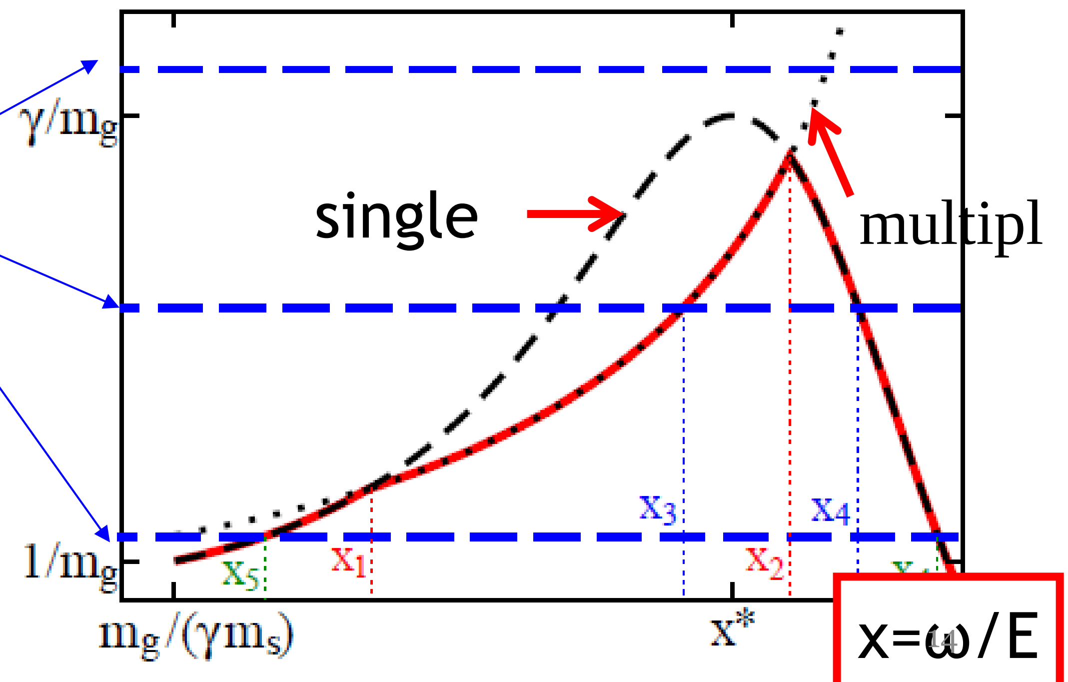
with

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

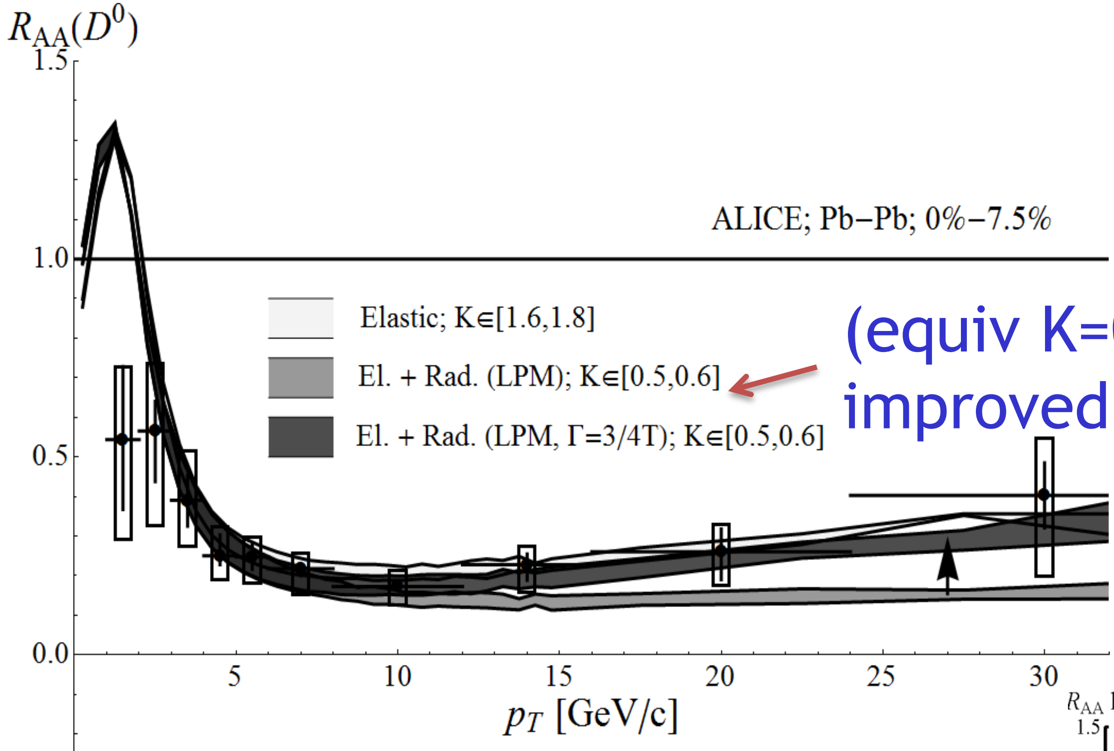
t_f

New timescale $1/\Gamma$

damping dominates radiation spectrum



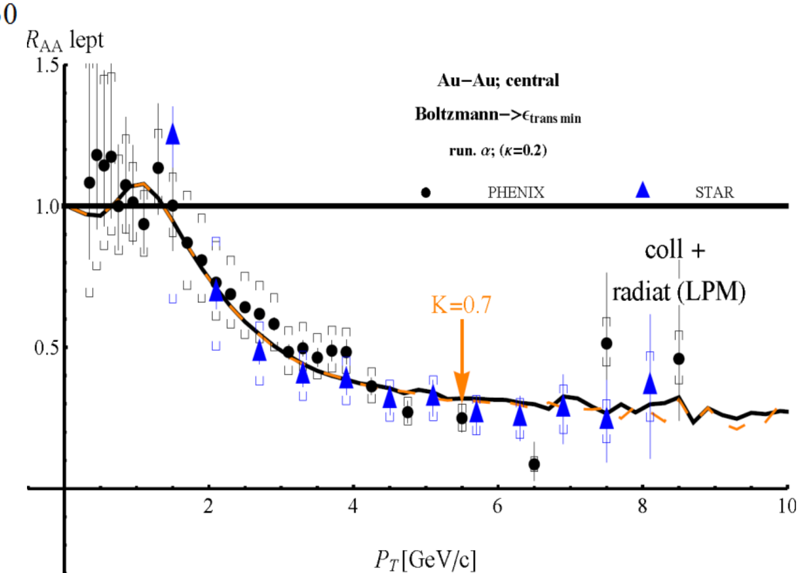
Consequences for HQ observables



Damping of radiated gluons reduces the quenching of D mesons

(equiv K=0.8 with improved radiation)

