Heavy quark quenching from RHIC to LHC and the consequences of gluon damping

Quark Matter 2012; Washington DC-USA

P.B. Gossiaux

SUBATECH, UMR 6457

Université de Nantes, Ecole des Mines de Nantes, IN2P3/CNRS

with

J. Aichelin, M. Bluhm, Th. Gousset, M. Nahrgang

Outline

I. Introduction; models for quenching and the RHIC case

II. Predictions for LHC

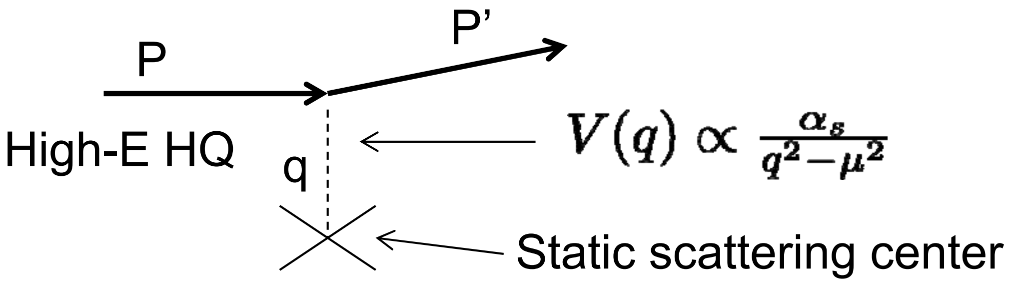
III. Effect of gluon damping on fundamental quantities

IV. Effect of gluon damping on observables

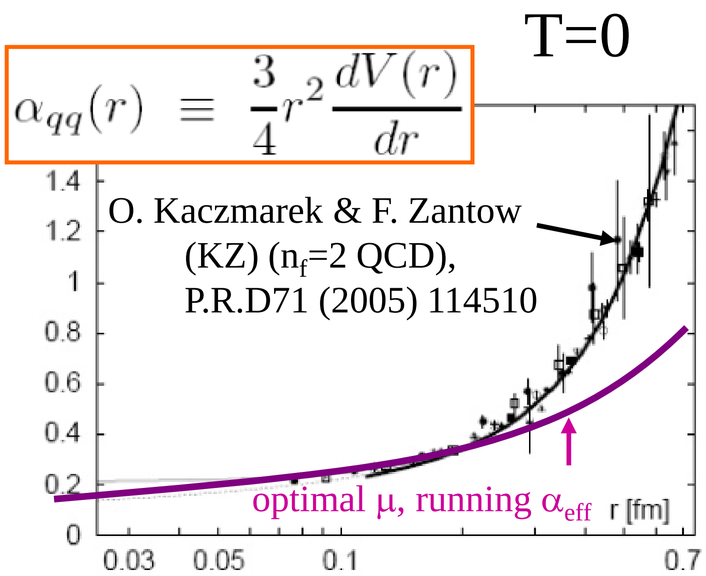
Insufficient control on energy loss theory

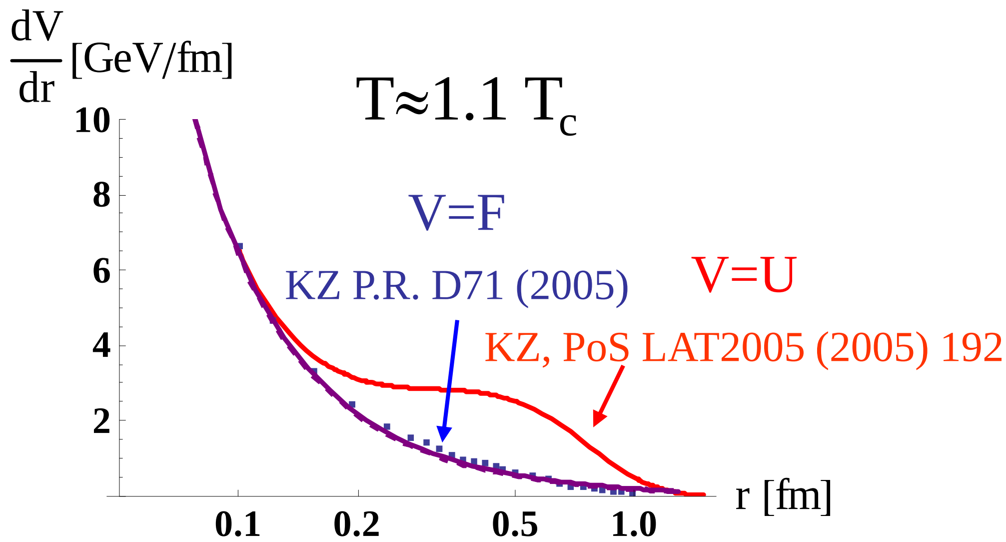
Non perturbative « corrections » even at large HQ energy

In most models:



Lattice QCD :

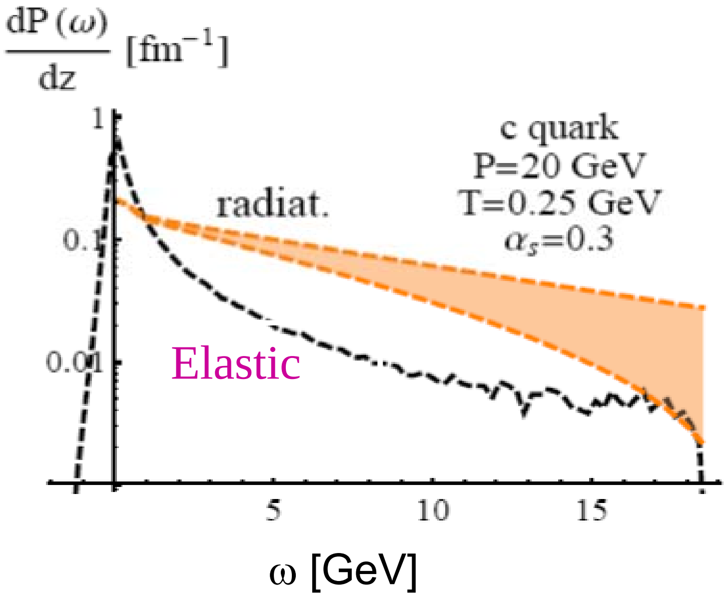




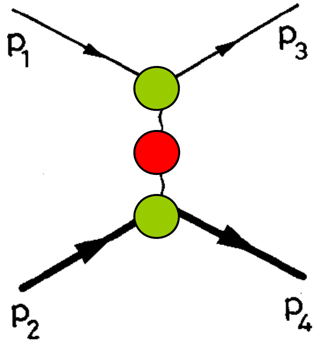
Significant r-tail in the transverse force acting on the high E HQ

Our basic ingredients for HQ energy loss

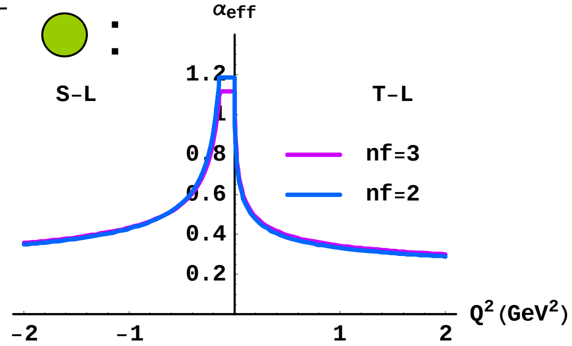
Probability P of energy loss *w* per unit length (T,M,…):



Elastic



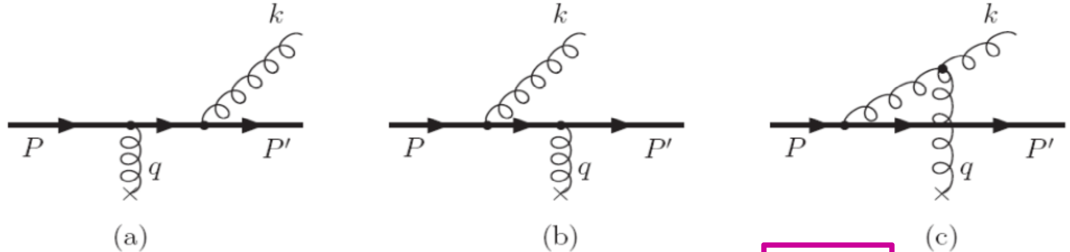
+ u and s channels



: OGE effective propagator

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

Incoherent Induced Radiative



Generalized Gunion-Bertsch for finite mass

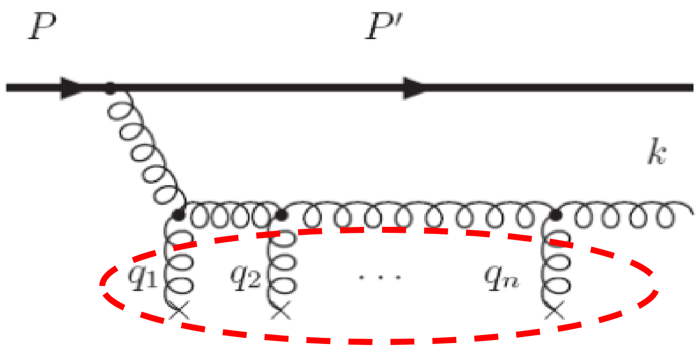
$$\omega \frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega d^2k_\perp dq_\perp^2} = \frac{N_c\alpha_s}{\pi^2}(1-x)\times\frac{J_{\rm QCD}^2}{\omega^2}\times\boxed{\frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}}$$

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

Our basic ingredients HQ for energy loss

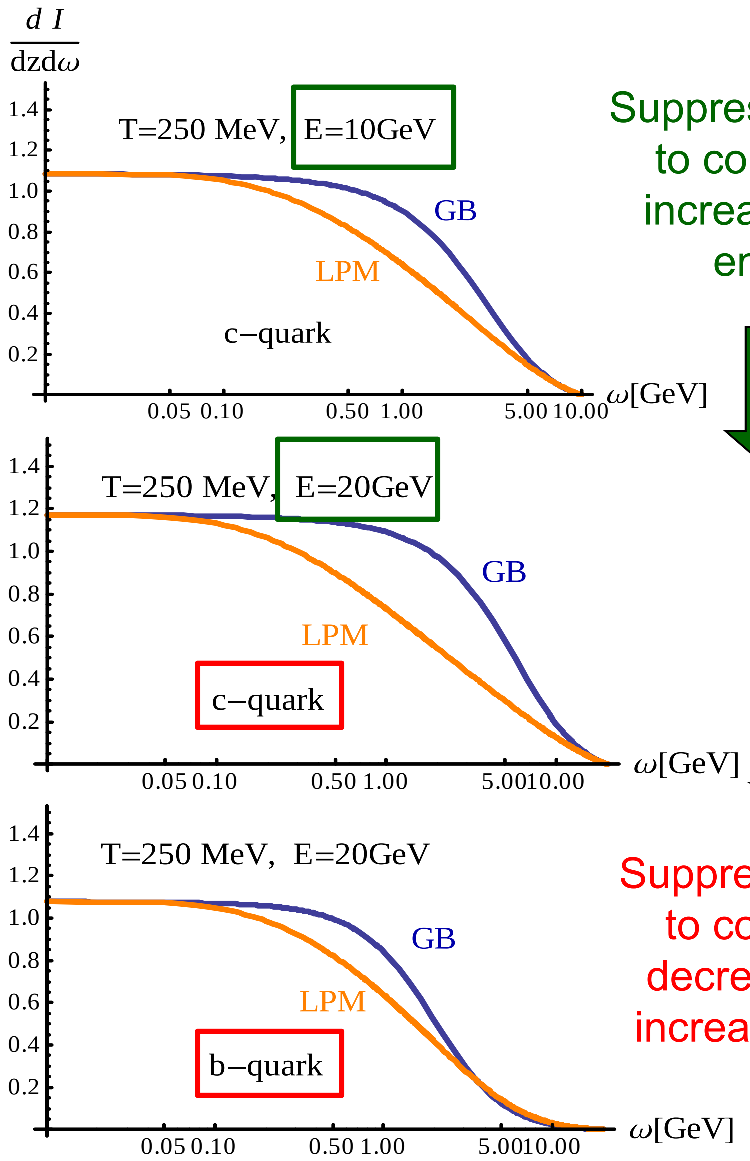
Coherent Induced Radiative

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

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



Suppression due to coherence increases with energy

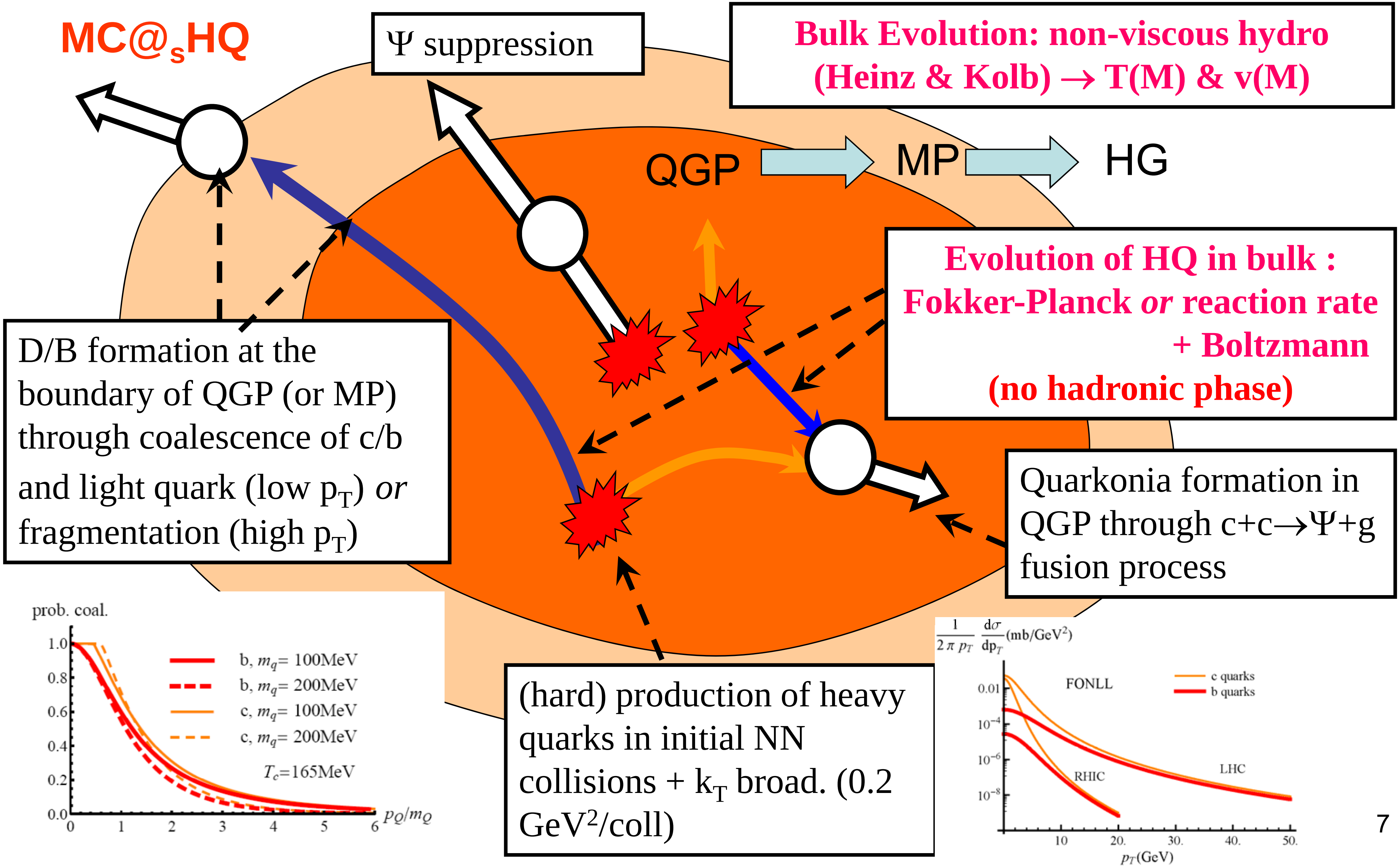
Suppression due to coherence decreases with increasing mass

Our phenomenological viewpoint

What we do:

- **Allow for one extra parameter: K (cranking of the interaction rate); mock up neglected effects, missing ressummations,…**
- Joint v_2-R_{AA} explanation to better constrain badly known parameters…
- Try to encompass as many systems as possible
- Try to address simple questions (parametric dependences, e.g. path length)
- Consider several Eloss mechanisms leaving other ingredients untouched. In this talk: a) purely elastic or b) elastic + radiative LPM cocktail

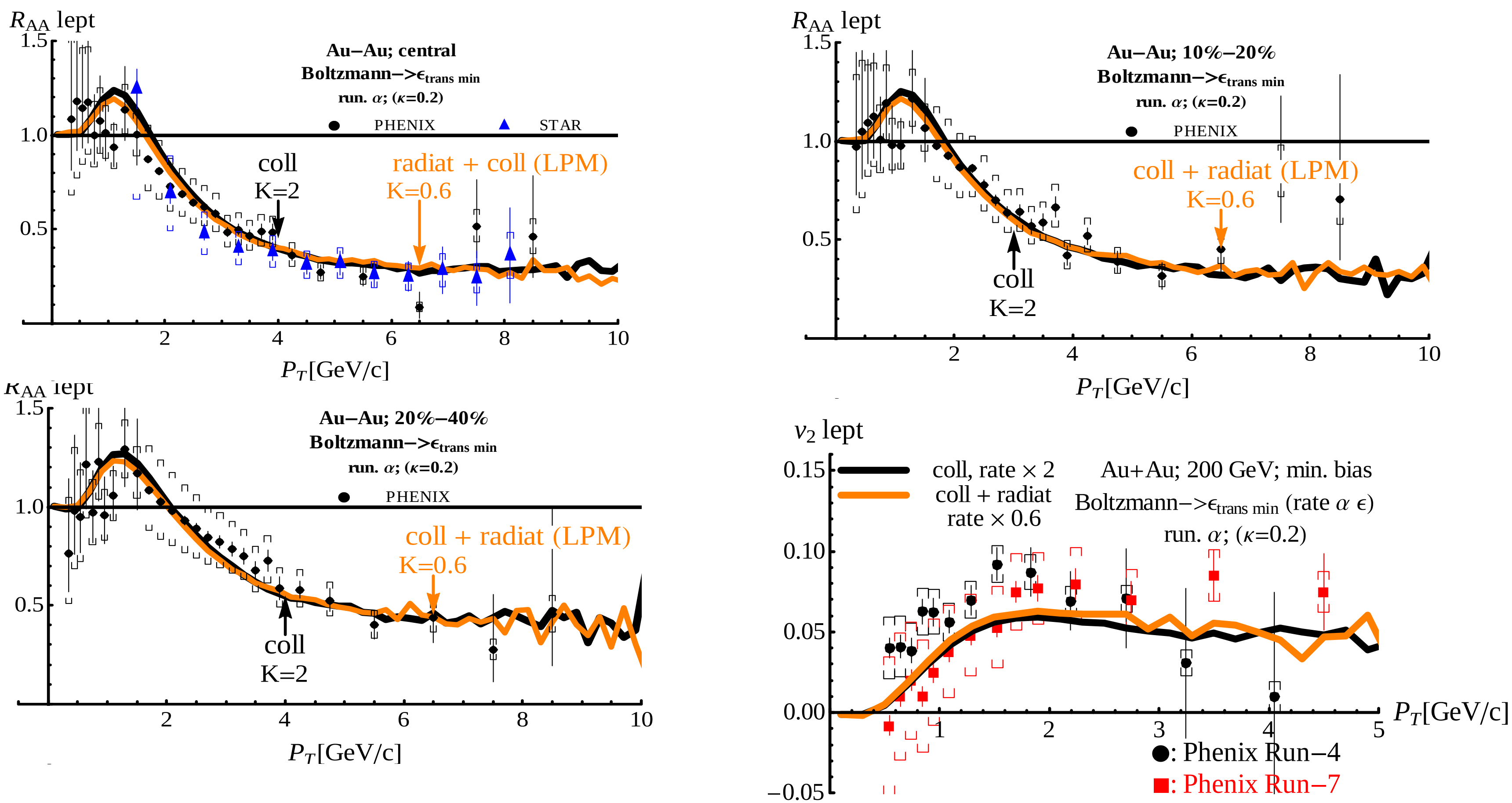
Schematic view of « Monte Carlo @ Heavy Quark » generator



{Radiative + Elastic} vs Elastic for leptons @ RHIC

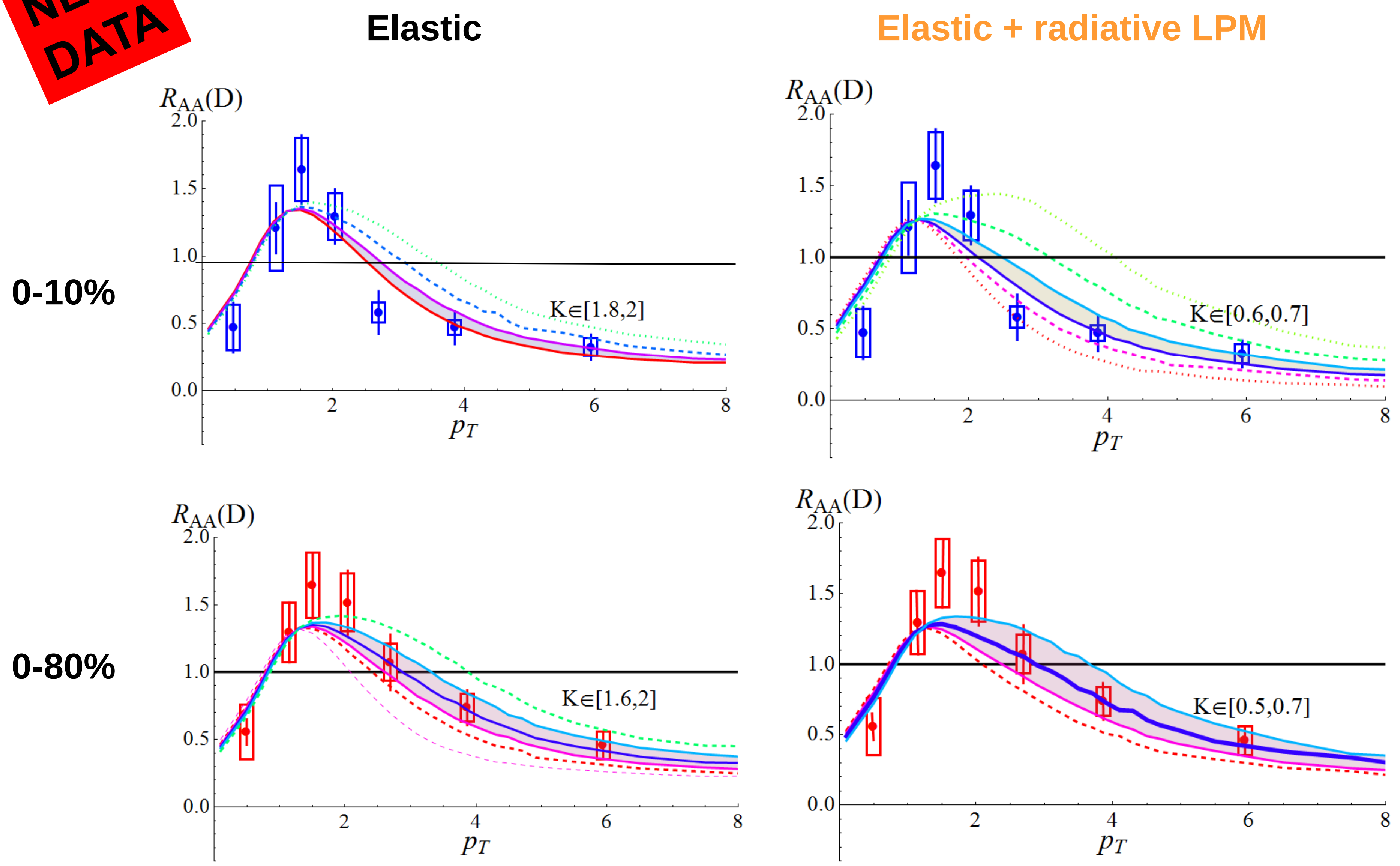
El. and rad. Eloss exhibit very different energy and mass dependences. However…

σ_{el} alone rescaling: K=1.8-2.2 | **σ_{el} & σ_{rad} cocktail: rescaling by K=0.6-0.7**



{Radiative + Elastic} vs Elastic D mesons @ RHIC

NEW DATA



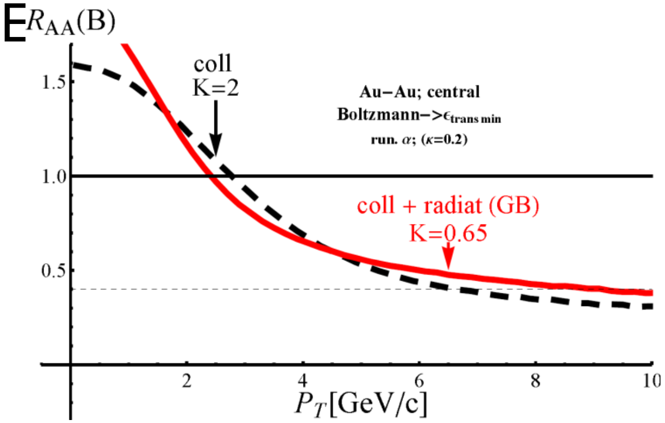
Conclusions from RHIC

- Present data at RHIC cannot decipher between the 3 local microscopic E-loss models (el., el. + rad GB, et. + rad. LPM) $\Rightarrow$ Not sensitive to the large-ω tail of the Energy-loss probability.