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

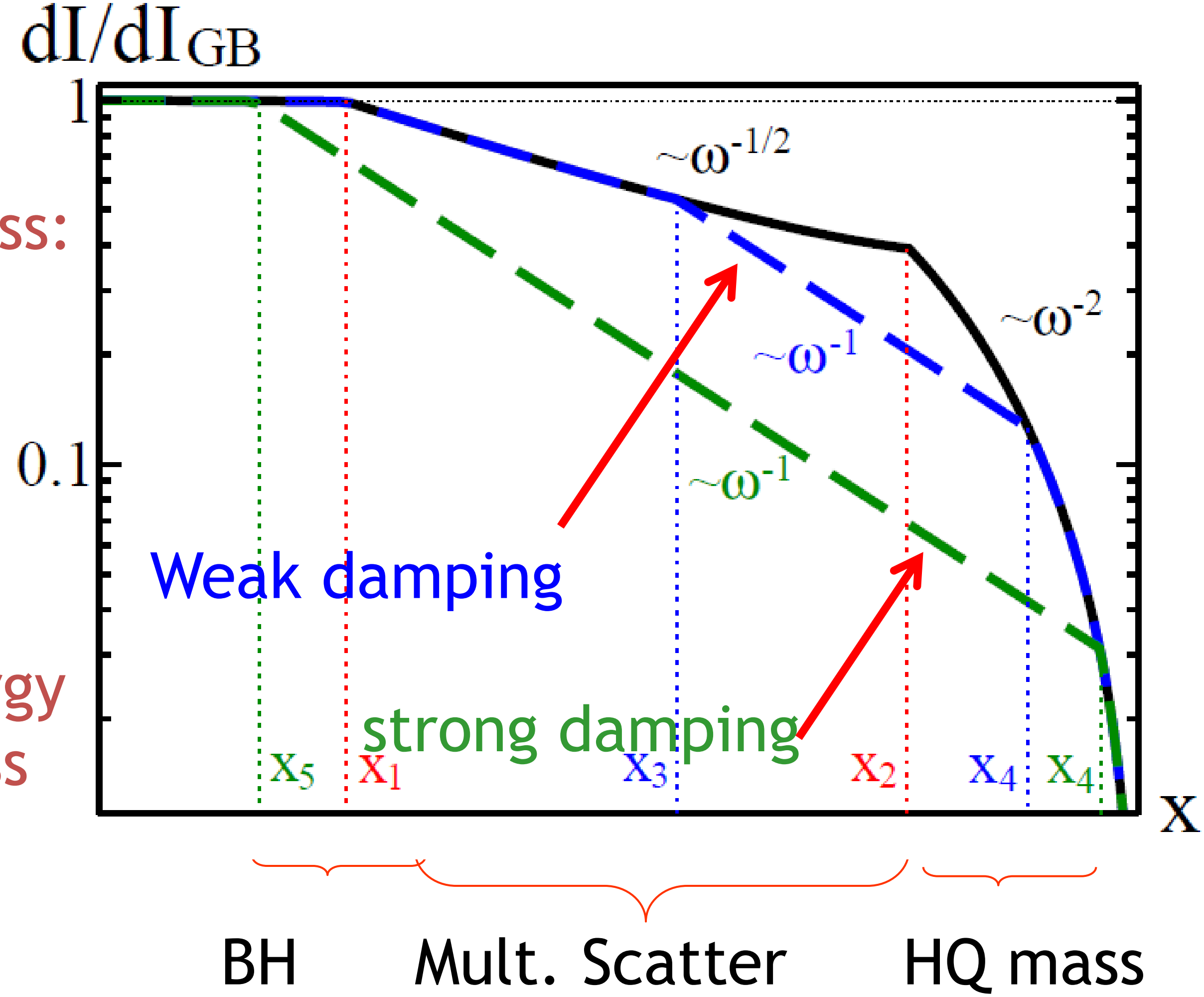


Influence of LPM and damping on radiation spectra

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

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

LPM:
increase with energy
decrease with mass



Calculations for RHIC and LHC

. 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.

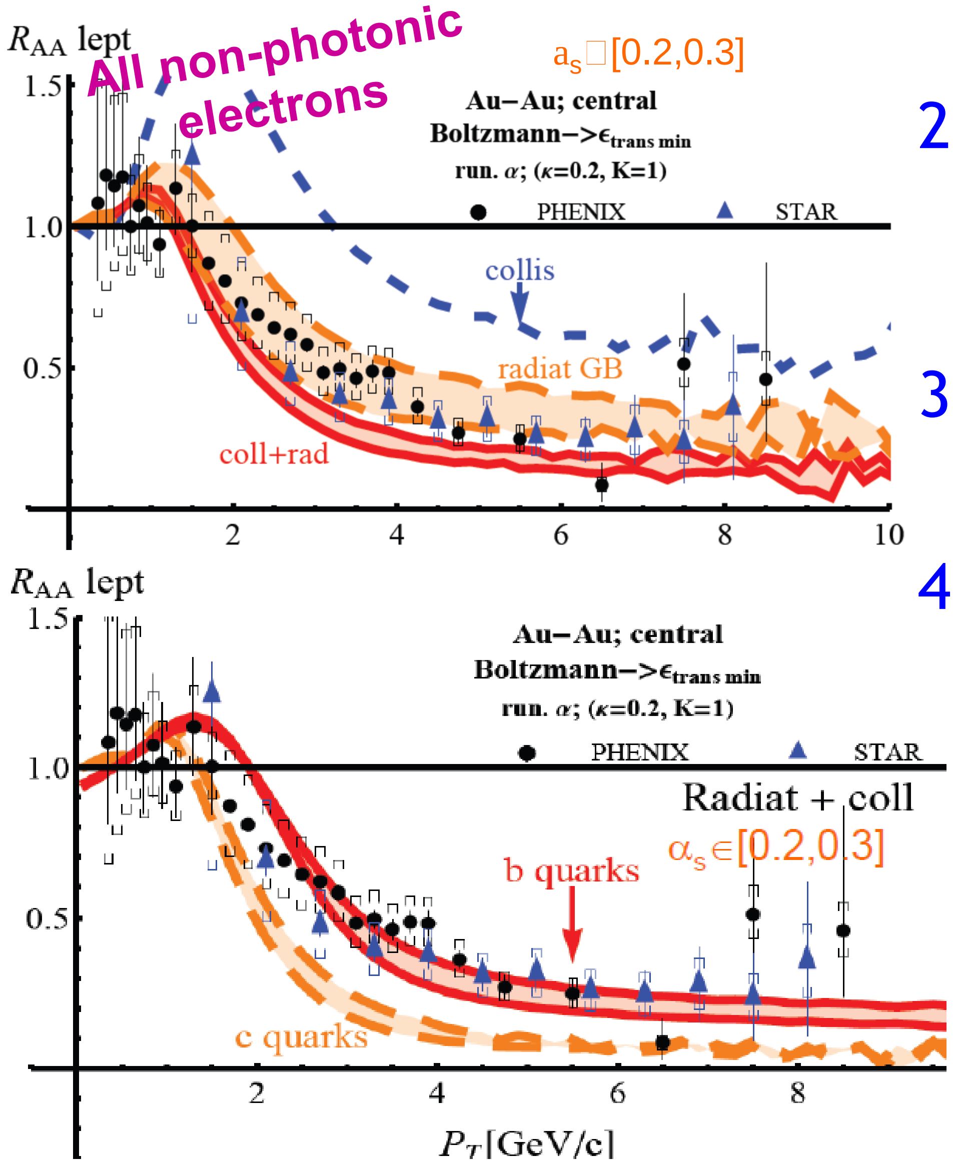
• c,b-quark rapidity distribution according to R.Vogt (Int.J.Mod.Phys. E12 (2003) 211-270) and priv comm.

• 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

RHIC I

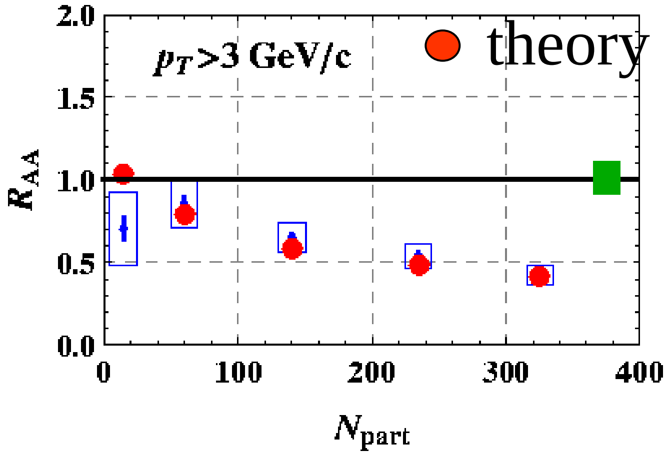


1. Too large quenching (but very sensitive to freeze out)
2. Radiative Eloss indeed dominates the collisional one
3. Flat experimental shape is well reproduced
4. $R_{AA}(p_T)$ has the same form for radial and collisional energy loss (at RHIC)

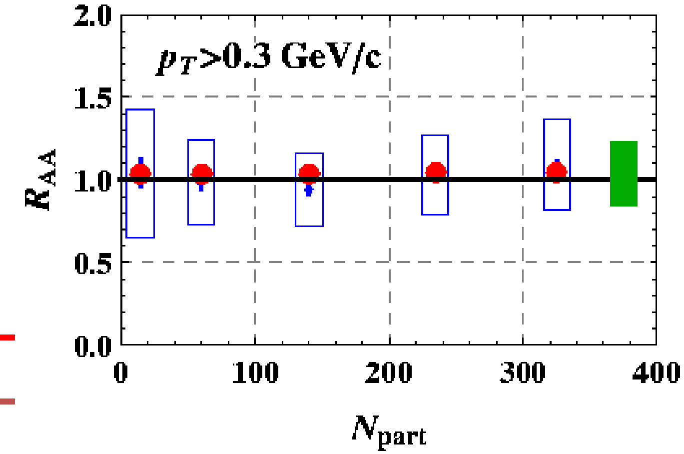
separated contributions e **from** D and e **from** B.