- One "explains" all open heavy flavor physics with ΔE probabilities per unit length).

- Good consistency between NPSE and D mesons (10% difference in K values)…

- … within a model with mass hierarchy (B puzzle ?)



Elastic

K	NPSE RHIC	D STAR central	D STAR min bias
1.4			
1.6			
1.8			
2.0			
2.2			

Elastic + radiative LPM

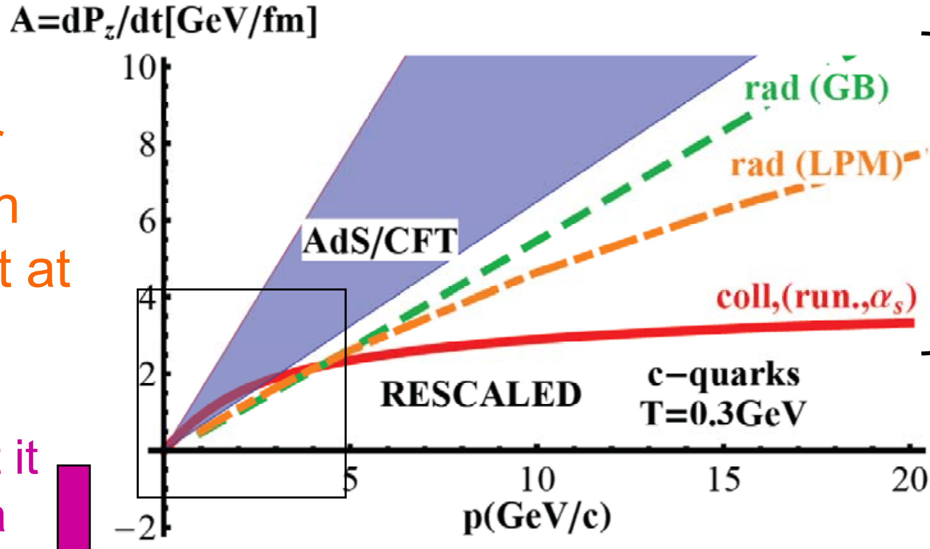
K	NPSE RHIC	D STAR central	D STAR min bias
0.4			
0.5			
0.6			
0.7			
0.8			

Good **Acceptable** **Marginal** **Wrong**

QGP properties from HQ probe at RHIC

Gathering all *rescaled* models (*coll. and radiative*) compatible with RHIC R_{AA}:

Similar diffusion coefficient at low p

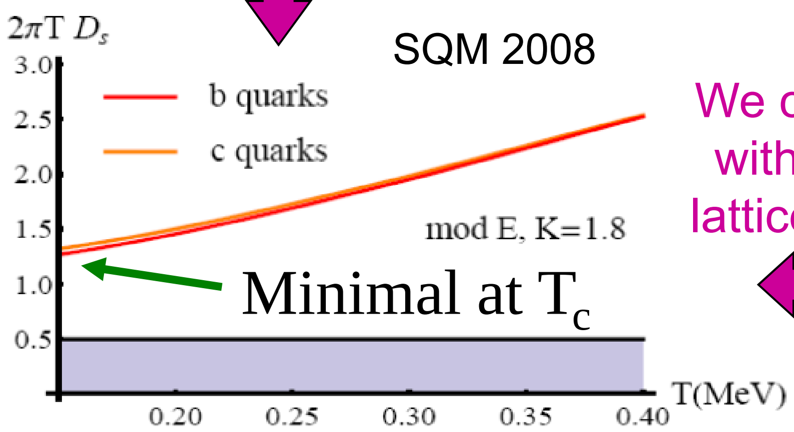


the drag coefficient reflects the average momentum loss (per unit time) => large weight on $x \sim 1$

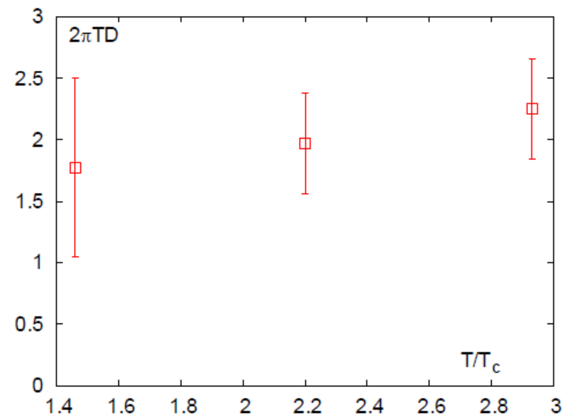
Present RHIC experiments cannot resolve between those various trends

We extract it from data

Hope that LHC will do !!!



We compare with recent lattice results



Kaczmarek
Bad Honnef
2011

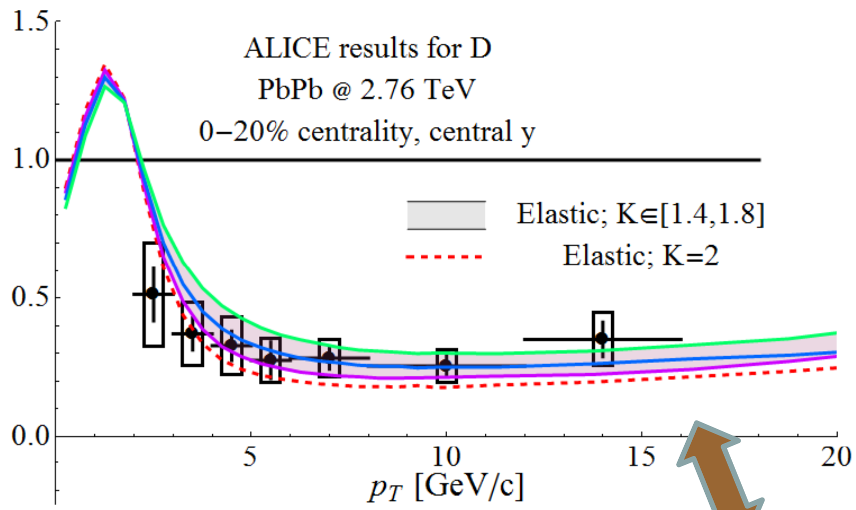
Lesson it seems possible to reveal some fundamental property of QGP using HQ probes

D mesons at LHC (vs ALICE 0%-20%)

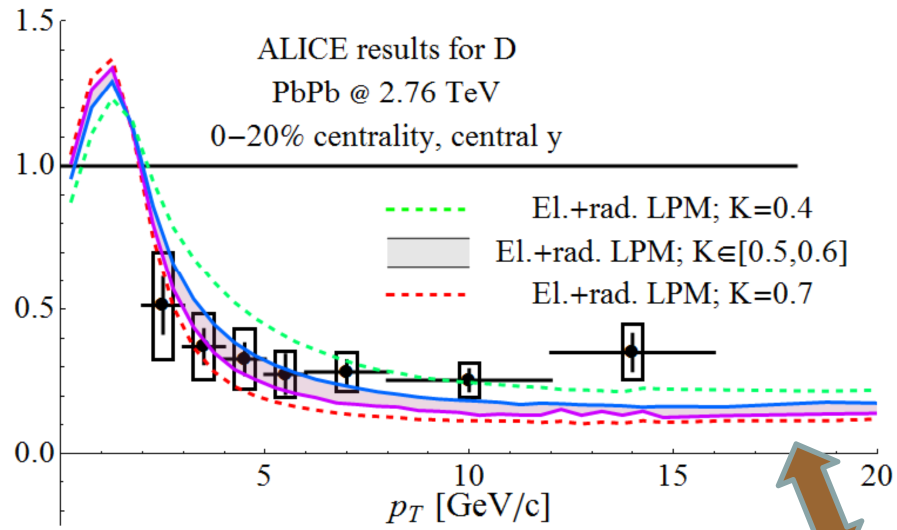
Same microscopic ingredients as for RHIC; NO SHADOWING (yet)

Kolb-Heinz Hydro adjusted to $dN_{ch}/dy = 1600$;

Elastic



Elastic + radiative LPMc

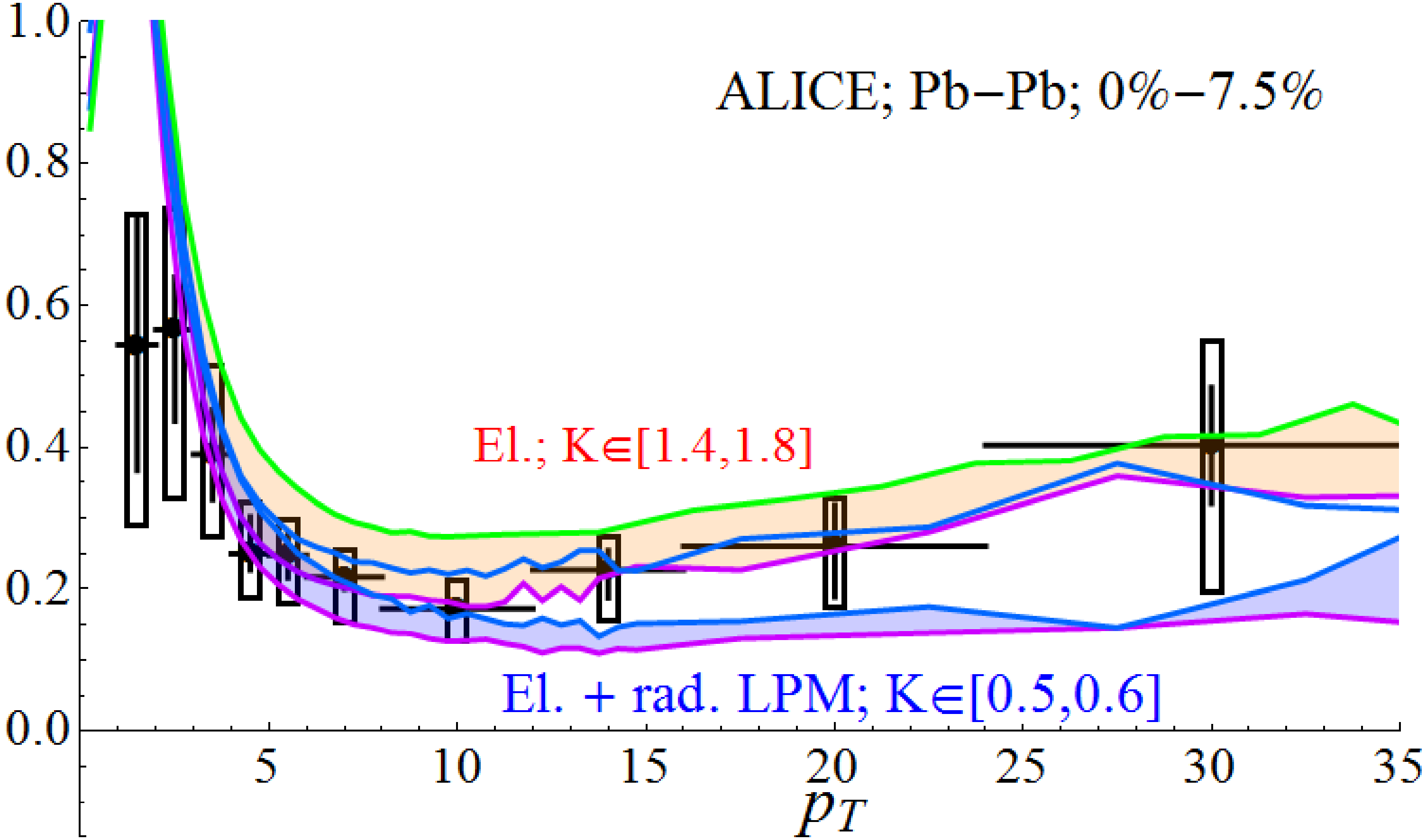


K	NPSE RHIC	D STAR central	D STAR min bias	D ALICE 0-20% (pT<15GeV/c)
1.4				
1.6				
1.8				
2.0				
2.2				