RHIC II

arXiv 1005.1627 (PHENIX)



collisional
K= 2

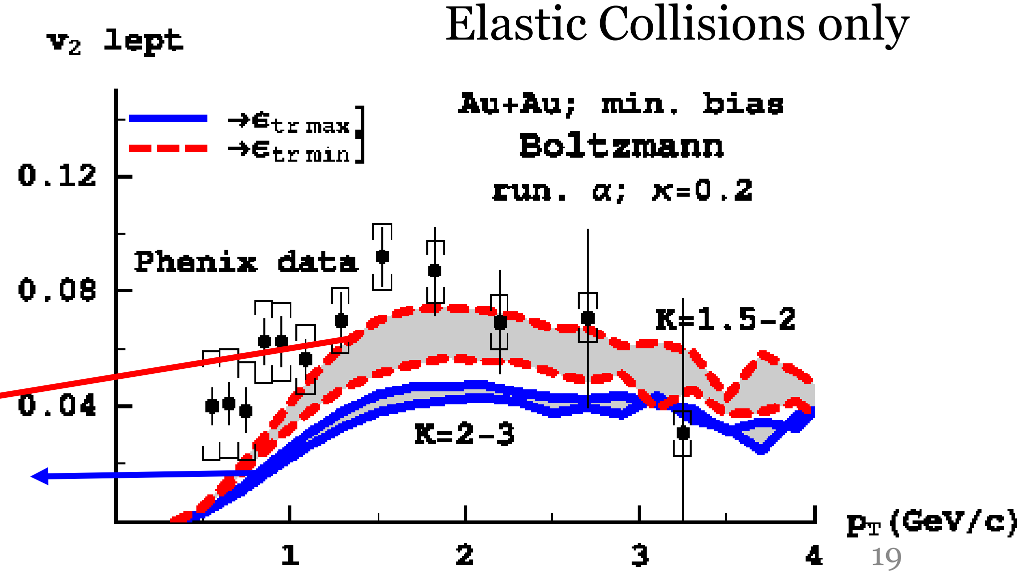


R_{AA} centrality dependence (PHENIX) well reproduced

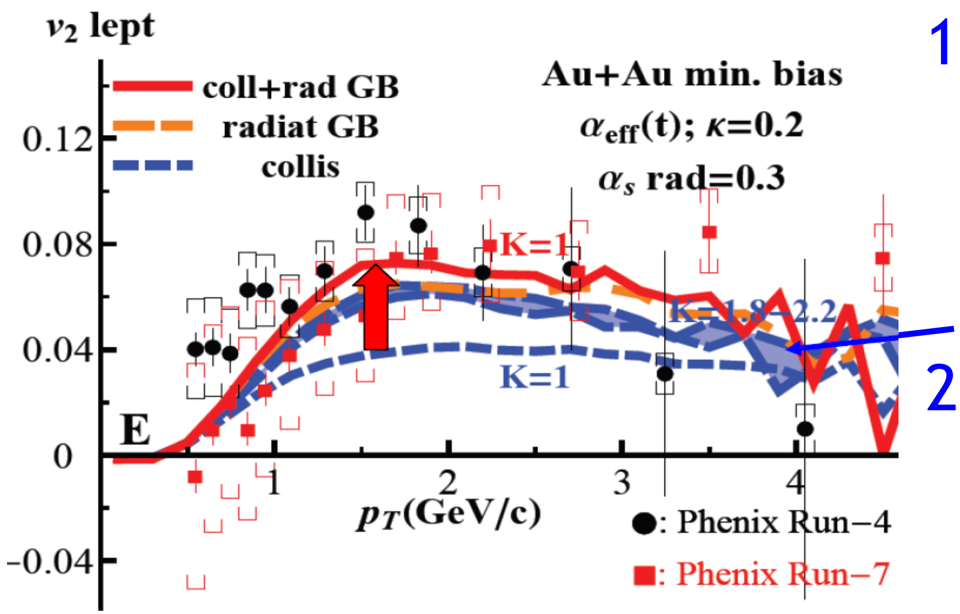
v_2 of heavy mesons depends on when fragmentation/ coalescence takes place