K	NPSE RHIC	D STAR central	D STAR min bias	D ALICE 0-20% (pT<15GeV/c)
0.4				
0.5				
0.6				
0.7				
0.8				

Correct agreement with ALICE data; 10-15% decrease of the rates needed for optimal agreement

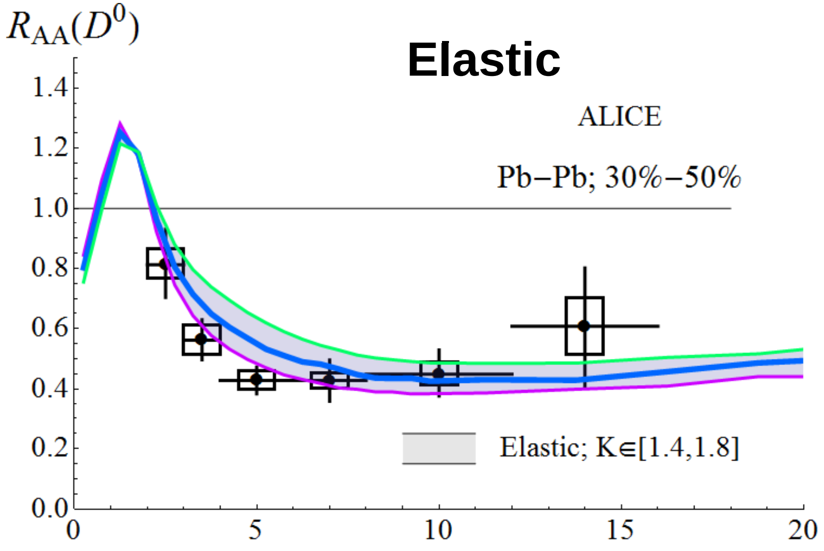
D mesons at LHC (vs ALICE 0%-7.5%)

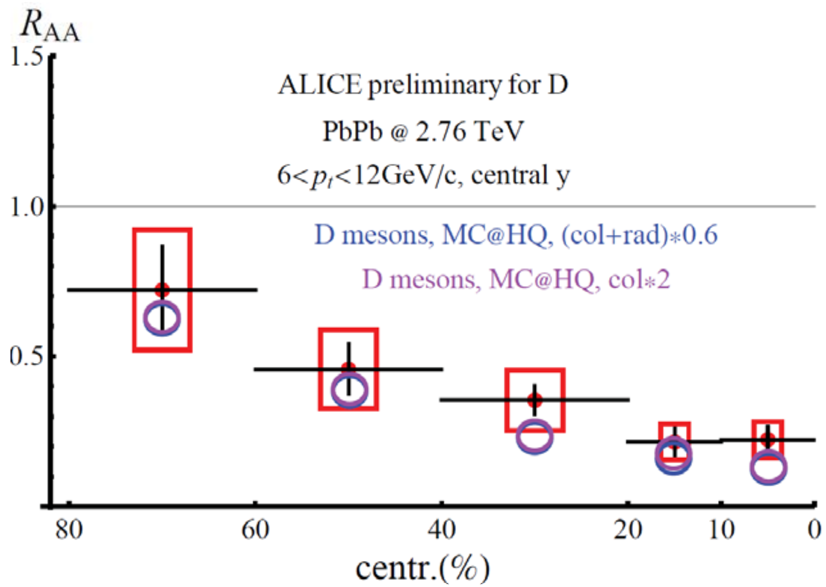


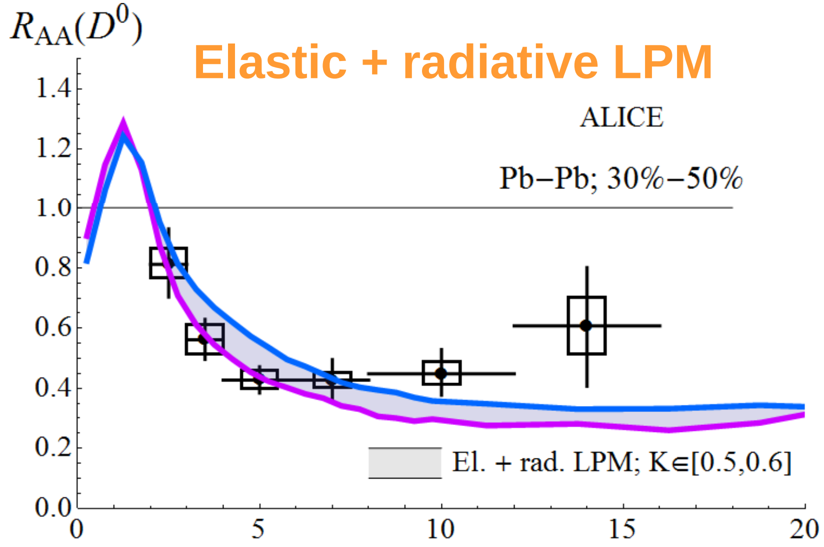
Big surprize: Better agreement with pure elastic Eloss; rather flat radiative Eloss on the 10-30 GeV/c p_T range

D mesons at LHC (at other centrality & vs centrality)

Important test of the path length dependence of Eloss scenario



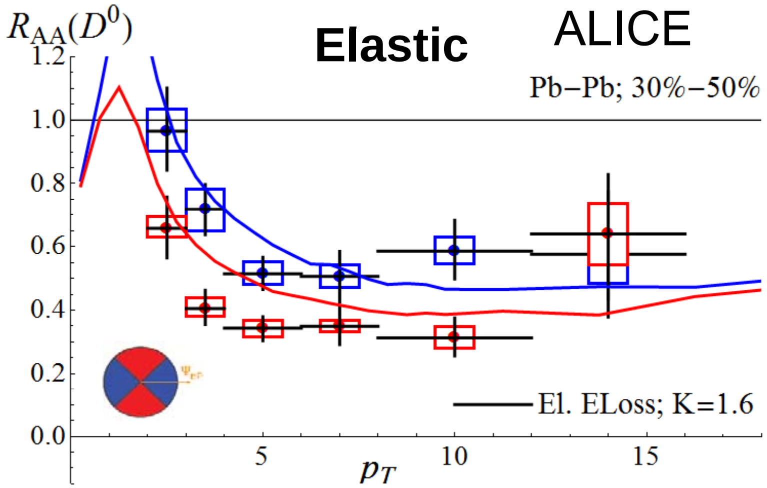


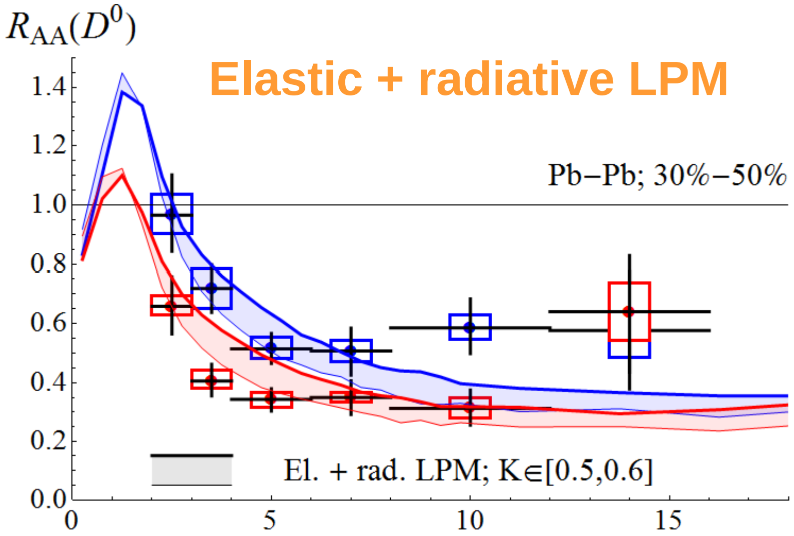


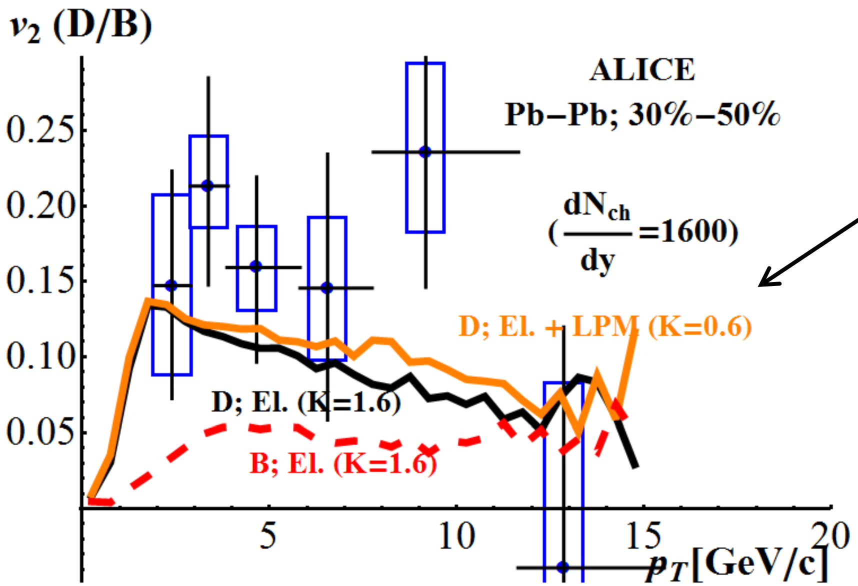
Good quantitative agreement, apart from the last p_T point in the el. + rad. LPM