end of mixed phase
beginning of mixed phase

Elastic Collisions only



RHIC III

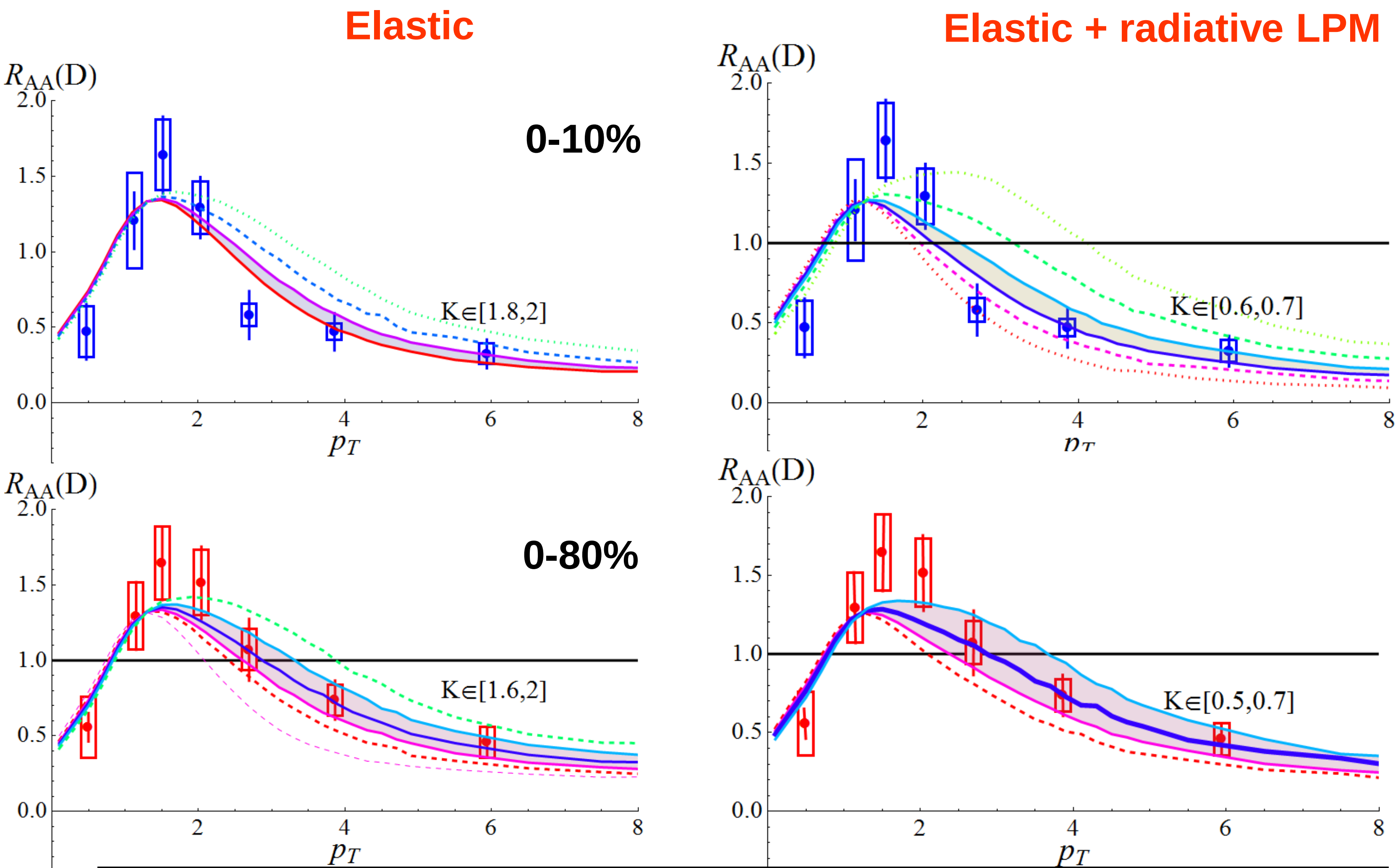


1. Collisional + radiative energy loss + dynamical medium : *compatible* with data
2. To our knowledge, one of the first model using radiative Eloss that reproduces v_2

For the hydro code of Kolb and Heinz:

K = 1 compatible with data
K = 0.7 best description – remember influence of expansion

RHIC IV: D mesons



No form difference between coll and coll + rad

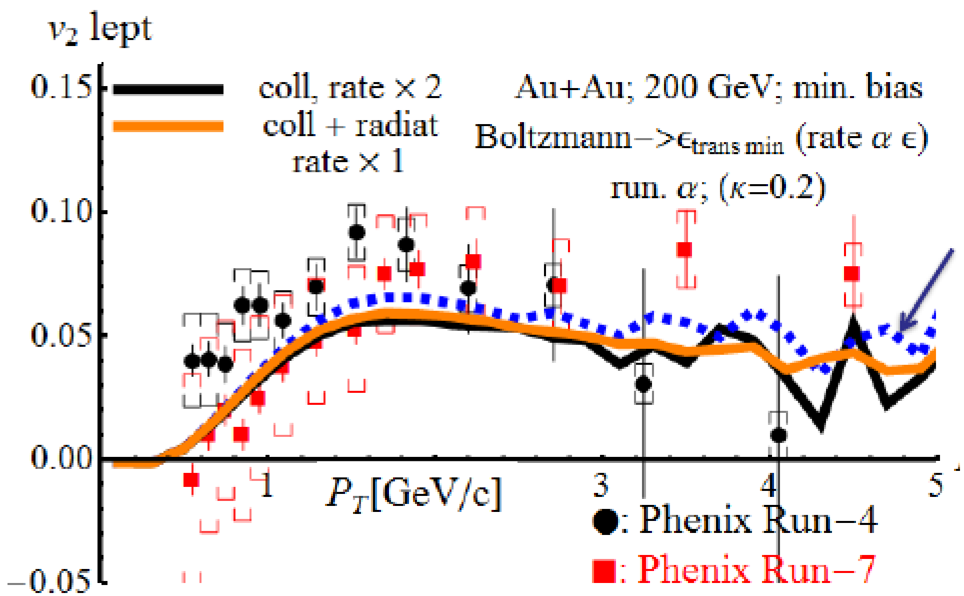
LHC I

v_2 very similar at RHIC and LHC

B and b flow identical

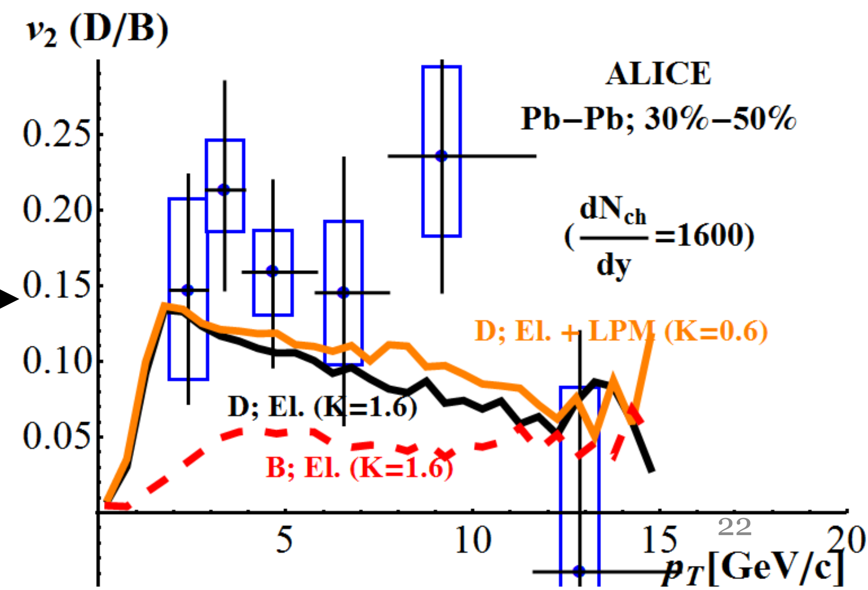
D and c 20% difference (hadronization)