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

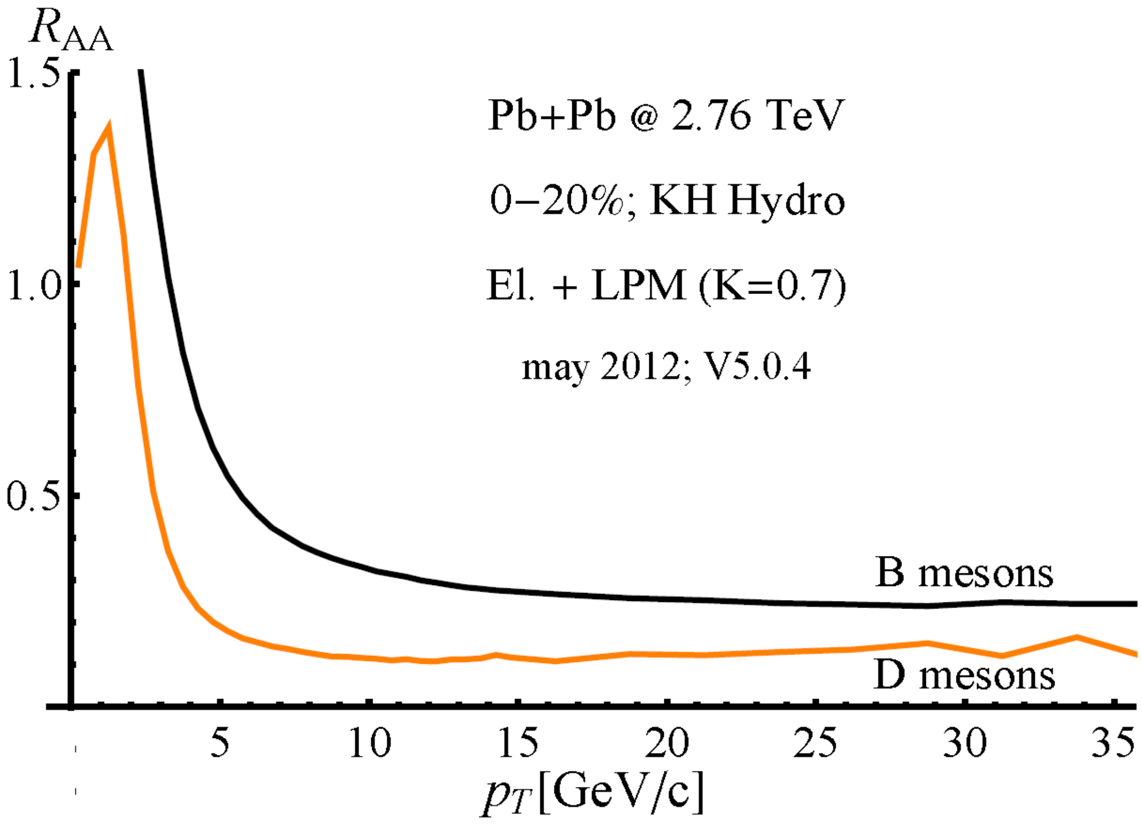
Late build up of the flow ⇒ Possible contribution from the hadronic phase (neglected in our approach) at intermediate p_T ?

D & B mesons at LHC

Same ingredients as for RHIC

Kolb-Heinz Hydro ajusted to $dN_{ch}/dy = 1600$;

No shadowing



Mass hierarchy; B mesons in good agreement with non prompt J/ψ from CMS

Consequences of radiation damping on energy loss

Basic question: Implications of a finite lifetime of the radiated gluon ?

Concepts

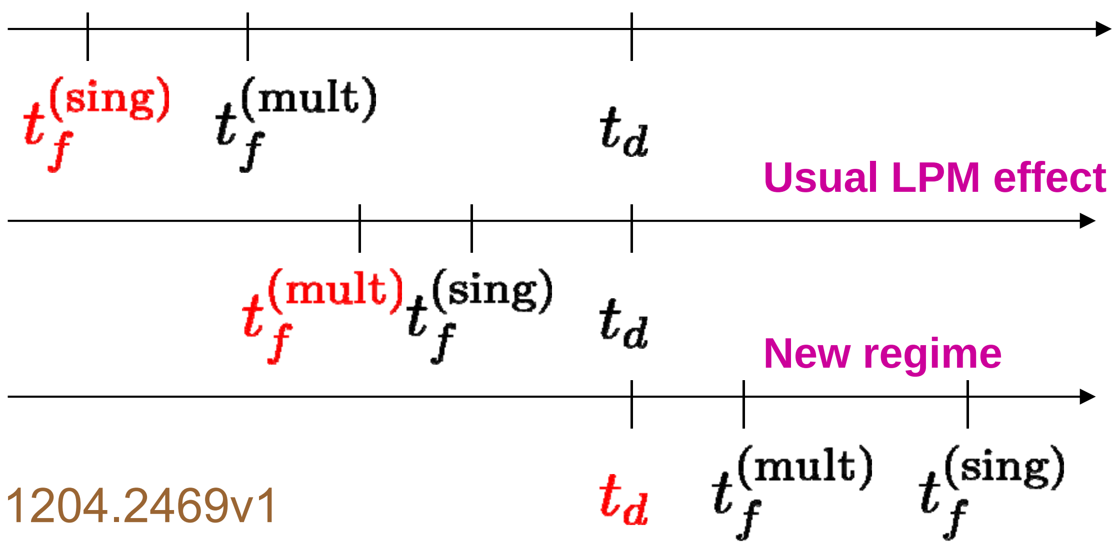
- In QED or pQCD, damping is a NLO process (damping time $t_d >> \lambda$); neglected up to now.
- However: formation time of radiation t_f increases with boost factor γ of the charge
- Expected effects when $t_f \approx t_d$ or $t_f > t_d$: in this regime, t_d should become the relevant scale (gluons absorbed being formed)

γ - hierarchy:

Small γ:

Interm. γ:

Large γ:

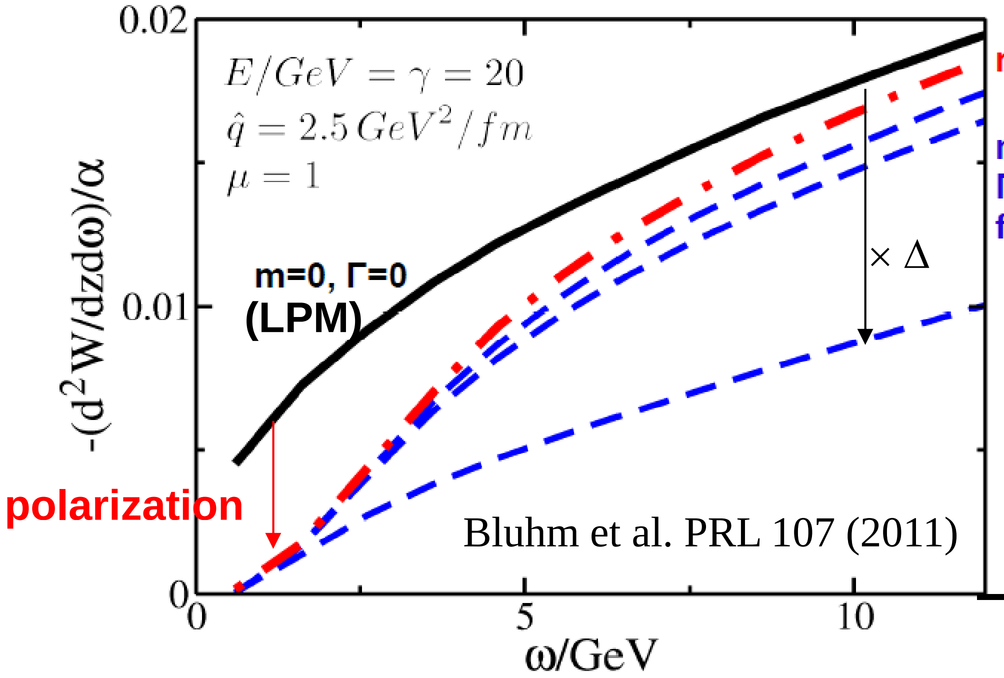


M. Bluhm, PBG & J. Aichelin, arXiv:1204.2469v1

Consequences of radiation damping on energy loss

PRL 107 (2011): Revisiting LPM effect in ED using complex index of refraction, focussing on the radiation at time of formation

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

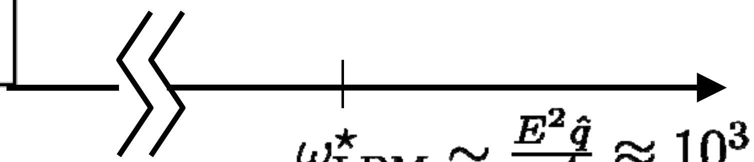


m=0.6 GeV, Γ=0 (Ter-Mikaelian; 1954)

m=0.6 GeV,
Γ=5, 10, 50 MeV
from top to bottom

Realistic numbers for QCD !

Strong reduction of radiation spectra and of coherence effects



$$\omega^{\star}_{\mathrm{LPM}} \sim \frac{E^2 \hat{q}}{m_s^4} \approx 10^3 \gg E$$

No “BH” limit

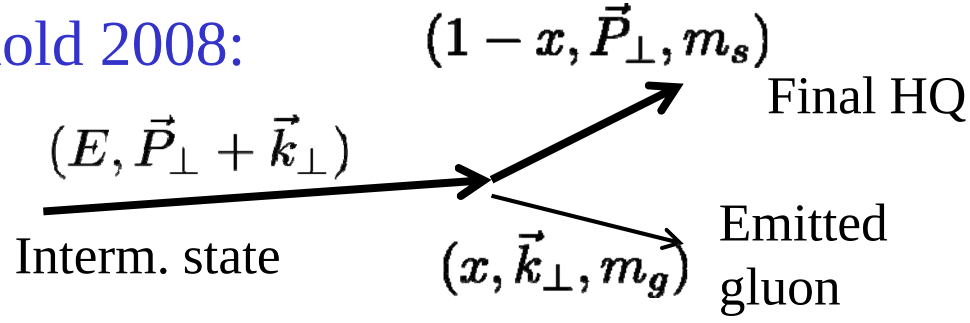
Scaling law:

$$\frac{\frac{dN}{d\omega}}{\frac{dN_{\mathrm{sing}}}{d\omega}} \approx \frac{\min(t_d, t_f^{(\mathrm{sing})}, t_f^{(\mathrm{mult})})}{t_f^{\mathrm{sing}}}$$

Allows for first phenomenological study in QCD case

Formation time of radiated gluon

Arnold 2008:



$$t_f \left[\frac{\langle p_B^2 \rangle + x^2 m_s^2 + (1-x) m_g^2}{2x(1-x)E} \right] \simeq 1$$

$$p_B^2 := \left((1-x)\vec{k}_\perp + x\vec{P}_\perp \right)^2 \quad \Rightarrow \quad \langle p_B^2 \rangle \approx (1-x)^2 \hat{q}_g t_f$$

In QCD: mostly gluon rescattering

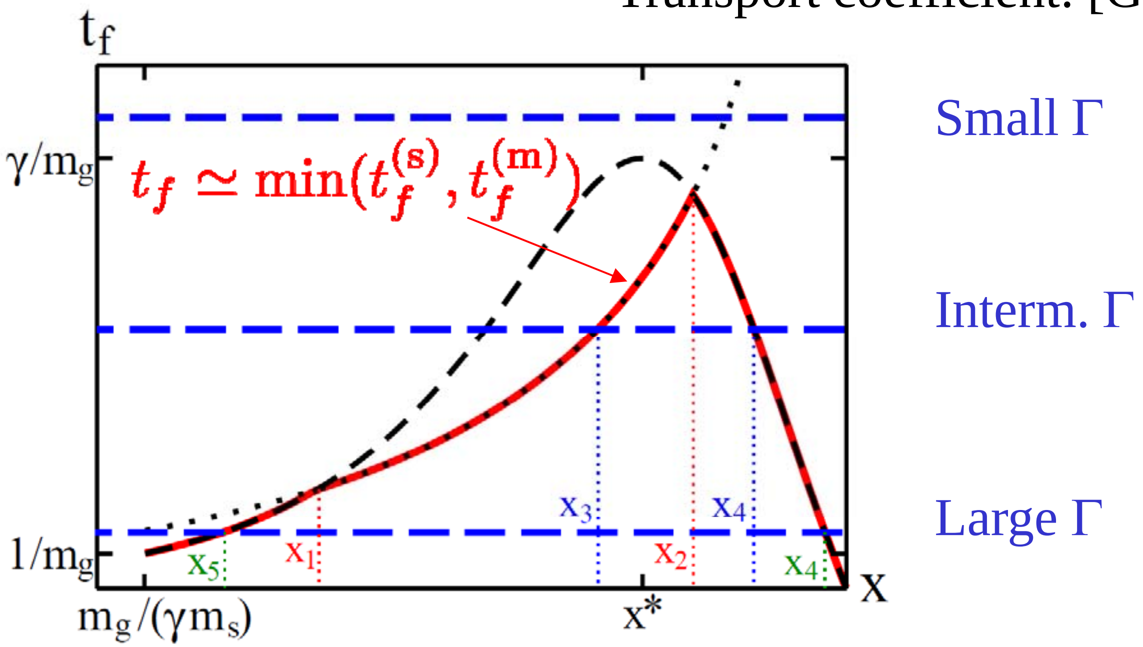
Transport coefficient: [GeV^2/fm]