RHIC



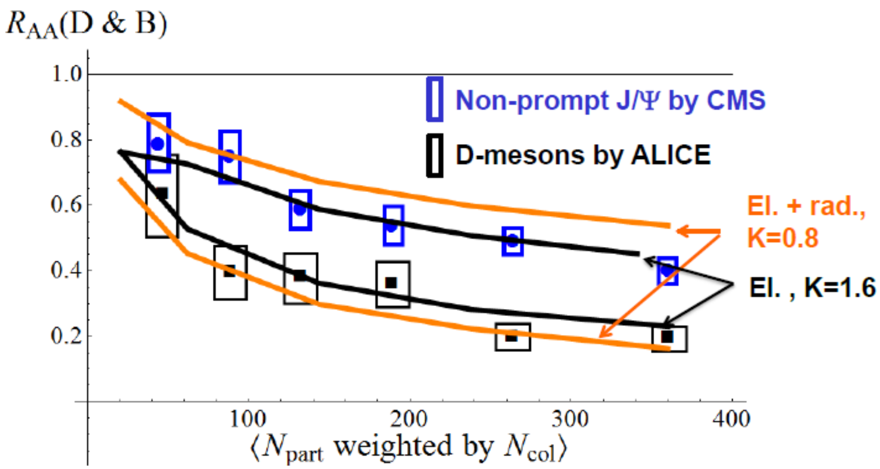
LHC

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



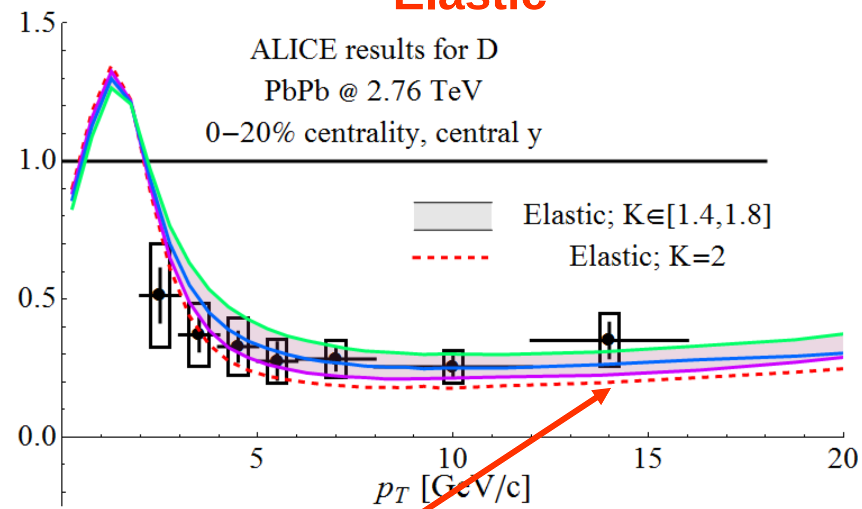
LHC II

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

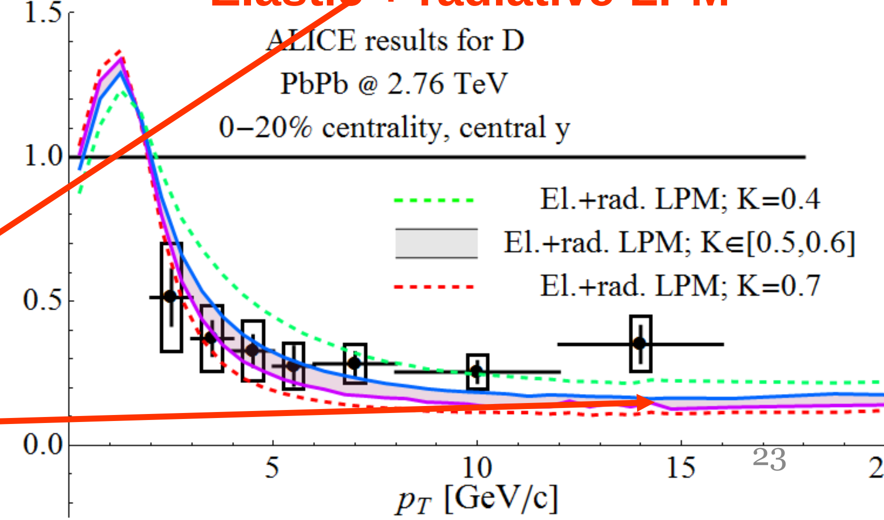


Centrality dependence well reproduced

Elastic



Elastic + radiative LPM

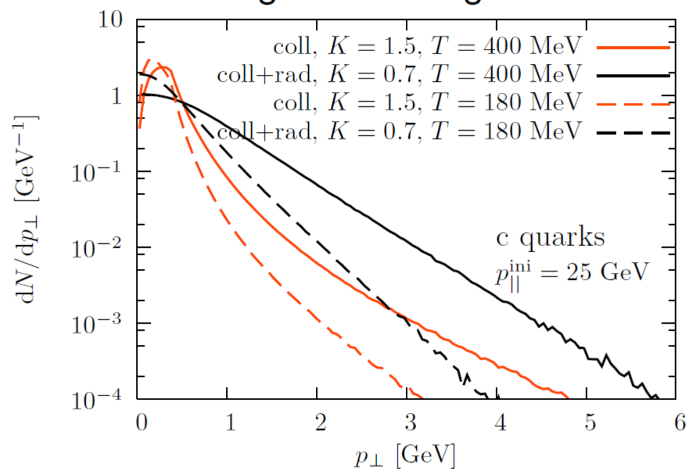


High pt: coll+rad gives
slightly more suppression

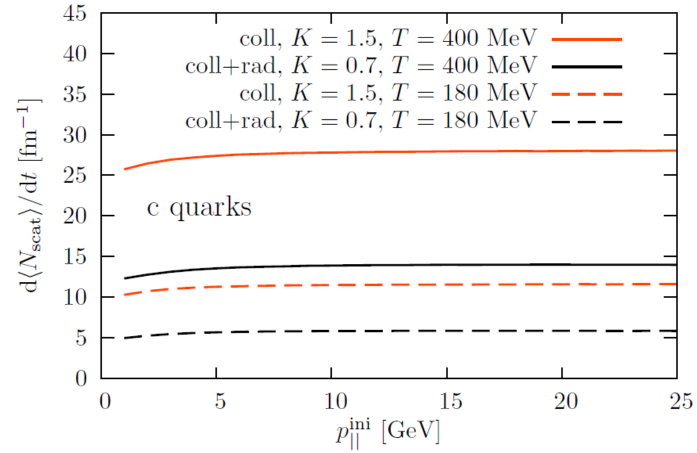
Is there a way to distinguish between radiative and collisional energy loss