=> Self consistent expression for t_f

- - - - $t_f^{(s)} \simeq \dfrac{2x(1-x)E}{x^2 m_s^2 + m_g^2(1-x)}$

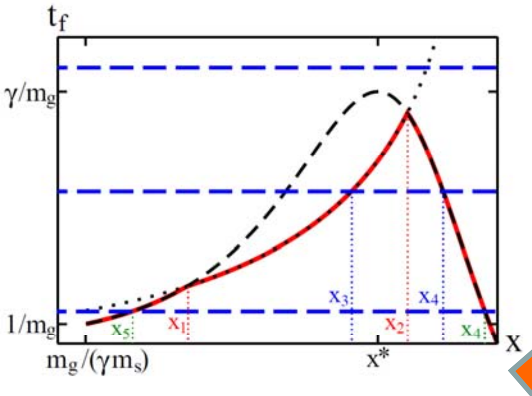
-------- $t_f^{(m)} \simeq \sqrt{\dfrac{2xE}{(1-x)\hat{q}_g}}$

— — $t_d = \frac{1}{\Gamma}$

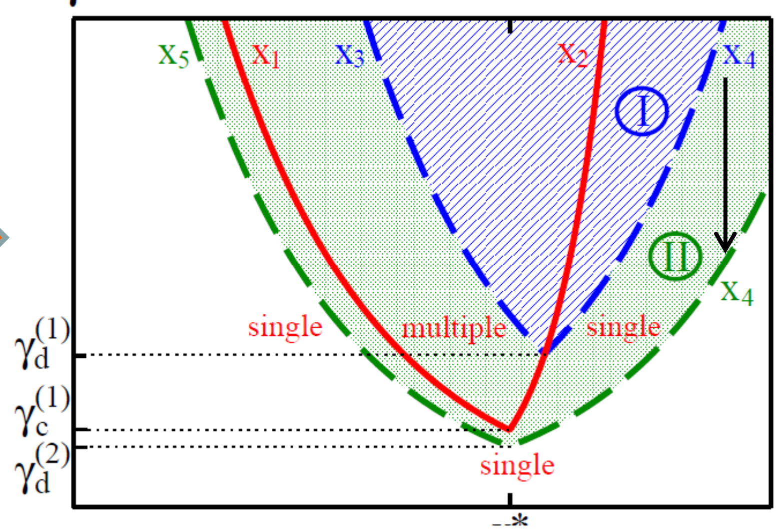


New regimes when including gluon damping

x-γ space for $\hat{q} < m_g^3$



Larger damping effect at large γ

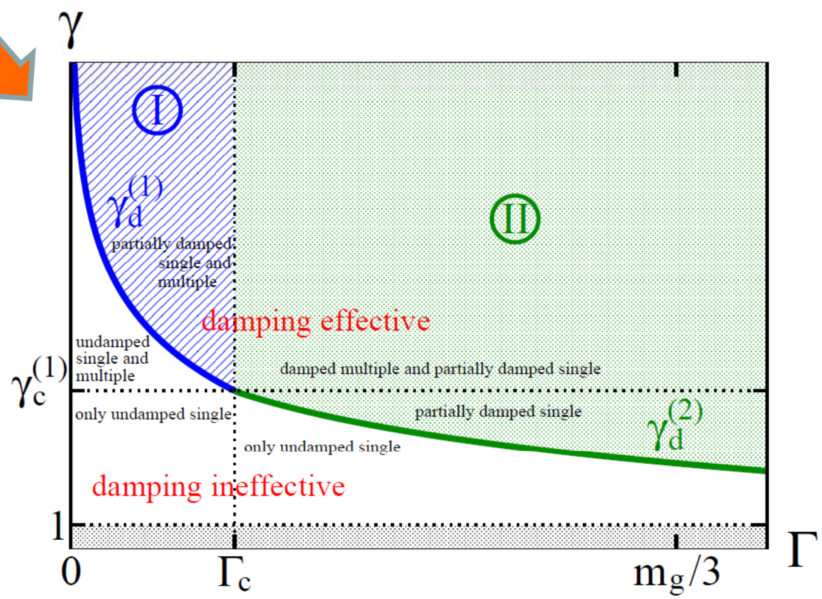


Increasing Γ

Larger and larger part of the spectrum affected by damping (shaded areas)

$x = \frac{\omega}{E}$

Γ–γ space

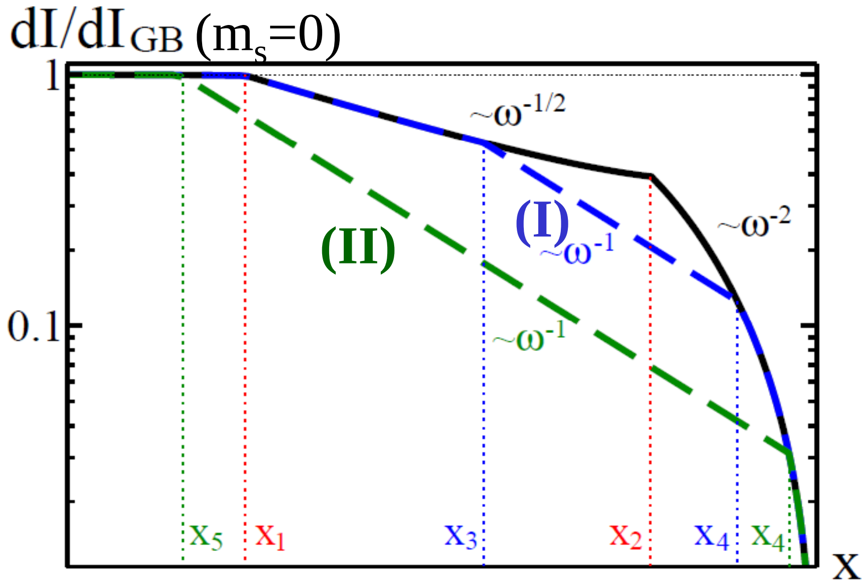


For $\Gamma > \Gamma_c \approx \frac{\hat{q}_g}{m_g^2}$ coherent radiation is totally superseeded by damping

γ-scales
$\gamma_c^{(1)} \sim m_g^3/\hat{q}_g$
$\gamma_d^{(1)} \sim \sqrt{\hat{q}_g/\Gamma^3}$
$\gamma_d^{(2)} \sim m_g/\Gamma$

Consequences on the power spectra

$\hat{q} < m_g^3$



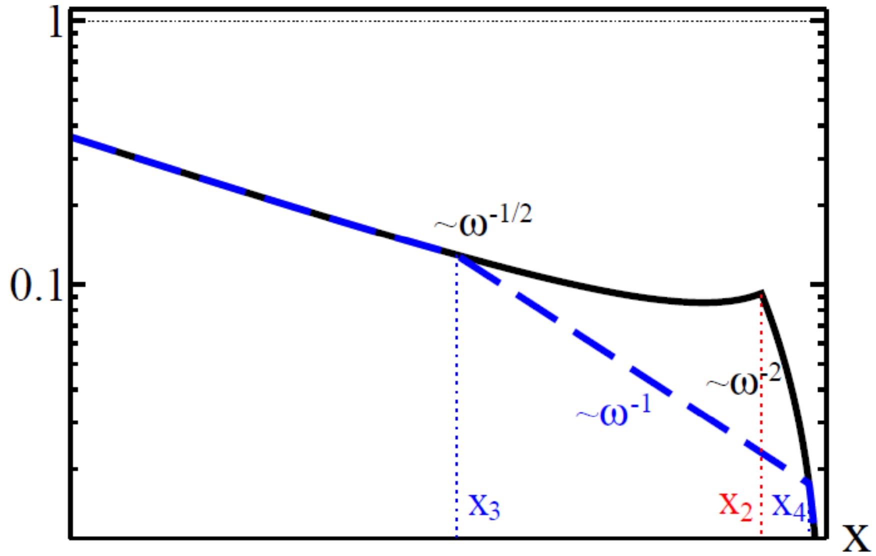
(I) and (II): moderate and large damping (see previous slide)

E= 45 GeV, m_s=1.5 GeV

m_g=0.6 GeV, $\hat{q} = 0.1\text{GeV}^2/\text{fm}$

Γ=0.05 GeV (I) & 0.15 GeV (II)