Yes: by D-Dbar correlations

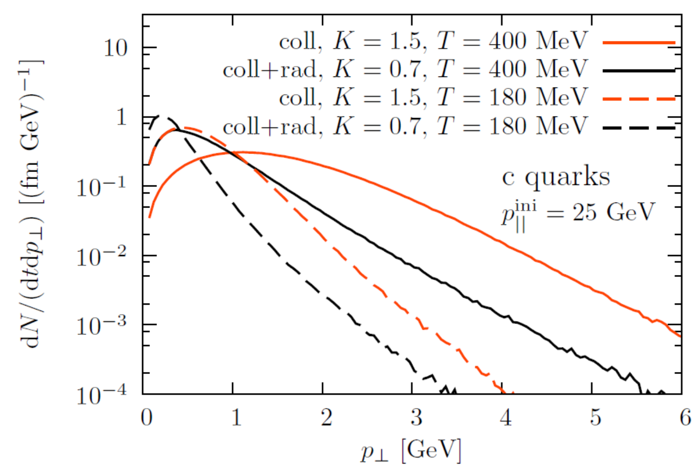
Single scattering:



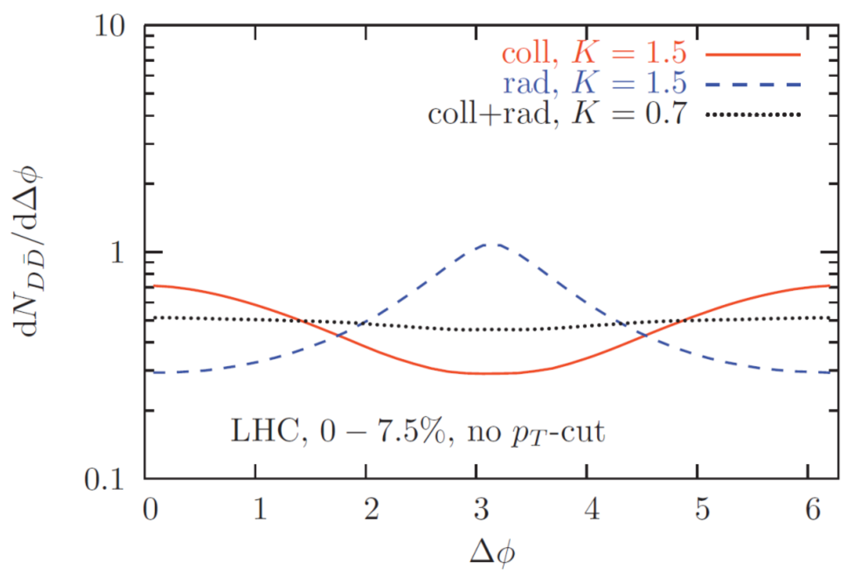
Evolution in a medium:

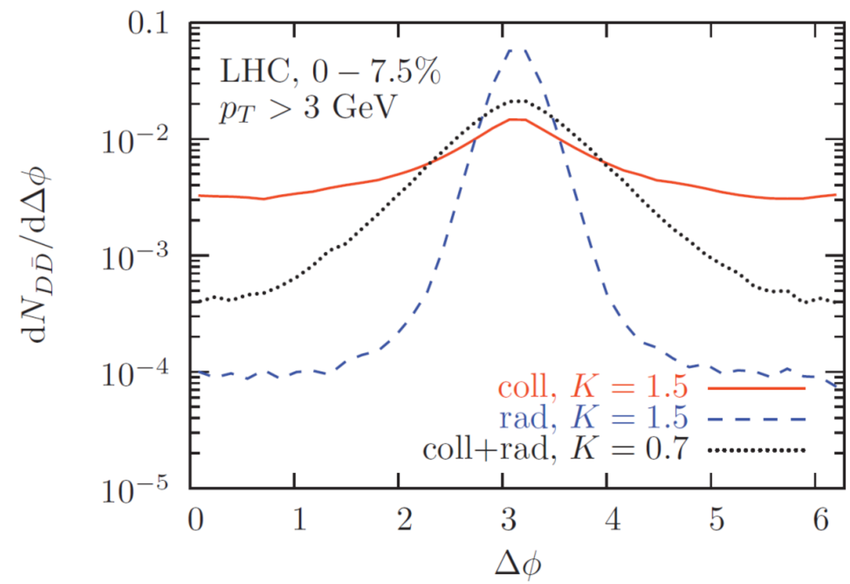


- p_T-distribution in a single scattering: larger $\langle p_T \rangle$ for **coll+rad ($K = 0.7$)**.
- Initialize in a static, infinite medium at temperature T with a given longitudinal momentum, evolve according to the Boltzmann equation for $\Delta t = 0.4$ fm.
- Scat. rate is larger for coll ($K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



Initially: back to back



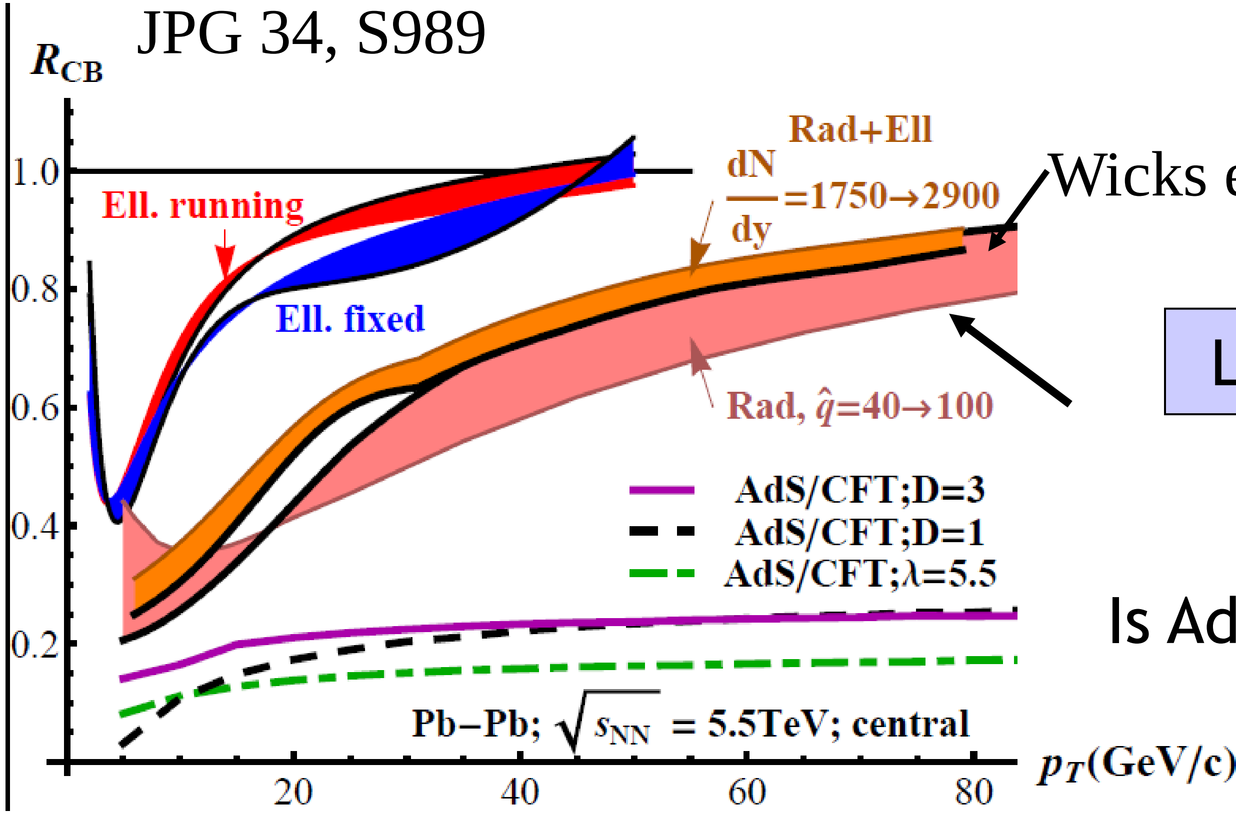


High p_T DDbar most sensitive

LHC III

Ratio charm/bottom (Horowitz et al.)

JPG 34, S989



Wicks et al NPA743,493

LHC 5.5 ATeV

Is AdS/CFT still valid?

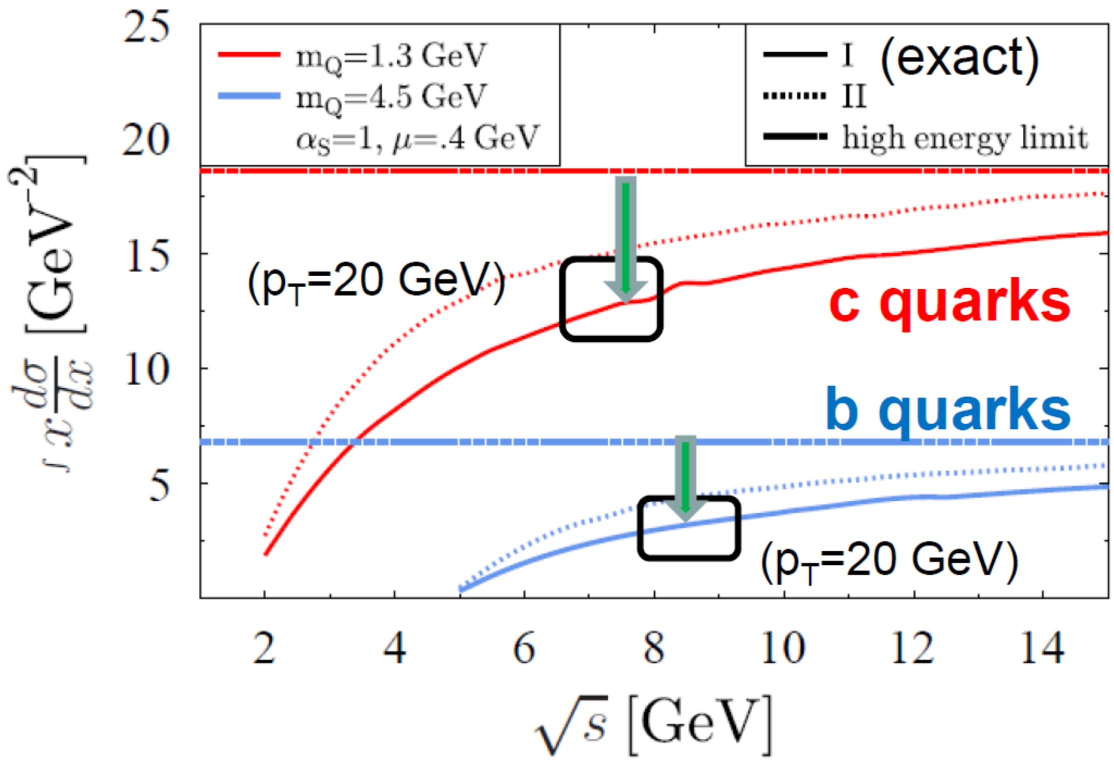
Charm/bottom ratio will show whether pQCD or AdS/CFT is the right theory to describe HI reactions

What remains to be done (before new data arrive):

- EPOS instead of Kolb&Heinz (reproduces light quark sector)

- Determine Γ by physical processes

- Replace the Gunion-Bertsch limit $\sqrt{s} \to \infty$ by full calculation



including
finite masses
finite energies
phase space limits

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 energy loss