$\hat{q} > m_g^3$



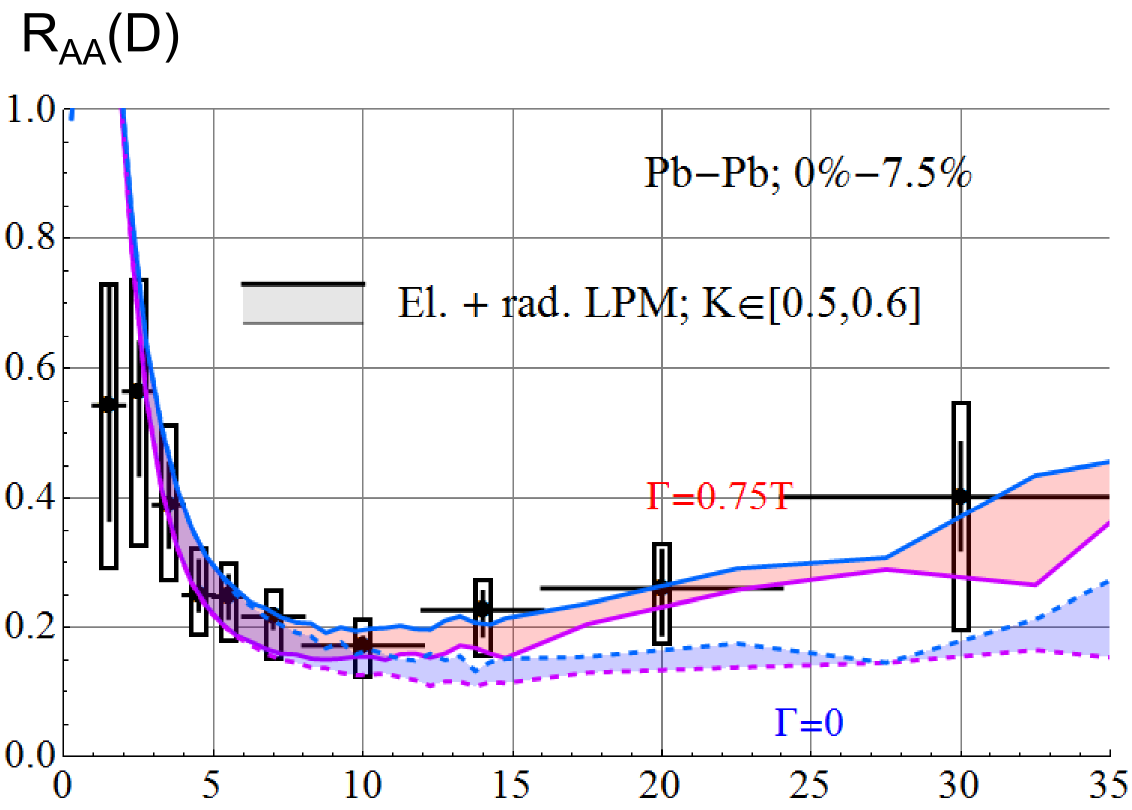
Same but

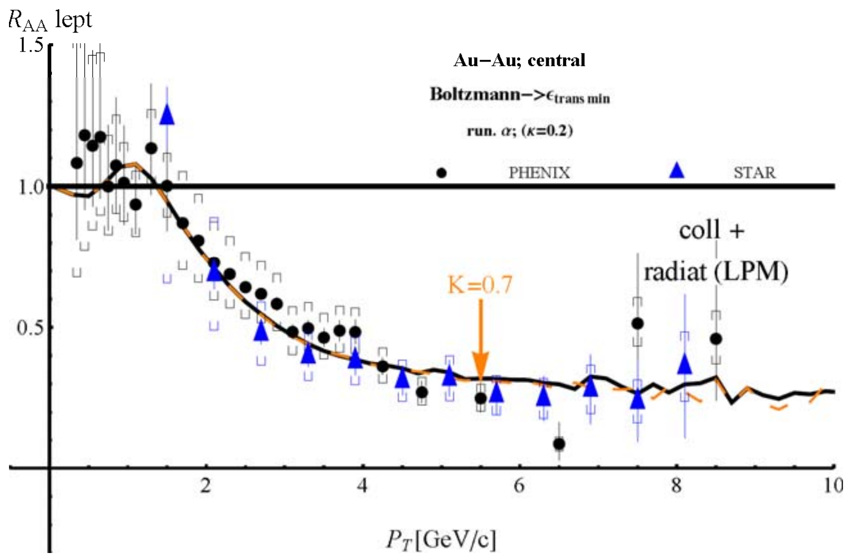
$\hat{q} = 2\text{GeV}^2/\text{fm}$

Γ=0.25 GeV

Consequences on the HQ observables

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

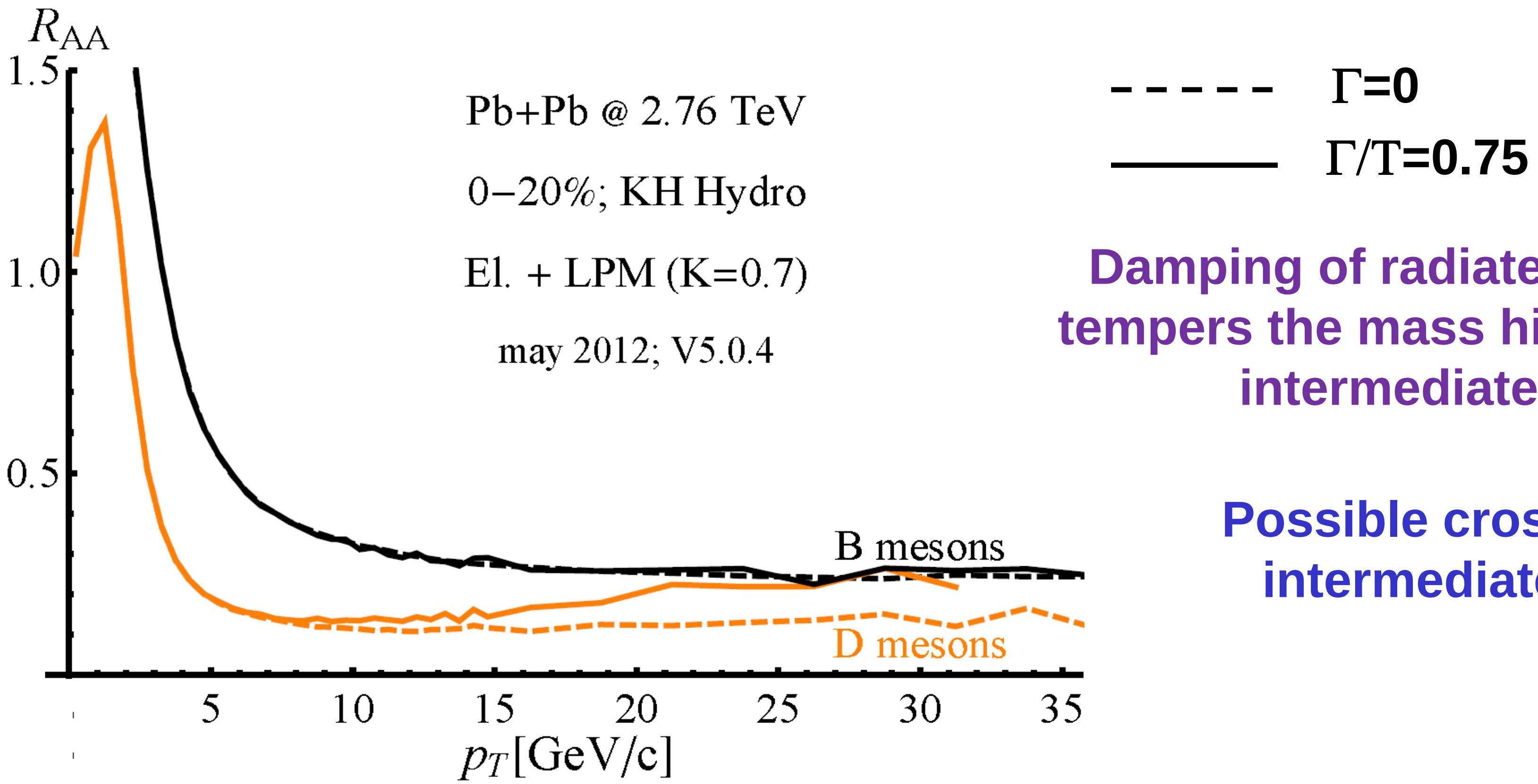




Damping of radiated gluons reduces the quenching of D mesons

Consequences on the HQ observables

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



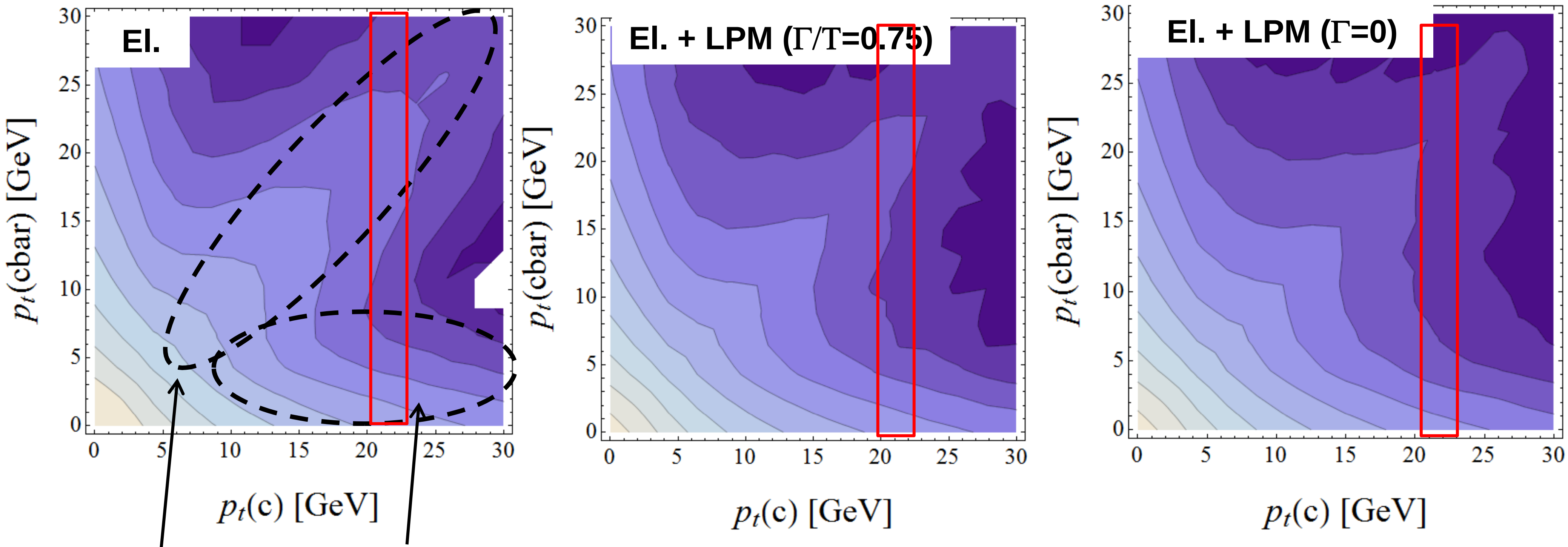
Damping of radiated gluons tempers the mass hierarchy at intermediate p_T

Possible crossing at intermediate p_T ?

Ideal situation to « reveal » Eloss mechanism: initiating one HQ in QGP with a fixed p_T…

Consequences on the observables: p_t-$p_t$bar correlations

Pb-Pb @ 2.76 TeV; 40-60%. **Toy study: back to back c-cbar**



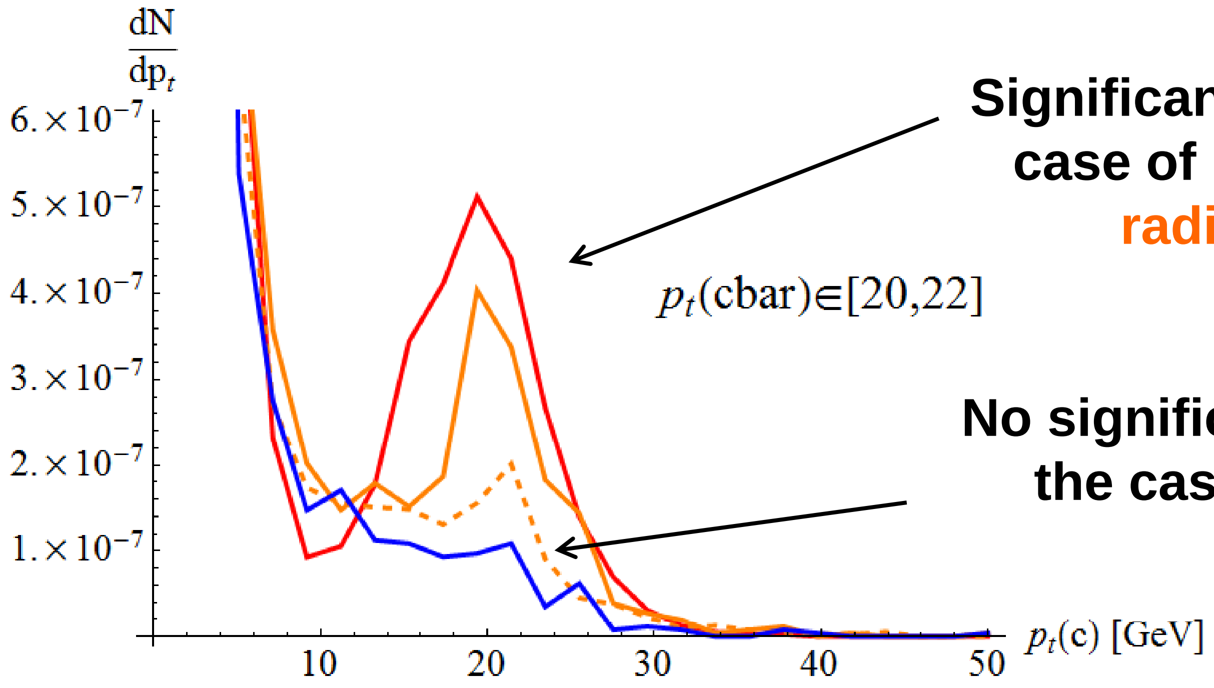
Background at small p_t

Tagging on 1 high p_T Qbar:

Residual correlation after evolution through QGP
(similar path length for most of HQ produced in the core of the reaction)

Consequences on the observables: p_t-$p_t$bar correlations

Pb-Pb @ 2.76 TeV; 40-60%. Toy study: back to back c-cbar



Significant residual correlation for the case of Elastic energy loss or LPM radiative + gluon damping

No significant residual correlation for the case of radiative GB or LPM radiative

Background at small p_t

Summary

- Description of HQ quenching and thermalization based on QCD inspired models
- No deviation from linear path length dependence mandatory from RHIC HQ data (that I know of)
- It is possible to extract some fundamental properties of the QGP (such as the diffusion coefficient), with successful comparison to the lattice calculations
- Predictions results are in gross agreement with early LHC (dislike at the RHIC time), and seem to favor models based on pQCD or pQCD + non perturbative ingredients.
- LHC opens the window for disentangling between various models although it requires a) more precision from the experiments as well as b) global approaches
- Focus on the consequences of gluon damping on radiative Energy loss, forgotten in standard approaches, which might be of phenomenological importance for $\Gamma/T \geq 0.5$
- New **mass-independent** scale $t_d=1/\Gamma$… might contribute in solving non-photonic single electron puzzle (B vs D crossing)
- Interest of pt(Q)-pt(Qbar) correlations for deciphering between different E loss models.

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

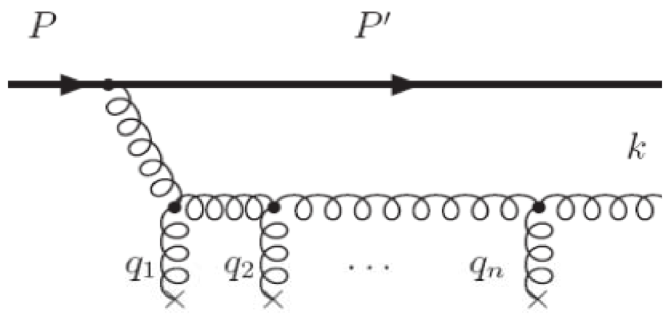
- Radiative and Collisional Energy Loss of Heavy Quarks in Deconfined Matter *Radiative*, J. Aichelin, P.B. Gossiaux, T. Gousset, [arXiv:1201.4192v1]
- On the formation of bremsstrahlung in an absorptive QED/QCD medium, M. Bluhm, P. B. Gossiaux, T. Gousset & J. Aichelin, [arXiv:1204.2469v1]

Back up

Insufficient control on energy loss theory

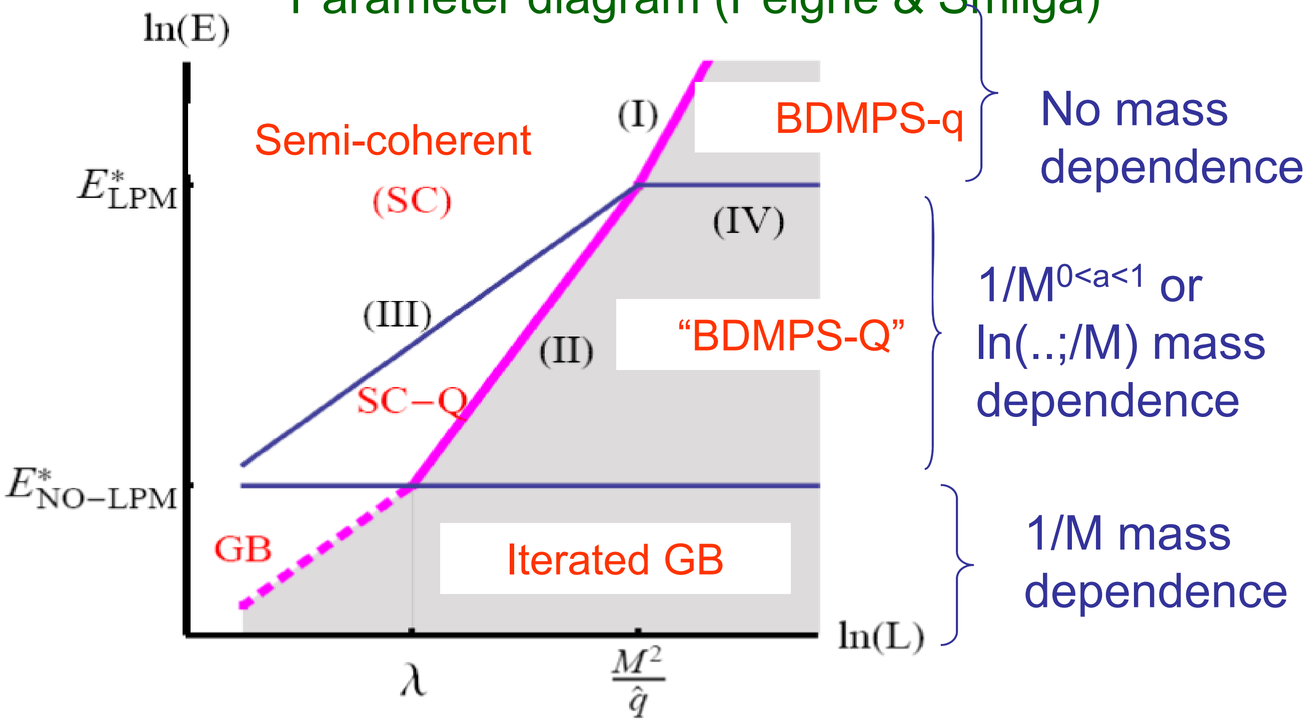
Expected dominance of radiative energy loss at high energy

When exactly ? Need for correct treatment of coherence (large formation times => LPM-like effect



Typical contribution to coherent radiative energy loss (Z-BDMPS approach)

Parameter diagram (Peigne & Smilga)



Not aware of a tractable theory that encompass all those regimes, especially in the strongly coupled case…

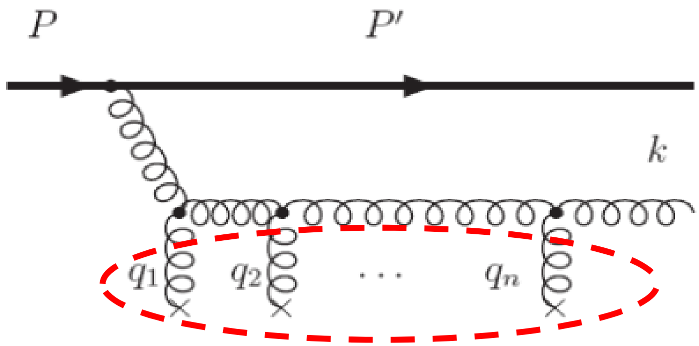
Not much considered up to now: role of dispersion relation in radiative E-loss: gluon "mass" (M. Djordjevic)… but also gluon width !

(High energy) gluon damping in pQCD and estimates for Γ

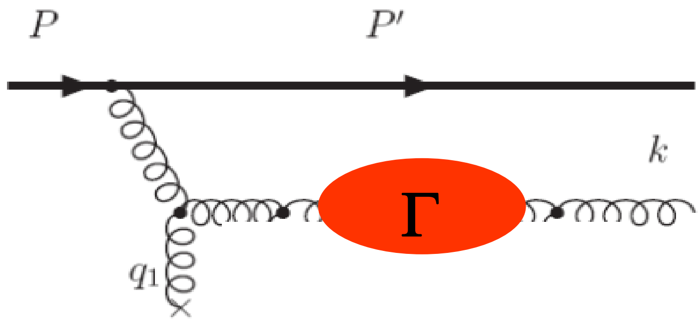
High energy: $\omega \gg T$

- Elastic process (collisionnal broadening): $\Gamma \approx g^2\, T\, (\ln 1/g)$ for $\omega = O(T)$;

  R. D. Pisarski, Phys. Rev. D 47 (93); no known result for $\omega \gg T$
- But double counting with original BDMPS description:

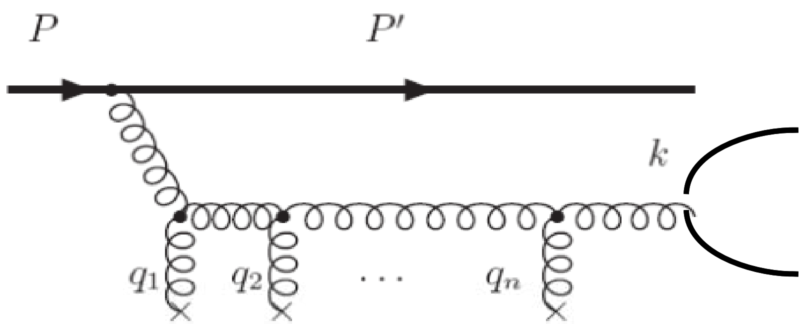


or



But not both !

- Genuine gluon absorption



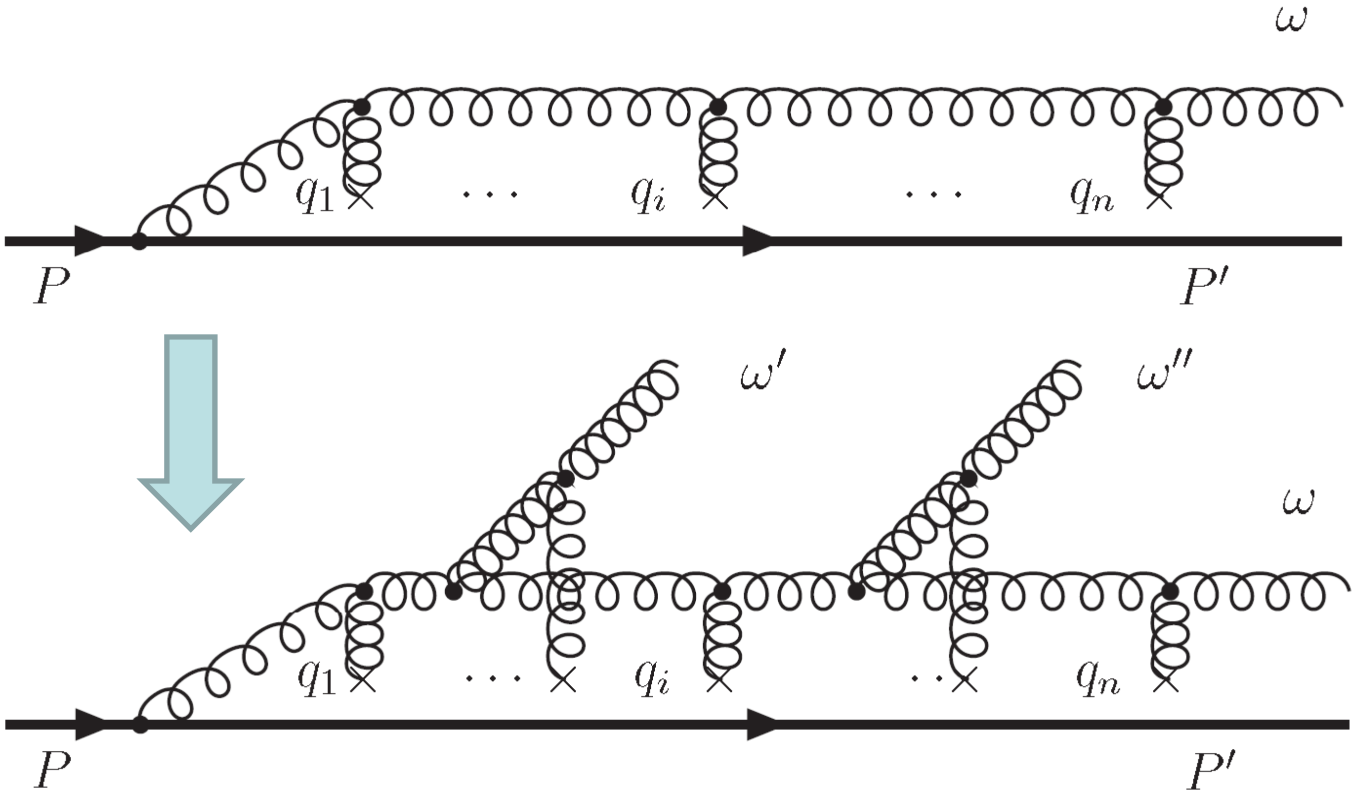
Hints that $\Gamma(\omega) \propto g^4\, T^2/\omega$

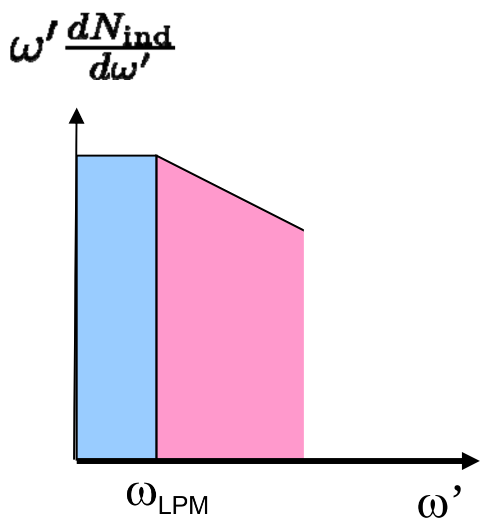
« damping rate of hard photon… »

Thoma, PRD51 (95)

(High energy) gluon damping in pQCD and estimates for Γ

- Considering the "pre-gluon" as a radiator itself and iterate (consistent if $\omega' < \omega$)





Emission of low energy quasi-isotropic gluons (ω', ω'')

$\Gamma \approx g^4\, T$

Possible candidate mechanism for di-jets imbalance and jet isotropisation observed by CMS !